# IIHE
# Annual Report
# 2019

Inter-University Institute For High Energies
**ULB - VUB**

Interuniversity Institue for High Energy

# ANNUAL REPORT
# 2019

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Directors

http://www.iihe.ac.be

# Contents

# 1 Introduction

## 1.1 The Interuniversity Institute for High Energies

The IIHE (ULB-VUB) was created in 1972 at the initiative of the academic authorities of the Université Libre de Bruxelles and the Vrije Universiteit Brussel. It is devoted to experimental research in elementary particle physics, using mainly high energy particle accelerators, and, more recently, in astroparticle physics with non-accelerator experiments.

The main goal of the experiments at accelerators, notably LHC at CERN, is the understanding of the strong, electromagnetic and weak interactions between the elementary building blocks of matter, which form the standard model of particle physics. Prominent in this endeavour are precision measurements of the parameters of the standard model, the search for missing pieces in the standard model and the search for physics beyond the standard model, possibly related to the dark matter in the Universe and to cosmology. Astroparticle physics is devoted to the study of the structure of the Universe, using particles as messengers of astrophysical activities in the Universe and using the techniques developed in particle physics. All these experiments are performed in the framework of large to very large international collaborations with several hundreds to several thousands of physicists and engineers.

Fundamental contributions to the understanding of the Universe, particle and astroparticle physics with experiments imply major R&D developments concerning particle detectors, computing and networking systems, frontier technologies in various fields (electronics, superconductivity, cryogenics, etc.), which lead to break-through progress in industrial and medical applications.

## 1.2 Overview of 2019

The present report presents the research performed at the IIHE in 2019, that spans from the smallest accessible scales, below $10^{-19}$ m for e.g. the Brout-Englert-Higgs boson, quarks and neutrinos, to the largest scales above hundreds of thousands of light years for e.g. the source of ultra-high energy neutrinos detected by IceCube. During the year 2019 the IIHE published with its national and international research partners about 180 journal papers.

The IIHE is deeply involved in the CMS experiment since its design phase in the early 1990's, and actively contributed to all aspects of this experimental project, i.e. building, operating and maintaining the CMS detector as well as to the data analysis for searches for new physics and precision measurements of the fundamental interactions and particle properties. All aspects of this work are done in collaboration with other Belgian and international teams. Since the first collisions in 2009, the LHC has performed extremely well, with steadily increasing luminosity. The so-called Run 1, started in 2010, accumulated proton collisions with a collision energy up to 8 TeV and has been ended in February 2013. Data taken in proton-proton collision mode were complemented Pb-Pb and proton-Pb data. After a two-year upgrade, the LHC began the so-called Run 2, in June 2015, with a collision energy of 13 TeV — the highest energy ever achieved in a laboratory. In the years 2016-2018 in total around 147 $\text{fb}^{-1}$ of proton collision data was recorded by the CMS experiment.

During 2019, in addition to operational activities around the detector and its continuous survey and calibration, the Brussels team in CMS contributed to physics analyses with a continuous development of reconstruction methods for objects detected in the final state as well as the identification and trigger techniques to differentiate the physics objects. With these reconstructed objects physics measurements and searches are performed related to the Brout-Englert-Higgs boson, top quark physics, dark matter, supersymmetry and in general new physics phenomena. Precision measurements of the strong interaction (QCD) and the electro-weak interaction (EW) provided as well numerous new results.

The LHC phase-2 program approved by the CERN council in 2016 will provide increased luminosity by a factor 5-7 above the present design parameters. The data taking expected to start around 2026 will allow a precise study of the scalar sector, as well as extending the discovery potential of the LHC for rare beyond-the-standard-model processes. To meet this luminosity challenge the CMS tracker must be completely replaced. The Belgian groups from the IIHE, from Universiteit Antwerpen, the Université Catholique de Louvain-la-Neuve, and from Universiteit Gent have decided to build together one endcap of the CMS phase-2 outer tracker. At the IIHE, about 2000 modules will be assembled and tested, before they are integrated onto the tracker endcap support structures. The module assembly has to be performed in controlled conditions of temperature, humidity and dust. In 2018, a large clean room of 122 $m^2$ started to be deployed at the IIHE (see picture Fig.6) and is being equipped to be ready for the pre-production of the modules expected in 2022.

The IIHE has a long history of research in the field of neutrino ($\nu$) physics. The IIHE has initiated together with national and international colleagues the SoLid experiment at the BR2 nuclear reactor at the SCK-CEN (Mol, Belgium). The complete phase-1 detector data taking has started in 2018. These data are analysed by the IIHE group in close collaboration with the Universiteit Antwerpen to determine the detector response and background contamination. The intention is to measure neutrino oscillation processes at very short distances between 5 and 10 meter from the reactor source.

The JUNO experiment consists of a large liquid scintillator detector aiming to measure antineutrinos from a nuclear reactor at a distance of 53 km and having as main goal to determine the neutrinos mass hierarchy after 6 years of data taking. Located in China, the detector will be at 700 m overburden and consists of 20 kton of liquid scintillator contained in a 35 m diameter sphere, instrumented by 20000 20-inch photomultiplier tubes (PMT). The required energy resolution to discriminate between the normal and inverted neutrinos hierarchies at 3-4 sigma of CL for about 6 years of data taking is 3% at an energy of 1 MeV. The start of the data taking is expected in 2022. The IIHE joined JUNO in 2016 and is contributing to the development and the construction of the electronic readout system.

In the field of astroparticle physics, the IIHE has been involved in the search and measurement of interactions of ultra-high energy neutrinos from cosmic origin in the South Pole ice, since the start of this quest in the late 1990's with the AMANDA and IceCube experiments. Since 2011 the fully deployed IceCube observatory operates as the largest ever particle detector (1 $km^3$). The most prominent research topics of the IIHE team are: the search for cosmic point sources, dark matter, high-energy neutrinos from transient events, from supernovae and from solar flares. The first hints of extra-galactic high-energy neutrinos came in April 2012 with the observation of two very high energy events (above 1000 TeV). Since then, with an intensified search more events have been found. This achievement marks the birth of neutrino astronomy.

The IceCube neutrino detector has shown the potential of the neutrino as a cosmic messenger. Detecting the TeV-PeV cosmic neutrino flux, as well as the first possible source identification allowed us to have a first look into the extremely energetic processes of the most violent phenomena in our universe. Beyond PeV energies, however, IceCube runs low in statistics, due to the steeply falling cosmic particle flux as function of energy. High-energy (cosmic-neutrino) induced particle cascades that produce in a medium a net macroscopic charge excess leading to coherent radio emission in the MHz-GHz regime. The detection of the corresponding radio signal would allow cosmic neutrino detection above 100 PeV. The IIHE made strong contributions to the first project of that kind, at the South Pole, in the Askaryan Radio Array (ARA) experiment. Since 2018 the IIHE is one of the main leading groups and contributor of the Radio Neutrino Observatory Greenland (RNO-G) project. As a pathfinder for the radio component of the proposed IceCube-Gen2 facility, this detector is complementary to ARA and aims to detect the cosmogenic neutrino flux with peak sensitivity at EeV energies. First stations of the RNO-G detector are expected to be deployed in 2021.

Since 2016, the IIHE has contributed the Pierre Auger Collaboration to study cosmic rays. The IIHE group analyses the ultra-high energy cosmic rays, which are messengers of the most violent phenomena in the Universe, to elucidate the origin of cosmic rays by performing mass-enhanced anisotropy studies and mass composition studies. In 2019 Belgium has joined officially the Pierre Auger Collaboration.

Being devoted to experimental particle physics, the IIHE has always been very active in technical developments and instrumentation. This tradition points back to automatized bubble chambers and nuclear emulsion measurements, with important contributions to detectors at high-energy particle colliders (DELPHI at LEP, H1 at HERA and CMS at the LHC), in neutrino oscillation experiments (CHARM II, CHORUS, OPERA, JUNO, SoLid) as well as in the more recent astroparticle experiments (AMANDA, IceCube, ARA, LOFAR and AUGER). Over the recent years, R&D activities are centred on the development of multi-purpose, very high-rate, robust and low-cost, industry-based data acquisition systems, aimed for particle and astroparticle experiments. The contributions have taken place in the framework of generic DAQ systems for future experiments at colliders, for the ARA experiment, and for the upgrade of the CMS central tracker and muon spectrometer in the forward region. Also in the medical area the IIHE keeps on contributing to neutron metrology and fast DAQ systems for future proton therapy centres.

To link the activities of their theoretical physics and experimental particle physics (ELEM) groups, a phenomenology group has been settled by the VUB in 2014 through a Strategic Research Program, namely HEP@VUB. The main topics of research are new physics models and their signatures at the LHC, as well as early universe physics and the phenomenology of cosmic rays propagation.

Finally, large computing resources are required by the experiments, in particular IceCube and CMS. The IceCube collaboration uses the IIHE cluster for large simulations of the optical structure of the ice at the South Pole. For CMS computing, a "Tier-2" cluster installed at the ULB-VUB Computing Centre is fully integrated in the Worldwide LHC Computing Grid, with very high performance and stability.

On 22 November 2019, IIHE members attended the IIHE annual meeting (see cover group picture), where a review of the activities in the different experiments, in computing and in R&D were presented and discussed, together with the plans for the coming years.

Research at IIHE has been supported by the Université Libre de Bruxelles (ULB), the Vrije Universiteit Brussel (VUB), the Fonds de la Recherche Scientifique (F.R.S.-FNRS), the Fonds voor Wetenschappelijk Onderzoek-Vlaanderen (FWO), the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA), the Instituut voor de Aanmoediging van Innovatie door Wetenschap en Technologie in Vlaanderen (IWT), the Belgian Federal Science Policy Office, the Odysseus programme, the ERC Grant programme of H2020.

Since 2015 the IIHE benefits from the support of the China Scholarship Council (CSC) through the agreement between them and ULB, providing PhD scholarships to Chinese students to achieve their PhD at ULB.

## 1.3 The IIHE team in 2019

### 1.3.1 The ULB personnel

#### Academic and scientific personnel

| | | |
|---|---|---|
| Juan Antonio AGUILAR SANCHEZ | Chargé de cours | IceCube |
| Isabelle ANSSEAU | PhD student (Assistante ULB) | IceCube |

| | | |
|---|---|---|
| Sebastian BAUR | Post-doc (IISN) | IceCube |
| Diego BEGHIN | PhD student (Aspirant F.R.S.-FNRS) | CMS |
| Bugra BILIN | Post-doc (IISN) | CMS |
| Koun CHOI | Post-doc (IISN) | Auger, IceCube |
| Barbara CLERBAUX | Professeure | CMS, JUNO |
| Hugo DELANNOY | PhD student (FRIA) until April | CMS |
| Gilles DE LENT-DECKER | Maître de Recherche F.R.S.-FNRS | CMS, DAQ R&D |
| Wendi DENG | PhD student (CSC-CNNU) | CMS, DAQ R&D |
| Brian DORNEY | Post-doc (IISN) until August | CMS |
| Wenxing FANG | PhD student (CSC-BUAA) | CMS |
| Laurent FAVART | Directeur de Recherche F.R.S.-FNRS; part-time Chargé de Cours; IIHE co-director | CMS, H1 |
| Xuyang GAO | PhD student (CSC-BUAA) until June | CMS |
| Anastasia GREBENYUK | Chargé de Recherche F.R.S.-FNRS until September | CMS |
| Nadège IOVINE | PhD student (FRIA) | IceCube |
| Aamir IRSHAD | PhD student (IISN) | CMS DAQ R&D |
| Amandeep Kaur KALSI | Post-doc (IISN) | CMS |
| Tomas KELLO | PhD student (EOS) CoPhD UA | CMS |
| Mostafa MAH-DAVIKHORRAMI | PhD student (EOS) | CMS |
| Inna MAKARENKO | Post-doc (IISN) until September Chargé de Recherche F.R.S.-FNRS since October | CMS |
| Ioana MARIS | Chargé de Cours | IceCube, Auger |
| Daniela MOCKLER | Post-doc (IISN) since January | IceCube, Auger |
| Louis MOUREAUX | PhD student (FRIA) | CMS |
| Pierre-Alexandre PETIT-JEAN | PhD student (Assistant ULB) | JUNO |
| Laurent PETRE | PhD student (FRIA) | CMS DAQ R&D |
| Yves PIERSEAUX | collaborateur scientifique | Hist. of Science |
| Andrey POPOV | Post-doc (EOS) | CMS |
| Nicolas POSTIAU | PhD student (Assistant ULB) | CMS |
| Christoph RAAB | PhD student (IISN) | IceCube |
| Giovanni RENZI | PhD student (IISN) | IceCube |
| Rachel SIMONI | PhD student (Amsterdam University); collaborateur scientifique | |
| Zixuan SONG | PhD student (CSC - CCNU) | CMS, DAQ R&D |
| Elizabeth STARLING | PhD student (FRIA) | CMS |
| Laurent THOMAS | Chargé de Recherche F.R.S.-FNRS | CMS |
| Raffaella TONCELLI | collaborateur scientifique | Hist. of Science |
| Simona TOSCANO | Chargée de Cours | IceCube, RadNu |
| Max VANDEN BEMDEN | PhD student (Assistant ULB) since September | CMS |
| Catherine VANDER VELDE | Professeur de l'Université | CMS |
| Pascal VANLAER | Chargé de Cours | CMS |
| David VANNEROM | PhD student (Aspirant F.R.S.-FNRS) until September | CMS |
| Hanwen WANG | PhD student (CSC-BUAA) | CMS |
| Liam WEZENBEEK | PhD student (EOS) since March - CoPhD Ugent | CMS |
| Gaston WILQUET | honorary Maître de Recherche F.R.S.-FNRS; Professeur invité | OPERA |

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|---|---|---|
| Orazio ZAPPARRATA | PhD student (IISN) since July | IceCube, Auger |

**Master students**

| | | |
|---|---|---|
| Alexandre DE MOOR | physics, until September | CMS |
| Charles DETEMMERMAN | physics, until September | CMS DAQ R&D |
| Maxence DRAGUET | physics, until September | CMS |
| Lucas LEONARDY | physics, until September | CMS |
| Ali SAFA | physics | CMS DAQ R&D |
| Max VANDEN BEMEN | physics, until September | CMS |

**Engineers, Technical and Logistic Personnel**

| | |
|---|---|
| Yannick ALLARD | Logisticien de Recherche ULB (half-time) |
| Patrick DE HARENNE | technician, general support |
| Benoît DENÈGRE | technician, electronics (half-time) |
| Denis DUTRANNOIS | computer scientist |
| Michael KORNTHEUER | electronics |
| Shkelzen RUGOVAC | computer scientist |
| Adriano SCODRANI | computer scientist |
| Audrey TERRIER | secretariat |
| René VANDERHAEGEN | technician, electronics |
| Yifan YANG | ULB electronics/computing |

### 1.3.2 The VUB personnel

**Academic and scientific personnel**

| | | |
|---|---|---|
| Aqeel AHMED | EOS scientific collaborator (post-doc) | Pheno |
| Freya BLEKMAN | ZAP hoofddocent | CMS |
| Emil BOLS | FWO scientific collaborator (PhD student) | CMS |
| Stijn BUITINK | ZAP hoofddocent | LOFAR |
| Simranjit Singh CHHIBRA | FWO scientific collaborator (post-doc) | CMS |
| Paul COPPIN | FWO scientific collaborator (PhD student) | IceCube |
| Pablo CORREA | FWO aspirant (PhD student) | IceCube |
| Arthur CORSTANJE | ERC scientific collaborator (post-doc) 50% since June | LOFAR |
| Catherine DE CLERCQ | Professor-emeritus | IceCube |
| Jarne De Clercq | FWO scientific collaborator (PhD student) | CMS |
| Simon DE KOCKERE | BAAP scientific collaborator (PhD student) | IceCube, RadNu |
| Krijn DE VRIES | FWO research fellow (post-doc) until January<br>ZAP Research Professor since February | IceCube, RadNu |
| Jorgen D'HONDT<br>SoLid | ZAP hoogleraar; IIHE co-director | CMS |
| Hesham EL FAHAM | Joint PhD UCL since September | CMS |

| | | |
|---|---|---|
| Jörg HÖRANDEL | guest professor | LOFAR |
| Tim HUEGE | 10% ZAP research professor | LOFAR |
| Enrique HUESCA SANTIAGO | ERC scientific collaborator (PhD student) since October | IceCube, RadNu |
| Sam Junius | Joint PhD ULB (PhD student) | Pheno |
| Godwin KOMLA KRAMPAH | ERC scientific collaborator (PhD student) | LOFAR |
| Denys LONTKOVSKYI | VUB scientific collaborator (post-doc) –<br>fellow from April until November | CMS |
| Steven LOWETTE | ZAP hoofddocent | CMS, milliQan |
| Vesna LUKIC | PhD student | LOFAR |
| Ivan MARCHESINI | FWO scientific collaborator (post-doc) until 14 April | CMS |
| Alberto MARIOTTI | ZAP docent | Pheno |
| Pragati MITRA | ERC scientific collaborator (PhD student) | LOFAR |
| Katharine MULREY | ERC scientific collaborator (post-doc) until September<br>FWO research fellow (post-doc) from October | LOFAR |
| Seth MOORTGAT | FWO aspirant (PhD student) until September<br>FWO research fellow (post-doc) from October | CMS |
| Saereh NAJJARI | VUB scientific collaborator (post-doc) | Pheno |
| Hershal PANDYA | ERC scientific collaborator (post-doc) since February | LOFAR |
| Quentin PYTHON | FWO scientific collaborator (PhD student) | CMS |
| Jörg Paul RACHEN | ERC scientific collaborator (post-doc) | LOFAR |
| Abanti Ranadhir SAHASRANSU | EOS scientific collaborator (PhD student) | CMS |
| Olaf SCHOLTEN | 10% ZAP Research Professor | IceCube |
| Dimitrios SIDIROPOULOS KONTOS | EOS scientific collaborator (PhD student) until October | CMS |
| Kirill SKOVPEN | FWO research fellow (post-doct) until September | CMS |
| Rose STANLEY | ERC Scientific Collaborator (PhD student) since October | IceCube, RadNu |
| Nicoals STYLIANOU | Joint PhD Bristol (PhD student) | CMS |
| Stefaan TAVERNIER | Professor-emeritus | Crystal Clear |
| Walter VAN DONINCK | Professor-emeritus | CMS |
| Nick VAN EIJNDHOVEN | ZAP gewoon hoogleraar | IceCube, RadNu |
| Petra VAN MULDERS | FWO research fellow (post-doct)<br>10% ZAP research professor | CMS, SoLid |
| David VANNEROM | Joint PhD ULB (until September) | CMS |

### Master students

| | | |
|---|---|---|
| Quinten GOENS | Student in physics | IceCube |
| Vichayanun WACHIRAPUSITANAND | Student in physics | CMS |
| Mathias MANCINI | Student in physics | CMS |

**Engineers, Technical and Logistic Personnel**

| | |
|---|---|
| Olivier DEVROEDE | computer scientist 80% |
| Stéphane GERARD | computer scientist - VSC |
| Marleen GOEMAN | secretariat |
| Annemie MOREL | engineer 100% until December, 50% since December |
| Romain ROUGNY | computer scientist – UA |
| Rosette VANDEN-BROUCKE | collaborator |

### 1.4 Associated institutes

The following members of the Particle Physics Group of Antwerp University (UA) have been working in close collaboration with the IIHE Institute:

Prof. Em. Dr. Eddi De Wolf, Prof. Dr. Pierre Van Mechelen, Prof. Dr. Nick Van Remortel, Prof. Dr. Albert De Roeck, Prof. Dr. Francesco Hautmann, Dr. Yamiel Abreu, Dr. Dr. Xavier Janssen, Dr. Aleksandra Lelek, Dr. Romain Rougny, Dr. Hans Van Haevermaet, Dr. Simon Vercaemer, Davide Di Croce, Mai El Sawy, Lissa Keersmaekers, Tomas Kello, Maxim Pieters, Haifa Rejeb Sfar, Aron Mees van Kampen, Senne Van Putte, Maja Verstraeten, Ir. Wim Beaumont, Ir. Eric Roose, Sarah van Mierlo

## 2 Research activities, development and support

(G. De Lentdecker, M. Korntheuer, Y. Yang)

Proton therapy uses proton beams with energies typically between 50 and 230 MeV to treat cancerous tumors very efficiently, while protecting as much as possible surrounding healthy tissues from radiation damage. Protons interacting with matter inevitably induce secondary radiation from which all people inside the proton therapy center have to be protected. The ambient dose equivalent H*(10) in such a facility is mainly due to neutrons, which can have energies up to 230 MeV. Although various dose monitoring systems sensitive to high energy neutrons have already been developed, the response function of these detectors is often insufficiently characterized, and so are the calibration factors appropriate for the specific neutron spectra encountered inside a proton therapy facility.

Since 2012 the IIHE is collaborating with the Institut de Recherche de l'Institut Supérieur Industriel de Bruxelles (IRISIB) and Ion Beam Applications S.A. (IBA) to study the response function of the extended-range rem meter WENDI-2 from thermal energies up to 5 GeV. Extensive Monte Carlo simulations using the MCNPX software are now routinely been running on the IIHE cluster.

A first part of this study focused on the study of the WENDI-2 response function and its comparison with the fluence-to-H*(10) conversion coefficients, to theoretically assess the accuracy in terms of H*(10) of our WENDI-2 measurements performed in proton therapy facility. Our experimental validation of the WENDI-2 response function is based on measurements performed with $^{252}$Cf and AmBe sources as well as with quasi-monoenergetic neutron beams at the TSL at peak energies of 21.8 MeV, 93.1 MeV and 173.4 MeV. The measurements tend to be lower than the simulated responses but smaller discrepancies were obtained than with previous experimental results. A detailed sensitivity study was also carried out with respect to the physics models for the proton and neutron interactions above 150 MeV.

Finally, since the WENDI-2 can not inform us on the accuracy of the simulated neutron fluence, especially above 100 MeV, spectrometry measurements have been performed with a WENDI-2 and an extended-range Bonner Sphere Spectrometer (BSS) in a proton therapy facility. The WENDI-2 measurements agree with the BSS H*(10) rates within 10%. It thus confirmed that the WENDI-2 allows measuring H*(10) with satisfactory accuracy in these neutron fields.

Many simulations have also been repeated with the GEANT-4 software, largely used within the High Energy Physics community. Compared to MCNPX, GEANT-4 allows to access and to modify the source code, which allows a detailed control of the program and therefore a better understanding of the simulation results in regards to any code modifications. Note that the accuracy of GEANT-4 with respect to neutron interactions has improved a lot the past decade thanks to the interest from the LHC community. Our GEANT-4 simulations of the WENDI-2 response function are typically in agreement with the MCNPX ones, and in several cases show a better agreement with the data.

From 2019, the research in this field is moving towards the development of a prompt-gamma detector, equipped with a new full digital electronics to improve the spatial resolution on the proton beam location with respect to the tumor being irradiated. From 2019 this research is performed in the framework of the PROton THERapy in WALlonia (PROTHER-WAL) project. After the study of the concept of the new electronics and of the gamma pulse processing algorithm to be run on this electronics, we have started some R&D on large (6 x 6 $mm^2$) SiPMs, in collaboration with the IIHE IceCube group 2.6.2.

## 2.1 The CMS experiment at the CERN LHC

(Y. Allard, D. Beghin, F. Blekman, B. Bilin, E. Bols, D. Burns, S. S. Chhibra, B. Clerbaux, J. D'Hondt, J. De Clercq, G. De Lentdecker, H. Delannoy, W. Deng, K. Deroover, O. Devroede, J. Dong, B. Dorney, H. El Faham, W. Fang, L. Favart, X. Gao, A. Grebenyuk, A. Irshad, A. K. Kalsi, T. Kello, D. Lontkovskyi, S. Lowette, I. Marchesini, M. Mahdavikhorrami, S. Moortgat, A. Morel, L. Moureaux, L. Petré, N. Postiau, A. Popov, Q. Python, A.R. Sahasransu, D. Sidiropoulos Kontos, K. Skovpen, D. Smith, Z. Song, E. Starling, N. Stylianou, L. Thomas, W. Van Doninck, M. Vanden Bemden, P. Van Mulders, C. Vander Velde, P. Vanlaer, D. Vannerom, H. Wang, Y. Yang, F. Zhang)

The following members of Antwerp university are also members of CMS: W. Beaumont, A. De Roeck, Eddi De Wolf (emeritus), Davide di Croce, X. Janssen, Ola Lelek, Mohamed Rashad Darwish, Haifa Rejeb Sfar, H. Van Haevermaet, T. Kello, M. Pieters, P. Van Mechelen, S. Van Putte, N. Van Remortel.

One of the two general-purpose detectors at CERN's Large Hadron Collider (LHC) is the Compact Muon Solenoid (CMS) experiment. The LHC provided proton-proton collisions during the so-called Run 1 in years 2010, 2011 and 2012, at a centre-of-mass energy of 7 and 8 TeV, corresponding to a total integrated luminosity of about 29 $fb^{-1}$ delivered by the machine to the experiments. The most important result in the LHC Run 1 is beyond doubt the observation of the last missing part of the Standard Model (SM), the $H$ scalar boson predicted by R. Brout, F. Englert and P. Higgs, at a mass of 125 GeV/$c^2$. In addition, the analysis of the Run 1 data allowed physicists to perform precision tests of the SM and to search for new physics beyond the Standard Model. About 650 CMS publications are based on the LHC Run 1 data in international scientific journals.

During the years 2013 and 2014, a long shutdown period took place to upgrade the LHC machine and the detectors in view of the high-energy and high intensity run. The Run 2 data taking started in year 2015 at a record energy of 13 TeV. The year 2015 was key in the optimisation of the new machine condition running at high energy and high intensity, with a 25 ns bunch crossing time separation, a factor two smaller compared to the Run 1 running condition. The data accumulated in 2015 correspond to an integrated luminosity of 4.2 $fb^{-1}$ delivered by the LHC. The full power of the machine was develop in year 2016, with a record integrated luminosity of 40.8 $fb^{-1}$ delivered by the LHC. An amount of 49.8 $fb^{-1}$ and of 67.9 $fb^{-1}$ was delivered to CMS in 2017 and 2018, respectively, summing up to a total Run 2 delivered luminosity of 162.9 $fb^{-1}$. The machine is presently in a shutdown period. The Run 3 data taking was planned to begin end of spring 2021 up to end of 2023. However due to COVID-19 pandemic, the schedule is slightly delayed, and the plan is to start the Run 3 early in 2022, for 3 years (with an expected integrated luminosity of about 80 $\mathrm{fb}^{-1}$ per year at an energy of 13 or 14 TeV).

While the discovery of the SM scalar boson is definitely the highlight of Run 1, the high-energy and high-intensity Run 2 dataset extends the phase space for discoveries. It allows physicists to study in detail the newly-discovered scalar particle, to search for possibly additional scalar particles, to make precise SM measurements in various sectors, and to search for new physics beyond the SM, among others for dark matter candidates.

CERN foresees to increase the luminosity of the LHC: up to 10 times the design luminosity in 2027 (the so-called HL-LHC project, where HL stands for High-Luminosity, with a corresponding Phase-2 upgrade of the experiments). The aim is to allow a precise study of the scalar sector, as well as extending the discovery potential of the LHC for rare beyond-the-standard-model processes. The HL-LHC was formally approved by the CERN council in June 2016. The IIHE is strongly involved in the CMS upgrade activities, coordinating the electronics of the GEM Phase-1 upgrade of the Muon system, and taking a leading role in the Phase-2 upgrade of the silicon tracker.

### 2.1.1 Data analysis

#### 2.1.1.1 Study of scalar bosons

Since the existence of the SM scalar was confirmed in 2012, the study of the SM scalar now involves questions such as whether this particle is the only element to be added to the SM in order to give masses to the particles, and questions regarding the consistency of the discovered particle with respect to SM predictions. The SM scalar could also interact with particles yet to be discovered, such as dark matter particles. Measurements of the properties of the SM scalar are thus essential to address. The large amont of data provided by the LHC Run 2 dataset taken in 2015-18 at 13 TeV provides a significant increase in sensitivity compared to Run 1.

Since 2018, the study of the scalar interactions in Belgium started to enjoy a new four-year support from the EoS project be.h - "The H boson portal to physics beyond the standard model" - which funds several research positions and supports collaborative efforts among the Belgian research groups.

The IIHE group contributed in 2019 to the SM scalar boson studies in several important areas: the discovery of the direct coupling of the $H$ boson to top quarks in the $t\bar{t}H$ production channel, the search for additional massive scalars in the $l^+l^-$ plus missing energy channel, the search for additional massive scalars or pseudoscalars in the $t\bar{t}$ final state. These studies are described below.

- **Discovery of the direct coupling of the $H$ boson to top quarks in the $t\bar{t}H$ production channel** The top quark being very massive, its coupling to the $H$ boson is expected to be large, but the production cross section of the $t\bar{t}H$ channel is very small due to the large masses of the particles produced. An IIHE team contributed to this important discovery via a study of the final states involving multiple leptons and hadronic tau decays. This study introduces an extensive event categorisation based on the number of reconstructed leptons. The analysis is optimised to provide the best sensitivity by using various multivariate analysis techniques. Within the study of the $t\bar{t}H$ production, a dedicated search for the SM process of the associated production of a single top quark with a $H$ boson is performed. This process has an even a smaller production cross section but is sensitive to the sign of the Yukawa coupling. This analysis resulted in stringent constraints on the anomalous values of this fundamental parameter with excluding the negative sign of the coupling. A strong expertise was developed on the analysis of the top-$H$ processes in the multileptonic final states at the IIHE. An event candidate collected by CMS is shown in Fig.1.

- **Search for a high-mass scalar in the $H \to ZZ \to l^+l^-\nu\bar{\nu}$ channel:** The $H \to ZZ \to l^+l^-\nu\bar{\nu}$ decay channel is a sensitive final state for the possible observation of an additional heavy scalar with SM-like couplings, thanks to its large branching ratio compared to the decay into four charged leptons, and to the smaller background compared to the $l^+l^-q\bar{q}$ channel. The IIHE team is strongly involved in this search, and is co-convening $H \to ZZ \to l^+l^-\nu\bar{\nu}$ working group. A joint paper combining the $H \to ZZ \to 4l$, $H \to ZZ \to l^+l^-\nu\bar{\nu}$ and

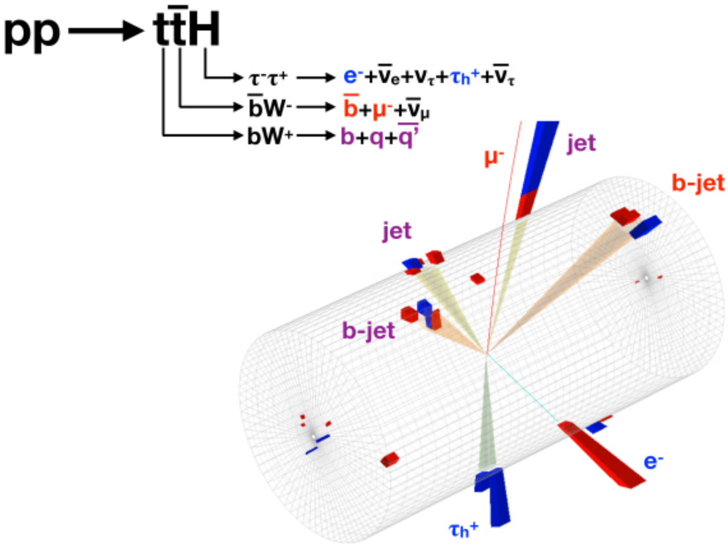


Figure 1: An event candidate for the production of a top quark and top anti-quark pair in conjunction with a $H$ boson in the CMS detector. The $H$ decays into a $\tau^+$ lepton and a $\tau^-$ lepton; the $\tau^+$ in turn decays into hadrons and the $\tau^-$ decays into an electron. The decay product symbols are in blue. The top quark decays into three jets (sprays of lighter particles) whose names are given in purple. One of these is initiated by a $b$-quark. The top anti-quark decays into a muon and $b$-jet, whose names appear in red.

$H \to ZZ \to l^+l^-q\bar{q}$ channels with 36 fb$^{-1}$ of data at 13 TeV, was published, with an IIHE member as a co-editor.

- **Search for a high-mass scalar or pseudoscalar in the $H/A \to t\bar{t}$ channel:** Because of their large mass, top quarks can be expected to have a large coupling to scalars. An IIHE member lead a search for a massive scalar in the $H/A \to t\bar{t}$ channel, and was co-editor of the paper. In this analysis, the invariant mass of the reconstructed top quark pair system and variables that are sensitive to the spin of the particles decaying into the top quark pair are used to search for signatures of the $H$ or $A$ bosons. Special care is taken in treating the interference with the standard model top quark pair background (it can be either constructive or destructive depending on the model parameters). The paper, based on 36 fb$^{-1}$ of data at 13 TeV, has been approved by the CMS collaboration and is submitted to JHEP.

### 2.1.1.2 Searches for high-mass resonances

Many scenarios beyond the SM are expected to be manifest through the production of new heavy resonances, typically above 1 TeV. For example, massive gravitons or new massive gauge bosons, Kaluza-Klein recurrences, are expected in the framework of extra spatial dimension models, as well as new heavy Z bosons in Grand Unified Theories. Additional scalar sector (spin-0) resonances are also investigated. Several final states are being analysed by the IIHE team: the diphoton final state, the dilepton final state and the lepton flavour violation (LFV) decay channels; they are detailed below. These analyses are considered as HPA (High Priority Analysis) by CMS in particular for the Run 2 data taking period where the new high energy frontier of 13 TeV allows to open considerably the phase space for discovery of new massive particles.

- **Search for heavy resonances decaying to a lepton pair:** Since 2006, physicists from the IIHE play a leading role in this channel; they initiated the creation of the HEEP (High Energy Electron Pairs) working group and were strongly involved in every step of the Run 1 CMS data analysis at 7 TeV and 8 TeV, as well as on the Run 2 data taking and analysis (data collected in 2015-2018) at 13 TeV. No excess was observed in the

2015-17 datasets and limits at 95% Confidence Level (CL) on the new resonance production cross section have been determined. The dielectron and dimuon channel results were combined. The results on the CMS data at 13 TeV taken in year 2015 and part of the 2016 dataset have been published. Updated results using the full 2016 dataset have been published and preliminary results on the 2017 data analysis have been presented at the Moriond 2018 conference. The results of the analysis including the full Run 2 dataset has been presented to the summer 2019 conferences and a publication with detail interpretation for various models and presenting both resoanant and non-resonant searches is in preparation.

Figure 2 presents the recent results obtained by the HEEP group : the dielectron invariant mass distribution resulting from the analysis of the full Run 2 dataset (on the left side) and the upper limits on the spin-1 resonance production (on the right side) for the dielectron and dimuon channels combined.

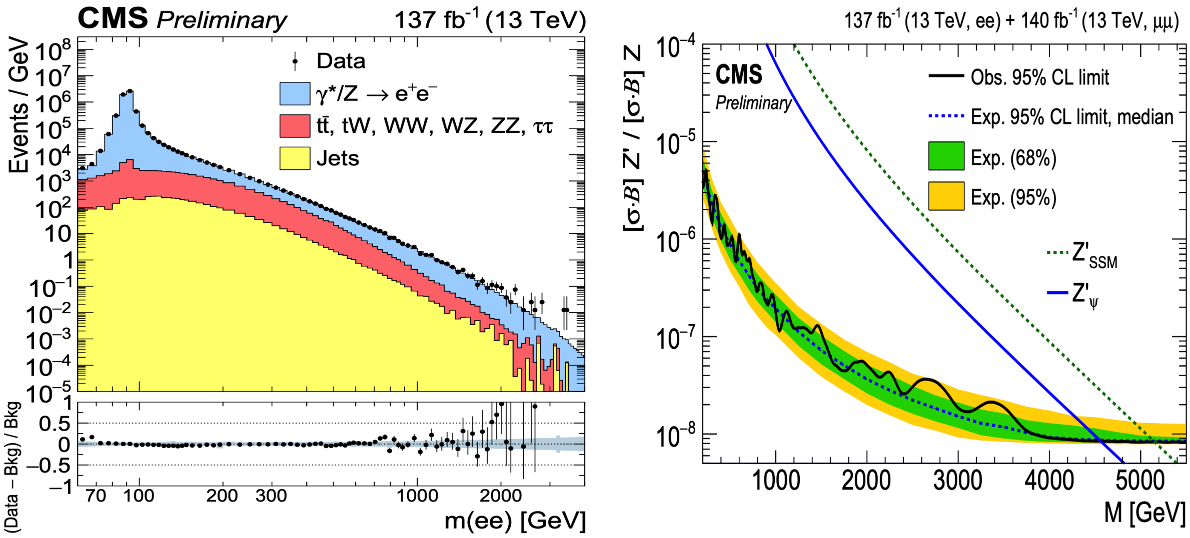


Figure 2: Left: The invariant mass spectrum of the dielectron events using the CMS data collected in 2016-2018, the full Run 2 dataset. Right: The 95% CL upper limits on the production cross section times branching fraction for a narrow spin-1 resonance, relative to the production cross section times branching fraction for a Z boson, using the full Run 2 dataset for the dielectron and dimuon channels combined.

- **Searches for new heavy resonances decaying with LFV:** In collaboration with ULB theorists, an additional analysis was performed to search for high mass resonances decaying with lepton flavor violation (LFV) into an electron-muon pair, using the 8 TeV dataset. The analysis was also performed using the data collected in 2015 and in 2016, leading to 2 CMS publications. The data were found to be in agreement with the SM expectation, and stringent limits on new physics parameters for different models have been put. The group is presently extending the search for LFV Z with final states including a tau lepton. The search for heavy resonances decaying with LFV is now performed in 3 different final states : the electron-muon, the electron-tau and the muon-tau final states, using the full Run 2 dataset collected in years 2016-2018. Recently the analysis has been optimized using the new tau lepton identification in CMS (the DeepTauId), based on deep machine learning technique. The use of this new multi-class DNN-based discriminator improves significantly the tau lepton identification performances with respect to the previously used BDT and cut-based discriminators.

#### 2.1.1.3 Heavy flavour jet identification

A crucial ingredient for many analyses in CMS is the accurate identification of jets originating from bottom and charm quarks. The importance of this topic is illustrated by the fact that about one third of all CMS publications relies on heavy-flavour jet identification. At the IIHE, particularly the subjects of SM scalar and top quark physics, as well as many searches for beyond the standard model phenomena, rely heavily on the identification of heavy-flavour jets. Under the leadership of FWO postdoc K. Skovpen (2018-2019) and as convener of the vertexing and heavy-flavour identification group (BTV) in the Physics Coordination of the experiment, CMS managed to smoothly and successfully complete the many challenges in heavy-flavour jet identification. K. Skovpen also co-organized a very succesful second edition of the CMS heavy-flavour tagging workshop in Dobrovnik, Croatia. Another coordinating role was observed by PhD student E. Bols, who is currently leading the algorithms and software subgroup of the heavy-flavour tagging group. In this new role, he steers the algorithm developments and took a leading role in developing the most state-of-the art heavy-flavour jet identification algorithms in CMS, based on advanced deep learning algorithms (referred to as "DeepJet"). He was appointed as one of the leading athors for a publication on this algorithm, which is currently under review. Furthermore, FWO postdoc S. Moortgat introduced a new method to calibrate the performance of the charm-jet identification algorithm, which was picked up by other members of the collaboration and was succesfully applied in the most sensitive measurement that tries to observe the Higgs boson decay into charm quarks. This works comprises an imporant part of the PhD thesis of S. Moortgat (defended 20th May 2019), where the new calibration was for the first time demonstrated in a measurement of top quark pair production with additional charm jets. Several IIHE members (S. Moortgat, E. Bols, A. R. Sahasransu, P. Van Mulders, K. Skovpen) had a leading role in the CMS collaboration in studying the training, performance, validation and implementation of the available heavy-flavour jet identification algorithms or in the commissioning of heavy-flavour tagging variables. The DeepJet algorithm was successfully commissioned to be used in the so-called "Legacy" dataset that contains all the data collected by the CMS experiment between 2016 and 2018. In parallel the algorithms were successfully calibrated on these data.

#### 2.1.1.4 Top quark physics

During the 2016-2018 Run 2 of the Large Hadron Collider, at 13 TeV centre of mass energy, the CMS experiment collected an enormous sample containing top quarks in pair production as well as single production.

IIHE physicists are measuring and studying very diverse aspects of the top quark sector, focusing not only on the SM but also on searches for physics beyond the SM. IIHE physicists remained visible in a leading role in the LHC top physics working group with ex-IIHE postdocs in leading roles as convener and multiple sub-conveners.

Using the Run 2 datasets the IIHE group are involved in the preparation of legacy papers on the high precision measurements of the production and decay properties of the top quark (some of these will not be possible to be performed as accurately in future LHC runs due to the high luminosity conditions) as well as searches for new physics in top-like final states. This results in a physics programme that reveals going from SM measurements via BSM-sensitive top quark physics to direct searches, with substantial roles in CMS by senior IIHE members in the internal peer-review inside the collaboration.

- **Flavour-Changing Neutral Currents in the top quark sector:** If new physics can not be directly observed at the LHC, it would in many cases still be possible to find evidence of such new physics processes through deviations to Standard Model rare processes. IIHE physicists coordinated by FWO postdoc Kirill Skopven, are preparing an inclusive approach using the full LHC Run 2 dataset at 13 TeV centre of mass energy, where all final states in top quark physics sensitive to Flavour-Changing Neutral Currents (FCNC) such as the rare decays $t \rightarrow Hc$ and $t \rightarrow Zc$, are examined and these processes are accurately measured in all possible final states. This work relies heavily on identification of b- and charm quarks so the same team is also developing the CMS experiment charm quark tagger for the 13 TeV LHC run.

- **Search for production of four tops:** The production of four top quarks, which in the SM is a very rare process with a cross section of the order of $1fb$ at 8 TeV and $9fb$ at 13 TeV, could be greatly enhanced by many new physics models, including Supersymmetry, but also more exotic models where gluon couplings are enhanced due to additional particles in the QCD sector. Depending on the physics model, these signatures will not display the typical Supersymmetry signature with large transverse missing energy. The IIHE team published an extremely competitive limit on Standard Model top quark production that includes the legacy result for the CMS 2016 dataset. New doctoral students N. Stylianou (working with the VUB on a shared PhD with University of Bristol) and V. Wachirapusitanand (working with the VUB on a shared PhD with Chulalongkorn Univesity in Thailand) have joined this effort, expecting an increased work load as this process is expected to be observed in the next iteration of this analysis. V. Wachirapusitanand was awarded the second prize for his poster "Application of Adversarial Networks in search for four top quark production in the lepton+jets channel in CMS" during the 2019 CMS week in December 2019, which describes his MSc thesis work.

### 2.1.1.5 SM precision measurements and QCD effects

To exploit the full discovery potential of CMS and to achieve the maximal precision on the BEH boson properties measurement, it is essential to reach the highest level of precision possible in SM physics area. For these reasons, the jet production associated to the Drell-Yan process is identified as a High Priority Analysis in CMS.

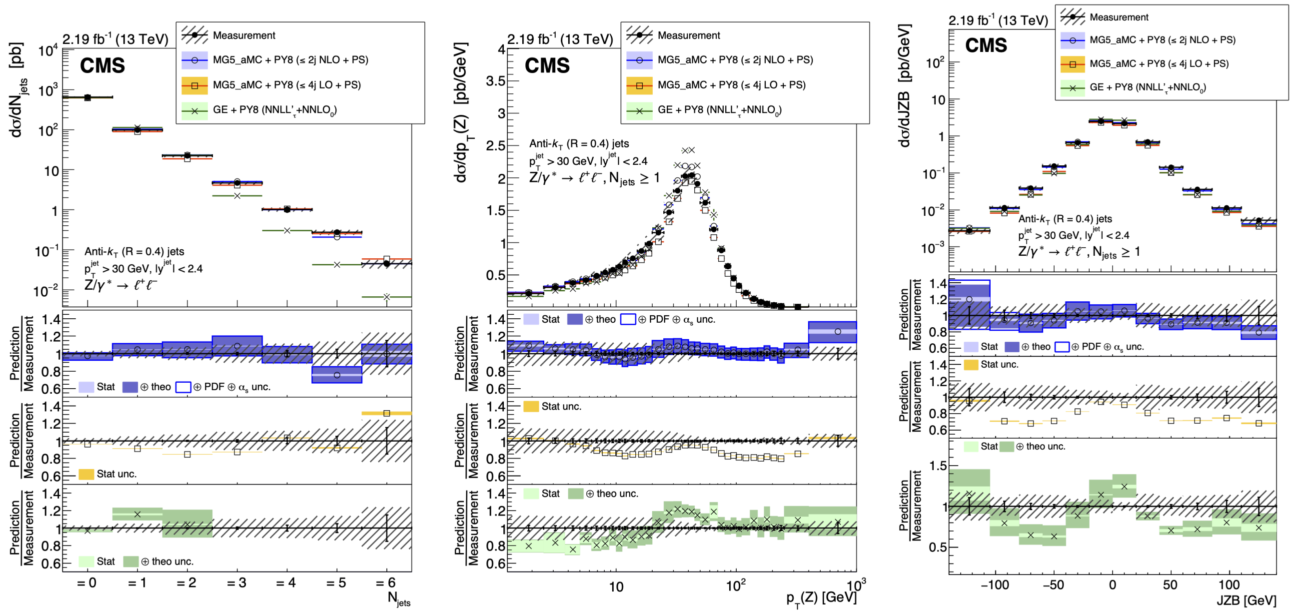

Figure 3: Measured cross section for Z+jets, using 13 TeV proton-proton data collected in 2015, are shown as a function of the jet multipicity (left), the transverse Z boson momentum in case of 1 jet associated production (middle) and the balance in momentum in the transverse plane between (right). The measurements are compared to predictions of multi leg Monte Carlo at NLO and LO (see legend) and GENEVA at NNLO with NNLL soft gluon resumation.

- **Drell-Yan production associated with jets:**
  The Drell-Yan production cross section on the $Z$ peak with jet production is one of the central reference measurement at the LHC. The leptonic decay of the $Z$ boson provides a background free and unbiased data selection to study in details the jet production and the reliability of its Monte Carlo simulation. The Drell-Yan cross section being known at NNLO in QCD for 1 jet process, the confrontation of the measurement to theoretical predictions provides a stringent test of perturbative QCD. Furthermore, the very high energy of the LHC allows producing many jets in the events. In particular Z events with more than 2 jets are frequently produced but beyond the scope of NNLO predictions. Alternative approaches are developed in Monte Carlos to predict many jets production. The IIHE group is leading the analysis at 13 TeV (2015-2018 data) measuring the $Z$ and $Z + jet$ cross sections for up to 4 jets with transverse momenta above 30 GeV and compared it to different Monte Carlo predictions. First results at 13 TeV have been obtained based on 2.5 $\mathrm{fb}^1$ of luminosity collected in 2015, for $Z$ boson decaying in two muons. The results published in [JHEP 78 (2018) 965] compare for the the measurement with the state of the art mulitleg Monte Carlo predictions at LO and NLO - see figure 3 - and for the first time with GENEVA which includes NNLO matrice element calculation plus NNLL resumation of soft gluons in the initial state.
- **Transverse Momentum Distributions:** To gain in precision for the Higgs measurement at the LHC, the multiple soft and semi-hard QCD radiations taking place in the production mechanism of the Higgs (and of many other processes) has to be better understood. In particular the transverse momentum distribution is very challenging to be described from first principles (i.e. without many parameter tunes) even for the most recent high order calculation including resummation. The Parton Branching Transverse Momentum Distribution (PB TMD) method is a Monte Carlo approach based on the DGLAP equation by simulation at every branching the radiated gluon or quark including its transverse momentum that will build step by step the transverse momentum of the parton reaching the partonic cross section. In other words it provide PDF including a $P_T$ distribution.

The ULB group started to contribute to PB TMD working group and Max Vanden Bemden (ULB) for his Master Thesis (2019) performed his own PB TMD calculations applied to the Drell-Yan measurement at the LHC.

#### 2.1.1.6 Dark matter and long-lived particle searches

Since many years, and especially starting at the exciting LHC Run-2 period in 2015, the IIHE has been searching for signatures of dark matter production at the LHC. Through leadership positions in the Exotica MET+X group (2016) and the Exotica long-lived search group (2017-2019), and delegations in LHC-wide working groups, the IIHE research in this area achieved high impact. While originally more classic searches were pursued (so-called "monojet", $t\bar{t}(2\ell)$+MET, and VBF+MET (invisible BEH boson) signatures), now the focus is on more exotic searches, either searching directly for dark matter, or for visible signs of a dark sector, with new physics mostly decoupled from the usual standard model particles. Such signatures are a topic with increasing impact in the LHC search program.

In 2019, a search for strongly interacting dark matter was continued, overcoming hurdles in simulation of its exotic signature, and now nearing completion. An off-the-beaten-path search for so-called sexaquarks, composite hadrons made of 6 quarks that could constitute the dark matter, was continued, culminating in the doctorate of PhD student Jarne De Clercq. Another search, for long-lived fractionally charged particles as a manifestation of dark photons coupling to a dark sector, by PhD student David Vannerom, also led to the completion of a doctorate in our lab. Related to this, finally, another impactful search was completed, led by IIHE postdoctoral researcher Simranjit Singh Chhibra (Phys.Rev.Lett. 124 (2020) 131802). This analysis was a highlight at the 2019 Lepton Photon conference, and also prominently featured in the CERN Courier (https://cerncourier.com/a/cms-goes-scouting-for-dark-photons/). In Figure 4 the reach of this last search is shown. Finally, Q. Python defended his doctorate with a work on the search for new physics in displaced lepton final states.

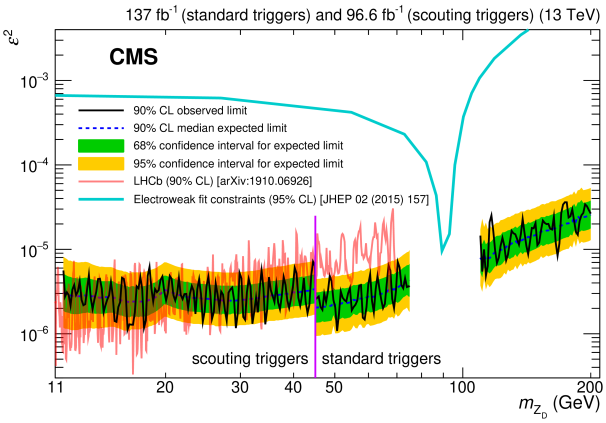


Figure 4: Exclusion limits in the plane of the kinetic mixing parameter versus dark photon mass, in a search for production of kinetically mixed dark photons decaying back to muon pairs in the CMS detector.

### 2.1.2 Contributions to the CMS upgrades

In the years 2020 and beyond, CERN will further increase the LHC luminosity. In these extremely intense experimental conditions, new detector technologies are needed, to which IIHE physicists are contributing.

#### GEM (GE11) upgrade

Since July 2011, the IIHE is contributing to the upgrade of the forward region ($1.5 < |\eta| < 2.2$) of the CMS muon spectrometer for the LHC high luminosity phase. The project called GE11 aims at installing 144 Triple-GEM detectors in the first ring of the first muon endcap disk, during the 2nd long LHC shutdown in 2019-2020. The installation in CMS started in July 2019 and by the end of October 2019 the first endcap was installed.

Fig 5 shows the assembly of one of the 72 Super-Chamber made of two Triple-GEM detectors back-to-back. In the upper left corner we can see the two 1m-long detectors equipped with their electronics; in the lower right corner we can see 10 Opto-Hybrid boards. Each detector is read-out by 24 VFAT3 front-end chips (small rectangles spread

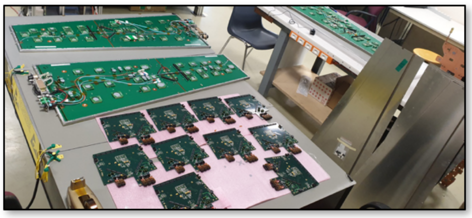

Figure 5: Assembly of one GE11 Super-Chamber made of two Triple-GEM detectors back-to-back. Each detector is equipped with its final electronics. Next to the two detectors we can see 10 Opto-Hybrid boards. The Opto-Hybrid board has been designed at the IIHE.

over the detector along 3 columns). These 24 chips are connected through a large PCB (the green layer covering the entire detector) to the Opto-Hybrid, still to be mounted in this case at the centre of the detector.

In this project the IIHE is leading the design of the trigger and data acquisition (DAQ) system of GE11. The new readout system is based on the micro-TCA standard as well as on the new optical link, called Versatile Link, and the GBT chipset, both developed by CERN for the LHC upgrade. In addition to the overall readout architecture the IIHE is also responsible for the design of the Opto-Hybrid. The board is equipped with an FPGA connected on one side to 24 front-end VFAT3 front-end chips and on the other side to the backend micro-TCA electronics through several optical fibers. This board being located on the detector, has to be tolerant to the radiation. The IIHE group has developed the largest part of the firmware of the readout system, in particular for the Opto-Hybrid, including Single Event Upset (SEU) mitigation techniques.

In 2019, the IIHE has largely contributed to the production and the quality control of the electronics as well as to the installation and the commissioning in CMS of the first endcap. The IIHE will continue those tasks in 2020 with the second GE11 endcap.

**Tracker Phase-2 upgrade**

From 2026 on, CERN has the goal to further increase the LHC luminosity by a factor 5-7 above the present design parameters. The aim is to allow a precise study of the scalar sector, as well as extending the discovery potential of the LHC for rare beyond-the-standard-model processes.

To meet the challenging data taking conditions at the HL-LHC, the CMS tracker must be completely replaced, for 3 reasons: first, the silicon sensors and their readout electronics must be more radiation-tolerant than those of the current tracker; second, the tracker data must be used in real time at the first level of event selection (L1 trigger) every 25 ns; and third, the tracker coverage must be extended towards the beam line (up to a pseudo-rapidity range $|\eta| < 4$) to optimize the potential of the experiment. The use of tracker data at L1 trigger level sets stringent requirements on the reliability of the outer tracker. The technical design report (TDR) describing the baseline technical choices for the building of the phase-2 tracker was submitted to the LHCC review committee beginning of July 2017, and approved in December 2017.

The Belgian groups from the IIHE (ULB-VUB), from Universiteit Antwerpen, the Université Catholique de Louvain-la-Neuve, and from Universiteit Gent have decided to build together one endcap of the phase-2 outer tracker. At the IIHE, about 2000 modules + spares will be assembled and tested, before they are integrated onto the tracker endcap support structures. These modules are composed of a stack of 2 silicon sensors of about 10x10 $cm^2$ size, read out on each side by a front-end hybrid (FEH) equipped with 8 amplifier ASICs of the CBC type, with 254 channels each, a concentrator chip (CIC) and serviced by a powering and optical transceiver hybrid. The correlation of the signals from both sensors inside the CBC chips allows the measurement of the particle incident angle and therefore the suppression of signals from low-momentum particles at the L1 trigger level.

The assembly of the modules is performed in controlled conditions of temperature, humidity and dust. In 2018, a large clean room of 122 $m^2$ was deployed at the IIHE, with the help of the VUB technical services. A picture of the newly-furbished clean room is visible in Fig.6 (left).

Figure 6: Left: the newly-furnished clean room at the IIHE. Right: the Hesse BondJet820 industrial bonding machine installed at the IIHE.

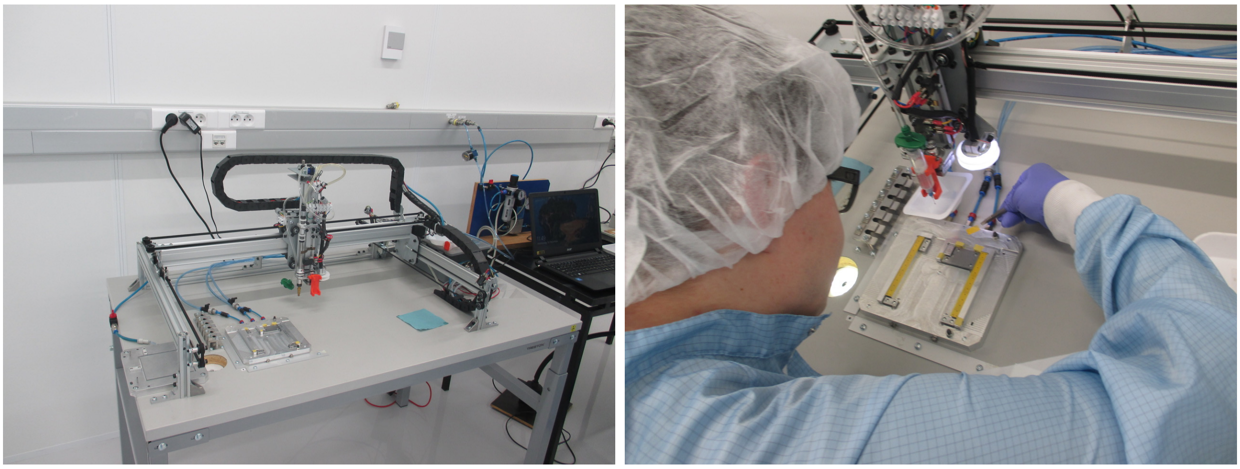

Figure 7: Left: gluing robot developed at the IIHE. Right: first trial assembly using the kapton gluing precision jig.

To connect the sensors to their readout electronics, a Hesse BondJet820 industrial bonding machine capable of making 3 to 7 microscopic bonds per second with a wire of 25 $\mu$m diameter was purchased and commissioned in 2018. The machine is visible in Fig.6 (right).

To exercise the assembly procedure, two mockup modules were assembled, composed of glass plates replacing the sensors, and spacers made of aluminium. The commercial pick-and-place machine modified at the IIHE to dispense glue on the kapton strips for electrical isolation between the sensor back electrode and the AlCF spacers is shown in Fig.7 (left). One of the precision jigs used is visible on Fig.7 (right), during a trial assembly of a mockup module.

At the Belgian level, regular Tracker phase-2 workshops are being held, to organise work and monitor progress of the different teams.

## 2.2 Future accelerators

Despite the excellent predictive powers of the SM it is vital to realise that is only an effective theory that will not work at substantially higher energy than the LHC. The SM also does not address a list of confirmed experimental phenomena, such as dark matter and the difference between the amount of matter and antimatter in the universe. To address these questions and study the behaviour of the relatively recently discovered Higgs boson, new colliders will be necessary.

IIHE member F. Blekman was involved as convener of top quark physics and made a leading contribution to the feasibility studies determining the physics and develop the detectors possible at the FCC-ee, the future electron-positron circular collider at CERN. The FCC-ee will run at different energies where it will produce Z bosons and top quarks and will produce more Higgs bosons than ever before, in conditions that make them much easier to study. These studies converged in a series of Conceptional Design Reports that aim to provide feedback on the feasibility of the FCC electron-positron collider project, both as far as what collider luminosity should be and what detector designs will be needed to optimally detect relevant particles. VUB masters student M. Mancini completed his master thesis on this topic in 2019.

These conceptual design reports will be essential for the decision making and design of future accelerators, and are an important input to the European Strategy Report that is in preparation in this topic. J.D'Hondt is involved with the European strategy report as the chairperson of the committee that will provide advice on the strategy and prioritisation of long-term development of large research structures such as the FCC.

Another highlight is the organisation of the 500-person FCC week in Brussels on 24-28 June 2019, where the VUB took the main local organising role. This week included visits to Brussels by various important stake holders from the scientific community, including the CERN Director General F. Gianotti, and featured key note speeches by for example Herman Van Rompuy and dedicated workshops on the "Economics of Science", co-organised with the EU funded H2020 RI-Paths project and the Belgium Alumni Association of the London School of Economics.

## 2.3 The SoLid experiment

(L. Kalousis, P. Van Mulders, S. Vercaemer)

The SoLid collaboration unites about 45 researchers from 10 institutes in the UK, France, US and Belgium. The researchers involved in the SoLid experiment aim to search for Short baseline neutrino Oscillations with a novel Lithium-6 composite scintillator (SoLid). The highly segmented plastic scintillation detector coated with Lithium-6 is designed to provide a measurement of the rate of electron antineutrinos at very short baseline distances between 5 and 11 metres from the BR2 research reactor core in SCK-CEN at Mol. This measurement will provide confirmation or exclusion of the so-called reactor anomaly present in the ratio of the observed to predicted number of electron antineutrino events at short baseline distances.

The detector consists of PVT scintillator cubes of 5cmx5cmx5cm coated with $^6LiF : ZnS$ to detect $\bar{\nu_e} + p \rightarrow n + e^+$. The antineutrinos produced by the reactor interact with the protons of the detector material and produce a neutron and positron. The positron will quickly annihilate with one of the electrons in the detector. While the neutron will be captured by the Lithium-6 ($n +^6 Li \rightarrow^3 H + \alpha + 4.78\ MeV$). The combination of the electromagnetic scintillation (ES) signal from the positron annihilation and the delayed neutron capture giving rise to nuclear scintillation (NS) allows for a clear identification of the antineutrino interaction. Fibers pass through each cube to read it out in two directions, which provides a precise localization of where the interaction happened. The light is collected at the fiber end using MPPCs. More details about the detector technology can be found in [1].

The collected data is transferred on a daily basis from the server at SCK-CEN to the computing center in Brussels. From the computing center in Brussels, the data is transferred to Imperial College in London and to the French computing centre in Lyon. Yamiel Abreu (Universiteit Antwerpen) is the data transfer coordinator for the collaboration. The data is then processed using the latest reconstruction and analysis software. This processing is typically done by several collaborators under the leadership of Simon Vercaemer (Universiteit Antwerpen) as software coordinator. Simon Vercaemer (Universiteit Antwerpen) is also responsible for the data certification since he developed the necessary tools and procedure during his PhD.

Within the collaboration it was agreed that the antineutrino event selection requirements would be optimized with only a part of the dataset, large enough to claim observation of the antineutrinos, but small enough to be unable to perform the oscillation analysis. This unblinded dataset consists of about 22 days when the reactor was on and 35 days when the reactor was off. With the unblinded dataset the signal-to-background ratio was optimized without introducing a bias when performing the oscillation analysis. The background processes were studied using this dataset and incorporating also the knowledge, experience from studying the data from the SM1 detector. At the Belgian institutes, Simon Vercaemer (Universiteit Antwerpen en Vrije Universiteit Brussel), Petra Van Mulders (Vrije Universiteit Brussel), Yamiel Abreu (Universiteit Antwerpen), Celine Moortgat (Universiteit Gent) and Giel Vandierendonck (Universiteit Gent) contributed to the background studies. They developed muon veto requirements, studied the evolution of different background processes over time and their correlation with environmental parameters and estimated the size of the various background contributions. Based on these studies, the topological event selection requirements have been optimized as well as energy requirements leading to a clear observation of antineutrinos with the unblinded dataset presented at the GDR Neutrino meeting in October 2019. An excess of 140 antineutrinos per day was observed, amounting to a significance of over 5 sigma for the whole period. The excess is in agreement with the expectations from the simulation, both concerning the observed energy and the rate of interactions as a function of the distance to the reactor.

In parallel, based on simulated antineutrino events and oscillation analysis framework has been developed by Leonidas Kalousis (Vrije Universiteit Brussel), lanthe Michiels (Universiteit Gent) and Lars Ghys (SCK-CEN). This oscillation analysis framework contains all the necessary features to measure the oscillation parameters in case of a discovery or to plot exclusion contours. Different methods have been implemented to produce the exclusion or discovery contours in the oscillation phase space.

Peer reviewed publications in 2019 are related to the development of a quality assurance process (JINST 14 (2019) P02014, [1811.05244]) and the commissioning and operation of the readout system (JINST 14 (2019) P11003, [1812.05425]).

# References


[1] Y. Abreu *et al.* [SoLid Collaboration], "A novel segmented-scintillator antineutrino detector," JINST **12**, no. 04, P04024 (2017) doi:10.1088/1748-0221/12/04/P04024 [arXiv:1703.01683 [physics.ins-det]].


## 2.4 The JUNO experiment at Jiangmen (China)

(Barbara Clerbaux, Benoît Denègre, Shuang Hang, Pierre-Alexandre Petitjean, Jieren Wu, Yifan Yang)

Neutrino physics today is one of the major challenges of our understanding of nature, and is a very active research area, in particular related to the observation of neutrino oscillations, with the 2015 Nobel prize of physics awarded to Takaaki Kajita and Arthur McDonald for this discovery. The very nature of these particles is still unknown and some key measurements still need to be performed. The IIHE laboratory has a long tradition in long baseline neutrinos physics with the participation to the CHARM2, CHORUS and OPERA experiments using neutrino beams from CERN, and it is presently very active in the IceCube neutrino telescope located at the South Pole, and in the SOLID experiment, a very short baseline neutrino experiment presently running at the BR2 MTR research reactor in Mol. In addition to its strong tradition in neutrino physics, the IIHE has a recognized expertise in detector R&D and instrumentation, in particular in state-of-the-art electronics and data acquisition system (DAQ). Since 2015, IIHE-ULB is participating to the Jiangmen Underground Neutrino observatory (JUNO) experiment, based in China, being responsible for design studies on the back-end electronics system, in particular for the back-end card. A JUNO equipment FNRS funding was requested and covers the cost of the design, prototype building and tests of the BECs, as well as the final production of the BEC boards, their shipping and installation in the experiment.

The JUNO experiment uses a large liquid scintillator detector aiming at measuring antineutrinos issued from nuclear reactors at a distance of 53 km. The precise measurement of the antineutrino energy spectrum will allow determining the neutrino mass hierarchy (NMH) and reducing the uncertainty below 1% on solar oscillation parameters, after 6 years of data taking. Moreover, sterile neutrinos with small $\Delta m^2$ value and at large mixing angle $\theta_{41}$ could be identified through a precise measurement of the antineutrino energy spectrum. The JUNO detector is also capable of observing neutrinos/antineutrinos from terrestrial and extra-terrestrial sources, including geoneutrinos, atmospheric neutrinos, solar neutrinos, supernova neutrinos, and diffuse supernova neutrino background.

The detector is located at 700 m underground and consists of 20 ktons of liquid scintillator contained in a 35 m diameter acrylic sphere, instrumented by more than 18000 20-inch photomultiplier tubes (PMT). Two vetoes are foreseen to reduce the different backgrounds: a 20 ktons ultrapure water Cerenkov pool around the central detector instrumented by 2400 20-inch PMTs will tag events coming from outside the neutrino target, and a muon tracker will be installed on top of the detector (top muon veto) in order to tag cosmic muons and validate the muon track reconstruction. The top muon veto will use the OPERA experiment target tracker, in which IIHE has been a contributor. The JUNO civil construction started in 2015 and the production has started for the main components (as for example the PMTs). The start of the data taking is expected in 2022.

The JUNO electronics system will have to cope with signals from 18000 large (20-inch) PMTs and 25600 small (3-inch) PMTs of the central detector as well as 2400 PMTs installed in the surrounding water pool. It consists of mainly two parts: (i) the front-end electronics system performing analog signal processing, and (ii) the back-end electronics system, sitting outside water and consisting of DAQ and trigger units for digital signal processing. Several schemes were studied and discussed inside the JUNO electronics teams. The schemes differ on the usage of the Ethernet cables and on the method used to provide the power supply. An important challenge is to ensure very high reliability of the system. Due to the big amount of connections between the front-end and back-end electronics systems and the complexity of the signal combination, the ULB group proposed to use back-end cards (BEC) as a concentrator and a bridge between the two parts, and concentrated on the design and the tests of the BECs.

During the years 2016-17, the option called the “BX scheme” was intensively studied, where one long cable is connected to one PMT, with the front-end electronics directly attached to the PMT : the Analog to Digital Unit (ADU) and the Global Control Unit (GCU), and then the BEC card outside water, as shown in Figure 8 (left). A first prototype was designed at ULB with two kinds of equalizers and cable drivers to verify the 250 Mb/s data link over 100 m Ethernet cable, and a second prototype was design to verifying the 48 channel data transfer as well as the power injection and communication with the DAQ and trigger system. The BEC prototype version 2 was working fine. Few issues were observed and resolved (lower the noise, improve the power distribution, channel crosstalk mitigation). Each BEC will handle signals from 48 PMTs, and in total 375 back-end cards are needed to read the 18000 PMTs. A first full prototype chain, including the BEC (version 2), was assembled in Padova in spring 2017, and tested successfully (100 Mb/s Ethernet for DAQ and Slow Control). This option was providing good signal to noise ratio, as the signal processing is performed on the PMT side. Final design and combined tests of the full JUNO electronics readout chain from PMTs to trigger/DAQ, using the “BX scheme”, has been reported in a document submitted to publication (arXiv:2003.08339, submitted in March 2020).

However this option had to be reconsidered because of the following three issues: (i) fragility issue when potting the electronics on the PMT, (ii) potentially high power consumption, and (iii) installation difficulty to manipulate the PMTs with its electronics and the 100 m cable attached to it. To mitigate these issues, the use of an underwater box was unavoidable, implying the presence of underwater connectors.

Since fall 2017, the so-called “1F3 scheme” was adopted as the new baseline design for the JUNO electronics. The main modification is the addition of underwater (UW) boxes that will collect, for each of them, the signals of 3 PMTs, via 3 short (about 1 m long) coax cables. One UW box will host 3 ADC, and one GCU, and will be connected to the outside water system via 2 Ethernet cables. Each BEC will handle signals from 48 underwater boxes. To test this new scheme, a BEC version 3 has been designed. This version is optimised to be flexible and can test both the BX and 1F3 schemes. The idea is to have a baseboard and various mezzanine cards. Various tests have been performed : the 250 Mb/s bi-directional data transfer (most importantly for synchronized link), the 15 W power delivery with resettable fuse protection, and the 1 Gb/s data transfer over the combined 4 asynchronized links. All the tests above were successful. A contribution (with proceedings), ”Design of a common verification board for different back end electronics options of the JUNO experiment”, has been sent to the RT IEEE conference in US in June 2018, and results of the tests to the TWEPP conference in September 2018.

At the beginning of 2019, due to a change of components at the GCU level (on the clock and data recovery chip) in the underwater box, the scheme had to be slightly modified with the clock not embeded in the data stream anymore, decreasing the speed from 250Mbps to 125Mbps, while adding a separate clock channel. A final scheme was proposed as shown in Figure 8(right). In this scheme, the link from the underwater box to the BEC only carry trigger and clock related data, which doubled the usage of equalizers and links to the mezzanine. The power is now delivered by two dedicated cables. In April 2019, the BECv4.0 was designed, see Figure 9 : the baseboard itself was changed to two parts, 6 extender and 1 power board, also the FMC connector was updated from custom defined LPC to standard HPC. With the help of one visiting researcher, we developed the Tool Command Language (TCL supported by Xilinx and vivado) based test system prepared for mass production test. A poster on the Design of the backend cards for the JUNO experiment was shown at the TWEPP 2019 conference at Santiago de Compostela in Spain. Finally a presentation (with proceeding) on "The JUNO experiment and its electronics readout system" and a poster on the BEC system were given at the EPS 2019 conference in Ghent.

In May 2020, the final prototype BECv4.1, which enhances the security and slow control function, was designed. In particular, the routing of DCDC power module was optimised according to reference design, several TVS diodes were added to protect the power supply as well as the direct signals from the TTIM (trigger timing interface mezzanine) FPGA, 3 temperature sensors were introduced for the slow control system, as well as two I2C lines to the connection to TTIM. The mounting hole arrangement was also optimised for better mechanical support and assembly. One poster describing the test system for the final BECv4.1 and and one talk describing a neural network based trigger algorithms have been accepted for the Real Time conference in fall 2020.

The ULB work in JUNO is appreciated and visible in the collaboration. Y. Yang is presently officially responsible (L3 manager) for the DLU (Data Link Unit) for JUNO and B. Clerbaux is the ULB representative at the JUNO institutional board and at the JUNO financial board. In 2019, B. Clerbaux was asked by the Collaboration to set up new awards in JUNO (individual JUNO young researcher awards and JUNO PhD awards). Since then, she chairs the JUNO award committee. The ULB team has organized two JUNO electronics workshops at the IIHE (on 14-16 November 2016 and on 14-15 May 2018) with about 50 participants, and one European JUNO collaboration meeting (plus satellite meetings) in May 23-24, 2019.

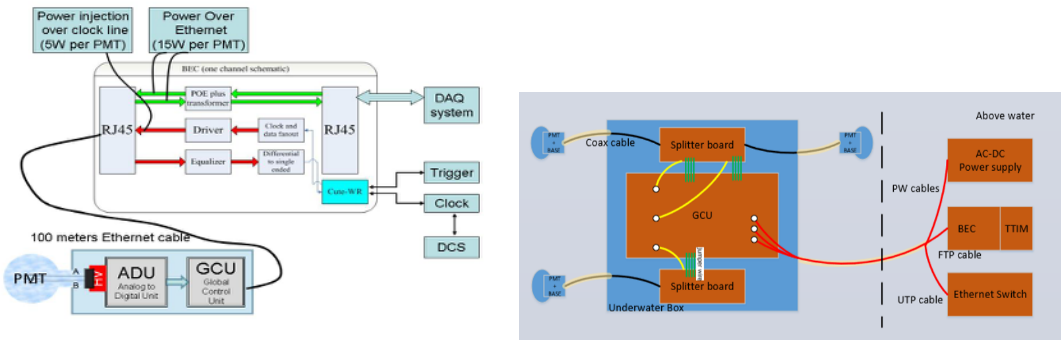


Figure 8: Schematic view of the JUNO readout with the front-end part (PMT, ADU, GCU – under water) and the back-end part (BEC, DAQ, trigger). Left: the first option with one GCU and one long cable per PMT ; Right: the latest version with 3 PMTs connected to one GCU via an underwater box and the back-end part (BEC, DAQ, power supply) above water.

## 2.5 OPERA experiment (CERN CNGS1)

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The OPERA long baseline neutrino oscillation experiment has been designed to discover the direct appearance of $\nu_\tau$ in a $\nu_\mu$ beam with a large signal/noise ratio through the identification of the $\tau^-$ lepton produced in their CC interactions. The domain of parameters space tested is the one primarily indicated by the atmospheric neutrinos experiments: compatible with full $\nu_\mu - \nu_\tau$ mixing and $|\Delta m^2_{32}| \approx 2.4\, eV^2$. The detector was installed in the underground Gran Sasso Laboratory of INFN (LNGS) and exposed from spring 2008 to December 2012 to the CERN CNGS $\nu_\mu$ beam over a baseline of 730 km, the achieved integrated neutrino beam flux corresponding to $18 \times 10^{19}$ protons on target. Detailed information on the detector and the analysis procedure may be found in previous reports and respectively in [1] and [2].

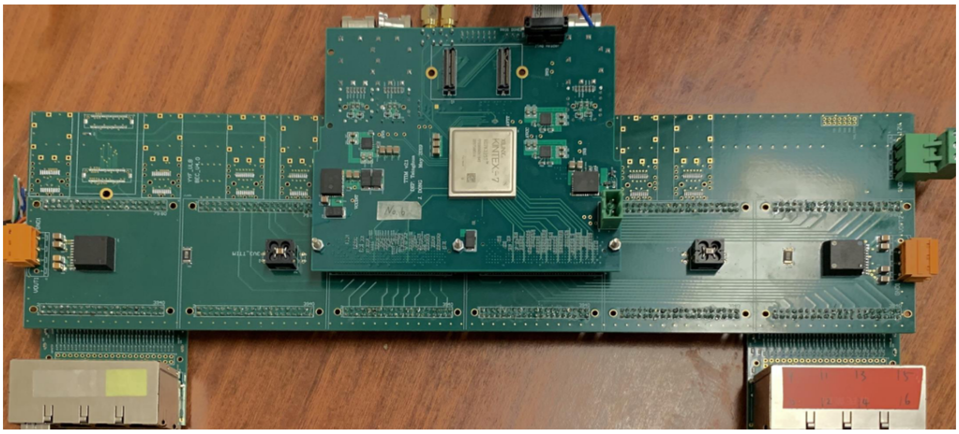

Figure 9: The BEC v4.0 (baseboard and mezzanine cards) developed at the ULB.

The confirmation of the discovery of $\nu_\tau$ appearance in a $\nu_\mu$ beam with a further improved significance of 6.1 $\sigma$ has been published in 2018 [3]. This was the main objective of the experiment. It has been reached with a significance that exceeds expectation.

In an analysis that closes the mainstream scientific programme of the experiment, the $\nu_\tau$ and $\nu_e$ appearance and the $\nu_\mu$ disappearance channels were jointly used to further test the existence of a hypothetical light sterile neutrino. Within the framework of the 3+1 neutrino model, a significant fraction of the sterile neutrino parameters space allowed by the LSND and MiniBooNE experiments is excluded at 90% C.L. In particular, the best-fit values obtained by MiniBooNE combining neutrino and antineutrino data is excluded with a significance larger than 3 $\sigma$ [4].

The studies of two other physics topics have led to very last publications:
- An interaction in which two short-lived particles are emitted has been found to be compatible with high significance with the production of a charmed particle in a $\nu_\tau$ CC interaction. The process is foreseen in the Standard Model but this is its first observation, the event being difficult to produce, to detect and to identify against several background sources [6].
- The cosmic ray muon flux seasonal variation has been measured and its correlation to the high atmosphere temperature verified [5].

The data sets corresponding to the ten candidate $\nu_\tau$ events have been published on the Open Data Portal at CERN. A paper describing these data in details is being finalised after submission to Nature – Scientific Data. It aims at being handled and analysed by a wide range of users [7].

In 2019, the OPERA Collaboration included about 150 physicists from 30 institutions in 11 countries.

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## 2.6 Astroparticle Physics with the IceCube Neutrino Observatory

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Astroparticle Physics revolves around phenomena that involve (astro)physics under the most extreme conditions. Black holes with masses a billion times greater than the mass of the Sun, accelerate particles to velocities close to the speed of light. The produced high-energy particles may be detected on Earth and as such provide us insight in the physical processes underlying these cataclysmic events.

Having no electrical charge and interacting only weakly with matter, neutrinos are special astronomical messengers. Only they can carry information from violent cosmological events at the edge of the observable universe directly towards the Earth. Furthermore, since they are hardly hindered by intervening matter, they are the only messengers that can provide information about the central cores of cosmic accelerators like Gamma Ray Bursts (GRBs) and Active Galactic Nuclei (AGN), which are believed to be the most violent cosmic events and the sources of the most energetic Cosmic Rays. Identification of related neutrino activity would unambiguously indicate hadronic activity and as such provide clues to unravel the nature of these mysterious phenomena.

Another mystery of the Universe is the illustrious Dark Matter, which has not yet been identified but which would explain various observed phenomena. According to some models, this dark matter may consist of Weakly Interacting Massive Particles (WIMPS) which can annihilate among themselves. In these annihilation processes some of the produced particles are high-energy neutrinos. Since these WIMPS are expected to get trapped in gravitational fields, there may be large concentrations of them at the center of massive objects like the Earth, the Sun or the Galactic Center. Consequently, observation of high-energy neutrinos from these objects could provide indirect evidence for the existence of these dark matter particles.

At the IIHE, we are involved in a world wide effort to search for high-energy neutrinos originating from cosmic phenomena or from dark matter particles. For this we use the IceCube neutrino observatory at the South Pole, the world's largest neutrino telescope which has now been taking data for several years.

### 2.6.1 The IceCube observatory

IceCube (http://www.icecube.wisc.edu) is a neutrino telescope consisting of an array of optical sensors, located in the icecap of the South Pole at depths between 1450 and 2450 m. The sensors are arrayed on vertical cables, called strings, each of which comprises 60 sensors spaced by 17 m. In the horizontal plane, the strings are arranged in a triangular pattern such that the distance between adjacent strings is always 125 m. The overall configuration (see Fig. 10) exhibits a hexagonal structure, which is the result of extensive optimization procedures based on simulation studies. At the end of 2010 the full 86-string detector, including its DeepCore extension (see here after), was completed and started taking data, representing an operational observatory with an instrumented volume of 1 km$^3$. Due to the geometrical configuration outlined above, the energy sensitivity for IceCube is ranging from a few hundred GeV up to several PeV.

Sensitivity to lower energies can be obtained by a smaller spacing between adjacent sensors. IceCube is equipped with a denser sub-array, called DeepCore, consisting of 8 strings arranged around the central IceCube volume with an inter-string spacing of 72 m as opposed to the 125 m standard IceCube string spacing. Each DeepCore string has 50 sensors at 7 m spacing covering depths between 2100 and 2450 m and 10 sensors at 10 m spacing between 1750 and 1860 m. Aside the in-ice instrumentation IceCube is also equipped with a surface cosmic-ray detector called IceTop. This surface array consists of 162 tanks of ice, each instrumented with two standard IceCube sensors, to detect showers of secondary particles generated by interactions of high-energy cosmic rays in the atmosphere.

Most of the high-energy neutrinos detected in IceCube originate from cosmic-ray particle interactions in the Earth's atmosphere. However, in 2013 IceCube detected a neutrino flux component incompatible with the atmospheric background hypothesis. This achievement was awarded the title *Breakthrough of the year 2013* by the Physics World magazine. Since then IceCube has observed more than 100 cosmic neutrino candidates of which the majority has a deposited energy $> 60$ TeV, which is incompatible with an atmospheric origin beyond the commonly accepted 5 sigma detection threshold. The level of observed extraterrestrial neutrino flux of $10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per neutrino flavor (Science **342** (2013) 1242856) implies a much richer hadronic activity in the non-thermal Universe than previously

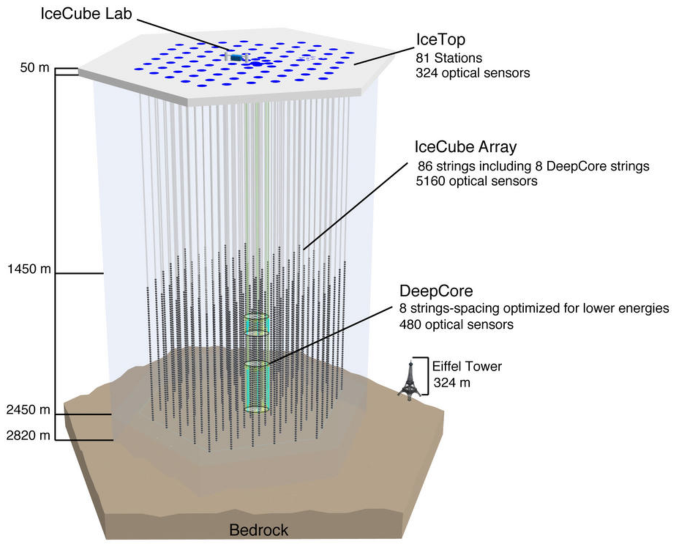


Figure 10: The IceCube observatory.

expected. The neutrino energy density matches the one observed for photons, indicating a much larger role of protons relative to electrons than previously anticipated.

The origin of these astrophysical neutrinos is not yet known. Clustering analyses performed on the sample are thus far unable to resolve statistically significant hot spots, or areas of event accumulation beyond the expectation of an isotropic flux. However, the recent observation of a gamma-ray flare from the blazar TXS 0506+056 (an active galaxy with a jet pointing at Earth) in spatial and temporal coincidence with an alert (IC170922A) of a high-energy neutrino event observed by IceCube may be the first evidence (at a $3\sigma$ level) of an extragalactic cosmic ray source (Science **361** (2018) eaat1378). Analysis of IceCube archival data also revealed enhanced neutrino activity of this same source in december 2014 (Science **361** (2018) 147), however that period did not display enhanced gamma-ray activity.

The current size of the IceCube observatory limits its ability to identify the sources of these high-energy neutrinos. For this reason expansions of the current detector are already planned. The second generation of IceCube, dubbed *IceCube-Gen2*, will be a future installation including a 10 km$^3$ volume expansion of detection volume of the clear Antarctic ice (Fig. 11) as well as a hybrid surface scintillator/radio array for cosmic-ray detection, and an in-ice Radio Array to explore the highest energies.

### 2.6.2 Research areas at the IIHE

Concerning research with the IceCube Neutrino Observatory, the IIHE has been involved in the following (astro)physics topics:

- **Search for high-energy neutrinos from transient events.**
  This study is aimed at the identification of high-energy neutrino production in relation with Gamma Ray Bursts, flares from Active Galactic Nuclei or any transient phenomena. The activities of the IIHE in this field are several:
  - **Stacking search for AGNs flares.**
    Active Galactic Nuclei are among the main candidates for particle acceleration to the highest energies of the Cosmic Ray spectrum. They are also sources of violent transient phenomena, in particular AGN with jets pointing to us (called Blazars) exhibit a high variability in their photon flux with sudden sequences of multiple flares that may last from minutes to months. Starting in 2015 we initiated an analysis using the light-curve information from $\gamma$-rays as a time-template to search for neutrinos. The novelty of this analysis compared to previous analyses in IceCube, is that the list of AGN is also stacked in order to search for a combined signal of all selected AGN during their flaring periods. The interest in this analysis is further

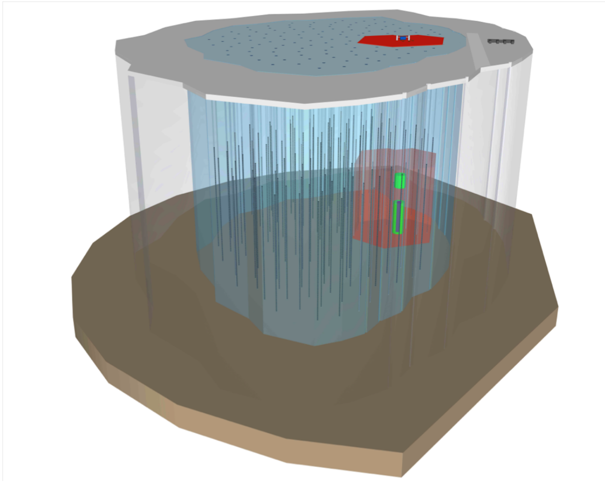

Figure 11: A possible *IceCube-Gen2* configuration. IceCube, in red, and the infill subdetector DeepCore, in green, show the current configuration

increased given the recent correlation of a flaring blazar with one of the high-energy neutrinos of IceCube. If flaring blazars are sources of cosmic rays, then the question arises why they have not been observed before in correlation with the cosmic neutrinos observed by IceCube. One possible answer is that this particular blazar belongs to a special sub-category of blazars, or that only a small fraction of the IceCube astrophysical flux comes indeed from flaring blazars.

- **GRB searches.**
  A first analysis (Nature **484** (2012) 351) has shown that the detected Gamma Ray Bursts (GRBs) cannot be the sole sources of the very energetic cosmic rays observed at Earth. This, rather shocking, result has ruled out a large number of mainstream theoretical models describing GRBs. The limits set by IceCube however only constrain neutrino emission during the prompt phase of GRBs. Since observations of precursor photon flashes occurring before the prompt phase suggest that neutrinos are emitted during the GRB precursor, we have initiated at the IIHE a study for emission of neutrinos during this phase leading up to the prompt flash of gamma-rays. Currently an analysis method has been developed to identify the precursor flashes and investigate their characteristics (arXiv:2004.03246), in order to optimize an analysis using the available IceCube data. Likewise, the afterglow of GRBs will be investigated, as these often contain high-energy X-ray flares which are excellent candidates for neutrino production.

- **Search for steady sources of neutrino emission.**
  Apart from the correlation studies using timing information, we have at the IIHE also worked on an analysis searching for steady sources of neutrino emission. Here the strategy is to search for an accumulation of events in a particular direction of the sky in a way incompatible with the isotropic atmospheric background. The identification of such "hot spots" or "hot regions" on the neutrino sky would enable us to locate the sources of the most energetic cosmic ray particles.

  - **Search for neutrino emission from Dust Obscured Sources**
    The energy budget of astrophysical neutrinos is equivalent to that of gamma-rays seen by Fermi. Since most of these sources in the Fermi diffuse flux are blazars from which we did not find any neutrino correlation, there is a slight tension between gamma-ray data and neutrinos. This tension could be resolved if the neutrino sources are opaque to gamma-rays.

    As mentioned before, blazars are a special class of AGN with their jets pointing towards Earth. These objects are very bright in the gamma-ray sky, very variable, and considered as prime neutrino source candidates. However, at the IIHE we developed a different approach and focused instead on a sub-category of blazars which appear bright in radio frequencies, but are rather dim when observed with more energetic radiation. The reason for this condition is that such a signature could indicate that X-ray luminosity has been obscured by a column of surrounding matter, such as dust. The latter could also provide an additional target for the produced cosmic rays and lead to enhanced high-energy neutrino production. In 2017 the

IceCube data was unblinded for this analysis and no significant excess from these dust-obscured blazars was found. In the meanwhile another subclass of sources that could explain the gamma-ray, neutrino discrepancy are Ultra-Luminous Infrared Galaxies (ULIRGs). With an infrared luminosity that exceeds $L_{\odot}^{12}$, ULIRGs have a vast energy budget which may serve to possibly accelerate cosmic rays, which will on their turn produce gamma-rays and neutrinos. Moreover, the bright infrared luminosity indicates the presence of large amounts of dust, which will block the gamma-rays on their way out of the sources while enhancing the neutrino production. As such, an analysis has been started at the IIHE to search for IceCube neutrinos originating from these ULIRGs.

- **Dark matter searches.**
  In addition to astrophysical neutrino searches, IceCube has proven to be an excellent Beyond-the-Standard-Model detector producing very interesting and competitive results on dark matter searches and sterile neutrinos. At the IIHE we are also working on indirect searches of dark matter from the center of the Galaxy and the center of the Earth. If dark matter consists of (supersymmetric) particles, it is interesting to search for annihilation signals of these particles from massive celestial objects in which an excess of dark matter is expected. The products of these annihilations are standard model particles among which we can find neutrinos. The dark matter searches in IceCube focused on the search for neutrino signatures from the center of our Earth, the Sun or the Galactic Center.

  - **Dark matter from the center of the Earth**
    A renovated effort has been initiated in the search for dark matter from the center of the Earth. A search including 8 years of IceCube data is on-going. The first sensitivities were presented at the ICRC conference in July 2019. These results show an improvement of a factor 3.5 compared to the 1-year analysis, developed at the IIHE and published in 2017 (European Physical Journal C 77 (2017) 82). Further improvements in the binned likelihood calculation are expected by using the energy as a variable in addition to the zenith angle and by optimizing the number of bins. A poster at the Neutrino 2020 conference with the latest results will be presented. The limits of this analysis will be the best limits in some parts of the parameter space for indirect searches of dark matter from the Earth.
  - **Dark matter from the Galactic Center**
    The Galactic Center region yields the highest signal expectation from dark matter annihilation, due to the high density of dark matter present at the center of the Milky Way. Unfortunately, IceCube is located at the South Pole and as such is not in a privileged position to observed the Galactic Center since it has to beat the large amount of atmospheric muon background. IceCube limits in this regard are comparable to a much smaller detector located in the Mediterranean Sea, the ANTARES neutrino telescope. For this reason, we have initiated a working group to combine data from both telescopes in order to enhance the discovery potential (or put stringer limits) of dark matter from the Galactic Center. Preliminary results not only showed a benefit of combining the two data sets, it also solved many of the ambiguities and assumptions that different experiments apply when calculating limits of a velocity averaged dark matter annihilation cross-section. Recently this analysis has been unblinded and a paper is in progress to reflect the final results.

- **R&D for future upgrades**
  The discovery of cosmic high-energy neutrinos has triggered feasibility studies for the extension of the existing IceCube observatory by an order of magnitude in size. This upgraded facility will increase the event rates of cosmic events from hundreds to thousands over several years making it possible to study the energy spectrum in more detail, identify the sources of astrophysical neutrinos as well as possibly the detection of cosmogenic neutrinos generated by ultra-high energy cosmic rays interactions during their travel towards the Earth. This major neutrino observatory facility has been dubbed IceCube-Gen2, a name that builds on the idea of a step forward in neutrino astronomy from the successful results of IceCube. In addition to the in-ice extension, the future observatory envisages as well the construction of an extension at the surface. This surface array will consist of scintillator panels in combination with radio antennas, deployed to complement the existing IceTop component to measure cosmic air showers and explore vetoing capabilities in order to reduce the large contamination of the atmospheric muon background in the Southern Sky. The facility also seeks to improve the sensitivity to neutrinos in the $10^{16} - 10^{20}$ eV energy range with the construction of an in-ice Radio Array. Because of the kilometer–scale attenuation length of radio waves in ice, a radio array that explores the coherently enhanced radio emission due to the Askaryan effect, can be built in a cost-effective way to detect neutrinos of energies of about $\sim 100$ PeV and above.

– **Surface scintillator array and SiPM**
As part of the IceCube-Gen2 facility a Surface Scintillator Array is being proposed. To complement c.q. improve the current technology used in IceTop, i.e. water tanks, the collaboration is exploring the possibility of using scintillator panels with a read-out consisting on SiPMs. A first phase will consist of upgrading the current IceTop detector with 37 scintillator panels. Several prototypes of these panels have been deployed at the South Pole. At the IIHE we are interested in the characterization and study of the charge response of these novel photodetector devices, the SiPMs. To this end, an optical lab has been installed at the IIHE where SiPM measurement will take place.

– **Radio Detection Techniques** The Askaryan Radio Array (ARA) is a first generation radio detector deployed at the South Pole aiming at the radio detection of cosmic neutrino interactions within the antarctic ice at about 100 PeV and above. On the other hand, IceCube is sensitive to high energy neutrinos up to several PeV, and consequently the energy region between PeV-EeV is largely unexplored. To fill this gap, novel detection techniques are being investigated at the IIHE towards a second generation radio detector, like the RNO-G array in Greenland. Further details about the radio detection of neutrino induced particle cascades can be found in a dedicated section elsewhere in this report.

## 2.7 Astroparticle Physics with the Pierre Auger Observatory

Stijn Buitink, Koun Choi, Ioana C. Mariş, Daniela Mockler, Katie Mulrey, Orazio Zapparrata

### 2.7.1 Ultra High Energy Cosmic Rays

Extremely energetic particles, ultra high energy cosmic rays (UHECRs), are entering the Earth's atmosphere constantly. Cosmic rays together with gamma rays, neutrinos and gravitational waves are part of the multi-messenger approach to investigate the highest energy phenomena in the Universe. After a century of experimental toil, the origin, the mass and the acceleration mechanisms of cosmic ray particles to energies above $10^{20}$eV still constitutes one of the main puzzles of modern astrophysics. Besides the astrophysical importance, these particles provide a unique way to study fundamental physics, like testing the Lorentz invariance violation and to study particle physics interactions at center of mass energies beyond the ones reached by man-made accelerators.

The Pierre Auger Observatory is a state-of-the-art experiment to measure UHECRs. It measures air-showers produced by cosmic rays with energies from $10^{17}$eV to above $10^{20}$eV. The results published by the Pierre Auger collaboration have contributed significantly to the understanding of cosmic rays via the measurements of their energy distribution, their arrival directions and their mass composition. Based on the results of the Pierre Auger Observatory it is clear now that the flux of cosmic rays is suppressed above 100EeV. The composition is evolving from a light one, dominated by proton at around 3EeV to a mixture of intermediate components. The arrival directions show a dipolar structure above 8EeV, with the dipol direction pointing in a different direction than the galactic center. This is a clear proof that the UHECRs are of extragalactic origin. The results of the photon limits have excluded the topological defects and the super heavy dark matter as origin of UHECRs. The Pierre Auger collaboration has also published the measurement of the proton-air and proton-proton cross-sections at a center of mass energy of 57TeV well above the energies reached at LHC, which allows this collaboration to test fundamental interactions at energies never reached by laboratory experiments.

Even though there has been an important advance in the UHECRs physics, several questions remain unanswered. The sources of cosmic rays have not been unveiled. This is a very difficult task as during the propagation UHECRs not only lose their energy in interactions with the cosmic microwave background, but also, being charged, they are deflected by the galactic and extragalactic magnetic fields. A hint that the UHECRs follow the starburst galaxies distribution ($\approx 4\sigma$) exists, but more statistics and a separation of the light component is required to be able to make a further step in this inquiry.

### 2.7.2 Research areas at IIHE

The IIHE has joined the Pierre Auger collaboration in February 2017 and in 2019 Belgium became a full membership country with two institutes VUB and ULB. The research is focused on the data analysis with a final goal to perform mass-enhanced anisotropy studies. A previous work on the energy spectrum of the UHERCs is also continued, with a focus on the comparison with the Telescope Array measurements.

The Pierre Auger Observatory exploits the phenomenon of extensive air-showers. Upon entering the atmosphere, a cosmic ray interacts with air nuclei and generates a cascade of secondary particles, a so called air-shower. The

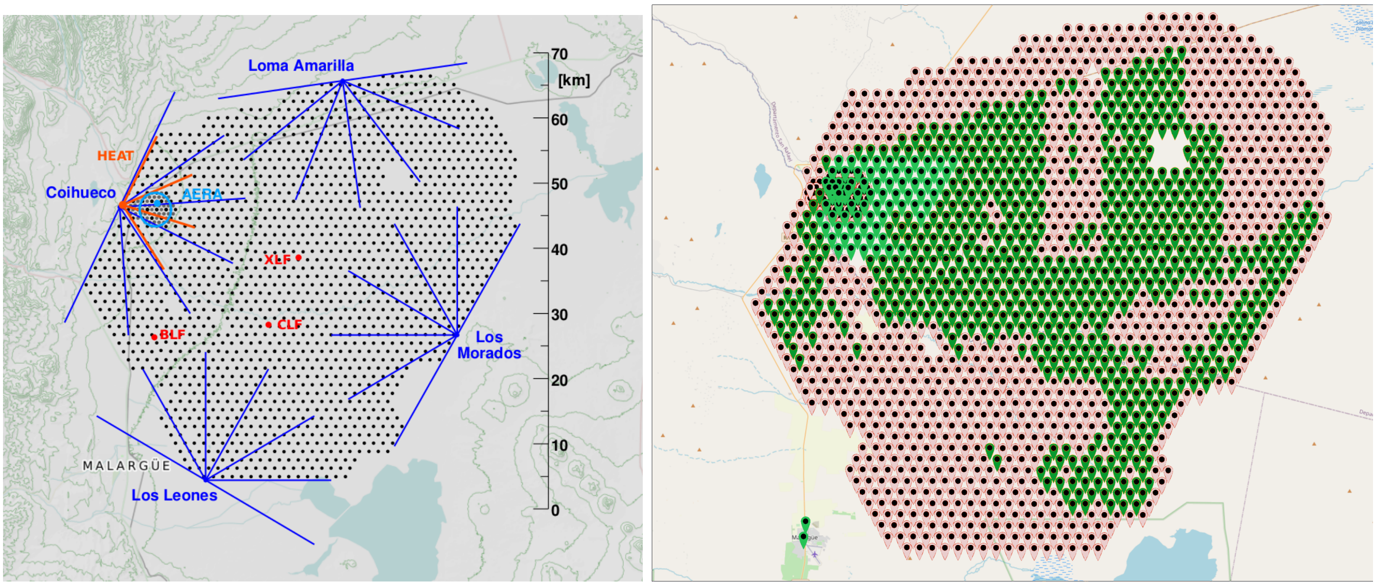


Figure 12: (left) The layout of the Pierre Auger Observatory. Each dot represents a surface detector, blue and red lines represent the field of view of the fluorescence telescopes. The red dots show the location of the atmosphere monitoring instruments. (right) The status of the deployment in December 2019, green markers represent the stations equipped with a scintillator.

Observatory is built as a hybrid detector, utilizing three complementary techniques to measure air-showers: the observation of the fluorescence signal produced by the secondary particles in the atmosphere, the measurement of a sample of the particles that reach the ground and the measurement of the radio emission. The layout of the detector is illustrated in Fig. 12. The distribution of particles on the ground is measured with 1664 water-Cherenkov detectors placed on a triangular grid over a surface of $3000 \mathrm{km}^2$ (SD) with a spacing of 1500m between the detectors. The longitudinal development of the air-showers is observed with 24 fluorescence telescopes (FD) placed on the border of the array. The Observatory was completed in 2008 and has since undergone some enhancements: an SD infill array with reduced detector spacing, a high elevation telescope (HEAT), buried scintillators (AMIGA) and a radio array (AERA). This allowed for extending the measurements of air-showers down to cosmic ray energies of less than $10^{17}$eV with multiple techniques.

The Observatory is currently undergoing the upgrade to *AugerPrime* to improve the composition sensitivity at the highest energies. A big part of the upgrade is the deployment of plastic scintillators on top of the surface detectors, assembling the so called Surface Scintillator Detector (SSD). The deployment has started in 2019 and there are currently 726 scintillators deployed (60%), as shown in Fig. 12. This upgrade aims at improving the capabilities of the surface detector to separate the muonic and electromagnetic components of the air-showers and thus to have a better resolution on mass sensitive variables.

Currently, the FD measurements provide a good sensitivity to the mass composition studies. However, as the FD operation is limited to moonless nights, the FD duty cycle is about 10%, and thus it cannot provide the statistics needed at the highest energies. The surface detector has a duty cycle of 100% and increasing its composition resolution will benefit the statistics at the highest energies. While upgrading the SD with scintillator detectors, the readout electronics of each SD detector is updated at the same time. With these upgrades, the Observatory is currently planning on running until 2030.

**Long term performance of the Observatory.** With an expected lifetime of the Observatory until 2030, the possible ageing and/or degradation of the surface detectors might influence the quality of data. I.C.Mariş is the task leader of the long term performance studies and the IIHE group, mostly Koun Choi and Orazio Zapparrata, has had a significant contribution to assess the evolution of the detector and predict the possible long-term effects on data quality. Two internal Auger notes have been written in the group related to the ageing of the detector. The studies related to the time evolution of the area over the peak of the signals showed that even if the average signal shape changes, this change will not affect too much the functioning of the surface detector. On the other hand, if the time distributions of the signals are exploited in the analysis, the systematic uncertainties might be significant. The latter is currently investigated. The results of the first study have been presented at the ICRC by Koun Choi for the Pierre Auger collaboration. This work has also been presented in presentations at three collaboration meetings.

**Towards the mass composition of UHECRs and AugerPrime** The AugerPrime scintillator data are currently taken using the old electronics. New electronics are being developed and Ioana Mariç was one of the members of the committee for the critical design review, being involved thus in the evaluation of the new FPGA boards. The new electronics are now in production phase and will be installed in the field within the next year. The IIHE has also been involved in the construction of the scintillators and two technicians from IIHE have been working for one month at the production site from the University of Grenoble. Almost all the SSDs have been produced and tested (90%) with about 60% of them installed in la Pampas Amarilla. The Observatory has already been taking data with these SSD and a first look at data and simulations is possible. A large effort within the collaboration is to develop methods that use deep neural networks (DNNs) to determine the mass composition of the cosmic rays. The training of the networks is based on ideal simulations that do not take into account the time evolution of the array. In this case, as the DNNs are fed with the time distribution of the signals in detectors, they might be sensitive to the ageing of the detectors. For the quatification of this effect Orazio Zapparrata is implementing as a novelty in Auger time-dependent simulations. The use of DNNs will provide a very good resolution on the determination of the mass composition of cosmic rays and the muon number in air-showers. This is the main research direction of the group.

**Mass enhanced full sky anisotropies** The second line of research at IIHE comprises of combining the measurements of the Telescope Array and the Pierre Auger Observatory with the aim at an analysis of the anisotropy with a full sky coverage. This work is done in collaboration with Peter Tinyakov (ULB), member of the Telescope Array collaboration. The energy spectra of the two experiments are very important for setting the relative energy scale of the two experiments which plays a crucial role in the The group at IIHE consists of experts on the determination of the energy spectrum of Auger and the comparison of the energy scales. Daniela Mockler and Ioana Mariş were involved in the analysis for the two energy spectra papers which are just being submitted by the collaboration. Moreover, based also on her previous expertise, Daniela presented at the ICRC the performance of the data reconstruction which is highly related to the energy spectrum. The spectra from the two experiments show a different flux shape at the highest energies. The group has been involved in understanding the differences between the two experiments: is it due to the observation of different parts of the sky or is it an experimental effect? The results are not conclusive by now, and the analysis is ongoing. Koun Choi started the analysis to assess the increase in sensitivity for the large scale anisotropies dipole by using a combined sky as well as the effect of including the mass composition information.

**Radio detection of air-showers** The VUB Auger group, Stijn Buitink and Katie Mulrey, is involved in the radio detection of air-showers and has two principal aims. The first is the cross-calibration of the energy scales between different experiments, which can be achieved using radio measurements of the radiation energy in an air shower. To this end, a paper is being prepared that compares the energy scales of LOFAR and Auger. A portable radio array is also being developed that will measure air showers at Auger and other sites, to make direct comparisons of the energy scales with low systematic uncertainties. The second aim is to participate in the deployment of the radio upgrade within AugerPrime. The radio emission is produced by the electromagnetic part of the air-showers and thus will help in the separation of the muonic and electromagnetic components of air-showers and as a result increase the resolution of mass sensitive parameters.

## 2.8 Air shower observations with LOFAR

(Tim Huege, Jörg Hoerandel, Katharine Mulrey, Hershal Pandya, Arthur Corstanje, Pragati Mitra and Godwin Krampah)

Finding the origins of cosmic rays and understanding the mechanism by which they are accelerated are key efforts in the field of astroparticle physics. Answering these complex questions require high-precision measurement using a variety of complementary techniques. Radio detection of extended air showers is a rapidly developing method that offers unique advantages over more traditional methods, combining the potential for accurate mass composition measurements with high duty cycle observations.

LOFAR is a digital radio telescope constructed in the Netherlands with satellite stations across Europe. It consists of thousands of dipole antennas, operating in the frequency range of $10 - 240$ MHz. It produces extremely detailed air shower radio data, by using the dense core region, or superterp, where 384 antennas are located within a circle of 320 m diameter.

A particle detector array, LORA, has been installed on the superterp and is used for triggering and reconstruction. Each antenna contains a ring buffer which is read-out in case of a trigger. The full waveform is stored for offline analysis.

During its first years of cosmic-ray observations, LOFAR has played a key role in our understanding of the radio emission processes in air showers and the development of new reconstruction techniques. We have produced the first high-resolution cosmic-ray mass composition measurement based on radio data as well as the most detailed comparisons of measured and simulated radio properties. We are currently finishing an update on the composition analysis based on more statistics and with reduced systematic uncertainties[1]. Another important and surprising result was that the strong electric fields inside thunderstorms leave complex imprints on the radio emission properties allowing a reconstruction of the strengths and directions of those fields. Moreover, the application of short-pulse reconstruction techniques to radio emission produced inside thunderstorm has kickstarted a new research direction: LOFAR is now the most accurate lightning radio imaging instrument in the world [2].

## LORA expansion

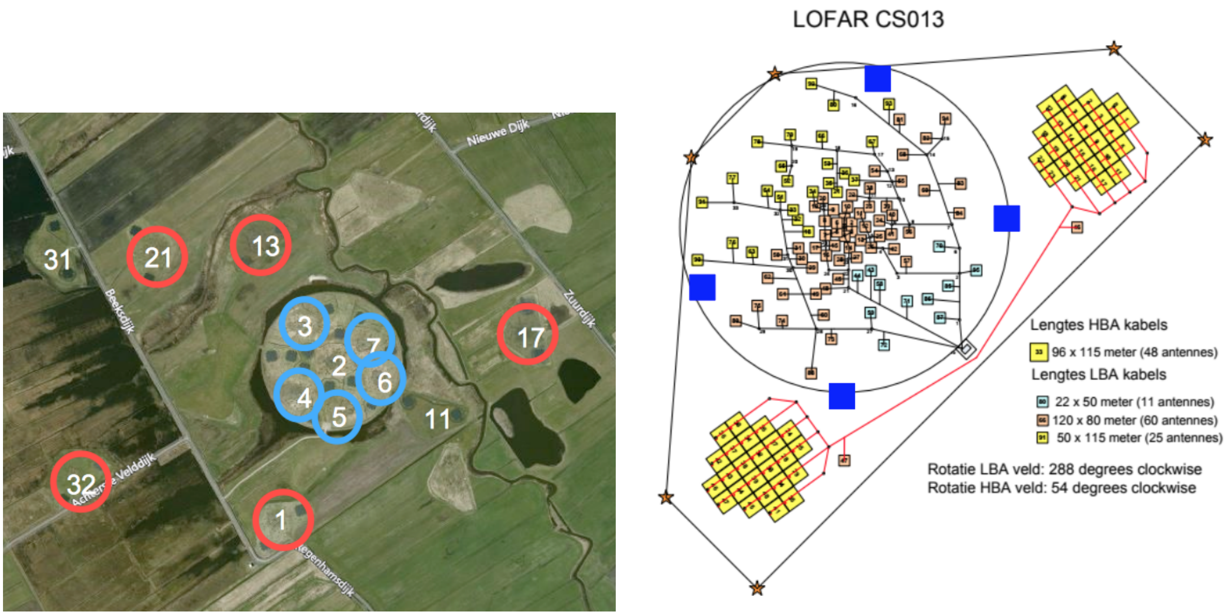


Figure 13: Left: Blue circles indicate stations that are part of the original LORA array. Red circles are stations at which new detectors are now installed. Right: At each new station, four detectors are deployed around the LBA field, indicated by the blue boxes.

We have built an expansion for the LORA triggering array that incorporates new detectors in five of the core stations around the superterp (see Figure 13). The new detector stations consist of the same scintillator detectors that were used in the original ones, but new and more stable digitizers have been used. Digitizers at the original stations are also scheduled to be replaced. In addition, a new main LORA DAQ computer has been installed to ensure stable operation and to allow for more complicated real-time triggering algorithms. The expansion will increase the number of measured cosmic-ray events with a strong radio signal by 45%, and also decrease the trigger bias against heavier elements prominent in low-energy events.

A study of the response of the scintillators has also been carried out. Measurements at the Karlsruhe Institute of Technology (KIT) muon tower have been performed to characterise the spatial response of the detectors, which will be taken into consideration in event simulation and reconstruction. Additionally, we calibrated all the new scintillators by measuring the energy deposits (integrated ADC counts) of single muons with the electronics that will be used in the field. System responses such as reflections in the cables are also treated in data processing, to ensure that trigger biases are handled correctly.

Currently, the new scintillator stations are functioning correctly and work is ongoing to include them in the global triggering system. To this end, a new LORA DAQ system has been developed that is currently being tested in the field.

## Antenna calibration on Galactic background

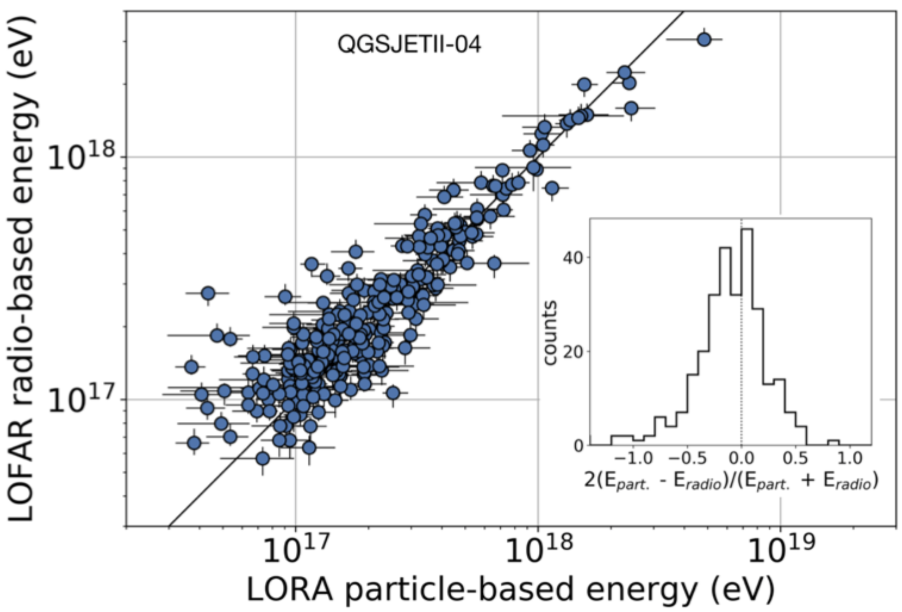


Figure 14: Comparison of energy reconstructed using radio and particle-based methods. Error bars indicate event-by-event uncertainties. Inset: Relative difference between particle-based and radio- based reconstructed energy.

Before 2019, the calibration of the low-band antennas was based on measurements with reference sources attached to drones or suspended from cranes. While these observations yielded a rough energy scale, they were not advanced enough to study the frequency spectrum of cosmic ray radio pulses. Frequency calibration of the low-band antennas is intrinsically hard because of the dipole design that comes with a strong resonance frequency. In addition, the spectrum of the reference source that we used in the previous calibration was also not known well enough.

We performed a full signal-chain calibration that incorporates different sources of frequency dependent noise using the Galactic background radiation as the calibration signal. With this new calibration, the frequency spectrum of the air shower radio pulses now matches the slope predicted by simulation[3].

The new calibration also allows for a more precise determination of the he absolute energy scale of the measured cosmic rays. Previously, the energy scale was based on LORA particle detector array. Our new calibration is in agreement with the LORA energy scale, but has much smaller systematic uncertainties. The uncertainty in the event-by-event uncertainty on the energy is reduced from $\sim 30\%$ to $\sim 15\%$.

Radio measurements of air shower energy also allow a precise cross-calibration between experiments. We have now shown that our energy scale is in agreement with that of the Pierre Auger observatory [4]. Energy cross-calibration between different cosmic-ray obervatories would be very beneficial for the field, and can be done with small systematic uncertainties by using a small portable array of radio antennas. The development of such an array is currently pursued in our group.

### Effects of atmospheric fluctuations

We have developed a new atmosphere pipeline that downloads weather information from an online database. These data are used to reconstruct the up-to-date atmospheric profiles for the density and index-of-refraction for each detected air shower. In addition, the CoREAS air shower simulation code has been modified to accept these complicated profiles. All modifications are made publicly available for the use of other air shower radio facilities, and are now used by various groups in the astroparticle community.

We have produced new simulations with realistic atmospheres for all our measured showers. We have found that the reconstruction of the atmospheric depth of the shower maximum (Xmax) is affected by these improvements. Especially at days of very low air pressure the reconstructed values deviate from the earlier ones that were based on linear corrections.

We have also included the effect of humidity in these simulations. While the humidity does not cause an observable effect in the LOFAR LBA range, simulations show that at higher frequencies (e.g. in the SKA-low 50-350 MHz band) the pulse amplitudes can change by $\sim 10\%$[5].

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## 2.9 RadNu: Radio detection of the cosmic neutrino flux project


Nick van Eijndhoven, Simona Toscano, Krijn de Vries, Stijn Buitink, Olaf Scholten, Tim Huege, Katie Mulrey, Simon de Kockere, Rose Stanley, Enrique Huesca Santiago


The IceCube neutrino detector has shown the potential of the neutrino as a cosmic messenger. Detecting the TeV-PeV cosmic neutrino flux, as well as the first possible source identification allowed us to have a first look into the extremely energetic processes of the most violent phenomena in our universe. Beyond PeV energies, however, IceCube runs low in statistics. Due to the steeply falling cosmic particle flux as function of energy, even the proposed IceCube-Gen2 facility, increasing IceCube's effective volume by roughly a factor of 10, does not allow us to probe cosmic neutrinos with reasonable statistics in the EeV region.

The primary interest to study this energy region is its link to the Ultra-High-Energy Cosmic-Ray flux detected at energies up to $10^{20}$ eV. Interactions of these extremely energetic cosmic rays either at their sources or during propagation to Earth will provide a guaranteed flux of cosmic neutrinos at EeV energies. Due to the steeply falling flux, huge detection volumes have to be observed to probe cosmic neutrinos at these extreme energies. This demands a signal which is able to traverse large distances through a dense interaction volume like ice, where its detector should be cost efficient. It is found that the radio signal with its attenuation length of O(km) and cheap radio antenna detectors provides the ideal signal to probe such large volumes.

### 2.9.1 Probing the radio emission from high-energy particle cascades in ice

In 1962 Askaryan already predicted that while a high-energy (cosmic-neutrino) induced particle cascade propagates in a medium, ambient electrons will be dragged along with the cascade due to the Compton scattering process. This effect induces a net macroscopic charge excess in the cascade front with dimensions O(cm-m) depending on the medium. Time variation of this excess charge in combination with Cherenkov effects will subsequently lead to coherent radio emission in the MHz-GHz regime. The method provides good detection efficiencies above 100 PeV.

To probe the cosmic neutrino flux at the highest energies, currently several Askaryan radio detectors are under development. At the IIHE, in 2018 we (re-)joined the Askaryan Radio Array (ARA) experiment, where it should be noted that in the past the group of Prof. Kael Hanson at the IIHE made very strong contributions to the first construction and analysis of the ARA experiment. The ARA experiment is still under construction deploying radio stations at a depth of roughly 50-150 below the ice surface at South Pole, with currently 6 out of the proposed 37 stations fully deployed. Besides the ARA experiment, VUB-IIHE became the main funder and one of the leading institutes of the proposed Radio Neutrino Observatory Greenland (RNO-G). As a pathfinder for the radio component of the proposed IceCube-Gen2 facility, this detector is complementary to ARA and aims to detect the cosmogenic neutrino flux with peak sensitivity at EeV energies. For this purpose, a simulation framework was set-up [1], and at the writing of this document, the RNO-G white paper is in preparation. First stations of the RNO-G detector are to be deployed in 2021 (due to the COVID-19 pandemic and the subsequent travel restrictions, foreseen deployment in 2020 was moved to the 2021 season).

In view of the ARA experiment, at the IIHE a simplified model has been constructed to show that a strong (background) signal from cosmic-ray air showers hitting a large altitude ice sheet is expected for in-ice radio detectors like ARA or RNO-G [2]. These investigations lead to the realization that coherent transition radiation applies equally well to a charge as to a current. This is of great importance for cosmic-ray air showers, which carry a net current that originates from charged leptons being deflected in Earth's magnetic field. Hence, if such an air shower hits a high-altitude surface such as the Antarctic ice sheet, typically at 2-3 km altitude, coherent transition radiation from this current cannot be ignored. A first study on the effect of this so-called geomagnetic transition radiation was performed, and it was shown that incorporating this into the models is crucial to understand the radio emission from cosmic-ray air showers hitting large altitude surfaces. More interestingly, it was shown that two, so-far unexplained events, detected by the ANITA baloon experiment, can be explained by coherent transition radiation in a perfectly natural way [3]. Where ANITA is located on a baloon high above the ice sheet, detection of this signal by an in-ice detector like ARA or RNO-G, would not only provide a means to study high-energy cosmic-ray air showers, but would immediately show the proof of concept for the neutrino detection channel and provide an in-nature calibration source for the detector. In 2019, therefore, a studie was initiated to construct a more detailed model of the radio emission from a particle cascade moving from air to ice, based on full Monte-Carlo (MC) cascade and radio-emission simulation. The particle output of the CORSIKA air shower simulation code, is used as input for a full MC GEANT4 simulation, providing a first full MC simulation of air shower cores penetrating large altitude ice sheets [4]. Current efforts focus on simulating the radio signal from the air shower itself, its transition into the ice, as well as the radio emission of the in-ice part of the cascade, providing a complete model of the emission seen at the detector.

With the ARA detector being in the vicinity of the IceCube detector a second very promising detection channel is investigated at the IIHE, which is the hybrid detection channel. In case of a charged current (CC) muon neutrino interaction, a large part of the initial energy is carried along by the associated lepton, in this case a muon. The remaining energy will produce a high-energy particle cascade at the interaction point. The combined detection of both the muon using the IceCube detector, as well as the particle cascade using ARA would provide an excellent handle on both energy as well as direction and flavour of the original neutrino. A first simulation study has been performed at the IIHE, showing that an event rate of a few neutrinos per year can be achieved for an optimised radio array with an energy threshold of 10 PeV. Currently, we are working on a full-chain simulation for the hybrid channel in collaboration with the radio group at Desy (Zeuthen, Germany) to establish the feasibility of this detection channel, and optimise the detector layout.

### 2.9.2 Radio detection of cosmic tau neutrinos through tau lepton decay in air

The CC interaction of an extremely energetic cosmic tau-neutrino in Earth, will induce a high-energy tau that is able to travel hundreds of meters up to even kilometers at EeV energies and above. Its subsequent decay will induce an electromagnetic cascade. In case of an Earth skimming tau neutrino interacting close to Earth's surface, or in a mountain, the associated tau lepton will be able to move out of the medium into our atmosphere to induce a horizontal or even upward moving particle cascade. The detection of this process is the aim of the GRAND experiment [5]. To acheive this goal, a proof of principle experiment, TREND, was performed to show the self-triggering capabilities of a stand-alone radio air shower detector [6]. Furthermore, a fast simulation method was developed to avoid the CPU heavy full MC simulations in light of sensitivity studies for the GRAND detector [7]. Currently, first stations are being deployed, with the goal to have 300 radio detection stations in the field near the end of 2020, that will be scaled up to a 10000 station configuration in the coming years.

### 2.9.3 Indirect radio detection of high-energy particle cascades in ice

As noted above, IceCube and even its proposed extensions IceCube-Gen2 will run low in statistics at the PeV level, where the Askaryan radio detectors have their peak sensitivity above 100 PeV. To cover the sensitivity gap in the PeV-EeV region, at the IIHE we investigate a new, novel, radar detection technique to probe neutrino induced particle cascades in this regime. This technique is based on the radio wave scattering off of the high-density ionization trail which is left behind by a neutrino induced particle cascade in ice. Since the scattered power scales directly with the transmitted power, the scattered signal strength is controlled externally which enables us to probe this signal at large distances for cascades at PeV energies and above [8]. As such the radar detection technique is a very promising method to cover the sensitivity gap in the PeV - EeV region.

The radar detection method, however, depends crucially on several parameters of the induced plasma, such as its lifetime and free charge collision rate. To probe these parameters and the efficiency of the method, in May 2018 a beam-test experiment was performed at the Stanford Linear Accelerator Center (SLAC). A bunch of $10^9$ electrons with 10 GeV/e energies, equivalent to a $10^{19}$ eV shower, was directed into a block of high-density polyetheleen. This material was used for practical reasons with its properties being very similar to ice. First data analysis has been performed showing very promising results [9]. These results lead to a second run in October 2019. Having characterized our main backgrounds in the first run, and using improved equipment, the results obtained in this second run lead to the first ever radar detection of a high-energy particle cascade [10]. These results lead to the formation of the Radar Echo Telescope (RET) collaboration under the lead of VUB-IIHE and the Ohio State University.

The Radar Echo Telescope collaboration aims to construct an in-nature radar detection set-up to: a) provide the proof of principle of the detection method in nature throug the RET-CR experiment, and b) detect the cosmic neutrino flux in the >PeV energy range. The RET-CR experiment aims to detect the air shower core penetrating the ice for which simulations have been initiated already in view of the Askaryan radio emission expected from this core. The RET-CR set-up will consist of a surface cosmic-ray detection set-up that will consist of a scintillator and radio detection unit to detect cosmic-ray air showers hitting the ice surface. Subsequently a trigger will be send to the in-ice radar detectors to detect the high-energy air shower core penetrating the ice. Currently, the RET-CR surface set-up is being developed at IIHE and detailed sensitivity studies have been initiated to determine the detector layout. Deployment is foreseen in 2021. Besides detector development, dedicated radar echo signal modeling and reconstruction studies have been initiated at the IIHE, already showing very promising sensitivities for the RET-CR and RET-N experiments. The RET-N detector will be deployed following the proof-of-principle for the radar echo technique in nature, given by the RET-CR detector.

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## 2.10 The milliQan experiment

(S. Lowette)

The milliQan experiment is a new effort that aims to install above the CMS cavern at the CERN LHC a small, standalone detector aimed at searching for millicharged particles. At the masses accessible to the LHC, the existence of new particles coupling through a feeble electromagnetic charge is poorly constrained, while they naturally arise in dark sector models coupled through a kinetically mixed dark photon. The experiment concept consists of an array of plastic scintillators coupled to photomultiplier tubes sensitive to a single photo-electron, where a depth segmentation is used to require hit coincidence as a tag of a particle originating from the LHC CMS interaction point. The collaboration formed around a letter of intent in 2016, and the VUB joined this effort in 2019. With the team of about 35 researchers from 11 institutes, a prototype had been installed in 2017, which took data in 2018 during and outside of LHC collisions, with as a main goal to validate the detector concept, learn about calibration procedures, and measure and monitor backgrounds in situ. In 2019, the data of this prototype has been analysed in view of a publication in the Spring after. In the mean time, funding is being applied for via various sources. At the IIHE, our involvement has been so far through a master student (VUB) who started in the Fall of 2019, studying internal radiation of the scintillators as well as cosmic backgrounds in more detail, in the absence of LHC collisions.

### 2.11 Phenomenology

(A. Ahmed, S. Junius, A. Mariotti, S. Najjari)

The phenomenology of Beyond Standard Model physics is an elemental topic of investigation in current high energy physics. The Large Hadron Collider (LHC) at CERN is exploring the fundamental physics at very high energy and will provide new informations about the dynamics at the base of the electroweak scale. At the same time, several experiments are looking for understanding the nature of the dark matter that populates our universe, through direct and indirect detection. The Pheno group at IIHE pursues outstanding research on Beyond Standard Model phenomenology, focusing on models addressing the hierarchy problem as well as on simplified models for dark matter and their experimental signatures.

The Pheno group has started in 2010 under the initiative titled "Supersymmetric models and their signatures at the Large Hadron Collider" financed through a five-year "Geconcerteerde Onderzoeksactie" (GOA) research project at the VUB. Now it is part of the Strategic Research Program "High Energy Physics" (HEP@VUB) whose purpose it to strengthen the research activity in high energy physics among the existing groups at VUB: Collider physics (CMS), Astroparticle physics (IceCube), High-energy Astrophysics (LOFAR), and Theoretical high-energy physics (TENA).

In 2019 the Pheno group comprised one VUB 100% ZAP member Prof. A. Mariotti, two postdocs A. Ahmed and S. Najjari, and one PhD students S. Junius. During 2019 the members of the pheno group have produced 5 scientific papers published on international peer reviewed Journals [1, 2, 3, 4, 5] and participated to a working group reports [6]. They have pursued different lines of research in BSM phenomenology achieving important results in a broad range of subjects.

In [1] the group has studied the reach of the LHC on scenarios featuring a well motivated new light scalar particle in the spectrum, that is the dilaton. Several simplified scenarios have been investigated and confronted with current and future experimental sensitivities.

In [2, 3, 4] the team has obtained results on extensions of the Standard Model addressing the hierarchy problem. In particular, novel phenomenological aspects of the Twin Higgs model have been explored in [2, 4]. The Twin Higgs is a BSM paradigm which assumes the existence of a twin sector of the SM, including a Twin Higgs boson.

The group has also contributed to the investigation of BSM physics scenarios which manifest in colliders with exotic signatures, specifically new long lived particles [5, 6]. In [5] it has been studied a class of simplified dark matter models characterized by a new mechanism of dark matter production in the early universe. These models lead to collider signatures such as charged tracks or displaced leptons, that have been analyzed.

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## 2.12 Computing and networking

( F. Blekman, O. Devroede, D. Dutrannois, S. Gérard, S. Rugovac, R. Rougny, A. Scodrani, P. Vanlaer)

### 2.12.1 Local computing services

The IIHE hosts a range of general IT services like DNS and DHCP servers for internet connectivity, web servers for the official website as well as all the intranet services. Most servers have been migrated to a virtual environment based on FOSS software: RedHat based OS, KVM virtualization and the OpenNebula orchestrator. This infrastructure consists of several hypervisors (for redundancy) as well as a High Availability (HA) storage.

The IIHE computing room serves as a disaster-recovery backup solution where important user data is preserved in case something happens to the main SISC (The VUB-ULB Shared ICT Service Center) datacenter.

The IIHE IT support team also manages a growing park of spare laptops, hence an image-based solution using a Clonezilla DRBL server has been implemented to efficiently administrate both Linux and Windows OS.

In 2019, particular care has been provided to all our WEB services. Specifically, security has been emphasized to be up-to-date with all current web standards, and an audit granted the highest possible rating. Along with this major overhaul of our web infrastructure, a couple of services have been added by the IT support team (implementation of Cachet for management of incidents and status of our services, and Matomo for web analytics).

### 2.12.2 Large scale and grid computing

The IIHE operates a computing cluster to which a large scale storage solution is attached. Both can be used through a local batch system (PBS), and via the Grid. The computing cluster offers resources and support to several large experiments (CMS, IceCube, SoLid, Auger, LOFAR, ENMR).

In 2019, the Brussels HTC/Grid team was comprised of four IT scientists (S. Rugovac, F.R.S.-FNRS; O. Devroede, VUB; S. Gérard, VSC, part time; Romain Rougny, UAntwerpen). Pascal Vanlaer (ULB) is in charge of the Belgian federated Tier2 sites and is the representative to the WLCG and CMS computing boards.

O. Devroede is the technical coordinator of the Belgian Tier2 sites. In addition, IIHE members act as representatives of ULB and VUB in regional bodies promoting the deployment of large computing infrastructures in Belgium: the 'Consortium des Equipements de Calcul Intensif' (CECI) in the Wallonia-Brussels Federation, and the 'Vlaams Supercomputer Centrum' (VSC) in Flanders. S. Rugovac is also involved in the work of the HEPiX Technology Watch Working Group, which is focused on monitoring relevant evolutions, both in terms of technology and markets, of the computing equipment that is relevant to the WLCG community.

By the end of 2019, the Tier2 provided around 8300 job slots to its community, spread over 200 worker nodes. Alongside that compute power, 30 storage nodes provided 6.8PB of mass storage to the users and the experiments.

#### 2.12.2.1 Overview per Experiment

**2.12.2.2 SoLid:** In order to transfer data from the 'SoLid' experiment, located in Mol at the SCK-CEN institute, to our mass storage, a dedicated 1Gbps network link was implemented by BELNET. This link also provides access and monitoring as well as control resources on-site, between the SoLid experiment and the Tier2 in Brussels. Since then, daily data transfers occur at full link speed: a day's worth of data-taking is transferred in approximately 8 hours. The DIRAC grid tools are used for transferring and cataloging the files, which allow easy replication of this critical data to ensure its safekeeping: copies are made on tape at the Tier1 in RAL (UK) and the Tier1 in Lyon (FR), and on disks at the Tier2 at Imperial College (UK).

In order to keep the storage used at a reasonable amount, an effort was made to compress the data extracted from the detector. The uncompressed stream is sent from the experiment to the T2 infrastructure, where the batch system is used to compress all the data files before they are sent out to the other computing centers. This has worked quite well, keeping usage of the storage at a similar amount of 500TB for 2019, and increasing speed of transfers to backup sites.

**2.12.2.3 IceCube:** The IceCube collaboration relies on its collaborating institutions to provide computing resources to generate simulated data sets. Producing these data sets requires vast amounts of CPU. In addition, specialized graphics processing units (GPU), containing the Tesla processing engine from NVIDIA, are used to simulate photon propagation in ice.

In 2019, due to the age of the GPU computing units in our cluster and their limited numbers, it was decided to retire them, as other sites in the collaboration have invested heavily in GPU computing units. On the other hand, brand new CPU compute hardware was bought to provide more computing capacity to local users and simulation through GRID.

**2.12.2.4 CMS:** The Brussels Tier2 contributes significantly to the computing resources of the CMS collaboration. It hosts the contributions of the UA, UGent, ULB and VUB universities, and is funded by the F.R.S.-FNRS and by the FWO. It is part of the Belgian federated Tier2 computing resources, together with another Tier2 site at UCL. The two sites support the analyses of the ∼100 Belgian CMS physicists, and have been a crucial tool to allow Belgian physicists to contribute in an important way in the analyses of the LHC data.

In 2019, the Grid-enabled storage system hosted 5.9 PB of CMS data. The data ranges from centrally managed datasets comprised of real collisions or Monte-Carlo simulations, to data produced by Belgian researchers. To that effect, 4 storage nodes adding a full 2PB of fresh storage where added in 2019.
As the collected data at the LHC keeps increasing, the analysis performed by the users has gradually become more and more I/O intensive, with sometimes tens of Terabytes read by a single researcher. Therefore, the network of the cluster is now fully utilizing the 40/100Gbps technologies of the core switches, with new storage nodes being connected to our network backbone directly with 100Gbps ports.

#### 2.12.2.5 Utilization of the cluster resources

The batch system performed quite well in 2019, with 54M of compute hours done on our infrastructure. Our batch system was fully utilized at around 88%. Due to some old hardware still being in production, a yearly average of 14% of our resources had to be forcefully kept down because of outside constraints (datacenter cooling issues, weather conditions).

As usual, GRID submission represented the bulk of our compute usage, with 43M compute hours, or 79.1% of the resources, while local users computed 11.3M hours. The GRID computing was mainly used by the CMS and IceCube Virtual Organizations, with respectively 39M and 3.5M compute hours (91.3% and 8% of the GRID computing), while the others mainly used our cluster in small bursts, accounting for the remaining 0.7%. On the other hand, local usage of our cluster compute resources is more diverse, with SoLid users having computed 1M hours (10.8%), IceCube users 0.7M hours (7.1%) and finally CMS still comprising the majority of our users with 8.2M compute hours (82.1%).

Other groups representing smaller experiments or new ones with yet few members, albeit rarely computing on the batch system, used our User Interfaces to perform their small calculations, in preparation to the future where bigger compute resources will be needed for them. This is also reflected in their usage of the mass storage alloted to them, which has slowly increased during 2019.

# 3 Activities

## 3.1 Contributions to experiments

### 3.1.1 Responsibilities in experiments

**Juan Antonio Aguilar Sánchez**

- IceCube local group leader and IceCube Institutional Board member
- Member of the IceCube Publication Committee

**Bugra Bilin**

- Participation in central shifts; DAQ and shift-leader, Tracker Detector on Call (DOC) shifts

**Freya Blekman**

- First ever CMS Physics Communications Officer (in Physics Coordination team)
- Top physics convener for the Future Circular Collider e+e- preparation study

**Emil Bols**

- CMS BTV L3 subgroup convener

**Stijn Buitink**

- co-PI of the LOFAR Cosmic Ray Key Science Project
- member of SKA High Energy Cosmic Particles Focus Group

**Barbara Clerbaux**

- Member and Chair of various Analysis Review Committees (ARC) in EXO, B2G, Higgs and Top groups in CMS
- Member of the JUNO Financial Board
- Member of the publication committee board (PUBCOM) for the EXOTICA and B2G groups
- ULB Deputy representative at the CMS board
- ULB representative at the JUNO board

**Paul Coppin**

- Maintainer of the GRBweb online tool

**Jorgen D'Hondt**

- Member of the CMS Collaboration Board
- PI of the Big Science project related to the Flemish contribution to the CMS experiment
- PI of the Hercules/EWI project related to the Belgian contribution to the CMS Tracker Upgrade project

**Catherine De Clercq**

- PI of VUB in the IceCube collaboration board

**Gilles De Lentdecker**

- Convener of the CMS GEM DAQ & Electronics Working Group

**Laurent Favart**

- Co-PI of the EoS project be.h
- Internal referee for CMS (ARC)

- Member of the CMS Publication Committee Board FSQ and PRF
- Member of the H1 Physics Board
- PI or co-PI of 4 FNRS IISN conventions

**Anastasia Grebenyuk**

- Convener of the "Jets and vector boson" sub-group of the LHC electroweak group
- Member of Analysis Review Committee of the SMP-18-015 analysis

**Godwin K. Krampah**

- Lunar Radio detection of Cosmic Rays and Neutrinos with LOFAR radio antennas and contact person

**Amandeep Kaur Kalsi**

- L3 in DQM-DC team responsible for providing JSONs for analysis, working in MET scanning team at CMS
- analysis: LFV decays of heavy mass resonances and QBH with full CMS Run2 data

**Tomáš Kello**

- Tracker Upgrade: Responsible for SW development for sensor TestBox

**Steven Lowette**

- Convener of the CMS Exotica Long-Lived Particle search group
- Flemish representative to the CMS Tracker Upgrade Steering Group
- VUB representative to the CMS Tracker Institution Board

**Inna Makarenko**

- Phase2 CMS OT Upgrade: FW developments for system tests

**Alberto Mariotti**

- Convener of WP3 (New scalar resonances) in EOS - BEH consortium

**Ioana Maris**

- Chair of the selection committee for the elections of the collaboration board chairs
- Editorial board member for four Auger papers
- Member of the critical design review committee for the new Auger eletronics
- Task leader of the long term performance of the Pierre Auger Observatory

**Daniela Mockler**

- IceCube monitoring shift
- Member of editorial board for the paper **A measurement of the cosmic ray energy spectrum above 2.5 EeV using the Pierre Auger Observatory**
- Member of editorial board for the paper **Features of the energy spectrum of cosmic rays above 2.5 EeV using the Pierre Auger Observatory**
- Member of editorial board for the paper **Reconstruction of Events Recorded by the Surface Detector of the Pierre Auger Observatory**

**Katie Mulrey**

- Leader for new Cross-Calibration Array for cosmic-ray energy scales

**Hershal Pandya**

- LOFAR Cosmic Ray Scintillator Array Data Acquisition

**Pierre-Alexandre Petitjean**

- PMT test shift in JUNO

**Nicolas Postiau**

- Validator for High-level Triggers for the CMS SMP analysis group
- Work on corrections on the missing transverse momentum, for the CMS MET group

**Simranjit Singh Chhibra**

- Analysis review committee member of 'search for top squark pair production in the dilepton final state using 137 $fb^{-1}$ of proton-proton collision integrated luminosity at $\sqrt{s} = 13$ TeV' [CMS-PAS-SUS-19-011]
- Author of CERN Courrier article titled 'CMS goes scouting for dark photons' [CERN Courier, Vol. 59, No. 6, Page 17, December 2019]
- Co-leader of the CMS muon high-level triggers group
- Contact person of 'search for a narrow resonance decaying to a pair of muons in proton-proton collisions at $\sqrt{s} = 13$ TeV' [Phys. Rev. Lett. 124, 131802 (2020)]

**Laurent Thomas**

- Contact person of a SUSY search with a same sign lepton pair (CMS-SUS-19-008)
- Convener (L2) of the Jets and Missing Et group of CMS (since July 2019)
- Convener (L3) of the Missing Et group of CMS (until July 2019)
- Member of the Analysis Review Committee of a paper describing the muon trigger performances in CMS

**Simona Toscano**

- Member of the IceCube publication committee

**Pascal Vanlaer**

- Academic person in charge of the ULB-VUB CMS Tier-2 computing cluster
- CMS ULB team leader
- CO-PI of EoS project be.h
- Co-coordinator of work package 2 of EoS be.h project
- Member and chair of CMS analysis review committees (ARCs)
- Member of the CMS PhD award committee
- Member of the CMS Tracker Institution Board
- Promotor-spokesperson of the FNRS IISN convention CMS Phase 2 upgrade (UCL-ULB) 4.4502.17
- co-promotor of FNRS IISN convention Frontier physics at the LHC 4.4502.15

**Liam Wezenbeek**

- Egamma POG EPR work
- TAU POG HLT EPR work

**Yifan Yang**

- JUNO BEC - L3 management

**Orazio Zapparrata**

- SD Shift, remote (Brussels), from 16/10/2019 to 31/10/2019

### 3.1.2 Presentations in collaboration meetings

**Juan Antonio Aguilar Sánchez**

- BSM summary working group - IceCube - Chiba, Japon from 14/09/2019 to 22/09/2019

**Sebastian Baur**

- Dark Matter sensitivity with the IceCube Upgrade - IceCube - Madison, USA from 30/04/2019 to 04/05/2019
- Event Selection for the IceCube Upgrade - Icecube - Madison, USA from 30/04/2019 to 04/05/2019

**Koun Choi**

- A/P Jumping PMTs, Long term performance ICRC2019 poster preparation - Pierre Auger - Malargue 11/03/2019

**Paul Coppin**

- GRB precursor stacking analysis - IceCube - Chiba, Japan 17/09/2019
- Kinematic angle in neutrino interactions - IceCube - Madison, United States 03/05/2019
- Neutrinos from GRB precursors - IceCube - Madison, United States 02/05/2019

**Pablo Correa**

- Ultra-Luminous Infrared Galaxies - Analysis Update - IceCube - Chiba, Japan from 14/09/2019 to 20/09/2019

**Gilles De Lentdecker**

- GE1/1 Installation Readiness Review - CMS - CERN 27/06/2019

**Nadège Iovine**

- Combined ANTARES-IceCube search for dark matter from the Galactic Centre - IceCube - Madison - USA 04/05/2019
- Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Centre with ANTARES and IceCube - IceCube - Chiba - Japan 18/09/2019

**Ioana Maris**

- A statistical method to combine the energy spectra - Pierre Auger - Malargue 24/11/2019

**Pragati Mitra**

- presentation at LOFAR cosmic ray group meeting - LOFAR - zoom meeting 02/01/2019

**Daniela Mockler**

- ICRC contribution: SD Reconstruction - Pierre Auger Collaboration - Nijmegen (Netherlands) 24/06/2019

**Rachel Simoni**

- SNR LMC N132D study with H.E.S.S. - H.E.S.S. - Krakow 16/04/2019

**Laurent Thomas**

- MET algorithms (CMS JetMET workshop) - CMS - Hamburg, Germany 09/04/2019
- Physics and the trigger menu at CMS (ATLAS/CMS trigger cross talks) - CMS - CERN 02/10/2019
- Triggers in the JetMET, beyond second generation and Supersymmetry groups: Run 2 feedback and Run 3 plans (CMS trigger workshop) - CMS - CERN 20/03/2019

**Yifan Yang**

- BEC FDR - JUNO - Beijing 07/11/2019
- BEC status - JUNO - Beijing 21/07/2019
- BECv4.0 JUNOEU - JUNO - Brussels 24/05/2019
- Back end card status - JUNO - Shanghai 12/01/2019
- becv4.0 design - JUNO - Rome 11/04/2019

**Orazio Zapparrata**

- The time evolution of the number of stations - Auger - Malargüe (Argentina) 18/11/2019

## 3.2 Completed Master and PhD theses

**Barbara Clerbaux**

- Yann Hugo
  Business plan Pousses et Vous
  Phd thesis, ULB, June 2019.
- Xuyang Gao
  Search for high mass resonances in electron-electron and electron-muon final states with CMS data and study of exotic states with BESIII data
  Phd thesis, ULB, June 2019.
- Wenxing Fang
  Search for new physics in dilepton final states at the CMS experiment
  Phd thesis, ULB, June 2019.
- David Vannerom
  Search for new physics in the dark sector with the CMS detector
  Phd thesis, ULB, September 2019.
- Maxence Draguet
  Searching for New Physics in Dilepton Events A Study of the Photon-Induced Process
  Master thesis, ULB, June 2019.

**Laurent Favart**

- Max Vanden Bemden
  Study of the Proton Transverse Momentum Distributions with the Parton Branching Method
  Master thesis, ULB, September 2019.

**Steven Lowette**

- David Vannerom
  Search for new physics in the dark sector with the CMS detector
  Phd thesis, ULB, September 2019.

**Alberto Mariotti**

- Seth Moortgat
  When charm and beauty adjoin the top
  Phd thesis, ULB, May 2019.

**Pascal Vanlaer**

- Alexandre De Moor
  Recherche de production resonante de matiere noire a l'experience CMS
  Master thesis, ULB, June 2019.
- Hugo Delannoy
  Search for a heavy scalar boson in the ZZ-¿2l2v channel with the CMS experiment at the LHC using 2016 data at 13 TeV
  Phd thesis, ULB, April 2019.

### 3.3 Representation in scientific councils and committees

**Aqeel Ahmed**

- EOS steering board meeting, representative of EOS postdocs

**Juan Antonio Aguilar Sánchez**

- MC member of Belgium of the COST Action CA18108-14
- Member of the Scientific Committee of the Centre de Physique des Particules de Marseille (CPPM) France

**Freya Blekman**

- Chairperson ATLAS-Canada Standing Review Committee, Natural Sciences and Engineering Research Council of Canada (NSERC), Canada
- Review panel on physics, RCN, Norway
- Review panel on subatomic physics, space physics and astronomy (NT-3), Swedish Research Council, Sweden
- Visiting Researcher at Oxford University

**Barbara Clerbaux**

- Belgian representative to the European Committee for Future Accelerators (ECFA)
- Chairperson of the JUNO award committee
- Member of the FWO (Fonds Wetenschappelijk Onderzoek) selection commission (expert)
- Member of the ULB comittee for the selection of permanent position (academic chaire)
- Member of the selection committee for the ULB Director General
- PI of the ULB-exp group for the Excellence Of Science (EOS) : The H boson gateway to physics beyond the Standard Model
- President or member of various PhD committees, ULB
- Referee for the Phys. Lett. B Journal

**Pablo Correa**

- IIHE-VUB representative in the committee for the organisation of the Solvay colloquia

**Jorgen D'Hondt**

- Chair of the European Committee for Future Accelerators (ECFA)
- Co-organiser of the European Strategy Open Symposium for particle physics
- Co-organiser of the JENAS event (Orsay, 2019)
- Deputy PI of the be.h Excellence of Science project
- FWO delegate in the International Oversight Funding Group (IOFG) of the IceCube experiment
- Local organiser of the Future Circular Collider (FCC) week in Brussels in June 2019
- Member and representing Europe in the International Committee for Future Accelerators (ICFA)
- Member of ApPEC
- Member of NuPECC
- Member of several international advisory boards for conferences and workshops
- Member of the CERN Council
- Member of the CERN Finance Committee

- Member of the CERN Science Policy Committee
- Member of the Dutch Panel for Large-Scale Research Infrastructures (the Netherlands)
- Member of the ECFA working group on Higgs at Future Colliders
- Member of the European Physical Society (HEPP) board
- Member of the European Strategy Group of the European Strategy for Particle Physics
- Member of the International Advisory Board of NIKHEF
- Member of the Physics Preparatory Group of the European Strategy for Particle Physics
- Member of the Secretariat of the European Strategy for Particle Physics
- Member of the VUB committee for Future Education Innovations
- Member of the VUB steering group for setting up an Honour Program
- Member of the review panel of the Spanish funding agency related to high-energy physics
- Permanent member of the International Advisory Board of the workshop series on Top Quark Physics
- Promotor of the Strategic Research Program HEP@VUB

**Catherine De Clercq**

- Member of the FNRS scientific committee *Hautes et Basses Energies*
- Representative of FWO in the APPEC General Assembly
- Representative of FWO in the CERN-CMS Resources Review Boards

**Gilles De Lentdecker**

- Referee for the Agence Nationale de Recherche (ANR), France
- Referee for the IEEE Journal
- Vice-President of the Belgian Physical Society

**Laurent Favart**

- FNRS delegate to the IOFG (International Oversight and Finance Group) of the IceCube experiment
- FNRS representation in the Finance Board of the Pierre Auger Collaboration
- Member of the Belgian committee for the selection of CERN fellows
- Representative of the FNRS at the ApPEC (Astroparticle Physics European Consortium)

**Tomáš Kello**

- PhD representative for EoS be.h program

**Steven Lowette**

- Member of the Local Organizing Committee for the EPSHEP2019 conference
- Member of the Organizing Committee for the 6th LHC LLP Workshop
- Member of the Scientific Advisory Board of the ALPS conference
- Member of the organizing committee for the Belgian-Dutch-German Graduate School in Particle Physics

**Louis Moureaux**

- ECFA Young Scientists Forum
- Scientific Secretary for the Heavy Ions session at EPS 2019

**Laurent Thomas**

- Member of the Early Career forum of the European Particle Physics Strategy Update

**Nick Van Eijndhoven**

- Adviser for the National Research Foundation (NRF) of South Africa
- Belgian representative in the HEP board of the European Physical Society
- Member of the IceCube Collaboration Board
- Scientific Programme Committee member of the European Cosmic Ray Symposium
- Scientific Programme Committee member of the International Cosmic Ray Conference

**Pascal Vanlaer**

- Referee for Physics Letters B
- Representative of the ULB in the CECI interuniversity high-performance computing infrastructure (FUNDP, UCL, ULB, ULg, UMons)

## 3.4 Diffusion of scientific results

### 3.4.1 Oral presentations at conferences and schools

**Aqeel Ahmed**

- A light scalar window at the LHC, EoS be.h meeting - Brussels, Belgium 18/06/2019
- Dilaton portal to composite twin Higgs, SCALARS 2019 - Warsaw, Poland from 11/09/2019 to 14/09/2019
- Neutral Naturalness at the LHC, PLANCK 2019 - Granada, Spain from 03/06/2019 to 07/06/2019

**Juan Antonio Aguilar Sánchez**

- BSM searches with IceCube, HEP at VUB - Brussels 24/10/2019
- Beyond Standard Model Searches in IceCube, NuFACT 2019 - Daegu, South Korea from 26/08/2019 to 30/08/2019
- Dark Matter Searches in IceCube, 31st Rencontres de Blois 2019 - Blois, France from 03/06/2019 to 07/06/2019

**Sebastian Baur**

- Indirect searches for dark matter with IceCube, Workshop on Particle Physics with Neutrino Telescopes - Uppsala, Sweden from 07/10/2019 to 09/10/2019
- Measurements of the very-forward energy in pp collisions at the LHC and constraints for cosmic ray air showers, International Cosmic Ray Conference - Madison, USA from 24/07/2019 to 01/08/2019
- Recent results from LHC (and SPS) and their implication for cosmic ray physics, COSPA meeting - Brussels, Belgium 04/10/2019

**Diego Beghin**

- Searches for new resonances decaying to leptons, photons or jets with CMS, EPS-HEP - Ghent 11/07/2019

**Bugra Bilin**

- Measurements of V+heavy flavor with CMS, LHCP2019 - Puebla Mexico 21/05/2019
- V+jets production and Jet cross sections at CMS and tests of QCD, Low-x 2019 - Nicosia Cyprus 29/08/2019

**Emil Bols**

- Deepjet training improvements, CMS Flavour Tagging Workshop - Dubrovnik from 29/04/2019 to 03/05/2019

- Machine Learning Techniques for Heavy Flavour Tagging, CMS ML Workshop - CERN from 17/06/2019 to 19/06/2019
- Machine Learning Techniques for Heavy Flavour Tagging at the CMS experiment, IML - CERN from 15/04/2019 to 18/04/2019

**Barbara Clerbaux**

- The JUNO experiment and its electronics readout system, EPSHEP 2019 - Ghent from 10/07/2019 to 17/07/2019

**Anastasia Grebenyuk**

- WG4 Summary, DIS2014 - Turin, Italy 12/04/2019

**Nadège Iovine**

- Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Centre using ANTARES and IceCube, ICRC 2019 - Madison - USA 30/07/2019
- Combined search for dark matter from the Galactic Center with ANTARES and IceCube, IRN Terascale - Brussels - Belgium 18/10/2019

**Aamir Irshad**

- Topical Workshop on Electronics for Particle Physics, TWEPP 2019 - Santiago de Compostela from 02/09/2019 to 06/09/2019

**Tomáš Kello**

- $H \to WW*$ anomalous couplings on-shell analysis, EoS PhD Days - Louvain-la-Neuve, Belgium 12/11/2019

**Steven Lowette**

- A search for millicharged particles at the LHC, 6th LHC Long-Lived Particle Workshop - Ghent, Belgium 29/11/2019
- Dark Matter Searches at the LHC, 3rd International Turkey-Iran Joint Conference on LHC Physics - Istanbul, Turkey 10/06/2019
- Dark Matter Searches at the LHC, LeptonPhoton2019 - Toronto, Canada 08/08/2019

**Alberto Mariotti**

- Beyond the Standard Model and Supersymmetry, HASCO Summer School 2019 - Gottingen 21/07/2019
- Feebly-interacting dark matter and long-lived particles at the LHC, Invited talk - Roma 3 University 21/11/2019
- Feebly coupled Dark Matter and long-lived particles at the LHC, Invited talk - DESY 06/05/2019

**Ioana Maris**

- Recent results from the Pierre Auger Observatory, EPSHEP - Ghent 15/07/2019

**Daniela Mockler**

- Measurement of the cosmic ray spectrum with the Pierre Auger Observatory, Annual meeting of the BPS - Brussels (Belgium) 22/05/2019
- The Pierre Auger Observatory - Latest results and future perspectives, International Conference on New Frontiers in Physics - Kolymbari (Crete) 29/08/2019
- The Pierre Auger Observatory - Latest results and future perspectives, COSPA - Brussels (Belgium) 04/10/2019

**Louis Moureaux**

- Prospects for measurements of H/Z production cross section ratios using CMS Run II data, Workshop on Resummation, Evolution, Factorization (REF 2019) - Pavia (I) from 25/11/2019 to 29/11/2019

- Prospects for measurements of H/Z production cross section ratios using CMS Run II data, Low-x 2019 - Lefkosía (CY) from 26/08/2019 to 31/08/2019

**Katie Mulrey**

- Detecting Cosmic Rays with LOFAR, SKA Science Meeting - Manchester, UK 10/04/2019
- The energy scale of cosmic rays detected with LOFAR, ICRC 2019 - Madison, WI, USA 27/07/2019

**Andrey Popov**

- Searches for rare Higgs decays and production modes at the LHC, Les rencontres de physique de la vallée d'Aoste - La Thuile, Italy from 10/03/2019 to 16/03/2019
- Search for $\Phi \to t\bar{t}$ with the CMS experiment, Higgs Couplings - Oxford, UK from 30/09/2019 to 04/10/2019
- Statistical fluctuations and artificial constraints on systematic uncertainties, IRN Terascale - Brussels, Belgium from 16/10/2019 to 18/10/2019

**Rachel Simoni**

- Upper limits on gamma-ray emission from supernovae observed with H.E.S.S., EPS-HEP - Ghent 11/07/2019

**Elizabeth Starling**

- Electronics System of the CMS GE1/1 Muon Upgrade and Performance of the Slice Test During the 2017-18 LHC Run, Topical Workshop for Electronics in Particle Physics - Santiago de Compostela, Spain from 02/09/2019 to 06/09/2019
- GE1/1 Sustained Operations Investigations, BPS Annual Meeting - Brussels, Belgium 22/05/2019
- Results from the Compact Muon Solenoid GE1/1 Slice Test and Status of the Installation and Commissioning of the GE1/1 Detectors, IEEE Nuclear Science Symposium and Medical Imaging Conference - Manchester, UK from 26/10/2019 to 02/11/2019

**Laurent Thomas**

- CMS Status Report, LHC Committee Open Session - CERN 20/11/2019
- Evolution and some prospects in BSM searches at CMS, International Research Network Terascale - Brussels, Belgium 17/10/2019
- LHC results and prospects on SM Higgs measurements, BE-HEP Solstice meeting - Liège, Belgium 21/06/2019
- Searches for strong Supersymmetry at CMS, European Physical Society Conference on High Energy Physics (EPS-HEP 2019) - Ghent, Belgium 11/07/2019

**Simona Toscano**

- High-energy neutrinos of cosmic origin, BLV2019 - Madrid (Spain) from 21/10/2019 to 24/10/2019
- Unveiling the mysteries of the high-energy universe with neutrinos in Antarctica., EWASS 2019 - Lyon (France) from 24/06/2019 to 28/06/2019

**Yifan Yang**

- Readout system for CMS triple-gem detectors, invited seminar for Chinese Academy of Sciences Jindai Physics Institute - Lanzhou 18/07/2019

### 3.4.2 Poster presentations at conferences and schools

**Sebastian Baur**

- Dark matter searches with the IceCube Upgrade, International Cosmic Ray Conference - Madison, USA from 24/07/2019 to 01/08/2019
- Probing physics beyond the standard model with IceCube, Joint ECFA-NuPECC-ApPEC Seminar - Orsay, France from 14/10/2019 to 16/10/2019

**Koun Choi**

- Long Term Performance of the Pierre Auger Observatory, ICRC2019 - Madison from 24/07/2019 to 01/08/2019

**Barbara Clerbaux**

- Design of the back end card for the JUNO experiment, TWEPP 2019 (Topical Workshop on Electronics for Particle Physics) - Santiago de Compostela from 02/09/2019 to 06/09/2019
- The backend electronics card of teh JUNO experiment, EPS HEP 2019 - Ghent from 10/07/2019 to 17/07/2019

**Paul Coppin**

- IceCube search for high-energy neutrinos produced in the precursor stages of GRBs, International Cosmic Ray Conference (ICRC) - Madison, United States from 25/07/2019 to 26/07/2019

**Pablo Correa**

- Investigation of Ultra-Luminous Infrared Galaxies as Obscured High-Energy Neutrino Source Candidates, International Cosmic Ray Conference - Madison, WI, USA from 24/07/2019 to 01/08/2019

**Aamir Irshad**

- 6th International Conference on Micro-Pattern Gaseous Detectors, MPGD 2019 conference - La Rochelle from 05/05/2019 to 10/05/2019
- 2019 IEEE Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC), 2019 IEEE NSS-MIC - Manchester, UK from 26/10/2019 to 02/11/2019

**Pragati Mitra**

- Reconstructing air shower parameters with LOFAR using event specific GDAS atmospheres, ICRC - Madison from 24/07/2019 to 1/08/2019

**Daniela Mockler**

- Reconstruction of vertical events recorded by the surface detector of the Pierre Auger Observatory, ICRC - Madison (WI, USA) from 30/07/2019 to 31/12/2019

**Katie Mulrey**

- Extension of the LOFAR Radboud Air Shower Array, ICRC 2019 - Madison, WI, USA 28/12/2019

**Pierre-Alexandre Petitjean**

- THE BACKEND ELECTRONICS CARDS OF THE JUNO EXPERIMENT, EPS-HEP - Gent, Belgium from 10/07/2019 to 17/07/2019

**Rachel Simoni**

- Upper limits on gamma-ray emission from supernovae observed with H.E.S.S., An Odyssey in Space after Stellar Death II - Chania, Greece from 03/06/2019 to 08/06/2019

**Elizabeth Starling**

- GE1/1 Sustained Operations Investigations, Topical Workshop for Electronics in Particle Physics - Santiago de Compostela, Spain from 02/09/2019 to 06/09/2019

**Simona Toscano**

- Hybrid detection of high-energy cosmic neutrinos with the next generation neutrino detectors at the South Pole., ICRC 2019 - Madison, WI (USA) from 24/07/2019 to 01/08/2019

**Yifan Yang**

- Design of the back end card for the JUNO experiment, TWEPP2019 - Santiago de Compostela from 02/09/2019 to 06/09/2019

## 3.5 Scientific training

### 3.5.1 Attendance to conferences and workshops

**Aqeel Ahmed**

- Sixth workshop of the LHC LLP Community - Searching for long-lived particles at the LHC - Ghent, Belgium from 27/11/2019 to 29/11/2019
- SOLVAY WORKSHOP - The Dark Side of Black Holes - Brussels, Belgium from 03/04/2019 to 05/04/2019

**Sebastian Baur**

- Joint ECFA-NuPECC-ApPEC Seminar - Orsay, France from 14/10/2019 to 16/10/2019
- Workshop on Particle Physics with Neutrino Telescopes - Uppsala, Sweden from 07/10/2019 to 09/10/2019
- International Cosmic Ray Conference - Madison, USA from 24/07/2019 to 01/08/2019
- COSPA meeting - Brussels, Belgium 04/10/2019

**Bugra Bilin**

- REF-2019 - Pavia Italy from 25/11/2019 to 29/11/2019
- DIS-2019 - Turin Italy from 08/04/2019 to 12/04/2019

**Emil Bols**

- CMS Flavour Tagging Workshop - Flavour tagging at CMS - Dubrovnik from 29/04/2019 to 03/05/2019
- FCC Week 2019 - Future Colliders - Brussels from 24/06/2019 to 28/06/2019
- CMS ML Workshop - Machine Learning at CMS - CERN from 17/06/2019 to 19/06/2019
- IML - Machine Learning in high energy physics - CERN from 15/04/2019 to 18/04/2019

**Koun Choi**

- EPS2019 - particle physics and astroparticle physics - Ghent from 10/07/2019 to 17/07/2019

**Barbara Clerbaux**

- EOS Winter Solstice meeting - co-organiser - ULB 19/12/2019
- JUNO Collaboration meeting - Shanghai, China from 13/01/2019 to 18/01/2019
- EOS Summer Solstice meeting - ULiège 21/06/2019
- JUNO electronic meeting - Roma, Italy from 10/04/2019 to 12/04/2019
- EOS WG5 meeting - Antwerpen 02/05/2019
- ESU 2019 - CERN council Open Symposium on the Update of the European Strategy for Particle Physics - Granada, Spain from 13/05/2019 to 16/05/2019

- EPS-HEP 2019 - Co-chair of the international EPS HEP 2019 conference (about 800 participants) - Ghent from 10/07/2019 to 17/07/2019
- EU JUNO 2019 - Organiser of the European JUNO workshop (60 participants) - ULB, Brussels from 23/05/2019 to 24/05/2019
- BPS 2019 - Session organiser of the Belgian Physical Society annual meeting - ULB 22/05/2019

**Paul Coppin**

- International Cosmic Ray Conference (ICRC) - Madison, United States from 24/07/2019 to 1/08/2019

**Pablo Correa**

- IceCube Spring Collaboration Meeting - Madison, WI, USA from 29/04/2019 to 04/05/2019
- International Cosmic Ray Conference - Madison, WI, USA from 24/07/2019 to 01/08/2019
- IceCube Fall Collaboration Meeting - Chiba, Japan from 14/09/2019 to 20/09/2019

**Simon De Kockere**

- IceCube Collaboration Meeting - Chiba, Japan from 13/09/2019 to 20/09/2019
- ICRC - UW Madison, Wisconsin, USA from 24/07/2019 to 01/08/2019
- IceCube Collaboration Meeting - Madison, Wisconsin, USA from 27/04/2019 to 04/05/2019
- COSPA - Brussels, ULB Campus 04/10/2019
- Radio-Workshop - Simulation techniques for the detection of air showers and neutrinos trhough radio with in-ice detectors - DESY, Zeuthen, Germany from 18/06/2019 to 20/06/2019

**Gilles De Lentdecker**

- TWEPP 2019 Workshop - Particle Physics Electronics - Saint-Jacques de Compostelle from 02/09/2019 to 06/09/2019

**Laurent Favart**

- Jenas 2019 - First Joint ECFA-NuPECC-ApPEC Seminar - Orsay - Paris from 14/10/2019 to 16/10/2019
- REF 2019 - Organisation of the Workshop on Resummation, Evolution, Factorization - Pavia - Italy from 25/11/2019 to 29/11/2019

**Anastasia Grebenyuk**

- DIS2019 - Turin, Italy from 08/04/2019 to 12/04/2019

**Enrique Huesca Santiago**

- COSPA - ULB 04/10/2019

**Aamir Irshad**

- Workshop - CMS GEM workshop - CERN from 30/09/2019 to 04/10/2019
- Workshop - Cadence Sigrity Workshop CERN - CERN, Switzerland 21/02/2019
- Conference - Embedded World Exhibition  Conference Nuremberg, Germany (ULB Funded) - Nuremberg, Germany from 27/02/2019 to 28/02/2019
- Workshop - Intel HLS Workshop CERN - CERN, Switzerland 16/05/2019
- Workshop - Software Carpentry Workshop - CERN, Switzerland from 27/11/2019 to 29/11/2019

**Sam Junius**

- Belgian Physical Society 2019 - Belgian Physical Society - Brussels, Belgium 22/05/2019

- The Dark Side of Black Holes - Dark side of black holes - ULB, Brussels from 03/04/2019 to 05/04/2019
- European Physical Society Conference on High Energy Physics (EPS-HEP) - European Physical Society Conference on High Energy Physics (EPS-HEP) - Ghent, Belgium from 10/07/2019 to 17/07/2019
- 2nd GNN Workshop on Indirect Dark Matter Searches with Neutrino Telescopes - Indirect Dark Matter Searches with Neutrino Telescopes - VUB, Brussels from 13/11/2018 to 14/12/2018

**Tomáš Kello**

- EPS-HEP2019 - EPS-HEP2019 - Ghent, Belgium from 10/07/2019 to 17/07/2019
- EoS PhD Days - Workshop - EoS PhD Days - Workshop - Louvain-la-Neuve, Belgium from 12/11/2019 to 14/11/2019
- FCC Week - FCC Week - Brussels, Belgium from 24/06/2019 to 28/06/2019
- HWW workshop - HWW workshop - CERN, Switzerland from 14/10/2019 to 15/10/2019

**Mostafa Mahdavikhorrami**

- The fifth International Future Circular Collider (FCC) - Conference - Brussels from 24/06/2019 to 28/06/2019
- The European Physical Society Conference on High Energy Physics (EPS-HEP) - Conference - International Convention Center and Ghent University - Campus Ledeganck, Ghent from 10/07/2019 to 12/07/2019
- Higgs and Effective Field Theory (HEFT) - Workshop - Center for Cosmology and Particle Physics Phenomenology (CP3) from 15/04/2019 to 18/04/2019

**Daniela Mockler**

- IceCube collaboration meeting - Chiba (Japan) from 16/09/2019 to 20/09/2019
- IceCube collaboration meeting - Madison (WI, USA) from 27/04/2019 to 04/05/2019

**Louis Moureaux**

- XVII International Workshop on Deep Inelastic Scattering - Torino (I) from 08/04/2019 to 12/04/2019

**Katie Mulrey**

- International Cosmic Ray Conference - Madison, WI, USA from 24/07/2019 to 01/08/2019
- New Science enabled by New Technologies in the SKA Era - SKA Science Meeting - Manchester, UK from 08/04/2019 to 12/04/2019

**Hershal Pandya**

- LOFAR Users Meeting - Leiden, Netherlands. from 20/05/2019 to 23/05/2019
- International Cosmic Ray Conference - Madison, WI, USA from 24/07/2019 to 01/08/2019

**Laurent Pétré**

- BPS 2019 Scientific Annual Meeting - Fundamental Interactions, Particle and Nuclear Physics - ULB, Brussels 22/05/2019

**Rose Stanley**

- COSPA - Brussels, ULB Campus 04/10/2019

**Elizabeth Starling**

- CMS Remote Week - Compact Muon Solenoid Activities - Bangkok, Thailand from 16/12/2019 to 20/12/2019

**Max Vanden Bemden**

- REF - Resummation, Evolution, Factorization - Pavia from 25/11/2019 to 29/11/2019

**Liam Wezenbeek**

- Belgian Physical Society - ULB 22/05/2019
- EPS-HEP - Ghent from 10/07/2019 to 17/12/2019
- Combine Workshop and Tutorial - CERN from 02/12/2019 to 04/12/2019
- Long-Lived Particle Workshop - Ghent from 27/11/2019 to 29/11/2019

### 3.5.2 Attendance to schools

**Xuyang Gao**

- CMS DAS 2019 - Electron short exercise - Peking University, Beijing, China 09/12/2019

**Aamir Irshad**

- conference - CMS Induction Course - CERN, Switzerland from 30/01/2019 to 01/02/2019
- Training Course (2 days) - Convincing Scientific Presentations ( Funded by ULB) - CERN Switzerland from 12/11/2019 to 10/12/2019
- Training Course - Scientific writing Training Course (Funded by ULB) - CERN Switzerland from 09/09/2019 to 12/09/2019

**Sam Junius**

- Theory of Fundamental Interactions - GGI Lectures on the Theory of Fundamental Interactions 2019 - GGI, Florence from 06/01/2019 to 25/04/2019
- Invisibles19 School - Neutrino's, Dark Matter  Dark Energy - Canfranc, Spain from 03/06/2019 to 07/06/2019

**Tomáš Kello**

- BND graduate school in particle physics - BND graduate school in particle physics - Spa, Belgium from 02/09/2019 to 13/09/2019
- StatUa at Antwerpen Doctoral School - Basic Principles of Statistics - Antwerp, Belgium from 04/06/2019 to 14/06/2019
- CMS Data Analysis School - CMS Data Analysis School - Pisa, Italy from 28/01/2019 to 01/02/2019
- VBScan Training Event - VBScan Training Event - Ljubljana, Slovenia from 12/02/2019 to 15/02/2019

**Mostafa Mahdavikhorrami**

- Belgian Dutch German graduate school in particle physics (BND) - School - Spa, Belgium from 02/09/2019 to 13/09/2019
- CMS Physics Objects School (CMS POS) - School - RWTH, Aachen University from 16/09/2019 to 20/09/2019

**Pierre-Alexandre Petitjean**

- BND school - Spa, Belgium from 01/09/2019 to 13/09/2019

**Laurent Pétré**

- BND School 2019 - Graduate School in Particle Physics - Spa (Belgium) from 02/09/2019 to 13/09/2019
- ISOTDAQ 2019 - Trigger and Data Acquisition - Royal Holloway, University of London from 03/04/2019 to 12/04/2019

**Elizabeth Starling**

- IEEE Nuclear Science Symposium and Medical Imaging Conference - Fast timing detectors for HEP and medical applications - Manchester, UK from 27/10/2019 to 28/10/2019

- IEEE Nuclear Science Symposium and Medical Imaging Conference - Integrated Circuits for Detector Signal Processing - Manchester, UK 26/10/2019

**Vichayanun Wachirapusitanand**

- BND School 2019 - Spa, Belgium from 01/09/2019 to 13/09/2019

**Liam Wezenbeek**

- CMS DAS - Pisa from 28/01/2019 to 01/02/2019
- BND - Spa from 02/09/2019 to 13/09/2019

## 3.6 Teaching and academics activities

### 3.6.1 Teaching activities

**Aqeel Ahmed**

- VUB - 1015267BNR : Statistical Physics, (26/0/0/0) BA3 Exercises

**Juan Antonio Aguilar Sánchez**

- ULB - PHYS-F314 : Electronique, (12/0/0/0) BA3
- ULB - PHYS-F210 : Laboratoires, statistique appliquée à la physique expérimentale et projet, (0/0/72/40) BA2
- ULB - PHYS-F311 : Laboratoires et Stage de recherche , (0/0/72/30) BA3
- ULB - PHYS-F467 : Physique des Astroparticules , (24/24/0/24) MA1 MA2

**Sebastian Baur**

- ULB - PHYS-F311 : Laboratoires et stage de recherche, (0/0/80/10) BA3
- ULB - PHYS-F467 : Physique des astroparticules, (0/2/0/2) MA1

**Diego Beghin**

- ULB - PHYS-F311 : Laboratoire, (0/0/32/0) BA3 Temps de vie du muon
- ULB - PHYS-F104 : Physique Générale, (0/12/0/0) BA1

**Freya Blekman**

- VUB - WE-DNTK-mobility : Coordinator external mobility, (0/0/0/20) MA1 MA2 coordinate the assignment of the obligatory mobility courses (6 ECTS credits)
- VUB - WE-DNTK-12965 : EXPERIMENTELE FYSICA, (10/0/70/40) BA1 This is the obligatory experimental physics laboratory for students in the first year of the Ba1
- VUB - IR-BIO-6763 : Measurement Techniques in Nuclear Science, (20/0/0/40) MA1 MA2 Optional course for students in the Master Biomedical Engineering
- VUB - WE-DNTK-7136 : Simulation of Physics Phenomena and Detectors in Modern Physics, (15/25/10/20) MA1 MA2 Course preparing students for their masters project, combining simulation/computing with physics to
- Other - University of Oxford : Top quark physics at the LHC and beyond, (10/0/0/10) Postgraduate lectures part of the obligatory doctoral training

**Stijn Buitink**

- VUB - WE-DNTK-4904 : Astroparticle Physics, (16/0/0/0) MA1 MA2
- VUB - WE-DNTK-6509 : Computational Physics, (26/0/0/0) MA1
- VUB - WE-DNTK-7743 : Extragalactic Astrophysics, (13/13/0/0) BA2 BA3

- VUB - WE-DNTK-6355 : Fysica: Inleiding Mechanica, (20/0/0/0) BA1
- VUB - WE-DNTK-6508 : High-Energy Astrophysics, (26/0/0/0) MA1

**Barbara Clerbaux**

- ULB - PHYS-F416 : Interactions fondamentales et particules, (18/12/12/0) MA1
- ULB - PHYS-F311 : Laboratoires et stage de recherche, (0/0/12/36) BA3
- ULB - PHYSF-311 : Organisation of the CERN visit for the BA3 students, (0/0/0/36) BA3 From 26 to 28 March 2019
- ULB - PHYS-F104 : Physique Générale, (24/00/0/0) BA1

**Paul Coppin**

- VUB - WE-DNTK-1001388CNR : Experimentele stralings- en kwantumfysica, (0/0/48/32) BA2
- VUB - WE-DNTK-1015456BNR : Experimentele studie van de micro- en macrokosmos, (0/0/0/15) BA2

**Pablo Correa**

- VUB - WE-DNTK-12965 : Experimentele fysica, (10/0/70/40) BA1

**Simon De Kockere**

- VUB - WE-DNTK-6323 : Physics: Electromagnetism, (0/0/24/18) BA2
- VUB - WE-DNTK-6355 : Physics: Introduction to Mechanics, (0/14/16/22) BA1
- VUB - WE-DNTK-6317 : Physics: mechanics waves and thermodynamics, (0/48/15/47) BA1
- VUB - WE-DNTK-6438 : Seminar on Current Science and Society, (20/0/0/15) BA1

**Gilles De Lentdecker**

- ULB - PHYS-F314 : Electronics, (12/6/18/0) BA3 Introduction to electronics
- ULB - PHYS-F205 : General Physics II, (0/12/0/0) BA2 Exercices of electromagnetism for Biologists
- ULB - PHYS-F312 : Particle Physics Laboratory, (0/0/36/0) BA3 Laboratory in Particle Physics
- ULB - PHYSF482 : Techniques Avancées en Physique Expérimentale, (4/0/0/0) MA1

**Olivier Devroede**

- VUB - WE-DNTK-14101 : Experimentele Fysica, (0/12/0/0) BA1 First Matlab Course
- VUB - 4015950FNR : Object Oriented Programming (C++) for Physicists, (12/12/12/60) MA1 MA2

**Laurent Favart**

- ULB - PHYS-F305 : Introduction à la Physique des Particules, (24/0/0/0) BA3 Physique
- ULB - PHYS-F477 : Physique auprès des collisionneurs, (24/0/0/0) MA1 MA2 Physique

**Sam Junius**

- VUB - WE-DNTK-1010183 ANR : Mechanica, (0/26/0/0) BA1 Exercise sessions

**Godwin K. Krampah**

- VUB - 007743 : Extragalactic astronomy, (0/4/0/0) BA2 BA3
- VUB - 010891 : Radio astronomy , (0/4/0/0) BA1 BA2

**Steven Lowette**

- VUB - 4015948FNR : Experimental Techniques in Particle Physics, (36/0/0/20) MA1 MA2

- VUB - 4012730CNR : Extensions of the Standard Model, (24/12/0/0) MA2
- VUB - 4015029ENR : External Mobility B, (0/0/0/0) MA1 MA2
- Other - BND : Long-Lived Particles, (4/0/0/0) MA2 BND Gradute Summer School
- VUB - 1019736ANR : Seminarie Actuele Wetenschappen en Samenleving, (13/13/0/13) BA1

**Alberto Mariotti**

- VUB - 1015267BNR : Statistical Physics, (26/0/0/0) BA3
- VUB - 4015689FNR : Subatomic Physics 2, (26/0/0/0) MA1

**Ioana Maris**

- ULB - PHYS-F210 : Laboratoires, statistique appliquée à la physique expérimentale et projet , (0/0/72/0) BA2
- ULB - PHYS-F311 : Laboratoires et Stage de recherche, (0/0/36/0) BA3

**Pragati Mitra**

- VUB - Inleiding astrofysic : introduction to astrophysics, (0/24/0/0) BA2 teaching assistant

**Louis Moureaux**

- ULB - PHYS-F305 : Introduction à la physique des particules, (0/12/0/0) BA3
- ULB - PHYS-F210 : Laboratoire de physique générale, (0/0/36/0) BA2

**Hershal Pandya**

- VUB - WE-DNTK-6509 : Computational Physics, (0/30/0/0) BA3

**Pierre-Alexandre Petitjean**

- ULB - MATH-H1002 : Analyse 1, (0/60/0/0) BA1
- ULB - MATH-H2000 : Analyse 2, (0/24/0/0) BA2
- ULB - MATH-H1001 : Eléments d'algèbre et d'analyse, (0/18/0/0) BA1
- ULB - TRAN-H100 : Introduction aux sciences appliquées, (0/28/0/0) BA1

**Nicolas Postiau**

- ULB - PHYS-F-104 : Physique Générale, (0/12/0/0) BA1 Students in BA1 Biol
- ULB - PHYS-F-110 : Physique Générale I, (0/44/0/0) BA1 Students in BA1 Math
- ULB - PHYS-F-110 : Physique Générale II, (0/95/23/0) BA1 Students in BA1 Phys/Chim
- ULB - PHYS-F-477 : Physique auprès des Collisionneurs, (0/24/0/0) MA1 Students in MA1 Phys. Exercises include simulation of physics processes using ROOT.
- ULB - PHYS-F-201 : Thermodynamique, (0/24/0/0) BA2 Students in BA2 Phys

**Laurent Thomas**

- ULB - PHYS-F-104 : Physique, (0/24/0/0) BA1 Exercice sessions for students in biology
- ULB - Master thesis : Searching for New Physics in Dilepton Events at CMS, a study of the Photon-Induced Process, (0/12/0/0) MA2 Supervision of the Master thesis of M. Draguet

**Simona Toscano**

- ULB - PHYS-F210 : Laboratoires, statistique appliquee a la physique experimentale et projet, (0/0/12/0) BA2
- ULB - PHYS-F311 : Laboratoires et stages de recherche, (0/0/72/0) BA3

**Nick Van Eijndhoven**

- VUB - WE-DNTK-6406 : Experimental Study of the Micro and Macrocosmos, (13/13/0/0) BA3
- VUB - WE-DNTK-6331 : Subatomic Physics I : Introduction to Nuclear and Particle Physics, (26/26/0/0) BA3

**Pascal Vanlaer**

- ULB - PHYS-F420 : Détection de particules, acquisition et analyse de données, (12/0/24/0) MA1 MA2 Physique
- ULB - PHYS-F-110 : Physique générale, (48/0/60/0) BA1
- ULB - PHYS-F482 : Techniques avancées de la physique expérimentale, (24/0/24/0) MA1

### 3.6.2 Membership to academic juries of Master and Phd theses

**Juan Antonio Aguilar Sánchez**

- Phd thesis, - Université de Gèneve, April 2019 - Tessa Carver : Time Integrated searches for Point-like Astrophysical Neutrino Sources using the IceCube
  Referee

**Gilles De Lentdecker**

- Phd thesis, - ULB, September 2019 - Iaroslav MELESHENKOVSKII : Medium Resolution Gamma-rays Spectroscopy for Safeguards Applications
  President
- Master thesis, - ULB, September 2019 - Nathan Stene : Spatial resolution of non-invasive brain electrophysiology: A multiplole expansion model
  Referee

**Laurent Favart**

- Phd thesis, - ULB, April 2019 - Hugo Delannoy : Search for a heavy scalar boson in the $ZZ \to 2l2$ channel with the CMS experiment at the LHC using 2016 data at 13 TeV
  President

**Anastasia Grebenyuk**

- Phd thesis, - ULB, Peking University, June 2019 - Qun Wang : Measurement of the differential crosssection of Z boson production inassociation with jets at the LHC
  Referee
- Master thesis, - ULB, August 2019 - Max Vanden Bemden : Study of the Proton Transverse Momentum Distributions with the Parton Branching Method
  Referee

**Steven Lowette**

- Phd thesis, - Vrije Universiteit Brussel, May 2019 - Seth Moortgat : First measurement of the cross section of top quark pair production with additional charm jets with the CMS experiment
  Referee
- Phd thesis, - Vrije Universiteit Brussel, September 2019 - Sybille Driezen : Geometrical approach to integrable and supersymmetric sigma models
  President

**Alberto Mariotti**

- Phd thesis, - VUB and Swansea University, September 2019 - Saskia Demulder : Duality and resurgence in integrable sigma-models
  Referee

**Ioana Maris**

- Phd thesis, - University of Ghent, July 2019 - Ward Van Driessche : Search for particles with anomalous charge in the IceCube detector
  Referee

### 3.6.3 Representation in academic councils and committees (in universities)

**Yannick Allard**

- Représentant CORSI au Département de Physique (Faculté des Sciences), ULB

**Freya Blekman**

- Chairperson of the Opleidingsraad (Education council) of the VUB Bachelor and Master of Physics and Astronomy, VUB
- IIHE website coordinator, Other

**Barbara Clerbaux**

- Elected as the representative of Academic Staff at the ULB Assemblée plénière (AP) , ULB
- Elected as the representative of Academic Staff at the ULB university board (CA), ULB
- Member of the Faculty committee of restructuration, ULB
- Member of the Science Faculty pedagogic committee, ULB
- Member of the ULB committee for the University strategic plan, ULB cap 2030, ULB
- Member of the administrative ULB committee (commission administrative), ULB
- Member of the group ULB4climate, ULB

**Pablo Correa**

- OAP representative in a selection committee for a 10% ZAP position at the DNTK, VUB
- OAP representative in the DNTK department council, VUB
- OAP representative in the DNTK education council, VUB
- OAP representative in the Sciences and Bio-Engineering Sciences faculty council, VUB

**Catherine De Clercq**

- VUB representative in the Board of the School of Arts KCB, VUB

**Gilles De Lentdecker**

- Membre de la commission enseignement du département de physique, ULB
- Membre de la commission finance du département de physique, ULB

**Steven Lowette**

- DNTK delegate to the faculty's doctoral committee, VUB
- DNTK delegate to the faculty's internationalisation committee, VUB
- President of the examination committee for the VUB Bachelor in de fysica en sterrenkunde , VUB
- Secretary of the examination committee for the VUB Master in physics and astrophysics, VUB

**Alberto Mariotti**

- Master examination committee voorzitter, VUB

**Ioana Maris**

- Secretaire du Jury de Bachelier, ULB

**Louis Moureaux**

- Conseil du département de physique, ULB

**Nick Van Eijndhoven**

- Chair of the curriculum board of the VUB dept. of Physics and Astronomy, VUB
- Member of the public relations board of the VUB Faculty of Science, VUB
- President or member of various PhD committees, VUB
- Responsible for plagiarism control of the VUB dept. of Physics and Astronomy, VUB

**Pascal Vanlaer**

- Coordinator of the Physics department in the AEQES higher-education quality assessment process in the French community, ULB
- Member of the Diploma Equivalence Committee - section Sciences for the Walloon-Brussels Federation , Other
- Member of the Observatory of the 1st year bachelor studies in sciences, ULB
- Member of the Physics department committee for teaching assistants hirings, ULB

## 3.7 Invited seminars at the IIHE

- Isabelle Wingerter-Seez - ATLAS detector upgrade towards the High Luminosity Large Hadron Collider - IIHE, 08/03/2019
- Elisabete Maria de Gouveia Dal Pino - Cosmic rays acceleration and high energy and neutrino emission around black holes and relativistic jets - IIHE, 29/05/2019
- Laura Molina Bueno - Future long baseline experiments - IIHE, 01/03/2019
- Dimitri Pourbaix - Gaia: an on-going revolution. - IIHE, 29/11/2019
- Luigi Marchese - Higgs boson width at the LHC - IIHE, 14/06/2019
- Salvatore Rappoccio - How understanding QCD helps us with BSM searches - IIHE, 21/06/2019
- Tanguy Pierog - LHC and Cosmic Rays : the Chicken or the Egg ? - IIHE, 05/04/2019
- Anatael Cabrera - LiquidO: Novel Opaque Neutrino Detection Technology - IIHE, 17/05/2019
- Ralph Engel - Recent progress in understanding ultra-high-energy cosmic rays - IIHE, 22/02/2019
- Paul de Jong - Recent results of Antares and status of the KM3NeT - IIHE, 08/11/2019
- Carlos Aguelles - Searching for New Physics With High-Energy Neutrinos at IceCube - IIHE, 18/10/2019
- Manuela Vecchi - Spectral features in galactic cosmic rays - IIHE, 11/10/2019
- Ans Pardons - The AWAKE Experiment at CERN - IIHE, 10/05/2019
- Aleksandra Lelek - Towards precise collider predictions: the Parton Branching method - IIHE, 24/04/2019
- Krijn de Vries - Towards the highest energies: Radar detection of the cosmic neutrino flux - IIHE, 24/05/2019
- Thiago Bezerra - 13 : From the 'discovery' to the percent precision era (2000 - 2030) - IIHE, 17/05/2019

### 3.8 Vulgarisation and outreach

**Juan Antonio Aguilar Sánchez**

- Master Class - Brussels, 30/01/2019
- Pint of Science - Brussels, 21/05/2019

**Barbara Clerbaux**

- Co-organiser of the Ilya Prigogine seminar, A-t-on tiré les leçons de la crise de 2008 ? - ULB, 04/04/2019
- Co-organiser of the Ilya Prigogine seminar, Quelles relations entre économie et écologie ? - ULB, 24/04/2019
- Cool physics Day - outreach event during the EPS 2019 international conference - Ghent, from 10/07/2019 to 17/07/2019
- Famous scientists exhibition - outreach event during the EPS 2019 international conference - Ghent, from 10/07/2019 to 17/07/2019
- Member of the interdisciplinary committee "Penser la Sciences" at the ULB, since 09/2017 - ULB, 01/09/2017

**Paul Coppin**

- IceCube Masterclass - IIHE, Brussels, Belgium, 30/02/2019

**Pablo Correa**

- 3rd edition of the South Pole Experiment contest - co-organiser - Brussels, Belgium, from 01/01/2019 to 15/05/2019
- 4th edition of the South Pole Experiment contest - co-organiser - Brussels, Belgium, from 01/09/2019 to 31/12/2019
- IceCube Masterclass 2019 - co-organiser - Brussels, Belgium, 30/01/2019
- Workshop in the context of a science bootcamp for children (ages 7-13) - co-organiser - Brussels, Belgium, 14/08/2019

**Simon De Kockere**

- IceCube masterclass - VUB Campus Etterbeek, 30/01/2019
- Workshop science camp - VUB Campus Etterbeek, 14/08/2019

**Nadège Iovine**

- IceCube Masterclass - iihe - Brussels, 30/01/2019

**Steven Lowette**

- Coordinator of the Standard Waffle newsletter at the EPSHEP2019 conference - Ghent, Belgium, from 10/07/2019 to 17/07/2019
- Intro CERN during CERN excursion BA2-BA3 students VUB - CERN, Geneva, Switzerland, 29/03/2019
- Intro CERN during teacher visit - CERN, Geneva, Switzerland, 04/03/2019
- Public lecture at the Volkssterrenwacht Armand Pien - Ghent, Belgium, 23/02/2019

**Christoph Raab**

- Support the organisers of IceCube Masterclass (registration management and statistics, flyers, setting up website, setting up Indico, user privacy) - Brussels, 30/01/2019

**Rachel Simoni**

- Core-collapse supernovae: promising candidates for PeV cosmic-ray acceleration? - H.E.S.S website : https://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2019/07/, from 01/07/2019 to 31/07/2019

**Elizabeth Starling**

- CERN Open Days - CERN, Meyrin, Switzerland, from 14/09/2019 to 15/09/2019

**Laurent Thomas**

- Video about my research activities for the FNRS (https://www.fnrs.tv/) - Brussels, 01/07/2019

**Simona Toscano**

- IceCube masterclass - IIHE, 19/02/2019

# 4 Publications

## 4.1 Refereed journals and conference proceedings

### 4.1.1 AUGER

1. *Auger-TA energy spectrum working group report*
   AbuZayyad, T et al. [AUGER Collaboration]
   EPJ Web Conf. 210 (2019) 01002

2. *Cosmic ray spectrum and composition from PeV to EeV using 3years of data from IceTop and IceCube*
   Aartsen, M et al. [AUGER Collaboration]
   Phys. Rev. D 100 (2019) 082002

3. *Data-driven estimation of the invisible energy of cosmic ray showers with the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   Phys. Rev. D 100 (2019) 082003

4. *Latest results and future perspectives*
   Mockler, D et al. [AUGER Collaboration]
   PoS ICNFP2019

5. *Limits on point-like sources of ultra-high-energy neutrinos with the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   JCAP 11 (2019) 004

6. *Long Term Evolution of the Area to Peak ratio*
   Koun Choi, Ioana C. Maris, Daniela Mockler[AUGER]
   GAP2019-028

7. *Measurement of the average shape of longitudinal profiles of cosmic-ray air showers at the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   JCAP 03 (2019) 018

8. *Multi-Messenger Physics with the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   Front. Astron. Space Sci. 6 (2019) 24

9. *Probing the origin of ultra-high-energy cosmic rays with neutrinos in the EeV energy range using the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   JCAP 10 (2019) 022

10. *Reconstruction of vertical events recorded by the surface detector of the Pierre Auger Observatory*
    Mockler, D et al.[AUGER Collaboration]
    PoS IRC2019 1177

11. *Rejecting Bad-Silent Stations in the SD Reconstruction*
    Ioana C. Maris [AUGER]
    GAP2019-049

12. *Review of the results from the Pierre Auger Observatory*
Maris, I et al. [AUGER Collaboration]
EPS-HEP 2019

13. *The time evolution of the number of stations triggered by air-showers*
Orazio Zapparrata, Koun Choi and Ioana C. Maris
$GAP2019_066$

### 4.1.2 CMS

1. *A search for pair production of new light bosons decaying into muons in proton-proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 796 (2019) 131-154

2. *An embedding technique to determine $\tau\tau$ backgrounds in proton-proton collision data*
Sirunyan, A et al. [CMS Collaboration]
JINST 14 (2019) P06032

3. *Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 773

4. *Centrality and pseudorapidity dependence of the transverse energy density in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. C 100 (2019) 024902

5. *Charged-particle angular correlations in XeXe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. C 100 (2019) 044902

6. *Combination of CMS searches for heavy resonances decaying to pairs of bosons or leptons*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 798 (2019) 134952

7. *Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 121803

8. *Combinations of single-top-quark production cross-section measurements and $\|f_{LV}V_{tb}\| determinationsat \sqrt{s} =$ 7 and 8 TeV with the ATLAS and CMS experiments*
Aaboud, M et al. [CMS Collaboration]
JHEP 05 (2019) 088

9. *Combined measurements of Higgs boson couplings in proton–proton collisions at $\sqrt{s} = 13\,TetextV$*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 421

10. *Constraints on anomalous $HVV$ couplings from the production of Higgs bosons decaying to $\tau$ lepton pairs*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 112002

11. *Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 797 (2019) 134826

12. *Inclusive search for supersymmetry in pp collisions at $\sqrt{s} = 13$ TeV using razor variables and boosted object identification in zero and one lepton final states*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 031

13. *Jet Shapes of Isolated Photon-Tagged Jets in Pb-Pb and pp Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 152001

14. *Measurement and interpretation of differential cross sections for Higgs boson production at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 792 (2019) 369-396

15. *Measurement of associated production of a W boson and a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 269

16. *Measurement of $B^0_{\mathrm{s}}$ meson production in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 796 (2019) 168-190

17. *Measurement of differential cross sections for inclusive isolated-photon and photon+jets production in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 20

18. *Measurement of differential cross sections for Z boson pair production in association with jets at $\sqrt{s} = 8$ and 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 789 (2019) 19-44

19. *Measurement of electroweak WZ boson production and search for new physics in WZ + two jets events in pp collisions at $\sqrt{s} = 13TeV$*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 795 (2019) 281-307

20. *Measurement of exclusive ho$(770)^0$ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 702

21. *Measurement of exclusive Υ photoproduction from protons in pPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 277

22. *Measurement of inclusive and differential Higgs boson production cross sections in the diphoton decay channel in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 01 (2019) 183

23. *Measurement of inclusive very forward jet cross sections in proton-lead collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 05 (2019) 043

24. *Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 790 (2019) 270-293

25. *Measurement of prompt* $\psi(2S)$ *production cross sections in proton-lead and proton-proton collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 790 (2019) 509-532

26. *Measurement of the* $\mathrm{t\bar{t}}$ *production cross section, the top quark mass, and the strong coupling constant using dilepton events in pp collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 368

27. *Measurement of the average very forward energy as a function of the track multiplicity at central pseudorapidities in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 893

28. *Measurement of the differential Drell-Yan cross section in proton-proton collisions at* $\sqrt{\mathrm{s}} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 12 (2019) 059

29. *Measurement of the energy density as a function of pseudorapidity in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 391

30. *Measurement of the top quark mass in the all-jets final state at* $\sqrt{s} = 13$ *TeV and combination with the lepton+jets channel*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 313

31. *Measurement of the top quark polarization and* tart *spin correlations using dilepton final states in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 072002

32. *Measurement of the top quark Yukawa coupling from* tart *kinematic distributions in the lepton+jets final state in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 072007

33. *Measurements of* $t\bar{t}$ *differential cross sections in proton-proton collisions at* $\sqrt{s} = 13$ *TeV using events containing two leptons*
Sirunyan, A et al. [CMS Collaboration]
JHEP 02 (2019) 149

34. *Measurements of differential Z boson production cross sections in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 12 (2019) 061

35. *Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 791 (2019) 96

36. *Measurements of the Higgs boson width and anomalous* $HVV$ *couplings from on-shell and off-shell production in the four-lepton final state*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 112003

37. *Measurements of the pp* $\rightarrow$ *WZ inclusive and differential production cross section and constraints on charged anomalous triple gauge couplings at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 04 (2019) 122

38. *Measurements of triple-differential cross sections for inclusive isolated-photon+jet events in pp collisions at* $\sqrt{s} = 8$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 969

39. *Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 8.16$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 791 (2019) 172-194

40. *Observation of Single Top Quark Production in Association with a Z Boson in Proton-Proton Collisions at* $\sqrt{s}$ *=13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 132003

41. *Observation of Two Excited* $B_c^+$ *States and Measurement of the* $B_c^+$*(2S) Mass in pp Collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 132001

42. *Performance of missing transverse momentum reconstruction in proton-proton collisions at* $\sqrt{s} = 13$ *TeV using the CMS detector*
Sirunyan, A et al. [CMS Collaboration]
JINST 14 (2019) P07004

43. *Pseudorapidity distributions of charged hadrons in xenon-xenon collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 799 (2019) 135049

44. *Search for* $\mathrm{t\bar{t}H}$ *production in the* $\mathrm{H} \to \mathrm{b\bar{b}}$ *decay channel with leptonic* $\mathrm{t\bar{t}}$ *decays in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 026

45. *Search for W boson decays to three charged pions*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 151802

46. *Search for a heavy pseudoscalar boson decaying to a Z and a Higgs boson at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 564

47. *Search for a heavy resonance decaying to a top quark and a vector-like top quark in the lepton+jets final state in pp collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 208

48. *Search for a light charged Higgs boson decaying to a W boson and a CP-odd Higgs boson in final states with $e\mu\mu$ or $\mu\mu\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 123 (2019) 131802

49. *Search for a low-mass $\tau^+\tau^-$ resonance in association with a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 05 (2019) 210

50. *Search for a standard model-like Higgs boson in the mass range between 70 and 110 GeV in the diphoton final state in proton-proton collisions at $\sqrt{s} = 8$ and 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 793 (2019) 320-347

51. *Search for a W' boson decaying to a $\tau$ lepton and a neutrino in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 792 (2019) 107-131

52. *Search for a W boson decaying to a vector-like quark and a top or bottom quark in the all-jets final state*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 127

53. *Search for an $L_\mu - L_\tau$ gauge boson using Z$\to 4\mu$ events in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 792 (2019) 345-368

54. *Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two muons and two b quarks in pp collisions at 13 TeV*

Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 795 (2019) 398-423

55. *Search for anomalous electroweak production of vector boson pairs in association with two jets in proton-proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 798 (2019) 134985

56. *Search for anomalous triple gauge couplings in WW and WZ production in lepton + jet events in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 12 (2019) 062

57. *Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 092005

58. *Search for charged Higgs bosons in the* $H^{\pm} \rightarrow \tau^{\pm}\ u_{\tau}$ *decay channel in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 07 (2019) 142

59. *Search for contact interactions and large extra dimensions in the dilepton mass spectra from proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 04 (2019) 114

60. *Search for dark matter in events with a leptoquark and missing transverse momentum in proton-proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 795 (2019) 76-99

61. *Search for dark matter particles produced in association with a top quark pair at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 011803

62. *Search for dark matter produced in association with a Higgs boson decaying to a pair of bottom quarks in proton–proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 280

63. *Search for dark matter produced in association with a single top quark or a top quark pair in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 141

64. *Search for dark photons in decays of Higgs bosons produced in association with Z bosons in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 10 (2019) 139

65. *Search for excited leptons in $\ell\ell\gamma$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 04 (2019) 015

66. *Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 01 (2019) 122

67. *Search for heavy neutrinos and third-generation leptoquarks in hadronic states of two $\tau$ leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 170

68. *Search for heavy resonances decaying into two Higgs bosons or into a Higgs boson and a W or Z boson in proton-proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 01 (2019) 051

69. *Search for Higgs and Z boson decays to J/$\psi$ or Y pairs in the four-muon final state in proton-proton collisions at s=13TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 797 (2019) 134811

70. *Search for Higgs boson pair production in the $\gamma\gamma\mathrm{b\overline{b}}$ final state in pp collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 788 (2019) 7-36

71. *Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 793 (2019) 520-551

72. *Search for long-lived particles decaying into displaced jets in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 032011

73. *Search for long-lived particles using delayed photons in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 112003

74. *Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 797 (2019) 134876

75. *Search for low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 112007

76. *Search for Low-Mass Quark-Antiquark Resonances Produced in Association with a Photon at $\sqrt{s}$ =13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 123 (2019) 231803

77. *Search for low-mass resonances decaying into bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 012005

78. *Search for MSSM Higgs bosons decaying to $\mu + \mu -$ in proton-proton collisions at s=13TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 798 (2019) 134992

79. *Search for narrow $H\gamma$ resonances in proton-proton collisions at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 081804

80. *Search for new particles decaying to a jet and an emerging jet*
Sirunyan, A et al. [CMS Collaboration]
JHEP 02 (2019) 179

81. *Search for new physics in final states with a single photon and missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 02 (2019) 074

82. *Search for new physics in top quark production in dilepton final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 886

83. *Search for nonresonant Higgs boson pair production in the* $\mathrm{b\overline{b}b\overline{b}}$ *final state at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 04 (2019) 112

84. *Search for pair production of first-generation scalar leptoquarks at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 052002

85. *Search for pair production of second-generation leptoquarks at $\sqrt{s}$ = 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 032014

86. *Search for pair production of vectorlike quarks in the fully hadronic final state*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 072001

87. *Search for pair-produced three-jet resonances in proton-proton collisions at $\sqrt{s}$ =13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 99 (2019) 012010

88. *Search for Physics beyond the Standard Model in Events with Overlapping Photons and Jets*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 123 (2019) 241801

89. *Search for production of Higgs boson pairs in the four b quark final state using large-area jets in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 01 (2019) 040

90. *Search for rare decays of Z and Higgs bosons to* $J/\psi$ *and a photon in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 94

91. *Search for resonances decaying to a pair of Higgs bosons in the* $\mathrm{b\bar{b}q\bar{q}}'\ell$ *u final state in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 10 (2019) 125

92. *Search for resonant* $\mathrm{t\bar{t}}$ *production in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 04 (2019) 031

93. *Search for resonant production of second-generation sleptons with same-sign dimuon events in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 305

94. *Search for single production of vector-like quarks decaying to a top quark and a W boson in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 90

95. *Search for supersymmetric partners of electrons and muons in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Lett. B 790 (2019) 140-166

96. *Search for supersymmetry in events with a photon, a lepton, and missing transverse momentum in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 01 (2019) 154

97. *Search for supersymmetry in events with a photon, jets,* b *-jets, and missing transverse momentum in proton–proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur. Phys. J. C 79 (2019) 444

98. *Search for supersymmetry in final states with photons and missing transverse momentum in proton-proton collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 06 (2019) 143

99. *Search for supersymmetry in proton-proton collisions at 13 TeV in final states with jets and missing transverse momentum*
Sirunyan, A et al. [CMS Collaboration]
JHEP 10 (2019) 244

100. *Search for supersymmetry using Higgs boson to diphoton decays at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 11 (2019) 109

101. *Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 08 (2019) 150

102. *Search for the associated production of the Higgs boson and a vector boson in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV via Higgs boson decays to* $\tau$ *leptons*
Sirunyan, A et al. [CMS Collaboration]
JHEP 06 (2019) 093

103. *Search for the Higgs boson decaying to two muons in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. Lett. 122 (2019) 021801

104. *Search for the pair production of light top squarks in the* $e^{\pm}\mu^{\mp}$ *final state in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 03 (2019) 101

105. *Search for the production of four top quarks in the single-lepton and opposite-sign dilepton final states in proton-proton collisions at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 11 (2019) 082

106. *Search for the production of* $W^{\pm}W^{\pm}W^{\mp}$ *events at* $\sqrt{s}$ *= 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys. Rev. D 100 (2019) 012004

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