IIHE
Annual Report
2018

Interuniversity Institue for High Energy

ANNUAL REPORT
2018

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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 2018

The present report presents the research performed at the IIHE in 2018, 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 2018 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 fb^{-1} of proton collision data was recorded by the CMS experiment.

During 2018, 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 IIHE has a long history of research in the field of neutrino (ν) 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). A new detector has been deployed in 2014, followed shortly after by the start of data taking. These data have been analysed to commission the experiment for future reactor cycles. The intention is to measure neutrino oscillation processes at very short distances between 5 and 10 meter from the reactor source.

The JUNO experiment consist in 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 more than 17000 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. This puts strong constraints on the quality of the detector components in particular on the PMT characteristics. The international collaboration of JUNO was established in 2014, the civil engineering started in 2015 and the R&D/production phase for the detector is ongoing. The start of the data taking is expected at the end of 2021 or the beginning of 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.

Since 2016, the IIHE has joined 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.

For the detection in the South Pole ice of "GZK" neutrinos, from the scattering of ultra-high energy cosmic rays off the cosmic microwave background, a sound-wave technique is being developed for the ARA experiment. A major activity at the IIHE in conjunction with the R&D group of the IIHE has been the development of a digital communication circuit to permit the deployment of digitization electronics under particularly stringent conditions. To cover the energy gap between IceCube and the Askaryan radio detectors, the IIHE initiated its investigations to use radar detection techniques.

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 multipurpose, 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 for future proton therapy centres.

To link the activities of their theoretical physics (TENA) 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 6 September 2019, IIHE members attended the IIHE annual meeting, 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 2018

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) since August	IceCube
Diego BEGHIN	PhD student (Aspirant F.R.S.-FNRS)	CMS
Bugra BILIN	Post-doc (IISN)	CMS
Hugues BRUN	Post-doc (IISN) until April	CMS
Koun CHOI	Post-doc (IISN) since July	Auger, IceCube
Barbara CLERBAUX	Chargée de Cours	CMS, JUNO
Hugo DELANNOY	PhD student (FRIA)	CMS
Gilles DE LENT-DECKER	”Maître de Recherche F.R.S.-FNRS;	
	Maître d’Enseignement”	CMS, DAQ R&D
Wendi DENG	”PhD student (CSC scholarship)	
	Co-tutelle with CNNU University”	CMS, DAQ R&D
Jianmeng DONG	”PhD student (CSC scholarship)	
	Co-tutelle with IHEP-China”	CMS DAQ R&D

Brian DORNEY	Post-doc (IISN)	CMS
Wenxing FANG	"PhD student (CSC scholarship) Co-tutelle with BUAA University"	CMS
Laurent FAVART	"Directeur de Recherche F.R.S.-FNRS; part-time Chargé de Cours; IIHE director"	H1, CMS
Xuyang GAO	"PhD student (CSC scholarship) Co-tutelle with BUAA University"	CMS
Reza GOLDOUZIAN	Post-doc (IISN) until August	CMS
Anastasia GREBENYUK	Chargé de Recherche F.R.S.-FNRS	CMS
Zigfried HAMPEL-ARIAS	Post-doc (BAEF grant) until October	IceCube
Amandeep Kaur KALSI	Post-doc (IISN)	CMS
Tomas KELLO	PhD student (EOS) since December	CMS
Aamir IRSHAD	PhD student (IISN) since November	CMS DAQ R&D
Mostafa MAH-DAVIKHORRAMI	PhD student (EOS) since November	CMS
Inna MAKARENKO	Post-doc (IISN) since May	CMS
Pierre MARAGE	"Professeur ordinaire émérite; Professeur de l'Université until September; past IIHE co-director"	Hist. of Science
Ioana MARIS	Chargé de Cours	IceCube, Auger
Kevin MEAGHER	Post-doc (IISN) until March	IceCube
Louis MOUREAUX	PhD student (FRIA)	CMS
David NDAYIZEYE	PhD student (Burundi grant) until December	Instrumentation
Pierre-Alexandre PETIT-JEAN	PhD student (Assistant ULB) since September	JUNO
Laurent PETRE	PhD student (FRIA) since October	CMS DAQ R&D
Yves PIERSEAUX	collaborateur scientifique	Hist. of Science
Nicolas POSTIAU	PhD student (Assistant ULB)	CMS
Andrey POPOV	Post-doc (EOS) since November	CMS
Christoph RAAB	PhD student (IISN)	IceCube
Giovanni RENZI	PhD student (IISN) since January	IceCube
Rachel SIMONI	"PhD student (Amsterdam University); collaborateur scientifique"	
Zixuan SONG	"PhD student (CSC scholarship) Co-tutelle with CCNU University"	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 since October	IceCube
Catherine VANDER VELDE	Professeur de l'Université	CMS
Pascal VANLAER	Chargé de Cours	CMS
David VANNEROM	PhD student (Aspirant F.R.S.-FNRS)	CMS
Hanwen WANG	"PhD student (CSC scholarship) since September Co-tutelle with BUAA University"	CMS
Qun WANG	"PhD student (CSC scholarship) until June Co-tutelle with PKU University"	CMS
Gaston WILQUET	"honorary Maître de Recherche F.R.S.-FNRS;	

Master students

Alexandre DE MOOR	physics, since September	CMS
Charles DETEMMERMAN	physics, since September	CMS DAQ R&D
Maxence DRAGUET	physics, since September	CMS
Lucas LEONARDY	physics, since September	CMS
Pierre-Alexandre PETITJEAN	physics, until September	CMS
Laurent PÉTRÉ	physics, until September	CMS
Morgane Raphaëlle RIGAUX	physics, until September	CMS
Ali SAFA	physics, since September	CMS DAQ R&D
Max VANDEN BEMEN	physics, since September	CMS

Engineers, Technical and Logistic Personnel

Yannick ALLARD	Logisticien de Recherche ULB (half-time)
Samir AMARY	computer scientist until January
Patrick DE HARENNE	technician, general support
Benoît DENÈGRE	technician, electronics (half-time)
Denis DUTRANNOIS	computer scientist since May
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

Shimaa ABU ZEID	ERASMUS MUNDOS (PhD student)	CMS
Aqeel AHMED	EOS scientific collaborator (post-doc) since October	Pheno
Freya BLEKMAN	ZAP hoofddocent	CMS
Emil BOLS	FWO scientific collaborator (PhD student) since November	CMS
Simranjit Singh CHHIBRA	FWO scientific collaborator (post-doc) since May	CMS
Paul COPPIN	FWO scientific collaborator (PhD student) since October	IceCube
Pablo CORREA	FWO aspirant (PhD student) since October	IceCube
Isabelle DE BRUYN	FWO scientific collaborator (PhD student)	CMS
Catherine DE CLERCQ	Professor-emeritus	IceCube
Jarne De Clercq	FWO scientific collaborator (PhD student)	CMS

Simon DE KOCKERE	BAAP scientific collaborator (PhD student) since September	IceCube
Krijn DE VRIES	FWO research fellow (postdoctoraal onderzoeker)	IceCube
Gwenhael DE WASSEIGE	FWO scientific collaborator (PhD student)	IceCube
Jorgen D'HONDT	ZAP hoogleraar; IIHE co-director	CMS, SoLid
Leonidas KALOUSIS	FWO scientific collaborator (post-doc)	SoLid
Denys LONTKOVSKYI	FWO scientific collaborator (post-doc)	CMS
Steven LOWETTE	ZAP docent	CMS
Ivan MARCHESINI	FWO scientific collaborator (post-doc) from July	CMS
Alberto MARIOTTI	ZAP docent	Pheno
Seth MOORTGAT	FWO aspirant (PhD student)	CMS
Lieselotte MOREELS	FWO scientific collaborator (PhD student)	CMS
Search NAJJARI	VUB scientific collaborator (post-doc) since October	Pheno
Quentin PYTHON	FWO scientific collaborator (PhD student)	CMS
Abanti Ranadhir SAHASRANSU	EOS scientific collaborator (PhD student) since September	CMS
Olaf SCHOLTE	10% ZAP professor	IceCube
Dimitrios SIDIROPOULOS KONTOS	EOS scientific collaborator (PhD student) since November	CMS
Kirill SKOVPEN	FWO research fellow (postdoctoraal onderzoeker)	CMS
Stefaan TAVERNIER	Professor-emeritus	Crystal Clear
Walter VAN DONINCK	Professor-emeritus	CMS
Nick VAN EIJNDHOVEN	ZAP hoogleraar	IceCube
Petra VAN MULDERS	FWO research fellow (postdoctoraal onderzoeker) 10% ZAP professor	CMS, SoLid
Isis VAN PARIJS	FWO scientific collaborator (PhD student)	CMS
Simon VERCAEMER	IUAP scientific collaborator (PhD student) 1/2 VUB – 1/2 UA	SoLid
Mathias VEREECKEN	FWO aspirant (PhD student)	Pheno

Master students

Louis DEHENNIN	Student in physics	CMS
Sam JUNIUS	Student in physics	Pheno
Florian PARTOUS	Student in physics	CMS
Kamal SAOUCHA	Student in physics	CMS

Engineers, Technical and Logistic Personnel

Olivier DEVROEDE	computer scientist
Stéphane GERARD	computer scientist - VSC
Marleen GOEMAN	secretariat
Annemie MOREL	engineer (since September)

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. Francesco Hautmann, Dr. Yamiel Abreu, Dr. Xavier Janssen, Dr. Aleksandra Lelek, Dr. Hans Van Haevermaet, Dr. Simon Vercaemer, Sarah Van Mierlo, Ir. Wim Beaumont, Ig. Tim Viaene, Davide Di Croce, Lissa Keersmaekers, Tomas Kello, Maxim Pieters, Senne Van Putte, Maja Verstraeten.

2 Research activities, development and support

2.1 The CMS experiment at the CERN LHC

(S. Abu Zeid, D. Beghin, B. Bilin, F. Blekman, E. Bols, H. Brun, S. S. Chhibra, B. Clerbaux, H. Delannoy, I. De Bruyn , J. De Clercq, G. De Lentdecker, W. Deng, J. D'Hondt , J. Dong, B. Dorney, W. Fang, L. Favart, X. Gao, R. Goldouzian, A. Grebenyuk, A. K. Kalsi, T. Kello, A. Irshad, D. Lontkovskyi, S. Lowette, M. Mahdavikhorrami, I. Makarenko, I. Marchesini, S. Moortgat, L. Moreels , L. Moureaux, L. Pétré, N. Postiau, A. Popov, Q. Python, A. R. Sahasransu, D. Sidiropoulos Kontos, K. Skovpen, Z. Song, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, W. Van Doninck , P. Van Mulders , I. Van Parijs , H. Wang, Q. Wang.)

The following members of Antwerp university are also members of CMS: W. Beaumont, A. De Roeck, E. De Wolf, D. Di Croce, F. Hautmann, X. Janssen, H. Van Haevermaet, Tomas Kello, Dr. Aleksandra Lelek , P. Van Mechelen, S. Van Mierlo, S. Van Putte, N. Van Remortel, T. Viaene, Maxim Pieters, Senne Van Putte

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 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 BEH 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 delivered by the LHC. The full power of the machine was develop in year 2016, with a record integrated luminosity of 40.8/fb delivered by the LHC. In 2017 in total 49.8/fb of integrated luminosity was delivered to the CMS experiment, with peak luminosities reaching far above the design values and producing up to about 60 simultaneous proton-proton collisions. The Run 2 continued until end 2018, with a total luminosity of about 150/fb. While the discovery of the SM scalar boson (Higgs particle) 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 gradually the luminosity of the LHC: up to twice the design luminosity was reached in 2017 and 2018 (with a corresponding Phase-1 upgrade programme for the experiments), and up to 10 times the design luminosity from 2026 onwards (the so-called HL-LHC project, 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, and is among the "landmark projects" in the European strategy roadmap for research infrastructures (ESFRI roadmap 2016). The IIHE is strongly involved in these activities, coordinating the electronics of the GEM Phase-1 upgrade of the Muon system, and taking a leading rôle in the Phase-2 upgrade of the silicon tracker.

Members of the IIHE were selected or elected for top-level managerial positions in the CMS Collaboration. Amongst others the position of Chairperson of the CMS Collaboration Board by Prof. Jorgen D'Hondt.

2.1.1 Data analysis

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 LHC Run 2 dataset taken in 2016 and 2017 at 13 TeV provides a significant increase in sensitivity.

In 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 2018 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 scalar(s) in the $\tau^+\tau^-$ final state, 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.

- **Studies of the $H \to \tau^+\tau^-$ channel:** In 2018, the IIHE team contributed to the search for a massive A/H/h boson decaying into a pair of tau leptons predicted by models with an extended scalar sector. This is the most powerful channel to uncover an MSSM scalar sector at the LHC. The team contributed to a detailed study of the performance of tau lepton reconstruction and selection algorithms: the selection efficiency and fake rate measurements are estimated using Drell-Yan $Z \to \tau\tau$ events, for the 13 TeV CMS datasets. These activities provide leading contributions from the IIHE to the recent CMS publication on the tau-lepton reconstruction and identification performance during Run 2. This tau lepton reconstruction expertise is also used in the search for heavy resonances in the dilepton final state (search for new resonances with lepton flavor violation decay), as explained later in this section.

- **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,

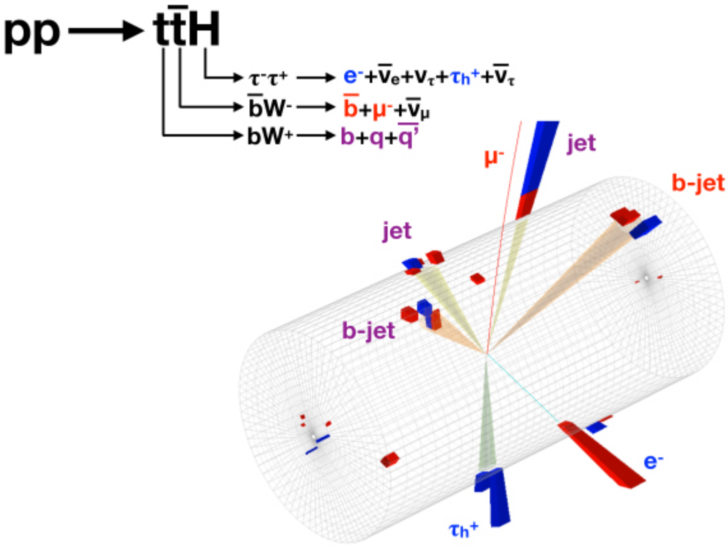

Figure 1: An event candidate for the production of a top quark and top anti-quark pair in conjunction with a H boson in the CMS detector. The H decays into a τ^+ lepton and a τ^- lepton; the τ^+ in turn decays into hadrons and the τ^- decays into an electron. The decay product symbols are in blue. The 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.

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 $H \to ZZ \to l^+l^-q\bar{q}$ channels with 36fb^{-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 36fb^{-1} of data at 13 TeV, has been approved by the CMS collaboration and is submitted to JHEP.

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.

The electromagnetic calorimeter of CMS, the ECAL, is the main detector used in the diphoton and dilepton analyses. Expertise has been acquired in the ECAL calibration, resolution and linearity measurement. Important contributions concern the ECAL energy scale and energy resolution estimation and corrections, in particular using the Z peak events from SM Drell-Yan process. In addition, the Brussels group has designed and developed a method based on the ECAL shower shape to cross check the ECAL calibration and linearity, and to correct for ECAL electronic readout saturation at very high energy. This sophisticated method is the only one available at very high energy and is crucial for the control of the ECAL response in view of the search for new physics at high energy.

- **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 recently published and preliminary results on the 2017 data analysis have been presented at the Moriond 2018 conference. Figure 2 presents the recent results obtained by the HEEP group : the dielectron invariant mass distribution resulting from the analysis of the 2017 CMS data (on the left side) and the upper limits on the spin-1 resonance production (on the right side).

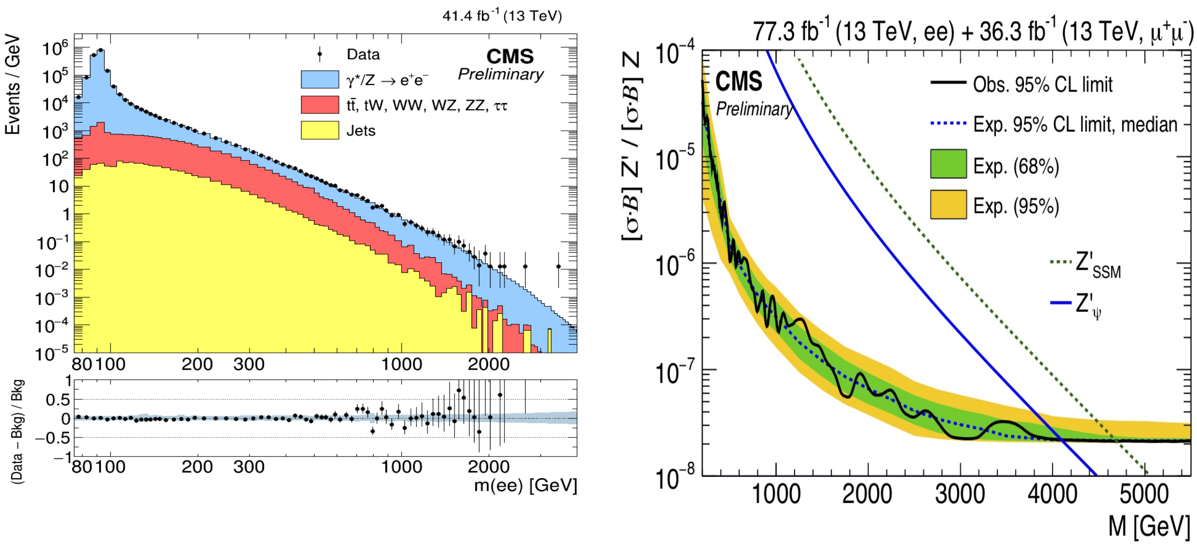

Figure 2: Left: The invariant mass spectrum of the dielectron events using the CMS data collected in 2017. Right: The 95% CL upper limits on the production cross section times branching fraction for a spin-1 resonance with a width equal to 0.6% of the resonance mass, relative to the production cross section times branching fraction for a Z boson, for the dielectron channel using the 2017 dataset in combination with the 2016 dataset (dielectron and dimuon channels).

- **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 Zẃith final states including a tau lepton: the electron-tau and muon-tau final states, using both the 2016 and 2017 datasets.

Heavy flavour jet identification

A crucial ingredient for many analyses in CMS is the accurate identification of jets originating from b 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. At the beginning of 2018, the Run 2 legacy paper on the status of heavy-flavour jet identification algorithms was published. This reference document of about 100 pages contains many contributions from the IIHE members and the editing was done by FWO postdoc P. Van Mulders. Under the leadership of postdoc I. Marchesini (2016-2018) and FWO postdoc K. Skovpen (2017-2018) as conveners 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. I. Marchesini and K. Skovpen also organized the first ever CMS heavy-flavour tagging workshop at the VUB. Another coordinating role was observed by S. Moortgat (FWO PhD student), who is currently leading the algorithms and software subgroup of the heavy-flavour tagging group, after previously coordinating the performance and validation activities in the same group. In this new role, he steers the algorithm developments and provides support to studies of the performance for future CMS detector upgrades, e.g. for the minimum ionizing particle timing detector (MTD). Several IIHE members (S. Moortgat, E. Bols, A. R. Sahasransu) had a leading role in the CMS collaboration in studying the training, performance and implementation of a new heavy-flavour jet identification algorithm based on a multiclassification neural network training referred to as "DeepJet" or in the commissioning of heavy-flavour tagging variables. The DeepJet algorithm was successfully commissioned in 2018. In parallel the algorithms were successfully calibrated on the data.

Top quark physics

During the 2016 run 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. In addition the precision measurements using the datasets collected in 2015 and 2012 at $\sqrt{s} = 8$TeV are still ongoing.

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 1 and Run 2 (collected in 2015-2018) 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 $t \to Hc$ and $t \to Zc$, 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. In 2018, this work also resulted in the doctoral theses of Isis Van Parijs and Shimaa AbuZeid.

- **Using precision techniques to measure the width of the top quark:** A team of IIHE physicists was involved with the direct measurement of the top quark width. The top quark width is extracted by performing a likelihood template fit on the scaled top quark mass distribution, defined as the reconstructed top quark mass divided by the average top quark mass. With this strategy the dependency on the jet energy scale uncertainty is largely reduced. As a result, the dominant uncertainty is expected to come from modelling uncertainties. The large amount of data allows to employ tight selection requirements for instance on the number of observed jets to reduce the dependency on these uncertainties. In addition, the sensitivity of the analysis is enhanced by weighting each event taking into account the resolution on their reconstructed object four-momenta. In late 2018, IIHE postdoc Petra Van Mulders started working as working group coordinator within the CMS experiment, with the focus on top quark mass and width measurements. Lieselotte Moreels received her PhD on the measurement of the top quark width in April 2018.

- **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 an IIHE team with postdoc Denys Lontkovskyi published an extremely competitive limit on Standard Model top quark production with expected publication in early 2019. Sensitivity studies for four top quark production were produced for the HL-LHC and HE-LHC yellow reports. Nikos Stylanou started his doctoral research in a shared PhD project with University of Bristol with the focus on four top production in the complete Run 2 dataset. With the full Run 2 dataset, it should be possible to achieve evidence for four top production after combination with all decay channels.

- **Search for third generation supersymmetric particles:** Supersymmetry is a popular extension of the SM, but invokes a large set of new parameters. Simplified benchmark models are developed to allow a general interpretation. There are many different scenarios, and IIHE members are involved in searches for the production of top squark pairs using boosted techniques and related searches in jets+missing energy and monojet final states, which are included in the PhD thesis of Dominic Smith who was also involved with searches for new physics in the jets+missing energy signature, that was published in 2018 and presented in Dominic Smith's PhD thesis in 2018.

- Many of the research previously listed relies on precision measurements of Standard Model observables, that are commonly experimentally limited by systematic uncertainties. IIHE postdoc Petra Van Mulders delivered a paper describing novel methods to reduce systematic uncertainties in such measurements JHEP 1906 (2019) 132.

SM precision measurements

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 Drell-Yan process with and without associated jet production are identified as a High Priority Analysis in CMS.

- **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. In 2018, first results at 13 TeV have been published (see Fig.3 based on 2.19fb^{1} of luminosity collected in 2015, for Z boson decaying in two muons.

Dark matter and long-lived particle searches

Since many years, the IIHE is actively involved in the search for signatures of dark matter (DM) production at the LHC, whether it be through cascades from heavy supersymmetric particles, or directly produced in generic signatures of DM production with observable SM particles, so-called DM + X. While these traditional searches for DM now need full Run-2 datasets (including 2018 data) before achieving further significant sensitivity, new alternative experimental as well as phenomenological avenues are increasingly being explored.

Searches for long-lived particles, in particular, are a topic with rising impact in the LHC new physics search program. Often, these searches are extensions of traditional searches for dark matter, but where experimentally macroscopic displacements are now included, that may arise from small mass splittings, decays through heavy particles in loops, or naturally occuring small couplings. S. Lowette from the IIHE took the lead mid-2017 and was appointed convener of the overall CMS Exotica long-lived analysis group, continuing throughout 2018, with several new public results emerging from analyses followed up within the group.

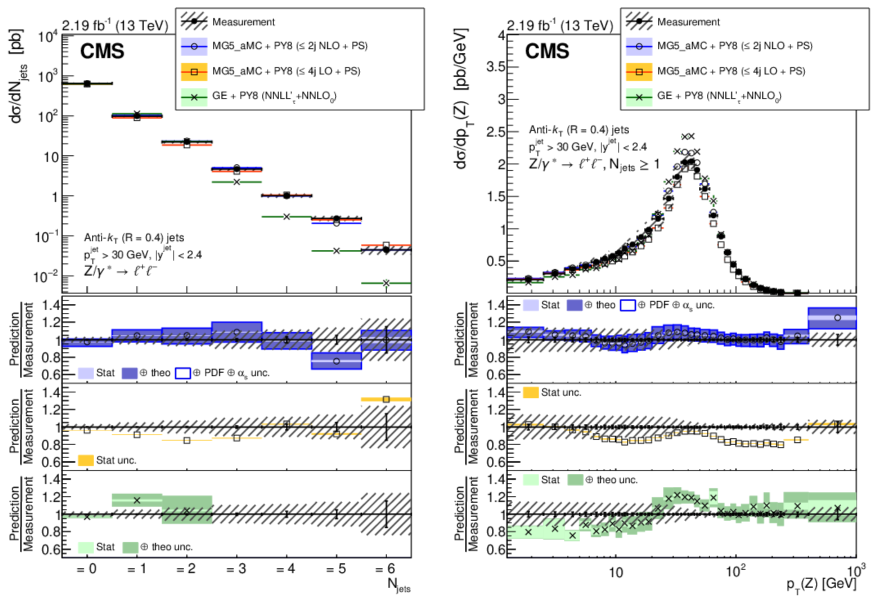

Figure 3: Measured cross section for Z+jets, using 13 TeV proton-proton data collected in 2015, are shown as a function of the jet multipicity, and the Z jet transverse momenta in case of one jet, compared to multileg prediction at NLO and LO from MadGraph 5 and at NLO including NNLL gluon resumation from GENEVA Monte Carlo [EPJ 78 (2018) 965]

Additionally, new avenues in more exotic dark matter searches were continued at IIHE, looking beyond into new physics from dark sectors in general. Searches for strongly interacting dark matter, Standard Model dark matter in the form of a 6-quark deeply bound state, and long-lived fractionally charged particles were continued in the context of a master thesis and 2 PhD thesises. In the next year, these efforts are expected to bear fruit with public results.

Also on the phenomenology side a new result emerged, with a publication on a novel displaced Z or Higgs boson signature, produced along with dark matter (JHEP 09 (2018) 037). This paper grew out of a fruitful collaboration between the experimental and phenomenological activities at the IIHE and the VUB theory research group.

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. From February 2017, 5 Super-Chambers (SC), each made of two back-to-back Triple-GEM detectors, have been operated in CMS, as a demonstrator. In January 2018 one SC has been replaced with a new one built with the final version of GE11 detectors and electronics, as seen in Fig 4. The 1m-long detector has a trapezoidal shape and it is subdivided into 3×8 sectors, each read-out by a front-end chip (small green rectangles). These 24 chips are connected through large PCBs (covering the detector) to an FPGA-based board, the opto-hybrid (lying on the middle of the detector).

In this project the IIHE is leading the design of the trigger and data acquisition (DAQ) system of the new detectors. 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, it 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

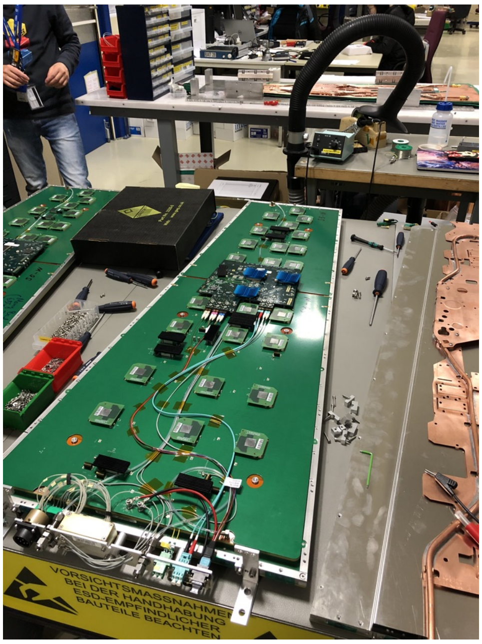

Figure 4: One GE11 detector equipped with the final electronics. Two of them have been deployed in CMS in January 2018. The opto-hybrid board designed at the IIHE is located in the middle of the detector.

Event Upset (SEU) mitigation techniques.

In 2018, the IIHE has largely contributed to the commissioning and the operation of the 10 detectors in CMS. With the installation in CMS of a SC equipped with the final electronics version, the IIHE has started the production of the GE11 electronics. The GE11 SC assembly will take place in 2019.

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

Figure 5: Left: the newly-furnished clean room at the IIHE. Right: the Hesse BondJet820 industrial bonding machine installed at the IIHE.

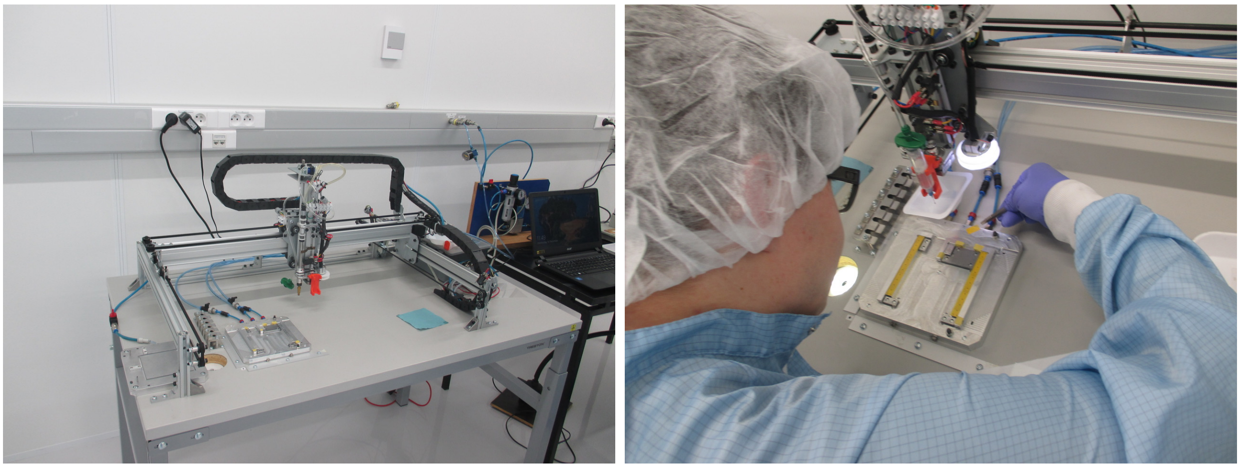

Figure 6: Left: gluing robot developed at the IIHE. Right: first trial assembly using the kapton gluing precision jig.

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.5 (left).

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 μm diameter was purchased and commissioned in 2018. The machine is visible in Fig.5 (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.6 (left). One of the precision jigs used is visible on Fig.6 (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 OPERA experiment (CERN CNGS1)

P. Vilain, G. Wilquet

The OPERA long baseline neutrino oscillation experiment has been designed to discover the direct appearance of ν_τ in a ν_μ beam with a large signal/noise ratio through the identification of the τ^- 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 ν_μ beam over a baseline of 730 km, the achieved integrated neutrino beam flux corresponding to 18×10^{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].

A new strategy based on looser selection criteria in conjunction with a multivariate approach for event identification has been used in the study of the $\nu_\mu \to \nu_\tau$ channel. The number of ν_τ candidate events has increased from 5 to 10 where respectively 6.8 and 2.0 signal and background events were expected. The discovery of ν_τ appearance is confirmed with a further improved significance of 6.1 σ. $|\Delta m^2_{32}|$ has been evaluated for the first time in appearance mode with an accuracy of about 20%. The ν_τ CC cross-section has also been measured for the first time and found to be in agreement with the SM expectation. A dedicated analysis of the $\tau \to \mu$ decay channel has provided the first direct evidence for the ν_τ lepton number with a significance of 3.7 σ [3].

New limits have been placed on the search for an exotic $\nu_\mu \to \nu_e$ oscillation signal, a signature for the existence of a hypothetical light sterile neutrino. Within the framework of the 3+1 neutrino model, a significant fraction of the sterile neutrino parameter space allowed by the LSND and MiniBooNE experiments are excluded at 90% C.L. In particular, OPERA is the only experiment able to exclude, in appearance mode, the parameter space at values of $|\Delta m^2_{41}|$ below $5.10^{-2} eV^2$ and down to $4.10^{-3} eV^2$ [4]. In an analysis that is being finalised, the ν_τ and ν_e appearance and the ν_μ disappearance channels are jointly used to further test the sterile neutrino hypothesis. In particular, the best-fit values obtained by MiniBooNE combining neutrino and antineutrino data will be excluded at a significance larger than 3 σ [5]. This analysis will close the mainstream scientific programme of the OPERA experiment.

The study of other physics topics has led or will lead to publications, among which:
- The evaluation of the high significance of an event compatible with the production of a charmed particle in a ν_τ CC interaction. This is the first observation of such an event, difficult to produce, detect and identify against several background sources [6].
- The measurement of the cosmic ray muon flux seasonal variation and its correlation to the high atmosphere temperature [7].
- Charged hadrons multiplicity distributions in ν_μ CC interaction vertices have been measured and shown to be compatible with extended KNO scaling [8].
- The data sets corresponding to the 10 ν_τ candidate events have been published on the Open Data Portal at CERN. A detailed description of these data sets is in preparation [9].

In 2018, the OPERA Collaboration included about 150 physicists from 30 institutions in 11 countries.

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2.3 Astroparticle Physics with the Pierre Auger Observatory

(Ioana C. Mariş)

2.3.1 The Pierre Auger Observatory

Extremely energetic particles, ultra high energy cosmic rays UHECRs, are entering the Earth's atmosphere constantly. Cosmic rays together with gamma rays and neutrinos 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 flux of cosmic rays decreases rapidly with the energy: above 10^{19} eV the rate of these particles is about one particle per square kilometer per year. Therefore large detectors are needed to accumulate the statistics required to understand their nature and origin and to perform particle-physics research at ultra-high energies.

The Pierre Auger Observatory located in the province of Mendoza, Argentina, and covering a surface of 3000km2 is a state-of-the-art experiment to measure the ultra-high energy cosmic rays. The commissioning of the experiment was completed in 2008. The results published by the Pierre Auger collaboration have contributed significantly in the understanding of cosmic rays. The propagation and the origin of cosmic rays influence the number of particles that enter the Earth's atmosphere. The evolution of the flux with energy, measured with the Pierre Auger Observatory, exhibits at the highest energies two features: the ankle, a flattening of the flux at about 4×10^{18} eV, and a strong suppression above 5×10^{19} eV. The flux suppression can be explained by the Greisen-Zatsepin-Kuzmin effect: during their propagation cosmic rays lose energy in the interaction with the cosmic microwave background radiation or it might be due to the maximum acceleration power at sources. The ankle can originate from either the transition from the galactic to the extragalactic components or from the production of $e^{\pm}$ by protons interacting with the cosmic microwave background. These hypothesis can not be distinguished from the spectral shape, but they differ by the mass composition of the cosmic rays that reach the Earth and their anisotropy properties. The cosmic rays suffer deflections during their trajectory from the source to the Earth depending on the strength of the magnetic fields and their mass. Nevertheless at the highest energies protons should point at their sources. Therefore it is not trivial to observe point-like correlations between UHECRs and sources and to find the specific origin of these particles. Nevertheless above 8×10^{18} eV the cosmic rays exhibit a dipolar structure with an amplitude of 6%. Moreover the direction of this dipole does not coincide with the Galactic center, which proves that above this energy the cosmic rays are extragalactic. The interpretation of the Auger measurements in terms of the mass composition indicate the presence of a heavier component, but a considerable change in the hadronic interaction models at ultra-high energies could make the measurement compatible with a pure light composition.

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 57 TeV well above the energies reached at LHC, which allows this collaboration to test fundamental interactions at energies never reached by laboratory experiments.

After the entrance in the atmosphere the cosmic ray interacts with air nuclei and generates a cascade of secondary particles, a so called air-shower. Currently two complementary techniques are employed to measure the air-showers: the observation of the fluorescence signal produced by the secondary particles in the atmosphere and the measurement of a sample of the particles that reach the ground. The Pierre Auger Observatory is built as a hybrid detector: the longitudinal development of the air-showers is observed with 24 fluorescence telescopes (FD), and the distribution of particles on the ground is measured with 1664 water-Cherenkov detectors (SD).

To advance in answering the remaining questions an upgrade of the Pierre Auger Observatory is currently being deployed. The most stringent information is the determination of the mass composition of the UHECRs with high statistics and a very good resolution. Currently the FD measurements provide a good sensitivity to for the mass composition studies, but as they can be operated only during moonless nights with a duty cycle of only about 10%, they cannot provide the required statistics. The upgrade of the Observatory, Auger Prime, aims at increasing the resolution of the surface detector (100% duty cycle) towards mass composition determination.

2.3.2 Research areas at IIHE

The IIHE has joined the Pierre Auger collaboration in February 2017. The research is focused on the data analysis of the upgrade detectors with a final goal of determining the mass composition. A previous work on the energy spectrum of the UHERCs is also continued, with a focus on the comparison with the Telescope Array measurements.

Analysis of the data from Auger Prime. The upgrade of the surface detector of the Pierre Auger Observatory has started in 2017. The plan of the collaboration is to deploy scintillators on top of the current Water-Cherenkov detectors and in the same time to update the readout electronics. A first analysis of the data from the prototype array has been performed by the summer student Zhang Tianliang. He has assessed the stability of the calibration constants of the new detectors and he has checked the possible changes in the signals due to the new faster electronics. This work will be continued at IIHE. The final goal, after the understanding of the response of the new detectors is to contribute to the determination of the mass composition of the UHECRs.

Full sky measurements of UHECRs. 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 a mass-composition enhanced anisotropy study. This work is done in collaboration with Peter Tinyakov (ULB), member of the Telescope Array collaboration. The energy spectra of 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. In the context of this work a workshop on the energy spectrum has been organised in Brussels in November 2017 with the participation of members from both collaborations.

2.4 Astroparticle Physics with the IceCube Neutrino Observatory

(J. A. Aguilar, I. Ansseau, S. Baur, K. Choi, C. De Clercq, P. Coppin, P. Correa, N. Van Eijndhoven, Z. Hampel-Arias, N. Iovine, S. De Kockere, I. C. Mariş, K. Meagher, C. Raab, G. Renzi, R. Rougny, O. Scholten, S. Toscano, K. D. de Vries, G. De Wasseige)

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.

2.4.1 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. 7) 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.

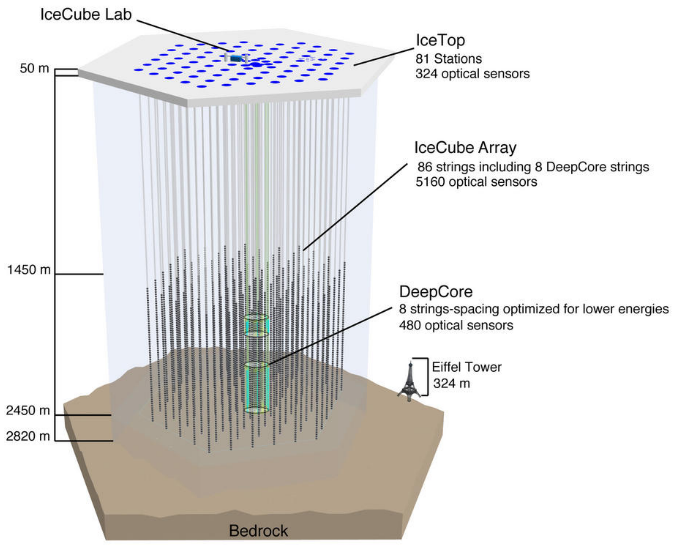

Figure 7: The IceCube observatory.

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 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 3σ 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, *IceCube-Gen2*, will be a future installation including a 10 km^3 volume expansion of detection volume of the clear Antarctic ice (Fig. 8) as well as a Surface Veto array for cosmic-ray detection, and a Radio Array to explore the highest energies.

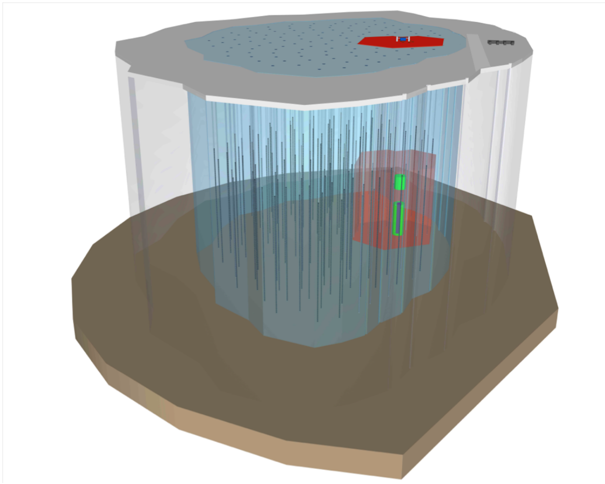

Figure 8: A possible *IceCube-Gen2* configuration. IceCube, in red, and the infill subdetector DeepCore, in green, show the current configuration

2.4.2 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 γ-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 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.
  - **Fast-response analysis.**
    In the same context of transient phenomena, but with a different approach, we have developed at the

IIHE an analysis to provide a fast-response from IceCube in case of an important astronomical event. The fast response analysis was implemented on April 2016. Soon after, on April 26 of 2016 a HESE event alert was sent out to our follow-up multimessenger partners. The optical telescope Pan-STARRS found a supernova compatible with a Ic type. This interesting finding triggered the fast response analysis, which was performed pointing to the SN candidate coordinates to search for an additional excess of less energetic neutrinos. Although no additional neutrinos were found, this was the first time that IceCube provided a fast response to an astronomical event. The fast response analysis has been invoked more than 20 times since its implementation. One remarkable event was the neutron star merger event detected by LIGO on September 2017 and associated with a short Gamma-Ray-Burst (sGRB) observed by Fermi two seconds after. This correlation proved for the first time, that the engine behind an sGRB can be a neutron star merger. IceCube, ANTARES and Pierre Auger performed a follow-up analysis to search for neutrinos. The fast-response analysis was also used in this search. Although no neutrinos were found, this result was compatible with an off-axis GRB as the electromagnetic observations seemed to indicate.

  - **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, 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.

  - **Search for extended neutrino emission.**
    In our team, also an analysis was performed, focusing on neutrino emission from extended regions. Some models predict neutrinos from extended regions like accelerators close to molecular-clouds or nearby star forming regions like the Cygnus region as a whole. The goal of the extended source analysis is an extension of the point source analysis in which the source spatial distribution is now assumed to cover a significant

extension of the sky (from 1° up to 5°) instead of only a point source. After unblinding of the data and performing this analysis no significant hot region was found. Consequently, upper limits on neutrino emission from different extensions were set.

- **Search for low-energy GeV neutrinos**
  IceCube is primarily optimized to search for signatures of neutrinos in the TeV-PeV energy range. However, this does not mean that neutrinos of lower energy scales of about a few GeV are not within the scientific scope of IceCube. To detect GeV neutrinos novel event selections, as well as a different treatment of the noise, were developed. With these new techniques, the energy threshold of IceCube can be lowered to about $\sim$ GeV, opening the window to a different kind of astrophysical observations.

  - **GeV neutrinos from solar flares.**
    Since the end of the eighties and in response to an increase in the total neutrino flux in the Homestake experiment in apparent coincidence with major solar flares, solar neutrino experiments are trying to identify neutrinos produced during these sudden flashes of energy. To date no confirmation of an increase in the neutrino rate due to solar flares has been found. Detection of neutrinos from solar flares would open a new window on these phenomena and increase our insight in the underlying physical processes. A novel analysis developed at the IIHE searched for low energy neutrinos in IceCube in coincidence with observations of solar flare gamma rays detected by the Fermi-LAT. The results have allowed to set the first experimental constraints on the flux of GeV neutrinos emitted during solar flares. This first effort within the IceCube Collaboration will be pursued and other analysis techniques will be developed in view of improving the current state-of-the-art.
  - **GeV neutrinos from GRBs** While TeV neutrinos are predicted as a consequence of the internal shocks in the prompt phase of GRBs, also GeV neutrinos should be produced by neutron and proton collisions following decoupling. A neutrino search in the GeV energy range would therefore be complementary to the existing limits that have been set by neutrino telescopes in the TeV range. Some models also predict neutrino emission before, or after the prompt phase. We have searched for an excess of GeV neutrinos in time windows from 3 s to 1000 s around gravitational wave events as possible counterparts of short GRBs. While all the time regions showed a p-value consistent with the pure background hypothesis, one case significantly deviates with a p-value of 9.33×10^5. The corresponding gravitational wave event was labeled GW170608 by the LIGO Collaboration. Interestingly, during the follow-up campaign triggered by the LIGO observation, the Fermi-LAT has observed gamma rays inside the LIGO probability map 1200 s after the merger time. It turned out that IceCube was stable at the moment of the merger and more detailed investigations are being performed to understand the origin of the potential extra events observed in IceCube.

- **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**
    In recent years the IIHE group focused on the search for neutrino signals from Weakly Interacting Massive Particle (WIMP) annihilation in the center of the Earth. Initial results using one year of data provided limits that were one order of magnitude better compared to the previously published AMANDA (predecessor of IceCube) results. The results of this first IceCube analysis were accepted for publication on December 2016 in the European Physical Journal C. Efforts to extend this analysis to combine several years of data are still on-going. We plan to explore a unified event selection, while exploring all the astrophysical uncertainties that could boost a neutrino signal, such as the existence of a dark disc.
  - **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. Currently this analysis is being unblinded and the final results are eagerly awaited.

- **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 a major Surface Veto array on the surface. This Surface Veto array will consist on scintillator panels deployed to measure cosmic air showers and explore the vetoing capabilities in order to reduce the large contamination of the atmospheric muons background in the Southern Sky. The facility also seeks to improve the sensitivity to to neutrinos in the $10^{16} - 10^{20}$ eV energy range with the construction of a 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 Veto and SiPM**
    As part of the IceCube-Gen2 facility a Surface Array of 75 km^2 is being proposed. With an infill factor of 10^{-3} this implies the deployment of 5000 to 7000 stations of at least 10 m^2 effective surface. Since such an area will be impossible to cover with 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 step will consist on upgrading the current IceTop detector with 37 scintillator pannels. Two 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 radio detector being deployed at the South Pole aiming at the radio detection of cosmogenic neutrino interactions with 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 strongly unexplored. To fill this gap, novel detection techniques are being investigated at the IIHE. Further details about the radio detection of neutrino induced particle cascades can be found in a dedicated section elsewhere in this report.

2.5 Measurement of the high-energy neutron dose in proton therapy

(G. De Lentdecker, D. Ndayizeye)

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.

In the future, the research in this field will move towards the developments 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 will be 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, the development of a first prototype should start in 2019.

2.6 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].

At the beginning of 2018 the installation of the full-scale Phase 1 detector at the BR2 reactor was completed. The installation was followed by an intense commissioning period and setting up a system to monitor the detector on a daily basis. The IIHE SoLid members took part in the commissioning and monitoring of the detector. Regular calibrations have been performed with radioactive sources as well as with cosmic muons entering the detector. S. Vercaemer has set up a way to determine the quality of a run in the collected data based on a comparison of various environmental measurements, file sizes as well as data rates collected with several triggers for a certain run range. A detailed study was performed to understand the low-energy accidental background when the reactor is on. Using the data, also time-correlated backgrounds were studied in detail, in particular the evolution of these background rates over time. A correlation between the cosmic-induced backgrounds and the atmospheric pressure was observed as expected. After correcting for changes in the atmospheric pressure, which influence the amount of background signals from cosmic rays in the detector, the high-energy part of the ES signal was compared in reactor on and off data, giving good agreement, validating this correction. An initial search was performed for antineutrinos. The limited amount of data and the low signal-to-background after an initial selection prevented an actual observation of the antineutrinos. These studies are summarized in the PhD thesis of S. Vercaemer, which he successfully defended in November 2018 and are at the basis for the run quality control today as well as for the optimization of the signal to background rate. In parallel, the oscillation analysis framework implemented by L. Kalousis has been developed further. More details about the detector performance studies can be found in [2].

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] Y. Abreu *et al.* [SoLid Collaboration], "Performance of a full scale prototype detector at the BR2 reactor for the SoLid experiment," JINST **13**, no. 05, P05005 (2018) doi:10.1088/1748-0221/13/05/P05005 [arXiv:1802.02884 [physics.ins-det]].

2.7 The JUNO experiment at Jiangmen (China)

(Barbara Clerbaux, Benoît Denègre, Jianmeng Dong, 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 in June 2016 and successfully obtained for the period 2017-2020. The budget 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 Δm^2 value and at large mixing angle θ_{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 17000 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 2000 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 17000 large (20-inch) PMTs and 25000 small (3-inch) PMTs of the central detector as well as 2000 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. The two key requirements for the BECs are to implement a 125 Mb/s bi-directional data transfer and to deliver 48-W low voltage power.

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, see Figure 9 (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, see Figure 10 (left). 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 355 back-end cards are needed to read the 17000 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. 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, see Figure 9 (right). 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, see Figure 10 (right). 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. The details of the these options and the BEC version 3 design are described in a poster sent to IEEE conference and in the corresponding proceeding. Various tests have been performed. Currently we have tested 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. The results of the tests have been sent as a contribution to the TWEPP conference in September 2018.

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. 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.

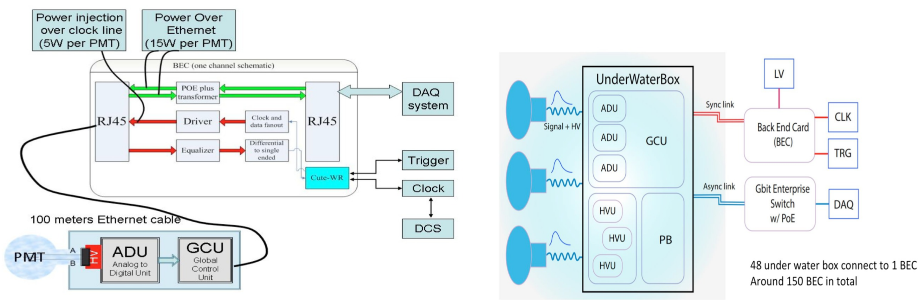

Figure 9: Schematic view of the JUNO readout with the front-end part (PMT, ADU, GCU – under water) and the back-end part (BEC, DAQ, trigger). Left: the first option with one GCU and one long cable per PMT ; Right: the latest version with 3 PMTs connected to one GCU via an underwater box.

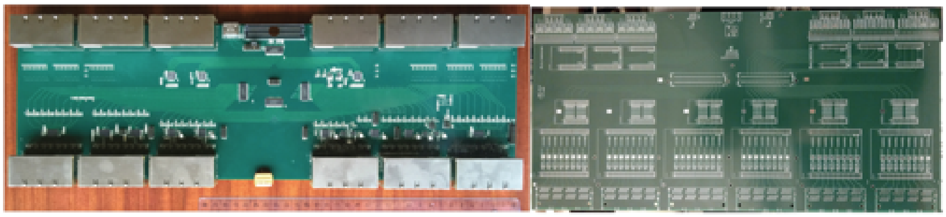

Figure 10: The baseboard of the BEC developed at the ULB (v2 on the left and v3 on the right).

2.8 Phenomenology

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

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, including supersymmetry and its signals at the LHC, as well as 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 2018 the Pheno group comprised one VUB 100% ZAP member Prof. A. Mariotti, two postdocs A. Ahmed and S. Najjari (from October 2018), and two PhD students M. Vereecken and S. Junius (from October 2018).

During 2018 the members of the pheno group have produced 3 scientific papers published on international peer reviewed Journals [1, 2, 3], one preprint [4], one proceedings [5], and participated to two working group reports [6, 7]. They have pursued different lines of research in BSM phenomenology achieving important results in a broad range of subjects.

One important topic of investigation has been the study of effective field theory (EFT) approach to new physics beyond the standard model (BSM), focusing on the top sector. The EFT framework provides a model independent parameterization of BSM physics in terms of higher dimensional operators involving the SM degrees of freedom. In [1, 5] the possibility to test the existence of BSM physics in $ttbb$ final states at the LHC has been explored, and novel bounds have been set on previously unconstrained SM EFT operators. Moreover, the beneficial impact of the use of machine learning techniques in discriminating signal from background as well as different EFT operators (specifically with different top chirality) has been investigated.

In [2] it has been proposed to test the existence of light Axion Like Particles, emerging in several well motivated BSM scenarios, in flavour factories. Public LHCb data has been employed to set the strongest existing bound on a BSM diphoton resonance in a mass window around the B_s mass. The potential reach of a future dedicated LHCb search on low mass diphoton resonances and its complementarity with existing and future constraints from ATLAS and CMS have been explored. Furthermore, the impact of BABAR searches and future reach of Belle2 have been derived.

The group has also produced important contributions in the study of BSM physics which manifests in colliders with exotic signatures, specifically new long lived particles [3, 4, 6]. In [3] the phenomenology of a simplified dark matter model in the freeze-in regime (very feeble couplings) has been studied in details. The signatures of this DM model at the LHC include disappearing charged tracks and displaced vertices. The interplay of these collider signals with the cosmological constraints on the model has been investigated.

In [4] the possibility of discovering the Twin Higgs scenario through displaced signatures at the LHC has been studied. The Twin Higgs is a BSM paradigm to address the (little) hierarchy problem of the SM, and implies the existence of a twin sector of the SM, including a Twin Higgs boson.

References

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[2] X. Cid Vidal, A. Mariotti, D. Redigolo, F. Sala and K. Tobioka, "New Axion Searches at Flavor Factories," JHEP **1901** (2019) 113 doi:10.1007/JHEP01(2019)113 [arXiv:1810.09452 [hep-ph]].

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2.9 Towards the highest energies: Radio detection of the cosmic neutrino flux

Nick van Eijndhoven, Olaf Scholten, Simona Toscano, Krijn de Vries, Simon de Kockere, Kian Goeloe

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 their falling flux, to probe cosmic neutrinos at these extreme energies, huge detection volumes have to be oberved. 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 1962 Askaryan already predicted that while a high-energy (cosmic-neutrino) induced particle 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. A dedicated section on the radio detection of cosmic-ray air showers using the LOFAR detector is provided elsewhere in this document. As such in the following we focus on the radio detection of the cosmic neutrino flux.

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 (N. van Eijndhoven,

S. Toscano, K.D. de Vries, S. de Kockere), where it should be noted that in the past IIHE made very strong contributions to the first construction and analysis of the ARA experiment (K. Hanson, T. Meures, A. O'Murchadha). The ARA experiment is still under construction deploying radio stations at a depth of rougly 50-150 below the ice surface at South Pole, with currently 6 out of the proposed 37 stations fully deployed. In view of the ARA experiment, at the IIHE a model has been constructed describing the (background) radio signal expected in the the ARA detector induced by a cosmic-ray air shower hitting the air-ice boundary [1]. As such, currently Simon de Kockere initiated an ARA analysis to search for this (background) signal. Detection of this signal would not only provide a means to study high-energy cosmic-ray air showers, but immediately show the proof of concept for the neutrino detection channel and provide an in-nature calibration source for the detector.

With the ARA detector being in the vicinity of the IceCube detector a second very promising detection channel is investigated by the group of Simona Toscano at the IIHE, which is the hybrid detection channel. In case of a charged current 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 Indirect radio detection of high-energy particle cascades

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 are sensitive 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 [2]. 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 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 that are currently under review [3]. These results lead to a second run in October 2019, of wich the data is currently being analyzed. In the near future a follow-up beam test is considered using an actual ice target. Furthermore, a proposal is under development to have a first in-nature test configuration. During this experiment IIHE radio detection equipment was used, which has been calibrated locally by K. Goeloe, performing a stage at IIHE. An overview of the calibration set-up as well as the SLAC experiment is shown in the figures.

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[2] K.D. de Vries, K. Hanson, T. Meures, Astropart.Phys. 60 (2015) 25-31
[3] S. Prohira, K.D. de Vries, et. al., arXiv:1810.09914, Submitted to PRD

2.10 Computing and networking

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

Figure 11: Construction of the DAQ for the calibration set-up at the IIHE. The radio detection set-up used at the SLAC experiment are calibrated.

Figure 12: Radio antenna set-up for the SLAC experiment.

2.10.1 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 also 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 CloudZilla DRBL server has been implemented to efficiently administrate both Linux and Windows OS.

2.10.2 Large scale and grid computing

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

In 2018, 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, UGent). 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 equipments that are relevant to the WLCG community.

By the end of 2018, the Tier2 provided around 7700 job slots to its community, spread over 200 worker nodes. Alongside that compute power, 30 storage node provided 5.3PB of mass storage to the users and the experiments.

2.10.3 Overview per Experiment

SoLid: In order to transfer data from the experiment in SCK-CEN to our mass storage, as well as access, monitor and control resources on-site, a dedicated 1Gbps network link was implemented by BELNET 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 allows 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).

The computing and storage needs of the SoLid experiment have increased significantly in 2018, as the experiment ran exceptionally well throughout the year. The experimental data collected, along with the Monte-Carlo simulations, take more than 500TB of storage as of end of 2018. Therefore, a compression campaign was started in December to gain a factor 2 in storage space and prepare for 2019 data.. More than 50 users from the SoLid collaboration have access to our infrastructure, either to use the cluster or to manage the experiment. With an increase of 1.1 percent point compared to 2017, they now represent 2.7% of the overall non-Grid computing time, totalling 146'707 hours of computing done in 2018. On the other hand, the collaboration usage of our resources using Grid middleware is a modest 0.2% of the grid computing time with 72'336 hours of compute performed.

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.

Since the integration of IceCube in 2016 with the Grid cluster, its use of Grid-enabled computing has been greatly beneficial to both the IceCube collaboration and the Tier2 itself, representing 14.4% of the computing time allocated to Grid experiments with 6.6M hours of computing done in 2018. The computing usage of local IceCube users also increased significantly, as efforts were done to help these users migrate from the Madison infrastructure - which is the central resource of the collaboration - to the Belgian Tier2. With 1.3M hours of compute done in 2018, they represent 23.8% of the overall non-Grid computing time.

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 2018, the Grid-enabled storage system hosted 4.2 PB of CMS data, from centrally managed datasets comprised of real collisions or Monte-Carlo simulations, to data produced by Belgian researchers. The CMS usage of the cluster through the Grid infrastructure represented 85.3% of the computing time allocated to Grid experiments with 39.1M hours of computing performed, an increase of 37% compared to 2017. Albeit an extremely well integrated usage of the Grid infrastructures by the CMS end-users, with tools like CRAB, a small portion of the analysis steps are performed locally on the Tier2 with non-Grid means mainly to allow rapid feedback when looking at the final results. With 3.9M hours of compute done in 2018, this usage represented 73.5% of the overall non-Grid computing time.

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, as collected data at the LHC keeps increasing. Therefore, the network of the cluster is now fully utilizing the 40/100Gbps technologies of the core switches, with the aggregated bandwidth between the worker nodes performing the calculations and the storage system increasing to ∼750Gbps in 2018, in order to sustain the CMS analyses.

3 Activities

3.1 Contributions to experiments

3.1.1 Responsibilities in experiments

Juan Antonio Aguilar Sánchez

- IceCube Reconstruction & Systematics Working Group coordinator
- 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

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

Koun Choi

- Fluorescence Detector on-site shift 01.09.2018 - 17.09.2018

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

- Chairperson of the CMS International Committee
- 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

Jarne De Clercq

- CMS central technical shifts
- Contribution to firmware developments for CMS tracker phase II test systems

Catherine De Clercq

- PI of VUB in the IceCube collaboration board

Gilles De Lentdecker

- Convener of the CMS GEM DAQ & Electronics Working Group

Krijn De Vries

- SLAC beam test experiment #1: May 2018
- SLAC beam test experiment #2: October 2018

Laurent Favart

- Internal referee for CMS (ARC)
- Member of the CMS Publication Committee Board FSQ and PRF
- Member of the H1 Physics Board
- Shift Leader - CMS data taking

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

Seth Moortgat

- L3 convener of the BTV software and algorithms working group

Nicolas Postiau

- Validator for High-level Triggers for the SMP analysis group

Laurent Thomas

- Contact person of the same sign dilepton/multilepton + jets SUSY analysis (full Run 2)
- Convener of the Missing transverse energy group (Sept 2018-July 2019)
- SUSY trigger convener (until Aug 2018)

Petra Van Mulders

- L3 coordinator of all top mass measurements in the CMS experiment
- Member of the SoLid publication and conference board
- Member of the institutional board of the SoLid collaboration

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

Gaston Wilquet

- Internal referee for OPERA publications
- Member of the OPERA Collaboration Board

3.1.2 Presentations in collaboration meetings

Aqeel Ahmed

- Clockwork perspective on BSM model building - EOS project be-h - VUB, Brussels 09/11/2018

Emil Bols

- Machine Learning Techniques for Jet Flavour Identification at CMS - CMS ML Workshop - CERN 02/07/2018

Gilles De Lentdecker

- GE11 Electronic System Review - CMS - CERN 22/01/2018

Saereh Najjari

- Phenomenology of Twin Higgs Models via the Higgs and Hypercharge Portal at colliders - EOS project be-h - IIHE, VUB 09/11/2018

3.2 Completed Master and PhD theses

Freya Blekman

- Douglas John Paul Burns
  Precision measurements of differential tt production cross sections as a function of kinematic event variables at 13 TeV at CMS
  Phd thesis, VUB, December 2018.
- Dominic Smith
  Search for new physics in $sqrts$ = 13 TeV proton-proton collisions, using jet substructure techniques with the CMS detector at the LHC
  Phd thesis, ULB, January 2018.

Barbara Clerbaux

- Morgane Rigaux
  Search for a heavy vector boson coupling to supersymmetric particles in the dilepton and missing transverse energy final state using the CMS detector
  Master thesis, ULB, September 2018.
- Pierre-Alexandre Petitjean
  Study of the effect of the anti-neutrino energy resolution using the JUNO detector on the measurement of the neutrino mass hierarchy, using Monte-Carlo simulations
  Master thesis, ULB, September 2018.

Jorgen D'Hondt

- Isis Van Parijs
  A search for flavour changing neutral currents involving a top quark and a Z boson, using the data collected by the CMS experiment at a centre-of-mass energy of 13 TeV
  Phd thesis, VUB, January 2018.
- Shimaa Abuzeid
  Search for Top Quark Flavour Changing Neutral Couplings with the CMS Experiment at the LHC
  Phd thesis, VUB, June 2018.

Gilles De Lentdecker

- Robin Tesse
  Quantitative methods to evaluate the radioprotection and shielding activation impacts of industrial and medical applications using particle accelerators
  Phd thesis, ULB, September 2018.

- Laurent Pétré
  Triple-GEM time resolution measurement for their installation in CMS
  Master thesis, ULB, September 2018.
- David Ndayizeye
  Validation de la réponse du détecteur de neutrons WENDI-2 dans un faisceau de neutrons quasi-monoénergétiques pour son utilisation dans un centre de protonthérapie
  Phd thesis, ULB, December 2018.

Laurent Favart

- Qun Wang
  Measurement of the differential cross section of Z boson production in association with jets at the LHC
  Phd thesis, ULB, June 2018.

Steven Lowette

- Isabelle De Bruyn
  Search for Dark Matter in the Monojet and Trackless Jets Final States with the CMS Detector at the LHC
  Phd thesis, VUB, January 2018.

Alberto Mariotti

- Sam Junius
  A new window for leptophilic dark matter
  Master thesis, VUB, July 2018.

Petra Van Mulders

- Simon Vercaemer
  Commissioning of the SoLid experiment for the observation of electron antineutrinos at the BR2 reactor
  Phd thesis, VUB, November 2018.
- Lieselotte Moreels
  Direct measurement of the top quark decay width in the muon+jets channel using the CMS experiment at the LHC
  Phd thesis, VUB, April 2018.

3.3 Representation in scientific councils and committees

Aqeel Ahmed

- EOS steering board meeting, representative of EOS postdocs

Juan Antonio Aguilar Sánchez

- 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
- Member CLiC physics and detector advisory board
- Review panel on subatomic physics, space physics and astronomy (NT-3), Swedish Research Council, Sweden
- Vice-Chairperson of WT2 (physics) funding review panel of the FWO, Flanders, Belgium

Barbara Clerbaux

- Belgian representative to the European Committee for Future Accelerators (ECFA)
- Chairperson of the JUNO award committee

- President of the Jury FRIA of the Belgian FNRS
- Referee for the Phys. Lett. B Journal

Jorgen D'Hondt

- Belgian representative in Restricted European Committee for Future Accelerators (RECFA)
- Chair of the European Committee for Future Accelerators (ECFA)
- Chair of the MYRRHA review committee of the Flemish Government
- Chair of the Scientific Advisory Committee of the Institute of Physics at the Universiteit van Amsterdam
- 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 the CERN Council
- Member of the CERN Finance Committee
- Member of the CERN Science Policy Committee
- 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 FWO Committee for International Collaboration
- Member of the IRFU review committee of the French State
- Member of the KVAB thinkers working group around Belgium/Flanders and CERN
- Member of the MYRRHA review panel of the Belgian Federal Government
- Member of the NWO selection committee for the VICI grants
- Member of the Physics Preparatory Group of the European Strategy for Particle Physics
- Member of the Science and Arts working group at BOZAR
- Member of the Secretariat of the European Strategy for Particle Physics
- Member of the VUB committee for Future Education Innovations
- Member of the VUB selection committee for grants for Education Projects
- 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

- Adviseur for EUROTALENTS - Marie Curie Actions FP7 EU
- FNRS delegate to the IOFG (International Oversight and Finance Group) of the IceCube experiment
- Member of the Belgian committee for the selection of CERN fellows
- Representative of the FNRS at the ApPEC (Astroparticle Physics European Consortium)

Steven Lowette

- 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

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 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

- Clockwork Mechanism: A 4D/5D perspective on BSM model building, MPIK Theory Seminar - Heidelberg 26/11/2018
- Neutral Naturalness at the LHC, Winter Solstice meeting - ULB, Brussels 20/12/2018

Juan Antonio Aguilar Sánchez

- Dark Matter Searches with IceCube, Very Large Volume Neutrino Telescopes - Dubna, Russia from 01/10/2018 to 05/10/2018
- Indirect searches of Dark Matter with IceCube, Exploring the Dark Side of the Universe - Point-à-Titre, Guadaloupe, France from 25/06/2018 to 02/11/2018

Diego Beghin

- Searching for charged lepton flavor violation with the CMS detector, NuFACT - Blacksburg, US 16/08/2018

Emil Bols

- ML Techniques for heavy flavour identification in CMS, Machine Learning for Jets 2018 - Fermilab 14/11/2018

Barbara Clerbaux

- Dark Matter searches with mono-X and other exotic searches @LHC, DSU 2018 - Annecy from 25/06/2018 to 29/06/2018

Krijn De Vries

- Modeling radio emission of air showers, GRAND - Paris, France 23/08/2018
- Radar detection of high-energy cosmic neutrinos, TEVPA 2018 - Berlin, Germany from 27/08/2018 to 31/12/2018
- Radar detection of high-energy neutrino-induced particle cascades, SUGAR 2018 - Brussels, Belgium from 24/01/2018 to 26/01/2018

Steven Lowette

- LLP Searches - CMS Snapshot, LLP2018: Third workshop of the LHC Long-Lived Particle Community - CERN, Geneva (Switzerland) 16/05/2018

Alberto Mariotti

- Dark Matter Freeze-in and LHC displaced signatures, GGI workhop - Beyond Standard Model: Where do we go from here? - Florence 27/08/2018
- Low mass diphoton resonances at the LHC, 53rd Rencontres de Moriond - EW 2018 - La Thuille from 10/03/2018 to 17/03/2018
- Singlet Doublet Dark Matter Freeze-in, LHC Long Lived Particle workshop - CERN from 16/05/2018 to 18/05/2018

Seth Moortgat

- Learning to pinpoint effective operators, IRN Terascale meeting - Durham, England from 04/09/2018 to 07/09/2018

Saereh Najjari

- Exploring Twin Higgs Models via the Higgs and Hypercharge Portal, MIPK - Heidelberg, Germany 27/11/2018

Nicolas Postiau

- Search for a new scalar resonance decaying to a pair of Z bosons and study of the off-shell Higgs boson in the $H \to 2\ell 2\nu$ channel with the CMS detector, BPS meeting - Antwerp 11/04/2018

Christoph Raab

- Gamma-ray lightcurve correlation search for IceCube neutrinos from TXS 0506+056 & other blazars, TeVPA 2018 - Berlin, Germany 27/08/2018
- -ray lightcurve correlation search for IceCube neutrinos from TXS 0506+056 & other blazars, VLVnT 2018 - Dubna, Russia 02/10/2018

Petra Van Mulders

- Top quark properties, Top2018: 11th international workshop on top quark physics - Bad Neuenahr (Germany) from 16/09/2018 to 21/12/2018

Pascal Vanlaer

- Challenges of the CMS tracker phase-2 upgrade, Invited seminar - PKU university Beijing 14/06/2018
- Challenges of the CMS tracker phase-2 upgrade, Invited seminar - Beihang University, Beijing 14/06/2018
- Challenges of the CMS tracker phase-2 upgrade, Invited seminar - Tsinghua University, Beijing 12/06/2018
- Prospects for Higgs physics at HL-LHC with the CMS experiment, Higgs Hunting - Paris from 23/07/2018 to 25/07/2018

Matthias Vereecken

- High energy neutrino emission from obscured sources through the pp channel, TeVPA 2018 - Berlin 31/08/2018

3.4.2 Poster presentations at conferences and schools

Barbara Clerbaux

- Design of a common verification board for different back-end electronics options of the JUNO experiment, IEEE2018 - Williamsburg, VA, United States from 09/06/2018 to 15/06/2018
- Design of the Back-End Card for the JUNO experiment, TWEPP2018 - Anvers from 17/09/2018 to 21/09/2018

Seth Moortgat

- Leanring to pinpoint effective operators at the LHC, TOP2018 - Bad Neuenahr, Germany from 17/09/2018 to 21/09/2018

3.5 Scientific training

3.5.1 Attendance to conferences and workshops

Diego Beghin

- NuFACT - Blacksburg, US from 13/08/2018 to 18/08/2018
- EXO Workshop - Athens from 01/11/2018 to 03/11/2018

Bugra Bilin

- Workshop on Resummation, Evolution, Factorization 2018 - Prospects for measurements of H/Z production cross section ratios using CMS Run II data. - Krakow, Poland from 19/11/2018 to 23/11/2018
- XXVI International Workshop on Deep Inelastic Scattering and Related Subjects - Vector Boson production with heavy flavor quarks from CMS - Kobe, Japan from 16/04/2018 to 20/04/2018

Emil Bols

- CMS ML Workshop - CERN from 02/07/2018 to 04/07/2018
- Machine Learning for Jets 2018 - Fermilab from 14/11/2018 to 16/11/2018

Koun Choi

- ISAPP School 2018 - LHC meets Cosmic Rays - cosmic ray - CERN from 28/10/2018 to 02/11/2018
- Dark Ghosts - dark matter - Brussels from 13/11/2018 to 14/11/2018

Barbara Clerbaux

- BPS - Anvers 11/04/2018
- CMS week - CERN from 17/04/2018 to 19/04/2018
- COSPA - Liège 31/01/2018
- CMS Week in Budapest - Budapest, Hongrie from 01/10/2018 to 05/10/2018
- EOS Solstice meeting - ULB, Brussels 20/12/2018
- APPEC Event - Brussels 09/01/2018
- EOS summer Solstice meeting - Ghent 21/06/2018
- JUNO Collaboration meeting - Nanjing, China from 19/01/2018 to 29/01/2018
- JUNO electronics workshop - workshop organiser - Brussels from 14/05/2018 to 15/05/2018

Paul Coppin

- IceCube collaboration conference - Stockholm, Sweden from 22/09/2018 to 28/09/2018
- IceCube collaboration conference - Atlanta, United States from 05/05/2018 to 12/05/2018

Pablo Correa

- IceCube Spring Collaboration Meeting - Atlanta, GA, USA from 04/05/2018 to 12/05/2018
- SuGAR - Brussels, Belgium from 23/01/2018 to 26/01/2018
- IceCube Fall Collaboration Meeting - Stockholm, Sweden from 23/09/2018 to 29/09/2018

Catherine De Clercq

- General Scientific Meeting of the BPS - Antwerpen, Belgium 11/04/2018

Gilles De Lentdecker

- TWEPP 2018 - Topical Workshop on Electronics for Particle Physics (TWEPP) - Antwerpen from 17/09/2018 to 21/09/2018

Krijn De Vries

- GRAND - Paris, France from 22/08/2018 to 24/08/2018
- SUGAR 2018 - Brussels, Belgium from 24/01/2018 to 26/01/2018
- TEVPA - Berlin, Germany from 27/08/2018 to 31/08/2018
- IceCube collaboration meeting - Atlanta, US from 05/05/2018 to 12/12/2018
- IC collaboration meeting - Stockholm, Sweden from 23/09/2018 to 29/12/2018

Laurent Favart

- REF 2018 - Workshop on Resummation, Evolution, Factorization (organiser) - Cracovie (Pologne) from 18/11/2018 to 23/11/2018

Christoph Raab

- VLVnT 2018 - Dubna, Russia from 02/10/2018 to 04/10/2018
- TeVPA 2018 - Berlin, Germany from 27/08/2018 to 31/08/2018
- TeVPA Pre-Workshop - Neutrinos and Gamma-rays from AGNs - Lessons learned from IceCube-170922A and TXS 0506+056 - Zeuthen, Germany 26/08/2018

3.5.2 Attendance to schools

Emil Bols

- CMSDAS 2018 - Fermilab from 08/01/2018 to 12/01/2018
- BND School 2018 - BND School 2018 - Berlin from 10/09/2018 to 21/12/2018

Paul Coppin

- International School of Cosmic Ray Astrophysics - Erice, Italy from 02/08/2018 to 06/08/2018

Pablo Correa

- International School of Cosmic Ray Astrophysics - Erice, Italy from 01/08/2018 to 07/08/2018

Jarne De Clercq

- ISOTDAQ - School on trigger and data acquisition for high energy physics - Vienna from 14/02/2018 to 21/02/2018

3.6 Teaching and academics activities

3.6.1 Teaching activities

Juan Antonio Aguilar Sánchez

- ULB - PHYS-F314 : Electronique, (12/0/0/0) BA3
- 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-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-F311 : Laboratoires et Stage de recherche , (0/0/72/30) BA3
- ULB - PHYS-F467 : Physique des Astroparticules , (24/24/0/24) MA1 MA2
- ULB - PHYS-F467 : Physique des Astroparticules , (24/24/0/24) MA1 MA2

Diego Beghin

- ULB - PHYS-F311 : Laboratoire, (0/0/32/0) BA3 Temps de vie du muon
- ULB - PHYS-F104 : Physique Générale, (0/24/0/0) 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

Emil Bols

- VUB - WE-DNTK-6331 : Subatomic Physics I: Introduction to Nuclear and Particle Physics, (0/26/0/0) BA3

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 21 to 23 March 2017
- ULB - PHYS-F104 : Physique Générale, (0/24/0/0) 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

Jarne De Clercq

- VUB - VUB - WE-DNTK-006317 : Fysica: trillingen, golven en thermodynamica, (0/24/6/30) BA1

Simon De Kockere

- VUB - WE-DNTK-6323 : Physics: Electromagnetism, (0/0/24/18) BA1
- VUB - WE-DNTK-6355 : Physics: Introduction to Mechanics, (0/14/16/22) 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

Krijn De Vries

- VUB - WE-DNTK-4134 : Elektrodynamica en Speciale Relativiteit, (0/18/0/0) BA2

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
- ULB - PHYS-F311 : Visite annuelle du CERN, (0/0/0/24) BA3 Physique

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
- 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

Seth Moortgat

- VUB - WE-DNTK-1001388CNR : Experimentele stralings- en kwantumfysica, (0/0/40/0) BA2
- VUB - WE-DNTK-1010221BNR : Statistische verwerking van experimentele gegevens, (0/12/0/0) BA2

Nicolas Postiau

- 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

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 - PHYSF110 : Physique générale 2, (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

Barbara Clerbaux

- Master thesis, - ULB, June 2018 - Paul Champion : Interacting Dark Matter : empreinte cosmologique
  Referee
- Phd thesis, - Cambridge university - Magdalene College, January 2018 - Benjamin Hylton Brunt : Searches for new physics with the ATLAS experiment
  Referee
- Phd thesis, - University of Aix Marseille (CPPM) and LCC Montpellier , November 2018 - Rima EL KOSSEIFI : Search for chargino and neutrino pair production in final states with one lepton, two b-jets consistent with a Higgs boson and missing transverse momentum with the ATLAS detector at the LHC Run2
  Referee

Gilles De Lentdecker

- Phd thesis, - UGhent, February 2018 - Sinem Salva : A Micro-pattern Gas Detector Based Muon System for the CMS Experiment at the High-luminosity LHC
  Referee

Krijn De Vries

- Phd thesis, - Vrije Universiteit Brussel, January 2018 - Isabelle De Bruyn : Search for dark matter in the monojet and trackless jets final states with the CMS detector at the LHC
  Referee

Laurent Favart

- Phd thesis, - ULB, December 2018 - David Ndayizeye : Validation de la réponse du détecteur de neutrons WENDI-2 dans un faisceau de neutrons quasi-monoénergétiques pour son utilisation dans un centre de protonthérapie
  President

Alberto Mariotti

- Phd thesis, - VUB, April 2018 - Lieselotte Moreels : Direct measurement of the top quark decay width in the muon+jets channel using the CMS experiment at the LHC
  Secretary
- Phd thesis, - VUB, July 2018 - Tim De Jonckheere : MEASURES OF CORRELATION IN HOLOGRAPHIC THEORIES
  Referee
- Phd thesis, - VUB, June 2018 - Shimaa AbuZeid : Search for top quark Flavour Changing Neutral Couplings with the CMS Experiment at the LHC
  Secretary

Petra Van Mulders

- Phd thesis, - Vrije Universiteit Brussel, January 2018 - Isis Van Parijs : A search for flavour changing neutral currents involving a top quark and a Z boson, using the data collected by the CMS experiment at a centre-of-mass energy of 13 TeV
  President

- Phd thesis, - Vrije Universiteit Brussel, July 2018 - Gwenhaël de Wasseige : Solar Flare Neutrinos in the Multi-Messenger Era: Flux Calculations and a Search with the IceCube Neutrino Observatory
  Referee
- Phd thesis, - Universiteit Gent, November 2018 - Celine Moortgat : The SoLid antineutrino detector: construction and commissioning with cosmic ray muons
  Referee

Pascal Vanlaer

- Phd thesis, - ULB and Peking University, June 2018 - Qun Wang : Measurement of the differential cross section of Z boson production in association with jets at the LHC
  Secretary
- Phd thesis, - VUB and Ain Shams University, June 2018 - Shimaa Abu Zeid : Search for Top Quark Flavour Changing Neutral Couplings with the CMS Experiment at the LHC
  Referee

3.6.3 Representation in academic councils and committees (in universities)

Freya Blekman

- Chairperson of the Opleidingsraad (Education council) of the VUB Bachelor and Master of Physics and Astronomy, VUB
- IIHE website coordinator, Other
- Organiser open days etc Department of physics, VUB
- PR chairperson VUB faculty of science and bio-engineering, VUB
- Secretary Bachelors Exam Committee, VUB
- Secretary Masters Exam Committee, VUB
- Seminar organiser IIHE, 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 of the , ULB
- Member of the Science Faculty pedagogic committee, ULB
- Member of the ULB Funding Committee (commission finance), ULB
- Member of the ULB committee for the University strategic plan, ULB cap 2030, ULB
- Member of the administrative ULB committee (commission administrative), ULB
- Representative of the ULB rector at the Scientific Olympiads proclamation, 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

Laurent Favart

- Membre de la commission du Plan stratégique, ULB

Steven Lowette

- DNTK delegate to the faculty's doctoral committee, VUB
- DNTK delegate to the faculty's internationalisation committee, VUB

Nick Van Eijndhoven

- Chair of the curriculum board of the VUB dept. of Physics and Astronomy, VUB
- Chair of the educational board of the VUB dept. of Physics and Astronomy, VUB
- Member of the education council 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 Observatory of the 1st year bachelor studies in sciences, ULB
- Member of the Physics department committee for teaching assistants hirings, ULB

3.7 Vulgarisation and outreach

Bugra Bilin

- Guiding tours to the CMS experiment, including visits to experimental cavern - CMS experiment at CERN, from 01/01/2018 to 31/12/2018

Freya Blekman

- Organiser of Dutch-language CERN teacher programme for Flanders - Geneva, Switzerland, from 25/09/2018 to 30/09/2018
- Organiser of two IPPOG CMS masterclasses at the VUB (one in Dutch, one in English) - Brussels, 07/03/2018

Paul Coppin

- IceCube Masterclass - Brussels, 14/03/2018

Pablo Correa

- 2nd edition of the South Pole Experiment contest - member of jury - Brussels, Belgium, from 01/01/2018 to 30/06/2018
- 3rd edition of the South Pole Experiment contest - co-organiser - Brussels, Belgium, from 01/09/2018 to 31/12/2018
- IceCube Masterclass 2018 - aiding in event organisation - Brussels, Belgium, 14/03/2018

Catherine De Clercq

- Verliefd op het zwarte gat - article in Trends, 07/06/2018

Krijn De Vries

- IceCube Masterclass - VUB-IIHE, 14/03/2018
- South Pole experiment contest - VUB-IIHE, from 01/09/2018 to 31/12/2018
- TADA toekomst atelier - VUB-IIHE, 24/02/2018

Alberto Mariotti

- Pint of Science Talk: A Journey in the Dark World - Brussels, 15/05/2018

Christoph Raab

- IceCube Masterclass 2018 - Brussels, Belgium, 30/01/2018

Petra Van Mulders

- How fundamental research is driving innovation - Nuclear forum – next year event, Brussels, Belgium, 06/02/2018

4 Publications

4.0.1 AUGER

1. *An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources*
   Aab, A et al. [AUGER Collaboration]
   Astrophys.J. 853 (2018) L29

2. *Ionization electron signal processing in single phase LArTPCs. Part I. Algorithm Description and quantitative evaluation with MicroBooNE simulation*
   Adams, C et al. [AUGER Collaboration]
   JINST 13 (2018) P07006

3. *Ionization electron signal processing in single phase LArTPCs. Part II. Data/simulation comparison and performance in MicroBooNE*
   Adams, C et al. [AUGER Collaboration]
   JINST 13 (2018) P07007

4. *Large-scale cosmic-ray anisotropies above 4 EeV measured by the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   Astrophys.J. 868 (2018) 4

5. *Observation of inclined EeV air showers with the radio detector of the Pierre Auger Observatory*
   Aab, A et al. [AUGER Collaboration]
   JCAP 1810 (2018) 026

6. *The Pandora multi-algorithm approach to automated pattern recognition of cosmic-ray muon and neutrino events in the MicroBooNE detector*
   Acciarri, R et al. [AUGER Collaboration]
   Eur.Phys.J. C78 (2018) 82

4.0.2 CMS

1. *Angular analysis of the decay $B^+o\ K^+mu^+mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV*
   Sirunyan, A et al. [CMS Collaboration]
   Phys.Rev. D98 (2018) 112011

2. *Azimuthal anisotropy of charged particles with transverse momentum up to 100 GeV/ c in PbPb collisions at $\sqrt{s}_{NN}$=5.02 TeV*
   Sirunyan, A et al. [CMS Collaboration]
   Phys.Lett. B776 (2018) 195-216

3. *Azimuthal correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at $\sqrt{s} = 13$ TeV*
   Sirunyan, A et al. [CMS Collaboration]
   Eur.Phys.J. C78 (2018) 566

4. *Bose-Einstein correlations in $pp, p\mathrm{Pb}$, and PbPb collisions at $\sqrt{s_{NN}} = 0.9 - 7$ TeV*
   Sirunyan, A et al. [CMS Collaboration]
   Phys.Rev. C97 (2018) 064912

5. *Charged-particle nuclear modification factors in XeXe collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.44$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1810 (2018) 138

6. *Combination of inclusive and differential* toverlinet *charge asymmetry measurements using ATLAS and CMS data at* $\sqrt{s} = 7$ *and 8 TeV*
Aaboud, M et al. [CMS Collaboration]
JHEP 1804 (2018) 033

7. *Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1803 (2018) 160

8. *Comparing transverse momentum balance of b jet pairs in pp and PbPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1803 (2018) 181

9. *Constraining gluon distributions in nuclei using dijets in proton-proton and proton-lead collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev.Lett. 121 (2018) 062002

10. *Constraints on models of scalar and vector leptoquarks decaying to a quark and a neutrino at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev. D98 (2018) 032005

11. *Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in* pPb *and PbPb collisions at the CERN Large Hadron Collider*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev. C97 (2018) 044912

12. *Constraints on the double-parton scattering cross section from same-sign W boson pair production in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1802 (2018) 032

13. *Electroweak production of two jets in association with a Z boson in proton–proton collisions at* $\sqrt{s} = 13$ *,extTeV*
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 589

14. *Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at* $\sqrt{s_{\mathrm{NN}}} = 8.16$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev.Lett. 121 (2018) 082301

15. *Event shape variables measured using multijet final states in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1812 (2018) 117

16. *Evidence for associated production of a Higgs boson with a top quark pair in final states with electrons, muons, and hadronically decaying au leptons at* $\sqrt{s} = 13$ *TeV*

Sirunyan, A et al. [CMS Collaboration]
JHEP 1808 (2018) 066

17. *Evidence for the associated production of a single top quark and a photon in proton-proton collisions at* $\sqrt{s}$ = *13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev.Lett. 121 (2018) 221802

18. *Evidence for the Higgs boson decay to a bottom quark–antiquark pair*
Sirunyan, A et al. [CMS Collaboration]
Phys.Lett. B780 (2018) 501-532

19. *Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV*
Sirunyan, A et al. [CMS Collaboration]
JINST 13 (2018) P05011

20. *Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev.Lett. 120 (2018) 071802

21. *Jet properties in PbPb and pp collisions at* $\sqrt{s_{\mathrm{N;N}}} = 5.02$ *TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1805 (2018) 006

22. *Measurement of angular parameters from the decay* $\mathrm{B}^0 o \mathrm{K}^{*0} mu^+ mu^-$ *in proton-proton collisions at* $\sqrt{s}$ = *8 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Lett. B781 (2018) 517-541

23. *Measurement of associated Z + charm production in proton-proton collisions at* $\sqrt{s}$ = *8 TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 287

24. *Measurement of charged particle spectra in minimum-bias events from proton–proton collisions at* $\sqrt{s} = 13, ext TeV$
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 697

25. *Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at* $\sqrt{s}$ = *13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev. D97 (2018) 112003

26. *Measurement of differential cross sections for Z boson production in association with jets in proton-proton collisions at* $\sqrt{s}$ = *13 TeV*
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 965

27. *Measurement of differential cross sections in the kinematic angular variable phi* for inclusive Z boson production in pp collisions at* $\sqrt{s}$ = *8 TeV*
Sirunyan, A et al. [CMS Collaboration]
JHEP 1803 (2018) 172

28. *Measurement of jet substructure observables in* toverlinet *events from proton-proton collisions at* $\sqrt{s} = 13 TeV$
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev. D98 (2018) 092014

29. *Measurement of normalized differential* toverlinet *cross sections in the dilepton channel from pp collisions at* $\sqrt{s} = 13\ TeV$
Sirunyan, A et al. [CMS Collaboration]
JHEP 1804 (2018) 060

30. *Measurement of prompt* D^0 *meson azimuthal anisotropy in Pb-Pb collisions at* $\sqrt{s_{NN}} = 5.02\ TeV$
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev.Lett. 120 (2018) 202301

31. *Measurement of prompt and nonprompt charmonium suppression in extPbPb collisions at 5.02 ,extTeextV*
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 509

32. *Measurement of quarkonium production cross sections in pp collisions at* $\sqrt{s} = 13\ TeV$
Sirunyan, A et al. [CMS Collaboration]
Phys.Lett. B780 (2018) 251-272

33. *Measurement of the* $Lambda_b$ *polarization and angular parameters in* $Lambda_b oJ/psi, Lambda$ *decays from pp collisions at* $\sqrt{s} = 7$ *and 8 TeV*
Sirunyan, A et al. [CMS Collaboration]
Phys.Rev. D97 (2018) 072010

34. *Measurement of the* Z$gamma^* oauau$ *cross section in pp collisions at* $\sqrt{s} = 13\ TeV$ *and validation of au lepton analysis techniques*
Sirunyan, A et al. [CMS Collaboration]
Eur.Phys.J. C78 (2018) 708

35. *Measurement of the associated production of a single top quark and a Z boson in pp collisions at* $\sqrt{s} = 13\ TeV$
Sirunyan, A et al. [CMS Collaboration]
Phys.Lett. B779 (2018) 358-384

36. *Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at* $\sqrt{s} = 13\ TeV$
Sirunyan, A et al. [CMS Collaboration]
JHEP 1808 (2018) 011

37. *Measurement of the groomed jet mass in PbPb and pp collisions at* $\sqrt{s_{\mathrm{NN}}} = 5.02\ TeV$
Sirunyan, A et al. [CMS Collaboration]
JHEP 1810 (2018) 161

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39. *Measurement of the inelastic proton-proton cross section at* $\sqrt{s} = 13\ TeV$
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40. *Measurement of the production cross section for single top quarks in association with W bosons in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
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116. *Search for resonant pair production of Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at 13 TeV*
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121. *Search for supersymmetry in events with at least three electrons or muons, jets, and missing transverse momentum in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*
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126. *Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at* $\sqrt{s}$ *= 13 TeV*
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129. *Search for third-generation scalar leptoquarks decaying to a top quark and a au lepton at $\sqrt{s}$ = 13 TeV*
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130. *Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s}$ = 13 TeV*
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132. *Search for vector-like T and B quark pairs in final states with leptons at $\sqrt{s}$ = 13 TeV*
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135. *Search for ZZ resonances in the 2ell2u final state in proton-proton collisions at 13 TeV*
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6. *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*
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4.0.5 LOFAR

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2. *Cosmic ray mass composition with LOFAR*
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3. *Expansion of the LOFAR Radboud Air Shower Array*
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7. *The effect of the atmospheric refractive index on the radio signal of extensive air showers using Global Data Assimilation System (GDAS)*
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