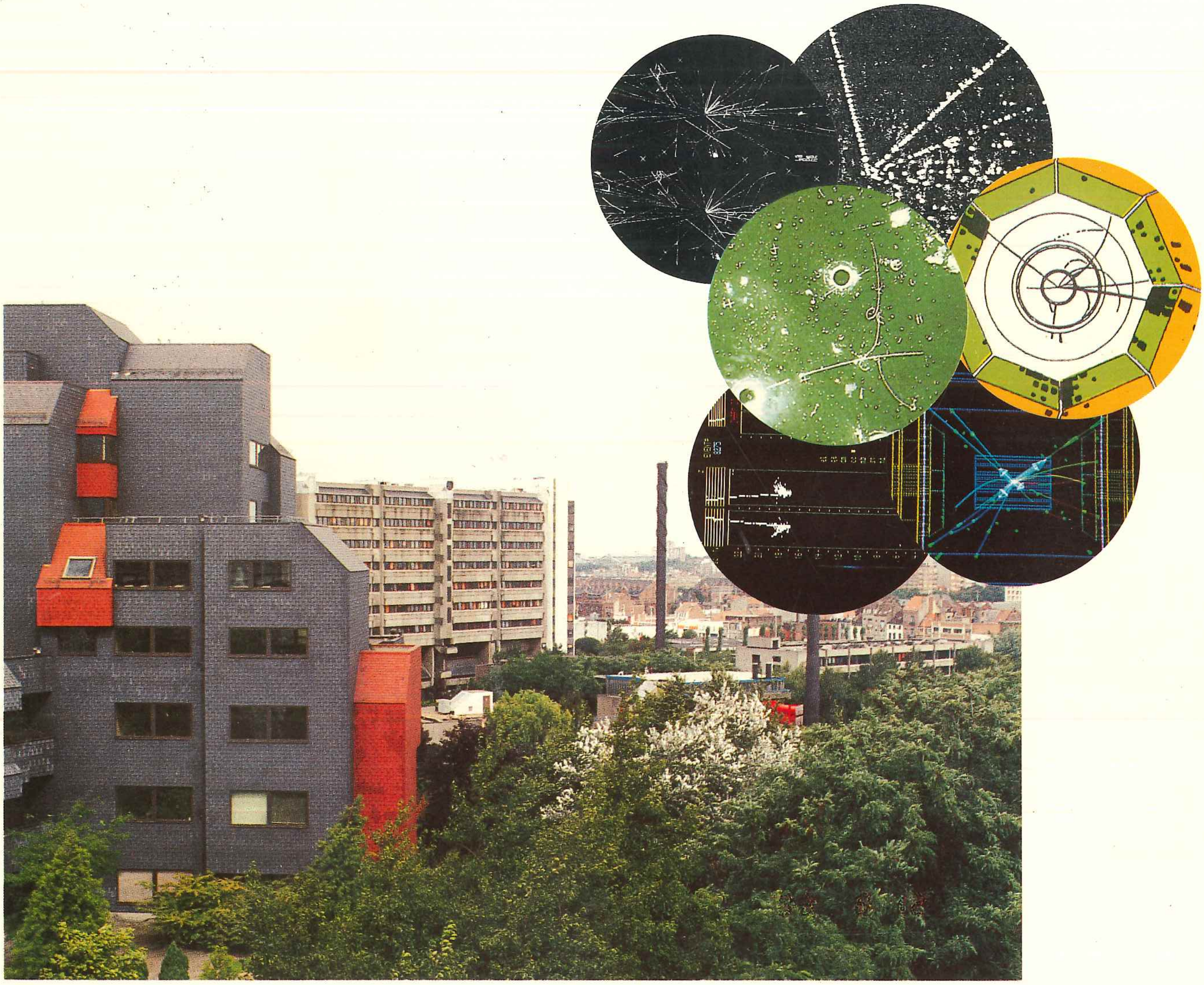
I.I.H.E.

Inter-University Institute for High Energies
(U. L. B . - V. U. B.)



1972 - 1992

scientific activity report

We also benefited from special research contracts in the framework of an "Action de Recherche Concertée" (ARC) and the LOTTO (Loterie Nationale, Nationale Loterij). In addition, applied research activities of the IIHE such as R & D in telecommunications and Positron Emission Tomography have been partly supported by the Commission of the European Communities.

It is our pleasure to emphasize the continuous help and support from our respective academic authorities.

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SCIENTIFIC ACTIVITY REPORT 1972 - 1992

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HISTORY

I. A FEW WORDS OF "HISTORY".

In 1947, soon after the end of the second World War, a research center for nuclear physics ("Centre de Physique Nucléaire") was created at the Université Libre de Bruxelles at the initiative of members from both the Faculties of Sciences and Applied Sciences. Part of the activities which developed in this Centre concerned the study of the properties of cosmic rays (the only source of elementary particles at that time) using the nuclear emulsion as particle detection technique. The Centre was dismantled in 1952 but, one year later, the Faculty of Applied Sciences set up a new department called "Service de Physique Nucléaire" where, in parallel with other activities, the cosmic ray studies could be pursued. However, with the advent of powerful particle accelerators of increasing energy this line of research was progressively abandoned; indeed, the use of monoenergetic beams of well identified particles quickly became the ideal tool for the study of both the intrinsic properties and the interactions of the various types of new particles, the so-called strange particles, which had been discovered during the cosmic ray investigations. The physicists from Brussels took an active part in this program of research on K mesons, Λ and Σ hyperons which was developing worldwide. In close collaboration with colleagues from other European universities they made, in particular, significant contributions to our knowledge of the interactions of Λ hyperons with matter through a systematic study of the production and decay properties of hypernuclei, i.e. ordinary nuclei containing a bound unstable Λ hyperon. The nuclear emulsion technique which had been pioneered in Brussels was particularly well suited for these studies because of its high spatial resolution enabling to "visualize" the tracks of the short-lived ($\sim 10^{-10}$ s) hypernuclei.

A "Belgian Interuniversity Laboratory for High Energies" was created in 1956 at the initiative of the Institut Interuniversitaire des Sciences Nucléaires (IISN) and the Interuniversitair Instituut voor Kernwetenschappen (IIKW); the group of Brussels was soon closely associated to the activities of this Institute.

During the sixties, bubble chambers of increasing sizes, filled with a variety of liquids - from hydrogen to heavy freon - were put in operation near all major particle accelerators. The "Service de Physique des Particules Elémentaires" which had been created in 1964 at the Faculty of Applied Sciences as a section of the "Service de Physique Nucléaire" was faced to adapt itself to this evolution. The acquisition of the equipment needed to scan and measure bubble chamber film was decided and rapidly allowed a progressive diversification of the scientific activities. Concurrently with the hypernuclear research program, various experiments were run by the Brussels physicists to study some K^+ meson decays (K_{e4}, K_{e3}, $K_{\mu 3}$) and the absorption mechanism of K^- mesons and Σ^- hyperons in different nuclei, to measure mass, lifetime and decay parameters of the Ξ^- and Ξ° hyperons and to investigate in a systematic way the interaction characteristics of fast hadrons with hydrogen and deuterium. At the end of the sixties the decision was taken to join the neutrino physics program which had been launched at the CERN Proton Synchrotron using as detector the big heavy liquid bubble chamber Gargamelle.

In 1970, the "Service de Physique des Particules Elémentaires" was transferred to the Faculty of Sciences. At about the same time, the Faculty of Sciences of the newly created Vrije Universiteit Brussel decided to develop a research program in experimental particle physics. A "Dienst Fysica der Elementaire Deeltjes" was created and accommodated at the U.L.B. in the same buildings as the "Service de Physique des Particules Elémentaires". From the very beginning, both groups decided to join their effort in a common research program based on the use of the bubble chamber technique to study the production and interaction properties of elementary particles. In 1972, the success of this initiative led the authorities of both universities to found the "Interuniversity Institute for High Energies ULB-VUB (IIHE)". This Institute soon served a purpose similar to that of the Belgian Interuniversity Laboratory for High Energies which was closed down in 1976. At the same time the IIHE was transferred to the Campus of the Vrije Universiteit Brussel where its laboratories, workshops and offices were accommodated on a 2500 m^2 area. An agreement between the ULB and the VUB forsees that both universities equally contribute to the running and maintenance costs of these buildings.

The total scientific staff of the IIHE presently amounts to fifty three physicists and engineers(*). Thirty one of them are involved in the particle physics research activities which are mainly presented in this report while the remaining contribute to two side programs which were launched in the eighties at the initiative of members of the Institute. The HELIOS group (18 scientists) led by P. Van Binst and R. Vandenbroucke is concerned, in particular, with high speed data transfer and Open Systems protocols, services and

(*) see list in Appendix A.

applications. A second team of four scientists led by S. Tavernier, works on problems of technology transfer from basic research to medical applications.

From about forty full time equivalent in the seventies, the technical and administrative staffs of the IIHE has been reduced to twenty eight today. This reduction was imposed partly by the profound changes in the activities of the Institute - from emulsion and bubble chamber work requiring large scanning teams to counter experiments depending on more specialized personnel - but also by severe financial constraints. Presently the technical and administrative staff consists of 9 FTE in mechanics, 6 in electronics, 9 in computer and data analysis and 4 in administration.

According to its statutes, the IIHE has continuously devoted its effort to promote scientific collaboration with other Belgian laboratories. Since 1974 a group of physicists from the Universitaire Instelling Antwerpen actively participates to most of the research activities of the Institute making use of its infrastructure and benefiting from the help of the technical staff. A very fruitful collaboration with physicists and engineers from the Université de Mons-Hainaut started in 1977 on the design and construction of particle detector components which were subsequently successfully operated at CERN in the European Hybrid Spectrometer and in DELPHI. More recently, physicists from the Université Catholique de Louvain-la-Neuve and from the IIHE have been closely associated with other European groups in the exploitation of a giant neutrino counter detector (CHARM II) operating at CERN and in the preparation of the long term future program for particle physics in Belgium.

NEUTRINO PHYSICS

II. NEUTRINO PHYSICS.

The systematic study of neutrino and antineutrino interactions with matter started in the early sixties at the Brookhaven National Laboratory and at CERN where the newly built proton synchrotrons were capable to provide the intense and energetic pion beams needed to produce the neutrinos. The participation of physicists from Brussels to this research program - which has proven to be so rich in fundamental discoveries - goes back to 1964. As a pilot experiment, a ten litre emulsion stack, sandwiched between two multiplate spark chambers and a set of scintillating counters for triggering and vetoing purposes, was exposed to the first CERN PS neutrino beam in an unsuccessful attempt to detect hypothetical neutrino produced short lived particles[1]. The observation of a few neutrino interactions had demonstrated the feasibility of the technique but no further consideration was given to this approach at that time because of the small neutrino event rate in that beam and the prohibitive emulsion scanning time.

II.1. GARGAMELLE AT THE CERN PS.

In 1971, the giant (visible volume ~ 8 m^3) heavy liquid bubble chamber Gargamelle which had been conceived by A. Lagarrigue from Orsay and built at Saclay was installed in the CERN PS separated neutrino and antineutrino beams of energies peaking around 2 GeV and extending to 12 GeV; the chamber was filled with heavy freon CF_3Br of radiation length 11 cm and interaction length 60 cm. The collaboration which had been set up to analyze the bubble chamber pictures consisted of physicists from Aachen, Brussels, CERN, Ecole Polytechnique-Paris, Milan, L.A.L.-Orsay and University College London. The first results obtained by the Gargamelle Collaboration were published in 1972[2] and concerned the observation of "elastic" Λ°hyperon production by antineutrinos : $\bar{\nu} + p \rightarrow \mu^+ + \Lambda^\circ$, a reaction which can be looked at as the inverse Λ° hyperon muonic decay.

From the analysis of a few hundred thousand pictures, two major results were reported in 1973 : the discovery of weak neutral currents and the observation of Bjorken scaling in neutrino interactions.

The evidence for the existence of weak neutral currents relied both on the detection of neutrino like interactions without muon or electron in the final state[3,4] and on the observation of one candidate for the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$[5]. As shown in figure 1, the muon- or electronless events were evenly distributed along the neutrino beam axis as expected for neutrino induced events; their characteristics were similar (almost identical) to those exhibited by the hadronic part of the neutrino events with charged leptons. Neutral hadrons produced by neutrinos interacting in the shielding upstream Gargamelle constituted the main source of background. Extensive Monte Carlo simulation of the background, complemented by empirical studies, failed to reproduce the observations. The bulk of the muon or electronless events was thus attributed to neutral current induced neutrino interactions. After background subtraction, the ratios of neutral current to charged current events in the ν_μ and the $\bar{\nu}_\mu$ beams were found to be respectively :

$$\frac{NC}{CC}(\nu) = 0.22 \pm 0.04 \qquad \frac{NC}{CC}(\bar{\nu}) = 0.43 \pm 0.12$$

leading to a first experimental estimate of $\sin^2\Theta_W$, the Weinberg parameter, in the range 0.3 to 0.5. These findings were soon confirmed by other groups at Fermilab, Brookhaven and Argonne.

The observation by the Gargamelle Collaboration of one clean candidate for the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ with an estimated background of 0.03 ± 0.02 event due to ν_e-nucleon interactions, came in strong support to the interpretation of the previous results in terms of neutral currents.

The evidence for Bjorken scaling, already observed at SLAC in deep inelastic electron-nucleon scattering experiments, came from the observation of the linear rise of the total interaction cross sections of neutrinos and antineutrinos with energies in the range 1 to 10 GeV (see figure 2)[6]. The slopes of the straight lines fitted to the experimental data were found to be :

$$\sigma_\nu/E = 0.74 \pm 0.02 \times 10^{-38}\ \mathrm{cm^2/GeV} \text{ and } \sigma_{\bar{\nu}}/E = 0.28 \pm 0.01 \times 10^{-38}\ \mathrm{cm^2/GeV}$$

and the ratio of the $\bar{\nu}$ to the ν cross sections was measured to be 0.38 ± 0.02, independently of the energy. The mean value of q^2, the square of the four-momentum transfer from the neutrino to the nucleon, was also found to increase linearly with energy, confirming precocious Bjorken scaling. These data were also used[7] to determine the shape of the distributions of the Bjorken variable $y = \frac{\nu}{E}$, and the Bloom-Gilman variable $x' = \frac{q^2}{2M\nu+M^2}$, where M is the mass of the target nucleon and ν the energy transfer from the neutrino to the nucleon. Again very good agreement was found with the predictions of the scaling and charge symmetry hypotheses in the framework of the naïve quark-parton model.

From 1973 to the end of 1975, more than one million pictures were taken with Gargamelle filled with heavy freon in order to increase the statistical significance of the above results. As a result two more candidates for the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ were observed[8]. These events together with the previously detected one, corresponded to a cross section for a recoil electron energy within the range $0.3 < E_e < 2$ GeV of $0.06 \times 10^{-41} E_{\bar{\nu}}$ (GeV) cm^2/electron. The calculated background being 0.44 ± 0.13 events, the probability that all three events could be due to background was 1 %. The signal had thus been definitely established. One of these events had been found in Brussels; it is shown in figure 3.
From the non-observation of the process $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ an upper limit (90 % confidence level) was obtained for its cross section of $3 \times 10^{-42} E_\nu$ (GeV) cm^2 per electron for a recoil electron energy above 0.3 GeV[9].

With increased statistics, more stringent selection criteria and a better understanding of the backgrounds, the neutral to charged current inclusive cross section ratios for ν and $\bar{\nu}$ interactions, R_ν and $R_{\bar{\nu}}$, were measured to be $R_\nu = 0.25 \pm 0.04$ and $R_{\bar{\nu}} = 0.56 \pm 0.08$ for events with hadron energy above 1 GeV[10]. Assuming the validity of scaling and a V and/or A type structure for the neutral currents, these ratios were corrected for the 1 GeV cut on the hadronic energy and used to estimate $\sin^2\Theta_W$:

$$\sin^2\Theta_W = 0.31 \pm 0.06 \quad \left(\text{from } R_\nu^{corr}\right)$$

and
$$\sin^2\Theta_W = 0.33^{+0.05}_{-0.08} \quad \left(\text{from } R_{\bar{\nu}}^{corr}\right)$$

Among the many other results obtained from the analysis of the film taken by this first Gargamelle Collaboration it is worth to mention :

- the first measurement of the total interaction cross sections of energetic ν_e and $\bar{\nu}_e$ which were found to be in good agreement with those measured in the same experimental conditions for ν_μ and $\bar{\nu}_\mu$ as expected from lepton universality[11]
- from a study of strange particles produced in neutrino and antineutrino neutral current interactions upper limits, at 90 % confidence level, were put on the fraction of the nucleon momentum carried by strange quarks (2 %)[12] and on the contribution of strangeness changing neutral currents (0.5 %)[13]
- evidence for charm production in charged current neutrino interactions from the observation of $\mu^- e^+ V^\circ$ events[14] interpreted as resulting from the reaction $\nu_\mu + N \rightarrow \mu^- +$ C + hadrons followed by the decay process $C \rightarrow e^+ + \nu_e +$ hadrons (S = -1). The first such event was found in Brussels and is shown in figure 4. This observation is at the

origin of a large number of studies making use of bubble chambers or emulsion exposed to neutrino beams and aiming at a better understanding of the production and decay properties of charmed particles via the analysis of dilepton events.

In the course of 1974 it had been decided to fill Gargamelle in alternance with heavy freon and with a liquid consisting of propane C_3H_8 with an admixture of about 10 molar per cent of CF_3Br. In such a mixture the ratio of freon to bound proton targets amounts to 31 % and about 85 % of the bound nucleons belong to light nuclei : carbon and fluorine. It is thus well suited to study separately interactions on neutrons and protons. Its density and radiation length being respectively 0.54 g/cm^3 and 60 cm, π° mesons can be reasonably well detected and identified.

The IIHE took part in the analysis of the propane film taken in the CERN PS neutrino beam (276,000 pictures) which has allowed a study of exclusive one-pion production in all neutrino induced neutral current channels : $\nu + p \rightarrow \nu + p + \pi^\circ$, $\nu + p \rightarrow \nu + n + \pi^+$, $\nu + n \rightarrow \nu + n + \pi^\circ$ and $\nu + n \rightarrow \nu + p + \pi^-$. From the measurement of the relative cross sections of these four processes and the observation of copious Δ-resonance production in the $p\pi^\circ$ and $p\pi^-$ systems it was shown[15] that the transition amplitudes for single pion production could well be described by two isovector amplitudes, with the transition to the $I = 3/2$ state of the $N\pi$ system dominating the transition to the $I = 1/2$ state, plus an admixture of an isoscalar amplitude(*). A pure isoscalar transition hypothesis had a probability of 10^{-4} and could thus be excluded.

This film was also used to measure the ratio R_{CC} of charged current neutrino cross sections on neutrons and protons and similarly R_{NC} for neutral current inelastic interactions. For energies ranging from 1 to 10 GeV, these ratios were found to be $R_{CC} = 2.08 \pm 0.15$[16] and $R_{NC} = 0.76^{+0.17}_{-0.15}$, [17], in agreement with the expectations of the Salam-Weinberg model : ~ 2 and from 0.8 to 1, respectively.

The operation of Gargamelle at the PS was stopped in December 1975 - more than three million pictures had been taken in the ν and $\bar{\nu}$ beams - and the chamber was moved to the West Area Neutrino Facility at the SPS.

(*) This isospin analysis assumed only that the structure of the weak neutral current was a linear combination of an isovector and an isoscalar.

II.2. GARGAMELLE AT THE CERN SPS.

The lifetime of Gargamelle at the SPS has been unfortunately quite short. The first physics runs in the neutrino and antineutrino wide band beams started in autumn 1977 and the chamber had to be stopped on 26 October 1978 because of a crack in the chamber body which opened under high pressure and could not be repaired. The chamber being filled with a 90 mole % C_3H_8/10 mole % CF_3Br mixture, two experiments had been planned : the WA14 experiment in the neutrino beam and the WA15 experiment in the antineutrino beam; the IIHE was involved in the latter. Only 20 % of the requested data could be accumulated in the one year running period and the physics output of this experiment was thus quite limited.

The aim of the WA15 experiment was to extend in the higher energy range accessible at the SPS the studies made at the PS energies on both the charged and neutral current interactions of antineutrinos with emphasis on rare processes such as $\bar{\nu}_\mu\, e^-$ scattering, dilepton production and $\bar{\nu}_e$ interactions. With 330 GeV incident protons on a beryllium target, the antineutrino spectrum peaked around 25 GeV and extended beyond 150 GeV.

From the analysis of 230,000 pictures, corresponding to about 7,000 charged current interactions, which showed no candidate for the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$, an upper limit for the cross section of this process was set at $1.6 \times 10^{-42}\, E_{\bar{\nu}}$ (GeV) cm^2 at 90 % confidence level[18]. This result, in agreement with preliminary data obtained in the 15' FNAL chamber with neutrinos and antineutrinos in the same energy range than at the CERN SPS, were at variance with observation made by the WA14 Collaboration of an unexpectedly large cross section for the process $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ which, interpreted in the framework of the Salam-Weinberg model, would have implied a value of $\sin^2\Theta_W$ as large as 0.7 ![19]

A sample of 3,800 completely measured antineutrino charged current events, selected with the help of an External Muon Identifier (EMI) made of two arrays of multiwire proportional chambers located behind the chamber and enabling to detect positive muons with energy down to 2 GeV, was used to measure the antineutrino charged current interaction cross section in the energy range 10 to 150 GeV. This cross section was found to continue to rise linearly with increasing energy, the slope being $\sigma/E_{\bar{\nu}} = (0.29 \pm 0.04) \times 10^{-38}$ cm^2/GeV nucleon[20]. Combining the data with those obtained under similar experimental conditions by the WA14 Collaboration (3,000 ν_μ CC interactions) has allowed to determine the nucleon structure functions $F_2(x, q^2)$ and $xF_3(x, q^2)$ which were found to exhibit a weak and varying q^2 dependence in the q^2 range 0.5 to 50 $(GeV/c)^2$, in disagreement with pure scaling (see fig. 5). The limited statistics prevented however to identify the origin of this behaviour : contribution from operators with twist higher than two which are expected to behave as $1/q^2$ or target mass effects[20,21].

At the end of 1977, the three massive detectors installed in the CERN West Area neutrino beam line - BEBC filled with a 75 mole % Ne-H_2 mixture, Gargamelle filled with CF_3Br and the giant counter set-up of the CERN, Dortmund, Heidelberg, Saclay Collaboration (CDHS) - participated in a "beam-dump" experiment in an attempt to look for neutral penetrating particles either produced directly in the dump or resulting from the decay of new short lived particles such as heavy leptons and hadrons with new flavours. The 400 GeV extracted proton beam, transported in a vacuum pipe was dumped onto a target consisting of a copper cylinder of 27 cm diameter and 2 m length which replaced the ordinary wide band neutrino beam target at about 1 km from Gargamelle. The target was followed by iron blocks to ensure that any flux of p and K mesons escaping from the dump did not enter the decay tunnel. The dumping of the hadron cascade reduced the normal neutrino flux by a factor of 2,000 to 3,000. The analysis of the 68,000 pictures taken with Gargamelle revealed a number of ν_e and $\bar{\nu}_e$ events greater than expected from *"established sources including recently reported heavy leptons and charmed particles unless branching ratios, cross sections and lifetimes reported from various experiments or theoretical estimates are not self consistent"*[22]. A similar conclusion was reached by the BEBC Collaboration but was not supported by the observations made in the CDHS detector. In an attempt to understand the discrepancy further beam dump runs were made in the following years in which Gargamelle being out of use did not take part. Done in better controlled experimental conditions, these further experiments did not reproduce the Gargamelle and BEBC effects.

Some months before Gargamelle had to be shut down, physicists from the IIHE, preparing an experiment to search for short lived particles, participated in a feasibility test to run the chamber with a 2.5 liter emulsion stack contained in a thermally insulated pressure vessel attached, inside the chamber, to the beam entrance window. It was shown that the presence of the stack did not affect the quality of the bubble chamber pictures; vertices of neutrino interactions occurring in the emulsion were reconstructed from the tracks observed in the chamber liquid. The experiment could unfortunately not be realized since the exploitation of the chamber had to be prematurely stopped.

II.3. THE IIHE PARTICIPATION TO THE BEBC NEUTRINO PROGRAM.

Located in the CERN West Area, the Big European Bubble Chamber (BEBC) constructed by a French-German-CERN consortium has been operational in different SPS neutrino beams from 1977 to 1984. This cryogenic chamber operating in a 3.5 Tesla magnetic field could be filled with either liquid hydrogen or deuterium or Ne/H2 mixtures of various compositions. It was equipped with an efficient External Muon Identifier consisting of an upstream veto counter to detect incoming charged particles and two planes of multiwire proportional chambers flanking and downstream of BEBC to detect outgoing muons; the time resolution of the system was 500 ns.

The IIHE has participated in three neutrino experiments making use of BEBC : the WA17 and WA24 experiments which both implied original technical developments and the WA59 experiment. Before presenting these three experiments in some details, it is worth to mention a couple of interesting results obtained with BEBC during the first technical run of the CERN SPS wide band neutrino beam. At this occasion indeed some 30,000 pictures were taken, the chamber being filled with a 74 mole percent Ne/H_2 mixture of radiation length 42 cm thus providing good conditions for electron identification and energy measurement. From the careful scanning of about 9,000 neutral induced events for the presence of one or more electrons or positrons at the interaction vertex, 125 events with an unpaired electron were found. In this sample, 20 events containing a positron and a leading negative muon provided additional evidence for neutrino production of charmed particles; five of them also had an associated neutral strange particle, supporting the charm interpretation. The failure to resolve two close vertices in these events set a limit on the lifetime of the charmed particles at 3 x 10^{-12} s (90 % C.L.)[23]. The measured rate of ν_e events, corrected for detection efficiency and losses, was found to agree with the rate expected from the calculated ν_e flux, assuming μ-e universality and no neutrino mixing. From this rate and the shape of the kinematic distributions of the observed ν_e events improved limits were put on $\nu_e \rightarrow \nu_x$, $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ mixings (see figure 6)[24].

II.3.a. The WA17 experiment.

This experiment intended *"to investigate the nature of neutrino induced dilepton events and of the recently observed new particles and to search for other such particles"*. Inspired by the success of a previous experiment performed at Fermilab by some of its proponents (see section II.4), the experiment was based on the use of large emulsion stacks placed in front of the chamber beam window and working as a sensitive target capable of detecting particle decay paths as short as a few microns. Tracks of particles emitted from neutrino interactions occurring in the emulsion were observed and measured in BEBC filled with liquid hydrogen and used to predict the position of the neutrino interaction vertices. For technical reasons the distance between the upstream edge of the emulsion stacks and the chamber liquid was quite large : about 40 cm. A three plane multiwire proportional chamber covering the BEBC window ensured the correlation of the chamber and emulsion reference systems. Extensive intercalibration of the set-up was done using energetic muons from the neutrino beam which enabled to locate vertices in the emulsion with an accuracy of respectively 8 and 1 mm along and across the beam. From the analysis of 200,000 BEBC pictures, 169 charged current neutrino interactions were found in 30 liter of emulsion; in eight cases the production and subsequent decay of a charmed particle was detected[25], providing definite confirmation of a previous observation (see section II.4). One of these particles was identified as the first Λ_c^+ baryon (see fig. 7); its mass was measured as 2.26 ± 0.02 GeV/c^2 and after a proper time of $(7.3 \pm 1.0) \times 10^{-13}$ s it decayed in three charged particles : $\Lambda_c^+ \rightarrow p + K^{*o} \rightarrow p + K^- + \pi^+$, the proton being identified in the bubble chamber and the invariant mass of the $K^- \pi^+$ system being equal to 866 ± 10 MeV/c^2. None of the other observed decays could be kinematically fitted; lifetime estimates of the parents were made from the distribution of the measured distances between the lines of flight of the decay products and the production vertices. Despite the small statistics (5 charged(*) and 3 neutral charm candidates), these first lifetime estimates

$$\tau^+ = 2.5^{+2.2}_{-1.1} \times 10^{-13}\ \text{s} \quad \text{and} \quad \tau^\circ = 0.53^{+0.57}_{-0.25} \times 10^{-13}\ \text{s}$$

provided a direct indication of a difference between charged and neutrals as already inferred from the leptonic decay branching ratios of charmed particles observed in e^+e^- collisions. The smallness of the above values as compared to the presently known lifetimes of D^+ and D° mesons, $(10.62 \pm 0.28) \times 10^{-13}$ s and $(4.21 \pm 0.10) \times 10^{-13}$ s respectively, can be partly explained by a loss of particles decaying far from their production vertex resulting from the scanning criteria applied in this experiment at a time when so little was known about these new short lived objects.

II.3.b. The WA24 experiment.

Hydrogen filled bubble chambers provide free proton targets but are inefficient for converting photons and thus for detecting π° mesons. Chambers filled with heavy liquids

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(*) Excluding the Λ_c^+ candidate but including the event observed previously in our Fermilab experiment [see section II.4].

allow good photon detection but the interpretation of the observed events is complicated by the secondary interactions occurring in the complex target nuclei. The use of Track Sensitive Targets (TST) placed inside heavy liquid bubble chambers aimed at combining the advantages of both techniques. Its application to neutrino physics presented, however, major technical difficulties because it called for very large TST.

The 3 m^3 rectangular TST used for the WA24 experiment was built in Lexan, a plastic transparent polycarbonate of high mechanical strength, with 2.5 cm thick top and bottom faces and side walls 1.9 cm thick. Its outer dimensions were 2.45 m along the beam, 1.4 m width and 1.0 m along the direction of the 3.5 T magnetic field. Filled with liquid H_2, it was suspended by springs in the chamber to allow the vessel to follow the movement of the liquid in the chamber, a Ne/H_2 mixture. In this configuration a substantial layer of heavy liquid, 140 cm, was available downstream the TST for γ ray conversion. The chamber was operated at 29.5° K so that visible tracks could be simultaneously formed in both the hydrogen of the TST and in the Ne/H_2 mixture of the chamber. A neutrino induced interaction occurring in the TST is shown in fig. 8.

A total of 250,000 pictures were taken in the neutrino wide band beam and 270,000 in the antineutrino beam. In running the experiment two technical problems were encountered. Early in the run some neon entered the hydrogen filling the TST via a supply-line leak. A small overpressure was thus maintained inside the TST to reverse the leak; as a result, the neon concentration in the chamber fell slowly during the course of the run from 77 to 68 mole %. Secondly, dirt progressively accumulated on the top wall of the TST and led to a loss of brightness in some regions of the fiducial volume which had to be partly compensated for by equalizing masks placed on the lenses of the BEBC cameras.

Despite these difficulties, some 2,000 and 700 neutral induced interactions occurring in the TST were detected. Using a multivariate discriminant analysis based on the kinematics of the events, they were separated into (anti)neutrino charged current and neutral current interactions and neutral hadron induced interactions. It was indeed observed that, in a space spanned by a large enough set of kinematical variables, the three types of events tended to cluster in three different regions. These variables depending on the hadron system were better determined than in bare H_2 or D_2 chambers because the BEBC-TST set-up permitted the detection and energy measurement of π° mesons leading to a significant reduction of the cluster spread. As long as the spread remained smaller than the separation between the clusters, this approach allowed individual assignment of the events to one of the clusters. It was thus possible to isolate neutral current induced interactions avoiding severe cuts on the data inherent in previous experiments. As a result of this analysis, the neutral to charged current cross section ratios for neutrino and antineutrino on protons were found to be $R^{\nu}_{p} = 0.47 \pm 0.04$[26] and $R^{\bar{\nu}}_{p} = 0.33 \pm 0.04$[27], in agreement with previous measurements. These two values were compatible with the predictions of the Standard Model for $\sin^2\theta_W = 0.24^{+0.06}_{-0.08}$ and $\rho = 1.07^{+0.06}_{-0.08}$, ρ being relative the neutral to charged current coupling strength[27].

Using an original method independent of the neutrino (antineutrino) flux, the film was also used to measure the ratio of charged current total and differential cross sections on neutrons and protons both for neutrinos and antineutrinos. Charged current interactions occurring on hydrogen in the TST were directly compared in the same pictures with interactions in a volume of neon downstream of the TST so that the neutrino (antineutrino) flux through both media was the same. All events were fully measured; in particular, neutral secondaries from the hydrogen interactions were detected in the neon surrounding the TST and measured as efficiently as those from neon interactions. Thus the unsmearing corrections and their inherently large systematic uncertainties were kept small. From the measured ratios of the cross section per nucleon on an isoscalar neon target to that on a free proton, the cross section ratios for neutrino and antineutrino charged current interactions on neutrons and protons were found to be[28] :

$$\left(\frac{\sigma_n}{\sigma_p}\right)_{\nu} = 1.88 \pm 0.18(\text{stat}) \pm 0.04(\text{syst}) \quad \text{and} \quad \left(\frac{\sigma_n}{\sigma_p}\right)_{\bar{\nu}} = 0.62 \pm 0.14(\text{stat}) \pm 0.02(\text{syst})$$

A detailed comparative study of the experimental distributions of the Nachtman variable(*) for neutrino and antineutrino events both in hydrogen and neon was made to measure nuclear effects such as those observed at the time in muon-nuclei interactions, the so-called EMC effect. Only small, if any, nuclear effects were seen and the apparent difference between the neutrino data and the muon results from the EMC collaboration was suggested to be due to shadowing.

An event was observed in the TST[29] which had a unique three constraint fit to the $\Delta S = -\Delta Q$ reaction $\nu + p \rightarrow \mu^- + p + K^- + \pi^+ + \pi^+ + \pi^\circ$ with both γ's from the π° decay detected and all charged particles identified. It was interpreted as due to the production of a charmed baryon Σ_c^+ of mass 2457 ± 4 MeV/c^2 ($\nu + p \rightarrow \mu^- + \Sigma_c^+ + \pi^+$) followed by the

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(*) $\xi = \dfrac{2x}{\left[1 + \left(1 + \dfrac{4M^2x^2}{q^2}\right)^{1/2}\right]}$ where x is the Bjorken variable, M the mass of the proton and q^2 the square of the moment transfer from the neutrino to the nucleon.

decay chain $\Sigma_c^+ \rightarrow \Lambda_c^+ + \pi^\circ$; $\Lambda_c^+ \rightarrow K^- + p + \pi^+$. The mass of the Λ_c^+ baryon being measured as 2290 ± 3 MeV/c^2, the mass difference $\Delta = M_{\Sigma_c^+} - M_{\Lambda_c^+}$ was found to be 168 ± 3 MeV/c^2, in agreement with the known mass difference between the Σ_c^{++} and Λ_c^+ baryons. Together with the Σ_c° baryon, Σ_c^{++} and Σ_c^+ are the three members of an isospin triplet Σ_c (2455) of $J^P = 1/2^+$. No other example of the Σ_c^+ baryon has been observed until now.

II.3.c. The WA59 experiment.

The data of this high statistics experiment were taken in 1980 in the SPS wide band neutrino and antineutrino beams, BEBC being filled with a heavy neon-hydrogen mixture (75 mole % neon) of density 0.704 g/cm^3 and radiation length 42 cm. The scanning of 61,000 pictures with incident $\bar{\nu}$ and 36,000 pictures with incident ν has provided some 16,000 $\bar{\nu}$ Ne (the largest sample ever accumulated in a single bubble chamber experiment) and 9,200 ν Ne charged current events in the energy range 5 to 200 GeV. The principal aim of the experiment was to measure with precision the nucleon structure functions $F_2(x, q^2)$ and $xF_3(x, q^2)$ using a single data set that covers a wide range of q^2 and of the hadronic invariant mass W with minimal systematic uncertainties.

The full measurement of the samples of ν and $\bar{\nu}$ events has allowed to extract the isoscalar nucleon structure functions in the range $0 < q^2 < 64$ (GeV/c)^2, $107 < W < 250$ GeV^2, $0 < x < 0{,}7$ (see fig. 9)[30]. Fitting these data to the predictions of QCD in the region $q^2 > 4$ (GeV/c)^2 and $W^2 > 10$ GeV^2, where scaling violations due to the effects of finite mass target and dynamical higher twist effects are expected to be negligible, yielded a value of the strong interaction parameter $\Lambda_{\overline{MS}}$ equal to 100^{+100}_{-85} MeV. Relaxing the cuts on the data to include events at low q^2 and W^2 decreased slightly the value of $\Lambda_{\overline{MS}}$ while contribution of positive higher twist terms in this kinematical region would have led to a rise of $\Lambda_{\overline{MS}}$. Previous neutrino experiments reaching such low W^2 values had yielded values of the strong interaction parameter in the range 300 to 700 MeV difficult to reconcile with the $\Lambda_{\overline{MS}}$ values around 100 MeV obtained in the higher q^2 range attained in muon scattering experiments.

These data were combined with those obtained in deuterium under almost identical conditions by the WA25 Collaboration to make a study of the EMC effect in ν and $\bar{\nu}$ interactions[31]. Based on 40,000 interactions evenly divided between the two target nuclei, neon and deuterium, this analysis has allowed a complete investigation of the whole Bjorken x region (excepting that dominated by Fermi motion effects) and simultaneously also of the Bjorken y distributions and total cross sections. The main conclusions were that :

(i) for q^2 values greater than 1 $(GeV/_c)^2$ no significant variation with q^2 was seen in the neon to deuterium ν and $\bar{\nu}$ cross section ratios; at the lowest values of q^2 some decrease in the neon cross sections was observed, consistent with shadowing

(ii) the ratios of the x distributions for $0.2 < x < 0.6$ indicated a decrease similar to that observed in electron and muon scattering off similar targets

(iii) the ratios of the y distributions ruled out the significant increase in the sea in neon required by some models of the EMC effect

(iv) the gluon and quark momentum fractions per nucleon were the same in both targets to within about 4 %.

A significant contribution was made by the WA59 Collaboration to low q^2 physics ($q^2 \lesssim$ 1-2 GeV^2) by providing basic tests of the PCAC hypothesis and of the hadron dominance model.

(i) the total cross sections for charged current neutrino and antineutrino interactions on neon and deuterium nuclei were compared by the WA25 and WA59 Collaborations[32]. An attenuation of the cross section per nucleon, corresponding to 4 standard deviations, was observed on neon for $x < 0.2$ and $q^2 < 1$ GeV^2. The appearance of this shadowing effect for the smallest ν-values as well as its absolute size are in agreement with Adler's theorem and the PCAC hypothesis, in the framework of the Glauber-Gribov approach. This was the first observation of shadowing in neutrino interactions.

(ii) the WA59 experiment provided the first convincing evidence[33] and detailed tests of coherent interactions of ν and $\bar{\nu}$ on neon. For coherent production of π mesons[34], the total cross sections as well as the differential cross sections are in agreement with predictions based on the PCAC hypothesis for diffractive scattering of the longitudinal component of the axial current, the strength of the process being fixed by the coupling constant of the pion to the weak current. The q^2-dependence of the cross sections is well described by a propagator containing a mass of the order of the a_1 mass, in agreement with the $a_1/\rho\pi$ dominance hypothesis. The coherent ρ meson production on nuclei[35] is also in agreement with the predictions of the hadron dominance model for the vector current behavior, thus providing a test of the CVC hypothesis in weak interactions. The coherent production of 3π systems[36] seems to be due to the production of $\rho\pi$ systems, either resonant or not. In spite of the model uncertainties and of the large experimental errors, the study of the differential and total cross sections favors the production of nonresonant $\rho\pi$ systems, with an effective mass lower than the a_1 mass, and a cross section higher than expected for a single meson.

Various studies of the hadron shower in charged current interactions were performed taking advantage of the high detection efficiency of neutral particles in the chamber liquid and of the good momentum resolution. In particular, the production rate and characteristics were studied for π° mesons and charged hadrons[37], for ρ° mesons[38] (with particular insight in spin alignment), for $\rho(970)$, $\eta(550)$, $\omega(783)$ and $f_2(1170)$ mesons[39], for neutral strange particles[40] and for D_s^{*-} mesons[41].

BEBC filled with a heavy Ne/H_2 mixture and equipped with its efficient EMI being an ideal tool to study dilepton events, the large samples of ν and $\bar{\nu}$ interactions accumulated by the WA59 Collaboration were searched for μe and $\mu\mu$ candidates as well as for multilepton candidates. From the detailed analysis of about 200 such events it was concluded that[42], as observed in other experiments - usually with much lower statistical significance - rates and kinematical characteristics of opposite sign dileptons were compatible with the expected production of charmed particles and their subsequent semi-leptonic decay. This conclusion was substantiated by the observation of a significant excess of neutral strange particles in dilepton events as compared to the normal charged current events. No evidence was found for the production of hadrons with beauty quarks, a process which had been suggested by Armenise et al[43] from the observation of an excess of antineutrino induced dilepton events with an hadronic system of mass around 6 GeV/c^2. No evidence was found for prompt like sign dilepton production, the few events observed being compatible with the expected background from π and K meson decays.

In the early eighties a proposal was put forward by a group of physicists from the IIHE, the University of Bari, the Ecole Polytechnique-Palaiseau and the University College London to install a solid neon and argon electromagnetic calorimeter inside BEBC as the best solution to the critical problem of precise hadron shower measurement of neutrino interactions. This proposal received a strong support by a large fraction of the BEBC users because of the demonstrated advantages of such a device (from technical tests and extensive Monte Carlo calculations) for several important problems such as : accurate measurement of the Weinberg angle, measurement of the nucleon structure function at high Bjorken x values, model independent measurement of the neutral current coupling constants. For budgetary reasons linked to the construction of LEP this proposal could not be supported by the CERN authorities despite its high scientific interest; BEBC was indeed shut down in 1984.

II.4. THE IIHE AT FERMILAB.

II.4.a. First direct observation of the decay of a charmed hadron.

The high spatial resolution of the photographic emulsion - a property that makes this technique unique for detecting tracks as short as a few microns - is unfortunately counter balanced by prohibitively long scanning times when studying processes of small cross sections. It had been shown however (see above and reference[1]) that by combining emulsion with other techniques able to detect the secondarly particles emitted in such processes it is possible to use the trajectories of these particles to predict the spatial position of the interaction in which they were produced, thus reducing by orders of magnitude the volume of emulsion to be scanned.

By the mid of the seventies various experimental proofs had been obtained of the existence of particles with lifetimes shorter than 10^{-12} s produced in e^+e^- collisions, high energy neutrino and photon interactions. An experiment was designed to directly observe such particles by using an hybrid emulsion-counter detector in the Fermilab high energy neutrino wide band beam. The set up (fig. 10) consisted basically in six emulsion stacks of a total volume of 17 litres followed by a spark chamber with two 15 cm gaps and a sensitive area of 100 x 80 cm^2 which by detecting secondaries enabled the location of the neutrino interactions in the emulsion. A number of scintillation counters provided a triggering system for selecting events of the desired type. An electromagnetic shower detector made of Pb plates and narrow gap spark chambers and a rudimentary muon identifier to help in the analysis of the events completed the set-up.

The emulsion stacks were exposed to neutrinos produced by a total of 7 x 10^{17} protons of energy 400 GeV on target. From the known neutrino flux and taking into account the various inefficiencies of the set-up it was estimated that some 140 neutrino interactions should have occurred in the emulsion; 37 events, were found from which all secondaries were followed until they interacted, decayed or left the emulsion. In one case an apparent decay into three charged particles was observed occurring after a distance of 182 μm corresponding to a flight time of about 6 x 10^{-13} s[44]. A microphotographic of this first directly observed charmed particle candidate is given in fig. 11 which also shows the correlation between the emulsion observations and the spark chamber pictures; note that there was no way of positively ascribing the V° particle observed in the spark chamber to the charm decay vertex.

II.4.b, The E632 experiment at the Fermilab Tevatron.

A new range of neutrino energies became available at the start-up in 1983 of the Fermilab Tevatron, the first proton superconducting supersynchrotron. At this machine an unseparated neutrino-antineutrino beam was formed by shooting 800 GeV protons on a beryllium oxyde target followed by a train of three quadrupole magnets tuned to focuss charged secondaries of momentum greater than 300 GeV/c. The ratio of the number of neutrinos to the number of antineutrinos in the beam was 2.5 to 1. The calculated mean energy of charged current events induced by neutrinos and antineutrinos was 155 and 110 GeV respectively. About 30 % of the neutrino events and 14 % of the antineutrino events had energies above 200 GeV, a region inaccessible to pre-Tevatron experiments.

The Fermilab 15-ft bubble chamber filled with heavy neon-hydrogen mixtures was exposed to this quadrupole triplet beam in 1985 and 1987. The chamber was equipped with an EMI and an Internal Picket Fence (IPF) both consisting of planes of proportional drift tubes; the IPF surrounding the chamber aided in determining the time of the event, a useful information to separate neutrino induced neutral current events from high momentum neutral hadron induced events. The chamber was viewed by three conventional cameras (resolution 500 μm) seeing 28 m^3 of liquid and one high resolution camera (resolution 200 μm) seeing ~1 m^3. This optical system was complemented by an holographic system (see fig. 12) that allowed to record with good contrast bubbles of diameter about 120 μm in a volume of 1.5 m^3. Physicists from the IIHE actively contributed to the design, construction and implementation of this system for which various new techniques had to be developed[45]. Some of them also participated in the construction of an hologram replay machine installed at the Rutherford & Appleton Laboratories as an european facility[46].

During the 1985 run, 153,000 conventional pictures and 100,000 holograms were recorded simultaneously; the quality of the latter varying throughout the run, they could not be used for physics but proved to be very useful for assessing the technique. In 1987, 293,000 pictures and 218,000 holograms, of which 110,000 with good track quality, were taken. An hologram showing the production and subsequent decay after 0.7 cm of a D^+ meson is shown in fig. 13. Although the analysis of this material is still in progress, preliminary results in the new energy domain accessible at the Tevatron confirmed observations made at lower energies. They mainly concerned the production of dimuons[47] and the coherent production of charged pions[48] in charged current interactions as well as a study of high energy neutral current interactions[49].

II.5. THE WA79 EXPERIMENT (CHARM-II).

After the shut down of BEBC, the IIHE, wishing to pursue a neutrino physics programme at CERN, decided in 1985 to join the so-called CHARM-II Collaboration which was building a new giant electronic detector to be located at the place previously occupied by the CDHS and CHARM experiments. The proposed experiment aimed at a precise measurement of the weak mixing parameter $\sin^2\theta_W$ from the purely leptonic neutral current processes : $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$.

The former CHARM group had already demonstrated that, in spite of the very low cross section of ν e scattering, these processes could be identified with a controllable background in a calorimetric device; a similar analysis was in progress at BNL (the E734 experiment). However, only about 100 events in each channel had been observed and the resulting precision on $\sin^2\theta_W$ was only at the 10 % level. To allow a meaningful test of the electroweak theory down to the level of higher order corrections an accuracy of 2 % was necessary, implying an increase in statistics by an order of magnitude and a substantial improvement in the energy and angular measurement accuracies.

The CHARM-II detector (fig. 14) consisted of a 700 tons target calorimeter, followed by a muon spectrometer[50]. The fine-grained low density calorimeter, composed of 420 modules of 3.7 x 3.7 m^2 active area, was designed to allow an efficient electron identification and a precise measurement of its energy and direction[51,52]. Each module was made of a 4.9 cm thick glass plate, interleaved with streamer tubes and scintillators as detecting elements. The whole detection system contained about 150,000 digital channels and 11,000 analog channels. The muon spectrometer, built by the former CDHS Collaboration, was composed of 6 modules of magnetised iron separated by drift chambers and scintillator planes. Its role was mainly to control the neutrino energy spectra by measuring the momentum spectra of muons produced in well-known charged current processes. The detector was operated from 1987 to 1991 in the neutrino CERN SPS wide-band beam at a rate of about 100 days per year. The accumulated data correspond to about 2×10^{19} protons interacting in the target, leading to 30 millions registered neutrino interactions in the calorimeter. After various steps of event selection and background subtraction some 5,000 examples of neutrino-electron scattering (equally shared between ν and $\bar{\nu}$ reactions) could be identified.

The best way of determining $\sin^2\theta_W$ from these data consists in measuring the ratio of the $\nu_\mu e^-$ and $\bar{\nu}_\mu e^-$ cross sections :

$$R = \frac{\sigma(\nu_\mu\, e^-)/E_\nu}{\sigma(\bar{\nu}_\mu\, e^-)/E_{\bar{\nu}}}$$

which, in the region of interest : $\sin^2\theta_W \approx 0.23$, is a very sensitive function of this parameter ($\Delta(\sin^2\theta_W) \approx \Delta R/8$). Moreover, the measurement of R does not require the knowledge of the absolute ν and $\bar{\nu}$ fluxes but only their relative values and therefore systematic uncertainties in the selection procedure and background evaluation largely cancel out.

As the data were accumulating, more and more precise values of the electroweak mixing angle were published[53,54,55]. The present, but still not final value obtained with the full statistics is :

$$\sin^2\theta_W = 0.2370^{+0.0062}_{-0.0077} \pm 0.007$$

where the first error is statistical and the second systematic.

Another way of analyzing the data is to fit the shapes of the differential cross sections $\frac{d\sigma}{dy}(\nu, e^-)$ and $\frac{d\sigma}{dy}(\bar{\nu}, e^-)$ expressed in terms of the vector and axial-vector couplings of the electron to the Z° boson[56]. Deviations from the Standard Model predictions would indicate the presence of extra bosons of higher masses. The observed values $g_V^e = -0.025 \pm 0.019$ and $g_A^e = -0.503 \pm 0.019$ allow to rule out an extra Z boson of mass below 300 GeV. The excellent agreement betwen the $\sin^2\theta_W$ value obtained in this experiment and the one obtained at LEP at the Z° pole provides a significant test of the electroweak theory since the two experiments investigate very different kinematical domains.

It is worth mentioning that a global analysis of all neutral current processes observed in different conditions becomes sensitive to second-order effects and allows, in particular, to put limits on the top quark mass and, to a less extent, to the Higgs mass.

The CHARM-II experiment also provided valuable results on other channels :

- The first significant observation of neutrino induced production of muon pairs in the electromagnetic field of a nucleus $\nu_\mu + A \rightarrow \nu_\mu + \mu^+ \mu^- + A$ was published in 1990[57]. Its cross section, although still poorly determined, was found to be in agreement with the Standard Model prediction.

- The cross section of the inverse muon decay reaction : $\nu_\mu \, e^- \rightarrow \mu^- \, \nu_e$ has also been measured with improved accuracy[58], which allowed to constrain a scalar coupling of W bosons to leptons by the limit $|g_s|^2 < 0.405$ at 90 % C.L.

An update of these results, using the full statistics now available, is in progress, as well as other topics like charm production, coherent pion production, search for ν_μ-ν_e oscillations and inclusive ν-nucleon cross sections.

II.6. THE "WA95" EXPERIMENT (CHORUS).

The idea that there exists between the three generations of leptons a mixing analog to the one observed between quark generations is very old. It is intimately connected to the question of neutrino masses and many experiments were performed, either to measure directly the mass of a neutrino species or to demonstrate the existence of transitions from one to another neutrino type. Until now, no convincing evidence has been found for neither of these effects but recent experimental and theoretical developments encourage physicists to continue the search : the new GALLEX measurement of a solar neutrino flux deficit, the astrophysical indications of "hot" dark matter in the universe, some popular models of Grand Unification Theory (like the "see-saw" mechanism) tend to favour the hypothesis of non-vanishing neutrino masses. In particular, for the ν_τ, a mass of about 10 eV, less than one order of magnitude below the present limit, would provide a natural explanation to many puzzling questions.

These considerations are at the origin of the CHORUS (CERN Hybrid Oscillation Research apparatUS) proposal, which was accepted by the CERN Council in September 1991. In this experiment, the identification of a ν_τ interaction relies on the observation of the produced τ^-. The very short lifetime (3×10^{-13} s) of this particle justifies the use, as neutrino target, of about 800 kg of nuclear emulsion. Much in the same spirit as in the previous hybrid experiments in which the IIHE had been involved (see II.3.a. and II.4.a.), the emulsion region to be scanned will be defined from the accurate measurement of the trajectories of the particles escaping the target. This task will be performed by a set of 22 tracker planes, each made of 7 layers of scintillating fibers located downstream the emulsion target. With a fiber diameter of 500 microns, one expects an accuracy of 100 microns on the particle exit point. The detector is complemented by an air core magnet, a high resolution calorimeter and an upgraded version of the CHARM-II muon spectrometer.

These devices will allow the selection, prior to emulsion scanning, of events kinematically compatible with the searched reactions

$$\nu_\tau + N \rightarrow \tau^- + X \quad \text{followed by} \quad \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$$

or

$$\nu_\tau + N \rightarrow \tau^- + X \quad \text{followed by} \quad \tau^- \rightarrow \pi^- \nu_\tau$$

Simulation has shown that, with proper kinematical cuts, 10 % only of the expected 500,000 neutrino interactions will need to be scanned in the emulsion, a work that can be achieved in less than 2 years.

The IIHE, in close collaboration with Louvain-la-Neuve, is mainly involved in the design, construction and operation of the scintillating fiber trackers. It is the first time that this technology is applied to such a large scale : fibers of several meters, more than 50 image intensifier chains, about 30 millions CCD pixels to be read-out and analyzed ... After considerable R & D effort the required performances could be reached and the serial production started. The detector construction is expected to be completed for the end of 1993 and its operation in the neutrino beam should take place in 94 and 95.

HADRONIC INTERACTIONS

III. HADRONIC INTERACTIONS.

It is well known that even at very high energies hadronic interactions are dominantly soft. Perturbative QCD-calculations are inapplicable to such interactions, characterised by low four momentum transfers. The dynamics of low multiplicity exclusive final states can be analysed in terms of Regge (meson, pomeron) exchanges. High multiplicity final states are very complex and results are generally concentrated on overall event descriptions (particle multiplicities including non statistical fluctuations, correlations, jet like properties, etc) and inclusive particle and resonance production characteristics. Perturbative QCD can only be applied to rare (relatively) high q^2 processes such as the hadroproduction of heavy (charm, beauty) flavours.

Production and decay processes of particles and resonances in soft hadronic interactions have been extensively studied at the IIHE for a variety of initial states over most of the energy range available at accelerators. Moreover, pioneering work has been performed concerning the hadroproduction of charm- and beauty particles.

III.1. K-NUCLEON INTERACTIONS.

III.1.a. K^-p interactions at low energies.

The study of the interactions of low energy K^--mesons with nucleons and nuclei started effectively more than 30 years ago when nuclear emulsions and bubble chambers were exposed to the first separated kaon beams with momenta below 1 GeV/c. In the early seventies there had been rather few experiments studying K^--interactions below 300 MeV/c and the available statistics were generally small, especially at momenta below 100 MeV/c. Some studies also pointed to inconsistencies between different experimental determinations. Therefore a new and detailed analysis of the characteristics of low momentum K^--meson interactions was undertaken. In 1973 about 1 million pictures were taken at the Rutherford High Energy Laboratory in the 1.5m bubble chamber filled with a hydrogen-neon mixture and equipped with a hydrogen filled Track Sensitive Target (TST). This composite set-up, using the then novel TST technique aiming at an improved γ-detection efficiency, was exposed to K^--mesons with momenta between 0 and 600 MeV/c.

Various branching ratios were determined[59] for K^--meson interaction processes at rest leading to the results :

$$\gamma = \frac{K^-p \to \Sigma^- \pi^+}{K^-p \to \Sigma^+ \pi^-} = 2.38 \pm .04 \ .$$

and $$R_c = \frac{K^-p \to \text{charged particles}}{K^-p \to \text{all final}} = .664 \pm .011$$

The cross sections of hyperon production and charge exchange processes were determined in 5 kaon momentum intervals between 80 and 280 MeV/c. The results were combined with those of previous experiments[60] and compared with the predictions of various $\underline{\underline{K}}$ and $\underline{\underline{M}}$ matrix element models.

III.1.b. K^-N interactions at medium energies.

An original on-line system built around a PDP-10 computer was designed at the IIHE in 1972 [61] in order to support both automatic (POLLY III) and manual devices used for the measurement of events recorded on bubble chamber film. POLLY[62] was a computer controlled CRT device originally designed in the Argonne National Laboratory (USA) and mainly suited to make (high statistics) studies of the topologically rather simple events observed in medium energy hadronic interactions in hydrogen and deuterium bubble chambers. At the IIHE, POLLY was used to analyse the film of a K^-d experiment at 4.5 GeV/c (216,000 frames taken in the MURA 30 inch chamber) and of a K^-p experiment at 6.5 GeV/c incident momentum (~ 10^6 pictures taken in the Argonne 12' bubble chamber)

The K^-d experiment produced results concerning elastic K^-d and K^-n scattering at the highest incident momentum available. The K^-n elastic scattering amplitude was shown [63] to be dominantly imaginary, as expected from dispersion relations. The exponential slope parameter of the t- (the four momentum transfer squared) distribution for K^-d elastic scattering at 4.5 GeV/c : $\alpha = (6.6 \pm .3)(\text{GeV/c})^{-2}$ was found to be equal within errors to that found for K^-n elastic scattering. This is an expected result in the light of spin-flip amplitude suppression and the near equality of the K^-n and K^-p differential elastic scattering slopes. A study [64] of the coherent reaction $K^-d \to K^-\pi^+\pi^-d$ based on a fractional channel analysis, a spin density matrix - and a partial wave analysis indicated that the $K\pi\pi$ combinations in the $\simeq$ 1.2 to 1.5 GeV/c^2 "Q-mass region" (now called K_1) dominantly correspond to the production of a $J^P = 1^+$ state via 0^+ (e.g. pomeron) exchange, whereas $\bar{K}^*$ production can be explained by 0^- exchange (e.g. π). The data can be described by a Deck-type mechanics.

The 6.5 GeV/c K^-p experiment was completed by 1980 and involved the semi-automatic measurement at the IIHE of over 50,000 events. Whereas[65] inclusive $\bar{K}^\circ$

production was found to proceed predominantly via beam fragmentation, the inclusive Λ°-differential cross section showed significant production of both beamlike and targetlike Λ°'s. The Q = S = 0 hadronic systems recoiling from the V°-particle were shown to exhibit universal aspects of multiparticle production which were first delineated in high incident momentum collisions and which provided motivation for quark-interaction models in $K^-p \rightarrow V^\circ + X$ processes at 6.5 GeV/c. Resonance production and exchange processes were studied on a sample of 3414 events of the type $K^-p \rightarrow K^-p\,\pi^+\pi^-$[66] using two complementary procedures : an analytical multichannel fit and multidimensional cluster methods. The invariant mass distributions of figure 15 illustrate examples of the most prominent two- and three body resonance phenomena and display the corresponding results of the multichannel fit. The main features of the multichannel analysis were confirmed by a multidimensional analysis of the data in the Van Hove and energy simplex variables. The multidimensional cluster analysis confirmed that Pomeron exchange is the dominating process (57 ± 2%), whereas non strange and strange meson exchange respectively contribute (26 ± 2)% and (13 ± 1)%. Baryon exchange amounts to (4.5 ± .4)% and is the main process responsible for Λ-resonance production.

III.2. K^+p INTERACTIONS.

When the IIHE was created, several physicists from the former Belgian Interuniversity Laboratory for High Energies joined the Institute. At that time they were all mainly involved in hydrogen and deuterium bubble chamber experiments with incident K^+ beams (K^+p at 16 GeV/c and K^+d at 4.6 GeV/c in the 2m CERN-HBC). In these experiments the global properties of resonance (e.g. K*(892), $K_2^*(1420)$, Δ*(1232) etc). and particle production were studied in inclusive and exclusive channels. The study of K^+p interactions was pursued at the IIHE until the end of the eighties in three subsequent experiments respectively performed at incident momenta of 32 -, 70 - and 250 GeV/c.

III.2.a. K^+p interactions at 32 GeV/c.

This experiment was carried out with the MIRABELLE hydrogen bubble chamber at the 70 GeV/c proton accelerator at Serpukhov (USSR), using a 32.1 GeV/c RF separated K^+ beam. In a first phase, started in 1971, 400K pictures were taken where all interactions were scanned and measured, yielding 110,000 events on DST. In the second phase, started in 1977, 600K pictures were taken but only events with neutral strange particles (K°, Λ°, $\bar{\Lambda}^\circ$)

were measured. The full statistics was reached in April 1981, the measurement being done either on SAAB measurement tables or on the SWEEPNIK semi-automatic device[67].

Results were published on a variety of subjects, including elastic scattering[68], inclusive reactions[69,70,71,72,73,74] and correlations[75,76,77]. Using longitudinal momentum distributions of stable particles and resonances, it was shown that the valence quarks play a dominant role in the fragmentation (see e.g.[69,70,71,72]). A value of the strangeness suppression factor $\lambda = \text{Prob}(s\bar{s})/\text{Prob}(u\bar{u}) \sim 0.25$ was measured[71], compatible with the one derived from deep-inelastic scattering $\lambda = 0.27 \pm 0.03$. Transverse momentum correlation studies[75] pointed towards a close connection between p_T-correlations and the impact-parameter structure of inelastic p_T conservation. Bose-Einstein correlations were studied[77] with the then recent technique proposed by Kopylov and Podgoretskii.

Finally, in the hadron spectroscopy sector, evidence was found for a new resonance decaying into $K^0_s K^0_s \pi^+ \pi^-$ ($M = 1.97 \pm 0.01$GeV, $\Gamma = 40 \pm 20$ MeV)[78] (see fig. 16).

III.2.b. K^+p interactions at 70 GeV/c.

This experiment, performed at CERN by the WA27 collaboration, studied the general features of K^+p interactions at 70 GeV/c, using an RF-separated beam and the BEBC bubble chamber filled with liquid hydrogen and equiped with an External Particle Identifier. The data taking took place between 1977 and 1980; it produced ~ 92,000 beam tagged events. Joint physics analyses have been performed using the data of this experiment and those of the 32 GeV/c K^+ Mirabelle experiment. The most important physics topics studied were K^+ diffraction dissociation and inclusive distributions for $K^+, K^\circ, \pi^-, \pi^+, \Lambda^\circ, \bar{\Lambda}^\circ$, p, $K^*(892)$, $\phi(1020)$ and Δ^{++} production. The WA27 collaboration reported many results of which only a few will be commented in the following. Apart from cross sections and charged particle multiplicity determinations[79], the jet-like properties of multiparticle systems produced[80] in these high energy interactions were examined and related to those observed in leptonic interactions. By comparing the energy and quantum number flow in K^+p and π^+p interactions at 32 and 70 GeV/c the charge to energy ratios $\frac{dQ}{dE}$ for "meson" jets (K^+ and π^+ fragmentation) were found to be independent of the beam[81], contrary to expectations based on dual-sheet models but in agreement with the LUND model implying the fragmentation of the colourstring stretched between valence quarks.

Inclusive particle production cross-sections were measured as a function of transverse momentum squared p_t^2 and the Feynman variable(*) x_F and compared to various theoretical models. A detailed analysis of inclusive K*(892), $K_2^*(1420)$, ϕ, $\rho°$ and f(1270) resonance production was performed. An interpretation of the results concerning fast K*(892), ϕ and $\rho°$-production provided evidence that the valence quark ($\bar{s}$ or u) fragmentation or recombination processes play a dominant role in these reactions. Arguments were presented[82] showing that the kaon valence strange $\bar{s}$-quark carries a much higher momentum fraction (approximately a factor 2) than the u-quark.

The study of baryon production was mainly oriented towards inclusive slow proton, Δ^{++}, Λ and $\bar{\Lambda}$ production. In the latter case the dependence of the Λ ($\bar{\Lambda}$) polarization was measured[83] as a function of x_F (see figure 17). The data exhibit a behaviour similar to that observed at 32 GeV/c with a negative $\bar{\Lambda}$ polarization in the high forward x_F-region.

III.2.c. π^+ and K^+ interactions at 250 GeV/c on hydrogen, Al and Au targets in RCBC : the NA22 experiment.

The EHS spectrometer at CERN (see section IV.1) with the Rapid Cycling Bubble Chamber (RCBC) as target and detector, was exposed in two runs (July 1982 and July 1983) to an enriched positive meson beam. This experiment yielded a useful sample of ~ 150,000 meson-proton interactions fully reconstructed (one third K^+p, two thirds π^+p). A large variety of rather classical subjects was studied in this experiment, ranging from elastic and diffractive scattering[84,85], over single particle and resonance production[86,87] and detailed studies of multiplicity distributions[88] (e.g. multiplicity distributions in narrow intervals of rapidity parametrized in terms of the negative binomial distribution) to correlations in rapidity and azimuthal angles[89].

The most remarkable observation was the so-called "spike event"[90], a 26 prong event with 10 particles in the very narrow rapidity interval of less than 0.1, thus with a local rapidity density of 100 (see figure 18). This event, and a well-known JACEE event, inspired theoreticians to study intermittency effects in high energy interactions, i.e. the study of non-statistical fluctuations and self-similar behaviour of particle production. Evidence for intermittency was found in the π^+p and K^+p interactions[91] and it was shown that the effect

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(*) The Feynman variable $x_F = p_L^*/p_{Lmax}^*$, where p_L^* is the longitudinal momentum component of the particle along the beam direction measured in the centre-of-mass system of the interaction.

is mostly concentrated at low p_T[92]. After several years of intensive work on this subject, the conclusion seems now to be that the intermittency effects observed are strongly correlated with the Bose-Einstein effect between identical pions.

Thin Al and a Au foils had been mounted in the RCBC, allowing the study of positive meson-nucleus interactions. The analysis of 4600 meson-Al and 400 meson Au interactions revealed that the negative binomial distribution describes quite well the multiplicity distributions in intervals of rapidity[93] and that the Additive Quark Model gives an overall consistent description of the rapidity and p_T^2 distributions of charged particles[94]. No significant intermittency effect was found in these collisions. In neutral strange particle production it was found that the average number of produced Λ's is proportional to the number of projectile collisions whereas the average number of K°'s is smaller. The relative production rate of strange to non-strange matter does not increase with increasing centrality of the collision[95].

III.3. ANTIPROTON-PROTON INTERACTIONS.

III.3.a. Fixed target experiments.

A high statistics exposure of BEBC filled with hydrogen to a $\bar{p}$-beam of 12 GeV/c was completed in 1975. The main purpose of this work was a search for narrow mass states decaying into a strange particle. A search for charmed particle decays conducted along these lines amongst 16,500 events with a visible V° (K_s^o, Λ, $\bar{\Lambda}$) turned out to be negative. Evidence was found[96] for the existence (~5 s.d.) of a narrow peak at 2.6 GeV in $K_s^o \pi^\pm \pi^+ \pi^-$ mass combinations, but the possible interpretation of this effect as a narrow resonance was not confirmed by other experiments. Finally, results concerning the inclusive production of one or two strange neutral particles were published[97]. In particular, K*(892), Σ(1385) and S*(993) production cross sections and properties were studied.

At 32 GeV/c, a total of 200K pictures taken with the 4.6 m long bubble chamber Mirabelle was measured. The 90K fully measured events were used a.o. for a study of baryonic resonance production[98] (Δ^{++}(1232), $\overline{\Delta^{++}}$(1232), Σ^+(1385) and $\overline{\Sigma^+}$(1385)), giving evidence for some central production besides the fragmentation contribution, and for a study of vector meson resonances[99]. In the exclusive channels $\bar{p}p \to \bar{p}p\, \pi^+ \pi^-$ and $\bar{p}p \to \bar{p}p\, 2\pi^+ 2\pi^-$, single and double diffractive contributions were determined and factorization at the p → p $\pi^+ \pi^-$ vertex was found to hold, after comparison with $K^{\pm}p$ and pp interactions at the same energy[100].

A search for direct electron production in $\bar{p}p$ interactions at 70 GeV/c was performed[101] using BEBC equipped with a hydrogen filled track sensitive target surrounded by a H_2/Ne blanket ensuring good $e^{\pm}$ and γ identification. No candidates for single electron production with momentum p_e > 500 MeV/c were found in a sample of 66,000 primary interactions. This result placed an upper limit (90% C.L.) of 2.5 μb on the cross-section for single $e^{\pm}$ production and a corresponding upper limit on the charmed particle production cross section of 14 μb. From the observation of 7 events producing an e^+e^- pair with mass $m_{e^+e^-} > m_{\pi^o}$, the $e^{\pm}/\pi^{\pm}$ ratio from this source was estimated to be (.7 ± .2) x 10^{-4}. This experiment was completed with an analysis of charged particle and π° multiplicity distributions[102] in which the contribution of annihilation was isolated. The high density of the neon-hydrogen mixture surrounding the TST in BEBC was exploited to scan for charged and neutral secondary particle interactions in the forward direction to determine the annihilation cross section σ_A. The value σ_A = 5.0 ± 1.6 mb obtained by this method is in satisfactory agreement with a measured value of 4.42 ± .41 μb for the difference between the pp and $p\bar{p}$ cross sections. A study of the inclusive production of neutral strange particles[103] confirmed the rise of the inclusive cross section for the production of K°-mesons with incident particle momentum and provided evidence for central $\Lambda\bar{\Lambda}$ production. The data suggest an increase with p_{lab} of the K°- yield in annihilation reactions which is substantial as compared to non-annihilation processes.

III.3.b. Collider experiments.

Stochastic cooling was proposed by J. Vander Meer as an efficient method to store useful currents of antiprotons in accelerator rings and was successfully used at the CERN ISR in 1974. Then came the idea by C. Rubbia to modify the CERN SPS into a single ring proton-antiproton collider. A new energy regime of $\sqrt{s}$ = 564 GeV was opened for particle physics when the CERN $Sp\bar{p}S$ collider entered into operation in October 1981. The two major experiment, UA1 and UA2, besides many results on particle production, mainly on jets and high p_T phenomena, discovered the $W^{\pm}$ and Z° vector bosons in 1983 and definitely established the Standard Model. A third experiment, UA4, was dedicated to the specific measurement of the elastic diffractive and total $\bar{p}p$ cross sections.

In 1979 a proposal was introduced by the UA5 collaboration, to build a detector that would allow a quick look at the $\bar{p}p$ physics at 546 GeV and, at the same time, be ready for the discovery of new phenomena that might occur. The main requirements in the design of the UA5 detector were : a visual inspection of the data, an almost 100% track and solid angle efficiency, a versatile trigger (unbiased or specific), an efficient γ detection, a good two-track resolution for multiplicity counting and a data acquisition rate in the 1-2 Hz range, matching well the event rate at the luminosity of the two early years of the collider ($L = 2\ 10^{-25}$ to $10^{26}\ cm^{-2}\ s^{-1}$). The heart of the detector consisted of two large streamer chambers of 6 x 1.25 x $0.5m^3$ each, placed above and below the beam pipe and covering 95% of the azimuthal space in the pseudorapidity domain $|\eta| < 3$; the efficiency decreased to 0 at $|\eta|$ as high as 5. A view of a typical event is shown on figure 19. A pair of large solid angle forward/backward scintillator hodoscopes at each chamber ends generated a 2-arm trigger more than 95% efficient for non-single diffractive inelastic events. After a period of test runs at the ISR, when the first $p\bar{p}$ interactions from colliding beams could be observed at $\sqrt{s} = 53$ GeV, the detector was installed at the Sp$\bar{p}$S in october 81 and took data during 7 days. A coarse calorimeter was added to the detector in 1982 covering 8% of the azimuthal space for $|\eta| < 1$. It was aimed to detect neutral baryons, a possible signature of Centauro like events observed in high energy cosmic ray interactions. These are characterized by a high charged multiplicity and no gammas from π° decays, thus suggesting that the charged particles are baryon/antibaryon pairs. Another 7 days of data taking in 1982, with increased luminosity and better background conditions, were followed by two runs in 1984 and 1985, the Sp$\bar{p}$S being operated into a pulsed mode allowing to collect data at $\sqrt{s}$ = 200 and 900 GeV.

In what follows, the results provided by the UA5 collaboration on the proton-antiproton interactions at $\sqrt{s} = 200$, 546 and 900 GeV are summarized; a detailed review of the results obtained at 546 GeV can be found in[104].

- Combining the ratio of the inelastic cross section measured at $\sqrt{s} = 200$ and 900 GeV the extrapolation of a fit of σ_{tot} at lower energies and a measurement of the σ_{el}/σ_{tot} ratio by UA4 at 546 GeV, σ_{tot} at 900 GeV was estimated[105] to be $65.3 \pm 0.7 \pm 1.5$ mb, in good agreement with the $\ln^2 s$ increase observed at lower energy, the maximum growth compatible with the Froissard bound (see fig. 20). The ratio σ_{SD}/σ_{tot}, σ_{SD} being the single diffractive cross-section, stays constant around 0.17 with increasing energy[106].
- The mean charged particle multiplicity $<n_{ch}>$ for non single diffractive (NSD) events smoothly increases from fixed target and ISR energies up to $\sqrt{s} = 900$ GeV[107].
- The KNO scaling for charged particle distributions in NSD interactions is violated at collider energies. It states that the shape of the multiplicity distribution rescaled by its mean value is independent of the energy. Its observation at fixed target and ISR energies is interpreted as the fortuitous consequence of a new empirical regularity : above

$\sqrt{s}$ = 10 GeV, and up to 546 GeV, pp and $\bar{p}$p charged multiplicities are remarkably well fitted by a negative binomial distribution at each energy, both in full and restricted pseudo-rapidity domains. Fig. 21 illustrates results obtained at 546 GeV[104]. At 900 GeV, however, the negative binomial cannot represent the multiplicity distribution in $|\eta|$ domains wider than 2.5[108].

- The height of the pseudo rapidity distribution plateau increases smoothly with ln s from fixed target energy to 900 GeV with a clear violation of the Feynman scaling. In the fragmentation region, scaling is verified to about 20% [109].
- Two particle correlations between charged particles and long range correlations between particles emitted in the forward (proton) and backward (antiproton) hemispheres have been studied. The former can be understood in terms of a cluster model[110].
- The picture of particle production has been successfully extendend to photon[111] and strange particles production[112].
- No evidence for Centauro-like events has been found up to $\sqrt{s}$ = 900 GeV. Either there exists a threshold between $\sqrt{s}$ = 900 and $\sqrt{s}$ = 1700 GeV (the lowest energy event observed in cosmics rays), or the observed Centauros do not result from nucleon-nucleon interactions, the projectile being, for example, an exotic object[113].

It is worth to say that UA5 has well fulfilled its basic aim by providing a reliable survey of the low p_T hadron physics responsible for the bulk of particle production from the ISR energy domain up to the TeV region. Many models could reproduce part of these data, often by ad hoc tuning, but none can still explain them by a rigourous theoretical understanding.

Hadroproduction of CHARM and BEAUTY Particles

IV. HADROPRODUCTION OF CHARM AND BEAUTY PARTICLES.

The discovery of the J/Ψ-particles in 1974, followed by that of charmed D-mesons in 1976 triggered an impressive research effort, both experimental and theoretical, to improve our understanding of the production and decay characteristics of charmed particles in hadronic interactions. In order to detect these short-lived particles with good efficiency, several types of detectors with high spatial resolution were exposed as active targets to a variety of hadronic beams. Nuclear emulsion, high resolution rapid cycling bubble chambers and holographic bubble chambers were used as well as counter techniques. The IIHE took part in a series of pioneering experiments, making use of hybrid systems combining visual and electronic detector means. These experiments have contributed significantly to our knowledge of the hadroproduction characteristics and decay properties of charmed particles in fixed target π^-p and pp interactions for beam momenta extending from 200 to 800 GeV/c. The cross section for charmed particle production in this domain is of the order of 20μb and exhibits a rise with energy which is compatible with the one expected from QCD calculations for the lowest order parton subprocesses such as gluon-gluon fusion and quark-antiquark annihilation. Such lowest order calculations tend however to underestimate the overall magnitude of the cross sections. On theoretical grounds one expects that this discrepancy should tend to disappear for the hadroproduction of the heavy beauty quarks ($m_b \approx < 5$ GeV). Beauty production in hadronic interaction is unfortunately extremely rare (the rate per interaction being of the order of 10^{-6}) and the experiments are difficult and delicate. Using nuclear emulsion and counter techniques our group has participated in two CERN experiments which succeeded in producing a definite beauty signal in π^--N interactions.

IV.1. HADROPRODUCTION AND DECAY PROPERTIES OF CHARMED PARTICLES.

The IIHE participated into one of the first experiments tending to detect the production of short lived particles in high energy proton-nucleus interactions. In 1975, an emulsion stack was exposed at FNAL[114] to a 300 GeV proton beam and 60,000 events were scrutinized for the presence of secondary interactions or decays occurring within less than 150 μm from the primary vertex. No example of the associated production of short lived particles was found. In a second attempt to search for direct topological evidence of charmed particle production (NA13 experiment), a small rapid cycling hydrogen bubble chamber LEBC of 20 cm diameter with a high spatial resolution(≃ 40 μm) was exposed at

CERN in 1979 to a π^- beam of 340 GeV/c. In this set-up the bubble chamber was only equipped with one camera, so that only projected track lengths could be measured. Clear evidence for the associated production of charmed particles identified by their short decay lengths was obtained for the first time in hadronic interactions. The analysis of 100,000 frames with 48,000 events corresponding to 2.5 events/μb showed a significant excess, above the expected strange particle background, of 12 events with two decay candidates of short lived particles which, interpreted as charm pairs, corresponds to a total cross section of the order of 40 μb[115]. In addition, 8 charged 3 prong events (see fig. 22) consistent with the decays of short lived $D^{\pm}$-mesons were observed with an expected background of ~ 2 events.

The NA13 experiment offered no possibility of measuring the momentum of the particles. At the time this experiment was performed the European Hybrid Spectrometer EHS, initially designed to study low energy hadronic interactions at SPS energies, was still under construction at CERN. The complex EHS system would provide good momentum resolution for charged particles and gammas and allow particle identification(*) over a wide momentum range. A new charm experiment (NA16) was then set up in which LEBC was used as a vertex detector placed in front of a preliminary version of EHS. During 1980, NA16 produced 350K pictures taken with a π^- beam of 360 GeV/c (7.8 evts/μb) and 500 K pictures (7.3 evts/μb) with incident protons of 360 GeV/c. The selected number of charmed particle decays with all neutral particles seen and at most one track not reconstructed was small : 30 identified charmed particles decays in 22 events in the π^-p sample and 33 identified charmed particles in 29 events in the pp sample amongst which there are 56 unambiguously identified D-meson and 4 D_S(F)-decays. This small sample was however particularly clean and provided amongst the first significant estimates of neutral and charged D-meson lifetimes. In addition, the experiment allowed an exploratory investigation of the hadroproduction properties of D-mesons.

The NA16 experiment allowed the observation of the first fully identified example of associated charm production in hadronic interactions : a $D^\circ\bar{D}^\circ$ pair produced in a 360 GeV/c π^-p interaction[117].

From an unbiased sample of 33 decays giving good kinematic fits the $D^{\pm}$ and D° lifetimes were estimated[118] to be :

$$\tau(D^\circ) = (4.1 {}^{+1.3}_{-.9}) \times 10^{-13}\ \mathrm{s} \quad \text{and} \quad \tau(D^{\pm}) = (8.4 {}^{+3.5}_{-2.2}) \times 10^{-13}\ \mathrm{s}$$

(*) The IIHE participated[116] into the design and construction of the Silica Aerogel Cerenkov detector SAD which was part of EHS.

The π^-p data showed evidence[119] for a leading quark effect both in the number of D-meson types and in the Feynman x_F-distributions. The Feynman x_F-distribution of D-mesons produced in pp-interactions is smooth and consistent with a $(1-x_F)^2$ dependence[120]. Both the π^- meson and proton induced D-meson productions are consistent with a simple exponential p_T^2 distribution having a slope $= (1.1 \pm .3)\ (\mathrm{GeV/c})^2$. Total cross section estimates based on exclusive topological branching ratios, expected to be least sensitive to systematic uncertainties, were derived. The following[121] cross sections were measured for single D-meson production in the forward region ($x_F > 0$) :

$$\sigma(\pi^- p \rightarrow D^\pm + X) = (4.5^{+2.2}_{-1.4})\ \mu b; \quad \sigma(\pi^- p \rightarrow D^\circ/\bar{D}^\circ + X) = (7.7^{+7.2}_{-3.5})\ \mu b$$

and

$$\sigma(pp \rightarrow D^\pm + X) = (5.3^{+2.4}_{-1.6})\ \mu b; \quad \sigma(pp \rightarrow D^\circ/\bar{D}^\circ + X) = (10.2^{+7.9}_{-4.3})\ \mu b$$

In spite of its pioneering role, the NA16 experiment suffered however from a lack of statistics and rather limited means of charged particle identification preventing to distinguish $D^\pm$ from $D_s^\pm$ or Λ_s^+ with good efficiency. With this in mind, the experiment NA27 was set up, using again a rapid cycling high resolution hydrogen bubble chamber (LEBC II) as a track sensitive target placed in front of the EHS spectrometer upgraded to its final design (see figure 23). The optical system of LEBC II provided stereoscopic recordings resolving 20μm diameter bubbles. The spectrometer had a large acceptance for particles with Feynman $x_F > 0$ and the momentum resolution for charged particles was better than 1%. Charged particle identification was provided by the drift chambers ISIS2, two Cherenkov counters, SAD and FC, and a transition radiation detector TRD. Additional components of the spectrometer allowed π° identification (IGD, FGD) and neutral hadron detection (INC, FNC).

Charmed particle production was studied in about 340,000 π^-p and about 100,000 pp interactions at beam momenta of respectively 360 GeV/c and 400 GeV/c. The total charm production cross section at positive Feynman x_F in 360 GeV/c π^-p interactions was measured to be[122] (20 ± 5)μb. This cross section is dominated by D-meson production : (10.1 ± 2.2)μb for $D^\circ/\bar{D}^\circ$ and (5.7 ± 1.5)μb for $D^\pm$. It includes a contribution of the order of (4 ± 4)μb for $\Lambda_c/\bar{\Lambda}_c$ production. The production of D* mesons accounts for nearly all the neutral D-mesons and for about half of all the charged D-mesons. New lifetime determinations of D° and $D^\pm$ were in good agreement with the NA16 values and the existing world averages leading to the life-time ratio[123] : $\tau(D^\pm)/\tau(D^\circ) = 2.6^{+.8}_{-.6}$, the shorter lifetime of D°-particles being attributed to the contribution of non spectator diagrams in which the light quark takes part in the decay process.

The 400 GeV/c pp experiment led to the observation of a sample of 233 interactions with a charm pair and 91 interactions where only one charm decay was observed. The cross section for inclusive D or $\bar{D}$ production[124] was found to be (30.2 ± 3.3)μb. The corresponding differential production cross section is well represented by the empirical form (see figure 24) :

$$d^2\sigma/dx_F\, dp_T^2 = \frac{1}{2}\ [\sigma(D/\bar{D}(n+1)b]\ (1-|x_F|)^n \exp(-b\, p_T^2)$$

with n = 4.9 ± .5 and b = (1. ± .1) $(GeV/c)^{-2}$

The QCD fusion model is compatible with these data except for the magnitude of the cross section which depends sensitively on the assumed mass of the charm quark. The value of the $D + \bar{D}$ pair production cross section was measured to be (14.6 ± .1.8)μb and the inclusive cross-section for D* production was found to be $\sigma(D^*/\bar{D}^*)$ = (15.0 ± 3.4)μb.

The inclusive $D/\bar{D}$ production cross section was measured[125] to be $\sigma(D/\bar{D}) = 59^{+22}_{-12}$ μb.by the LEBC-MPS collaboration using LEBC exposed to a 800 GeV/c proton beam in front of the Multi Particle Spectrometer MPS at Fermilab. A comparison with the 400 GeV/c pp data obtained with LEBC at CERN indicates a $D/\bar{D}$ cross section increase by a factor 2, in good agreement with fusion model calculations.

The energy dependence of the charm production cross section in proton-nucleon interactions was also tested in the CERN-NA25 experiment in which a small heavy liquid rapid cycling holographic bubble chamber HOBC filled with Freon C_3F_8 was exposed to proton beams of 200 GeV/c and 360 GeV/c. The main advantage of the holographic bubble chamber technique is the possibility to obtain high spatial resolution (~ 10μm) and a large depth of field simultaneously. Assuming a linear dependence of the charm cross section on the atomic number A, the total charm pair production cross section was found to be equal to[126] $(3.9\ ^{+2.5}_{-1.9})$μb at 200 GeV/c and $(24.6\ ^{+12}_{-8.3})$μb at 360 GeV/c. Again, the strong energy dependence of the cross section found here is in agreement with most QCD based model calculations.

The problem of the dependence on the mass number A of charm production on complex nuclei has been studied in detail by members of the IIHE in the framework of the WA78 collaboration in an experimental set-up consisting of a variable density target calorimeter followed by a muon spectrometer. Using a 320 GeV/c π^- [127] and a 300 GeV/c proton[128] beam incident on three different target materials Al\Fe and U, the A-dependence of charm production has been estimated by measuring the yield of prompt single muons. Parameterising the charm cross section as $\sigma_{ss}(A) = \sigma_o A^{\alpha h}$ the measured α-values in the kinematical region $x_F > .1$ are :

$$\alpha_\pi(\mu^+) = .76 \pm .08 \quad \text{and} \quad \alpha_\pi(\mu^-) = .83 \pm .06$$

$$\alpha_p(\mu^+) = .79 \pm .12 \quad \text{and} \quad \alpha_p(\mu^-) = .76 \pm .13$$

These results indicate α values less than 1, in fair agreement with other measurements. The results should however be handled with care as systematic effects are important and delicate to estimate. Moreover, the power-law parametrisation of the A-dependence could be only approximate and α could be x_F dependent as suggested by similar measurements concerning the production of light quarks.

IV.2. HADROPRODUCTION OF BEAUTY PARTICLES.

After the discovery in 1977 of the Y resonance at FNAL the search for $B\bar{B}$ meson pairs produced in hadronic interactions has been undertaken in fixed target experiments as well as at the CERN pp (ISR) and $\bar{p}p$ ($Sp\bar{p}S$) colliders. The first direct evidence for the hadroproduction of $B\bar{B}$-pairs was obtained in 1985 by the WA75 collaboration[129] using an emulsion target inserted in an area of silicon strip detectors. These detectors were placed in front of a first version of the spectrometer also used in the WA78 experiment and exposed to a π^- beam of 350 GeV/c. By selecting events with a high p_T muon amongst 3×10^8 interactions recorded in the emulsion, one event containing a B^--$\bar{B}^\circ$ pair was observed (see figure 25). Assuming a linear A-dependence of the cross section, this single event indicated a production cross section for beauty particles in the region of 10nb, a value compatible with QCD calculations from which one expects cross sections of a few nb per nucleon.

The production cross section of beauty particles in π^--U interactions at 320 GeV/c was studied by the WA78 collaboration in a dump calorimeter followed by a magnetic spectrometer. Searching for $B\bar{B}$-signals in event samples containing either like-sign dimuons or three muons, the average production cross section was found to be[130] :

$$\sigma(B\bar{B}) = (2.0 \pm .3 \pm .9)\text{nb/nucleon}$$

assuming a linear A dependence.

THE LEP-DELPHI EXPERIMENT

V. THE LEP-DELPHI EXPERIMENT

In 1982 CERN decided to build a new collider with a circumference of 27 km in which electrons and positrons could be accelerated in opposite directions up to energies of 55 GeV per beam. The basic version of this Large Electron-Positron accelerator LEP is in operation since 1989. Experiments with LEP have allowed a detailed investigation of the standard model of elektroweak and strong interactions at annihilation energies covering the pronounced cross section peak produced by the Z°-intermediate boson, mediator of the neutral weak current.

A collaboration between 4 Belgian institutes (IIHE/ULB-VUB, UIA and UMH) and the laboratories of Oxford and Rutherford has constructed the muon detection system of DELPHI[131] (see figure 26), one of the four large multipurpose detectors built to analyse the LEP data. The Belgian groups have constructed the forward muon identifier consisting of 16 detector modules (see figure 27) called "quadrants". The assembly of these quadrants took place at the IIHE, which also had the responsibility of the design and production of a large fraction of the mechanical and electronic components. Each of the quadrants covers a sensitive area of about 4.4 x 4.4 m^2 and is made of two orthogonally crossed layers of 22 drift chambers. Four such quadrants assembled into a square of approximately 9 x 9 m^2 provide one detection plane of the forward muon identifier. Two such detection planes are installed in both end caps of DELPHI, the outer plane being situated at the outer edge of the forward part of the magnet yoke. The inner detection plane is imbedded in the iron yoke itself separated from the outer plane by 30 cm of which 20 cm are steel.

The basic detector cell consists of a drift chamber with a sensitive volume of ~ 4.4m x 19cm x 2cm[132]. The chamber body is an extruded aluminium tube equipped with PVC profiles into which copper strip electrodes have been coextruded to provide the drift field of about 700 V/cm. A 100 micron diameter stainless steel anode wire is strung along the chamber axis. One of the cathodes facing the anode wire consists of a flat solenoïdal delay line with an inverse velocity of about 580 ns/m. The drift chambers are operated in the limited streamer mode using a gas mixture of 70% CO_2, 14.4% Ar, 14.4% iC_4H_{10} and 1.2% of isopropyl alcohol vapour at an anode voltage of about 5000V.

The coordinates of a hit are determined from three time measurements; the drift time and the arrival times of the induced pulse at both ends of the delay line. The left-right ambiguity, inherent to drift chambers with a central anode wire, is resolved using the delay line of the crossed layer. The efficiency, resolution and calibration of the quadrants have been determined in cosmic hodoscopes as well as during DELPHI runs. The precision on the drift distance was found to be better than 1 mm, whereas the resolution on coordinates measured by the delay lines is $\lesssim$ 3 mm.The read-out of the chambers is based on the Fastbus standard; it makes use of a partly multiplexed set of time digitizers with a precision of 2 ns. Special trigger cards have been designed and built in order to integrate the muon chamber data into the second level trigger system of DELPHI.

Further contributions have been made to the completion of the software[133] needed for the analysis of muon data as well as to the general purpose software of the DELPHI detector, including graphical event representation[134].

The first results of DELPHI were published[135] soon after the starting up of LEP in 1989. Measurements of the mass and width of the Z°-particle from hadronic final states were reported. This initial fit of the Z°-line shape, based on a small sample of 1066 Z°-events collected at seven beam energy points, already strongly favoured the existence of only three light neutrino species (see fig. 28). At present DELPHI has collected about ~ 1.2 million Z°-events and results were published on a wide variety of topics using steadily increasing subsets of the available event samples. As in other LEP experiments, and impressive agreement with the predictions of the Standard Model with 3 particle generations has been found. From a sample of ~ 150,000 hadronic and leptonic events collected in 1989 and 1990, the number of light neutrino species was determined to be $N_\nu = 2.94 \pm .10$ from an estimate of the invisible Z° width[136].
Parameterising in an improved Born-approximation the effective electroweak vector and axial-vector coupling constants to charged leptons from fits to the Z°-line shapes and forward-backward decay asymmetries one finds $\sin^2\theta_W^{eff} = .241 \pm .009$ for the effective electroweak mixing angle.

Results based on the analysis of a sample of approximately 450,000 Z°-decays accumulated during the 1990 and 1991 DELPHI runs were reported at ICHEP 92[137]. Allowing for independent couplings for the different lepton species a 9 parameter fit to the hadronic cross sections and to the leptonic cross sections and forward-backward asymmetries A_{FB} yields the following parameters :

The Z° mass	M_Z	$= 91.188 \pm 0.010$ GeV
The Z° total width	Γ_Z	$= 2.488 \pm 0.012$ GeV
The Born-cross section at the pole	σ_0	$= 40.86 \pm 0.28$ nb

Hadronic to leptonic cross-section ratios
$$\begin{cases} R_e = 20.79 \pm 028 \\ R_\mu = 20.92 \pm 0.22 \\ R_\tau = 20.69 \pm 0.30 \end{cases}$$

Forward-backward asymmetries at the pole
$$\begin{cases} A^{o\,e}_{FB} = 0.013 \pm 0.013 \\ A^{o\,\mu}_{FB} = 0.015 \pm 0.008 \\ A^{o\,\tau}_{FB} = 0.033 \pm 0.010 \end{cases}$$

These results correspond to :

Partial leptonic widths
$$\begin{cases} \Gamma_e = 83.03 \pm .68 \text{ MeV} \\ \Gamma_\mu = 82.50 \pm 1.07 \text{ MeV} \\ \Gamma = 83.43 \pm 1.36 \text{ MeV} \\ \Gamma_l = 82.95 \pm .51 \text{ MeV} \end{cases}$$

The invisible width $\Gamma_{inv} = 512.0 \pm 10.$ MeV

The hadronic width $\Gamma_{had} = 1727 \pm 12$ MeV

Assuming lepton universality one finds :

$$g^2_{Vl} = (1.69 \pm .49) \times 10^{-3}$$
$$g^2_{Al} = .2479 \pm .0016$$

for the squares of the vector and axial vector leptonic coupling constants.

Various τ-decay modes were studied[138] in which the average polarization P_τ of τ's produces in $Z° \rightarrow \tau^+ \tau^-$ decays was determined to be $P_\tau = -.24 \pm .07$ corresponding to the ratio $g_{V\tau}/g_{a\tau} = + 0.12 \pm .05$. The lifetime of the tau lepton was measured to be (31± 25)fs[139] using in particular a silicon microvertex detector installed around the beam pipe at the center of DELPHI. The ratio of the Fermi coupling constant from τ-decay relative to that from muon decay was found to be .95 ± .04, compatible with lepton universality.

Inclusive searches for new particles such as the top quark, charged and neutral heavy leptons, leptoquarks, Higgs particles and SUSY-particles remained unsuccessful and only lower mass bounds could be established. For example[140], the search for a minimal standard model neutral Higgs boson H° in processes of the type $e^+e^- \rightarrow H° +$ (lepton, antilepton) restricts the H°-mass to be above 38 GeV/c^2 at the 95% C.L.

Results have been published concerning many other topics such as the production of strange, charm and beauty particles in hadronic Z-decays including measurements of partial decay widths and asymmetries for annihilations into quark-antiquark pairs of known flavour. A measurement[141] of the average lifetime of B-hadrons based on the impact parameter distributions of high p_T-muons and hadrons led to the result $\tau_B = (1.28 \pm .10)$ps.

The particle multiplicity and jet structure of hadronic events was studied in considerable detail. For example, an analysis[142] of the orientation of 3-jet events in hadronic Z°-decays was found to be in good agreement with QCD-predictions, the scalar gluon theory being excluded by these data. These studies have allowed several measurements of the strong coupling constant α_s. For instance, the value of $\alpha_s(M_Z^2) = .113 \pm .007$ was obtained[143] from a study of eight event shape variables in a sample of ~ 120,000 hadronic Z° decays.

The study of eP COLLISIONS at HERA

VI. THE STUDY OF ep COLLISIONS AT HERA.

HERA, the first electron (30 GeV)-proton (820 GeV) collider, has come in operation at DESY-Hamburg in 1992. Two 4π-multi purpose detectors, H1 and ZEUS, are installed in two of the four interaction regions of the machine. In February 1987, the IIHE and the UIA joined the H1 collaboration.

Of the five chambers of the H1 central tracking detector, one was built at the IIHE : the COP chamber[144] (Central Outer Proportional Chamber). The signals of the COP and CIP chambers (a detector similar to the COP but with smaller radius) are combined into the first level trigger. The chamber time resolution is of ~ 60 ns, well below the 96 ns bunch crossing time of HERA.

The COP consists of a set of two coaxial cylindrical multiwire proportional chambers of 2.2 m length and with an inner diameter of 1m. The radial annular space occupied by these chambers is 33 mm. Both chambers contain about 1,500 wires, the wire pitch being 2 mm and the gapsize 4mm. One of the cathodes of each chamber is segmented in z and phi, giving 2 x 288 pads of dimensions 190 x 123 mm^2, which are read-out. The chamber walls are of sandwich type with Rohacell as basic material, faced on either side with A1 (or Kapton) foils 25 micron thick. This sandwich structure, necessary to give the cylinders the required mechanical stability, also allows a means of transporting the signals to one of the chamber ends. Figure 29 illustrates the complexity of the central tracking system of the H1 detector photographed during the installation of the C.O.P.

A second responsibility of the IIHE group within the H1 collaboration was the design and construction of the front-end data acquisition system of all the proportional chambers of the H1 detector i.e. 6 chambers, of 2 to 3 planes each, with around 4500 electronic channels in total. It consists of 4 sub branches for which there are 280 receiver cards distributed between 16 crates. Each receiver card consists of a discriminator which feeds a pipeline, keeping synchronisation with the collider 10 MHz clock. Controller cards interface these crates with the central Data Acquisition System via VME branch driver cards. The whole of the MWPC read-out system is under software control and runs on a VME based 68020 CPU connected with the central data acquisition via an optical fibre crate interconnect.

Beginning of May 1992, the first collisions (figure 30) between 26.7 GeV electrons and 820 GeV protons were recorded by the H1 experiment. The luminosity was only 2 ‰ of the design luminosity, with only 10 colliding particle bunches, instead of 210. In the first data taking period, in June-July, an integrated luminosity of about 1.5 nb^{-1} was recorded. In a second run, from September to November 1992 the H1 detector took additional data corresponding to an integrated luminosity of 10 nb^{-1}. During both runs, the COP chamber worked correctly. It had been observed, during a full scale test of the H1 detector using cosmic ray data, in 1991, that the central proportional chambers, and particularly COP, suffered severely from electronic noise related to the H1 environment. By the time of the e-p data taking, this difficult problem had been mastered and, apart from a dead sector due to a broken wire, the COP chamber behaved efficiently and was used in the first level trigger. The data acquisition system of the multi-wire proportional chambers worked properly as well.

The data from the first e-p run, in June-July 1992, led to several physics results which were published in the beginning of 1993. Although very high q^2 -values can be reached at HERA ($q^2 \lesssim 5 \times 10^4$ GeV^2), the cross section dependence is such that at present the data are concentrated at $q^2 \lesssim 40$ GeV^2, a value only slightly (about a factor 2) higher than for the existing fixed target data. However, the kinematical domain is already considerably extended in the Björken scaling variable x (down to 5×10^{-5}, about a factor 20 lower than before) and in the hadronic energy W (up to $W \simeq 200$ GeV, a factor 10 higher than before). This explains the high significance and interest of the H1 results obtained with rather small statistics. The data collected during the second e-p run in September-November 1992 are still being analysed and are not reported here.

The total e-p cross section[145] is dominated by very low q^2 interactions with a quasi-real intermediate photon. This allows to determine with very little uncertainty the total γp cross section. Using two independent methods, it was found to be $(159 \pm 7 \pm 20)$ μb at an average center of mass energy of 195 GeV. Various theoretical models make quite different (by as much as a factor 5) predictions for the high energy behaviour of this cross section. The measured value does not support extreme mini-jet models predicting a strong rise of the γp cross section with energy but is in a good agreement with the Regge motivated parametrisations.

The high energy available at HERA allows to investigate the details of the interactions of quasi-real photons with protons[146]. The single particle spectra (pseudo-rapidity and p_T distributions) as well as the jet formation (multi-jet correlation, jet p_T and jet energy flow distributions) show the presence of a hard scattering component, as predicted by QCD; the photon is "resolved" into a $q\bar{q}$ pair, of which one component interacts with the proton and the other fragments independently. In contrast, the "direct" interaction of the photon with the target, followed by a soft hadronisation, is not sufficient to account for the characteristics of the hadronic final state.

One of the major goals of the HERA experiments is to measure the proton structure functions up to very high q^2-values and down to very low x-values[147]. In this domain, several parametrisations compete, predicting widely different behaviour. The first e-p run allowed to collect about hundred deep inelastic events with $q^2 > 5$ GeV^2 and x as low as 6×10^{-4}, with little background and small smearing effects in x and q^2. These small statistics do not allow to discriminate as yet between several structure function parametrisations, but shows that this goal could be reached using the data collected during the second e-p run.

Already with the small statistics available, the study of the energy flow, transverse momentum and rapidity distributions of the hadronic final states in deep inelastic interactions[148] provides significant tests of QCD. The hadronization models based on first order matrix element calculations with additional parton shower evolution and on colour dipole radiation are both able to describe the present data without parameters adjustment.

The data sample of 27 nb^{-1} accumulated in 1992 shows no evidence for the production of new particles such as leptoquarks, leptogluons and excited leptons.

R & D

VII. GENERAL TECHNOLOGICAL R&D

VII.1. INTERACTIVE GRAPHICS SOFTWARE FOR ELECTRONIC DETECTORS.

With the advent of complex multipurpose electronic detectors like the LEP-DELPHI detector the necessity of an analog presentation of the recorded data became evident for two essential reasons :

- it is the only way to get a global view of the overall working mode of the detector
- the high number of channels (> 100,000) makes a standard (digital) manual scanning of the data on listings impossible.

Moreover, the complexity of the detector requires the use of sophisticated pattern recognition techniques. An interactive control of the efficiency of the algorithms is needed in order to develop the reconstruction programs.

A general system[149,150] based on 3D graphics was developed in the laboratory in order to cope with these requirements. Its general structure illustrated in figure 31 is based on two main components :

- TANAGRA : a general data base handler with entity relationship which gives access to the detector data in a secure environment
- DELGRA : the graphics handler which allows to perform 3D graphics in a similar way, on various platforms thanks to an architecture based on a kernel common to all implementations complemented by a device dependent part.

The interactivity of the system is realized through portable user friendly menus displayed on standard terminals.

The system took 4 years of development and was ready for the start up of the DELPHI data taking. It is still in evolution in function of the experimental conditions and is heavily used by the DELPHI collaboration.

VII.2. DEVELOPMENT OF A POSITRON EMISSION TOMOGRAPHY SCANNER WITH IMPROVED RESOLUTION.

The photosensitive wire chamber technology was developed over the last decade in a number of high energy physics research institutes. It allows to detect and localise very weak light signals over large areas and is now used in a number of instruments like the DELPHI Ring Image Cherenkov detector. The aim of the project was to use this technology to build a

Positron Emission Tomograph camera with improved performance compared to commercial systems.

The first phase of the project took place between 1987 and 1991 in the framework of an international collaboration. Its aim was to study a new technique for gamma ray detection using BaF_2 scintillator and photosensitive wire chambers. In 1991 it was proposed to apply the technique to Positron Emission Tomography (PET) and to build a small high resolution tomograph.

PET is an atraumatic and non-invasive technique used to obtain a three-dimensional image of the density distribution of a radioactively-labeled substance in a living organism. It takes advantage of the fact that positrons from a radioactive β^+ tracer annihilate with electrons from the surrounding tissue after a short range, typically less than 1 mm. In this annihilation two nearly back-to-back gamma rays are produced. If both gamma rays are detected and localised, the annihilation is known to have occurred on the line joining the interaction points of the two gamma rays. From the observation of a large number of such annihilations it is possible to reconstruct the three dimensional distribution of the tracer in the organism.

Nearly all commercially available PET scanners use BGO scintillation crystals and photomultiplier readout. The best systems achieve a position resolution in the image of 6 mm FWHM. The principle of operation of the alternative technology proposed here is illustrated in fig 32. A matrix with a large number of small BaF_2 crystals is mounted inside a gas-tight vessel together with the wire chamber which consists of a series of wire planes and wire meshes at suitable potentials. Typical values for the potentials are indicated. The scintillation light leaves the crystal and ionizes the tetrakis-dimethylamino-ethylene (TMAE) vapour in the first gap between wire planes. The wire chamber amplifies this signal and gives the position and timing information on the detected gamma ray.

With technical prototypes using BaF_2 crystals measuring 3 x 3 x 20 mm^3 the following results were obtained[151,152].

- stable operation at a total gas gain of a few 10^6
- time resolution for gamma rays of 511 keV : 4,6 ns rms
- position resolution : 1.46 mm rms
- detection efficiency for one gamma ray : ~ 40%.

These results are sufficiently encouraging so that we are now building a small, high resolution PET scanner using this technique. It contains 3060 BaF_2 crystals measuring 3 x 3 x 20 mm^3, forming a cylinder, 6 cm long, with a diameter of 20 cm. This scanner will be used for studies with small laboratory animals.

COMPUTING

VIII. COMPUTING AND NETWORKING.

The amount and complexity of the data volumes to be handled in elementary particle experiments have known an explosive growth during the last 20 years. This was made possible thanks to the ever increasing means and speed offered by computers both for on - and off-line treatment of the data. Moreover, the international organisation of high energy physics activities of many laboratories around a small number of accelerator centers has highly stimulated the use of networks for data handling and communication.

In 1972, a first computer, a DECsystem10 from Digital Equipment Corporation, made its entry at the IIHE. This DEC-10 was purchased for the control of the POLLY III automatic measurement device for bubble chamber film. However, it was also adequate to process data of manual measurement machines and for interactive processing. Indeed one of the greatest advantages of the DEC-10 was that it permitted multi-user interactive access and this at a time when punched cards and batch processing were the common tools for working with computers. This computer through several upgrades and adaptations remained at the IIHE for 18 years. In the mean time other computers had entered the laboratory. In 1976 a PDP-8 and two PDP-11's were used to control measurement devices primarily built to measure film from the BEBC bubble chamber and later from the UA5 streamer chamber experiment. In a first instance, measurement data were "manually" (by magnetic tape) transferred from the PDP-11's to the DEC-10 for further processing. Later on (1979), an interactive on-line processing system of the data was however developed. This resulted in the connection of the DEC-10 with the two PDP-11's : the first steps of the IIHE in data communication were set.

In the beginning of the 80's, data communication in Europe was characterised by the introduction of public packet switched networks based on the X.25 protocol. At the very end of 1982, the Belgian PTT opened its public packet switched network and the IIHE was among the first customers. The use of public packet switched networks evolved from an asynchronous access at 300 bits/sec from one dedicated terminal to a synchronous access at 9600 bits/sec available from each terminal in the laboratory.

High energy physics and computer technology did not come to a standstill. In 1984, computers of the VAX series found their way to the IIHE. Three MicroVAXII computers were bought to cope with the increased computing needs resulting from the participation of the IIHE in new experiments such as DELPHI and CHARM II.

In 1986, a data communication project, termed HELIOS-B, started up at the IIHE. This project in collaboration with the French HELIOS project aimed at high speed data transfer by means of a satellite. It not only brought a VAX8200 to the laboratory but was also the push to install a local area network based on Ethernet and on introduction into research networks in Europe. Out of this project grew a new research group, the HELIOS-B group, which concentrated on research in data communication and counts now almost 20 researchers at the ULB and VUB. In the last 6 years, the way in which experiment data became available drastically changed. The bubble chamber technique was progressively abandoned in favour of experiments using exclusively counter techniques. To visualise events, graphical workstations and graphical software had to be used. Workstations of different types (VAXstations, DECstations) were introduced for that goal.

Micro-informatics did not pass unnoticed in the IIHE : several PC's and Macintoshes are now used for such various tasks such as data acquisition, CAD and word-processing.

At present, all computers in the IIHE are linked through a local area network connected to the FDDI backbone from VUBnet, the VUB local area network. The X.25 infrastructure of the IIHE is in turn connected to RESULB, the ULB local area network. In 1990, the European research network IXI (International X.25 Infrastructure) came into existence. Mainly sponsored by the European Commission, IXI realised a connection between national research networks. In the absence of a Belgian research network, the ULB/VUB connected to IXI giving their researchers the opportunity to use computers all around Europe. The scene of European networking is however constantly moving and at the end of 1992 this situation became unfortunately unstable for high energy physics and now needs reevaluation. With the start of the HERA-H1 experiment and the increased data rates of the DELPHI experiment ,the computing and networking possibilities of the IIHE needs anyhow to be constantly reconsidered and adapted. Moreover, this has to be done in the light of new projects foreseen for the near (CHORUS) or far future (LHC).

OUTLOOK

IX. OUTLOOK.

The DELPHI, H1 and CHORUS experiments will probably not be entirely completed before the end of this decade. They form the basis of a broad and extremely interesting research program of the IIHE for many years to come. Physics with HERA has only just started. The HERA experiments will probe the standard model along different paths than those explored up to now in lower energy lepton-nucleon interactions or in e^+e^- annihilations. They will certainly examine the structure of the nucleon with a fantastic resolution and might reveal unexpected details. The upgrade of the LEP energy to $\sqrt{s}$ ~ 180 GeV which is presently prepared should be completed by the end of 1994. This will allow the study of new phenomena such as $e^+e^- \rightarrow Z^o \rightarrow W^+W^-$ which imply crucial tests of the electroweak theory. Moreover, $W^\pm$ gauge bosons will be copiously produced in clean conditions and their intrinsic properties will be measured with great accuracy. Both the LEP and HERA experiments will extend our searches for new particles (Higgs, supersymmetric particles, etc.) into a new mass range. If neutrino oscillations are observed by CHORUS, it might solve astrophysical puzzles and, above all, prove that neutrino species are massive.

It is almost certain that maybe some but not all the fundamental questions which rose in the wake of recent theories and measurement results will be answered by the present experiments. Some answers might require experiments performed at interaction energies between point like particles, such as leptons and quarks, which are an order of magnitude higher than those presently available. With this aim new superconducting multi-TeV proton-proton colliders are either firmly considered (LHC-CERN) or under construction (SSC-Dallas). Experiments at these very high energy colliders, which should be operational just after the year 2000, will be much more gigantic and complex than those presently performed.They will require especially developed detector technologies. The IIHE is participating in one of the experimental proposals, the Compact Muon Solenoid experiment (CMS), which are being prepared for the Large Hadron Collider (LHC) at CERN. R & D work has already been undertaken on a new high resolution track chamber technique, that of "Micro Strip Gas Counters". This technology should be used to build part of the central tracking system of this new detector. The scintillating fiber technique already applied in CHORUS, offers an interesting alternative. By conducting this R & D work in parallel with the experiments already undertaken, the IIHE is paving the way to an undisrupted participation, beyond the year 2000, in one of the most fantastic scientific endeavours of mankind : the understanding of the most ultimate structure of matter and the fundamental forces which govern its behaviour and evolution.

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[142] P. Abreu et al., Phys. Lett. B279 - 498 - 1992

[143] P. Abreu et al., Z. Phys. C54 - 55 - 1992.

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[145] T. Ahmed et al., Phys. Lett. B299 - 374 - 1993.

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[147] T. Ahmed et al., Phys. Lett. B299 - 385 - 1993.

[148] T. Ahmed et al., Phys. Lett. B298 - 469 - 1993.

[149] D. Bertrand, CAD/CAM Benelux 6 - 37 - 1986

[150] D. Bertrand, Computer Physics Communications 45 - 207 - 1987

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FIGURE CAPTIONS

FIGURE CAPTIONS.

Fig. 1. Distributions along the neutrino beam axis of :

a. NC events in the ν beam

b. CC events in the ν beam (based on a reference sample)

c. Ratio $\frac{NC}{CC}$ in the ν beam (normalized)

d, e, f. idem in the $\bar{\nu}$ beam

g. Measured neutron stars with $100 < E < 500$ MeV having protons only

h. Computed distribution of the background events from Monte Carlo calculations (taken from reference 3 - Gargamelle Collaboration).

Fig. 2. Total neutrino and antineutrino cross sections as a function of energy (taken from reference 6 - Gargamelle Collaboration).

Fig. 3. An example of the reaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$ as observed in the Gargamelle bubble chamber; this event, the second out of 3, was found in Brussels (Gargamelle Collaboration).

Fig. 4. First evidence for charm production in charged current neutrino interactions. This event observed in Gargamelle was found in Brussels; it is of type $\mu^- e^+$ (K^0_s or $\Lambda°$) and other hadrons (taken from reference 14a - Gargamelle Collaboration).

Fig. 5. Measurement of the structure functions $F_2(x, q^2)$ and $xF_3(x, q^2)$ made in Gargamelle at the SPS and showing a weak and varying q^2 dependence, in disagreement with pure scaling (taken from reference 21 - WA15 experiment).

Fig. 6. The 90 % confidence limits showing the allowed regions (below the curves) for the mixing angles and the neutrino mass squared differences for the processes $\nu_e \rightarrow \nu_x$, $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ as measured in BEBC filled with an heavy Ne/H_2 mixture (taken from reference 24 - BEBC test run).

Fig. 7. First direct observation of a charmed baryon :

a. microphotograph of the event seen in the emulsion; the charmed baryon produced at point A decays at point B after a parth of 354 ± 3 μm into a proton, a π^+ and a K^- meson

b. the event as seen in BEBC (the decay proton undergoes an elastic scattering on H_2) (taken from reference 25b - WA17 experiment).

Fig. 8. A neutrino induced interaction occurring in the TST installed in BEBC (WA24 experiment).

Fig. 9. Measurement of the structure functions (a) $F_2(x, q^2)$ and (b) $xF_3(x, q^2)$ made in BEBC filled with a heavy Ne/H_2 mixture. Statistical and systematic errors have been summed in quadrature. The enveloppe of the various fits made on the data is also shown. Data points depicted as open triangles were not used in the fits (taken from reference 30 - WA59 experiment).

Fig. 10. Diagram illustrating the hybrid emulsion-counter set up by E.H.S. Burhop et al. at Fermilab to search for short lived particles produced in neutrino interactions. V is a veto counter, C_o and WG are spark chambers, E are the emulsion stacks, S_o is a scintillation counter, SD is the shower detector made of 4 spark chambers (C_1 to C_4), 4 scintillation counters (S_1 to S_4) and 5 lead plates (L_1 to L_5) and M is the muon identifier (taken from reference 44b).

Fig. 11. a. Microphotograph of the first directly observed example of a charmed particle decay. The charmed particle is produced in a neutrino interaction occurring in nuclear emulsion at point A and after a path of 182 μm it decayed at point B into three charged particles (taken from reference 44a).

b. Schematic drawing of the event as seen in the counter set-up; tracks seen in the WG spark chambers are shown by thick lines (taken from reference 44b).

Fig. 12. A side view of the 15 foot Fermilab bubble chamber showing the both conventional and holographic recording systems (E632 experiment).

Fig. 13. An hologram taken in the 15 foot Fermilab bubble chamber and showing the neutrino production of a D^+ meson decaying into 3 charged particles after a path of 0.7 cm (E632 experiment).

Fig. 14. The CHARM II detector.

Fig. 15. Most prominent resonances observed at 6.5 GeV/c incident momenta in the $K^-p \rightarrow K^-p\pi^+\pi^-$ channel studied in the Argonne 10-ft bubble chamber. Effective mass distributions are shown for : (a) the $K^-\pi^+\pi^-$ system, (b) the $p\pi^+\pi^-$ system, (c) the $K^-\pi^+$ system and (d) the $p\pi^+$ system.
Full lines represent the results of the multichannel fit. Resonances whose contributions were considered are indicated by arrows.

Fig. 16. Inclusive $K^0_S K^0_S \pi^+ \pi^-$ invariant mass distributions observed in 4-prong K^+p interactions at 32 GeV/c (Mirabelle experiment) showing the evidence for the existence of a resonance with mass M = 1.97 ± .01 GeV and width Γ = 40 ± 20 MeV.

Fig. 17. The polarisation of $\Lambda(\bar{\Lambda})$ baryons as a function of Feynman x_F as measured in inclusive $K^+p \rightarrow \Lambda(\bar{\Lambda})\ X^{++}$ processes at 70 GeV/c.

Fig. 18. Evidence for intermittency effects in the distribution of the rapidity y of the charged particles of the most prominent sprike event observed in the NA22 experiment.

Fig. 19. A stereo photograph of a high multiplicity $\bar{p}p$ event at $\sqrt{s}$ = 546 GeV observed in one of the streamer chambers of the UA5-experiment.

Fig. 20. Center of mass energy dependence of the total cross sections for pp and $\bar{p}p$ interactions illustrating the contribution of the UA5-experiment.

Fig. 21. Corrected single diffractive charged particle multiplicity (n) distributions in the pseudorapidity intervals $|\eta| < .5$, 1.5, 3.0 and 5.0. The curves illustrate fits of negative binomial distributions.

Fig. 22. An example of a 3-prong candidate of a charmed particle decay observed at CERN in the rapid cycling bubble chamber LEBC exposed to a π^--beam of 340 GeV/c (NA13 experiment)

Fig. 23. Schematic lay-out of the EHS-spectrometer as used for the pp - 400 GEV/c data taking in the NA27-experiment. The spectrometer has a total length of more than 40 m and comprises :

i) A rapid cycling bubble chamber LEBC as active target

ii) A tracking system with two magnets (M1, M2) for momentum determinations using coordinates measured in LEBC , multiwire proportional chambers and drift chamber.

iii) Charged particle identification is provided by :
- the Silica Aerogel Detector SAD
- a large pictorial drift chamber ISIS
- a Cerenkov detector FC
- a Transition Radiation Detector TRD

iv) Calorimeters, both electromagnetic (IGD, FGD) and hadronic (INC, FNC).

Fig. 24 (a) $d\sigma/dx_F$ and (b) $d\sigma/dp_T^2$ distribution for $D/\bar{D}$ meson production from pp interactions at $\sqrt{s} = 27.4$ GeV observed in the NA27 experiment. The solid curves are fits to the data using distributions of the form $(1 - x_F)^n \exp(- bp_T^2)$. The fits determine $n = 4.9 \pm 0.5$ and $b = (1.0 \pm 0.1)\ (GeV/c)^{-2}$.

Fig. 25 Sketch of the $B^- \text{-} \bar{B}^\circ$ event observed by the WA75 collaboration using an emulsion target inserted in an area of silicon strip detectors exposed to a beam of 350 GeV/c, π^--mesons.

Fig. 26 Perspective view of the DELPHI detector showing the geometrical lay-out of the various subdetectors in the barrel part and in one of the end-caps.

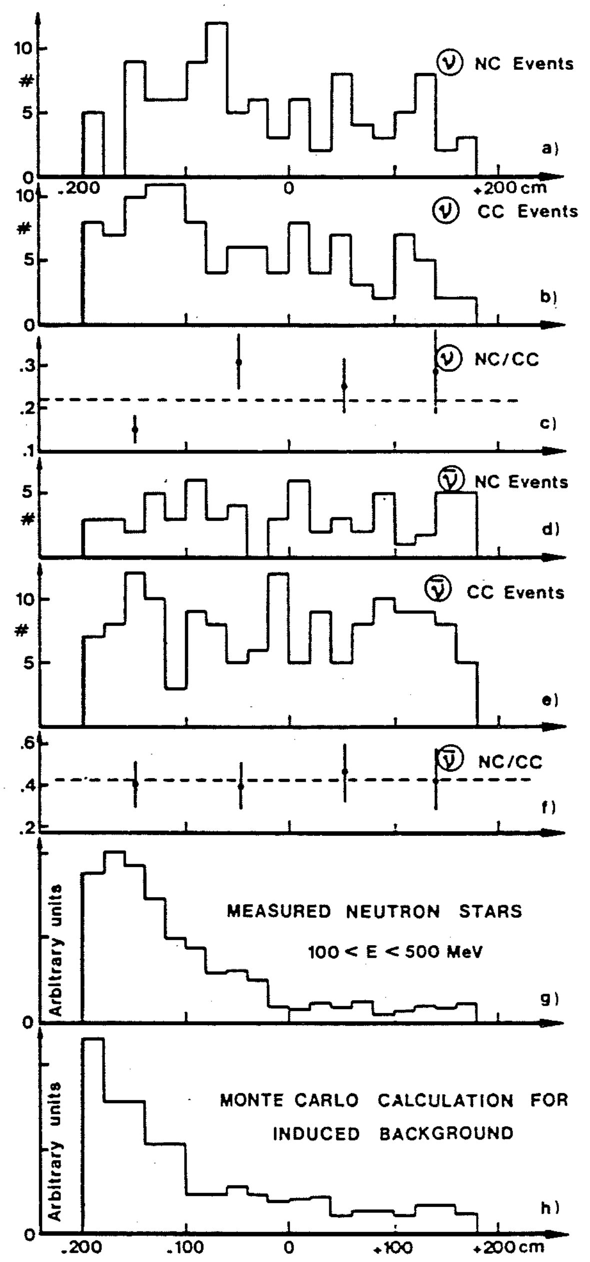
Fig. 27 Four quadrants of forward muon chambers installed in the LEP-DELPHI detector.

Fig. 28 Cross section for $e^+e^- \rightarrow$ hadrons as measured in DELPHI at ten different energies together with the two parameter fit (M_Z and overall normalization) assuming three neutrino species (full line). Also shown is the cross section as predicted by the Standard Model assuming two (dotted line) and four (dashed lined) massless neutrino species.

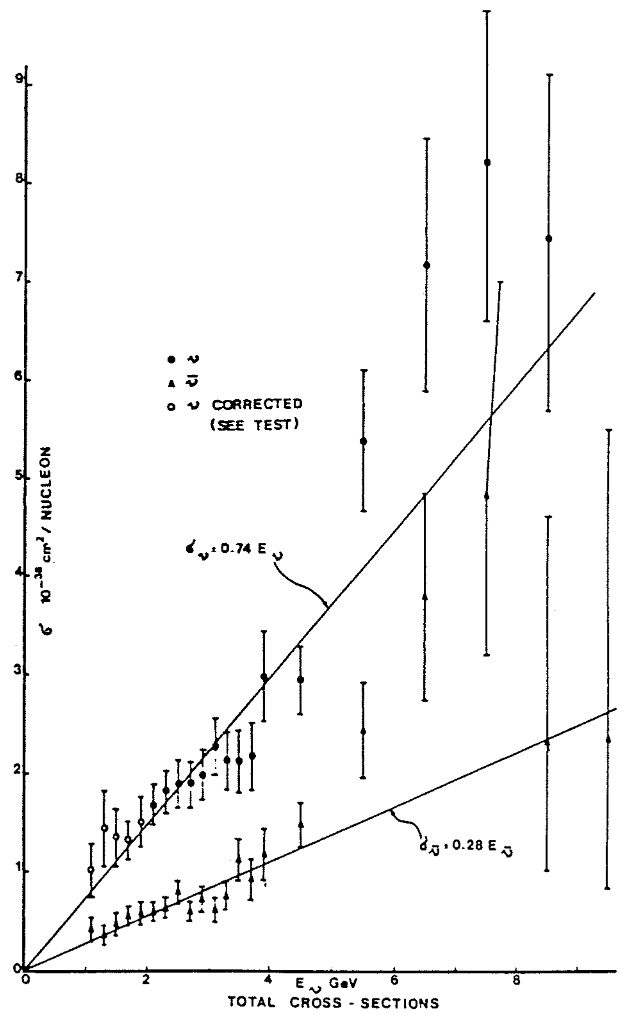
Fig. 29 The COP-multiwire proportional chamber being installed in the central tracking part of the HERA H1-detector.

FIGURES

fig.3



NC Events
a)
CC Events
b)
NC/CC
c)
NC Events
d)
CC Events
e)
NC/CC
f)
Arbitrary units
MEASURED NEUTRON STARS
100 < E < 500 MeV
g)
Arbitrary units
MONTE CARLO CALCULATION FOR
INDUCED BACKGROUND
h)
-200
-100
0
+100
+200cm



CORRECTED
(SEE TEST)
σ 10^{-38} cm^2 / NUCLEON
σ_ν = 0.74 E_ν
$\sigma_{\bar\nu}$ = 0.28 $E_{\bar\nu}$
E_ν GeV
TOTAL CROSS - SECTIONS

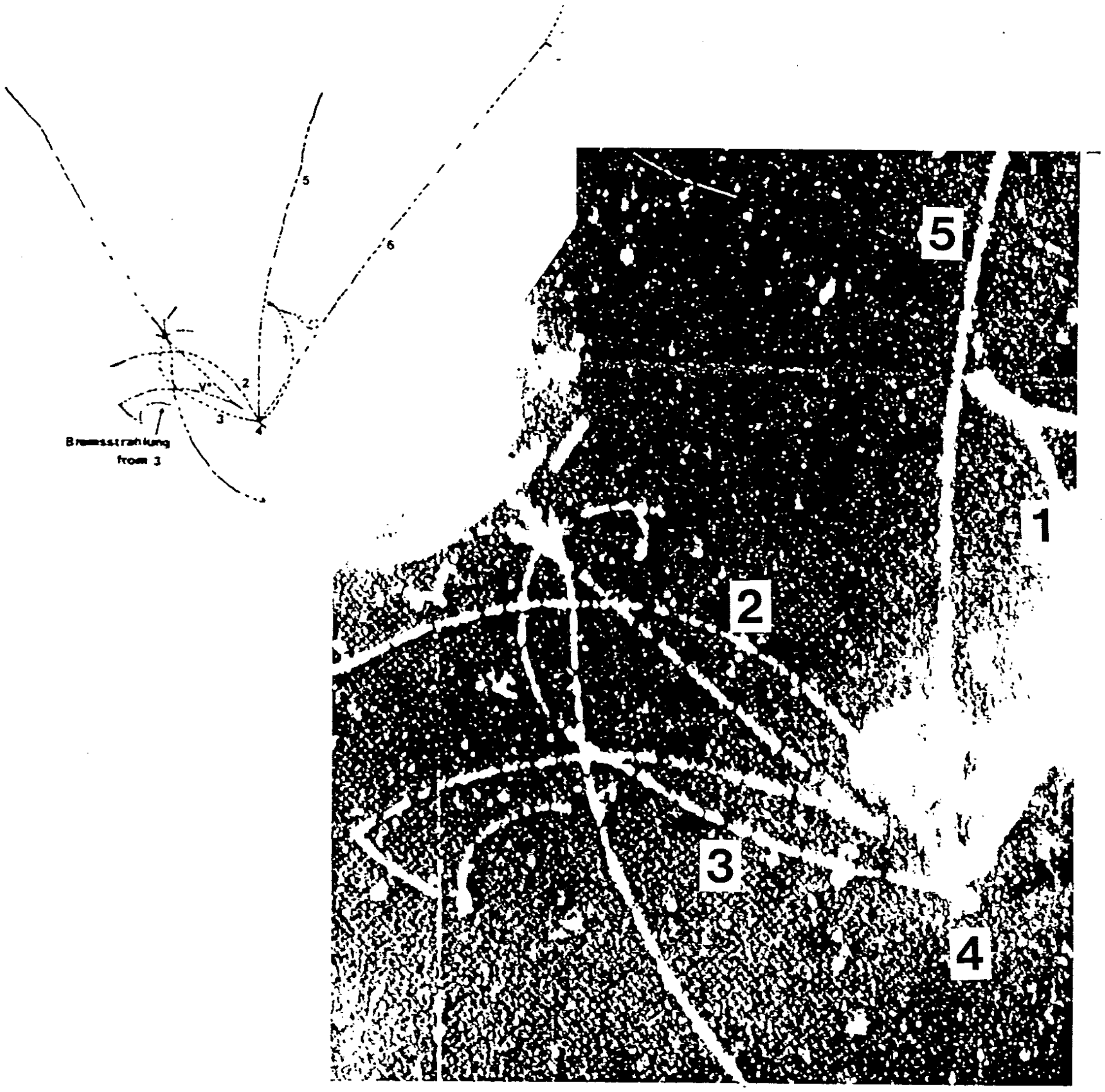
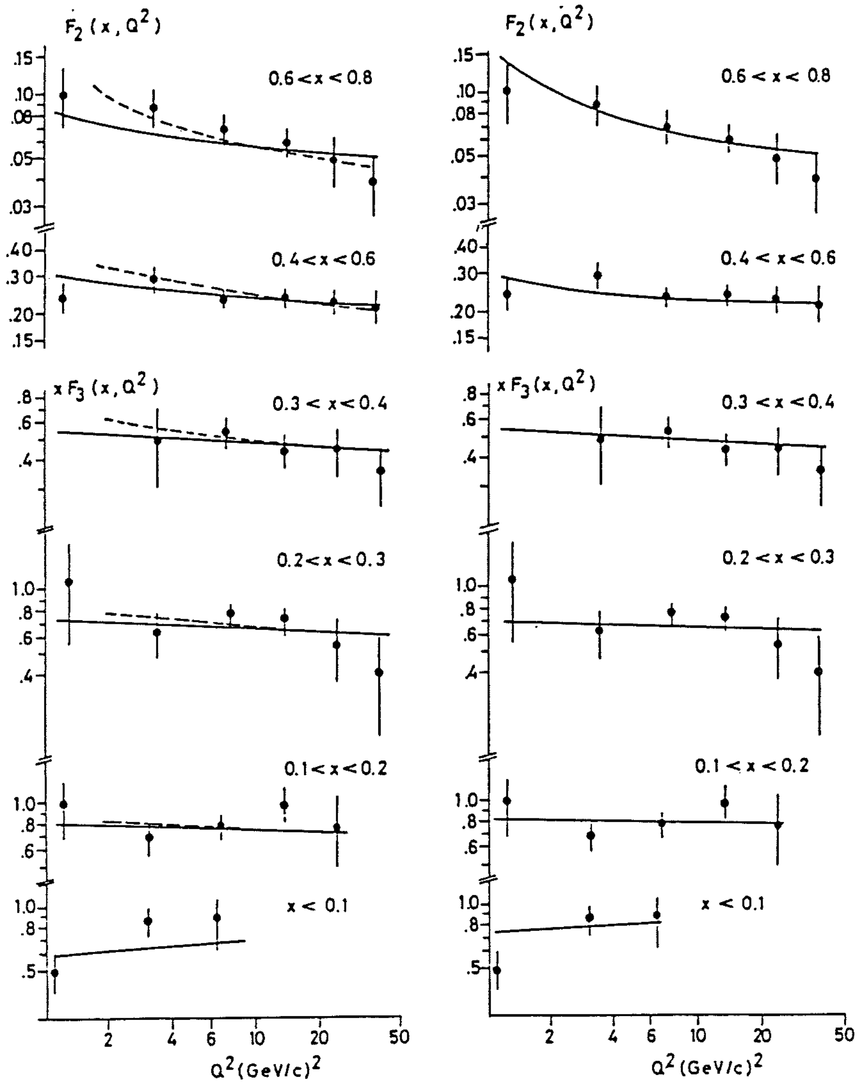
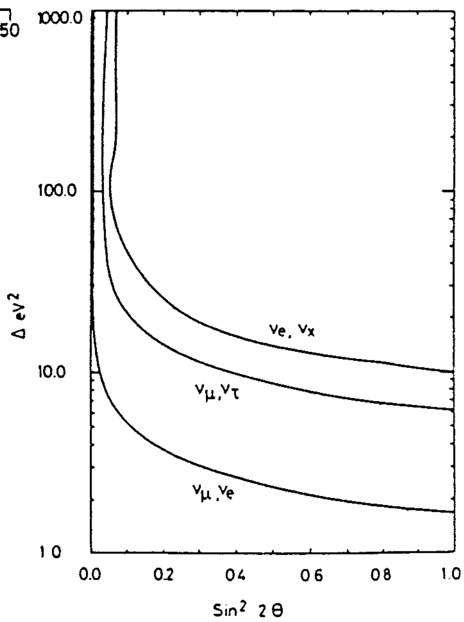


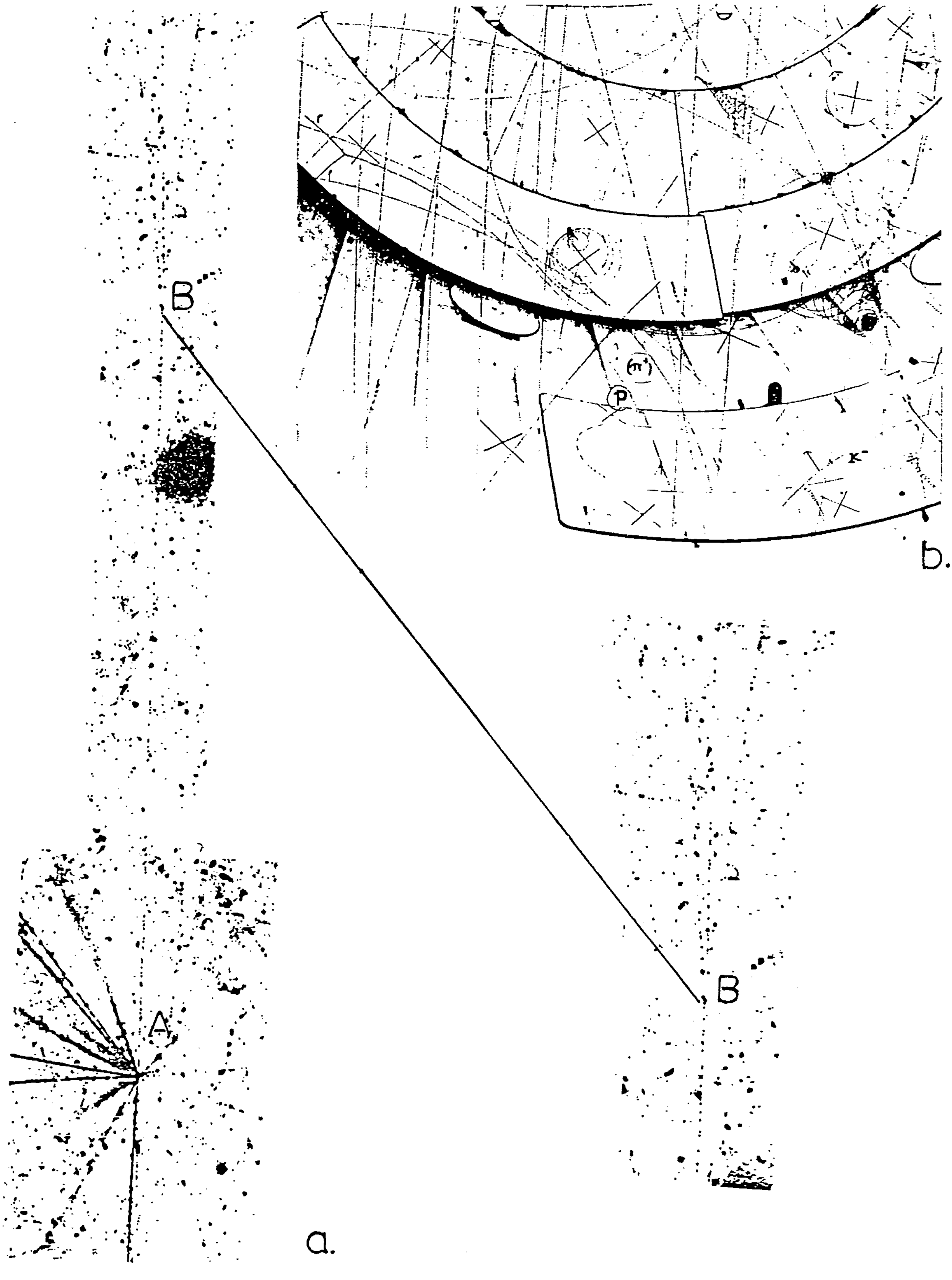
fig.4



$F_2(x, Q^2)$
0.6<x<0.8
0.4<x<0.6
$xF_3(x, Q^2)$
0.3<x<0.4
0.2<x<0.3
0.1<x<0.2
x<0.1
$Q^2 (GeV/c)^2$



ΔeV^2
ν_e, ν_x
ν_μ, ν_τ
ν_μ, ν_e
$Sin^2\ 2\theta$


B
B
A
a.
b.
π^+
p
K^-

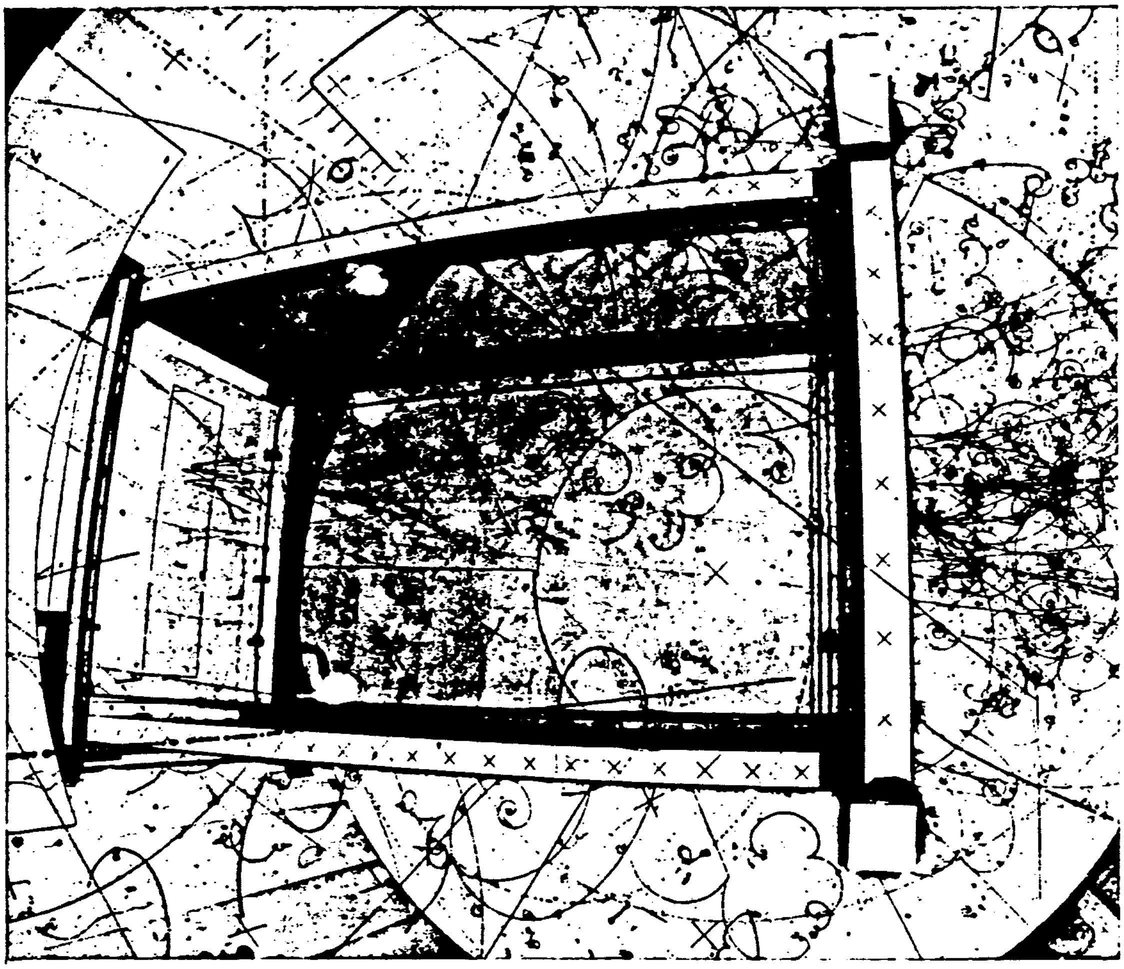
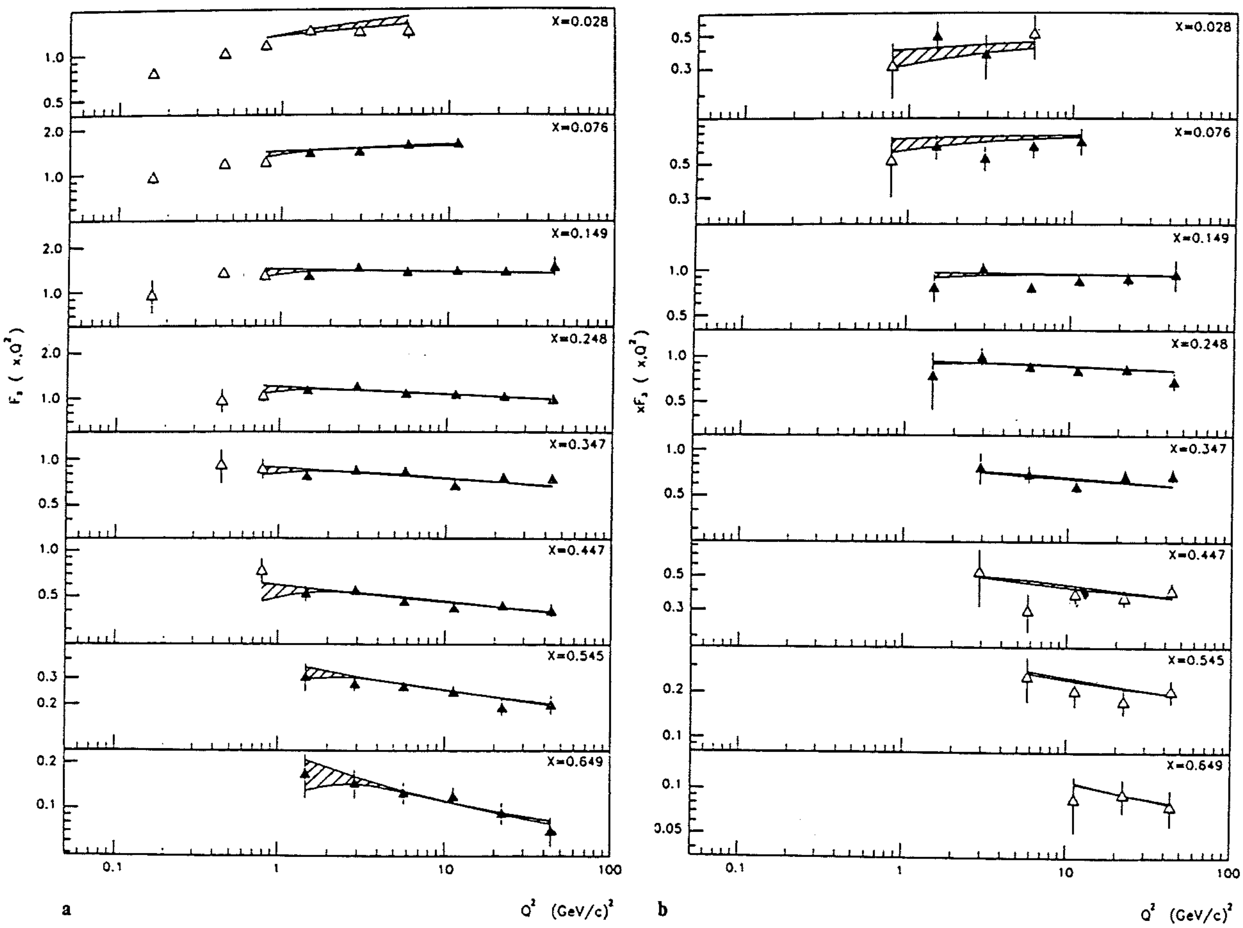
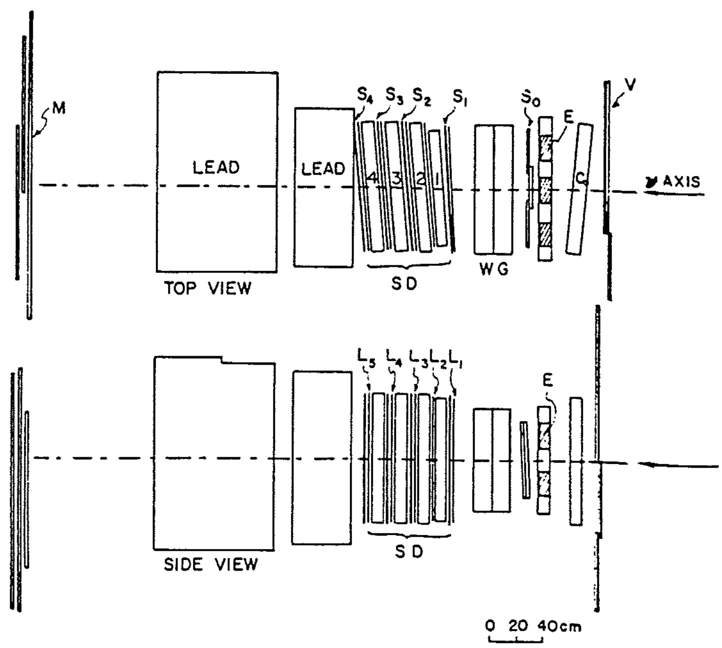


fig.8


X=0.028
X=0.076
X=0.149
X=0.248
X=0.347
X=0.447
X=0.545
X=0.649
F₂ (x,Q²)
xF₃ (x,Q²)
Q² (GeV/c)²
a
b


M
LEAD
LEAD
TOP VIEW
S4 S3 S2 S1
S0
E
V
C
AXIS
SD
WG
SIDE VIEW
L5 L4 L3 L2 L1
E
SD
0 20 40cm

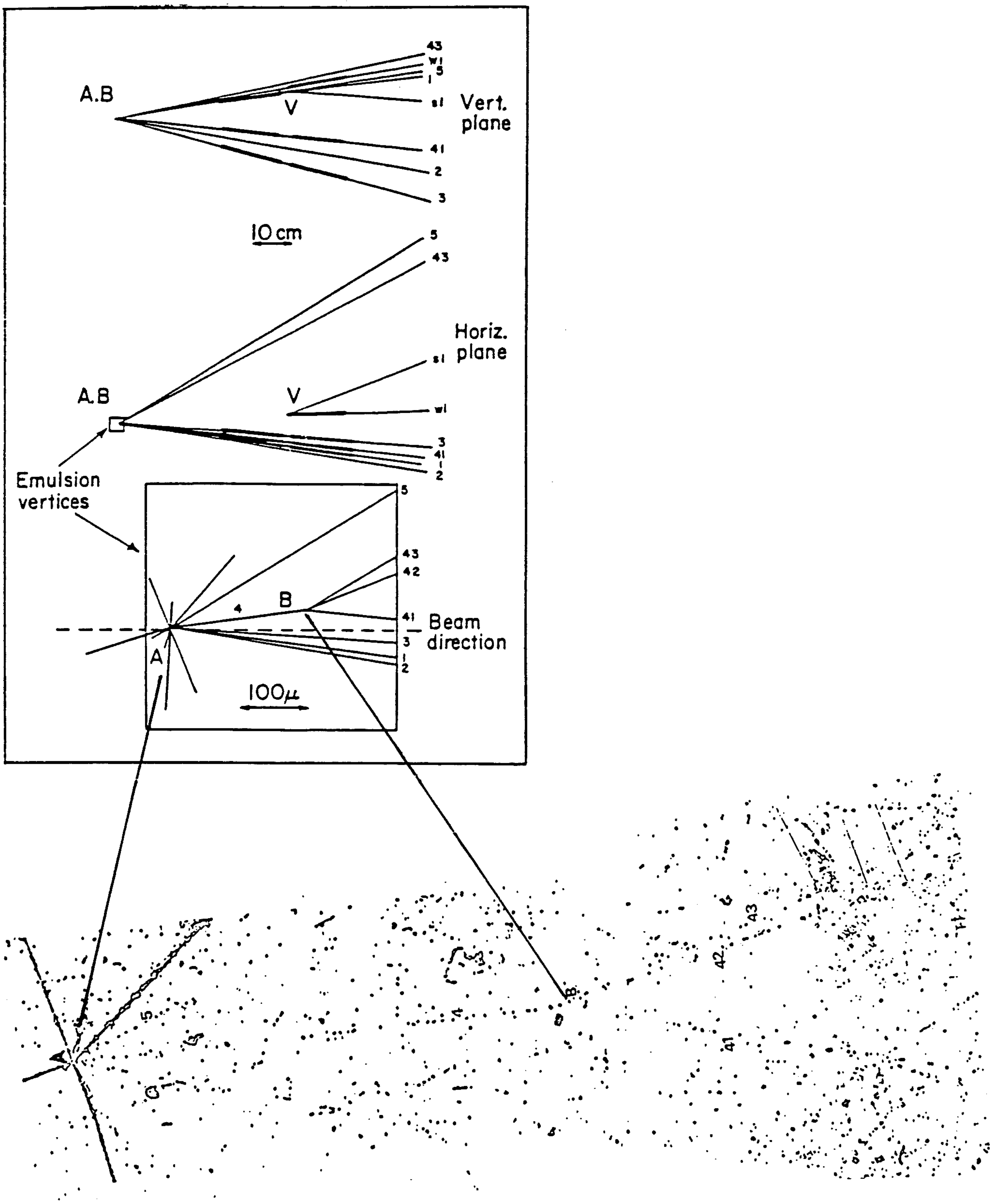
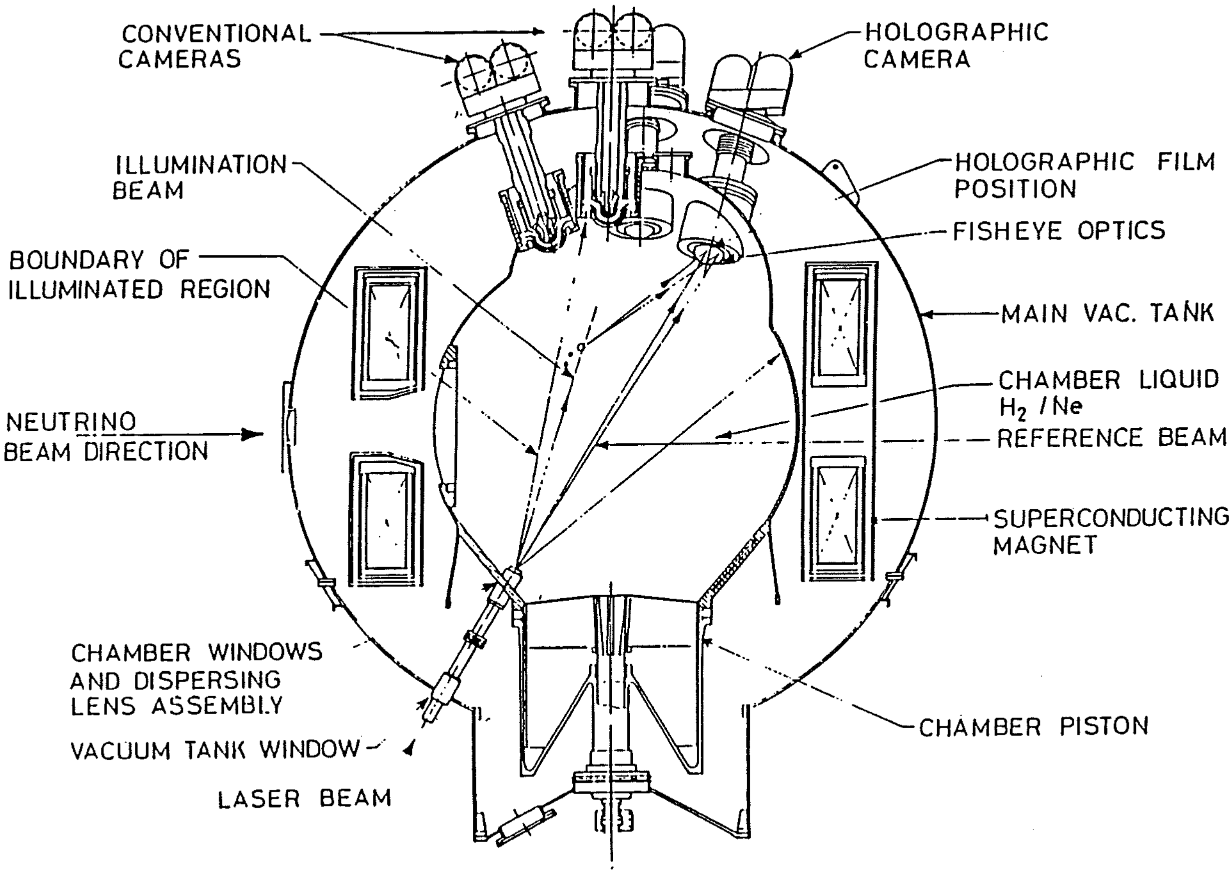

A.B
V
Vert.
plane
43
5
1
41
2
3
10 cm
Horiz.
plane
A.B
V
Emulsion
vertices
5
43
42
4
B
41
Beam
direction
3
1
2
A
100μ

fig.11


CONVENTIONAL
CAMERAS
HOLOGRAPHIC
CAMERA
ILLUMINATION
BEAM
HOLOGRAPHIC FILM
POSITION
FISHEYE OPTICS
BOUNDARY OF
ILLUMINATED REGION
MAIN VAC. TANK
CHAMBER LIQUID
H_2 / Ne
NEUTRINO
BEAM DIRECTION
REFERENCE BEAM
SUPERCONDUCTING
MAGNET
CHAMBER WINDOWS
AND DISPERSING
LENS ASSEMBLY
CHAMBER PISTON
VACUUM TANK WINDOW
LASER BEAM

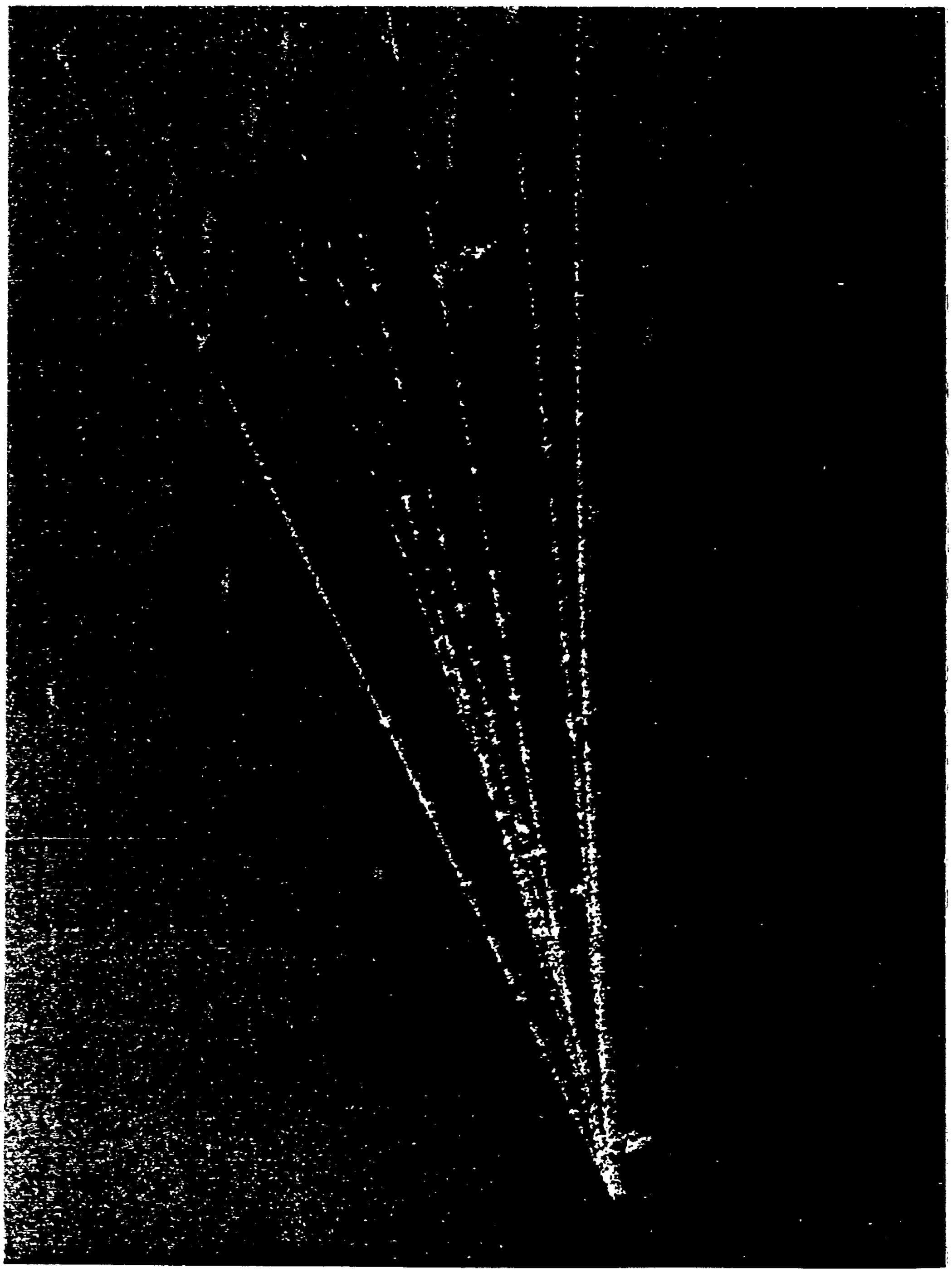


fig.13

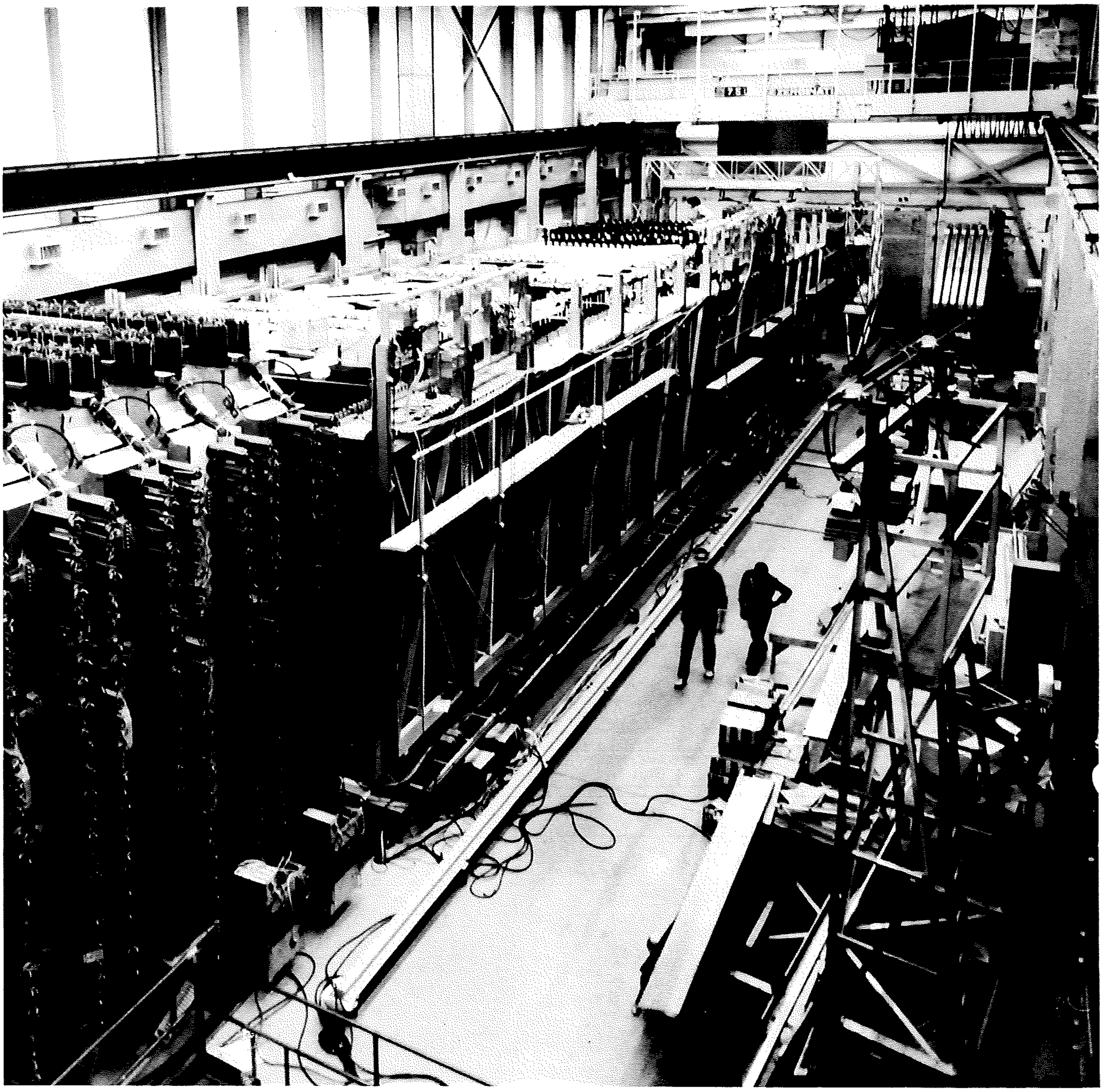


fig.14

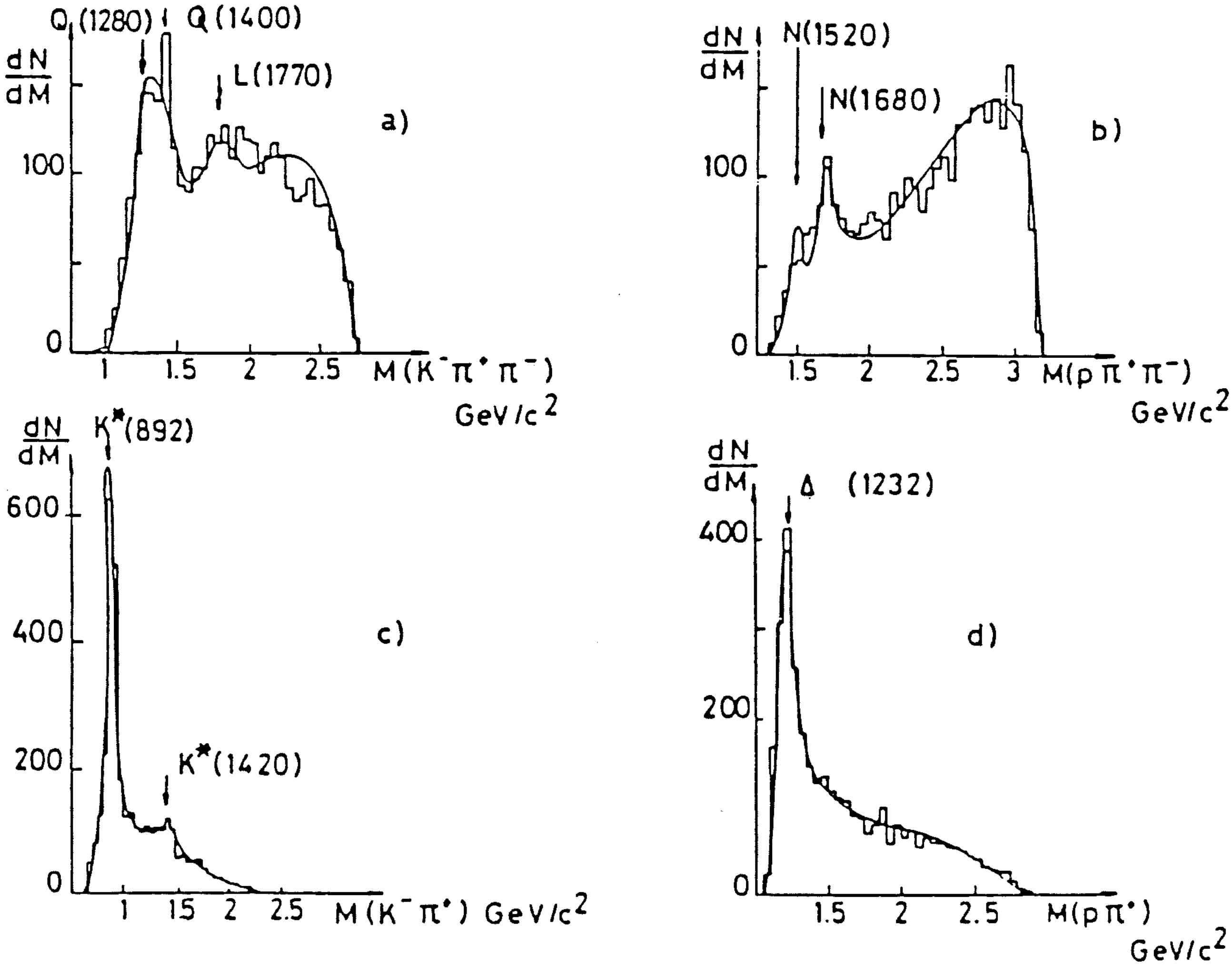
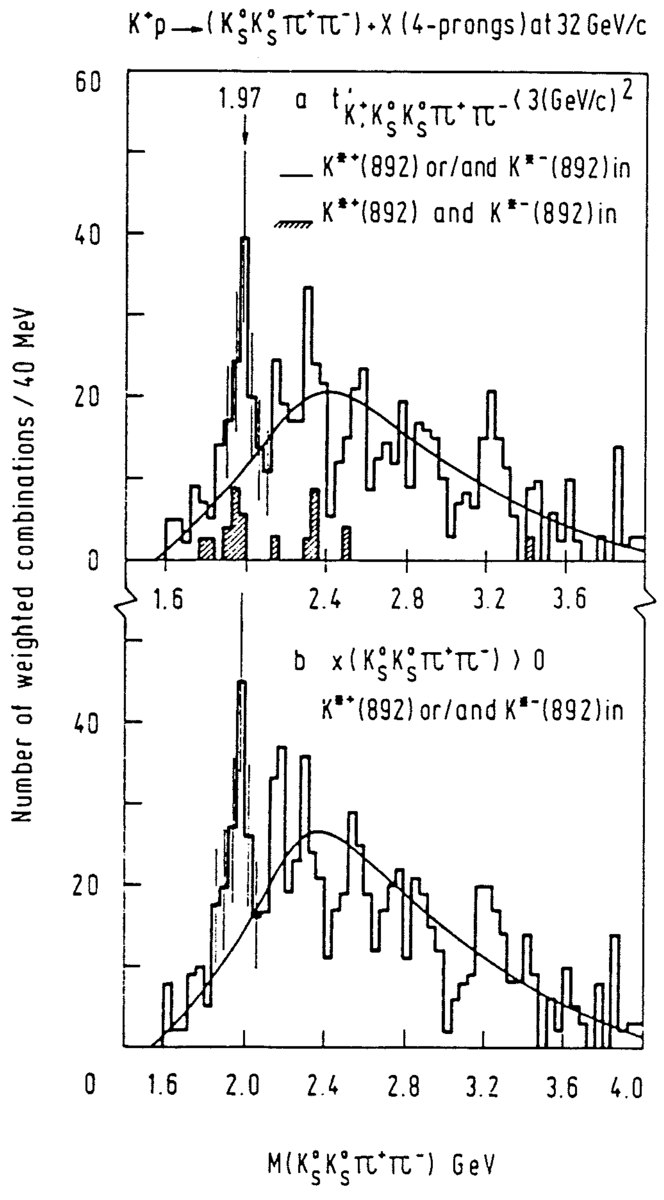

Q (1280)
Q (1400)
L (1770)
dN/dM
100
0
1
1.5
2
2.5
M (K⁻π⁺π⁻)
GeV/c²
a)
N(1520)
N(1680)
dN/dM
100
0
1.5
2
2.5
3
M(pπ⁺π⁻)
GeV/c²
b)
K*(892)
K*(1420)
dN/dM
600
400
200
0
1
1.5
2
2.5
M (K⁻π⁺) GeV/c²
c)
Δ (1232)
dN/dM
400
200
0
1.5
2
2.5
M(pπ⁺)
GeV/c²
d)

fig.15


K⁺p → (K°s K°s π⁺π⁻) + X (4-prongs) at 32 GeV/c
Number of weighted combinations / 40 MeV
1.97
a t'K⁺;K°sK°sπ⁺π⁻ < 3(GeV/c)²
K*⁺(892) or/and K*⁻(892) in
K*⁺(892) and K*⁻(892) in
b x(K°sK°sπ⁺π⁻) > 0
K*⁺(892) or/and K*⁻(892) in
0
20
40
60
1.6
2.0
2.4
2.8
3.2
3.6
4.0
M(K°sK°sπ⁺π⁻) GeV

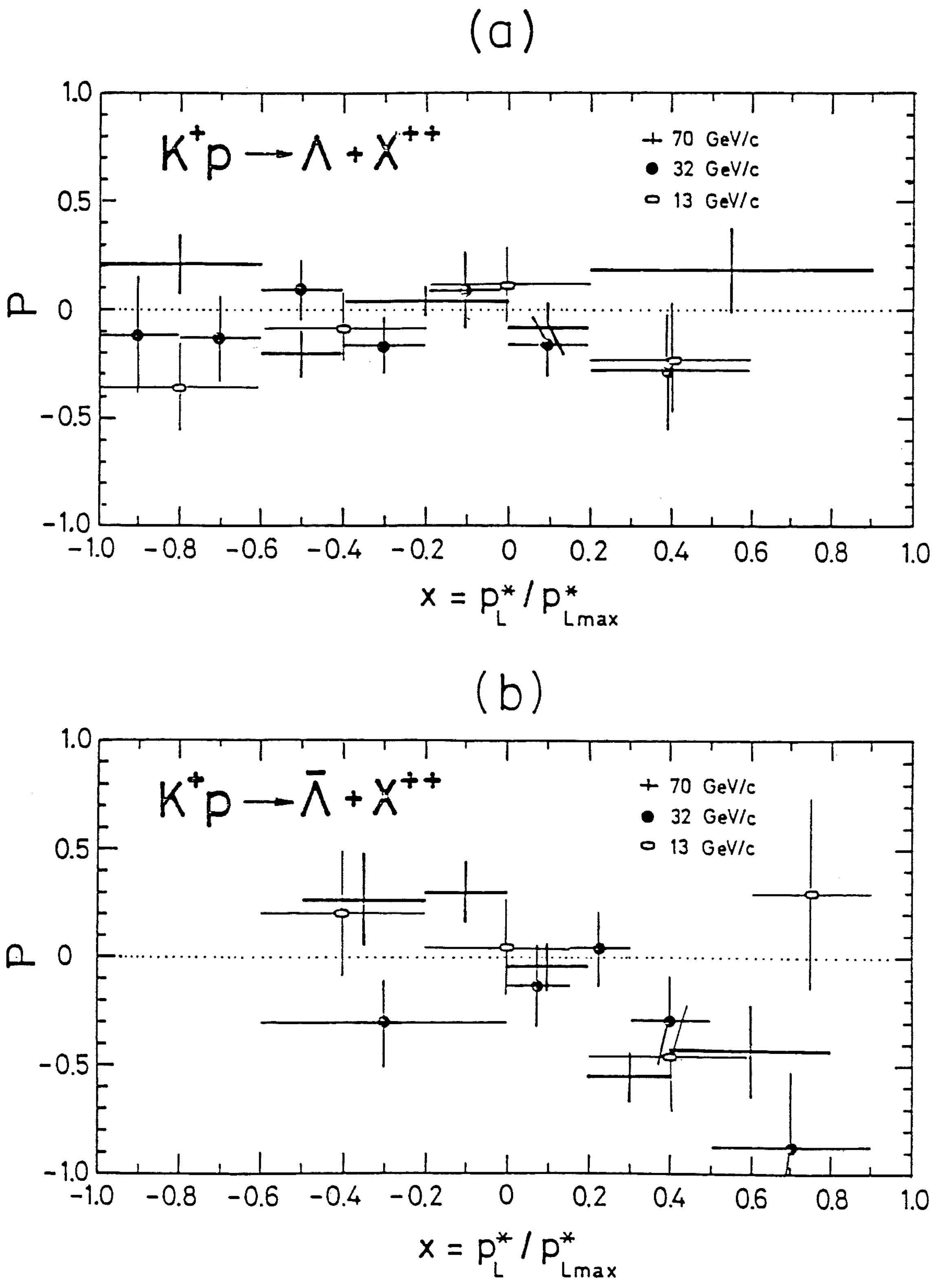
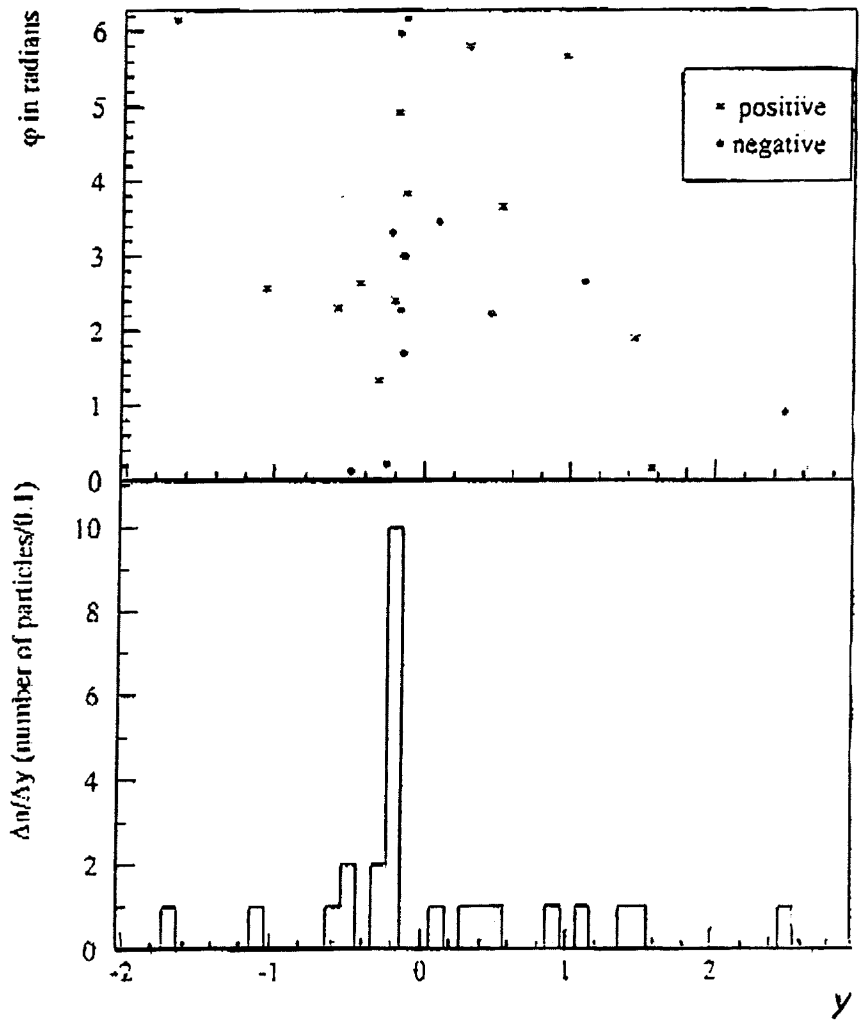
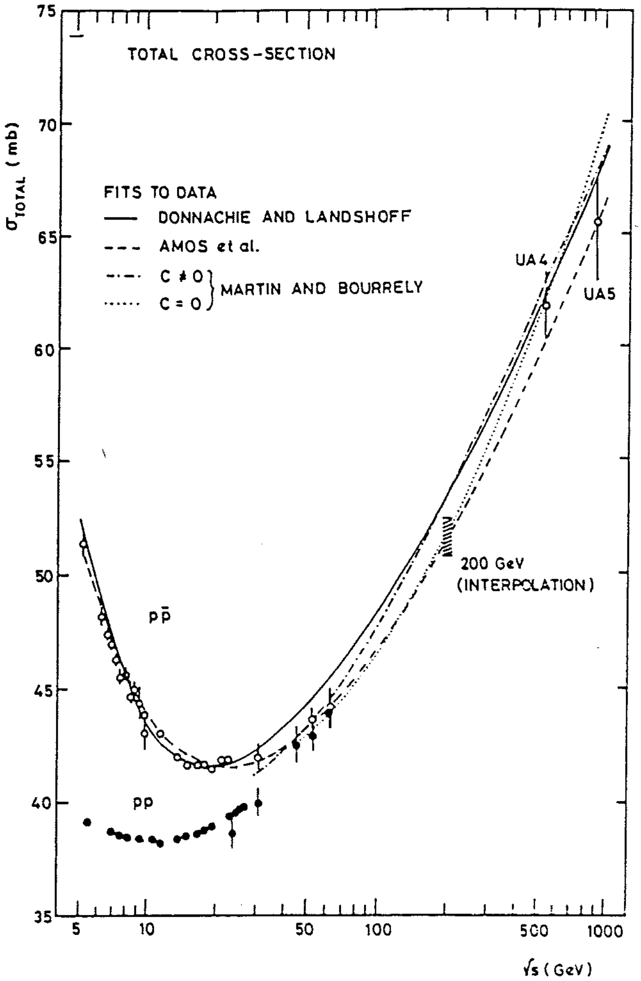

(a)
$K^+p \to \Lambda + X^{++}$
70 GeV/c
32 GeV/c
13 GeV/c
P
$x = p_L^* / p_{Lmax}^*$
(b)
$K^+p \to \bar{\Lambda} + X^{++}$
70 GeV/c
32 GeV/c
13 GeV/c
P
$x = p_L^* / p_{Lmax}^*$

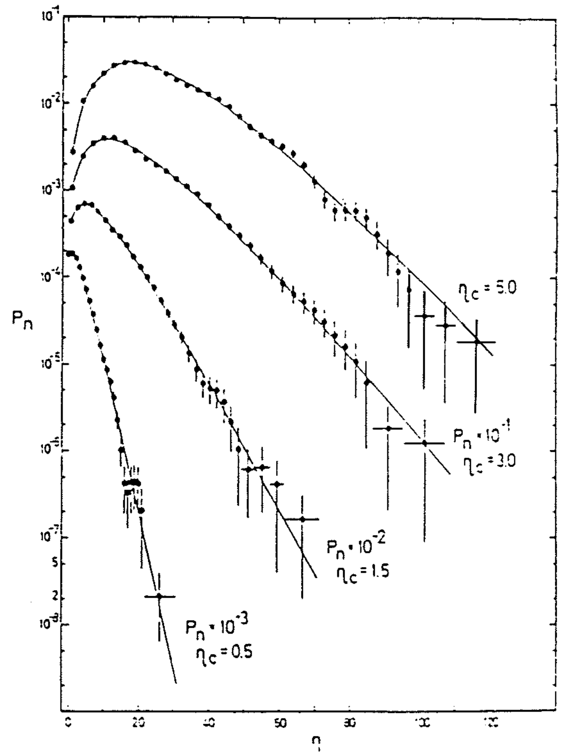
fig.17



φ in radians
6
5
4
3
2
1
0
× positive
• negative
Δn/Δy (number of particles/0.1)
10
8
6
4
2
0
-2
-1
0
1
2
y

fig.19


TOTAL CROSS-SECTION
σTOTAL (mb)
FITS TO DATA
DONNACHIE AND LANDSHOFF
AMOS et al.
C ≠ 0
C = 0
MARTIN AND BOURRELY
UA4
UA5
200 GeV
(INTERPOLATION)
pp̄
pp
√s (GeV)


Pn
ηc = 5.0
Pn · 10⁻¹
ηc = 3.0
Pn · 10⁻²
ηc = 1.5
Pn · 10⁻³
ηc = 0.5
n

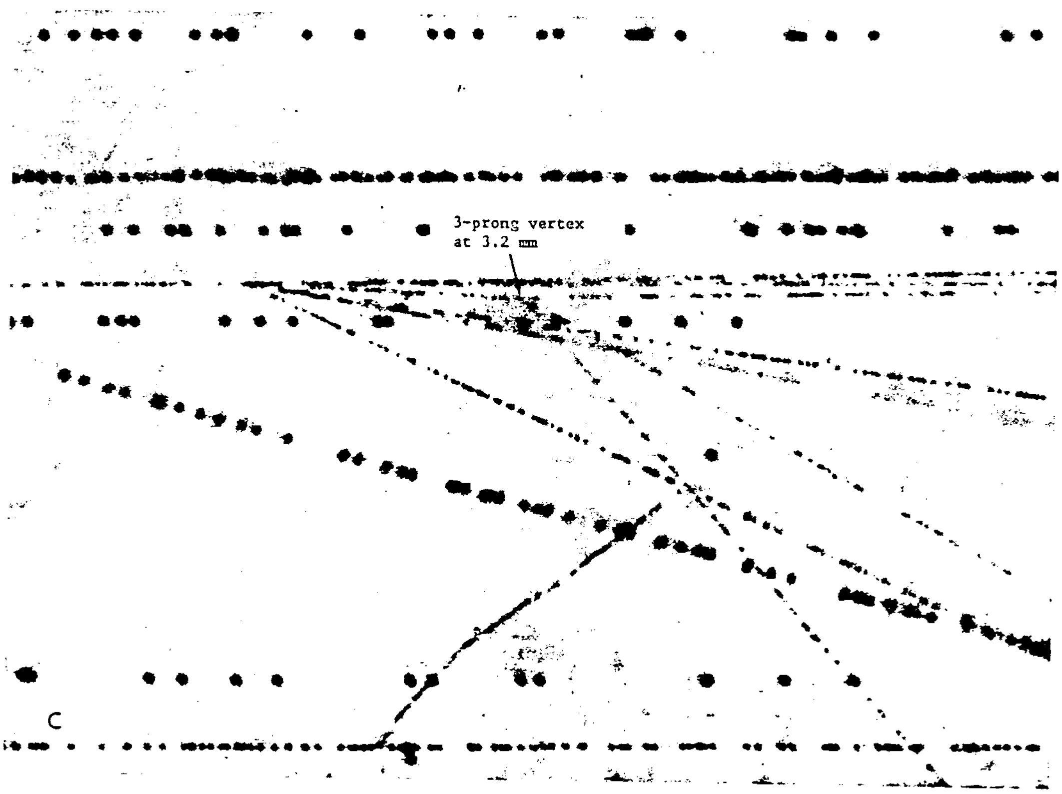
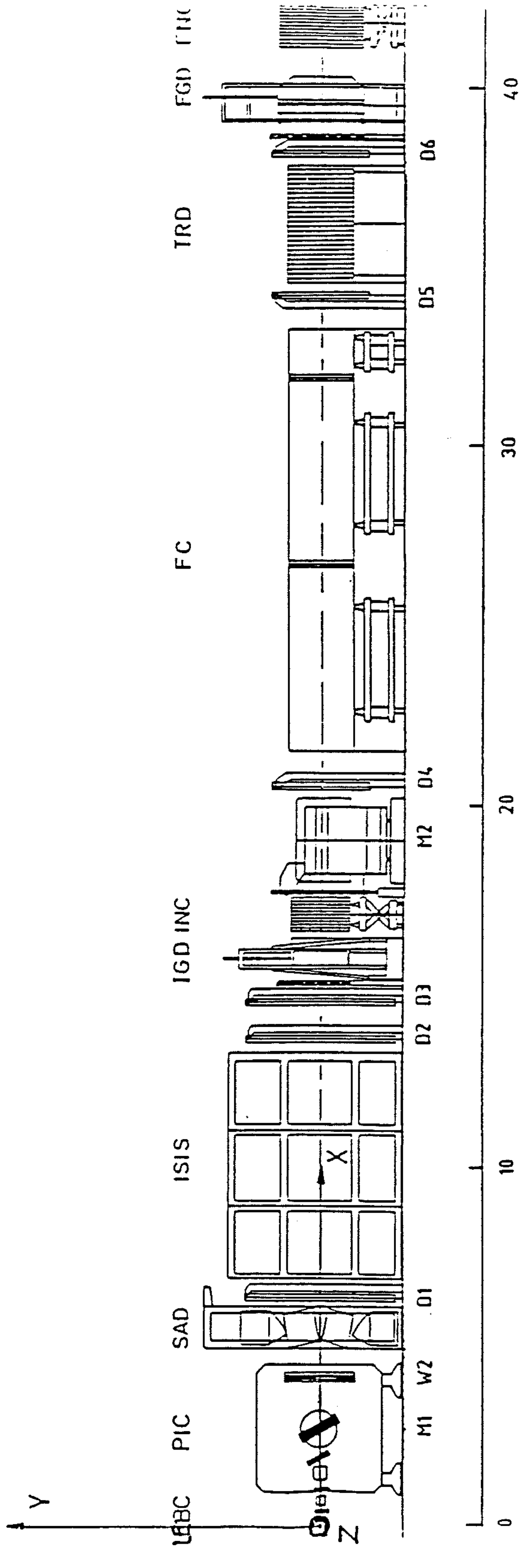
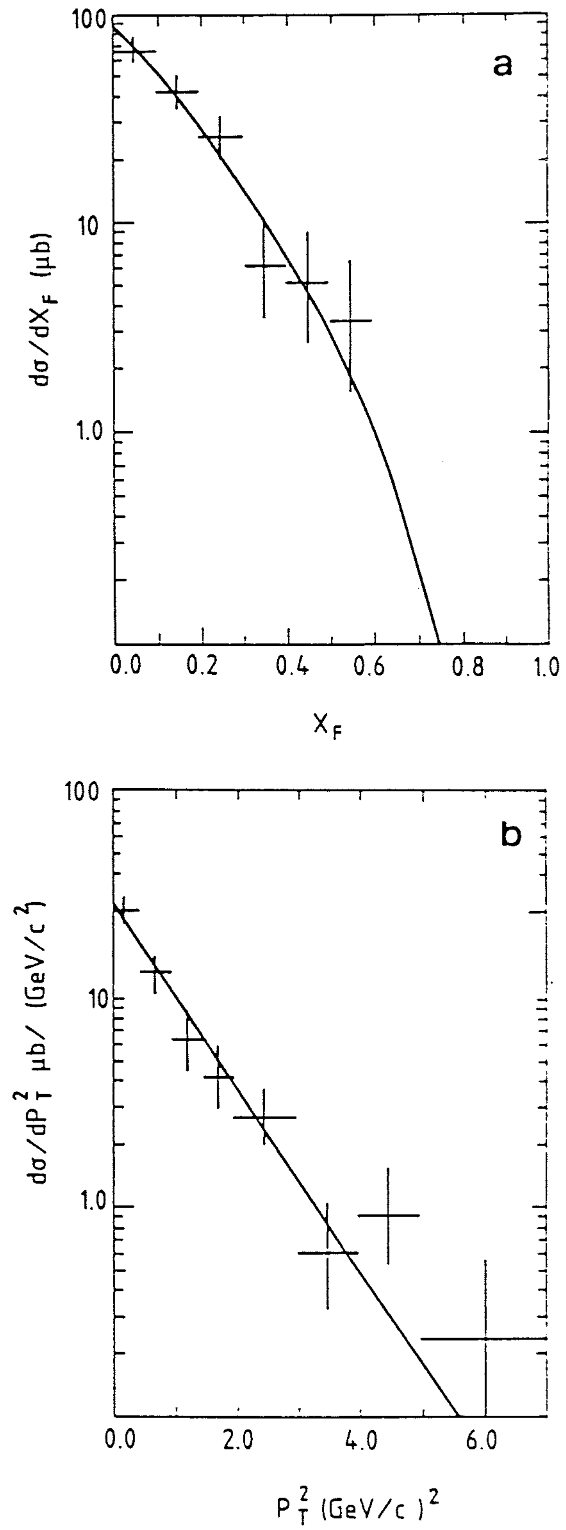


fig.22


FGD
TRD
FC
IGD INC
ISIS
SAD
PIC
LEBC
D1
D2
D3
D4
D5
D6
M1
M2
W2
X
Y
Z
0
10
20
30
40


a
b
dσ/dX_F (μb)
X_F
dσ/dP_T^2 μb/ (GeV/c^2)
P_T^2 (GeV/c)^2
100
10
1.0
0.0
0.2
0.4
0.6
0.8
1.0
2.0
4.0
6.0

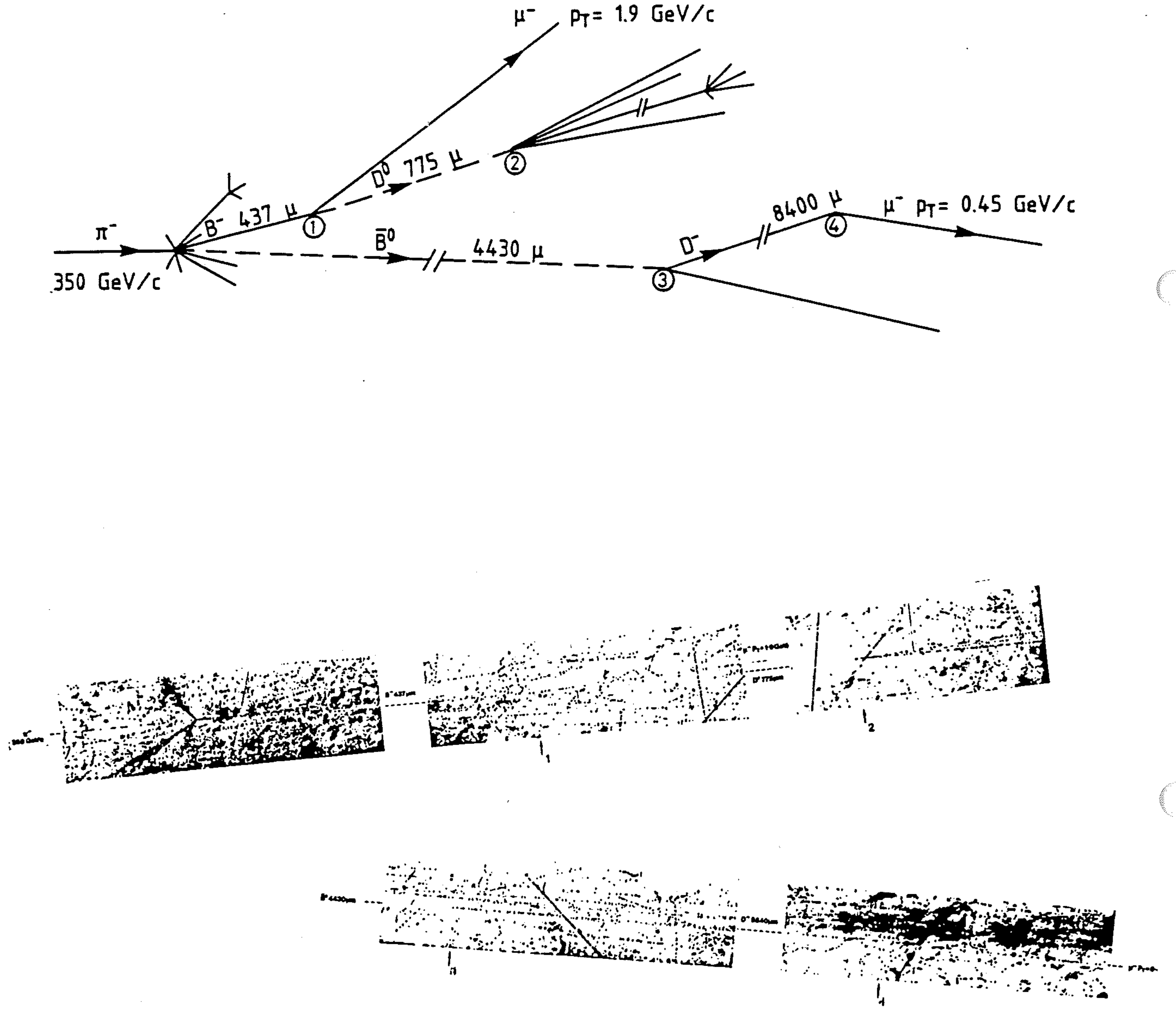
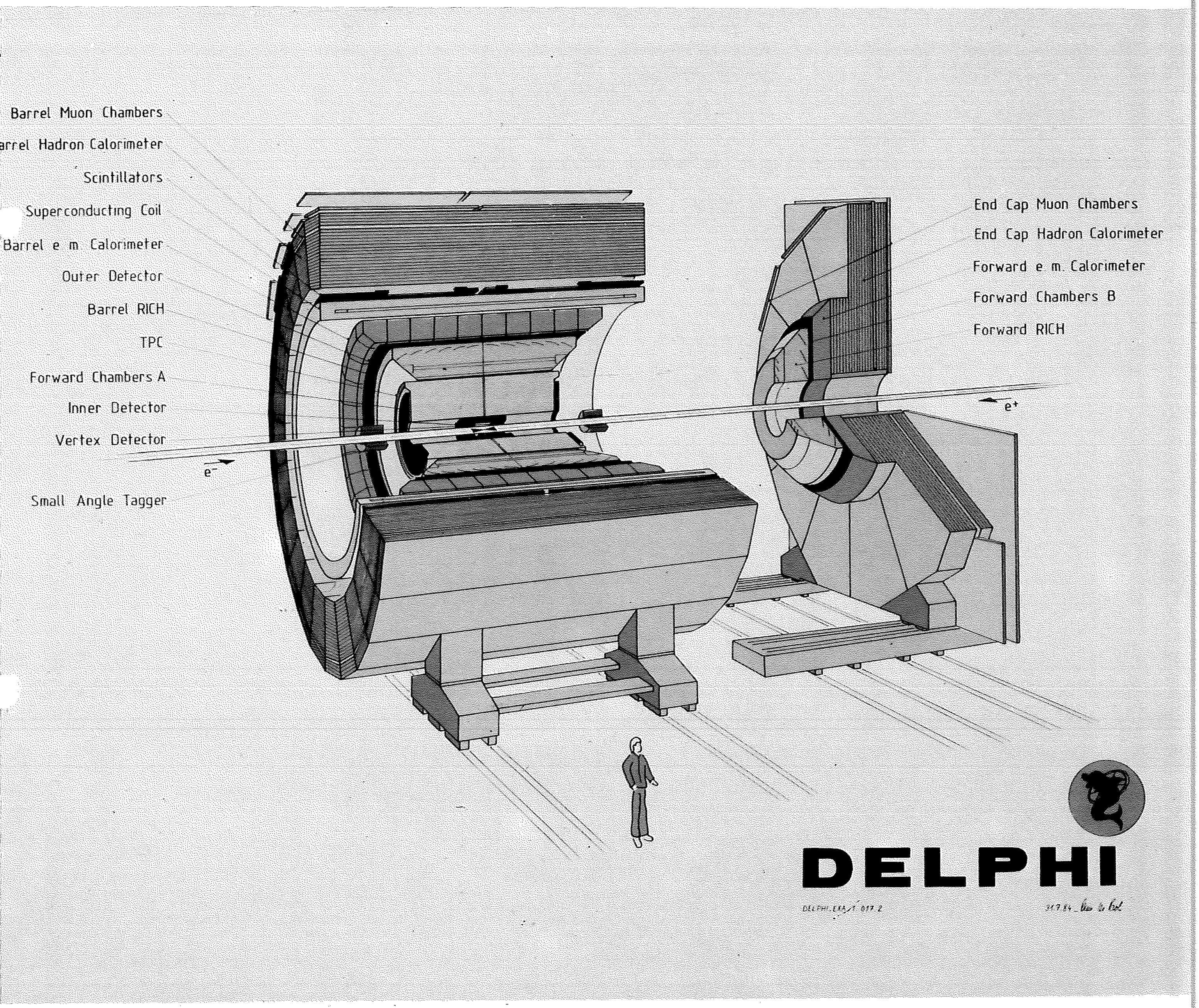

μ⁻ p_T = 1.9 GeV/c
D⁰ 775 μ
②
B⁻ 437 μ
①
π⁻
350 GeV/c
B̄⁰
4430 μ
③
D⁻
8400 μ
④
μ⁻ p_T = 0.45 GeV/c

fig.25



Barrel Muon Chambers
arrel Hadron Calorimeter
Scintillators
Superconducting Coil
Barrel e m. Calorimeter
Outer Detector
Barrel RICH
TPC
Forward Chambers A
Inner Detector
Vertex Detector
e⁻
Small Angle Tagger
End Cap Muon Chambers
End Cap Hadron Calorimeter
Forward e m. Calorimeter
Forward Chambers B
Forward RICH
e⁺
DELPHI

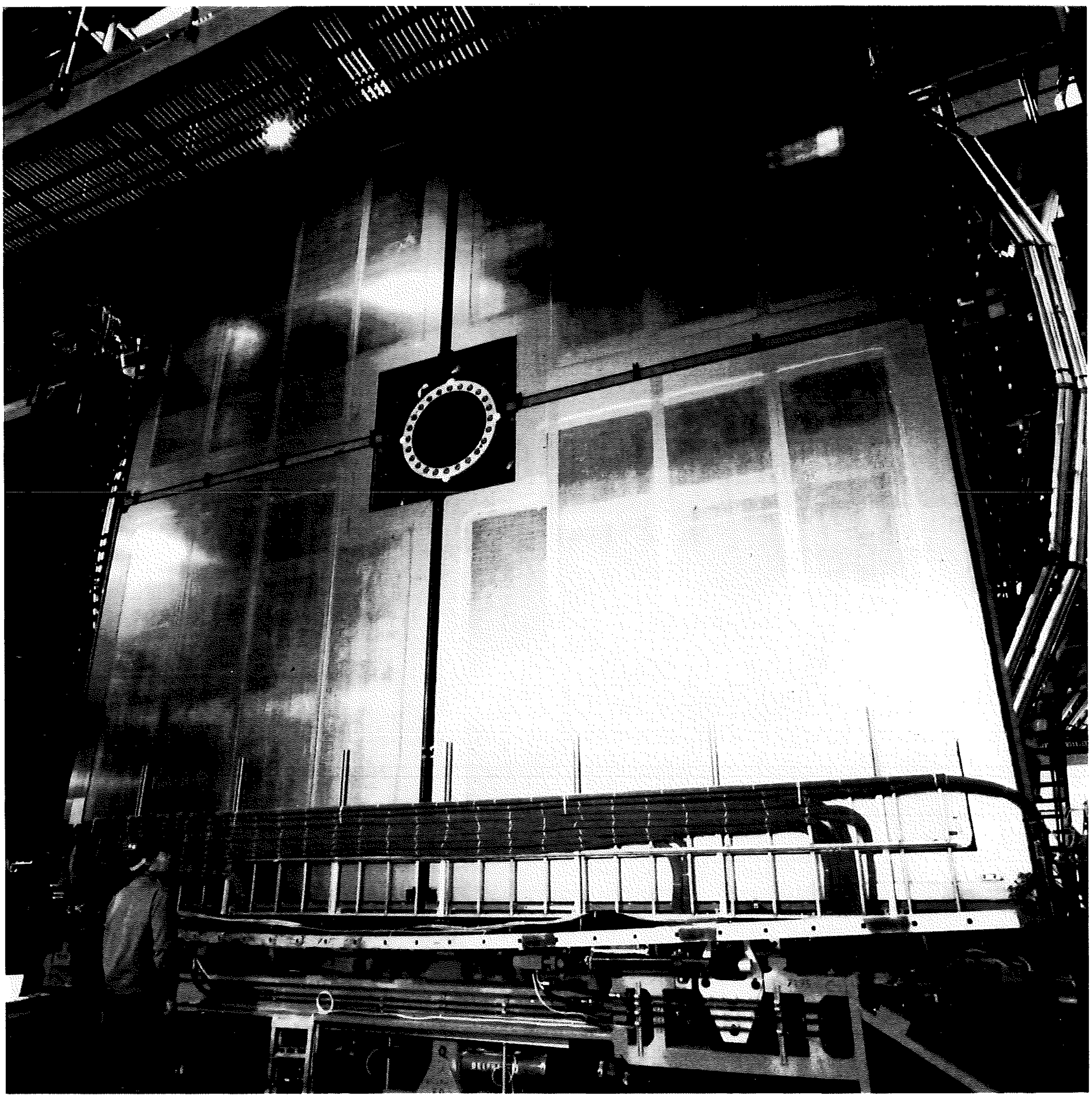


fig.27

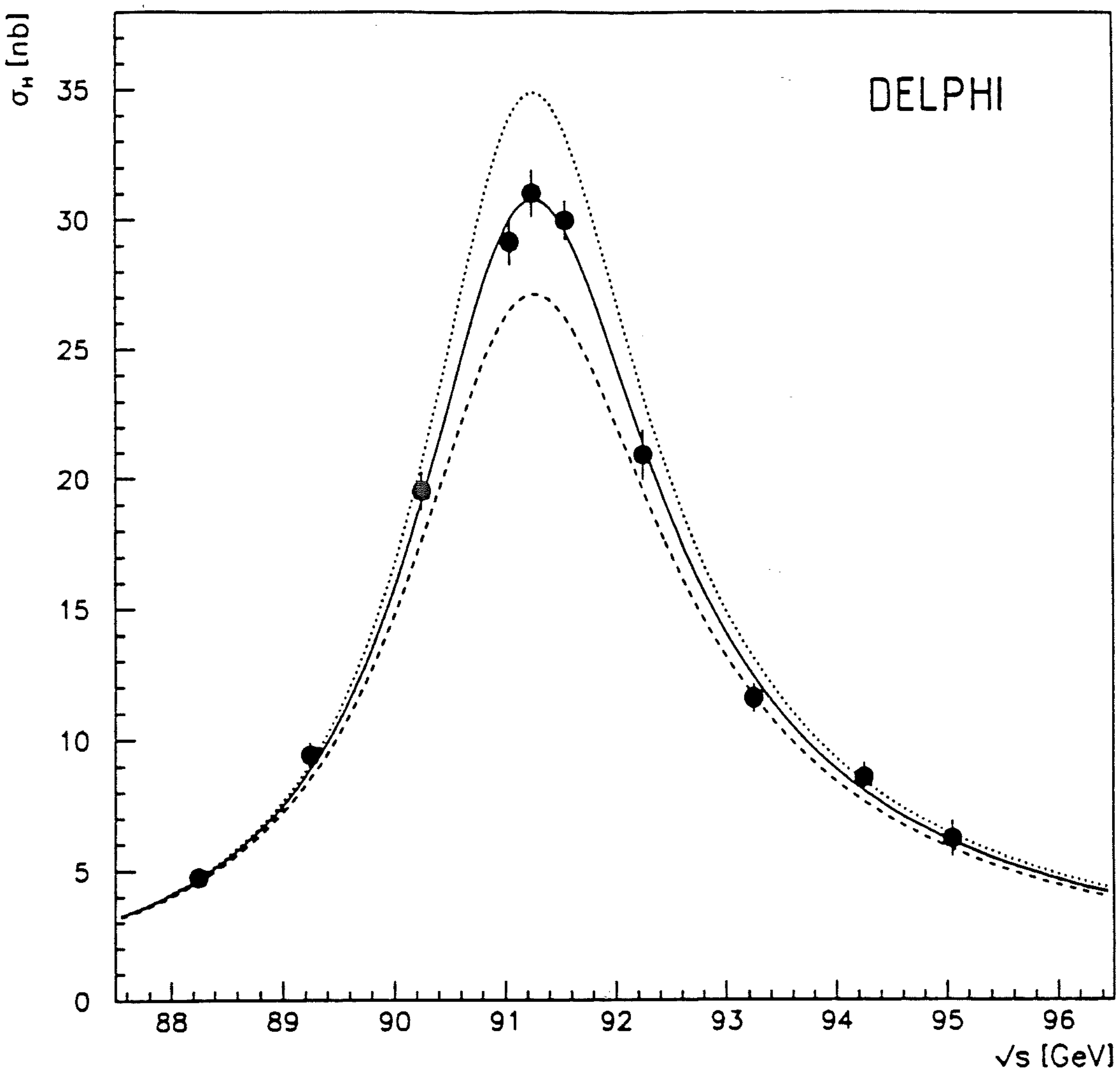


fig.28

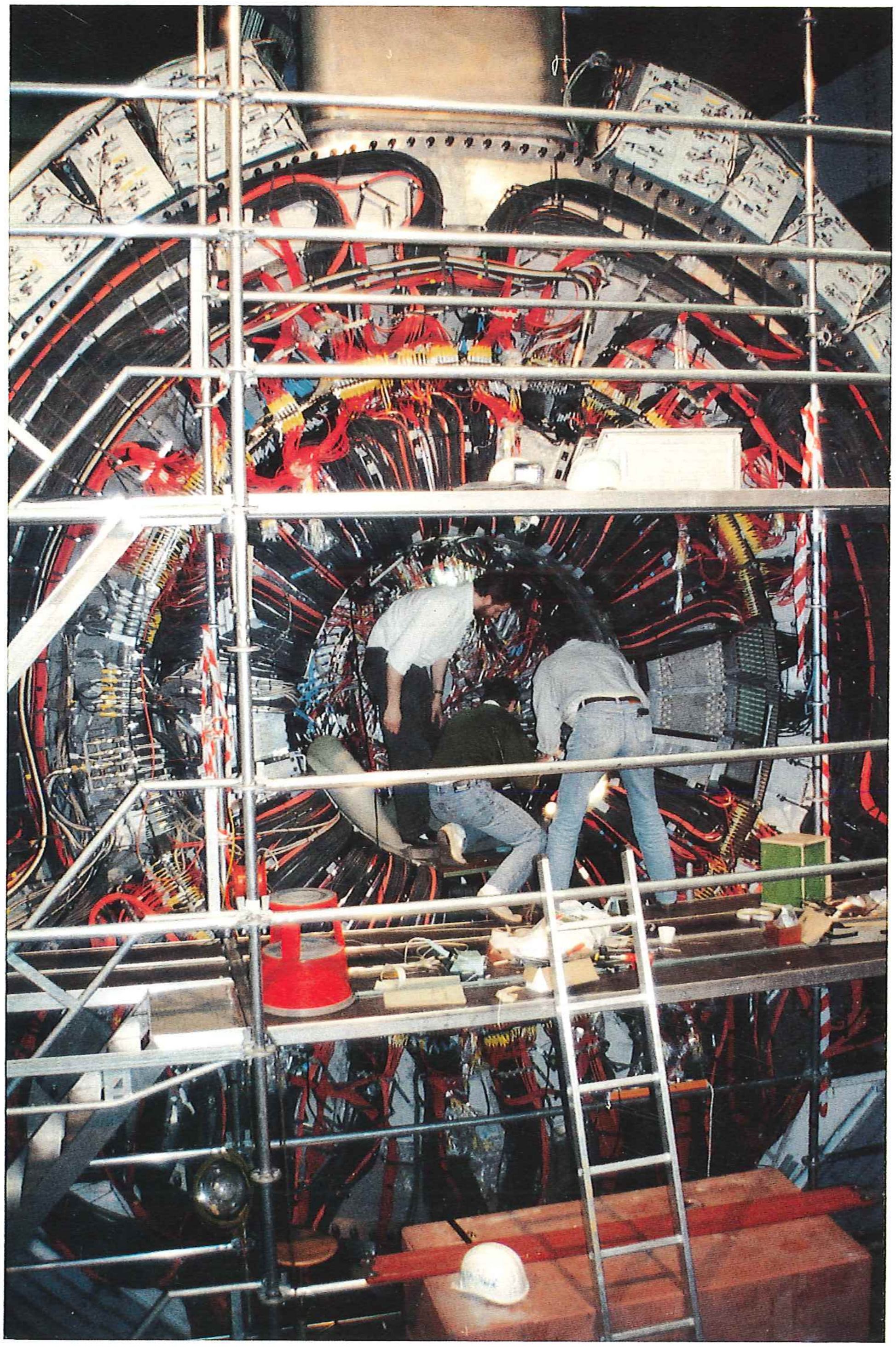
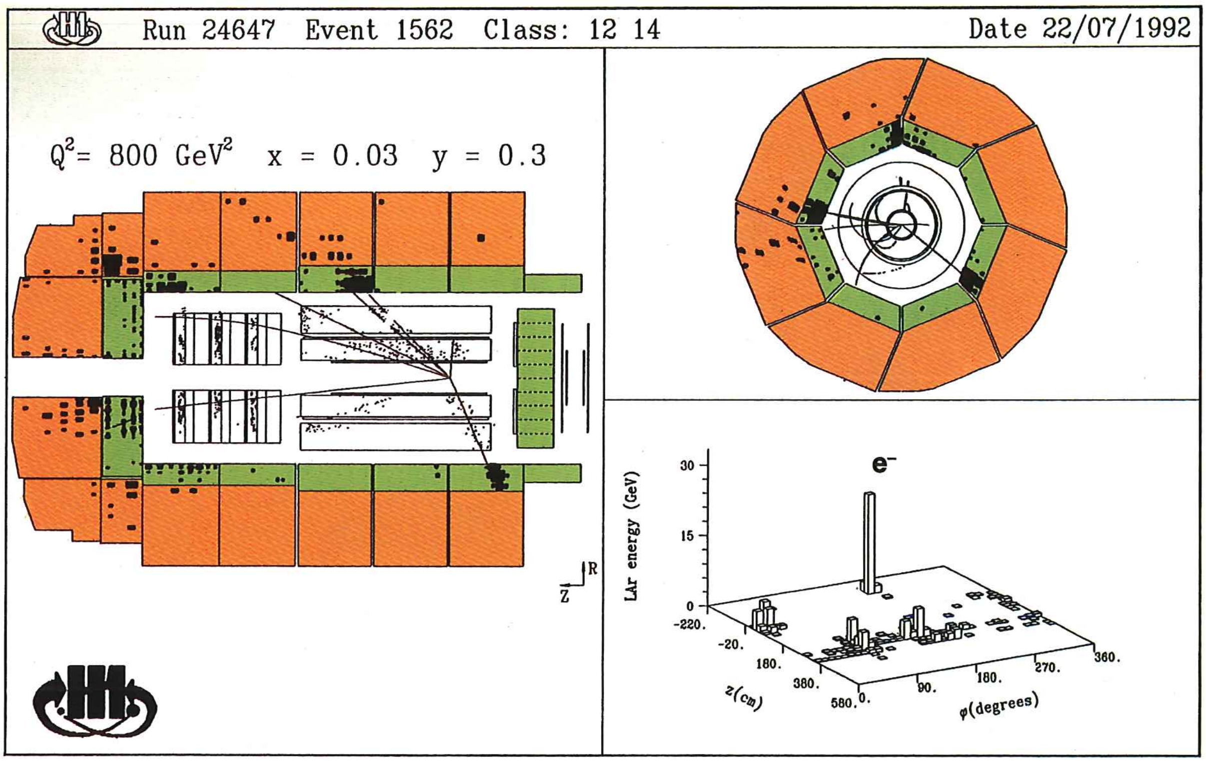


fig.29



Visualisation d´une réaction produite et mesurée dans le détecteur H1. L´électron entre en collision avec un constituant du proton; il est dévié vers le bas à droite sur la vue longitudinale ci-dessus. L´énergie et la direction de l´électron diffusé, du jet issu du quark frappé, et des autres particules émises, sont mesurées dans le calorimètre.

DELPHI INTERACTION SCHEME

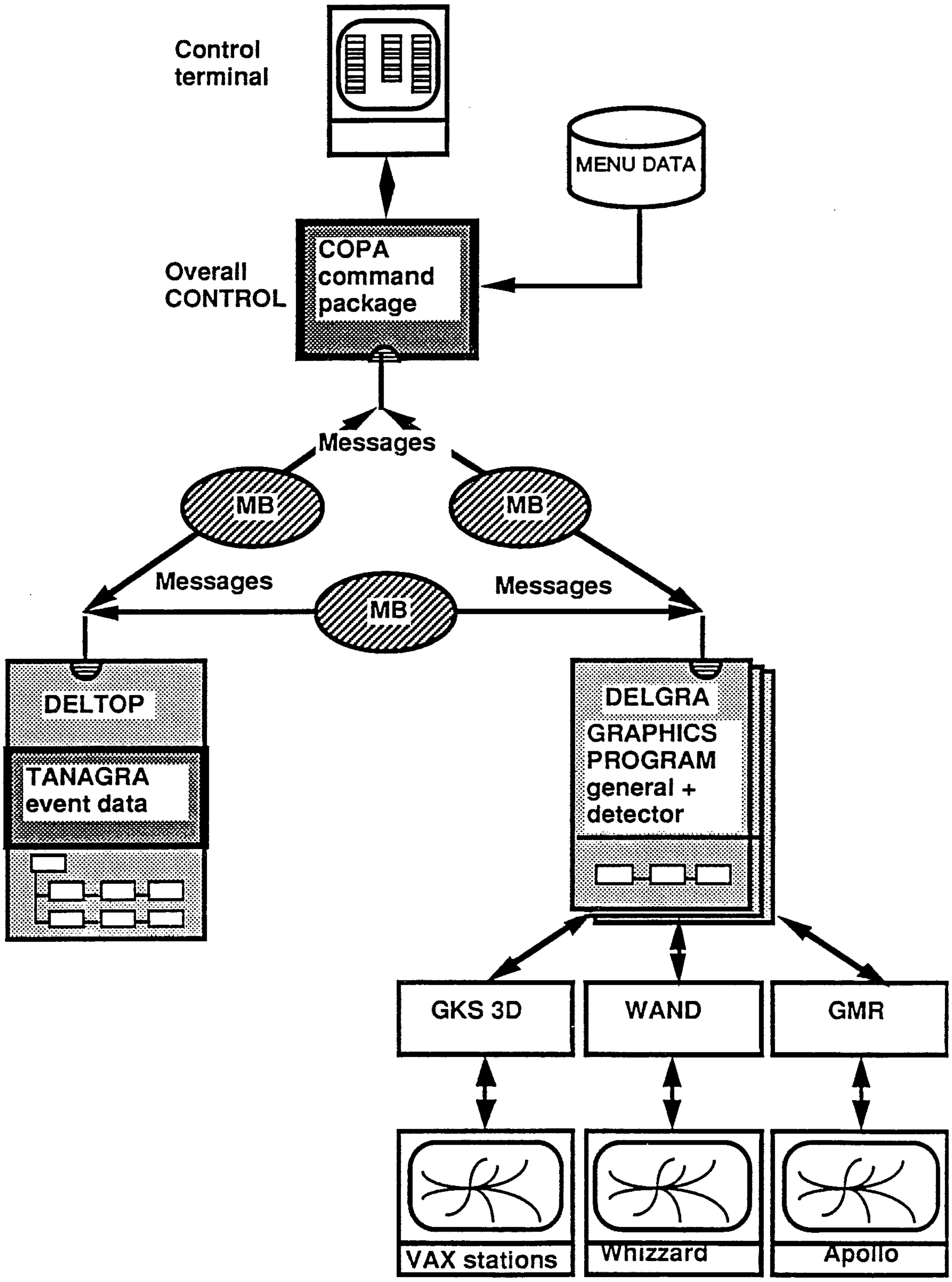


fig.31

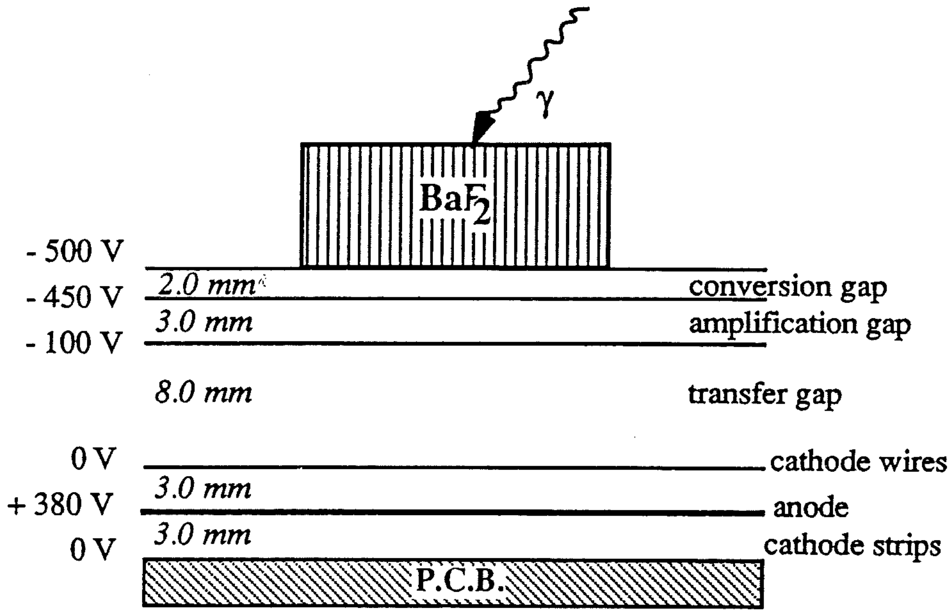

γ
BaF_2
- 500 V
- 450 V
- 100 V
0 V
+ 380 V
0 V
2.0 mm
3.0 mm
8.0 mm
3.0 mm
3.0 mm
conversion gap
amplification gap
transfer gap
cathode wires
anode
cathode strips
P.C.B.

fig.32

APPENDIX A

APPENDIX A

PERSONNEL OF THE IIHE

I. SCIENTIFIC PERSONNEL HAVING PARTICIPATED IN THE ACTIVITIES OF THE IIHE DURING THE PERIOD 1972-1992

HIGH ENERGY PHYSICS

ULB
BARTH, M. (maître de recherche FNRS)
BEILLIERE, P. (chercheur CNRS) *
BERTRAND, D. (chercheur qualifié FNRS)
BERTRAND-COREMANS, G. (chef de travaux)
DE JODE, M. (boursier IRSIA) *
DEWIT , M. (boursier IRSIA, aspirant FNRS, chercheur IISN) *
DUMONT, J.J. (chercheur IISN) *
FAVART, L. (boursier IRSIA)
GRUWE, M. (boursier IRSIA)
HEUGHEBAERT, J. (chercheur IISN) *
HUET, Ph. (boursier IRSIA, aspirant FNRS)
KIELCZEWSKA, D. (chercheur IISN) *
MARAGE, P. (chef de travaux)
MULKENS, H. (chercheur IISN) *
SACTON, J. (professeur ordinaire)
SCHOROCHOFF, G. (coopération Université du Zaïre) *
SHAMS EL DIN, N. (stagiaire Egypte) *
STICHELBAUT, F. (boursier IRSIA, collaborateur FNRS)
TYMIENIECKA, T. (chercheur IISN) *
VILAIN, P. (chercheur qualifié FNRS)
VAN BINST, P. (professeur ordinaire)
VANDER VELDE, C. (ch. de cours ass.)
WILQUET, G. (chercheur qualifié FNRS)
WICKENS, J. (chercheur IISN)
WILLOCQ, S. (doctorant) *

VUB
CAO FANG (VUBAROS-beurs)
COBBAERT, H. (vorser IIKW) *
DE CLERCQ, C. (logistiek medewerker IIKW)
DE VOS, E. (assistent) *
DE WINTER, K. (assistent) *
DEJONGH, G. (vorser IIKW) *
EVRARD, E. (vorser IIKW)
GEIREGAT, D. (vorser IIKW) *

(*) No longer at the I.I.H.E.

GIJSEN, M. (vorser IIKW) *
GOOSSENS, M. (vorser IIKW) *
HEIREMANS, T. (vorser IIKW)
JOHNSON, D. (vorser IIKW, VESALIUS College)
KLUIT, P. (vorser IIKW)*
LEMONNE, J. (gewoon hoogleraar)
MEYNAERTS, J. (vorser IIKW) *
MOMMAERT, C. (vorser IIKW)
MOREELS, J. (aangesteld navorser NFWO)
PEETERS, P. (eerst aanwezend assistent, werkleider) *
RENTON, P. (vorser IIKW) *
ROOSEN, R. (bevoegdverklaard navorser NFWO)
TAVERNIER, S. (bevoegdverklaard navorser NFWO)
THEOCHAROPOULOS, T. (vorser IIKW) *
VAN DONINCK, W. (bevoegdverklaard navorser NFWO)
VAN ESCH, P. (vorser IIKW)
VAN HAMME, L. (vorser IIKW, aspirant NFWO) *
VANDENBOUCKE, R. (logistiek medewerker IIKW)
VONCK, B. (vorser IIKW) *
WULLEMAN, J. (assistent OZR)
VANHOMWEGEN, G. (vorser IIKW) *

UIA
BREUSERS M. (vorser IIKW) *
BUYTAERT, J. (vorser IIKW) *
CHARLET M. (vorser IIKW) *
DE BOECK, H. (vorser IIKW)
DE BRABANDERE S. (vorser IIKW)
DE ROECK A. (vorser IIKW) *
DE WOLF, E. (bevoegdverklaard navorser NFWO)
GAUDAEN, J. (vorser IIKW) *
MICHALOWSKA, B. (beurshouder) *
TOMARADZE, A. (beurshouder)
VAN IMMERSEEL, M. (vorser IIKW) *
VAN MECHELEN, P. (vorser IIKW)
VANDENBOGAERT, F. (vorser IIKW) *
VERBEURE, F. (gewoon hoogleraar)
VERLUYTEN, L. (vorser IIKW) *

HELIOS-B PROJECT

ULB
ALEXANDRE, F. (chercheur sous contrat)
COHEN, A. (assistant)
COLIN, M. (chercheur sous contrat)
GUILLEN LAZO, A. (boursier)
HANON, C. (assistant de recherche) *
MAES, D. (assistant de recherche)
MALISSE, P. (chercheur sous contrat) *
MANNIE (E. (chercheur sous contrat)
MASSART, T. (assistant de recherche) *

(*) No longer at the I.I.H.E.

MRABET, R. (chercheur sous contrat)
NAJMABADI KIA, R. (chercheur sous contrat)
NGUYEN, T.A. (chercheur sous contrat)
PARIDAENS, O. (chercheur sous contrat)
PARIDANS, P. (chercheur sous contrat)
SALES, B. (assistant de recherche)
SATTARI SADAT, R. (chercheur sous contrat)
VAN BINST, P. (professeur Ordinaire)
VERBERGT, J.M. (chercheur sous contrat)

VUB
CEKRO, Z. (vorser op kontrakt)
MEULEMANS, N. (vorser op kontrakt,)
VANDENBROUCKE, R. (logistiek medewerker IIKW)

POSITRON EMISSION TOMOGRAPHY

VUB
BRUYNDONCKX, P. (beurshouder IWONL)
GOLDBERG, M. (sabathical grant NFWO)
GUERARD, B. (E.G. beurs) *
TAVERNIER, S. (onderzoeksdirecteur, NFWO)
ZHANG S. (rectorale beurs)

II. ADMINISTRATIVE AND TECHNICAL PERSONNEL (as on 31/12/1992)

ULB
CASTERA, J.; DE SCHUTTER, M.; DELASORTE, M.; DEPIESSE, G.; DEWULF, J.P.; ETIENNE, L.; FRANCHOMME, S.; GARNIER, M.; GINDROZ, R.; LIESEN, J.; PEYMANS, D.; PINS, M.; PINS, R.; ROUSSEAU, G.; RUIDANT, R.; VAN BEEK, G.; VANDERHAEGEN, R.; VINCENT, G.;

VUB
ALLUYN, R.; CARLIER, C.; DE BRUYNE, J.; DE COSTER, A.; DE NIL, H.; GOEMAN, M.; GOORENS, R.; LIEVENS, E.; PIRNAY, D.; RASPOET, E.; VAN LANCKER, L.; VANBEGIN, J.; WASTIELS, C.;

(*) No longer at the I.I.H.E.

APPENDIX B

APPENDIX B

LIST OF EXPERIMENTS IN WHICH THE IIHE HAS PARTICIPATED DURING THE PERIOD 1972-1992

(the year of approval is mentioned in brackets)

CERN-GARGAMELLE/PS (1971)
A bubble chamber experiment to study high energy neutrino and antineutrino interactions in heavy freon (CF_3Br)
Collaboration : Aachen, IIHE Brussels, CERN, E.P. Paris, Milano, L.A.L. Orsay U.C. London

SERPUKHOV/MIRABELLE (1971)
Study of K^+p interactions at 32 GeV/c incident momentum
Collaboration : France - Soviet Union and CERN Soviet Union

ARGONNE NATIONAL LABORATORY (1972)
Study of 4.5 GeV/c K^--interactions in the ANL 30 inch deuterium filled bubble chamber
IIHE Brussels

RUTHERFORD APPLETON LABORATORY (1973)
K^-p interactions at low energy in a hydrogen filled TST surrounded by a H_2-Ne mixture
Collaboration : Birmingham, IIHE Brussels, Durham, U.C. London, Warsaw

ARGONNE NATIONAL LABORATORY (1973)
A study of 6.5 GeV/c K^--interactions in the ANL 12-ft hydrogen bubble chamber
Collaboration : ANL, IIHE Brussels, Kansas, Michigan, Tufts-Boston

SERPUKHOV/MIRABELLE (1973)
Study of $\bar{p}p$ interactions at 32 GeV/c incident momentum
Collaboration : France - Soviet Union and CERN - Soviet Union

CERN GARGAMELLE/PS (1974)
High energy ν and $\bar{\nu}$-nucleon interactions in propane-freon mixture
Collaboration : Aachen, IIHE Brussels, Bergen, Strasbourg, U.C. London

CERN T243 (1975)
Study of $\bar{p}p$ interactions at 12 GeV/c in BEBC
Collaboration : IIHE Brussels, CERN, I.C. London, Mons, Orsay

FERMILAB E247 (1976)
Exposure of a hybrid nuclear emulsion counter set-up to a wide band neutrino beam
Collaboration : U.K. London, FNAL, IIHE-Brussels, U.C. Dublin, CERN, I.C. London, Open University Milton, Mulhouse, INFN/Roma, Strasbourg

CERN WA17 (1976)
Search for new short-lived particles produced in neutrino interactions in an emulsion stack coupled to BEBC
Collaboration : YEFAM (Ankara, Adana, Istanbul) Turkey, IIHE Brussels, CERN, Dublin Univ. College, London UCL, Milton-Keynes Open Univ. Pisa INFN, Rome INFN, Turin Univ.

CERN WA24 (1976)
High energy neutrino and antineutrino interactions using a hydrogen TST in BEBC
Collaboration : Bari, Birmingham, IIHE Brussels, UCL London, Ecole Polytechnique Palaiseau, Rutherford Appleton Lab, CEN DPhPE Saclay

CERN WA27 (1976)
K^+p interactions in BEBC at 70 GeV/c
Collaboration : IIHE Brussels, CERN, Genoa INFN, Mons, Nijmegen, IHEP Serpukhov

CERN WA31 (1976)
The study of prompt lepton production in antiproton-proton interactions at 70 GeV/c in BEBC equipped with a track sensitive target
Collaboration : IIHE Brussels, Helsinki, Liverpool, Mons, Stockholm

CERN WA15 (1977)
A wide band beam antineutrino experiment in Gargamelle to study purely leptonic and other rare $\bar{\nu}$ interactions
Collaboration : Aachen, Bergen, IIHE Brussels, Strasbourg, U.C. London

CERN WA43 (1977)
Observation of an excess of ν_e $\bar{\nu}_e$ events in a beam dump experiment at 400 GeV in Gargamelle
Collaboration : Aachen TH, Univ. Bari, Univ. Bergen, IIHE Brussels, CERN, UCL London, INFN/Milan, LAL Orsay, Ecole Polytechnique Palaiseau, Univ. Strasbourg

CERN WA53 (1978)
A second generation beam dump experiment in Gargamelle
Collaboration : TH Aachen, Univ. Bari, Univ. Bergen, IIHE Brussels, CERN, UCL London, INFN/Milan, LAL Orsay, Ecole Polytechnique Palaiseau, Univ. Strasbourg

CERN NA13 (1978)
Search for direct evidence for charm in hadronic interactions using a high resolution bubble chamber
Collaboration : IIHE Brussels, CERN, Univ. Oxford, INFN/Padova, INFN/Rome, Rutherford Appleton Lab., Trieste/INFN

CERN WA59 (1979)
Measurement of nucleon structure functions in horn focused neutrino and antineutrino beams in BEBC filled with neon
Collaboration : Athens Demokritos, Bari, Birmingham, IIHE Brussels, CERN, Imperial College London, UC London, MPI Munich, Oxford, Ecole Polytechnique Palaiseau, Rutherford Appleton Lab., CERN, DPhPE Saclay.

CERN NA16 (1979)
Study of the hadronic production and the properties of new particles with a lifetime 10^{-13} *s* $< \tau < 10^{-10}$ *s using LEBC-EHS*
Collaboration : NIKHEF Amsterdam, IIHE Brussels, CERN, CIEMAT Madrid, Poly. Mons, Nijmegen, Univ. Oxford, INFN/Padova, Univ VI Paris, INFN/Rome, Rutherford Appleton Lab., IHEP Serpukhov, Univ. Stockholm, Univ. Strasbourg, Univ. Turin, INFN/Trieste, Östr. Akad. Wissensch. Vienna

CERN NA19 (1979)
Direct observation of beauty particles selected by muonic decay in emulsion
Collaboration : Bari, IIHE Brussels, CERN, Univ. College Dublin, Birbeck College London, UCL London, Milton-Keynes Open Univ., INFN/Rome, Univ. Turin

CERN R703 (1979)
Study of pp and $p\bar{p}$ *collisions at* $\sqrt{s}$ *= 53 GeV at the ISR*
Collaboration : Bonn, IIHE Brussels, Cambridge, CERN, Stockholm

CERN UA5 (1979)
Investigation of $p\bar{p}$ *events at 540 GeV c.m. energy with a streamer chamber detection system*
Collaboration : Univ. Bonn, IIHE Brussels, Univ. Cambridge, CERN, Univ. Stockholm

CERN NA22 (1980)
The influence of parton structure on hadronic interactions in EHS with a $K^+/\pi^+/p$ *beam at 250 GeV/c.*
Collaboration : TH Aachen, IHEP Berlin, IIHE (ULB-VUB) Brussels, Cracow Inst. Nucl. Phys., Erevan Phys. Inst. Univ. Helsinki, Nijmegen, Rio de Janeiro Phys. Res. Center, IHEP Serpukhov, Univ. Warsaw

CERN NA25 (1981)
Study of charm and bottom particle production using a holographic bubble chamber
Collaboration : Univ. Bari, IIHE Brussels, CERN, Univ. Mons, UC London, Univ. VI Paris, Univ. Strasbourg, Östr. Akad. Wissensch. Vienna

CERN NA26 (1981)
A prototype experiment to study charmed particle production and decay using a holographic high resolution hydrogen chamber (HOLEBC) and the European Hybrid Spectrometer
Collaboration : IIHE Brussels, CERN, Univ. Oxford, INFN/Padova, INFN/Rome, Rutherford Appleton Lab., Univ. Stockholm, INFN/Trieste, Oestr. Akad. Wissensch. Vienna.

CERN NA27 (1981)
An experiment to measure accurately the lifetime of the $D^0 D^{\pm} F^{\pm}$ Λ_c charm particles and to study their hadronic production and decay properties
Collaboration : TH Aachen, IIHE Brussels, Univ. Bombay, CERN, Univ. Duke, INFN/Genoa, U.G. Japan, Univ. Liverpool, CIEMAT Madrid, Univ. Mons, Univ. Oxford, INFN/Padova, Collège de France Paris, Univ VI Paris, INFN/Rome, Univ. Rutgers, Rutheford Appleton Lab., IHEP Serpukhov, Univ. Stockholm, Univ. Strasbourg, Univ. Knoxville Tennessee, Univ. Turin, INFN/Trieste, Oestr. Akad. Wissensch. Vienna, IHEP Zeuthen.

CERN WA75 (1982)
An experiment to observe directly beauty particles selected by muonic decay in emulsion and to estimate their lifetimes
Collaboration : Bari, IIHE Brussels, CERN, Univ. College Dublin, U.G. Japan, UCL London, INFN/Rome, Turin

CERN DELPHI (1982)
Study of electron-positron annihilations at LEP with the DELPHI detector
Collaboration : NIKHEF Amsterdam, Univ. Antwerp, NCSR/Athens Demokritos, Univ. Athens, Nat. Tech.Univ. Athens, Univ. Bergen, INFN/Bologna, IIHE Brussels, CERN, Niels Bohr Inst. Copenhagen, Inst. Nucl. Phys. Cracow, JINR Dubna, INFN/Genoa, ISN Grenoble, Univ. Helsinki, Univ. Ames Iowa State, IEKP Karlsruhe, Univ. Lancaster, LIP Lisbon, Univ. Liverpool, Univ. Lund, Univ. of Lyon I (IPNL) Univ. Complutenze Madrid, Univ. Aix-Marseille II, INFN/Milan, Univ. Mons, LAL Orsay, Univ. Oslo, Univ. Oxford, INFN/Padova, College de France Paris, LPNHE-P. et M.Curie Univ. Paris, Pont. Univ. Catolica - Rio de Janeiro, Cent. Bras. Pesq. - Rio de Janeiro, Univ. Fed. Rio de Janeiro, INFN/Rome Sanita, INFN/Rome Univ., Rutherford Appleton Lab., CEN DPhPE Saclay, Santander Univ., IHEP Serpukhov, Univ. Stockholm, Univ. Strasbourg, INFN/Trieste, INFN/Turin, INFN/Udine, Uppsala Univ., Valencia Univ., Oestr. Akad. Wissensch. Vienna, Warsaw Univ., Wuppertal Univ.

CERN WA79 (1983)
Study of neutrino-electron scattering at the SPS
Collaboration : YEFAM (Ankara, Adana, Istanbul) Turkey, IIHE Brussels, CERN, INFN/Ferrara, DESY Hamburg, UC Louvain, ITEP Moscow, Munich, INFN/Naples, INFN/Rome, IHEP Zeuthen

CERN UA5/2 (1983)
An exploratory investigation of $p\bar{p}$ interactions at 200-900 GeV CM energy at the SPS collider
Collaboration : Univ. Bonn, IIHE Brussels, Univ. Cambridge, CERN, Univ. Stockholm

FERMILAB E743 (1985)
Charm production in pp-interactions at 800 GeV
Collaboration : Aachen, Berlin, IIHE Brussels, CERN, Duke, Fermilab, Kansas, Michigan (Ann Arbor), Michigan SU, Mons, Notre Dame, Bombay, Vanderbilt, Vienna

FERMILAB E632 (1985)
Neutrino and antineutrino interactions in the 15' bubble chamber filled with an heavy H_2/Ne mixture and exposed to the Tevatron high energy neutrino beam
Collaboration : Berkeley, Birmingham, IIHE Brussels, CERN, Chandigarh, Fermilab, Hawaii, Illinois Institute of Technology, Jammu, I.C. London (Part I only), ITEP-Moscow, IHEP-Protvino, Moscow S. U., Munich, Oxford (Part I only), Rutgers, Rutherford (Part I only), Saclay (Part I only), Stevens Institute of Technology, Tufts

EC/SCIENCE (1986)
Development of gamma-ray detectors based on BaF_2 and photosensitive wire chambers
Collaboration : Brunel, Brussels, CERN, Orsay

CERN WA84 (1987)
Study of the production and decay properties of beauty flavoured hadrons
Collaboration : IIHE Brussels, CERN, Imperial College London, INFN/Pisa, INFN/Rome, Rutherford Appleton Lab, Univ. Southampton

DESY/H1 (1987)
A study of e- (30 GeV)-p (820 GeV) interactions at the HERA collider
Collaboration : Aachen I - III, Birmingham, IIHE Brussels, RAL, Cracow, California, Dortmund, Saclay, Glasgow, DESY, Hamburg I-II, Heidelberg, Kiel, Kosice, Lancaster, Liverpool, Queen Mary and Westfield College London, Lund, Manchester, Moscow ITEP, Moscow Lebedev, Munchen, LAL Orsay, LPNHE Palaiseau, LPNHE Paris, Inst. of Physics Praha, Nuclear Center Praha, INFN/Roma, Wuppertal, IM Zurich, Univ. Zurich, Stanford

CERN WA95 (1991)
A new search for ν_μ-ν_τ oscillations
Collaboration : Aichi Educational Univ., NIKHEF Amsterdam, YEFAM (Ankara, Adana, Istanbul) Turkey, Bari, Humboldt Univ Berlin, IIHE Brussels, CERN, Changwon Nat. Univ., Chonnam Nat. Univ., INFN/Ferrara, Univ. Gifu, Nat. Univ. Jinju Gyeongsang, Univ. Kinki, Univ. Kobe, UC Louvain, ITEP Moscow, Univ. Muenster, Univ. Nagoya, INFN/Naples, City Univ. Osaka, Science Educ. Inst. of Osaka, INFN/Rome, INFN/Salerno, Univ. Toho, Univ. Utsunomiya, Nat. Univ. Yokohama

EC/JOINT RESEARCH PROPOSAL (1992)
Study and development of new scintillating materials for basic research and nuclear medicine
Collaboration : Brussels, CERN, Ecole Polytechnique (Paris), Shanghai

CERN RD28 (1992)
Development of gas micro-strip chambers for radiation detection and tracking at high rates
Collaboration : Aarhus Univ., NIKHEF Amsterdam, INP and IME of NCSR Demokritos Attiki, IIHE Brussels, Comenius Univ. Bratislava CS, CERN, Frascati Nat. Lab./INFN, MPI Heidelberg, Kosice Phys. Inst. CS, Legnaro Nat. Lab./INFN, Univ. Liverpool, ULC London, Univ. of Lyon I (LPCML), Univ. Mons, Novosibirsk Inst. Nulc. Phys., CRPP-Ottawa, Carleton Univ. Ottawa, Academy of Sciences Praha CS, Weizmann Inst. Rehovot, Rutherford Appleton Lab., Saclay DAPNIA, Texas A&M Univ., Turin/INFN, TRIUMF Vancouver.