Neutrino physics at high energy (1971 -1992)

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The advent of new proton synchrotron accelerators with energies above 300 GeV at Fermilab and CERN enabled a new era of neutrino physics from 1971 onwards. The goals were first the search for the W boson, search for neutral current weak interactions and for new particles, and later tests of the quark-parton model and measurement of scaling violations due to quantum chromodynamics, as well as precision studies of the neutral weak coupling. The first accelerator high energy neutrino was detected at Fermilab in November 1971 by the Caltech group of Barish and Sciulli (called experiment 21). The neutrino laboratory was ready in May 1972, and experiments 1A (Harvard-Penn-Wisconsin) and exp. 21 (Caltech-Fermilab-Rochester) started early in 1973, the 15-ft bubble chamber followed a year later. First results came in 1974, some of them surprising. At the Aachen Neutrino Conference 1976, they were reported. At CERN, construction of the SPS accelerator started in 1971, 4 years after Fermilab. The first proposals for counter neutrino experiments, P1 and P3, came in 1973. The experiment of the CDHS collaboration was approved in April 1974. The West Area neutrino beam started operations in 1976. First results were published in 1977. The BEBC bubble chamber and later the experiment WA18 CHARM (CERN-Hamburg-Amsterdam-Rome-Moscow) used the same beam line. The physics results of these twenty years of accelerator neutrino experiments are reviewed in their historical context.

1 Deep elastic neutrino scattering.

Since neutrinos only interact by the weak force, they are an ideal tool to explore the inner structure of nucleons. In deep inelastic scattering (see Figure 1), a neutrino (four-momentum k) impinges on a nucleon at rest (four-momentum p). In charged-current interactions, we observe the outgoing muon (k'=($E_\mu, \mathbf{p}$)) and a shower of hadrons (energy E_h). In neutral-current interactions, the outgoing neutrino (k') escapes detection and the hadron shower is observed.

2 The first experiments at Fermilab.

The first high energy proton accelerator with superconducting magnets was founded in 1967 at Fermilab near Chicago. The protons generated the first neutrino beam in 1971, and the first high energy accelerator neutrino interaction was observed in November 1971 by the experiment of the

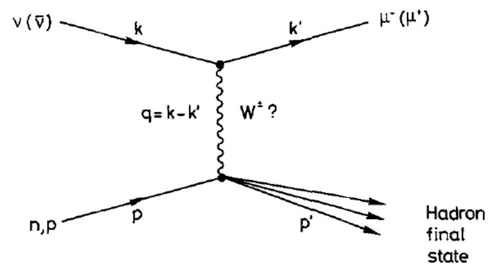

Figure 1 – Diagram illustrating the charged current (CC) neutrino scattering process. (Note the question mark after the W, which has been discovered only in 1983).

Caltech-Fermilab collaboration, dubbed experiment 21. Later, this experiment included physicists from Caltech, Fermilab, and Rochester. Other neutrino experiments were performed by the Harvard-Pennsylvania-Wisconsin collaboration (exp. 1A) and the CERN-Berkeley-Hawaii-Wisconsin collaboration using the 15-ft bubble chamber at Fermilab (exp. 28A).

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Both the HPW and CIT-FNAL electronic experiments employed a Hadron calorimeter followed by a Muon Spectrometer to measure E_h and the muon momentum **p**, while the bubble chamber was able to measure details of the hadron shower. From the observed quantities, one obtains the Bjorken scaling variables x and y (Figure 2), and the expectation was to observe scaling in inelastic scattering from a point-like target.

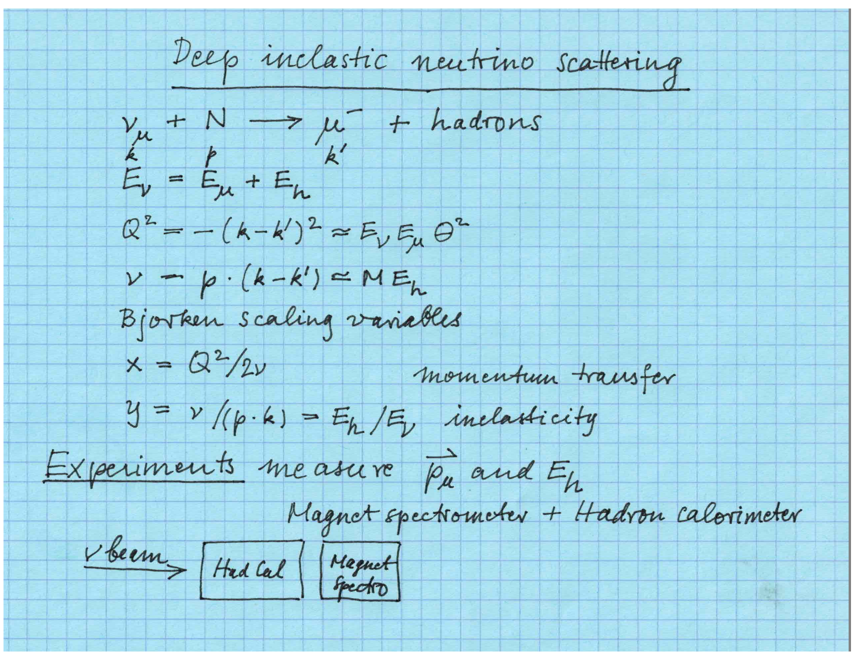

Figure 2 – Kinematics of inelastic neutrino scattering.

The first publication from the HPW group deals with "Scaling variable Distributions in High-Energy Inelastic Neutrino Interactions" [1]. A possible effective deviation from charge-symmetry invariance is observed, which could be the result of new particle production. The deviation showed up in the comparison of antineutrino- and neutrino-induced events.

Another surprising phenomenon was published in February 1975 [2]. Fourteen events with two muons in the final state were observed, which require the existence of one or more new particles with a mass between 2 and 4 GeV that decay through the weak interaction. The particle is either a hadron related to the scaling anomaly or a heavy lepton. The authors "would like to call such particles Y particles because of the probable relation of the dimuon signal to the violation of charge-symmetry violation observed in the antineutrino y distributions. An alternative explanation ... is through the production of a heavy lepton... ".

In a further paper in November 1975 the HPW collaboration on dimuon production [3] concludes that a new neutral lepton is present in most of the events.

The situation is illustrated by the article in the internal Fermilab journal "The Village Crier" of 8 January 1976:

- The HPW Experiment #1A reports on two important research results: –evidence of the neutral current—finding of an unusual particle, the Y particle (published in the Scientific American).
- And the 15-ft bubble chamber group announces a Major Discovery [4]: four neutrino events detected in 15-ft bubble chamber of type $\mu^- + e^+ + K^0$, which is the observation of production and decay of a charmed hadron (Figure 3).

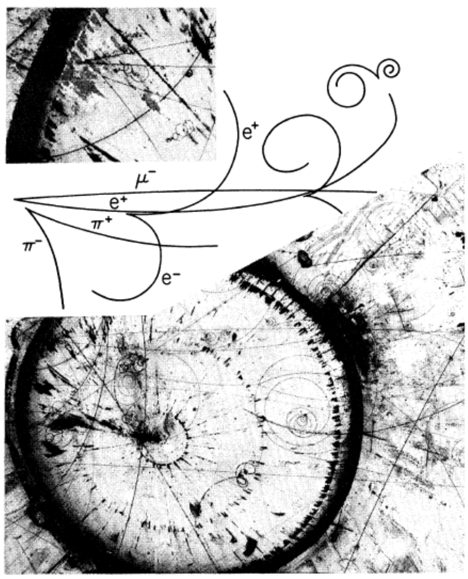

Figure 3 – Observation of charm production and decay in the 15-ft bubble chamber at Fermilab [4].

In April 1976, the CIT-FNAL collaboration also published their results on Dimuon production: "Observation of neutrino-induced dimuon events" [5]. They concluded that the events are due either to the decay of a neutral heavy lepton or of new hadrons (e.g. charm).

In June 1976, the HPW collaboration published "Further Data on the High-y Anomaly in Inelastic Antineutrino Scattering" [6]. They concluded that "the anomaly cannot be explained by scattering from antiquarks in the three-quark model". However, the effect was seen as strong evidence for new particle production by antineutrinos.

One month later, the HPW collaboration presented additional evidence for a new effect: the ratio of total cross-sections of antineutrino and neutrino showed a sudden increase at 50 GeV neutrino energy, while scaling law predicts a constant ratio [7]. Below 30 GeV, the ratio was 0.38 ± 0.06, in agreement with the bubble chamber measurement, and 0.6 ± 0.1 above 30 GeV.

The state-of-the-art end of 1976 can be summarized as follows: dimuon and $\mu^- e^+$ events had been observed, their origin was either hadron (charm) or heavy lepton. Bjorken scaling works for neutrinos, but not for antineutrinos—there seems to exist an anomaly in the y distributions of antineutrino-induced events. The ratio of total cross sections of antineutrino and neutrino shows a threshold effect at high neutrino energy. After the discovery of leptonic neutral weak currents at CERN in the Gargamelle bubble chamber, also hadronic neutral weak currents were observed.

3 Neutrino Experiments at the CERN SPS.

At CERN, construction of the SPS accelerator started in 1971, 4 years after Fermilab. The first proposals for counter neutrino experiments, P73-1 and P73-3, came in 1973. The proposal of the CERN-Dortmund-Heidelberg-Saclay collaboration consisted of a 6 m long hadron calorimeter for the measurement of the hadron energy, followed by a 24 m long iron core magnet measuring the muon momentum. The proposal P73-3 of a collaboration CERN-Hamburg-Karlsruhe-Oxford-Rutherford Lab-Westfield College had a Liquid-Argon/Fe-Calorimeter(340 t) in front of an air core solenoid magnet (820 t). The SPS committee was not convinced by either proposal, and wanted to urge the collaborations to merge, without success. In February 1974 came a new idea by Heinrich Wahl: he saw the enormous advantage of combining the calorimeter and the magnet by instrumenting the Iron Core Magnet (ICM) with scintillators (Memo M25). The ICM then serves as calorimeter and magnet at the same time. With this modification, the SPSC and NPRC approved the CDHS proposal as experiment "West Area 1" (WA1) in April 1974. The P73-3 group made then a new proposal P49 (Oct. 1975) aiming at neutral current interactions. This was approved in March 1976 as WA18-CHARM experiment (CERN-Hamburg-Amsterdam-Roma-Moscow collaboration). The CDHS and CHARM detectors are shown in Figure 4.

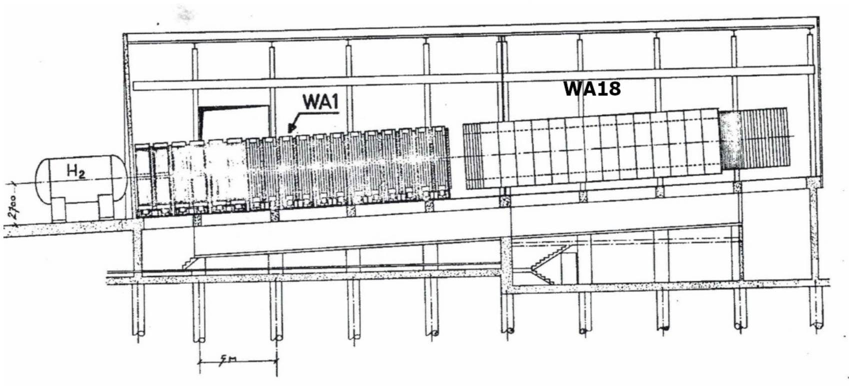

Figure 4 – Experiments WA1 (left) and WA18 (right) in the SPS West Area of CERN.

The West Area neutrino beam started operations in 1976 with experiment WA1. First results were published in 1977. The BEBC bubble chamber and later the experiment WA18 CHARM (CERN-Hamburg-Amsterdam-Rome-Moscow) used the same beam line.

Results of the CDHS experiment from 1977 include the following:

1. Dimuons of opposite sign [8]: 315 events show "remarkable agreement with hypothesis of charm production and decay" ; the data present "evidence against models with heavy lepton". They also show "evidence against bottom quark production by antineutrinos" (Fig. 5).

2. Dimuons with like sign [8]: 47 events, mostly background from pion decays of the hadron shower; excess is $(3 \pm 2) \times 10^{-4}$ of CC events, may well be due to hadronic production of c-$\bar{c}$ pair; no evidence for cascading heavy leptons.

3. There is no High y Anomaly [10]: the data show perfect agreement with Bjorken scaling in the y distribution, and the ratio of total cross-sections of antineutrino and neutrino is

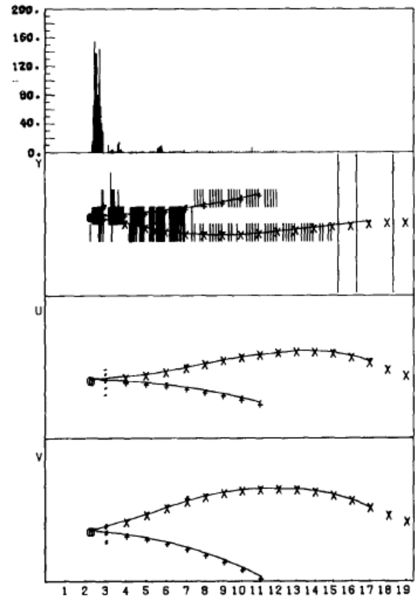

Figure 5 – Side view of a dimuon event in the CDHS detector [8].

constant with neutrino energy, the value is 0.48 ± 0.02 in the energy range from 30 to 190 GeV (Fig. 6).

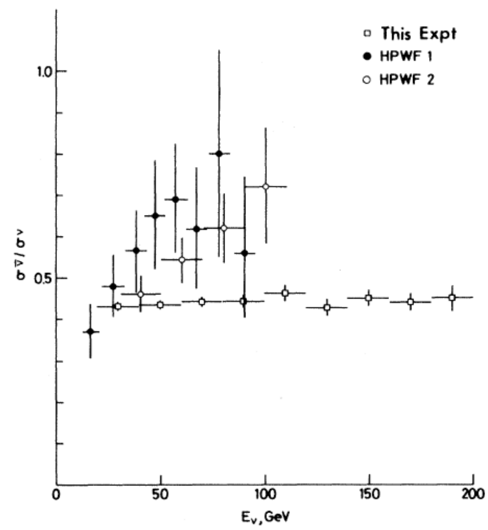

Figure 6 – Ratio between antineutrino and neutrino total cross-sections as a function of neutrino energy from CDHS (open squares) and HPWF (circles) experiments.

4. The y distributions of neutrino and antineutrino events show perfect scaling, and they are consistent with the quark-parton model, as shown in Fig. 7 [11].

The observation of dimuons in CDHS was accompanied by the observation of muon-electron dileptons in the BEBC bubble chamber [12].

4 Measurements of structure functions.

The neutrino experiments at CERN confirmed the quark-parton model and Bjorken scaling.

The large data sets of charged-current neutrino events which were recorded in the following years allowed a detailed study of the nucleon structure functions and a comparison to the

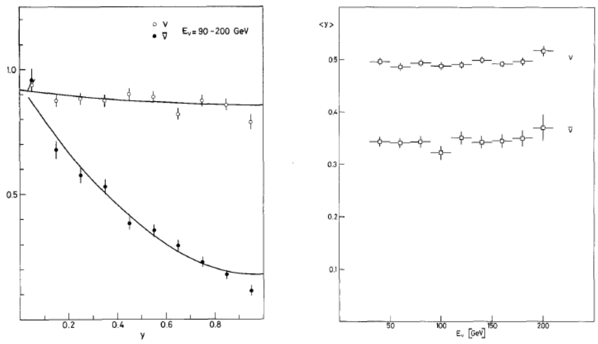

Figure 7 – Left: y distributions for neutrino (top) and antineutrino (bottom) interactions. Right: average y as a function of neutrino energy from 30 to 190 GeV.

emerging Quantum Chromo Dynamics (QCD) calculations.

The structure functions are obtained from the differential cross-sections of neutrino and antineutrino interactions, as given in the Fig. 8.

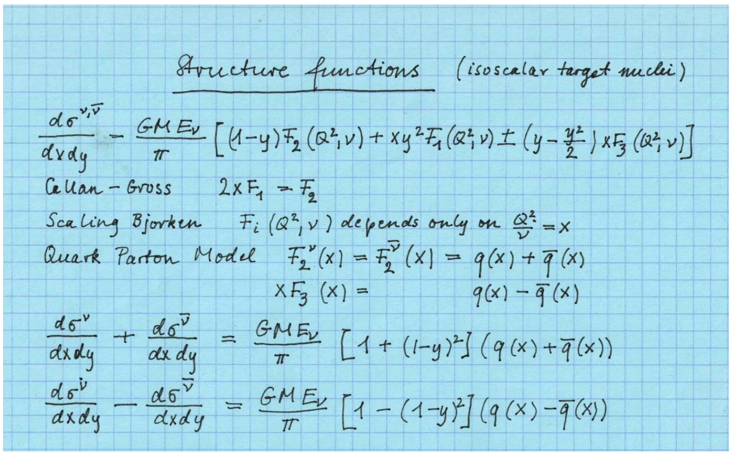

Figure 8 – Structure functions.

The data (Fig. 9) show deviations from scaling in the x distributions, as expected from QCD. This is due to gluon bremsstrahlung and quark-antiquark production from gluons.

With the help of the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations, a QCD analysis can be performed which separates the contributions from gluon bremsstrahlung and quark pair production to the structure function F_2 and quark sea structure function $\bar{q}$ $(\bar{\nu})$; the analysis shows that the observed violations in x- or Q^2 distributions agree with QCD predictions (Fig. 10. From the measured moments of the valence structure function xF_3 it appears that vector gluons are preferred. Alternative field theories, like Abelian vector gluons, Abelian scalar gluons, Non-Abelian scalar gluons are excluded by the data [13].

In the following decade, measurements of structure functions F_2 and xF_3 were performed by many experiments: at Fermilab by the CCFR collaboration [14]; at CERN by the CHARM collaboration [15] and by the CDHSW collaboration [16], by the muon scattering experiments [17], and the BCDMS collaboration [18].

The early steps towards quarks using neutrino interactions in bubble chambers were described by Don Perkins [19].

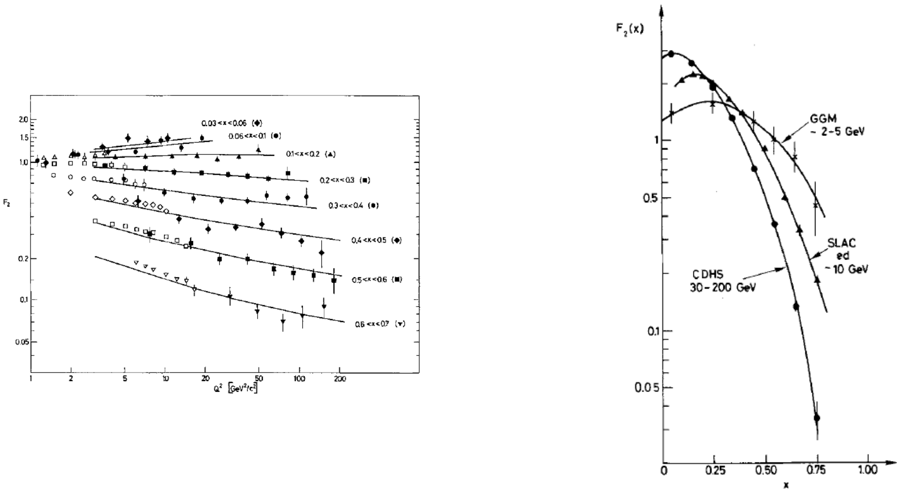

Figure 9 – Right: Scaling violations in Q^2 distributions from CDHS and eD-scattering at SLAC; b) Left: Scaling violations in the F_2 structure function, x-distributions from SLAC, Gargamelle and CDHS. From ref. [11].

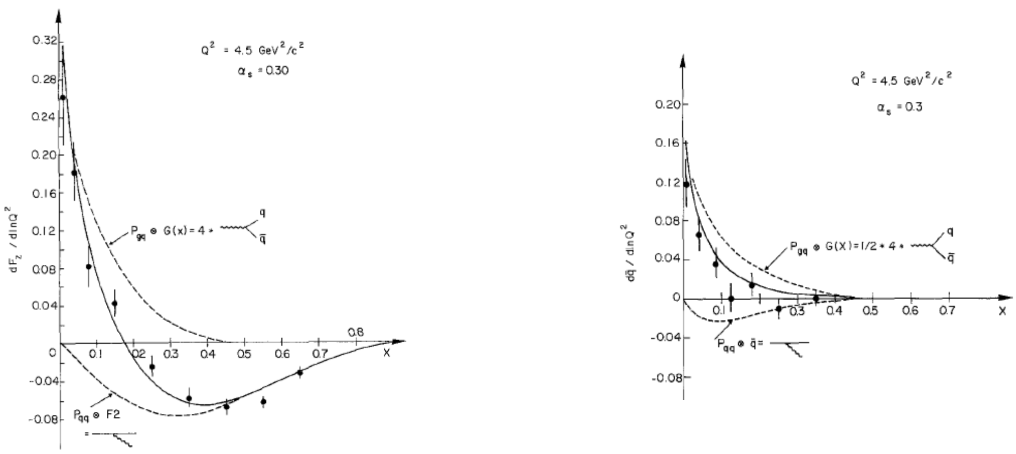

Figure 10 – Left: Slope of structure function $dF_2/dlnQ^2$ versus x and contributions from gluon bremsstrahlung and gluon pair production. Right: Slope of structure function $d\bar{q}/dlnQ^2$ versus x. From ref. [13].

5 Neutral currents.

The early story of experiments searching for and discovering neutral current interactions (NC) was addressed by Dieter Haidt in these proceedings. In the following years, every neutrino experiment, apart from charged-current interactions, also measured the ratio NC/CC for neutrinos and antineutrinos, and deduced the Weinberg parameter $\sin^2\theta_W$. They include the following experiments: HPW 1977 [20], CFR 1977 [21], CDHS 1977 [22], CHARM 1981 [23], BEBC 1983 [24], CCFR 1985 [25], CDHS 1985 [26], CHARM 1987 [27] and CDHS [28].

In 1990, the average of two most precise measurements was: $\sin^2\theta_W$=0.232 ± 0.006. From this value of $\sin^2\theta_W$ one can predict the predict the mass of the W boson to be 81 ± 2.5 GeV and of the Z boson to be 92.2 ± 2.2 GeV. In this way, the simplest Grand Unified Theory (GUT), SU(5), is excluded by this value of $\sin^2\theta_W$.

Further developments in this sector are summarized by Alain Blondel [29] and U. Dore et al. [30].

6 Conclusion

The conclusions from 20 years of experiments are:

1. Scaling in y is valid in agreement with the quark-parton model.
2. Scaling violations in x are agree with QCD, but not with Abelian field theories or scalar gluons.
3. Dimuon and muon-electron dileptons are due to charm production and decay.
4. Neutral currents exist and agree with the Glashow-Weinberg-Salam model. The measured Weinberg parameter $\sin^2\theta_W = 0.232 \pm 0.006$ points to W and Z masses in agreement with the UA1 and UA2 discoveries at the CERN p-$\bar{\text{p}}$ collider.

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