Probing Subnuclear Structure with Neutrinos [a]

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Abstract

This manuscript addresses selected aspects of neutrino physics based mainly on the results of deep inelastic scattering off nuclei in the CDHS neutrino experiment at CERN. The measurements contributed to the establishment of the quark-parton model, to the details of quantum-chromodynamics (QCD) and the electro-weak theory.

Introduction

The Neutrino

The neutrino entered the physics stage in 1930 when W. Pauli postulated a neutral, lightweight spin ½ particle in order to maintain energy and angular momentum conservation in beta decay. In his theory of the beta decay as a four-fermion interaction[1], Enrico Fermi gave the particle the name "neutrino" (symbol ν) and estimated its mass to be much smaller than that of the electron. Based on the Fermi theory, H. Bethe and R. Peierls[2] estimated the cross section for neutrino interactions with matter to be less than 10^{-44} cm^2 "*corresponding to a penetrating power of 10^{16} km in solid matter*". They concluded, "*there is no practically possible way of observing the neutrino*". History showed that the cross-section was correct (within a factor two) for low energy neutrinos close to threshold, but the conclusion for the future was far too pessimistic.

More than 25 years after Pauli's proposal, neutrinos produced in a powerful nuclear reactor interacting with protons in a heavy target through the inverse reaction of the beta decay: $\overline{n}_e + p \rightarrow n + e^+$ allowed Reines and Cowan in 1956 to claim discovery[3] of the (anti)-neutrino. In 1957 Goldhaber et al.[4] determined the helicity of neutrinos to be negative (left handed). Antineutrinos, which are produced in beta decays with an electron in the final state, are supposed to be right-handed while left-handed neutrinos are produced in decays emitting a positron. In 1962, Lederman, Schwarz and Steinberger demonstrated that neutrinos from pion decay (e. g. $\pi^+ \rightarrow \mu^+ + \nu$) were different from those emerging from beta decay[5], therefore two flavours of neutrinos existed, the electron neutrino ν_e and the muon neutrino ν_μ, each with their proper lepton number conservation. The third kind of neutrinos associated with the third charged lepton tau was only observed in 2001 by the DONUT collaboration[6]. At the electron positron collider LEP, it had been shown that there are three and only three generations of light neutrinos. During the past decade oscillation between neutrino flavours have been observed for solar, atmospheric, reactor and beam neutrinos. Therefore it is clear that the neutrinos have nonzero masses and the question whether neutrinos are their own antiparticles (Majorana fermions) is still open. In this lecture we do not cover in detail the nature of neutrinos but are rather interested in using neutrinos to probe the subnuclear structure.

The Quark Model

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In the middle of the 20th century there was an inflation of newly discovered “elementary” particles. In 1961 M. Gell-Mann and Y. Ne’eman proposed an initial classification scheme[7] “the Eightfold Way” arranging mesons and spin ½ baryons in octets and spin $^3/_2$ baryons in a decuplet according to electric charge and a quantum number called “strangeness”. The theory gained recognition when a particle predicted in the decuplet, the Ω^-, was found experimentally. In 1964 constituents of mesons and baryons were postulated independently by M. Gell-Mann (who called them quarks)[8] and G. Zweig (who called them ACES)[9]. The quarks (the name that was retained) have spin ½ and fractional charge. In 1964 the known particles were supposed to be composed of three types of quarks: up-quarks with charge $^2/_3$ (in units of proton charge), down-quarks and strange-quarks, each with charge $-^1/_3$. Baryons are composed of three quarks while a meson is composed of a quark and an anti-quark.

Deep Inelastic scattering

Rutherford has discovered in 1909 the atomic nucleus as very small compared to the overall atomic size by scattering alpha particles off atoms and observing large angle deflections. Similarly, in 1968 electron scattering experiments at the 2-mile linear accelerator SLAC have found scattered electrons at large angles relative to the beam direction indicating the existence of small constituents inside nuclei initially called partons.

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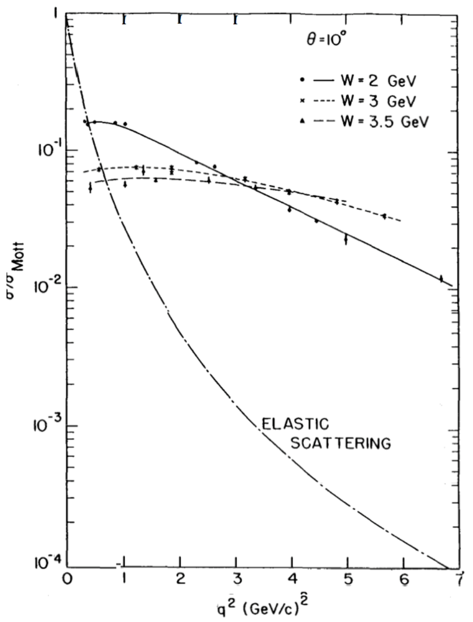


Fig. 1: $(d^2\sigma/d\Omega dE')/\sigma_{Mott}$, in GeV^{-1}, vs. q^2 for W = 2, 3 and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic e-p scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{Mott}$, calculated for θ = 10°, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

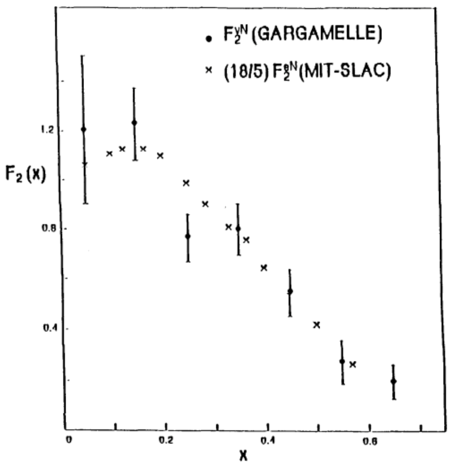


Fig. 10: Early Gargamelle measurements of $F_2^{\nu N}$ compared with $(18/5)F_2^{eN}$ calculated from the MIT-SLAC results.

Though it was obvious to identify the partons with the quarks, additional evidence had to wait until the scattering experiments were repeated with neutrinos instead of electrons. In contrast to the electrons that “see” the electrical charge of the constituents, neutrinos only interact with the weak charge. By comparing the two, one can deduce the electrical charge of the constituents.

Already in the early bubble chamber experiments with neutrinos (Gargamelle at CERN) it could be shown that the neutrino structure function F_2 is a factor 3.4±0.7 higher than that of electron scattering. This is well compatible with the value expected from the quark charge argument for isoscalar targets (nuclei with equal numbers of protons and neutrons):

$\frac{2}{(2/3)^2+(-1/3)^2} = {}^{18}/_{5} = 3.6$. As we shall see, this conclusion was later confirmed in electronic experiments with neutrino beams at the CERN SPS with higher neutrino energy and substantially increased statistics. The Gargamelle experiment also showed that the neutrino and the antineutriono-nucleon total cross-sections rise linearly with energy as expected for scattering off pointlike particles. This cross section rise together with the high-intensity neutrino and antineutrino beams and massive detectors allowed high-statistics experiments. Now, instead of the estimation of Bethe mentioned above, the absorption length in iron for 30 GeV neutrinos is 10^{10} m. That means for an iron target of 10 m length (typical fiducial length in CDHS), about 10^9 neutrinos are required for one interaction. With several 10^{18} protons targeted several million neutrino interactions could be observed.

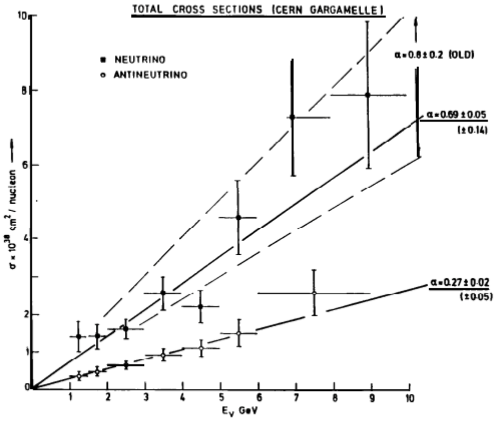


Fig. 9: Early Gargamelle measurements of neutrino nucleon and anti-neutrino nucleon cross sections as a function of energy. These results were presented at the XVI International Conference on High Energy Physics, NAL-Chicago, 1972, Ref. [44].

Neutrino Beams

The muon-neutrino beams used in accelerator experiments stem from the decay of positive pions or kaons in flight. At the CERN SPS, the pions are generated by impinging a high intensity proton beam of 350 and 400 GeV energy on a target. The secondaries generated are charge selected and focused by a magnetic horn towards a 300 m evacuated decay tunnel. The muons from the decay and the remaining hadrons are subsequently absorbed by a 450 m iron and earth shield leaving only the neutrinos to enter the detector. When the field in the magnetic horn is inverted, negatively charged hadrons are selected and antineutrinos are produced instead of neutrinos. These so called wide-band beams (WBB) have an energy spectrum falling off exponentially after a peak at about 20 GeV.

In a second setting, instead of the magnetic horn accepting a wide spectrum of hadrons, a system of dipole magnets and collimators selects a narrow momentum band of 200±10 GeV/c. In this narrow-band beam (NBB) – at a large expense of intensity – the neutrinos are significantly more energetic and the decay kinematic leads to a correlation between the neutrino energy and the radial position in the detector – separately for pion and for kaon decays.

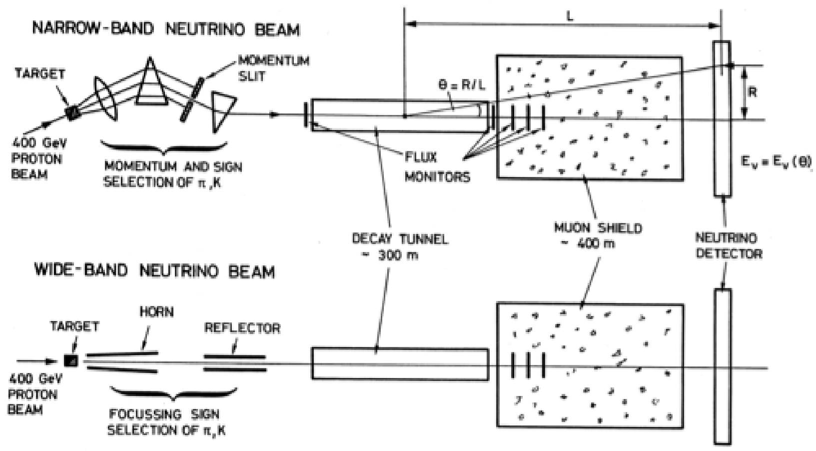


Fig. 1: Schematic layout of the narrow-band and wide-band neutrino beams.

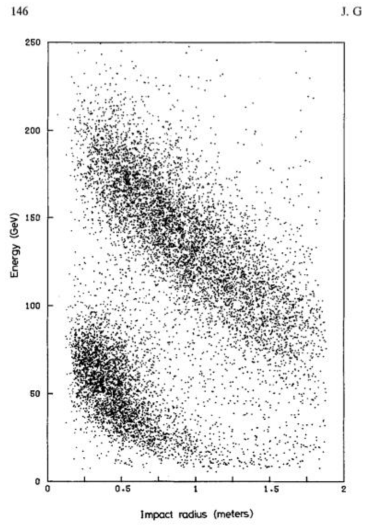


Fig. 2. Scatter plot of measured neutrino energy (muon + hadron energy) versus detector radius for a sample of events. The separate bands are due to neutrinos from pion and kaon decay

The Neutrino Experiment WA1 at CERN

There have been numerous accelerator based neutrino experiments between 1980 and now as can be seen from the insert of Fig. xyz. Based on my own experience, I shall in the following concentrate on the WA1 experiment at CERN.

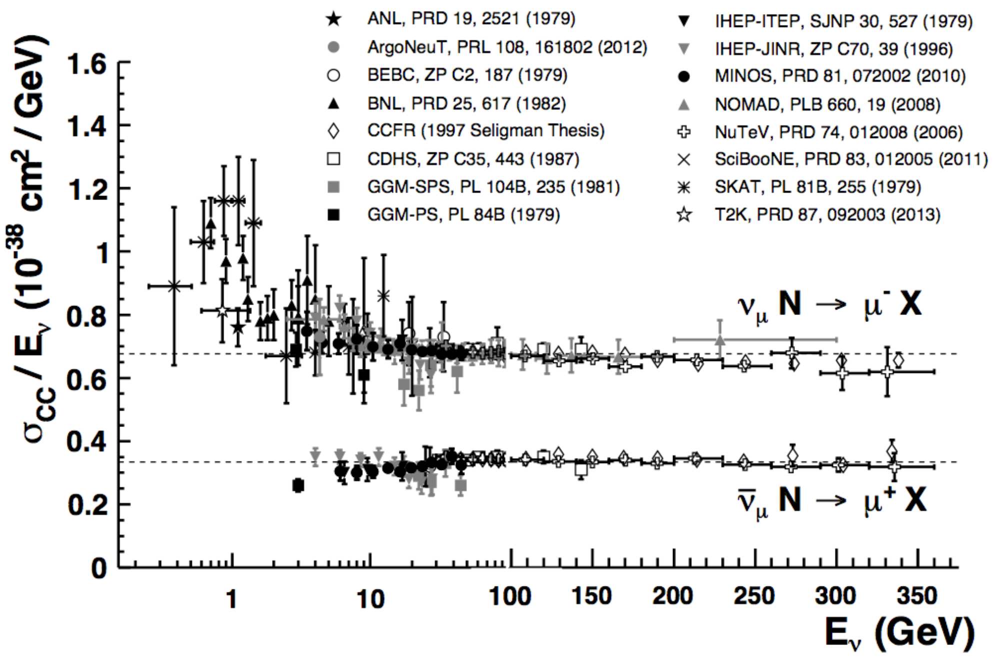


Figure 48.1: Measurements of ν_μ and $\overline{\nu}_\mu$ CC inclusive scattering cross sections divided by neutrino energy as a function of neutrino energy. Note the transition between logarithmic and linear scales occurring at 100 GeV. Neutrino cross sections are typically twice as large as their corresponding antineutrino counterparts, although this difference can be larger at lower energies. NC cross sections (not shown) are generally smaller but non-negligible compared to the CC scattering case.

The experiment was a collaboration of CERN, Dortmund, Heidelberg, Saclay and (later) Warsaw, known as CDHS. Physics topics were amongst others: nucleon structure functions, electroweak couplings, QCD, and search for neutrino oscillations.

In December 1976, the WA1 experiment started data taking in the CERN SPS neutrino beam. The detector consisted of 19 iron modules combining the functions of target, muon absorber, spectrometer magnet and hadron calorimeter interspersed with three-layer drift chambers. The 1250-ton detector was exposed to wide-band and narrow-band neutrino beams up to 400 GeV from 1976 to 1984 studying deep inelastic neutrino scattering on iron (and later also on hydrogen and deuterium).

One of the first publications could falsify an effect called "high-y anomaly" where a competing experiment at Fermilab had observed unexpected behaviour in antineutrino events. Two years after the discovery of charmed quarks, neutrino interactions offered a unique possibility to study the coupling of charm to other quark flavours by measuring elements of the Cabibbo–Kobayashi–Maskawa matrix. The most frequent events, charged current interactions, have a negative (leading) muon in the final state for neutrino interactions and a positive one for antineutrinos. Charm manifests itself in an extra muon in the final state mostly of opposite charge to the leading muon. As the magnetic field polarity was set to focus the leading muon, and the second muon generally has lower momentum and was bent away from the axis. Neutrino interactions mediated via neutral current do not produce an energetic muon in the final state. They are characterized by a short length of the event due to the rapid absorption of the hadronic shower in the iron calorimeter.

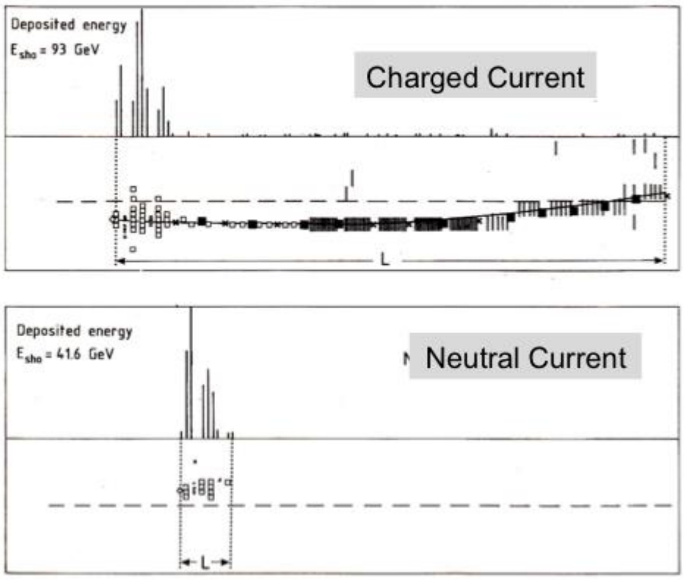


Figure 1: Typical neutrino events in the CDHS detector. Top: a charged current event; bottom: a neutral current candidate. The histograms give the energy deposited in the scintillators of the calorimeter in units MIP (Minimum Ionizing Particle).

Total Cross Section

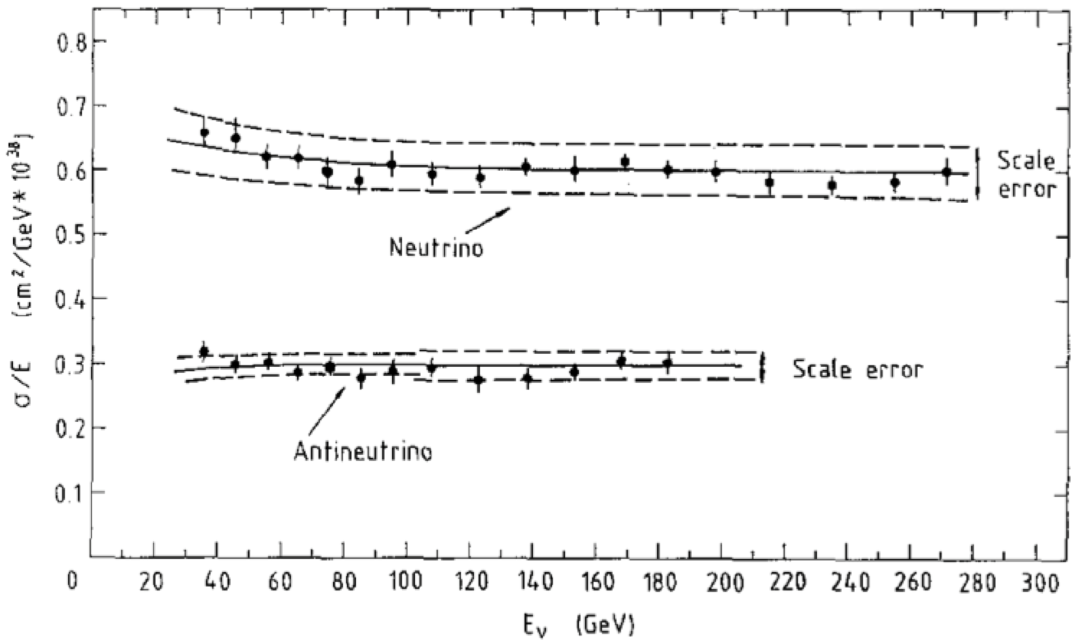
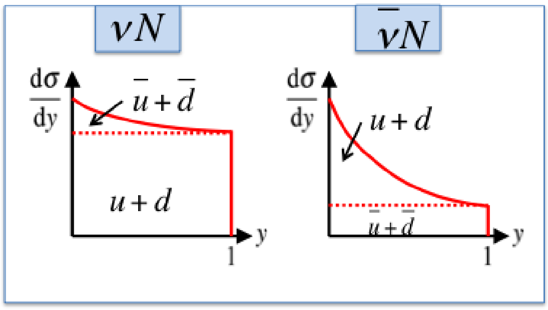


Fig. 7. Energy dependence of the total neutrino and antineutrino cross-sections. The error bars include an estimate of systematic point-to-point errors. The solid line shows the energy dependence as expected from the observed scaling violation of the structure functions. The dashed lines indicate the over-all scale errors

$$\frac{d\sigma(\nu+N)}{dydx} = \frac{G^2}{\pi} M E_\nu \left[\mathbf{q}(x) + (1-y)^2 \overline{\mathbf{q}}(x)\right] ; \quad \frac{d\sigma(\bar{\nu}+N)}{dydx} = \frac{G^2}{\pi} M E_{\bar{\nu}} \left[(1-y)^2 \mathbf{q}(x) + \overline{\mathbf{q}}(x)\right]$$

where $x = Q^2/2MyE_\nu$ *and* $y = E_{hadrons}/E_\nu$



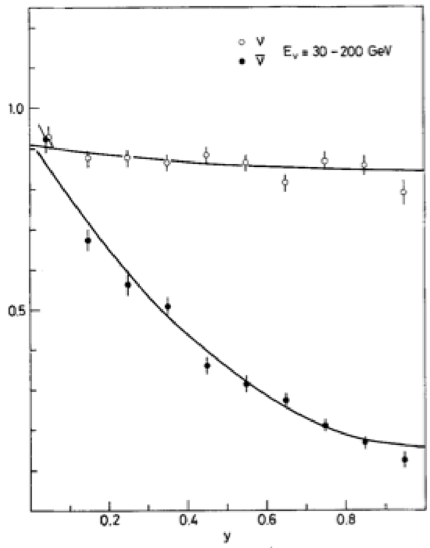


Fig. 12. Distributions in y for neutrinos and antineutrinos, after corrections for acceptance, resolution and flux

Summary and Conclusion

We have seen over the past four decades tremendous changes:

The size of physics collaborations has increased from order $\mathcal{O}(10)$ to several thousand. The computing requirements have vastly exceeded the possibilities of a single institution. 40 years ago, one or very few physicists located within earshot did the software development; now, hundreds of developers working on a single package are spread around the globe.

The combined computing capacity of DESY and CERN in 1970 represented one per mill of the power of a single modern smartphone. Over four decades, resources in CPU and storage used for subnuclear physics have increased by eight orders of magnitude. Currently, there are now about 10^{18} bits of data storage for the LHC experiments.

To address the main question of this lecture series: “What we would like LHC to give us?” - computing has been essential to enable physics experiments answering the fundamental questions. This has become even more so at LHC than previously. Computing is as important as any other subsystem of the experiments. But also, LHC computing has required pushing technology to new heights enabling other sciences and domains to profit from the new technologies.

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