Physics with charm particles produced in neutrino interactions. A historical recollection.

Ubaldo Dore
Dipartimento di Fisica, Università di Roma “La Sapienza”
I.N.F.N., Sezione di Roma, P. A. Moro 2, I-00185 Roma, Italy

Contents

1 Introduction 2
2 The discovery of the charm quark 3
3 The mechanisms of charm production in neutrino nucleon scattering 4
4 Experiments on charm physics with neutrino beams 6
  4.1 Neutrino beams ................................. 7
  4.2 List of experiments ............................. 9
    4.2.1 Fermilab experiments ........................ 9
    4.2.2 CERN experiments ........................... 11
5 Charm physics with opposite-sign dimuons 15
  5.1 Introduction ................................... 15
  5.2 The analysis of dimuon events .................. 18
6 Multimuon events and associated charm production 23
  6.1 Wrong-sign muons .............................. 25
  6.2 Same-sign dimuons .............................. 25
  6.3 Trimuons ...................................... 26
7 Emulsion experiments 27
  7.1 E531 ........................................... 28
  7.2 CHORUS ....................................... 28
1 Introduction

This paper presents a historical recollection of the neutrino experiments aimed at the study of charm physics in the last 40 years. In the seventies, many experimental facts indicated the existence of new particles made by a new quark called “c” for charm. After the discovery of the J/Psi in 1974 [1, 2] clear-cut evidence for the c quark was expected from the measurement of the lifetime of particles with naked c. Lifetimes of the expected magnitude were indeed first measured in 1976 by a neutrino experiment using the high spatial resolution of emulsion detectors. Since then, neutrino experiments have continued to collect valuable information in different domains of charm physics. Because of the tiny neutrino cross-sections huge detectors are needed and this make direct observation difficult. Most of the experiments have identified charm production in their heavy detectors by tagging the production of leptons from charm decay. However, important results were also obtained by the direct observation of the decay of charmed particles in emulsion targets.

This paper provides the basic information about all neutrino experiments relevant to the study of charm physics. We then summarize the present knowledge derived from these experiments on various issues, namely important between them the mass of the c quark, the s quark content of the nucleon, and the $V_{cd}$ and $V_{cs}$ elements of the CKM matrix.

The paper is organized in the following way. First, in section 2, we recall the discovery of charm, which marked the beginning of neutrino experiments in the field. Then, in section 3 we summarize the basic theoretical formalism nowadays in use to describe the process of charm production in high energy neutrino-nucleon scattering. A complete list of neutrino experiments on charm, together with their main characteristics is given in section 4. The following sections contain a description of the experimental results. Results on opposite-sign dilepton events are summarized in section 5 where the analysis of
these events is described. Information on double charm production and on multi-lepton events other than opposite-sign dilepton is discussed in section 6. Finally, section 7 deals with the few experiments which made use of nuclear emulsions to directly detect the short lived charmed particles. Brief concluding remarks can be found in section 8.

2 The discovery of the charm quark

The existence of a fourth quark was predicted by Glashow, Iliopoulos and Maiani [3] in 1970. This quark was named charm by Bjorken and Glashow [4] and its existence was experimentally proven by the discovery in 1974 of the $J/\psi$ [1, 2], the charm anti-charm meson state. Naked charms, i.e. hadron states containing a charm quark were first discovered in 1976 in $e^+e^-$ annihilations at SLAC, by the observation of the $D^+$ [5] and $D^0$ [6, 7] mesons. The characteristics of the detected narrow states made the authors of [5] write:

... strongly suggest they are the predicted isodoublet ($D^0$ and $D^+$) of charm mesons.

However, the definite conclusion that these particles were charmed hadrons required a determination of their lifetimes. In fact, the charm quantum number being conserved in strong and electromagnetic interactions, charmed hadrons were expected to decay weakly with lifetimes of the order of $10^{-13}$ s. The measurement of the lifetimes then required to use detectors with high spatial resolution, allowing to observe short decay paths.

In 1975 Marcello Conversi [8] proposed to combine emulsion, bubble chamber and counter techniques to study new shortlived particles produced by neutrinos. An experiment using spark chambers and emulsions was performed in 1976 at Fermilab [9] [10] and produced evidence for short-lived particles produced in neutrino interactions. An
experiment conducted by Conversi, was then performed at CERN. Results were published in 1979 and succeeded to provide the first measurements of lifetimes for neutral and charged D particles \[11, 12\]. Charmed baryons were also observed \[13\]. These fundamental experiments opened the way to the study of charm physics with neutrino beams, subject of our paper.

Before concluding this section, we should add a comment on the first observation of naked charm. We like to recall that 5 years before the discovery at SLAC, events later ascribed to associated production of charmed hadrons were observed in Japan in 1971 in studies of cosmic ray events with emulsion technique \[14\]. A historical review on charm physics with emulsions in Japan is given in \[15\].

3 The mechanisms of charm production in neutrino nucleon scattering

We shall now outline the theoretical framework which is currently used to describe the process of charm production in neutrino nucleon scattering. We shall limit our discussion to the basic formulae which illustrate which are the quantities involved in the scattering process, and that can hence be studied by the experiments. For a more detailed treatement of the theory and of the experimental techniques of charm physics with neutrinos we refer the reader to the review paper \[16\]. Charm particles are produced mainly by neutrinos through the charged current (CC) reaction

\[
\nu_\mu + N \rightarrow \mu^- + C + X
\]

where N is the target nucleon, C the charmed particle, X the remaining hadrons here and in the rest of this section we use as an example $\nu_\mu$ scattering; similar relations hold for the $\nu_e$ scattering.

Charm production on a fixed target requires neutrino energies above the threshold for production of the lightest charmed meson ($m(D) = 1.8$ GeV). Actually, the majority of neutrino experiments studying charm, use neutrino beams with energies from ten to a few hundreds
GeV. In this energy domain the deep inelastic neutrino nucleon scattering is well described by the interaction of the neutrino with the quarks inside the nucleon. In this picture, the charm quark can be produced by a CC interaction on a constituent d quark, or on a d or s quark of the sea. To the lowest order, the scattering formula is written as [17]

$$d^2\sigma_{c}(\nu_{\mu} \rightarrow \mu^{-} cX)/dxdy =$$

$$2G^2 ME_{\nu_{\mu}}/\pi[V_{cd}^2[[(u(\xi, Q^2) + d(\xi, Q^2))/2 + V_{cs}^2 s(\xi, Q^2)]]$$

where $E_{\nu_{\mu}}$ is the neutrino energy, $M$ the nucleon mass, $Q^2$ the four-momentum transfer squared, $y$ the inelasticity, and $x$ the Bjorken scaling variable (following the conventions given in [18]). The variable $\xi$ gives the actual fraction of nucleon momentum carried by the struck quark, taking into account kinematical effects, and is written as

$$\xi = x(1 + m_c^2/Q^2)(1 - x^2 M^2/Q^2)$$

where $m_c$ is the mass of the c quark. $V_{cd}^2$ and $V_{cs}^2$ are elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. They take into account the two channels of production of the c quark, namely the transitions $d \rightarrow c$ and $s \rightarrow c$. The classification of quark in doublets, with the c and s quarks belonging to the same doublet makes $s \rightarrow c$ the natural transition for charm production. The transition $d \rightarrow c$ is also allowed, because of the mixing described by the Cabibbo angle. In neutrino scattering on nucleon both contributions represent only a few percent of the total cross-section. The transition $s \rightarrow c$ is disfavored because it involves the s quark, which is only present in the sea. The $d \rightarrow c$ channel is in turn suppressed by the smallness of the Cabibbo angle.

A similar formalism can be used to describe $\overline{\nu}_{\mu}$ nucleon scattering. An important difference is that with antineutrino the CC process leads to the production of the charm antiquark $\overline{c}$. The production of charm is then obtained from the scattering on $\overline{d}$ or $\overline{s}$, present only in the sea.

Many corrections and details have to be studied, when applying to real data the formalism described above. For instance, the passage from quarks to the observed particles is usually parameterized in terms of
the so called fragmentation function $D(z)$, where $z$ is the fraction of the charm quark energy carried by the charmed hadron. The basic formulae given above clearly show how measurements of total and differential cross-sections for charm production with neutrino and antineutrino beams can give very important information on the structure functions and the structure of the nucleon, on the elements of the CKM quark mixing matrix, and on the mass of the $c$ quark. Note that besides single charm production in CC interactions, other rarer processes have also been studied, like $c\bar{c}$ production in neutral current scattering (single $c$ production can not happen by Z exchange, since the Z can not produce a change of quark flavor).

4 Experiments on charm physics with neutrino beams

Charm physics has been studied with high energy neutrino beams by many different experiments at Fermilab (Fermi National Accelerator Laboratory) and at CERN (European Organization for Nuclear Research). Most of the experiments made use of general purpose neutrino detectors. Because of the smallness of the neutrino cross-sections, these detectors are very massive and serve at the same time as target. They usually have limited granularity and do not allow to identify single hadrons. Measurements of hadrons are in this case restricted to the energy and direction of the hadronic shower. Charged muons instead, are penetrating particles and can therefore be identified, and their momentum be measured in a magnetic field. The usual event classification in CC or NC (Charged or Neutral Current) interactions is then based, for $\nu_\mu$ interactions for example, on the presence or absence of a $\mu^-$ in the final state. With this kind of detector, charm physics could be studied exploiting the semileptonic decay of the $c$ quark, $c \rightarrow s(d) + \mu^+ + \nu_\mu$. A typical example is the reaction

$$\nu_\mu + N \rightarrow \mu^- + C + X$$
where C is a charmed hadron and X the system of the remaining hadrons. C can decay with a substantial branching ratio producing a $\mu^+$. The final state is then characterized by the simultaneous presence of a $\mu^-$ and a $\mu^+$. Events of this kind are called "opposite sign dimuons"}

and constitute the largest sample of charm events studied with neutrino beams. A background is present, mainly due to pions of the hadronic shower, which occasionally decay or simulate the behaviour of muons. Nevertheless, statistical analysis of the data have yielded very accurate measurements of differential cross-sections for charm production, and allowed the studies mentioned in the previous section. More in general, the identification of muons, and in some case of electrons, has been the main tool of investigation of charm physics with neutrino beams. Note however that other important results were obtained by a few experiments using emulsion targets. In this case the high spatial resolution allowed to directly identify charmed hadrons through the observation of decay paths of few millimeters. Then, properties of the charmed hadrons, like lifetimes and branching ratios could be directly investigated.

In this section, after briefly recalling how neutrino beams are produced, we list all experiments that provided significant results on charm physics, giving a short description for each of them. Physics results obtained by the experiments will then be illustrated and summarized in the following sections 5 to 7.

4.1 Neutrino beams

Neutrino beams for charm studies were operated at CERN and at Fermilab using their respective proton accelerators. Different setups were adopted to vary the energy spectrum and flavour content of the beam, but the basic principle of operation is always the same. To illustrate it, we take the example of the Wide Band Beam (WBB) generated with the 400 GeV Super Proton Synchrotron (SPS) at CERN. A scheme of the beam layout is shown in figure [1] (sizes and distances are not in scale). Protons extracted from the accelerator im-
p + C \rightarrow (interactions) \rightarrow \pi^+, K^+ \rightarrow (decay in flight) \rightarrow \mu^+ + \nu_\mu

Polarity change foreseen!

Figure 1: Setup of the CERN Wide Band neutrino Beam (WBB)

...
neutrino energy spectrum and better control of the contamination of neutrinos of the wrong flavor. Similar techniques were adopted at Fermilab where the proton beam of the Tevatron accelerator ran with energies up to 1000 GeV. A list of the Fermilab neutrino beams can be found in ref [19].

4.2 List of experiments

In the following we list, first for Fermilab, then for CERN, all experiments that provided significant results on charm physics. For each experiment we give schematically the characteristics of the detector, the year of first data taking, and a list of the main studies performed, other than those on charm. Reference is made to some of the most representative publications.

4.2.1 Fermilab experiments

- **E247 (1976)**
  The E247 experiment consisted of an emulsion target followed by a set of spark chambers. It took data in the wide band neutrino beam produced by 600 GeV protons. It produced the first evidence for the production of charmed hadrons in neutrino interactions [9].

- **HPWF (1974)**
  The detector of the HPWF collaboration [20] consisted of an iron target, a liquid scintillator calorimeter [21] and an iron-plates muon identifier [22]. The experiment ran in the quadrupole-triplet and in the bare-target-sign-selected beams at Fermilab in the seventies. In 1975 it made the first observation of dimuon events [23]. It must be noted that in 1974 the collaboration made one of the first confirmation of the existence of neutral currents [24].

- **CCFR, E616, E701, E744, E760 (1976)**
  In 1976 the E616 experiment initiated by the collaboration of the California Institute of Technology, the Chicago University, Fermilab, the University of Rochester and the Rockefeller University,
was the first to use high energy neutrinos (energies up to 300 GeV) in the LabE at Fermilab. The calorimeter of the Collaboration was equipped with spark chambers that limited the data acquisition to one event per extraction. Measurements of neutral current electroweak parameters were reported by experiments E616 and then E701 [25].

The collaboration then became the CCFR collaboration (California, Columbia, Fermilab and Rochester). The CCFR detector consisted of on heavy target calorimeter, a muon spectrometer and drift chambers [26] that replaced the E616 spark chambers. The E744 and E770 experiments took data in 1987-1988 in the neutrino beam from the Tevatron (neutrino energies up to 600 Gev). Main results refer to:

- structure functions [27]
- strange quark content of the nucleon [28]
- neutral currents [29]
- dimuons [30]

Some of these results have been obtained together with the NuTeV collaboration

• 15-foot bubble chamber (1974)

The so-called 15-foot bubble chamber was at the time of construction the largest liquid hydrogen bubble chamber. It started its operation in 1974. In 1987-1988 the E632 Collaboration used the 15-foot chamber, filled with a neon-hydrogen mixture and equipped with an external muon identifier. E632 took data with the quadrupole-triplet neutrino beam at the Tevatron and was the only bubble chamber experiment to study neutrino interactions at Tevatron energies. Studies were made on:

- dimuons [31]
- neutral currents [32]
- strange particles production [33]
- holography [34]
• **E531 (1981)**

The E531 experiment was an hybrid emulsion experiment made of a 23 liter emulsion target, a large aperture analysis magnet, drift chambers, time of flight hodoscopes for charged particles identification, a lead glass array and an electromagnetic calorimeter followed by a muon identifier. The experiment ran in the eighties at Fermilab in the wide band neutrino beam produced by 350 GeV protons and peaked at an energy of 25-30 GeV. The experiment was designed to study the production and decay of short lived particles produced in neutrino interactions \[35\] and also searched for $\nu_\mu \rightarrow \nu_\tau \[36\]$ oscillations.

• **NuTeV (1996)**

NuTeV (E815) was an upgraded version of the CCFR detector. It consisted of an iron scintillator sampling calorimeter interspersed with drift chambers and followed my a muon toroidal magnet \[37\]. The experiment took data in 1996-2001. NuTeV was the last experiment to run in the Fermilab LabE. Results have been obtained on:

- dimuons \[17\]
- neutrino cross sections \[38\] \[39\]
- oscillations \[40\]
- $\sin^2 \theta_W \[41\]$

4.2.2 **CERN experiments**

• **Gargamelle (1970)**

The Gargamelle bubble chamber was built in the Saclay laboratory in France. Filled with propane or freon it was operated from 1970 to 1978 in the CERN neutrino beam. In 1972 data collected with Gargamelle led to the discovery of neutrino neutral current interactions \[42\], providing a fundamental step in the understanding of particle physics. Many important results refer to:

- dileptons \[43\]
– structure functions [44]
– cross sections [45]
– neutral current [46]
– beam dump experiment [47]
– production of strange particles [48]
– neutrino oscillations [49].

• BEBC (1973)
The Big European Bubble Chamber (BEBC) was installed at CERN in the early 70’s and was dismantled in 1985. The vessel was filled with 35 cubic meters of hydrogen or deuterium or neon-hydrogen mixture. The addition of a external muon identifier, an external particle identifier, an internal picket fence and a track sensitive target later converted BEBC in a hybrid detector. BEBC took data from 1973 in a PS beam then from 1977 to 1984 in a SPS beam and concluded his life with a PS oscillation experiments [50].

In 1979 for the first time decays of charmed particles were observed in a bubble chamber [11, 13, 12]. A complete list of BEBC results can be found in [51]. Out of the many studies dedicated to neutrino physics, we recall:

– measurements of neutrino cross sections [52]
– oscillation experiments [53]
– dimuons [54]
– beam-dump [55]

• Conversi (1976)
The hybrid experiment of Conversi at CERN consisted of an emulsion target, followed by a bubble chamber and various electronic detector. The experiment ran in the CERN wide band PS neutrino beam and observed in emulsion the decay of charmed hadrons, providing the first measurements of lifetimes for neutral and charged D particles [11, 12].
• CDHS (1977)
The CDHS collaboration (CERN, Dortmund, Heidelberg, Saclay), initially led by J. Steinberger, took data from 1977 in the neutrino beam of the CERN SPS. In 1983 the CDHS detector was split in two parts and used for a neutrino oscillation experiment in the PS neutrino beam [56].
The detector [57] consisted of circular magnetized iron plates, interspersed with drift chambers, for a total mass of 1250 tonnes. In 35 publications the experiment made contributions in the following fields:

– neutrino and anti-neutrino cross-sections [58]
– structure functions [59]
– beam-dump experiment [60]
– CKM mixing matrix [61]
– electroweak parameters [62]
– multimuon events [61, 63, 64]
– neutrino oscillations [56]

• CHARM (1978)
The CHARM (CERN, Hamburg, Amsterdam, Rome, Moscow) Collaboration started to operate his detector in 1978, taking data with the CERN SPS neutrino beam. The detector was a low density, low Z calorimeter optimized for the detection of neutral currents. It consisted of 78 marble plates interspersed with planes of proportional tubes and scintillators. The marble plates were surrounded by magnetized iron frames. The calorimeter was followed by a muon spectrometer with magnetized iron toroids [65]. Main results refer to:

– structure functions [66]
– neutrino electron scattering [67]
– beam-dump experiment [68]
– polarization of positive muons [69]
- neutrino oscillations [70]
- the electroweak mixing angle [71]

- CHARMII (1982)
  The CHARMII detector was designed to study neutrino electron scattering. It ran in the CERN SPS neutrino beam. It was a massive fine grained calorimeter (692 t) of low density (target material glass) followed by a magnetic spectrometer [72].
  Results were obtained on:
  - neutrino and antineutrino electron scattering and determination of the electroweak mixing angle [73]
  - inverse muon decay [74]
  - search for $\nu_\mu \rightarrow \nu_\tau$ oscillations [75]
  - search for muon to electron oscillations [76]
  - QCD analysis of dimuons events [77]

- NOMAD (1994)
  The NOMAD experiment [78] was designed to detect $\nu_\mu \rightarrow \nu_\tau$ oscillations. It ran in the CERN SPS neutrino beam. The active target consisted of a set of drift chambers (target mass 2.7 ton) located in a magnetic field (0.4 T). The active target was followed by a transition radiation detector to identify electrons, by an electromagnetic and a hadronic calorimeter, and by muon chambers.
  Results were obtained on:
  - neutrino cross-sections [79]
  - neutrino oscillations [80]
  - dileptons [81]
  - production of strange particles [82]
  - meson resonances production [83]
  - D* production [84]

- CHORUS (1994)
The CHORUS experiment took data from 1994 to 1997 in the SPS CERN neutrino beam. The detector [85] was specially designed to detect $\nu_\mu \rightarrow \nu_\tau$ oscillations. It was a hybrid detector with a large (770Kg) emulsion target followed by planes of high resolution fiber trackers used to predict the position in the emulsion of the neutrino interaction vertex by extrapolating backwards particle tracks.

Limits on $\nu_\mu \rightarrow \nu_\tau$ oscillations are published in [86]. The results on charm physics will be described in section 7.

5 Charm physics with opposite-sign dimuons

5.1 Introduction

Opposite-sign dimuons have been the main tool of investigation of charm physics with neutrino beams. In that process, described in the previous sections, the leading muon (the muon of highest energy) is interpreted as originating from the neutrino vertex, while the opposite-sign muon (or electron in bubble chamber detectors) as due to the leptonic decay of the charm inside the hadronic shower.

The history of dimuons starts already in 1974, the year of the J/Psi discovery, when the HPWF Collaboration at Fermilab found two events attributed to the reaction $\nu_\mu + N \rightarrow \mu + \text{hadrons}$ followed by a muonic decay inside the hadronic shower. In their paper the authors mention the following interpretation [23]: One possibility is that the particle jet produced by very high energy neutrinos has an anomalously large probability to decay into a (positive) muon. Models generating this type of effect due to the presence of novel hadronic quantum numbers (charm) have been recently suggested by Glashow, Iliopoulos and Maiani [3].

The HPWF experiment was also the first to confirm in 1975 charm
production in a neutrino beam by publishing results obtained with a sample of about 100 dimuons [87]. From then on, all neutrino experiments searched for dimuon events and a complete list of dimuon (or better dilepton) experiments is given in the following table.

| n | Experiment | authors | reference | technique       |
|---|------------|---------|-----------|-----------------|
| 1 | HPWF       | A. Benvenuti et al. 1988 | [88]       | counter exp     |
| 2 | BEBC       | G. Gerbier et al. 1985   | [89]       | bubble chamber  |
| 3 | Gargamelle | N. Armenise et al. 1979, | [90]       | bubble chamber  |
| 4 | Gargamelle | A. Haatuft et al. 1983   | [43]       | bubble chamber  |
| 5 | LBL coll.  | H.C. Ballagh et al. 1981 | [31]       | bubble chamber  |
| 7 | CB coll.   | N.J. Baker et al. 1985   | [91]       | bubble chamber  |
| 6 | CDHS coll. | Abramowicz et al. 1982   | [61]       | counter exp     |
| 9 | E616       | K.Lang et al. 1987       | [92]       | counter exp     |
| 10| CCFR       | A.Rabinowitz et al. 1993 | [93]       | counter exp     |
| 11| NUTEV      | M. Goncharov et al. 2001 | [17]       | counter exp     |
| 11| CHARMII    | P. Vilain et al. 1999    | [94]       | counter exp     |
| 12| CHORUS     | A.Kays-Topaksu et al. 2008 | [95]       | counter exp     |
| 13| NOMAD      | P. AStier et al. 2000    | [81]       | counter exp     |

Table 1: Dilepton experiments

The CDHS Collaboration at CERN reached in the early eighties the largest statistics, with 9922 dimuons collected in neutrino beam, and 3123 in antineutrino beam. The picture was later completed with the high energy data collected in 2001 by the NuTeV experiment [17] using the neutrino beam produced by the 1 TeV protons of the Fermilab Tevatron.

The large statistics collected at various energies in $\nu_\mu$ and $\bar{\nu}_\mu$ beams allowed to investigate in detail the production mechanism of charm outlined in section 3. Quality and statistics of the data collected by the various experiments between 1975 and 2000 are well illustrated by the plot shown in Fig. 2.

The figure comes from a review paper of 2002 [96] where the measurements of the opposite-sign dimuon cross-section $\sigma_{+-}$ are combined in a single plot. The plot gives the ratio of $\sigma_{+-}$ to the CC cross-section for $\nu_\mu$ N scattering as a function of $E_{\nu_\mu}$. At low energy it shows with high precision the kinematical suppression generated by the large mass of the c quark. At high energy it gives the plateau value of 0.9% and shows that the c quark contribution to the CC cross-
Figure 2: Neutrino dimuon cross-section from [96]
section behaves similarly to all other hadronic processes. Note how-
never that the review did not include the high energy data of NuTeV

[17].

Dimuons data taken with neutrino and antineutrino beams were ex-
tensively analyzed in order to extract information on the process of
charm production. The results obtained for each of the physics prop-
erties involved in the scattering process will now be presented and
discussed.

5.2 The analysis of dimuon events

The basic formalism adopted by the experiments to analyze dimuons
was discussed in section 3, where the QCD lowest order cross-section
for charm production is given. Then, when analyzing dimuons, one
has to take into account the fragmentation of the quark into hadrons
and the branching ratio \( B_\mu \) for the inclusive muonic decay of the
charmed hadron. The usual description has the form

\[
d^3(\sigma_{+-})/d\xi dy dz = d^2\sigma_c(\nu_\mu N \rightarrow cX)D(z)B_\mu /d\xi dy
\]

Here \( D(z) \) is the fragmentation function for the charm quark, with
\( z = E_c/E(\text{hadrons}) \) defined as the fraction of the total hadronic energy
taken by the charmed hadron. \( D(z) \) and \( B_\mu \) are usually both averaged
over all charmed hadrons produced.

The basic formalism is then used to fit with MonteCarlo techniques
the experimental distributions generally obtained from the measure-
ments of the momenta of the two muons, of the energy and direction
of the hadron shower, and from the known direction of the incoming
neutrino. Similar analysis techniques were used by all experiments
and their various results are summarized hereafter.

- \( m_c \), the mass of the charm quark

Unlike leptons, quarks are confined inside hadrons and are not
observable as free particles. Therefore, quark masses cannot be
directly measured and must be defined within a theoretical frame-
work. However, quantitative kinematical effects are produced by
the mass of the charm quark, which in particular generates threshold effects on the dimuon cross-section. This effect is usually taken into account using the so-called slow rescaling formalism [97]. Fig 3 shows the effect of $m_c$, the c quark mass, on the low energy behavior of cross sections, and the correction obtained by the CCFR collaboration using a leading order low-rescaling formalism [93].

Values of $m_c$ obtained by different experiments using the slow-rescaling formalism are given in Table 2.

| Experiment | $N_{2\mu}(\nu_{\mu})$ | $N_{2\mu}(\overline{\nu}_{\mu})$ | $m_c$(GeV) | $k$ | $B_{\mu}$ |
|------------|-----------------|-----------------|-------------|-----|---------|
| CDHS [61]  | 9922            | 3123            | 1.26 ± 0.18 | 0.52 ± 0.09 | 0.071 ±0.013 |
| CCFR [93]  | 5044            | 1062            | 1.31 +0.20+0.12 -0.22−0.11 | 0.373 ± 0.09 | 0.084 ± 0.014 |
| CHARMII [94] | 3100          | 700             | 1.8 ± 0.4    | 0.39 ± 0.09 | 0.091 ±0.010 |
| NOMAD [81] | 2714            | 655             | 1.3 ± 0.4    | 0.48 ± 0.17 | 0.095 ± 0.015 |
| NUTEV [98] | 5102            | 1458            | 1.24 ± 0.25  | 0.42 ± 0.08 | 0.101 ± 0.012 |
| CHORUS [95] | 8910           | 430             | 1.26 ± 0.18  | 0.33 ± 0.07 | 0.096 ± 0.008 |

Table 2: Parameters determined from dimuon events

Attempts have been made to determine the value of $m_c$ to the next to leading order. For example, the CCFR Collaboration with such analysis quotes [28] a value of 1.6 ± 0.16 GeV for $m_c$, while at the leading order the same Collaboration gets $m_c = 1.31$ GeV (see table 2).

It is worth mentioning that the value of $m_c$ enters also in the determination of $\sin^2 \vartheta_w$ from the ratio NC/CC in neutrino-nucleon scattering. For example, the CHARM Collaboration [99] quotes his measurement in the form

$$\sin^2 \vartheta_w = 0.234 + 0.012( m_c - 1.5 \text{ GeV}) \pm 0.0051 \pm 0.0024.$$  

- $k$: the strange quark content of the nucleon

Since the charm quark is produced in neutrino interactions also by the scattering off the s quark, which is only present in the sea, the study of dimuon differential cross-sections can be used to determine the strange quark content of the nucleon. Neutrino experiments usually give results for $k$, where $k$ is defined as the ratio of strange quark over sea $\overline{d}$ and $\overline{u}$ antiquarks,
Figure 3: Neutrino and antineutrino cross-section ratios from ref [93]. Squares: data. Circles: data corrected with the low rescaling formalism.
The values of $k$ obtained by various experiments are given in table 2. They agree with each other and show a marked asymmetry of the strange quark sea compared to the $\bar{d} + \bar{u}$ average.

The CCFR Collaboration [93] has also studied:

a) the ratio of the strange quark distribution $s$ over that of the valence quark $u+d$. They find $\eta(x) = 2s/(u + d) = 0.064 \pm 0.008 \pm 0.002$

b) the $x$ dependence of the sea quark defined as

$$s(x) = (1 - x)^{\beta}/x$$

The obtained value, $\beta = 9.45$, shows that the strange sea is softer than the total sea ($\beta = 6.95$).

It must be noted that no difference between $s$ and $\bar{s}$ distributions has been found [28].

- **$B_{\mu}$**: the muonic charm branching ratio

$B_{\mu}$, the average inclusive muonic branching ratio of charmed hadrons, is usually treated in the full analysis of the dimuons differential cross-sections as an overall normalization factor. Values of $B_{\mu}$ obtained by the various dimuon experiments are given in table 2. There is also a direct measurement of the muonic branching ratios performed in emulsions by the CHORUS experiment. This will be discussed in section 7.

- **The fragmentation of the charm quark**

The hadronization of the charm quark is usually described by a phenomenological fragmentation function $D(z)(z=E_C/E(\text{hadrons}))$. Many neutrino experiments obtained a satisfactory description of the data using for $D(z)$ the Peterson parameterization [100]

$$D(z) = [1/z(1 - 1/z - \epsilon_p/(1 - z))]^{-2}$$

where $\epsilon_p$ is a parameter to be determined by the fit to the dimuons distributions. Results of the fits performed by the various experiments are shown in table 3 by quoting the value of the average
z and, for those experiments adopting the Peterson parameterization, the value of $\epsilon_p$.

| Experiment          | $z$ average | $\epsilon_p$     |
|---------------------|-------------|-------------------|
| BEBC [101]          | 0.59±0.09   |                   |
| E531 [102]          | 0.61±0.02   | 0.076±0.014       |
| CHORUS calorimeter  | 0.61±0.05   | 0.040±0.015       |
| CHORUS emulsions(*) | 0.63±0.103  | 0.108±0.017±0.013 |
| NOMAD [84]          | 0.67±0.03   | 0.075±0.046       |
| CDHS [61]           | 0.68±0.08   |                   |
| CCFR [93]           | 0.56±0.03   | 0.22±0.05         |
| CHARM II [94]       | 0.66±0.03   | 0.072±0.017       |

Table 3: Values of $z$ average and $\epsilon_p$. (*) for Chorus emulsions see section [7]

Other fragmentation properties of charm have been obtained by NOMAD, studying the D$^{+*}$ production [84], by E531 [35] from the study of inclusive charm production, by BEBC from the study of D$^{+*}$ [101] and by CHORUS from its large sample of D$^0$ [104].

- Measurements of the CKM matrix elements $V_{cd}$ and $V_{cs}$
  
  The cross-section for charm production in neutrino and antineutrino scattering on nucleons is directly related to the relative strength of the coupling of the c quark with the s and d quarks. Fits to the dimuons differential cross-sections have therefore been used to determine the $V_{cd}$ and $V_{cs}$ elements of the CKM matrix. These matrix elements have been measured in many different reactions and a recent review of all measurements, including those from neutrino experiments, can be found in ref [105]. It turns out that dimuons give the best overall determination of $V_{cd}$, while the measurement of $V_{cs}$ in neutrino scattering suffers from the uncertainties on the sea quark content of the nucleon. The results on $V_{cd}$ and $V_{cs}$ from the analysis of dimuons are the following.

  Measurements of $V_{cd}$
  
  The determination of $V_{cd}$ is derived from the difference of the dimuon over single-muon cross-section ratios for neutrinos and antineutrinos, a difference which is proportional to $B_\mu V_{cd}^2$. This method was first used in 1982 by the CDHS Collaboration, and then adopted in all neutrino experiments. The results of their
analyses are given in table 4.

| Experiment | $B_u V_{cd}^2$ | $B_u$ | $V_{cd}$ | ref |
|------------|---------------|-------|----------|-----|
| CDHS       | $4.11\pm0.07\cdot10^{-3}$ | $7.1\pm1.3\cdot10^{-2}$ | $0.24\pm0.03$ | [61] |
| CCFR       | $5.34^{+0.038}_{-0.21}\cdot10^{-3}$ | $9.9\pm1.2\cdot10^{-2}$ | $0.232^{+0.018}_{-0.020}$ | [28] |
| CHARMII    | $4.75\pm0.27\cdot10^{-3}$ | $9.1\pm1.0\cdot10^{-2}$ | $0.227\pm0.006\pm0.011$ | [24] |
| CHORUS     | $0.74\pm0.27\cdot10^{-3}$ | $9.6\pm0.8\cdot10^{-2}$ | $0.222\pm0.016$ | [95] |

Table 4: $V_{cd}$ values

A combined analysis of the results from dimuons shown in table 4 gives $V_{cd}=0.230\pm0.011$ [105], which represents the best determination of $V_{cd}$, compared to those obtained in any other sector.

Measurements of $V_{cs}$

Measurements of the matrix element $V_{cs}$ with dimuons have been reported by the CDHS, CCFR and CHARM2 Collaborations. Their results have been combined in a review paper of 2000 [106] giving $V_{cs}=1.04\pm0.16$. This value can be compared with the world average $V_{cs}=1.023\pm0.036$ computed by the Particle Data Group [105].

6 Multimouon events and associated charm production

The main channel for open charm production in neutrino interaction is the CC reaction described in section 3 and experimentally studied with dimuons as described in section 5. However, many experiments have also searched for the rarer process of associated production of open charm. Theoretically $c\bar{c}$ production is expected both in NC and CC processes. The main contribution should come from the so-called "gluon-boson fusion" process [107] shown in fig 4 in NC reactions, and from the "gluon-quark bremsstrahlung" process [108] shown in fig 5 in CC reactions.

Both processes are rare, mostly because of the higher threshold of 3.7 GeV for two charmed mesons, and difficult to isolate. Many searches for $c\bar{c}$ production were performed using the massive electronic detectors and looking for muons from charm decay. The first evidence only came in year 2000 from the high statistics, high energy NuTeV-
Figure 4: Gluon-boson fusion graph, NC reaction

Figure 5: Gluon-quark bremsstrahlung graph, CC reactions
E815 experiment at Fermilab. Its result was then confirmed by the CHORUS experiment at CERN, by detecting the decay of charmed hadrons in its emulsion target. In this section we recall the main results obtained from the multimuon searches with electronic detectors. The results from emulsion experiments are given in the next section.

6.1 Wrong-sign muons

A signature for $c\bar{c}$ production in NC interactions is given by the so-called wrong-sign muon events. These are events in which the single muon in the final state has a lepton number opposite to that of the incident neutrino. The event is a NC interaction since the muon with the incoming neutrino lepton number is missing. The wrong-sign muon is then attributed to the decay of a charmed hadron. Since there is no single charm production in NC interactions, it is assumed that a second undetected charmed hadrons is present in the hadron shower. First searches for wrong-sign muons only led to negative results. For instance, data taken with the CCFR detector at Fermilab are analyzed in a 1989 paper [109] resulting in a number of wrong sign muons compatible with that expected from background. First evidence for $c\bar{c}$ production, and up to now the only evidence with wrong-sign muon events, was obtained in year 2000 by the NuTeV-E815 experiment at Fermilab. The experiment running in a narrow-band beam with an average neutrino energy of 154 GeV quotes the following cross-section [110]:

$$\sigma(\nu_\mu N \rightarrow c\bar{c}X) = 0.21^{+0.18}_{-0.15} \text{ fb.}$$

The existence of the process was proved, although the errors were too large to allow a quantitative analysis of the signal.

6.2 Same-sign dimuons

Same-sign dimuons can be a signature for $c\bar{c}$ production in CC reactions. For this to be true, it is required the presence of a leading muon with the sign corresponding to the lepton number of the incoming neutrino and of a second muon within the hadron shower, with the same sign of the leading muon. The second muon is associated
to the decay of a charmed hadron. It is then assumed that a second, undetected, charmed hadron is present, since in the case of single charm production the muon from charm decay would have opposite sign with respect to the leading muon. Several experiments have observed same-sign dimuon events, but no experiment could provide clearcut evidence for $c\bar{c}$ production. The statistics collected by the more important experiments are shown in table 5.

| Experiment | $\mu^{++}$ | $\mu^{--}$ | ref   | year |
|------------|------------|------------|-------|------|
| CDHS       | 52         | 74         | [63]  | 1979 |
| CHARM      | 52         | 74         | [111] | 1982 |
| CCFR       | 25         | 220        | [112] | 1993 |
| NuTeV      | 15         | 101        | [113] | 1988 |

Table 5: Same-sign dimuons

Because of many different background processes contributing to those samples, no firm conclusion on the interpretation of these events has been reached. We quote as an example the statement made in the NuTeV paper [113]: The small excess of $\mu^-\mu^-$ is consistent with but does not require $c\bar{c}$ production.

6.3 Trimuons

Events with three muons in the final state can indicate $c\bar{c}$ production in CC reactions, similarly to the same-sign dimuons described above. The signature is cleaner, but the rates are further reduced because both charmed hadrons are required to decay into a muon. Again, several experiments have collected a sample of few trimuons events, but none of them was able to prove $c\bar{c}$ production. The statistics collected are given in table 6.

The largest statistics is that of the emulsion experiment CHORUS, which used for this analysis its hadron calorimeter as target for the neutrinos. In their paper [115] the authors attribute the 42 events to various processes, without requiring a contribution from $c\bar{c}$ production.
Four neutrino experiments have investigated charm physics using nuclear emulsions as target and detector. The spatial resolution of nuclear emulsions makes possible the direct detection of charmed particles through the observation of the few millimeters long decay-paths. Contrary to the electronic experiments described in the previous sections, the charmed hadrons detected in emulsions are then practically background free and so single events can give relevant information. In fact, following the proposal of Conversi [8] two fundamental experiments, E247 at Fermilab and WA17 at CERN were carried on in the late seventies. The two experiments made use of an emulsion target followed by few electronic detectors to identify and measure momenta of charged particles. In 1976 E247 [9, 10] was the first to measure the lifetimes of the new hadrons showing that these were consistent with the expectation for hadrons with charm. In 1979 the few events collected by WA17 [11, 13] allowed to establish a difference in lifetime between charged and neutral charmed hadrons, confirming theoretical predictions for the decay process involving the c quark. WA17 also observed the decay of one charmed baryon [12].

After the two historical experiments, emulsion target were rarely used for the study of charm physics with neutrino beam, mainly because the analysis of emulsion film has to be performed manually at microscopes and the scanning phase makes it long and difficult to collect large statistics. Nevertheless, few important measurements were reported in the eighties by the E531 experiment at Fermilab. Ten years later a large sample of charm events was collected by the CHORUS experiment at CERN, which exploited the huge progress in the au-

| Experiment | $\mu^{--}$ or $\mu^{+-}$ | ref | year |
|------------|-------------------------|-----|------|
| HPFW       | 39                      | 20  | 1978 |
| FNAL       | 3                       | 114 | 1977 |
| Gargamelle  | 10                      | 43  | 1982 |
| CDHS       | 2                       | 64  | 1978 |
| CHORUS     | 42                      | 115 | 2003 |

Table 6: Results on trimuon detection

7 Emulsion experiments

tomation of the process of emulsion scanning. We shall now give some detail on these two experiments.

7.1 E531

The E531 experiment at Fermilab has collected in the early eighties a total of 3855 neutrino interactions and identified 121 decays of charmed hadrons. As shown in Table 7, E531 was able to identify the different charmed hadrons and to provide evidence for the production, besides of $D^0$ and $D^+$, also of $D_s^+$ and $\Lambda_c^+$.

| particle | number |
|----------|--------|
| $D^0$    | 57     |
| $D^+$    | 41     |
| $D_s^+$  | 6      |
| $\Lambda_c^+$ | 14 |

Table 7: E531 charmed hadrons

E531 described in [102] characteristics of the charm production by neutrinos and reported in [35] the measurement of the ratio of cross-sections, $\sigma(\text{charm})/\sigma(\text{total}) = 5.4 \pm 0.7\%$. That value, although less precise than the measurements performed by electronic experiments using dimuon events, does not depend from $B_\mu$, the average branching ratio for charmed hadrons into muons.

7.2 CHORUS

The CHORUS experiment, shortly described in section 4, took data in the wide-band neutrino beam at the CERN SPS from 1994 to 1997 and identified the decay of 2059 charmed hadrons in the 770 kg emulsion target. The collection of such a huge sample was made possible by the automation of the scanning with computer driven microscopes, and by the use of a new analysis technique, the so-called ’netscan method’, originally developed for the DONUT experiment and described in [116]. The ’netscan method’ uses all the microtracks which at the scanning level were found by joining emulsion grains, and reconstructs primary and secondary vertices and tracks of the neutrino interactions.
The 2059 events with hadron decays were classified following the topology at the decay vertex, as \( V_n \), for neutral charms, and as \( C_n \) for charged, where \( n \) is the number of charged tracks from the decay vertex. The number of events for each topology is given in Table 8.

| topology | number |
|----------|--------|
| C1       | 461    |
| V2       | 841    |
| C3       | 501    |
| V4       | 230    |
| C5       | 23     |
| V6       | 3      |

Table 8: CHORUS topologies of charm decays

The analysis has led to various results. About 15 papers were published from the first 1998 [117] to the last in 2011 [118]. We list in the following the most relevant studies.

- **Cross-sections**
  
The E531 measurement of the total neutrino cross-section for charm production, independent from \( B_\mu \), was repeated by CHORUS and completed with the measurement of the antineutrino cross-section [119].

- **The production of the \( \Lambda_c \)**
  
  CHORUS had limited capabilities of particle identification, nonetheless it succeeded to identify a sample of \( \Lambda_c \) on statistical basis, by using the different flight lengths of \( \Lambda_c \) and D particles. The total neutrino cross-section for \( \Lambda_c \) production relative to the CC cross-section was measured to be
  \[
  \sigma(\Lambda_c)/\sigma(CC) = \left(1.54 \pm 0.35 \pm 0.18\right) \times 10^{-2} \quad [120]
  \]
  
  This result indicates that about 40% of all charmed hadrons produced in neutrino interaction at an average neutrino energy of 27 GeV are \( \Lambda_c \). The production mechanisms of the \( \Lambda_c \) were also investigated and, using topological and kinematical criteria, it was possible to separately measure the contribution of the quasi-elastic process obtaining:
  \[
  \sigma(\Lambda_c(QE))/\sigma(CC) = 0.23^{+0.12}_{-0.06} \times 10^{-2} \quad [121].
  \]
- **Associated charm production**

  The search for $c\bar{c}$ associated charm production with electronic detectors has been discussed in sect 6, where we recalled that the only positive signal was found in NC events by the NuTeV collaboration. CHORUS has directly searched for $c\bar{c}$ production by looking for events with two charmed particles decays. Double charm production in neutrino NC interactions was confirmed by the observation [122] of three double-decay events, corresponding to the following cross-sections ratio:

  $$\frac{\sigma(c\bar{c}_{NC})}{\sigma(NC)} = (3.62^{+2.46}_{-2.42} \text{ (stat)} \pm 2.0 \text{ (syst)} \times 10^{-3}).$$

  The experiment also found a candidate consistent with double charm production in CC interaction, but preferred to quote just the upper limit

  $$\frac{\sigma(c\bar{c}_{CC})}{\sigma(CC)} \leq 9.69 \times 10^{-4}.$$  

- **$D^0$ decay branching ratios**

  CHORUS has studied in detail the topological branching ratios of the $D^0$ meson, an interesting subject given that at the time of publication (2005) only 64% of the $D^0$ branching ratios had been measured. The results were given for the different charm decays topologies in terms of number of prongs, i.e. the number of charged particles from the decay vertex. CHORUS measured the rates of the 2,4,6 prongs decays and used as normalization factor the PDG value [123] for the 4-prongs decay, $\Gamma(4\text{prongs})/\Gamma(\text{total}) = .146 \pm 0.005$. With that normalization, by subtraction, also the 0-prong b.r. was obtained. The published results [104] are the following:

  $$\Gamma(0\text{prongs})/\Gamma(\text{total}) = 0.218 \pm 0.049 \pm 0.036$$  

  $$\Gamma(2\text{prongs})/\Gamma(\text{total}) = 0.647 \pm 0.049 \pm 0.031$$  

  $$\Gamma(6\text{prongs})/\Gamma(\text{total}) = (1.2^{+1.3}_{-0.9} \pm 0.2) \times 10^{-3}.$$  

- **Muonic branching ratios**

  $B_\mu$, the inclusive branching ratio of charmed hadrons for decays with a muon, is an important normalization factor for the charm
physics studied by the electronic detectors using dimuon events. CHORUS has performed an independent measurement of $B_\mu$ analyzing the muonic decay associated to the various decay topologies. The results \cite{124} are summarized in table 9 which gives for each topology background and efficiency, and the resulting corrected $B_\mu$.

| topology | selected | background (%) | efficiency | $B_\mu$   |
|----------|----------|----------------|------------|-----------|
| C1       | 20       | 0.8            | 36.0 ± 3.4 | 10.8 ± 2.4 ± 0.5 |
| C3       | 17       | 8.4            | 26.4 ± 2.6 | 6.1 ± 1.6 ± 0.6  |
| V2+V4    | 36       | 9.8            | 30.1 ± 1.5 | 8.1 ± 1.5 ± 0.3  |

Table 9:Muon branching ratios and values of $B_\mu$

From the results given in table 9 an average $\overline{B}_\mu$ of $(8.5 \pm 0.9 \pm 0.6) \times 10^{-2}$ has been derived.

\section{Conclusion}

Our recollection has summarized the many important results on properties of the $c$ quark and of charmed hadrons collected in thirty years of experimentation with neutrino beams, together with a brief description of the techniques adopted. Nowadays experiments with neutrino are designed to study oscillations, aiming at a complete understanding of the pattern of neutrino masses and mixings, and perhaps of CP violations in the neutrino sector (a review on neutrino oscillation experiments can be found in \cite{125}). So, after having played an important role in the measurement of the CKM matrix, neutrino experiments are now engaged in the new task of unveiling the complete Pontecorvo-Maki-Nakagawa-Sakata matrix.

We should add that in our opinion, charm physics with neutrinos has strongly influenced the evolution of the overall picture of quarks in particle physics. By studying the role of valence and virtual quarks,
the role of quark masses in the scattering and hadronization processes, neutrino charm physics has contributed to our current understanding of quarks in the Standard Model.

Acknowledgments

We gratefully acknowledge the enlightening contribution of P.F. Loverre in discussing and revising many different aspects of the paper, and the critical reading of L. Ludovici and B. Saitta.

References

[1] J. Augustin et al. Discovery of a narrow resonance in e+e- annihilations. *Phys.Rev.Lett.*, 33:1406, 1974.

[2] J.J. Aubert et al. Experimental observation of a heavy particle. *J. Phys.Rev.Lett.*, 33:1404, 1974.

[3] S.L. Glashow J.Iliopoulos and L.Maiani. Weak interactions and lepton hadron symmetry. *Phys.Rev*, D2:1285, 1970.

[4] J. D. Bjorken and S. L. Glashow. Elementary Particles and SU(4). *Phys.Lett.*, 11:255, 1964.

[5] I.Peruzzi et al. Observation of a narrow charge state at 1876 MeV decaying in exotic combination of $K\pi\pi$. *Phys.Rev.Lett.*, 37:569, 1976.

[6] M. Piccolo et al. D meson production and decay in e+ e- annihilation at 4.03 GeV and 4.41 GeV center of mass energy. *Phys.Lett.*, B70:260, 1977.

[7] G. Goldhaber et al. D and $D^*$ meson production near 4 GeV in $e^+ e^-$ annihilation. *Phys.Lett.*, B69:503, 1977.

[8] M. Conversi. Feasibility of combining emulsion, bubble chamber and counter techniques to study new shortlived particles produced by neutrinos. *CERN NP Internal Report 75-17*, 1975.
[9] E.H.S. Burhop et al. Observation of a likely example of the decay of a particle produced in high energy neutrino interaction. *Phys.Lett.*, B65:299, 1976.

[10] A.L. Read et al. Search for shortlived particles in high-energy neutrino interactions identified using a hybrid emulsion spark chamber arrangement. *Phys.Rev.*, D19:1287, 1979.

[11] D. Allasia et al. First direct observation of the decay of neutral charm particles produced by neutrinos in emulsions. *Phys.Lett.*, B87:287, 1979.

[12] D. Allasia et al. Investigation of decay of charmed particles produced in neutrino interactions. *Nucl.Phys.*, B176:13, 1980.

[13] C. Angelini et al. On the lifetime of charged charm particles: First direct observation of a charged baryon decay. *Phys.Lett.*, B84:150, 1979.

[14] K. Niu et al. A possible decay in flight of a new type of particle. *Prog.Theor.Phys.*, 46:1644, 1971.

[15] K. Niu. Discovery of naked charm particles and lifetime differences among charm species using nuclear emulsions innovated in Japan. *Proc.Japan.Acad.*, B84:1, 2008.

[16] P. Migliozzi G. De Lellis and P. Santorelli. Charm physics with neutrinos. *Phys.Rep.*, 399:227, 2004.

[17] et al. M. M. Goncharov. Precise measurement of dimuon production cross-sections in muon neutrino Fe and muon antineutrino Fe deep inelastic scattering at the tevatron. *Phys.Rev*, D64:112006, 2001.

[18] J. Steinberger. Experiments with high-energy neutrino beams, Nobel lecture. *Rev.Mod.Phys.*, 61:533, 1989.

[19] S. Kopp. Accelerator-based neutrino beams. *Phys.Rep.*, 439:101, 2007.

[20] A. Benvenuti et al. Further observation of trimuon production by neutrinos and antineutrinos. *Phys.Rev.Lett.*, 40:488, 1978.
[21] A. Benvenuti et al. A liquid scintillator total absorption hadron calorimeter for the study of neutrino interactions. *Nucl.Instr. and Meth.*, 125:447, 1975.

[22] A. Benvenuti et al. A large area magnetic spectrometer for the study of high-energy interactions. *Nucl.Instrum.Meth.*, 125:457, 1975.

[23] B. Aubert et al. Experimental observation of $\mu^+\mu^-$ pairs produced by very high energy neutrinos. *AIP Conf.Proc.*, 22:201, 1974.

[24] A. Benvenuti et al. Measurements of the rates of muonless deep inelastic neutrino and antineutrino interactions. *Phys.Rev.Lett.*, 82:1454, 1974.

[25] P. G. Reutens et al. A Measurement of the neutral current electroweak parameters using the Fermilab narrow band neutrino beam. *Z.Phys.*, C45:539, 1990.

[26] W. K. Sakumoto et al. Calibration of the CCFR target calorimeter. *Nucl.Instrum.Meth.*, A294:179–192, 1990.

[27] W.G. Seligman. Improved determination of alfa strong. *Phys.Rev.Lett.*, 79:1213, 1997.

[28] C. Bazarko et al. Determination of the charm quark content of the nucleon from a next-to-leading-order QCD analysis from neutrino charm production. *Z.Phys.*, C65:189, 1995.

[29] C.G. Arroyo et al. Precise measurement of the weak mixing angle in neutrino nucleon scattering. *Phys.Rev.Lett.*, 72:3452, 1994.

[30] C. Foudas et al. Production of opposite sign dimuons at Fermilab Tevatron energies. *Phys.Rev.Lett.*, 64:1207, 1990.

[31] H.C. Ballagh et al. Dilepton production by neutrinos in fermilab 15-foot chamber. *Phys.Rev.*, D24:7, 1981.

[32] M. Aderholz et al. Study of high-energy neutrino neutral current interactions. *Phys.Rev.*, D45:2232, 1992.
[33] D. DeProspo et al. Neutral strange particle production in neutrino and anti-neutrino charged current interactions on Neon. *Phys.Rev.*, D50:6691, 1994.

[34] G.G. Harigel. Holography in the Fermilab 15-foot bubble chamber. *Nucl.Instr.Meth.*, 257:614, 1987.

[35] N. Ushida et al. Cross section for neutrino production of charmed particles. *Phys.Lett.*, B206:375, 1988.

[36] N. Ushida et al. Search for numu-nutau oscillations. *Phys.Rev.Lett.*, 47:1694, 1981.

[37] D. Harris et al. Precision calibration of the NuTeV calorimeter. *Nucl.Instrum.Meth.*, A447:377, 2000.

[38] S. Boyd et al. Cross section measurements and charm production in the NuTeV experiment. *AIP Conference Proc.*, 698:95, 2004.

[39] A. Bodek et al. A Measurement of $R = \sigma_L / \sigma_T$ in deep inelastic neutrino - nucleon scattering at the Tevatron. *J.Phys.G*, G22:775, 1996.

[40] S. Avvakumov et al. Search for muon neutrino and antineutrino oscillations at NuTev. *Phys.Rev.Lett.*, 89:011804, 2002.

[41] G. P. Zeller et al. A measurement of $\sin^2 \theta_w$ in $\nu$ N scattering from NuTeV. *arxiv:hep-ex/9906024*, 1999.

[42] F.J. Hasert et al. Observation of neutrino like interactions without muon or electron in the Gargamelle neutrino experiment. *Phys.Lett.*, B73:1, 1974.

[43] A. aatuft et al. Dilepton and trilepton production by neutrinos in Gargamelle at the CERN SPS. *Nucl.Phys.*, B222:365, 1983.

[44] D. Allasia et al. Measurement of the neutron and proton structure functions from neutrino and anti-neutrinos scattering in deuterium. *Phys.Lett.*, B135:231, 1984.
[45] D. Allasia et al. Measurement of The muon-neutrino and anti-muon-neutrino nucleon charged current total cross sections, and the ratio of muon-neutrino neutron to muon-neutrino proton charged current total cross sections. *Nucl.Phys.*, B239:301, 1984.

[46] D. Allasia et al. Measurement of the neutral current couplings in neutrino and antineutrino interactions in deuterium. *Phys.Lett.*, B133:129, 1983.

[47] P. Alibran et al. Observation of an excess of electron-neutrino, antielectron-neutrino events in a beam dump experiment at 400-GeV. *Phys.Lett.*, B74:134, 1978.

[48] O. Erriquez et al. Production of Strange Particles in anti-neutrino interactions at the CERN PS. *Nucl.Phys.*, B140:123, 1978.

[49] N. Armenise et al. Search for neutrino oscillations in Gargamelle at SPS. *Phys.Lett.*, B100:182, 1981.

[50] C. Angelini et al. New experimental limits on muon-neutrino → electron-neutrino oscillations. *Phys.Lett.*, B179:307, 1986.

[51] G.G. Harigel. List of publications covering BEBC experiments. *CERN/EP*, 85-06, 1985.

[52] P. Bosetti et al. Total cross-sections for muon-neutrino and anti-muon-neutrino charged current interactions between 20 GeV and 200 GeV. *Phys.Lett.*, B110:167, 1981.

[53] O. Erriquez et al. Limits on neutrino oscillations from a study of electron-neutrino charged current interactions. *Phys.Lett.*, B102:73, 1981.

[54] N. Armenise. Dimuon events produced in high-energy antineutrino interactions observed in BEBC. *Phys.Lett.*, B94:527, 1980.

[55] H. Grassler et al. Prompt neutrino production in 400 GeV proton-copper interactions. *Nucl.Phys.*, B273:253, 1986.
[56] F. Dydak et al. A Search for Muon-neutrino Oscillations in the Delta M**2 Range 0.3-eV**2 to 90-eV**2. Phys.Lett., B134:281, 1984.

[57] M. Holder et al. A detector for high energy neutrino interactions. Nucl.Instrum.Meth., 148:235, 1978.

[58] J.G.H. de Groot et al. Inclusive interactions of high-energy neutrinos and anti-neutrinos in Iron. Zeit.Phys., C1:143, 1979.

[59] J.G.H. de Groot et al. QCD Analysis of Charged Current Structure Functions. Phys.Lett., B82:456, 1979.

[60] T. Hansl et al. Results of a Beam Dump experiment at the CERN SPS Neutrino Facility. Phys.Lett., B74:139, 1978.

[61] H. Abramowicz et al. Experimental study of opposite sign dimuons in neutrino and antineutrino interactions. Z.Phys, C15:19, 1982.

[62] A. Blondel et al. Electroweak parameters from a high statistics neutrino nucleon scattering experiment. Z.Phys., C45:361, 1990.

[63] J.G.H. de Groot et al. Investigation of like-sign dimuon production in neutrino and anti-neutrino reactions. Phys.Lett., B86:103, 1979.

[64] M. Holder et al. Observation of trimuon produced in neutrino and antineutrino interactions. Phys.Lett., B70:393, 1977.

[65] A. N. Diddens et al. A detector for neutral current interactions of high energy neutrinos. Nucl.Instrum.Meth., 178:27, 1980.

[66] F. Bergsma et al. Experimental study of the nucleon structure functions and of the gluon distribution from charged-current neutrino and antineutrino interaction. Phys.Lett., B123:269, 1983.

[67] J. Dorenbosch et al. Experimental results on neutrino electron scattering. Z.Phys., C41:567, 1989.
[68] J. V. Allaby et al. Prompt neutrino production in 400 Gev proton copper interactions. Z.Phys., C40:497, 1988.

[69] M. Jonker et al. Measurement of the polarization of positive muons produced in high-energy antineutrino interactions. Z.Phys., 17:211, 1983.

[70] F. Bergsma et al. A search for neutrino oscillations. Z.Phys., C40:171, 1988.

[71] J. V. Allaby et al. A precise determination of the electroweak mixing angle from semileptonic neutrino scattering. Phys.Lett., B177:281, 1987.

[72] K.De Winter et al. A detector for the study of electron neutrino scattering. Nucl.Instrum.Meth., A278:670, 1989.

[73] P. Vilain et al. Precision measurement of the electroweak parameters from the scattering of muon neutrino on electrons. Phys.Lett., B335:246, 1994.

[74] P. Vilain et al. A precision measurement of the cross section of the inverse muon decay $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$. Phys.Lett., B364:321, 1995.

[75] M.Gruwe et al. Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations. Phys.Lett., B309:463, 1993.

[76] P. Vilain et al. Search for muon to electron neutrino oscillations. Z.Phys., C64:539, 1994.

[77] P. Vilain et al. Leading order QCD analysis of neutrino induced dimuon events. Eur.Phys.J., C11:19, 1999.

[78] J. Altegoer et al. The NOMAD experiment at the CERN SPS. Nucl.Instr.Meth., A404:96, 1998.

[79] Q. Wu et al. A precise measurement of the muon neutrino-nucleon inclusive charged current cross-section off an isoscalar target in the energy range 2.5 to 40 Gev by NOMAD. Phys.Lett, B660:25, 2008.
[80] P.Astier et al. Search for $\nu(\mu) \rightarrow \nu(e)$ oscillations in the NOMAD experiment. *Phys.Lett.*, B570:19, 2003.

[81] P.Astier et al. Neutrino production of opposite sign dimuons in the NOMAD. *Phys.Lett.*, B486:35, 2000.

[82] D. Naumov et al. A study of strange particles produced in neutrino neutral current interactions in the NOMAD experiment. *Nucl.Phys.*, B700:51, 2004.

[83] P. Astier. Inclusive production of $\rho^0(770)$, $f(0)(980)$ and $f(2)(1270)$ mesons in muon-neutrino charged current interactions. *Nucl.Phys.*, B601:23, 2001.

[84] P. Astier et al. Study of $D^{*+}$ production in neutrino charged current interactions in the NOMAD experiment. *Phys.Lett.*, B526:278, 2002.

[85] E. Eskut et al. The CHORUS experiment to search for $\nu(\mu) \rightarrow \nu(\tau)$ oscillation. *Nucl.Instrum.Meth.*, A401:7, 1997.

[86] E. Eskut et al. Final results on $\nu(\mu) \rightarrow \nu(\tau)$ oscillation from the CHORUS experiment. *Nucl.Phys.*, B793:326, 2008.

[87] A. Benvenuti et al. Further observation of dimuons production by neutrinos. *Phys.Rev.Lett.*, 35:1199, 1075.

[88] A. Benvenuti et al. Rates and properties of opposite sign dimuons produced by neutrino and antineutrinos. *Phys.Rev.Lett.*, 41:1204, 1978.

[89] G. Gerbier et al. Dilepton and trilepton production by neutrinos and antineutrinos in Neon. *Z.Phys.*, C33:483, 1987.
[93] S. Rabinowitz et al. Measurement of the strange sea distribution in neutrino charm production. *Phys.Rev.Lett.*, 70:134, 1993.

[94] P. Vilain et al. Leading order analysis of neutrino induced events. *Eur.Phys.J.*, C11:19, 1999.

[95] A. Kayis-Topaksu et al. Leading order analysis of dimuon events in the CHORUS experiment. *Nucl.Phys.*, B798:1, 2008.

[96] A. Marotta G. De Lellis and P. Migliozzi. A combined analysis of all data on $\nu_\mu$ and $\bar{\nu}_\mu$ induced single-charm cross section. *Journal Physics*, G28:713, 2002.

[97] H. Georgi and H.D Polizer. Freedom at moderate energies. *Phys.Rev.*, D14:1829, 1976.

[98] T. Adams et al. Strange content of the nucleon (NuTeV). *arXiv:hep-ex/9906038v1*, 1999.

[99] J.V. Allaby et al. Determination of the electroweak mixing angle from semileptonic neutrino scattering. *Phys.Lett.*, B177:446, 1986.

[100] C. Peterson et al. Scaling violations in inclusive e+e- annihilation spectra. *Phys.Rev.*, D27:105, 1983.

[101] A. E. Asratyan. et al. Study of of $D^{*+}$ and search for $D^0$ production by neutrinos in BEBC. *Z.Phys.*, C68:43, 1995.

[102] N. Ushida et al. Production characteristics of charm production in neutrino interactions. *Phys.Lett.*, B206:381, 1988.

[103] A. Kayis-Topaksu et al. Measurement of fragmentation properties of charmed particle production in neutrino charged-current interactions. *Phys.Lett.*, B604:145, 2004.

[104] G. Onengut et al. Measurement of $D^0$ production and branching fractions in neutrino nucleon interactions. *Phys.Lett.*, B613:105, 2005.

[105] Particle Data Group. Present knowledge of the CKM Cabibbo-Kobayashi-Maskawa matrix. *JPG*, 37:146, 2010.
[106] M. Bargiotti et al. Present knowledge of the CKM matrix. *Riv.Nuovo Cim.*, 23N3:1, 2000.

[107] M. Gluck et al. Heavy flavour production at high energy e p colliders. *Z.Phys.*, C38:441, 1988.

[108] K. Hagiwara. Gluon bremsstrahlung production of heavy particles in neutrino and antineutrino scattering. *Nucl.Phys.*, B173:487, 1980.

[109] S.M. Mishra. A study of wrong sign single muon production in muon-neutrino nucleon interactions. *Z.Phys.*, C44:187, 1989.

[110] A. Alton et al. Observation of neutral current charm production in $\nu_\mu$ Fe scattering at the Fermilab Tevatron. *Phys.Rev.*, D64:012002, 2001.

[111] M.Jonker et al. Experimental study of opposite sign and same sign dimuon events produced in wide band neutrino and antineutrino beams. *Phys.Lett.*, B109:133, 1982.

[112] P.H. Sandler et al. Neutrino production of same sign dimuons at the fermilab tevatron. *Z.Phys.*, C57:1, 1993.

[113] B. A. Schumm. Neutrino production of same sign dimuons. *Phys.Rev.Lett.*, 60:618, 1988.

[114] B.C. Barish et al. Observation of trimuon production by neutrinos. *Phys.Rev.Lett.*, 38:577, 1977.

[115] A. Kayis-Topaksu et al. Experimental study of trimuon events in neutrino charged-current interactions. *Phys.Lett.*, B596:44, 2004.

[116] K.Kodama et al. Detection and analysis of tau neutrino interactions in Donut emulsion target. *Nucl.Instrum.Meth.*, A493:45, 2002.

[117] P. Annis et al. Observation of neutrino induced diffractive $D_s^*$ production and subsequent decay. *Phys.Lett.*, B435:458, 1998.
[118] A. Kayis-Topaksu et al. Measurement of uascharm production in neutrino charged current interactions. *New Journal of Physics*, 13:093002, 2011.

[119] A. Kayis-Topaksu et al. Measurement of charm production in antineutrino charged current interactions. *Phys.Lett.*, B575, 2003.

[120] A. Kayis-Topaksu et al. Measurement of $\Lambda_c^+$ production in neutrino charged-current interactions. *Phys.Lett.*, B555:156, 2003.

[121] A. Kayis-Topaksu et al. Cross section measurement of quasi elastic production of charmed baryons in neutrino charged-current interaction. *Phys.Lett.*, B575:198, 2003.

[122] A. Kayis-Topaksu et al. Associated charm production in neutrino nucleus interactions. *Eur.Phys.J*, C52:543, 2007.

[123] Particle Data Group. Meson particle listings D0. *JPG*, B592:675, 2004.

[124] A. Kayis-Topaksu et al. Measurement of topological muonic branching ratios of charmed hadrons produced in neutrino charged current interactions. *Phys.Lett.*, B636:24, 2005.

[125] U.Dore and D.Orestano. Experimental results on neutrino oscillations. *Rept.Prog.Phys.*, 71:106201, 2008.