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HEAVY QUARK STUDIES WITH NUCLEAR EMULSIONS

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Foreword^a

Although in 1964 CERN already had about 2000 staff members (though the number of visitors, about 250, was much smaller than today), the human environment maintained the spirit of friendship and cooperation typical of smaller organisations. For instance, to come to CERN from Geneva in the morning pedestrians simply had to stand at a given corner in Rue de la Servette: the tacit understanding was that anybody passing would give them a lift to CERN. I wonder when and why this good habit was lost: too many people, too many cars?

Indeed, it was also a very practical way to get to know each other. A friend of mine freshly arrived at CERN was given a lift by "a" senior physicist, whom he had not met before. Very frankly, he expressed his worry because "they" were so late that morning and hoped that this would not be noticed by the bosses. A few weeks later the CERN Director General of that time, Viktor Weisskopf, started a new habit: a regular meeting with newcomers, to get to know each other. My friend was present at the first of these meetings. The Director General started the meeting by explaining, through a story, how he had understood the need for the initiative. The story of a newcomer to whom he gave a lift one morning and, without recognising him as the Director General, That was CERN at that time and that was Viktor Weisskopf: a great scientist who was very keen to communicate with people at all levels and who was capable of doing it very spontaneously and naturally.

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So, I first met Roberto Salmeron when he gave me a lift to CERN. I was immediately impressed by his culture and enthusiasm for physics and society, as well as by his open, warm and human approach. My view of Roberto has never changed.

It was only many years later, starting in the late seventies, that I had the opportunity of closely collaborating with Roberto in the NA10 experiment at CERN. The experiment had been designed for the study of muon pair production by quark-antiquark annihilation in the so-called Drell-Yan process, using an intense pion beam to profit from the valence antiquark content of the pions. Hence the experiment was aimed at the study of hadron structure functions. When the beauty quark was discovered at Fermilab, we realised that a special trigger for events with three muons would have allowed us to carry out one of the first measurements of the beauty production cross-section in hadronic interactions. The motivation for writing the present paper on heavy quark production stems from the memory of the splendid collaboration with Roberto at that time.

1. A historical introduction

Photographic emulsions initiated accidentally their role in particle physics more than 100 year ago, when H. Becquerel discovered natural radioactivity by observing the blackening of photographic plates by uranium salts ¹. It was the beginning of a history which led to the discovery of the “new world” of the elementary particles.

Soon after the Second World War an intense R&D carried out in collaboration between the C. Powell group and Ilford led to the development of the so called “nuclear emulsions”. They are characterised by very high sensitivity and grain uniformity, hence they are capable of observing tracks of single particles with submicrometric space resolution. This technique, specially suitable for the observation of short lived particles, led to the discovery of the pion ² in 1947 and to many important contributions to the development of particle physics. Many cosmic ray experiments were carried out in the '50's and the '60's, contributing among other observations to the discovery of the strange particles in cosmic ray (see Ref. ³ and references therein).

In the meanwhile a new type of detector was proposed ⁴ and then developed mainly in Japan, the so called Emulsion Cloud Chamber (ECC). The ECC consists of a sandwich structure made of thick metal plates (passive material) and thin emulsion layers (tracking device). This detector was

quite successful in cosmic ray experiments, having the advantages of cost effectiveness and of particle identification capabilities. Most of the detector mass consists of metal plates, allowing for a substantial cost reduction ($\sim 1/100$) compared with stacks of pure emulsions and allowing to reach higher detector masses. In addition, the ECC allows the identification of particles and the measurement of their kinematical parameter by observing in detail specific ionisation, showering and multiple Coulomb scattering.

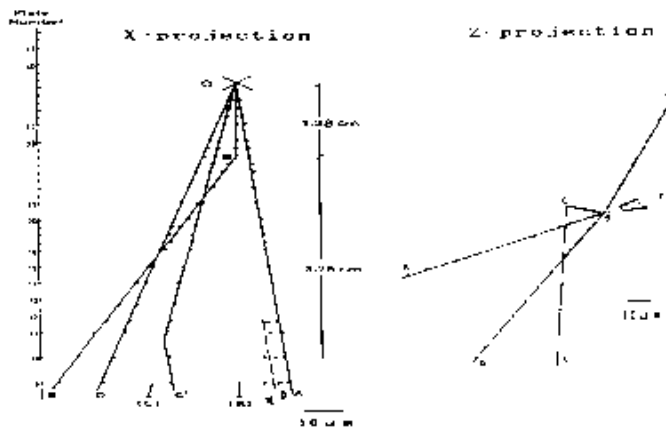


Figure 1. Schematic drawing of the first evidence for the production and decay of short lived “X particles”, now known as charmed particles, in cosmic rays.

Among cosmic ray interactions detected in ECC, a very peculiar event (see Fig. 1) was observed in 1971⁵, three years before the discovery of charm with the observation of the J/Ψ ^{6, 7, 8}. The event is due to a neutral primary in the energy range of 10 TeV. The short track segment originating from the interaction vertex was attributed to an “X particle” of mass 2-3 GeV decaying after $\sim 10^{-13}$ s into a charged particle and a π^0 meson. The event was interpreted as the first example of the associated production of a massive short-lived particle with a new quantum number. After this observation, further examples of X-particles (singly or pair produced) were then detected or dug out from previous cosmic ray exposures, supporting the above interpretation⁹. By the time of the J/Ψ discovery and of the identification of the X-particle with a charmed meson, about 20 X-particle decays had been observed by using the ECC technique.

Thanks to the high space resolution of the ECC technique, both the

production and decay vertexes are reconstructed. Therefore, lifetime studies started soon after the observation of the first X particle. Just after the discovery of the J/Ψ , groups working with the ECC could thus first report on the lifetime difference between charged and neutral charmed particles. This early result obtained by using cosmic rays was confirmed a decade later by the E531 experiment, on the Fermilab neutrino beam. In E531, about 120 charmed particles were observed into an emulsion target and fully analysed by using an electronic detector for a complete kinematical reconstruction (see Ref. ⁹ and references therein).

After the discovery in 1977 ¹⁰ of a new heavy quark, i.e. of the beauty, experiments with nuclear emulsions aimed at the direct observation of production and decay of beauty hadrons. A successful search was first performed by the WA75 experiment at CERN, using a π^- beam of 350 GeV. In the WA75 event, shown in Fig. 2, both beauty hadrons are observed to decay into a charmed particle. Nine beauty events were later observed by the E653 experiment ¹¹.

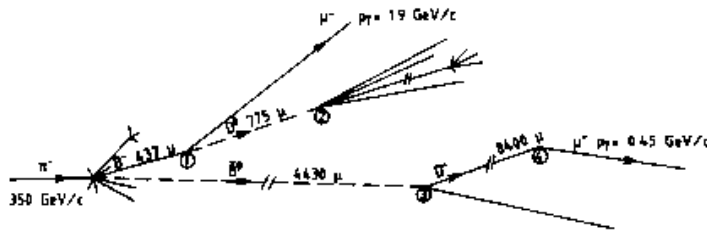


Figure 2. Schematic drawing of the first hadro-produced $B\bar{B}$ pair event observed in nuclear emulsions by WA75.

2. Heavy quarks, neutrinos and nuclear emulsions

The high sensitivity and grain uniformity of nuclear emulsions, make them capable of observing tracks of single particles with submicrometric space resolution and therefore specially suitable for the observation of short lived particles. One can say that nuclear emulsions were the ancestor technique of heavy quark physics. The present success of the emulsion technique is linked to the impressive achievements in the development of the automatic scanning systems and the conceptual design of the experiments. In the latter the adoption of the “hybrid” technique allow electronic detectors to

complement emulsions, to save time and to improve the event reconstruction, as well as to complete the event reconstruction.

Neutrino and anti-neutrino induced charm-production is specially interesting because it allow to isolate the strange-quark parton distribution function and to study the transition to heavy quarks. In particular, the understanding of the threshold behaviour associated with the charm-production is critical for the extraction of $\sin^2 \theta_W$ from neutrino deep-inelastic data. Nowadays, this is very important in relation with the recent measurement of $\sin^2 \theta_W$ performed by the neutrino experiment NuTeV, giving a value of $\sin^2 \theta_W$ which is more than 3σ away from the average value measured at LEP ¹².

A better understanding of the inclusive charm-production cross-section is also needed for the background determination of future experiments aiming at the study of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations.

Many electronic and bubble chamber experiments have studied indirectly neutrino and anti-neutrino charm-production by looking at the presence of two oppositely charged leptons in the final state. In the case of neutrino scattering, the underlying process is a neutrino charged-current (CC) interaction with an s or d quark, producing a charm-quark that fragments into a charmed hadron. The charmed hadron may decay semi-leptonically producing opposite sign di-leptons through the process:

$$\begin{aligned} \nu_\mu + N &\longrightarrow \mu^- + c + X \\ &\qquad \qquad \qquad \hookrightarrow s + l^+ + \nu_l \end{aligned} \tag{1}$$

Analogously an anti-neutrino can interact with a \bar{s} or \bar{d} anti-quark, producing a charm anti-quark that fragments into a charmed hadron, again leading to a final state with two oppositely charged leptons.

This technique was first used in 1974 ¹³ when neutrino induced charm-production was discovered. Since then several experiments ^{14, 15} have used this technique to study charm-production.

Calorimetric experiments are characterised by a massive (iron) target and a muon spectrometer to identify the muon and measure its charge. Pion and kaon decays constitute the main background, in spite of the high density and hence the short interaction length in the target material. A further background reduction is obtained by requiring a minimum momentum, typically $p_\mu > 5$ GeV, for each muon. The drawback of such a selection is that it prevents the search for charm-production at low neutrino energies: for a typical calorimetric experiment it is not possible to investigate energy

regions below 15 GeV, where the slow-rescaling threshold effect is more important.

The main characteristic of a bubble chamber filled with a mixture of heavy liquids (Ne-H₂, freon-propane) is its high efficiency in identifying electrons. Therefore, they searched for charm-production looking at μ^-e^+ events. The low threshold, $p_{e^+} > 0.3$ GeV, combined with high statistics for $E_\nu < 30$ GeV, gives good sensitivity to the slow-rescaling threshold behaviour. The main background sources are π^0 Dalitz decays and $\bar{\nu}_e CC$ interactions.

The main advantage of nuclear emulsion experiments studying charm production is that, the charmed particle being identified through the direct observation of its decay, the background is very low and very loose kinematical cuts are applied. This gives a very good sensitivity to the slow-rescaling threshold behaviour and consequently to the charm-quark mass. Furthermore, inclusive and exclusive studies can be performed and important results can thus be obtained in spite of the statistics being much smaller than electronic experiments.

So far only two experiments, E531¹⁶ and CHORUS¹⁷, have searched for charm-production through the direct identification of charm decays in emulsions, using neutrino beams.

These experiments have a “hybrid” design, emulsions are used as active targets. The main background for D^0 detection in emulsion comes from K^0 and Λ decays, and from neutron, K^0 and Λ interactions without any visible nuclear break-up at the interaction point. For charged charmed-hadrons the main backgrounds are π and K decays in flight, and the so called “white kinks” (hadron interaction without any visible track from nuclear break-up) giving an apparent decay vertex. These backgrounds can be effectively suppressed by applying a loose cut on the transverse momentum at the decay vertex ($p_T > 250$ MeV), so that they can be reduced to a level of the order of $10^{-4}/CC$.

3. An example of hybrid technique: the CHORUS detector

The CHORUS detector¹⁷ is a hybrid set-up that combines a nuclear emulsion target with various electronic detectors. The detector was designed to search for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. Since charmed particles and the τ lepton have similar lifetimes, the detector is equally well suited for the observation of the production and decay of charmed particles.

The nuclear emulsions act both as target for neutrino interactions and

as a high resolution detector, allowing three-dimensional reconstruction of short-lived particles. The emulsion target has a total mass of 770 kg and is segmented into four stacks, each consisting of eight modules, each in turn composed of 36 plates with a size of $36 \times 72 \text{ cm}^2$. Each plate has a $90 \text{ }\mu\text{m}$ plastic support coated on both sides with a $350 \text{ }\mu\text{m}$ emulsion layer¹⁸. Each stack is followed by a set of scintillating fibre tracker planes as electronic detector. Three interface emulsion sheets act as interface with a $90 \text{ }\mu\text{m}$ emulsion layer on both sides of an $800 \text{ }\mu\text{m}$ thick plastic base and by a set of scintillating fibre tracker planes. The interface sheets and the fibre trackers provide accurate predictions of particle trajectories into the emulsion stack for the location of the vertex positions. The accuracy of the fibre tracker prediction is about $150 \text{ }\mu\text{m}$ in position and 2 mrad in the track angle.

The additional electronic detectors downstream of the emulsion target and associated trackers include a hadron spectrometer which measured the bending of charged particles in an air-core magnet, a calorimeter where the energy and direction of showers are measured and a muon spectrometer which determines the charge and the momentum of muons.

4. Nuclear emulsions analysis by automatic microscopes

Emulsion analysis has been fully visual for several decades. Thus for a long time emulsion were suitable only for low statistic experiments. In the eighties, the development of semi-automatic systems opened a new era characterised by the revival of nuclear emulsions. Nowadays fully-automatic systems allow the reconstruction of several hundred thousand interactions as in CHORUS. In the following we summarise the original approach for automatic scanning developed in Japan¹⁹ with the so-called Track Selector (TS).

When observing an emulsion plate at the microscope, we observe a “tomographic slice” with a thickness of $\sim 5 \text{ }\mu\text{m}$ corresponding to the of microscope focal depth. As emulsion plates are exposed perpendicularly to the beam particle, in the tomographic image tracks appear as grains. By raising or lowering the focal plane of the microscope objective lens through the depth of the emulsion layer, the three dimensional structure of tracks is reconstructed by connecting aligned grains. The development of the automatic recognition system for penetrating tracks has followed the model of human track recognition. It is based on an integrated combination of mechanical control and video image processing.

With an objective lens of magnification 50, the field of view is about

$120 \times 150 \mu\text{m}^2$. Several tomographic (typically 16) images are taken while changing the focal plane. Each image is suitably treated to reconstruct the grains and then tracks are formed from consecutive grains. This processing is carried out by hardware, with a 3 Hz frequency. A tracking efficiency of more than 98% is obtained for angles in the $[-0.4, 0.4 \text{ rad}]$ range.

An upgrade of this system (UTS) with fast parallel processors working at the same frequency has been performed in 1999²⁰. A new automatic scanning system (S-UTS) is currently under development. It will increase the frequency up to 30 Hz. Key features of the S-UTS are the high speed CCD camera with 3 kHz frame rate and a piezo-controlled moving objective-lens, synchronised to the stage motion in order to avoid stop-go of the microscope stage while taking images. Other approaches for high speed emulsion analysis are being followed in Europe. In recent years, the scanning speed has increased by one order of magnitude every few years. The present aim is to reach a scanning capability of $20 \text{ cm}^2/\text{s}$.

The impressive increase in scanning speed which has been achieved allows scanning of large areas to locate events and to study their topology. In addition, it makes it possible to perform in an automatic way, measurements of kinematical parameters such as the momentum measurement or electron identification through the measurement of the multiple Coulomb scattering. In addition electron energy measurement on the basis of the shower development can also be made.

5. Charm-production in deep-inelastic neutrino interactions

5.1. Leading-order (LO) charm-production

At leading order, only the Born diagram (the first diagram in Fig. 3a)) is considered for charm-production and only the s - and d -quarks of the nucleon are involved. In terms of the quark distributions, for an isoscalar target the c production cross-section by neutrinos can be written as

$$\frac{d^2\sigma(\nu N \rightarrow c\mu^-)}{d\xi dy} = \frac{G_F^2 ME}{\pi(1 + Q^2/M_W^2)^2} \{ [u(\xi, \mu^2) + d(\xi, \mu^2)] |V_{cd}|^2 + 2s(\xi, \mu^2) |V_{cs}|^2 \} \times \left[\frac{1 + R(\xi, \mu^2)}{1 + \left(\frac{2M\xi}{Q}\right)^2} \left(1 - y - \frac{Mxy}{2E} + \frac{xy}{\xi} \right) \right] \quad (2)$$

where M is the nucleon mass, E is the neutrino energy, Q^2 is the negative square of the four-momentum transfer, y is the inelasticity, R is a

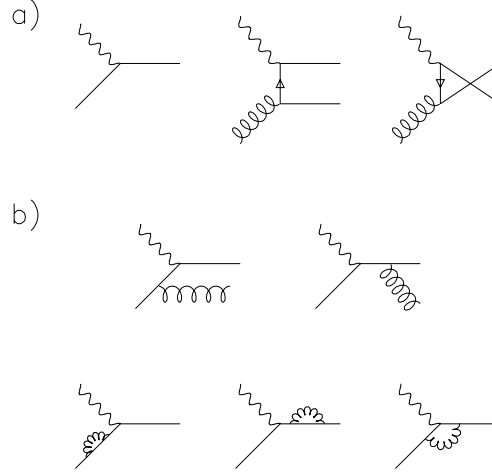


Figure 3. Diagrams contributing to neutrino production, mediated by charged gauge bosons, of charm-quark up to $\mathcal{O}(\alpha_S)$. **a)** The dominant diagrams: the leading order quark-initiated diagram and the next-to-leading order t-channel and u-channel gluon-initiated diagrams. **b)** The radiative-gluon and self-energy diagrams.

longitudinal structure function which accounts for violation of the Callan-Gross relation, ξ is the momentum fraction of the struck quark and μ^2 is the scale at which quark momentum distributions are given. The dependence of the parton distributions on the scale μ^2 is specified by QCD²¹. ξ is related to the Bjorken scaling variable x through the relation

$$\xi = x \left(1 + \frac{m_c^2}{Q^2} \right) \left(1 - \frac{x^2 M^2}{Q^2} \right)$$

For charm-production induced by $\bar{\nu}$, Eq. 2 holds with the substitution of quarks by anti-quarks.

The LO expression illustrates the sensitivity of the process to the strange quark sea. Charm (anti-charm) production from scattering off $d(\bar{d})$ -quarks is Cabibbo suppressed. In the case of charm-quark produced by neutrinos, approximately 50% is due to scattering off s -quarks, even though the d -quark content of the proton is approximately ten times larger. In the case of anti-neutrino scattering, where only sea \bar{d} -quarks contribute, roughly 90% is due to scattering off \bar{s} -quarks. Hence when neutrinos interact the

flavour of the struck quark is relatively well defined, so that it IS possible to study specific flavour transitions.

5.2. Next-to-leading order (NLO) corrections

Because charm-production at LO is a process dominated by sea quark contributions, the gluon-initiated contributions are expected to be significant although they are nominally at NLO ²¹. The gluon distribution, which is an order of magnitude larger than the sea quark distribution, compensates for the extra power of α_s involved in the diagram (see Fig. 3). Calculations including the NLO formalism have recently become available ²².

5.3. Hadronisation of charm-quarks to charmed hadrons

In the previous Sections we discussed the charm-production at the quark level, whereas the experiments only observe hadrons. The problem of building hadrons (the so-called hadronisation) out of the quarks emerging from a hard scattering process is characterised by a relatively low scale, of the order of typical hadron masses, so that perturbative QCD is not applicable.

However, the factorisation theorem is not limited to the perturbative region and is applicable to the hadronisation process in the same way it is used when describing the initial state hadron. Just as the parton distribution functions are universal, independent of the scattering process through which they are probed, we may expect the fragmentation description to be universal. In particular, one can assume that quarks, emerging from $e^+e^- \rightarrow q\bar{q}$ scattering, form hadronic final states through processes which are similar, if not identical, to the processes which build hadronic final states in lepton-nucleon scattering.

The differential cross-section for charmed-hadron production by neutrinos can be written as

$$\frac{d\sigma(\nu N \rightarrow \mu^- CX)}{dx dy dz dp_T^2} = \frac{d\sigma(\nu N \rightarrow \mu^- cX)}{dx dy} \times \sum_h f_h \times D_c^h(z, p_T^2) \quad (3)$$

Here, $D_c^h(z, p_T^2)$ is the probability distribution for the charm-quark to fragment into a charmed hadron of type $h(= D^0, D^+, D_s^+, \Lambda_c^+)$ carrying a fraction z of the quark longitudinal momentum and transverse momentum p_T with respect to the quark direction. The number f_h is the mean multiplicity of the hadron h in neutrino charm-production. A similar expression holds for anti-neutrinos.

Since only one c -quark is produced in a CC interaction, one can set the normalisation conditions as

$$\int_0^1 dz \int_0^\infty D_c^h(z, p_T^2) dp_T^2 = 1 \quad \text{and} \quad \sum_h f_h = 1. \quad (4)$$

Usually, $D_c^h(z, p_T^2)$ is written as

$$D_c^h(z, p_T^2) \propto D(z) \times e^{-bp_T^2} \quad (5)$$

where $D(z)$ is commonly parameterised either as ²³

$$D(z) \propto \frac{1}{z(1 - \frac{1}{z} - \frac{\varepsilon_P}{1-z})} \quad (6)$$

or as ²⁴

$$D(z) \propto \frac{\frac{1-z}{z} + \frac{\varepsilon_C(2-z)}{1-z}}{1 - \frac{1}{z} - \frac{\varepsilon_C}{1-z}} \times (1 + z^2) \quad (7)$$

Qualitatively, the shape of the $D(z)$ can be understood as follows. The charm-quark emerges from the hard scattering process and is relatively energetic. Attaching a light anti-quark \bar{q} to it to form a charmed meson decelerates the heavy quark only slightly, so that we expect the variable z to be peaked toward 1. The ε parameter is different for different mesons, but it can be expected to scale as $1/m_Q^2$, with m_Q the mass of the heavy quark.

Finally, we stress that all the parameters discussed above (f_h , b , ε_P , ε_C) cannot be predicted theoretically and must be determined experimentally.

6. Physics results and perspectives

6.1. Cross-section measurements

Inclusive charm-production cross-sections can be only measured in emulsion experiments, while exclusive measurements can also be performed by electronic experiments like NOMAD ²⁵. As already mentioned, another important advantage of the emulsion technique is the possibility to observe charm-production down to very low energies with a very low background, allowing the investigation of the threshold behaviour and the extraction of the strange-quark parton distribution function at low Q^2 .

The total charmed-particle production inclusive cross-section relative to CC interactions measured by the E531 experiment is: $\sigma(\nu_\mu N \rightarrow \mu^- cX) / \sigma(\nu_\mu N \rightarrow \mu^- X) = 4.9_{-0.6}^{+0.7}\%$.

The inclusive D^0 production cross-section times its branching ratio into charged particles has been measured by the CHORUS experiment ²⁶ and it amounts to $\sigma(\nu_\mu N \rightarrow D^0 \mu^- X)/\sigma(\nu_\mu N \rightarrow \mu^- X) = (1.99 \pm 0.13 \pm 0.17)\%$.

The total charmed-particle production inclusive cross-section in anti-neutrino induced events has never been measured. Its measurement is currently in progress in the CHORUS experiment.

6.2. Charm-hadronisation studies

6.2.1. Charmed fractions and semi-muonic branching ratio

So far, the charmed fractions f_h have been directly measured only by the E531 experiment ²⁷. A bias was later detected in the extraction of the charmed fractions by E531 and the data was refit with the bias removed ²⁸.

When comparing results from neutrino measurements with e^+e^- experiments with similar kinematics, one should account for the fact that neutrinos have the peculiarity to undergo not only deep-inelastic interactions, but also diffractive and quasi-elastic charm-production (see Section 7). The results of the refit to E531 data together with a prediction based on e^+e^- experiments plus the corrections for neutrino ‘‘peculiarities’’ ²⁹ are consistent with the assumption that the charm quark hadronises independently of the process through which it has been produced.

Recently, a direct measurement of the semileptonic branching ratio B_μ has been performed by CHORUS using about 1000 charm events reconstructed in nuclear emulsions ³⁰. Out of these, $(88 \pm 10 \pm 8)$ dimuon events have been reconstructed, which correspond to

$$B_\mu = (9.3 \pm 0.9 \pm 0.9)\%$$

in agreement with previous indirect measurements by electronic experiments. A precise determination of B_μ is particularly important for a high precision extraction of the CKM element matrix V_{cd} from dimuon experiments ²¹.

The CHORUS experiment is now analysing a charm sample ten times larger than the E531 one, with the aim to both measure accurately the charmed fractions and reduce the error on B_μ .

6.2.2. Transverse momentum distribution

The transverse momentum squared (p_T^2) distribution of charmed hadrons with respect to the direction of the hadronic system has been measured by

E531 ²⁷ and, using electronic detectors, by NOMAD ²⁵. The p_T^2 distribution from E531 and NOMAD are consistent. The averaged value of the exponential slope parameter b (see Eq. 5) is $3.31 \pm 0.27 \text{ GeV}^{-2}$.

CHORUS is currently analysing about 1000 events with a charmed hadron in the final state and is expected to provide a new insight in the understanding of the p_T^2 distribution of charmed hadrons.

6.2.3. Fragmentation studies

The parameter ε which characterises the fragmentation functions (see Eqs. 6 and 7) of heavy quarks can be determined by using two different approaches:

- Direct measurements: the z distribution is reconstructed and fitted in order to extract the parameter ε . Such analysis has been performed by E531 and NOMAD. It is currently in progress in CHORUS;
- Indirect measurements: ε is left as one of a free parameters of the fit to dimuon data. For details of dimuon analyses performed by the electronic experiments CDHS, CCFR, CHARM II and NuTeV we refer to ³¹.

The available results from both approaches are summarised in Table 1, together with the results from e^+e^- experiments (CLEO and ARGUS) at $\sqrt{s} = 10.55 \text{ GeV}$.

Table 1. Summary of all available determinations of ε from neutrino experiments. For comparison results from e^+e^- (CLEO+ARGUS) experiments are also given.

Collaboration	ε_P	ε_C	Comments
E531 ²⁷	0.076 ± 0.014	—	All charmed hadrons are used
NOMAD ²⁵	0.075 ± 0.046	0.13 ± 0.14	Only D^{*+} are used
CDHS ³³	$[0.02 \div 0.14]$	—	
CCFR (LO) ³⁴	0.22 ± 0.05	0.88 ± 0.12	All charmed hadrons are used
CHARM II ³⁵	0.072 ± 0.017	—	All charmed hadrons are used
CLEO+ARGUS ³²	0.14 ± 0.01	—	Only D^0 are used
CLEO+ARGUS ³⁶	0.156 ± 0.022	—	Only D^+ are used
CLEO+ARGUS ³⁶	0.10 ± 0.02	—	Only D_s are used
CLEO+ARGUS ³²	0.25 ± 0.03	—	Only Λ_c are used
CLEO+ARGUS ³²	0.078 ± 0.008	—	Only D^{*+} are used

Given the large charm statistics of the CHORUS experiment, it will be possible in the near future to study with high accuracy fragmentation parameters as a function of the charmed hadron type and compare them with the results obtained by e^+e^- experiments.

7. Low multiplicity charm-production

We classify as “low multiplicity” those processes (diffractive $D_s^{(*)}$ and quasi-elastic (QE) charm-production) with at most two particles produced at the primary vertex, besides the charmed hadron.

Quasi-elastic charm-production, is particularly interesting for the measurement of the absolute branching ratio (BR) of the Λ_c ³⁷. In fact, events quasi-elastically produced have a peculiar topology which allows to define an almost pure sample of Λ_c and consequently to extract a model independent measurement of the absolute BR of the Λ_c ³⁷. In the past this process has been studied with a small statistics (less than 10 events total world statistics) ³⁸. Presently, the CHORUS experiment is performing a dedicated search and several events consistent with a QE topology have been already measured. With the final statistics of a few hundred events, CHORUS will measure for the first time both the differential cross-section of the process and the absolute BR of the Λ_c .

8. Associated charm-production in neutral-current and charged-current interactions

Associated charm-production in NC interactions proceeds through a gluon-boson fusion process. Only one event has been “directly” observed by the E531 experiment ¹⁶, while an indirect observation has been recently published by the NuTeV experiment ³⁹. Both experiments measured a rate of the order of 10^{-3} , normalised to CC neutrino interactions.

In CC interactions, charm-anti charm pairs originate from a gluon emitted through the bremsstrahlung off a light quark. In the past, indirect evidence for this process was obtained by studying trimuon and same-sign dimuon events ⁴⁰. The puzzle was that the observed rate of trimuons and same-sign dimuons was larger than theoretical predictions ⁴¹ by more than one order of magnitude. Although, given the small statistics and the uncertainties related to the background subtraction, the result was not conclusive, the observed large discrepancy motivates further theoretical and experimental studies. Recently a direct search for this process has started in the emulsions of the CHORUS experiment. So far the observation of one

event ⁴² has been reported.

9. Conclusions

Emulsions have started particle physics with the discovery of natural radioactivity by Becquerel in 1896. The development of the “nuclear emulsions” made it possible to detect tracks of single particle and to perform detailed measurements of their interactions. The discovery of the pion in 1947 was the first, spectacular demonstration of their unique features for the direct observation of the production and decay of short-lived particles, with negligible or very low background. In particular, these features are now exploited for studies of heavy quark physics in experiments where nuclear emulsions are combined with electronic detectors and profit is taken of the remarkable technological progress in automated analysis. In these experiments, neutrinos provide a selective probe for specific quark flavors. Interesting results on charm production and decay are expected in the very near future, well in time to celebrate with physics results the 90th anniversary of Roberto Salmeron.

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