Determination of Charm Production Cross-Sections for Neutrinos and Antineutrinos

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Abstract. It is shown that existing data for production rates of opposite-sign dileptons by neutrinos and antineutrinos are mutually consistent when acceptance corrections are calculated using a standard four-quark parton model, and a flat fragmentation function for charmed quarks. Together with a corrected cross-section, model calculations which adequately describe the data are presented.

1. Introduction
The charm origin of neutrino induced dileptons is by now fairly well established. The relevant experimental distributions can be explained by the standard GIM version of the quark parton model [1], and assuming a flat fragmentation function $D(z)$ for charmed quarks [2-5]. (See also [6]).

Several experiments have measured dilepton rates (normalized to charged current event rates) with incident neutrino and antineutrino beams. Corrections for acceptance losses must be applied to the raw data in order to obtain the "true" rates, and to make possible a comparison among the various data sets.

Such corrections are strongly model-dependent, the most critical input being the fragmentation function $D(z)$ for charmed quarks. Previous attempts of a comparison of this kind have indicated possible inconsistencies among the existing data [7-9].

In this paper, we study the dependence of acceptance corrections on the specific fragmentation function assumed. We do this for the various data sets, taking into account the relevant experimental conditions (beam fluxes and acceptance cuts).

We find that there is a fair agreement among the data when a flat fragmentation function $D(z)$ is used, whereas some distinct disagreement develops at low energies if a softer $D(z)$ is assumed.

We also present a model (GIM version of the quark-parton model, with slow rescaling and a flat $D(z)$), which reproduces reasonably well the energy dependence of the corrected dilepton cross-sections for neutrinos and antineutrinos.

Such a model can be used to make checks on neutrino events representing possible candidates for "visible" production of charm, by simply substituting in it the semileptonic decay of charm with its decay into the relevant non-leptonic channels.

Section 2 contains a discussion on the relevant experimental data. In Sect. 3 we state the theoretical assumptions which have been used to calculate the acceptance corrections. In Sect. 4 the calculated corrections for acceptance losses which apply to the various sets of data are presented. Sect. 5 deals with a charm production model reproducing the energy dependence of dilepton cross-sections for neutrinos and antineutrinos. Sect. 6 contains the conclusions.

2. The Data
Data of dilepton production cross-section normalized to single-lepton production (charged current events) are listed in Tables 1 and 2. Bubble-chamber and counter-calorimeter data have been classified into distinct sets, because the information one can extract from them is somewhat complementary.

The distinctive feature of the bubble-chamber experiments is the high efficiency in detecting the slow leptons, and thus a high sensitivity to the low-$z$ behaviour of the fragmentation function $D(z)$.

In most cases the muons are identified as the fastest charged tracks leaving the chamber without interacting, and—in the hybrid systems—by requiring the association of the tracks with hits in the external muon identifiers (EMI). The criteria for electron or positron...
Table 1. Bubble-chamber data on dilepton production rates. The average visible energy $\langle E_{\text{vis}} \rangle$ corresponds to a mean on the observed events. Rates are uncorrected for acceptance losses

<table>
<thead>
<tr>
<th>$\langle E_{\text{vis}} \rangle$ (GeV)</th>
<th>$E^\mu_{\text{cut}}$ (GeV)</th>
<th>$E^\nu_{\text{cut}}$ (GeV)</th>
<th>$N(\mu)/N(\nu)$</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>—</td>
<td>0.2</td>
<td>0.05 ± 0.02</td>
<td>Gargamelle-CERN PS Neutrino</td>
<td>11</td>
</tr>
<tr>
<td>41</td>
<td>—</td>
<td>0.3</td>
<td>0.5 ± 0.15</td>
<td>Brookhaven-Columbia (BNL-Col) Neutrino</td>
<td>10</td>
</tr>
<tr>
<td>44</td>
<td>2.5</td>
<td>2.5</td>
<td>0.18 ± 0.05</td>
<td>Gargamelle-CERN SPS Neutrino</td>
<td>4</td>
</tr>
<tr>
<td>52</td>
<td>—</td>
<td>0.3</td>
<td>0.41 ± 0.15</td>
<td>BEBC-Wide Band Beam Neutrino</td>
<td>14</td>
</tr>
<tr>
<td>55</td>
<td>—</td>
<td>0.8</td>
<td>0.77 ± 0.3</td>
<td>Fermilab-Wisconsin-Hawaii-LBL-CERN (FWHBC) Neutrino</td>
<td>12</td>
</tr>
<tr>
<td>62</td>
<td>4</td>
<td>0.8</td>
<td>0.22 ± 0.07</td>
<td>Fermilab-HEP-JTEP-Michigan (FIIM) Antineutrino</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 2. Counter data on dilepton production rates. Data are uncorrected for acceptance losses

<table>
<thead>
<tr>
<th>$E^\nu_{\text{cut}}$ range (GeV)</th>
<th>$E_{\text{cut}}$ (GeV)</th>
<th>$E^\nu_{\text{cut}}$ (GeV)</th>
<th>$N(\mu^-)/N(\nu^-)$</th>
<th>$N(\mu^+)/N(\nu^+)$</th>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>45-175</td>
<td>5.5</td>
<td>4.5</td>
<td>Neutrino ~ 0.5</td>
<td>Antineutrino ~ 0.5</td>
<td>CERN-Dortmund-Heidelberg-Saclay (CDHS)</td>
<td>15</td>
</tr>
<tr>
<td>40-175</td>
<td>5</td>
<td>5</td>
<td>0.4 ± 0.08</td>
<td>0.27 ± 0.04</td>
<td>Harvard-Pennsylv. Wisconsin-Fermilab Ohio-Rutgers (HPWFOR)</td>
<td>5</td>
</tr>
<tr>
<td>45-205</td>
<td>6</td>
<td>2.5</td>
<td>~ 1</td>
<td>~ 0.5</td>
<td>Caltech-Fermilab Rockefeller (CITFR)</td>
<td>16</td>
</tr>
</tbody>
</table>

Identification consist in one or more of the following:
- bremsstrahlung with or without a visible $\gamma \rightarrow e^+ e^-$ conversion,
- direct pair production,
- spiralling track with minimum ionisation,
- fast $\delta$-ray emission.

The main sources of background in these experiments are due to $\pi \rightarrow \mu, \kappa \rightarrow \mu$ decays in flight from conventional charged current events, asymmetric Dalitz or $\gamma$-ray pairs at the neutrino vertex, $\nu_e$ contamination in the $\nu_e$ beams, random association of hits in the EMI.

We list in Table 1 all the bubble-chamber experiments which reported dilepton rates with considerable statistics [4, 10-14] together with the experimental cuts relevant to our analysis. The reported rates have been corrected for background contamination, but not for the acceptance losses.

A further point on the bubble-chamber data concerns the missing energy fraction due to unobserved neutrals, which affects the measurement of the hadronic energy $E_H$. An estimate given [14] indicates that this fraction is substantial, whereas no discussion on this point is contained in [10]. (See also [3]).

The counter-calorimeter experiments, listed in Table 2, [5, 15, 16] are blind to the slow leptons ($E_L \lesssim 3-5$ GeV), but allow for a good identification of the fast ones, and therefore are sensitive to the high-$z$ behaviour of the fragmentation function $D(z)$.

The most serious source of background in these experiments arises from the $\pi \rightarrow \mu, \kappa \rightarrow \mu$ decays from conventional charged current events. All the experimental groups evaluate this background by means of Monte Carlo calculations, accurate to $\sim 25\%$ (the quoted error is $100\%$ in the case of [16]), based on measured energy spectra and multiplicities of $\pi$'s and $\kappa$'s produced in neutrino or antineutrino interactions. In [5] an empirical check on the calculated background subtraction is reported, using different density targets to measure the dimuon rates as a function of hadronic absorption lengths. In all the experiments the quoted dilepton rates and energy distributions have been corrected for this background, but no correction is made for acceptance losses. It should be observed that in [5] the quoted errors in the energy distributions of dilepton rates are statistical only, and do not contain the systematic uncertainties due to background subtraction.

3. Theoretical Assumptions

In order to calculate the acceptance corrections to the observed dilepton rates, we use the standard models meant to describe the relevant charged current and dilepton event distributions.

For the inclusive distributions of ordinary charged current events we use the well known formulas

$$
\frac{d\sigma_{CC}}{dE} = \frac{G_F^2 M_N E_L}{\pi} [2 \times q(x, Q^2) + 2 \times \bar{q}(x, Q^2)(1 - y)^2] dxdy
$$

(1)

$$
\frac{d\sigma_{\bar{CC}}}{dE} = \frac{G_F^2 M_N E_L}{\pi} [2 \times q(x, Q^2)(1 - y)^2 + 2 \times \bar{q}(x, Q^2)] dxdy
$$

(2)