LIKE-SIGN DIMUON PRODUCTION BY NEUTRINOS AND ANTINEUTRINOS

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ABSTRACT

The CDHS group has reported evidence for a prompt like-sign dimuon signal in both ν and ν̄ beams. A possible explanation for these μ⁻μ⁻ and μ⁺μ⁺ events is that they arise from the production and decay of a pair of charmed particles. We examine a possible c̄c model and estimate the magnitude of the cross-section for the reaction ν(ν̄) + N → μ⁻μ⁺ + c̄c + X. The antineutrino μ⁺μ⁺ events are used to set limits on the production and decay of b quarks via the reaction ν̄μ + u → μ⁺ + b, b → c + X, c → μ⁺ + νμ + s.

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The existence of a like-sign dimuon signal in neutrino physics has recently been clarified by the CERN-Dortmund-Heidelberg-Saclay (CDHS) collaboration\(^{1}\). They have examined a large sample of \(\mu^-\mu^-\) and \(\mu^+\mu^+\) events produced in neutrino and antineutrino wide band beams. After extensive Monte Carlo studies of backgrounds from meson decays, they came to the conclusion that there is a prompt signal and

\[
\frac{\sigma_\nu(\mu^-\mu^-)}{\sigma_\nu(\mu^-\mu^+)} = (4.1 \pm 2.2) \times 10^{-2} ; \quad \frac{\sigma_\bar{\nu}(\mu^+\mu^+)}{\sigma_\bar{\nu}(\mu^+\mu^-)} = (4.2 \pm 2.2) \times 10^{-2}
\]  

(1)

where the energy of each muon is larger than 6.5 GeV and the beam energy is larger than 30 GeV. These numbers should be compared to a previous measurement from the same group\(^{2}\), but based on fewer events, that

\[
\frac{\sigma_\nu(\mu^-\mu^-)}{\sigma_\nu(\mu^-\mu^+)} = (5 \pm 3) \times 10^{-2}
\]  

(2)

Other evidence for a prompt signal includes the result from the Fermilab-Harvard-Ohio-Pennsylvania-Rutgers-Wisconsin (FHOPRW) group\(^{3}\) that

\[
\frac{\sigma_\nu(\mu^-\mu^-)}{\sigma_\nu(\mu^-\mu^+)} = (6 \pm 5) \times 10^{-2} ; \quad (12 \pm 5) \times 10^{-2}
\]  

(3)

for muon energies larger than 5 and 10 GeV, respectively. Also a rate has recently been reported by Fisk\(^{4}\) from the Caltech-Fermilab-Northwestern-Rockefeller-Rutgers (CFNRR) group, namely \(\sigma_\nu(\mu^-\mu^-)/\sigma_\bar{\nu}(\mu^-\mu^+) \leq 0.2\) for \(E_\mu > 10\) GeV. However, this experiment has very limited statistics.

Although the result reported by the CDHS group is only a two standard deviation effect, there is now evidence from all three counter experiments for a genuine but small signal in the \(\mu^-\mu^-\) and \(\mu^+\mu^+\) channels. The Fermilab results are larger than the CERN results, but this is probably caused by the harder neutrino spectrum. In terms of absolute rates the CDHS group quote that

\[
\frac{\sigma_\nu(\mu^-\mu^-)}{\sigma_\nu(\mu^-)} = (3.4 \pm 1.8) \times 10^{-5} ; \quad \frac{\sigma_\bar{\nu}(\mu^+\mu^+)}{\sigma_\bar{\nu}(\mu^+)} = (4.3 \pm 2.3) \times 10^{-5}
\]  

(4)
with the same conditions that $E_\mu > 6.5 \text{ GeV}$ and $E_\nu > 30 \text{ GeV}$. This result seems rather low compared to that given in Eq. (1), but it is due to the fact that
\[ \sigma_\nu (\mu^+ \mu^-) / \sigma_\nu (\mu^+) = 1 \times 10^{-3} \]
with their cuts and spectra, rather than the usually quoted value of approximately $5 \times 10^{-3}$. The corresponding result from the FHOPKW group is $\sigma_\nu (\mu^- \mu^-) / \sigma_\nu (\mu^-) = (40 \pm 20) \times 10^{-5}$ averaged over the energy range 30-250 GeV. For comparison we note that the trimuon rates are
\[ \sigma_\nu (\mu^- \mu^- \mu^-) / \sigma_\nu (\mu^-) = (3.0 \pm 0.4) \times 10^{-5} ; \quad \sigma_\nu (\mu^+ \mu^- \mu^-) / \sigma_\nu (\mu^+) = (1.8 \pm 0.6) \times 10^{-5} \]
for the CDHS experiment\(^5\) ($E_\nu > 4.5 \text{ GeV}, E_\nu > 30 \text{ GeV}$) and
\[ \sigma_\nu (\mu^- \mu^- \mu^-) / \sigma_\nu (\mu^-) = (6.4 \pm 2.3) \times 10^{-5} \]
for the FHOPKW experiment\(^6\) (same cuts). Hence the same sign dimuon rate is comparable to and probably larger than the trimuon rate. We have to find an explanation of these events. To be specific we concentrate on the CDHS results reported in Eq. (4), and use their experimental cuts and spectra (350 GeV wide-band neutrino beam and 330 GeV antineutrino beam).

Our present understanding ofmultimuon events is that the bulk of the trimuon events ($\mu^- \mu^- \mu^+$ in $\nu$ beams and $\mu^+ \mu^- \mu^-$ in $\bar{\nu}$ beams) are due to the electromagnetic and hadronic radiation of dimuon pairs\(^5\)-\(^9\)). On the other hand, the opposite sign dimuon events ($\mu^- \mu^+$ in $\nu$ beams and $\mu^+ \mu^-$ in $\bar{\nu}$ beams) are explained by single charm production and decay\(^10\). So far there has been no necessity to include more exotic mechanisms such as associated production and decay of charmed particles\(^11\)-\(^13\) or the production and decay of heavier quarks and leptons\(^14\),\(^15\). The existence of prompt $\mu^- \mu^+$ and $\mu^+ \mu^-$ signals forces us to revise our understanding ofmultimuon physics because there is no mechanism for such events in the conventional framework. The only way to obtain same-sign dimuon signals is via misidentified trimuon events. To exclude this possibility we can take the two conventional trimuon mechanisms and calculate the size of the $\mu^- \mu^+$ ($\mu^+ \mu^-$) signals if the $\mu^- (\mu^+)$ does not survive the acceptance cut of 4.5 GeV. Note that the other muon energies must be larger than 6.5 GeV. The results are

\[ \frac{\sigma_\nu (\mu^- \mu^- \mu^+)}{\sigma_\nu (\mu^-)} \leq 0.1 \times 10^{-5} ; \quad \frac{\sigma_\nu (\mu^+ \mu^- \mu^-)}{\sigma_\nu (\mu^+)} \leq 0.5 \times 10^{-5} \quad (5) \]

where the brackets around the $\mu^+$ or $\mu^-$ mean that it is not detected. Thus the $\mu^- \mu^- \mu^+$ and $\mu^+ \mu^- \mu^-$ events are most likely not misidentified trimuon events. However a caveat should be added here because the values for the trimuon rates are sensitive to the parameters used for the hadronic model and the numbers given in Eq. (5) may be too small. Nevertheless, with the present data it is reasonable to conclude that the rate from the trimuon overflow is too small to explain the same-sign dimuon signal by a factor of at least three.
We are therefore forced to consider alternative mechanisms to explain the like-sign dimuon signal. Heavy lepton production and decay seem completely excluded because the secondary leptons originate in the hadron shower\cite{1}. The most likely explanation seems to be either the associated production and decay of charmed particles or some new heavy quark production and decay. Let us discuss these separately.

1.1 $\bar{c}c$ production and decay

The idea that $\bar{c}c$ production and decay is required to explain part of the multimuon signal seen in neutrino interactions is not new\cite{11,12,13}. The main problem is to construct a reasonable model which will explain the rates. The gluon bremsstrahlung model, per se, yields a cross-section which is too small to account for either the like-sign dimuon or trimuon rates\cite{11,12}. Nevertheless it leads to acceptable distributions. We will therefore use this model to investigate the consequences of changing the muon energy cuts and therefore find an estimate for the true $\bar{c}c$ production rate. This is important because the production of $\bar{c}c$ pairs in hadronic, electromagnetic and weak interactions is still poorly understood, both experimentally and theoretically\cite{16}. The fact that we now have some results for $\nu$ and $\bar{\nu}$ interactions allows us to extend our previous work in this area and make our conclusions more firm. The rough equality of the rates for $\sigma_\nu(\bar{\nu}^-\bar{\nu}^-)/\sigma_\nu(\nu^-)$ and $\sigma_\nu(\nu^+\nu^+)/\sigma_{\bar{\nu}}(\bar{\nu}^+)$ strongly indicates that the origin of these events is due to some new particles which are produced with equal probability in both $\nu$ and $\bar{\nu}$ beams. Hence a $\bar{c}c$ model seems the most likely explanation.

We therefore assume that $\bar{c}c$ pairs are produced by gluon bremsstrahlung from the up and down valence quarks in $\nu$ and $\bar{\nu}$ interactions. The quark distribution functions are assumed to be the same as in Ref. 12. We use $\alpha_s = 0.4$, a flat fragmentation function for the charmed particles and a $V$-A three-body beta decay to describe the decay of the charmed hadrons into physical particles. Note that we neglect any $p_T$ dependence inherent in the fragmentation process. Our previous calculations, which were only for $\nu$ beams, showed that the like-sign dimuon distributions were similar to those expected from hadronic backgrounds. The CDS group used a similar model and concluded that there was no difficulty in fitting the $\bar{\nu}^-\bar{\nu}^-$ and $\nu^+\nu^+$ distributions with approximately 80% hadronic background from $\pi$ and $K$ decays and 20% $\bar{c}c$ decays. Therefore, there is no reason to present distributions here, and we concentrate on the rates. Even though the gluon bremsstrahlung model yields rates which are too low in absolute magnitude, the relative rates can be compared to see if there is a consistent picture.
We normalize our rates by assuming that 20% of the hadronic trimuon events seen by the CDHS group are really due to the associated production and decay of a \( \bar{c}c \) pair. This causes no problem with the trimuon distributions\(^{12}\). The quoted relative rate for the hadronic \( \mu^-\mu^+\mu^\mp \) events, with 4.5 GeV cuts, is \( (2.2 \pm 0.4) \times 10^{-5} \). Therefore, we take the rate for the process \( \nu_\mu + N \rightarrow \mu^- + c + \bar{c} + X, c \rightarrow \mu^+ + \nu_\mu + s, \bar{c} \rightarrow \mu^- + \bar{\nu}_\mu + \bar{s} \) as \( 0.5 \times 10^{-5} \) of the normal charged current interaction, in the 350 GeV wide-band neutrino beam, with muon energy cuts of 4.5 GeV and \( E_\nu > 30 \) GeV. We next calculate the antineutrino trimuon rate using the 330 GeV antineutrino beam again with energy cuts of 4.5 GeV and \( E_\nu > 30 \) GeV. Then we calculate the \( \mu^-\mu^- \) rate in the 350 GeV beam and the \( \mu^+\mu^- \) rate in the 330 GeV beam with energy cuts of 6.5 GeV on each muon and \( E_\nu > 30 \) GeV. These rates are larger because we now have a hadronic charmed particle decay branching ratio of 90% rather than a semi-leptonic one of 10%. For the moment we ignore the problem of the trimuon overflow. The results of these calculations are given in the Table, together with the experimental values. For the \( \bar{\nu} \) experimental trimuon rate we take 20% of the hadronic component assuming that the hadronic and electromagnetic components contribute equally to the \( \mu^+\mu^- \) signal. The theoretical numbers are in good agreement with the experimental results.

To find the true \( \bar{c}c \) production cross-section is more questionable. We have to assume that our model is valid over the whole of phase space rather than the small portion which survives the energy cuts. As we are using a model this number may be wrong by factors of two or more. Nevertheless the result is interesting. The average energy of the \( \bar{\nu} \) beam is approximately 107 GeV and 78 GeV for the \( \bar{\nu} \) beam. For these energies we find that

\[
\sigma (\nu + N \rightarrow \mu^- + c + \bar{c} + X) / \sigma (\nu + N \rightarrow \mu^+ + X) \approx 2 \times 10^{-3}
\]

and

\[
\sigma (\bar{\nu} + N \rightarrow \mu^+ + c + \bar{c} + X) / \sigma (\bar{\nu} + N \rightarrow \mu^- + X) \approx 1 \times 10^{-3}
\]

These values can be compared to the beam dump results from the CDHS, BEBC and Gargamelle groups\(^{17}\). They indicate that the cross-section for the hadronic production of charm is in the range between 30-300 \( \mu b \) in 400 GeV pp collisions, i.e.,

\[
\sigma (c\bar{c}) / \sigma_{\text{tot}} = (1-7) \times 10^{-3}.
\]

It is probably best to use the c.m. energy as a variable in the pp case and compare with the hadronic mass in the \( \nu \) collision.

Then the pp results hold for \( \sqrt{s} \simeq 28 \) GeV, while the neutrino results are for \( W = \sqrt{s} \simeq 10 \) GeV. The rates are compatible indicating that the \( \bar{c}c \) model is probably the correct explanation of the same-sign dimuon events.
More data is clearly needed to substantiate this conclusion. It is not
easy to reduce the errors on the magnitudes of the $\mu^-\mu^-$ and $\mu^+\mu^-$ signals
due to the large background subtraction. A dual density target would help. An
unambiguous way to resolve the like-sign dimuon question would be to isolate
$\mu^-e^-$ events in a bubble chamber and identify the $c\bar{c}$ masses by track recon-
struction. The presence of a neutrino in the final state means that this cannot
be done exactly but the identification of a charmed meson or baryon via its
hadronic decays together with an $e^-$ and $K^0$ would be proof that a $c\bar{c}$ state
had been found.

1.2 Quark production and decay

There is great interest in trying to find evidence for $b$ quark production
in neutrino collisions. It is well known that the standard model of weak interac-
tions\(^{18}\) extended by the GIM mechanism\(^{19}\) is now in good agreement with theory\(^{20}\).
The six-quark version of this model, originally investigated by Kobayashi and
Maskawa\(^{21}\) has extra mixing angles coupling the charge $-1/3$ quarks $d$, $s$ and $b$.
Some of these angles are bounded by known meson and hyperon decay rates\(^{22}\), and
other theoretical considerations, such as the $K^0$-$\overline{K^0}$ mass difference. The coupling of the $b$ quark to the $u$ valence quark is not anticipated to be larger
than approximately six per cent of the normal weak interaction coupling constant
$G_F$. We have already investigated threshold factors for the antineutrino reaction
$\bar{\nu}_\mu + u \rightarrow \mu^+ + b$ and found that for typical beams the large mass of the $b$ quark
causes another reduction by a factor of around $1/6$ compared to the reaction
$\bar{\nu}_\mu + u \rightarrow \mu^+ + d$.\(^{14}\). Hence one may expect that $\sigma(\bar{\nu}_\mu + u \rightarrow \mu^+ + b)/$
$\sigma(\bar{\nu}_\mu + u \rightarrow \mu^+ + d)$ $\approx 0.6 \times 10^{-8}$ at the average antineutrino energy of 75 GeV.
Phillips has come to similar conclusions\(^{14}\).

To identify the $b$ quark we need to analyse the multilepton decay modes.
Present indications are that the dominant decay will be through the chain $b \rightarrow c \rightarrow s$. If the $b$ quark decays via $b \rightarrow c + X$, $c \rightarrow s + \mu^+ + \nu_{\mu}$, then the opposite sign dimuon rate is much smaller than the normal event rate from charm production and decay.
We expect that the best way to search for the $b$ is via the cascade $b \rightarrow c + X$, $c \rightarrow s + \mu^+ + \nu_{\mu}$, leading to $\mu^+\mu^-$ events. Rough numbers for the branching ratios
are given because the $b$ quark couples with approximate strength $0.5 G_F$ to a $c$ quark giving a factor of around 0.25 for the first branching ratio, while the second decay has a branching ratio of 0.1. Hence we expect a like-sign dimuon signal $\sigma_Q(\mu^+\mu^-)/\sigma_Q(\mu^+) \approx 2 \times 10^{-5}$, which will be reduced by acceptance cuts on
the muons to approximately $1 \times 10^{-5}$, close to the observed signal.

The estimates given above are rather crude, but they point out how interesting
it is to do a careful analysis of the $\mu^+\mu^-$ signal and try to place bounds on the
mixing angles connecting the heavy $b$ quark to the lighter $c$ and $u$ quarks.
Unfortunately there is not much hope in deriving similar limits from the $\mu^-\mu^-$ data because there is no valence quark coupling in this case and the cross-section ratio for $\sigma(\bar{\nu}_\mu + u \to \mu^- + b)/\sigma(\nu_\mu + d \to \mu^- + u)$ is therefore at least one order of magnitude smaller than $\sigma(\nu_\mu + u \to \mu^- + b)/\sigma(\bar{\nu}_\mu + u \to \mu^- + d)$.

The signal for the production and decay of a particle containing a $b$ quark is usually the detection of a secondary lepton which has a large $p_T$ with respect to the hadron shower direction. For instance, the opposite-sign dimuon signal would contain a lepton with large $p_T$ coming from the decay $b \to \mu^- + \bar{\nu}_\mu + c$. In the like-sign dimuon case this assumption is not necessarily true because we need a two stage decay so the $p_T$ of the secondary muon reflects more the mass of the $c$ quark than that of the $b$ quark. Models for the production and decay have already been described in our previous papers\textsuperscript{14,15}. Using the standard inputs of slow rescaling variables, flat fragmentation functions, etc., we find the $p_T$ distribution shown in Fig. 1. The data given in the figure include the muons from $\pi$ and $K$ decays, because there is no way to identify and subtract out these events. From the figure we see that it is very difficult to extract a limit because the $p_T$ signal resembles the hadronic background and the distribution expected from $c\bar{c}$ decays\textsuperscript{11,12}. There are actually two events (out of 60) with a $p_T$ above 2 GeV/c in the $\bar{\nu}$ events and one event (out of 300) in the $\nu$ beam. It is tempting to assume that these events are manifestations of $b$ quark production and decay. However, if that were true, one would expect a large contribution near $p_T$ of 1 GeV/c where the events are predominantly background. Hence at the moment the origin of the events above 2 GeV/c is completely open. To obtain a limit, we exploit the fact that the $b$ quark production and decay cannot play any role in the $\mu^-\mu^-$ events (unless the mixing angles in the KM model are incorrect). Therefore, we assume that the real explanation of the same-sign dimuon events is $c\bar{c}$ production and decay, and set a limit on the $b$ production and decay by allowing it to contribute maximally 10\% of the $\mu^+\mu^+$ rate. This is a reasonable limit. Hence we have that

$$\frac{\sigma(\bar{\nu}_\mu + u \to \mu^+ + b)}{\sigma(\nu_\mu + u \to \mu^+ + d)} \times B(b \to cX) \times B(c \to \mu^+ + \nu_\mu + s) \times \text{Acc.} \leq 4 \times 10^{-6} \tag{7}$$

The cross-section ratio for $b$ production in the $\bar{\nu}$ beam is $\sim 0.2 \, g^2$ if we take the $u$-$b$ transition coupling constant as $g_{\bar{c}}$. The $c \to \mu^+ + \nu_\mu + s$ branching ratio is 0.1 and the acceptance reduces the rate by a factor of two. Thus $0.2 \times g^2 \times 0.5 \times 6 \times 10^{-6}$ or $g^2 B < 4 \times 10^{-4}$. Therefore the $b$ quark coupling constant is restricted by the $\mu^+\mu^+$ data. For instance, if
the branching ratio for $b \rightarrow c + \chi$ is really 0.25, then $g < 4\%$, which is slightly better than the theoretical estimate of 6\%. Even allowing that all the $\mu^+\mu^+$
events are due to $b$ decay we find $g^2 B < 4 \times 10^{-3}$ or for $B = 0.25, g < 13\%$.

Clearly further $\mu^+\mu^+$ events with higher energy will be needed before we can tighten up these conclusions and/or hopefully identify the contribution of the $b$ quark. For the moment a safe conclusion is that the limit from the present sample of events is consistent with the expected upper bound of $g \leq 6\%$.

ACKNOWLEDGEMENTS

We would like to acknowledge useful discussions with the members of the CDHS group on the origin of their like-sign dimuon signal.

**Table**

Experimental and theoretical rates for like-sign and trimuon events arising from $c\bar{c}$ production and decay. The cuts and spectra are given in the text.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Experiment</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\sigma_{\nu}(\mu^-\mu^+)}{\sigma_{\nu}(\mu^-)}$</td>
<td>$0.5 \times 10^{-5}$</td>
<td>$0.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\frac{\sigma_{\bar{\nu}}(\mu^+\mu^-\mu^-)}{\sigma_{\bar{\nu}}(\mu^+)}$</td>
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<td>$0.2 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\frac{\sigma_{\nu}(\mu^-\mu^-)}{\sigma_{\nu}(\mu^-)}$</td>
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<td>$5.0 \times 10^{-5}$</td>
</tr>
<tr>
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<td>$(4.3 \pm 2.3) \times 10^{-5}$</td>
<td>$2.4 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
REFERENCES


9) See the review talks by D. Cline in Proceedings of the Topical Conference on Neutrino Physics at Accelerators, Oxford (1978) p. 423 and by J. Smith in Neutrinos 78, Purdue University, p. 551.


**Figure caption**: The spectrum in the $p_T$ of the secondary $\mu^+$ along the hadron shower direction. The primary $\mu^+$ is defined to be the one with the larger $p_T$ with respect to this direction.