LATEST RESULTS ON MULTIMUON PRODUCTION BY NEUTRINOS AND ANTINEUTRINOS

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Abstract: We discuss models for trimuon and same-sign dimuon production in neutrino and antineutrino beams and compare the theoretical predictions with the recent results from the CDHS and FHOPRW groups.

Résumé: Nous discutons des modèles pour la production de trimuons et dimuons de même signe dans les faisceaux neutrino et antineutrino et comparons les predictions theoriques avec les résultats rècents des groupes CDHS et FHOPRW.

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The study of multimuon production in neutrino and antineutrino beams is interesting to pursue because it may lead to some new physics [1]. For example the opposite sign dimuon results are proof of charmed particle production and decay [2]. However, it is now clear that the neutrino trimuon events are well explained by the more conventional processes of electromagnetic and hadronic radiation of dimuon pairs in regular inclusive interactions [3]. This result, coupled with the fact that the six quark version of the standard model [4] seems to fit all the available data, has led to a decrease of interest in multimuon final states. Neutrino interactions are now being regarded as only a useful tool to study QCD. Nevertheless it is important to continue the analysis of multimuon events because there is the possibility of producing b and/or t quarks or even more exotic particles.

At this meeting we have heard presentations by representatives of the CDHS [5] and CFNRR [6] groups on their like-sign dimuon events. The trimuon rate for antineutrinos has also been reported by the CDHS group [7]. This means that we now have information on opposite-sign dimuon, same-sign dimuon and trimuon rates in both neutrino and antineutrino beams. It is now possible to make a comparison of all these signals with theoretical models and begin to look for deviations from our conventional picture. The opposite-sign multileptons show no surprises and are well fitted by the single charm model involving valence and sea quark distributions. Let me therefore concentrate first on the trimuon events and later discuss the same-sign dimuon events.

I. Trimuon events.

The conventional processes behind trimuon events are (a) the electromagnetic production of dimuon pairs and (b) the hadronic production of dimuon pairs.

(a). The electromagnetic model is well tested by the $\mu^-\mu^-\mu^+$ events. For the CDHS experiment we calculate that $\sigma(\mu^-\mu^-\mu^+)/\sigma(\mu^-) = 0.9\times10^{-5}$ in the 350 GeV wide-band neutrino beam and $\sigma(\mu^+\mu^+\mu^-)/\sigma(\mu^+) = 0.5\times10^{-5}$ in the 330 GeV antineutrino beam with muon energy cuts of 4.5 GeV and beam energy larger than 30 GeV. We expect the antineutrino rate to be smaller because the spectrum is softer. Note that the electromagnetic model is not very sensitive to the change in the y distribution between neutrino and antineutrino charged current interactions because no matter how the energy is shared between the muons and the hadrons the important point is that charged particles are accelerated.

(b). The hadronic model assumes that dimuon pairs are produced in the neutrino inclusive final states in a fashion analogous to purely hadronic interactions. A final state is formed with mass W and, in the current fragmentation region, this yields dimuons with the same mass, transverse momentum and Feynman x dependence as seen, for instance, in π N interactions at the same W. Of course one has to rotate the neutrino final state so that the hadronic shower direction is the same as the beam direction in the hadronic collision. This model is rather crude and we should probably not expect it to yield the exact rate for the hadronic trimuon component. The distributions, however, in particular the correlation of the secondary dimuon pair along the hadronic shower direction, are well reproduced. When one tries to make absolute calculations then the rate for this component invariably comes out too small. For instance, even though the CDHS group [3] claim that this model gives a rate of approximately 2×10^{-5} my calculations show [8] that a more reasonable estimate is closer to 1×10^{-5} . The same conclusion has been reached by Barger et al. [9] who found that they needed an extra factor of 2.5 to fit the $\mu^-\mu^-\mu^+$ rate. One year ago there was no reason to be concerned over the exact magnitude of the hadronic rate, but now that there is evidence for prompt like-sign dimuons we have to examine this question more carefully. If there is another mechanism which is hadron-like and strongly energy dependent, then it is bound to complicate our understanding of the trimuon events.

(c). Neutrino data.

Recently the FHOPRW group [10] have released their final results on their neutrino induced trimuons and, even though all their secondary dimuons have low invariant masses, the plot of the events in the variable $\varphi_{1,(2+3)}$ is considerably different than that for the CDHS data. Remember that we are discussing the azimuthal angle between the initial muon and the secondary dimuon pair when their momenta are projected on the plane perpendicular to the neutrino beam. We show these two distributions in Fig.1. It is not clear how to interpret the φ plot for the FHOPRW data. There are several events near $\varphi = 90^\circ$ which cannot be explained on the basis of electromagnetic and hadronic radiation. One problem with their events is that most of them occur in the iron target so that the hadronic energy is not measured making a complete reconstruction impossible. Their total $\mu^-\mu^-\mu^+$ rate is $(6.4\pm2.3)\times 10^{-5}$ which is consistent with the CDHS result.

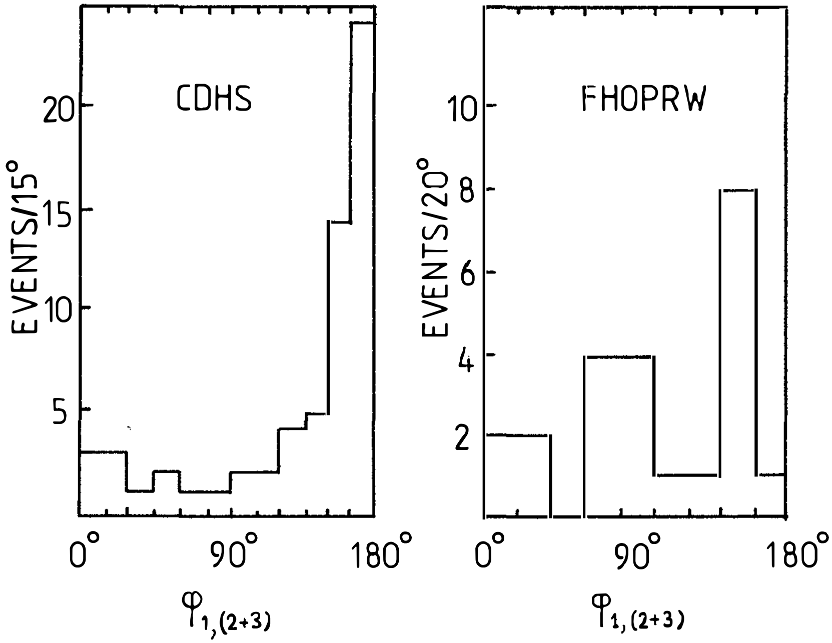

Fig.1. The azimuthal angular difference between the momenta of the leading muon and the secondary pair, projected on a plane perpendicular to the neutrino beam. All events have muon energies larger than 4.5 GeV.

(d). Antineutrino data.

The antineutrino rate for $\mu^+\mu^+\mu^-$ events expected from the hadronic model is around 0.2×10^{-5}. This number is very low reflecting both the softer spectrum and the change in the y distribution. The two effects conspire to seriously reduce the the number of trimuons which can survive the 4.5 GeV cut, yielding a rate which is five times lower than the neutrino rate. If we allow ourselves a compensating factor of three in the hadronic cross section then the final result for $\sigma(\mu^+\mu^+\mu^-)/\sigma(\mu^+)$ is approximately 1.1×10^{-5} for muon energy cuts of 4.5 GeV. This number should be compared with the CDHS experimental rate of $(1.8\pm0.6)\times10^{-5}$ based on eight events. Such poor statistics makes it meaningless to compare distributions but we can check the averages. There should be a reduction in $\langle\varphi_{1,(2+3)}\rangle$ and in $\langle x\rangle$ because the electromagnetic process makes a larger contribution to the total rate. Both effects are seen in the data. The conclusion is therefore that the $\mu^+\mu^+\mu^-$ rate and distributions are in reasonable agreement with the conventional model. It is only unfortunate that there are so few events.

II. Like-sign dimuons.

We now turn to the question of the like-sign dimuon signal. The recent CDHS results [5] for neutrinos are that $\sigma(\mu^-\mu^-)/\sigma(\mu^-\mu^+) = (4.1\pm 2.2)\times 10^{-2}$ and for antineutrinos $\sigma(\mu^+\mu^+)/\sigma(\mu^+\mu^-) = (4.2\pm 2.2)\times 10^{-2}$ with energy cuts of $E \gtrsim 6.5$ GeV and beam energy larger than 30 GeV. These results show that a signal exists at the two standard deviation level. However the statistical significance is increased when we add the published FHOPRW neutrino result [11] that $\sigma(\mu^-\mu^-)/\sigma(\mu^-\mu^+) = (12\pm 5)\times 10^{-2}$ and the result reported by Fisk[6] that $\sigma(\mu^-\mu^-)/\sigma(\mu^-\mu^+) \lesssim 20$ %. Both these results are for muon energies larger than 10 GeV. The corresponding rates compared to charged current events are $\sigma(\mu^-\mu^-)/\sigma(\mu^-) = (3.8\pm 1.8)\times 10^{-5}$ and $\sigma(\mu^+\mu^+)/\sigma(\mu^+) = (4.3\pm 2.3)\times 10^{-5}$, for the CDHS group (because $\sigma(\mu^-\mu^+)/\sigma(\mu^-) \simeq \sigma(\mu^+\mu^-)/\sigma(\mu^+) \simeq 10^{-3}$ with the same cuts) . The FHOPRW rate is larger presumably because the neutrino spectrum is harder at Fermilab. They quote $\sigma(\mu^-\mu^+)/\sigma(\mu^-) = (40\pm 20)\times 10^{-4}$. Note that these events cannot be interpreted as misidentified trimuon events because the rates for such processes are too small. Therefore we have to find out what new physics gives rise to these like-sign dimuon events and check whether this modifies our understanding of the trimuon events.

One reasonable explanation for the new events is that they are caused by the associated production and decay of charmed particles [12,13]. If such particles are made in neutrino (antineutrino) interactions then the secondary $\mu^-(\mu^+)$ would be emitted along the hadron shower direction which is consistent with the experimental data. Hence we have to estimate the cross section for the reaction $\nu(\bar{\nu})+N\to\mu^-(\mu^+)+c+\bar{c}+X$. The like-sign dimuons arise from the decays $\bar{c}\to\mu^-+\bar{\nu}_\mu+\bar{s}$, $c\to s+X$. The same model gives contributions to the opposite sign dimuons at a tiny rate via the decays $\bar{c}\to\bar{s}+X$, $c\to\mu^+ +\nu_\mu+s$, and to trimuon events when both charmed particles decay semileptonically. Analogous statements hold for the antineutrino channel. If the rate for $c\bar{c}$ pair production is comparable to that inferred in pp collisions from the CERN beam dump experiments [14], then we expect one pair of charmed particles to be produced in approximately 10^3 neutrino /antineutrino interactions. Adding branching ratios and a rough estimate for acceptance therefore yields same-sign dimuons at the level of 5×10^{-5} of normal charged current events. This model also yields trimuon events at the level of 5×10^{-6} so some of the hadronic trimuon events (maybe 20 %)

are presumably due to $c\bar{c}$ decays. The estimates given above are very rough. In practise it is essential to correctly incorporate the effects due to different cuts, spectra, etc. However it is clear that the existence of the like-sign dimuon events makes the whole multimuon production more complicated and/or interesting.

In order to substantiate the $c\bar{c}$ explanation it is necessary to have some model which will reproduce the observed dimuon rates and distributions. This is not an easy problem as everyone knows who has looked at $c\bar{c}$ production in hadron beams. At present the only model investigated which predicts an absolute rate is the single gluon bremsstrahlung model [12]. The $c\bar{c}$ pair is coupled to the quarks via single gluon exchange and the problem of colour rearrangement is ignored. This is probably not the dominant production mechanism near threshold where other Feynman diagrams are also important. Indeed exact calculations of the rate expected from this model yield dimuon and trimuon rates which are too small by at least one order of magnitude [12]. Until a better model is found, one approach we can follow is to use the gluon bremsstrahlung model to check consistency between the measured rates and distributions. This is not unreasonable because the cuts on the final muons are so severe that we only measure a small portion of phase space. One can subsequently remove the cuts to find an estimate of the $c\bar{c}$ production rate. Note that the real matrix element probably has a different dependence on the kinematic variables so our predictions could easily be incorrect by a factor of two or three.

Before we give any numbers we should mention the importance of checking the $c\bar{c}$ explanation by identifying $\mu^- e^-$ events in bubble chambers, where the rate is larger because the cut on the energy of the secondary lepton is not so severe. One could hope for approximately 10 $\mu^- e^-$ events from $c\bar{c}$ decay in 10^5 measured neutrino interactions. In a bubble chamber the events can be reconstructed exactly so we can find out whether the other hadrons are the decay products of charmed mesons and/or hadroms. This seems the cleanest way to settle the $c\bar{c}$ issue. Even a limit on the cross section would be important because it would add another constraint into the picture.

In the meantime we have to content ourselves with the available dimuon and trimuon events. Therefore we have taken the $c\bar{c}$ model and used Monte Carlo methods to calculate the rates and distributions for the neutrino production (in the 350 GeV wide-band beam) of $\mu^-\mu^-$ and $\mu^-\mu^-\mu^+$ events and the antineutrino production (in the 330 GeV beam) of $\mu^+\mu^+$ and $\mu^+\mu^+\mu^-$

events. To fix the overall normalization we assume that 20 % of the hadronic trimuon events are due to $c\bar{c}$ production and decay. To compare with the antineutrino trimuons we assume that 10 % of the experimental signal in that channel is also due to $c\bar{c}$ pairs. (ie., 20 % of the hadronic signal which we take equal in magnitude to the electromagnetic signal). We use a 10 % branching ratio for the channel $c \to \mu^+ + \nu_\mu + s$ and incorporate all the experimental cuts given by the CDHS group. The input for the model is discussed more fully in Ref.12. The results of the calculations are given in the following table and agree very well with the experimental numbers.

Reaction	Experiment	Theory
$\dfrac{\sigma(\mu^-\mu^-\mu^+)}{\sigma(\mu^-)}$	0.5×10^{-5}	0.5×10^{-5}
$\dfrac{\sigma(\mu^+\mu^+\mu^-)}{\sigma(\mu^+)}$	0.2×10^{-5}	0.2×10^{-5}
$\dfrac{\sigma(\mu^-\mu^-)}{\sigma(\mu^-)}$	$(3.4\pm1.8)\times10^{-5}$	5.0×10^{-5}
$\dfrac{\sigma(\mu^+\mu^+)}{\sigma(\mu^+)}$	$(4.3\pm2.3)\times10^{-5}$	2.4×10^{-5}

An examination of the distributions indicates that there is no conflict there either. To demonstrate this we show in Fig.2. the distributions expected for the opening angle $\Delta\varphi$ between the leptons on the plane perpendicular to the beam and in the transverse momentum of the secondary lepton along the shower axis. Note that most of the events in these plots are due to the background muons from π and K decays. There is no way known at present to clearly extract a signal from this noise. All the distributions from the $c\bar{c}$ model resemble those of the background events, and it is only the measured rate , which is too high, which really allows the CDHS group to conclude that a signal exists.

By removing all the cuts we find that the magnitude of the basic $c\bar{c}$ cross section is $\sigma(\nu_\mu(\bar{\nu}_\mu)+N\to\mu^-(\mu^+)+c+\bar{c}+X)/\sigma(\nu_\mu(\bar{\nu}_\mu)+N\to\mu^-(\mu^+)+X) \doteq 1\times10^{-3}$ at a beam energy of around 90 GeV. This is in agreement with the beam-dump measurements. Further theoretical work is needed to find a model which can reproduce this cross section and further experimental work is needed to reduce the error bars on the dimuon and trimuon rates.

Before finishing I should mention that there is another very interesting

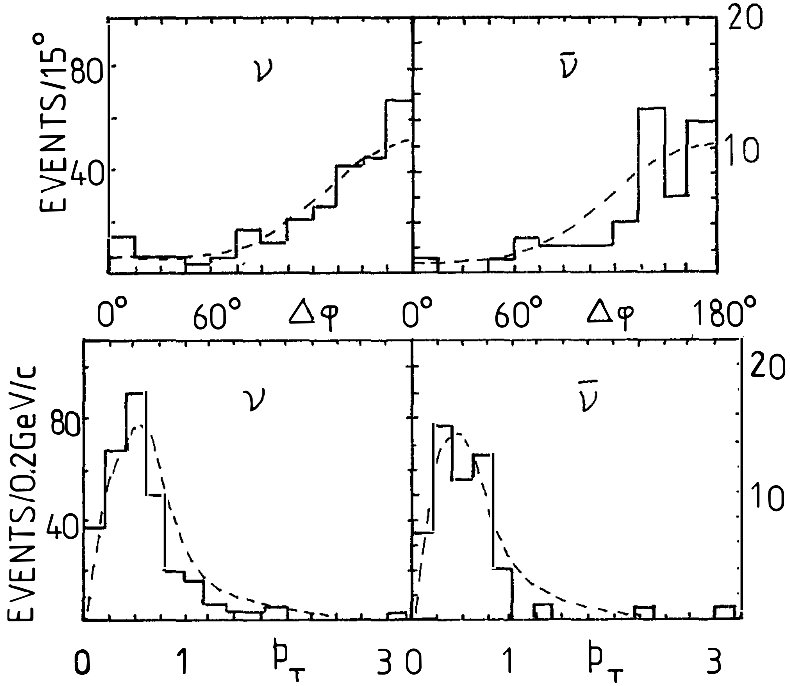

Fig.2. Distributions in $\Delta\varphi$ and in p_T of the secondary muon for the CDHS neutrino and antineutrino events.

source of like-sign dimuons, namely the production and decay of b quarks. In the standard six-quark model [4] b quarks are probably excited via a u-b coupling which could be as large as 10 % of G_F. Assuming a cascade decay b–c–s leads to same sign dimuons in antineutrino beams through the transitions $\bar{\nu}_\mu + u \rightarrow \mu^+ + b$, $b \rightarrow c + X$, $c \rightarrow \mu^+ + \nu_\mu + s$. The rate for this reaction can be estimated as follows. There is a threshold suppression factor of ~ 0.2 due to the heavy mass of the b quark, a coupling constant of say 6 %, a branching ratio for $b \rightarrow c + X$ of approximately 0.25 , a branching ratio of 0.1 for the semileptonic decay of the charmed quark and finally an acceptance factor (muon energy $\gtrsim$ 6.5 GeV) of around 0.5. Taking these numbers leads to a $\mu^+\mu^+$ event rate of $\sim 1 \times 10^{-5}$ of the normal charged current events. Hence it is obvious that the $\mu^+\mu^+$ data places some constraint on the b quark coupling constant. This problem is being investigated in more detail [15]. At present it seems clear from the p_T distributions given by Peyaud and shown in Fig.2. that there is not much room for b quarks in the data. The decay muons from b quark decays are expected to have a large p_T reflecting the heavy mass of the quark, but there are only two events (out of 60) above a transverse momentum of 2 GeV/c. If these particular events are manifestations of b quark decay then most of the signal below p_T = 2 GeV/c would also be caused by the same reaction which is not the case. Hence the possible event rate from b quark production and decay must be smaller than 4×10^{-5}. Even assuming that it is only 1×10^{-5} means that the u-b coupling constant is being pushed down to the theoretical upper limit. Better data in this channel could yield some meaningful constraint on the mixing angles in the six-quark model.

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