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TRILEPTON PRODUCTION BY NEUTRINOS AND ANTINEUTRINOS

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A B S T R A C T

We calculate the electromagnetic and hadronic contributions to neutrino production of $\mu^-e^+e^-$ events and antineutrino production of $\mu^+e^+e^-$ events. Due to an increase in cross-section and acceptance, these rates are much larger in bubble chamber experiments than the corresponding rates for trimuon events in counter experiments. Verification of these rates would confirm our understanding of the physics behind trilepton events. We stress the importance of measuring also a rate for μ^-e^- events to determine the cross-section for the associated production of charmed particles.

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1. - INTRODUCTION

Trimuon production by neutrino and antineutrino beams has been the subject of several experimental ¹⁾⁻³⁾ and theoretical ⁴⁾⁻⁹⁾ papers. In general it seems clear that the bulk of the events seen up to now can be explained in terms of a two-component model consisting of electromagnetic and hadronic pair production in regular deep inelastic neutrino and antineutrino collisions. The recent results by the CERN-Dortmund-Heidelberg-Saclay (CDHS) group ¹⁾ on $\mu^-\mu^-\mu^+$ events and $\mu^+\mu^+\mu^-$ events fit this picture rather well apart from some minor problem with the normalization of the hadronic rate ⁴⁾. Due to cuts of 4.5 GeV on the muon energies, the acceptance in the muon counter experiments is limited so the total rates are rather low, ranging from 10^{-5} to 10^{-4} of the regular inclusive cross-section as the energy increases from 50 GeV to 150 GeV.

One way to improve this acceptance is to look at reactions involving e^+e^- pairs in bubble chambers. This is, of course, not an easy matter because such pairs are copiously made by external bremsstrahlung and π^0 decays. In fact, up to now, there has only been one report of an upper limit on the rate for $\mu^-e^+e^-$ events in a neutrino exposure at Fermilab ¹⁰⁾. Nevertheless there can be no doubt that the multilepton reactions $\nu_\mu N \rightarrow \mu^-e^+e^-X$ and $\bar{\nu}_\mu N \rightarrow \mu^+e^+e^-X$ do exist with reasonably large cross-sections. Whether these reactions are interesting or not depends on one's point of view. The search for unusual events in bubble chamber experiments has not been an easy one but it is often the only way to identify certain reactions. If the rates for $\mu^-e^+e^-$ and $\mu^+e^+e^-$ events are confirmed then not only do we check our understanding of the trimuon physics but, at the same time, we place better limits on charm changing neutral currents, heavy lepton production and decay, etc. If at the same time a μ^-e^- or μ^+e^+ signal can be identified, we may learn something new about the like-sign dimuon events ¹¹⁾. We would therefore like to advocate that some effort be made to check the rates for these processes. In particular, if our predictions for the multilepton event rates are not confirmed, it would be a positive indication that our present understanding of trilepton physics is incomplete.

Therefore what we propose to do here is to give some idea of the rates and distributions expected for $\mu^-e^+e^-$ and $\mu^+e^+e^-$ events arising from the electromagnetic and hadronic models. We make a cut in the mass of the e^+e^- pair to eliminate the dominant background coming from π^0 decays.

We assume that $m(e^+e^-) > m_\pi$ and give the distributions expected in this mass, so that rates can be estimated when this cut is varied. A cut is made on the energy of the primary muon at 4.5 GeV, which has practically no effect on the rates. Also we assume cuts of 0.25 GeV on the electron and positron energies. For convenience we will give results for a range of $v(\bar{v})$ energies. Calculations using actual spectra can be made later.

In the next section, we briefly outline the models and describe quantitatively the expected results. Then in Section 3 we give the actual rates and a discussion of the distributions to help in identifying these particular events from other background reactions.

2. - MODELS

The present data on ν production of $\mu^-\mu^+\mu^+$ events and $\bar{\nu}$ production of $\mu^+\mu^+\mu^-$ events are consistent with a two-component model based on electromagnetic radiation and hadronic radiation of $\mu^+\mu^-$ pairs ¹⁾. Given this fact, it is relatively straightforward to predict what will happen when we consider the channels $\mu^-e^+e^-$ and $\mu^+e^+e^-$. The hadronic model takes data from the reactions $\pi N \rightarrow \mu^-\mu^+X$ and uses it in the $\nu(\bar{\nu})$ reaction. If it is true that all the $\mu^+\mu^-$ events in πN collisions come from the decays of mesons, i.e., $\rho \rightarrow \mu^+\mu^-$, $\eta \rightarrow \mu^+\mu^-\gamma$, etc., then the hadronic rates for e^+e^- pairs should be similar in size. There is, of course, some difference due to the increased phase space for the particle decays but, to a first approximation, this should not matter. A direct confirmation of this assumption can be found in an examination of the direct lepton yields in hadron reactions ¹²⁾. At moderate p_T and x_F there is evidence for the e/π ratio and the μ/π ratio being identical. Hence the only approximation involved is the extrapolation below the $\mu^+\mu^-$ threshold of the large low-mass enhancement seen in $\pi N \rightarrow \mu^+\mu^-X$ reactions ¹³⁾. We assume here that this background is a smooth exponential which is only cut off at the mass $2m_e$, rather than $2m_\mu$. This assumption leads to a large increase in the cross-section for $\pi N \rightarrow e^+e^-X$ compared to the cross-section for $\pi N \rightarrow \mu^+\mu^-X$.

To be more specific we will assume that the reaction $\pi N \rightarrow e^+e^-X$ can be parametrized by

$$E \frac{d\sigma}{d^3p dm} = a(m) \exp(-5.7 m_t) (1 - |x_F|)^{c(m)} \quad (1)$$

where E , p and m are the energy, momentum and mass of the dilepton pair in the πN system and $m_t^2 = p_T^2 + m^2$. The function $a(m)$, in units of $\mu b/\text{GeV}^3$, includes a smoothly falling background with Breit-Wigner peaks for the (ρ, ω) and ϕ contributions, namely

$$\begin{aligned} a(m) &= a_c + a_{\rho\omega} + a_{\phi} \\ a_c &= 2.3 \times 10^4 \left(\frac{m - 2m_e}{2m_\mu} \right)^2 \exp\left(-3.2 \frac{m}{2m_\mu}\right) \\ a_{\rho\omega} &= 2m / \left[(m^2 - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho^2 \right] \\ a_{\phi} &= 0.15 m / \left[(m^2 - m_\phi^2)^2 + m_\phi^2 \Delta\Gamma^2 \right] \end{aligned} \quad (2)$$

The parameter m now ranges from $2m_e$ to $\sim 1.2 \text{ GeV}$ and

$$c(m) = 1 + \left[0.5/m(\text{GeV}) \right]^2 \quad (3)$$

The cross-section is normalized to the πN cross-section by dividing by $\sigma_{\text{tot}}(\pi N) = 25 \text{ mb}$. Hence the only change in going from muons to electrons is in the threshold factor in a_c . We now take $(m - 2m_e)^2$ rather than $(m - 2m_\mu)^2$. With this change, Eq. (1) predicts that $\sigma(\pi N \rightarrow e^+e^-X) = 4.0 \mu b$ at $E_\pi = 100 \text{ GeV}$, $x_F > 0.15$ whereas the corresponding result for muons is that $\sigma(\pi N \rightarrow \mu^+\mu^-X) = 0.74 \mu b$.

To illustrate what we are doing, let us look at a typical mass spectrum as measured by, say, Anderson et al.¹³⁾ and depicted in Fig. 1. There is evidence for a large low-mass enhancement which is cut off by acceptance near $m = 2m_\mu$. The revised data shown in the thesis of Henry¹³⁾ actually shows a larger contribution in the low mass bins, while the region around the ρ meson and the ϕ meson is the same. If we assume that there is some exponentially falling background then we can try to extrapolate the curve backwards to the e^+e^- pair threshold. Of course, this produces large cross-sections for the $\nu_\mu N \rightarrow \mu^- e^+e^-X$ reaction. To eliminate the low-mass region containing uninteresting π^0 decays, we

have to make a cut in the e^+e^- pair mass. The location of this cut is very important in fixing the magnitude of the resulting cross-section. A cut somewhere between m_π and $2m_\pi$ will remove most of the Dalitz decays. Clearly if the cut is put at around $4m_\pi$ then one is essentially measuring the inclusive production of (ρ, ω) mesons, which by itself is not uninteresting. Up to now the energy resolution of the neutrino induced trimuon events has not been good enough to separate the (ρ, ω) from background.

The remainder of the hadronic trimuon calculation is rather easy. We take the cross-section for $\nu_\mu + N \rightarrow \mu^- + X$ calculated according to the structure functions given in Ref. 4), which fit the recent CDHS data ¹⁴⁾, and fold it with the normalized πN cross-section calculated at the same invariant mass W of the hadron shower and with the laboratory pion direction along the hadron axis. Results will be discussed later.

Now we make some comments on the electromagnetic calculations. This goes through identically to the previous calculations ⁴⁾⁻⁷⁾ only the $\mu^+\mu^-$ pair mass is replaced by the e^+e^- pair mass. Here we expect the rate to go up by approximately a factor of five, because the pair mass spectrum has the usual infra-red behaviour associated with inner bremsstrahlung and we now have a much lower cut-off at $2m_e$ rather than $2m_\mu$. Alternatively, the cross-section, instead of containing a factor $\log(s/m_\mu^2)$ now contains the factor $\log(s/m_e^2)$ and numerically $\log(m_\mu^2/m_e^2) \simeq 5$. However easy this may seem in theory, it is not so trivial in practice because we are evaluating the total cross-section by computing multidimensional integrals using Monte Carlo methods and the cancellations between different terms in the square of the matrix element are difficult to control when small electron masses play an essential rôle. Although technically the invariant mass of the e^+e^- pair can get as low as $2m_e$, in the situation where the cut-off in W is around the pion mass our program can handle the problem. Hence we carefully reduced the secondary muon masses in our trimuon program, checking that there were no uncontrollable divergences in the limit. As we are now cutting away most of the low mass events we expect the electromagnetic rate to be only approximately twice the old trimuon rate. This suffices to explain our model, now we turn to the results.

3. - RESULTS

Let us start this section by illustrating the size of the trimuon cross-section when we remove the severe acceptance cuts associated with a typical counter experiment. Suppose we calculate the cross-sections for the hadronic and electromagnetic trimuon production with cuts on the primary muon at $E_\mu = 4.5$ GeV and cuts on the secondary muons at $E_\mu = 0.25$ GeV. Figure 2 shows these results. By comparing them to the trimuon rates given in Ref. 4), with cuts of 4.5 GeV on all the muons we see that we have gained almost a factor of ten in the hadronic rate and a factor of two in the electromagnetic rate. If we now switch the final muon pair to an electron pair then the rates will increase even further because we pick up the additional cross-section in the region between $W = m_\pi$ and $W = 2m_\mu$. The magnitude of this extra enhancement depends crucially on where we place the cut on the pair mass. For multilepton rates we therefore only show cross-section ratios with a cut on the e^+e^- pair mass at $W = m_\pi$, and cuts on the electron energies of 0.25 GeV as well as a cut on the muon energy at 4.5 GeV. As mentioned previously our electromagnetic program would have to be modified if it were not for this cut in W . Some of the integrals would have to be done analytically to keep the cancellations in the matrix element under control. Actually it is possible to find an asymptotic expansion for the cross-section in the high energy limit but we have not attempted such a calculation. Figure 2 shows the values for the hadronic and electromagnetic trilepton production rates. With the cut at $W = m_\pi$ we have gained a factor of four in the hadronic rate and a factor of two in the electromagnetic rate. However, the final increase in the hadronic rate is very sensitive to the extrapolation of the low mass pair spectrum so the numbers should be taken with some caution.

In the case of the trimuon events the hadronic rate predicted from Eq. (1) is too small to explain the observed signal and an extra factor of two to three is required. If we first ignore this fact and simply add the trilepton cross-sections, then at 100 GeV we see that the total rate for the trilepton events is around 5×10^{-4} . Including the additional factor means that the rate could be as large as 1.5×10^{-3} . Hence at this energy the trilepton rates are up to fifteen times larger than the CDHS trimuon rate. There is only a small change in reducing the beam energy to, say, 50 GeV because the threshold for these reactions is very small and the cross-sections reach their asymptotic values rather quickly. These final trilepton rates are so large that there should be no difficulty in seeing such events in a bubble chamber exposure.

Now let us present some distributions. Of course, the most crucial one is the electron positron mass distribution. In Fig. 3, we compare the hadronic and electromagnetic distributions for a beam energy of 50 GeV. The electromagnetic case shows essentially a universal infra-red divergent curve which is now cut off at the mass $W=m_{\pi}$. The curve for the hadronic distribution shows a similar behaviour. In fact the low mass contribution is so large that it is difficult to see the contributions from the vector mesons. We have reduced the hadronic cross-section by a factor of ten to get it on the same figure.

Other distributions are shown in Figs. 4-6. First we show the energy spectra of the muons and electrons in Fig. 4, and the p_T spectra with respect to the neutrino beam in Fig. 5. The rates are normalized by dividing the hadronic rate by a factor of ten. The other distribution which is interesting is the azimuthal angle between the muon and the dilepton pair on the plane perpendicular to the neutrino beam. This distribution, shown in Fig. 6, has a clear backward peak at 180° for the hadronic trilepton events, which is expected because the electron-positron pair is emitted preferentially along the hadron shower direction. On the other hand, the electromagnetic reaction shows a clear forward peak demonstrating that the pair radiation from the muon is preferred. As the hadronic component dominates over the electromagnetic one by a factor of approximately ten it may be difficult to see this component.

We finish by adding a comment on the expected magnitude of a μ^-e^- or μ^+e^+ signal. The recent results from the CDHS group¹⁵⁾ on the like-sign dimuon events indicate that $\sigma(\mu^-\mu^-)/\sigma(\mu^-) \simeq \sigma(\mu^+\mu^+)/\sigma(\mu^+) \simeq 4 \times 10^{-5}$ with an energy cut of 6.5 GeV on each muon. If these events are due to the associated production and decay of charmed particles⁹⁾ then there must also be a μ^-e^- and μ^+e^+ signal. However, the basic reaction is the same, namely $\nu_\mu + N \rightarrow \mu^- + c + \bar{c} + X$, so we only gain in acceptance in switching from muons to electrons. The production cross-section still has a threshold set by the mass of the $c\bar{c}$ pair. Our calculations for $E_\nu = 100$ GeV, i.e., for the CDHS experiment, indicate that a factor of approximately three can be gained in going from dimuons (each $E_\mu \geq 6.5$ GeV) to dileptons ($E_\mu \geq 4.5$ GeV, $E_e \geq 0.25$ GeV). Thus the maximum μ^-e^- rate is around 1×10^{-4} and is probably smaller because bubble chamber experiments have softer neutrino beams so the basic cross-section for $\nu_\mu + N \rightarrow \mu^- + c + \bar{c} + X$ is therefore smaller. It is important to try to set some limit on μ^-e^- events (or actually measure a rate)

because our explanation of the like-sign dimuons could be incorrect. If the explanation of the events is not associated production then the μ^+e^- signal may not be correlated with the $\mu^+\mu^-$ signal.

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FIGURE CAPTIONS

Figure 1 A typical $\mu^+\mu^-$ pair mass spectrum predicted from Eq. (1). We show results for $E_\pi = 100$ GeV and $x_F > 0.15$. The dashed curves give the approximate contributions due to the vector meson resonances and the extrapolation of the low mass peak when it is not cut off by acceptance and we can measure the part of the spectrum below the dimuon threshold. The dot-dashed line shows the position of a cut at $W = m_\pi$.

Figure 2 Cross-section ratios for

- (a) $\sigma(3\mu)/\sigma(\mu)$ with cuts on the muons at $E_1 = 4.5$ GeV, $E_2 = E_3 = 0.25$ GeV together with
- (b) $\sigma(\mu ee)/\sigma(\mu)$ with cuts on E_μ at 4.5 GeV and $E_{e^+} = E_{e^-} = 0.25$ GeV and a cut on $W = m_\pi$. The hadronic and electromagnetic rates are shown separately. The solid curves are for the neutrino reactions and the dashed curves are for the antineutrino reactions.

Figure 3 The dilepton mass spectra for the reaction $\nu_\mu + N \rightarrow \mu^- + e^+ + e^- + X$ with $E_\nu = 50$ GeV. The solid curve shows the hadronic component (times 1/10) while the dashed curve shows the electromagnetic component.

Figure 4 The energy spectra of the leptons in the reaction $\nu_\mu + N \rightarrow \mu^- + e^+ + e^- + X$. In (a) we show the electron spectrum and in (b) we show the muon spectrum. In each case the hadronic component (solid line) is reduced by a factor of ten.

Figure 5 Same as Fig. 4, but for the transverse momenta along the beam direction.

Figure 6 The distribution in the angle $\varphi_{1,(2+3)}$ for the reaction $\nu_\mu + N \rightarrow \mu^- + e^+ + e^- + X$. The hadronic component, shown by the solid line is again reduced by a factor of ten.

FIG.1

FIG.2

FIG.3

FIG. 4a

FIG. 4b

FIG.5a

FIG.5b

FIG.6