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Multimuon production in deep-inelastic μ-nucleus scattering

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Multimuon production in deep-inelastic μ-nucleus scattering is estimated using the quark-parton model and the assumption that the secondary muons come from the production of a charmed-particle-antiparticle pair out of the $c\bar{c}$ pair in the sea of the nucleon and the subsequent semileptonic decay of these charmed particles. The calculated x, y, and Q^2 distributions are in agreement with the preliminary data reported by Chen of the Cornell–Michigan State–UCB–UCSD group.

I. INTRODUCTION

Recently, Chen has reported[1] the observation of 38 multimuon events by the Cornell–Michigan State–UCB–USCD group. Their data sample consists of 25 560 single-muon events, 27 dimuon, and 11 trimuon events. In 15 of the dimuon events the two muons have opposite charge; in 12 cases they have the same charge. No wrong-sign trimuons have been observed. Three of the trimuon events are highly inelastic, five are quiet, and for the remaining three the inelasticity is not known. The dimuons show a leading-particle effect, $\langle P_1\rangle/\langle P_2\rangle \approx 2.8$, and no visible peak in $M(\mu^+\mu^-)$, which makes a neutral heavy lepton as their origin unlikely. On the other hand, these two characteristics as well as others [such as approximate equality of the same-sign pairs (SSP) and opposite-sign pairs (OSP), small $\langle x\rangle$, high $\langle y\rangle$, no wrong-sign trimuons, etc.], discussed in Chen's talk, suggest strongly that the additional muons come from the associated production of charmed particles and their subsequent semileptonic decay. The observed ratio

$$\frac{\sigma(\mu\to\mu\mu)}{\sigma(\mu\to\mu)}=(1.0\pm0.5)\times10^{-3}$$

is also roughly what is expected in this picture.

In this paper, we have estimated more quantitatively the dimuon and trimuon production, using the quark-parton model. We assume that a $D\bar{D}$ pair (D means any charmed particle) is produced if the virtual photon hits a charmed quark in the sea of the nucleon, and that the subsequent semileptonic decay of these charmed particles gives rise to the additional muons. In Sec. II, we give the calculation for the x, y, and Q^2 distributions for various masses of the charmed quark and the produced $D\bar{D}$ system. The experimental cuts mentioned in Chen's[1] paper, and to be discussed in Sec. II, have been included in the calculation.

We give the results for

$$m_c=2\text{ GeV},\quad m_{D\bar{D}}=3.8\text{ GeV}$$

and

$$m_c=4\text{ GeV},\quad m_{D\bar{D}}=8\text{ GeV}.$$

The first choice for $m_{D\bar{D}}$ is motivated by the recent observation of D-$\bar{D}^*$ at SLAC. The second value has been chosen in order to reproduce exactly the experimentally observed threshold. The calculated distributions are compared with the preliminary data in Figs. 2–6. Whereas the y distribution is compatible with the data, the agreement is not that good for the Q^2 distribution, which may be because of the experimental acceptance, not reported in Chen's paper.

Using a distribution

$$c(x)=0.2\,\xi(x) \tag{1}$$

for the charmed quark, where

$$\xi(x)=\bar{\mathcal{P}}(x)=\bar{\mathfrak{N}}(x)=\lambda(x)=\bar{\lambda}(x)\,, \tag{2}$$

we obtain a semileptonic branching ratio for the decay of the charmed particles of the order of 3–7%, which is not incompatible with the dimuon production in neutrino scattering. Finally, in Sec. III, we compare our results with the data reported by Chen. We also discuss the probable signature of a possible excitation of a particle with both hadronic and leptonic quantum numbers in this experiment.

II. CALCULATION

Crucial for our estimate is the distribution function of the charmed quark. We assume that $c(x)$ has the same shape as the usual sea distribution and that, however, the absolute magnitude is smaller, owing to the large mass of the c quark. Sivers[2] has shown that considerations of all aspects of the present data on charmed-particles production, strongly indicate

$$c(x)=0.2\times 2^{\pm 1}\times \xi(x)\,. \tag{3}$$

For the parametrizations of the valence and sea contributions we used those given by Barger and Phillips,[3] Mc Elhaney and Tuan,[4] and Nandi[5] and found that our results depend very little on which parametrization we use. The results are reported for the parametrization of Barger, Phillips

$$xv(x)=\sqrt{x}\,[0.333(1-x^2)^3+0.334(1-x^2)^5 + 0.621(1-x^2)^7]\,, \tag{4}$$

$$x\,\xi(x)=0.145(1-x)^9\,, \tag{5}$$

and of Nandi.

$$xv(x)=\sqrt{x}\,[0.25(1-x^2)^3+1.35(1-x^2)^9]\,, \tag{6}$$

$$x\,\xi(x)=0.17(1-x)^{11}\,, \tag{7}$$

where

$$v(x)+\xi(x)\equiv\tfrac{1}{2}[\mathcal{P}(x)+\mathfrak{N}(x)]\,.$$

The first parametrization corresponds to 6.9% sea, i.e.,

$$\frac{\int x\xi(x)dx}{\int xv(x)dx}=0.069\,, \tag{8}$$

and the second one to 7% sea.

To take into account the effect of the large mass of the charmed quark we have replaced the $x\equiv Q^2/2M\nu$ by the slow rescaling variable,[6] as suggested by the following simple parton-model consideration (Fig. 1):

$$(q+zp)^2=m_c^{\,2}\,. \tag{9a}$$

With $p^2=M^2=(\text{mass of the proton})^2$ and $y=\nu/E$, one gets

$$z=\frac{1}{M}[-Ey+(E^2y^2+2MExy+m_c^{\,2})^{1/2}]\,. \tag{9b}$$

In terms of x and y, the differential cross section per nucleon for the Fe target is given by

$$\frac{d\sigma}{dxdy}=\frac{2\pi\alpha^2}{EM}\,\frac{1}{x^2}\left\{\frac{x}{2z}+\frac{1-y}{y^2}\left[1-\frac{Mxy}{2E(1-y)}\right]\right\}zf(z)\,. \tag{10}$$

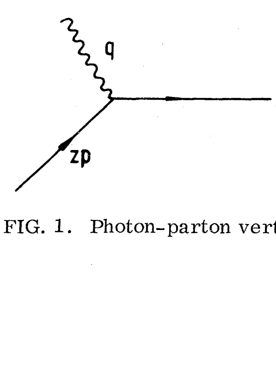

FIG. 1. Photon-parton vertex.

For the case of charm production one has

$$f(z)=\tfrac{8}{9}\,c(z)\,, \tag{11}$$

and we have used the $c(z)$ as given in (3).

The total cross section is obtained by putting

$$zf(z)=\nu W_2(z)\equiv\tfrac{1}{2}(\nu W_2^{ep}+\nu W_2^{en})\,. \tag{12}$$

In terms of $Q^2=-q^2$ and y, the cross section is

$$\frac{d\sigma}{dQ^2dy}=\frac{\pi\alpha^2}{MEQ^2}\left(\frac{1}{z}+\frac{4ME}{Q^2}\,\frac{1-y}{y}-\frac{M}{Ey}\right)zf(z)\,, \tag{13}$$

where z is given, using Q^2 instead of x, by the expression

$$z=\frac{1}{M}\left[-Ey+(E^2y^2+Q^2+m_c^{\,2})^{1/2}\right]. \tag{14}$$

The various kinematical cuts in the experiment are

$$\theta\geq\theta_{\min}=13\text{ mrad},\quad \nu\leq 140\text{ GeV}\,,$$

where θ is the scattering angle and ν the energy loss of the primary muon. These cuts impose the following restrictions on x and y:

$$x\geq\frac{2E}{M}\,\frac{1-y}{y}\,\sin^2(\tfrac{1}{2}\theta_{\min})\,,$$
$$y\leq\frac{140}{E}\,,\quad E=150\text{ GeV}\,, \tag{15}$$
$$y\geq\frac{1}{1+Mx/2E\sin^2(\tfrac{1}{2}\theta_{\min})}\,.$$

From the fact that the hadronic final state has to contain at least the $D\bar{D}$ pair and one nucleon, one gets the condition

$$y(1-x)\geq\frac{m_{D\bar{D}}^{\;2}+2m_{D\bar{D}}M}{2ME}\,. \tag{16}$$

Since z is interpreted as the fraction of the proton momentum that is carried by the struck quark, z has to be smaller than one, which means that x and y have to satisfy the further inequality

$$x\cong z-\frac{m_c^{\,2}}{2MEy}\leq 1-\frac{m_c^{\,2}}{2MEy}\,. \tag{17}$$

Taking all these restrictions into account, the final bounds on x for a given (allowed) y are

$$\frac{2E}{M}\,\frac{1-y}{y}\,\sin^2(\tfrac{1}{2}\theta_{\min})\leq x\leq 1-\frac{m_{D\bar{D}}^{\;2}+2m_{D\bar{D}}M}{2MEy}\,, \tag{18}$$

and the bounds on y for a given (allowed) x are

$$\max\left\{\frac{1}{1+Mx/2E\sin^2(\tfrac{1}{2}\theta_{\min})}\,,\ \frac{m_{D\bar{D}}^{\;2}+2m_{D\bar{D}}M}{2ME(1-x)}\right\}\leq y\leq\frac{140}{150}\,. \tag{19}$$

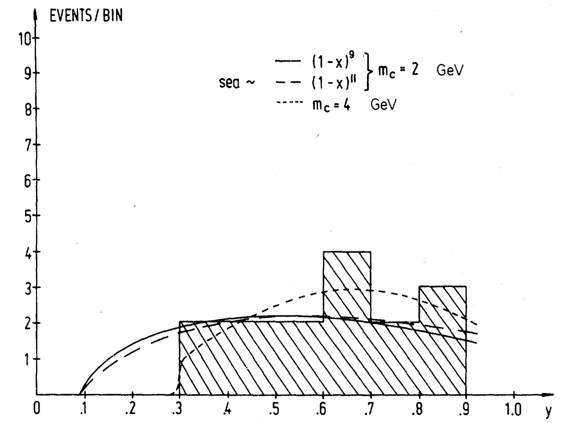

FIG. 2. The calculated distributions for $m_c = 2$ GeV for both the sea parametrizations and for $m_c = 4$ GeV with the parametrization $x\xi(x) = 0.15(1-x)^9$ are compared with the OSP dimuons only. The curves are normalized in such a way that the area under the curves is equal to the shaded area.

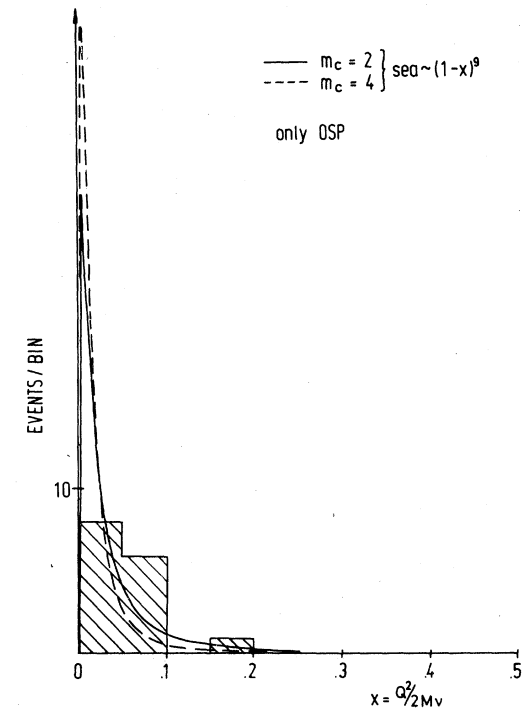

FIG. 3. The calculated x distributions compared with the 15 OSP dimuon events. The sea parametrization of Barger and Phillips (Ref. 3) is used.

III. COMPARISON WITH EXPERIMENT

As far as the dimuons are concerned, it is clear only in the case of the OSP which muon is the scattered one and which is the produced one, and only for these events x and y are uniquely de-

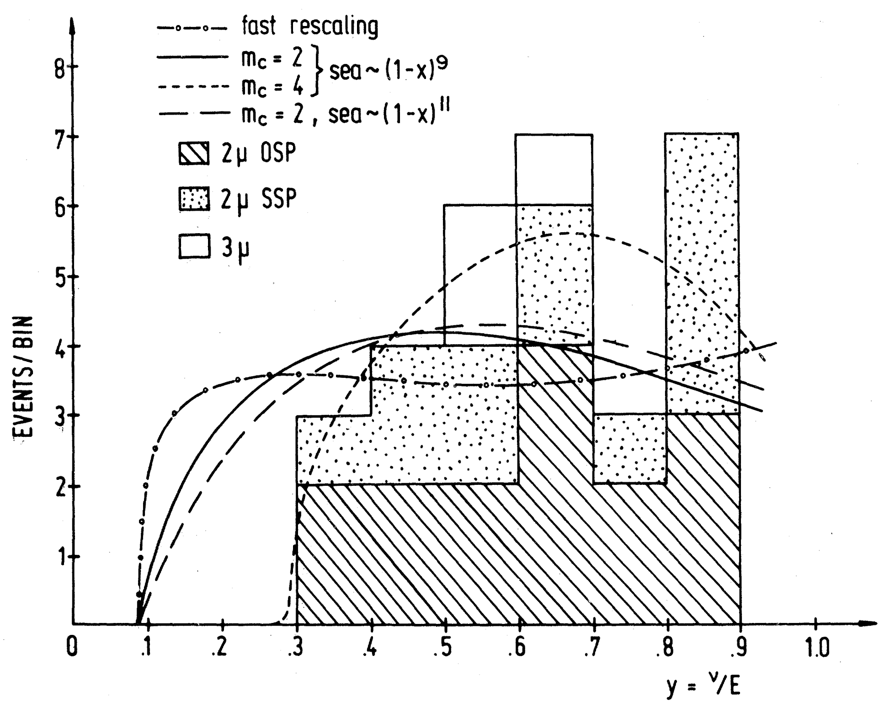

FIG. 4. The same as Fig. 2, but now the comparison is made with all the dimuons plus the highly inelastic trimuons. The dash-dotted curve shows the distribution which is obtained by using the fast-rescaling variable with a sea $\sim(1-x)^9$.

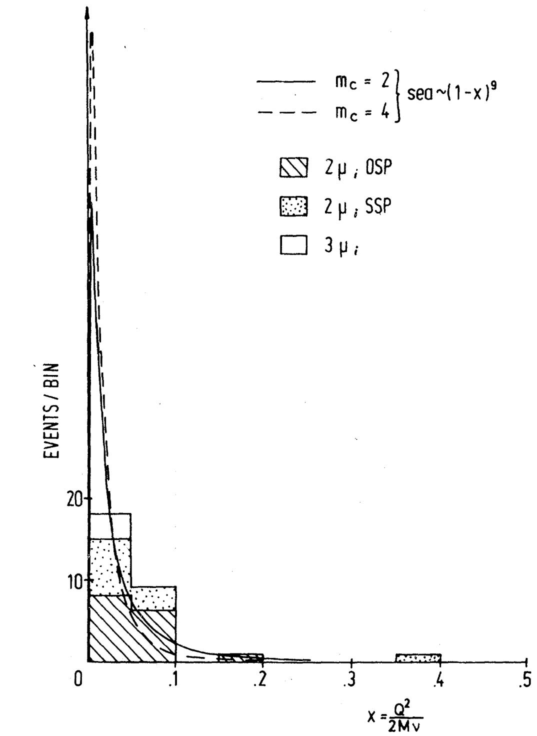

FIG. 5. The same as Fig. 3, but all dimuons and the highly inelastic trimuons are included.

termined. Therefore, we compare our calculated distributions in Fig. 2 and Fig. 3 only with the data for the 15 OSP dimuons. In Fig. 2, the y distributions are given for $m_c = 2$ GeV and both the sea distributions given in (5) and (7). For $m_c = 4$ GeV, we give only the curve that corresponds to the distribution (5); the other parametrization gives essentially the same result. Although $m_c = 4$ GeV agrees better with the observed threshold, we think that the agreement for both cases $m_c = 2$ and $m_c = 4$ GeV is quite good. The x distribution (Fig. 3) is only compared with the curve that we obtain, using the sea parametrization (5); the other one gives an essentially indistinguishable result.

For the 12 same-sign dimuon events and the 3 highly inelastic trimuon events we assume a leading-particle effect. Then, the x, y, and Q^2 values for them are determined and are the same as reported by Chen.[1] In Figs. 4, 5, and 6, these events are included in the comparison with our curves. The quiet trimuons most probably do not come from the same mechanism as the diumons, because there are no dimuon events in this range of the inelasticity. Therefore, we have excluded them from the data to compare with our results, and also the trimuon events of unknown inelasticity.

We have also calculated the total single and

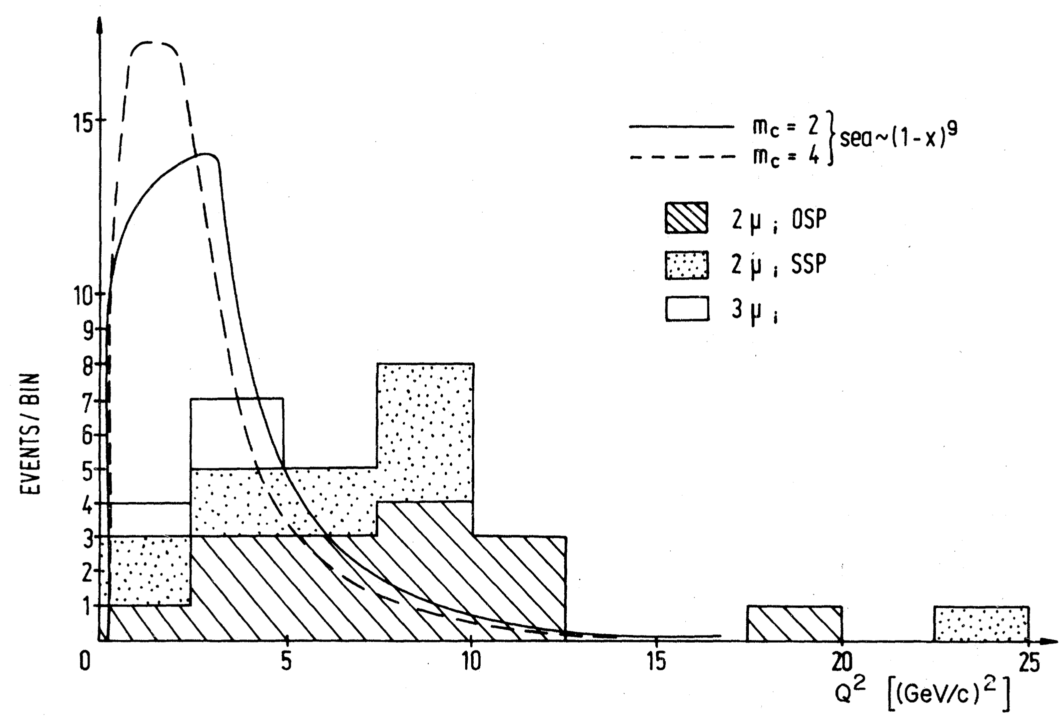

FIG. 6. The calculated Q^2 distribution is compared with the measured distribution, both for $m_c = 2$ and $m_c = 4$ GeV. The sea parametrization of Barger and Phillips (Ref. 3) is used.

TABLE I. The average quantities $\langle x\rangle$, $\langle y\rangle$, $\langle Q^2\rangle$ are given for the different parton distributions and charmed-quark masses and compared with the measured ones. B is the semileptonic branching ratio.

Parametrization of the quark distribution functions	m_c (GeV)	$m_{D\bar{D}}$ (GeV)	B	$\langle x\rangle$	$\langle y\rangle$	$\langle Q^2\rangle$ [(GeV/c)^2]
Barger and Phillips (Ref. 3)	2	3.8	2.3%	0.04	0.532	3.90
	4	8	6.45%	0.027	0.636	3.47
Nandi (Ref. 5)	2	3.8	2.9%	0.036	0.551	
Measured quantities (dimuons only)				0.048	0.65	7.5

multimuon cross sections.[7] Together with the observed ratio of multimuon production compared to the single-muon events (30 multimuons, if the ambiguous trimuons are excluded, and 25 560 single muons), we obtain a semileptonic branching ratio of the D between 2.4 and 6.5%. This seems to be a little bit low, compared to the fact that there are 3 trimuon events among the 30 multimuons. Furthermore, to explain the magnitude of the dimuon production in ν and $\bar{\nu}$ scattering, one has to assume a branching ratio of 5–10% for the semileptonic decay of the D. But the statistics of the data is certainly not good enough to draw any conclusion, and secondly, the factor 0.2 in our assumed quark distribution

$$c(x)=0.2\,\xi(x)$$

may be a slight overestimate. The calculated numbers for the semileptonic branching ratio B and for $\langle x\rangle$, $\langle y\rangle$, and $\langle Q^2\rangle$, together with the experimental values, are given in Table I.

Finally, we discuss the possibility of the excitation of a heavier quark, such as the b quark, which seems to be excited in the deep-inelastic $\bar{\nu}$ scattering,[5,8,9,10] and the excitation of the newly proposed particle with both hadronic and leptonic quantum numbers (H_L).[11] As noted in Refs. 5 and 9, in order to be compatible with the x distribution in $\bar{\nu}$-induced dimuon events, the semileptonic branching ratio for the b quark has to be negligible compared to that for the charmed quark. The contribution of a H_L excitation is difficult to estimate because of the absence of any guide about the distribution function for the H_L-$\bar{H}_L$ pair in the sea of the nucleon. So, at the moment, the only thing one could say is that if there is an excess of events at high y, then they may be due to the excitation of such an H_L of large mass. The data are, up to now, not sufficient at all, to say anything in this regard.

Note added. After the completion of this work, we received a report by V. Barger and R. J. N. Phillips, [Phys. Lett. 65B, 167 (1976)], the contents of which greatly overlaps that of our paper. Their results are in agreement with ours except that they obtain a higher value of $\langle Q^2\rangle$, which is closer to the measured one, by folding in a smooth acceptance function. Also, the acceptance cut on the decay muon improves the branching ratio and the threshold behavior. They do not use the slow-rescaling variable.

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[7]We mention here that though the contribution of the sea in $\nu W_2(x)$ is usually $\sim$10%, in the total cross-section, because of the $1/x^2$ factor, the sea contribution is $\sim$30%.

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