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B. Dasskowski, D. Kohaupt, K. Steffen, G.-A. Voss

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Trimuons from Charm

Bing-Lin Young
Ames Lab. ERDA and Department of Physics
Iowa State University, Ames, Iowa, 50010, USA

T.F. Walsh
Sektion Physik
Universität Wuppertal
and
DESY

T.C. Yang
Physics Department
University of Massachusetts
Amherst 01003, USA

Abstract

We have calculated charm pair production in $\nu_\mu N$ collisions using quantum chromodynamics (QCD). The resulting trimuon rate turns out to be small at present energies - $\sigma(3\mu)/\sigma(1\mu) \lesssim 10^{-6}$ at $E_\nu = 200$ GeV for $\alpha_s = 0.2$. (However, this process may be measurable at the high energies attainable with colliding beam ep machines.) We emphasize the general importance of looking for inclusive J/ψ or the bound states of heavier flavors in deep inelastic reactions, as a signal for the pair production of heavy quarks.

It has long been recognized that pair production and semileptonic decay of charm is a potentially important source of trimuons and like sign dimuons in neutrino interactions, e.g.,

$$\nu_\mu(\bar{\nu}_\mu) N \longrightarrow \mu^-(\mu^+) + \underset{\hookrightarrow \mu^+ + \cdots}{C} + \underset{\hookrightarrow \mu^- + \cdots}{\bar{C}} + \cdots \qquad (1)$$

(We denote a charmed quark by c and a charmed particle by C.) We report here on a calculation of this process in the framework of quantum chromo-dynamics (QCD), the gauge theory of quarks and vector gluons carrying color. (1) Our results can also be applied to pair production of flavors heavier than charm. They also serve as a test of the ideas of QCD.

We also call attention to trimuon production via

$$\nu_\mu(\bar{\nu}_\mu) + N \longrightarrow \mu^- (\mu^+) + \underset{\hookrightarrow \mu^+\mu^-}{J/\psi} + \cdots \qquad (2)$$

Our estimates indicate that (2) is at least as important a trimuon source as (1). We encourage experimentalists to look for it as a signal for $c\bar{c}$ production in νN.

In our view, $c\bar{c}$ production followed by $c\bar{c} \to C + \bar{C} + \ldots$ or $c\bar{c} \to J/\psi + \ldots$ in neutrino beams is effectively a two-current process. It involves the weak current at large space-like q^2 and the QCD color current at large timelike momentum transfer ($\gtrsim 4m_c^2$). These large momentum transfers justify the use of perturbation theory in the running coupling constant of QCD, $\{4\pi\alpha_s/Q^2\}^{1/2}$ (1),(2).

Production of a charmed quark pair is shown in Fig. 1. This is bremsstrahlung off a struck quark ($\nu_\mu q \to \mu^- q c\bar{c}$; q is a light quark in the target). We ignore the possibility that the weak and color currents couple to different quarks. Such amplitudes will be highly suppressed in the Bjorken limit due to the damping caused by the large $c\bar{c}$ mass. However, they may be important in kinematic regions where the contribution of Fig. 1 is small .

The only large Q^2 hadronic process in Fig. 1 is $c\bar{c}$ production itself. The color of $c\bar{c}$ arising from the exchange of a single color gluon will be compensated by low Q^2 processes involving the fragments of the struck nucleon in processes (1) and (2).[3] We will assume in the spirit of the parton model that the effects of dressing to color singlet states affects neither the total rate for (1) or (2), nor the distributions of the $c\bar{c}$ pair. This last assumption is admittedly speculative. We can test it in principle, however, as it allows us to predict the kinematic distributions of $J/\psi = c\bar{c}$, independent of further assumptions. The decay muon distributions in (1) require further information - e.g., from $e^+e^- \to c\bar{c} \to C\bar{C} + \ldots \to \mu^\pm + \ldots$.+)

We calculate (1) and (2) using the parton model. The cross section for $\nu_\mu N \to \mu^- c\bar{c} + \ldots$ is

$$\frac{d^3\sigma}{dx\,dy\,d\tau} = \sum_i \int_{x+\tau/y}^{1} d\xi\, q_i(\xi)\, \frac{d^4\sigma_i}{dx\,dy\,d\tau\,d\xi} \tag{3}$$

where $d\sigma_i$ is the cross section from Fig. 1 for the i^{th} quark of longi-

tudinal momentum ξ , and $q_i(\xi)$ is the density in ξ. The variables are $x = -q^2/2M_N\nu$, $y = \nu/E_\nu$ and $\tau = m_{c\bar{c}}^2/2M_N E_\nu$.

The cross section $d\sigma_i$ from Fig. 1 (including all color factors) has been calculated analytically for any m_c, but with $m_q = 0$. As the exact result is quite complicated, we first discuss the high energy limit, turning later to exact numerical results.

Picking out the leading term for small τ and very high energy (also assuming $\tau \ll xy$) we find in units of $G_F^2 M_N E_\nu/\pi$,

$$\frac{d^3\sigma_i}{dx\,dy\,d\tau\,d\xi} \xrightarrow[E_\nu\ \text{large}]{} \frac{2}{9}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{a(m_{c\bar{c}}^2)}{\tau}\, \frac{x}{\xi^2}\, \frac{\xi^2+x^2}{\xi-x}\, \ln\left(\frac{[\xi y-\tau][\xi-x]}{x\tau}\right)$$

$$* \begin{cases} 1 & \text{for } \nu_\mu q,\ \bar{\nu}_\mu \bar{q} \\ (1-y)^2 & \text{for } \bar{\nu}_\mu q,\ \nu_\mu \bar{q} \end{cases} \tag{4}$$

where $a(m_{c\bar{c}}^2) = (1 + 2m_c^2/m_{c\bar{c}}^2)(1 - 4m_c^2/m_{c\bar{c}}^2)^{1/2}$ and $\alpha_s = \alpha_s(m_{c\bar{c}}^2)$, the running coupling in QCD. The $\ln\tau$ dependence in (4) arises from integration over the fractional energy of the current carried off by the $c\bar{c}$ pair,

$$\frac{\tau}{y(\xi-x)} \le z = E_{c\bar{c}}/\nu \le 1$$

This distribution has the asymptotic form

$$\frac{d\sigma_i}{dz} \propto \frac{1}{z - \tau/\xi y} \tag{5}$$

typical for bremsstrahlung. A non-negligible fraction of produced $c\bar{c}$ have large z.

Assuming that a nucleon is made out of three quarks at all energies, and ignoring the $m^2_{c\bar{c}}$ dependence of α_s, we find from (4) the following crude estimate of the fraction of deep inelastic events with $c\bar{c}$,

$$\frac{\sigma(\nu_\mu N \to \mu^- c\bar{c} + \cdots)}{\sigma(\nu_\mu N \to \mu^- + \cdots)} \sim \frac{1}{9}\left(\frac{\alpha_s}{\pi}\right)^2 \ln^3\left(\frac{2M_N E_\nu}{4m_c^2}\right) \tag{6}$$

(This estimate cannot be used where the log is large, due to our neglect of the $m^2_{c\bar{c}}$ dependence of α_s.) Asymptotically, x and y distributions for events with $c\bar{c}$ are the same as for all events. With $m_c = m_D$ and putting $\alpha_s = 0.20$ the total $c\bar{c}$ fraction is at the percent level - as one would expect on counting powers of α_s/π.

What about the exact results? They look quite different at present neutrino energies (E_ν = 10-300 GeV). Fig. 2a shows the exact $\sigma(\nu_\mu N \to \mu^- c\bar{c} + \cdots)$ in units of $G_F^2 M_N E_\nu/\pi$, also for $m_c = m_D$ and a constant $\alpha_s = 0.20$ (thus cross sections can be easily scaled for different α_s). Fig. 2b shows $\sigma(3\mu)/\sigma(1\mu)$, the trimuon fraction, assuming that the entire process goes through reaction (1) with C = D and BR($D \to \mu + \ldots$) = 11 % [4]. In all cases, we used the $q_i(\xi)$ from reference (5), ignoring possible energy dependences. Figs. 3a-c show x, y and τ distributions at E_ν= 150 GeV. Note the large fraction of the incident energy which is carried off by the $c\bar{c}q$ system.

Our calculated trimuon rate at low E_ν is obviously far below the naïve estimate $(\alpha_s/\pi)^2 [BR(D \to \mu + \cdots)]^2 \sim 10^{-4}$, and it rises rapidly with energy. We have traced this to a large nonleading term contributing one less $\ln \tau$ to (4) or (6). A better approximation than (4) turns out to be

$$\frac{d\sigma}{dx\,dy\,d\tau\,d\xi} \xrightarrow[\text{large } E_\nu]{} \frac{2}{9}\left(\frac{\alpha_s}{\pi}\right)^2 \frac{\alpha(m^2_{c\bar{c}})}{\tau}\frac{x}{\xi^2}\left[\frac{\xi^2+x^2}{\xi - x}\ln\left(\frac{(\xi y - \tau)(\xi - x)}{x\tau}\right) - \frac{3}{2}\frac{x\xi}{(\xi - x)^2}(\xi - x - \tau/y)\right] * \tag{4'}$$

$$* \begin{cases} 1 & \text{for } \nu_\mu q,\ \bar{\nu}_\mu \bar{q} \\ (1-y)^2 & \text{for } \bar{\nu}_\mu q,\ \nu_\mu \bar{q} \end{cases}$$

(the cross section using (4') is shown as a dashed line on Fig. 2a)

As a consequence of our steeply falling $m^2_{c\bar{c}}$ distribution, we conclude that low $c\bar{c}$ masses are favored, leading to an appreciable rate for (2) relative to (1). We estimate this as follows. Suppose that $c\bar{c}$ in the mass range $m_{J/\psi} \lesssim m_{c\bar{c}} \leq 2m_D$ end up in J/ψ - either directly or via $c\bar{c} \to {}^3P_J \to J/\psi + \gamma$, $c\bar{c} \to \psi' \to J/\psi + \cdots$ Our justification for this is the empirical fact that J/ψ and ψ' production in e^+e^- annihilation, via 1γ is roughly averaged by continuum $c\bar{c}$ production with a low m_c. [6] So we are assuming that the same holds for a color gluon. [3] Then we use (6) and $BR[J/\psi \to \mu^+\mu^-]/[BR(D \to \mu + \cdots)]^2 \sim 6$ to estimate

$$\left.\frac{\sigma(3\mu)}{\sigma(1\mu)}\right|_{\text{from (2)}} : \left.\frac{\sigma(3\mu)}{\sigma(1\mu)}\right|_{\text{from (1)}} \gtrsim 2:1 \tag{7}$$

The inequality is due to the fact that our exact $m_{c\bar{c}}$ distribution falls faster than that in (4) or (6).

Including (2) as a trimuon source will increase the ratio $\sigma(3\mu)/\sigma(1\mu)$ shown on Fig. 2b by a factor three or so. Nevertheless, we find $\sigma(3\mu)/\sigma(1\mu) \lesssim 10^{-6}$ for $\alpha_s = .2$, $E_\nu = 200$ GeV. (Note, however, that $\sigma(3\mu)/\sigma(1\mu)$ increases tenfold on going to $E_\nu = 800$ GeV). Our calculation using Fig. 1 may be slightly unreliable at very low energies, ++) but we do not expect the principal features to change. We conclude that charm trimuons appear only at a small level at present accelerator energies;+++) (even increasing α_s slightly will not alter this). Thus charm represents only a small background to trimuon signatures for the production of other new particles.++++) In this connection we emphasize the importance of checking our conclusion by looking for the easily recognized process (2).

At very high energies where $\sigma(c\bar{c})$ is not small - appropriate to colliding beam ep machines, for example - these processes can serve as a test of QCD. It will be easiest to look for

$$e^-p \to \nu_e \, J/\psi + \cdots \quad (J/\psi \to \mu^+\mu^-) \quad \text{a} \quad e^-p \to \nu_e \, \Upsilon + \cdots \quad (\Upsilon \to \mu^+\mu^-) \tag{8}$$

(cross sections for Υ (12) can be estimated using scaling in $m^2_{Q\bar{Q}}/2M_N E$).

The methods we have employed for $c\bar{c}$ production in $\nu_\mu N$ can be extended to calculate the production of $c\bar{c}$ or heavier flavors in other processes (e.g. $\mu N \to \mu \, c\bar{c} + \ldots$, $e^+e^- \to 2c\bar{c}$ or production of $c\bar{c}$ in high p_T

hadron reactions). We emphasize the importance of searching in these processes for inclusive J/ψ , as a signal for $c\bar{c}$ production.

Footnotes

+) We implicitly assume that a produced $c\bar{c}$ always ends up as $C\bar{C}$ + ... or a charmonium $c\bar{c}$ state.

++) Unreliable in the sense that at very low energies charm production may proceed as in hadronic processes rather than as we suggest. Charm production in pp collisions is very small (7), so this has no practical effect on our conclusions.

+++) Trimuons at a level much too high for (1) or (2) have been reported (8). (For another viewpoint, see reference (9).) After this work was completed, we learned of related considerations on this topic (10).

++++) It appears that the only deep inelastic trimuon background may be due to QED, namely, $\nu_\mu q \rightarrow \mu^- q \gamma_{virt} \rightarrow \mu^- q \mu^+ \mu^-$. We have estimated this, finding $\sigma(3\mu)/\sigma(1\mu)$ to be typically a few times 10^{-5} and much more weakly energy dependent that (1) or (2). (See also reference (11)).

Figure Captions

Fig. 1: Diagrams for $\nu q \rightarrow \mu q c\bar{c}$

Fig. 2a: $\sigma(\nu_\mu N \rightarrow \mu^- c\bar{c} + \dots)$ in units $G_F^2 M_N E_\nu/\pi$. The solid line is the exact result for $\alpha_s = 0.20$; the dashed line is an approximation described in the text.

Fig. 2b: The ratio $\sigma(\nu_\mu N \rightarrow 3\mu + \dots)/\sigma(\nu_\mu N \rightarrow 1\mu + \dots)$ using the exact cross section, $\alpha_s = 0.20$, and BR($D \rightarrow \mu$ + ...) = 11 %, as described in the text.

Fig. 3: Distributions in $\nu_\mu N \rightarrow \mu^- c\bar{c} + \dots$ at E_ν = 150 GeV. a) is $d\sigma/dx$, b) $d\sigma/dy$ and c) $d\sigma/d\tau$ with $m_c = m_D$. Note the changed scale in Fig. 3c.

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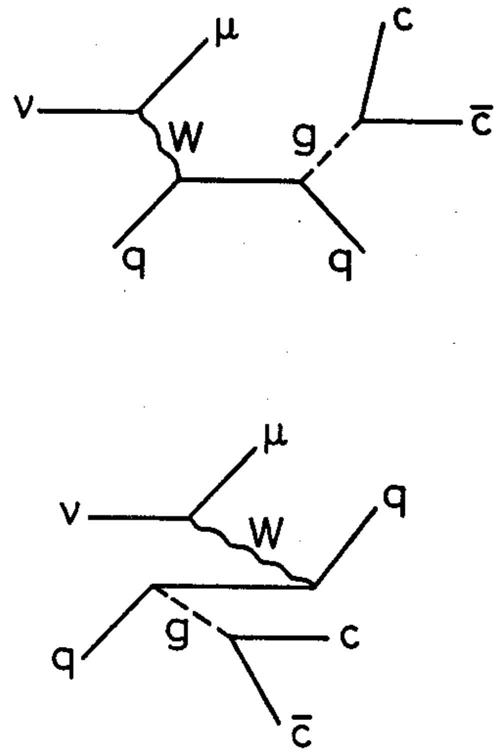

Fig.1

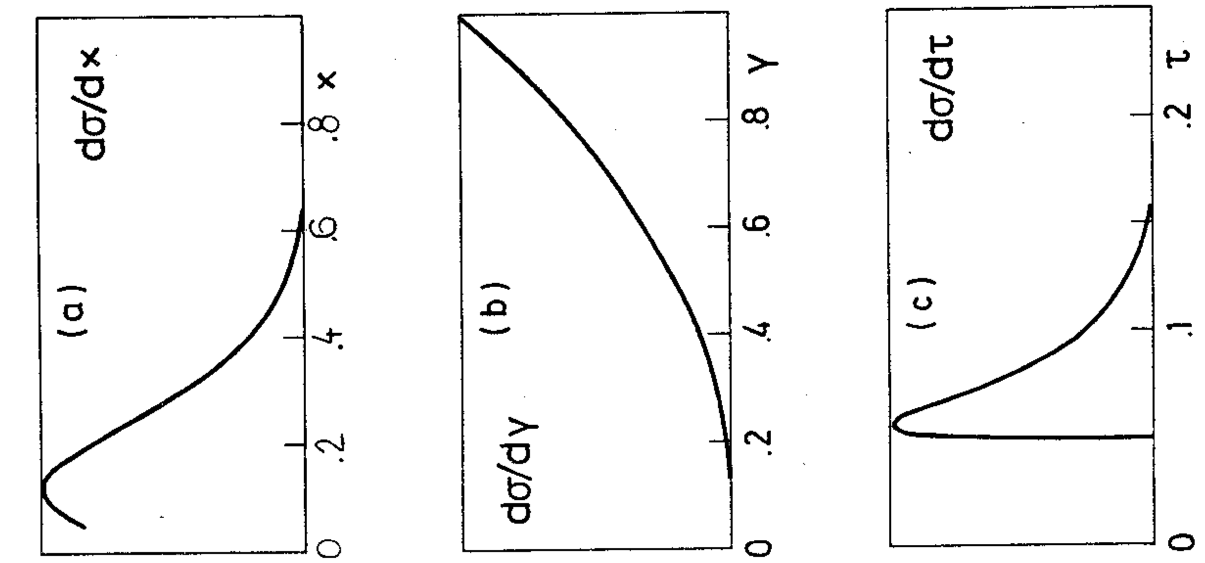

Fig. 3

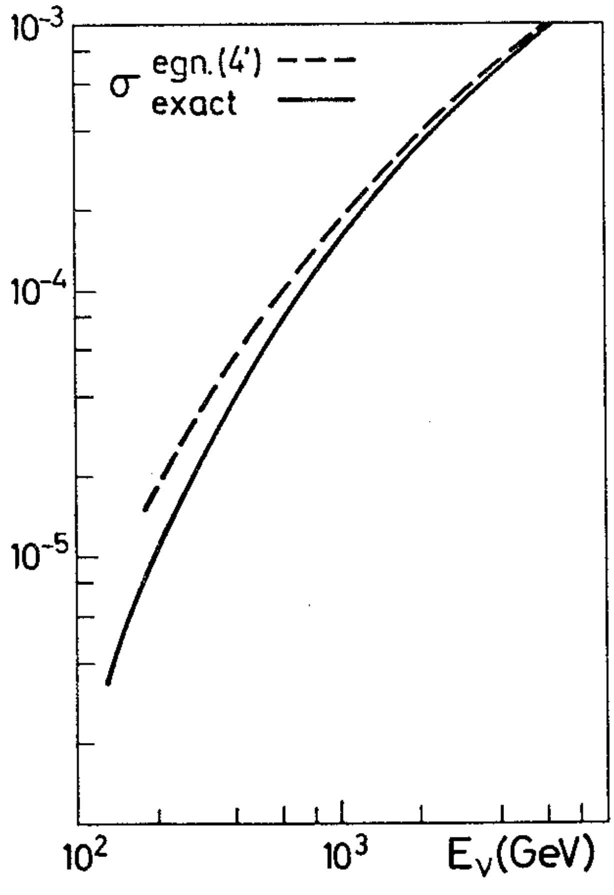

Fig. 2a

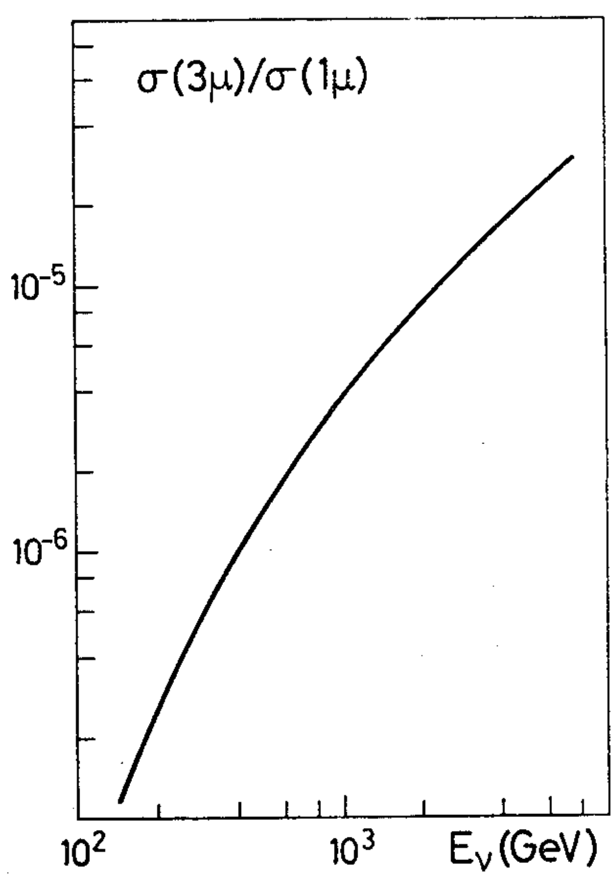

Fig. 2b