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Soft color enhancement of the production of J/ψ's by neutrinos

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We calculate the production of J/ψ mesons by neutrino-nucleon collisions in fixed target experiments. Soft color, often referred to as color evaporation effects, enhances production cross sections due to the contribution of color octet states. Though still small, J/ψ production may be observable in present and future experiments such as NuTeV and μ colliders.

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I. INTRODUCTION

The power of neutrino beams for probing the structure of the nucleon as well as general properties of QCD has been demonstrated by many experiments [1–3]. Here we reexamine the measurement of charm production in neutrino-nucleon interactions, which has been extensively studied [4–7]. Because of its striking experimental signature into dimuons, the neutral current production of charm as a J/ψ bound state is of particular interest [8]. This process only occurs at an observable rate, provided color octet states also lead to the formation of charmonium in addition to the traditional color singlet contributions [9].

It is now clear that J/ψ production is a two-step process where a heavy quark pair is produced first, followed by the nonperturbative formation of the colorless asymptotic state. As a consequence, color octet states as well as singlet $c\bar{c}$ states contribute to the production of J/ψ. This is clearly supported by the data [10–13]. Two formalisms were proposed to incorporate these features: nonrelativistic QCD (NRQCD) [14], and the soft color (SC) scheme [15,16]. Experiments measuring the polarization of bound charm and b-flavored mesons, or, more precisely, the absence of it, now clearly favor the second framework.

Here we therefore reevaluate the production of J/ψ by neutrino beams in the SC scheme; for comparison, see Ref. [17] which contains the NRQCD results. The basic SC assumption is that no observable dynamics is associated with the soft processes that connect the color of the perturbative produced charm pair with the colorless charmonium bound state. This scheme, although far more restrictive than other proposals, successfully accommodates all features of charmonium and bottomonium production. Earlier quarkonium production computations already referred to this as the color evaporation model [15]. It correctly predicts the energy and final state momentum dependence of charmonium and bottomonium hadroproduction and photoproduction at all energies, as well as their production in electron-positron colliders. This approach to color is also used to formulate a successful prescription for the production of rapidity gaps between jets at the fermilab Tevatron [18–20] and DESY ep Collider HERA [20,21].

The SC formalism predicts that the sum of the cross sections of all charmonium and open charm states is described by [16,18]

$$\sigma_{\text{onium}}=\frac{1}{9}\int_{2m_c}^{2m_D} dM_{c\bar{c}}\frac{d\sigma_{c\bar{c}}}{dM_{c\bar{c}}} \tag{1}$$

and

$$\sigma_{\text{open}}=\frac{8}{9}\int_{2m_c}^{2m_D} dM_{c\bar{c}}\frac{d\sigma_{c\bar{c}}}{dM_{c\bar{c}}}+\int_{2m_D} dM_{c\bar{c}}\frac{d\sigma_{c\bar{c}}}{dM_{c\bar{c}}}, \tag{2}$$

where $M_{c\bar{c}}$ is the invariant mass of the $c\bar{c}$ pair. The factor 1/9 stands for the probability that a pair of charm quarks formed at a typical time scale $1/M_\psi$ ends up as a color singlet state after exchanging an uncountable number of soft gluons with the reaction remnants. One attractive feature of this model is the above relation between the production of charmonium and open charm which allows us to use the open charm data to normalize the perturbative QCD calculation, and consequently to make more accurate predictions for charmonium cross sections.

The fraction ρ_ψ of produced onium states that materialize as ψ,

$$\sigma_\psi=\rho_\psi\sigma_{\text{onium}}, \tag{3}$$

has been inferred from low energy measurements to be a constant [22,23]. From the charmonium photoproduction, we determined that $\rho_\psi=0.43$–0.5 [13], and even this parameter can be accounted for by statistical counting of final states [24]. The fact that all ψ production data are described in terms of this single parameter, fixed by J/ψ photoproduction, permitted us to correctly predict a rate for Z-boson decay into prompt ψ [25] an order of magnitude larger then the color singlet predictions, and to explain the observed production at the Tevatron [26] and HERA [27]. Therefore, let us study the SC prediction for charmonium production in neutrino–nucleon collisions.

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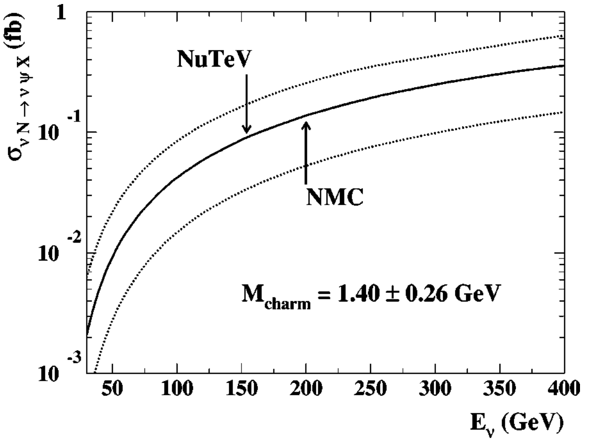

FIG. 1. Cross section of the reaction $\nu N \to \nu J/\psi X$ as function of the energy of the incident neutrino beam for three values of the charm quark mass. The central (upper and lower) curve was obtained using $m_c = 1.40$ (1.14 and 1.66) GeV. The arrows indicate the average beam energy for the NuTeV experiment and a future muon collider (NMC).

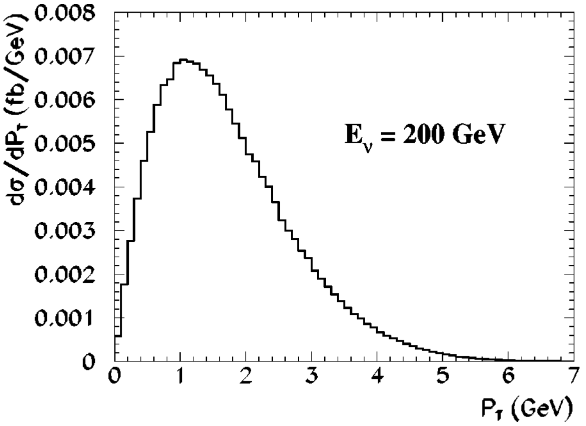

FIG. 3. Transverse momentum differential cross section of the produced J/ψ's.

II. RESULTS

The NuTeV Collaboration recently reported on the first observation of open charm production in neutral current deep inelastic neutrino scattering [7]. The observed production rate is consistent with a pure gluon-Z^0 boson fusion, and the observed level of charm production was used to determine the effective charm mass. They found that a value of

$$m_c = 1.40^{+0.83}_{-0.36} \pm 0.26 \text{ GeV} \tag{4}$$

best describes the total open charm production for an average neutrino energy $\langle E_\nu \rangle = 154$ GeV.

The SC contribution for the prompt J/ψ is directly connected to open charm total cross section; see Eqs. (1) and (2). The same value of the naked charm mass that best describes the open charm production rate must also describe the bound states, as they are both produced through the same leading perturbative subprocess $\nu + g \to \nu + c\bar{c}$. To evaluate the J/ψ production via neutral current we used the package MADGRAPH [28] and HELAS routines [29] to obtain the full-tree level scattering amplitude. We used the 1994 Glock-Reya-Vogt (GRV94) leading order (LO) [30] parton distribution function, adjusting the renormalization and factorization scales as appropriate for a leading order calculation; we choose $\mu_R = \mu_F = Q^2 + 4m_c^2$, where Q^2 is the momentum transferred from the leptonic system. The strong coupling constant was evaluated in leading order with $\Lambda_{QCD} = 300$ MeV, and the fraction of color singlet $c\bar{c}$ pairs with invariant mass below the open flavor threshold that hadronizes as J/ψ was assumed to be $\rho_\psi = 0.5$. Using the central value $m_c = 1.40$ GeV, we obtained

$$\sigma(\nu N \to \nu J/\psi X) = 9.0^{+8.1}_{-5.7} \times 10^{-2} \text{ fb} \tag{5}$$

for the NuTeV experiment, where the errors reflect the systematic uncertainty on the charm mass measurement.

Using these same choices of parameters we extrapolated the total J/ψ production cross section for other values of $\langle E_\nu \rangle$; the result is presented in Fig. 1, where we pinpoint the

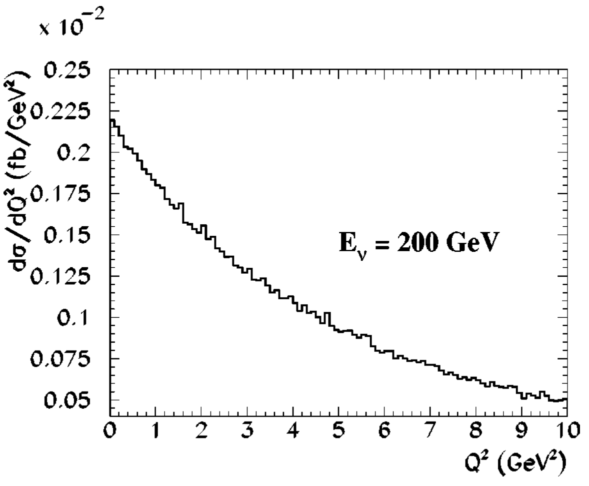

FIG. 2. Differential cross section of J/ψ as function of the squared momentum transferred by the leptonic system.

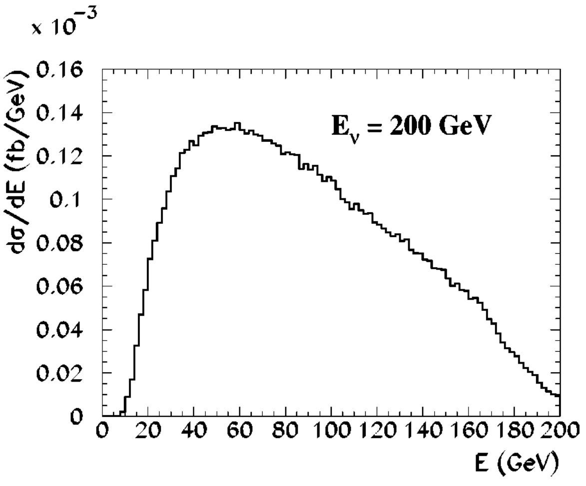

FIG. 4. J/ψ energy distribution for an incident neutrino beam of 200 GeV.

mean neutrino beam energy achieved at NuTeV, as well as the value expected at planned muon collider facilities. In order to show the cross section dependence on the uncertainty of the charm mass, in this figure we also present the error band that corresponds to the systematic error on the charm mass as measured by NuTeV.

These results clearly indicate that the detection of J/ψ's at NuTeV is a challenging task. For instance, taking into account that NuTeV observed about 1.3×10^6 deep inelastic scattering events, with $\sigma_{total}=0.82$ pb, we could expect between 3 and 16 dimuons events to be produced from J/ψ decays.

The planned muon colliders should be able to generate neutrino beams with sufficient high luminosity to clearly observe J/ψ events. Moreover, at these machines the neutrino flux can be accurately calculated [31], allowing more precise predictions. For instance, a 2×250 GeV muon collider produces a collimated neutrino beam with average energy $\langle E_\nu\rangle=200$ GeV [31]. If we assume the general purpose detector suggested by King [32] with $\simeq$ 50 g/cm^2 density, we should have the production of 35–180 dimuons events per year originated from J/ψ decays, which would allow a more detailed study of its production properties.

In Fig. 2 we present the Q^2 distribution for a neutrino beam with average energy $\langle E_\nu\rangle=200$ GeV [31]. Figure 3 shows that J/ψ's will be mostly produced with a small transverse momentum; however, the J/ψ's will carry a rather large energy (on average 88.7 GeV) (see Fig. 4).

III. CONCLUSION

Using the NuTeV analysis of open charm production, we calculated the J/ψ cross section in the soft color model. We found that $\sigma(\nu_\mu N\rightarrow\nu_\mu J/\psi X)=9.0^{+8.1}_{-5.7}\times10^{-2}$ fb at the average neutrino beam energy of the NuTeV experiment. We subsequently calculated the dependence of the J/ψ cross section as a function of the average energy of the incident neutrino beam, and displayed some differential cross sections for a neutrino beam associated with a future muon collider.

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