

TIFR/TH/95-57
IISc-CTS-6/95
hep-ph/9511433

J/ψ production via fragmentation at HERA

R.M. Godbole*,

Centre for Theoretical Studies, Indian Institute of Science, Bangalore-560012, India.

D.P. Roy[†] and K. Sridhar[‡]

*Theory Group, Tata Institute of Fundamental Research,
Homi Bhabha Road, Bombay 400 005, India.*

ABSTRACT

We compute the contributions to large- p_T J/ψ production at HERA coming from fragmentation of gluons and charm quarks. We find that the charm quark fragmentation contribution dominates over the direct production of J/ψ via photon-gluon fusion at large- p_T , while the gluon fragmentation is negligibly small over the whole range of p_T . An experimental study of p_T distributions of J/ψ at HERA will provide a direct probe of the charm quark fragmentation functions.

November 1995

*rohini@cts.iisc.ernet.in

†dproy@theory.tifr.res.in

‡sridhar@theory.tifr.res.in

The anomalously large cross-section for J/ψ production at large transverse momentum, p_T , measured [1] recently in the CDF experiment at the Tevatron has led to a revision of earlier ideas based on the lowest order QCD process of parton fusion. In this approach [2, 3], the dominant contribution to quarkonium production was expected to come from quark-antiquark or gluon-gluon fusion, leading to the formation of a heavy-quark pair in a colour-singlet state with the correct spin, parity and charge-conjugation assignments projected out. Several recent works [4, 5, 6, 7] have drawn attention to additional contributions to quarkonium production coming from the fragmentation of gluons and heavy quark jets. Even though the fragmentation contributions are of higher order in α_s compared to fusion, they are enhanced by powers of p_T^2/m^2 , where m is the heavy quark mass. Consequently, they can overtake the fusion contribution at $p_T \gg m$. Indeed, the CDF J/ψ production data [1] has been successfully explained by several authors [8] by taking into account both the fusion and fragmentation contributions. The gluon fragmentation contribution is found to dominate over fusion at large p_T ($p_T > 5$ GeV), while the charm quark fragmentation contribution is much too small. As we shall see in this letter, the photoproduction of J/ψ at HERA presents a complementary process – i.e. the charm quark fragmentation is expected to overtake fusion at large- p_T , while the gluon fragmentation remains small. Thus a measurement of the large- p_T J/ψ production cross-section at HERA will provide a valuable probe for the charm quark fragmentation contribution.

A brief discussion of the colour-singlet model, used in the computation of both fusion and fragmentation contributions, is in order. Strictly speaking, the colour-singlet model is a non-relativistic model where the relative velocity between the heavy quarks in the bound state is ignored. However, in general, the relative velocity, v , in quarkonium systems is not negligible and $O(v)$ corrections need to be taken into account. Starting from a non-relativistic QCD Lagrangian, a systematic analysis using the factorisation method has been recently carried out by Bodwin, Braaten and Lepage [9]. In this formulation, the quarkonium wave-function admits of a systematic expansion in powers of v in terms of Fock-space components : for example, the wave-functions for the P -state charmonia have the conventional colour-singlet P -state component at leading order, but there exist additional contributions at non-leading order in v , which involve octet S -state components; i.e.

$$|\chi_J\rangle = O(1)|Q\bar{Q}[{}^3P_J^{(1)}]\rangle + O(v)|Q\bar{Q}[{}^3S_1^{(8)}]g\rangle + \dots \quad (1)$$

In spite of the fact that the octet component in the wave-function is suppressed by a factor of v , it is important for the decays of P -states [10] for the following reasons : 1) The P -state wave-function is already suppressed by a factor of v owing to the angular-momentum barrier; but the corresponding colour-octet component is an S -state which is unhindered by this barrier. The colour-octet component can, therefore, easily compete with the colour-singlet. 2) The second reason is even more compelling : the

perturbative analyses of P -wave decays of quarkonia [11] reveal a logarithmic infrared singularity. But the octet component allows the infrared singularity to be absorbed via a wave-function renormalisation, without having to introduce an arbitrary infrared cut-off. So a consistent perturbative treatment of P -state decays necessarily involves the octet component. The price to pay for this is that two independent matrix-elements, viz., the singlet and the octet matrix elements are needed, unlike the case of the colour-singlet model where the entire long-distance information could be factorised into a *single* non-perturbative matrix-element. As in the case of the P -state decay widths, the P -state fragmentation functions also involve the octet component [5]. The octet component appears in the computation of the fusion contribution as well, but is negligible in the large- p_T region of our interest.

For S -state resonances like the J/ψ and the ψ' , the octet contribution is suppressed by powers of v . Further, the S -wave amplitude is not infrared divergent and can, therefore, be described in terms of a single colour-singlet matrix-element. But recently, the CDF collaboration has measured [12] the ratio of J/ψ 's coming from χ decays to those produced directly and it turns out that the direct S -state production is much larger than the theoretical estimate. It has been suggested [13] that a colour octet component in the S -wave production coming from gluon fragmentation as originally proposed in Ref. [14], can explain this J/ψ anomaly. This corresponds to a virtual gluon fragmenting into an octet 3S_1 state which then makes a double E1 transition into a singlet 3S_1 state. While this process is suppressed by a factor of v^4 as compared to the colour-singlet process, it is enhanced by a factor of α_s^2 . One can fix the value of the colour-octet matrix-element by normalising to the data on direct J/ψ production cross-section from the CDF experiment. The colour-octet contribution to S -state production has also been invoked [14] to explain the large ψ' cross-section measured by CDF [1], but there can be a large contribution to this cross-section coming from the decays of radially excited P -states [15]. Independent tests of the S -state colour octet enhancement are important and there have been recent suggestions [16] as to how one can use e^+e^- collisions to probe the octet contribution. Thus, the possibility of a large colour-octet contribution to the S -state fragmentation function remains open, though theoretically less compelling than for the P -state. We shall see below that the inclusive photoproduction of J/ψ is insensitive to the former, but it is sensitive to the latter.

In this letter, we study inclusive J/ψ production in ep collisions at HERA. The fusion contribution to the photoproduction of J/ψ in the colour-singlet model [2] comes from photon-gluon fusion. Recently, the next-to-leading order corrections to this process have been computed within the colour-singlet model [17] and compared [18] with the results on integrated cross-sections from HERA; and it has been found that the integrated cross-sections at next-to-leading order are in reasonable agreement with the data. The integrated cross-sections are, however, insensitive to the fragmentation contributions, because the latter dominate only at large p_T . To get a handle on the

fragmentation contributions to J/ψ production at HERA it is important to study the p_T distributions, rather than integrated cross-sections.

The fusion contribution to the photoproduction of J/ψ in the colour-singlet model takes place through the following subprocess:

$$\gamma + g \rightarrow c\bar{c}[{}^3S_1^{(1)}] + g, \quad (2)$$

where the J/ψ is taken to be the colour-singlet 3S_1 $c\bar{c}$ state. The p_T differential cross-section for the photoproduction of J/ψ in the colour-singlet model is given as

$$\frac{d\sigma}{dp_T} = \int dz \frac{128\pi^2\alpha_s^2\alpha p_T x G(x) z(1-z) M e_c^2 R_0^2}{27[M^2(1-z) + p_T^2]^2} \cdot f(z, p_T^2), \quad (3)$$

where

$$f(z, p_T^2) = \frac{1}{(M^2 + p_T^2)^2} + \frac{(1-z)^4}{[p_T^2 + M^2(1-z)^2]^2} + \frac{z^4 p_T^4}{(M^2 + p_T^2)^2 [p_T^2 + M^2(1-z)^2]^2}. \quad (4)$$

In the above equation, the variable z is the inelasticity variable, defined as

$$z = \frac{p_\psi \cdot P_p}{p_\gamma \cdot P_p}, \quad (5)$$

and x is related to p_T and z ,

$$x = \frac{1}{s} \left[\frac{M^2}{z} + \frac{p_T^2}{z(1-z)} \right], \quad (6)$$

where $s = 4E_p\nu$ is the photon-proton c.m. energy. As usual, M and R_0 denote the J/ψ mass and wave function at the origin.

The fragmentation contribution is computed by factorising the cross-section for the process $\gamma p \rightarrow (J/\psi, \chi_i)X$ into a part containing the hard-scattering cross-section for producing a gluon or a charm quark and a part which specifies the fragmentation of the gluon or the charm quark into the required charmonium state, i.e.

$$d\sigma(\gamma p \rightarrow (J/\psi, \chi_i)X) = \sum_c \int_0^1 d\omega \, d\sigma(\gamma p \rightarrow cX) D_{c \rightarrow (J/\psi, \chi_i)}(\omega, \mu), \quad (7)$$

where c is the fragmenting parton (either a gluon or a charm quark). $D(\omega, \mu)$ is the fragmentation function and ω is the fraction of the momentum of the parent parton

carried by the charmonium state¹. The fragmentation function is computed perturbatively at an initial scale μ_0 which is of the order of m_c . If the scale μ is chosen to be of the order of p_T , then large logarithms in μ/m_c appear which have then to be resummed using the usual Altarelli-Parisi equation:

$$\mu \frac{\partial}{\partial \mu} D_{i \rightarrow (J/\psi, \chi_i)}(\omega) = \sum_j \int_{\omega}^1 \frac{dy}{y} P_{ij}(\frac{\omega}{y}, \mu) D_{j \rightarrow (J/\psi, \chi_i)}(y), \quad (8)$$

where the P_{ij} are the splitting functions of a parton j into a parton i . We consider the fragmentation of gluons and charm quarks alone since the light quark contributions are expected to be very small. The gluons are produced via the Compton process:

$$\gamma + q \rightarrow q + g, \quad (9)$$

whereas the charm quarks are produced via the Bethe-Heitler process:

$$\gamma + g \rightarrow c + \bar{c}. \quad (10)$$

Using these cross-sections, we compute the fragmentation contribution to $d\sigma/dp_T$ which is given by a formula similar to Eq. 3, but with an extra integration over ω , or equivalently over x , because of the relation

$$\omega = \frac{M^2 + p_T^2}{xsz} + z. \quad (11)$$

For the fragmentation functions at the initial scale $\mu = \mu_0$, we use the results of Refs. [4] and [5] for the gluon fragmentation functions into J/ψ or χ states, and Refs. [6] and [7] for the corresponding fragmentation functions of the charm quark. These fragmentation functions include the colour-octet component in the P -state, but do not include any colour-octet contribution in the S -state. For the case of gluon fragmentation, we have separately studied the effect of the S -state colour-octet component by modifying the fragmentation functions as in Ref. [14]. For the charm fragmentation, the S -state colour-octet contributions are sub-dominant and we have neglected these contributions. In principle, at HERA energies we can also expect contributions from B -decays but these turn out to be dominant at values of $z \leq 0.1$ [19], and can, therefore, be safely neglected in our analysis.

We have computed the cross-sections for two representative values of the photon energy, ν , using the MRSD-' structure functions [20] and we have used $Q = p_T/2$ as the choice of scale. In principle, one can integrate over the photon energy spectrum; but for the purposes of studying the relative magnitudes of the fusion and fragmentation contributions to the cross-sections, it is enough and indeed more transparent to

¹We use the notation ω instead of the more usual z to avoid confusion with the inelasticity parameter, defined in Eq. 5.

present the results for fixed values of ν . In Fig. 1, we present the results for $d\sigma/dp_T$ as a function of p_T , for $\nu = 40$ and 100 GeV. For the inelasticity parameter, we use the cuts $0.1 \leq z \leq 0.9$, as used in the ZEUS experiment at HERA [21]. We find that the fusion contribution, shown by the solid line in Fig. 1, is dominant at low p_T , but the charm quark fragmentation contribution (shown by the dashed-dotted line) becomes important for values of p_T greater than about 10 GeV. The gluon fragmentation contribution (shown by the dashed line in the figure) is smaller by over an order of magnitude throughout the range of p_T considered. Also shown as the dotted line in the figure is the gluon fragmentation contribution including the octet contribution for the S -state, where the numerical value of the octet S -wave matrix element has been determined [13, 14] from the CDF data [12] as mentioned above. The major uncertainty in the prediction is due to the limited information we have on the colour-octet matrix elements; the normalisation of the fragmentation contribution can change by a factor of 2-3, due to this uncertainty [8]. Moreover, next-to-leading order corrections will also change the absolute normalisation of our predictions – for the fusion prediction this is expected to give an enhancement (K-factor) upto a factor of 2 [18] and similar K-factors are also expected in the case of fragmentation contributions. However, our choice of $p_T/2$ as the scale (instead of p_T) is expected to account for the K -factor enhancement, at least in part.

The charm fragmentation subprocess (Eq. 10) is gluon-initiated while the gluon fragmentation subprocess (Eq. 9) is quark-initiated. This explains why the charm fragmentation process dominates. It is important to note that gluon fragmentation turns out to be the most important source of J/ψ production at the Tevatron, while the complementary information on the fragmentation of charm quarks can be studied at HERA. An experimental study of p_T distributions at HERA will provide us with the first direct measurement of the charm quark fragmentation functions.

Since the J/ψ 's produced in the fragmentation process are softer in energy than those produced *via* fusion, it turns out that the average value of z for the former are smaller than the latter. To enhance the fragmentation contribution, it is efficient to use a stronger upper cut on z . In Fig. 2, we have shown the cross-sections for J/ψ 's produced via fusion and from charm quark fragmentation with $z < 0.5$. We find that this cut helps to cut down the fusion contribution to J/ψ without significantly affecting the charm fragmentation contribution, thereby providing a better signal for the fragmentation process.

To summarise, we have studied the p_T distribution of J/ψ cross-sections at HERA coming from the fusion and fragmentation processes. We find that the large- p_T end is dominated by contributions from charm quark fragmentation. The information that can be obtained from HERA is thus complementary to that obtained from the large- p_T J/ψ production at the Tevatron, which is dominated by the gluon fragmentation

contribution. By applying judicious cuts on the inelasticity parameter z it is possible to enhance the charm fragmentation contribution relative to the fusion contribution.

References

- [1] F. Abe et al., *Phys. Rev. Lett.* **69** (1992) 3704; *Phys. Rev. Lett.* **71** (1993) 2537; K. Byrum, CDF Collaboration, Proceedings of the 27th International Conference on High Energy Physics, Glasgow, (1994), eds. P.J. Bussey and I.G. Knowles (Inst. of Physics Publ.) p.989.
- [2] E.L. Berger and D. Jones, *Phys. Rev.* **D 23** (1981) 1521.
- [3] R. Baier and R. Rückl, *Z. Phys.* **C 19** (1983) 251.
- [4] E. Braaten and T.C. Yuan, *Phys. Rev. Lett.* **71** (1993) 1673.
- [5] E. Braaten and T.C. Yuan, *Phys. Rev.* **D 50** (1994) 3176.
- [6] Y.Q. Chen, *Phys. Rev.* **D 48** (1993) 5181.
- [7] T.C. Yuan, *Phys. Rev.* **D 50** (1994) 5664.
- [8] E. Braaten, M.A. Doncheski, S. Fleming and M. Mangano, *Phys. Lett.* **B 333** (1994) 548; D.P. Roy and K. Sridhar, *Phys. Lett.* **B 339** (1994) 141; M. Cacciari and M. Greco, *Phys. Rev. Lett.* **73** (1994) 1586.
- [9] G.T. Bodwin, E. Braaten and G.P. Lepage, *Phys. Rev.* **D 51** (1995) 1125.
- [10] G.T. Bodwin, E. Braaten and G.P. Lepage, *Phys. Rev.* **D 46** (1992) R1914.
- [11] R. Barbieri, R. Gatto and E. Remiddi, *Phys. Lett.* **B 61** (1976) 465.
- [12] G. Bauer, CDF Collaboration, presented at the "Xth Topical Workshop on $p\bar{p}$ collisions", Fermilab (1995).
- [13] M. Cacciari, M. Greco, M. Mangano and A. Petrelli, CERN Preprint CERN-TH/95-129; P. Cho and A.K. Leibovich, Caltech Preprint CALT-68-1988.
- [14] E. Braaten and S. Fleming, *Phys. Rev. Lett.* **74** (1995) 3327.
- [15] F.E. Close, *Phys. Lett.* **B 342** (1995) 369; D.P. Roy and K. Sridhar, *Phys. Lett.* **B 345** (1995) 537.
- [16] E. Braaten and S. Fleming, Northwestern University Preprint NUHEP-TH-95-9; K. Cheung, W. Keung and T.C. Yuan, Fermilab Preprint FERMILAB-PUB-95/300-T; P. Cho, Caltech Preprint CALT-68-2020.
- [17] M. Krämer, J. Zunft, J. Steegborn and P.M. Zerwas, *Phys. Lett.* **B 348** (1995) 657.

- [18] M. Krämer, DESY Preprint DESY 95-155.
- [19] A.D. Martin, C.-K. Ng and W.J. Stirling, *Phys. Lett.* **B 191** (1987) 200.
- [20] A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Lett.* **B 306** (1993) 145;
Phys. Lett. **B 309** (1993) 492.
- [21] M. Derrick et al., contribution to the International Europhysics Conference on High Energy Physics, Brussels, 1995.

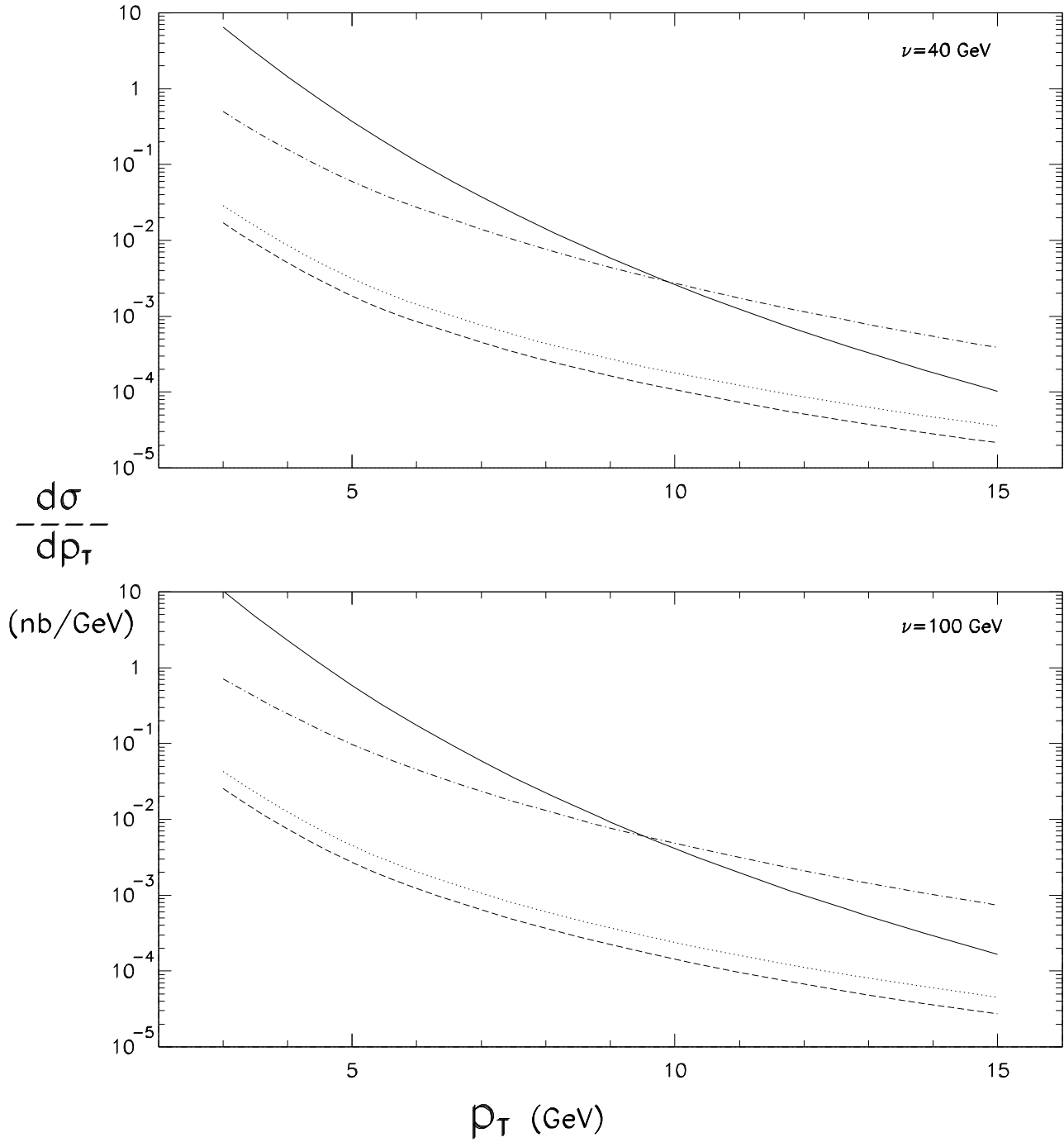


Figure 1: $d\sigma/dp_T$ (in nb/GeV) for inclusive J/ψ production at HERA for photon energy $\nu = 40$ GeV (upper figure) and $\nu = 100$ GeV (lower figure). The solid line represents the fusion contribution and the dashed-dotted line the charm quark fragmentation contribution. The dotted and dashed lines represent the gluon fragmentation contributions with and without a colour-octet component for the S -state. The cut on the inelasticity parameter, z , is $0.1 < z < 0.9$.

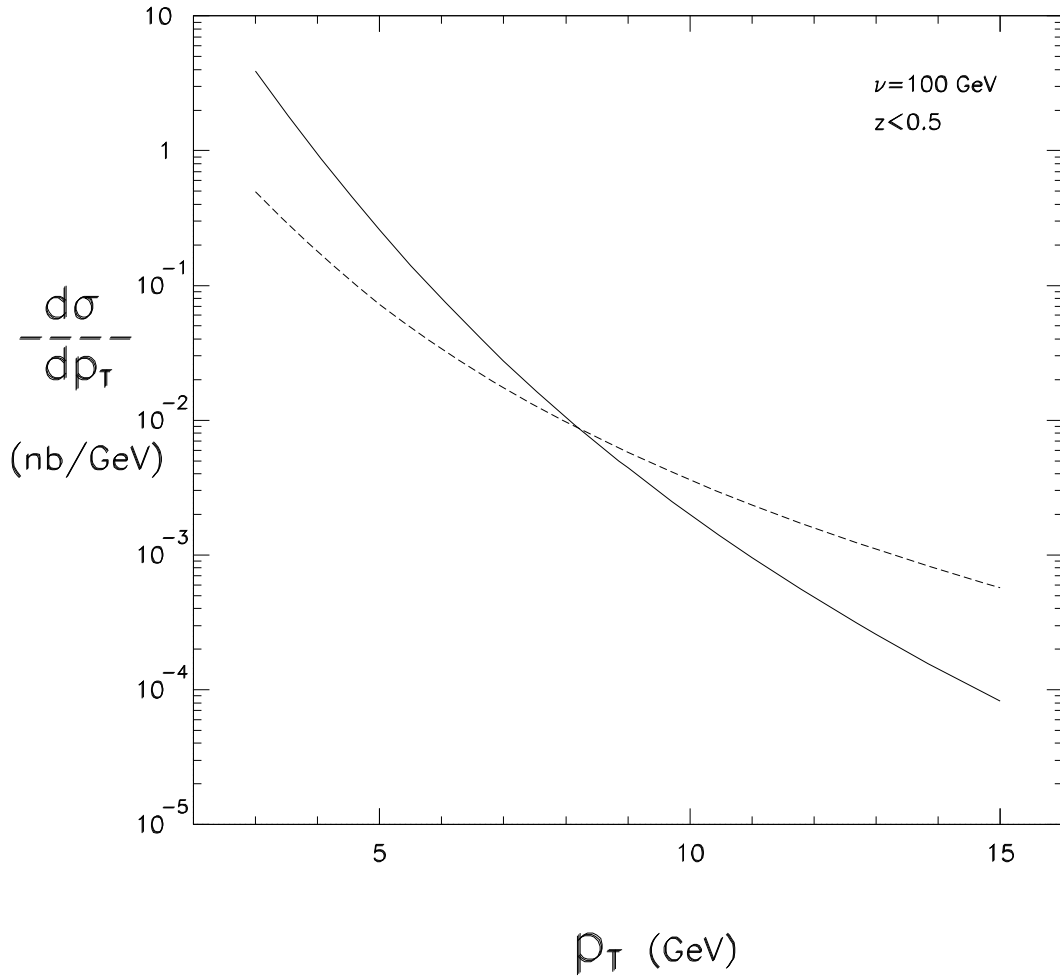


Figure 2: $d\sigma/dp_T$ (in nb/GeV) for photon energy $\nu = 100$ GeV. The solid line represents the fusion contribution, and the dashed line the charm quark fragmentation contribution, using a cut $z < 0.5$.