DIFFRACTIVE CHARM PRODUCTION AT HERA*

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We describe recent perturbative QCD calculations of diffractive J/ψ and open $c\bar{c}$ production at HERA and show that they offer a sensitive probe of the gluon density at small x. We discuss briefly the Q^2 and β dependence of the cross section and show that estimates of the higher order corrections indicate a strong enhancement of the open charm production.

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1. Introduction

To lowest order the diffractive $\gamma^* p \to (c\bar{c})p$ amplitude can, at high energy, be factorized into the product of the $\gamma \to c\bar{c}$ transition, followed by the scattering of the $c\bar{c}$ system on the proton via (colourless) two gluon exchange. The process is sketched in Fig. 1. The crucial observation is that the scattering on the proton occurs over a much shorter timescale than the $\gamma \to c\bar{c}$ fluctuation time. Moreover, the two gluon exchange *amplitude* can be shown to be proportional to the gluon density $g(x, \overline{Q}^2)$ with

$$x = (M^2 + Q^2)/W^2, \qquad \overline{Q}^2 \approx \tfrac{1}{4}\,(M^2 + Q^2)\,, \tag{1}$$

where W is the γp centre of mass energy and M is the invariant mass of the produced $c\bar{c}$ system. Let us first describe briefly the case of J/ψ production, where $M = M_\psi$.

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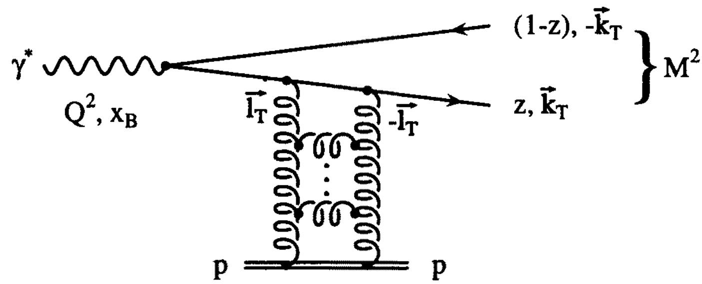

Fig. 1. Diffractive charm production in high energy $\gamma^* p$ collisions, where z is the fraction of the energy of the photon that is carried by the charm quark.

2. Diffractive J/ψ production

To lowest order the cross section for diffractive J/ψ production is [1, 2]

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi p)\bigg|_0 = \frac{\Gamma_{ee} M_\psi^3 \pi^3}{48\alpha} \frac{\alpha_s(\overline{Q}^2)^2}{\overline{Q}^8} \left[xg(x, \overline{Q}^2) \right]^2 \left(1 + \frac{Q^2}{M_\psi^2} \right), \quad (2)$$

where the last term allows for electroproduction from longitudinally polarised virtual photons with $\sigma_L/\sigma_T \approx Q^2/M_\psi^2$. Ref. [3] scrutinizes the approximations used to derive (2) and, more important, implements corrections which enable quantitative information on the gluon density to be obtained. In particular (i) the authors go beyond the leading $\ln Q^2$ approximation and integrate the (unintegrated) gluon distribution over the gluon transverse momentum ($\vec{\ell}_T$ in Fig. 1), (ii) the Fermi motion of the c and $\bar{c}$ quarks in the J/ψ is taken into consideration, and (iii) corrections due to the rescattering of the $c\bar{c}$ pair as it transverses through the proton are estimated.

Correction (ii) is the most problematic. It depends on the wave function $\psi^J(z, k_T)$ of the J/ψ meson. One has to integrate the diffractive production amplitude over the c quark momentum variables z, k_T and compare the result with the simple non-relativistic approximation in which $z = \frac{1}{2}$ and $k_T = 0$. For J/ψ photoproduction this results in the correction factor [3]

$$F^2 = \left| \frac{\int (1+v_T^2)^{-3}\, xg(x, m_c^2(1+v_T^2))\, \psi^J(z, k_T) dv_T^2}{xg(x, m_c^2) \int \psi^J(z, k_T) dv_T^2} \right|^2 \simeq 0.5 \quad (3)$$

with $v_T^2 = \frac{2}{3} v^2 = k_T^2/m_c^2$. The suppression due to the factor $(1 + v_T^2)^{-3}$ is partly compensated by the larger scale at which the gluon is evaluated. [1] We note that (2) is written in terms of M_ψ^2 whereas in the perturbative QCD calculation the current quark mass m_c enters. It therefore turns out that the total relativistic correction factor is $F^2(M_\psi/2m_c)^8 \approx 1$, but clearly with a very large uncertainty of at least $\pm 30\%$. However, the crucial observation is that the uncertainty mainly affects the normalization of the predicted cross section, and *not* the x dependence.

The QCD predictions, obtained using three recent sets of gluon distributions, are compared with data in Fig. 2. We see that the different distributions lead to a big variation in the theoretical prediction for diffractive J/ψ production and that the shape of the HERA data favours the MRS(A′) gluon.

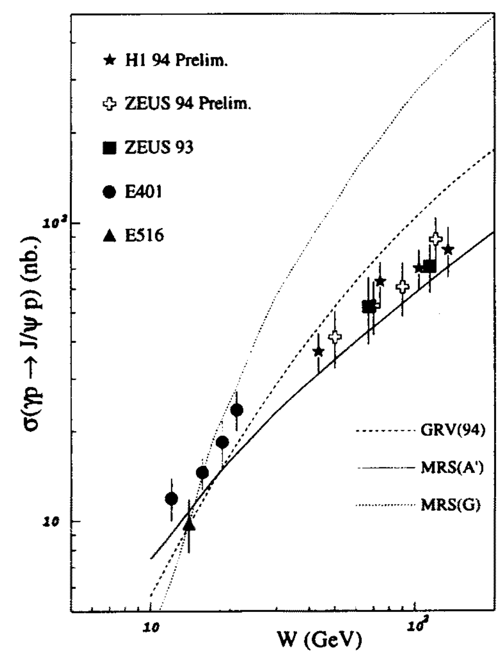

Fig. 2. Measurements and predictions for diffractive J/ψ photoproduction. The figure is taken from [3].

[1] The modification of the scale is omitted in ref. [4] and a suppression F^2 of at least a factor of 3 is obtained. Other differences are that [3] uses a Gaussian form of the k_T dependence of the wave function, whereas ψ^J in [4] has a longer tail in k_T. Ref. [4] does not include $2m_c \neq M_\psi$ effects.

3. Diffractive open charm production

Open $c\bar{c}$ production avoids the ambiguities associated with the J/ψ wave function. The QCD formulae, based on Fig. 1, are given in [5, 6]. The numerical predictions in [6] use the leading–log–approximation, whereas in [5] the gluon ℓ_T is integrated over and higher order contributions are estimated. (These last two effects are important, and lead to enhancements of about 2 and 3, respectively.) For moderate values of $\beta \equiv Q^2/(Q^2+M^2)$ (that is $0.3 \lesssim \beta \lesssim 0.8$) the QCD predictions for σ_L and σ_T have the approximate relative behaviour

$$\sigma_L : \sigma_T \;\approx\; 2\langle m_T^2\rangle \beta^3/Q^4 \;:\; \beta(1-\beta)^2/Q^2\,, \tag{4}$$

where $\langle m_T^2\rangle$ is the average value of $m_c^2 + k_T^2$.

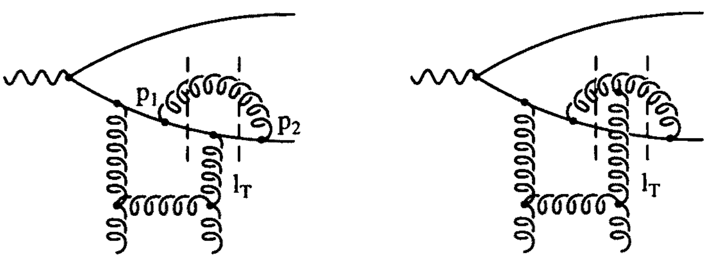

Fig. 3. Diagrams responsible for the π^2 enhancement to diffractive open $c\bar{c}$ production. The discontinuities indicated by the dashed lines each give a factor of $i\pi$.

The higher order corrections for open charm are particularly interesting [5]. The real gluon emission contribution $c\bar{c}g$ is relatively small, except for $M^2 \gtrsim 30$ GeV^2 at low Q^2. On the other hand the virtual corrections lead to a π^2 enhancement, as in Drell–Yan production, though the origin is different and quite novel. The relevant diagrams are shown in Fig. 3. Note that the exchanged gluon has virtuality $\ell_T^2 < 0$, whereas the quarks have $p_i^2 > 0$. This results in the appearance of the product of two logarithms with negative arguments, yielding the enhancement factor π^2. Of course there may be other $\mathcal{O}(\alpha_s)$ contributions but these are expected to be much smaller than the π^2 terms. Resumming these leading contributions gives the K–factor $\exp(\alpha_s C_F \pi) \approx 3$ or more.

Fig. 4 shows our prediction for the diffractive production of open charm for three recent sets of partons MRS(A′,G) [7] and GRV [8] and $m_c =$ 1.5 GeV. Again the sensitivity to the square of the gluon density is evident. For comparison the dotted curve in Fig. 4 shows the prediction for $m_c = 1.7$ GeV for the MRS(A′) gluon.

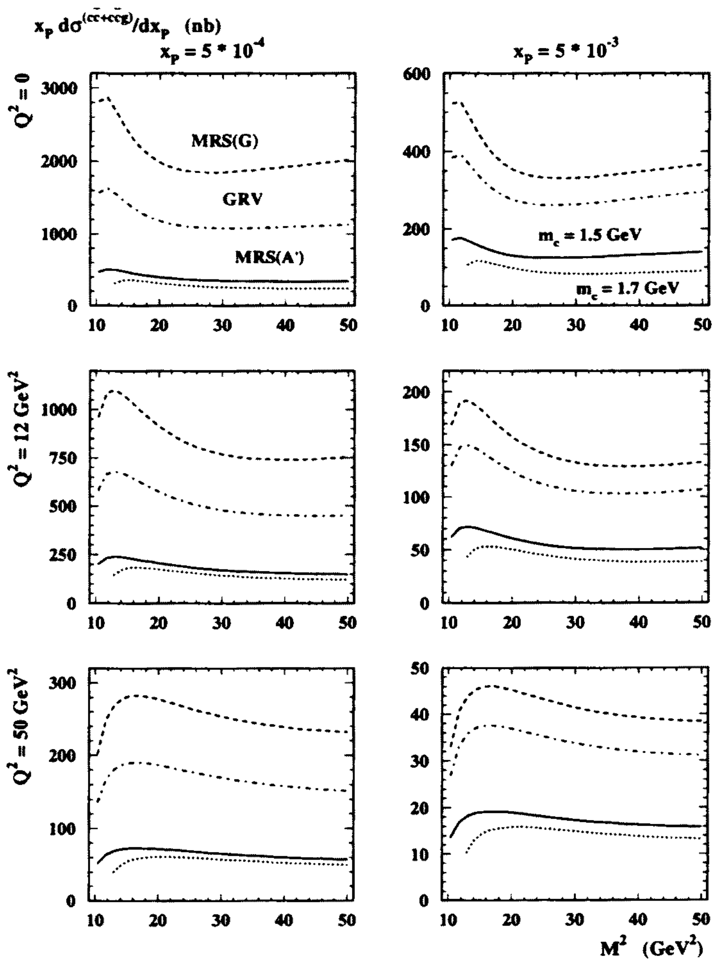

Fig. 4. The cross section $x\mathrm{d}\sigma/\mathrm{d}x$ (in nb) for the diffractive production of open charm using MRS(A$'$,G) (continuous, dashed) and GRV (dot-dashed) partons (with $m_c = 1.5$ GeV). The dotted curve corresponds to a charm quark mass $m_c = 1.7$ GeV for the MRS(A$'$) gluon.

In the Pomeron exchange model the cross section can be written in the factorized form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}t} \sim F_2^P(\beta, Q^2, t) \left(\frac{1}{x}\right)^{2\alpha_P(t)-1}, \tag{5}$$

where F_2^P can be regarded as the structure function of the Pomeron and the power $n = 2\alpha_P(t) - 1$ does not depend on β and Q^2. The x dependence

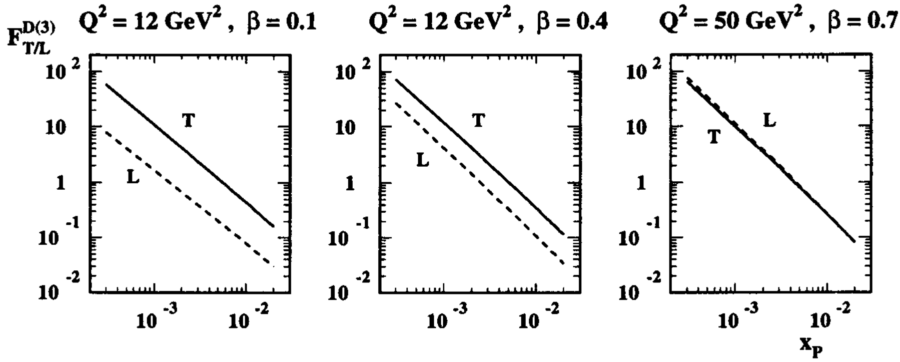

Fig. 5. Plots of $F^{D(3)}(x_{\mathbb{P}}, \beta, Q^2)$, defined in (6), versus $x_{\mathbb{P}}$ for different values of β and Q^2. The continuous (dashed) curves correspond to $F_T(F_L)$.

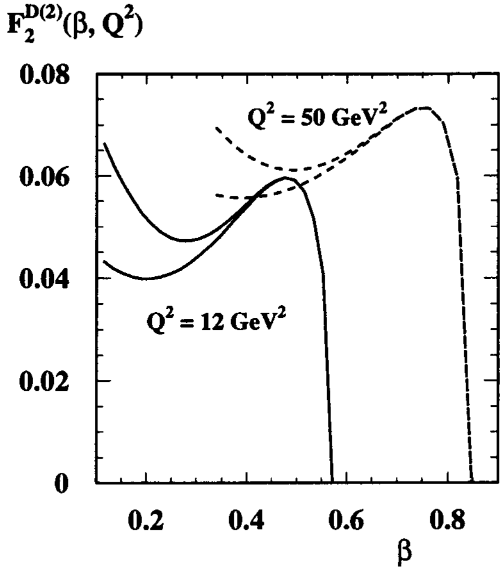

Fig. 6. The QCD estimate of the $c\bar{c}$ component of the diffractive structure function $F_2^{D(2)}(\beta, Q^2)$ for two values of Q^2, integrated over the interval $0.0003 < x < 0.05$.

can so be treated as a flux factor. It is therefore informative to display our predictions for the diffractive open charm cross sections in the form

$$F_{L,T}^{D(3)}\,(x_{\mathbb{P}}, \beta, Q^2) \;\equiv\; \frac{Q^2}{4\pi^2\alpha} \int \mathrm{d}t\, \frac{\mathrm{d}\sigma^{L,T}}{\mathrm{d}x_{\mathbb{P}}\mathrm{d}t} \qquad (6)$$

on a $\ln F^{D(3)}$ versus $\ln x_{\mathbb{P}}$ plot to check whether a linear $x_{\mathbb{P}}^{-n}$ form is obtained. The results are shown in Fig. 5 for different values of β and Q^2. We see that QCD predicts that the behaviour is only approximately linear. n also depends on Q^2 and β, varying in Fig. 5 from $n \approx 1.4$ for $Q^2 = 12\ \mathrm{GeV}^2$, $\beta = 0.1$ to $n \approx 1.6$ for $Q^2 = 50\ \mathrm{GeV}^2$, $\beta = 0.7$. This is to be expected, as for the diffractive production of heavy quarks we can trust the purely perturbative QCD calculation based on two-gluon exchange; we are not in the regime of (non-perturbative or "soft") Pomeron exchange, where $n = 2\alpha_{P}(\bar{t}) - 1$.

Integrating $F^{D(3)}$ over $x_{\mathbb{P}}$ gives the charm component of the diffractive structure function $F_2^{D(2)}(\beta, Q^2)$. In Fig. 6 we show our prediction for $F_2^{D(2)}(\beta, Q^2)$. With the K-factor enhancement, the $c\bar{c}$ component is 25–30% of the total diffractive production at the same β, Q^2. Moreover, we see the characteristic $c\bar{c}$ threshold and subsequent peak in the region $\beta \lesssim Q^2/(Q^2 + 4m_c^2)$, while $c\bar{c}g$ production only becomes important at much lower β. To observe the threshold behaviour will require the experimental determination of the mass of the $c\bar{c}$ system.

4. Conclusions

The presence of m_c enables perturbative QCD predictions to be made for diffractive J/ψ and open $c\bar{c}$ production at HERA. These processes allow a sensitive probe of the gluon behaviour at small x, due to their *quadratic* dependence on $g(x, K^2)$. The relevant scale is $K^2 = (m_c^2 + \langle k_T^2 \rangle)(1 + Q^2/M^2)$. For J/ψ, the normalization is uncertain due to the Fermi motion of the c and $\bar{c}$, though the W (or x) dependence of the HERA data serves as a powerful discriminator between gluon distributions. For open charm, the normalization is particularly dependent on virtual QCD effects, for which only estimates can at present be made. Observation of these diffractive processes at HERA should illuminate novel QCD effects and give valuable information about the gluon at small x.

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