Small x Gluon From Exclusive J/ψ Production

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HERA data for exclusive J/ψ production is used to determine the gluon distribution of the proton in the region $10^{-4} \lesssim x \lesssim 10^{-2}$ and $2 \lesssim \mu^2 \lesssim 10$ GeV^2, where the uncertainty on the gluon extracted from global parton analyses is large.

1 Introduction

Global fits of parton distribution functions currently do not reliably determine the gluon at small x and small to medium scales. This is due to both the lack of precise structure function data for $x \lesssim 10^{-4}$ and due to the limited sensitivity of the inclusive F_2 data to the gluon, which is determined only by the evolution. However, data for the exclusive $\gamma^* p \to J/\psi\, p$ process offer an attractive opportunity to determine the low x gluon density, since here the gluon couples *directly* to the charm quark and the cross section is proportional to the gluon density *squared* [2]. The mass of the $c\bar{c}$ vector meson, $M_{J/\psi}$, introduces a relatively hard scale, allowing for a description within perturbative QCD, even for J/ψ photoproduction. In leading order (LO) the diffractive scattering is described by (colourless) two-gluon exchange, see Fig. 1. To leading logarithmic accuracy, the amplitude is directly proportional to the gluon density, and the cross section is given by

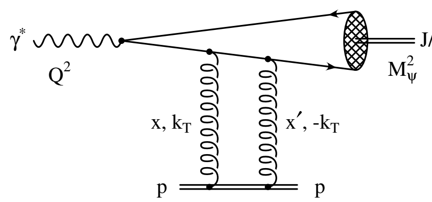

Figure 1: Leading order diagram for diffractive production of J/ψ.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}\left(\gamma^* p \to J/\psi\ p\right)\Big|_{t=0} = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \frac{\alpha_s(\bar{Q}^2)^2}{\bar{Q}^8} \left[xg(x,\bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right), \qquad (1)$$

where Γ_{ee} is the electronic width of the J/ψ. As usual $x = (Q^2 + M_{J/\psi}^2)/(W^2 + M_{J/\psi}^2)$, with Q^2 the photon virtuality and W the $\gamma^* p$ c.m. energy, and the effective scale $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4$. To obtain the total cross section from forward scattering, $t = 0$, we assume an exponential behaviour and divide by the experimentally measured slope parameter $b = 4.5$ GeV^2. Equation (1) assumes $x = x'$ and is only correct to leading $\ln 1/x$ in the high energy limit. For a realistic description of elastic vector meson production at HERA energies, effects from skewing ($x \neq x'$) and from the real part of the amplitudes have to be taken into account. The effect of skewing is calculable at small x. If we assume a gluon behaviour $xg(x,\mu^2) \sim x^{-\lambda}$, then the correction factor to $O(x)$ accuracy is [3] $R_g = \left(2^{2\lambda+3}/\sqrt{\pi}\right)\,\Gamma(\lambda + \frac{5}{2})/\Gamma(\lambda + 4)$.

Contributions from the real part of the amplitudes are taken into account by dispersion relation methods, see e.g. [4], and can be approximated by $\text{Re}\mathcal{A} = \pi\lambda\,\text{Im}\mathcal{A}/2$.

2 Next-to-leading order corrections

At higher order a variety of corrections arise. Relativistic corrections from the J/ψ wave function have to be considered together with higher-order Fock components $c\bar{c}g$ of J/ψ. As shown in [5], when using the experimentally measured Γ_{ee}, these corrections are small and of $\mathcal{O}(4\%)$. We will hence neglect them in the following. However, going beyond the leading logarithmic approximation and performing the integral over the gluon transverse momentum k_T leads to large corrections [4, 6, 7]. This is done by employing k_T factorization and using the unintegrated gluon, thus replacing the leading order amplitude

$$\mathcal{A}^{\text{LLA}} \sim \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} \int^{\bar{Q}^2} \frac{\mathrm{d}k_T^2}{k_T^2} f(x, k_T^2) = \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x, \bar{Q}^2) \tag{2}$$

by an integral over the unintegrated gluon distribution,

$$\mathcal{A}^{\text{NLO}} \sim \frac{\alpha_s(Q_0^2)\, xg(x, Q_0^2)}{\bar{Q}^4} + \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^2} \int_{Q_0^2}^{Q^2_{\max}} \frac{\mathrm{d}k_T^2}{\bar{Q}^2 + k_T^2} \frac{\partial xg(x, k_T^2)}{\partial k_T^2}\,. \tag{3}$$

Here a transition parameter Q_0^2 has been introduced to take into account contributions from the infrared regime in which the unintegrated gluon distribution is ill-defined. We note that varying Q_0^2 leads only to very modest modifications of the results discussed below, for more details see [8]. Also, in the naive definition of the unintegrated gluon in Eq. (3) we have neglected the Sudakov suppression factor. For the kinematical regime studied here these additional corrections are small.

In addition to these corrections there are higher-order α_s corrections to the photon impact factor, i.e. to the $c\bar{c}gg$ vertex. They have not yet been calculated within the k_T factorization scheme, but are part of the next-to-leading order (NLO) corrections studied in [9] within the collinear factorization scheme. Part of these corrections generates the running of α_s, while a part is similar to the gluon Reggeization in the BFKL approach. However, large corrections of this sort are absorbed by the choice of the factorization scale. It is therefore expected that the k_T factorization approach accounts for the major part of the NLO corrections, and that the resulting 'NLO' gluon may be compared to that of NLO global parton fits.[a] For a more detailed discussion of these issues see [8].

3 Results

Equation (1), supplemented by skewing and real part corrections, is used to determine the leading order gluon distribution from a fit to HERA data for exclusive J/ψ production [10, 11]. Having tried different ansätze for the gluon distribution, it has turned out that the

[a]The global partons are defined in the $\overline{\text{MS}}$ regularization scheme. The NLO partons obtained in the following should also be considered to be in the $\overline{\text{MS}}$ scheme, since the $\overline{\text{MS}}$ definition of α_s is used, and moreover the factorization scale which provides the cancellation of the $\alpha_s \ln 1/x$ correction also is specified in the $\overline{\text{MS}}$ scheme.

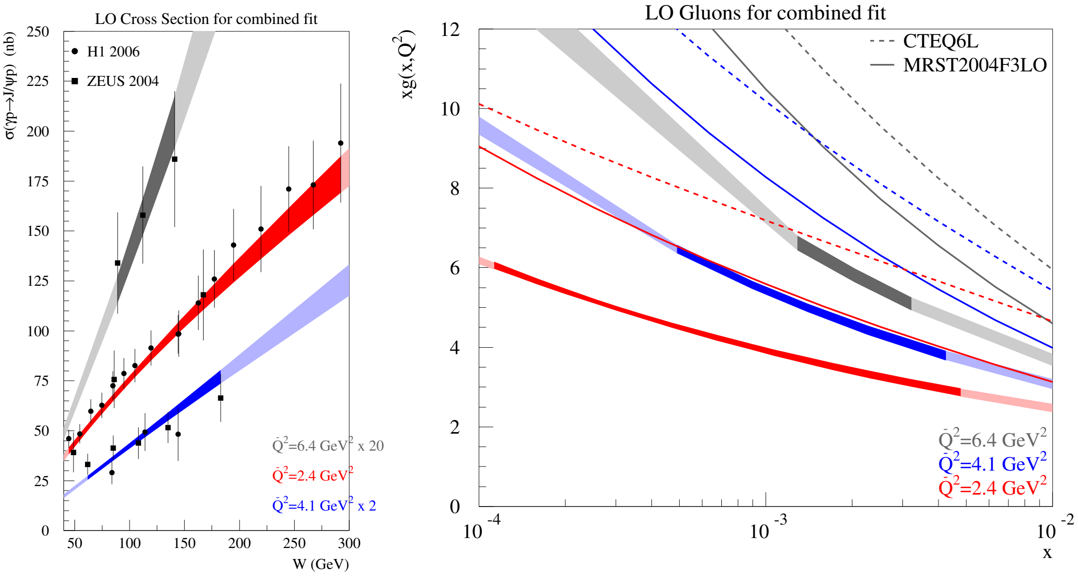

Figure 2: Left panel: Fit of the LO formula Eq. (1), including skewing and real part corrections and using a gluon with form (4), to diffractive J/ψ data, shown for selected Q^2 values. Right panel: Corresponding gluon distribution of the LO fit compared to global fits.

simple ansatz[b]

$$xg(x, \mu^2) = N \cdot x^{a - b\ln(\mu^2/0.45\,\mathrm{GeV}^2)} \tag{4}$$

gives a good fit to the J/ψ data, with a $\chi^2_{\mathrm{min}}/(d.o.f. = 48) = 0.86$. The results of the LO fit for the cross section and the resulting gluon are shown in Figs. 2 for a choice of Q^2 values. The width of the bands indicates the uncertainties and stronger shading the range of the available data. On the right panel, gluon global fits from the MRST [13] and CTEQ [14] collaborations are shown for comparison. Our fitted gluon shows a slightly milder growth with decreasing x and is smaller in normalization. Employing our 'NLO' description using k_T factorization and the integral over the unintegrated gluon as described above, a fit with similar quality, $\chi^2_{\mathrm{min}}/(d.o.f. = 48) = 1.1$, is obtained. However, as demonstrated in the left panel of Fig. 3, the fit slightly undershoots the data at higher Q^2, which has lower weight. The corresponding gluon is shown in the right panel of Fig. 3, again together with curves for two different examples of gluons from recent global fits. The gluons determined in this fit are in good agreement with the MRST gluon at very low scales and in the upper x range, but show much less evolution at larger scales. This is a consequence of the sizeable contributions to the k_T integral from larger scales k_T due to the rising anomalous dimension of the gluon. In contrast, in standard DGLAP fits based on collinear factorization with strong k_T ordering no such large scale contributions exist, but similar corrections are captured order-by-order through the coefficient functions. In this context it is interesting to note that NNLO gluons

[b] Such a form has already successfully been used in [12] for the analysis of inclusive diffractive DIS data.

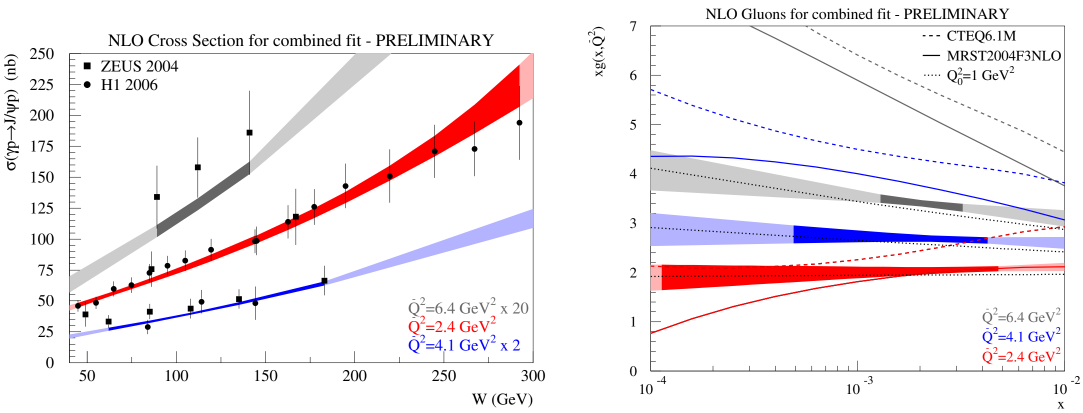

Figure 3: NLO fit as desribed in the text, obtained with $Q_0^2 = 2$ GeV^2. Left panel: Cross section for selected Q^2 values. Right panel: Corresponding gluon compared to NLO gluons from global fits. (The dotted lines are obtained with $Q_0^2 = 1$ GeV^2.)

are much flatter (and even start to decrease at smaller x) compared to NLO fits. In light of this the behaviour of the 'NLO' gluon fits presented here may be viewed as more physical and could be used directly in predictions of different processes based on k_T factorization. Further work to scrutinize the connection between the different schemes is ongoing with the goal to better constrain the gluon at small x.

4 Acknowledgments

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