Using the elastic $\gamma^* p \to J/\psi p$ cross-section to probe the small x gluon density

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Abstract

A Regge-motivated LO approach and the soon to be released HERAPDF1.5LO are used to describe the elastic $\gamma^* p \to J/\psi p$ photoproduction cross-section. It is shown, that the latter is able to describe the available experimental data well, especially in the previously not reachable region of $x < 10^{-5}$.

1 Introduction

There has recently again been rising interested in the elastic J/ψ-cross-section, both from the theoretical side as well as from the experimental. The latest H1 data [6] is able to constrain the theoretical models further and at the same time, LHCb has published new data extracted from η dependencies of the cross-section [8], leading to data in the before unreachable region of $x < 10^{-5}$. Also ALICE will presumably publish data extracted from the η dependency of the cross-section.
These developments have led to a series of newly released theoretical papers, including V. Guzey [1], S.P. Jones [2], the latter being an improvement of the earlier paper from A.D. Martin [3].
This cross-section is interesting, because the not too low mass of the J/ψ allows perturbative QCD to still work, while at the same time the production rate is high enough to provide enough statistics, as compared to in the beauty-sector.
Also, in principle the charm-sector provides an almost unique possibility to probe the gluon distribution of the proton at very low x, since the cross-section depends quadratically on the gluon density already in first order.

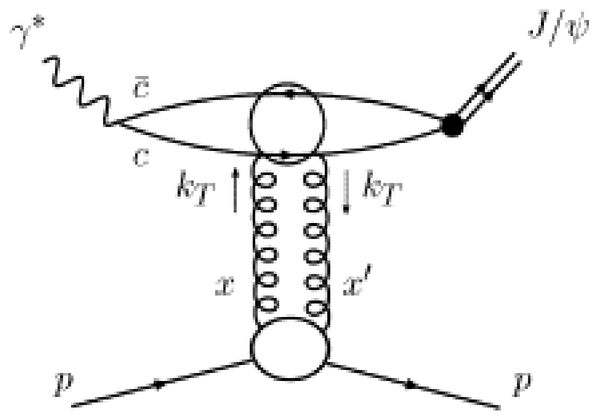

Figure 1: Schematics of the photoproduction of $J\psi$'s. k_T corresponds to the momentum transfer by the two gluons and x, x' to their respective fraction of the proton momentum.

2 Theory

In leading logarithmic order the cross-section for the process $\gamma^* p \to J/\psi p$ is given by the Regge-motivated approach by M.G. Ryskin [4]:

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi p) = \frac{\Gamma_{ee} M_{J/\psi}^3 \pi^3}{48\alpha} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x, \bar{Q}^2)\right]^2 \left(1 + \frac{Q^2}{M_{J/\psi}^2}\right)^2 \qquad (1)$$

where Γ_{ee} is the electronic width of the J/ψ, $M_{J/\psi}$ its mass and:

$$\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \quad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2).$$

Here Q^2 is the virtuality of the photon, which to a good approximation is zero in experiments, putting the factorization scale $\bar{Q}^2$ at about 2.4GeV^2, and $W_{\gamma p}$ is the center-of-mass energy.
To get the integrated cross-section, the integration is carried out assuming $\sigma \propto \exp(-Bt)$, with B the slope parameter:

$$B(W) = (4.9 + 4\alpha' \ln(W/W_0))\,\mathrm{GeV}^{-2}$$

with $\alpha' = 0.06$.
To get the correct cross-section, two correction terms are taken into account.
First,it is more likely, that one gluon has a significantly lower x than the other one, resulting in a skewed gluon density. This can be estimated by multiplying the amplitude with:

$$R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda + \frac{5}{2})}{\Gamma(\lambda + 4)}$$

Second, the gluon PDF correpsonds only to the imaginary part of the amplitude. Assuming $A \propto x^{-\lambda} + (-x)^{-\lambda}$:

$$\frac{\Re A}{\Im A} \simeq \frac{\pi}{2}\lambda \simeq \frac{\pi}{2} \frac{\partial \ln A}{\partial \ln(1/x)} \simeq \frac{\pi}{2} \frac{\partial \ln(xg(x, \bar{Q}^2))}{\partial \ln(1/x)},$$

and therefore multiplying with:

$$1 + \tan^2\left(\frac{\pi}{2}\lambda\right)$$

takes care of this as well.

3 Results

On the following pages in Fig. 2–4 different graphs are presented, with different assumed gluon densities. All are compared to the measurements of the J/ψ cross-section by different experiments.

4 Conclusions

As can be seen in Fig. 2–5, a simple exponential parametrisation of the gluon density, as in [2] LO, is not sufficient to describe the drop off at low $W_{\gamma p}$ (higher x). At the same time, the soon to be released HERAPDF1.5LO is able to describe this dropoff, however, the overall scale is not completely understood. This becomes apparent, since using $\mu^2 = 3.0$GeV^2 instead of the commonly used $\mu^2 = 2.4$GeV^2 yields a better overall agreement.

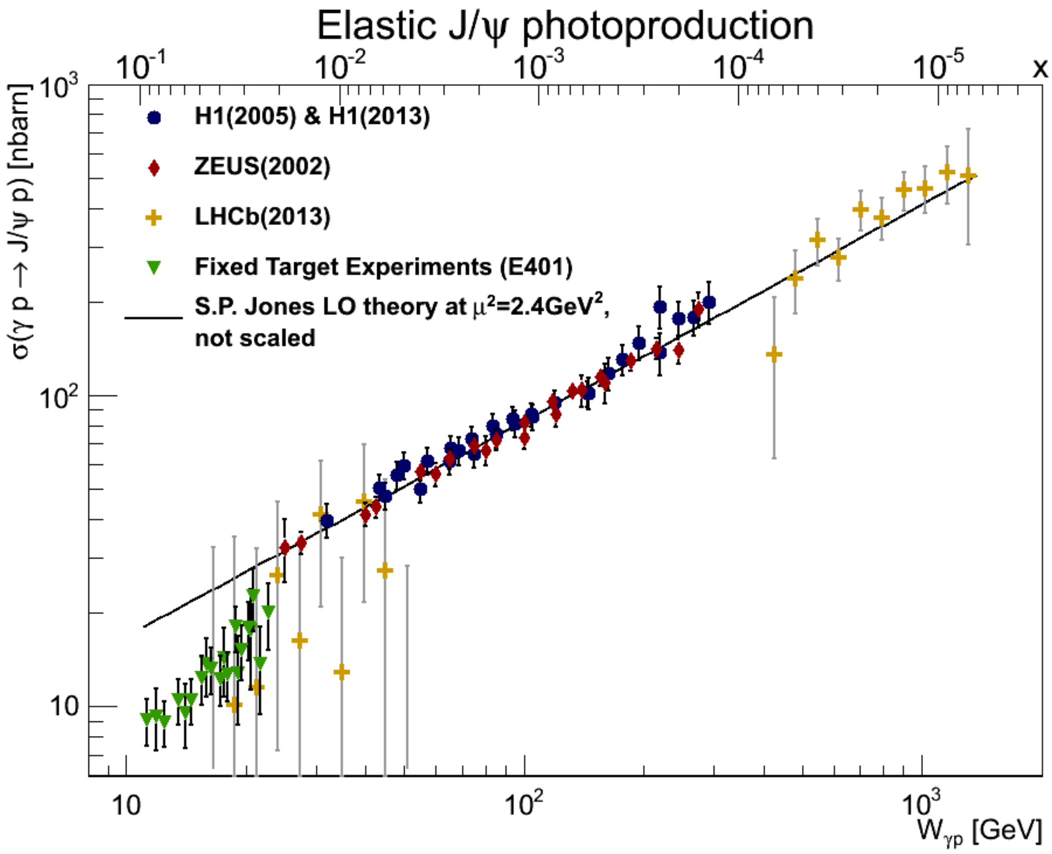

Figure 2: J/ψ photoproduction cross-section versus $\gamma^{*}p$ center-of-mass energy $W_{\gamma p}$ and Bjorken x, including experimental data from H1 from 2005 and 2013 (violet) [5, 6], earlier data from ZEUS (red) [7], recent LHCb results (high and low $W_{\gamma p}$ points are ambiguous solutions extracted from η dependency of cross-section) (orange) [8], as well as earlier fixed target experiments (green) [9]. In black the leading logarithmic order cross-section calculation according to Eq. 1, assuming $xg(x,\mu^2) = Nx^{-\lambda}$, is shown, according to the LO approach of S.P. Jones [2].
It can be seen, that while this approach nicely describes the overall slope and even the high $W_{\gamma p}$ LHCb-points, the data from fixed target experiments is not described by this Regge-motivated approach. The fitted parameters can be found in [2].

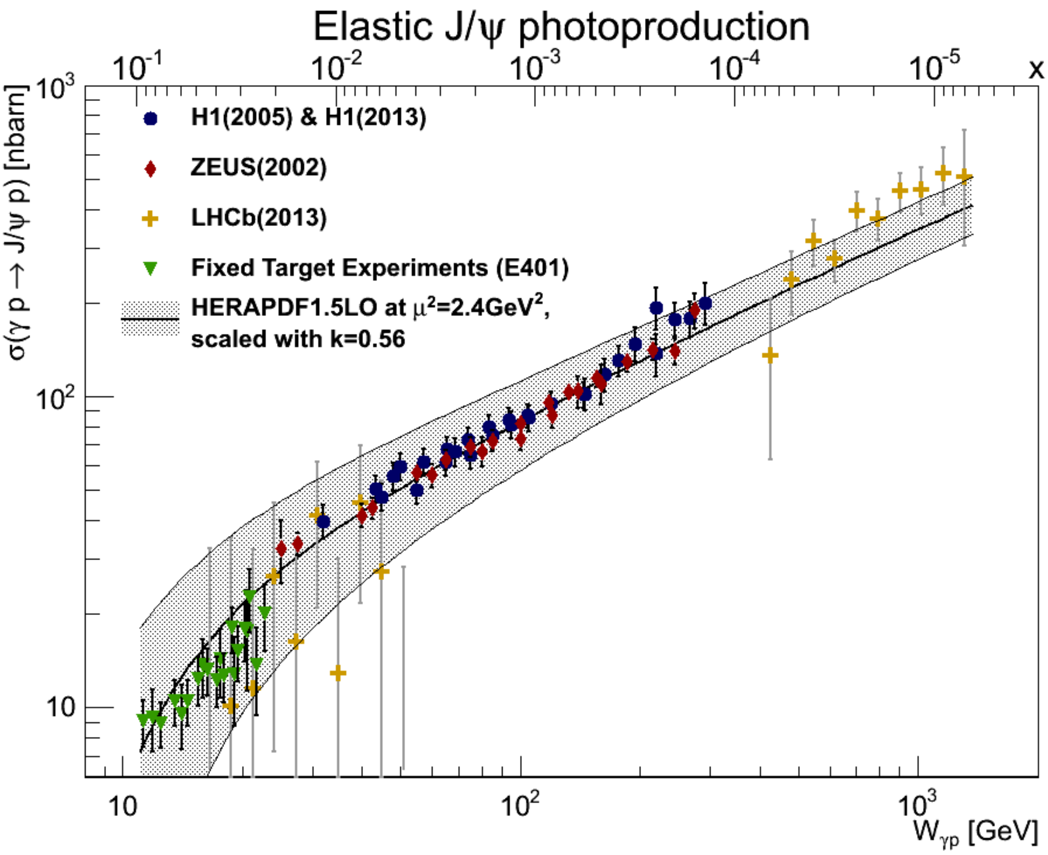

Figure 3: Same experimental data as in Fig. 2, but with the newly released HERAPDF1.5LO as gluon density. The error bands shown correspond to 1σ errors on the parameters of the pdf.
It can be seen that the data is well described, when choosing $\mu^2 = 2.4\text{GeV}^2$ as the factorization scale. The cross-section is scaled with a factor $k = 0.56 \pm 0.01$ afterwards, but it is not expected that this dataset would have a high sensitivity to the normalization, anyway.
This plot clearly shows the universality of the gluon density, since the J/ψ-data has not been included in any fits to determine the parameters for HERAPDF1.5LO. It can also be seen, that the data in the J/ψ-sector should allow additional constraints to the PDF, even at low x (high $W_{\gamma p}$). The overall normalization of the LHCb points is not entirely clear and depends on the procedure used to extract them from the η dependency of the cross-section.
Previous theoretical LO approximations always assumed gluon densities of the form $xg(x, \mu^2) = N \exp(-\lambda x)$, whereas this LO parametrization shows, that one can take the drop-off at low $W_{\gamma p}$ into account as well.

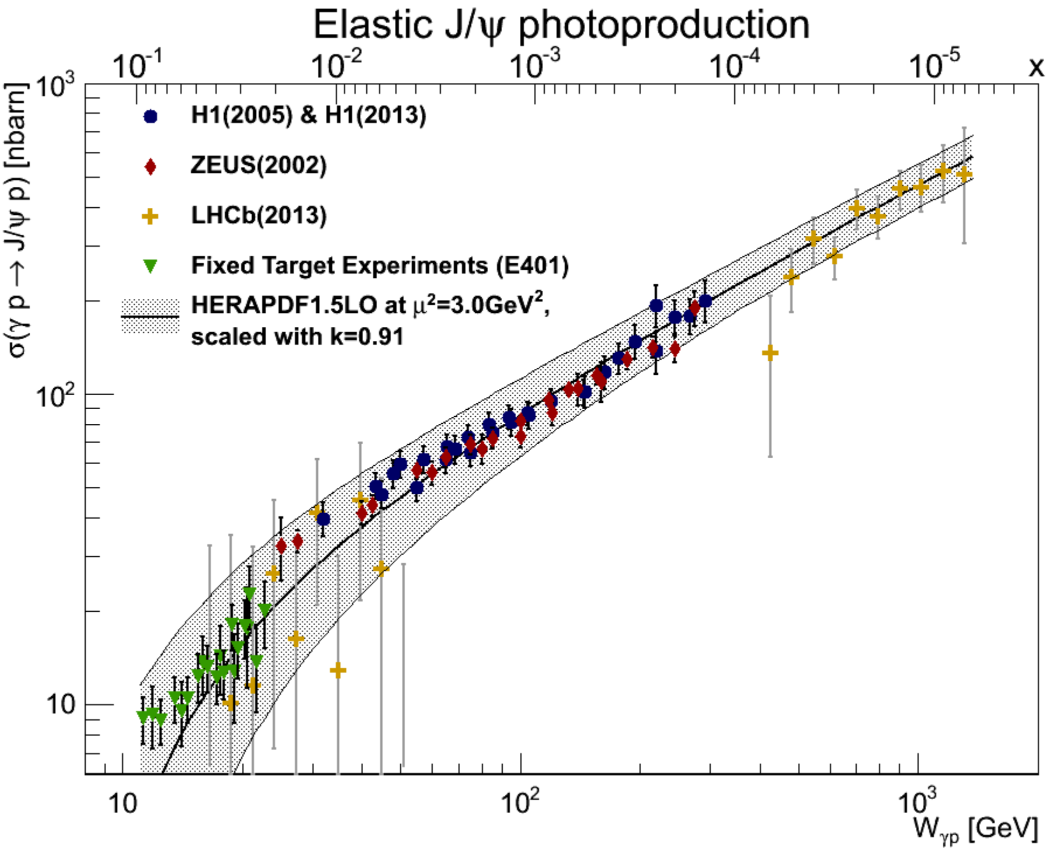

Figure 4: Same experimental data as in Fig. 2, but at the factorization scale $\mu^2 = 3\text{GeV}^2$. This time the cross-section barely needs to be scaled down, showing the high uncertainty on the correct factorization scale. The normalization constant is fit to be $k = 0.91 \pm 0.01$, where only the experimental errors are taken into account and the PDF uncertainty is additionally shown.
The data from the different experiments is well described over the whole range of $W_{\gamma p}$, covering a range in x from roughly 0.04 down to $0.8 \cdot 10^{-5}$.

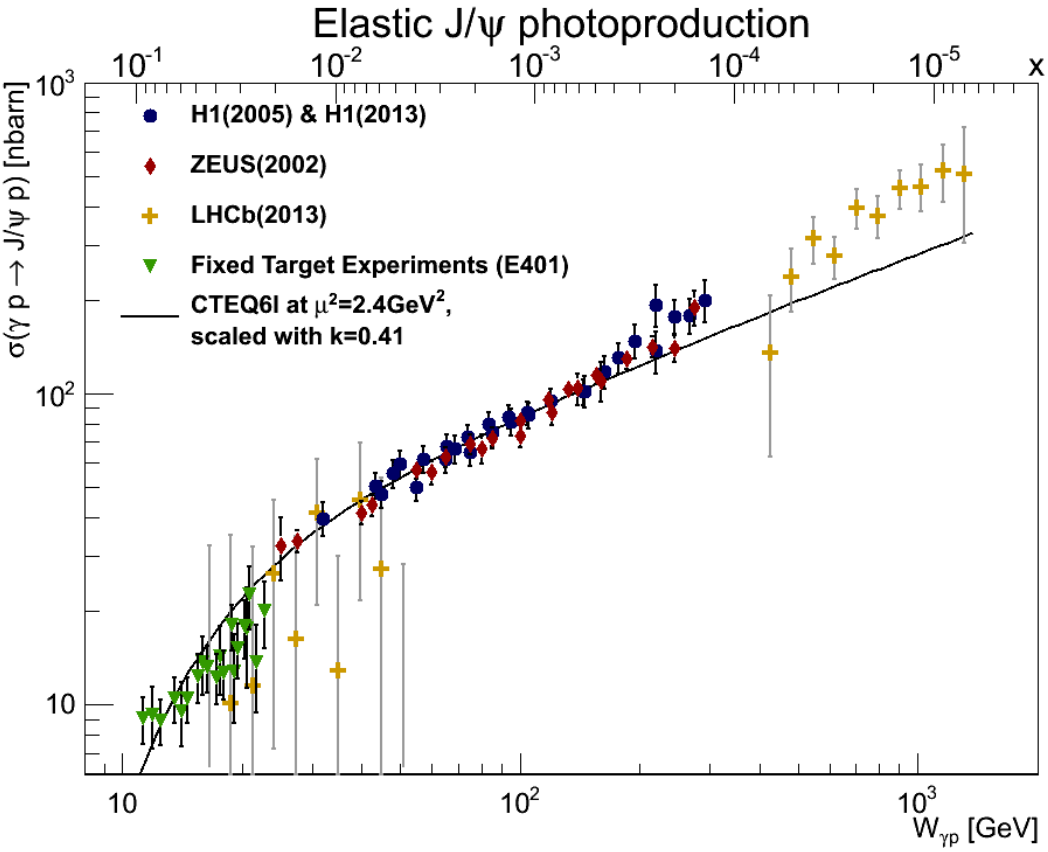

Figure 5: Same experimental data as in Fig. 2, but using CTEQ6l at the factorization scale $\mu^2 = 2.4\text{GeV}^2$.
It can be seen that this parametrization falls short in the high $W_{\gamma p}$ region, even more so than HERAPDF1.5LO at $\mu = 2.4\text{GeV}^2$.

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