Exclusive vector meson production at the LHeC

G. Watt*

September 17, 2010

The colour dipole model has proven to be very successful in describing a wide variety of small-x inclusive and diffractive processes at HERA. The amplitude for an exclusive diffractive process, $\gamma^* p \to E + p$, shown in Fig. 1(a), such as vector meson production, $E = V$, or deeply virtual Compton scattering (DVCS), $E = \gamma$, can be expressed as

$$\mathcal{A}_{T,L}^{\gamma^* p\to E+p}(x,Q,\Delta) = \mathrm{i}\int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}\int \mathrm{d}^2\boldsymbol{b}\;(\Psi_E^*\Psi)_{T,L}\;\mathrm{e}^{-\mathrm{i}[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\boldsymbol{\Delta}}\;\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}. \tag{1}$$

Here, z is the fraction of the photon's light-cone momentum carried by the quark, $r = |\boldsymbol{r}|$ is the transverse size of the $q\bar{q}$ dipole, while $\boldsymbol{b}$ is the impact parameter, that is, $b = |\boldsymbol{b}|$ is the transverse distance from the centre of the proton to the centre-of-mass of the $q\bar{q}$ dipole; see Fig. 1(a). The transverse momentum lost by the outgoing proton, $\boldsymbol{\Delta}$, is the Fourier conjugate variable to the impact parameter $\boldsymbol{b}$, and $t \equiv (p-p')^2 = -\Delta^2$. The forward overlap function between the initial-state photon wave function and the final-state vector meson or photon wave function in Eq. (1) is denoted $(\Psi_E^*\Psi)_{T,L}$, while the factor $\exp[\mathrm{i}(1-z)\boldsymbol{r}\cdot\boldsymbol{\Delta}]$ in Eq. (1) originates from the non-forward wave functions [1]. The differential cross section for an exclusive diffractive process is obtained from the amplitude, Eq. (1), by

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p\to E+p}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\to E+p}\right|^2, \tag{2}$$

up to corrections from the real part of the amplitude and from skewedness ($x' \ll x \ll 1$). Taking the imaginary part of the forward scattering amplitude immediately gives the formula for the total $\gamma^* p$ cross section (or equivalently, the proton structure function $F_2 = F_T + F_L$):

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \mathrm{Im}\,\mathcal{A}_{T,L}^{\gamma^* p\to\gamma^* p}(x,Q,\Delta=0) = \sum_f \int \mathrm{d}^2\boldsymbol{r}\int_0^1 \frac{\mathrm{d}z}{4\pi}(\Psi^*\Psi)_{T,L}^f \int \mathrm{d}^2\boldsymbol{b}\;\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}}. \tag{3}$$

The dipole picture therefore provides a unified description of both exclusive diffractive processes and inclusive deep-inelastic scattering (DIS) at small x.

*Theory Group, Physics Department, CERN, CH-1211 Geneva 23, Switzerland

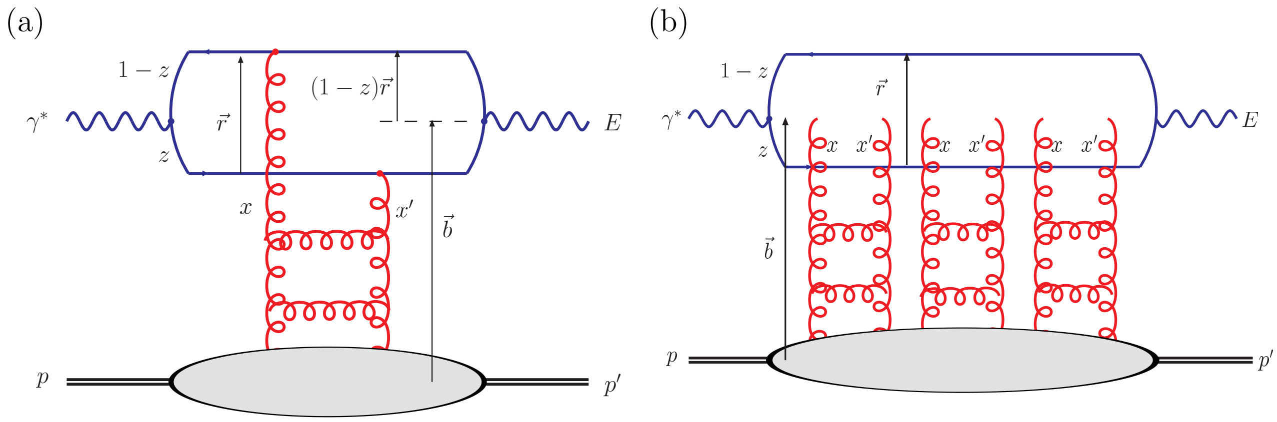

Figure 1: Diagrams representing the $\gamma^* p$ scattering amplitude proceeding via (a) single-Pomeron and (b) multi-Pomeron exchange, where the perturbative QCD Pomeron is represented by a gluon ladder. For exclusive diffractive processes, such as vector meson production ($E = V$) or DVCS ($E = \gamma$), we have $x' \ll x \ll 1$ and $t = (p - p')^2$. For inclusive DIS, we have $E = \gamma^*$, $x' = x \ll 1$ and $p' = p$.

The unknown quantity common to Eqs. (1) and (3) is the b-dependent dipole–proton cross section,

$$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\boldsymbol{b}} = 2\,\mathcal{N}(x, r, b), \tag{4}$$

where $\mathcal{N}$ is the imaginary part of the dipole–proton scattering amplitude, which can vary between zero and one, where $\mathcal{N} = 1$ is the unitarity ("black disc") limit. The scattering amplitude $\mathcal{N}$ is generally parameterised according to some theoretically-motivated functional form, with the parameters fitted to data. Most dipole models assume a factorised b dependence, $\mathcal{N}(x, r, b) = T(b)\,\mathcal{N}(x, r)$, with $\mathcal{N}(x, r) \in [0, 1]$ and, for example, $T(b) = \Theta(R_p - b)$, so that the b-integrated $\sigma_{q\bar{q}} = (2\pi R_p^2)\,\mathcal{N}(x, r)$. However, (i) the "saturation scale" is strongly dependent on impact parameter, (ii) the b-dependence should be made consistent with the t-dependence of exclusive diffraction at HERA, and (iii) the non-zero effective "Pomeron slope" $\alpha'_{\mathbb{P}}$ measured at HERA implies a correlation between the x- and b- dependences of $\mathcal{N}(x, r, b)$. Therefore, $\mathcal{N}(x, r, b)$ should be determined from a *simultaneous* description of inclusive DIS and exclusive diffractive processes measured at HERA.

An impact-parameter-dependent saturation ("b-Sat") model [2, 3] has been shown to be very successful in describing a wealth of HERA data on exclusive diffractive vector meson (J/ψ, ϕ, ρ) production and DVCS, including almost all aspects of the Q^2, W and t dependence with the exception of $\alpha'_{\mathbb{P}}$, together with the inclusive structure functions F_2, $F_2^{c\bar{c}}$, $F_2^{b\bar{b}}$ and F_L.[1] The "b-Sat" parameterisation is based on LO DGLAP evolution of an initial gluon density, $xg(x, \mu_0^2) = A_g\, x^{-\lambda_g}\,(1 - x)^{5.6}$, with a Gaussian b dependence, $T(b) \propto \exp(-b^2/2B_G)$. The

[1] An alternative "b-CGC" model [3–5] was successful in describing $\alpha'_{\mathbb{P}}$ at HERA, but failed to reproduce the W dependence of HERA data on exclusive J/ψ photoproduction [5], and therefore will not be considered here.

dipole scattering amplitude is

$$\mathcal{N}(x,r,b) = 1 - \exp\left(-\frac{\pi^2}{2N_c}r^2\alpha_S(\mu^2)\,xg(x,\mu^2)\,T(b)\right), \tag{5}$$

where the scale $\mu^2 = 4/r^2 + \mu_0^2$, $B_G = 4$ GeV^{-2} was fixed from the t-slope of exclusive J/ψ photoproduction at HERA, and the other three parameters ($\mu_0^2 = 1.17$ GeV^2, $A_g = 2.55$, $\lambda_g = 0.020$) were fitted to ZEUS F_2 data with $x_{\rm Bj} \leq 0.01$ and $Q^2 \in [0.25, 650]$ GeV^2 [3]. The eikonalised dipole scattering amplitude of Eq. (5) can be expanded as

$$\mathcal{N}(x,r,b) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n!}\left[\frac{\pi^2}{2N_c}r^2\alpha_S(\mu^2)\,xg(x,\mu^2)\,T(b)\right]^n, \tag{6}$$

where the nth term in the expansion corresponds to n-Pomeron exchange; for example, the case $n = 3$ is illustrated in Fig. 1(b). The terms with $n > 1$ are necessary to ensure unitarity.

The plots in Fig. 2 show t-integrated predictions for exclusive J/ψ photoproduction ($Q^2 = 0$) calculated with Eqs. (1) and (2), using the eikonalised "b-Sat" dipole scattering amplitude given in Eq. (5) together with a "boosted Gaussian" vector meson wave function [3, 6]. Also shown is the single-Pomeron exchange contribution obtained by keeping just the first term in the expansion of Eq. (6), which is linearly dependent on the gluon density, without refitting any of the input parameters. The difference between the "eikonalised" and "1-Pomeron" predictions therefore indicates the importance of unitarity corrections, which increase significantly with increasing γp centre-of-mass energy W. The maximum kinematic limit accessible at the LHeC, $W = \sqrt{s}$, is indicated with different options for electron beam energies (E_e) and not accounting for the angular acceptance of the detector. The precise HERA data [7, 8] are overlaid, together with sample LHeC pseudo-data points with the errors (statistical only) given by an LHeC simulation [9] with $E_e = 150$ GeV. The central values of the LHeC pseudo-data points were obtained from a Gaussian distribution with the mean given by extrapolating a power-law fit to the HERA data [7, 8] and the standard deviation given by the statistical errors from the LHeC simulation [9]. The plots in Fig. 2 show that the errors on the LHeC pseudo-data are much smaller than the difference between the "eikonalised" and "1-Pomeron" predictions. Therefore, exclusive J/ψ photoproduction at the LHeC may be an ideal observable for investigating unitarity corrections at a perturbative scale provided by the charm-quark mass.

Similar plots for exclusive Υ photoproduction are shown in Fig. 3. Here, the unitarity corrections are smaller than for J/ψ production due to the larger scale provided by the bottom-quark mass and therefore the smaller typical dipole sizes r. The simulated LHeC pseudo-data points also have larger statistical errors than for J/ψ production due to the much smaller cross sections. Note that only very sparse data are currently available on exclusive Υ photoproduction at HERA [10–12] and that a factor $\sim$2 is required to bring the "b-Sat" predictions into agreement with the HERA data for the purposes of extrapolation (a similar factor is required for other calculations using the dipole model, see e.g. Ref. [13]).

The plots in Figs. 2 and 3 are integrated over $t \equiv (p - p')^2 = -\Delta^2$, where $\boldsymbol{\Delta}$ is the Fourier conjugate variable to the impact parameter $\boldsymbol{b}$. Unitarity effects are more important

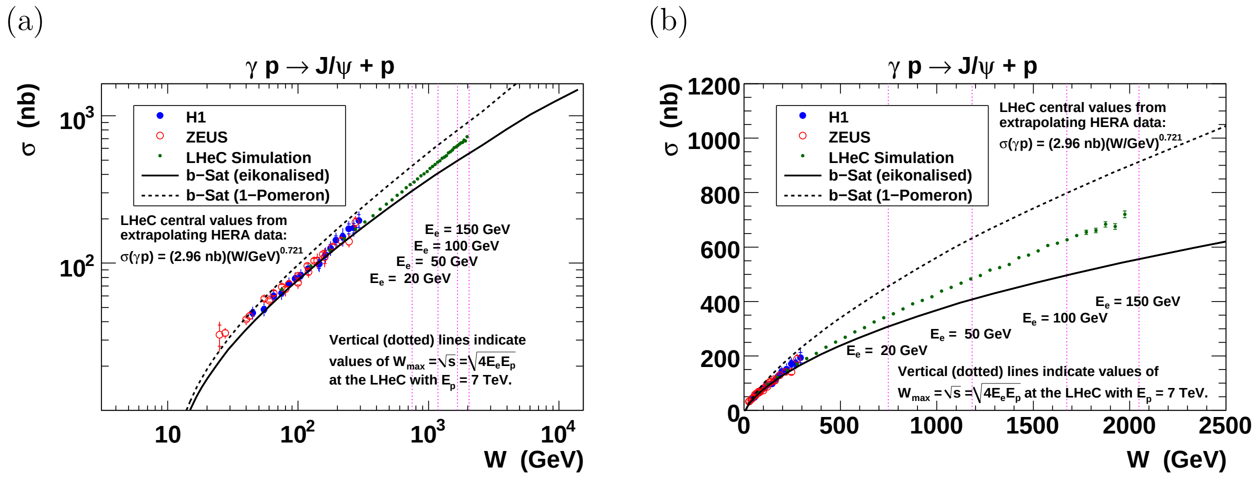

Figure 2: Exclusive J/ψ photoproduction at the LHeC, as a function of the γp centre-of-mass energy W, plotted on a (a) log–log scale and (b) linear–linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections compared to pseudo-data from an LHeC simulation.

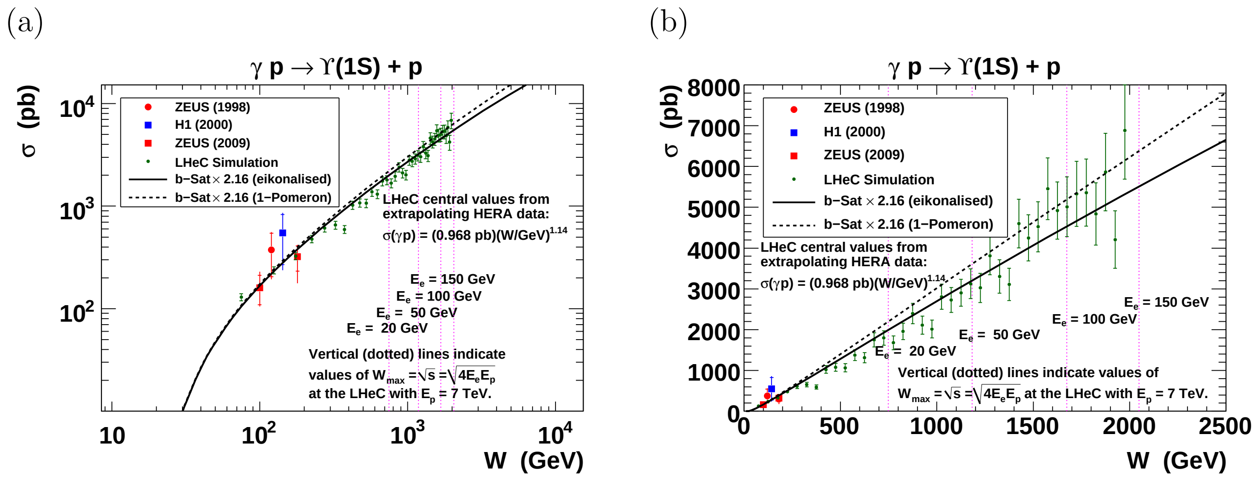

Figure 3: Exclusive Υ photoproduction at the LHeC, as a function of the γp centre-of-mass energy W, plotted on a (a) log–log scale and (b) linear–linear scale. The difference between the solid and dashed curves indicates the size of unitarity corrections compared to pseudo-data from an LHeC simulation. The "b-Sat" theory predictions have been scaled by a factor 2.16 to best-fit the existing HERA data.

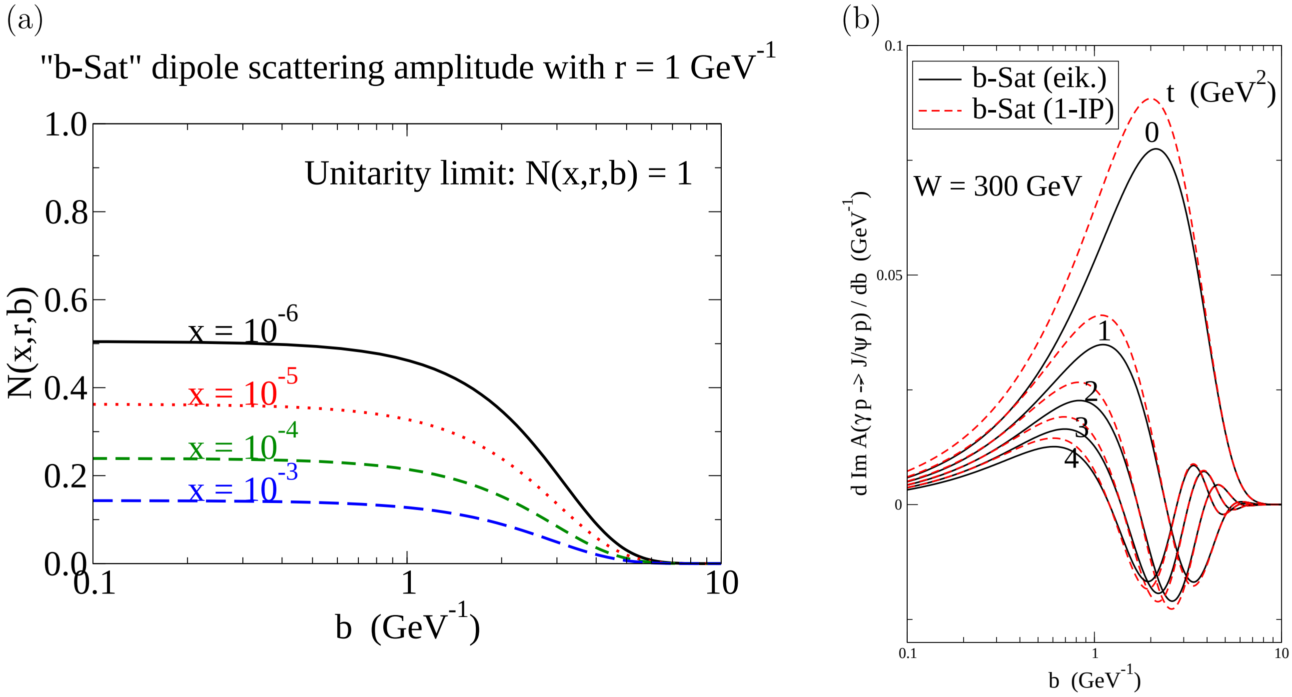

Figure 4: (a) The (imaginary part of the) dipole scattering amplitude, $\mathcal{N}(x,r,b)$, as a function of the impact parameter b, for $r = 1$ GeV^{-1} (typical for exclusive J/ψ photoproduction) and different x values. (b) The (r-integrated) amplitude for exclusive J/ψ photoproduction as a function of b, for $W = 300$ GeV and $|t| = 0, 1, 2, 3, 4$ GeV^2.

closer to the centre of the proton (smaller b), and at higher energies (smaller x), where the proton is more dense; see Fig. 4(a) showing the dipole scattering amplitude as a function of b for various x values. Measurements of exclusive diffraction at larger $|t|$ are more sensitive to smaller b, see Fig. 4(b), and therefore potentially more sensitive to unitarity effects. Indeed, the eikonalised dipole model of Eq. (5) leads to "diffractive dips" in the t-distribution of exclusive J/ψ photoproduction at large $|t|$ (reminiscent of the dips seen in the t-distributions of proton–proton elastic cross sections), departing from the exponential fall-off in the t-distribution seen with single-Pomeron exchange [2]. The HERA experiments have only been able to make precise measurements of exclusive J/ψ photoproduction at relatively small $|t| \lesssim 1$ GeV^2, and no significant departure from the exponential fall-off behaviour, $\mathrm{d}\sigma/\mathrm{d}t \sim \exp(-B_D|t|)$, has been observed. Precise measurements of large-$|t|$ exclusive J/ψ photoproduction at the LHeC would have significant potential sensitivity to perturbative unitarity effects.

For the studies presented here we have concentrated on vector meson *photoproduction* ($Q^2 = 0$), where the HERA data are most precise due to the largest cross sections and where unitarity effects are most important. Of course, studies are also possible in *DIS* ($Q^2 \gtrsim 1$ GeV^2), where the extra hard scale Q^2 additionally allows a perturbative treatment of exclusive *light* vector meson (e.g. ρ, ϕ) production. Again, perturbative unitarity effects are expected to be important for light vector meson production when $Q^2 \gtrsim 1$ GeV^2 is not too large.

References

[1] J. Bartels, K. Golec-Biernat and K. Peters, Acta Phys. Polon. B **34** (2003) 3051 [arXiv:hep-ph/0301192].

[2] H. Kowalski and D. Teaney, Phys. Rev. D **68** (2003) 114005 [arXiv:hep-ph/0304189].

[3] H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D **74** (2006) 074016 [arXiv:hep-ph/0606272].

[4] E. Iancu, K. Itakura and S. Munier, Phys. Lett. B **590** (2004) 199 [arXiv:hep-ph/0310338].

[5] G. Watt and H. Kowalski, Phys. Rev. D **78** (2008) 014016 [arXiv:0712.2670 [hep-ph]].

[6] J. R. Forshaw, R. Sandapen and G. Shaw, Phys. Rev. D **69** (2004) 094013 [arXiv:hep-ph/0312172].

[7] S. Chekanov *et al.* [ZEUS Collaboration], Eur. Phys. J. C **24** (2002) 345 [arXiv:hep-ex/0201043].

[8] A. Aktas *et al.* [H1 Collaboration], Eur. Phys. J. C **46** (2006) 585 [arXiv:hep-ex/0510016].

[9] P. R. Newman, private communication, 24th August 2009.

[10] J. Breitweg *et al.* [ZEUS Collaboration], Phys. Lett. B **437** (1998) 432 [arXiv:hep-ex/9807020].

[11] C. Adloff *et al.* [H1 Collaboration], Phys. Lett. B **483** (2000) 23 [arXiv:hep-ex/0003020].

[12] S. Chekanov *et al.* [ZEUS Collaboration], Phys. Lett. B **680** (2009) 4 [arXiv:0903.4205 [hep-ex]].

[13] B. E. Cox, J. R. Forshaw and R. Sandapen, JHEP **0906** (2009) 034 [arXiv:0905.0102 [hep-ph]].