Exclusive vector meson production in *ep* collisions at the LHeC

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CERN PH-TH

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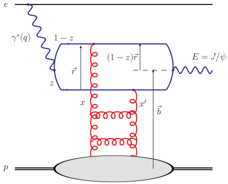
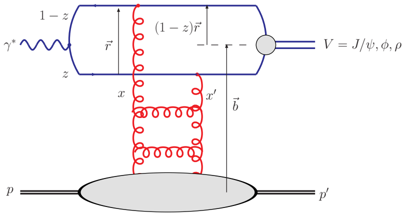


Introduction

- **Motivation:** exclusive vector meson (VM) production at the LHeC as a probe of unitarity effects at a perturbative scale.
- Increase unitarity corrections by (i) increasing energy in *ep* (this talk) or (ii) moving to *eA* collisions (→ H. Kowalski).



Aim to extract dipole–proton scattering amplitude: $\mathcal{N}(x, r, b)$

[cf. Munier, Staśto, Mueller, hep-ph/0102291]

"Experimental" variables

$$W^2 = (q+p)^2, \quad Q^2 = -q^2$$

$$t = (p-p')^2 = -|\vec{\Delta}|^2$$

"Theoretical" variables

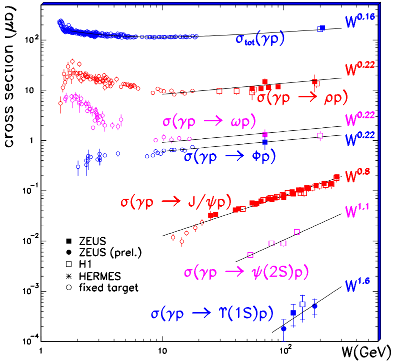
$$\text{Mom. frac.}, x \simeq \frac{Q^2 + M_V^2}{Q^2 + W^2} \ll 1$$

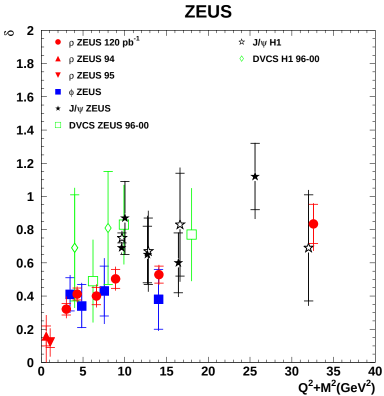
$$\text{Dipole size}, r = |\vec{r}| \quad (\vec{r} \overset{\text{F.T.}}{\leftrightarrow} \vec{k})$$

$$\text{Impact parameter}, \vec{b} \overset{\text{F.T.}}{\leftrightarrow} \vec{\Delta}$$

W dependence of exclusive VM cross sections at HERA

- Transition between "soft" and "hard" energy dependence.

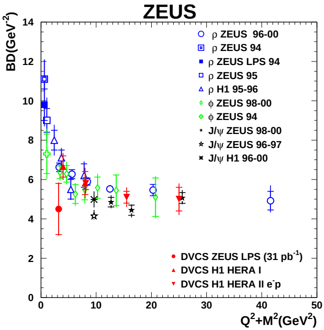


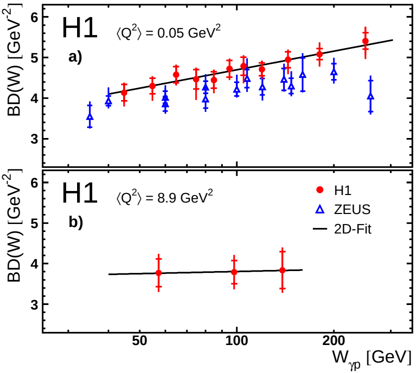


Regge phenomenology for "effective" Pomeron trajectories

$$\sigma(\gamma p \to V+p) \propto W^{\delta}, \quad \delta = 4[\alpha_{\mathbb{P}}(\langle t\rangle)-1], \quad \alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0)+\alpha'_{\mathbb{P}}\, t$$

t dependence of exclusive VM cross sections at HERA



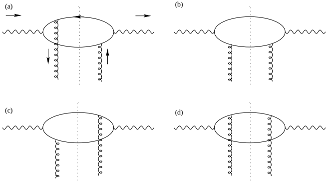


- Parameterise as exponential: $\mathrm{d}\sigma/\mathrm{d}t \propto \exp(-B_D|t|)$.
- t-slope parameter B_D gives transverse proton size $\langle b^2 \rangle$.

- Regge phenomenology: $B_D = B_0 + 4\,\alpha'_{\mathbb{P}}\ \ln(W/W_0)$.
- Non-zero $\alpha'_{\mathbb{P}}$ for $\gamma p \to J/\psi + p$, $\sim$ half value from elastic p–p.

Dipole picture in the non-forward direction

[Bartels, Golec-Biernat, Peters, hep-ph/0301192]



- Non-forward photon impact factor calculated in the high-energy limit.
- Fourier transform from momentum space to coordinate space ($\vec{k} \to \vec{r}$), then to impact parameter space ($\vec{\Delta} \to \vec{b}$), with $t = -|\vec{\Delta}|^2$.

- Results obtained in colour dipole picture: amplitude factorises into (wave function)·(dipole cross section)·(wave function).
- Non-forward wave functions can be written as forward wave functions multiplied by $\exp[\pm\mathrm{i}(1-z)\vec{r}\cdot\vec{\Delta}/2]$.

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

Unified description of exclusive and inclusive processes

Exclusive diffractive processes

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

with corrections from the *real part* and from *skewedness* ($x \neq x'$).

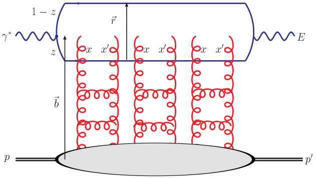
Inclusive deep-inelastic scattering (DIS) at small x

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

$\frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\vec{b}} = 2\,\mathcal{N}(x,r,b)$, where $\mathcal{N}\in[0,1]$ and $\mathcal{N}=1$ is the unitarity limit.

- $\mathcal{N}(x,r,b)$ should be determined from a **simultaneous** description of *inclusive* DIS and *exclusive* diffractive processes.

Impact-parameter-dependent saturation (“b-Sat”) model



Golec-Biernat, Wüsthoff [hep-ph/9807513]
→ Bartels, Golec-Biernat, Kowalski [hep-ph/0203258]
→ Kowalski, Teaney [hep-ph/0304189]
→ Kowalski, Motyka, G.W. [hep-ph/0606272]

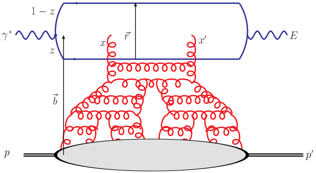
- Eikonalised DGLAP-evolved gluon density with Gaussian b dependence:

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

$$xg(x,\mu_0^2) = A_g\,x^{-\lambda_g}\,(1-x)^{5.6},\quad T(b)=\frac{1}{2\pi B_G}\mathrm{e}^{-\frac{b^2}{2B_G}},\quad \mu^2=\frac{4}{r^2}+\mu_0^2$$

- $B_G = 4$ GeV^{-2} from t-slope of exclusive J/ψ photoproduction.
- Fit to 163 ZEUS F_2 points with $x_{\rm Bj}\leq 0.01$ and $Q^2\in[0.25,650]$ GeV^2 gives a $\chi^2/\mathrm{d.o.f.} = 1.21$ with parameters:
  $\mu_0^2 = 1.17$ GeV^2, $A_g = 2.55$, $\lambda_g = 0.020$.

Impact-parameter-dependent CGC ("b-CGC") model



Iancu, Itakura, Munier (IIM) [hep-ph/0310338]
→ Kowalski, Motyka, G.W. [hep-ph/0606272]
→ Soyez [arXiv:0705.3672]
→ G.W., Kowalski [arXiv:0712.2670]

(N.B. Charm quarks not included by IIM.)

- Original CGC model of IIM assumed b dependence: $\Theta(b_{\rm max} - b)$.
- Introduce Gaussian b dependence into the saturation scale Q_s:

$$\mathcal{N}(x,r,b) = \begin{cases} \mathcal{N}_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/rQ_s)}{9.9\lambda \ln(1/x)}\right)} & : \quad rQ_s \leq 2 \\ 1 - \mathrm{e}^{-A\ln^2(BrQ_s)} & : \quad rQ_s > 2 \end{cases}$$

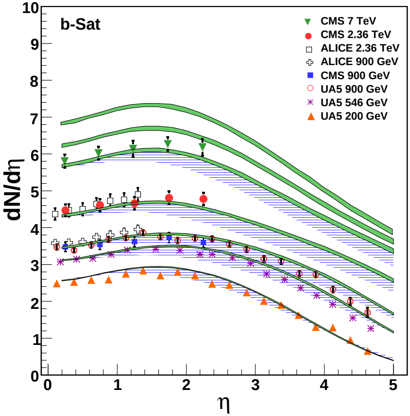
$$Q_s \equiv Q_s(x,b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \left[\exp\left(-\frac{b^2}{2B_{\rm CGC}}\right)\right]^{\frac{1}{2\gamma_s}}$$

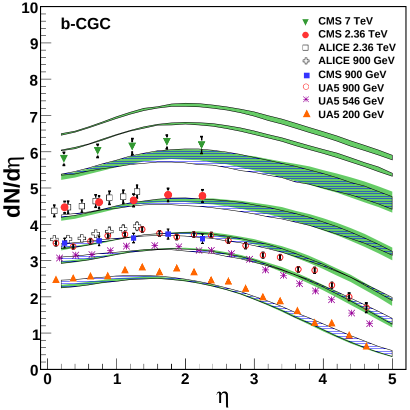
- $B_{\rm CGC} = 7.5$ GeV^{-2} from t-slope of exclusive J/ψ photoproduction.
- Fit to 133 ZEUS F_2 points with $x_{\rm Bj} \leq 0.01$ and $Q^2 \in [0.25, 45]$ GeV^2 gives a $\chi^2/\mathrm{d.o.f.} = 0.92$ with parameters:
  $\mathcal{N}_0 = 0.558$, $\gamma_s = 0.46$, $x_0 = 1.84 \times 10^{-6}$, $\lambda = 0.119$.

Aside: b-Sat and b-CGC models in LHC *pp* minimum-bias

[Tribedy, Venugopalan, arXiv:1011.1895 (see also Levin, Rezaeian, arXiv:1005.0631)]

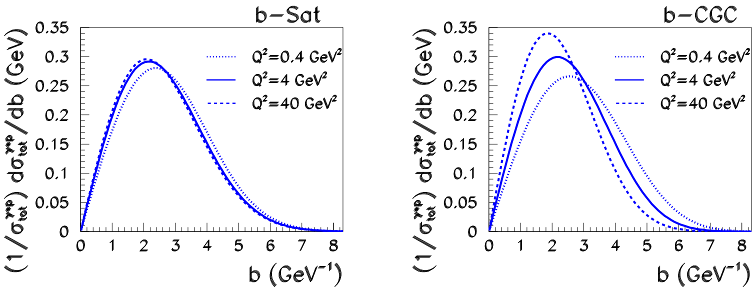
- Charged-hadron pseudorapidity distributions, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$:





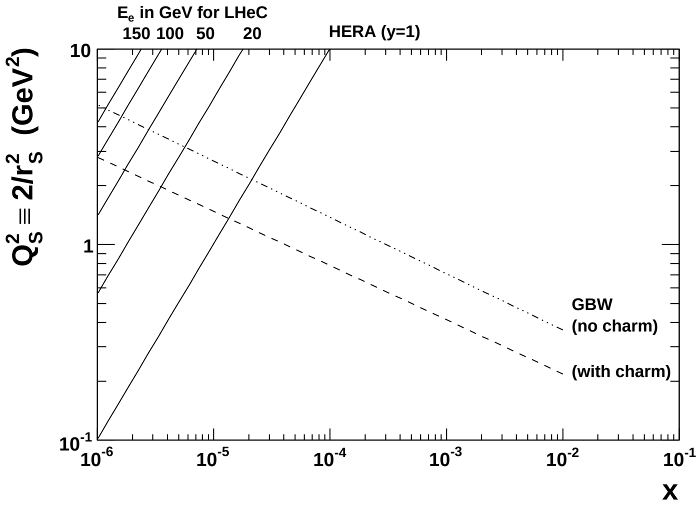
- *b-dependent dipole cross sections* crucial for successful description.

Impact-parameter dependence of total $\gamma^* p$ cross section



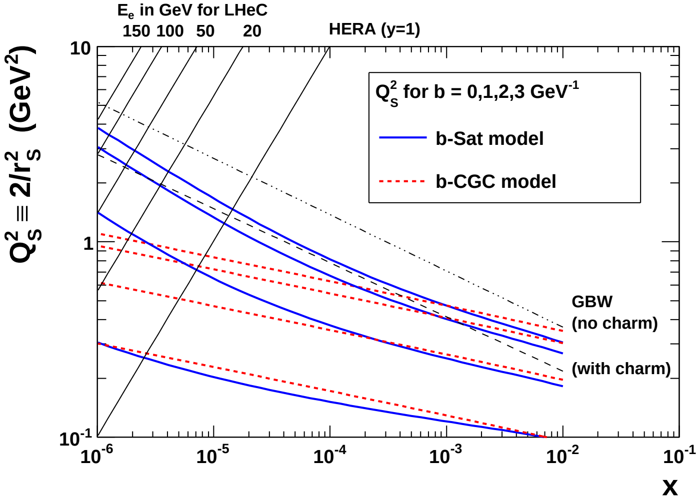
- $Q^2 = 0.4$, 4, 40 GeV^2 with $x = 10^{-4}$, 10^{-3}, 10^{-2} respectively.
- Median impact parameters b are all between 2 and 3 GeV^{-1}.

Saturation scale $Q_S^2 \equiv 2/r_S^2$ from GBW dipole model



- Define r_S as the dipole size where $\mathcal{N}(x, r_S[, b]) = 1 - \mathrm{e}^{-1/2} \simeq 0.4$.

Saturation scale $Q_S^2 \equiv 2/r_S^2$ from b-Sat and b-CGC models



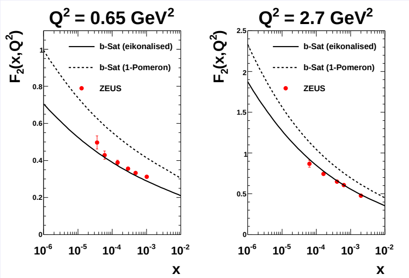
- $Q_S^2 \lesssim 0.5$ GeV^2 in HERA regime for relevant $b \sim 2$–3 GeV^{-1}.

Size of unitarity corrections for F_2 and F_L in b-Sat model

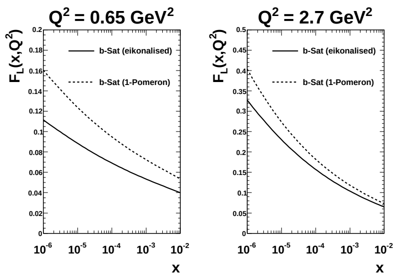
$$\mathcal{N}(x,r,b) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n!} \left[\frac{\pi^2}{2N_c} r^2 \alpha_S(\mu^2)\, xg(x,\mu^2)\, T(b)\right]^n$$

Compare "eikonalised" ($n = 1, \ldots, \infty$) with "1-Pomeron" ($n = 1$):

Proton structure function F_2



Longitudinal structure function



- Large unitarity corrections *only* at low $Q^2 \lesssim 1$ GeV^2.

Exclusive vector meson production at the LHeC

- Focus on exclusive J/ψ photoproduction ($Q^2 = 0$).
- **Hard scale** provided by charm-quark mass, $m_c = 1.4$ GeV.
- Overlap between photon and V ($= J/\psi$) wave functions:

$$(\Psi_V^*\Psi)_T = \frac{2}{3} e \, \frac{N_c}{\pi z(1-z)} \left\{ m_c^2 K_0(m_c\, r)\phi_T(r,z) - \left[z^2 + (1-z)^2\right] m_c K_1(m_c\, r)\partial_r \phi_T(r,z) \right\}$$

- Consider two alternatives for the scalar part of Ψ_V:

"Gaus-LC" [Dosch *et al.*, hep-ph/9608203; Kowalski *et al.*, hep-ph/0304189]

$$\phi_T(r,z) = N_T [z(1-z)]^2 \exp(-r^2/2R_T^2)$$

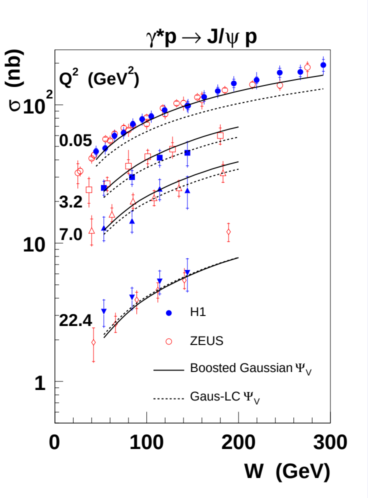
"Boosted Gaussian" [Nemchik *et al.*, hep-ph/9405355, hep-ph/9605231; Forshaw, Sandapen, Shaw, hep-ph/0312172 (set Coulomb part to zero)]

$$\phi_T(r,z) = \mathcal{N}_T z(1-z) \exp\left(-\frac{m_c^2\mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m_c^2\mathcal{R}^2}{2}\right)$$

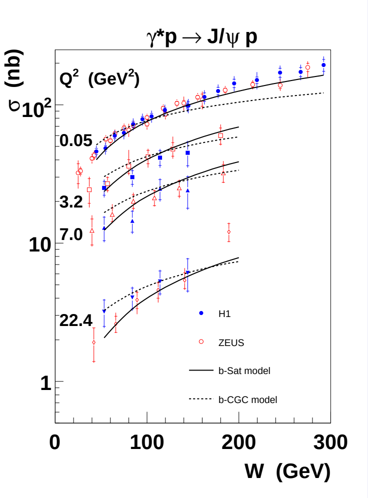
- Parameters determined by normalisation and measured $\Gamma_{V\to e^+e^-}$.

Exclusive J/ψ production at HERA

b-Sat model with different Ψ_V

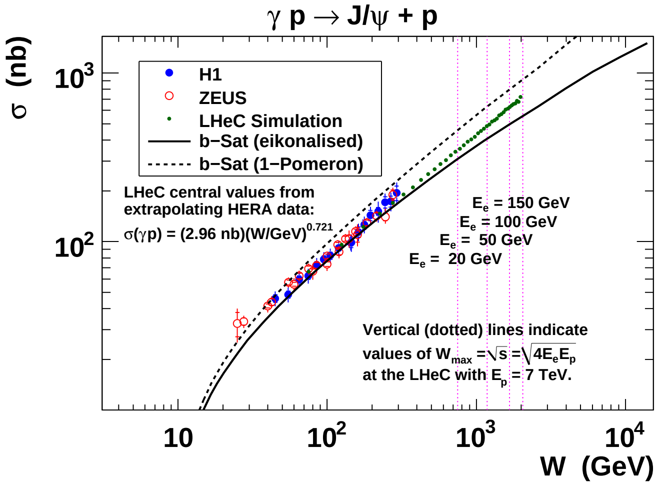


BG Ψ_V with b-Sat or b-CGC



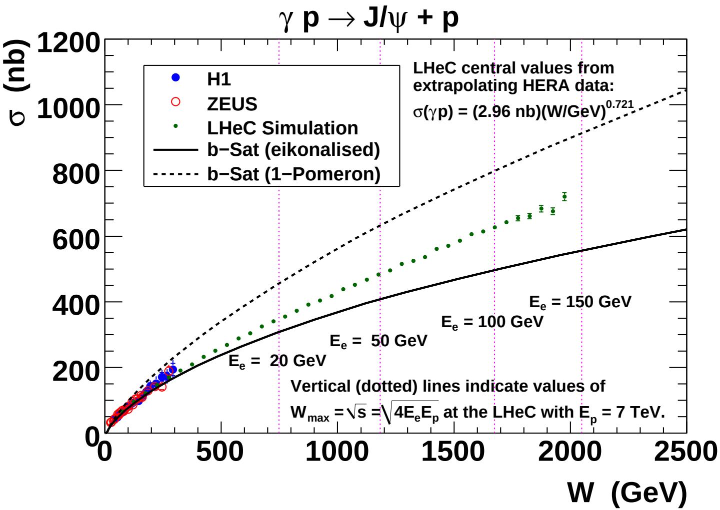
$\Rightarrow$ Use **b-Sat model** with BG Ψ_V for extrapolation to LHeC.

Extrapolation to LHeC energies for J/ψ (log–log plot)



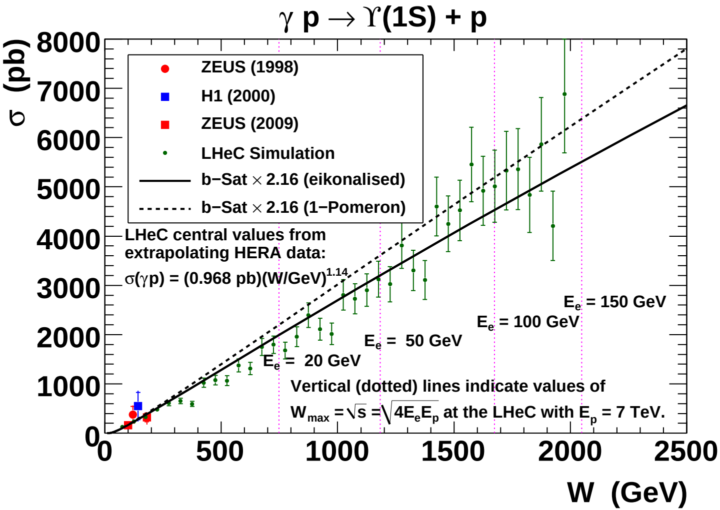
- **LHeC Simulation:** pseudo-data points with only statistical errors ($E_e = 150$ GeV, 1° angular acceptance, $L = 1\ \text{fb}^{-1}$) [P. Newman].

Extrapolation to LHeC energies for J/ψ (linear–linear plot)



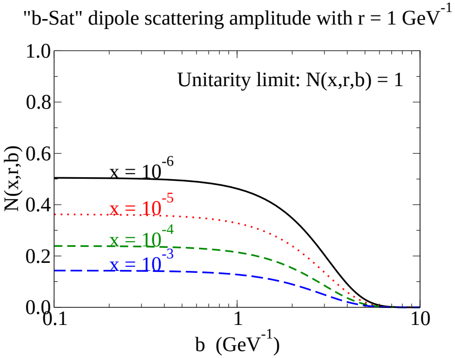
- Significant unitarity corrections with increasing energy W.

Extrapolation to LHeC energies for Υ (linear–linear plot)

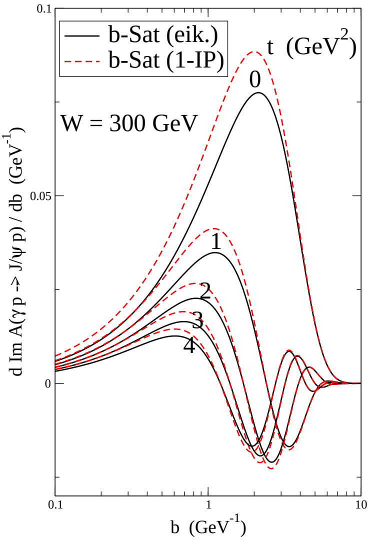


- Unitarity corrections smaller due to larger scale $m_b = 4.5$ GeV.

Probe smaller impact parameter b by going to larger $|t|$



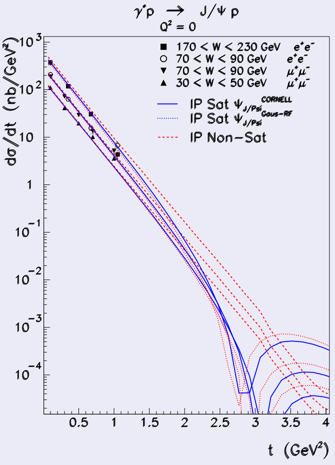
- Recall impact parameter $\vec{b}$ is Fourier conjugate variable to $\vec{\Delta}$, where $t = -|\vec{\Delta}|^2$.
- $\Rightarrow$ Central b region enhanced at large momentum transfer $|t|$.



"Diffractive dips" in elastic $\mathrm{d}\sigma/\mathrm{d}t$ at large $|t|$

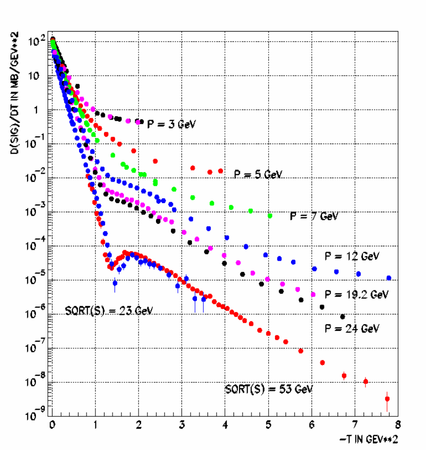
$\gamma p \to J/\psi + p$ in b-Sat

[Kowalski, Teaney, hep-ph/0304189]

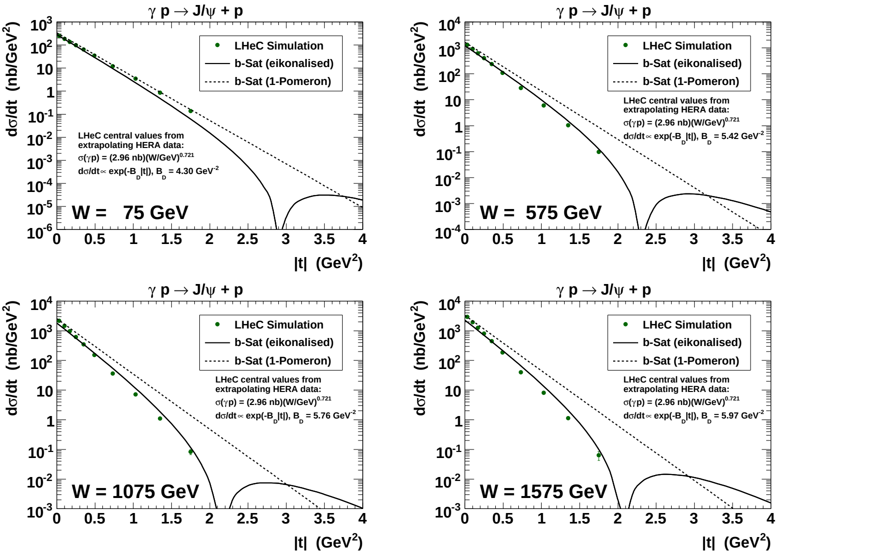


cf. pp elastic cross section data

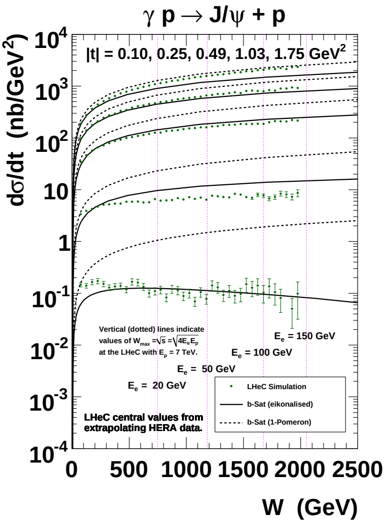
[Arneodo, Diehl, hep-ph/0511047]



"Diffractive dips" for exclusive J/ψ at the LHeC



$d\sigma/dt$ versus W for different $|t|$ at the LHeC



HERA extrapolation

- Fit both H1 and ZEUS data.
- Power-law fit of σ vs. W:
  $\sigma = (2.96\ \text{nb})(W/\text{GeV})^{0.721}$.
- Parameterise:
  $d\sigma/dt = \sigma \cdot B_D \exp(-B_D|t|)$.
- Linear fit to B_D vs. W:

$B_D = B_0 + 4\,\alpha'_{\mathbb{P}} \ln(W/90\ \text{GeV})$,
with $B_0 = 4.400\ \text{GeV}^{-2}$
and $\alpha'_{\mathbb{P}} = 0.137\ \text{GeV}^{-2}$.

- Largest $|t| = 1.75\ \text{GeV}^2$ close to the "diffractive dip" at large energies W.

Summary

Impact-parameter-dependent saturation ("b-Sat") model

- Eikonalised gluon density with DGLAP evolution.
- Inclusion of Gaussian impact-parameter dependence.
- Validated against a wide range of HERA data.
- Simple estimate of size of unitarity corrections via comparison of "eikonalised" versus "1-Pomeron" predictions.

Exclusive diffractive J/ψ photoproduction at the LHeC

- Ideal observable for investigating **unitarity effects** at a **perturbative scale** provided by the charm-quark mass.
- Extrapolation of W dependence indicates sizeable unitarity corrections at large W beyond the reach of HERA.
- Large $|t|$ provides access to *central* impact parameters b: "diffractive dips" measurable at LHeC (proton taggers)?