Exclusive J/ψ photoproduction in *ep* collisions within the dipole picture

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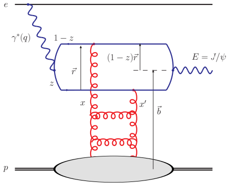
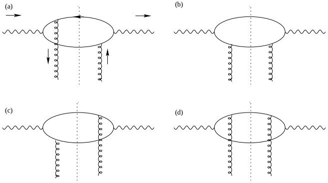


Dipole picture in the non-forward direction

[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 ($\mathbf{k} \rightarrow \mathbf{r}$), then to impact parameter space ($\mathbf{\Delta} \rightarrow \mathbf{b}$), with $t = -\Delta^2$.
- 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 $\exp[\pm \mathrm{i}(1-z)\mathbf{r}\cdot\mathbf{\Delta}/2]$.

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

Unified description of exclusive and inclusive processes

Exclusive diffractive processes

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

with corrections from the real part of the amplitude and from skewedness ($x' \ll x \ll 1$) [Shuvaev *et al.*, hep-ph/9902410].

Inclusive deep-inelastic scattering (DIS) at small x

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

Inclusive diffractive DIS [Kowalski *et al.*, arXiv:0805.4071] $\longrightarrow$ C. Marquet.

Importance of explicit impact parameter dependence

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

- Most dipole models assume a factorised b dependence:

$$\mathcal{N}(x,r,b) = T(b)\,\mathcal{N}(x,r), \quad \text{with } \mathcal{N}(x,r) \in [0,1],$$

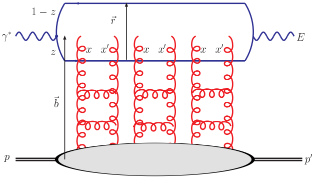
  e.g. $T(b) = \Theta(R_p - b)$, so that the b-integrated $\sigma_{q\bar{q}}$ is

$$\sigma_{q\bar{q}} = 2\int \mathrm{d}^2\mathbf{b}\,\mathcal{N}(x,r,b) = 2\int \mathrm{d}^2\mathbf{b}\;T(b)\,\mathcal{N}(x,r) = \sigma_0\,\mathcal{N}(x,r).$$

- But . . .
  1. "*Saturation scale*" is strongly dependent on impact parameter.
  2. $T(b)$ should be fixed from t-dependence of exclusive diffraction.
  3. Non-zero $\alpha'_{\mathbb{P}}$ measured at HERA $\Rightarrow$ b and x dependence correlated.

$\Rightarrow$ $\mathcal{N}(x,r,b)$ 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]

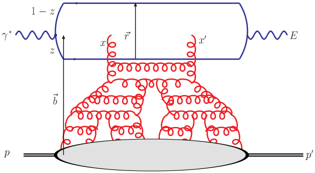
- Eikonalised DGLAP-evolved gluon density with Gaussian b dependence:

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

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

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

Impact parameter dependent CGC (b-CGC) model



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

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

- Approximate solution of the Balitsky–Kovchegov (BK) equation.
- Original colour glass condensate (CGC) model of Iancu, Itakura and Munier assumed a factorised b dependence, $\Theta(R_p - b)$.
- Introduce b dependence into the saturation scale:

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

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

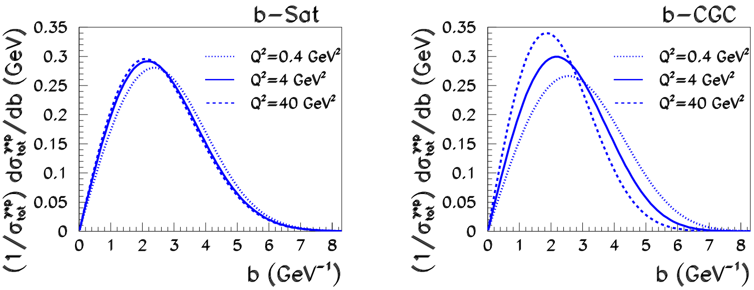
Parameters of b-CGC model [arXiv:0712.2670]

Fit to 133 ZEUS F_2 points with $x_{\rm Bj} \leq 0.01$ and $Q^2 \in [0.25, 45]$ GeV^2:

γ_s	$B_{\rm CGC}/\text{GeV}^{-2}$	$\mathcal{N}_0$	x_0	λ	χ^2/d.o.f.
0.63 (fixed)	5.5	0.417	5.95×10^{-4}	0.159	1.62
0.46	**7.5**	**0.558**	$\mathbf{1.84 \times 10^{-6}}$	**0.119**	0.92
0.43 (no sat.)	7.5	0.565	1.34×10^{-6}	0.109	0.96

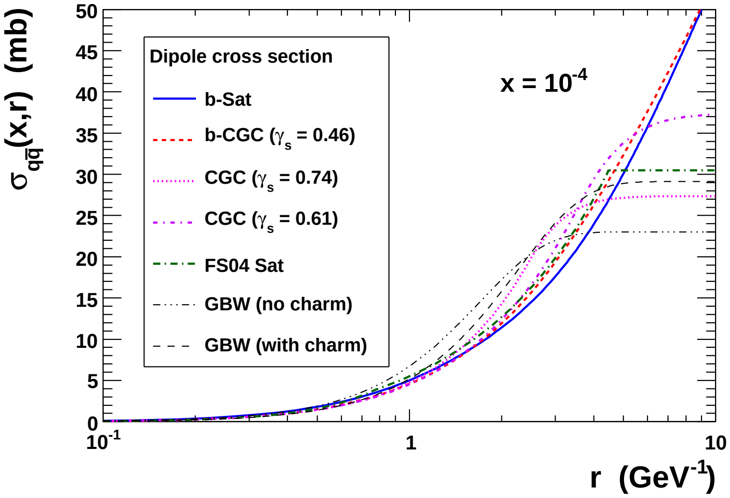
- $B_{\rm CGC}$ from t-slope of exclusive J/ψ photoproduction.
- Value of $\gamma_s = 0.63$ fixed in hep-ph/0606272, but not good χ^2.
- Value of $\gamma_s = 0.46$ close to value of 0.44 obtained from solution of BK equation [Boer, Utermann, Wessels, hep-ph/0701219].
- . . . But value of $\lambda = 0.119$ lower than $\lambda \sim 0.3$ expected from perturbative calculation [Triantafyllopoulos, hep-ph/0209121].
- "**no sat.**" model: fit without explicit unitarisation.

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

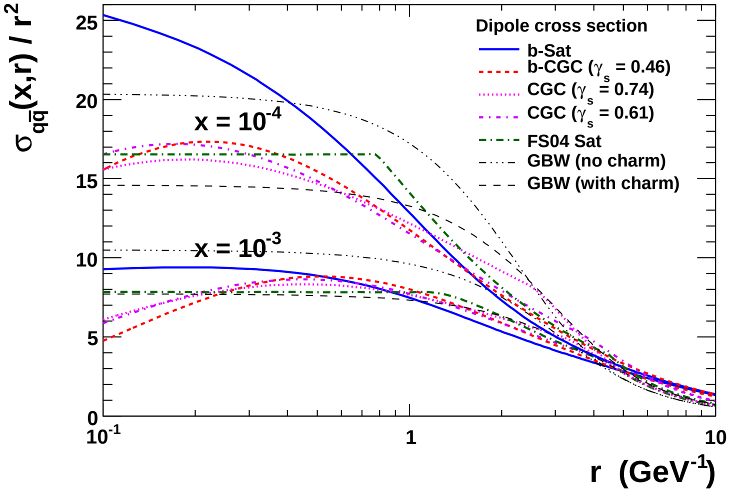


- $Q^2 = 0.4,\ 4,\ 40\ \text{GeV}^2$ with $x = 10^{-4},\ 10^{-3},\ 10^{-2}$ respectively.
- Median impact parameters are all between 2 and 3 GeV^{-1}.

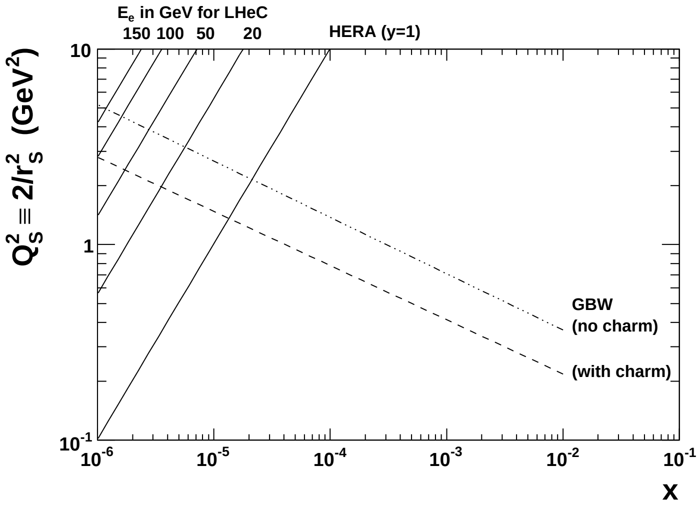
b-integrated dipole cross sections from different models



b-integrated dipole cross sections divided by r^2

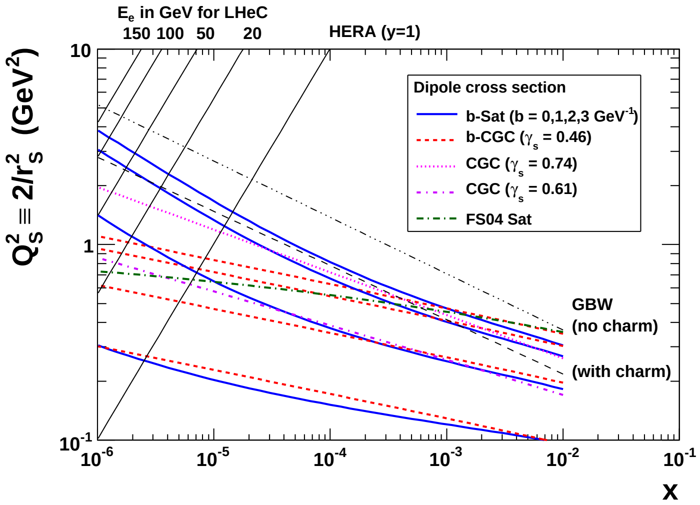


Saturation scale $Q_S^2 \equiv 2/r_S^2$ from GBW dipole model



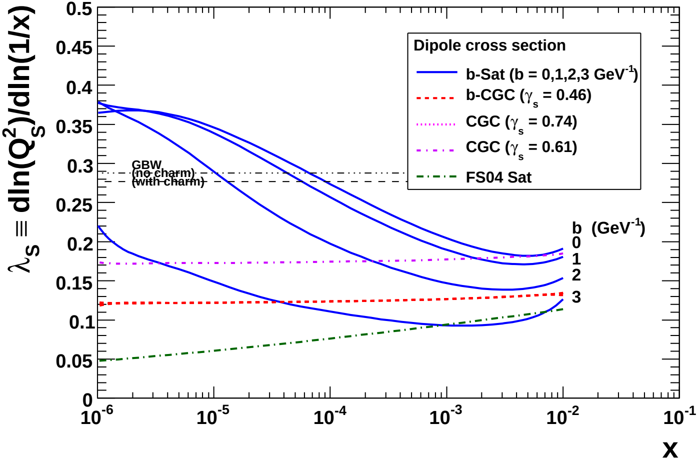
- Define r_S as the dipole size where $\mathcal{N}(x, r_S[, b]) = 1 - \mathrm{e}^{-1/2} \simeq 0.4$.

Saturation scale $Q_S^2 \equiv 2/r_S^2$ from different dipole models



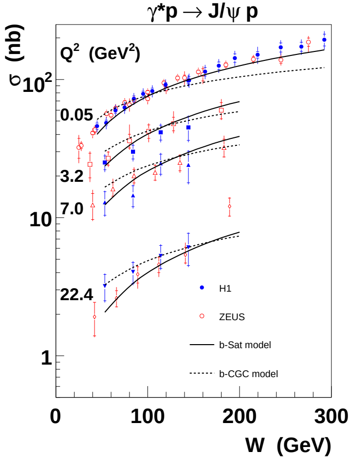
- $Q_S^2 \lesssim 0.5$ GeV^2 in HERA regime for relevant $b \sim 2$–3 GeV^{-1}.

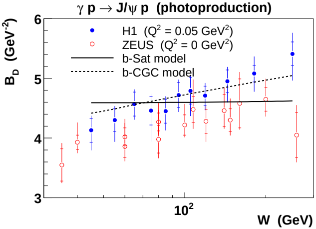
Saturation exponent $\lambda_S \equiv \partial \ln(Q_S^2)/\partial \ln(1/x)$

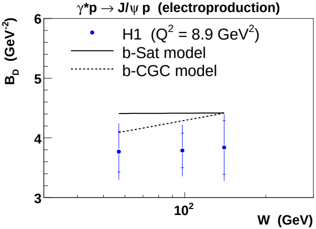


- Generally lower than perturbatively expected $\lambda_S \sim 0.3$.

Exclusive J/ψ photoproduction at HERA

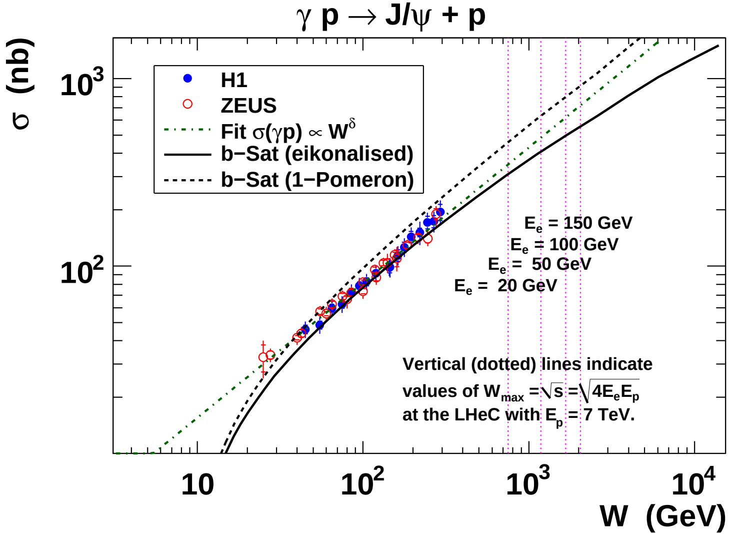




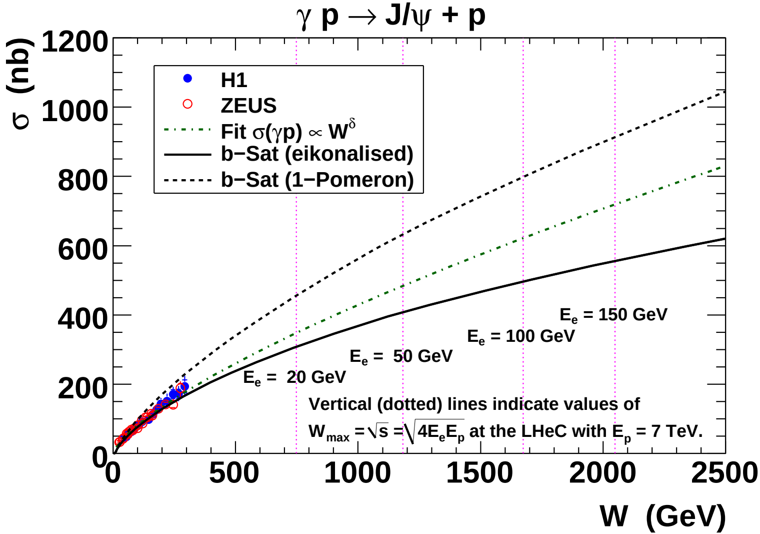


- W dependence of J/ψ photoproduction favours b-Sat model.
- Slope of B_D (t-slope) vs. W, i.e. $\alpha'_{\mathbb{P}}$, favours b-CGC model.

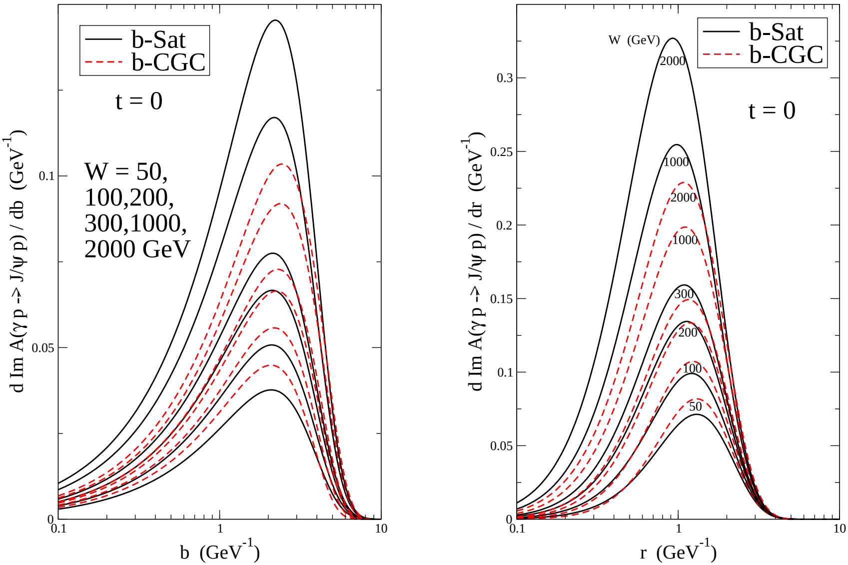
Extrapolation to LHeC energies (log–log plot)



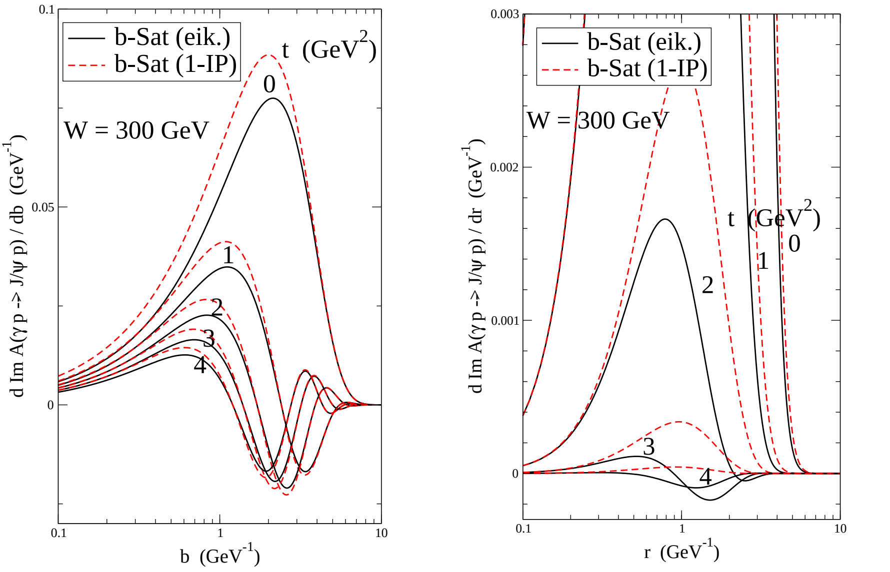
Extrapolation to LHeC energies (linear–linear plot)



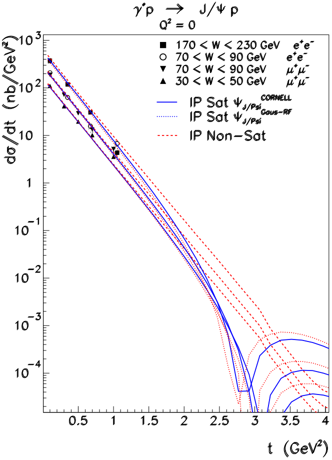
Amplitudes $\mathcal{A}(\gamma p \to J/\psi\, p)$ versus b and r for $t = 0$



Amplitudes $\mathcal{A}(\gamma p \to J/\psi\, p)$ versus b and r for $t \neq 0$

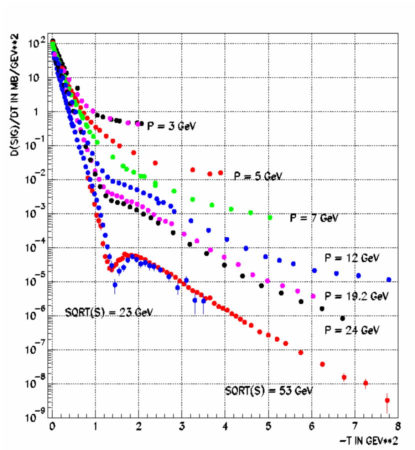


"Diffractive dips" in elastic $\mathrm{d}\sigma/\mathrm{d}t$ at large t



[Kowalski, Teaney, hep-ph/0304189]

Compilation of *pp* elastic cross section data:



[Arneodo, Diehl, hep-ph/0511047].

Summary

Impact parameter dependent dipole cross sections

b-Sat : eikonalised gluon density with DGLAP evolution.

b-CGC : improvement to the BK-inspired model of IIM.

- Consistent results for the saturation scale between the two models.

Description of exclusive diffractive processes at HERA

- Both dipole models generally give a good description of data.
- b-Sat better description of W dependence for J/ψ production.
- b-CGC better description of $\alpha'_{\mathbb{P}}$, i.e. correlation between x and b.

Exclusive diffractive J/ψ photoproduction at the LHeC

- Presented extrapolation of W dependence to LHeC energies.
- "Diffractive dips" at large $|t|$: measurable at LHeC?