

Exclusive diffractive processes within the dipole picture

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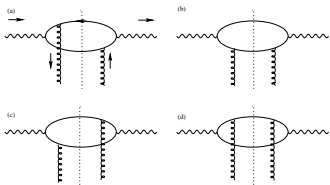
University College London

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In collaboration with H. Kowalski and L. Motyka
([hep-ph/0606272](https://arxiv.org/abs/hep-ph/0606272), [arXiv:0712.2670](https://arxiv.org/abs/0712.2670), [arXiv:0805.2113](https://arxiv.org/abs/0805.2113))

Dipole picture in the non-forward direction

Bartels, Golec-Biernat, Peters [[hep-ph/0301192](https://arxiv.org/abs/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 $\exp[\pm i(1-z)\mathbf{r} \cdot \mathbf{\Delta}/2]$.

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

Unified description of exclusive and inclusive processes

Exclusive diffractive processes

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

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

Inclusive deep-inelastic scattering (DIS) at small x

$$\begin{aligned} \sigma_{T,L}^{\gamma^* p}(x, Q) &= \text{Im} \mathcal{A}_{T,L}^{\gamma^* p \rightarrow \gamma^* p}(x, Q, \Delta = 0) \\ &= \sum_f \int d^2\mathbf{r} \int_0^1 \frac{dz}{4\pi} (\Psi^* \Psi)_{T,L}^f \int d^2\mathbf{b} \frac{d\sigma_{q\bar{q}}}{d^2\mathbf{b}} \end{aligned}$$

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

Importance of explicit impact parameter dependence

- Most dipole models assume a factorised b dependence:

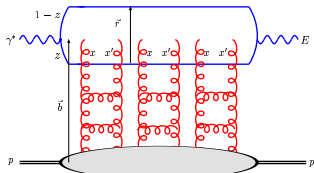
$$\mathcal{N}(x, r, b) = T(b)\mathcal{N}(x, r), \quad \text{with } \mathcal{N}(x, r) \in [0, 1],$$

so that the b -integrated dipole–proton cross section is

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

- But ...
 - ① $T(b)$ should be fixed from t -dependence of exclusive diffractive processes $\Rightarrow \sigma_0$ should **not** be an additional free parameter.
 - ② Non-zero $\alpha'_{\mathbb{P}}$ measured at HERA $\Rightarrow b$ dependence of $\mathcal{N}(x, r, b)$ is **not** independent of the x dependence.
 - ③ Saturation scale is strongly dependent on impact parameter.
- Determine $\mathcal{N}(x, r, b)$ 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](#)]

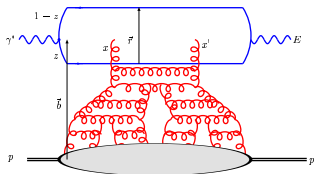
- DGLAP-evolved gluon density with Gaussian b dependence:

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

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

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

Impact parameter dependent CGC (b-CGC) model



Iancu, Itakura, Munier [[hep-ph/0310338](https://arxiv.org/abs/hep-ph/0310338)]

→ Kowalski, Motyka, G.W. [[hep-ph/0606272](https://arxiv.org/abs/hep-ph/0606272)]

→ G.W. [[arXiv:0712.2670](https://arxiv.org/abs/0712.2670)]

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

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

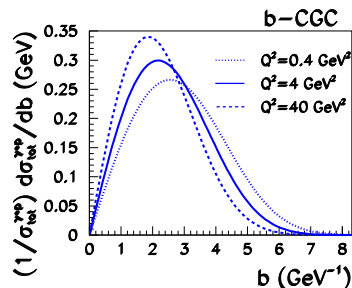
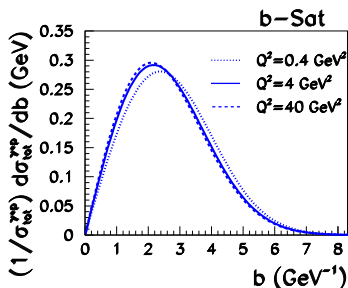
$$Q_s \equiv Q_s(x, b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \left[\exp\left(-\frac{b^2}{2B_{\text{CGC}}}\right) \right]^{\frac{1}{2\gamma_s}}$$

Parameters of b-CGC model

Fit to 133 ZEUS F_2 points with $x_{Bj} \leq 0.01$ and $Q^2 \in [0.25, 45]$ GeV²:

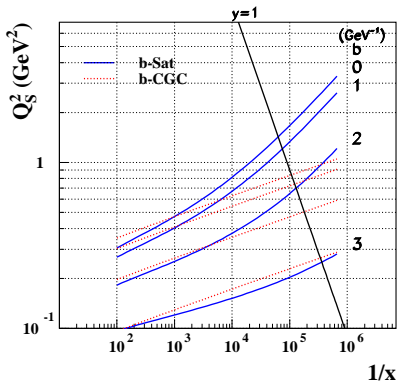
γ_s	B_{CGC}/GeV^{-2}	\mathcal{N}_0	x_0	λ	$\chi^2/\text{d.o.f.}$
0.63 (fixed)	5.5	0.417	5.95×10^{-4}	0.159	1.62
0.46	7.5	0.558	1.84×10^{-6}	0.119	0.92
0.43 (no sat.)	7.5	0.565	1.34×10^{-6}	0.109	0.96

- B_{CGC} from t -slope of exclusive J/ψ photoproduction.
- Value of $\gamma_s = 0.46$ close to value of 0.44 obtained from numerical 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](#)].

Impact parameter dependence of total γ^*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} .

Saturation scale Q_S^2 from different dipole models

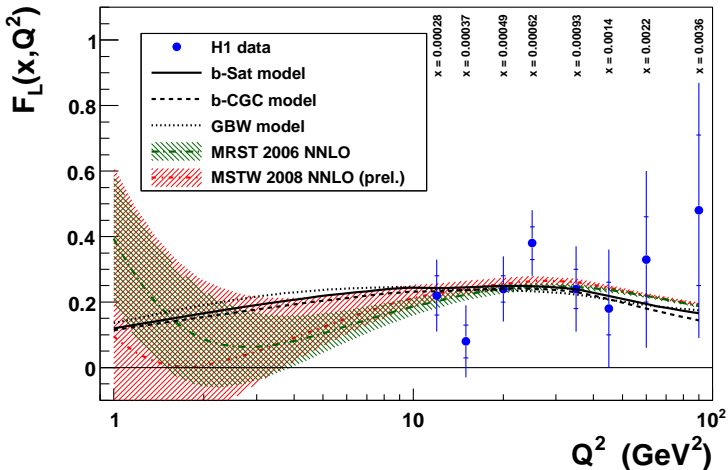


- HERA kinematic limit:
 $y \simeq Q_S^2 / (4E_e E_p x) = 1$.

- Define **saturation scale**
 $Q_S^2 \equiv 2/r_S^2$, where r_S is the dipole size where

$$\mathcal{N}(x, r_S, b) = 1 - e^{-1/2} \simeq 0.4.$$

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

Description of longitudinal structure function $F_L(x, Q^2)$ 

- H1 F_L data from [arXiv:0805.2809](https://arxiv.org/abs/0805.2809).

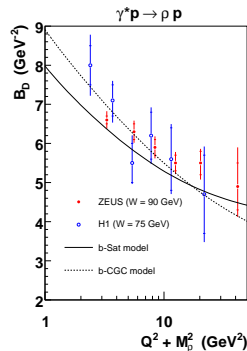
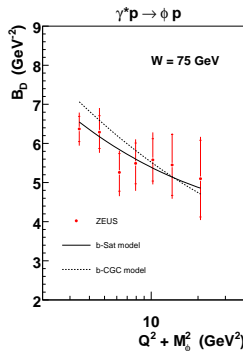
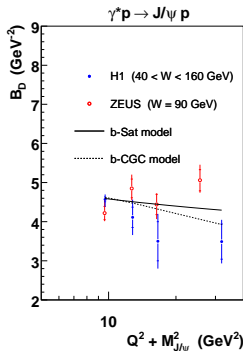
Predictions for exclusive diffraction at HERA

- Confront **b-Sat** and **b-CGC** model predictions with wealth of HERA data on exclusive diffractive vector meson production (J/ψ , ϕ , ρ) and deeply virtual Compton scattering (DVCS).

	ZEUS	H1
J/ψ	hep-ex/0201043 , hep-ex/0404008	hep-ex/0510016 .
ϕ	hep-ex/0504010	—
ρ	arXiv:0708.1478	hep-ex/9902019
DVCS	hep-ex/0305028 , ZEUS-prel-07-016	hep-ex/0505061 , arXiv:0709.4114

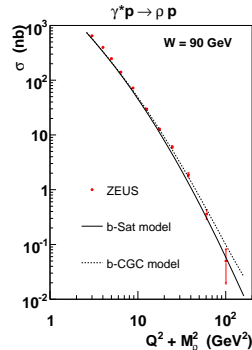
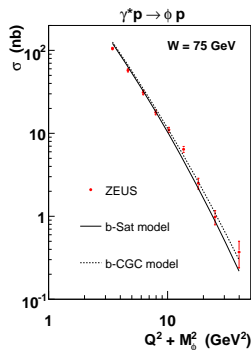
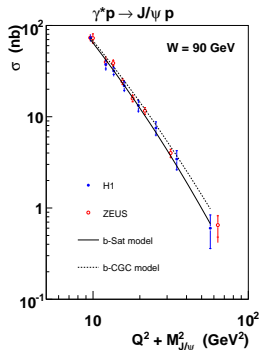
- Significant challenge to simultaneously describe all aspects of the Q^2 , W and t dependence.
- Use a “boosted Gaussian” vector meson wave function: see [hep-ph/0606272](#) for details. Different wave functions mostly affect overall normalisation and ratio of σ_L/σ_T .

Q^2 dependence of B_D , where $d\sigma/dt \propto \exp(-B_D|t|)$



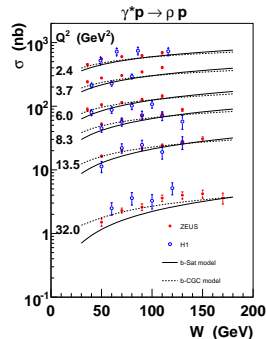
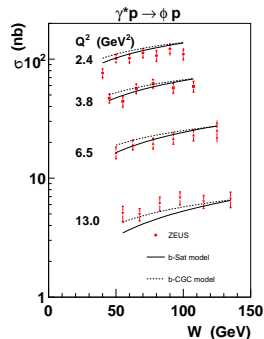
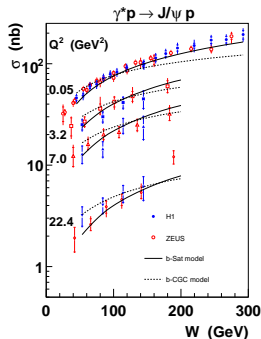
- Recall only **one** free parameter fixed from B_D for J/ψ photoproduction (which also gives normalisation of the b -integrated dipole cross section).
- Factor $\exp[i(1-z)\mathbf{r} \cdot \mathbf{\Delta}]$ from non-forward wave functions mainly responsible for dependence of B_D on Q^2 and M_V^2 .

Q^2 dependence of vector meson cross sections



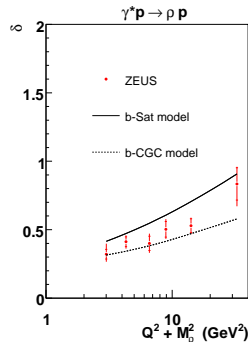
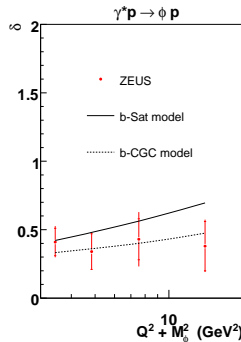
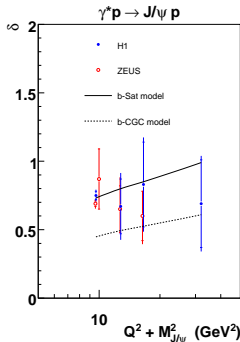
- Both dipole models describe the data well in both shape and normalisation.

W dependence of vector meson cross sections



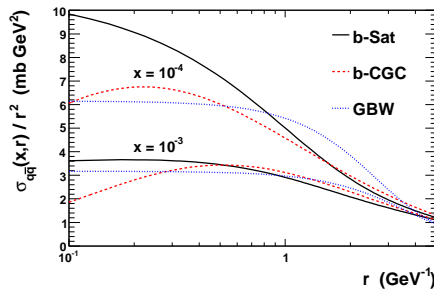
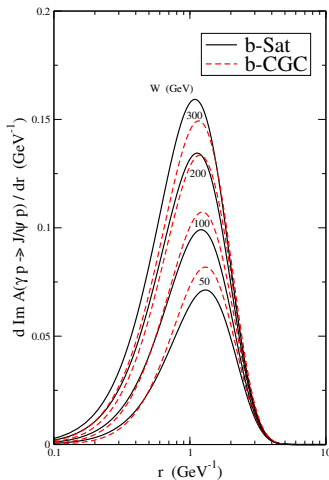
- W dependence of J/ψ photoproduction favours b-Sat model.

Q^2 dependence of δ , where $\sigma \propto W^\delta$



- W dependence of J/ψ photoproduction favours b-Sat model.

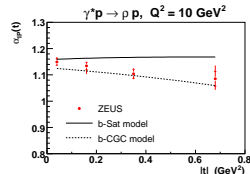
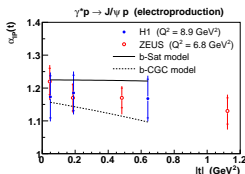
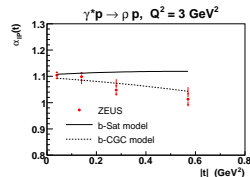
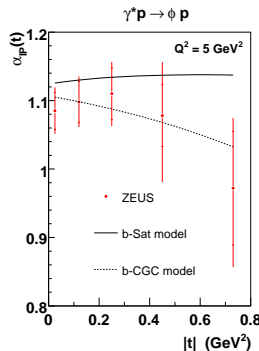
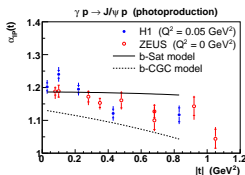
W dependence sensitive to details of dipole cross section



- Relatively small differences between b-Sat and b-CGC dipole cross sections around $r \sim 1 \text{ GeV}^{-1}$, but J/ψ data can discriminate.

Effective Pomeron trajectories: $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$

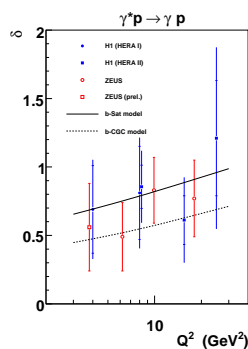
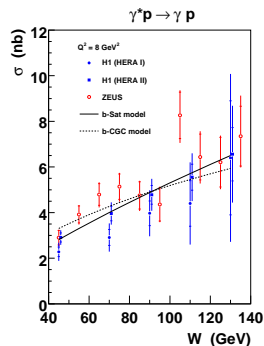
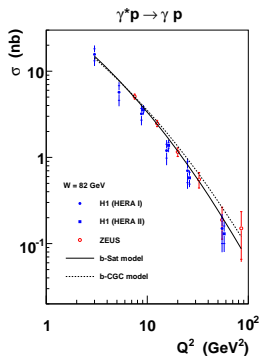
- Determine $\alpha_{\mathbb{P}}(t)$ by fitting $d\sigma/dt \propto W^4[\alpha_{\mathbb{P}}(t)-1]$.



- Interplay between x and b better modelled in b-CGC model
 \Rightarrow better agreement of $\alpha'_{\mathbb{P}}$ with data.

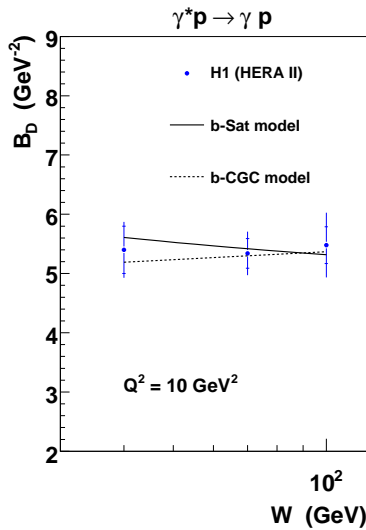
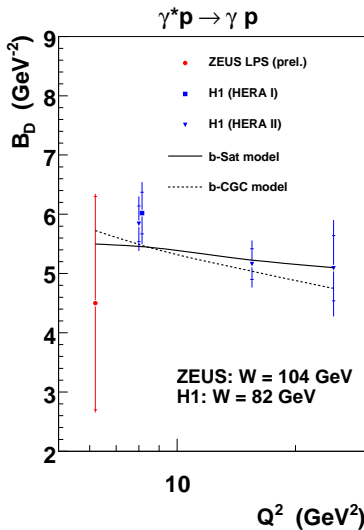
Deeply virtual Compton scattering (DVCS): $\gamma^* p \rightarrow \gamma p$

- DVCS theoretically cleaner than vector meson production since no uncertainty from wave function.



- Data not yet precise enough to distinguish different W dependence of the two models.

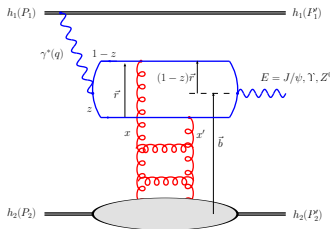
B_D vs. Q^2 and W for DVCS, where $d\sigma/dt \propto \exp(-B_D|t|)$



Exclusive photoproduction in hadron–hadron collisions

Motyka, G.W. [arXiv:0805.2113]

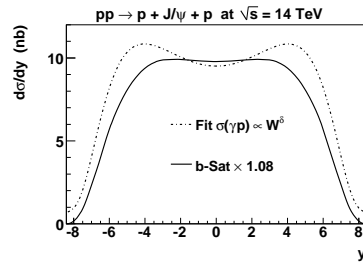
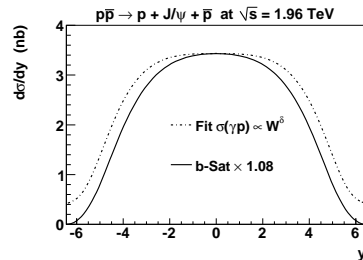
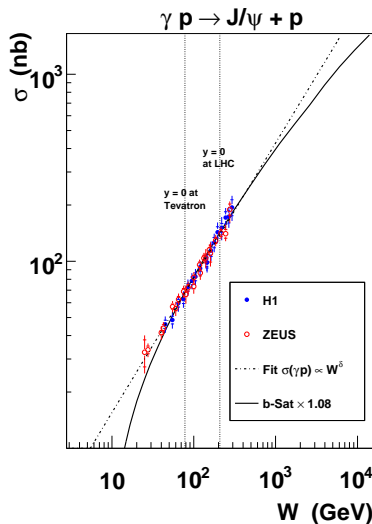
- Exclusive final state
 $E = J/\psi, \Upsilon, Z^0$ with rapidity y .
- Flux dn/dk of quasi-real photons with energy
 $k \simeq (M_E/2) \exp(y) \simeq W^2/(2\sqrt{s})$, following Klein and Nystrand [hep-ph/0311164].



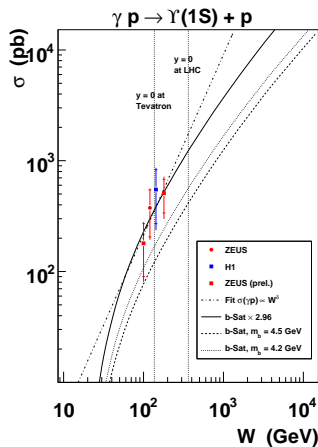
$$\frac{d\sigma}{dy}(h_1 h_2 \rightarrow h_1 + E + h_2) = k \frac{dn}{dk} \sigma(\gamma p \rightarrow E + p) + (y \rightarrow -y)$$

Disclaimer

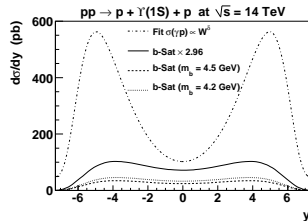
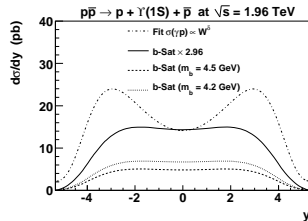
- Neglect interference between photon–Pomeron and Pomeron–photon fusion, and effect of absorptive corrections from soft rescattering.
- Only present cross sections integrated over final state momenta, then these effects will be largely washed out. (Rapidity gap survival factor $S^2 \sim 0.7\text{--}0.9$.)

Exclusive J/ψ photoproduction at Tevatron and LHC

Exclusive Υ photoproduction at Tevatron and LHC



- Uncertainty in m_b and Ψ_Υ
 \Rightarrow Scale to HERA data.



- Sensitive to W dependence of γp cross section.

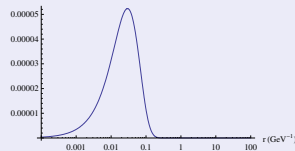
Wave functions for exclusive Z^0 photoproduction

- Exclusive Z^0 photoproduction ($\gamma p \rightarrow Z^0 + p$) at the Tevatron and LHC is a potentially interesting process: cross section estimates requested by [M. Albrow](#).
- Wave functions for an incoming Z^0 with **space-like** virtuality $q^2 = -Q^2 < 0$ are known from application of the dipole model to charged-current DIS [[Fiore, Zoller, hep-ph/0509097](#)].
- For an outgoing Z^0 , or for time-like Compton scattering ($\gamma p \rightarrow \gamma^* + p$), need to generalise the dipole picture to the **time-like** case ($q^2 = M^2 > 0$).
- Amplitude for $\gamma p \rightarrow Z^0 + p$ is **not** simply the DVCS amplitude at $Q^2 = M_Z^2$ with a different coupling.
- Pick up **real** contribution to the amplitude related to contribution of an on-shell $q\bar{q}$ pair in addition to the usual imaginary part.

Technical aside: tricky r integration in Z^0 amplitude

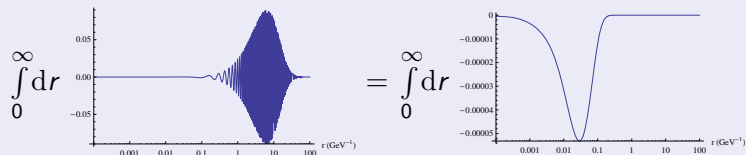
Space-like case (incorrect, \sim DVCS at $Q^2 = M_Z^2$)

Plot imaginary part of d quark contribution to $\gamma p \rightarrow Z^0 + p$ amplitude for $z = 0.5$, $t = 0$, $x = M_Z/\sqrt{s}$ at LHC ($y = 0$).



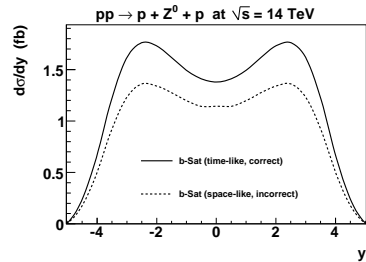
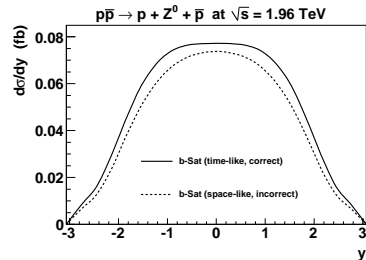
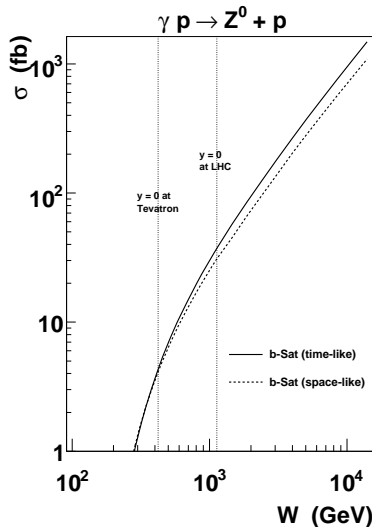
Time-like case (correct): highly oscillatory integrand

Use contour integration $\Rightarrow \int_0^\infty dr f(r) = \int_0^\infty dr i f(ir)$



After z integration, $|\text{Im } \mathcal{A}|$ only $\sim 3\%$ greater than in space-like case. But also significant $\text{Re } \mathcal{A} \sim 40\% \text{ Im } \mathcal{A}$.

Exclusive Z^0 photoproduction at Tevatron and LHC



Summary of predictions for J/ψ , Υ and Z^0 production

J/ψ	$d\sigma/dy _{y=0}$ (nb)	σ (nb)	Event rate (s^{-1})
Tevatron	3.4	28	0.33
LHC	9.8	120	71

$\Upsilon(1S)$	$d\sigma/dy _{y=0}$ (pb)	σ (pb)	Event rate (hr^{-1})
Tevatron	14	115	2.0
LHC	72	1060	946

Z^0	$d\sigma/dy _{y=0}$ (fb)	σ (fb)	Event rate (yr^{-1})
Tevatron	0.077	0.30	0.065
LHC	1.4	13	135

- Event rates include leptonic branching ratio and assume a luminosity $\mathcal{L} = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ (Tevatron) and $\mathcal{L} = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (LHC). No gap survival factor included.

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 .

Extension to Tevatron and LHC

- Predictions given for rapidity distributions of exclusive photoproduced J/ψ , Υ and Z^0 expected at the Tevatron and LHC.