Exclusive diffractive processes within the dipole picture

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(`hep-ph/0606272`, `arXiv:0712.2670`, + work in progress)

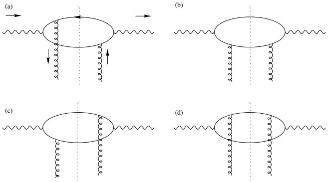
Introduction

- **NLO corrections** to exclusive meson production are huge at small x within the collinear factorisation framework [Diehl, Kugler, `arXiv:0708.1121`].
- Power corrections due to the **transverse momentum** of the partons entering the hard scattering are known to be important. Small-x resummation needed.
- These effects are partially included in the $\mathbf{k_t}$ **factorisation** approach or the related **colour dipole picture**.
- Colour dipole picture is phenomenologically successful, although not yet worked out beyond LO.

$$\boxed{\mathcal{A}(\gamma^* p \to Vp) \sim \text{(photon wave function)} \cdot \text{(dipole cross section)} \cdot \text{(meson wave function)}}$$

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

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

Unified description of exclusive and inclusive processes

Exclusive diffractive processes

$$\frac{\mathrm{d}\sigma_{T,L}^{\gamma^* p\to Ep}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right|^2 \left(1+\tan^2\left(\frac{\pi\lambda}{2}\right)\right), \ \lambda \equiv \frac{\partial \ln\left(\mathcal{A}_{T,L}^{\gamma^* p\to Ep}\right)}{\partial \ln(1/x)}$$

Also include skewness factor ($x' \ll x \ll 1$) according to Shuvaev *et al.* [hep-ph/9902410]: crucial to get the right normalisation.

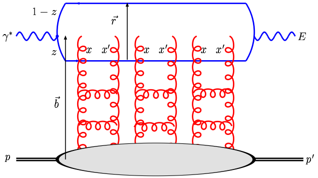
Inclusive deep-inelastic scattering at small x

$$\sigma_{T,L}^{\gamma^* p}(x,Q) = \mathrm{Im}\,\mathcal{A}_{T,L}^{\gamma^* p\to\gamma^* p}(x,Q,\Delta=0)$$

$$= \sum_f \int \mathrm{d}^2\mathbf{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} (\Psi^*\Psi)_{T,L}^f \int \mathrm{d}^2\mathbf{b}\, \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}^2\mathbf{b}}$$

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

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]

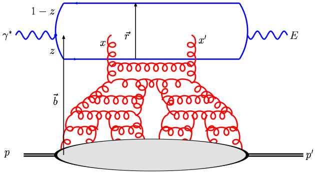
- DGLAP-evolved gluon density with Gaussian *b* dependence:

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

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

- $B_G = 4$ 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 [hep-ph/0310338]
→ Kowalski, Motyka, G.W. [hep-ph/0606272]
→ G. Soyez [arXiv:0705.3672]
→ G.W. [arXiv:0712.2670]

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

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

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

Parameters of b-CGC model

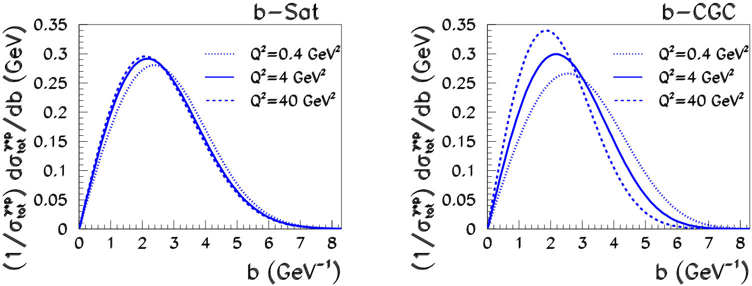
Fit to 133 ZEUS F_2 points with $x_{\rm Bj} \leq 0.01$ and $Q^2 \in [0.25, 45]$ GeV^2:

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

- Value of $\gamma_s = 0.46$ close to value 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`].
- Consider also original CGC model with factorised b dependence:

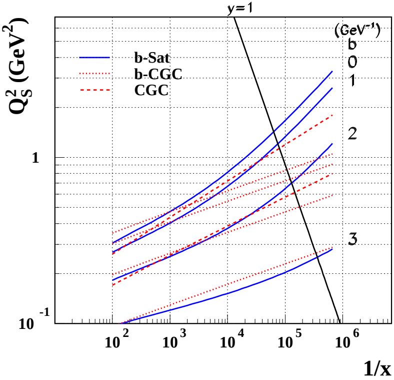
γ_s	σ_0/mb	x_0	λ	$\chi^2/\text{d.o.f.}$
0.74	27.4	1.63×10^{-5}	0.216	0.86
0.61	37.4	1.09×10^{-7}	0.170	0.89
0.44 (fixed)	46.3	2.21×10^{-11}	0.122	1.39

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 values of b are all between 2 and 3 GeV^{-1}.

Saturation scale Q_S^2 from different dipole models



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

$$\mathcal{N} = 1 - \mathrm{e}^{-1/2} \simeq 0.4.$$

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

- Recall both CGC solutions ($\gamma_s = 0.74, 0.61$) have similar χ^2. Solution with lower Q_S^2 more consistent with b-CGC result at some average b. Not strong evidence for CGC solution with higher Q_S^2 favoured by G. Soyez [`arXiv:0705.3672`, and talk at DIS 2008].

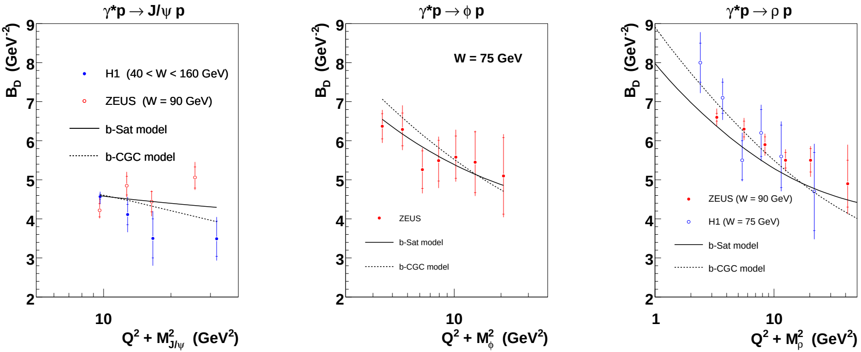
Predictions for exclusive diffraction at HERA

- 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`

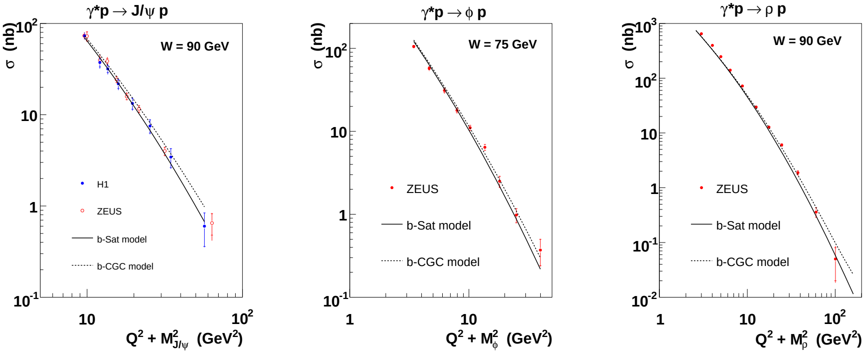
- Significant challenge to simultaneously describe all aspects of the Q^2, W and t dependence.
- Use a "boosted Gaussian" [Forshaw, Sandapen, Shaw, `hep-ph/0312172`] vector meson wave function: see `hep-ph/0606272` for details. Different wave functions mostly affect overall normalisation and ratio of σ_L/σ_T.

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



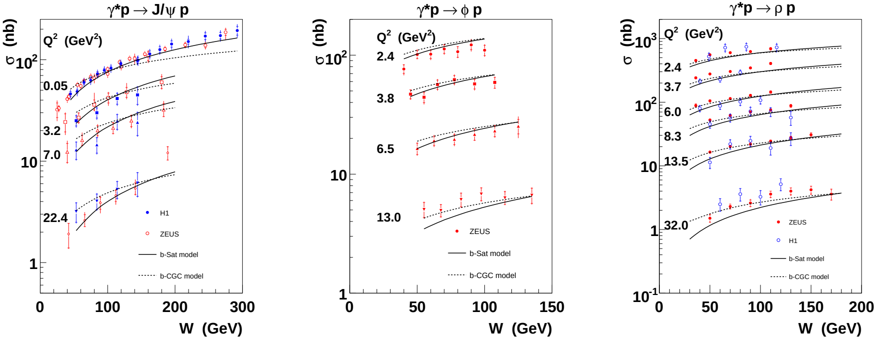
- Recall only **one** free parameter fixed from B_D for J/ψ photoproduction (which also gives normalisation of the b-integrated dipole cross section).
- Factor $\exp[\mathrm{i}(1-z)\mathbf{r}\cdot\mathbf{\Delta}]$ from non-forward wave functions mainly responsible for dependence of B_D on Q^2 and M_V^2.

Q^2 dependence of vector meson cross sections



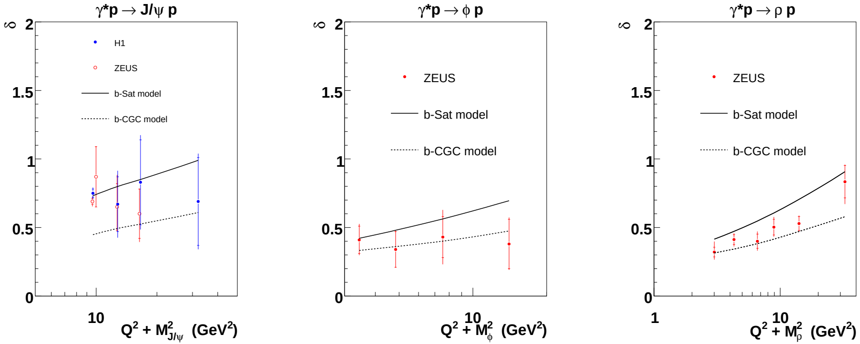
- Both dipole models describe the data well in both shape and normalisation.

W dependence of vector meson cross sections



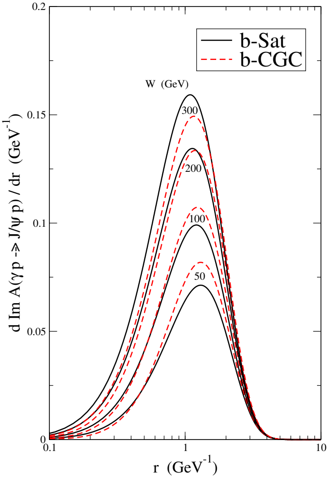
- W dependence of J/ψ photoproduction favours b-Sat model.

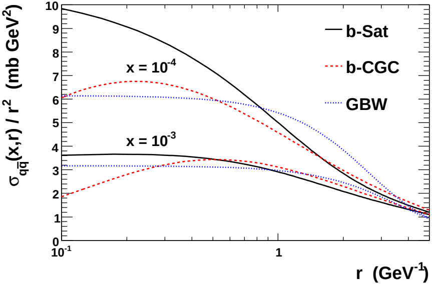
Q^2 dependence of δ, where $\sigma \propto W^\delta$



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

W dependence sensitive to details of dipole cross section

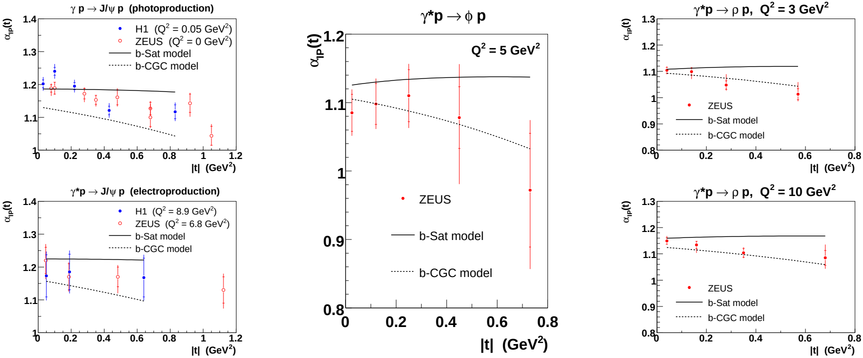




- Relatively small differences between b-Sat and b-CGC dipole cross sections around $r \sim 1$ GeV^{-1}, but J/ψ data can discriminate.

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

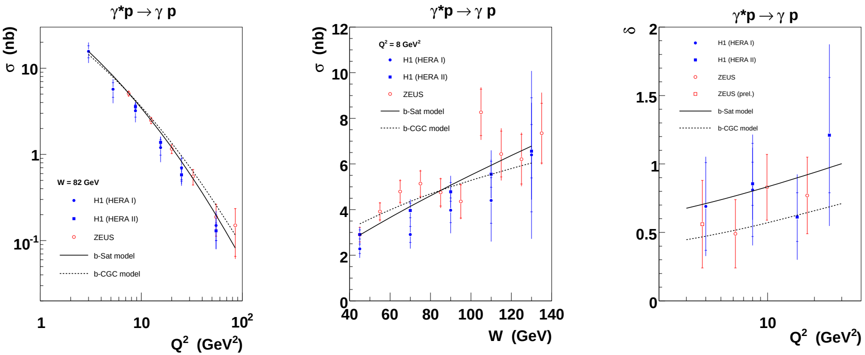
- Determine $\alpha_{\mathbb{P}}(t)$ by fitting $\mathrm{d}\sigma/\mathrm{d}t \propto W^{4[\alpha_{\mathbb{P}}(t)-1]}$.



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

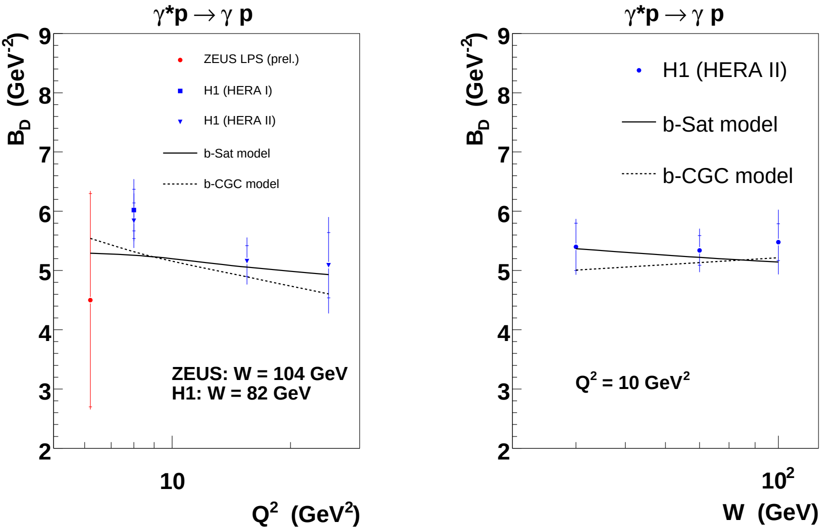
Deeply virtual Compton scattering (DVCS): $\gamma^* p \longrightarrow \gamma p$

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

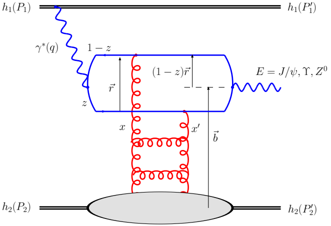


- Data not precise enough to distinguish different *W* dependence of the two models.

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



Exclusive photoproduction in hadron–hadron collisions



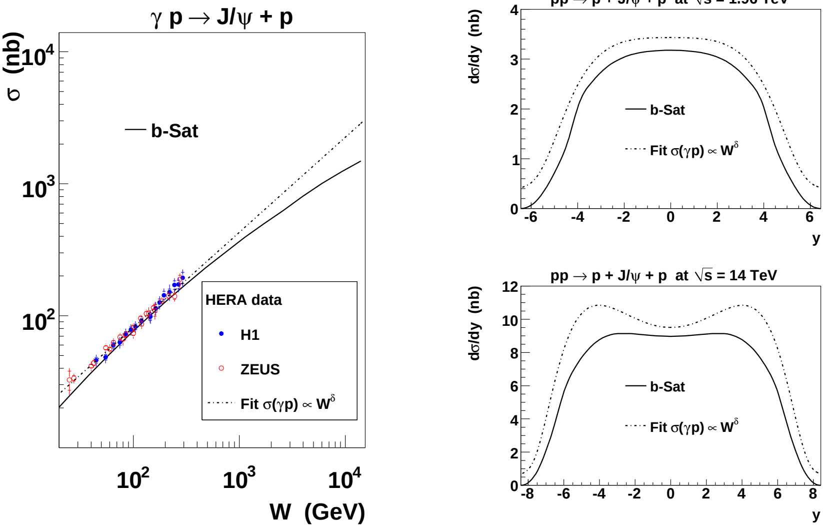
- Follow Klein and Nystrand [hep-ph/0311164].
- Exclusive final state $E = J/\psi, \Upsilon, Z^0$ with rapidity y.
- Flux $\mathrm{d}n/\mathrm{d}k$ of quasi-real photons with energy $k \simeq (M_E/2)\exp(y)$.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(h_1 h_2 \to h_1 + E + h_2) = k\frac{\mathrm{d}n}{\mathrm{d}k}\sigma(\gamma p \to E + p) \quad + \quad (y \leftrightarrow -y)$$

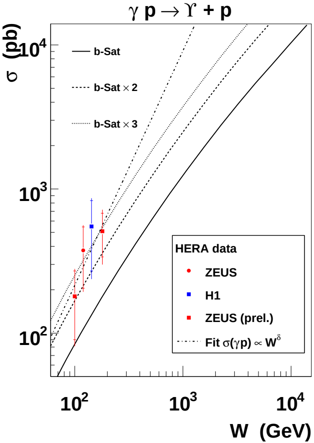
Disclaimer

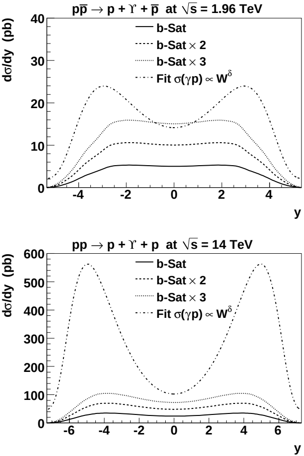
- Neglect interference between photon–Pomeron and Pomeron–photon fusion, and effect of absorptive corrections from soft rescattering.
- Only present cross sections integrated over final state momenta, then these effects will be largely washed out. (Rapidity gap survival factor $S^2 \sim 0.8$–1.0.)
- Detailed treatment of these effects by Khoze, Martin and Ryskin [hep-ph/0201301] (and also by Schäfer and Szczurek [arXiv:0705.2887]).

Exclusive J/ψ photoproduction at Tevatron and LHC



Exclusive Υ photoproduction at Tevatron and LHC





- Uncertainty in m_b and Ψ_Υ $\Rightarrow$ Scale by a factor 2–3.
- Sensitive to W dependence of γp cross section.

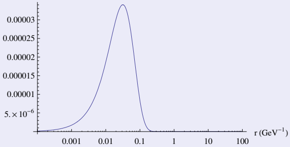
Wave functions for exclusive Z^0 photoproduction

- Wave functions for an incoming Z^0 with **spacelike** 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, need to generalise the dipole picture to the **timelike** case ($q^2 = M^2 > 0$). Wave functions for $q\bar{q} \to Z^0/\gamma^*$ have been derived by L. Motyka.
- Amplitude for $\gamma p \to Z^0 + p$ 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

Spacelike case (incorrect, $\sim$ DVCS at $Q^2 = M_Z^2$)

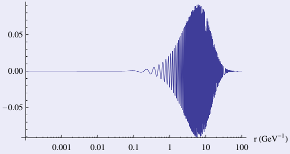
Plot imaginary part of d quark contribution to $\gamma p \to Z^0 + p$ amplitude for $z = 0.5$, $t = 0$, $x = M_Z/\sqrt{s}$ at LHC ($y = 0$).



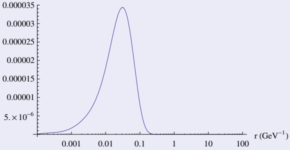
Timelike case (correct): highly oscillatory integrand

Use contour integration $\Rightarrow \int_0^\infty \mathrm{d}r\, f(r) = \int_0^\infty \mathrm{d}r\, \mathrm{i}\, f(\mathrm{i}r)$

$$\int_0^\infty \mathrm{d}r$$

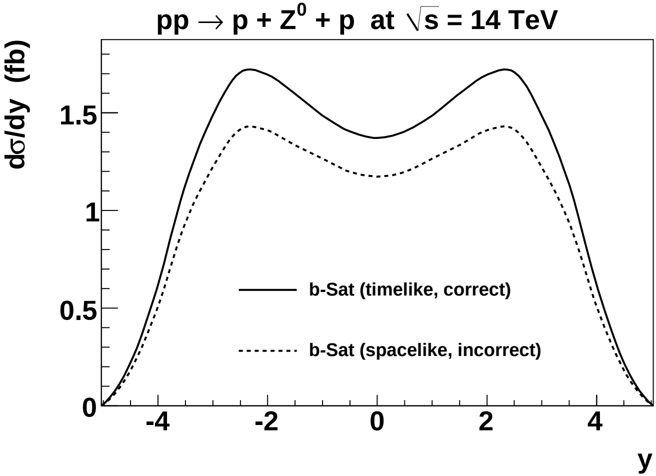


$$= \int_0^\infty \mathrm{d}r$$



After z integration, $\mathrm{Im}\,\mathcal{A}$ only $\sim$ 5% greater than in spacelike case.
But also significant $\mathrm{Re}\,\mathcal{A} \sim 30\%\ \mathrm{Im}\,\mathcal{A}$.

Exclusive Z^0 rapidity distribution at LHC



- $\sim$ 20% difference between timelike and spacelike formulae.

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

$\mathrm{d}\sigma/\mathrm{d}y$ at $y=0$	J/ψ (nb)	Υ (pb)	Z^0 (fb)
Tevatron	3.2	5.0	0.12
LHC	9.0	24	1.4

σ	J/ψ (nb)	Υ (pb)	Z^0 (fb)
Tevatron	27	40	0.39
LHC	112	173	12

Event rate	J/ψ (s^{-1})	Υ (hr^{-1})	Z^0 (yr^{-1})
Tevatron	0.31	0.71	0.084
LHC	66	320	130

- Event rates include leptonic branching ratio and assume a luminosity $\mathcal{L} = 2\times10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Tevatron) and $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (LHC).

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

- Preliminary predictions given for total rates of exclusive J/ψ, Υ and Z^0 photoproduction expected at the Tevatron and LHC.