Opportunities with diffraction

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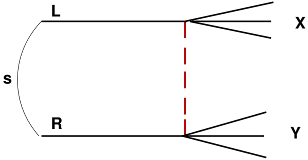
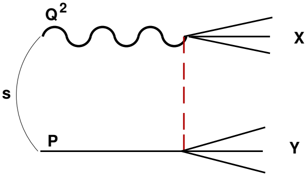
Plan

- Diffraction and the pomeron
- Hera perspective
- Exclusive diffractive processes - from Hera to LHC
- Shock wave approach to diffraction



- $s \gg |t|,\ m_X^2,\ m_Y^2$
- single diffraction SD
- double dissociation DD
- vacuum quantum number exchange



- DIS: $s \gg Q^2, |t|,\ m_p^2$
- semihard process

$$\Lambda_{QCD} \ll Q^2 \ll s \quad => \quad x = \frac{Q^2}{s} \ll 1$$

- perturbative QCD applicable

Diffraction and pomeron

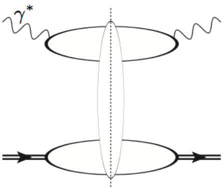
- Diffraction is about the structure of pomeron - vacuum quantum number exchange.
- Regge theory - soft pomeron trajectory with intercept above one

$$\alpha(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t = 1.08 + (0.25\,\mathrm{GeV}^{-2}) \cdot t$$

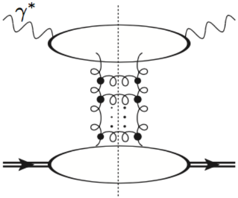
  Gives asymptotic behaviour when $s \to \infty$

$$A(s,t) \sim i\beta(t)\, s^{\alpha(t)} \qquad => \qquad \sigma_{\rm tot} \sim s^{\alpha_{I\!P}(0)-1}$$

- QCD - two gluon color singlet exchange, BFKL pomeron - $\alpha_{I\!P}(0) = 1.3$



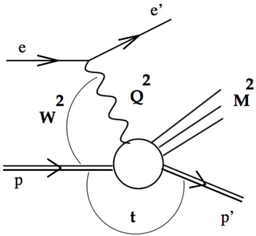
Regge theory



BFKL

Diffraction at HERA

- Large rapidity gaps in DIS



- pomeron momentum fraction

$$x_{IP} = \frac{Q^2 + M^2}{Q^2 + W^2} \ll 1$$

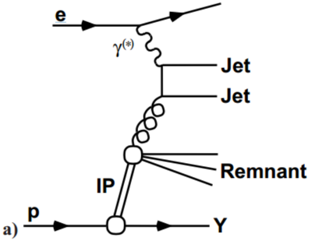
- Diffractive structure functions

$$F^D_{2,L}(x, Q^2; x_{IP}, t)$$

- More exclusive measurements, e.g. dijets, vector mesons, heavy quarks, γ

Soft pomeron exchange

- Collinear factorization approach



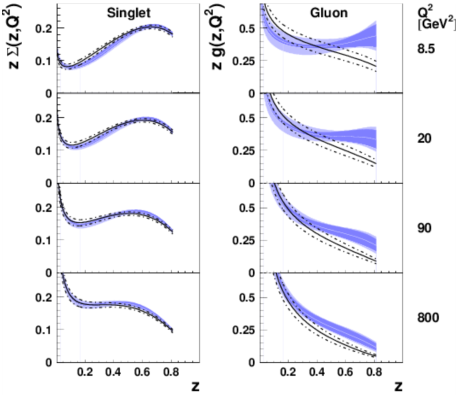
- Soft pomeron with partonic structure - Ingelman-Schlein model ('80)

$$F_2^D = f_{I\!P}(x_{I\!P}, t) \sum_q \beta \left\{ q_{I\!P}(\beta, Q^2) + \overline{q}_{I\!P}(\beta, Q^2) \right\}$$

- $\beta = x/x_{I\!P}$ is a pomeron momentum fraction carried by a parton.
- Pomeron flux $f_{I\!P} \sim x_{I\!P}^{1-2\alpha_{I\!P}(t)}$ and pomeron PDFs $\{q_{I\!P}, \overline{q}_{I\!P}, g\}$

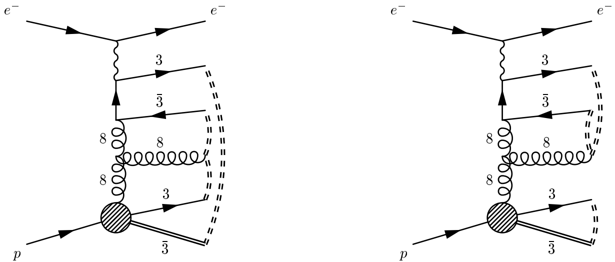
Pomeron PDFs

- Pomeron PDFs evolved with DGLAP equations fitted to diffractive data.



- Pomeron is gluon dominated (in comparison to normal PDFs).

- Soft gluon exchanges neutralize color but do not change momenta.
  (A. Edin, G. Ingelman, J. Rathsman, Phys.Lett. B366 (1996) 371)



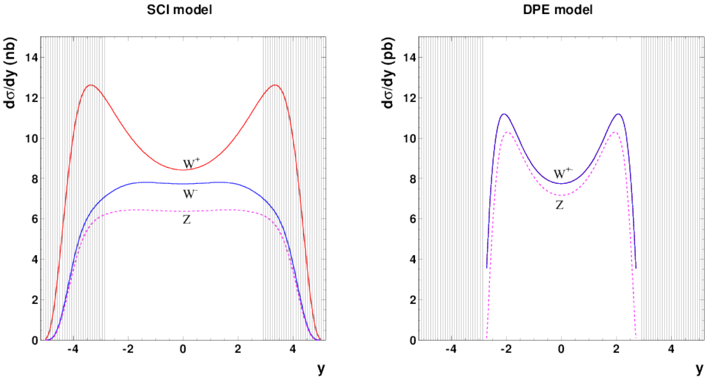
- To check this mechanism studying $W^{\pm}$ production asymmetry in rapidity

$$A(y) = \frac{d\sigma_{W^+} - d\sigma_{W^-}}{d\sigma_{W^+} + d\sigma_{W^-}}$$

(KGB, C. Royon, L. Schoeffel, R. Staszewski, Phys.Rev. D84 (2011) 114006)

Diffractive $W^{\pm}$ production asymmetry

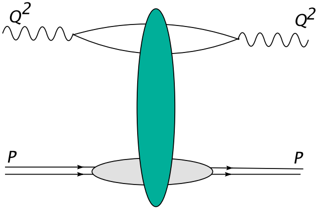
- In LO $W^{\pm}$ from fusion of two quarks ($u\overline{d}$ or $d\overline{u}$)
- In SCI model quarks from the proton - asymmetry $A(y) \neq 0$
- Quark distributions in the pomeron are flavour blind - $A(y) = 0$



- Study also the ratio $R = \sigma_{W^{\pm}}/\sigma_Z$.

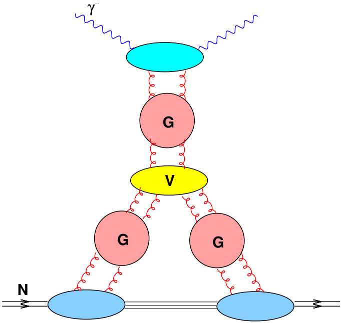
BFKL pomeron and its unitarization

- DIS at small x (high energy) can be viewed as a quark dipole interaction.



- Two gluons – $\sigma_{\gamma^* p} \sim const$
- BFKL pomeron – $\sigma_{\gamma^* p} \sim x^{-0.3}$
- Unitarized pomeron – $\sigma_{\gamma^* p} \sim \ln(1/x)$

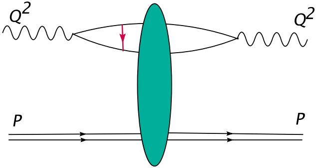
Approaches to unitarization



- Color dipoles of Mueller and Kovchegov
- Shock wave approach of Balitstky
- Color Glass Condensate and McLerran and Venugopalan
- QCD reggeon field theory of Bartels and Lipatov

Saturation model

- A quark dipole of transverse size r interacting with the proton



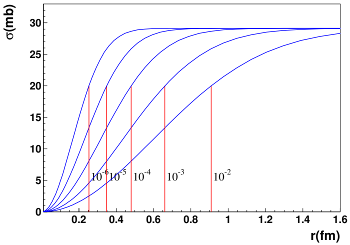
- Dipole cross section with saturation scale $Q_s \sim 1\ \mathrm{GeV}$ in perturb. domain

$$\hat{\sigma}_{dip}(r,x) = \sigma_0 \left\{ 1 - \exp(-r^2 Q_s^2(x)) \right\} \qquad Q_s(x) = Q_0\, x^{-\lambda}$$

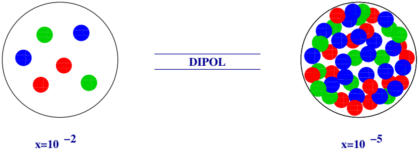
- Red parameters fitted DIS data on F_2 for $x \leq 10^{-2}$

$$F_2(x,Q^2) \sim \int d^2r\, |\Psi_{\gamma^* \to q\bar{q}}(r,Q^2))|^2\ \hat{\sigma}_{dip}(r,x)$$

(KGB, M. Wüsthoff, PRD 59 (1998) 014023)



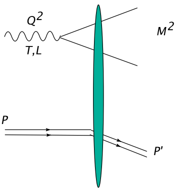
- For a given dipole size cross section saturates when $x \to 0$

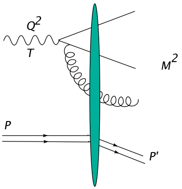


- Parton saturation confirmed by the Balitsky-Kovchegov equation.

  (I. Balitsky, Nucl.Phys. B463 (1996) 99; Y. Kovchegov, PRD 60 (1999) 034008)

Saturation in diffraction

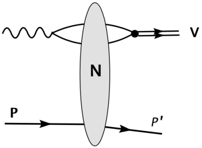




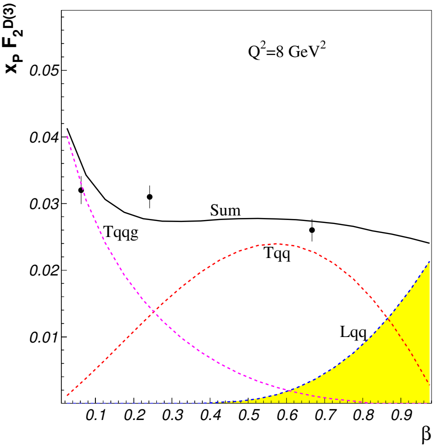
- Two diffractive states: $q\bar{q}$ and $q\bar{q}g$ interacting with $\hat{\sigma}_{dip} = \int d^2b\, N(b)$

$$F_2^D = F_T^{q\bar{q}} + F_L^{q\bar{q}} + F_T^{q\bar{q}g}$$

- Can also be applied to diffractive vector meson production

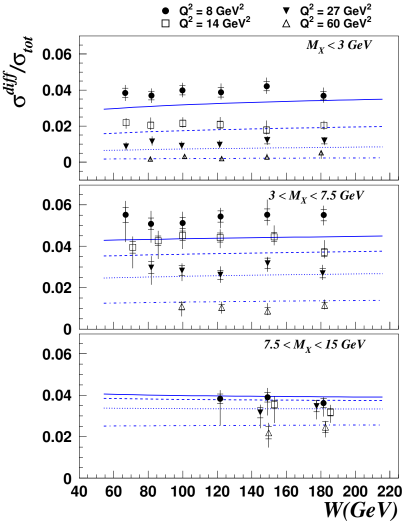


Comparison with HERA diffractive data



- The three contributions to diffractive structure function.
- $F_L^{q\overline{q}}$ is higher twist which dominates for $\beta = \frac{Q^2}{Q^2+M^2} \to 1$.

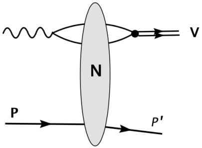
Constant ratio $\sigma_{diff}/\sigma_{\gamma^* p}$



- Explained by the saturation model (KGB, M. Wüsthoff, PRD 60 (1999) 114023)

Vector meson production

(H. Kowalski, L. Motyka, G. Watt, PRD 74 (2006) 074016)



- Scattering amplitude

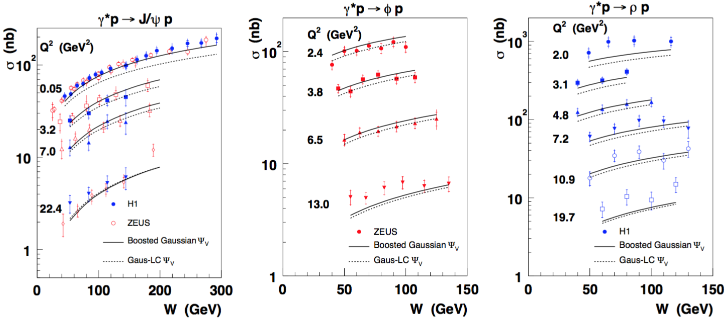
$$A(\gamma + p \to V + p) = (\Psi_V)^* \otimes N_{dip}(x, r, b) \otimes \Psi_\gamma$$

- New element - impact parameter b (or t) dependence
- Improved dipole scattering amplitude

$$N(x, r, b) = 1 - \exp\{-r^2 Q_s(x, b)\}$$

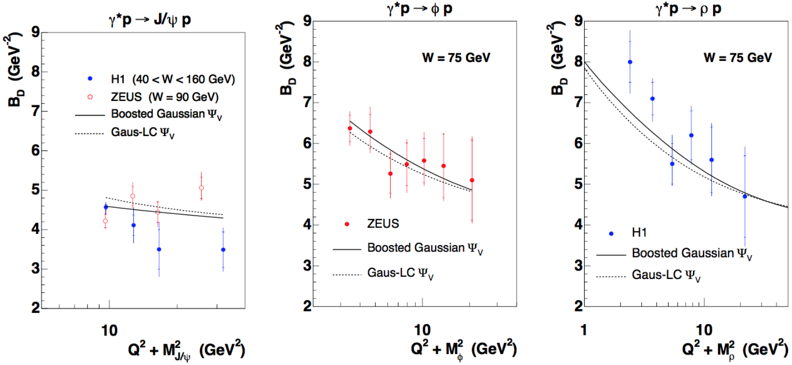
- b-dependent saturation scale Q_s ($b-$CGC model)

VM production - energy dependence



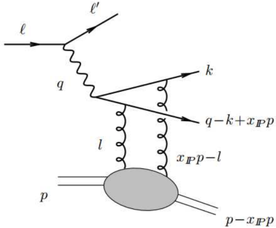
- Change of energy dependence with VM and Q^2 and a slight dependence on the choice of the VM wave function.

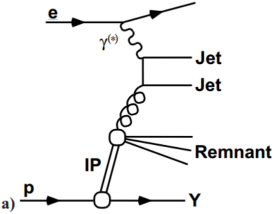
VM production - t dependence



- Eikonal form of dipole scattering amplitude with saturation scale $Q_S(x, b)$ crucial for these results.

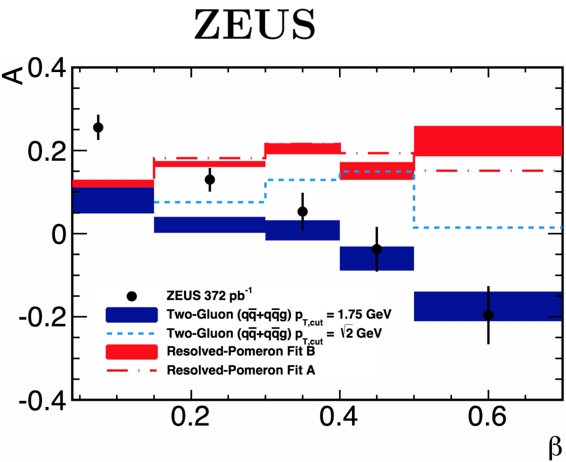
Exclusive diffractive dijet production





- Two gluon exchange in k_T-factorization versus collinear approach (Bartels, Ewertz, Lotter, Wüsthoff,Jung,...)
- Look at azimuthal dependence:

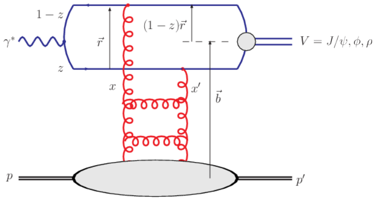
$$\frac{d\sigma}{d\phi} \sim (1 + A\cos\phi)$$



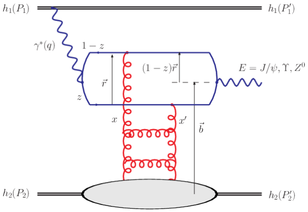
- Two gluon exchange model works better then resolved pomeron model.

LHC perspective

- Such processes can also be measured at the LHC in *pp*, *pA* or ultraperipheral *AA* collisions.



ep



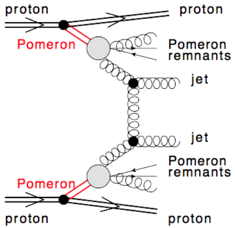
pp, *pA*, *AA*

- Details of the description in *ep* collisions transferred to hadronic collisions.

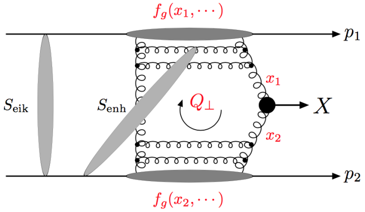
Central diffractive production production at the LHC

(LHC forward physics, J.Phys. G43 (2016) 110201, arXiv:1611.05079 [hep-ph])

- Program to build very forward detectors to tag protons at small angles



Double pomeron exchange

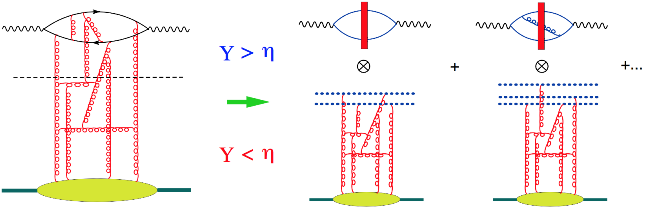


Central exclusive production

- Absorptive factors which reduce cross sections are important - gap survival factors.

Systematic studies within shock wave approach

(I. Balistky, Nucl.Phys. B463 (1996) 99)



- At high energy particles move along straight lines - Wilson lines

$$\hat{U}(x_\perp) = \exp\left\{ ig \int_{-\infty}^{\infty} dx^+ \hat{A}^-(x^+, x_\perp) \right\}$$

- High energy scattering amplitude with factorization parameter η

$$\mathcal{A}(s) = \int d^2x_\perp d^2y_\perp \underbrace{I_A(x_\perp, y_\perp; \eta)}_{Impact\ \ factor} \langle B | \underbrace{\mathrm{Tr}[\hat{U}_\eta(x_\perp)\hat{U}_\eta^\dagger(y_\perp)]}_{dipole\ \ operator} - N_c | B \rangle$$

Balitsky-Kovchegov equation

- Balitsky-JIMWLK equations evolve dipole operators into multidipoles

$$\frac{\partial \hat{U}^{\eta}_{12}}{\partial \eta} = \frac{\alpha_s N_c}{2\pi^2} \int d^2\vec{z}_3 \, \frac{\vec{z}^{\,2}_{12}}{\vec{z}^{\,2}_{13}\,\vec{z}^{\,2}_{32}} \left\{ \hat{U}^{\eta}_{13} + \hat{U}^{\eta}_{32} - \hat{U}^{\eta}_{12} \; - \hat{U}^{\eta}_{13}\,\hat{U}^{\eta}_{32} \right\}$$

$$\frac{\partial \hat{U}^{\eta}_{13}\,\hat{U}^{\eta}_{32}}{\partial \eta} = \ldots$$

- Kovchegov equation for dipole operator only in large N_c limit

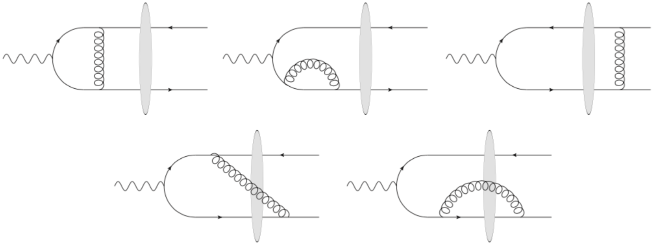
$$\frac{\partial \langle \hat{U}^{\eta}_{12} \rangle}{\partial \eta} = \frac{\alpha_s N_c}{2\pi^2} \int d^2\vec{z}_3 \, \frac{\vec{z}^{\,2}_{12}}{\vec{z}^{\,2}_{13}\,\vec{z}^{\,2}_{32}} \left\{ \langle \hat{U}^{\eta}_{13} \rangle + \langle \hat{U}^{\eta}_{32} \rangle - \langle \hat{U}^{\eta}_{12} \rangle \; - \langle \hat{U}^{\eta}_{13} \rangle \langle \hat{U}^{\eta}_{32} \rangle \right\}$$

BFKL/BKP eq. saturation

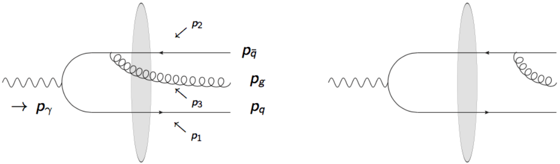
$q\bar{q}g$ impact factors in NLO approximation

(R. Boussarie, A. V. Grabovsky, S. Wallon, L. Szymanowski, D. Yu. Ivanov, JHEP 409 (2014) 026, JHEP 1611 (2016) 149, arXiv:1612.08026 [hep-ph])

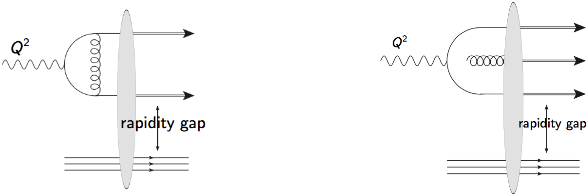
- NLO $q\bar{q}$ production graphs



- plus LO real gluon emission

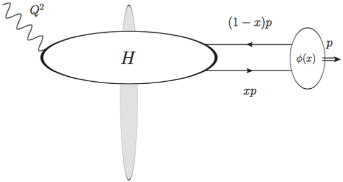


Application to diffractive production



- exclusive diffractive dijet electroproduction with merged gluon using jet cone algorithm
- exclusive diffractive dijet photoproduction ($Q^2 = 0$) with jet $k_\perp$ or M_J as hard scale
- non-exclusive diffractive dijet production - trijet production
- photoproduction of open charm or charmonium production

- Exclusive diffractive production of light vector mesons: $\gamma^* p \to \rho p$



- Additional collinear factorization with distribution amplitude $\phi_{||}(x)$

$$\mathcal{A} = \int_0^1 dx\, H(x, \ldots) \times \phi_{||}(x, \mu)\,, \qquad \mu = Q^2, |t|$$

- Amplitude infrared finite for both longitudinal and transverse photons, and also in photoproduction limit (no end point sigularity).

Summary

- Diffractive processes with a hard scale probe the QCD nature of the pomeron:
    - resolved pomeron
    - BFKL pomeron
    - parton saturation as unitarization mechanism.
- VM production supports saturation mechanism.
- Natural applications to *pp*, *pA* and ultraperipheral *AA* collisions
- Shock wave approximation program is theoretically sound and promissing.