NLO impact factor for diffractive dijet production in DIS in the shockwave formalism

Renaud BOUSSARIE
renaud.boussarie@th.u-psud.fr

Laboratoire de Physique Théorique, Université Paris-Sud XI, Orsay

DIS 2016, DESY Hamburg

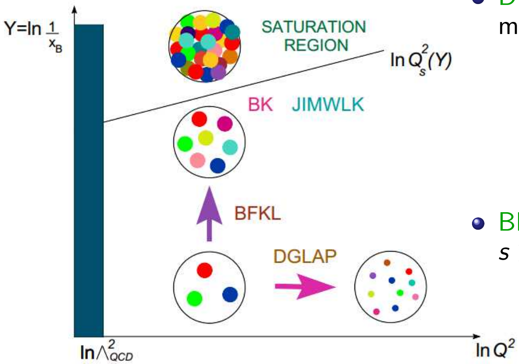
RB, A.Grabovsky, L.Szymanowski, S.Wallon

Paper in redaction. See JHEP 409 (2014) 026 (arXiv:1405.7676) 1512.00774[hep-ph] 1511.02785[hep-ph] and 1503.01782[hep-ph] for previews

Overview

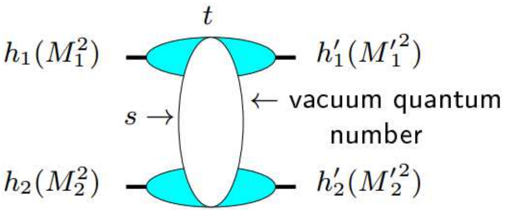
1. DGLAP regime vs BFKL regime
2. Diffractive DIS
   - Rapidity gap events at HERA
   - Collinear factorization approach
   - k_T-factorization approach : two exchanged gluons
   - Confrontation of the two approaches with HERA data
3. Diffractive production of jets : our approach
   - Leading Order Impact Factor
   - NLO Impact Factor : Virtual Corrections

Two regimes of perturbative QCD



- DGLAP dynamics : $Q^2 \to \infty$ moderate x_B
  - Governed by collinear dynamics
  - Resummation of Q^2 logs : $(\alpha_s \ln Q^2)^n$, $\alpha_s(\alpha_s \ln Q^2)^n$...
- BFKL dynamics (Regge limit) $s \gg Q^2 \gg \Lambda_{QCD}$ ($x_B \ll 1$)
  - Governed by soft dynamics
  - Resummation of $\frac{1}{x_B} \sim s$ logs : $(\alpha_s \ln s)^n$, $\alpha_s(\alpha_s \ln s)^n$...

BFKL dynamics



$$\sigma = \frac{1}{s}\mathrm{Im}\mathcal{A} \sim s^{\alpha(0)-1}$$

$$\alpha(0) - 1 = C\alpha_s$$

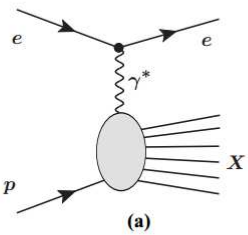
$$C > 0$$

$\Rightarrow$ Violation of the Froissart bound

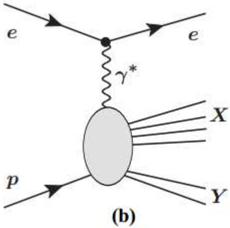
Diffractive DIS

Rapidity gap events at HERA

Experiments at HERA : about 10% of scattering events reveal a rapidity gap



DIS events

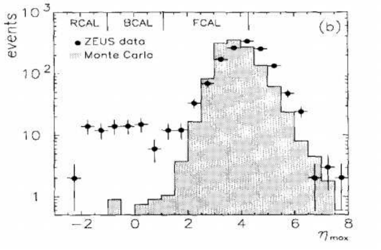


DDIS events

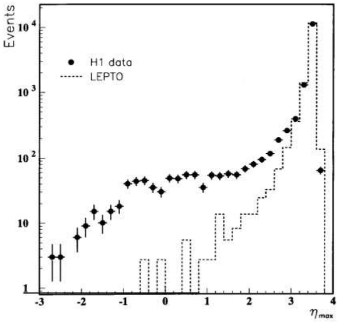
Diffractive DIS

Rapidity gap events at HERA

Experiments at HERA : about 10% of events reveal a rapidity gap



ZEUS, 1993



H1,1994

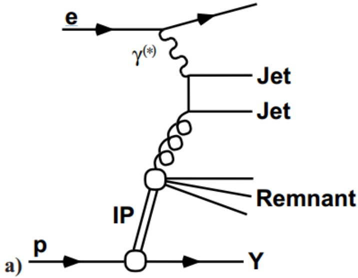
Diffractive DIS

Theoretical approaches for DDIS using pQCD

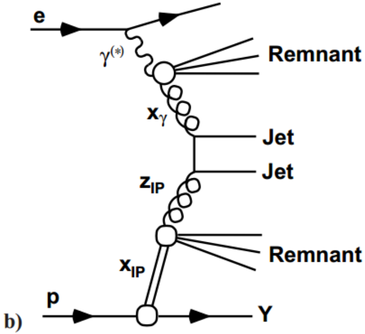
- Collinear factorization approach
  - Relies on QCD factorization theorem, using a hard scale such as the virtuality Q^2 of the incoming photon
  - One needs to introduce a diffractive distribution function for partons *within a pomeron*
- k_T factorization approach for two exchanged gluons
  - low-x QCD approach : $s \gg Q^2 \gg \Lambda_{QCD}$
  - The pomeron is described as a two-gluon color-singlet state

Theoretical approaches for DDIS using pQCD

Collinear factorization approach



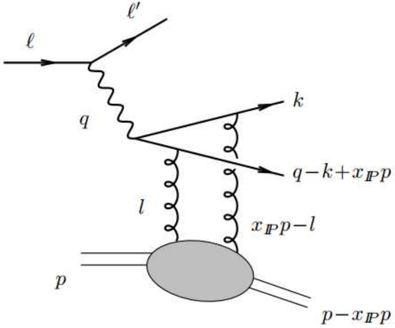
Direct



Resolved

Theoretical approaches for DDIS using pQCD

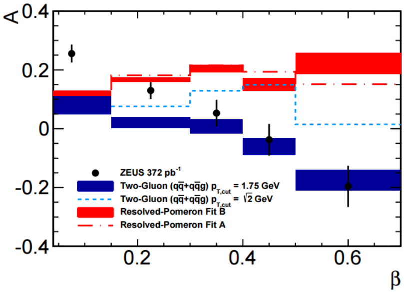
k_T-factorization approach : two gluon exchange



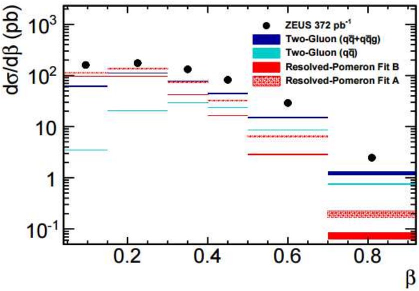
Bartels, Ivanov, Jung, Lotter, Wüsthoff
Braun and Ivanov developed a similar model in collinear factorization

Theoretical approaches for DDIS using pQCD

Confrontation of the two approaches with HERA data



ZEUS collaboration, 2015



ZEUS collaboration, 2015

Assumptions

- Regge limit : $s \gg Q^2 \gg \Lambda_{QCD}$
- No approximation for the outgoing gluon, contrary to e.g. :
  - Collinear approximation [Wüsthoff, 1995]
  - Soft approximation [Bartels, Jung, Wüsthoff, 1999]
- Lightcone coordinates $(p^+, p^-, \vec{p})$ and lightcone gauge $n_2 \cdot \mathcal{A} = 0$
- Transverse dimensional regularization $d = 2 + 2\epsilon$, longitudinal cutoff

$$p_g^+ < \alpha p_\gamma^+$$

- Shockwave (Wilson lines) approach [Balitsky, 1995]

The shockwave approach

One decomposes the gluon field $\mathcal{A}$ into an internal field and an external field :

$$\mathcal{A}^\mu = A^\mu + b^\mu$$

The internal one contains the gluons with rapidity $p_g^+ > \alpha p_\gamma^+$ and the external one contains the gluons with rapidity $p_g^+ < \alpha p_\gamma^+$. One writes :

$$b^\mu(z) = \delta(z^+) B(\vec{z}) n_2^\mu$$

Intuitively, large boost λ along the $+$ direction :

$$b^+(x^+, x^-, \vec{x}) \to \frac{1}{\lambda} b^+\left(\lambda x^+, \frac{1}{\lambda} x^-, \vec{x}\right)$$

$$b^-(x^+, x^-, \vec{x}) \to \lambda b^-\left(\lambda x^+, \frac{1}{\lambda} x^-, \vec{x}\right)$$

$$b^i(x^+, x^-, \vec{x}) \to b^i\left(\lambda x^+, \frac{1}{\lambda} x^-, \vec{x}\right)$$

Propagator through a shockwave

$$G\left(z_2,\, z_0\right) = -\int d^4 z_1 \theta\left(z_2^+\right)\delta\left(z_1^+\right)\theta\left(-z_0^+\right) G\left(z_2 - z_1\right)\gamma^+ G\left(z_1 - z_0\right) U_1$$

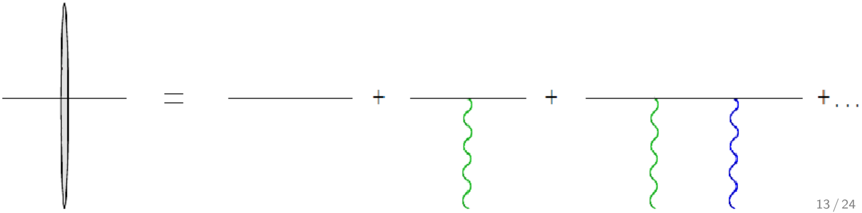
$$G\left(q,\, p\right) = \left(2\pi\right)\theta\left(p^+\right)\int d^D q_1 \delta\left(q + q_1 - p\right) G\left(q\right)\gamma^+ \tilde{U}_{\vec{q}_1} G\left(p\right)$$

Wilson lines :

$$U_i = U_{\vec{z}_i} = U\left(\vec{z}_i, \eta\right) = P\exp\left[ig\int_{-\infty}^{+\infty} b_\eta^-\left(z_i^+, \vec{z}_i\right) dz_i^+\right]$$

$$U_i = 1 + ig\int_{-\infty}^{+\infty} b_\eta^-\left(z_i^+, \vec{z}_i\right) dz_i^+ + (ig)^2\int_{-\infty}^{+\infty} b_\eta^-\left(z_i^+, \vec{z}_i\right) b_\eta^-\left(z_j^+, \vec{z}_j\right)\theta\left(z_{ji}^+\right) dz_i^+ dz_j^+$$

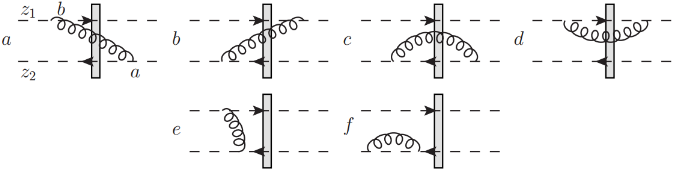
...



The BK equation

Dipole operator

$$\mathbf{U}_{12} = \frac{1}{N_c}\mathrm{Tr}\left(U_1 U_2^{\dagger}\right) - 1$$

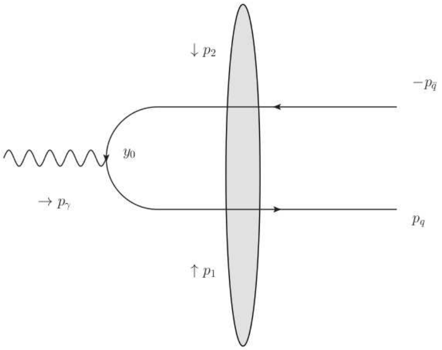


BK equation [Balitsky, 1995] [Kovchegov, 1999]

$$\frac{d\mathbf{U}_{12}}{d\ln\sigma} = \frac{\alpha_s N_c}{2\pi^2}\int d\vec{z}_3 \frac{\vec{z}_{12}^{\,2}}{\vec{z}_{13}^{\,2}\vec{z}_{23}^{\,2}}\left[\mathbf{U}_{13} + \mathbf{U}_{32} - \mathbf{U}_{12} - \mathbf{U}_{13}\mathbf{U}_{32}\right]$$

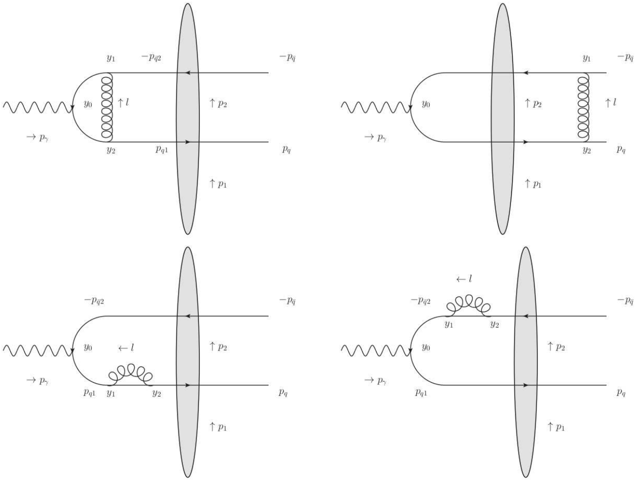
Non-linear term : saturation

Leading Order



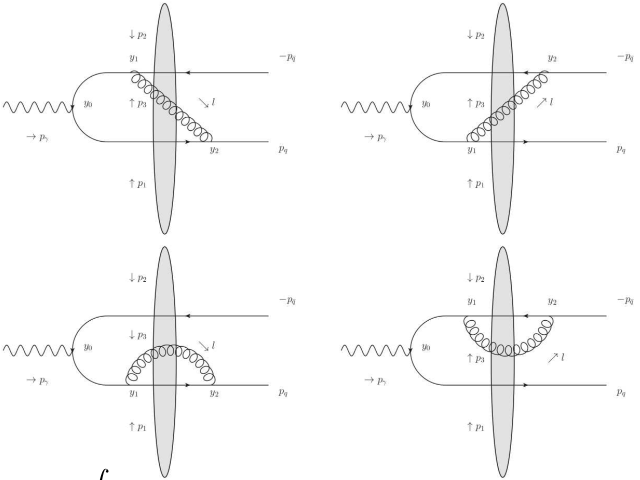
$$\mathcal{A}_0 = \varepsilon_\alpha N_c \int d^d\vec{p}_1 d^d\vec{p}_2 \Phi_0^\alpha(\vec{p}_1, \vec{p}_2)\, \delta(\vec{p}_{q1} + \vec{p}_{\bar{q}2})\, \tilde{\mathbf{U}}_{12}$$

First kind of virtual corrections



$$\mathcal{A}_{V1} \quad \propto \quad \varepsilon_\alpha N_c \int d^d \vec{p}_1 d^d \vec{p}_2 \Phi^{\alpha}_{V1} \left(\vec{p}_1,\ \vec{p}_2\right) \delta \left(\vec{p}_{q1} + \vec{p}_{\bar{q}2}\right) \left(\frac{N_c^2 - 1}{N_c}\right) \tilde{\mathbf{U}}_{12}$$

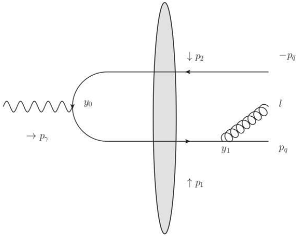
Second kind of virtual corrections

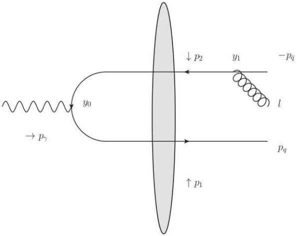


$$\mathcal{A}_{V2} \propto \varepsilon_\alpha N_c \int d^d\vec{p}_1 d^d\vec{p}_2 d^d\vec{p}_3 \Phi^\alpha_{V2}(\vec{p}_1,\, \vec{p}_2,\, \vec{p}_3)\delta(\vec{p}_{q1}+\vec{p}_{\bar{q}2}-\vec{p}_3)$$

$$\left[\delta(\vec{p}_3)\left(\frac{N_c^2-1}{N_c}\right)\tilde{\mathbf{U}}_{12} + N_c\left(\tilde{\mathbf{U}}_{13}\tilde{\mathbf{U}}_{32}+\tilde{\mathbf{U}}_{13}+\tilde{\mathbf{U}}_{32}-\tilde{\mathbf{U}}_{12}\right)\right]$$

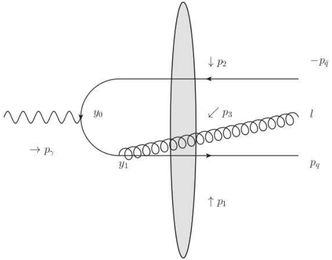
First kind of real corrections

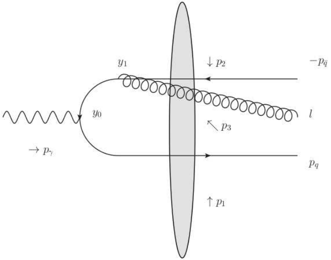




$$\mathcal{A}_{R1} = \varepsilon_\alpha N_c \int d^d\vec{p}_1 d^d\vec{p}_2\, \Phi^{\alpha}_{R1}(\vec{p}_1,\ \vec{p}_2)\,\delta(\vec{p}_{q1}+\vec{p}_{\bar{q}2}+\vec{p}_g)\left(\frac{N_c^2-1}{N_c}\right)\tilde{\mathbf{U}}_{12}$$

Second kind of real corrections





$$\mathcal{A}_{R2} = \varepsilon_\alpha N_c \int d^d\vec{p}_1 d^d\vec{p}_2 d^d\vec{p}_3 \Phi^\alpha_{R2}(\vec{p}_1,\, \vec{p}_2,\, \vec{p}_3)\delta(\vec{p}_{q1}+\vec{p}_{\bar{q}2}+\vec{p}_{g3})$$
$$\left[\left(\frac{N_c^2-1}{N_c}\right)\tilde{\mathbf{U}}_{12}\delta(\vec{p}_3) + N_c\left(\tilde{\mathbf{U}}_{13}\tilde{\mathbf{U}}_{32}+\tilde{\mathbf{U}}_{13}+\tilde{\mathbf{U}}_{32}-\tilde{\mathbf{U}}_{12}\right)\right]$$

Divergences

- UV divergence $\vec{p}_g^{\,2} \to +\infty$

$$\Phi_{V1}\Phi_0^* + \Phi_0\Phi_{V1}^*$$

- Soft divergence $p_g \to 0$

$$\Phi_{V1}\Phi_0^* + \Phi_0\Phi_{V1}^*, \Phi_{R1}\Phi_{R1}^*$$

- Collinear divergence $p_g \propto p_q$ or $p_{\bar{q}}$

$$\Phi_{R1}\Phi_{R1}^*$$

- Soft and collinear divergence $p_g = \frac{p_g^+}{p_q^+}p_q$ or $\frac{p_g^+}{p_{\bar{q}}^+}p_{\bar{q}}$, $p_g^+ \to 0$

$$\Phi_{R1}\Phi_{R1}^*$$

- Rapidity divergence $p_g^+ \to 0$

$$\Phi_{V2}\Phi_0^* + \Phi_0\Phi_{V2}^*$$

Rapidity divergence

BK equation

$$\frac{\partial \tilde{\mathbf{U}}_{12}^{\alpha}}{\partial \log \alpha} = 2\alpha_s N_c \mu^{2-d} \int \frac{d^d \vec{k}_1 d^d \vec{k}_2 d^d \vec{k}_3}{(2\pi)^{2d}} \delta\left(\vec{k}_1 + \vec{k}_2 + \vec{k}_3 - \vec{p}_1 - \vec{p}_2\right) \left(\tilde{\mathbf{U}}_{13}\tilde{\mathbf{U}}_{32} + \tilde{\mathbf{U}}_{13} + \tilde{\mathbf{U}}_{32} - \tilde{\mathbf{U}}_{12}\right)$$
$$\left[2\frac{\left(\vec{k}_1 - \vec{p}_1\right)\cdot\left(\vec{k}_2 - \vec{p}_2\right)}{\left(\vec{k}_1 - \vec{p}_1\right)^2\left(\vec{k}_2 - \vec{p}_2\right)^2} + \frac{\pi^{\frac{d}{2}}\Gamma\left(1-\frac{d}{2}\right)\Gamma^2\left(\frac{d}{2}\right)}{\Gamma(d-1)}\left(\frac{\delta\left(\vec{k}_2 - \vec{p}_2\right)}{\left[\left(\vec{k}_1 - \vec{p}_1\right)^2\right]^{1-\frac{d}{2}}} + \frac{\delta\left(\vec{k}_1 - \vec{p}_1\right)}{\left[\left(\vec{k}_2 - \vec{p}_2\right)^2\right]^{1-\frac{d}{2}}}\right)\right]$$

η typical rapidity for the lower impact factor

$$\tilde{\mathbf{U}}_{12}^{\alpha}\Phi_0 \to \Phi_0 \tilde{\mathbf{U}}_{12}^{\eta} + \log\left(\frac{e^{\eta}}{\alpha}\right)\mathcal{K}_{BK}\Phi_0\left(\tilde{\mathbf{U}}_{13}\tilde{\mathbf{U}}_{32} + \tilde{\mathbf{U}}_{13} + \tilde{\mathbf{U}}_{32} - \tilde{\mathbf{U}}_{12}\right)$$

Then $\tilde{\mathbf{U}}_{12}^{\alpha}\Phi_0 + \Phi_{V2}$ is finite.

Soft and collinear divergence

Jet cone algorithm

We define a cone width for each pair of particles with momenta p_i and p_k, rapidity difference ΔY_{ik} and relative azimuthal angle $\Delta\phi_{ik}$

$$(\Delta Y_{ik})^2 + (\Delta\phi_{ik})^2 = R_{ik}^2$$

If $R_{ik}^2 < R^2$, then the two particles together define a single jet of momentum $p_i + p_k$.

Applying this to our results in the small R^2 limit cancels the soft and collinear divergence.

Remaining divergence

Soft real emission

$$(\Phi_{R1}\Phi_{R1}^*)_{soft} \propto (\Phi_0\Phi_0^*) \int_{\text{outside the cones}} \left| \frac{p_q^\mu}{(p_q.p_g)} - \frac{p_{\bar{q}}^\mu}{(p_{\bar{q}}.p_g)} \right|^2 \frac{dp_g^+}{p_g^+} \frac{d^d p_g}{(2\pi)^d}$$

Collinear real emission

$$(\Phi_{R1}\Phi_{R1}^*)_{col} \propto (\Phi_0\Phi_0^*)\,(\mathcal{N}_q + \mathcal{N}_{\bar{q}})$$

Where $\mathcal{N}$ is the number of jets in the quark or the antiquark

$$\mathcal{N}_k = \frac{(4\pi)^{\frac{d}{2}}}{\Gamma(2-\frac{d}{2})} \int_{\alpha p_\gamma^+}^{p_{jet}^+} \frac{dp_g^+ dp_k^+}{2p_g^+ 2p_k^+} \int_{\text{in cone k}} \frac{d^d\vec{p}_g d^d\vec{p}_k}{(2\pi)^d\,\mu^{d-2}} \frac{\mathrm{Tr}\,(\hat{p}_k\gamma^\mu\hat{p}_{jet}\gamma^\nu)\,d_{\mu\nu}(p_g)}{2p_{jet}^+\left(p_k^- + p_g^- - p_{jet}^-\right)^2}$$

Those two contributions cancel exactly the virtual divergences (both UV and soft)

Conclusion and applications

- The paper is being written. The results will be used for HERA phenomenology and for predictions for an Electron Ion Collider
- Our results can also be used for photoproduction at large t or with a large diffractive mass
- They can be adapted to ultraperipheral collisions at the LHC
- They can be used to compute the impact factor for the production of a ρ meson
- In the future, we can study the massive quark case, and later on adapt it for the production of a J/ψ meson using the Color Evaporation Model [see tomorrow's talk]