Inclusive hadron and photon production at LHC in dipole momentum space

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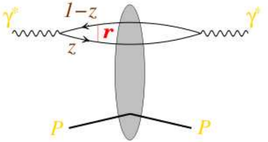
Outline

- ⇒ Saturation
- ⇒ Dipole formalism
- ⇒ Traveling wave method
- ⇒ Momentum space AGBS model
- Hadron and photon production
  - Comparison with LHC data: k_t factorization
  - LHC predictions: Hybrid factorization
- Summary

Saturation and Dipole Frame

- e-P scattering at HERA: strong rise of the gluon dist. function for small-x
  - Untamed rising should violate unitarity
  - For $Q^2 \leq Q_s^2(x)$, parton recombination should happen
  - Semihard scale from pQCD $\mathbf{Q_s(x)}$: Saturation scale
- **Dipole frame** is convenient to investigations on small-x



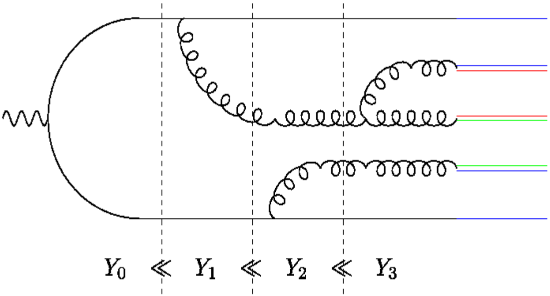
z: longitudinal photon momentum fraction carried by the quark
$\mathbf{r}$: transverse size of the pair $q\bar{q}$

  - γ^* splits into the $q\bar{q}$ pair and the cross section factorizes as [Nikolaev & Zakharov '90; Mueller '94]

$$\sigma_{L,T}^{\gamma^* P}(x, Q^2) = \int_0^1 dz \int d^2\mathbf{r} |\Psi_{L,T}(z, r; Q^2)|^2 \sigma_{dip}(r = |\mathbf{r}|, x) \quad (1)$$

Dipole formalism

- Considers the energy evolution ($Y = \ln(1/x)$) of the pair $q\bar{q}$



- Large N_c limit: gluon $\equiv q\bar{q}$
- $\sigma_{dip}(r, Y) = \int d^2\mathbf{b}\mathcal{N}(r, \mathbf{b}, Y) \approx \pi R^2_{target}\mathcal{N}(r, Y)$
- $\mathcal{N}(r, Y)$ describes the interaction through gluon cascade ($\equiv$ non abelian phases $\rightarrow$ Wilson lines)

Dipole evolution

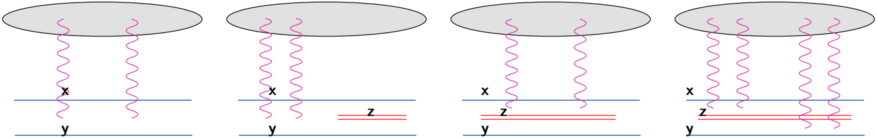
- Balitsky-JIMWLK hierarchy $\mathcal{M}(\mathbf{x},\mathbf{y},\mathbf{z}) = \frac{(\mathbf{x}-\mathbf{y})^2}{(\mathbf{x}-\mathbf{z})^2(\mathbf{y}-\mathbf{z})^2}$ $\bar{\alpha} = \alpha_s N_c/\pi$

$$\frac{\partial}{\partial Y}\langle\mathcal{N}(\mathbf{x},\mathbf{y})\rangle_Y = \frac{\bar{\alpha}}{2\pi}\int d^2\mathbf{z}\mathcal{M}(\mathbf{x},\mathbf{y},\mathbf{z}) \times\Big\{-\langle\mathcal{N}(\mathbf{x},\mathbf{y})\rangle_Y + \langle\mathcal{N}(\mathbf{x},\mathbf{z})\rangle_Y + \langle\mathcal{N}(\mathbf{z},\mathbf{y})\rangle_Y - \langle\mathcal{N}(\mathbf{x},\mathbf{z})\mathcal{N}(\mathbf{z},\mathbf{y})\rangle_Y\Big\}$$

$$\vdots$$

- Mean field: $\langle\mathcal{N}(\mathbf{x},\mathbf{z})\mathcal{N}(\mathbf{y},\mathbf{z})\rangle_Y \approx \langle\mathcal{N}(\mathbf{x},\mathbf{z})\rangle_Y\langle\mathcal{N}(\mathbf{y},\mathbf{z})\rangle_Y \Rightarrow$ Balitsky-Kovchegov (BK) equation

$$\frac{\partial}{\partial Y}\langle\mathcal{N}(\mathbf{x},\mathbf{y})\rangle_Y = \frac{\bar{\alpha}}{2\pi}\int d^2\mathbf{z}\mathcal{M}(\mathbf{x},\mathbf{y},\mathbf{z}) \times\Big\{-\langle\mathcal{N}(\mathbf{x},\mathbf{y})\rangle_Y + \langle\mathcal{N}(\mathbf{x},\mathbf{z})\rangle_Y + \langle\mathcal{N}(\mathbf{z},\mathbf{y})\rangle_Y - \langle\mathcal{N}(\mathbf{x},\mathbf{z})\rangle_Y\langle\mathcal{N}(\mathbf{z},\mathbf{y})\rangle_Y\Big\}$$



HEQCD amplitudes and traveling waves

- Asymptotic forms of BK solutions obtained through the mapping: QCD $\Rightarrow$ Reaction-diffusion processes
- Geometric scaling of the BK amplitudes seen as traveling waves
- In momentum space BK equation reads

$$\partial_Y N_Y = \bar{\alpha}\chi(-\partial_L) N_Y - \bar{\alpha} {N_Y}^2,$$

where

$$\chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$$

is the **BFKL** kernel and $L = \log(k^2/k_0^2)$, with k_0 denoting a soft scale.

- Change of variables: $t \sim \bar{\alpha} Y$, $x \sim L$ e $u \sim N$, BK $\rightarrow$ FKPP [Munier e Peschanski '2004]

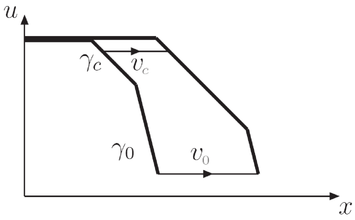
$$\partial_t\, u(x,t) = \partial_x^2\, u(x,t) + u(x,t) - u^2(x,t)$$

- Dynamics essentially determined by the linear part (BFKL)
- FKPP admits *traveling wave solutions*: $u(x,t) \overset{t\rightarrow\infty}{\sim} u(x - v_c t)$ ("geometric scaling")

HEQCD amplitudes and traveling waves

- TW conects $u = 0$ unstable and $u = 1$ stable fixed points.
- $\gamma_0 > \gamma_c$
- $u(x,t) = \int_{c-\imath\infty}^{c+\imath\infty} \frac{d\gamma}{2\imath\pi} u_0(\gamma) e^{-\gamma(x_{wf}+vt)+\omega(\gamma)t}$

$$v_c = \frac{\omega(\gamma_c)}{\gamma_c} = \partial_\gamma \omega(\gamma)|_{\gamma_c}$$



- In QCD variables : $\omega(\gamma_c) = \chi(\gamma_c) \Rightarrow \gamma_c = 0.6275$
- TW translates into geometric scaling of BK amplitudes [Munier e Peschanski '2004]

$$N_Y(k) \overset{k \gg Q_s}{\approx} \left(\frac{k^2}{Q_s^2(Y)}\right)^{-\gamma_c} \log\left(\frac{k^2}{Q_s^2(Y)}\right) \exp\left[-\frac{\log^2\left(k^2/Q_s^2(Y)\right)}{2\bar{\alpha}\chi''(\gamma_c)Y}\right],$$

$$Q_s^2(Y) = Q_0^2 \exp\left(\lambda Y - \frac{3}{2\gamma_c}\log Y\right), \qquad \lambda = \bar{\alpha} v_c = \bar{\alpha}\chi(\gamma_c)/\gamma_c$$

- Geometric scaling window

$$\log\left(k^2/Q_s^2(Y)\right) \lesssim \sqrt{2\bar{\alpha}\chi''(\gamma_c)Y}$$

AGBS model for σ_{dip}

- Parametrization in momentum space for the dipole-proton scattering amplitude [Amaral, MBGD, Betemps and Soyez '2007]
  - The model uses the traveling wave BK solutions for the large L (dilute) region
  - A Fourier transform of a Theta function models the saturated region

$$N(k) \overset{k \ll Q_s}{=} c - \log\left(\frac{k}{Q_s(Y)}\right)$$

  - The AGBS model interpolates between the two behaviors through ($\rho \equiv \ln(k^2/k_0^2)$ and $\rho_s \equiv \ln(k_0^2/Q_s^2)$):

$$N^{\mathrm{AGBS}}(\rho, Y) = L_F\left(1 - e^{-N_{\mathrm{dil}}}\right),$$

where

$$N_{\mathrm{dil}} = \exp\left[-\gamma_c(\rho - \rho_s) - \frac{\mathcal{L}^2 - \log^2(2)}{2\bar{\alpha}\chi''(\gamma_c)Y}\right],$$

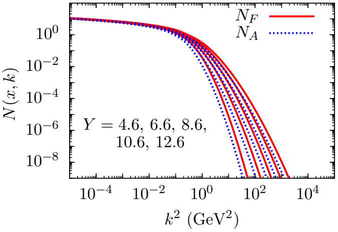
$$\mathcal{L} = \ln\left[1 + e^{(\rho-\rho_s)}\right] \qquad \text{with} \quad Q_s^2(Y) = k_0^2\, e^{\lambda Y},$$

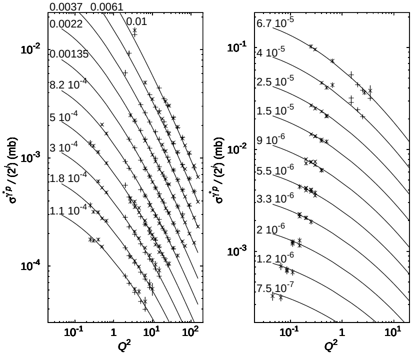
and

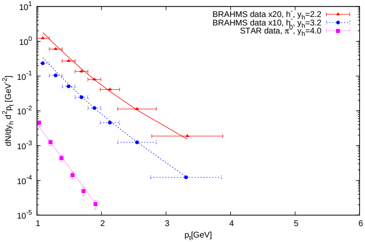
$$L_F = 1 + \ln\left[e^{\frac{1}{2}(\rho-\rho_s)} + e^{-\frac{1}{2}(\rho-\rho_s)}\right]$$

AGBS model for σ_{dip}

- Model complements the coordinate space description
- Describes quite well the HERA data on F_2^p
- Globally fitted to HERA and RHIC data







Hybrid formalism:
large K-factors when compared with LHC data

Comparison with LHC data

[E. Basso, MBGD and de Oliveira '2013]

- Central rapidity region
- k_t-factorization formalism naturally includes large-x contributions from one of the colliding hadrons (not present in the hybrid formalism)

- Both colliding hadrons treated in the same way (emphasize p_t dependence) $\eta \sim 0 \to k_t^1 \approx k_t^2$ $\quad \eta_{\text{forward}} \to k_t^1 \ll k_t^2$
- Cross section reads [Braun '2000, Kovchegov e Tuchin '2003]

$$\frac{d\sigma^{A+B\to g}}{dy d^2 p_t d^2 R} = K \frac{2}{C_F p_t^2} \int^{p_t} \frac{d^2 k_t}{4} \times \int d^2 b\, \alpha_s(Q) \varphi\left(\frac{|p_t + k_t|}{2}, x_1; b\right) \varphi\left(\frac{|p_t - k_t|}{2}, x_2; R - b\right),$$

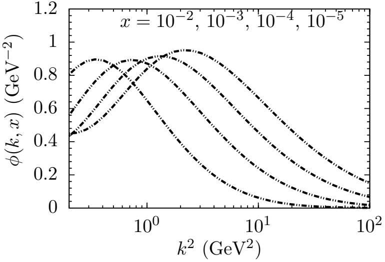
where $x_{1,2} = (p_t/\sqrt{s})e^{\pm y}$ and $C_F = (N_c^2 -)/2N_c$

- Large N_c limit, UGDs are related to the dipole amplitude through [Braun '2000]

$$\varphi(k, x; b) = \frac{N_c\, S_t}{2\pi^2 \alpha_s(k)} k^2 F_g(k, x; b).$$

k_t-factorization

$$F_g(k, x; b) = \frac{1}{2\pi}(\nabla_k^2 N_G(k, x; b) + \delta(k))$$



- invariant cross section

$$\frac{dN_{ch}}{d\eta d^2 p_t} = \frac{h(\eta)}{\sigma_{nsd}} \int d^2 R \int \frac{dz}{z^2} \frac{d\sigma^{A+B\to g}}{dy d^2 p_t d^2 R} D_h(z = p_t/k_t)$$

with D_h denoting the FFs and h is the Jacobian for the y to η transform

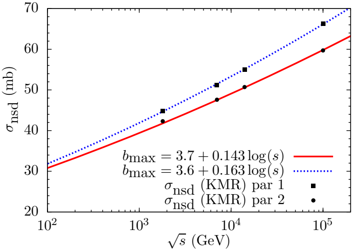
$$y(\eta, p_t, m) = \frac{1}{2} \ln \left[\frac{\sqrt{m^2 + p_t^2 \cosh^2 \eta} + p_t \sinh \eta}{\sqrt{m^2 + p_t^2 \cosh^2 \eta} - p_t \sinh \eta} \right]$$

- σ_{nsd} describes the efective area of interaction; model dependent.

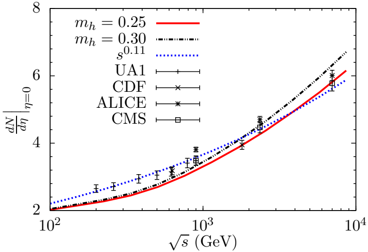
k_t-factorization

- $\sigma_{\rm nsd} \equiv \sigma_{\rm nsd}(s)$, fitting the KMR model [Khoze, Martin e Ryskin '2011]

$$\sigma_{nsd} \to \pi b_{max}^2,$$
$$b_{max} = b_0 + C\log(s).$$



- If using the central produced hadrons to get a and b

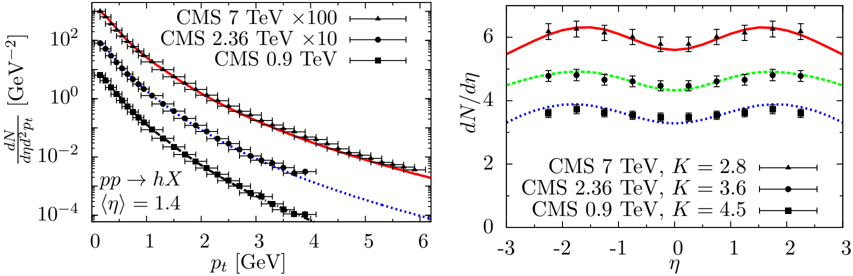


$$b_{\rm max} = 0.1 + 0.198\log(s)$$

Results: $p + p$ at LHC

- Large-x effects ($\beta = 0.4$ and $\lambda_0 = 0 - 0.2$, $x_0 = 0.01$) [Gelis, Staśto and Venugopalan '2006]

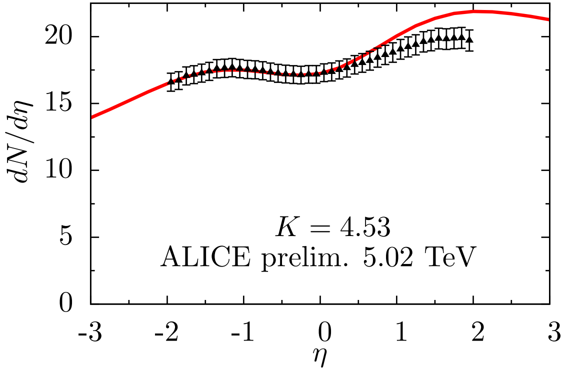
$$\varphi(k, x; b) = \left(\frac{1-x}{1-x_0}\right)^{\beta} \left(\frac{x_0}{x}\right)^{\lambda_0} \varphi(k, x_0; b)$$



- As expected, smaller K factors compared to the hybrid formalism
  - k_t-factorization: more suitable in the central region ($\eta \sim 0$)

Results: $p + A$ at LHC

- $Q_s^A = A_{\rm eff}^{1/3} Q_s^p$, $A_{\rm eff} \simeq 20$ for lead

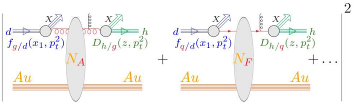


$x_A \equiv x_1 \sim e^y$
$x_p \equiv x_2 \sim e^{-y}$

- p fragmentation region: small $x_1 \to$ nuclear target small-x effects
- Pb fragmentation region: large $x_1 \to$ EMC and Fermi motion effects must be included

LHC predictions at forward regions [E. Basso, MBGD and de Oliveira '2013]

- Hybrid formalism more suitable in the hadron fragmentation region (small-x)

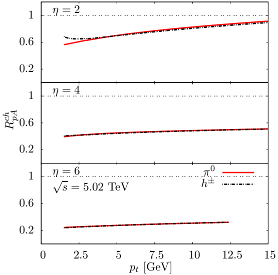


$$\frac{dN_h(d\,Au \to h(p_t, y_h)\,X)}{dy_h d^2 p_t} = \frac{K(y_h)}{(2\pi)^2}\int_{x_F}^{1} dx_1\,\frac{x_1}{x_F}\Big[f_{q/p}(x_1,p_t^2)\,N_F\,(q_t,x_2)\,D_{h/q}\left(x_F/x_1,p_t^2\right)$$
$$+ f_{g/p}(x_1,p_t^2)\,N_A\,(q_t,x_2)\,D_{h/g}\left(x_F/x_1,p_t^2\right)\Big]$$

- CTEQ6 LO PDF
- Nuclear modification factor for hadrons

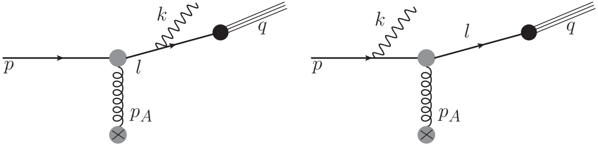
$$R^h_{pA} = \frac{dN^{pA\to hX}}{d^2p_t d\eta}\Bigg/\frac{dN^{pp\to hX}}{d^2p_t d\eta}\Bigg/ N_{\rm coll}\,.$$

$N_{\rm coll} = 6.9 \to$ *minimum bias* $\sqrt{5.02}$ Tev
$K(y_h)\sim 1$ expected



Photon production

- LO p-A scattering $(q + A \to \gamma + X)$



- Contributions from direct and fragmentation photons [Rezaeian e Jalilian-Marian '2012]

$$\frac{d\sigma^{\text{Direct}}}{d^2\mathbf{b}d^2k_t d\eta_\gamma} = \frac{e_q^2\alpha_{\text{em}}}{\pi(2\pi)^3} z^2[1+(1-z)^2]\frac{1}{k_t^4}\int^{k_t^2} d^2\mathbf{l}_t l_t^2 N_F(\bar{x}_g, b_t, l_t)$$

e

$$\frac{d\sigma^{\text{Fragmentation}}}{d^2\mathbf{b}d^2k_t d\eta_\gamma} = \frac{1}{(2\pi)^2}\frac{1}{z}D_{\gamma/q}(z,Q^2)N_F(x_g, b_t, k_t/z),$$

being the LO quark-photon fragmentation function given by [Owens '1986]

$$D_{\gamma/q}(z,Q^2) = \frac{e_q^2\alpha_{\text{em}}}{2\pi}\frac{1+(1-z)^2}{z}\ln\left(\frac{Q^2}{\Lambda_{\text{QCD}}^2}\right).$$

Photon production at LHC

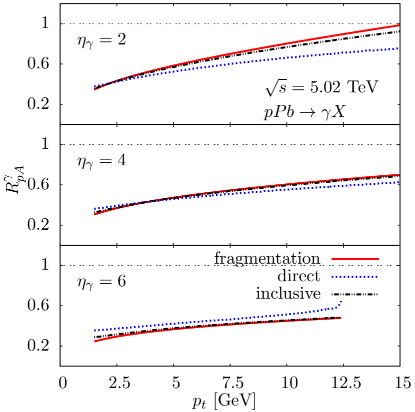
- Using CTEQ6 LO PDF for quarks and antiquarks densities

$$\frac{d\sigma^{pT\to\gamma(k)X}}{d^2\mathbf{b}d^2k_t d\eta_\gamma} = \int_{x_q^{\min}}^{1} dx_q[f_q(x_q,Q^2)+f_{\bar{q}}(X_Q,q^2)]\frac{d\sigma^{q(p)T\to\gamma(k)X}}{d^2\mathbf{b}d^2k_t d\eta_\gamma},$$

- Nuclear modification factor

$$R_{pA}^{\gamma} = \frac{d\sigma^{pA\to\gamma X}}{d^2p_t d\eta} \bigg/ \frac{d\sigma^{pp\to hX}}{d^2p_t d\eta} \bigg/ N_{\text{coll}}$$

- $N_{\text{coll}} = 6.9$ for 5.02 TeV proton-lead collisions [d'Enterria '2003]

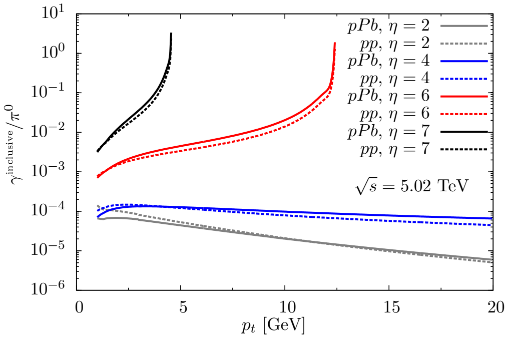


Photon production at LHC

- Neutral pions to photon ratio

$$\frac{\gamma^{\text{inclusive}}}{\pi^0} = \frac{d\sigma^{pT\to\gamma X}}{d^2p_t d\eta} \Bigg/ \frac{d\sigma^{pT\to\pi^0 X}}{d^2p_t d\eta}. \quad (2)$$

- $k_t^{\pi^0} = k_t^{\gamma}$ e $\eta_{\pi^0} = \eta_\gamma$
- π^0 produced via gluon induced processes
  dominant in the central region
- γ^0 radiated by quarks
  enhanced contribution in the fragmentation region
  $x \to 1$



Summary

- Study of a momentum space dipole amplitude through the traveling wave method of QCD – AGBS
- Model describes quite well both DIS HERA data and RHIC inclusive charged hadron yield
- Predictions to hadron and photon production at LHC
- Two distinct factorizations:
- k_t-factorization
  - ⇒ Good description of LHC data at central rapidity region
- Hybrid factorization
  - ⇒ Predictions for the nuclear modification factors at forward rapidities
    - ⇒ Good region to compare collinear (DGLAP) and saturation formalisms