Saturation in central-forward jet production in p-Pb collisions at LHC

Sebastian Sapeta

IPPP, Durham

in collaboration with Krzysztof Kutak, arXiv:1205.5035

pA@LHC Workshop, 4-8 June 2012 CERN
Central-forward jet production

\[ S = 2P_1 \cdot P_2 \]

\[
x_1 = \frac{1}{\sqrt{S}} (p_{t1} e^{y_1} + p_{t2} e^{y_2}) \quad y_1 \sim 0, y_2 \gg 0 \sim 1
\]

\[
x_2 = \frac{1}{\sqrt{S}} (p_{t1} e^{-y_1} + p_{t2} e^{-y_2}) \quad \ll 1
\]
High energy factorization

\[
\frac{d\sigma}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \sum_{a,c,d} \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \mathcal{M}_{ag \rightarrow cd} x_1 f_{a/A}(x_1, \mu^2) \phi_{g/B}(x_2, k^2) \frac{1}{1 + \delta_{cd}}
\]

\[
k^2 = p_{t1}^2 + p_{t2}^2 + 2p_{t1} p_{t2} \cos \Delta\phi
\]

\[
x_1 f_{a/A}(x_1, \mu^2) \quad - \quad \text{collinear pdf in } A, \text{ suitable for } x_1 \sim 1
\]

\[
\phi_{g/B}(x_2, k^2) \quad - \quad \text{unintegrated gluon distribution in } B, \text{ suitable for } x_2 \ll 1
\]

\[
\mathcal{M}_{ag \rightarrow cd} \quad - \quad \text{matrix element with off-shell gluon}
\]
Unified BK/DGLAP evolution equation

\[ \phi_p(x, k^2) = \phi_p^{(0)}(x, k^2) \]

\[ + \frac{\alpha_s(k^2)N_c}{\pi} \int_x^1 \frac{dz}{z} \int_{k_0^2}^\infty \frac{dl^2}{l^2} \left\{ \frac{l^2 \phi_p\left(\frac{x}{z}, l^2\right)}{\theta\left(\frac{k^2}{z} - l^2\right) - k^2 \phi_p\left(\frac{x}{z}, k^2\right)} + \frac{k^2 \phi_p\left(\frac{x}{z}, k^2\right)}{|4l^4 + k^4|^{1/2}} \right\} \]

\[ + \frac{\alpha_s(k^2)}{2\pi k^2} \int_x^1 \frac{dz}{z} \left( P_{gg}(z) - \frac{2N_c}{z} \right) \int_{k_0^2}^k d l^2 \phi_p\left(\frac{x}{z}, l^2\right) + \frac{\alpha_s(k^2)}{2\pi} \int_x^1 \frac{dz}{z} P_{gq}(z) \Sigma\left(\frac{x}{z}, k^2\right) \]

\[ - \frac{2\alpha_s^2(k^2)}{R^2} \left[ \left( \int_{k_0^2}^k \frac{dl^2}{l^2} \phi_p(x, l^2) \right)^2 + \phi_p(x, k^2) \int_{k_0^2}^\infty \frac{dl^2}{l^2} \ln\left(\frac{l^2}{k^2}\right) \phi_p(x, l^2) \right] \]

Proton radius

Initial condition

\[ \phi_p^{(0)}(x, k^2) = \frac{\alpha_s(k^2)}{2\pi k^2} \int_x^1 dz P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}, k_0^2 = 1\text{GeV}^2\right) \]

\[ xg(x) = N(1 - x)^\beta (1 - Dx) \]
Fits to $F_2$

- fit in range: $x < 0.01$, all $Q^2$
- very good fit of non-linear gluon ($\chi^2 = 1.73$)
- fit of linear gluon has problems at low $Q^2$ and low $x$ ($\chi^2 = 3.86$)
Fits to $F_2$

- fit in range: $x < 0.01$, all $Q^2$
- very good fit of non-linear gluon ($\chi^2 = 1.73$)
- fit of linear gluon has problems at low $Q^2$ and low $x$ ($\chi^2 = 3.86$)
- some mechanism damping the gluon density at low $x$ and low $Q^2$ seems to be needed
- strong preference of non-linear evolution!
Unintegrated gluon distribution in proton

**non-linear gluon**

![Graph of non-linear gluon distribution](image)

\[ \phi_p(x, k_t^2) = k_t^2 \phi_p(x, 1 \text{ GeV}^2) \] [non-linear]

\[ \phi_p(x, k_t^2) = \phi_p(x, 1 \text{ GeV}^2) \] [linear]

- \( k_t > 1 \text{ GeV} \): gluon from the unified BK/DGLAP equation
- \( k_t < 1 \text{ GeV} \):

\[ \phi_p(x, k_t^2) = k_t^2 \phi_p(x, 1 \text{ GeV}^2) \] [non-linear]

\[ \phi_p(x, k_t^2) = \phi_p(x, 1 \text{ GeV}^2) \] [linear]

- significant differences between linear and non-linear gluon at low \( k_t \) and low \( x \)
- dynamically generated maximum of non-linear gluon at low \( x \)
Now we take all the ingredients (off-shell matrix element, collinear gluon, unintegrated gluon) and plug them to the high energy factorization formula

\[ d^2\sigma/dp_t^2 \] [pb/GeV]

\[ \sqrt{s} = 7 \text{ TeV} \]
\[ p_t > 35 \text{ GeV} \]

central: |\( \eta \)| < 2.8
forward: 3.2 < |\( \eta \)| < 4.7

the result reproduces the pattern of CMS data
excess at low \( p_t \) is due to our simple modeling with a jet being just a parton; it is a know effect which can be improved by adding parton shower
Modeling the nucleus

- Radius of nucleus
  \[ R_{\text{Pb}} = R A^{1/3} \]

- Unintegrated gluon distribution
  \[ \phi_{\text{Pb}}(x, k^2) \equiv A \phi_{\text{Pb}/A}(x, k^2) \]
  where \( \phi_{\text{Pb}/A}(x, k^2) \) is the distribution of gluons per nucleon

The evolution equation

\[ \phi_{\text{Pb}/A}(x, k^2) = \left[ \hat{L}_1 - \frac{A^{1/3}}{R^2} \hat{L}_2 \right] \bullet \phi_{\text{Pb}/A}(x, k^2) \]

- \( \hat{L}_{1,2} \) – linear and non-linear operators as in the equation for proton
- for the nucleus the non-linear term is enhanced by \( A^{1/3} \)
Unintegrated gluon distribution in the Pb nucleus

- Significant suppression of gluon density in the Pb nucleus wrt the proton at low and moderate $k_t$

- Gluon’s transverse momentum: $k_t^2 = p_{t1}^2 + p_{t2}^2 + 2p_{t1}p_{t2} \cos \Delta \phi$
  - Low and moderate $k_t$ probed by configurations with $\Delta \phi \sim \pi$
Dijet azimuthal distance and rapidity distributions at 7 TeV

\[ \frac{d\sigma}{d\Delta\phi} = \left[ \mu_b \right] \quad \sqrt{s} = 7 \text{ TeV} \]

\[ p_t > 15 \text{ GeV} \]

Central: \( 0 < y < 2.8 \)

Forward: \( 3.2 < y < 4.7 \)

\[ \frac{d\sigma}{dy} = \left[ \mu_b \right] \quad \sqrt{s} = 7 \text{ TeV} \]

\[ p_t > 25 \text{ GeV} \]

Central: \( 0 < y < 2.8 \)

Forward: \( 3.2 < y < 4.7 \)

\[ \frac{d\sigma}{dy} = \left[ \mu_b \right] \quad \sqrt{s} = 7 \text{ TeV} \]

\[ p_t > 35 \text{ GeV} \]

Central: \( 0 < y < 2.8 \)

Forward: \( 3.2 < y < 4.7 \)

Sebastian Sapeta (IPPP, Durham)
Dijet azimuthal distance at 5 and 8.8 TeV

- significant suppression due to saturation for both energies
- dip near $\Delta \phi \simeq \pi$ comes from $\sim k^2$ behaviour of the unintegrated gluon at low $k^2$; hence $\Delta \phi$ distribution useful to test shape of gluon in this region
Summary

We presented analysis of e-p, p-p and p-Pb collisions in the framework of high energy factorisation – single approach which allows one to study saturation using hard final states

- We found that the above formalism with the unintegrated gluon density determined from nonlinear QCD evolution equation can successfully account for features of e-p and p-p data

Then we used the non-linear framework to estimate effects of gluon saturation in the nucleus

- We found that saturation in the Pb nucleus can manifest itself as a factor two suppression of central-forward jet decorrelation in the region $\Delta \phi \sim \pi$
- It also leads to $\sim 30\%$ suppression of rapidity spectra