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

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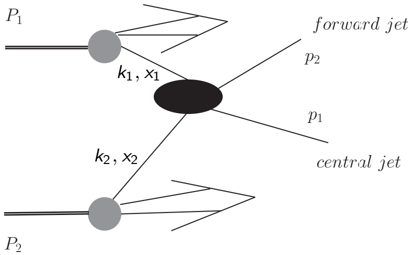
Central-forward jet production

$S = 2P_1 \cdot P_2$



$$x_1 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{y_1} + p_{t2}e^{y_2}\right) \xrightarrow{y_1 \sim 0,\, y_2 \gg 0} \sim 1$$

$$x_2 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{-y_1} + p_{t2}e^{-y_2}\right) \qquad \ll 1$$

High energy factorization

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

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

$x_1 f_{a/A}(x_1, \mu^2)$ – collinear pdf in A, suitable for $x_1 \sim 1$

$\phi_{g/B}(x_2, k^2)$ – unintegrated gluon distribution in B, suitable for $x_2 \ll 1$

$\mathcal{M}_{ag\to cd}$ – matrix element with off-shell gluon

Unified BK/DGLAP evolution equation

[Kwieciński, Martin, Staśto; Kwieciński, Kutak]

kinematic constraint

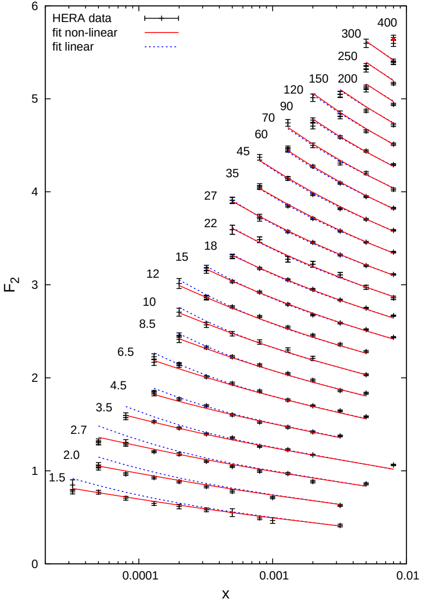
$$
\begin{aligned}
\phi_p(x,k^2) &= \phi_p^{(0)}(x,k^2) \\
&+ \frac{\alpha_s(k^2)N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_0^2}^{\infty}\frac{dl^2}{l^2}\left\{\frac{l^2\phi_p(\frac{x}{z},l^2)\,\theta(\frac{k^2}{z}-l^2) - k^2\phi_p(\frac{x}{z},k^2)}{|l^2-k^2|} + \frac{k^2\phi_p(\frac{x}{z},k^2)}{|4l^4+k^4|^{\frac{1}{2}}}\right\} \\
&+ \frac{\alpha_s(k^2)}{2\pi k^2}\int_x^1 dz\,\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_0^2}^{k^2} dl^2\,\phi_p\left(\frac{x}{z},l^2\right) + \frac{\alpha_s(k^2)}{2\pi}\int_x^1 dz\,P_{gq}(z)\Sigma\left(\frac{x}{z},k^2\right) \\
&- \frac{2\alpha_s^2(k^2)}{R^2}\left[\left(\int_{k^2}^{\infty}\frac{dl^2}{l^2}\phi_p(x,l^2)\right)^2 + \phi_p(x,k^2)\int_{k^2}^{\infty}\frac{dl^2}{l^2}\ln\left(\frac{l^2}{k^2}\right)\phi_p(x,l^2)\right]
\end{aligned}
$$

proton radius

Initial condition

$$
\begin{aligned}
\phi_p^{(0)}(x,k^2) &= \frac{\alpha_S(k^2)}{2\pi k^2}\int_x^1 dz P_{gg}(z)\frac{x}{z}g\left(\frac{x}{z},k_0^2=1\mathrm{GeV}^2\right) \\
xg(x) &= N(1-x)^{\beta}(1-Dx)
\end{aligned}
$$

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 ($\chi^2 = 3.86$)

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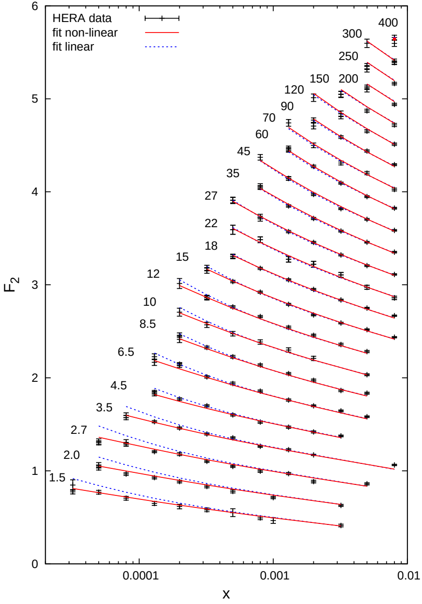

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- very good fit of non-linear gluon ($\chi^2 = 1.73$)
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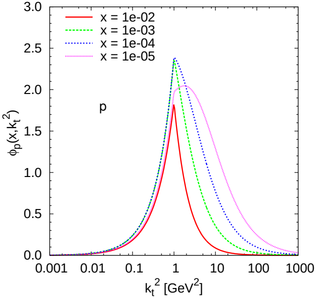
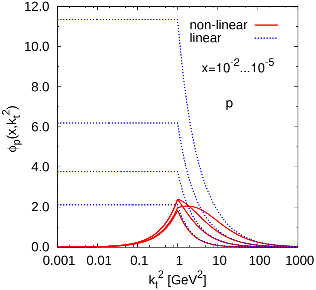
- **some mechanism damping the gluon density at low x and low Q^2 seems to be needed**
- **strong preference of non-linear evolution!**

Unintegrated gluon distribution in proton

non-linear gluon



non-linear vs linear



$k_t > 1\,\text{GeV}$: gluon from the unified BK/DGLAP equation

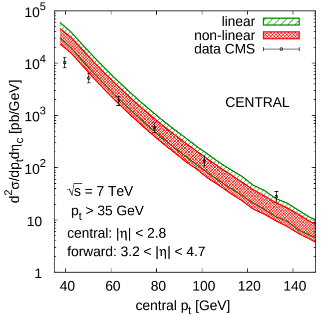
$k_t < 1\,\text{GeV}$: $\phi_p(x,k^2) = k^2\phi_p(x, 1\,\text{GeV}^2)$ [non-linear]

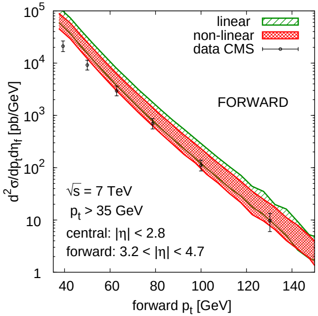
$\phi_p(x,k^2) = \phi_p(x, 1\,\text{GeV}^2)$ [linear]

- 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

Central-forward dijets in p-p collisions at LHC

- Now we take all the ingredients (off-shell matrix element, collinear gluon, unintegrated gluon) and plug them to the high energy factorization formula





- 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

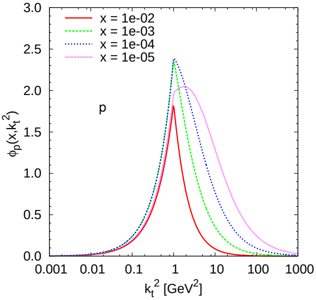
The evolution equation

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

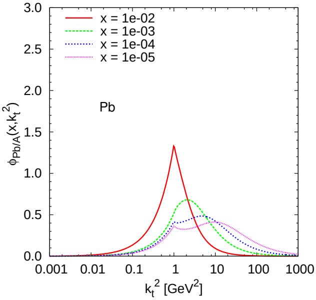
- $\hat{L}_{1,2}$ – linear and non-linear operators as in the equation for proton
- for the nucleus the non-linear term is enhanced by $A^{1/3}$

Unintegrated gluon distribution in the Pb nucleus

non-linear gluon in the proton

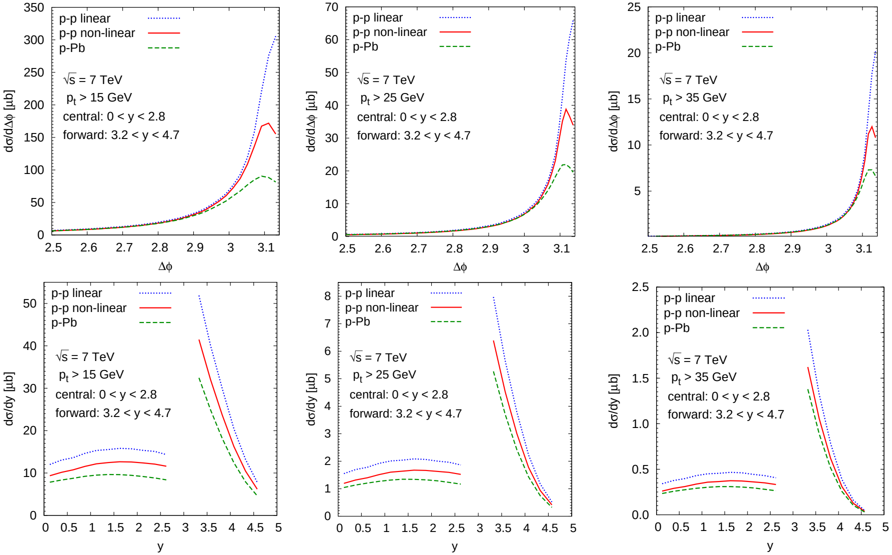


non-linear gluon in Pb nucleus

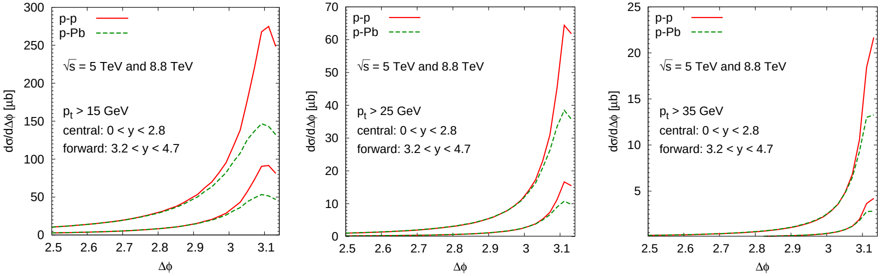


- significant suppression of gluon density in the Pb nucleus wrt the proton at low and moderate k_t
- gluon's transverse momentum: $k_t^2 = p_{t1}^2 + p_{t2}^2 + 2p_{t1}p_{t2}\cos\Delta\phi$
  - low and moderate k_t probed by configurations with $\Delta\phi \sim \pi$

Dijet azimuthal distance and rapidity distributions at 7 TeV



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 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