Towards tomography of quark-gluon plasma using double inclusive di-jets in Pb-Pb collisions

Michal Deák

Institute of Nuclear Physics PAN, Kraków

In collaboration with Krzysztof Kutak, IFJ PAN and Konrad Tywoniuk, CERN

arXiv:1706.08434

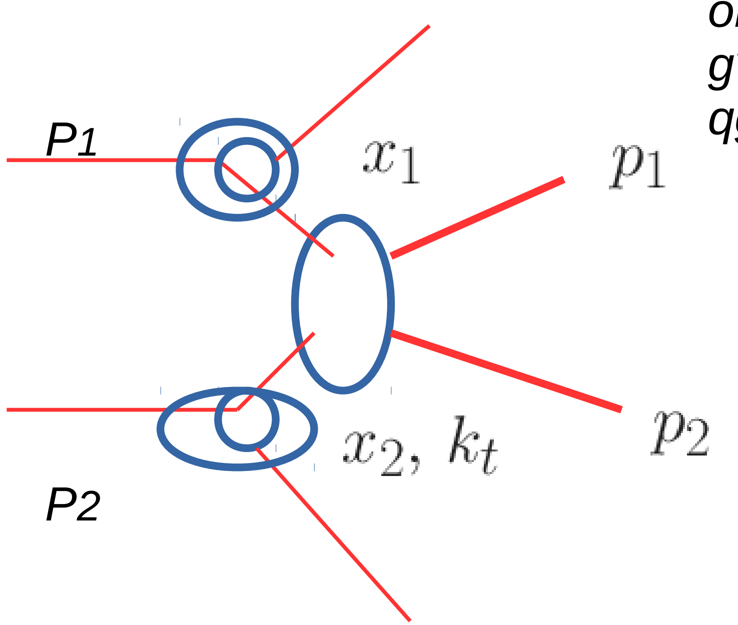
Contents

- Motivation
  - High Energy Factorization (HEF)
- Multiple soft scattering
- HEF in heavy ion collisions
- Numerical results
- Conclusions and Outlook

First attempt: hybrid factorization and dijets
High energy factorization and forward jets

$$\frac{d\sigma_{\rm SPS}^{P_1P_2\to {\rm dijets}+X}}{dy_1 dy_2 dp_{1t} dp_{2t} d\Delta\phi} = \frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2 \quad \mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$

conjecture
Deak, Jung, Kutak, Hautmann '09



obtained from CGC after neglecting all nonlinearities
*g*g → gg Iancu,Laidet*
qg → qg Van Hameren, Kotko, Kutak, Marquet, Petreska, Sapeta*

resummation of logs of x

logs of hard scale

knowing well parton densities at large x one can get information about low x physics

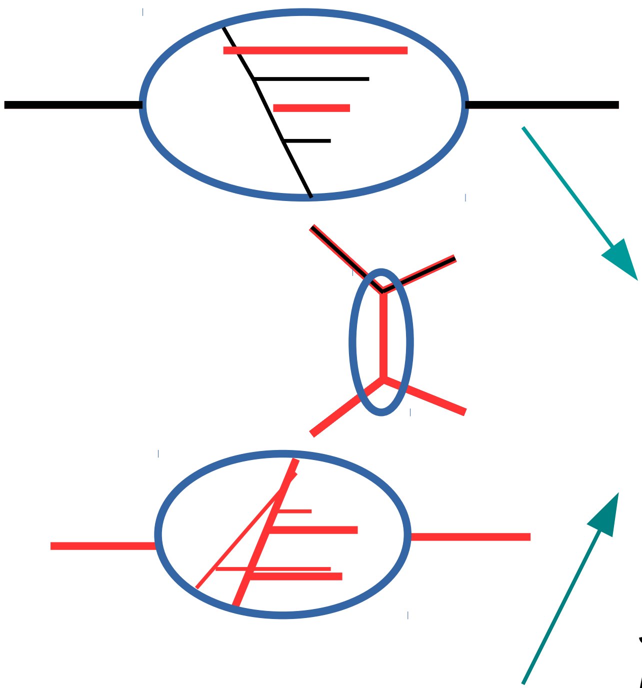
$$x_1 = \frac{1}{\sqrt{s}}\left(|\vec{p}_{1t}|e^{y_1} + |\vec{p}_{2t}|e^{y_2}\right) \qquad\longrightarrow\qquad x_1 \sim 1$$

$$x_2 = \frac{1}{\sqrt{s}}\left(|\vec{p}_{1t}|e^{-y_1} + |\vec{p}_{2t}|e^{-y_2}\right) \qquad\qquad x_2 \ll 1$$

Inbalance momentum:

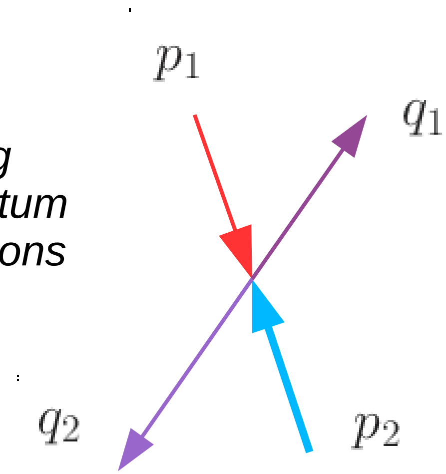
$$|\vec{k}_t|^2 = |\vec{p}_{1t}+\vec{p}_{2t}|^2 = |\vec{p}_{1t}|^2 + |\vec{p}_{2t}|^2 + 2|\vec{p}_{1t}||\vec{p}_{2t}|\cos\Delta\phi$$

hybrid High Energy Factorization

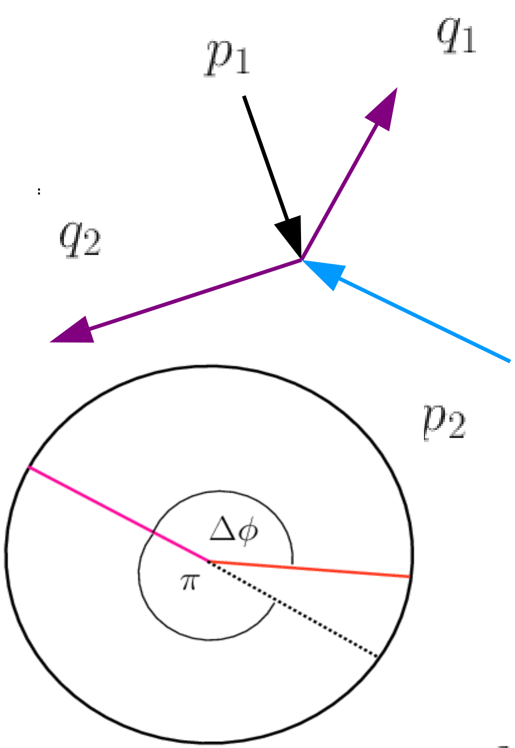


Strongly decreasing transversal momentum of DGLAP like partons

Strongly decreasing Longitudinal momentum fractions of off-shell partons



$$p_1 + p_2 = q_1 + q_2$$



$$p_1 + p_2 = q_1 + q_2 + k$$

High Energy Factorization (HEF)

- Hybrid HEF formula for Pb-Pb collision:

M.D., K. Kutak, K. Tywoniuk, arXiv:1706.08434

$$\frac{d\sigma_{acd}}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta\phi} = \frac{p_{t1} p_{t2}}{8\pi^2 (x_1 x_2 S)^2} \overline{|\mathcal{M}_{ag^* \to cd}|}^2 x_1 f_{a/A}^{Pb}(x_1, \mu^2)\, \mathcal{F}_{g/B}^{Pb}(x_2, k_t^2, \mu^2) \frac{1}{1 + \delta_{cd}}$$

- Exact kinematics at leading order in α_s
  - Jets not necessarily back to back
- Transversal momentum dependent (TMD) nuclear parton density function (nPDF)

$$\mathcal{F}_{g/B}^{Pb}(x_2, k_t^2, \mu^2)$$

Kimber, Martin, Ryskin;
Watt, Martin, Ryskin

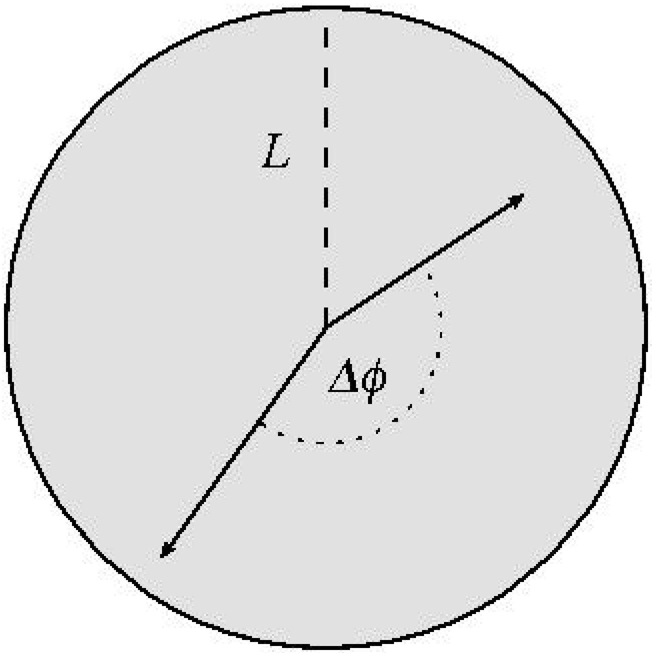
- Collinear nPDF

$$x_1 f_{a/A}^{Pb}(x_1, \mu^2)$$

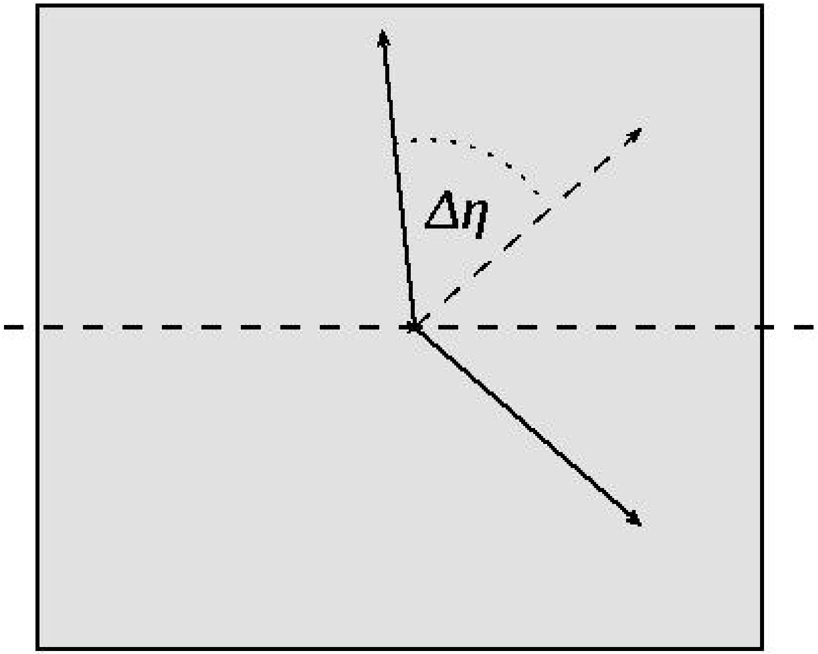
- Implemented in the Monte Carlo program **`KaTie`** (used in this analysis)

A. van Hameren, arXiv:1611.00680

Jets passing through the medium



Azimuthal cross section of the medium



Longitudinal cross section of the medium

- Kinematics:

$$k_t^2 = p_{t1}^2 + p_{t2}^2 + 2p_{t1}p_{t2}\cos\Delta\phi, \text{ and}$$

$$x_1 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{y_1} + p_{t2}e^{y_2}\right)\,, \qquad x_2 = \frac{1}{\sqrt{S}}\left(p_{t1}e^{-y_1} + p_{t2}e^{-y_2}\right)$$

Multiple Soft Scattering (MSS)

- Emission spectrum of medium induced bremsstrahlung in MSS:

$$\omega \frac{dI_R(\chi)}{d\omega} = \frac{\alpha_s C_R}{\omega^2} 2\mathrm{Re} \int^{\chi\omega} \frac{d^2\boldsymbol{q}}{(2\pi)^2} \int_0^\infty dt' \int_0^{t'} dt \int d^2\boldsymbol{z} \exp\left[-i\boldsymbol{q}\cdot\boldsymbol{z} - \frac{1}{2}\int_{t'}^\infty \mathrm{d}s\, n(s)\sigma(\boldsymbol{z})\right] \\ \times \partial_{\boldsymbol{z}} \cdot \partial_{\mathbf{y}} \left[\mathcal{K}(\boldsymbol{z},t';\mathbf{y},t|\omega) - \mathcal{K}_0(\boldsymbol{z},t';\mathbf{y},t|\omega)\right]_{\mathbf{y}=0} ,$$

with

$$\mathcal{K}(\boldsymbol{z},t';\mathbf{y},t|\omega) = \int_{\boldsymbol{r}(t)=\mathbf{y}}^{\boldsymbol{r}(t')=\boldsymbol{z}} \mathcal{D}\boldsymbol{r} \exp\left\{\int_t^{t'} \mathrm{d}s \left[i\frac{\omega}{2}\dot{\boldsymbol{r}}^2 - \frac{1}{2}n(s)\sigma(\boldsymbol{r})\right]\right\}$$

- Describes propagation of a quark through nuclear medium
- Gluon emission spectrum in MSS:

$$P_R(\epsilon) = \Delta(L) \sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \int_0^L \mathrm{d}t \int \mathrm{d}\omega_i \frac{\mathrm{d}I_R(\chi)}{\mathrm{d}\omega_i \mathrm{d}t} \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i\right)$$

- Probability resulting from resummation of in medium emissions
- “Drag” in the longitudinal direction – transversal momentum “kicks” neglected

$$n(s)\sigma(\boldsymbol{r}) \approx \hat{q}(s)\boldsymbol{r}^2/2$$

harmonic oscillator approximation

$$\hat{q} \sim g^4 T^3$$

transport coefficient

C. Salgado, U. Wiedemann, Phys.Rev. D68 (2003) 014008

HEF in Heavy Ion Collisions

- Cross section formula with medium effects included:

M.D., K. Kutak, K. Tywoniuk, arXiv:1706.08434

$$\frac{d\sigma}{dy_1 dy_2 dp_{t1} dp_{t2} d\Delta\phi} = \sum_{a,c,d} \int_0^\infty d\epsilon_1 \int_0^\infty d\epsilon_2 \, P_a(\epsilon_1) P_g(\epsilon_2) \left. \frac{d\sigma_{acd}}{dy_1 dy_2 dp'_{t1} dp'_{t2} d\Delta\phi} \right|_{\substack{p'_{1t}=p_{1t}+\epsilon_1 \\ p'_{2t}=p_{2t}+\epsilon_2}}$$

$$P(\xi, r) = C_1 \, \delta(\xi) + C_2 \, D(\xi, r)$$

$$\xi = \epsilon/\omega_c \text{ with } \omega_c = \hat{q}L^2/2$$

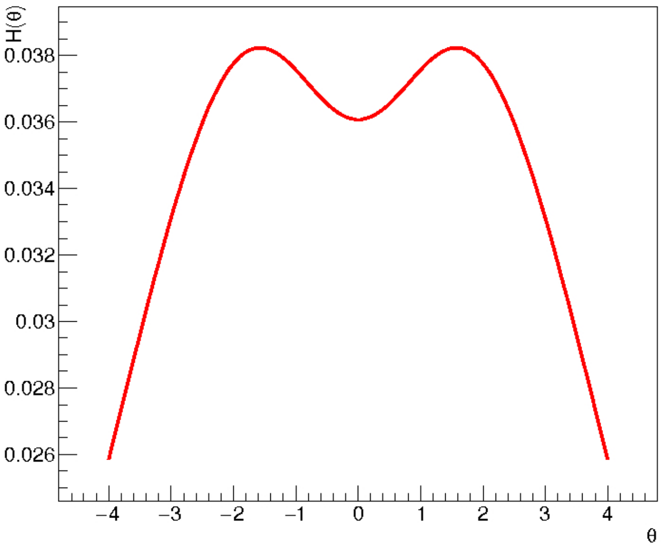
$$r = \hat{q}L^3/2$$

- Probability density has 2 components:
  - discrete – no-suppression ↔ coefficient C_1
  - continuous ↔ coefficient C_2

- Algorithm:
  1. generate random $0 < R < 1$
     if $R < C_1$ no suppression occurs $\xi = 0$; go to next event
     else
  2. generate ξ according to $D(\xi, r)$; go to next event

Model of rapidity dependence and other parameters

- A model of the rapidity dependence of the nuclear medium:



T. Renk, J. Ruppert, C. Nonaka, S. A. Bass, Phys. Rev. C75 (2007) 031902

$$\hat{q} = 2\,K\,\varepsilon^{3/4}$$

$$\varepsilon = \varepsilon_{\mathrm{tot}} W\left(\mathbf{x},\mathbf{y};\mathbf{b}\right)\ H\left(\eta\right)$$

- We neglect the dependence on in impact parameter → $W(\mathbf{x,y;b})=1$
- K=1 (not fitted)
- $\epsilon_{\mathrm{tot}} = 143\ \mathrm{GeV/fm^3}$ total energy density corresponding to $\hat{q}$ = 1 GeV/fm at mid rapidities (not fitted)
- $L = 5\ \mathrm{fm}$ constant

- A fit to ALICE (0 - 5% centrality) data:

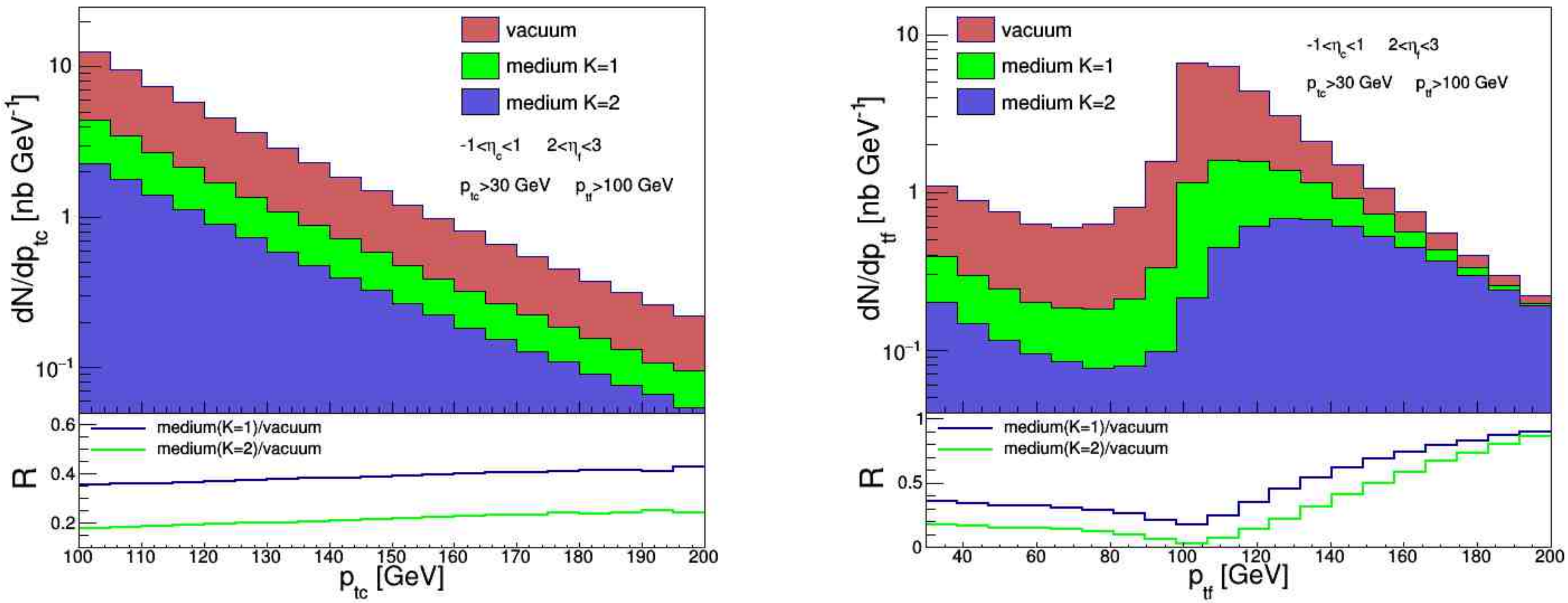
$$H\left(\eta\right) = \frac{1}{\sqrt{2\pi}\left(a_1\,b_1 - a_2\,b_2\right)}\left[a_1\,e^{-|\eta|^2/\left(2\,b_1^2\right)} - a_2\,e^{-|\eta|^2/\left(2\,b_2^2\right)}\right]$$

$$a_1 = 2108.05,\ b_1 = 3.66935,\ a_2 = 486.368,\ b_2 = 1.19377$$

Transversal momenta of jets

$$p_{tc} > 100 \text{ GeV} \qquad p_{tf} > 30 \text{ GeV}$$

$$-1 < \eta_c < 1 \qquad 2 < \eta_f < 3$$

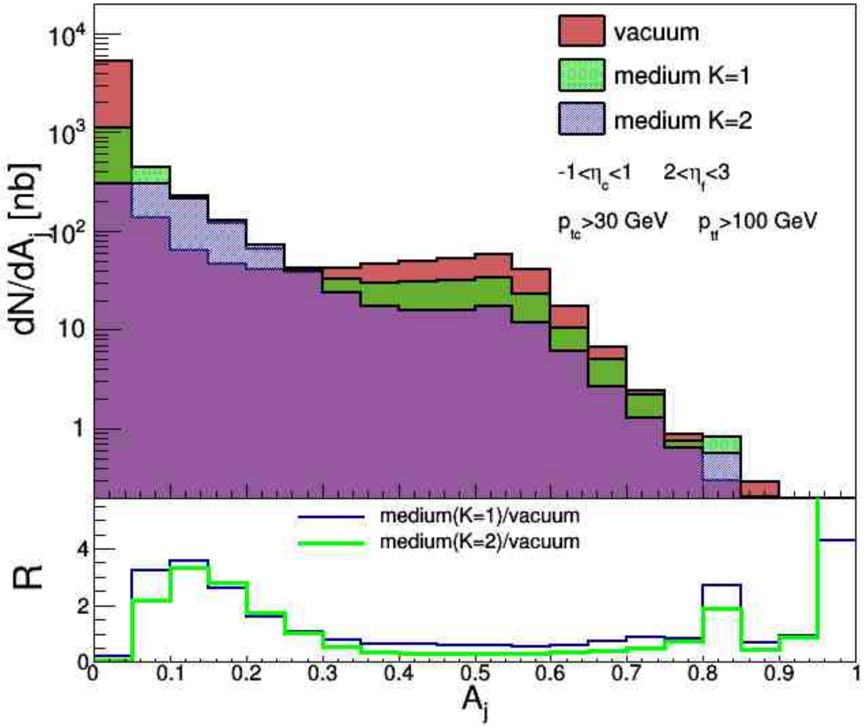


- back-to-back peak in the plot on the right

Relative transversal momentum difference

$p_{tc} > 100 \text{ GeV}$ $p_{tf} > 30 \text{ GeV}$

$-1 < \eta_c < 1$ $2 p_{tc} > 100 \text{ GeV}$



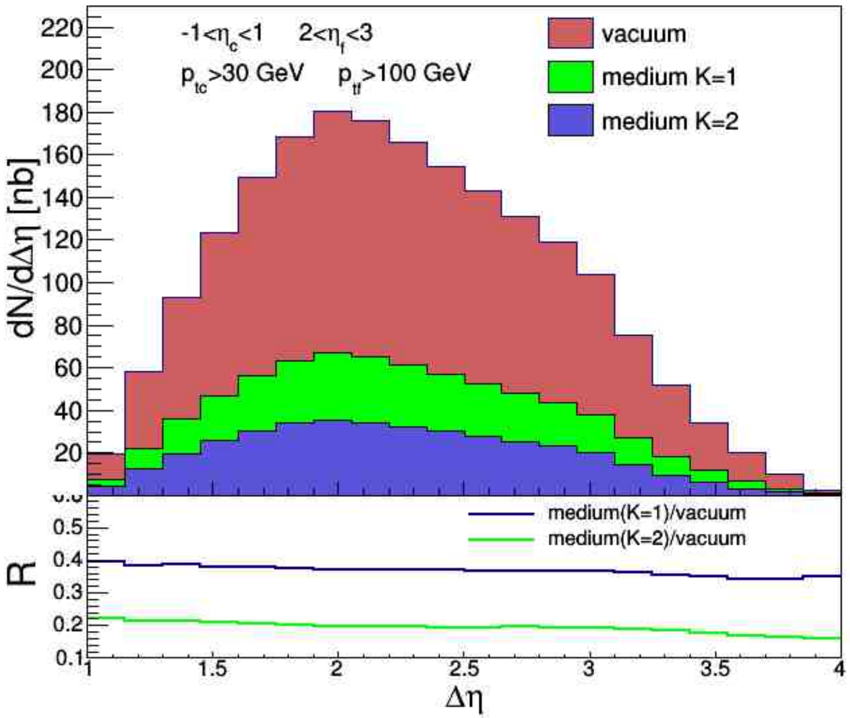
$$A_j = (p_{tc} - p_{tf}) / (p_{tc} + p_{tf})$$

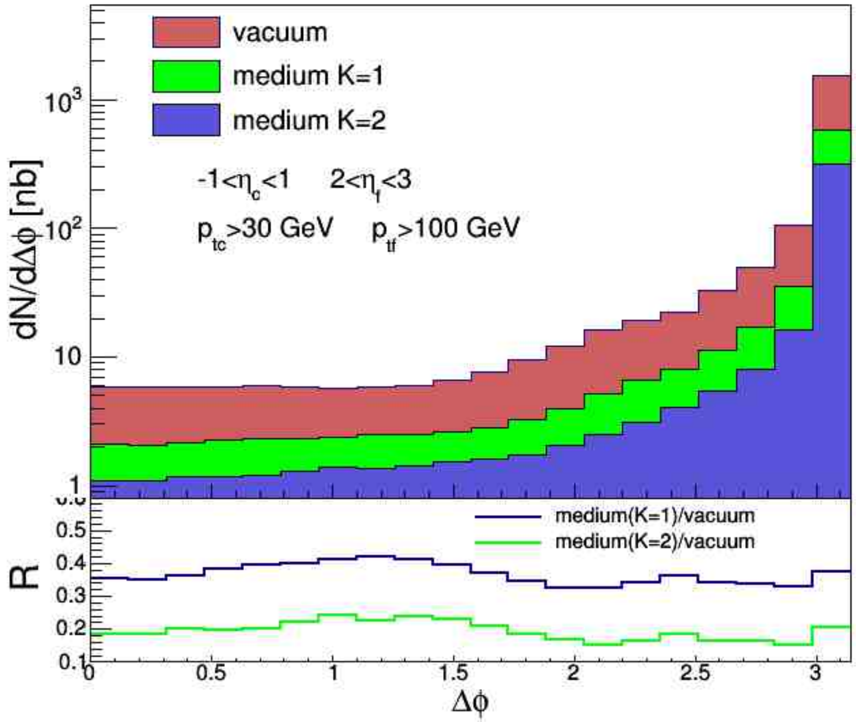
- Nuclear medium is shuffling dijets from back-to-back configuration to less balanced configuration – effect increases with bigger constant K (bigger $\hat{q}$)

Rapidity and azimuthal angle distance

$p_{tc} > 100\ \mathrm{GeV}$ $\qquad p_{tf} > 30\ \mathrm{GeV}$

$-1 < \eta_c < 1$ $\qquad 2 < \eta_f < 3$





- Slow increase of medium suppression with $\Delta\eta$
- “re”-emergence of $\Delta\varphi$ dependence for low $\Delta\varphi$

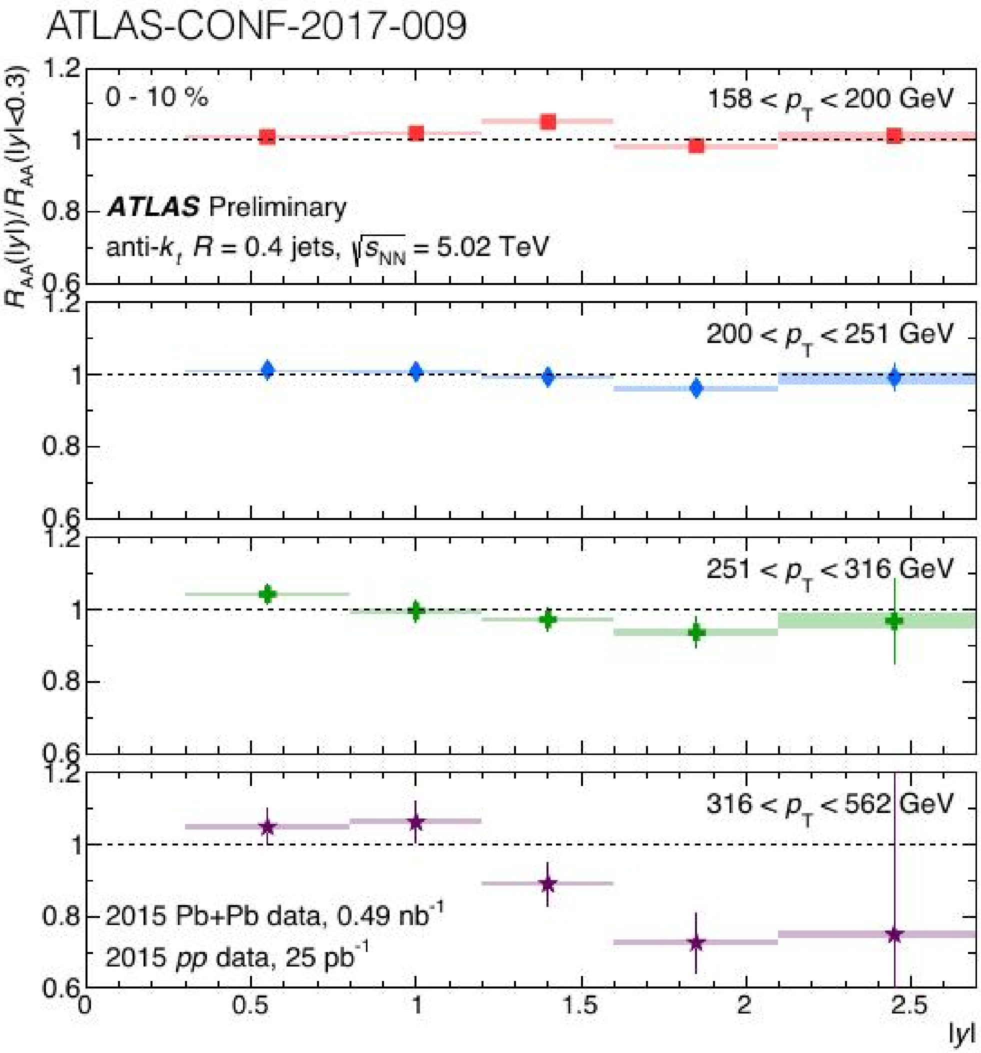
Summary and Outlook

- Implementation of nuclear medium effects into a HEF Monte Carlo program

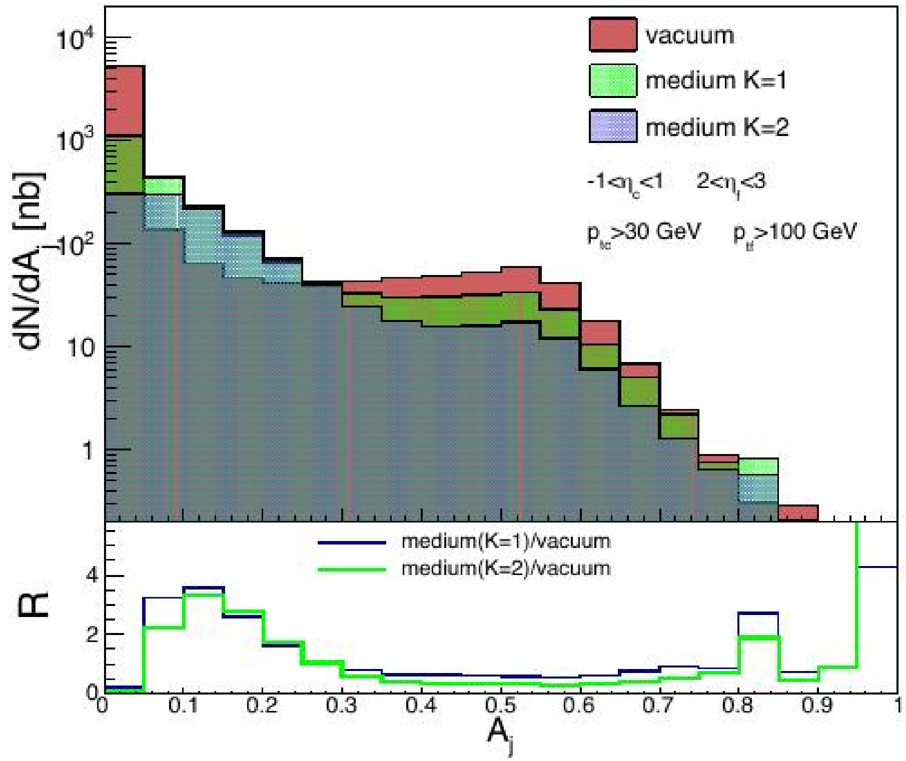
Planned:

- More precise description for nucleus-nucleus collision (impact parameter dependence, event by event treatment, variable medium length)
- Inclusion of saturation effects
  - Complicates the factorization formula
- More precise treatment of the medium jet interactions

Back Up



increasing p_T^{jet}



➡ *proposal for central + forward dijet corr.*

Deak, Kutak, Tywoniuk,
hep-ph/1706.08434

$\underline{R_{AA}(|y|) / R_{AA}(|y|<0.3)}$, measured out to $|y| = \pm 2.7$

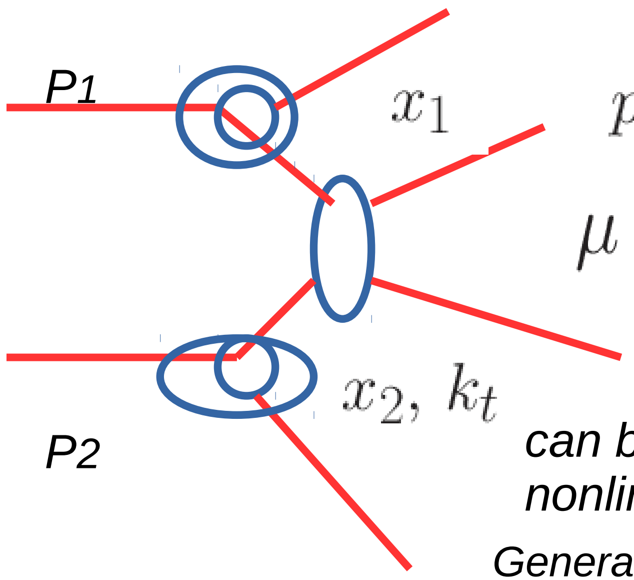
➡ *visible y-dependence for p_T > 300 GeV jets*

➡ *interplay of (1) path length, (2) spectral shape, (3) flavor?*

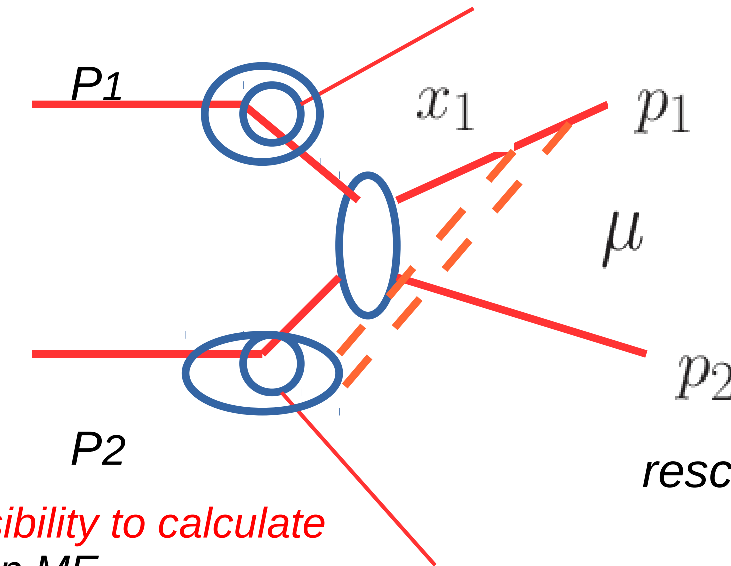
Improved TMD for dijets
High energy factorization and forward jets

$$\frac{d\sigma_{\rm SPS}^{P_1P_2\to {\rm dijets}+X}}{dy_1dy_2dp_{1t}dp_{2t}d\Delta\phi}=\frac{p_{1t}p_{2t}}{8\pi^2(x_1x_2s)^2}\sum_{a,c,d}x_1f_{a/P_1}(x_1,\mu^2)\,|\overline{\mathcal{M}_{ag^*\to cd}}|^2\quad\mathcal{F}_{g/P_2}(x_2,k_t^2)\frac{1}{1+\delta_{cd}}$$

can be be used for estimates of saturation effects.



can be derived but no nonlinearities



rescatterings

Generalization but no possibility to calculate decorelations since no kt in ME
Dominguez, Marquet, Xiao, Yuan '11

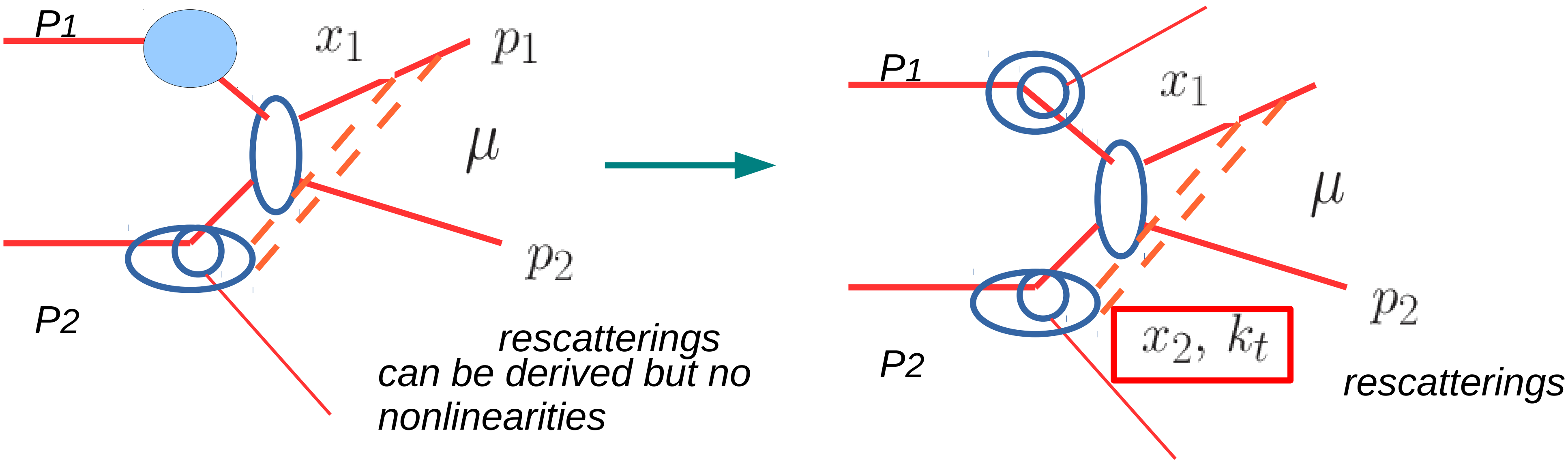
Application to differential distributions in d+Au
Stasto, Xiao, Yuan '11

$$\frac{d\sigma^{pA\to cdX}}{d^2P_td^2k_tdy_1dy_2}=\frac{\alpha_s^2}{(x_1x_2s)^2}\,x_1f_{q/p}(x_1,\mu^2)\sum_{i=1}^{n}\mathcal{F}_{ag}^{(i)}H_{ag\to cd}^{(i)}\frac{1}{1+\delta_{cd}}$$

Improved TMD for dijets

High energy factorization and forward jets

can be be used for estimates of saturation effects



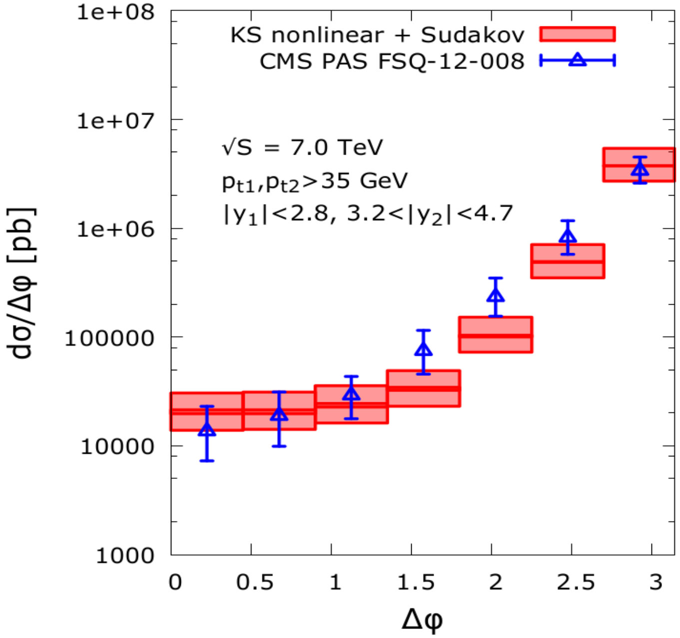
We found a method to include kt in ME and express the factorization formula in terms of gauge invariant sub amplitudes → more direct relation to two fundamental gluon densities: dipole gluon density and Weizacker-Williams gluon density

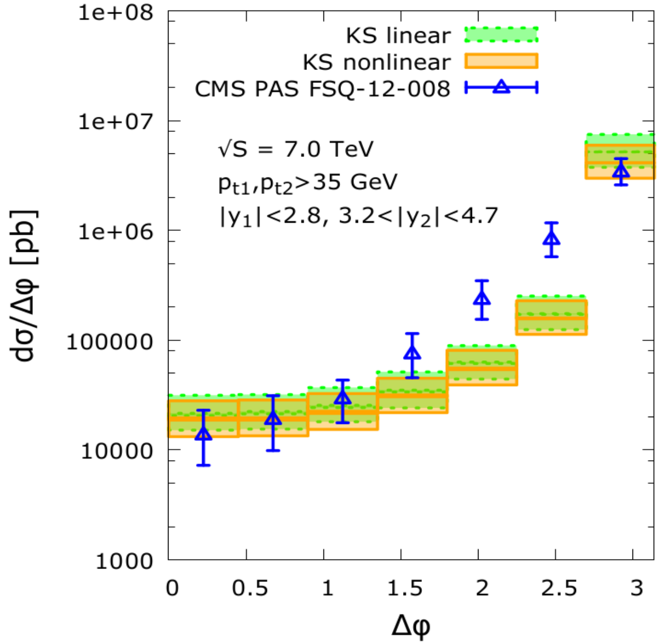
Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15

$$\frac{d\sigma^{pA\to \text{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2)\sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}\Phi^{(i)}_{ag\to cd}\,\frac{1}{1+\delta_{cd}}$$

Decorelations inclusive scenario forward-central

Kotko, K.K, Sapeta, van Hameren '14



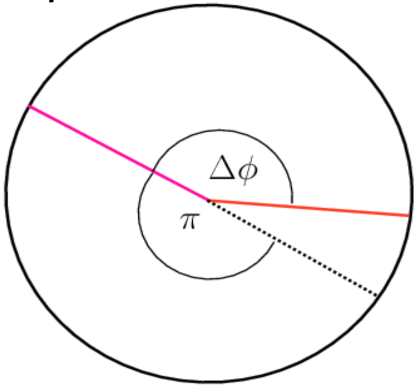


$$p_{t1},\, p_{t2} > 35\, GeV$$

$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

Leading jets, no further requirement



In DGLAP approach i.e 2 →2 + pdf one would get delta function

Observable suggested to study BFKL effects
Sabio-Vera, Schwensen '06

Studied also context of RHIC
Albacete, Marquet '10