

Azimuthal and rapidity correlations of forward-central dijets in heavy ion collisions and TMD PDFs

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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

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

conjecture

Deak, Jung, Kutak, Hautmann '09

obtained from CGC after neglecting all nonlinearities

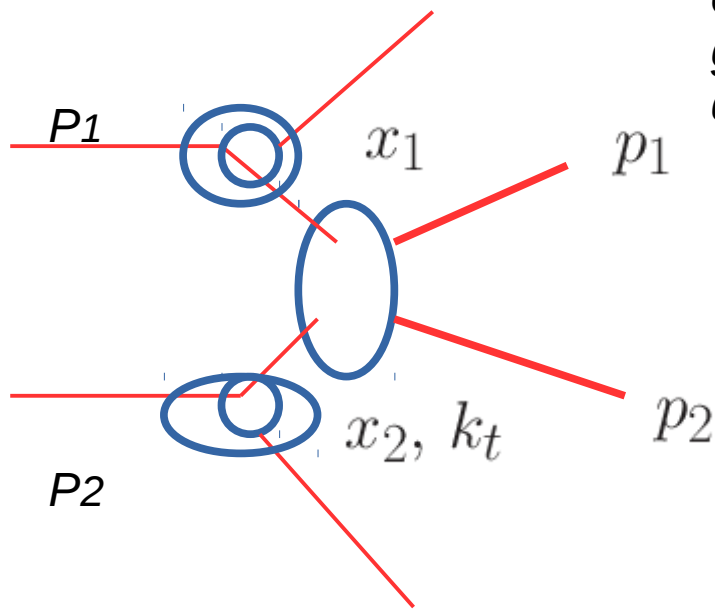
$g^*g \rightarrow gg$ *Iancu, Laidet*

$qg^* \rightarrow qg$ *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



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

$$x_1 \sim 1$$

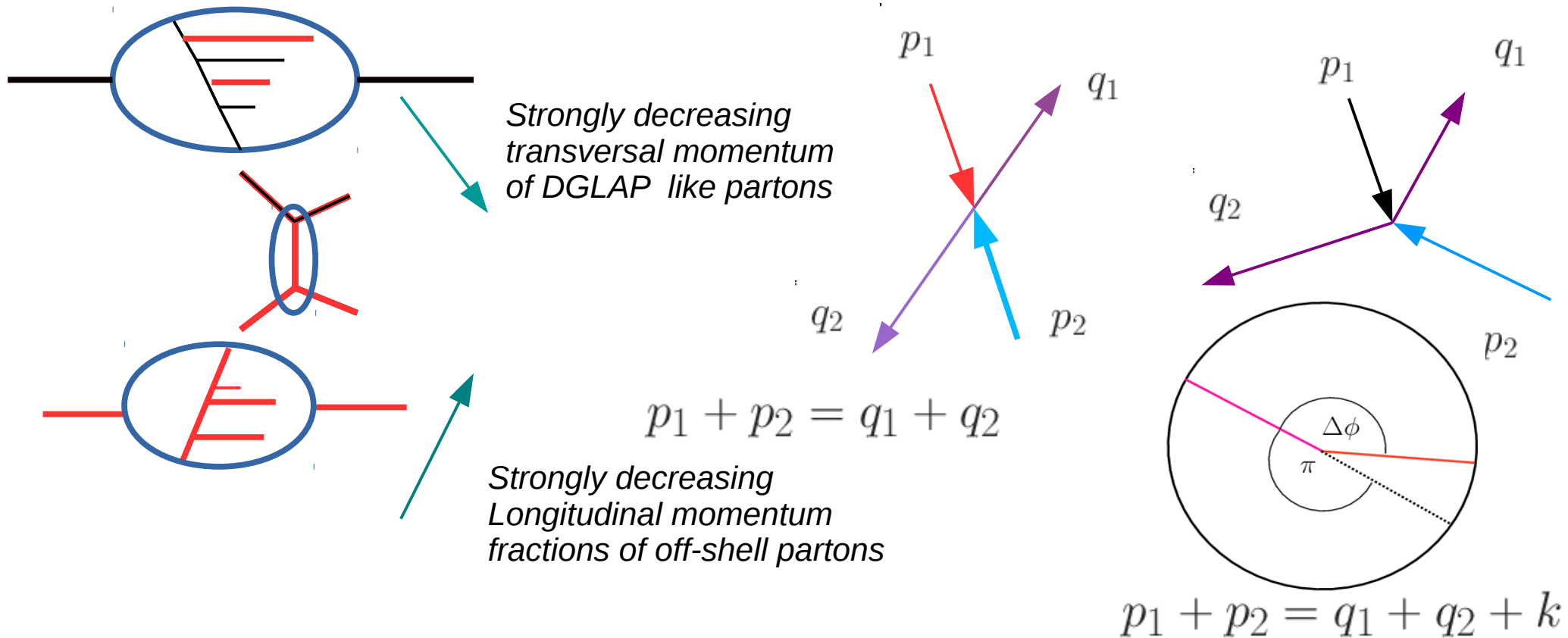
$$x_2 = \frac{1}{\sqrt{s}} (|\vec{p}_{1t}| e^{-y_1} + |\vec{p}_{2t}| e^{-y_2})$$

$$x_2 \ll 1$$

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



High Energy Factorization (HEF)

- Hybrid HEF formula for Pb-Pb collision:

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

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

- 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

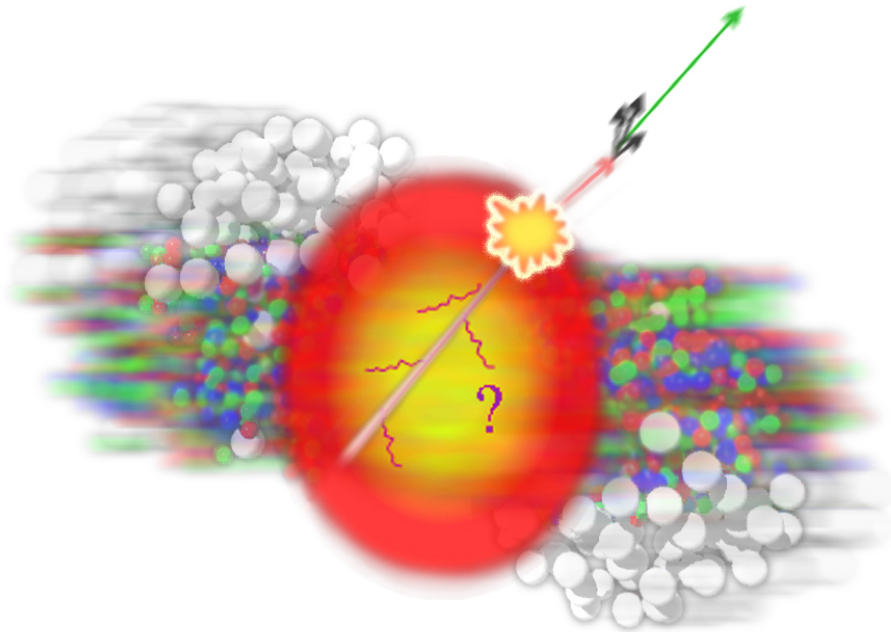
$$x_1 f_{a/A}^{Pb}(x_1, \mu^2)$$

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

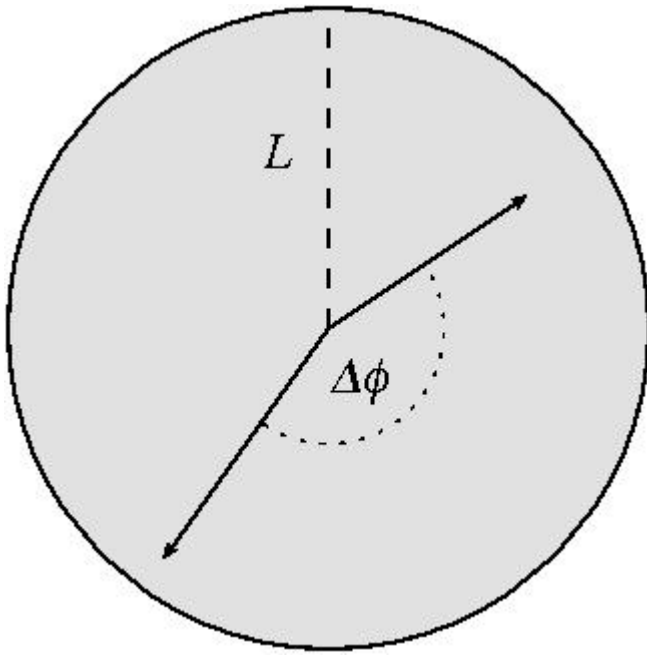
A. van Hameren, arXiv:1611.00680

Quark Gluon Plasma

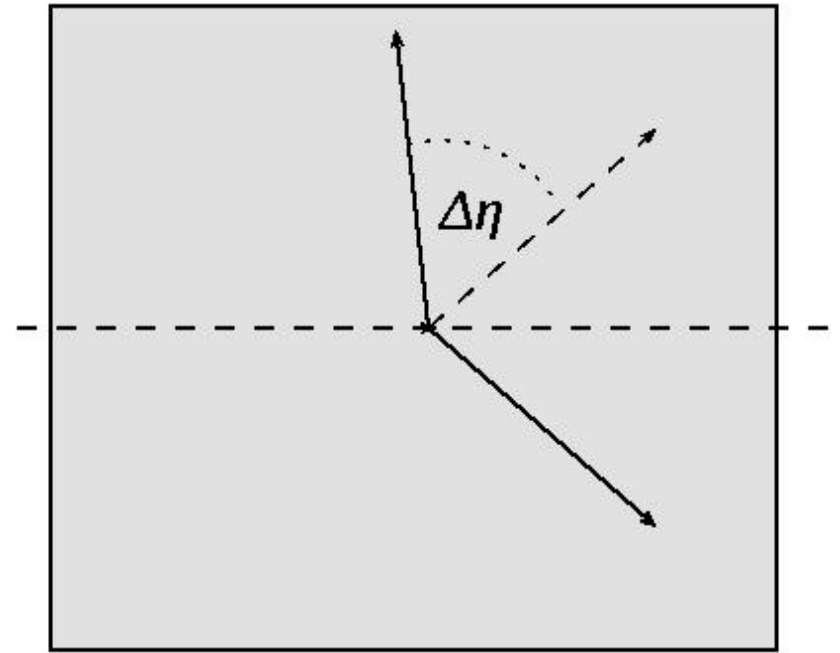
- QCD matter state at high temperature and density
- Asymptotically free quarks and gluons



Jets passing through the medium



Azimuthal cross section of the medium



Longitudinal cross section of the medium

- Kinematics:

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

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

Multiple Soft Scattering (MSS)

- Emission spectrum of medium induced bremsstrahlung in MSS:

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

with

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

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

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

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

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

harmonic oscillator
approximation

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

**transport
coefficient**

HEF in Heavy Ion Collisions

- Cross section formula with medium effects included:

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

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

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

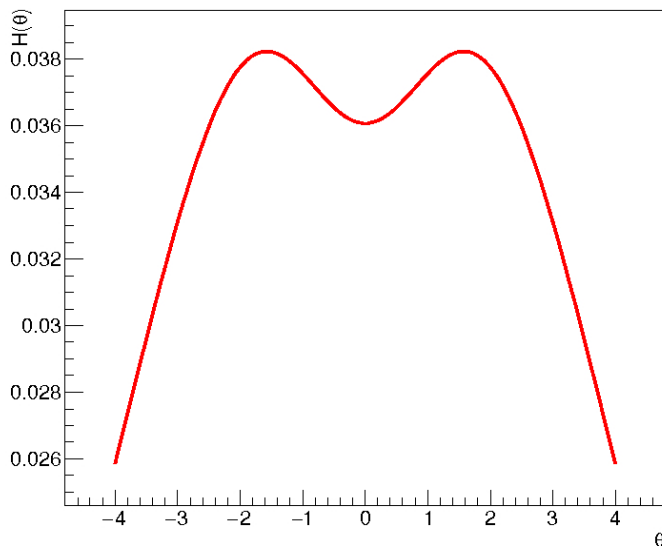
$$\xi = \epsilon/\omega_c \text{ with } \omega_c = \hat{q}L^2/2$$

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

- Probability density has 2 components:
 - discrete – no-suppression \leftrightarrow coefficient C_1
 - continuous \leftrightarrow 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

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

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

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

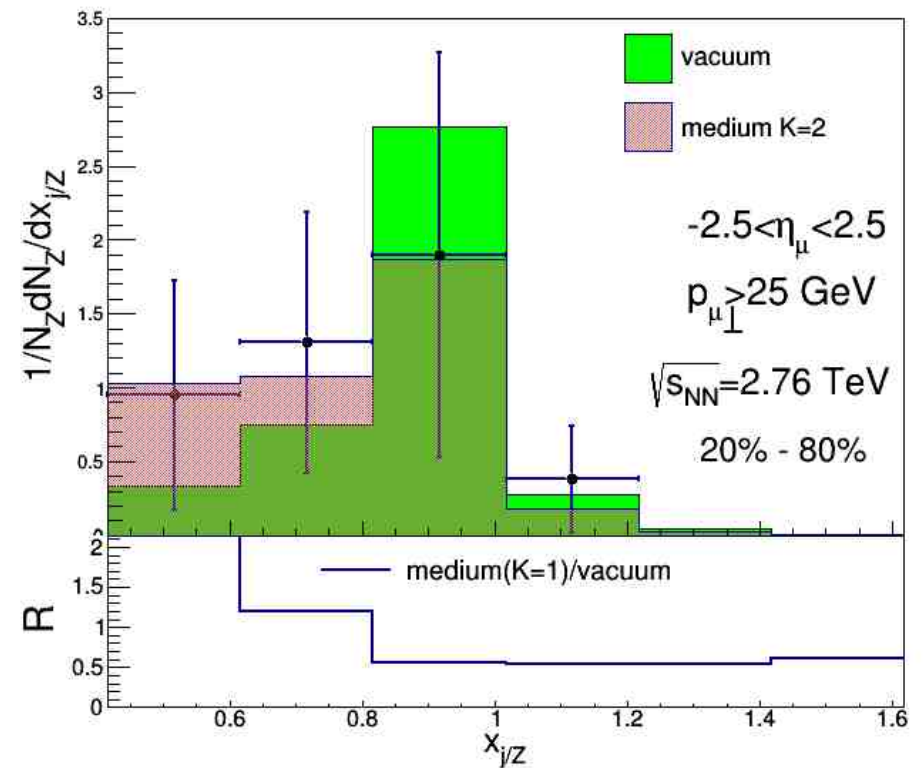
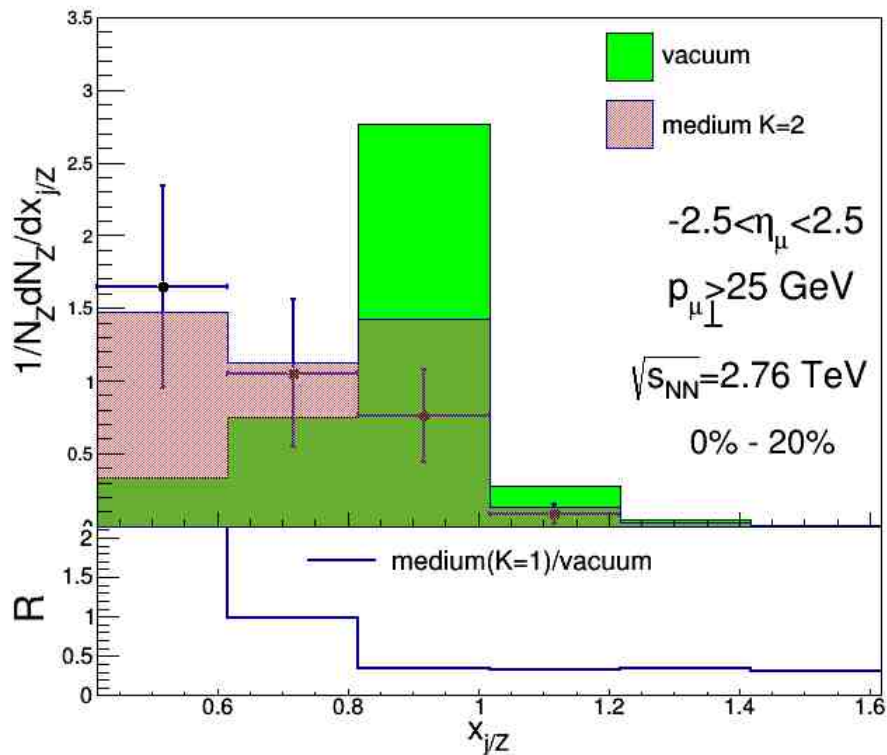
- A fit to ALICE (0 - 5% centrality) data:

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

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

Comparison of the model with Z + jet central rapidity data

- Z (colorless object) instead of one of the jets
- $x_{j/Z} = p_{j\perp}/p_{Z\perp}$

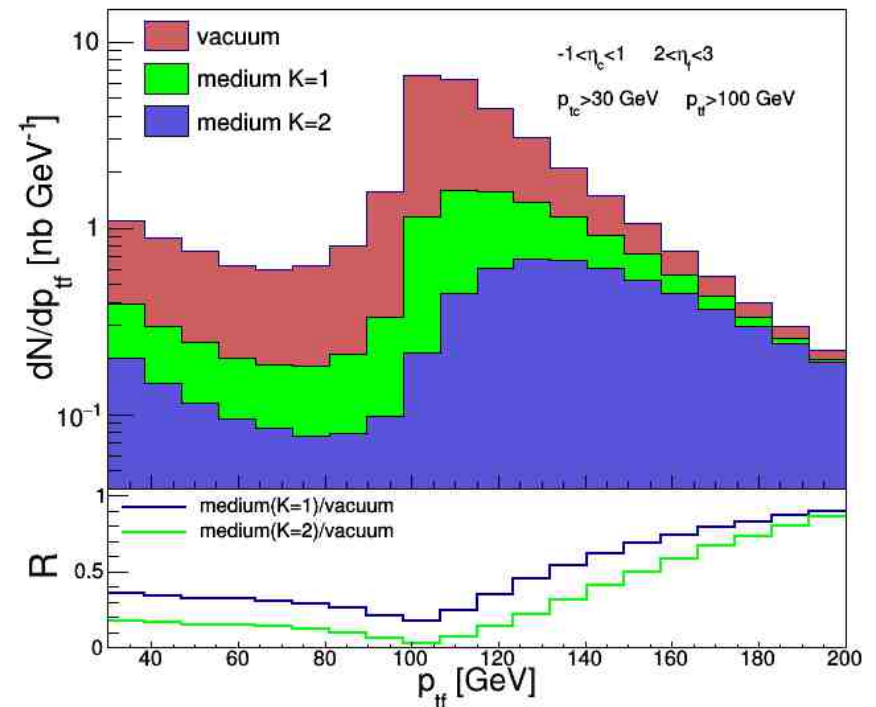
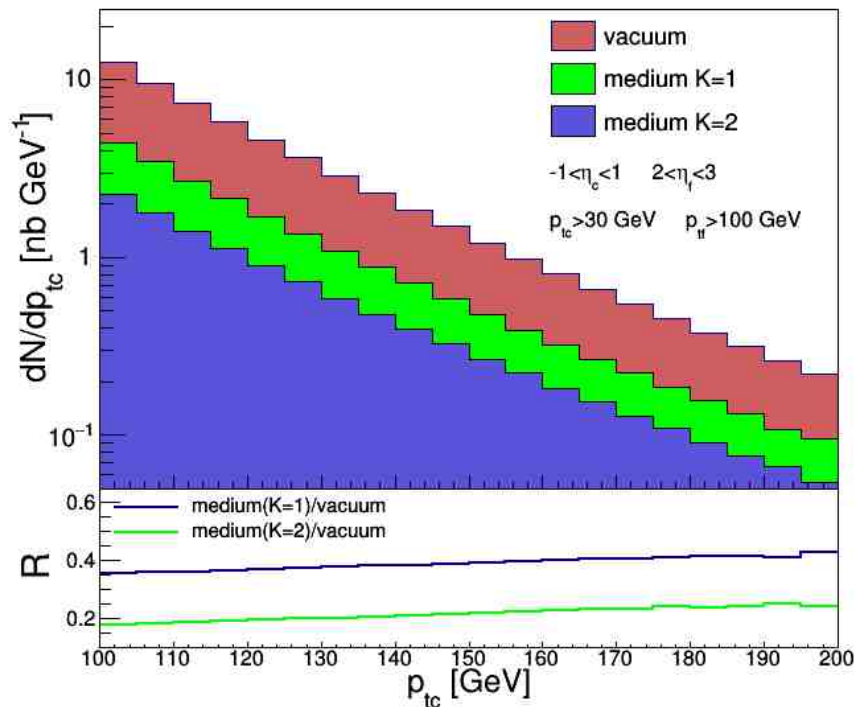


preliminary

Transversal momenta of jets

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

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



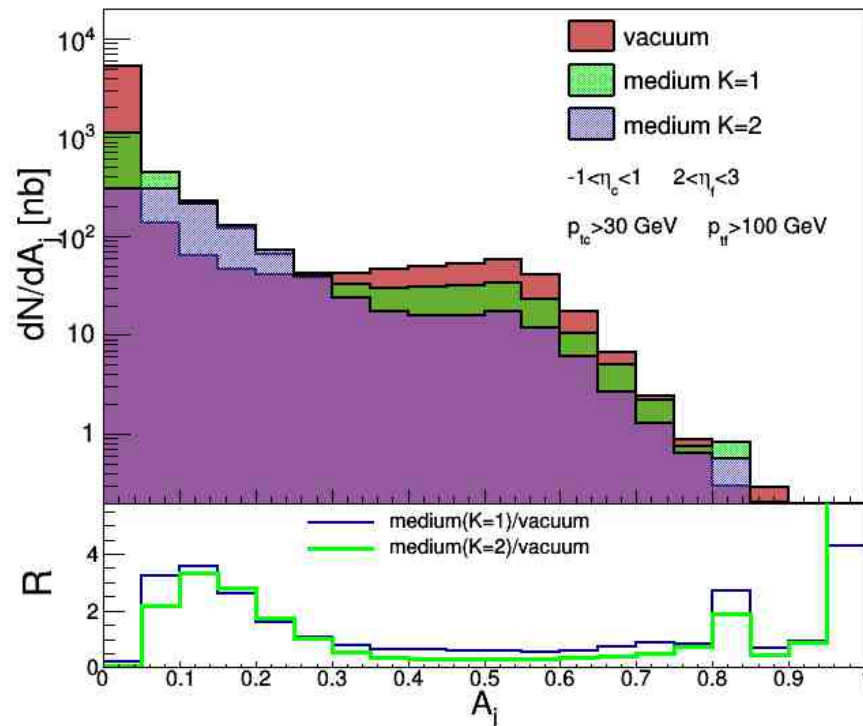
- back-to-back peak in the plot on the right

Relative transversal momentum difference

$$p_{t_c} > 100 \text{ GeV} \quad p_{t_f} > 30 \text{ GeV}$$

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

$$2p_{t_c} > 100 \text{ GeV}$$



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

$$A_j = (p_{t_c} - p_{t_f}) / (p_{t_c} + p_{t_f})$$

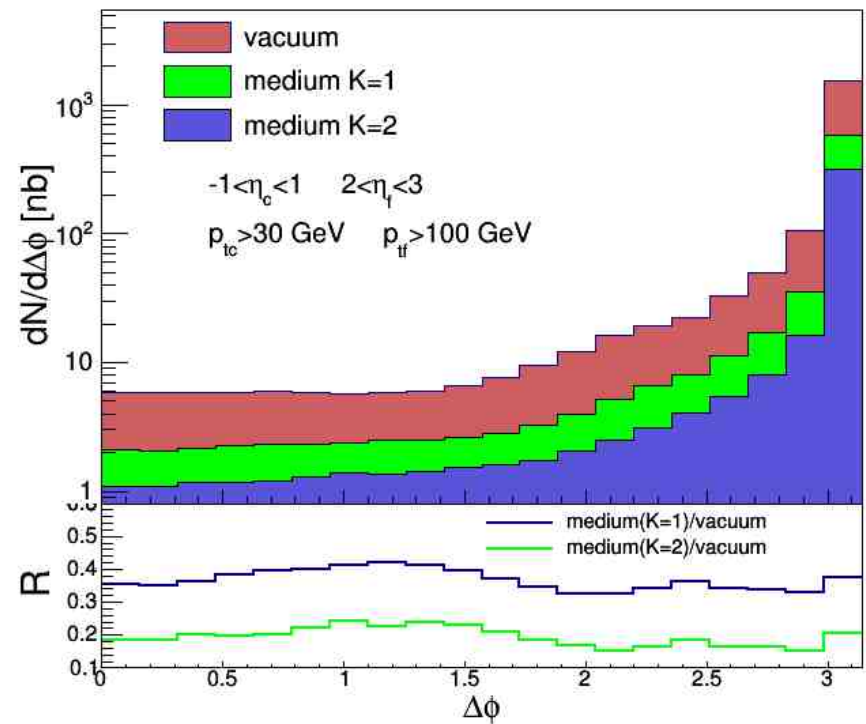
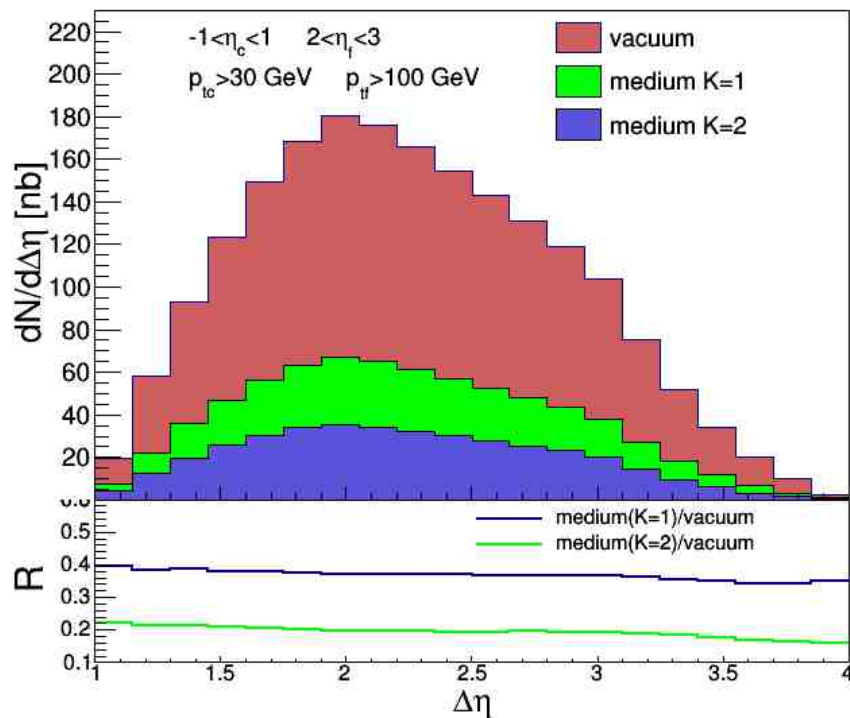
Rapidity and azimuthal angle distance

$$p_{t_c} > 100 \text{ GeV}$$

$$-1 < \eta_c < 1$$

$$p_{t_f} > 30 \text{ GeV}$$

$$2 < \eta_f < 3$$



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

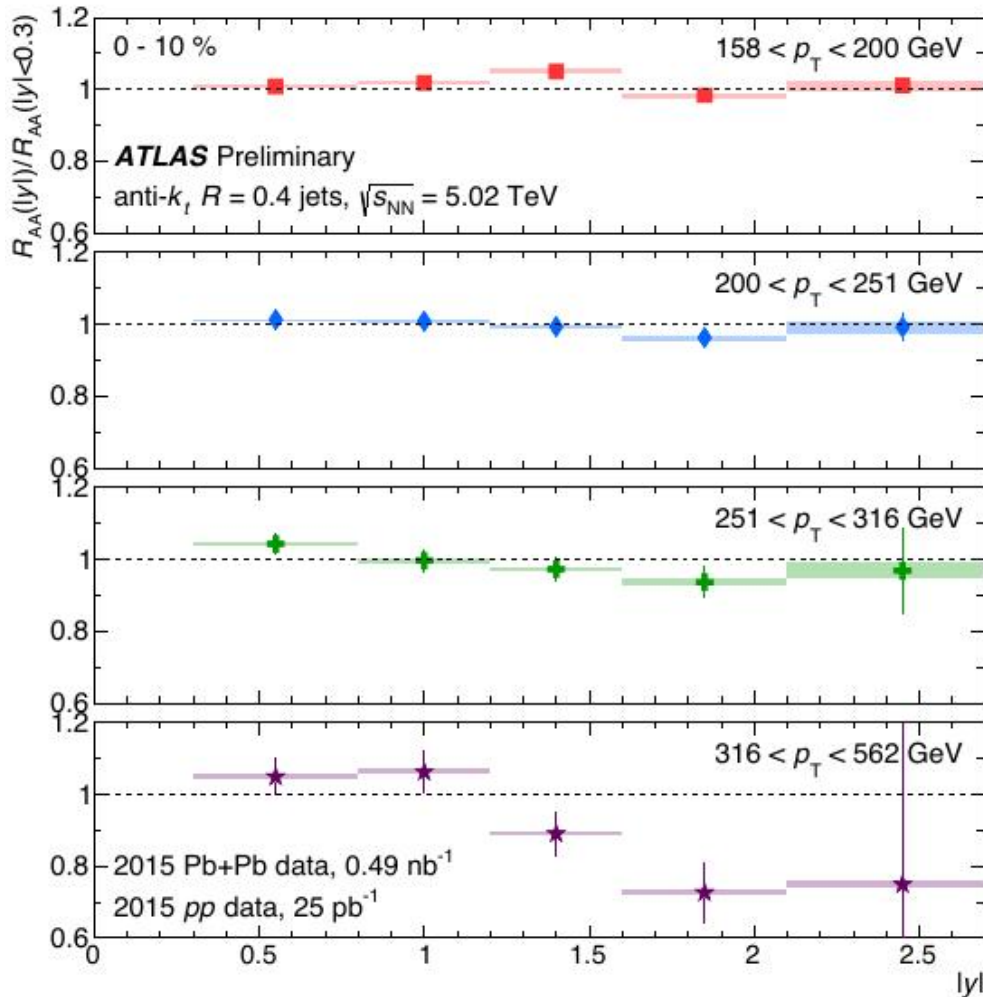
Summary and Outlook

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

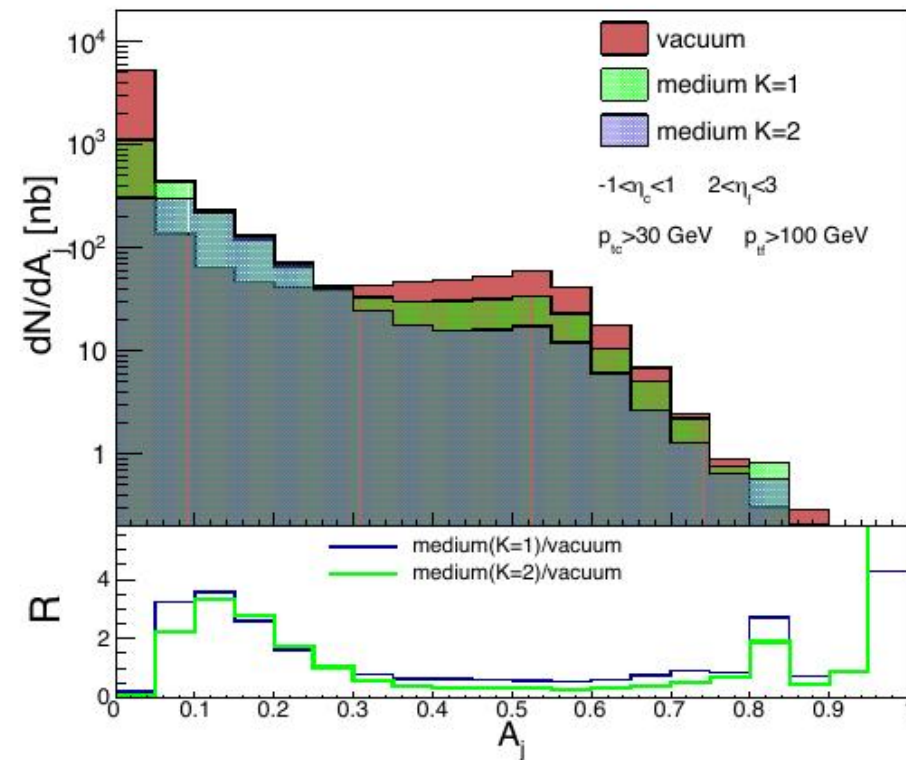
Planned:

- 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_{Tjet}



→ *proposal for central + forward dijet corr.*

Deak, Kutak, Tywoniuk,
[hep-ph/1706.08434](https://arxiv.org/abs/hep-ph/1706.08434)

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

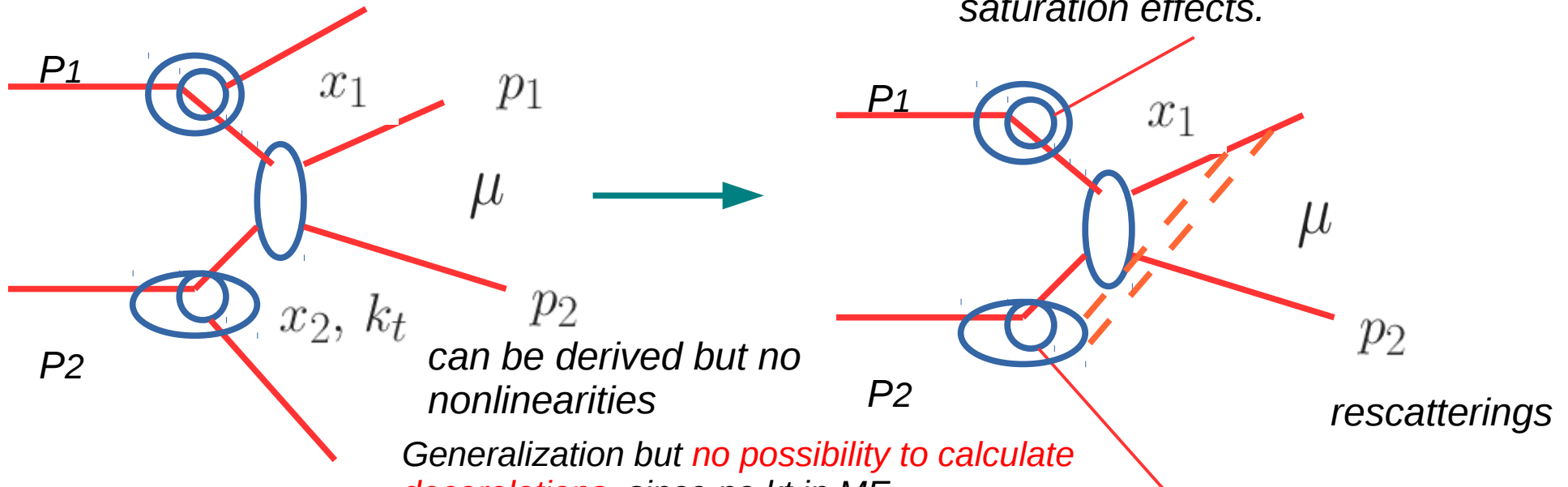
→ *visible y -dependence for $p_T > 300$ GeV jets*

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

Improved TMD for dijets High energy factorization and forward jets

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

can be used for estimates of saturation effects.

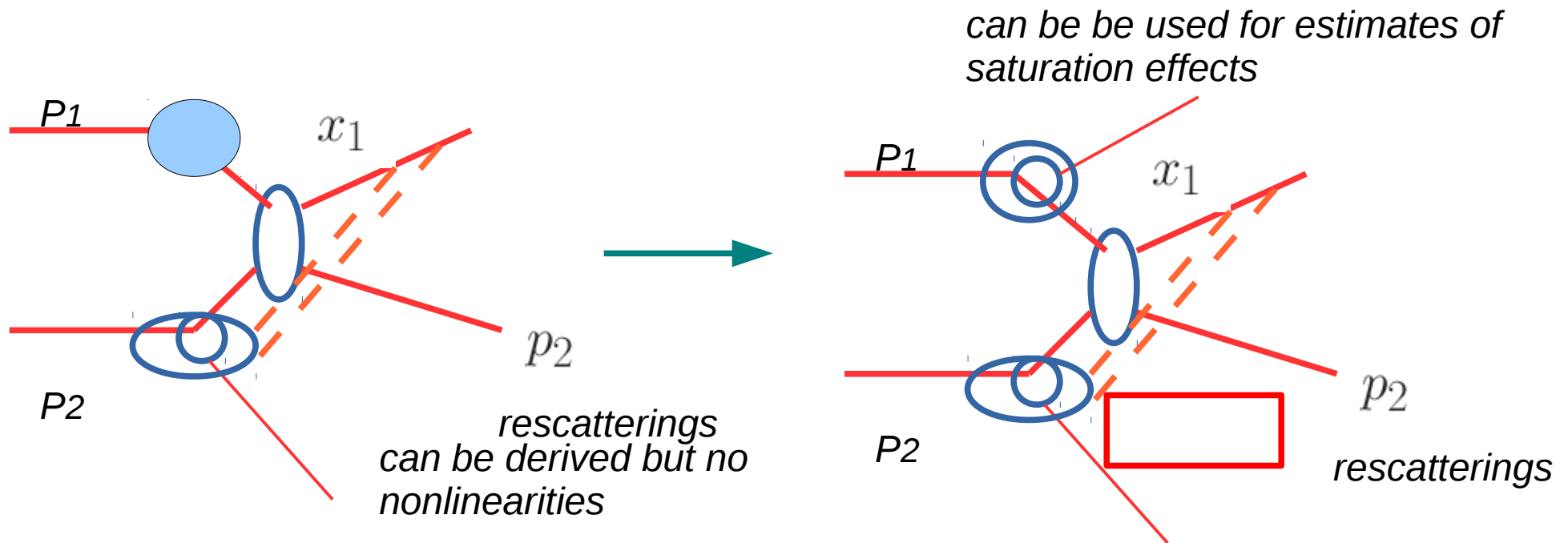


Dominguez, Marquet, Xiao, Yuan '11

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

$$\frac{d\sigma^{pA \rightarrow cdX}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} x_1 f_{q/p}(x_1, \mu^2) \sum_{i=1}^n \mathcal{F}_{ag}^{(i)} H_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}$$

Improved TMD for dijets High energy factorization and forward jets

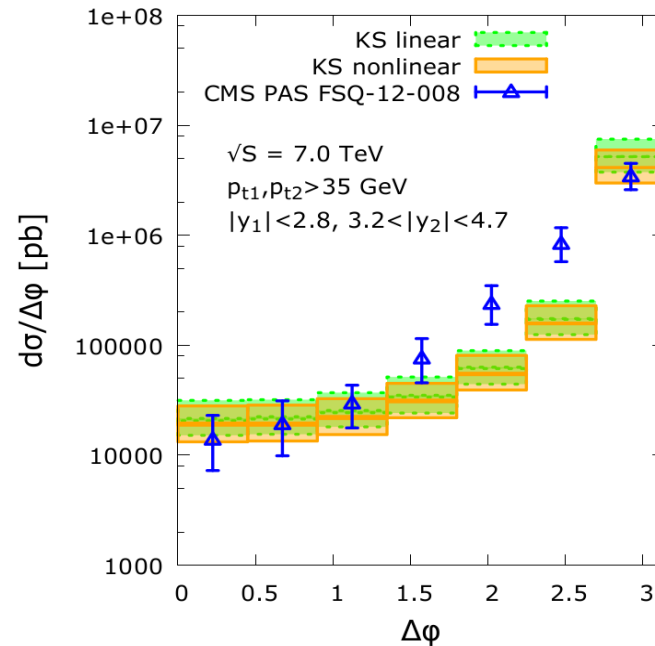
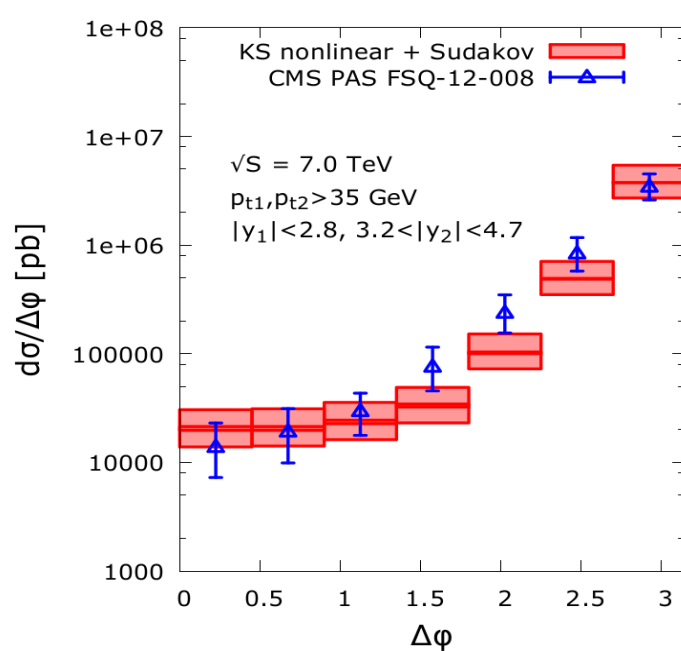


We found a method to include k_t in ME and express the factorization formula in terms of gauge invariant sub amplitudes \rightarrow more direct relation to two fundamental gluon densities: **dipole gluon density** and **Weizacker-Williams gluon density**
 Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren '15

$$\frac{d\sigma^{pA \rightarrow \text{dijets} + X}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1, \mu^2) \sum_{i=1}^2 K_{ag^* \rightarrow cd}^{(i)} \Phi_{ag \rightarrow cd}^{(i)} \frac{1}{1 + \delta_{cd}}$$

Decorelations inclusive scenario forward-central

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

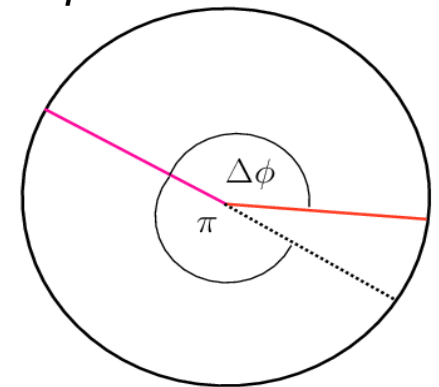


$$p_{t1}, p_{t2} > 35 \text{ GeV}$$

$$3.2 < |y_2| < 4.7$$

$$|y_1| < 2.8$$

Leading jets, no further requirement



In DGLAP approach
i.e $2 \rightarrow 2$ + pdf one would get delta
function

Observable suggested to
study BFKL effects

Sabio-Vera, Schwensen '06

Studied also context of RHIC

Albacete, Marquet '10