

Dijets in heavy ion collisions and the rapidity dependence of the nuclear medium

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 - High Energy Factorization (HEF)
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High Energy Factorization (HEF)

- Hybrid HEF formula for Pb-Pb collision:

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

- ! integrate over momentum fractions, initial state transversal momentum !
- Exact kinematics at leading order in α_s
 - Jets not necessarily back to back
- Transversal momentum dependent (TMD) nuclear parton density function (nPDF)

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

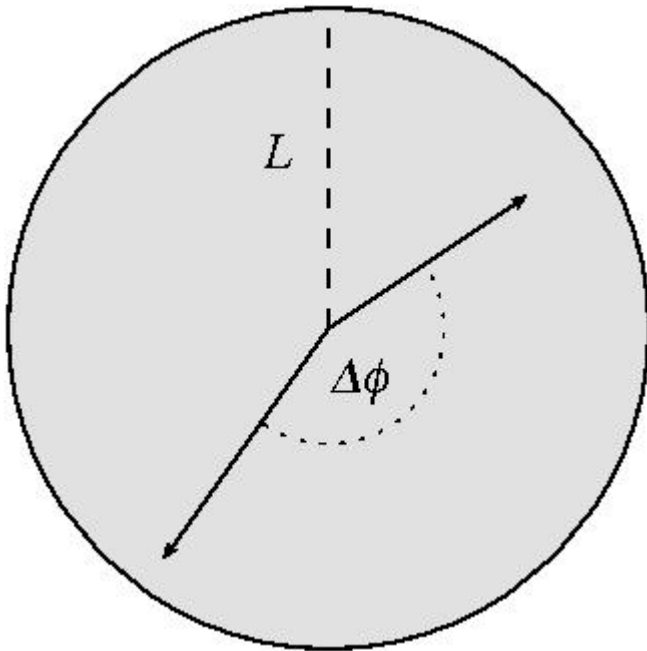
- Collinear nPDF

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

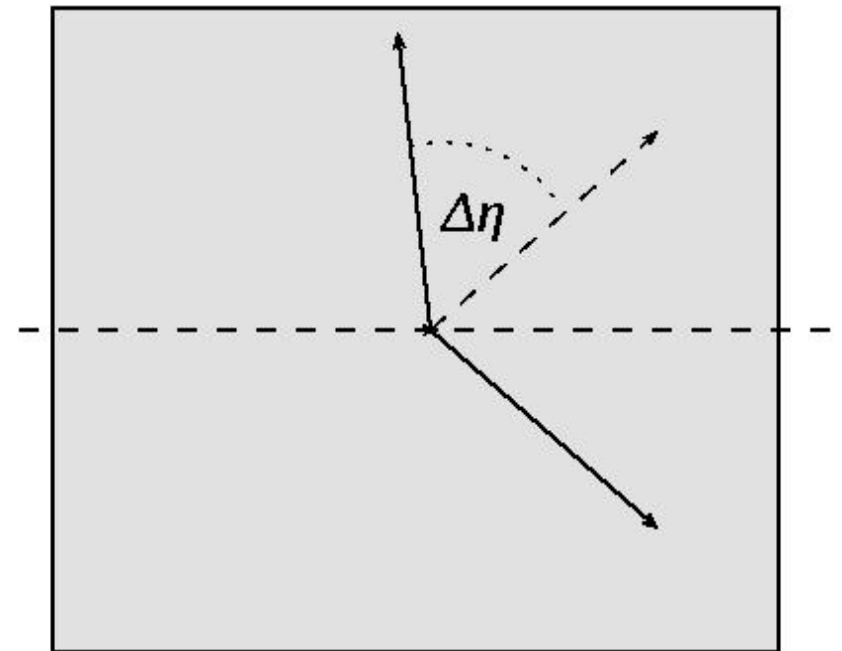
- Implemented in the Monte Carlo program **KaTie** (used in this analysis)

A. van Hameren, arXiv:1611.00680

Jets passing through the medium



Azimuthal cross section of the medium



Longitudinal cross section of the medium

- Kinematics:

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

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

Multiple Soft Scattering (MSS)

- Emission spectrum of medium induced bremsstrahlung in MSS:

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

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
- Glueon 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:

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

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

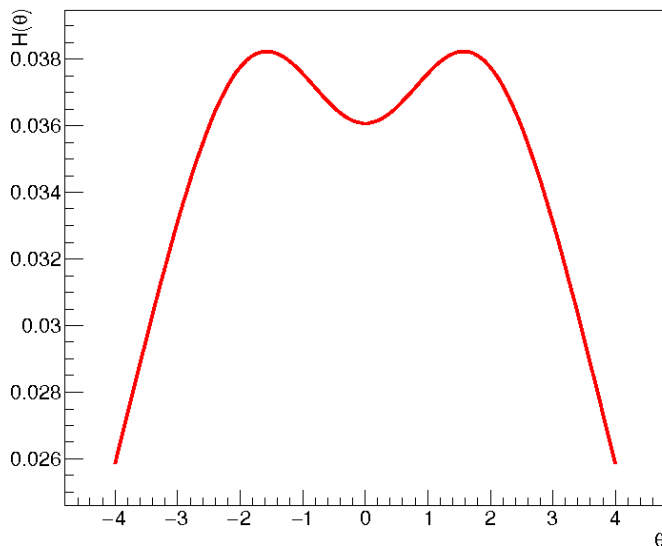
$$\xi = \epsilon/\omega_c \text{ with } \omega_c = \hat{q}L^2/2$$

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

- 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:



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

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

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

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

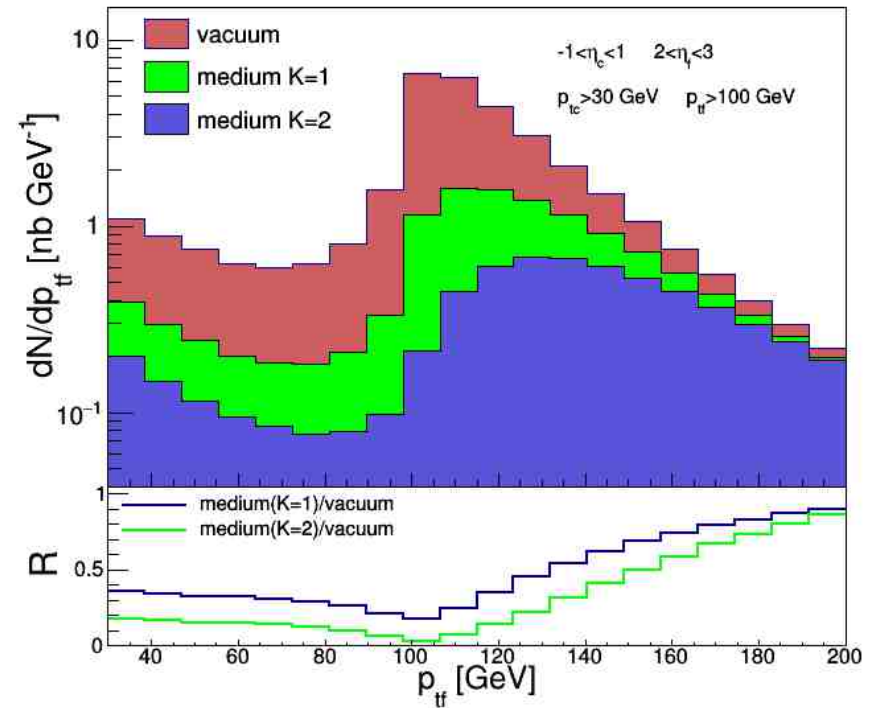
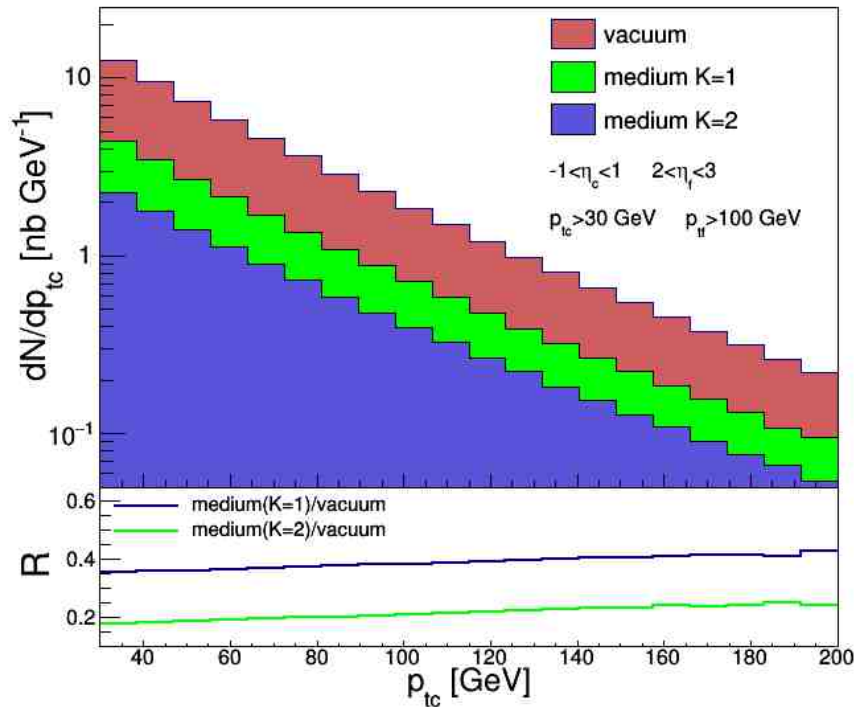
$$H(\eta) = \frac{1}{\sqrt{2\pi} (a_1 b_1 - a_2 b_2)} \left[a_1 e^{-|\eta|^2/(2b_1^2)} - a_2 e^{-|\eta|^2/(2b_2^2)} \right]$$

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

Transversal momenta of jets

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

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

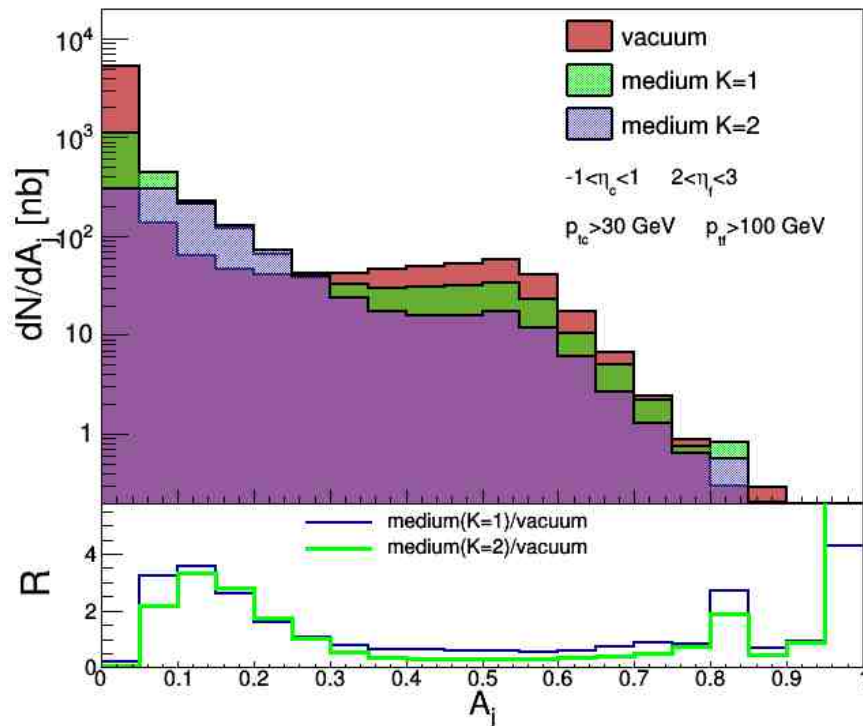


- back-to-back peak in the plot on the right

Relative transversal momentum difference

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

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



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

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

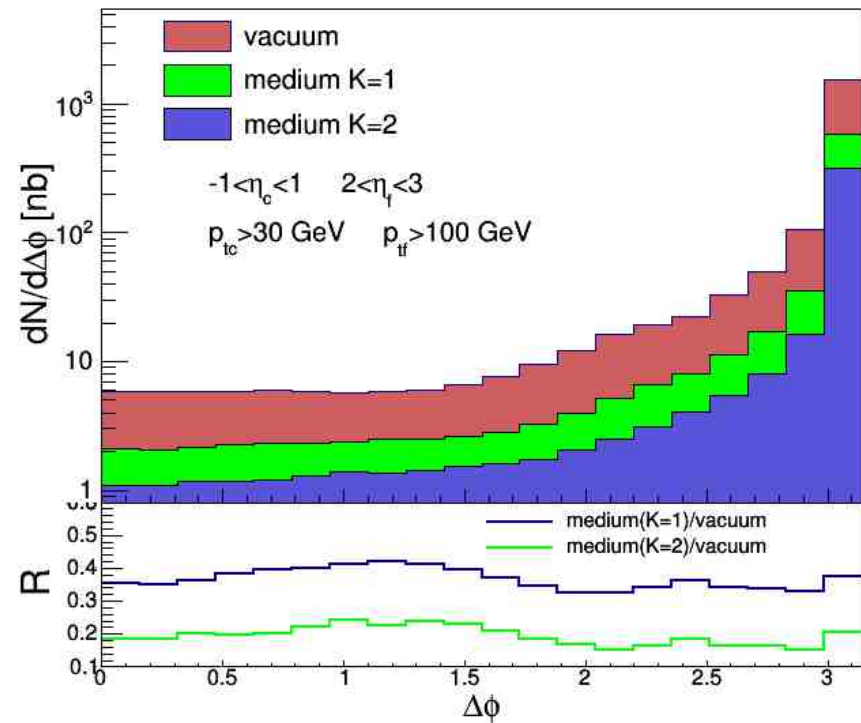
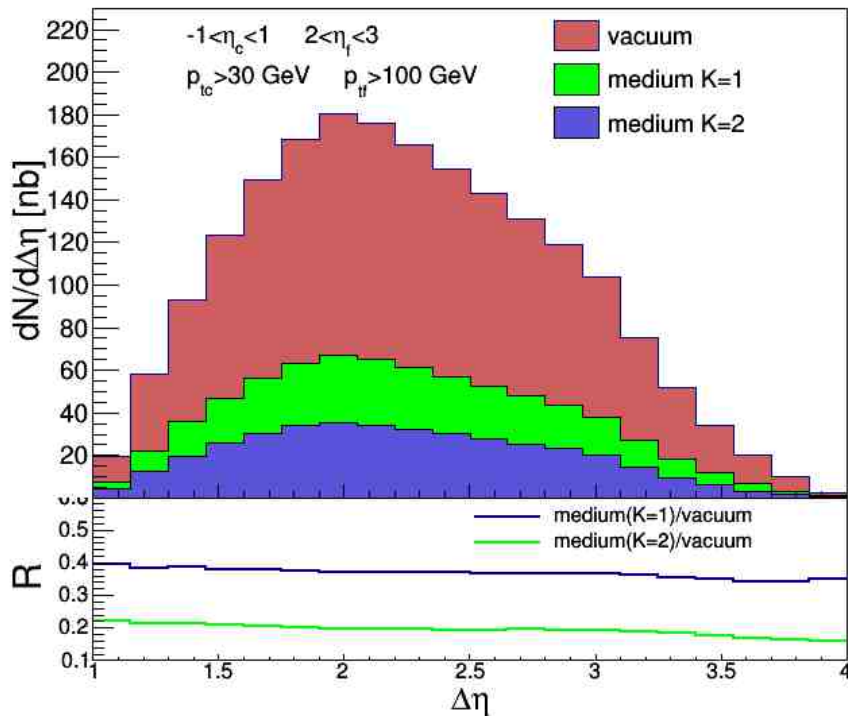
Rapidity and azimuthal angle distance

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

$$-1 < \eta_c < 1$$

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

$$2 < \eta_f < 3$$



- 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
- More precise treatment of the medium jet interactions