Asymmetric jet shapes with 2D jet tomography

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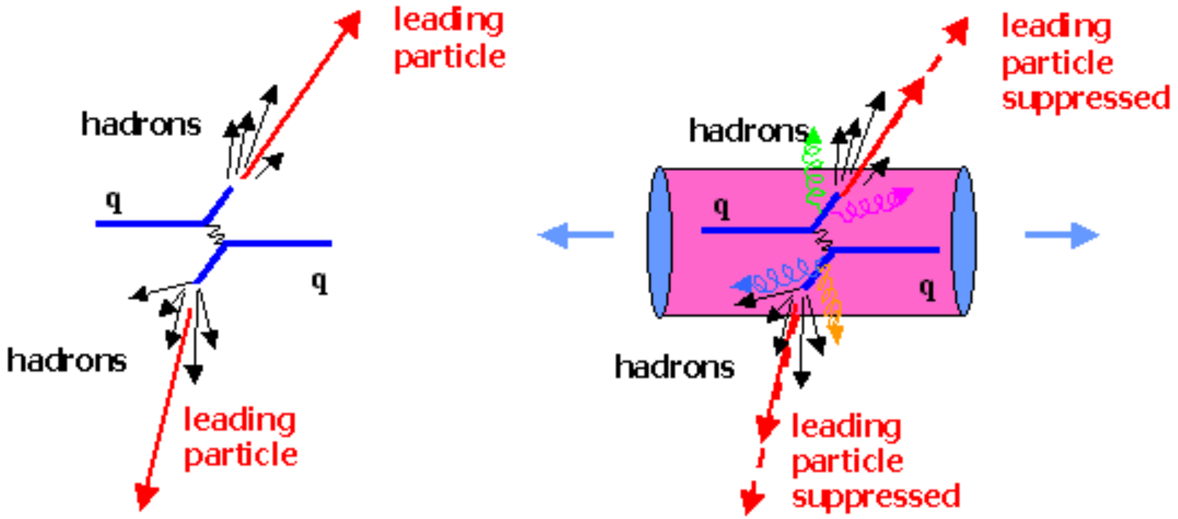
Based on *"YX Xiao, YY He, LG Pang, HZ Zhang, XN Wang, PRC109(2024)054906"*

HF-HNC 2024, Guangzhou, 12/14/24

Outline

- Introduction
- LBT transport model for γ-jets in HIC
  - Jet shape、 $\hat{q}$ gradient、 asymmetry $A_N^{\vec{n}}$
- Medium-modified jet shapes
  - Jet modifications via 2D jet tomography
  - Asymmetric jet shape due to $\hat{q}$ gradient
- Summary

Heavy-ion collisions



p-p collision VS A-A collision

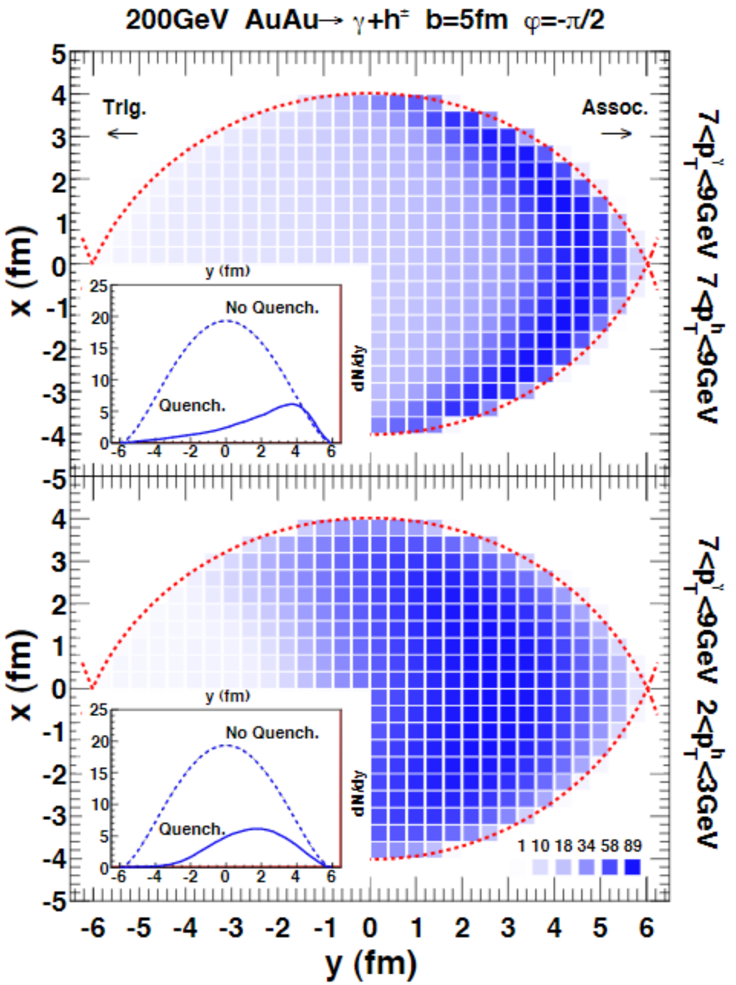
- Quark Gluon Plasma (QGP) produced in heavy-ion collisions.
- Jet quenching is an important probe to investigate QGP.
- Jet transport coefficient $\hat{q}$ is a parameter of jet quenching.

$$\hat{q}_a(x) = \sum_{bcd} \rho_b(x) \int d\hat{t} q_\perp^2 \frac{d\sigma_{ab\to cd}}{d\hat{t}}$$

M. Gyulassy and M. Plumer, Phys. Lett. B 243, 432(1990)

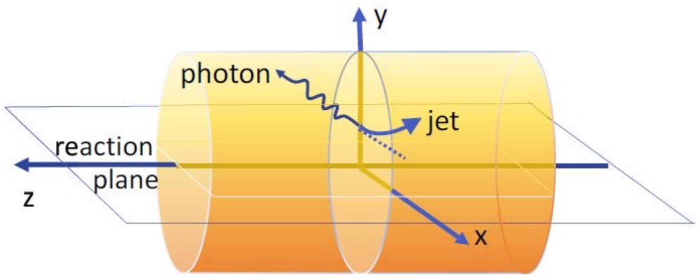
The density is not uniform, so $\hat{q}$ gradient tells the non-uniform spatial distribution of JQ strength.

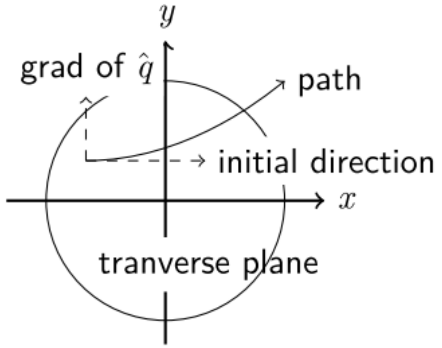
2D jet tomography – A promising tool for jet modification



H.-Z. Zhang, J. F. Owens, E.-K. Wang, and X.-N. Wang, PRL103 (2009) 032302

- **Longitudinal tomography** to localize initial γ-jet positions along the jet propagating directions
- **Selections with hadron p_T: surface and volume emissions**

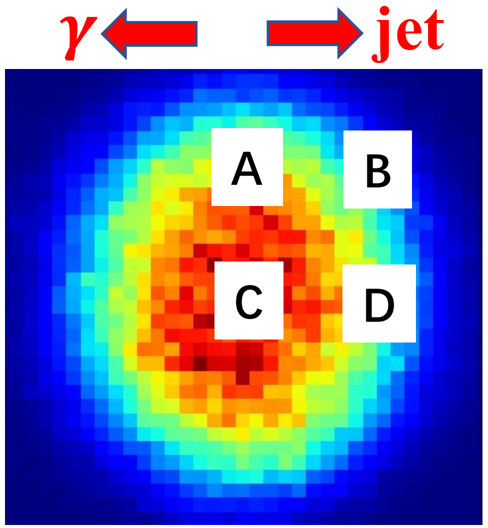




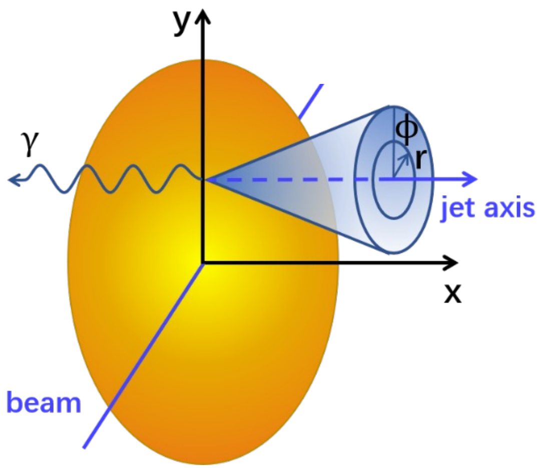
Y. He, L.-G. Pang, and X.-N. Wang, Phys. Rev. Lett. 125 (2020) 12, 122301

- **Transverse (gradient) tomography** with an asymmetry $A_N^{\vec{n}}$ to localize initial γ-jet positions transverse to the jet directions
- **The jet deviates from its initial direction due to $\hat{q}$ gradient perpendicular to the jet propagation direction**

Motivation - Asymmetric jet shapes: a new observable



- Relative to the propagation direction of the jet,
  - p_T^{jet} localizes longitudinal positions,
  - $A_N^{\vec{n}}$ localizes transverse positions
- Different selections of p_T^{jet} and $A_N^{\vec{n}}$ give 2D localizations, which help to understand the properties of the surface and deeper layers of QGP.



- The jet shape is expected to be modified due to the non-uniform JQ strength with different production positions of the jets.
- **Motivation - Medium-modified jet shape via longitudinal and transverse tomography. We find the jet shape is asymmetric.**

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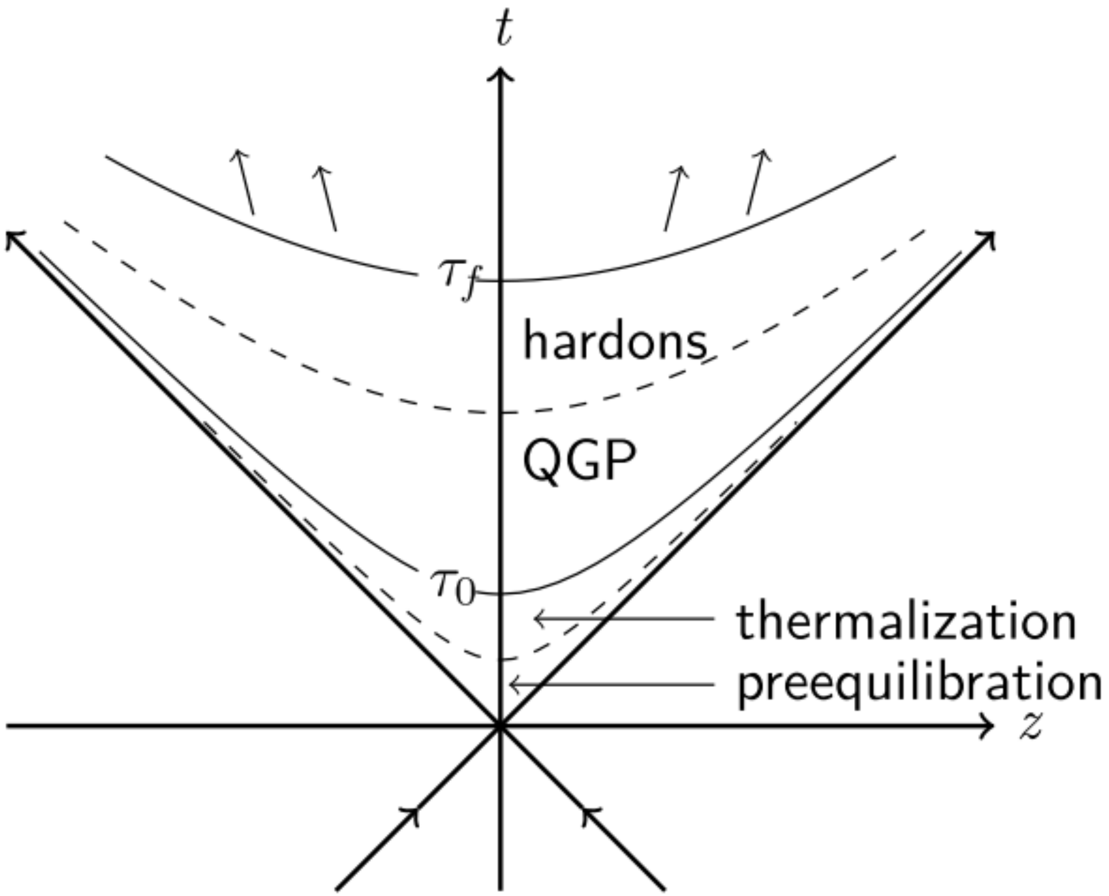
Model simulation of heavy ion collisions



PYTHIA8
Initial parton shower

AMPT
Initial condition of A-A collisions

↓

CLVisc (3+1)D viscous Hydrodynamic model
Background evolution

LBT model
Jet transport In medium

↓

Fastjet code package
Reconstruction for the final jets

Y. He, T. Luo, X.-N. Wang, and Y. Zhu, Phys. Rev. C 97 (2018) 1, 019902
S. Cao, T. Luo, G.-Y. Qin, and X.-N. Wang, Phys. Rev. C 94 (2016) 1, 014909

The LBT model

Boltzmann transport equation:

$$p_a \cdot \partial f_a = \int \prod_{i=b,c,d} \frac{d^3 p_i}{2E_i(2\pi)^3} \frac{\gamma_b}{2} (f_c f_d - f_a f_b) |\mathcal{M}_{ab\to cd}|^2 \times S_2(\hat{s}, \hat{t}, \hat{u}) 2\pi^4 \delta^4 (p_a + p_b - p_c - p_d)$$

+ inelastic

$$S_2(\hat{s}, \hat{t}, \hat{u}) = \theta(\hat{(s)} \geq 2\mu_D^2)\theta(-\hat{s} + \mu_D^2 \leq \hat{t} \leq -\mu_D^2), \quad \mu_D^2 = \frac{3}{2} g^2 T^2$$

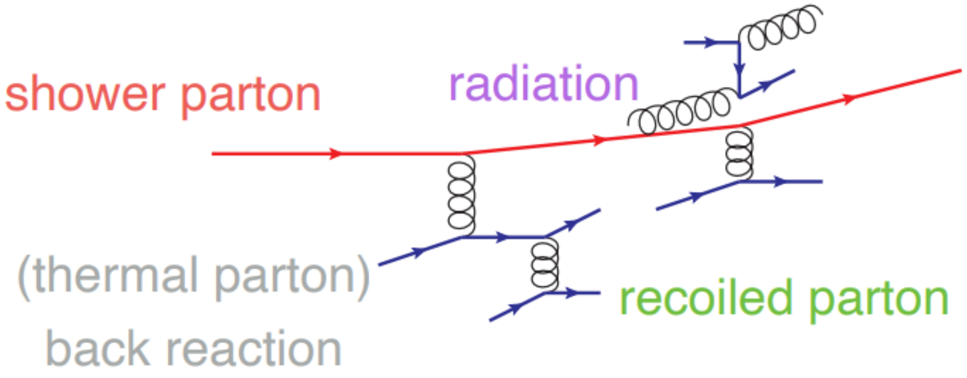
Y. He, T. Luo, X.-N. Wang, and Y. Zhu, Phys. Rev. C 97 (2018) 1, 019902

Elastic: $$\Gamma_a^{el} = \frac{p \cdot u}{p_0} \sum_{bcd} \rho_b(x) \sigma_{ab\to cd}$$

J. Auvinen, K. J. Eskola, and T. Renk, Phys. Rev. C 82 (2010) 024906

Inelastic: $$\frac{d\Gamma_a^{inel}}{dz dk_\perp^2} = \frac{6\alpha_s P_a(Z) k_\perp^4}{\pi(k_\perp^2 + z^2 m^2)^4} \frac{p \cdot u}{p_0} \hat{q}_a(x) \sin^2 \frac{\tau - \tau_i}{2\tau_f}$$

X.-F. Guo, and X.-N. Wang, Phys. Rev. Lett. 85 (2000) 3591-3594
B.-W, Zhang, E.-K. Wang, and X.-N. Wang, Phys. Rev. Lett. 93 (2004) 072301

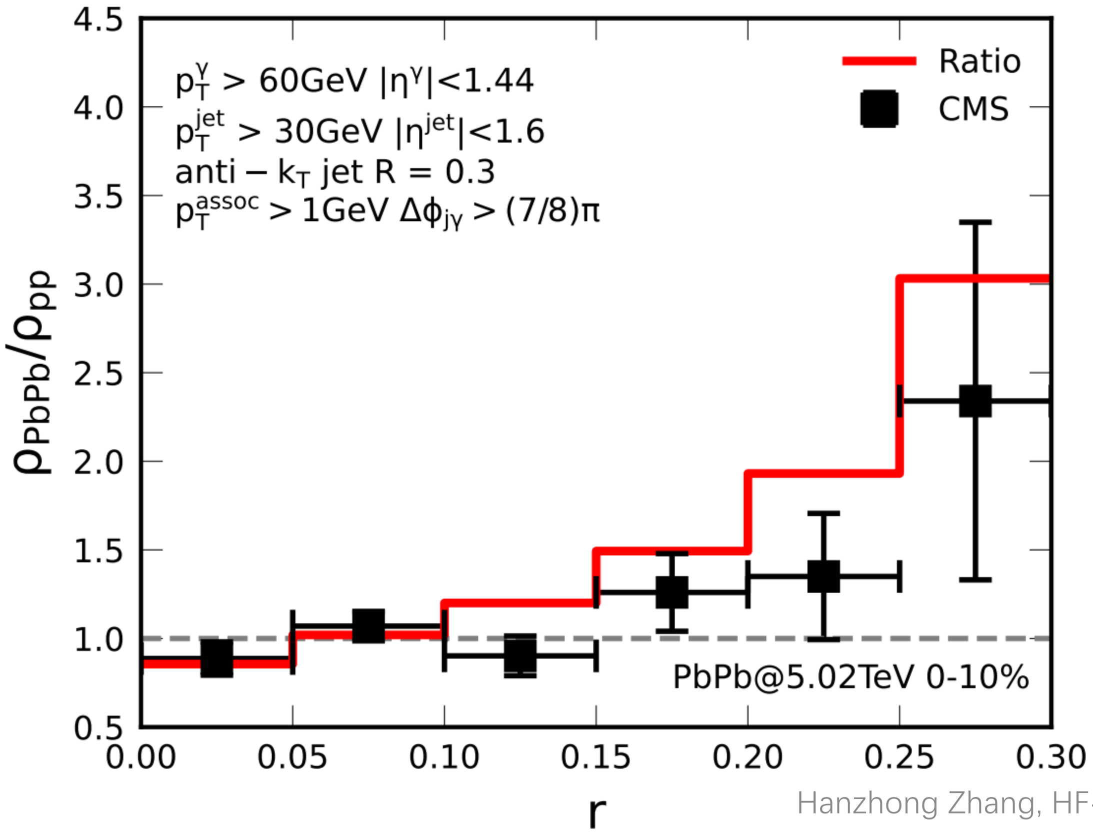


Jet shape of gamma-tagged jets

Jet shape definition :

$$\rho(r) = \frac{1}{\Delta r}\frac{\sum_i^N p_T^i(r-\Delta r/2, r+\Delta r/2)}{\sum_i^N p_{Ti}^{jet}}, p_T^i = \sum_{assoc\in\Delta r} p_T^{assoc}, p_{Ti}^{jet} = \sum_{assoc\in[0,R]} p_T^{assoc}$$

for the possibility density of transverse momentum distribution inside a jet cone.



- **Numerical results fit data well.**
- **Enhancement at the large-r region. Partially due to gluon radiation, but most of the enhancement is caused by the medium response.**

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Spatial gradient of jet transport coefficient

$$\Delta E \propto \hat{q}$$

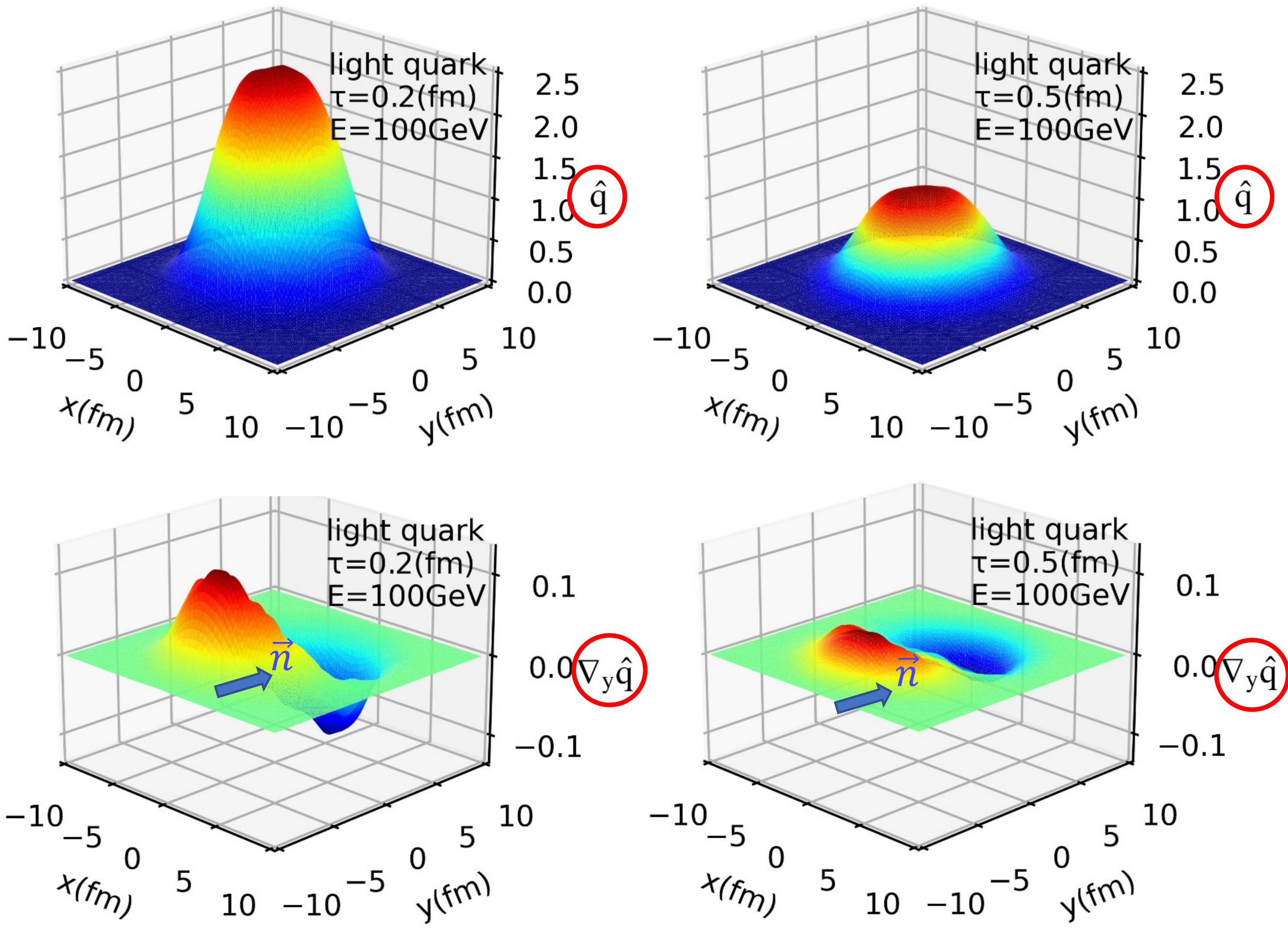
The jet transport coefficient $\hat{q}$:

$$\hat{q} = \langle q_\perp^2/\lambda \rangle_a \approx C_a \frac{42\zeta(3)}{\pi} \alpha_s^2 T^3 \ln \frac{s^*}{4\mu_D^2}$$

$$T = T(x, y, z, \tau), s^* = 5.8 E_0 T$$

Y. He, T. Luo, X.-N. Wang, and Y. Zhu, Phys. Rev. C 91, 054908 (2015)
X.-N. Wang, S.-Y. Wei, and H.-Z. Zhang, Phys. Rev. C 96, 034903 (2017)

JQ strength is not uniform.

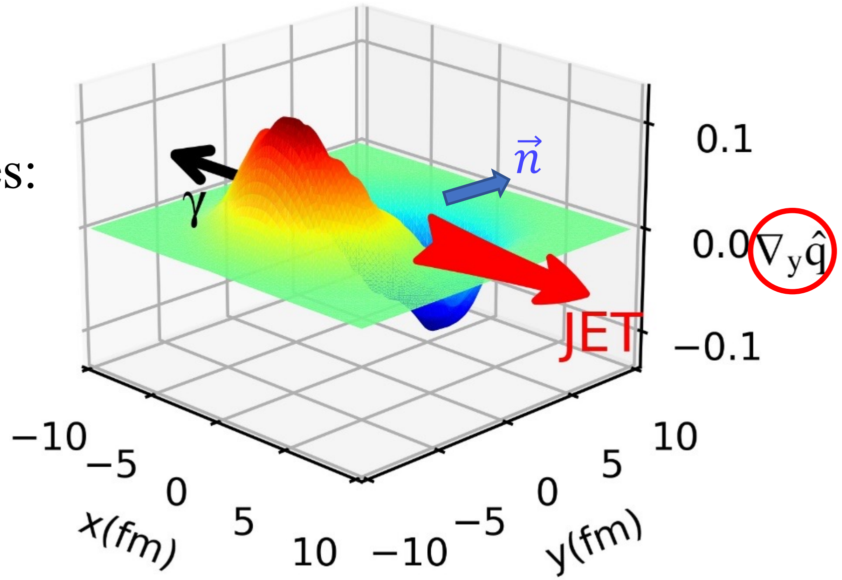


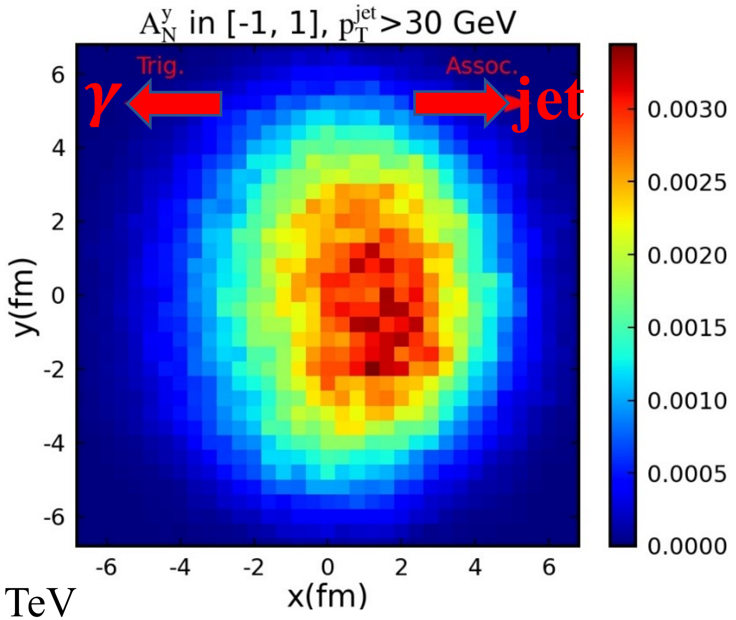
γ-jet production rate as a function of initial jet locations, selected with A_N^y

Asymmetry A_N^y describes the **collective transverse distribution** of final particles:

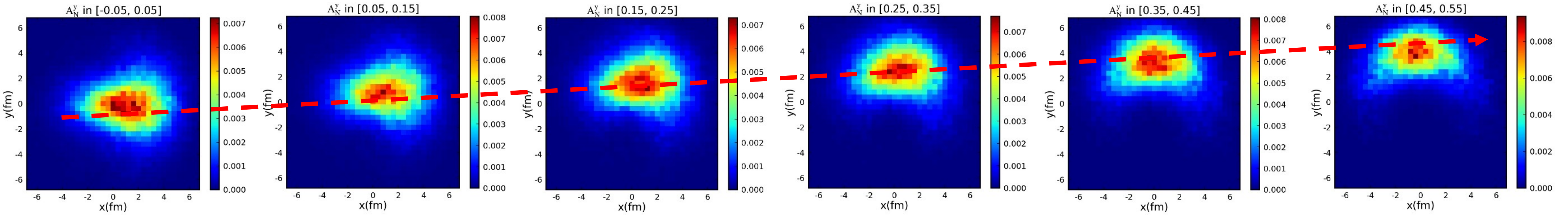
$$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k},\vec{r}) \mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f_a(\vec{k},\vec{r})}$$

Y. He, L.-G. Pang, and X.-N. Wang, Phys. Rev. Lett. 125 (2020) 12, 122301





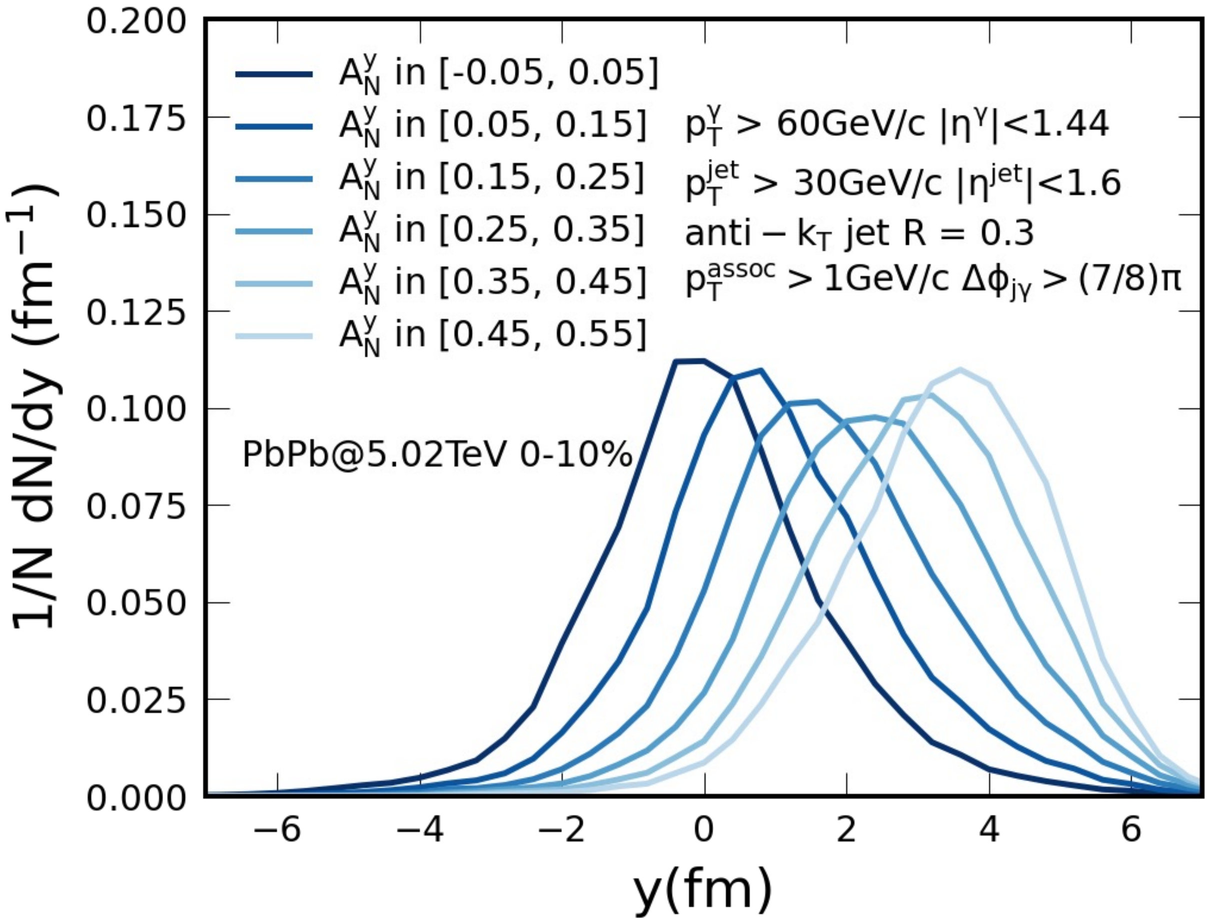
0-10% PbPb 5.02 TeV



The typical initial transverse position (y) shifts from the center to the outer region: transverse tomography

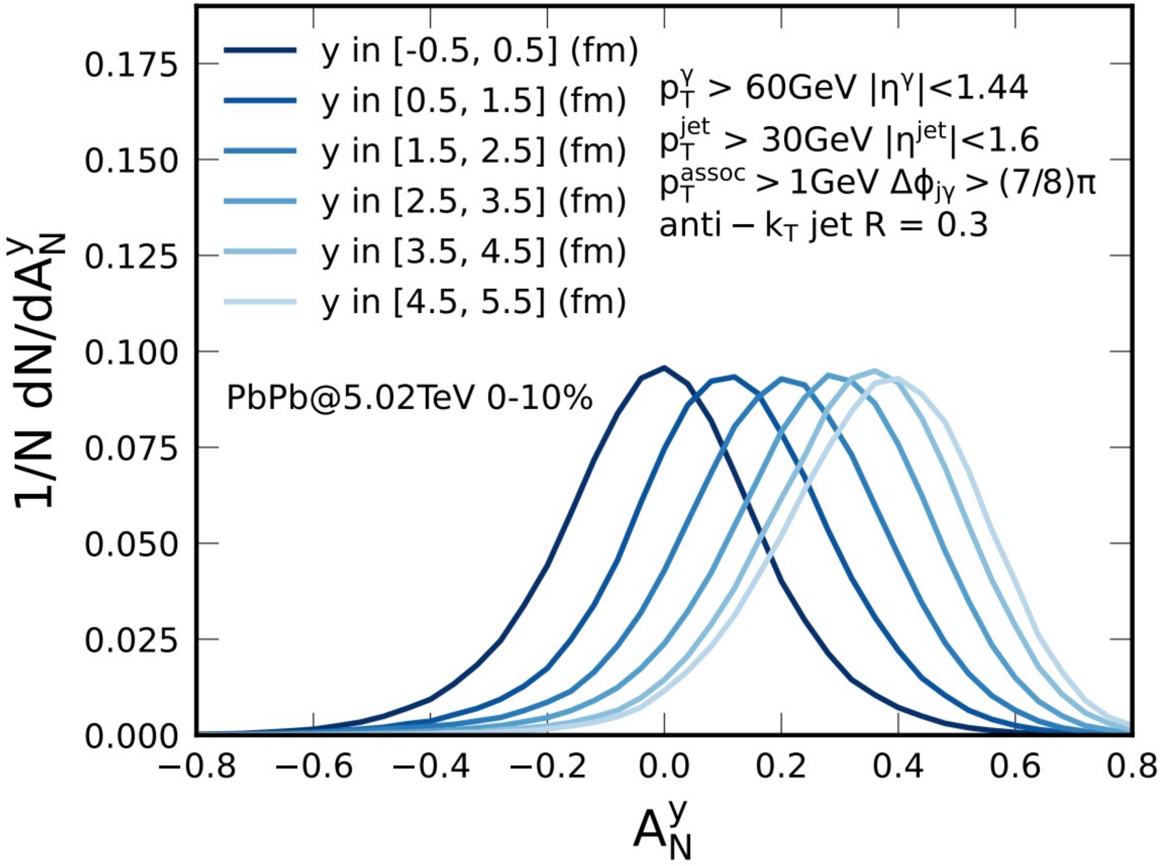
Small A_N^y, traverse whole volume. Large A_N^y, emerge from surface areas, tangentially to the surface.

γ-jet production rate as a function of y for initial jet locations, selected with A_N^y



- Projections onto y-axis: final γ-jet rate as a function of y for initial jet positions, selected with A_N^y
- With A_N^y from 0 to 0.5, the peak of γ-jet production rate moves from the center to the outer corolla of the medium
- **A_N^y can be used to select events and then give the typical initial γ-jet positions**

γ-jet production rate as a function of A_N^y, with given initial transverse positions of γ-jets

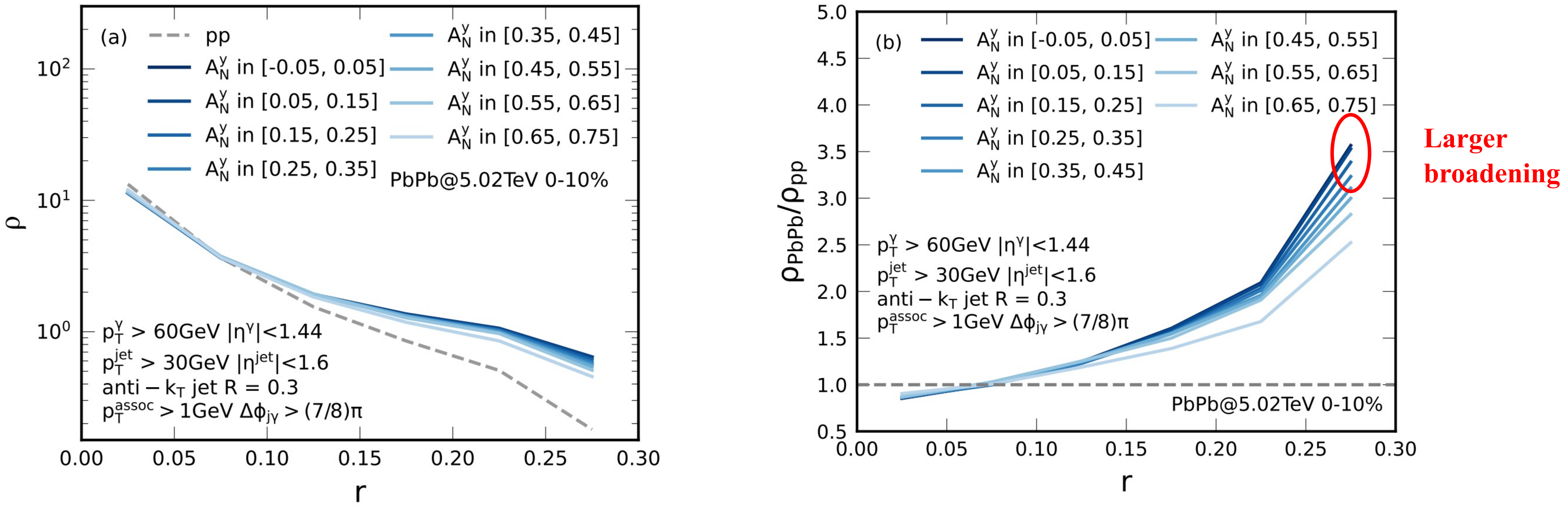


- With given initial transverse positions of γ-jets from y = 0 to 5 fm, the peak of final γ-jet production rate moves with A_N^y from 0 to 0.5
- **Consistent with A_N^y localizations**. **Asymmetry A_N^y localizes initial positions of γ-jets which are sources of final γ-jets**
- Hard parton transport tends to the dilute area due to JQ gradient, whereas soft transport towards the opposite, so jet reconstructions will be affected for the locations of initial jets

Modifications to jet shapes, selected with A_N^y

$$\rho(r) = \frac{1}{\Delta r}\frac{\sum_i^N p_T^i(r - \Delta r/2,\ \ r + \Delta r/2)}{\sum_i^N p_{Ti}^{jet}}$$

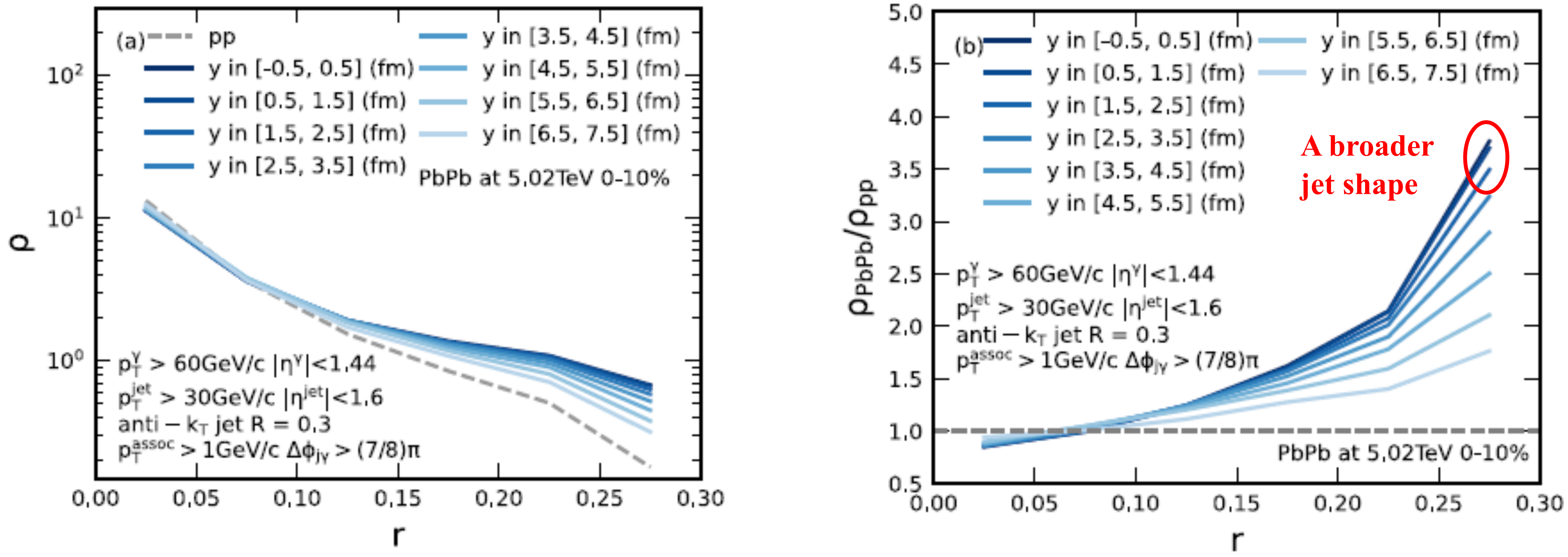
(via transverse tomography)



- $\rho(r)$ **of AA larger than pp when** r **>0.1 : energy loss by hard partons at the core is transported to larger angles by soft particles (radiated gluons and medium response).**
- **broader with small** A_N^y **than large** A_N^y**: small** A_N^y **tells a center location, a long path and the strong JQ, then a large-broadening jet shape.**

Modifications to jet shapes, with given initial transverse positions

(via transverse tomography)

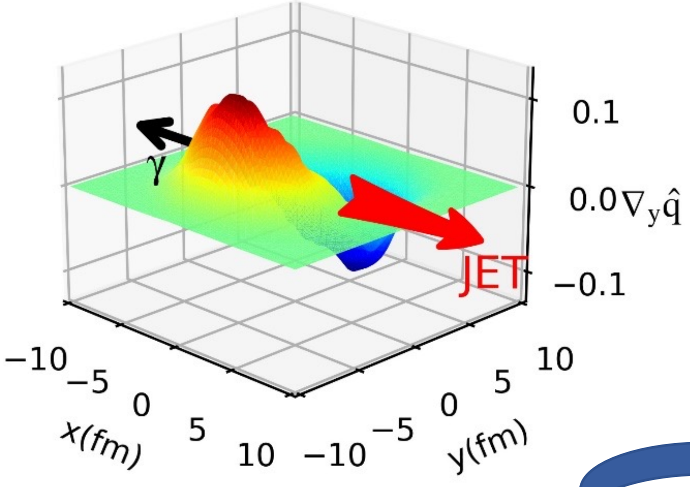


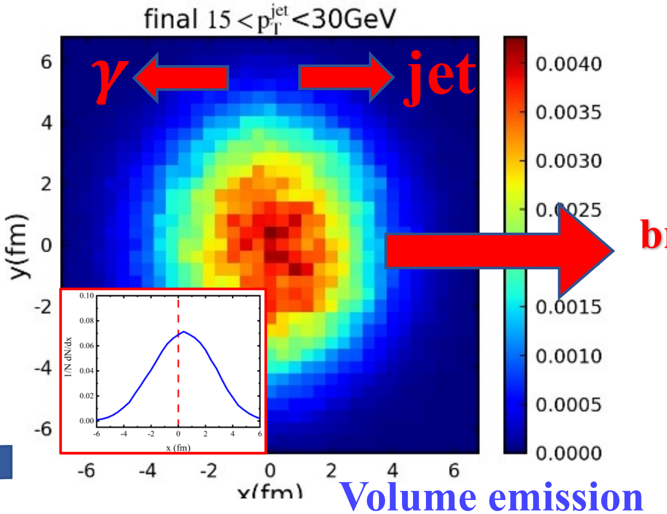
- Jets with initial central positions are more "broader" than with the outer corolla, consistent with A_N^y.
- The broadening is caused by the jet-medium interaction. A slight suppression of the jet shape at the core r < 0.05 due to JQ.
- This lost energy is carried by radiated gluons and the medium-response to large angles.

Modifications to jet shapes with p_T^{jet}: Longitudinal tomography

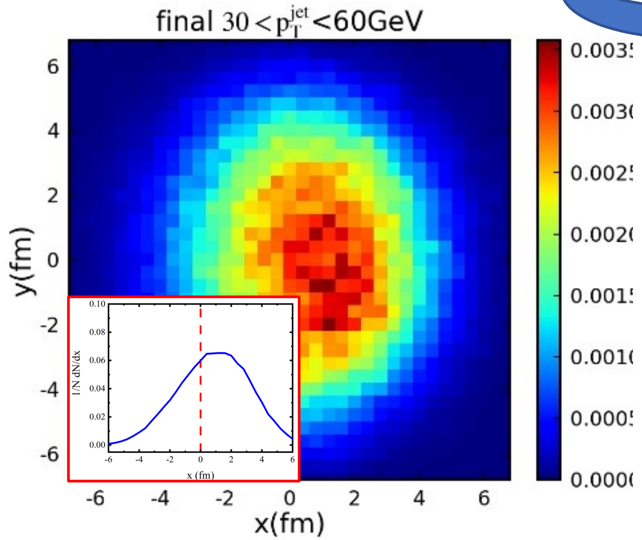
γ-jet production rate as a function of initial jet locations

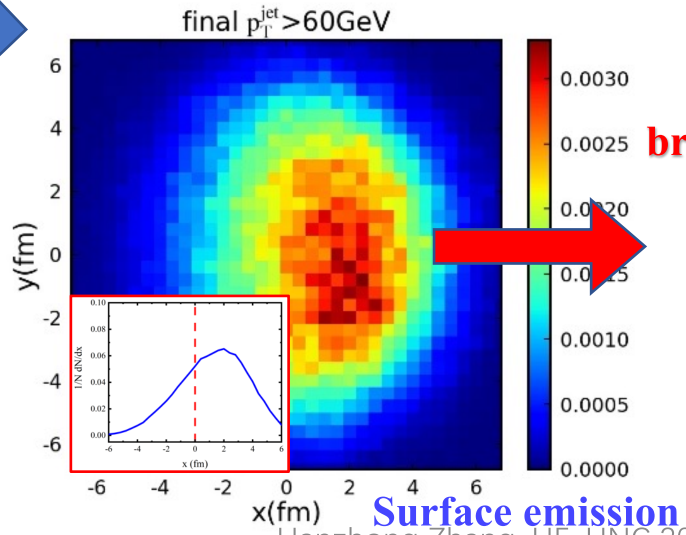
$$\rho(r) = \frac{1}{\Delta r}\frac{\sum_i^N p_T^i(r-\Delta r/2,\ \ r+\Delta r/2)}{\sum_i^N p_{Ti}^{jet}}$$



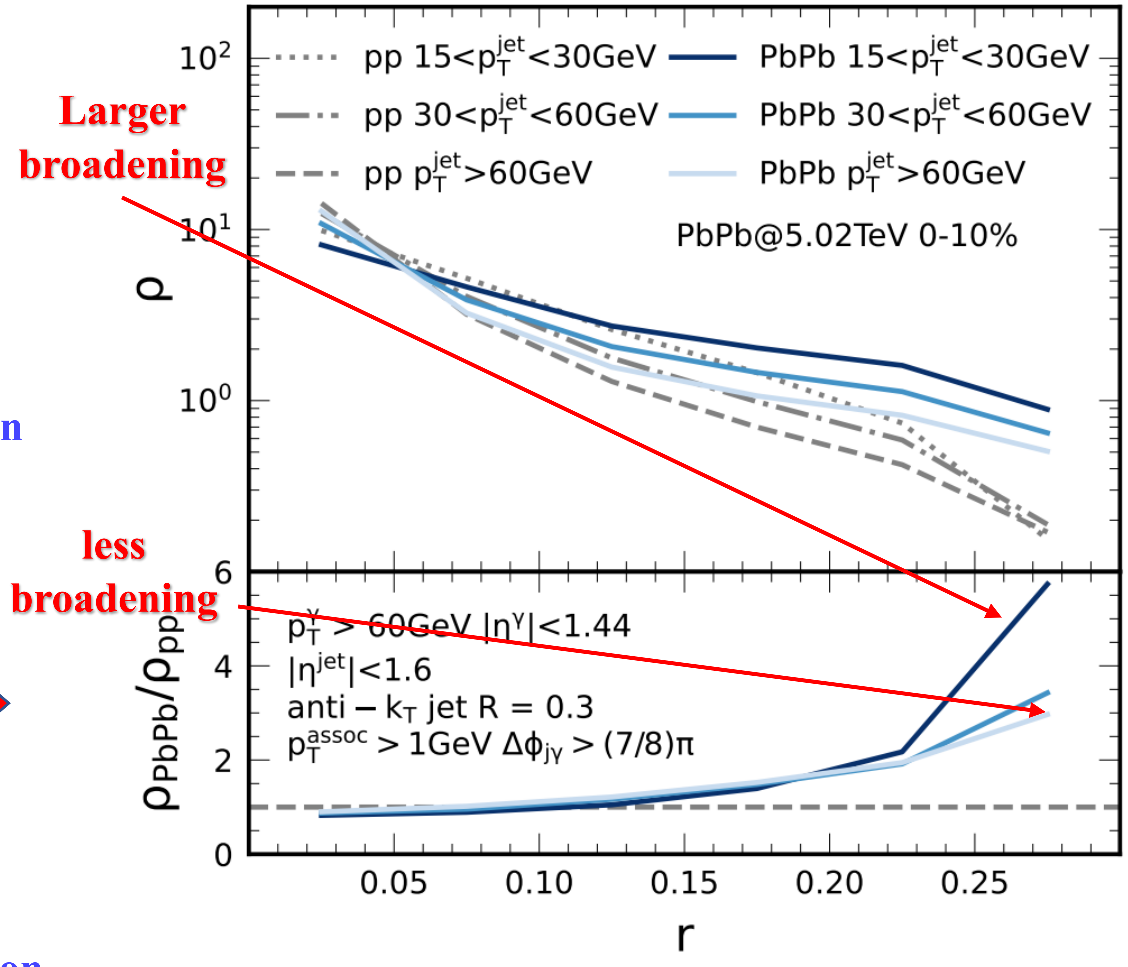


Volume emission

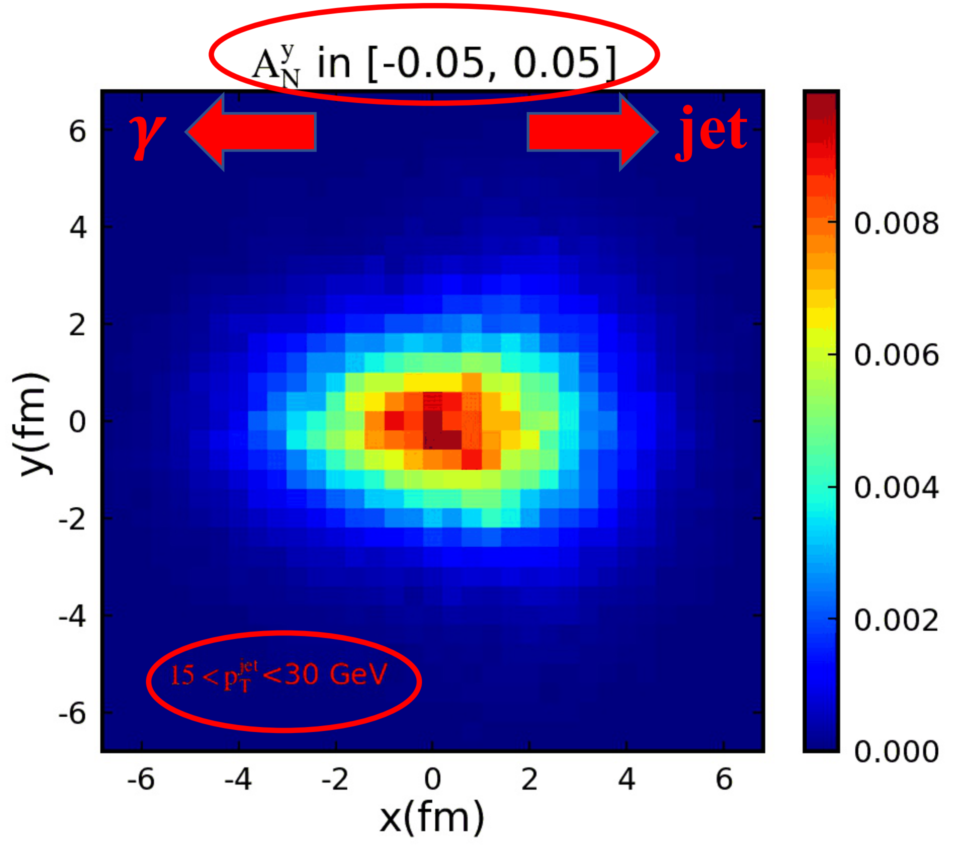


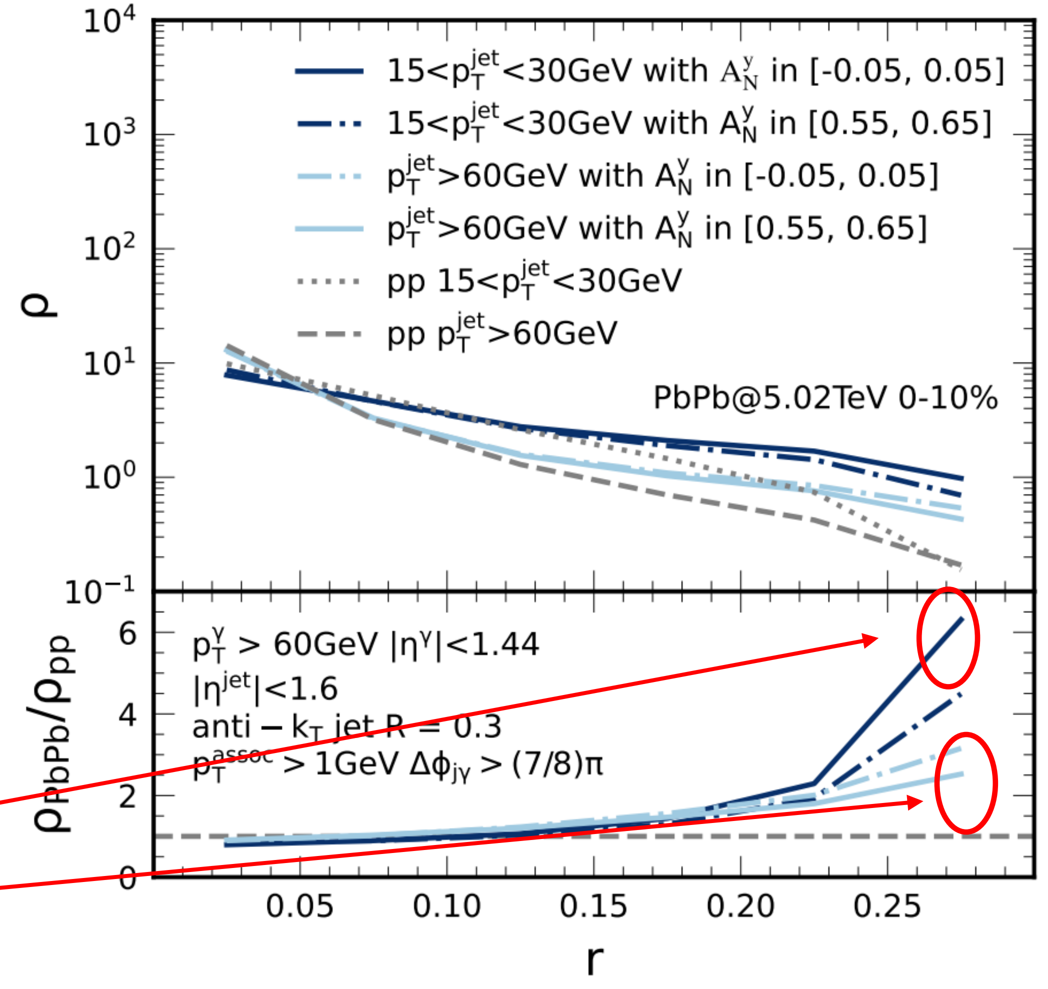


Surface emission



Medium-modified jet shapes via transverse and longitudinal (2D) tomography

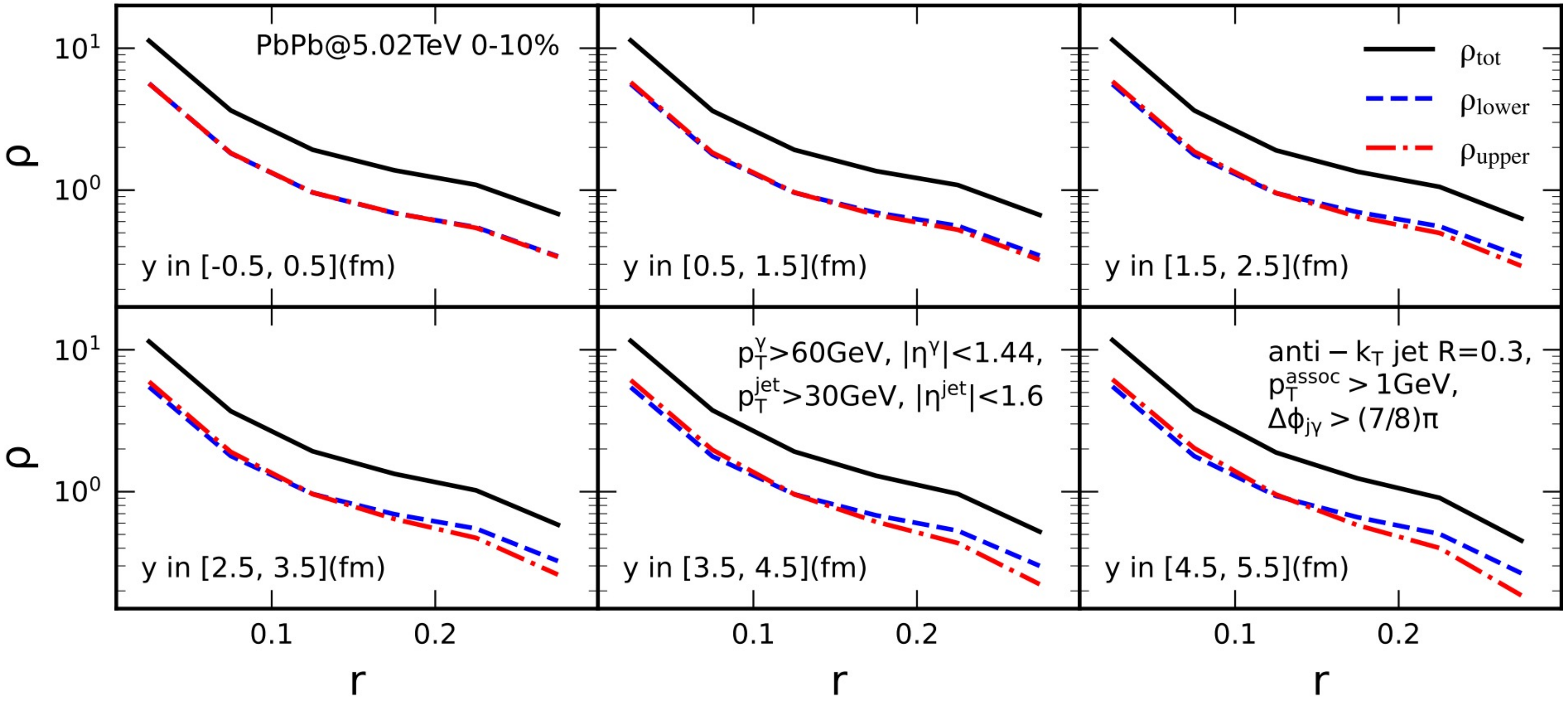


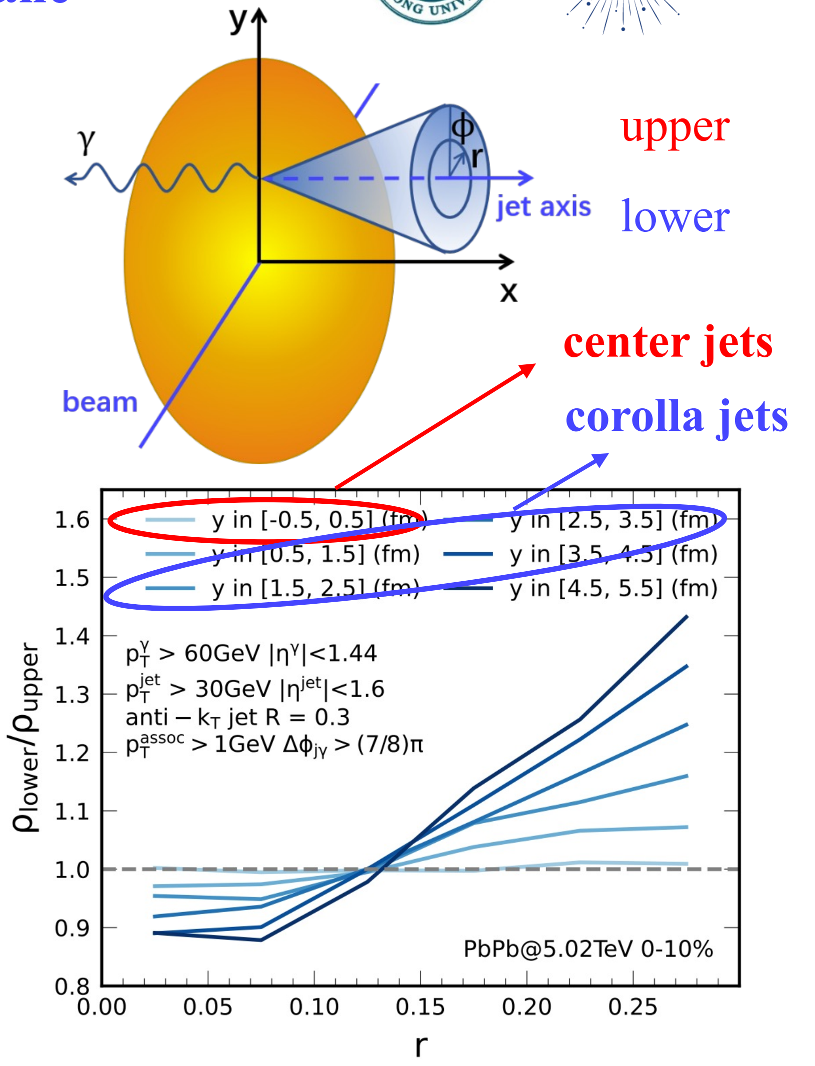


- small A_N^y + small p_T^{jet}: volume emissions, "**Fat**" jet
- large A_N^y + large p_T^{jet}: surface emissions, "**Thin**" jet
- Others: large A_N^y + small p_T^{jet}, small A_N^y + large p_T^{jet}

Asymmetric jet shape - Jet shapes divided by jet-axis and beam plane

$$\rho(r)_{upper/lower} = \frac{1}{\Delta r}\frac{\sum_i^N p_T^i(r-\Delta r/2,\ \ r+\Delta r/2)\Theta(+/-\vec{p}_T^{asso}\cdot\vec{n})}{\sum_i^N p_{Ti}^{jet}}$$





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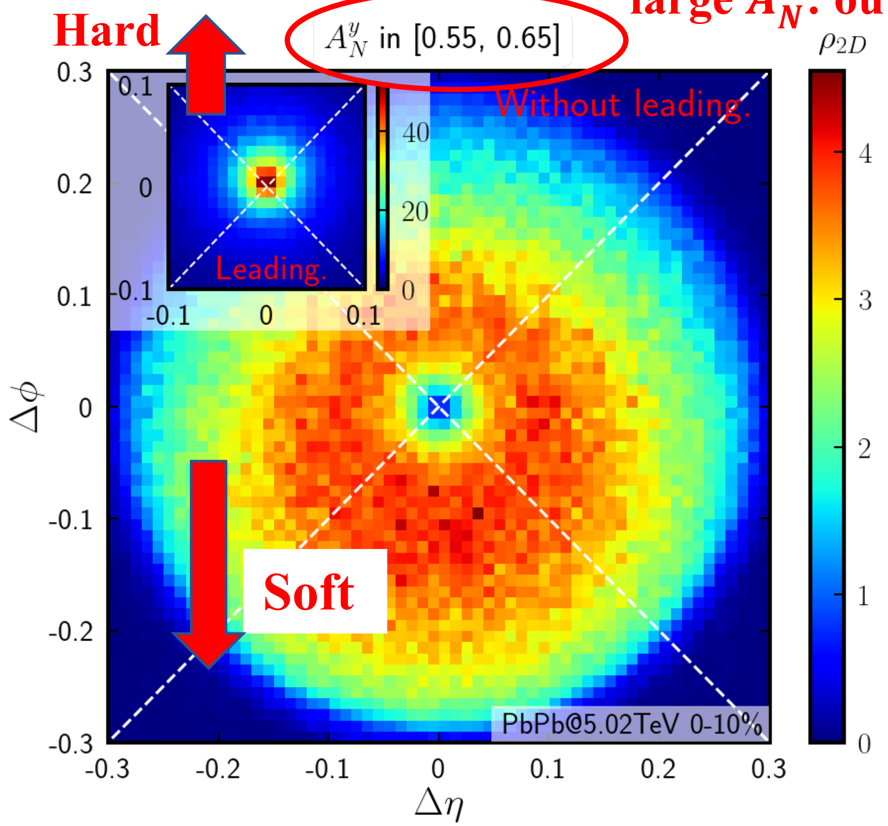
The transverse momentum inside a jet cone is transported from small to large angles away from jet axis.

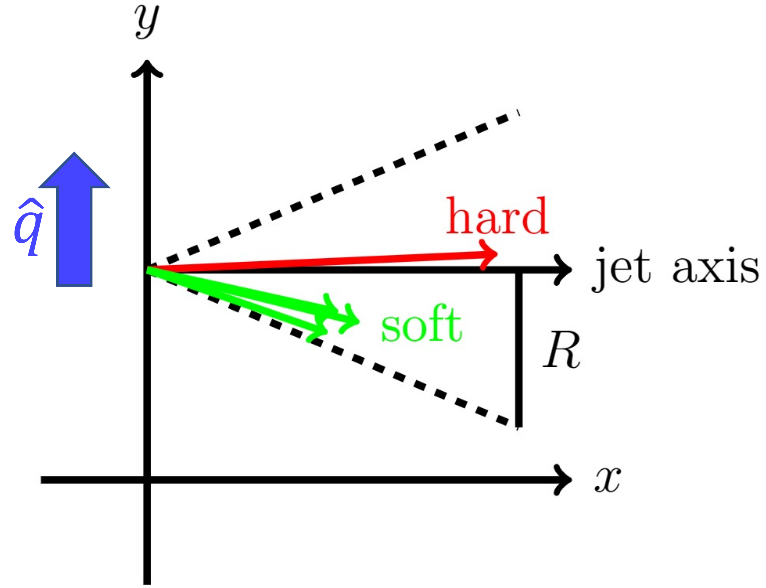
It is stronger in the lower cone than in the upper cone, especially for a corolla jet than a center jet

Asymmetric jet shape – energy distributions of hard and soft

$$\rho_{2D} = \frac{1}{\delta(\Delta\eta)\delta(\Delta\phi)} \frac{\sum_{jet} \sum_{(\Delta\eta,\Delta\phi)}^{(\Delta\eta+\delta\Delta\eta,\Delta\phi+\delta\Delta\phi)} r_{assoc}(p_T^{assoc}/p_T^{jet})}{\sum_{jet} \sum_{r_{assoc}<R} r_{assoc}(p_T^{assoc}/p_T^{jet})}$$

large A_N^y: outer jet





- **Hard and soft centers are divorced.**
- **Hard partons are deflected away from dense regions due to transverse $\hat{q}$ gradient.**
- **Soft partons from the medium response are more likely to be created in dense regions.**

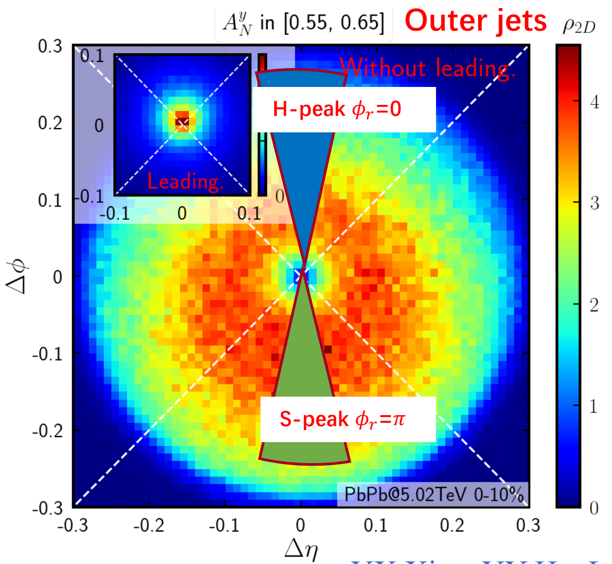
- **Such an asymmetric jet shape is more pronounced for the final γ-jets with a large A_N^y.**

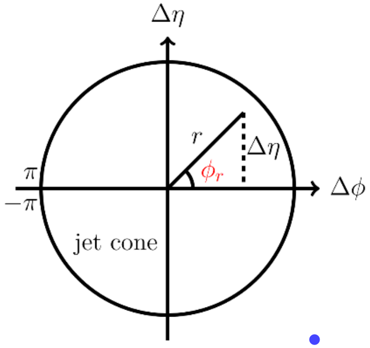
Asymmetric jet shape – angular energy distribution

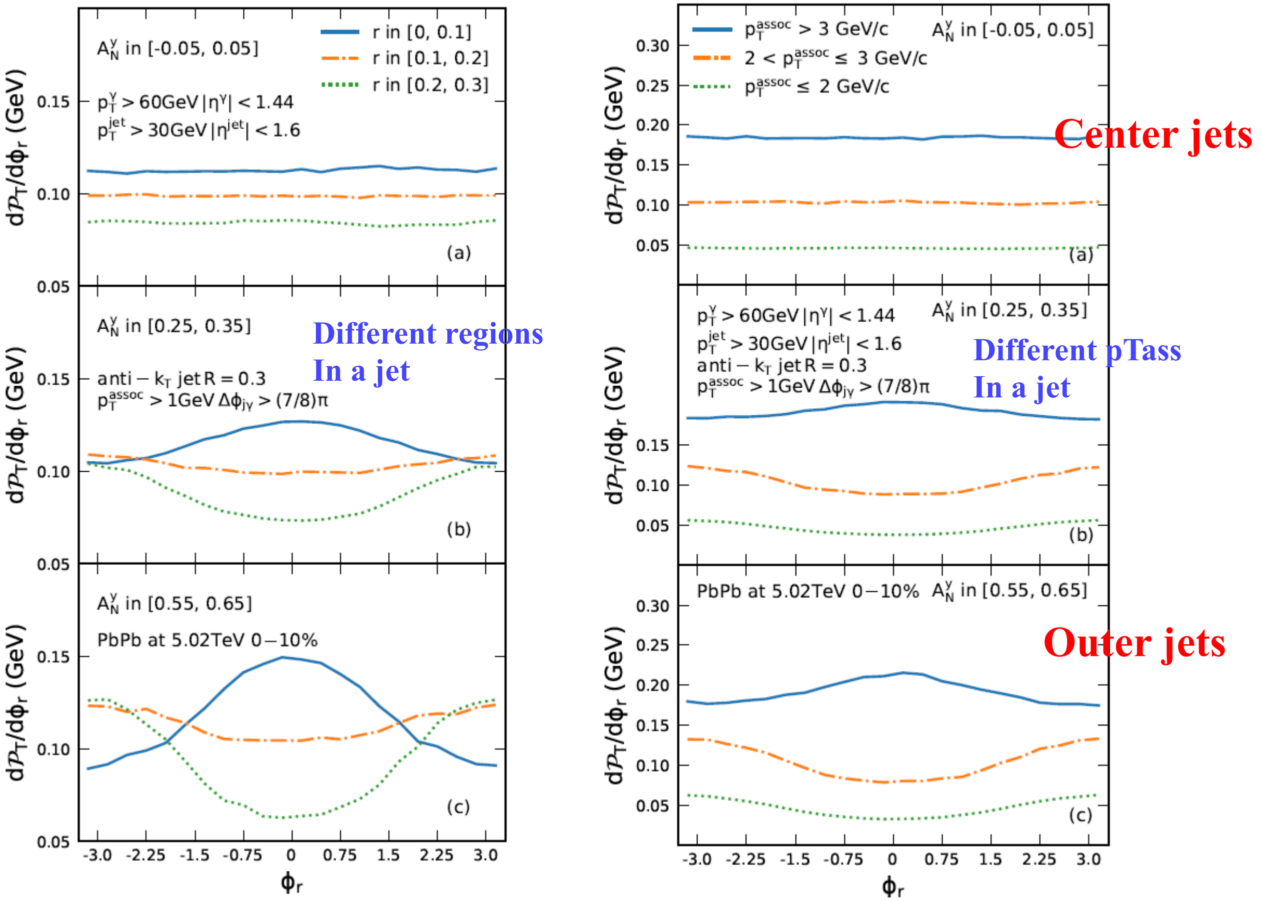
$$\frac{d\tilde{p}_T}{d\phi_r} = \frac{1}{N}\frac{\sum_{\phi_r}^{\phi_r+d\phi_r} r_{assoc}p_T^{assoc}}{d\phi_r}$$

$$\begin{cases} \phi_r = \arcsin\left(\frac{\Delta\eta}{r}\right), (\Delta\phi \geqslant 0) \\ \phi_r = \pi - \arcsin\left(\frac{\Delta\eta}{r}\right), (\Delta\phi < 0, \Delta\eta \geqslant 0) \\ \phi_r = -\pi - \arcsin\left(\frac{\Delta\eta}{r}\right), (\Delta\phi < 0, \Delta\eta < 0). \end{cases}$$

different locations inside QGP
different regions inside a jet
different pTass inside a jet







- In the direction at ϕ_r=0, hard partons contribute to the peak while the soft has a valley distribution.
- In the direction at ϕ_r=π, it's the soft that contributes to the peak while the hard has a valley. Consistent with the 2D shape.
- The case with different pTass is similar to different region.

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Summary

- We study medium-modified jet shape via transverse and longitudinal tomography of γ-jets in heavy ion collisions.
- A broader jet shape is gotten with small A_N^y or p_T^{jet} from volume emissions, while a less broader jet shape with large A_N^y or p_T^{jet} from surface emissions.
- The spatial gradient of $\hat{q}$ leads to an asymmetric jet shape of γ-jets. Inside a jet cone, medium "kick" or $\hat{q}$ gradient pushes the hard transversely, while the soft is reversely redistributed.
- We have proposed a new physical observable: asymmetric jet shape, and are awaiting experimentalists to measure it to testing QCD and parton transport.

Thank for your attentions！