The Gradient Tomography of Dijet Production in Heavy-ion Collisions

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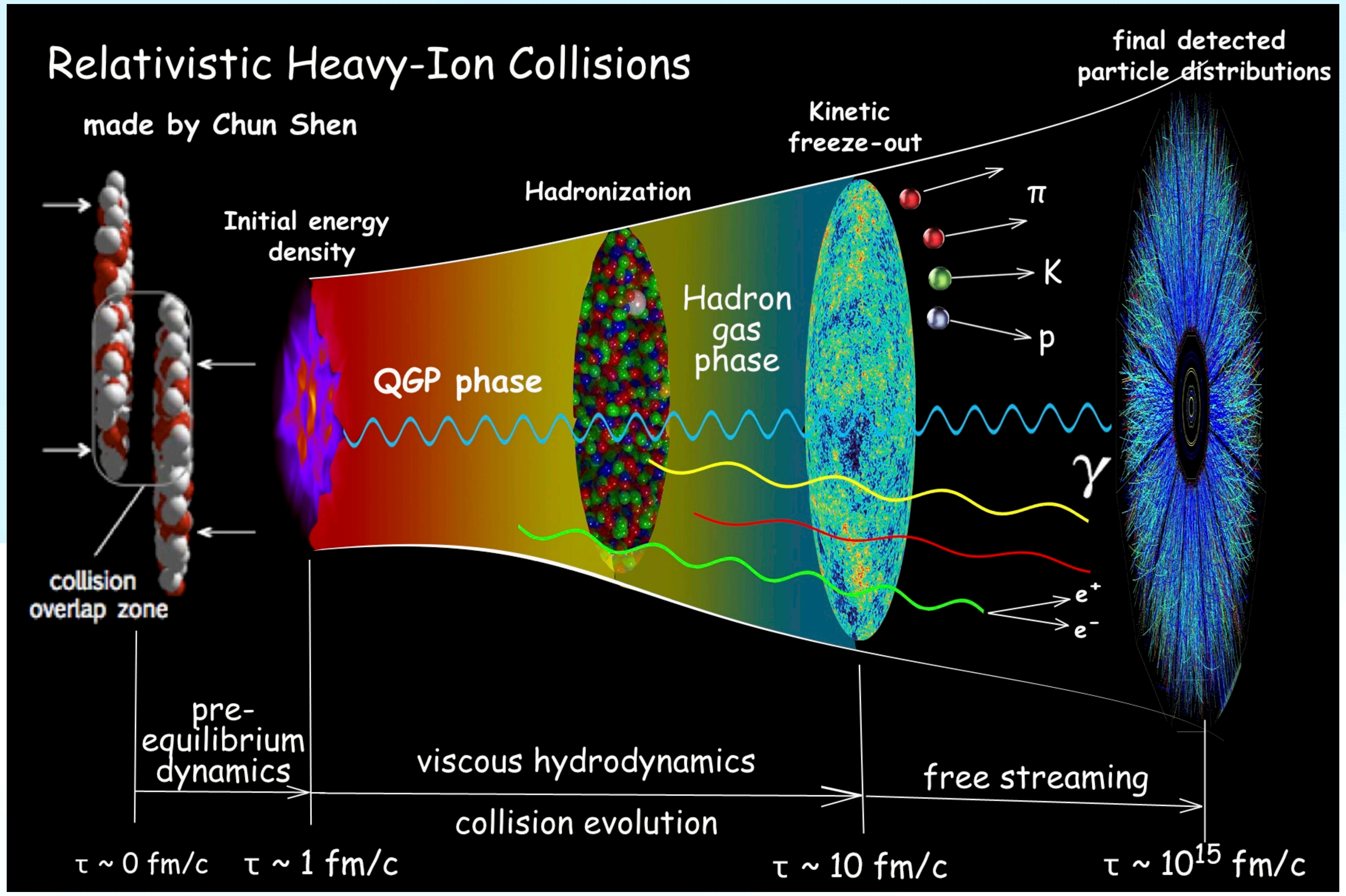
Outline

- Motivation
- The linear Boltzmann transport (LBT) Model
- Dijet tomography
- Summary

Motivation

The "little bang" creates the quark-gluon plasma, like the early universe



high-energy heavy ion collision

pre-equilibrium

QGP phase

hadron phase

detection

The quark-gluon plasma (QGP), predicted by QCD and confirmed at RHIC and LHC experiments, is a hot and dense medium.

Motivation

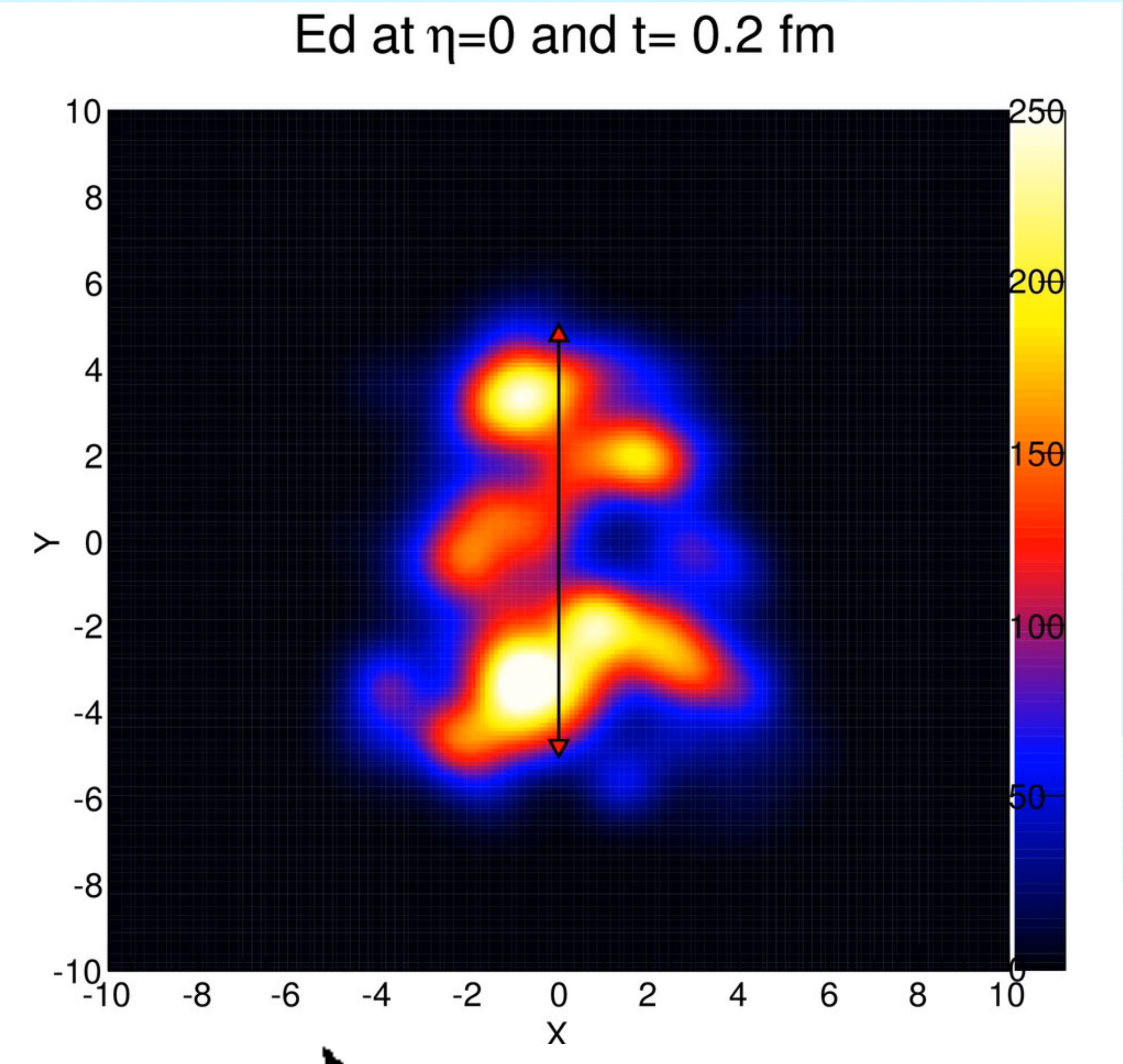
QGP Probes

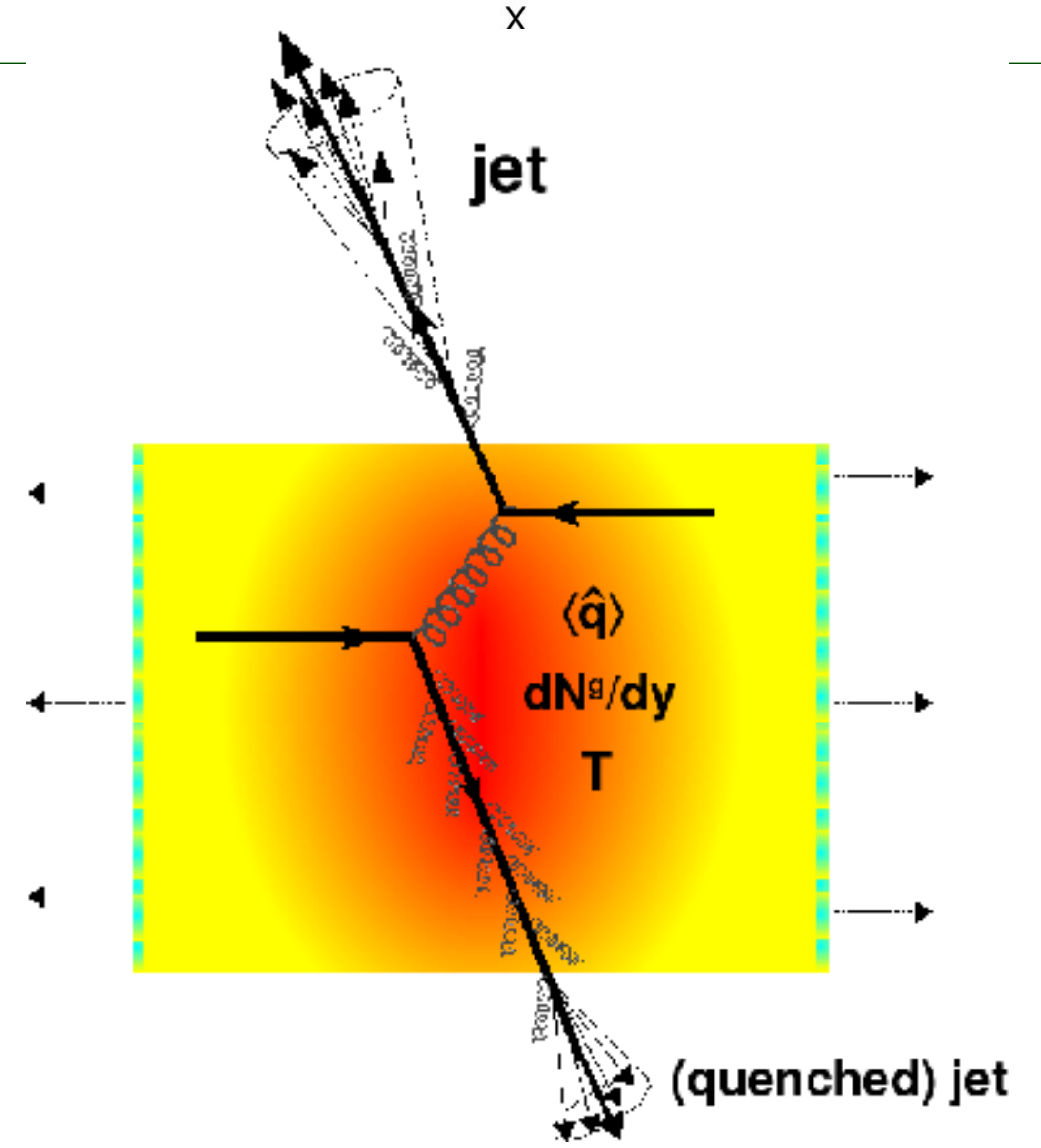
hard probes: large momentum or short distance, such as jets, high-pT hadrons, heavy quark.

jet: a spray of collimated hadrons with high transverse momentum

jet quenching:

jet energy loss when a jet propagates in the medium





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Jet transport coefficient

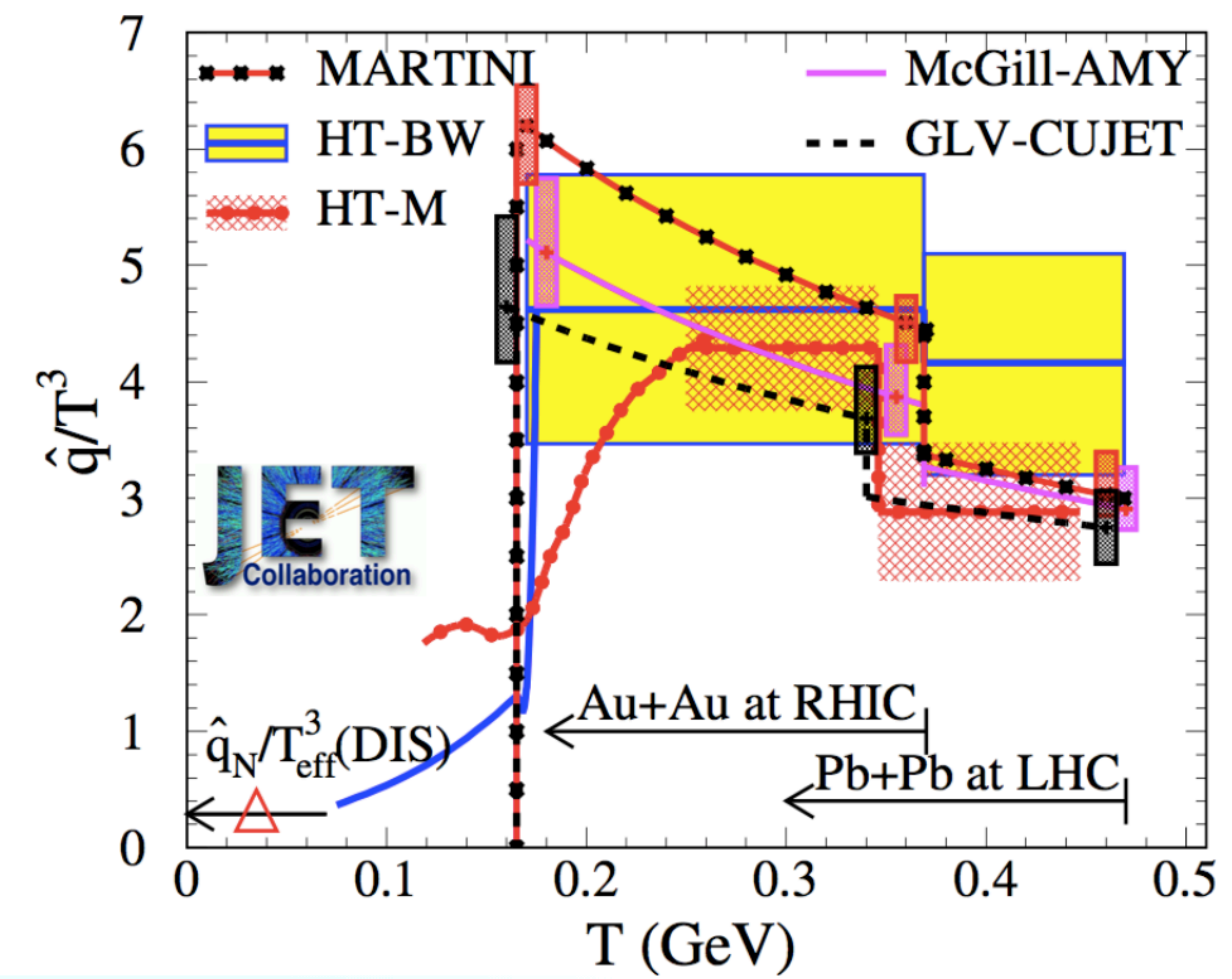

Fig: Extracted jet transport coefficient.
JET Collaboration, Phys. Rev. C 90, 014909 (2014)

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

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV}^2/\mathrm{fm} \ \ \mathrm{at} \ \ \begin{matrix} \mathrm{T=370\ MeV} \\ \mathrm{T=470\ MeV} \end{matrix}$$

RHIC
LHC

Jet transport coefficient is crucial for jet quenching calculations

Motivation

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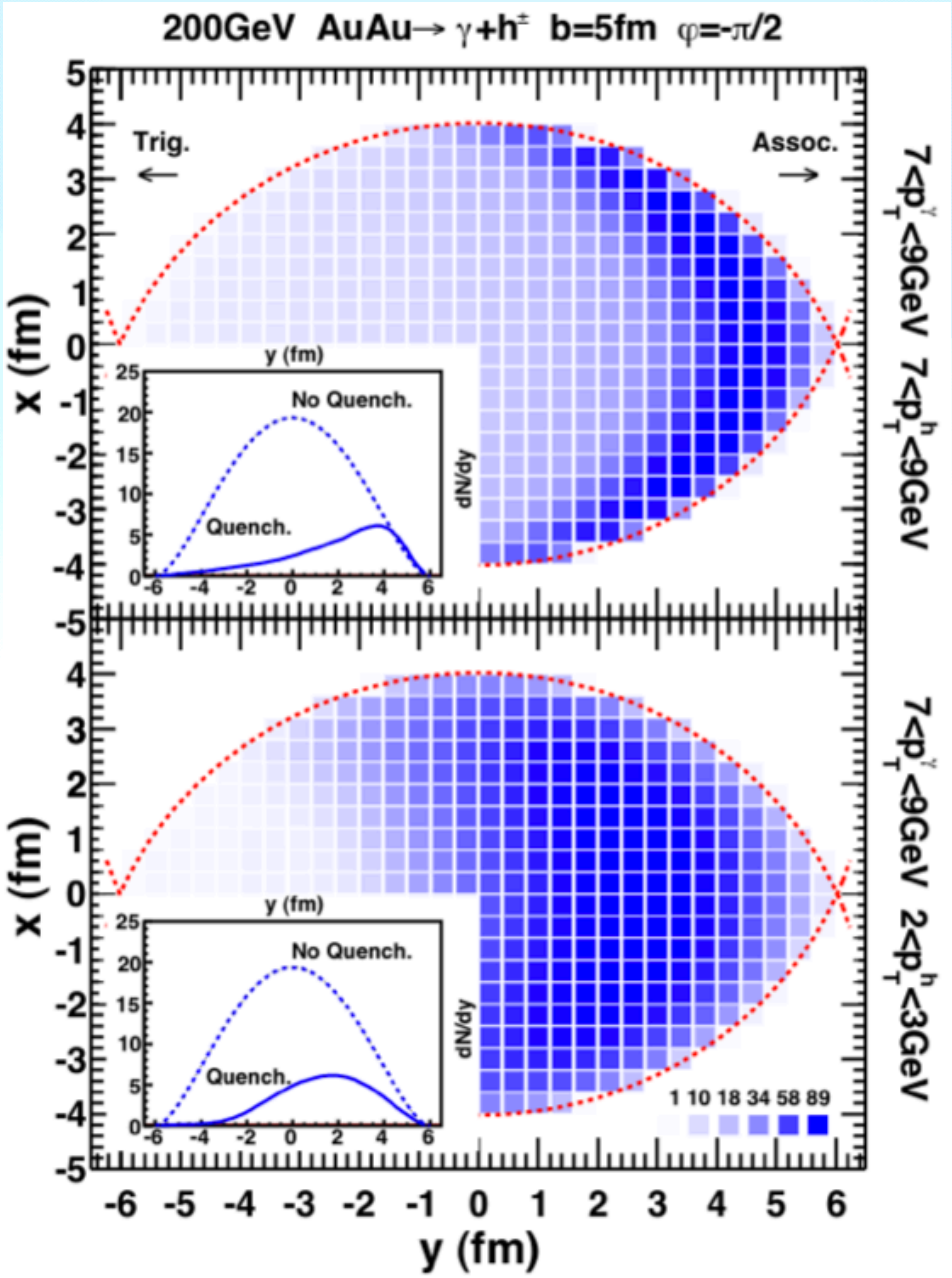
Longitudinal jet tomography in heavy-ion collisions

length dependence
of parton energy loss



$p_T^h/p_T^\gamma \sim 0.9$

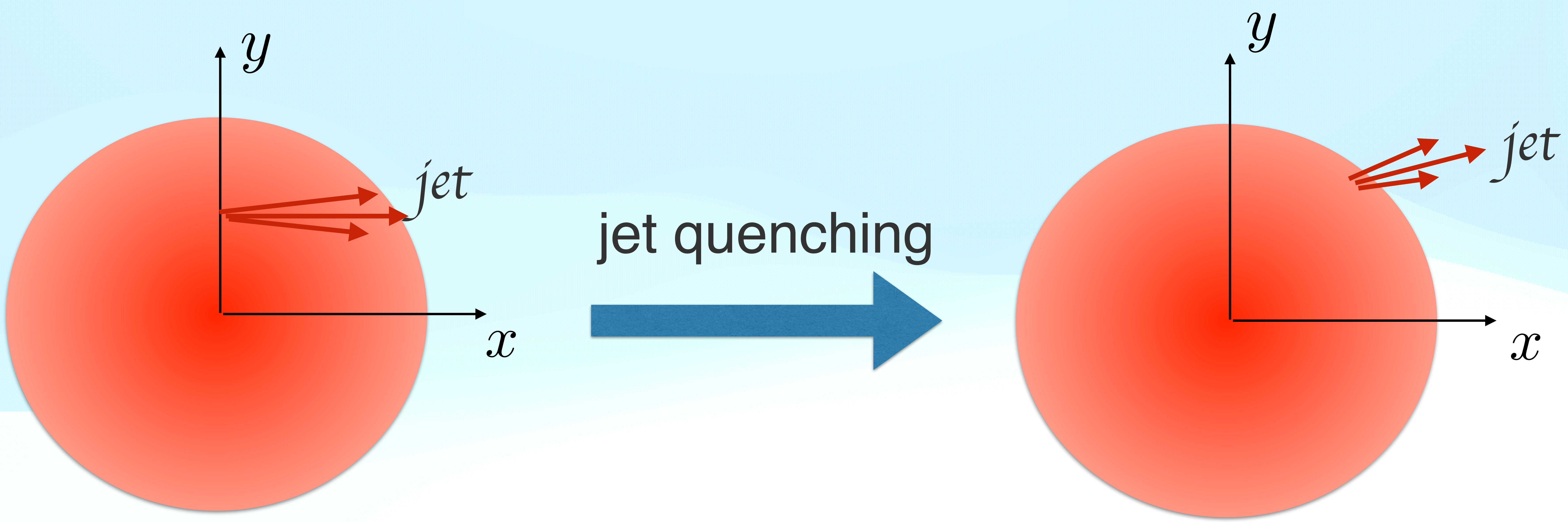
less energy loss:
surface emission

$p_T^h/p_T^\gamma \sim 0.3$

more energy loss:
volume emission

Zhang, Owens, Wang and Wang, Phys. Rev. Letts. 103, 032302 (2009)

What about the transverse jet tomography?



jet quenching leads to:

✓ jet energy loss

✓ transverse momentum broadening.

Motivation

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Boltzmann equation for an elastic scattering:

Small angle scattering, and neglect the effect of flow and drag term:

$$\frac{k^\mu}{\omega}\partial_\mu f_a(\vec{k},\vec{r}) = \frac{\hat{q}_a}{4}\vec{\nabla}^2_{k_\perp} f_a(\vec{k},\vec{r})$$

$$\hat{q}_a = \sum_{bcd}\prod_{i=b,c,d}\int \frac{d^3k_i}{2E_i(2\pi)^3} f_b(k_b)(\vec{k}_{a\perp}-\vec{k}_{c\perp})^2 \times |\mathcal{M}_{ab\to cd}|^2 \frac{\gamma_b}{2}(2\pi)^4\delta^4(k_a+k_b-k_c-k_d)$$

For, $\hat{q}_a = \text{constant}$ $\quad f_a(\vec{k},\vec{r},t) = 3\left(\frac{4\omega}{\hat{q}_a t^2}\right)^2 e^{-(\vec{r}_\perp - \frac{\vec{k}_\perp}{2\omega}t)^2\frac{12\omega^2}{\hat{q}_a t^3} - \frac{k_\perp^2}{\hat{q}_a t}}$

Diffusion width: $\sqrt{\langle k_\perp^2\rangle} = \sqrt{\hat{q}_a t}$ and $\sqrt{\langle r_\perp^2\rangle} = t\sqrt{(\hat{q}_a t/3)}/\omega$

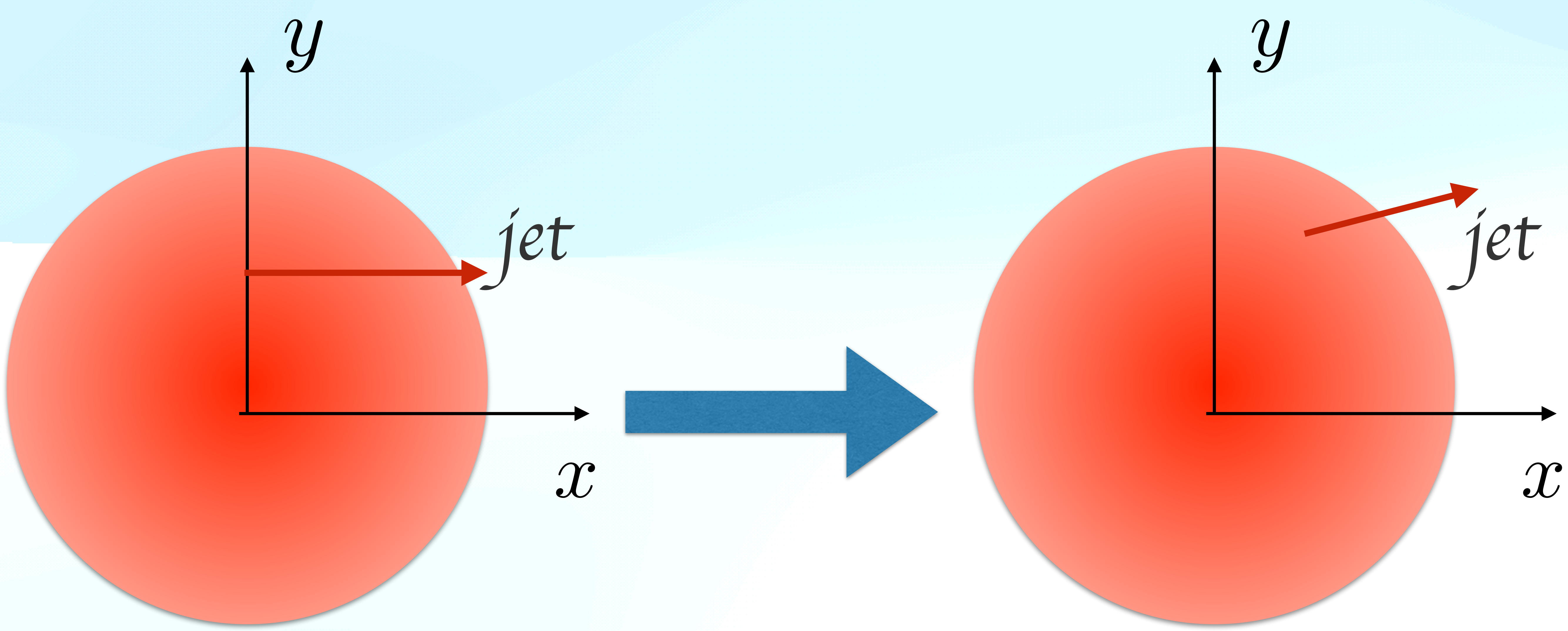
Drift: $\vec{r}_\perp = (\vec{k}_\perp/2\omega)t$

Yayun He, Long-Gang Pang, Xin-Nian Wang. Phys. Rev. Lett. 125 (2020) 122301

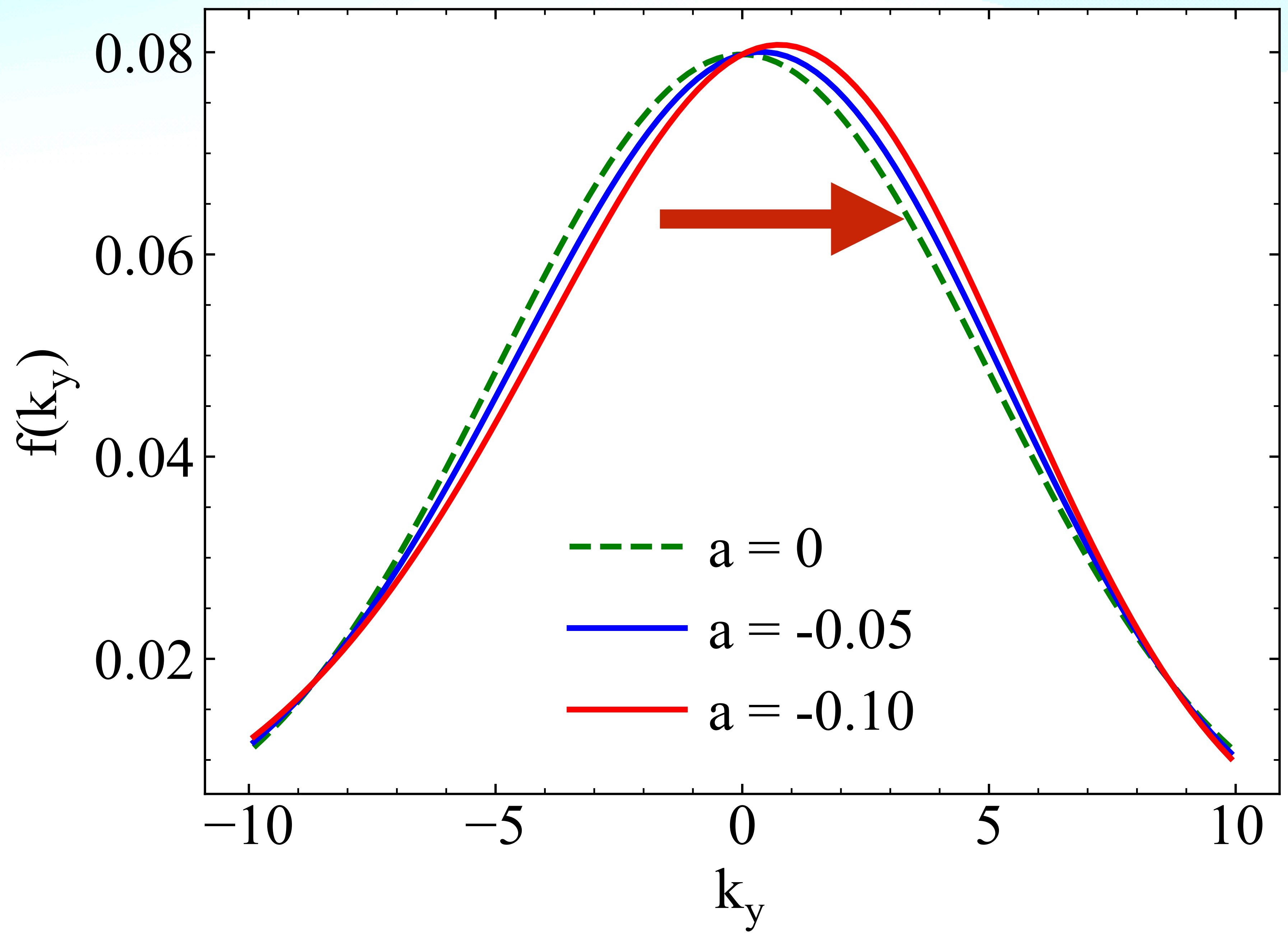
Motivation

For $\hat{q} = \hat{q}_0 + \vec{a} \cdot \vec{r}_\perp$ $\quad f(\vec{k}_\perp, t) = [1 - \frac{t}{3\hat{q}_0 w} \vec{a} \cdot \vec{k}_\perp (1 - \frac{1}{2\hat{q}_0 t} \vec{k}_\perp^2)] f_s(\vec{k}_\perp, t)$

If a is small enough, linear dependence



distorted Gaussian

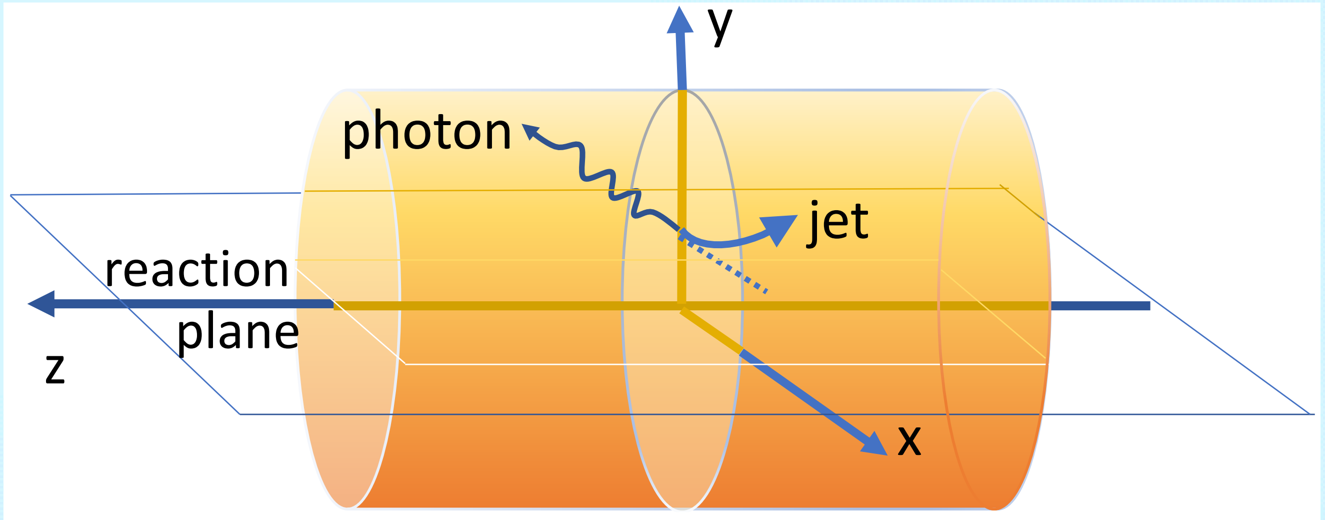


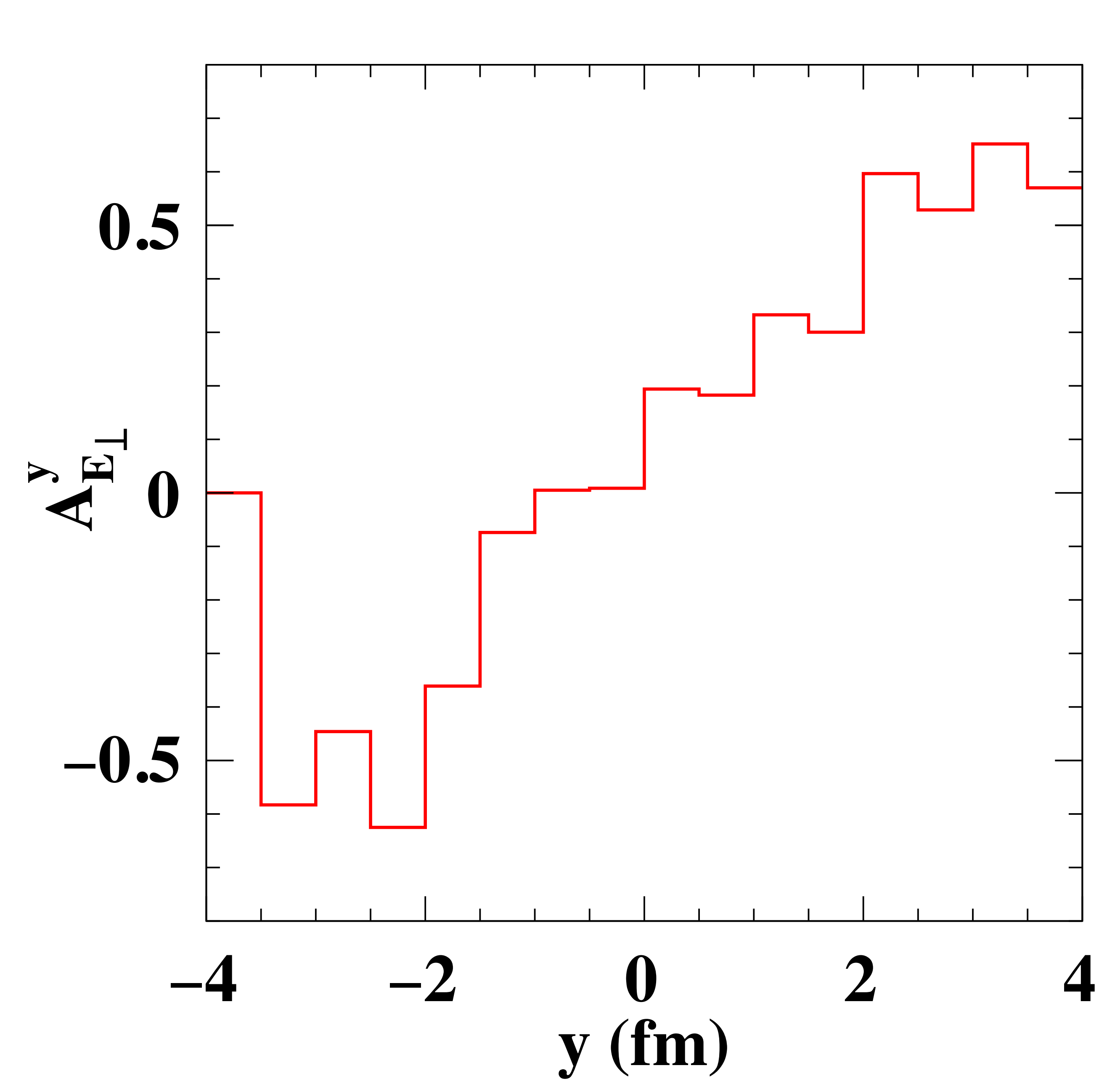
Jets tend to propagate to lower-qhat region!

The LBT Model: gamma jet

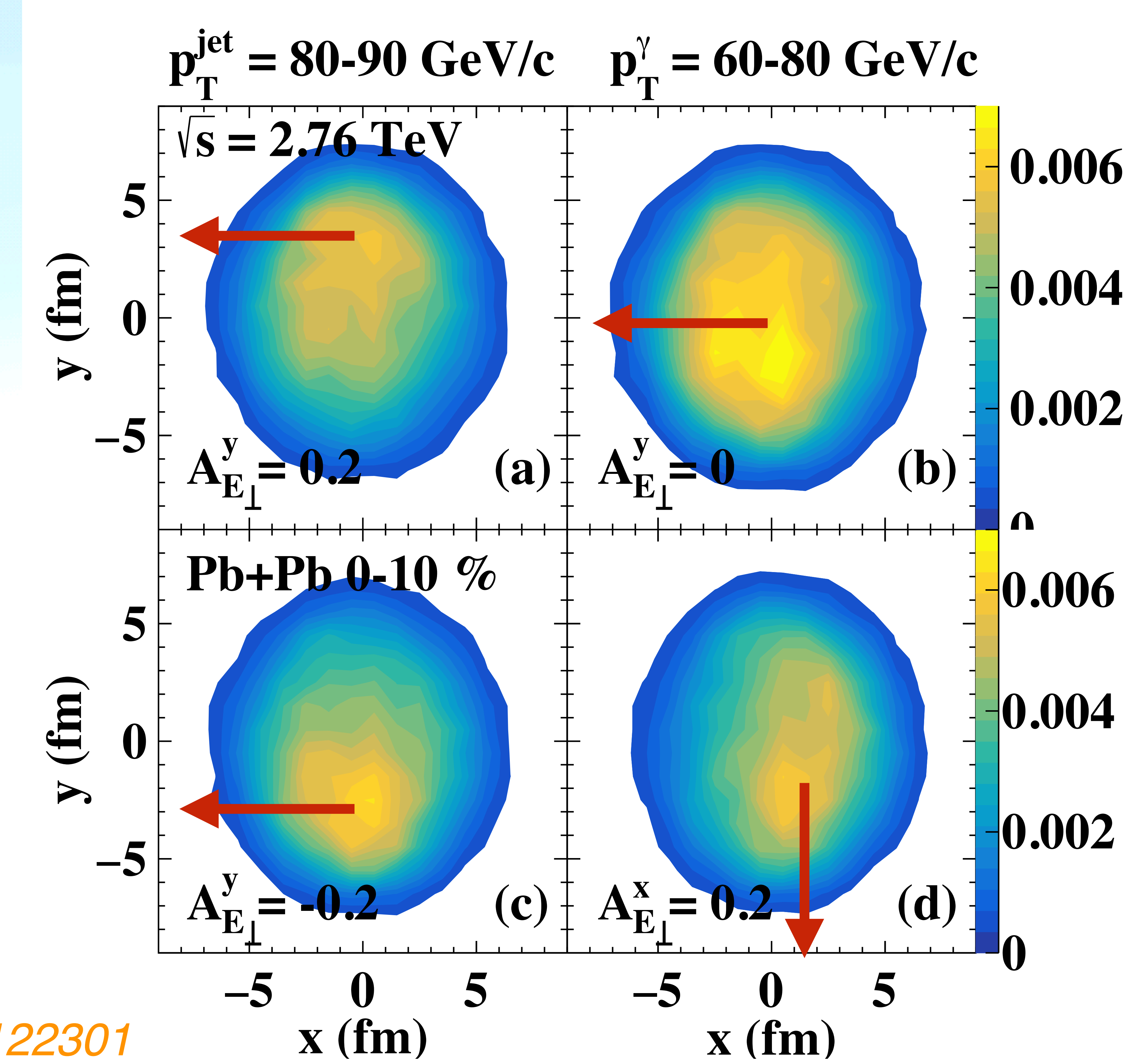
transverse energy asymmetry:

$$A_{E_\perp}^{\vec{n}} = \frac{\int d^3r d^3k f(\vec{k},\vec{r})\vec{k}\cdot\vec{n}}{\int d^3r d^3k f(\vec{k},\vec{r})|\vec{k}\cdot\vec{n}|}$$





LBT+CLVisc hydro $p_T > 3$ GeV/c



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

The LBT Model

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

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

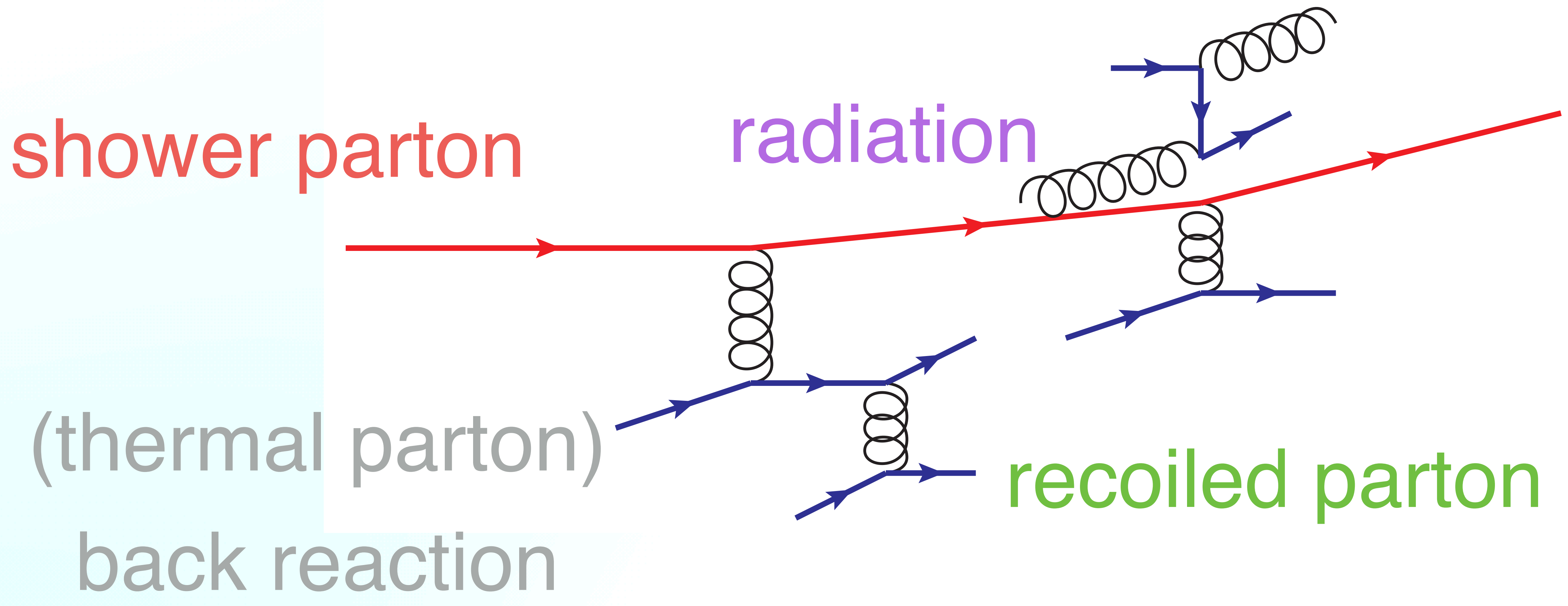
Elasitic: $\Gamma_a^{\text{el}} \equiv \frac{p\cdot u}{p_0}\sum_{bcd}\rho_b(x)\sigma_{ab\to cd}$ LO perturbative QCD *J. Auvinen et al, Phys.Rev. C 82(2010) 024906*

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

High twist approach

Guo and Wang, PRL 85 (2000) 3591

Zhang, Wang and Wang, PRL 93 (2004) 072301

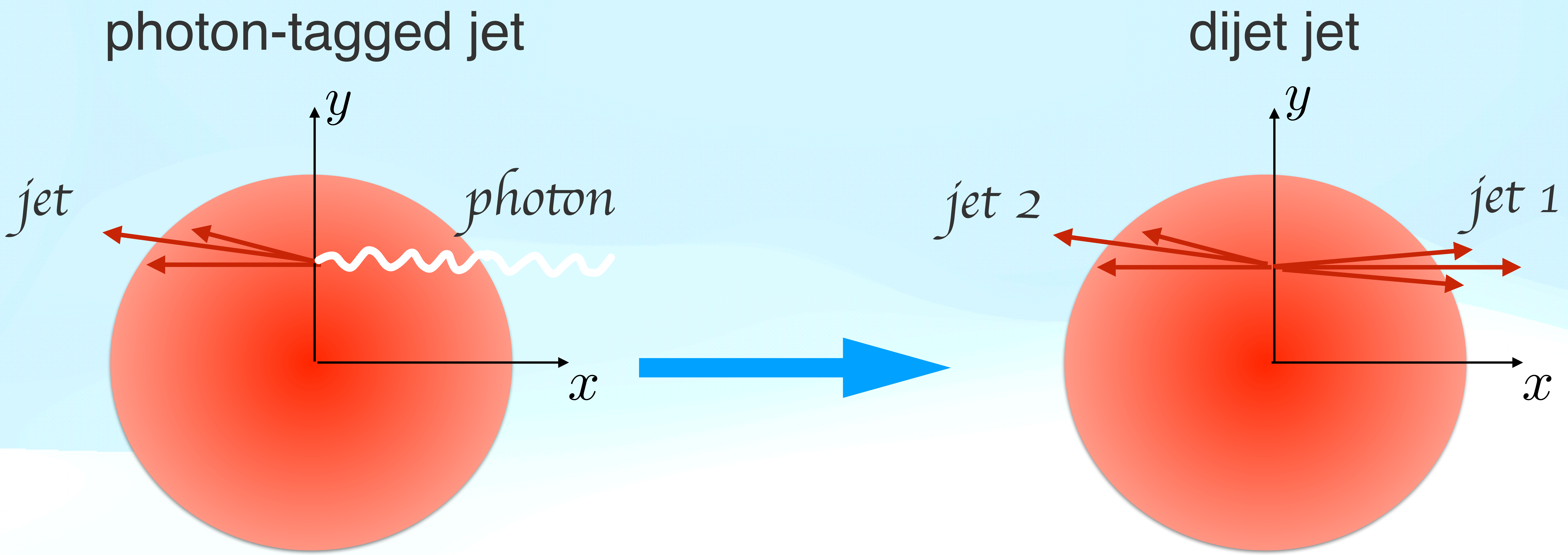


Model features:

- re-scattering
- back reaction
- Linear approximation, and valid for $\delta f \ll f$

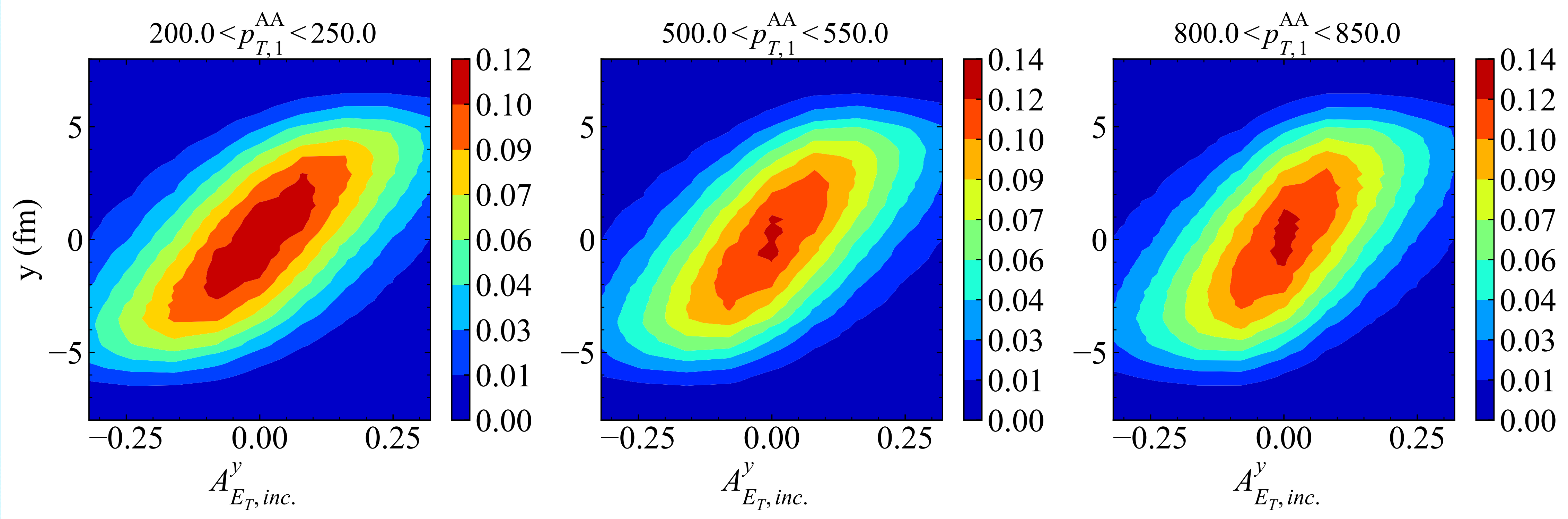
How about the gradient tomography in dijet production?

Dijet Tomography: bias

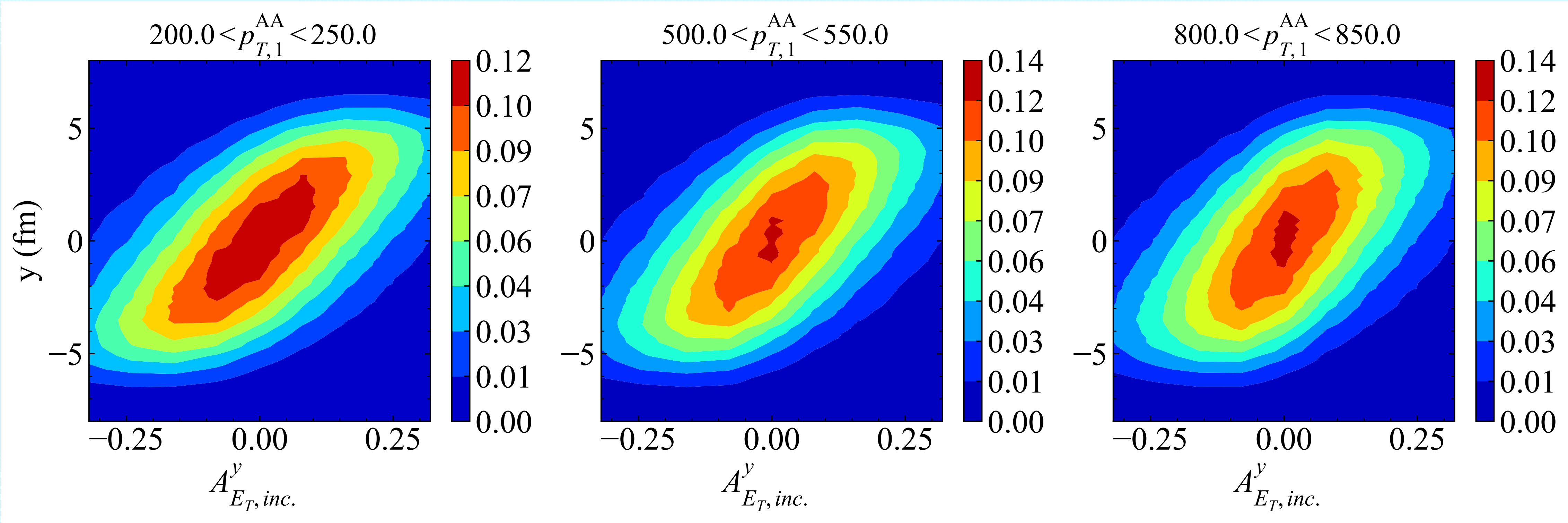


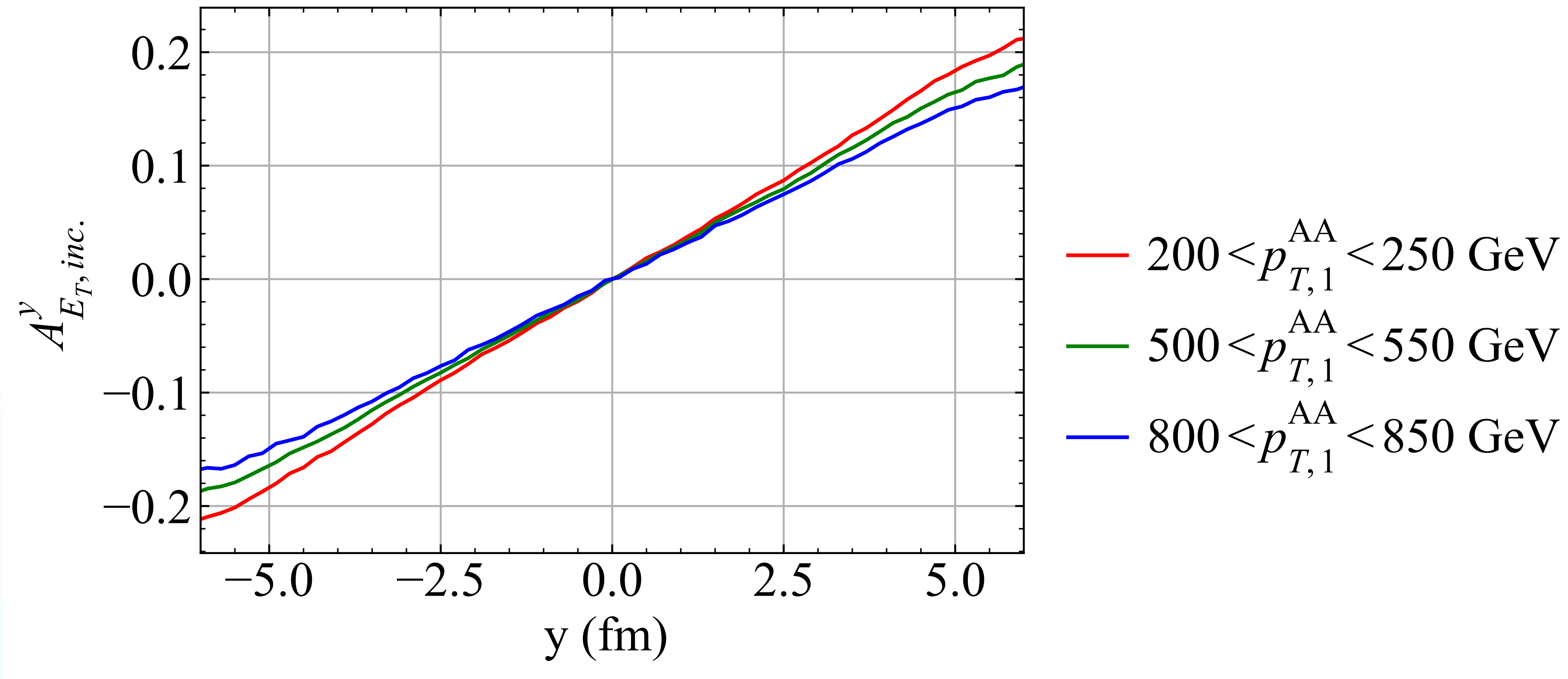
- The trigger propagates along x direction initially
- photon-tagged jet: photon as the trigger
- dijet: leading jet as the trigger

Dijet Tomography



Dijet Tomography





Dijet Tomography

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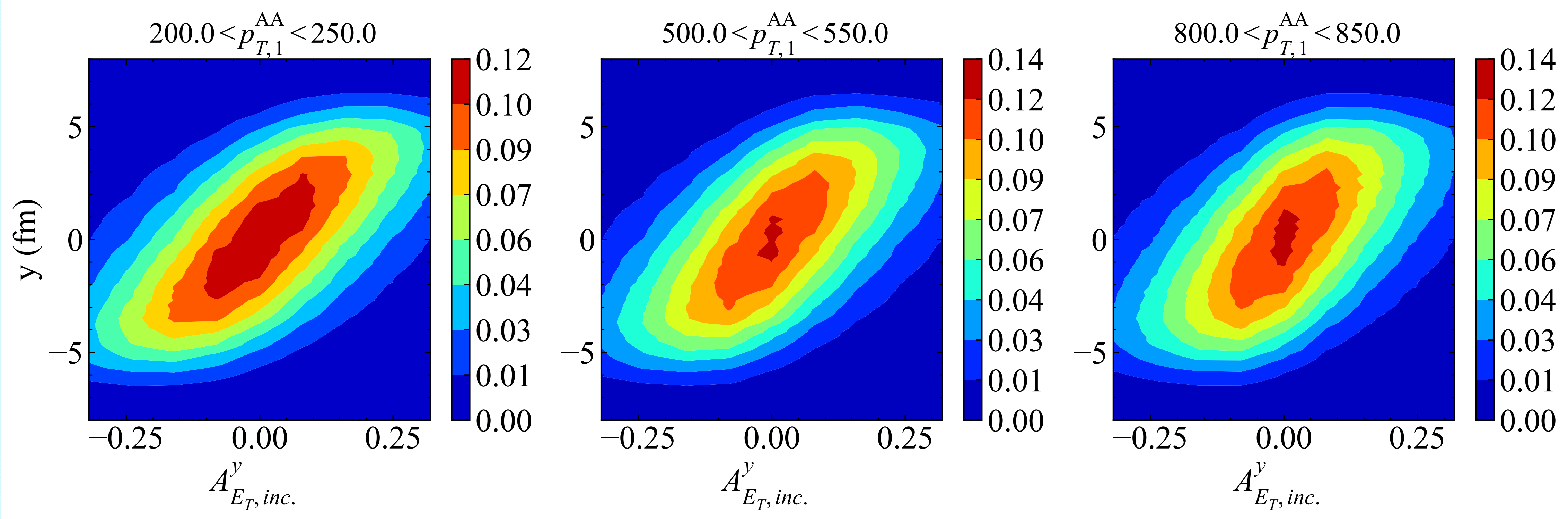
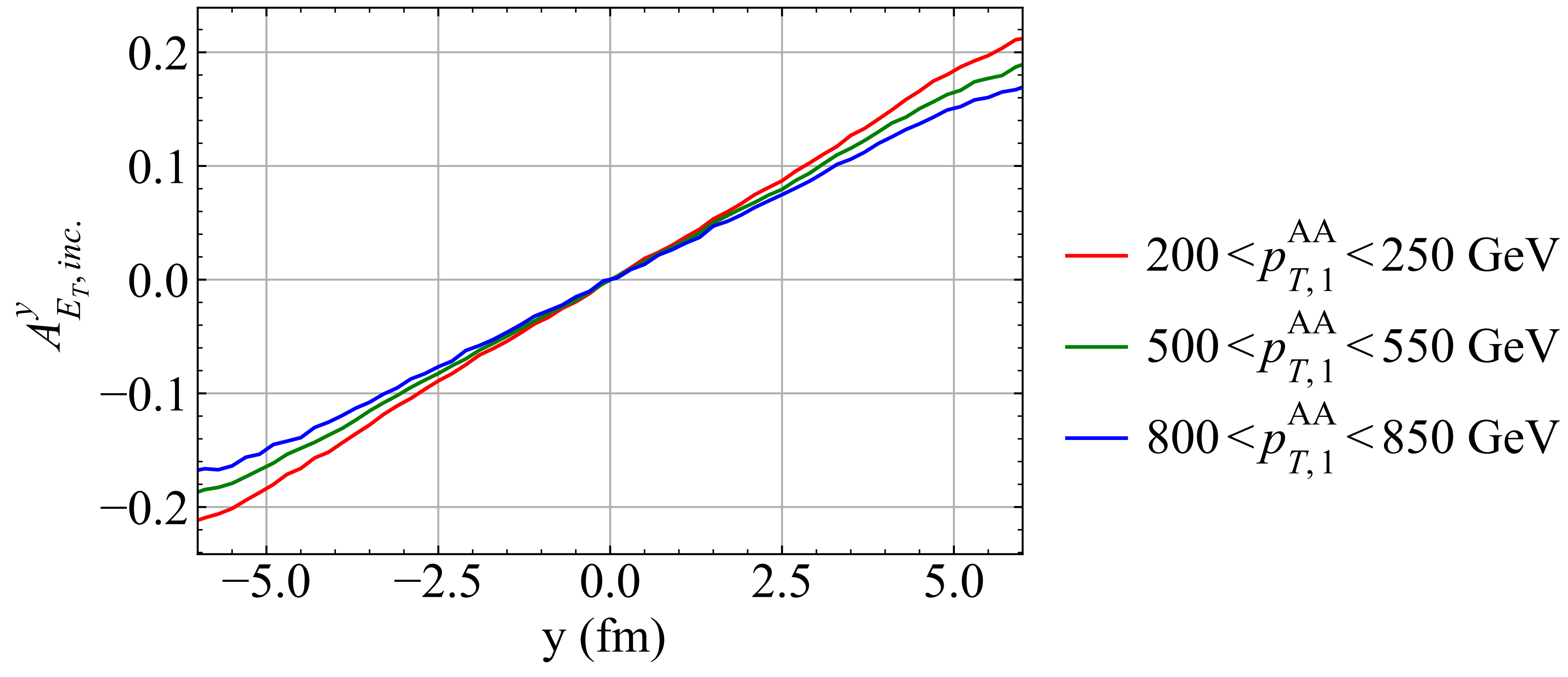
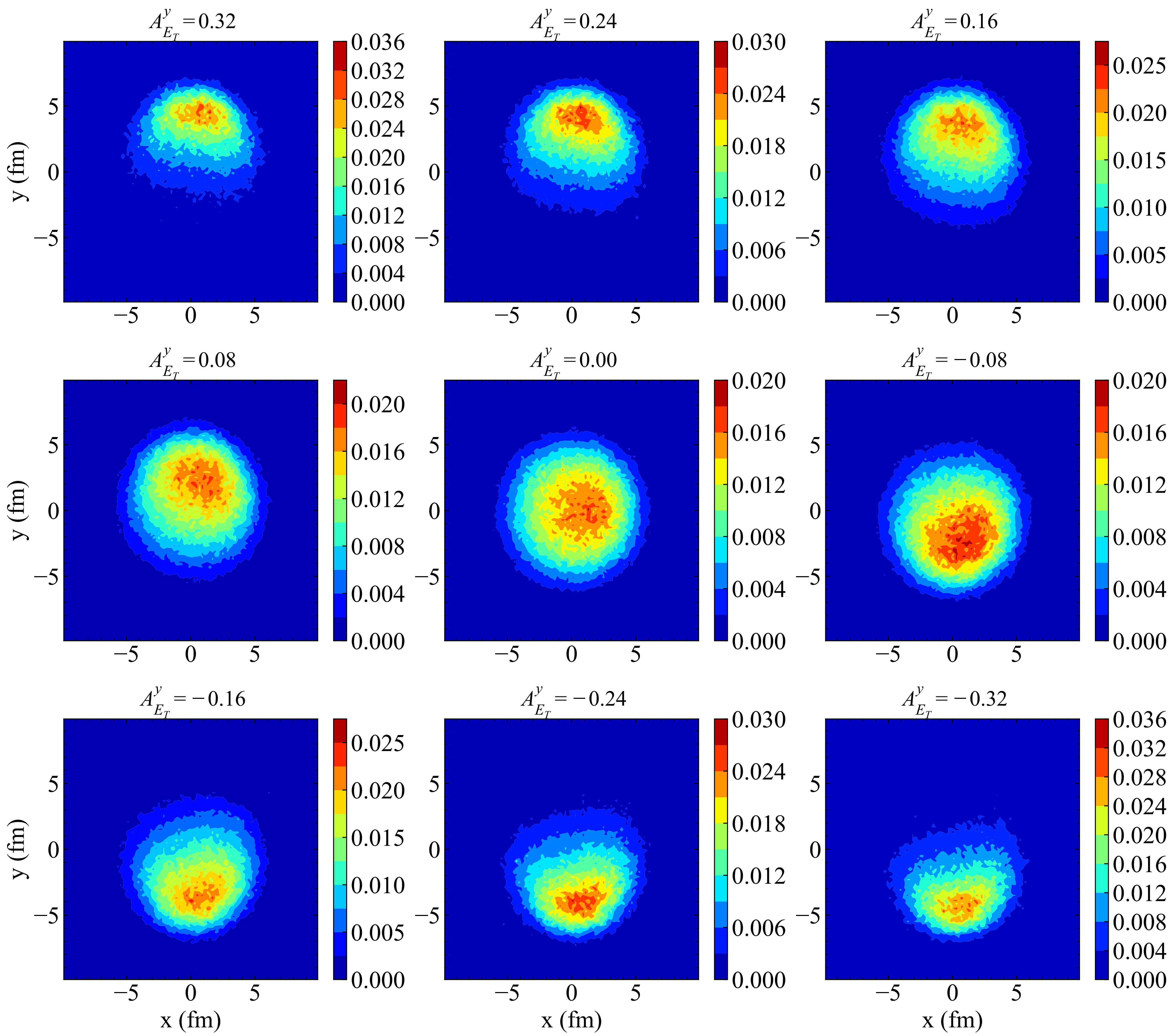
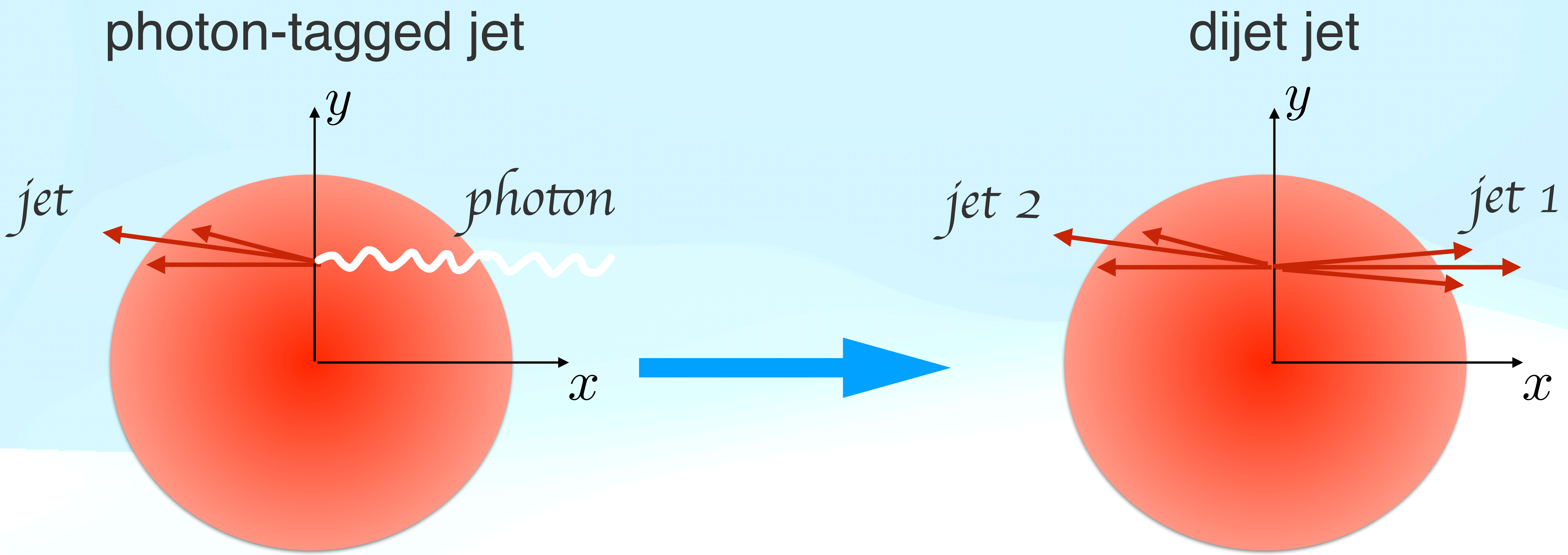
$500 < p_{T,1}^{AA} < 550$ GeV/c







Dijet Tomography: bias

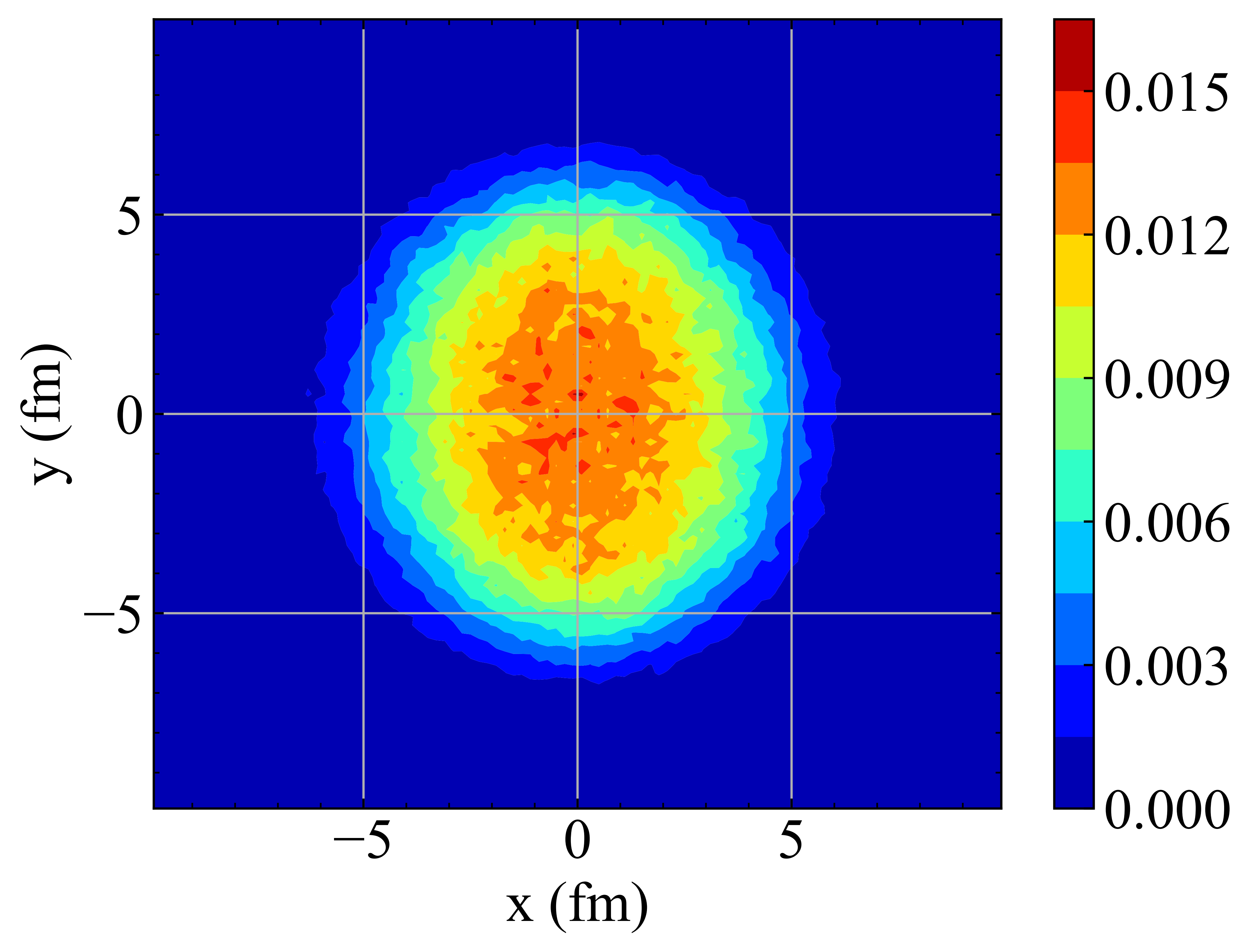


- photon-tagged jet is free of bias, emitted mainly from the center.
- dijet is biased, the leading jet also has energy loss, emitted mainly from the right region.

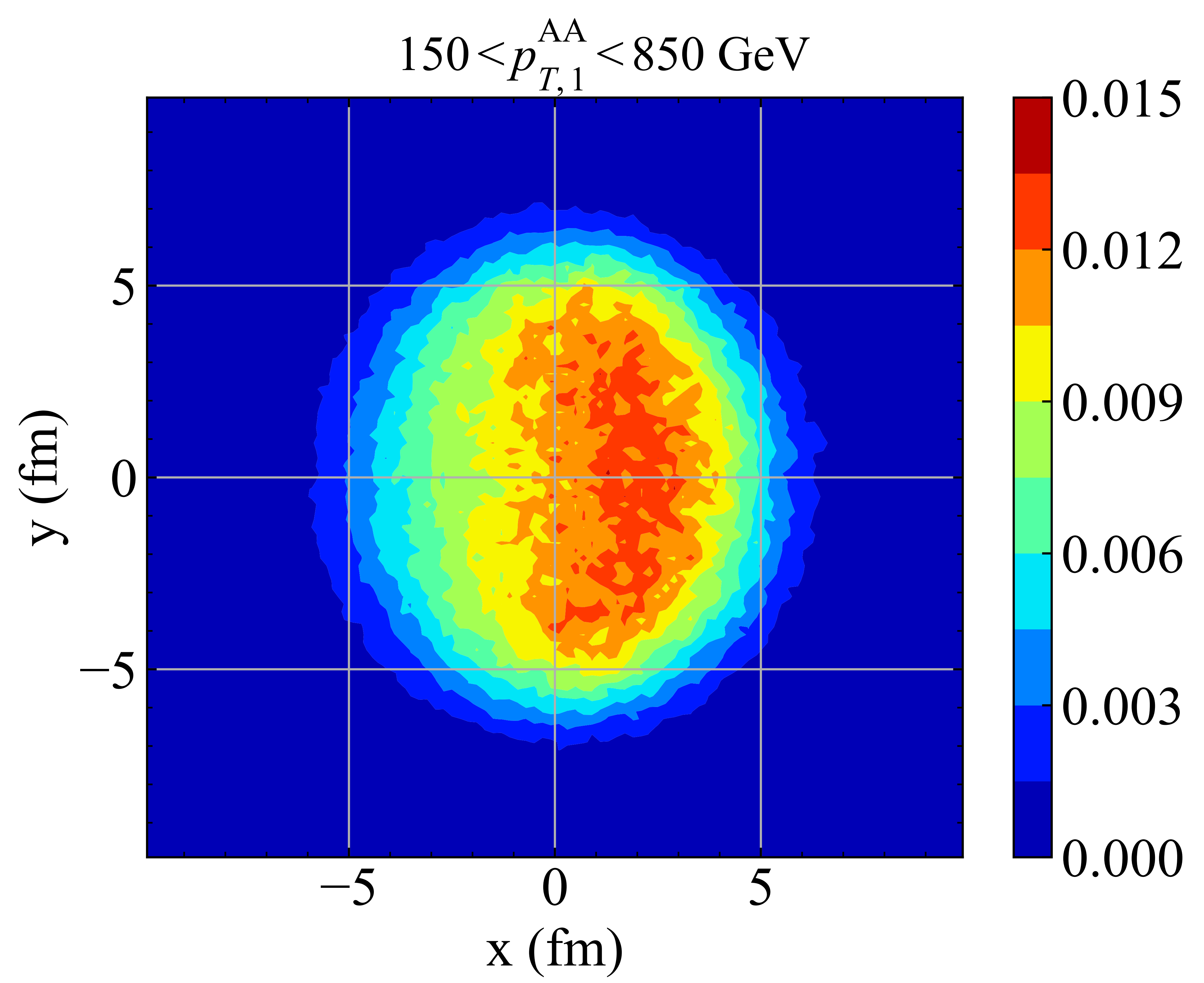
Dijet Tomography: bias

Pb+Pb 0-10% 5.02 TeV

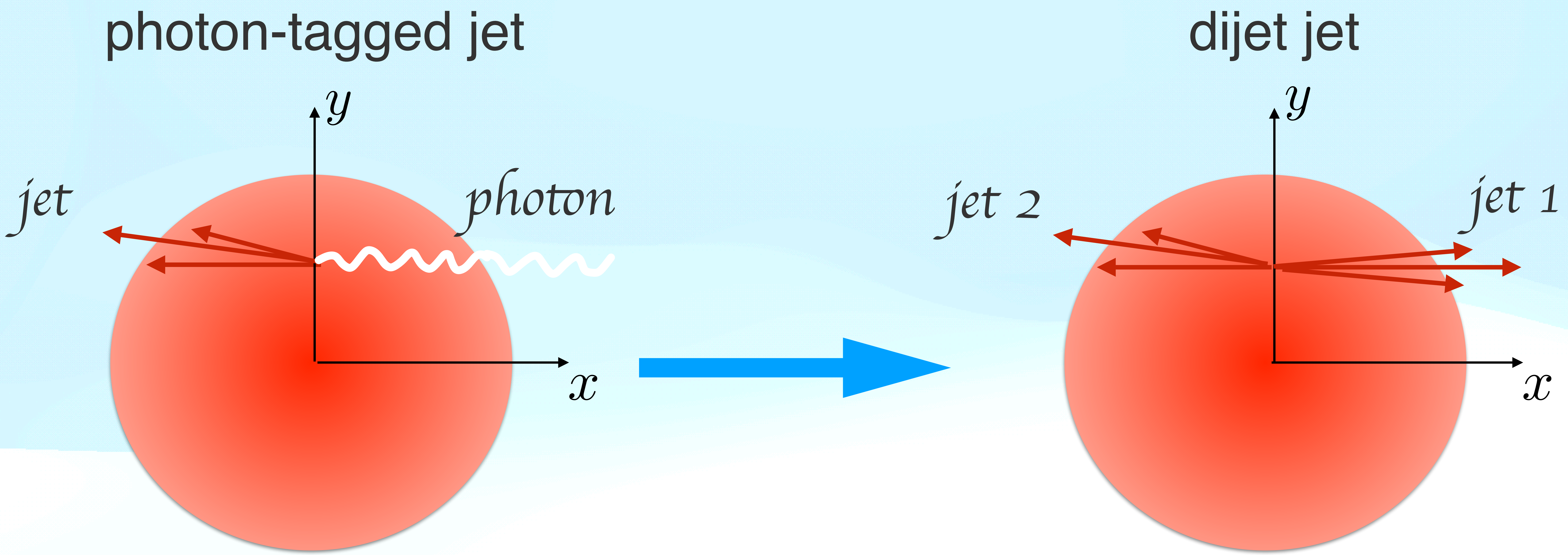
Initial production without jet quenching



with jet quenching



Dijet Tomography: another bias



The leading jet initially from pp collisions could become the final subleading jet in AA collisions due to energy loss, “id exchange”

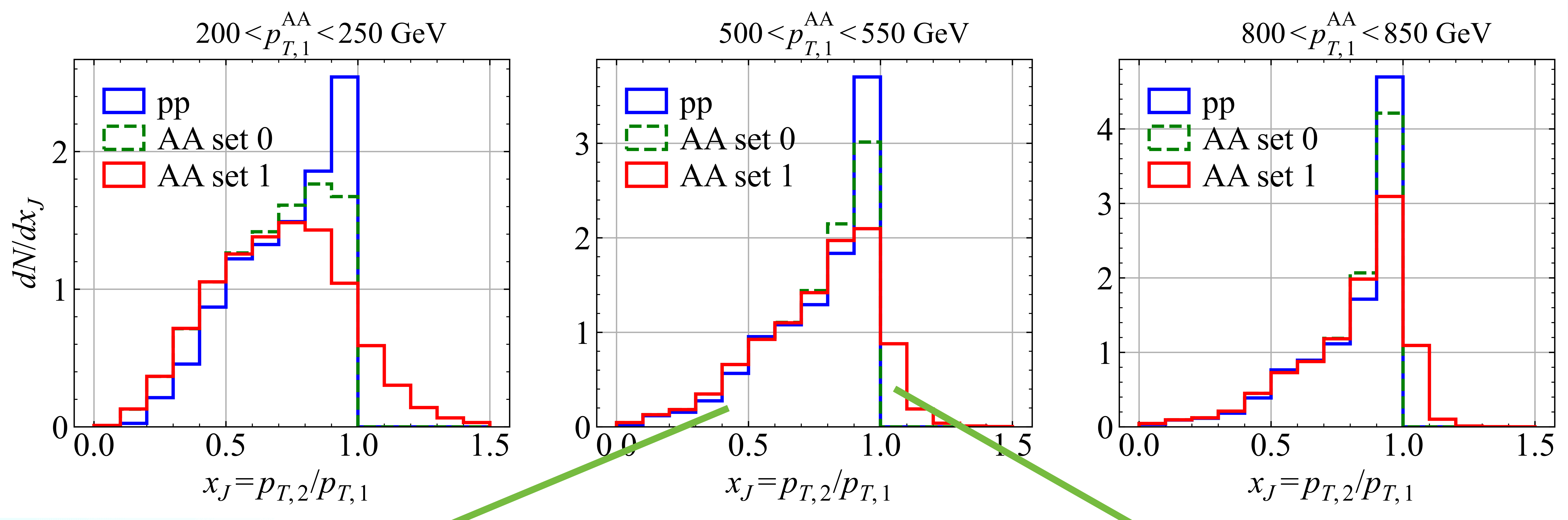
How much does the bias affect the dijet tomography?

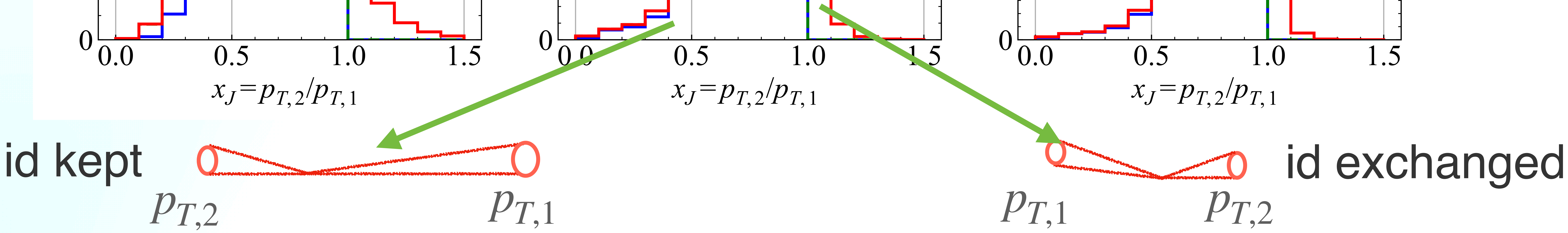
Dijet Tomography: bias

pp: $p_{T,1}$ is leading, $p_{T,2}$ is subleading

AA set 0: $p_{T,1}$ is leading, $p_{T,2}$ is subleading; potential id exchange

AA set 1: $p_{T,1}$ is leading from pp, $p_{T,2}$ is subleading from pp; no id exchange



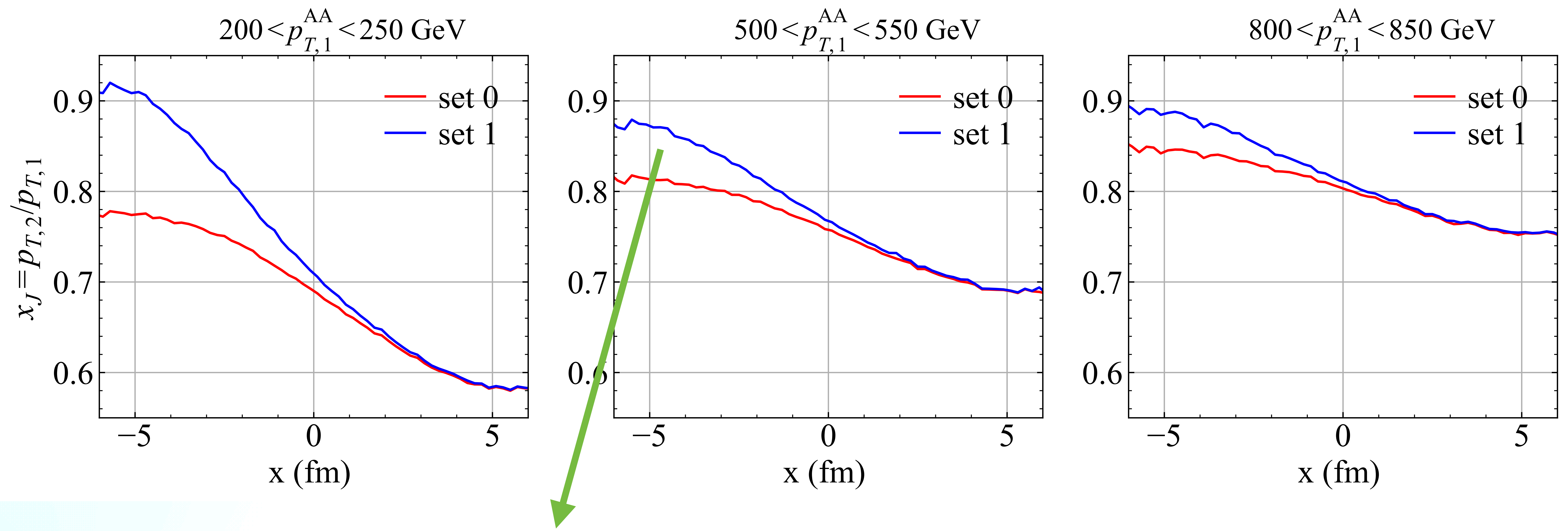


Dijet Tomography: bias

pp: $p_{T,1}$ is leading, $p_{T,2}$ is subleading

AA set 0: $p_{T,1}$ is leading, $p_{T,2}$ is subleading; potential id exchange

AA set 1: $p_{T,1}$ is leading from pp, $p_{T,2}$ is subleading from pp; no id exchange



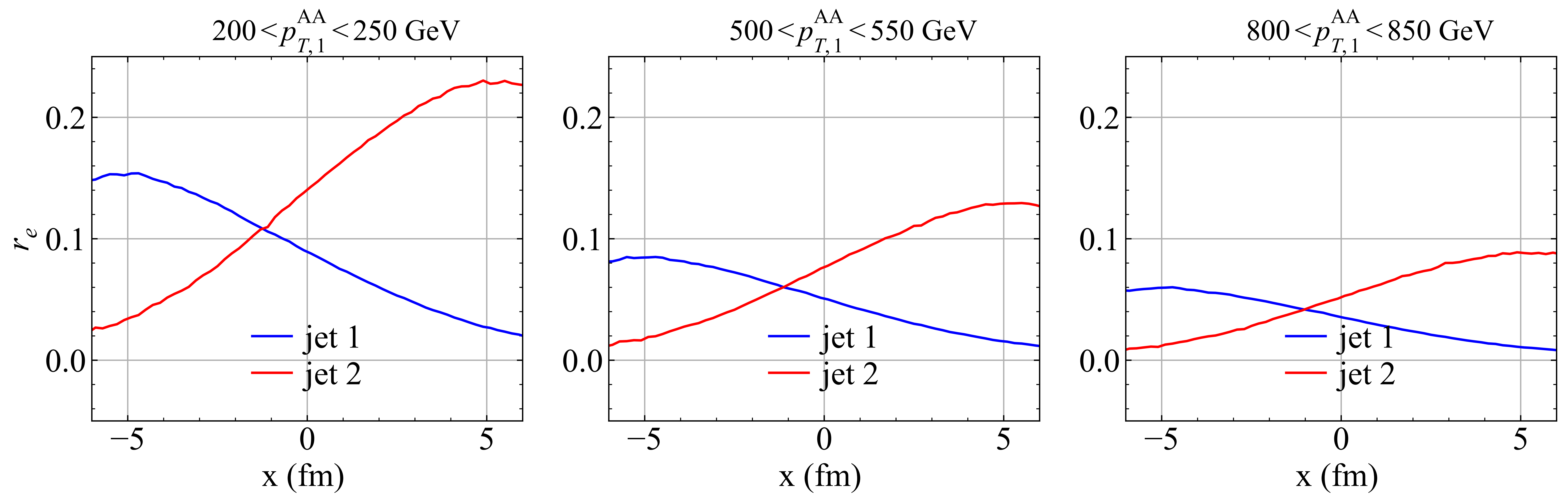
More energy loss for $p_{T,1}$ at this initial production region leads to the id exchange

Dijet Tomography: energy loss ratio

Track the leading and subleading jet from pp

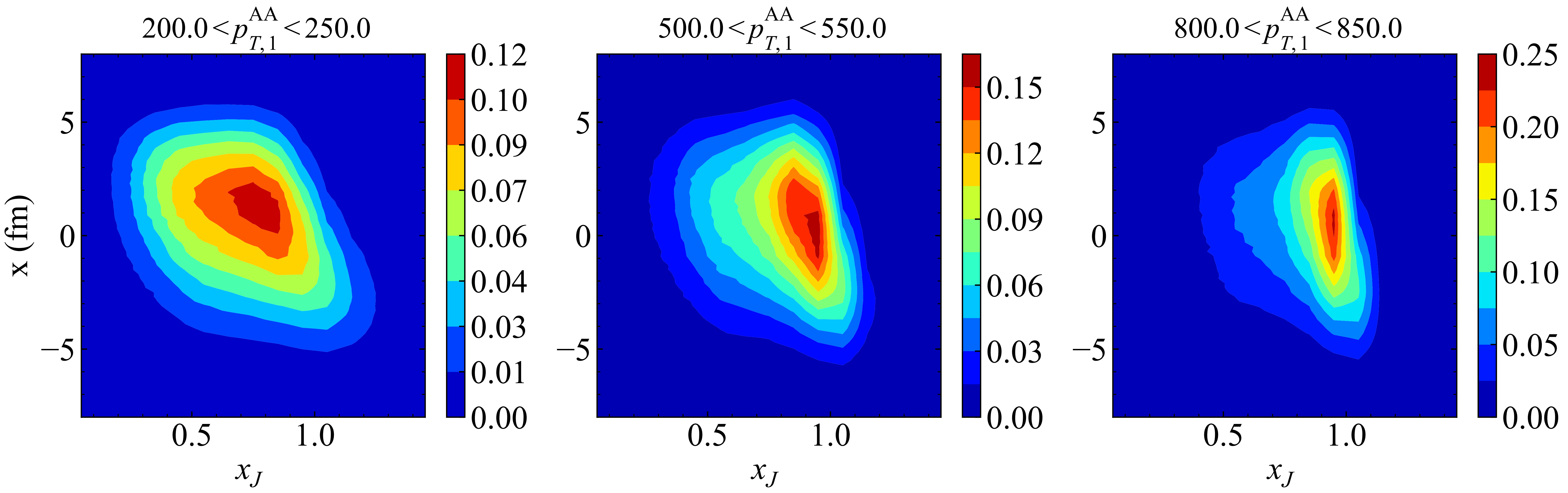
leading jet energy loss ratio: $r_{e,1} = (p_{T,1}^{\mathrm{pp}} - p_{T,1}^{\mathrm{AA}})/p_{T,1}^{\mathrm{pp}}$

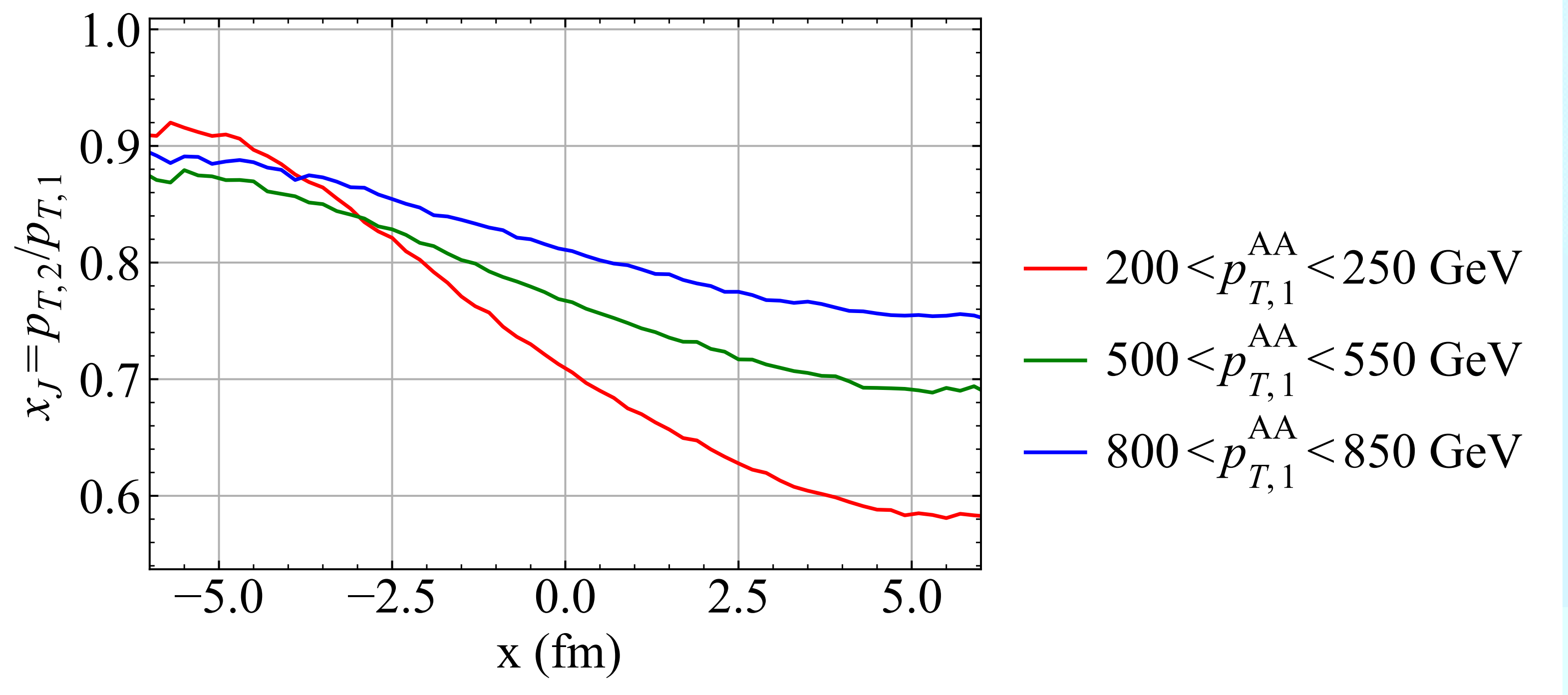
subleading jet energy loss ratio: $r_{e,2} = (p_{T,2}^{\mathrm{pp}} - p_{T,2}^{\mathrm{AA}})/p_{T,2}^{\mathrm{pp}}$

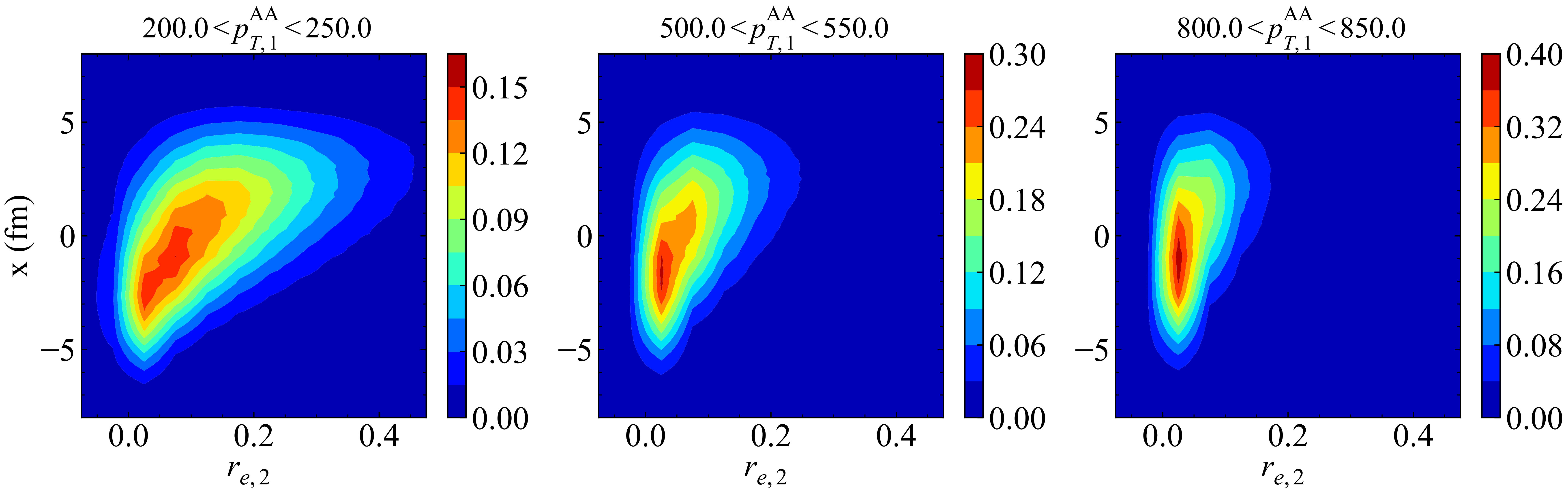


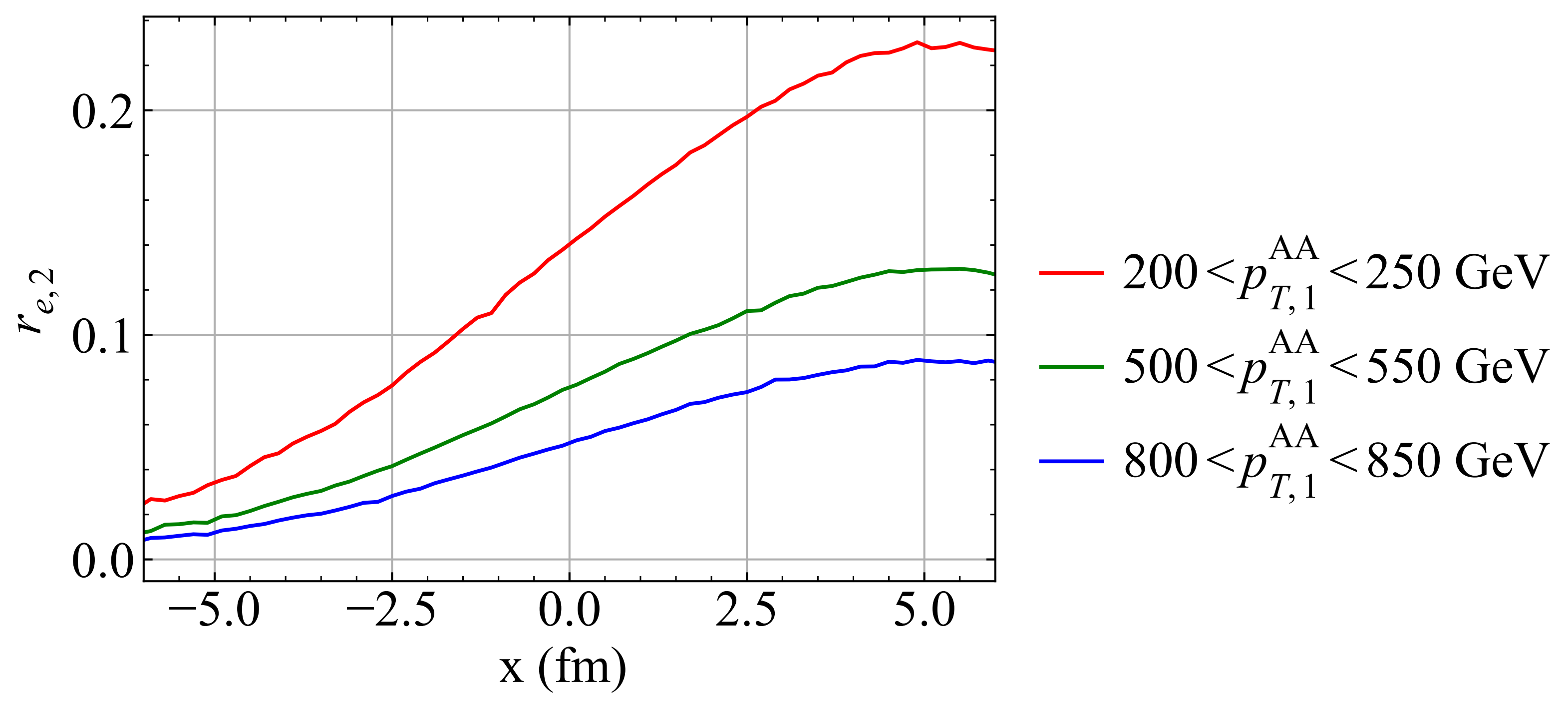
Despite of the bias , x_J and r_e can be good quantities to localize jet production regions

Dijet Tomography: localize x



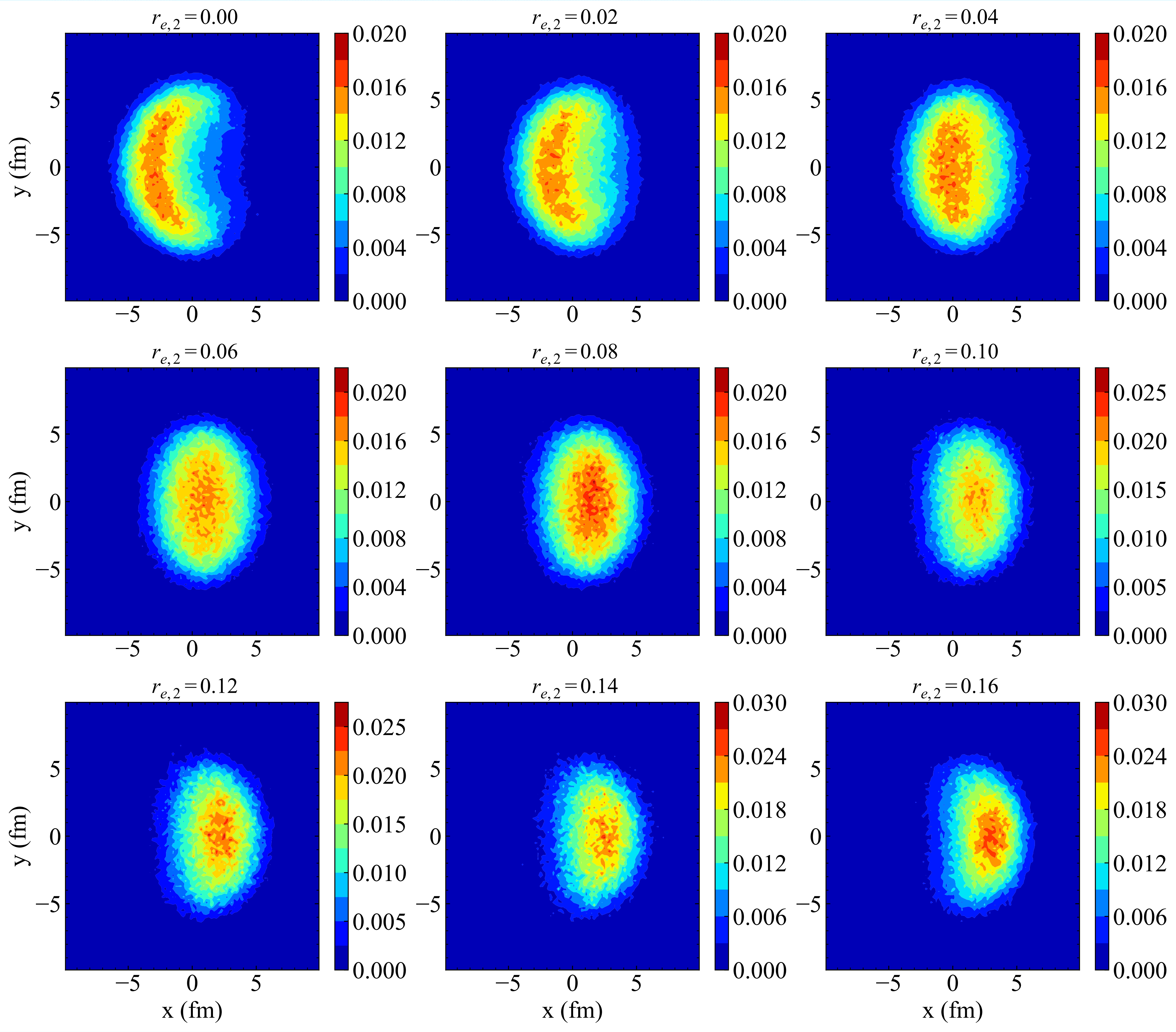






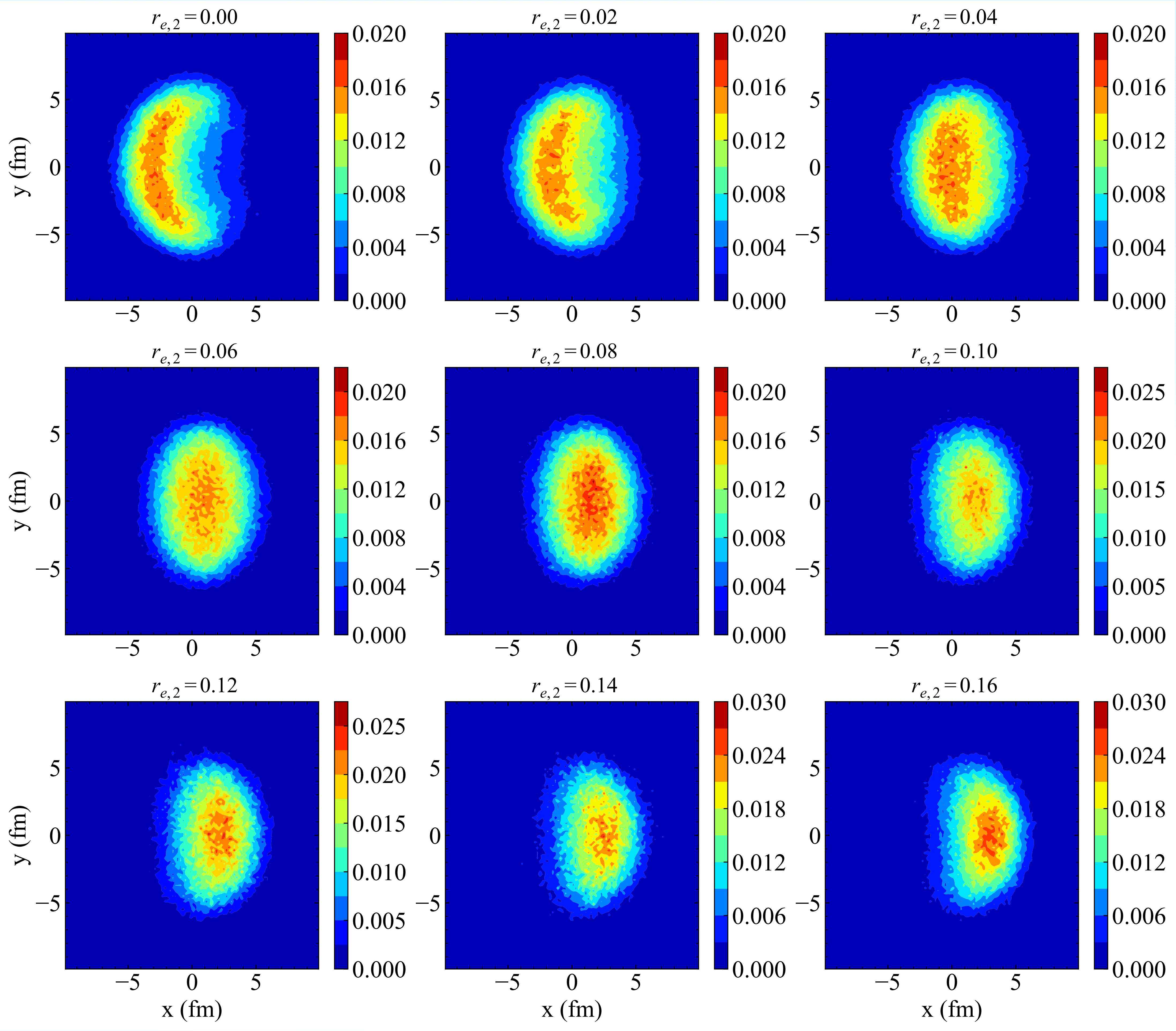
Dijet Tomography: localize x

$500 < p_{T,1}^{AA} < 550$ GeV/c



Dijet Tomography: localize x

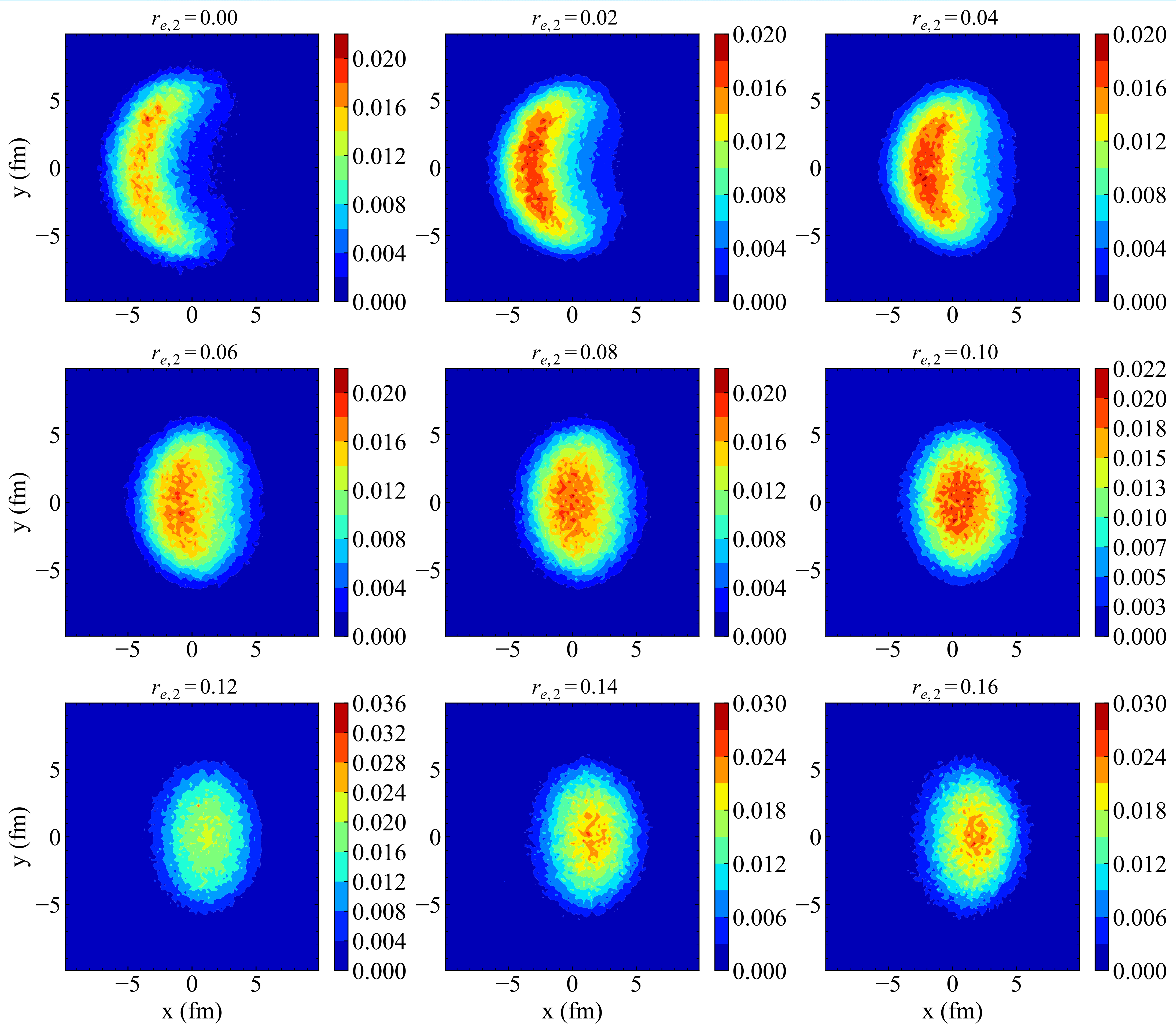
$500 < p_{T,1}^{\mathrm{AA}} < 550$ GeV/c



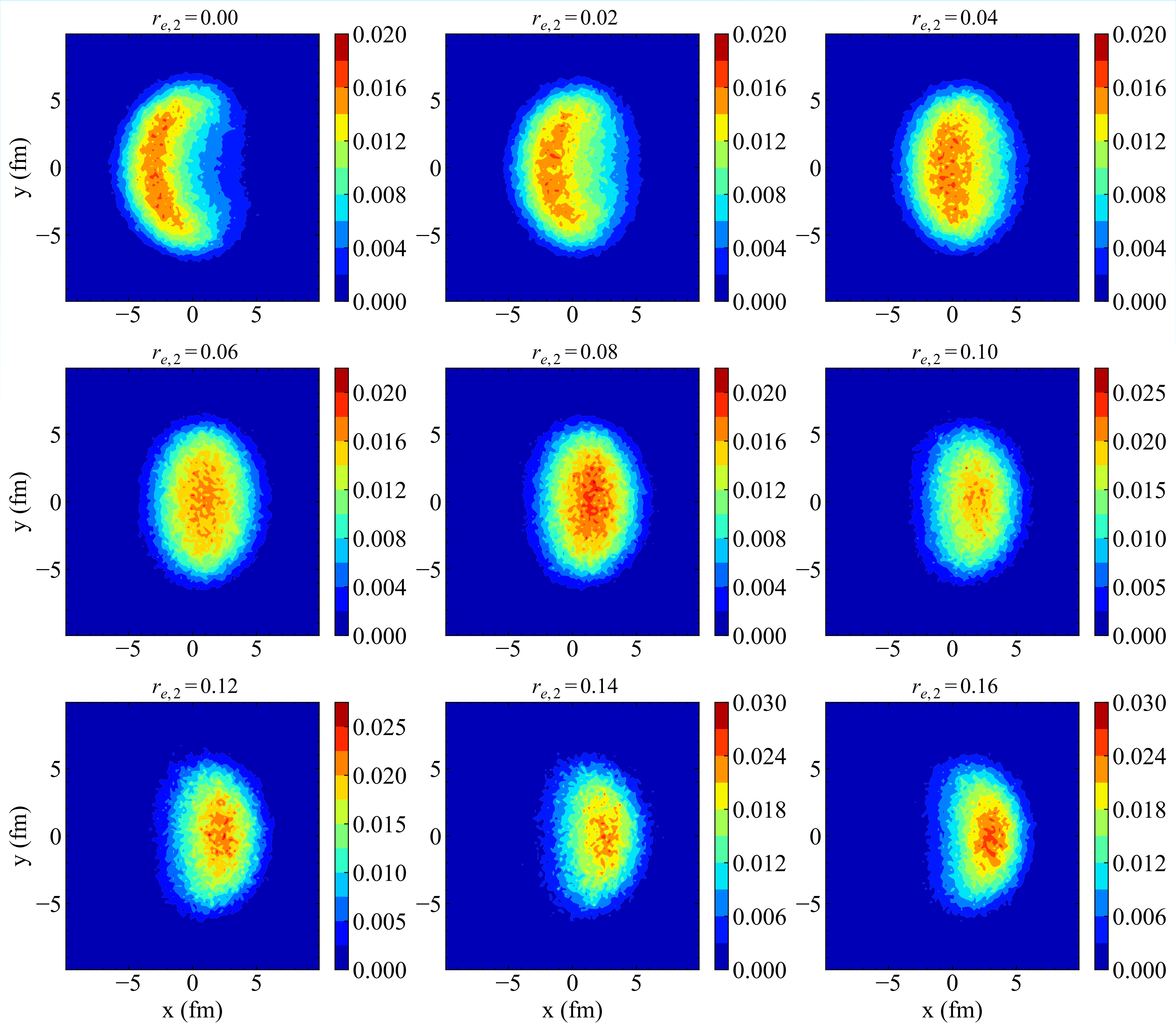
lunar phases

Dijet Tomography: localize x

$500 < p_{T,1}^{\rm pp} < 550$ GeV/c



$500 < p_{T,1}^{\rm AA} < 550$ GeV/c



Dijet Tomography: localize y

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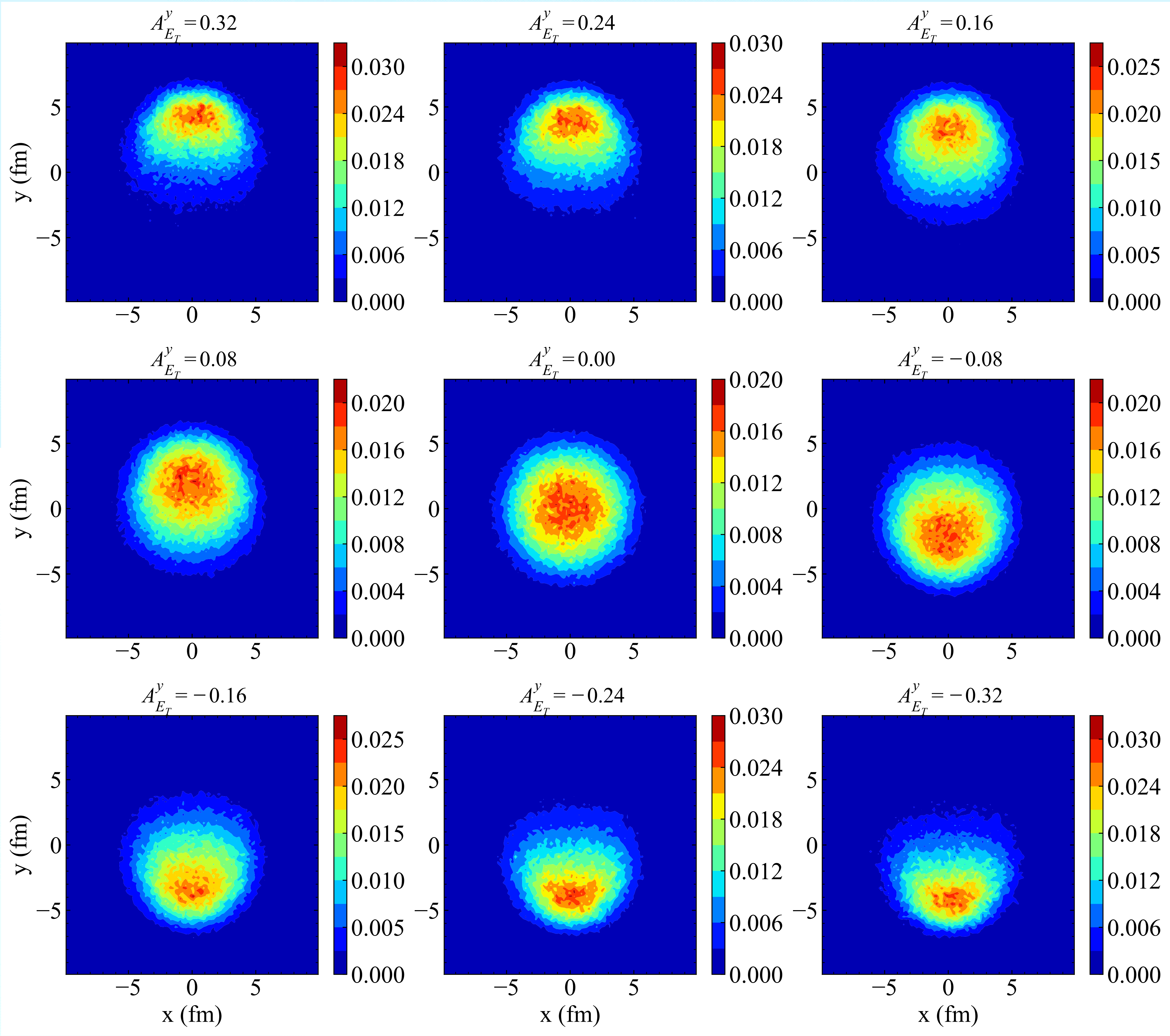
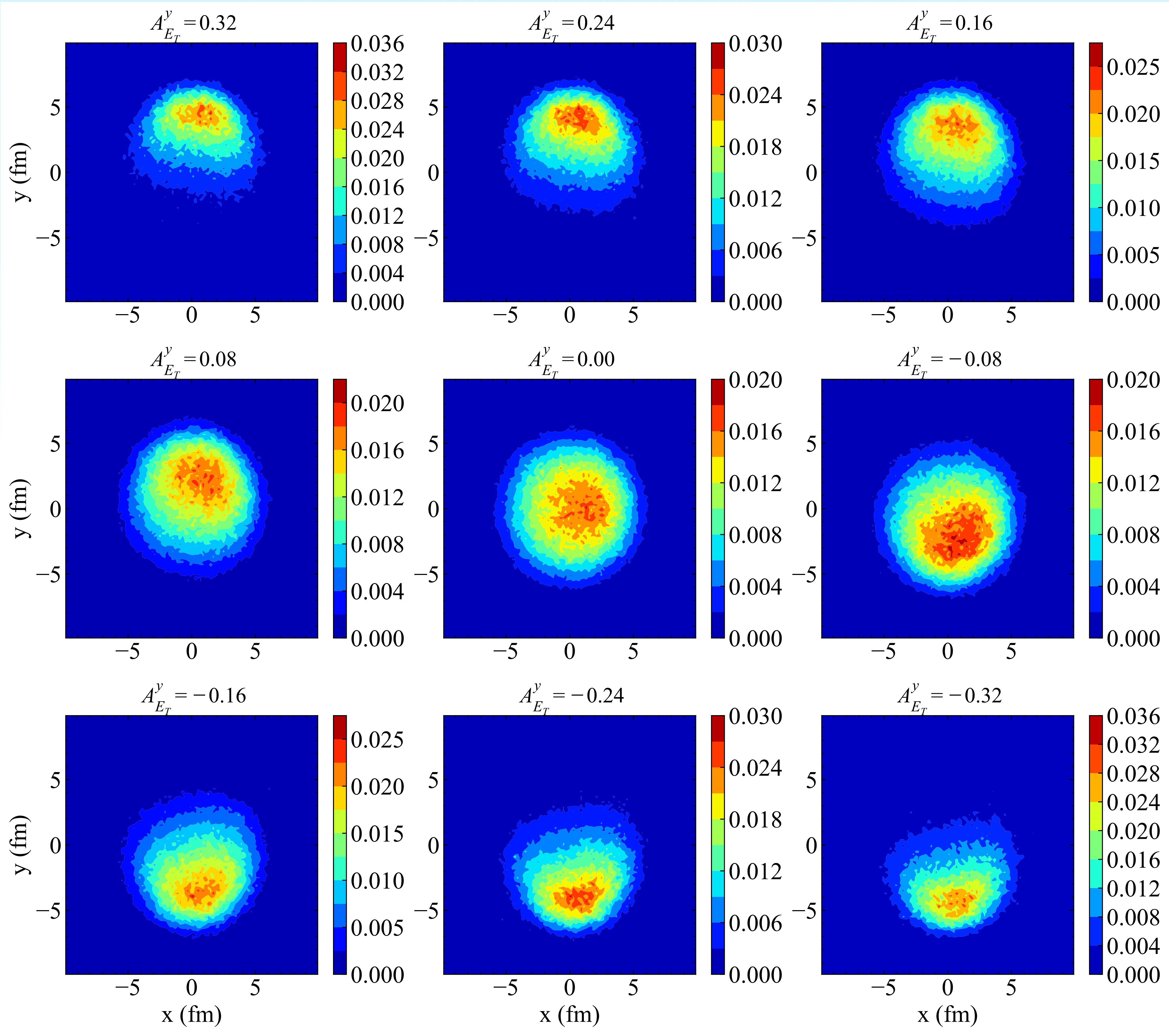
Don't forget transverse jet tomography

Dijet Tomography: localize y

$500 < p_{T,1}^{\mathrm{pp}} < 550$ GeV/c

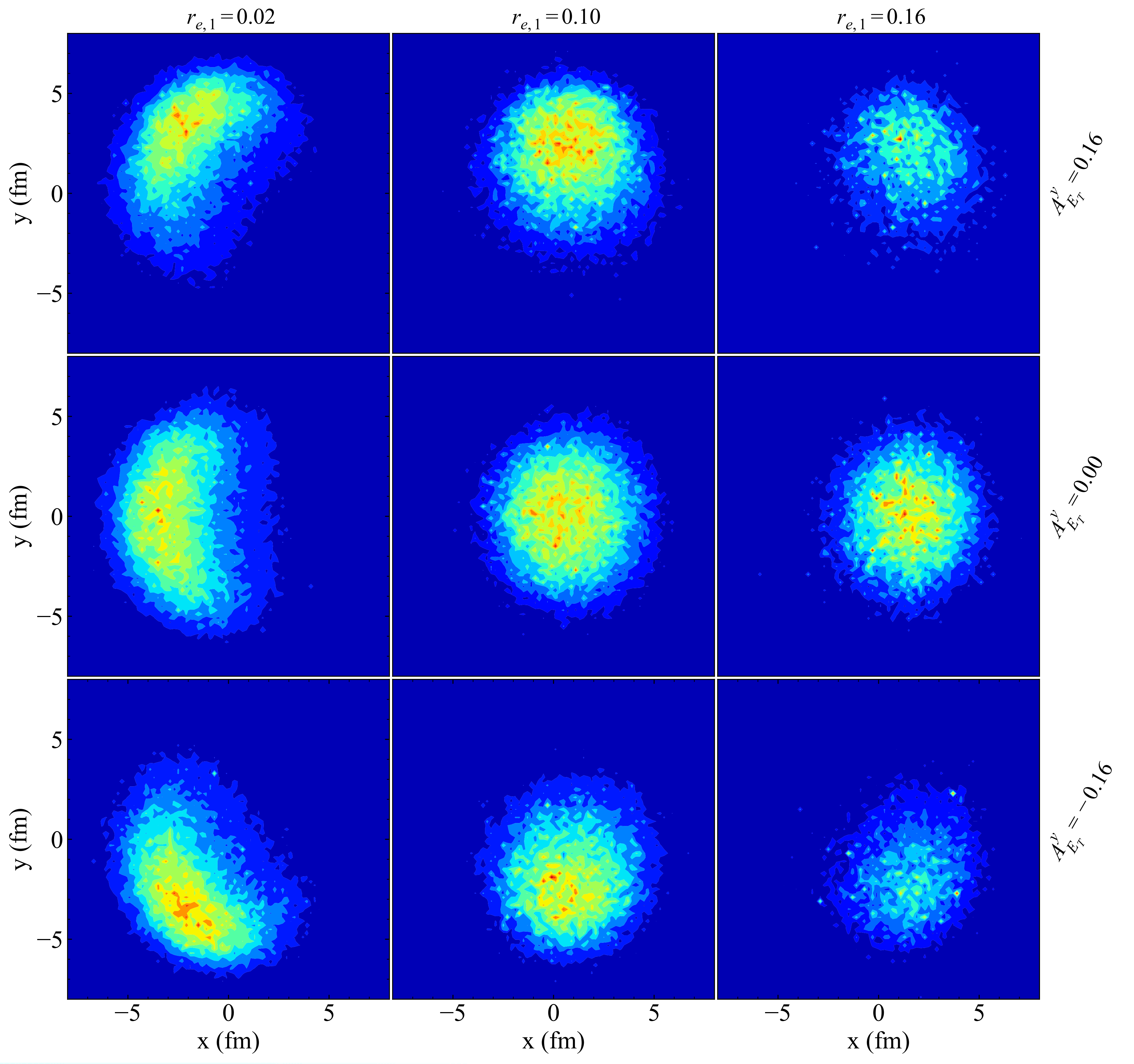


$500 < p_{T,1}^{\mathrm{AA}} < 550$ GeV/c

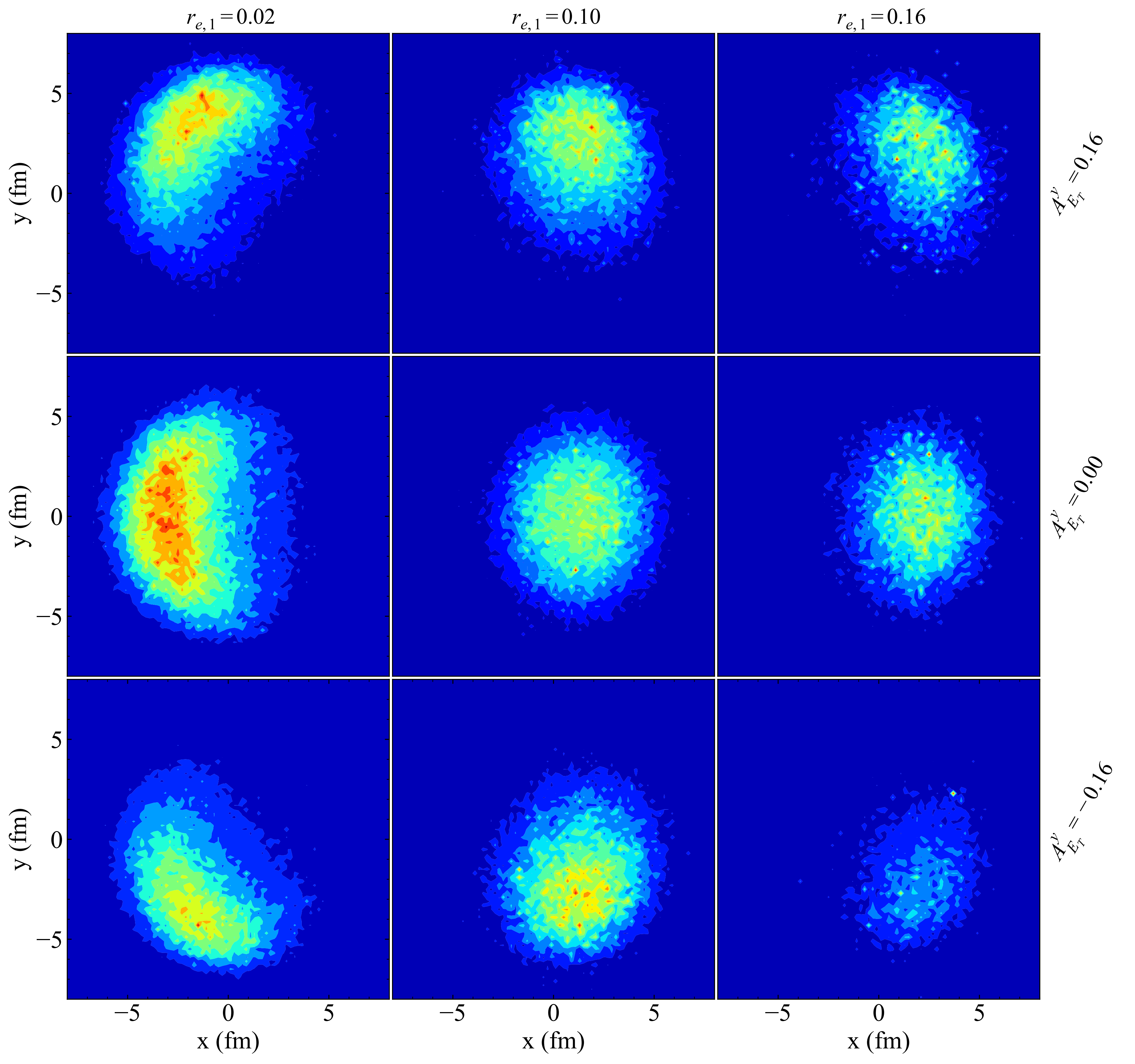


Dijet Tomography: localize x and y

$500 < p_{T,1}^{\rm pp} < 550$ GeV/c

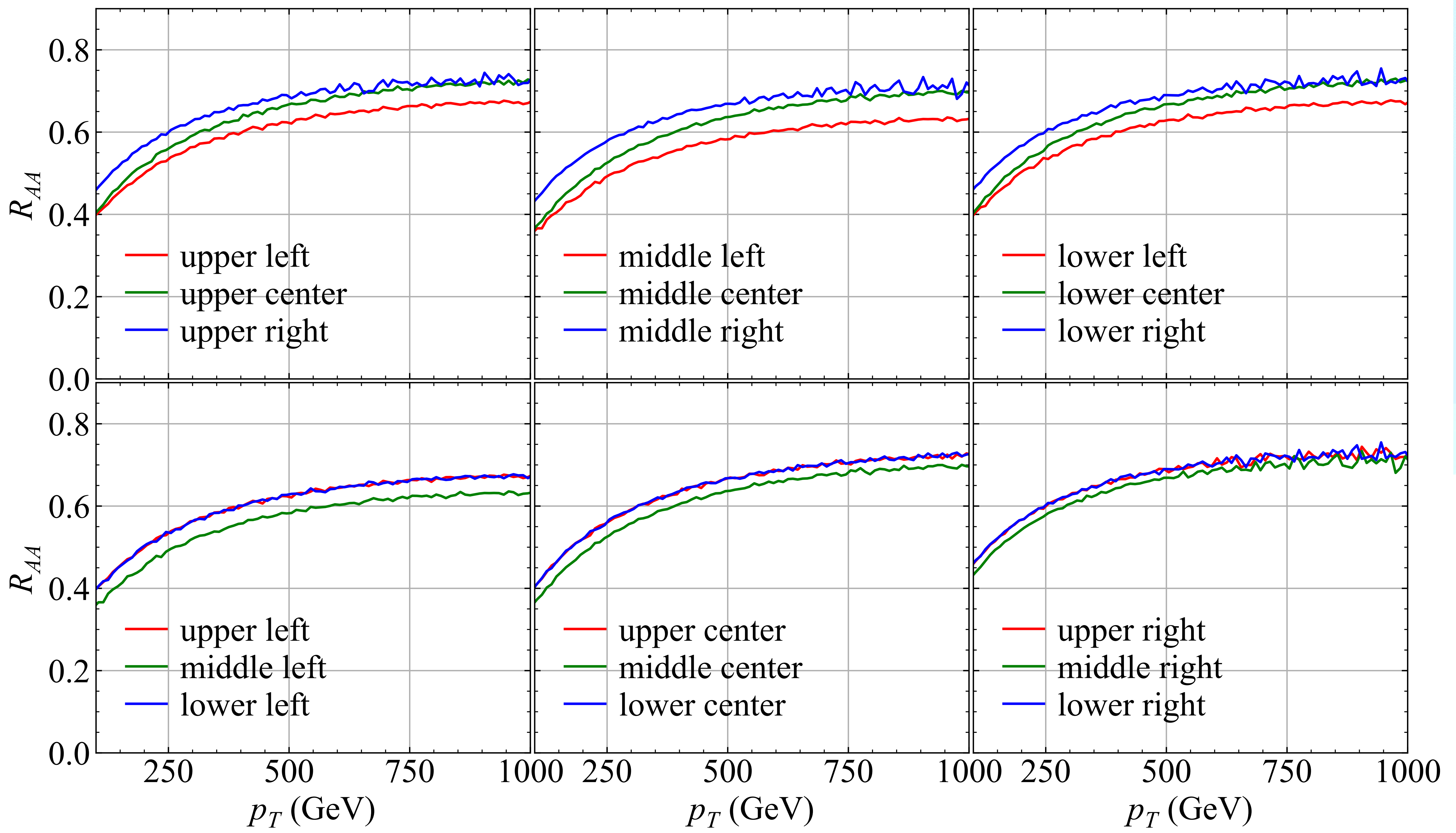


$500 < p_{T,1}^{\rm AA} < 550$ GeV/c



Summary

- The longitudinal and transverse jet tomography are studied simultaneously in dijet events.
- They are shown to strongly correlate with the initial jet production positions.
- The effect of dijet bias is also investigated.
- Jet tomography can be used to study jet-medium interactions in detail, such as the leading jet RAA for initial jet production at different region of the medium.



Thanks for your attention!