Event-by-event jet anisotropy and hard-soft tomography of the quark-gluon plasma

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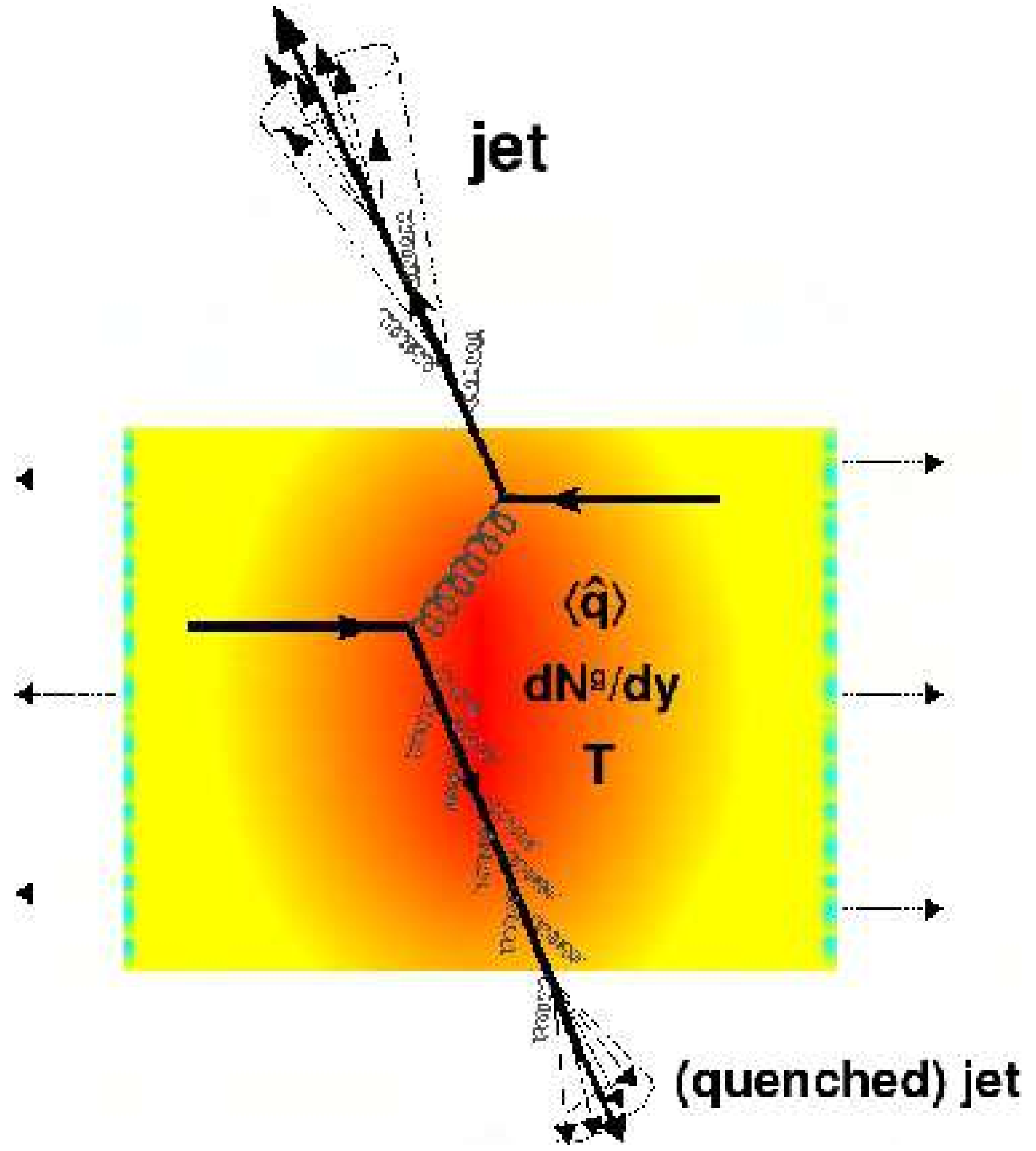
arxiv: 2201, 08408



第一届“粤港澳”核物理论坛，珠海
July 2-6, 2022

Motivation

QGP: a hot and dense quark-gluon “soup”, created by “the little bang”, like an early universe

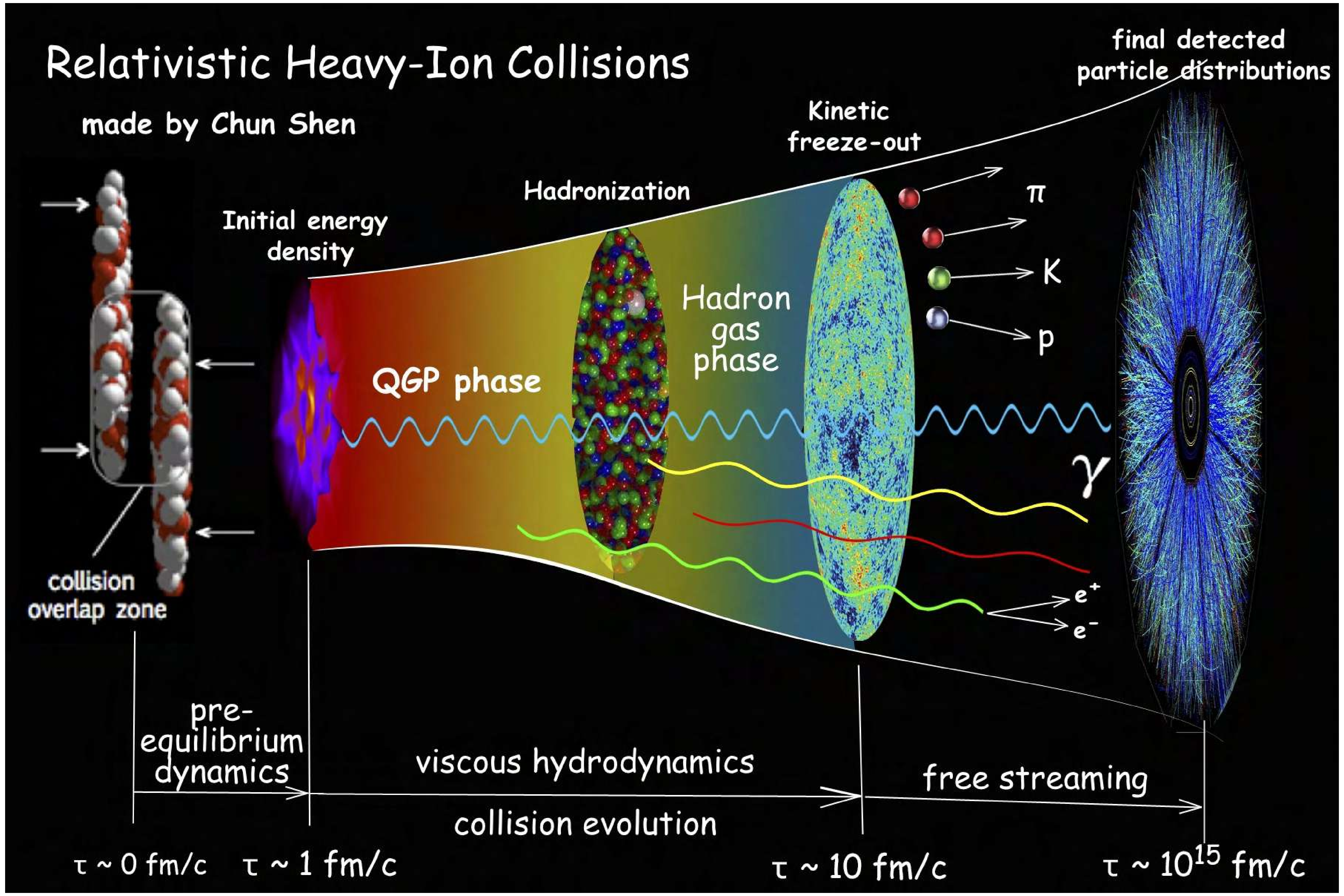


Fig: A schematic diagram of relativistic heavy-ion collisions.
Made by Chun Shen, https://u.osu.edu/vishnu/category/visualization/

Nucleus collision

Pre-equilibrium

Initial state

QGP evolution

Hadron rescattering

Detection

Motivation

How to probe the QGP?

- ✦ Soft probes: hydrodynamics, ...
- ✦ Hard probes: large transverse momentum, such as jets, hadrons and heavy flavors

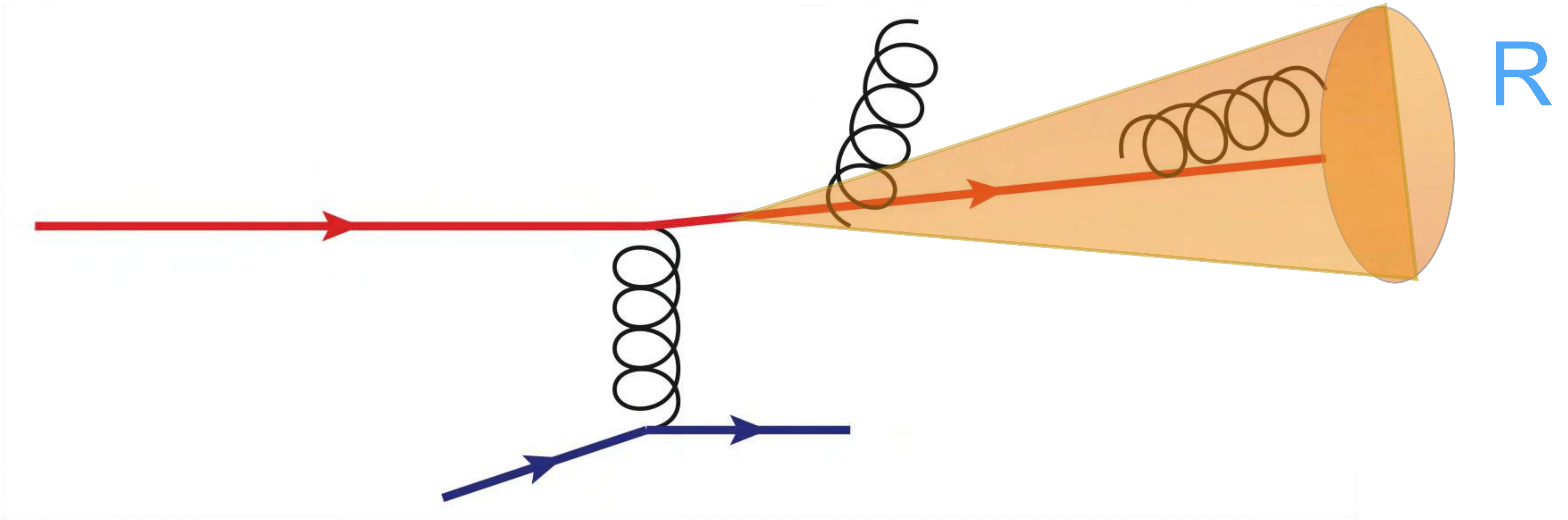


Fig: An illustration of a jet.

Jet : a collimated spray of high p_T particles

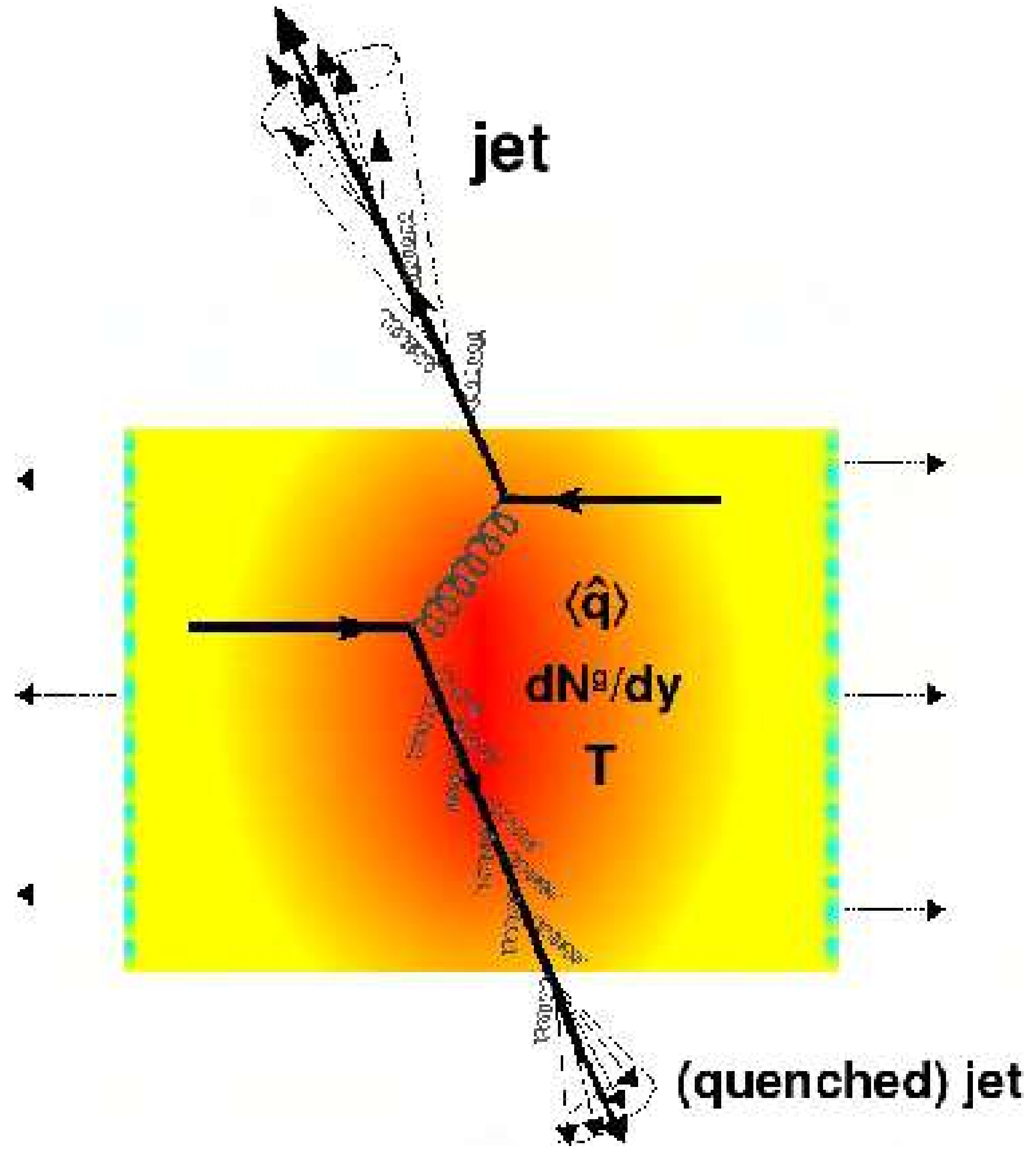


Fig: An illustration of jet quenching.

D. d'Enterria & B. Betz, (2009). 10.1007/978-3-642-02286-9_9.

Jet quenching: jet energy loss and transverse momentum broadening due to jet-medium interaction

Motivation

Jet quenching observables:

➡ The inclusive jet nuclear modification factor

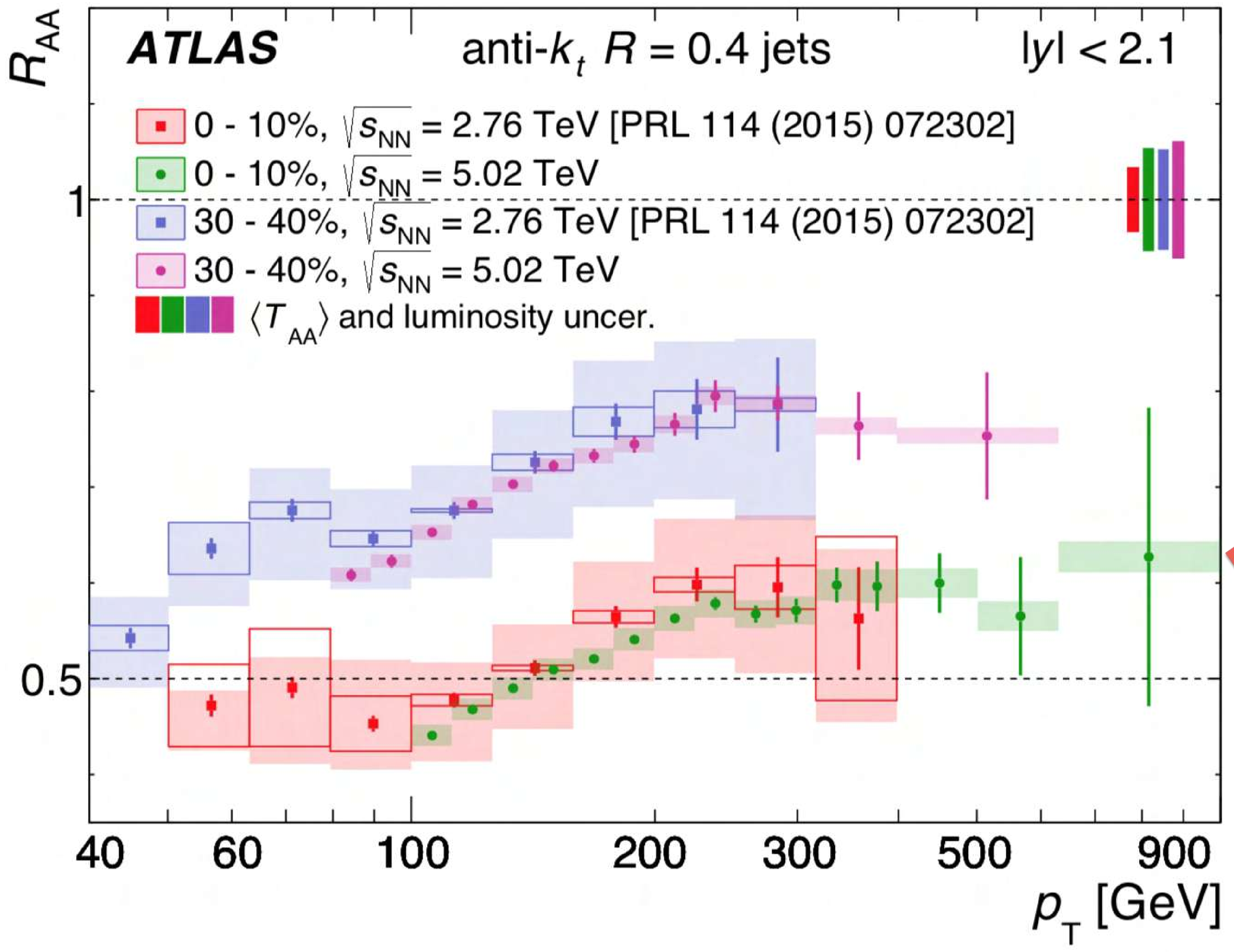


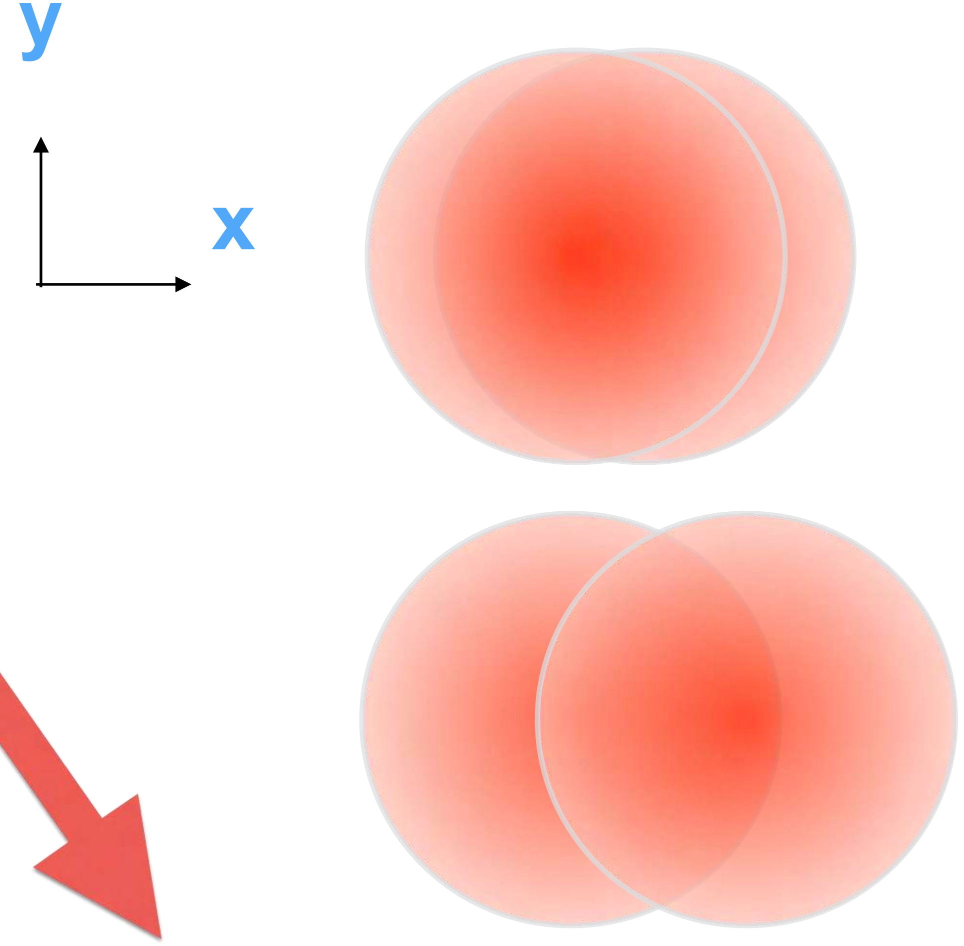
Fig: Inclusive jet nuclear modification factor

ATLAS, PRL 114 (2015),072302
ATLAS, PLB 790 (2019) 108

$$R_{AA} = \frac{1}{\langle N_{coll}\rangle}\frac{d\sigma^{jet}_{AA}}{d\sigma^{jet}_{pp}}$$

$R_{AA} = 1$ Suppression? *No*

$R_{AA} < 1$ Suppression? *Yes*



0-10% central collision

30-40% semi-central collision

A smaller R_{AA} implies a stronger suppression.

Jet quenching effect !

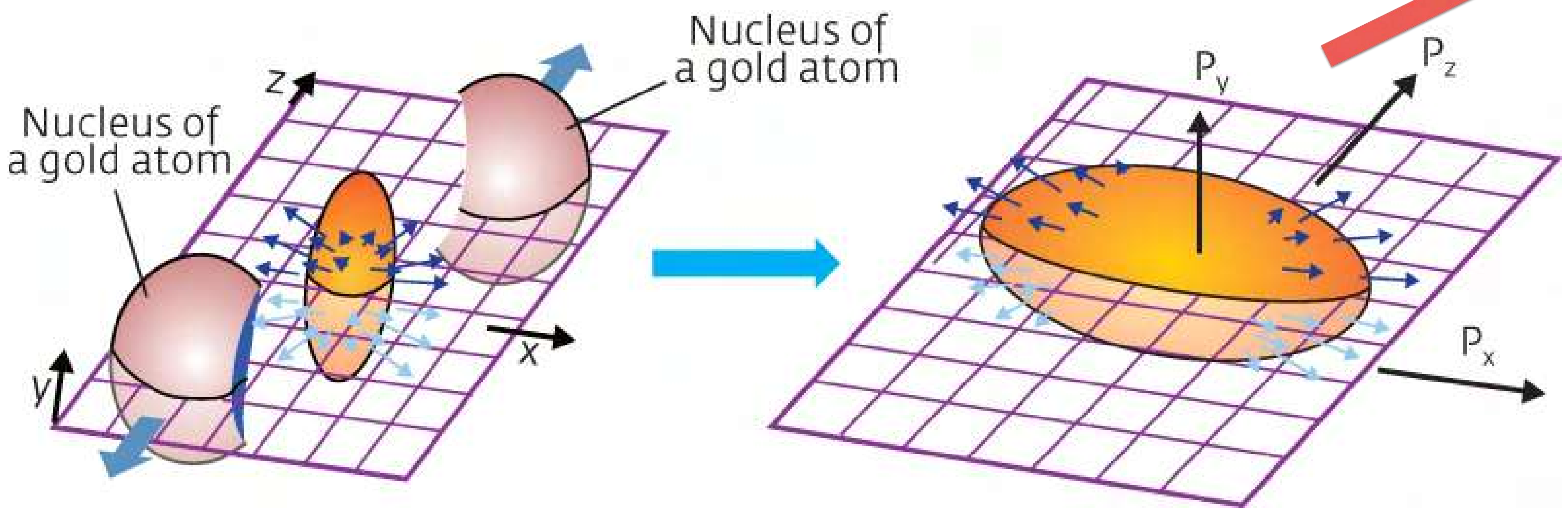
Motivation

Jet quenching observables:

- ➡ The inclusive jet nuclear modification factor
- ➡ The inclusive jet anisotropy flow $v_n^{\text{jet, EP}} = \langle\langle \cos[n(\phi^{\text{jet}} - \Psi_n)]\rangle\rangle$

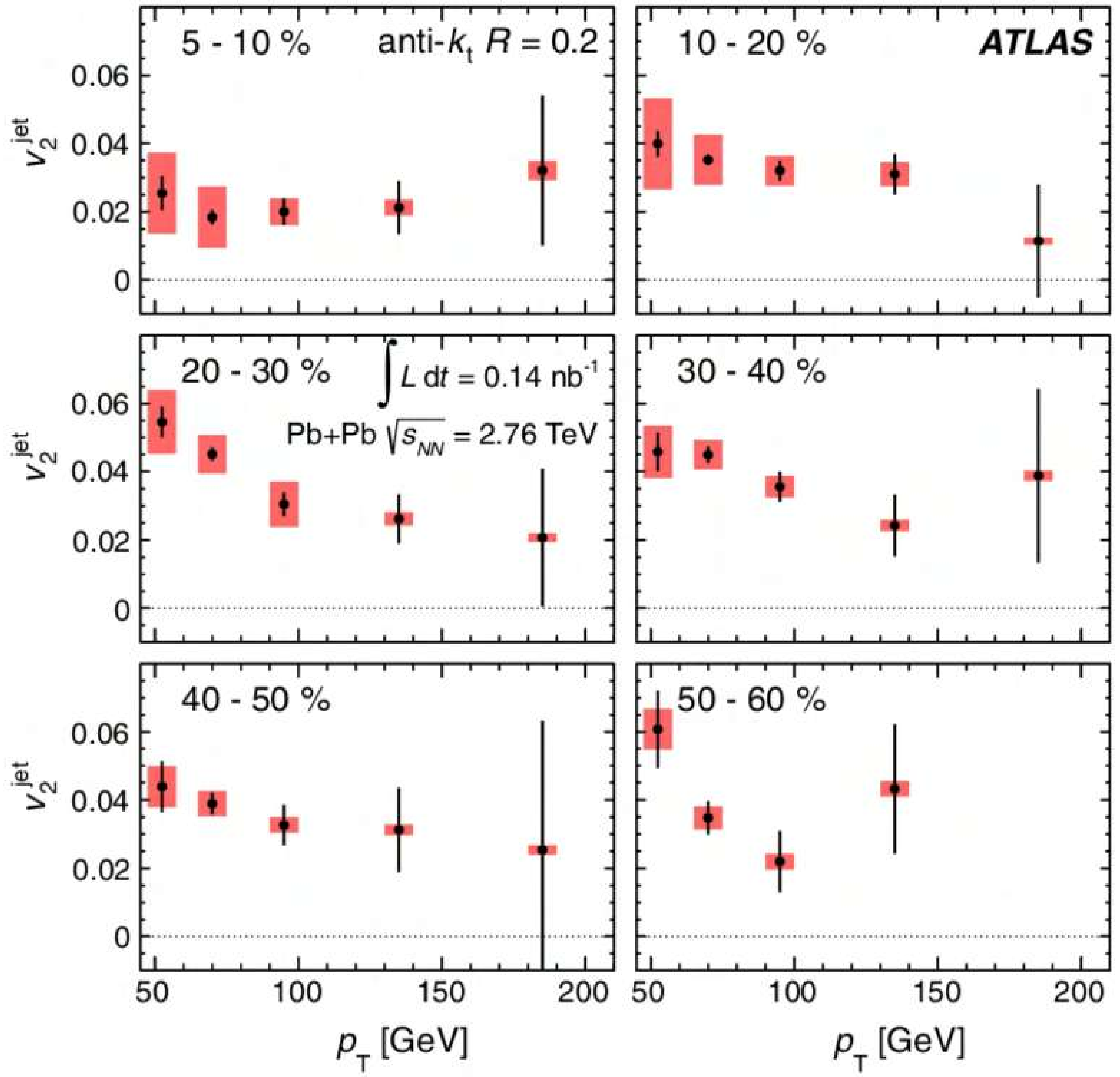
- ➢ n=1, direct flow
- ➢ n=2, elliptic flow
- ➢ n=3, triangle flow

$$\frac{dN}{d\phi} = C(1 + 2\Sigma_n v_n \cos[n(\phi - \Psi_n)])$$



$$\epsilon_2 = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle} \longrightarrow v_2 = \frac{\langle p_y^2 - p_x^2\rangle}{\langle p_y^2 + p_x^2\rangle}$$

path-length dependence



ATLAS, PRL 111 152301 (2013)

- ✓ Jet quenching leads to jet suppression
- ✓ Path-length dependence of jet quenching leads to jet anisotropy
- ⋆ Can we describe both jet R_{AA} and v_2^{jet} in a unified framework?

The linear Boltzmann transport (LBT) model

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

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

Elasitic: $\Gamma_a^{\text{el}} \equiv \dfrac{p \cdot u}{p_0} \sum_{bcd} \rho_b(x) \sigma_{ab\to cd}$

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

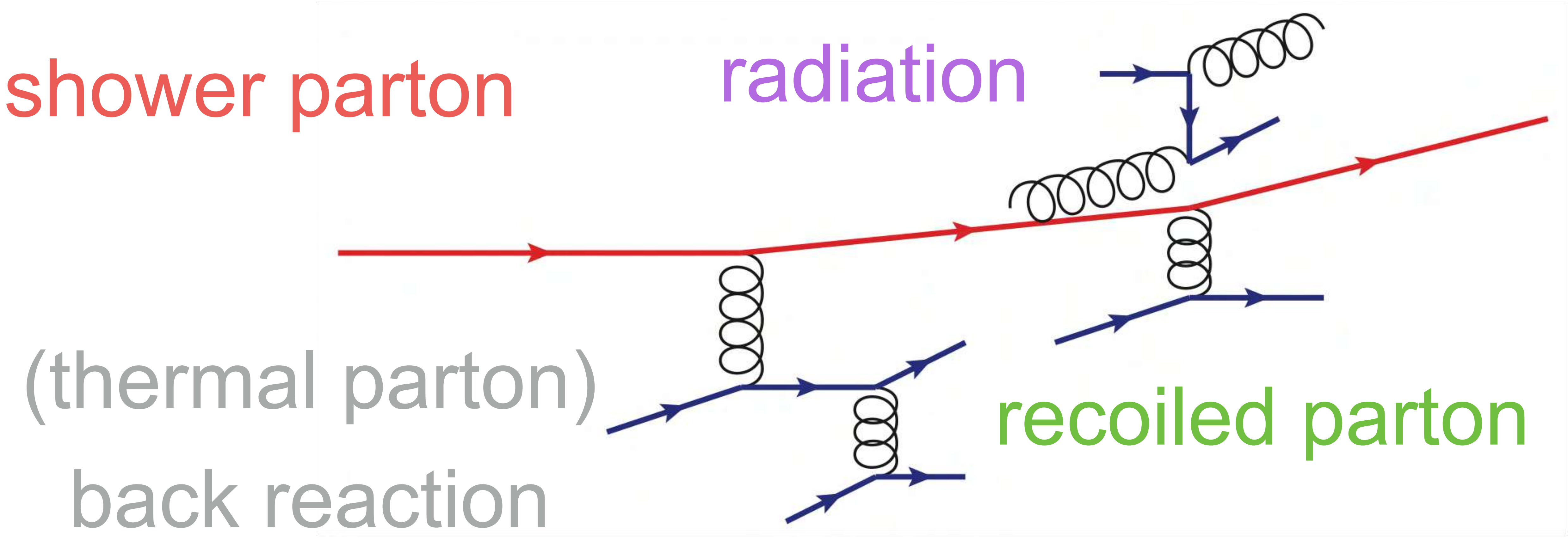
LO perturbative QCD

J. Auvinen et al, PRC 82(2010) 024906

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 $\delta f \ll f$

The LBT model with a QGP-like medium: framework

The inclusive jet shower partons from PYTHIA 8

T. Sjostrand, S. Mrenna, and P. Z. Skands, JHEP 05 (2006) 026.

Initial condition from AMPT

Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, PRC 72, 064901 (2005).

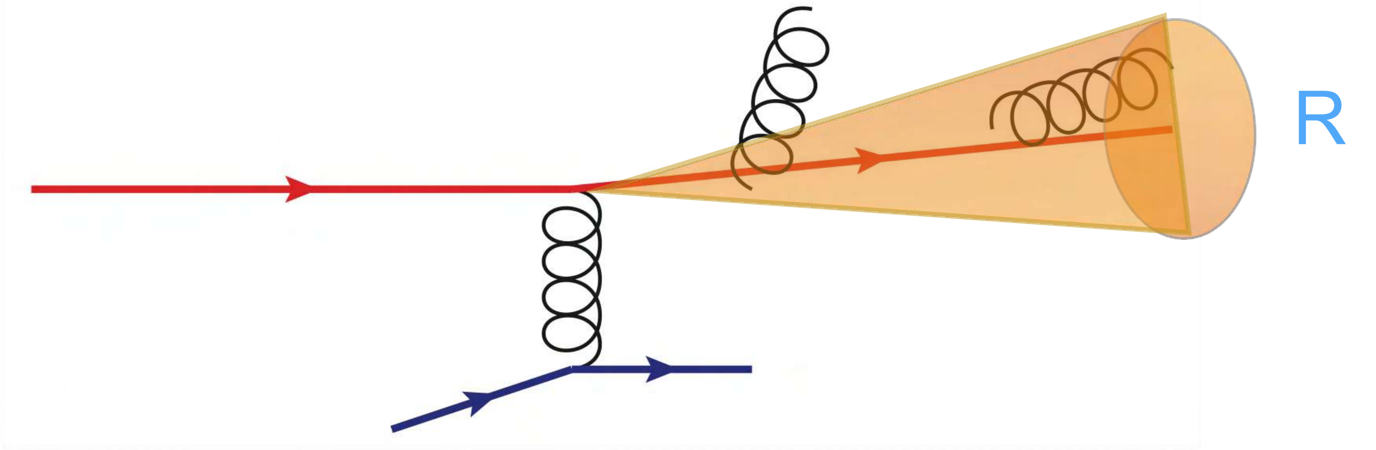
e-by-e 3+1D CLVisc:

Pang, Wang & Wang, PRC 86 (2012) 024911

Pang, Hatta, Wang & Xiao, PRD 91 (2015) 074027

evolution with a hydro background:
collisional + radiation in QGP phase,
free streaming in hadron phase

out-of-cone jet energy loss

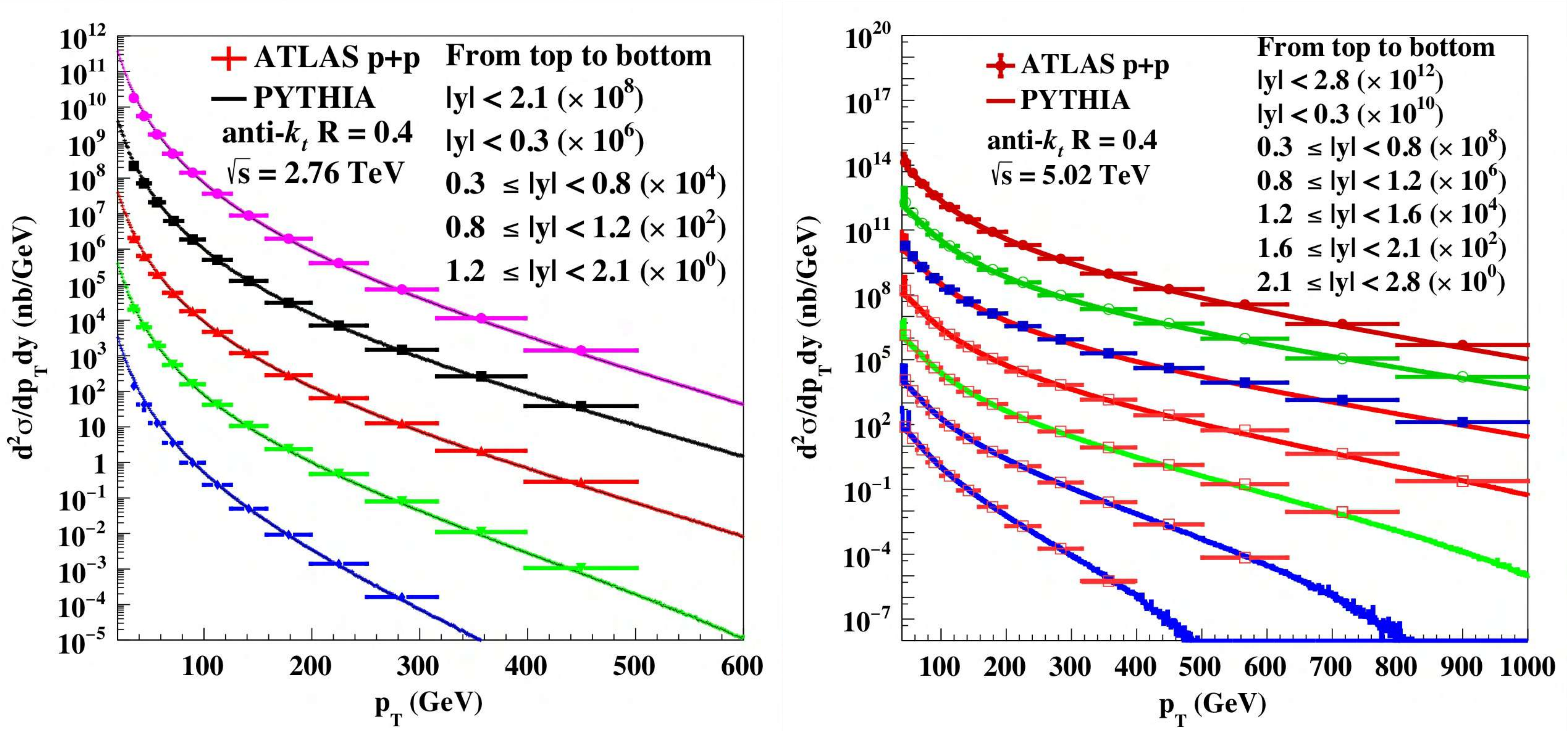


freeze-out temperature: $T_f = 137\ \mathrm{MeV}$

Final inclusive jet

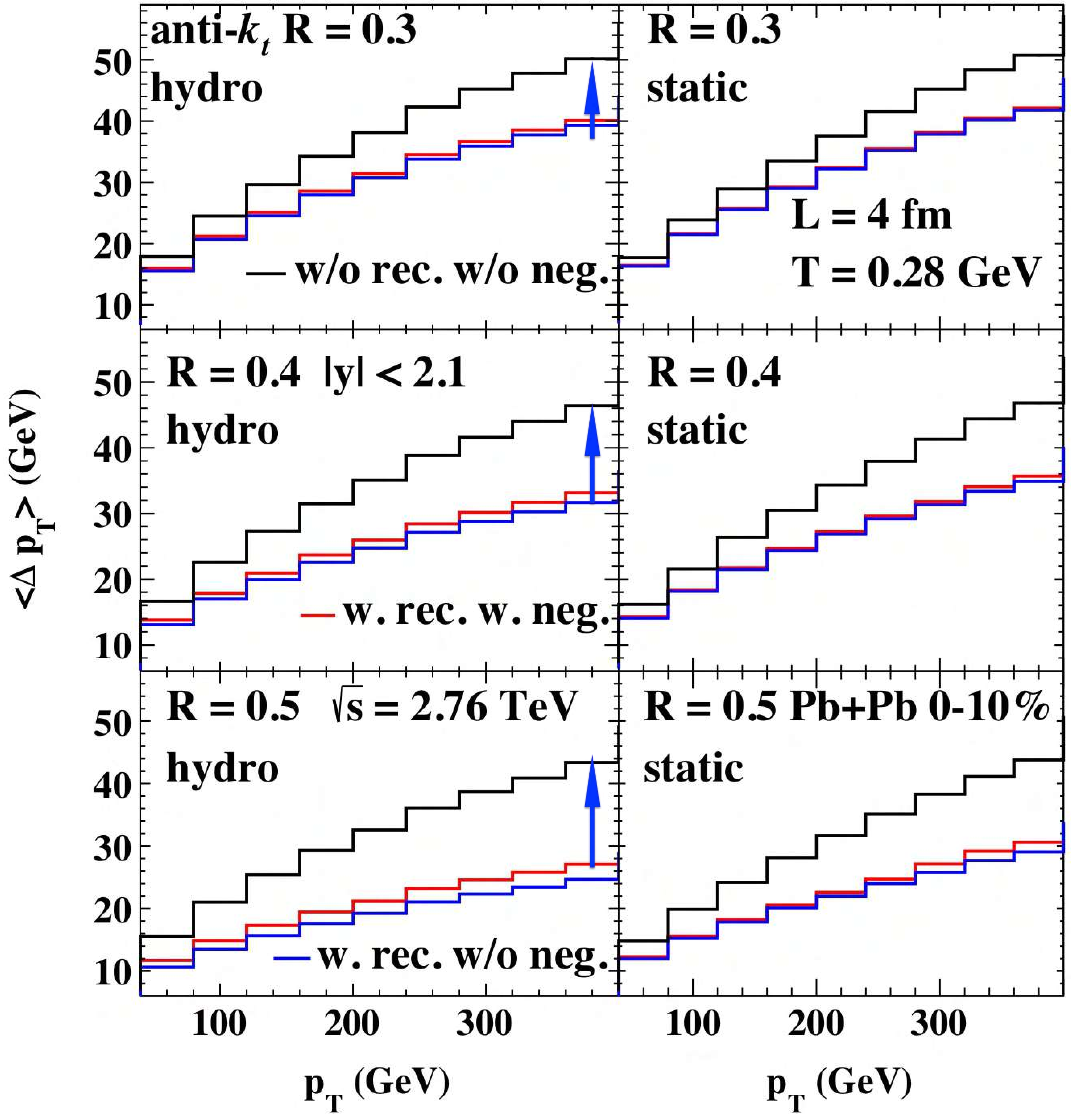
The inclusive jet in pp collisions

p_T distribution of pp collision within PYTHIA 8



PYTHIA 8 can well describe the experimental data at LHC energies for different rapidity ranges.

Energy loss in the LBT model



medium recoil effect up to 15%

back reaction not negligible

larger cone size and radial expansion
enlarges the effects above.

Jet energy loss: LBT & Bayesian extraction

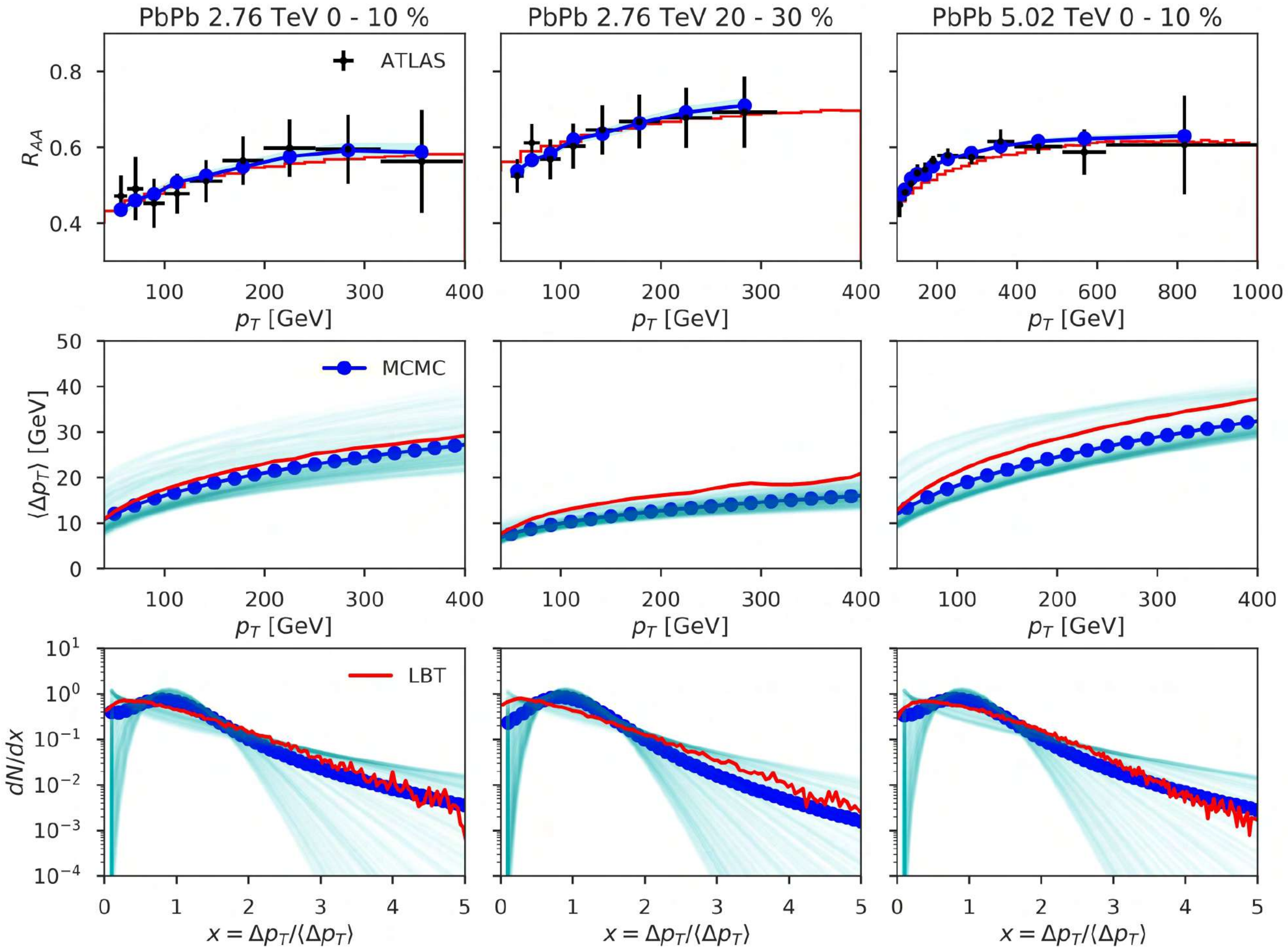
$$\frac{d\sigma^{\rm jet}_{AA}}{dp_T dy}(p_T,R) \approx N_{\rm bin}(b)\int d\Delta p_T\, \frac{d\sigma^{\rm jet}_{pp}}{dp_T dy}(p_T+\Delta p_T,R)\, W_{AA}(\Delta p_T, p_T+\Delta p_T, R)$$

$$R_{AA} = \frac{1}{\langle N_{coll}\rangle}\frac{d\sigma^{jet}_{AA}}{d\sigma^{jet}_{pp}}$$

$$\langle \Delta p_T\rangle = \beta(p_T/p_{T,0})^{\gamma}\log(p_T/p_{T,0})$$

$$W_{AA}(x) = \frac{\alpha^{\alpha}x^{\alpha-1}e^{-\alpha x}}{\Gamma(\alpha)}$$

$$x = \frac{\Delta p_T}{\langle \Delta p_T\rangle}$$

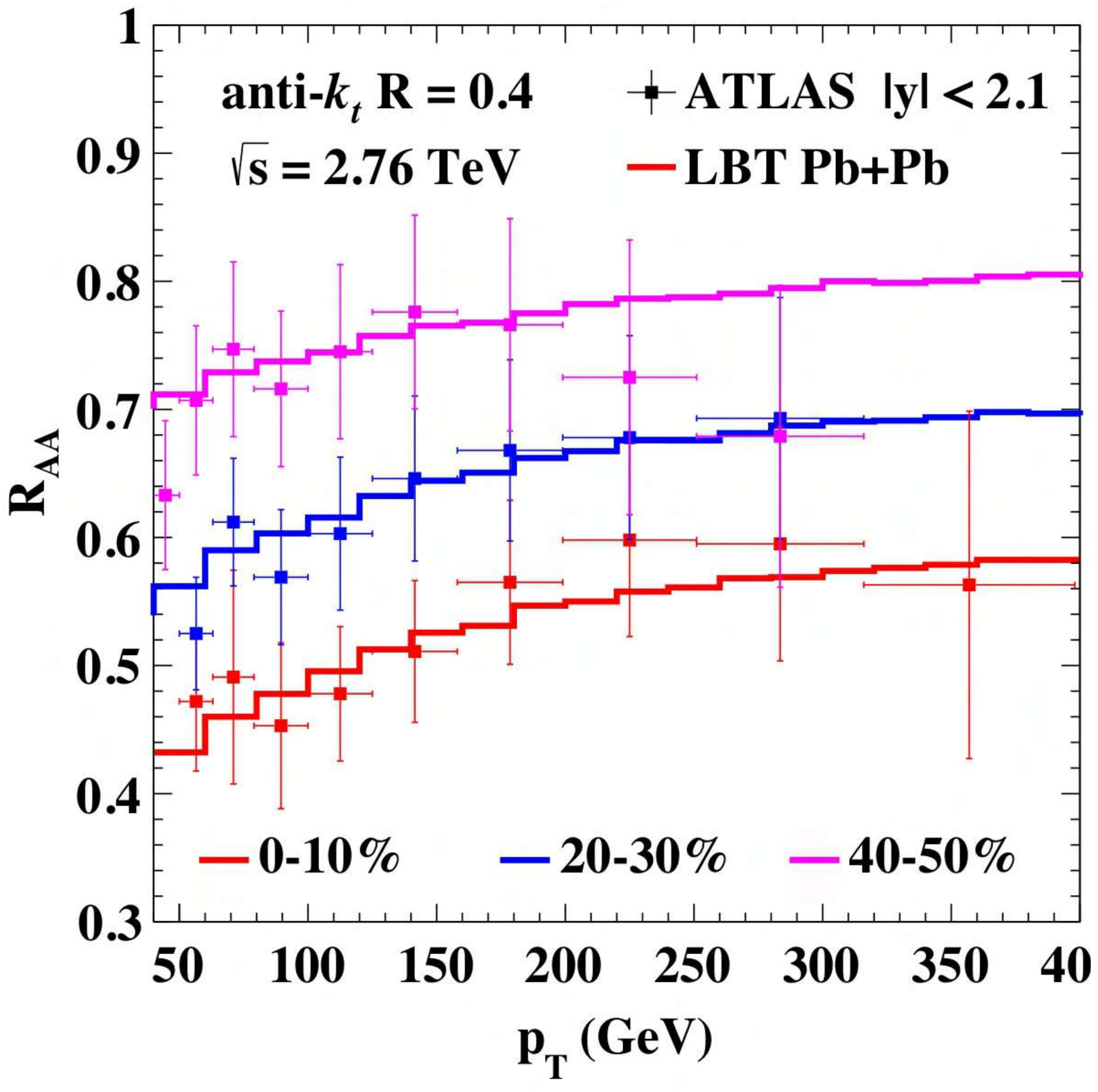


贺亚运, Long-Gang Pang, Xin-Nian Wang. PRL 122 (2019) 252302

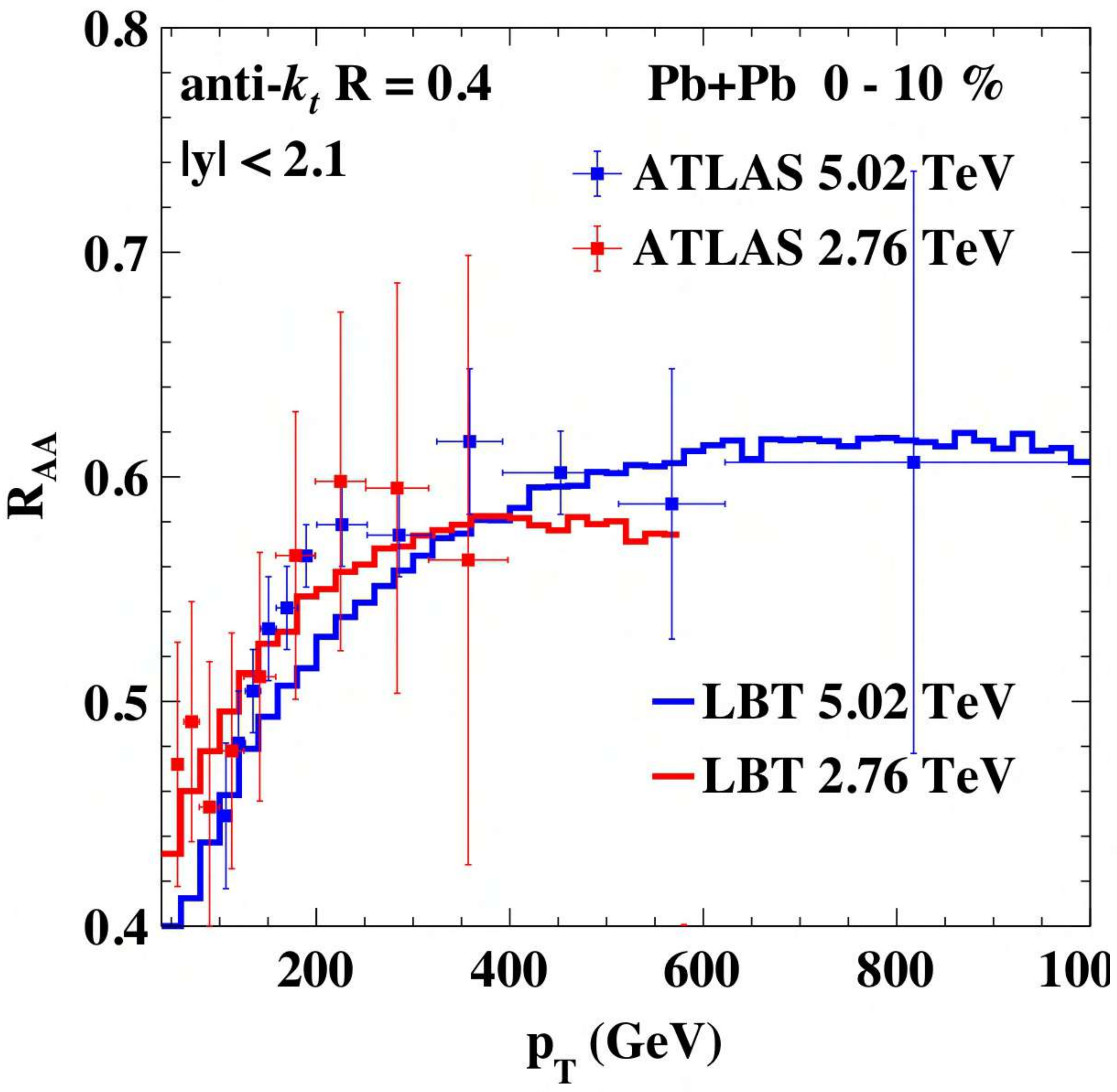
The inclusive jet R_{AA}

贺亚运, Shanshan Cao, Wei Chen, Tan Luo, Long-Gang Pang and Xin-Nian Wang. PRC 99 (2019) 054911

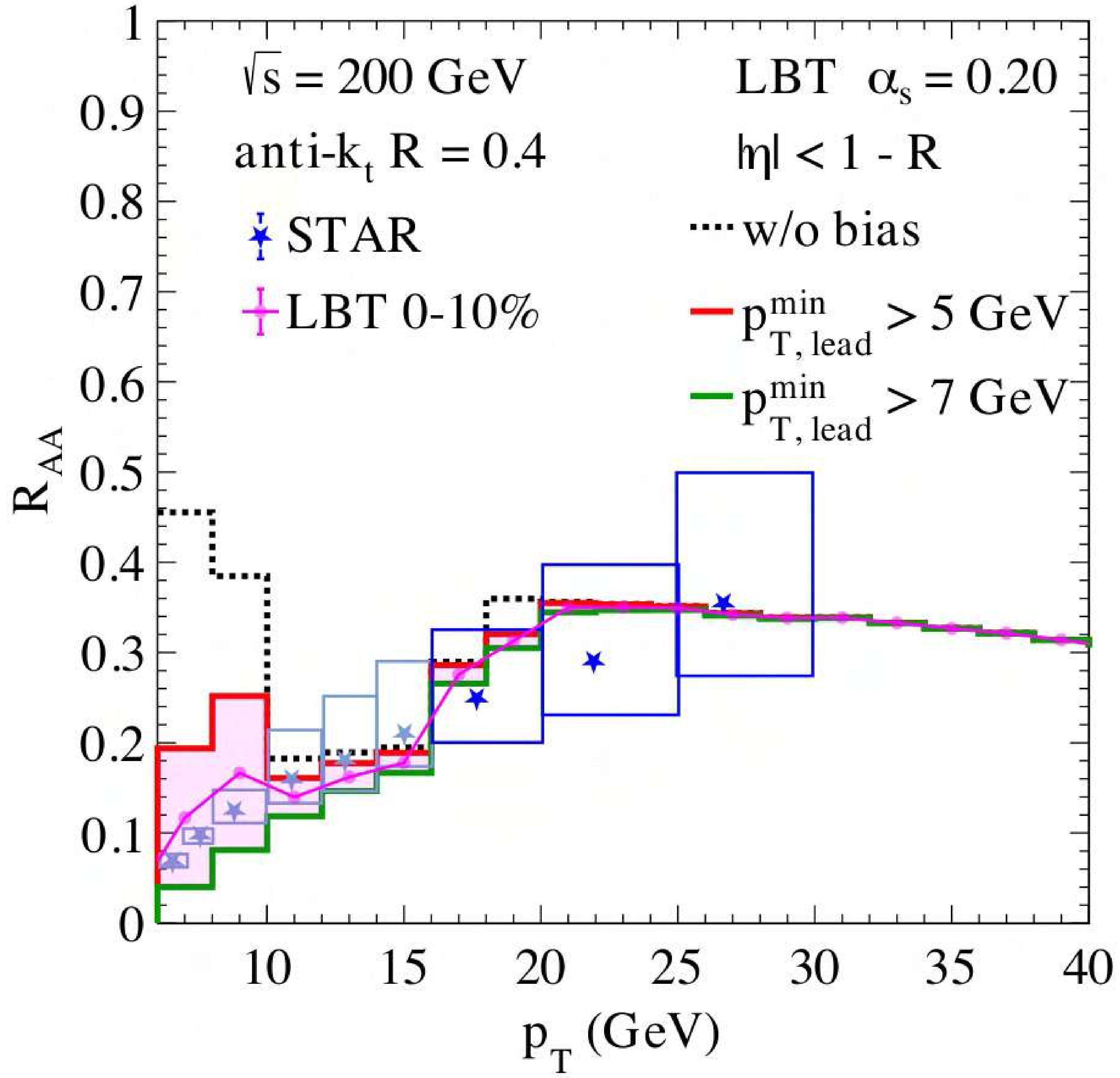
Pb+Pb 2.76 TeV



Pb+Pb 5.02 TeV



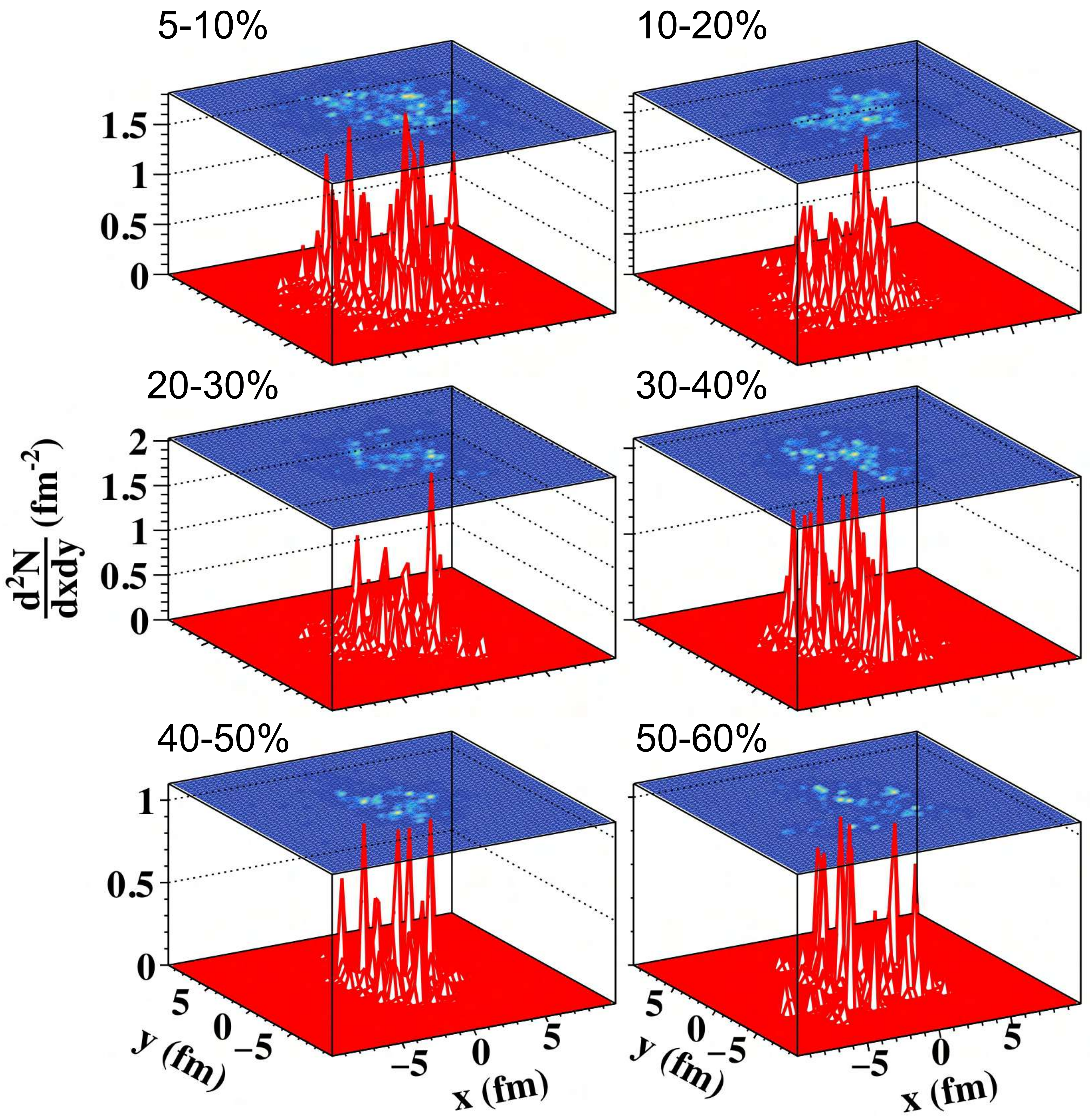
Au+Au 200 GeV



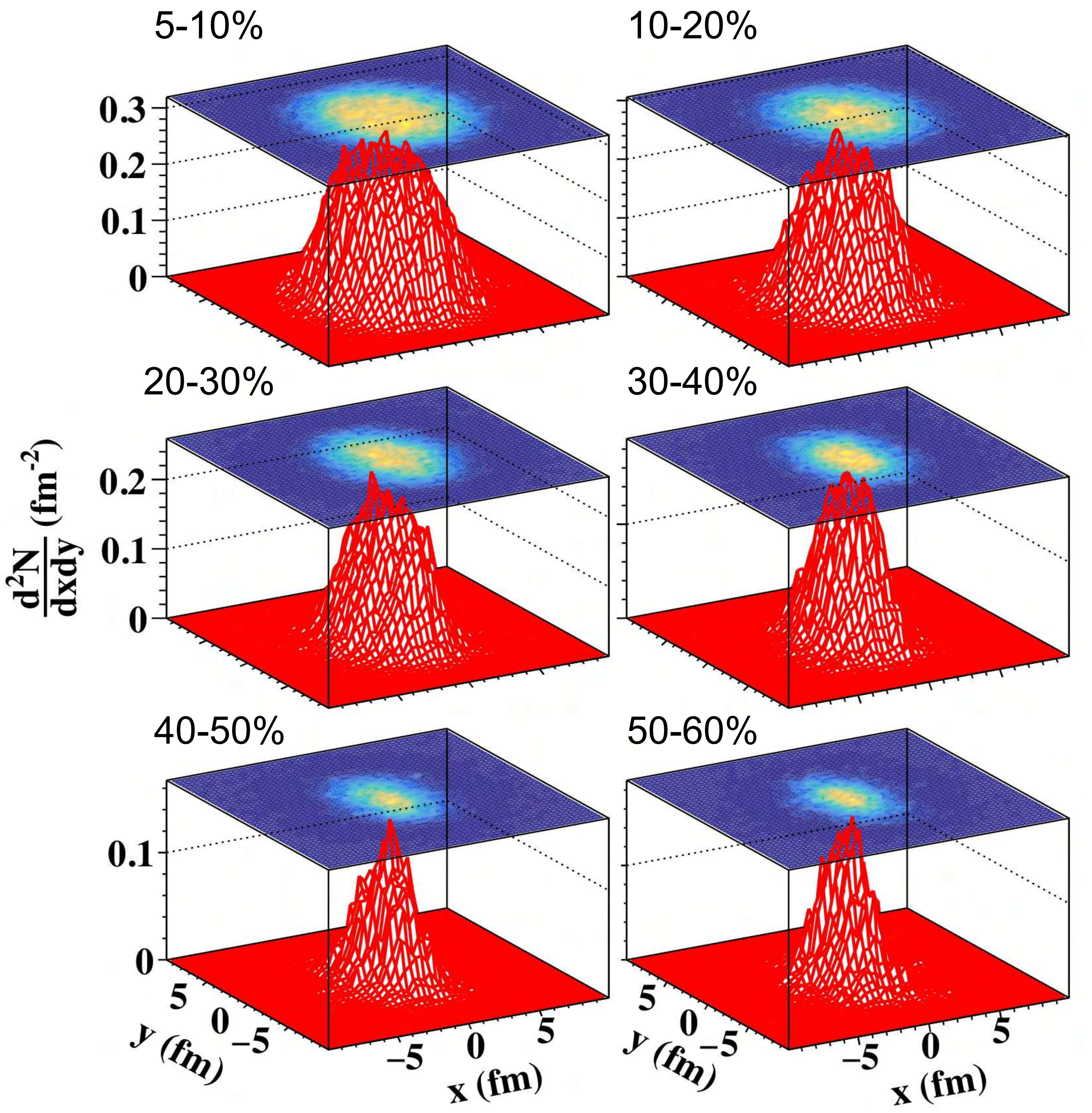
Jet R_{AA} has a weak p_T dependence in the high p_T range

The inclusive jet anisotropy v_n

Initial jet producation at 2.76 TeV



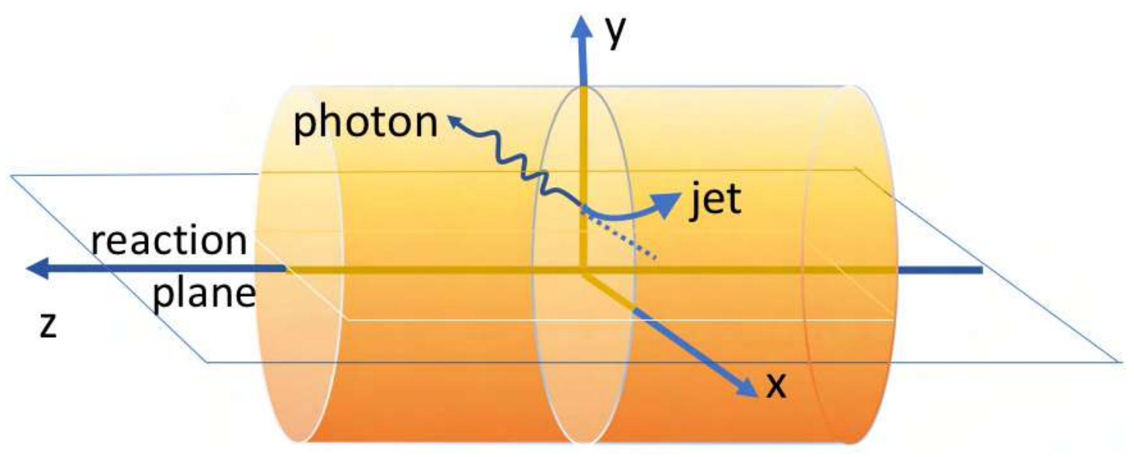
single hydro event: fluctuating

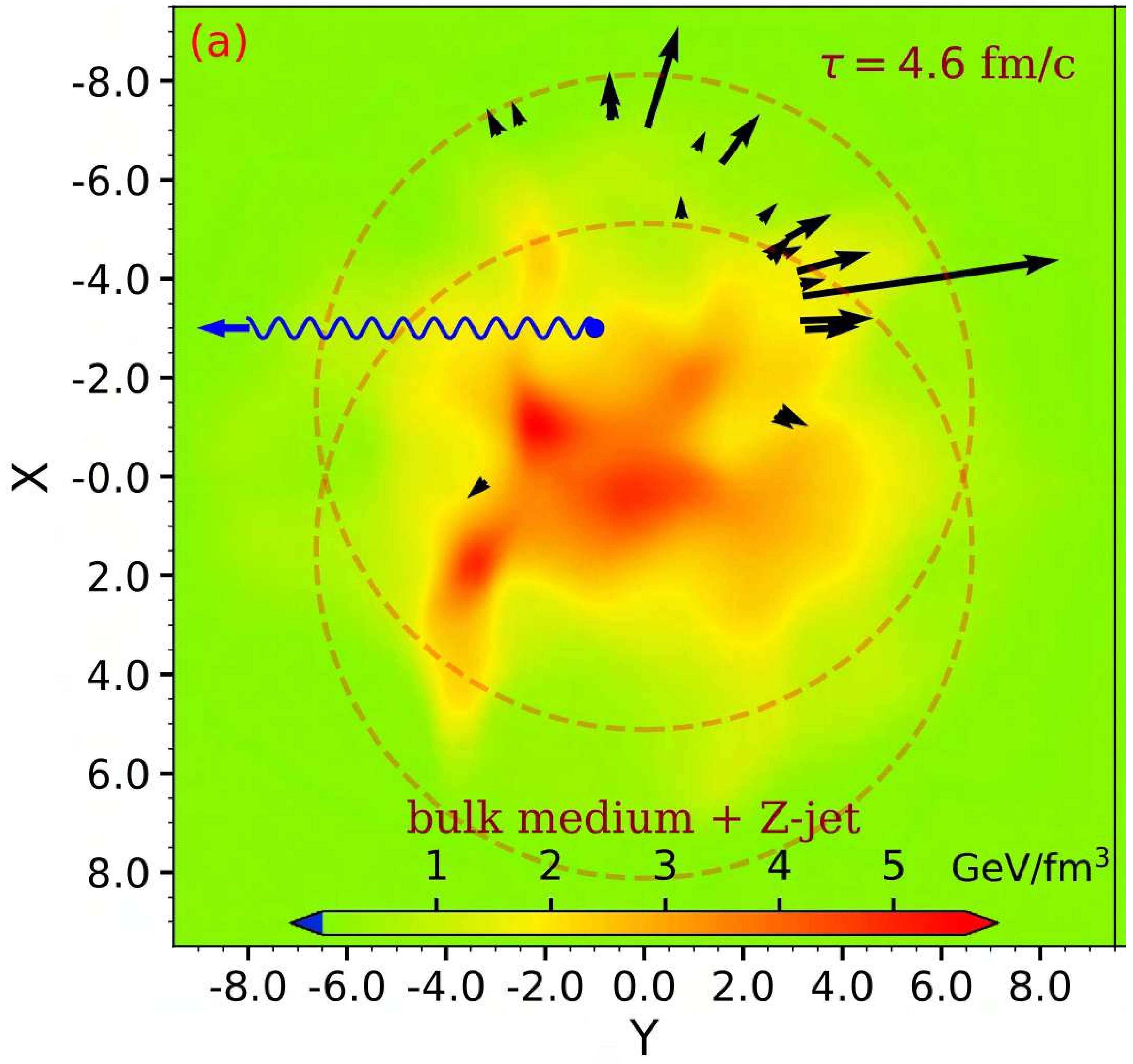


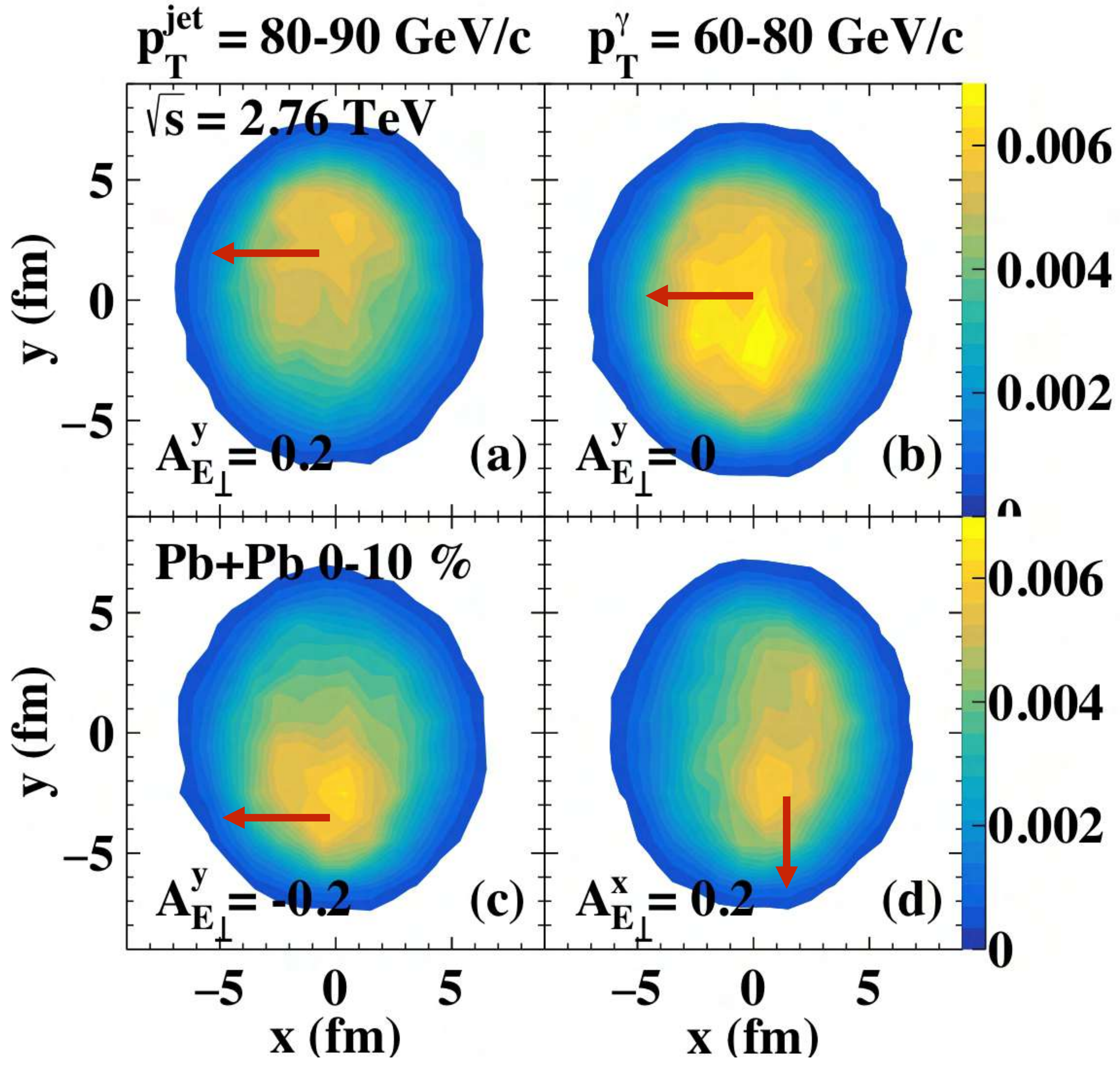
averaged over 200 hydro events: smooth

Initial jet production localization

$$\frac{\partial f}{\partial t} + \frac{\vec{k}_\perp}{\omega}\cdot\frac{\partial f}{\partial \vec{r}_\perp} = \frac{\hat{q}}{4}\vec{\nabla}^2_{k_\perp} f_a(\vec{k},\vec{r}) \qquad A^{\vec{n}}_{E_\perp} = \frac{\int d^3r\, d^3k\, |\vec{k}|\, f(\vec{k},\vec{r})\,\mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r\, d^3k\, |\vec{k}|\, f(\vec{k},\vec{x})}$$







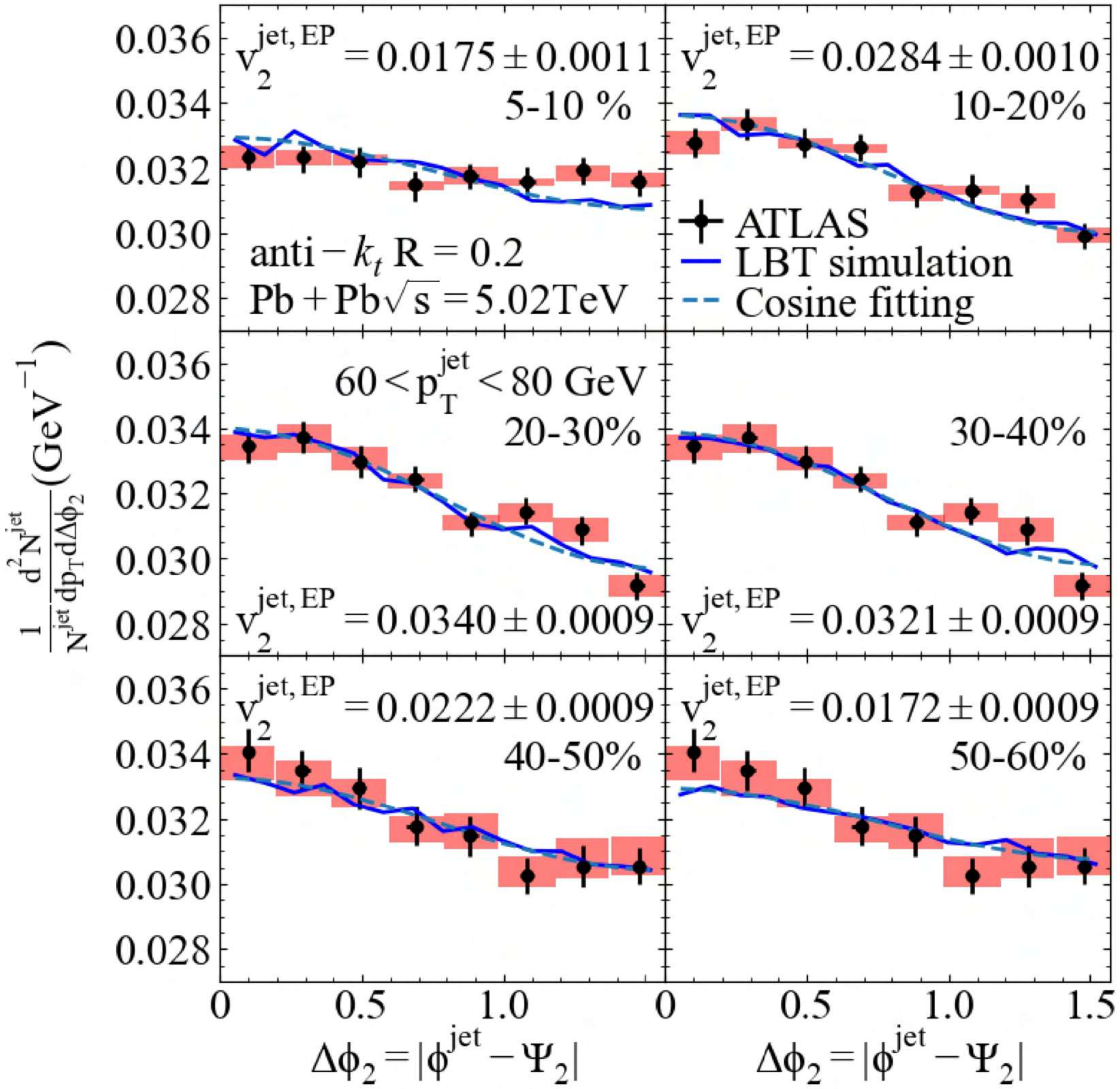
- ✓ transverse jet asymmetry correlates with initial jet production position quantitatively
- ✓ Jet localization can be used to study jet-medium interaction in detail, such as diffusion wake

贺亚运, Long-Gang Pang, Xin-Nian Wang. PRL 125 (2020) 122301
Wei Chen, Zhong Yang, 贺亚运, Weiyao Ke, Long-Gang Pang and Xin-Nian Wang, RRL 127, (2021) 082301

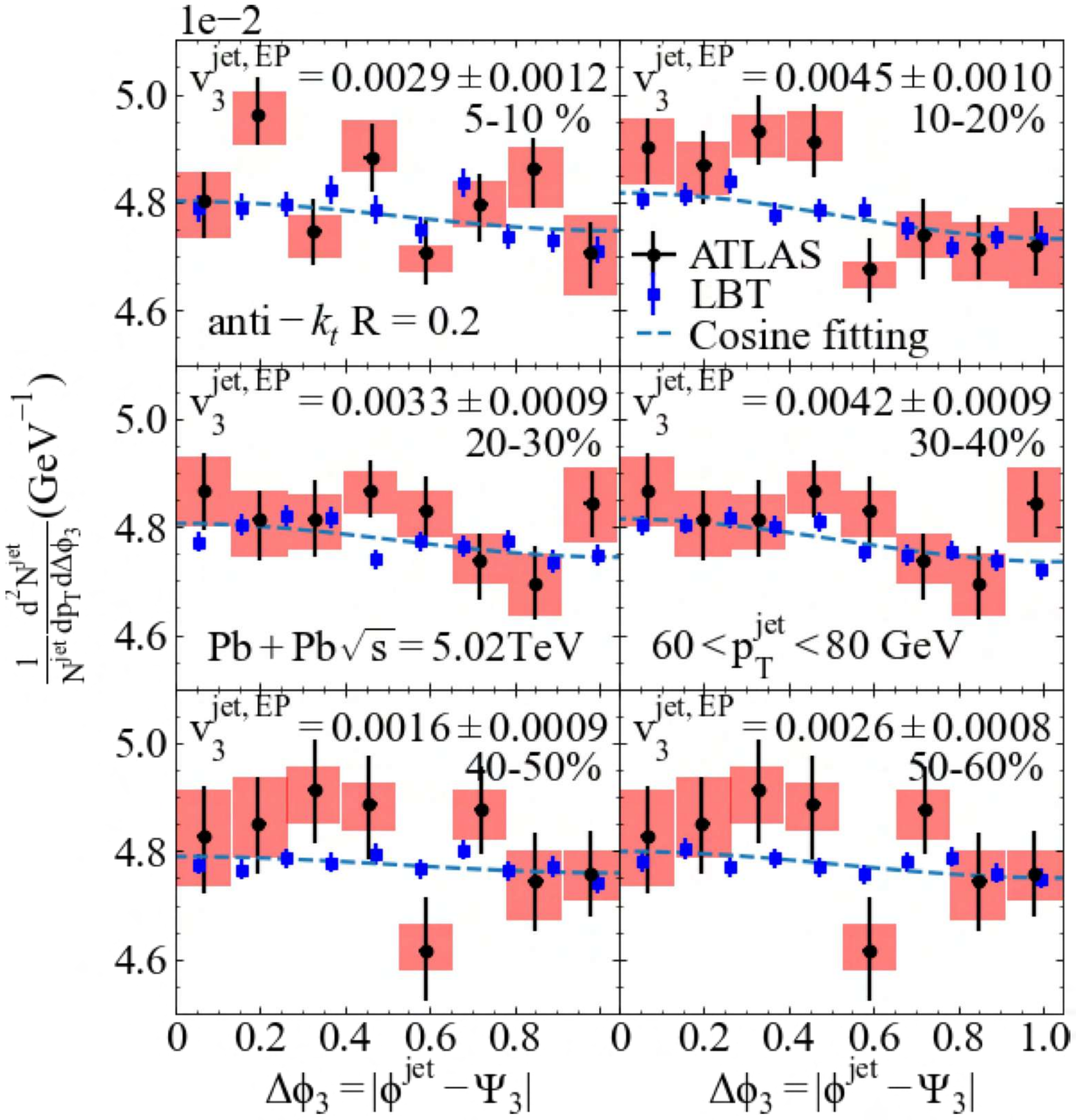
Jet azimuthal anisotropy

$$\frac{1}{N^{\text{jet}}}\frac{dN^{\text{jet}}}{d\Delta\phi_n} \propto 1 + 2v_n^{\text{jet,EP}}\cos(n\Delta\phi_n)$$

jet v_2 at 5.02 TeV



jet v_3 at 5.02 TeV

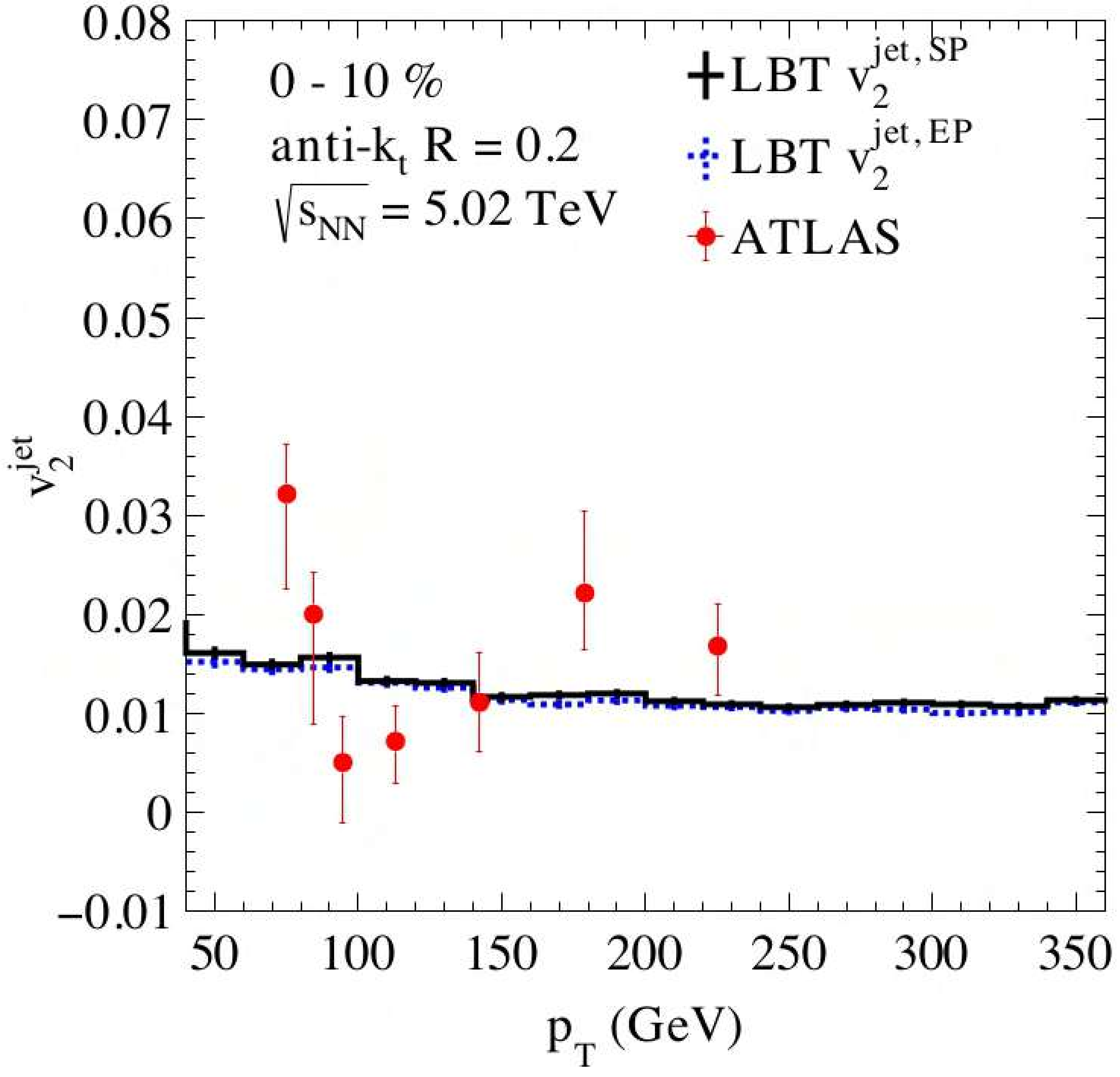


Azimuthal angle distributions clearly show the existence of jet v_2 and v_3.

p_T dependence of inclusive jet v_2 and v_3

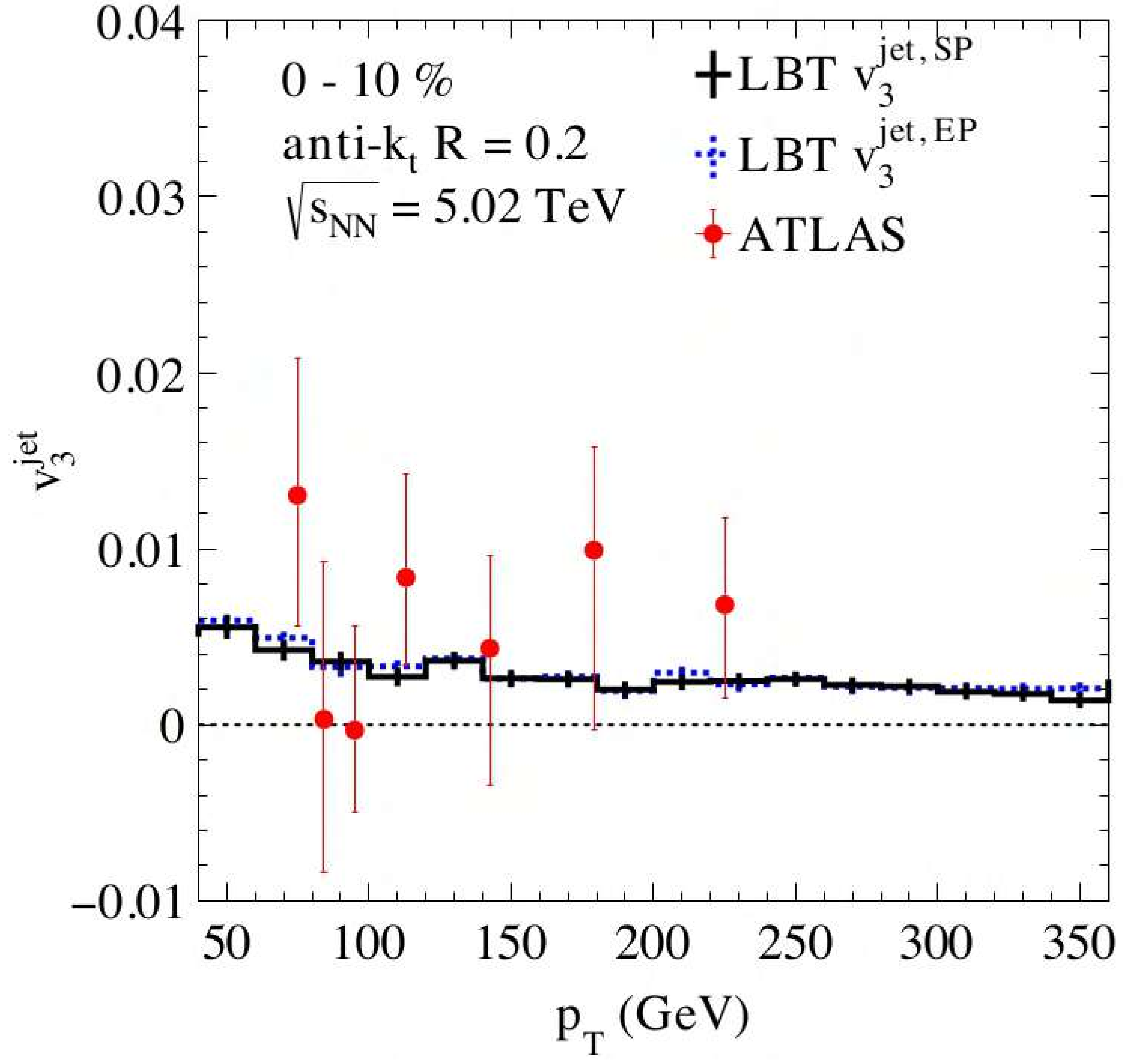
Event plane method:

$$v_n^{\text{jet,EP}} = \langle\langle \cos(n[\phi^{\text{jet}} - \Psi_n])\rangle\rangle$$



Scalar product method:

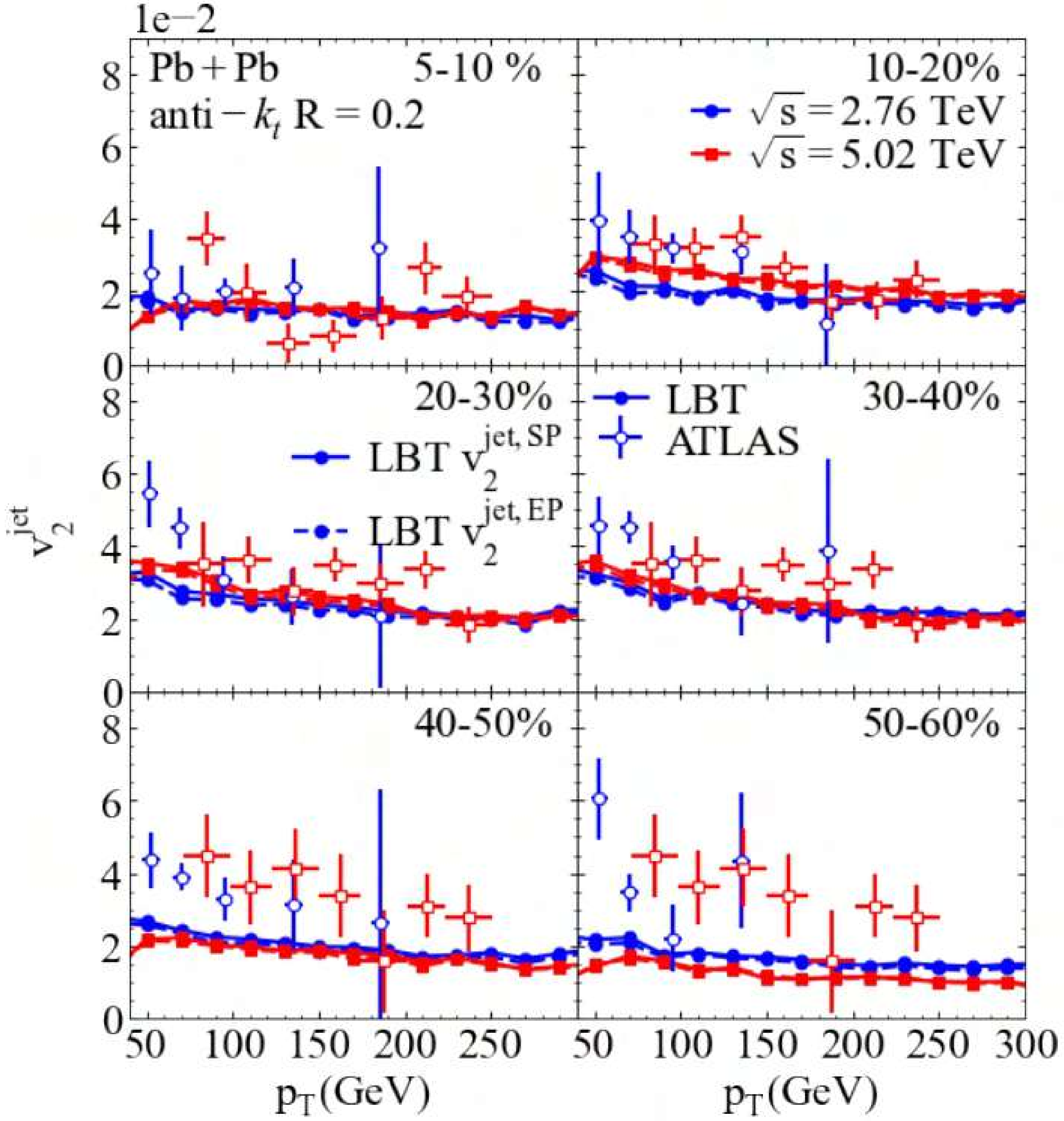
$$v_n^{\text{jet,SP}} = \frac{\langle\langle v_n^{\text{soft}} \cos(n[\phi^{\text{jet}} - \Psi_n])\rangle\rangle}{\sqrt{\langle {v_n^{\text{soft}}}^2\rangle}}$$



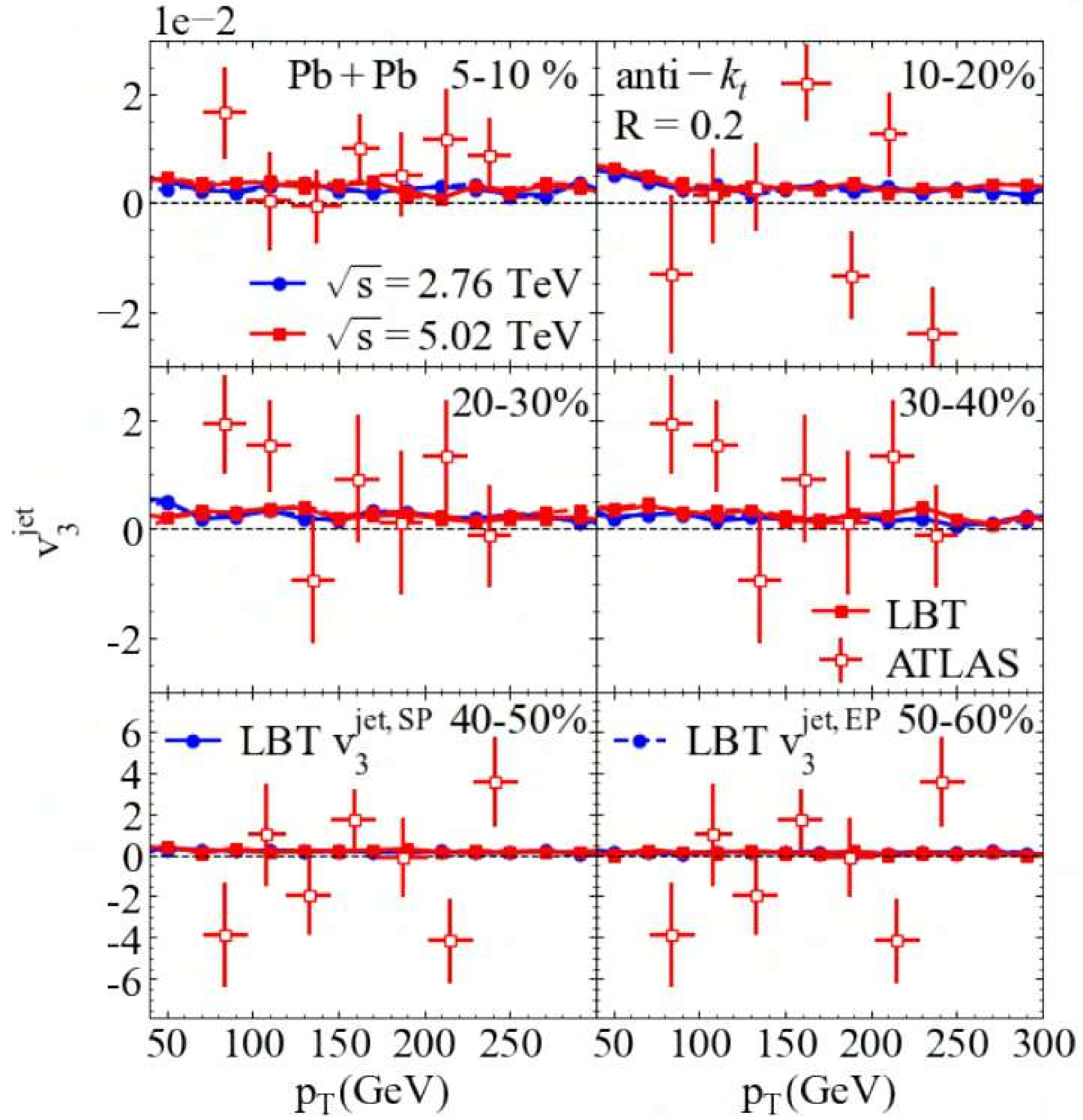
Weighted with bulk v_2 from e-by-e hydro profiles, slightly larger than event plane method

pT dependence of inclusive jet v_2 and v_3

Jet v_2



Jet v_3

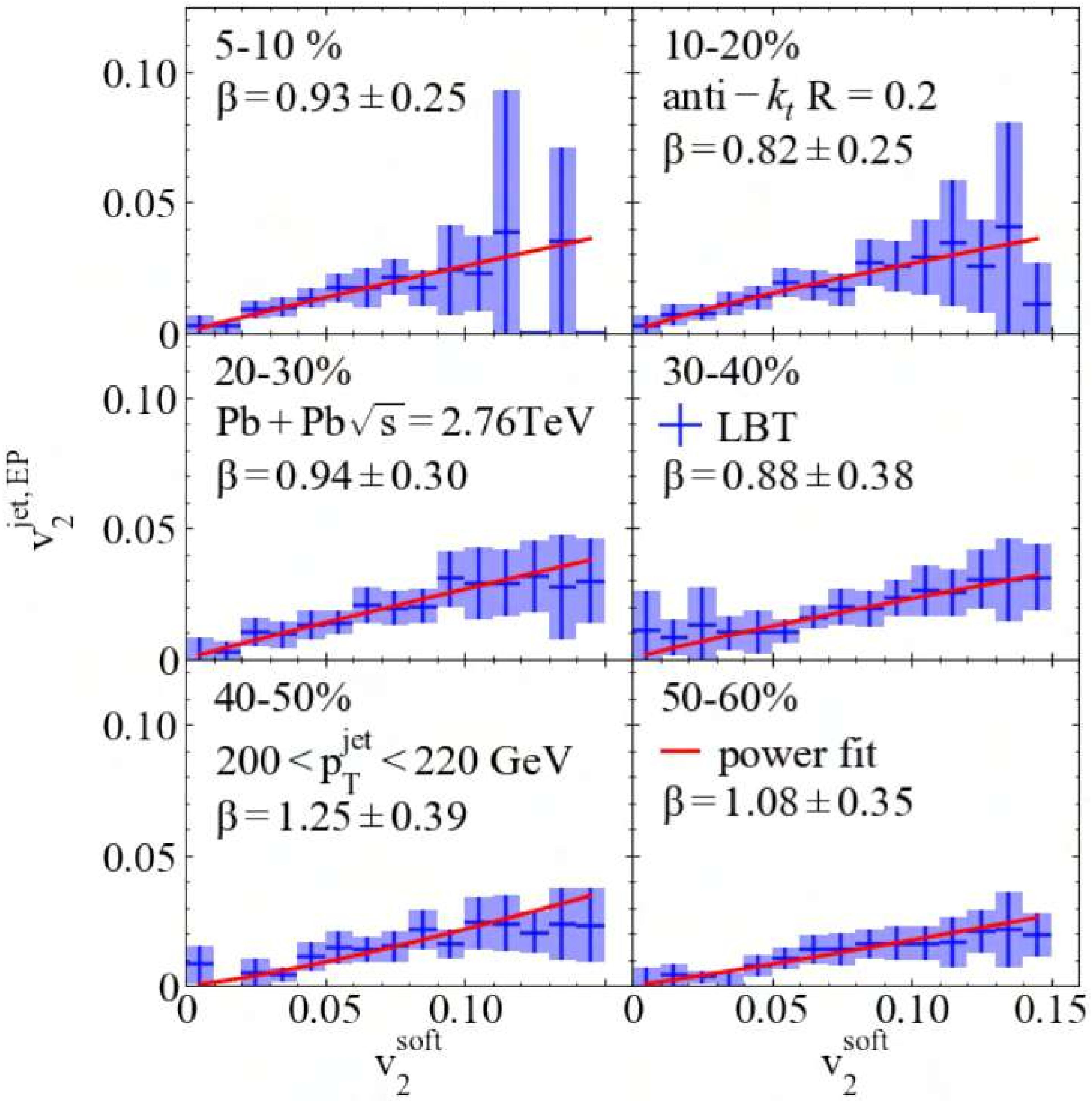


Jet v_2 at both colliding energy are almost the same and have a weak p_T dependence

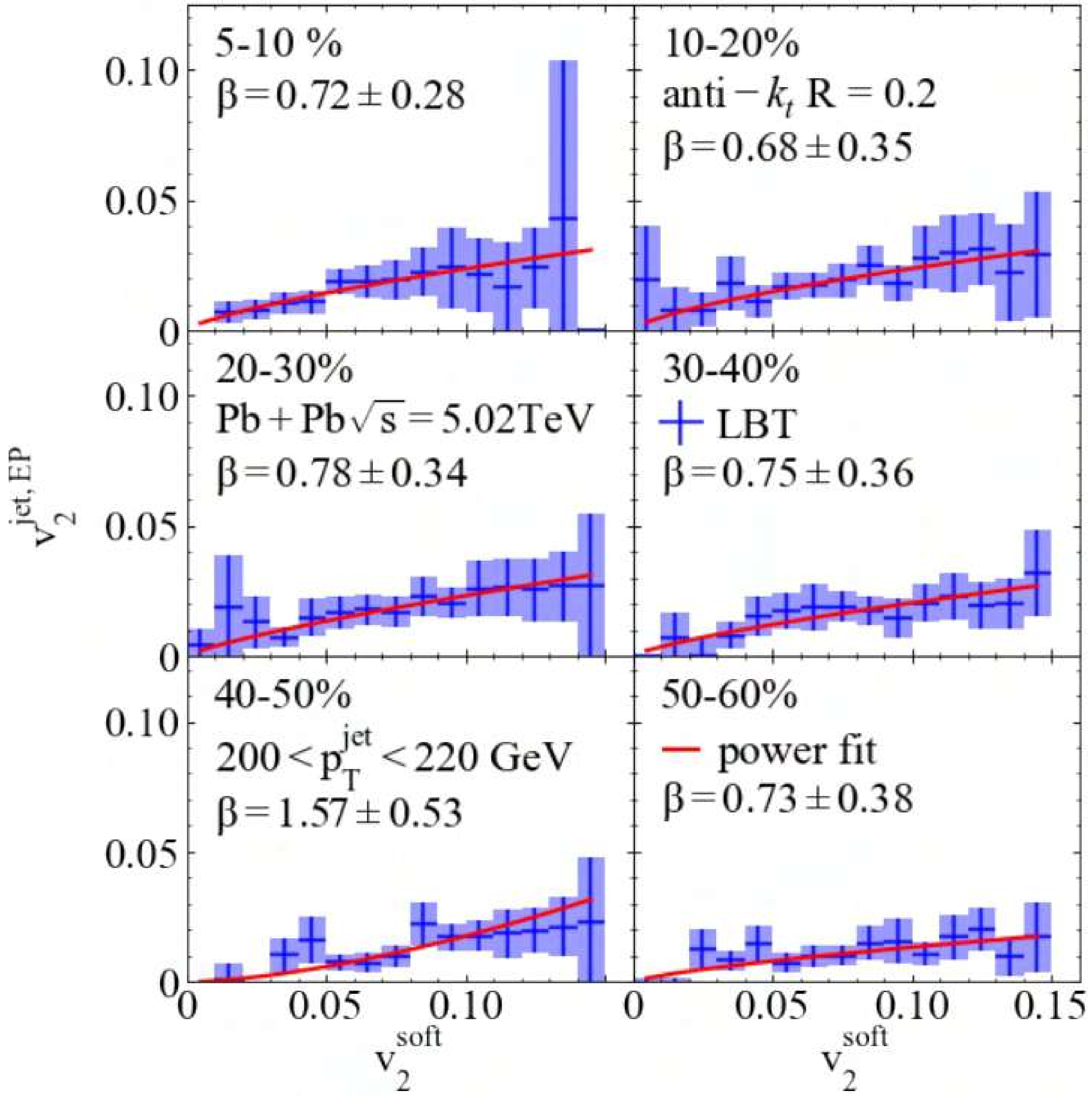
Hard-soft tomography

$$v_2^{\mathrm{jet}} = \alpha(v_2^{\mathrm{soft}})^{\beta}$$

2.76 TeV



5.02 TeV



Almost linear dependence!

Summary

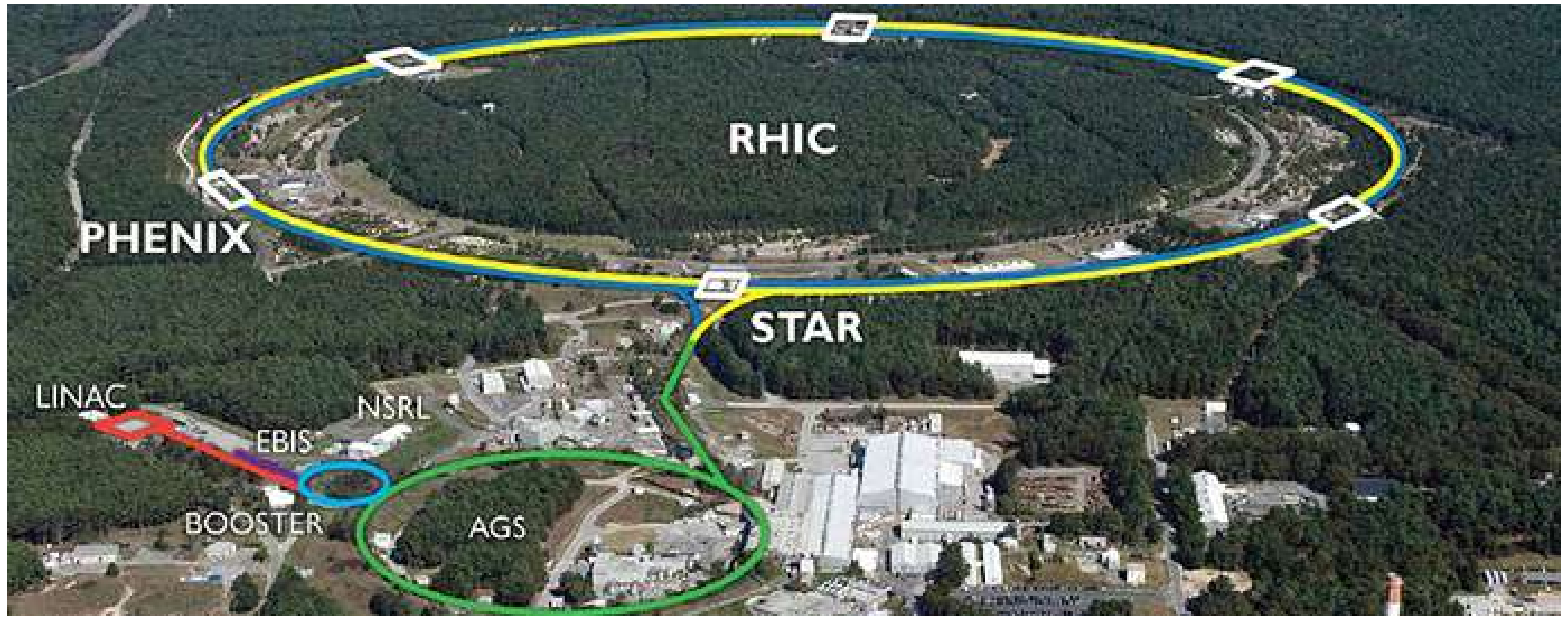
- ✓The LBT model can describe both jet suppression and jet anisotropy flow
- ✓Jet energy loss distribution can be extracted from experimental data
- ✓Jet anisotropy correlates with medium anisotropy
- ✓Initial jet production localization can be used to study jet-medium inteaction in detail

Outlook

- ➢ Extract path length dependence of jet quenching from experimental data on jet R_{AA} & v_2

Thanks for your attention!

Motivation



RHIC at BNL, operation in 2000

Au+Au at 200 GeV

LHC at CERN, operation in 2010

Pb+Pb at 2.76 TeV, 5.02 TeV

Fig: RHIC and LHC, from https://www.innovationnewsnetwork.com/technology-in-relativistic-heavy-ion-collider-physics-research/6466/

Motivation

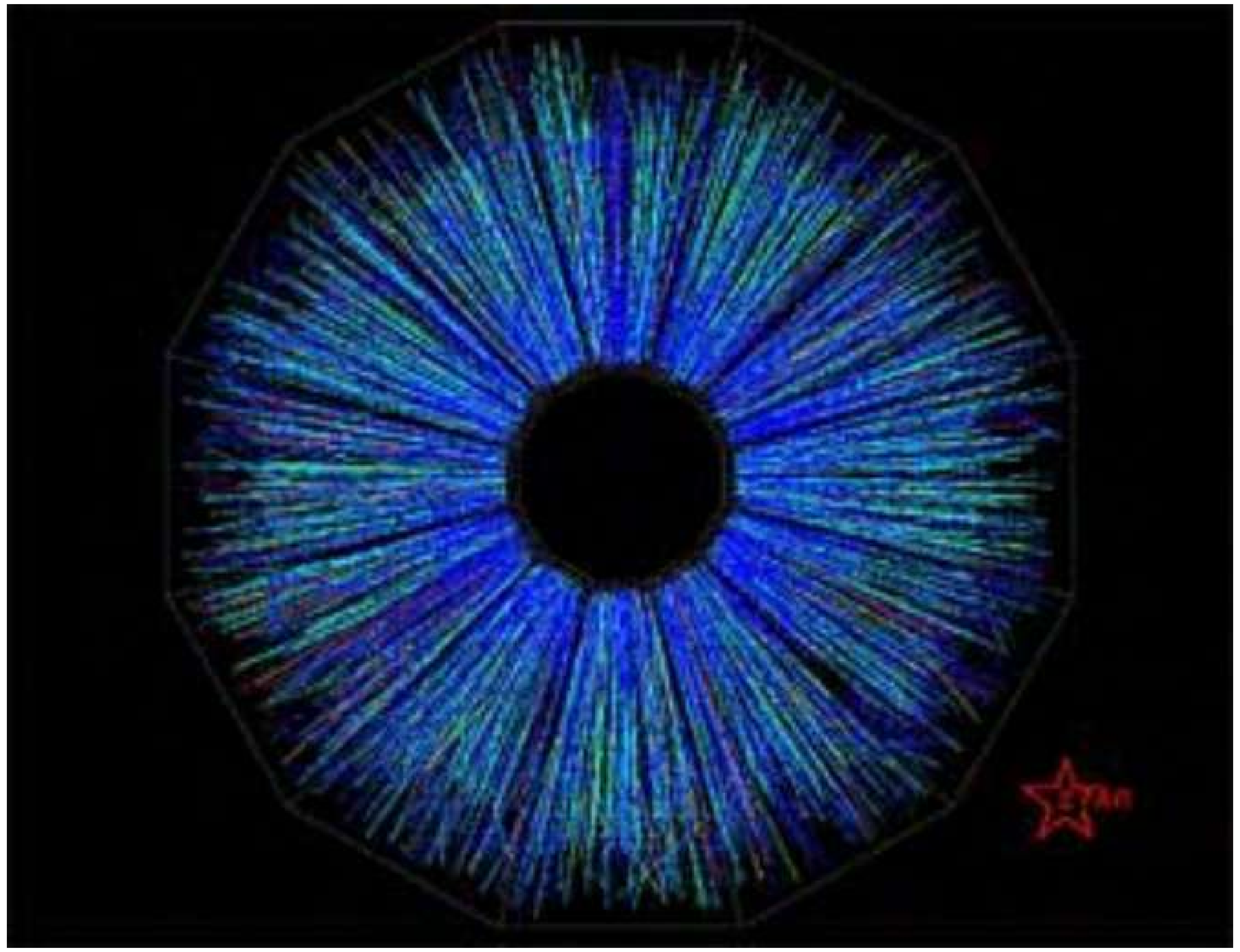


Fig: Two gold ions collide head-on in the STAR detector, from http://www.rhic.bnl.gov/STAR/)

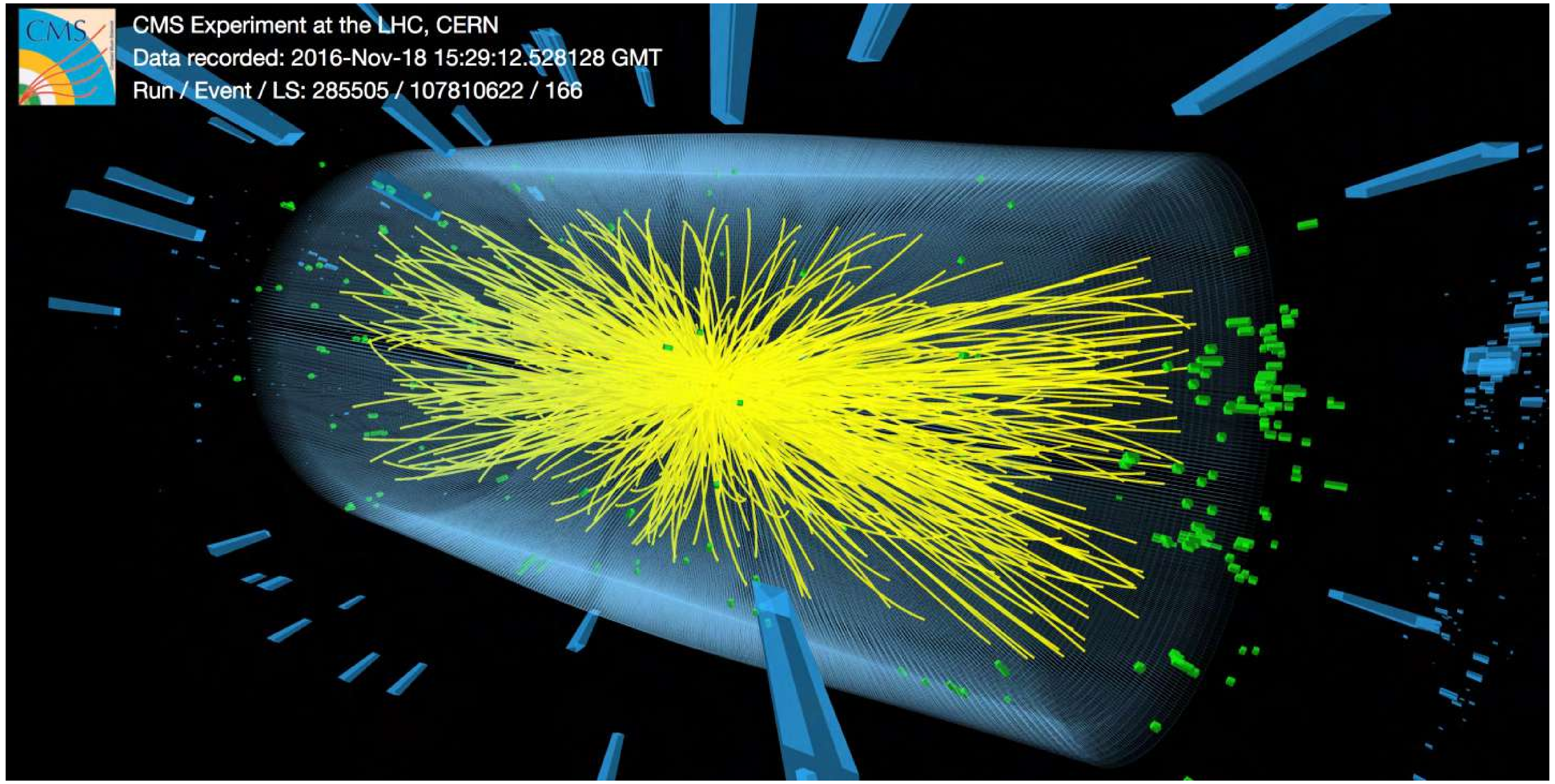


Fig: Proton-lead ion run for which no fewer than 449 particles tracks were reconstructed.(Image from CMS/CERN)

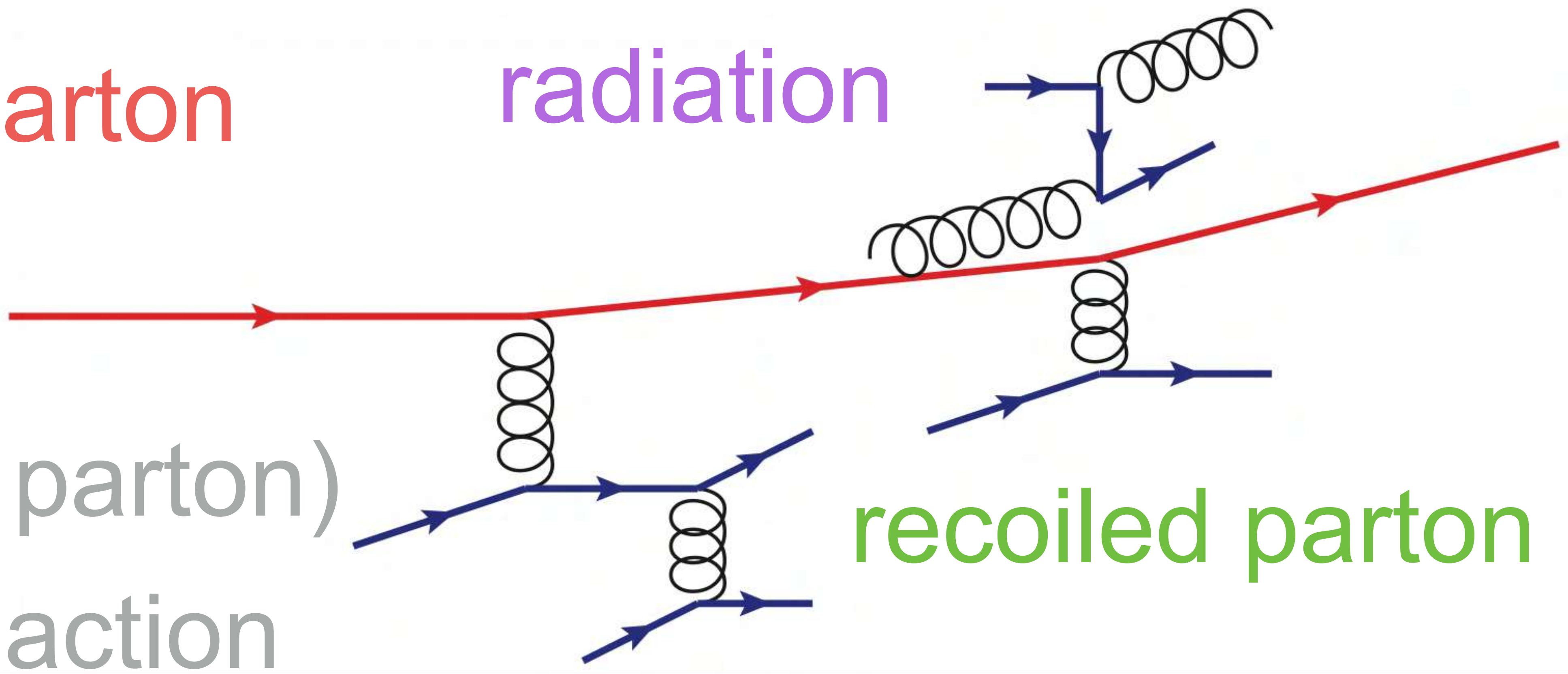
The linear Boltzmann transport (LBT) model

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

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

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

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

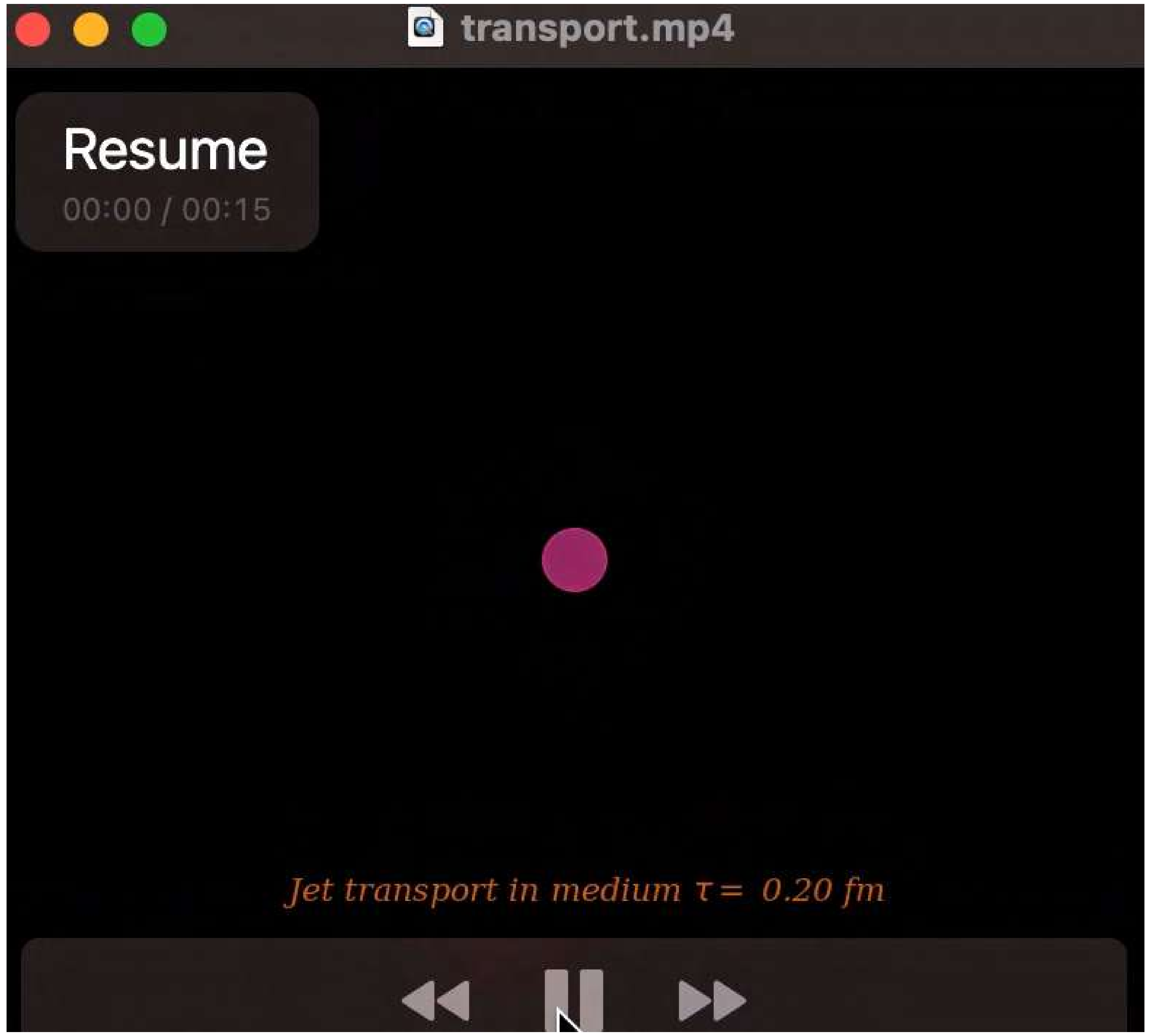


shower parton

radiation

(thermal parton)
back reaction

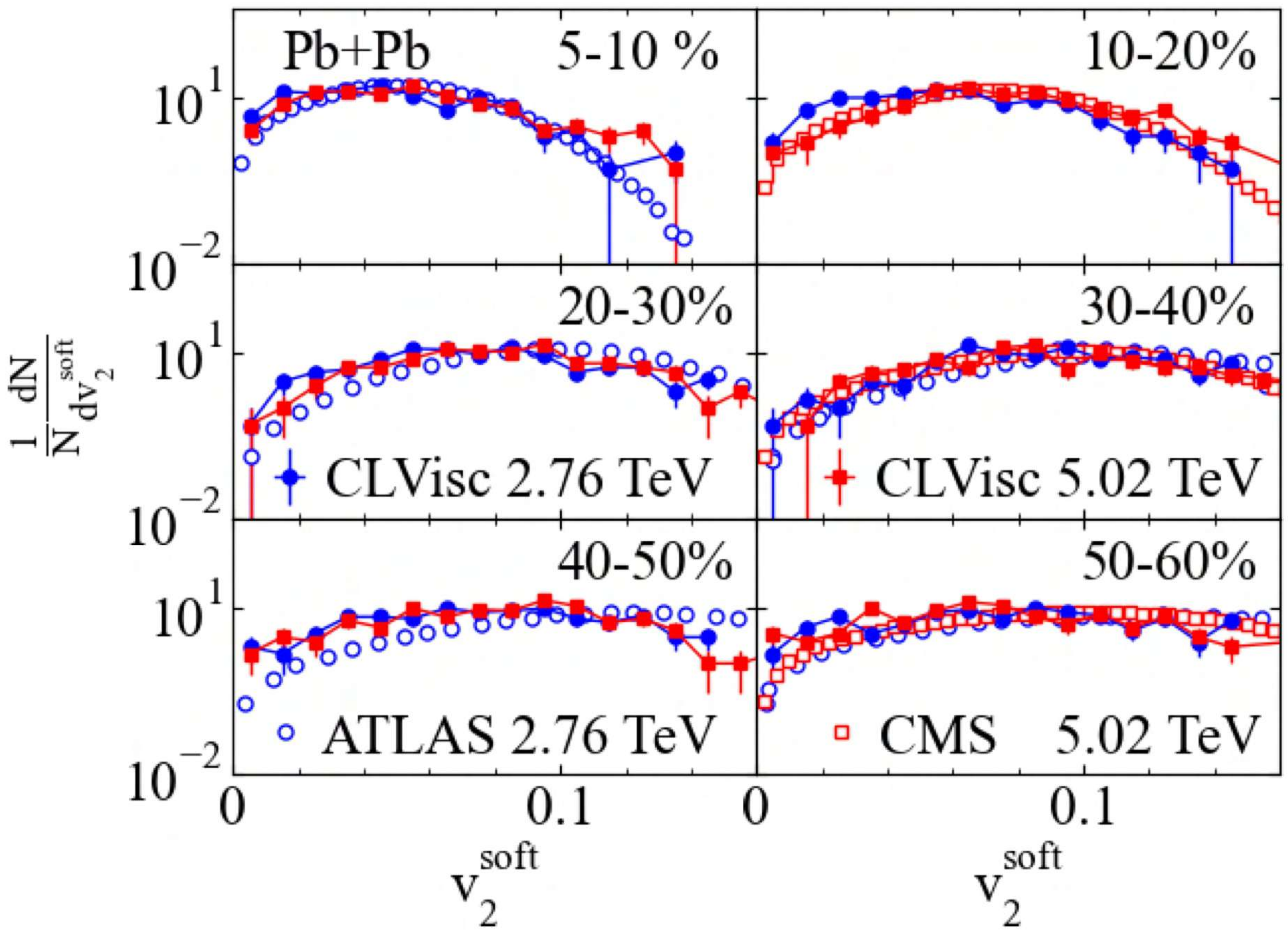
recoiled parton



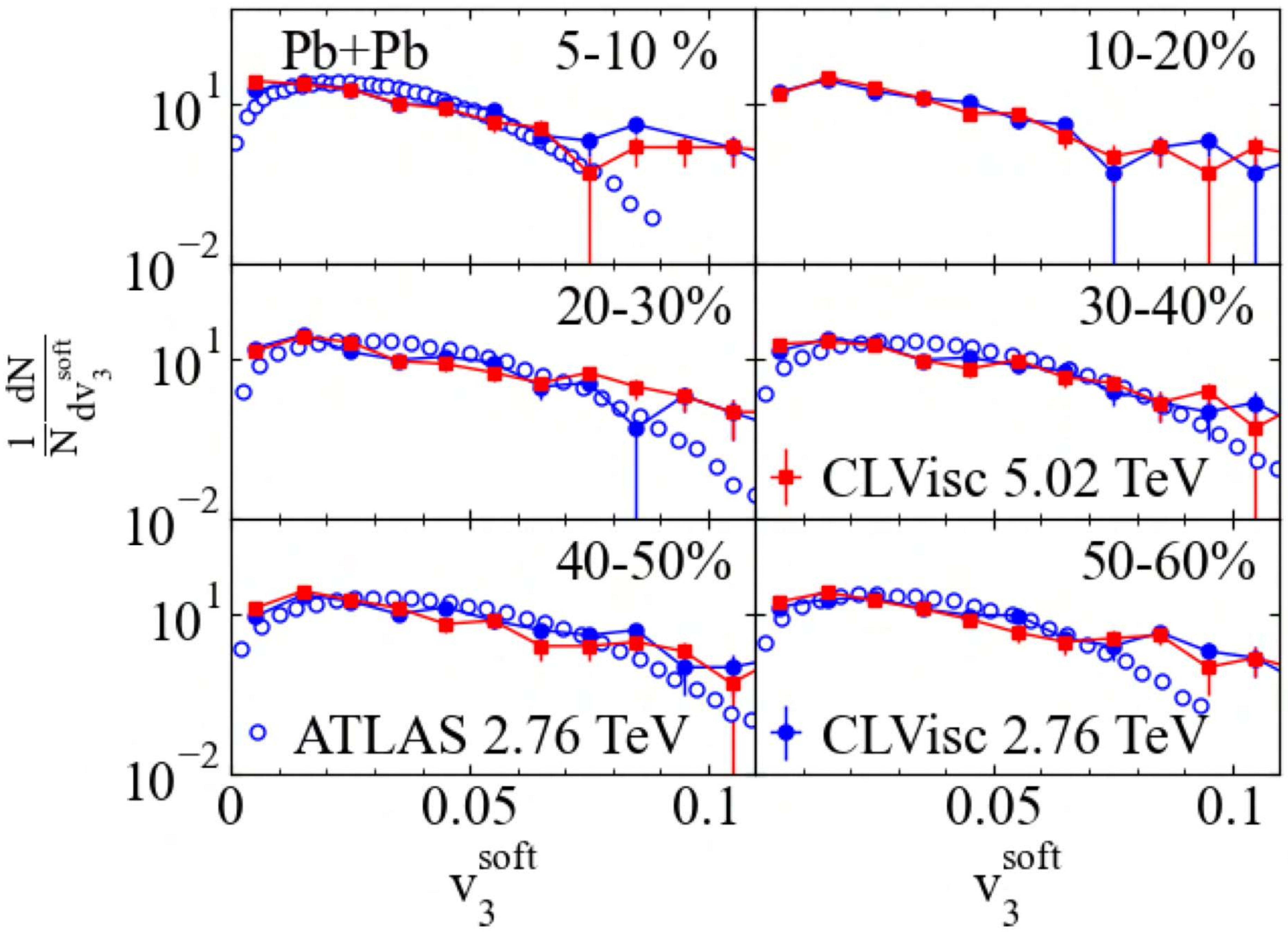
Jet transport in medium $\tau = 0.20$ fm

Soft hadron anisotropy: v_2 and v_3

soft hadron v_2



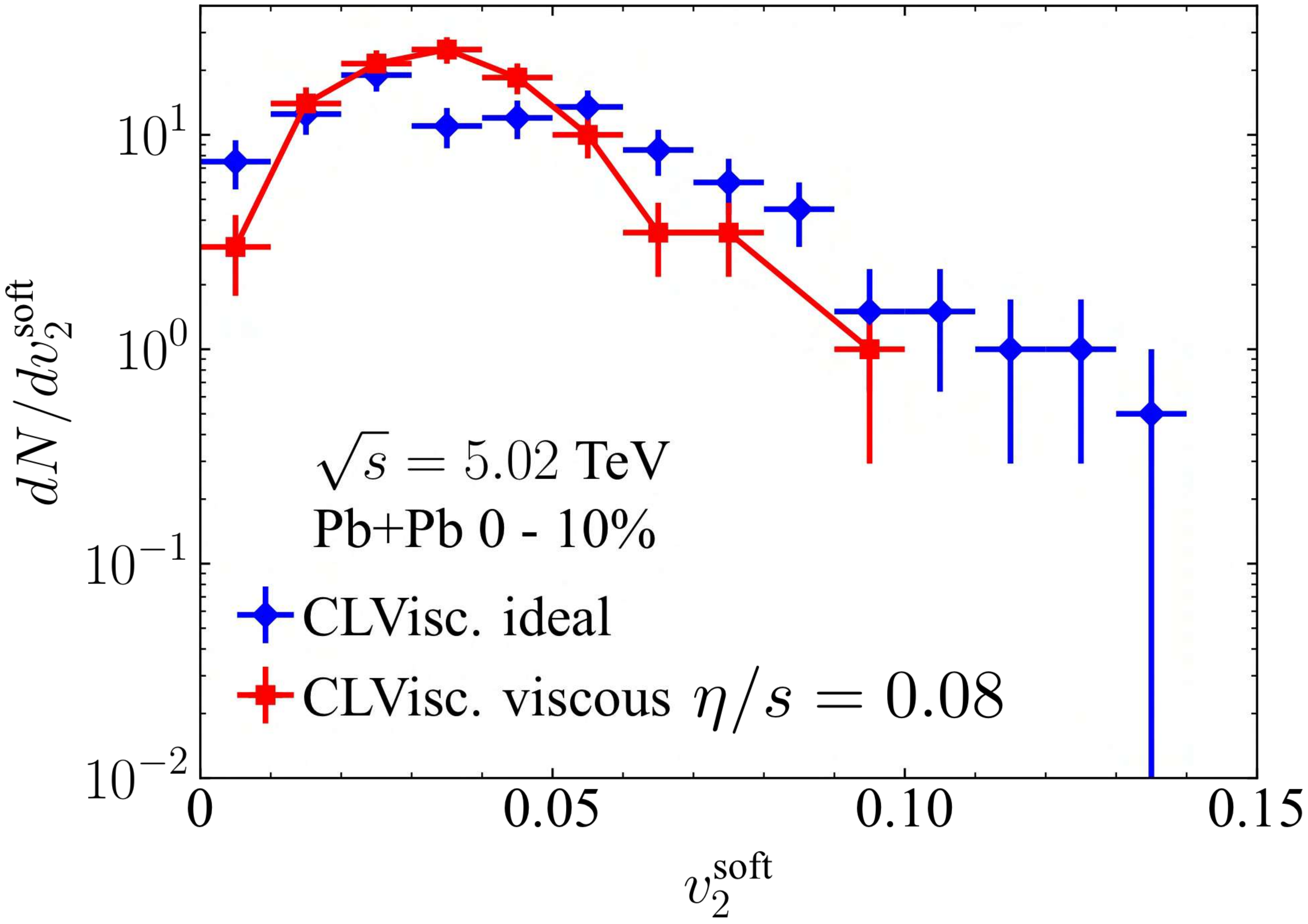
soft hadron v_3



CLVisc hydro model can well describe the experimental data of anisotropy

Effects of viscosity on jet v_2

Effects of viscosity: v_2 distributions



No significant difference between ideal and viscous hydro

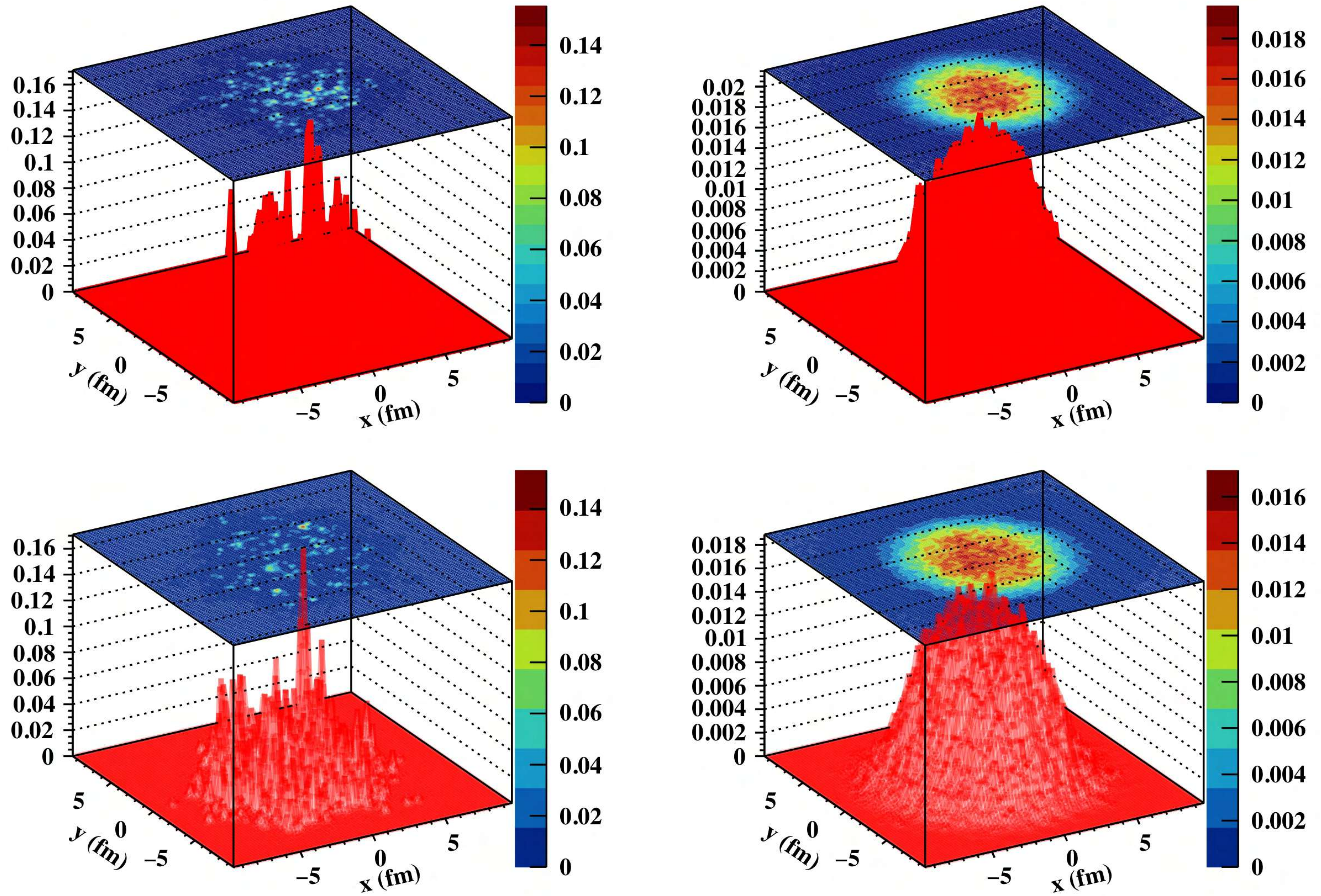
Effects of viscosity: initial geometry

single hydro event

1000 hydro events

ideal hydro

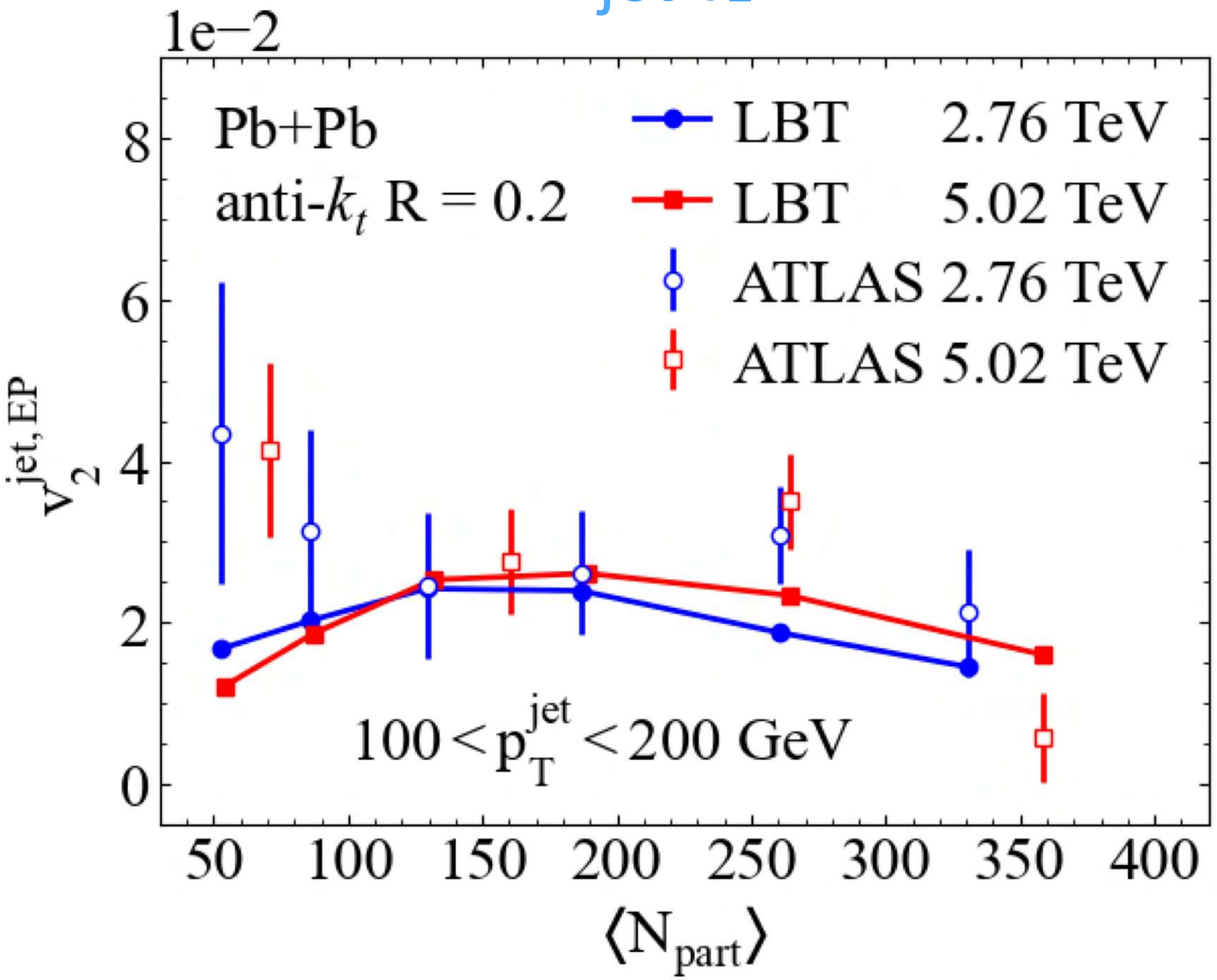
viscous hydro



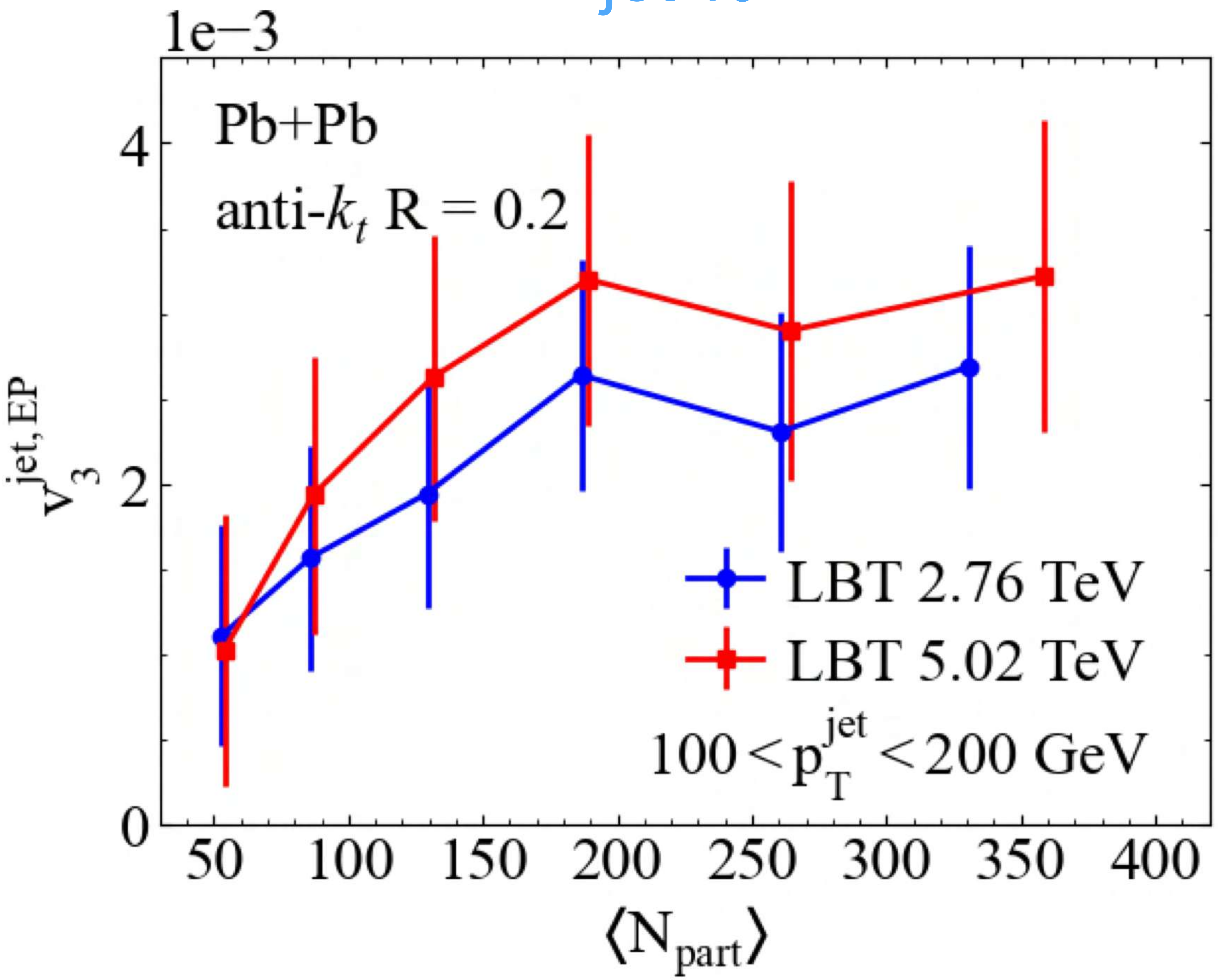
No significant difference between ideal and viscous hydro

Centrality and colliding energy dependence

jet v_2

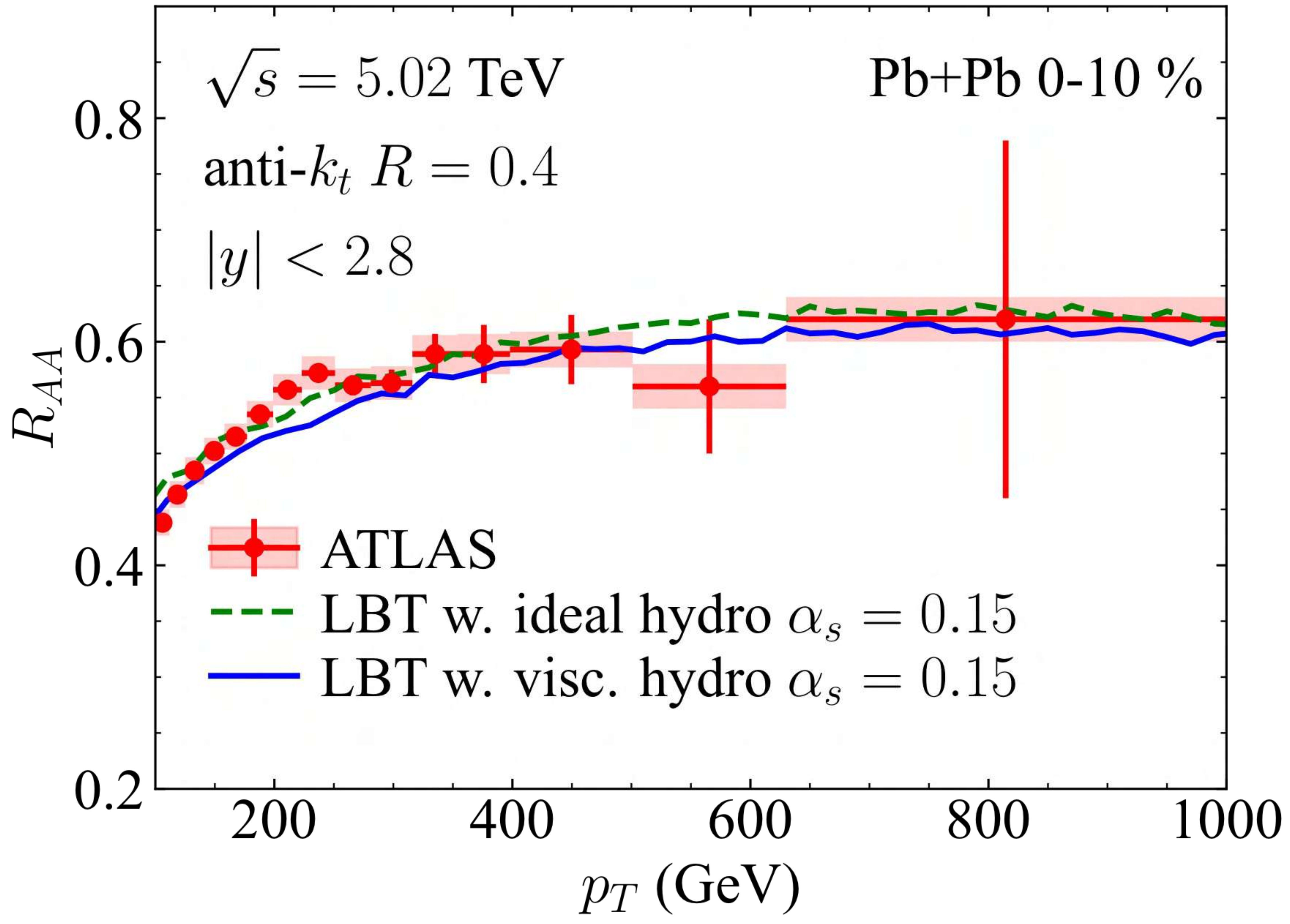


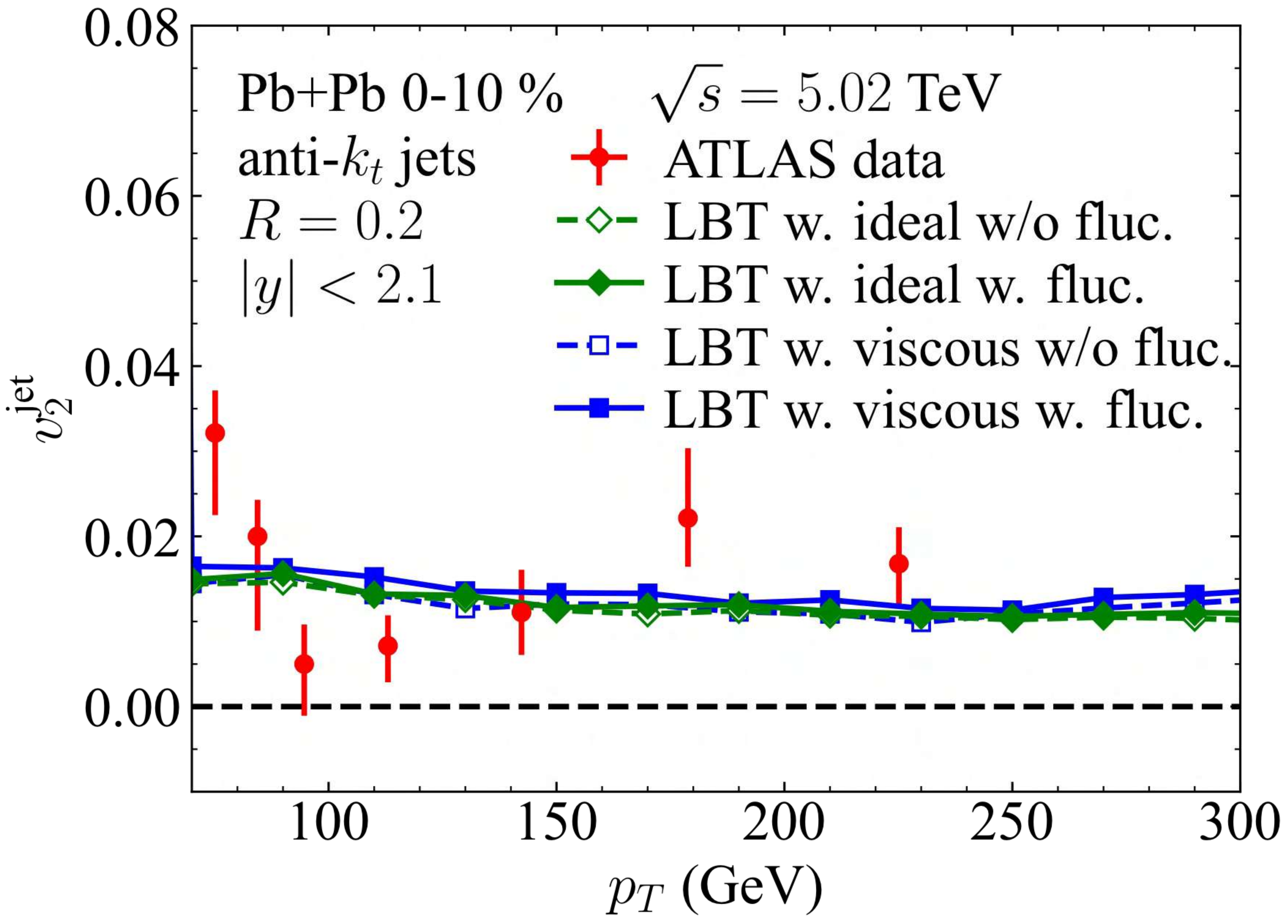
jet v_3



The LBT model can well describe the experimental data of jet anisotropy v_2 in the most and middle central collisions.

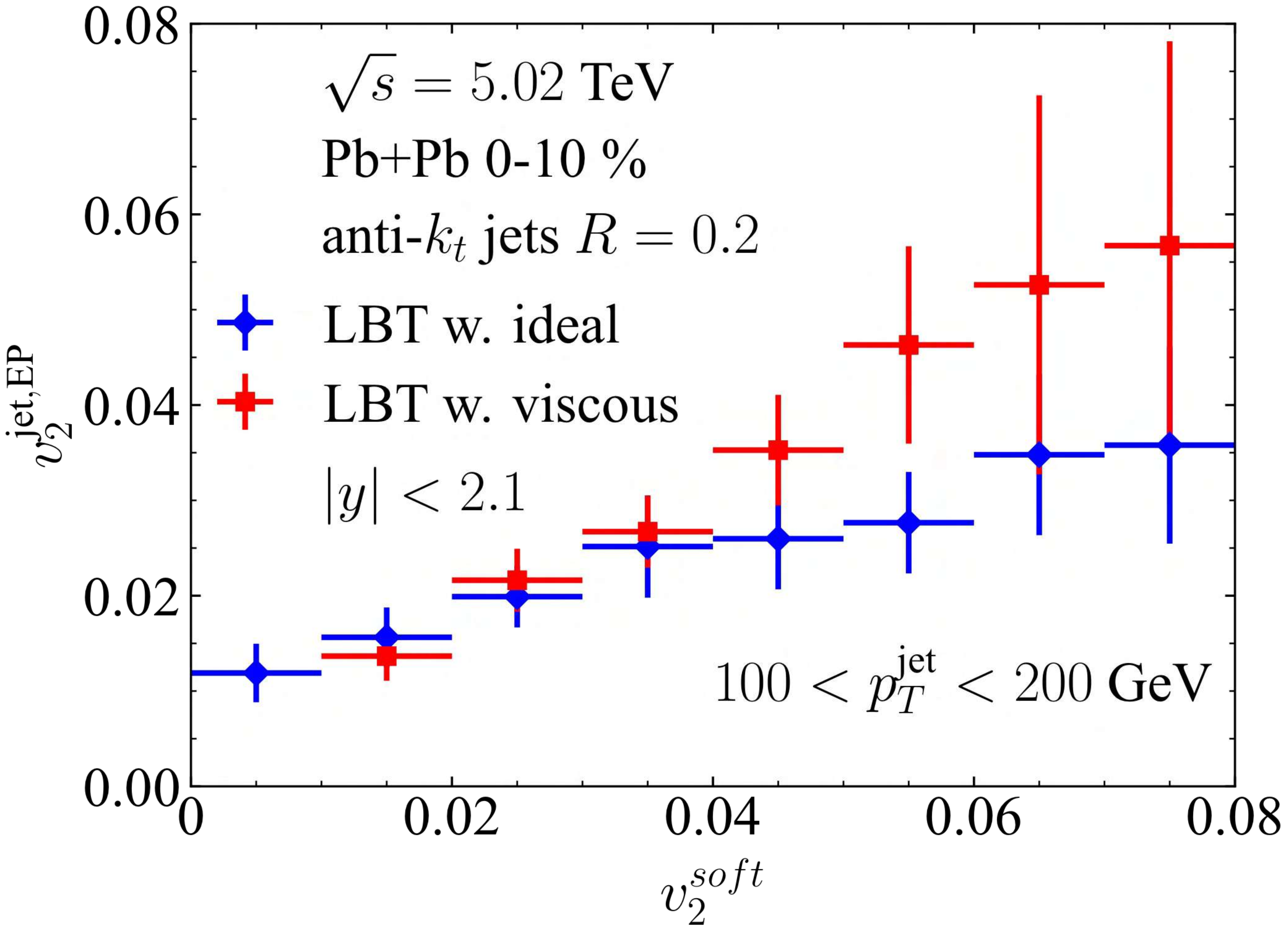
Effects of viscosity: jet R_{AA} and jet v_2





Viscosity slightly increases jet suppression and jet anisotropy v_2

Effects of viscosity: hard-soft correlations

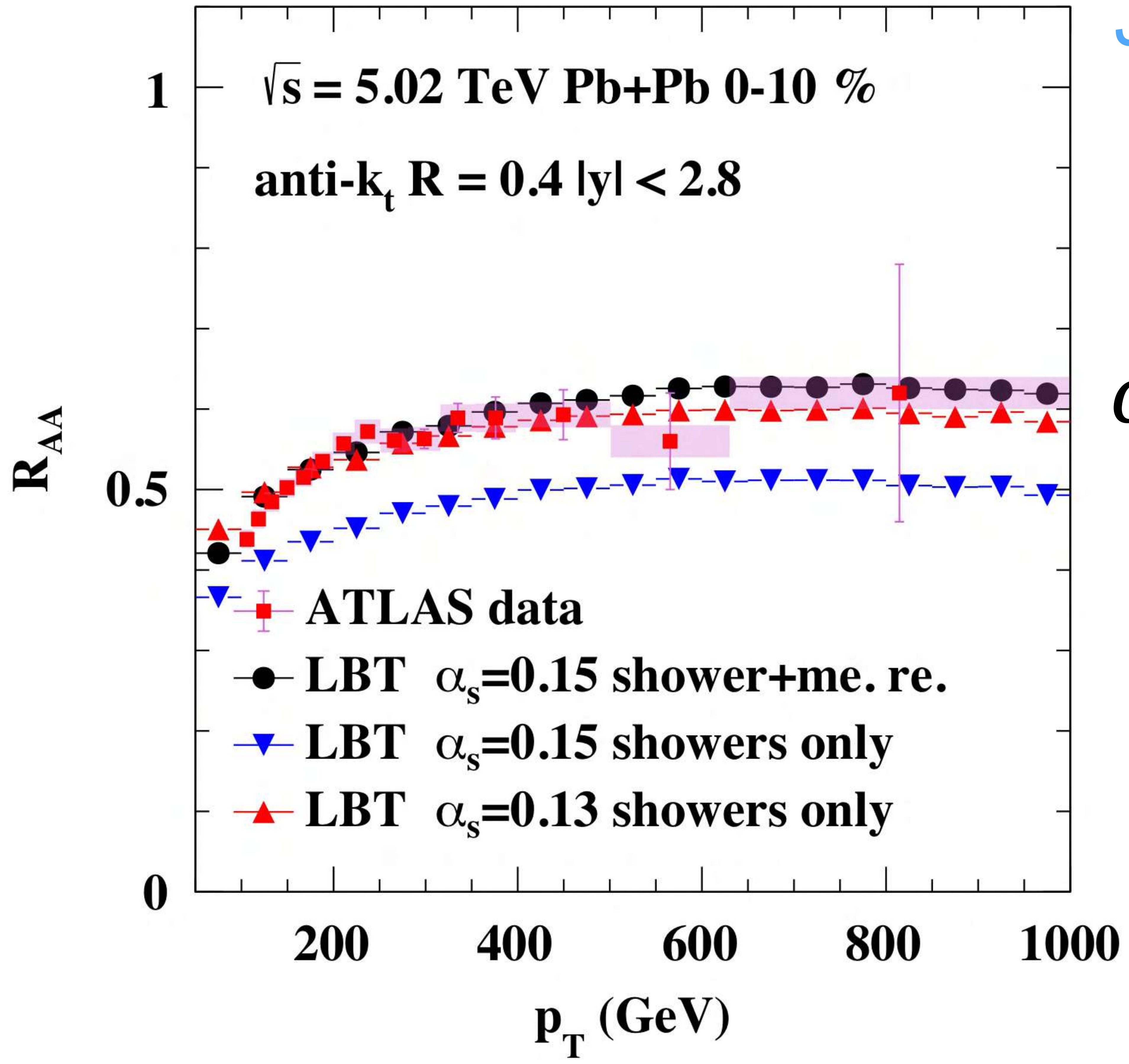


No significant difference between ideal and viscous hydro

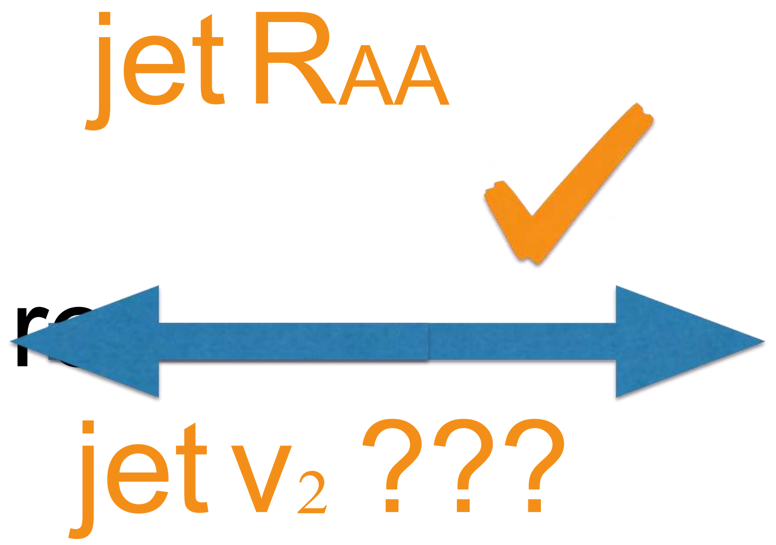
Effects of medium response on jet v_2

Effects of medium response:

medium response (me. re.) : medium recoil + back reaction.



Jets without medium response get more quenched



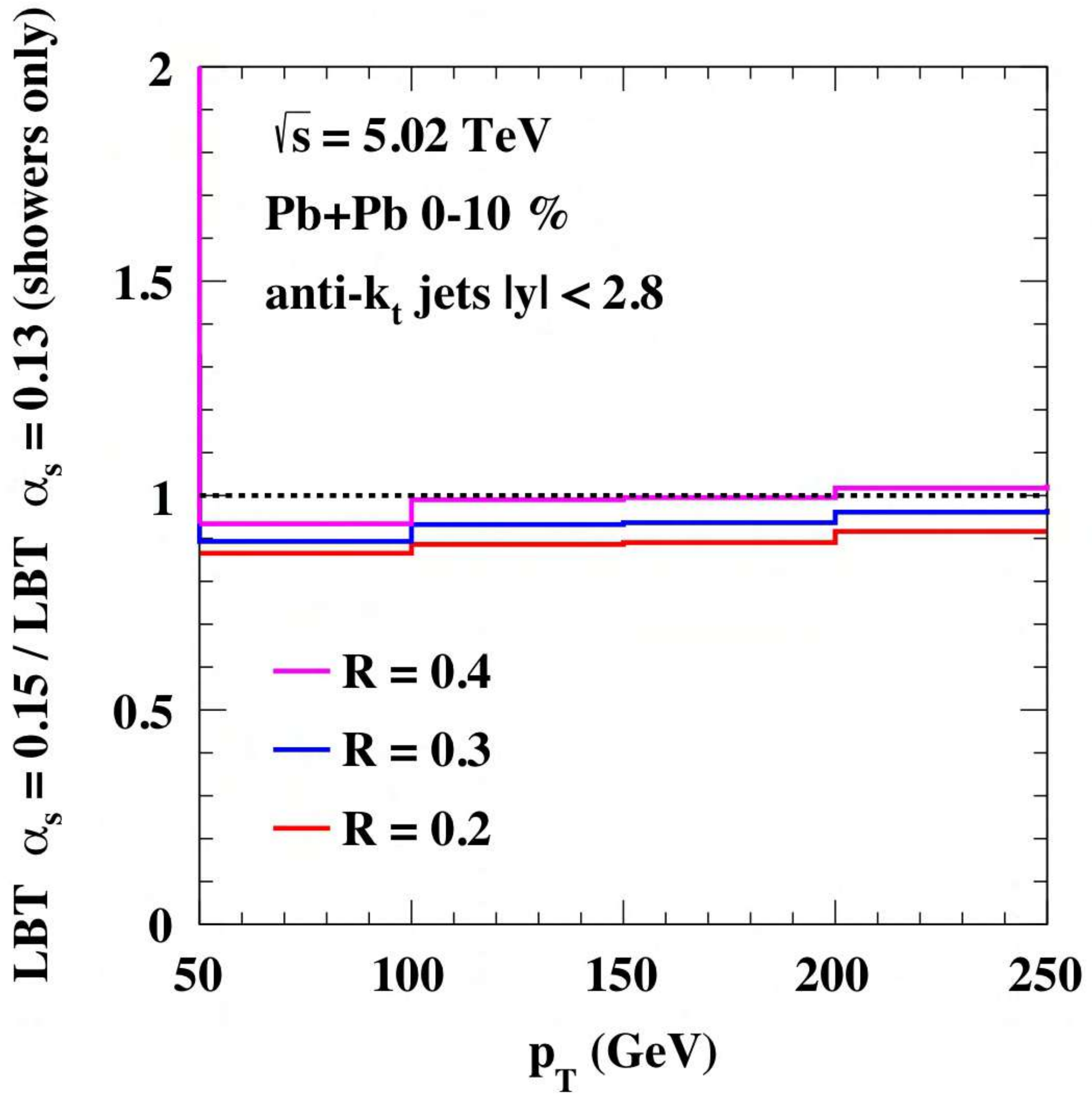
$\alpha_s = 0.15$ with me. r

$\alpha_s = 0.13$ w/o me.

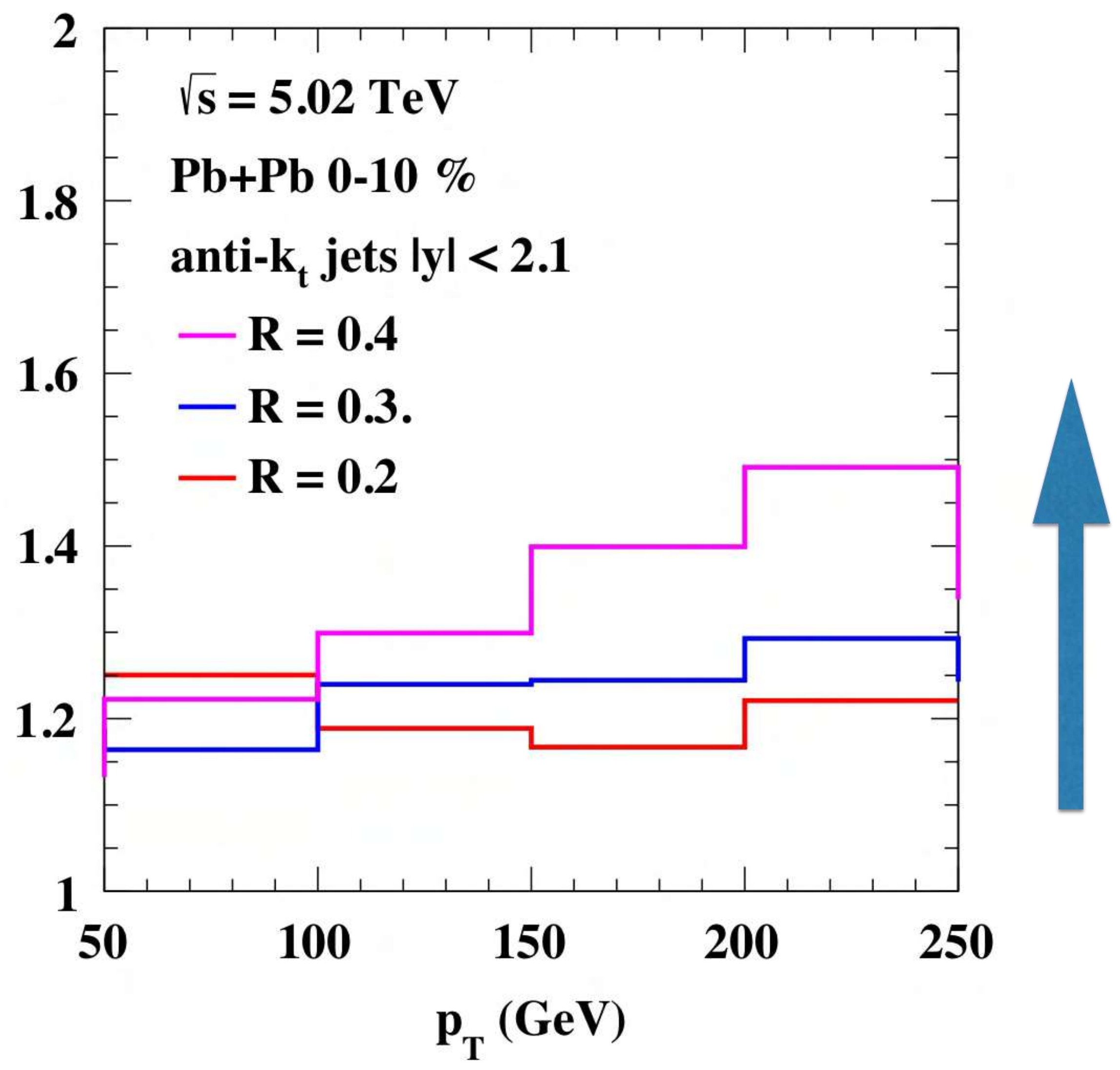
Effects of medium response:

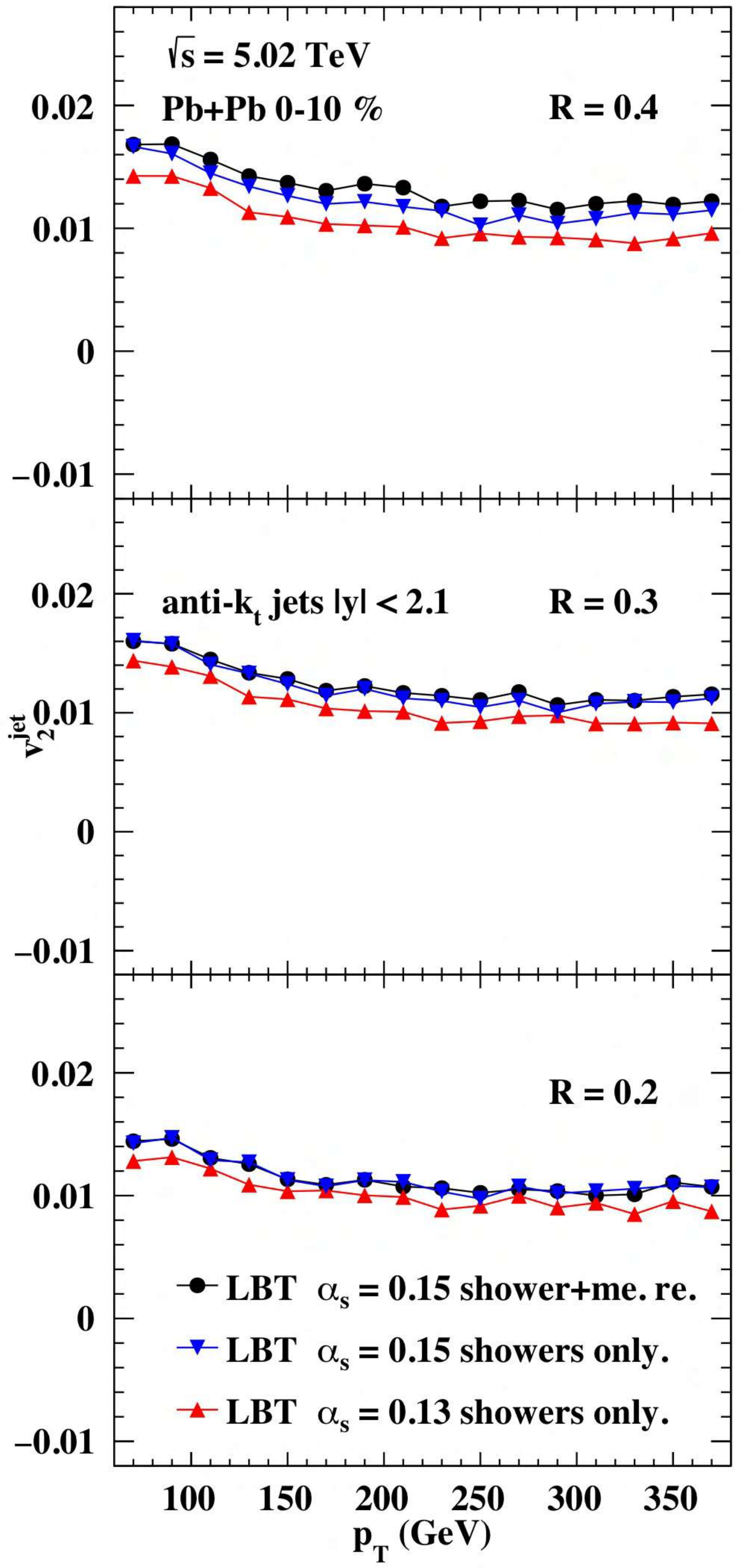
$$\text{ratio}=\frac{\text{LBT } \alpha_s = 0.15 \text{ with medium response}}{\text{LBT } \alpha_s = 0.13 \text{ w/o medium response}}$$

jet R_{AA} ratio



jet v_2 ratio



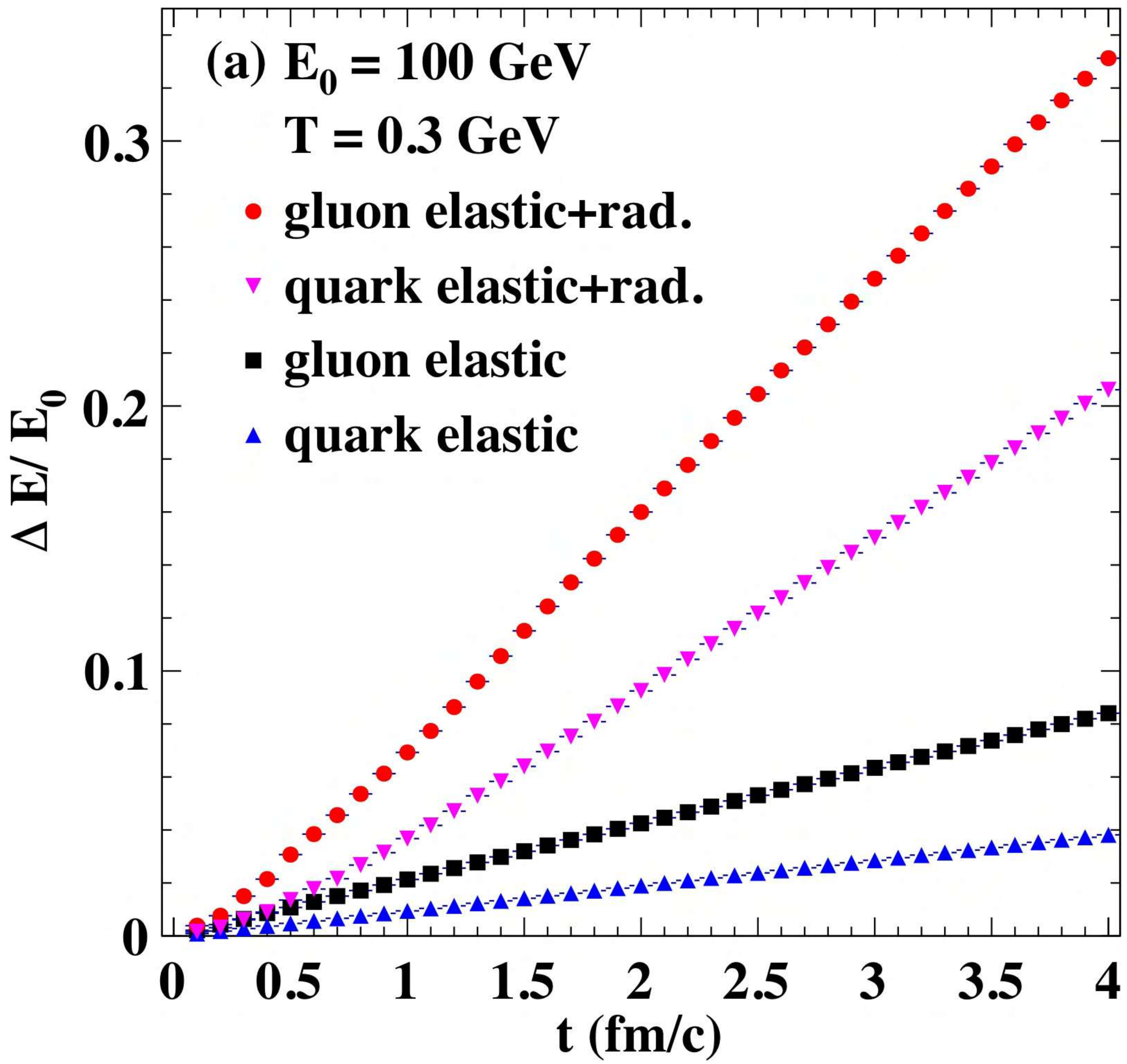


Larger cone size -> larger effect of medium response

The LBT model with a uniform and static medium

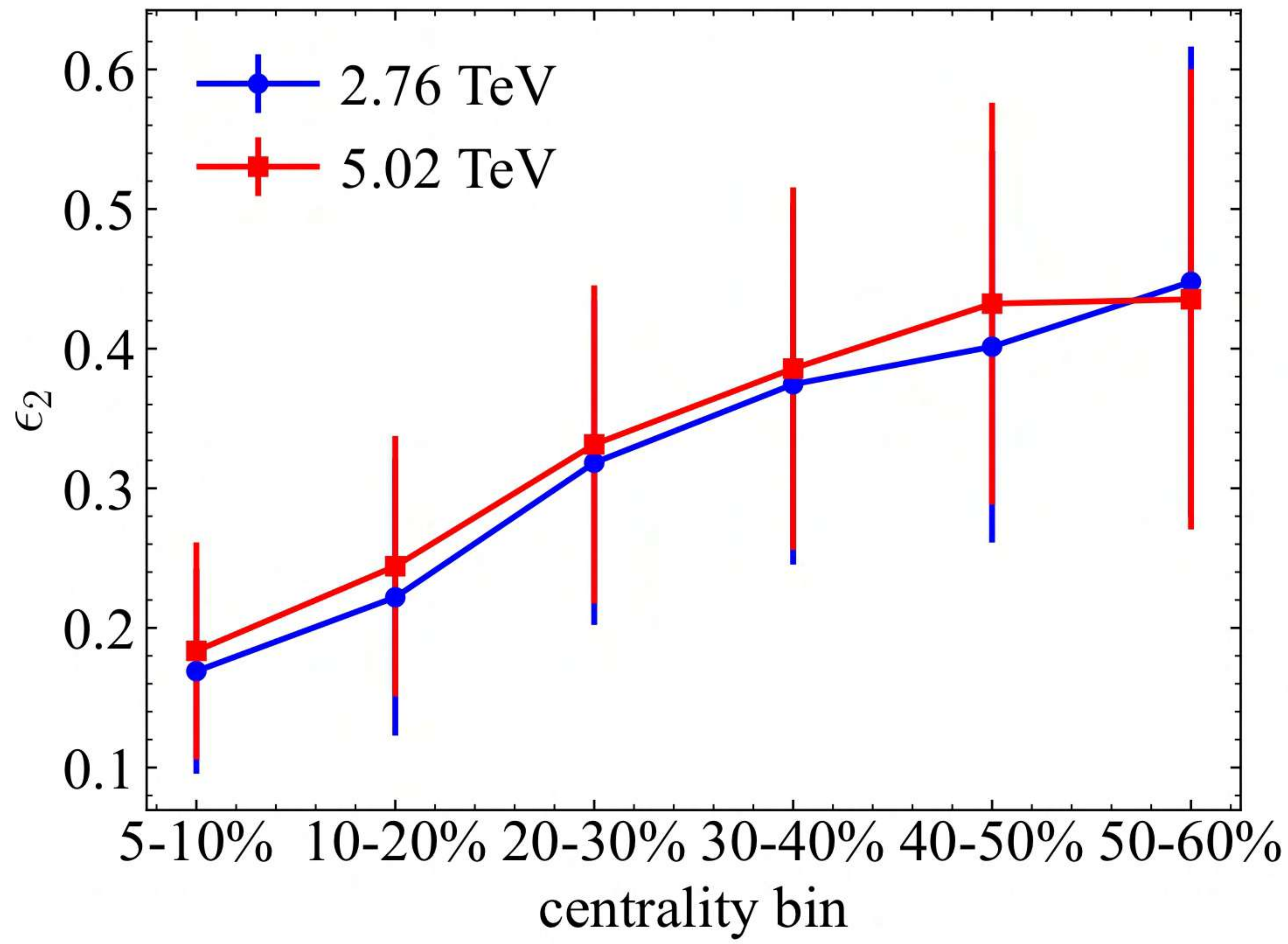
Yayun He, Tan Luo, Xin-Nian Wang, Yan Zhu. Phys. Rev. C 91 (2015) 054908. arXiv:1503.03313.

parton energy loss



Inelastic energy loss: quadratic in the first stage

Elastic energy loss: linear


2.76 TeV
5.02 TeV
ϵ_2
0.1
0.2
0.3
0.4
0.5
0.6
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
centrality bin

$\langle v_2^{\mathrm{soft}} \rangle \pm \delta v_2^{\mathrm{soft}}$

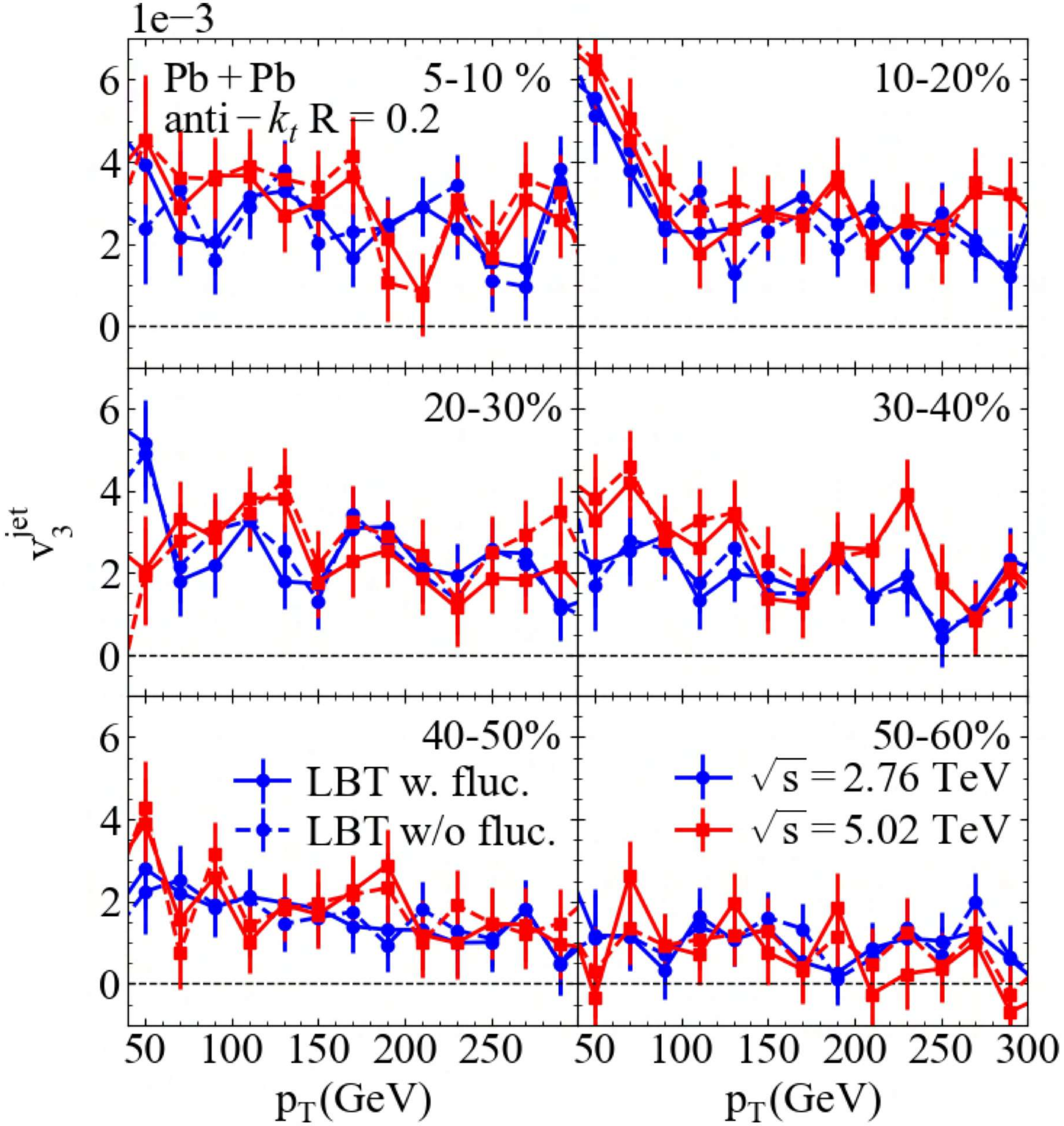
	2.76 TeV	5.02 TeV
$5-10\%$	0.047 ± 0.007	0.054 ± 0.008
$10-20\%$	0.060 ± 0.008	0.076 ± 0.007
$20-30\%$	0.076 ± 0.008	0.086 ± 0.008
$30-40\%$	0.089 ± 0.008	0.095 ± 0.009
$40-50\%$	0.079 ± 0.008	0.086 ± 0.009
$50-60\%$	0.078 ± 0.009	0.078 ± 0.009

TABLE I. The mean values and standard deviations of soft hadron v_2^{soft} in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV and 5.02 TeV in centrality bins $5-10\%, 10-20\%, 20-30\%, 30-40\%, 40-50\%$ and $50-60\%$ from the CLVisc model.

$\langle v_3^{\mathrm{soft}} \rangle \pm \delta v_3^{\mathrm{soft}}$

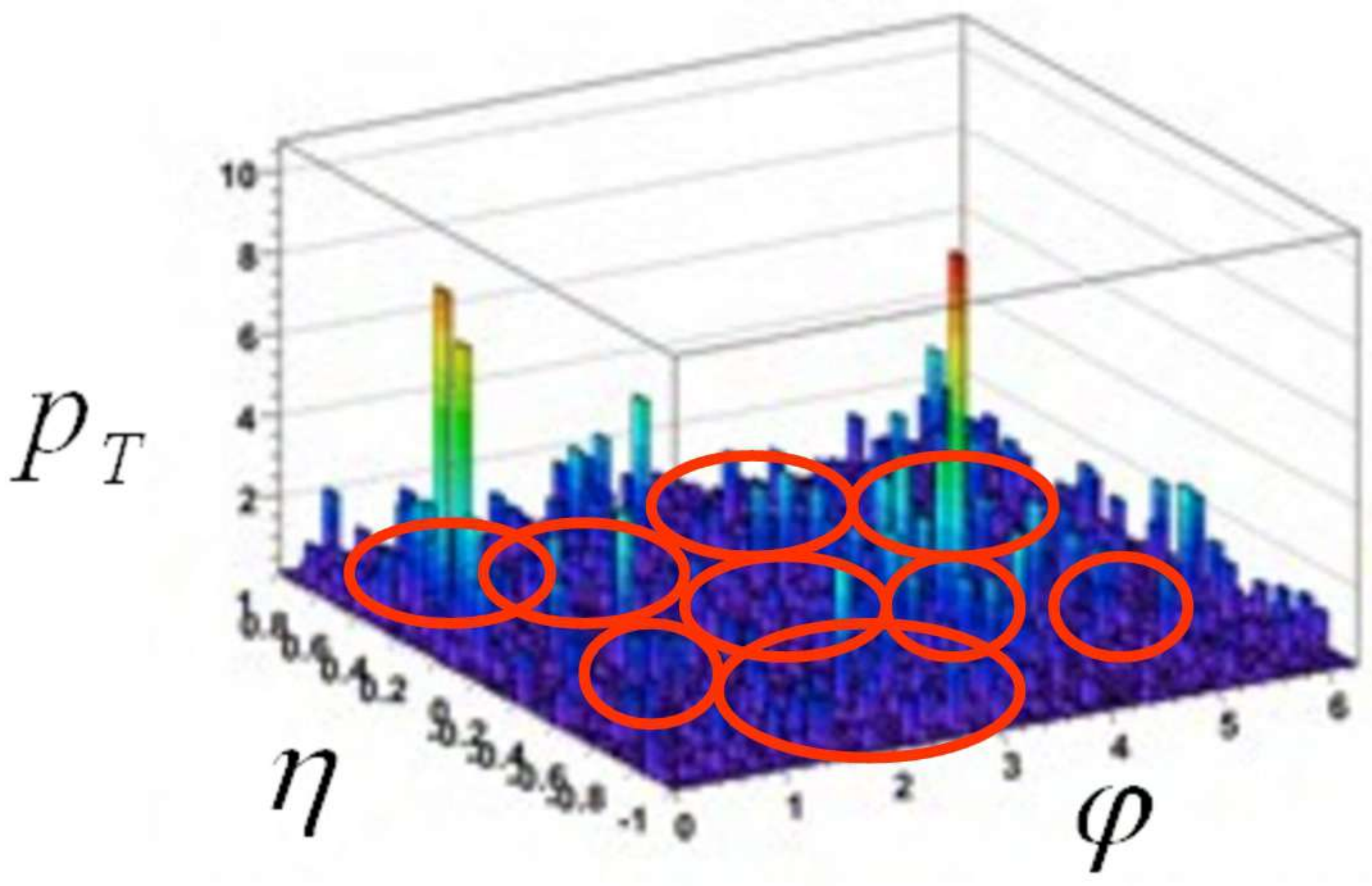
	2.76 TeV	5.02 TeV
$5-10\%$	0.031 ± 0.007	0.027 ± 0.007
$10-20\%$	0.031 ± 0.007	0.029 ± 0.007
$20-30\%$	0.032 ± 0.007	0.035 ± 0.008
$30-40\%$	0.034 ± 0.007	0.035 ± 0.008
$40-50\%$	0.038 ± 0.007	0.034 ± 0.008
$50-60\%$	0.035 ± 0.007	0.032 ± 0.008

TABLE II. The mean value and standard deviation of soft hadron v_3^{soft} in Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV and 5.02 TeV in centrality bins $5-10\%, 10-20\%, 20-30\%, 30-40\%, 40-50\%$ and $50-60\%$ from the CLVisc model.


1e−3
Pb + Pb
anti − k_t R = 0.2
5-10 %
10-20%
20-30%
30-40%
40-50%
50-60%
LBT w. fluc.
LBT w/o fluc.
$\sqrt{s} = 2.76$ TeV
$\sqrt{s} = 5.02$ TeV
v_3^{jet}
0
2
4
6
50
100
150
200
250
300
p_T(GeV)

Underlying Event Subtraction (UES)

UE: collisions of beam remnant, fluctuation of the background, non-perturbative effects. Subtraction is needed to exclude the soft particles.



Seed jet: $E_T > 3\,\mathrm{GeV}$ for at least one parton, and

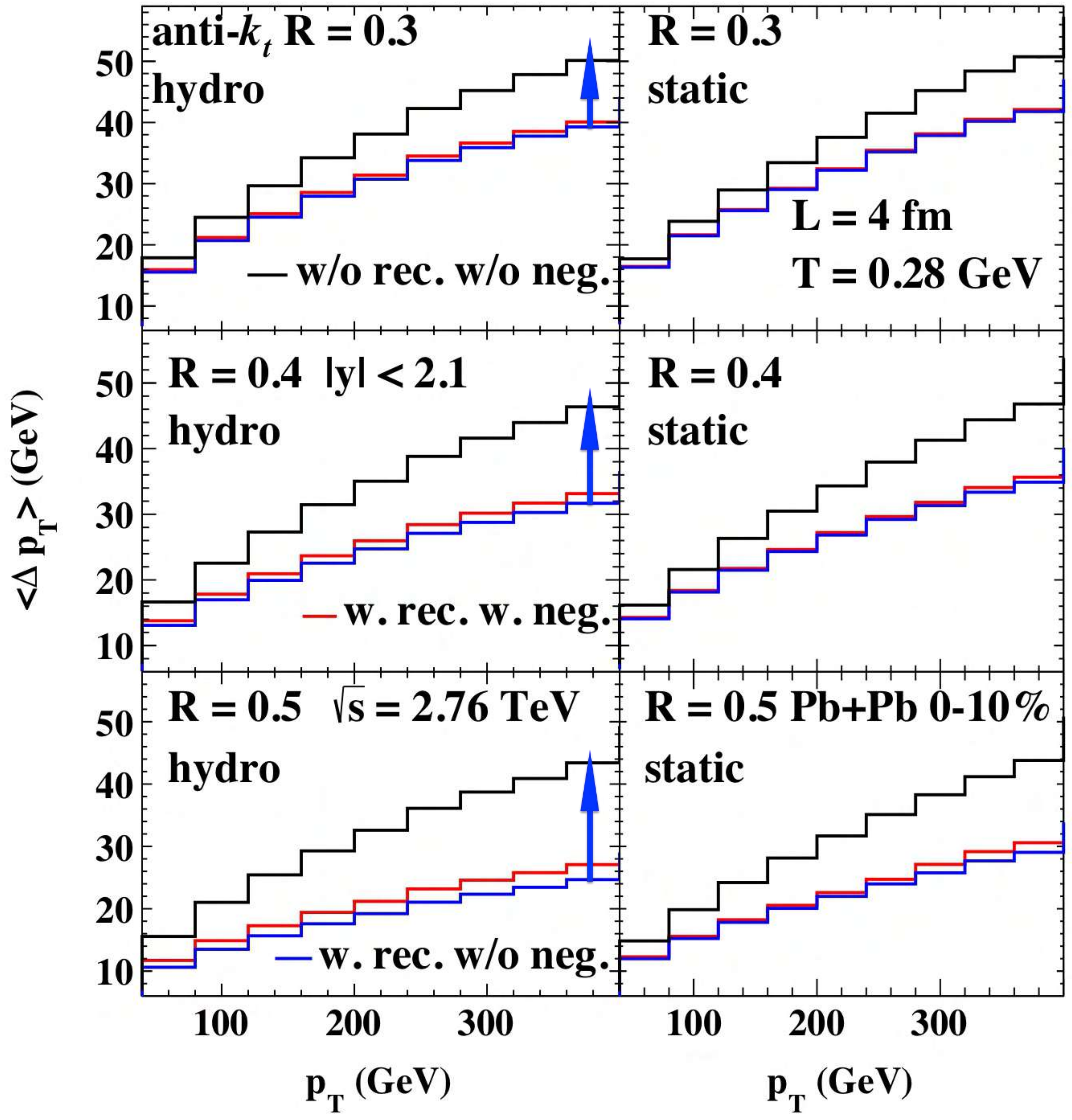
$$E_T^{max} / E_T^{ave} > 4$$

ATLAS Collaboration, Phys. Lett. B 719, 220 (2013).

$$E_T^{UES} = E_T^{seedjet} - A^{seedjet} \rho (1 + 2 v_2 \cos[2(\phi_{jet} - \Psi_2)])$$

We only subtract the energy of seed jets, and count all the final jets!

Effects of medium response and radial expansion



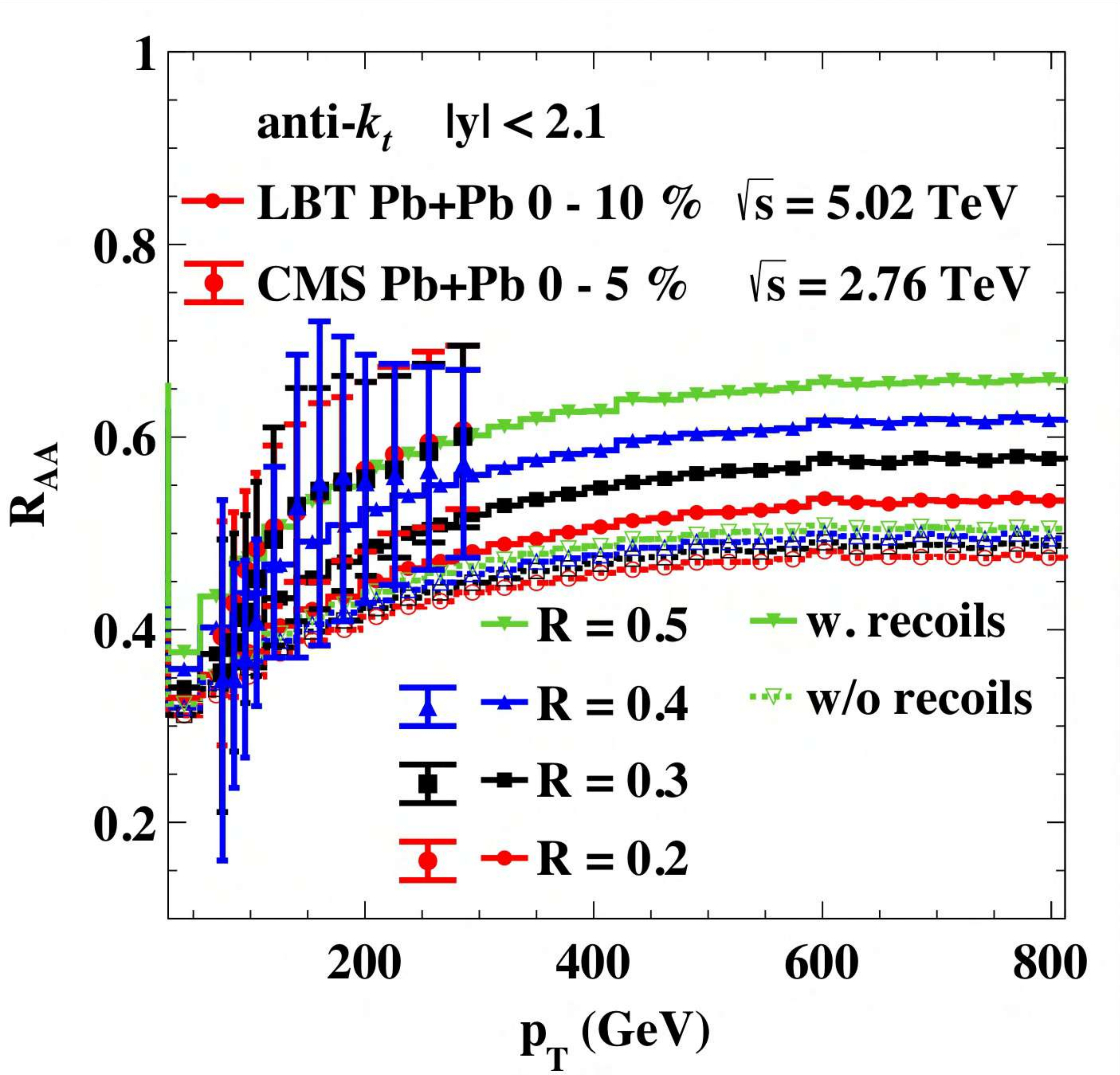
2.76 TeV

medium recoil effect up to 15%

back reaction not negligible

larger cone size and radial expansion enlarges the effects above.

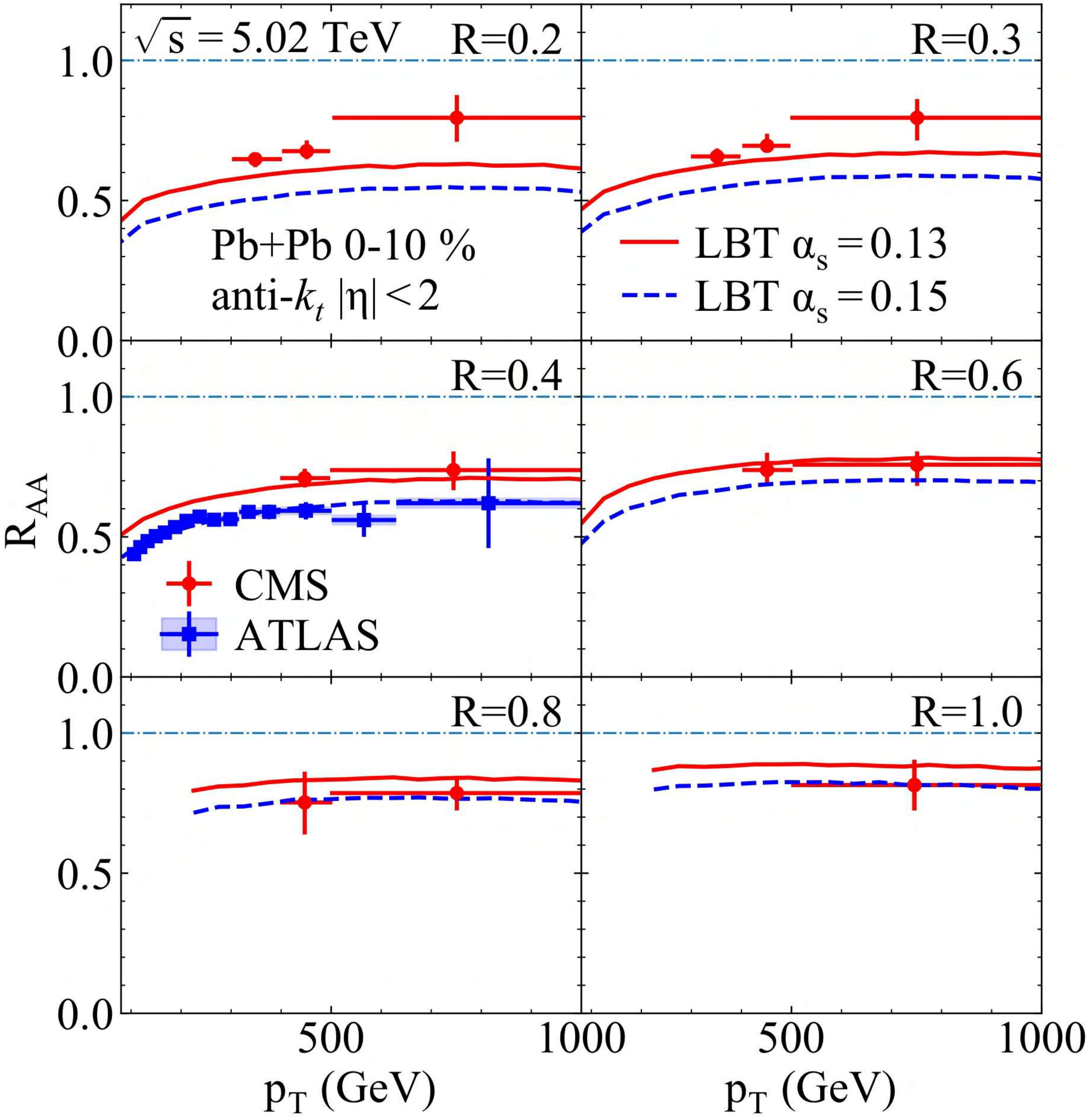
Cone size dependence of R_{AA}



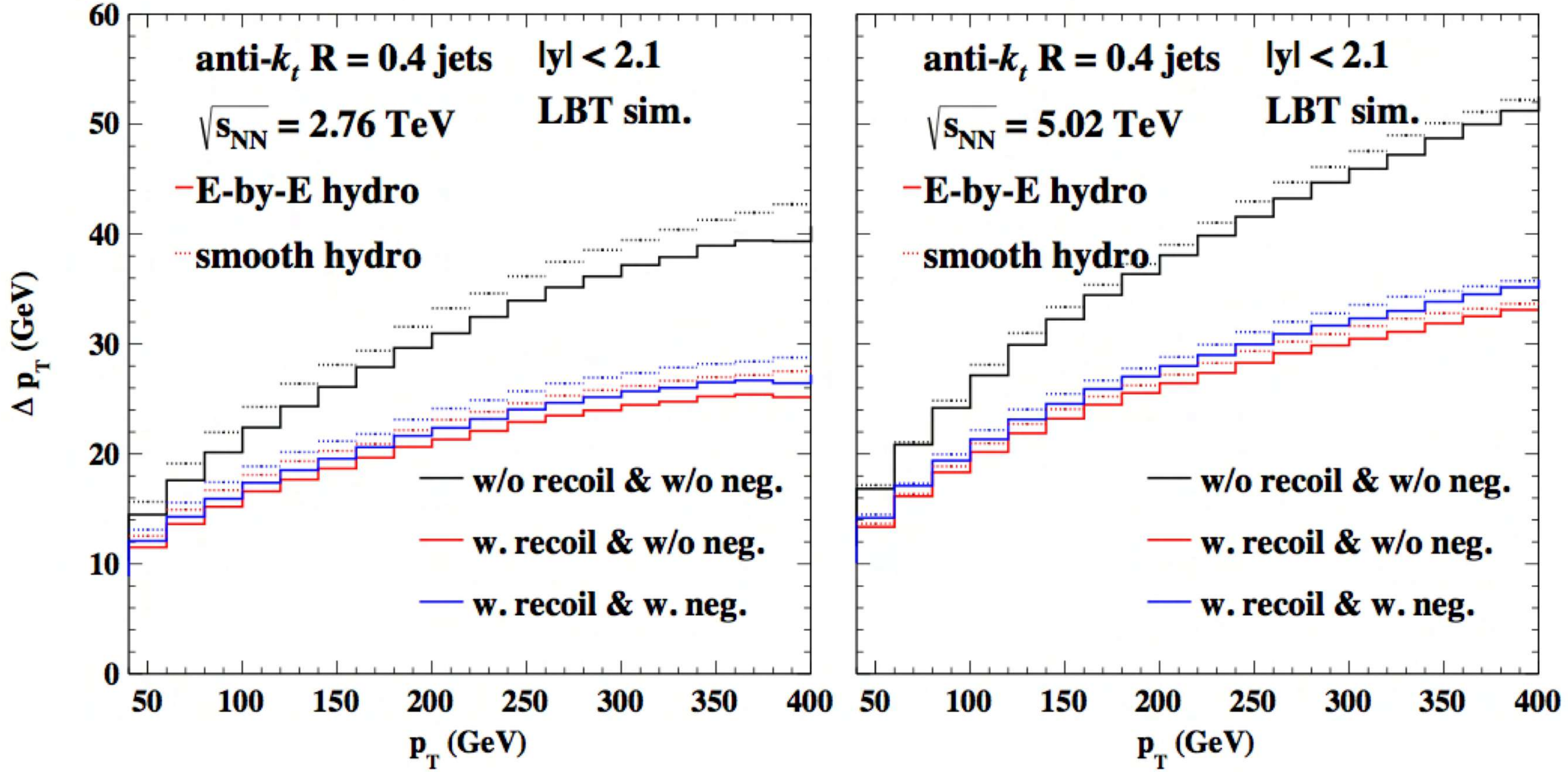
larger R : flatter initial spectrum + smaller energy loss

-> less suppression

quantitatively relates to medium response

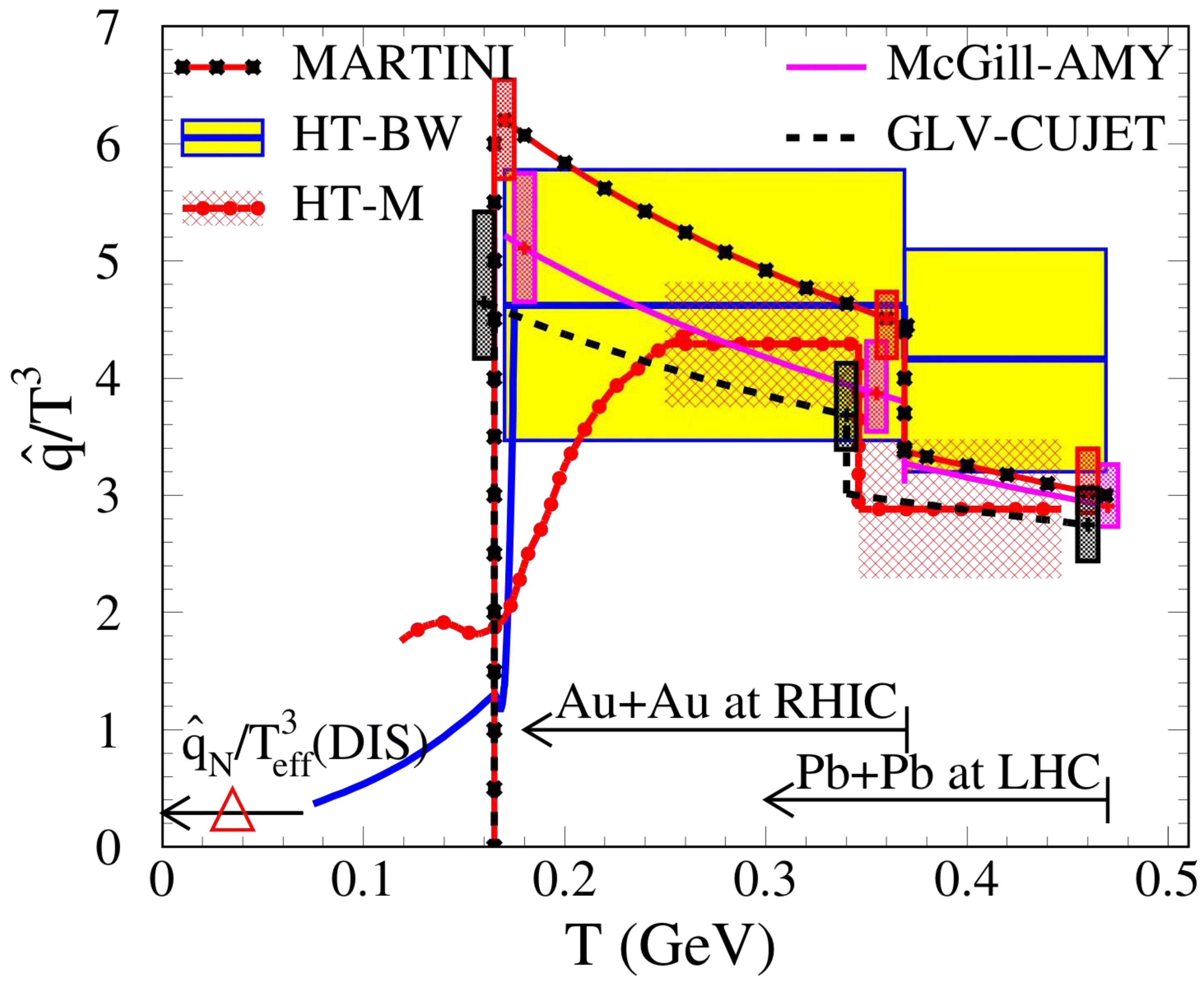


$\sqrt{s} = 5.02$ TeV
R=0.2
R=0.3
R=0.4
R=0.6
R=0.8
R=1.0
Pb+Pb 0-10 %
anti-k_t $|\eta| < 2$
LBT $\alpha_s = 0.13$
LBT $\alpha_s = 0.15$
CMS
ATLAS
R_{AA}
0.0
0.5
1.0
500
1000
p_T (GeV)

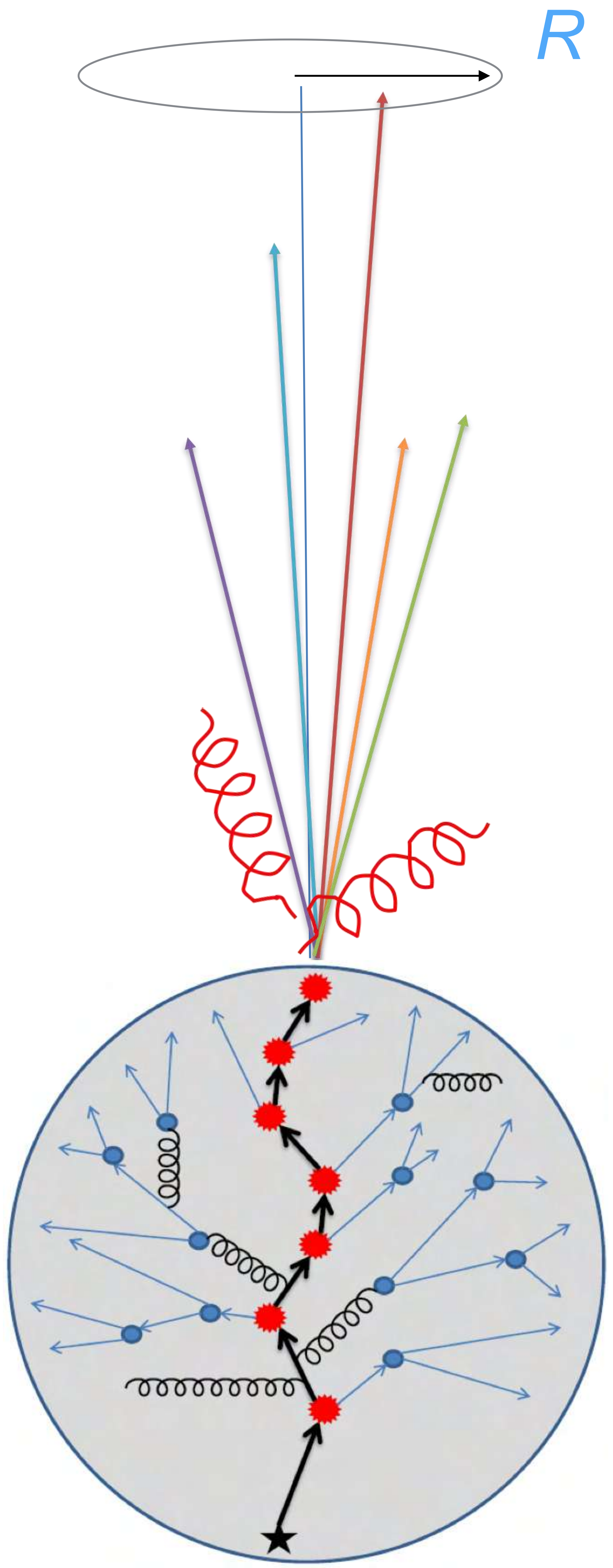

anti-k_t R = 0.4 jets
|y| < 2.1
$\sqrt{s_{NN}}$ = 2.76 TeV
LBT sim.
E-by-E hydro
smooth hydro
w/o recoil & w/o neg.
w. recoil & w/o neg.
w. recoil & w. neg.
anti-k_t R = 0.4 jets
|y| < 2.1
$\sqrt{s_{NN}}$ = 5.02 TeV
LBT sim.
E-by-E hydro
smooth hydro
w/o recoil & w/o neg.
w. recoil & w/o neg.
w. recoil & w. neg.
Δ p_T (GeV)
0
10
20
30
40
50
60
50
100
150
200
250
300
350
400
p_T (GeV)

jet-medium transport coefficient

$$\hat{q} = \frac{< \Delta p_T^2 >}{\lambda}$$



Jet reconstruction including medium recoils and back reaction



$$\sqrt{(\eta-\eta_J)^2+(\phi-\phi_J)^2}<R$$

M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C 72, 1896 (2012).

consider all the jets

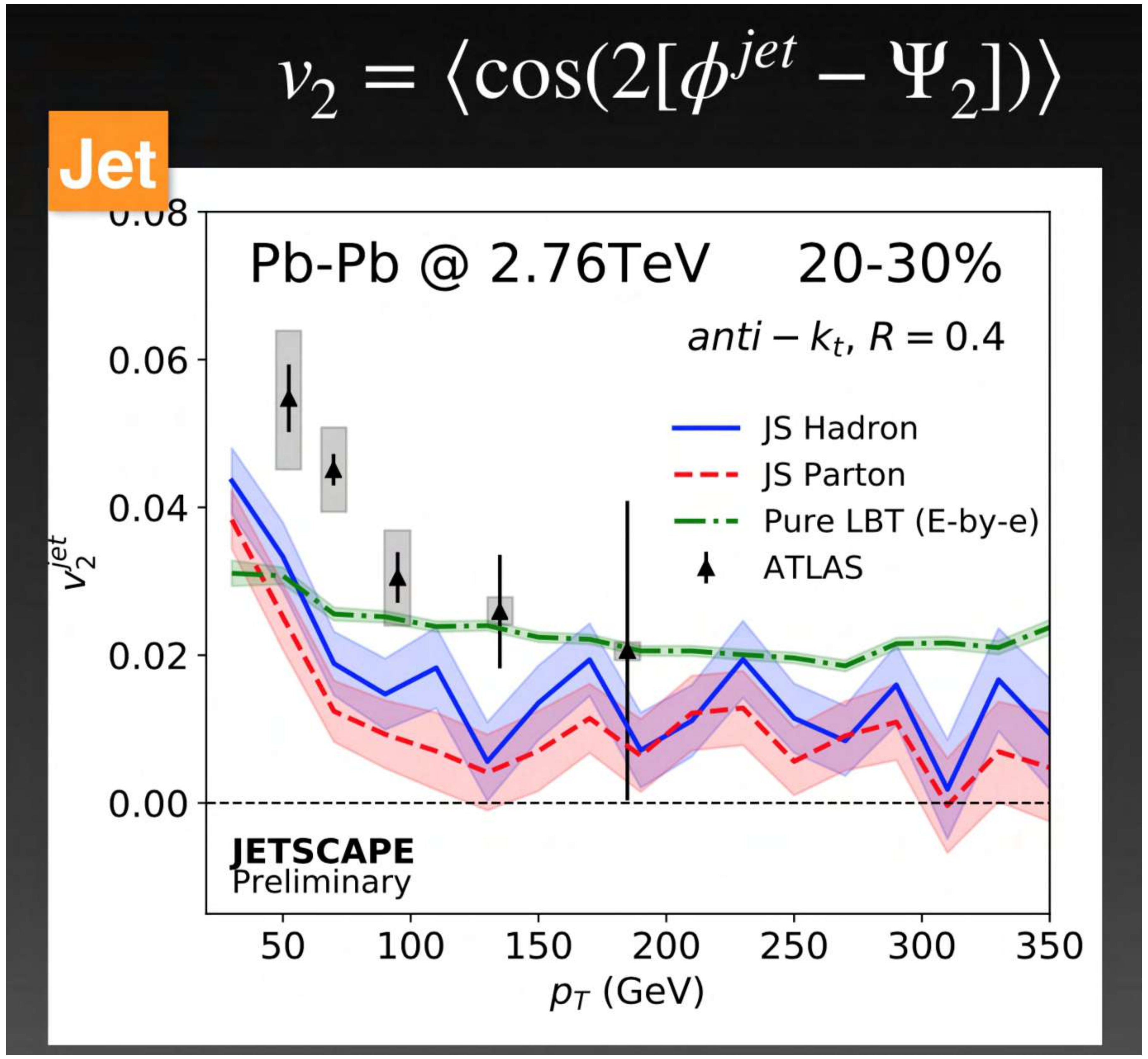
modified FASTJET,

subtract the "negative" particles

medium recoil re-scattering,

back reaction ("negative particles")

Inclusive jet anisotropy



Multistage evolution, see：Chanwook Park, HP 2018

Main Course: jet energy loss distributions

Yayun He, Long-Gang Pang, Xin-Nian Wang. Phys. Rev. Lett. 122 (2019) 252302, arXiv:1808.05310

$$\frac{d\sigma^{\rm jet}_{AA}}{dp_T dy}(p_T, R) \approx N_{\rm bin}(b)\int d\Delta p_T \, \frac{d\sigma^{\rm jet}_{pp}}{dp_T dy}(p_T+\Delta p_T, R)\, W_{AA}(\Delta p_T, p_T+\Delta p_T, R)$$

MC transport models:

$$\left.\begin{matrix}\sigma^{\rm jet}_{pp}(p_T) \\ W_{AA}(p_T, \Delta p_T)\end{matrix}\right\} \Longrightarrow \sigma^{\rm jet}_{AA}(p_T)$$

Bayesian analysis:

$$\left.\begin{matrix}\sigma^{\rm jet}_{pp}(p_T) \\ \sigma^{\rm jet}_{AA}(p_T)\end{matrix}\right\} \Longrightarrow W_{AA}(p_T, \Delta p_T)$$

Data-driven & model-independent

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}, Y: data, X: W_{AA}$$

Parametrization:

$$W_{AA}(x) = \frac{\alpha^\alpha x^{\alpha-1} e^{-\alpha x}}{\Gamma(\alpha)}$$

$$x = \frac{\Delta p_T}{\langle \Delta p_T \rangle}$$

$$\langle \Delta p_T \rangle = \beta (p_T/p_{T,0})^\gamma \log(p_T/p_{T,0})$$

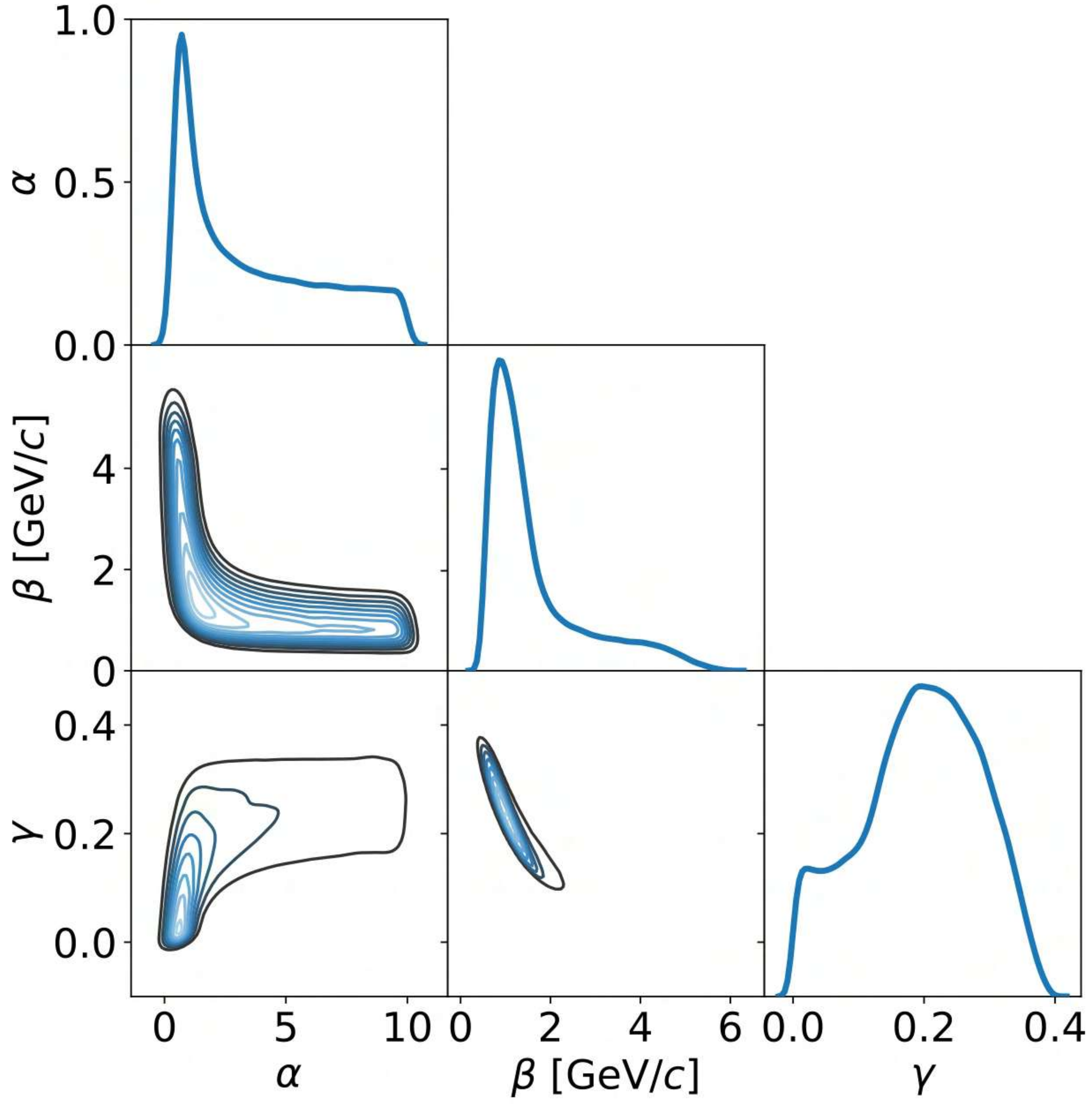
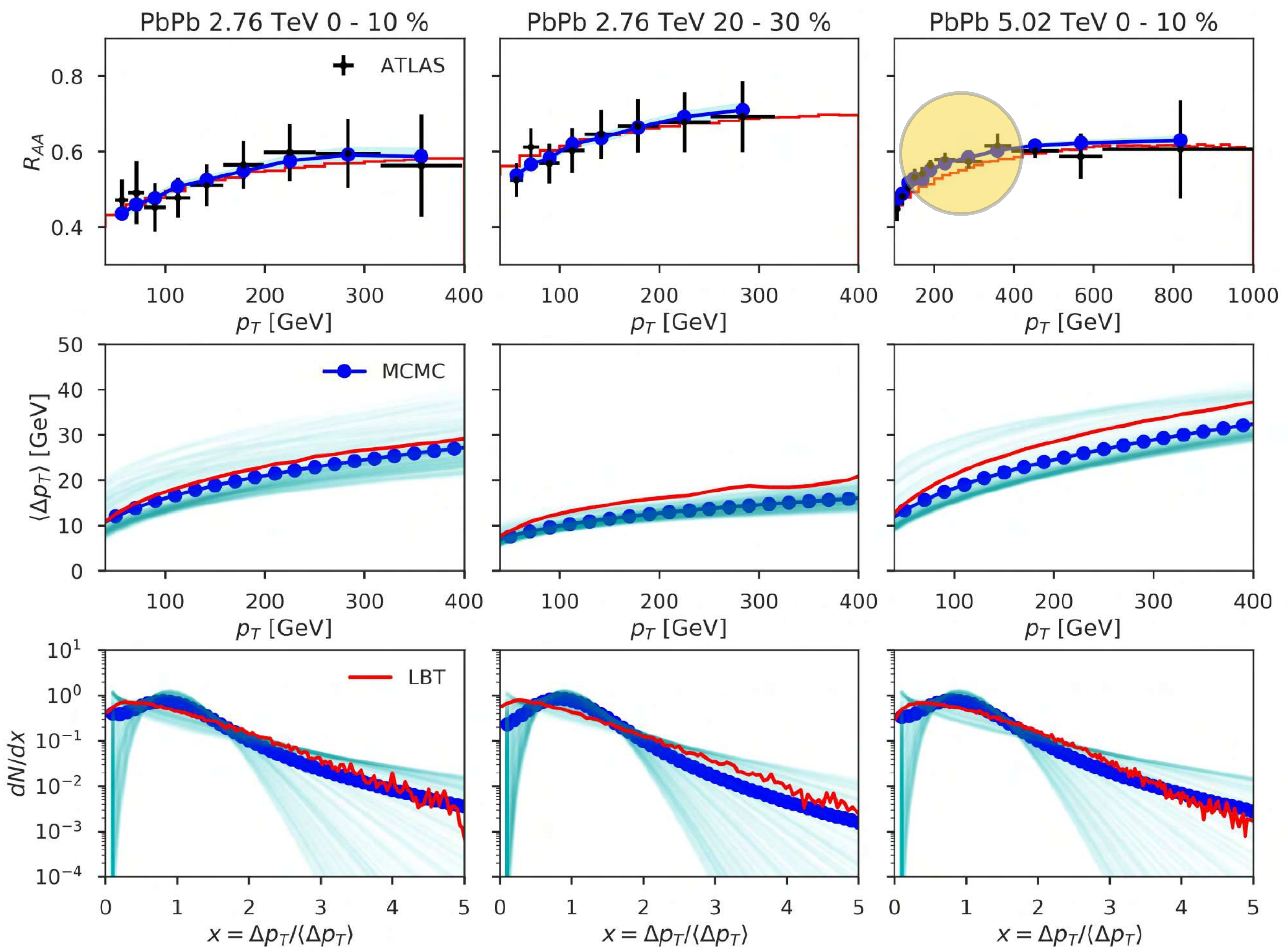


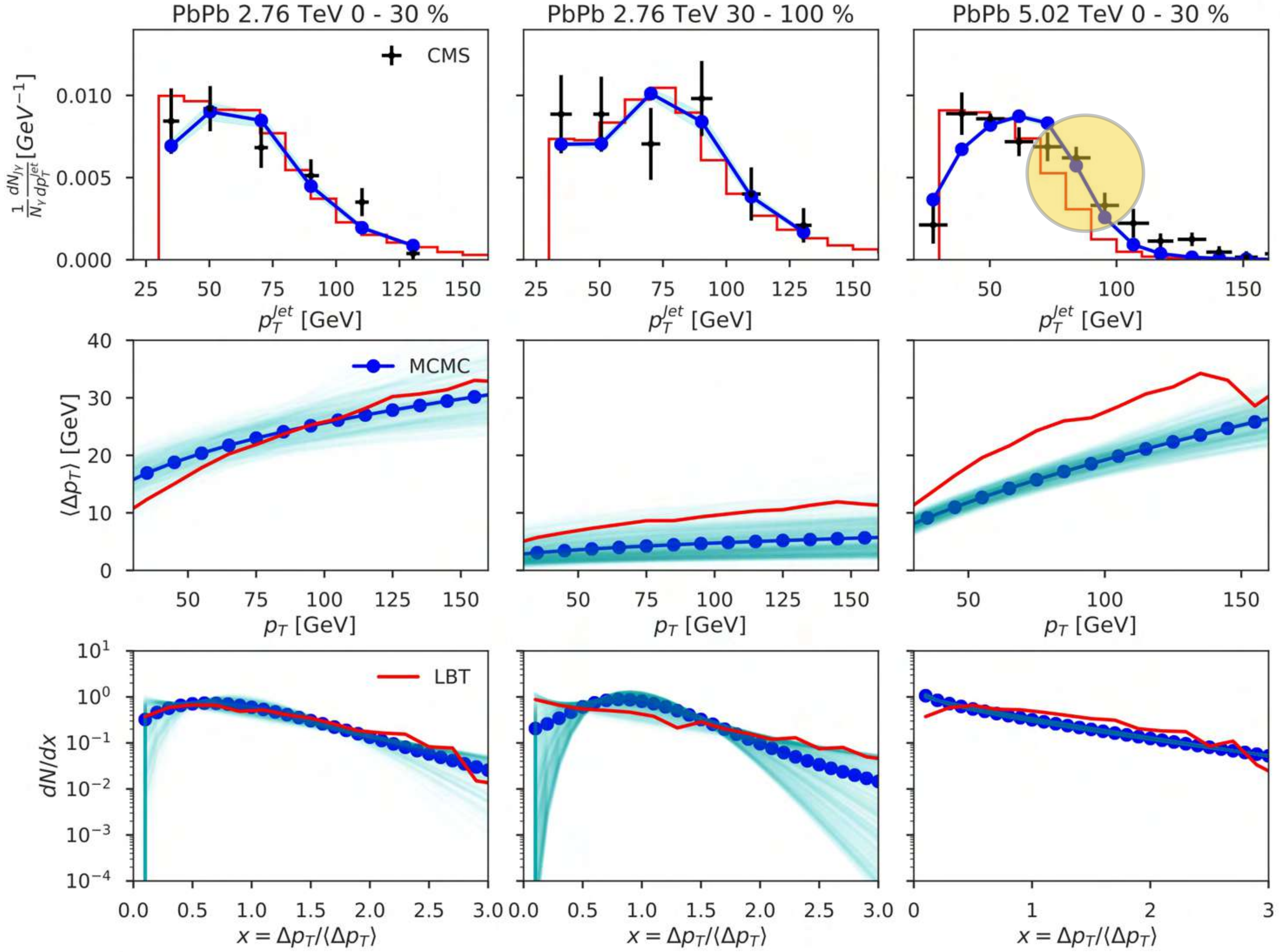
Fig: correlations of extracted parameters with 8 millions Monte Carlo Markov Chain samplings

Main Course: jet energy loss distributions

	single inclusive jet in Pb+Pb		
	(0-10%)2.76 TeV	(20-30%)2.76 TeV	(0-10%)5.02 TeV
α	3.87 ± 2.93 (1.45 ± 0.01)	4.47 ± 2.83 (1.33 ± 0.02)	4.41 ± 2.86 (1.58 ± 0.02)
β	1.40 ± 1.12 (1.39 ± 0.06)	1.12 ± 0.47 (1.08 ± 0.07)	1.06 ± 0.97 (1.56 ± 0.06)
γ	0.21 ± 0.09 (0.21 ± 0.01)	0.15 ± 0.07 (0.20 ± 0.01)	0.26 ± 0.06 (0.23 ± 0.01)

	γ-triggered jet in Pb+Pb		
	(0-30%)2.76 TeV	(30-100%)2.76 TeV	(0-30%)5.02 TeV
α	2.13 ± 1.28 (1.95 ± 0.12)	3.75 ± 2.81 (1.04 ± 0.06)	0.90 ± 0.09 (1.84 ± 0.13)
β	2.68 ± 1.40 (0.72 ± 0.06)	0.55 ± 0.44 (0.53 ± 0.04)	1.50 ± 0.85 (0.50 ± 0.04)
γ	0.16 ± 0.14 (0.44 ± 0.02)	0.13 ± 0.18 (0.30 ± 0.02)	0.21 ± 0.12 (0.56 ± 0.02)





Main Course: jet-induced diffusion wake