Hard-soft tomography with event engineering in heavy-ion collisions

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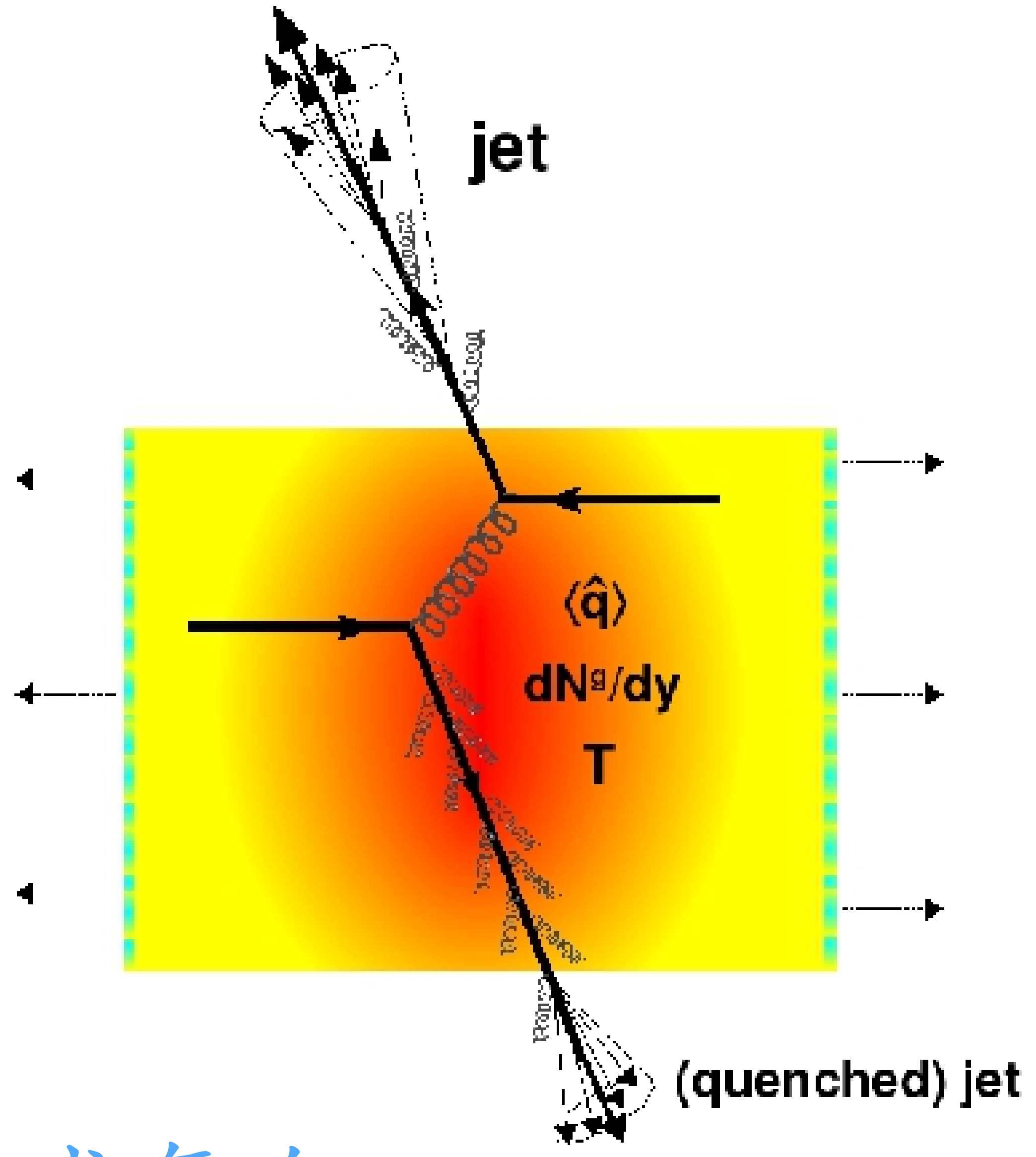
arxiv: 2201, 08408



中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Aug. 10, 2022

Motivation

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

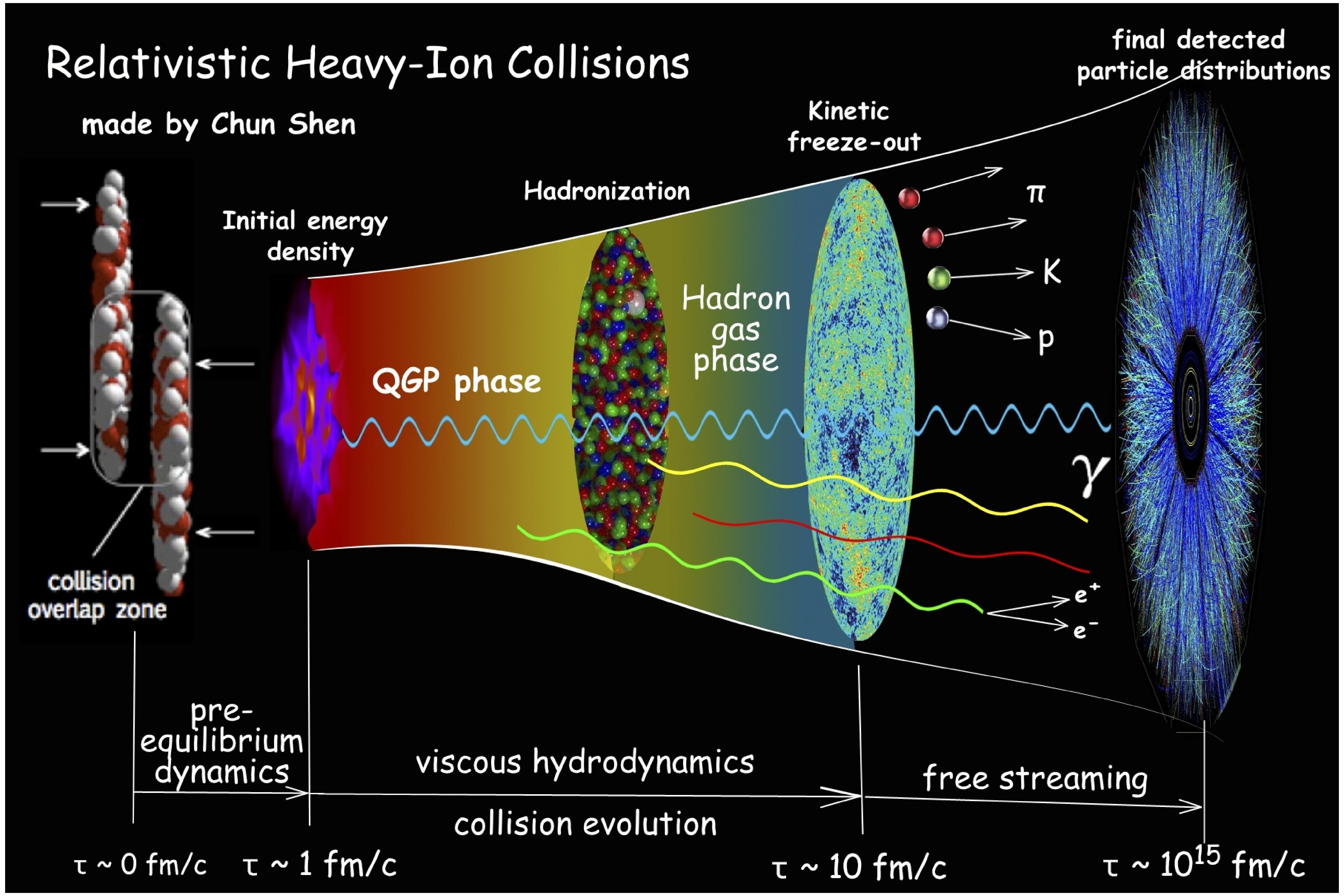


Fig: A schematic diagram of relativistic heavy-ion collisions.

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

Jet : a collimated spray of high p_T particles

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

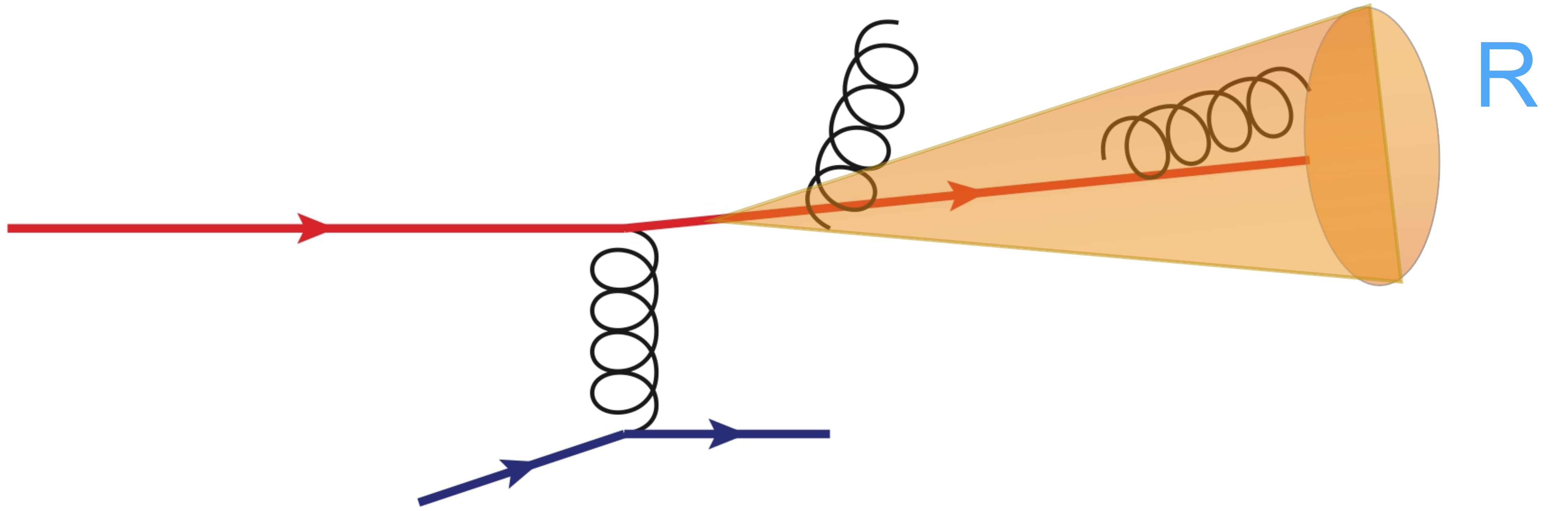


Fig: An illustration of a jet.

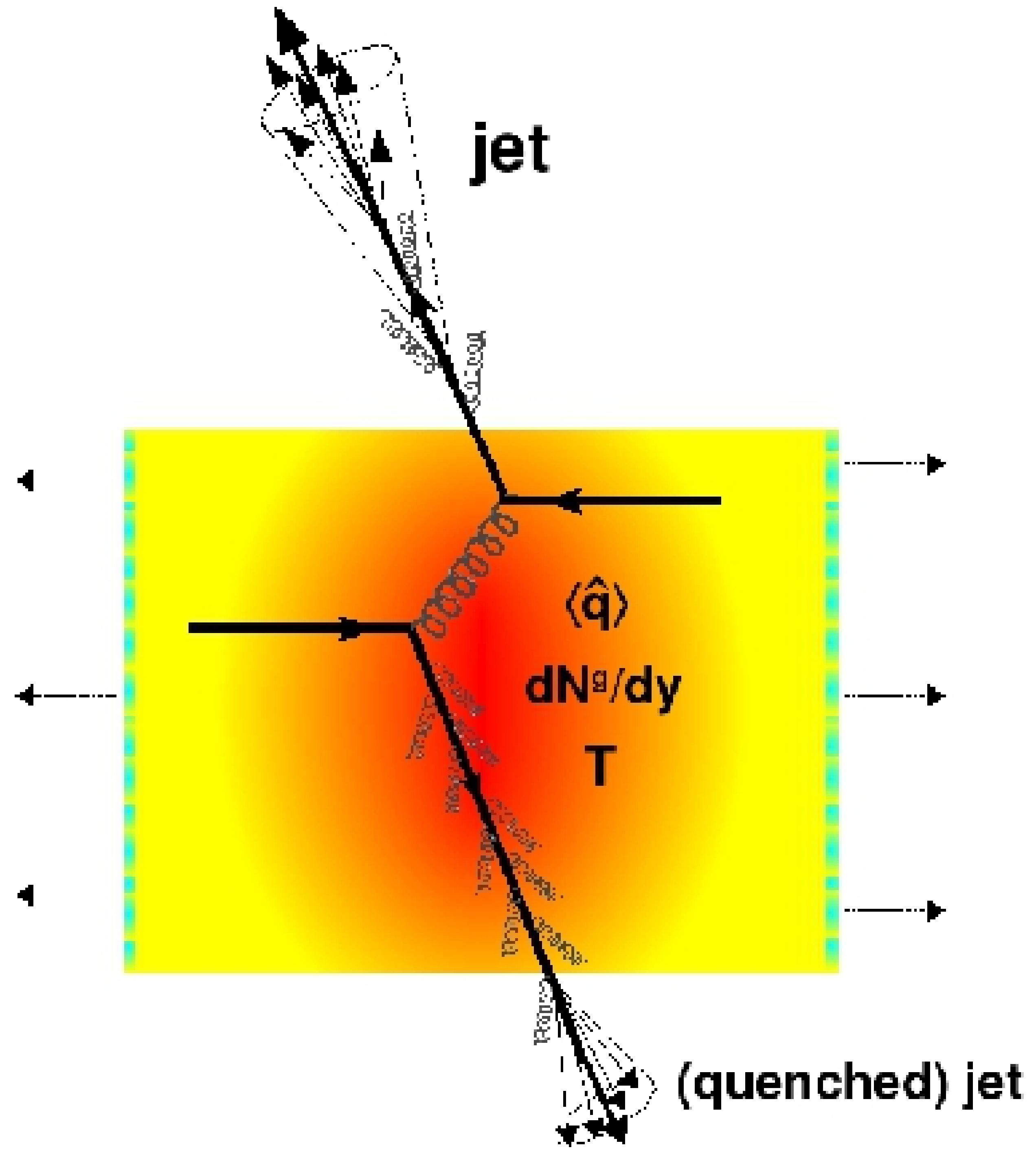


Fig: An illustration of jet quenching.

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

Motivation

Jet quenching observables:

➡ The inclusive jet nuclear modification factor

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

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

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

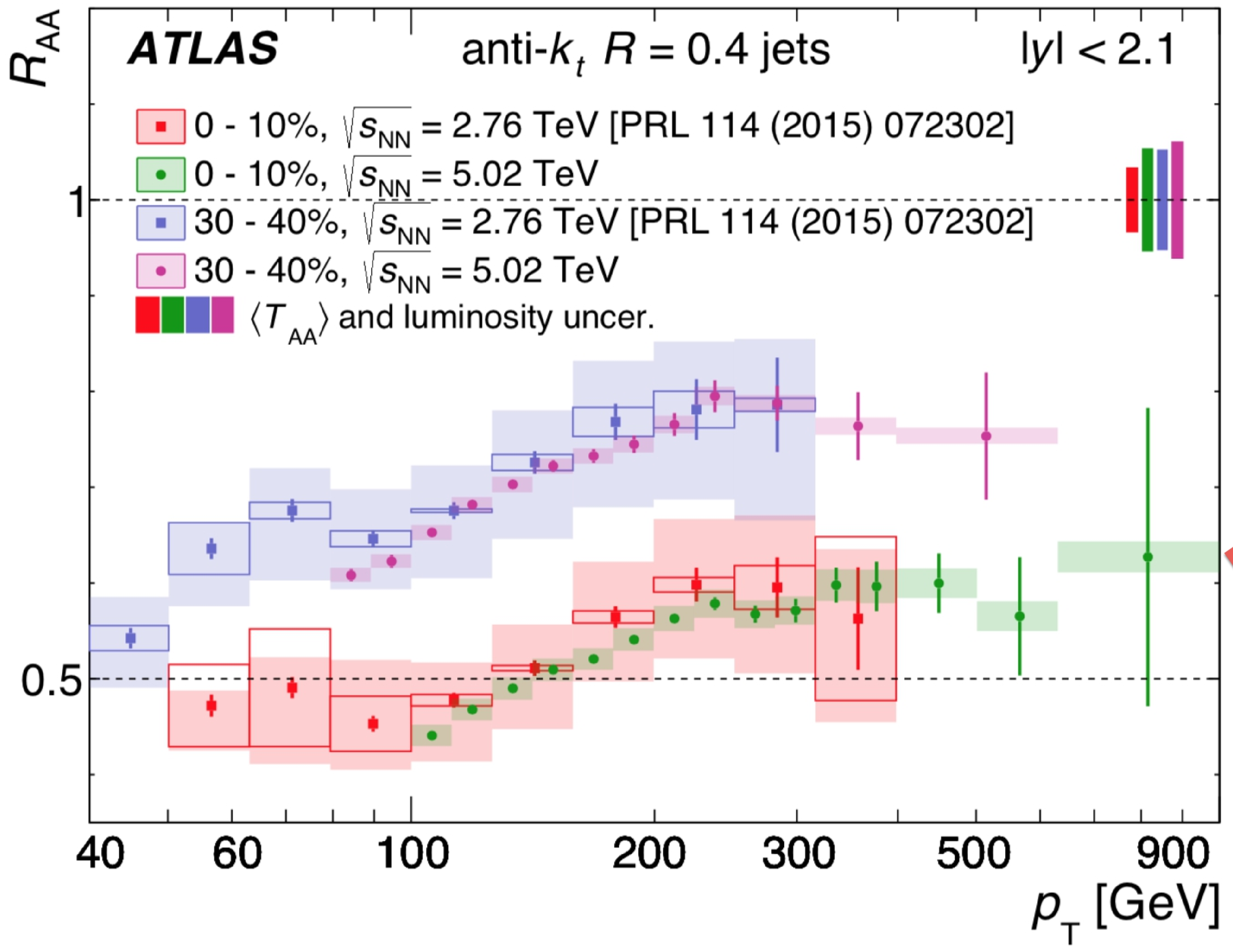
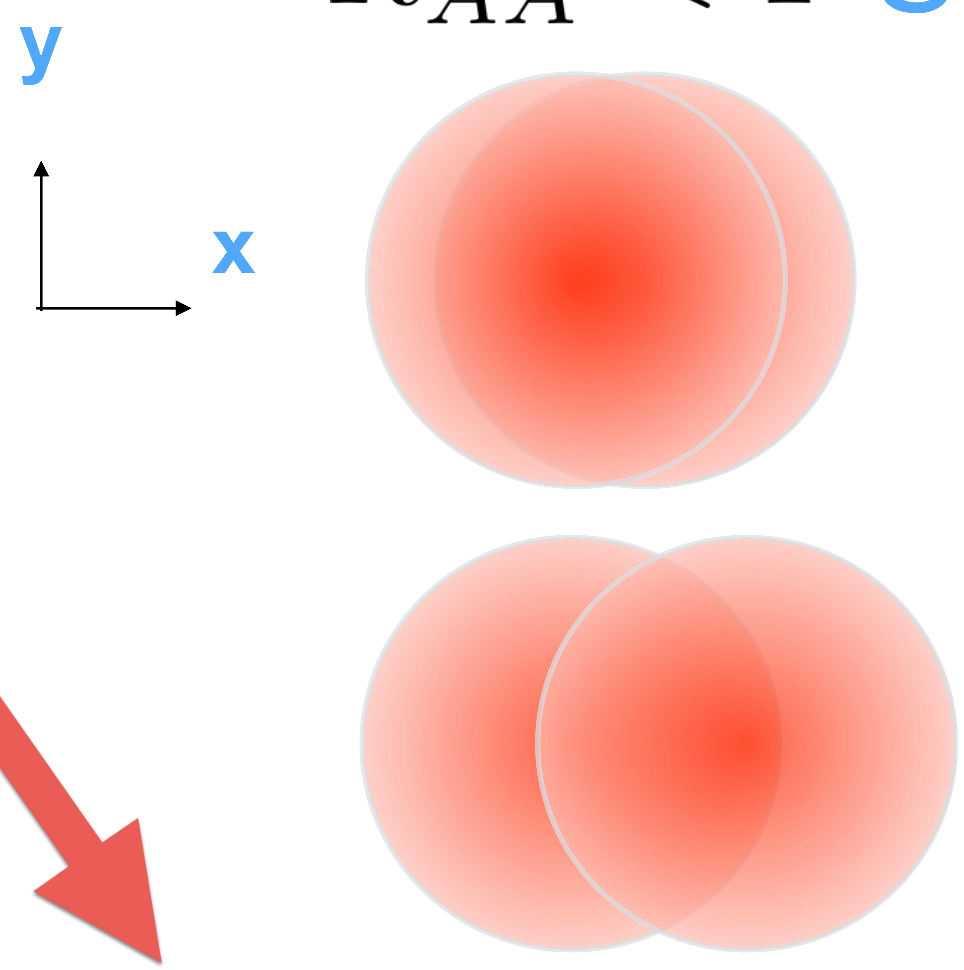


Fig: Inclusive jet nuclear modification factor

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



0-10% central collision

30-40% semi-central collision

A smaller R_{AA} implies a stronger suppression.

Jet quenching effect !

Motivation

Jet quenching observables:

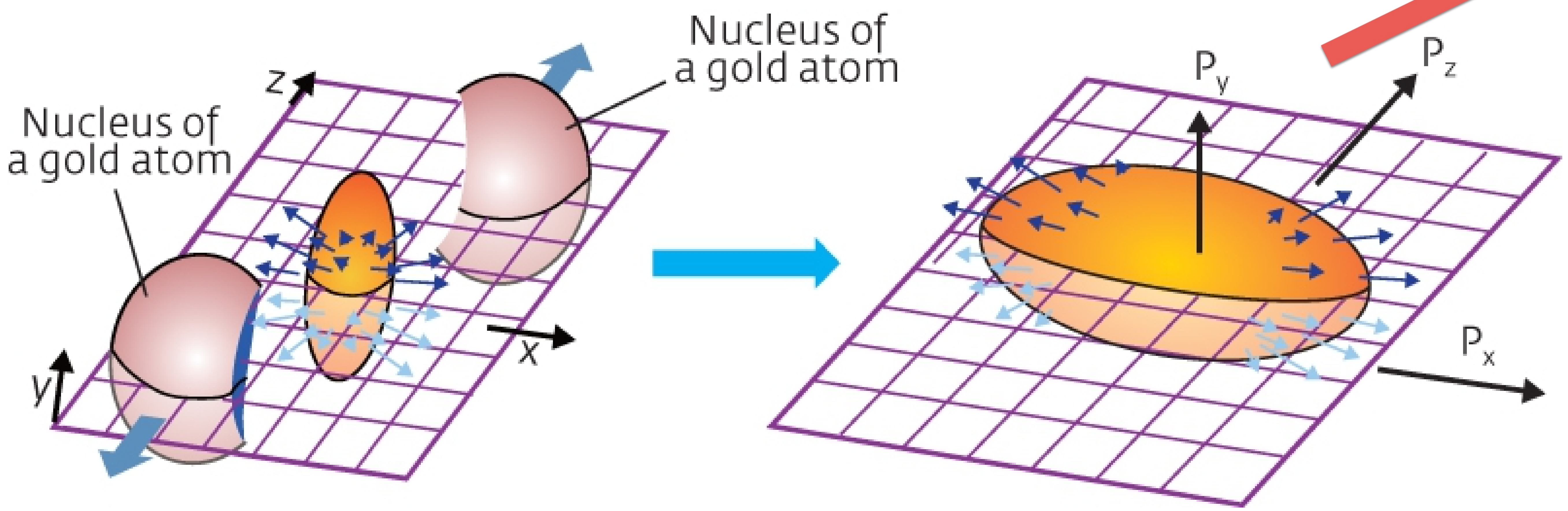
➡ The inclusive jet nuclear modification factor

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

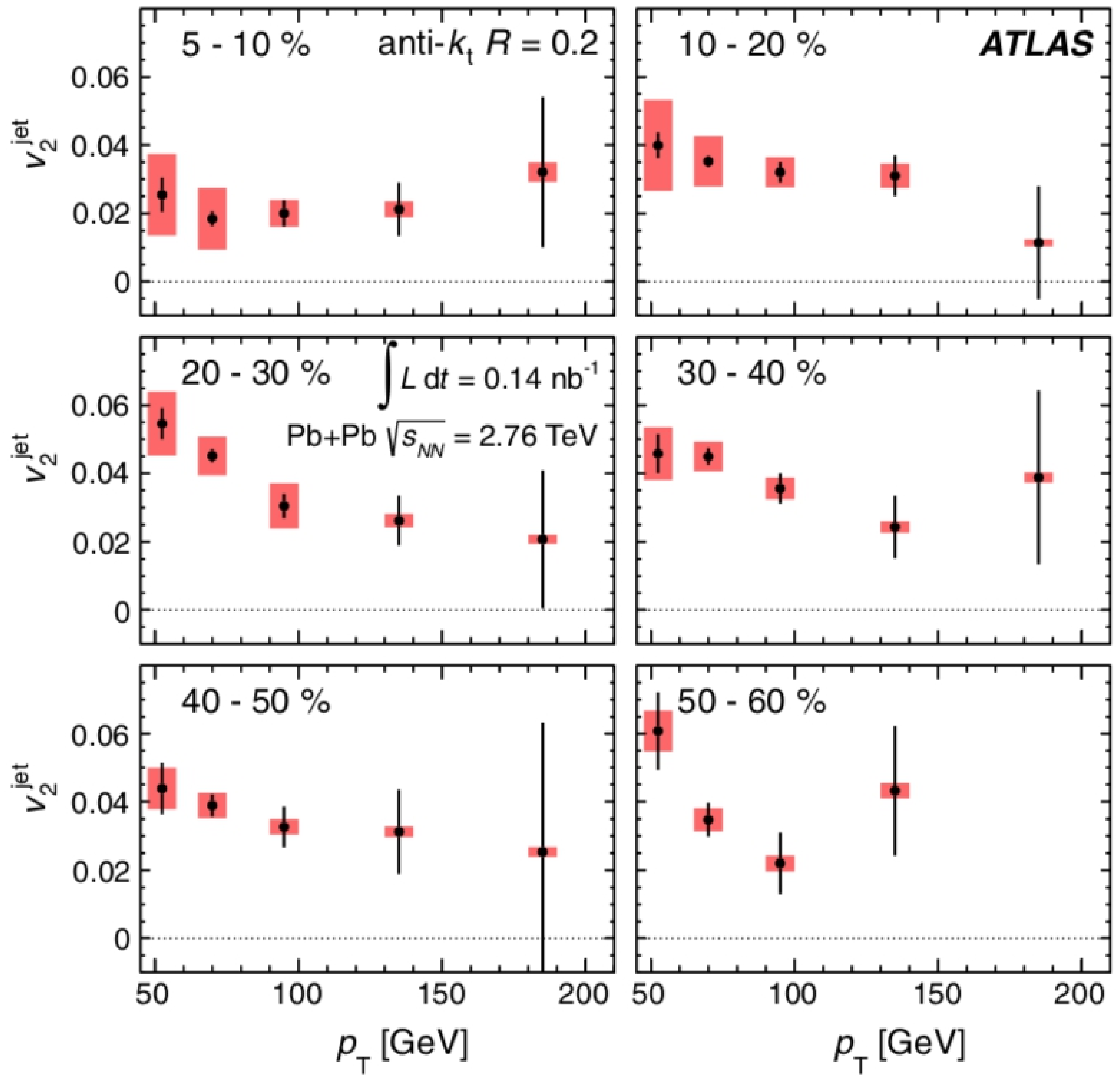
- ➢ n=1, direct flow
- ➢ n=2, elliptic flow
- ➢ n=3, triangle flow

path-length dependence

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



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



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

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

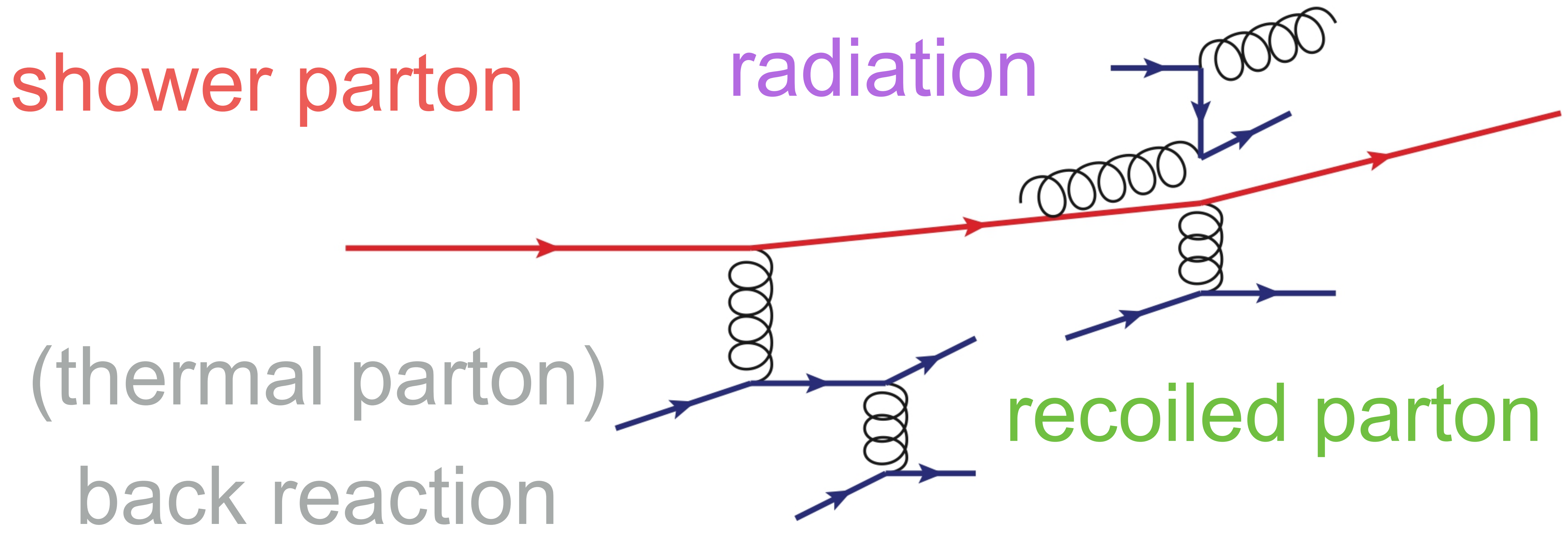
LO perturbative QCD

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).

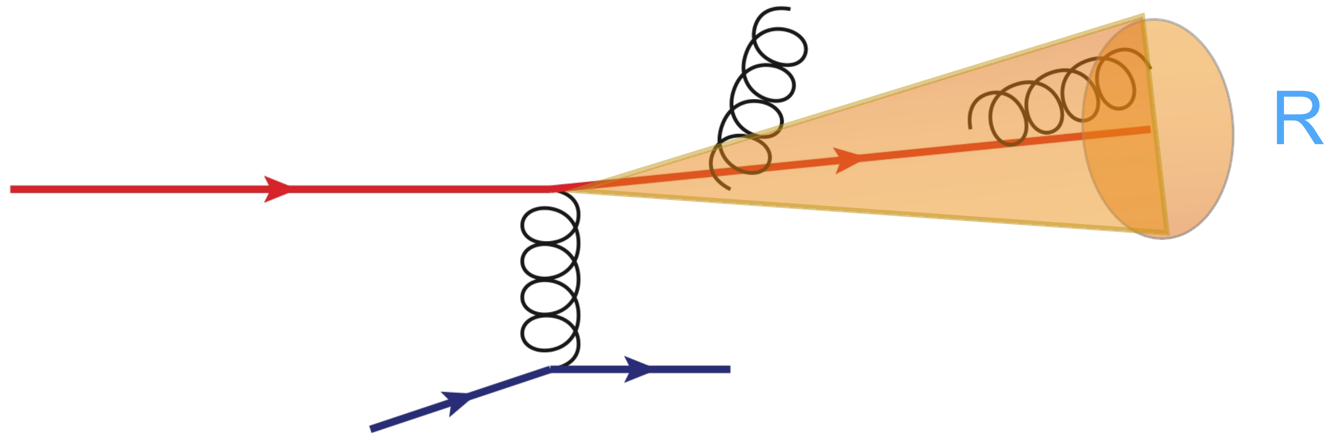
e-by-e 3+1D CLVisc:

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

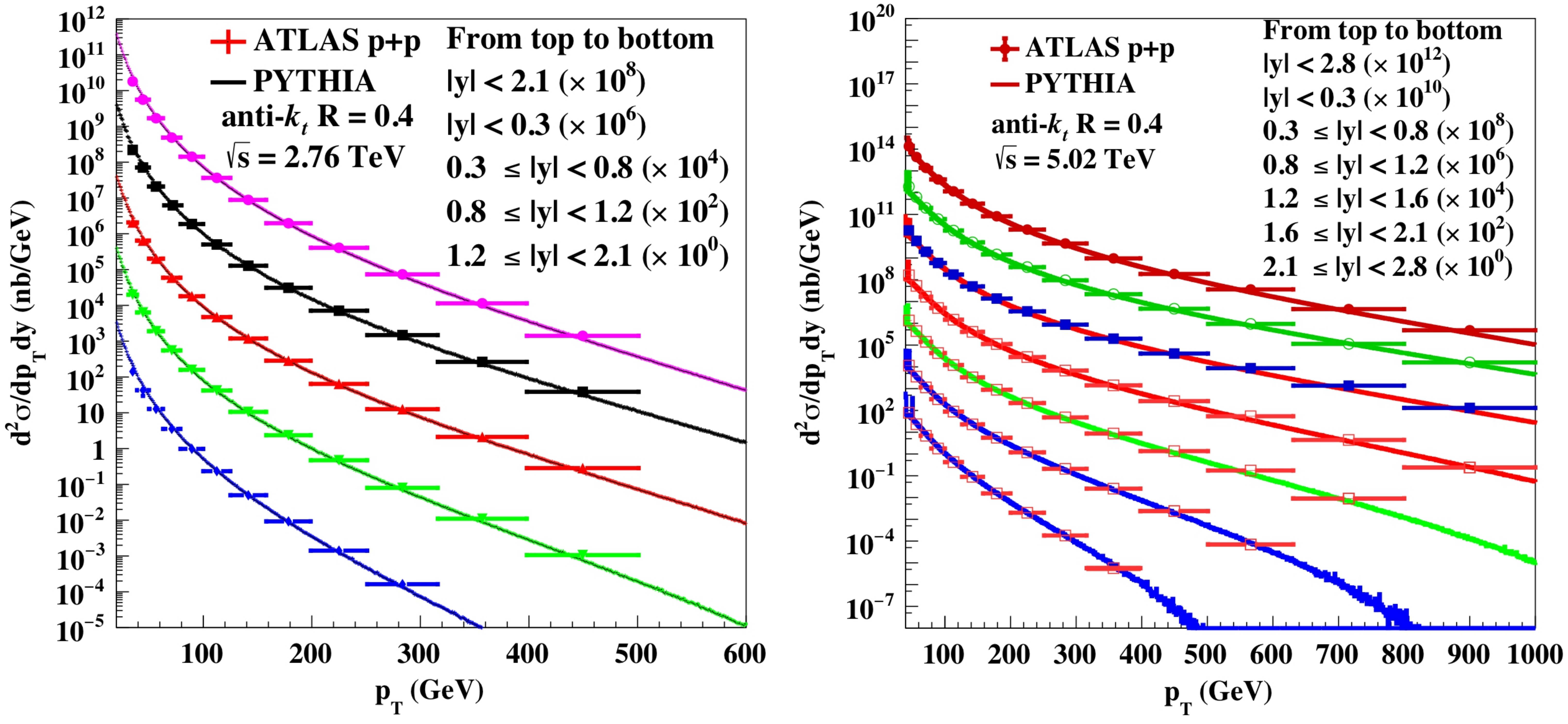


freeze-out temperature: $T_f = 137\ \mathrm{MeV}$

Final inclusive jet

The inclusive jet in pp collisions

p_T distribution of pp collision within PYTHIA 8

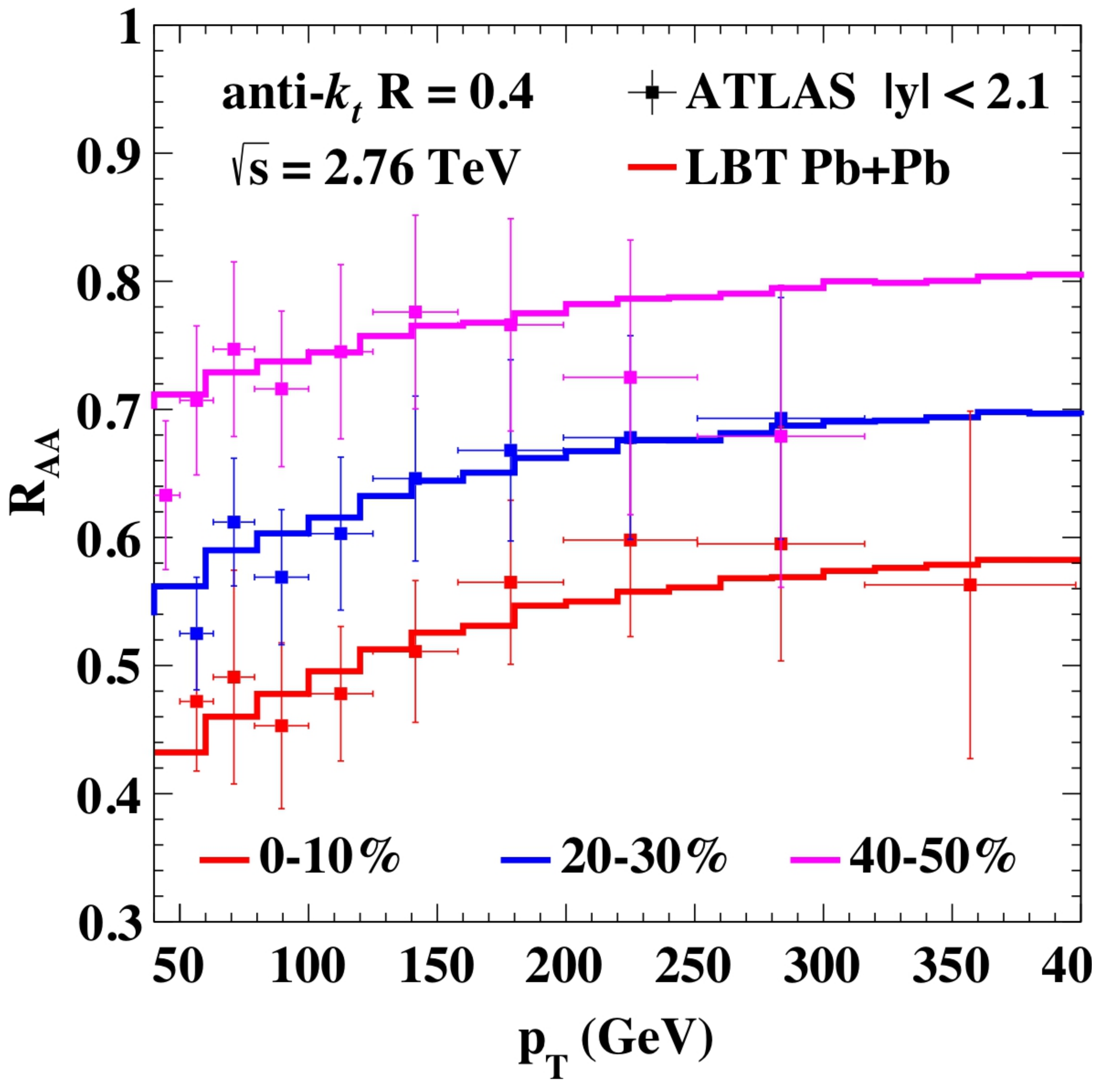


PYTHIA 8 can well describe the experimental data at LHC energies for different rapidity ranges.

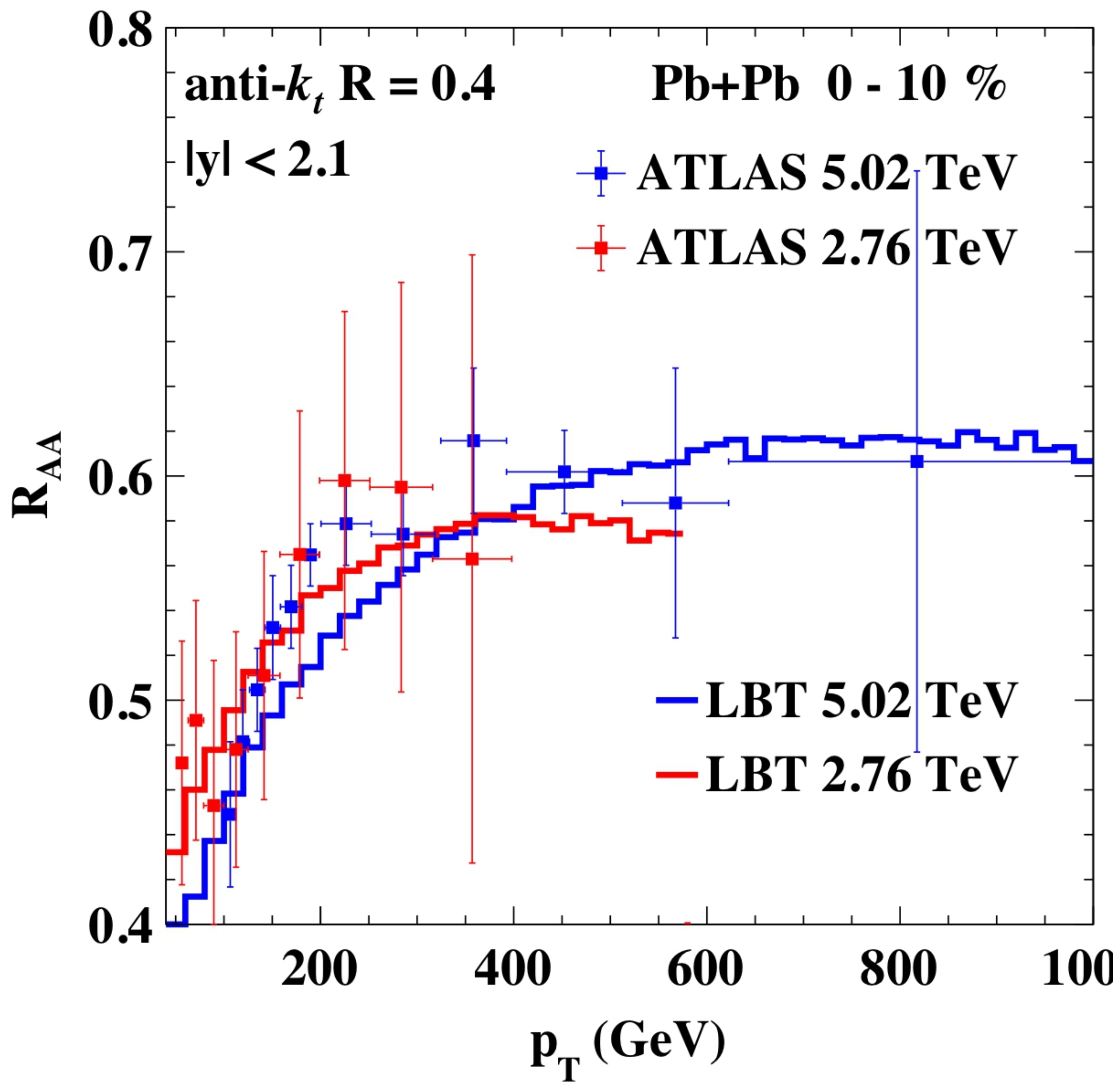
The inclusive jet R_{AA}

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

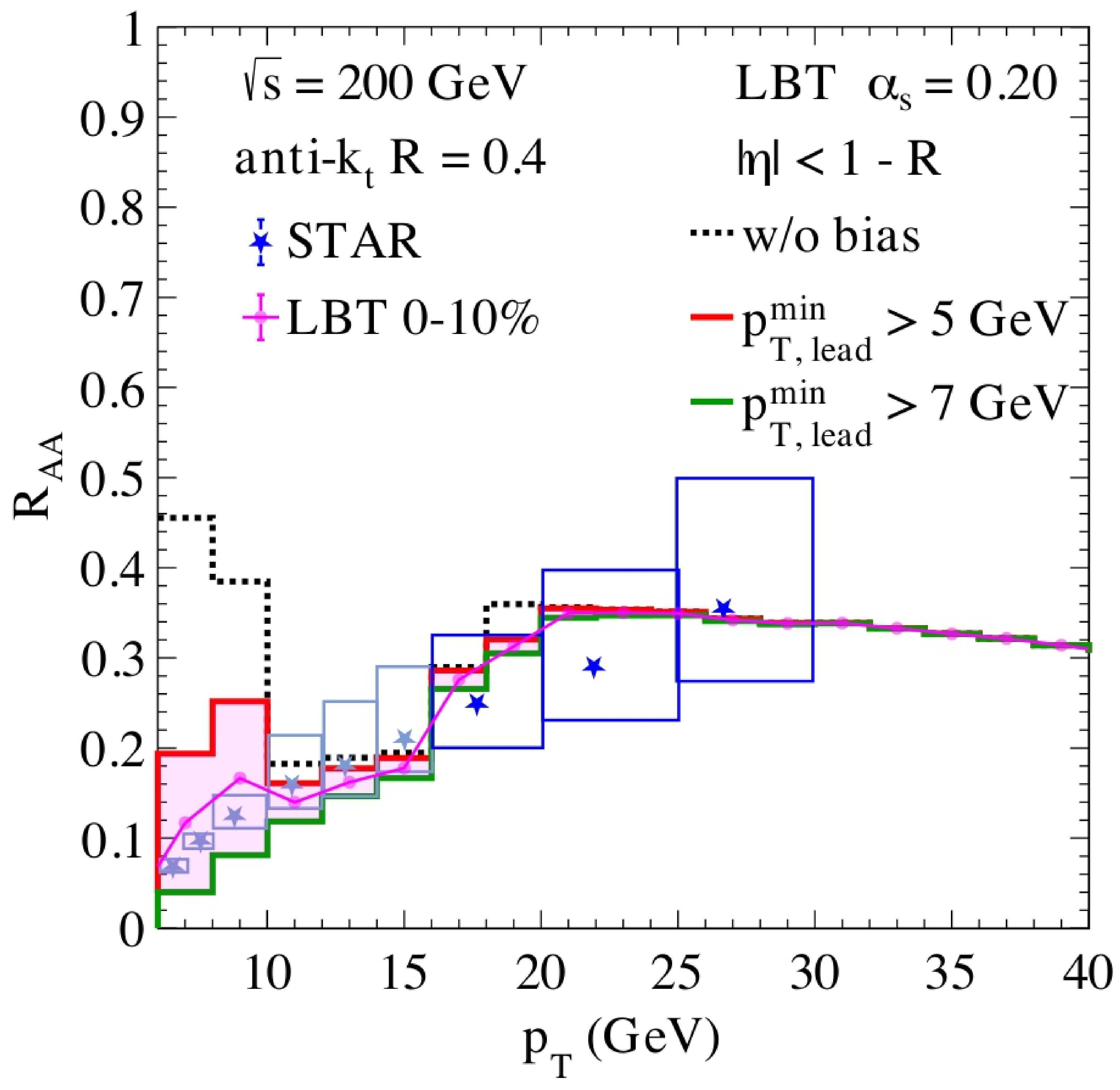
Pb+Pb 2.76 TeV



Pb+Pb 5.02 TeV



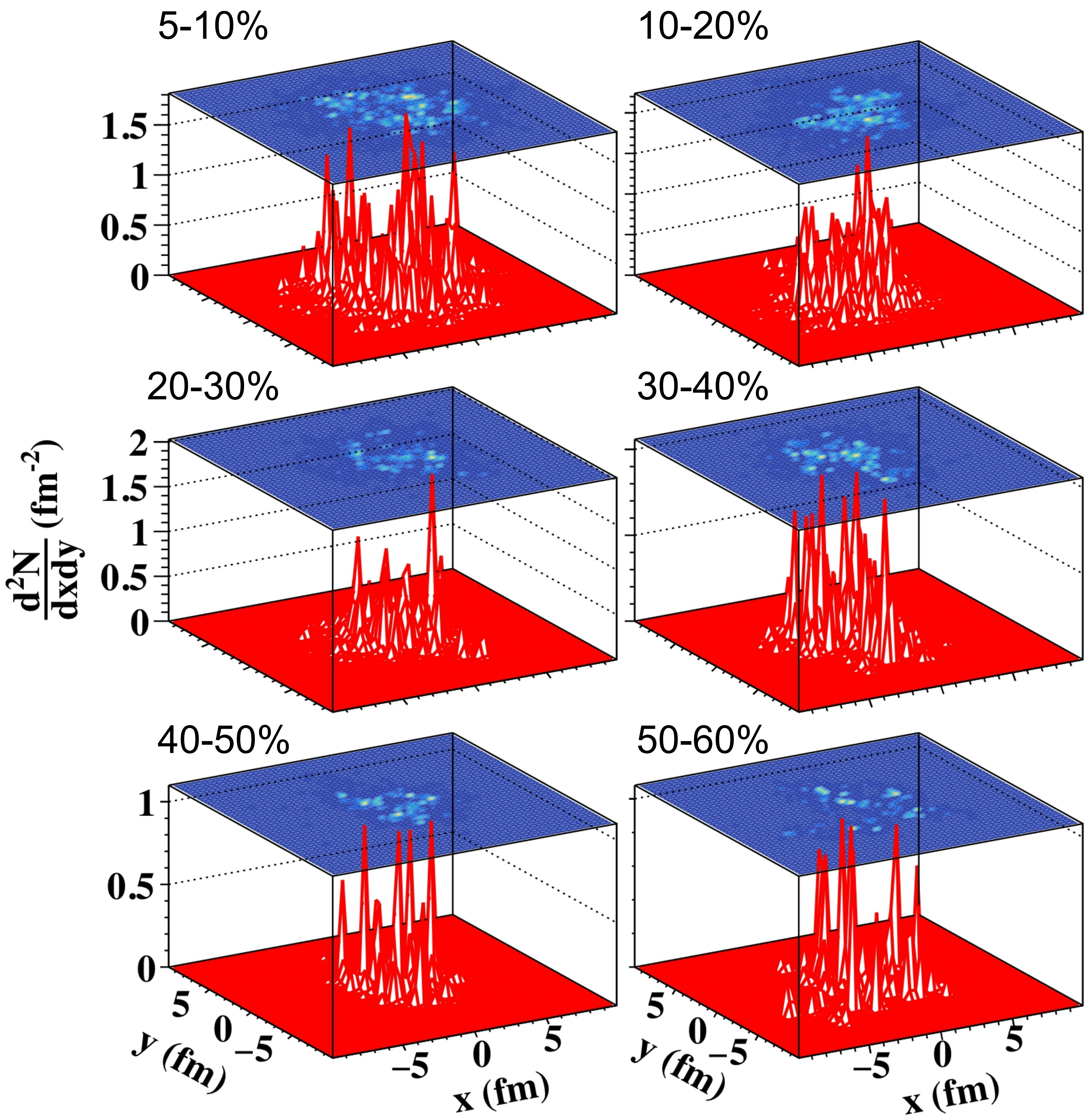
Au+Au 200 GeV



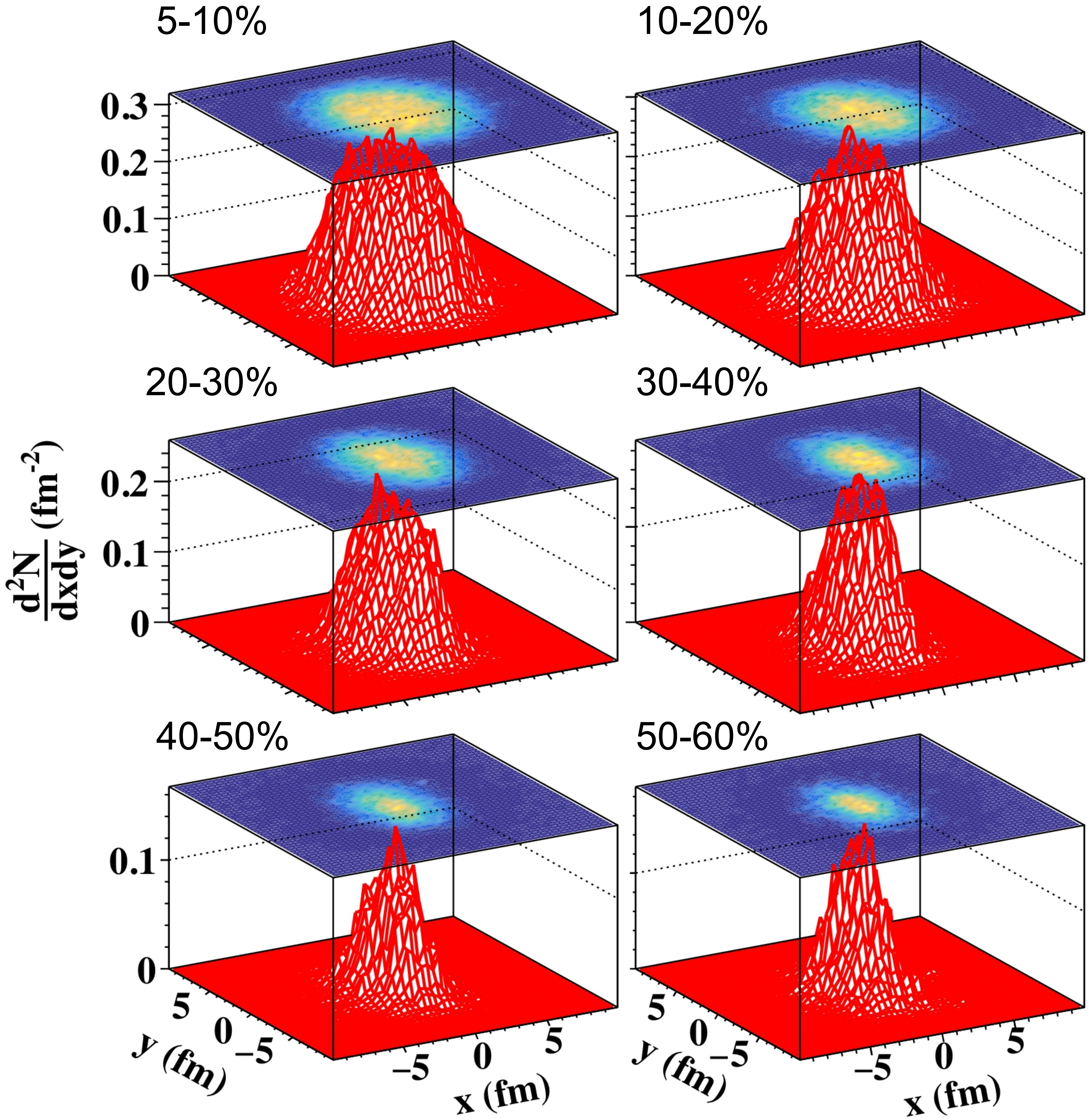
Jet R_{AA} has a weak p_T dependence in the high p_T range

The inclusive jet anisotropy v_n

Initial jet producation at 2.76 TeV



single hydro event: fluctuating

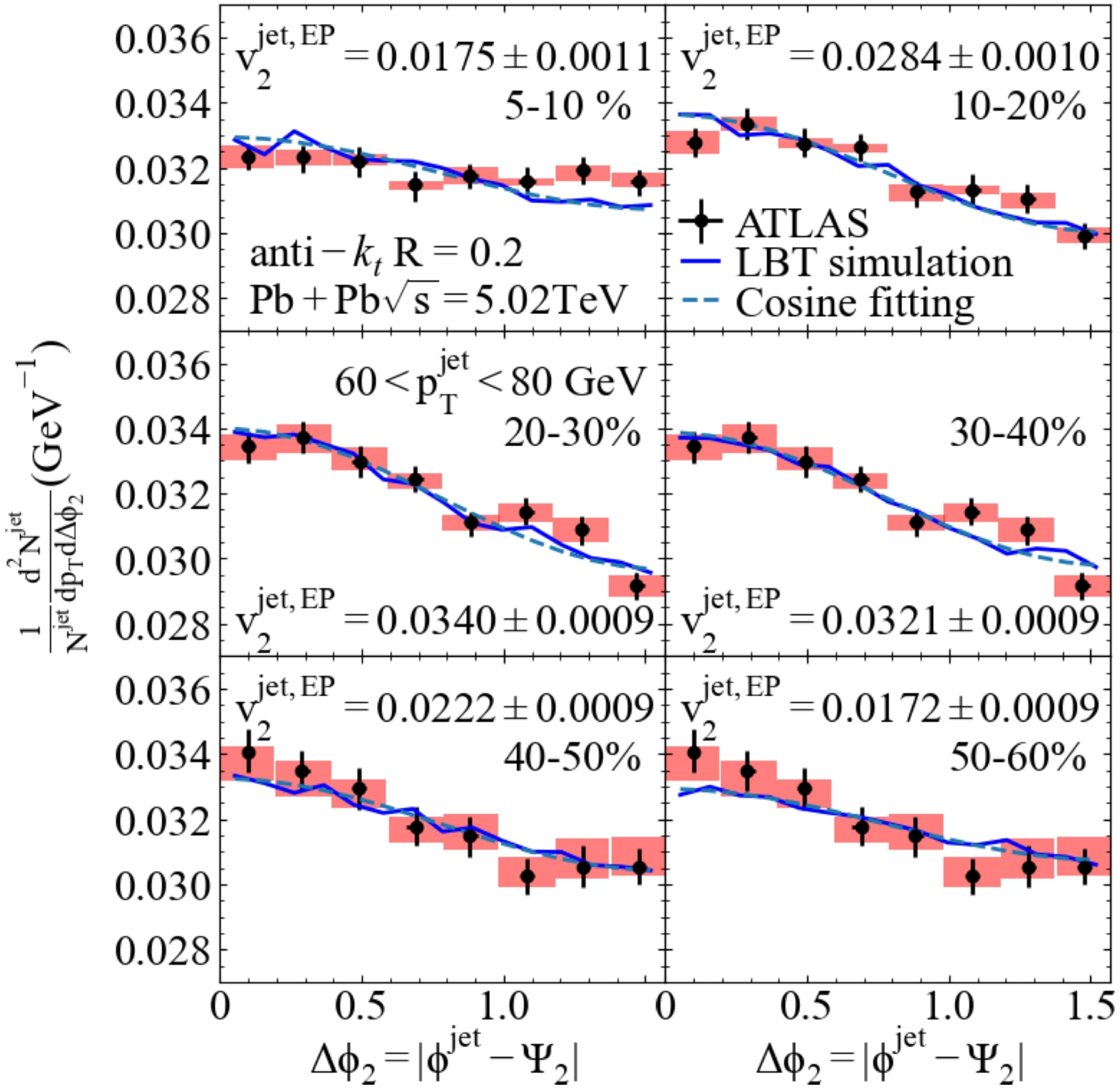


averaged over 200 hydro events: smooth

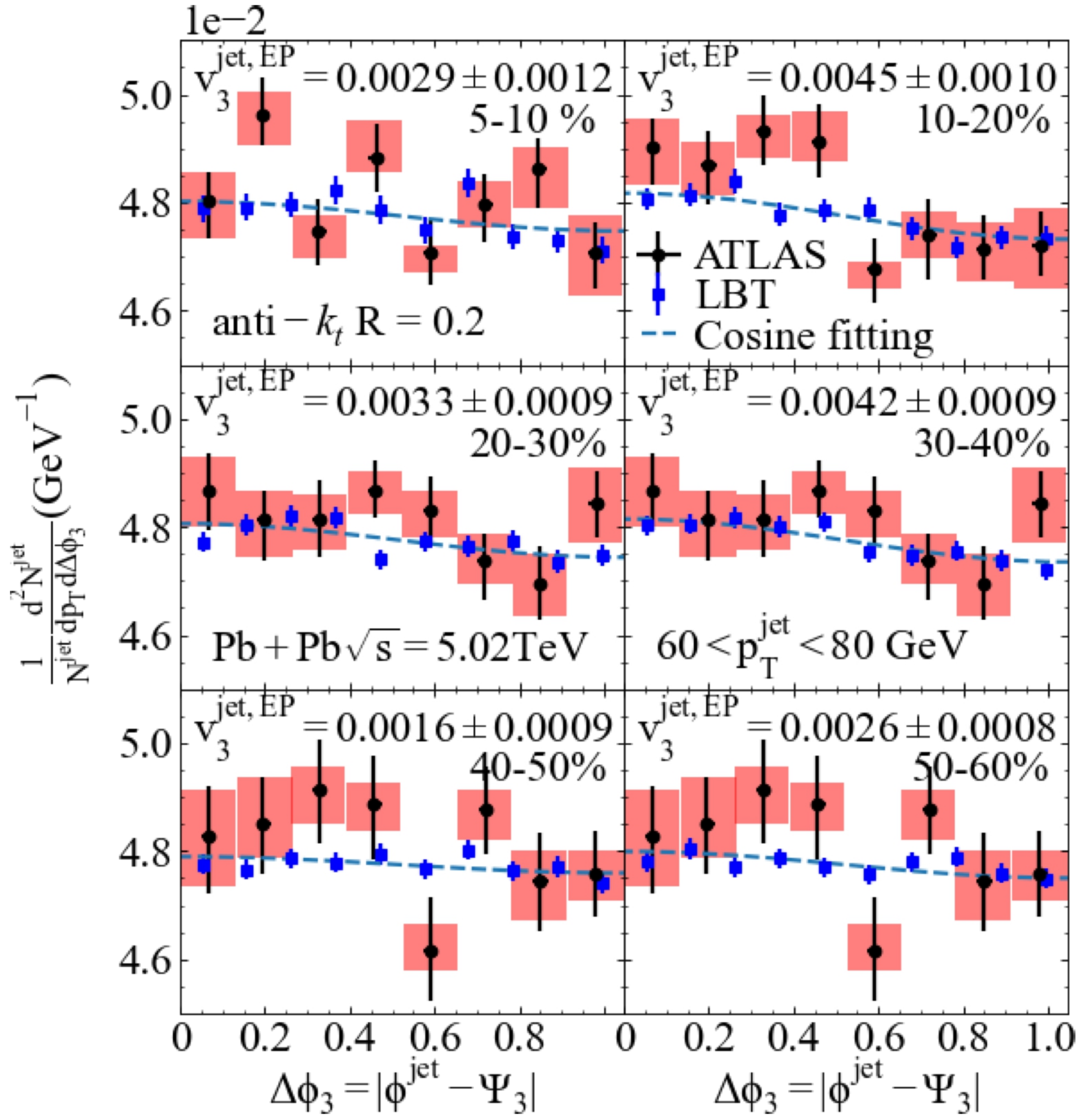
Jet azimuthal anisotropy

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

jet v_2 at 5.02 TeV



jet v_3 at 5.02 TeV

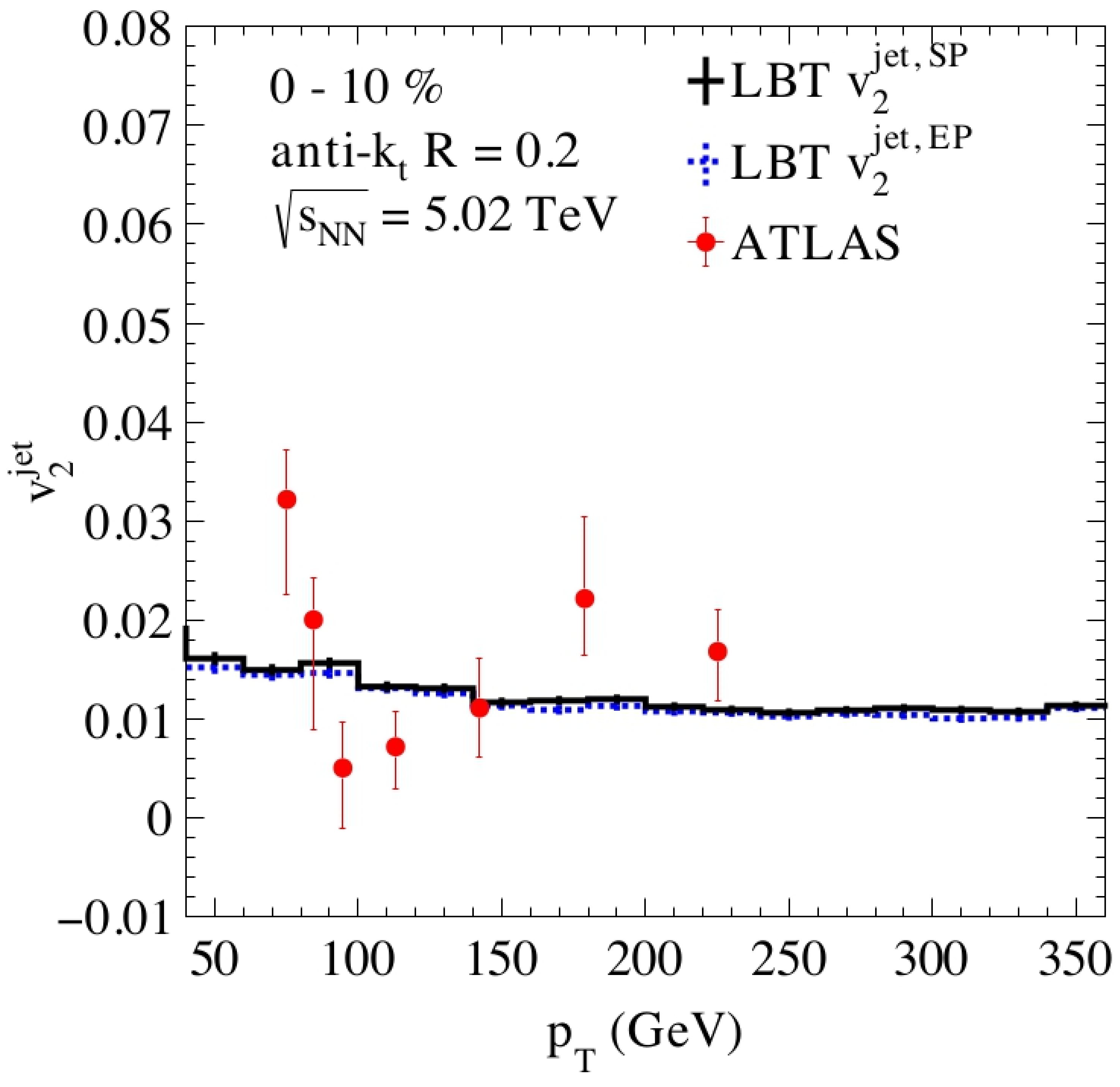


Azimuthal angle distributions clearly show the existence of jet v_2 and v_3.

p_T dependence of inclusive jet v_2 and v_3

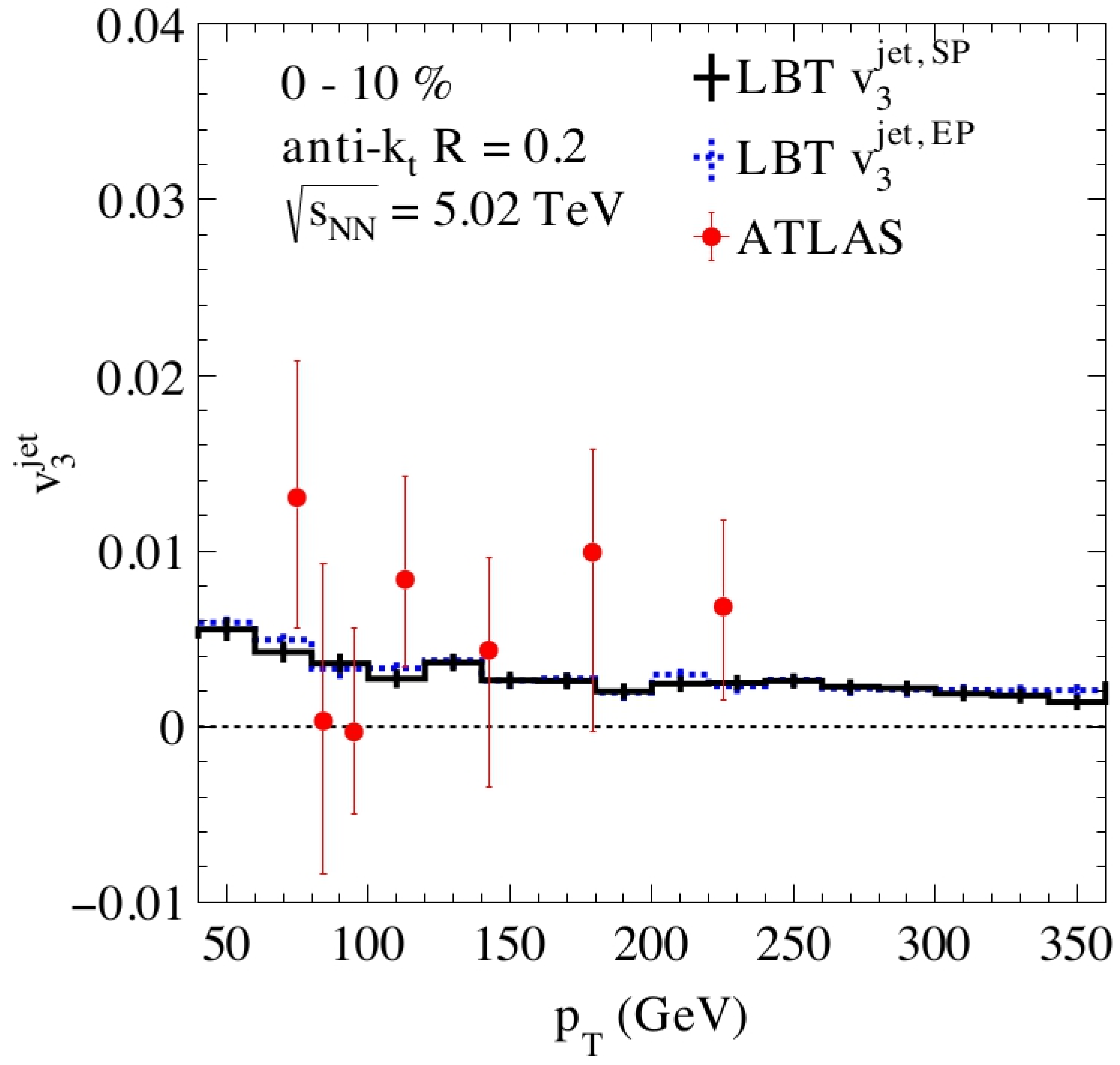
Event plane method:

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



Scalar product method:

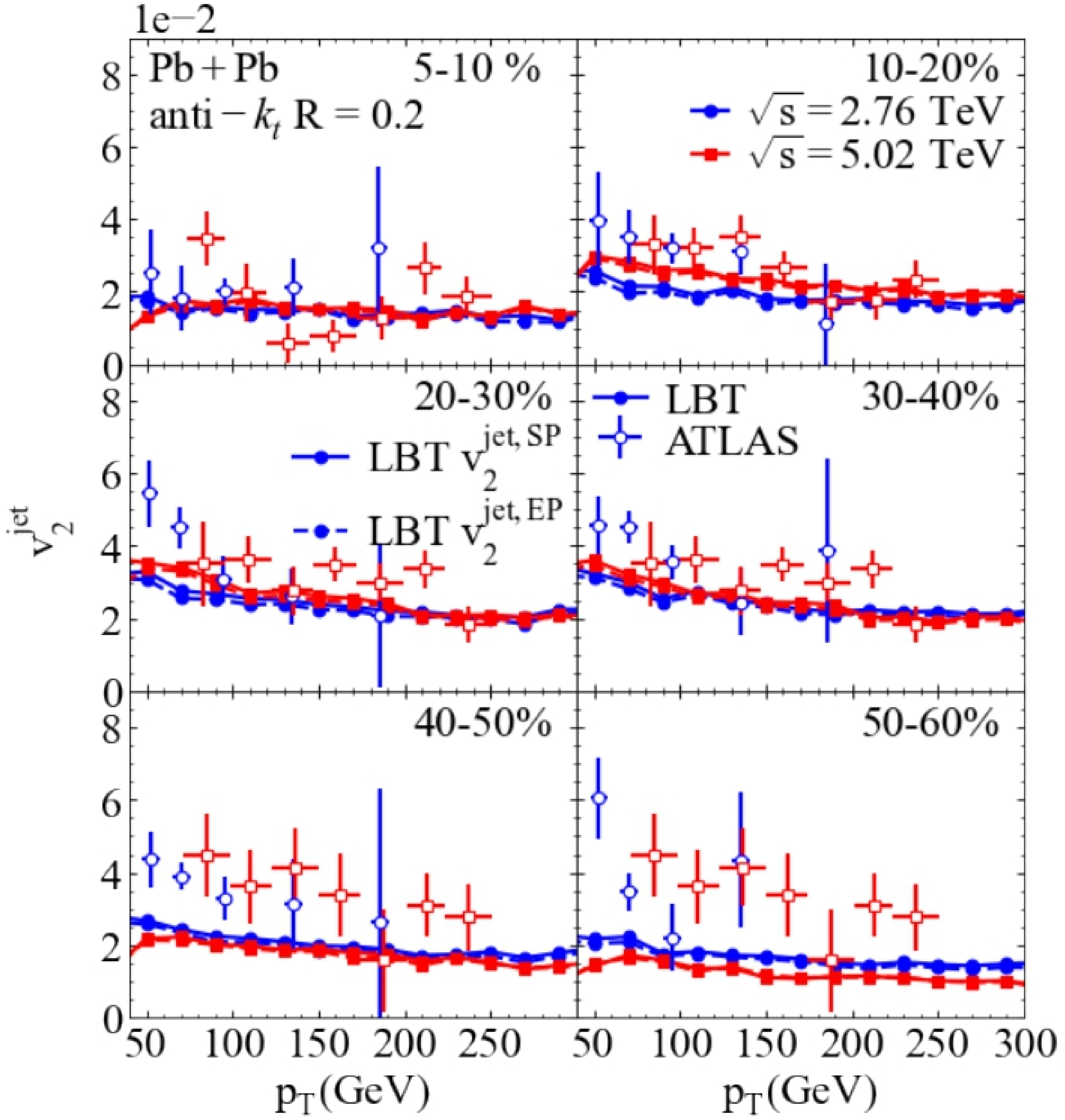
$$v_n^{\mathrm{jet,SP}} = \frac{\langle\langle v_n^{\mathrm{soft}} \cos(n[\phi^{\mathrm{jet}} - \Psi_n])\rangle\rangle}{\sqrt{\langle v_n^{\mathrm{soft}\,2}\rangle}}$$



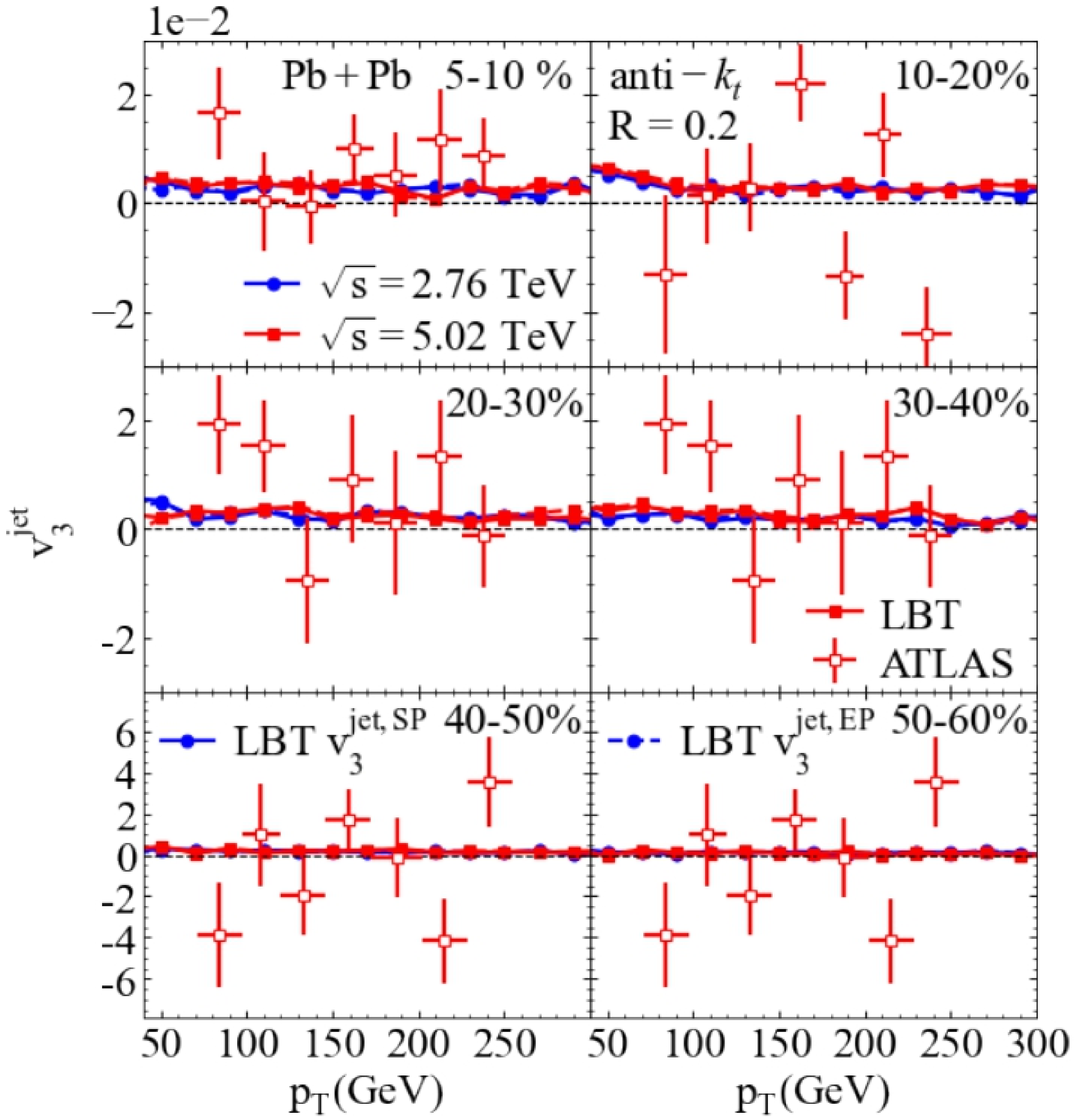
Weighted with bulk v_2 from e-by-e hydro profiles, slightly larger than event plane method

p_T dependence of inclusive jet v_2 and v_3

Jet v_2



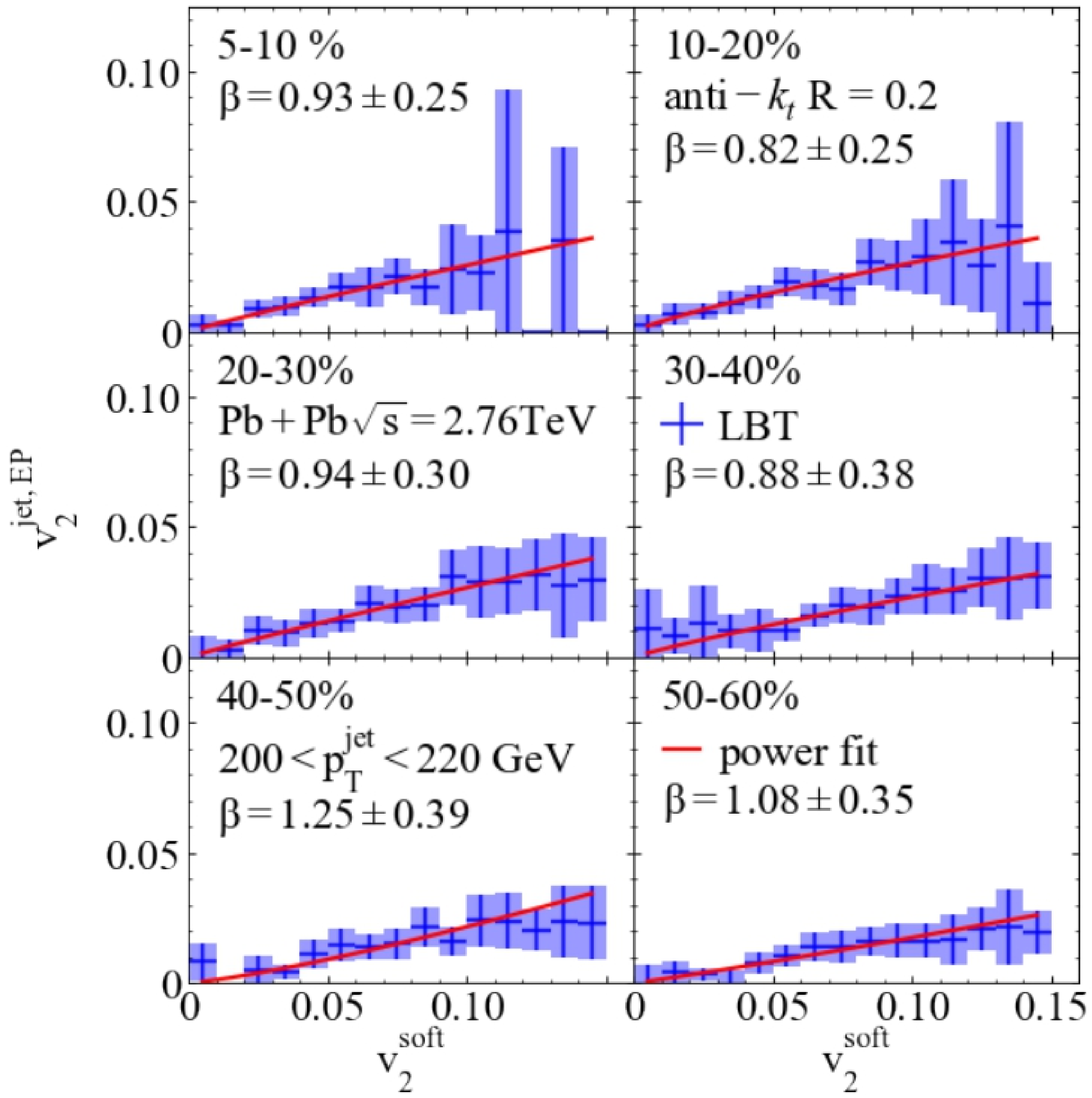
Jet v_3



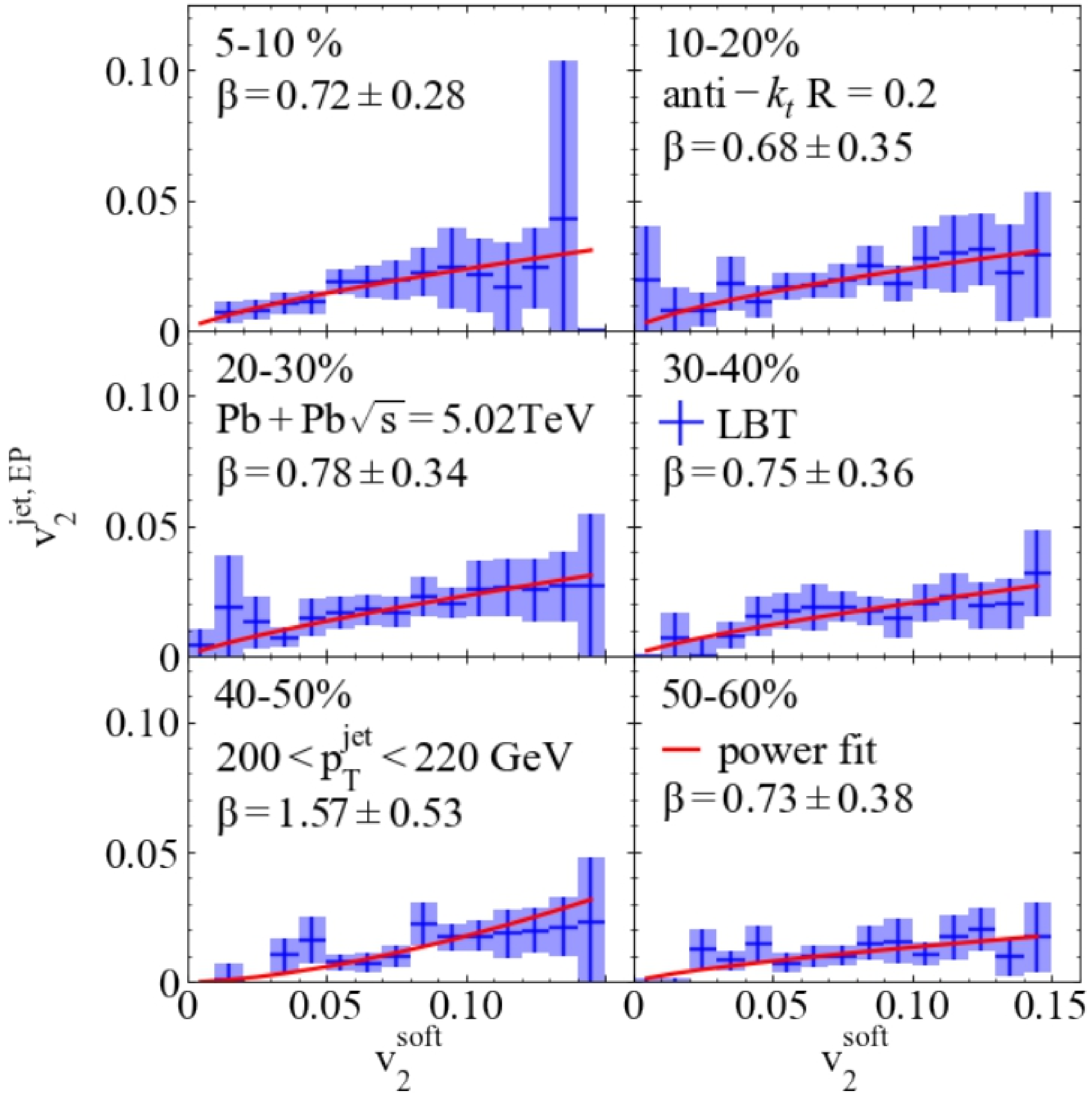
Jet v_2 at both colliding energy are almost the same and have a weak p_T dependence

Hard-soft tomography $v_2^{\rm jet} = \alpha (v_2^{\rm soft})^\beta$

2.76 TeV



5.02 TeV



Almost linear dependence!

Summary

✓The LBT model can describe both jet suppression and jet anisotropy flow

✓Jet anisotropy correlates with medium anisotropy

Outlook

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

Thanks for your attention!