

# Event-by-event jet anisotropy and hard-soft tomography in heavy-ion collisions

Yayun He (CCNU)

Collaborators: Shanshan Cao, Wei Chen, Tan Luo,  
Long-Gang Pang & Xin-Nian Wang



Online, Hard Probes 2020  
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# Outline

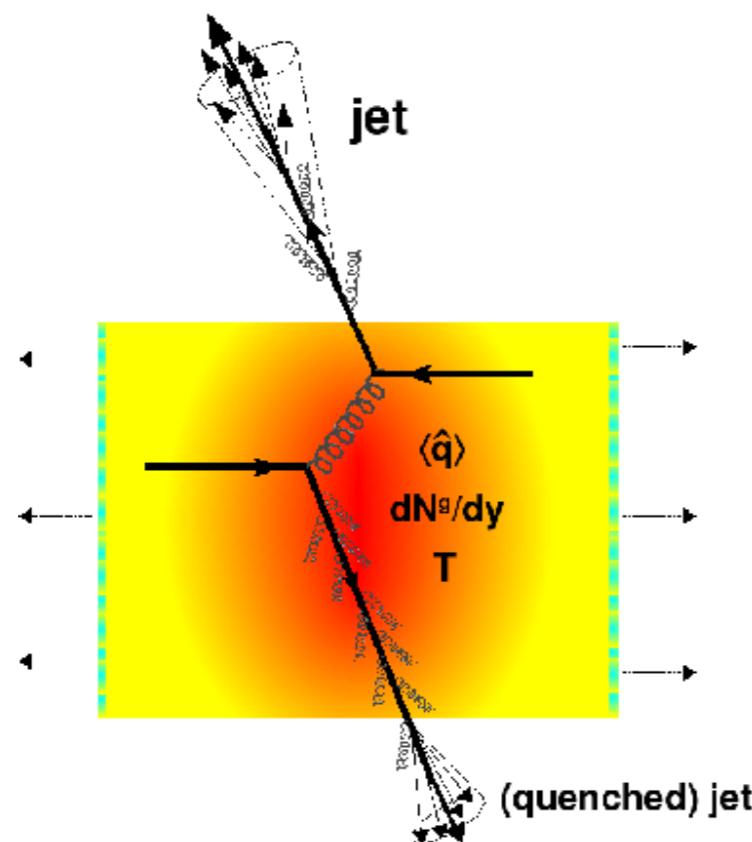
- I. Motivation
- II. The Linear Boltzmann Transport (LBT) Model
- III. Results: jet anisotropy
- IV. Summary



# Motivation

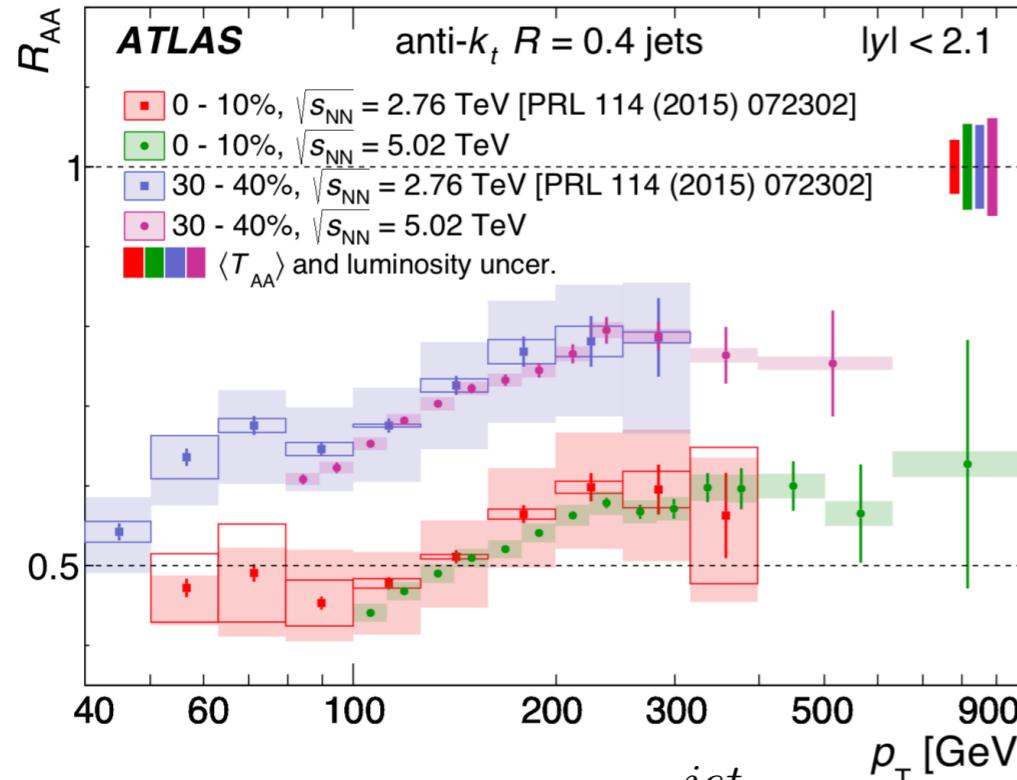
QGP Probes:

**hard probes**: large momentum or short distance.  
**jets**, high- $p_T$  hadrons, heavy quarks,...



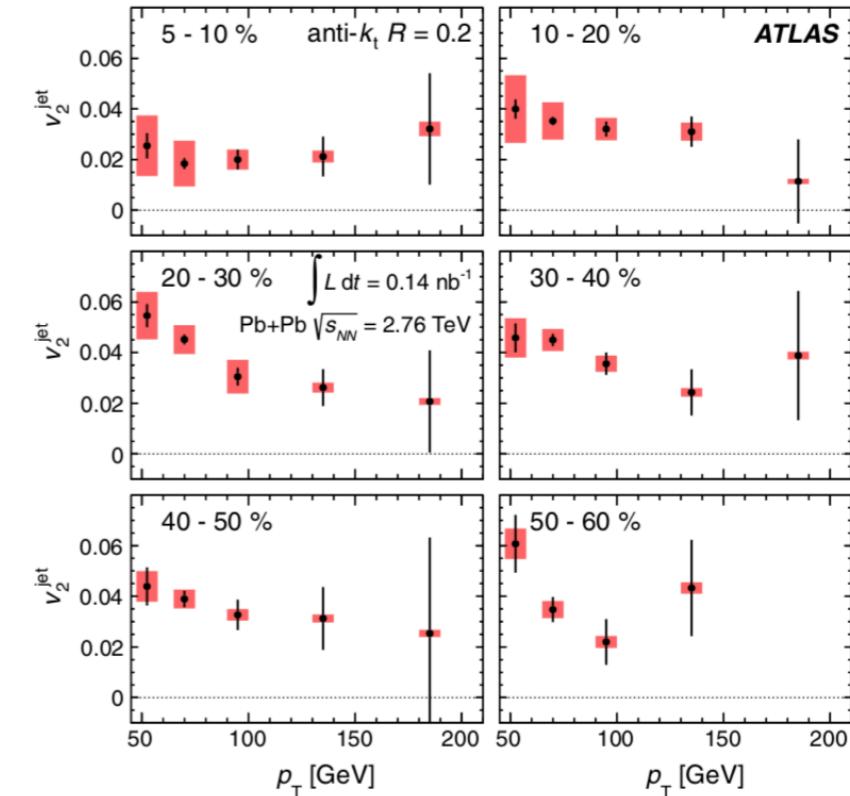
jet quenching:  
jet energy loss when a jet propagates in the medium

# Motivation



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

arXiv:1411.2357, arXiv:1805.05635



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

ATLAS, Phys. Rev. Lett. 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  $v_2$  in a unified framework?



# The LBT model

$$p_a \cdot \partial f_a = \int \sum_{bcd} \prod_{i=b,c,d} \frac{d^3 p_i}{2E_i(2\pi)^3} (f_c f_d - f_a f_b) |\mathcal{M}_{ab \rightarrow cd}|^2$$

$$\times \frac{\gamma_b}{2} S_2(\hat{s}, \hat{t}, \hat{u}) (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + \text{inelastic}$$

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

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

**LO perturbative QCD**

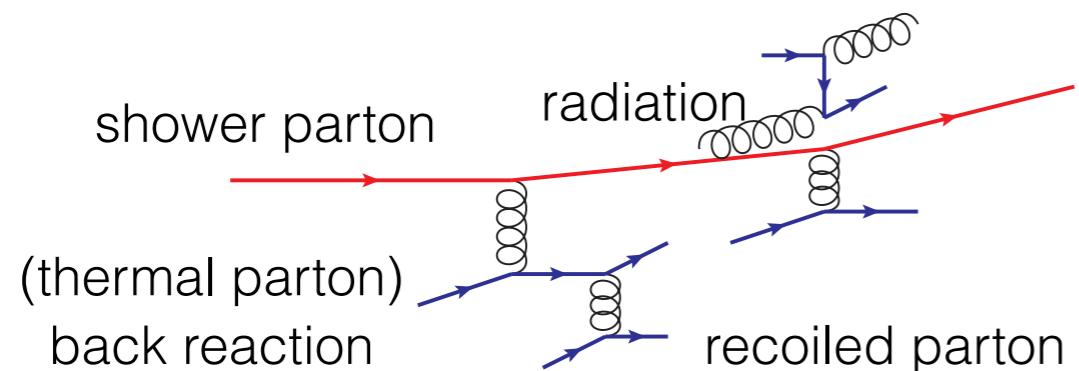
J. Auvinen et al, Phys. Rev. C 82(2010) 024906

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

**LO+NLO twist-4**

Guo and Wang, PRL 85 (2000) 3591

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



- ◆ re-scattering
- ◆ back reaction

- ◆ Linear approximation, and valid for  $\delta f \ll f$

# 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

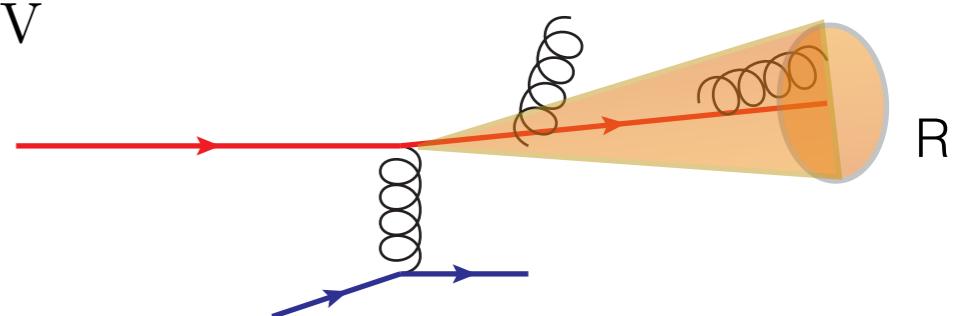
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal,  
Phys. Rev. C 72, 064901 (2005).

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

*out-of-cone  
jet energy loss*

freeze-out temperature:  $T_f = 137$  MeV

Final inclusive jet



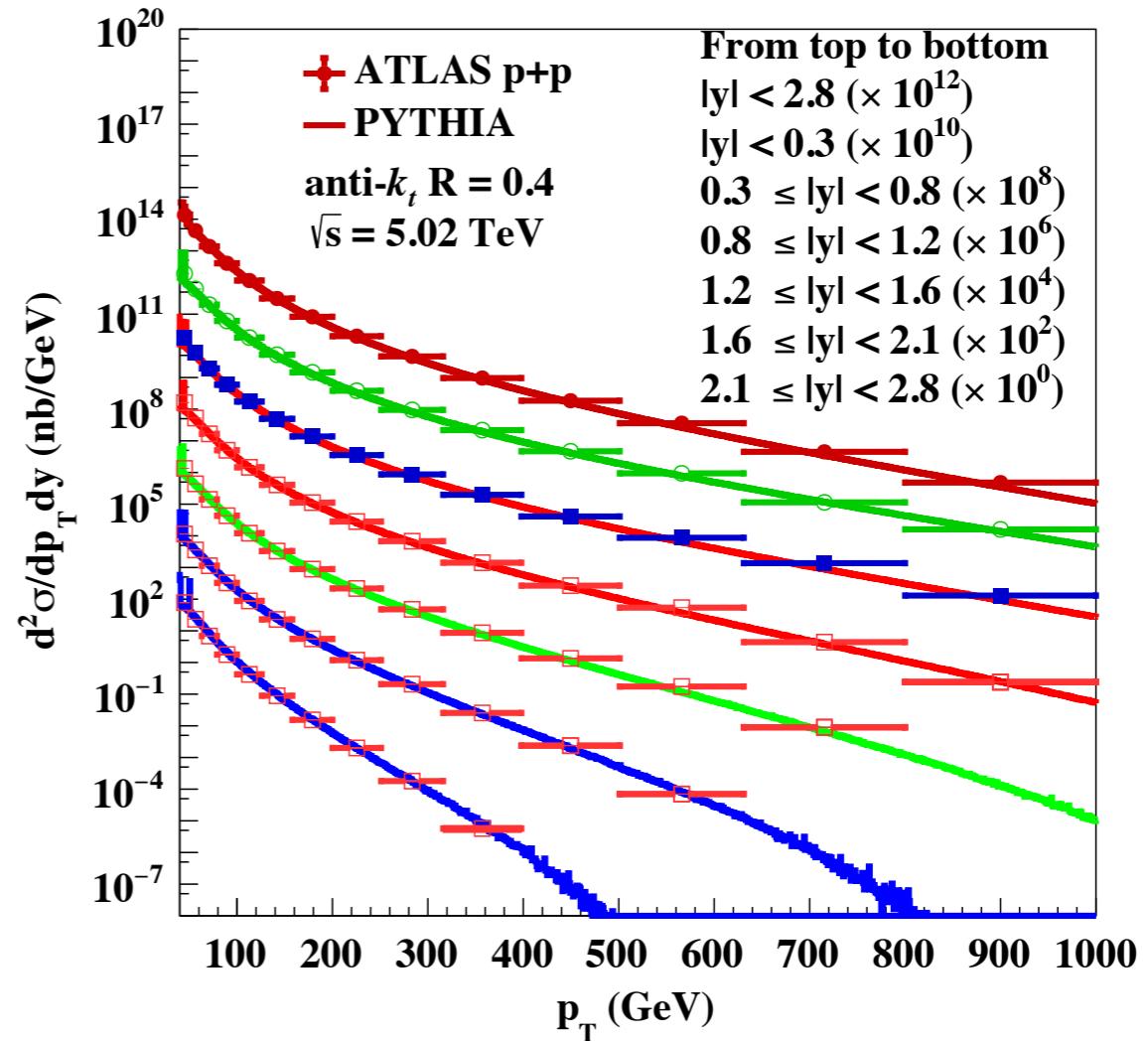
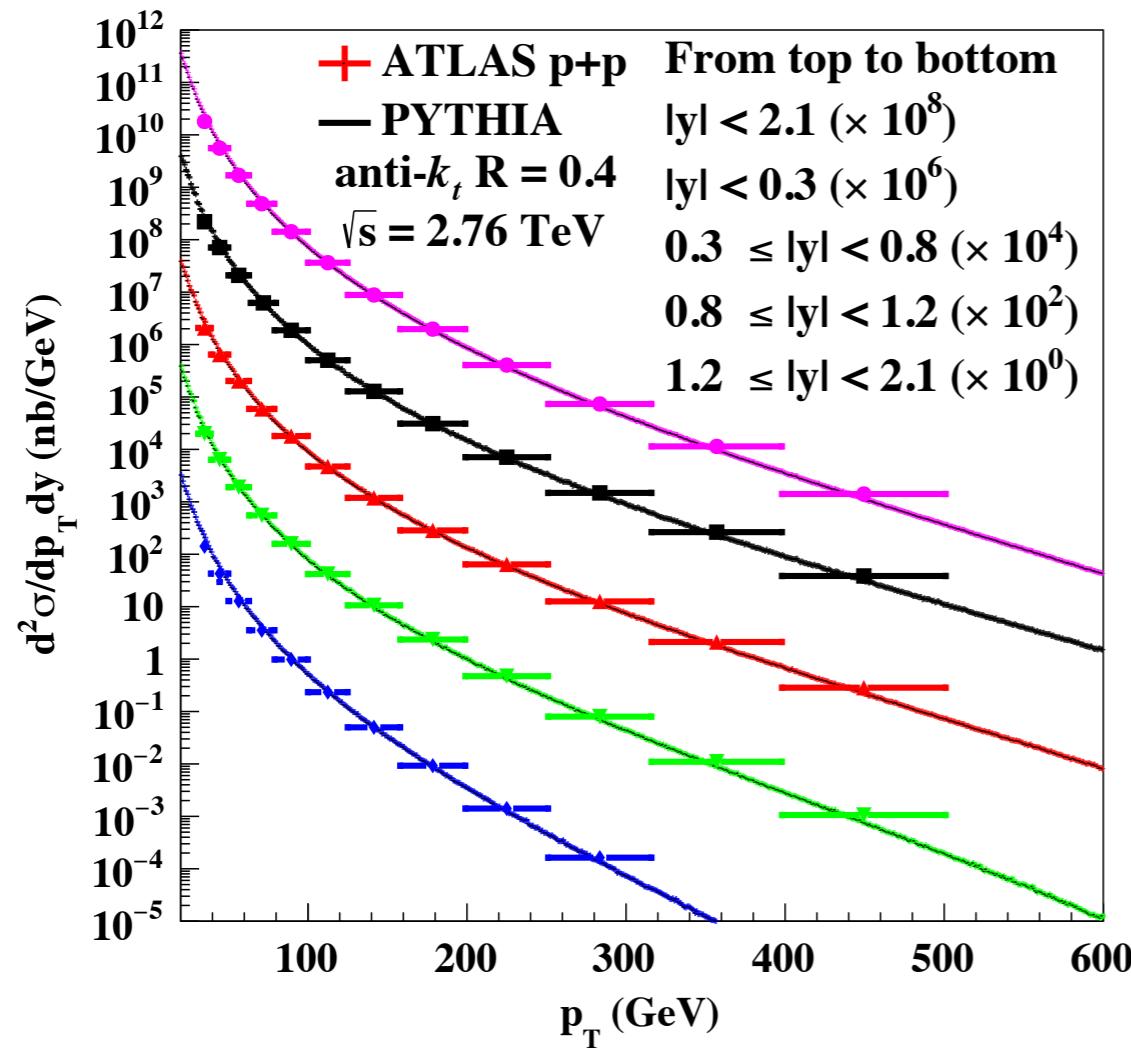
e-by-e 3+1D CLVisc: Pang, Wang & Wang, Phys. Rev. C86 (2012) 024911

Pang, Hatta, Wang & Xiao, Phys. Rev. D91 (2015) 074027



# The inclusive jet in pp collisions

$p_T$  distribution of  $pp$  collision within PYTHIA 8

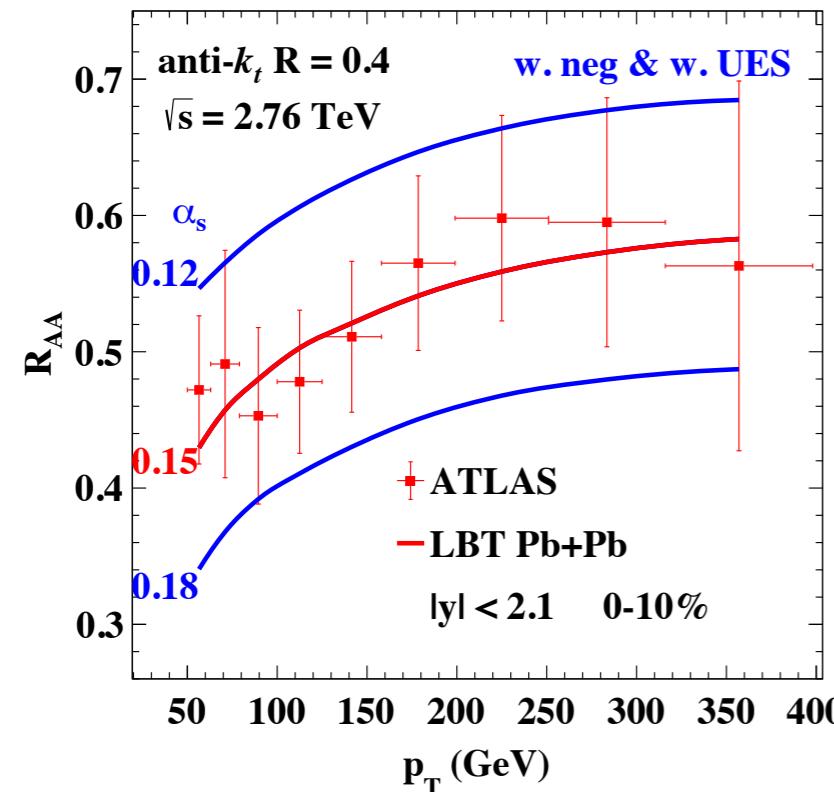
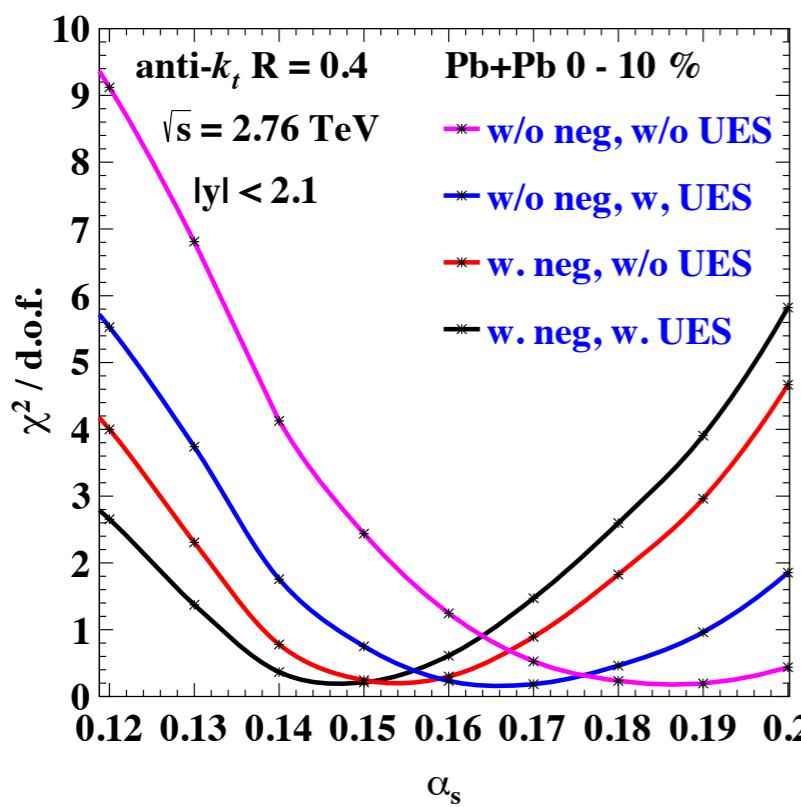


PYTHIA 8 can well describe the experimental data at LHC energies for different rapidity ranges.



# Fix strong coupling constant

Y. He et al, arXiv:1809.02525

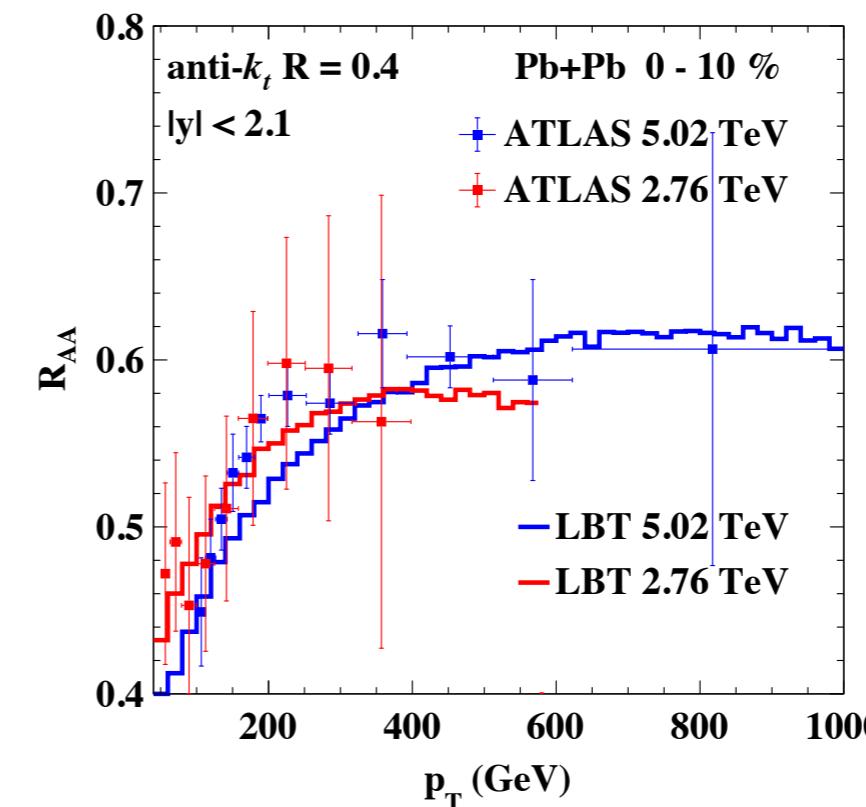


$$\chi^2 = \frac{(Theo. - Exp.)^2}{(\delta Exp.)^2}$$

Effective  $\alpha_s$ : collisional, radiation,  
Debye screening mass,

$$\Gamma_g \approx \sum_{b=g, q_i, \bar{q}_i} \Gamma_{gb \rightarrow gb} \approx 42 C_A \zeta(3) \frac{\alpha_s^2 T^3}{\pi \mu_D^2},$$

$$\alpha_s = 0.15$$



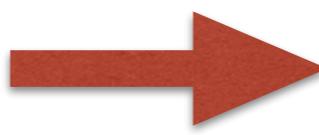
# Bulk anisotropy

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

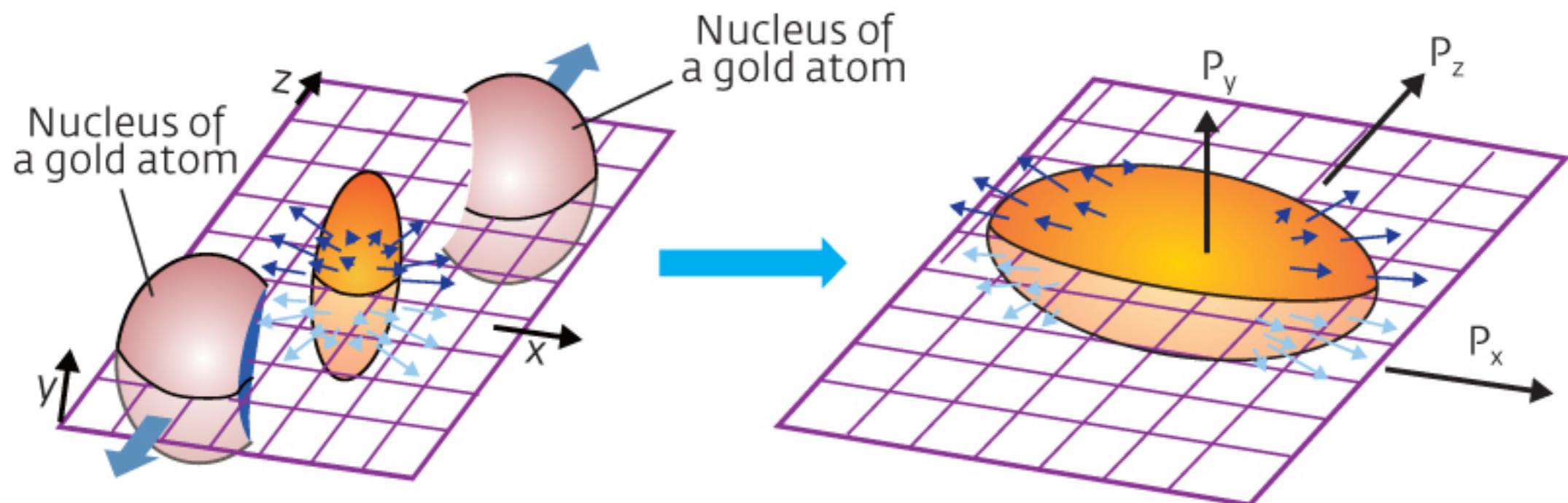
elliptic flow:  $n=2$

$$v_2 = \langle \cos[2(\phi - \Psi_2)] \rangle$$

Coordinate space:  
initial asymmetry



Momentum space:  
final asymmetry

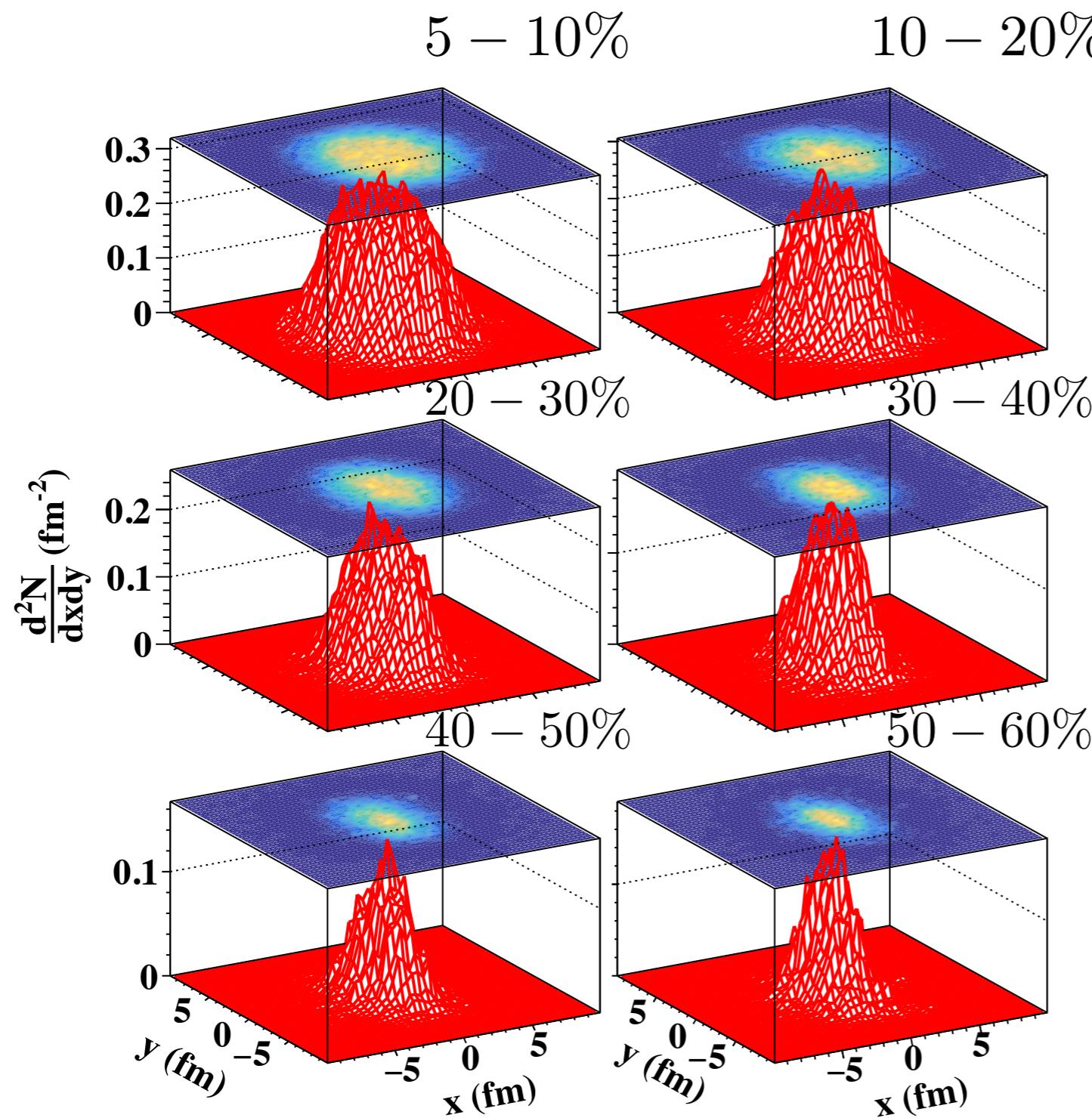


$$\epsilon = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

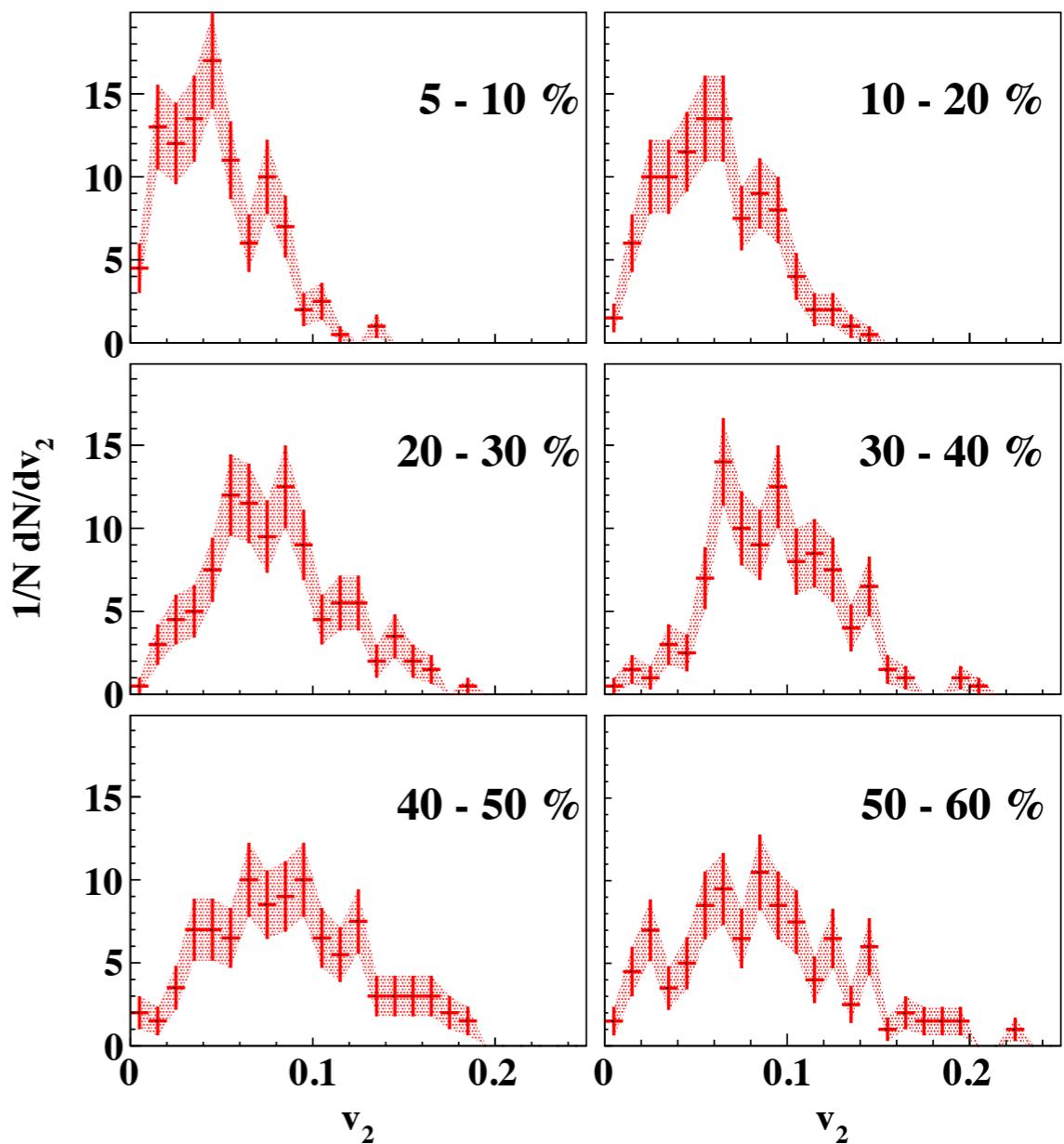


$$v_2 = \left\langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \right\rangle$$

# Bulk anisotropy



final bulk  $v_2$  at 2.76 TeV

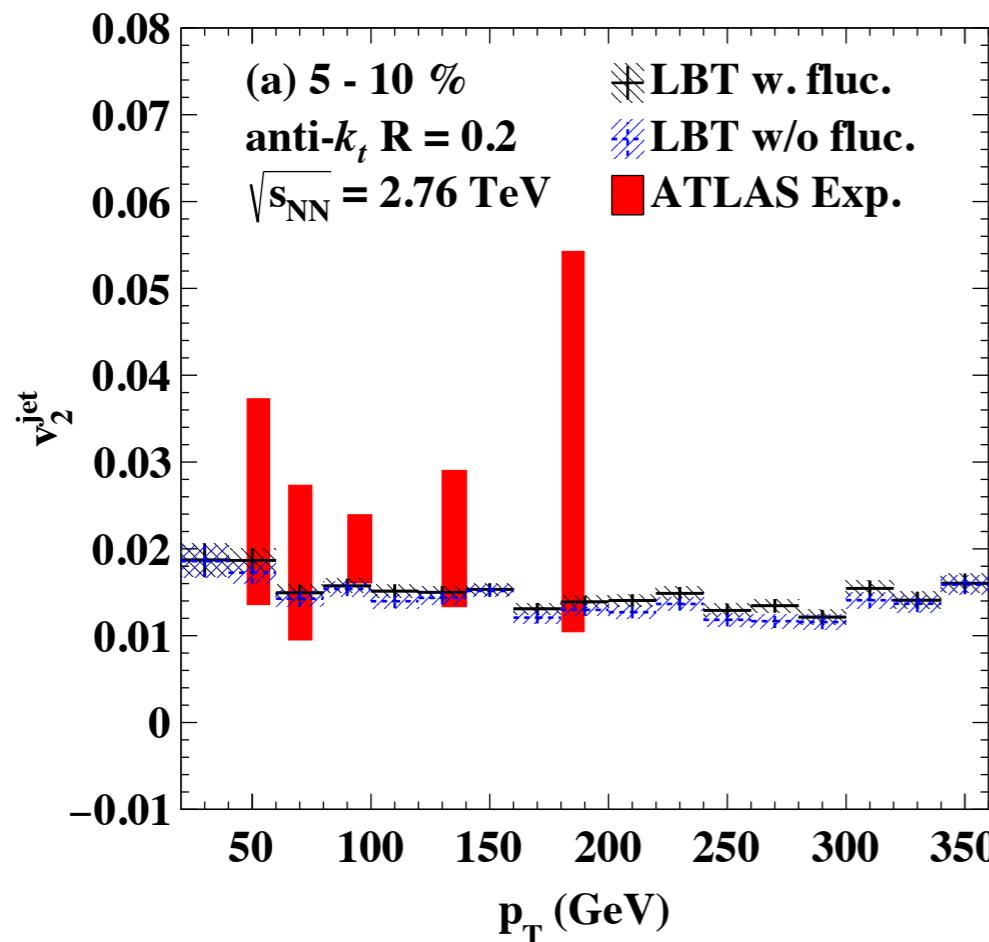


Initial geometry averaged over 200 3+1D event-by-event  
hydro profiles

# Inclusive jet anisotropy $v_2$

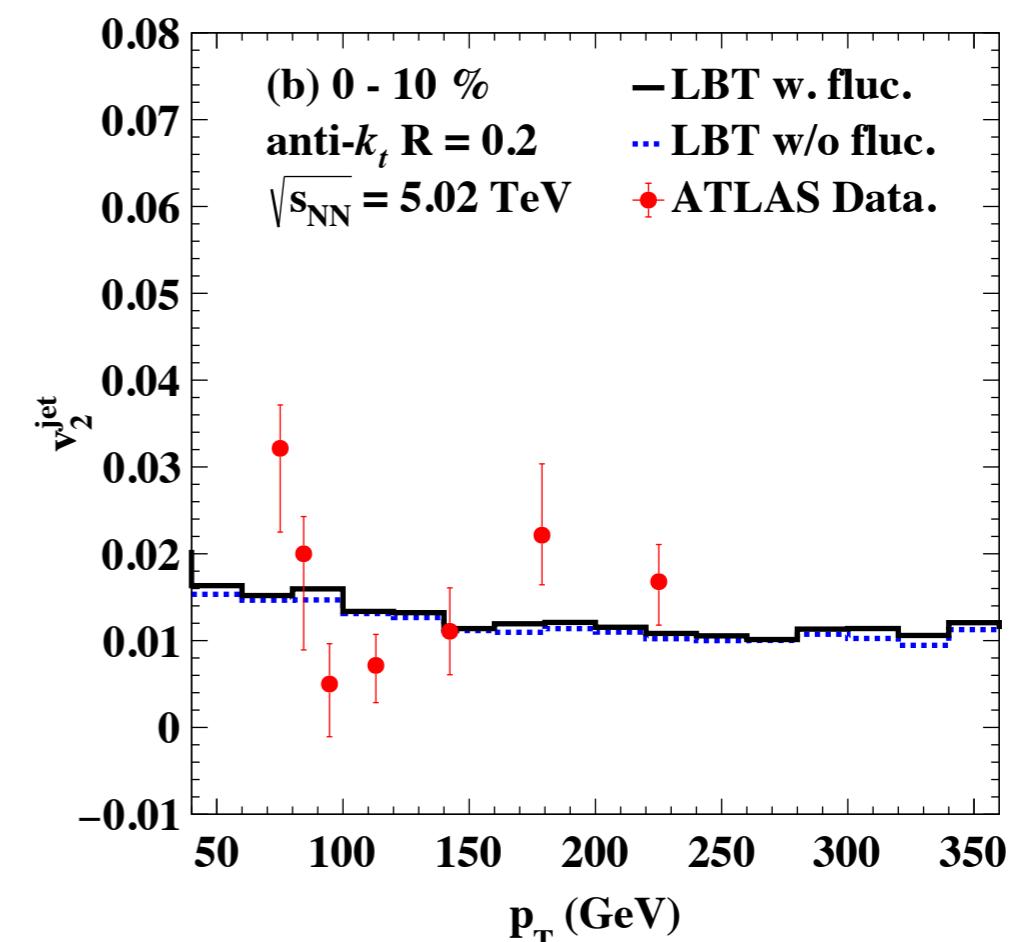
Scalar Product Method  
(labelled as w. fluc.)

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



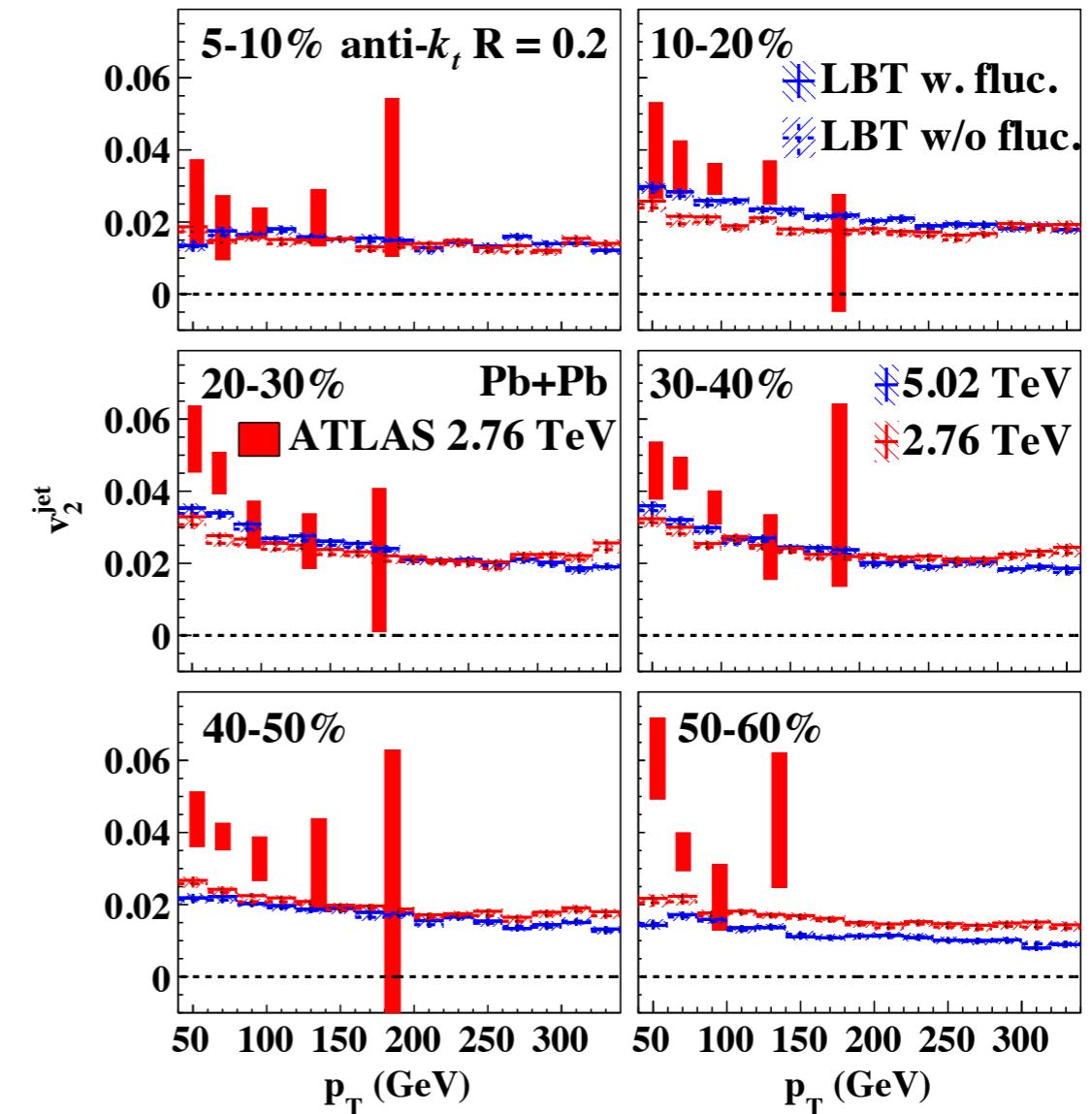
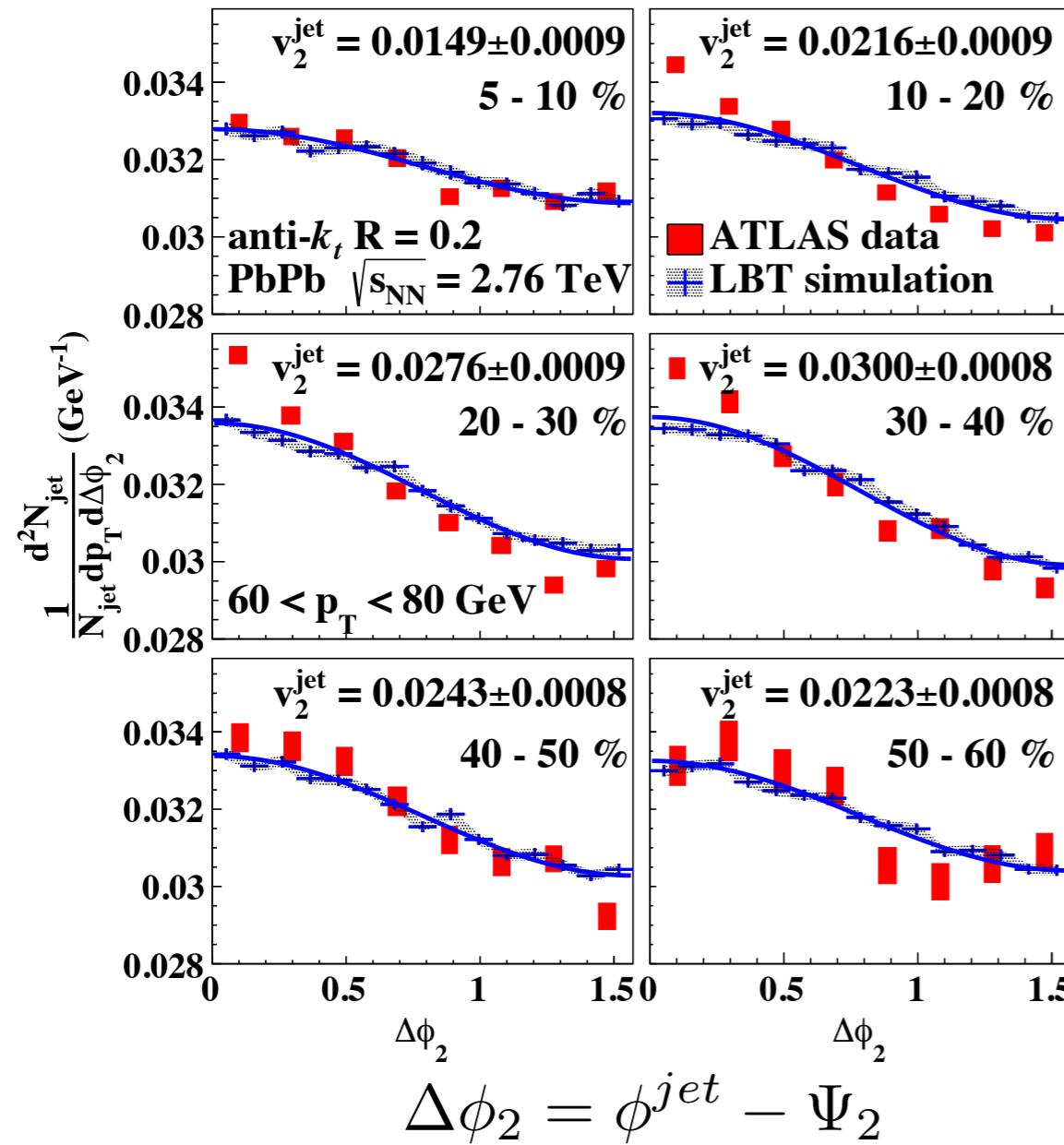
Event Plane Method  
(labelled as w/o fluc.)

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



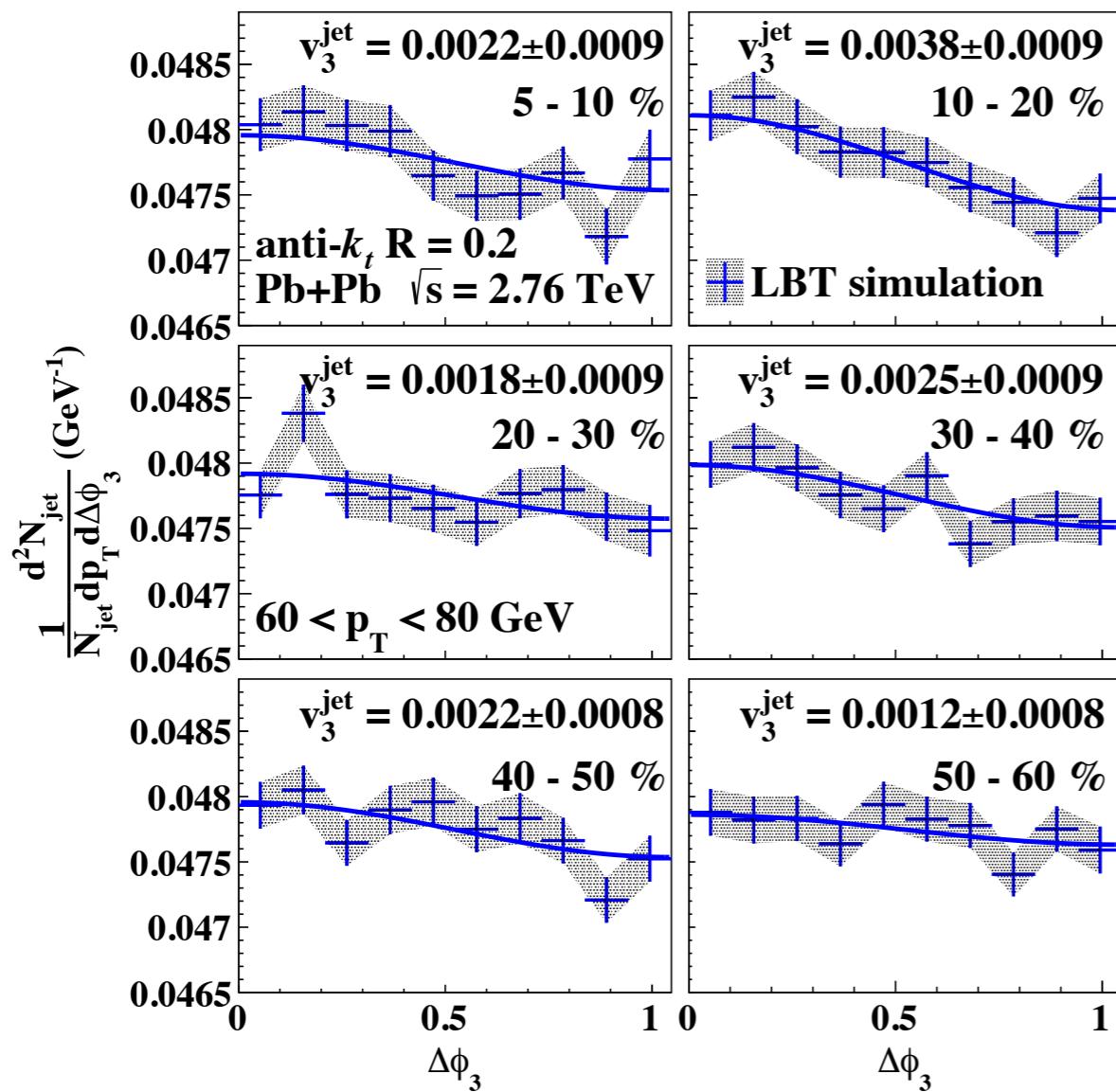
Weighted with bulk  $v_2$  from e-by-e hydro profiles,  
slightly larger than event plane method

# Inclusive jet anisotropy $v_2$

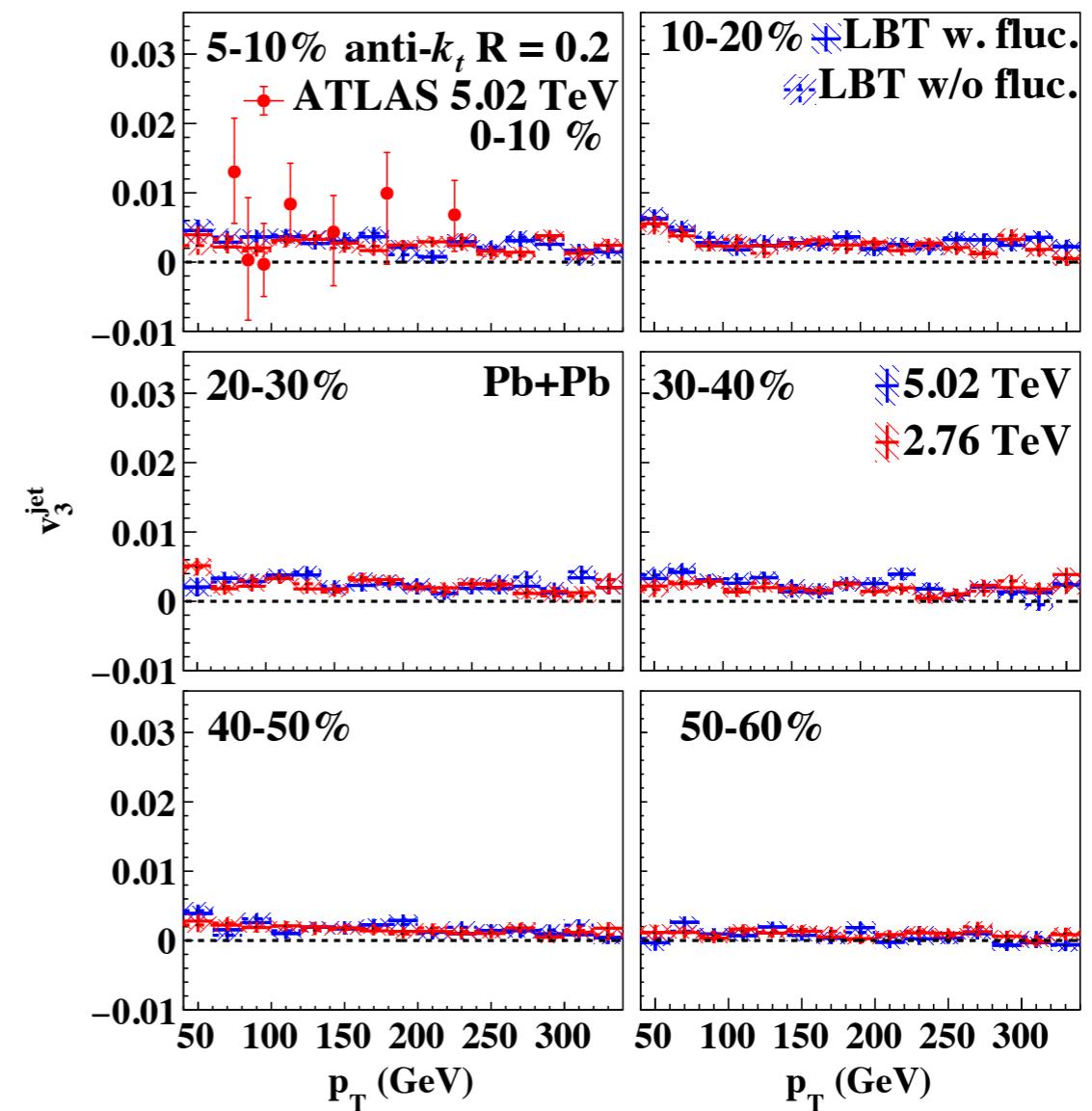


Azimuthal angle distributions clearly show the existence of jet  $v_2$ . Jet  $v_2$  at both colliding energy are almost the same and have a weak  $p_T$  dependence, similar with  $p_T$  dependence of jet  $R_{\text{AA}}$

# Inclusive jet anisotropy V<sub>3</sub>



$$\Delta\phi_3 = \phi^{\text{jet}} - \Psi_3$$

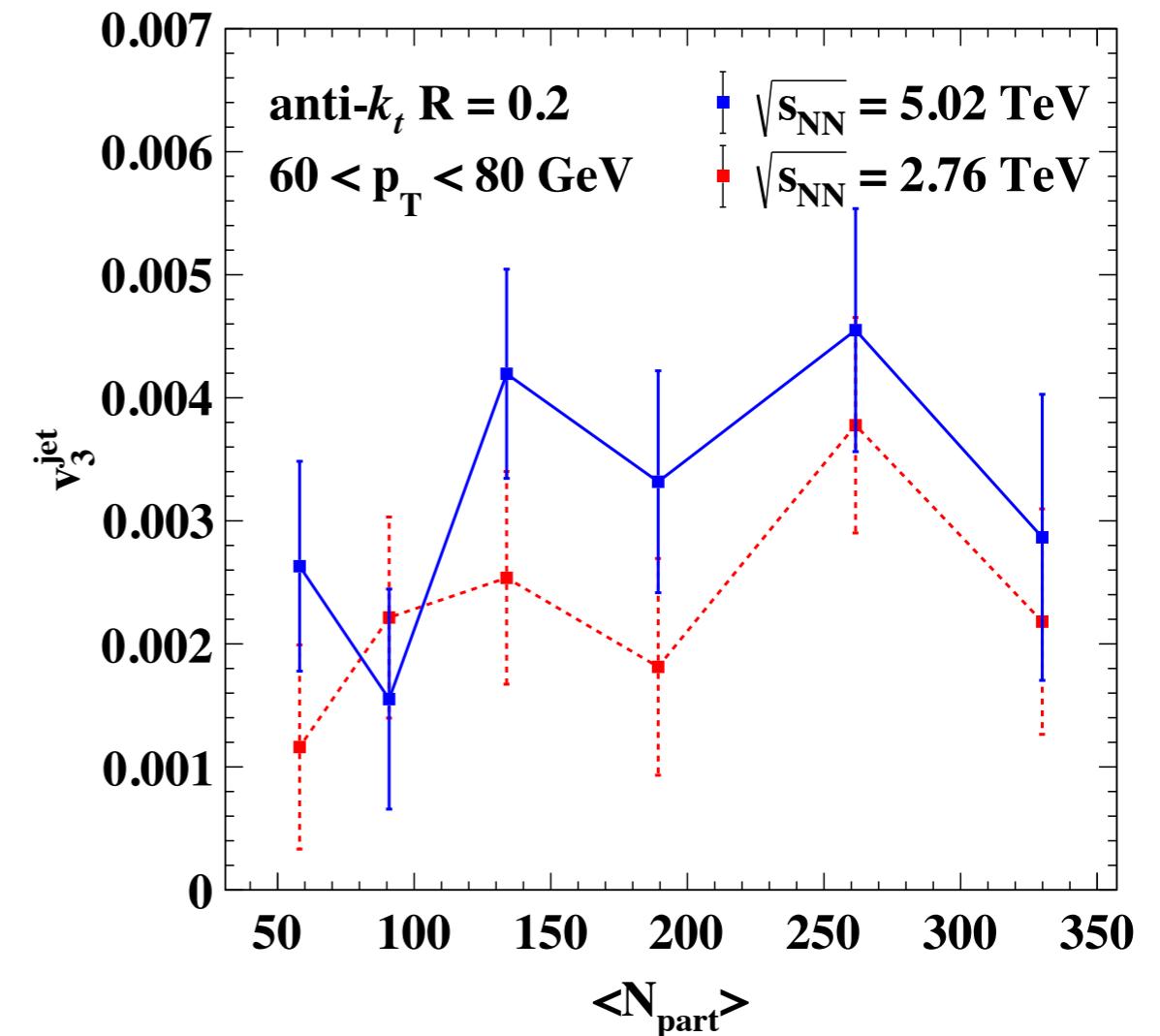
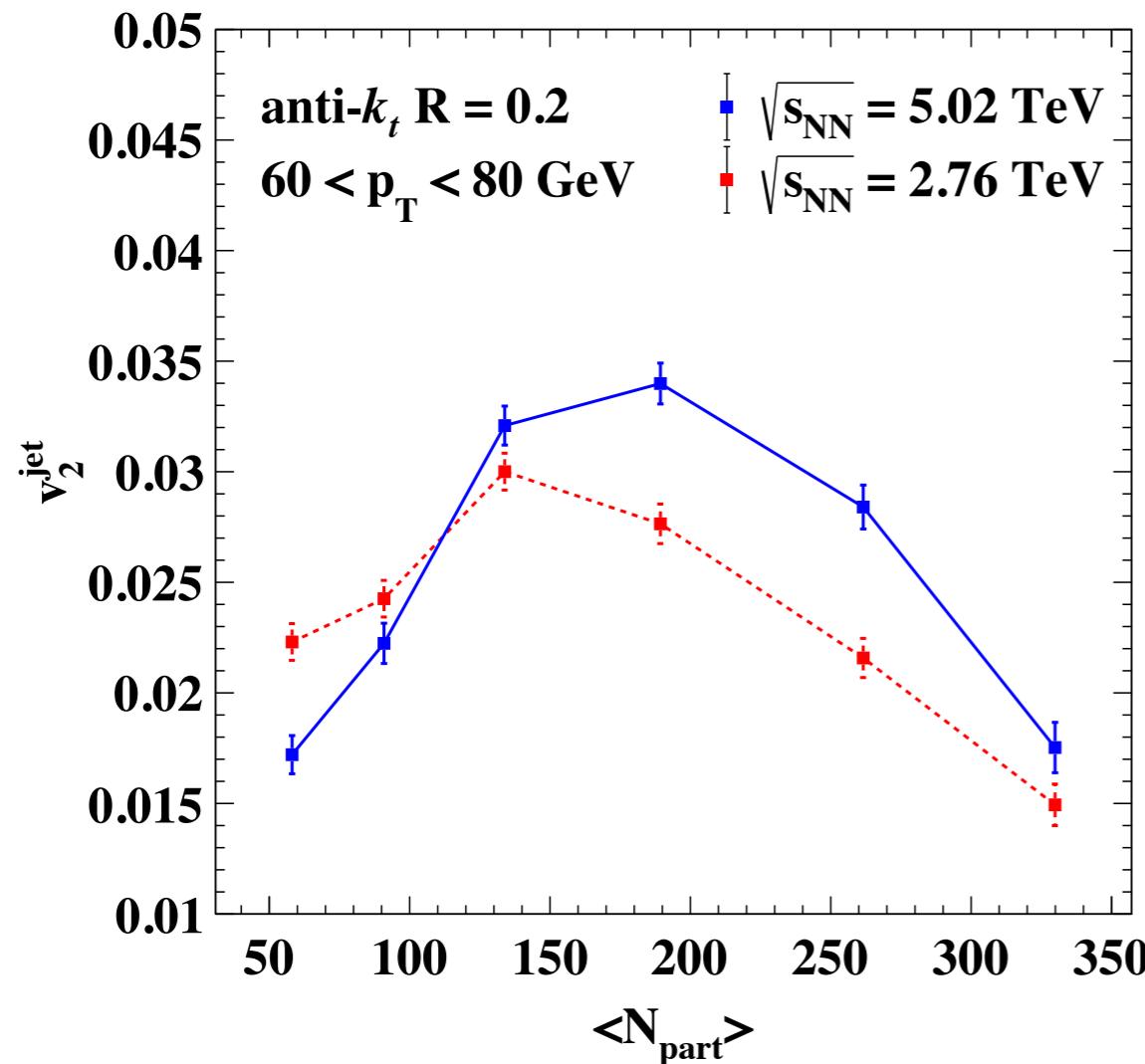


jet  $v_3$  is small, but not zero.

Jet  $v_3$  also shows a weak dependence of colliding energy and jet  $p_T$ .



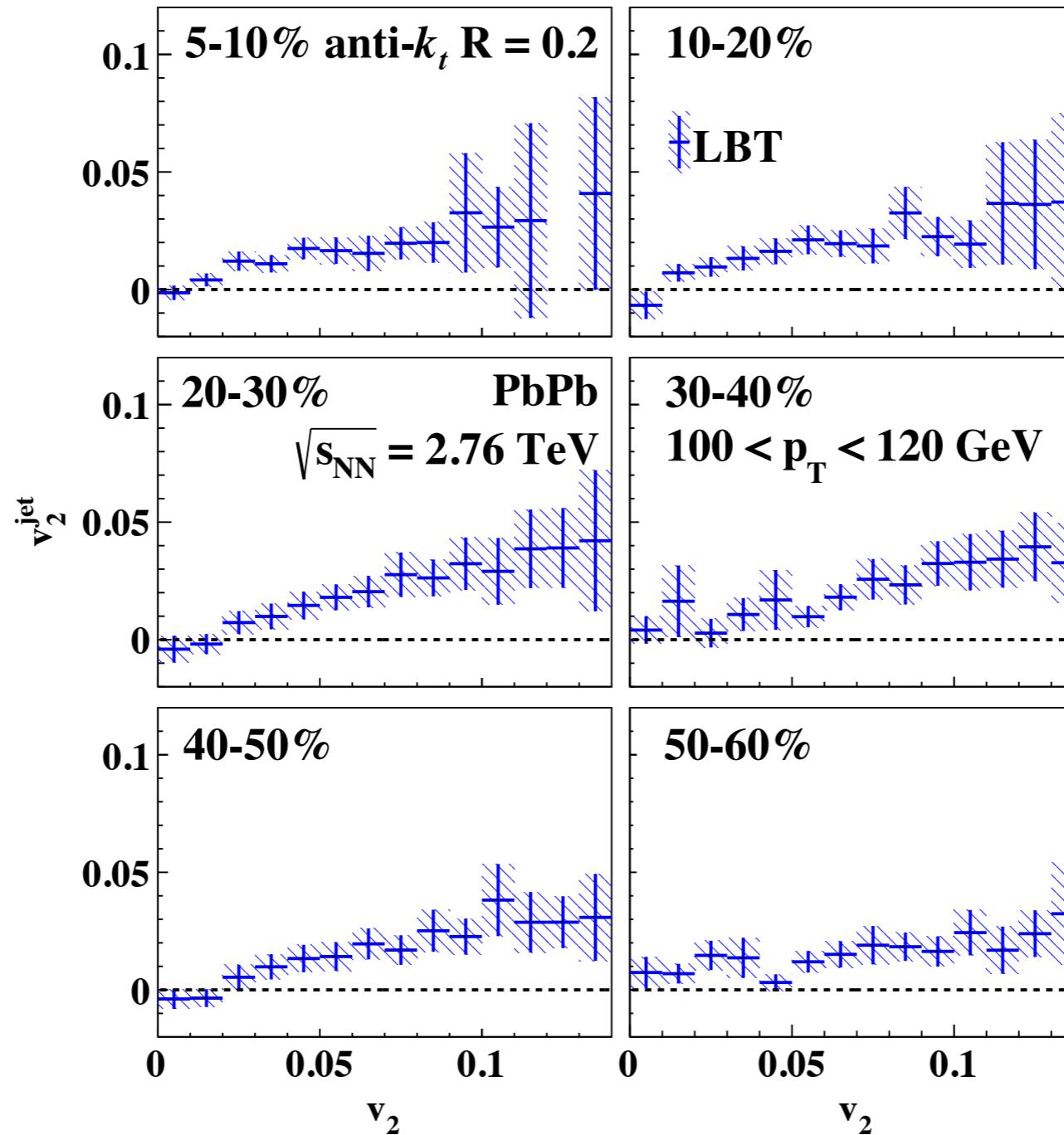
# Centrality dependence of jet anisotropy



jet  $v_n$  closely follows the centrality dependence of soft  $v_n$



# Hard-soft correlation



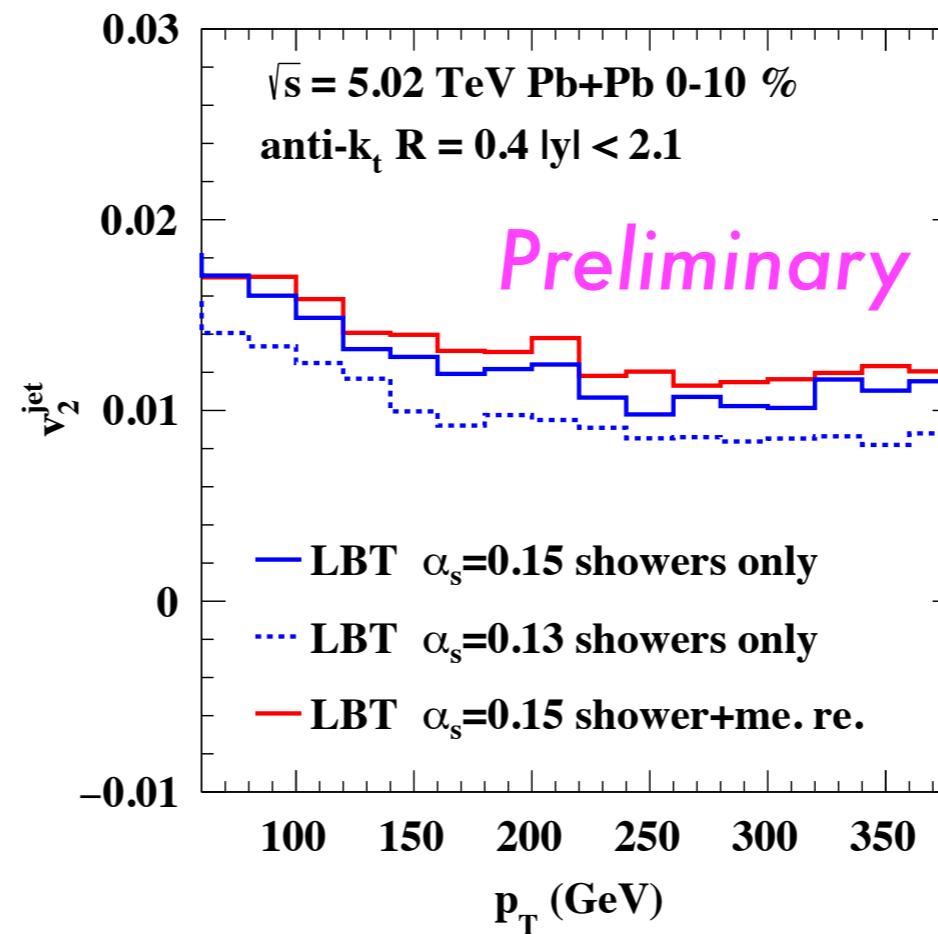
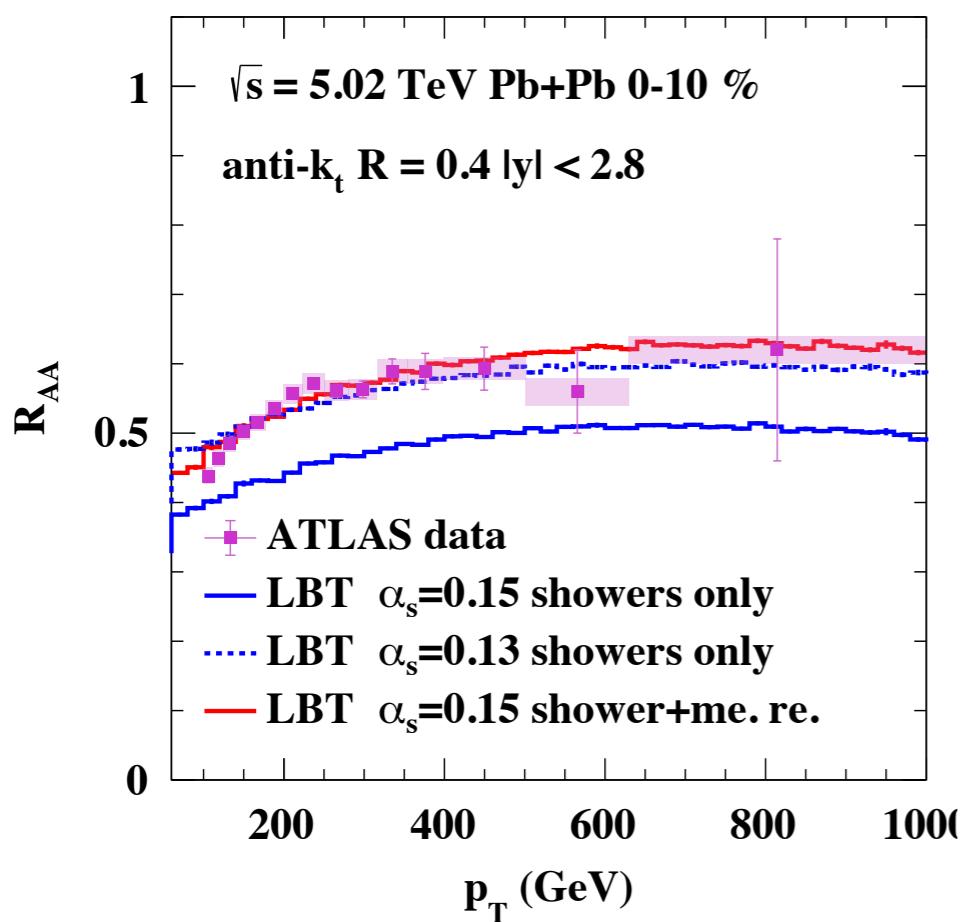
Approximately linear correlation btw jet and bulk anisotropy

The slope should be related to the strength of jet quenching during jet propagation.



# Effect of medium response

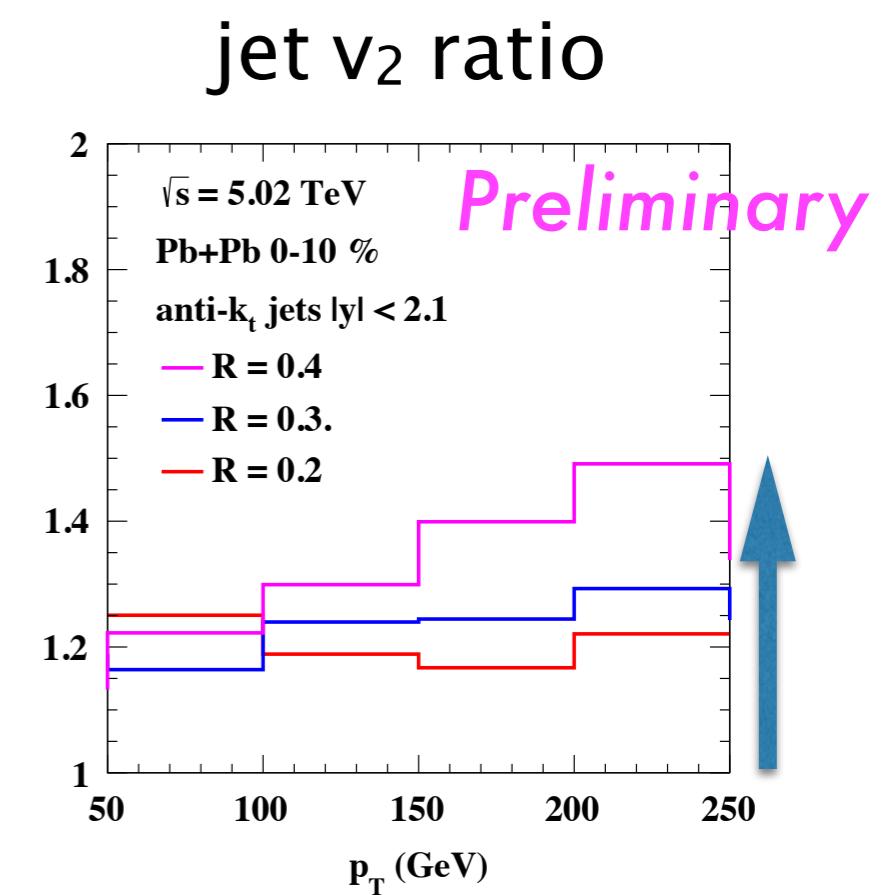
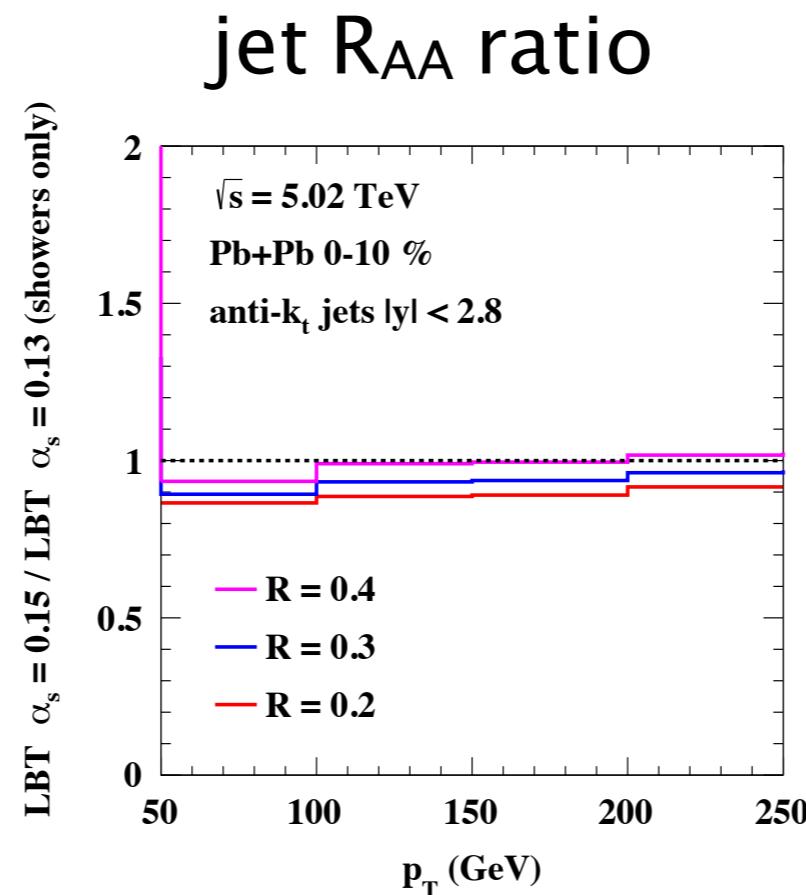
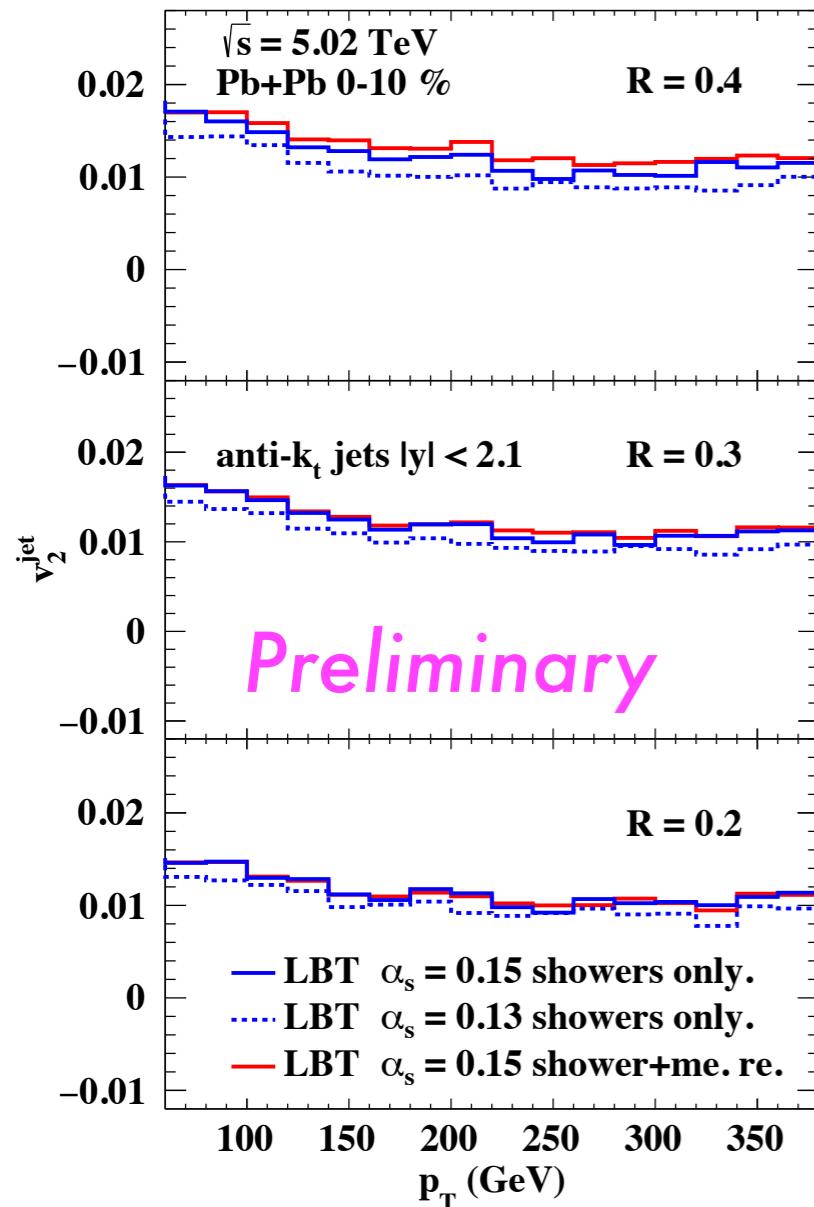
medium response (me. re.) : medium recoil + back reaction.



Jets without medium response get more quenched



# Cone size dependence



Larger cone size  $\rightarrow$  larger effect of medium response



# Summary

- The LBT model can describe both jet suppression and jet anisotropy flow.
- Jet anisotropy correlates with medium anisotropy
- Medium response enhances jet anisotropy, which effect increases for a larger jet cone size

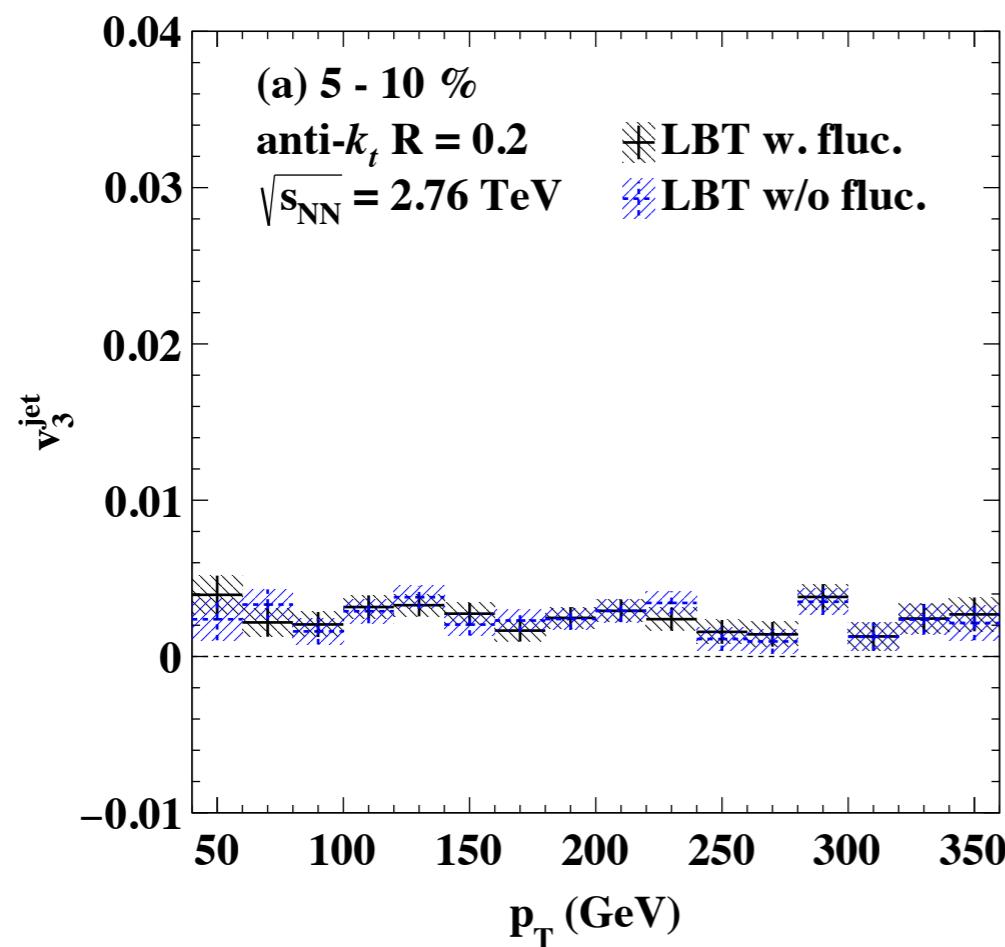
*Thanks for your attention!*



# Inclusive jet anisotropy V<sub>3</sub>

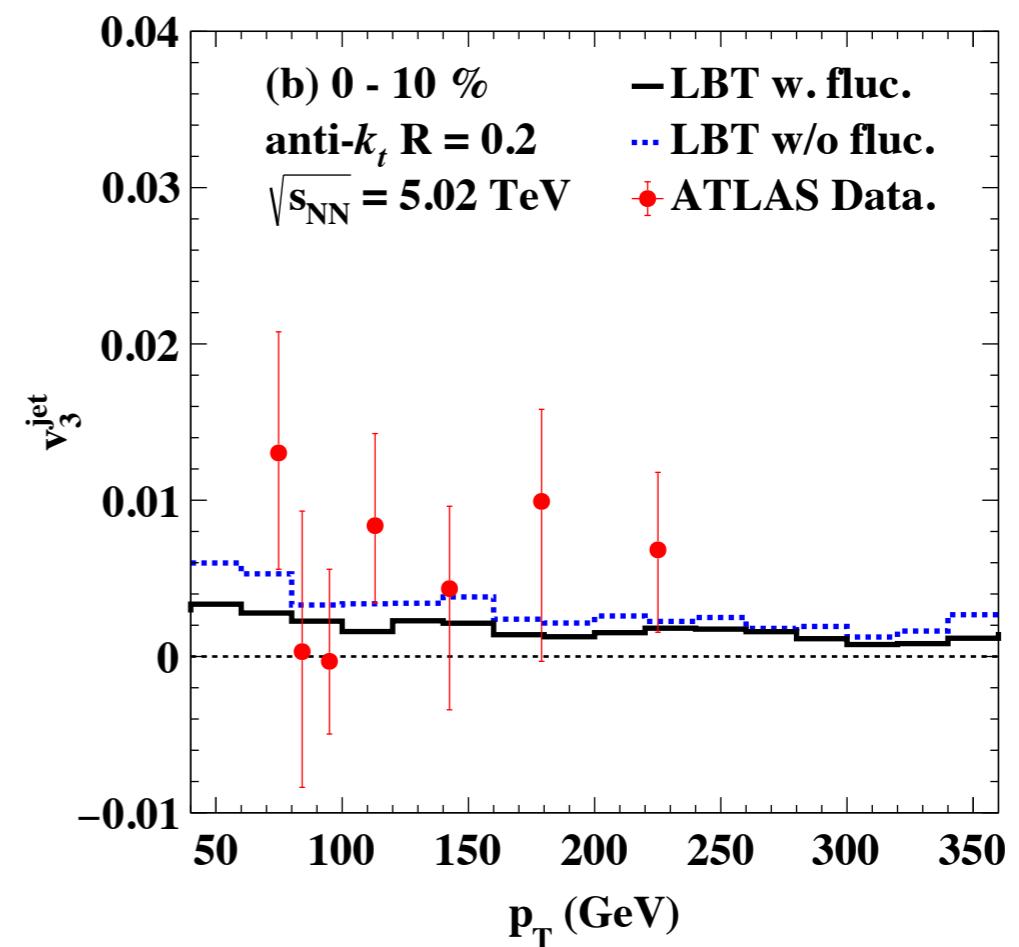
Scalar Product Method  
(labelled as w. fluc.)

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



Event Plane Method  
(labelled as w/o fluc.)

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



jet v<sub>3</sub> is small, but not zero.



# Nontrivial path length dependence on parton energy loss

Propagation of a single initial jet parton in a uniform medium

$$E = 100 \text{ GeV}$$

$$T = 0.4 \text{ GeV}$$

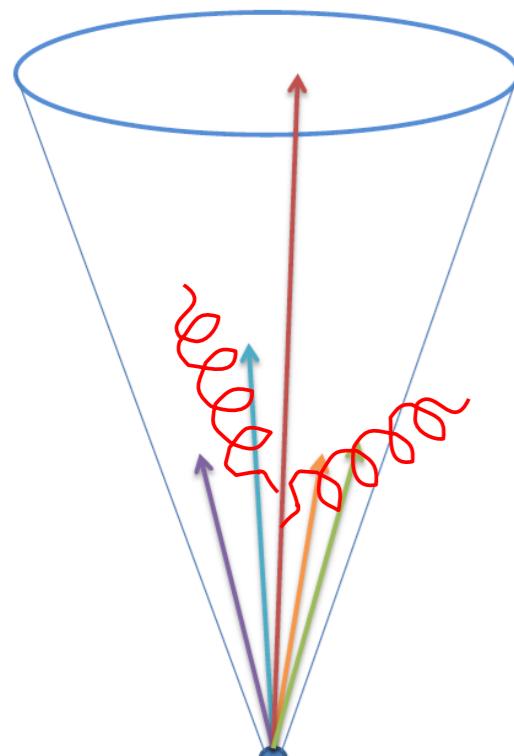
$$\alpha_s = 0.3$$

*Leading parton energy loss*

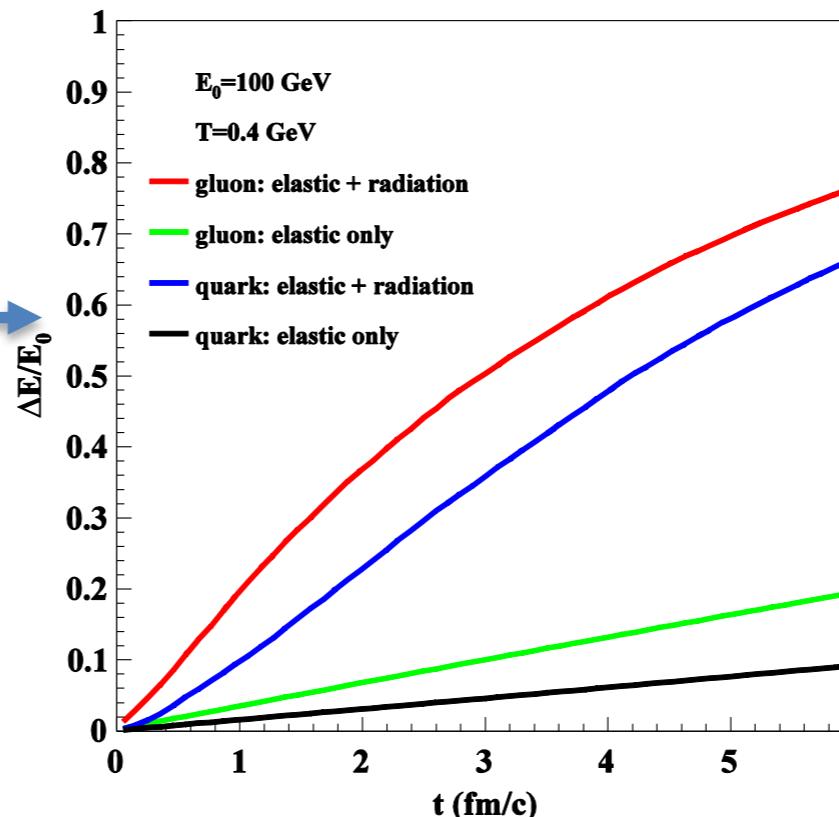
$$\frac{dE_{\text{el}}^a}{d\lambda} = C_a \frac{3\pi}{2} \alpha_s^2 T^2 \ln\left(\frac{s^*}{4\mu_D^2}\right)$$

*Leading jet energy loss*

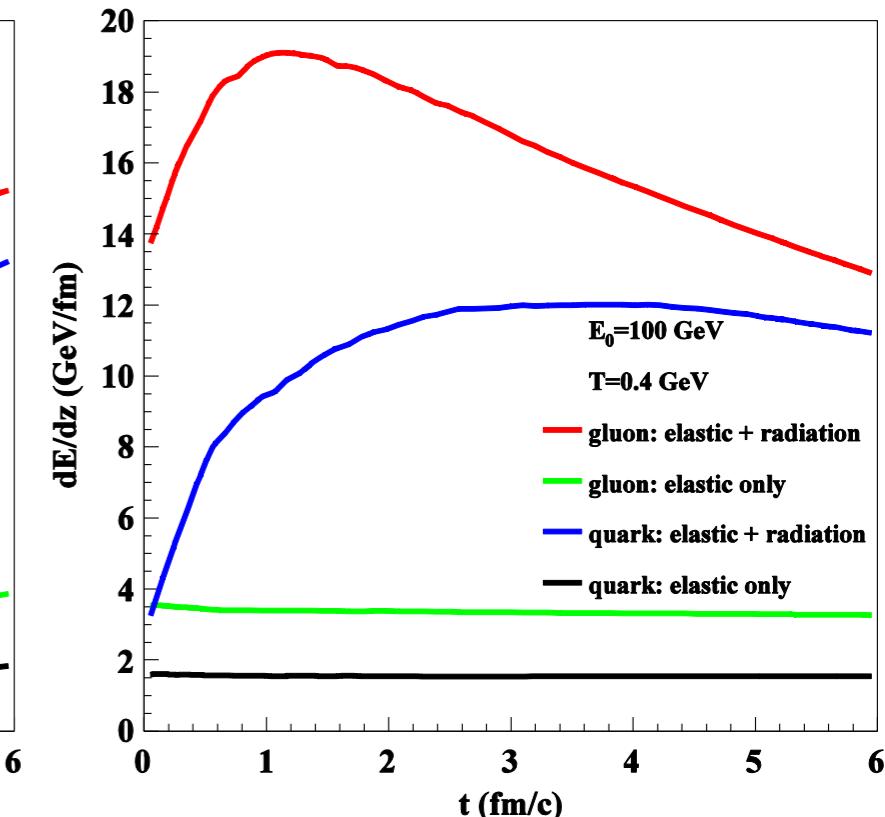
Leading jet only



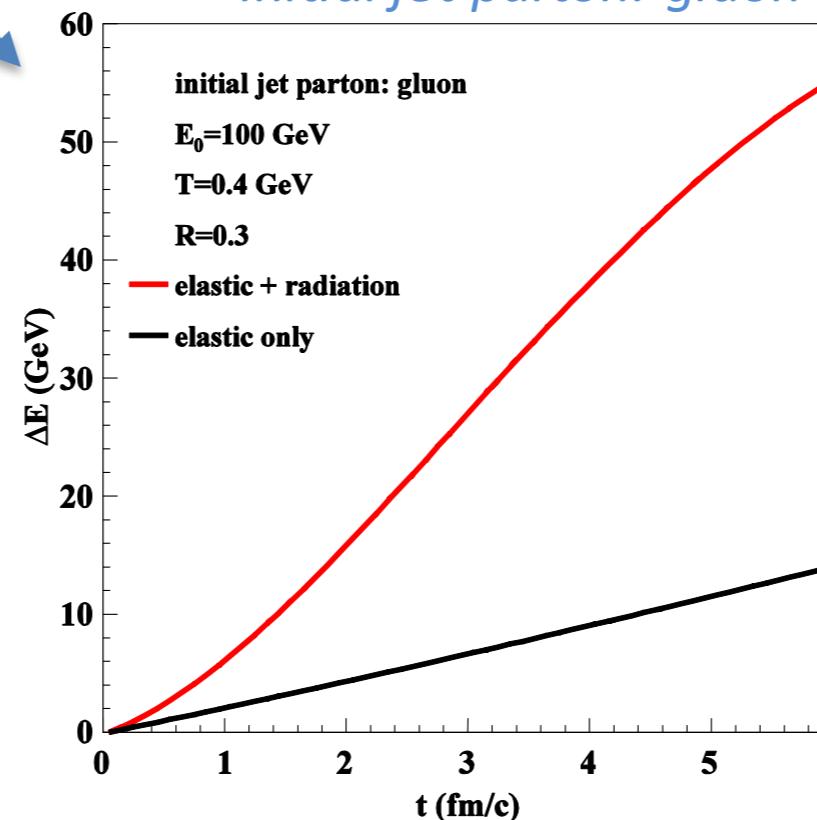
Fractional energy loss



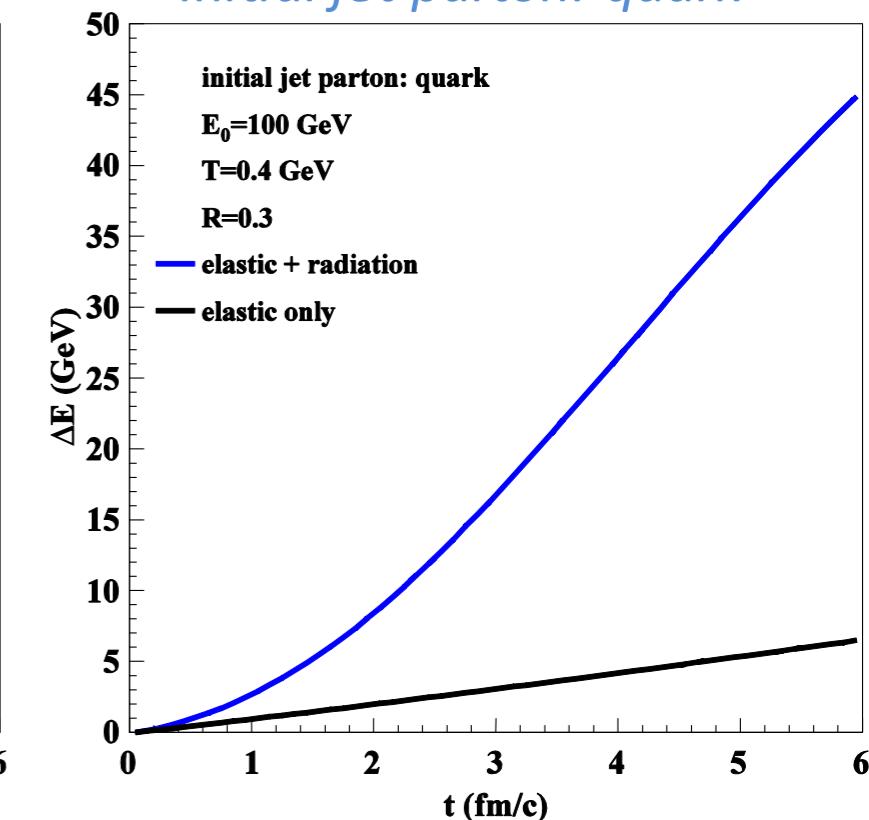
Energy loss per unit length

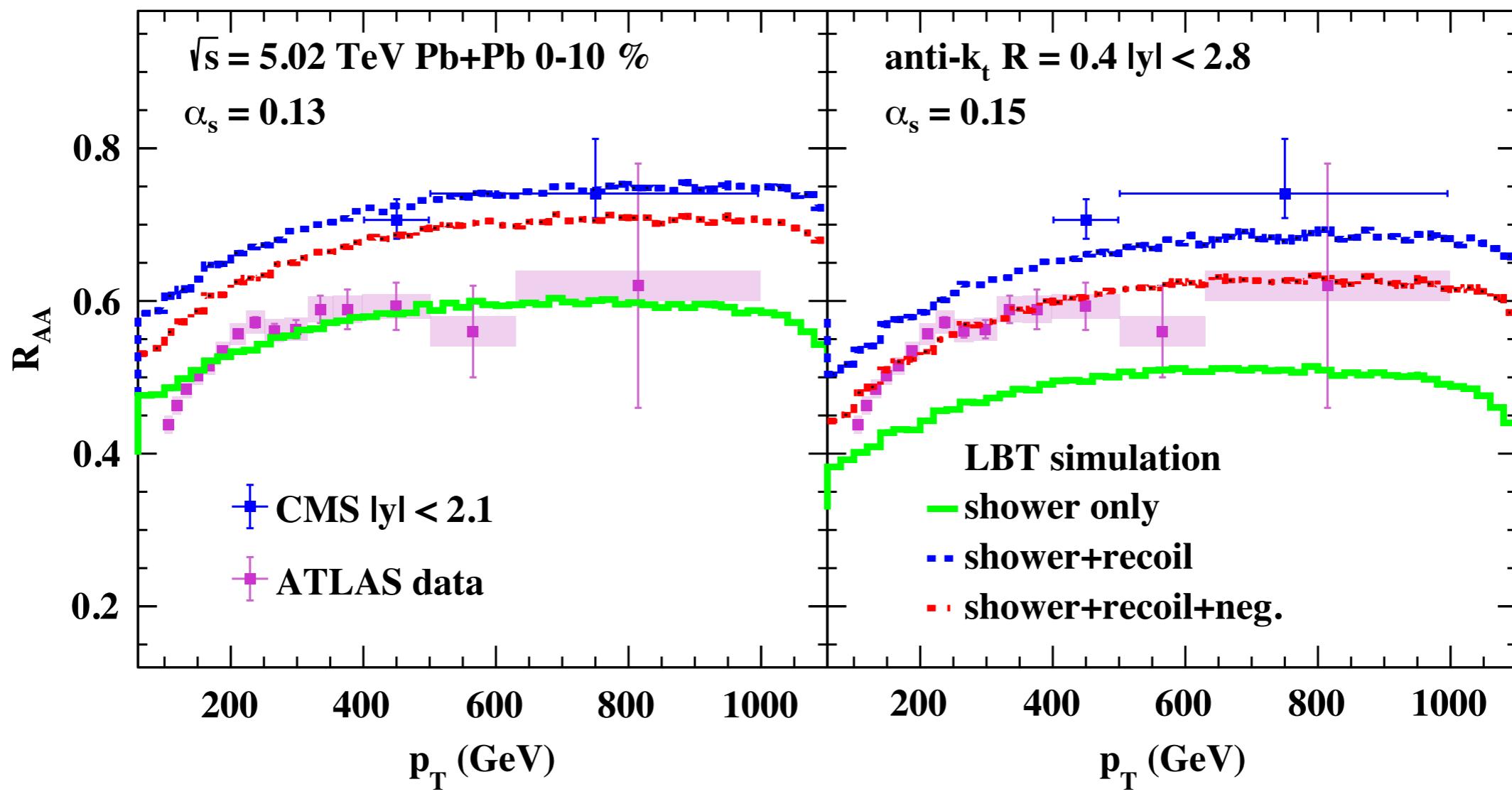


Initial jet parton: gluon



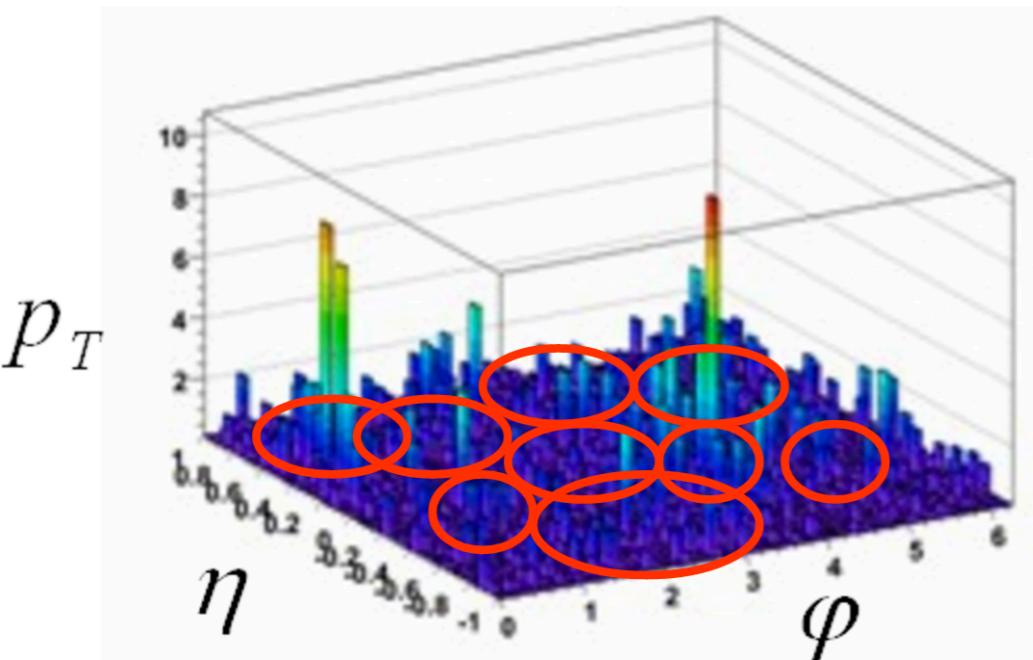
Initial jet parton: quark





# Underlying Event Subtraction (UES)

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



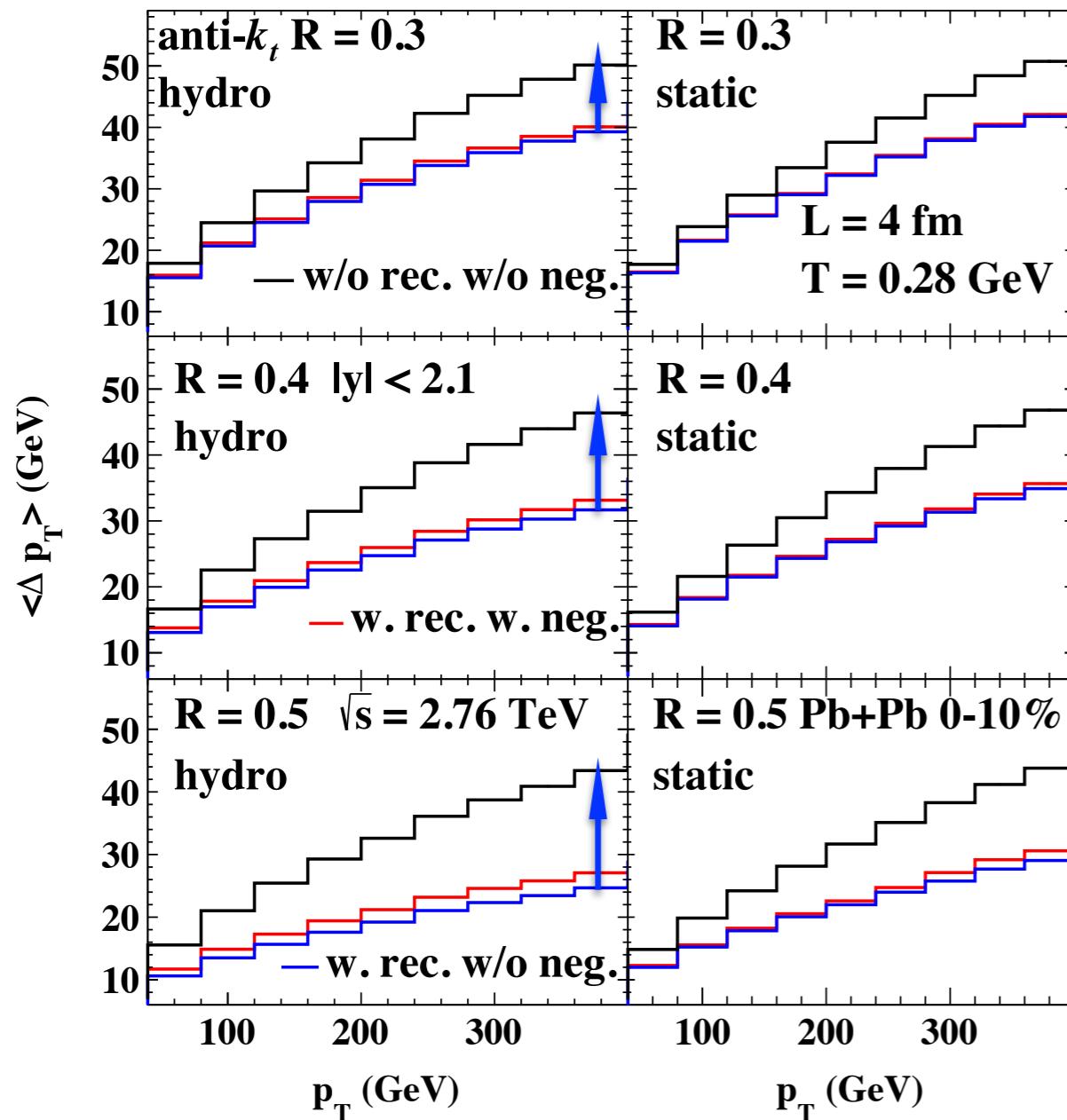
Seed jet:  $E_T > 3 \text{ GeV}$  for at least one parton, and  $E_T^{\max} / E_T^{\text{ave}} > 4$

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

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

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

# Effects of medium response and radial expansion



medium recoil effect up to 15%

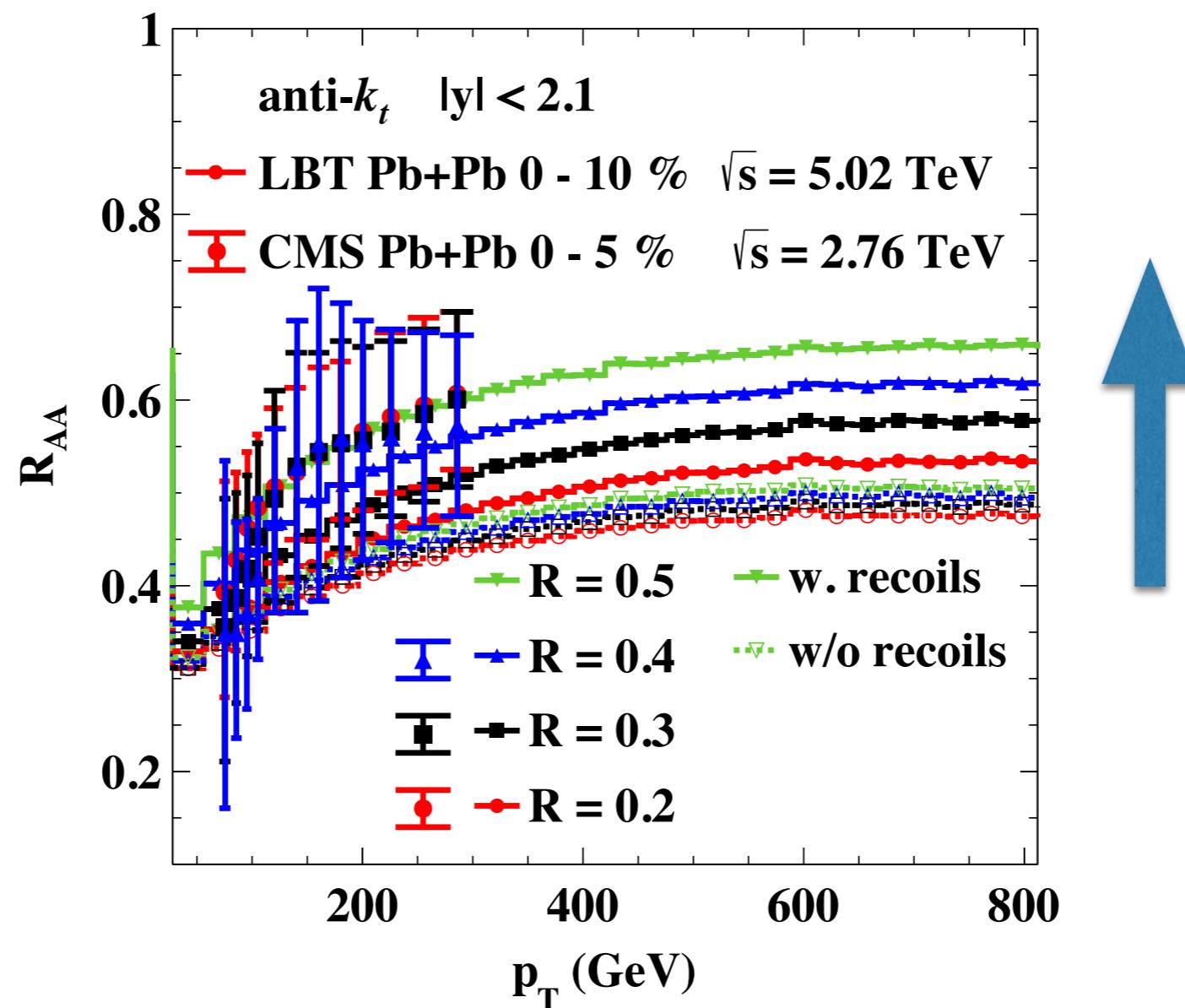
back reaction not negligible

larger cone size and radial expansion  
enlarges the effects above.

2.76 TeV



# Cone size dependence of $R_{AA}$

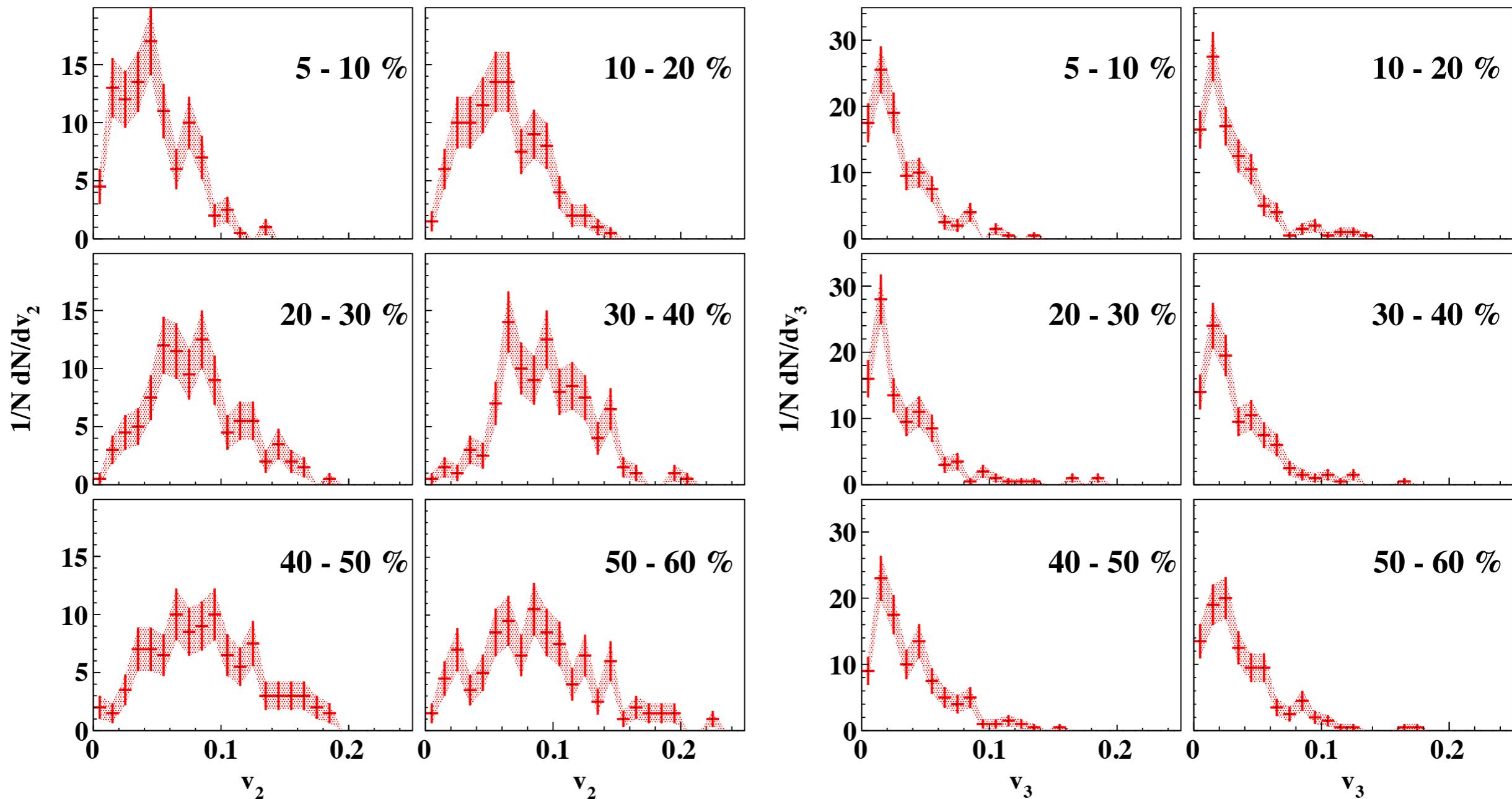


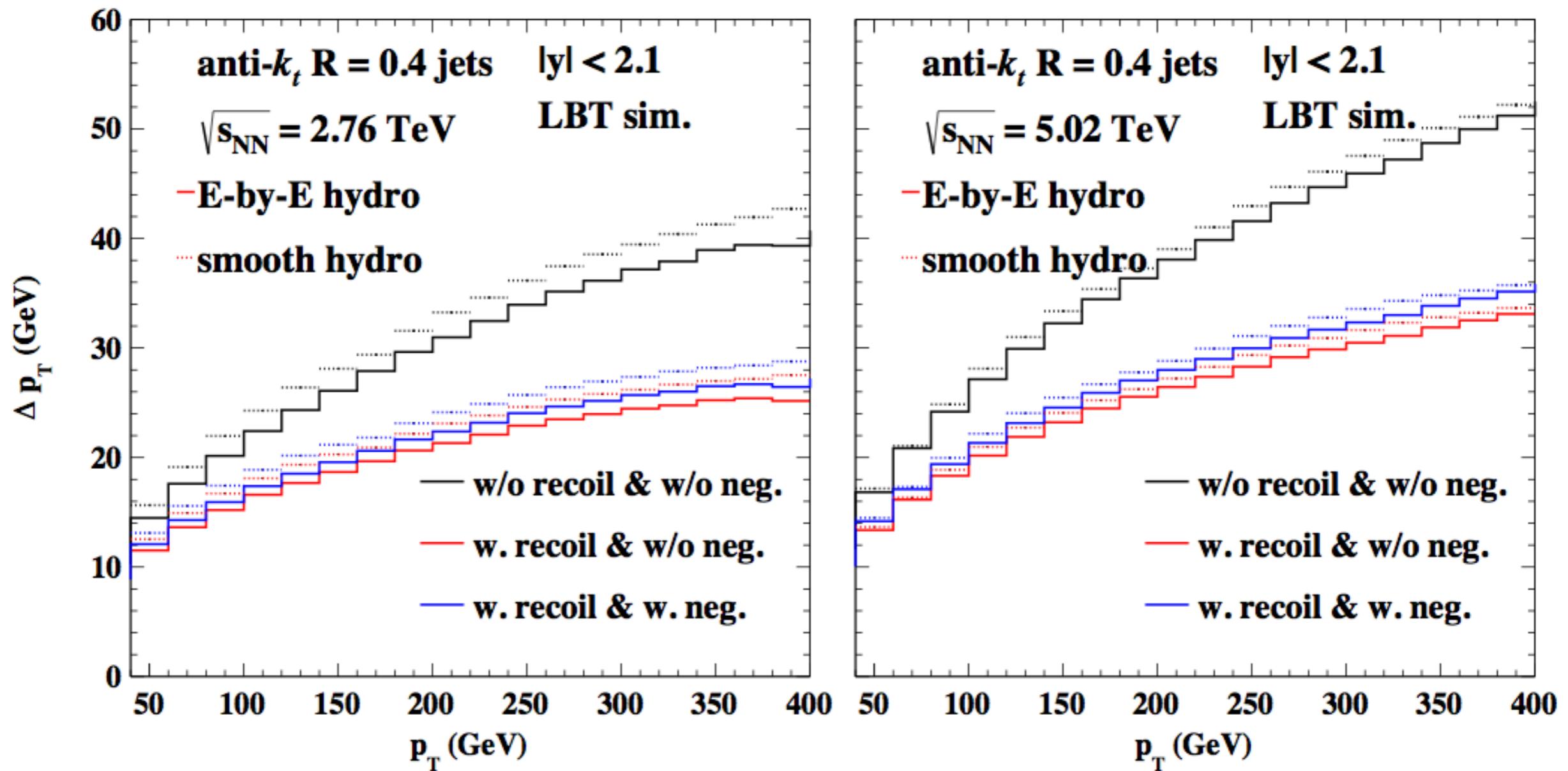
larger R: flatter initial spectrum + smaller energy loss  
-> less suppression

quantitatively relates to medium response



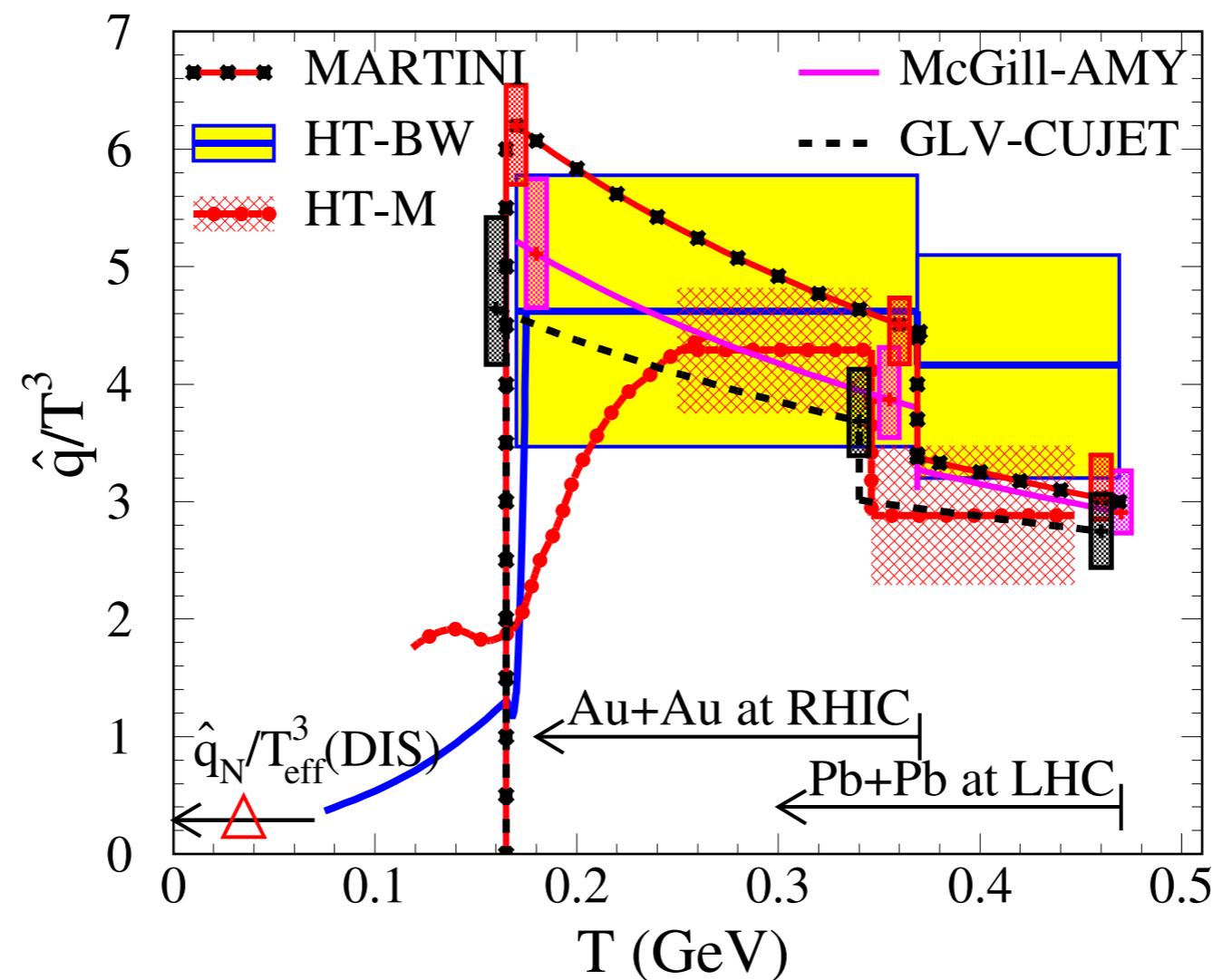
# $v_2$ of soft particles from hydro profiles





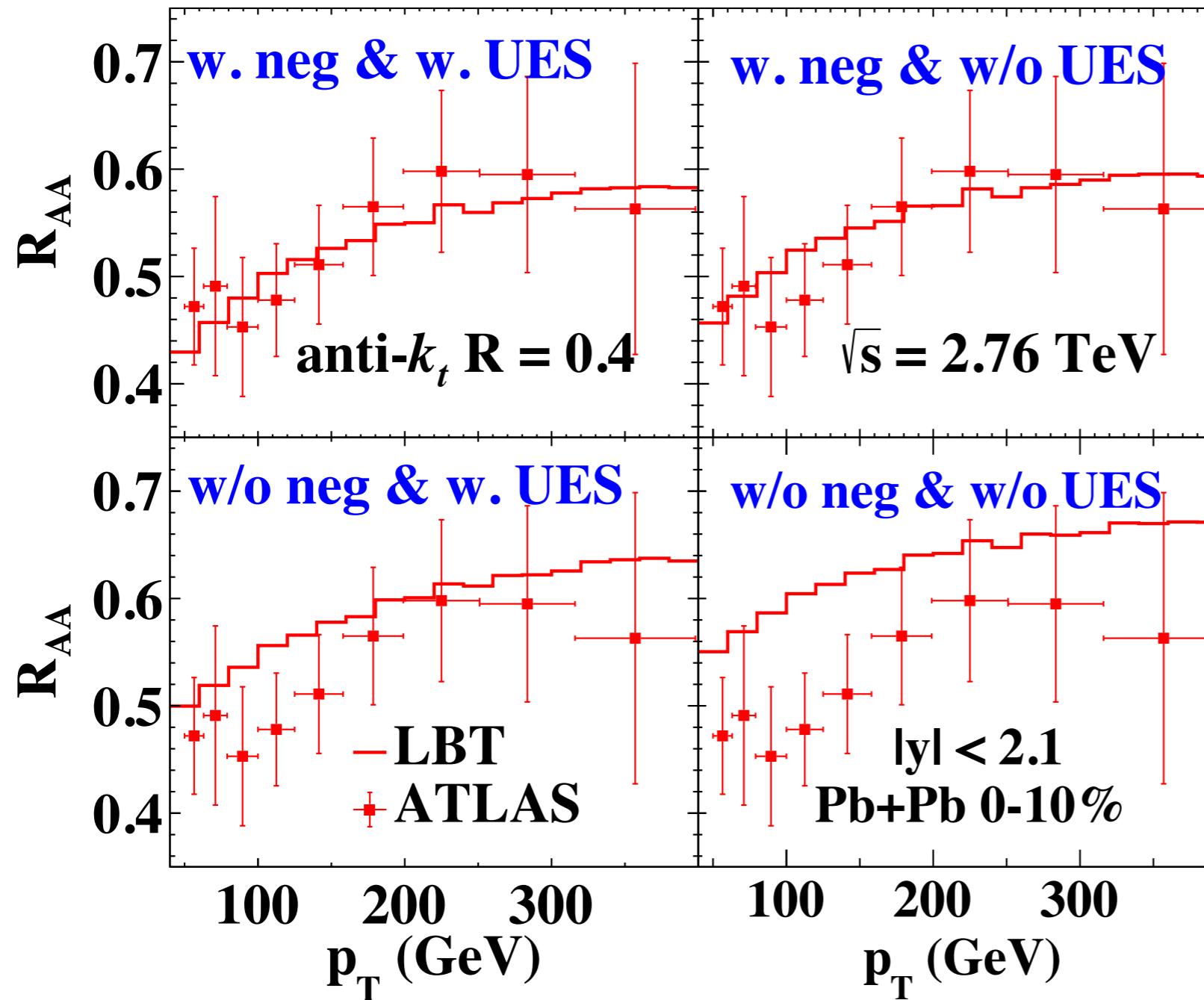
# jet-medium transport coefficient

$$\hat{q} = \frac{\langle \Delta p_T^2 \rangle}{\lambda}$$



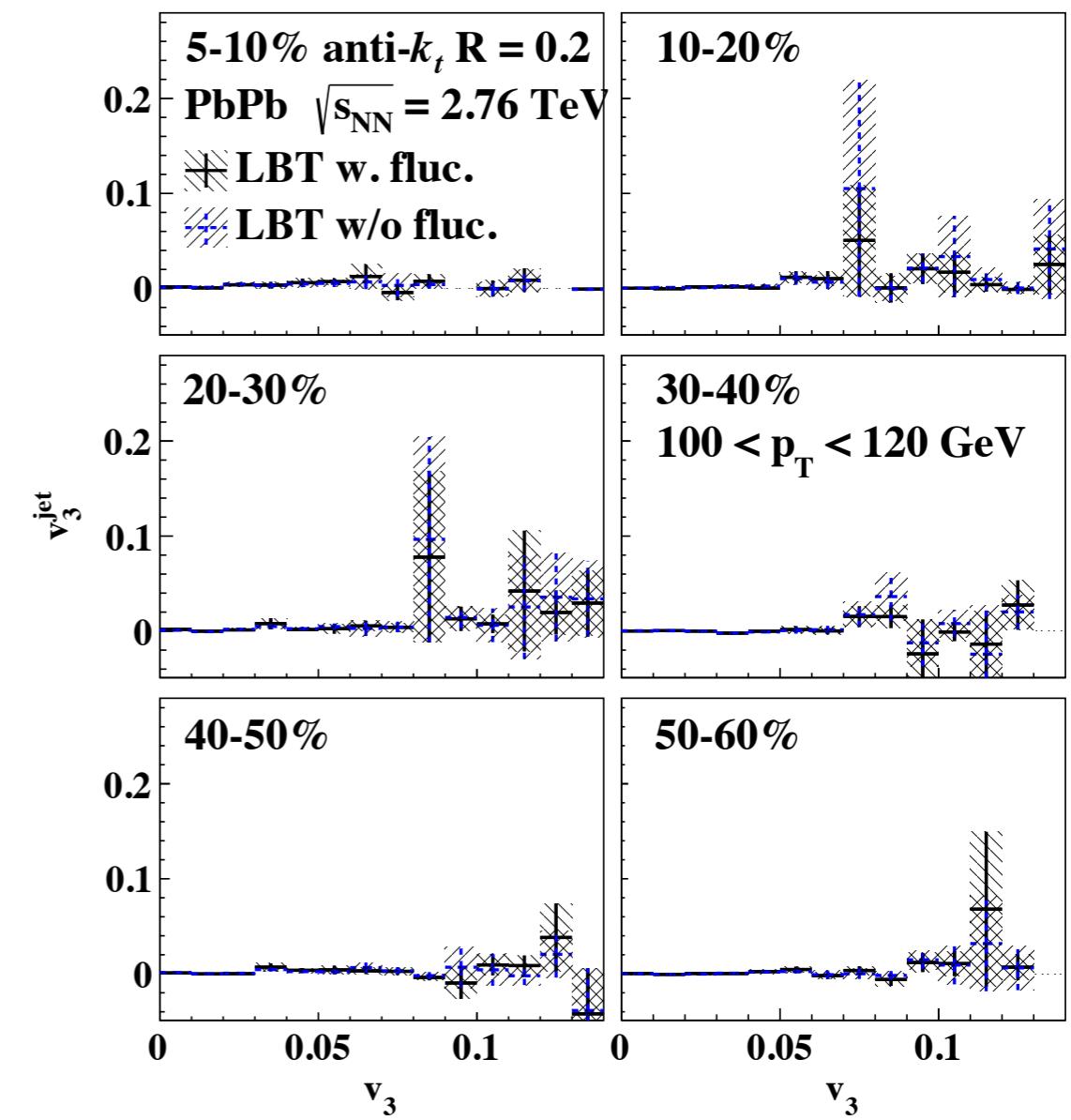
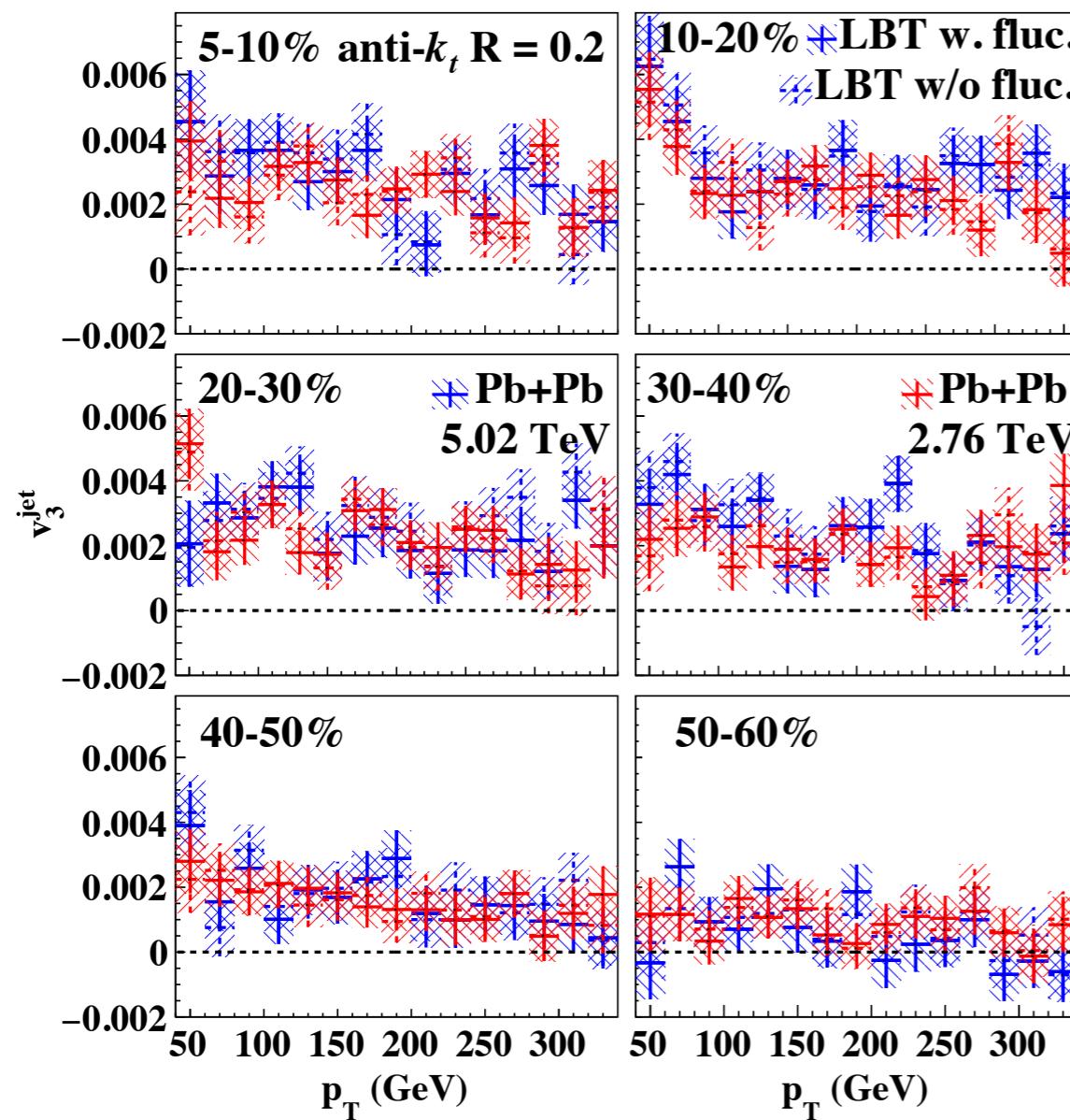
# Results: Inclusive jet suppression

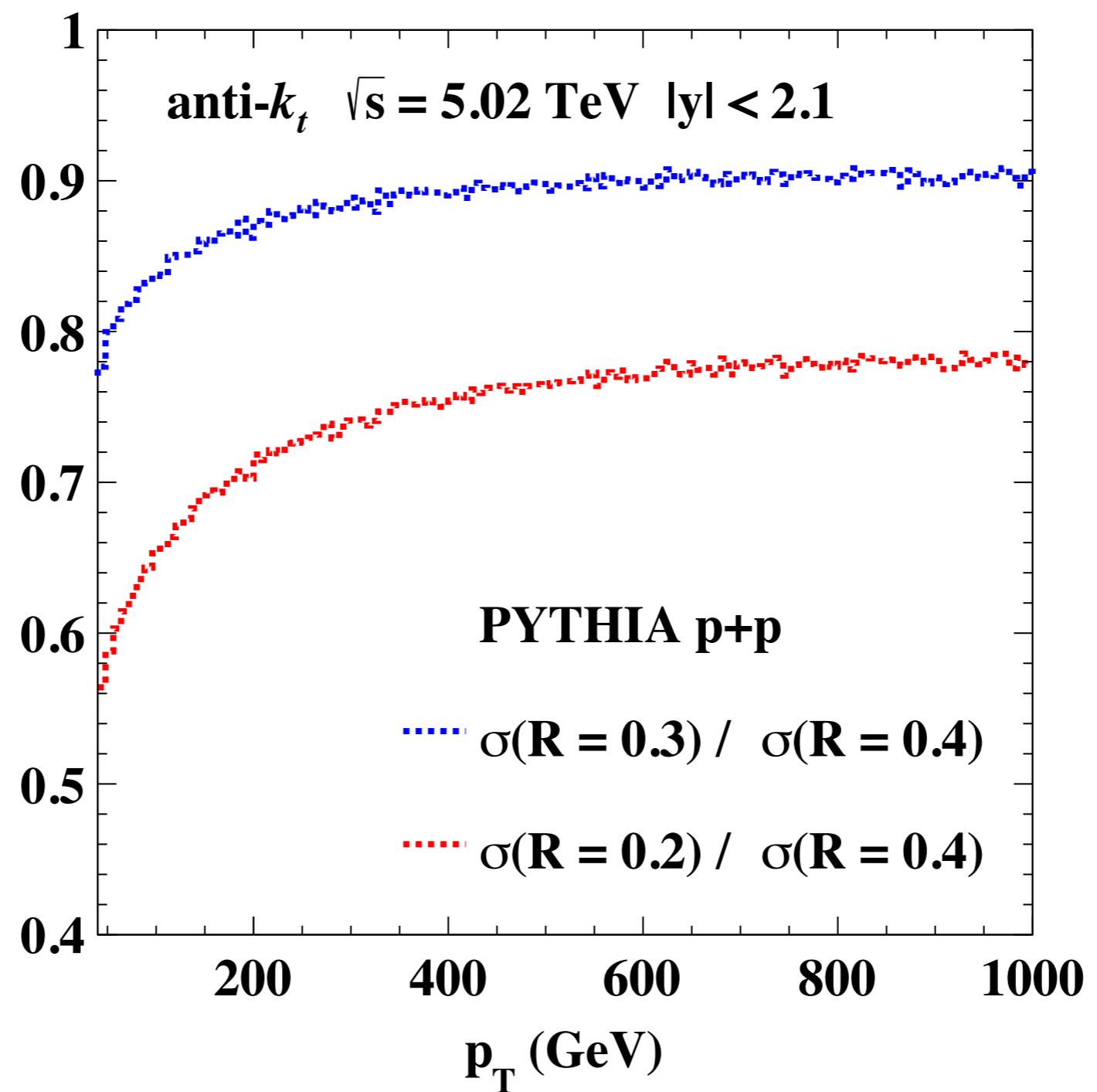
fixed  $\alpha_s = 0.15$



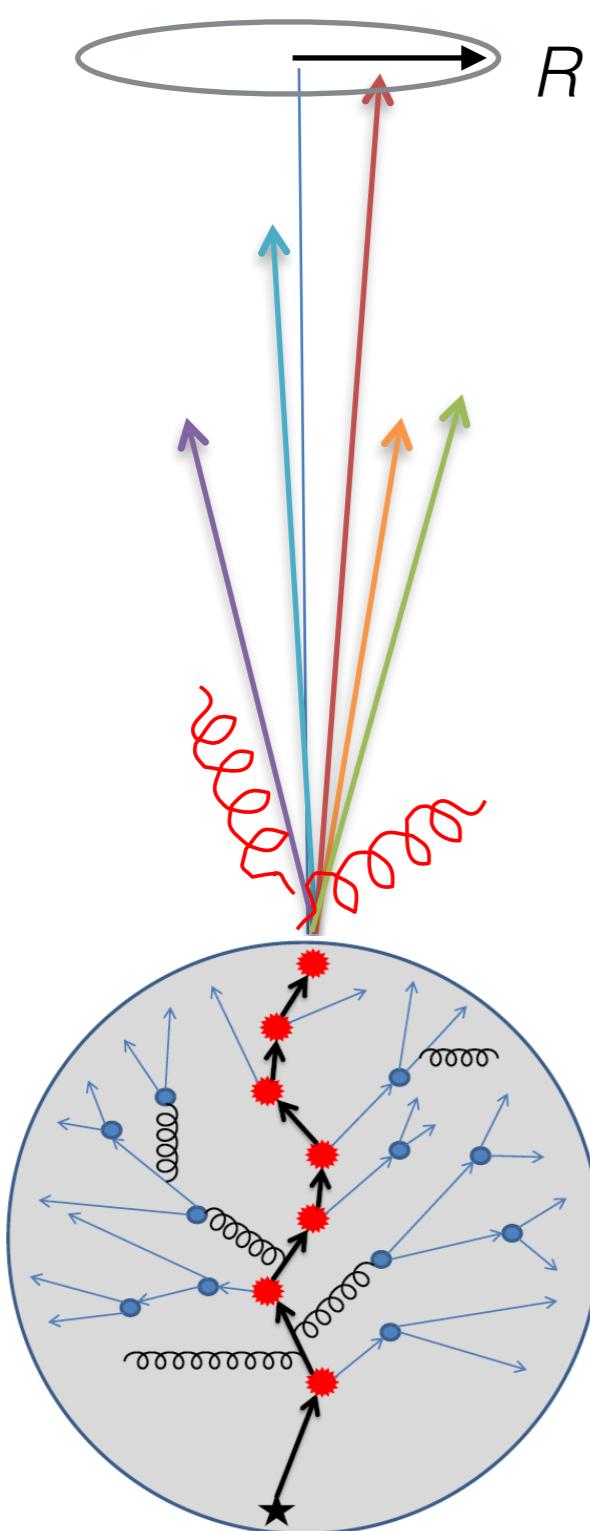
*Suppression!!!*  
w. neg (whole  $p_T$  range);  
w. UES (low  $p_T$  range)







# Jet reconstruction including medium recoils and back reaction



anti- $k_t$  algorithm in FASTJET package is used to reconstruct jets

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

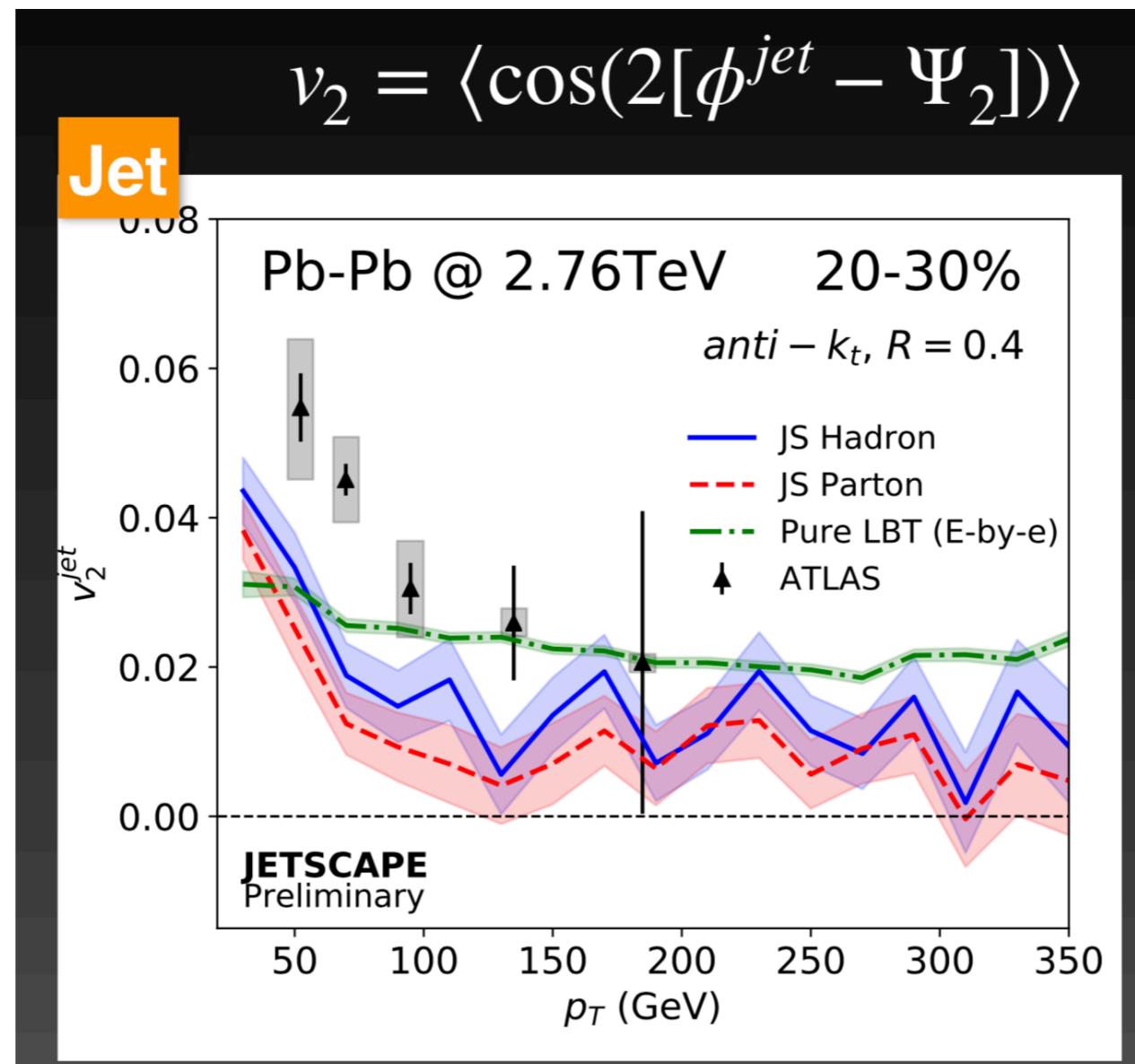
M. Cacciari, G. P. Salam and G. Soyez, Eur. Phys. J. C 72, 1896 (2012).

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

$$v_{\{2\}}^{\{jet\}} = \frac{\langle v_{\{2\}}^{\{soft\}} \cos(2[\phi^{\{jet\}} - \psi_{\{2\}}]) \rangle}{\sqrt{\langle (v_{\{2\}}^{\{soft\}})^2 \rangle}}$$

