

Event-by-event jet suppression, anisotropy and hard-soft tomography



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Aix-Les-Bains, Hard Probes 2018
04 Oct 2018



Outline

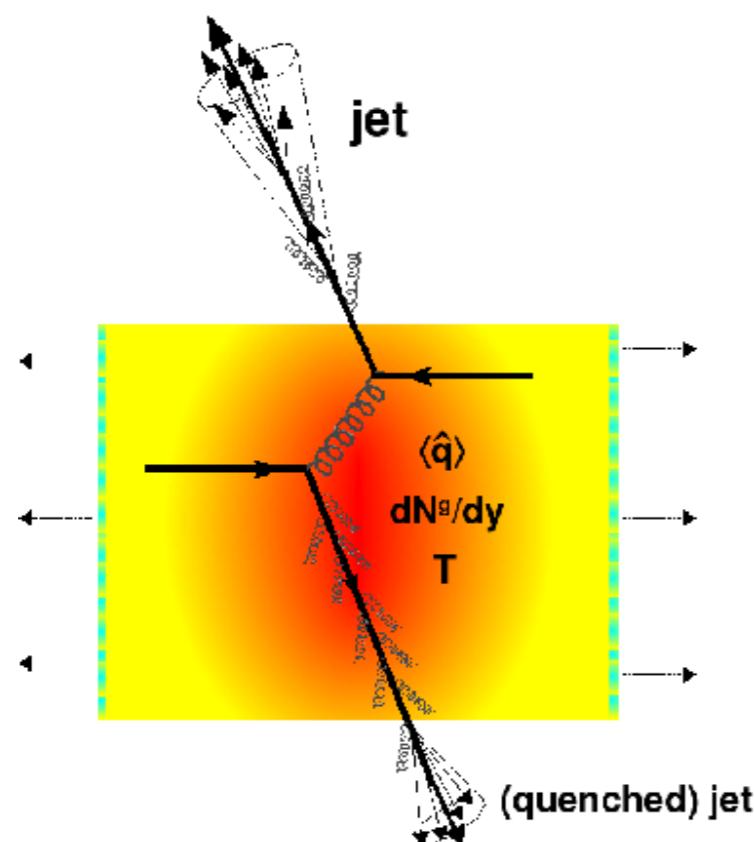
- I. Motivation
- II. The Linear Boltzmann Transport (LBT) Model
- III. Results: jet suppression & anisotropy
- IV. Summary & Outlook



Motivation

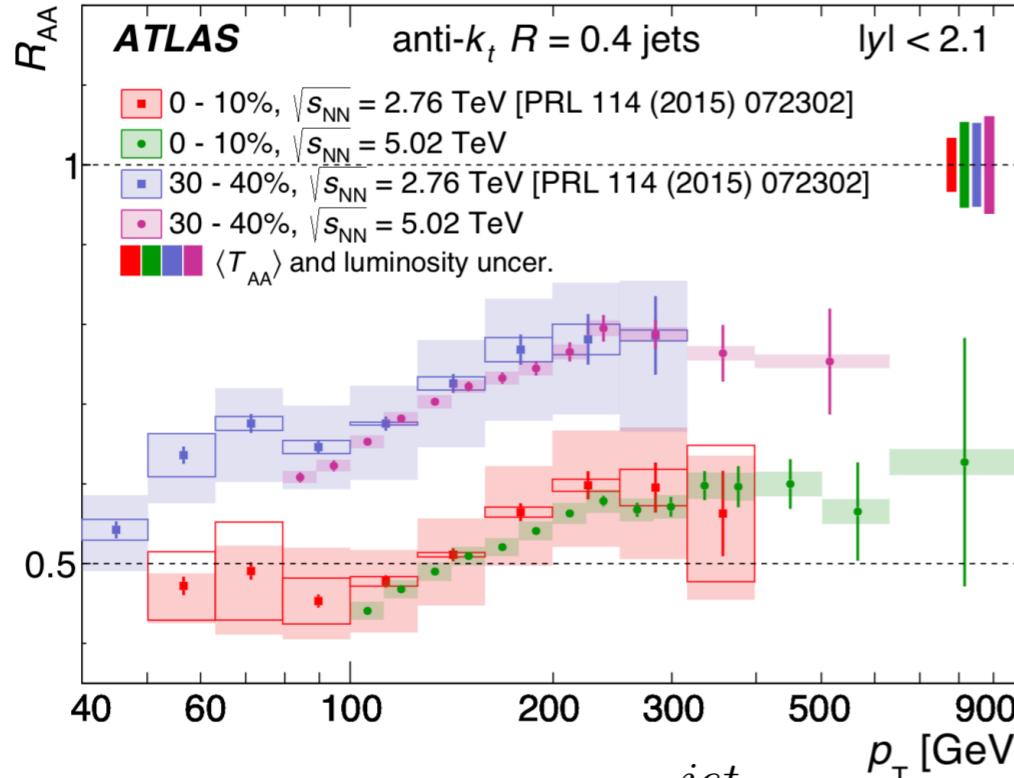
QGP Probes:

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



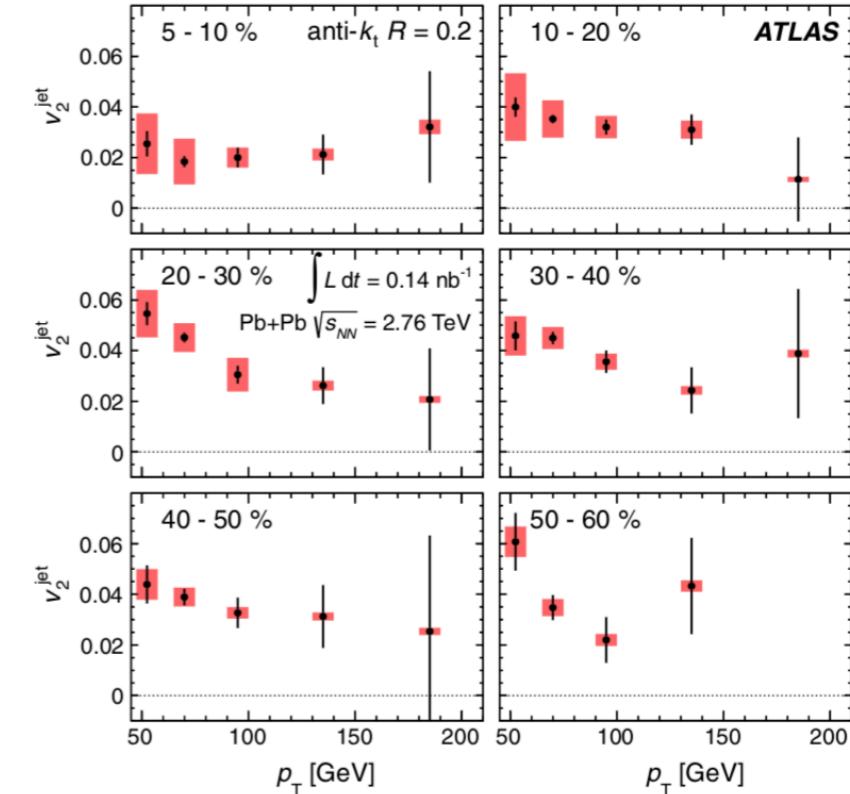
jet quenching:
jet energy loss when a jet
propagates in the medium

Motivation



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

arXiv:1411.2357, arXiv:1805.05635



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

arXiv:1306.6469

Jet R_{AA} are almost the **same and go flat** for 2.76 TeV and 5.02 TeV. Why ?

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

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

NLO twist-4

Guo and Wang, PRL 85 (2000)

Re-scattering for shower partons, medium recoils and radiated gluons.

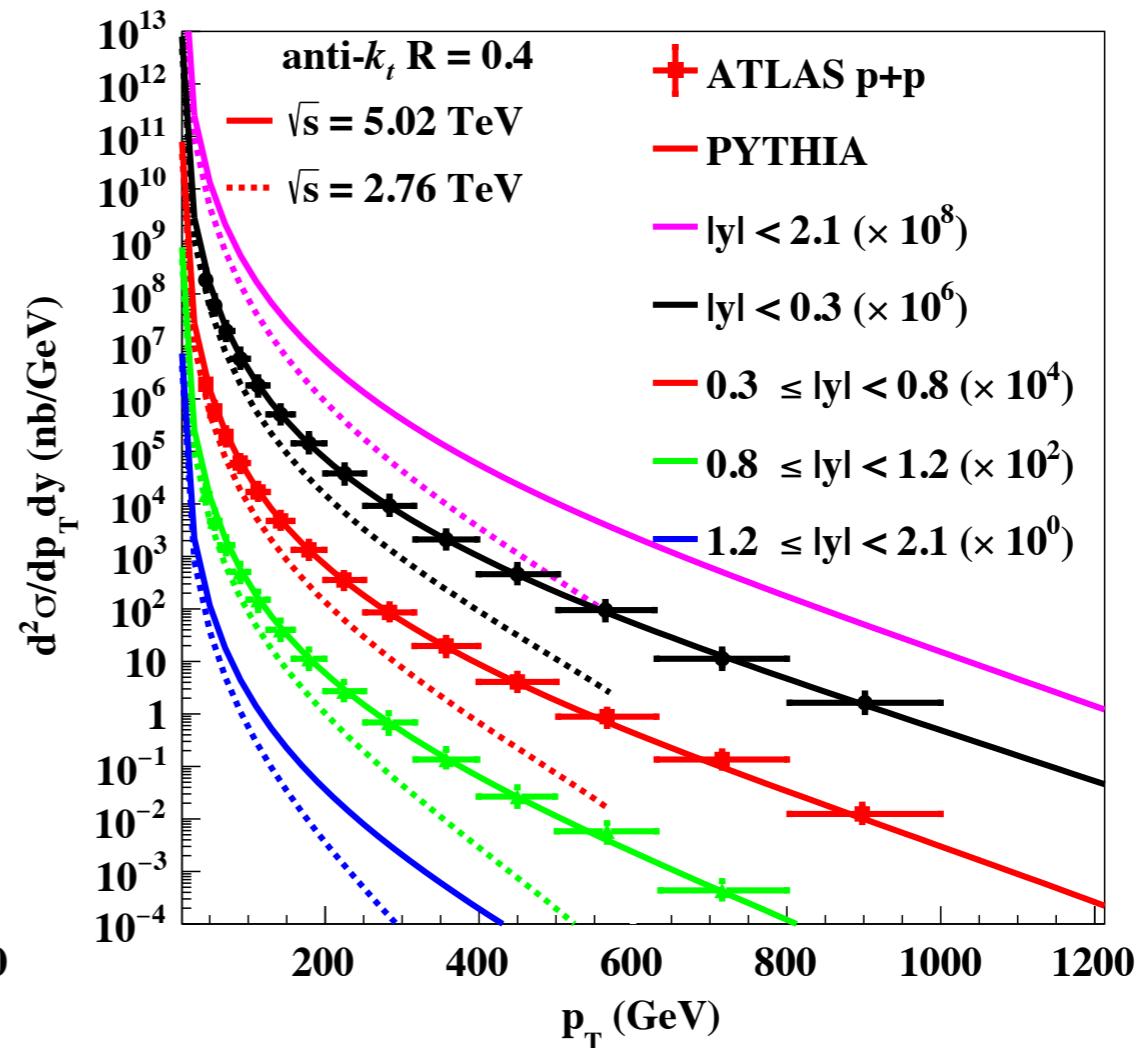
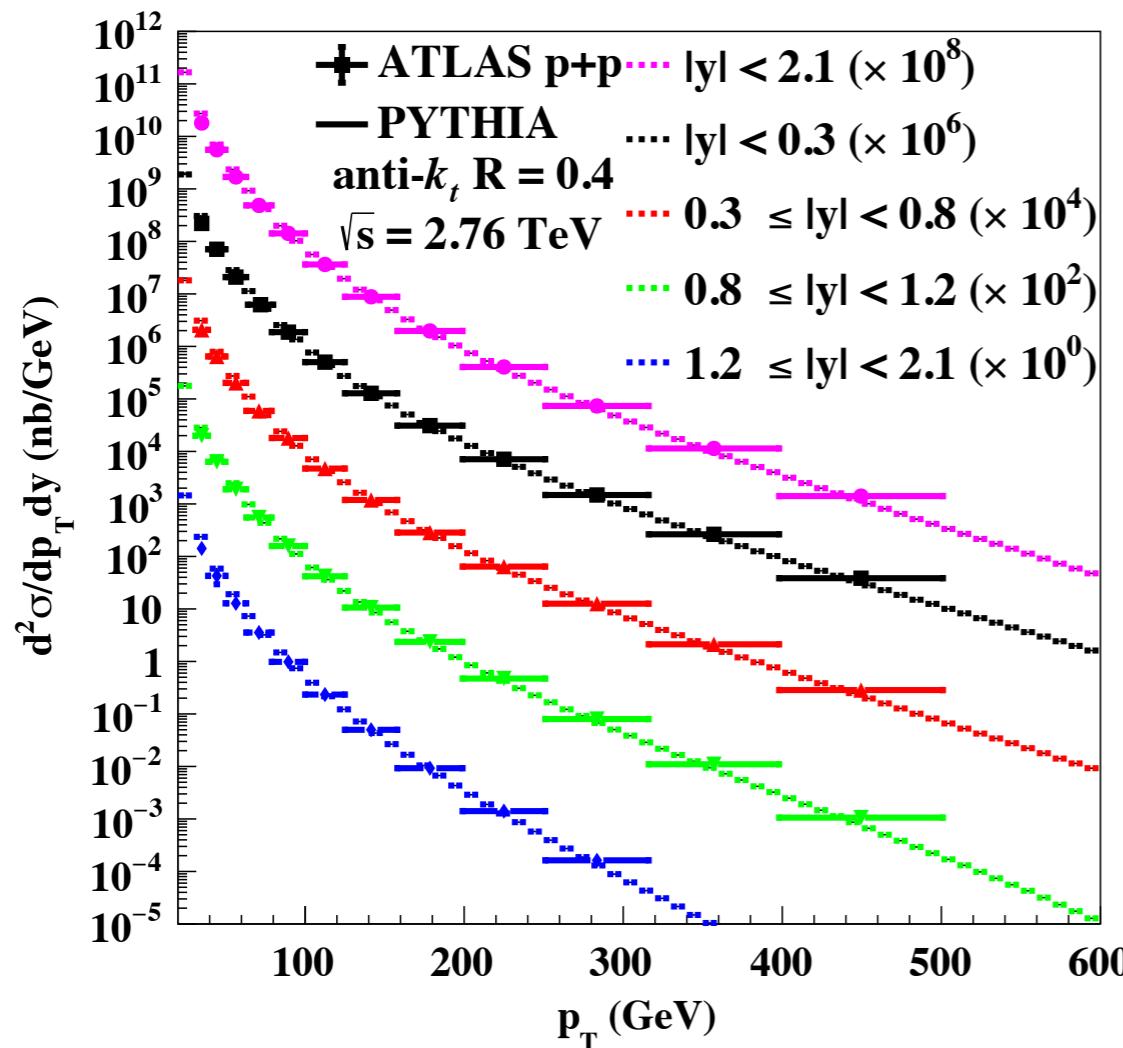
Include back reaction for E-M conservation, subtracted.

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



The inclusive jet in pp collisions

p_T distribution of pp collision within PYTHIA 8

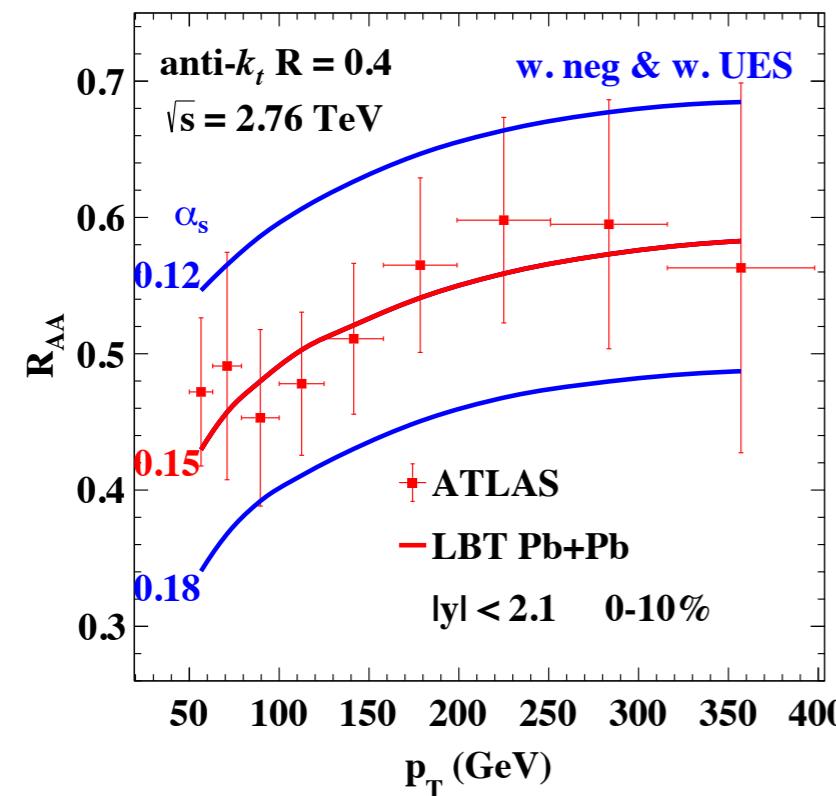
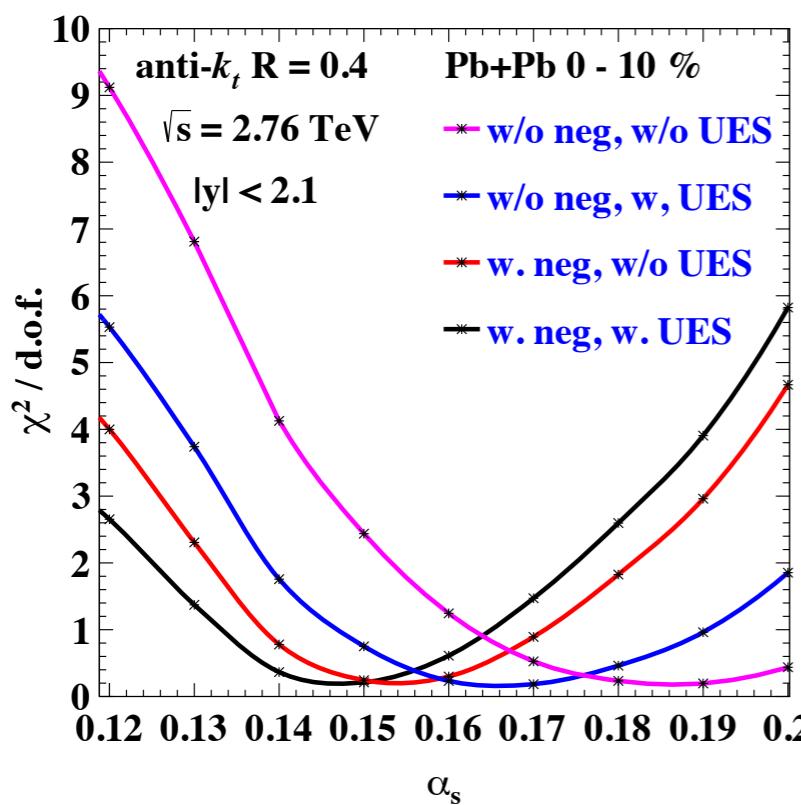


The spectrum at 5.02 TeV is higher and much flatter than at 2.76 TeV, which originates from PDFs.



Fix strong coupling constant

Y. He et al, arXiv:1809.02525



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

neg.: “negative particles”, back reaction.

UES: underlying event subtraction.

Inclusion of neg. or UES decreases jet energy

Effective α_s : collisional, radiation,
Debye screening mass,

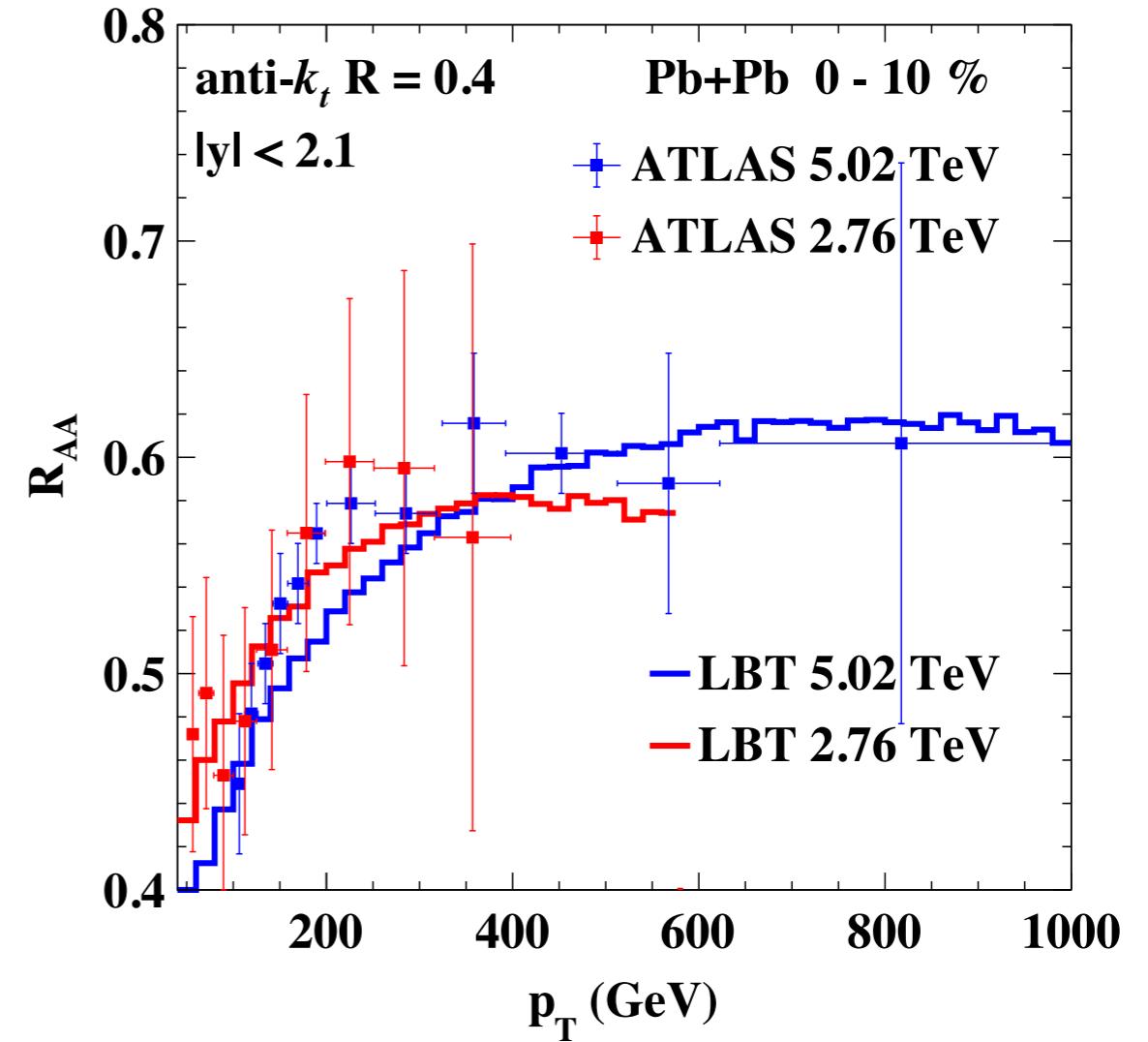
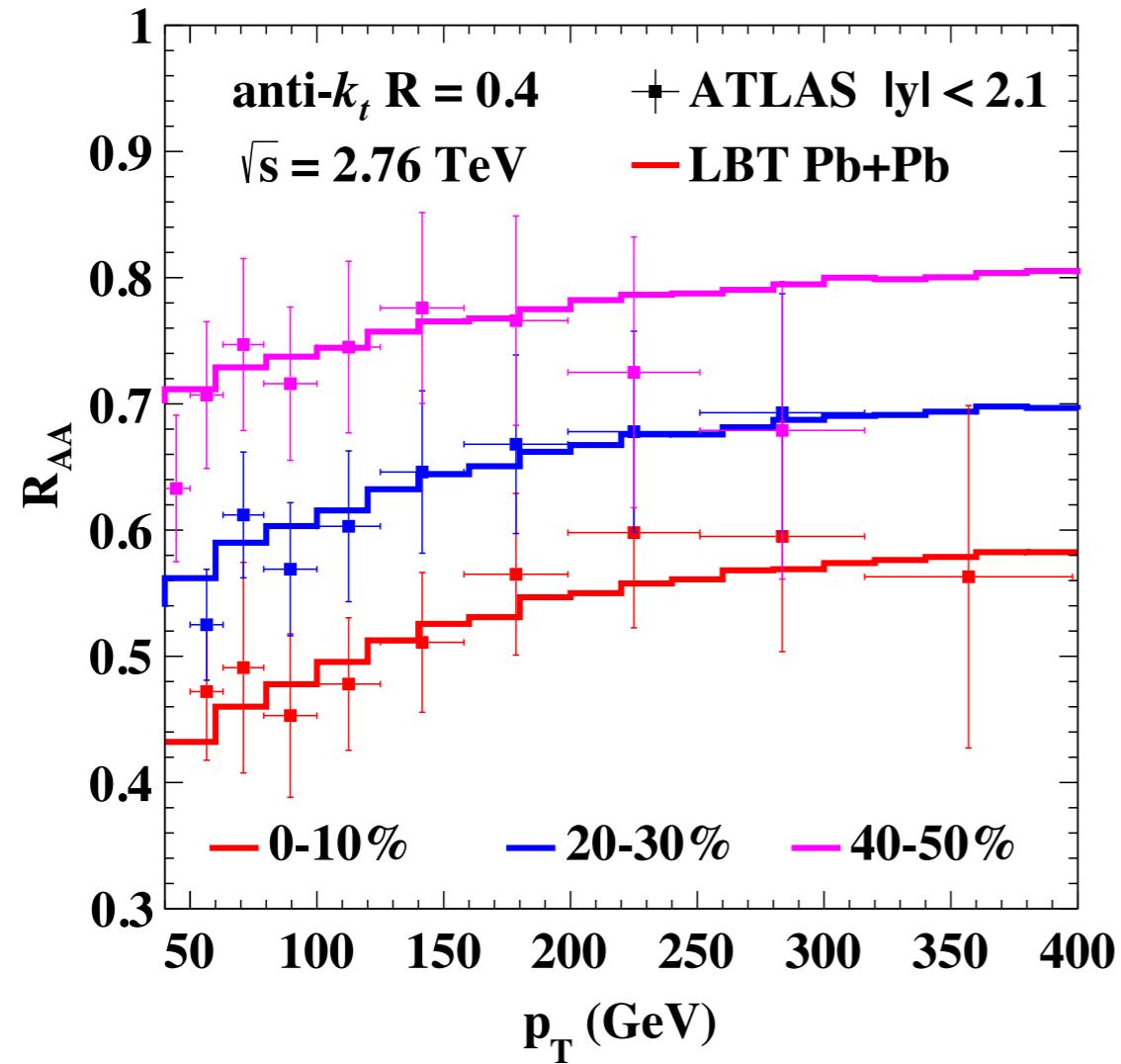
$$\Gamma_g \approx \sum_{b=g, q_i, \bar{q}_i} \Gamma_{gb \rightarrow gb} \approx 42 C_A \zeta(3) \frac{\alpha_s^2 T^3}{\pi \mu_D^2},$$

$$\alpha_s = 0.15$$

will be larger in a multistage evolution

see: Chanwook Park, HP 2018

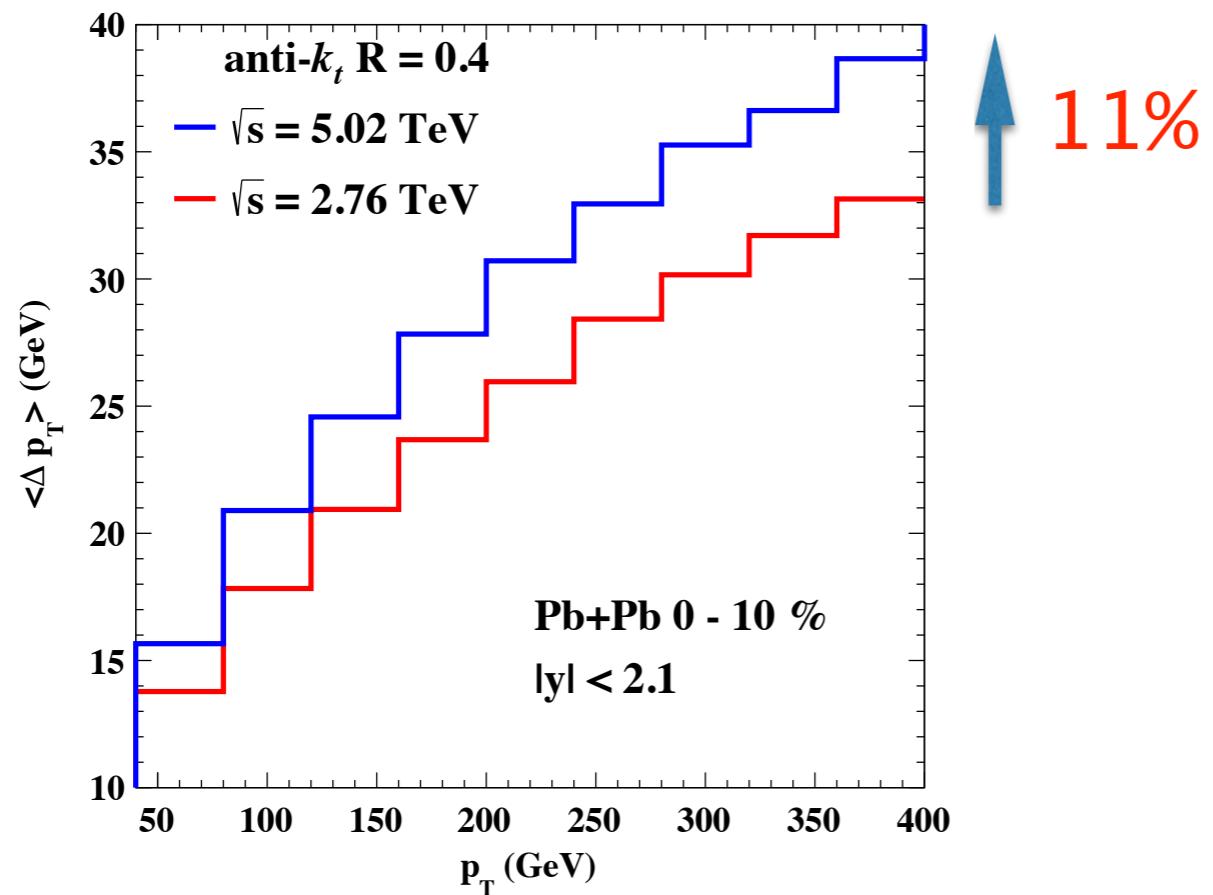
Inclusive jet suppression



R_{AA} slightly increases with jet p_T for 2.76 TeV and 5.02 TeV.



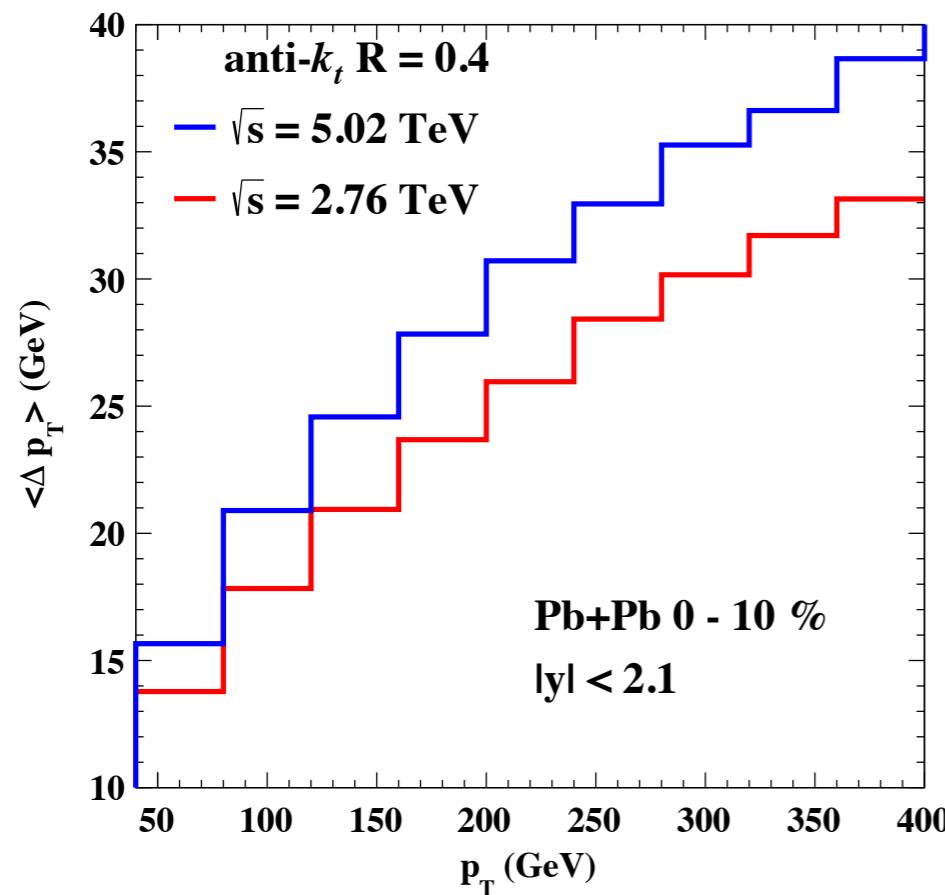
Understanding jet R_{AA}



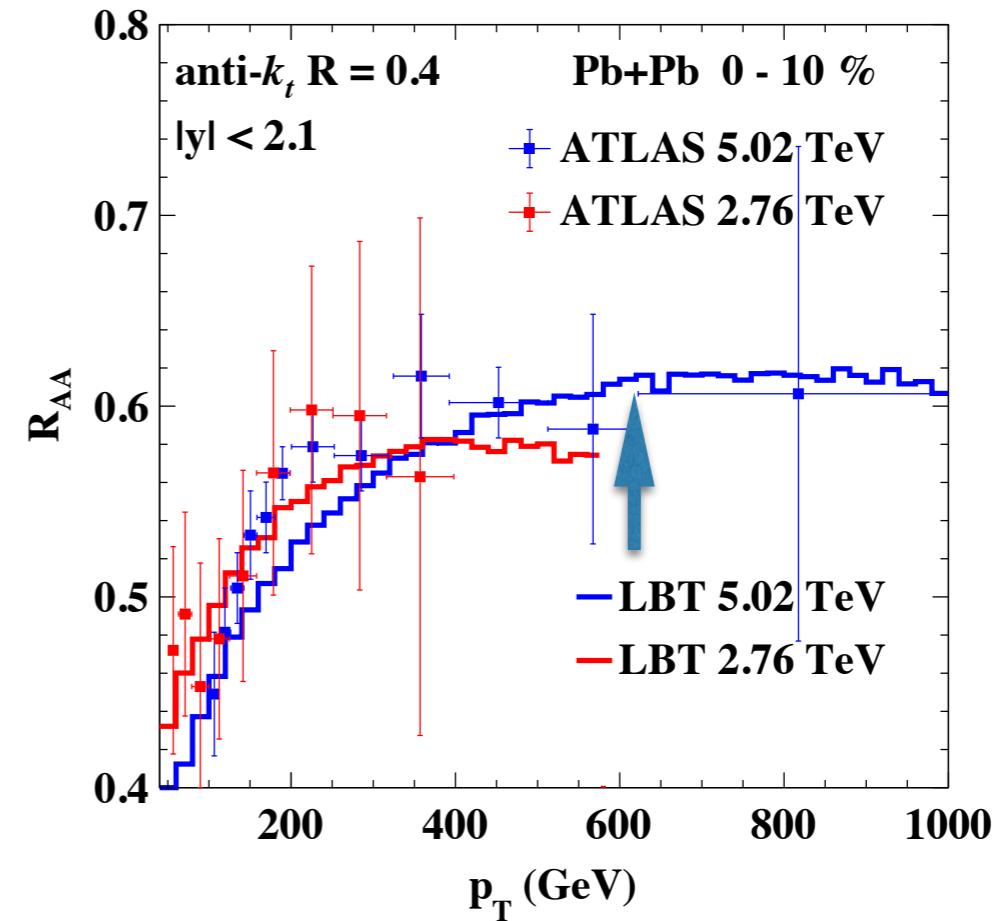
Jet energy loss at 5.02 TeV is indeed **larger** than at 2.76 TeV.



Understanding jet R_{AA}



↑ 11%

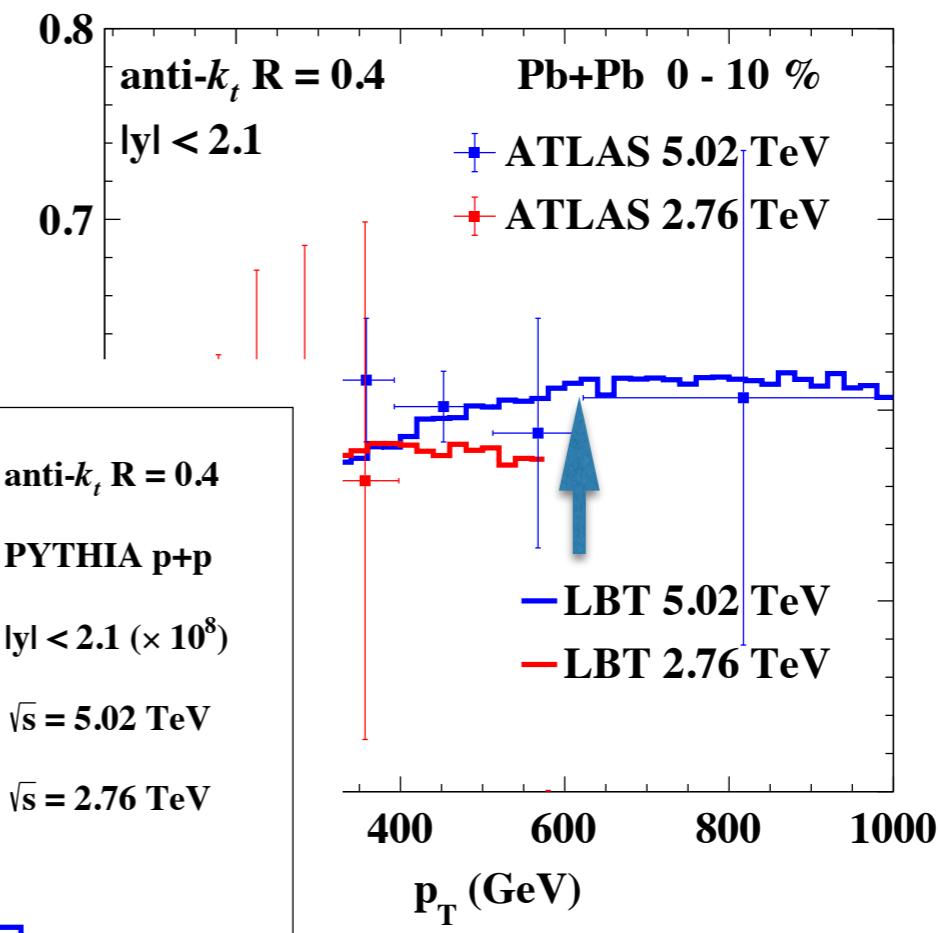
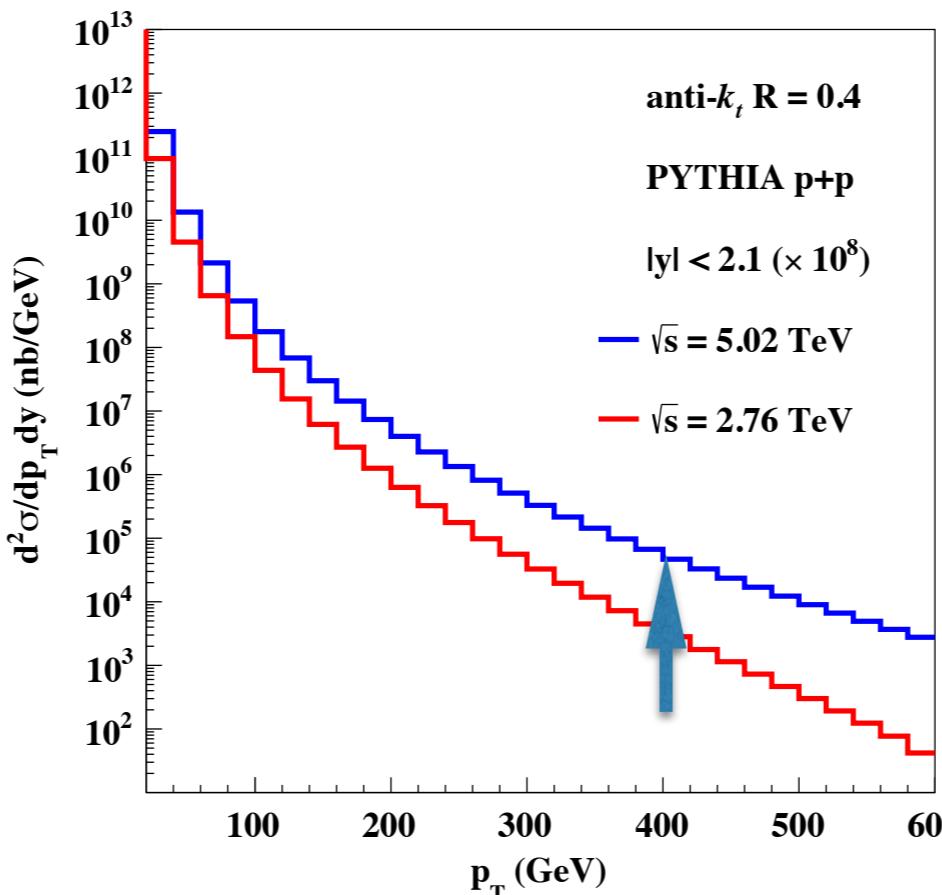
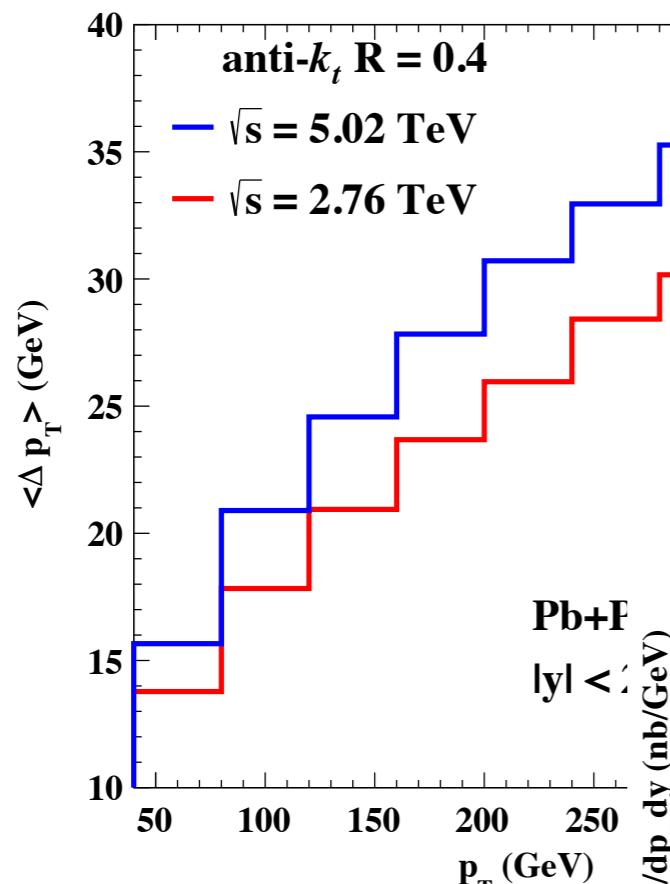


Jet energy loss at 5.02 TeV is indeed **larger** than at 2.76 TeV.

But jet R_{AA} at 5.02 TeV is **higher** than at 2.76 TeV. at large p_T range

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

Understanding jet R_{AA}



Jet energy loss at 5.02 TeV is larger than at 2.76 TeV.

But Jet R_{AA} at 5.02 TeV is smaller than at 2.76 TeV.

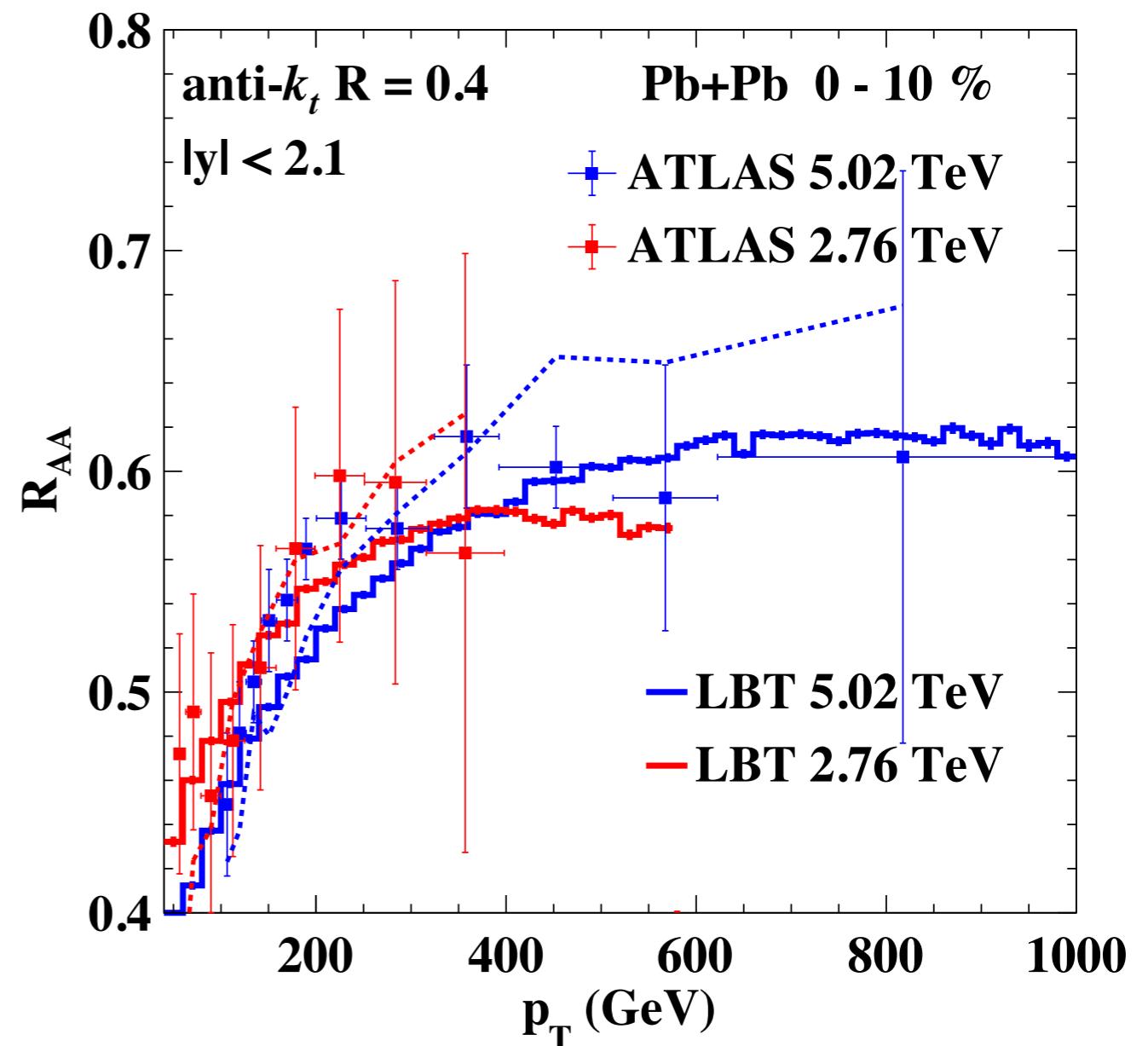
Because p_T spectrum at 5.02 TeV is much **flatter** than at 2.76 TeV.



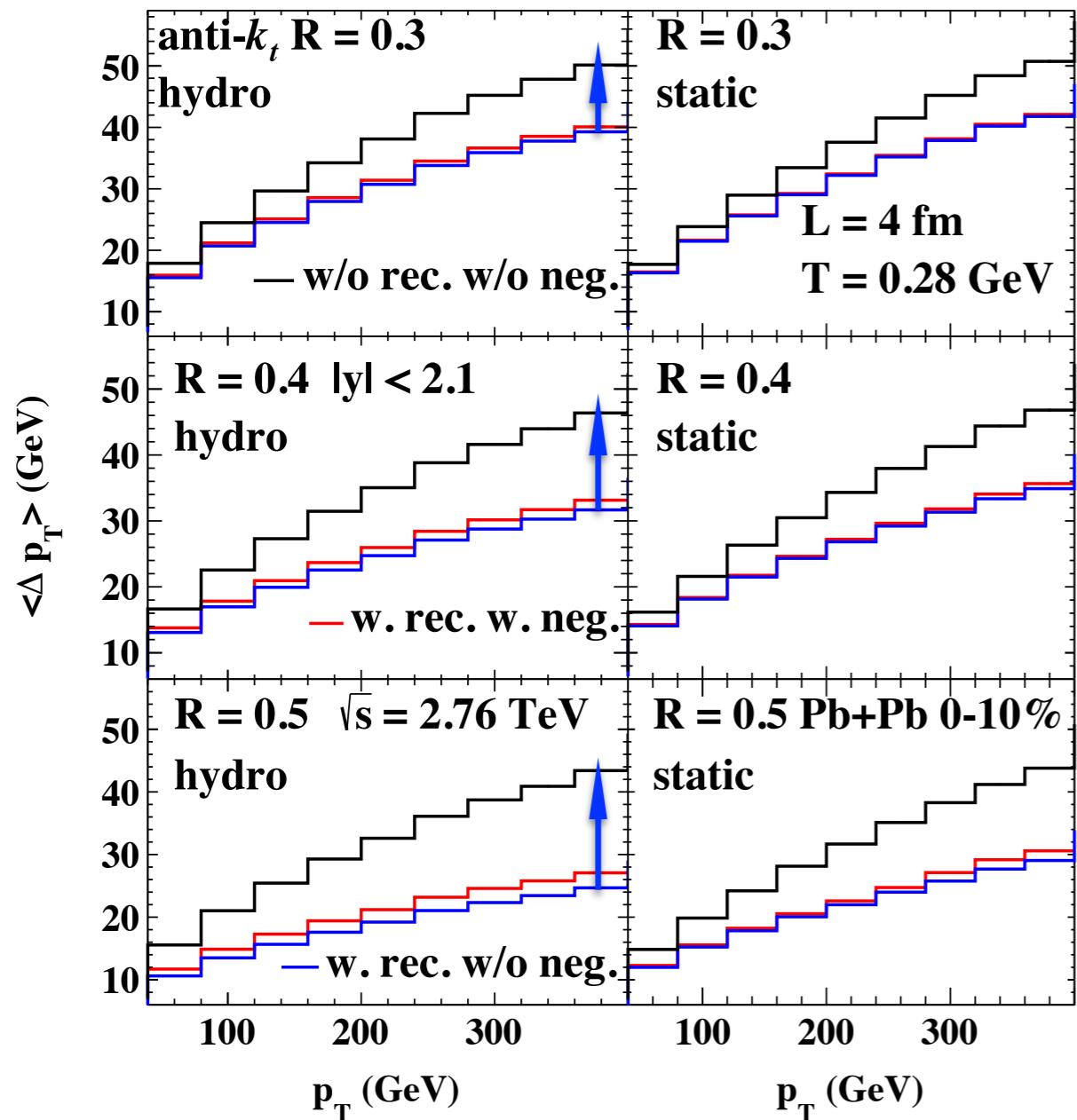
Understanding jet R_{AA}

If $\langle \Delta p_T \rangle / p_T$ is small,

$$R_{AA}(p_T) \approx \frac{d\sigma_{p+p}^{\text{jet}}(p_T + \langle \Delta p_T \rangle)}{d\sigma_{p+p}^{\text{jet}}(p_T)}$$



Effects of medium response and radial expansion



medium recoil effect up to 15%

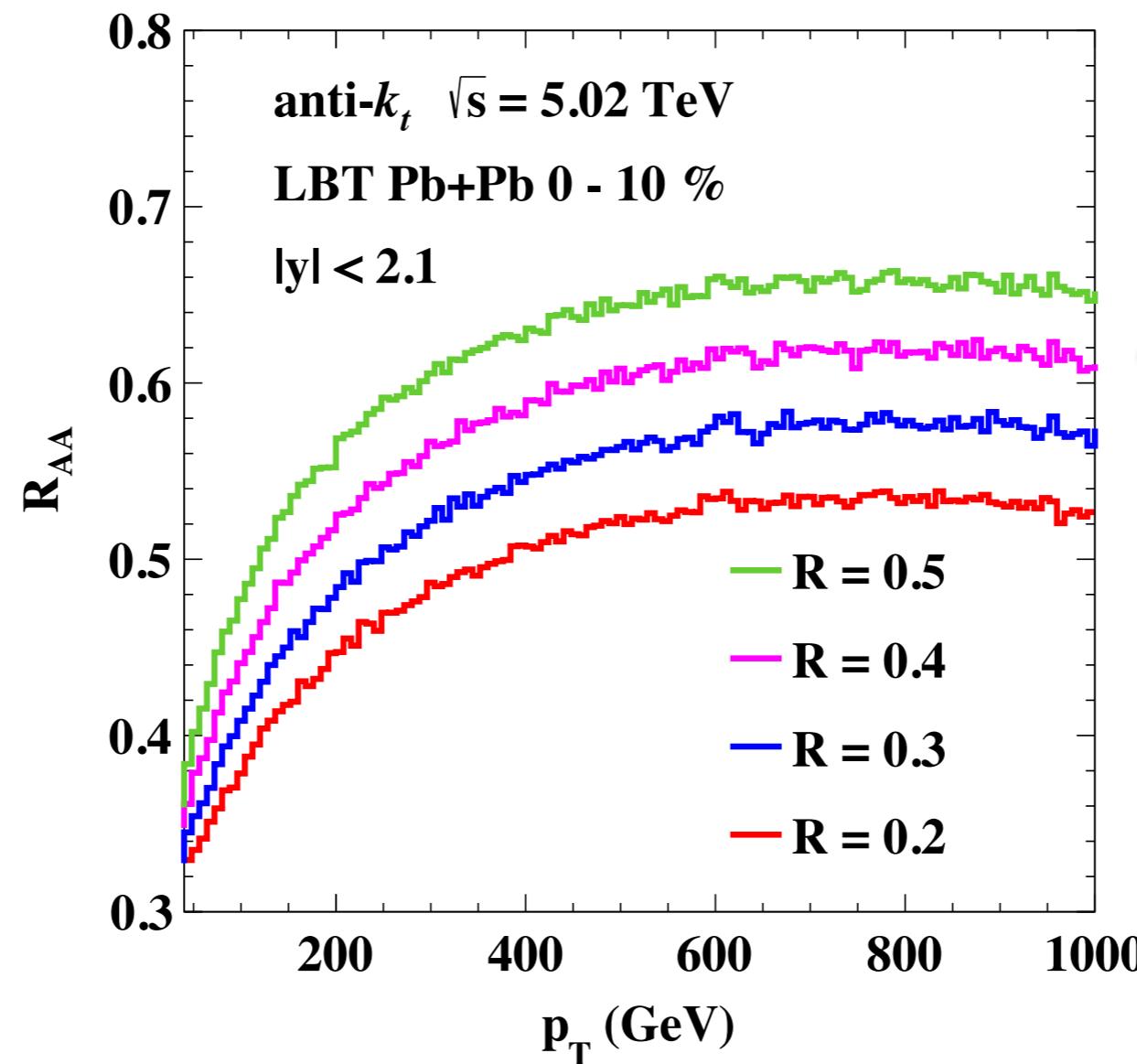
back reaction not negligible

larger cone size and radial expansion
enlarges the effects above.

2.76 TeV



Cone size dependence of R_{AA}

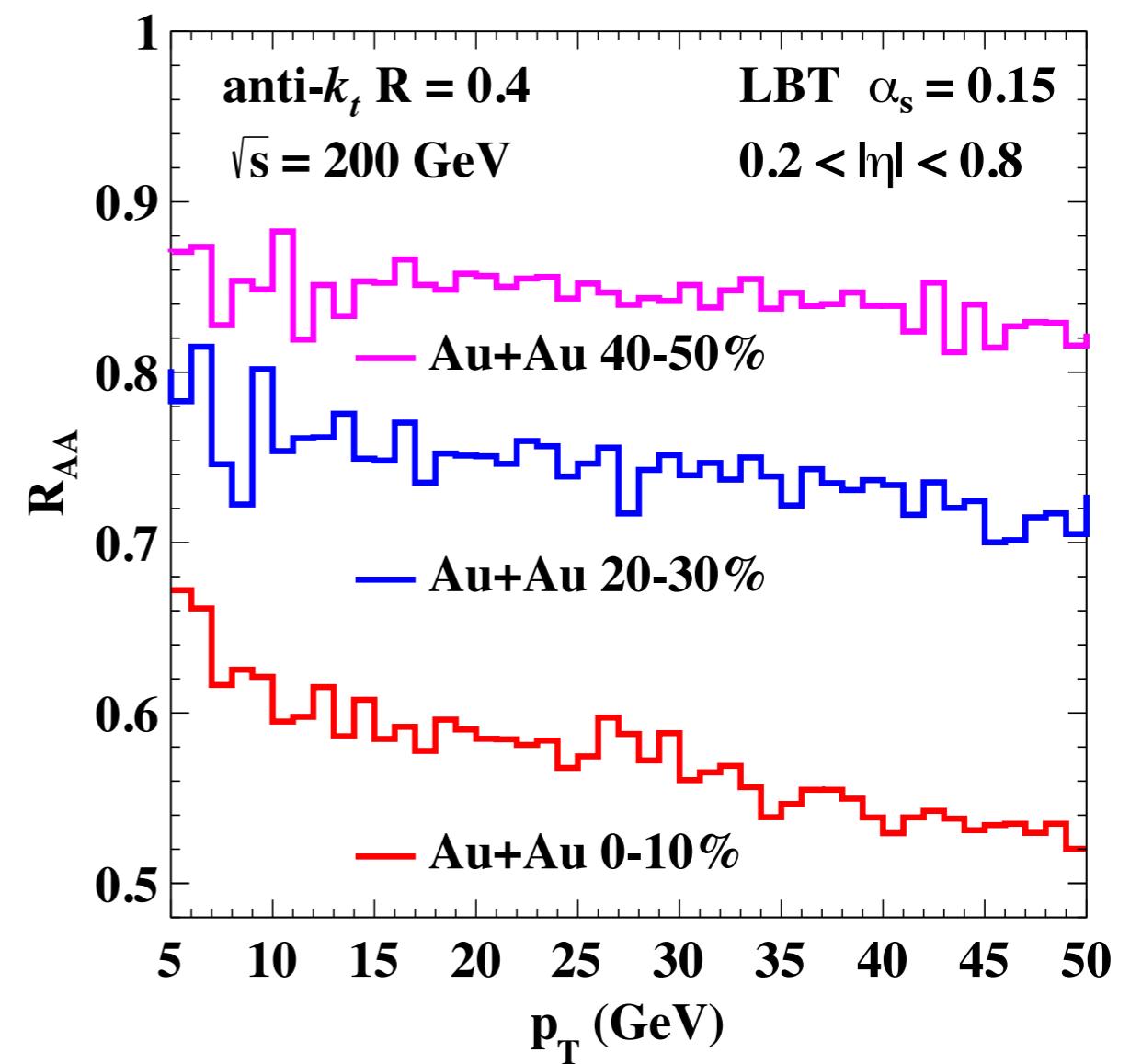
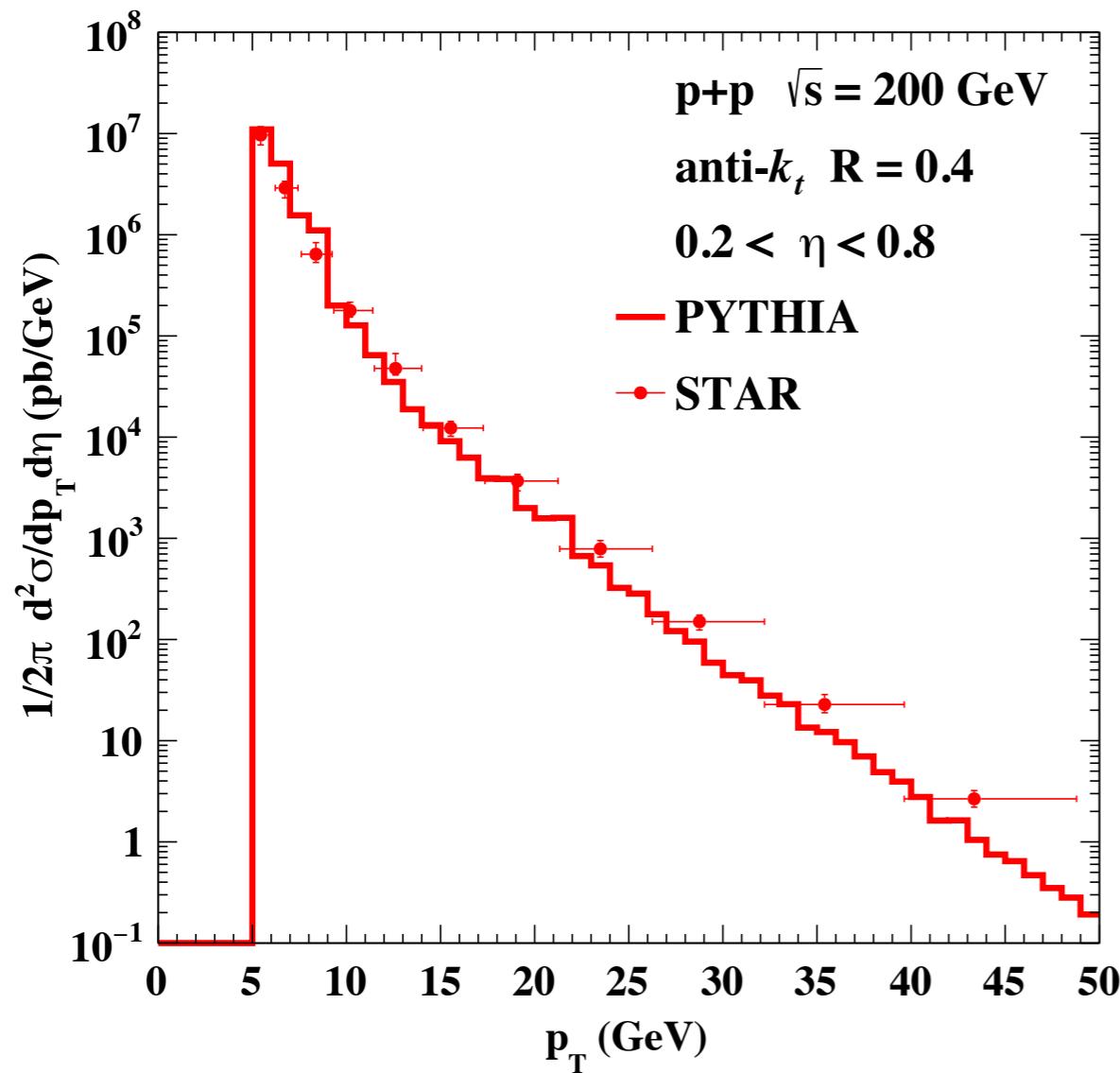


larger R: flatter initial spectrum + smaller energy loss
-> less suppression

quantitatively relates to medium response



R_{AA} at RHIC energy



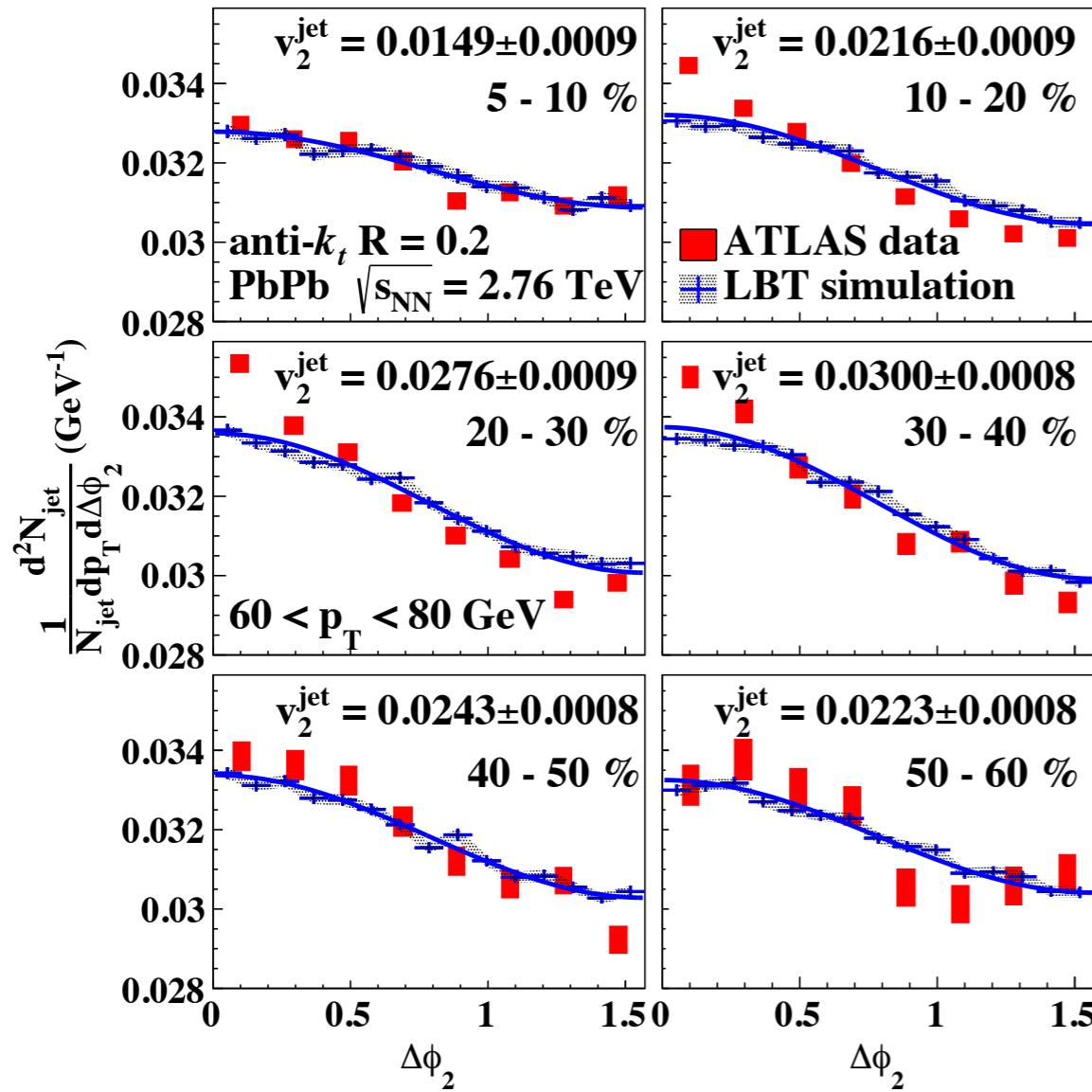
Slightly **decreases** with jet energy because of **steeper** initial spectrum, although the energy loss is **smaller** than at LHC energy.



Inclusive jet anisotropy

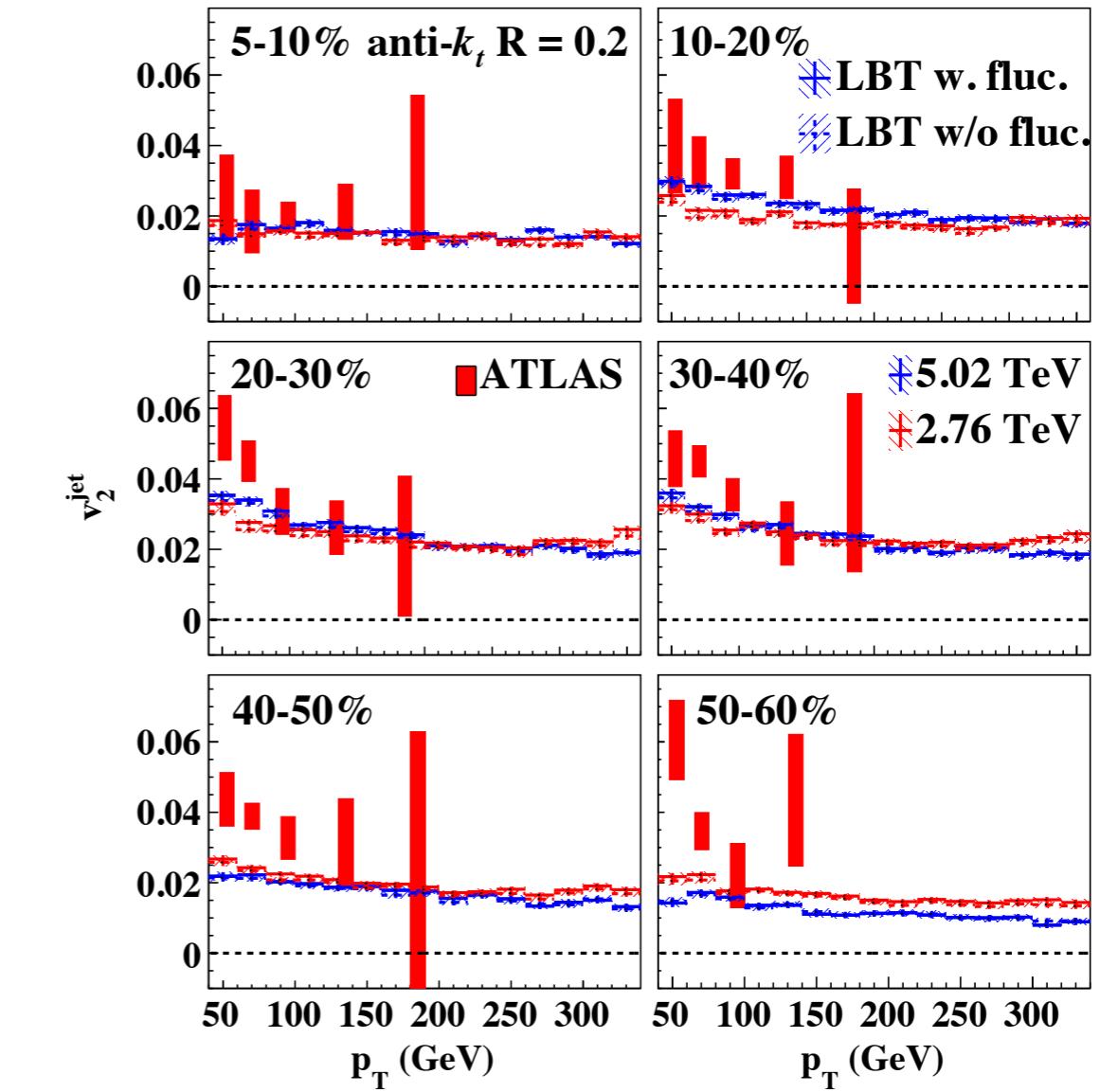
$$v_n^{jet} = \frac{\langle\langle v_n^{soft} \cos(n[\phi^{jet} - \Psi_n]) \rangle\rangle}{\sqrt{\langle(v_n^{soft})^2\rangle}}$$

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

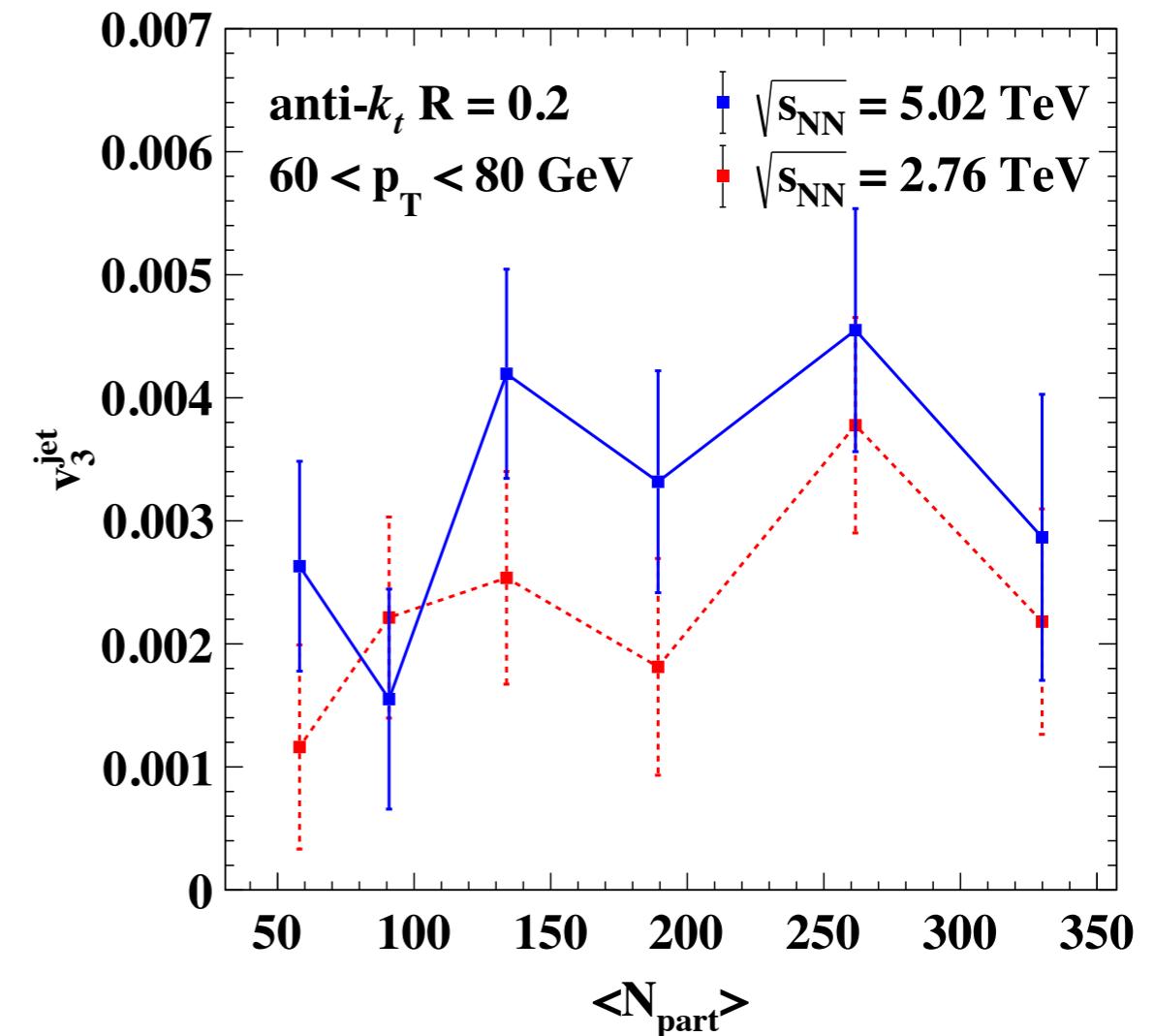
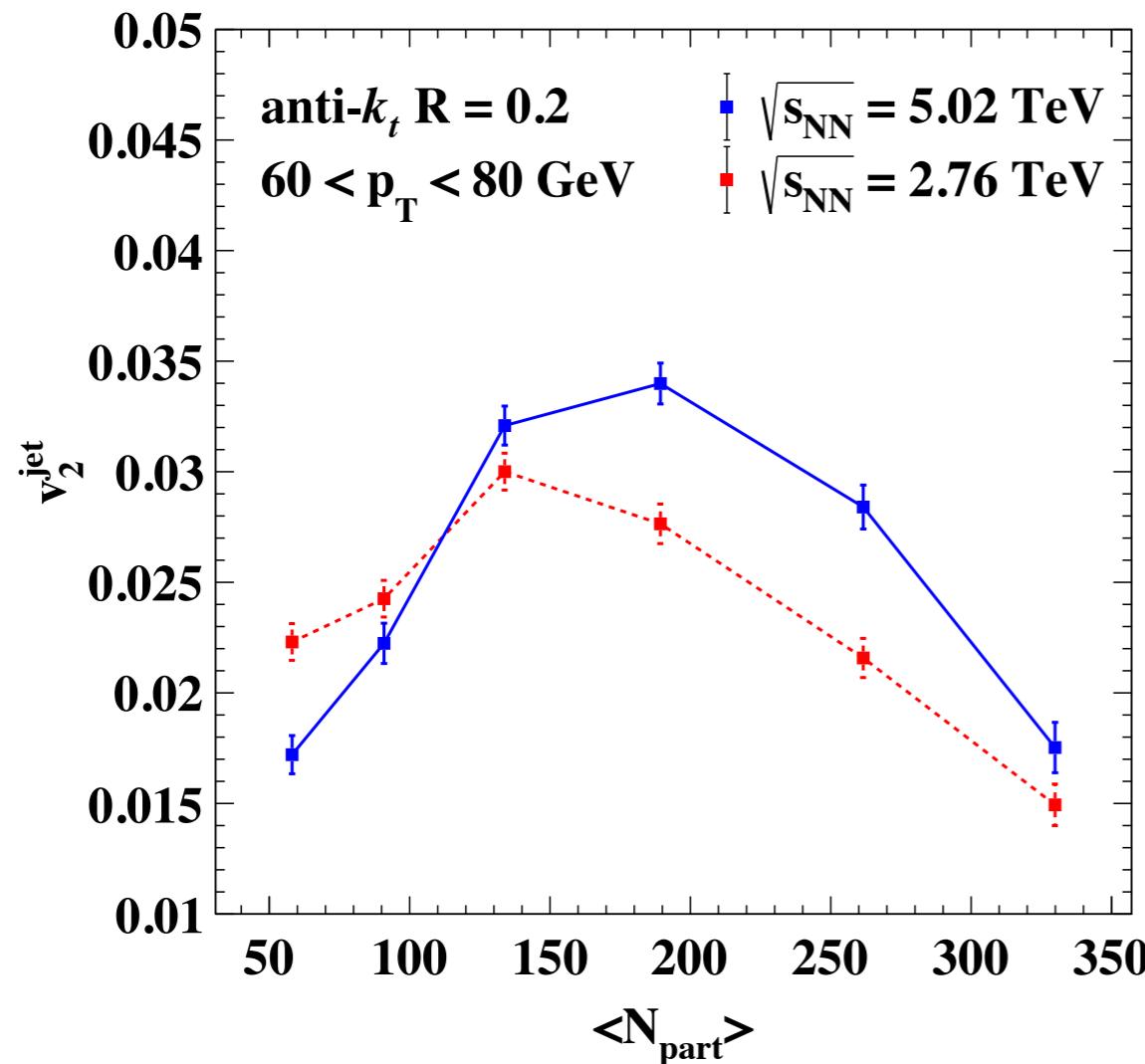


$$\Delta\phi_2 = \phi^{jet} - \Psi_2$$

ATLAS, Phys. Rev. Lett. 111 152301 (2013)



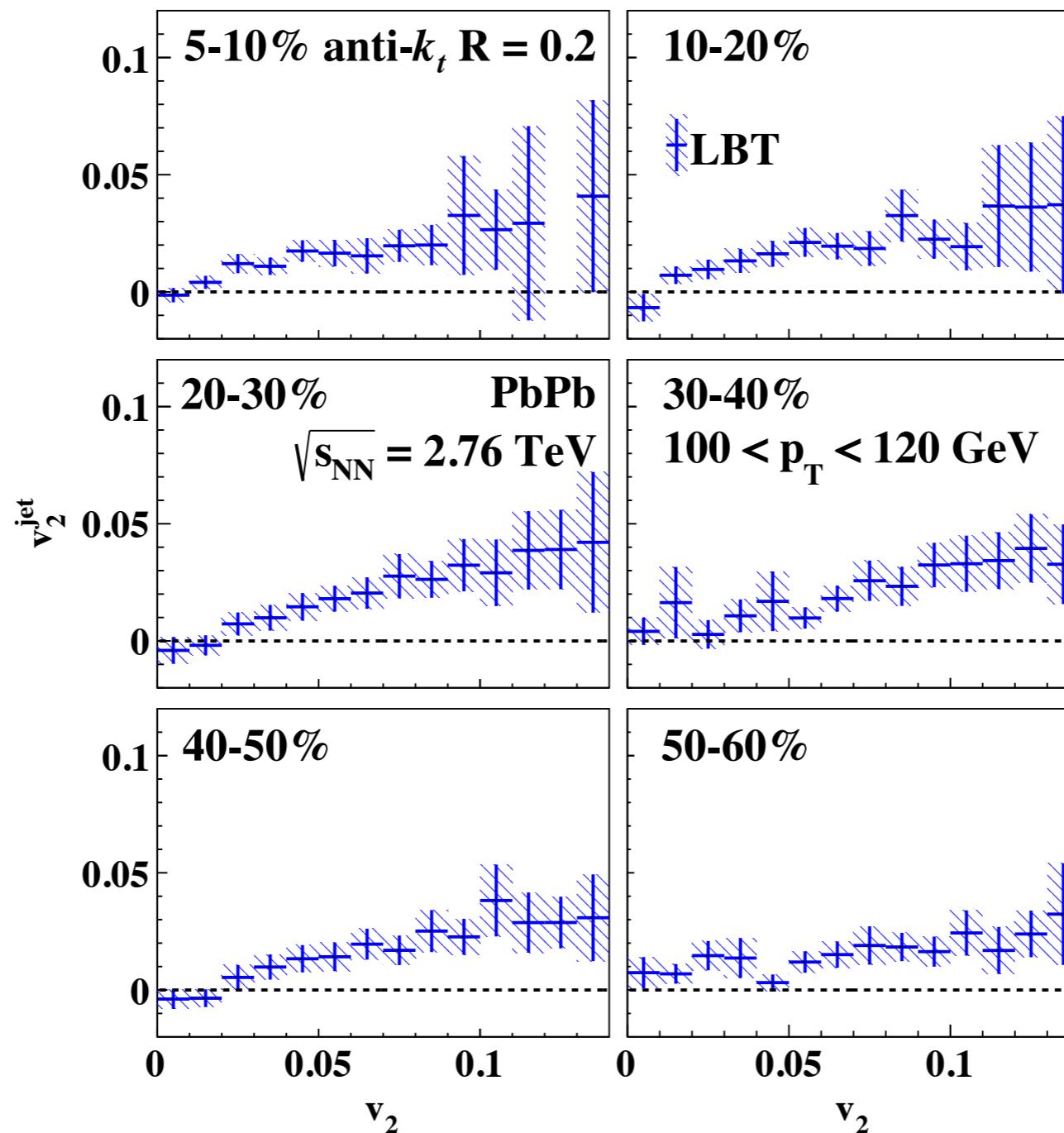
Centrality dependence of jet anisotropy



jet v_n closely follows the centrality dependence of soft v_n
jet v_3 is small, but not zero.



Hard-soft correlation



Approximately linear correlation btw jet and bulk anisotropy



Summary & outlook

- The inclusive jet suppression is determined by the initial pp spectrum and jet energy loss, on which medium response has a significant effect.
- The LBT model can describe both jet suppression and anisotropy flow. Jet anisotropy correlates with medium anisotropy

Future work:
Effects of smooth & e-by-e, ideal & viscous hydro on the jet suppression and anisotropy

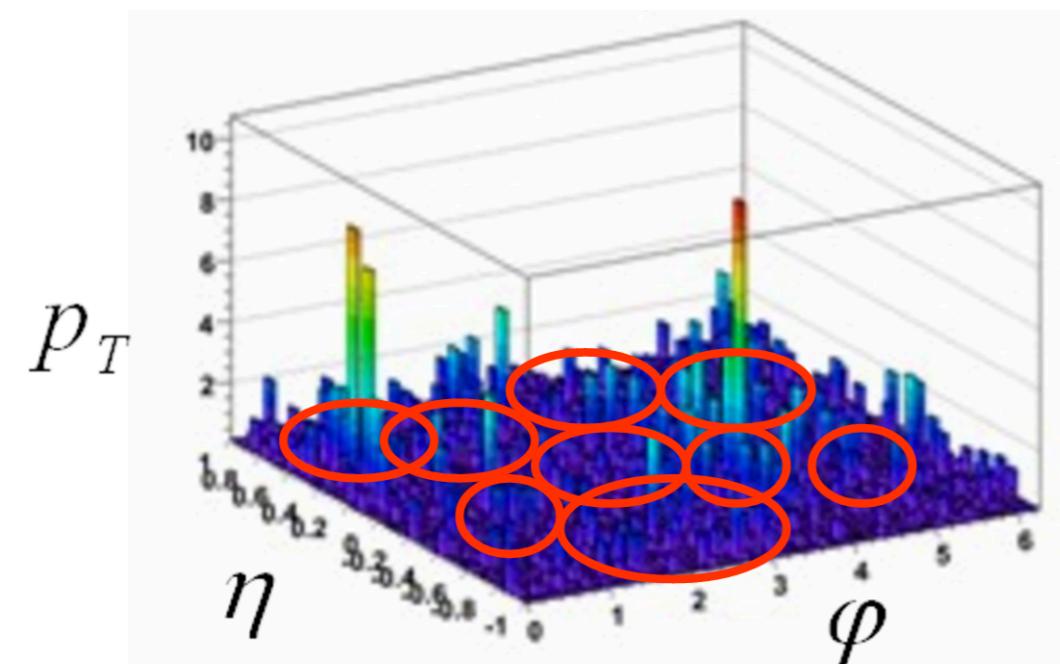


Thanks!



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

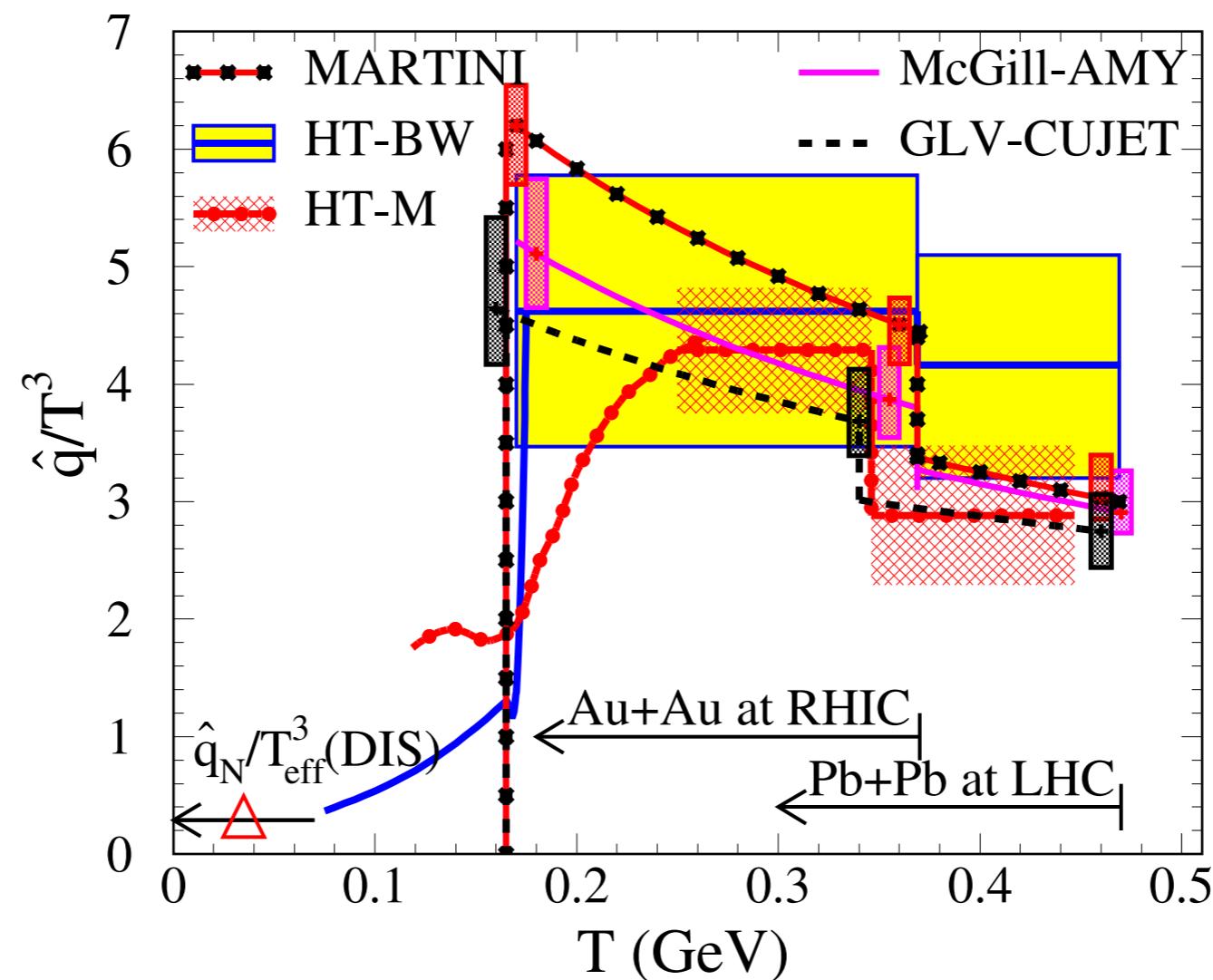
ATLAS Collaboration, Phys. Lett. B 719, 220 (2013).

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

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

jet-medium transport coefficient

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



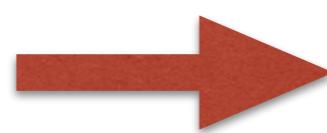
Azimuthal Anisotropy v_2

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

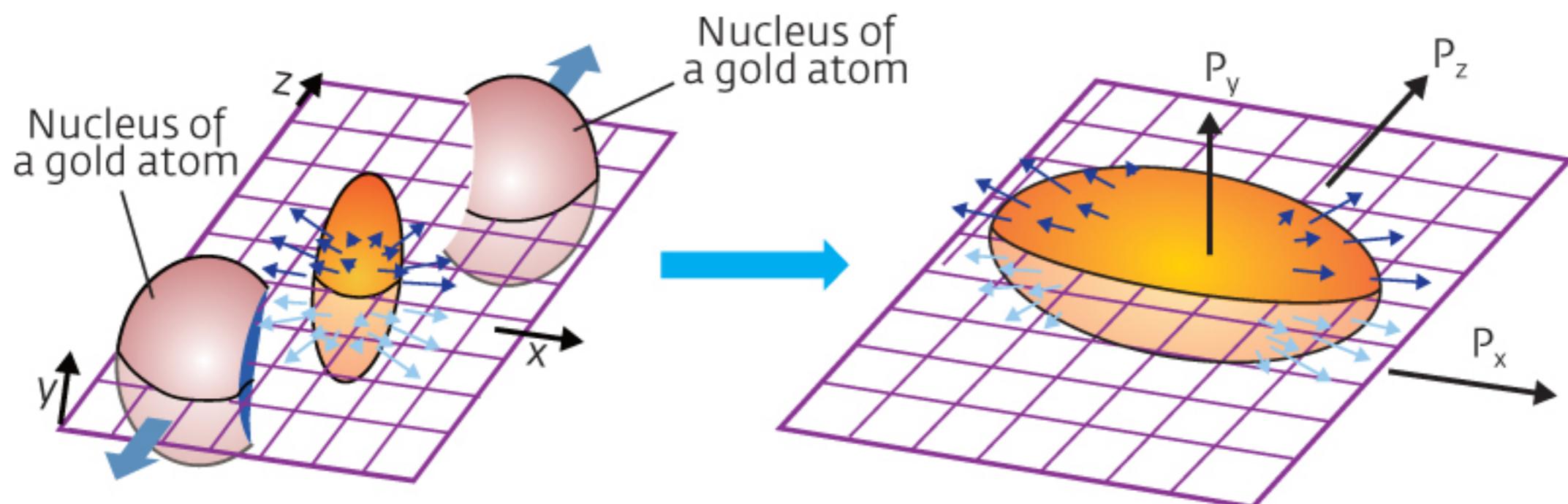
elliptic flow: $n=2$

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

Coordinate space:
initial asymmetry



Momentum space:
final asymmetry

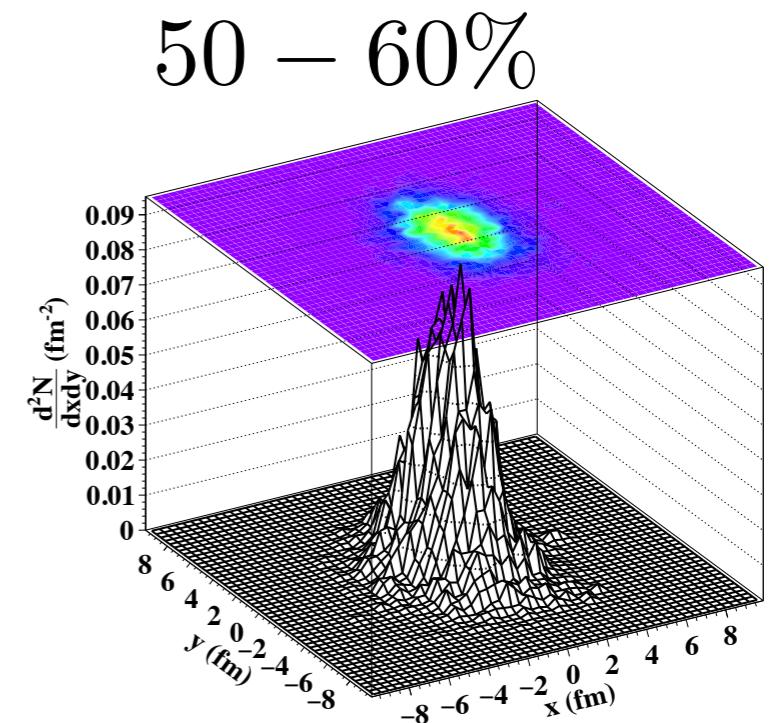
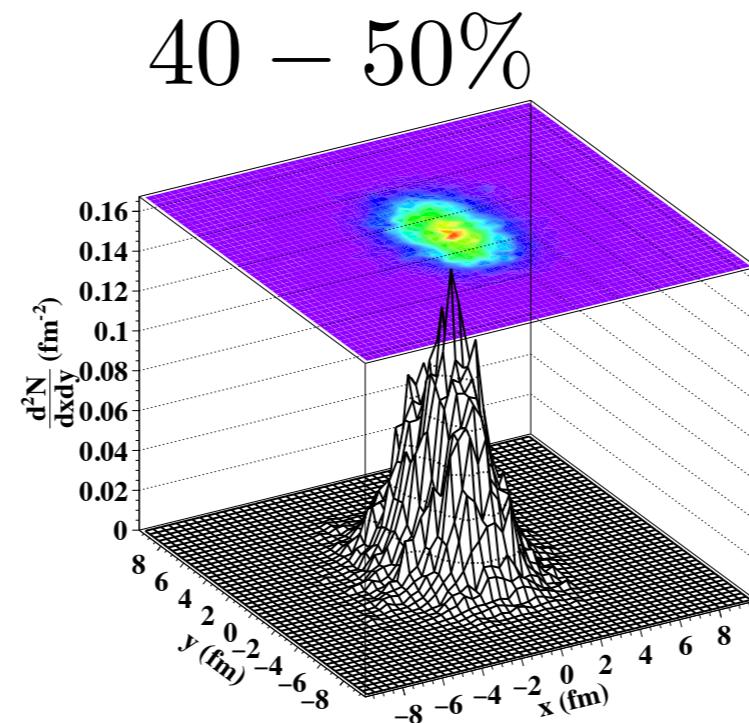
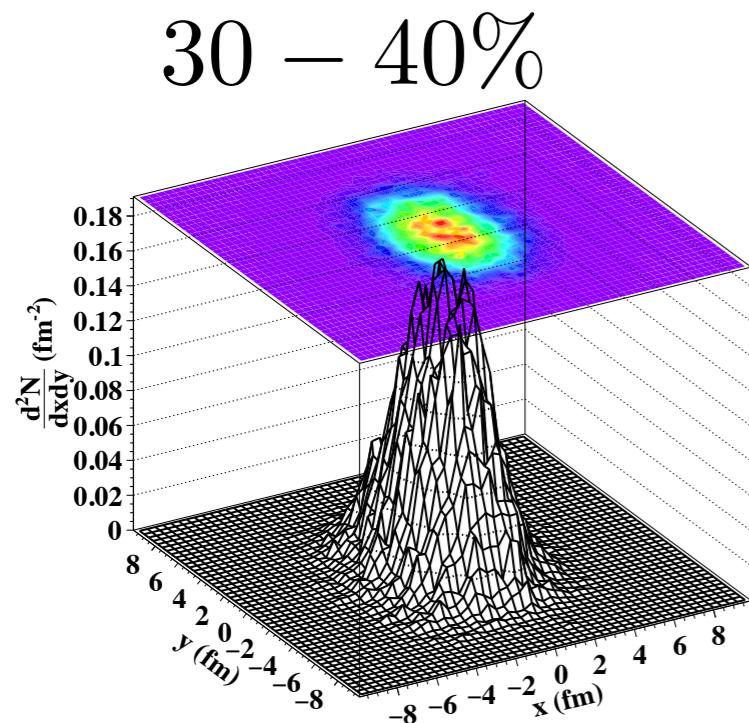
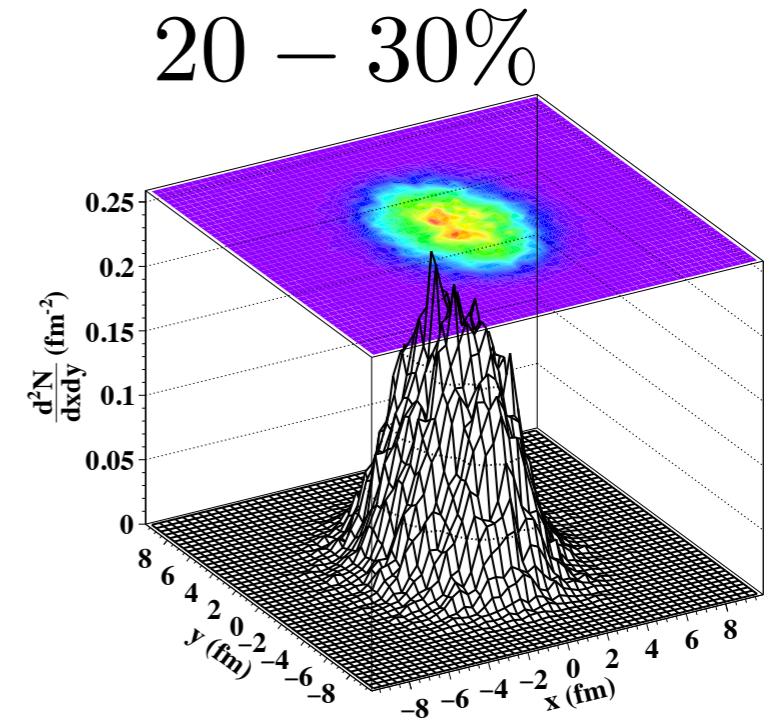
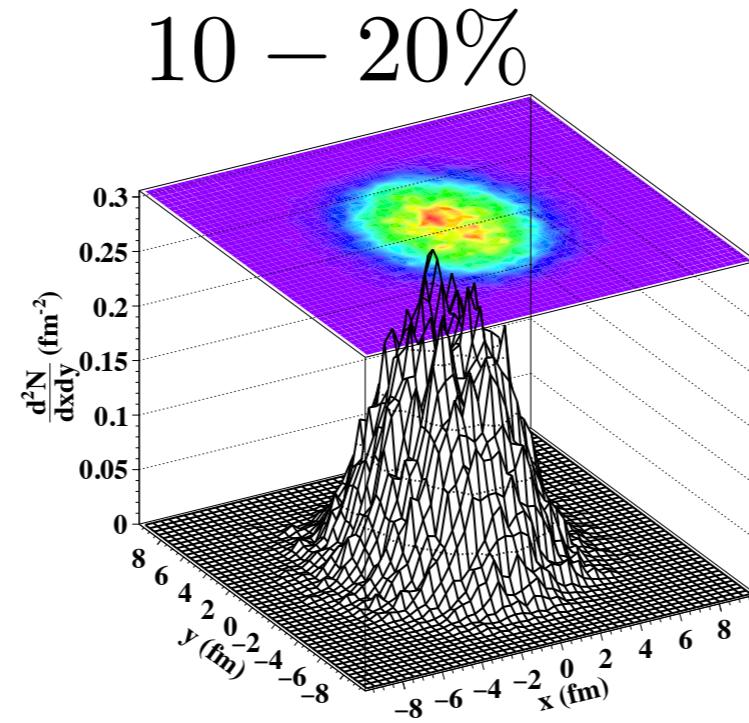
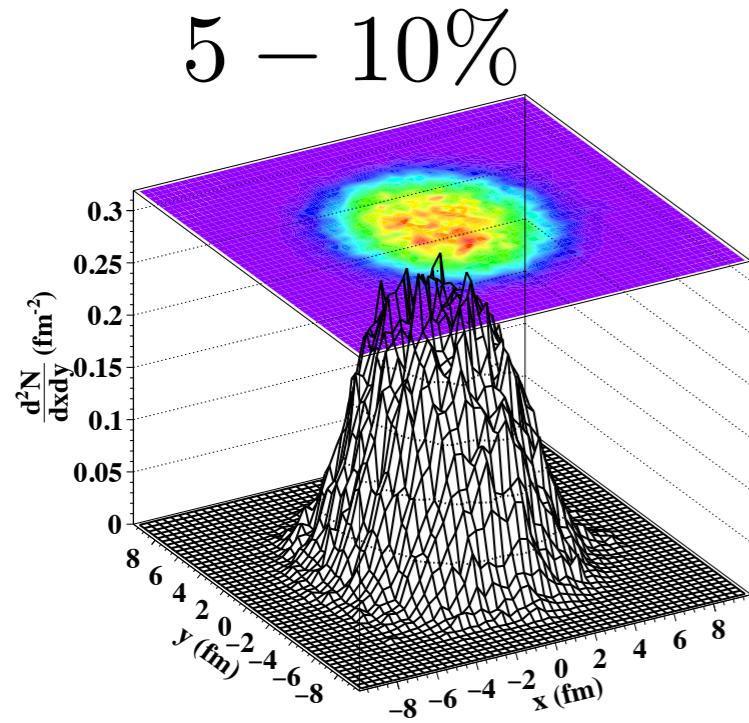


$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$



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

Initial Geometry at 2.76 TeV

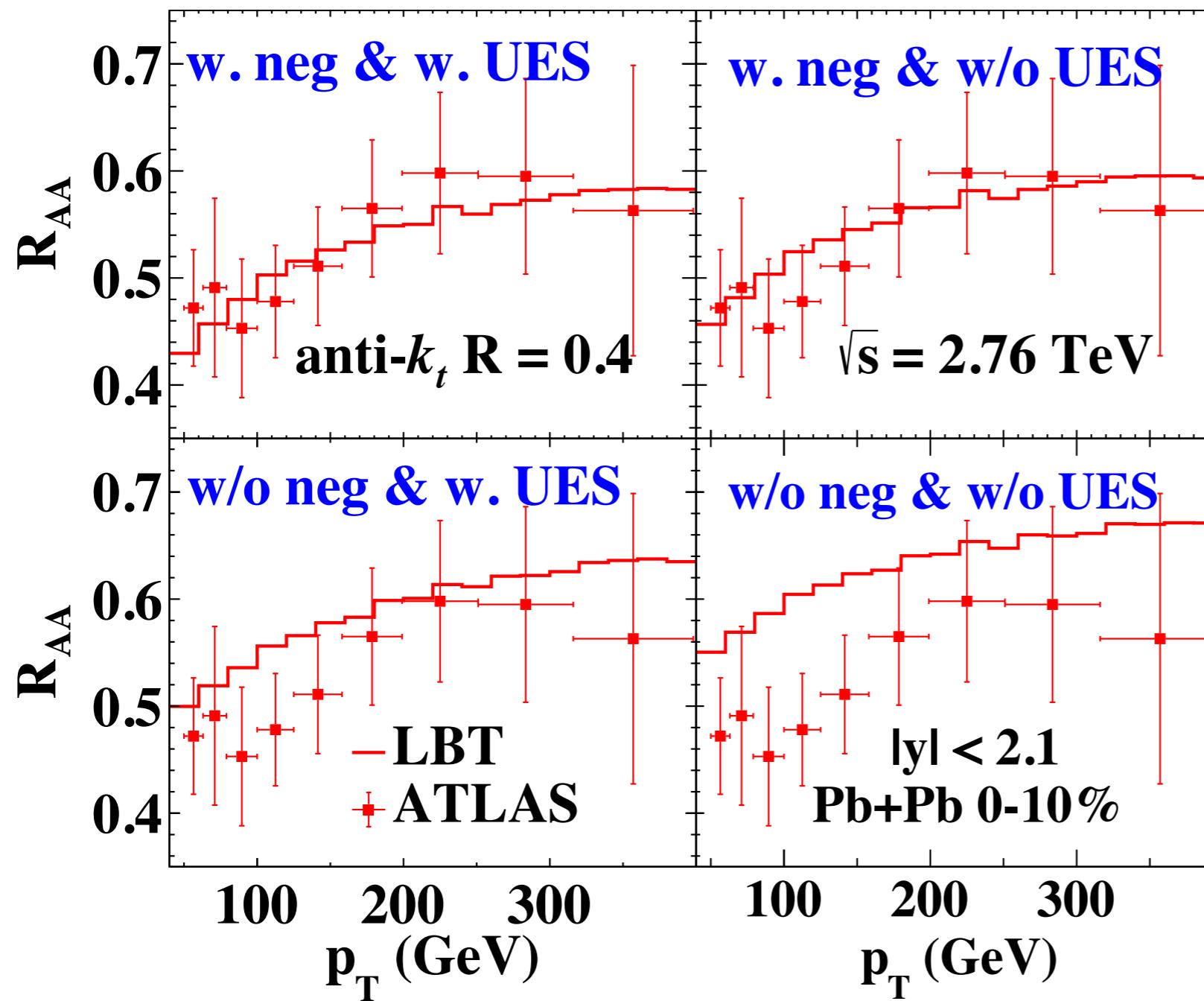


averaged over 200 3+1D event-by-event hydro profiles
Pang, Wang & Wang, arXiv:1205.5019



Results: Inclusive jet suppression

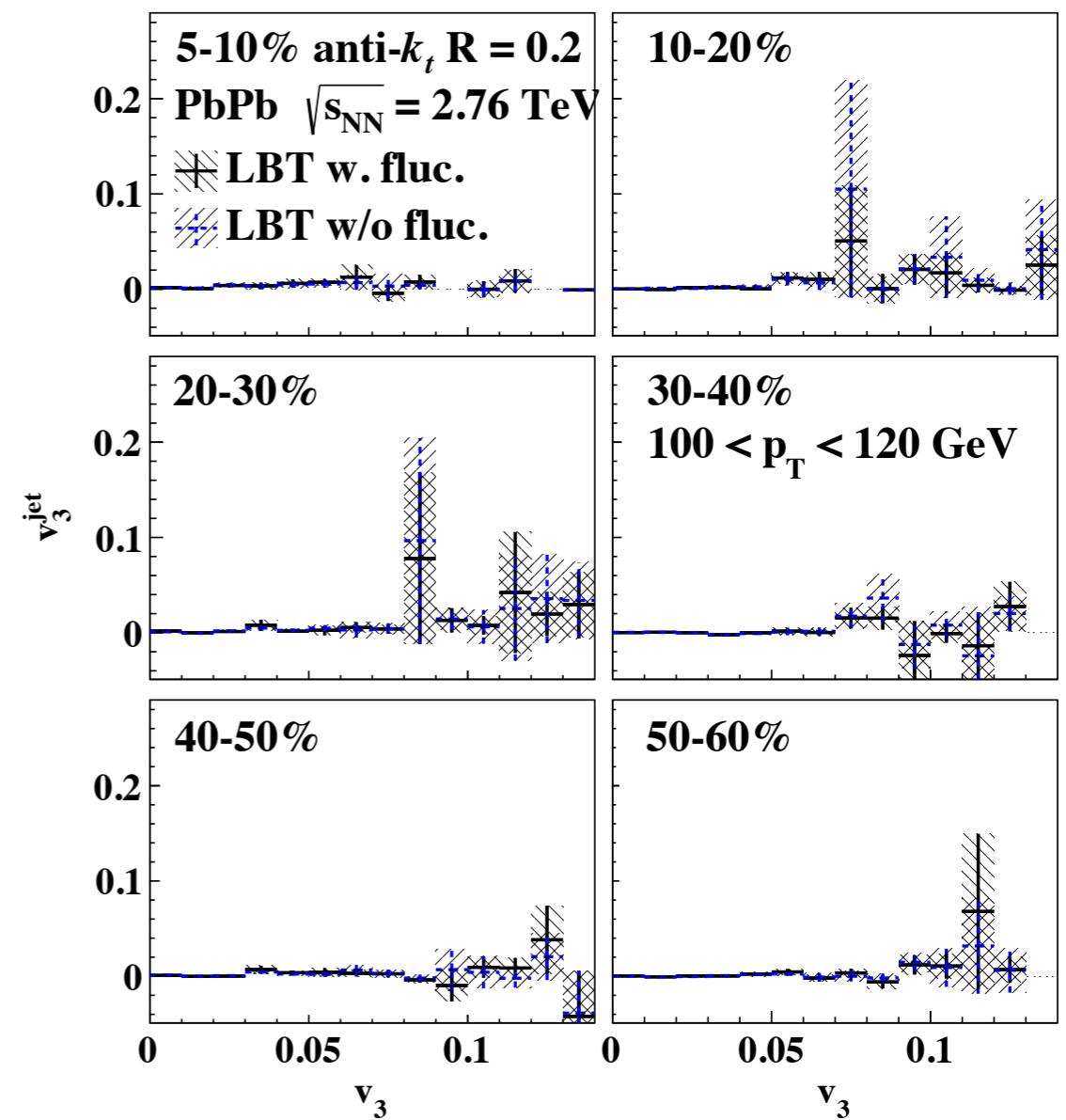
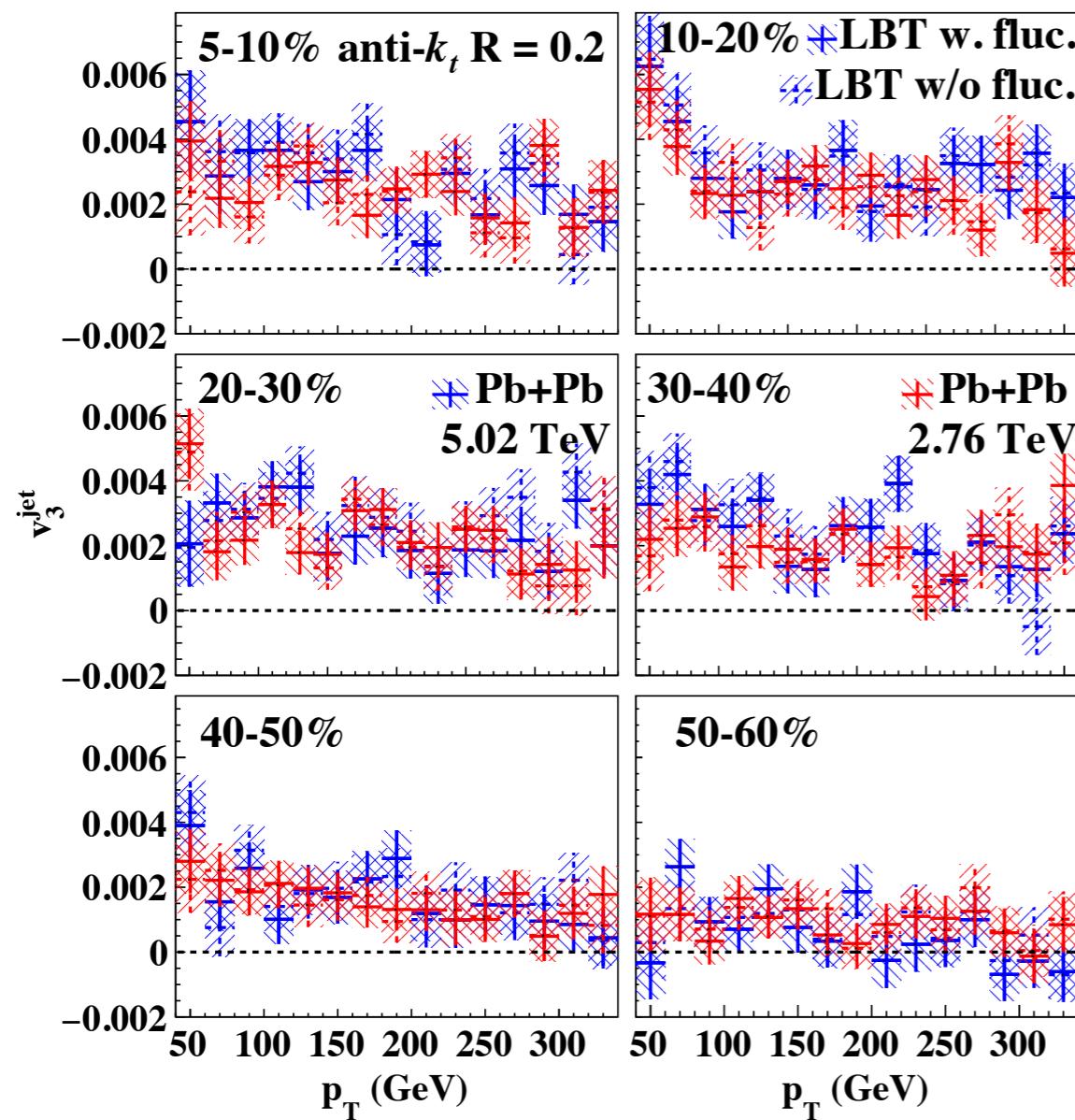
fixed $\alpha_s = 0.15$



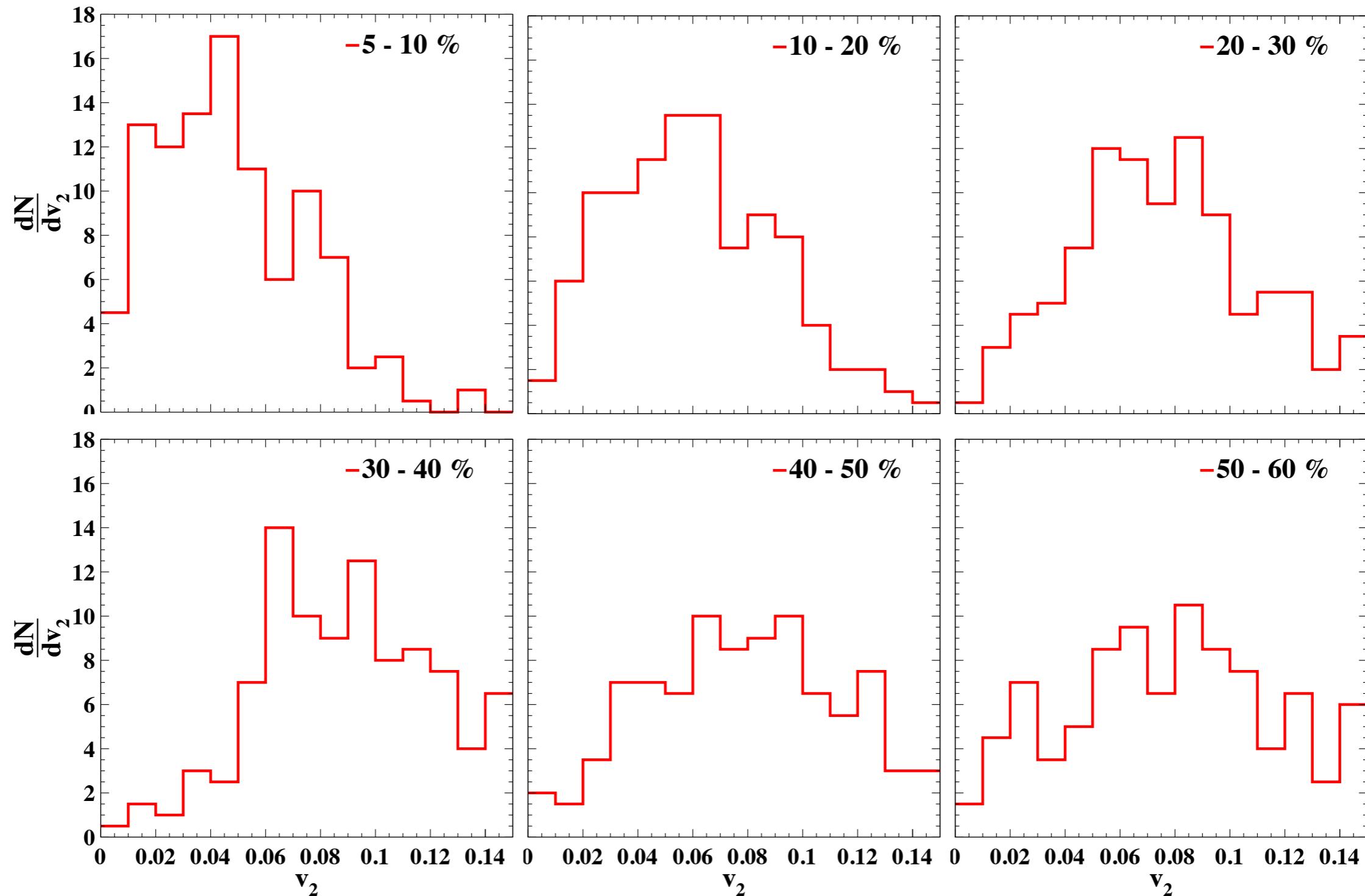
Suppression!!!

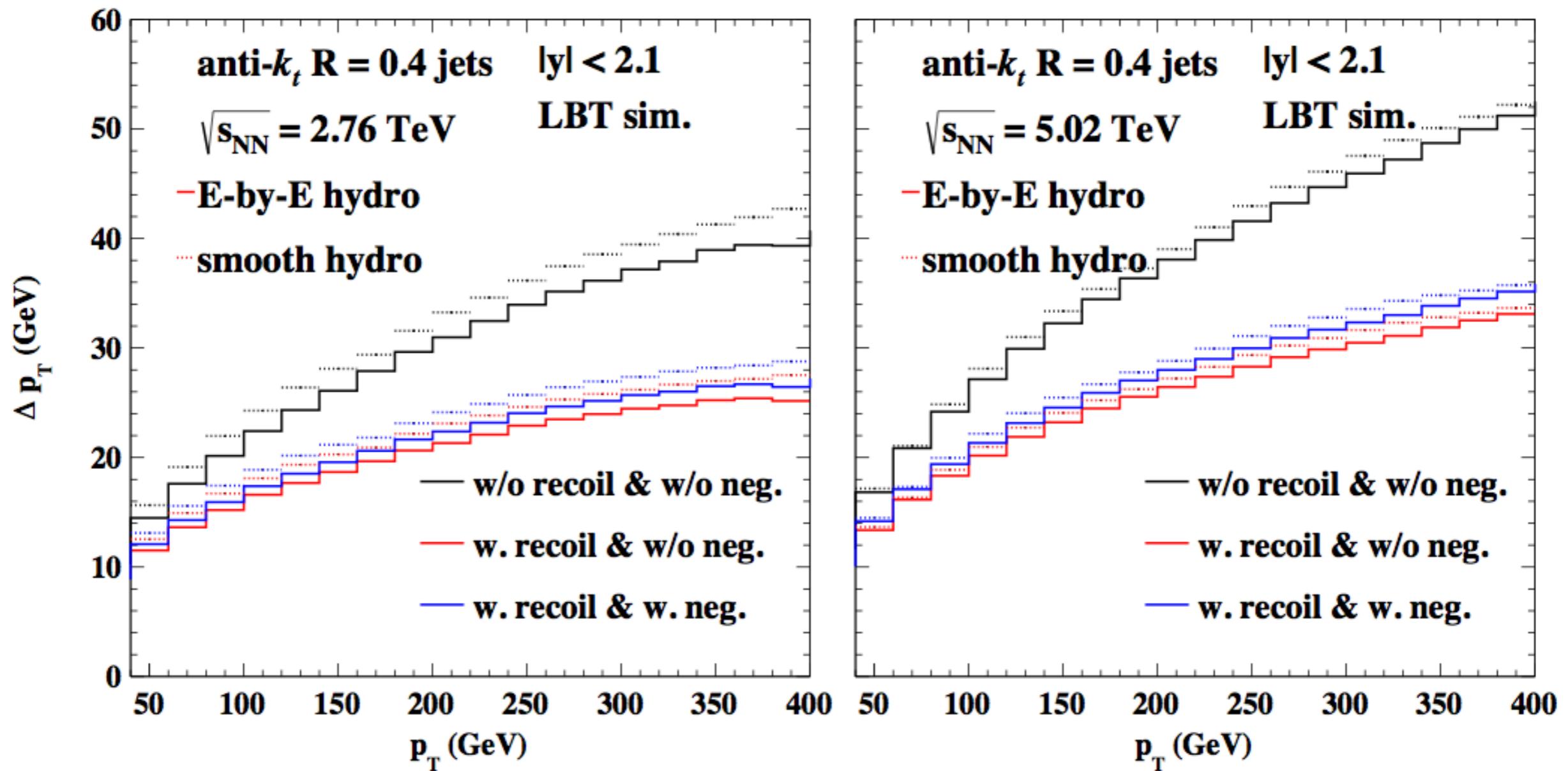
$w. \text{ neg} (\text{whole } p_T \text{ range});$
 $w. \text{ UES} (\text{low } p_T \text{ range})$

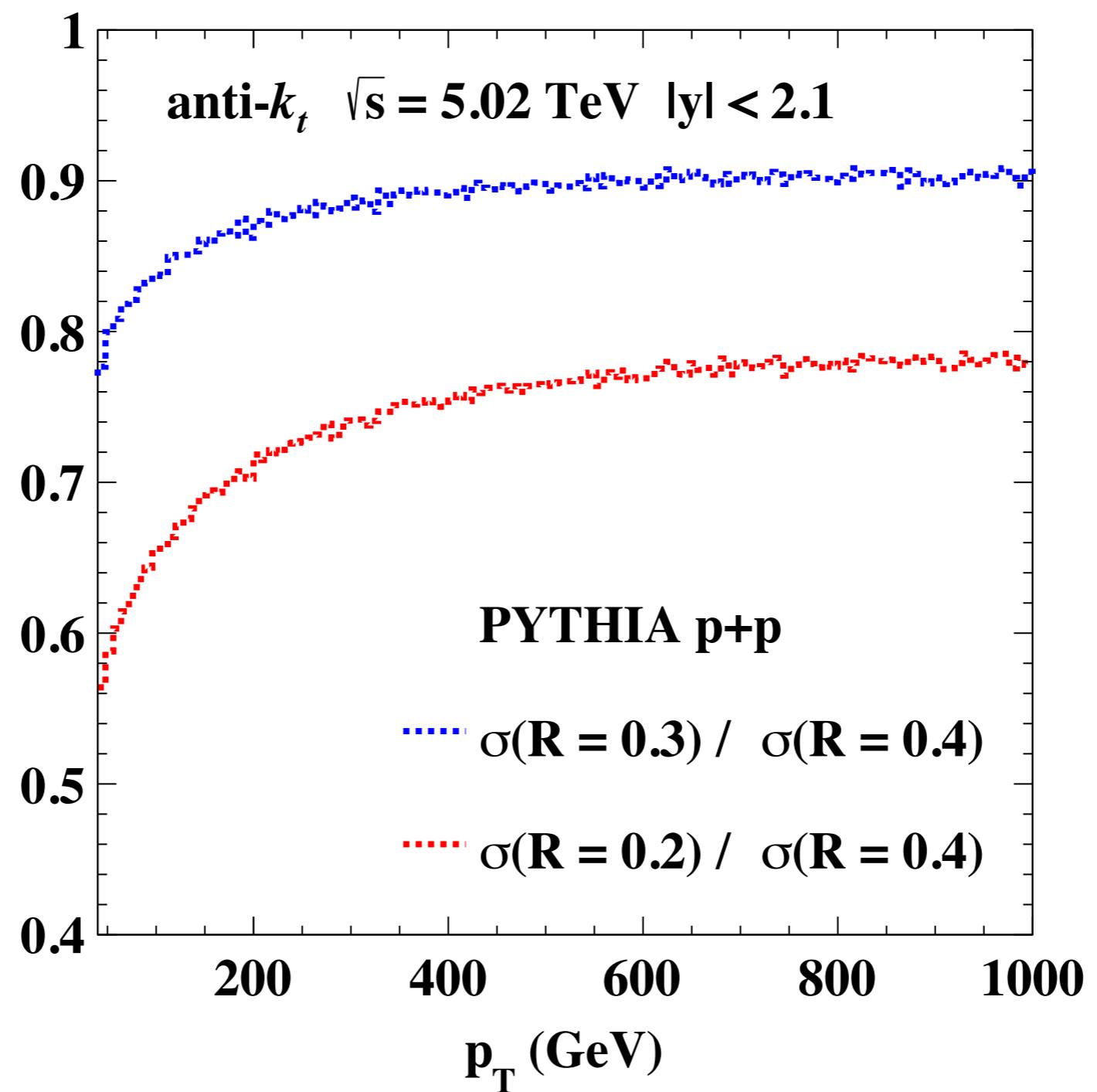




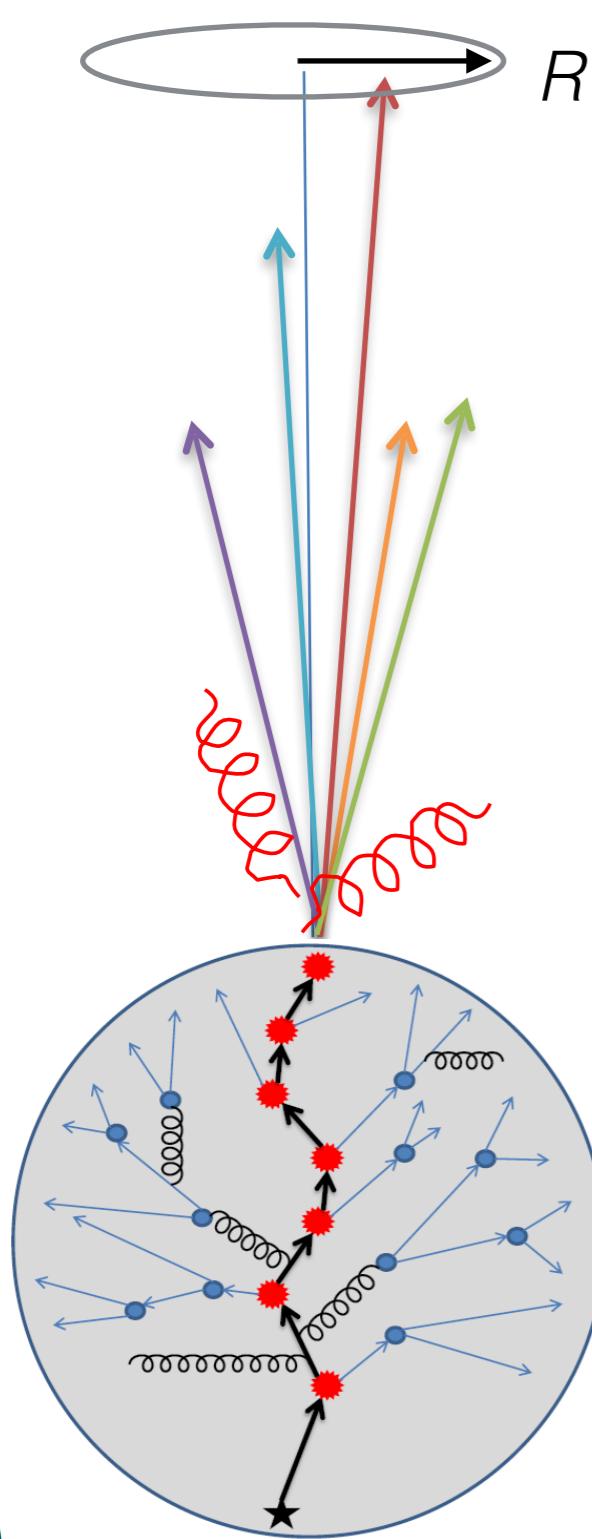
v_2 of soft particles from hydro profiles







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”)

Framework

The inclusive jet shower partons from PYTHIA 8



Initial geometry from AMPT



$e\text{-}by\text{-}e \ 3+1\mathcal{D}$

Pang, Wang & Wang, arXiv:1205.5019

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

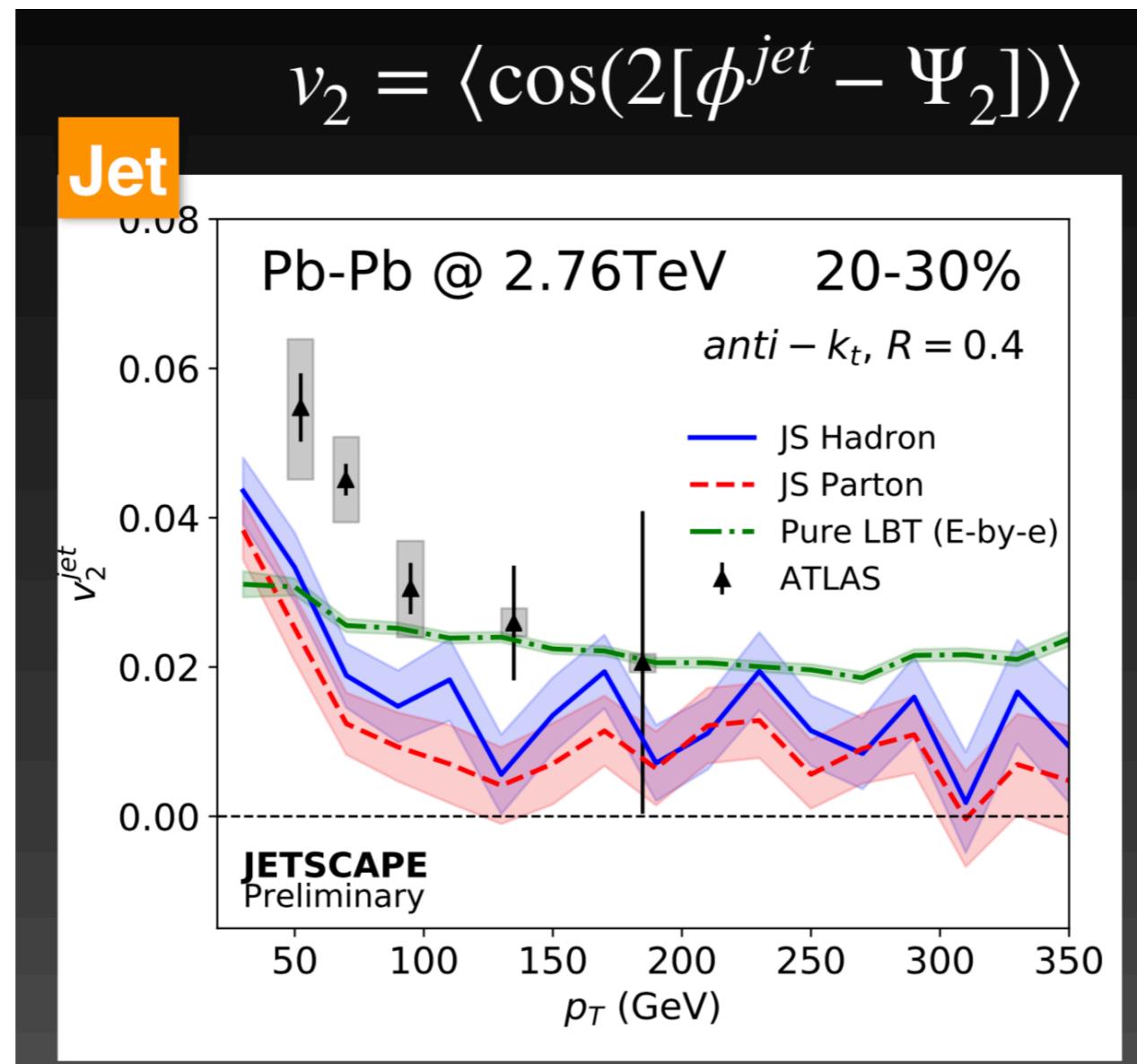
Energy loss!!!



Final inclusive jet



Inclusive jet anisotropy



Multistage evolution, see: Chanwook Park, HP 2018



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

