Weak p_T dependence of inclusive jet R_{AA} and extraction of jet energy loss distributions

Yayun He (贺亚运)

Central China Normal University
(华中师范大学)

第十七届全国核物理大会
10月8-12日 2019

Outline

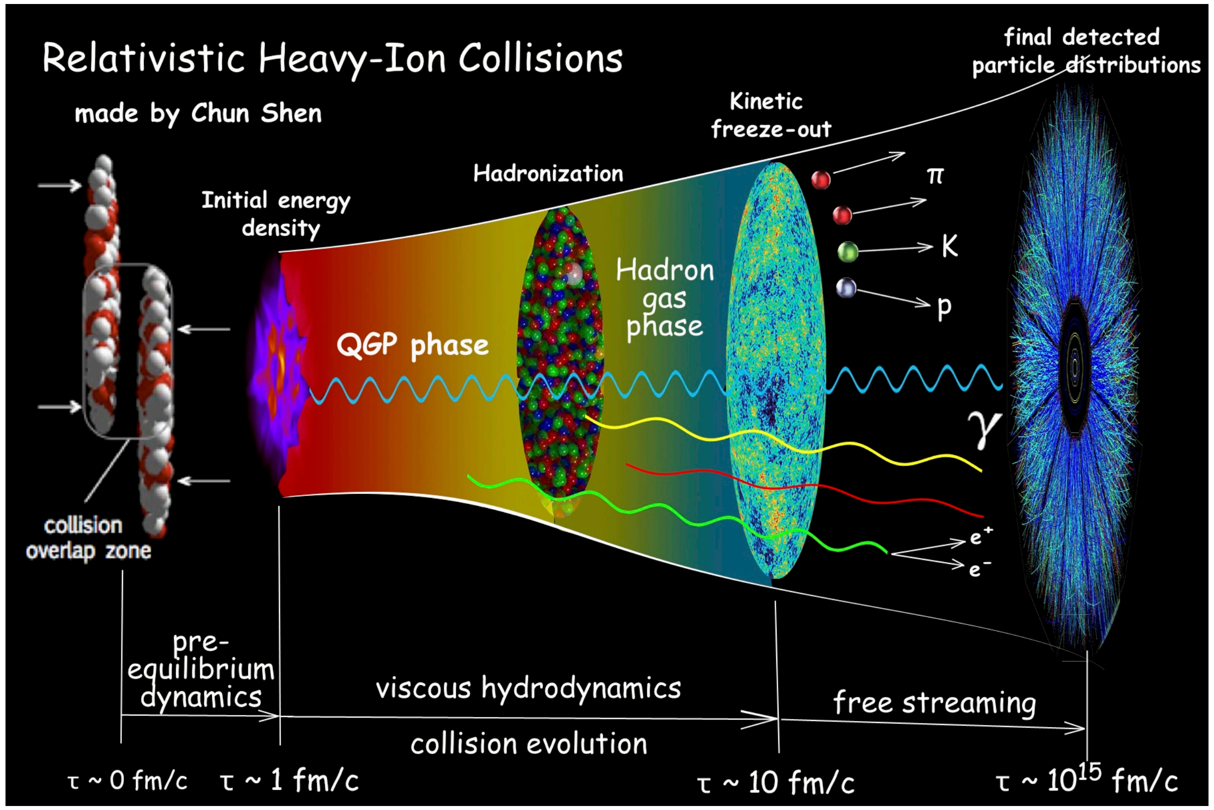
I. Motivation

II. The Linear Boltzmann Transport (LBT) Model

III. Results: suppression of inclusive jet,
jet energy loss distributions

IV. Summary

Motivation

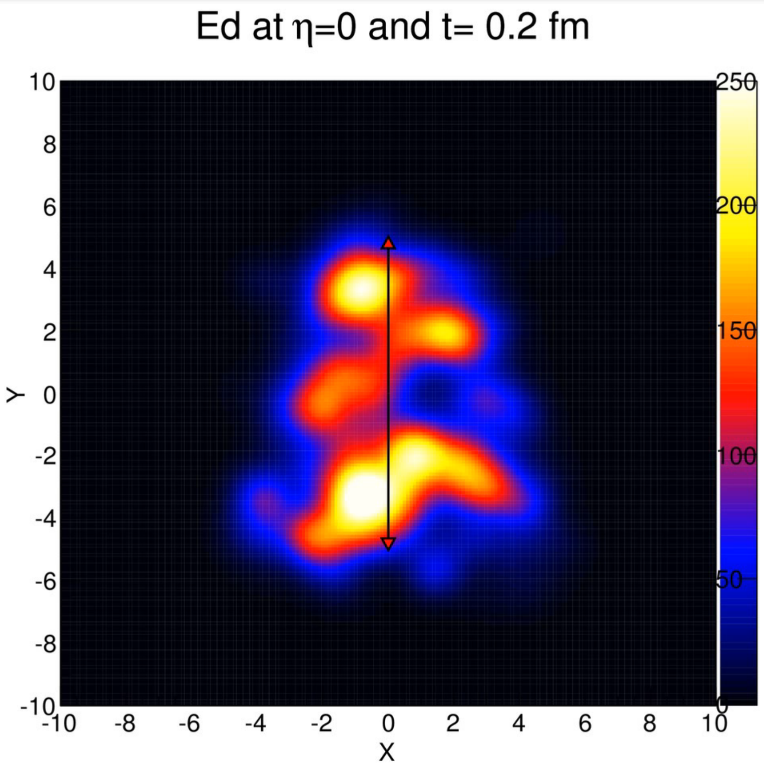


(made by Chun Shen, https://u.osu.edu/vishnu/category/visualization/

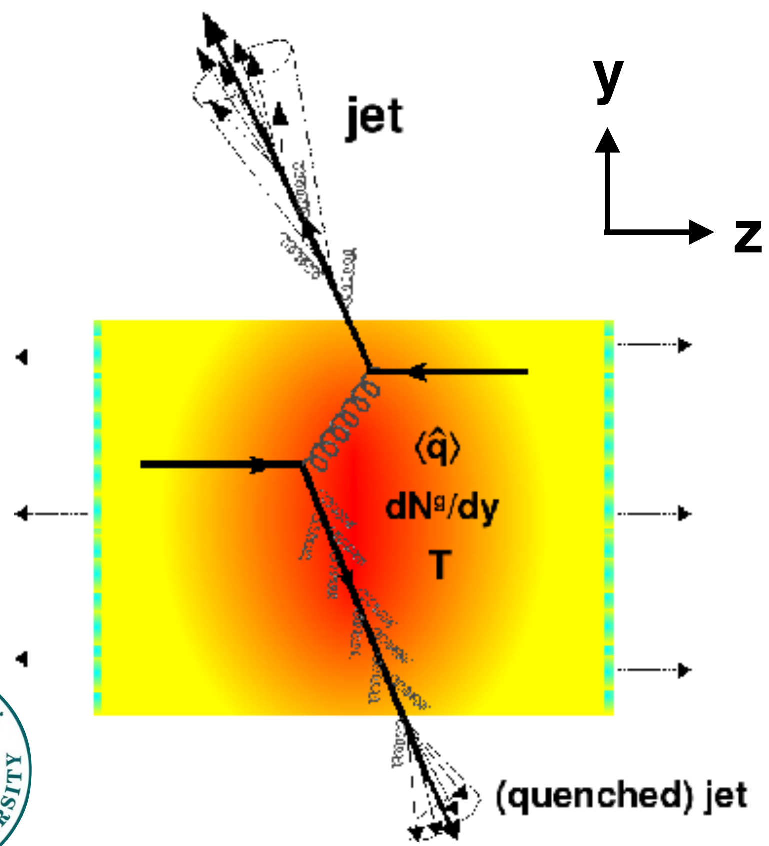
Two beams of nuclei colliding,
large energy density deposits.
Quark and gluon de-confine,
"little bang" like early universe.
QGP expandes,
cooling down to hadron phase.
Hadrons re-scatter,
and go free streaming,
detected by the detector.

The quark-gluon plasma (QGP), predicted by QCD and confirmed at RHIC and LHC experiments, is created in high-energy heavy-ion collisions. It is a hot and dense medium.

Motivation



W. Chen, et al, Phys. Lett. B 777 (2018) 86–90

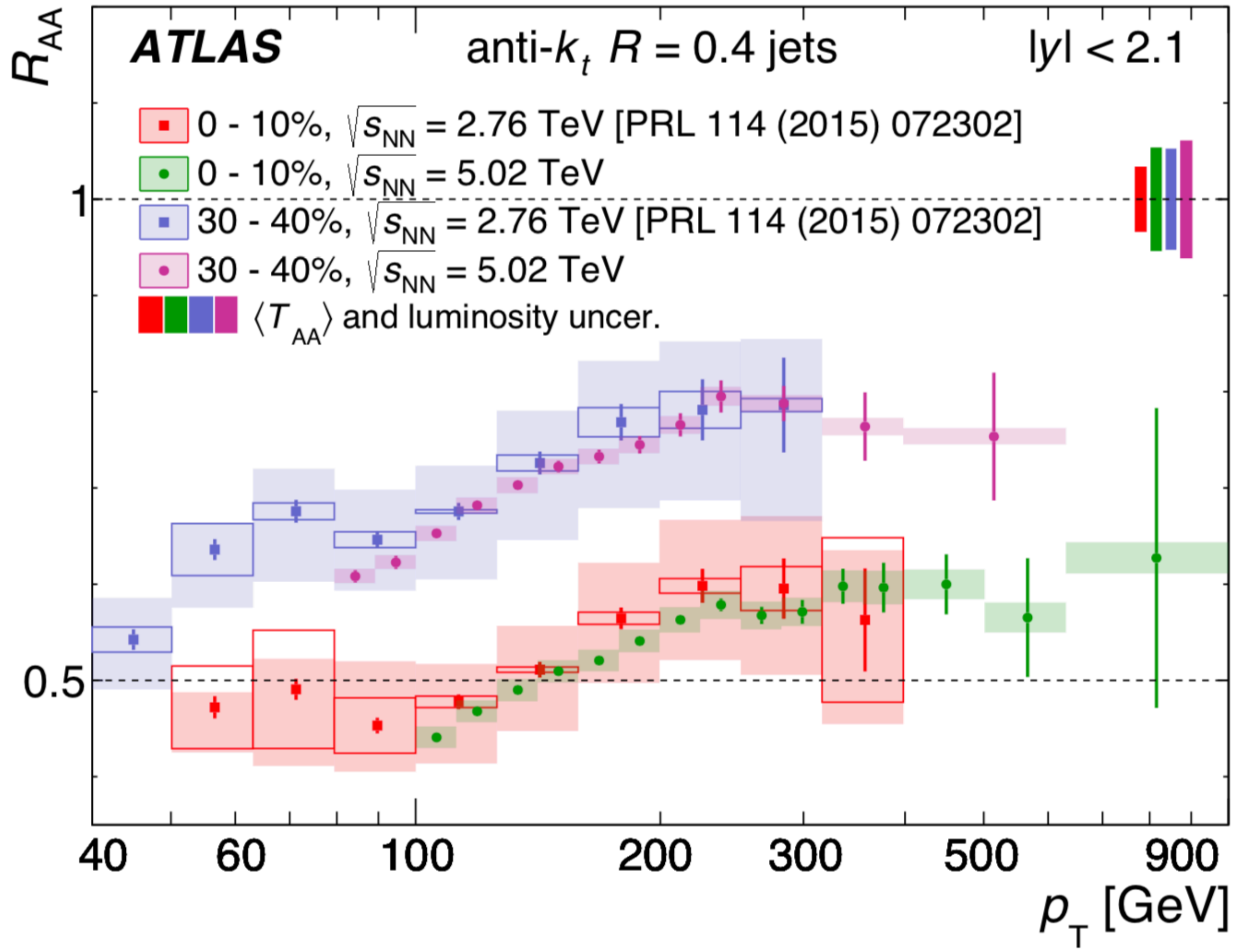


QGP Probes:
hard probes: large momentum or short distance, such as **jets,** high-p_T hadrons, heavy quark.

jet: a spray of collimated hadrons with high transverse momentum

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

Motivation



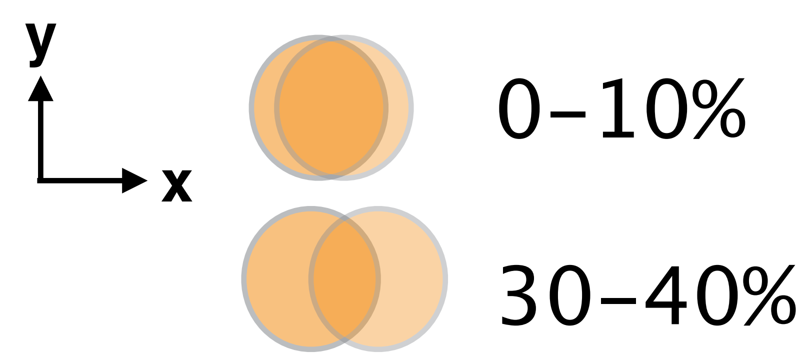
ATLAS, Phys. Rev. Lett. 114 (2015),072302 arXiv:1411.2357,
ATLAS, Phys. Lett. B 790 (2019) 108, arXiv:1805.05635

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

$R_{AA} = 1$ No suppression;

$R_{AA} < 1$ suppression arises;

The smaller R_{AA} means the stronger suppression.



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

The LBT model

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

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

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

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

LO perturbative QCD

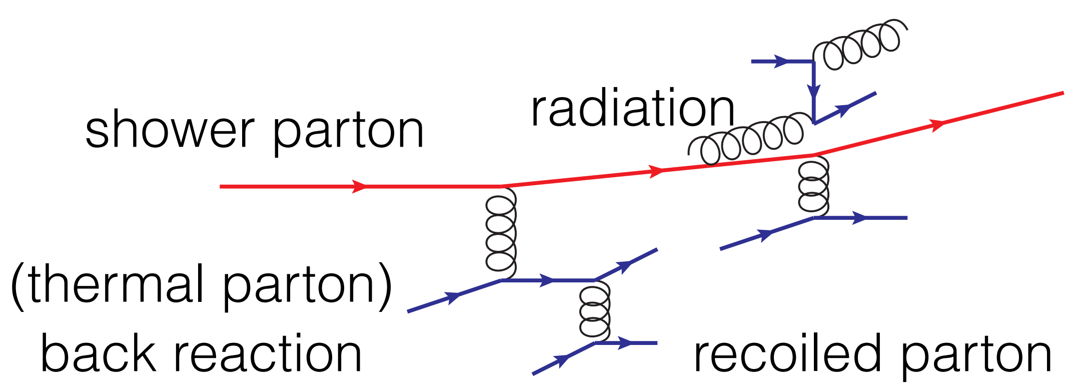
J. Auvinen et al, Phys.Rev. C 82(2010) 024906

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

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 $\delta f << f$

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

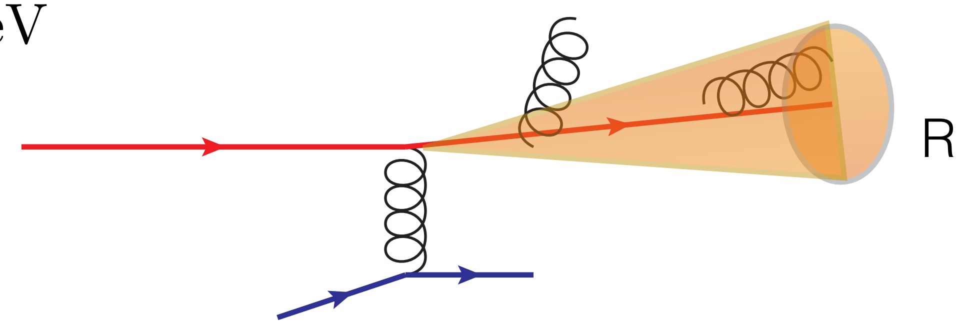
Z.-W. Lin, C. M. Ko, B.-A. Li, B. Zhang, and S. Pal, Phys. Rev. C 72, 064901 (2005).

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

out-of-cone jet energy loss

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

Final inclusive jet

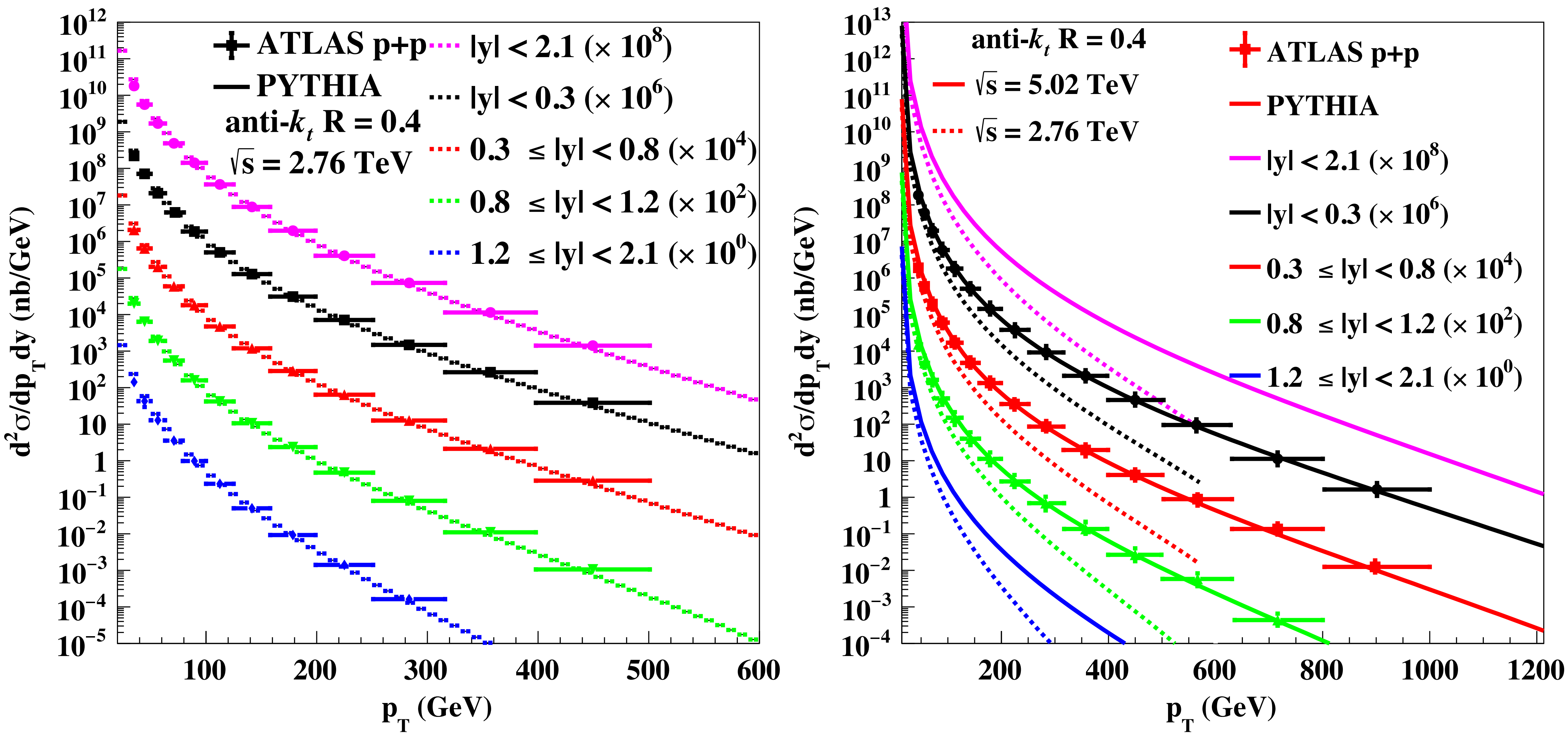


e-by-e 3+1D CLVisc: Pang, Wang & Wang, Phys. Rev. C86 (2012) 024911

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

The inclusive jet in pp collisions

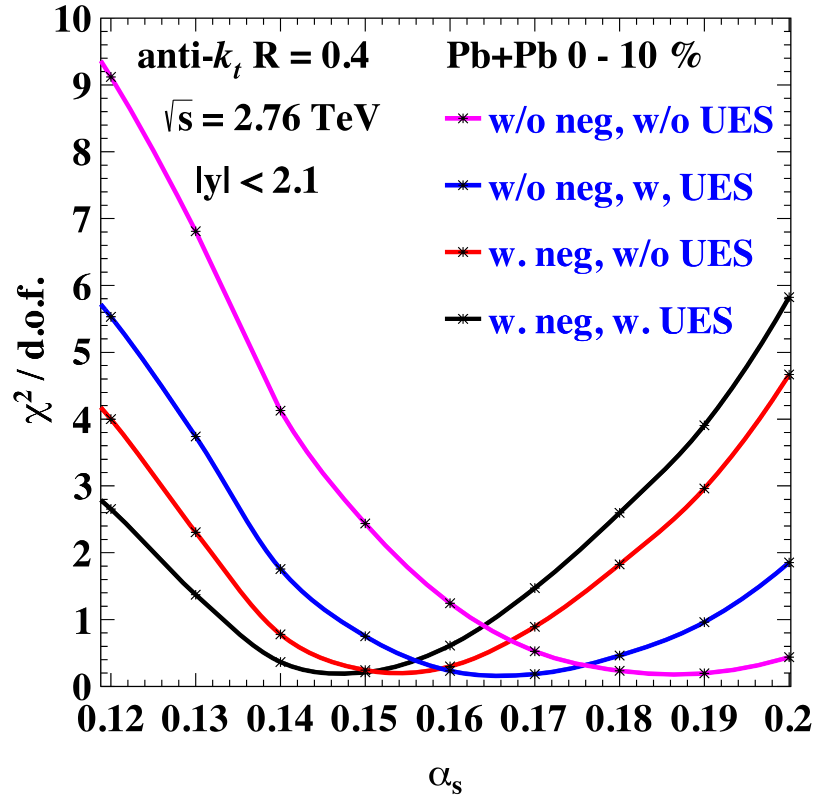
p_T distribution of pp collision within PYTHIA 8

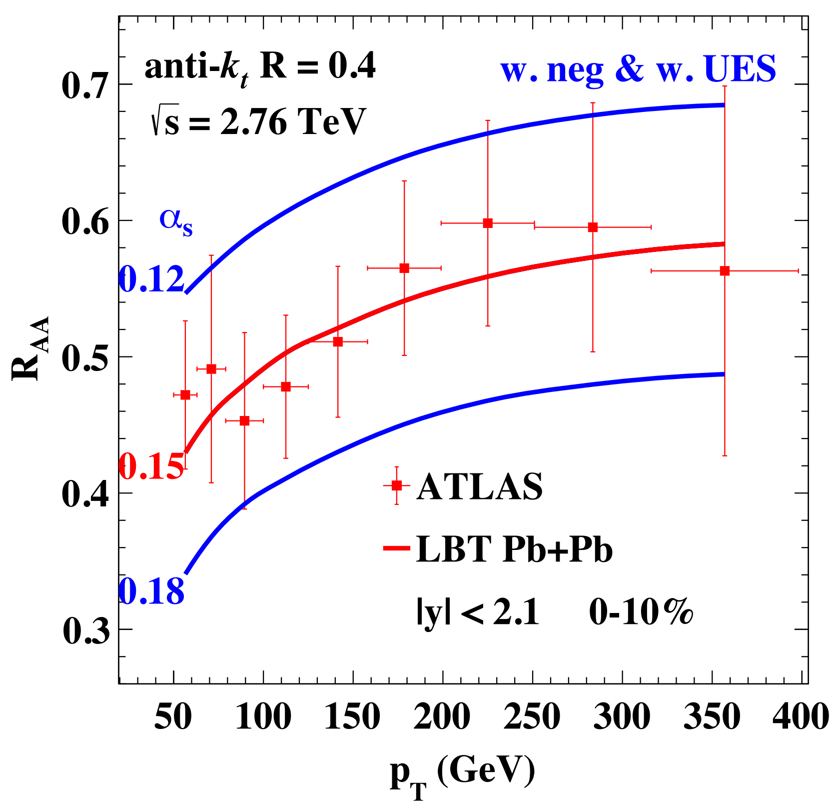


The spectrum at 5.02 TeV is higher and much flatter than at 2.76 TeV, which originates from PDFs.

Fix strong coupling constant

Y. He et al, PRC 99 (2019) 054911





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

neg.: "negative particles", back reaction.

UES: underlying event subtraction.

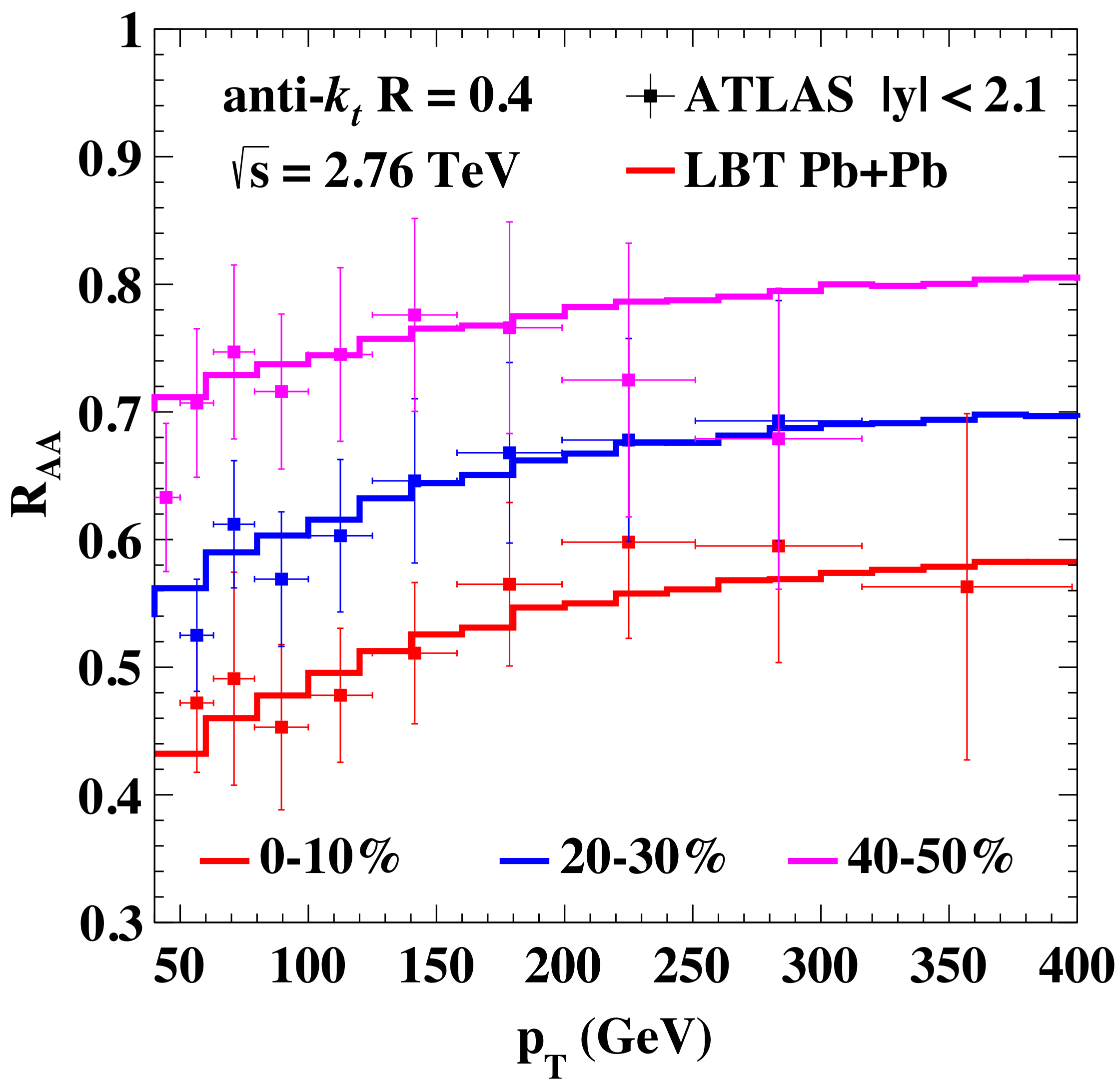
Inclusion of neg. or UES decreases jet energy

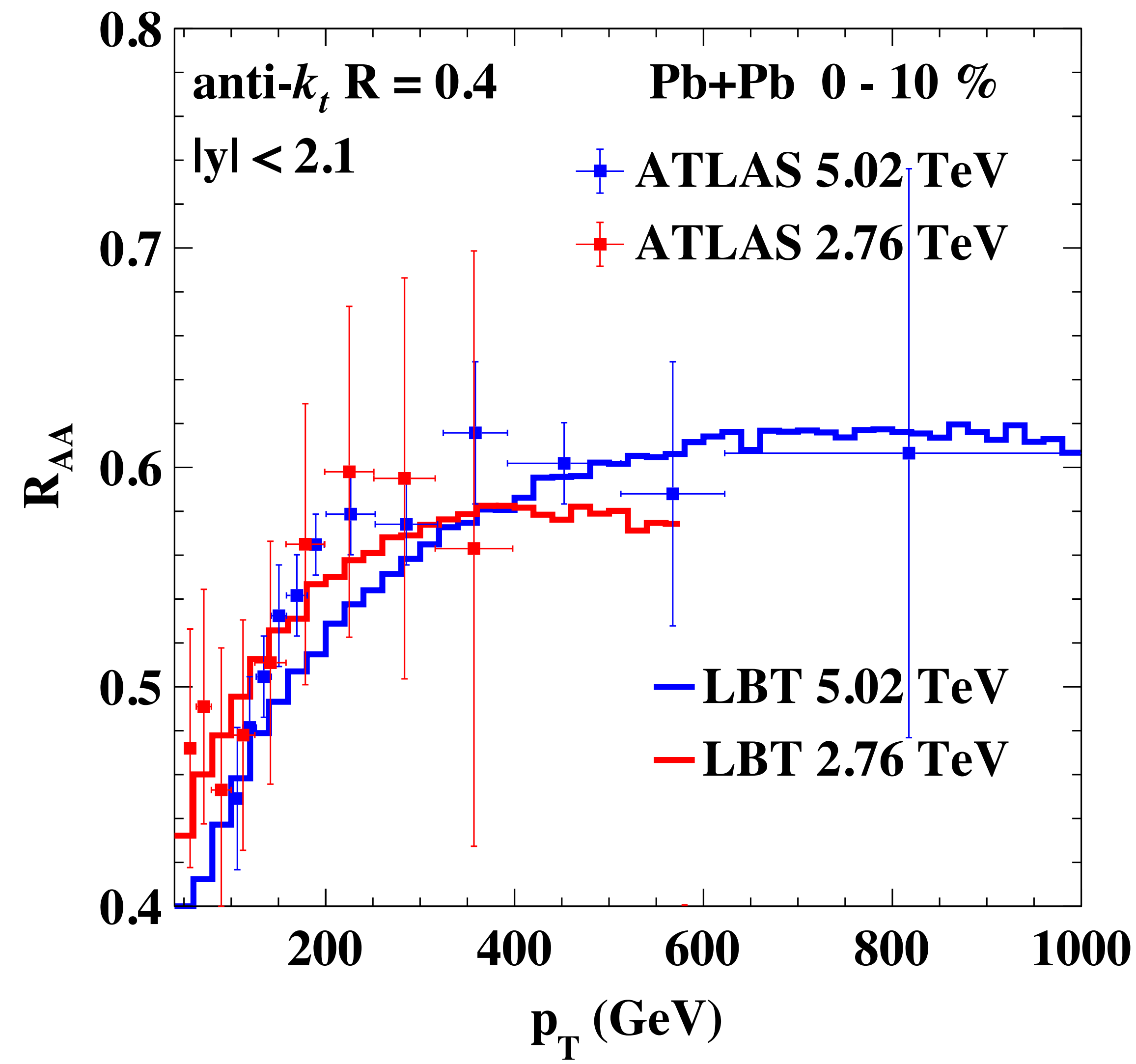
Effective α_s: collisional, radiation, Debye screening mass,

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

$$\alpha_s = 0.15$$

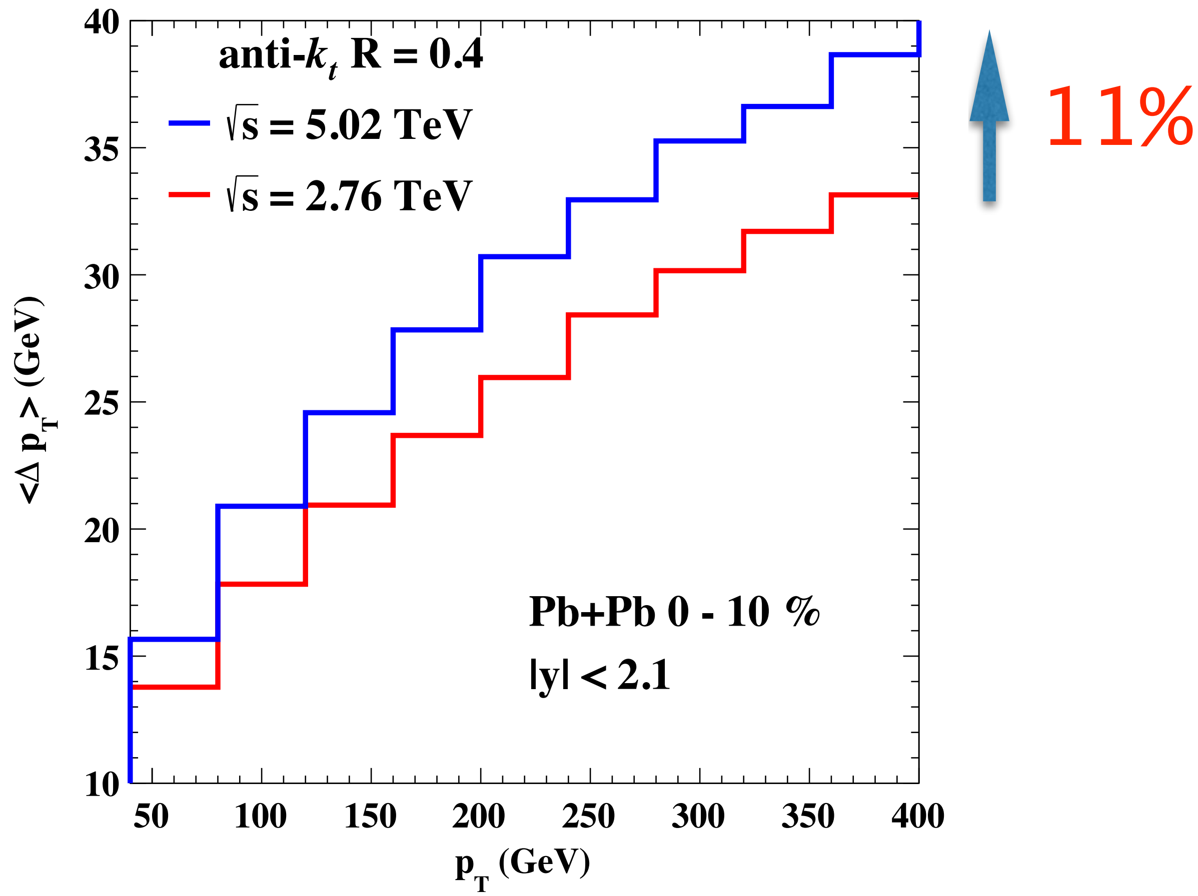
Inclusive jet suppression





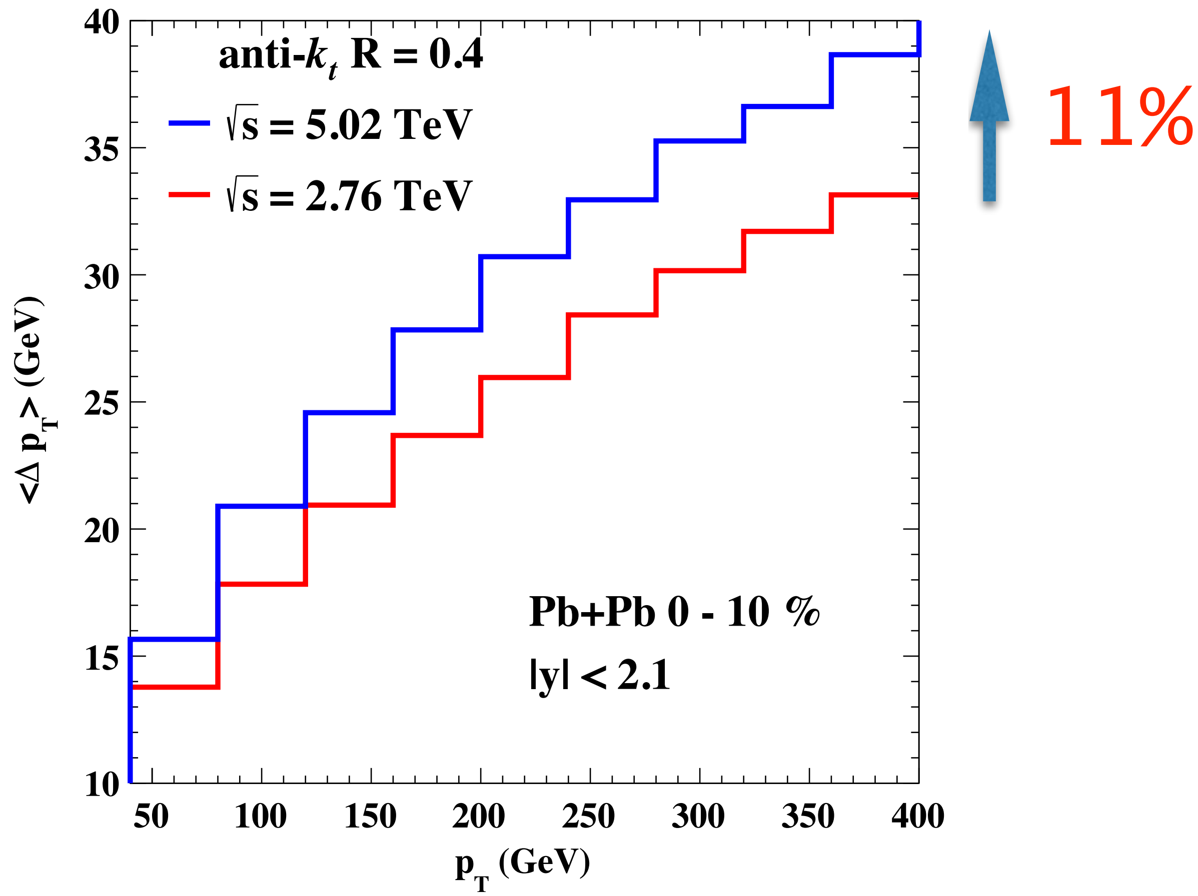
R_{AA} slightly increases with jet p_T for 2.76 TeV and 5.02 TeV.

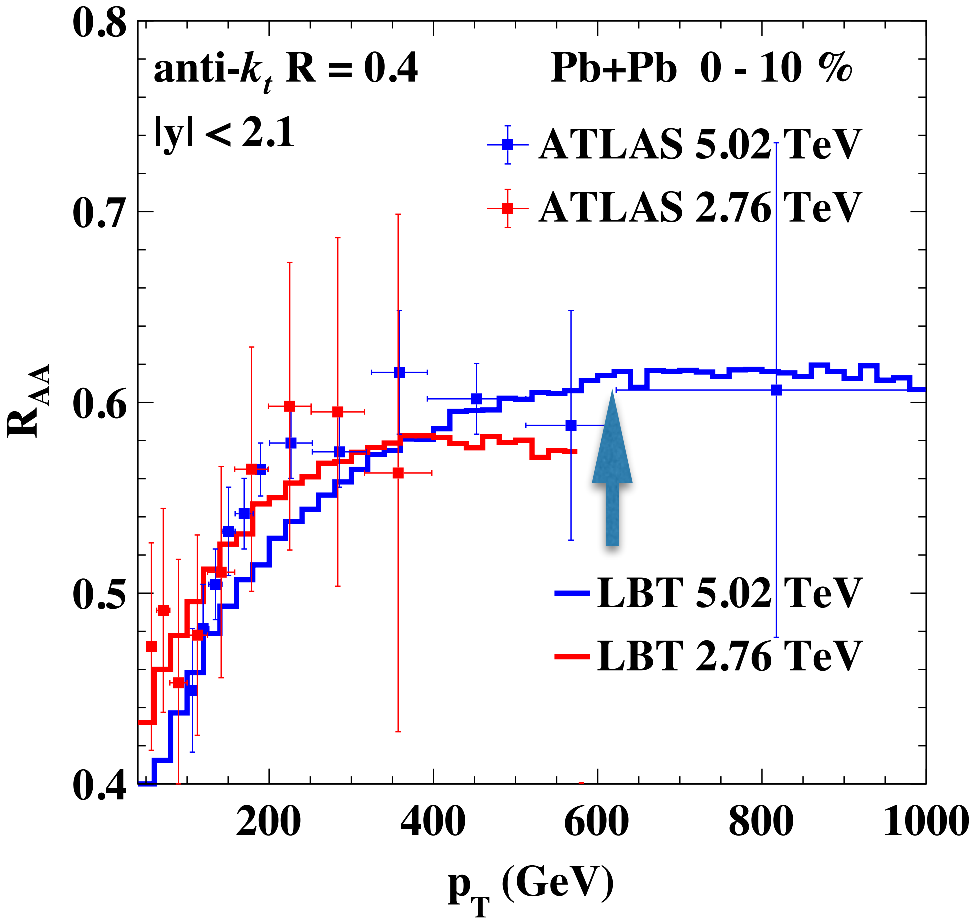
Understanding jet R_{AA}



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

Understanding jet R_{AA}



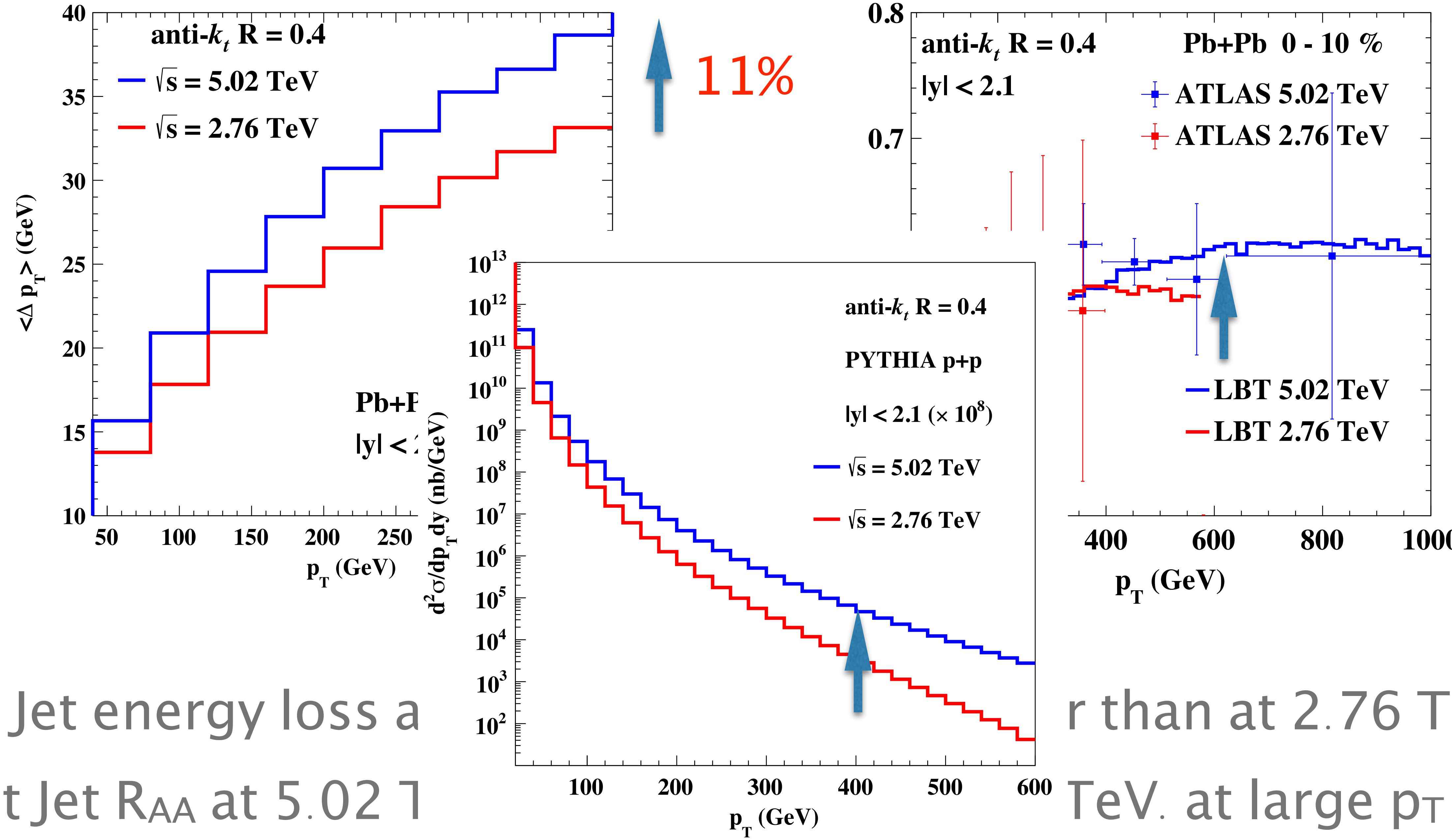


Jet energy loss at 5.02 TeV is indeed larger than at 2.76 TeV.

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

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

Understanding jet R_{AA}



Jet energy loss a r than at 2.76 TeV.

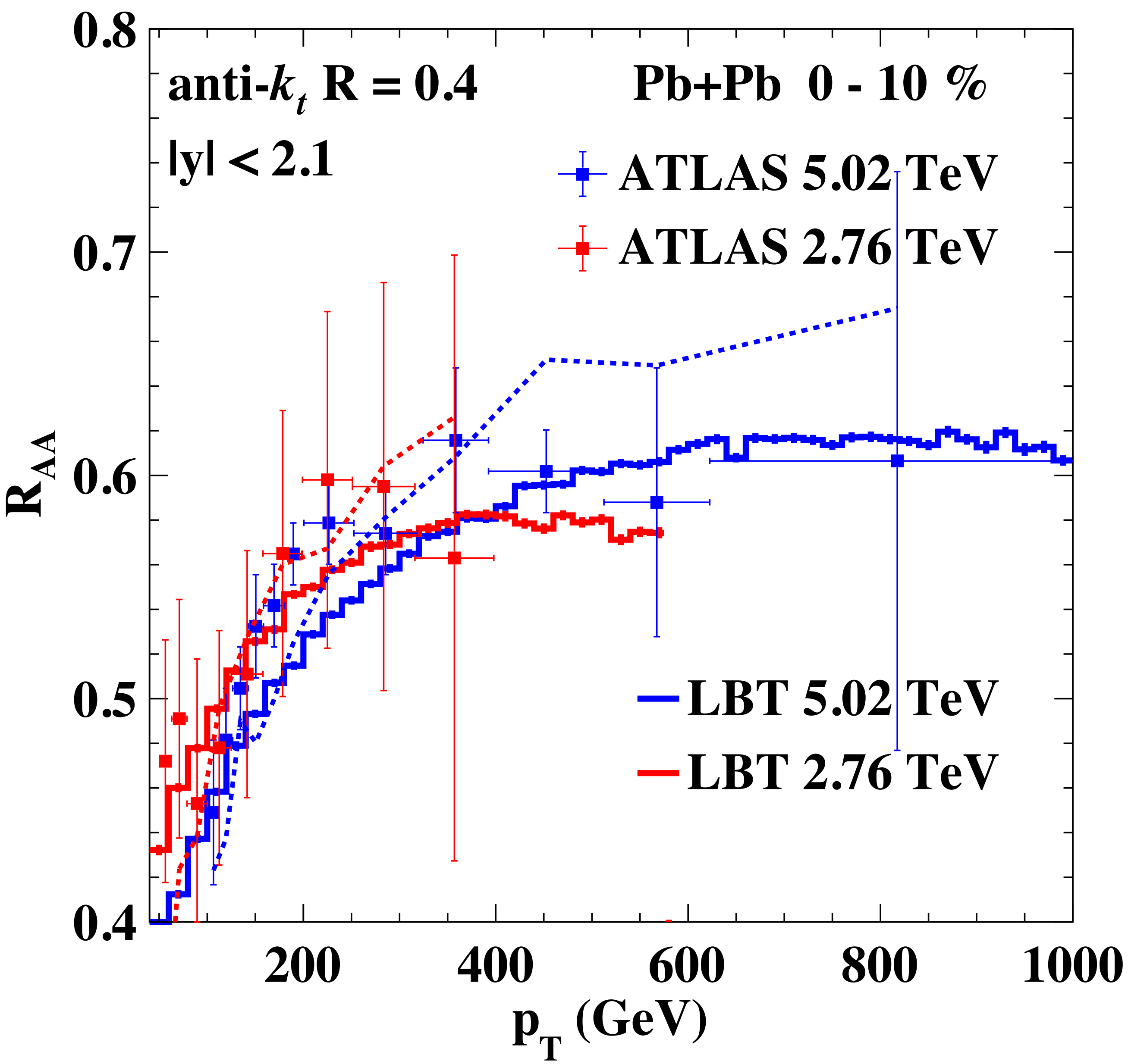
But Jet R_{AA} at 5.02 T TeV. at large p_T range

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

Understanding jet R_{AA}

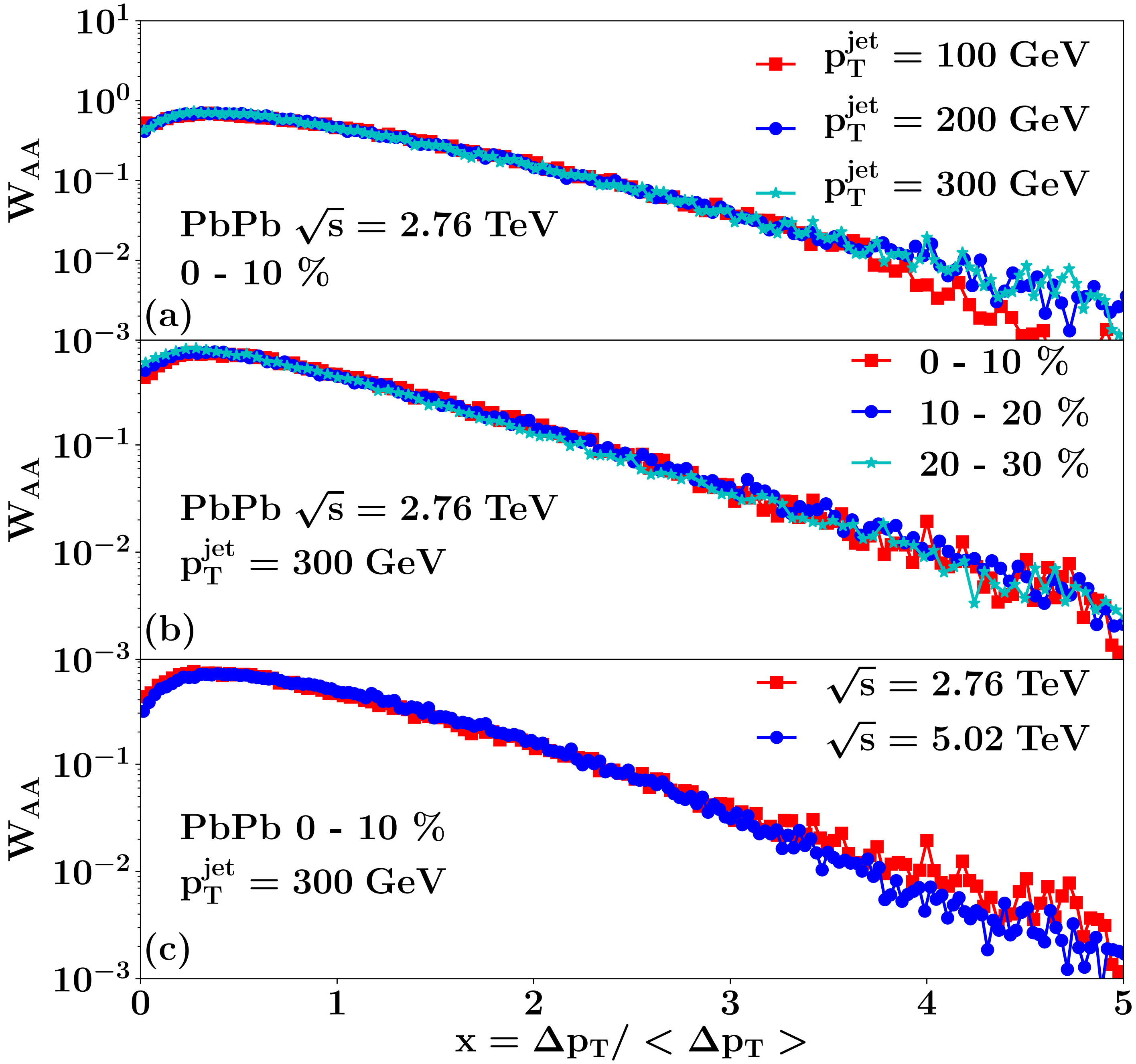
If $\langle \Delta p_T \rangle / p_T$ is small,

$$R_{\mathrm{AA}}(p_T) \approx \frac{d\sigma^{\mathrm{jet}}_{\mathrm{p+p}}(p_T + \langle \Delta p_T \rangle)}{d\sigma^{\mathrm{jet}}_{\mathrm{p+p}}(p_T)}$$



Jet energy loss distribution

$$\frac{d\sigma^{AA}_{jet}}{dp_T dy}(p_T, R) = \int d\Delta p_T W_{AA}(\Delta p_T, p_T + \Delta p_T, R) \frac{d\sigma^{pp}_{jet}}{dp_T dy}(p_T + \Delta p_T, R)$$



leading jet energy loss distribution

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

Scaling behavior at a given centrality class:

$$\langle \Delta p_T \rangle = \langle \Delta p_T \rangle (p_T, \sqrt{s})$$

Bayesian extraction from experimental data

$$\frac{d\sigma_{jet}^{AA}}{dp_T dy}(p_T, R) = \int d\Delta p_T W_{AA}(\Delta p_T, p_T + \Delta p_T, R) \frac{d\sigma_{jet}^{pp}}{dp_T dy}(p_T + \Delta p_T, R)$$

Y. He, L-G Pang, X-N Wang, PRL 122 (2019) 252302

LBT model: $\left.\begin{matrix} \sigma_{jet}^{pp}(p_T) \\ W_{AA}(p_T, \Delta p_T) \end{matrix}\right\} \Longrightarrow \sigma_{jet}^{AA}(p_T)$

Bayesian analysis: $\left.\begin{matrix} \sigma_{jet}^{pp}(p_T) \\ \sigma_{jet}^{AA}(p_T) \end{matrix}\right\} \Longrightarrow W_{AA}(p_T, \Delta p_T)$

Data-driven,
model independent

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}$$

Y : data

$X : W_{AA}$

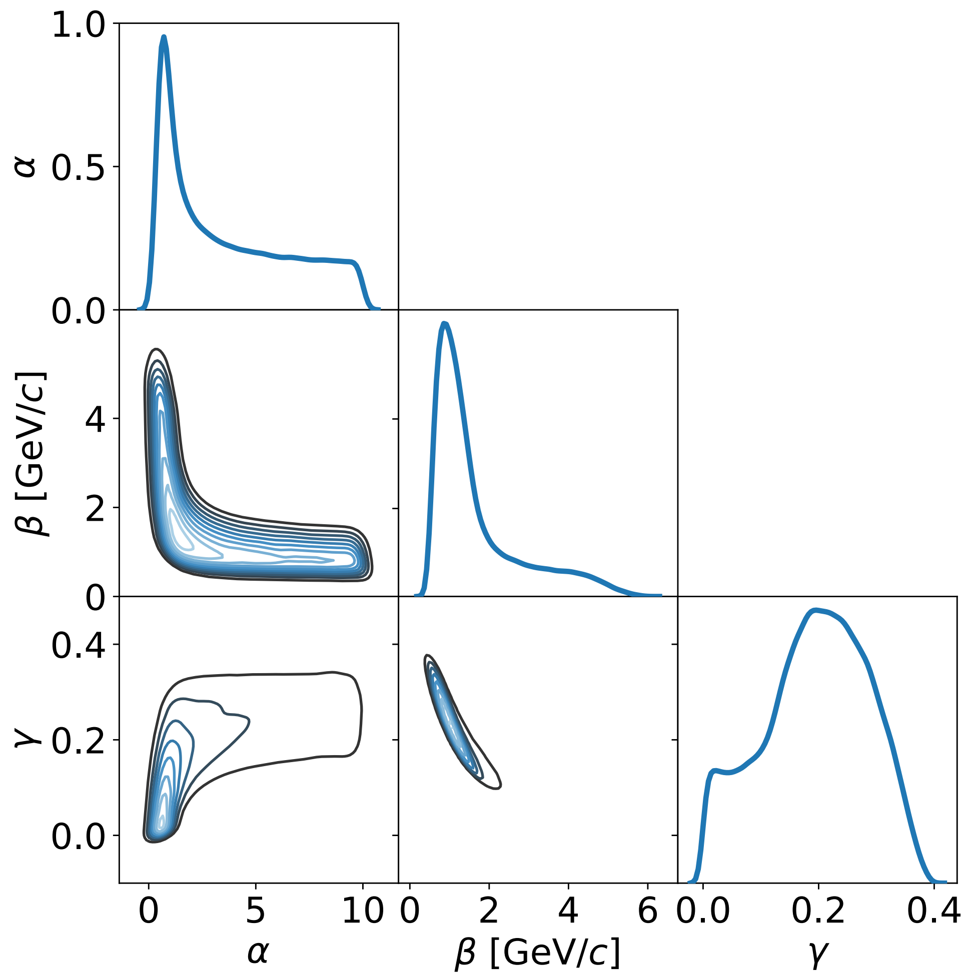
Bayesian extraction from experimental data

Bayesian analysis:

Markov Chain Monte Carlo

$$P(X|Y) = \frac{P(Y|X)P(X)}{P(Y)}$$

8,000,000 samplings



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

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

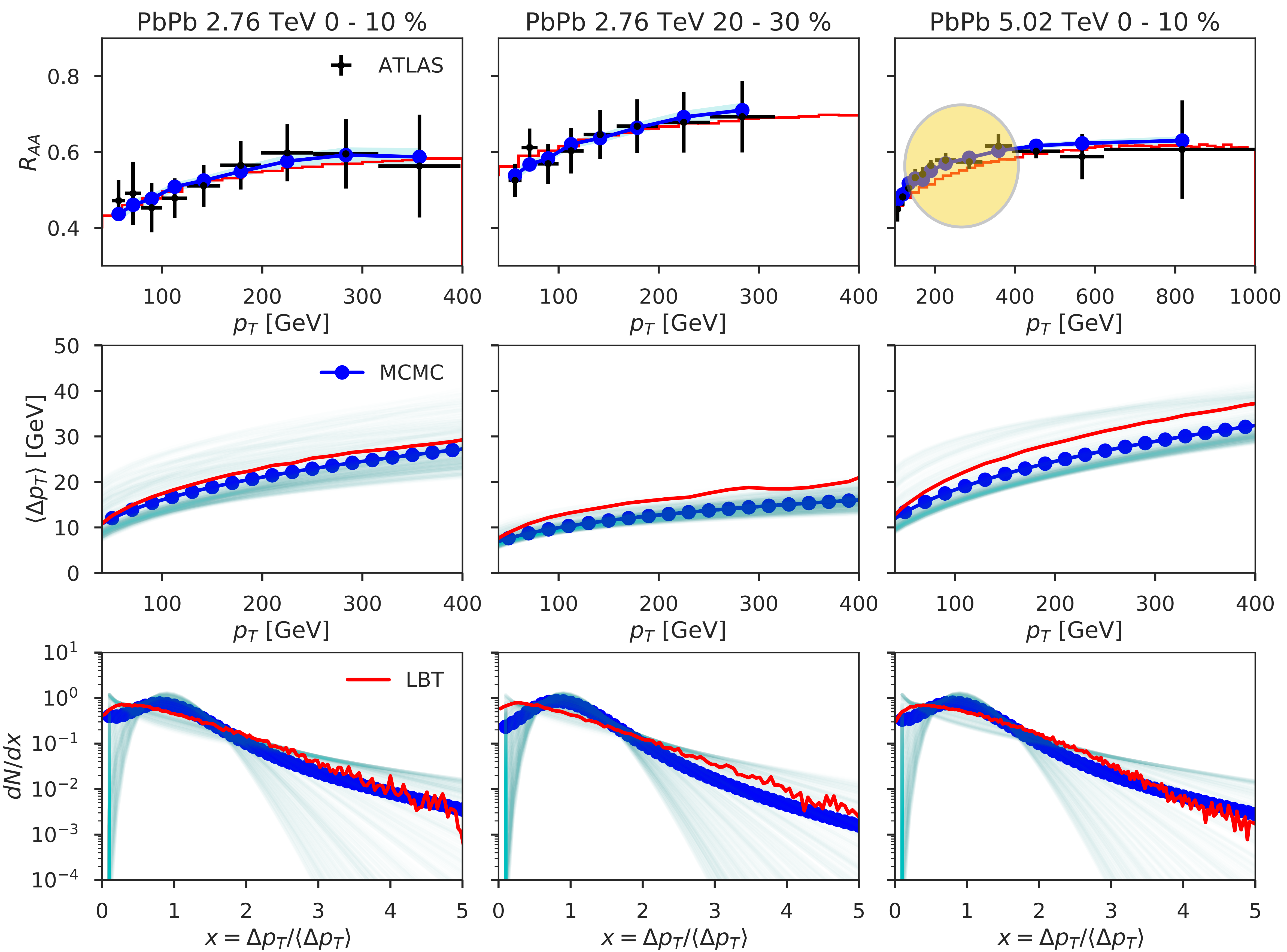
$$W_{AA}(x) = \frac{\alpha^\alpha}{\Gamma(\alpha)} x^{\alpha-1} e^{-\alpha x}$$

$$\equiv \int \prod_{i=1}^{a} dx_i e^{-\sum_i^a x_i} \delta(x - \sum_{i=1}^{a} x_i)$$

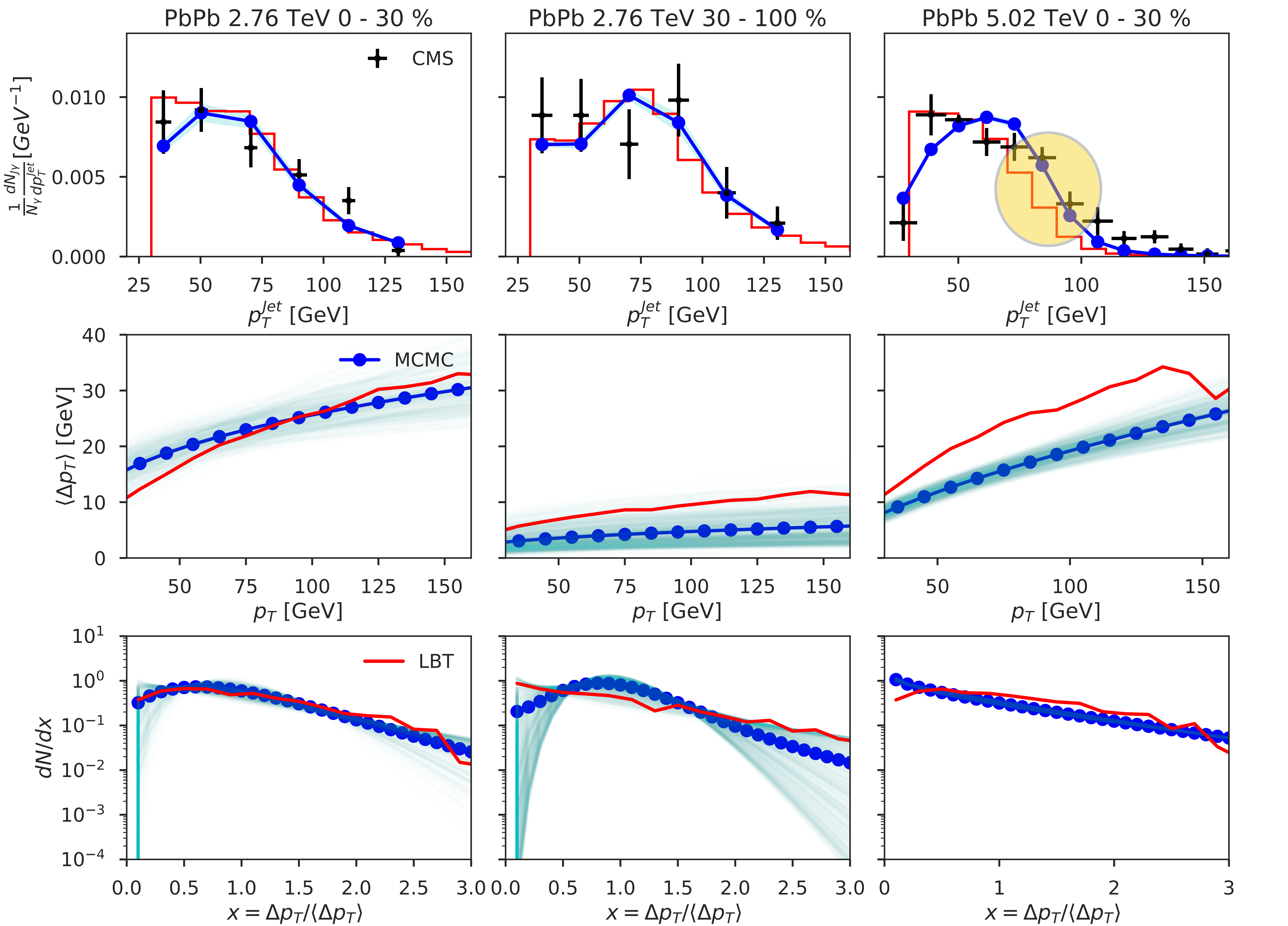
$$\langle \Delta p_T \rangle = \beta p_T^\gamma \log(p_T)$$

α : number of out-of-cone scatterings

Bayesian extraction from experimental data



Bayesian extraction from experimental data



Bayesian extraction from experimental data

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)

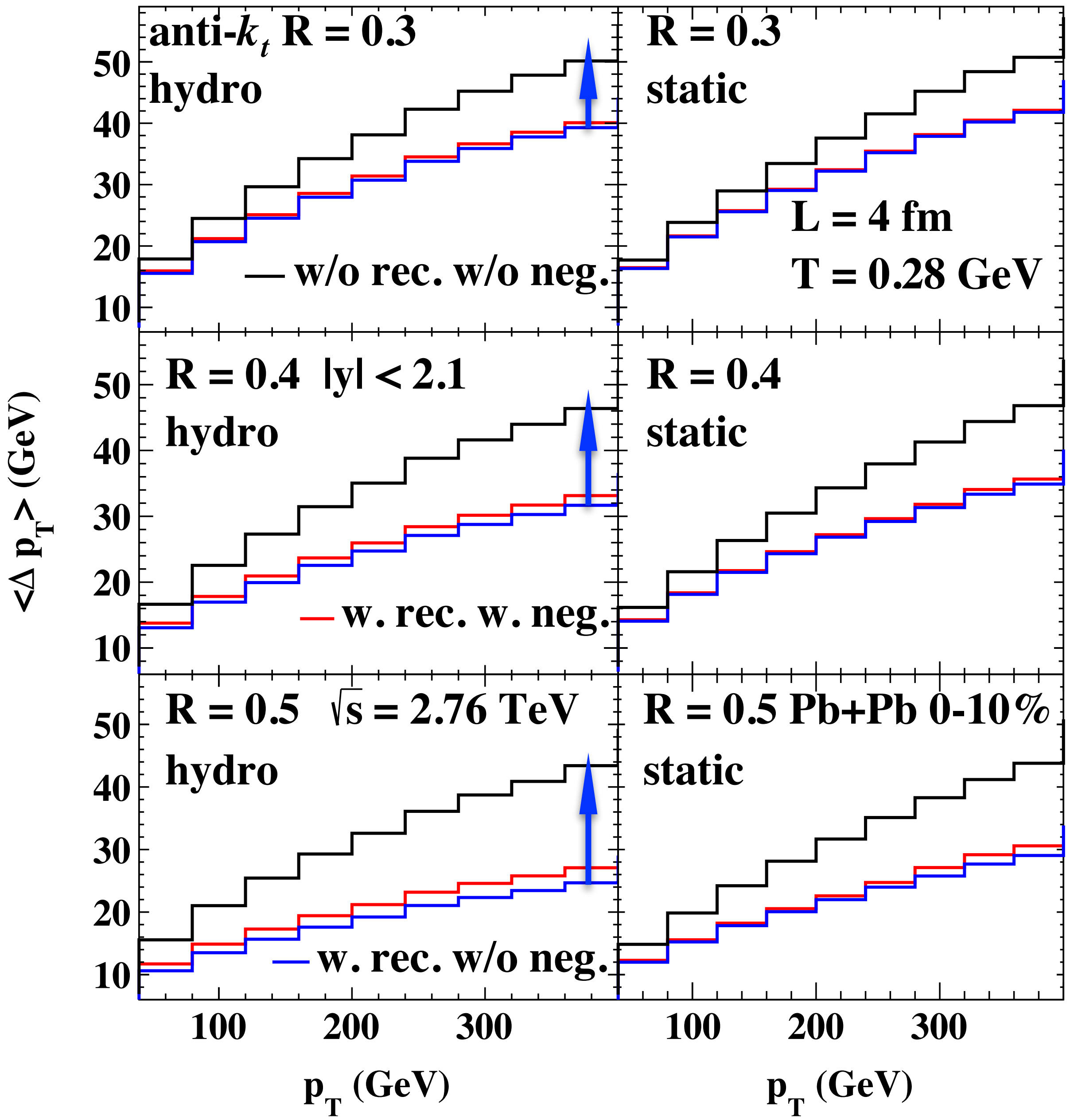
TABLE I. Parameters $[\alpha, \beta, \gamma]$ of the jet energy loss distribution from Bayesian fits to single inclusive and γ-triggered jet spectra in Pb+Pb collisions at $\sqrt{s} = 2.76$ and 5.02 TeV. Numbers in parentheses are from fits to LBT results.

Summary

- The inclusive jet suppression is determined by the initial pp spectrum and jet energy loss distribution.
- Jet energy loss distribution has a scaling behavior
- Bayesian analysis can extract jet energy loss distribution and averaged jet energy loss directly from experimental data.
- Jet energy loss is mainly caused by a few out-of cone scatterings in the hot and dense medium.

Thanks!

Effects of medium response and radial expansion



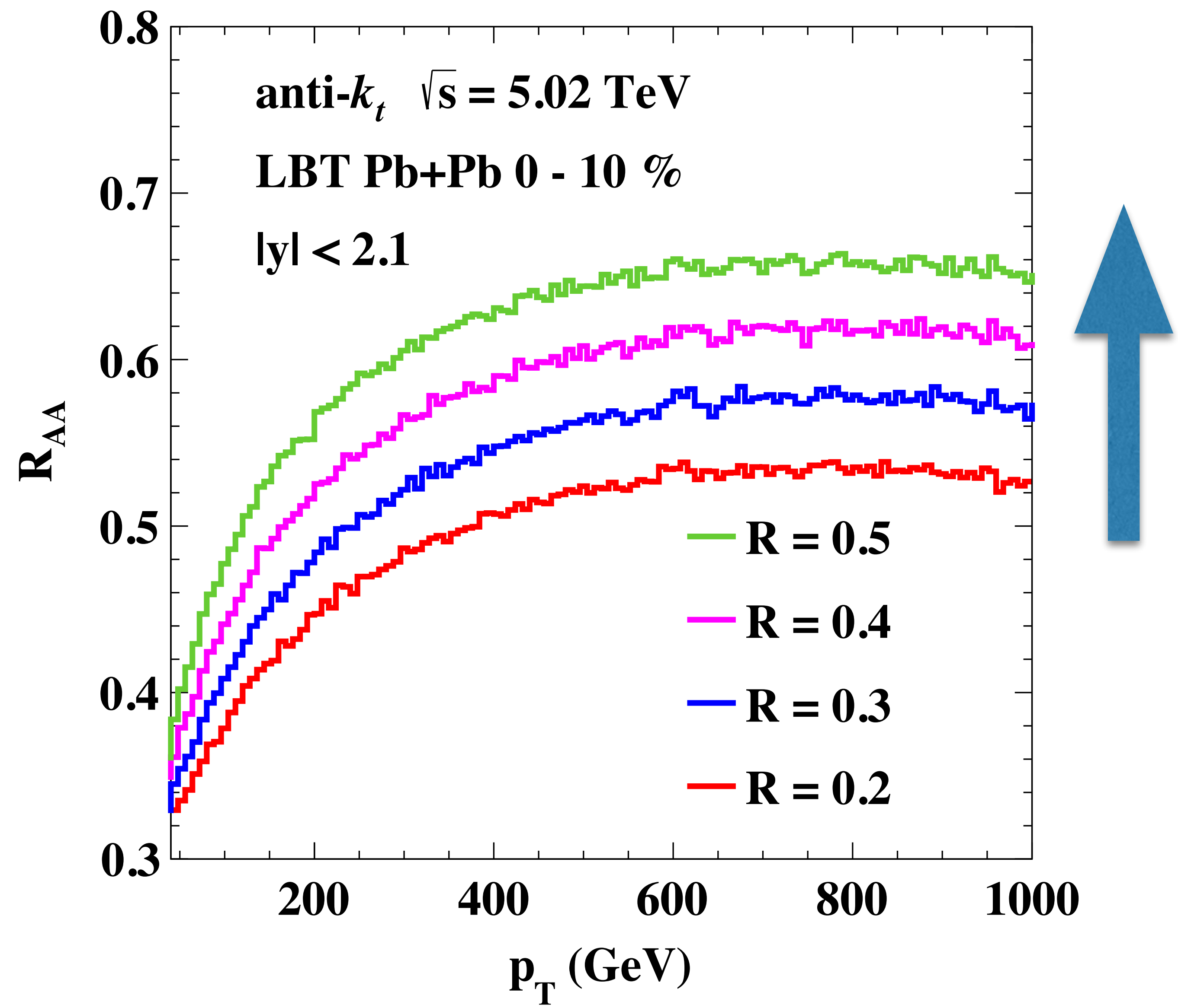
2.76 TeV

medium recoil effect up to 15%

back reaction not negligible

larger cone size and radial expansion enlarges the effects above.

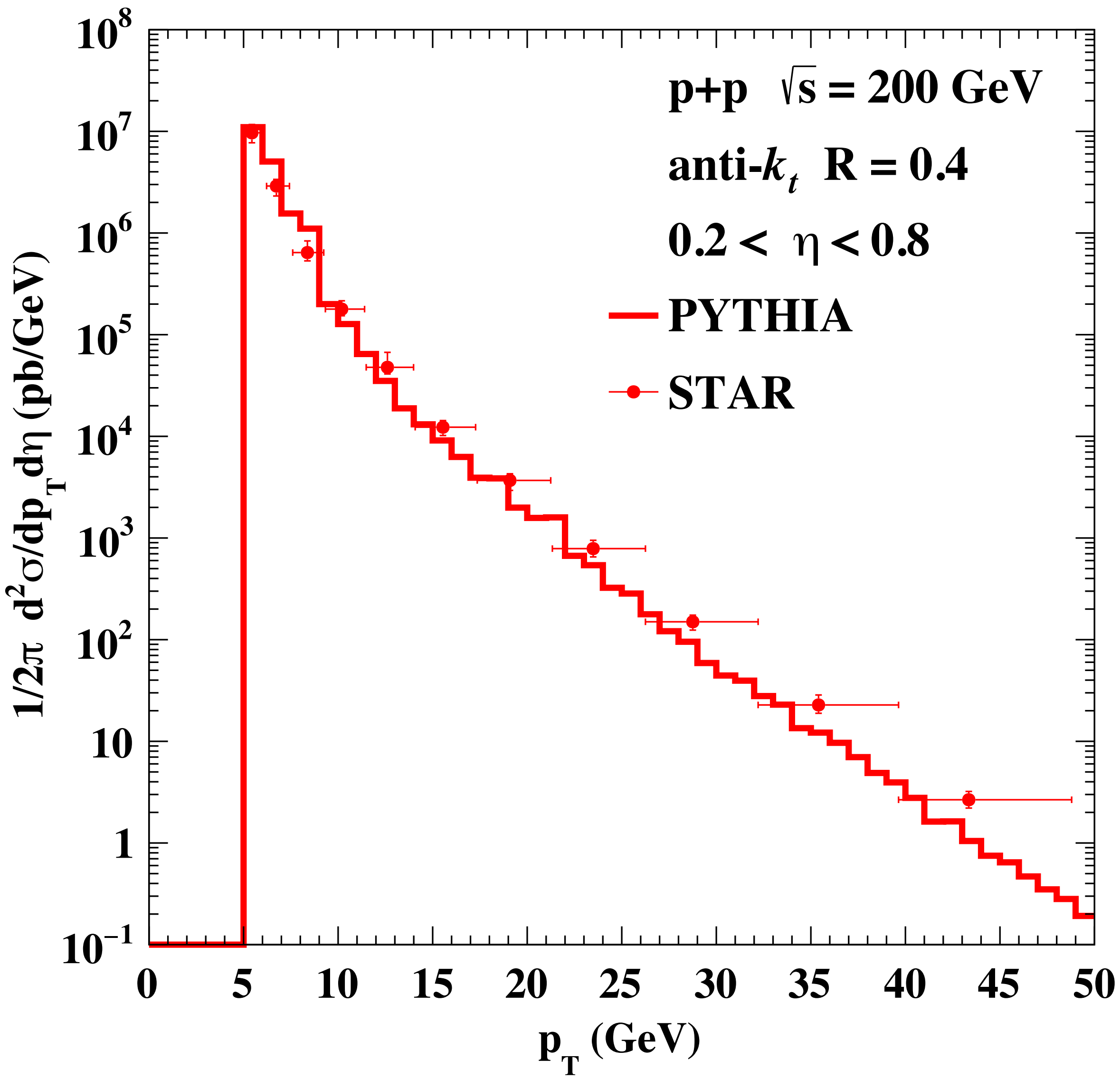
Cone size dependence of R_{AA}

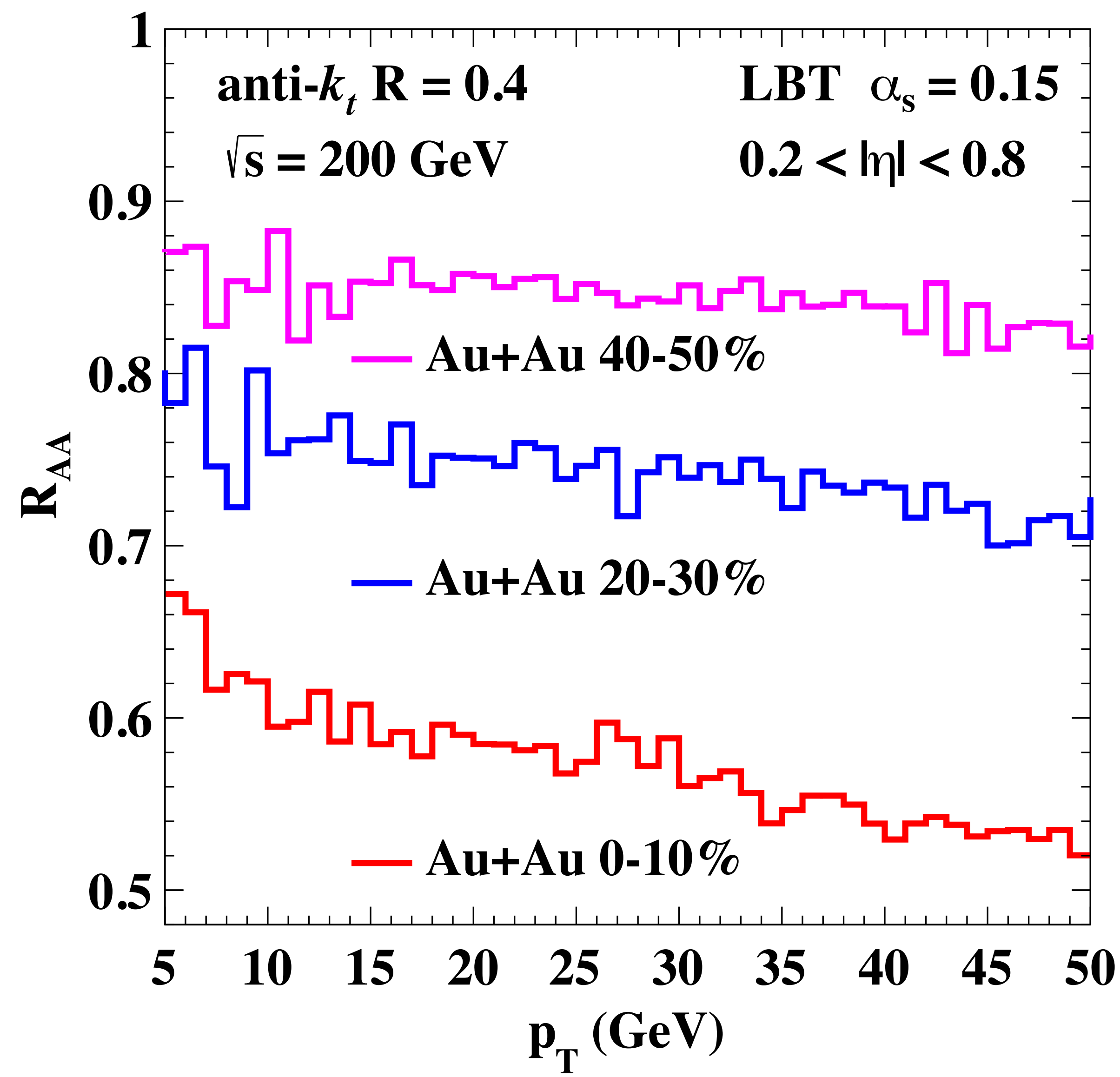


larger R: flatter initial spectrum + smaller energy loss
->less suppression

quantitatively relates to medium response

R_{AA} at RHIC energy

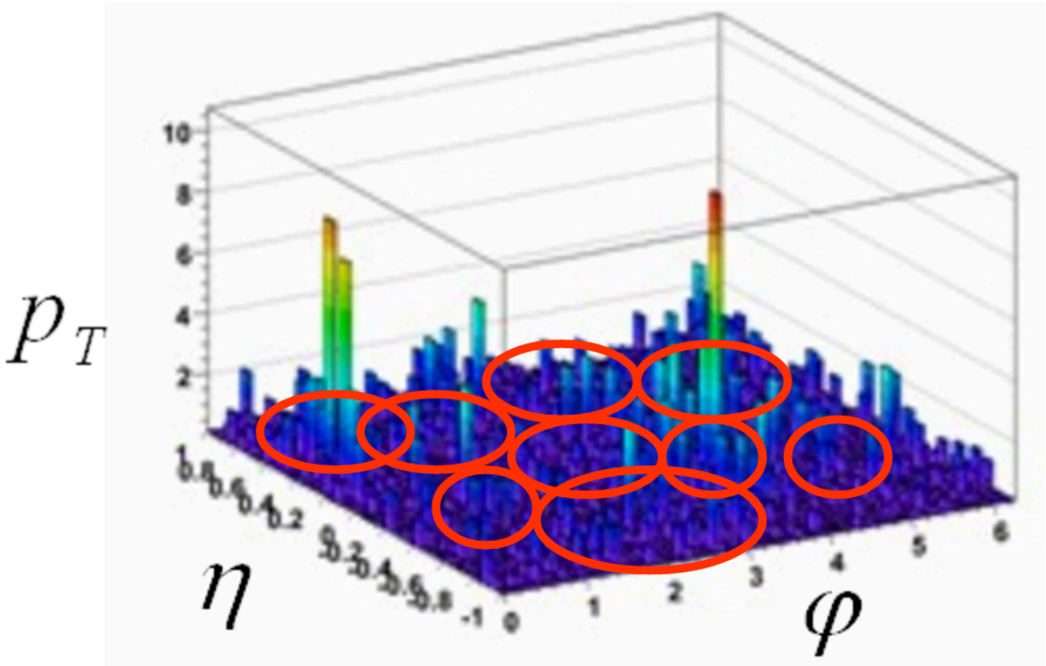




Slightly decreases with jet energy because of steeper initial spectrum, although the energy loss is smaller that at LHC energy.

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

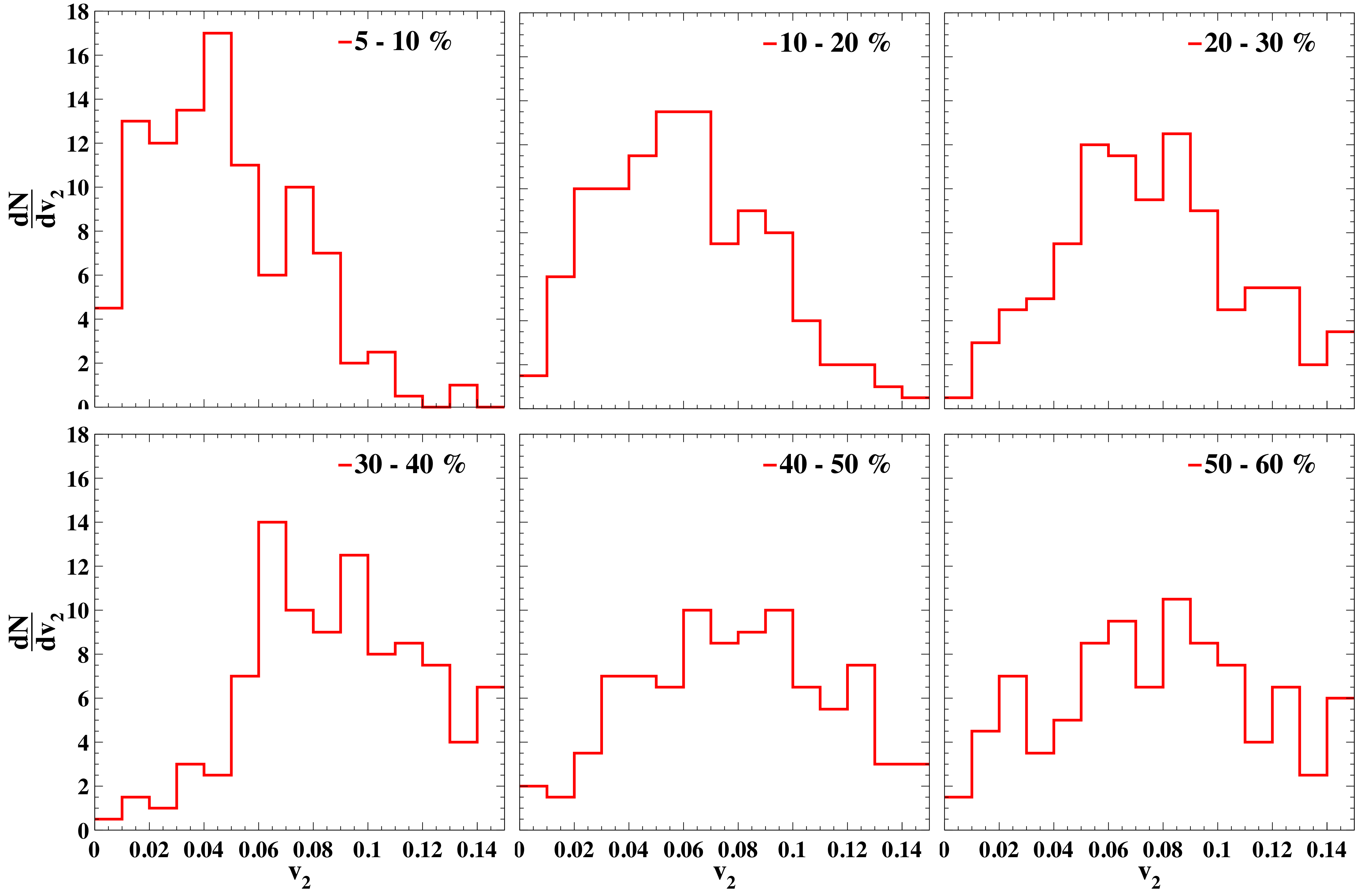
$$E_T^{max}/E_T^{ave} > 4$$

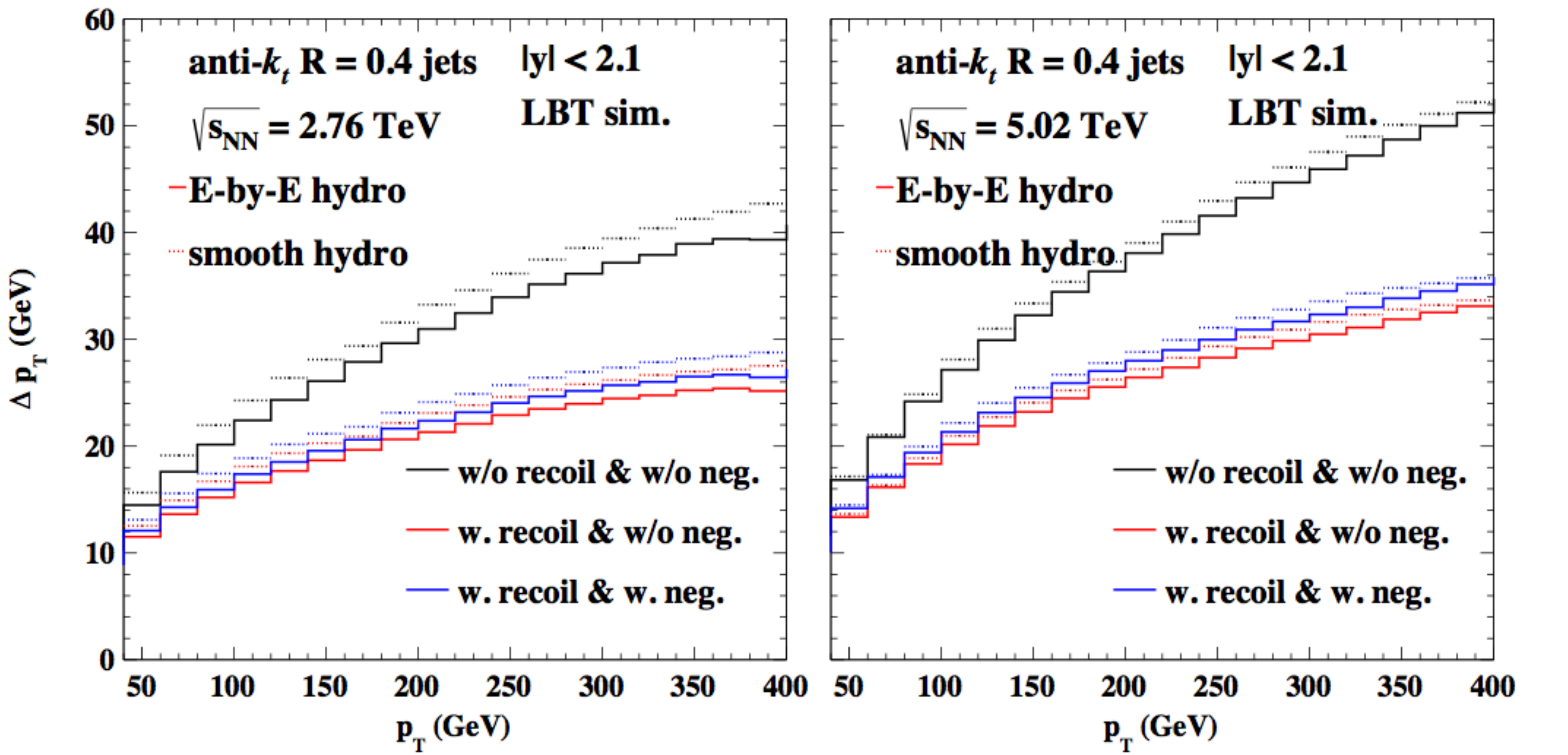
ATLAS Collaboration, Phys. Lett. B 719, 220 (2013).

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

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

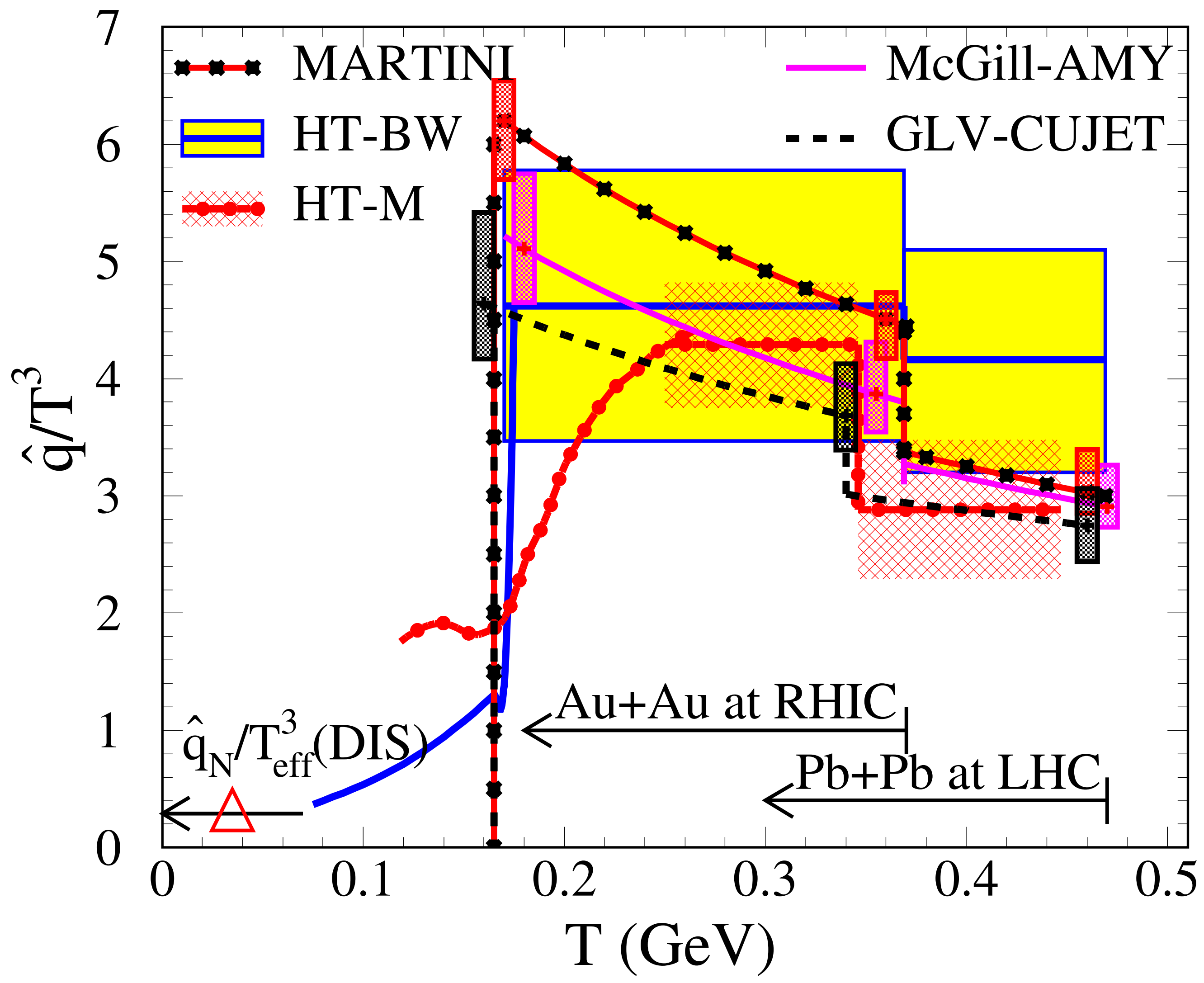
v_2 of soft particles from hydro profiles




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.
Δp_T (GeV)
p_T (GeV)
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.
p_T (GeV)

jet-medium transport coefficient

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



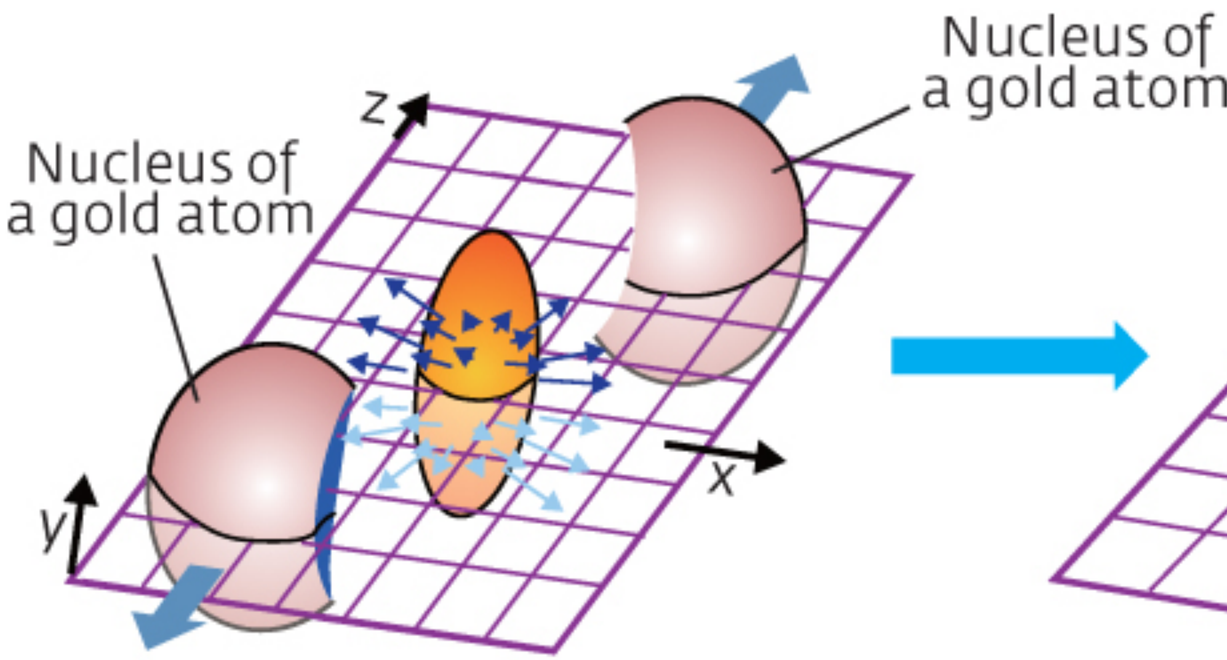
Azimuthal Anisotropy v_2

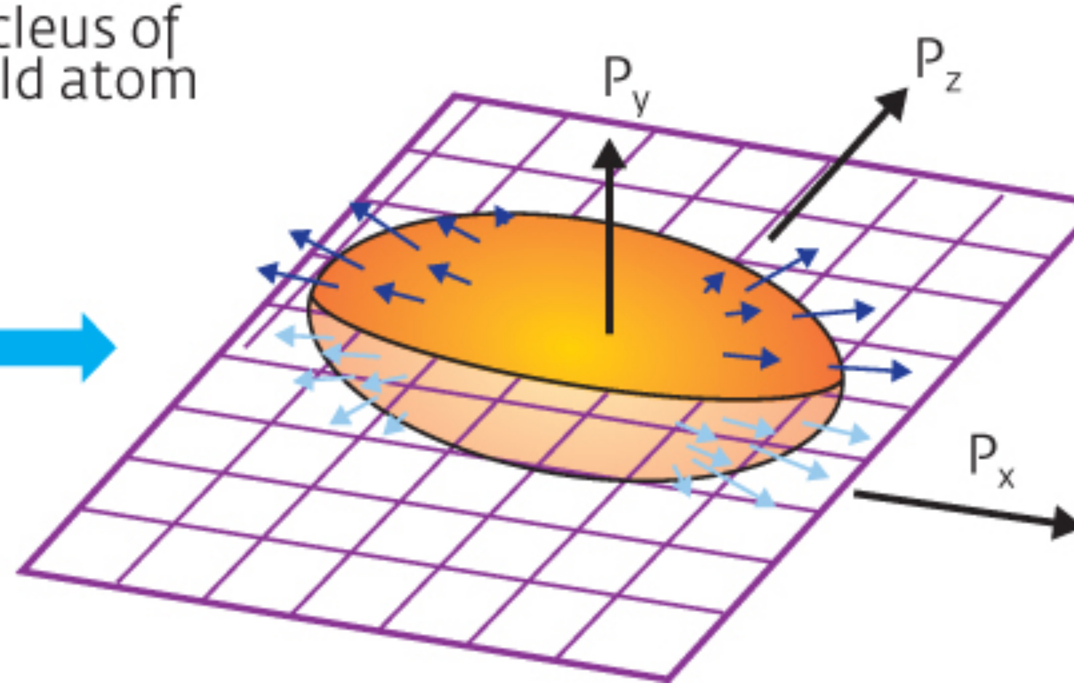
$$\frac{dN}{d\phi} = C(1 + 2\Sigma_n v_n \cos[n(\phi - \Psi_n)])$$

elliptic flow: n=2

$$v_2 = < \cos[2(\phi - \Psi_2)] >$$

Coordinate space: initial asymmetry → Momentum space: final asymmetry

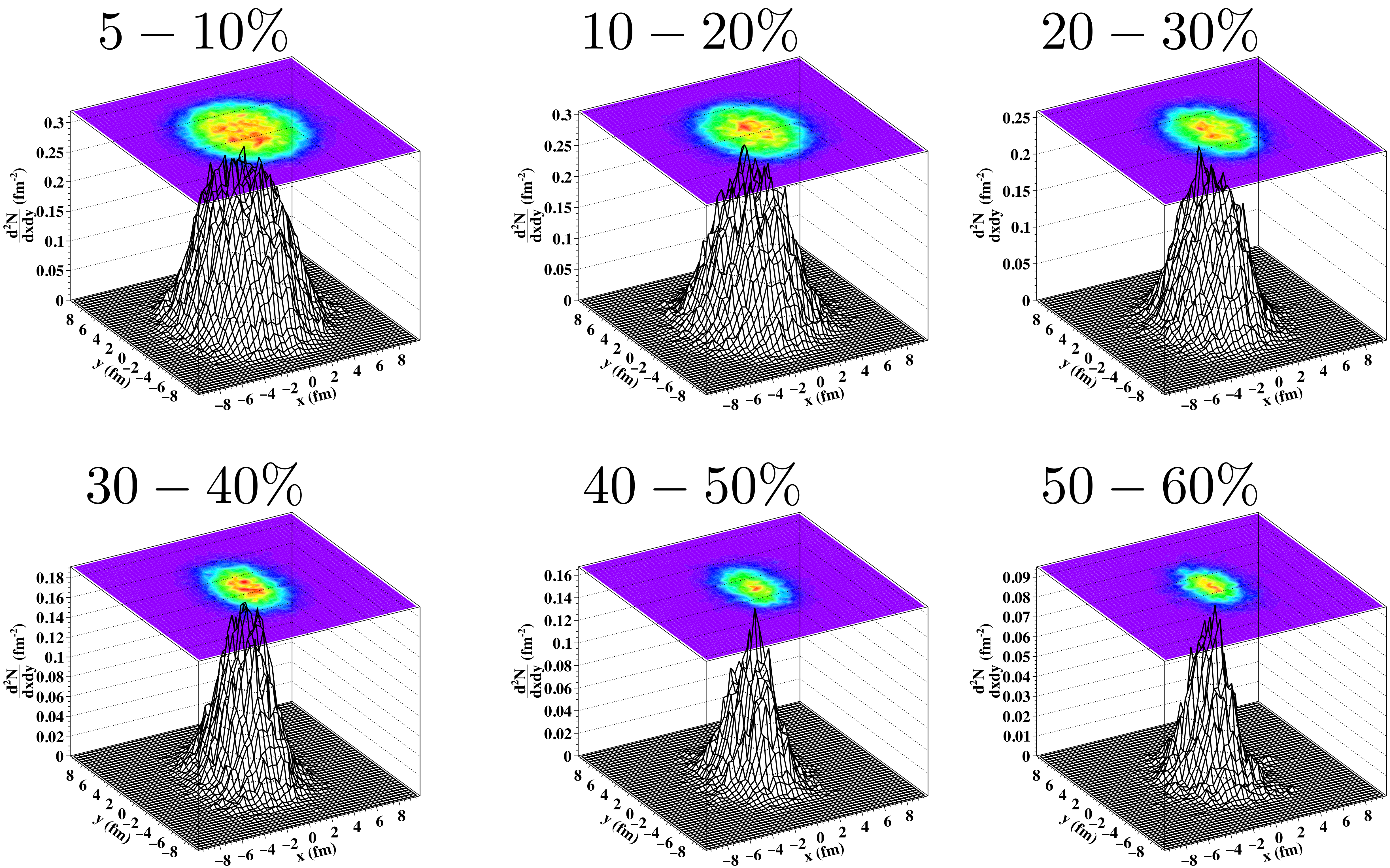




$$\epsilon = \frac{< y^2 - x^2 >}{< y^2 + x^2 >}$$

$$v_2 = \frac{< p_y^2 - p_x^2 >}{< p_y^2 + p_x^2 >}$$

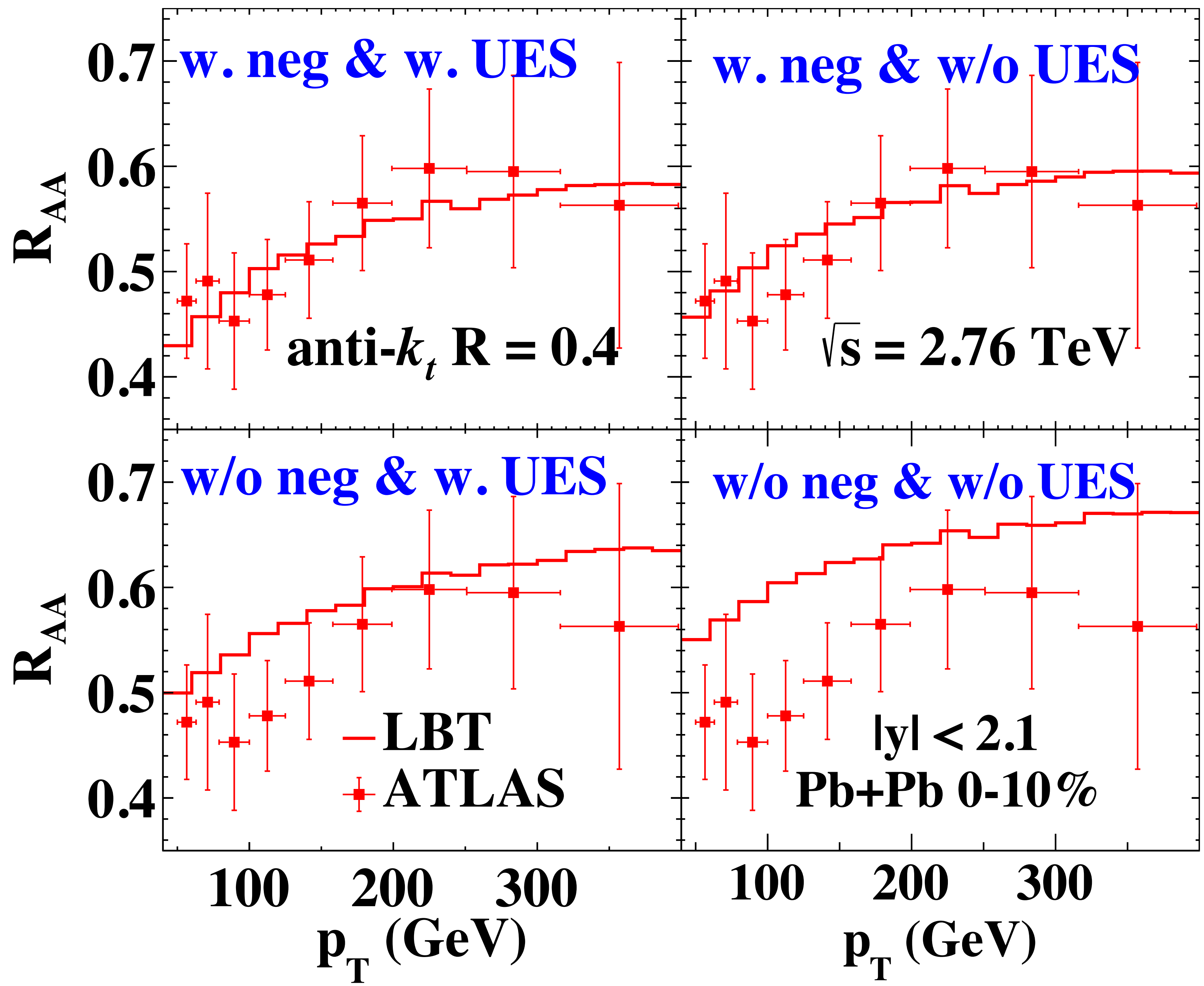
Initial Geometry at 2.76 TeV



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

Results: Inclusive jet suppression

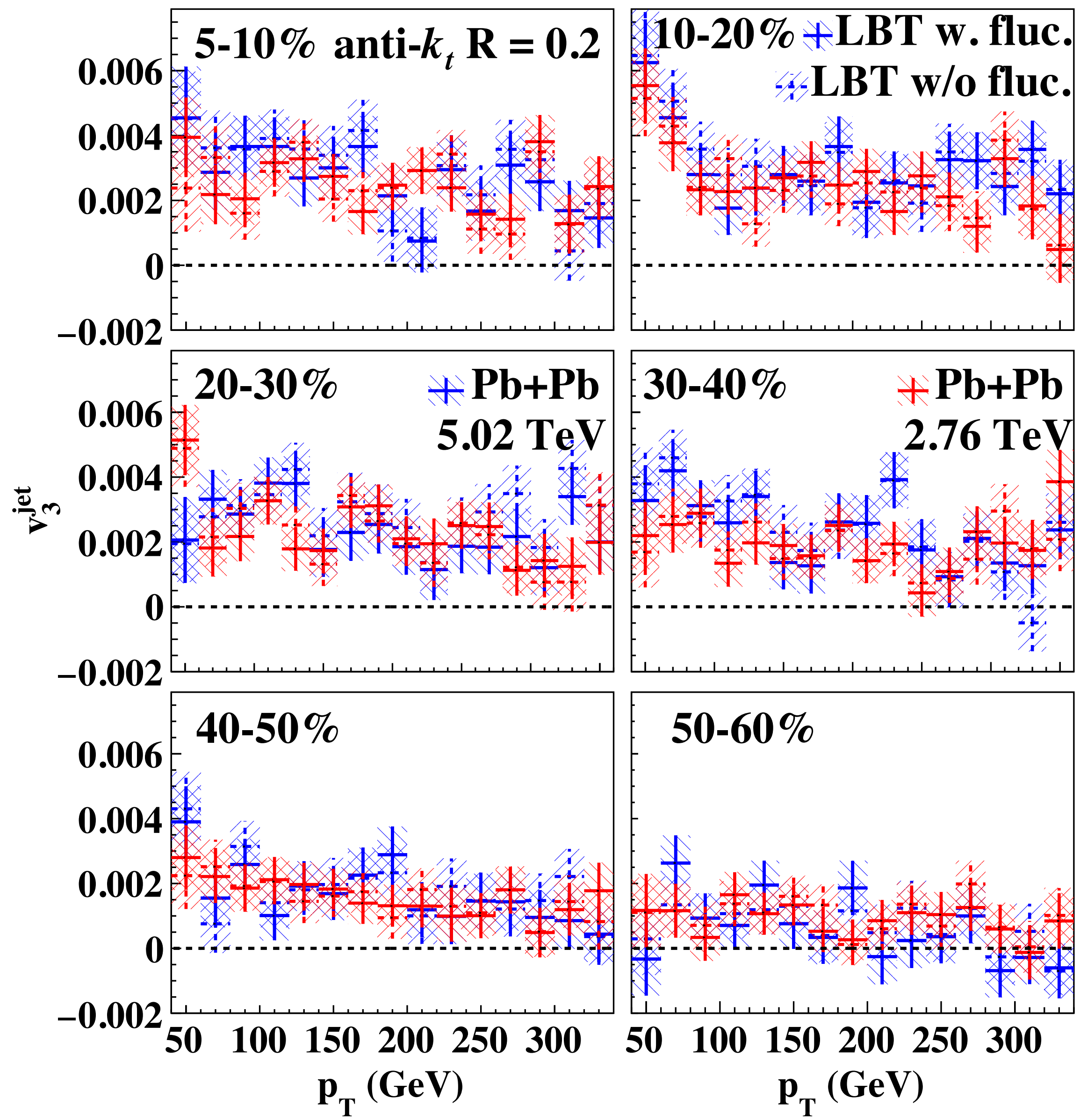
fixed $\alpha_s = 0.15$

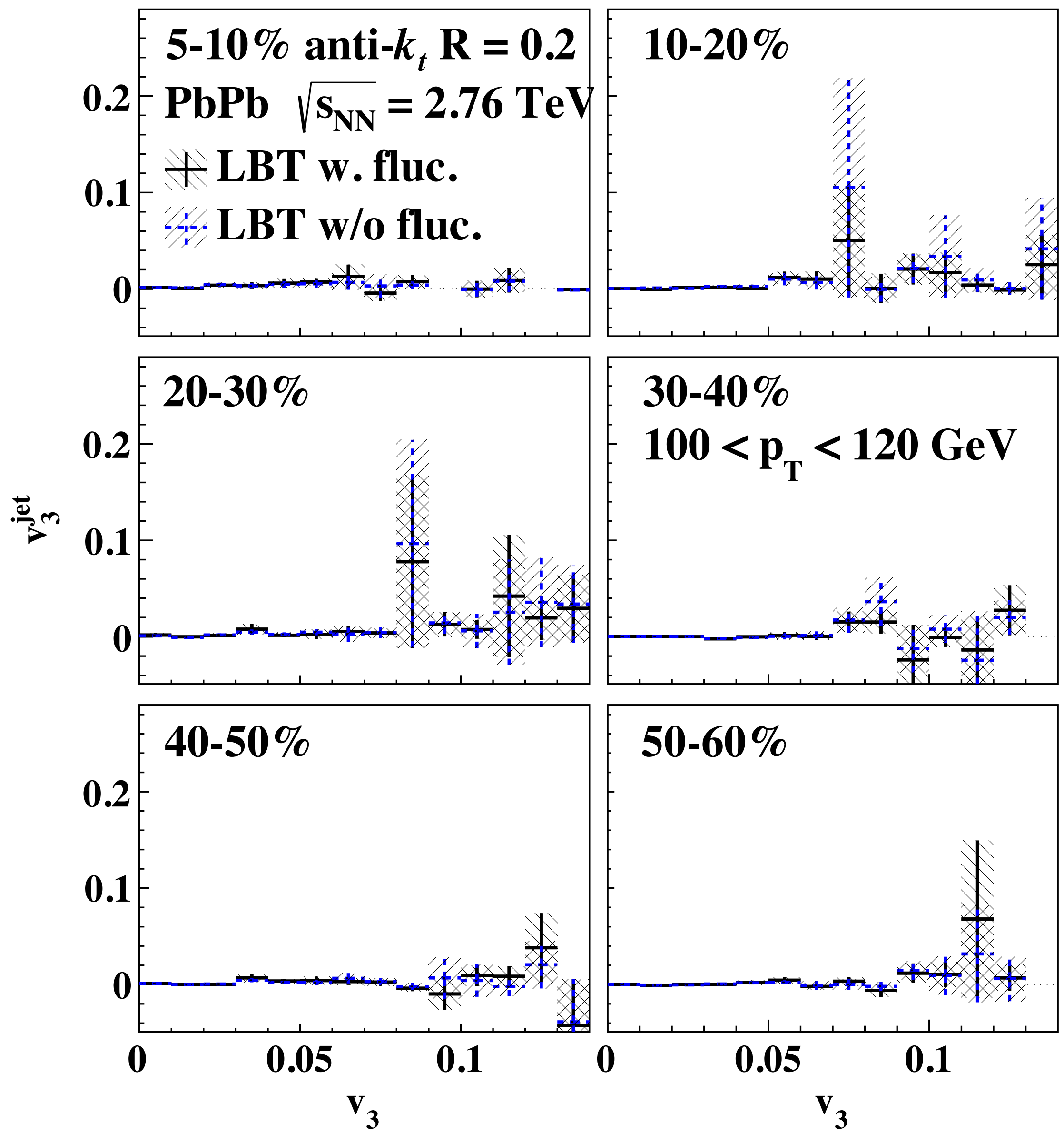


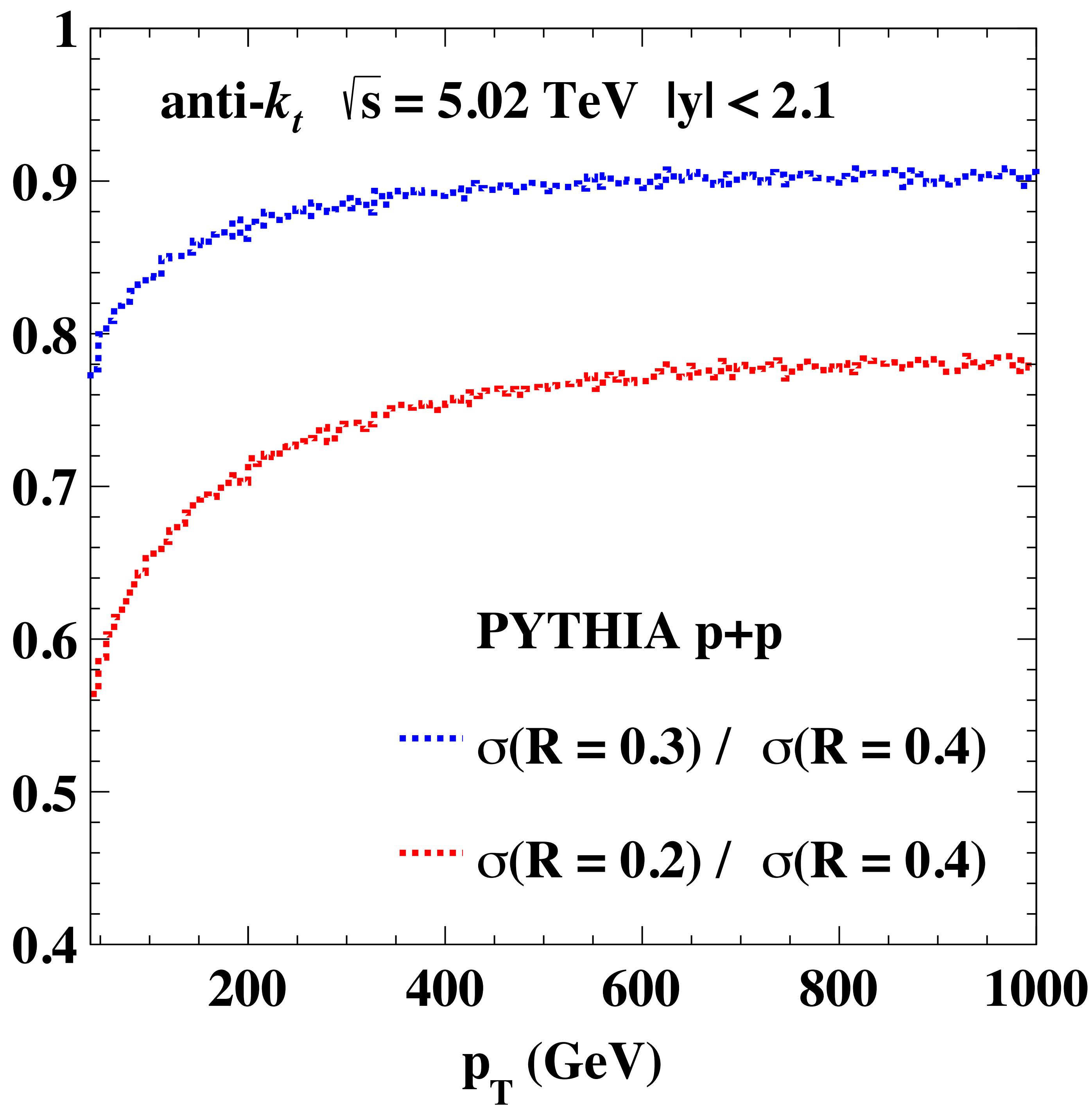
Suppression!!!

w. neg (whole p_T range);

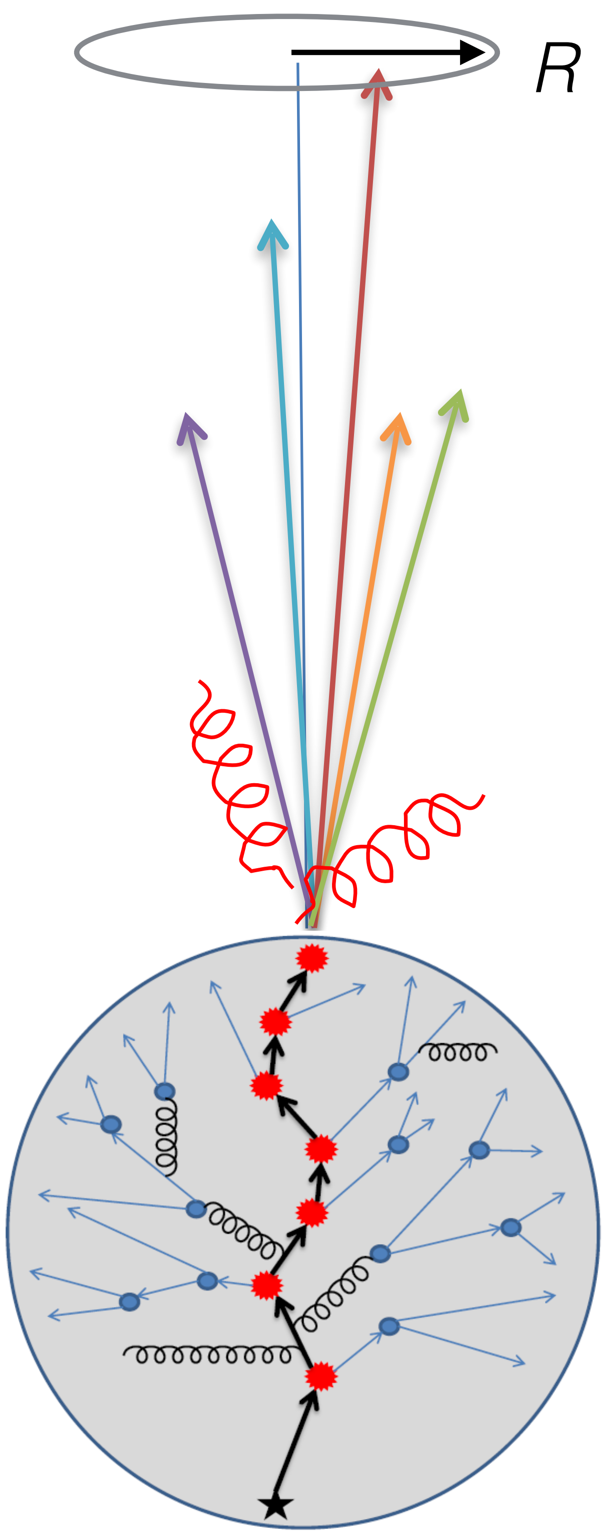
w. UES(low p_T range)


5-10% anti-k_t R = 0.2
10-20%
LBT w. fluc.
LBT w/o fluc.
20-30%
Pb+Pb 5.02 TeV
30-40%
Pb+Pb 2.76 TeV
40-50%
50-60%
v_3^{jet}
p_T (GeV)


5-10% anti-k_t R = 0.2
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
LBT w. fluc.
LBT w/o fluc.
10-20%
20-30%
30-40%
100 < p_T < 120 GeV
40-50%
50-60%
v_3^{jet}
v_3


anti-k_t $\sqrt{s}$ = 5.02 TeV |y| < 2.1
PYTHIA p+p
σ(R = 0.3) / σ(R = 0.4)
σ(R = 0.2) / σ(R = 0.4)
1
0.9
0.8
0.7
0.6
0.5
0.4
200
400
600
800
1000
p_T (GeV)

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).

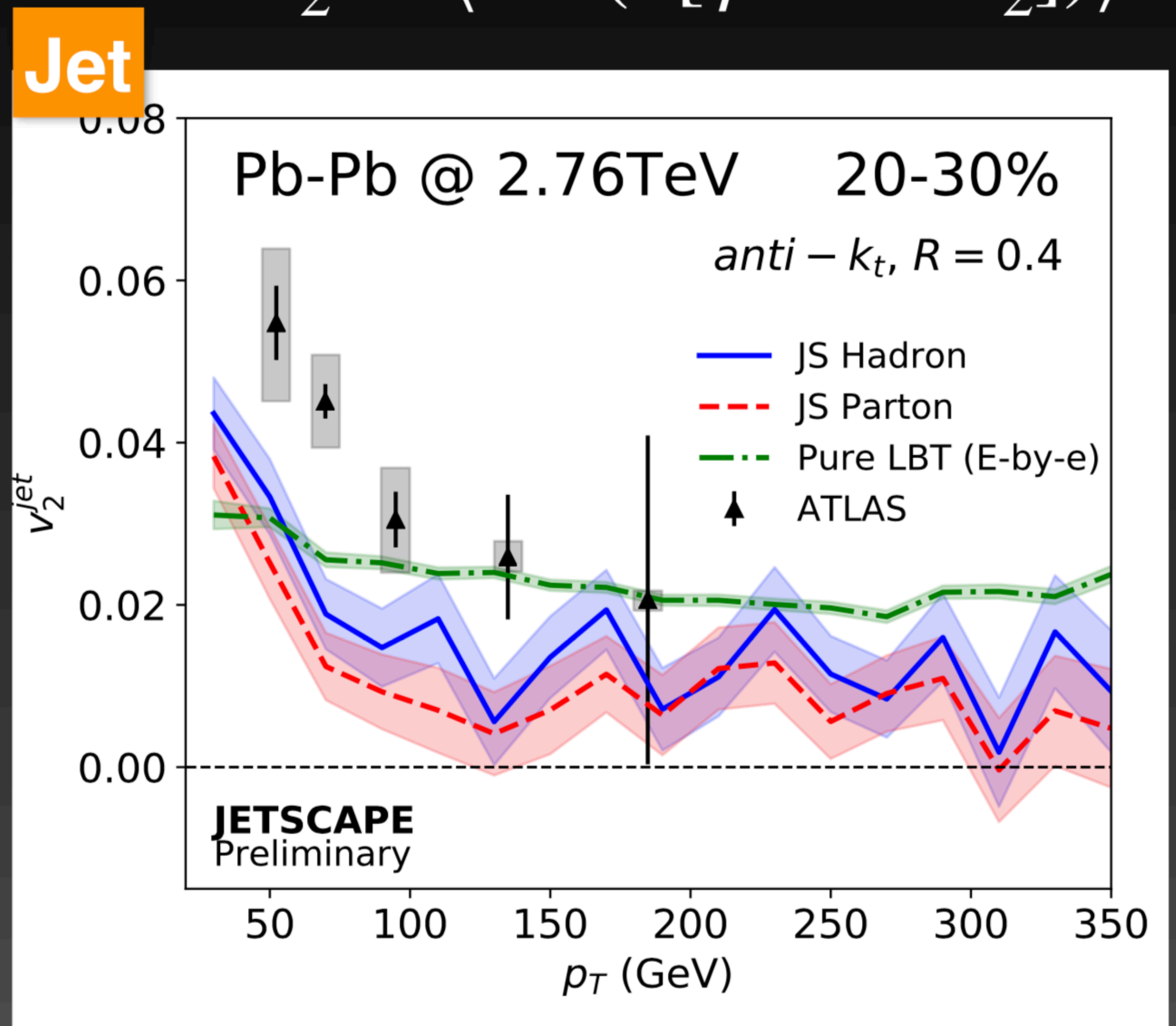
consider all the jets

modified FASTJET,
subtract the “negative” particles

medium recoil re-scattering,
back reaction (“negative particles”)

Inclusive jet anisotropy

$$v_2 = \langle \cos(2[\phi^{jet} - \Psi_2]) \rangle$$



Multistage evolution, see: Chanwook Park, HP 2018

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

$$\frac{d \sigma^{AA}_{jet}}{dp_T dy} (p_T, R)= \int d\Delta p_T W_{AA} (\Delta p_T, p_T + \Delta p_T, R) \frac{d\sigma^{pp}_{jet}}{dp_T dy} (p_T + \Delta p_T, R)$$

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

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

$$\equiv \int \prod_{i=1}^{a} dx_i e^{-\sum_{i}^{a} x_i} \delta(x - \sum_{i=1}^{a} x_i)$$

$$\sigma^{pp}_{jet} (p_T) + W_{AA}(p_T, \Delta p_T) \rightarrow \sigma^{AA}_{jet} (p_T)$$

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