

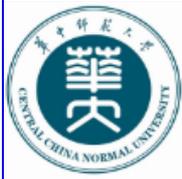


May 13-19

E-by-e jet suppression, anisotropy and hard-soft tomography

Xin-Nian Wang
CCNU/LBNL

In collaboration with S. Cao, W. Chen, Y. He, T. Luo, LG Pang

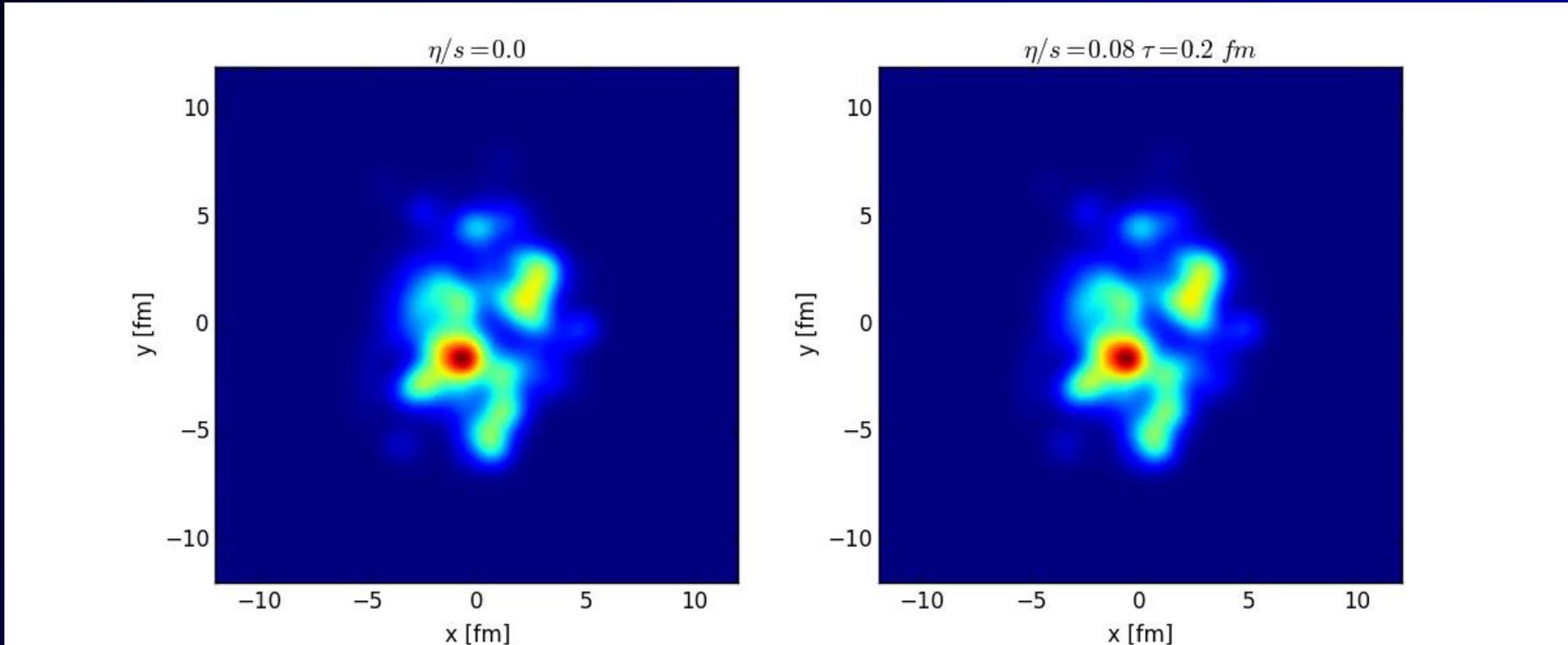


Extreme properties of sQGP

- The most perfect fluid ($\eta/s \sim (1 - 2)/4\pi$)
- The most opaque fluid to jets ($\hat{q}/T^3 = 4 - 8$)
- The most vortical fluid ($\omega/T \sim 0.001$)

Sounds of QGP

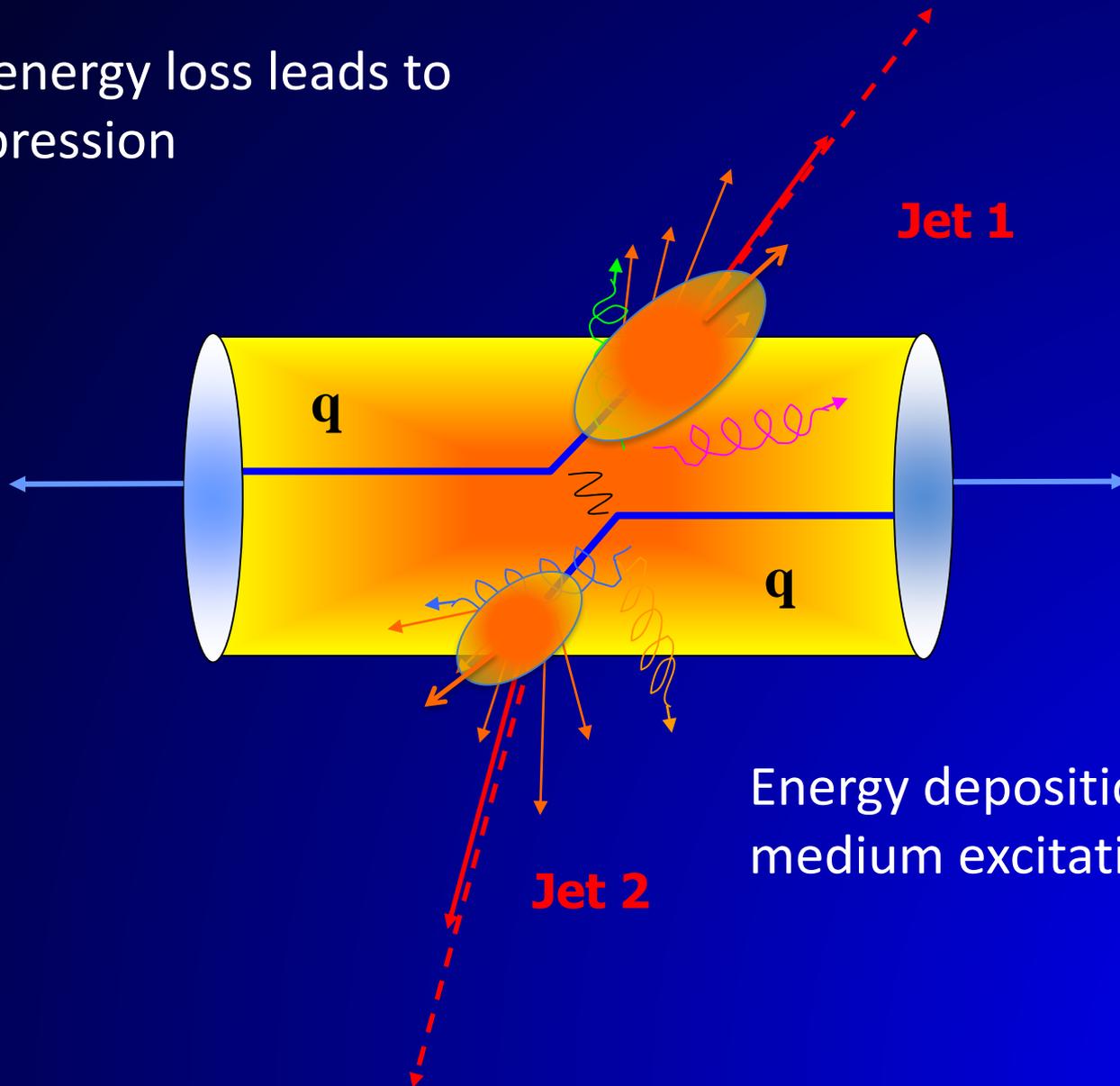
Propagation of primordial sound waves in a rapidly expanding fireball
sensitivity to viscosity and initial condition L.G Pang (2016)



What happens to jets propagating through this fluctuating fluid and medium response?

Jet quenching in heavy-ion collisions

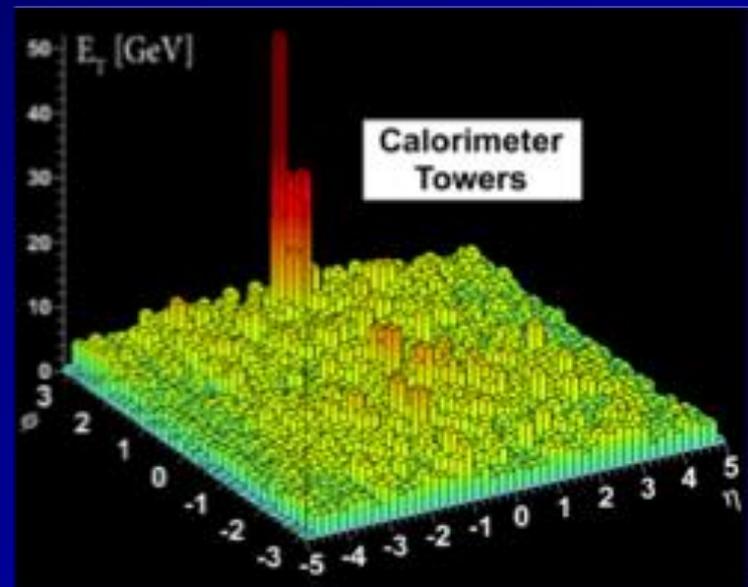
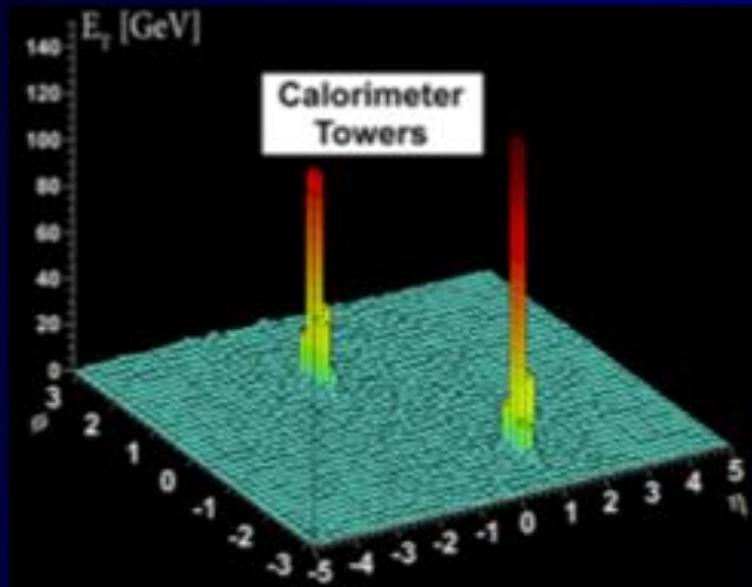
Parton energy loss leads to
jet suppression



Energy deposition leads to
medium excitation

Tomography with full jets

Jet profile and jet yield sensitive to jet-medium interaction
less sensitive to non-perturbative hadronization



Background subtraction is non-trivial

Jet-induced medium excitation becomes relevant

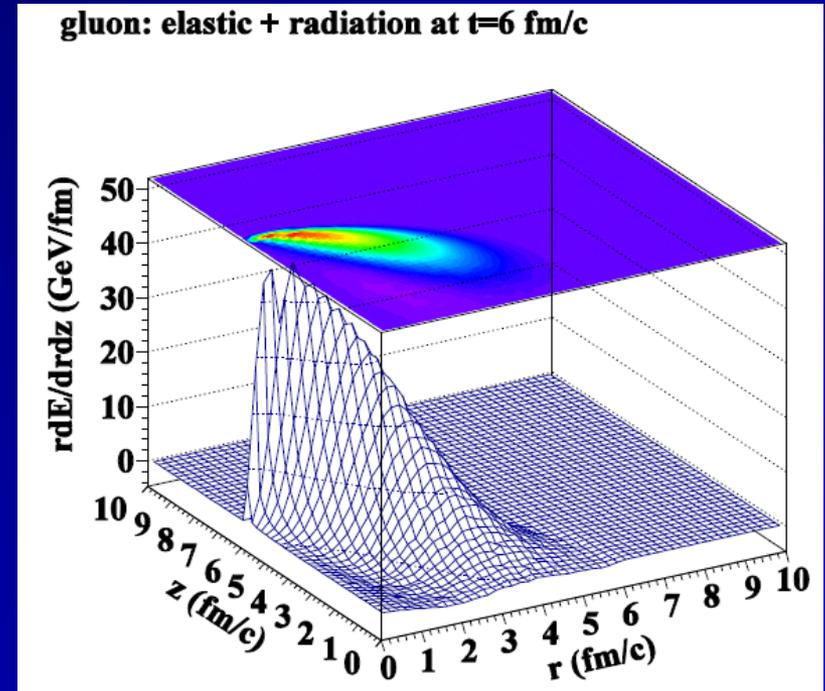
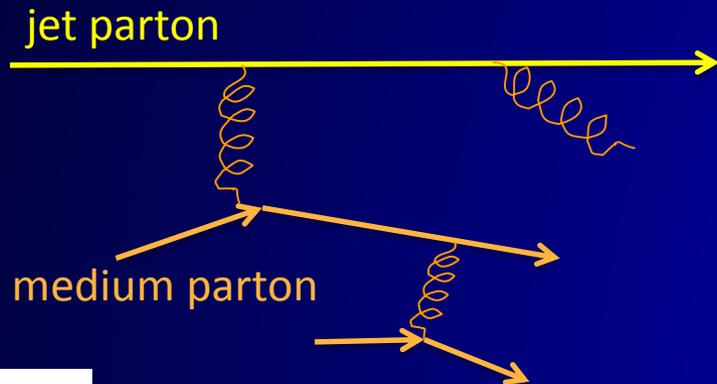
Some of the energy lost by leading partons remain inside jet-cone

LBT: Linear Boltzmann Transport

$$p_1 \cdot \partial f_1(p_1) = - \int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) |M_{12 \rightarrow 34}|^2 (2\pi)^4 \delta^4(\sum_i p_i),$$

Induced radiation $\frac{dN_g}{dz d^2 k_{\perp} dt} = \frac{2\alpha_s N_c}{\pi k_{\perp}^4} P(z) (\hat{p} \cdot u) \hat{q} \sin^2\left(\frac{t-t_0}{2\tau_f}\right)$

- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons
- 3+1D hydro bulk evolution



Li, Liu, Ma, XNW and Zhu, PRL 106 (2010) 012301
 XNW and Zhu, PRL 111 (2013) 062301
 He, Luo, XNW & Zhu, PRC91 (2015) 054908;

CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

$$p \cdot \partial f(p) = -C(p) \quad (p \cdot u > p_{cut}^0)$$

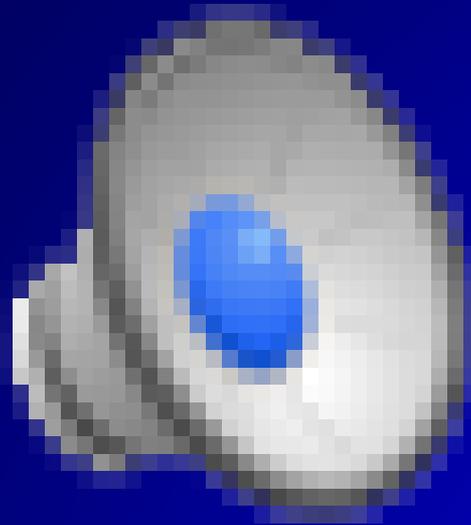
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i) \theta(p_{cut}^0 - p \cdot u)$$

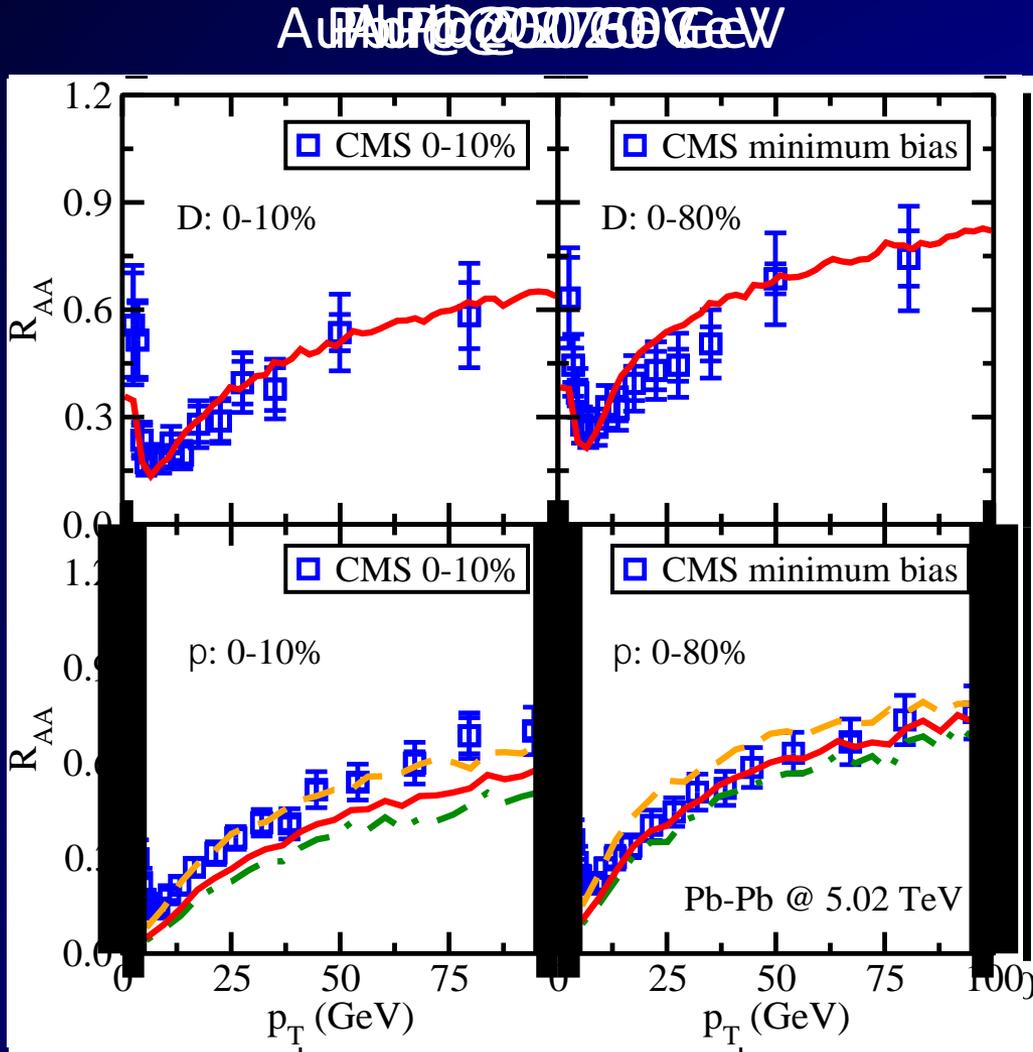
- LBT for energetic partons (jet shower and recoil)
- Hydrodynamic model for bulk and soft partons: CLVisc

CLVisc: (3+1)D viscous hydrodynamics parallelized on GPU using OpenCL

γ -jet propagation within CoLBT-hydro



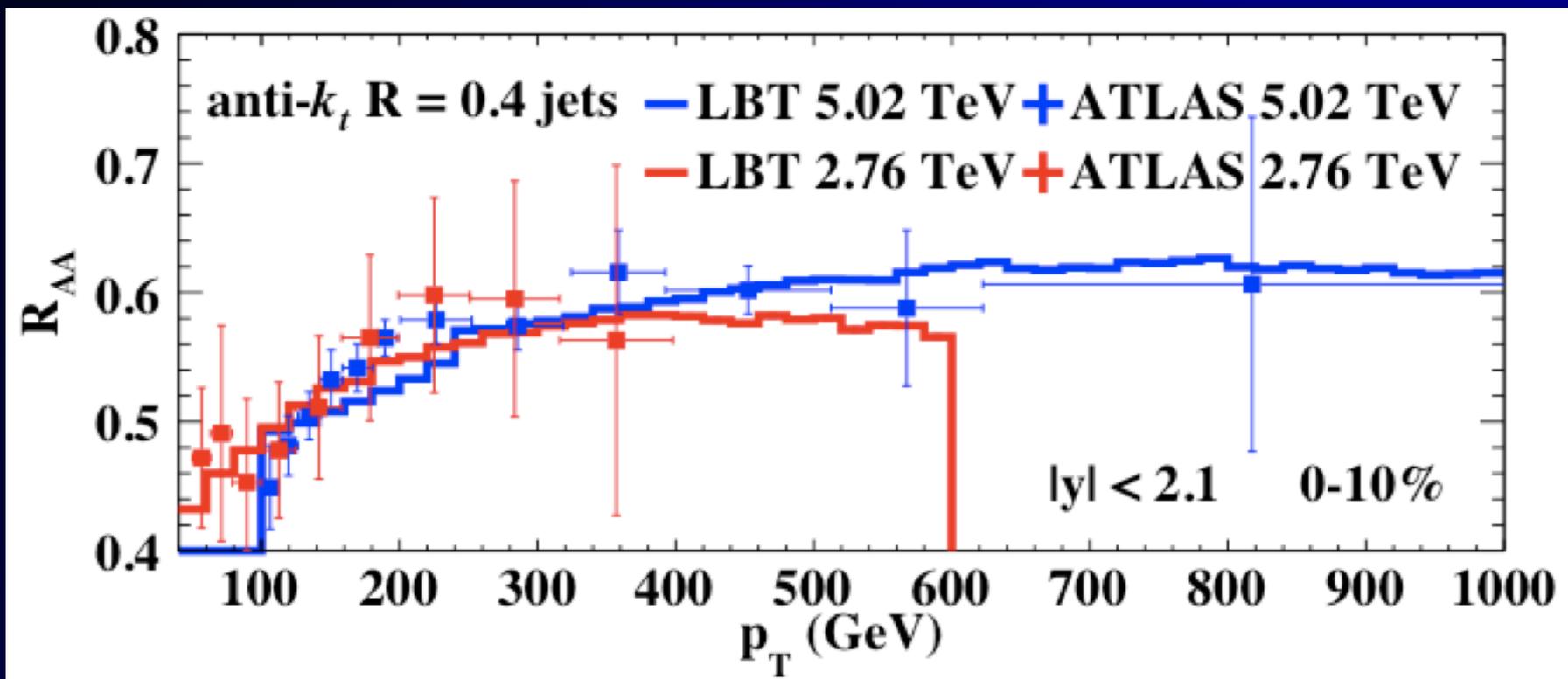
Light and heavy quark hadron suppression



Cao, Luo, Qin & XNW, PRC94 (2016) 014909



Single jet suppression at LHC

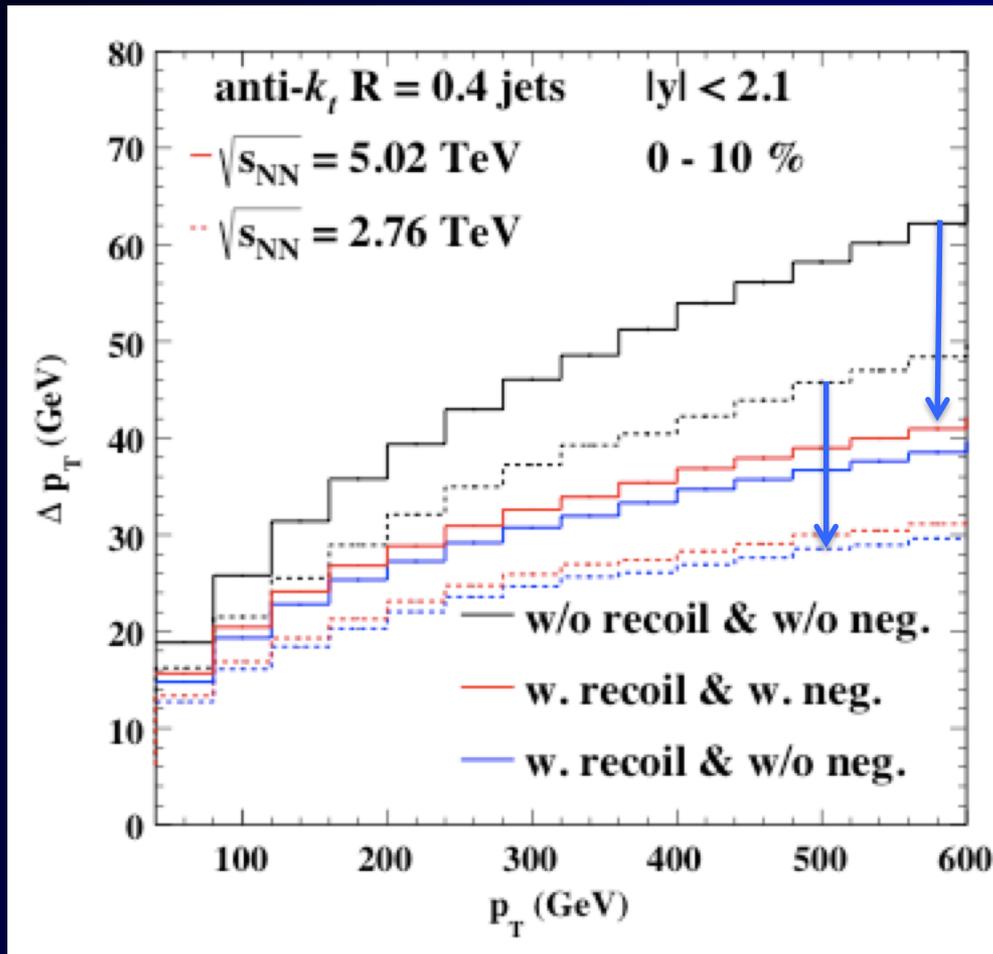


He, Cao, Luo & XNW to be published

Weak p_T dependence: initial jet spectra and p_T dependence of energy loss ΔE

Weak energy dependence: increase of jet energy loss and the slope of initial spectra

Effect of recoil partons and diffusion wake on jet energy loss

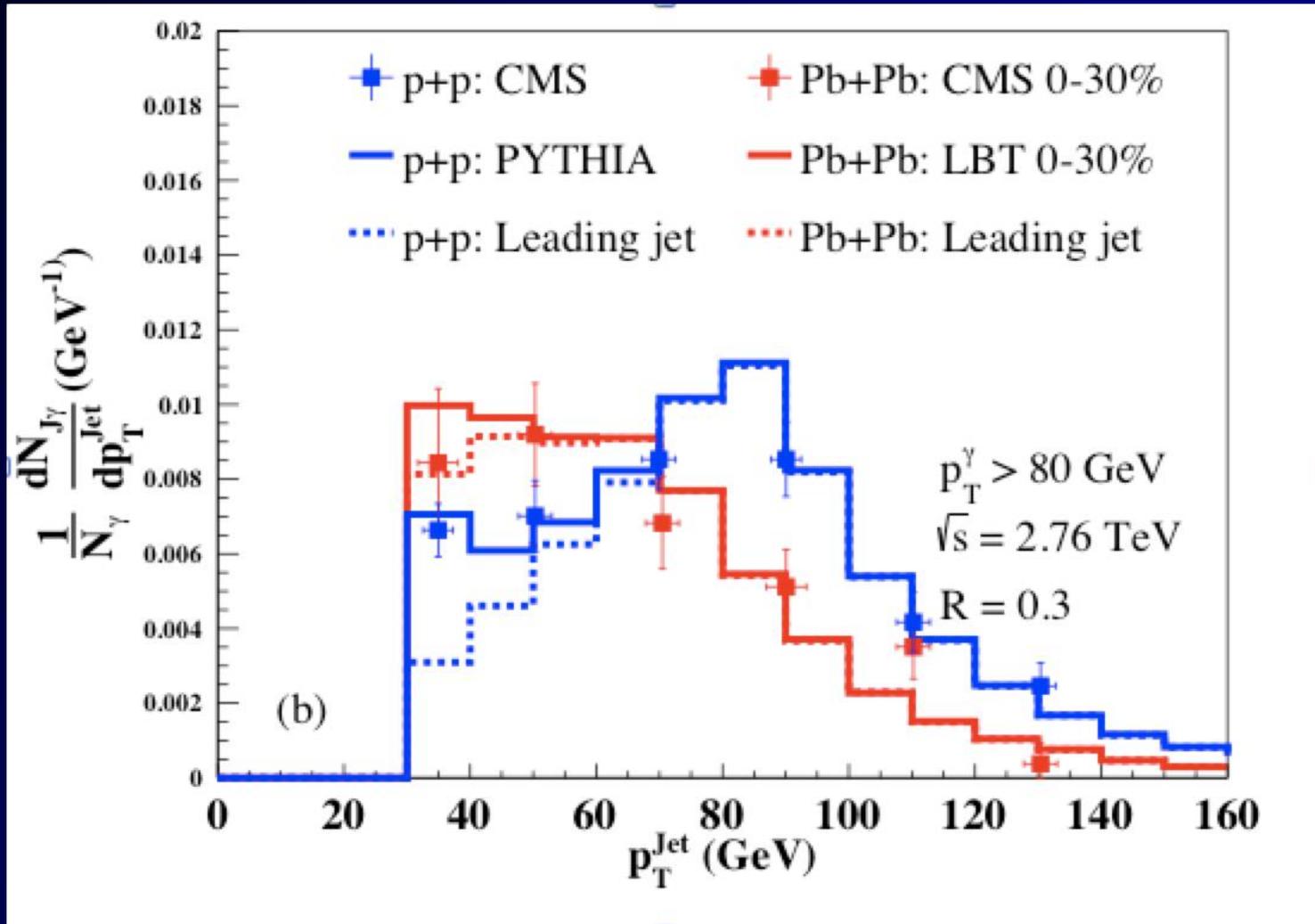


Recoil partons within the jet cone reduce the net jet energy loss

Diffusion wake (backreaction) reduces the thermal background, if taken into account, increase the net jet Energy loss with given cone-size

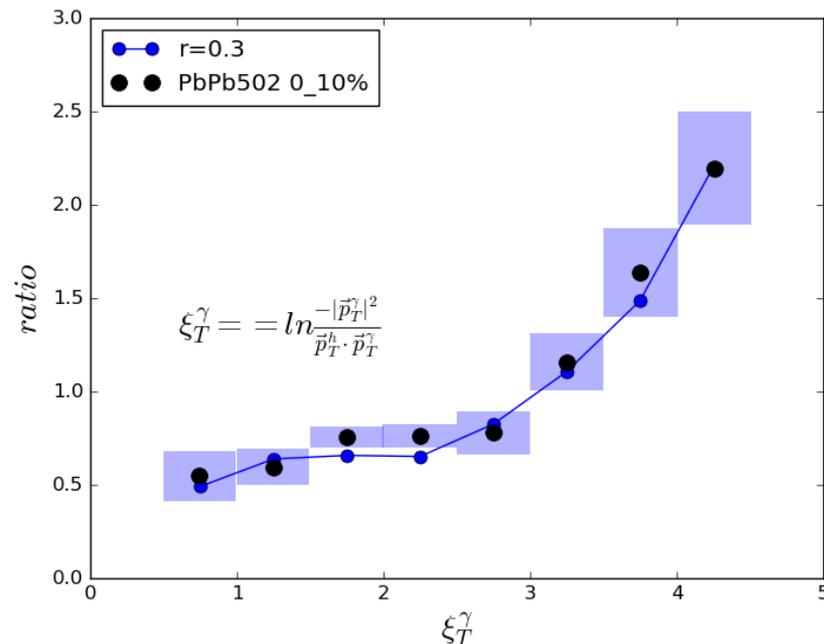
Depend on jet cone-size R
Sensitive to radial flow

Jet energy loss and γ -jet asymmetry

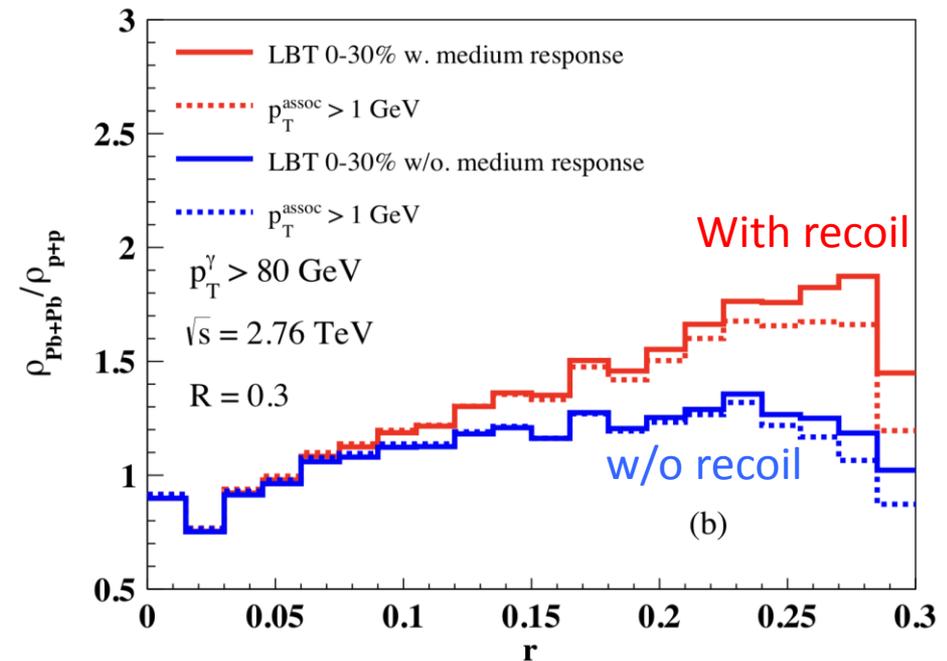


Effect of medium response

Enhancement of Frag Function at small z



Enhancement of jet shape at larger r



Phy Letters B777(2018)86

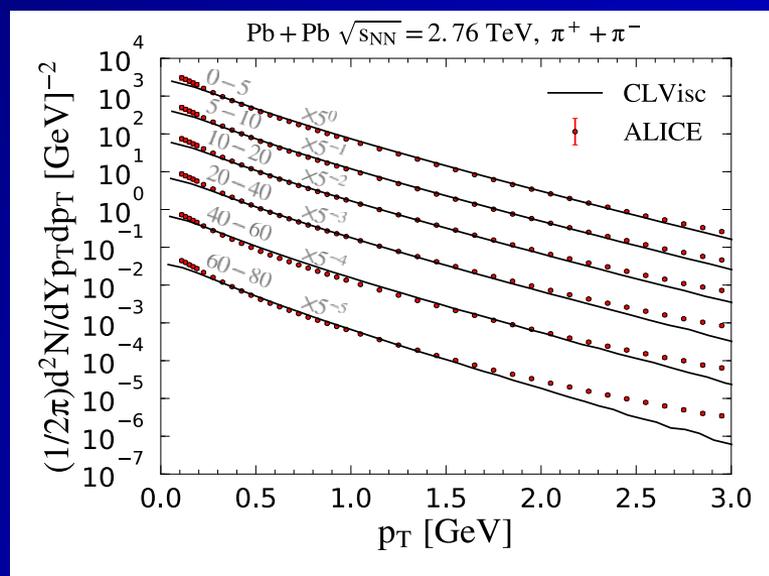
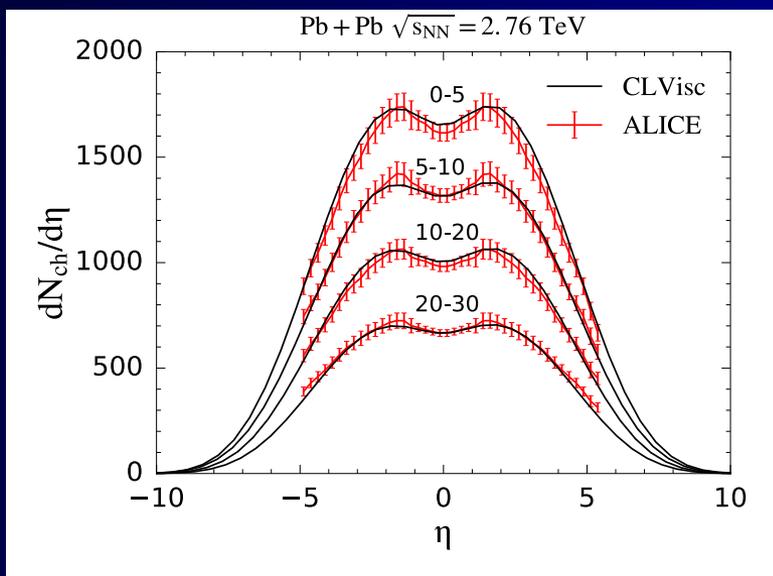
Luo, Cao, He & XNW, arXiv:1803.06785

Poster: JET 18 T Luo

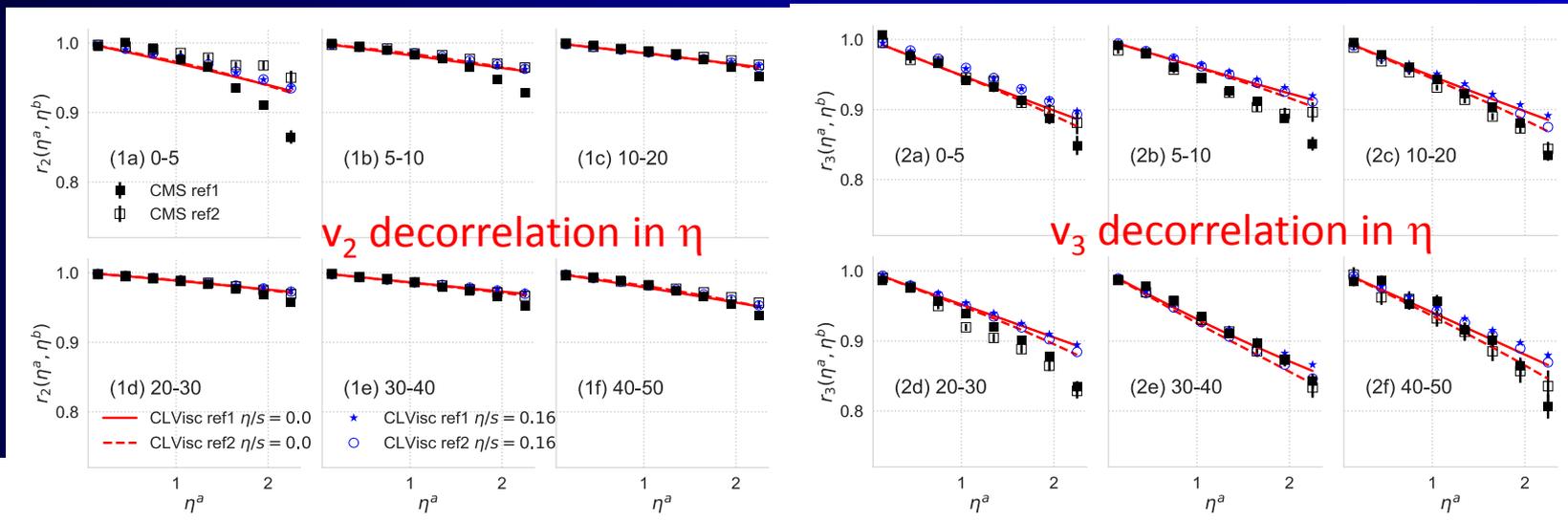
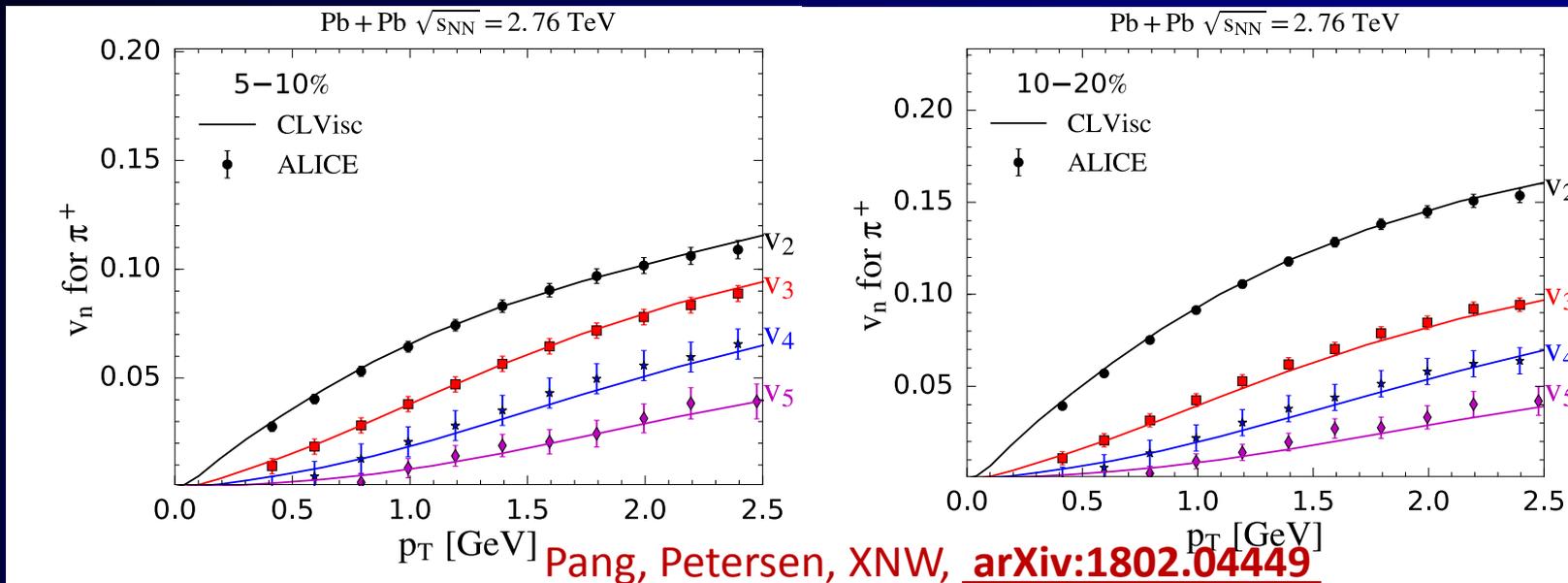


CLVisc Hydrodynamic model

- 3+1D viscous hydrodynamic model
- Fully parallelized on GPU with OpenCL
 - 100x faster than comparable than on CPU
- Fluctuating initial conditions from AMPT

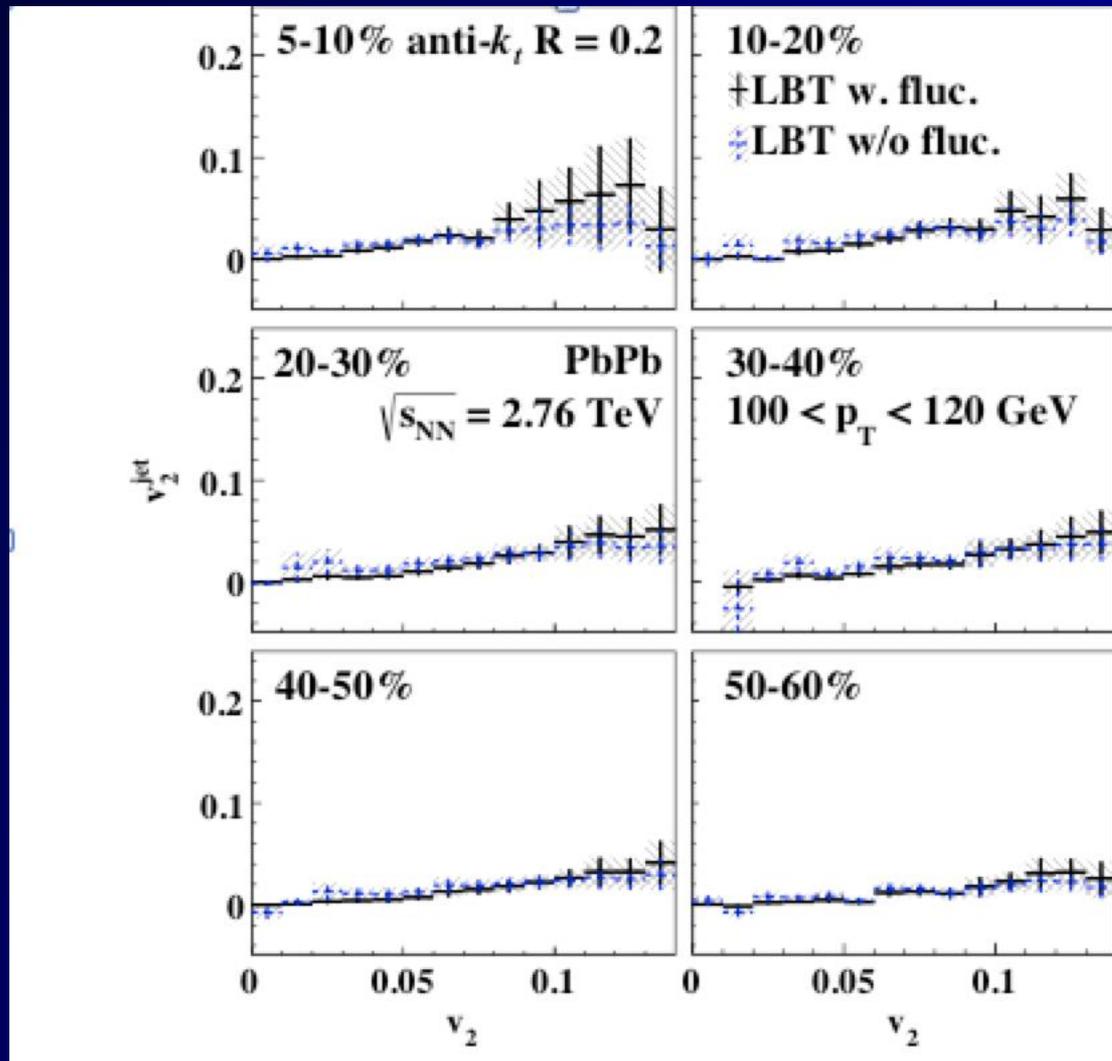


Anisotropic flow and decorrelation



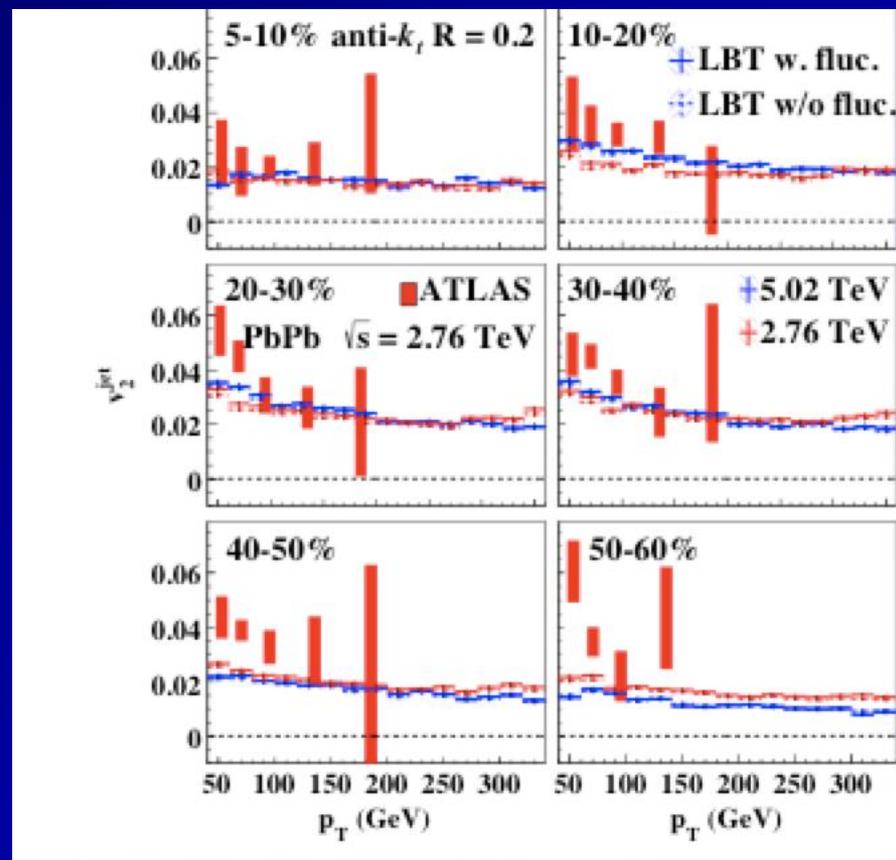
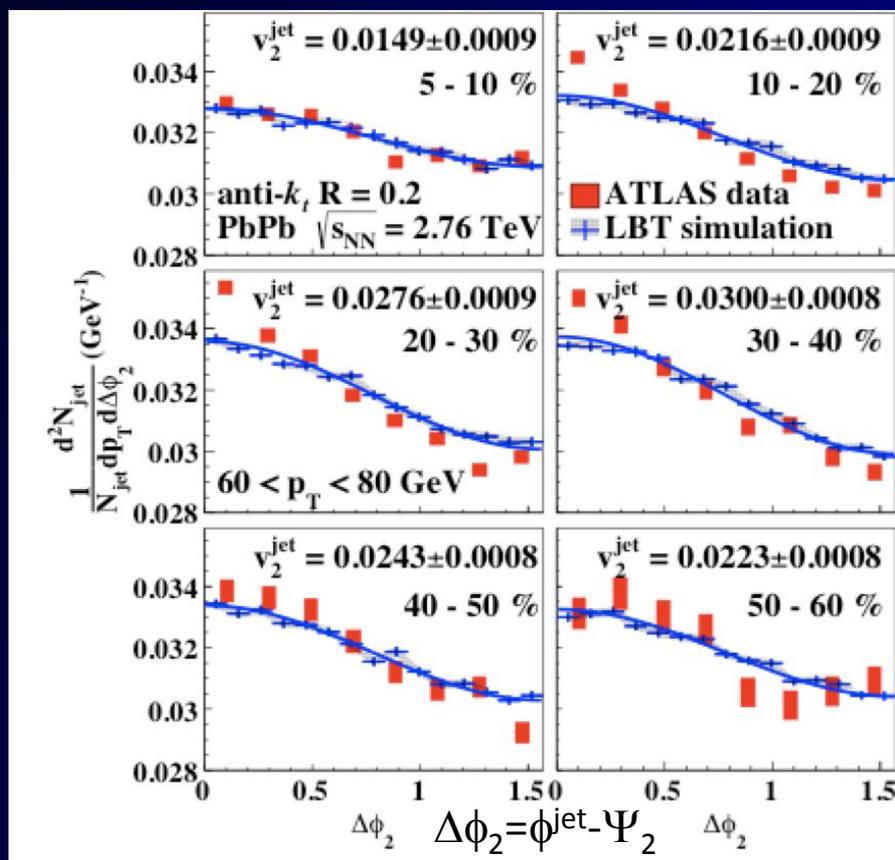
Correlation btw jet and bulk anisotropy

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

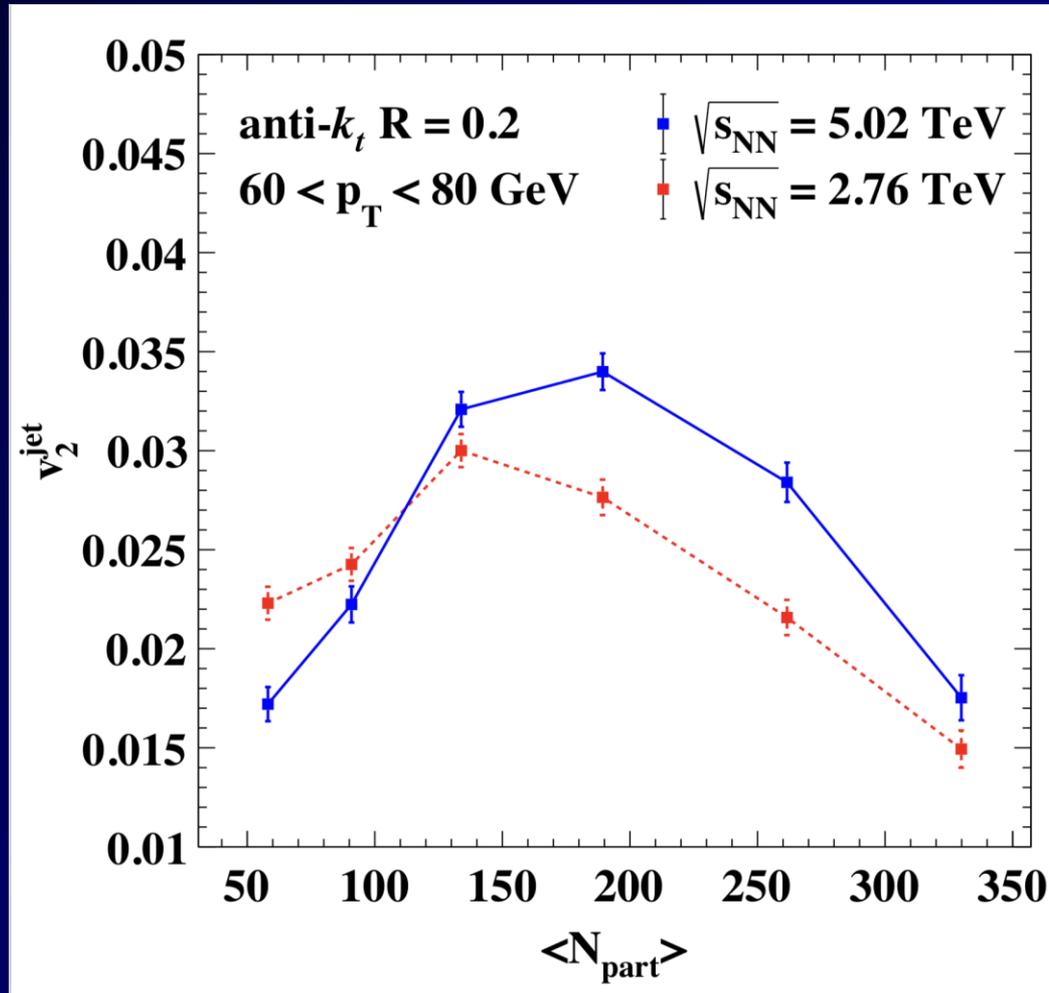


Single jet anisotropy

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

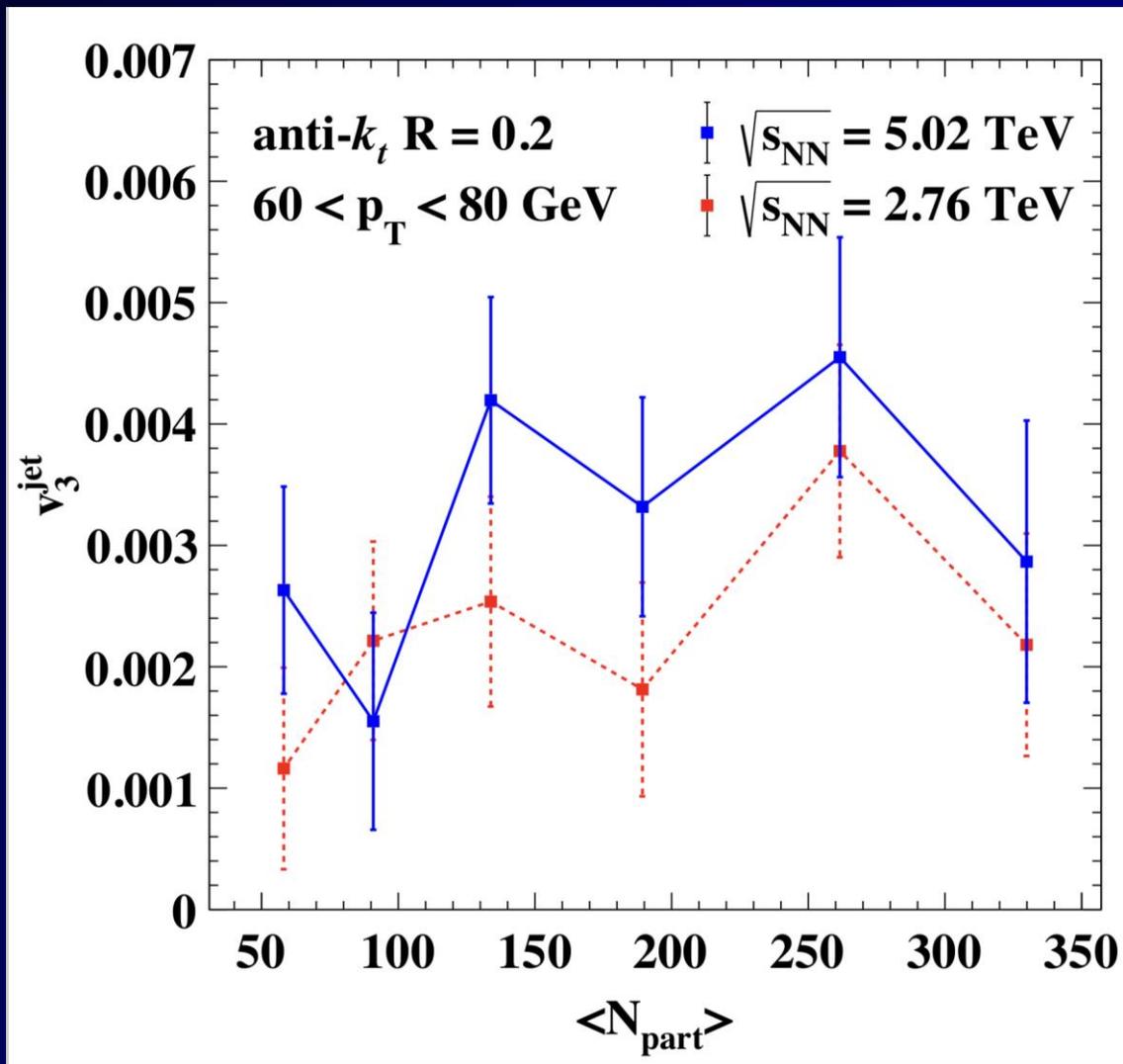


Centrality dependence of v_2^{jet}



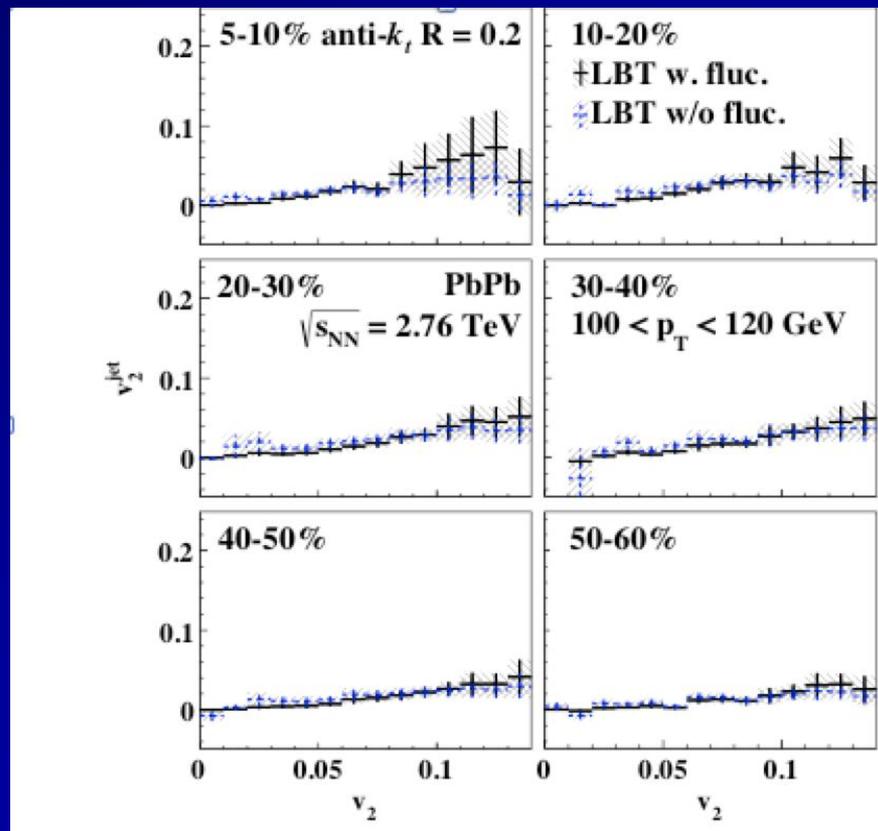
v_2^{jet} closely follows the centrality dependence of $v_2(\text{soft})$

Very small triangular jet anisotropy

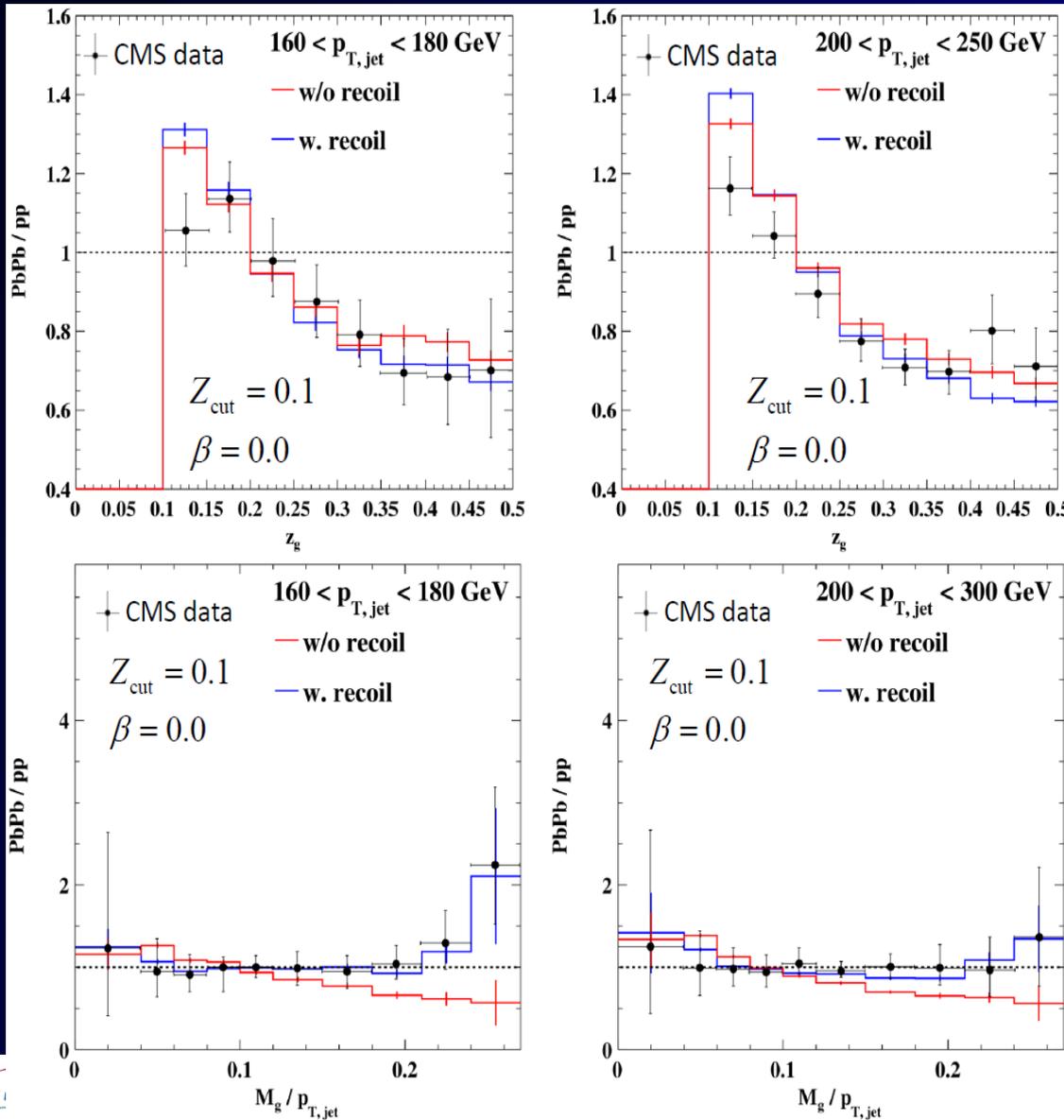


Summary

- Suppression of high p_t hadrons caused by energy loss of leading partons
- Jet (with R) energy loss influenced by transport shower partons & medium response
- Medium response leads to modification of jet frag function and jet shape
- Anisotropy of jet suppression correlates well with medium anisotropy



Effect of medium response on jet substructure



jet splitting function

- The inclusion of medium response will lead to stronger modification of the groomed jet splitting function.

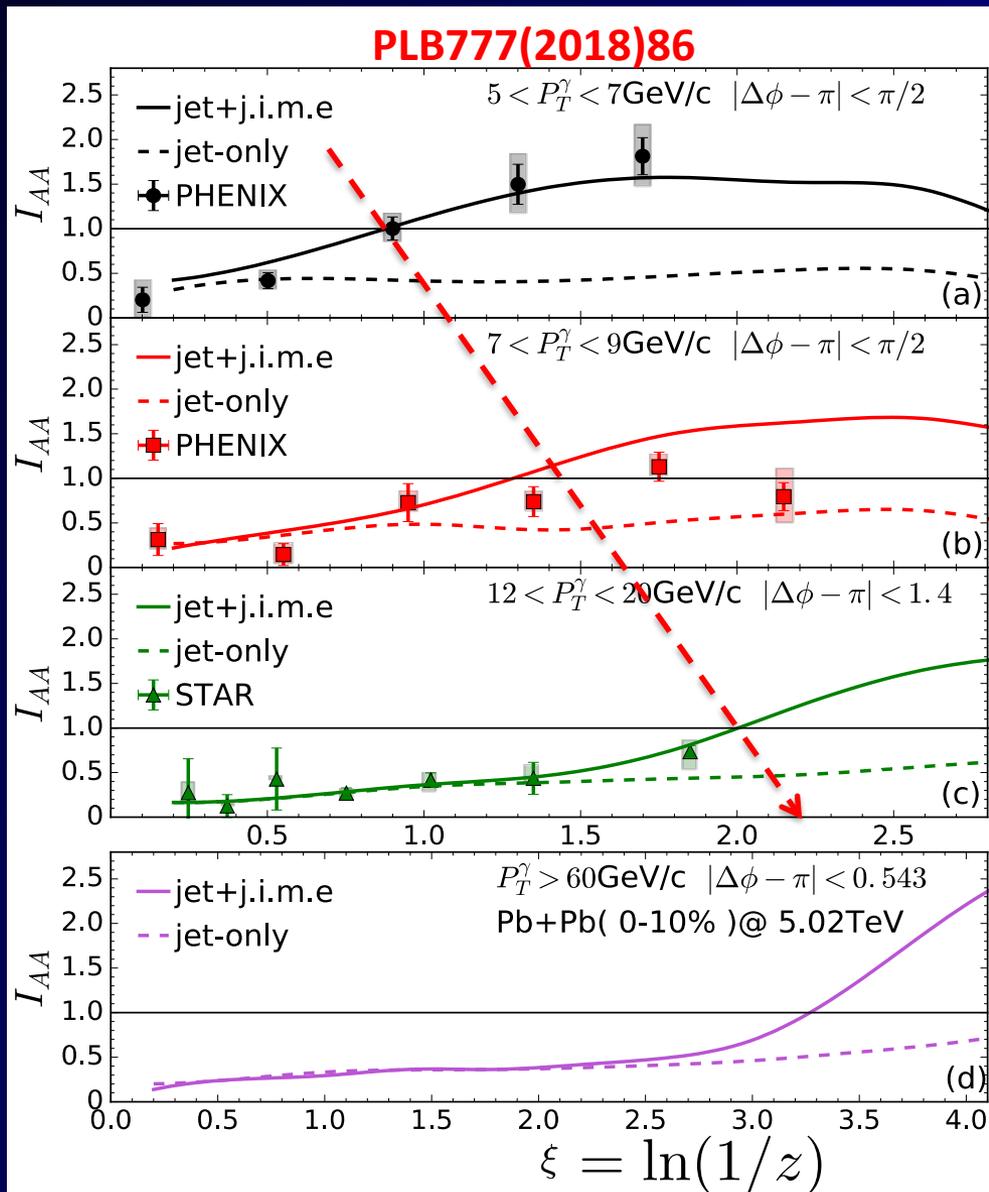
groomed jet mass

- Large angle scattering leads to the enhancement of the mass tail.



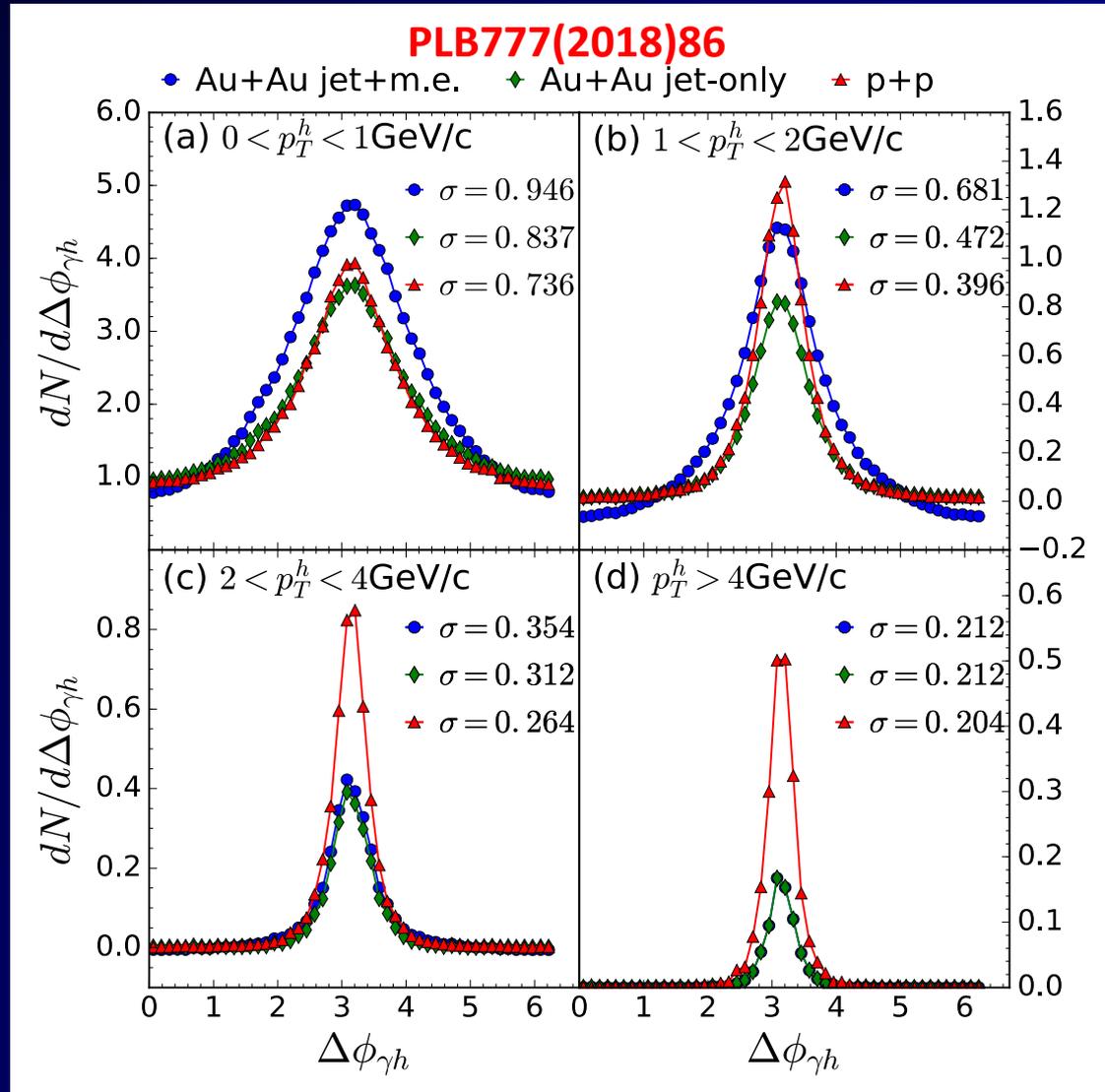


Enhancement of soft hadrons

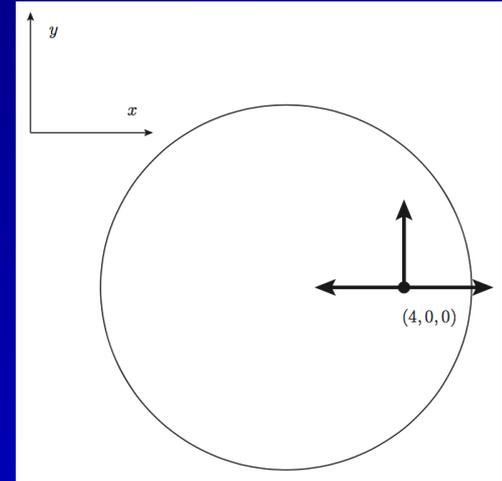
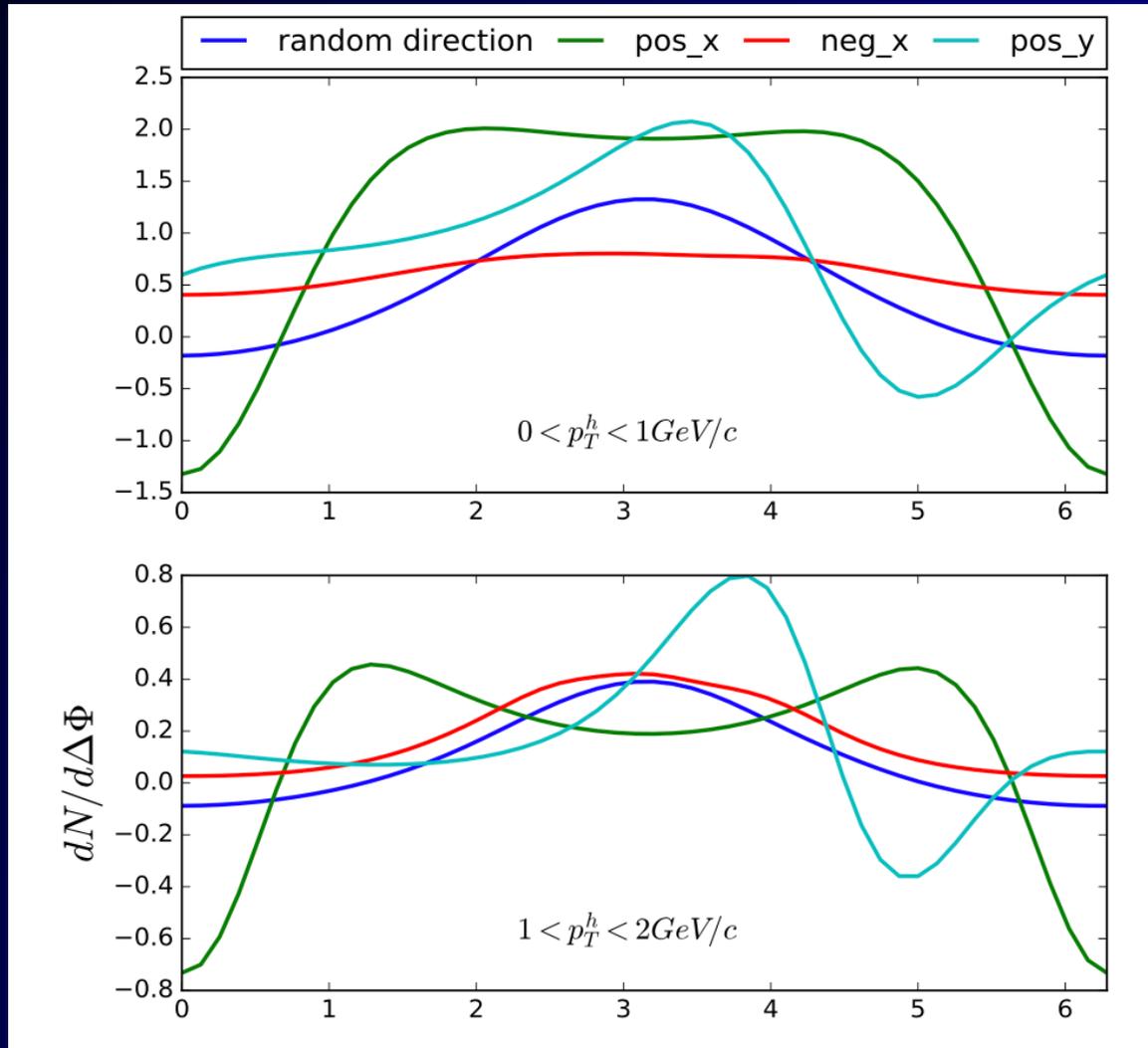


Onset of soft hadron enhancement is at fixed $p_t \sim 1.6 \text{ GeV}$

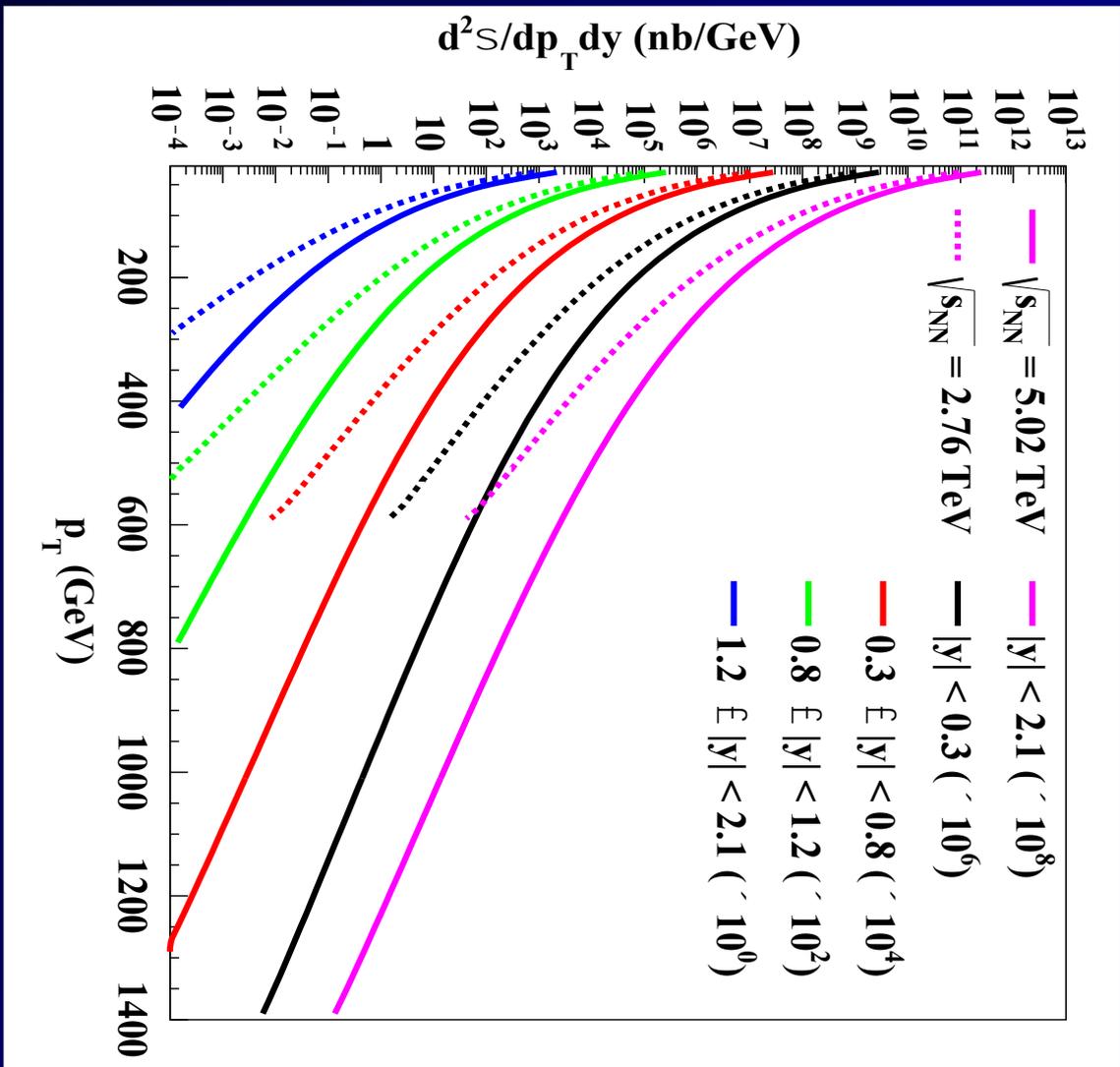
Azimuthal distribution of soft hadrons from jet-induced medium excitation



Wide angle distribution of soft hadrons



Energy dependence of jet spectra



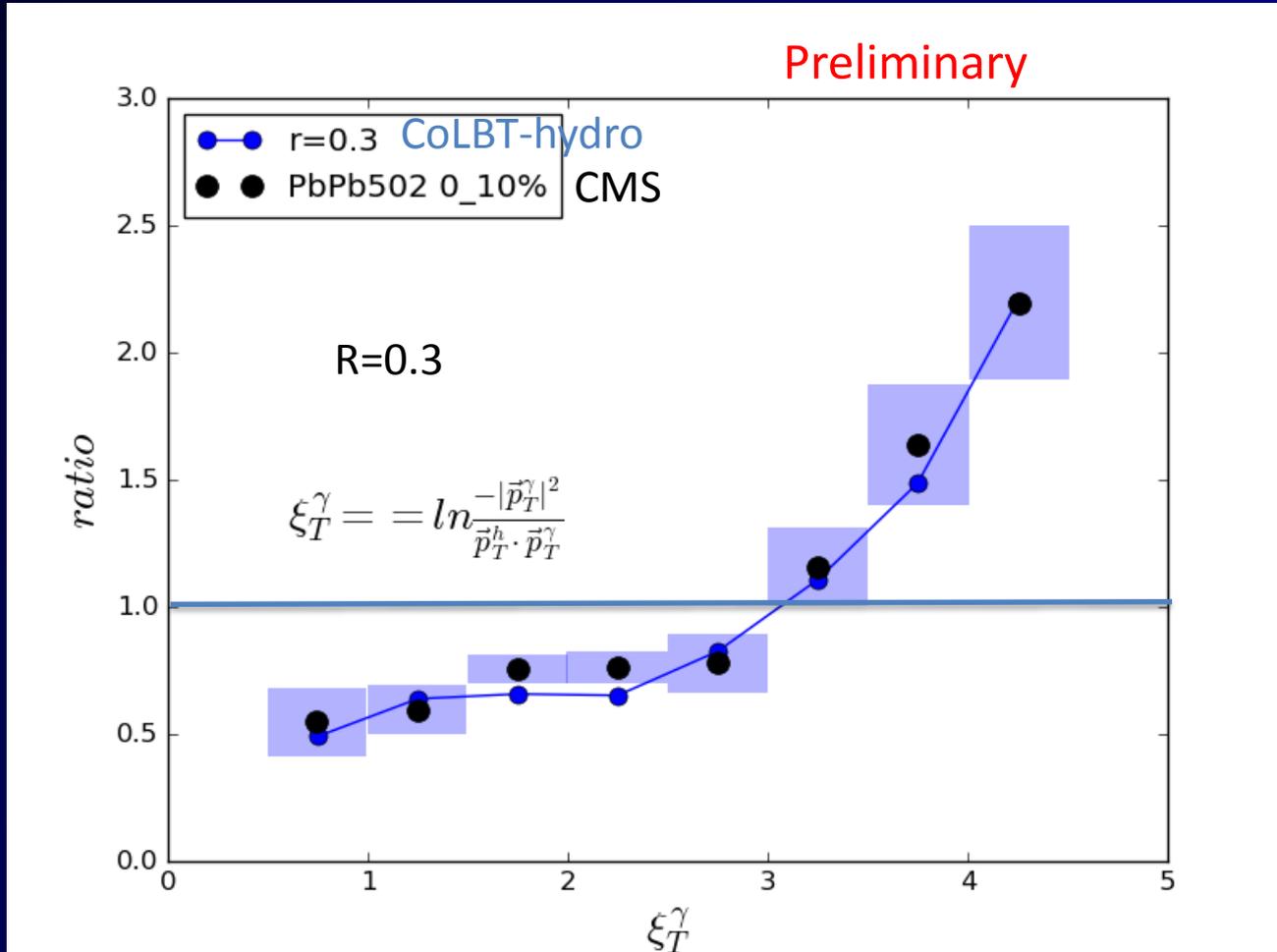
Relativistic hydrodynamics

$$\partial_{\mu} T^{\mu\nu} = 0$$

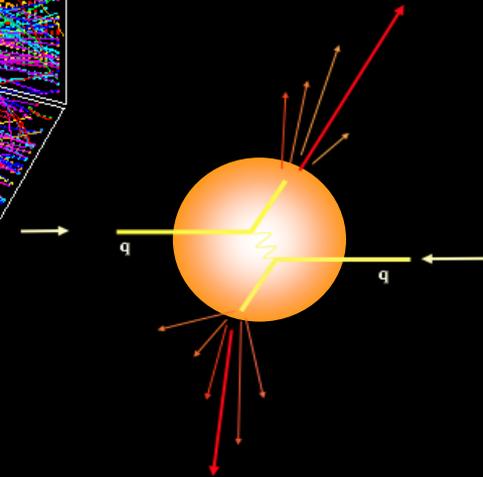
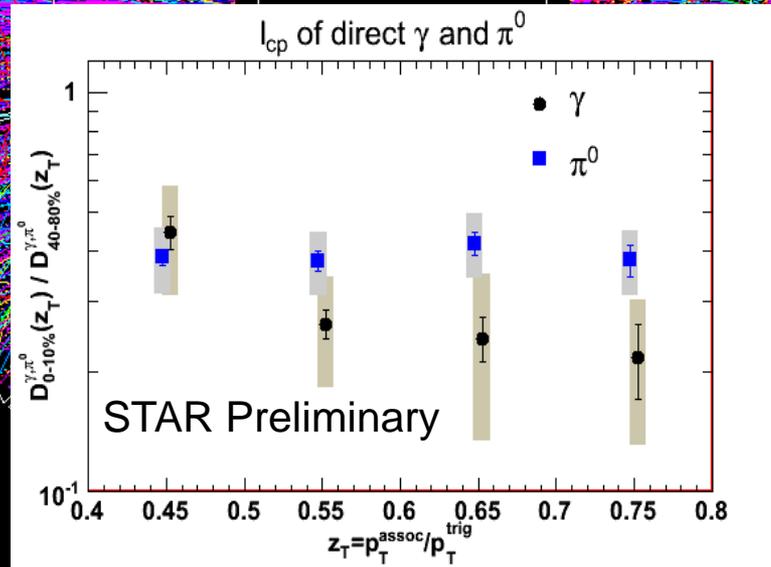
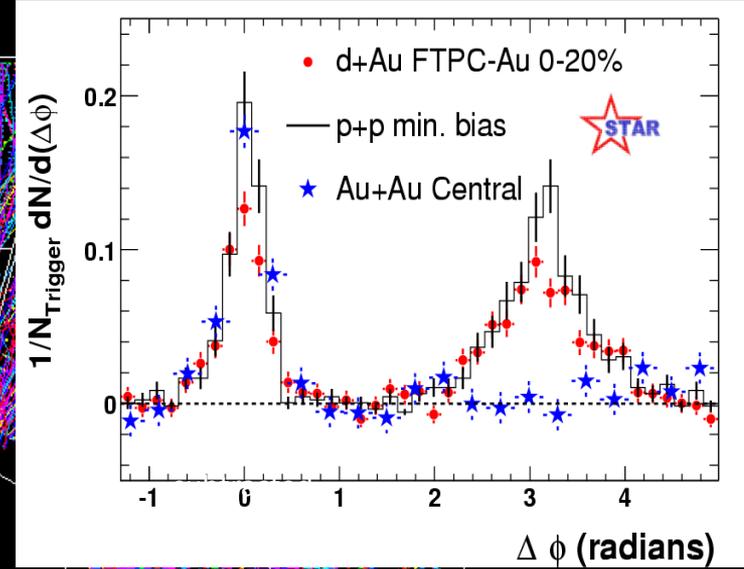
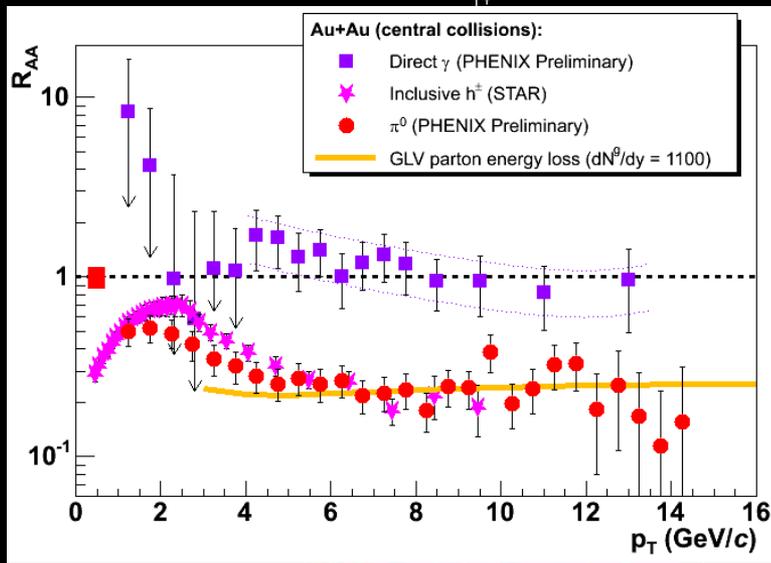
$$\Delta T^{\mu\nu} = \pi^{\mu\nu}(\eta) - \Pi(\zeta)(g^{\mu\nu} - u^{\mu}u^{\nu})$$

- a low-momentum effective theory
- Inputs from first principle QCD (e.g. lattice QCD)
EoS $p=p(\varepsilon)$, transport coefficients $\eta(T)$, $\zeta(T)$
- Initial condition: parton prod. & thermalization time

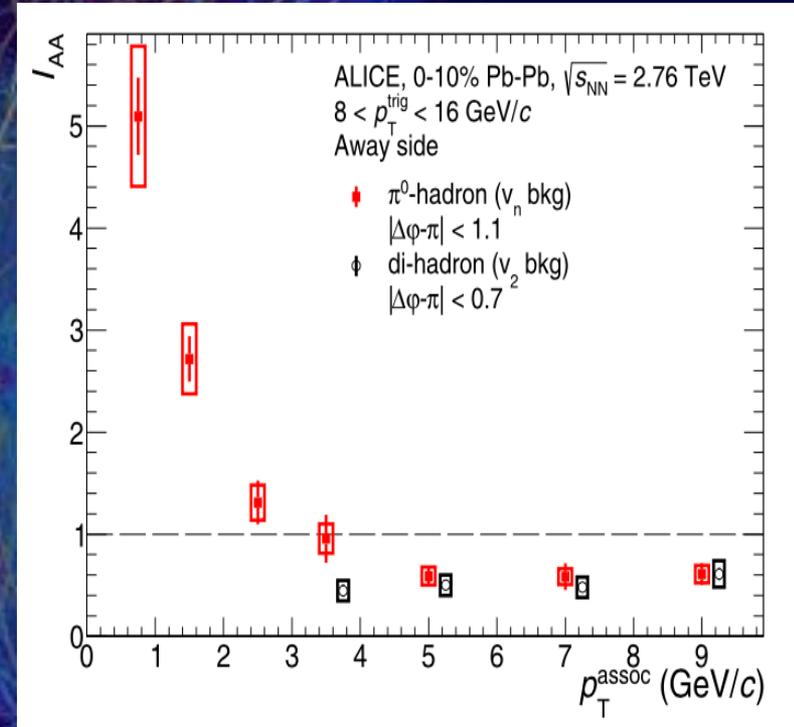
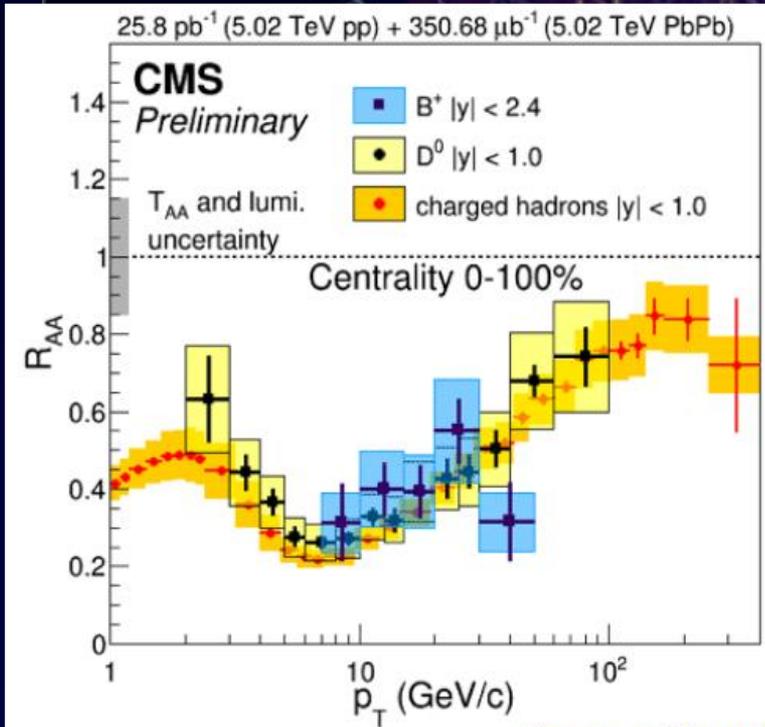
gamma-jet fragmentation function



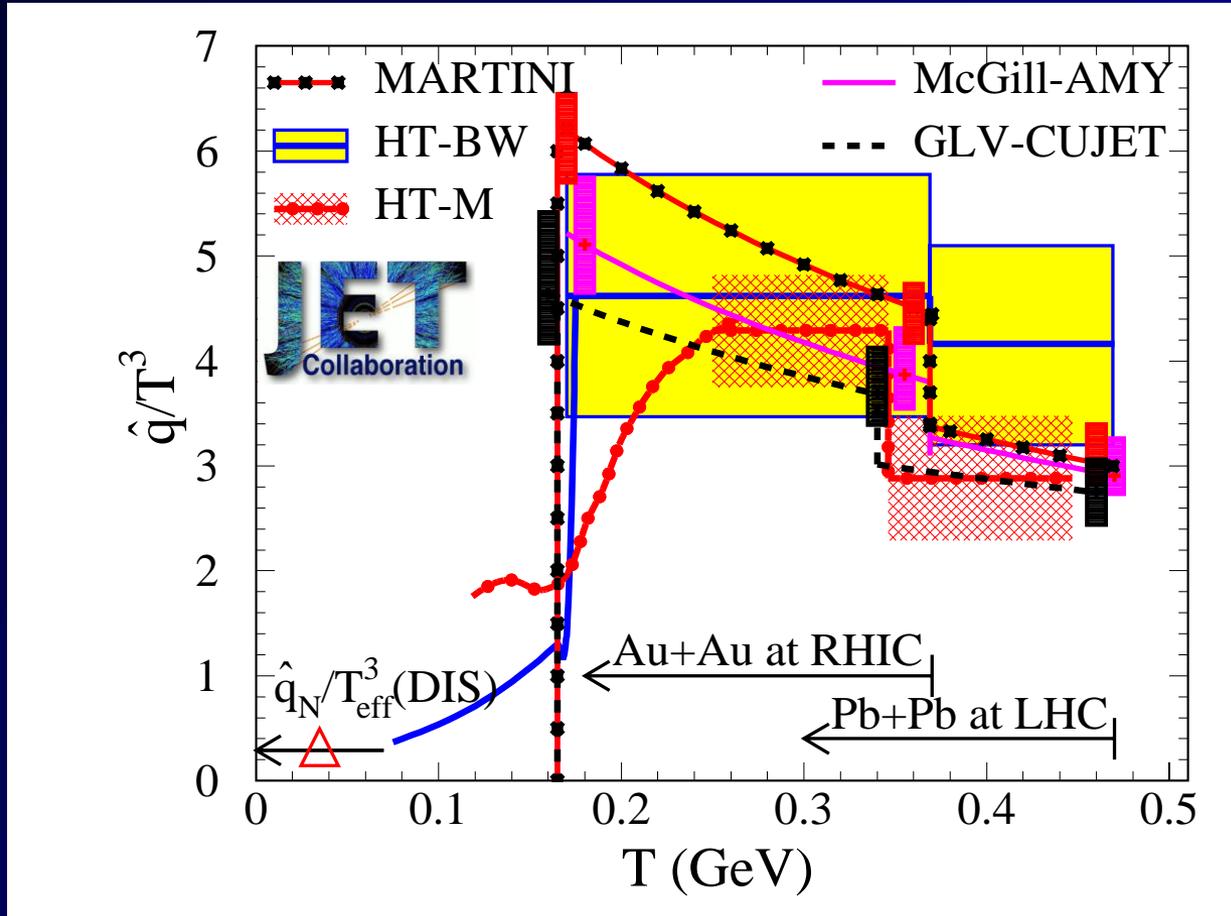
Jet Quenching phenomena at RHIC



Jet Quenching phenomena at LHC

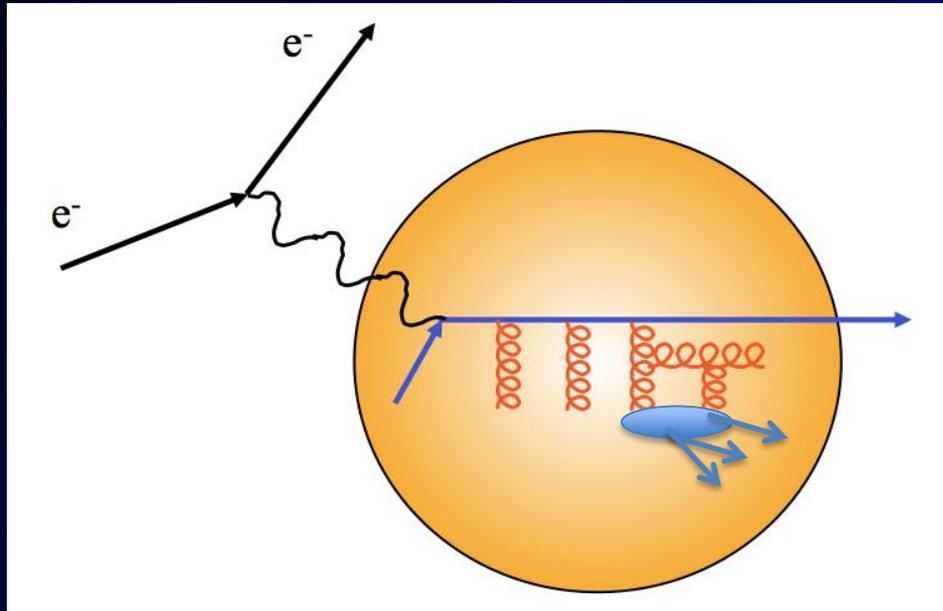


Jet transport coefficient



JET Collaboration: *Phys.Rev. C90 (2014) 1, 014909*

Hard probes of medium properties



$$x_D = \frac{q_T^2 - 2\vec{q}_T \cdot \vec{\ell}_T}{2p^+ q^- z}$$

$$x_L = \frac{\ell_T^2}{2p^+ q^- z(1-z)}$$

TMD gluon distribution or
Jet transport coefficient q

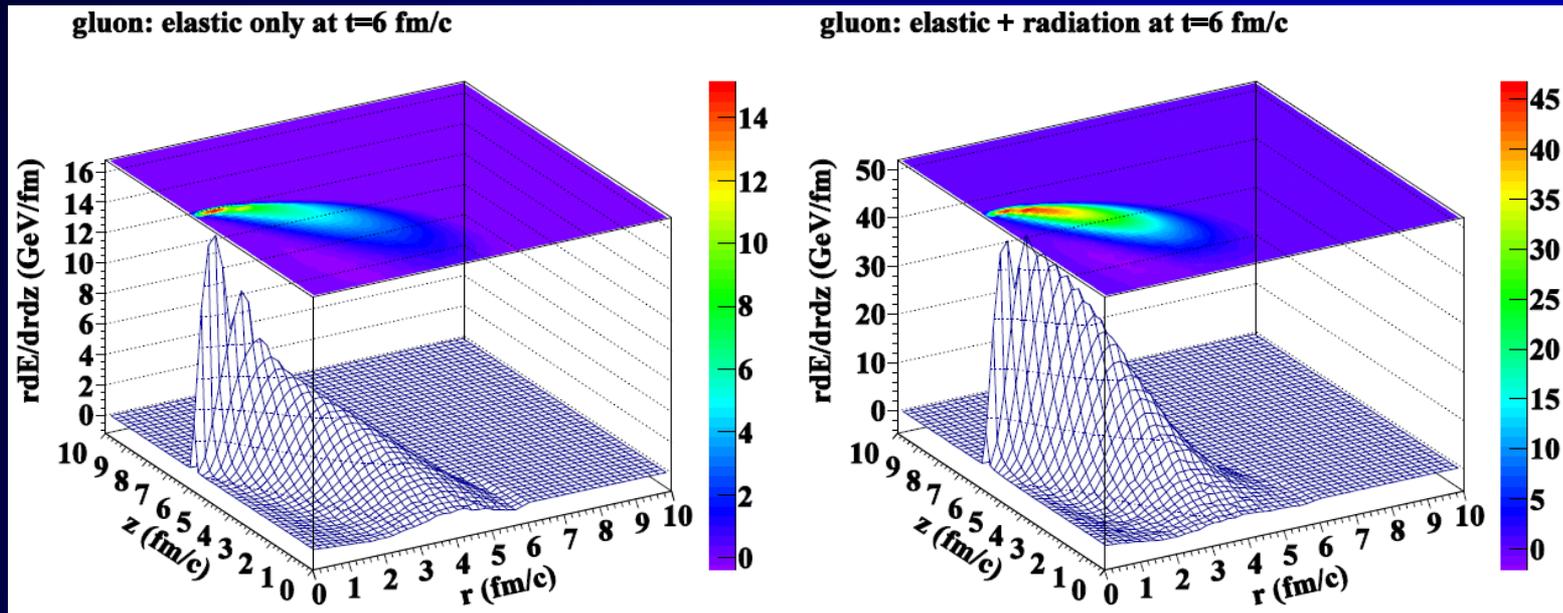
$$\frac{dN}{d\ell_T^2 dz} = 2\pi \frac{C_2 C_A}{d_A} P(z) \int dy \rho(y) \int \frac{d^2 q_T}{(2\pi)^2} \phi(x_D, q_T) \\ \times \frac{2\vec{q}_T \cdot \vec{\ell}_T}{q_T^2 \ell_T^2 (\vec{\ell}_T - \vec{q}_T)^2} \left[1 - \cos\left[\left(x_L + \frac{x_D}{1-z}\right) p^+ y^- \right] \right]$$

Linear Boltzmann Transport (LBT)

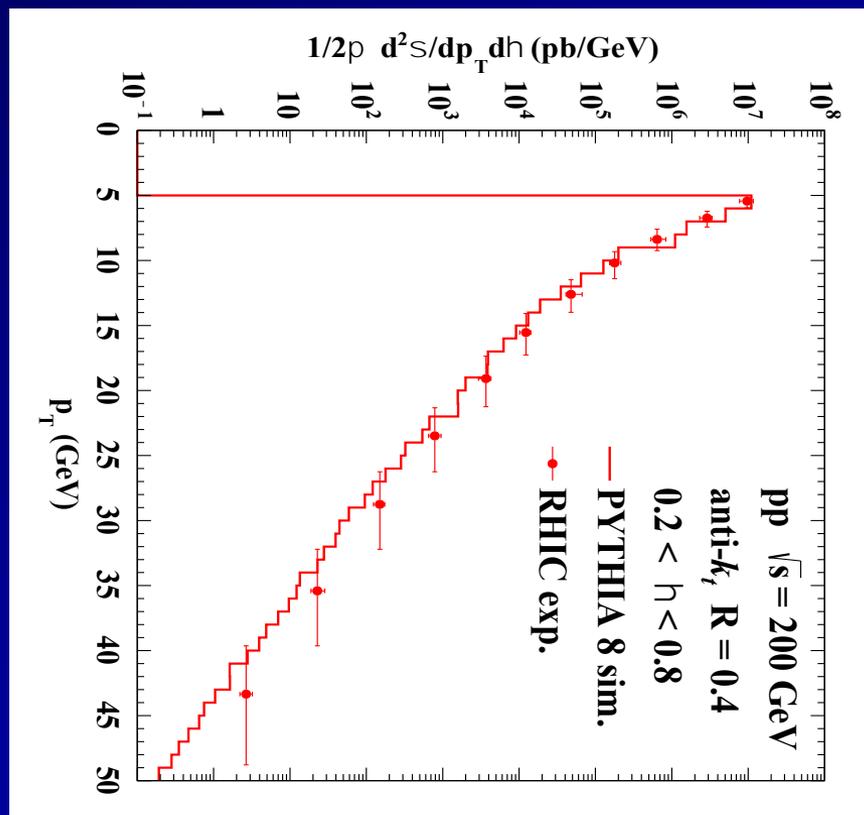
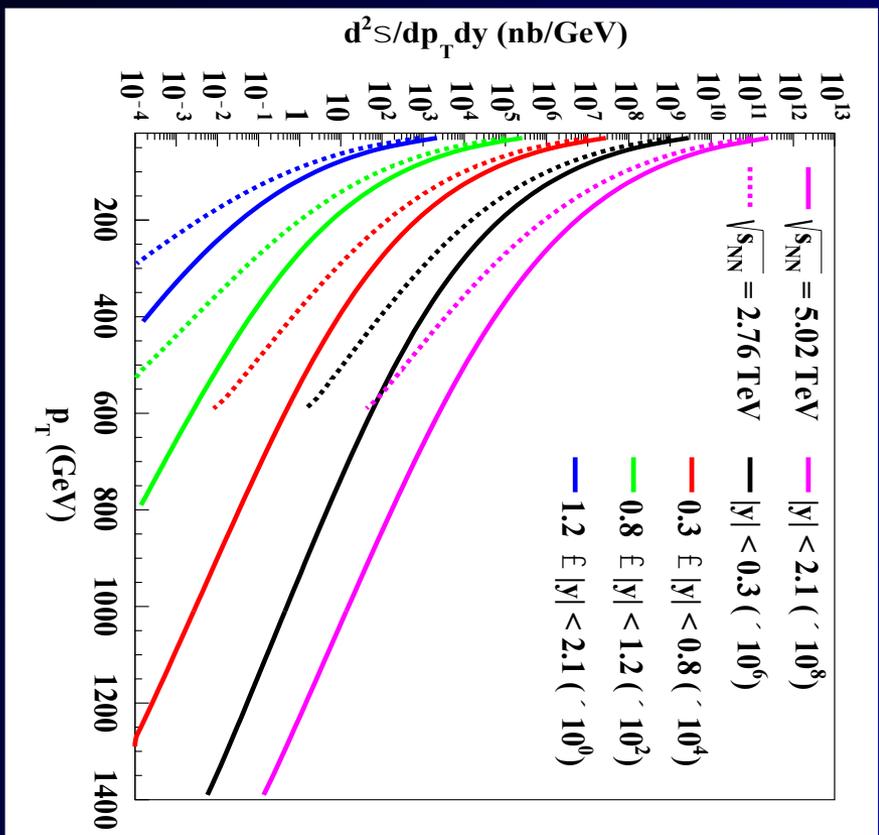
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Li, Liu, Ma, XNW & Zhu, PRL 106 (2011)012301
XNW & Zhu, PRL 111 (2013), 062301

He, Luo, XNW & Zhu, PRC91 (2015) 054908;



Energy dependence of jet spectra



Gamma-jet profile

Pb+Pb @ 2.76 TeV

p+p @ 2.76 TeV

