

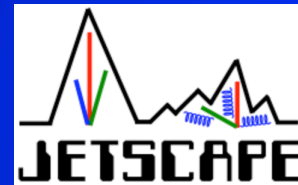
Workshop on Probing quark-gluon matter with jets

BNL, July 22-25, 2018

LBT model for jet transport and the unavoidable effect of medium response

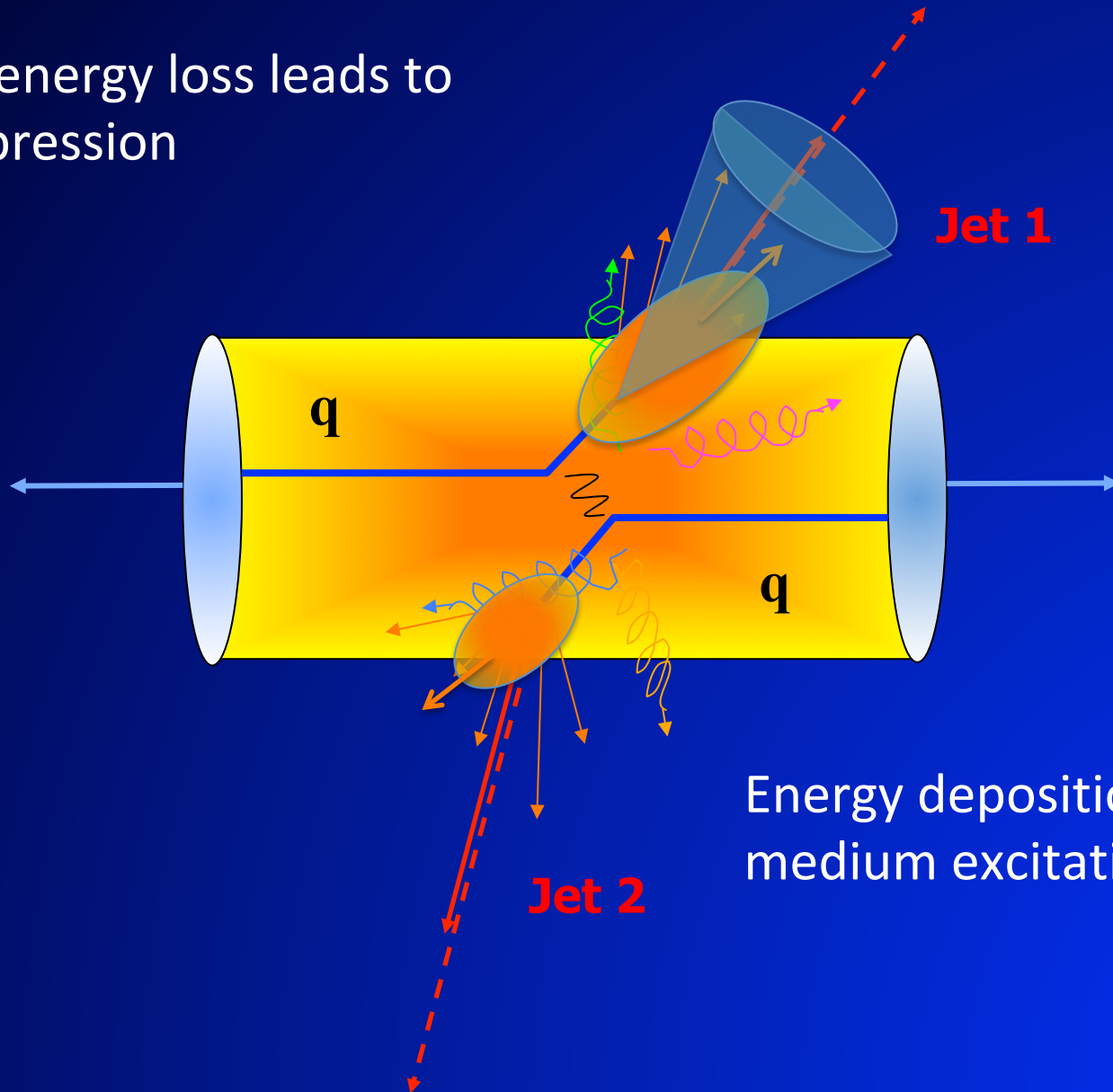
Xin-Nian Wang
CCNU/LBNL

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

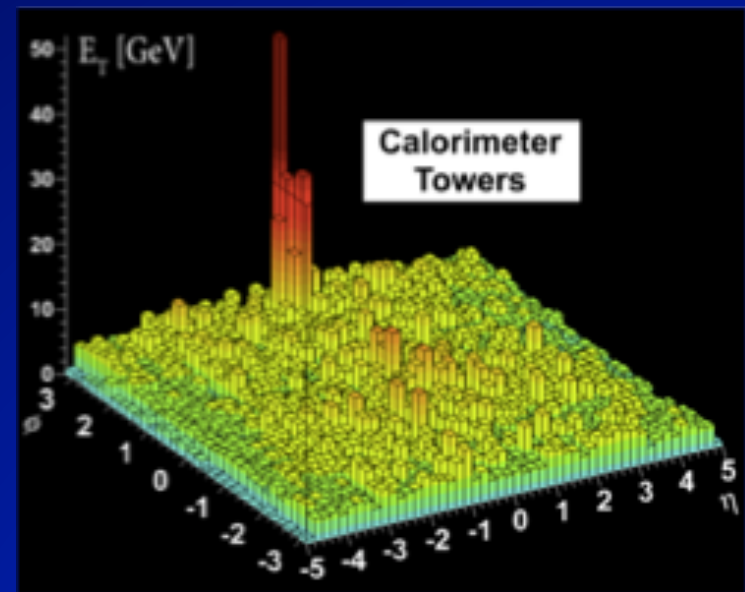
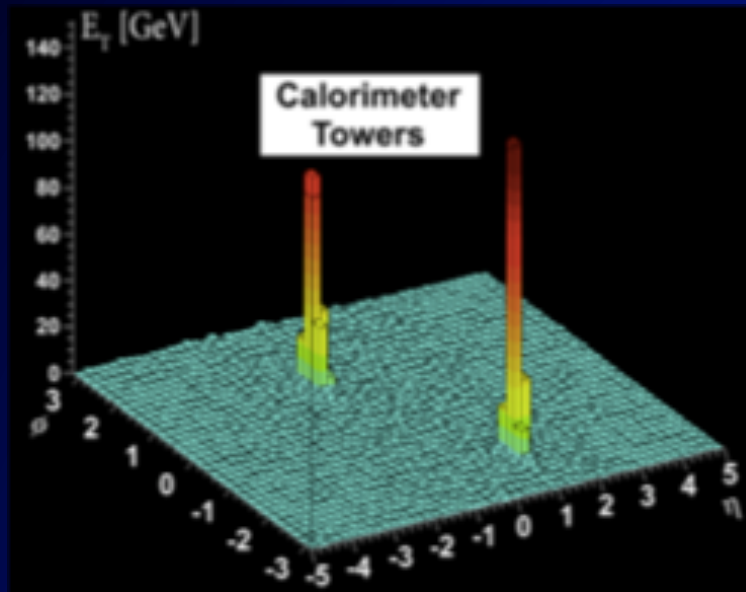


Jet quenching in heavy-ion collisions

Parton energy loss leads to
jet suppression



Jet energy and background subtraction



- Jet energy as defined in the jet reconstruction algorithm
- Uncorrelated background should be subtracted
- Jet-induced medium response is correlated with jet: not background
- Some of the energy lost by leading partons remain inside jet-cone

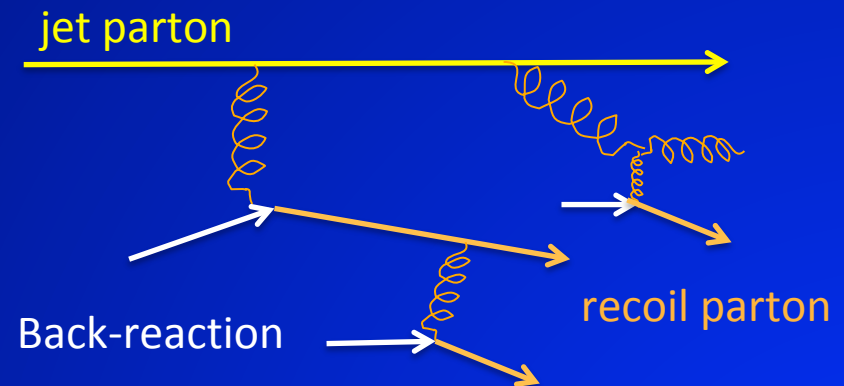
LBT: Linear Boltzmann Transport

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

Induced radiation

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

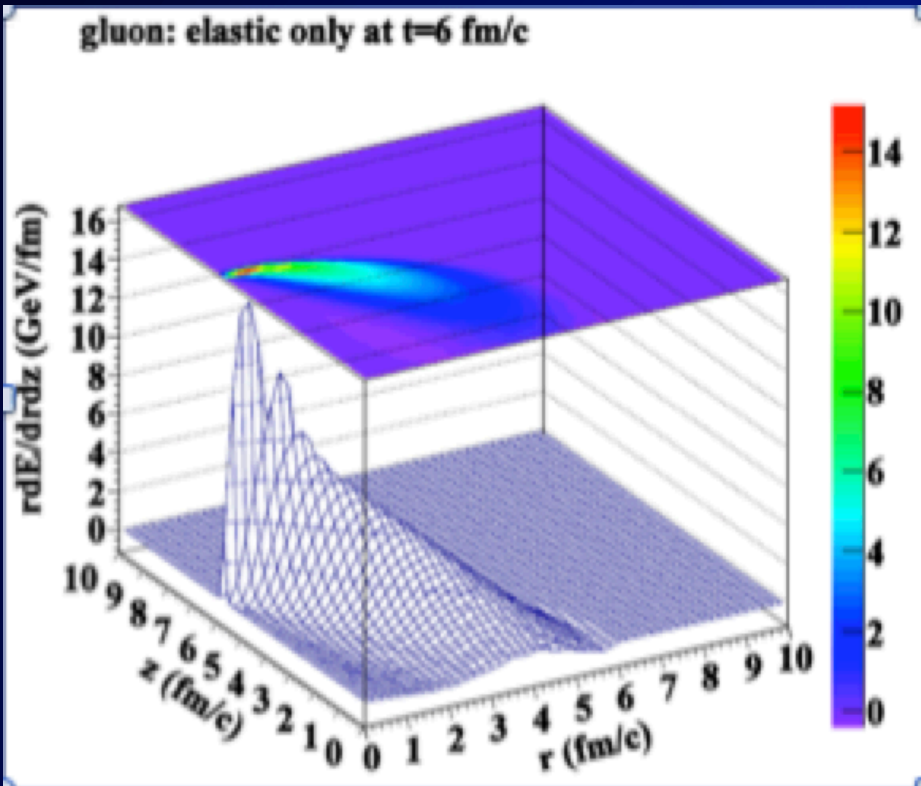
- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)
- 3+1D hydro bulk evolution



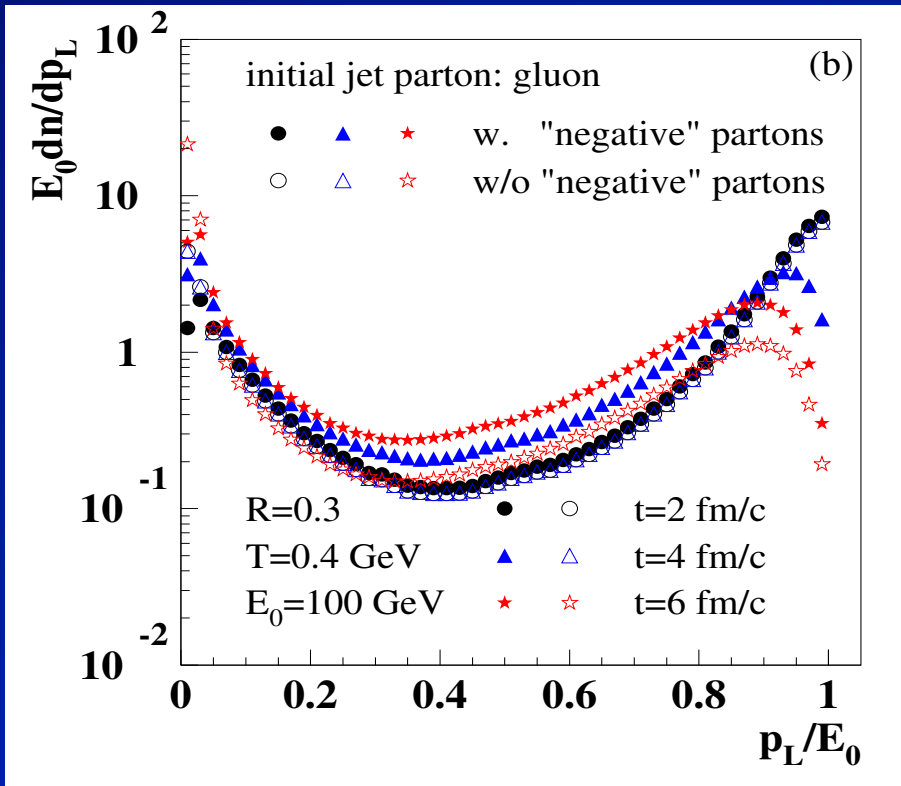
Li, Liu, Ma, XNW and Zhu, PRL 106 (2010) 012301

XNW and Zhu, PRL 111 (2013) 062301; He, Luo, XNW & Zhu, PRC91 (2015) 054908;

LBT: Jet-induced medium response



Energy distr. of medium response



Parton distr. from elastic scattering

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

CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

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

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

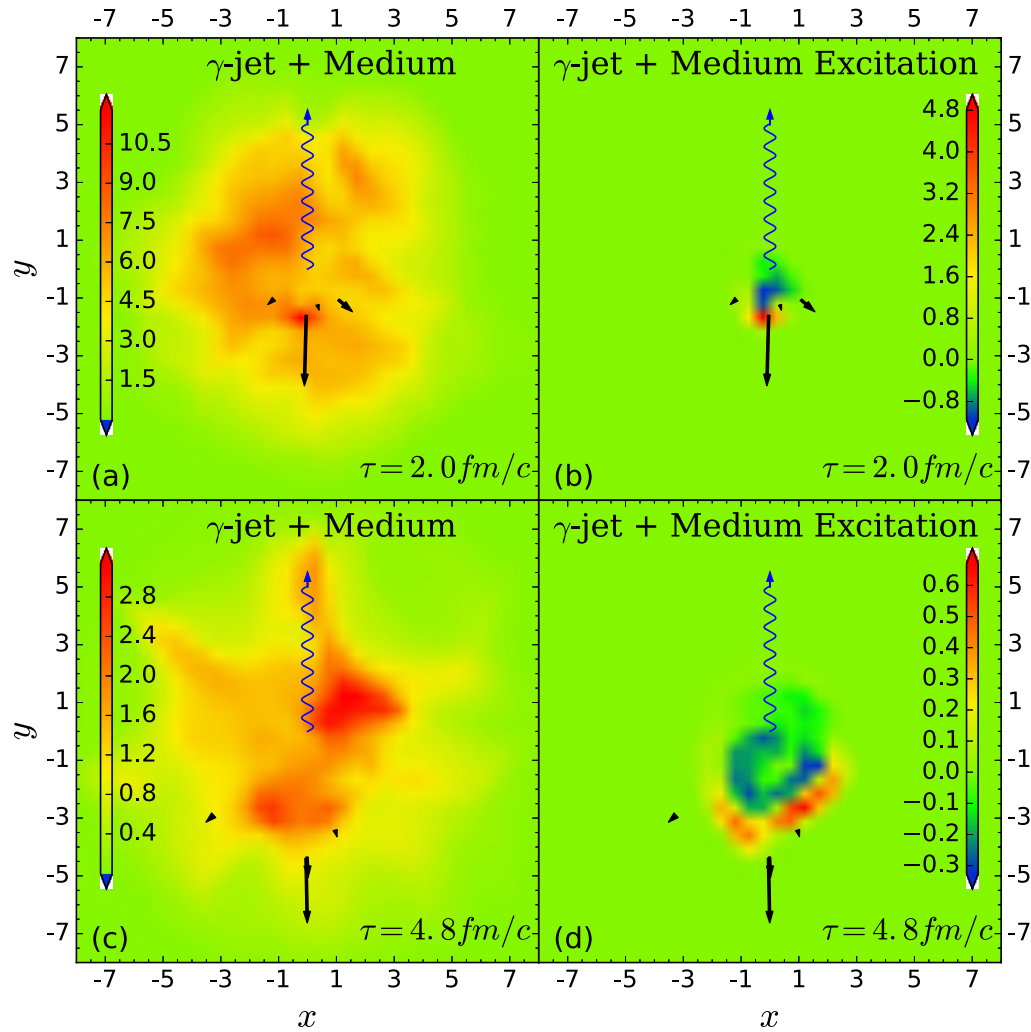
$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i) \theta(p_{cut}^0 - p \cdot u)$$

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

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

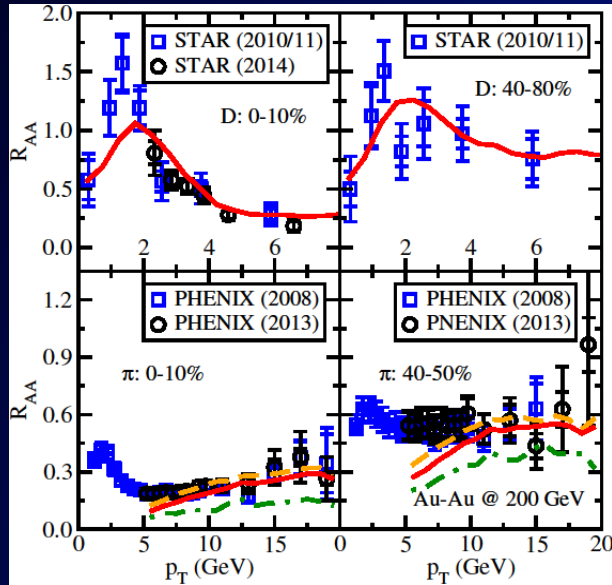
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86

γ -jet propagation within CoLBT-hydro

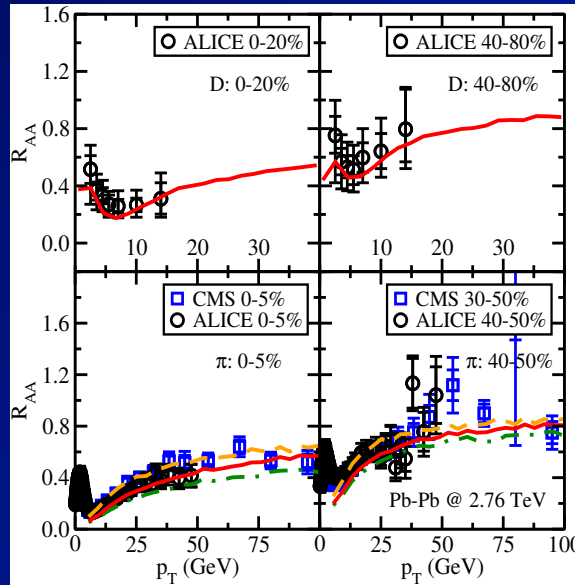


Light and heavy quark hadron suppression

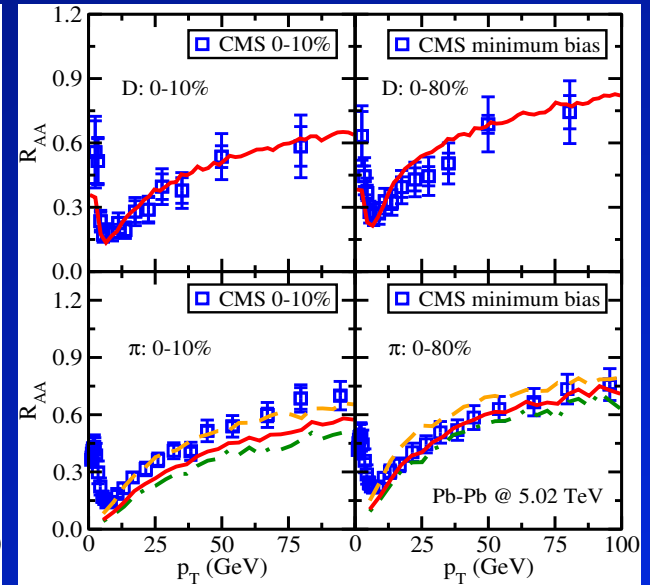
AuAu@200 GeV



PbPb@2760 GeV

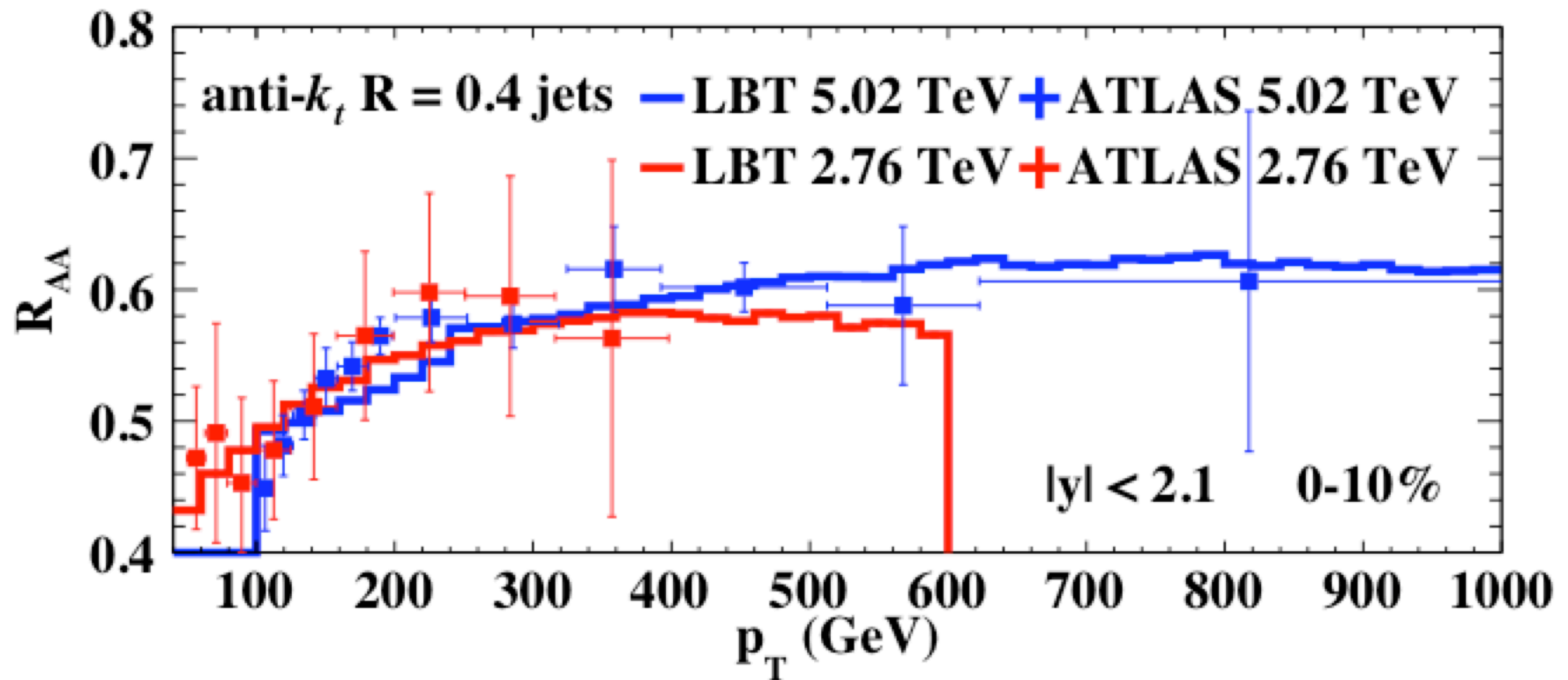


PbPb@5020 GeV



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

Single jet suppression at LHC

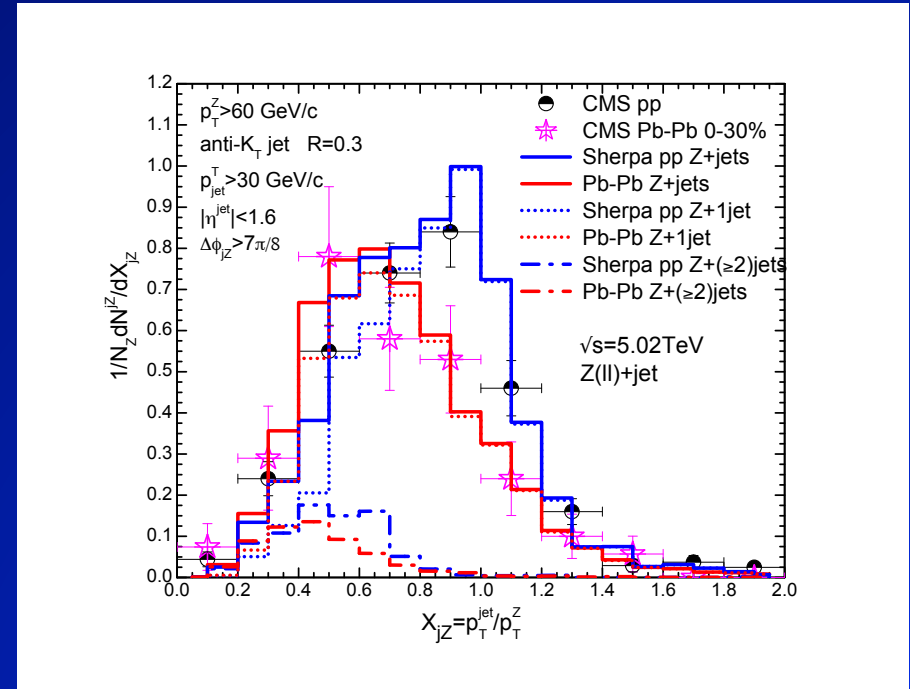
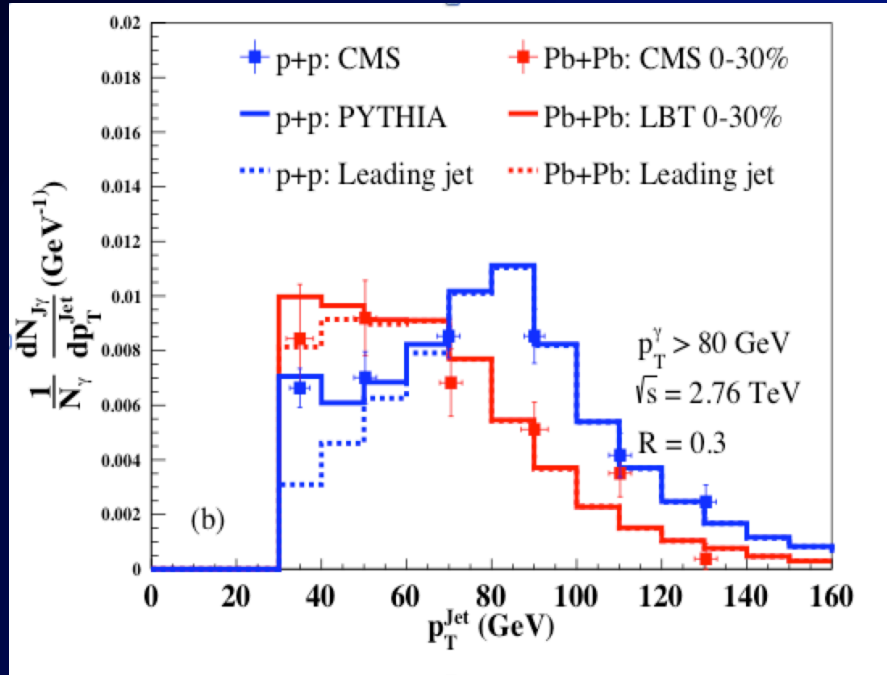


He, Cao, Luo & XNW to be published

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

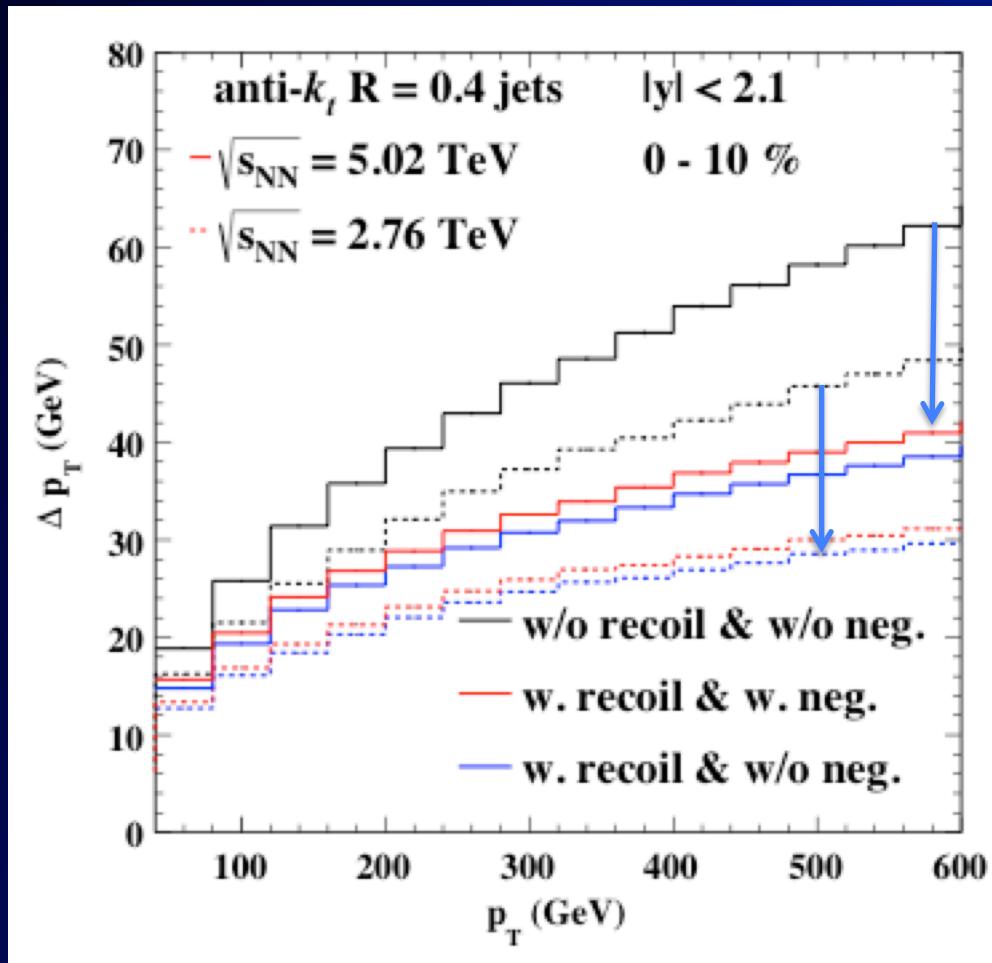
Jet energy loss and $\gamma(Z^0)$ -jet asymmetry



Luo, Cao, He & XNW, PLB782(18)707

Zhang, Luo, XNW, Zhang, arXiv:1804.11041

Medium response reduces jet energy loss



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

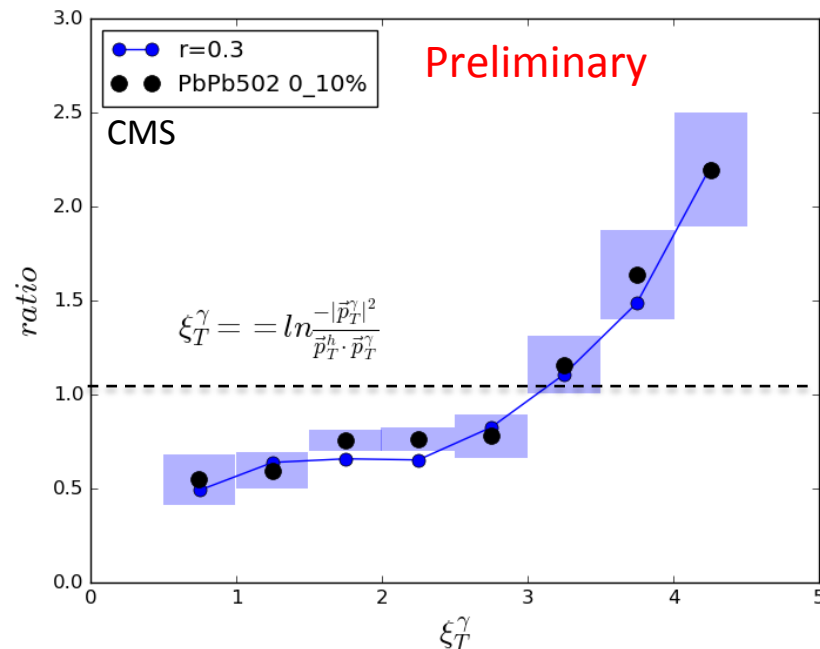
Diffusion wake (backreaction) reduces the thermal background, if taken into account, increase the net jet Energy loss with given cone-size

Depend on jet cone-size R
Sensitive to radial flow

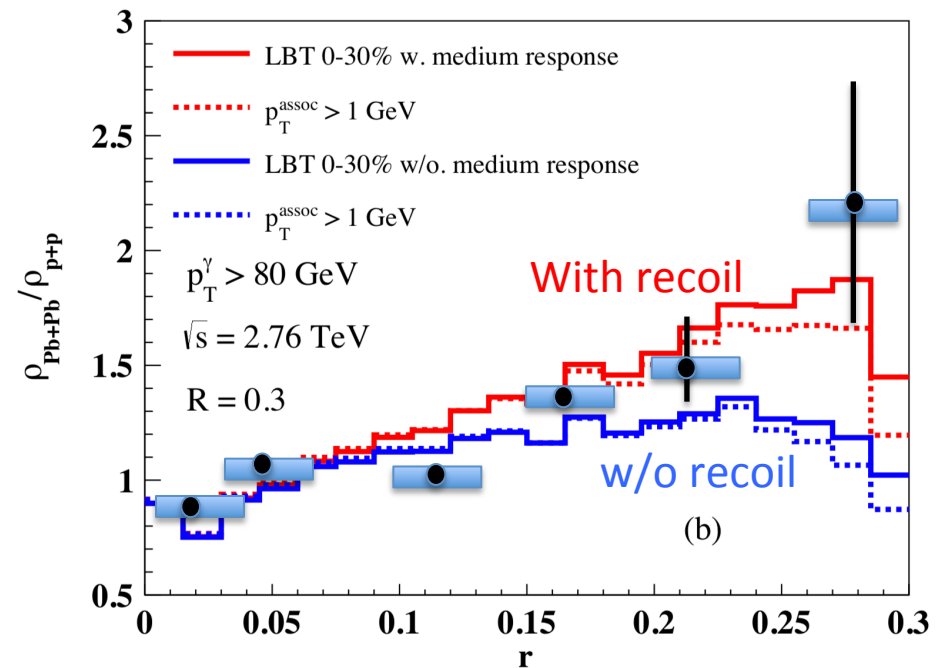
Can be estimated from elastic scattering: [PRC96\(2017\)034903](#)

Effect of medium response

Enhancement of Frag Function at small z

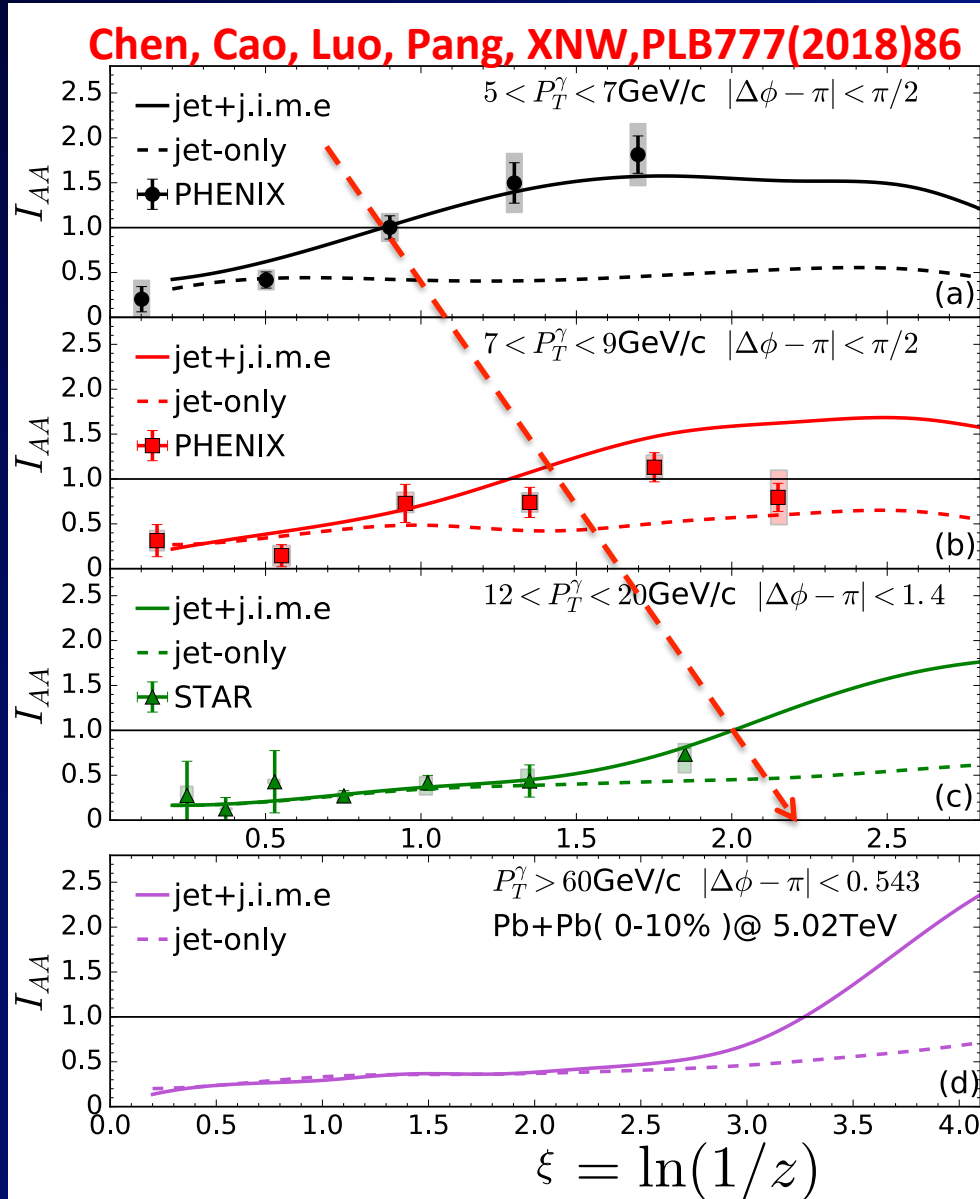


Enhancement of jet shape at larger r



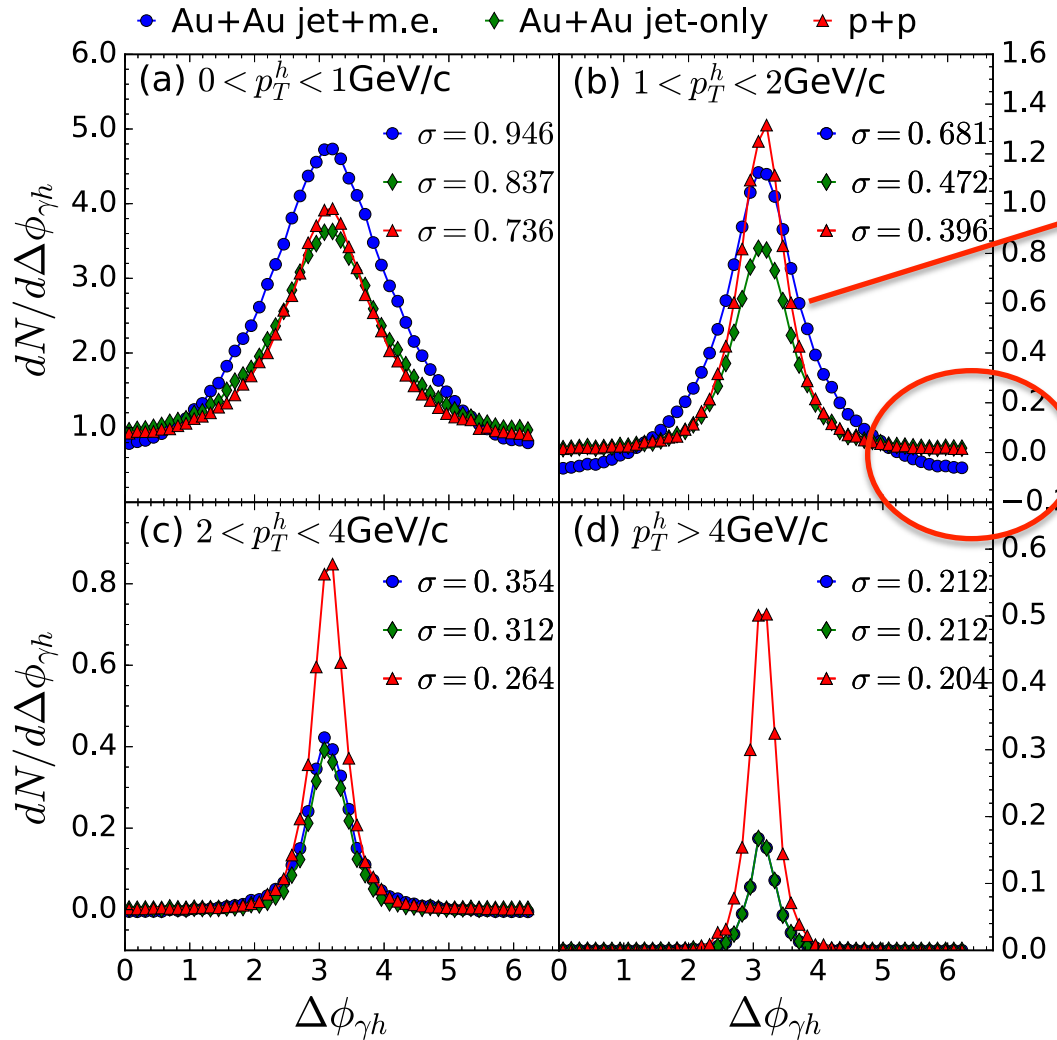
Luo, Cao, He & XNW, arXiv:1803.06785

Enhancement of soft hadrons



Onset of soft hadron enhancement is at fixed $p_T \sim 2 \text{ GeV}$

Azimuthal distribution of soft hadrons from medium response in γ -jet

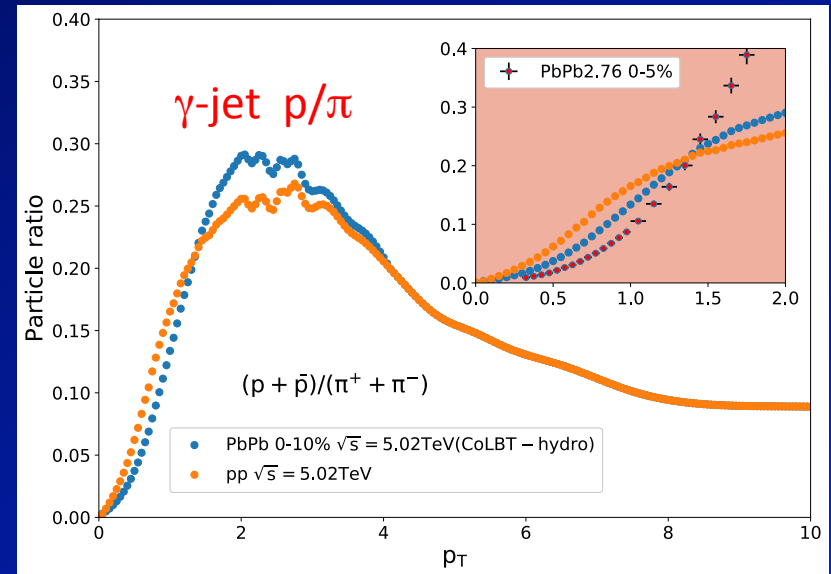
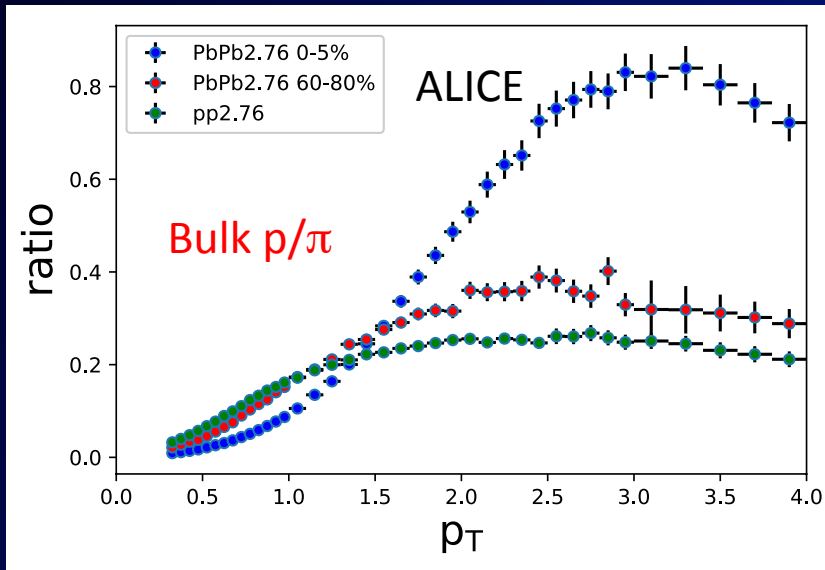


Broadening of jet peak

Depletion of the background
In the γ direction

Chen, Cao, Luo, Pang, XNW,
PLB777(2018)86

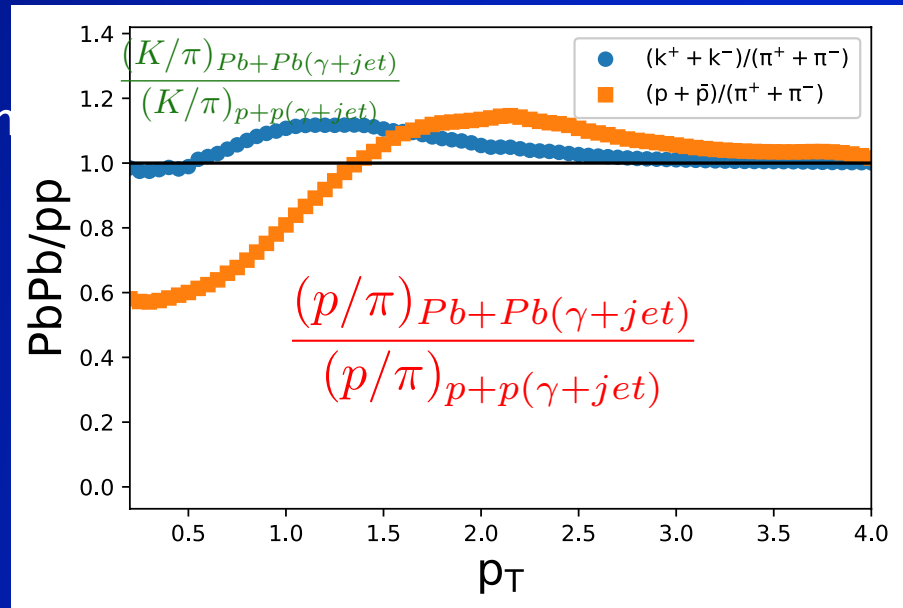
The flavor of medium response



Enhancement of p/π in bulk medium

Dominance of medium response of soft hadron inside jet $p_T < 2$ GeV

p/π , K/π ratios resemble to bulk



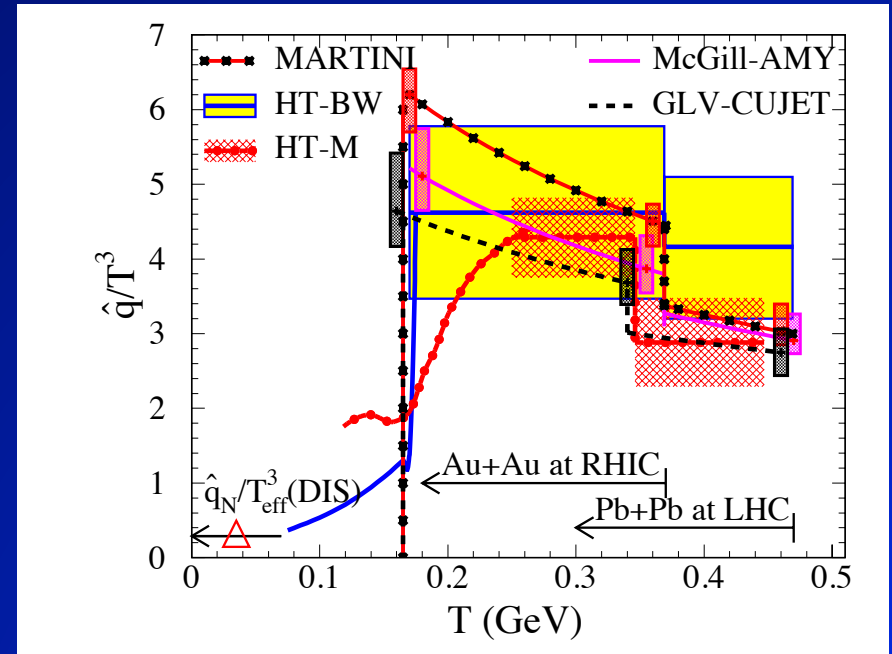
Summary on medium response

- Suppression of high p_T hadrons caused by energy loss of leading partons, not medium response
- Jet (with R) energy loss influenced by both transport shower partons & medium response
- Medium response leads to modification of jet shape, jet frag function, hadron flavor modification
- Diffusion wake $\rightarrow$ depletion of hadron in the gamma-direction

Data-driven extraction of jet energy loss

Extraction of $\hat{q}$ is model dependent

Extraction of jet energy loss is mostly model independent



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

Jet cross section in p+p and A+A

$$\frac{d\sigma_{\text{jet}}}{dp_T d\eta} = \sum_{a,b,c} d\sigma_{ab}^c \otimes J_c(p_T, p_{Tc}, R)$$

Kang, Ringer & Vitev, PLB769(2017)242

Medium modified jet function and jet energy loss distribution:

$$\tilde{J}_c(p_T, p_{Tc}, R, \mathbf{r}, \mathbf{b}) = \int d\Delta p_T w_c(\Delta p_T, p_T, R, \mathbf{r}, \mathbf{b}, \phi) J_c(p_T + \Delta p_T, p_{Tc}, R)$$

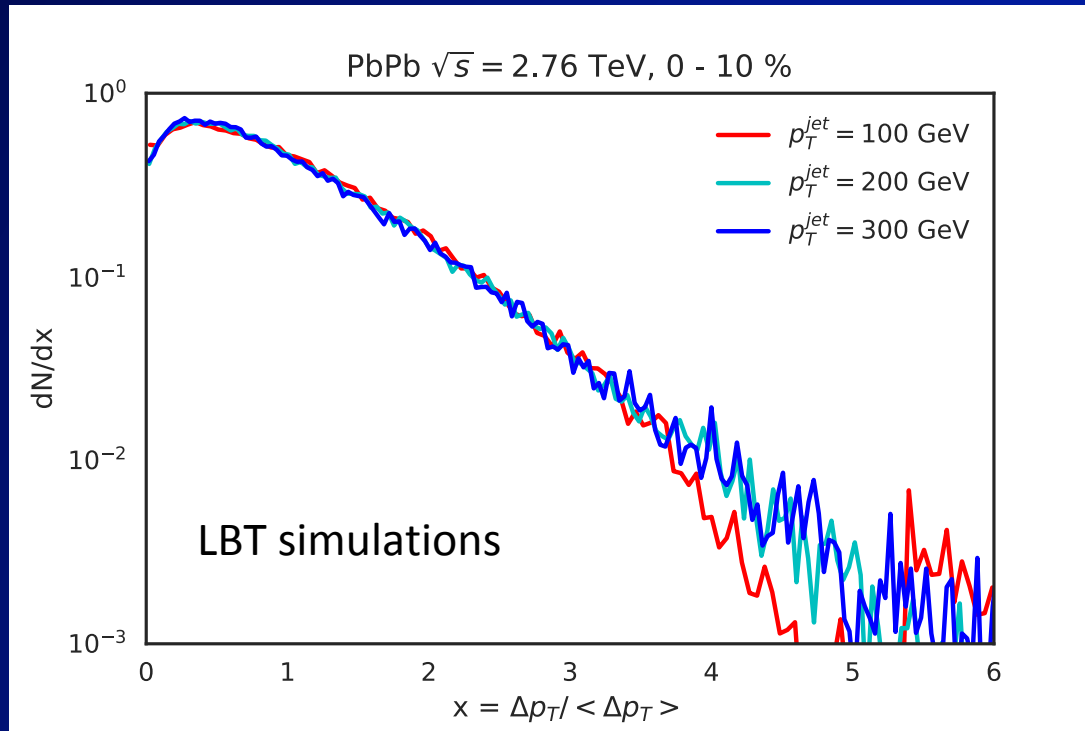
$$W_{AA}^c(\Delta p_T, p_T, R) = \frac{\int d^2r d^2b t_A(r) t_A(|\mathbf{b} - \mathbf{r}|) \frac{d\phi}{2\pi} w_c(\Delta p_T, p_T, R, \mathbf{r}, \mathbf{b}, \phi)}{\int d^2r d^2b t_A(r) t_A(|\mathbf{b} - \mathbf{r}|)}.$$

Medium modified jet production cross section $p_T(p_{Tc}) \rightarrow \text{jet } p_T \text{ in vacuum}$

$$\frac{d\sigma_{\text{jet}}^{AA}}{dp_T dy} = \int d\Delta p_T \sum_{a,b,c} W_{AA}^c(\Delta p_T, p_T + \Delta p_T, R) d\sigma_{ab}^c \otimes J_c(p_T + \Delta p_T, p_{Tc}, R)$$

Data-driven extraction of jet energy loss

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



$$W_{\text{AA}}(\Delta p_T, p_T, R) \approx W_{\text{AA}}(\Delta p_T / \langle \Delta p_T \rangle, R)$$

Flavor averaged jet energy loss distribution

Bayesian analysis of experimental data

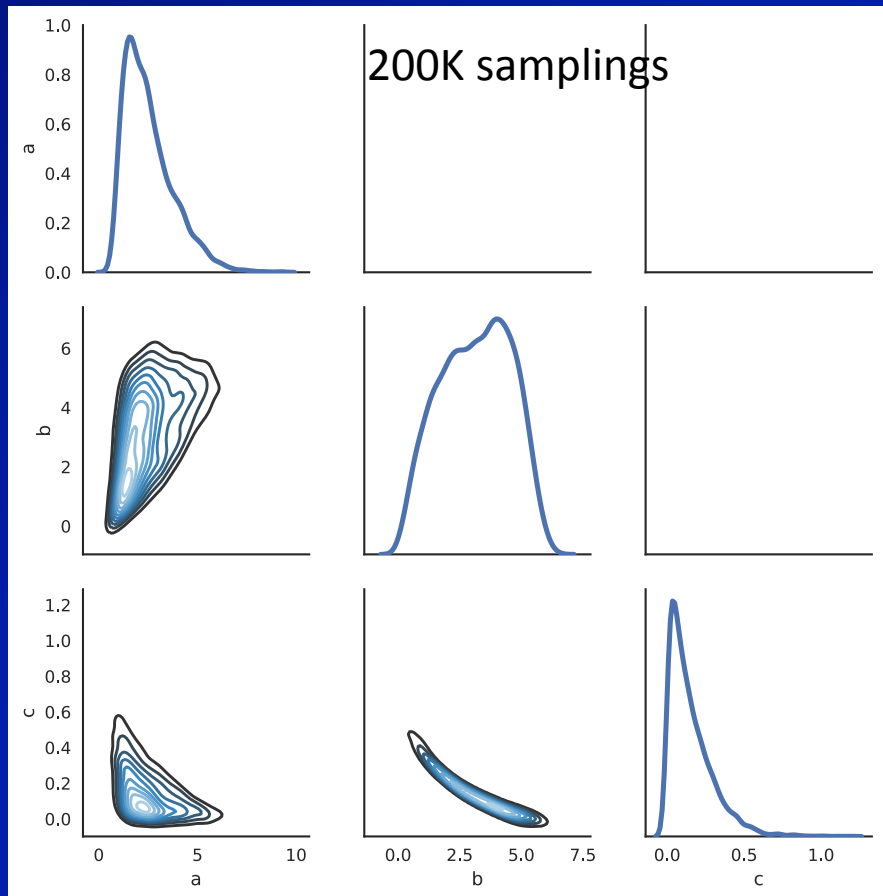
$$\sigma_{\text{jet}}^{pp}(p_T) \xrightarrow[\uparrow]{W_{AA}(\Delta p_T, p_T, R)} \sigma_{\text{jet}}^{AA}(p_T)$$

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

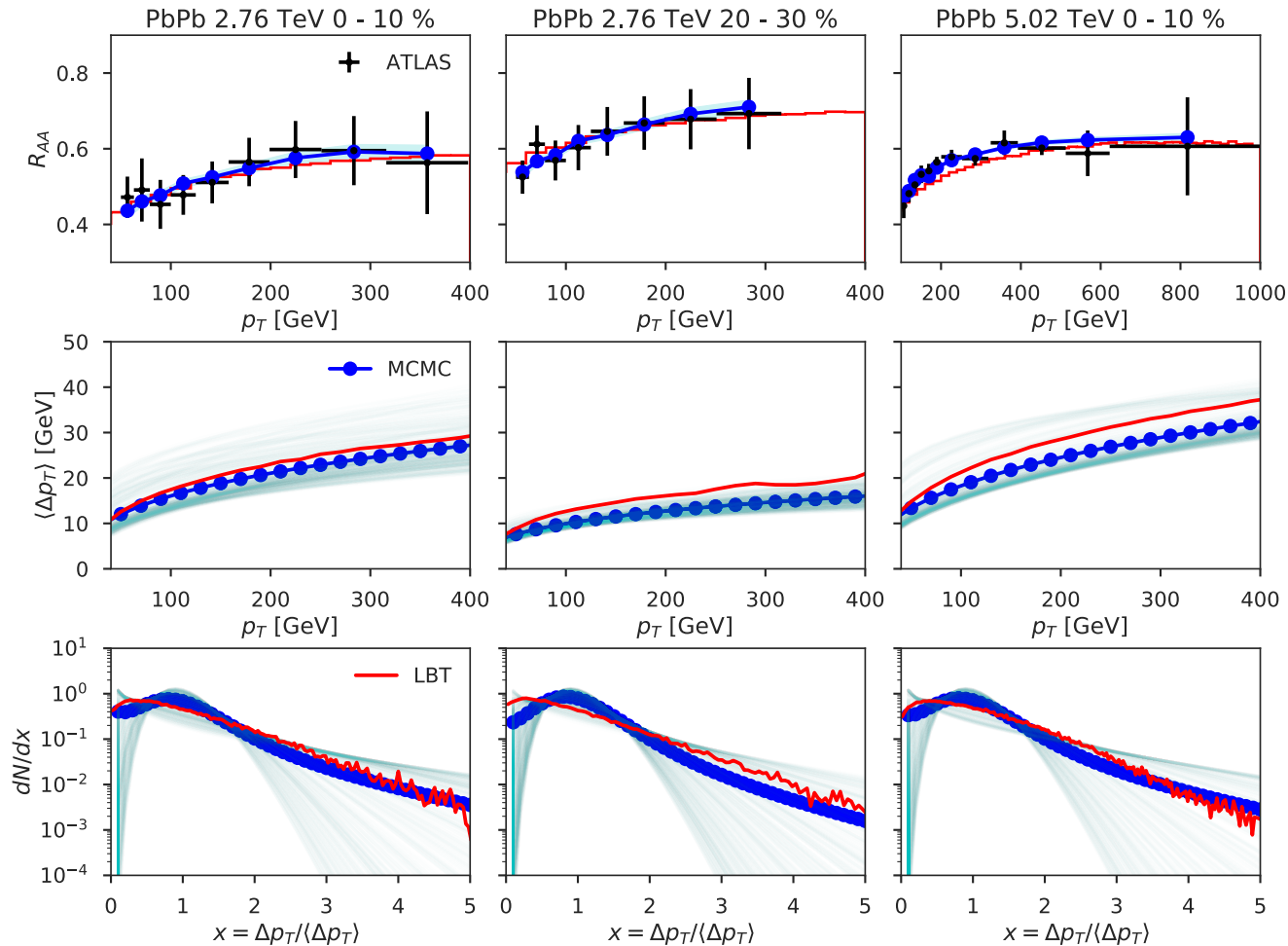
$$x = \frac{\Delta p_T}{\langle \Delta p_T \rangle}$$

$$\langle \Delta p_T \rangle = b p_T^c \log(p_T)$$

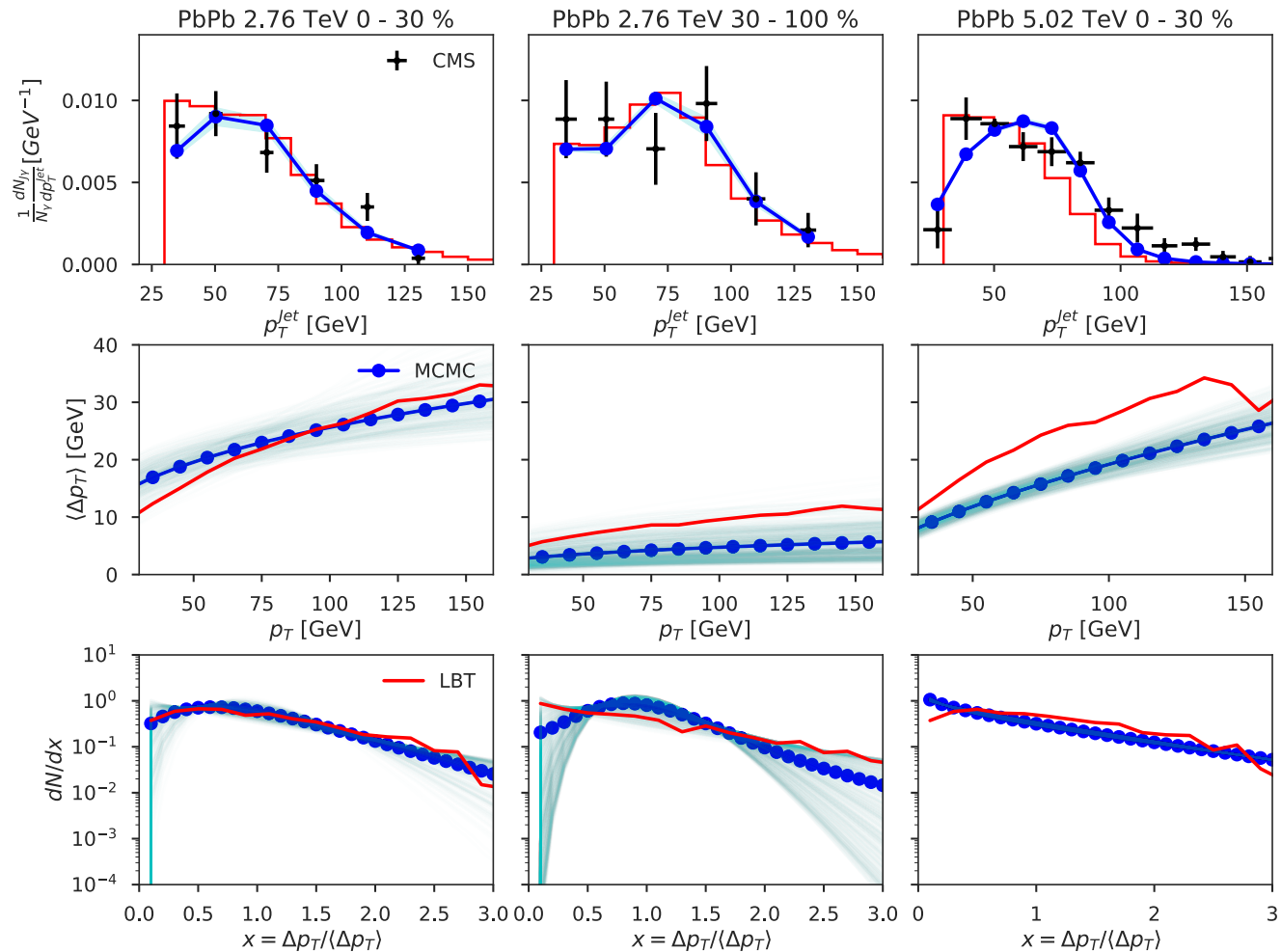
Markov chain Monte Carlo
to sample parameters based
on uniform prior distributions



Jet energy loss: single inclusive jet



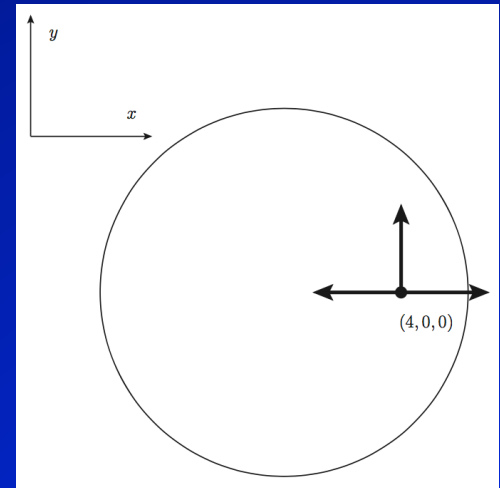
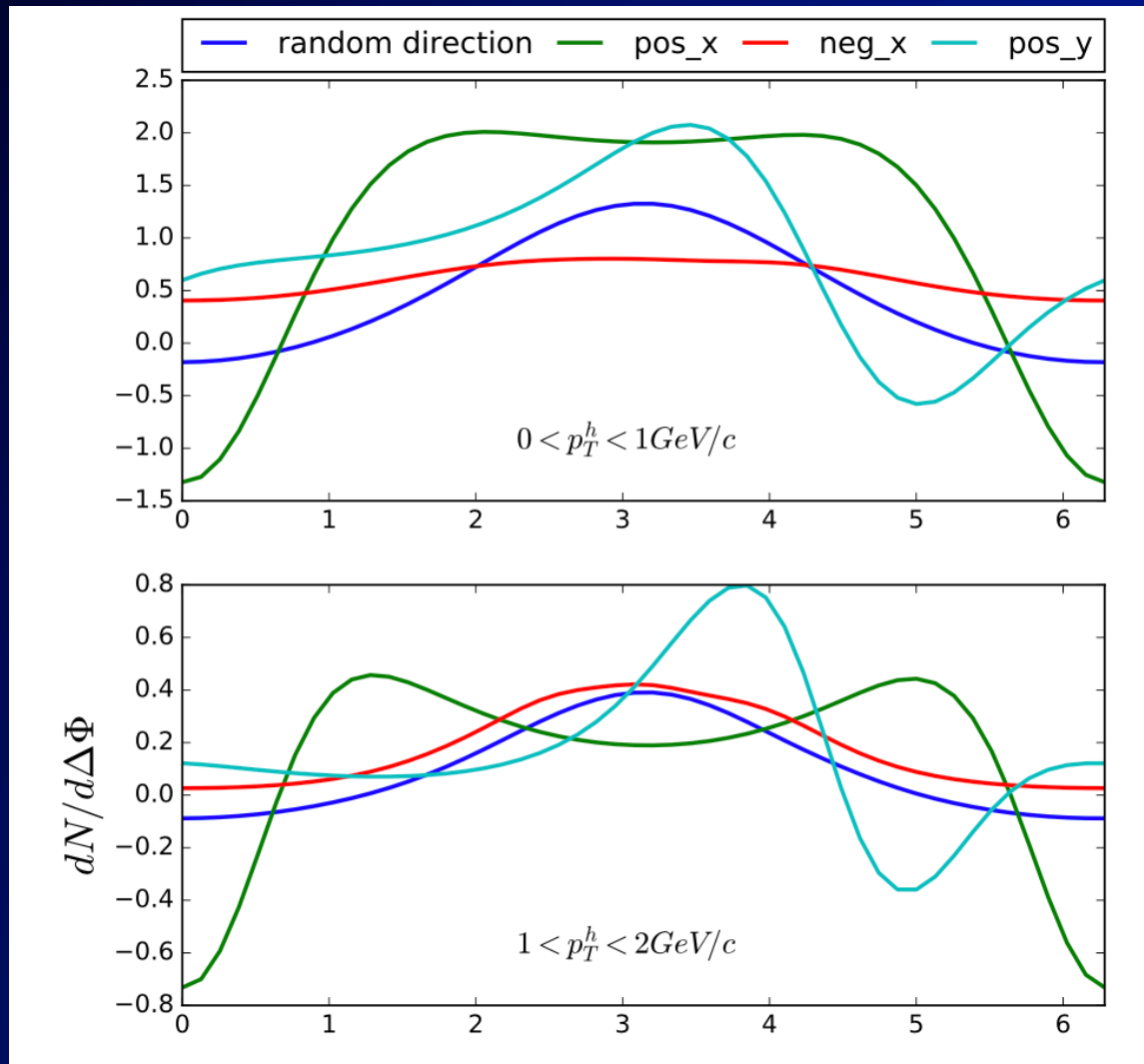
Jet energy loss: γ + jet



Summary on extraction of jet energy loss

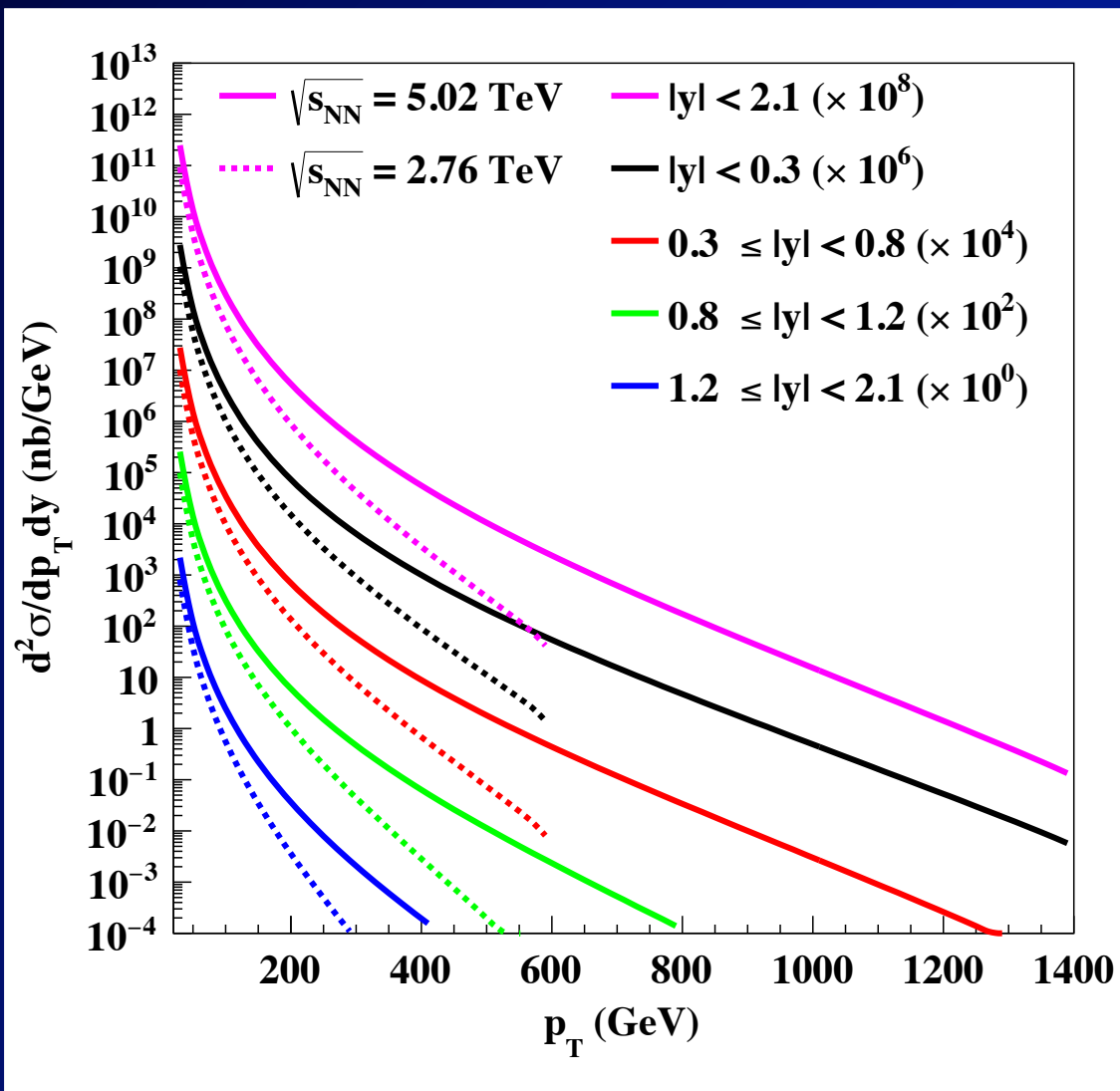
- Using factorized pQCD jet cross section, A+A jet cross section can be obtained from p+p cross section with an energy loss distribution
- Using Bayesian method, one can extract jet energy loss distribution and average jet energy loss from experimental data on jet cross section in p+p and A+A collisions

Wide angle distribution of soft hadrons

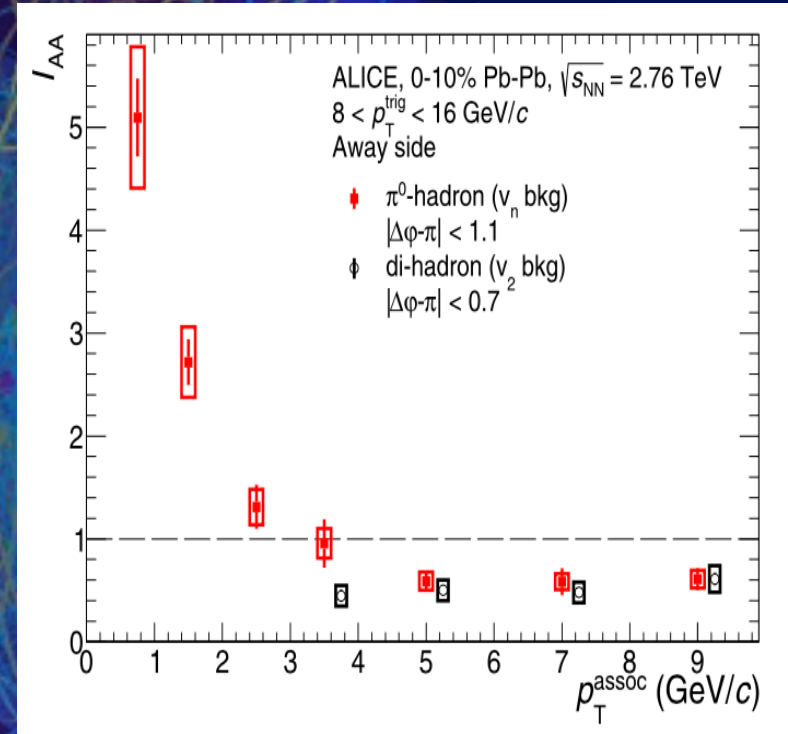
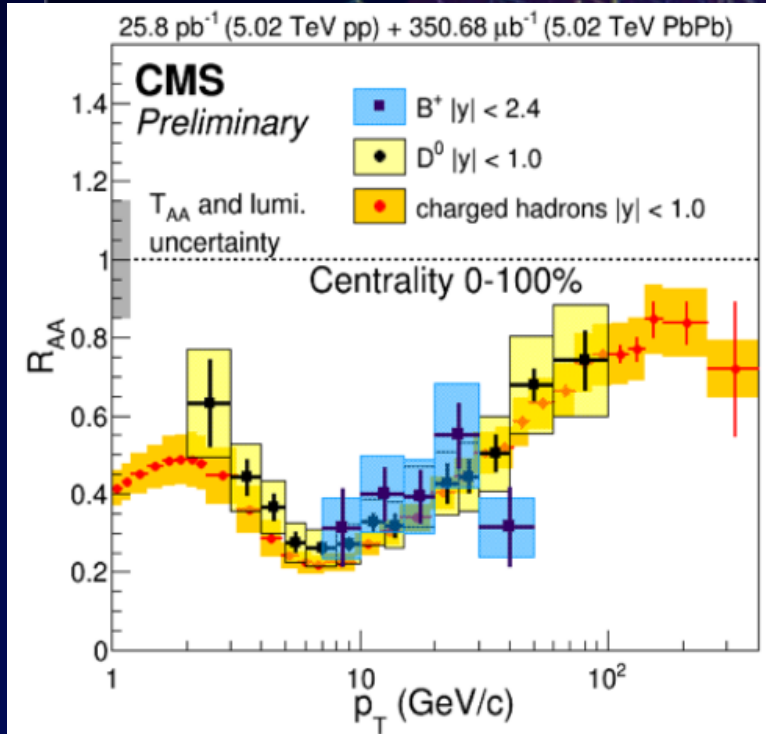


$\Delta\Phi$

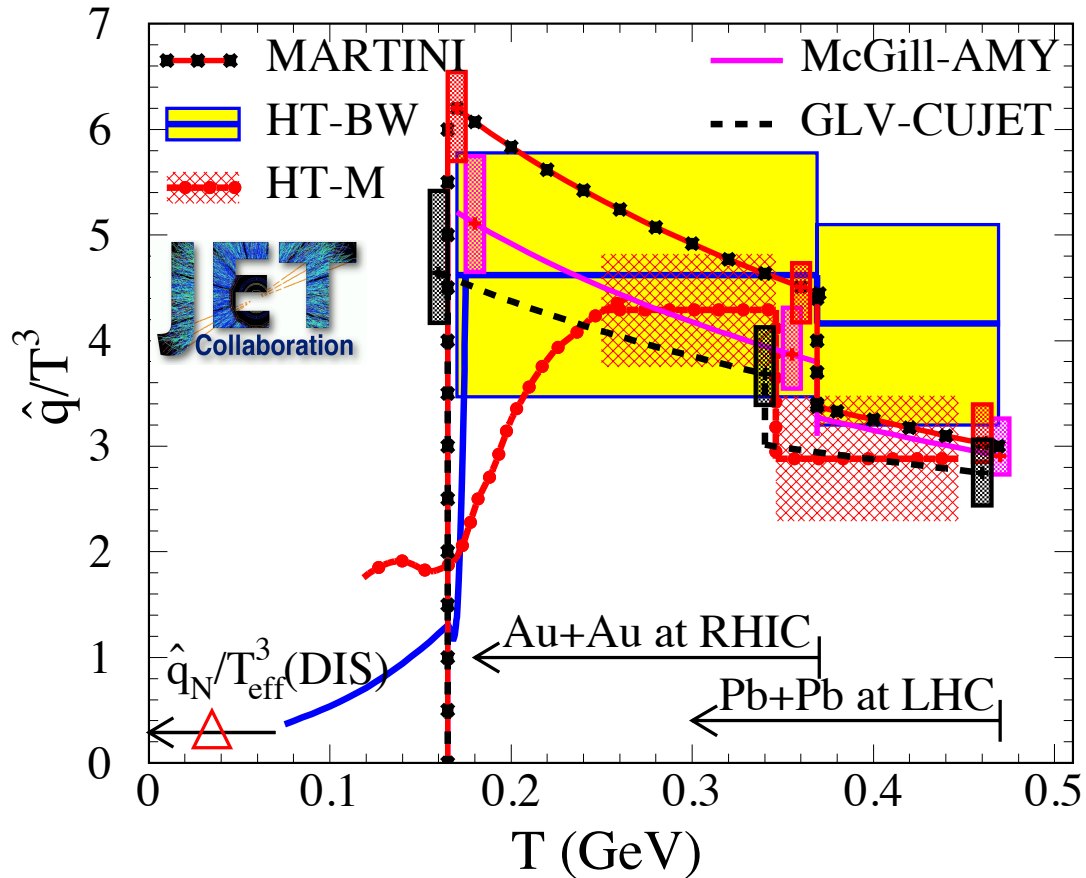
Energy dependence of jet spectra



Jet Quenching phenomena at LHC

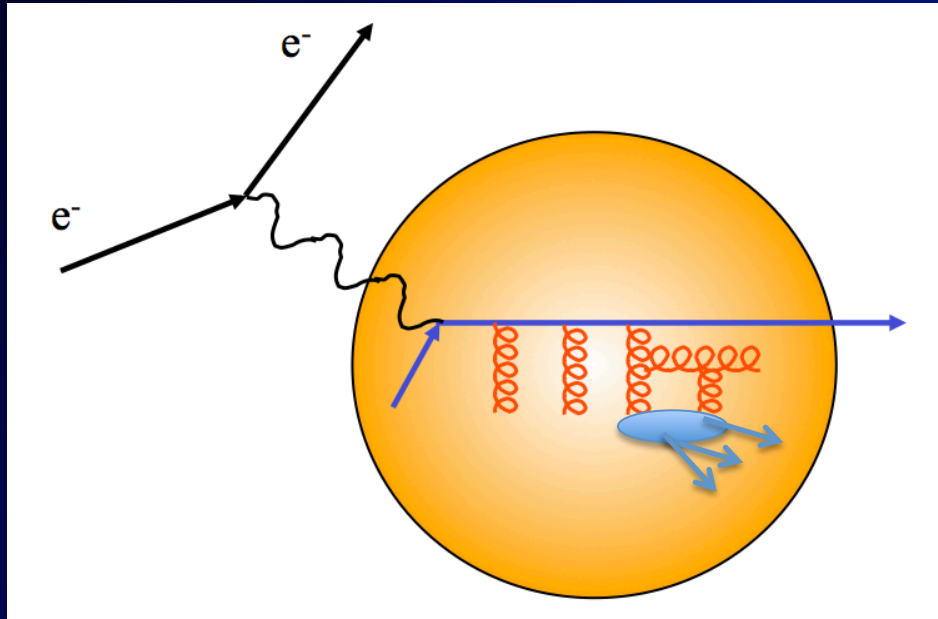


Jet transport coefficient



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

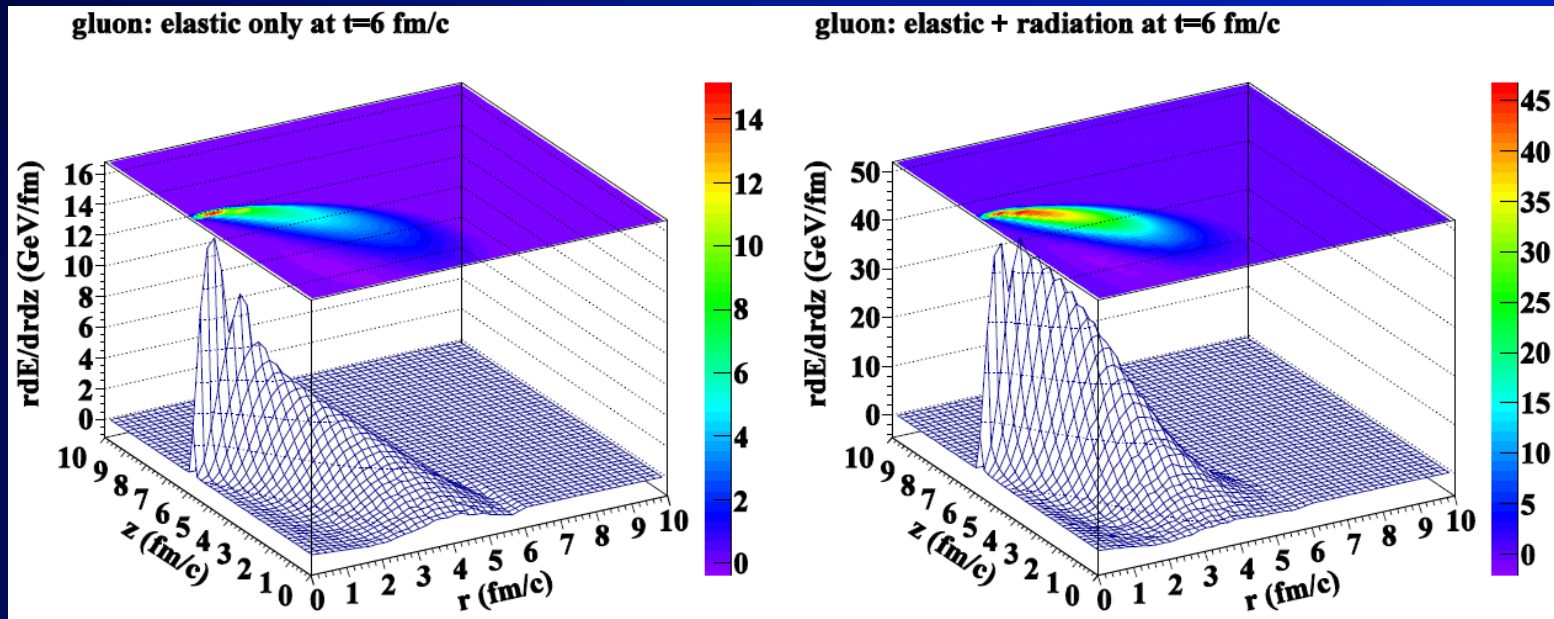
$$\begin{aligned} \frac{dN}{d\ell_T^2 dz} &= 2\pi \frac{C_2 C_A}{d_A} P(z) \int dy \rho(y) \int \frac{d^2 q_T}{(2\pi)^2} \phi(x_D, q_T) \\ &\times \frac{2\vec{q}_T \cdot \vec{\ell}_T}{q_T^2 \ell_T^2 (\vec{\ell}_T - \vec{q}_T)^2} \left[1 - \cos\left[\left(x_L + \frac{x_D}{1-z}\right)p^+ y^-\right] \right]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

Linear Boltzmann Transport (LBT)

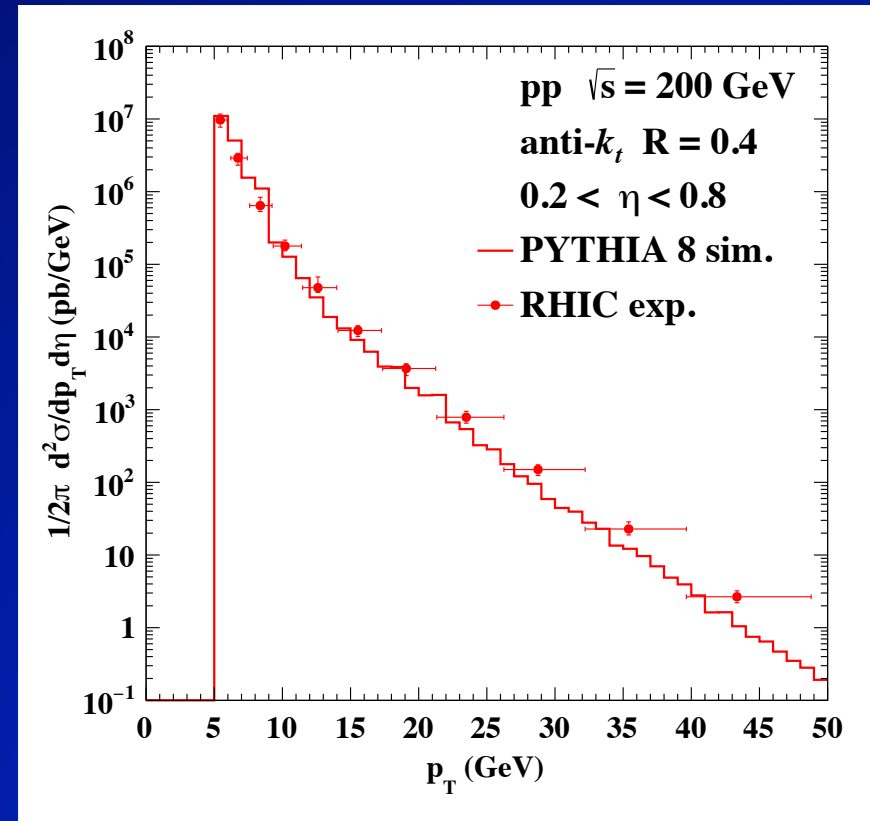
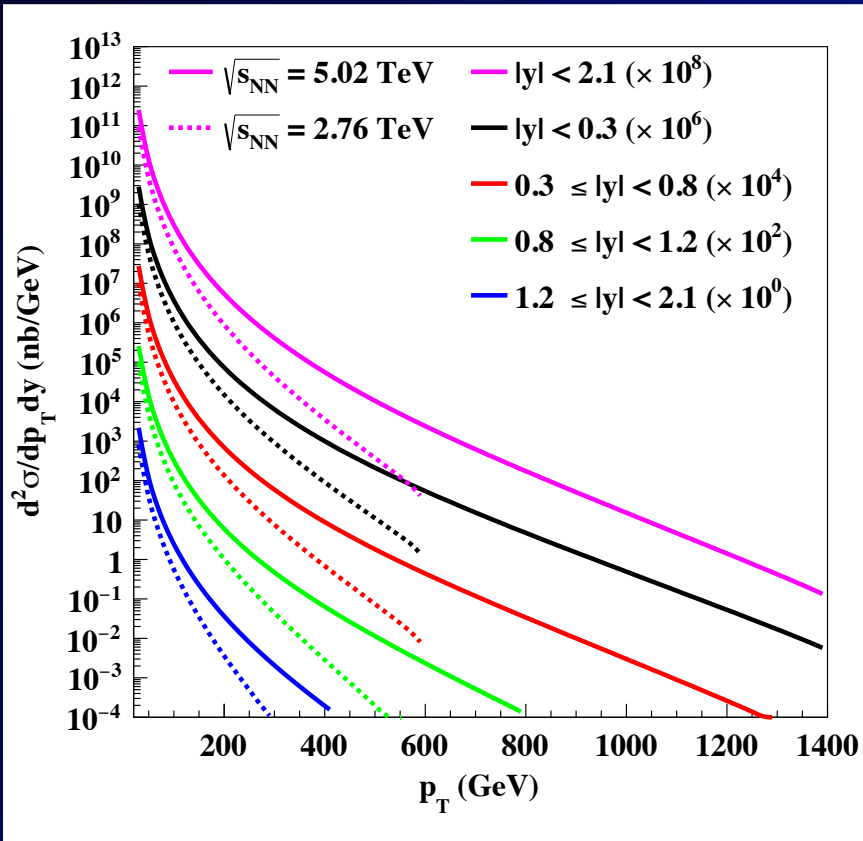
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Li, Liu, Ma, XNW & Zhu, PRL 106 (2011) 012301
XNW & Zhu, PRL 111 (2013), 062301

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

