Jet quenching and medium response

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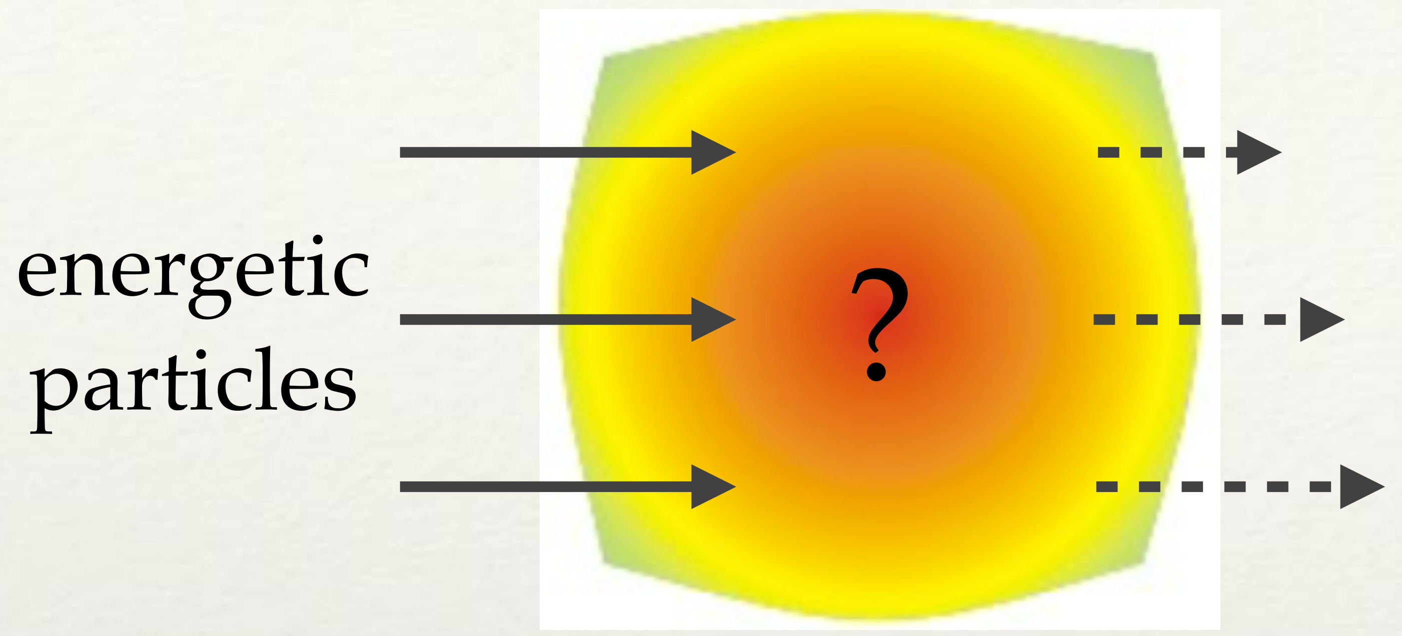
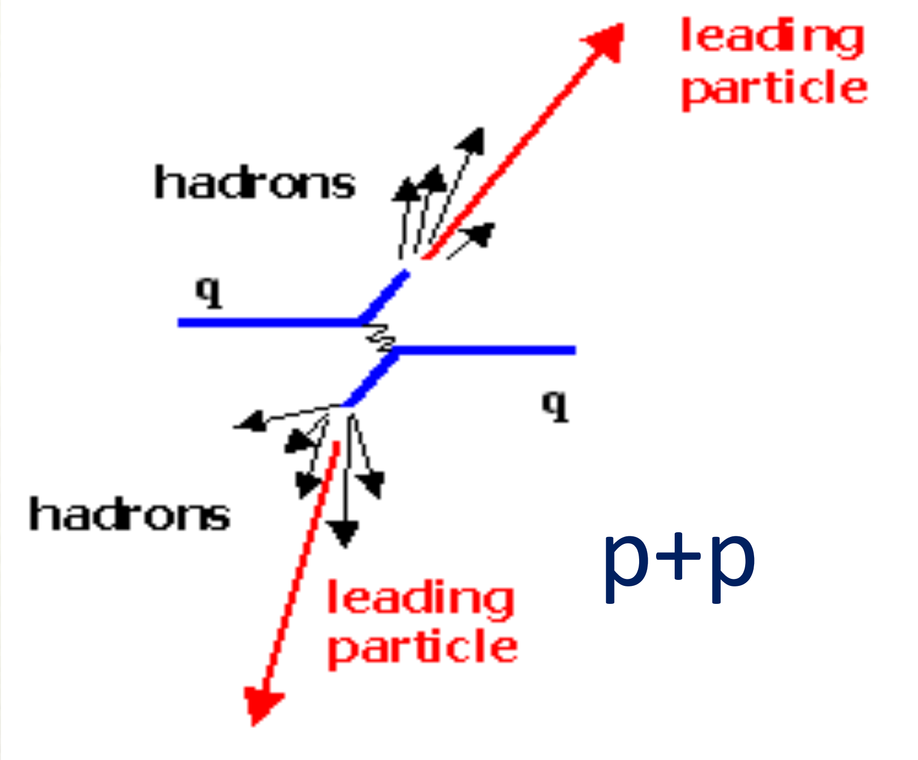
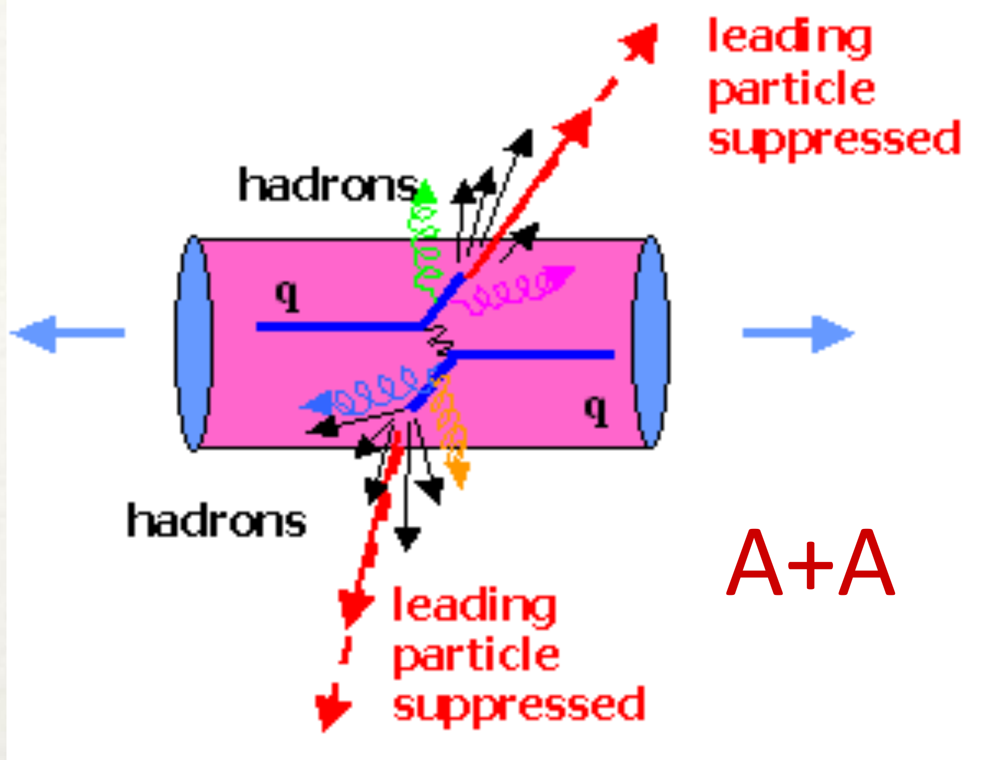
Shandong University

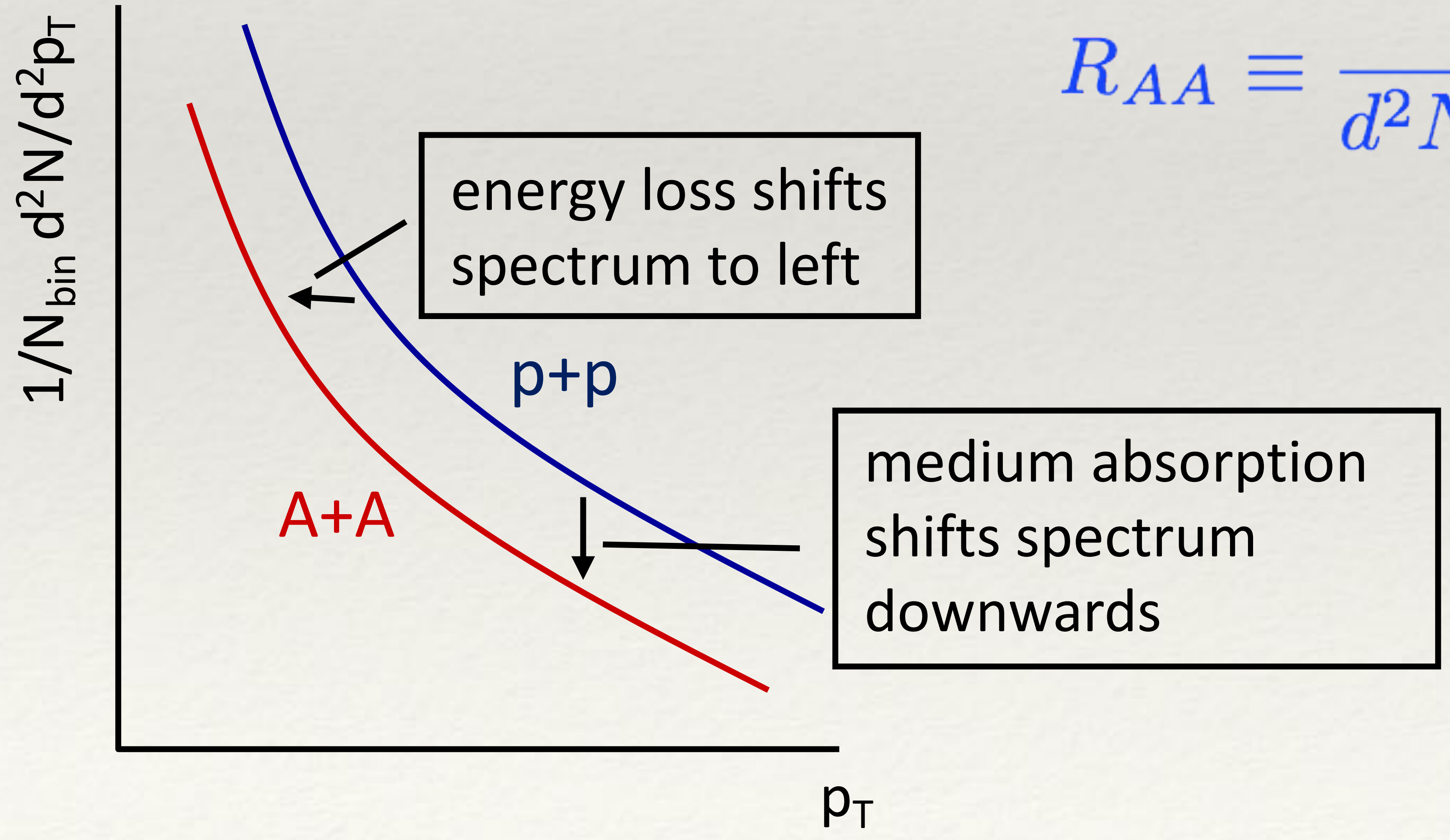
Hard probes of QGP



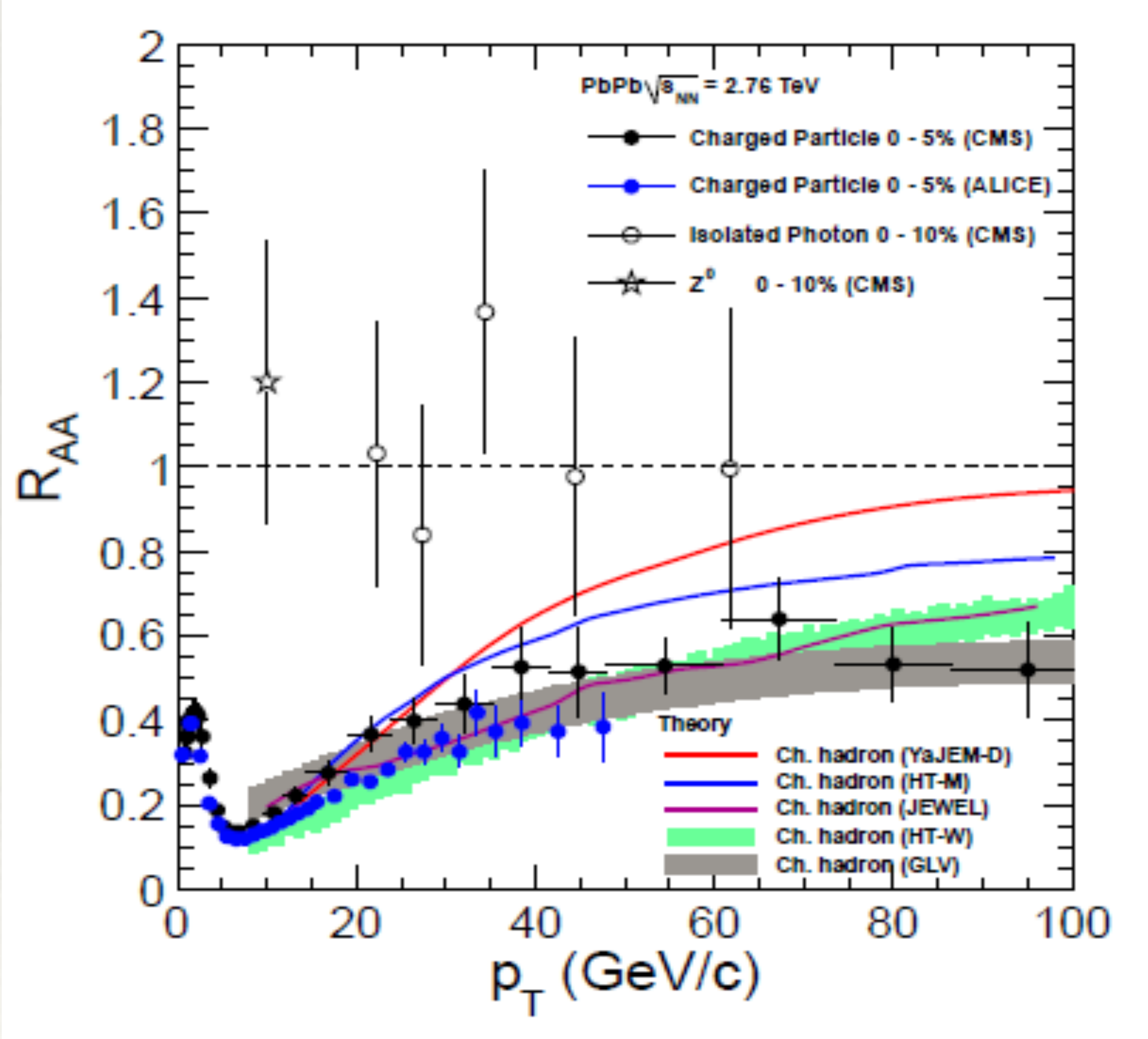




Nuclear modification factor

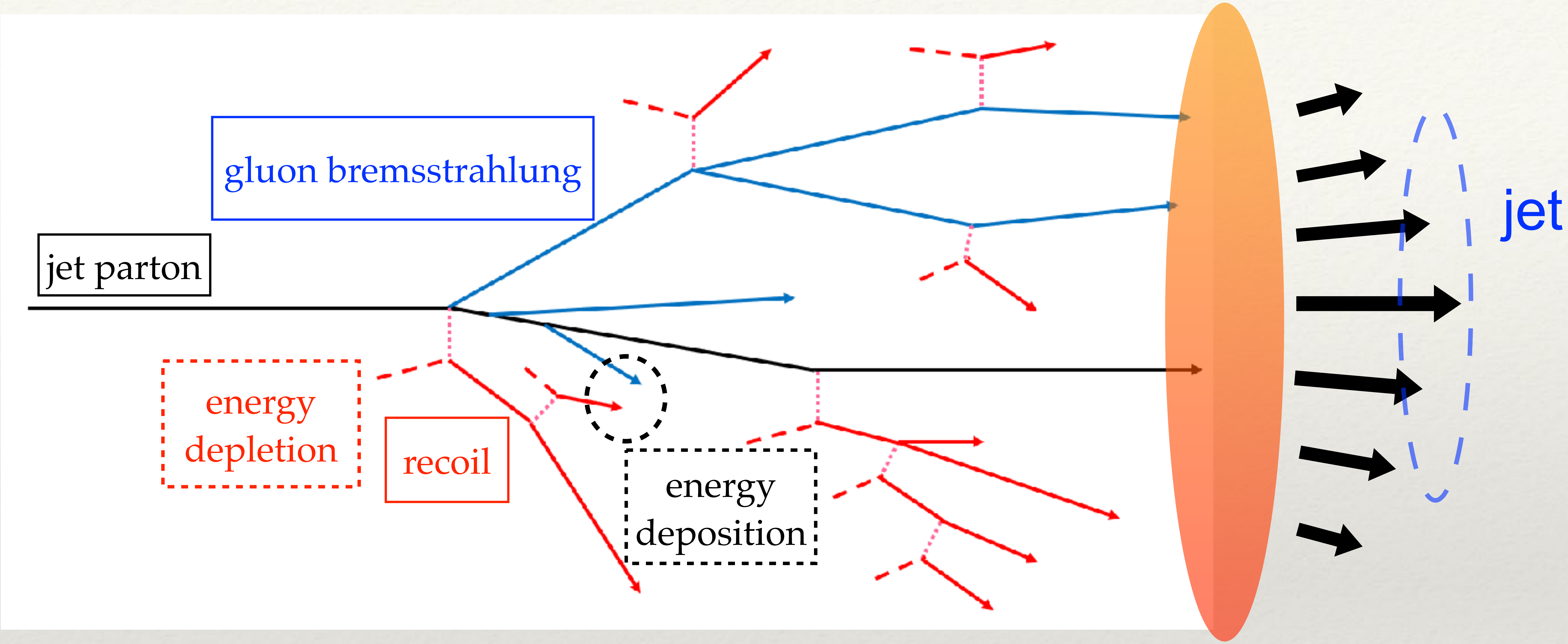


$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA}\rangle}$$



Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)

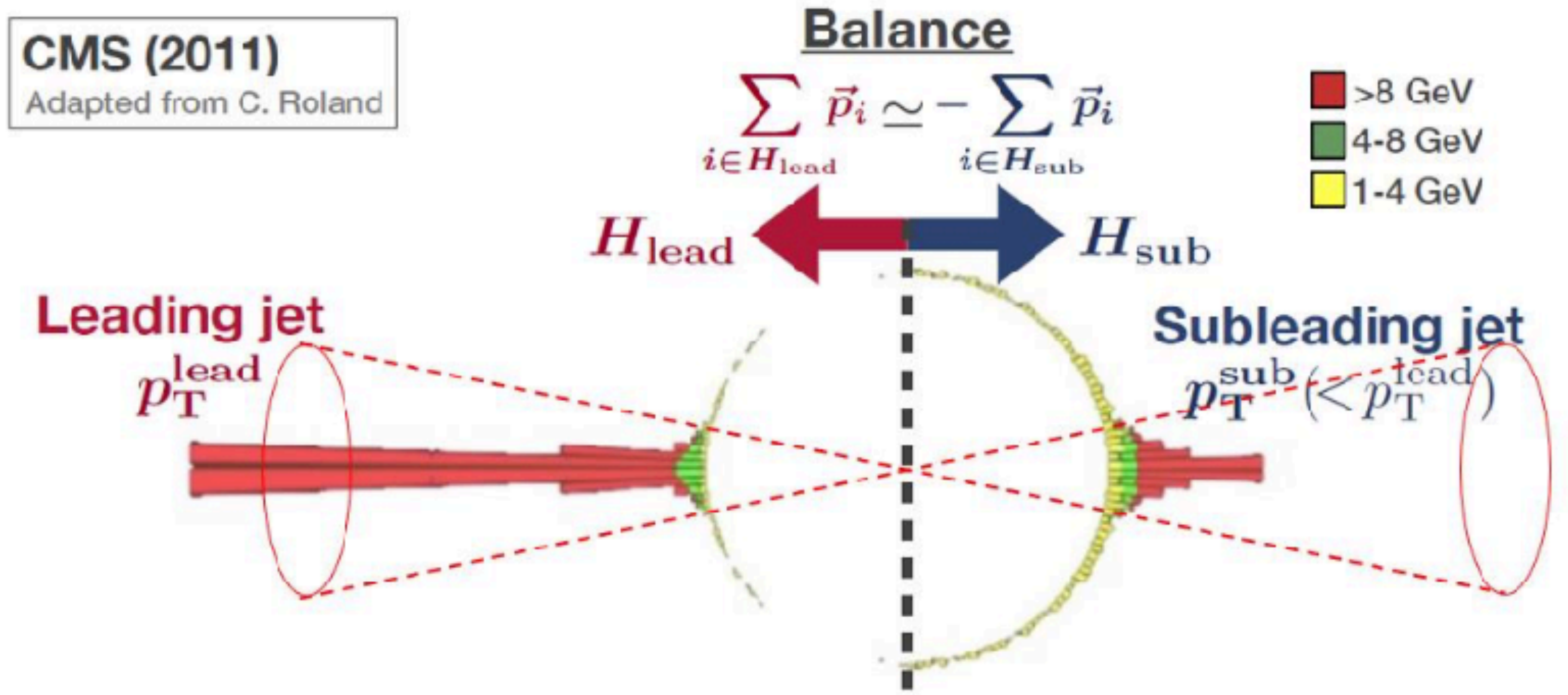
Jet-medium interaction

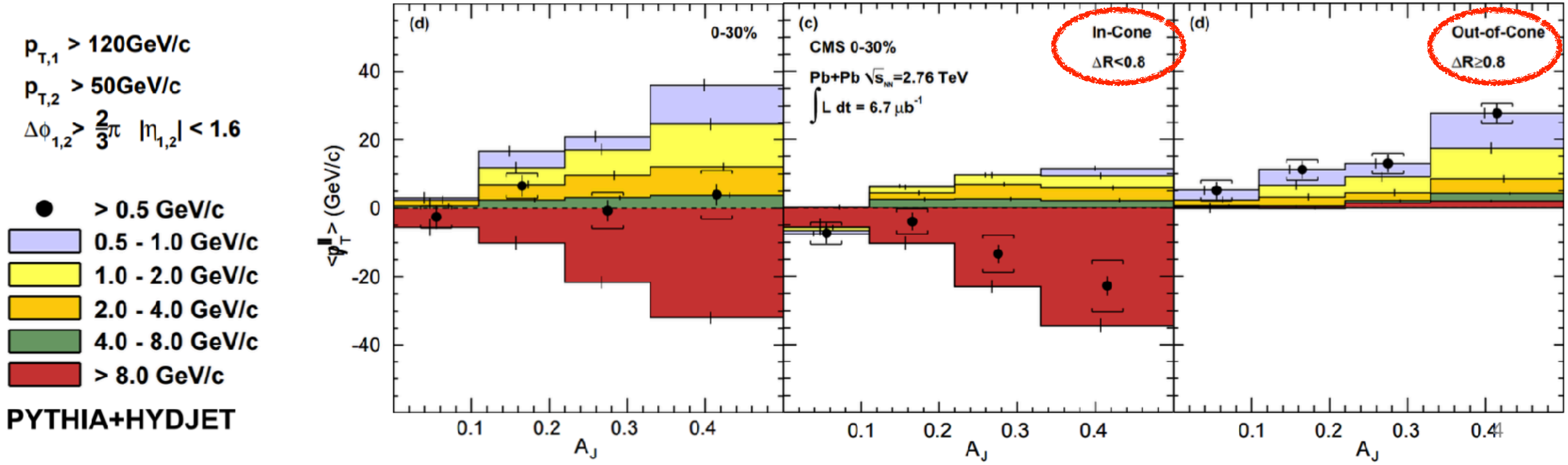


- Medium modification of jets: initial state jet parton → final state jet parton + gluon
- Jet modification of medium (medium response): recoil + energy depletion
- Observed jets: contribution from both

Why we need medium response

The energy and momentum deposited by the jet shower into the medium appear at large angles away from the jet axis.





Different implementations of medium response

Linear hydrodynamic response

Hydrodynamics with a source: $\partial_\mu T^{\mu\nu}(x) = J^\nu(x).$ $\quad J^\nu(x) = [dE/d^4x, d\vec{p}/d^4x]$

Linear approximation: $T^{\mu\nu} \approx T_0^{\mu\nu} + \delta T^{\mu\nu}; \quad \partial_\mu T_0^{\mu\nu} = 0, \quad \partial_\mu \delta T^{\mu\nu} = J^\nu.$

Decomposition: $\delta T^{00} \equiv \delta\epsilon, \quad \delta T^{0i} \equiv g^i,$ $\quad \delta T^{ij} = \delta^{ij} c_s^2 \delta\epsilon + \frac{3}{4}\Gamma_s(\partial^i g^j + \partial^j g^i + \frac{2}{3}\delta^{ij}\nabla\cdot\vec{g}),$

Fourier transformation of $\partial_\mu \delta T^{\mu\nu} = J^\nu$:

$$J^0 = -i\omega\delta\epsilon + i\vec{k}\cdot\vec{g},$$

$$\vec{J} = -i\omega\vec{g} + i\vec{k}c_s^2\delta\epsilon + \frac{3}{4}\Gamma_s\left[k^2\vec{g} + \frac{\vec{k}}{3}(\vec{k}\cdot\vec{g})\right],$$

→

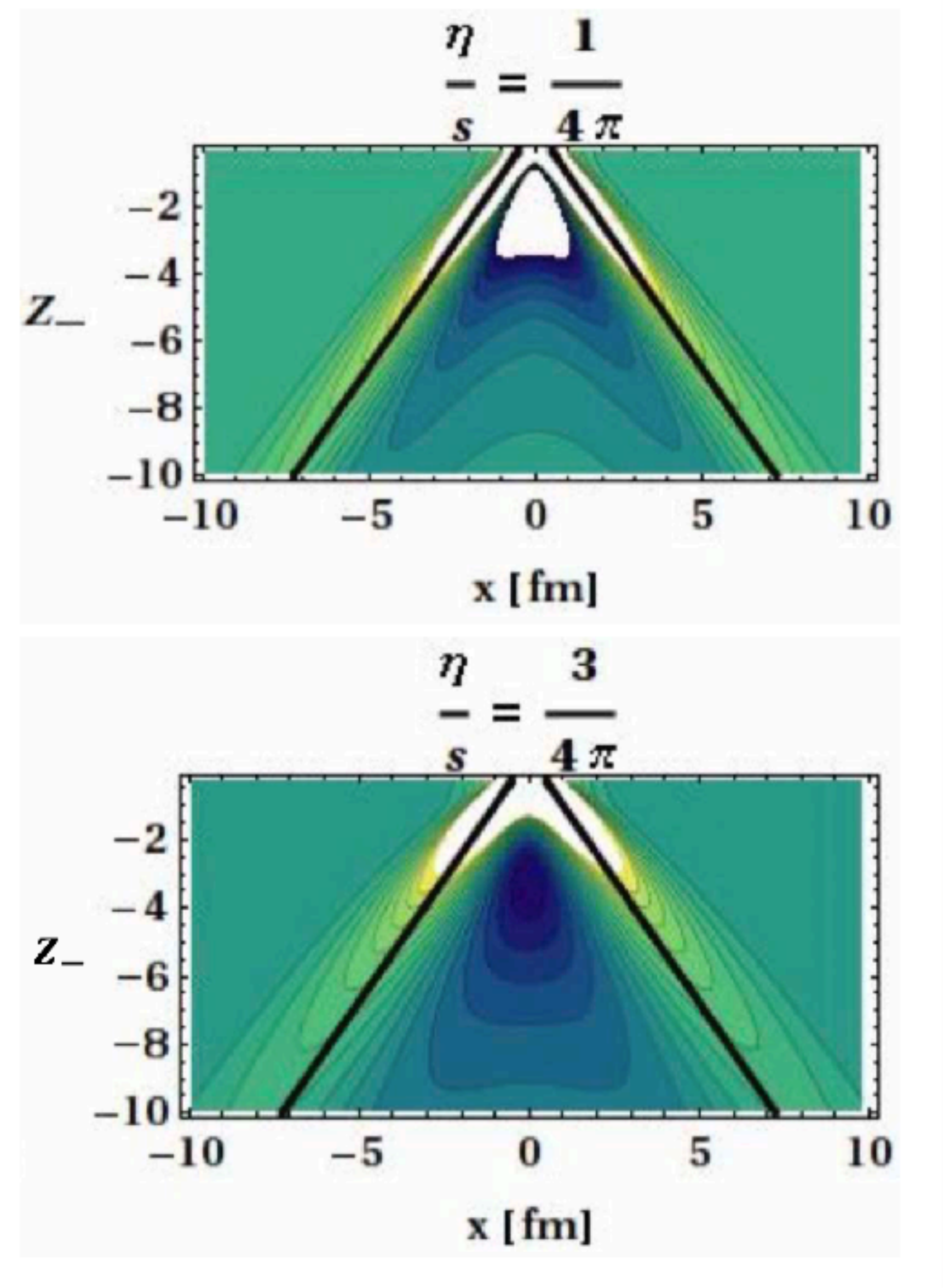
$$\delta\epsilon(\vec{k},\omega) = \frac{(i\omega - \Gamma_s k^2)J^0(\vec{k},\omega) + ikJ_L(\vec{k},\omega)}{\omega^2 - c_s^2k^2 + i\Gamma_s\omega k^2},$$

$$\vec{g}_L(\vec{k},\omega) = \frac{ic_s^2\vec{k}J^0(\vec{k},\omega) + i\omega\hat{k}J_L(\vec{k},\omega)}{\omega^2 - c_s^2k^2 + i\Gamma_s\omega k^2},$$

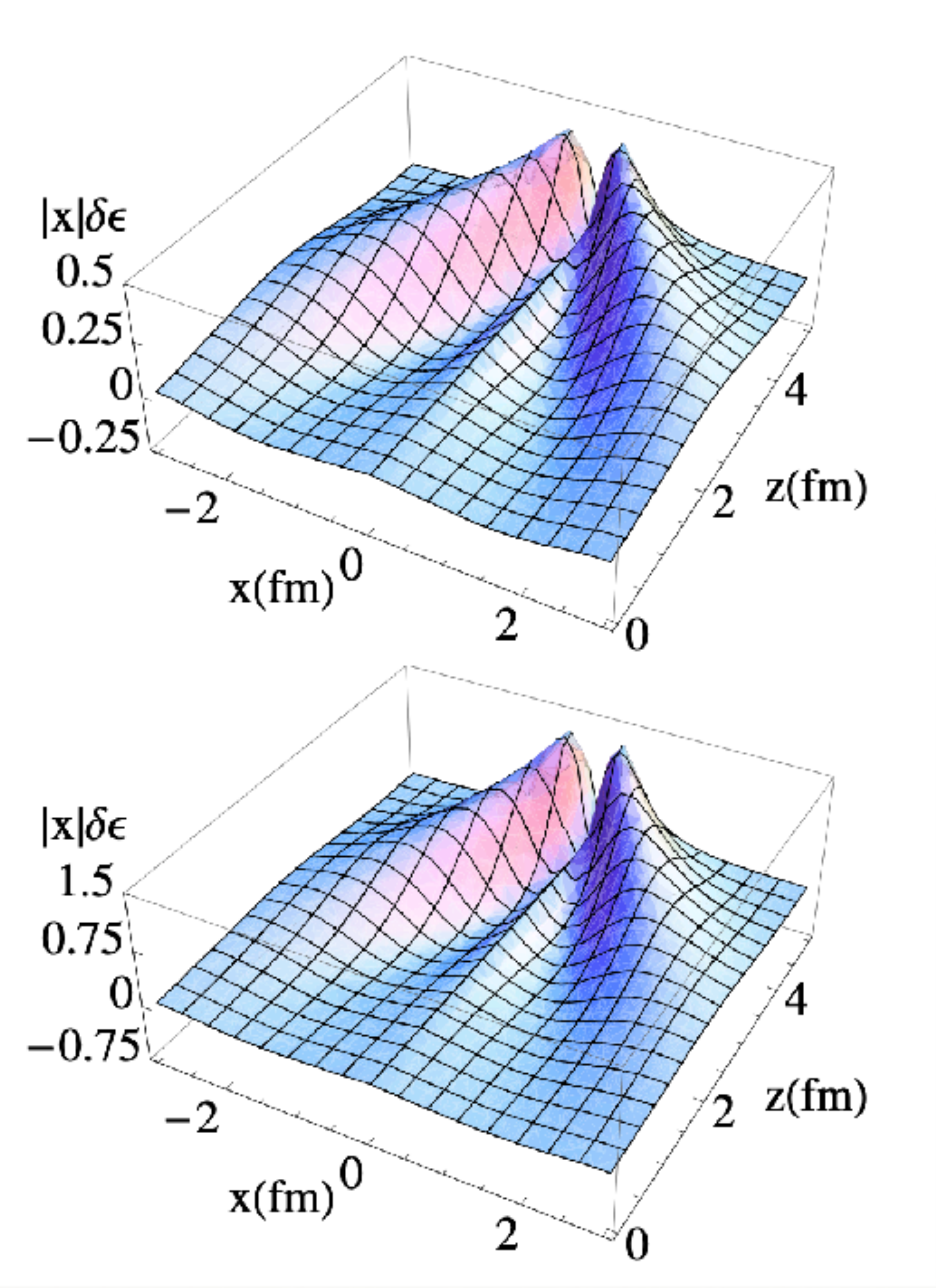
$$\vec{g}_T(\vec{k},\omega) = \frac{i\vec{J}_T(\vec{k},\omega)}{\omega + \frac{3}{4}i\Gamma_s k^2}.$$

Solution

Linear hydrodynamic response



Neufeld, PRC 79 (2009) 054909



Qin, Majumder, Song, Heinz, PRL 103 (2009) 152303

Viscosity dependence of the Mach cone structure

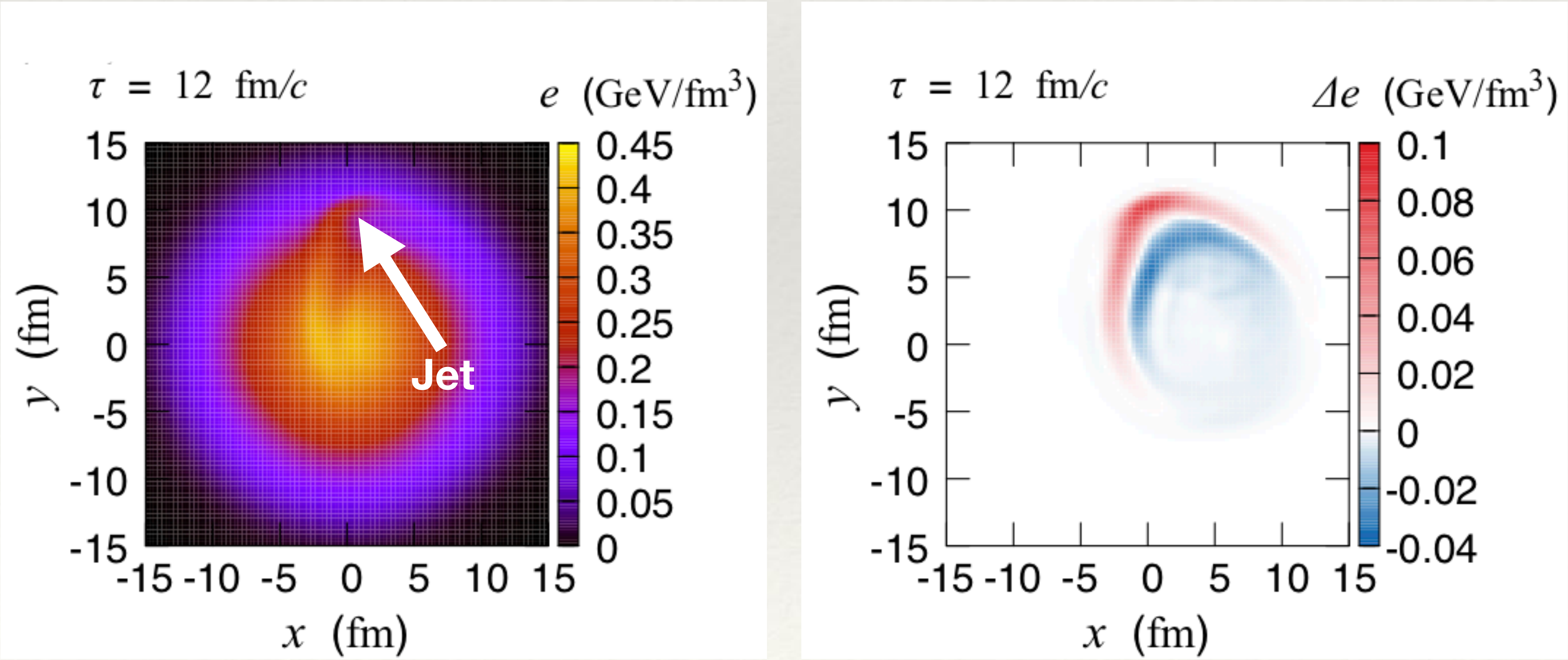
Energy deposition from single quark vs. quark jet shower

Full hydrodynamic response

When energy deposition is comparable to the unperturbed medium density

Directly solve $\partial_\mu T^{\mu\nu} = J^\nu$

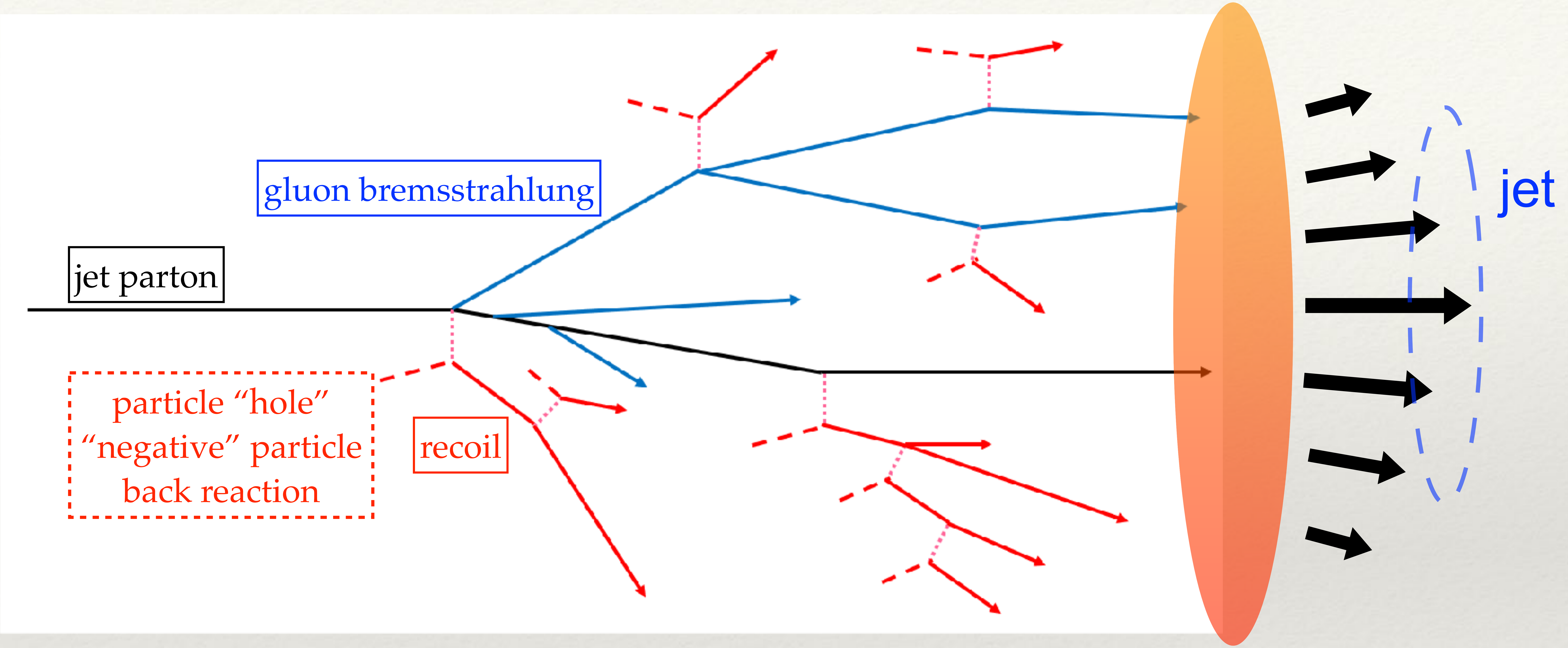
- (1+1)-D hydro Floerchinger, Zapp, EPJC 74 (2014) 12
- (2+1)-D hydro Chaudhuri, Heinz, PRL 97 (2006) 062301
- (3+1)-D hydro Noronha, Torrieri, Gyulassy, Rischke, PRL 105 (2010) 222301; Tachibana, Hirano, PRC 90 (2014) 2, 021902



- Need background subtraction
- Distortion of Mach cone by the QGP flow

Tachibana, Chang, Qin,
PRC 95 (1017) 4, 044909

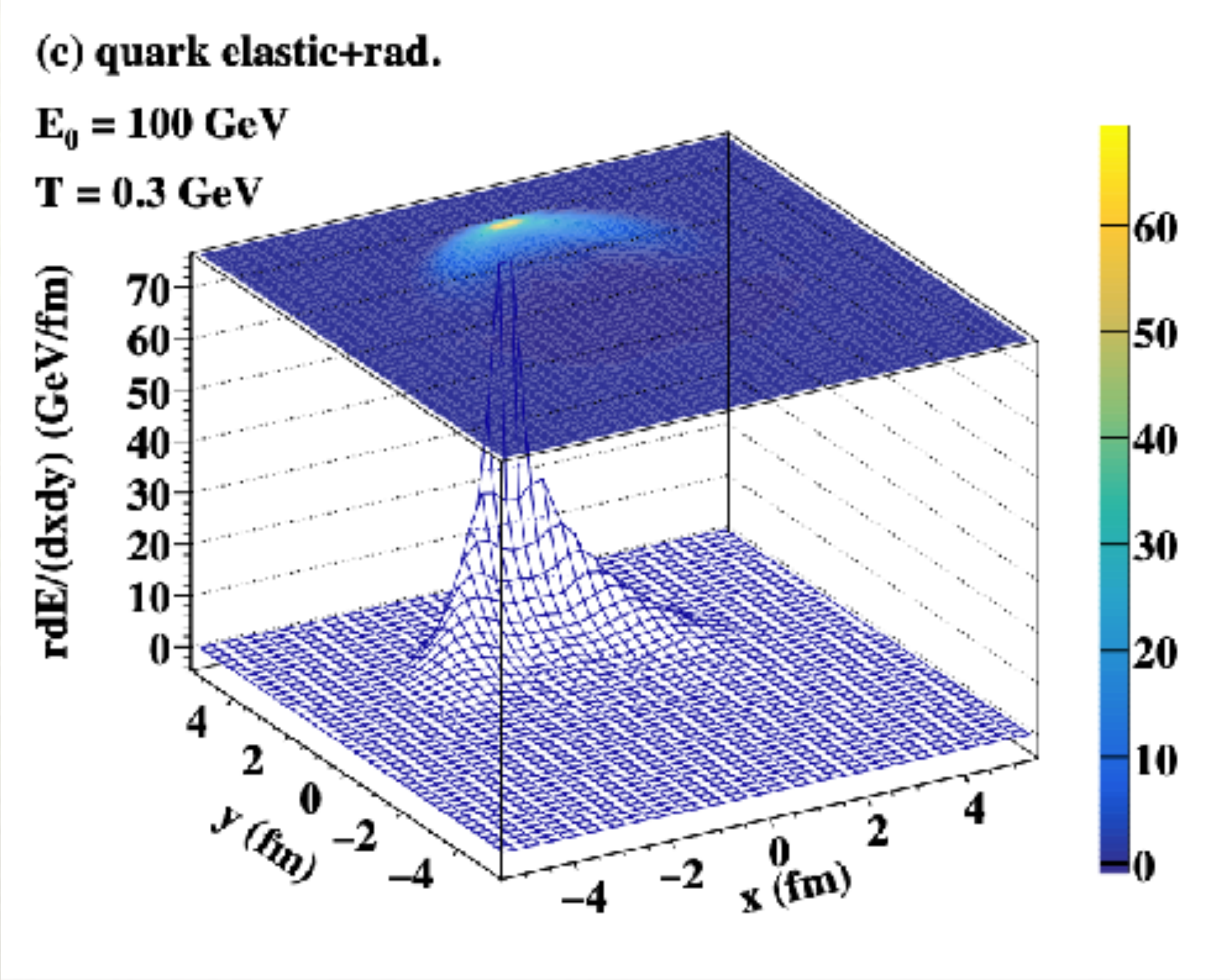
Perturbative approximation of medium response



Describe jet partons, radiated gluons, recoil partons and “negative” partons within the same perturbative transport framework, e.g. linear Boltzmann transport (LBT)

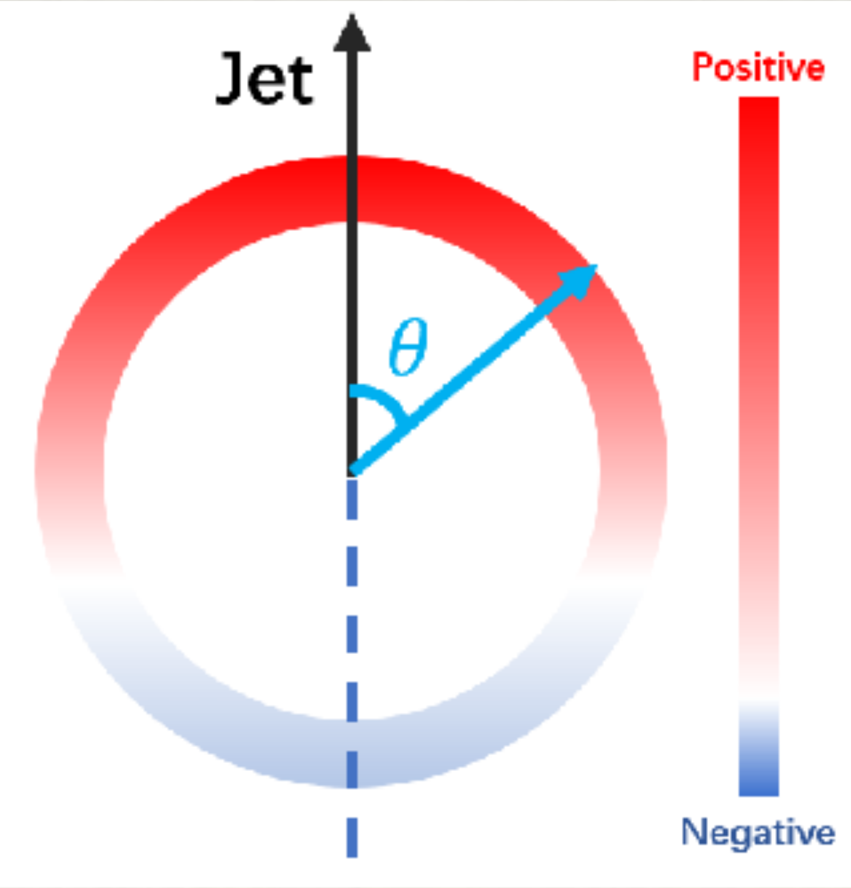
$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\text{el}} + \mathscr{C}_a^{\text{inel}})$$

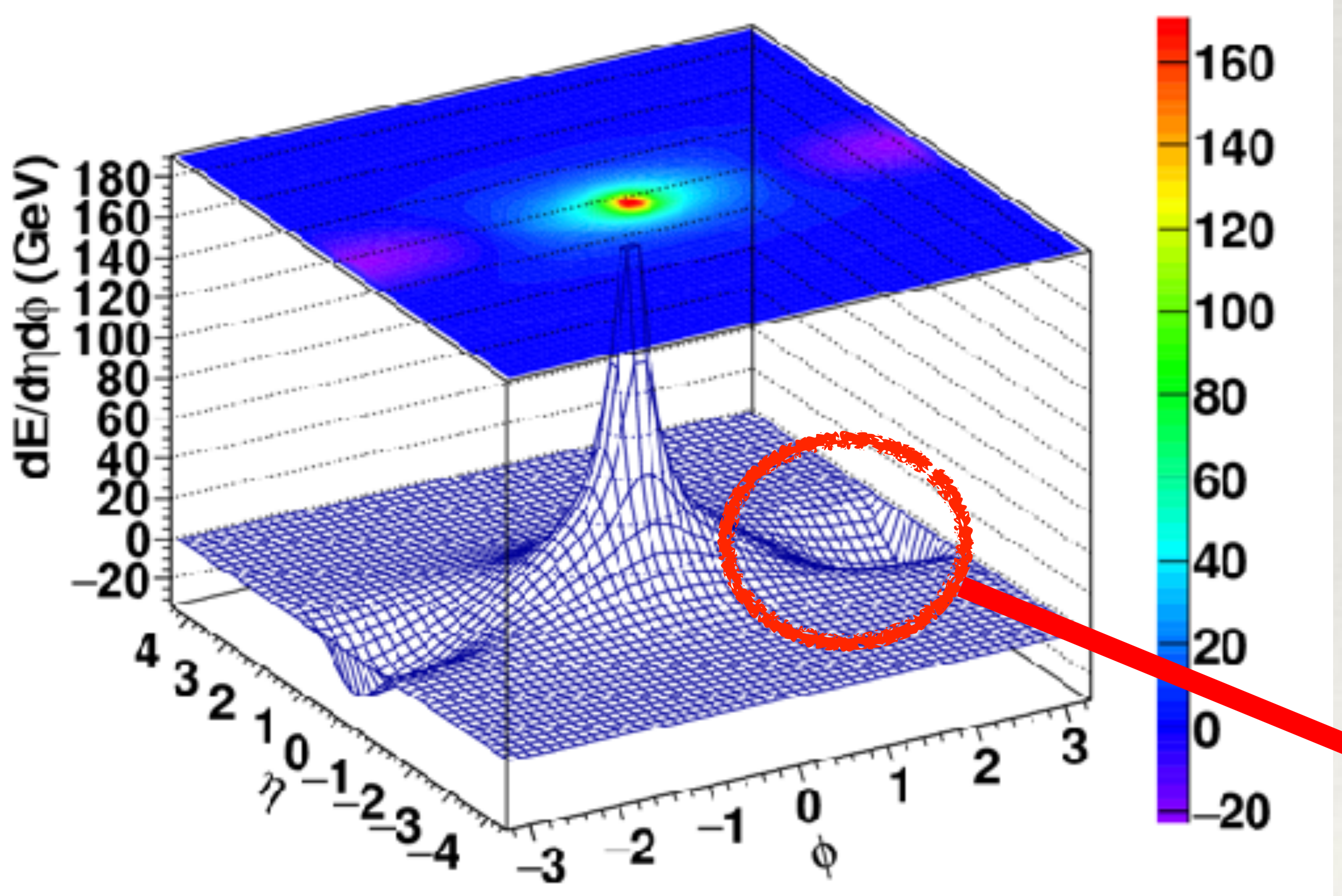
Perturbative approximation of medium response



- Energy (observable) distribution: positive - negative contribution
- Cone structure at t = 4 fm

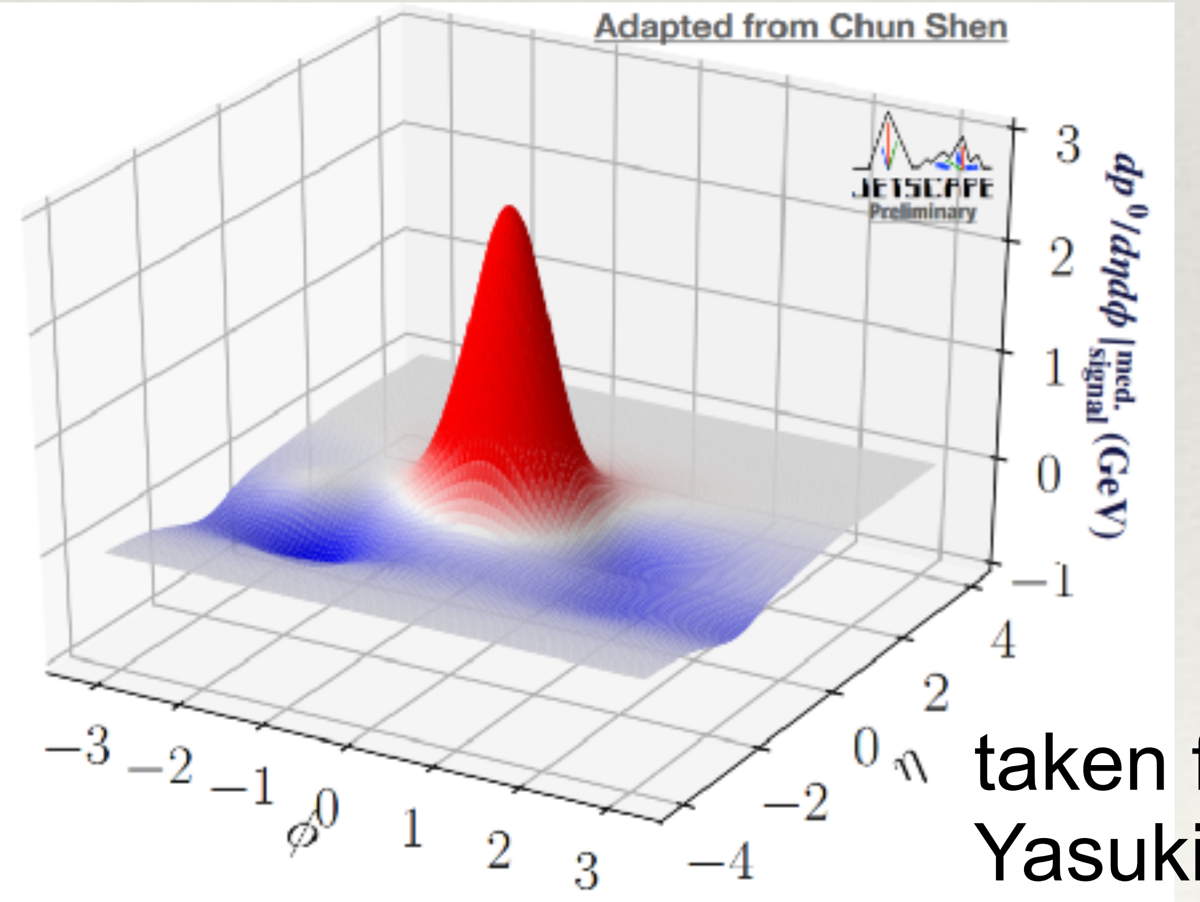
LBT simulation by Tan Luo





Reasonable approximation

diffusion wake (尾流)



taken from Yasuki Tachibana

LBT with recoil approximation

JETSCAPE, put recoil into hydro evolution

State-of-the-art concurrent simulation of jet+hydro

QGP medium

Hydrodynamics

Going beyond the linear approximation

energetic partons

LBT

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

local medium information

$\epsilon, T, \mathbf{u}\ \ldots$

$$\frac{1}{p \cdot u} p^\mu \partial_\mu f = \mathscr{C}$$

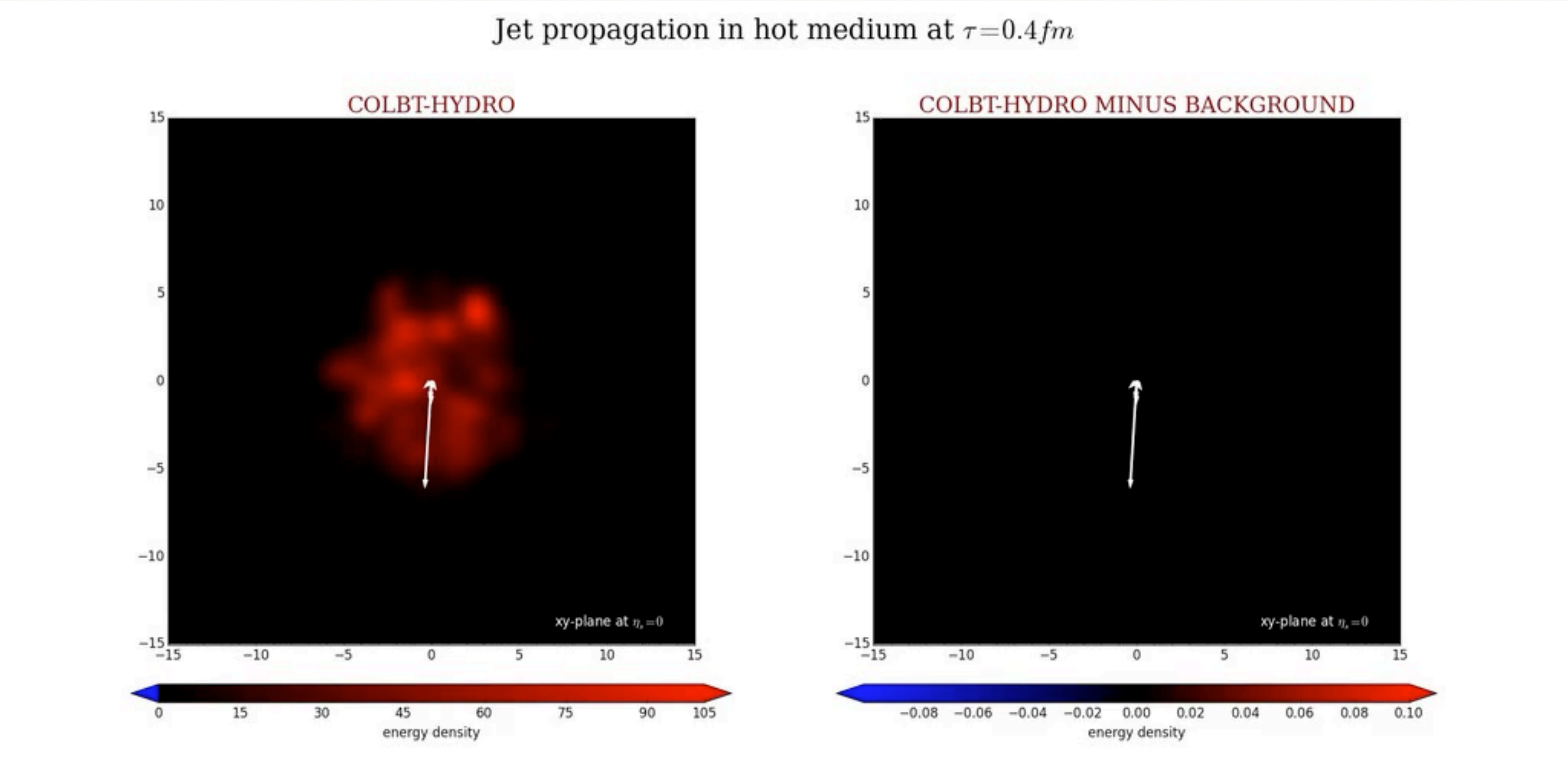
source term

jet and recoil partons with ***E* < *E*$_{\mathbf{cut}}$** (comoving frame) [positive] + back reaction [negative]

CoLBT-hydro

$$j^\nu = \sum_{i=1}^{n} \frac{dp_i^\nu}{d\tau} \delta^3(\mathbf{x} - \mathbf{x_i})$$

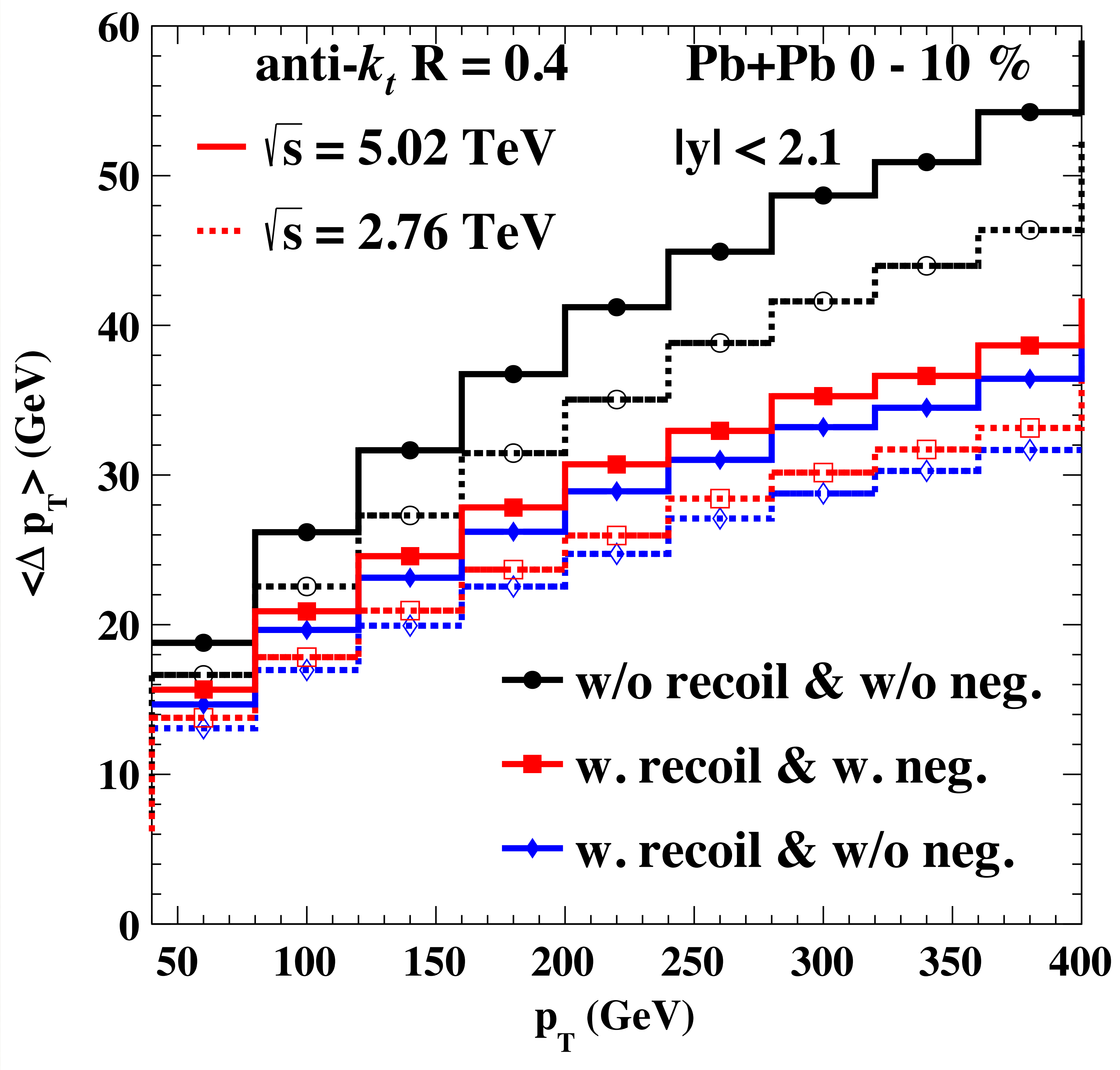
Concurrent simulation of jet and medium (CoLBT-hydro)



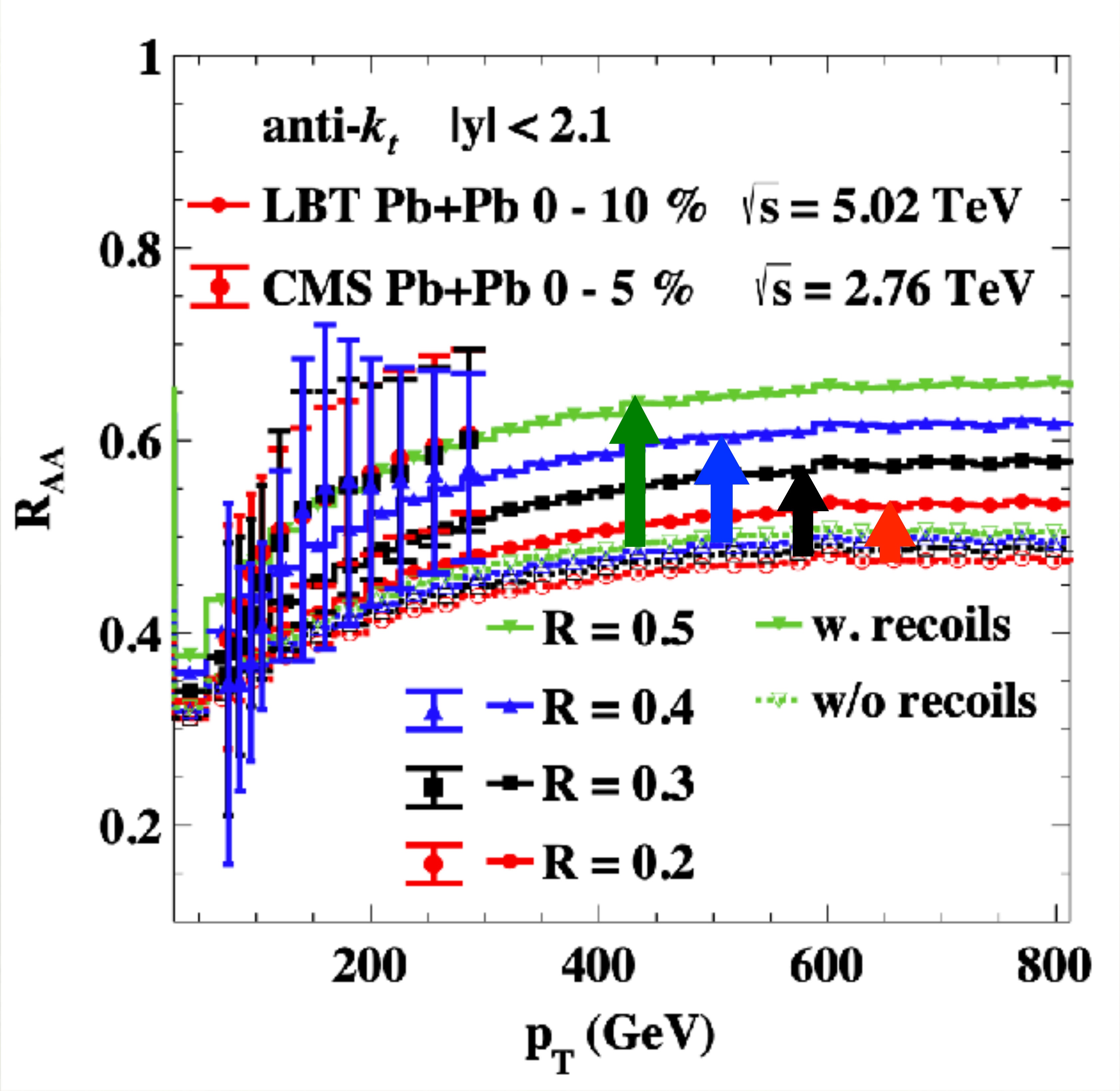
Effects on experimental observables

Jet R_{AA}

Energy loss

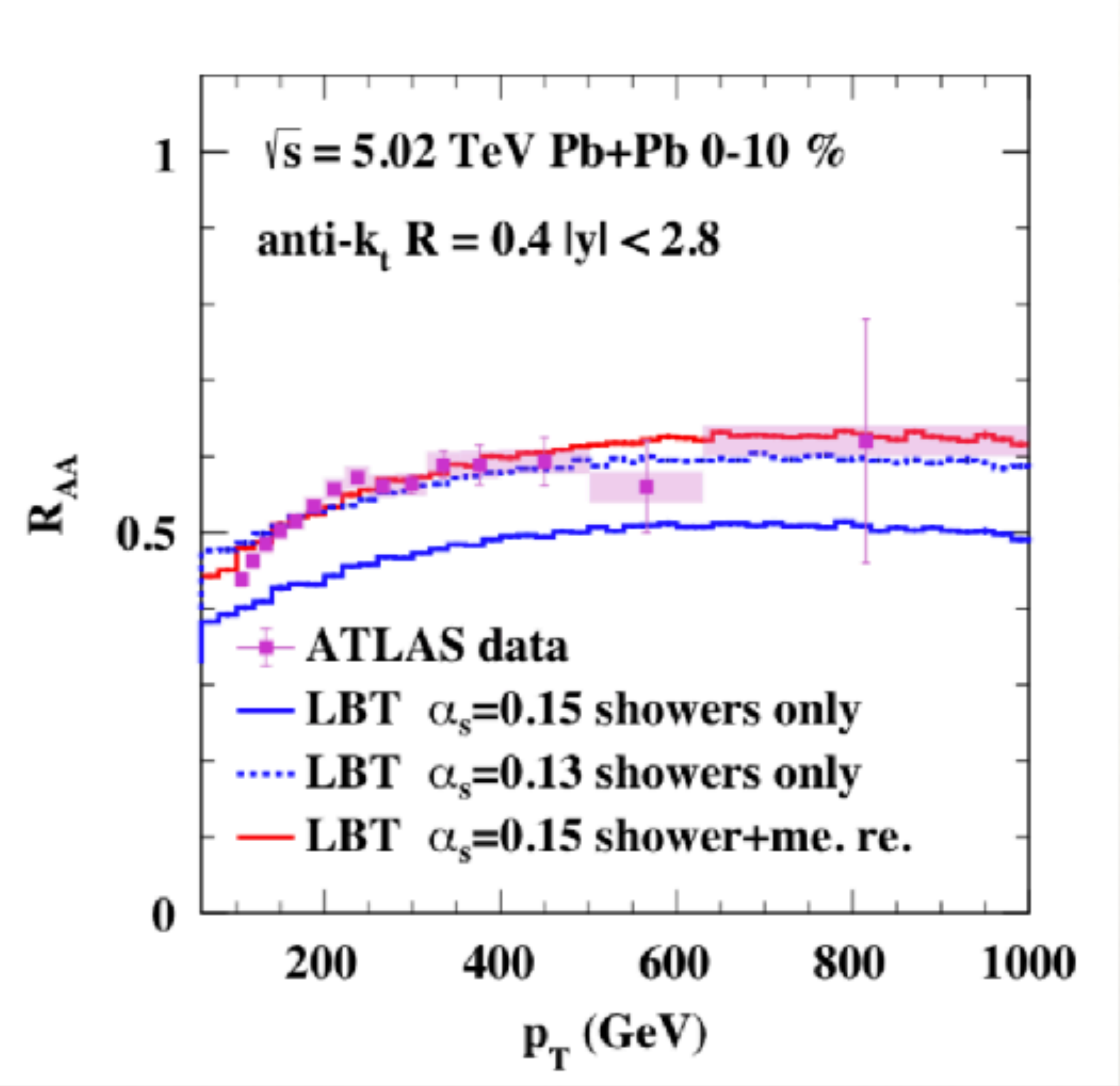


R_{AA}

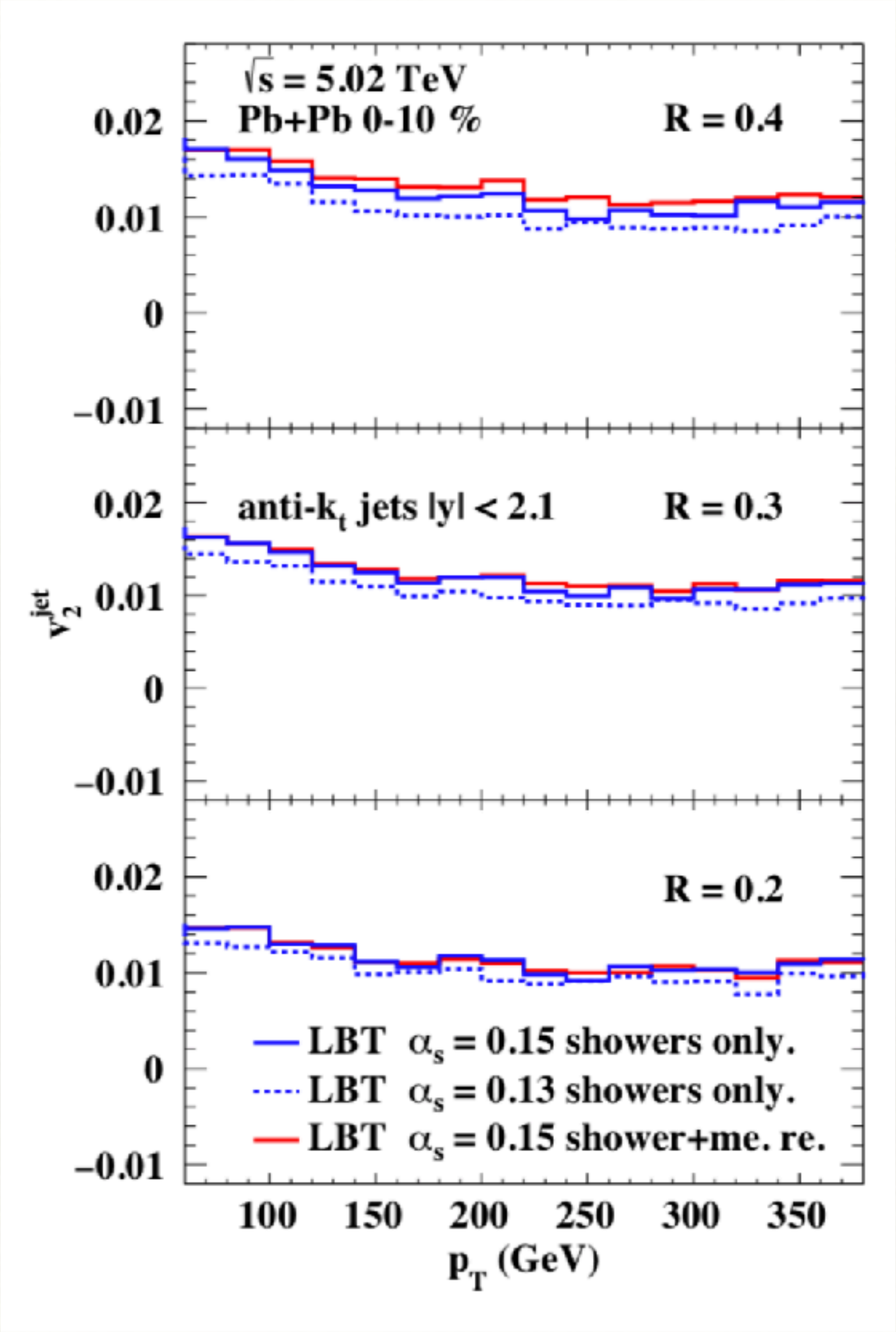


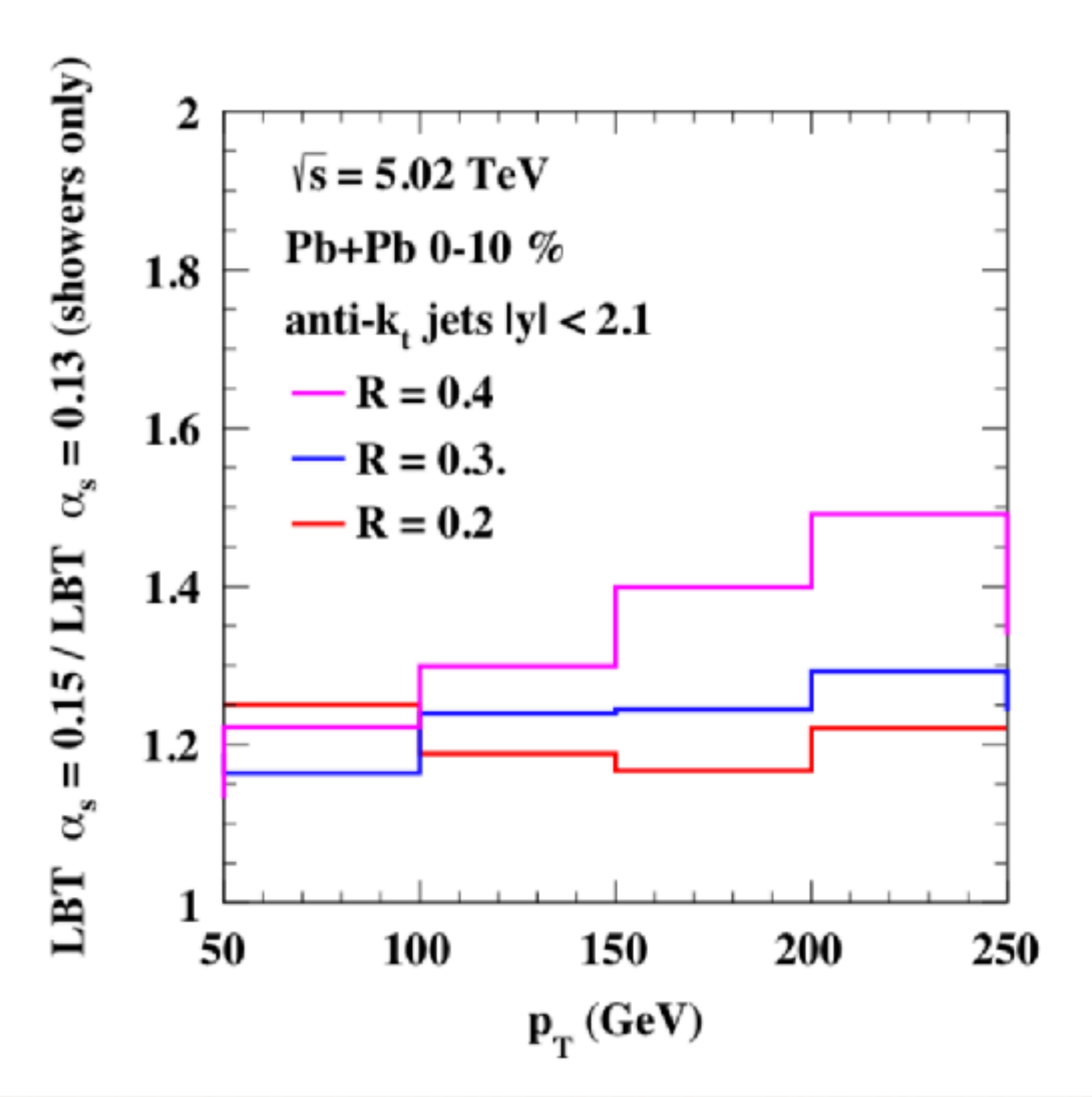
He, Cao, Chen, Luo, Pang, Wang, PRC 99 (2019) 5, 054911

Jet v_2



Re-adjust α_s to fit R_{AA} with and without medium response



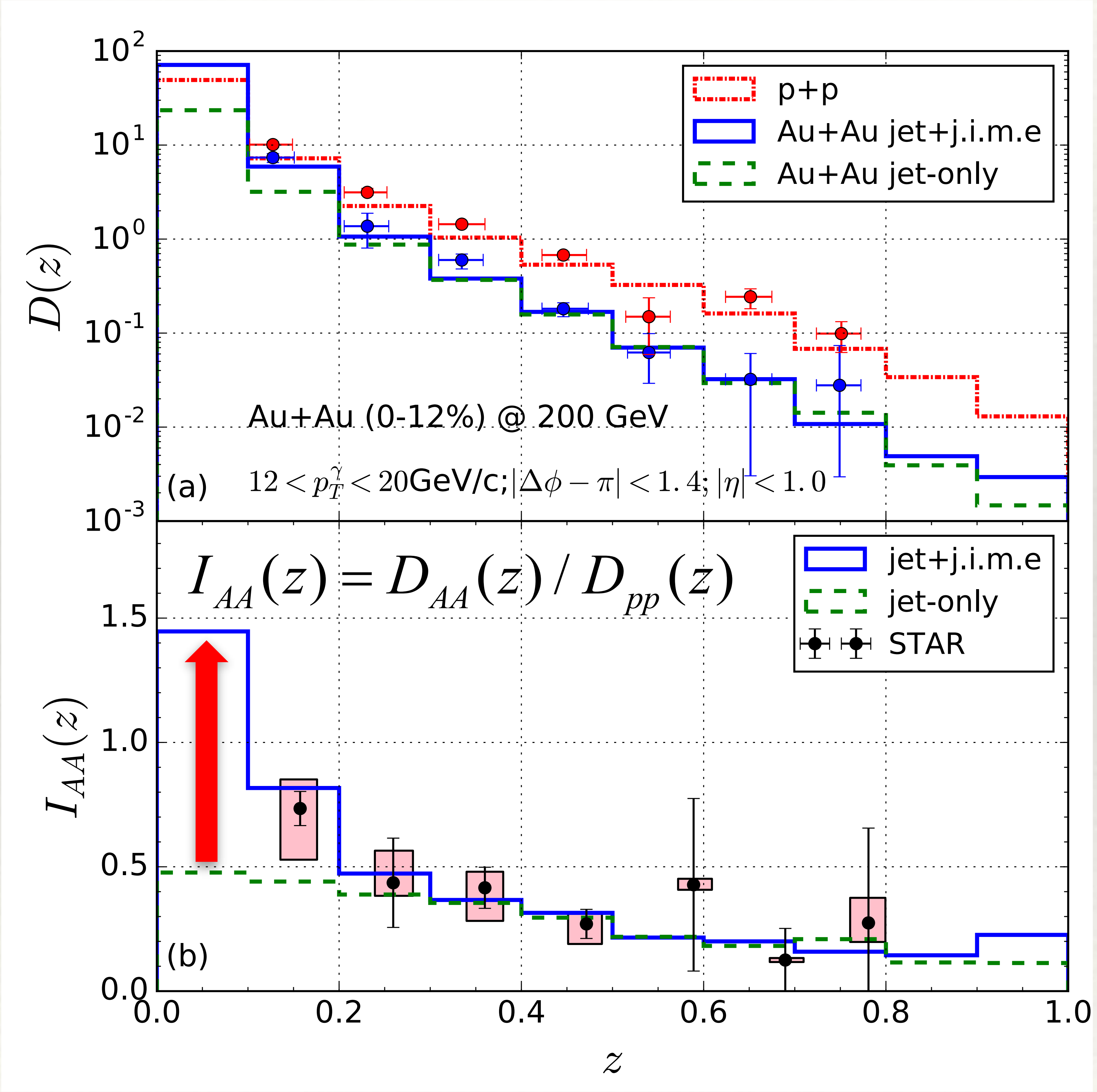


Path-length vs. flow effects

LBT calculation from Yayun He

Medium modification of γ-triggered hadron yield

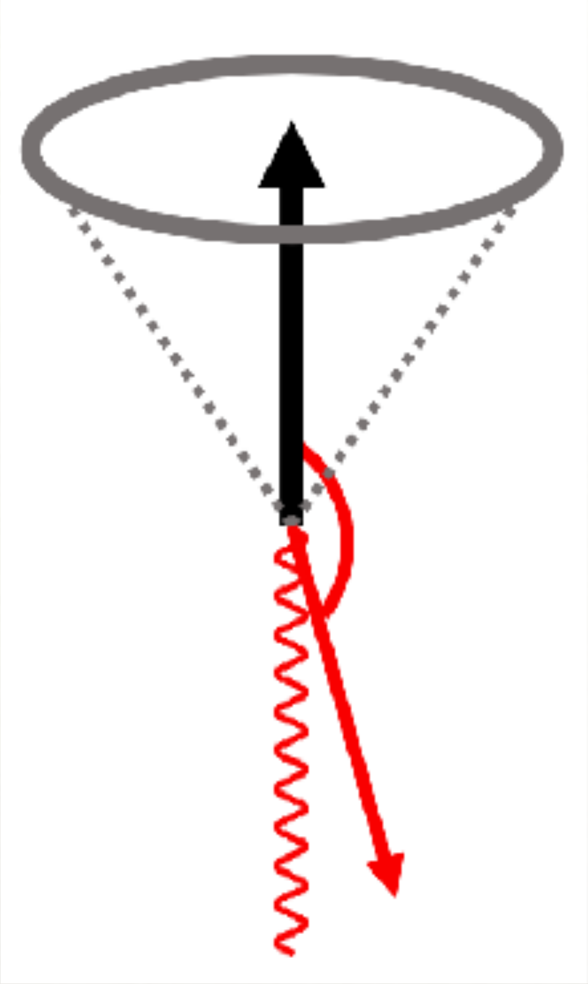
CoLBT-hydro: $$D(z) = \frac{dN_h}{dydz}\Big|_{LBT} + \frac{dN_h}{dydz}\Big|^{w/\,jet}_{hydro} - \frac{dN_h}{dydz}\Big|^{w.o/\,jet}_{hydro} \qquad z = p_T^h / p_T^\gamma$$



Suppression of leading hadrons at intermediate and large z

LBT:

hard parton energy loss



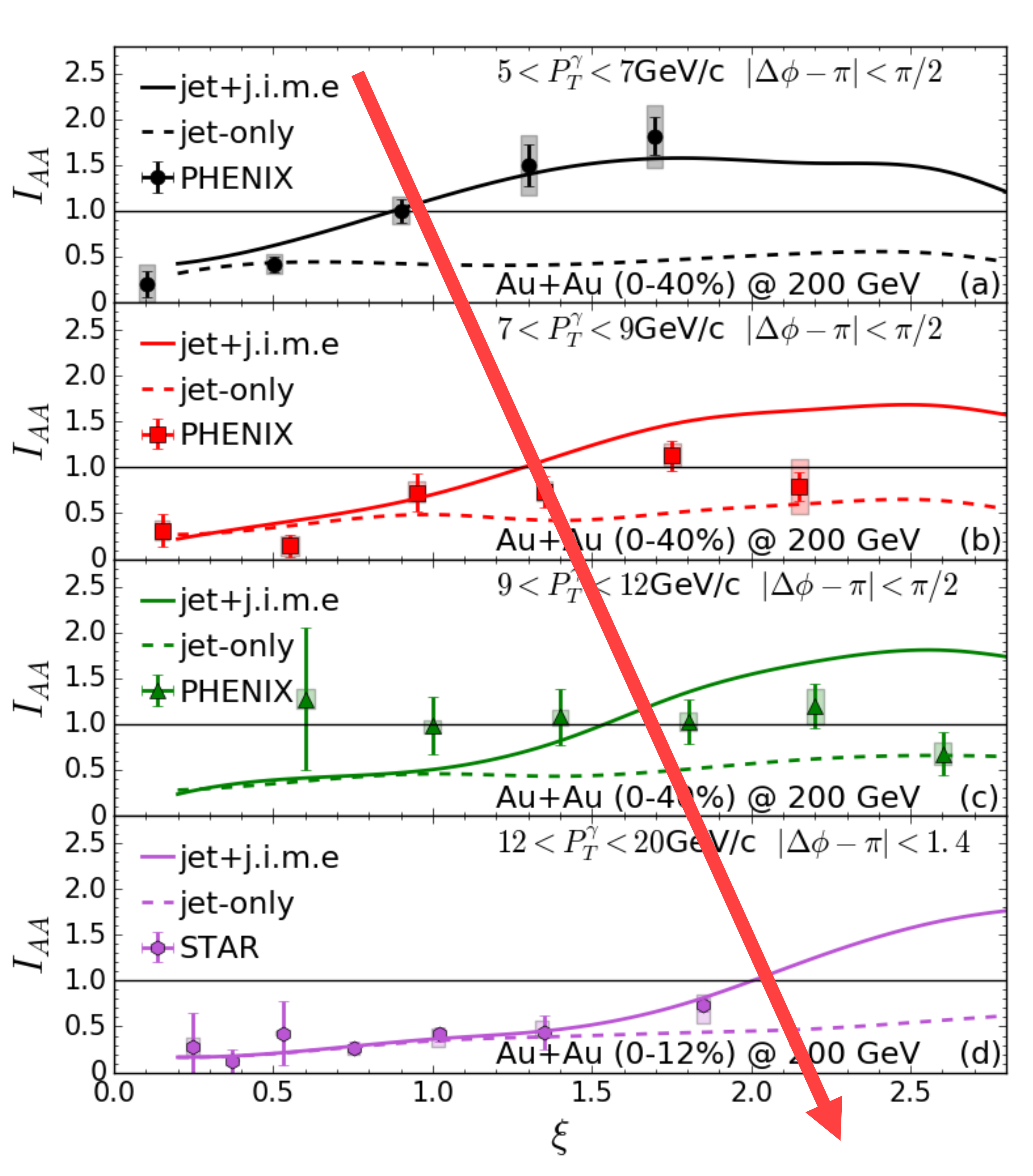
Enhancement of soft hadrons at small z

Hydro:

jet-induced medium excitation (j.i.m.e.)

Chen, Cao, Luo, Pang, Wang, PLB 777 (2018) 86

Medium modification of γ-triggered hadron yield



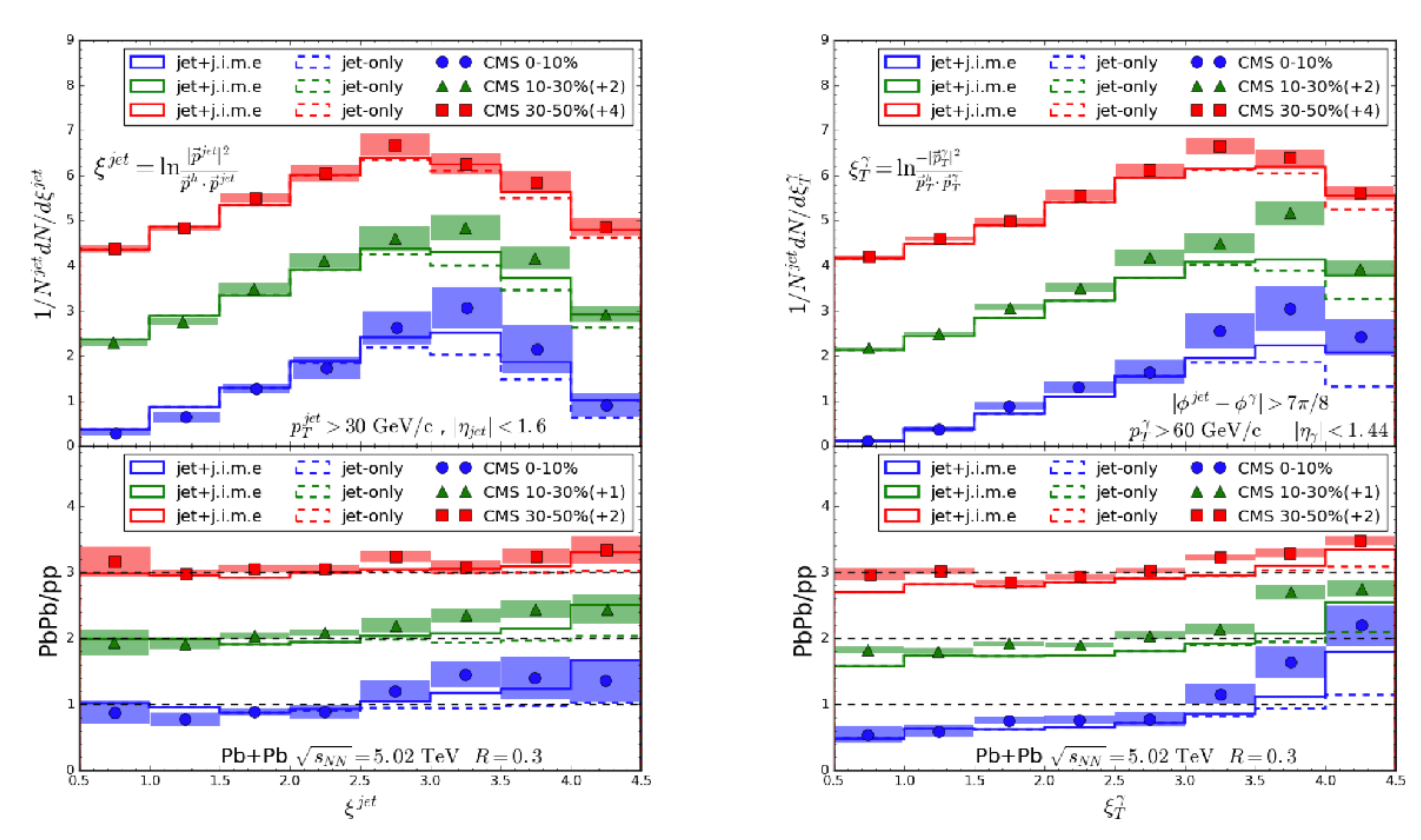
Change of variable: $z = p_T^h \,/\, p_T^\gamma \longrightarrow \xi = \log \frac{1}{z}$

Suppression of hadrons at small ξ (large z), enhancement at large ξ (small z)

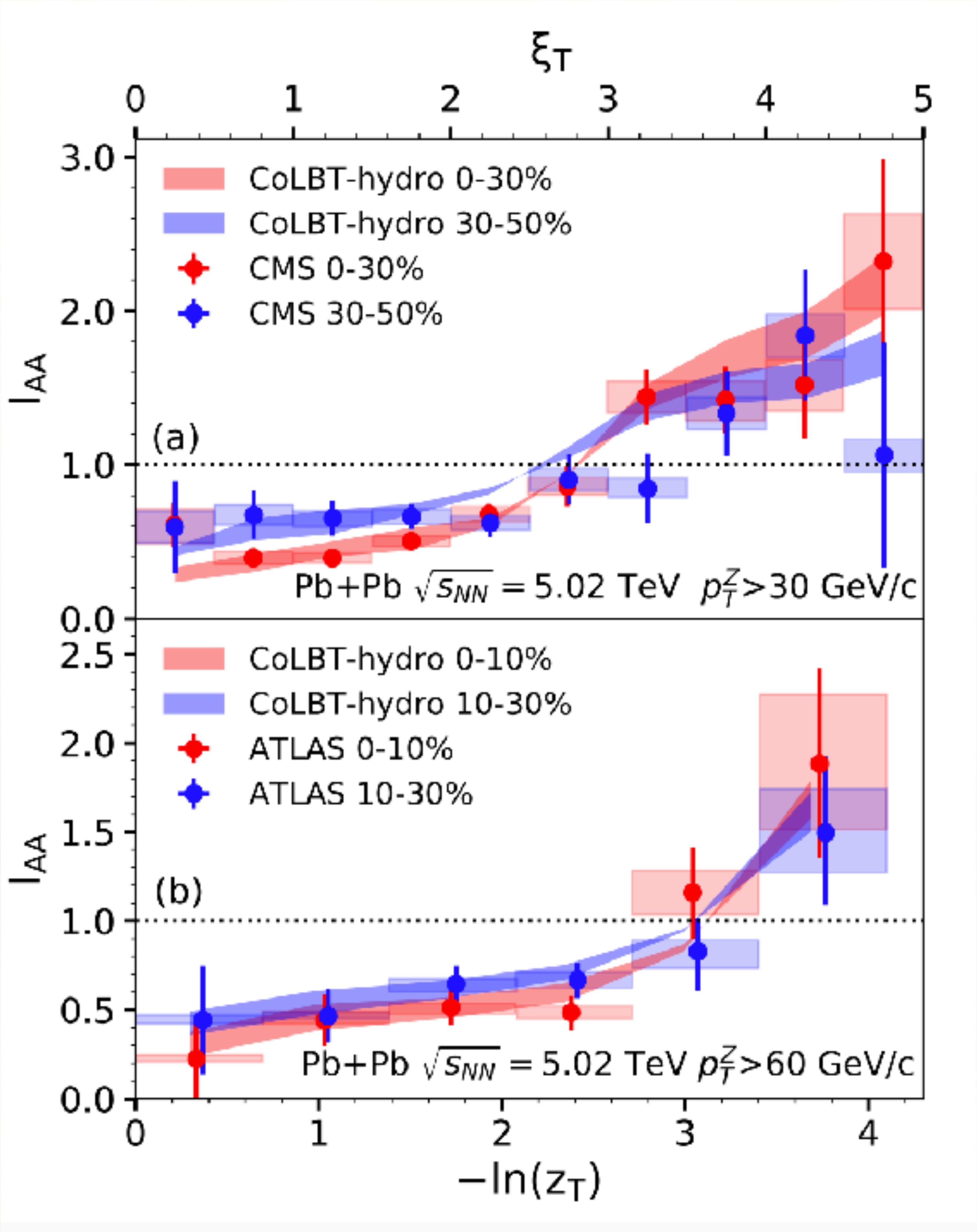
With increasing photon (γ) p_T

- Transition point from suppression to enhancement shifts to larger ξ
- Transition point corresponds to a fixed p_T range of soft hadrons (~ 2GeV)
- Unique feature of j.i.m.e. — thermal property of the medium, independent of the jet energy

γ-jet fragmentation function and Z-triggered hadron yield

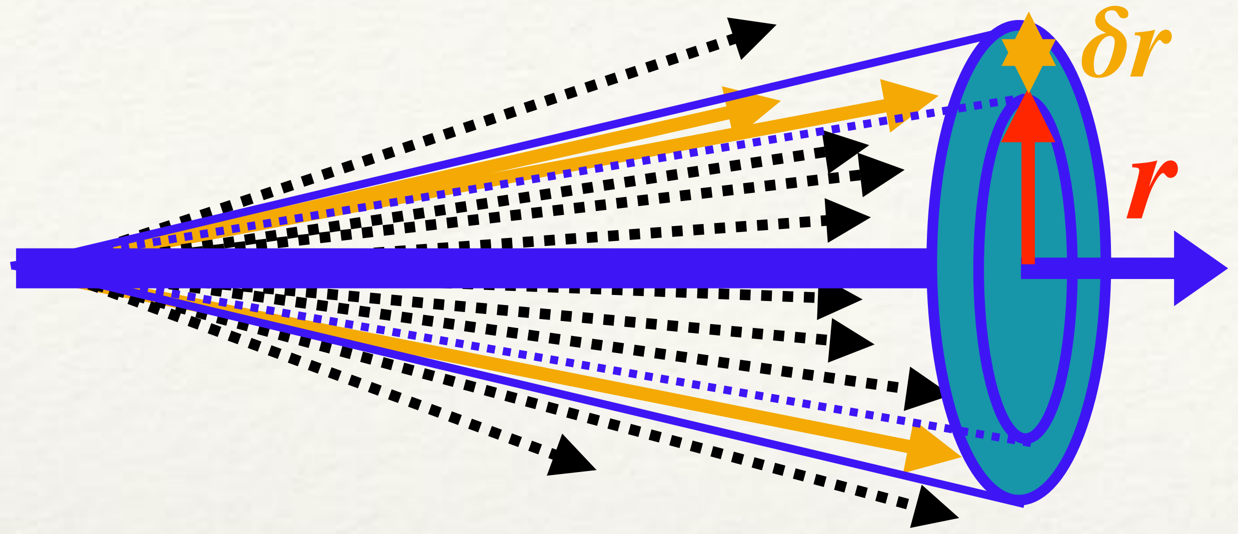


Chen, Cao, Luo, Pang, Wang, PLB 810 (2020) 135783

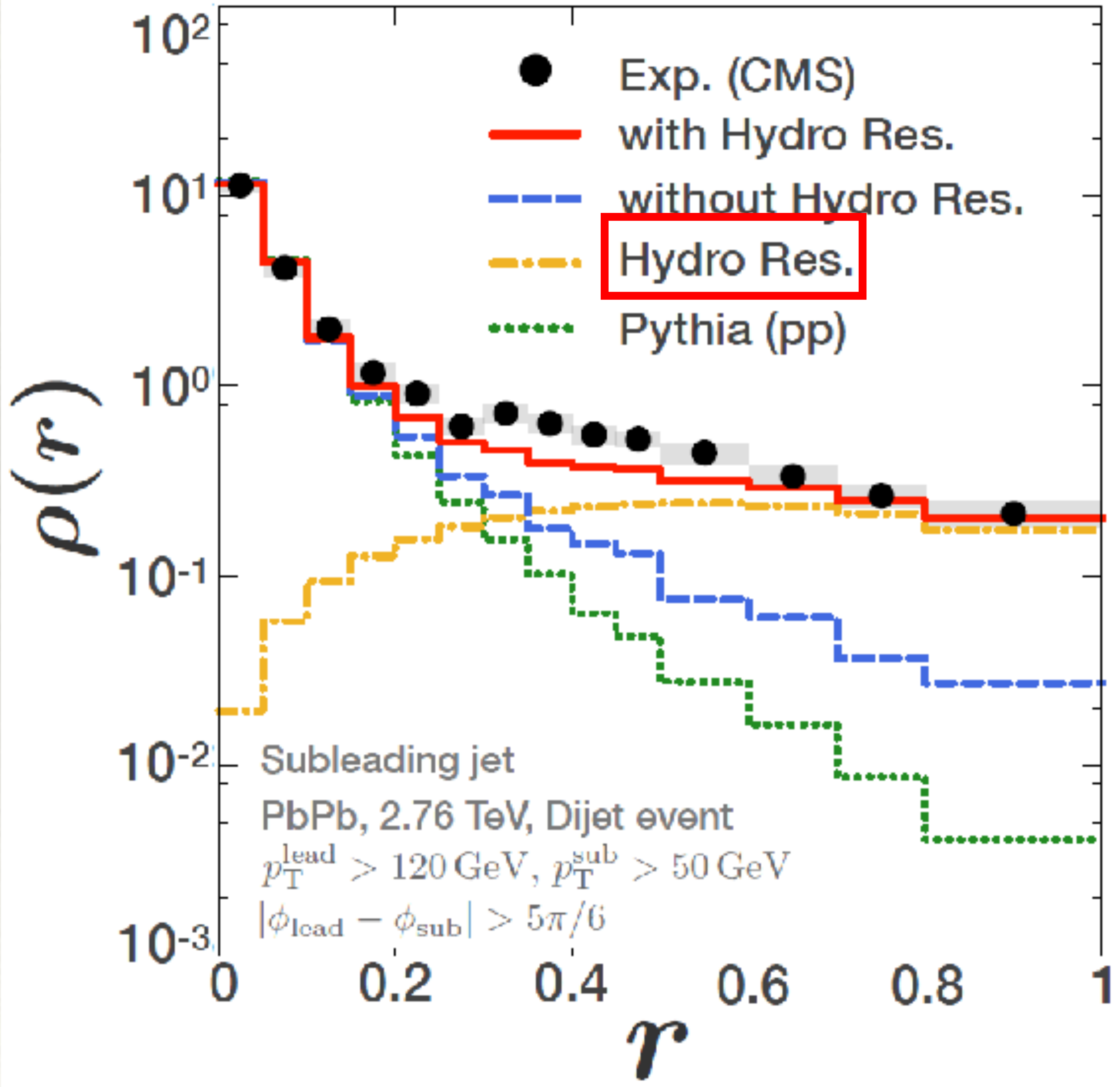


Chen, Yang, He, Ke, Pang, Wang, arXiv:2010.05422

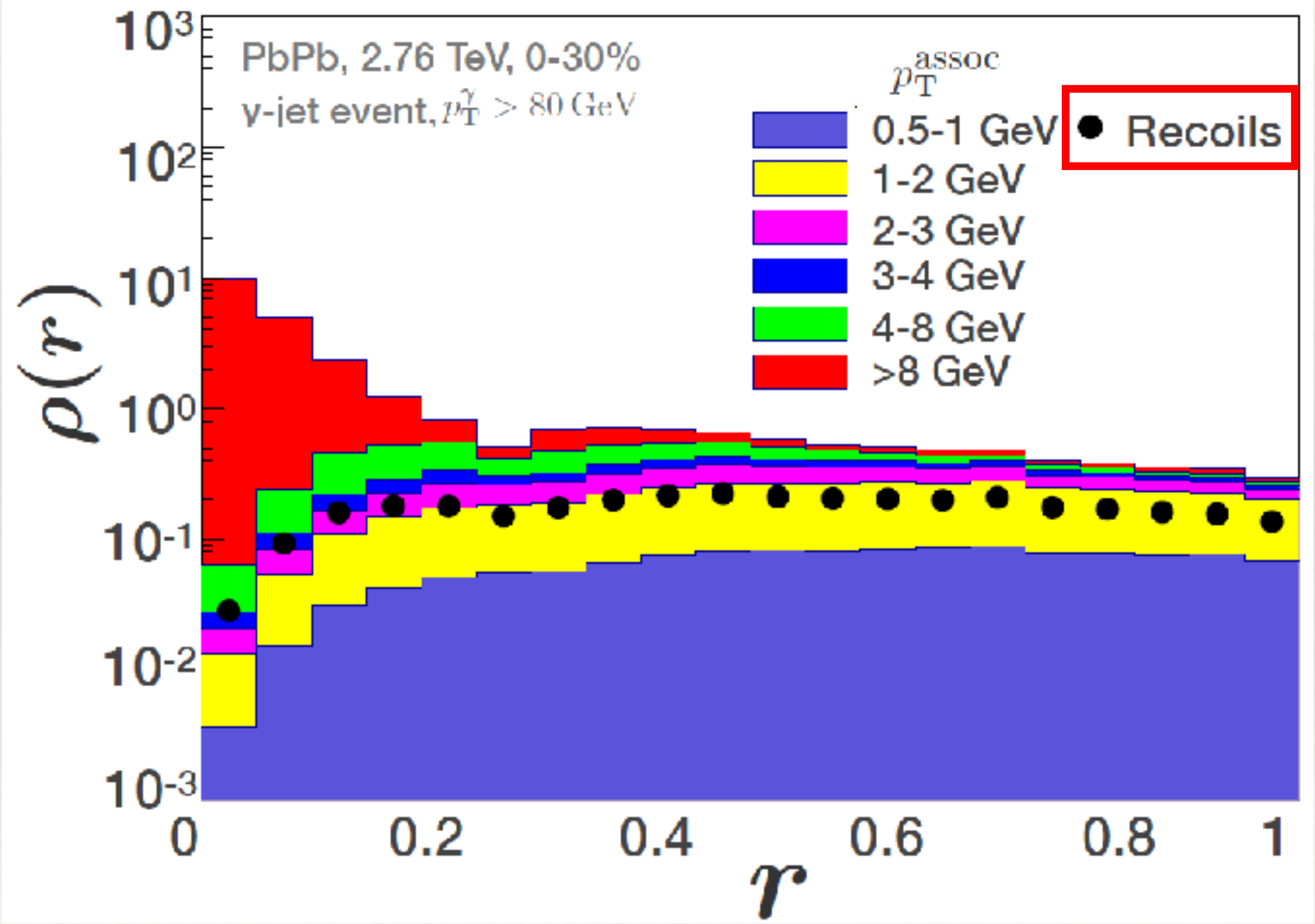
Jet shape



$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{i\in(r-\delta r/2,\, r+\delta r/2)} p_T^i}{\sum_{i\in(0,R)} p_T^i} \qquad \left(r = \sqrt{(\eta_p - \eta^{\mathrm{jet}})^2 + (\phi_p - \phi^{\mathrm{jet}})^2} \right)$$

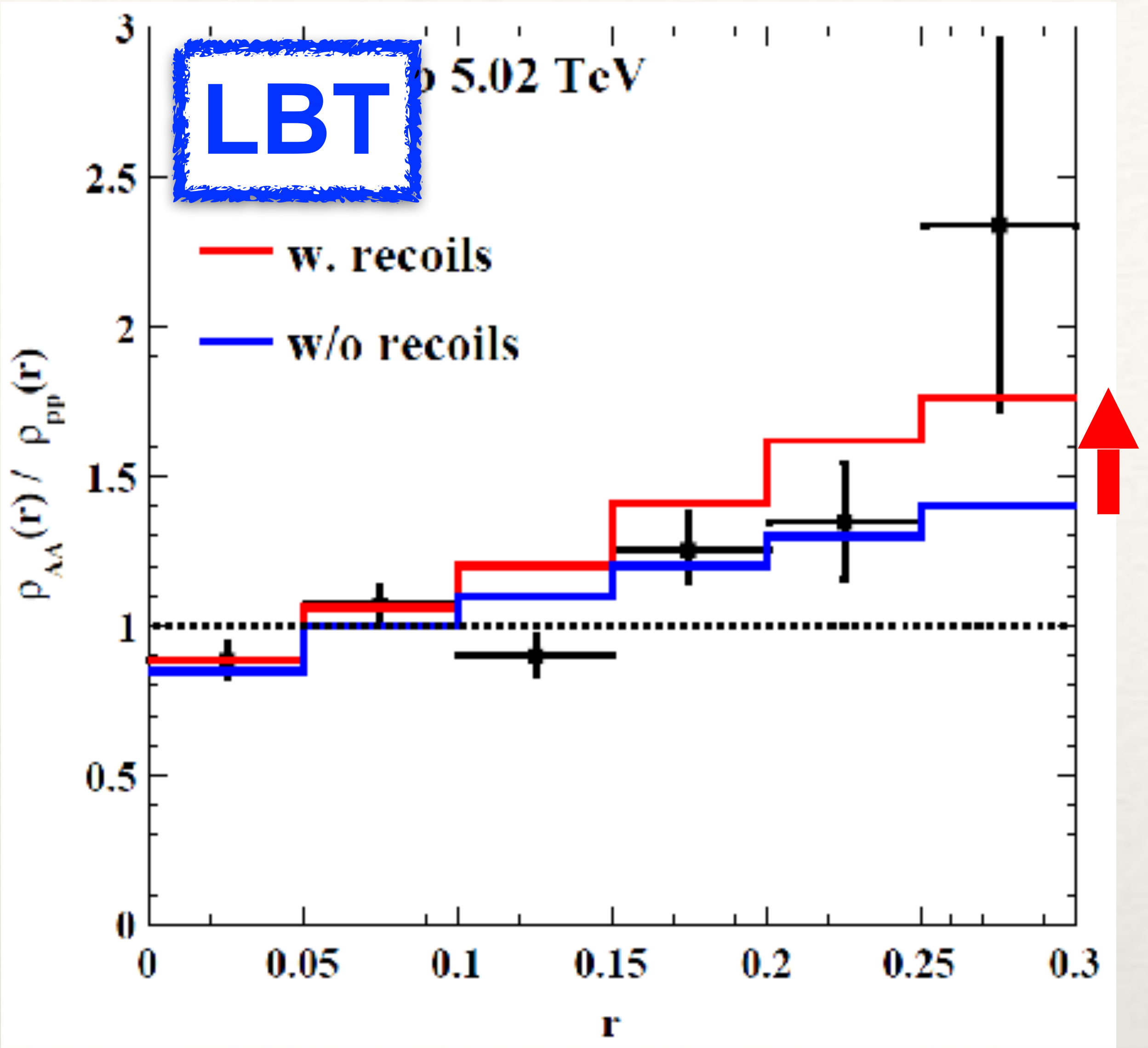


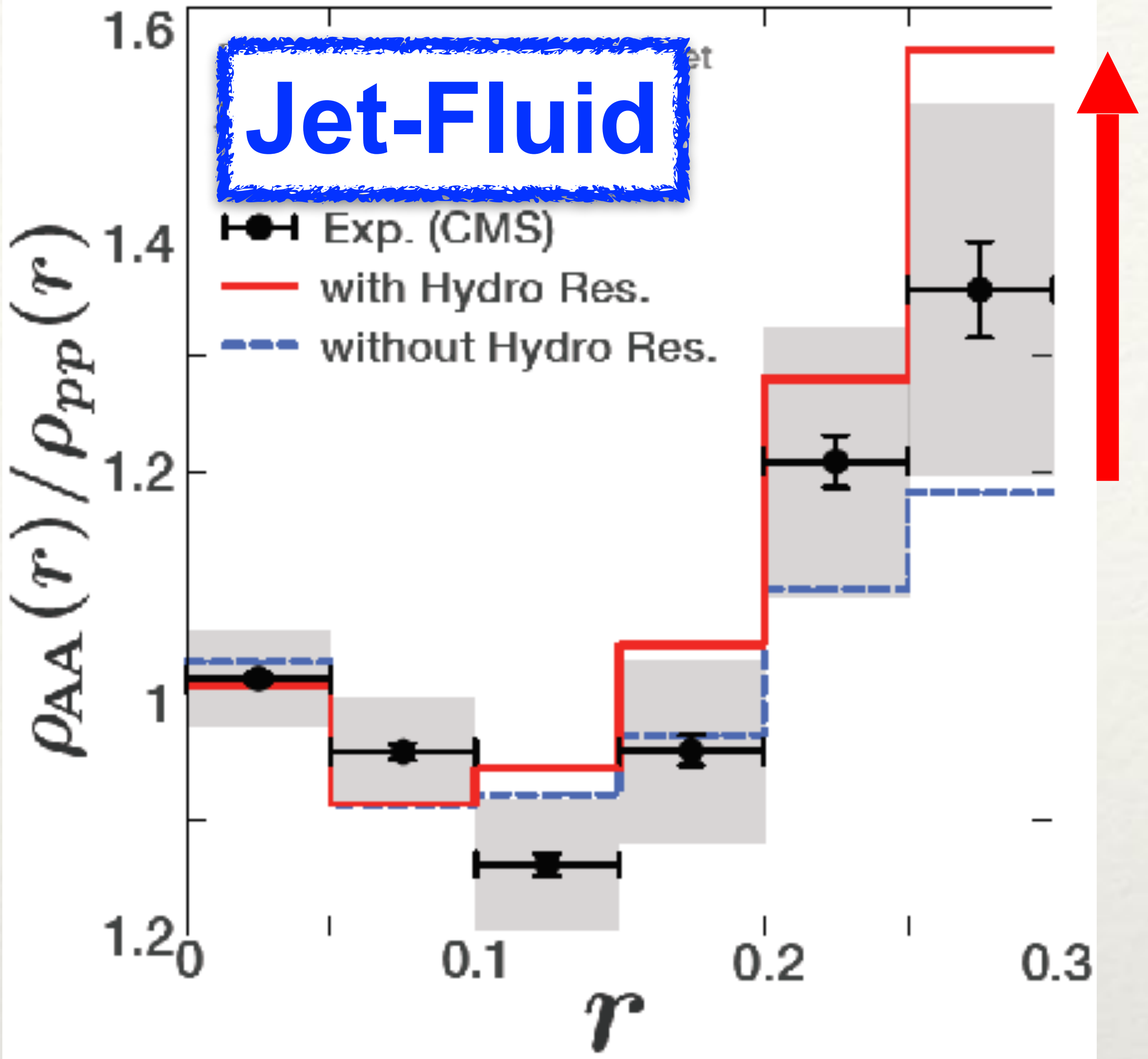
Tachibana, Chang, Qin, PRC 95 (2017) 4, 044909

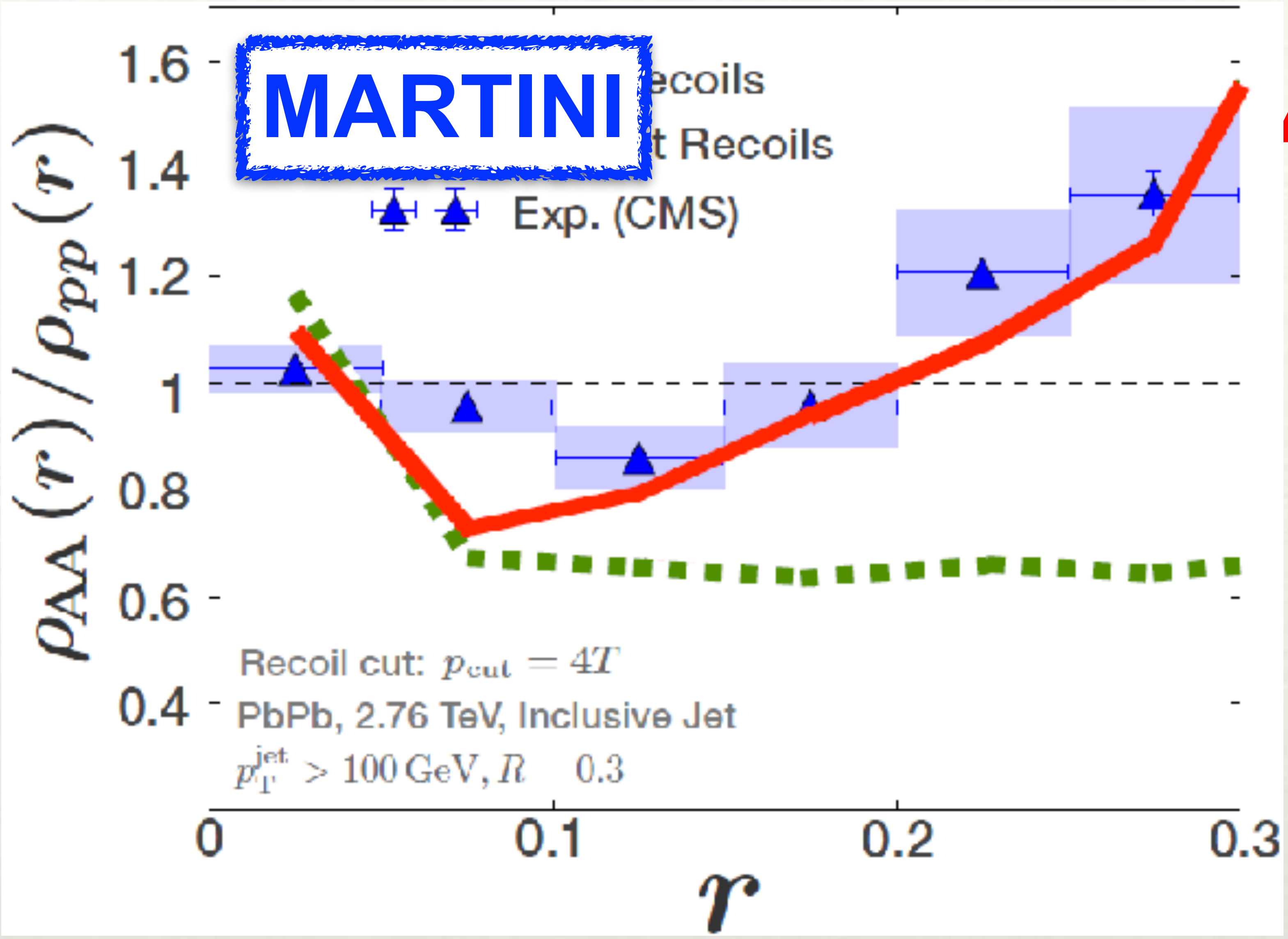


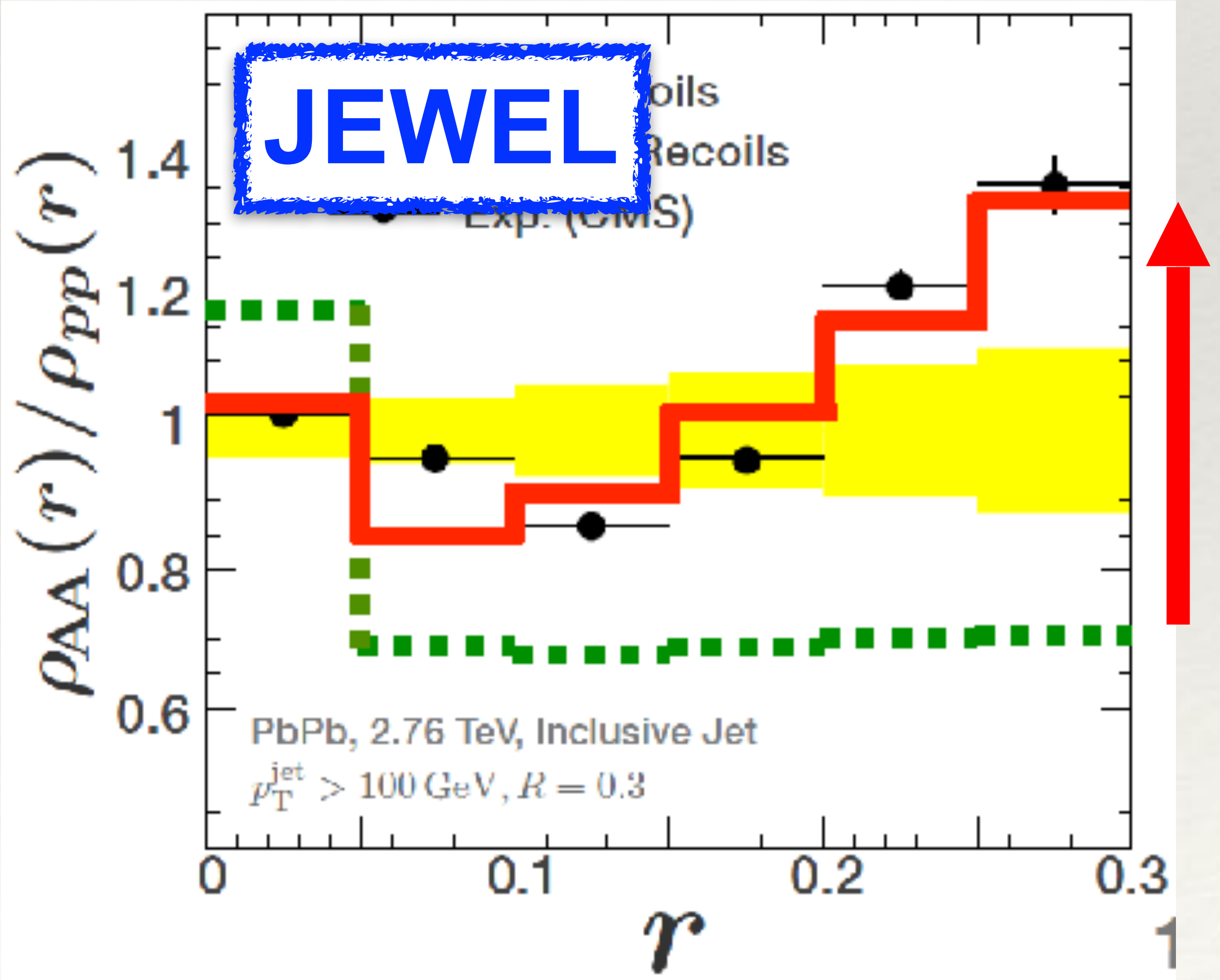
Luo, Cao, He, Wang, PLB 782 (2018) 707

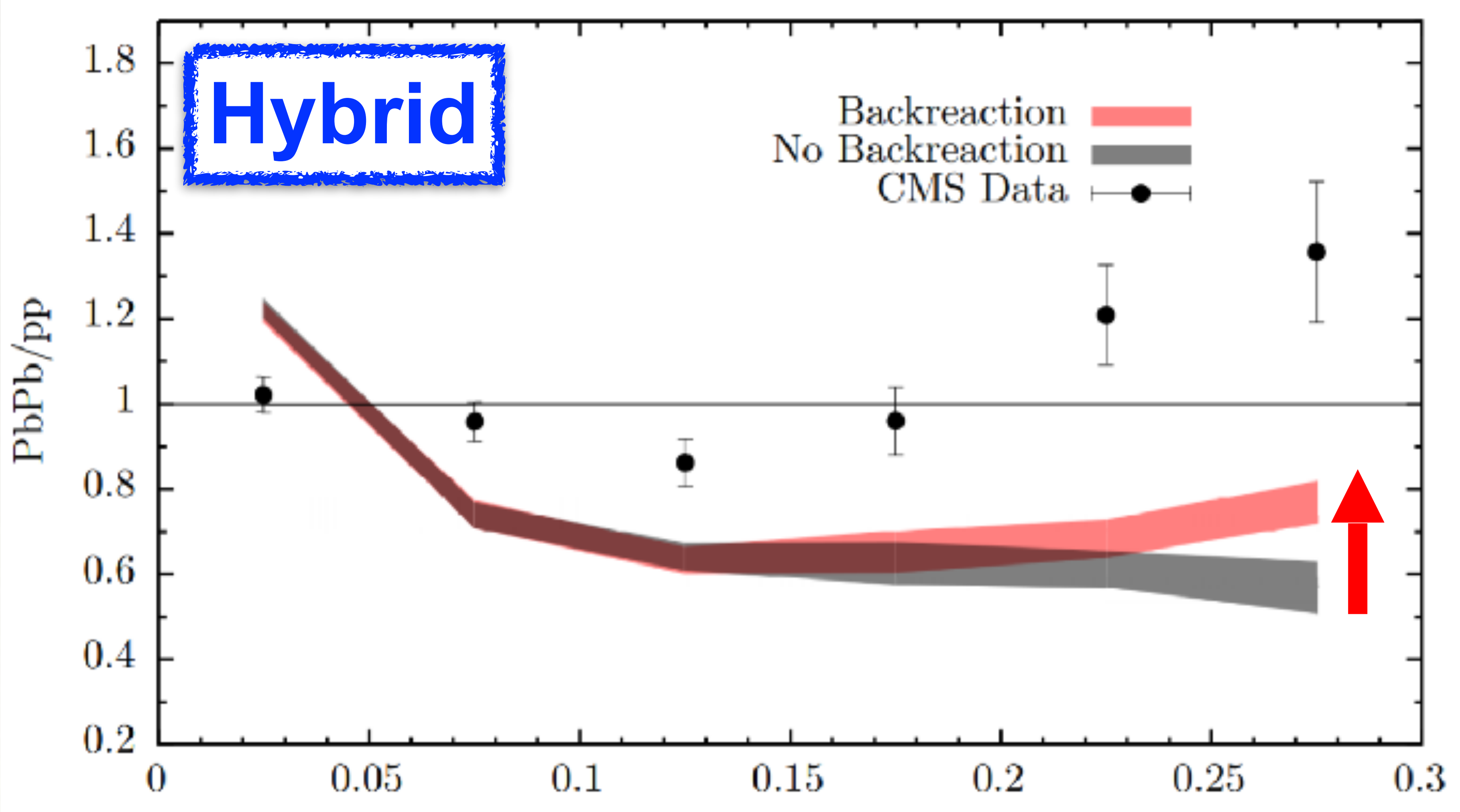
Medium modification of jet shape











LBT: PLB 782 (2018) 707

Jet-Fluid: PRC 95 (2017) 4, 044909

MARTINI: NPA 982 (2019) 643

JEWEL: JHEP 07 (2017) 141

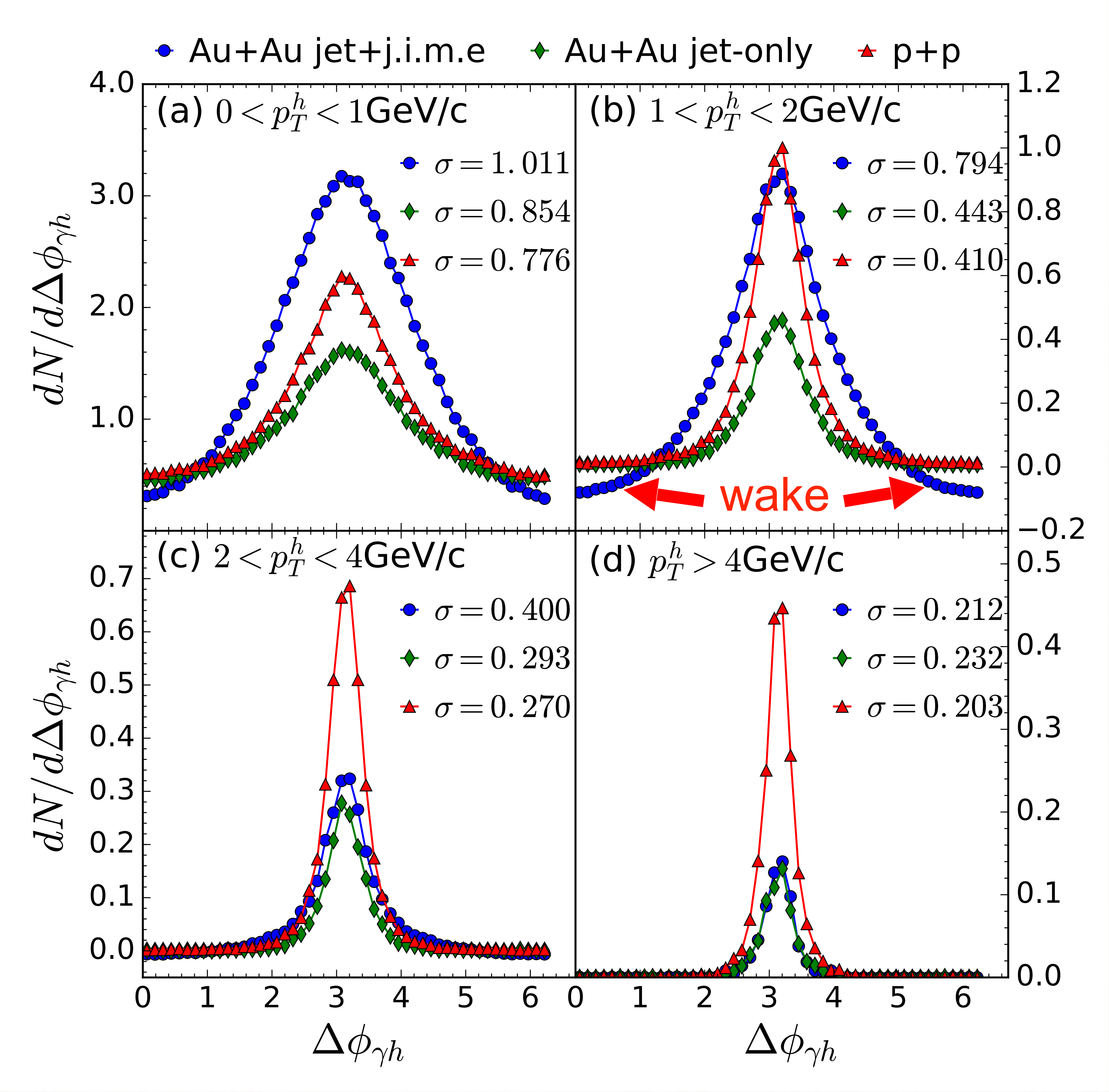
Hybrid: JHEP 03 (2017) 135

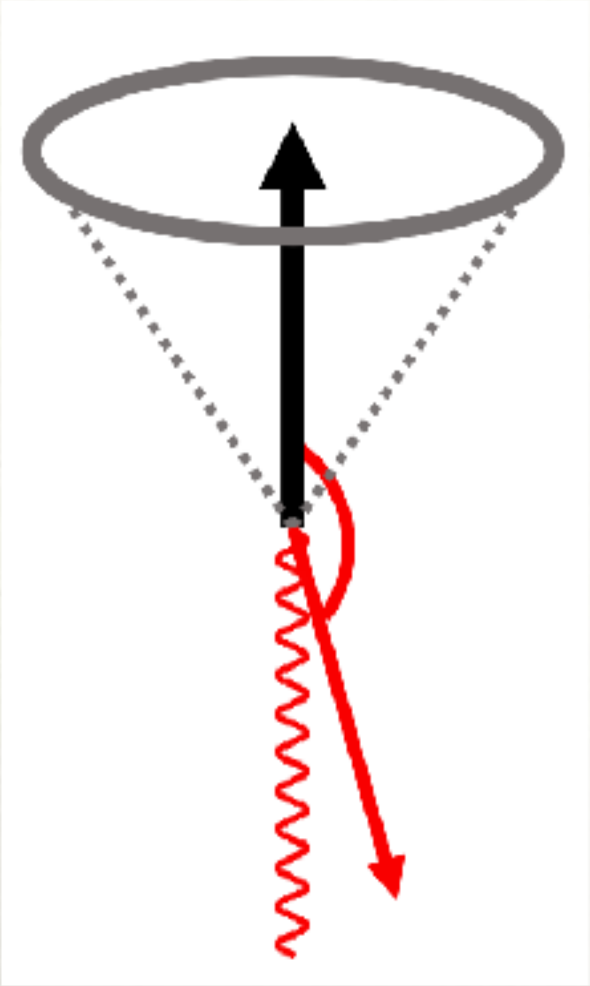
Criticism on medium response study

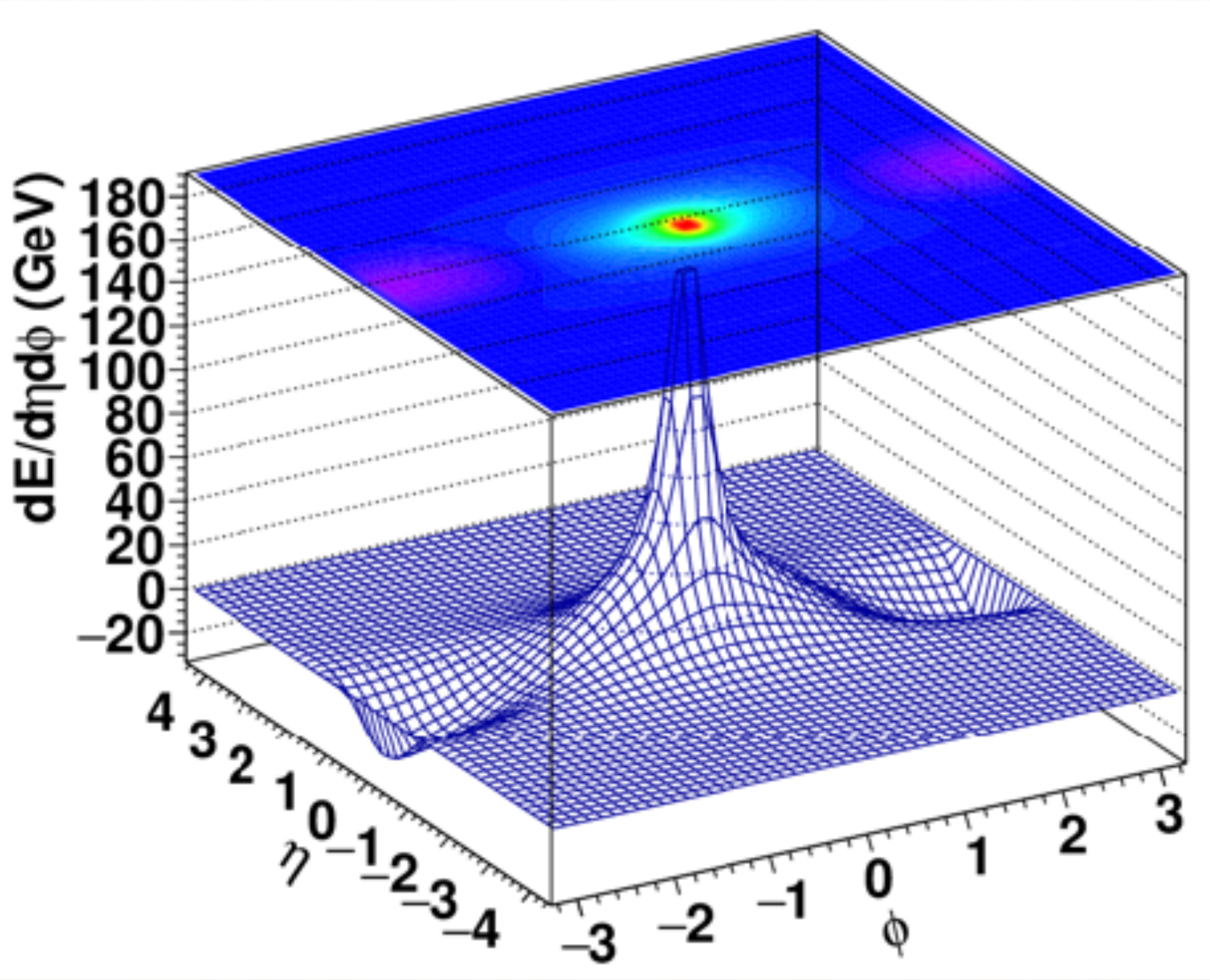
- **Theories without medium response effects can also describe data, why we need medium response?**

- Motivation: we should search for unambiguous signatures of medium response

Diffusion wake





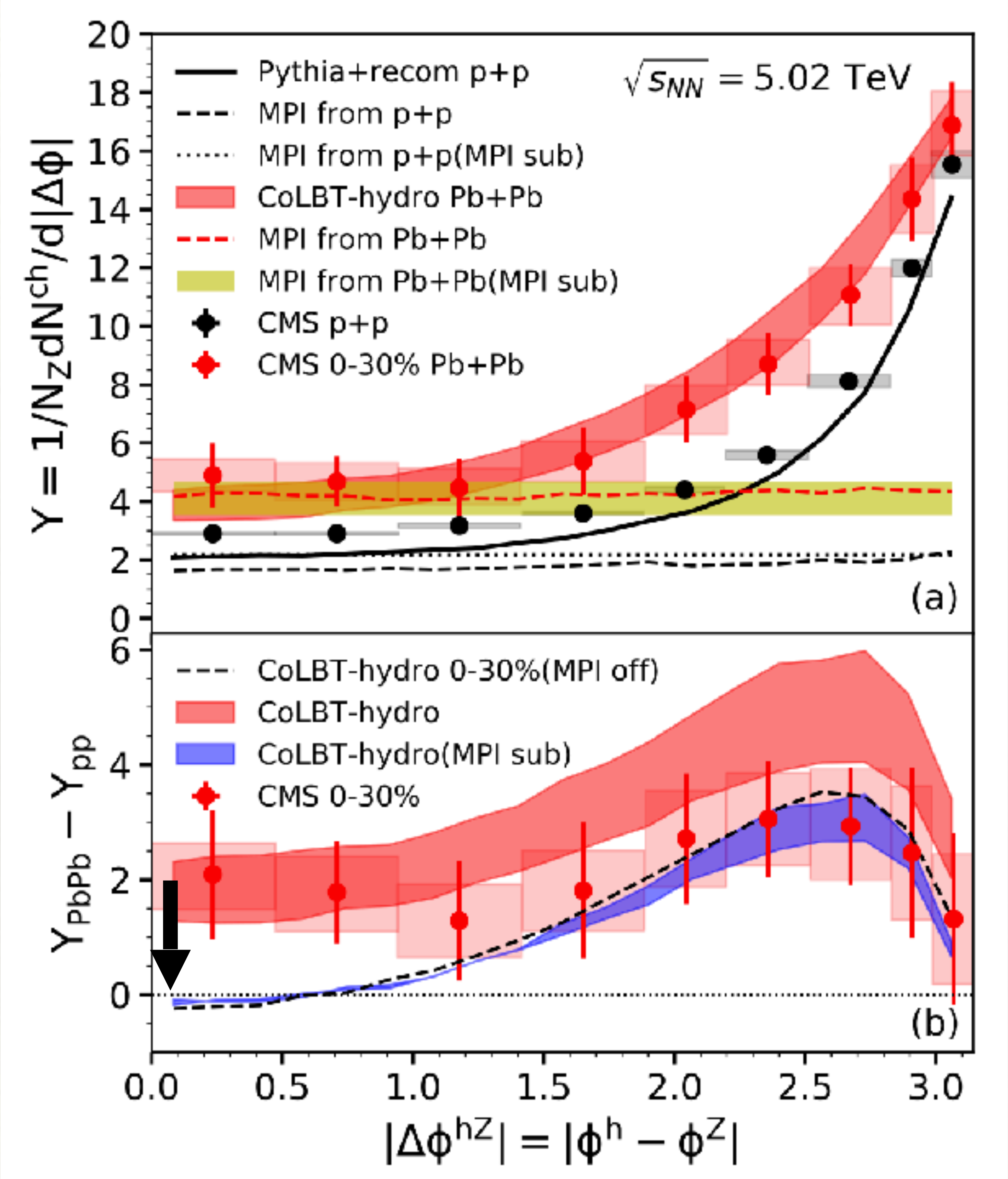


- High p_T, suppression, no broadening
- Low p_T, enhancement, broadening
- Diffusion wake predicted in $1 < p_T < 2$ GeV bin

Chen, Cao, Luo, Pang, Wang, PLB 777 (2018) 86

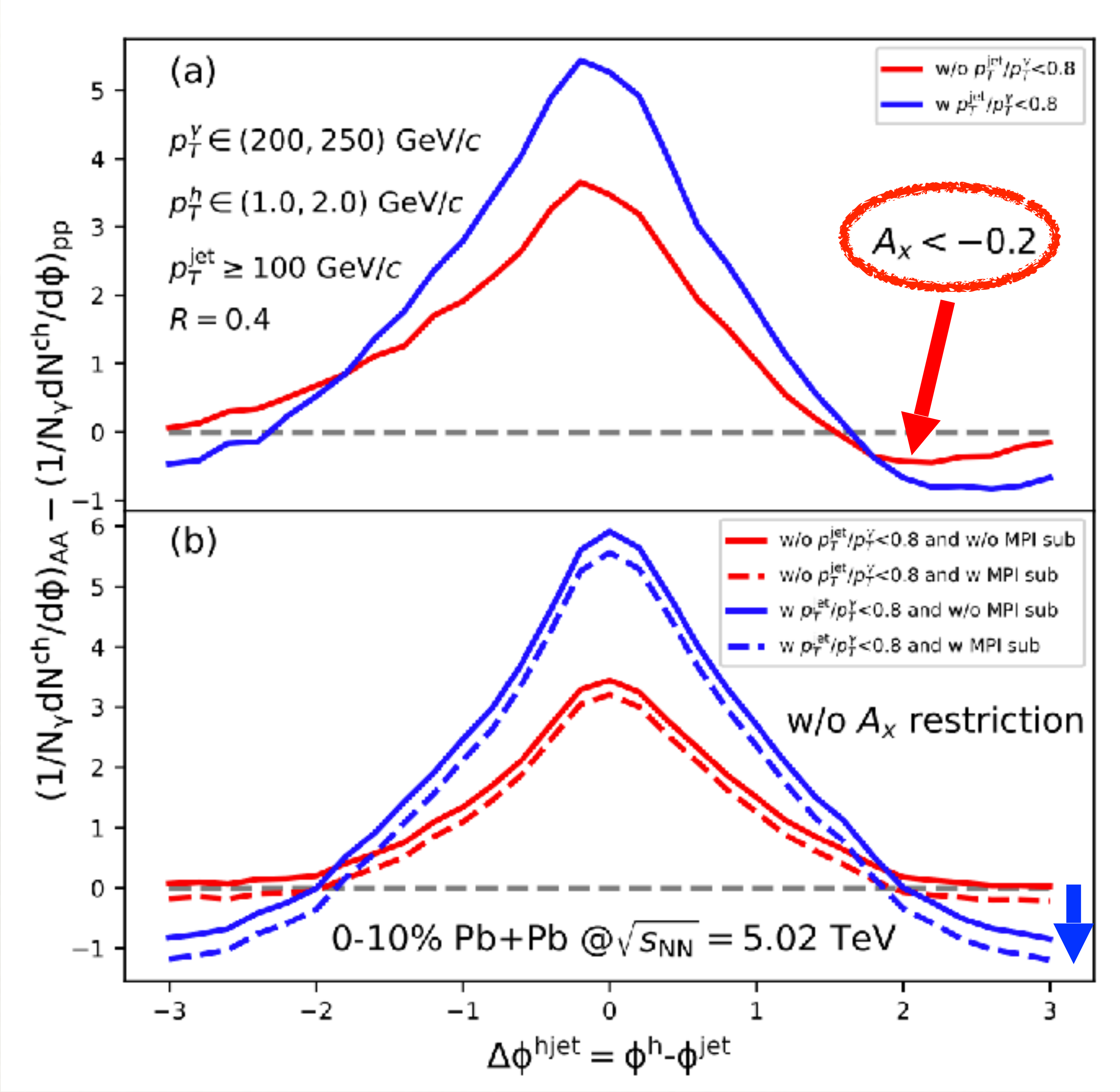
Enhancing diffusion wake effects

Subtract MPI in Z-hadron correlation



$$\frac{dN^{hZ}_{\rm MPI}}{d\phi} \approx \frac{dN^{hZ}_{\rm mix}}{d\phi} - \int_1^{\pi} \frac{d\phi}{\pi}\left(\frac{dN^{hZ}}{d\phi} - \frac{dN^{hZ}}{d\phi}|_{\phi=1}\right)$$

Apply 2D jet tomography



$$A_{\vec{n}} = \frac{\int d\phi[(dN^h/d\phi)_{\phi-\phi_n>0} - (dN^h/d\phi)_{\phi-\phi_n<0}]}{\int d\phi dN^h/d\phi}$$

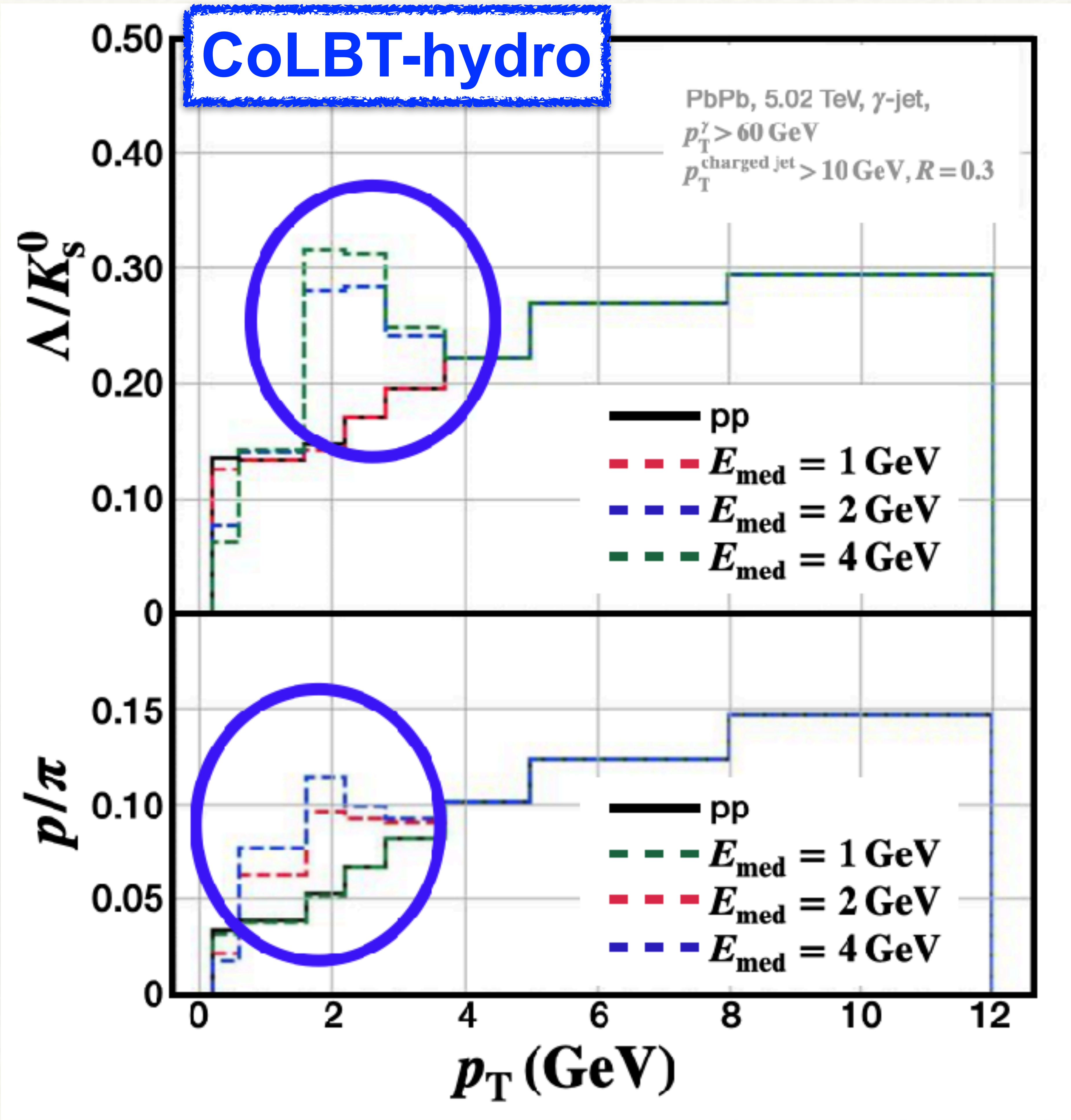
azimuthal asymmetry of soft hadron dist. w.r.t. $\hat{n}$

Direction and path-length bias with:

- A_x cut
- $p_T^{jet}/p_T^{Z/\gamma}$ cut

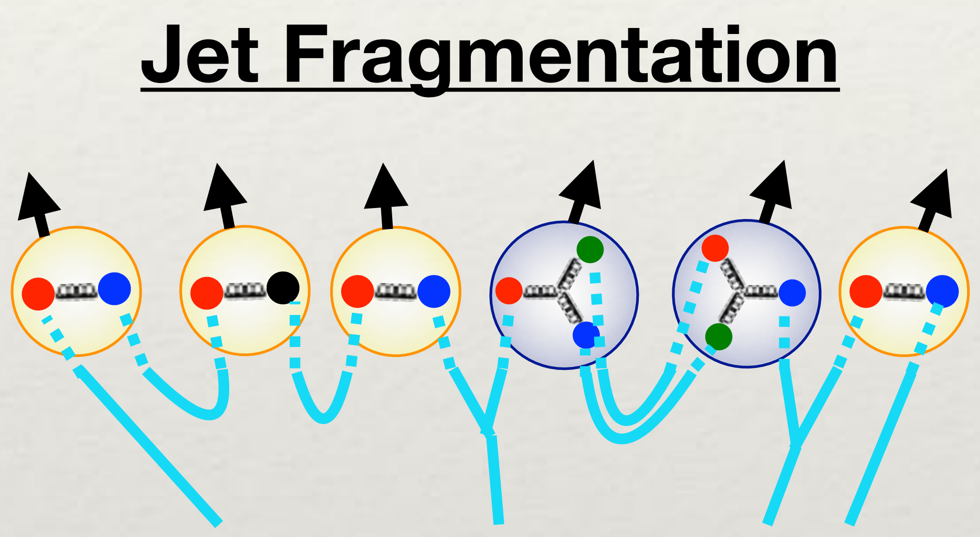
Chen, Yang, He, Ke, Pang, Wang, arXiv:2101.05422

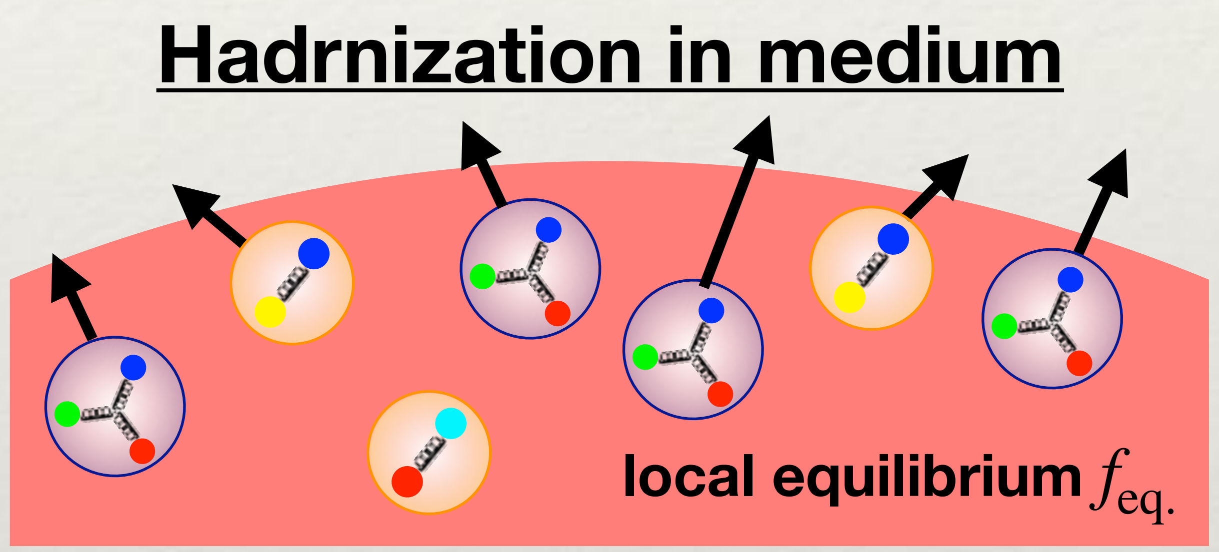
Hadron chemistry inside jets



CoLBT-hydro calculation from Wei Chen (QM 2019)

- Different mechanism between showering partons and medium
- More baryons form medium





Baryon meson ratio in jet

- Enhancement around 2 GeV
- Sensitive to E_{med}

Summary

- **Overview of different medium response implementations**

  Linear response, full hydrodynamic response, recoil, concurrent jet+hydro simulation

- **Effects on experimental observables**

  Jet R_{AA}, v_2, fragmentation function, shape, (mass, splitting function, momentum imbalance), etc.

- **Search for unambiguous signatures of medium response**

  Diffusion wake, hadron chemistry inside jets