

ICHEP2024, July 17-24, 2024, Prague

Jet tomography of QGP and medium response

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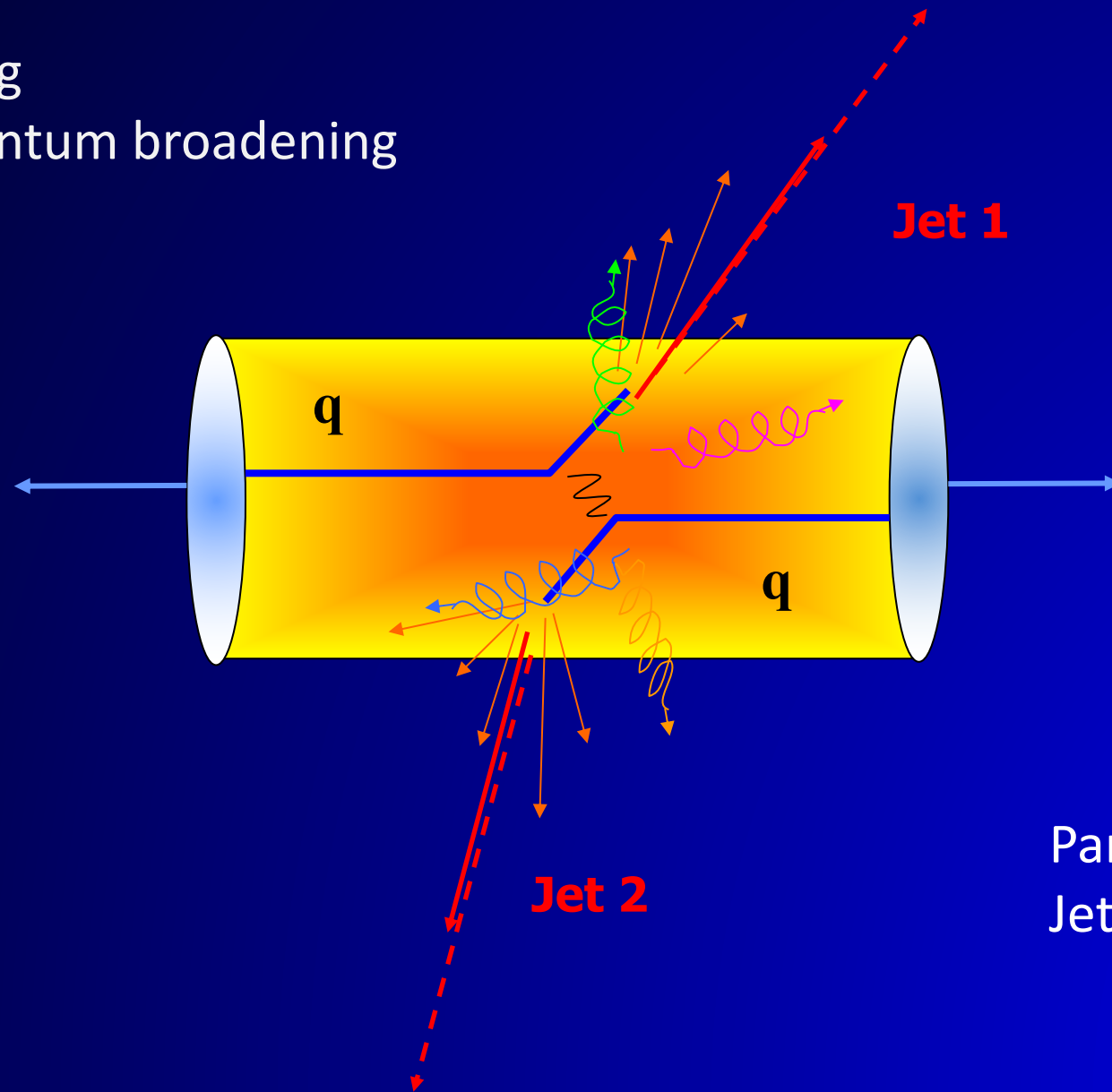
Central China Normal University/Lawrence Berkeley National Laboratory



Jets in heavy-ion collisions

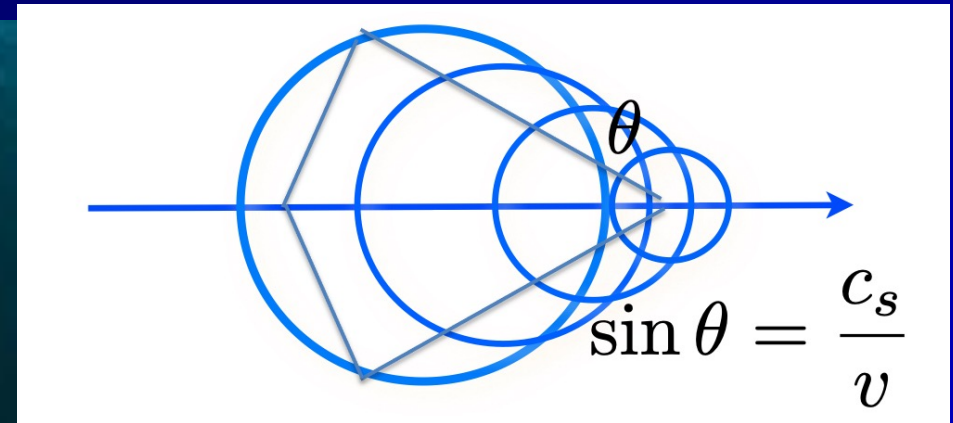
Multiple scattering

Transverse momentum broadening



Parton energy loss
Jet suppression

Bow waves, Mach waves



Jet-induced medium excitation

Casalderrey-Solana, Shuryak & Teaney (2005), Stoecker (2005)

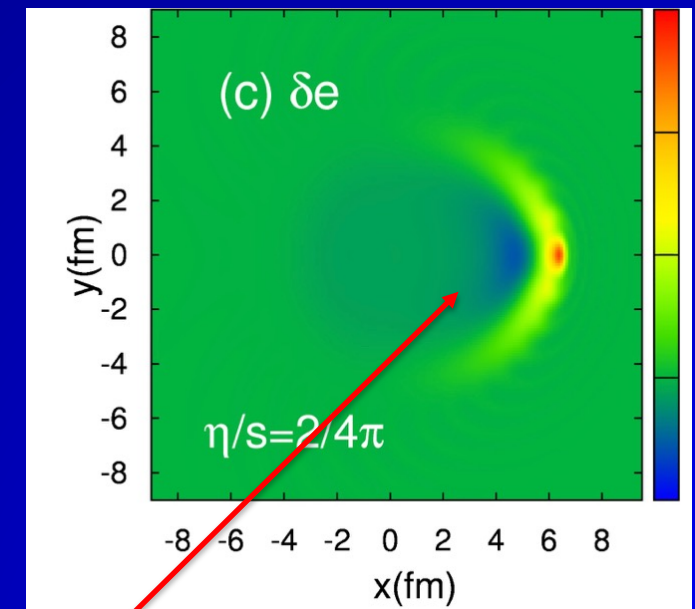
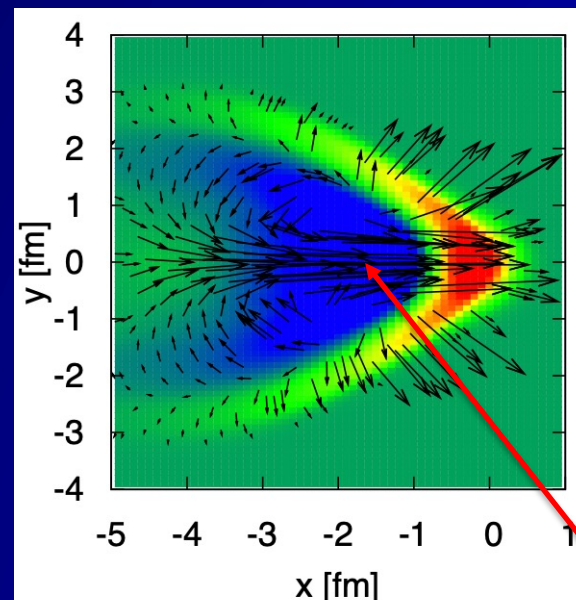
Jet induced Mach-cone in QGP

$$v = p/E > c_s$$

Hydrodynamic approach

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

J^ν : energy-momentum deposited by jet



Betz, Noronha, Giorgio, Gyulassy, Mishudtin, Rischke (2009)

Li Yan, S. Jeon, C. Gale (2018)

Diffusion wake



Microscopic picture of Mach wave

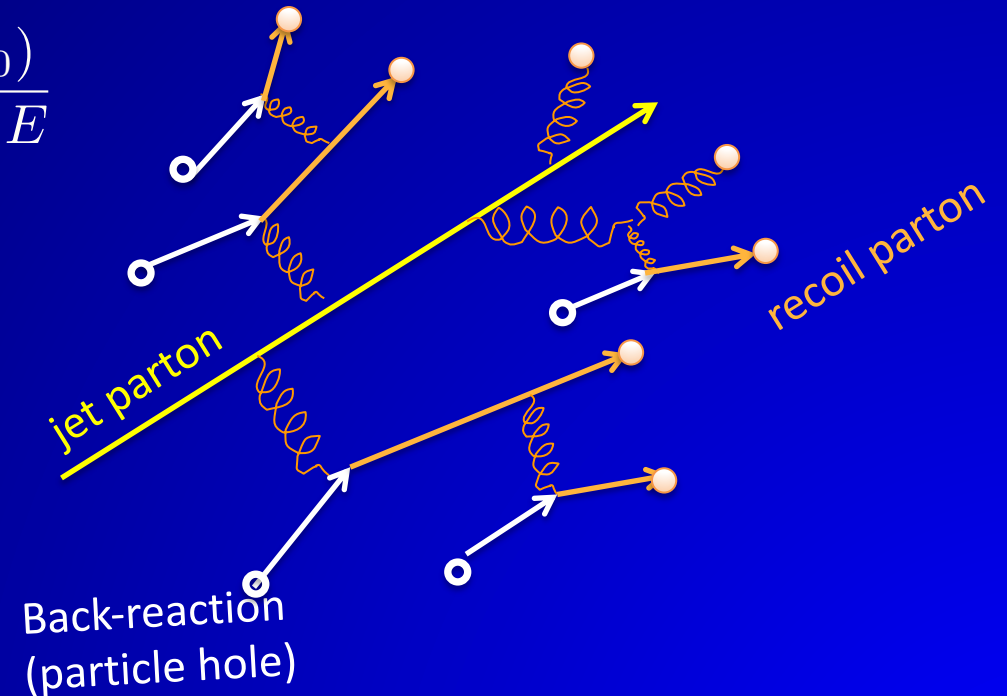
LBT: Linear Boltzmann Transport

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

Induced radiation

$$\frac{dN_g}{dz d^2 k_\perp dt} \approx \frac{2C_A \alpha_s}{\pi k_\perp^4} P(z) \hat{q} (\hat{p} \cdot u) \sin^2 \frac{k_\perp^2 (t - t_0)}{4z(1-z)E}$$

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



CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

Concurrent and coupled evolution of bulk medium and jet showers

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

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

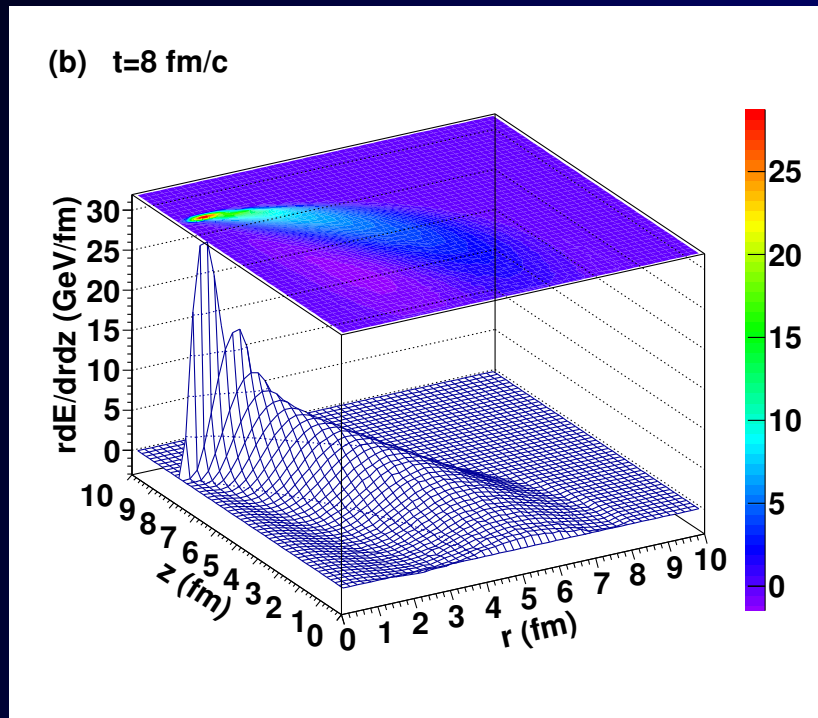
$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i) \theta(p_{cut}^0 - p \cdot u)$$

- LBT for energetic partons (jet shower and recoil)
- Hydrodynamic model for bulk and soft partons: CLVisc
- Parton coalescence (thermal-shower)+ jet fragmentation
- Hadron cascade using UrQMD

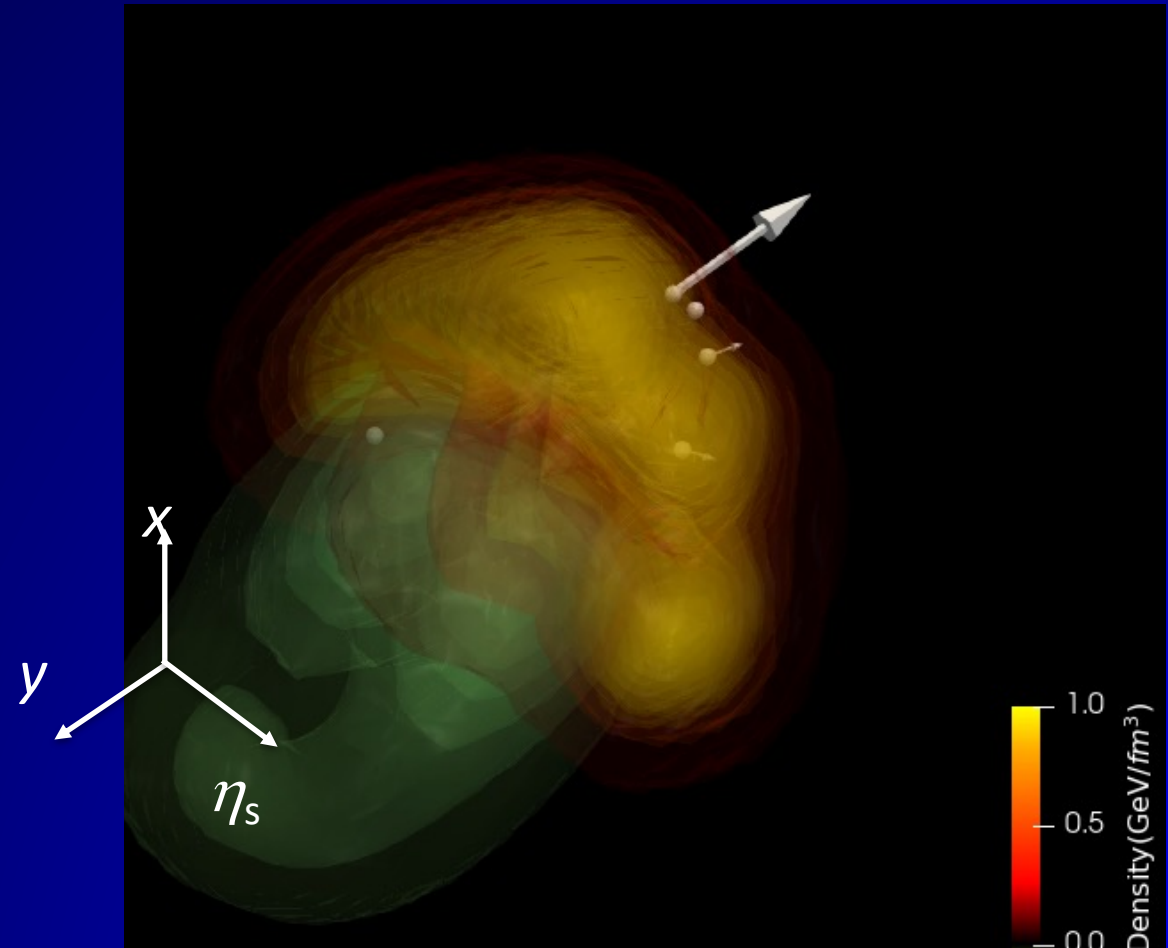
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86



LBT & CoLBT: Jet-induced medium response



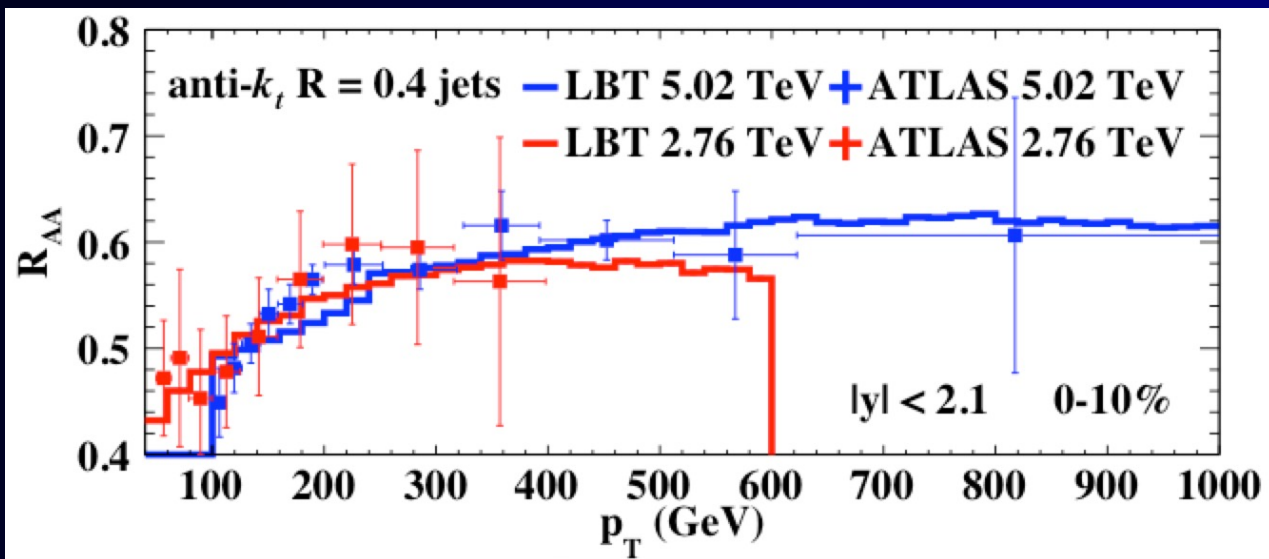
Energy transverse distribution of medium response in a static medium



3D energy density distribution of the medium response induced by a γ -jet in a 0-10% Pb+Pb event

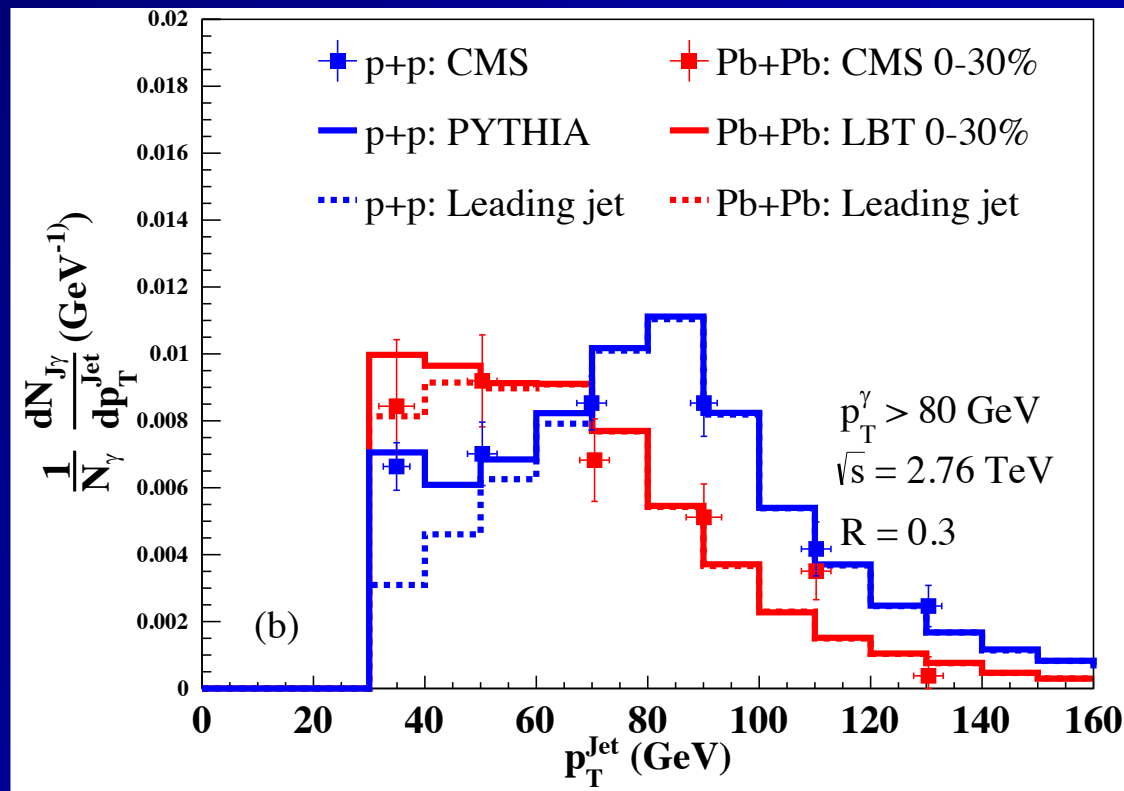
Jet suppression and energy loss

Single inclusive jets



- 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
- Medium response reduce jet net energy loss

γ - jets



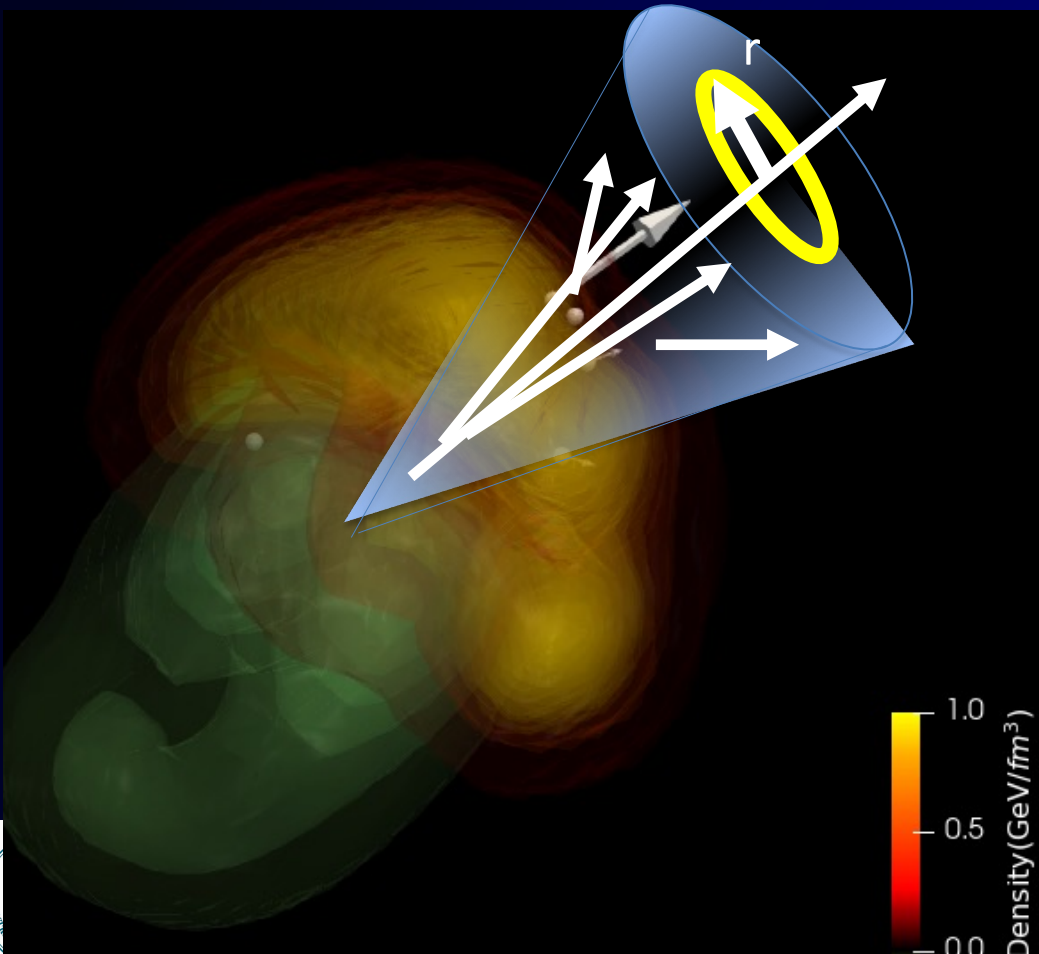
Luo, Cao, He & XNW, arXiv:1803.06785

He, Cao, Chen, Luo, Pang & XNW 1809.02525



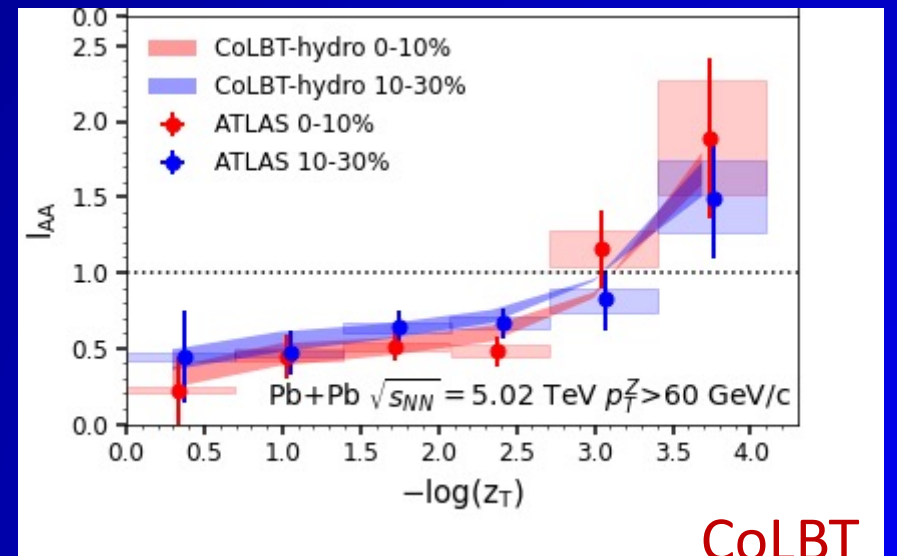
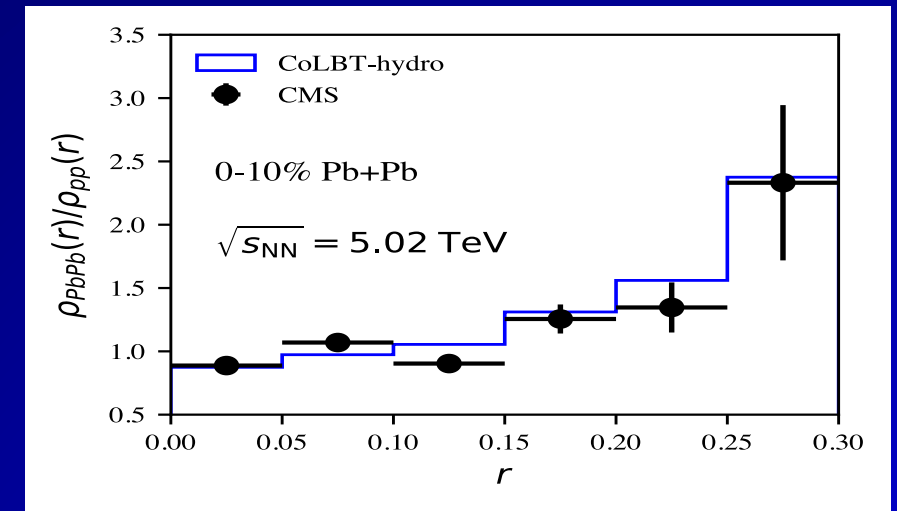
Modification of jets and medium response

$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{jet}} \sum_{jet} \frac{p_T^{jet}(r - \Delta r/2, r + \Delta r/2)}{p_T^{jet}(0, R)}$$



$$\frac{\rho_{AA}(r)}{\rho_{pp}(r)}$$

$$I_{AA} = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$

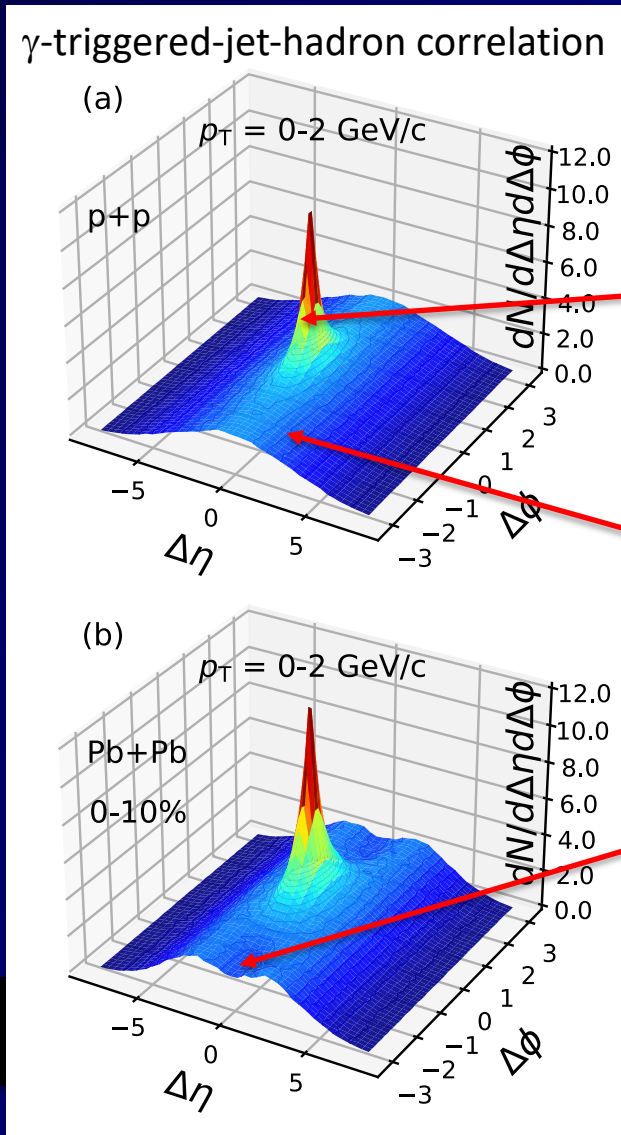
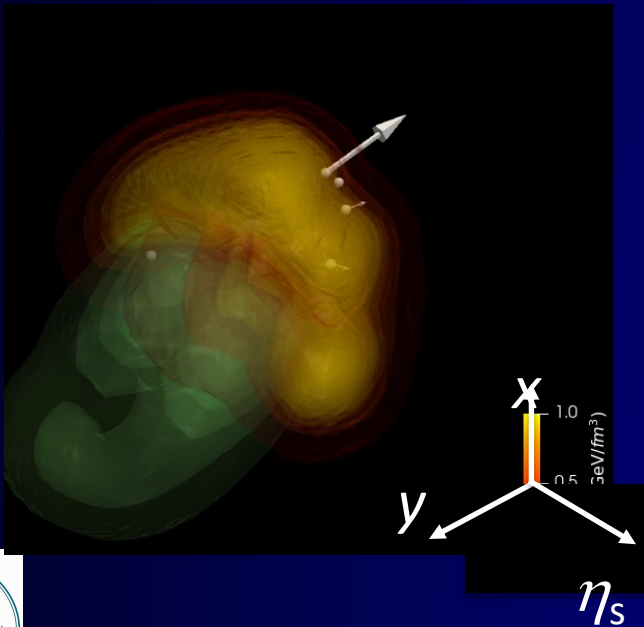


CoLBT

Search for jet-induced diffusion wake

Diffusion (DF) wake leads to depletion of soft hadron yield in the back of jet direction

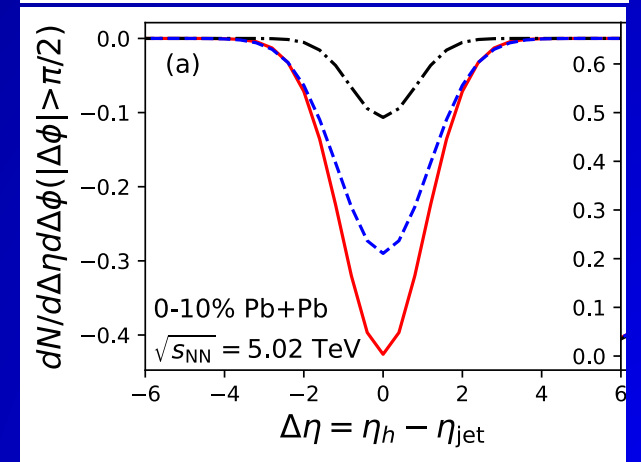
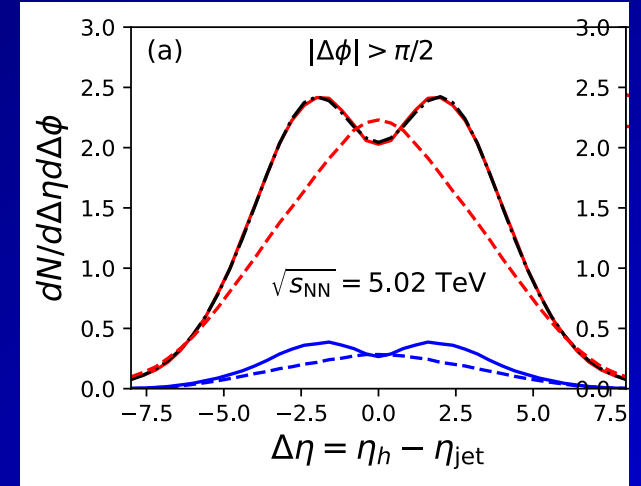
Yang, Tan, Chen, Pang & XNW,
PRL, 130 (2023), 052301



Jet

MPI

DF-wake

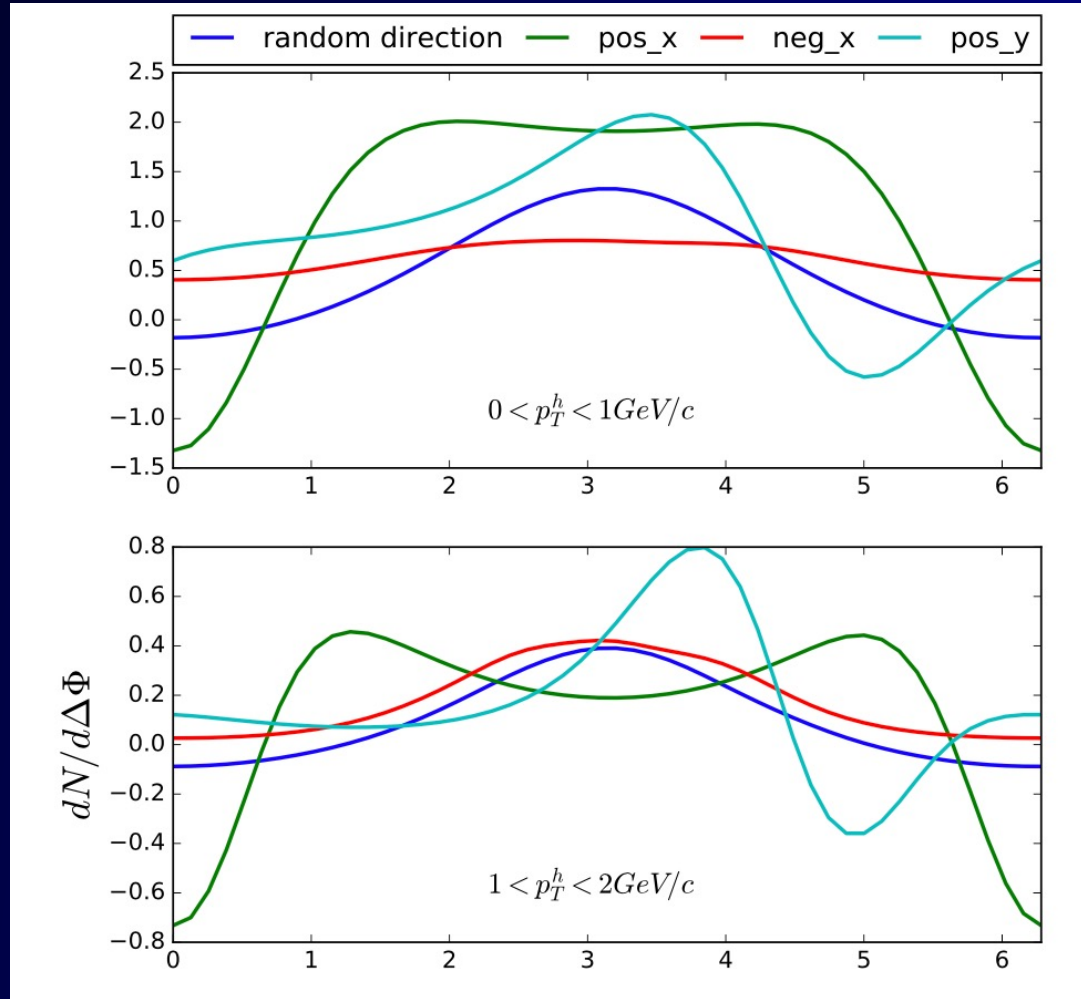


$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j) (F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)),$$

↑ Jet-distr ↑ MPI ↑ DF-wake

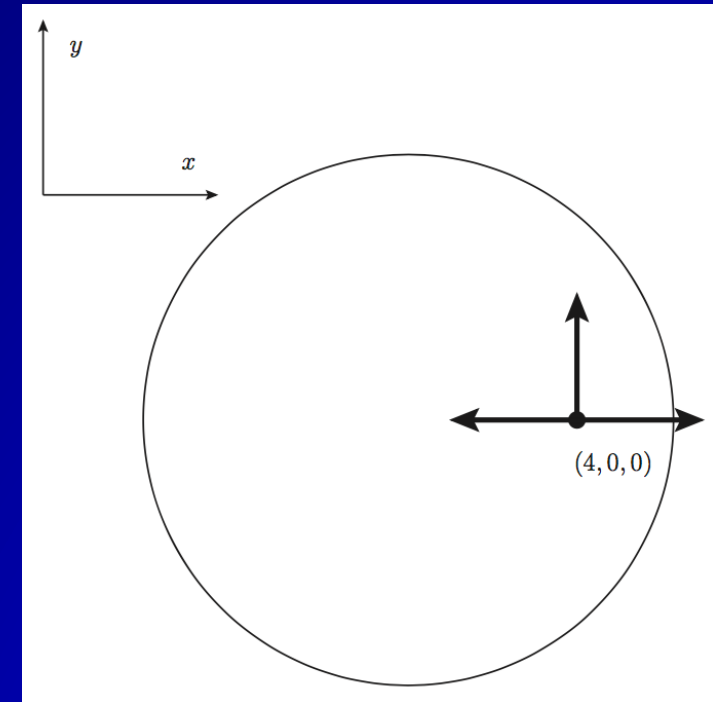


Initial position & azimuthal correlation



$\Delta\Phi$

γ -hadron correlation



W Chen & XNW (2018)

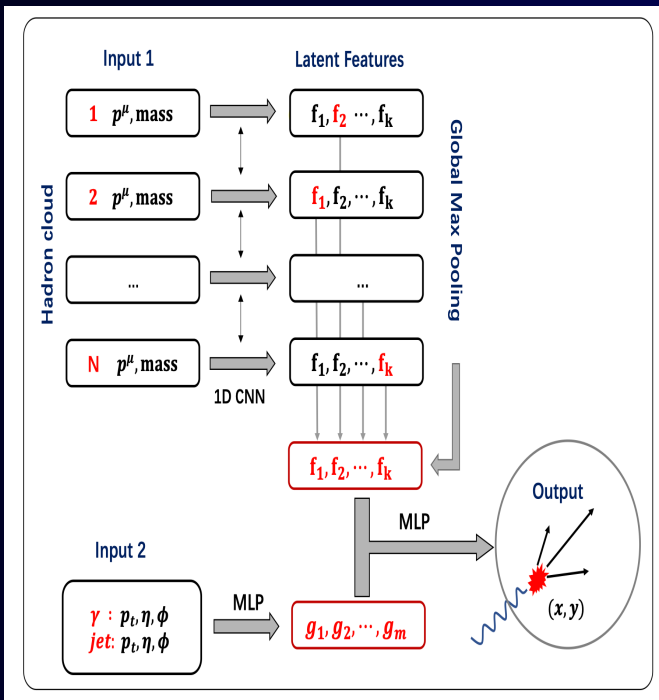
Li, Liu, Ma, XNW and Zhu, Phys. Rev. Lett. 106, 012301 (2011)

Tachibana, Shen & Majumder [2001.08321](#) (2020)



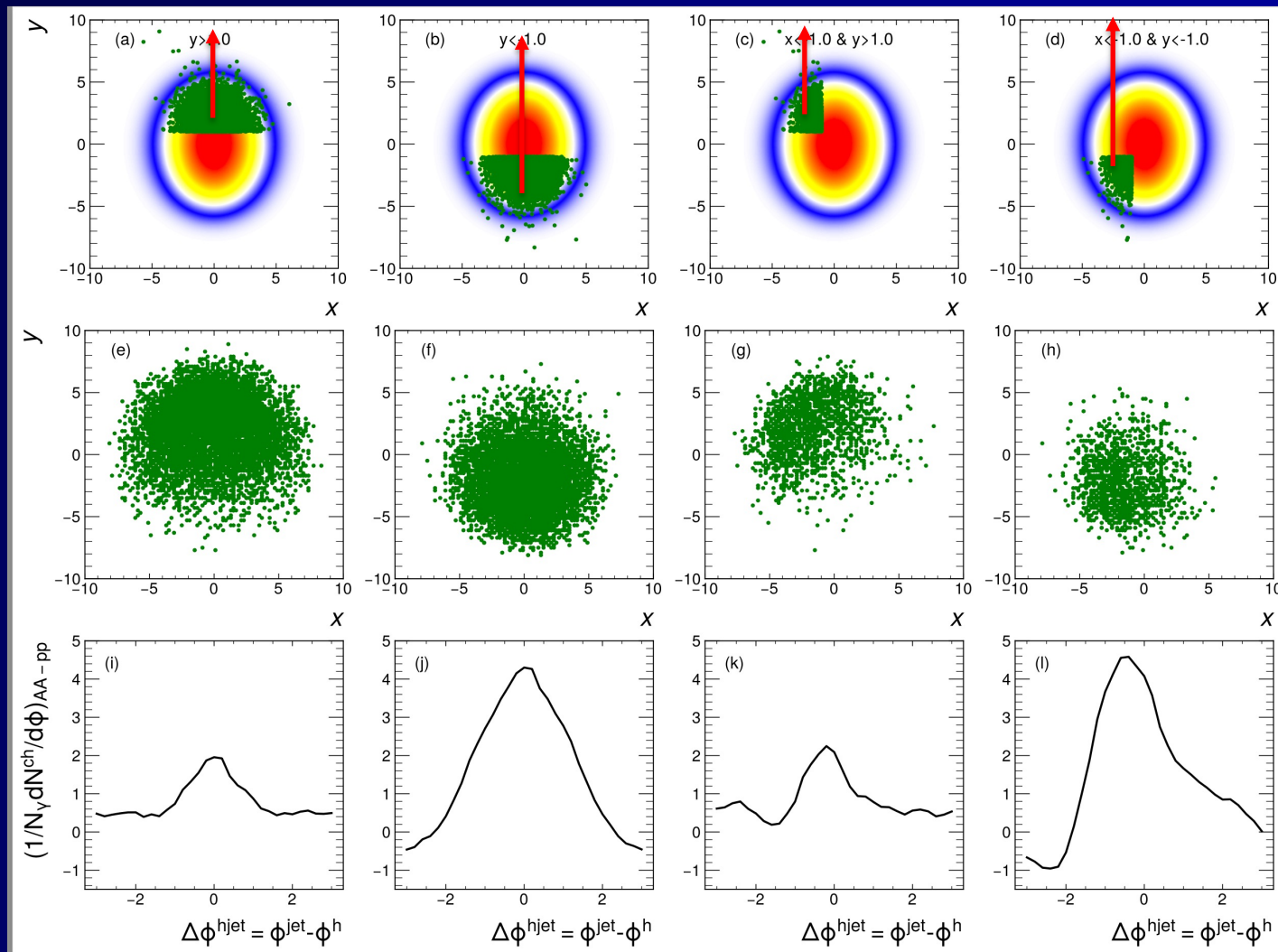
Deep learning assisted jet tomography

PCN (point cloud network)



Eur.Phys.J.C 83 (2023) 7, 652

Yang, He, Chen, Ke, Pang & XNW



DL network selection

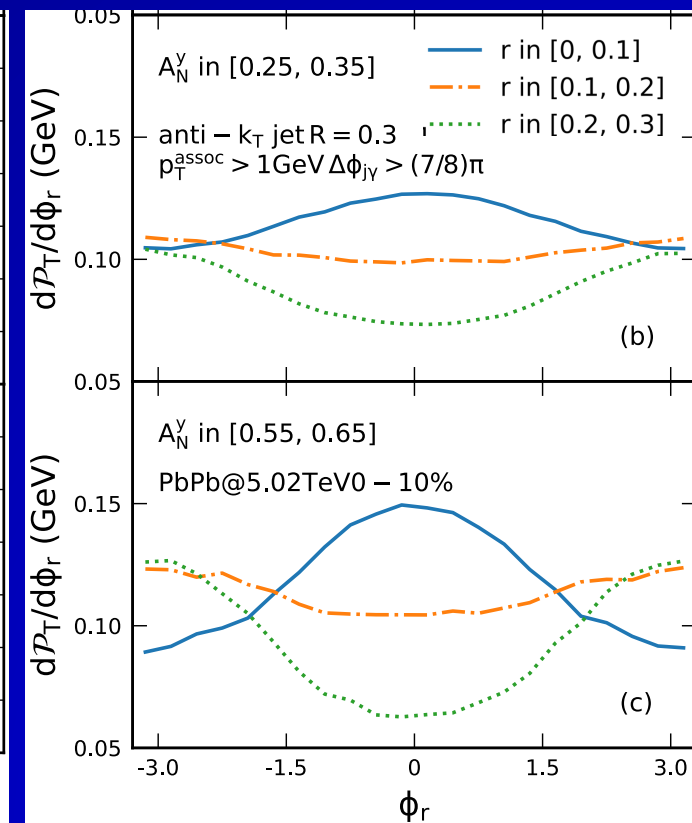
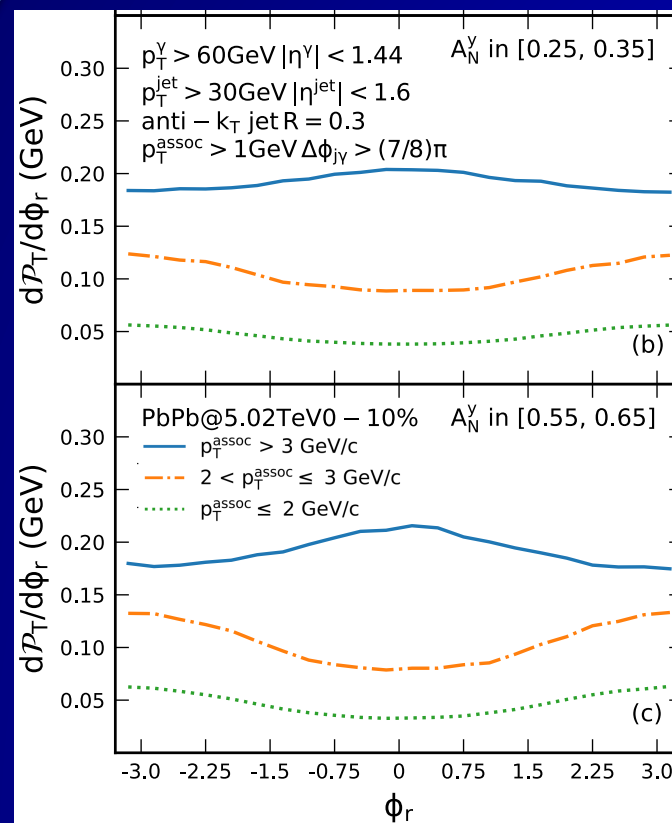
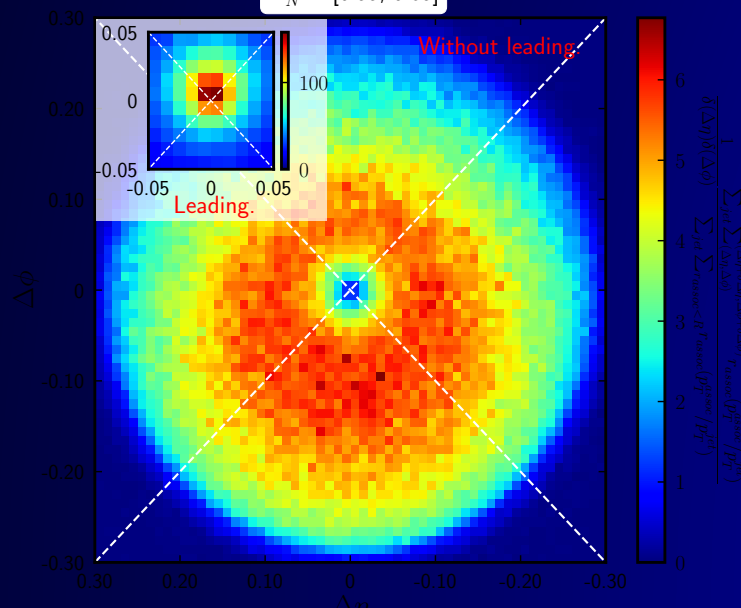
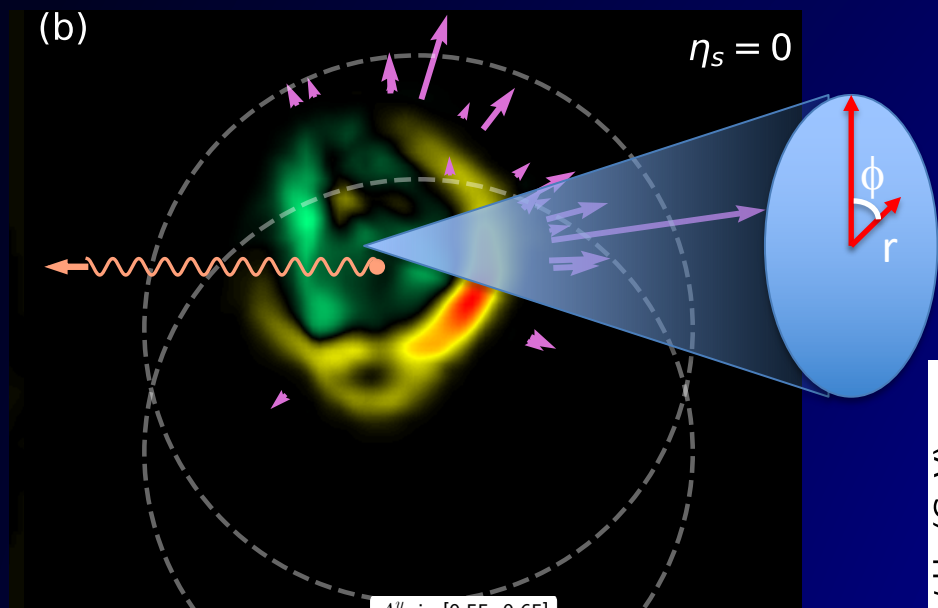
Actual distribution

γ -soft hadron correlation

Asymmetric jet shape

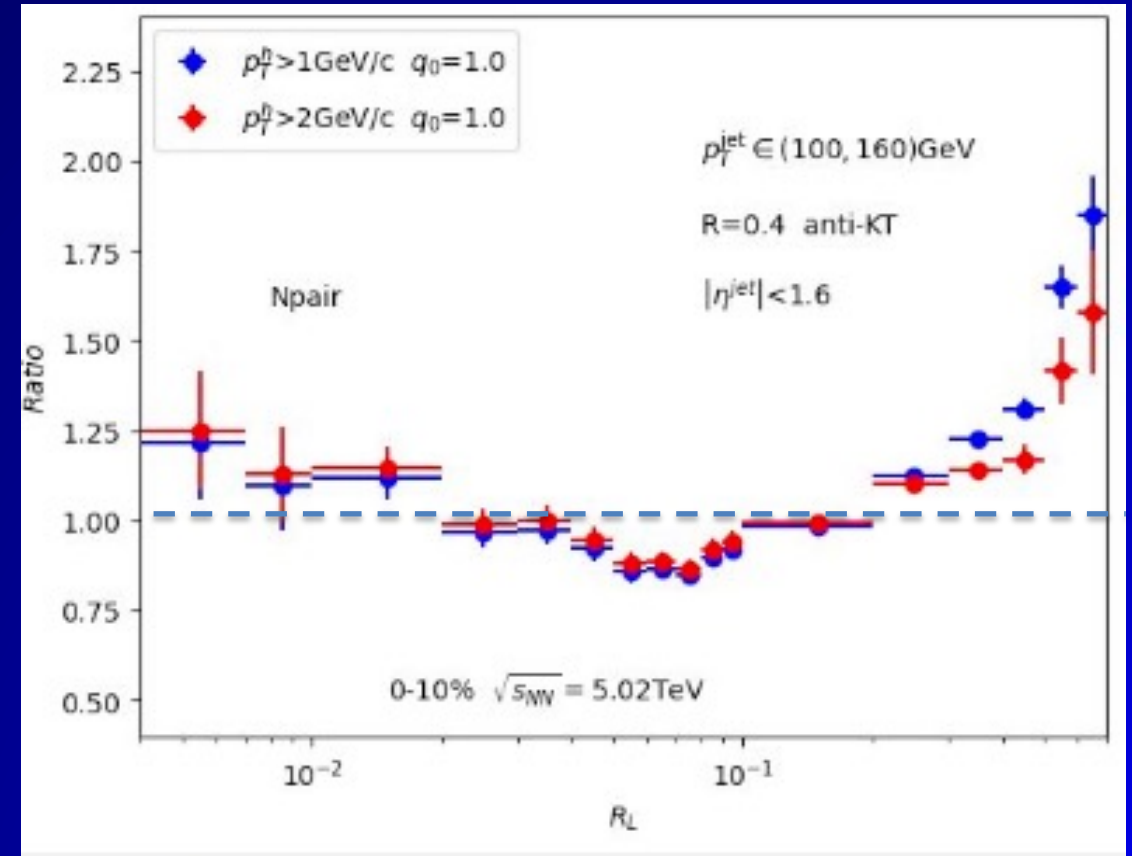
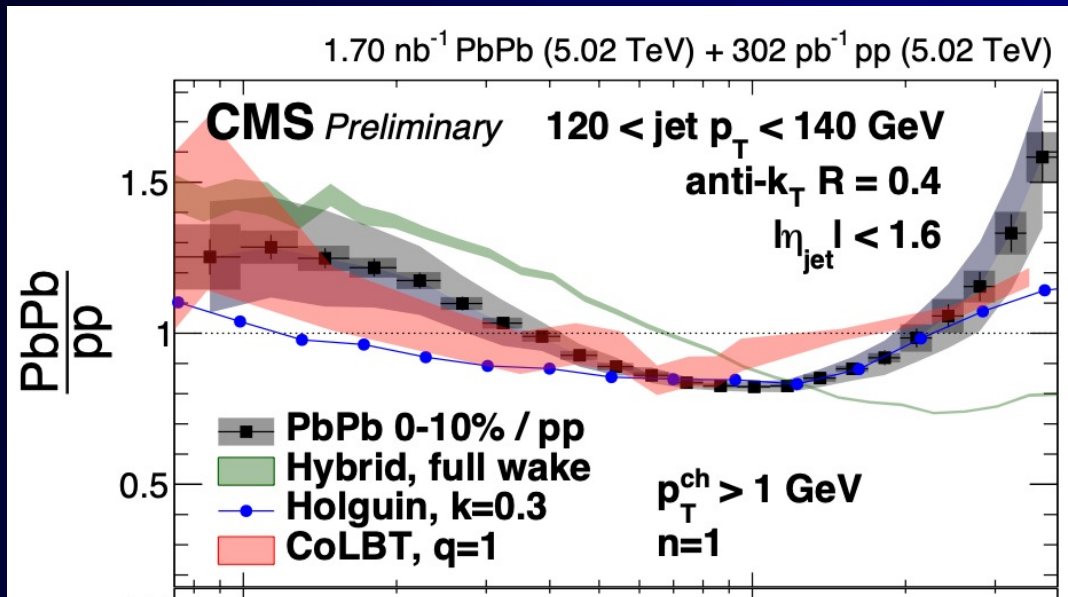
Energetic hadrons at the core of jet deflected away from center
 Soft hadrons from medium response at large angle flow into center

$$A_{E_{\perp}}^{\vec{n}} = \frac{\int d^3r d^3p f_a(\vec{p}, \vec{r}) \vec{p}_T \cdot \vec{n}}{\int d^3r d^3p f_a(\vec{p}, \vec{r})}$$



Single jet energy-energy correlator from CoLBT

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma} \sum_{i \neq j} \int d\vec{n}_{i,j} \frac{d\sigma_{ij}}{d\vec{n}_{i,j}} \frac{E_i^n E_j^n}{Q^{2n}} \delta(\vec{n}_1 \cdot \vec{n}_2 - \cos\theta)$$

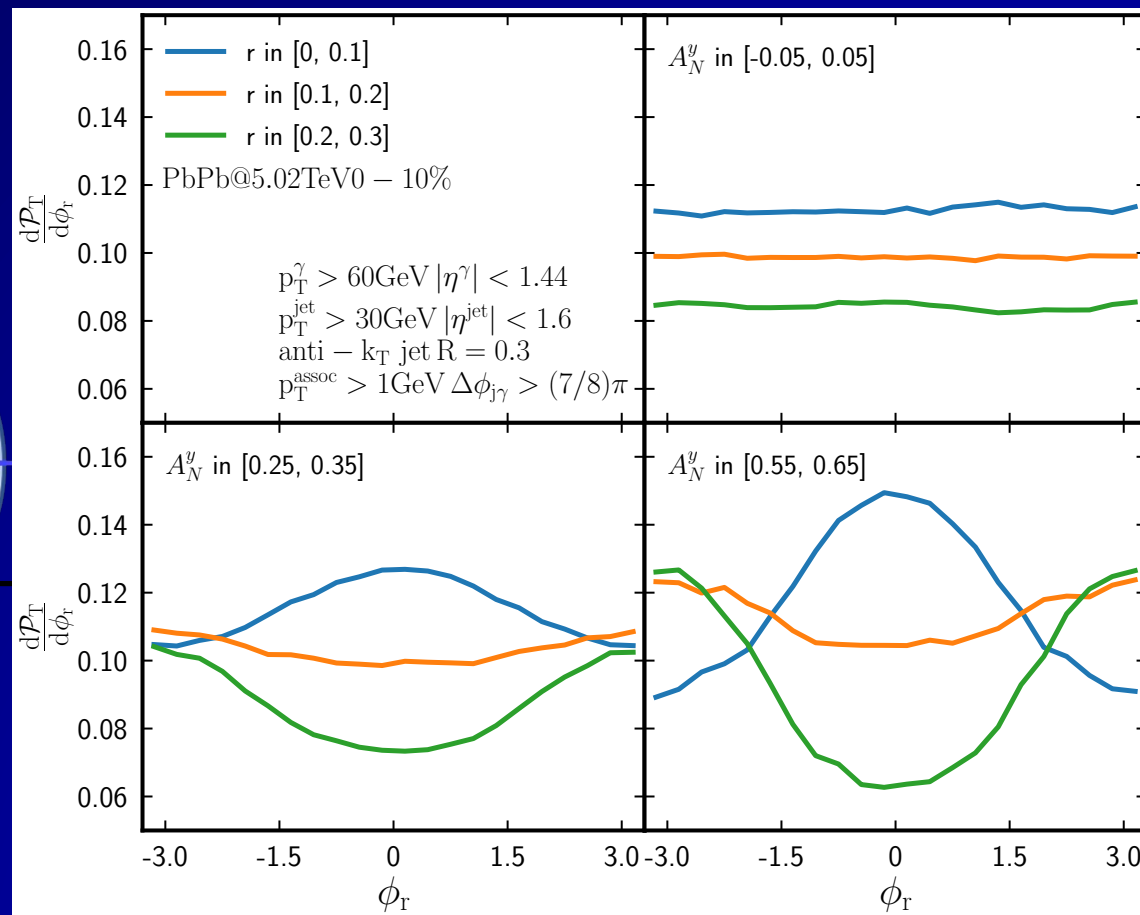
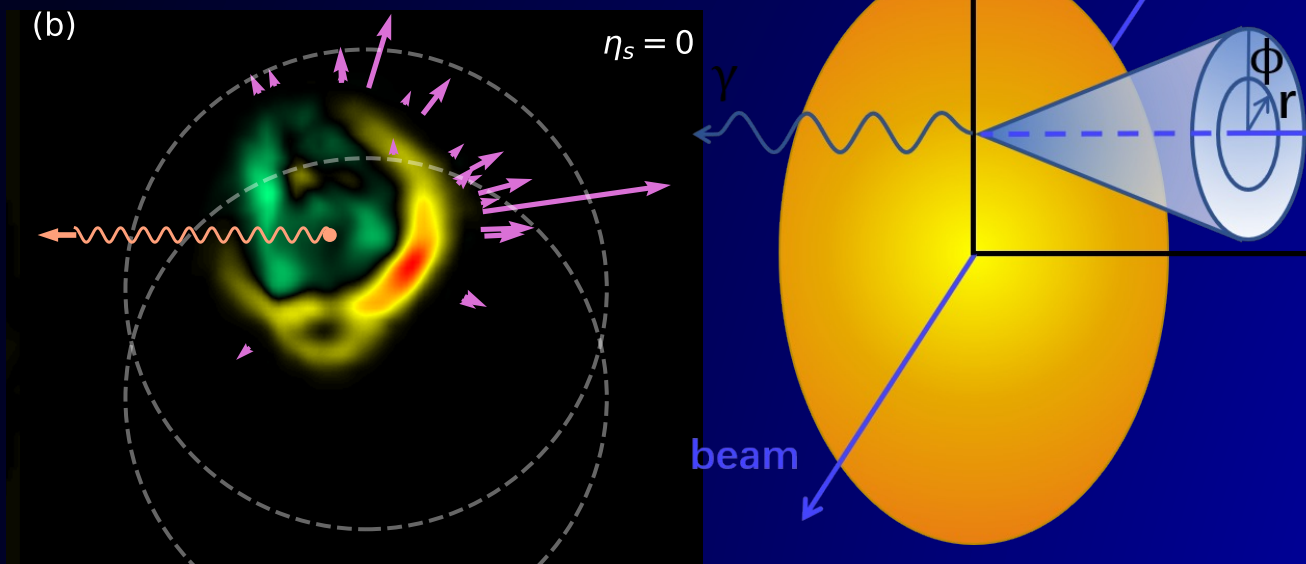


- Increased virtuality scale in medium leads to enhancement of EEC at small angle
- Medium response leads to enhancement at large angle $R_L > 0.3$



Asymmetric jet shape

$$A_{E_{\perp}}^{\vec{n}} = \frac{\int d^3r d^3p f_a(\vec{p}, \vec{r}) \vec{p}_T \cdot \vec{n}}{\int d^3r d^3p f_a(\vec{p}, \vec{r})}$$



Energetic hadrons at the core of jet deflected away from center

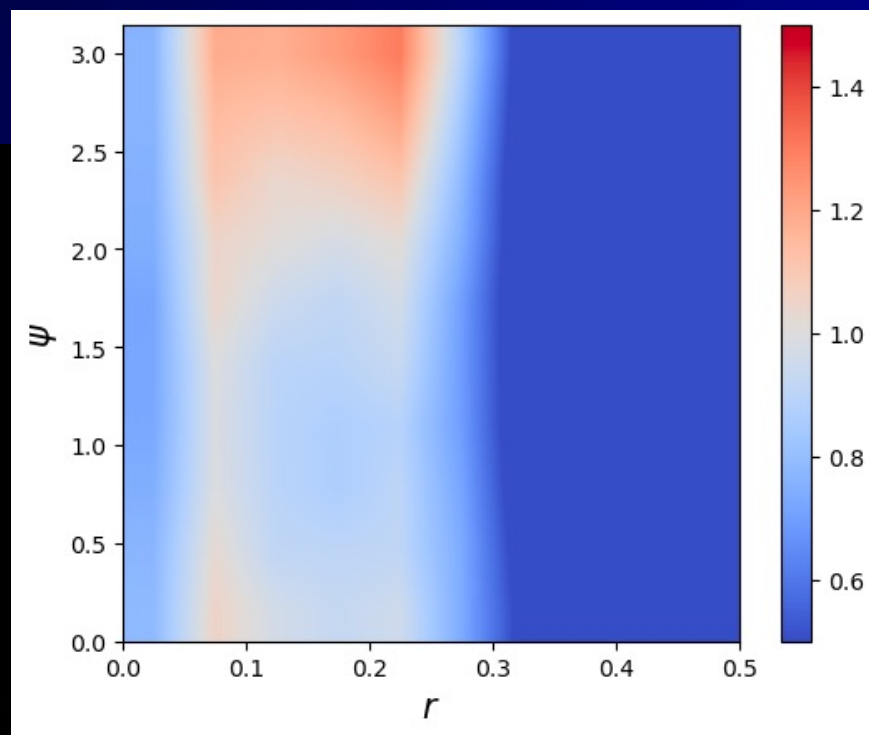
Soft hadrons from medium response at large angle flow into center

Xiao, He, Pang, Zhang & XNW, *PRC* 109 (2024) 5, 054906

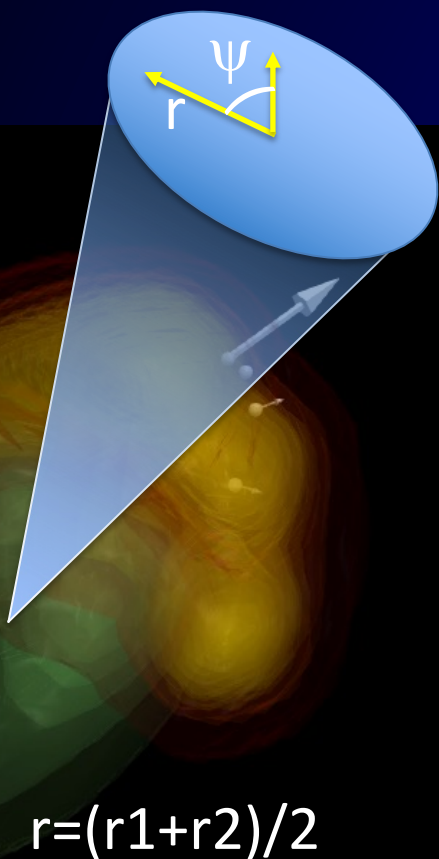
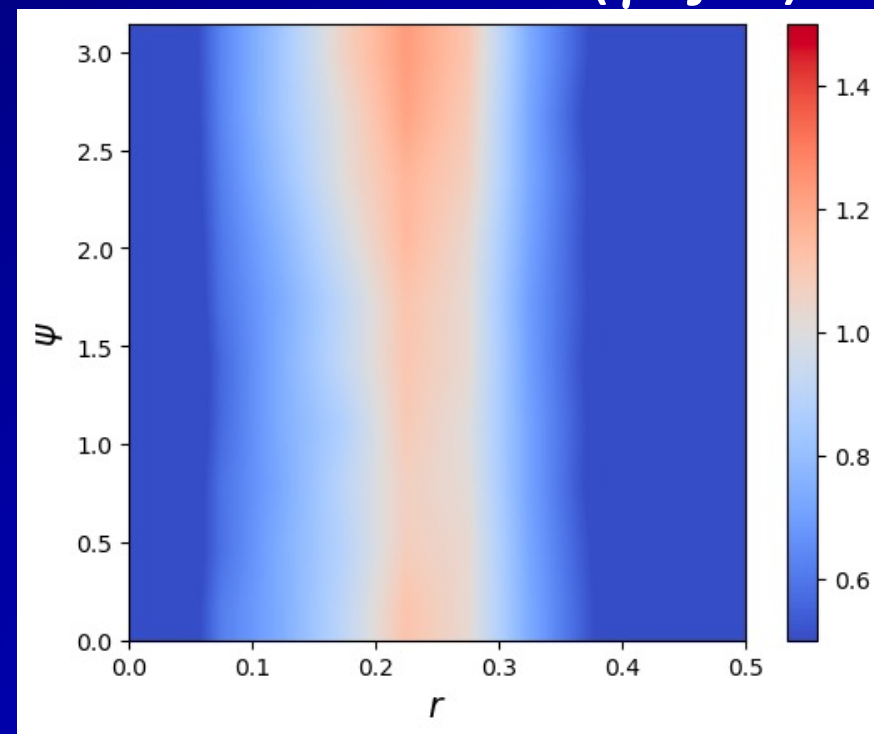
(e-print: [2402.00264](https://arxiv.org/abs/2402.00264))

Seeing Mach-cone through 3p Azimuthal Correlation

p+p (γ +jet) $p_T > 40$ GeV/c



0-10%Pb+Pb (γ +jet)



Back-to-back correlation due to momentum conservation of parton splitting

Azimuthal uniform correlation due to medium-response: Mach-cone – sound velocity?

Summary

- Medium response reduces net jet energy loss
- Medium response leads to
 - enhancement of soft hadrons in jet direction
 - depletion of soft hadron on the away side
- Unique 3D structure of diffusion wake
- Use 2D jet tomography to reveal the angular structure of Mach-cone excitation
- Future studies: ML improved 2D tomography and constraint on EoS, transport coefficients



