华中师范大学
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Jet Quenching and Medium Response

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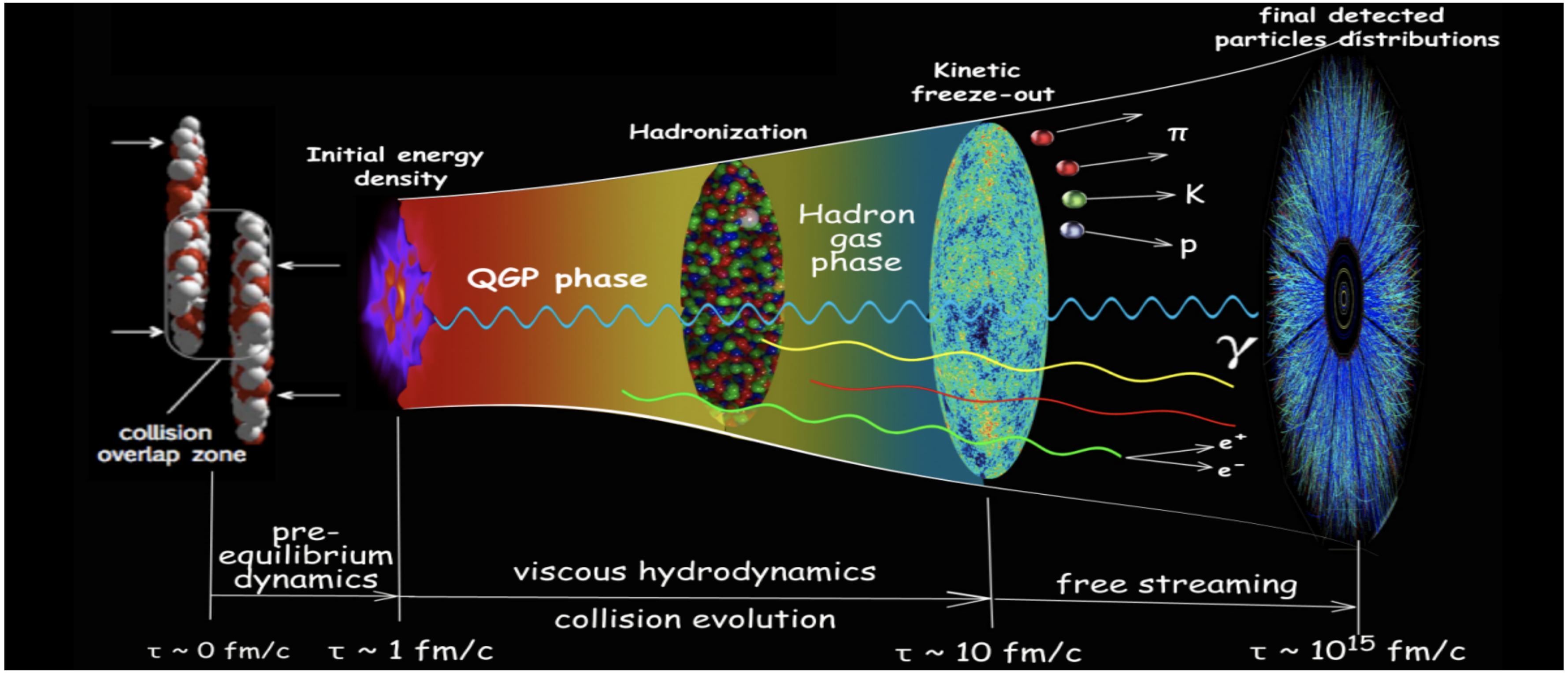
Advances, Innovations, and Prospects in High-Energy Nuclear Physics
Wuhan China

Outline

- Introduction
- LBT/CoLBT-hydro model
- Jet-induced medium response
  - Jet-induced diffusion wake
  - 3D structure of diffusion wake
- Summary and Outlook

Introduction



Chun Shen

Looking for and studying QGP are the main programs in high-energy heavy-ion collisions

Jet in heavy-ion collisions

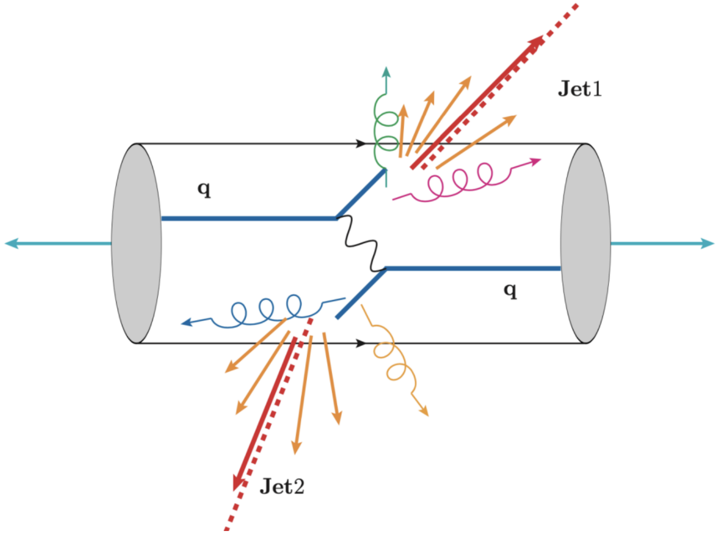
Jet: a collimated cluster of hadrons produced by the fragmentation of high-energy quarks or gluons.

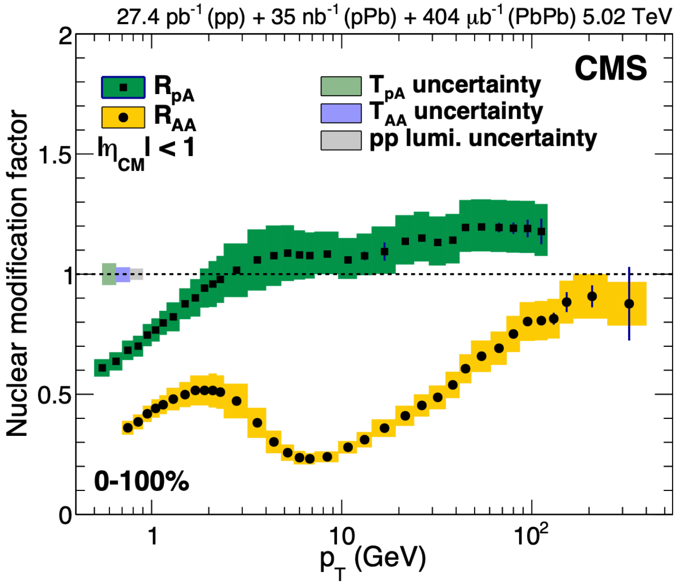
$$d\sigma_{\text{jet}} = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab\to jd} \otimes J_i$$

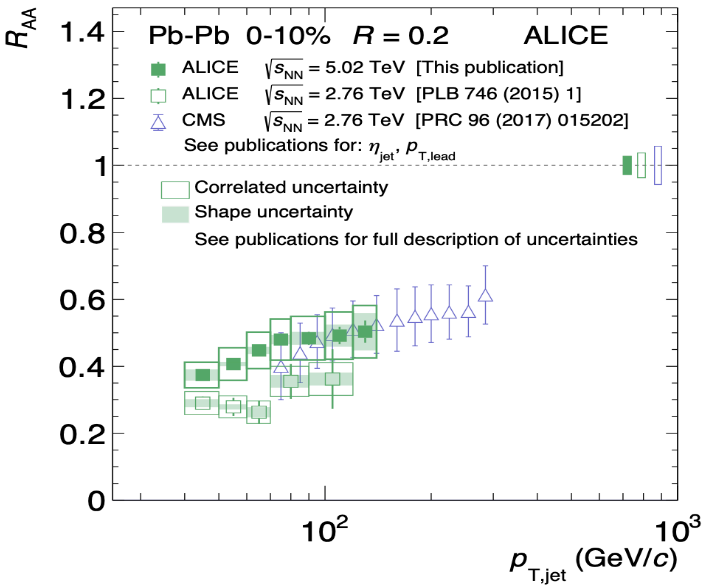
Jet quenching: jet energy loss caused by interaction between jet and QGP medium.

Nuclear modification factor: $$R_{AB} = \frac{1}{N_{coll}} \frac{d^2N_{AB}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

Khachatryan V, et al. *JHEP* 04 (2017) 039
ATLAS Collaboration. *JHEP* 07 (2023) 074
Shreyasi Acharya,et al. *PRC* 101 (2020) 3, 034911



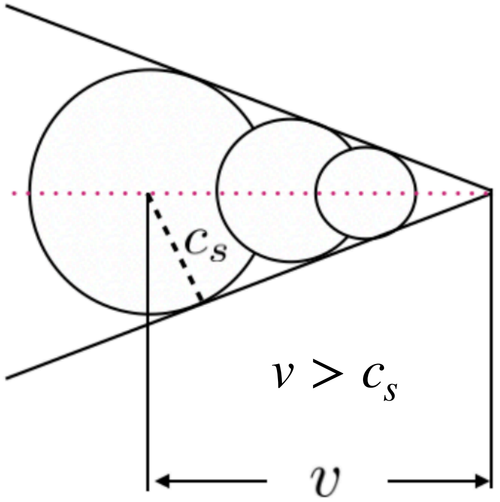


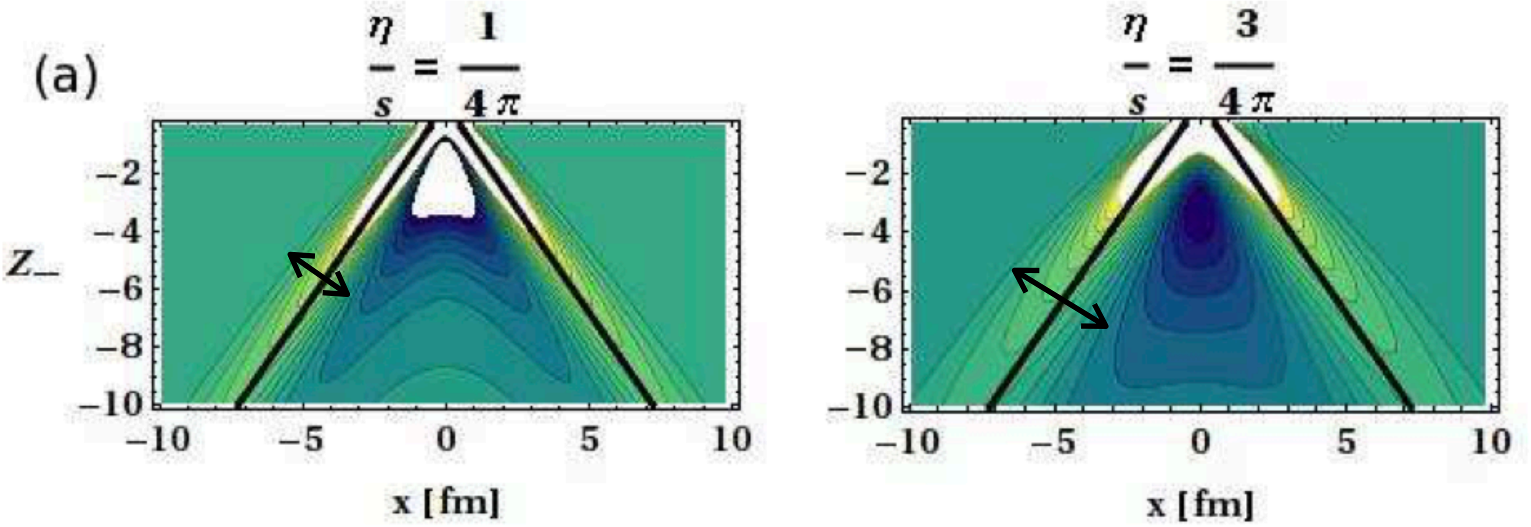


Jet-induced medium response

Energy lost by jet induces medium response which takes the form of Mach-cone-like excitation.

[Casalderrey-Solana, Shuryak, Teaney, 2005; Ruppert, Muller, 2005; Gubser, Pufu, 2008; Qin, Majumder, Song, Heinz, 2009; Yan, Jean, Gale, 2017; …]





R.B.Neufeld Phys.Rev.C 79 (2009) 054909

Sensitive to medium properties

Jet-induced medium response

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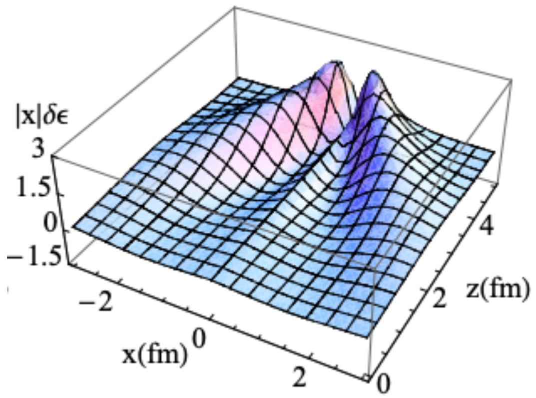
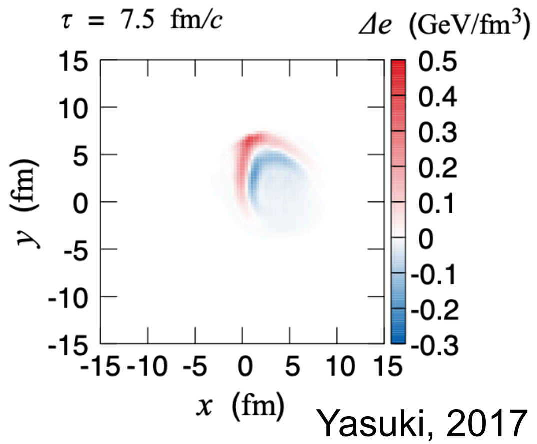
Hydro response

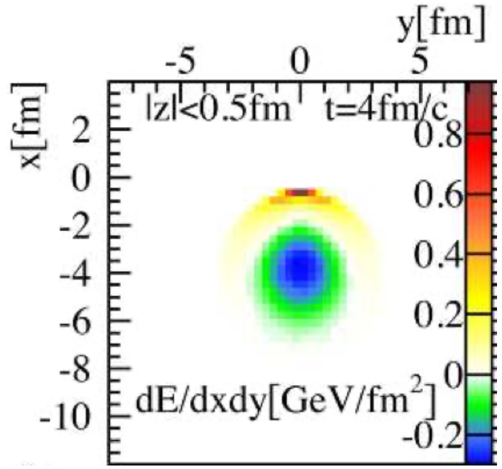


Qin, 2009



Yasuki, 2017

Transport model



Li, 2011

1. LBT
2. Hybrid
3. Jewel

Linear Boltzmann Transport(LBT) model

$$p_1\partial f_1 = -\int dp_2 dp_3 dp_4 (f_1 f_2 - f_3 f_4) \left|M_{12\to34}\right|^2 (2\pi)^4 \delta^4(\sum_i p^i) + inelastic$$

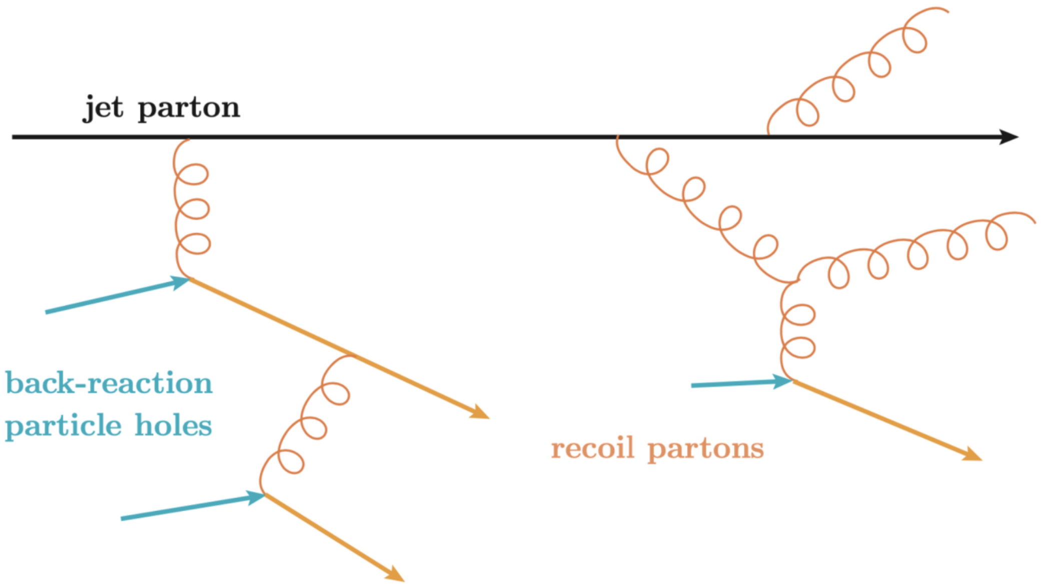
Medium-induced gluon(High-Twist):

[Wang, Guo, 2001]

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

Tracked partons:

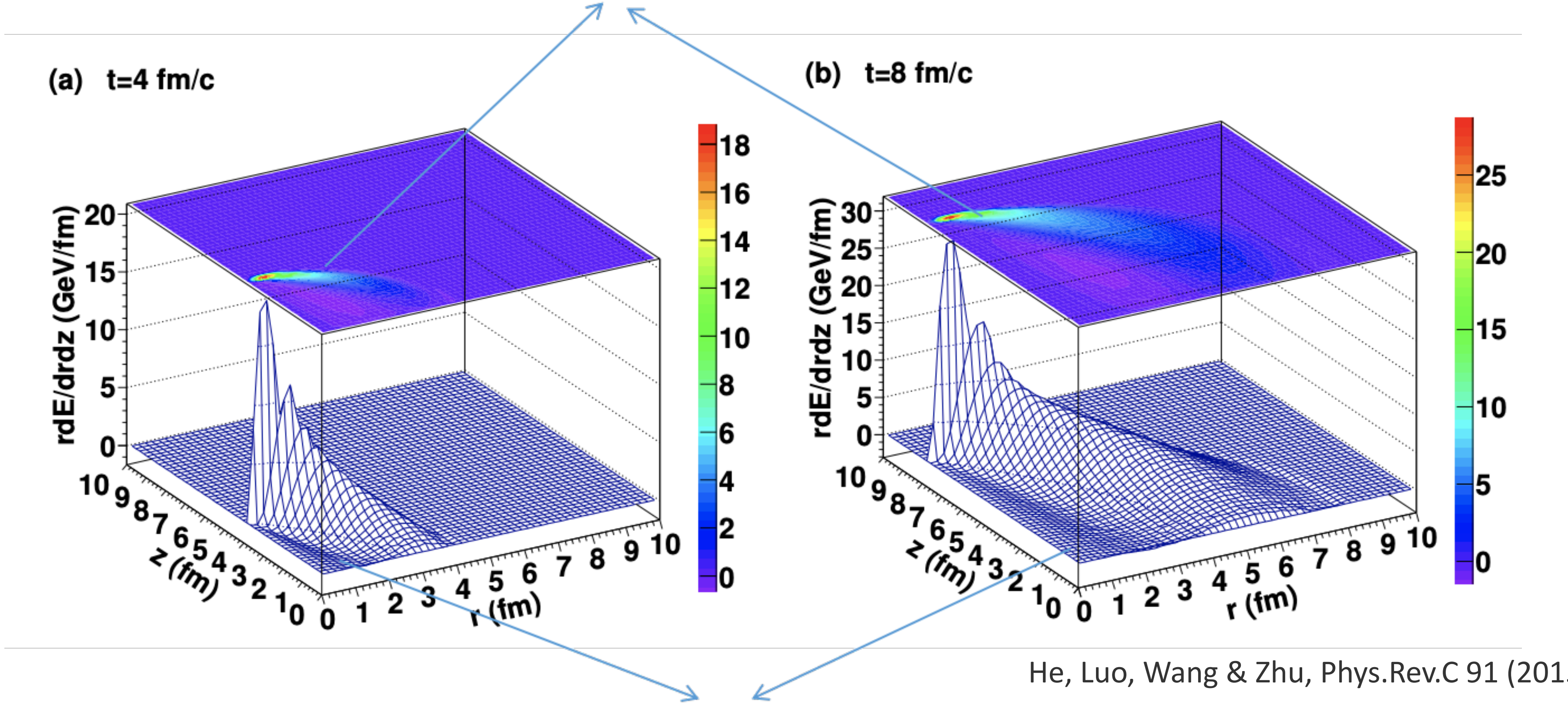
Jet shower partons
Thermal recoil partons
Radiated gluons
Negative partons



LBT: Pure pQCD description of parton transport

LBT: jet-induced medium response

Shock wave: propagation of recoil particles



He, Luo, Wang & Zhu, Phys.Rev.C 91 (2015) 054908

Diffusion wake: propagation of negative partons

Medium response: recoil and negative particles

CoLBT-hydro model

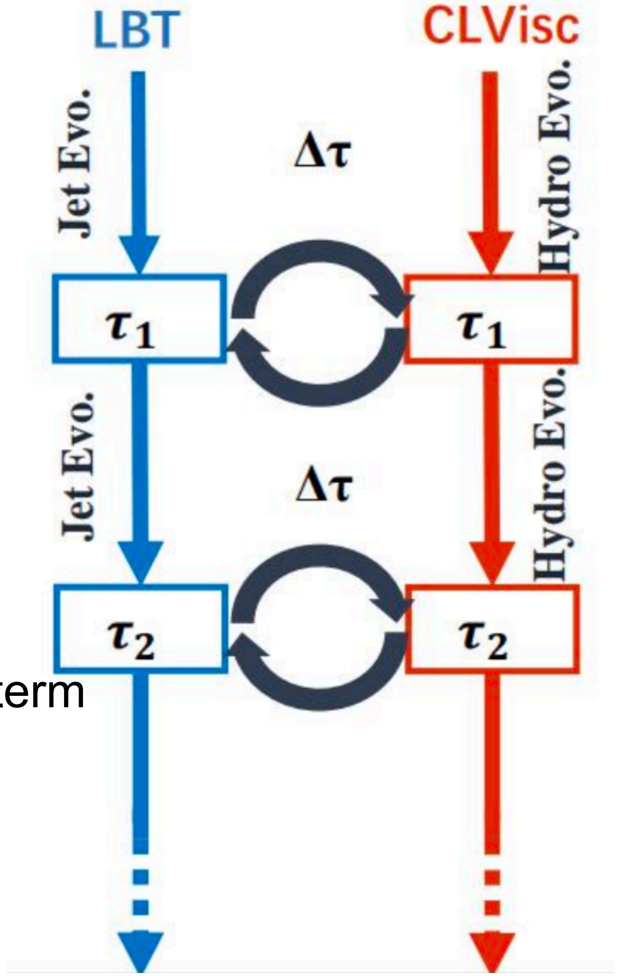
1. LBT for energetic partons(jet shower)

2. Hydrodynamic model for bulk and soft particles: CLVisc

3. Sorting partons according to a cut-off parameter p^0_{cut} (2 GeV)
   Hard partons: $p\partial f(p) = -C(p) \quad (p \cdot u > p^0_{cut})$
   Soft and negative partons:
$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

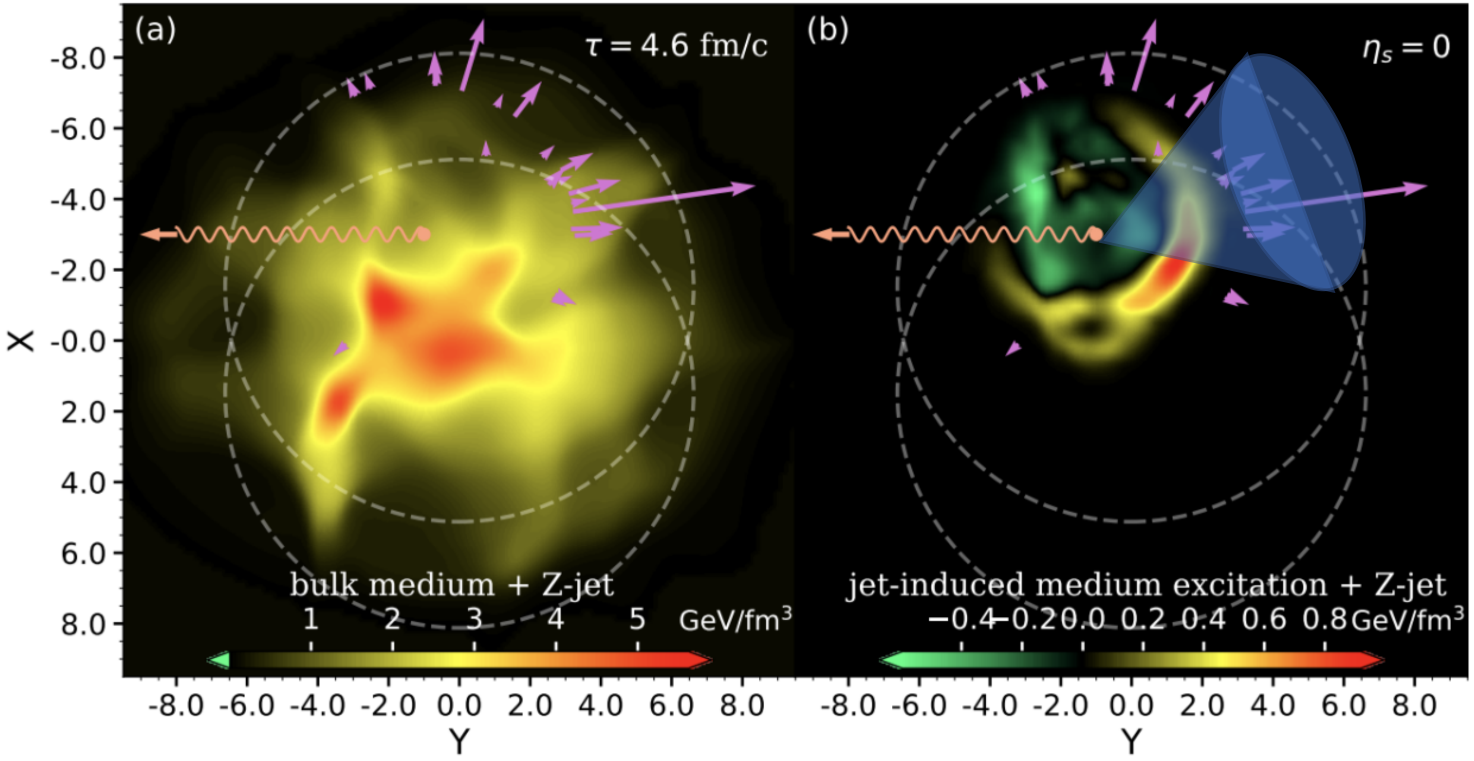
4. Updating medium information by solving the hydrodynamics equation with source term
$$\partial_\mu T^{\mu\nu} = j^\nu$$

5. The final hadron spectra:
   (1) hadronization of hard partons within a parton hadronization model
   (2) jet-induced hydro response via Cooper-Frye freeze-out



Wei Chen

CoLBT-hydro: Jet-induced medium response

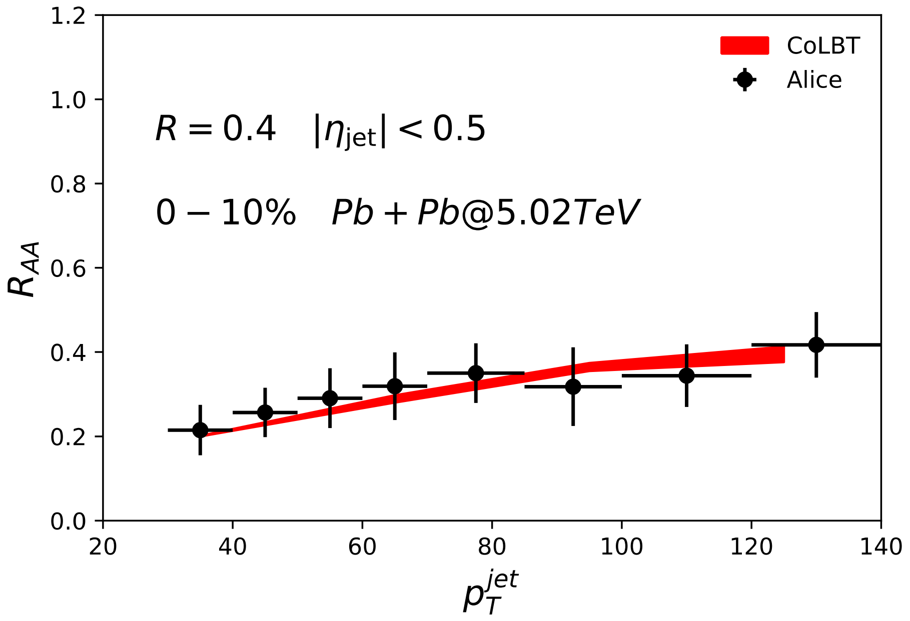


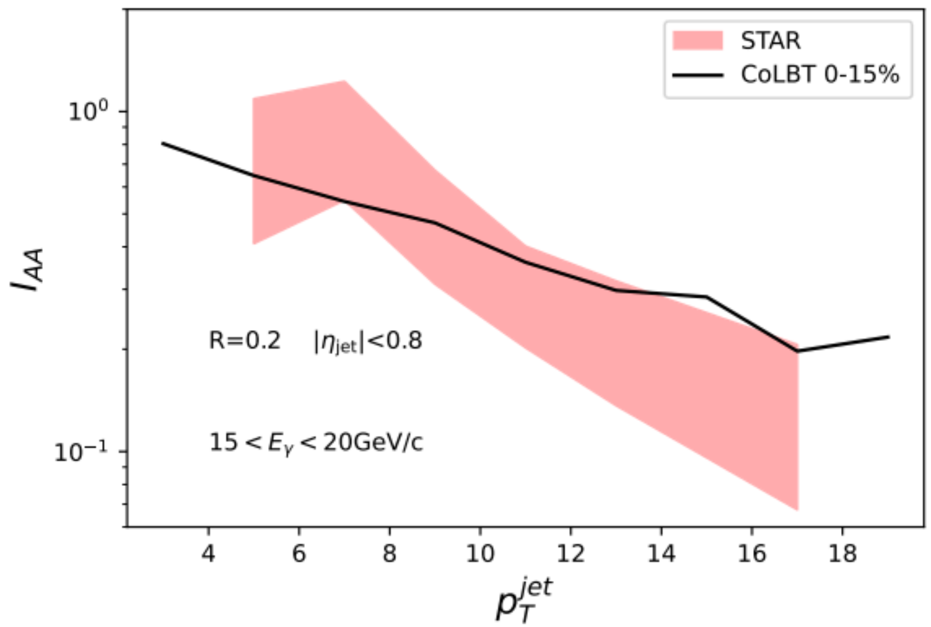
Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

We run model twice with and without jet to subtract hydro background

The Mach-cone-like jet-induced medium response including the diffusion wake is clearly seen in the right panel.

Jet energy loss simulated by CoLBT-hydro





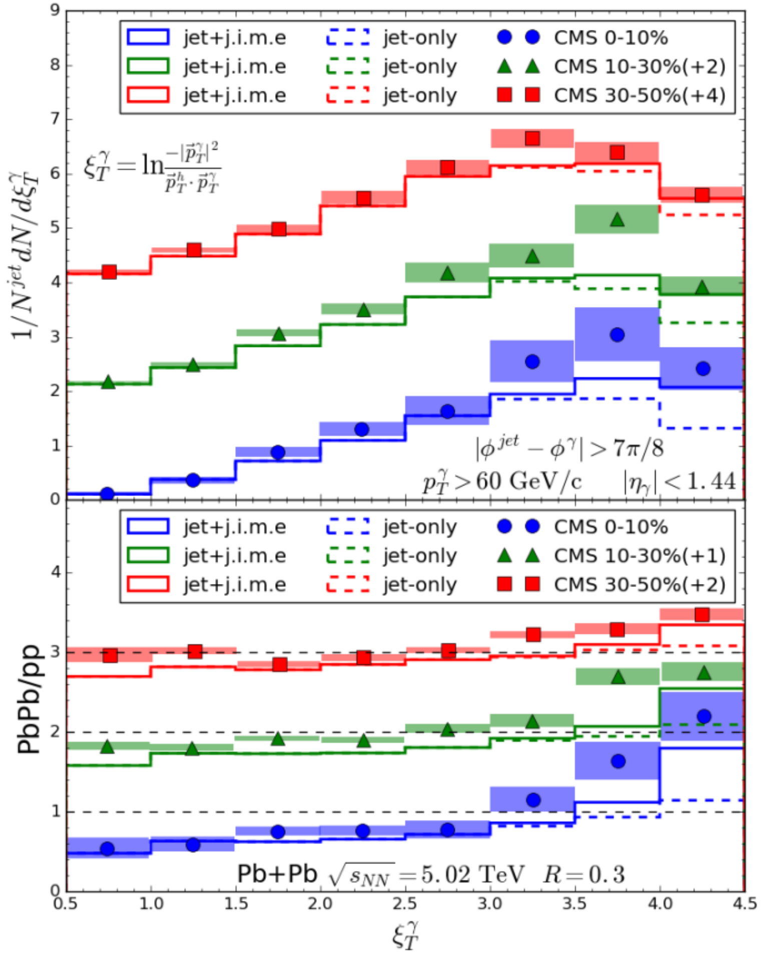
$$R_{\mathrm{AA}} = \frac{d\sigma_{\mathrm{jet}}^{\mathrm{AA}}}{\langle N_{bin}\rangle d\sigma_{\mathrm{jet}}^{pp}}$$

$$I_{\mathrm{AA}} = \frac{dN_{\mathrm{AA}}}{dp_T^{\mathrm{jet}}} / \frac{dN_{\mathrm{pp}}}{dp_T^{\mathrm{jet}}}$$

CoLBT-hydro model is an effective model to describe jet energy loss in QGP (RHIC, LHC, single jet and trigger-jet)

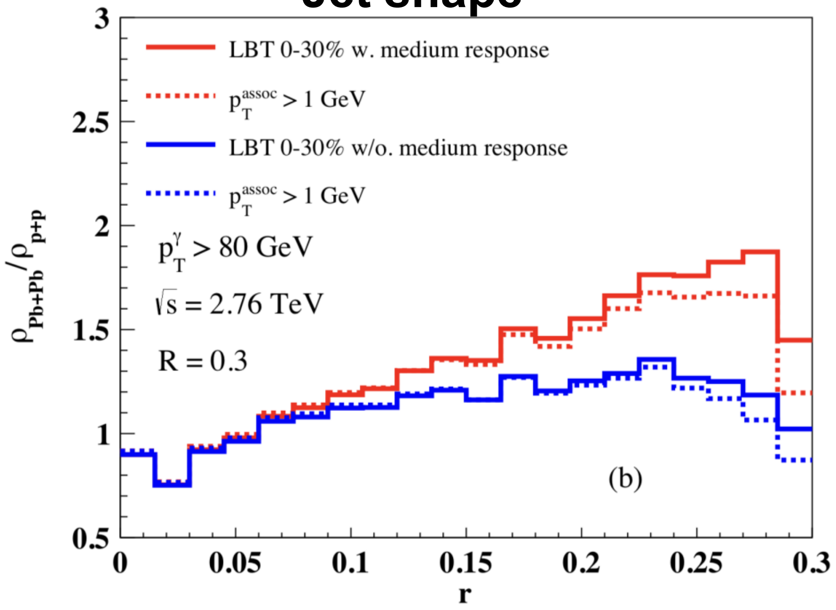
Studying of jet-induced medium response

Jet fragmentation function



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

Jet shape



Luo, Cao, He & Wang, PLB 782 (2018) 707-716

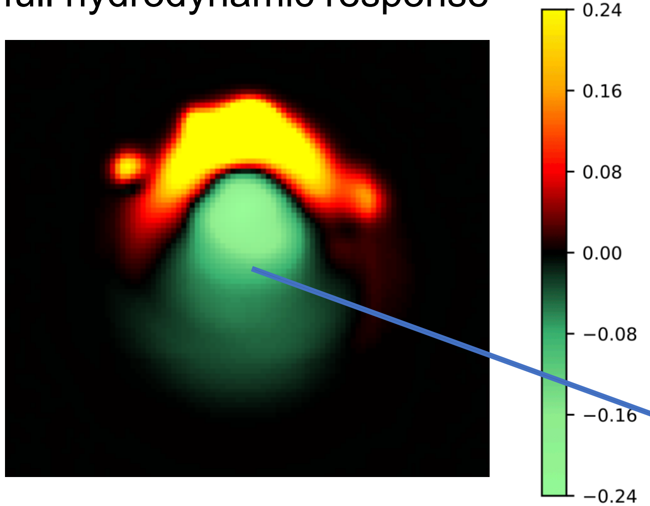
$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{\rm jets}\sum_{r<r_{\rm trk}<r+\delta r}(p_T^{\rm trk}/p_T^{\rm jet})}{\sum_{\rm jets}\sum_{r_{trk}<R}(p_T^{\rm trk}/p_T^{\rm jet})}$$

Jet-induced medium response leads to enhancement of soft hadrons at large angle inside jet

Medium response and soft gluon radiation

Medium response leads to enhancement of soft hadrons along the direction of jet.
Medium-induced gluon radiation has the similar effect.

full hydrodynamic response



Zhong Y, et al. arXiv:2206.02393

Medium response: $\delta f(p) \sim e^{-p\cdot u/T}$

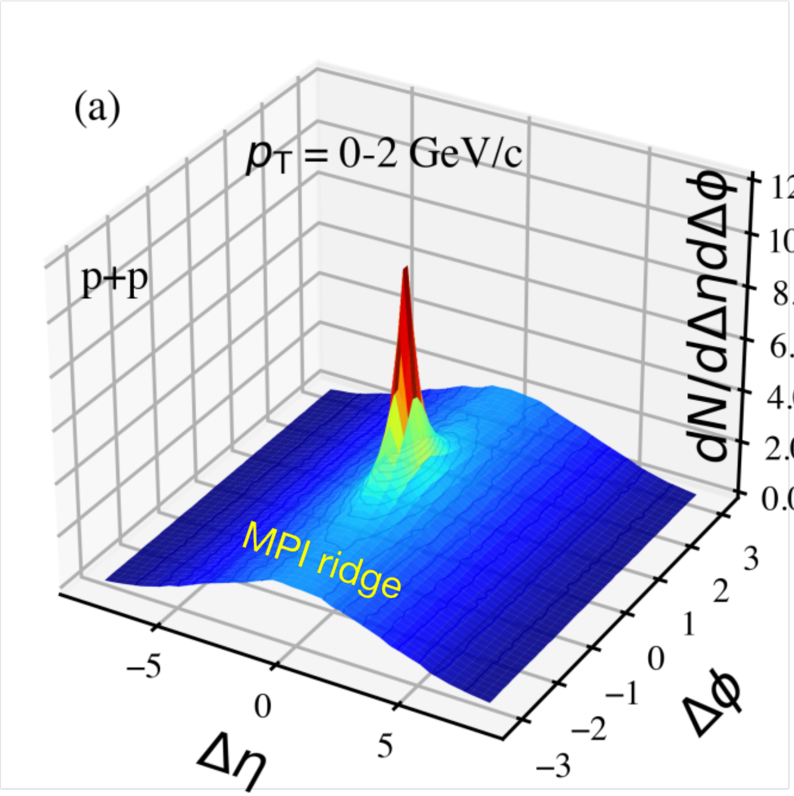
Medium induced gluon radiations: $\omega \approx \lambda^2 \hat{q}/2 \sim T$

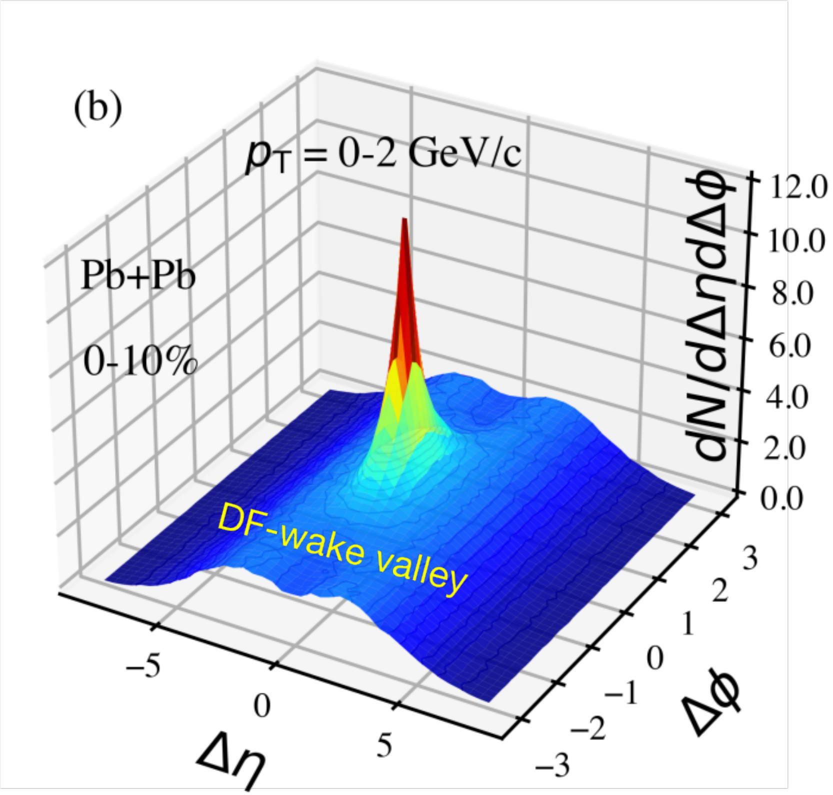
Formation time: $\tau_f = \dfrac{2\omega}{k_T^2}$ $\quad k_T^2 = \hat{q}\tau_f$ $\quad \tau_f \approx \sqrt{2\omega/\hat{q}}$

Mean-free-path limits the formation time: $\tau_f \leq \lambda \sim 1/T \qquad \hat{q} \sim T^3$

Diffusion wake: an unambiguous part of the jet-induced medium response. It can lead to depletion of soft hadrons in the opposite direction of the jet.

3D structure of diffusion wake





$$\Delta\eta = \eta_h - \eta_{\text{jet}}$$

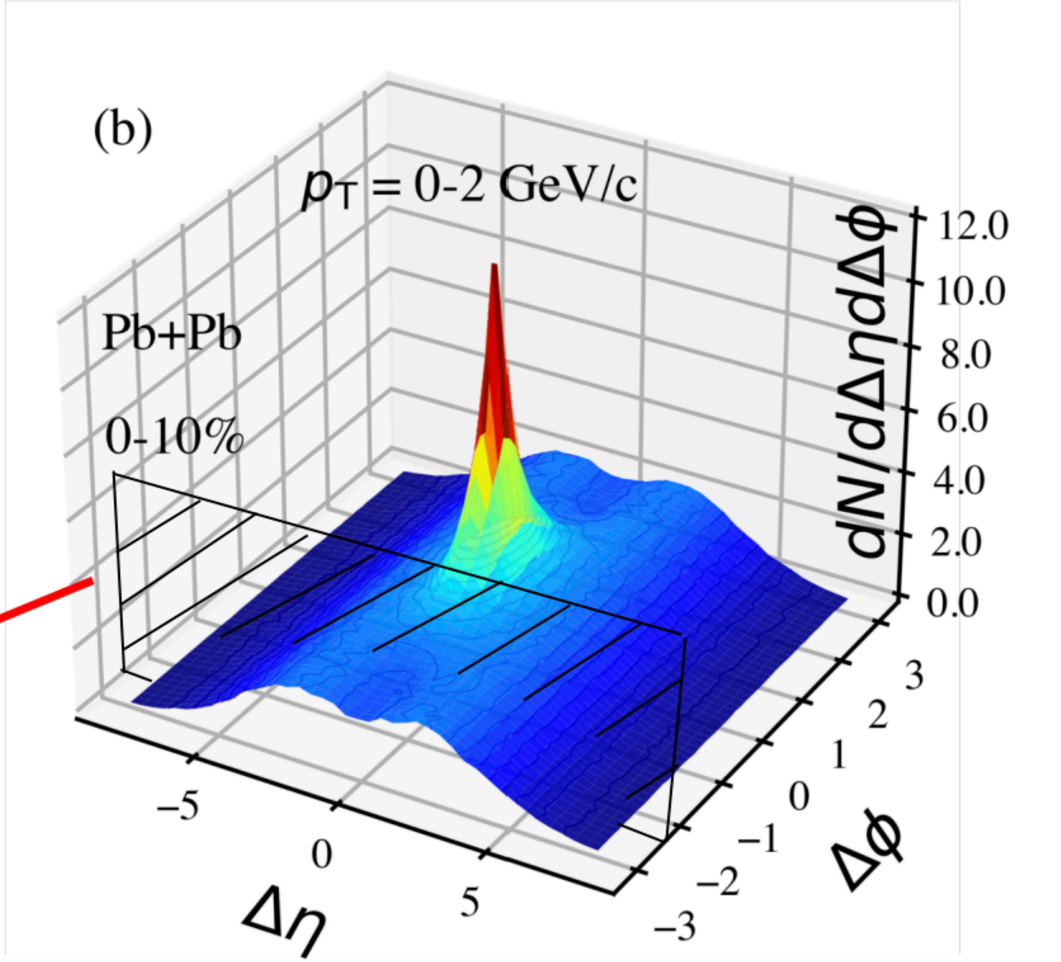
$$\Delta\phi = \phi_h - \phi_{\text{jet}}$$

Diffusion wake valley(DF-wake valley): a valley is formed on top of the MPI ridge due to the depletion of soft hadrons by jet-induced diffusion wake.

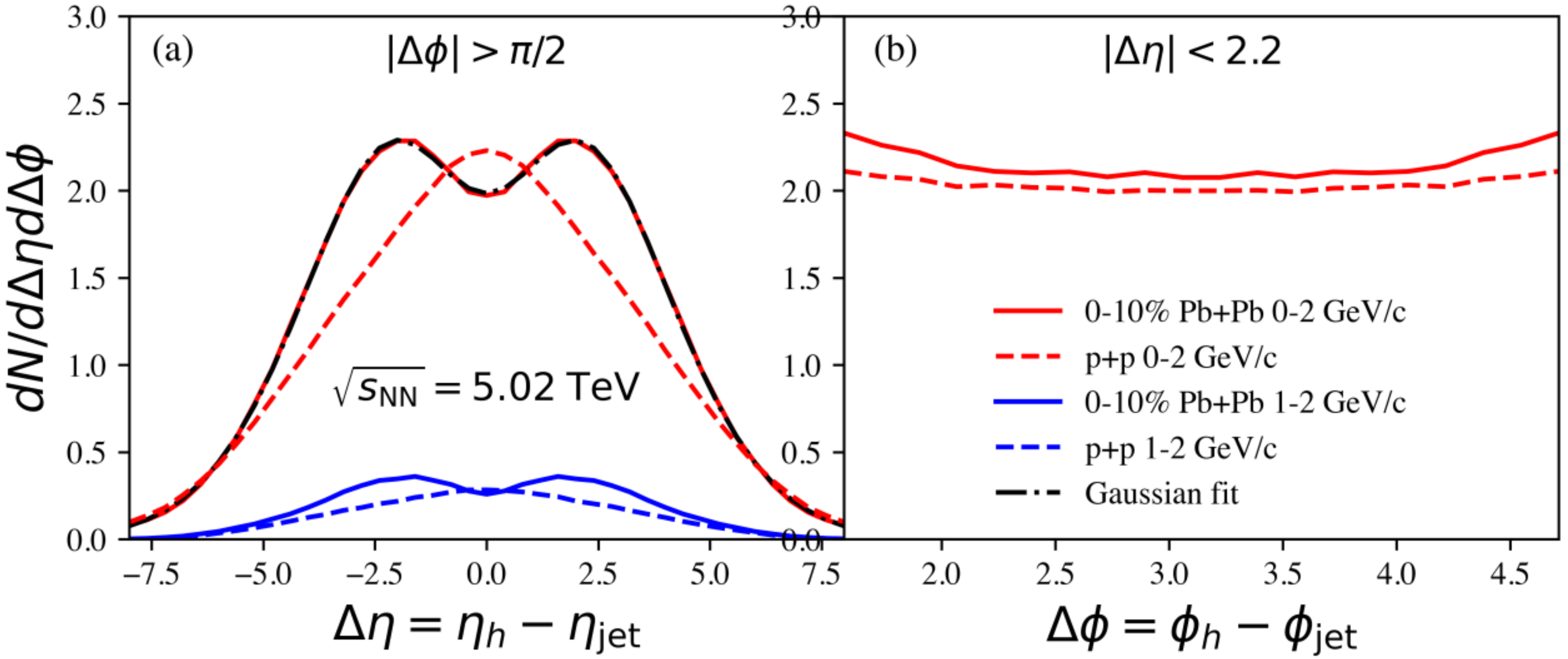
3D structure of diffusion wake

Gamma side

$$|\Delta\phi| > \pi/2$$



3D structure of diffusion wake



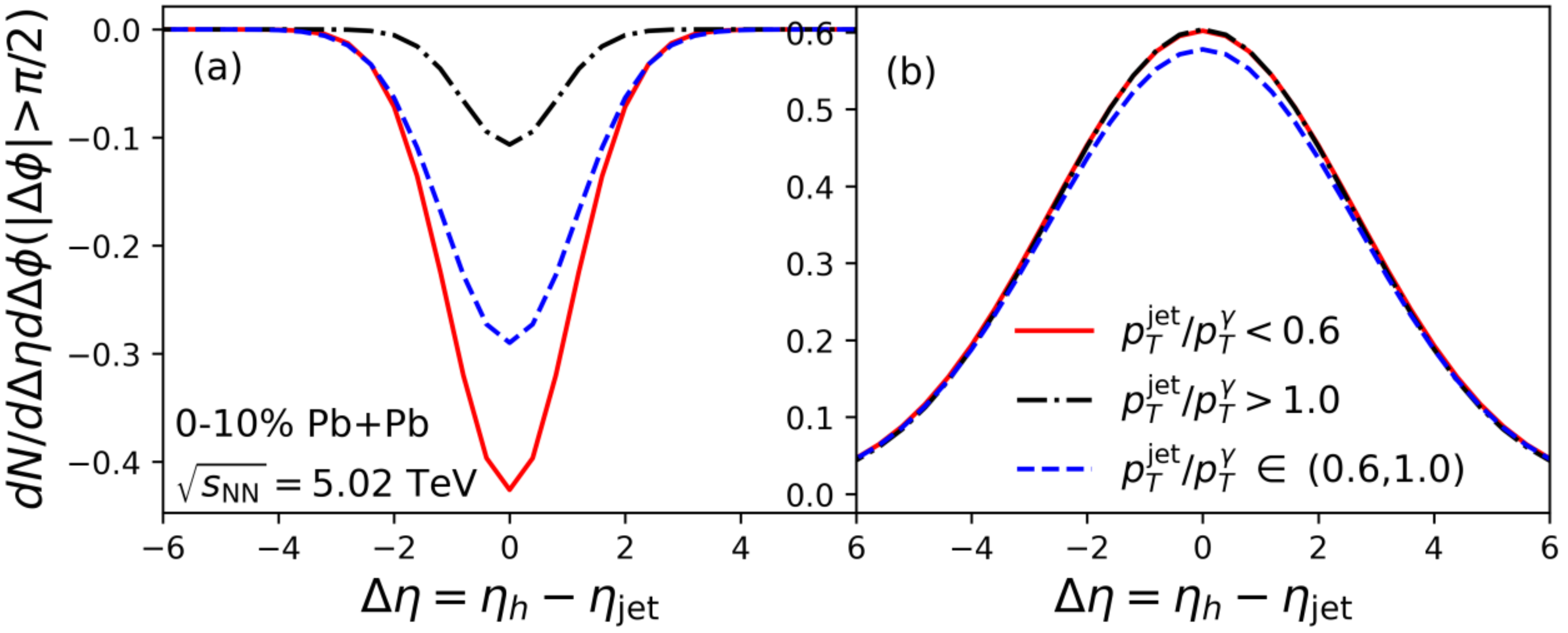
2-Gaussian fitting:

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

$$F_1(\Delta\eta) = A_1 e^{-\Delta\eta^2/\sigma_1^2}$$

$$F_2(\Delta\eta, \eta_j) = A_2 e^{-(\Delta\eta+\eta_j)^2/\sigma_2^2}$$

Sensitivity to jet energy loss



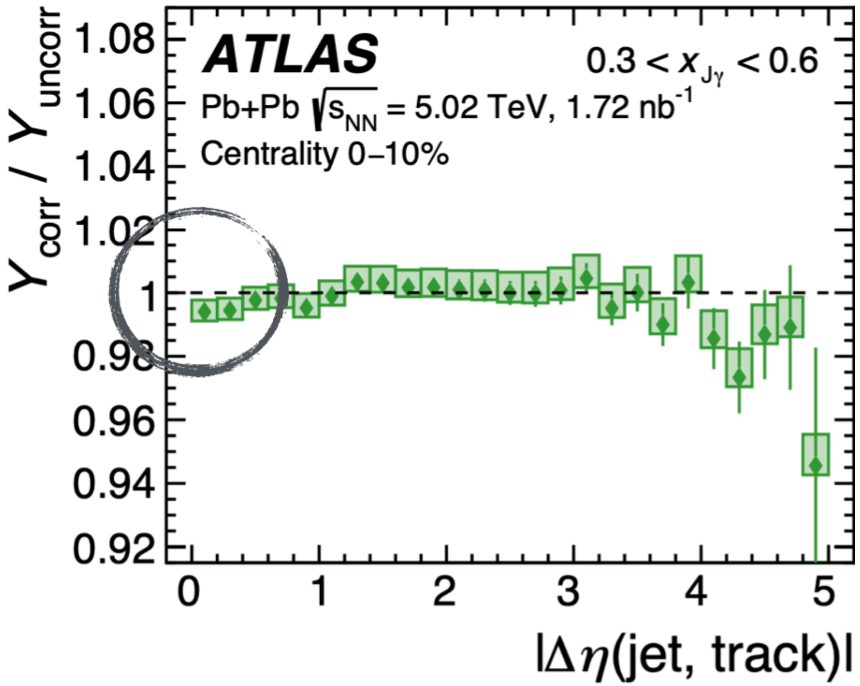
Longer propagation length and larger jet energy loss leads to deeper DF-W valley.

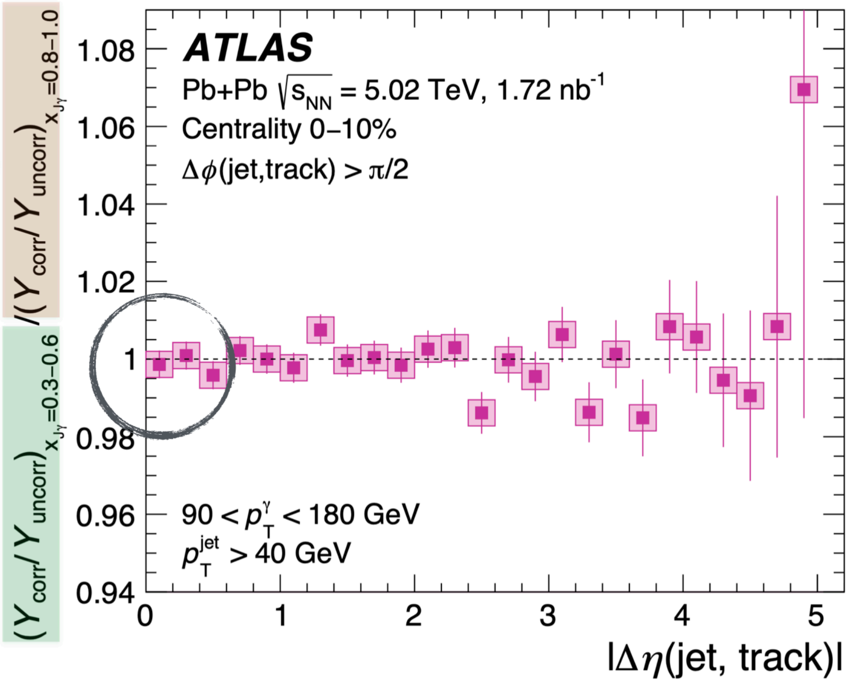
The MPI ridge has a very weak and non-monotonic dependence on $x_{j\gamma}$ due to the non-monotonic dependence of the propagation length on $x_{j\gamma}$ for mini-jets from MPI.

Measurement of 3D structure at LHC

ATLAS Jet-hadron correlation

arXiv:2408.08599





$$Y_{corr} = \frac{1}{N^{\gamma-jet}} \frac{d^2 N^{jet-track}}{d\Delta\eta\Delta\phi}$$

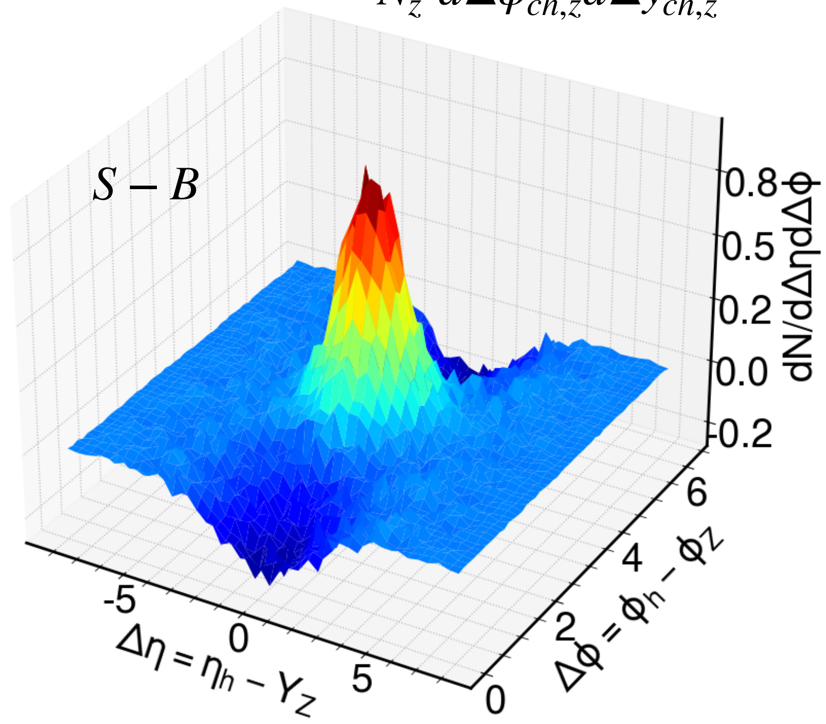
1. The signal to background ratio is very small(~0.5%).
   Consistent with our model prediction.
2. No significant $x_{j\gamma}$-dependence of the diffusion wake is found.

Measurement of 3D structure at LHC

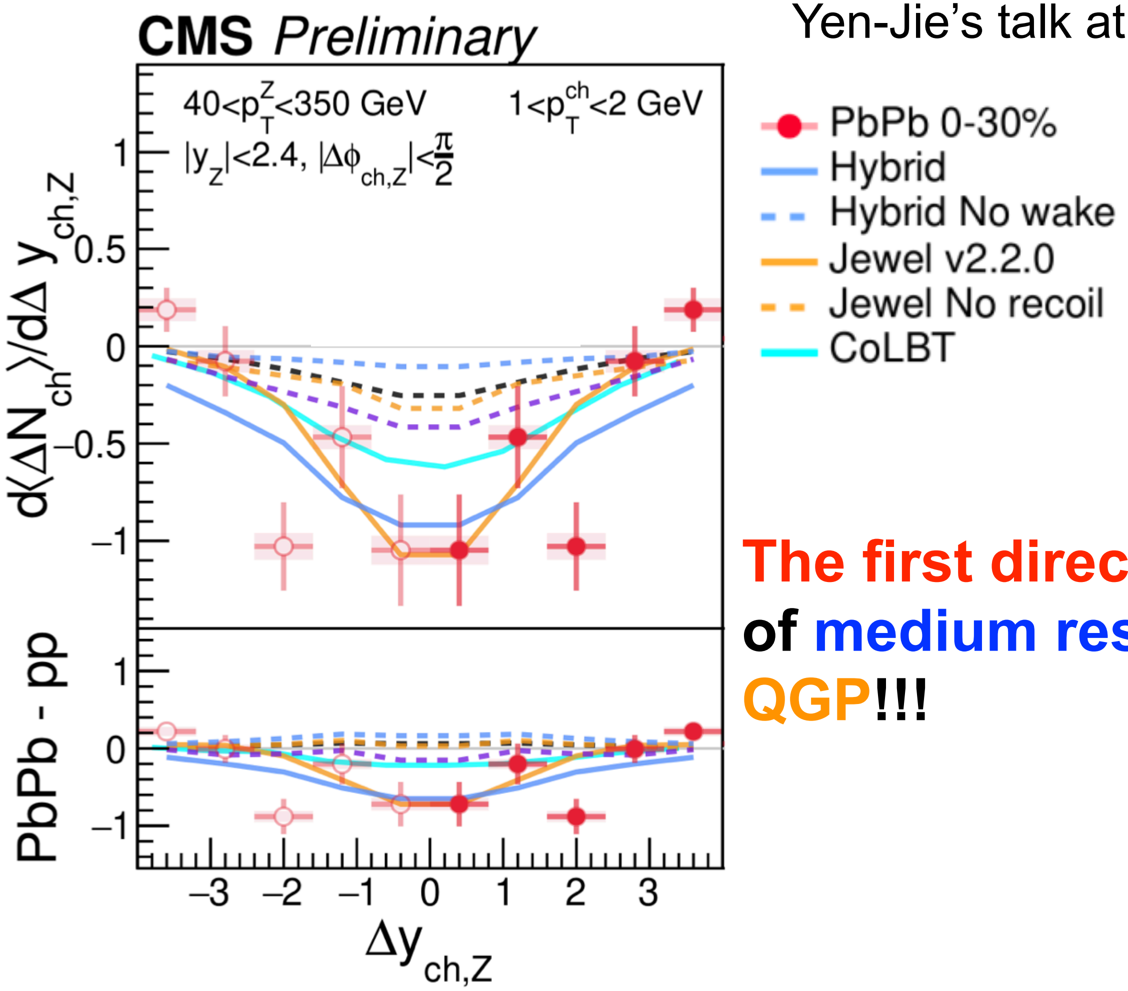
CMS Z-hadron correlation

$$S(\Delta\phi_{ch,z}, \Delta y_{ch,z}) = \frac{1}{N_z}\frac{d^2N^{same}}{d\Delta\phi_{ch,z}d\Delta y_{ch,z}}$$

$$B(\Delta\phi_{ch,z}, \Delta y_{ch,z}) = \frac{1}{N_z}\frac{d^2N^{mix}}{d\Delta\phi_{ch,z}d\Delta y_{ch,z}}$$



Yen-Jie's talk at HP2024



The first direct evidence of medium response in QGP!!!

Summary and Outlook

Summary:

1. Studying of jet-induced medium response can help us understand QGP properties.

2. CoLBT-hydro model is an effective model to study jet quenching and jet-induced medium response.

3. Jet-induced diffusion wake is an unambiguous part of medium response which leads to depletion of hadrons in the opposite direction of jet.

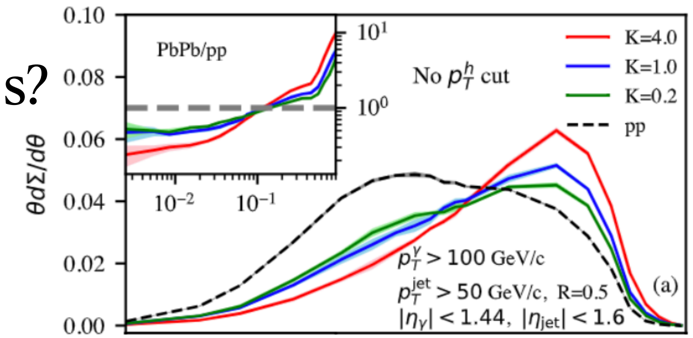
CMS finds it

4. The double-peak structure of jet-hadron correlation in rapidity direction is a unique signal of diffusion wake, and it's sensitive to jet energy loss.

Outlook:

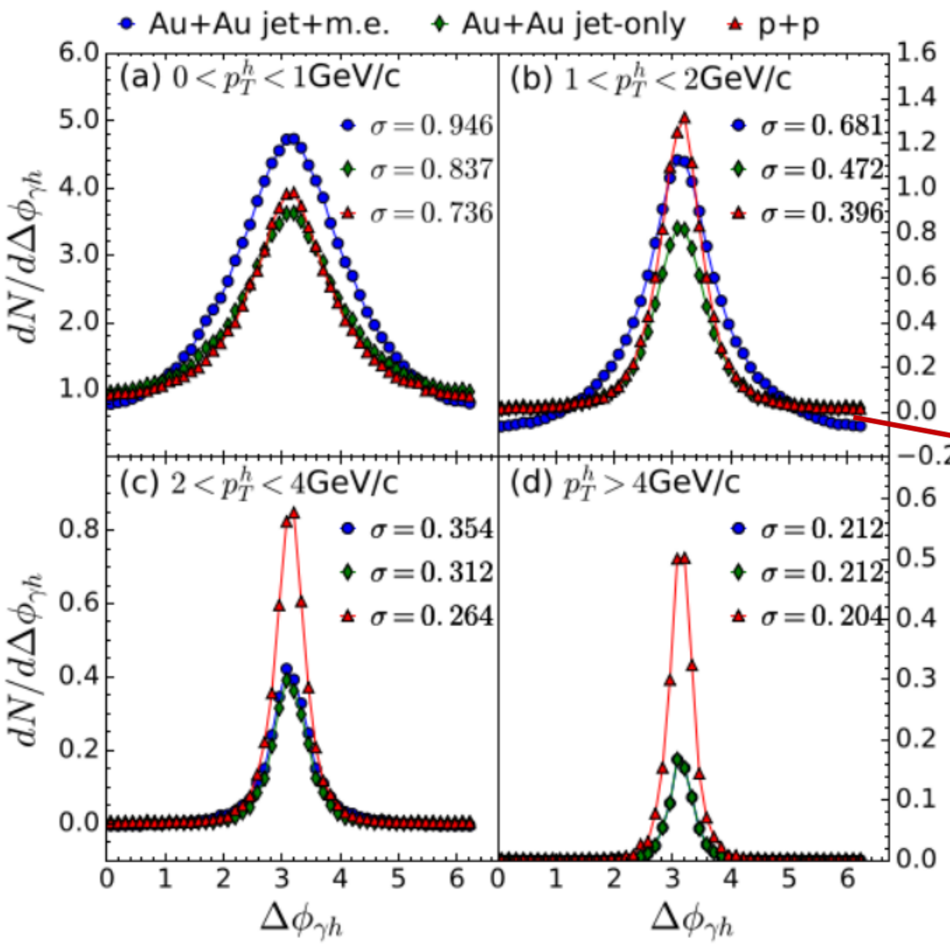
1. What the effect of jet quenching and medium response on EECs?

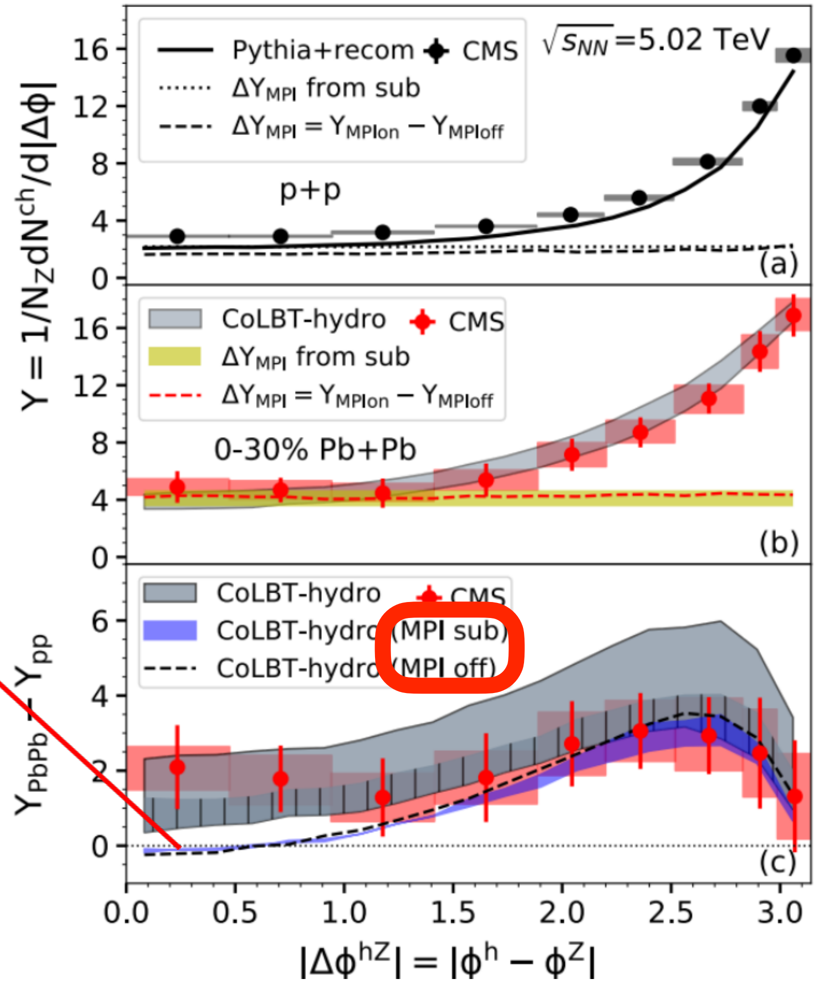
2. Can we distinguish the hadrons from medium response and medium-induced gluon radiation?



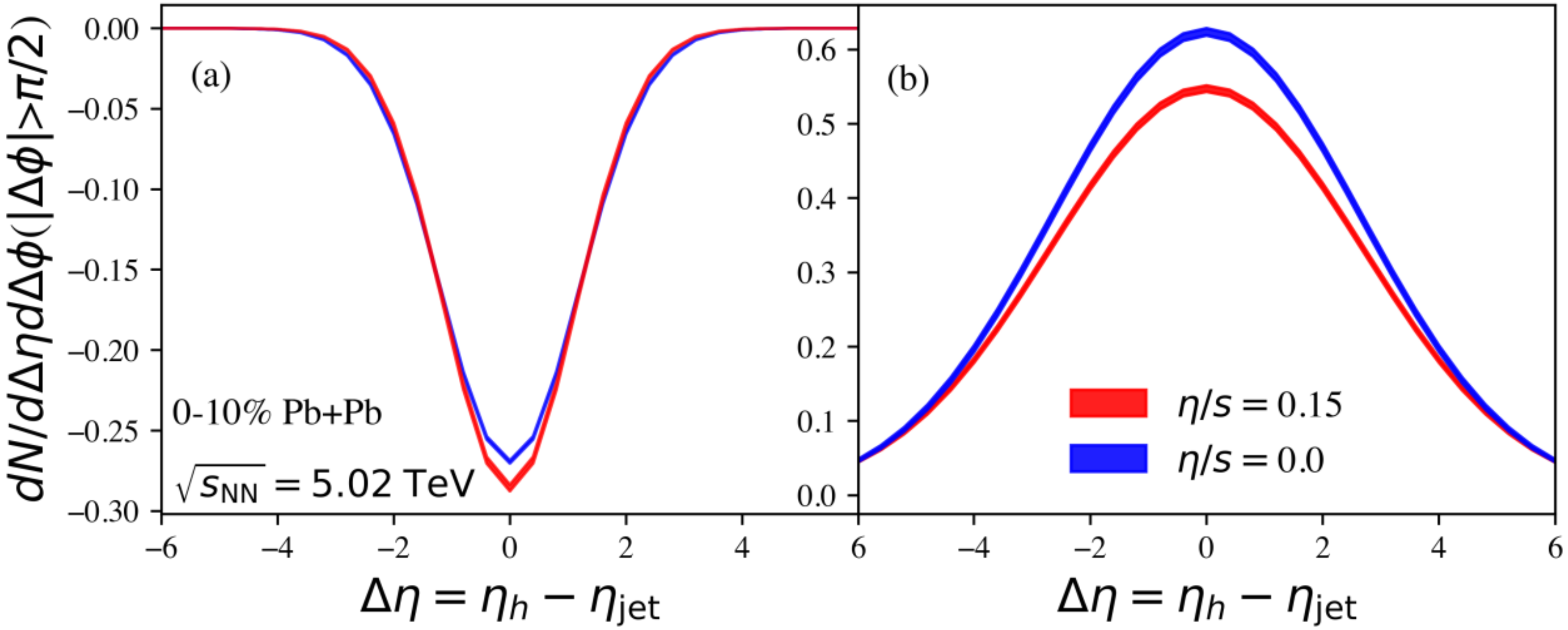
Thank You

Azimuthal distribution of soft hadrons



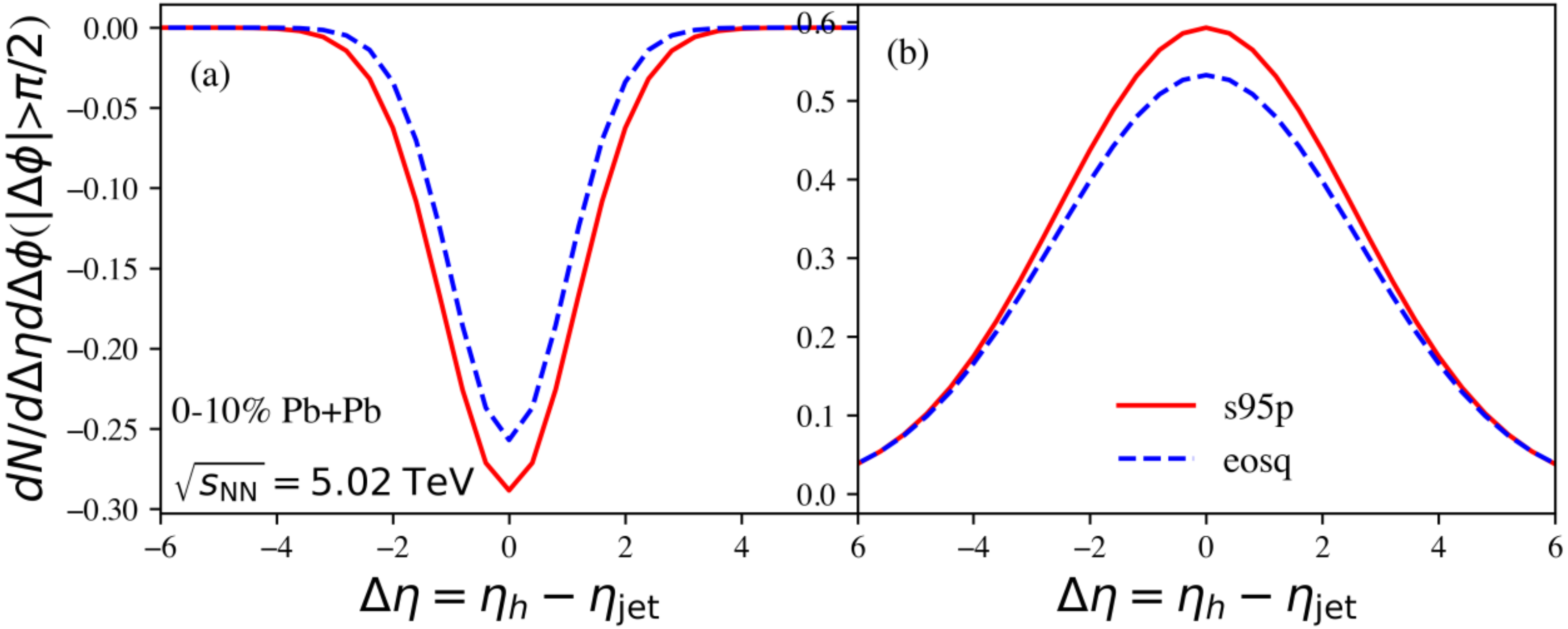


Sensitivity to shear viscosity



Competition between increased radial flow and negative longitudinal pressure in the shear correction of the energy momentum tensor leads to a a slightly smaller MPI ridge and a deeper DF-wake valley in viscous hydro than in an ideal hydro.

Sensitivity to equation of state



The effective speed of sound is higher in eosq than s95.

High speed of sound → a larger Mach cone angle → shallower DF-wake valley

High speed of sound → a stronger radial flow → reduce soft hadrons → small MPI ridge