Jet Modification and Hard-Soft Correlations (SoftJet 2024)

Study of jet-induced medium response in high-energy heavy-ion collisions within the CoLBT-hydro model

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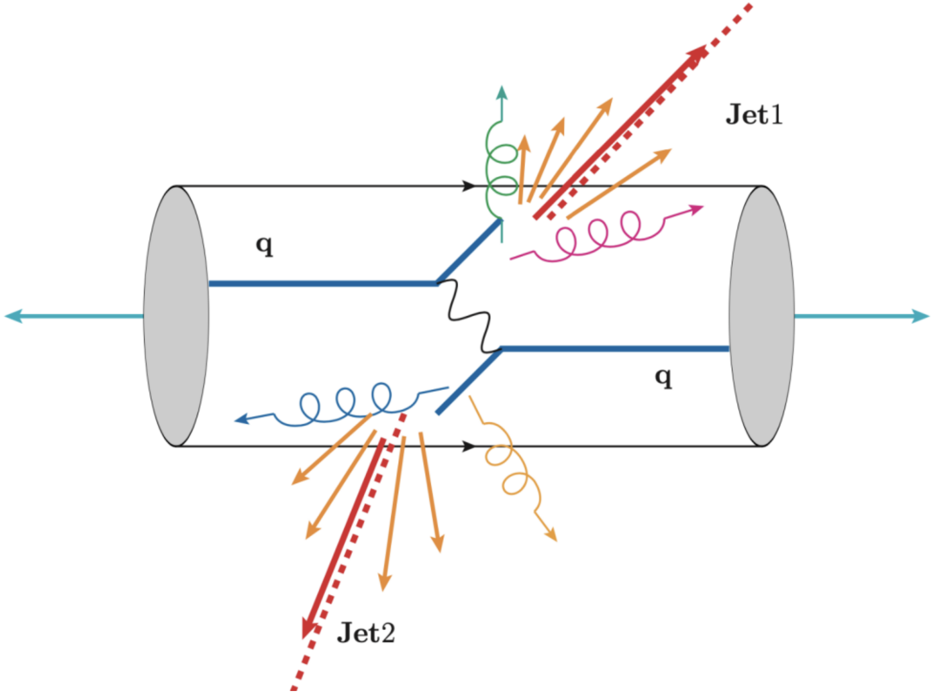
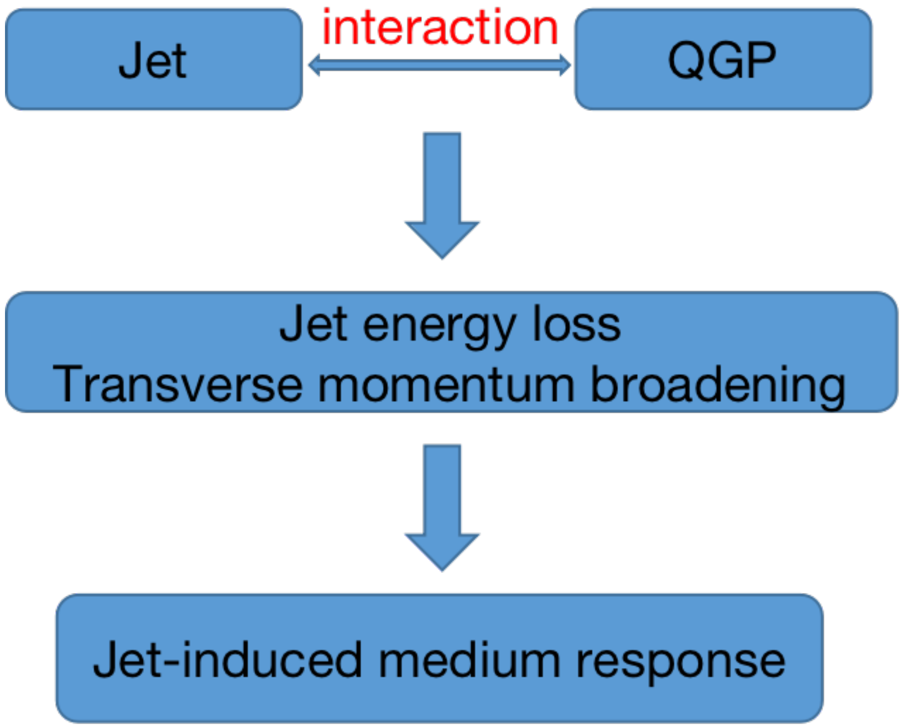
2024.9.27-2024.9.30

Outline

- Introduction
- LBT/CoLBT-hydro model
- Jet-induced medium response
    - Jet-induced diffusion wake
    - 3D structure of diffusion wake
    - EECs in realistic heavy-ion collisions
- Summary and Outlook

Jet in heavy-ion collisions





Jet

interaction

QGP

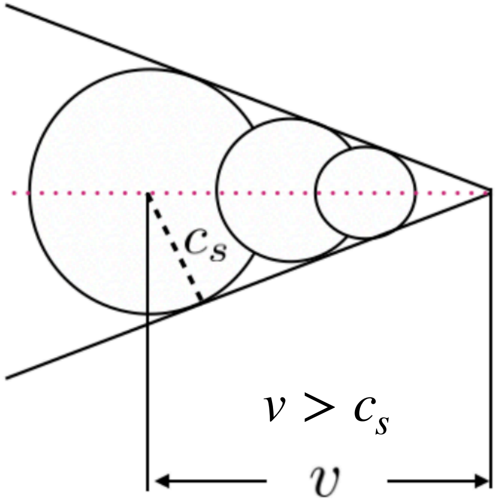
Jet energy loss
Transverse momentum broadening

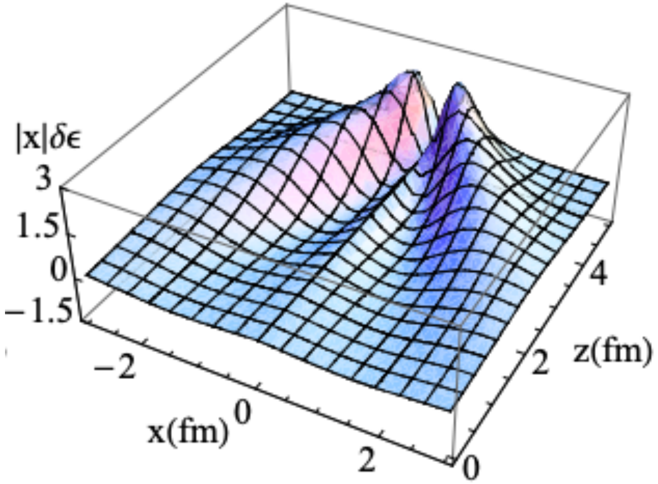
Jet-induced medium response

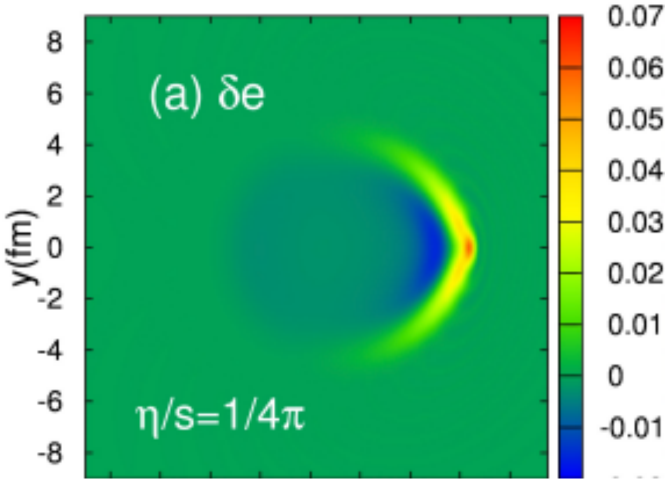
Jet-induced medium response

Jet-induced medium response in 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; …]



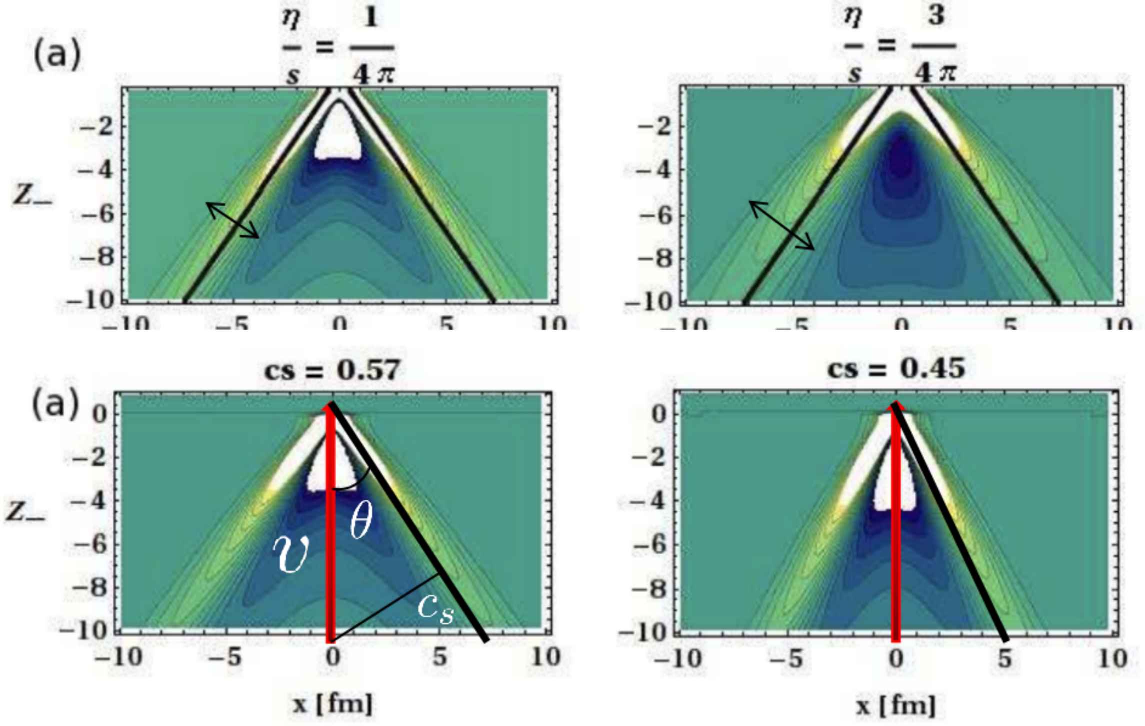




The front wake which is along with the jet direction will modify the particles distribution in jet.

Jet-induced medium response

Jet-induced Mach-cone could extract the QGP properties



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

(1) **Width of front wake** of Mach cone is related with viscous properties of QGP medium;

(2) **Mach cone angle** is sensitive to EoS.

$$sin\theta = \frac{c_s}{v}$$

Linear Boltzmann Transport(LBT) model

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

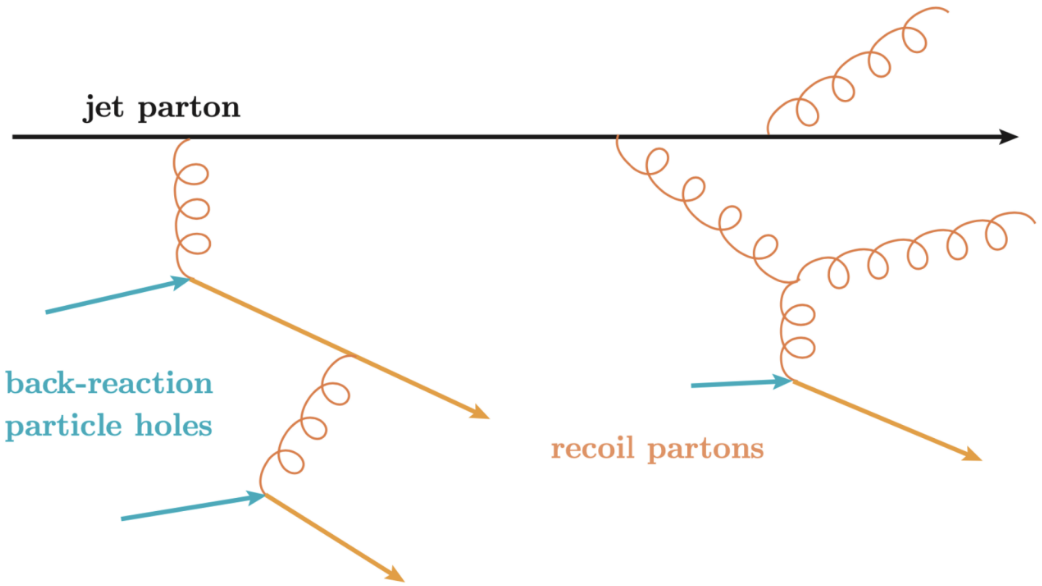
Medium-induced gluon(High-Twist):

[Wang, Guo, 2001]

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

Tracked partons:

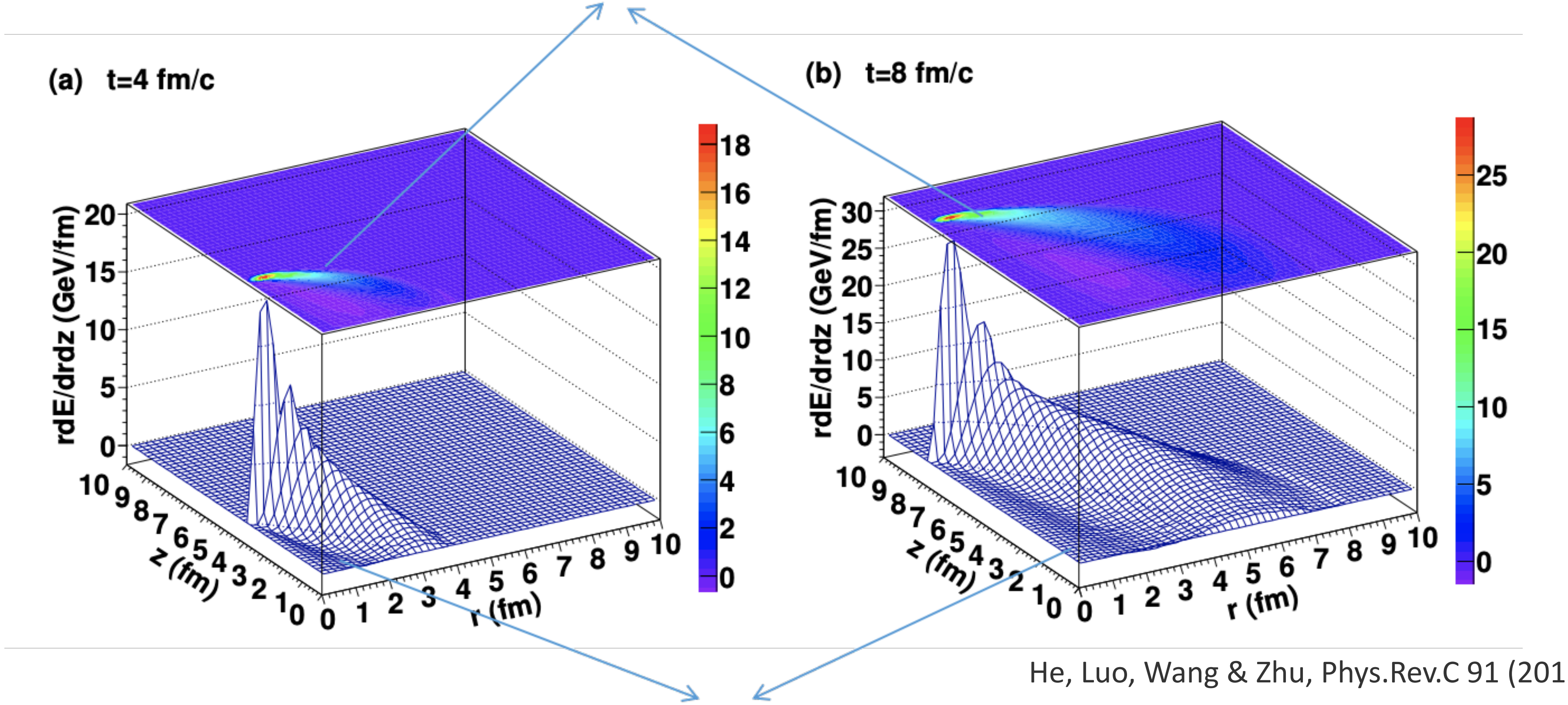
- Jet shower partons
- Thermal recoil partons
- Radiated gluons
- Negative partons



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 and recoil)
2. Hydrodynamic model for bulk and soft particles: CLVisc
3. Sorting partons according to a cut-off parameter p_{cut}^0 (2 GeV)

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

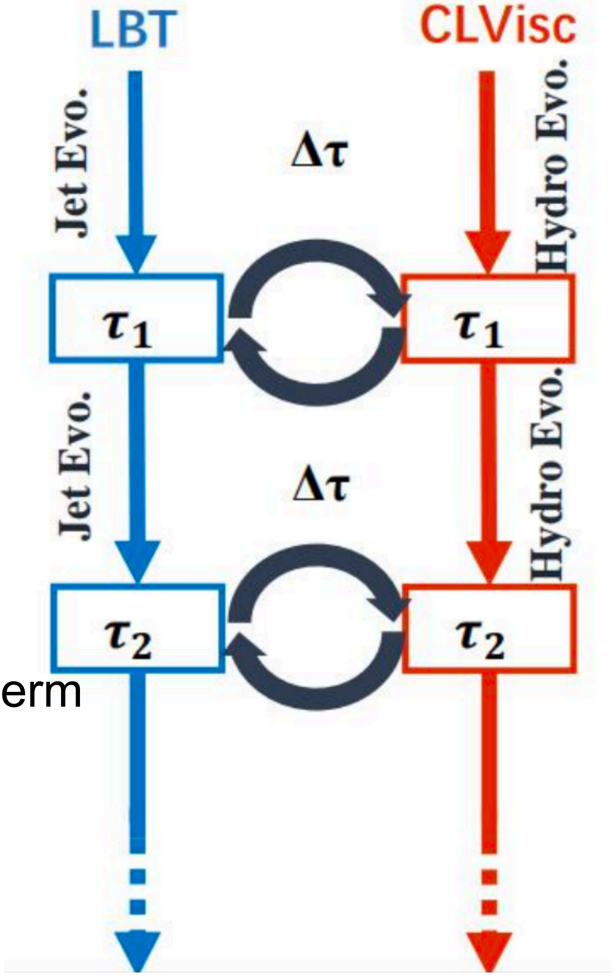
   Soft and negative partons:

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

4. Updating medium information by solving the hydrodynamics equation with source term

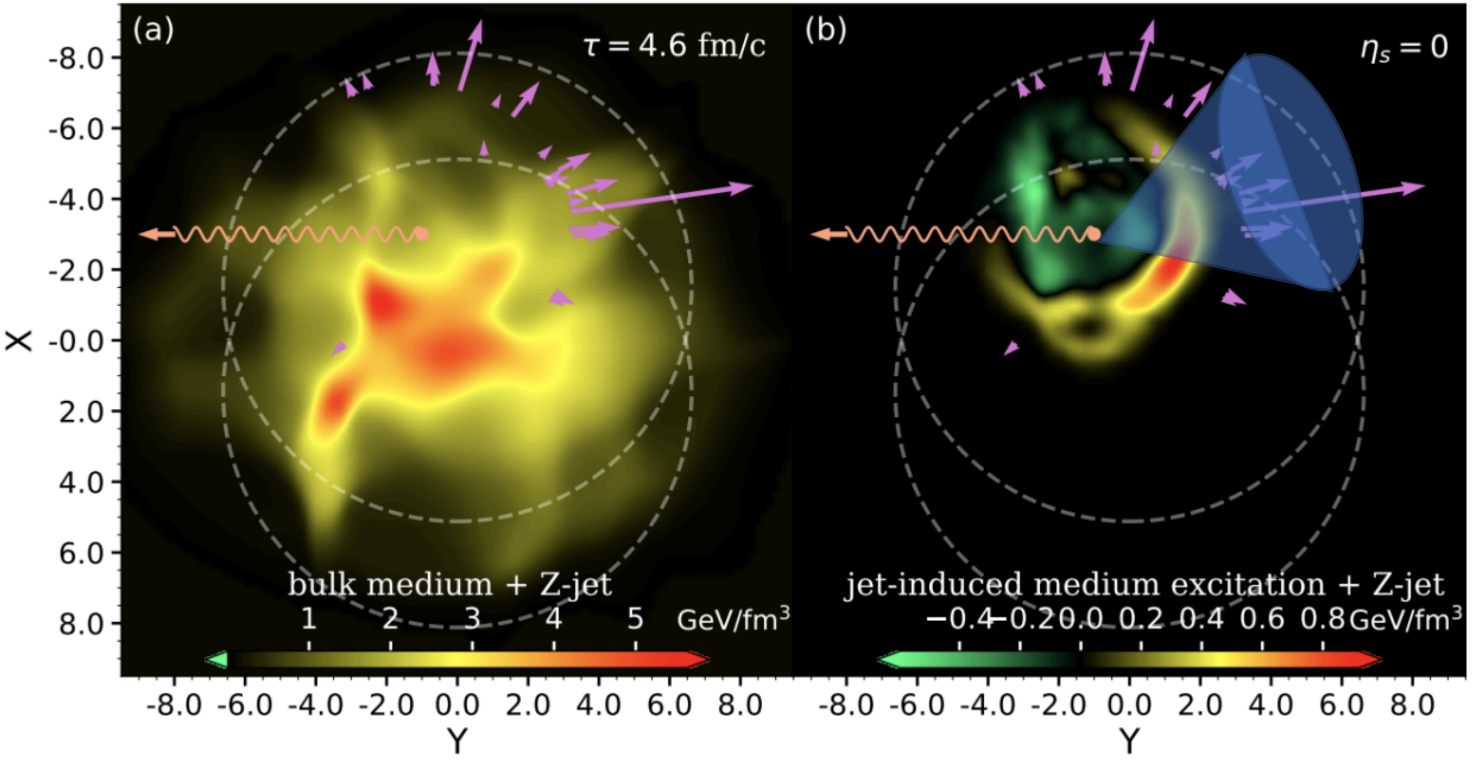
$$\partial_\mu T^{\mu\nu} = j^\nu$$

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



Wei Chen

CoLBT-hydro: Jet-induced medium response

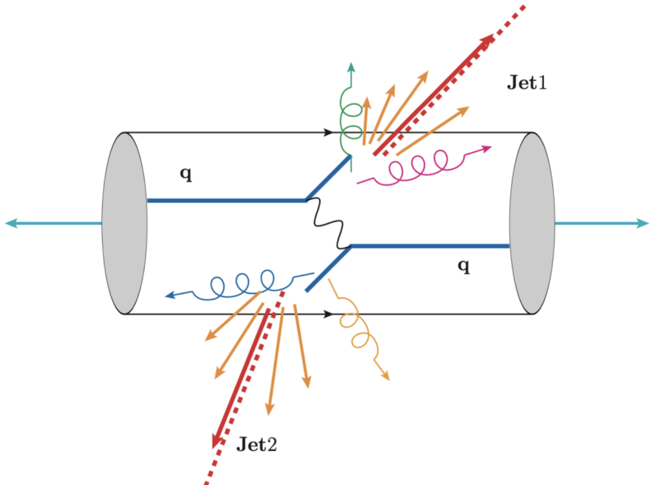


Chen, Yang, He, Ke, Pang and Wang, PRL 127 (2021) 8, 082301

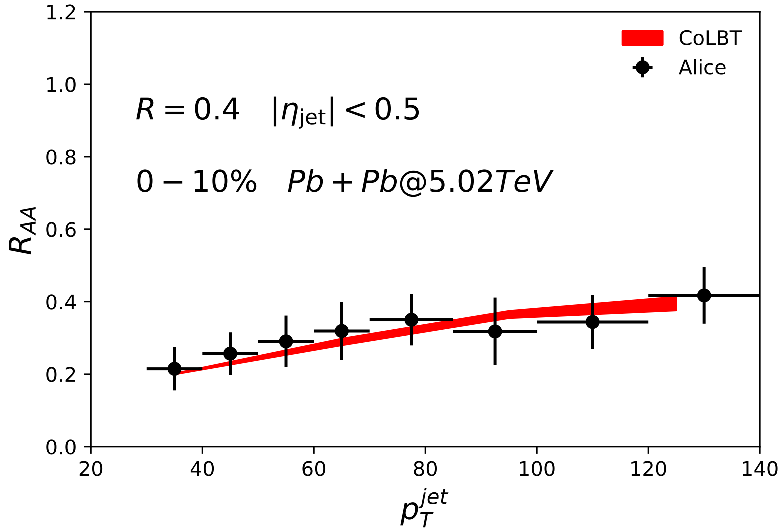
We run model twice with and without jet to subtract hydro background

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

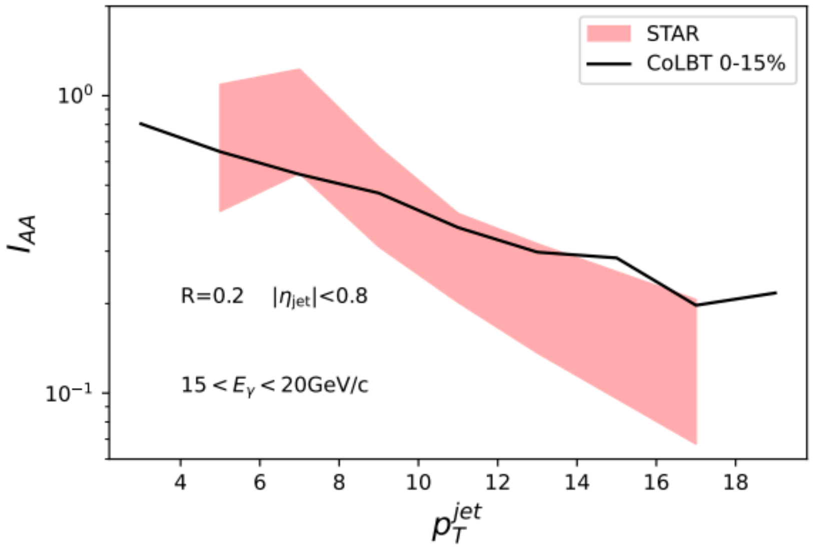
Jet energy loss simulated by CoLBT-hydro



Jet-medium interaction:
the suppression of large transverse momentum jets and hadrons in AA collisions



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

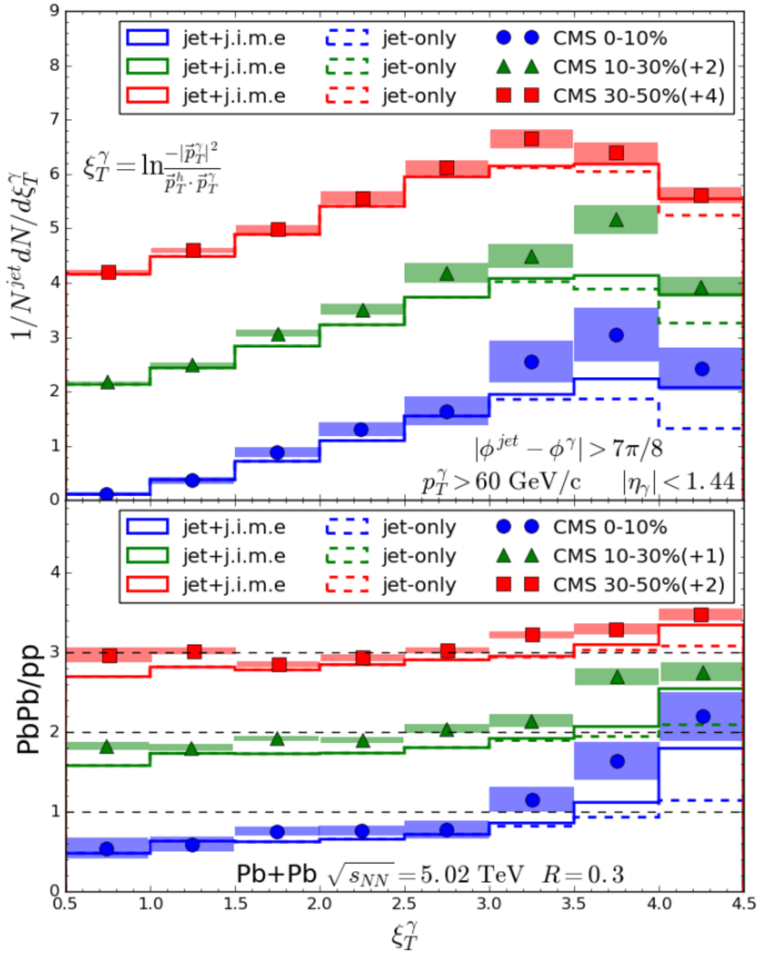


$$I_{\rm AA} = \frac{dN_{\rm AA}}{dp_T^{\rm jet}} / \frac{dN_{\rm pp}}{dp_T^{\rm jet}}$$

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

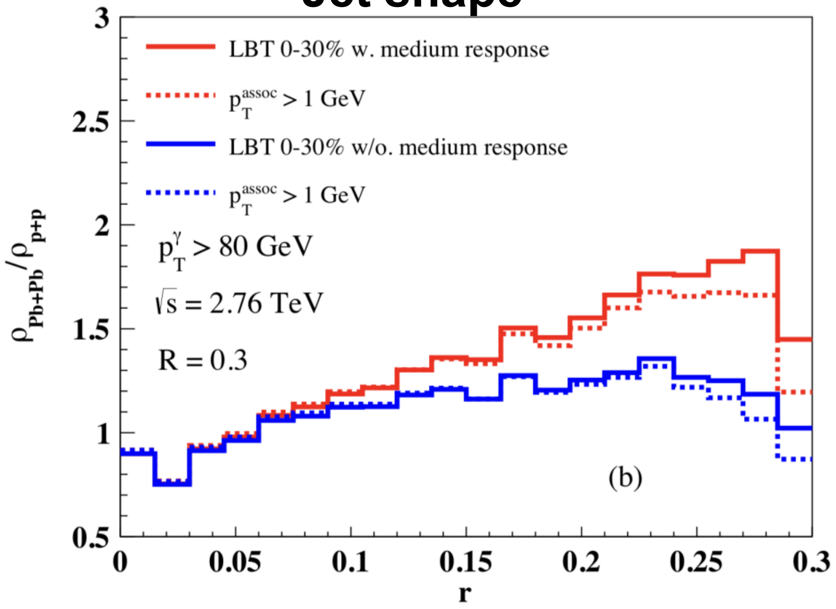
Studying of jet-induced medium response

Jet fragmentation function



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

Jet shape



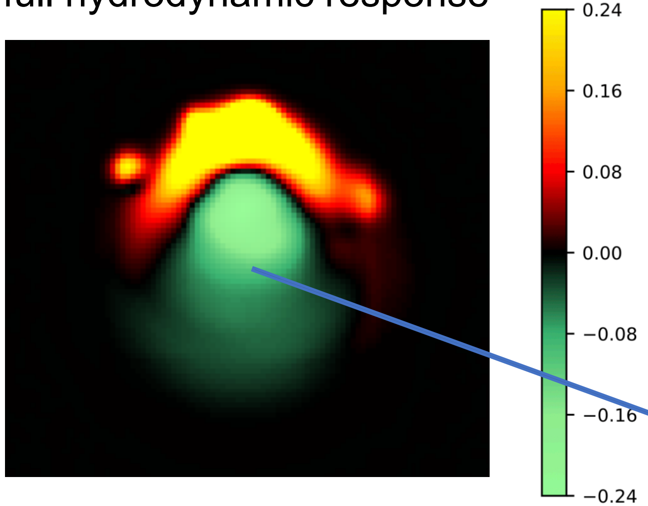
Luo, Cao, He & Wang, PLB 782 (2018) 707-716

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

Jet-induced medium response lead 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: $\delta f(p) \sim e^{-p\cdot u/T}$

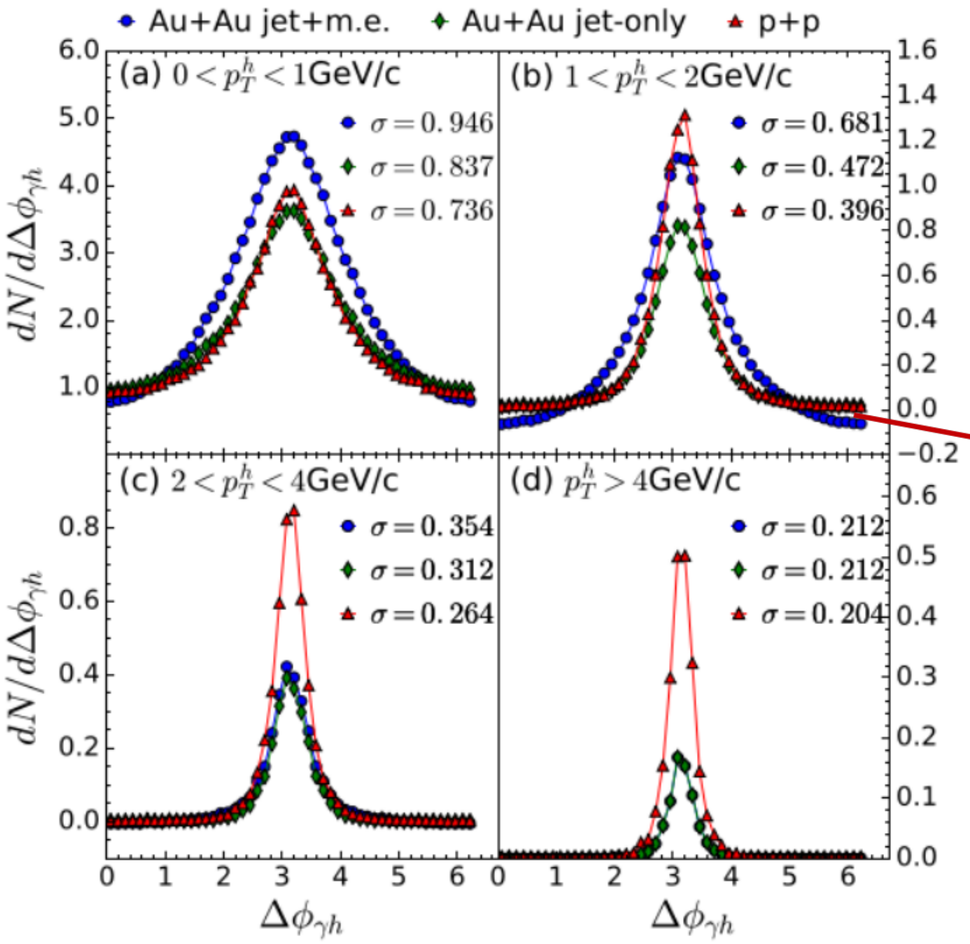
Medium induced gluon radiations: $\omega \approx \lambda^2 \hat{q}/2 \sim T$

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

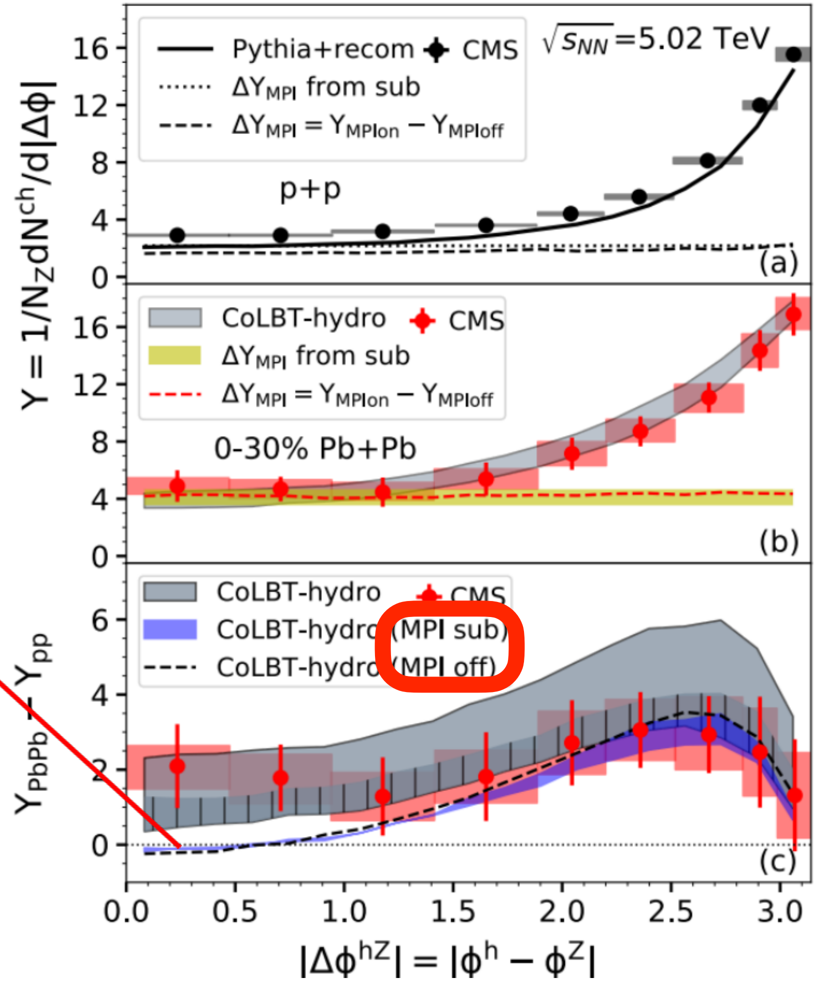
Mean-free-path limits the formation time: $\boxed{\tau_f \leq \lambda \sim 1/T \quad \hat{q} \sim T^3}$

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.

Azimuthal distribution of soft hadrons



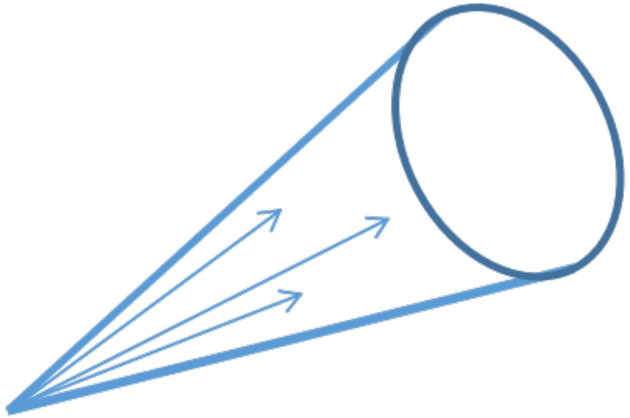
Diffusion wake

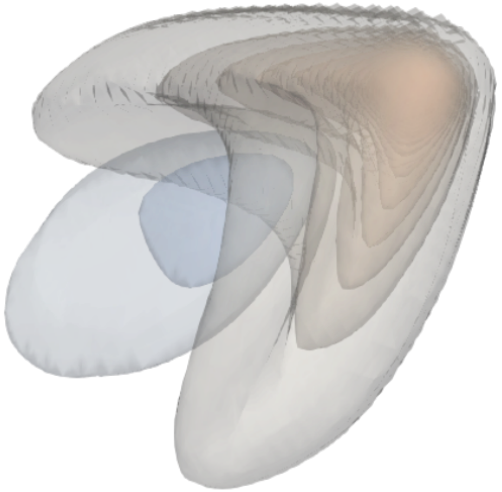


Motivation to study 3D structure of DW

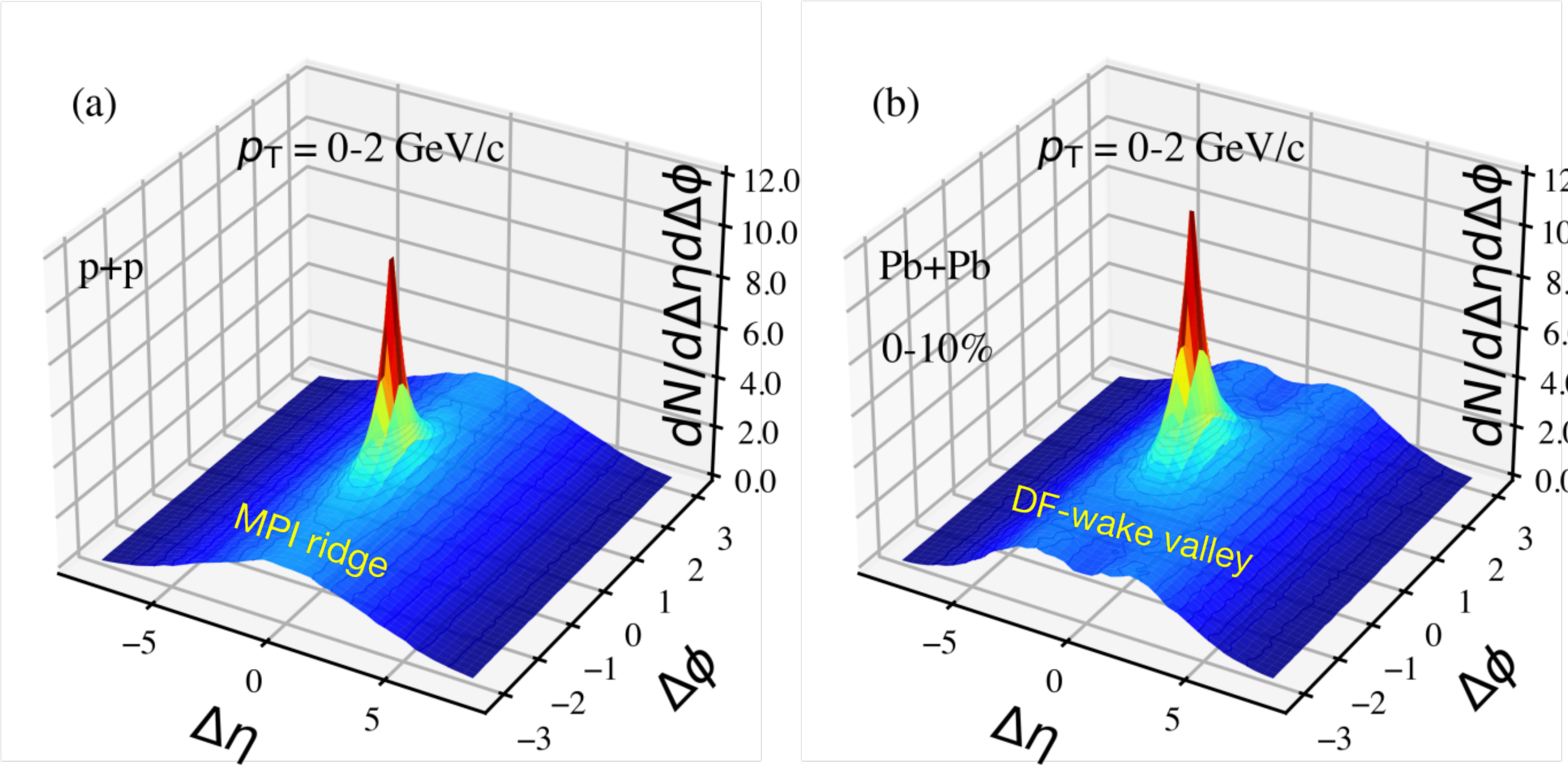
(1) The previous studies of diffusion wake focus on the azimuthal angle.

(2) The jet is a 3D observable, thus the diffusion wake should also have a 3D structure.





3D structure of diffusion wake



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

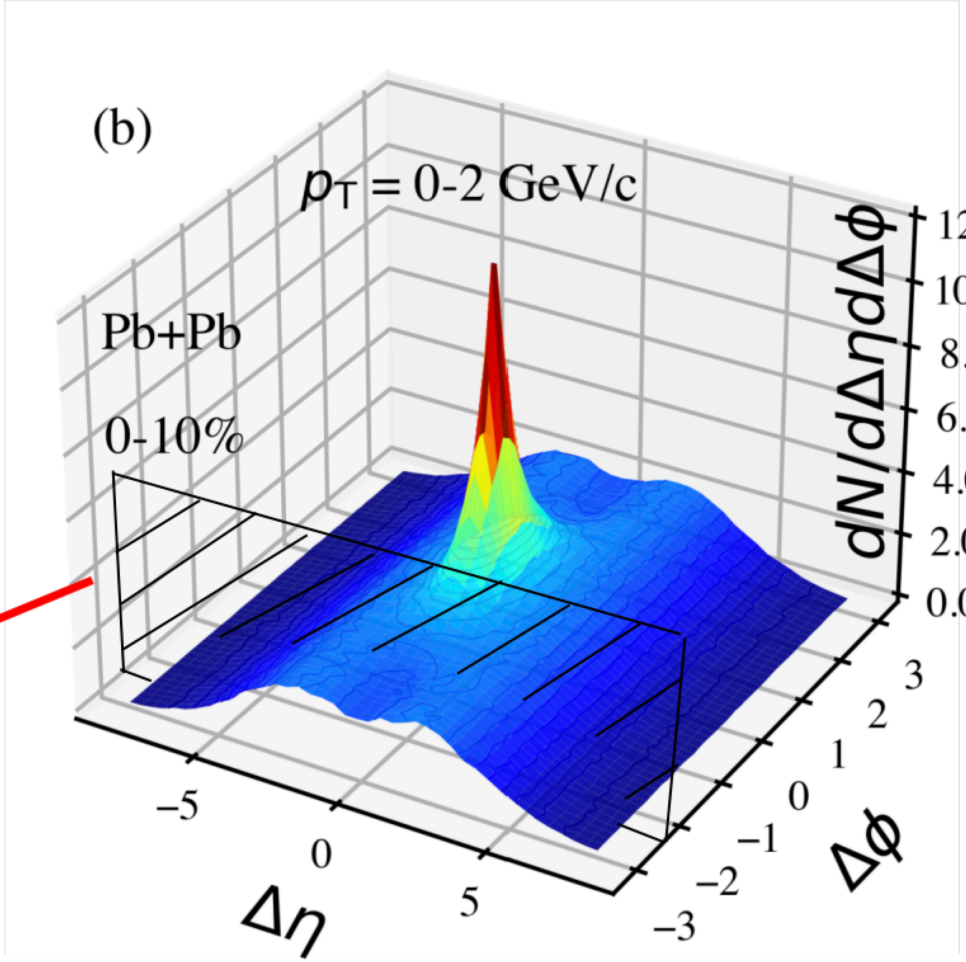
$$\Delta\phi = \phi_h - \phi_{\rm jet}$$

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.

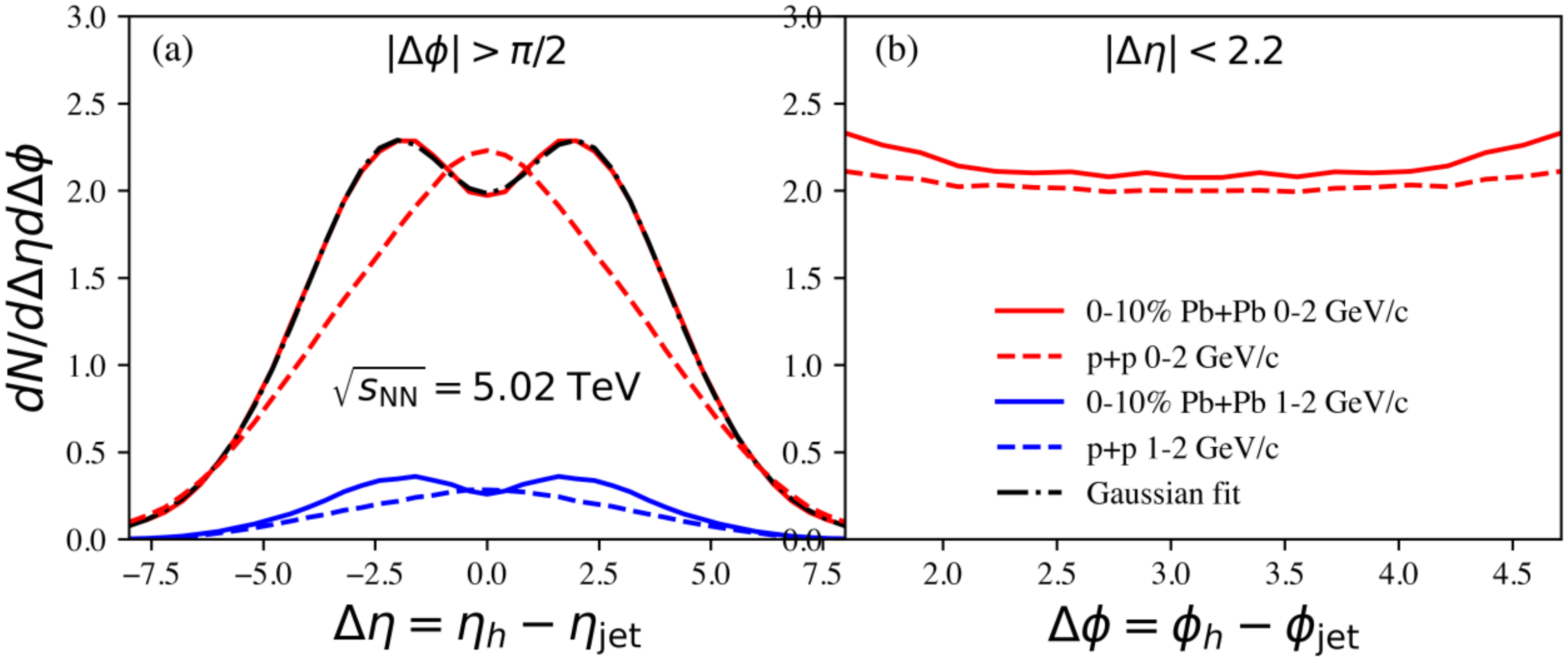
3D structure of diffusion wake

Gamma side

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



3D structure of diffusion wake



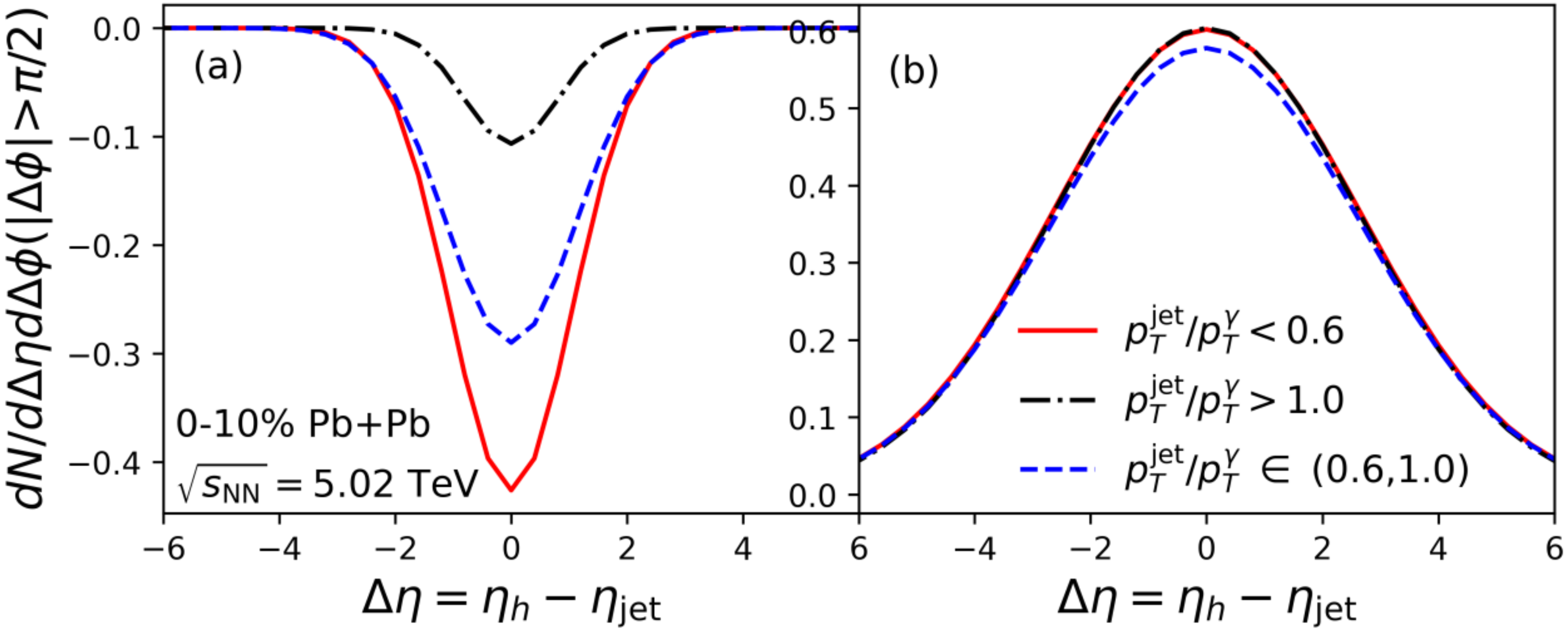
2-Gaussian fitting:

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

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

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

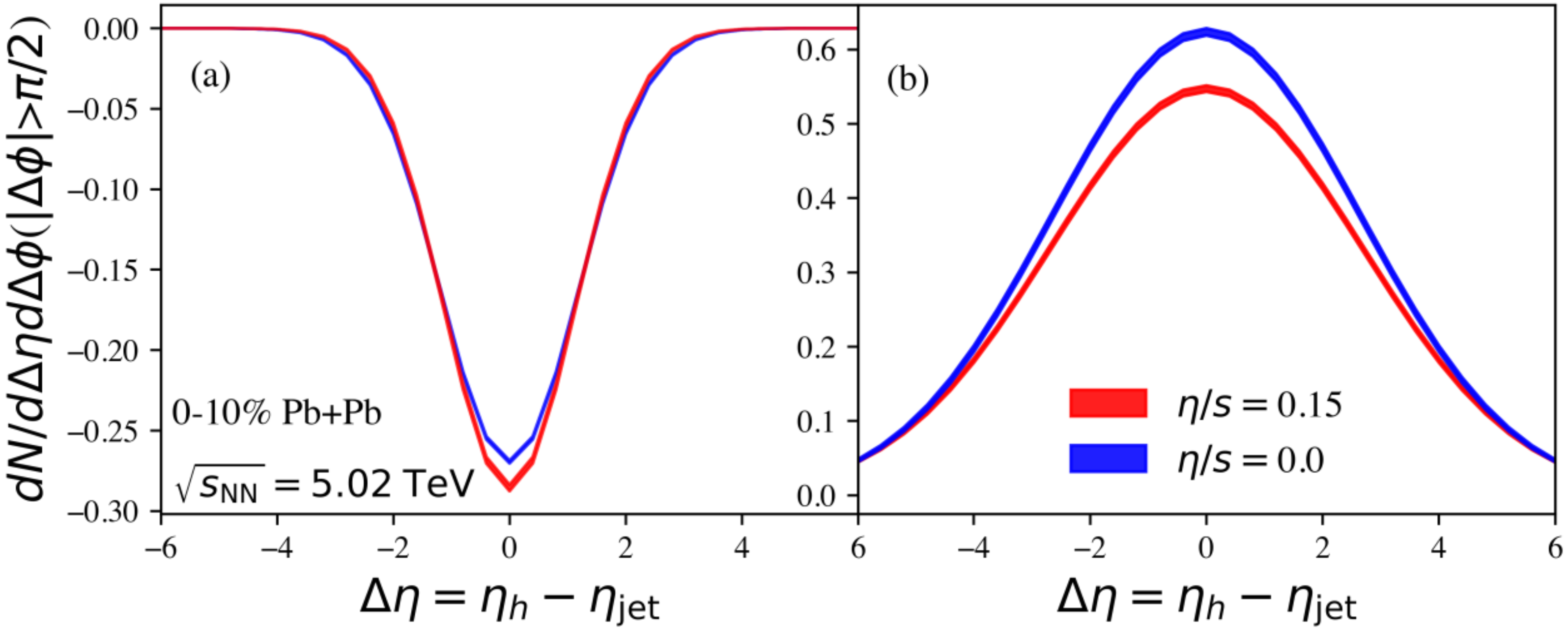
Sensitivity to jet energy loss



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

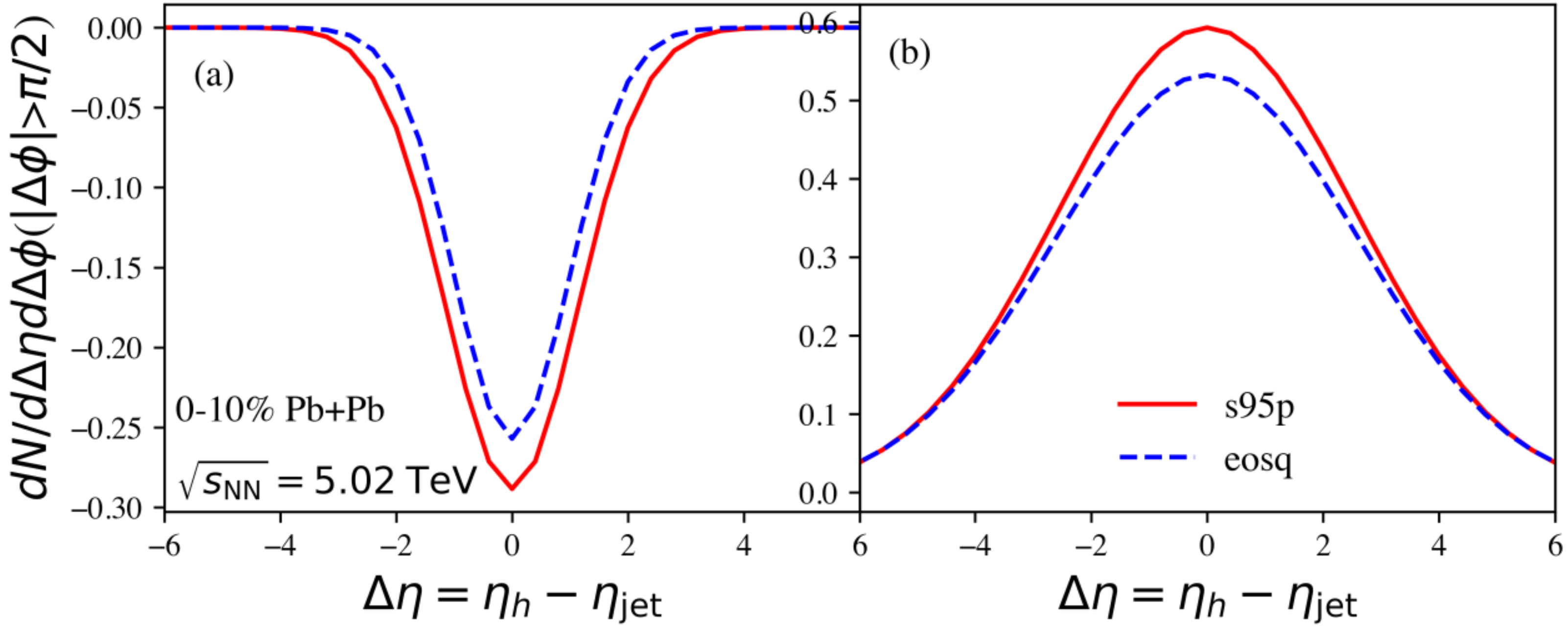
The MPI ridge has a very weak and non-monotonic dependence on $x_{j\gamma}$ due to the non-monotonic dependence of the propagation length on $x_{j\gamma}$ for mini-jets from MPI.

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.

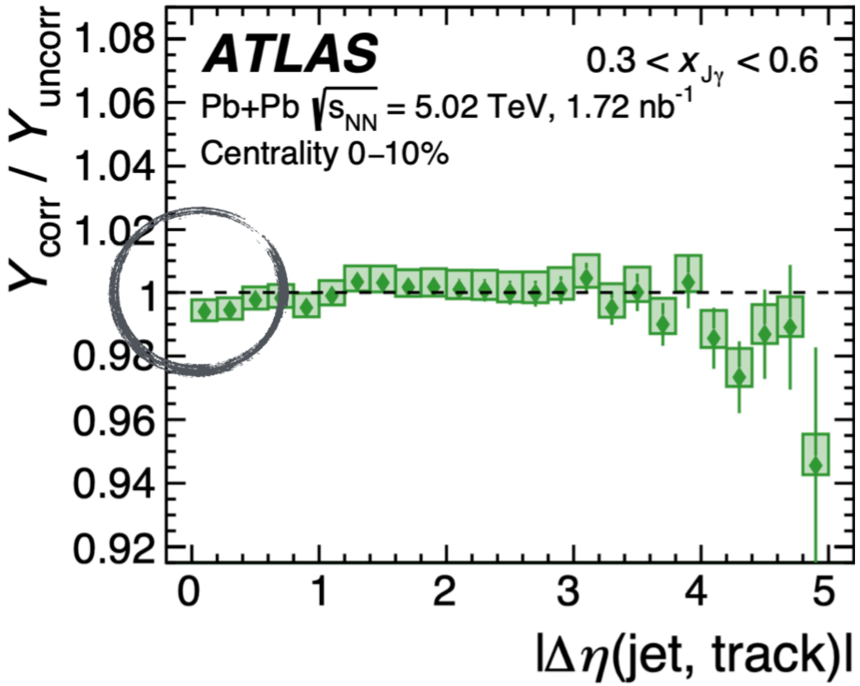
High speed of sound → a larger Mach cone angle → shallower DF-wake valley

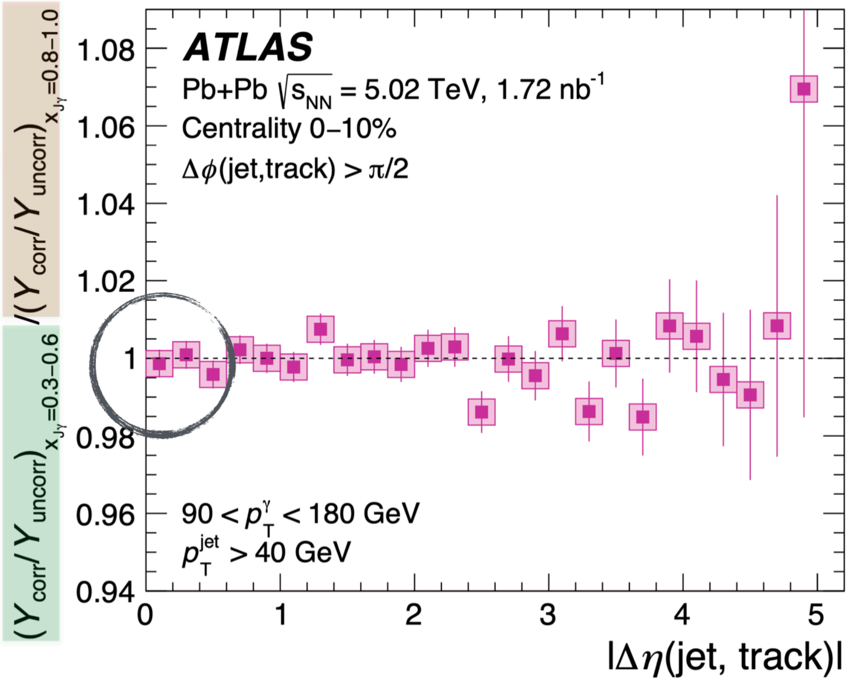
High speed of sound → a stronger radial flow → reduce soft hadrons → small MPI ridge

Measurement of 3D structure at LHC

ATLAS Jet-hadron correlation

arXiv:2408.08599





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

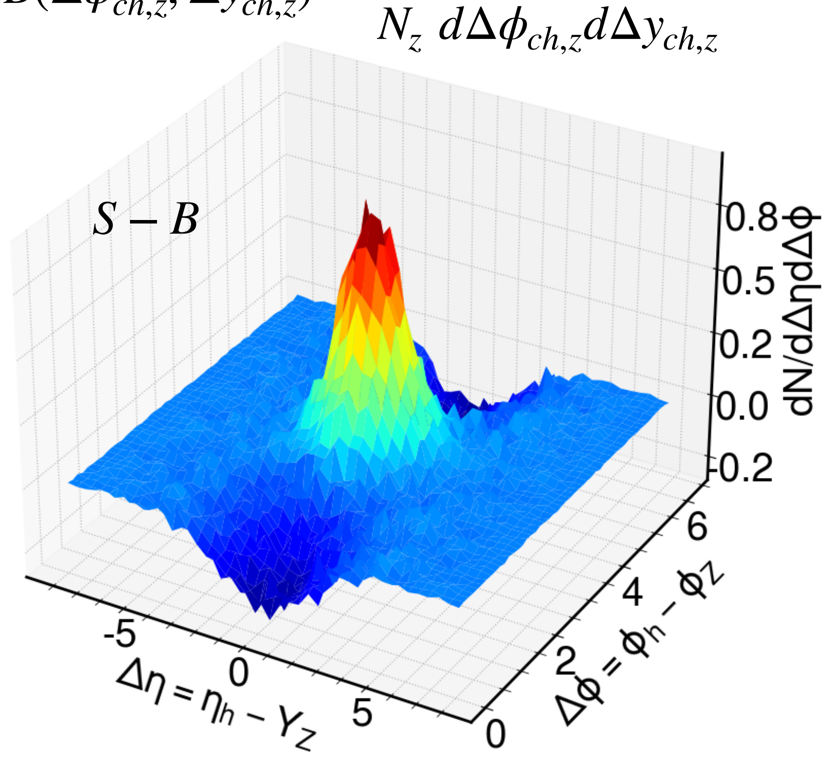
The ratio of diffusion wake compared to hydro background is a few. No significant $x_{j\gamma}$-dependence of the diffusion wake is found.

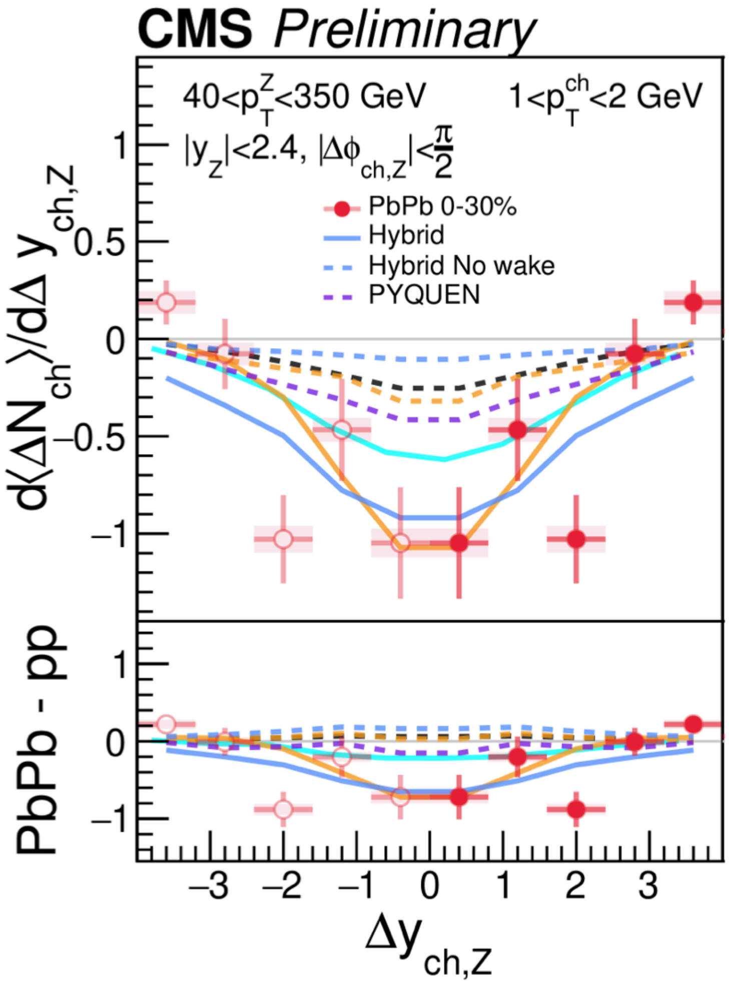
Measurement of 3D structure at LHC

CMS Z-hadron correlation

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

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



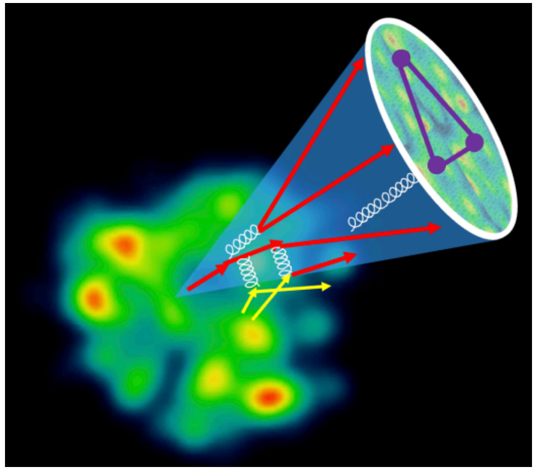


Yen-Jie's talk at HP2024

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

Energy-energy correlators

Energy-energy correlators(EEC) have recently emerged as excellent jet substructure observables for studying the space-time structure of the jet shower.



$$\langle \varepsilon^{(n)}(\overrightarrow{n_1}) \dots \varepsilon^{(n)}(\overrightarrow{n_k}) \rangle$$

$\varepsilon^{(n)}(\overrightarrow{n_1})$ measures the asymptotic energy flux in the direction $\overrightarrow{n_1}$

$$\varepsilon^{(n)}(\overrightarrow{n_1}) = lim_{r\to\infty} \int dt r^2 n_1^i T_{0i}(t, r\overrightarrow{n_1})$$

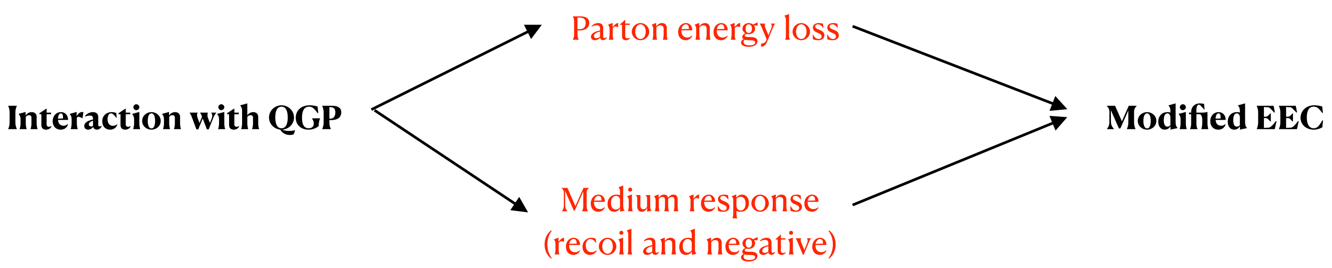
The n-th weighted normalized two-point correlation:

$$\frac{\langle \varepsilon^{(n)}(\overrightarrow{n_1}) \varepsilon^{(n)}(\overrightarrow{n_2}) \rangle}{Q^{2n}} = \frac{1}{\sigma} \sum_{ij} \frac{d\sigma_{ij}}{d\overrightarrow{n_i} d\overrightarrow{n_j}} \frac{E_i^n E_j^n}{Q^{2n}} \delta^{(2)}(\overrightarrow{n_i} - \overrightarrow{n_1}) \delta^{(2)}(\overrightarrow{n_j} - \overrightarrow{n_2}) \qquad n = 1$$

$$\frac{d\Sigma^{(n)}}{d\theta} = \int dn_{\vec{1},2} \frac{\langle \varepsilon^{(n)}(\vec{n_1}) \varepsilon^{(n)}(\vec{n_2}) \rangle}{Q^{2n}} \delta(\vec{n_1} \cdot \vec{n_2} - cos\theta) \qquad cos\theta = \vec{n_1} \cdot \vec{n_2}$$

EECs from a quark going through the QGP brick

EECs from a quark going through the QGP brick


Interaction with QGP

Parton energy loss

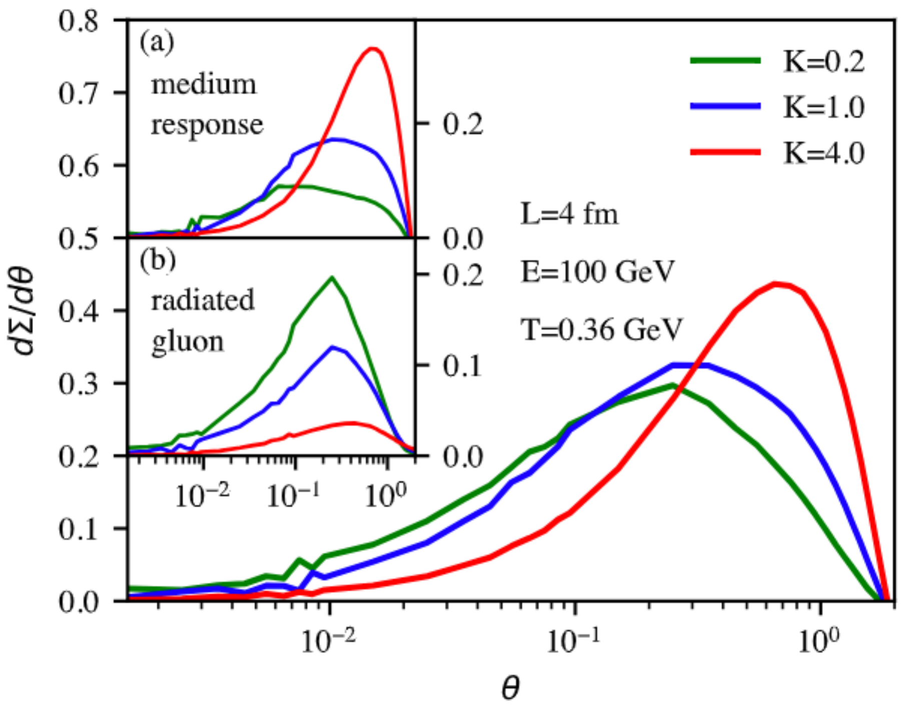
Medium response
(recoil and negative)

Modified EEC

LBT model has a cut-off in the transverse momentum transfer in terms of the Debye screening mass.

$$\mu_D^2 = \frac{3}{2}Kg^2T^2 \qquad K = 1(default),0.2,4.0$$

It determines the typical momentum and angular scale of the in-medium interaction.



Transverse momentum transfer: $q_\perp \sim \mu_D$

Energy transfer to the medium: $\delta E \sim \mu_D^2/T$

The EEC distribution from the medium response shifts to a larger angle with an enhanced magnitude if μ_D increases.

While the quark-radiated-gluon correlator decreases with μ_D and peak shifts slightly to large angles.

EECs from a parton shower going through the QGP brick

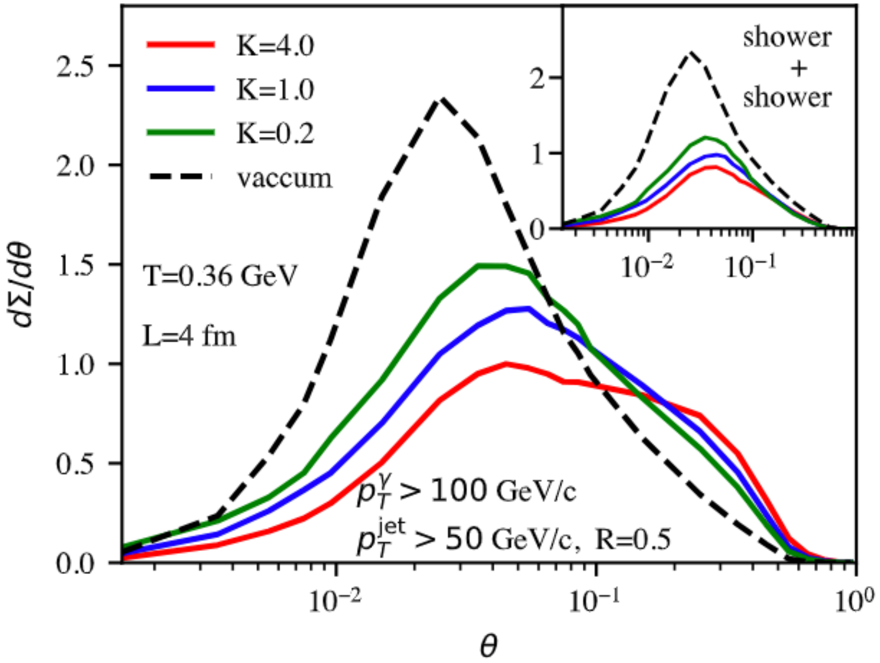
EECs from a parton shower going through the QGP brick

$R = 0.5 \quad p_T^{\gamma} \geq 100 GeV/c \quad p_T^{\text{jet}} \geq 50 GeV/c$

Jet → Parton showers → Multiple elastic and inelastic scatterings

↓

Transverse momentum broadening and energy loss



EEC distributions from correlation between shower partons suppressed at both small and large angles relative to the vacuum EEC (dashed).

The total correlator of all partons (shower, medium-response and radiated gluons) inside the modified jet enhances at large angles due to correlations involving medium response or/and radiated gluons.

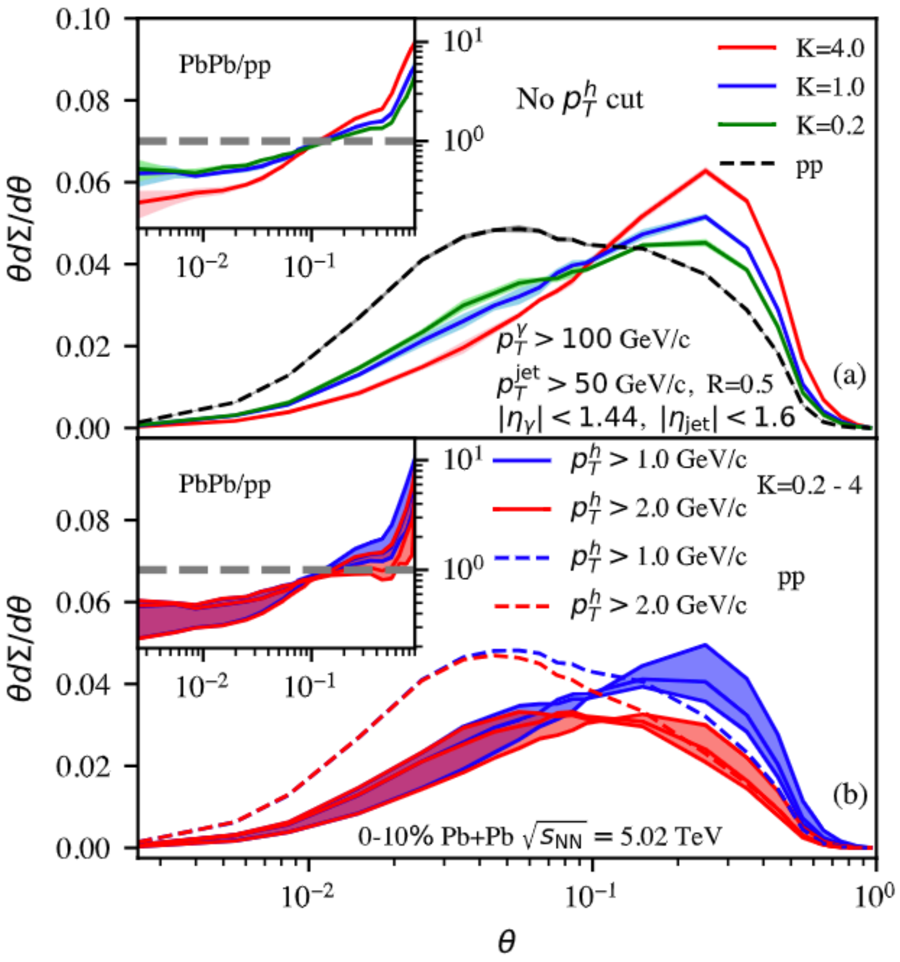
EECs in Pb+Pb collisions at LHC

EECs of γ-jets in Heavy-Ion Collisions.

1. Similar to the case of a QGP brick, the EEC's in Pb+Pb collisions are suppressed at small angles due to energy loss, while they are enhanced at large angles.

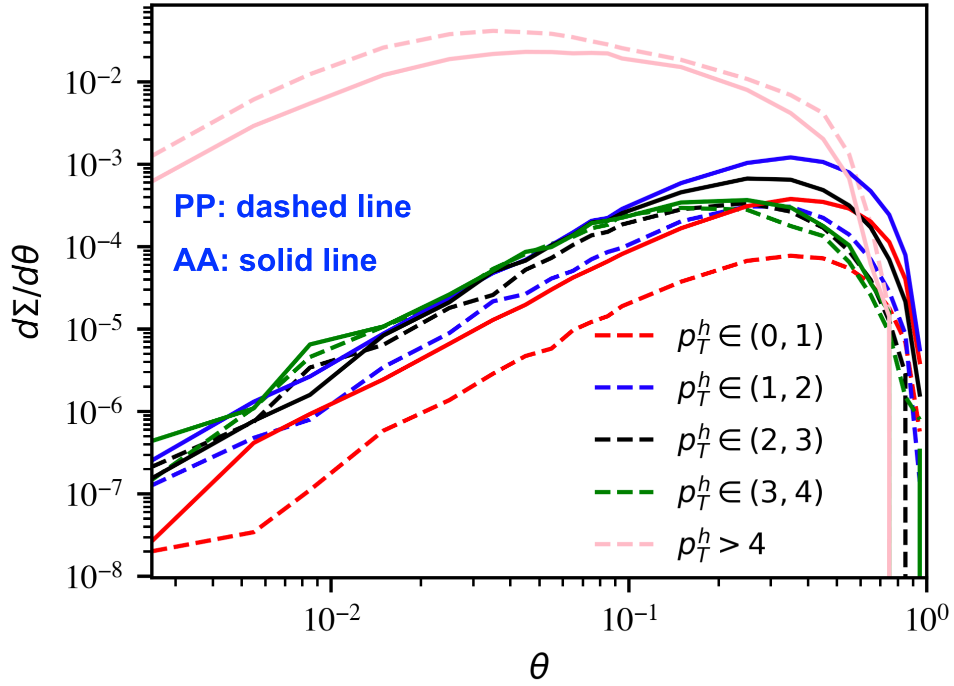
2. This modification is sensitive to the Debye mass, μ_D, which determines the angular scales of each jet-medium scattering and characterizes the structure of the QGP medium in the CoLBT simulations.

3. The enhancement at large angles is reduced but still survives if a $p_T > 1GeV/c$ cut is imposed on the final hadrons for the purpose of reducing the background in experimental analysis. If $p_T > 2GeV/c$ cut is used, the medium enhancement at large angles is mostly gone except for the case of $K = 4$.



Transverse momentum dependence of EECs

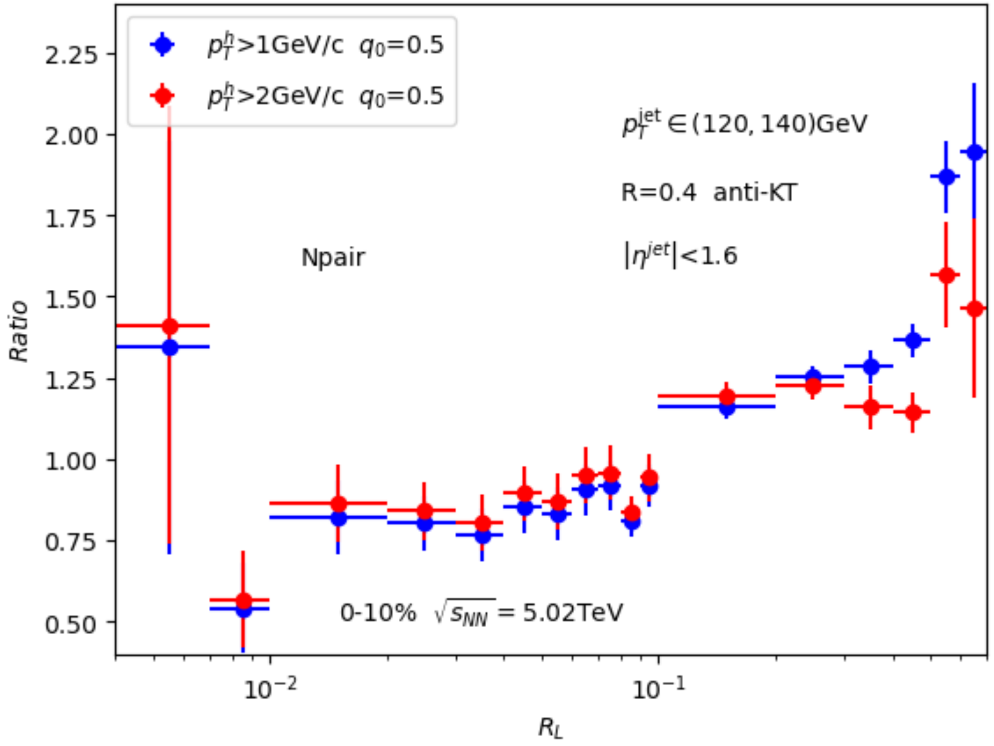
EECs of γ-jets in Heavy-Ion Collisions.

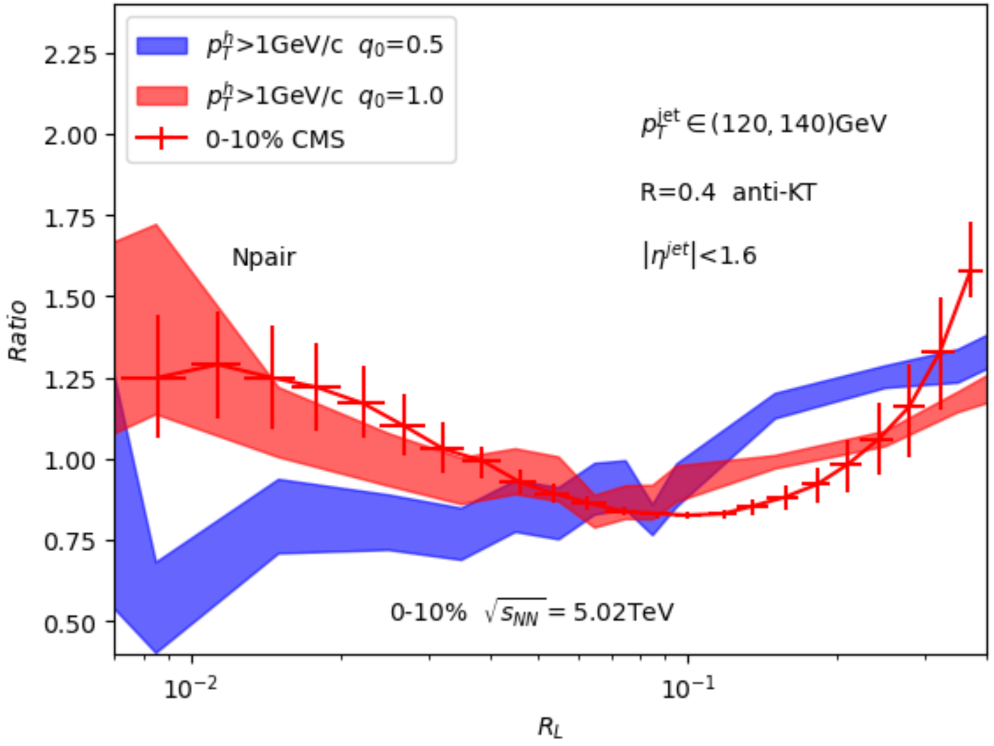


For high p_T hadrons, PP result is greater than AA result.
But, AA results becomes greater when you decrease p_T^h.

EECs of single inclusive jets

EECs of single inclusive jets in Heavy-Ion Collisions.





q_0 is the minimum value for vacuum splitting in Pythia model

Summary

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

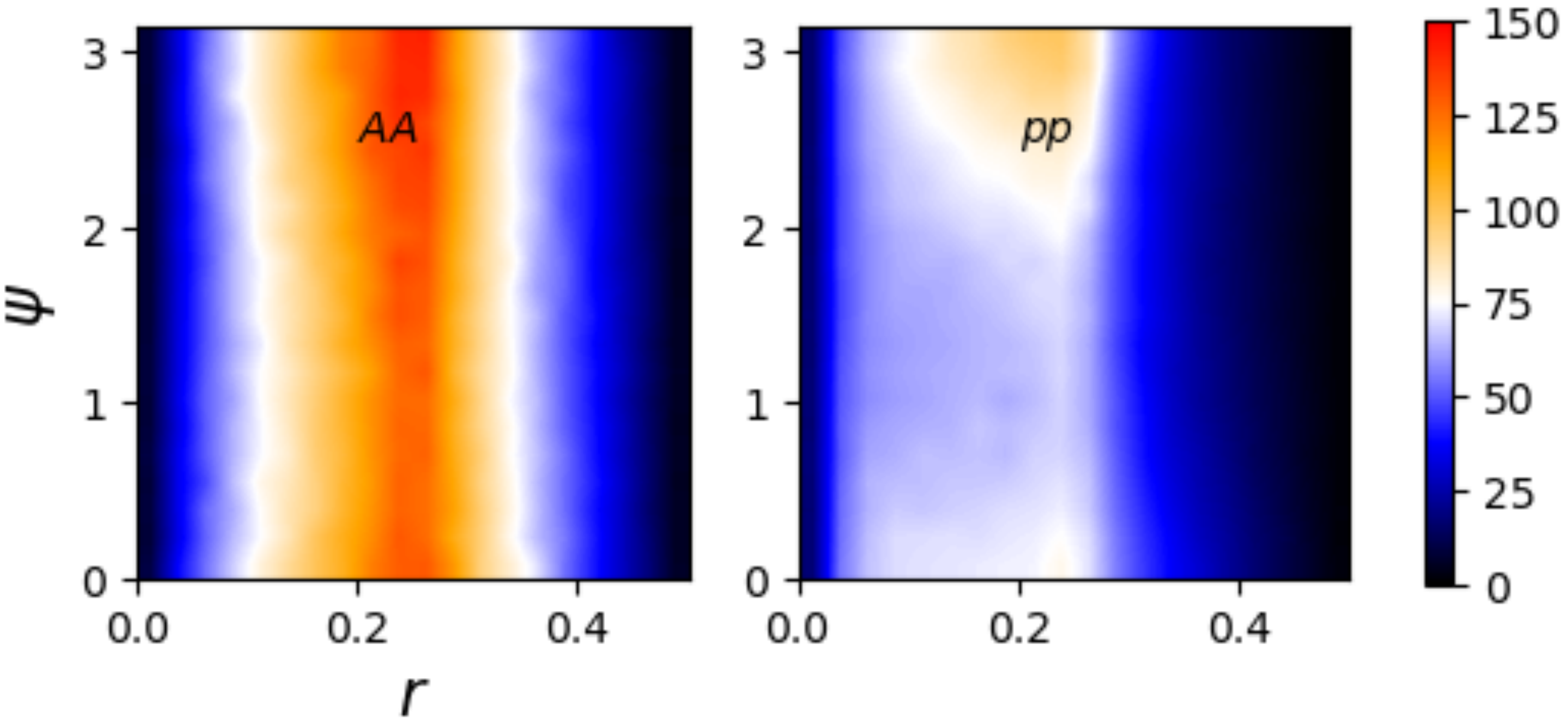
2. CoLBT-hydro model is an effective model to study jet quenching and jet-induced medium response.

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

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

5. Jet-medium interaction will modify the EECs inside jet(γ-jet and single inclusive jet). And this modification of EECs shows a clear sensitivity to Debye screening mass. The coming experimental result can help us constrain this value of models.

Outlook



Coming 3-particles correlation, sensitive to medium properties…

Thank You

EECs in vacuum and medium-induced emissions

We focus on the normalized two-point energy correlates

For a quark with energy E and initial virtuality Q=E, the vacuum splitting $q \rightarrow q + g$ at small angles and leading order (LO) in pQCD leads to the angular distribution of the energy correlators.

$$\frac{d\Sigma_q^{\text{vac}}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz\ z(1-z) P_{qg}(z) \int_{\mu^2}^{Q^2} \frac{d\mathbf{k}_\perp{}^2}{\mathbf{k}_\perp{}^2} \delta(\theta - \frac{|\mathbf{k}_\perp|}{z(1-z)E})$$

$\mu \ll Q$ the collinear cut-off scale below which non-perturbative effects become dominant.

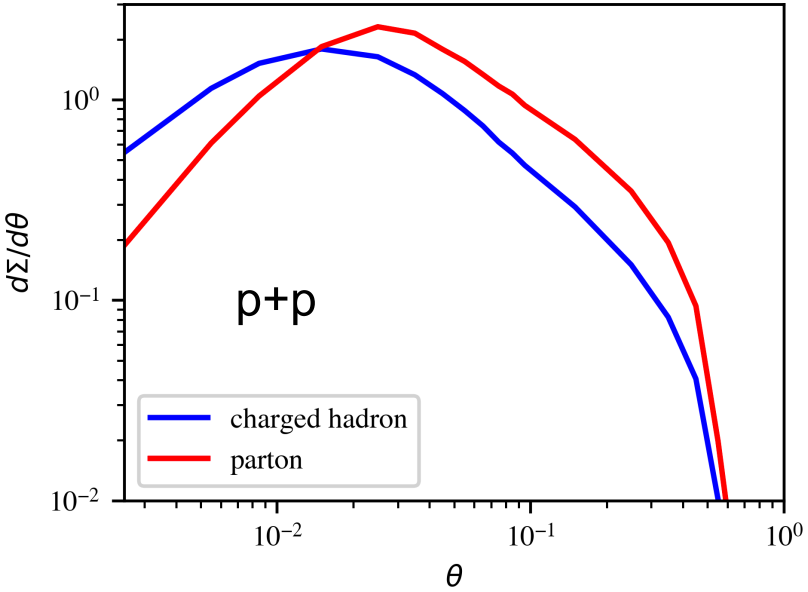
$$P_{qg}(z) = \frac{1+(1-z)^2}{z}$$

Splitting function

$$\frac{d\Sigma_q^{\text{vac}}}{d\theta} \approx \frac{\alpha_s}{2\pi} \frac{C_F}{2\theta} \left(3 - \frac{2\mu}{E\theta}\right) \sqrt{1 - \frac{4\mu}{E\theta}}$$

$\theta > 4\mu/E :\quad d\Sigma_q^{vac}/d\theta \sim 1/\theta$

$\theta \rightarrow 4\mu/E :$ **non-perturbative effects take over and its behavior will be be influenced by hadronization processes.**



EECs in vacuum and medium-induced emissions

The medium-induced gluon radiation is modeled by hist-twist approach

For a massless parton, the formation time for radiated gluon is

$$\theta_{12} = \frac{2\ell_\perp}{Ez(1-z)} \qquad \tau_f = \frac{2Ez(1-z)}{\ell_\perp^2} = \frac{8}{\theta_{12}^2 z(1-z)E}$$

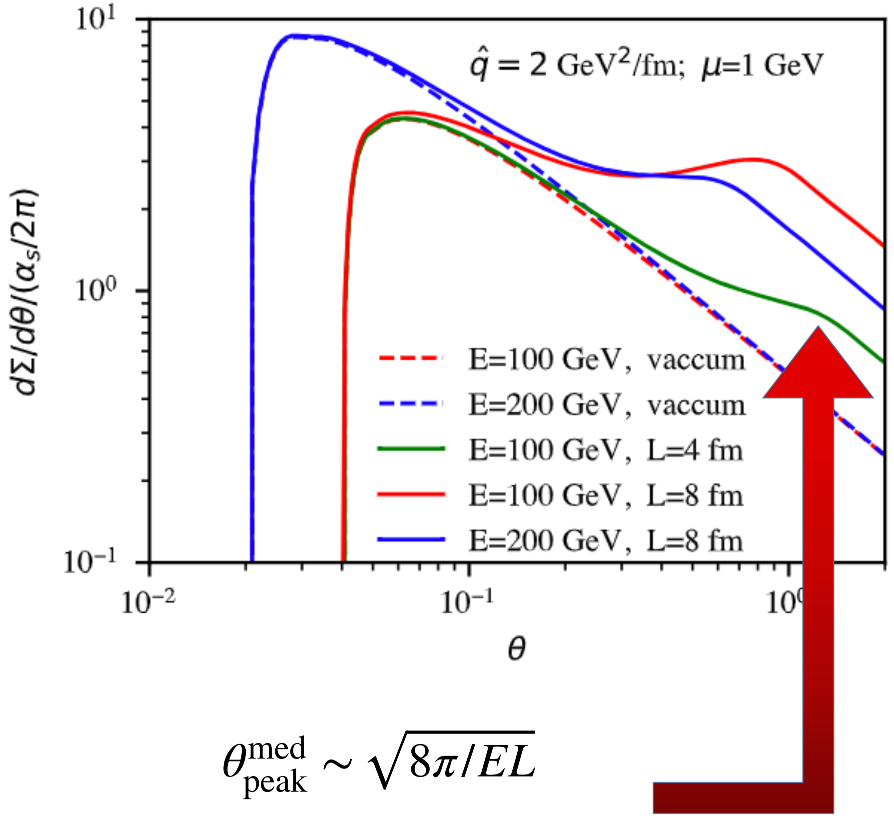
The corresponding angular contribution to EEC is,

$$\begin{aligned}\frac{d\Sigma_q^{\rm med}}{d\theta} &= \frac{16\alpha_{\rm s}C_A}{\pi E^2\theta^3}\int dx dz \frac{\hat{q}P_{qg}(z)}{z(1-z)}\sin^2\left(\frac{x}{2\tau_f}\right)\\ &= \frac{L^{5/2}\hat{q}}{\pi\sqrt{E}}\frac{8\alpha_{\rm s}C_A}{(\sqrt{EL}\theta)^3}\int dz\frac{P_{qg}(z)}{z(1-z)}\times\left[1-\frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]\end{aligned}$$

$$\theta < \sqrt{8\pi/EL}: \quad d\Sigma_q^{\rm med}/d\theta \approx L^3\hat{q}\alpha_{\rm s}C_A\theta/(64\pi) \sim \theta$$

$$\theta > \sqrt{8\pi/EL}: \quad \frac{d\Sigma_q^{\rm med}}{d\theta} \approx \frac{L^2\hat{q}}{2E}\frac{\alpha_{\rm s}C_A}{\theta}\left[1+\mathcal{O}\left(\frac{1}{EL\theta^2}\right)\right] \sim 1/\theta$$

vacuum + medium-induced emissions

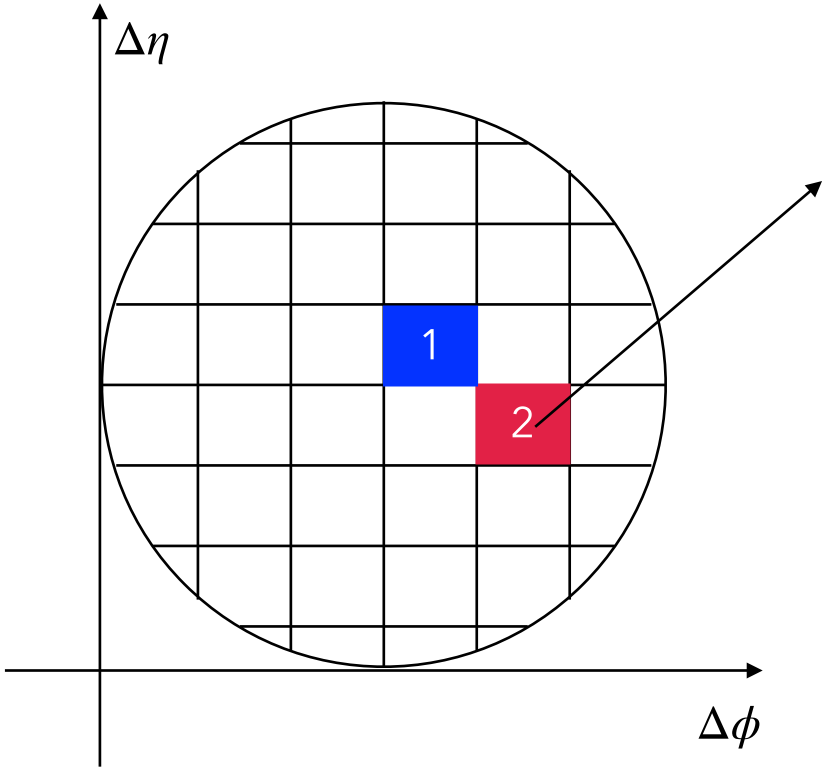


$$\theta_{\rm peak}^{\rm med} \sim \sqrt{8\pi/EL}$$

$$\Sigma_{\rm peak}^{\rm med} \sim \alpha_s\hat{q}L^{5/2}/\sqrt{E}$$

How to calculate EEC in LBT model

How to deal with the negative parton in LBT model



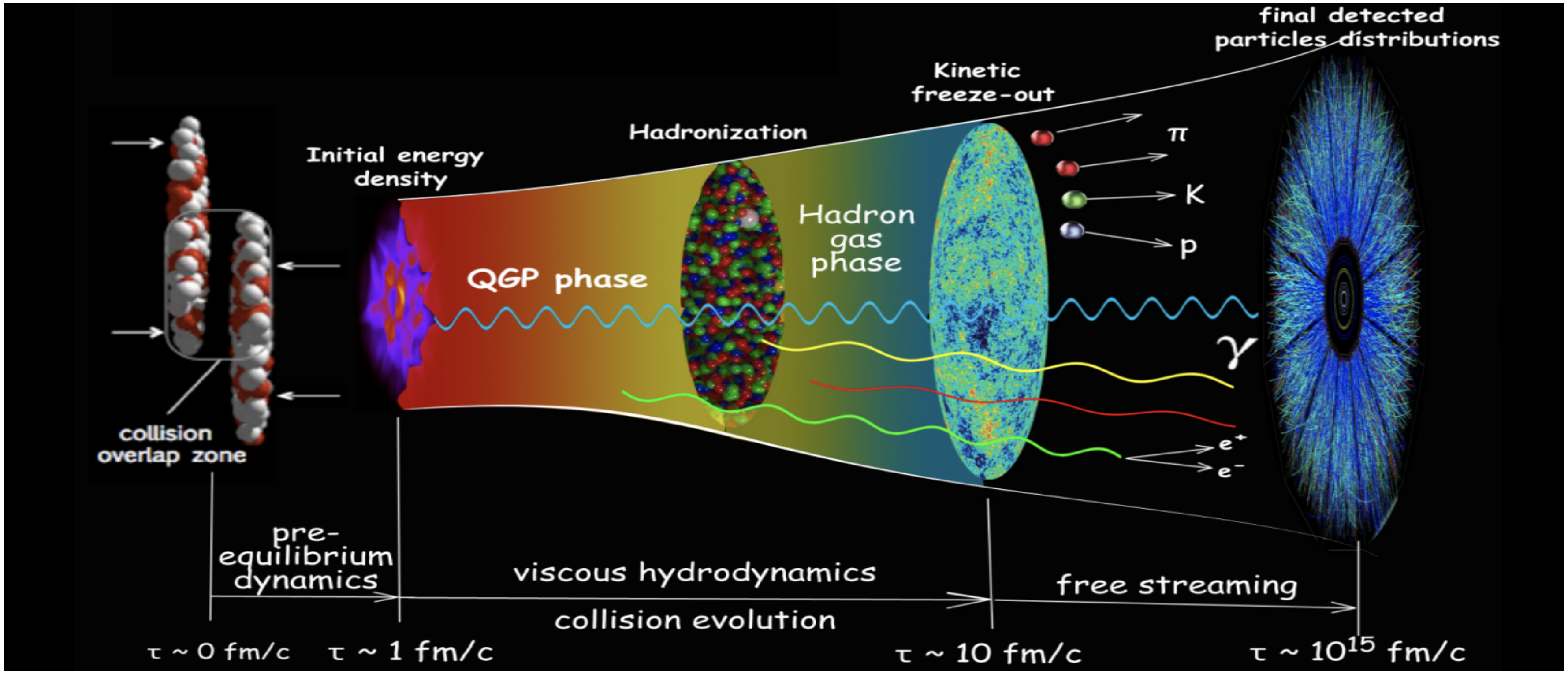
The energy deposited in this cell equals $E_{pos} - E_{neg}$

Therefore, energy correlation between different cells is

$$(E^1_{pos} - E^1_{neg})(E^2_{pos} - E^2_{neg}) = E^1_{pos}E^2_{pos} - E^1_{pos}E^2_{neg} - E^1_{neg}E^2_{pos} + E^1_{neg}E^2_{neg}$$

Sign	**Pair**
+	**pos+pos**
-	**pos+neg**
+	**neg+neg**

Introduction



Chun Shen

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