3D structure of jet-induced diffusion wake in an expanding quark-gluon plasma

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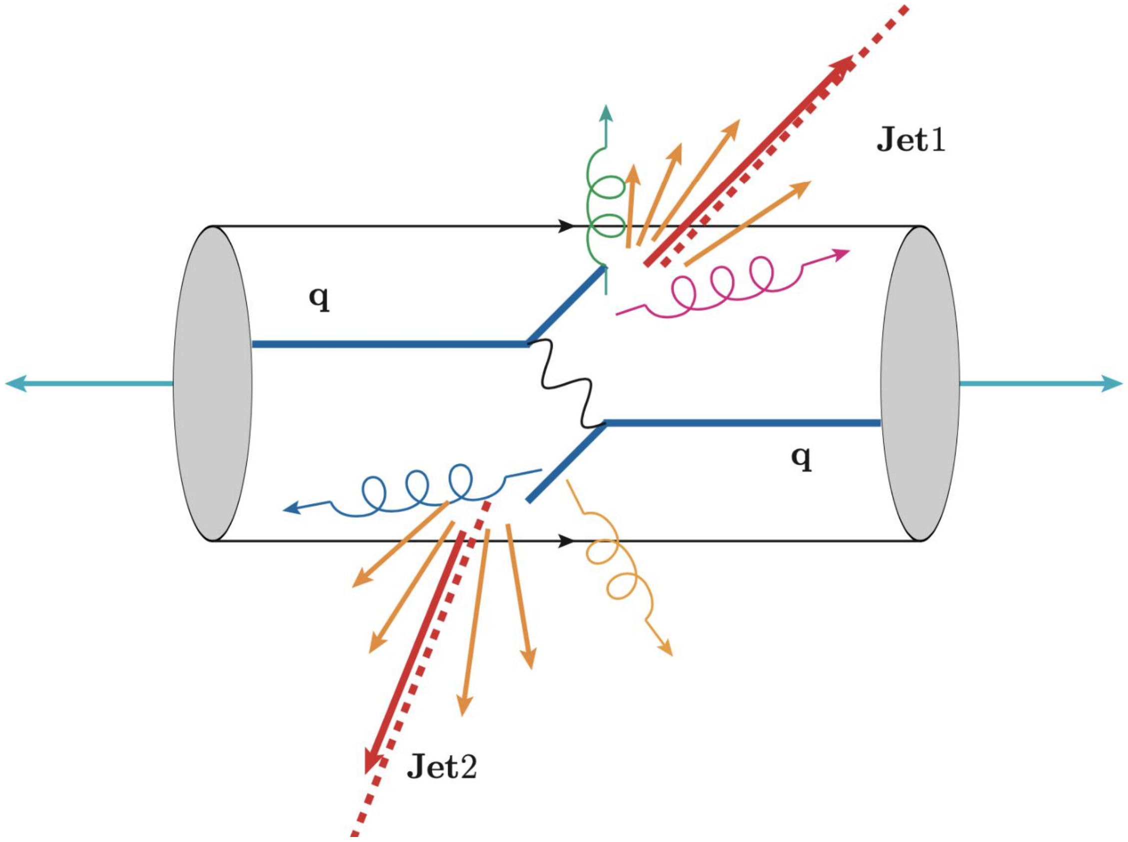
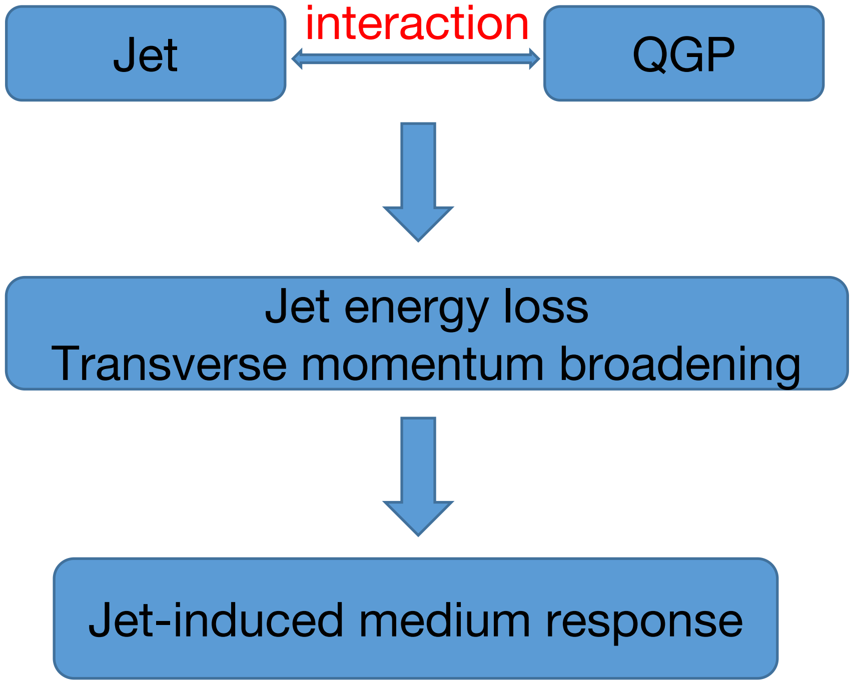
Hard Probes 2023
26-31 Mar 2023

Jet in heavy-ion collisions



QGP(quark-gluon plasma): A deconfined strongly interacting matter that behaves like a perfect fuild



Jet

interaction

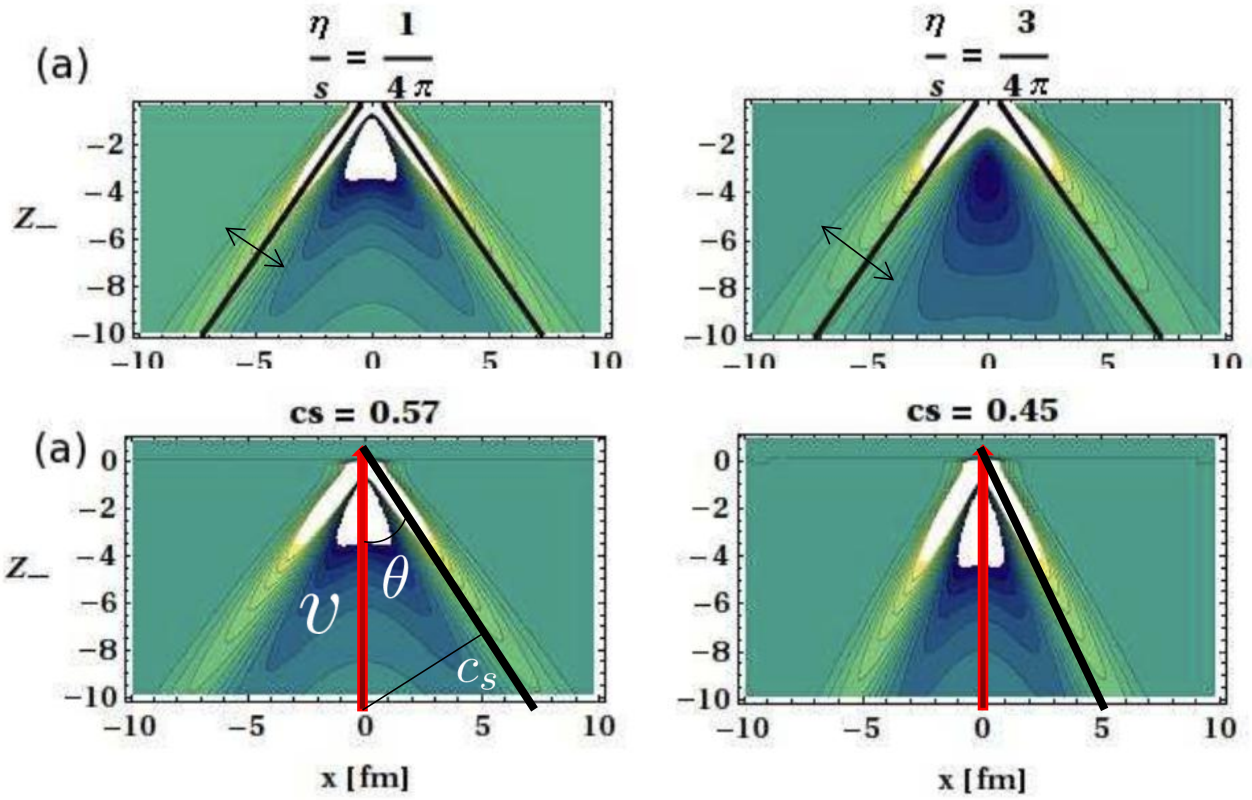
QGP

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.



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- Width of front wake of Mach cone is related with viscous properties of QGP medium;
- Mach cone angle is sensitive to EoS.

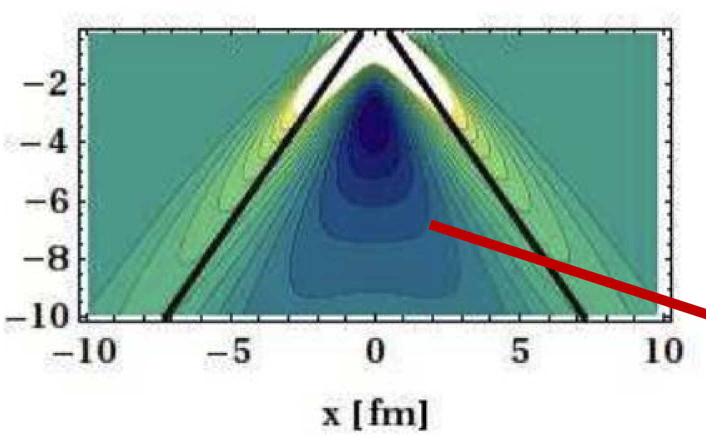
$$sin\theta = \frac{c_s}{v}$$

Medium response and soft gluon radiation

Medium response leads to enhancement of soft hadrons in the direction of jet. (Jet shape, I_{AA}...)
Medium-induced gluon radiation has the similar effect.

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

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



It is difficult to separate their contribution to enhancemet of soft hadrons.

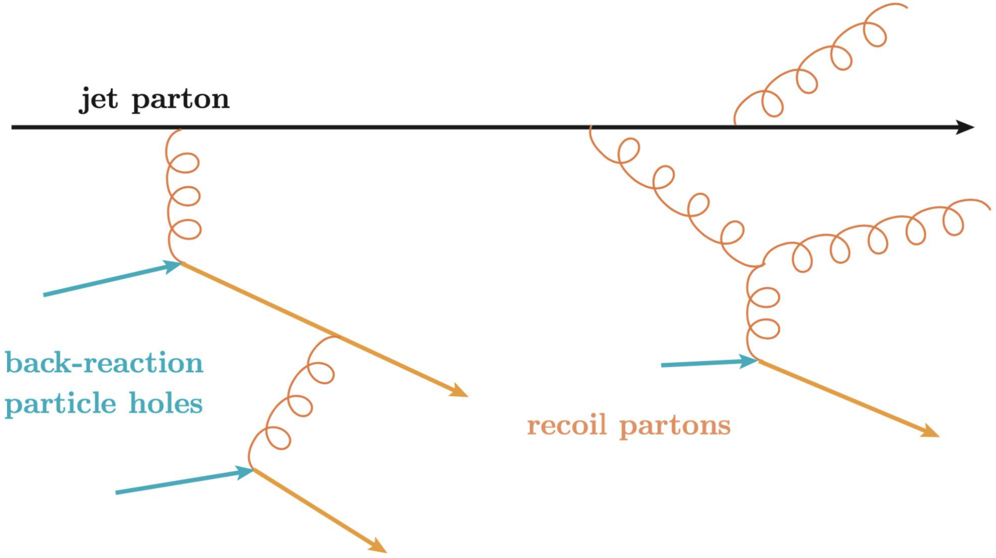
Diffusion wake: an unambiguous part of the jet-induced medium response. It can lead to depletion of soft hadrons in the opposite direction of the jet.

LBT: Linear Boltzmann Transport

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

Medium-induced gluon(HT):

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



Tracked partons:

- Jet shower partons
- Thermal recoil partons
- Radiated gluons
- Negative partons(Back reaction induced by energy-momentum conservation)

CoLBT-hydro model

1. LBT for energetic partons(jet shower and recoil)

2. Hydrodynamic model for bulk and soft hadrons: CLVisc

3. Sorting jet partons according to a cut-off parameter p^0_{cut}

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

   soft and negative partons:

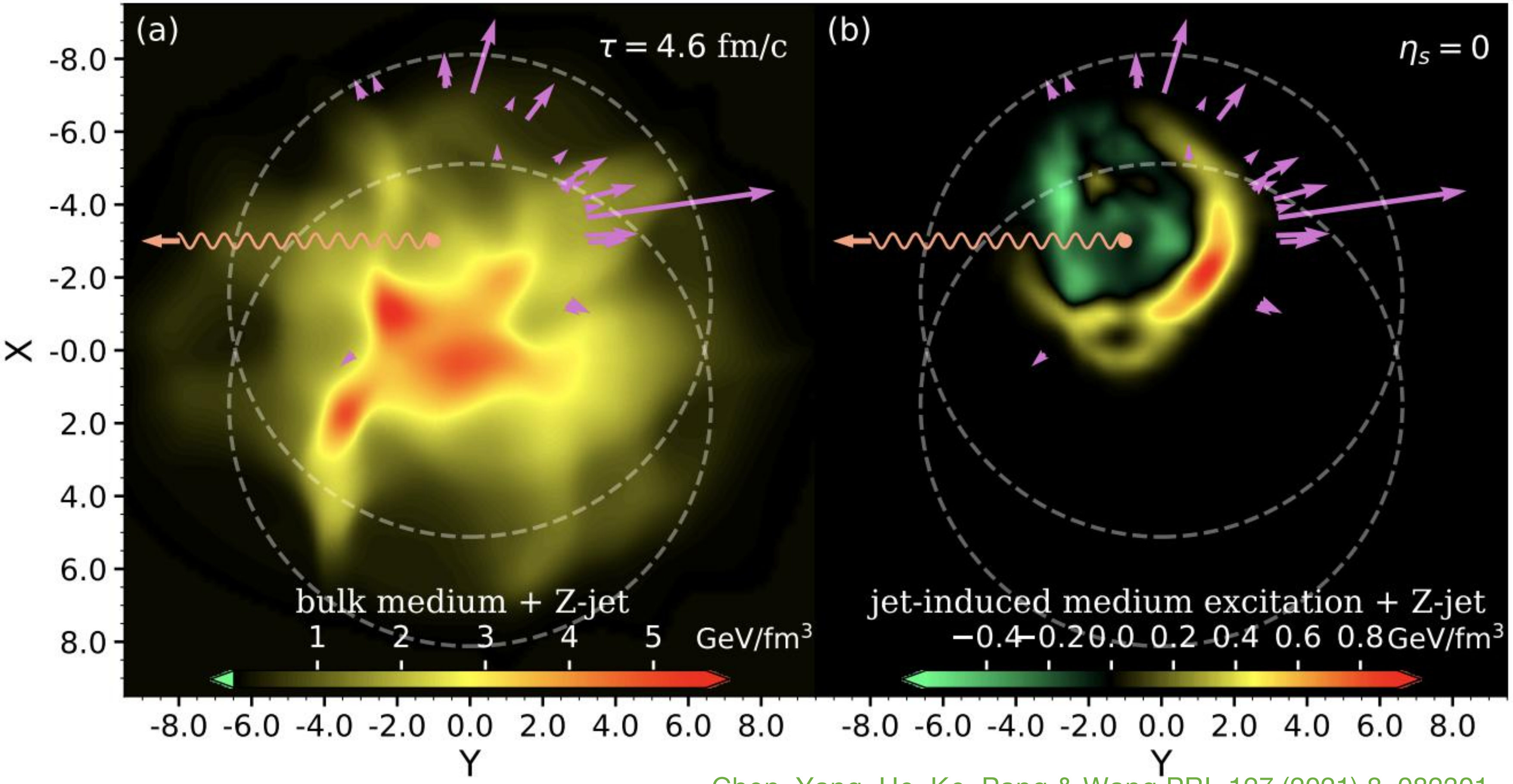
$$j^\nu = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

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

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

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

CoLBT-hydro: Jet-induced medium response

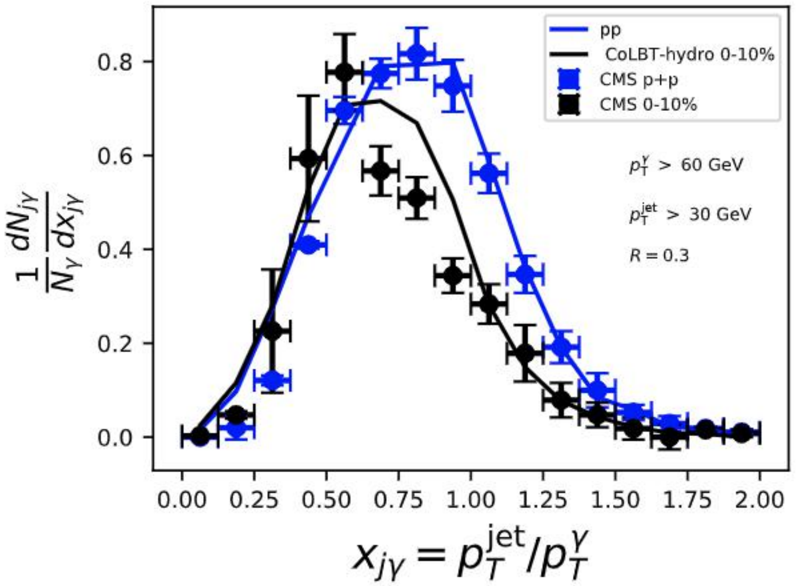


Chen, Yang, He, Ke, Pang & Wang,PRL 127 (2021) 8, 082301

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

Gamma-jet substructure within CoLBT-hydro

Jet asymmetry



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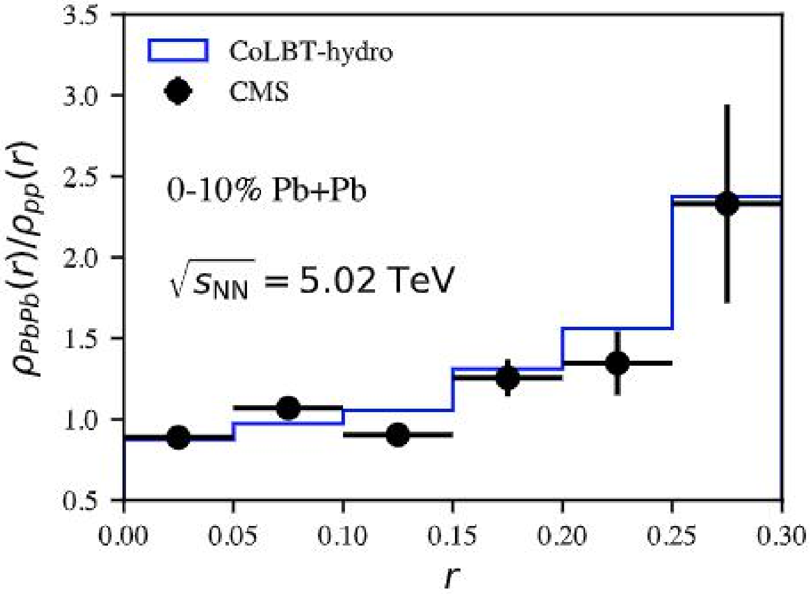
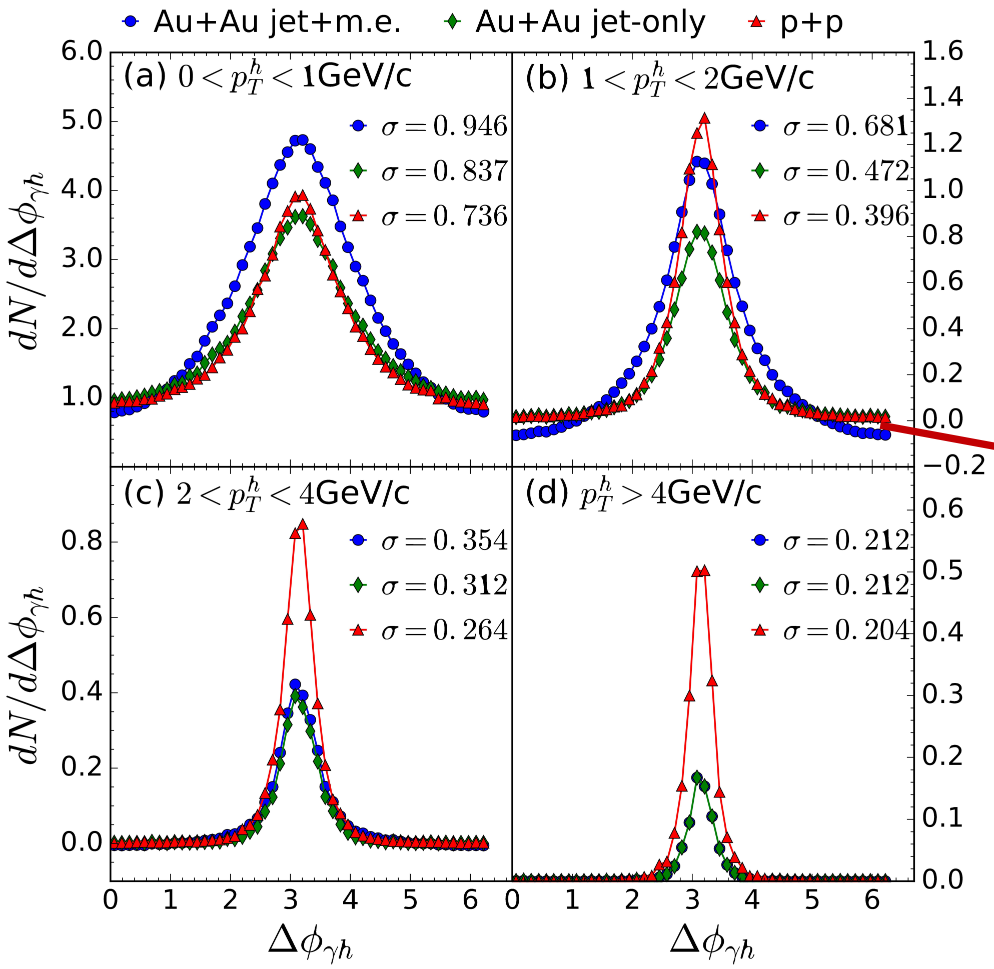
Jet profile



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

CoLBT-hydro model can describe both jet energy loss and its redistribution in QGP

Azimuthal distribution of soft hadrons at RHIC



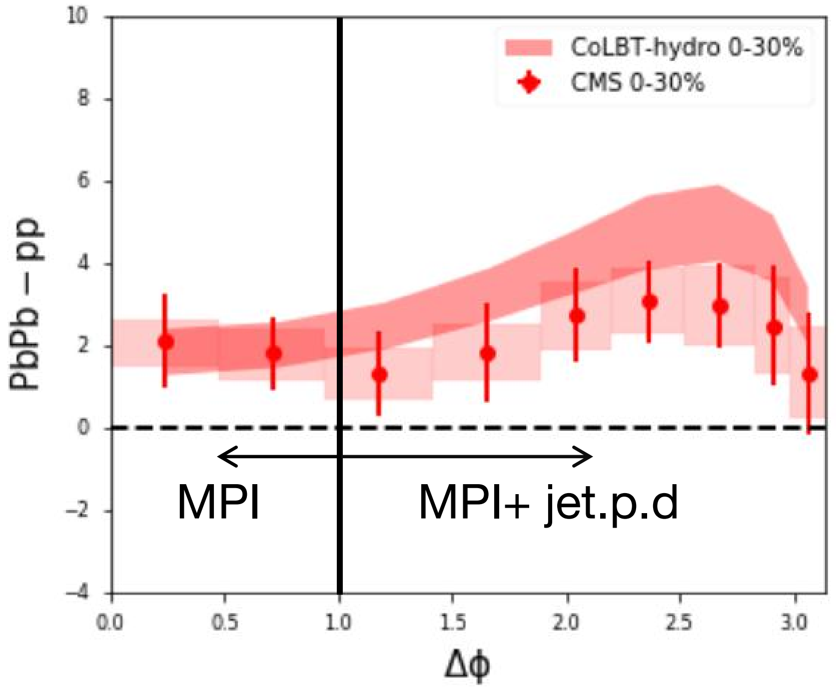
It is the signal of diffusion wake which leads to the depletion of soft hadrons in the γ direction

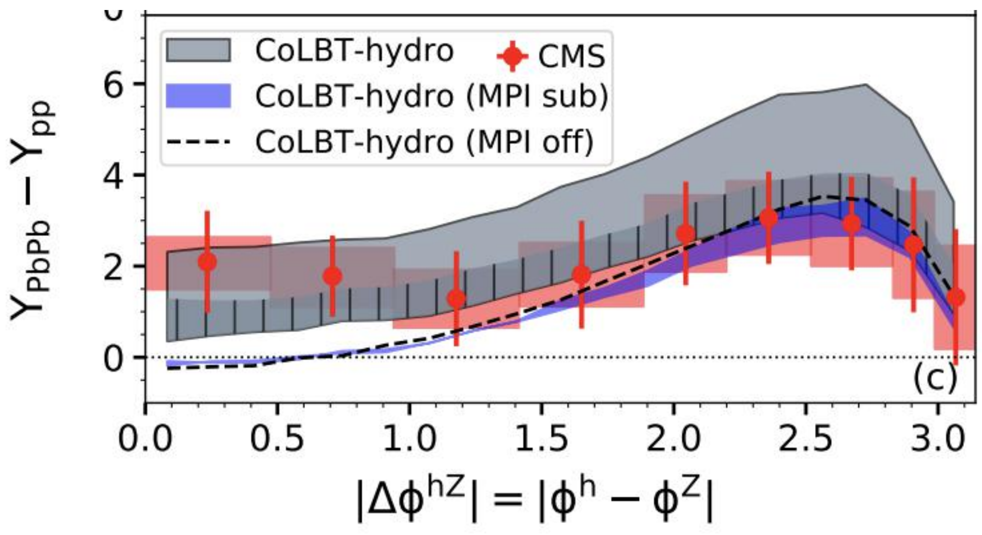
Chen, Cao, Luo, Pang & Wang, PLB777(2018)86

Azimuthal distribution of soft hadrons at LHC

Mixed event MPI(Initail Multiple parton intercation) subtraction:

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





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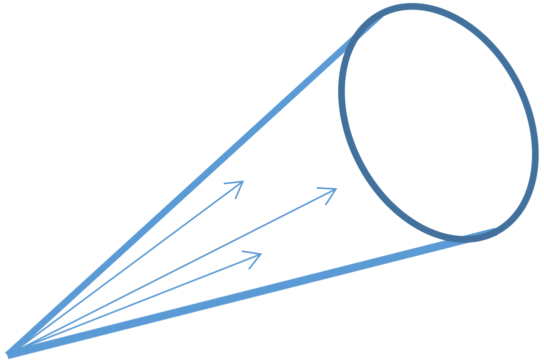
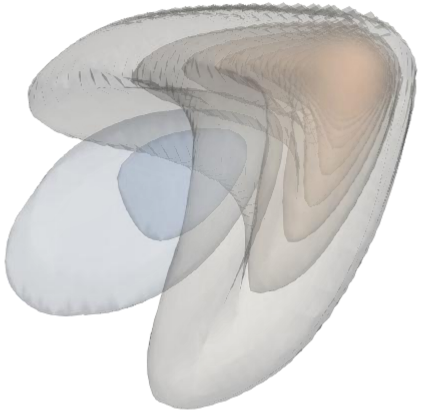
Motivation to sutdy 3D structure of DW

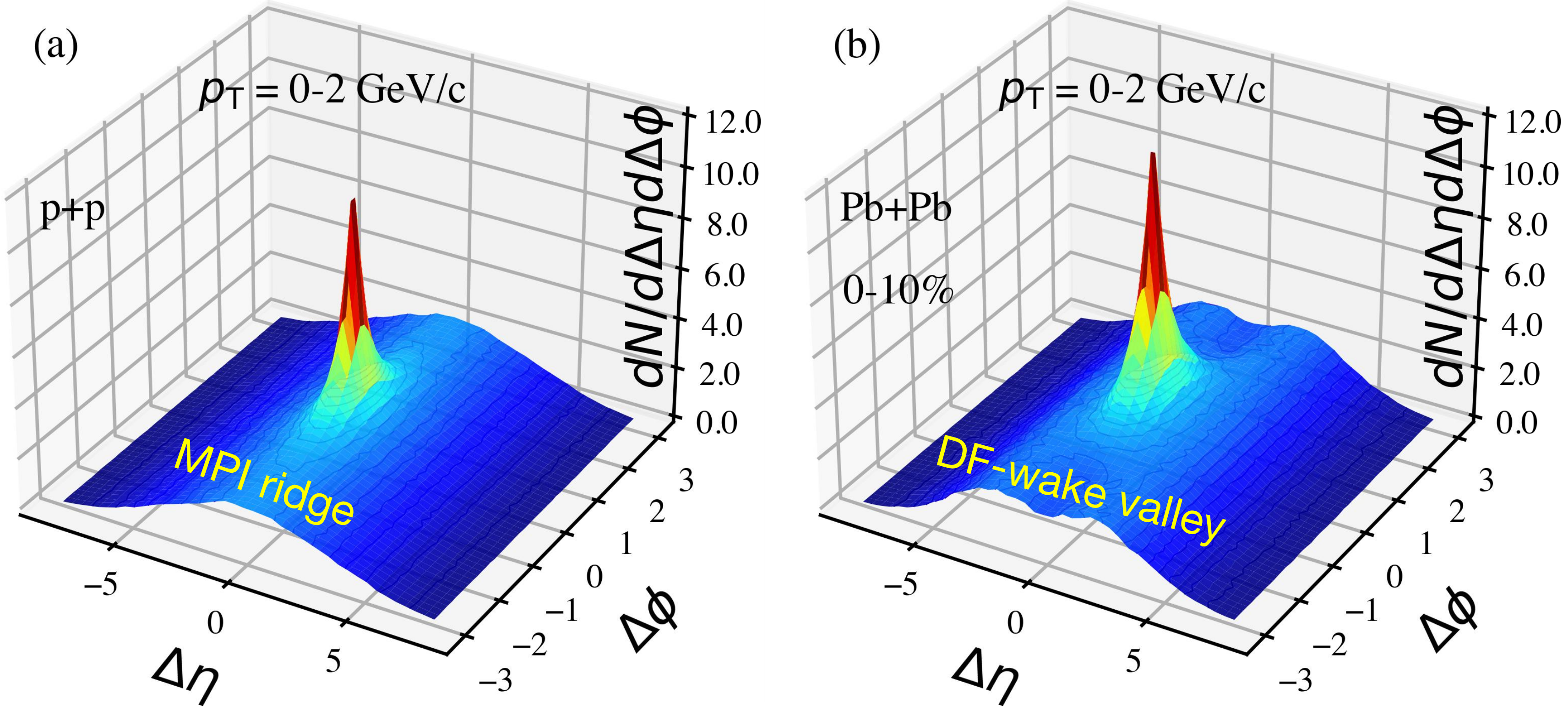
(1) The previous studies of diffusion wake focus on the azimuthal angle.

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





3D structure of diffusion wake



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

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

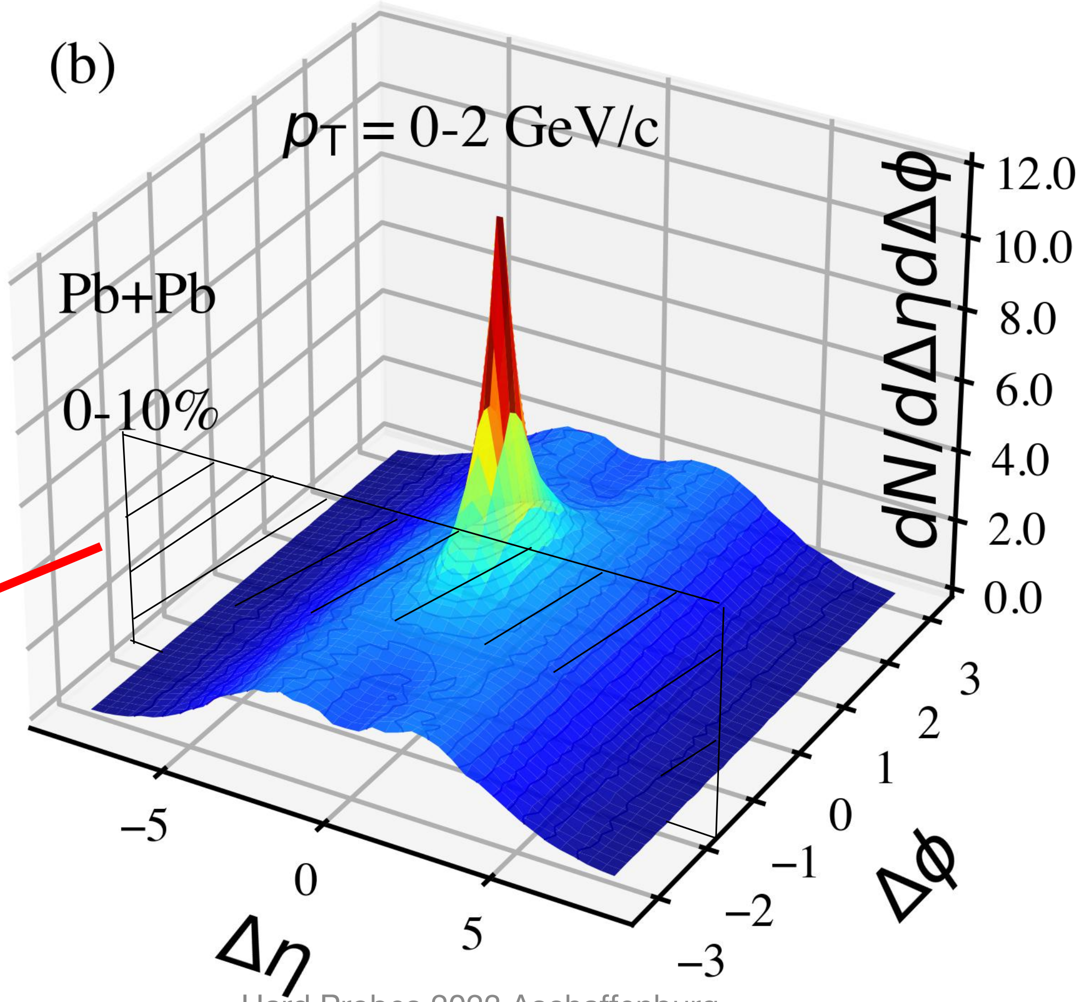
Yang, Luo, Chen, Pang, Wang, Phys.Rev.Lett., 2023,130(5):052301

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.

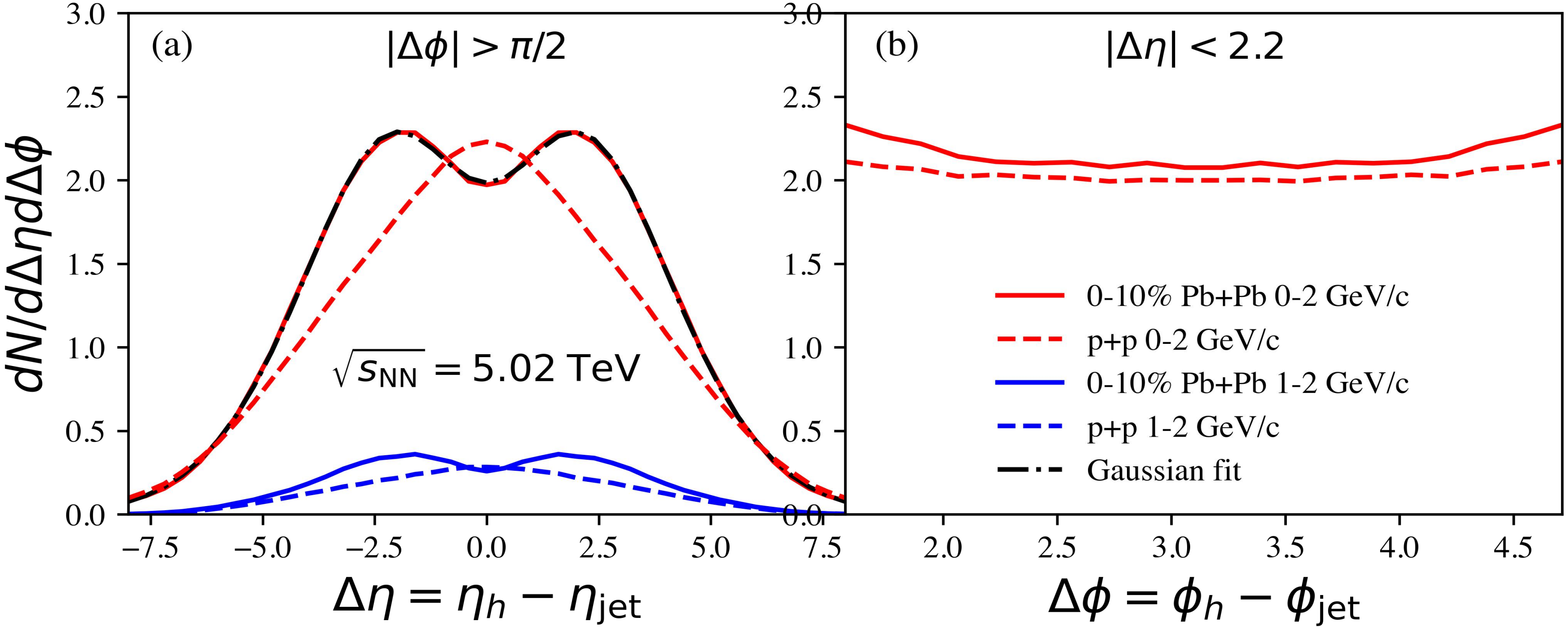
3D structure of diffusion wake

Gamma side

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



3D structure of diffusion wake



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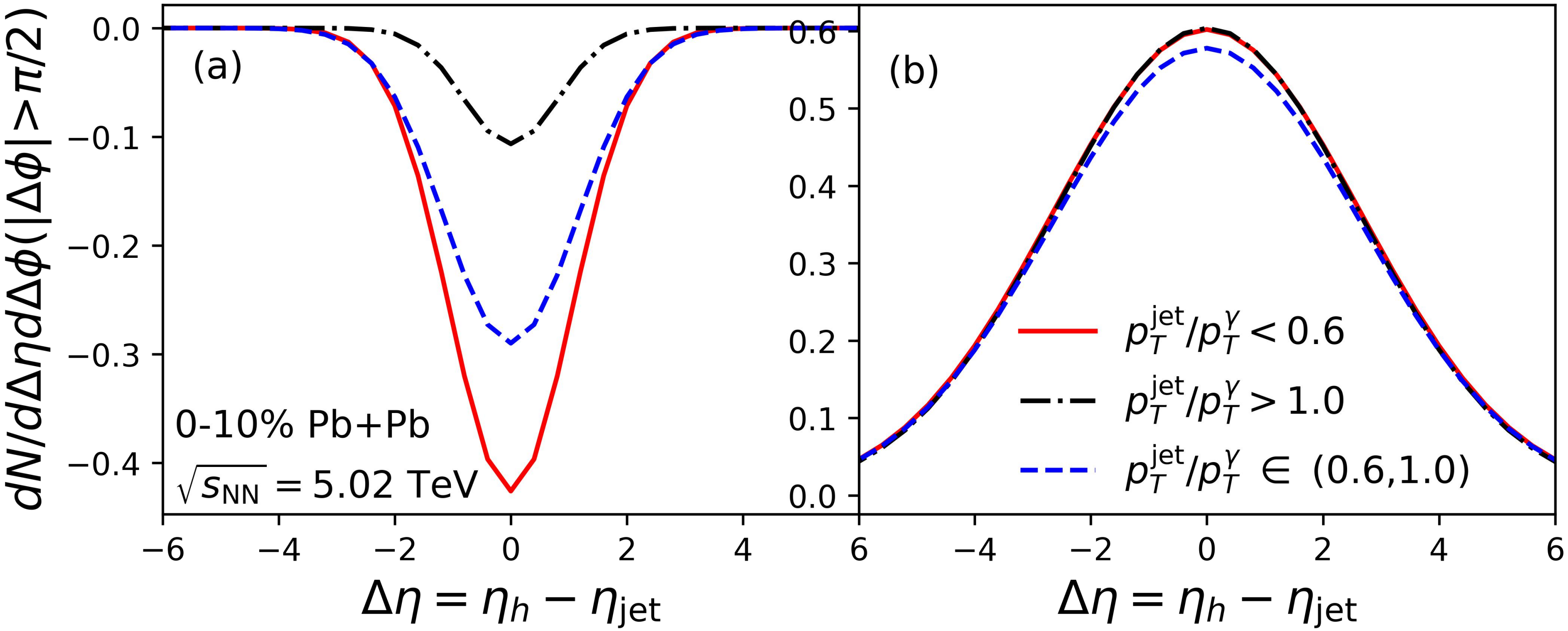
$$F_1(\Delta\eta) = A_1 e^{(-\Delta\eta^2/\sigma_1^2)}$$

Double Gaussian fitting: $F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j)(F2(\Delta\eta,\eta_j) + F_1(\Delta\eta))$

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

Sensitivity to Jet energy loss



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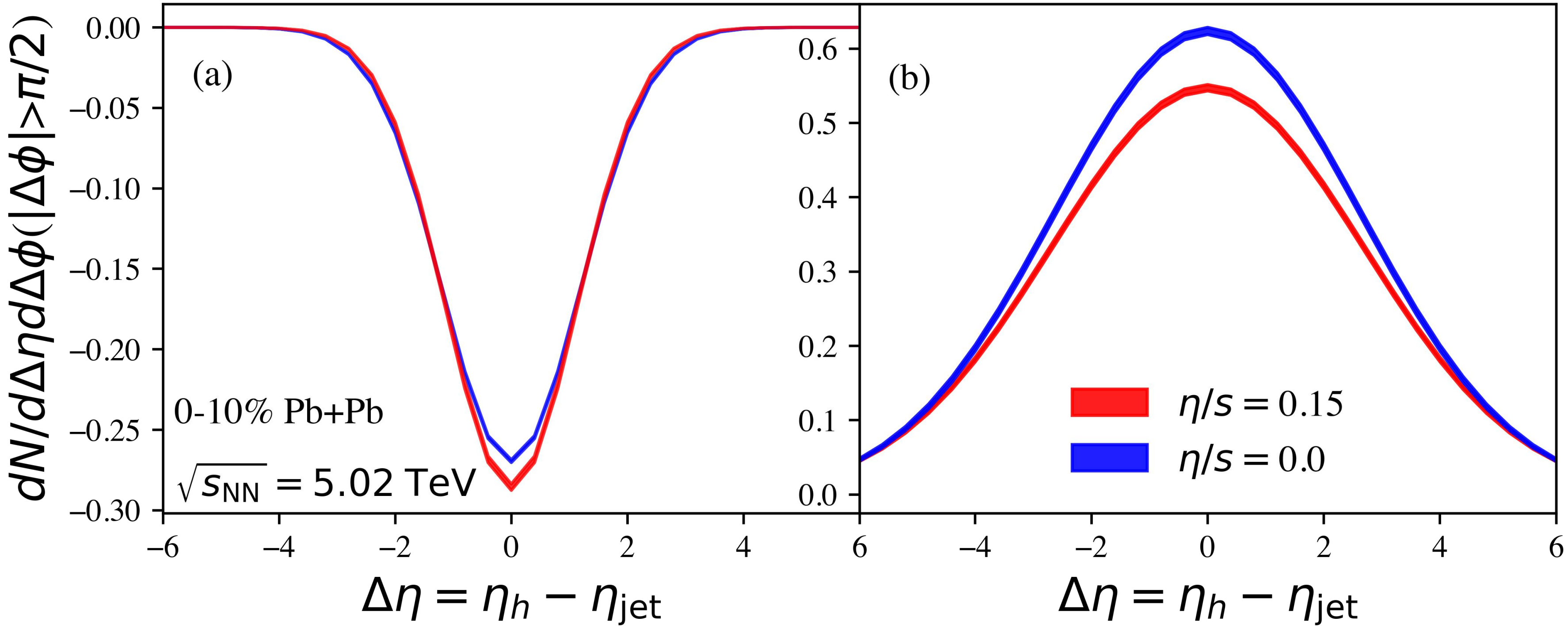
Longer propagation length and larger jet energy loss leads to deeper DF-W valley.

The MPI ridge has a very weak and non-monotonic dependence on xjγ due to the non-monotonic dependence of the propagation length on xjγ for minijets from MPI.

Sensitivity to shear viscosity



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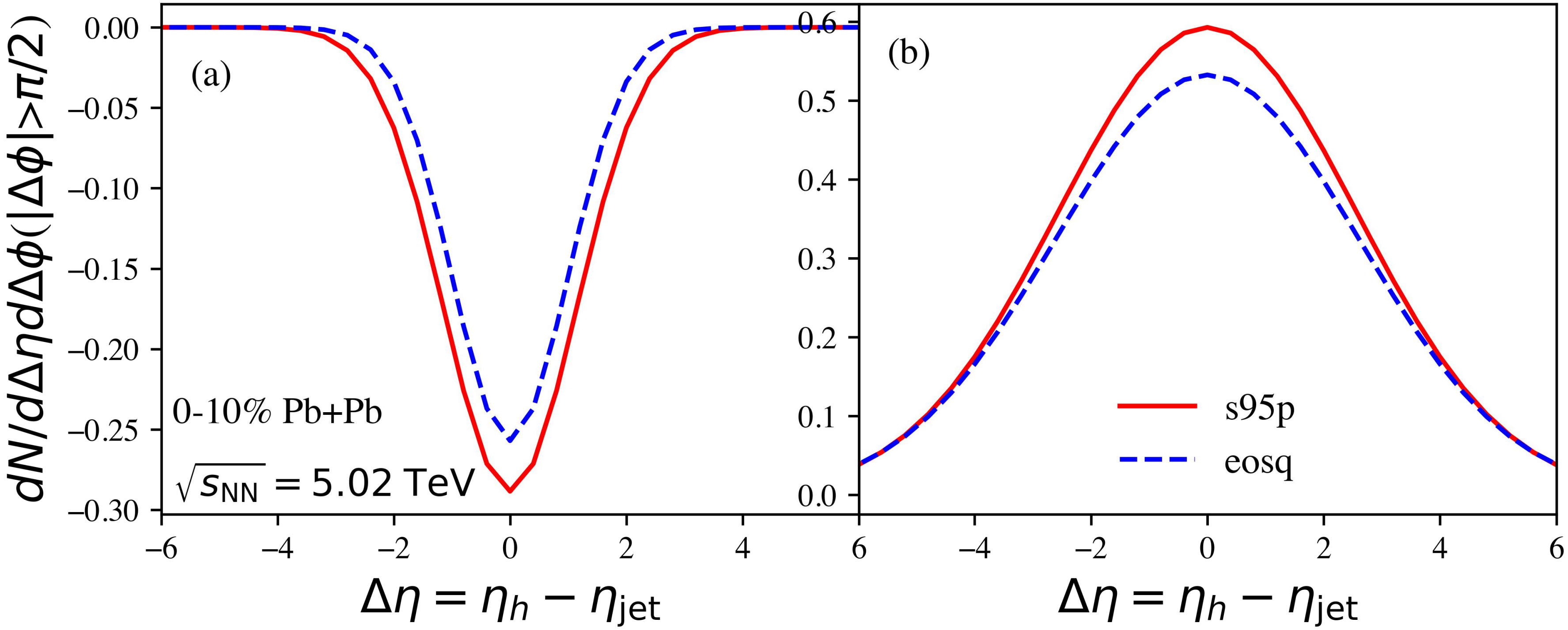
Competition between increased radial flow and negative longitudianal pressure in the shear correction of the energy momentum tensor leads to a a slightly smaller MPI ridge and a deeper DF-wake valley in viscous hydro than in an ideal hydro.

Sensitivity to equation of state



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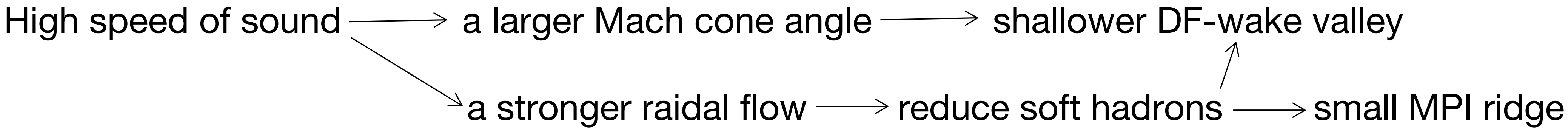
The effective speed of sound is higher in eosq than s95.



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

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

reduce soft hadrons → shallower DF-wake valley

Summary

1. Jet-induced medium response can help us glean QGP properties.

2. With MPI subtraction, we can get signal of diffusion wake at LHC.

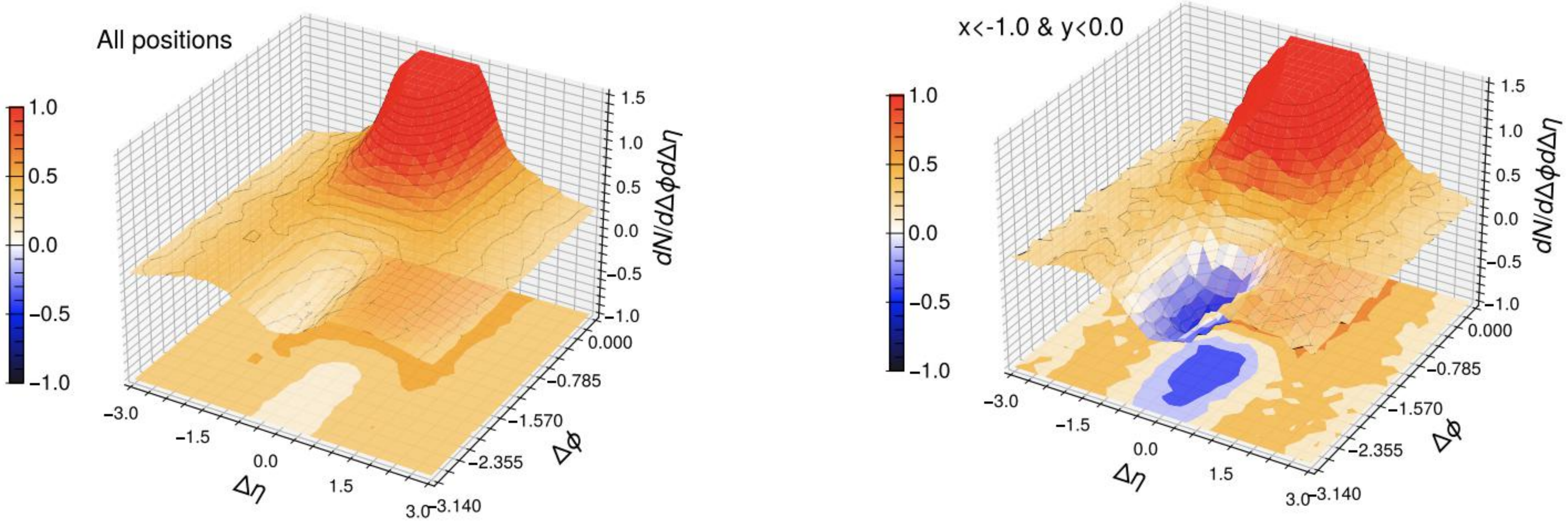
3. There is a unique signal of DF-wake in rapidity distribution of jet-hadron correlation.

4. By double Gaussian fit method, we studied DF-wake valley's sensitivity to jet energy loss, shear viscosity and EoS.

Thanks for your attention

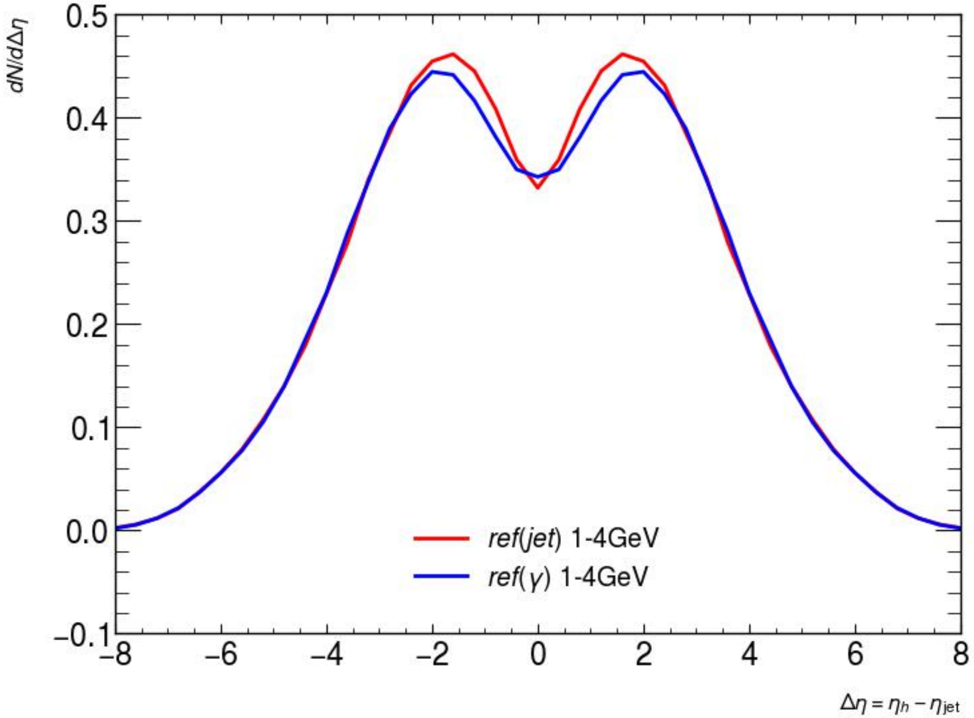
Backup

3D structure of diffusion wake after ML selection

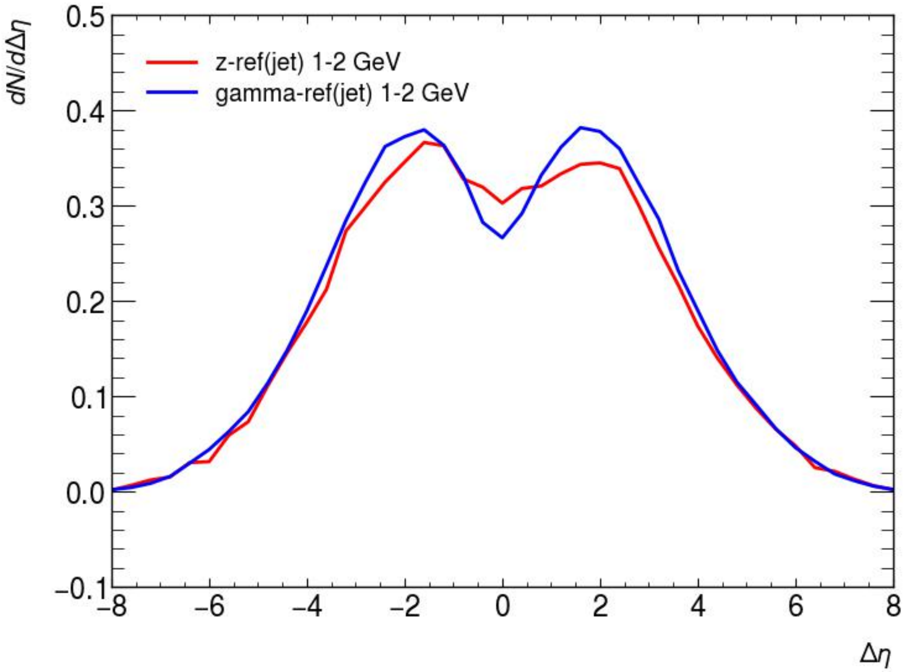


Jet initial positions are selected by the ML associated 2D jet tomography

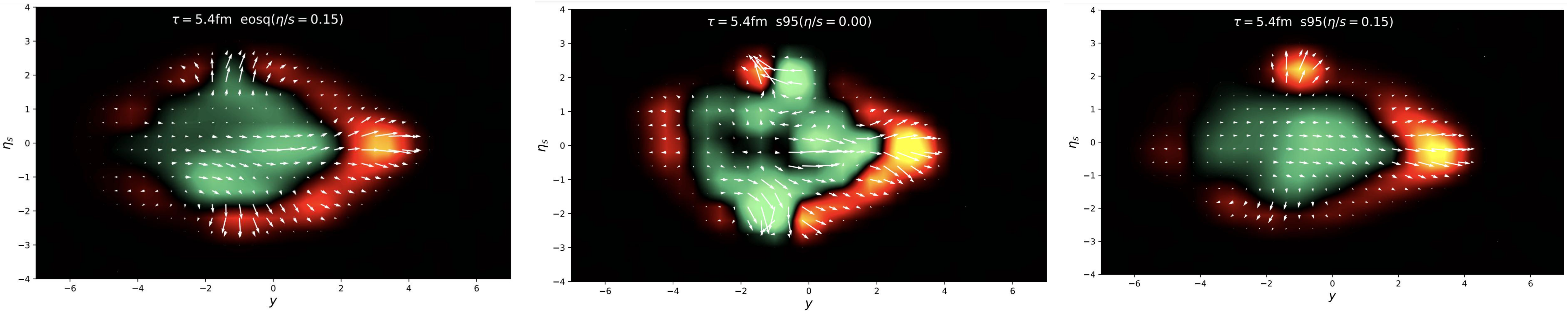
Gamma reference



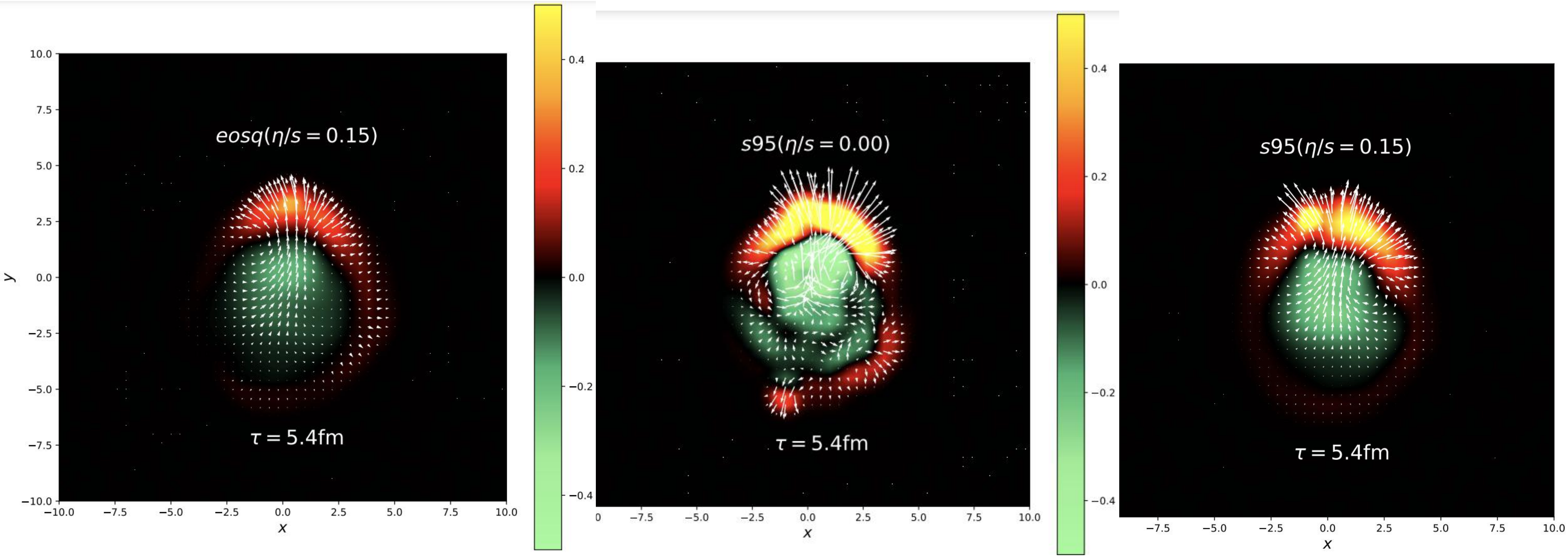
Z-hadron correlation



Energy density and quiver plot

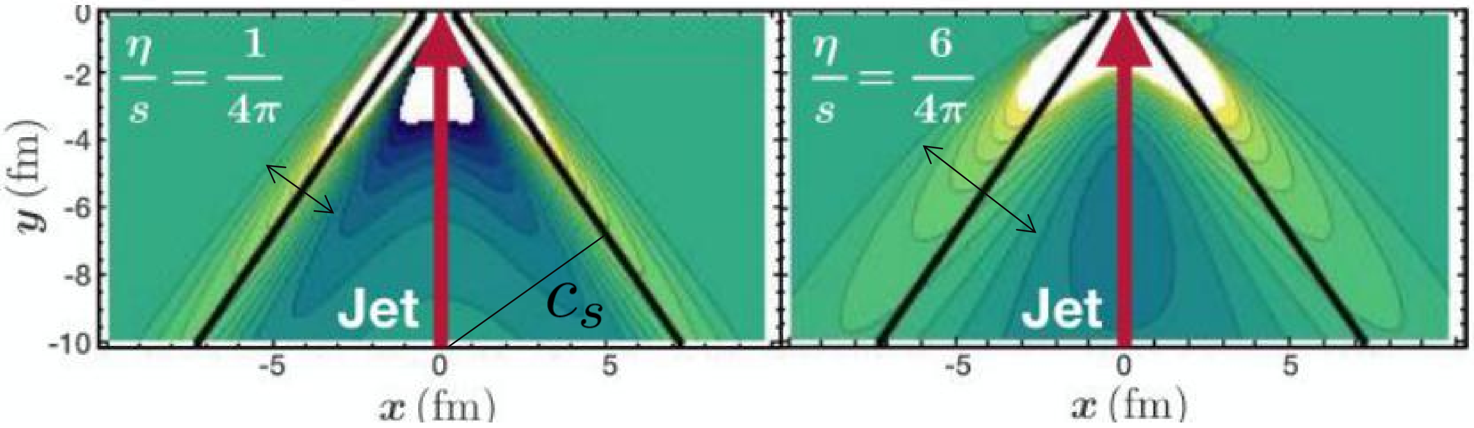


Energy density and quiver plot



Jet-induced medium response

Jet-induced medium response in the form of Mach-cone-like excitation.



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- Mach cone angle is sensitive to EoS; $sin\theta = \frac{c_s}{v}$
- Width of front wake of Mach cone is related with viscous properties of QGP medium

Medium response and soft gluon radiation

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

Medium-induced gluon radiation:

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

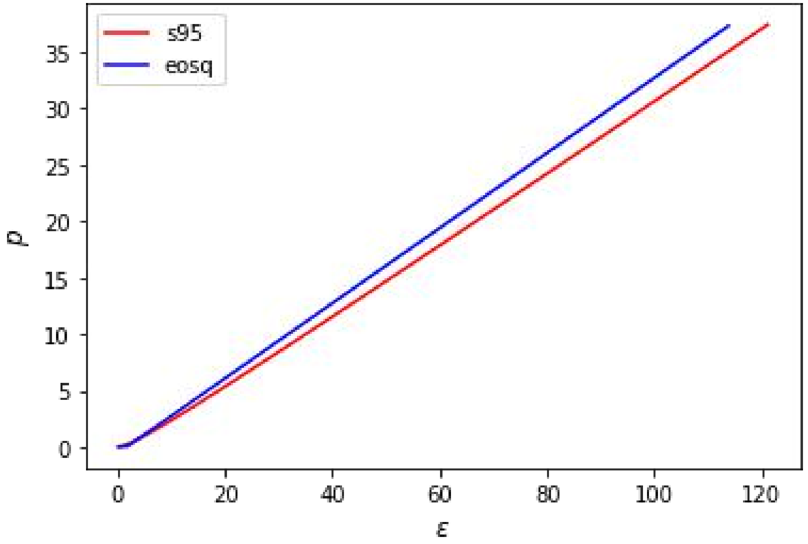
Mean-free-path limits the formation time:

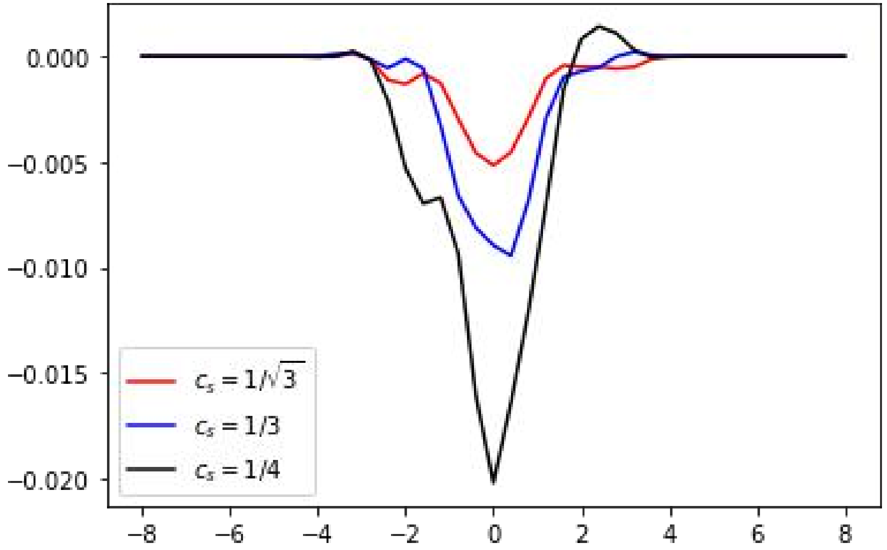
$$\tau_f \leq \lambda \sim 1/T \quad \hat{q} \sim T^3$$

$$\omega \approx \lambda^2 \hat{q}/2 \sim T$$

It is difficult to separate contribution to enhancemet of soft hadrons from medium-induced soft gluon radiation or medium response.

Equation of state





$$c_s^2 = \frac{\partial p}{\partial \varepsilon}$$

MPI Subtraction

(1) We first calculate the uniform correlation between Z/γ in one event and hadrons
from another similar Z/γ-jet event.

(2) We assume the effect of the diffusion wake on the total Z/γ-hadron yield in the mixed events is negligible.

(3) Contributions from jets to the Z/γ-hadron correlation in these mixed events, which are assumed to be the same as the integrated Z/γ-hadron yield within an angle $|\Delta\phi| > 1$ in Z/γ-jet events in addition to the MPI background.