Search for the elusive diffusion wake with 2D jet tomography

Wei Chen(UCAS)

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In collaboration with: Zhong Yang, Yayun He, Weiyao Ke, Longgang Pang, Xin-Nian Wang

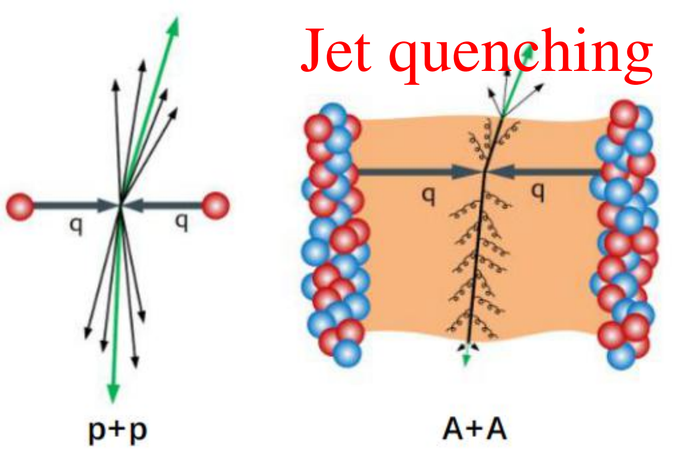
arXiv:2101.05422

Jet quenching

QGP: A deconfined strongly interacting matter that behaves like a perfect fluid.

When hard partons propagate in the medium, the medium can:

- Quench jet ---> jet energy-momentum loss
- Redistribute jet shower partons ---> jet broadening
- Induce gluon radiation
- Get swept up and heated by jet and get reconstructed as part of jet.



The modified jet in A+A are expected to carry info of the medium.

How to determine the modified jet is important for the study of QGP

Modified jet in A+A

- leading jet shower partons
- recoil partons
- induced radiated gluons
- Medium response

Jet-induced medium response

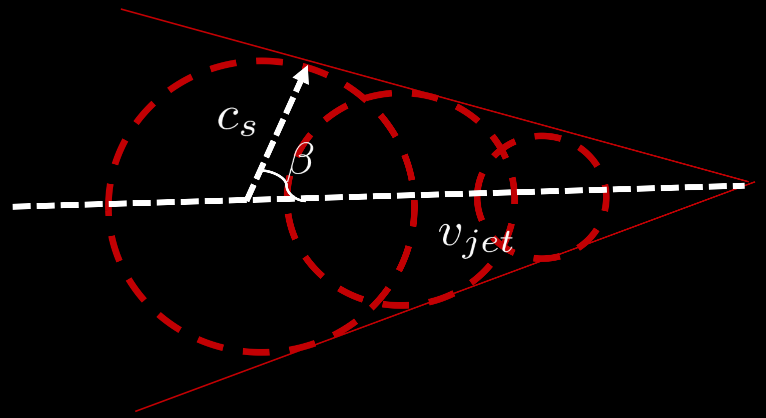
QGP: hot dense medium

Strong interaction

Jet: energetic with $v_p > c_s$

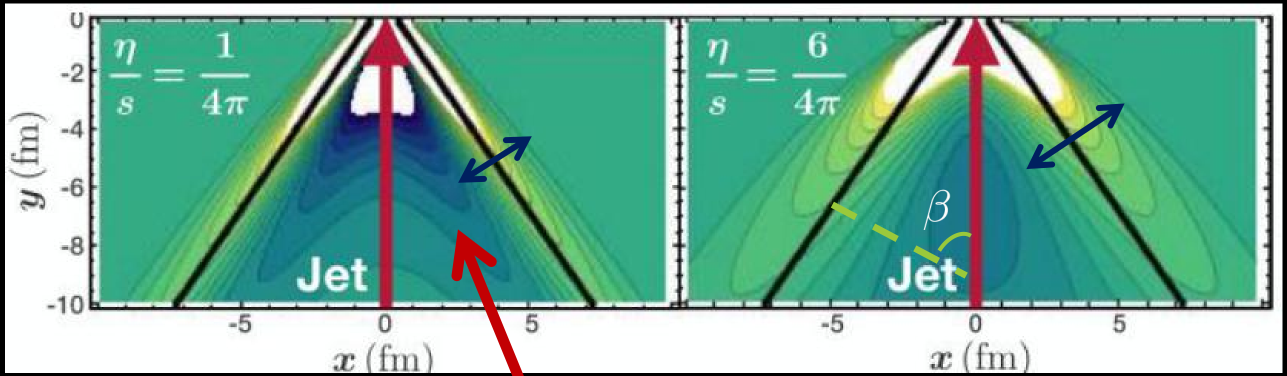
Continuous E-M loss deposited into medium

the interference of wave front induced



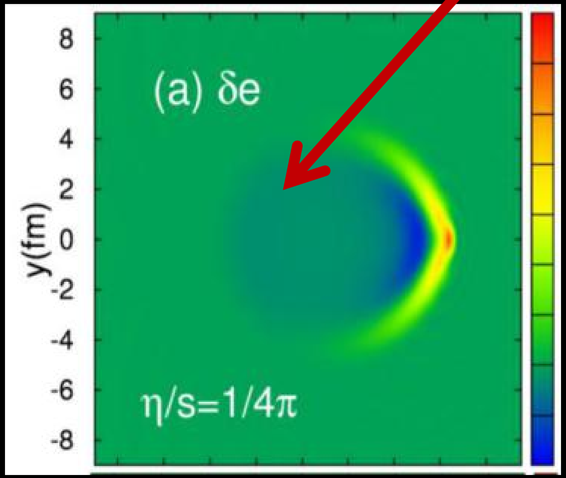
- Strong jet-medium interaction lead to jet-induced medium response in the form of Mach-cone-like excitation.

Jet-induced Mach Cone

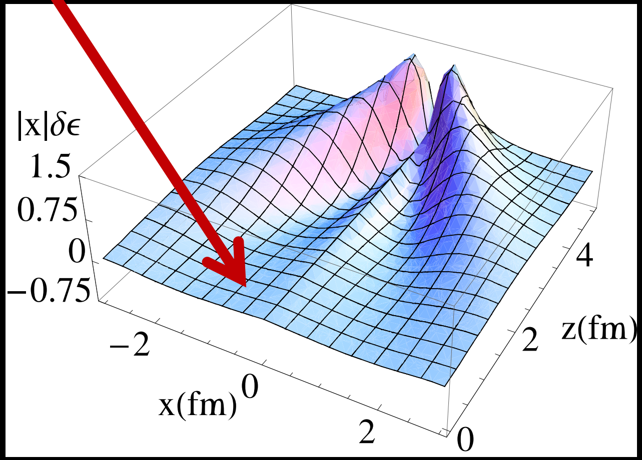


R.B.Neufeld. PRC79,054909(09')

diffusion wake



Yan Li ,S,Jeon and C.Gale(17)



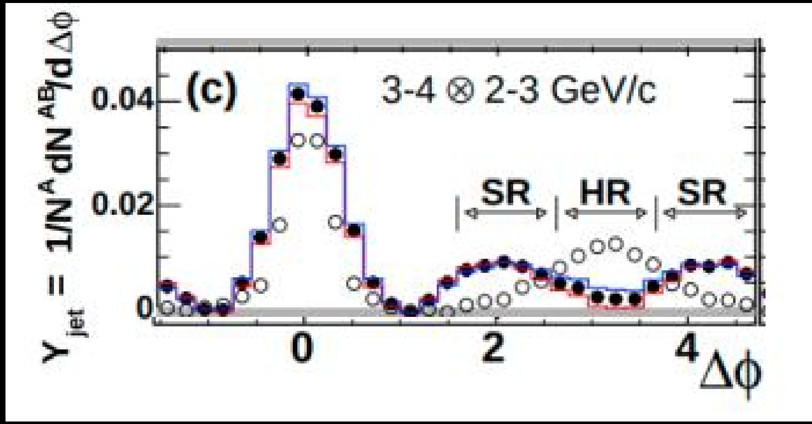
Qin, Majumder, Song & Heinz (08)

Mach cone structure induced in fluid characterized by fluid properties

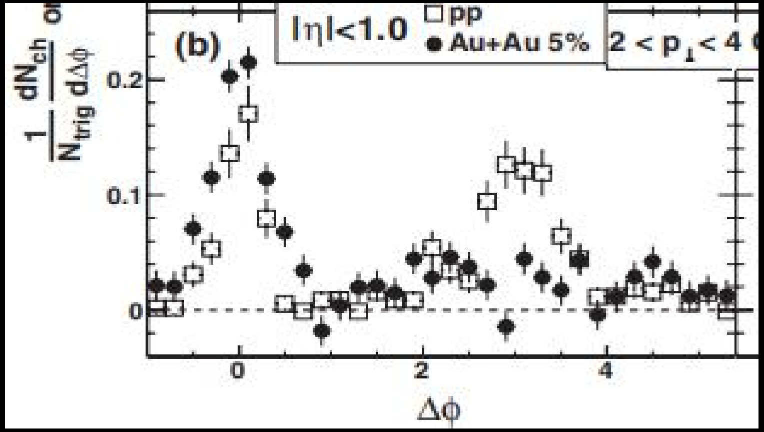
- Mach cone angle sensitive to EoS;
- Front wake width of Mach cone related with viscous properties of QGP medium.
- Diffusion wake can be seen in the opposite to jet progation.

Signals of jet-induced Mach Cone?

- double-peak structure on the away side of soft-hadron correlations.



PHENIX Phys. Rev., C 77, 011901(2008)



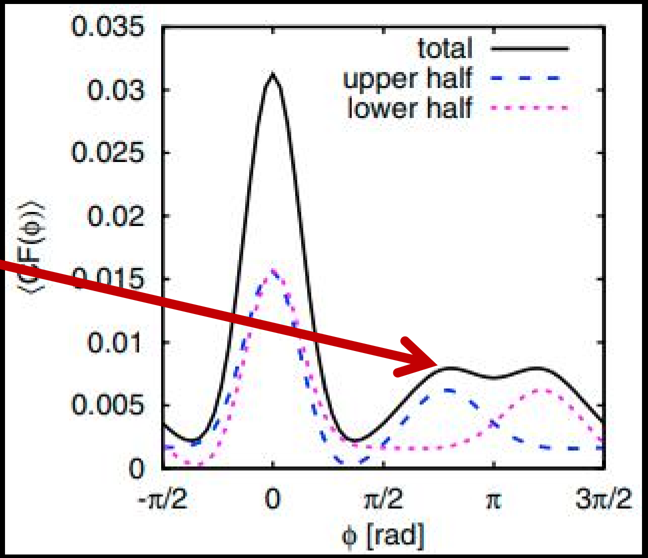
STAR PRL 102, 052302 (2009)

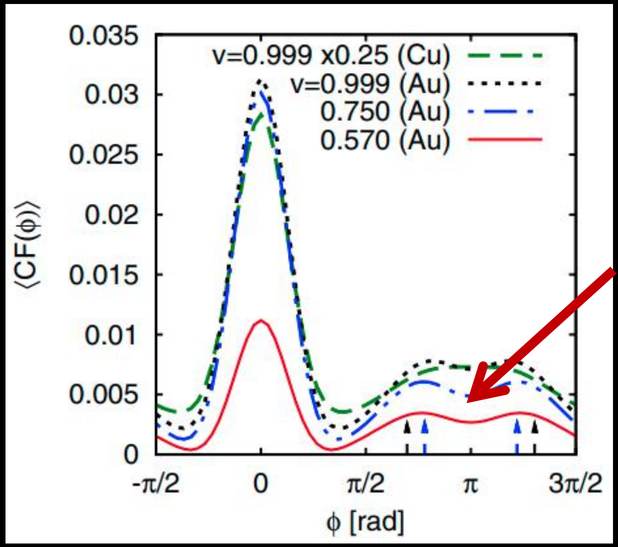
Is the double-peaked structure due to a Mach cone formation?

NO

triangular flow due to initial asymmetry

average wake front in different events.

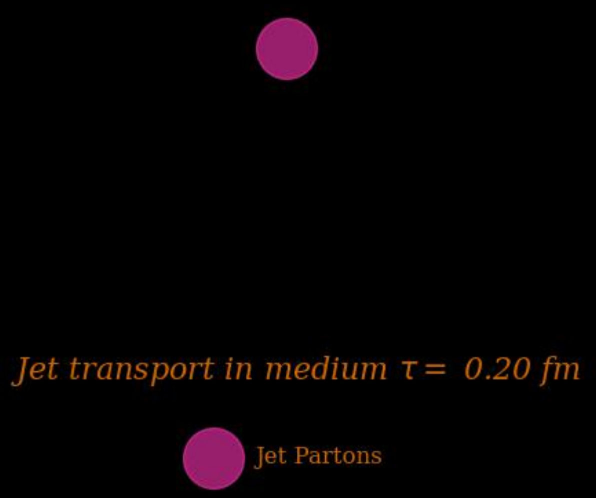




No formed Mach cone, but double structure still exists

Betz, Noronha, Torrieri, Gyulassy & Rischke (2010)

LBT model: Linear Boltzmann Transport Model



Baseline:

$$p_a \cdot \partial f_a = \int \sum_{bcd} \prod_{i=b,c,d} \frac{d^3 p_i}{2E_i(2\pi)^3} (f_c f_d - f_a f_b) |\mathcal{M}_{ab\to cd}|^2 \times \frac{\gamma_b}{2} S_2(\hat{s}, \hat{t}, \hat{u}) (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + \text{inelastic}$$

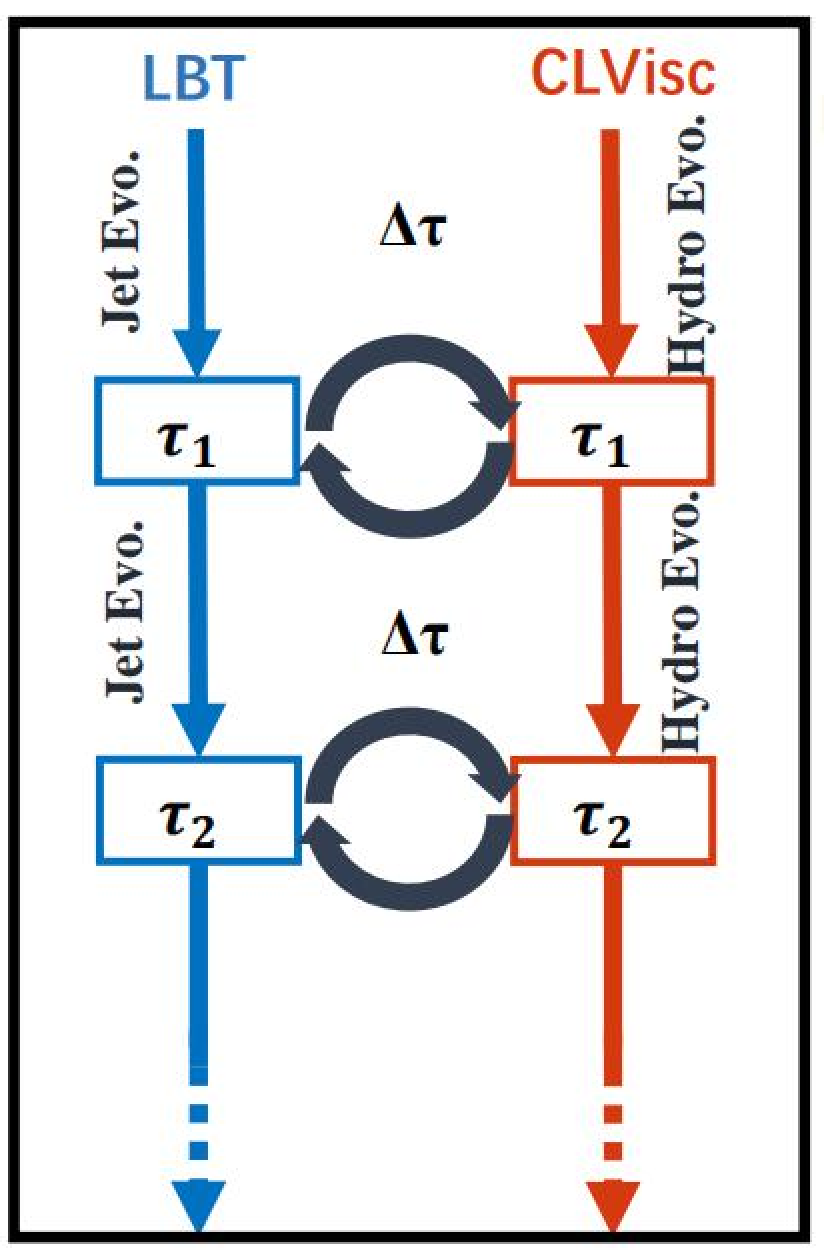
Medium-induced gluon radiation(HT method):

$$\frac{d\Gamma_a^{\text{inel}}}{dz dk_\perp^2} = \frac{6\alpha_s P_a(z) k_\perp^4}{\pi (k_\perp^2 + z^2 m^2)^4} \frac{p \cdot u}{p_0} \hat{q}_a(x) \sin^2 \frac{\tau - \tau_i}{2\tau_f}$$

Tracked Partons:

- **Jet shower partons,**
- **thermal recoil partons**
- **radiated gluons.**
- **negative partons (Back reaction included for EM conservation)**

CoLBT-hydro model



CoLBT-hydro model

LBT
（Linear Boltzmann jet transport model ）

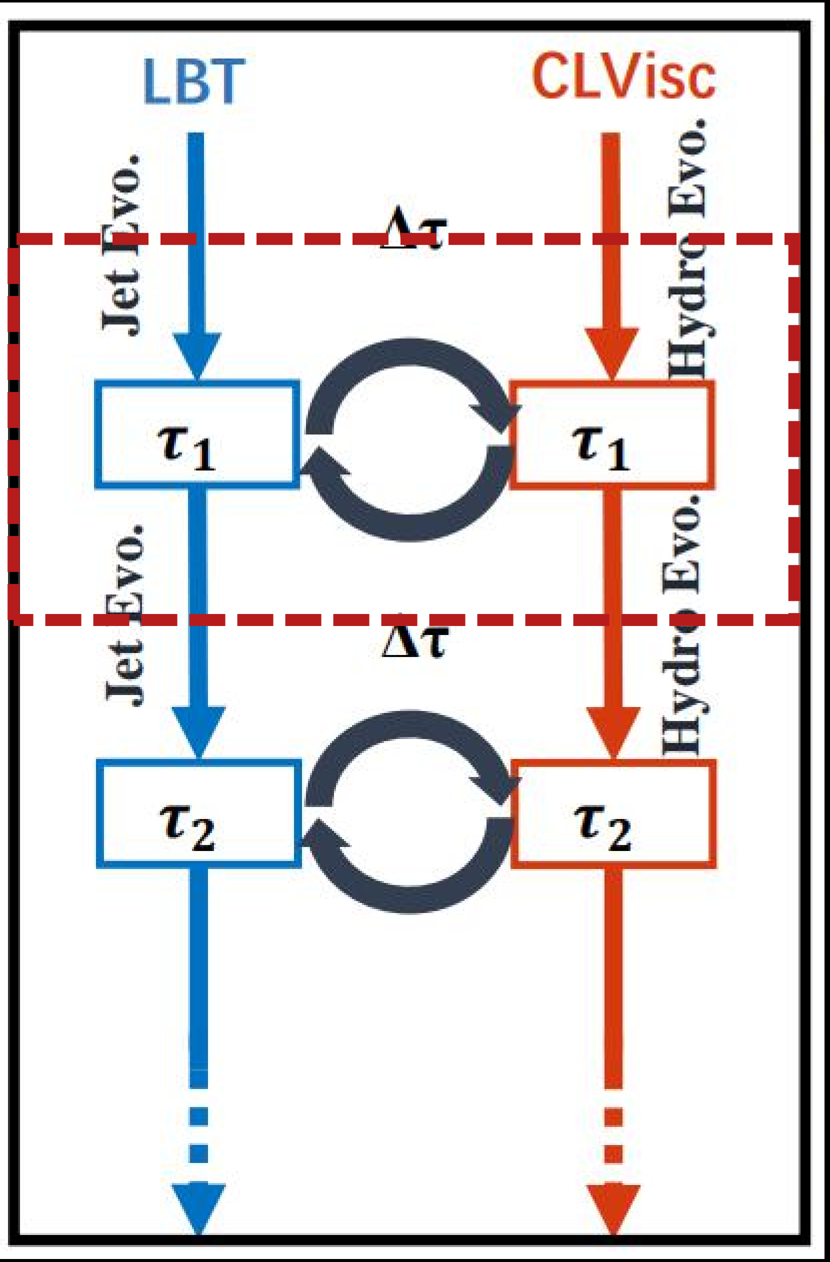
CLVisc
（3+1D hydrodynamical model ）

Concurrently to describe:

- space-time evolution of hot-dense medium (CLVisc)
- jet propagation and transport(LBT)
- medium response to jet energy-momentum loss

in real time.

CoLBT-hydro model



How to describe the interaction between jet partons and medium?

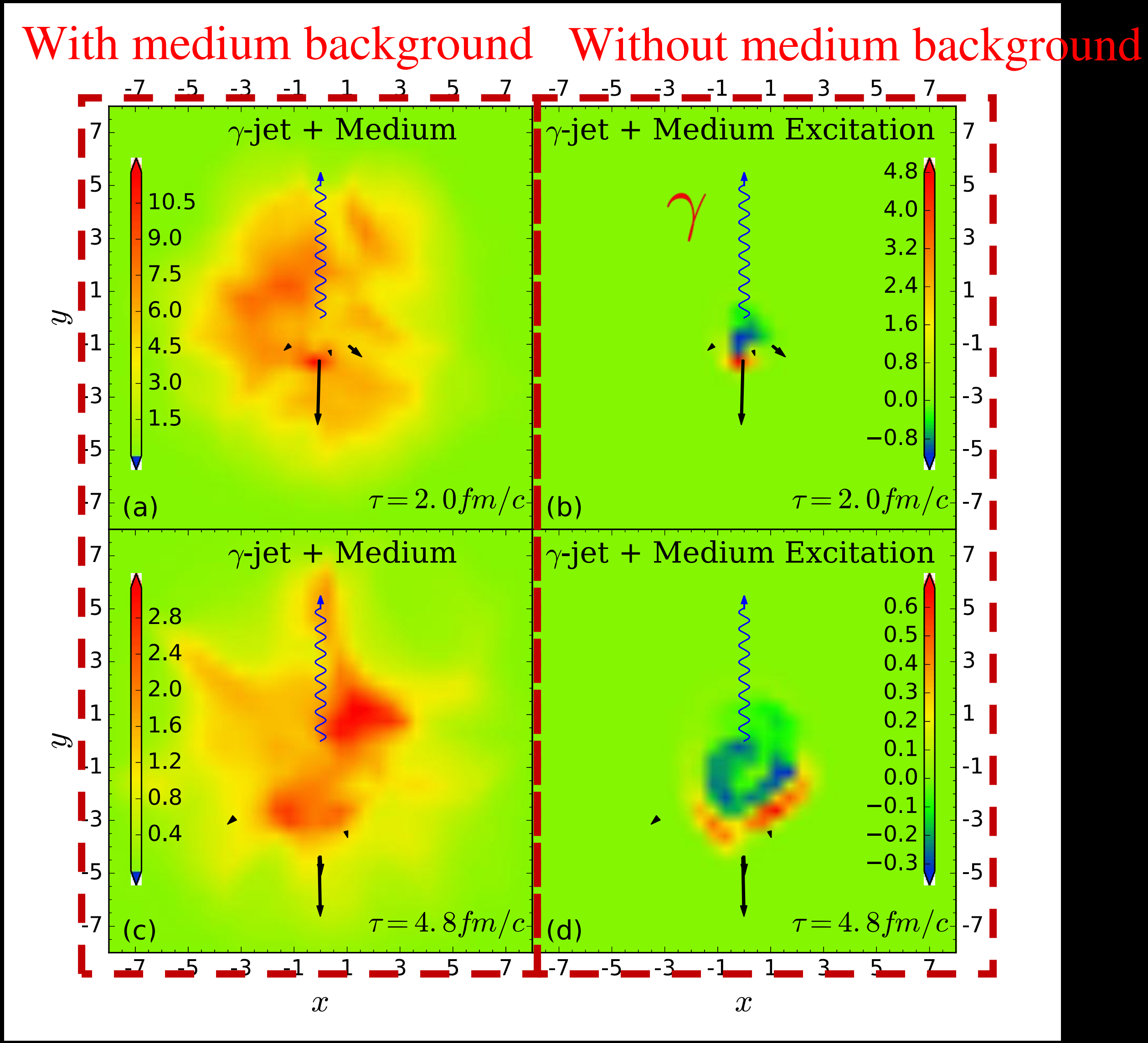
- Carry out jet partons transport according to the surrounding medium info
- Sort jet partons according to a cut-off parameter p^0_{cut}
  - hard partons $\quad p\cdot\partial f(p) = -C(p) \quad (p\cdot u > p^0_{cut})$
  - soft and negative partons.

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

- Update medium information by solving the hydrodynamic equations with source term.

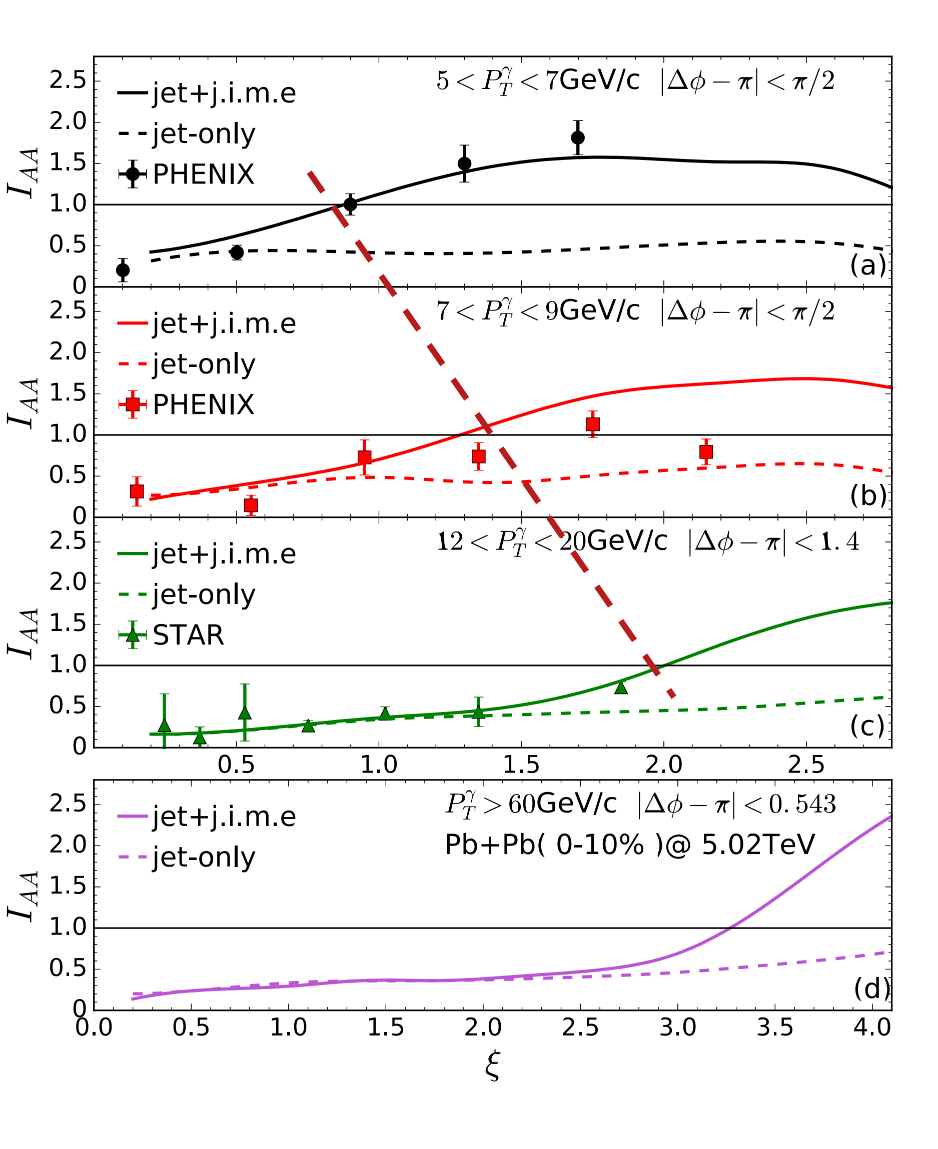
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

gamma-jet propagation within CoLBT-hydro



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

gamma-hadron correlation at RHIC



$$\xi = -\ln \frac{p_T^h}{p_T^\gamma}$$

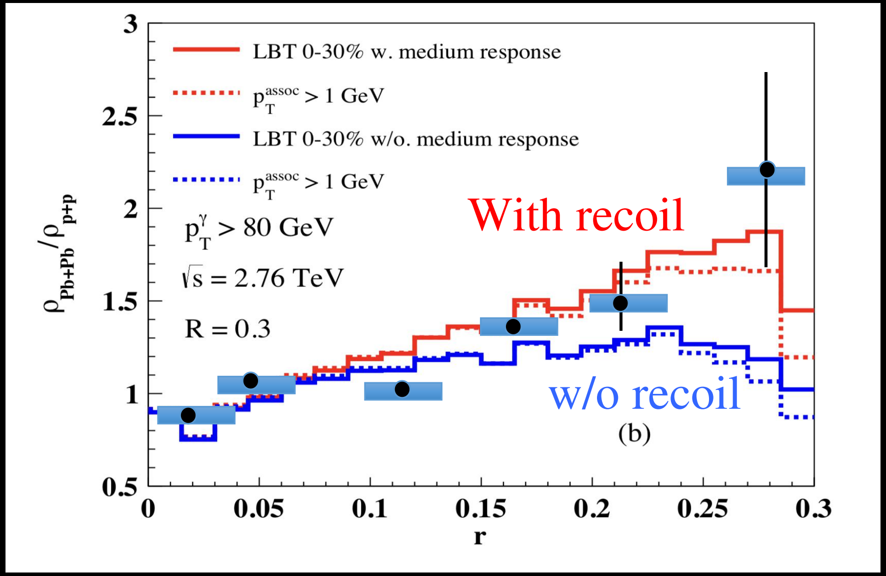
- the suppression of hadrons at small ξ
- the enhancement of hadrons at large ξ
- The onset of soft hadron enhancement ($I_{AA} \geq 1$) due to j.i.m.e. occurs at a constant $p_T^h \sim 2$

soft hadrons from j.i.m.e. carry an average thermal energy

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

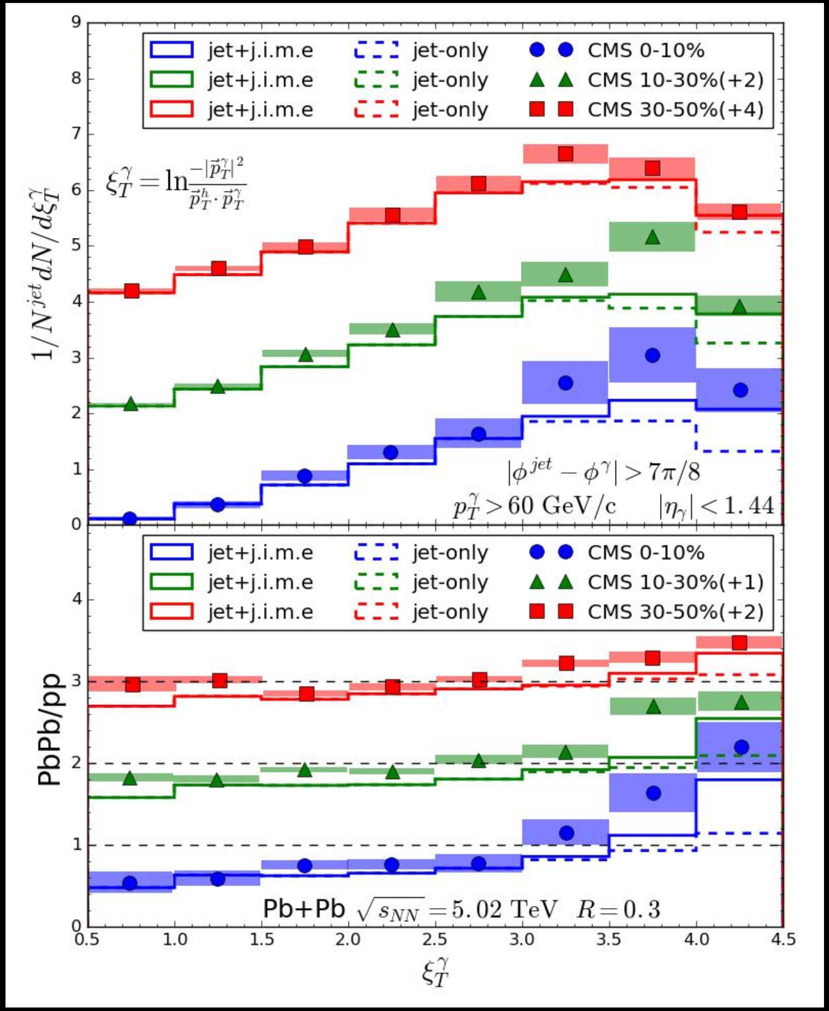
Medium modification of gamma-jets at LHC

Jet Profile



Luo, Cao, He & XNW, arXiv:1803.06785

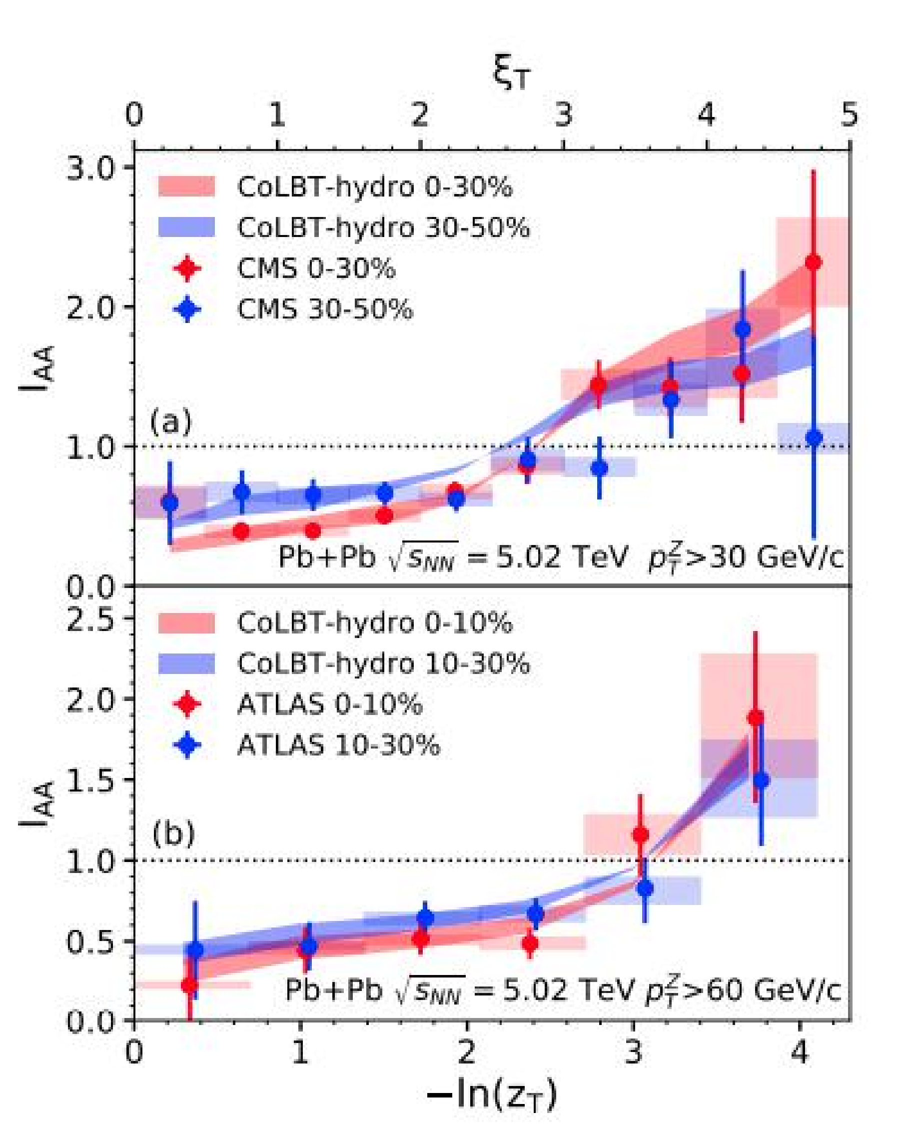
Jet fragmentation Function



The effect of medium response on jet substructure on tranverse and longitudinal direction is significant.

Chen, Cao, Luo, Pang & XNW, 2005.09678

Z-hadron correlations at LHC



arXiv:2101.05422

The band is variation of α_s within 95% credible region of the Bayesian fitting probability.

Could the enhancement of soft hadron yield in jet direction be considered as a signal of jet-induced medium excitation?

Medium response & soft gluon radiation

For the enhancement of soft hadrons, It is difficult to distinguish the contribution from medium response or medium-induced soft gluon radiation.

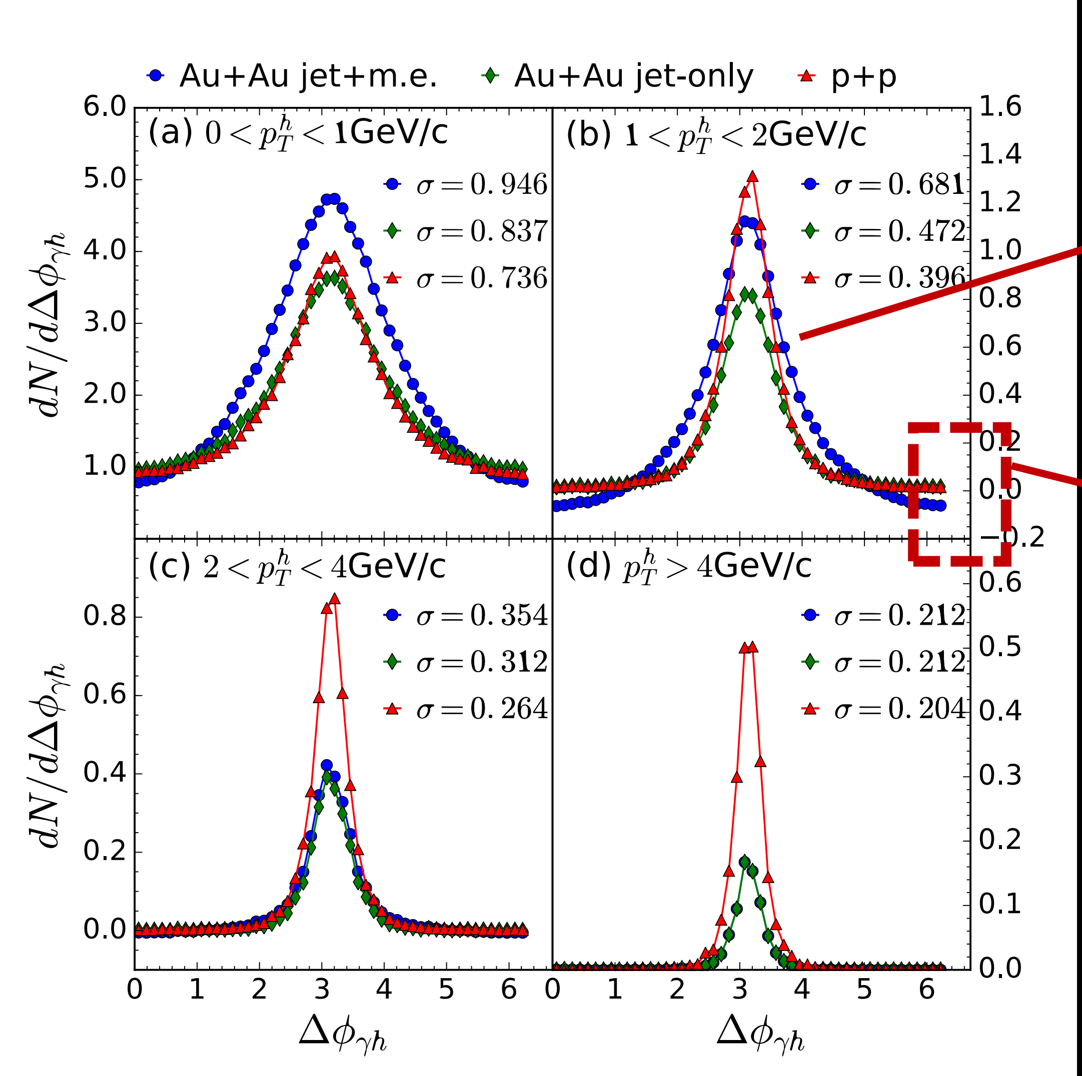
Medium responce: $\delta f(p) \sim e^{-p\cdot u/T}$ Energy scale: $\omega \sim T$

Soft radiated gluons: $\omega_g \sim \hat{q}\lambda^2 \sim T$

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

limited by the mean-free-path: $\tau_f \leq \lambda \sim 1/T$ $\hat{q} \sim T^3$

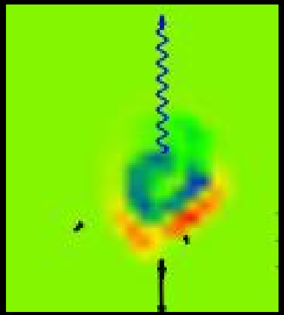
Azimuthal distribution of soft hadrons at RHIC



Jet peak broadened.

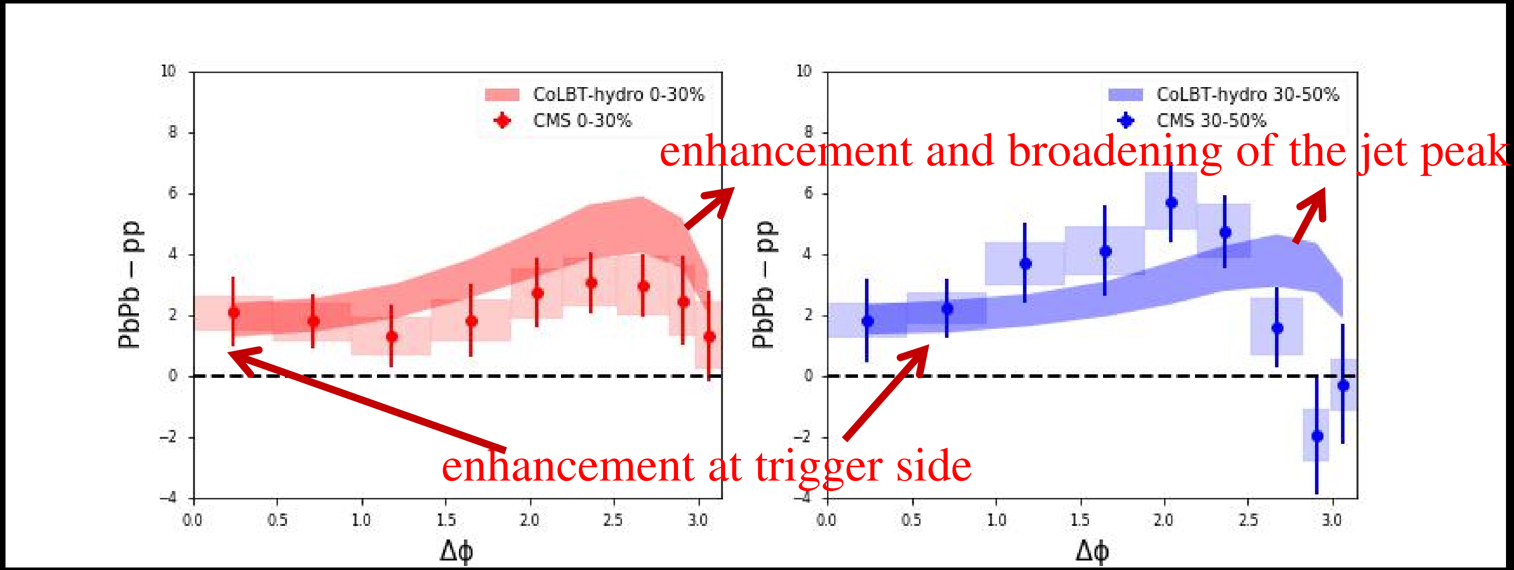
the depletion of soft hadrons in the γ direction

the diffusion wake left behind by the jet in QGP.



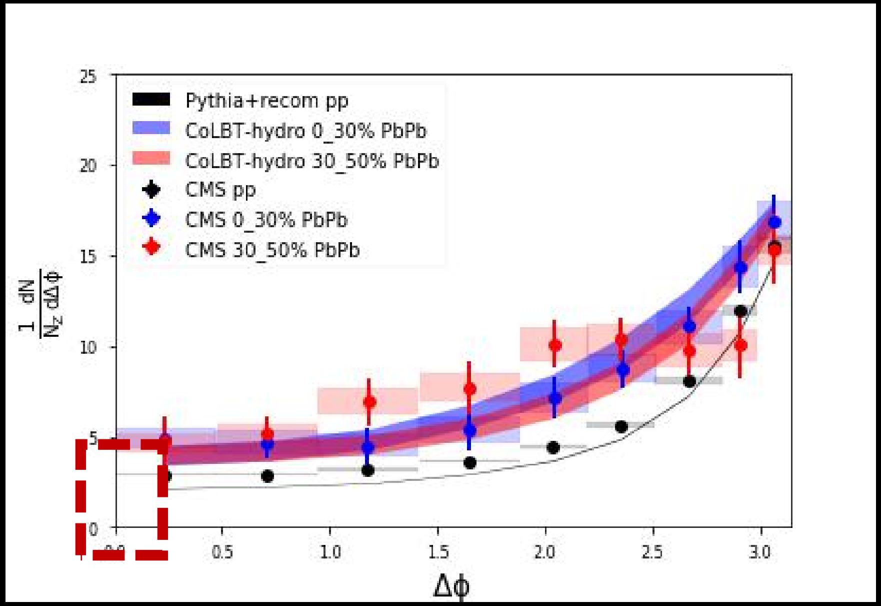
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86

Azimuthal distribution of soft hadrons at LHC



- CMS show an enhanced soft Z-hadron yield in the Z direction in Pb+Pb collisions instead of expected depletion.
- CoLBT-hydro results agree with CMS data.

where are these hadrons in Z direction from in p+p collision



MPI: Multiple Parton Interaction

Hadrons in the Z direction comes mainly from MPI associated with a triggered hard process in p+p collisions.

The probability of multiple jet production in pp:

$$g_j(b) = \frac{[\sigma(p_0)T(b)]^j}{j!} e^{-\sigma(p_0)T(b)}$$

Probability of multiple minjets ($p_T > p_0$) with at least one jet with $p_T > p_T^{trig}$

$$g_j^{\rm trig}(b) = \frac{[\sigma(p_0)T(b)]^j}{j!} \left\{ 1 - \frac{[(\sigma(p_0) - \sigma(p_T^{\rm trig})]^j}{\sigma(p_0)^j} \right\} e^{-\sigma(p_0)T(b)} \approx j \frac{\sigma(p_T^{\rm trig})}{\sigma(p_0)} g_j(b)$$

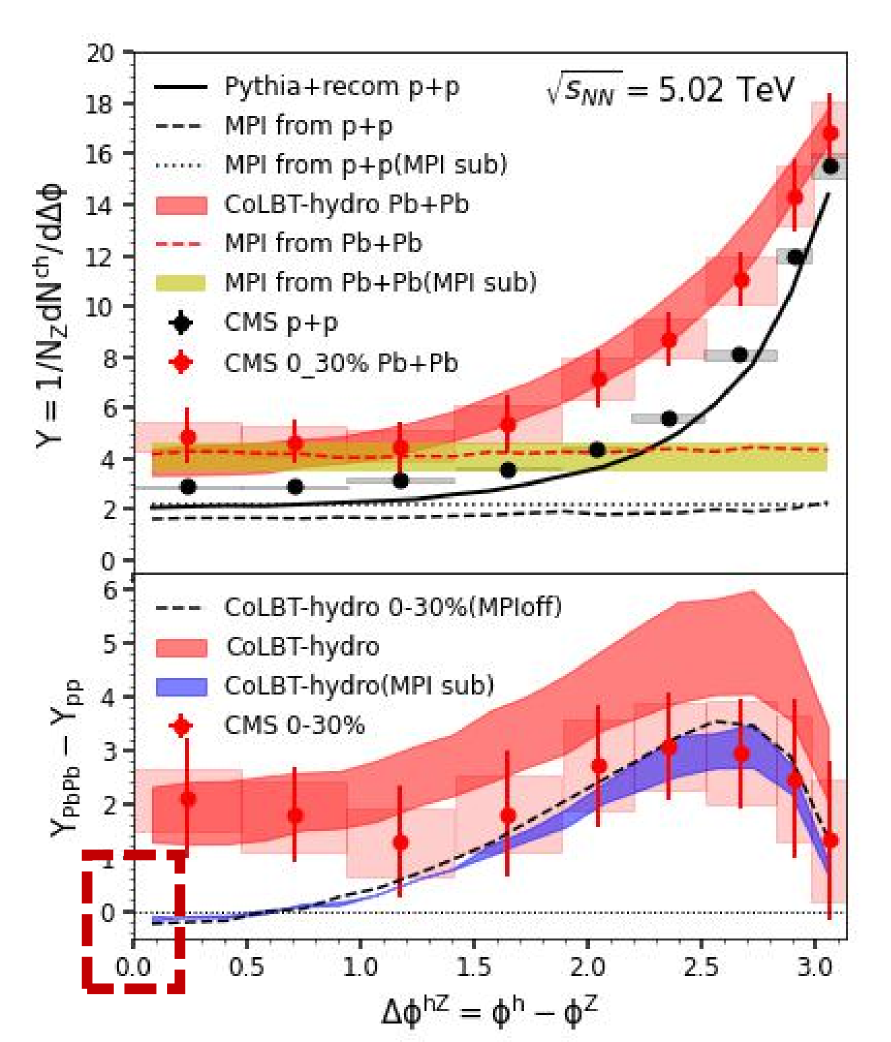
The corresponding conditional probability:

$$G_j^{trig} \approx \frac{\sigma_{in}}{\sigma_{jet}(p_0)} j G_j$$

more probable to produce multiple jets due to the triggering on a high p_T jet XNW & Gyulassy (1991)

Enhanced multiple minijet production in triggered jet events

MPI subtraction in Z-hadron correlation



Two ways to subtract MPI in the simulation:

- subtract from initial state.

  switch off the MPI processes

- subtract from final state(MPI sub).

  using a devised procedure

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

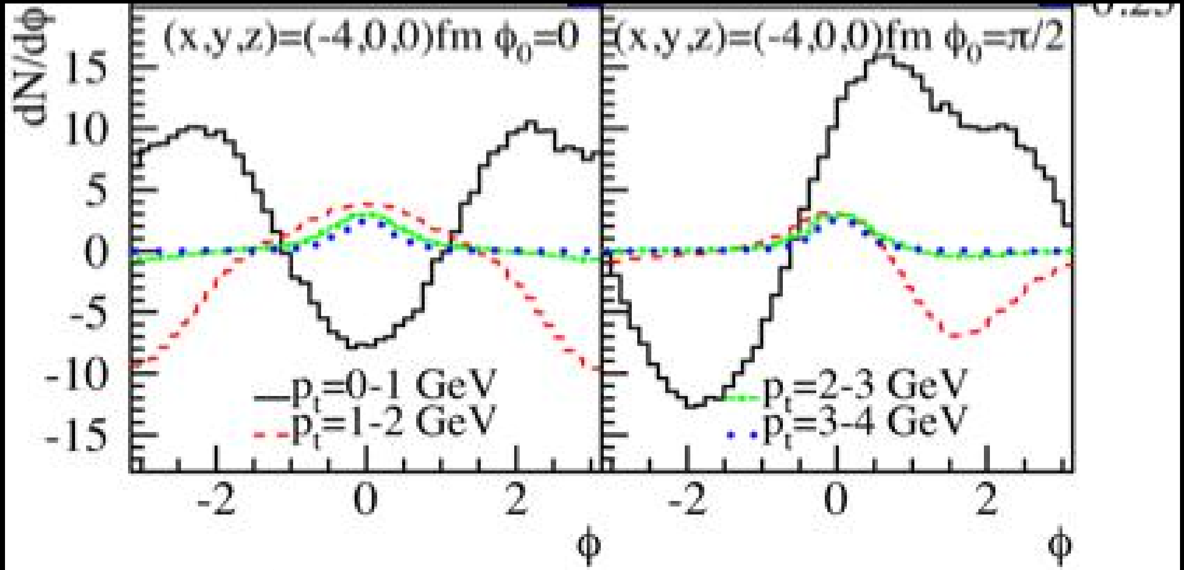
What can we get:

- hadron yield from MPI effect is uniform in the azimuthal angle.
- The Z-hadron correlation in the Z direction indeed becomes slightly negative after MPI sub

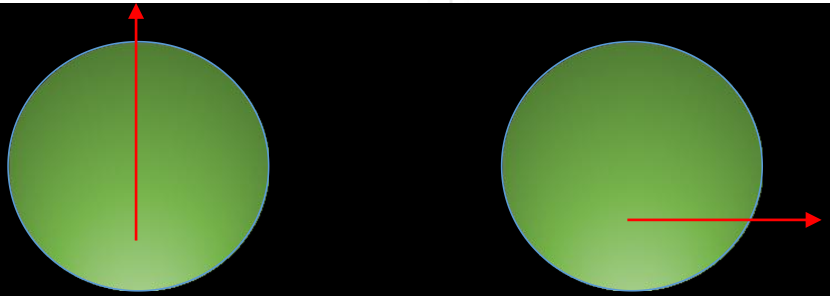
How to enhance diffusion wake effect?

The Z/γ hadron correlation in CoLBT-hydro results and experimental data are averaged over

- the initial transverse position
- the direction of the Z/γ -jets



Distorted Mach-cone-like excitation.



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

Tachibana, Shen & Majumder 2001.08321 (2020)

How to enhance diffusion wake effect?

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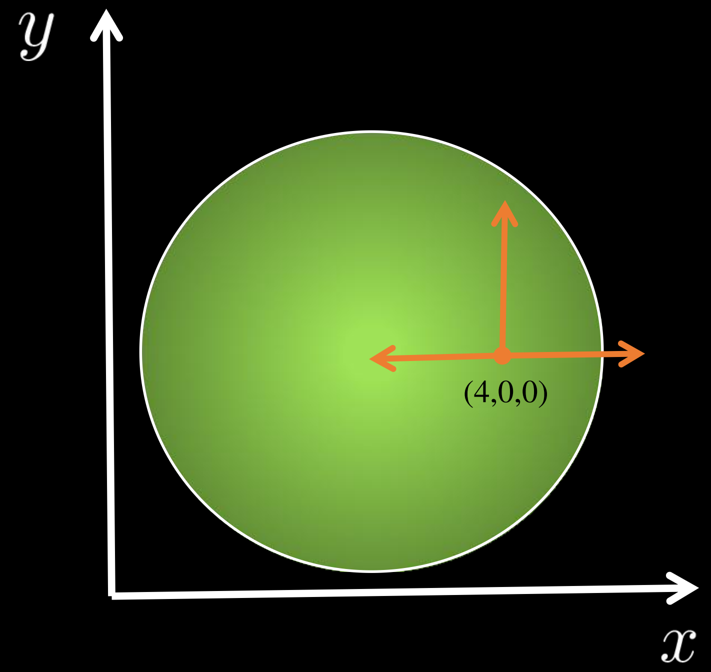
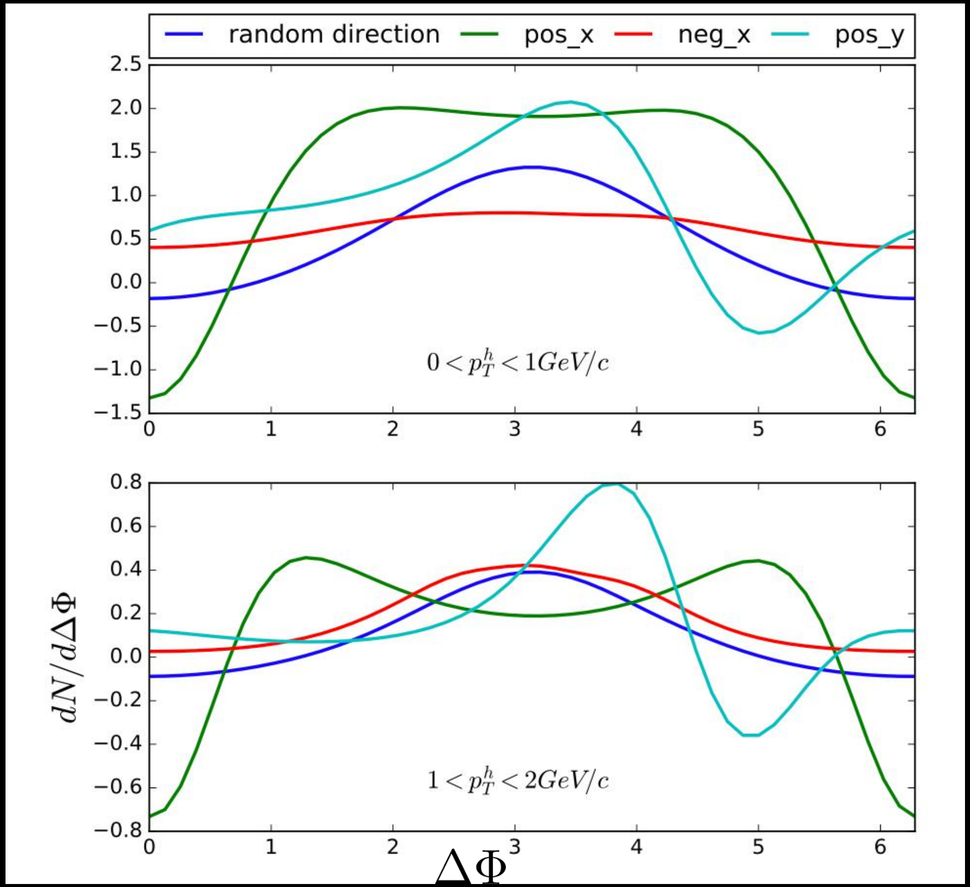


γ-hadron correlation



The structure of the azimuthal correlation is depend on the initial position, but smeared out in averaged events.

How to enhance diffusion wake effect?

The Z/γ hadron correlation in CoLBT-hydro results and experimental data are averaged over

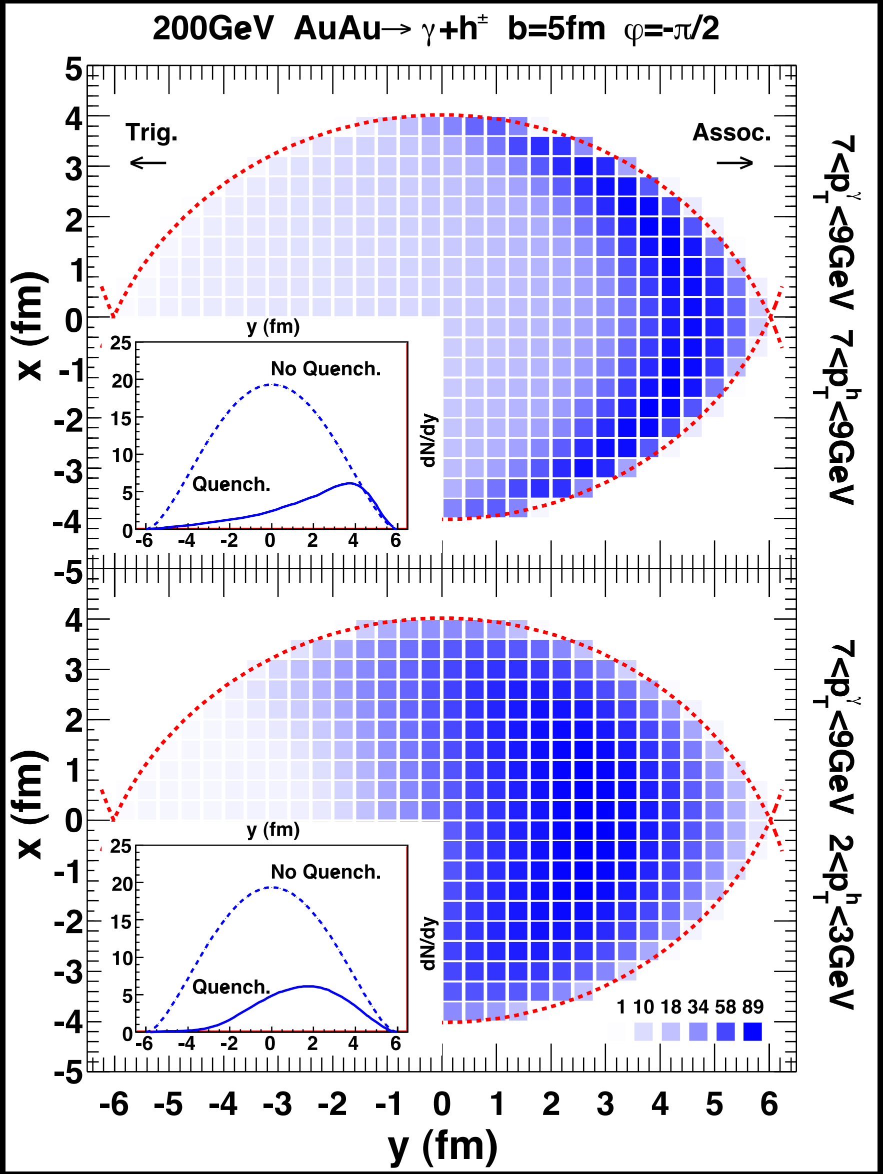
- the initial transverse position
- the direction of the Z/γ -jets

The way to enhance diffusion wake effect: choose specific events with

- specific initial production region ← **transverse gradient jet tomography**
- larger jet path length in medium ← **longitudial jet tomography**

2D jet tomography

Longitudinal jet tomography



$$p_T^h/p_T^\gamma \sim 1$$

The contribution to γ-hadron yield come mostly from the surface.

$$p_T^h/p_T^\gamma \sim 0.3$$

From mostly the whole volume.

Zhang, Owens, Wang and XNW, Phys. Rev. Lett. 103, 032302 (2009)

Transverse jet gradient tomography

Transverse jet gradient tomography can be used to localize the initial jet production position for more detailed study of jet quenching.

Jet transport coefficient $\hat{q}$:

- determine the difussion in both transverse momentum and coordinate of a propagating jet parton.
- lead to a drift in the final partons' transverse momentum and spatial distribution.

Transverse momentum asymmetry characterize the drift (depend on the path length and transverse gradient of $\hat{q}$)

Drift-diffusion equation: uniform medium

Boltzmann equation under approximation of small angle elastic scattering, no drag:

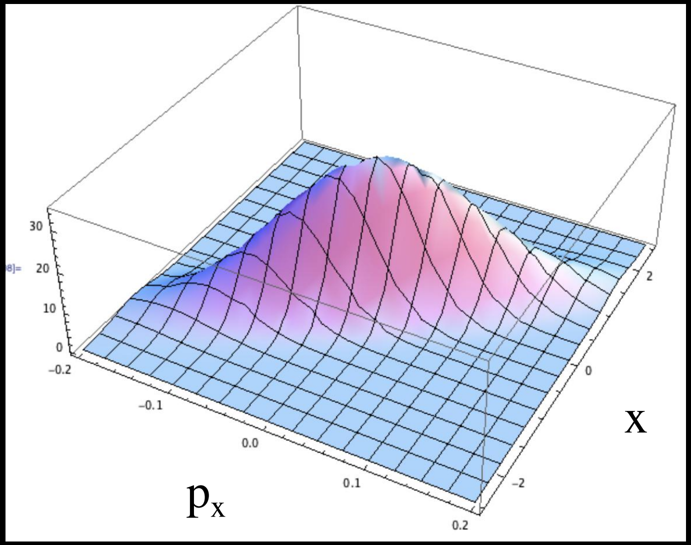
$$\frac{\partial f}{\partial t} + \frac{\vec{p}_\perp}{E} \cdot \frac{\partial f}{\partial \vec{r}_\perp} = \frac{\hat{q}}{4} \vec{\nabla}^2_{p_\perp} f(\vec{p}, \vec{r})$$

With initial distribution: $f(\vec{p}, \vec{r})_{t=0} = (2\pi)^2 \delta^2(\vec{r}_\perp) \delta^2(\vec{p}_\perp)$

$$f = 3\left(\frac{4E}{\hat{q}t^2}\right)^2 \exp\left[-(\vec{r}_\perp - \frac{\vec{p}_\perp}{2E}t)^2 \frac{12E^2}{\hat{q}t^3} - \frac{p_\perp^2}{\hat{q}t}\right]$$

$$\downarrow \int d^2 p_\perp \qquad\qquad \downarrow \int \frac{d^2 r}{(2\pi)^2}$$

$$4\pi \frac{3E^2}{\hat{q}t^3} \exp\left(-r_\perp^2 \frac{3E^2}{\hat{q}t^3}\right) \qquad \frac{1}{\pi \hat{q} t} \exp\left(-\frac{p_\perp^2}{\hat{q}t}\right)$$



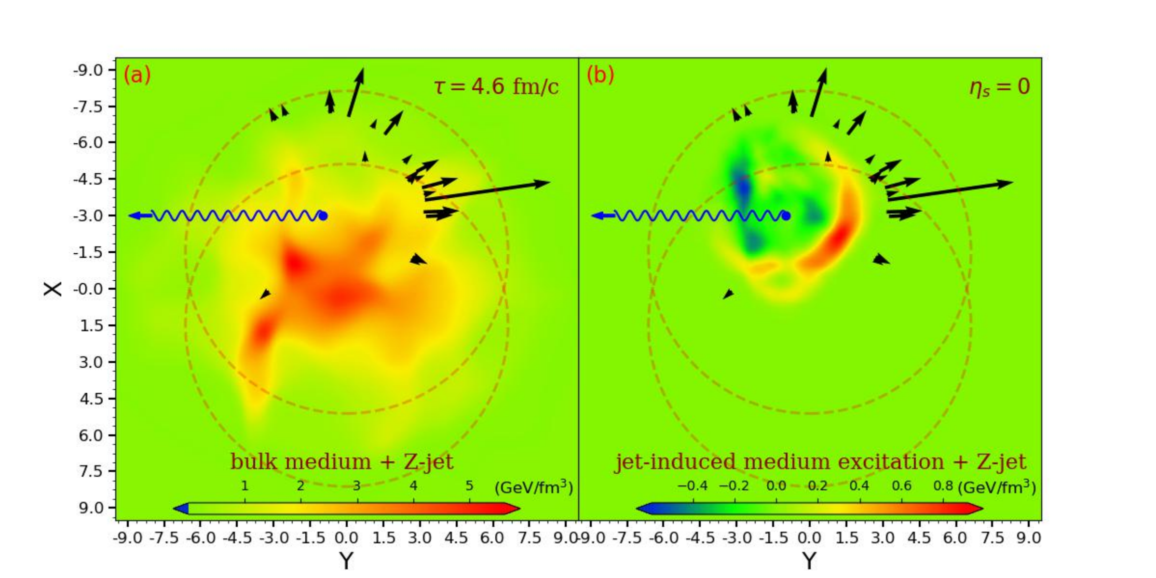
difusion in both coordinate space and transverse momentum

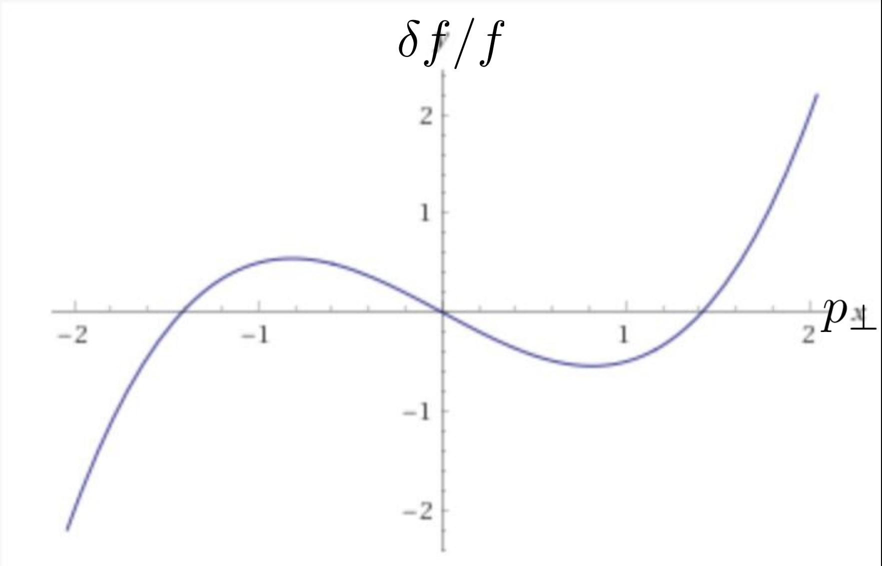
He, Pang & XNW, *PRL* 125 (2020) 12, 122301

Drift-diffusion equation: non-uniform medium

Linear spatial dependence: $$\hat{q} = \hat{q}_0 + \vec{x}_\perp \cdot \vec{a}$$

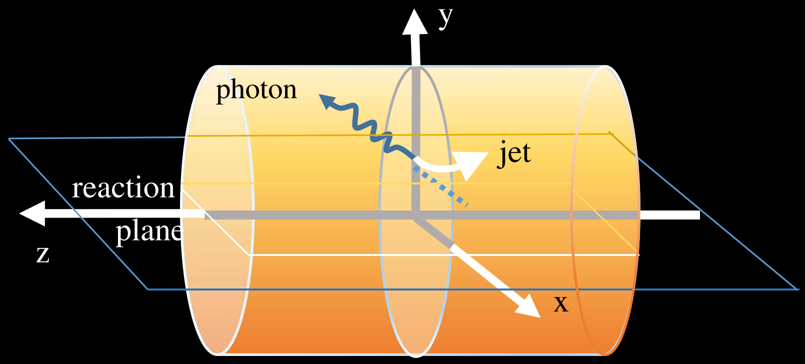
Momentum asymmetry: $$\delta f(\vec{p}_\perp) = -\frac{t}{3\omega \hat{q}_0} \vec{a} \cdot \vec{p}_\perp \left(1 - \frac{p_\perp^2}{2\hat{q}_0 t}\right) f_s(\vec{p}_\perp, t).$$

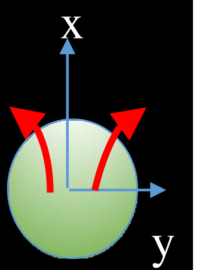


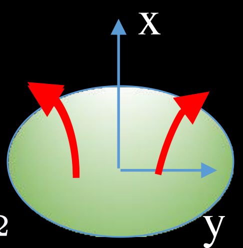


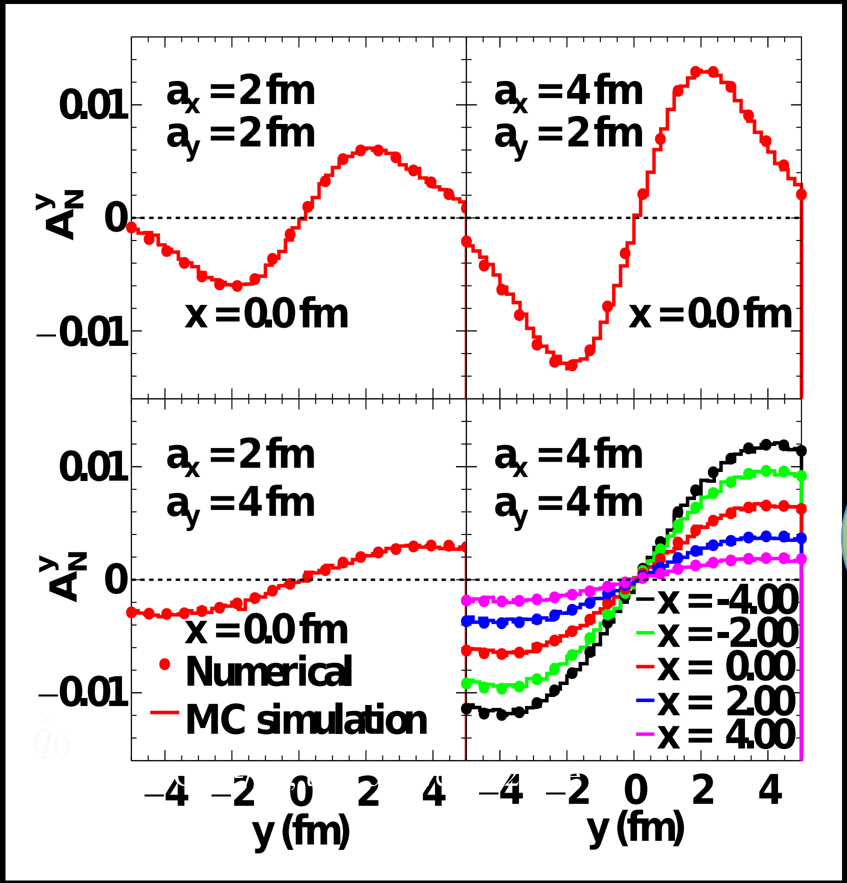
Diffusion in a non-uniform medium

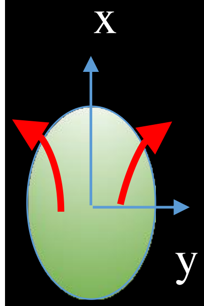
Momentum asymmetry: $$A_N^{\vec{n}} = \frac{\int d^3r d^3k f_a(\vec{k},\vec{r})\mathrm{Sign}(\vec{k}\cdot\vec{n})}{\int d^3r d^3k f_a(\vec{k},\vec{r})}$$

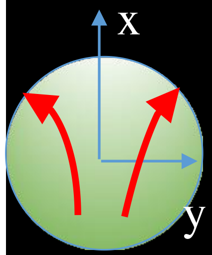








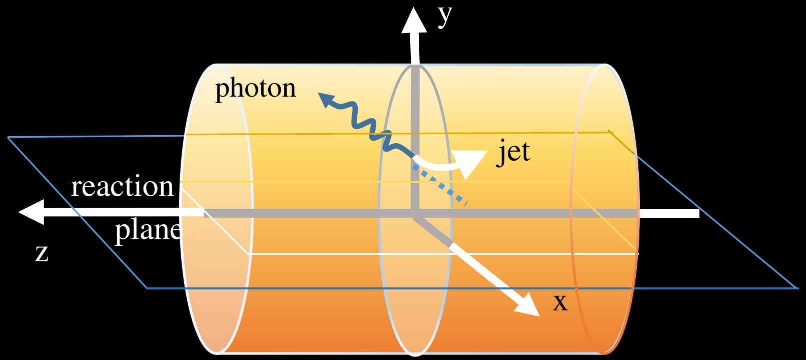


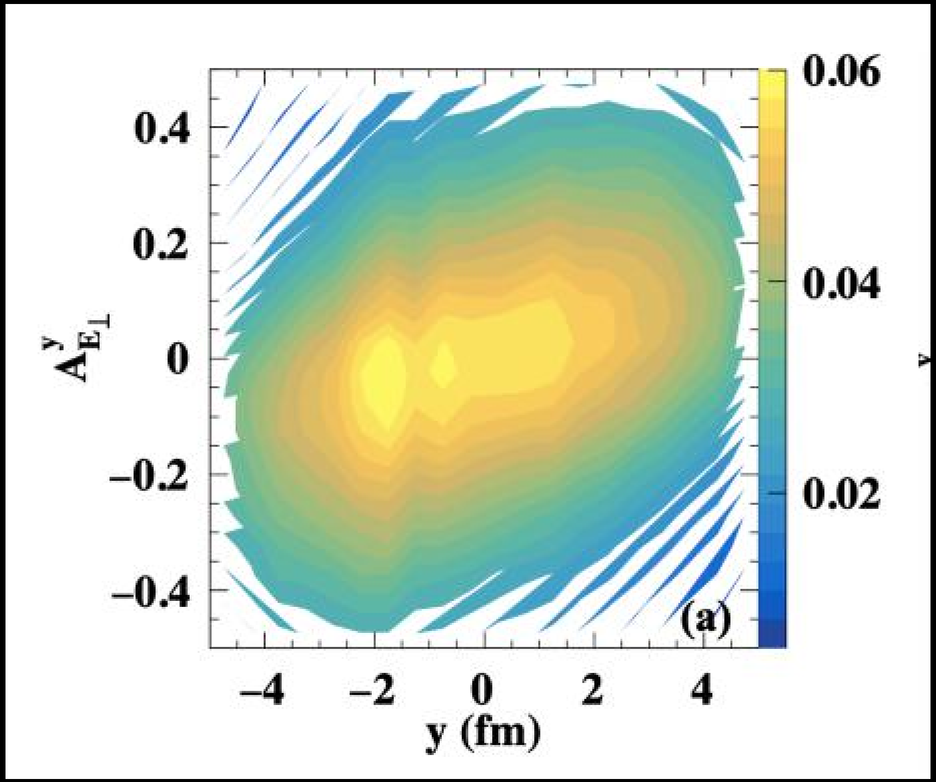


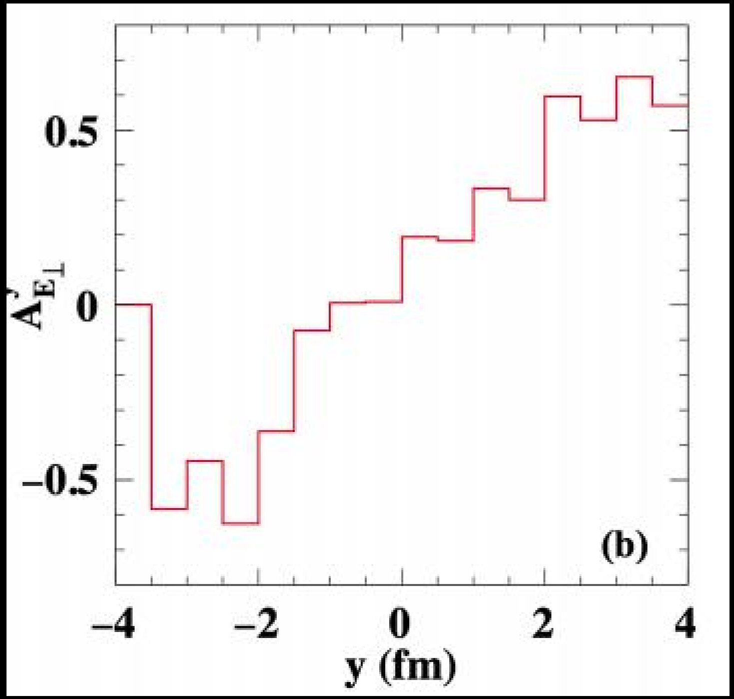
$$\hat{q}(\vec{r}_\perp, t) = \frac{\hat{q}_0 t_0}{t_0 + t} e^{-x^2/a_x^2 - y^2/a_y^2}$$

Momentum asymmetry

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

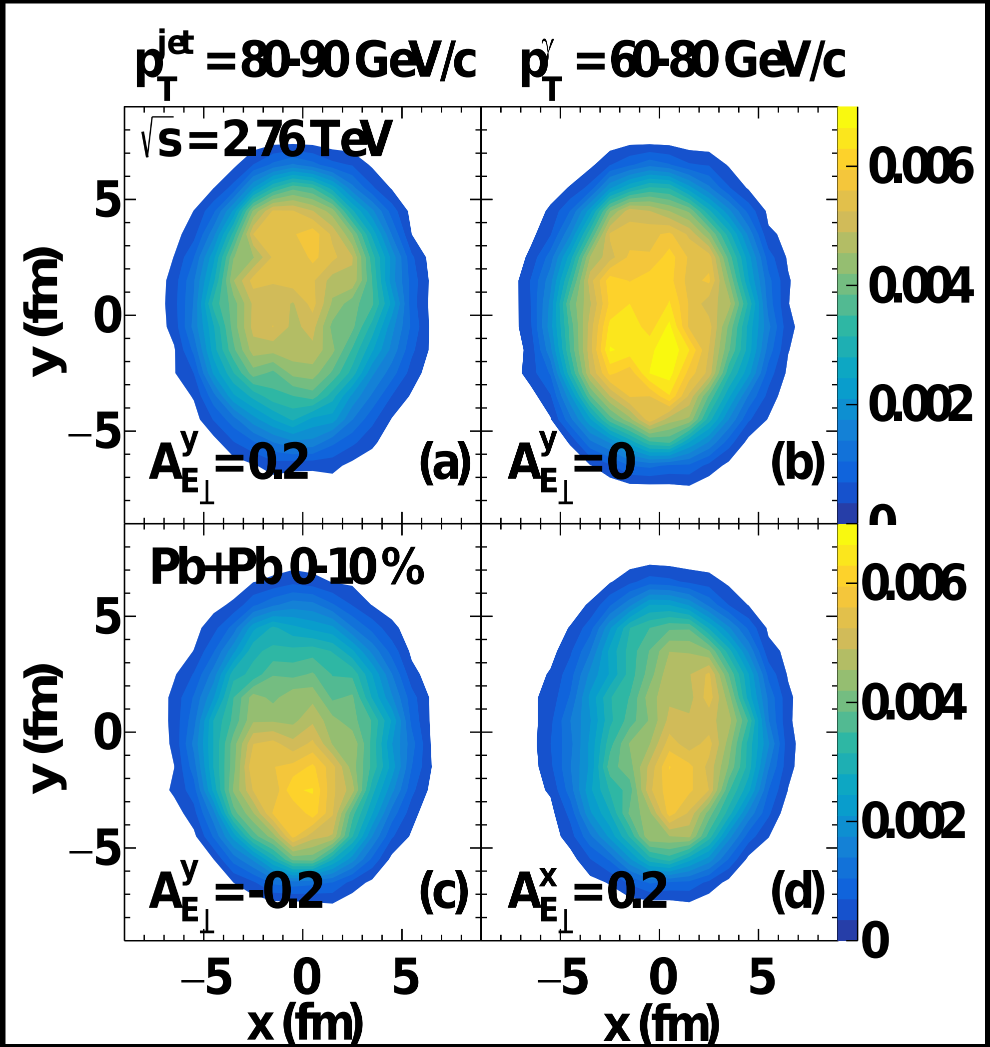




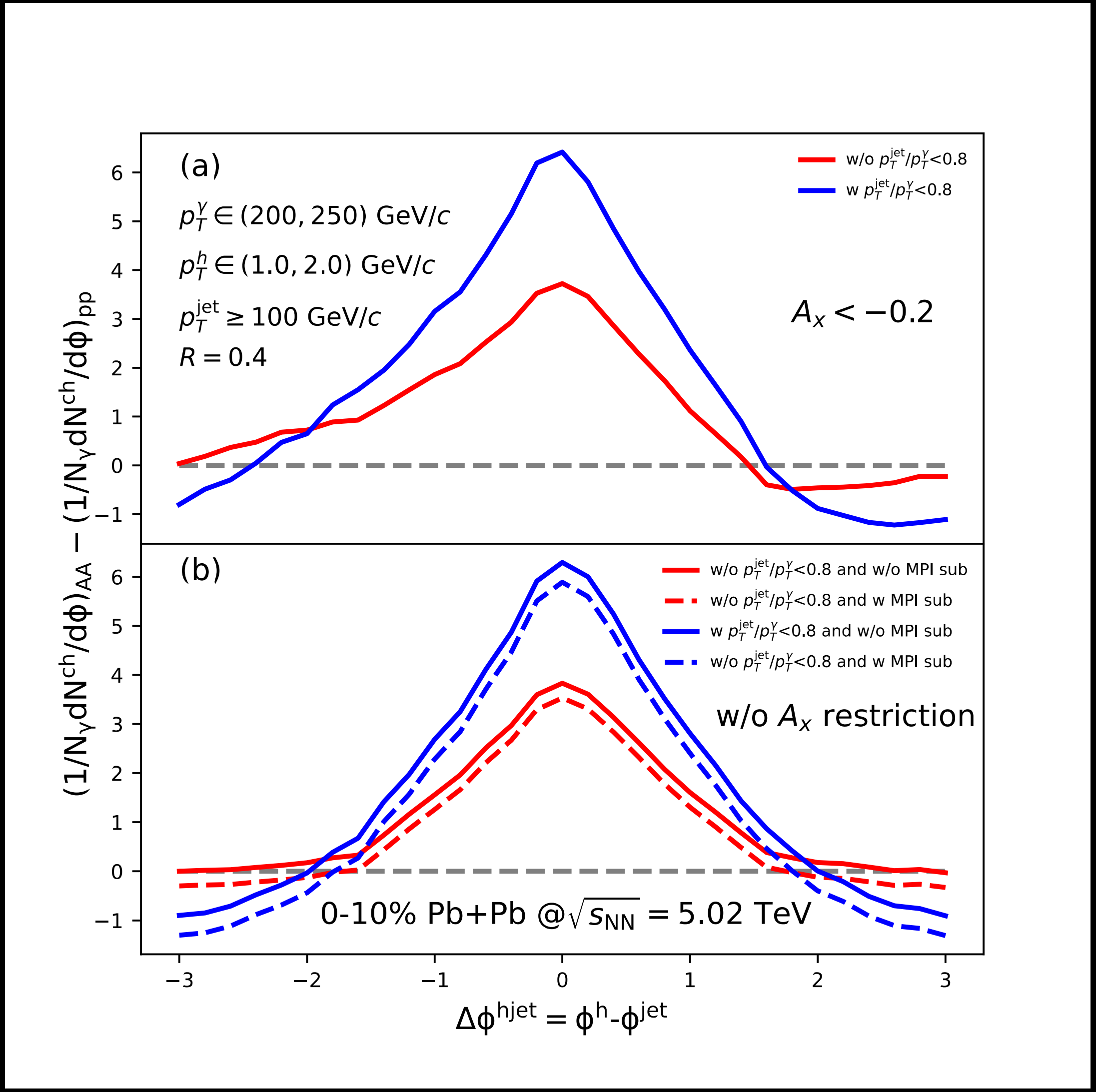


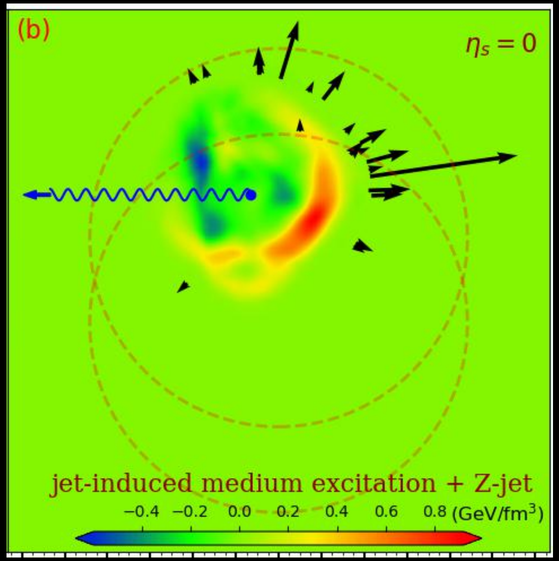
Drift-diffusion equation: dynamic and nonuniform medium

With trigger on the transverse asymmetry of energetic hadrons one can localize the initial production point of gamma-jet in the transverse plane



Enhancing the diffusion wake





Conclusion & discussion

- Jet-induced medium response leads to
  - enhancement of soft hadrons in jet direction
  - depletion of soft hadron on the trigger side
- MPI contribute to a uniform of soft hadrons
- 2D jet tomography can help to reveal the angular structure of Mach-cone excitation
- Future studies: sensitivity to bulk viscosity and EoS