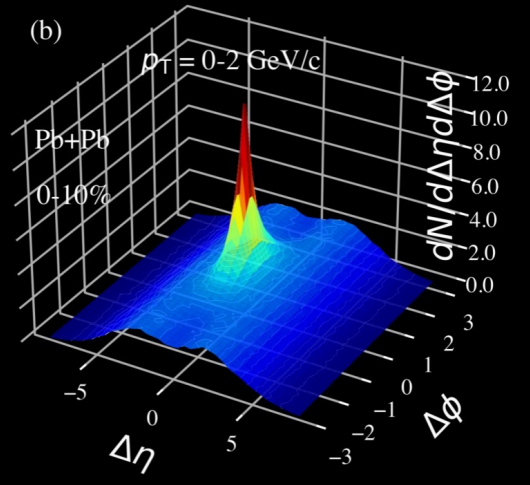


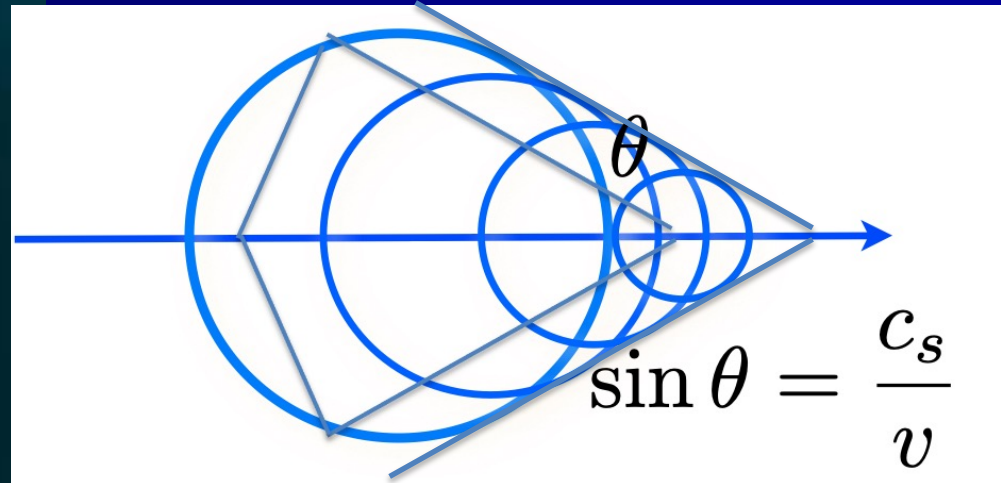
3D structure of jet-induced diffusion wake in high-energy heavy-ion collisions



Xin-Nian Wang

Lawrence Berkeley National Laboratory

Jets, bullets, bow waves & Mach cones



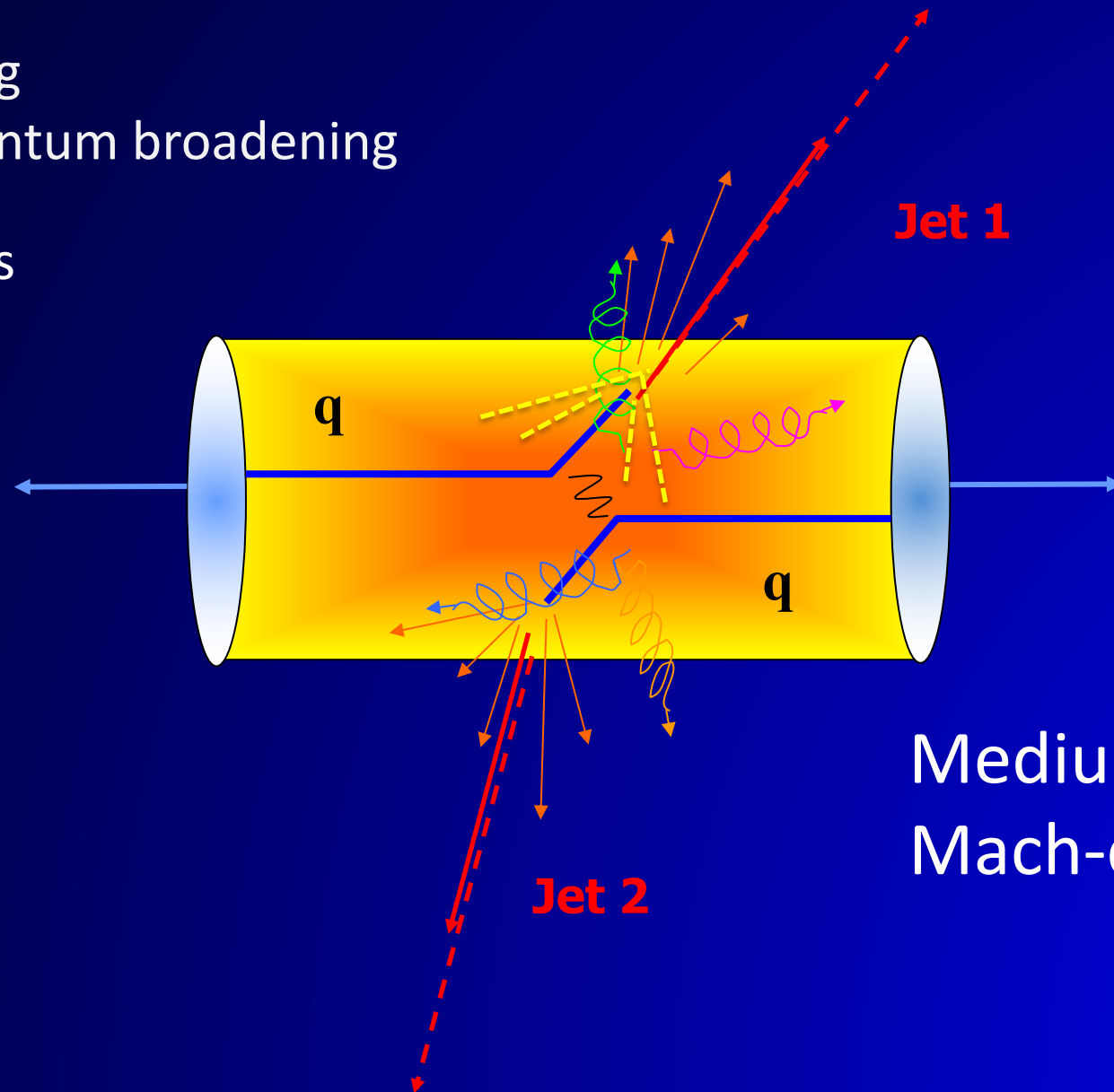
Jets and Mach cones in heavy-ion collisions

Multiple scattering

Transverse momentum broadening

Parton energy loss

Jet suppression



Medium response
Mach-cone excitation

Jet-induced medium excitation

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

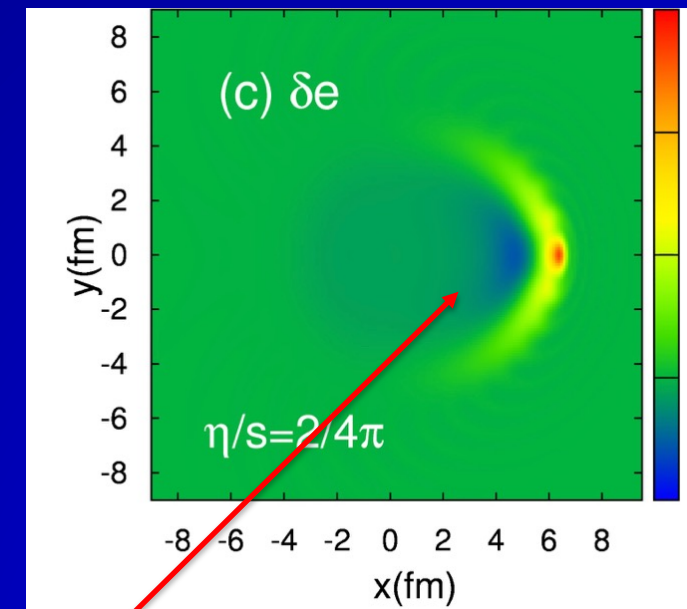
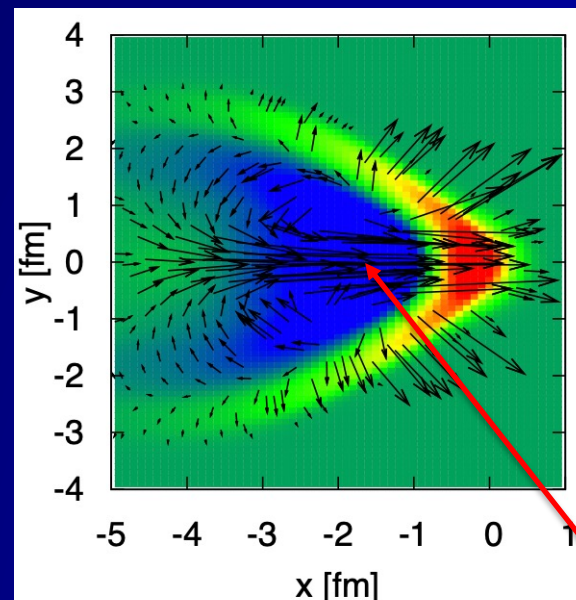
Jet induced Mach-cone in QGP

$$v = p/E > c_s$$

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

Mach cone from linear hydro response

$$T^{\mu\nu} \rightarrow T_0^{\mu\nu} + \delta T^{\mu\nu} \quad \partial_\mu \delta T^{\mu\nu} = J^\nu$$

$c_s^2 \rightarrow$ EOS \rightarrow Mach-cone angle

$\eta \rightarrow$ shock-wave width

$$\delta T^{00} \equiv \delta\epsilon, \quad \delta T^{0i} \equiv g^i, \quad \Gamma_s = \frac{4\eta}{3(\epsilon_0 + p_0)}$$

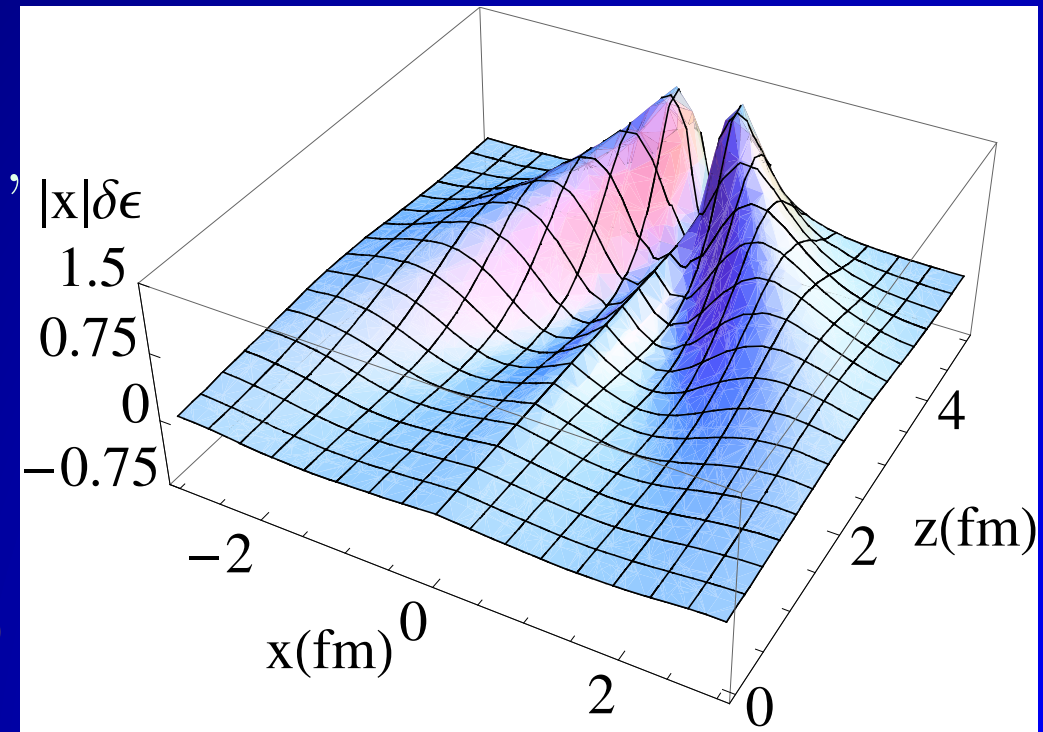
$$\delta T^{ij} = \delta^{ij} c_s^2 \delta\epsilon + \frac{3}{4} \Gamma_s (\partial^i g^j + \partial^j g^i + \frac{2}{3} \delta^{ij} \nabla \cdot \vec{g}),$$

$$J^0 = -i\omega\delta\epsilon + i\vec{k} \cdot \vec{g},$$

$$\vec{J} = -i\omega\vec{g} + i\vec{k}c_s^2\delta\epsilon + \frac{3}{4}\Gamma_s \left[k^2\vec{g} + \frac{\vec{k}}{3}(\vec{k} \cdot \vec{g}) \right]$$

Casalderrey-Solana, Shuryak & Teaney (2004) (hep-ph/0411315)

R. B. Neufeld and B. Müller (2009) (0902.2950)



Qin, Majumder, Song & Heinz (2008) (0903.2255)

Status of searching for Mach-cone

- No sign of the signature of Mach-cone
- False signature: v_3 – anisotropic flow
- Lack of more realistic simulations of jet propagation in heavy-ion collisions

Microscopic picture of Mach wave

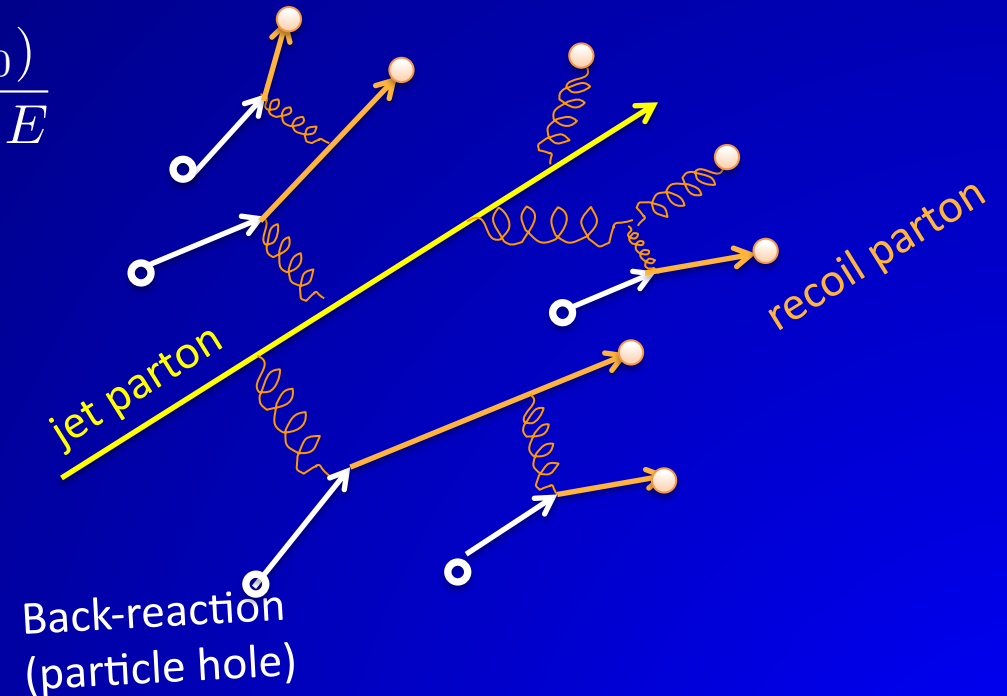
LBT: Linear Boltzmann Transport

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

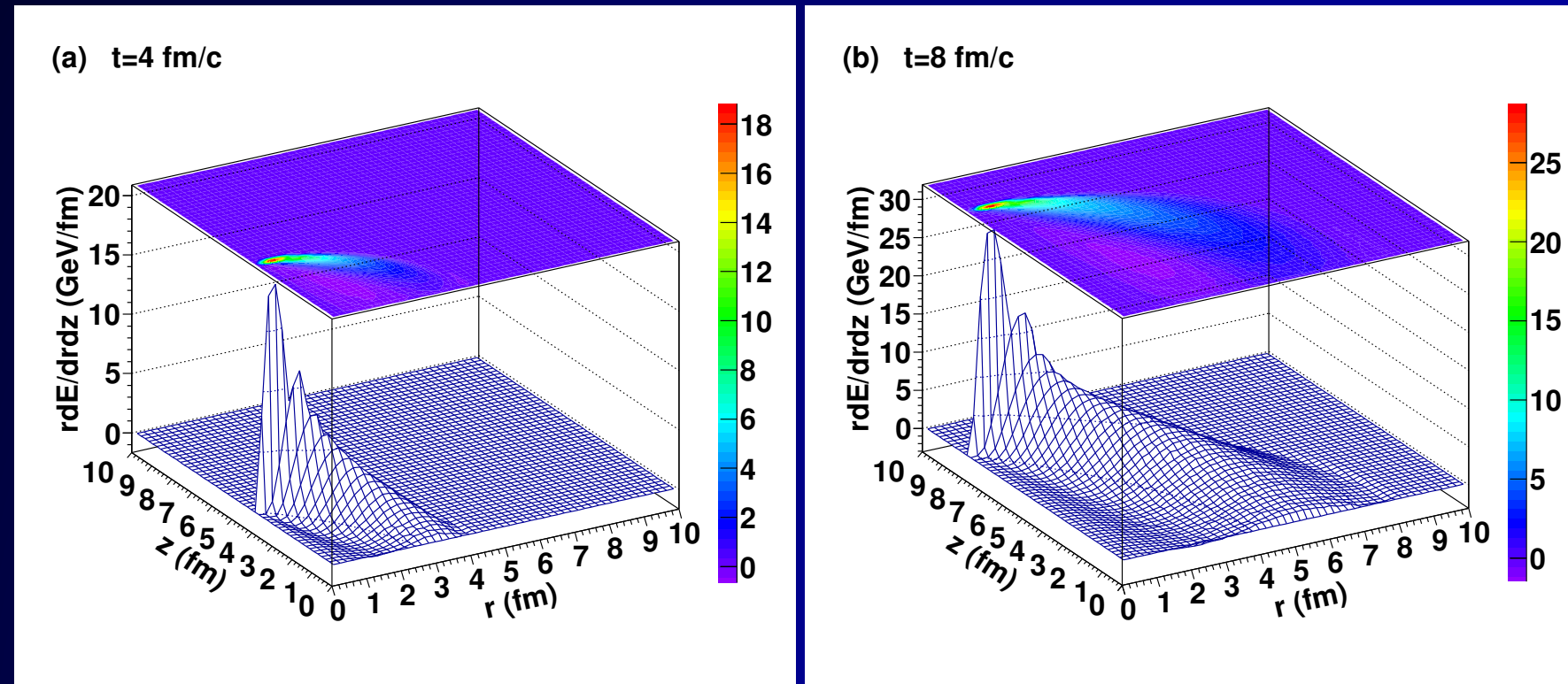
Induced radiation

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

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



LBT: Jet-induced medium response



Energy distr. of medium response to an energetic parton in a static medium

He, Luo, XNW & Zhu, PRC91 (2015) 054908

CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

Concurrent and coupled evolution of bulk medium and jet showers

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

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

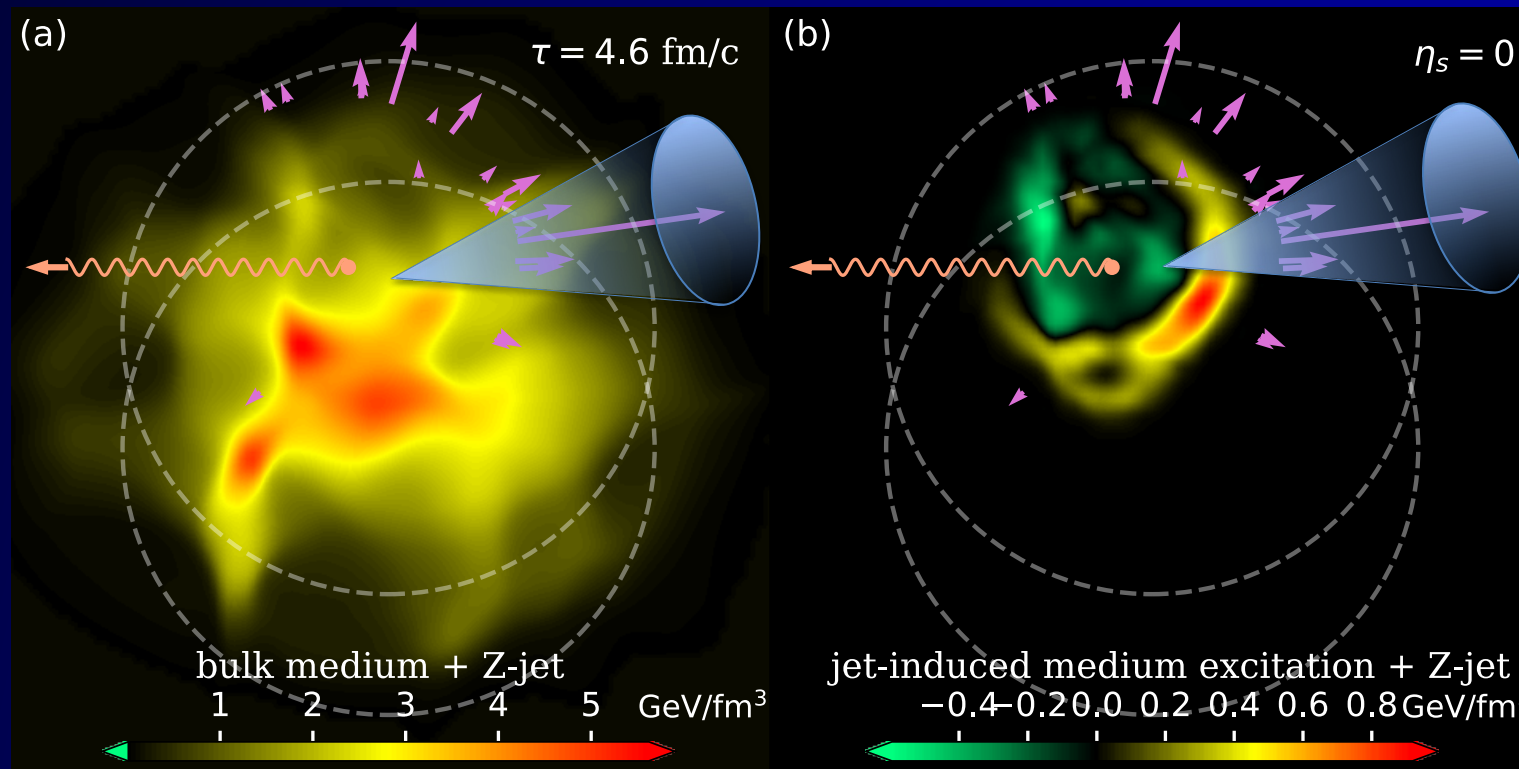
$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i) \theta(p_{cut}^0 - p \cdot u)$$

- 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

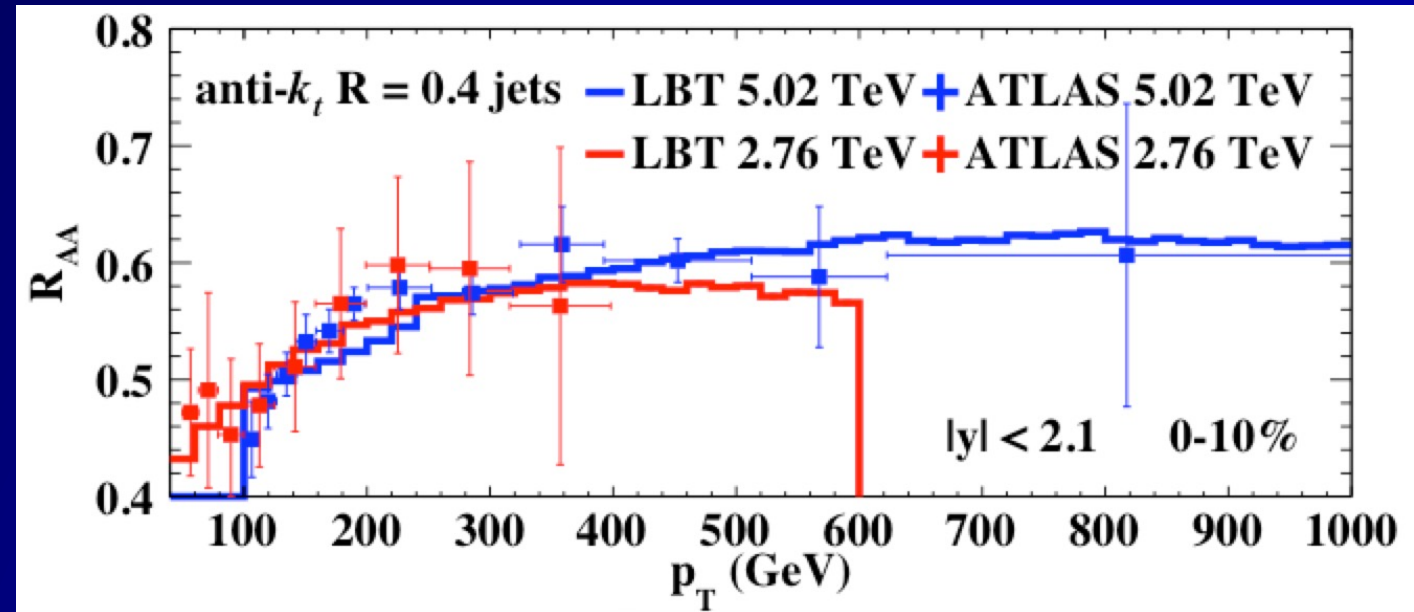
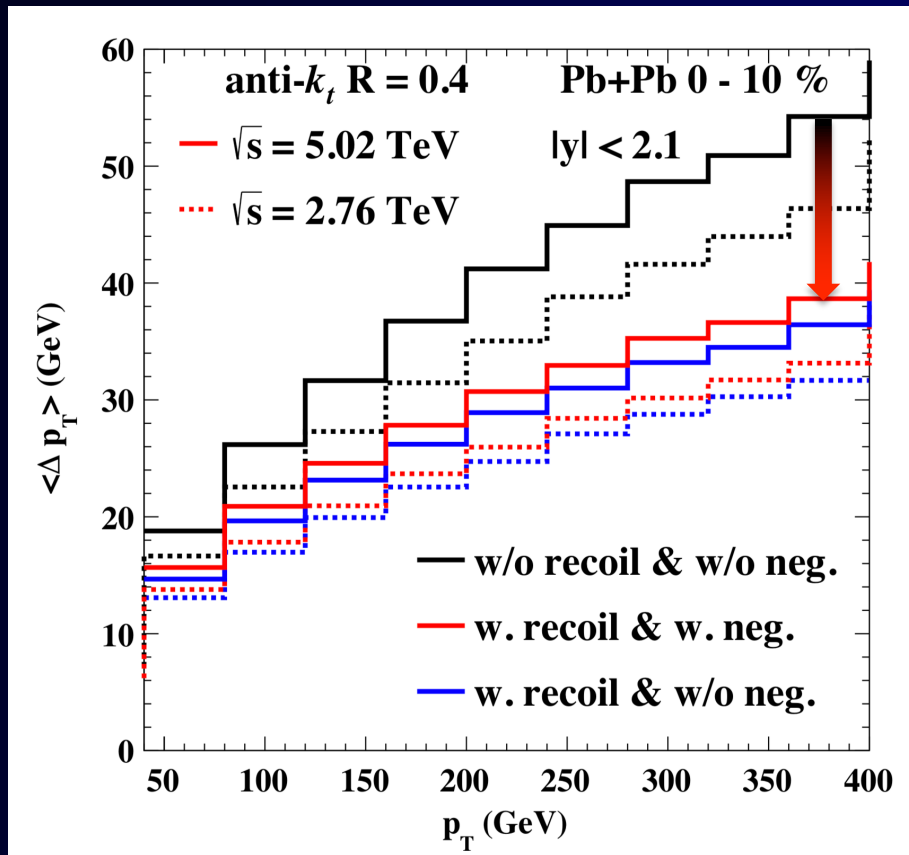
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86



Z/ γ -jet: probing QGP



Jet suppression, energy loss & medium response

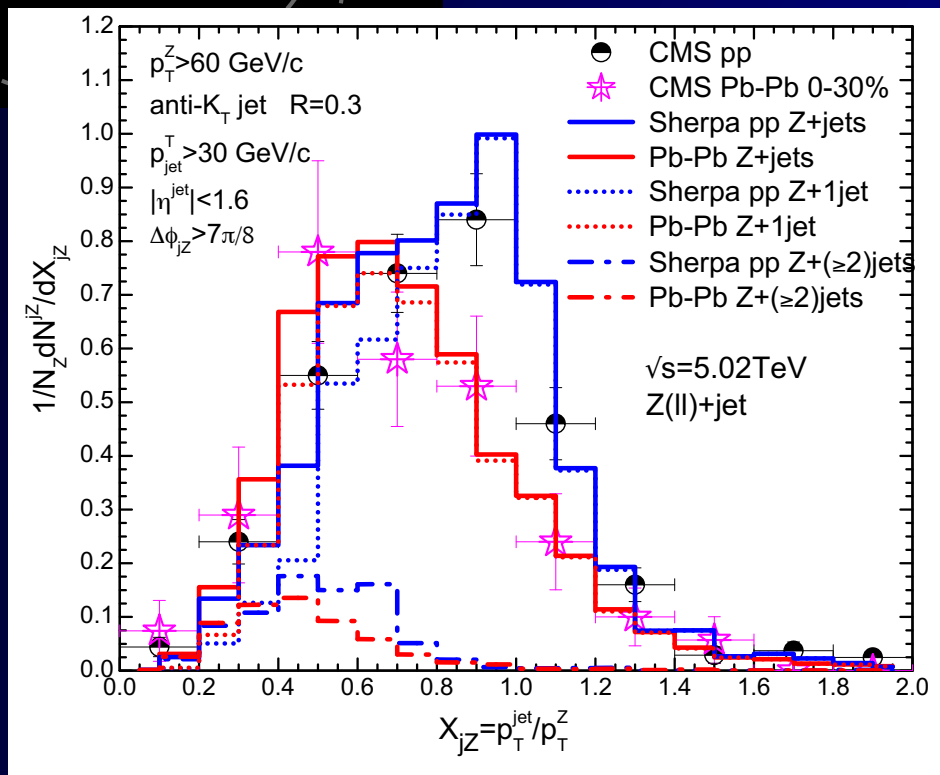
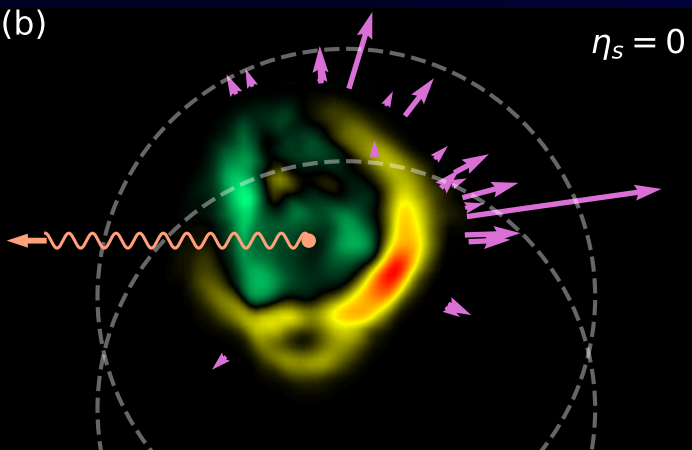


He, Cao, Chen, Luo, Pang & XNW 1809.02525

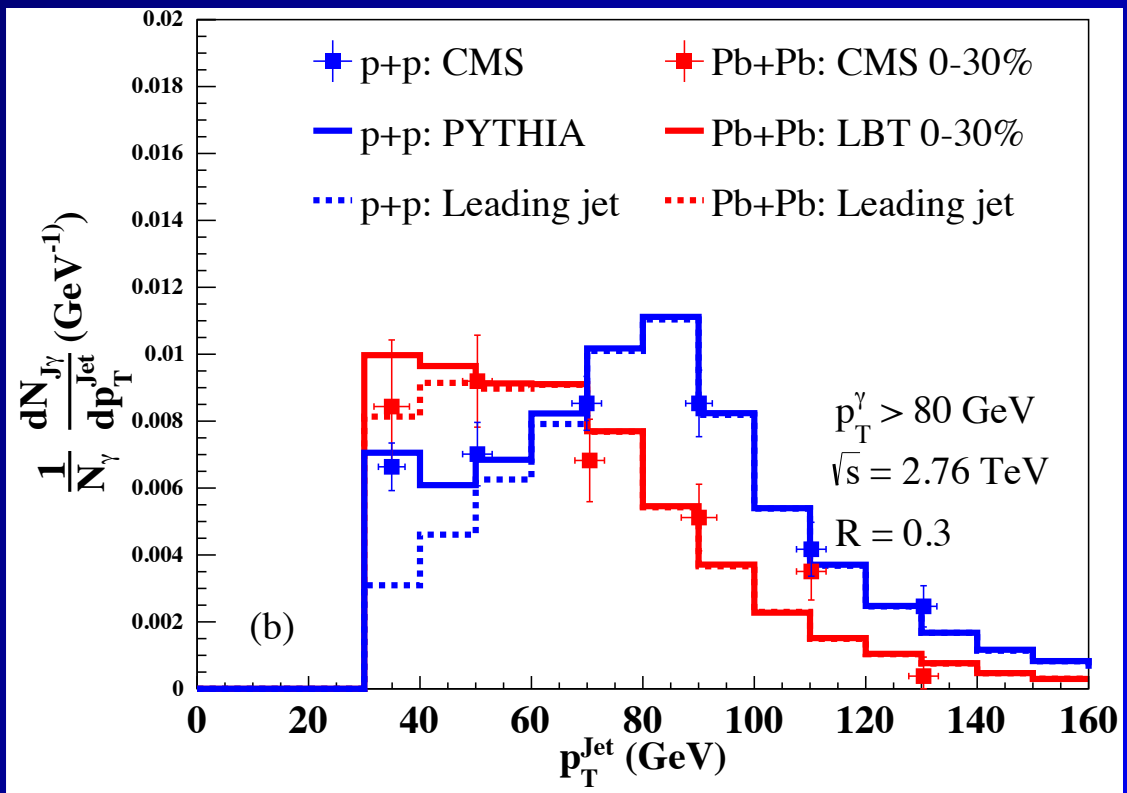
- Weak p_T dependence: initial jet spectra and p_T dependence of energy loss ΔE
- Weak energy dependence: increase of jet energy loss and the slope of initial spectra
- Medium response reduce jet net energy loss

Energy loss in γ/Z -jet at LHC

Suppression of leading and multiple jets



Zhang, Luo, XNW, Zhang, arXiv:1804.11041

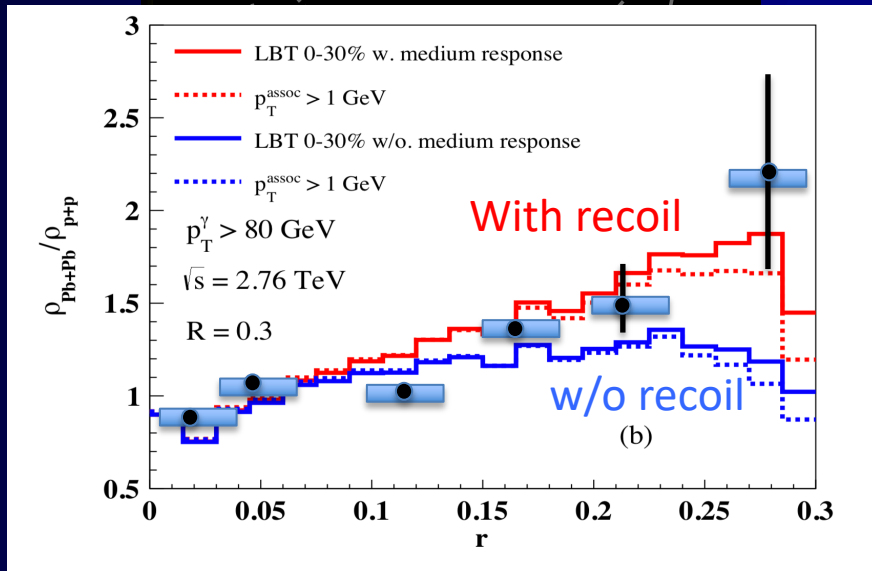
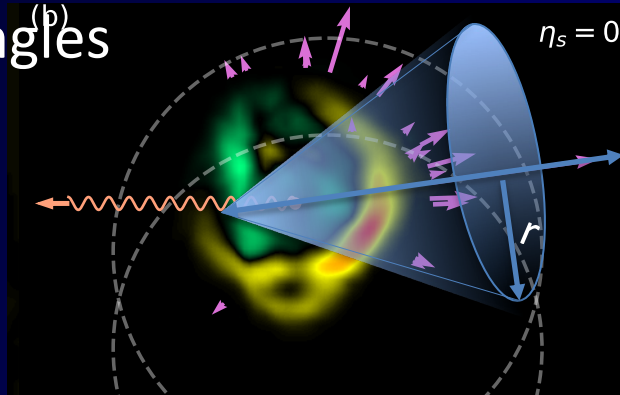


Luo, Cao, He & XNW, arXiv:1803.06785

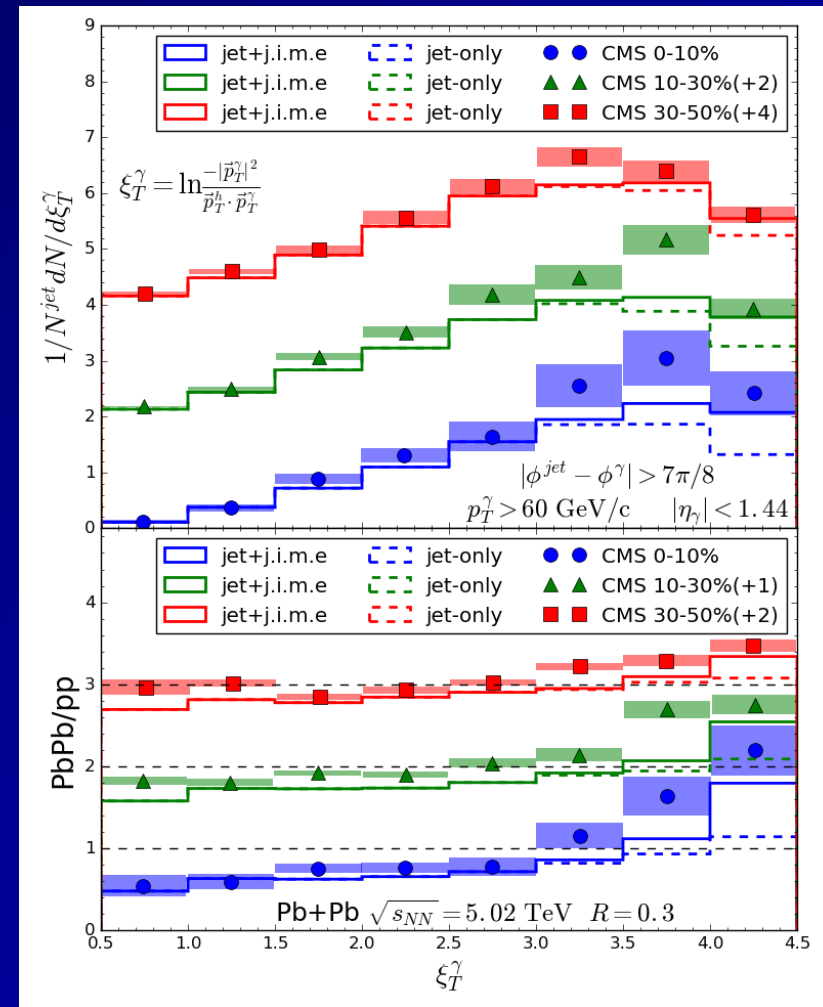


Medium modification of γ -jets

Enhancement of soft hadrons
in large angles^(b)



Luo, Cao, He & XNW, arXiv:1803.06785



Chen, Cao, Luo, Pang & XNW, 2005.09678

Medium response & soft gluon radiation

Jet is not a classical projectile: It radiates during propagation

Medium response:

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

Medium-induced gluon radiation:

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

Mean-free-path

limits the formation time

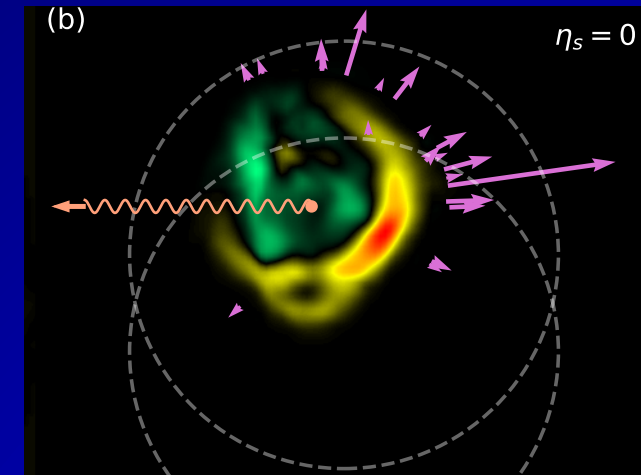
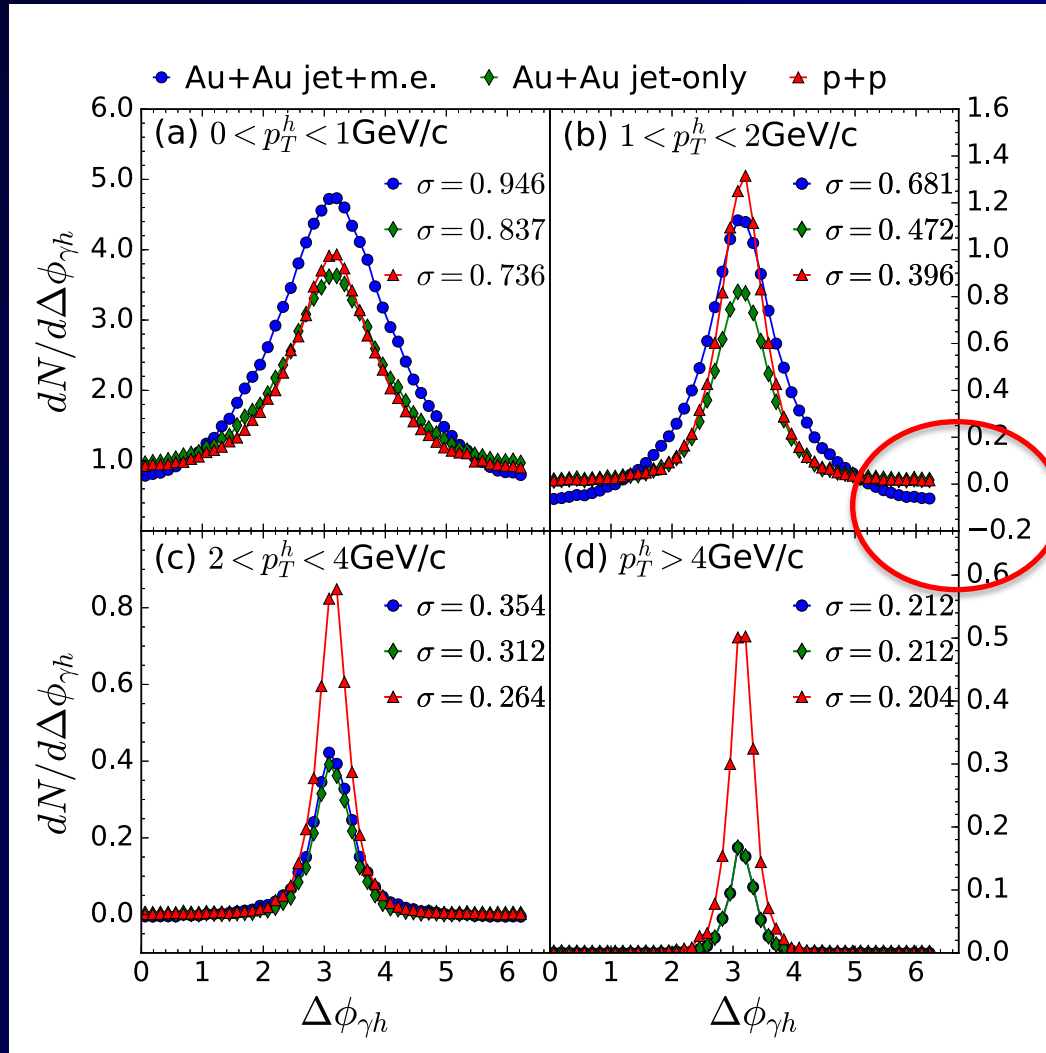
$$\tau_f \leq \lambda \sim 1/T$$

$$\hat{q} \sim T^3$$

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



Signal of diffusion wake (DFW)



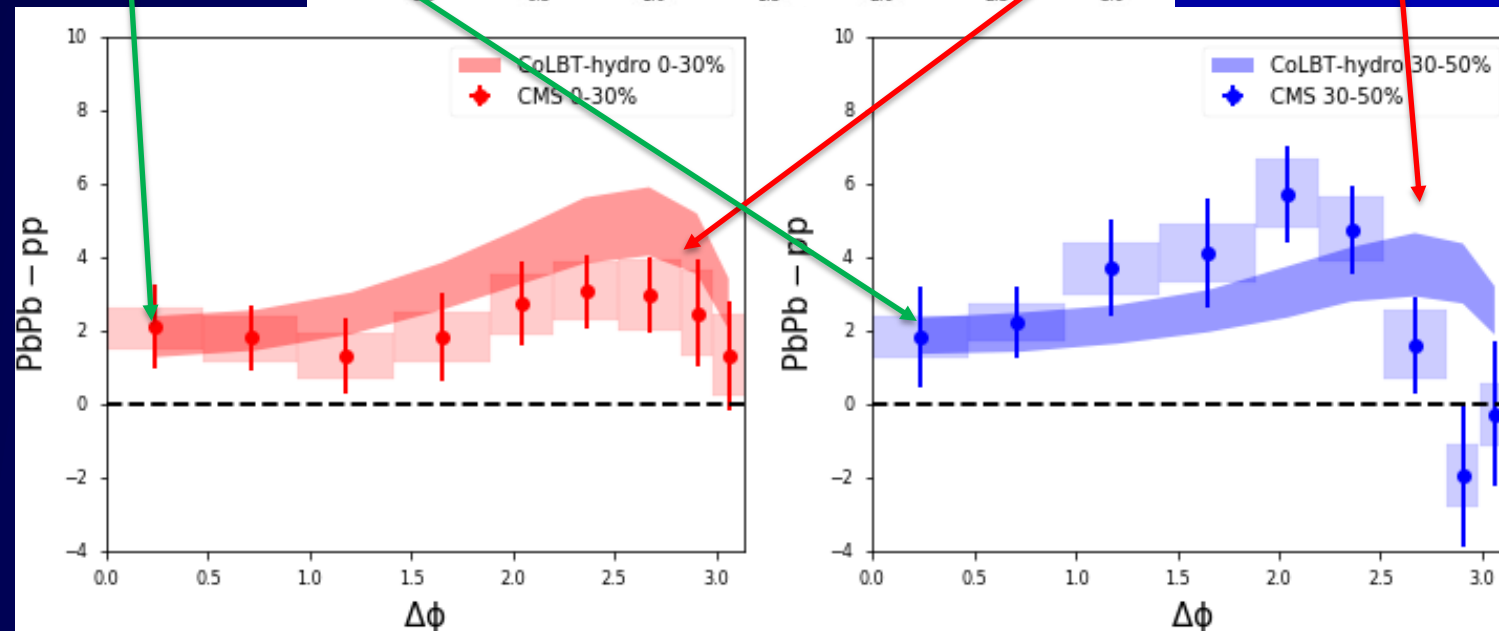
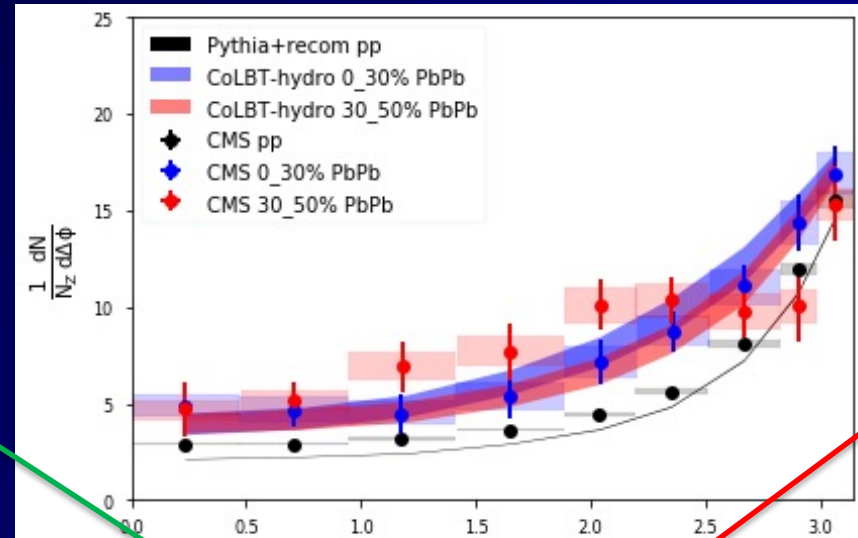
Depletion of the background
In the γ direction

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

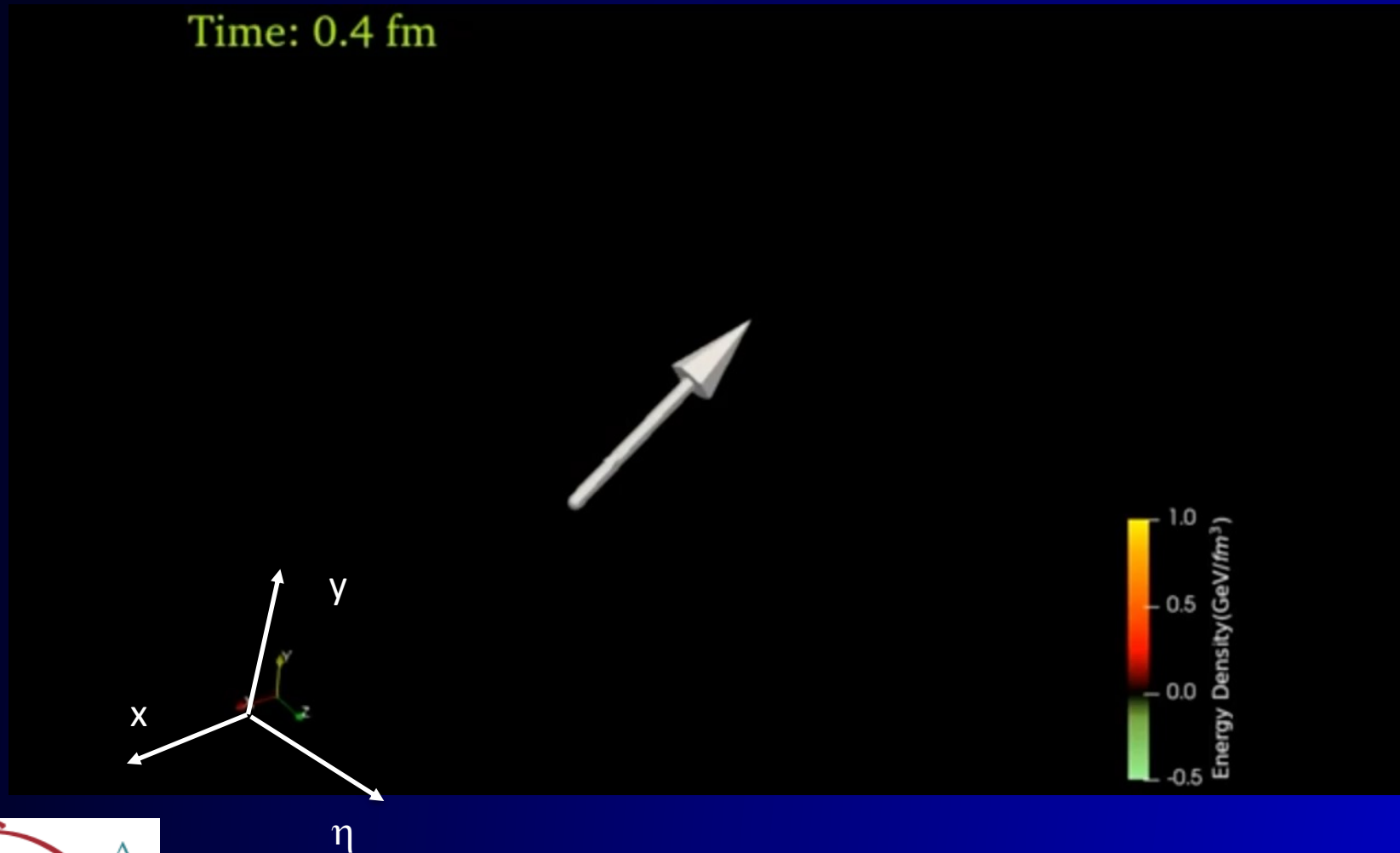
Z-hadron correlation: MPI & medium response

enhancement
of the away-side
MPI background

enhancement
and broadening
of the jet peak

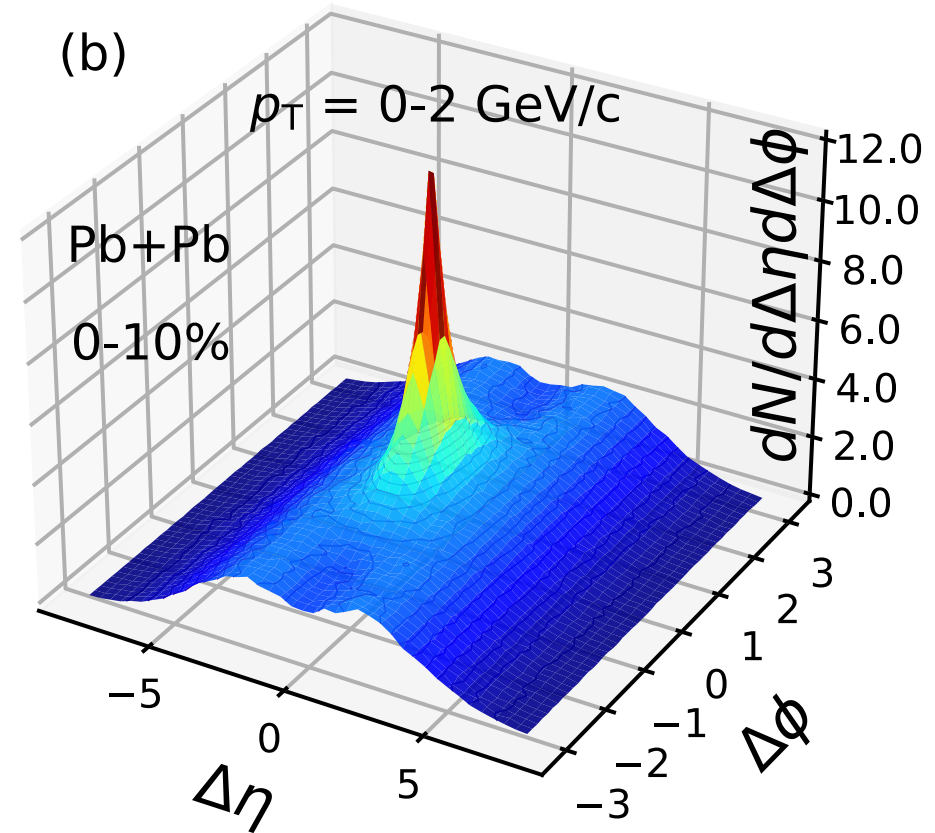
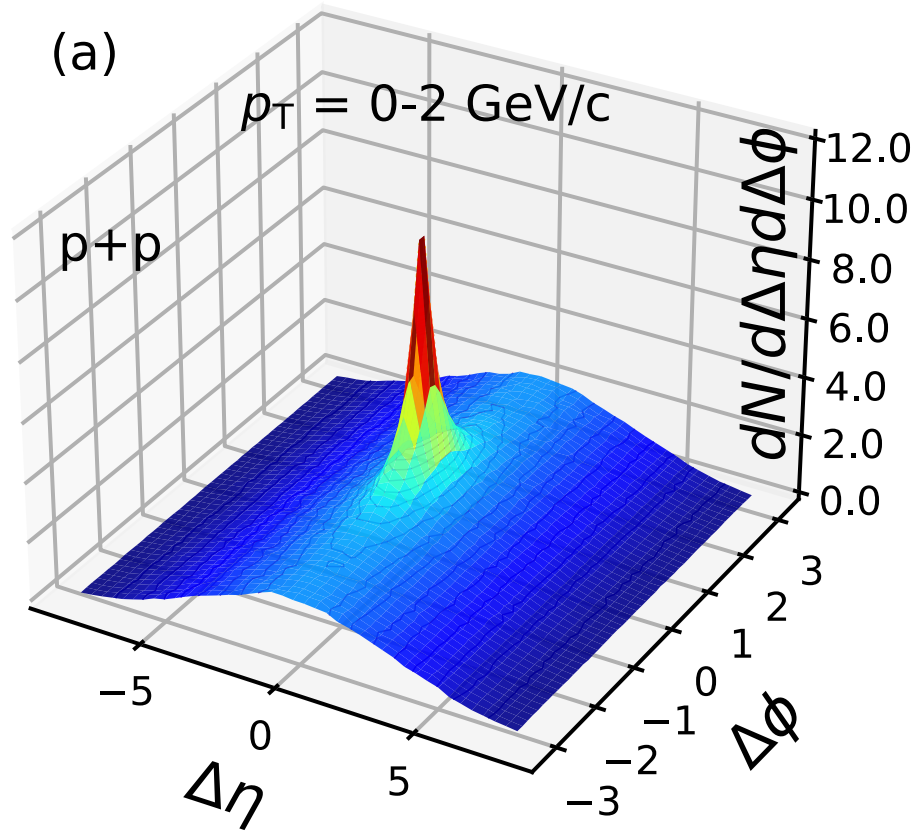


3D structure of diffusion wake

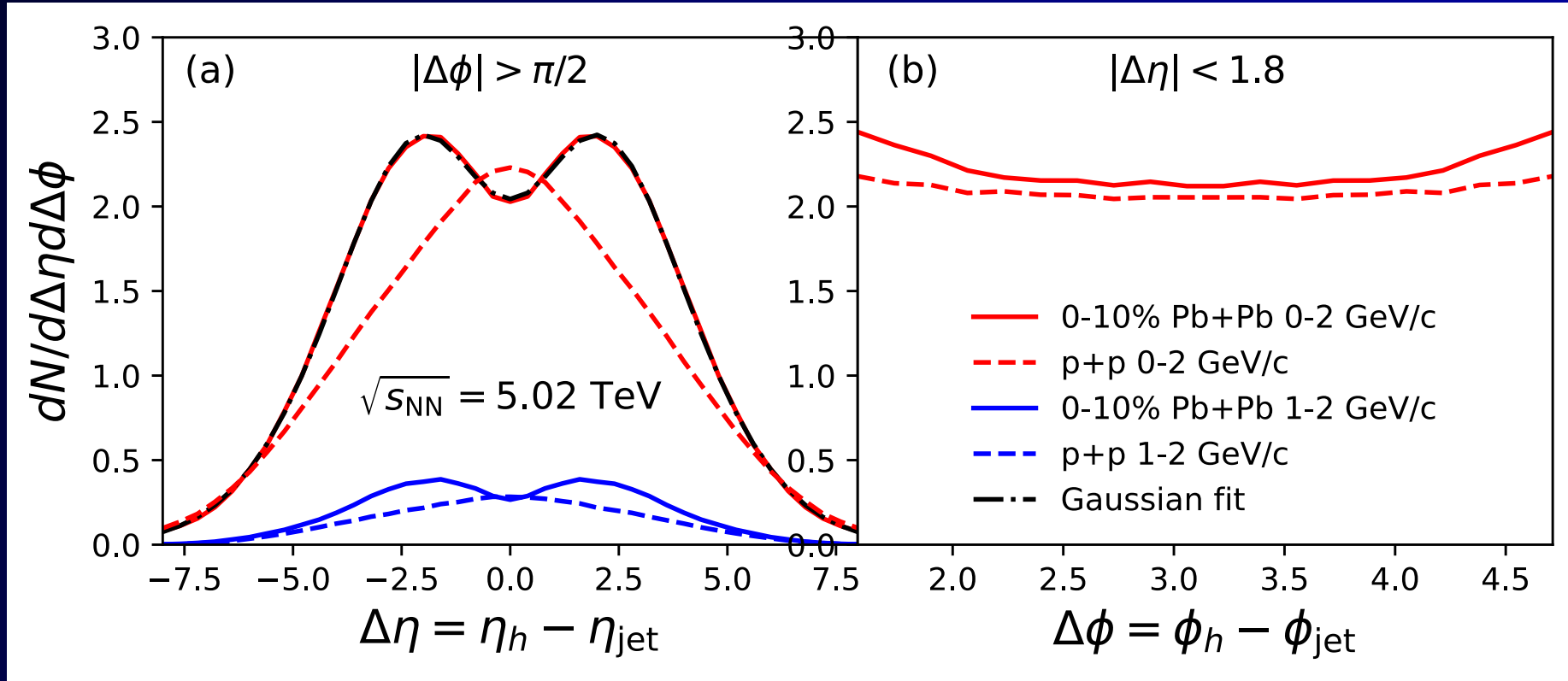


3D structure of diffusion wake

Jet-hadron correlation in γ /jet events



Double peak structure in η



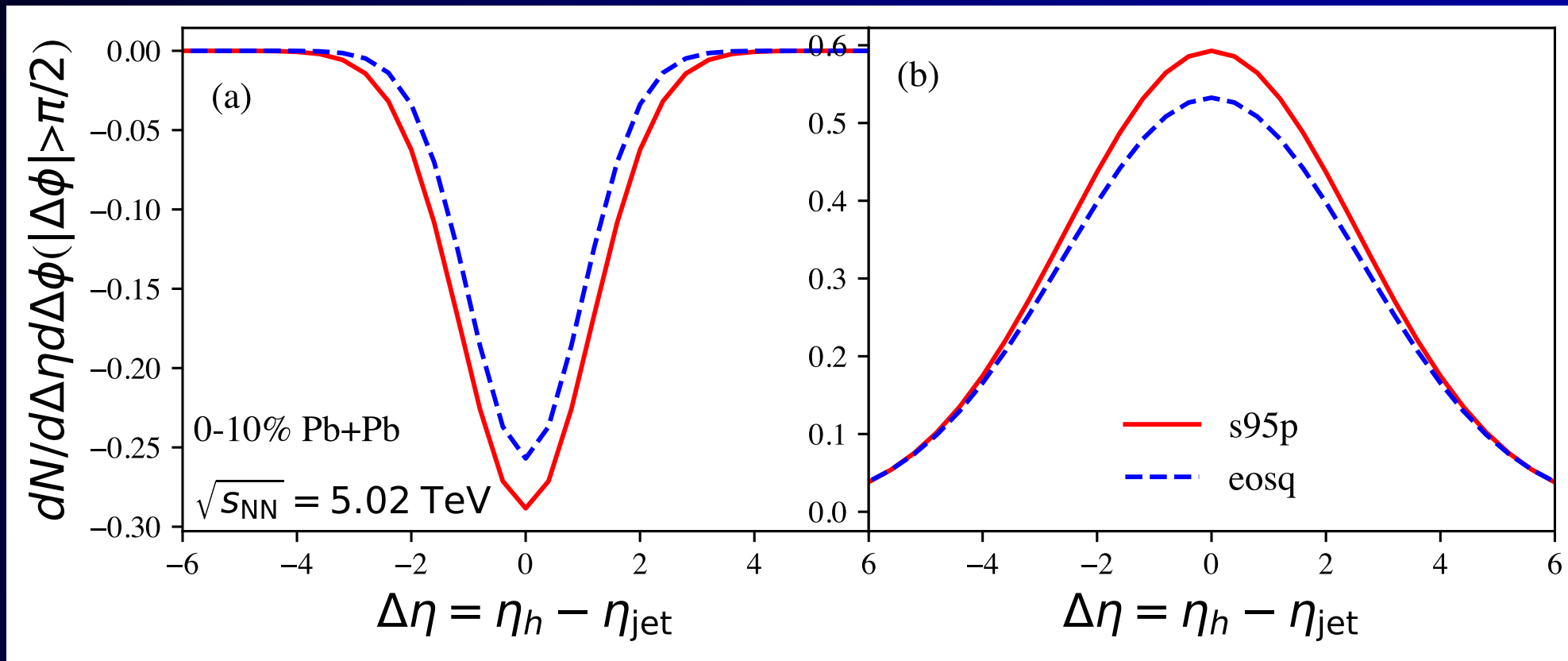
$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j) (F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)),$$

↑
↑
↑

Jet-distr
MPI
DF-wake

Diffusion wake and EoS

(hydro models with different EoS are adjusted to give the same $dN_{ch}/d\eta$)



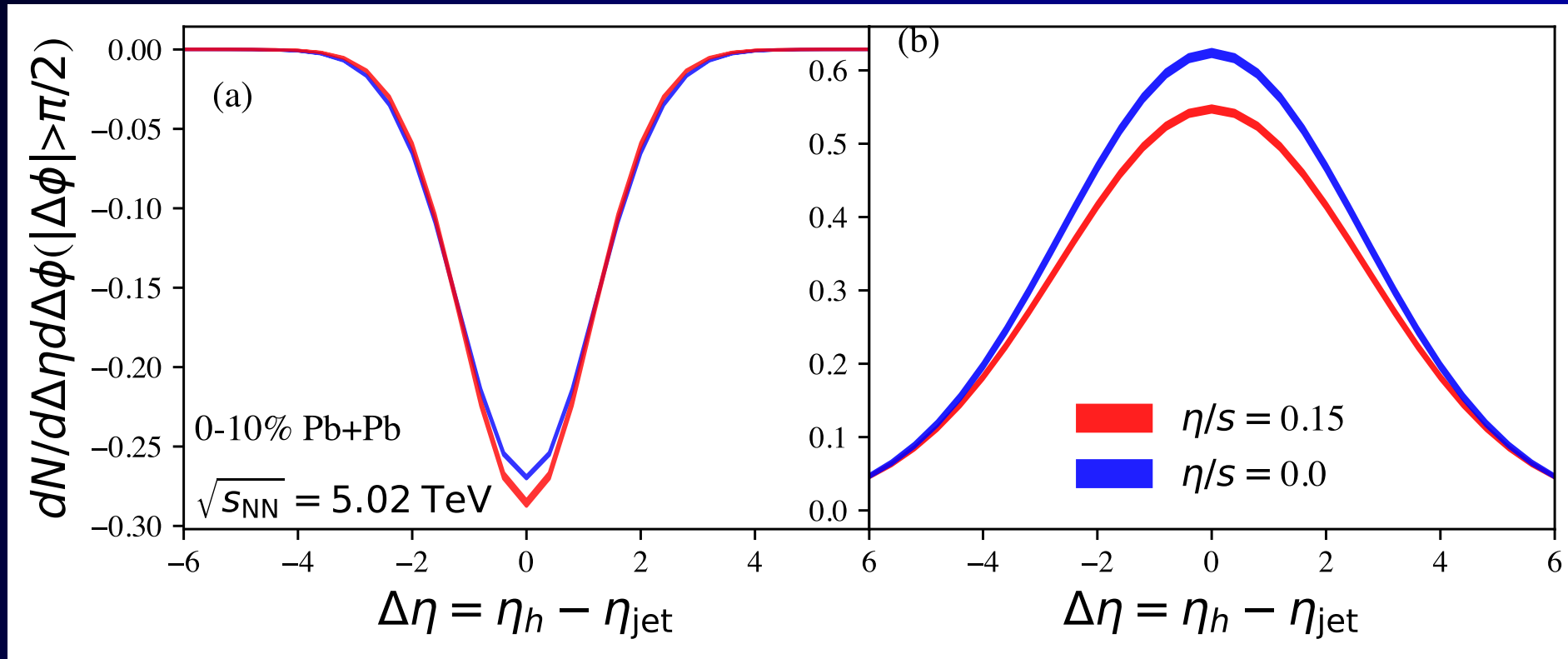
$$\langle c_s \rangle_{eosq} > \langle c_s \rangle_{s95p}$$

Hardening of spectra \rightarrow reduction of soft hadron yield & DFW valley

Larger Mach cone angle \rightarrow shallower DFW valley

Diffusion wake and viscosity

(hydro models with different η/s are adjusted to give the same $dN_{ch}/d\eta$)

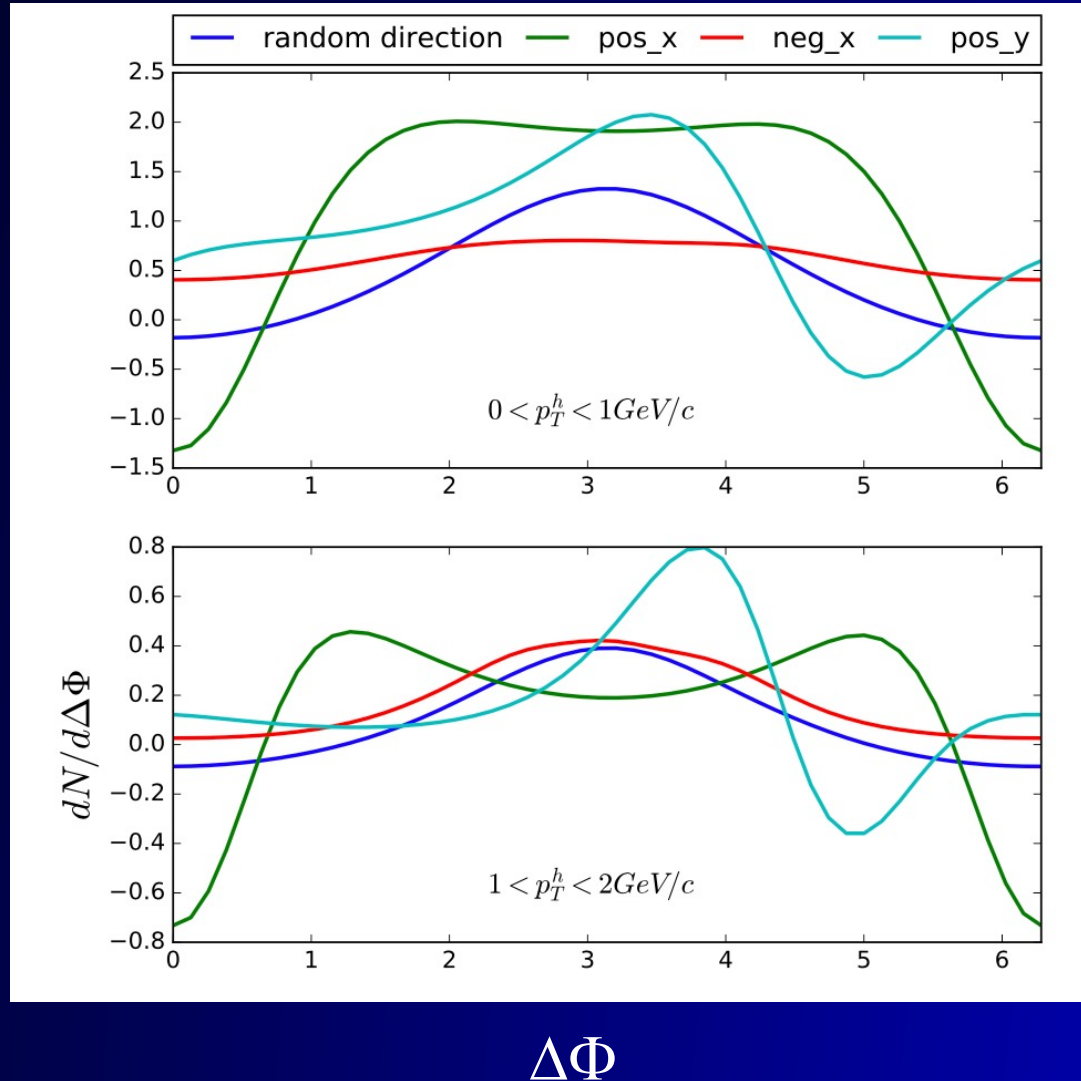


Negative longitudinal shear correction \rightarrow slows down longitudinal expansion \rightarrow deepen DFW valley

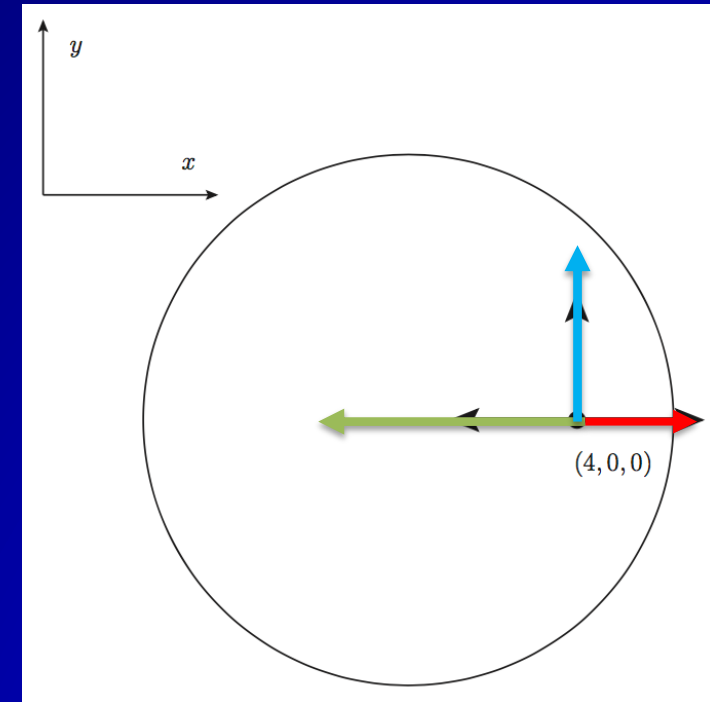
$$\pi^{\eta\eta} \approx -(\pi^{xx} + \pi^{yy})/\tau^2$$

η/s hardens hadron spectra \rightarrow reduction of soft hadron yield

Initial position & azimuthal correlation



γ -hadron correlation

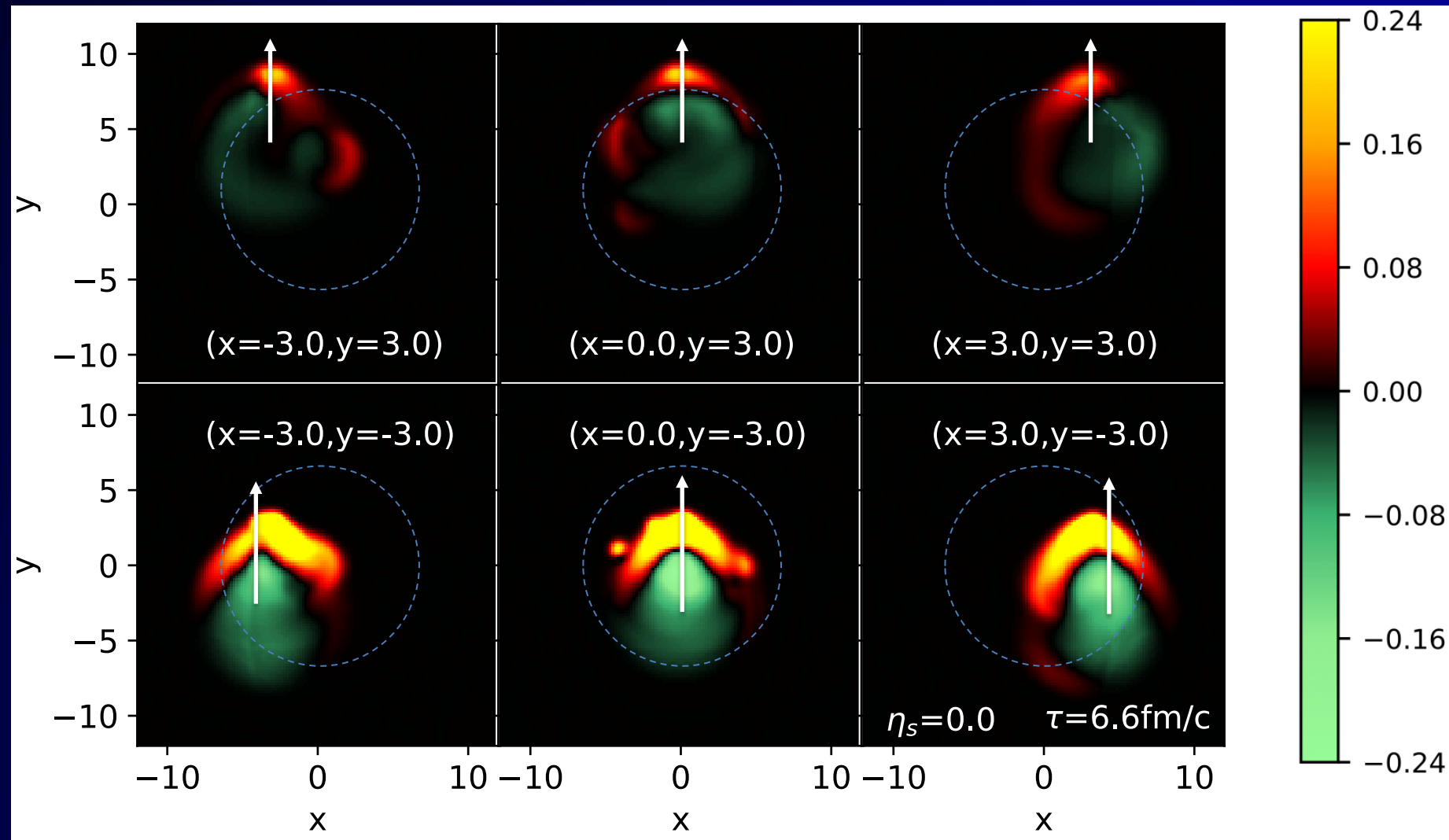


W Chen & XNW (2018)

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

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

Jet trajectories & Mach cone shapes



$p_T^\gamma=200-250 \text{ GeV}/c$, $p_T^{\text{jet}}>100 \text{ GeV}/c$ in 0-10% Pb+Pb @ 5.02 TeV

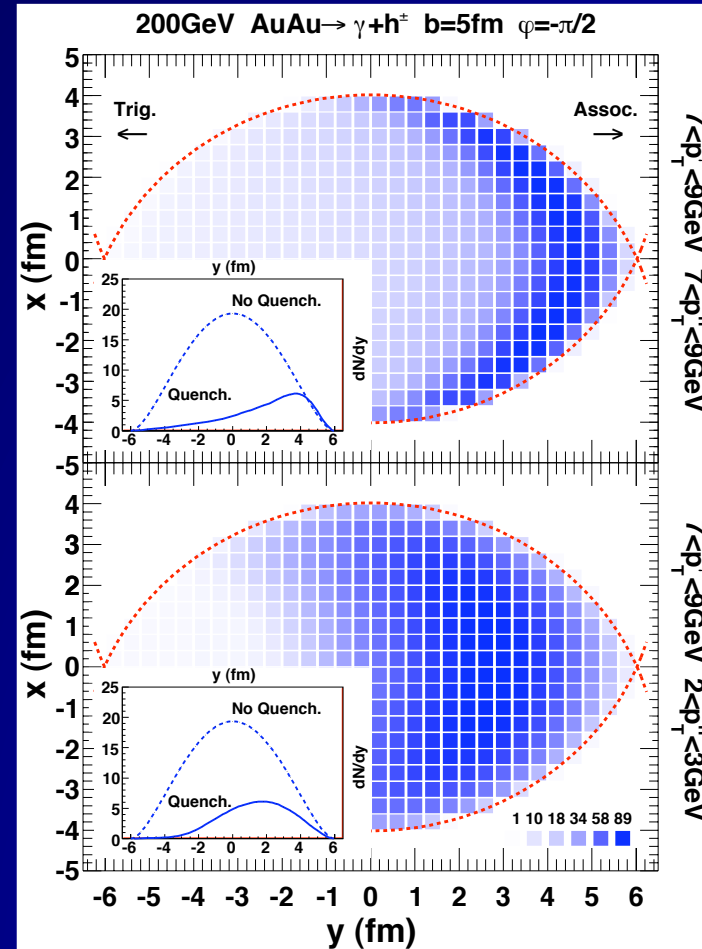
Longitudinal jet tomography

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

length dependence
of parton energy loss

γ -jet asymmetry $x_{\gamma\text{jet}} = p_T^{\text{jet}}/p_T^\gamma$

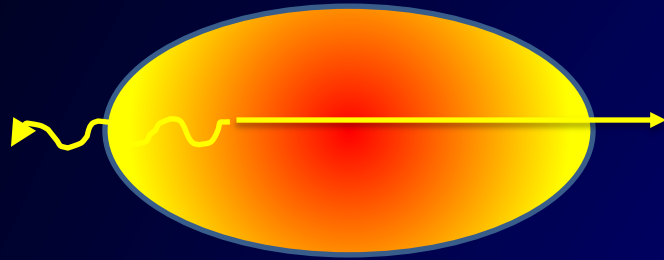
Can be used to select
propagation length $<L>$



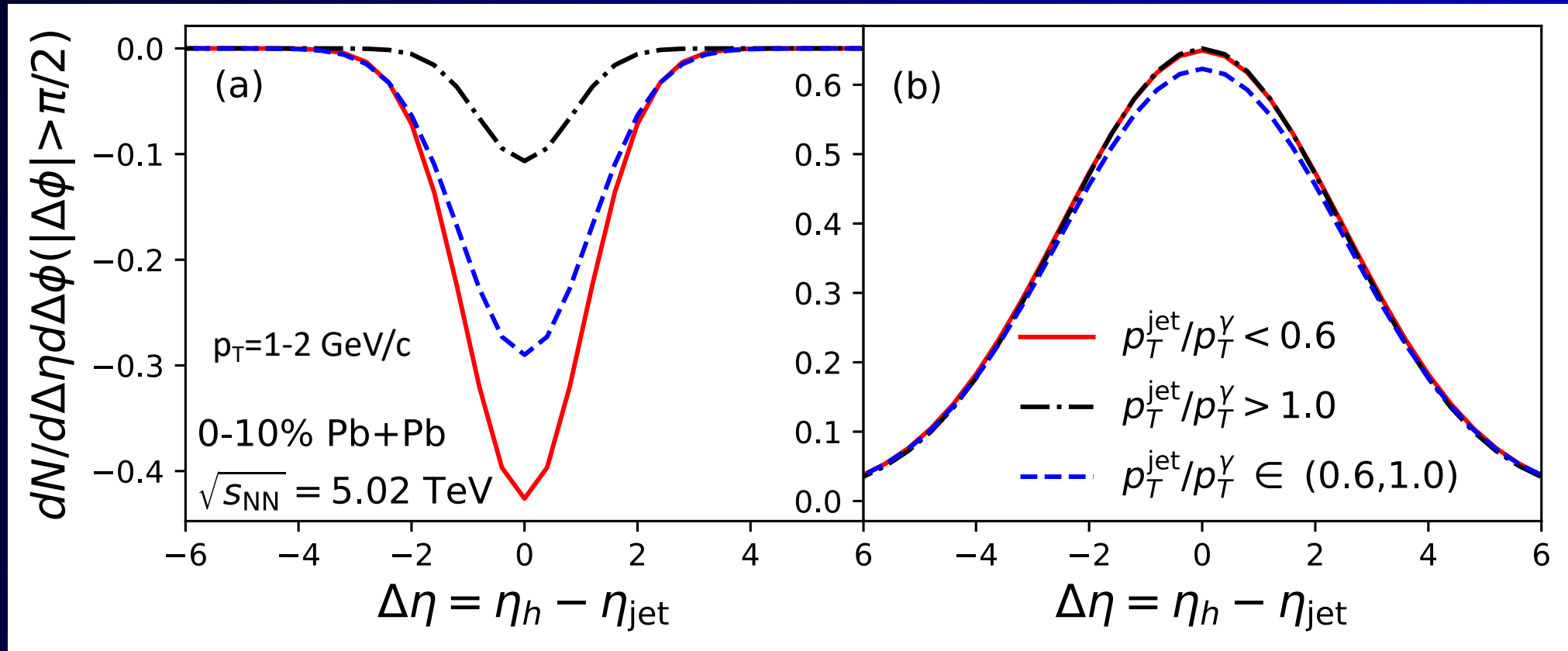
$$p_T^h / p_T^\gamma \sim 1$$

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

γ /jet asymmetry and diffusion wake

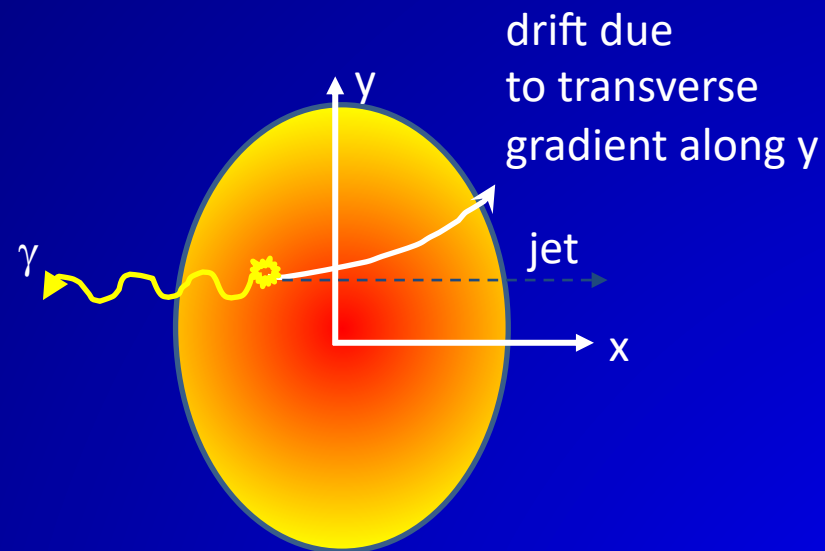
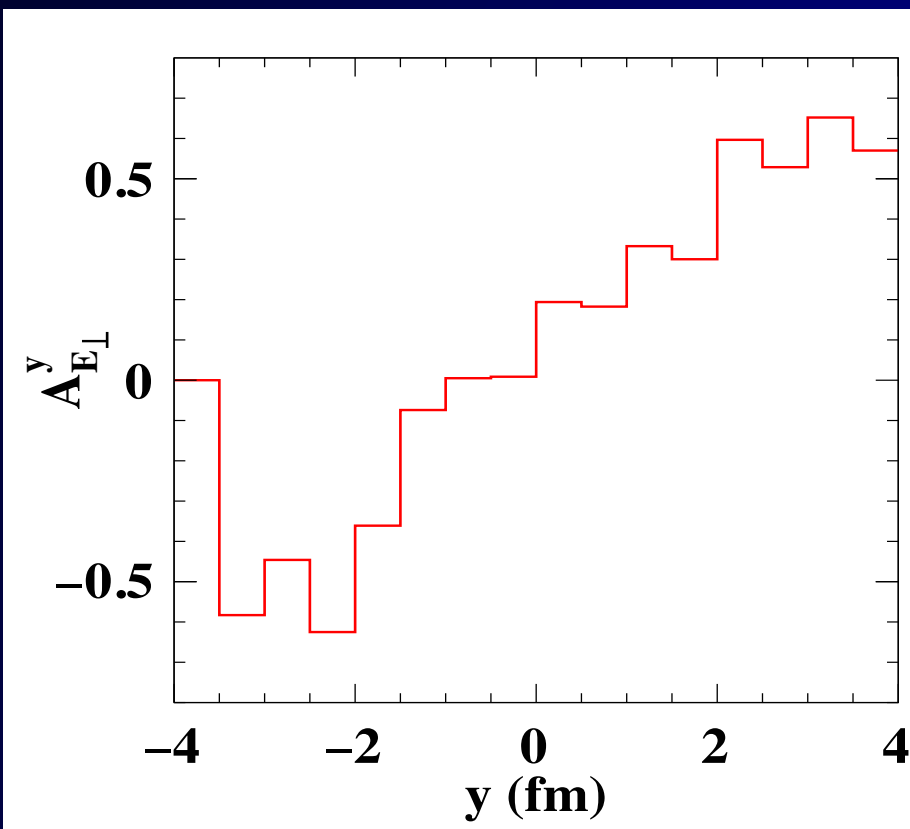


Larger γ /jet asymmetry \rightarrow more energy loss
 \rightarrow long propagation length \rightarrow larger diffusion wake



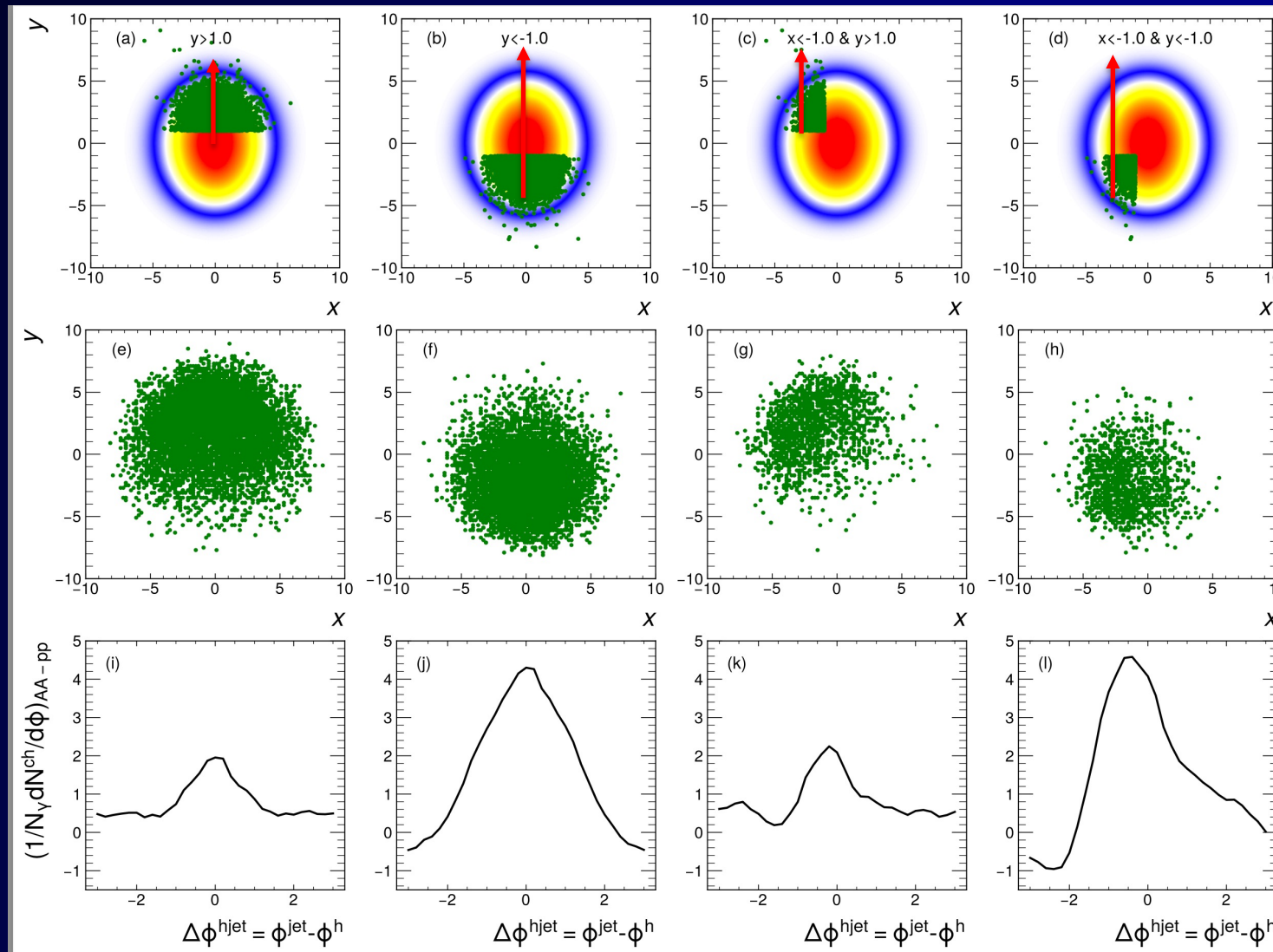
Transverse gradient tomography

$$A_{E_{\perp}}^{\vec{n}} = \frac{\int d^3r d^3p f_a(\vec{p}, \vec{r}) \vec{p}_T \cdot \vec{n}}{\int d^3r d^3p f_a(\vec{p}, \vec{r})} \quad (p_T > 3 \text{ GeV}/c)$$



He, Pang & XNW, *Phys Rev Lett* 125 (2020) 12, 122301

Deep learning assisted jet tomography



DL network selection

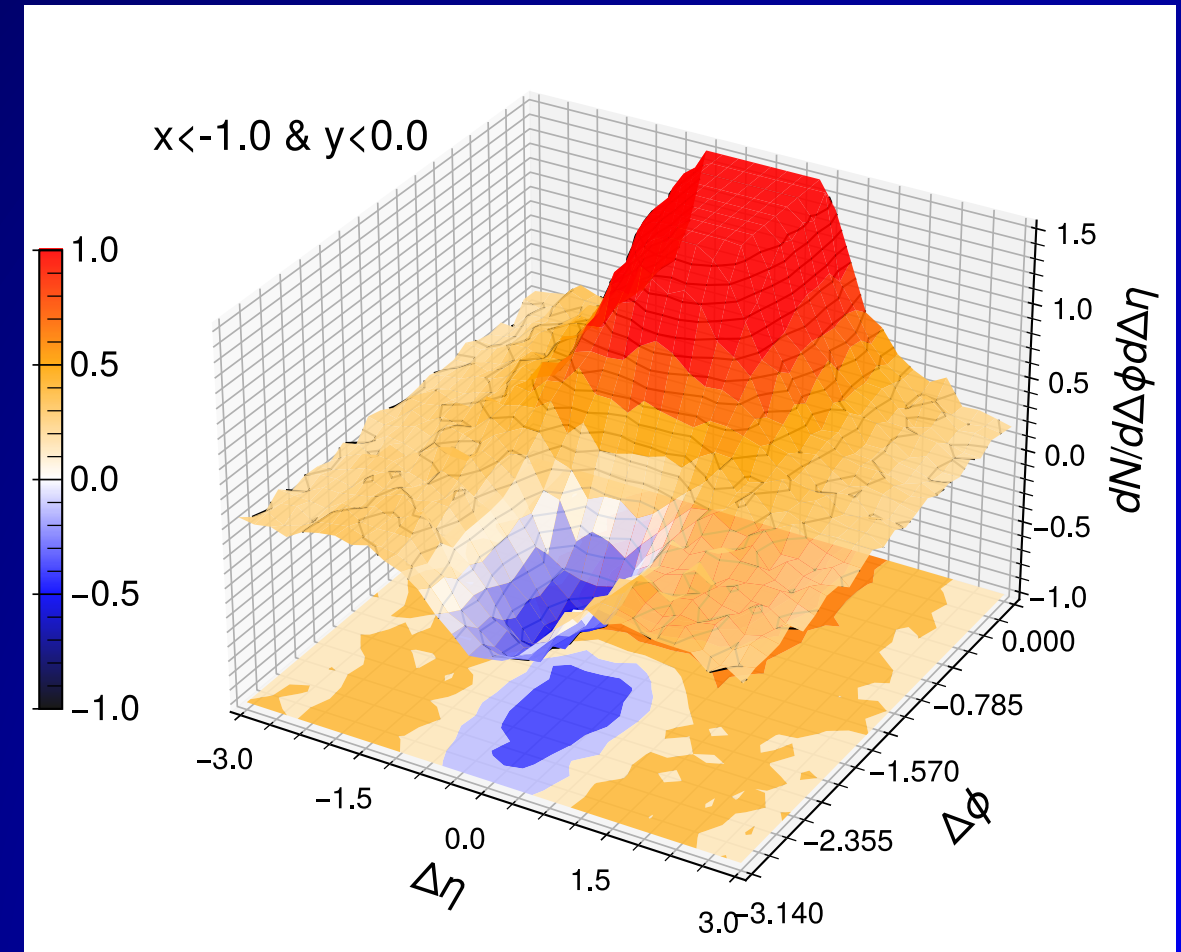
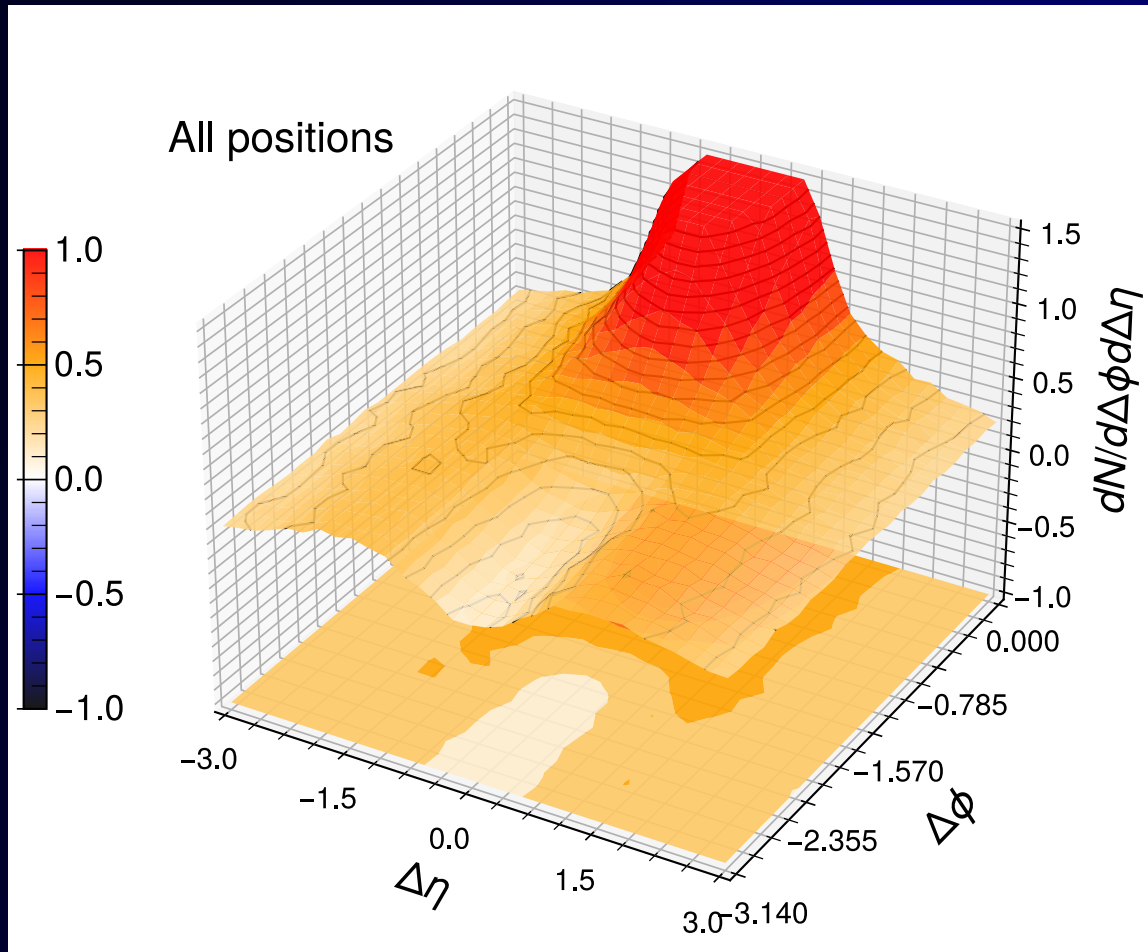
Actual distribution

γ -soft hadron correlation

Yang, He, Chen, Ke, Pang
and XNW, [2206.02393](#)

$p_T^\gamma = 200-250$ GeV/c, $p_T^{jet} > 100$ GeV/c, $p_T^h = 1-2$ GeV/c in 0-10% Pb+Pb @ 5.02 TeV

Enhanced DFW signal with ML jet tomography



$p_T^\gamma = 200-250$ GeV/c, $p_T^{\text{jet}} > 100$ GeV/c, $p_T^h = 1-2$ GeV/c in 0-10% Pb+Pb @ 5.02 TeV

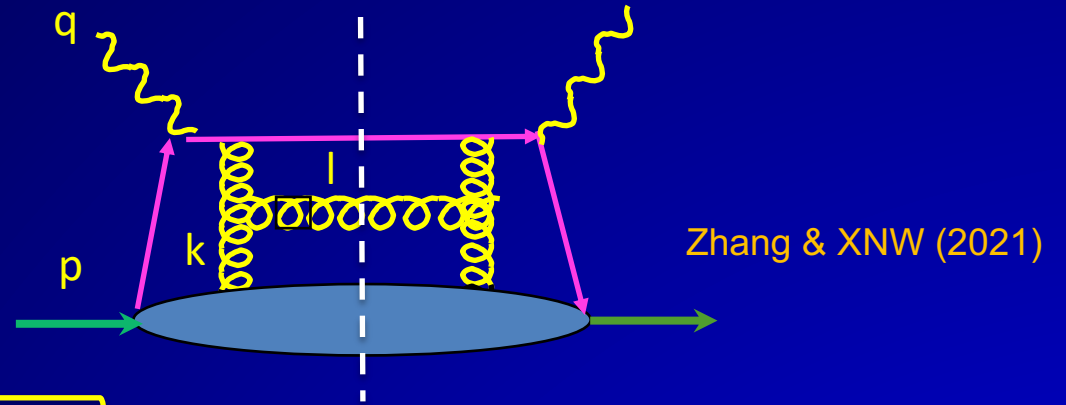
Summary & future perspective

- 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





Parton propagation in QCD medium



$$\frac{dN_g}{dl_{\perp}^2 dz} = \int_{y^-}^{\infty} dy_1^- \left[\rho_A(y_1^-, \vec{y}_{\perp}) \frac{2\pi\alpha_s}{N_c} \pi \int \frac{dk_{\perp}^2}{(2\pi)^2} \frac{\phi_N(0, \vec{k}_{\perp})}{k_{\perp}^2} \right] \pi \frac{\alpha_s}{2\pi} P_{qg}(z) \frac{C_A}{l_{\perp}^2} \mathcal{N}_g(\vec{l}_{\perp}, \vec{k}_{\perp})$$

medium TMD gluon distr.

$$\mathcal{N}_g^{static+soft} = \int \frac{d\varphi}{2\pi} \frac{2\vec{k}_{\perp} \cdot \vec{l}_{\perp}}{(\vec{l}_{\perp} - \vec{k}_{\perp})^2} \left(1 - \cos\left[\frac{(\vec{l}_{\perp} - \vec{k}_{\perp})^2}{2q^- z(1-z)} y_1^- \right] \right) \rightarrow \text{GLV}$$

τ_f Formation time of the gluon emission y_1^- / τ_f

Parton energy loss and jet transport

$$\frac{dE_{rad}}{dx} \approx E \frac{2C_A\alpha_s}{\pi} \hat{q}(x) \int dz \frac{d\ell_{\perp}^2}{\ell_{\perp}^4} z P(z) \sin^2 \frac{\ell_{\perp}^2 (x - x_0)}{4z(1-z)E} \quad \text{(High-twist approach)}$$

$$\frac{dE_{el}}{dx} = \int \frac{d^3k}{(2\pi)^3} dq_{\perp}^2 f(k) \frac{q_{\perp}^2}{2k} \frac{d\sigma}{dq_{\perp}^2} \approx \left\langle \frac{1}{2\omega} \right\rangle \hat{q} \quad \text{Elastic energy loss}$$

Jet transport coefficient:

$$\hat{q}(y) = \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1} \rho(y) x G(x)|_{x \approx 0} = \frac{\langle q_{\perp}^2 \rangle}{\lambda}$$

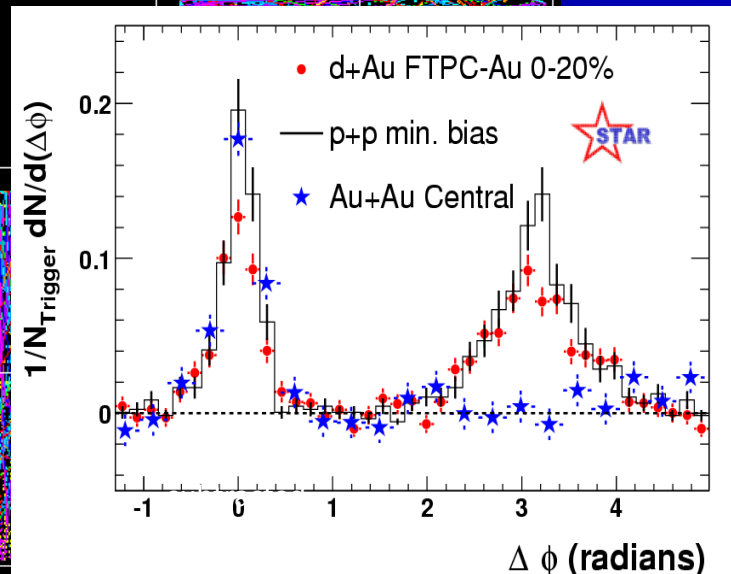
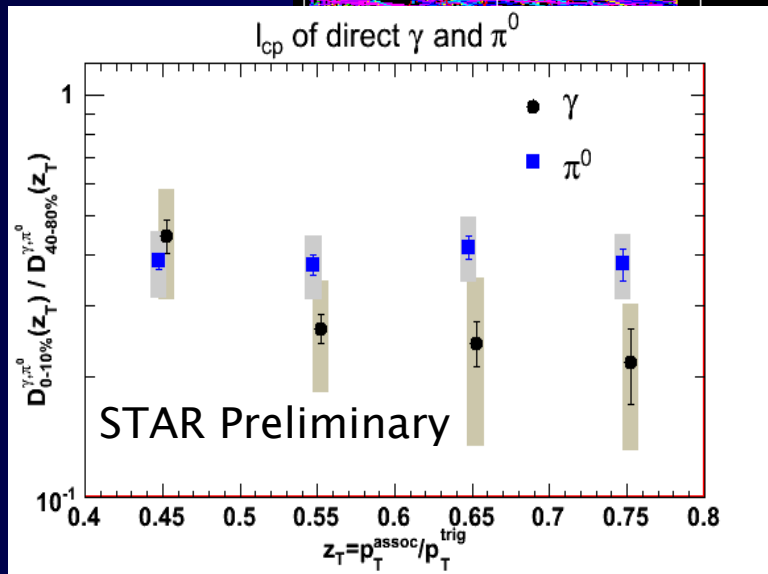
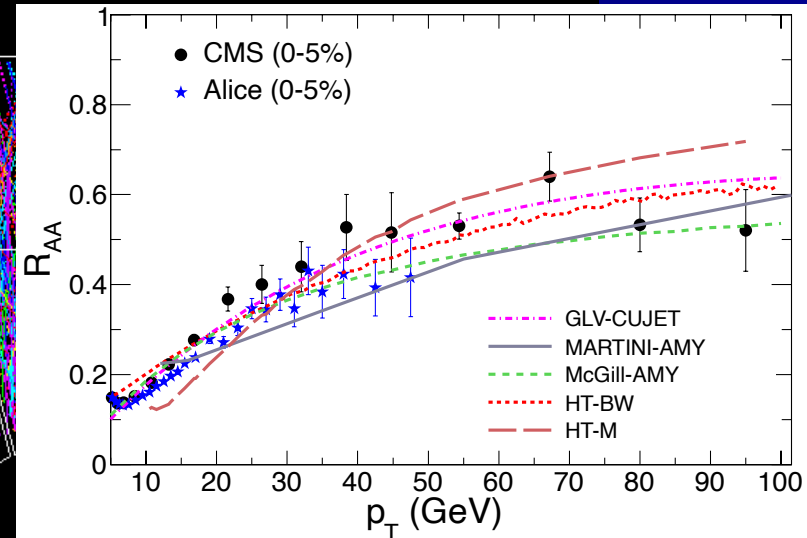
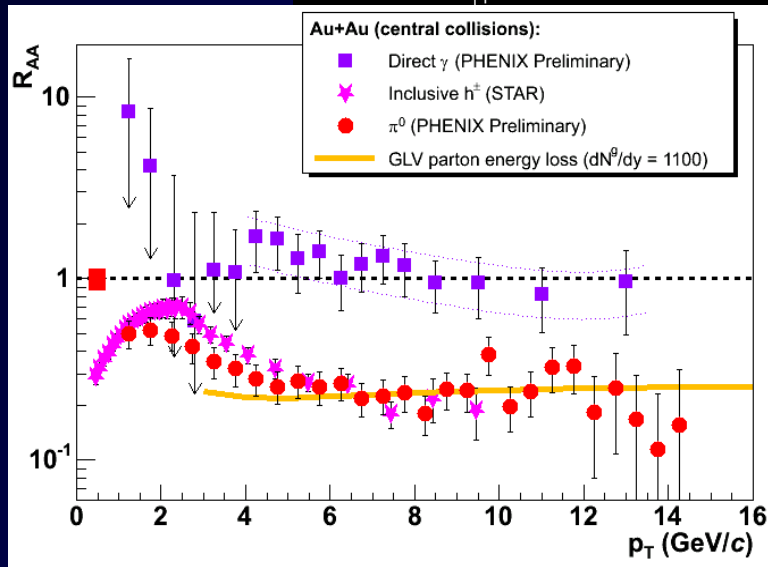
pQCD (BDMPS'96)

AdS/CFT (Liu, Rajagopal & Wideman'06)

lattice QCD (Majumder'12)



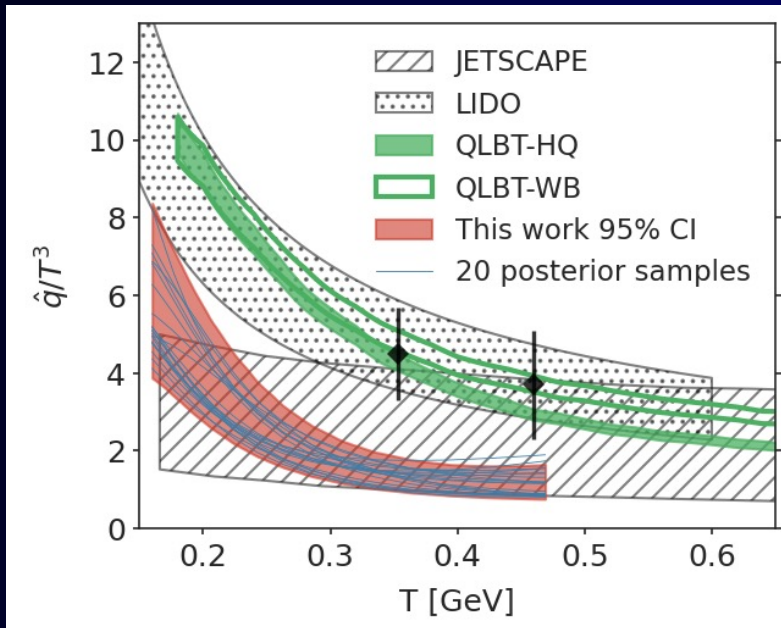
Jet Quenching phenomena at RHIC & LHC



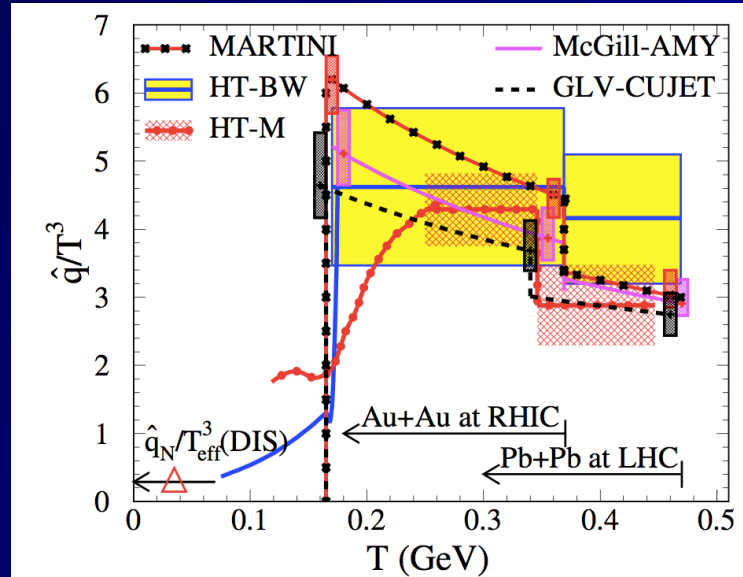
Jet Quenching at RHIC & LHC

JET Collaboration:
e-Print: 1312.5003

e-Print: 2206.01340

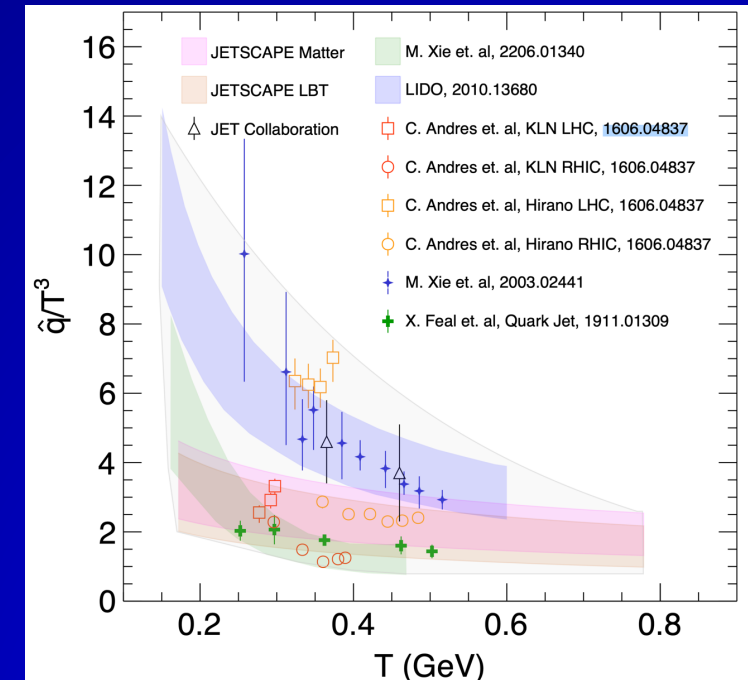


Xie, Ke, Zhang & XNW (2022)



$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{ GeV}^2/\text{fm} \text{ at } \begin{cases} T=370 \text{ MeV,} \\ T=470 \text{ MeV,} \end{cases}$$

e-Print: 2203.16352

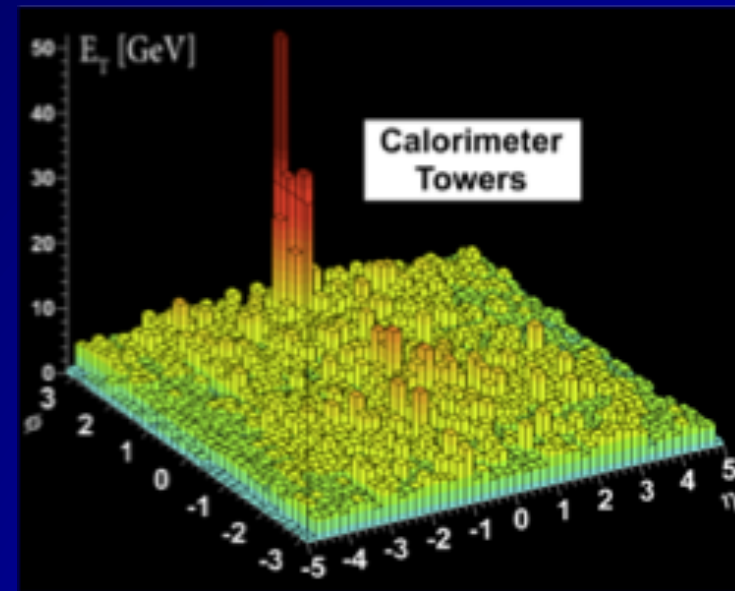
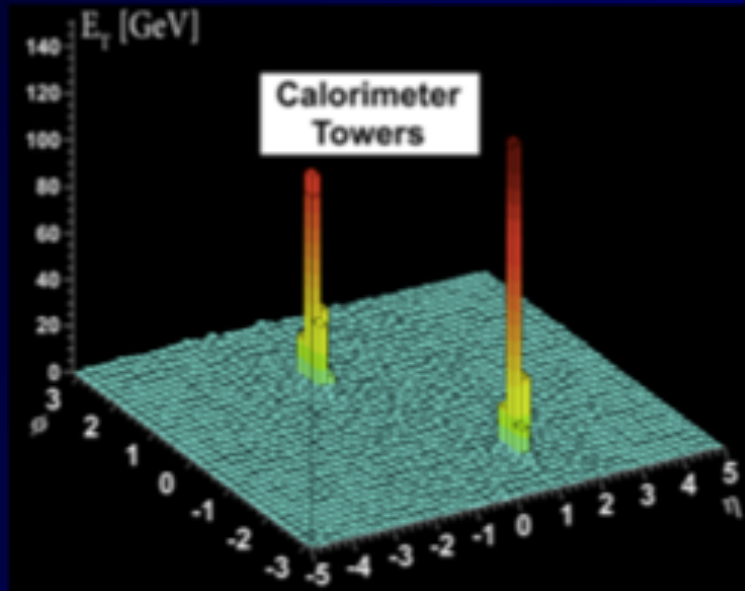


Apolinario, Lee & Winn

Uncertainties reduced by IF Bayesian



Jet energy, medium response and background



- Jet energy as defined in the jet reconstruction algorithm with a jet cone R
- Uncorrelated background should be subtracted
- Jet-induced medium response is correlated with jet: not background
- Some of the energy lost by leading partons remain inside jet-cone

MPI: Multiple parton interaction

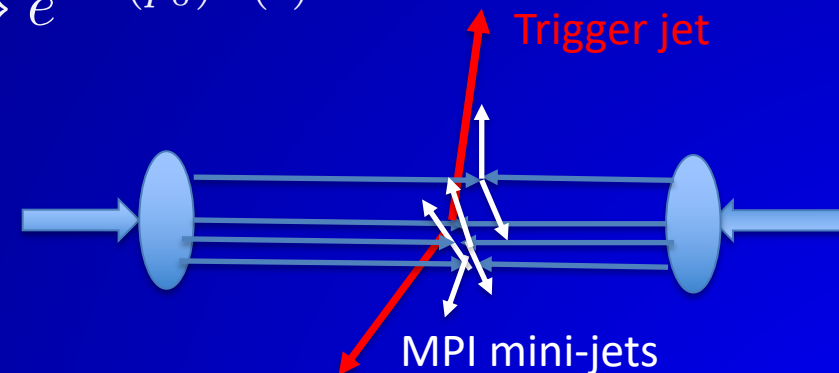
XNW & Gyulassy (1991)

Multiple jet production in pp:
$$g_j(b, p_T) = \frac{[\Delta\sigma(p_T)T(b)]^j}{j!} e^{-\Delta\sigma(p_T)T(b)}$$

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

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

$$\approx j \frac{\sigma(p_T^{\text{trig}})}{\sigma(p_0)} g_j(b)$$

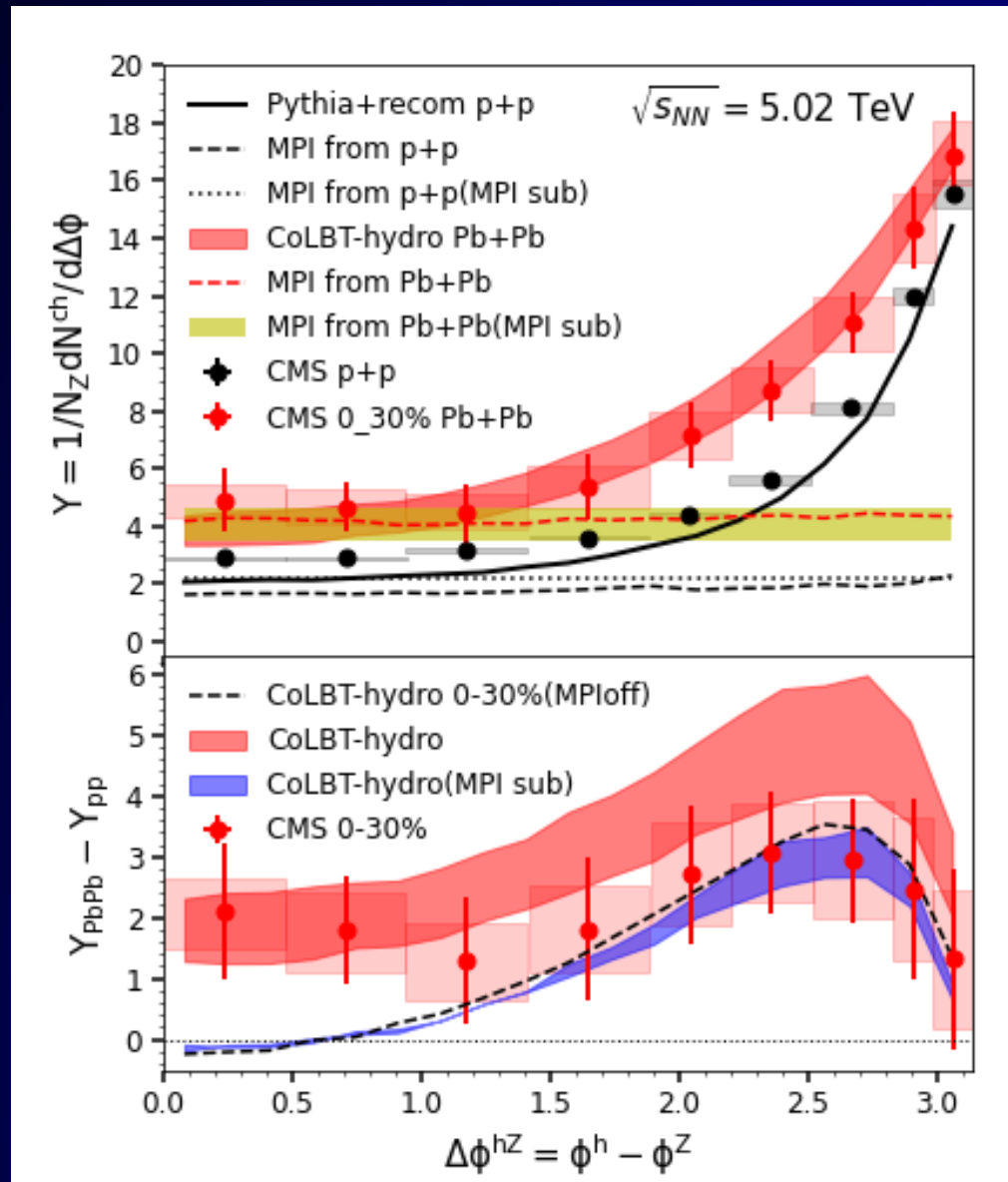


Enhanced multiple minijet

Production in triggered jet events

→ Azimuthal uncorrelated background from MPI

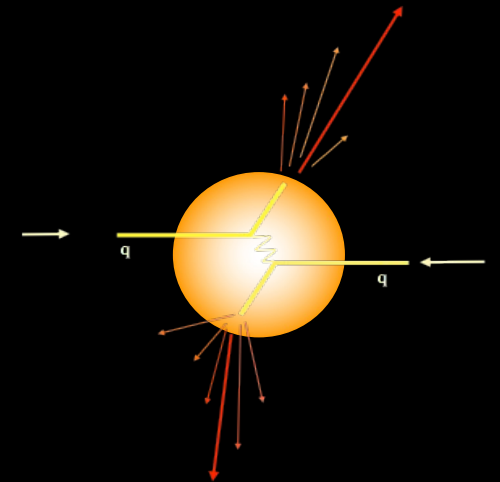
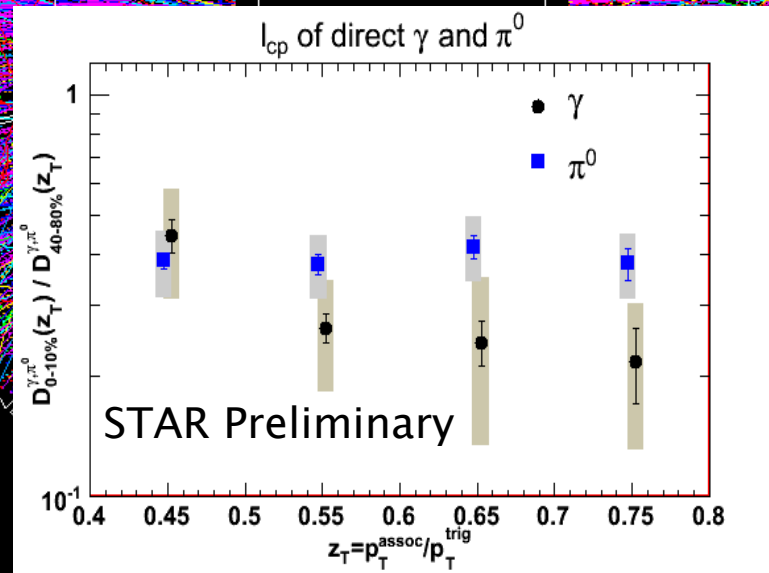
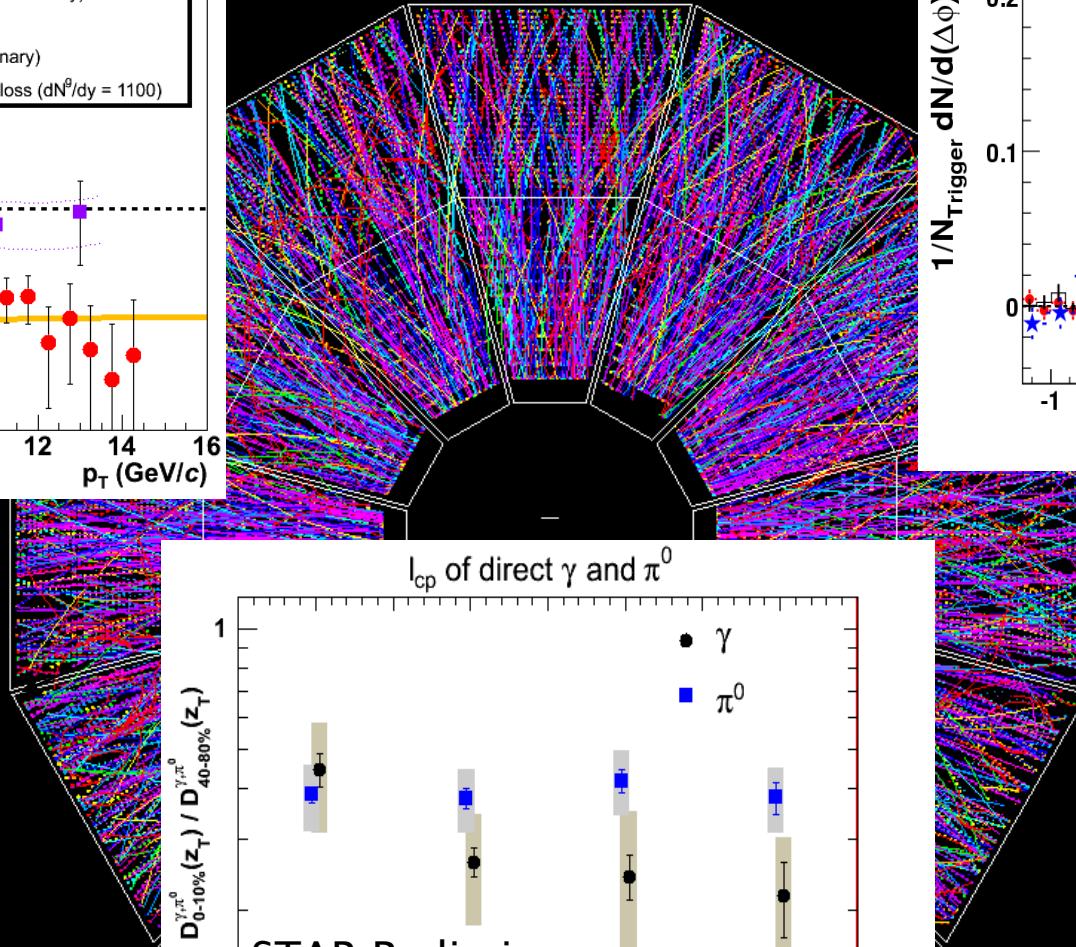
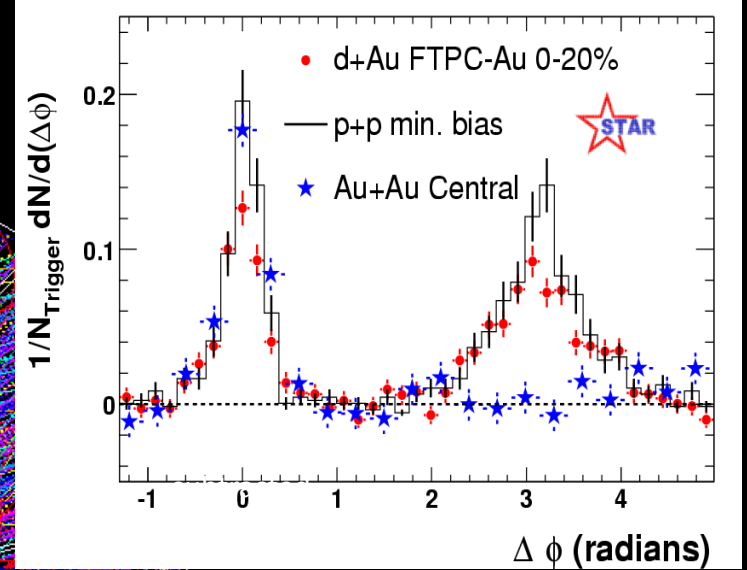
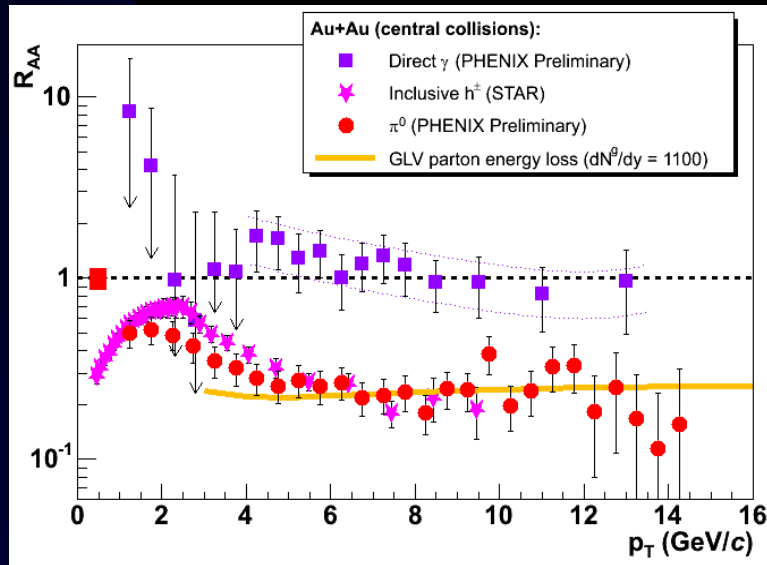
MPI subtraction in Z-hadron correlation



Mixed event subtraction

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

Jet Quenching phenomena at RHIC



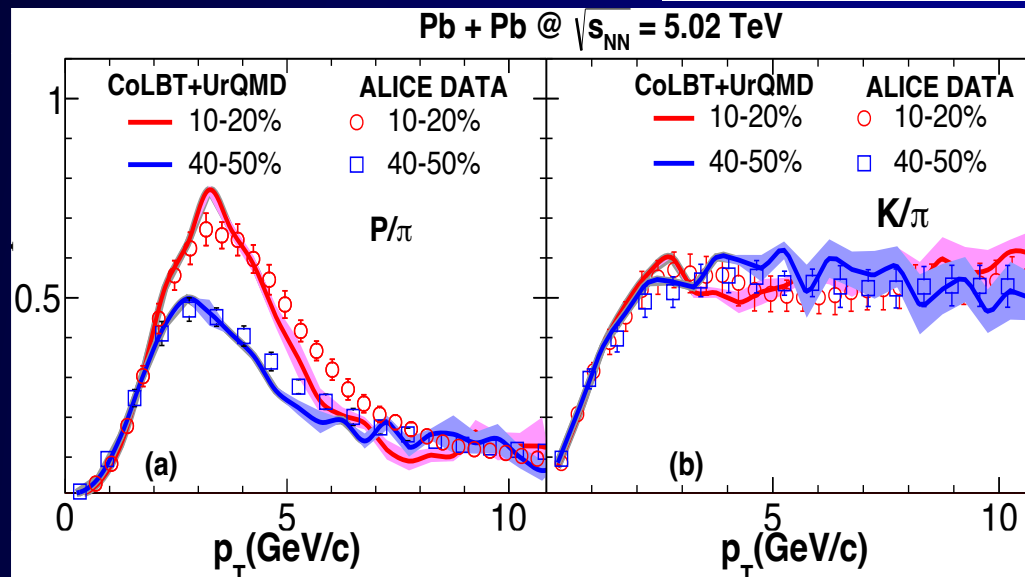
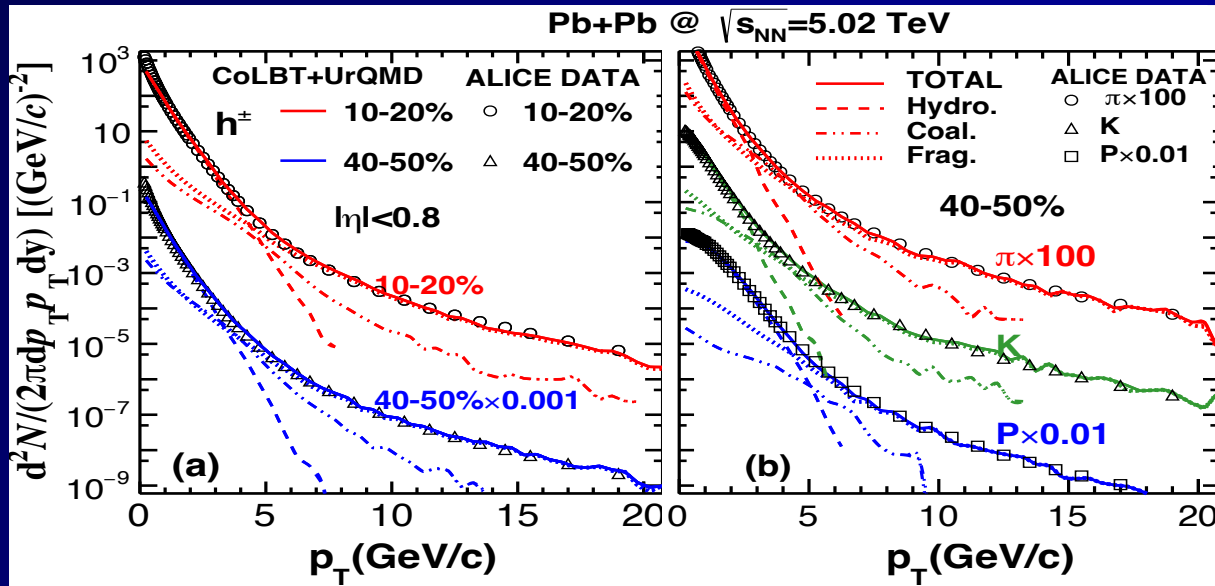
Hadron spectra from low to high p_T

CoLBT-hydro:

Hydro : $p_T < 2$ GeV/c

Coal.: $2 < p_T < 6$ GeV/c

Frag.: $p_T > 5$ GeV



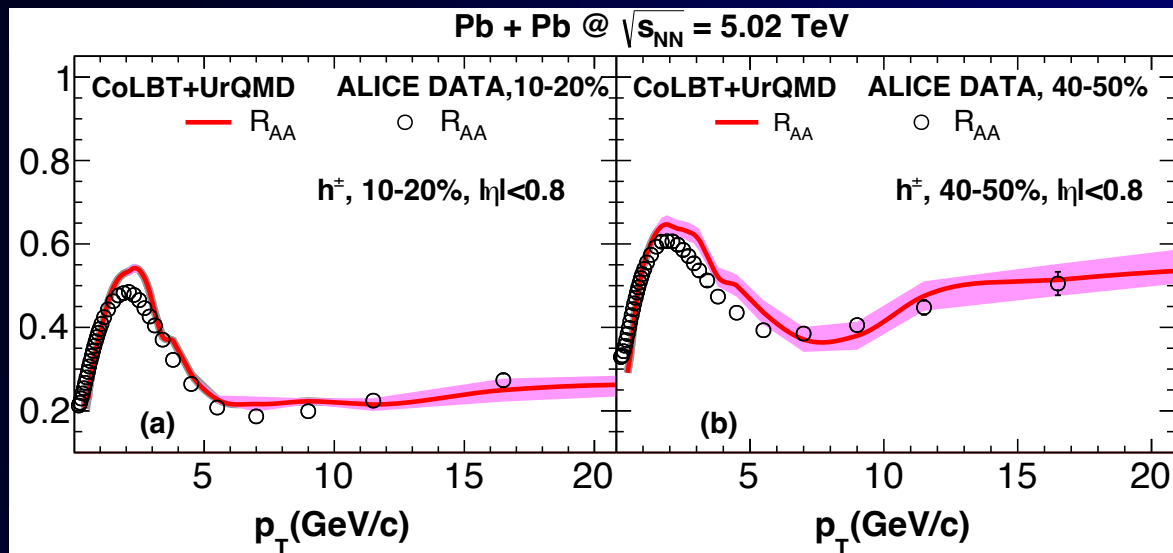
$p_T < 2$ GeV/c: radial flow

$2 < p_T < 6$ GeV/c: coalescence

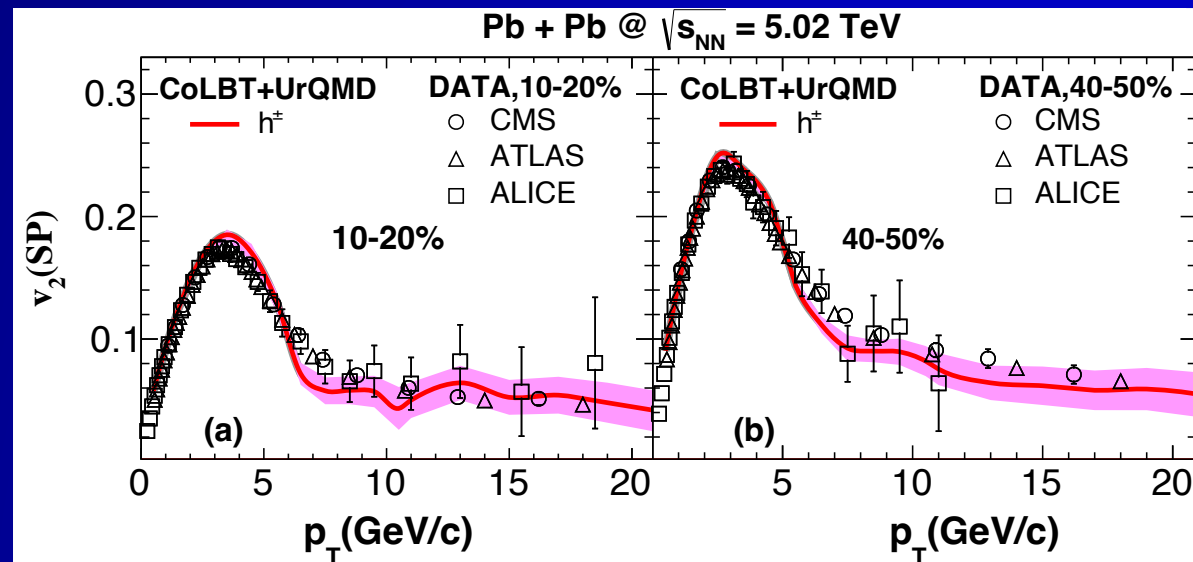
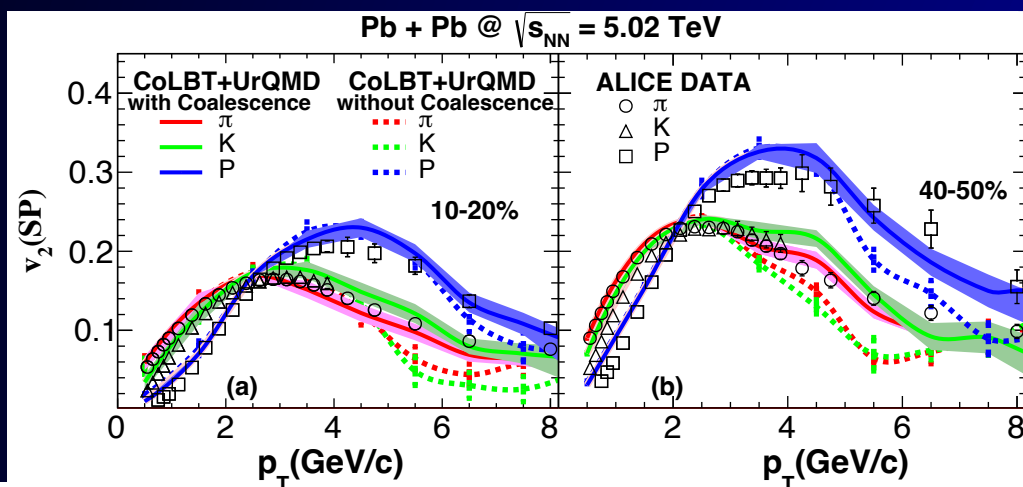
$p_T > 10$ GeV/c: energy loss

Zhao, Ke, Chen, Luo & XNW,
 PRL 128 (2022) 2, 022302 ([2103.14657](https://doi.org/10.1103/PhysRevLett.128.022302))

Solving R_{AA} - v_2 puzzle



Zhao, Ke, Chen, Luo & XNW,
PRL 128 (2022) 2, 022302 ([2103.14657](https://doi.org/10.1103/PhysRevLett.128.022302))



Asymmetric-diffusion in nonuniform medium

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

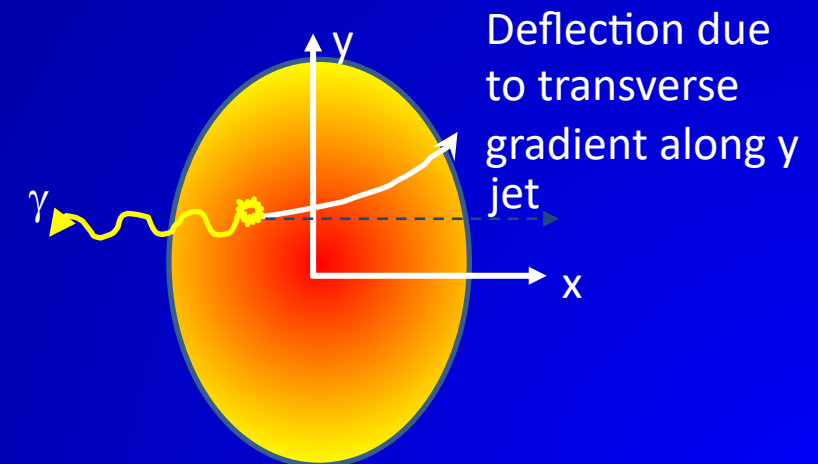
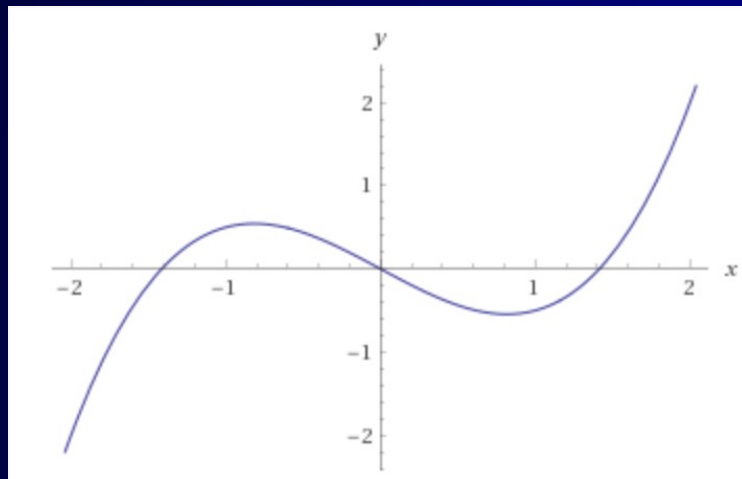
Boltzmann equation under approximation of small angle elastic scattering, no drag:

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

$$\hat{q} = \hat{q}_0 + \vec{x}_\perp \cdot \vec{a}$$

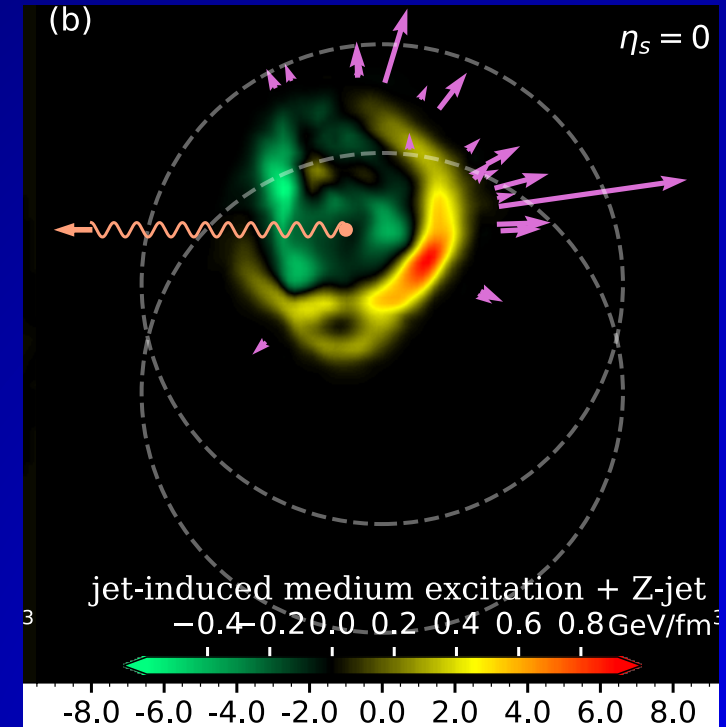
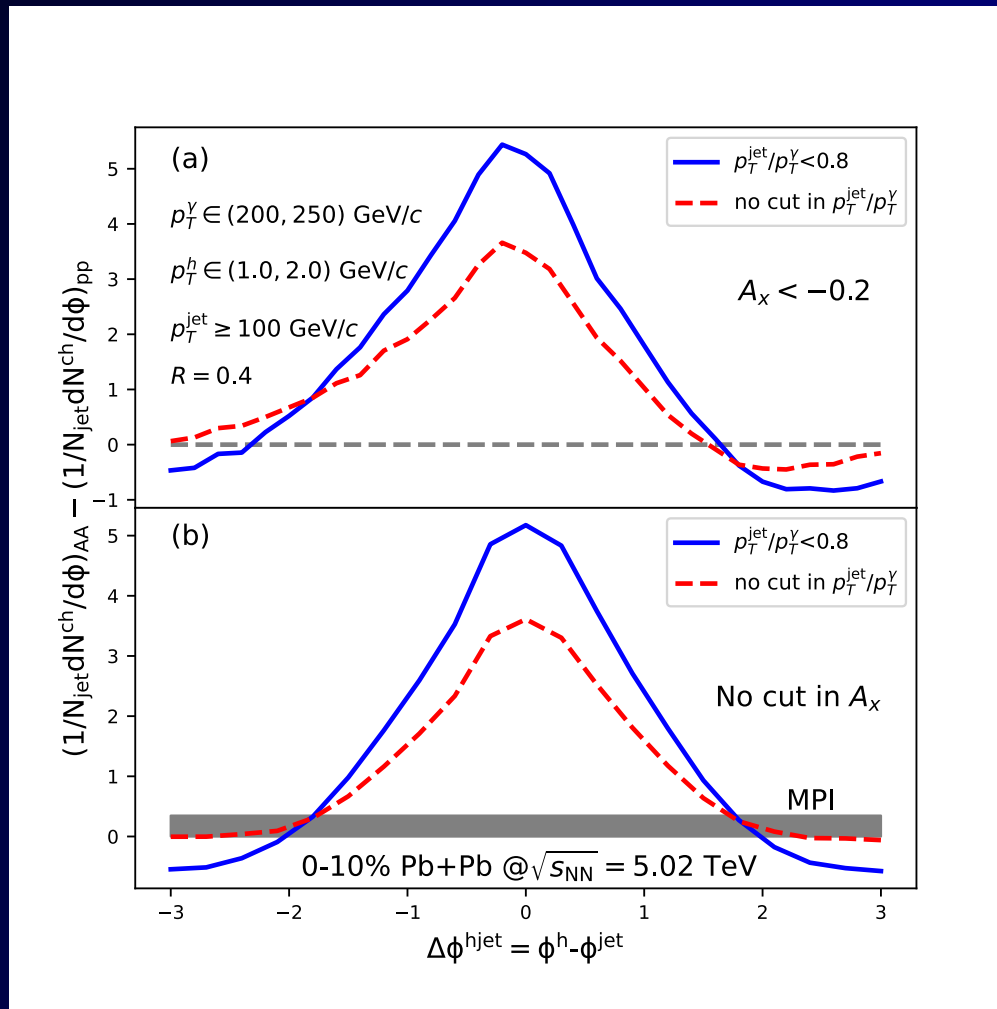


Momentum asymmetry:
$$\delta f(\vec{p}_\perp) = -\frac{t}{3\omega\hat{q}_0} \vec{a} \cdot \vec{p}_\perp \left(1 - \frac{p_\perp^2}{2\hat{q}_0 t} \right) f_s(\vec{p}_\perp, t) + \mathcal{O}(a^2)$$



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

Enhancing the diffusion wake



Chen, Yang, He, Ke, Pang and XNW, *Phys. Rev. Lett.* 127 (2021) 8, 082301