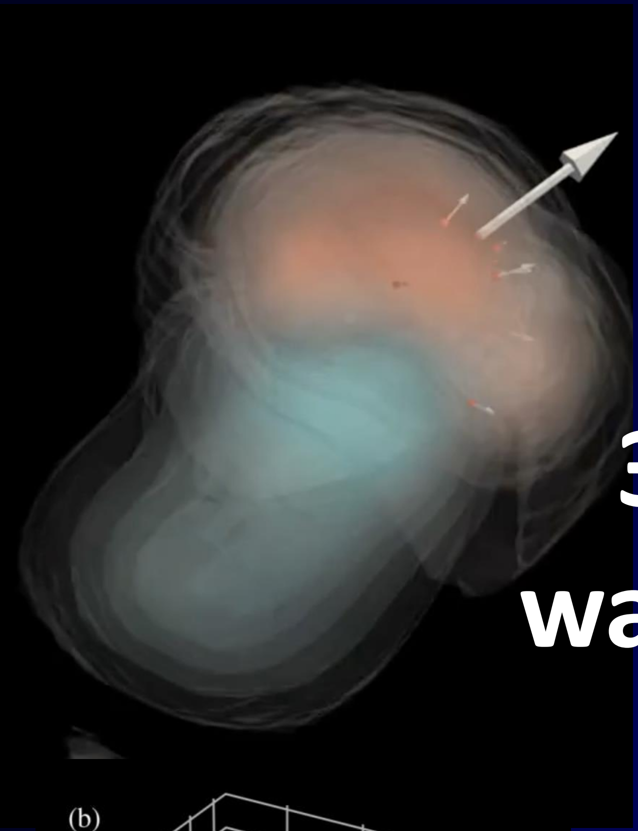
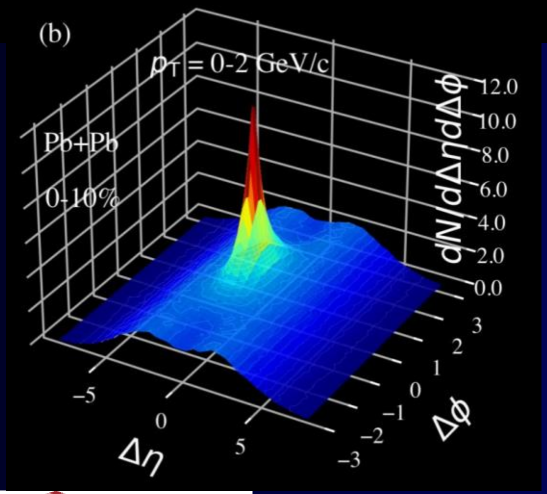


S

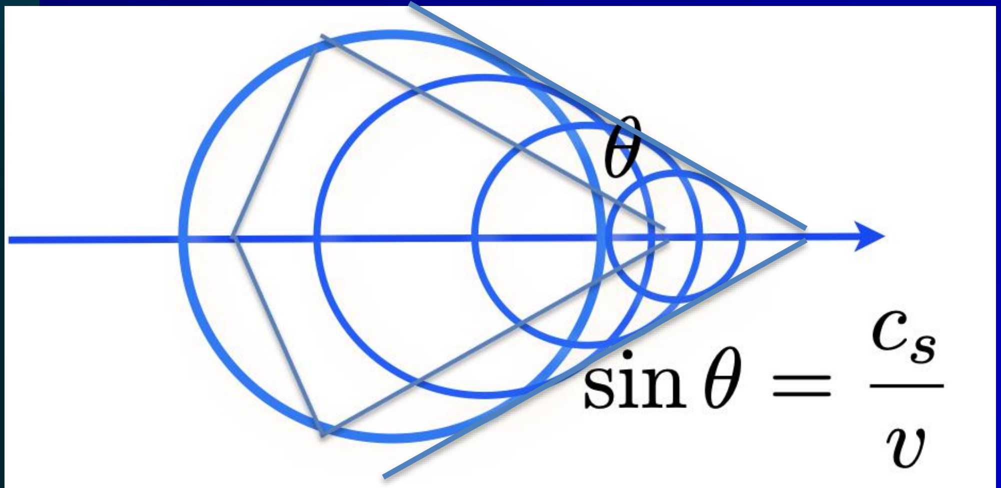
3D structure of jet-induced diffusion wake in high-energy heavy-ion collisions

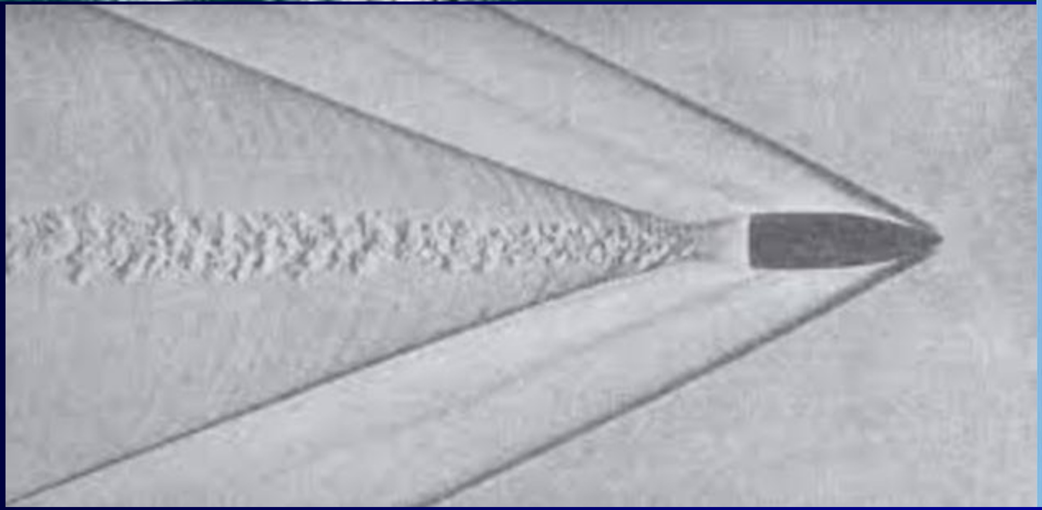


Xin-Nian Wang

Lawrence Berkeley National Laboratory

Jets, bullets, bow waves & Mach cones

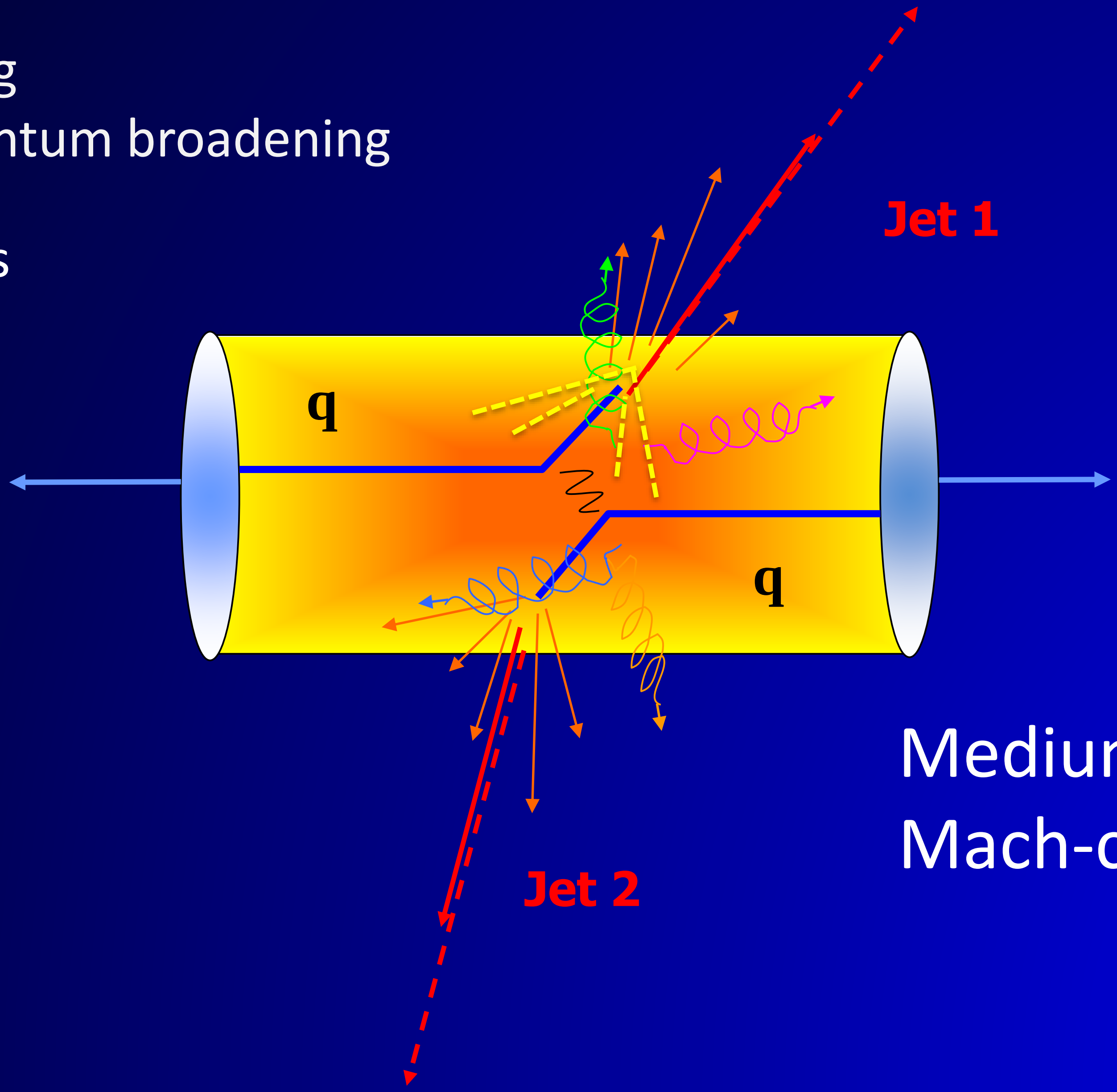




Jets and Mach cones in heavy-ion collisions

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)



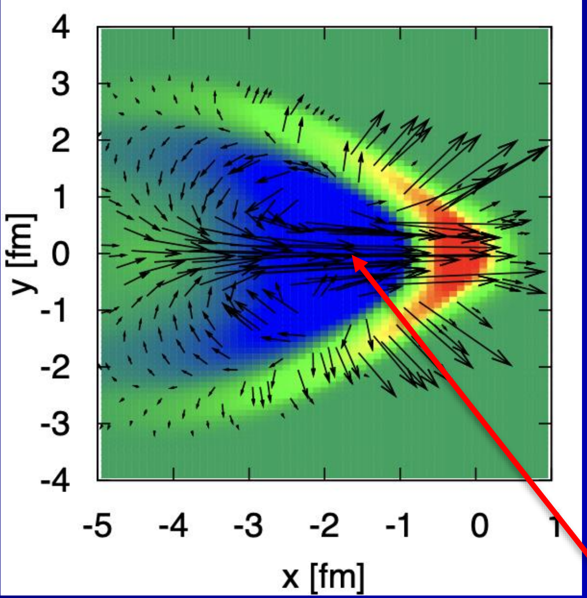

Jet induced Mach-cone in QGP

$$v = p/E > c_s$$

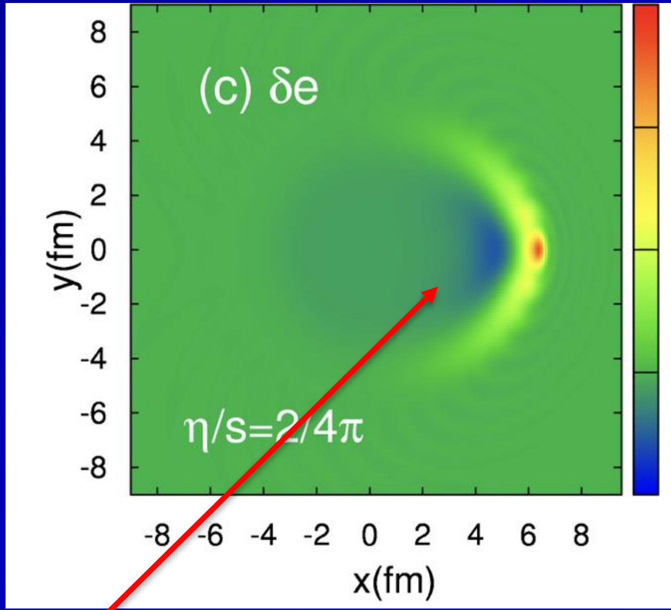
Hydrodynamic approach

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

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

$$T^{\mu\nu} \to T_0^{\mu\nu} + \delta T^{\mu\nu} \qquad \partial_\mu \delta T^{\mu\nu} = J^\nu$$

c_s^2 → EOS → Mach-cone angle

η → shock-wave width

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

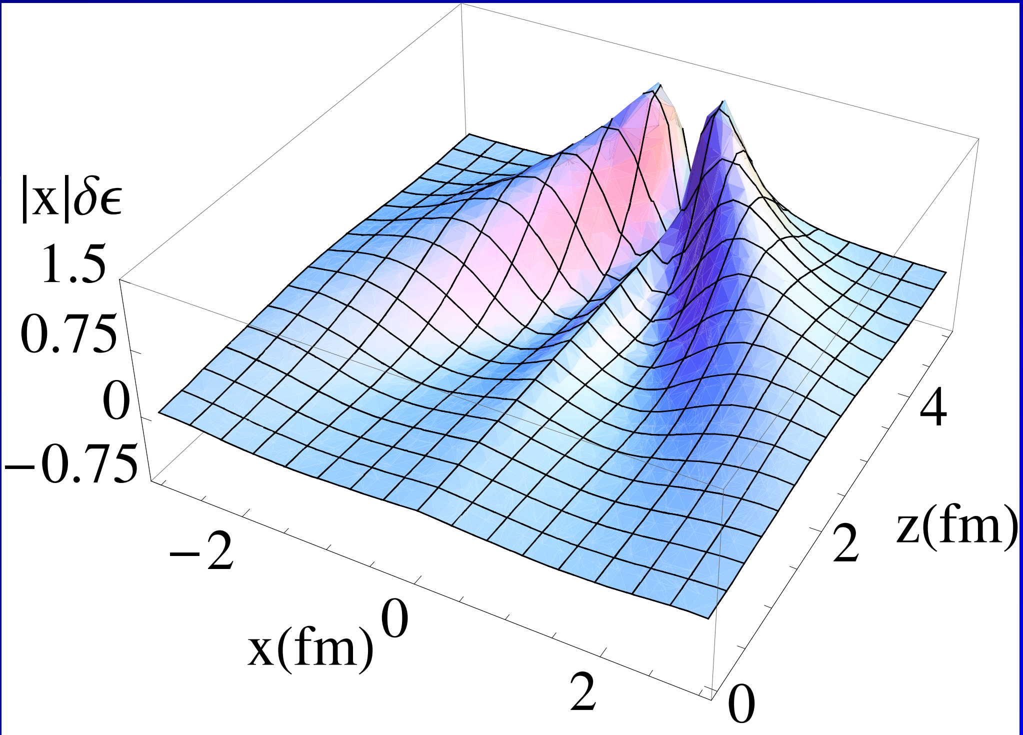
$$\delta T^{ij} = \delta^{ij} c_s^2 \delta\epsilon + \frac{3}{4}\Gamma_s\left(\partial^i g^j + \partial^j g^i + \frac{2}{3}\delta^{ij}\nabla\cdot\vec{g}\right),$$

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

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

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

R. B. Neufeld and B. Mu¨ller (2009) (0902.2950)



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

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Status of searching for Mach-cone

- No sign of the signature of Mach-cone
- False signature: v3 – anisotropic flow
- Lack of more realistic simulations of jet propagation in heavy-ion collisions

Microscopic picture of Mach wave

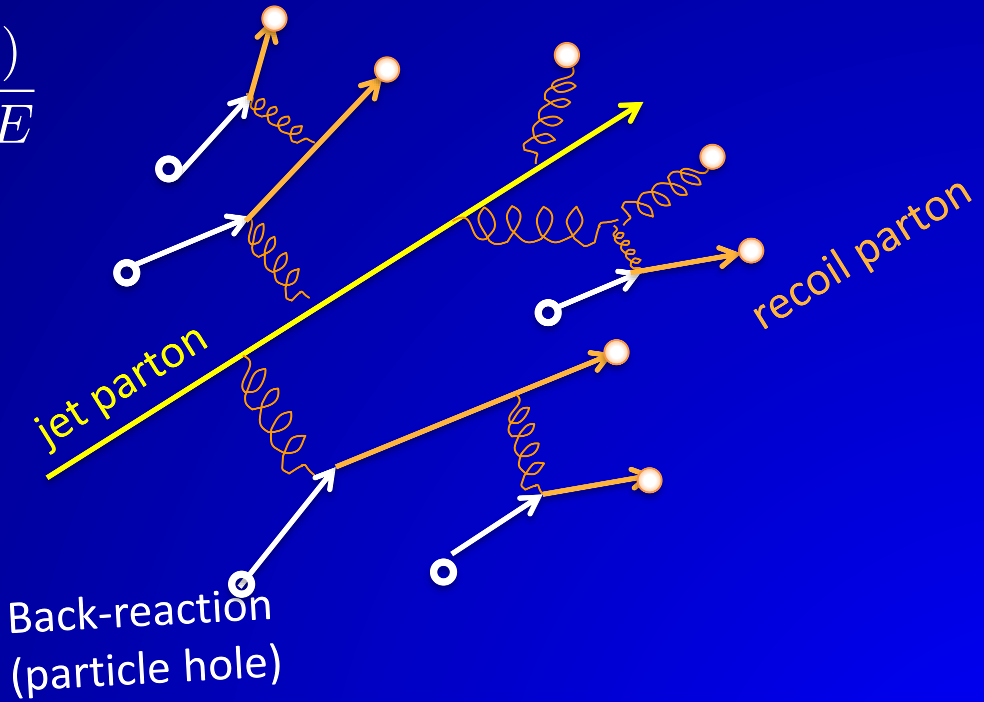
LBT: Linear Boltzmann Transport

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

Induced radiation

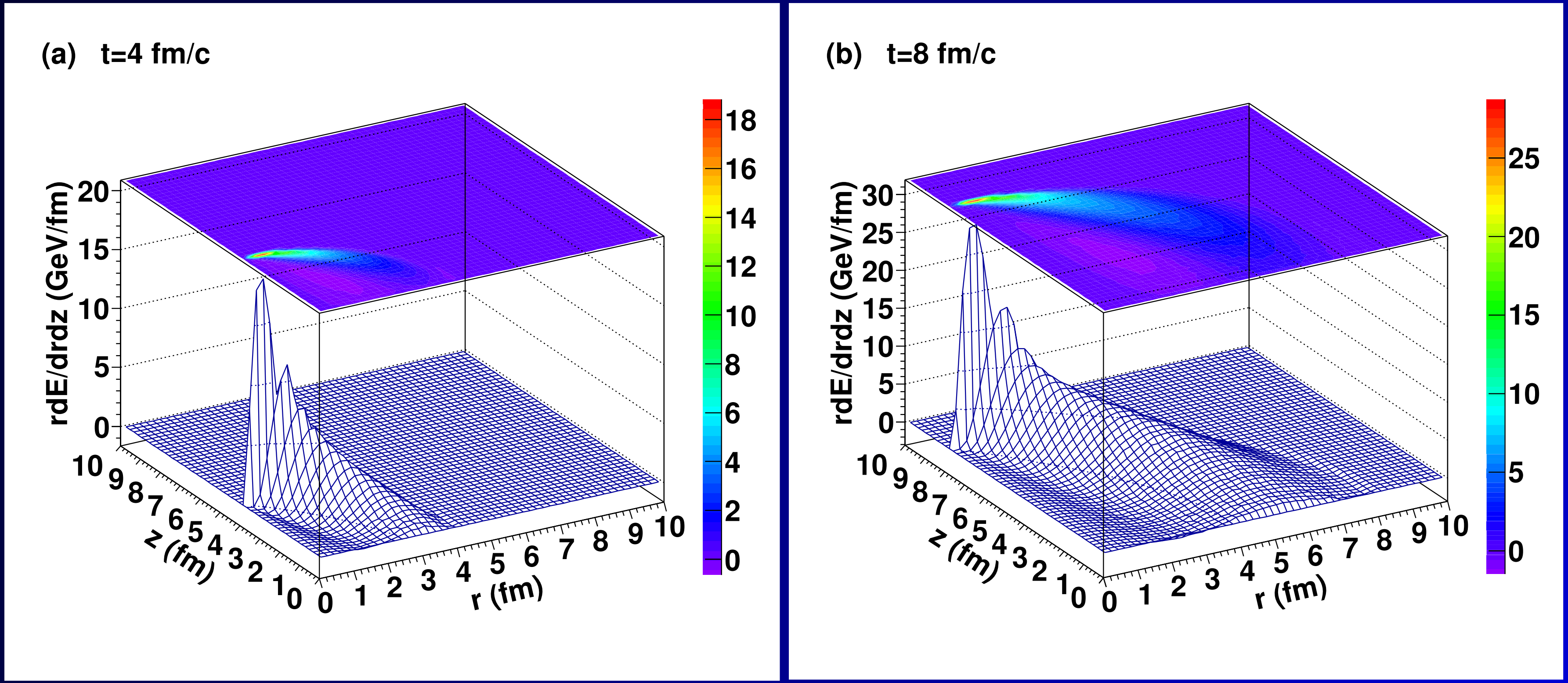
$$\frac{dN_g}{dz d^2 k_\perp dt} \approx \frac{2C_A \alpha_s}{\pi k_\perp^4} P(z) \hat{q}(\hat{p}\cdot u) \sin^2 \frac{k_\perp^2 (t-t_0)}{4z(1-z)E}$$

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



He, Luo, Zhu & XNW, *PRC* 91 (2015) 054908

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

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

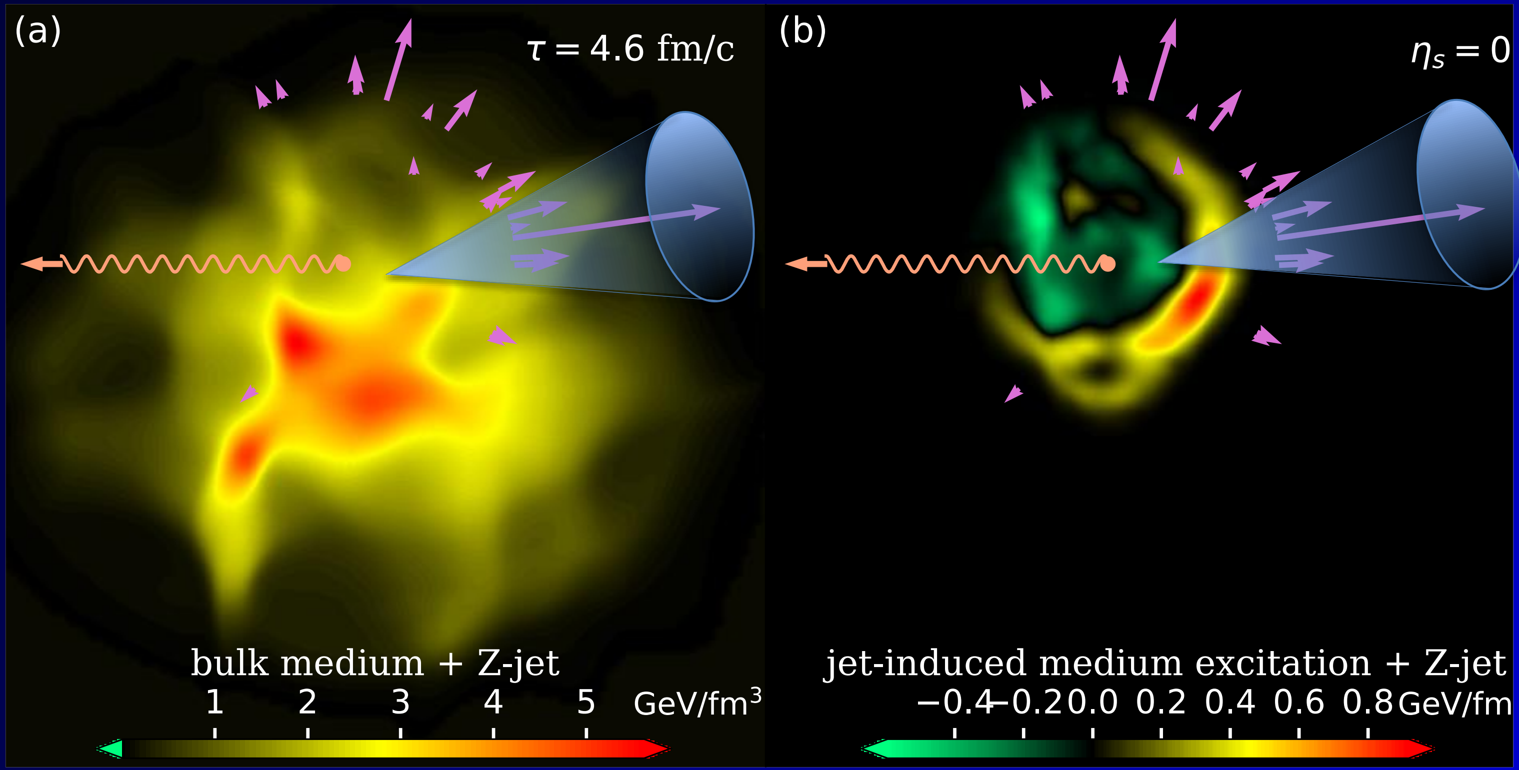
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

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

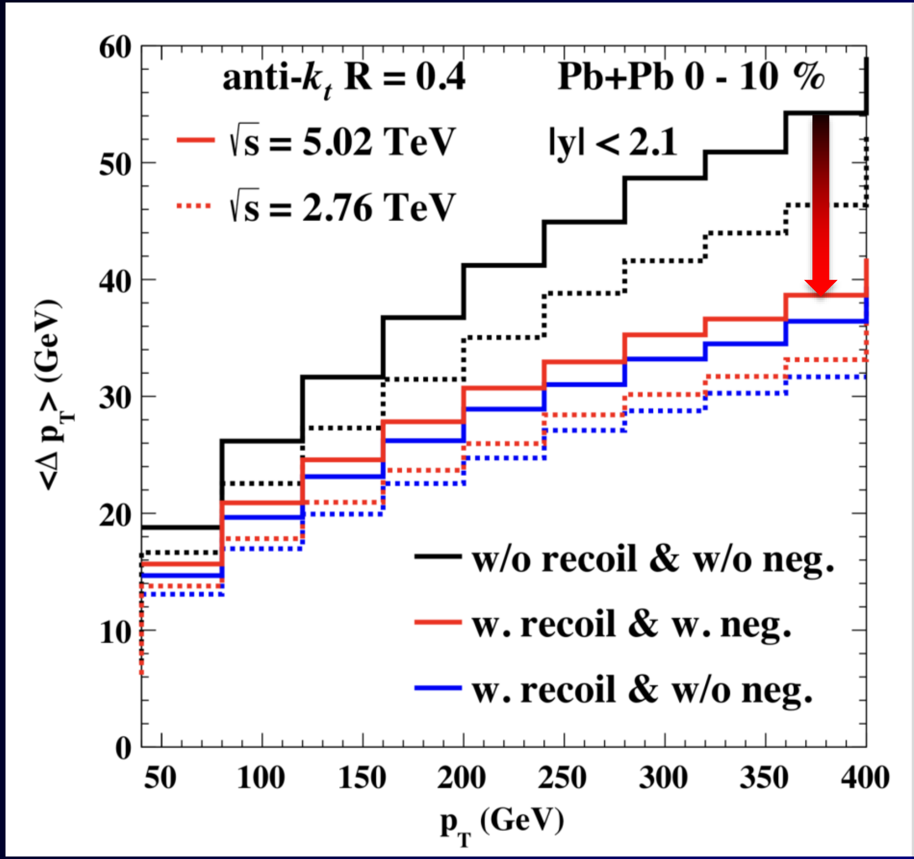
- LBT for energetic partons (jet shower and recoil)
- Hydrodynamic model for bulk and soft partons: CLVisc
- Parton coalescence (thermal-shower)+ jet fragmentation
- Hadron cascade using UrQMD

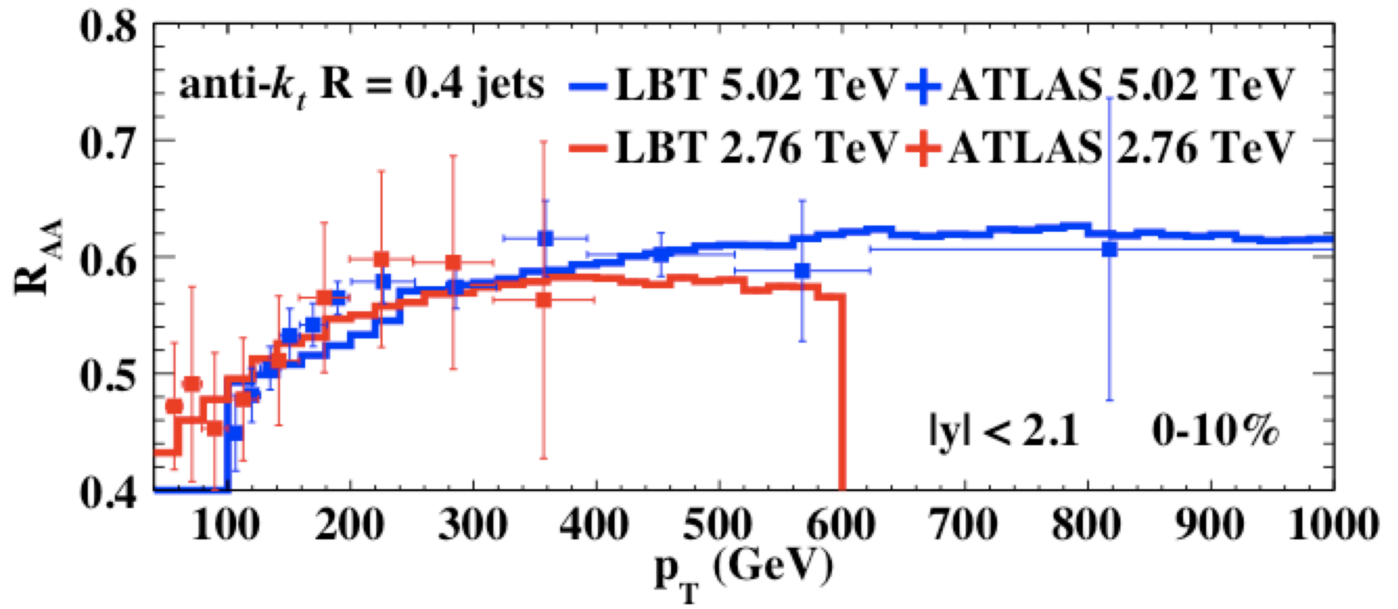
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86

Z/γ-jet: probing QGP



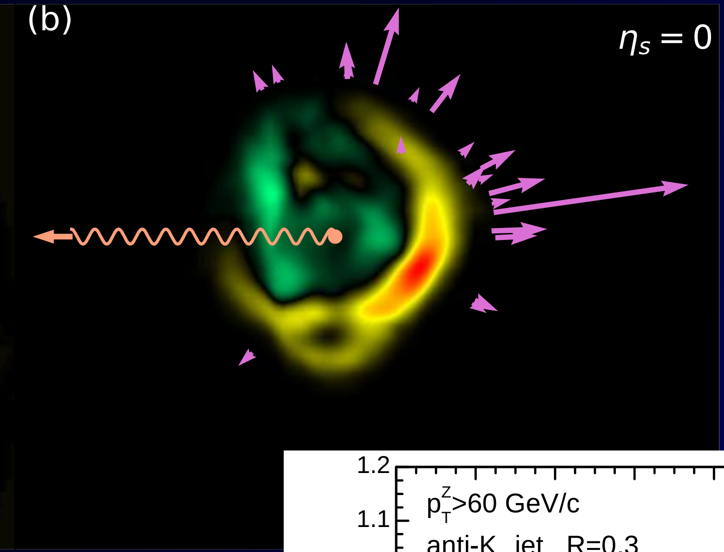
Jet suppression, energy loss & medium response





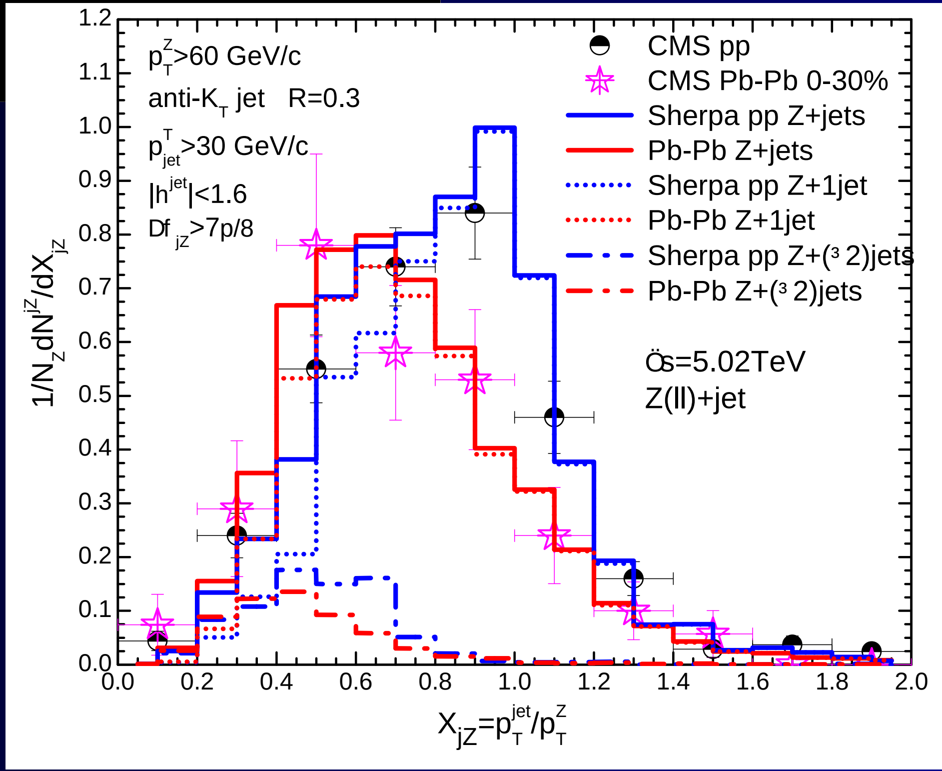
He, Cao, Chen, Luo, Pang & XNW 1809.02525

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

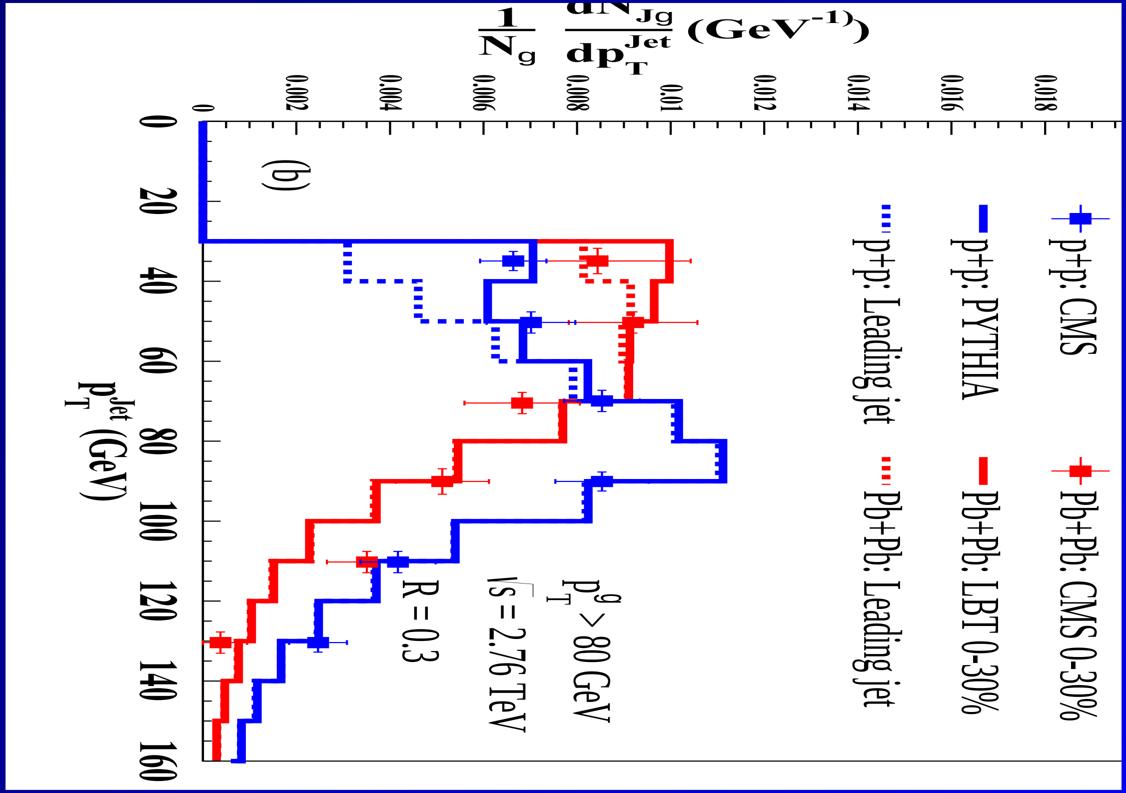


Energy loss in γ/Z-jet at LHC

Suppression of leading and multiple jets



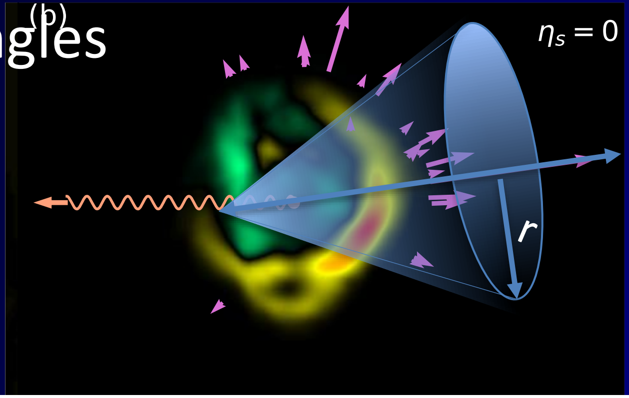
Zhang, Luo, XNW, Zhang, arXiv:1804.11041

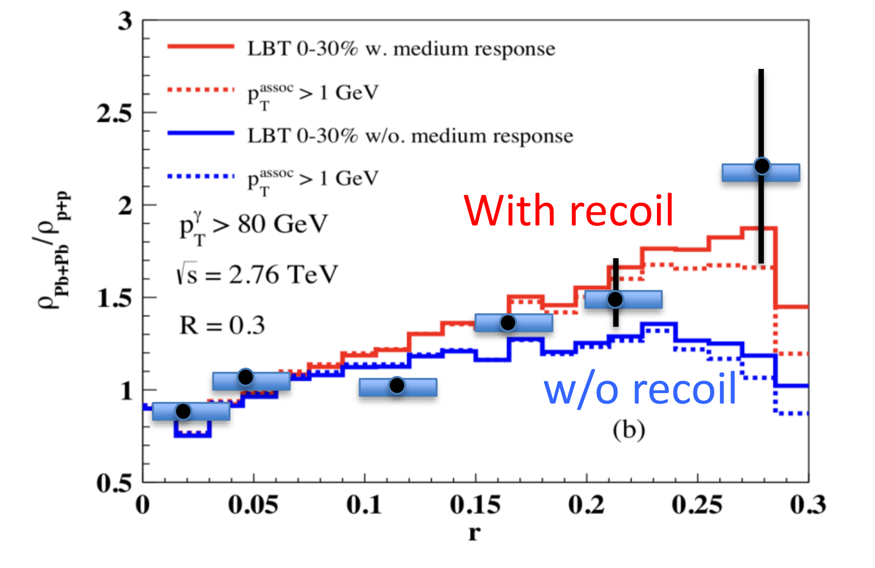


Luo, Cao, He & XNW, arXiv:1803.06785

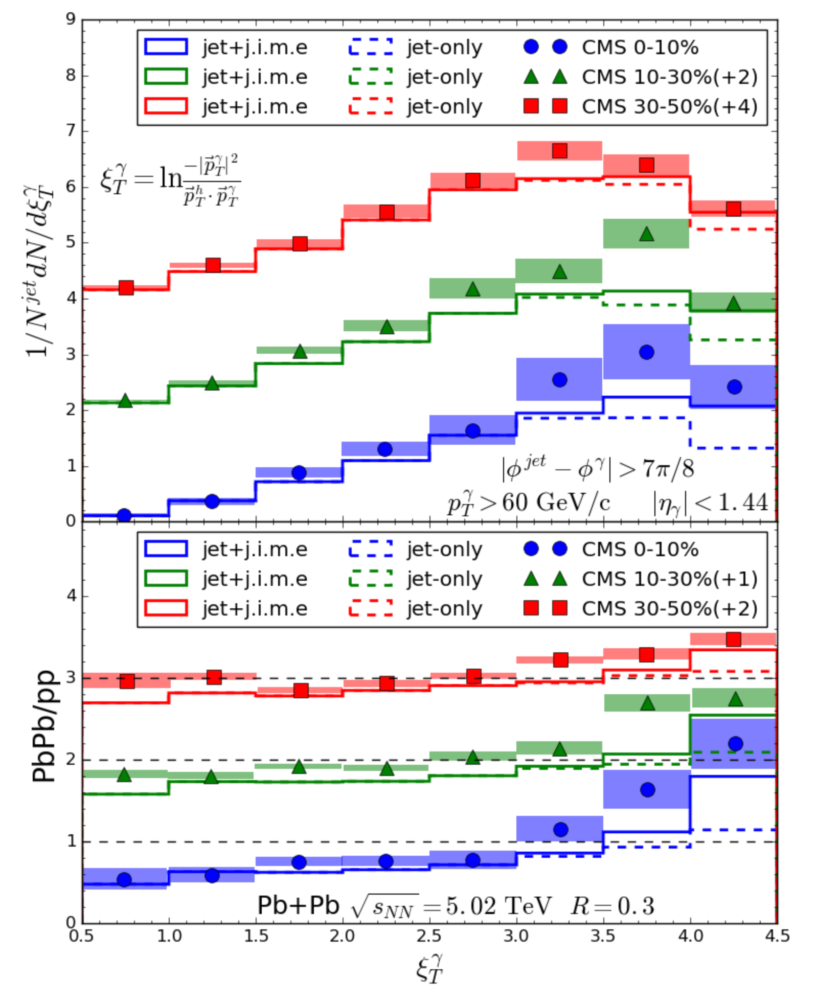
Medium modification of γ-jets

Enhancement of soft hadrons
in large angles





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 $\tau_f \leq \lambda \sim 1/T$ $\hat{q} \sim T^3$ $\omega \approx \lambda^2 \hat{q}/2 \sim T$

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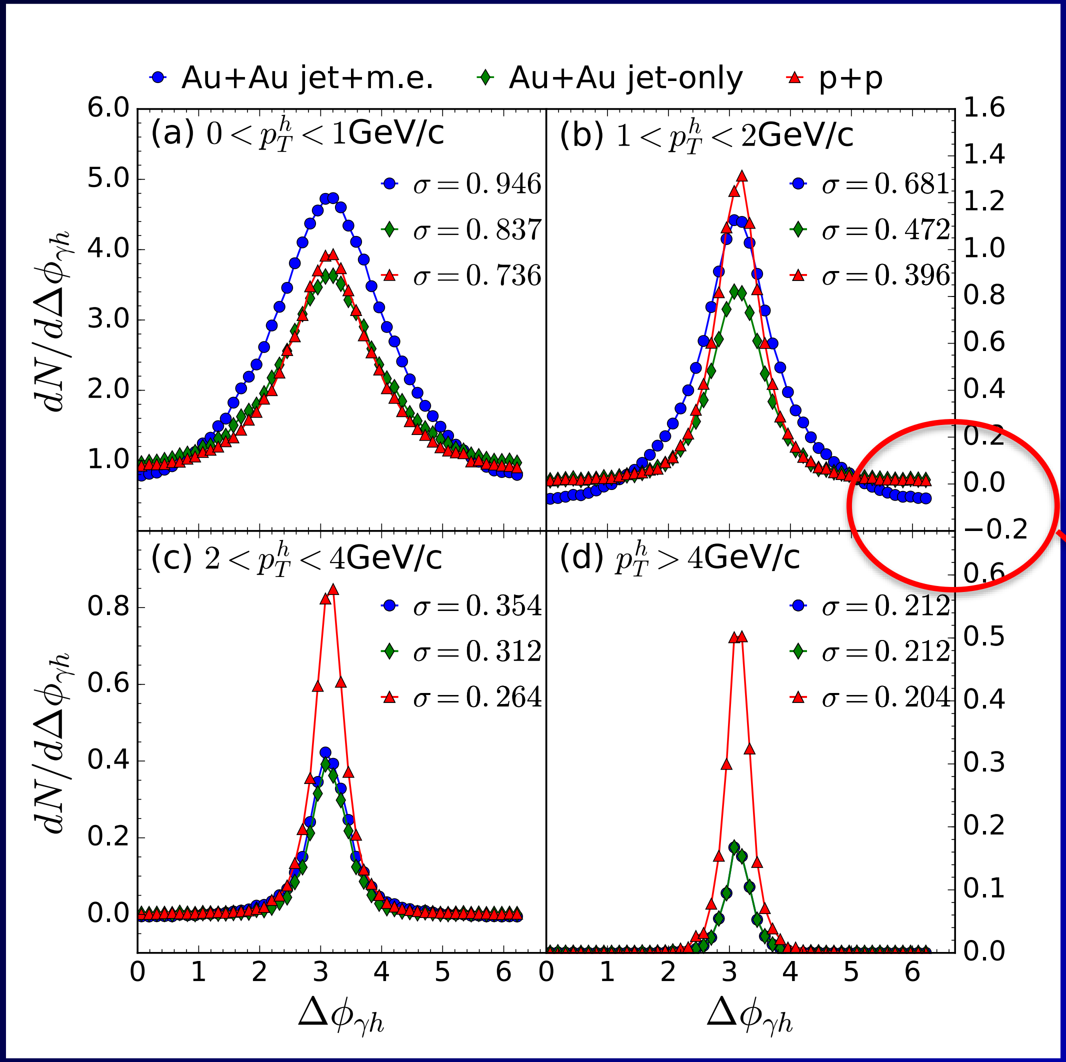
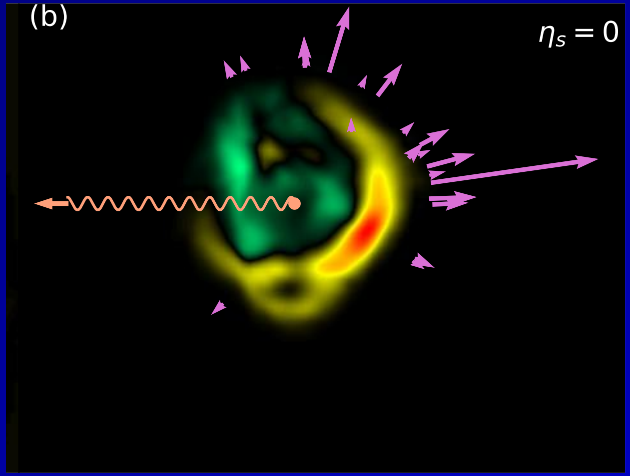
Signal of diffusion wake (DFW)





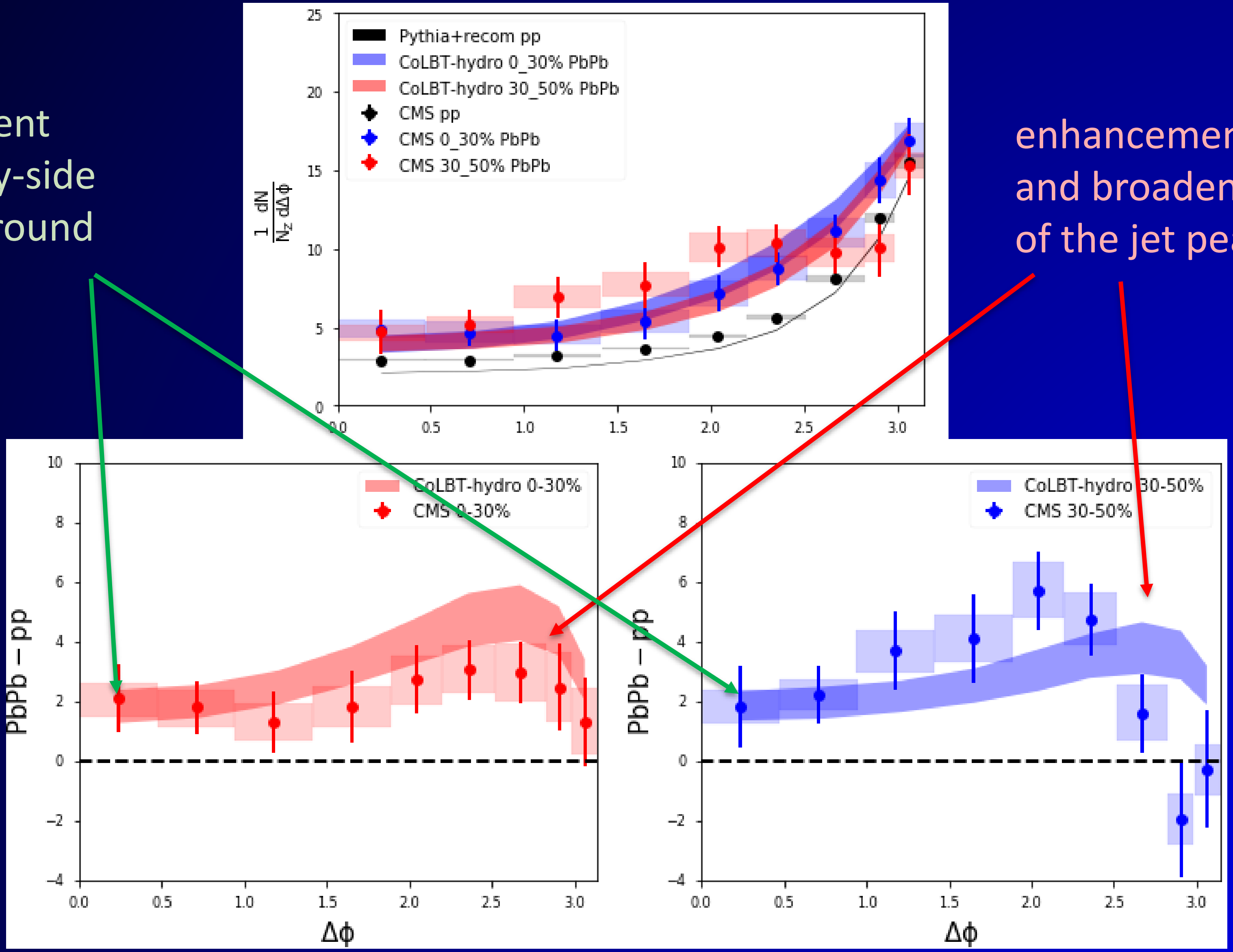
Depletion of the background
In the γ direction

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

Z-hadron correlation: MPI & medium response

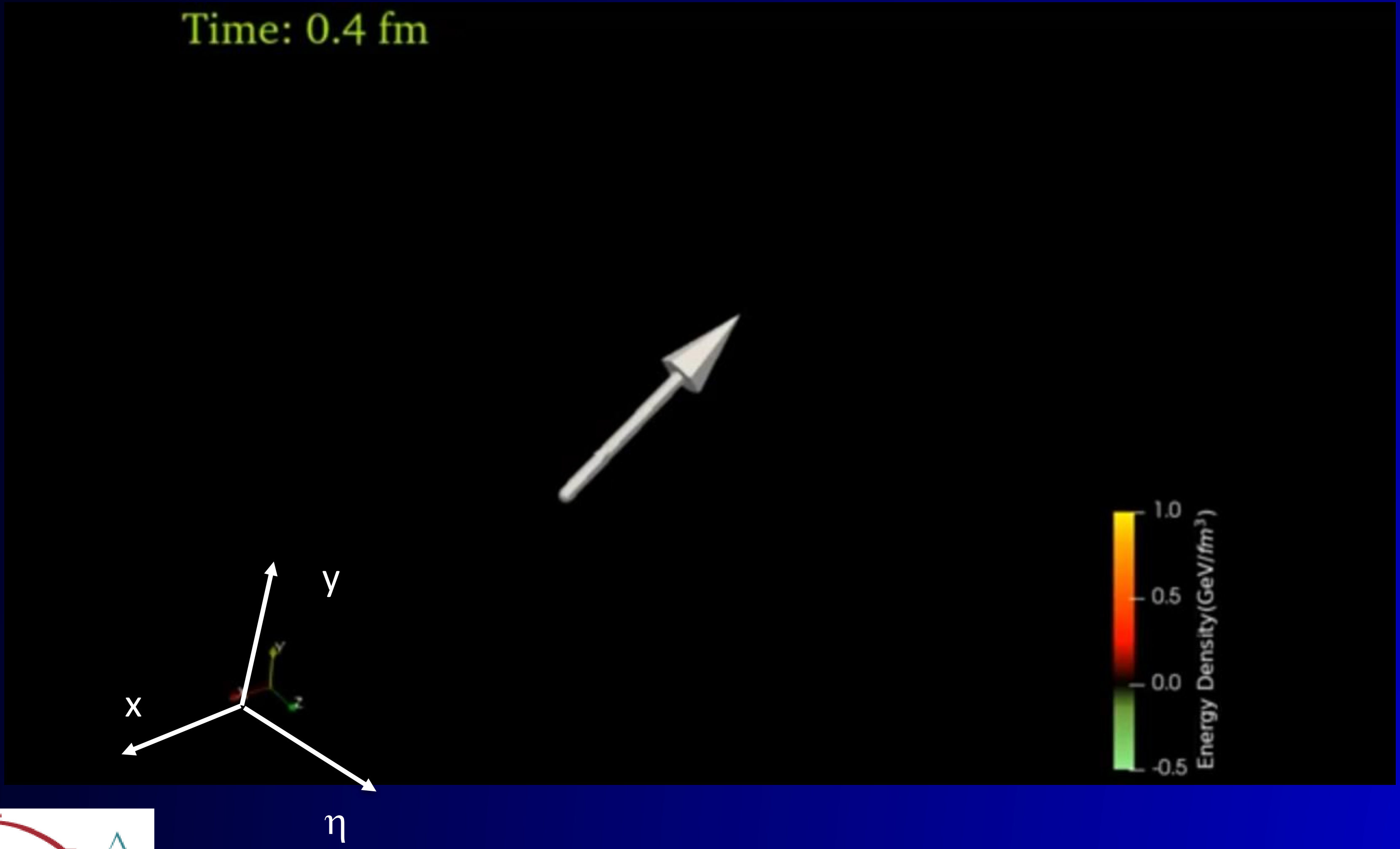
enhancement of the away-side MPI background

enhancement and broadening of the jet peak



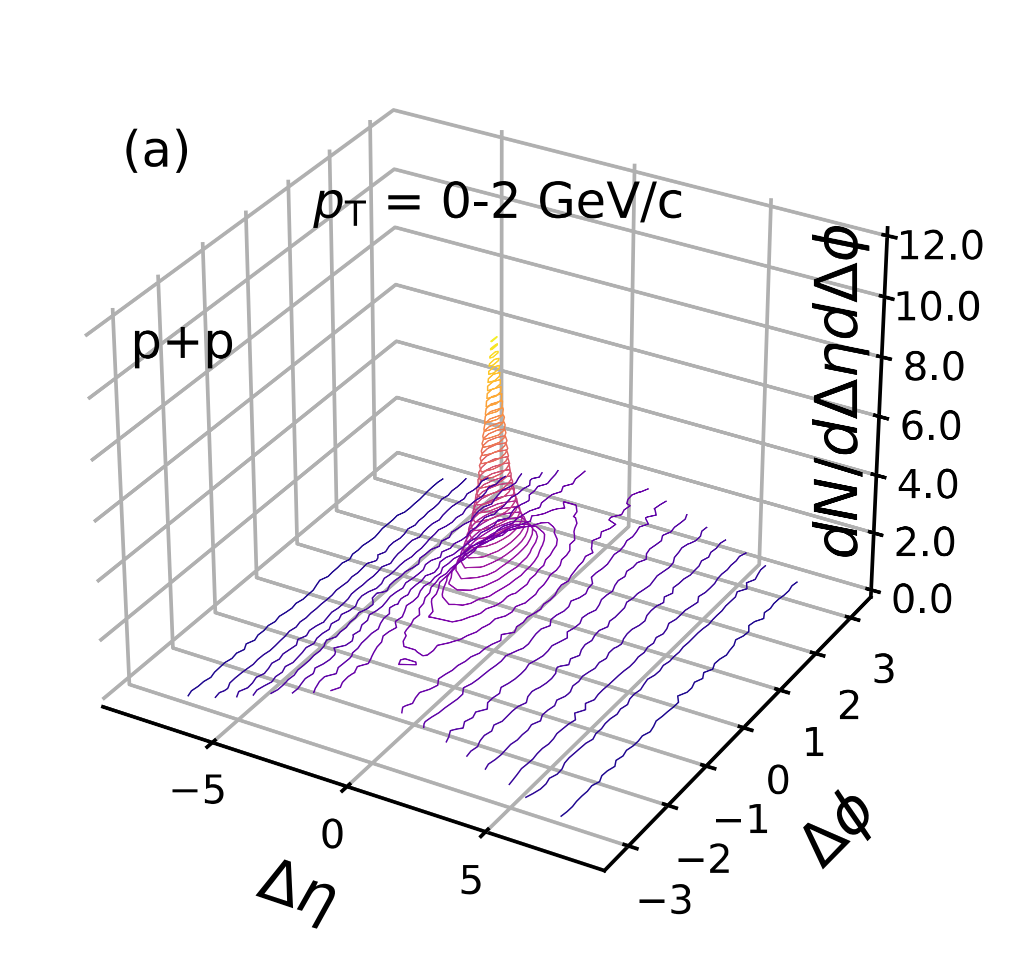
Chen, Yang, He, Ke, Pang and XNW, 2101.05422

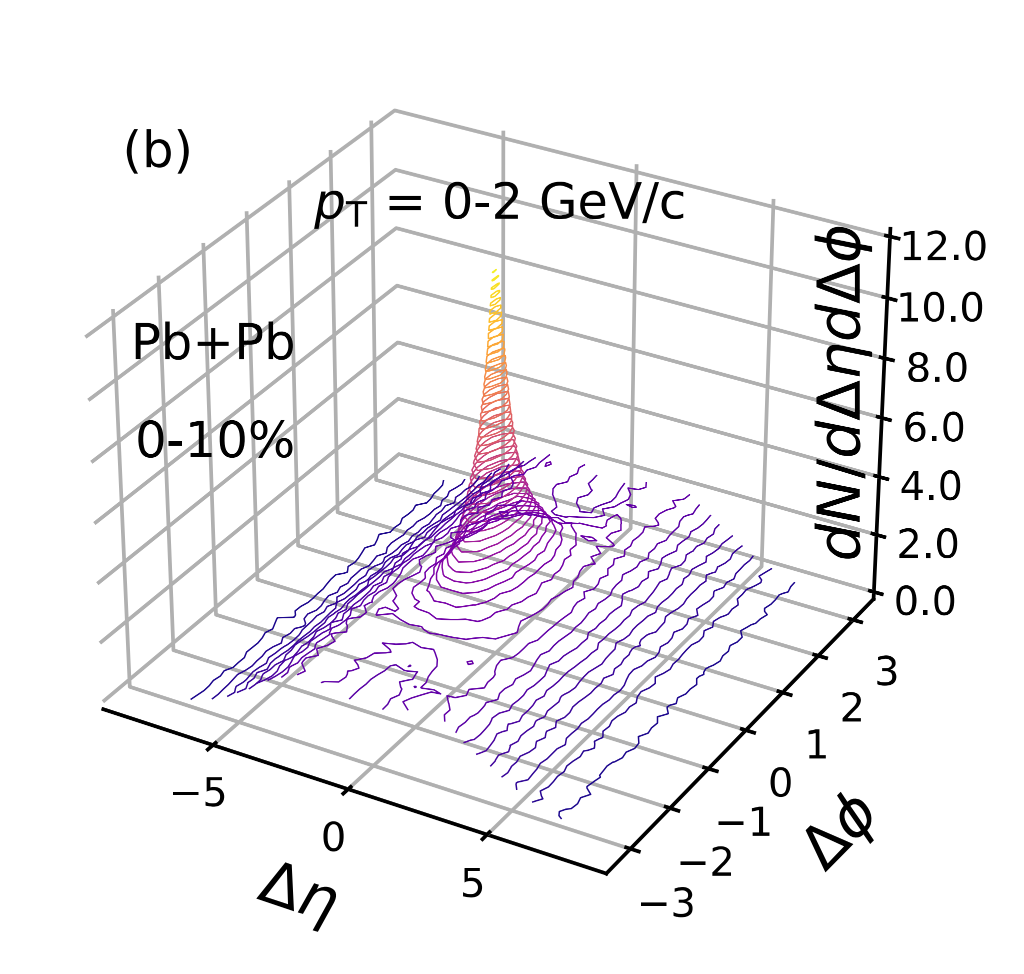
3D structure of diffusion wake



3D structure of diffusion wake

Jet-hadron correlation in γ/jet events





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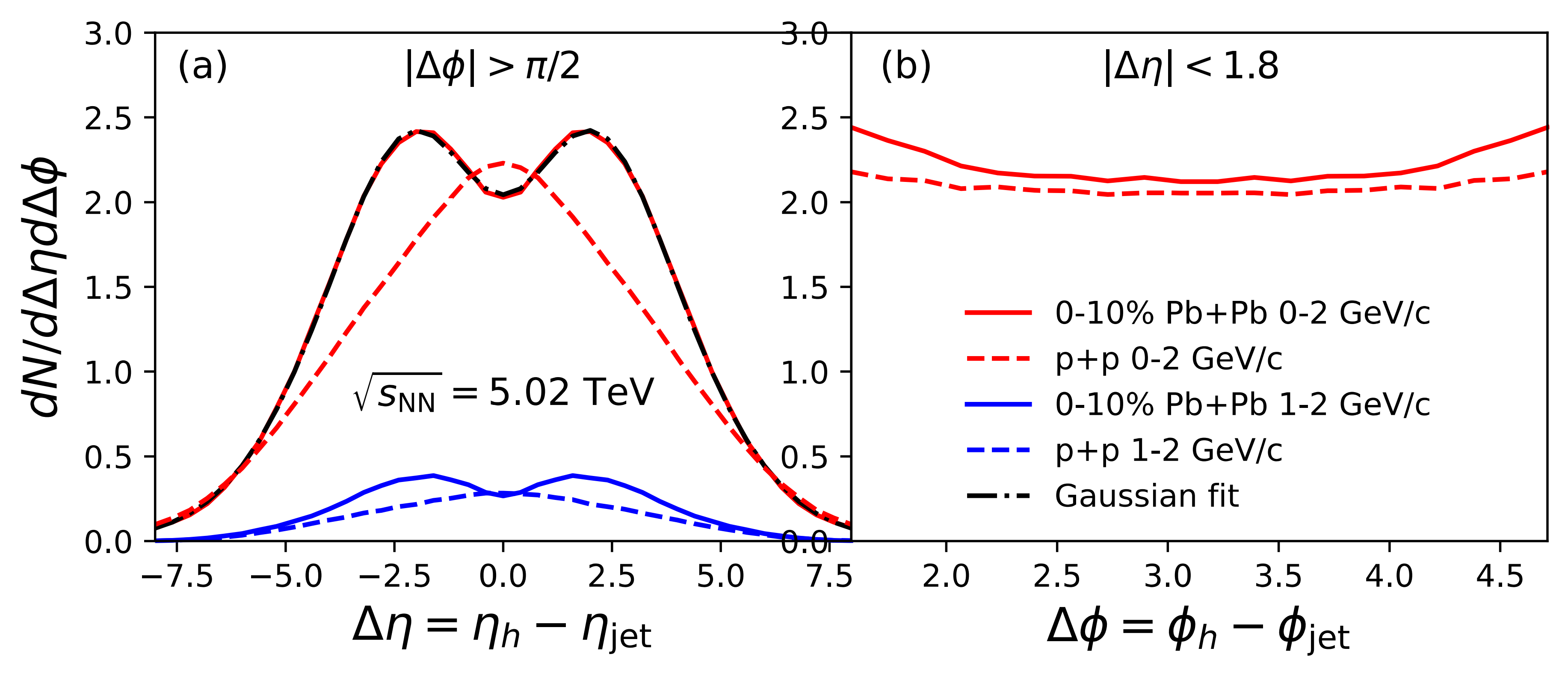
Double peak structure in η

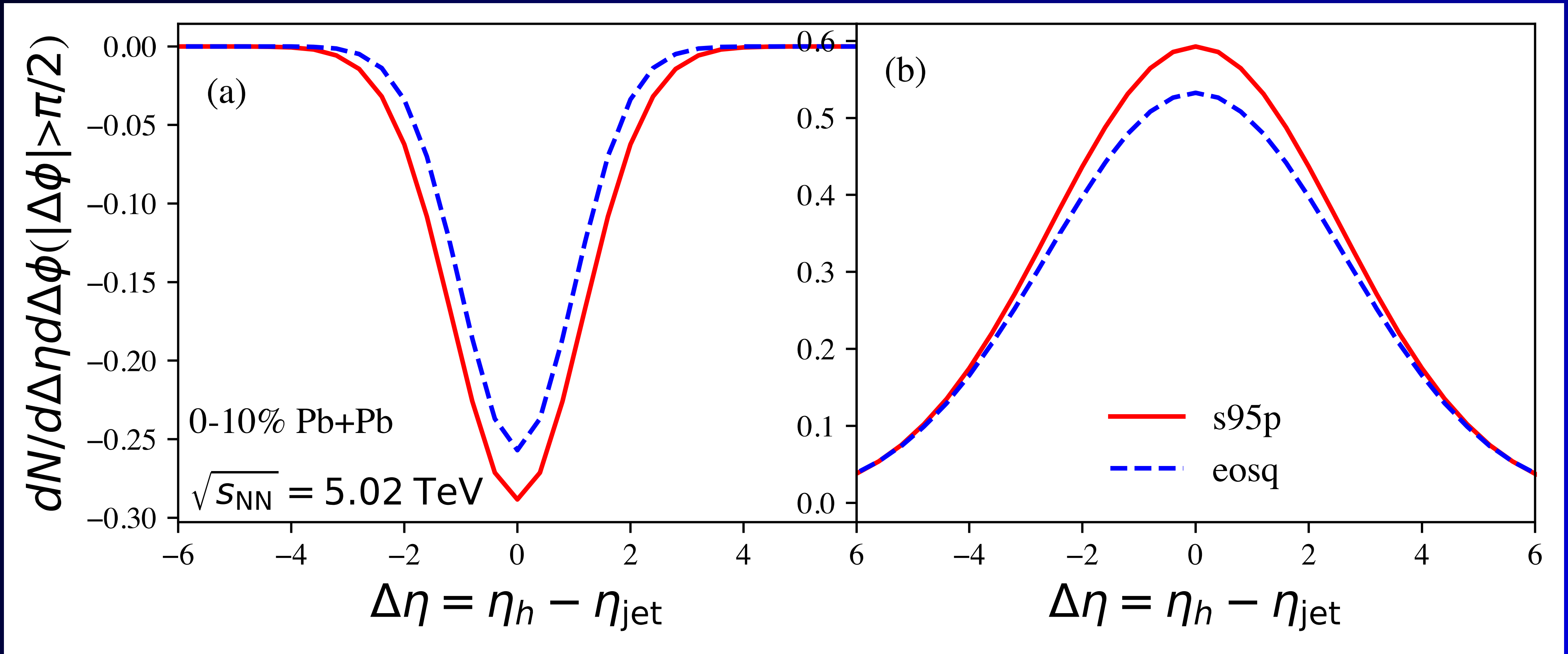


$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j)(F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)),$$

Jet-distr (F_3) — MPI (F_2) — DF-wake (F_1)

Diffusion wake and EoS

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



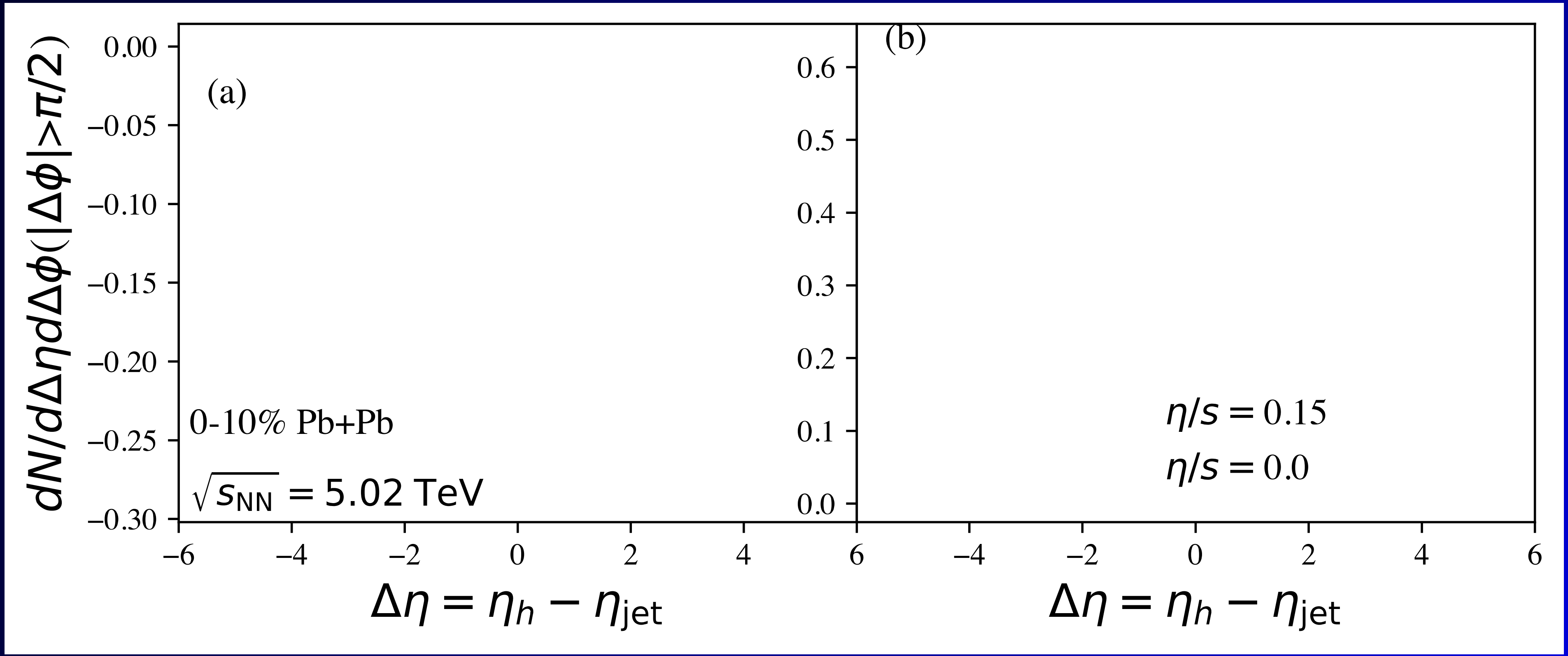
$$\langle c_s \rangle_{\mathrm{eosq}} > \langle c_s \rangle_{\mathrm{s95p}}$$

Hardening of spectra → reduction of soft hadron yield & DFW valley

Larger Mach cone angle → 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 → slows down longitudinal expansion → deepen DFW valley

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

η/s hardens hadron spectra→ reduction of soft hadron yield

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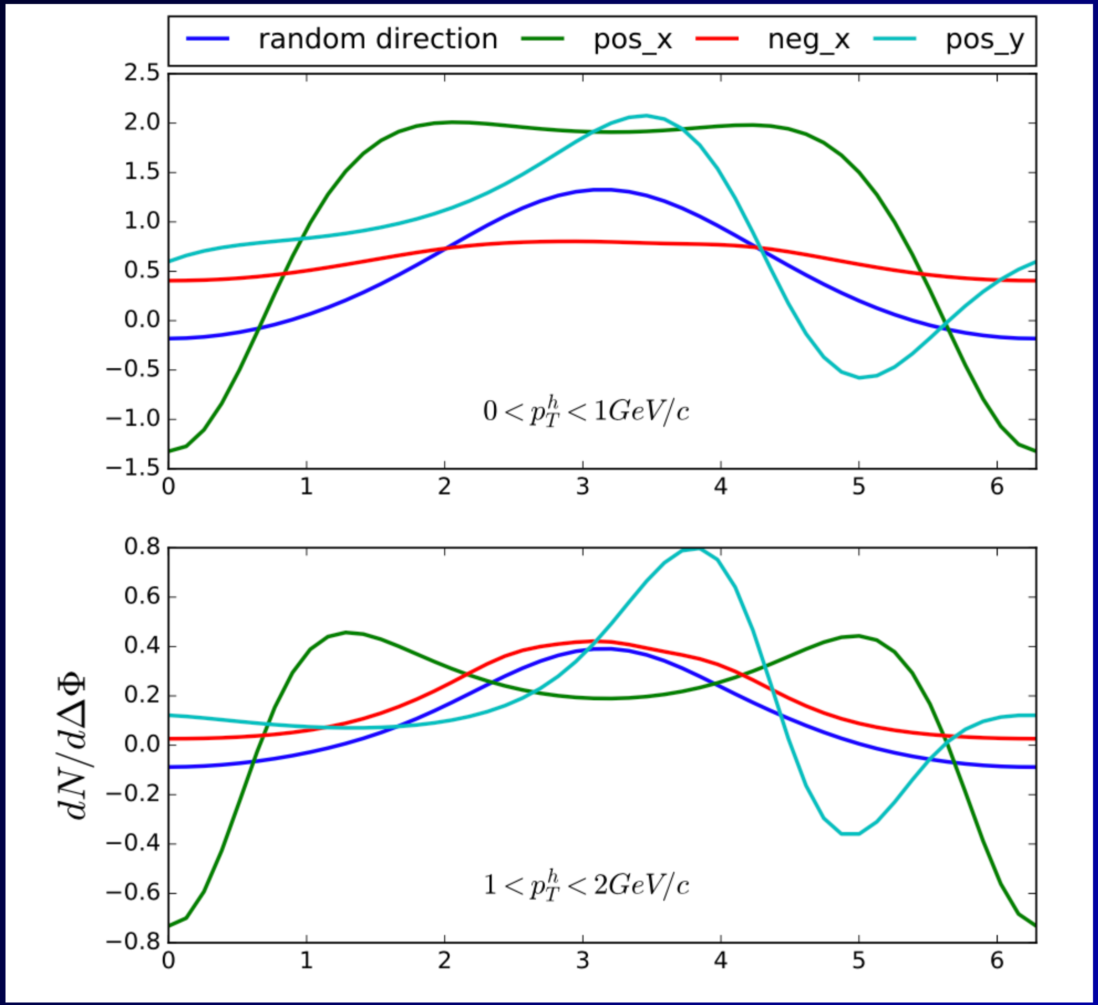
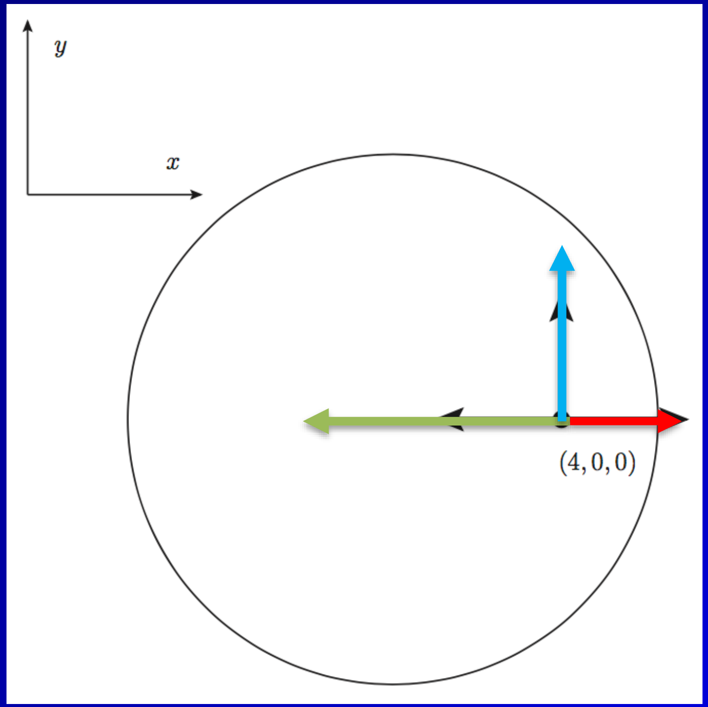
Initial position & azimuthal correlation



$\Delta\Phi$

γ-hadron correlation

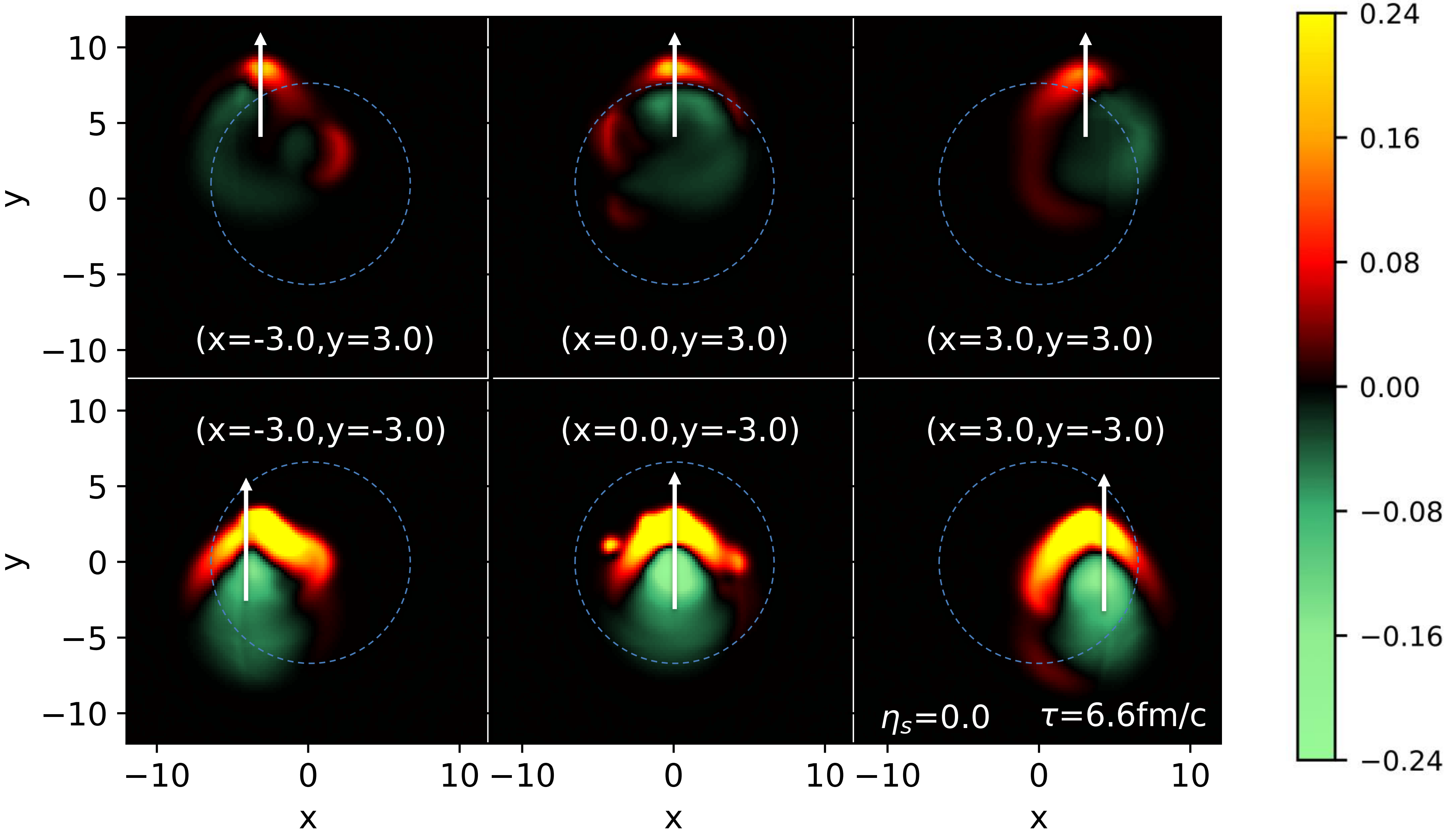


W Chen & XNW (2018)

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

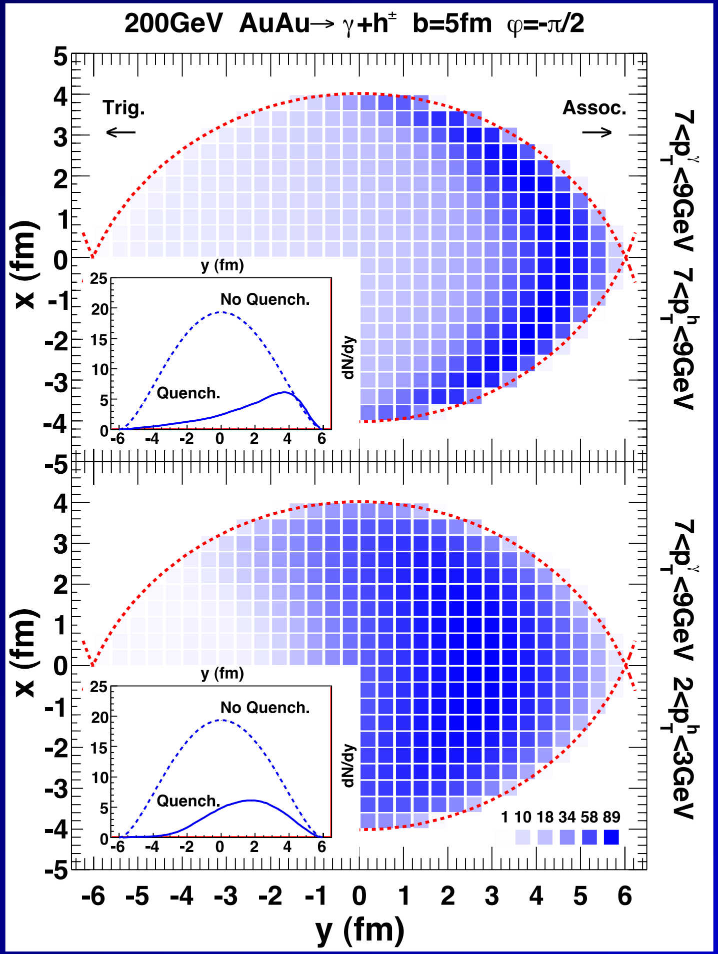
Longitudinal jet tomography

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

length dependence
of parton energy loss

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

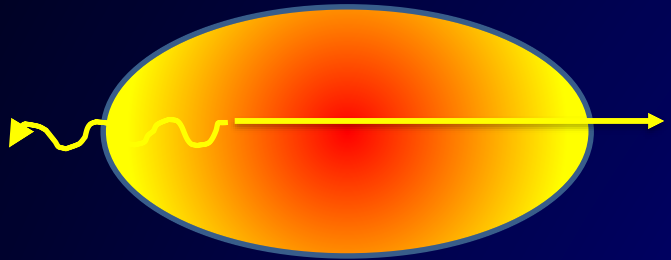
Can be used to select
propagation length <L>



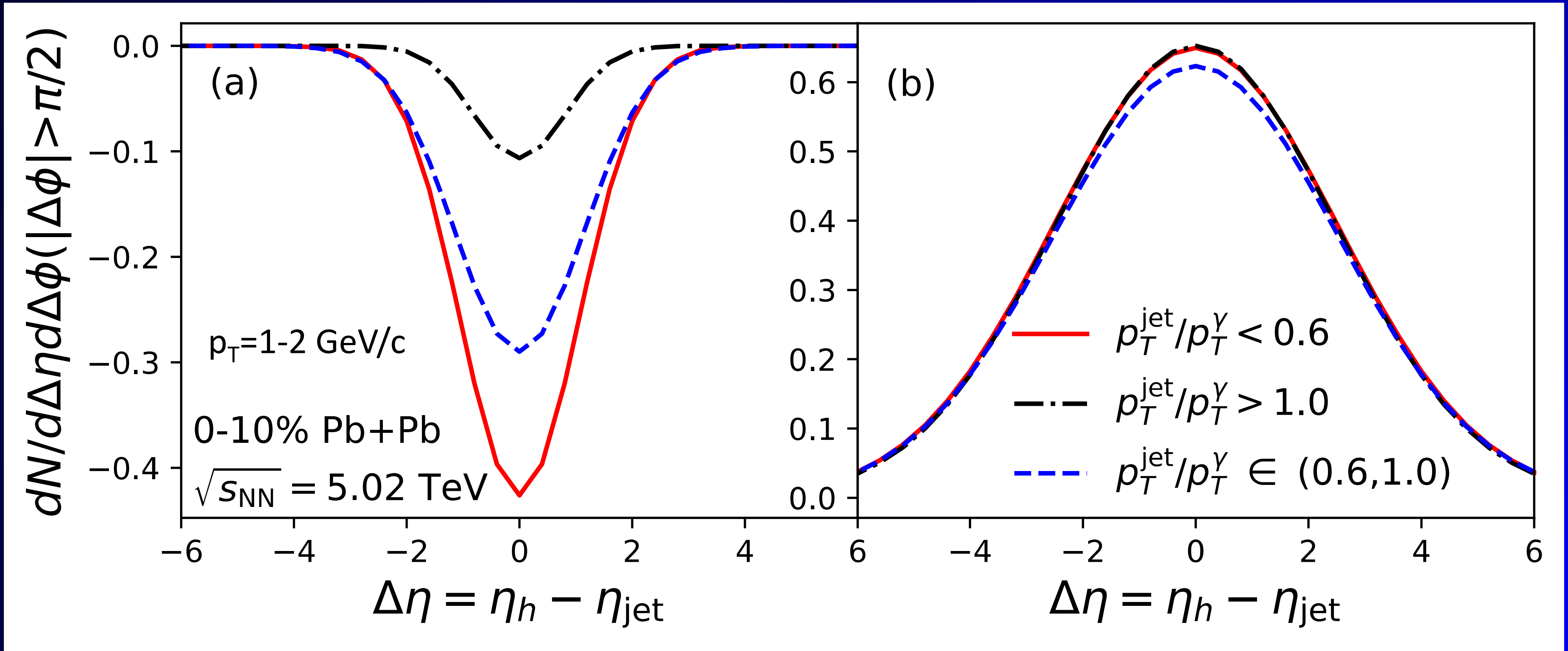
$p_T^h/p_T^\gamma \sim 1$

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

γ/jet asymmetry and diffusion wake



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



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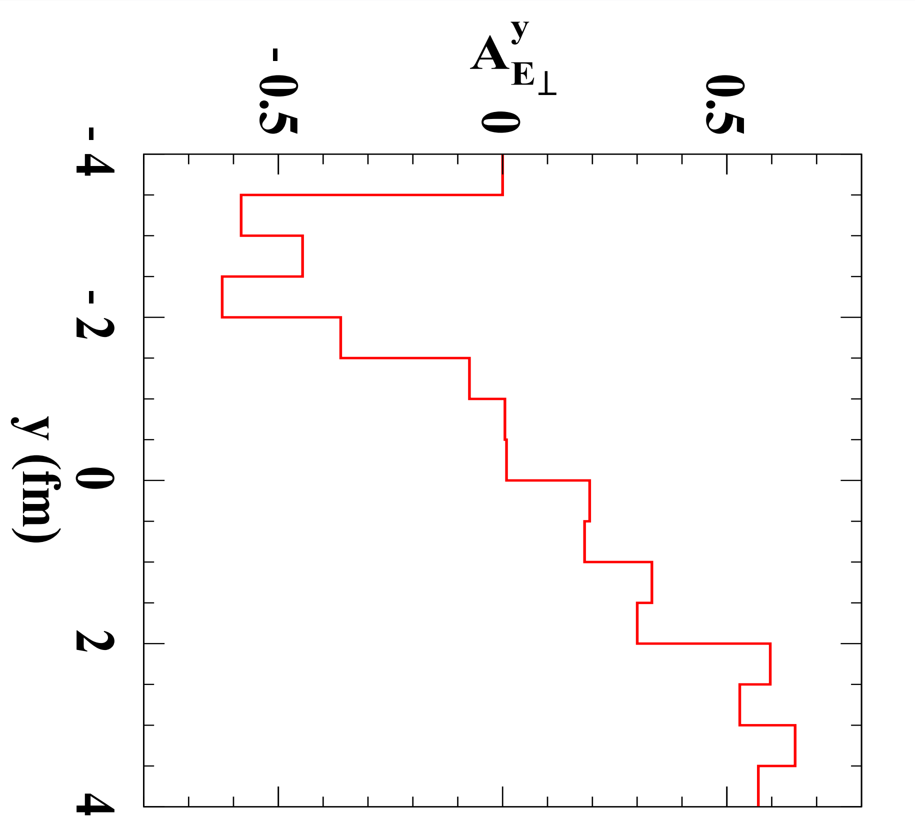
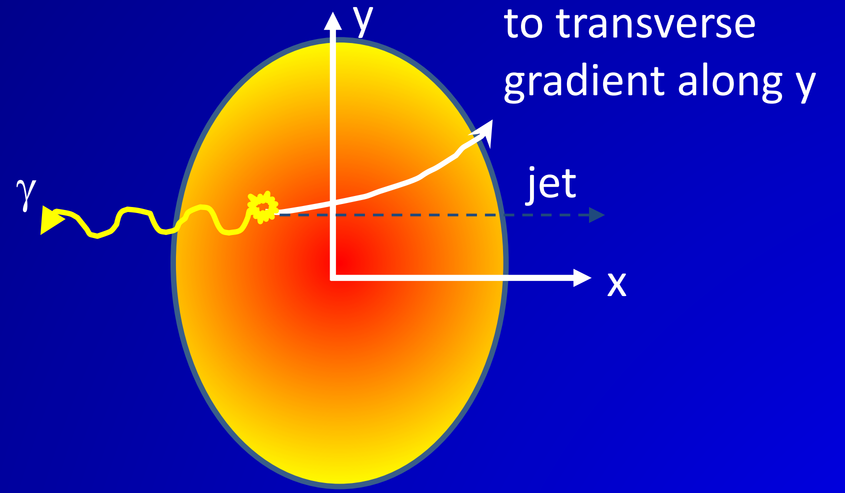
Transverse gradient tomography

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

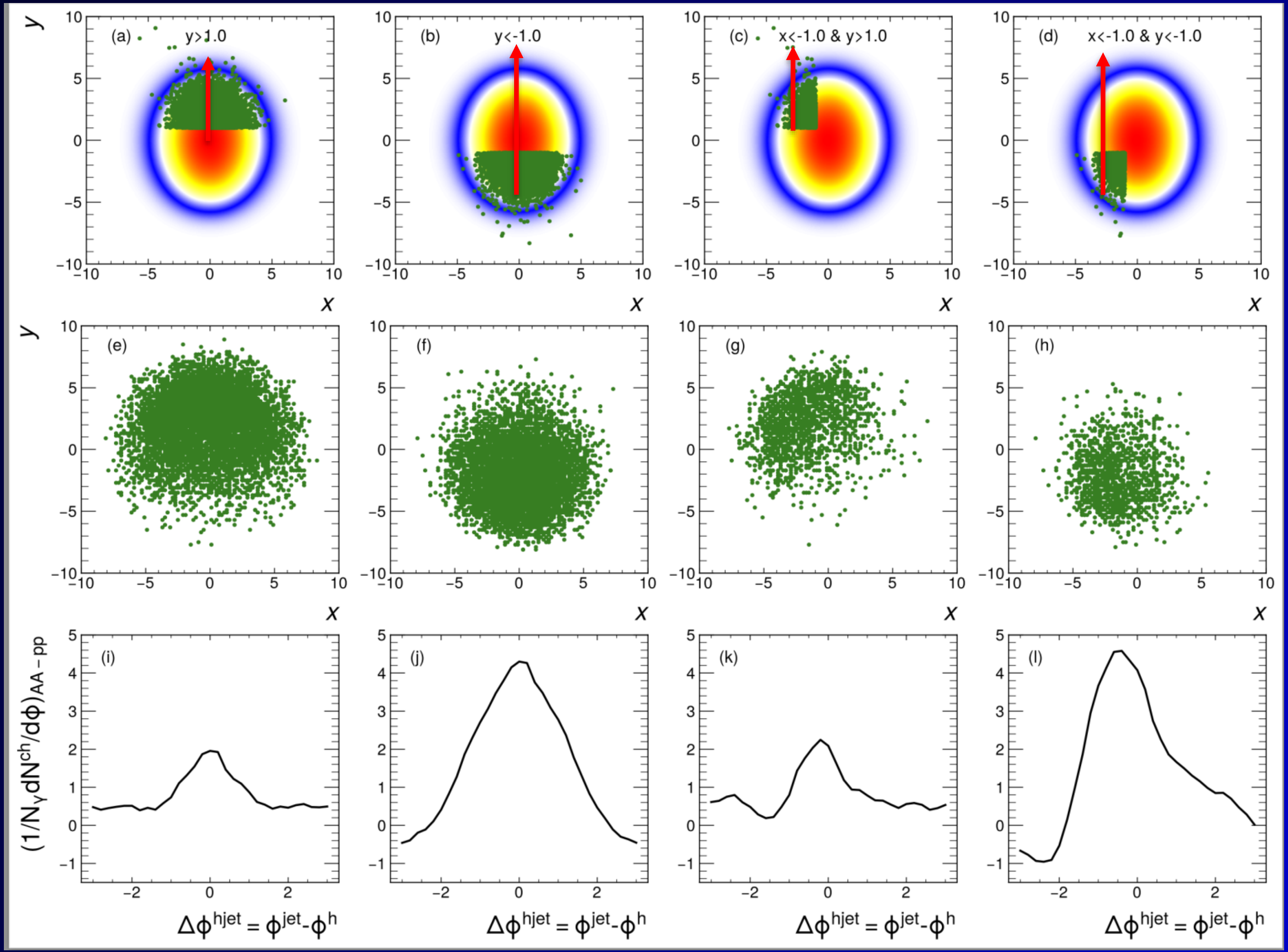
(p_T>3 GeV/c)





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

Deep learning assisted jet tomography



DL network selection

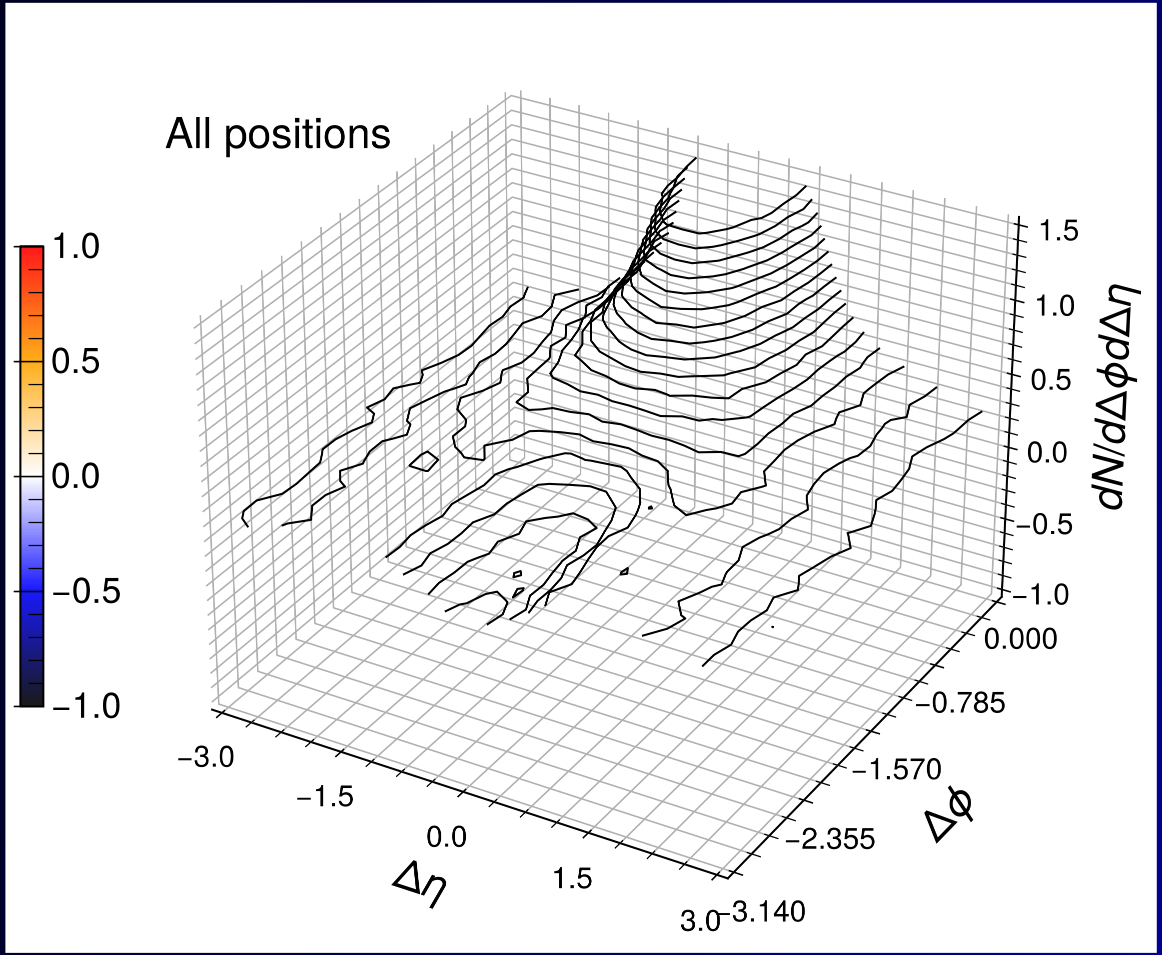
Actual distribution

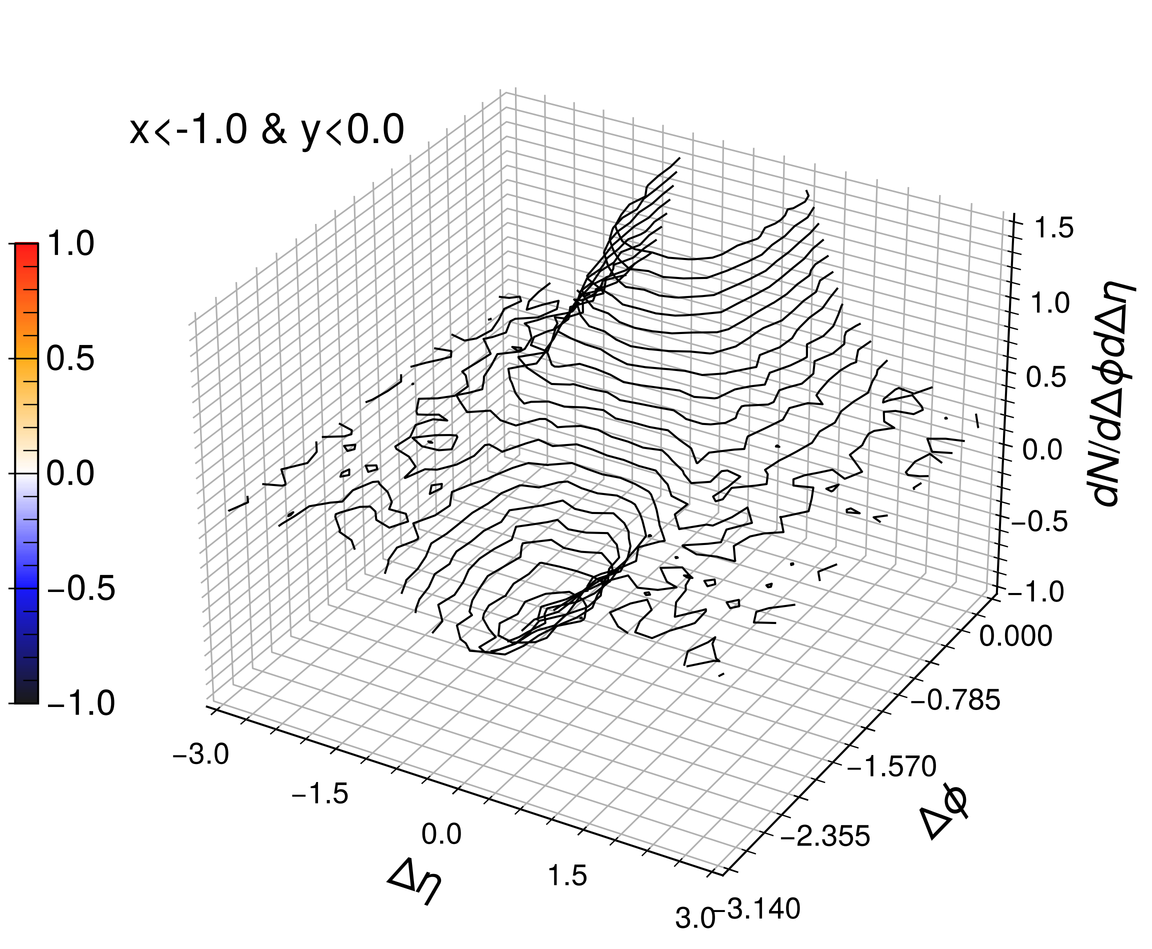
γ-soft hadron correlation

Yang, He, Chen, Ke, Pang and XNW, 2206.02393

p_T^γ=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



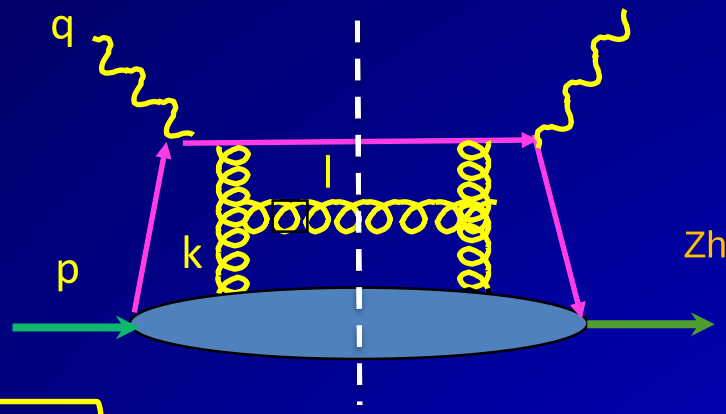


p_T^{γ}=200-250 GeV/c, p_T^{jet}>100 GeV/c, p_T^{h}=1-2 GeV/c in 0-10% Pb+Pb @ 5.02 TeV

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



Zhang & XNW (2021)

$1/\lambda_q$

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

medium TMD gluon distr.

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

→ GLV

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

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Parton energy loss and jet transport

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

(High-twist approach)

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

Elastic energy loss

Jet transport coefficient:

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

pQCD (BDMPS'96)
AdS/CFT (Liu,Rajagopal &Wideman'06)
lattice QCD (Majumder'12)

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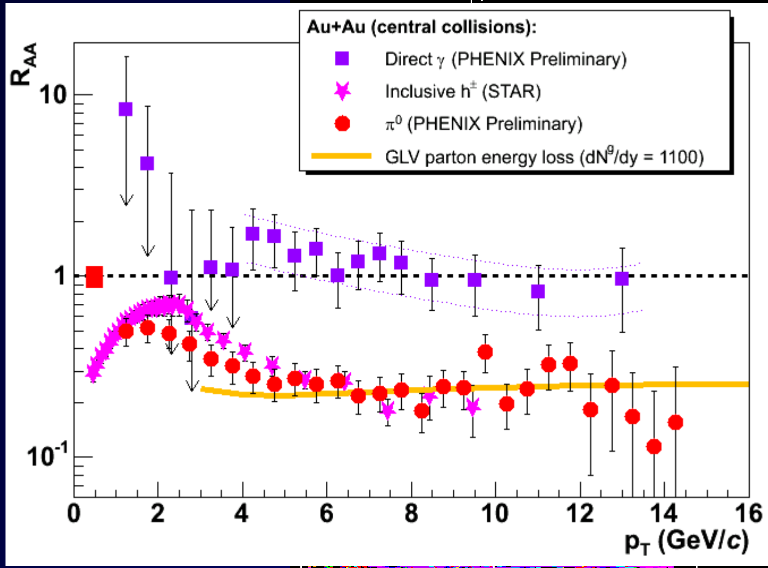
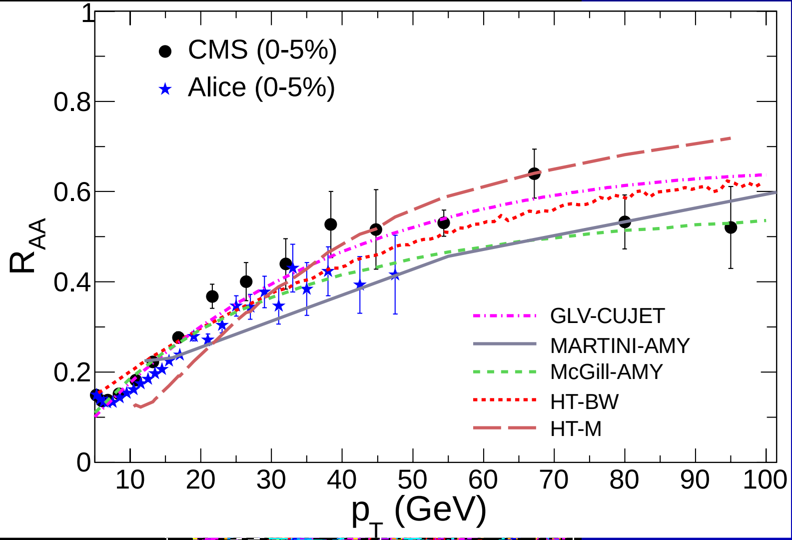
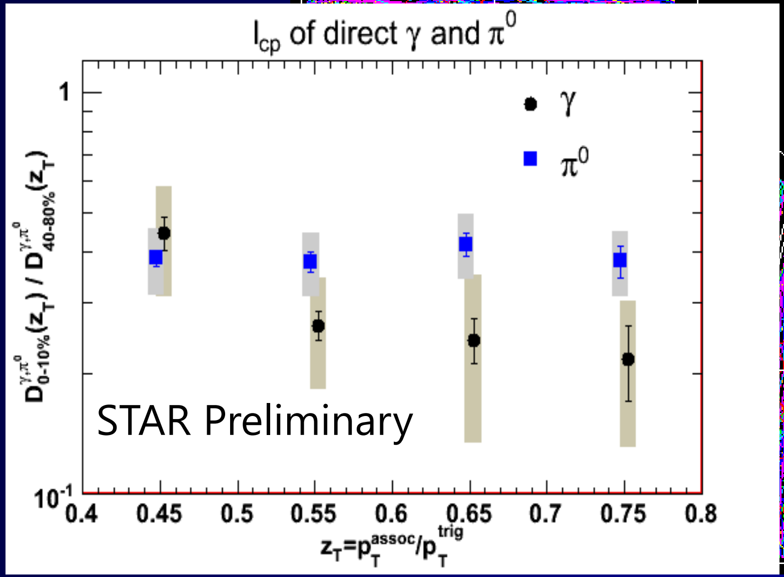
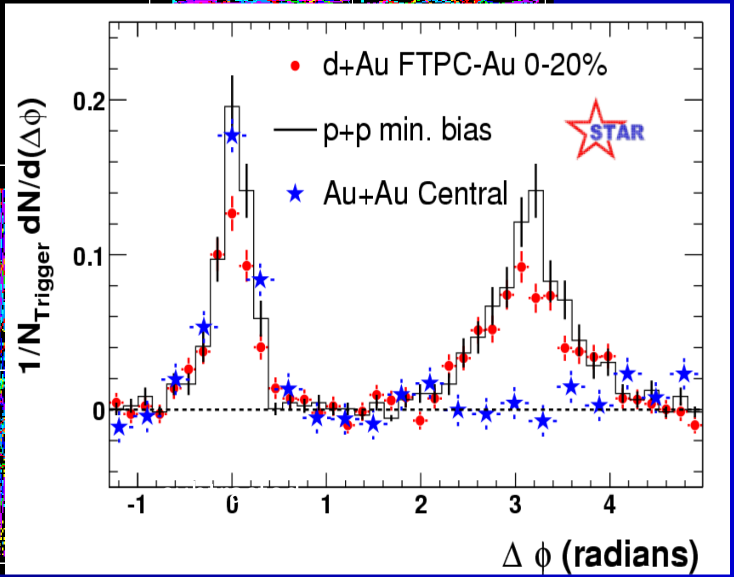
Jet Quenching phenomena at RHIC & LHC



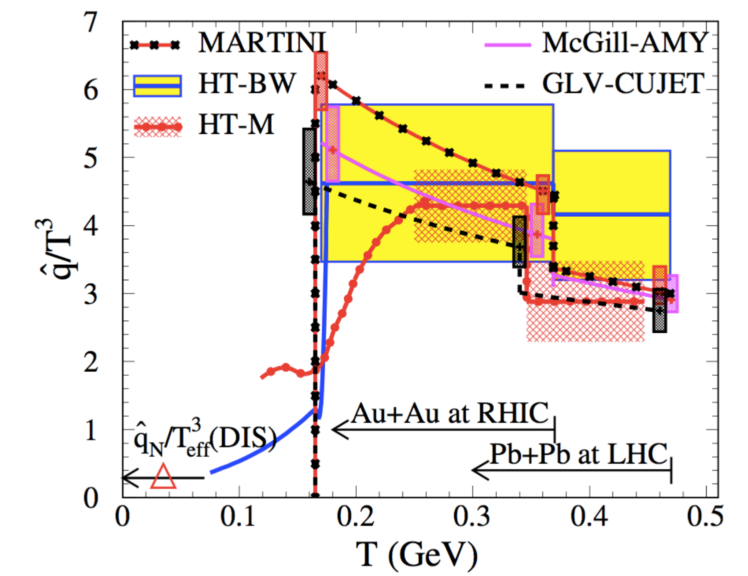






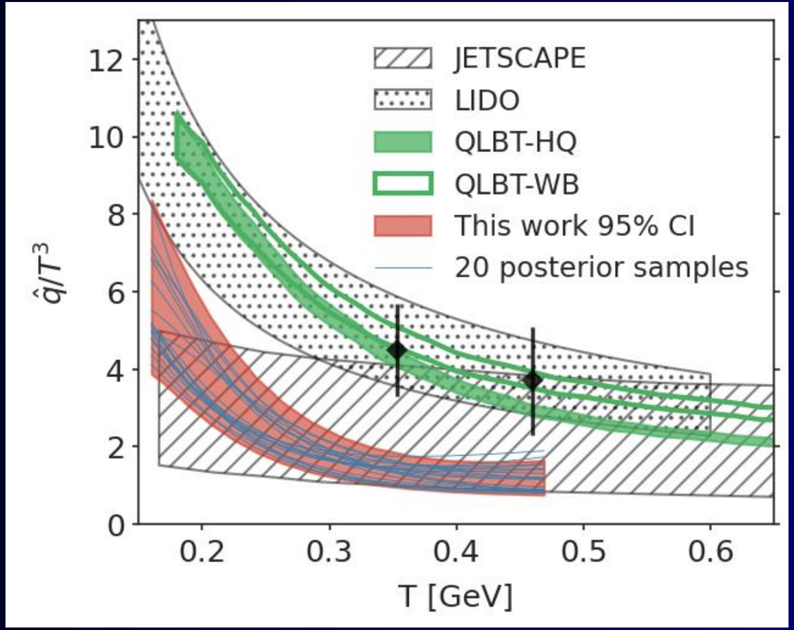
Jet Quenching at RHIC & LHC

JET Collaboration:
e-Print: 1312.5003



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

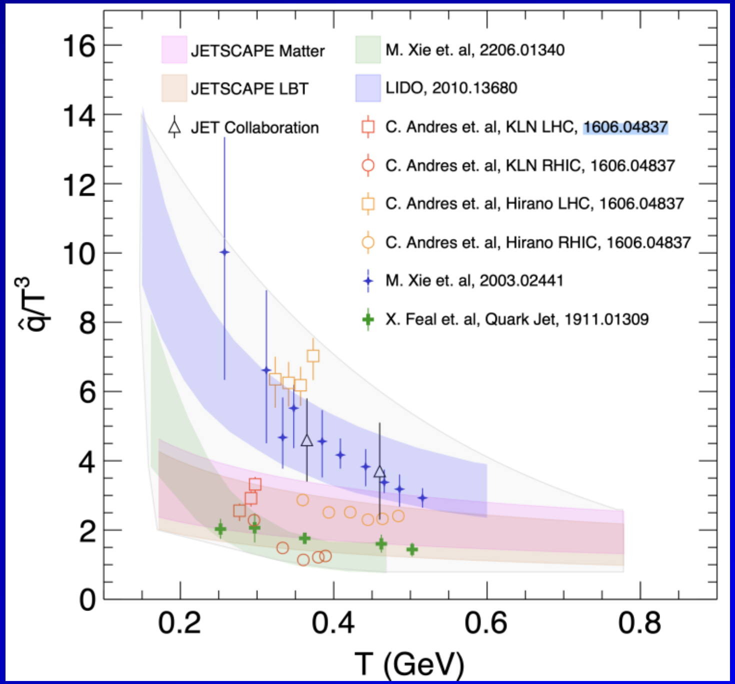
e-Print: 2206.01340



Xie, Ke, Zhang & XNW (2022)

Uncertainties reduced by IF Bayesian

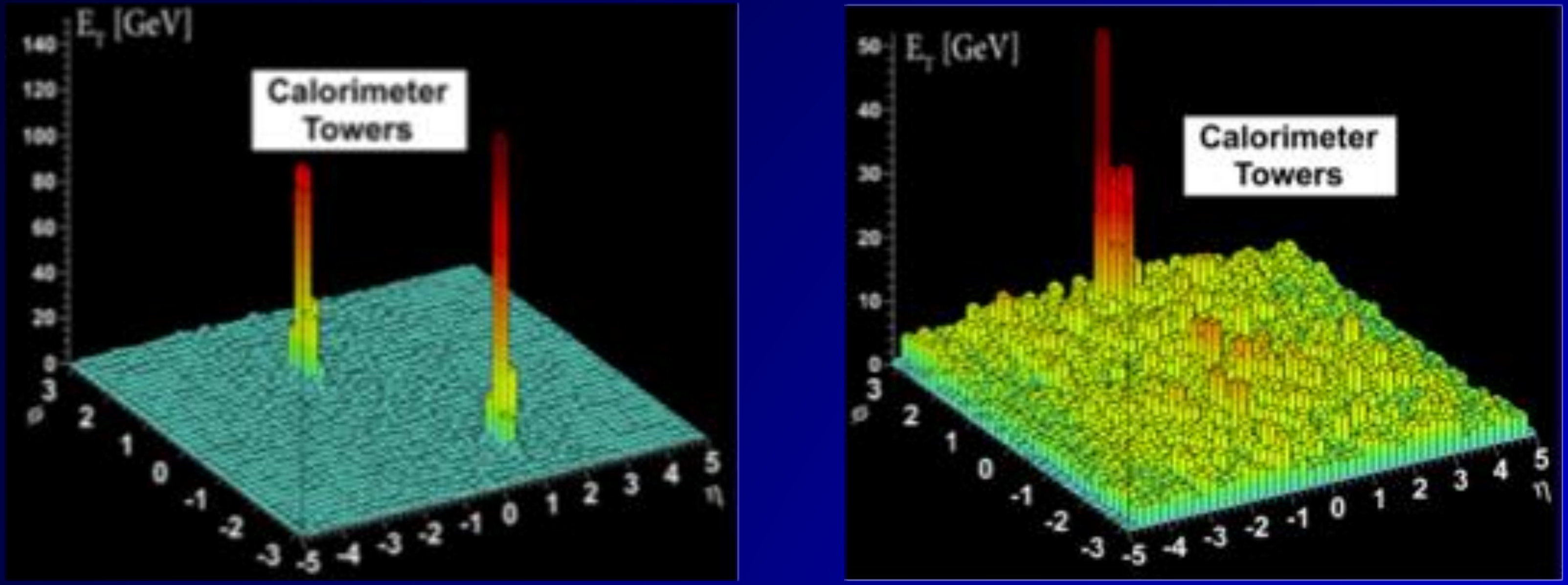
e-Print: 2203.16352



Apolinario, Lee & Winn

BERKELEY LAB

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

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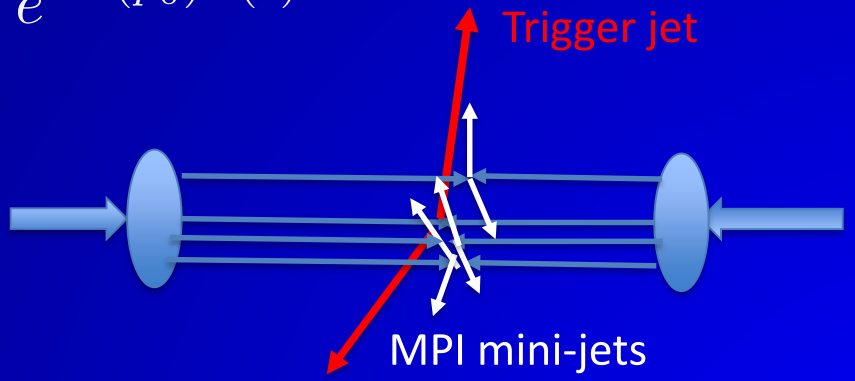
MPI: Multiple parton interaction

XNW & Gyulassy (1991)

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

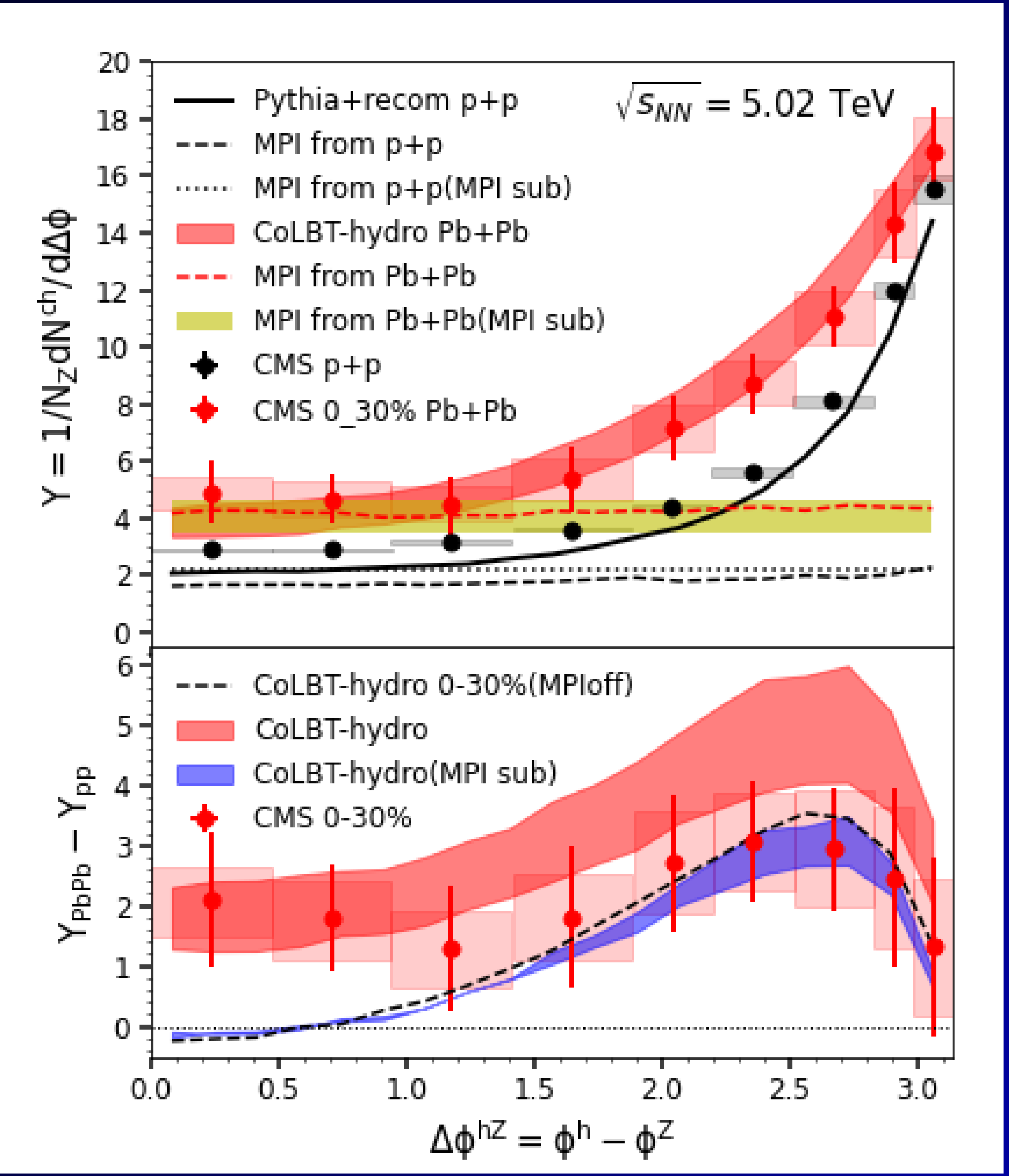
Probability of multiple jets ($p_T > p_0$) with at least one jet with $p_T > p_T^{trig}$

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



Enhanced multiple minijet
Production in triggered jet events
→ Azimuthal uncorrelated background from MPI

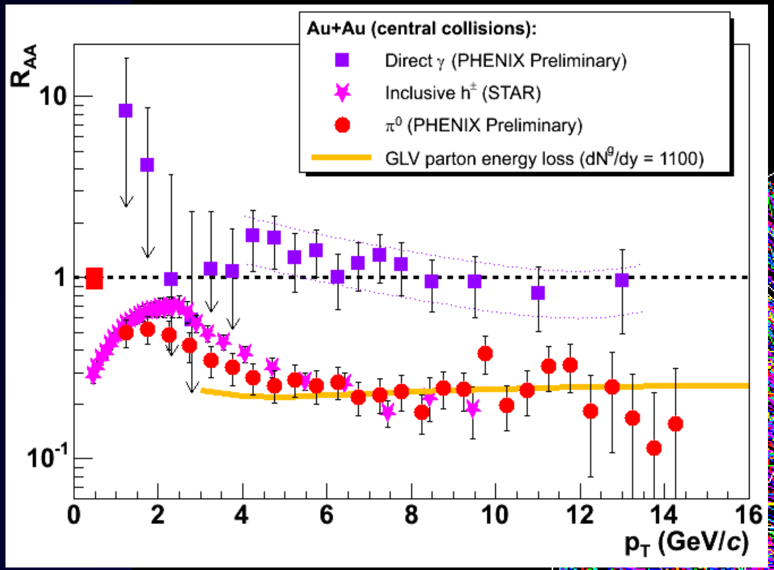
MPI subtraction in Z-hadron correlation

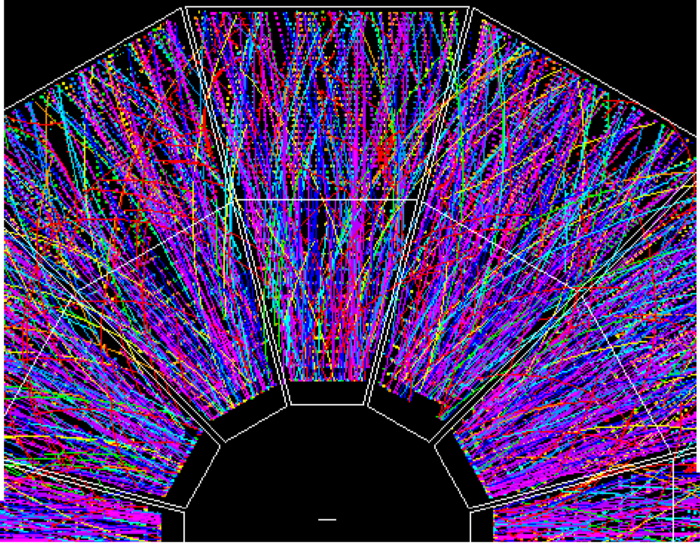


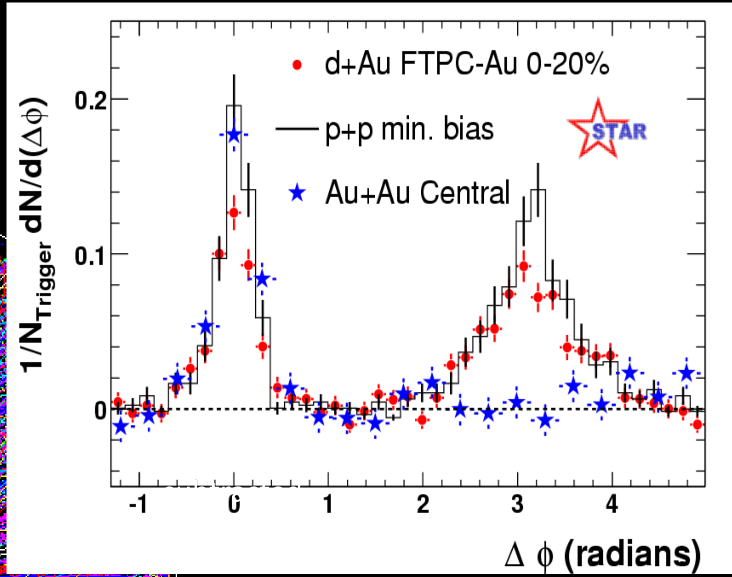
Mixed event subtraction

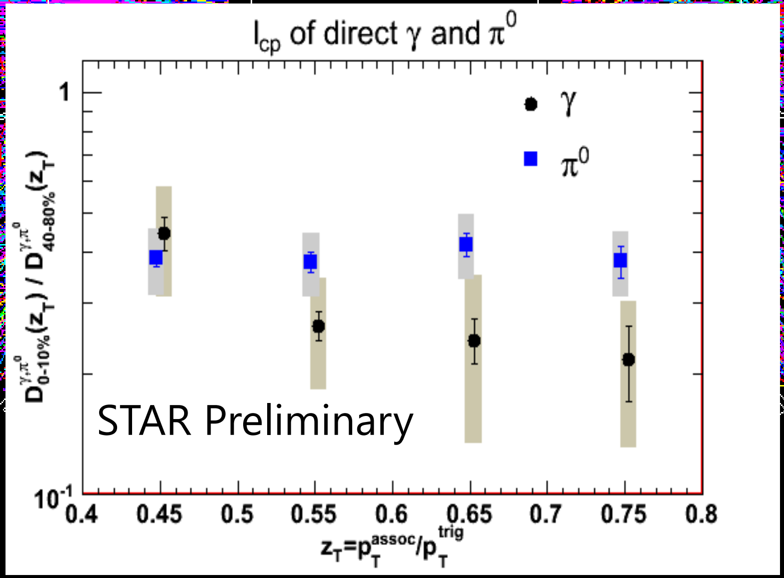
$$\frac{dN^{hZ}_{\rm MPI}}{d\phi} = \frac{dN^{hZ}_{\rm mix}}{d\phi} - \int_1^\pi \frac{d\phi}{\pi}\left(\frac{dN^{hZ}}{d\phi} - \frac{dN^{hZ}}{d\phi}|_{\phi=1}\right)$$

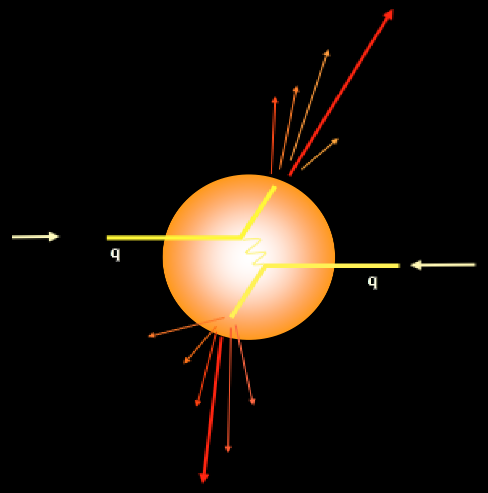
Jet Quenching phenomena at RHIC











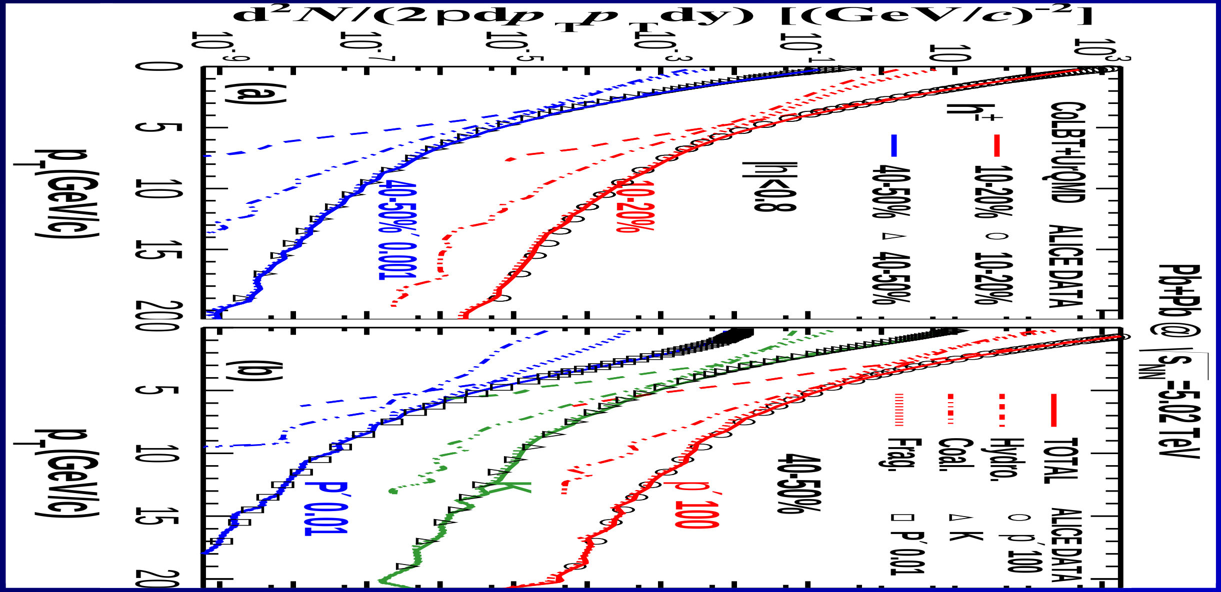
Hadron spectra from low to high p_T

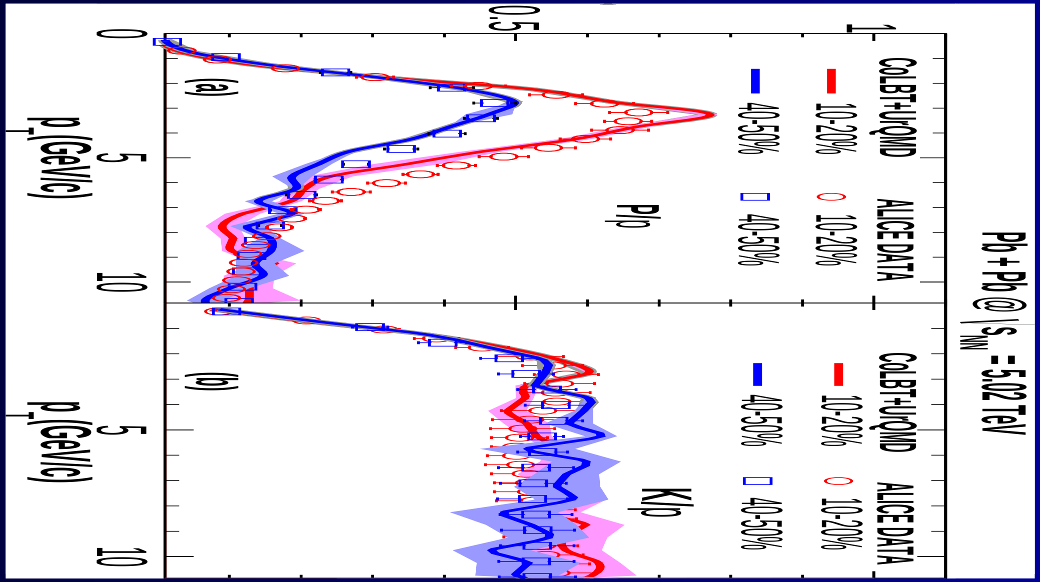
CoLBT-hydro:

Hydro : p_T<2 GeV/c

Coal.: 2<p_T<6 GeV/c

Frag.: p_T>5 GeV





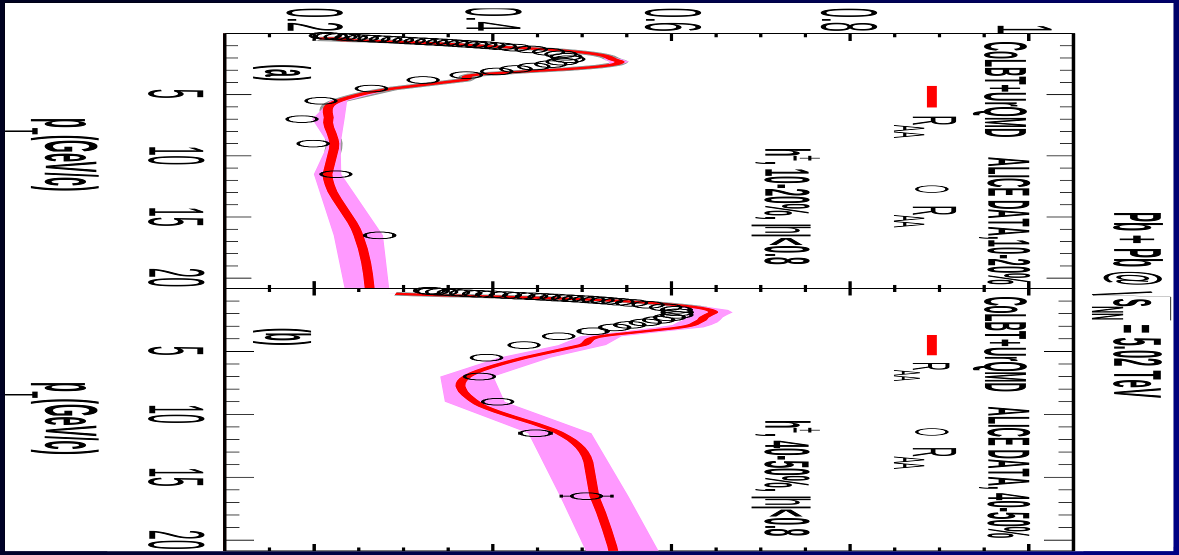
pT<2 GeV/c: radial flow

2<pT<6 GeV/c: coalescence

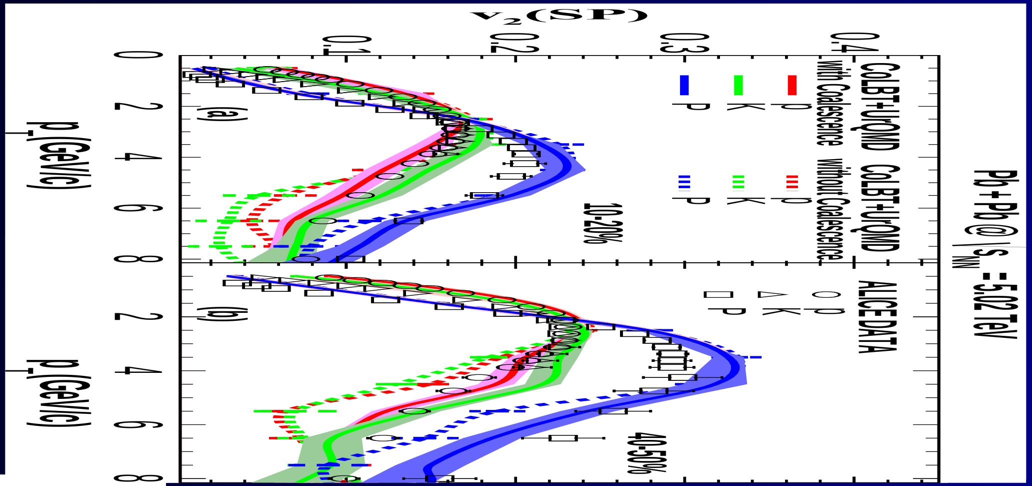
pT>10 GeV/c: energy loss

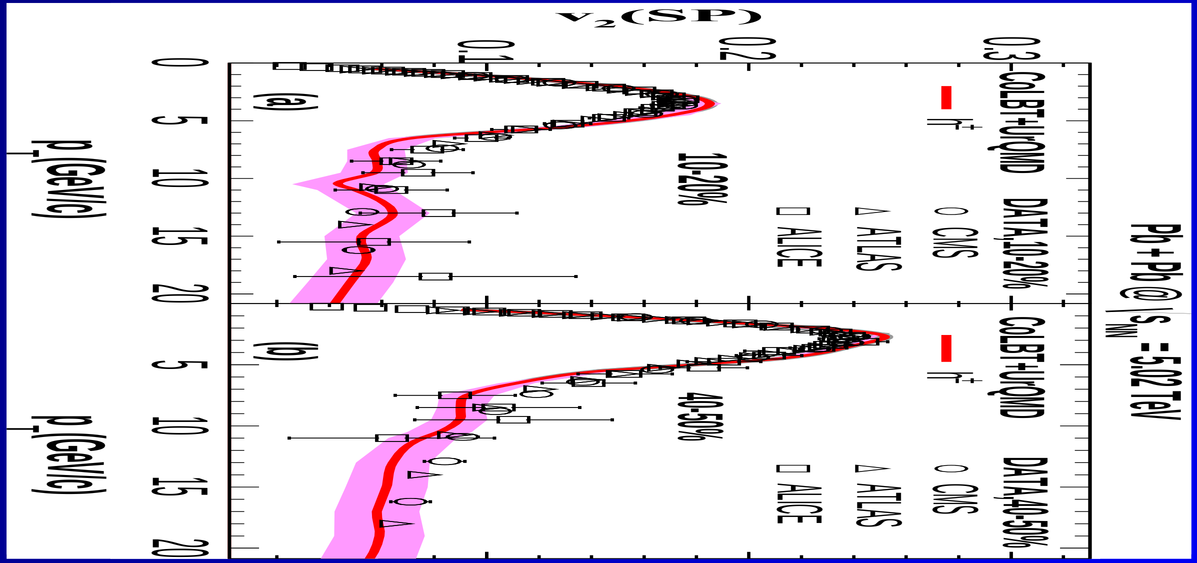
Zhao, Ke, Chen, Luo & XNW,
PRL 128 (2022) 2, 022302 (2103.14657)

Solving R_{AA}-v_2 puzzle



Zhao, Ke, Chen, Luo & XNW,
PRL 128 (2022) 2, 022302 (2103.14657)





Asymmetric-diffusion in nonuniform medium

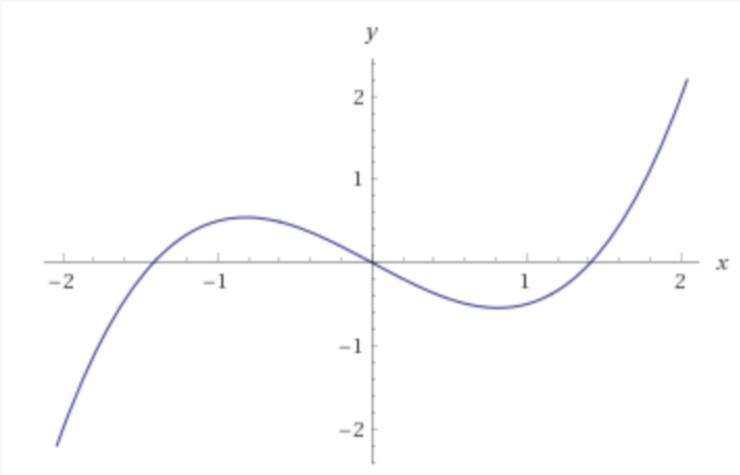
$$\frac{\partial f}{\partial t} + \frac{\vec{p}_\perp}{E} \cdot \frac{\partial f}{\partial \vec{r}_\perp} = \frac{\hat{q}}{4} \vec{\nabla}^2_{p_\perp} f(\vec{p}, \vec{r})$$

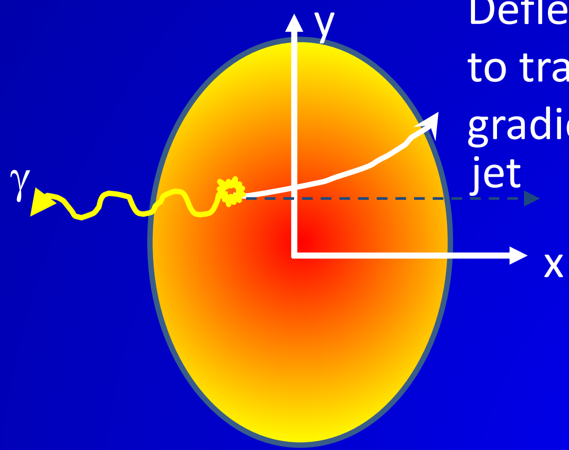
Boltzmann equation under approximation of small angle elastic scattering, no drag:

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

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

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

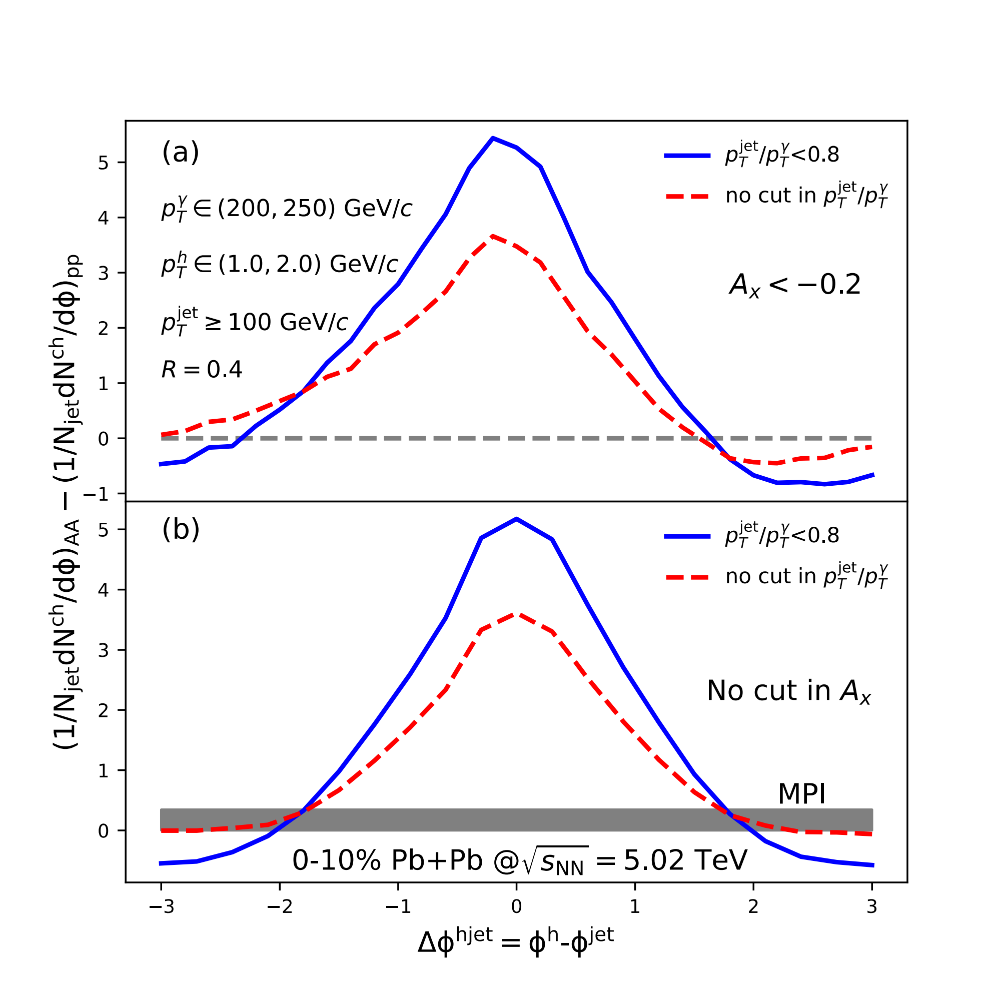


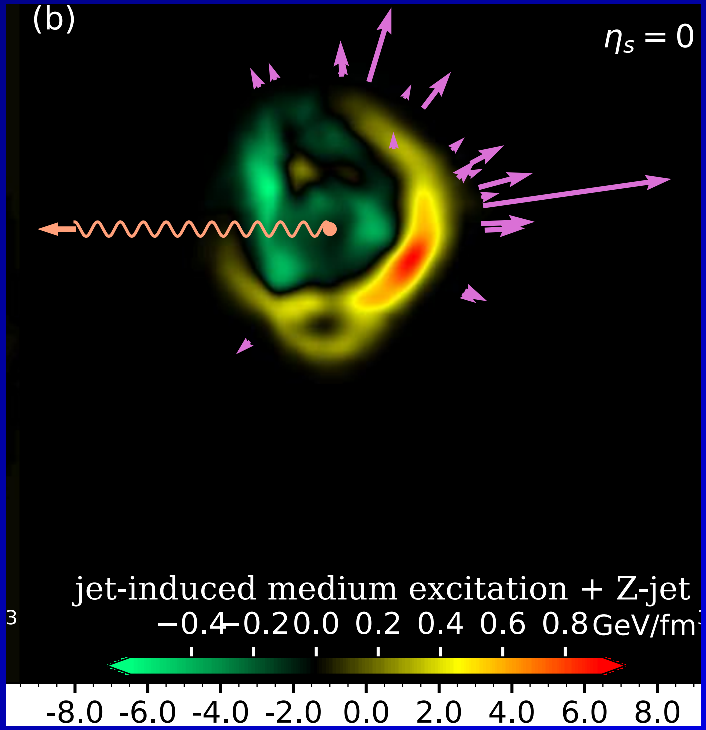


Deflection due to transverse gradient along y

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