ECT*, Trento, November 15-18, 2021

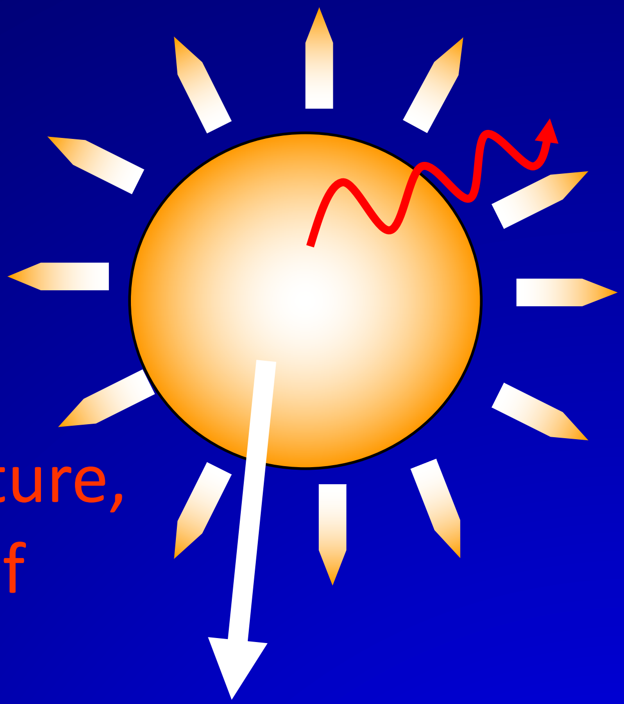
From jet quenching to recombination and hydrodynamics: solving R_{AA}-v_2 puzzle

In collaboration with: Wenbin Zhao, Weiyao Ke, Wei Chen and Tan Luo

Xin-Nian Wang (LBNL)

Properties of QGP in A+A Collisions

Dynamical System:



- Soft probes: collective flow - bulk properties, EoS, transport properties
- EM Probes: EM emission – Temperature, EM response, medium modification of resonances
- Hard probes: Jet quenching – Jet transport coefficients

Collective flow of QGP

- Hydrodynamics: $\partial_\mu T^{\mu\nu} = 0$

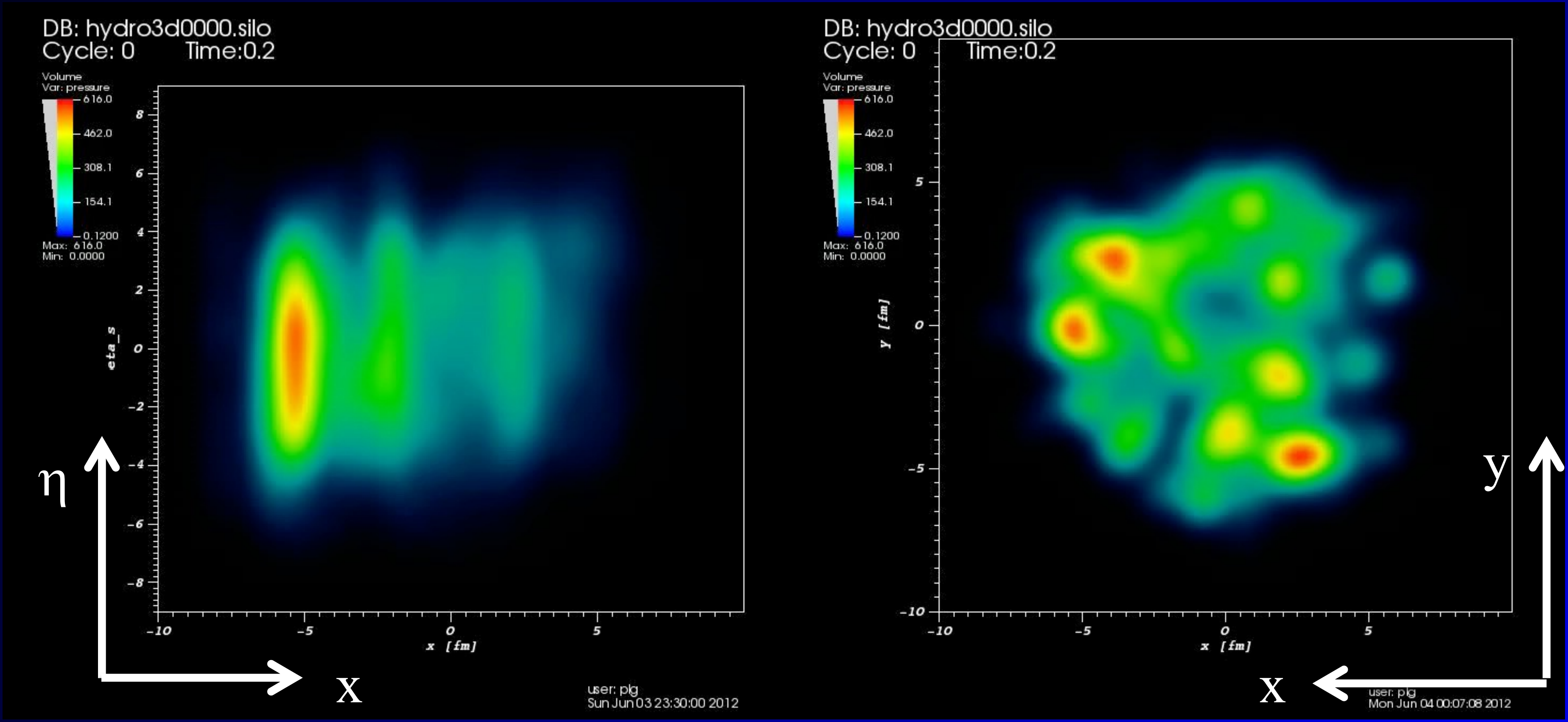
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Delta T^{\mu\nu}$$

$$\Delta T^{\mu\nu} = \eta(\Delta^\mu u^\nu + \Delta^\nu u^\mu) + (\frac{2}{3}\eta - \zeta)H^{\mu\nu}\partial_\rho u^\rho$$

  - a low-momentum effective theory
  - Inputs from first principle QCD (lattice QCD) EoS p(ε), transport coefficients ξ(T), ζ(T)
  - Initial condition: parton prod. & thermalization

Anisotropic hydro expansion

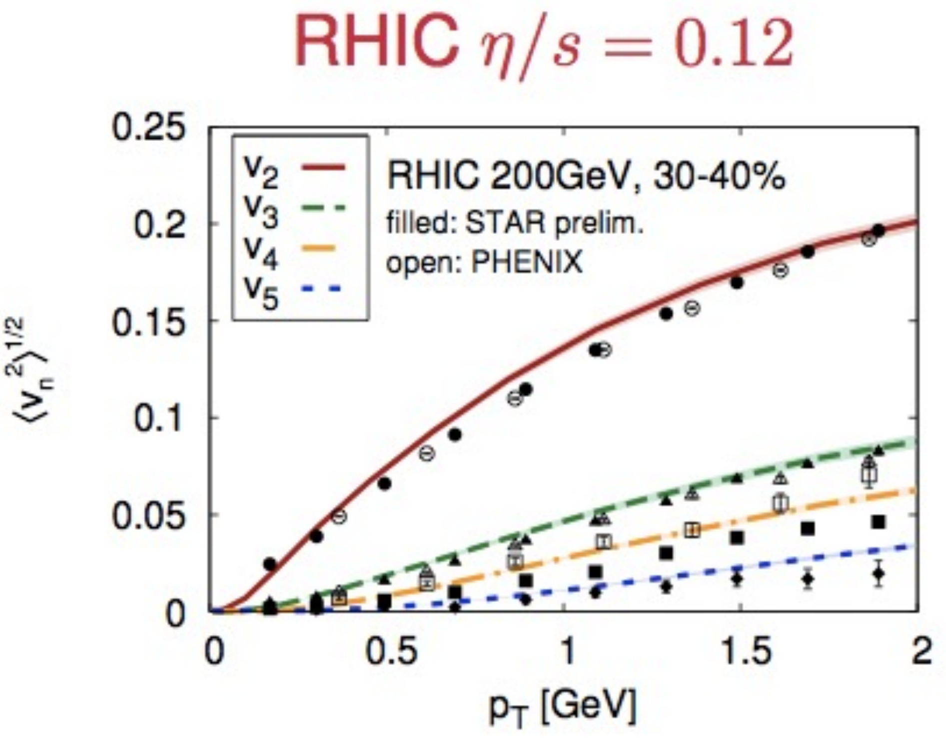
with 3D fluctuating initial conditions



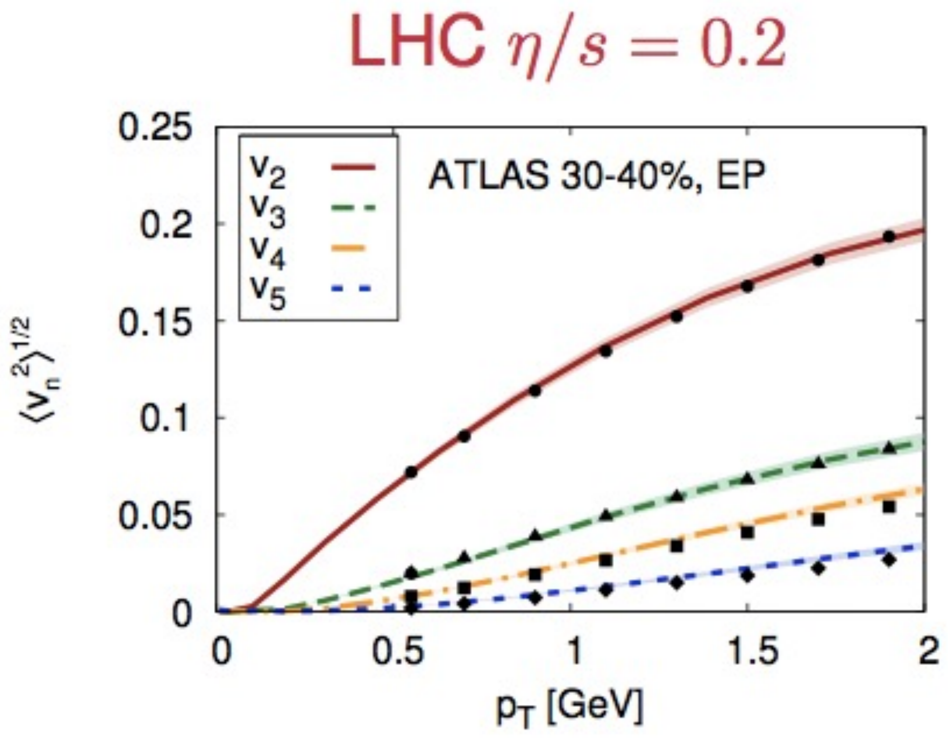
(3+1)D ideal hydro with AMPT initial condition (Pang & XNW'13)

Viscosity of QGP in A+A collisions

Heinz & Song 2010



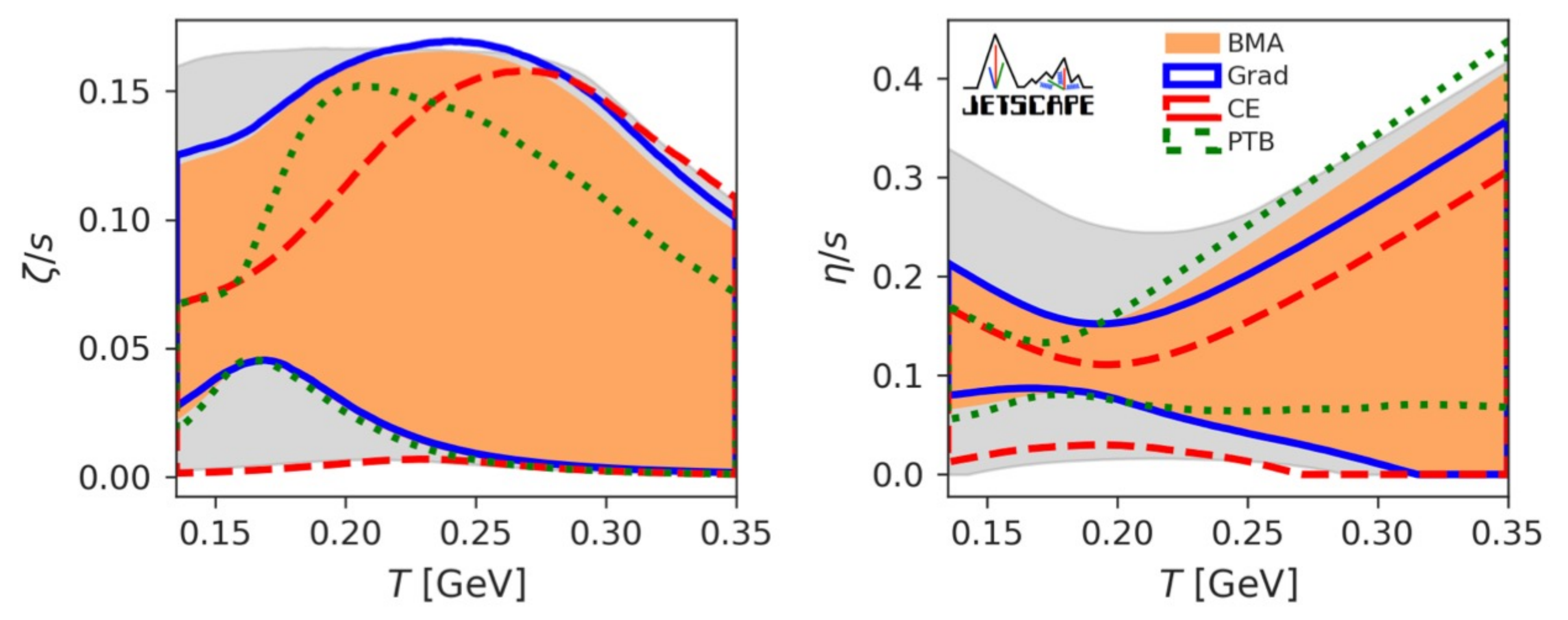
Gale, Jeon, Schenke, Tribedy & Venugopalan 2013



Fluctuation + viscous hydro required to fit all v_n

Viscosity at LHC is larger than at RHIC

Extraction of bulk transport coefficients



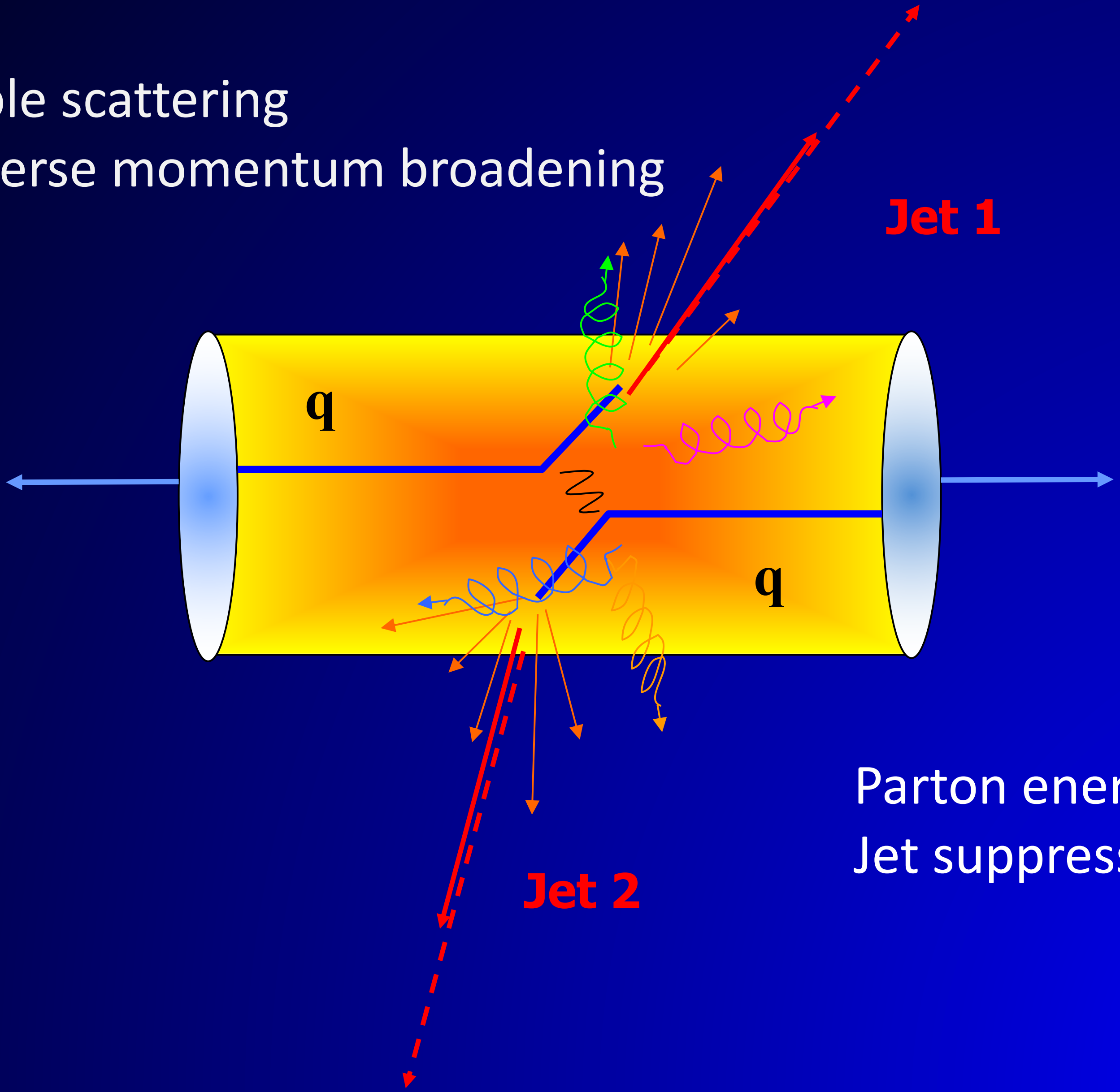
Constraints with Bayesian inference

JETSCAPE, Phys. Rev. Lett. 126, no.24, 242301 (2021)

Jets in heavy-ion collisions

Multiple scattering

Transverse momentum broadening



Parton energy loss

Jet suppression

Parton energy loss and jet transport

$$\frac{dE_{rad}}{dx} \approx \frac{\alpha_s N_c}{4} \hat{q} L$$

Radiative energy loss (BDMPS'96)

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

Elastic energy loss

Jet transport coefficient:

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

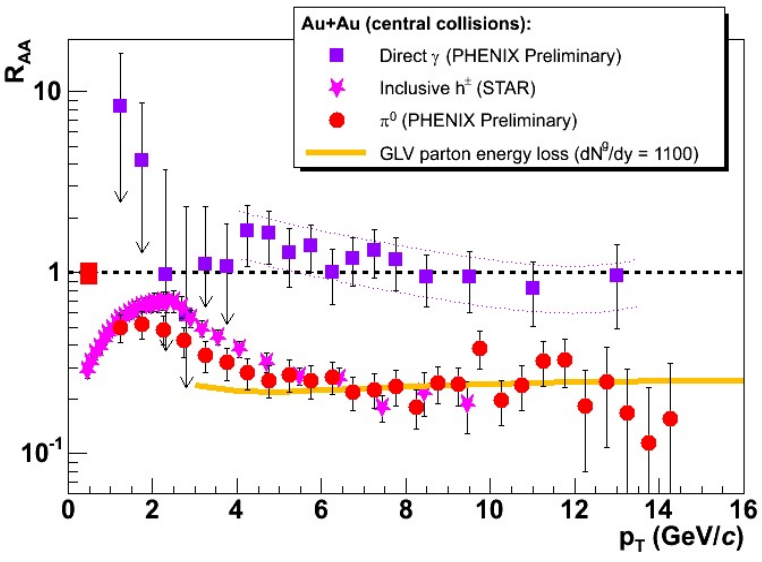
pQCD (BDMPS'96)

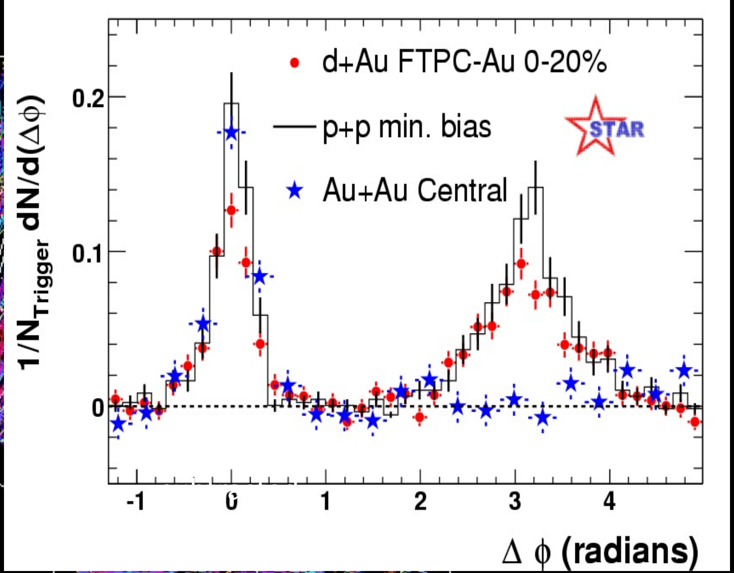
AdS/CFT (Liu,Rajagopal &Wideman'06)

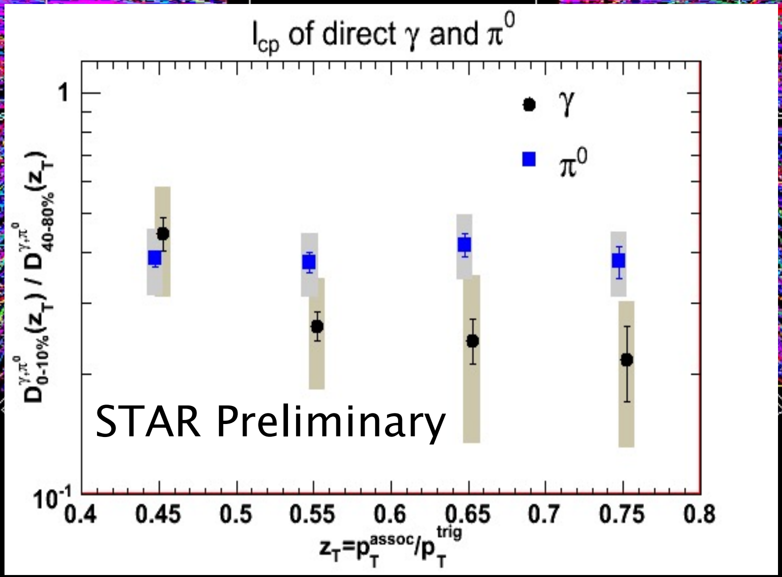
lattice QCD (Majumder'12)

Extract jet transport coefficient from parton energy loss

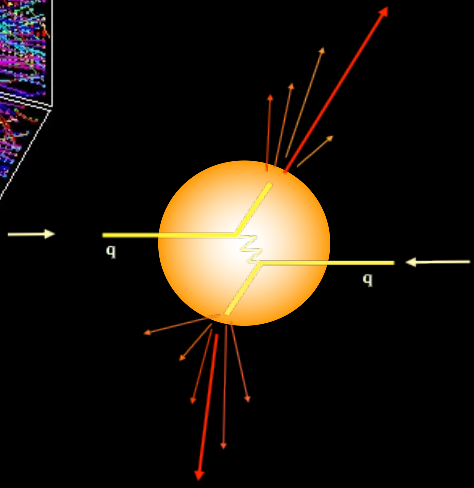
Jet Quenching phenomena at RHIC



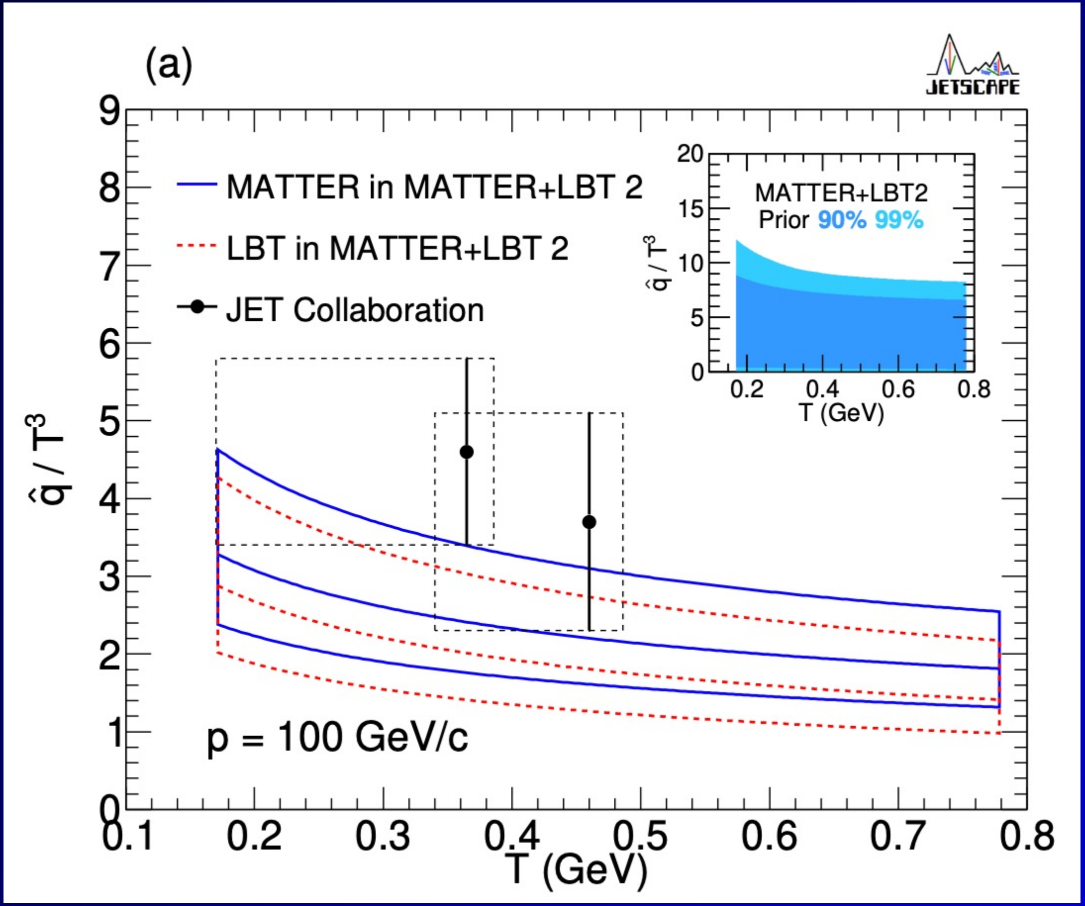




STAR Preliminary

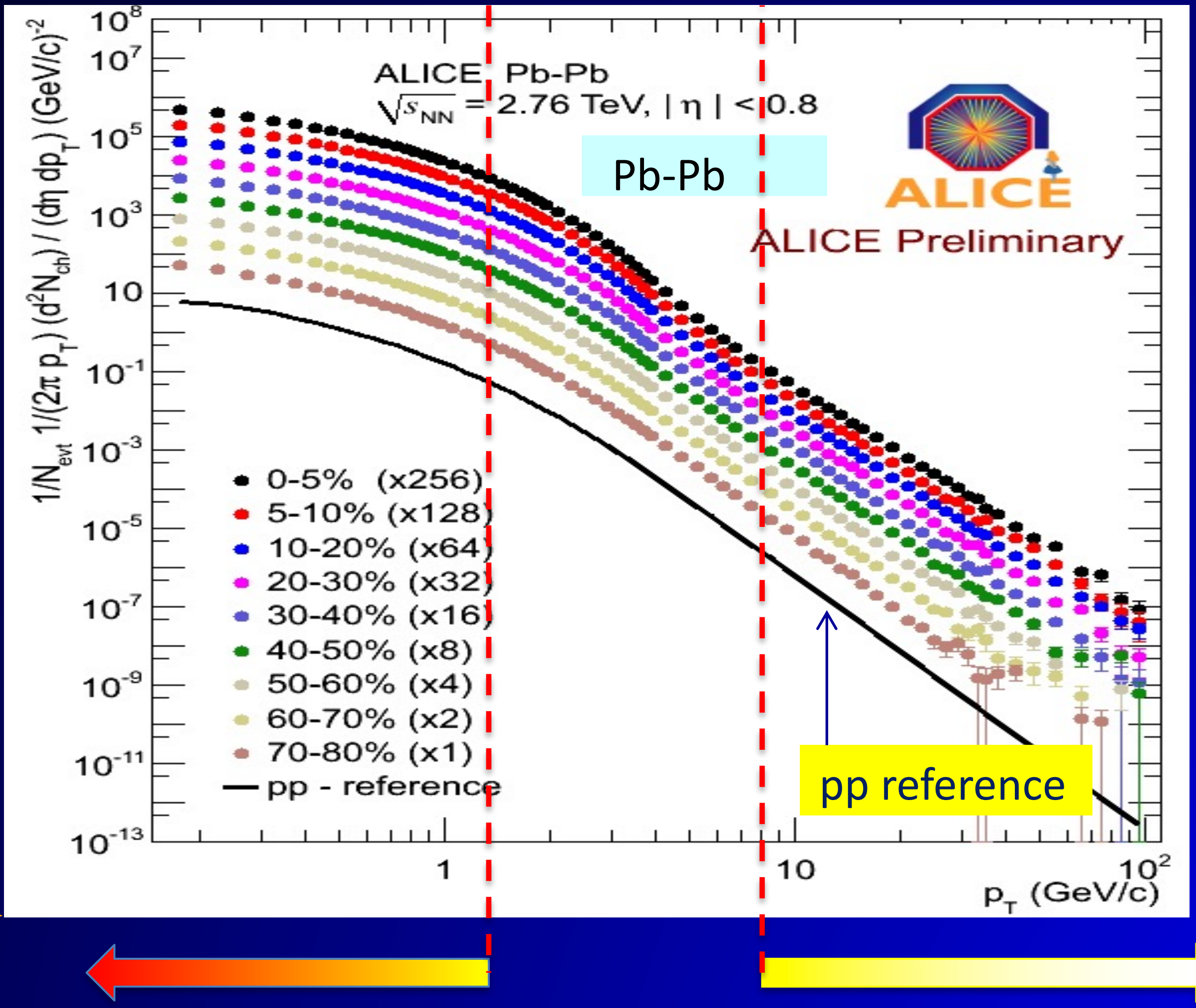


Extraction of jet transport coefficient



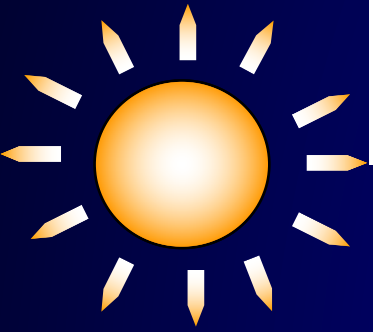
JET: *Phys.Rev.C 90 (2014) 1, 014909*
JETSCAPE: 2102.11337

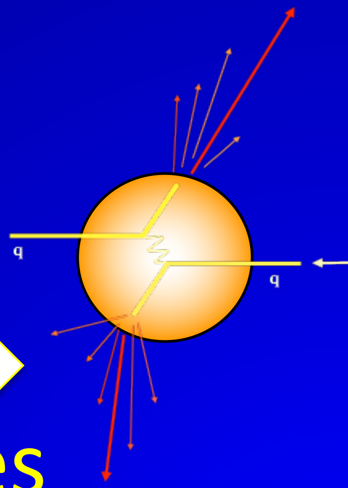
Parton energy loss & medium response



Pb-Pb

pp reference





soft response

hard probes

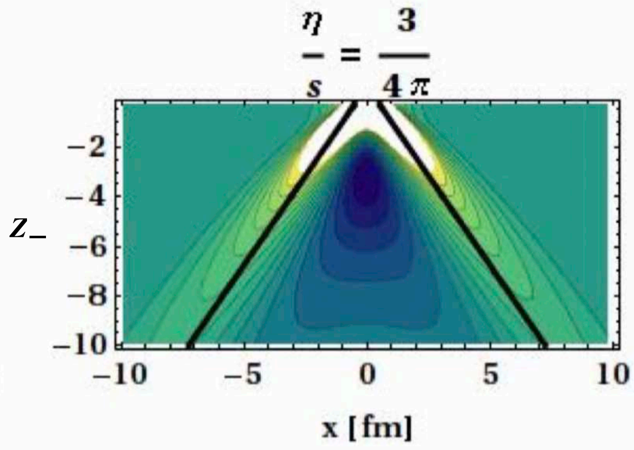
Physics at Intermediate pT

Jet-induced medium excitation

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

Jet induced Mach-cone in QGP

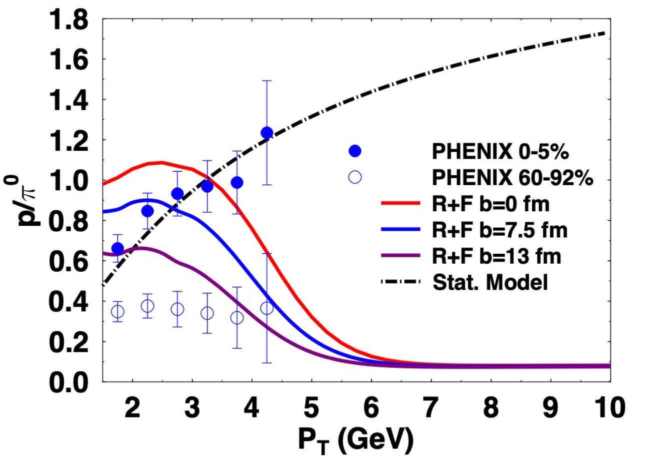
$$v = p/E > c_s$$



Ruppert & Muller (2005)

Parton recombination

Bayron/meson ratio,
NCQ scaling of v2



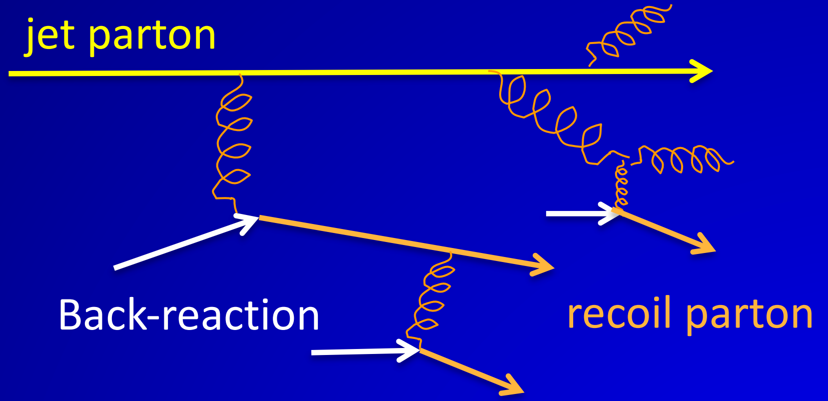
Fries, Muller, Nonaka and Bass, Phys. Rev. C 68, 044902 (2003)

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

- pQCD elastic and radiative processes (high-twist)
- Transport of medium recoil partons (and back-reaction)



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

CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

Concurrent and coupled evolution of bulk medium and jet showers

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

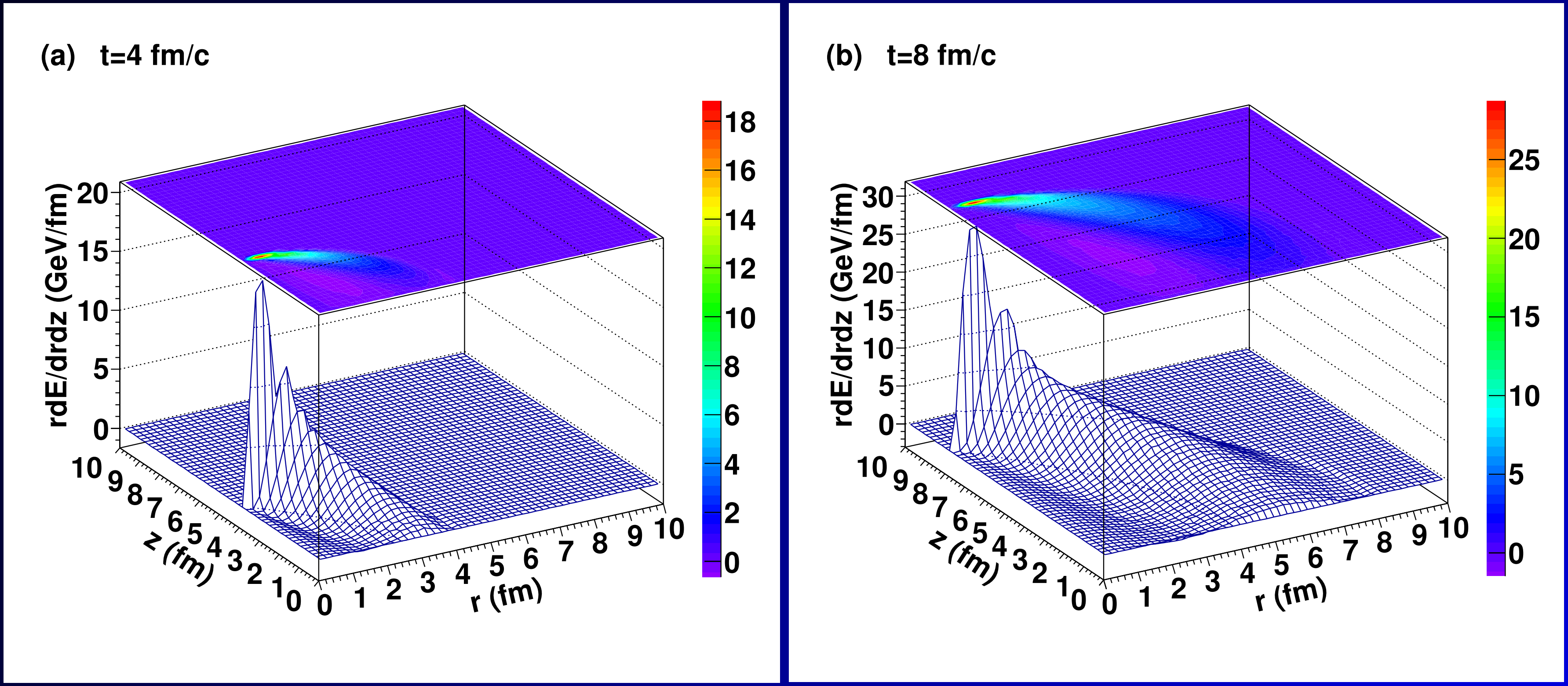
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

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

- 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

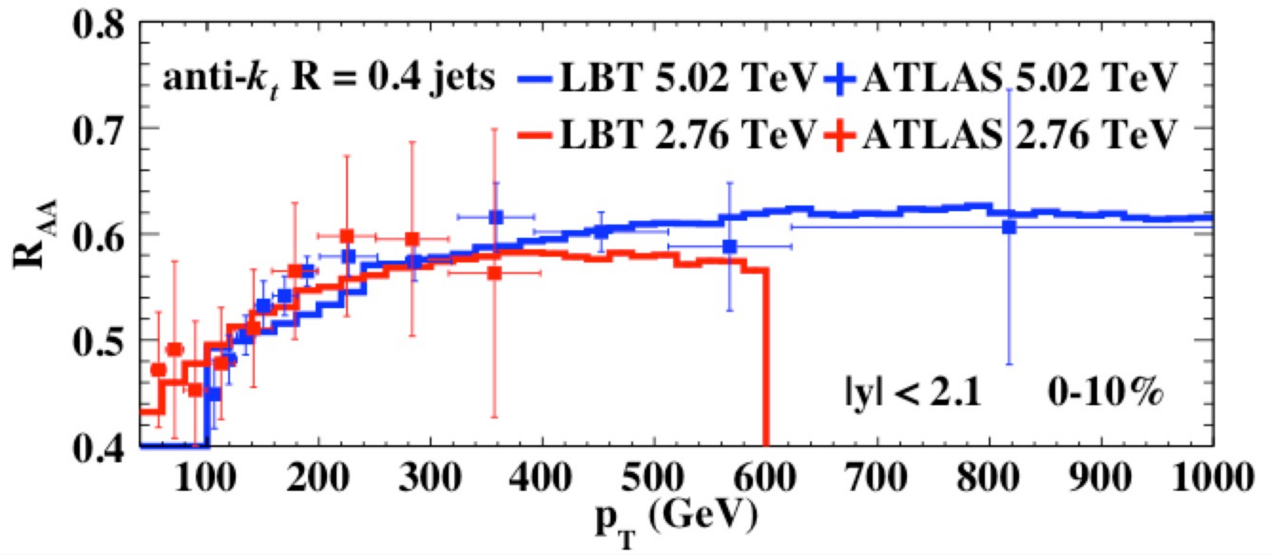
LBT: Jet-induced medium response

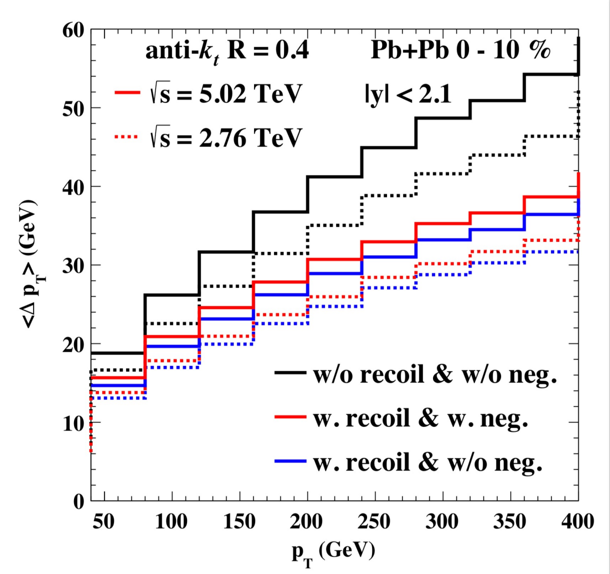


Energy distr. of medium response in a static medium

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

Jet suppression and energy loss



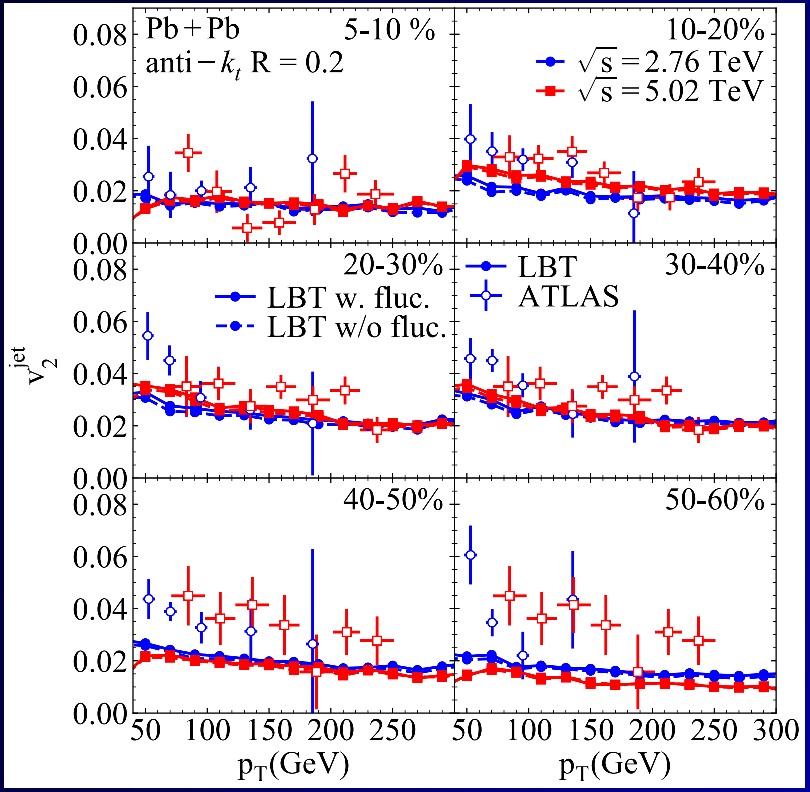


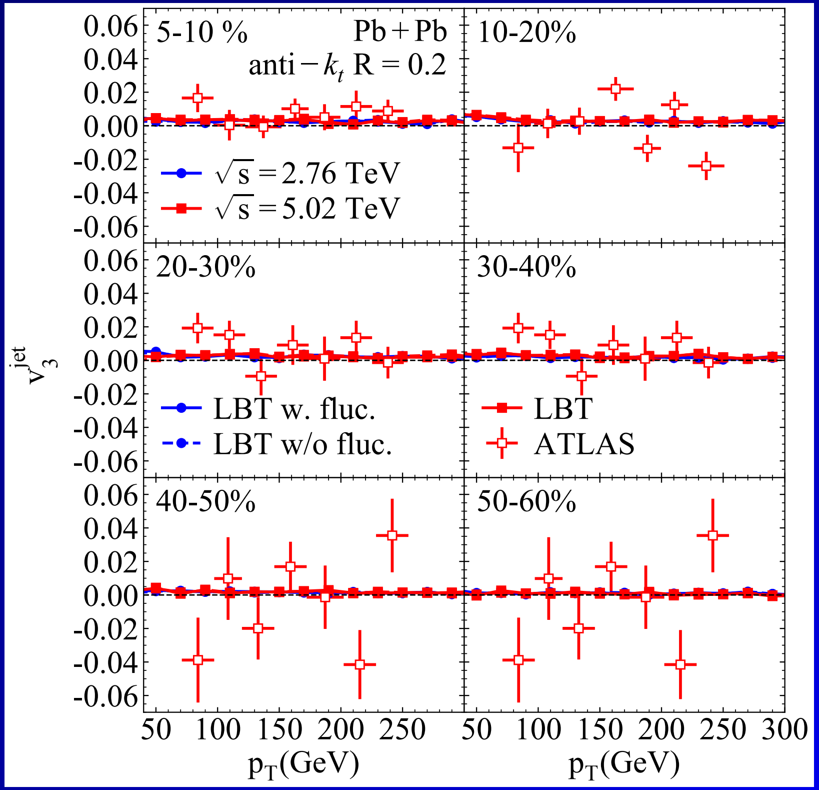
He, Cao, Chen, Luo, Pang & XNW 1809.02525

- 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

Single jet anisotropy

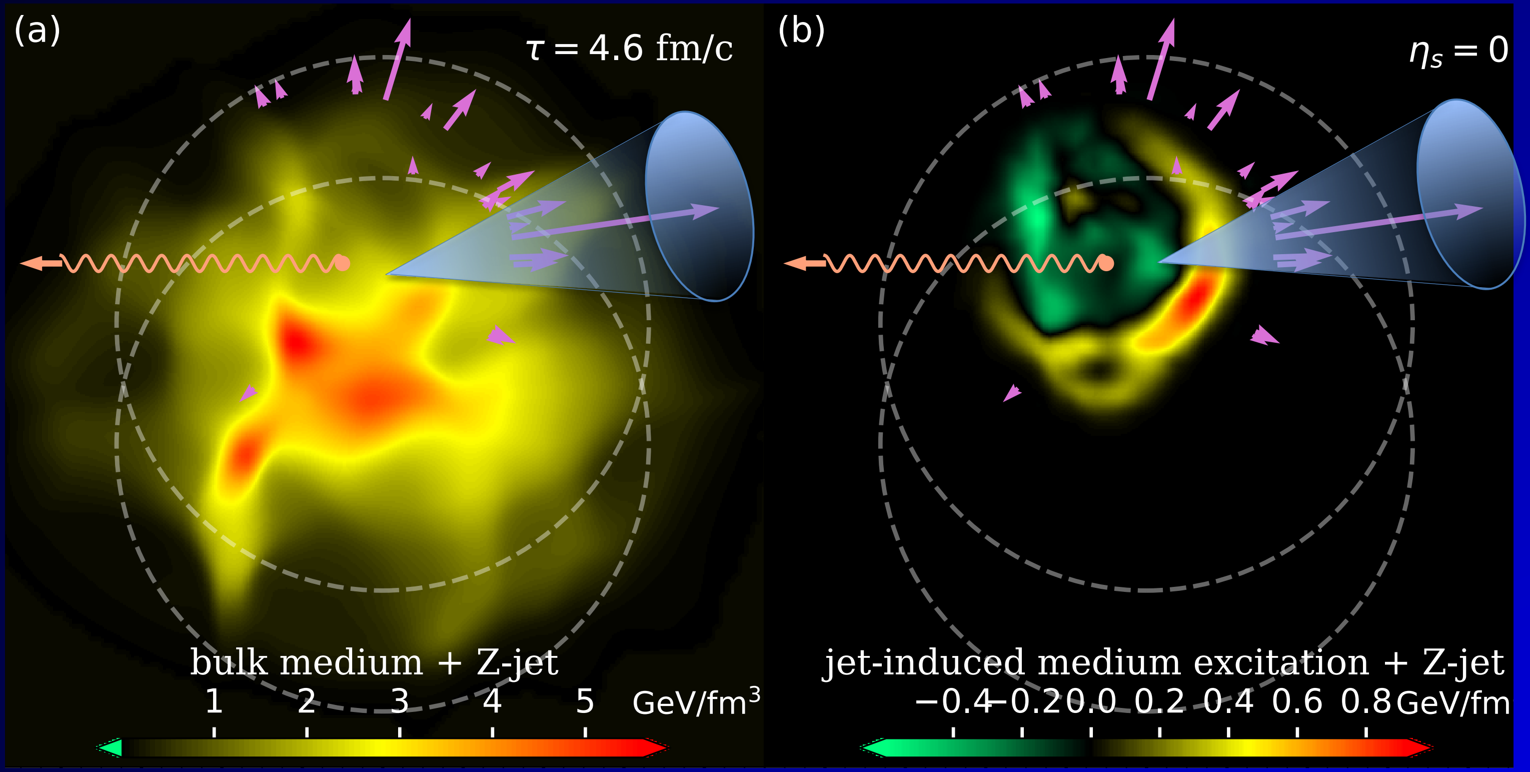
$$v_n^{\text{jet}} = \frac{\langle\langle v_n \cos[n(\phi^{\text{jet}} - \Psi_n)]\rangle\rangle}{\sqrt{\langle v_n^2\rangle}}$$





He, Cao, Luo, Pang & XNW, in preparation

Z/γ-jet: a better probe

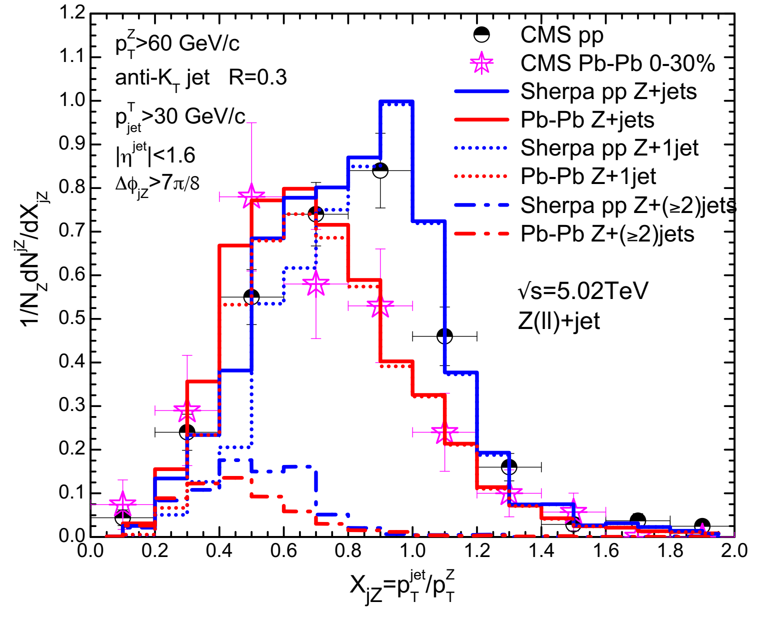


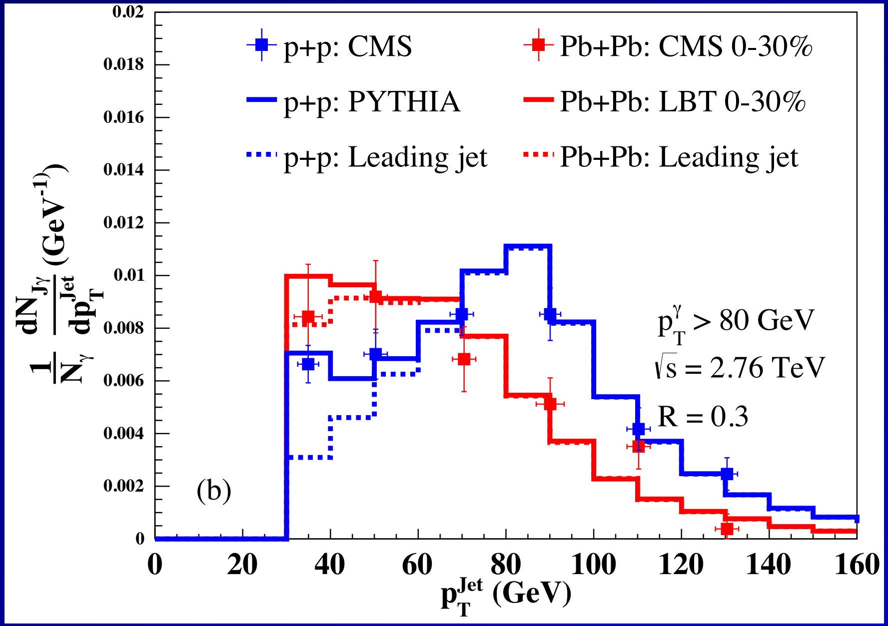
Chen, Cao, Luo, Pang & XNW, PLB777(2018)86

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

Energy loss in γ/Z-jet at LHC

Suppression of leading and multiple jets



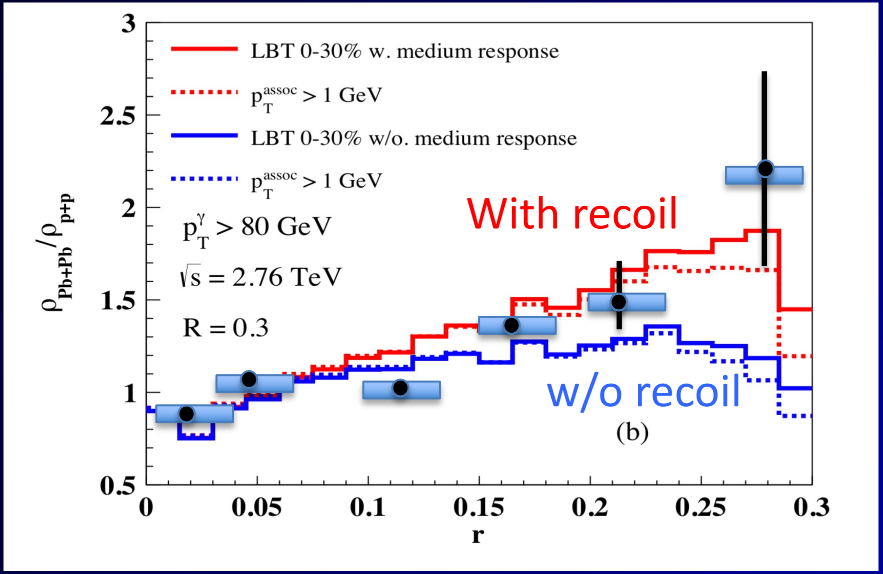


Zhang, Luo, XNW, Zhang, arXiv:1804.11041

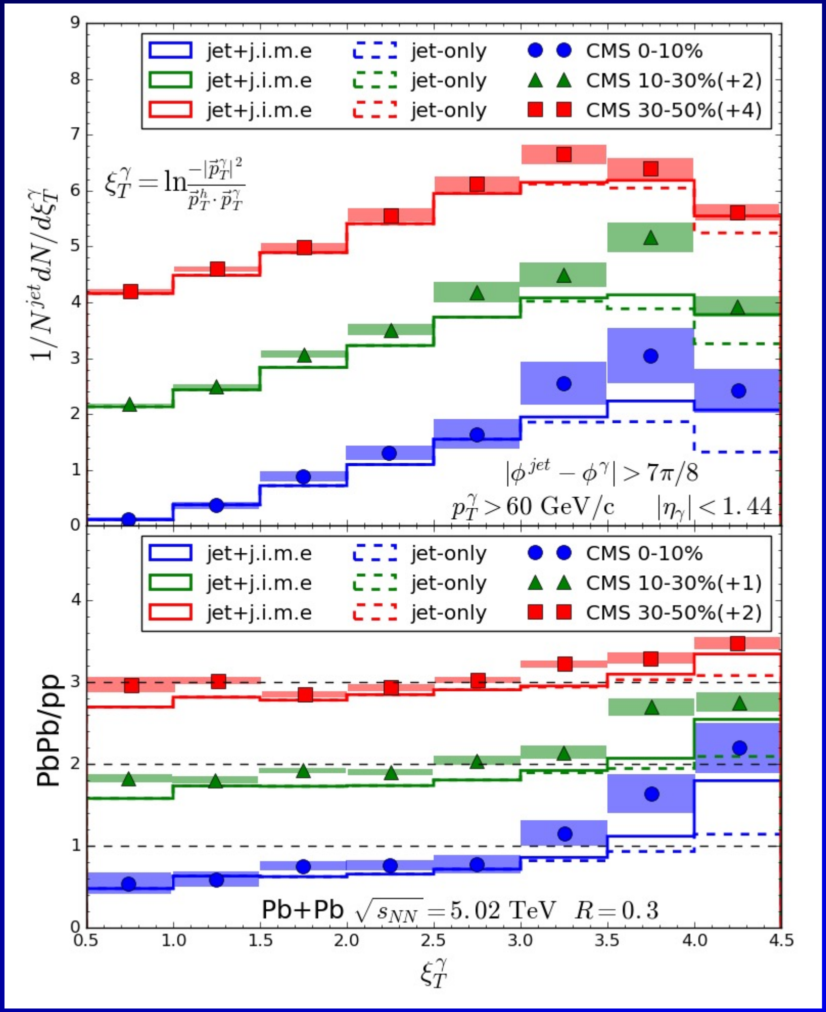
Luo, Cao, He & XNW, arXiv:1803.06785

Medium modification of γ-jets

Enhancement of soft hadrons in large angles

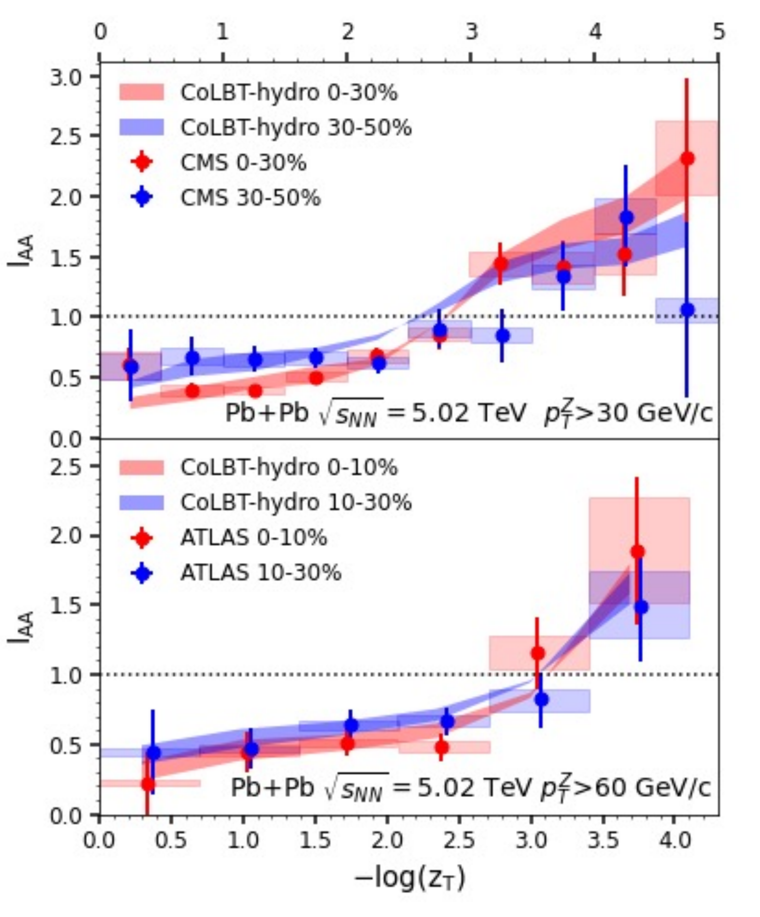


Luo, Cao, He & XNW, arXiv:1803.06785



Chen, Cao, Luo, Pang & XNW, 2005.09678

Z-hadron correlation at LHC



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

Medium response & soft gluon radiation

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

Medium-induced gluon radiation:

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

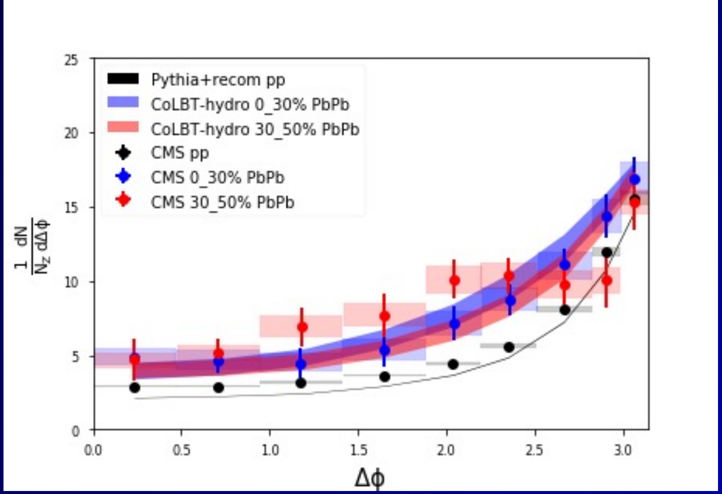
$$\hookrightarrow \quad \tau_f \approx \sqrt{2\omega/\hat{q}}$$

Mean-free-path
limits the formation time

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

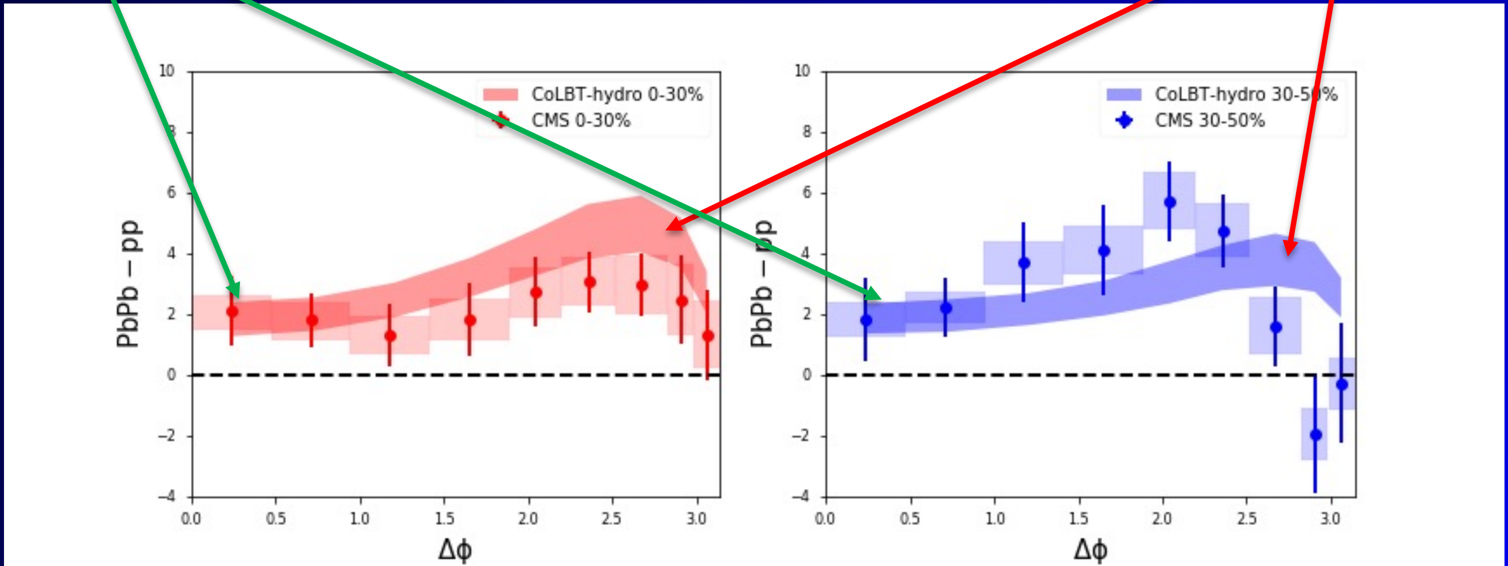
$$\omega \approx \lambda^2 \hat{q}/2 \sim T$$

Z-hadron correlation



enhancement
of the away-side
background

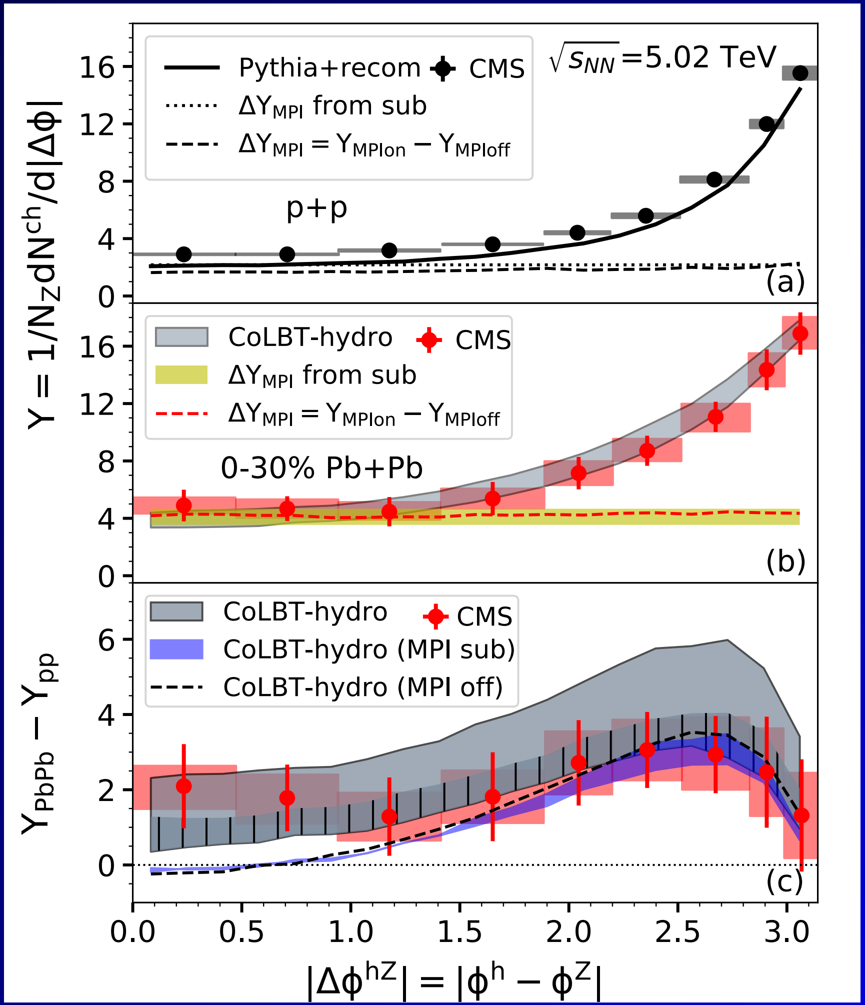
enhancement
and broadening
of the jet peak



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

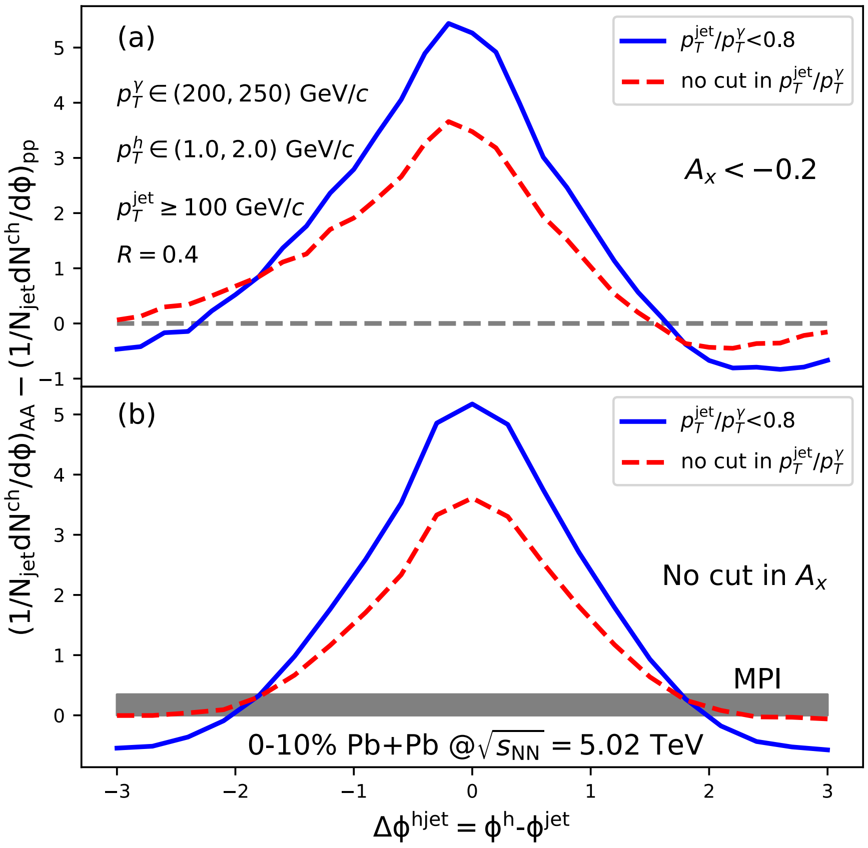
MPI subtraction in Z-hadron correlation

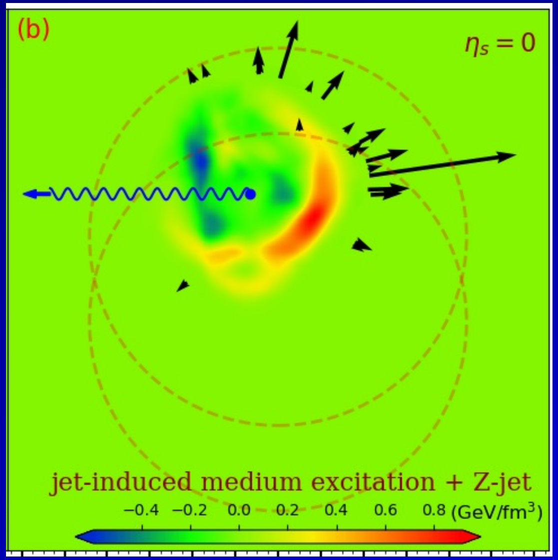
Mixed event subtraction



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

Enhancing the diffusion wake



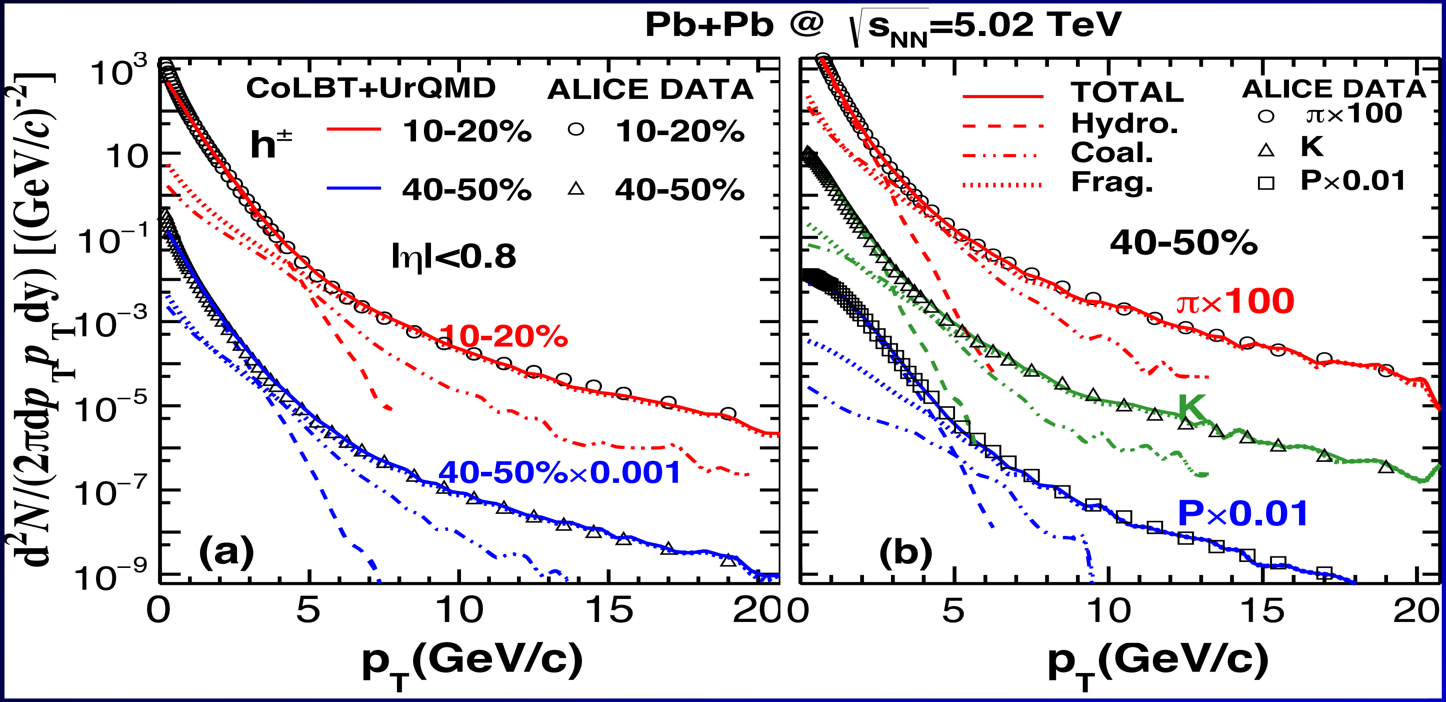


Chen, Yang, He, Ke, Pang and XNW, 2101.05422

Hydro, coalescence, fragmentation and hadron cascade

- Thermal hadrons (CLVisc)
  - Hydro with Cooper-Frye (pT<pT1)
- Coalescence hadrons
  - Include thermal-thermal, thermal-hard and hard-hard coalescence
- Fragmentation hadrons
  - Lund fragmentation
- UrQMD hadronic afterburner
  - All hadons are fed into UrQMD for hadronic evolution and decay

Hadron spectra from low to high p_T



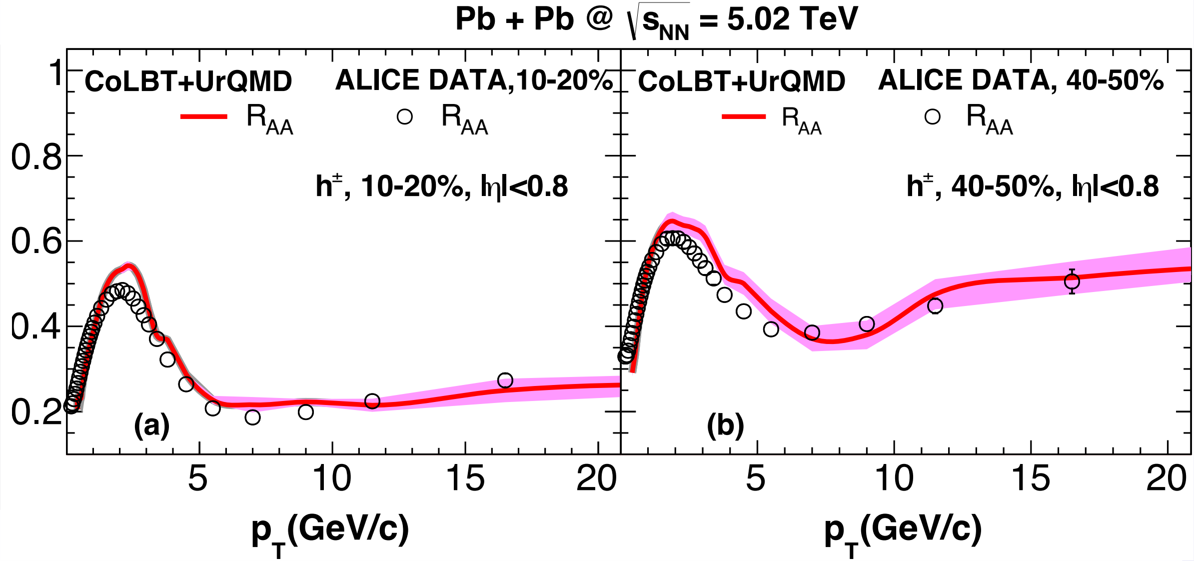
Hydro : p_T<2 GeV/c — radial flow

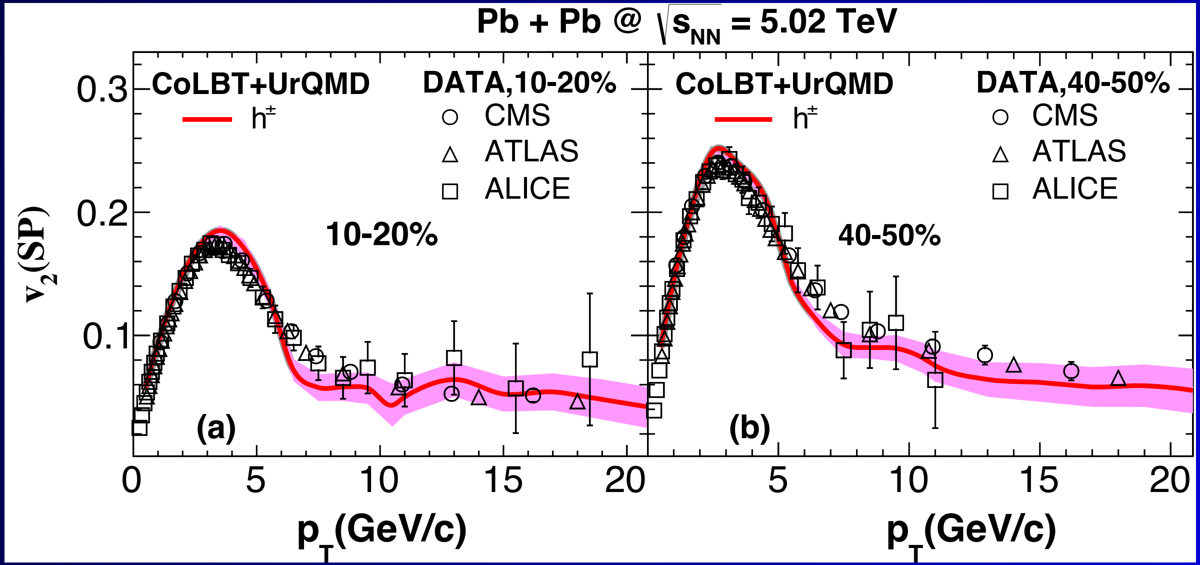
Coal.: 2<p_T<6 GeV/c — Coalescence

Frag.: p_T>5 GeV — energy loss

Zhao, Ke, Chen, Luo and XNW, [arXiv:2103.14657 [hep-ph]]

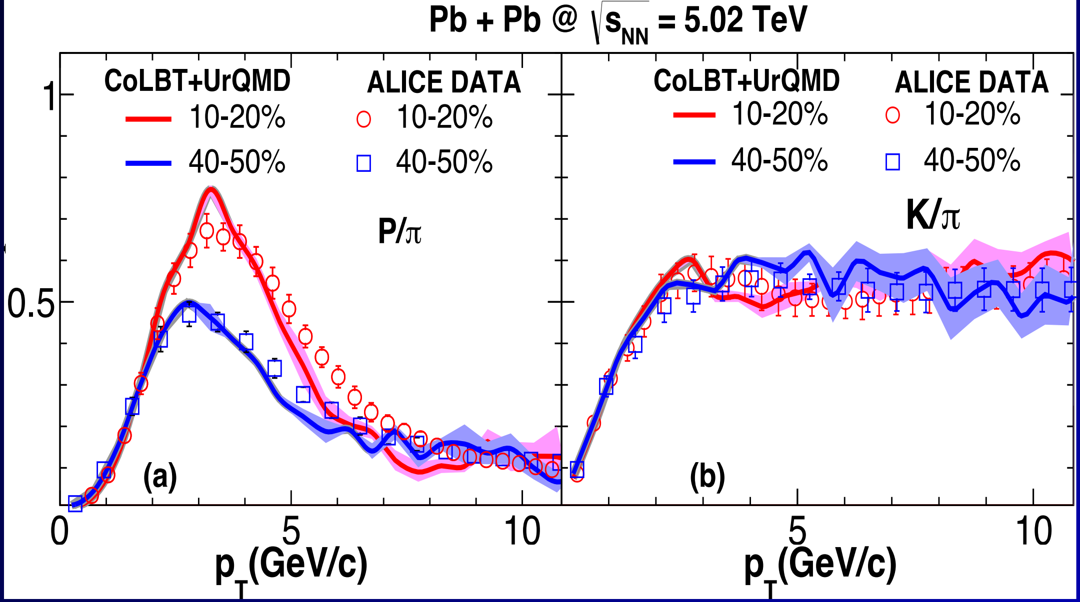
Solving R_{AA}-v_2 puzzle

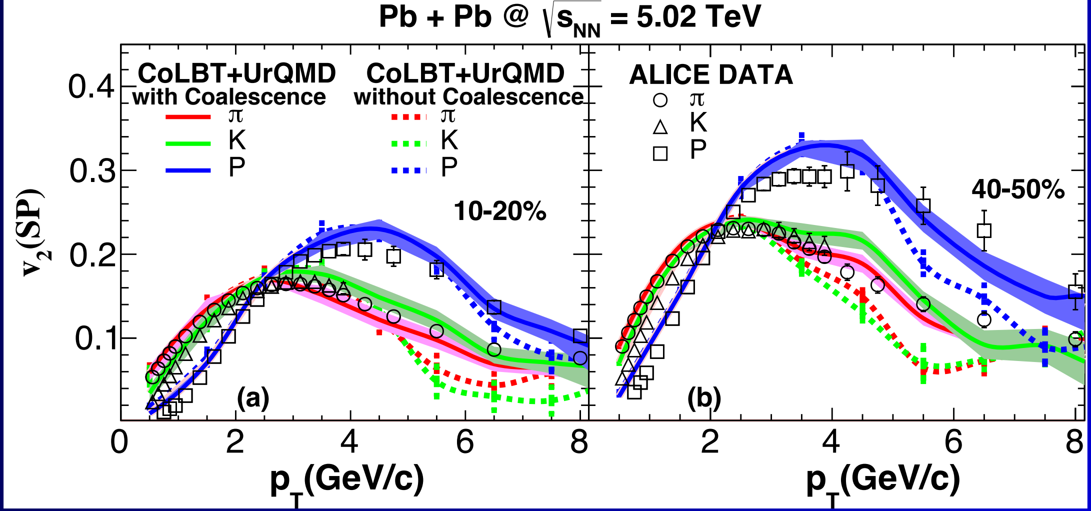




Zhao, Ke, Chen, Luo and XNW, arXiv:2103.14657

Flavor dependence



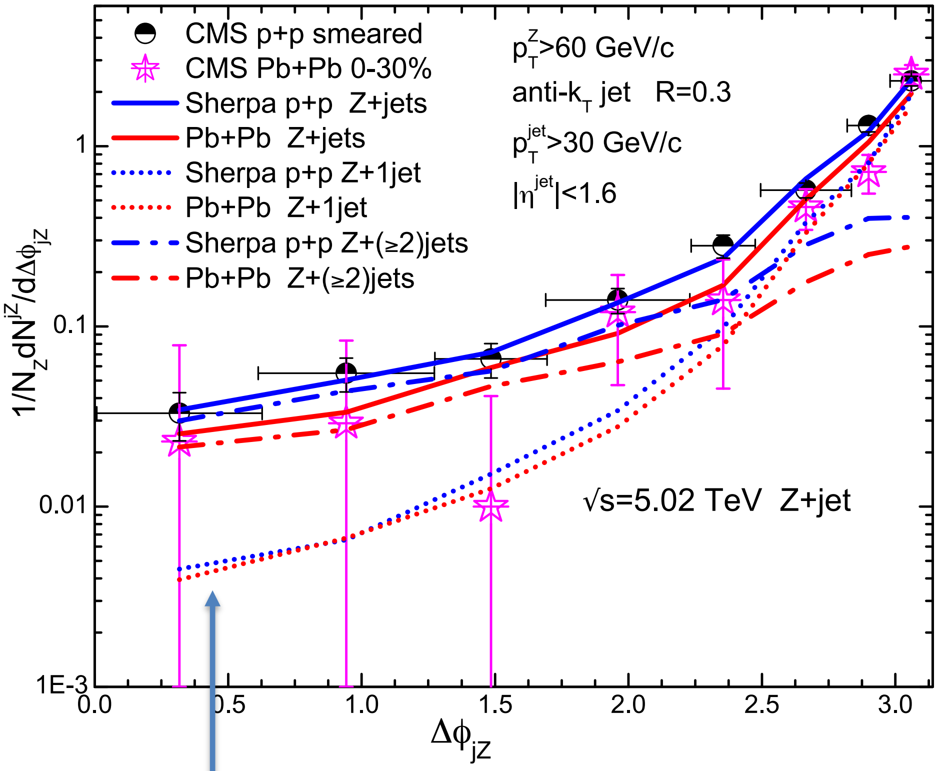


Zhao, Ke, Chen, Luo and XNW, arXiv:2103.14657

Conclusion & Discussion

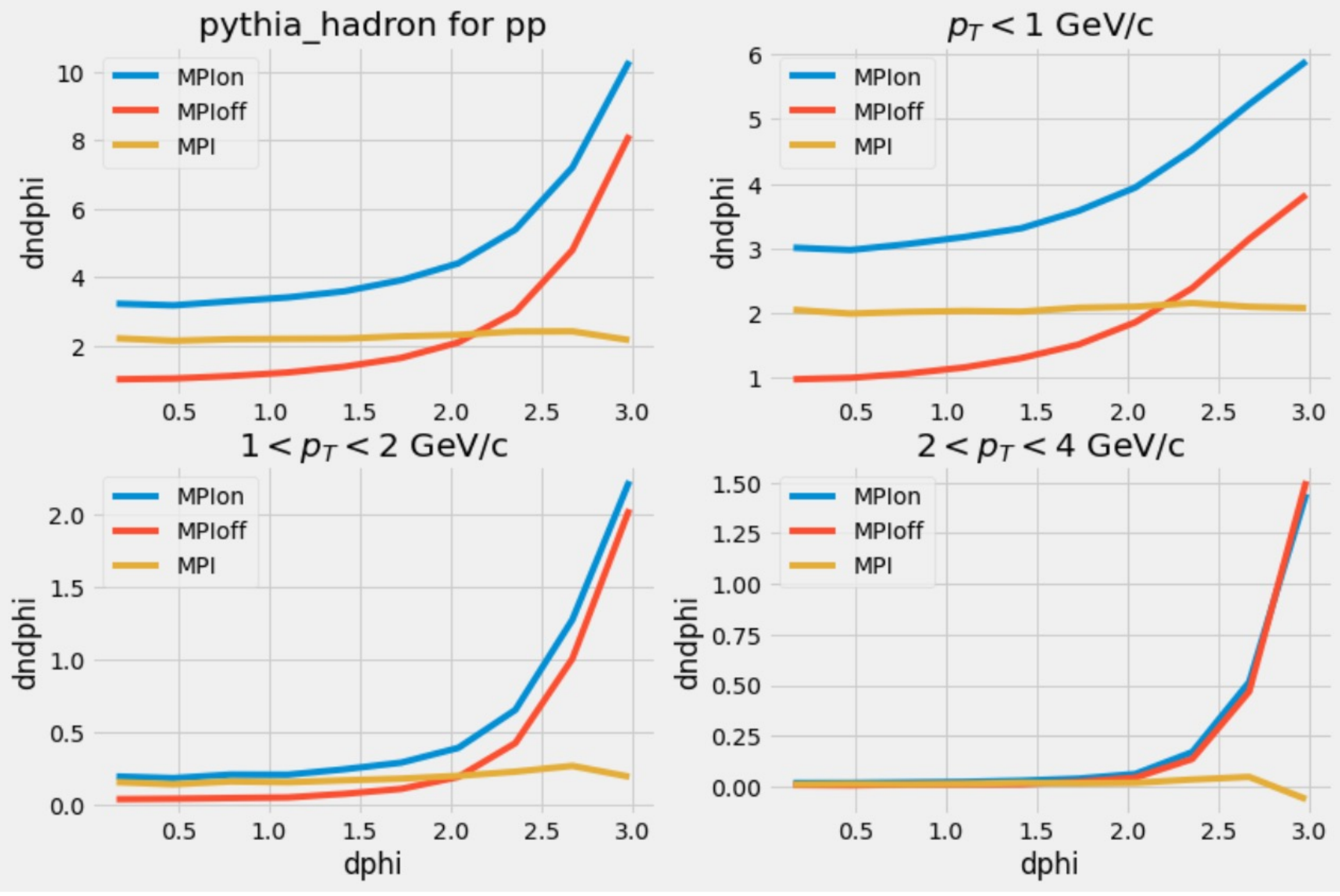
- CoLBT-hydro: describe h spectra from lot to high p_T
- Coalescence at intermediate p_T solves R_{AA} v_2 puzzle
- Flavor dependence of spectra and v2
- Medium response leads to
  - enhancement of soft hadrons in jet direction
  - depletion of soft hadron on the away side
- Use 2D jet tomography to reveal the angular structure of Mach-cone excitation

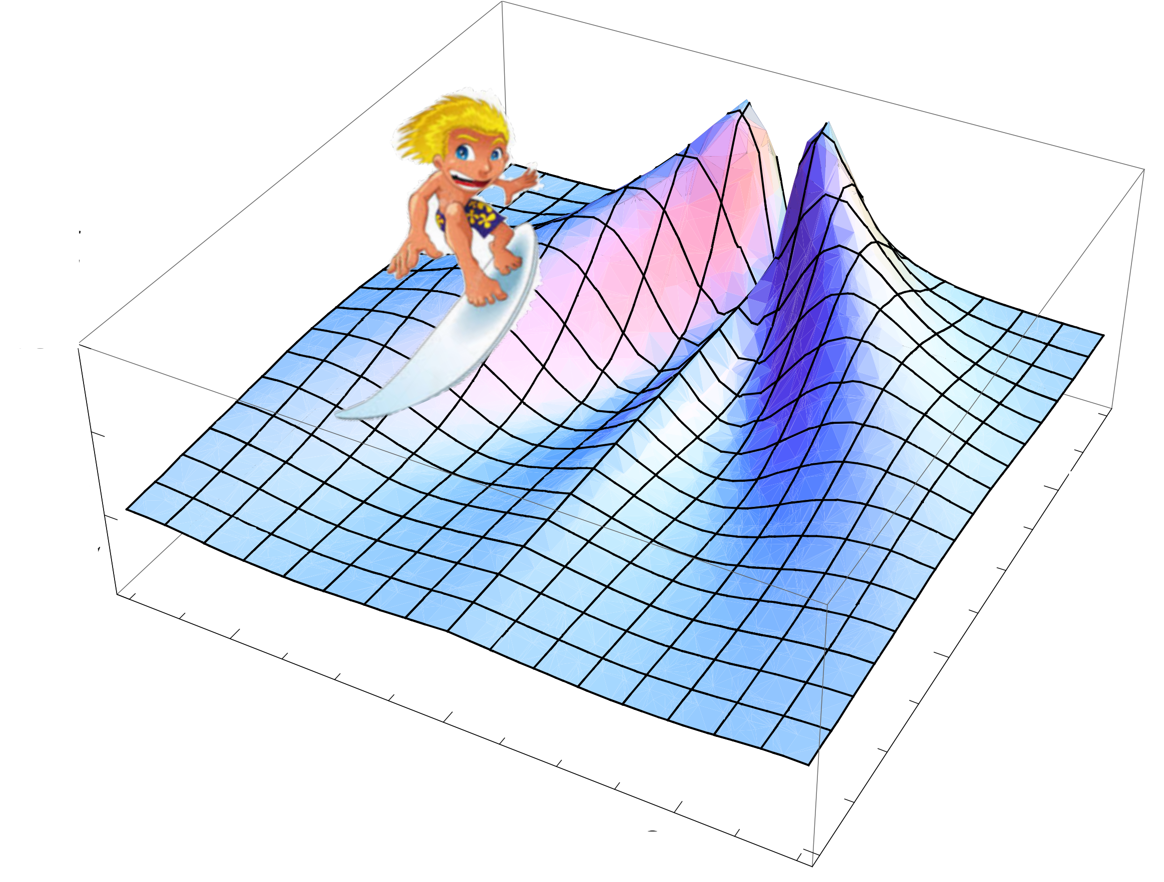
Multiple jets in Z-jet events



Multiple jets contribution is negligible in Z direction

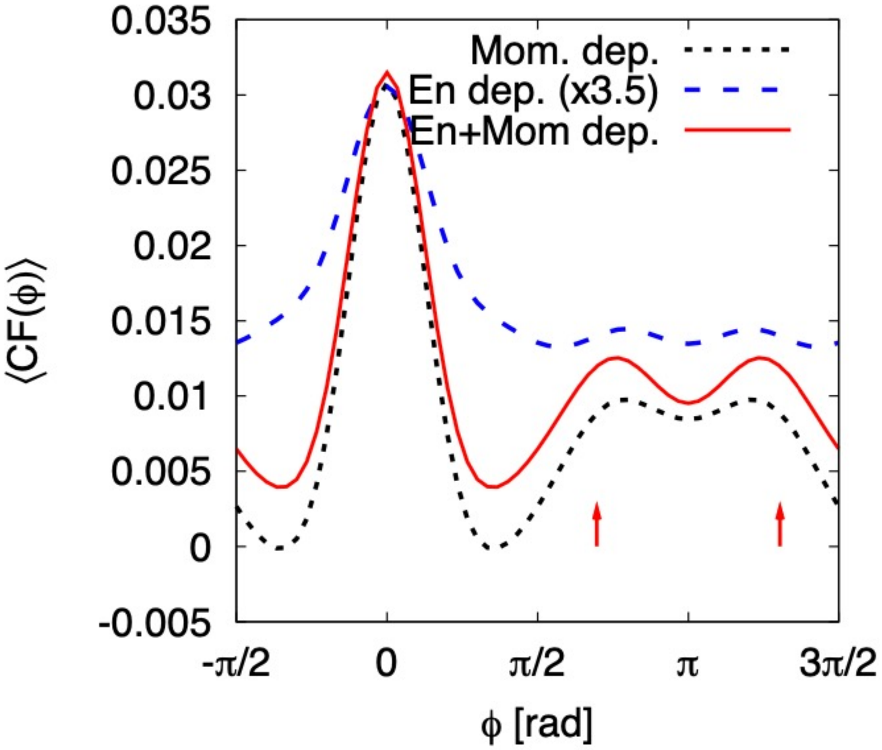
MPI at RHIC


pythia_hadron for pp
$p_T < 1$ GeV/c
$1 < p_T < 2$ GeV/c
$2 < p_T < 4$ GeV/c
MPIon
MPIoff
MPI
dndphi
dphi
0.5
1.0
1.5
2.0
2.5
3.0
2
4
6
8
10
1
3
5
0.0
0.25
0.50
0.75
1.00
1.25
1.50



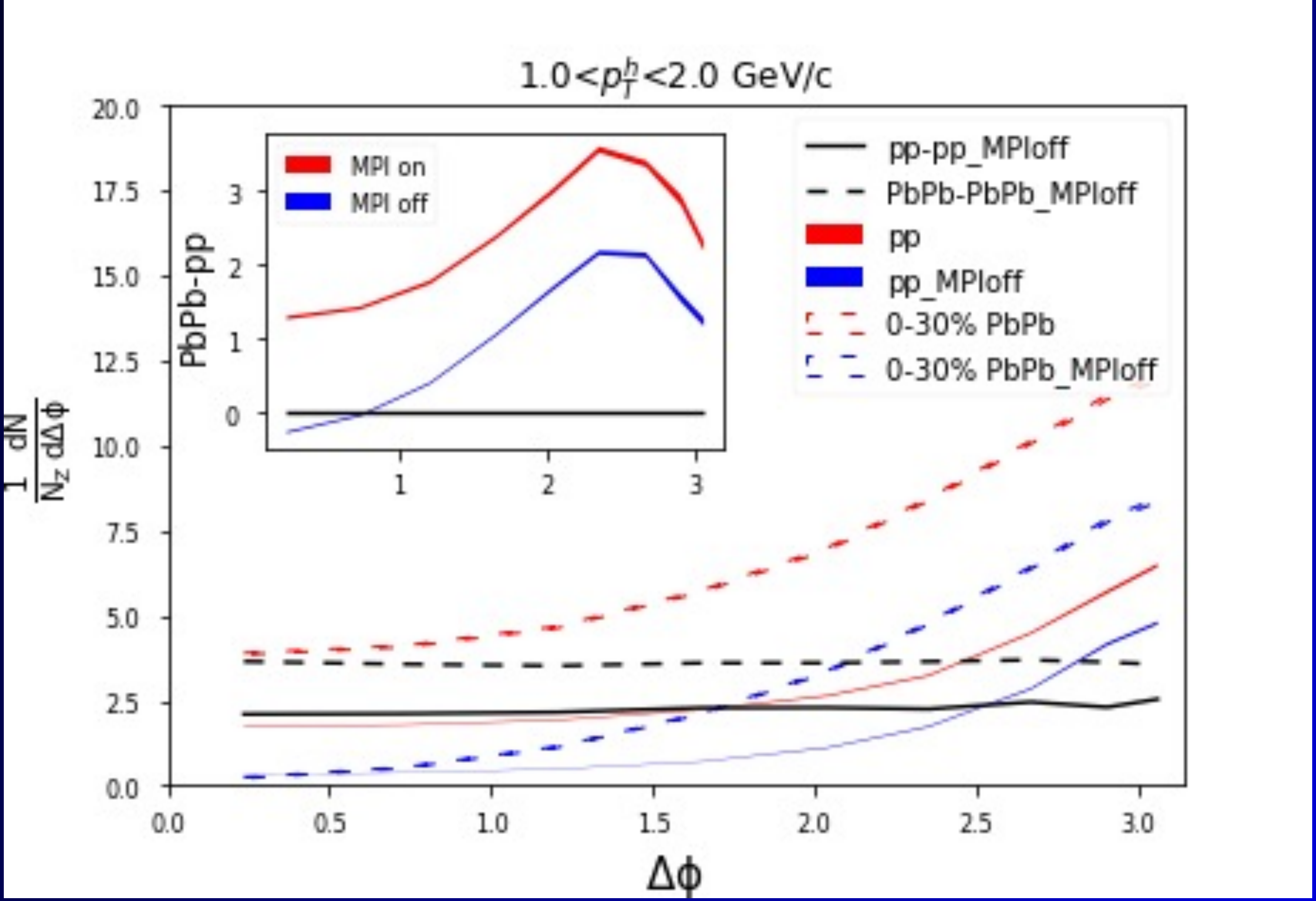
Signals of Mach-cone?

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



- Angular structure disappears after average over initial production points
- Medium-induced gluon radiation can overwhelm in some phase-space
- Complication by anisotropic flow v_n

MPI contribution to Z-hadron correlation



MPI negligible at RHIC

MPI: Multiple parton interaction

XNW & Gyulassy (1991)

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

Multiple jet production in pp:

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

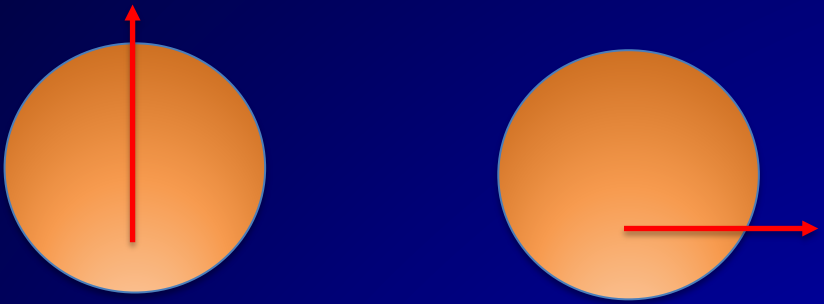
Probability of multiple jets ($p_T > p_0$) with at least one jet with $p_T > p_T^{\mathrm{trig}}$

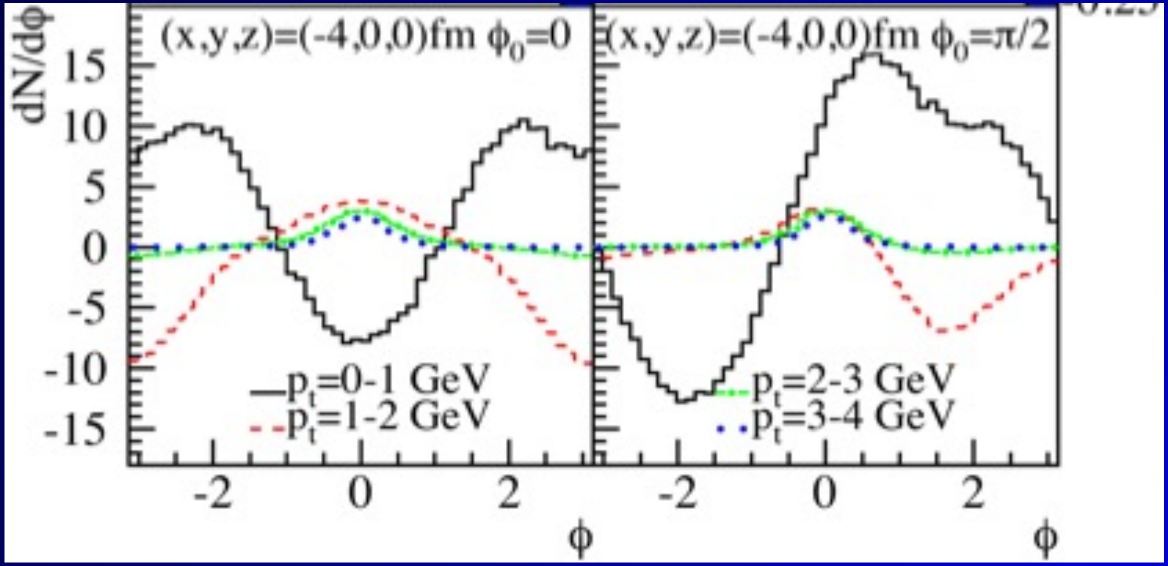
$$g_j^{\mathrm{trig}}(b) = \frac{[\sigma(p_0)T(b)]^j}{j!} \left\{ 1 - \frac{[(\sigma(p_0) - \sigma(p_T^{\mathrm{trig}})]^j}{\sigma(p_0)^j} \right\} e^{-\sigma(p_0)T(b)}$$

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

Enhanced multiple minijet
Production in triggered jet events

Distorted Mach-cone-like excitation





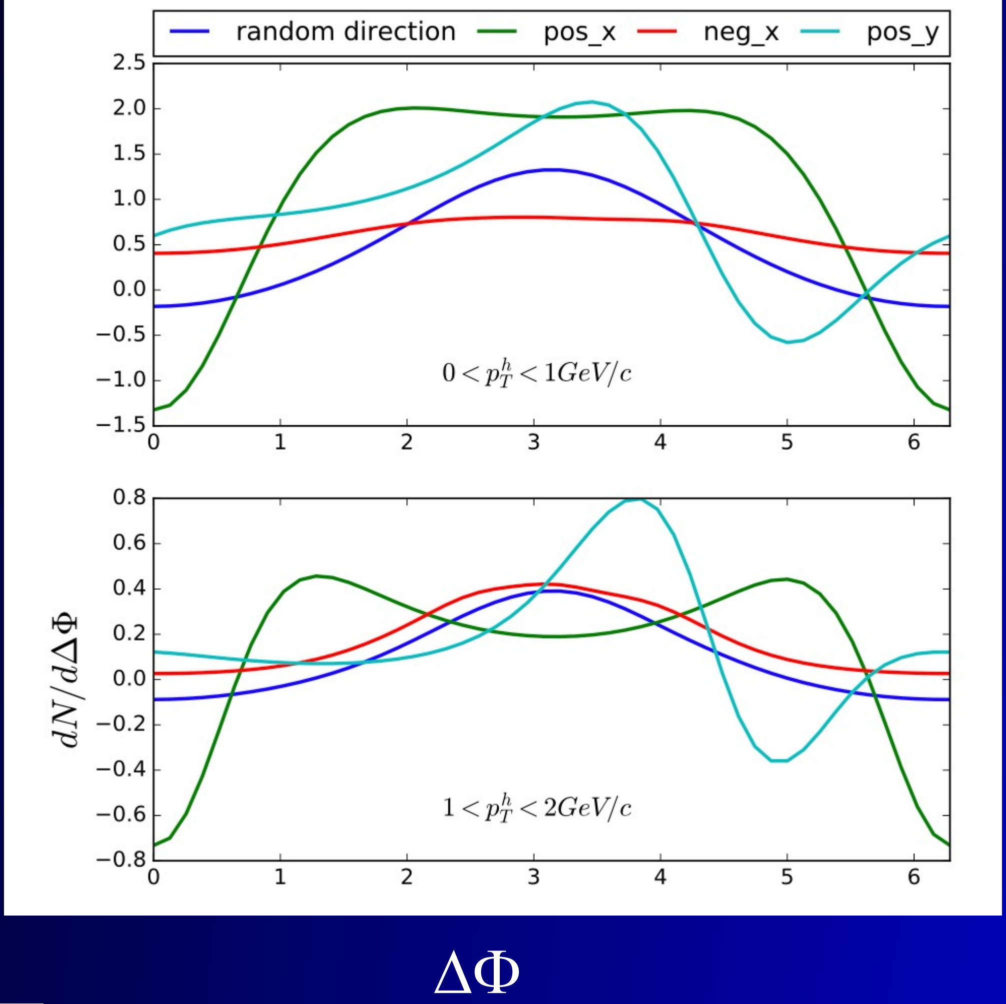
Li, Liu, Ma, XNW and Zhu, Phys. Rev. Lett. 106, 012301 (2011)

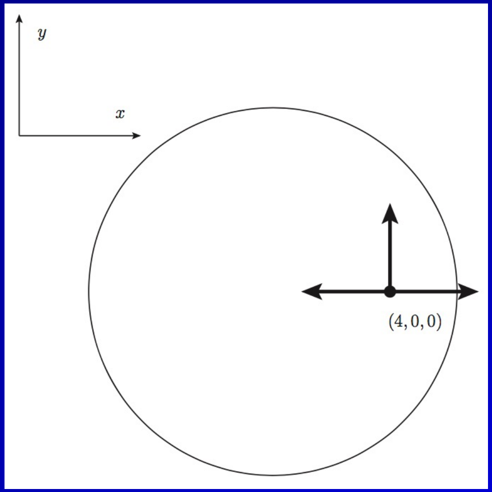
Tachibana, Shen & Majumder 2001.08321 (2020)

Initial position & azimuthal correlation

W Chen & XNW (2018)

γ-hadron correlation

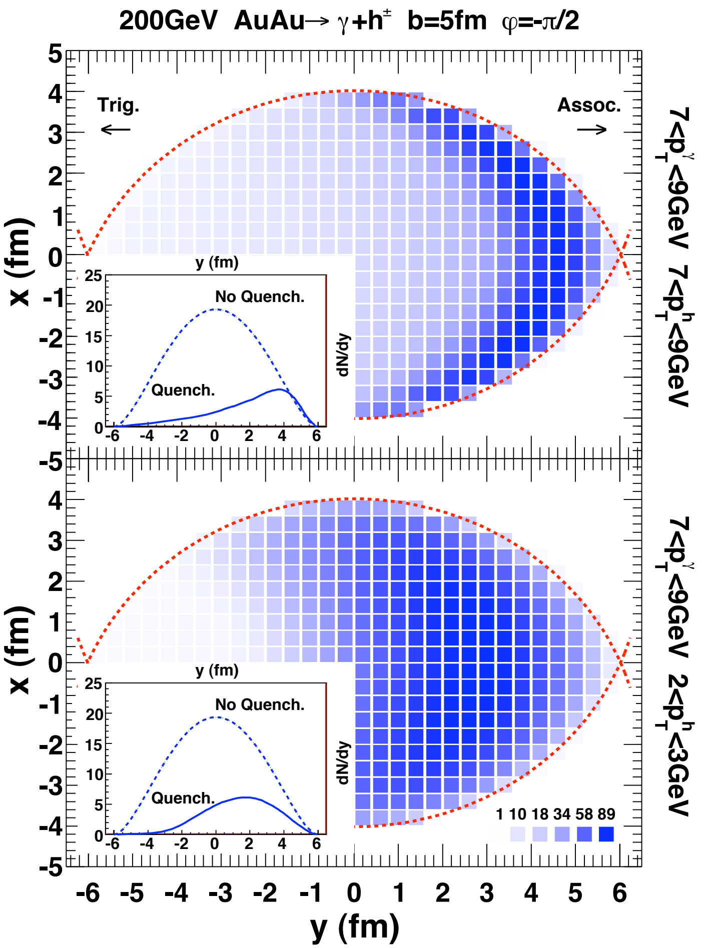




Longitudinal jet tomography

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

length
dependence
of parton
Energy loss

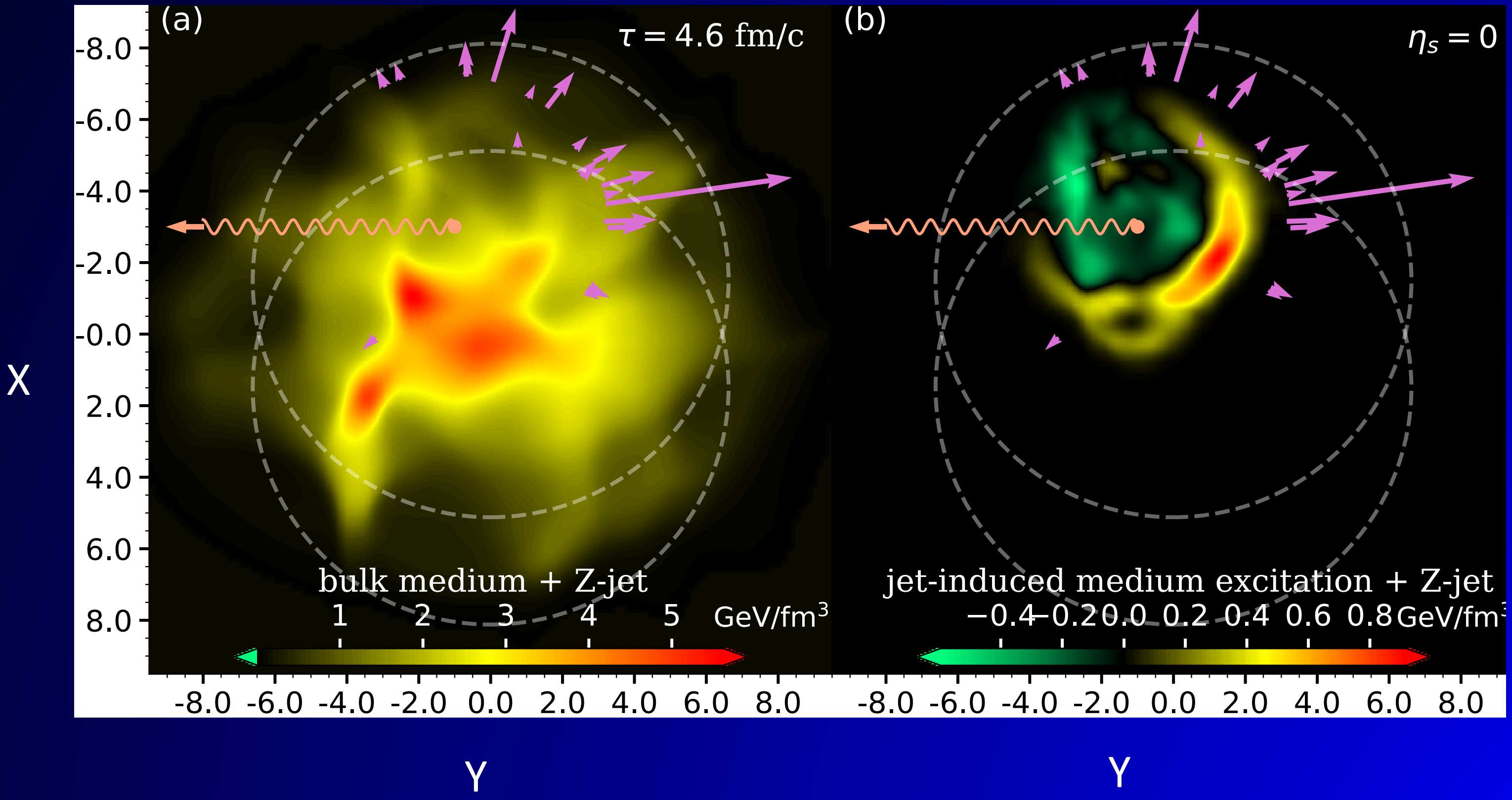


$$p_T^h/p_T^\gamma \sim 1$$

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

Transverse gradient tomography

gradient dependence of p_T broadening

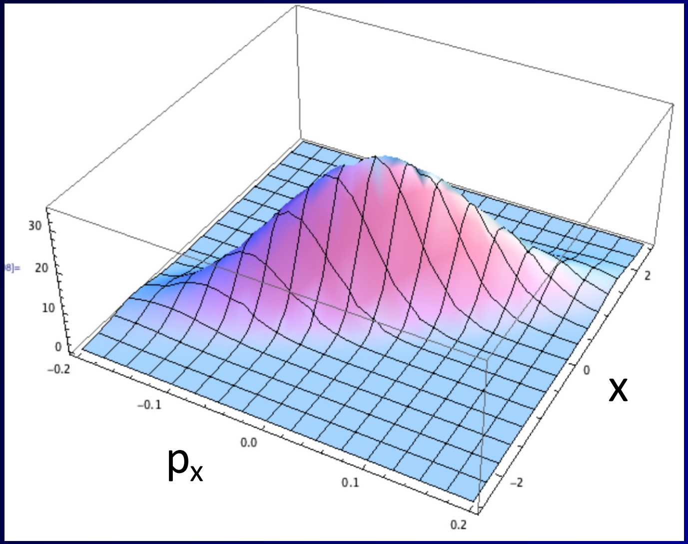


Drift-diffusion equation: uniform medium

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

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

Initial distr. $f(\vec{p}, \vec{r})_{t=0} = (2\pi)^2 \delta^2(\vec{r}_\perp) \delta^2(\vec{p}_\perp)$



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

$$\begin{array}{cc} \Big\downarrow \int d^2p_\perp & \Big\downarrow \int \frac{d^2r}{(2\pi)^2} \\ 4\pi \frac{3E^2}{\hat{q}t^3} \exp\left(-r_\perp^2 \frac{3E^2}{\hat{q}t^3}\right) & \frac{1}{\pi \hat{q}t} \exp\left(-\frac{p_\perp^2}{\hat{q}t}\right) \end{array}$$

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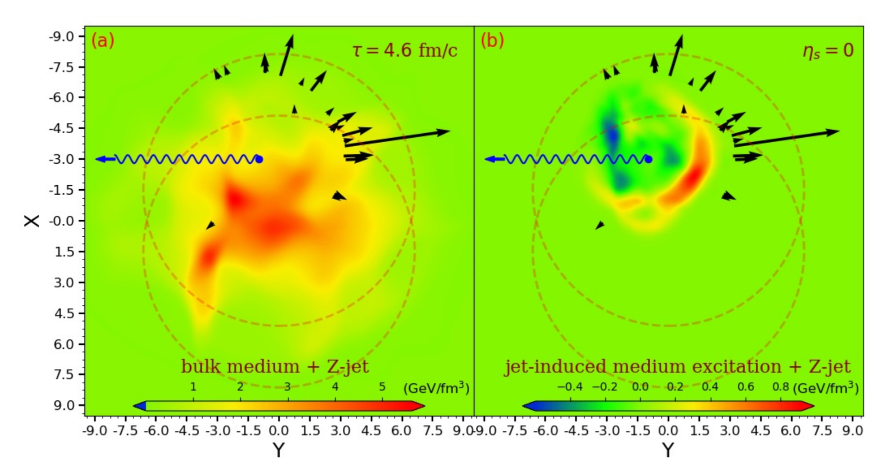
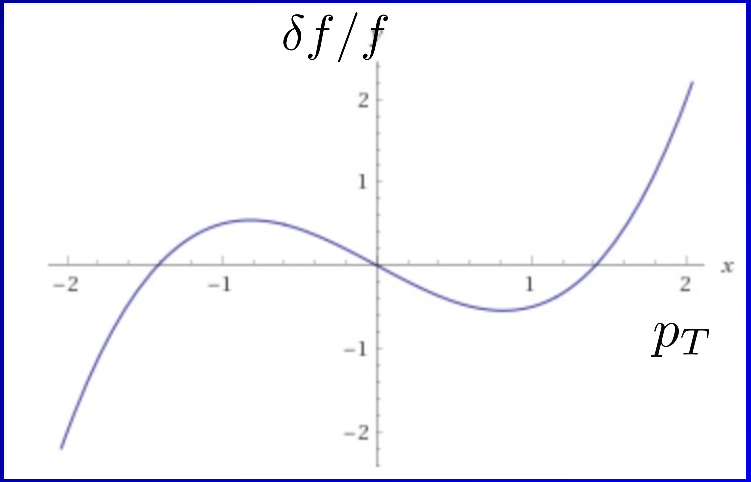
Drift-diffusion equation: non-uniform medium

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

Momentum asymmetry:

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

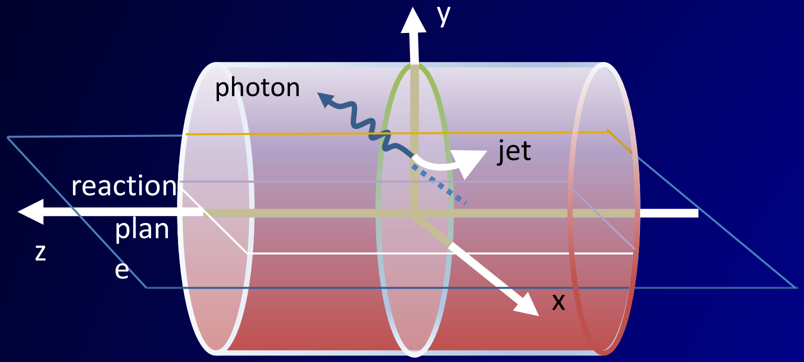


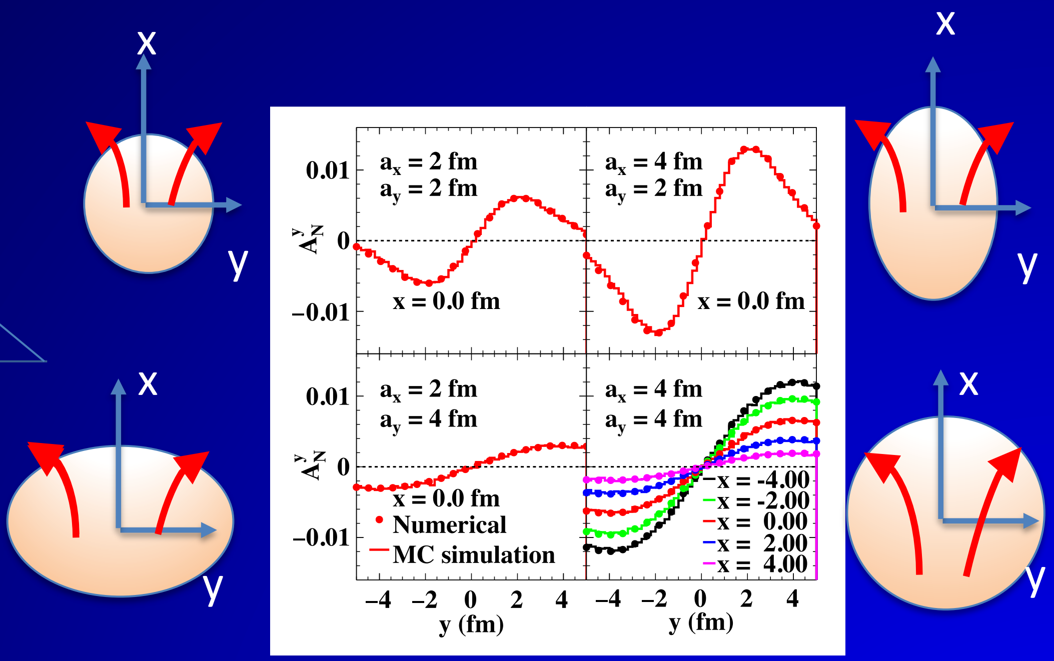


Diffusion in a non-uniform medium

Momentum asymmetry

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





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

$\hat{q}_0$ =5 GeV^2/fm, t_0=0.5 fm/c, E=20 GeV

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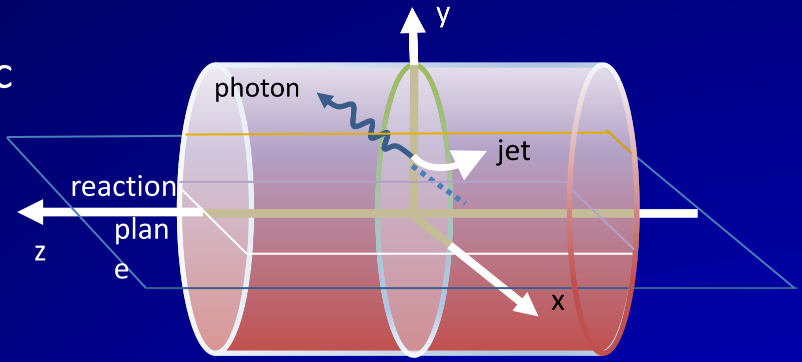
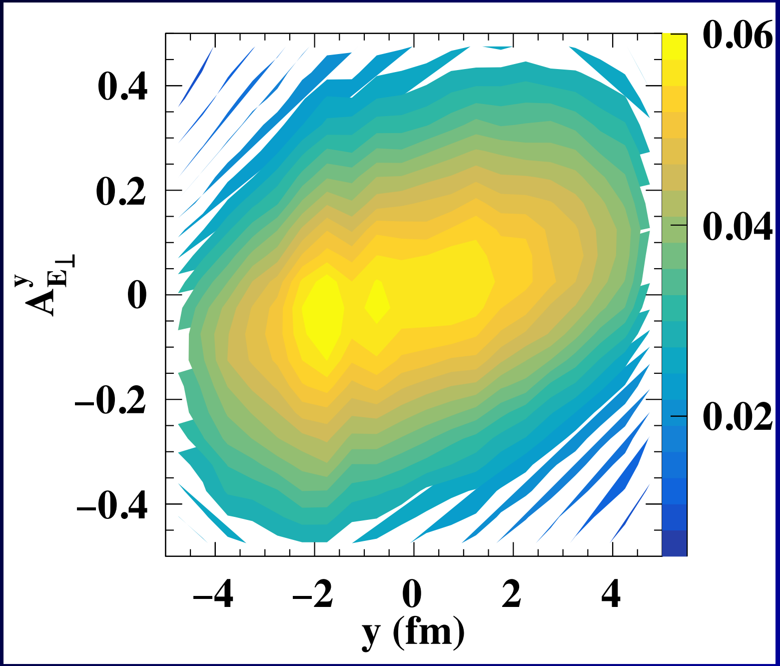
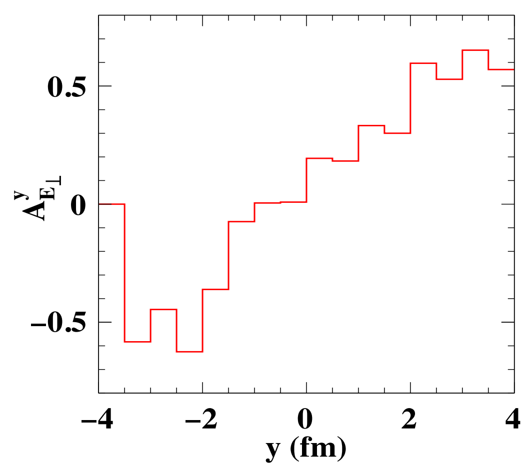
Momentum asymmetry wrt event plane

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

p_T>3 GeV/c







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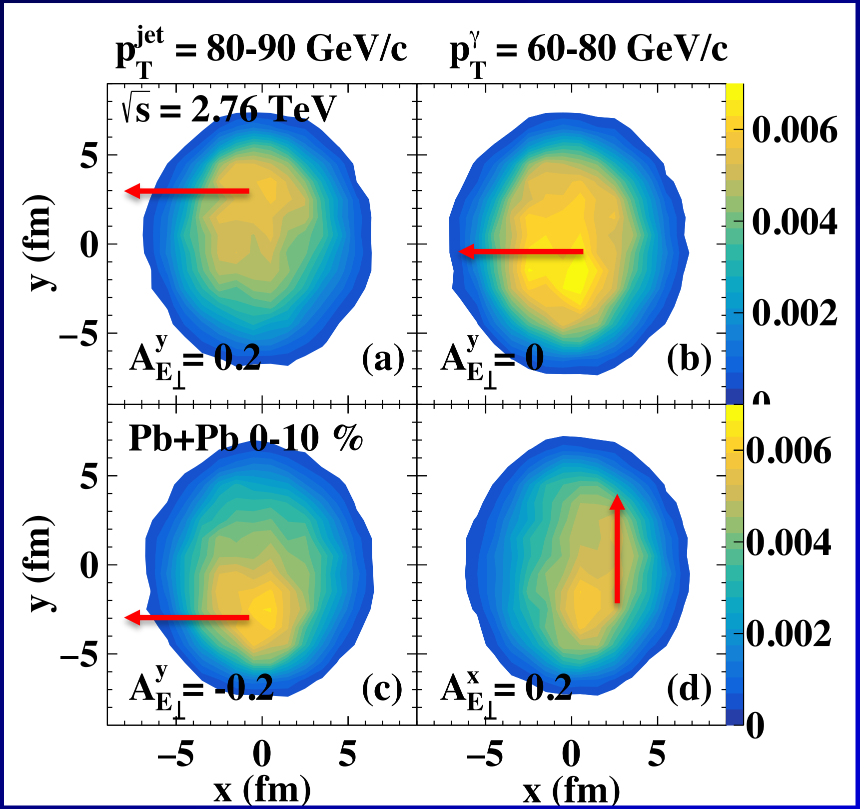
Gradient tomography

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



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