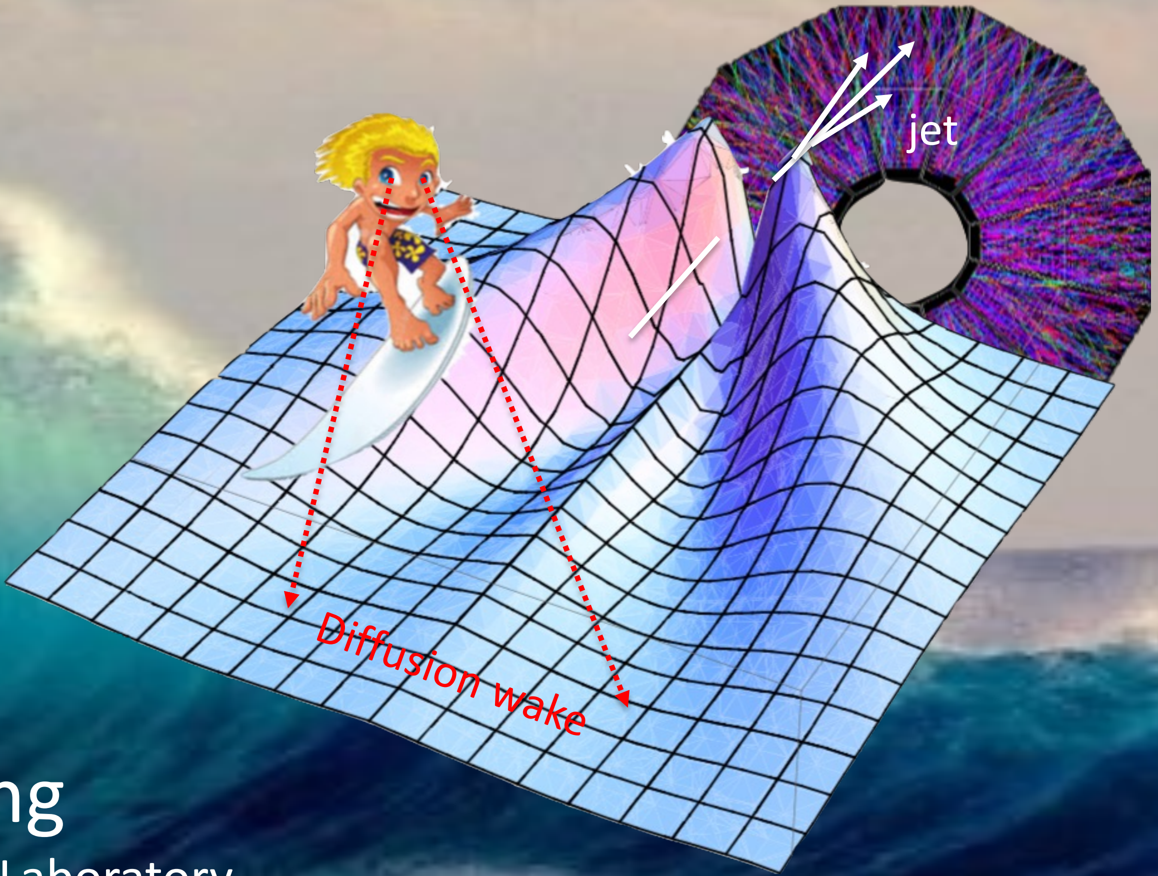
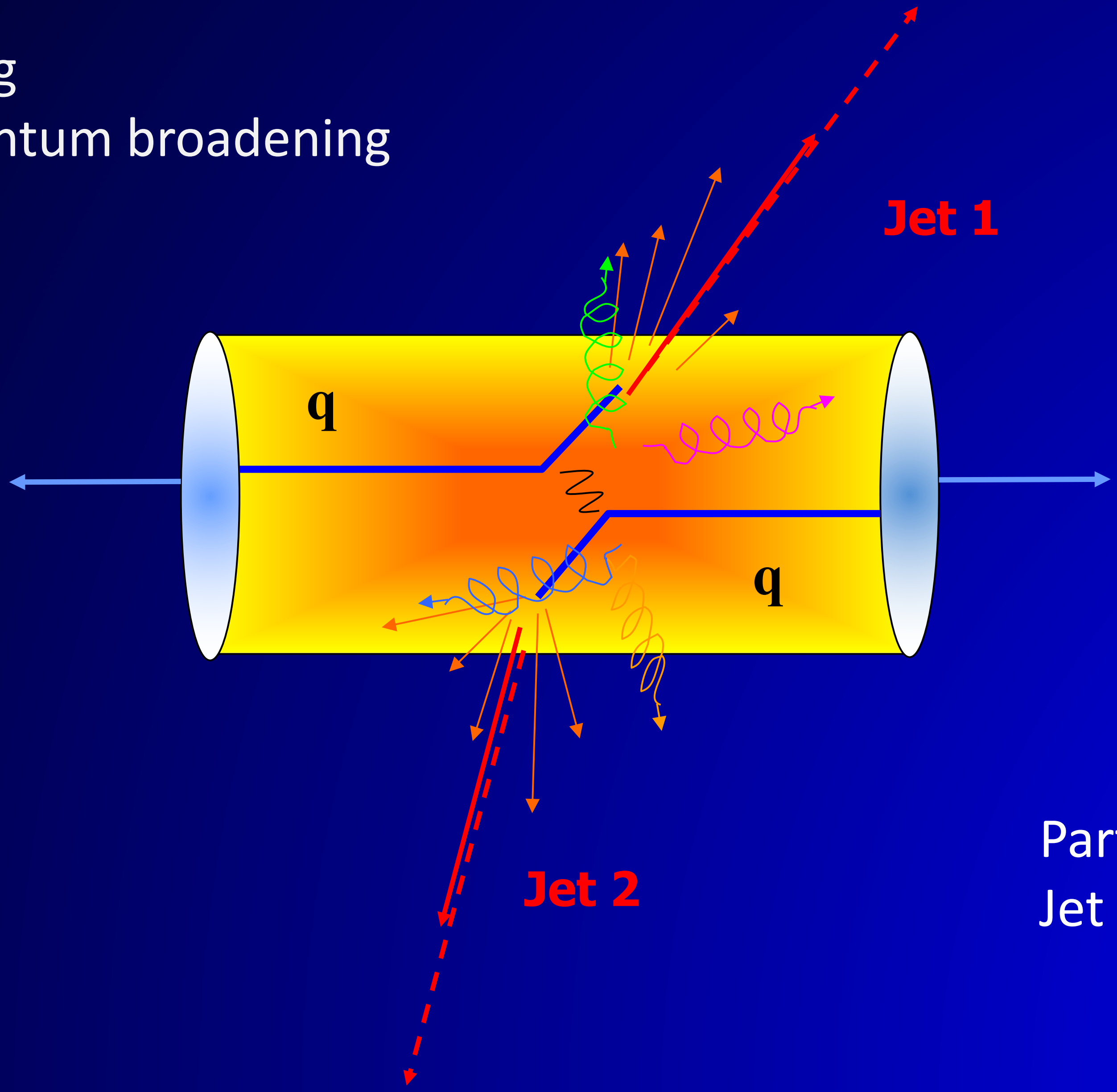


Heavy-ion Physics 2

Xin-Nian Wang
Lawrence Berkeley National Laboratory

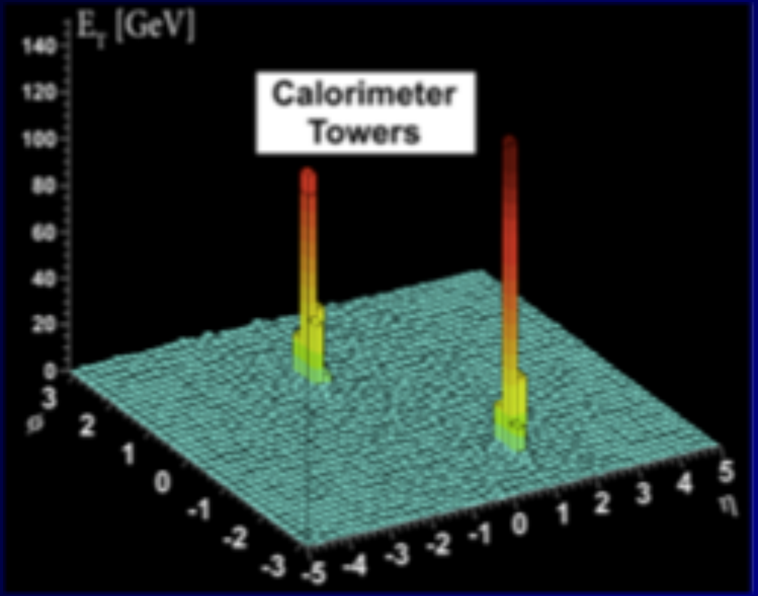
Jets in heavy-ion collisions

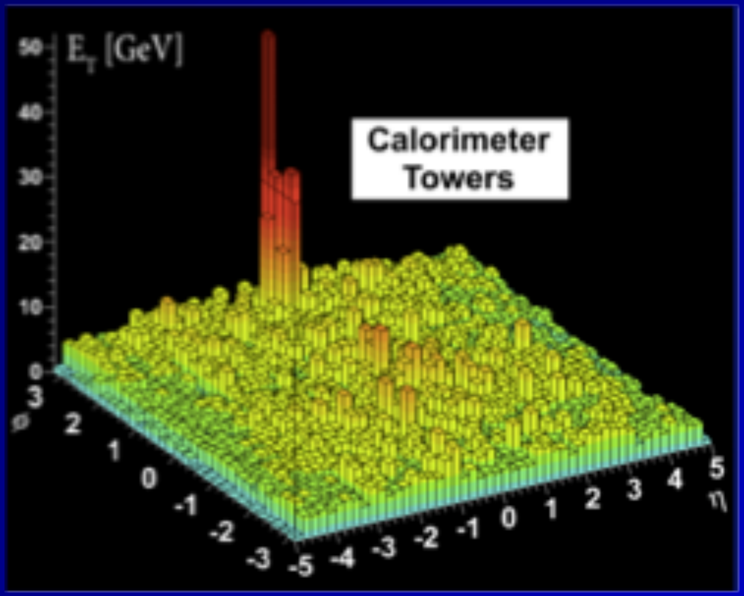
Multiple scattering
Transverse momentum broadening



Parton energy loss
Jet suppression

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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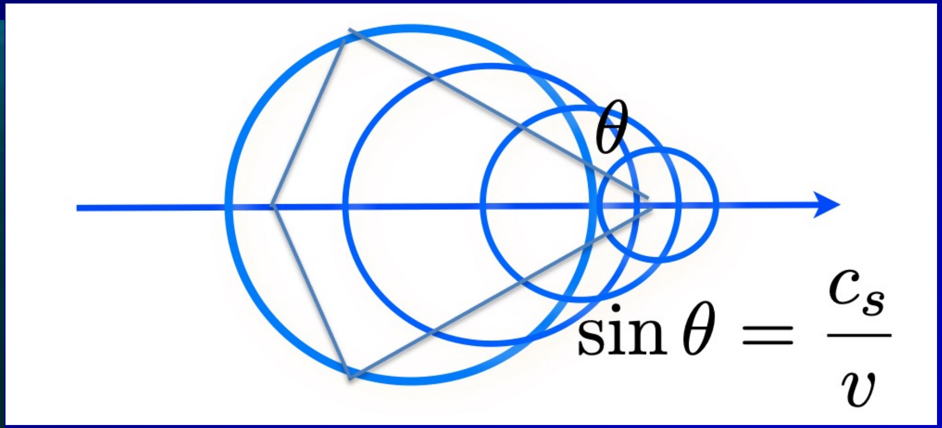
Bow waves, Mach waves



Jet-induced medium excitation

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



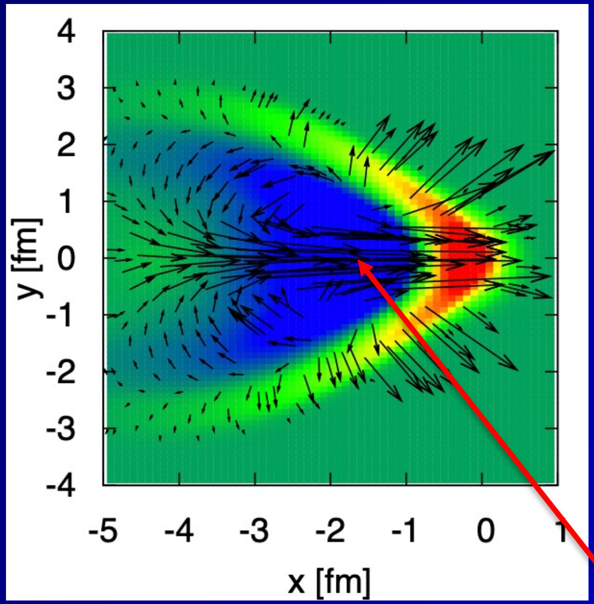

Jet induced Mach-cone in QGP

$$v = p/E > c_s$$

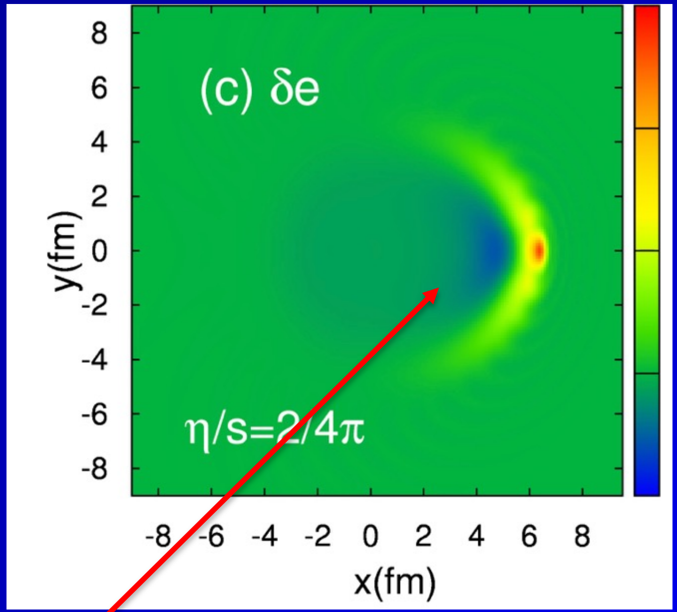
Hydrodynamic approach

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

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 response

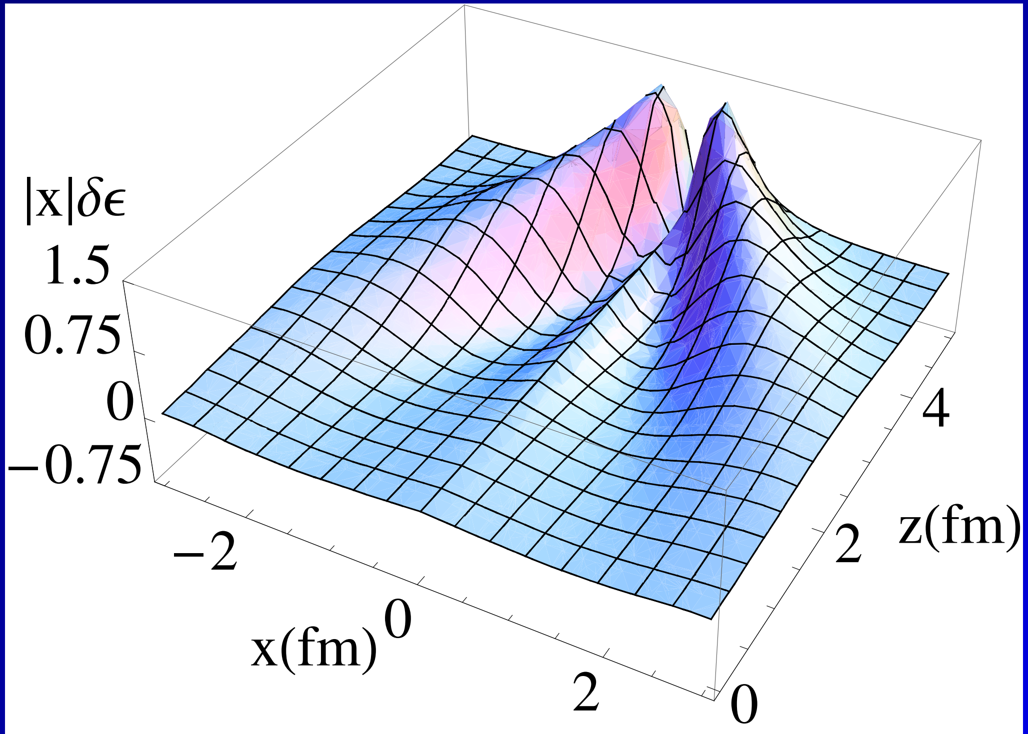
$$T^{\mu\nu} \to T_0^{\mu\nu} + \delta T^{\mu\nu} \qquad \partial_\mu \delta T^{\mu\nu} = J^\nu$$

$$\delta T^{00} \equiv \delta\epsilon, \quad \delta T^{0i} \equiv g^i,$$

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

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

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



Qin, Majumdrr, Song & Heinz (2008)

Microscopic picture of Mach wave

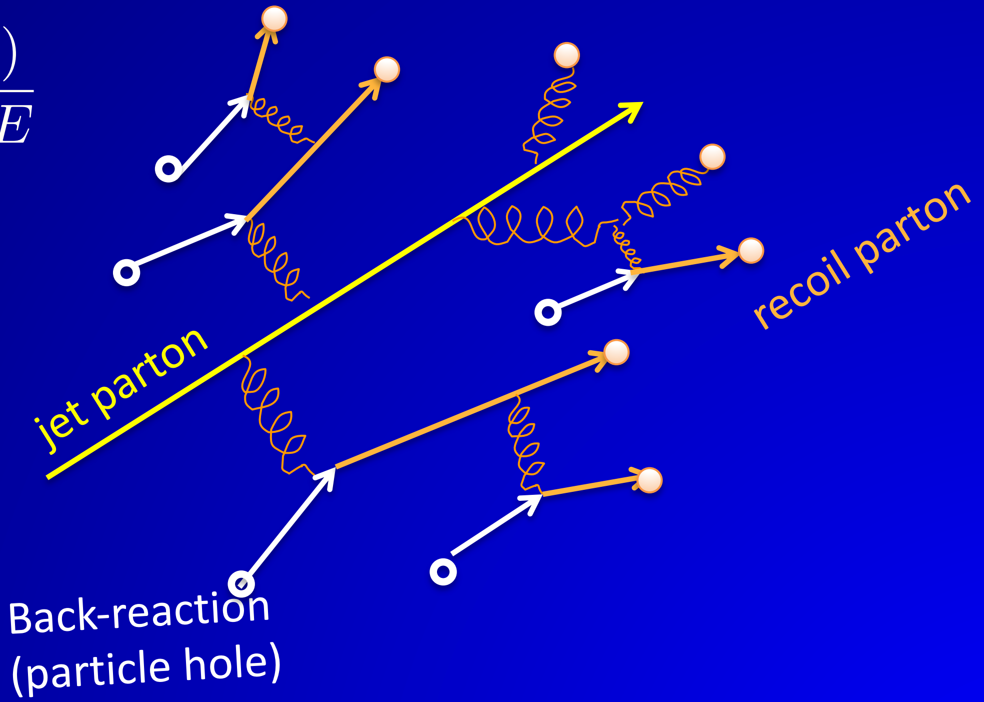
LBT: Linear Boltzmann Transport

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

Induced radiation

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

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



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

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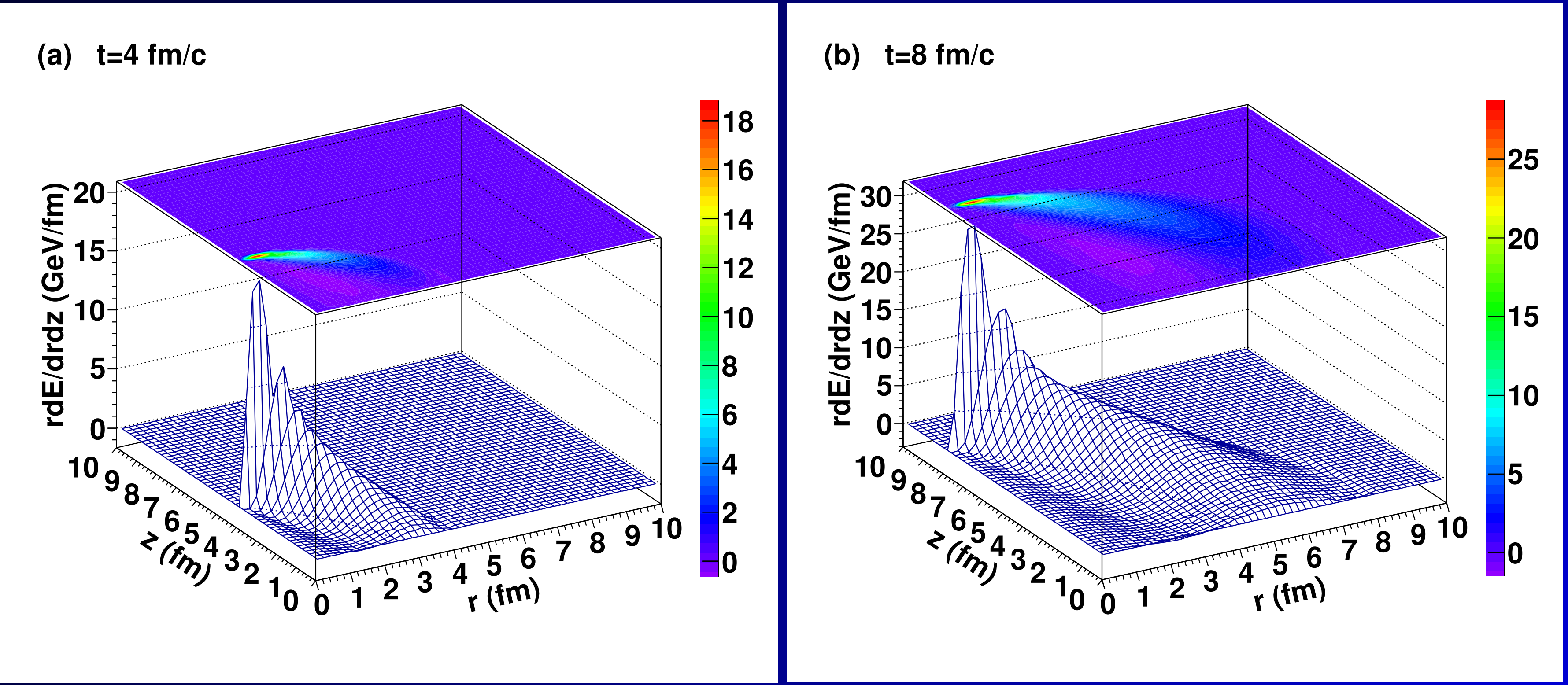
LBT: Jet-induced medium response



Energy distr. of medium response 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

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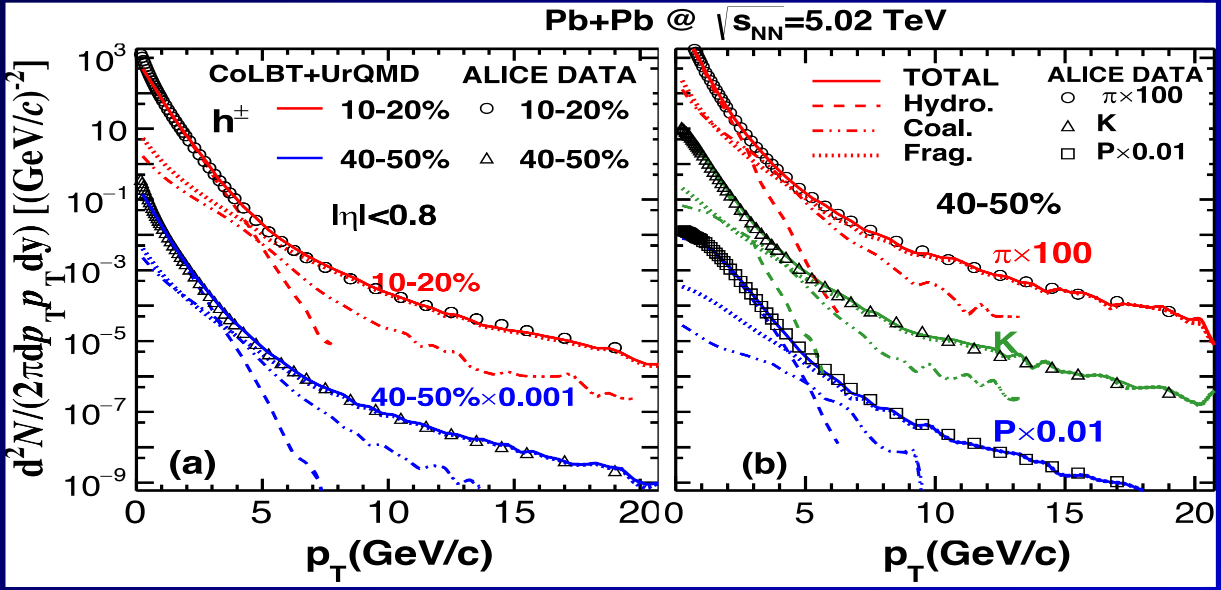
Hadron spectra from low to high p_T

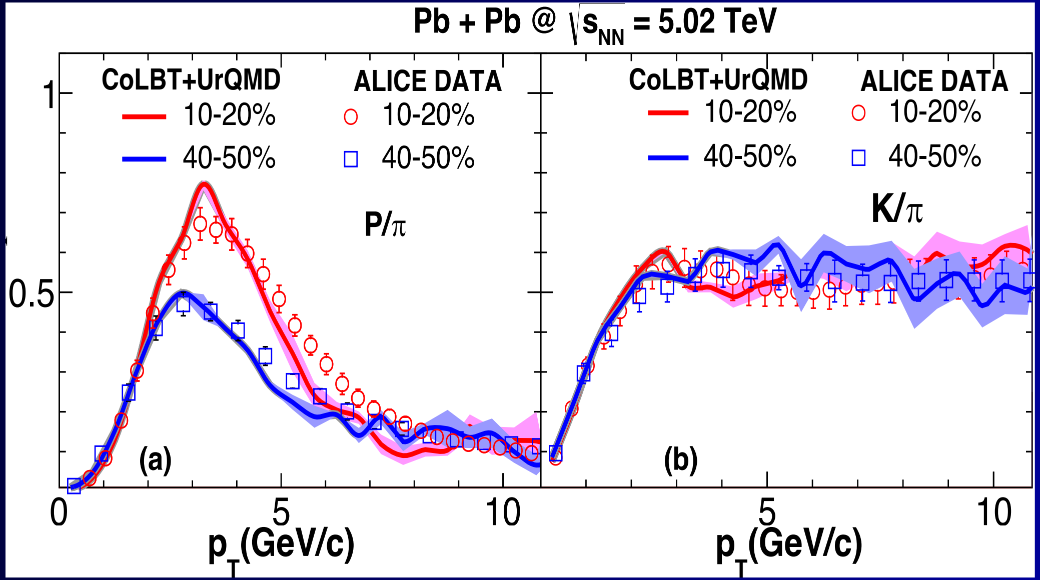
CoLBT-hydro:

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)

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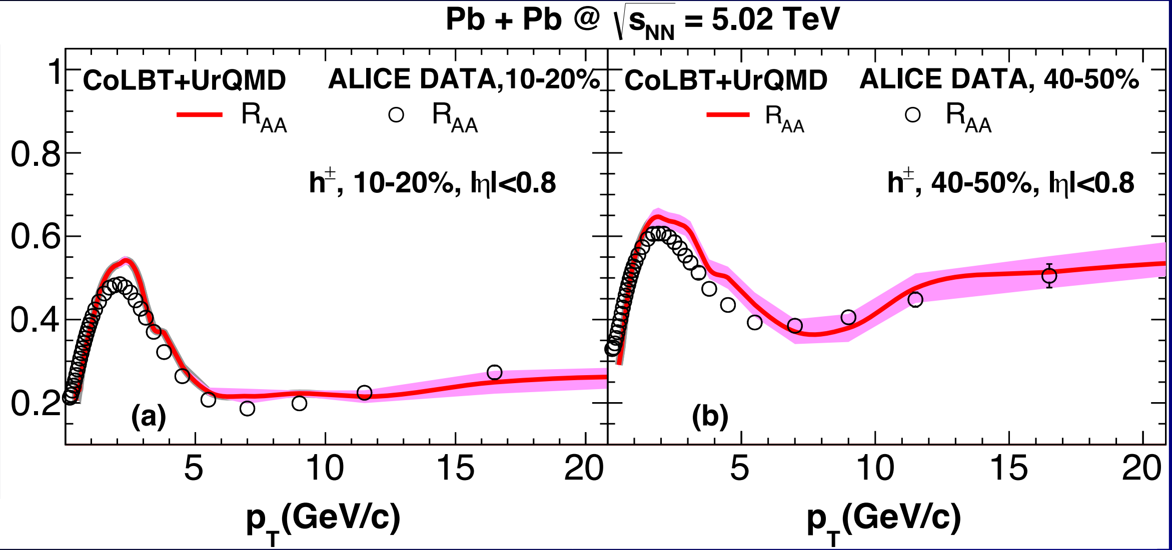
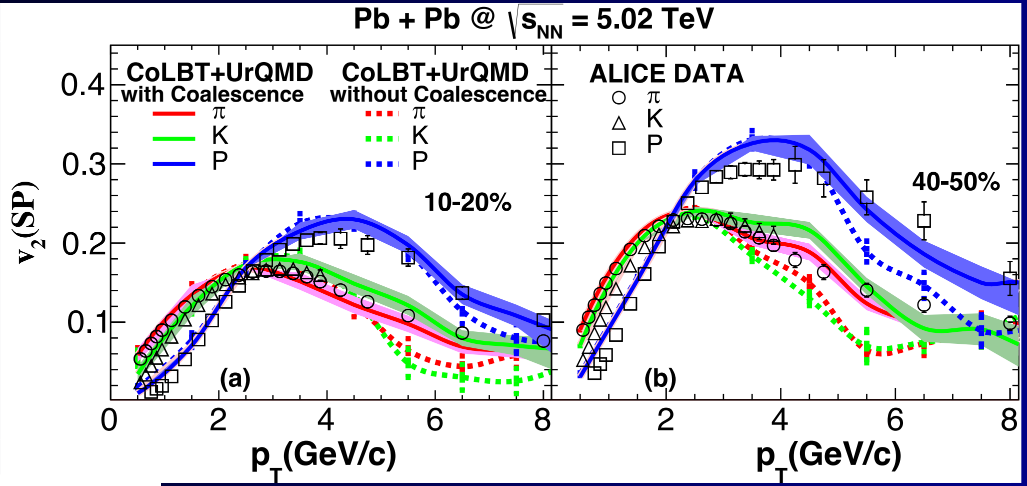
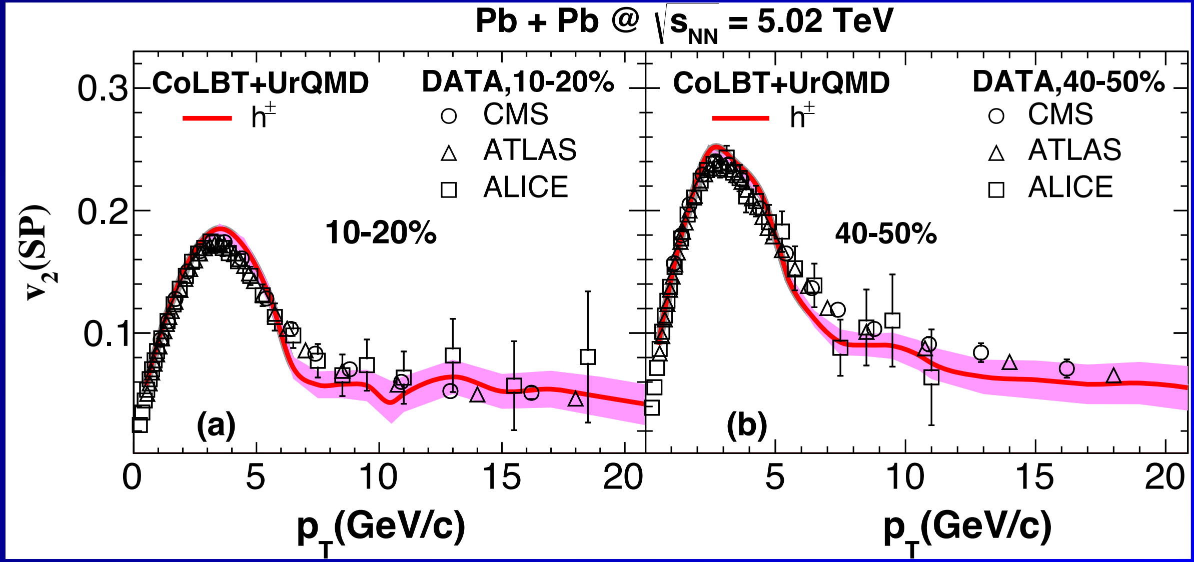
Solving R_{AA}-v_2 puzzle

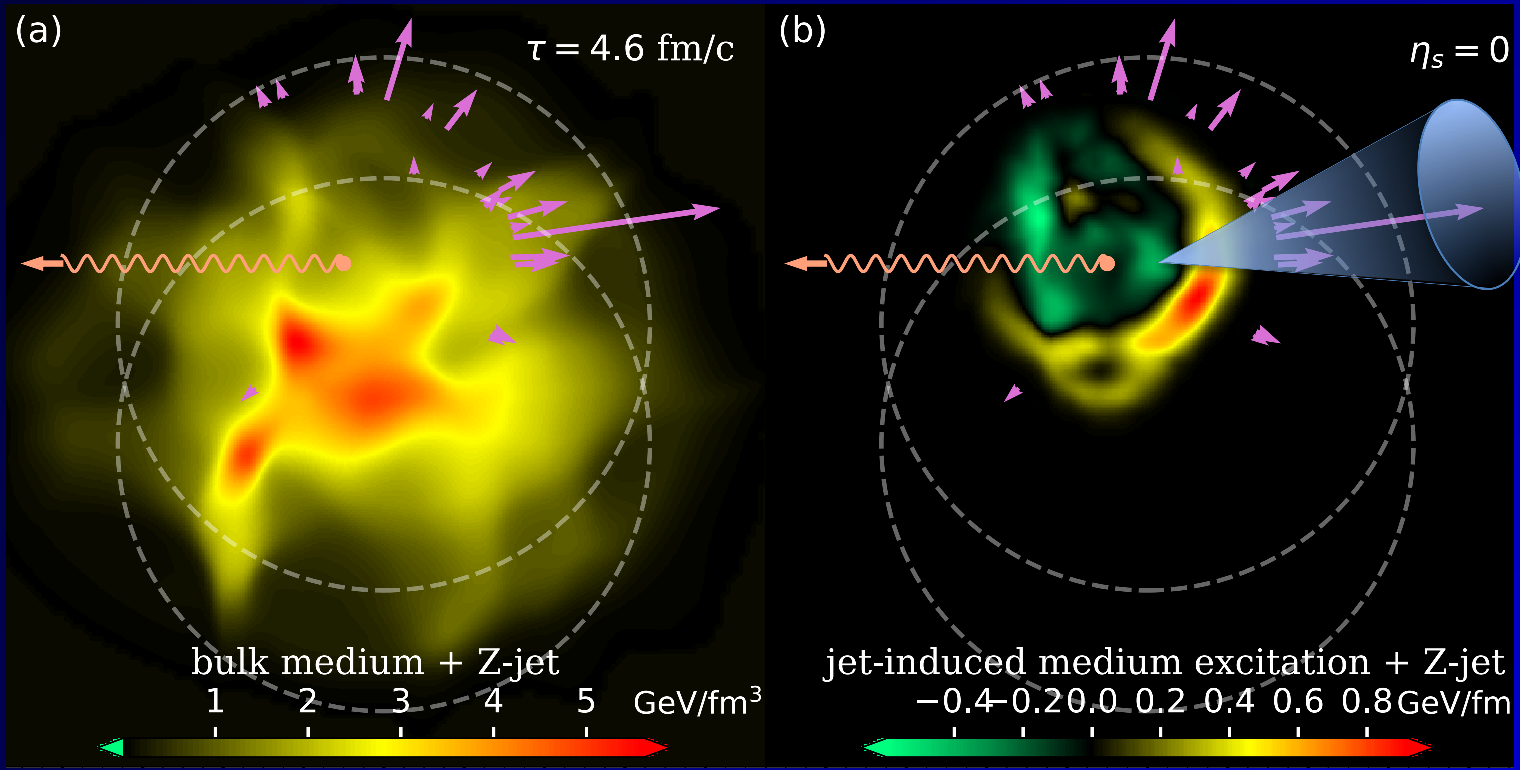


Zhao, Ke, Chen, Luo & XNW,
PRL 128 (2022) 2, 022302 (2103.14657)

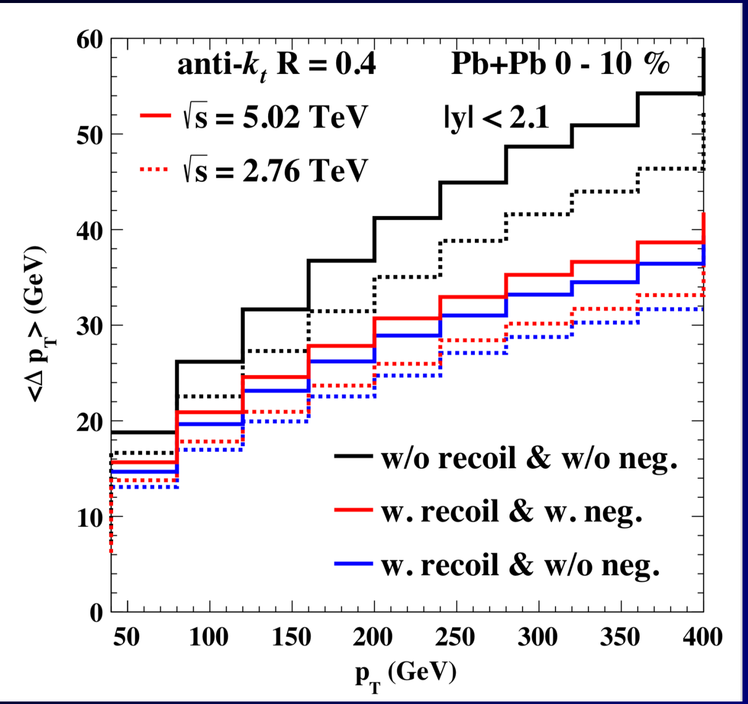


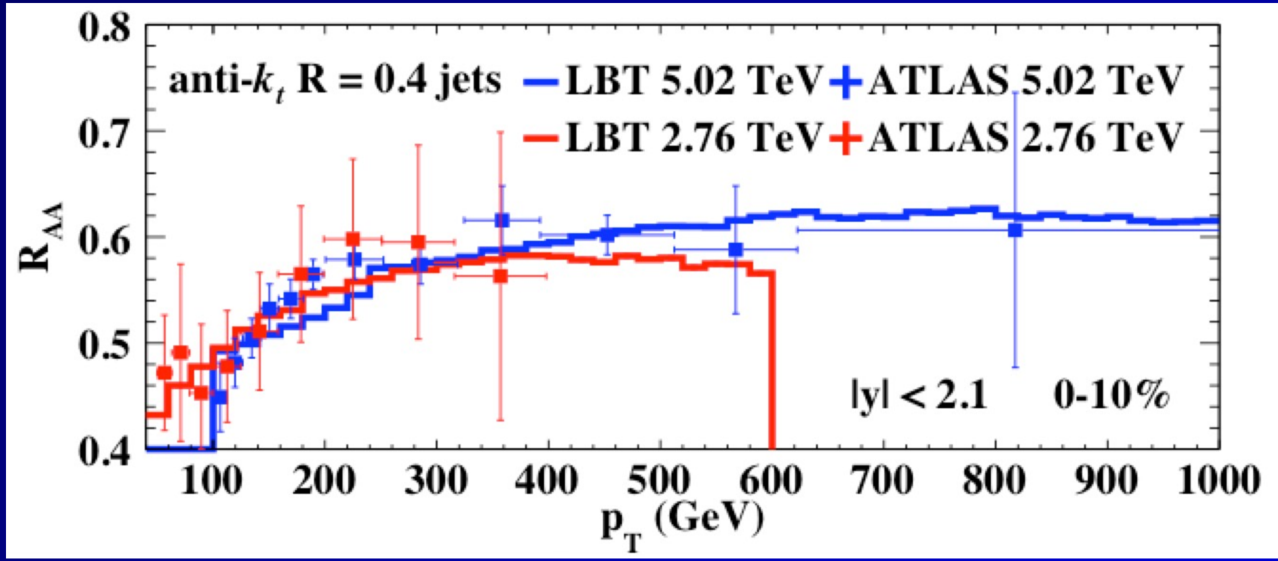


Z/γ-jet: probing QGP



Jet suppression and energy loss



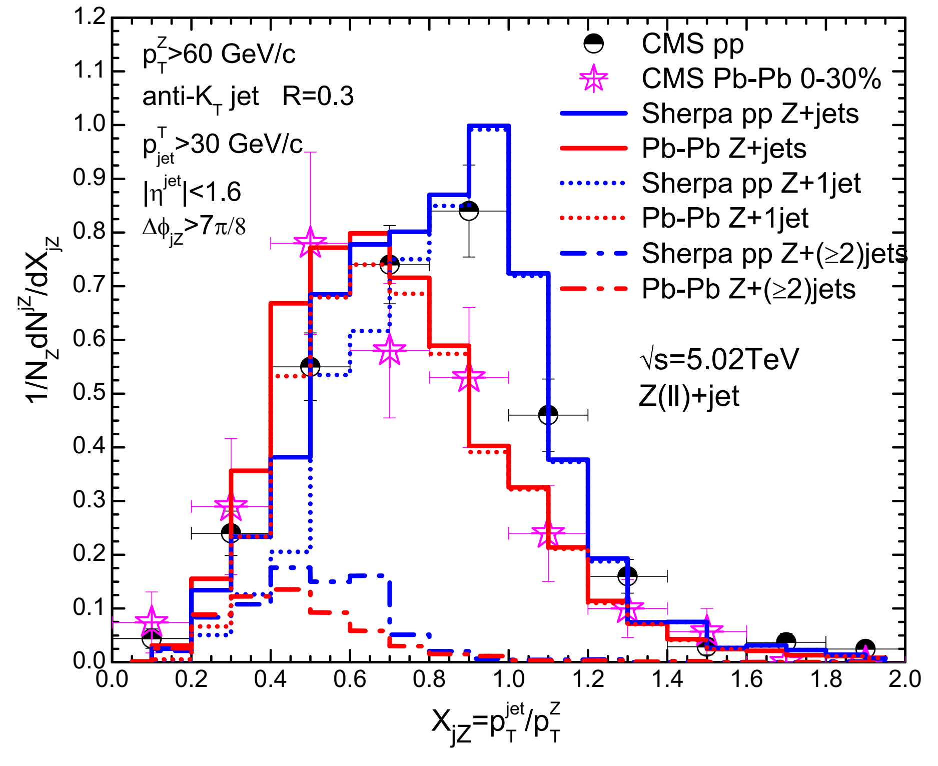


He, Cao, Chen, Luo, Pang & XNW 1809.02525

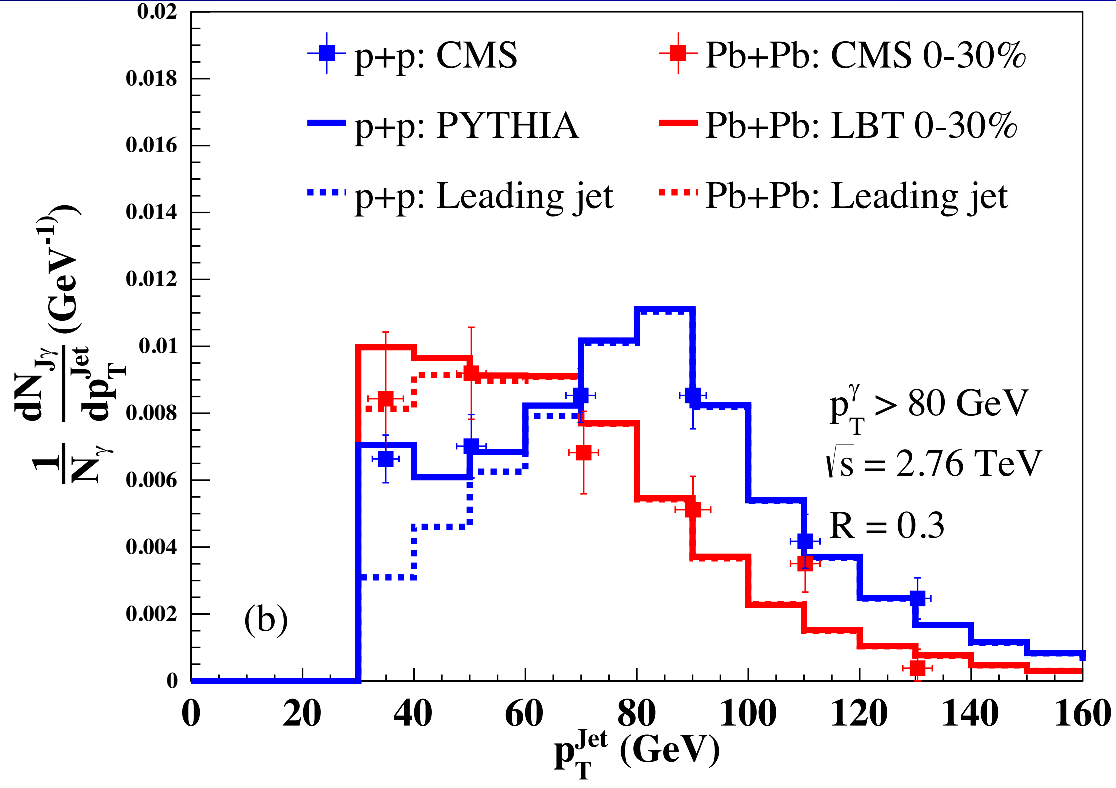
- Weak p_T dependence: initial jet spectra and p_T dependence of energy loss ΔE
- Week energy dependence: increase of jet energy loss and the slope of initial spectra
- Medium response reduce jet net energy loss

Energy loss in γ/Z-jet at LHC

Suppression of leading and multiple jets



Zhang, Luo, XNW, Zhang, arXiv:1804.11041

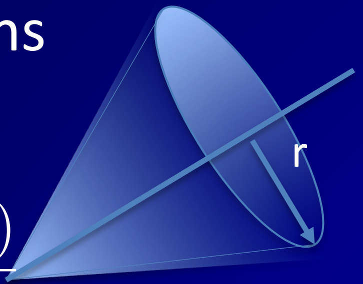


Luo, Cao, He & XNW, arXiv:1803.06785

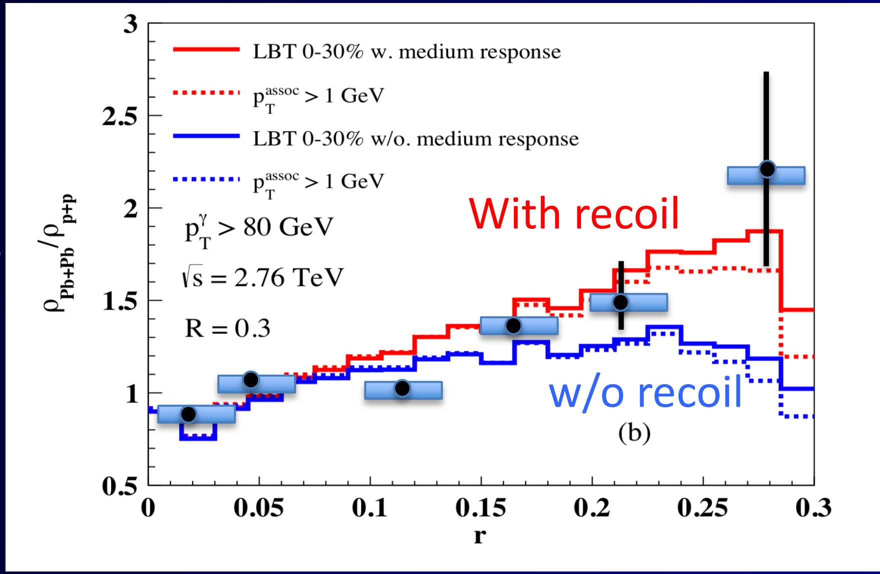
Medium modification of γ-jets

Enhancement of soft hadrons in large angles

$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{p_T^{jet}(r-\Delta r/2, r+\Delta r/2)}{p_T^{jet}(0,R)}$$

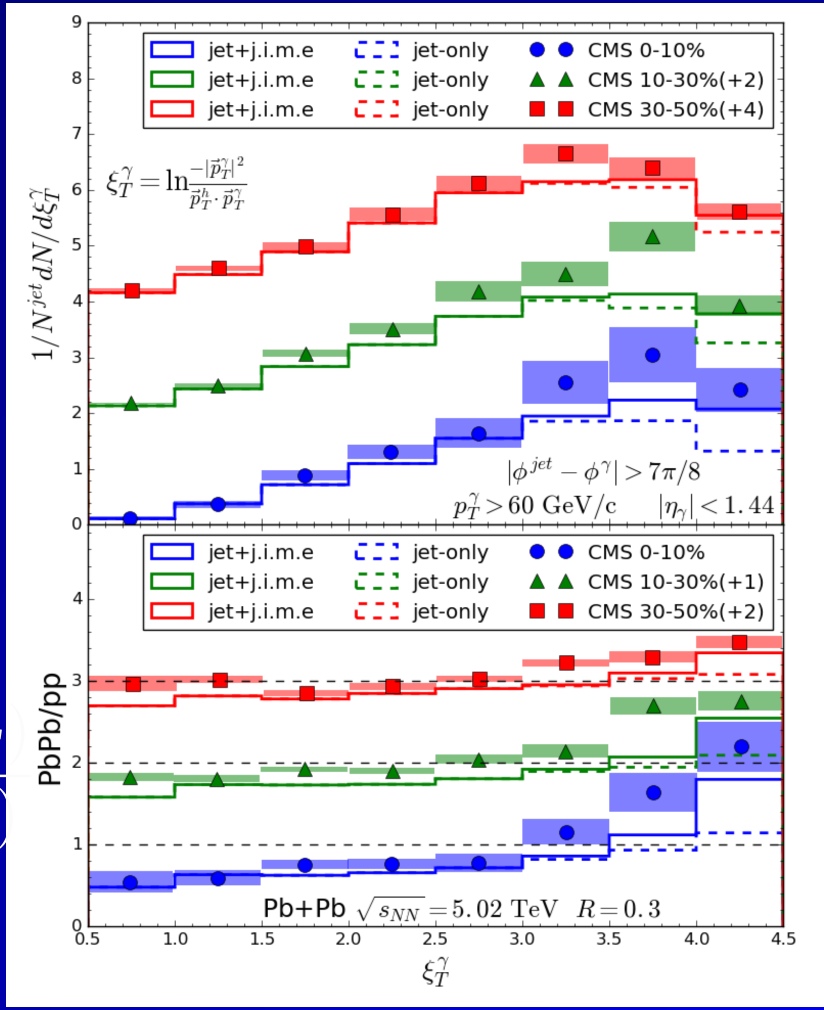


$$\frac{\rho_{AA}(r)}{\rho_{pp}(r)}$$



Luo, Cao, He & XNW, arXiv:1803.06785

$$I_{AA} = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$



Chen, Cao, Luo, Pang & XNW, 2005.09678

Medium response & soft gluon radiation

Medium response:

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

Medium-induced gluon radiation:

Formation time:

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

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

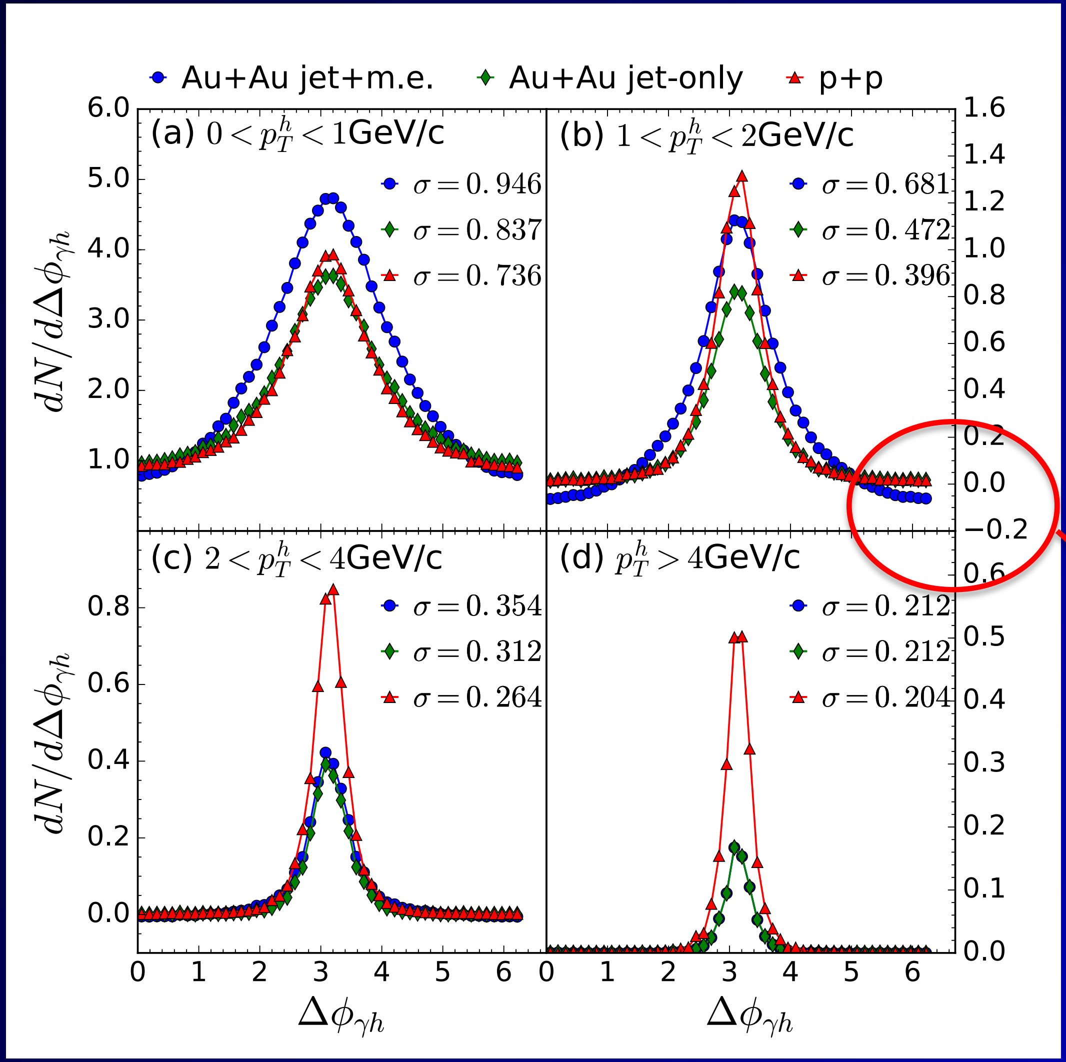
Mean-free-path
limits the formation time

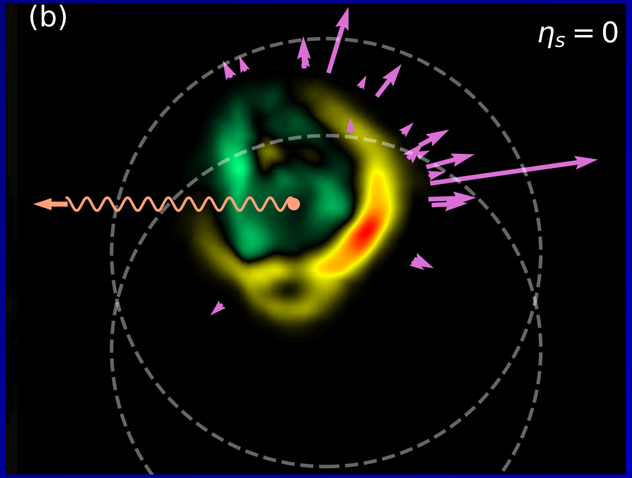
$$\tau_f \leq \lambda \sim 1/T \quad \hat{q} \sim T^3$$

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

Berkeley Lab

Signal of diffusion wake





Depletion of the background
In the γ direction

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

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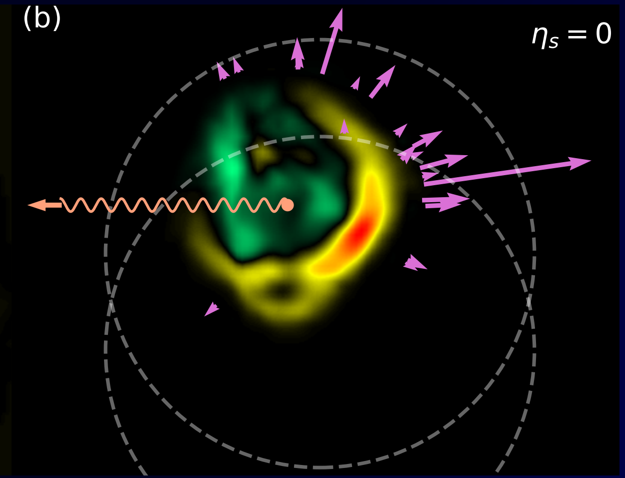
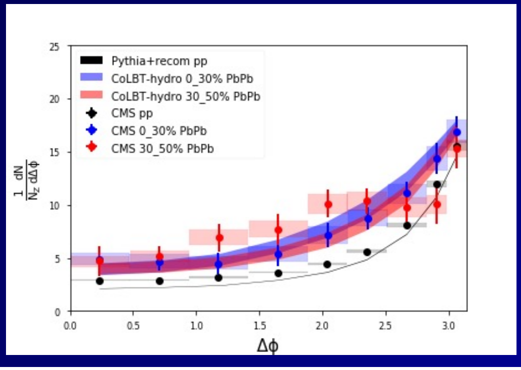
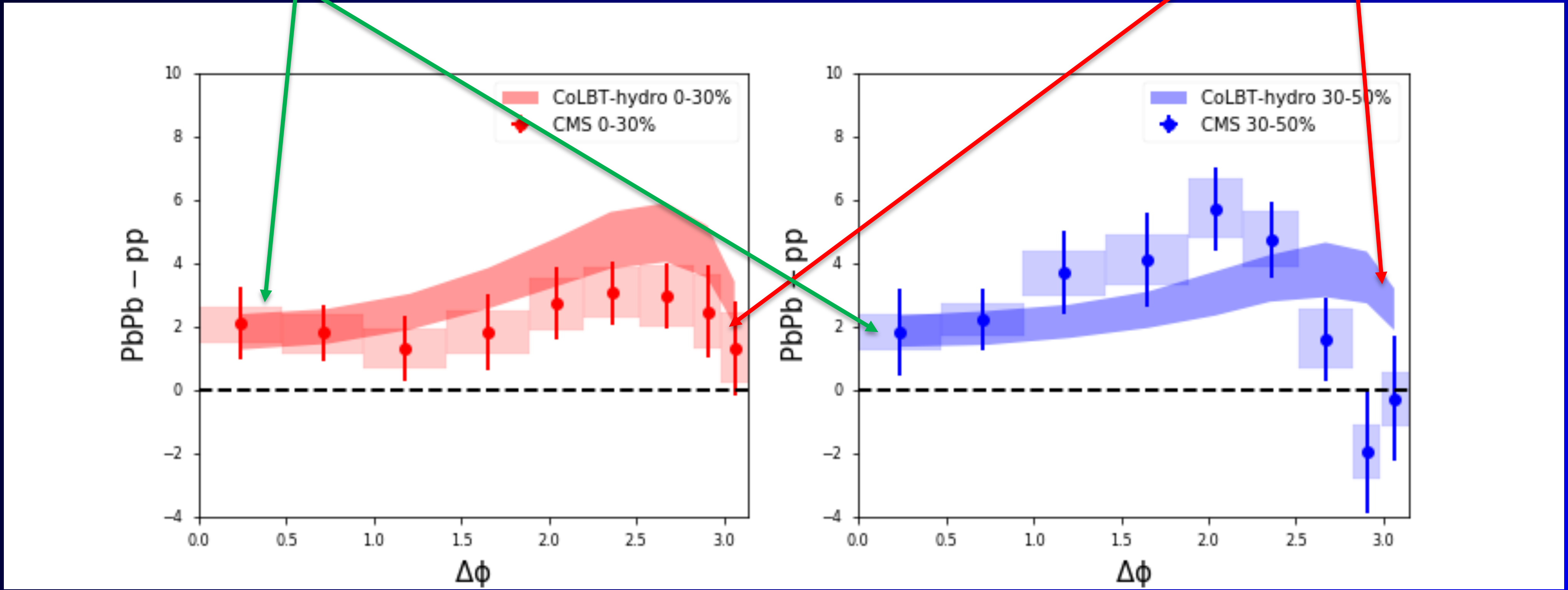
Z-hadron correlation





enhancement
of the away-side
background

enhancement
and broadening
of the jet peak



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

MPI: Multiple parton interaction

XNW & Gyulassy (1991)

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

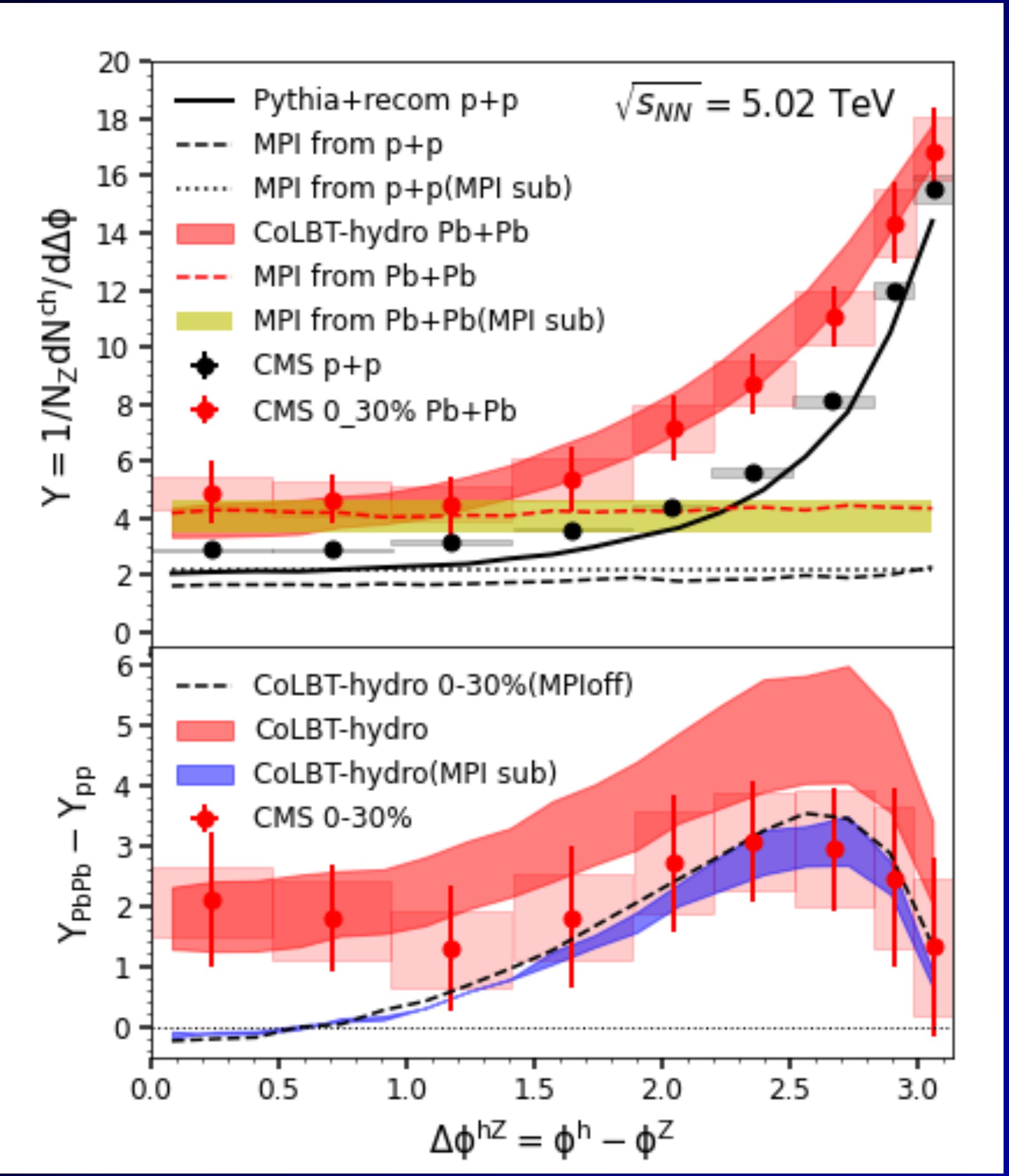
Probability of multiple jets ($p_T > p_0$) with at least one jet with $p_T > p_T^{trig}$

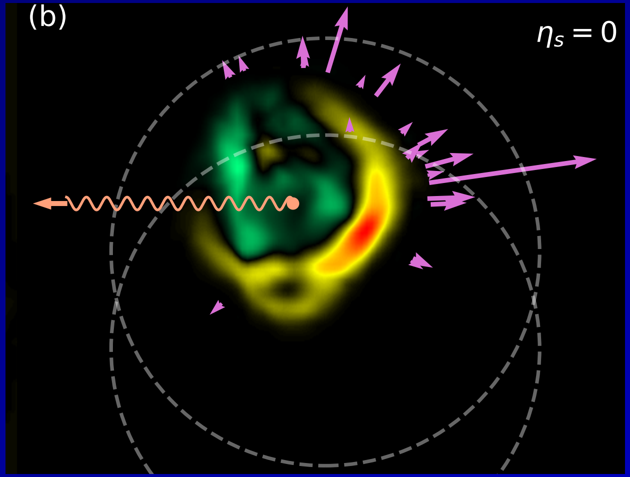
$$g_j^{\rm trig}(b) = \frac{[\sigma(p_0)T(b)]^j}{j!}\left\{1 - \frac{[(\sigma(p_0) - \sigma(p_T^{\rm trig})]^j}{\sigma(p_0)^j}\right\} e^{-\sigma(p_0)T(b)}$$

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

Enhanced multiple minijet
Production in triggered jet events

MPI subtraction in Z-hadron correlation

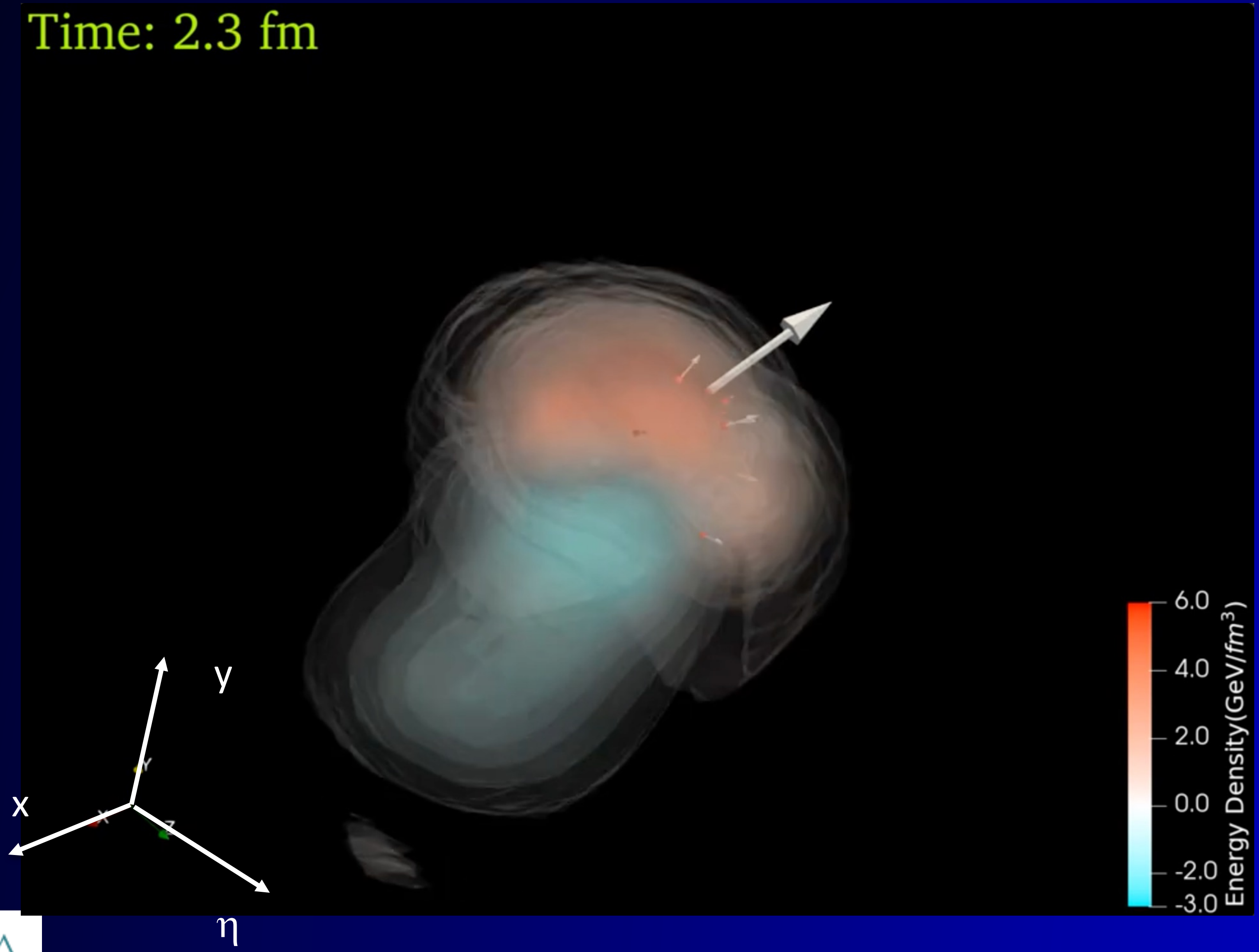




Mixed event subtraction

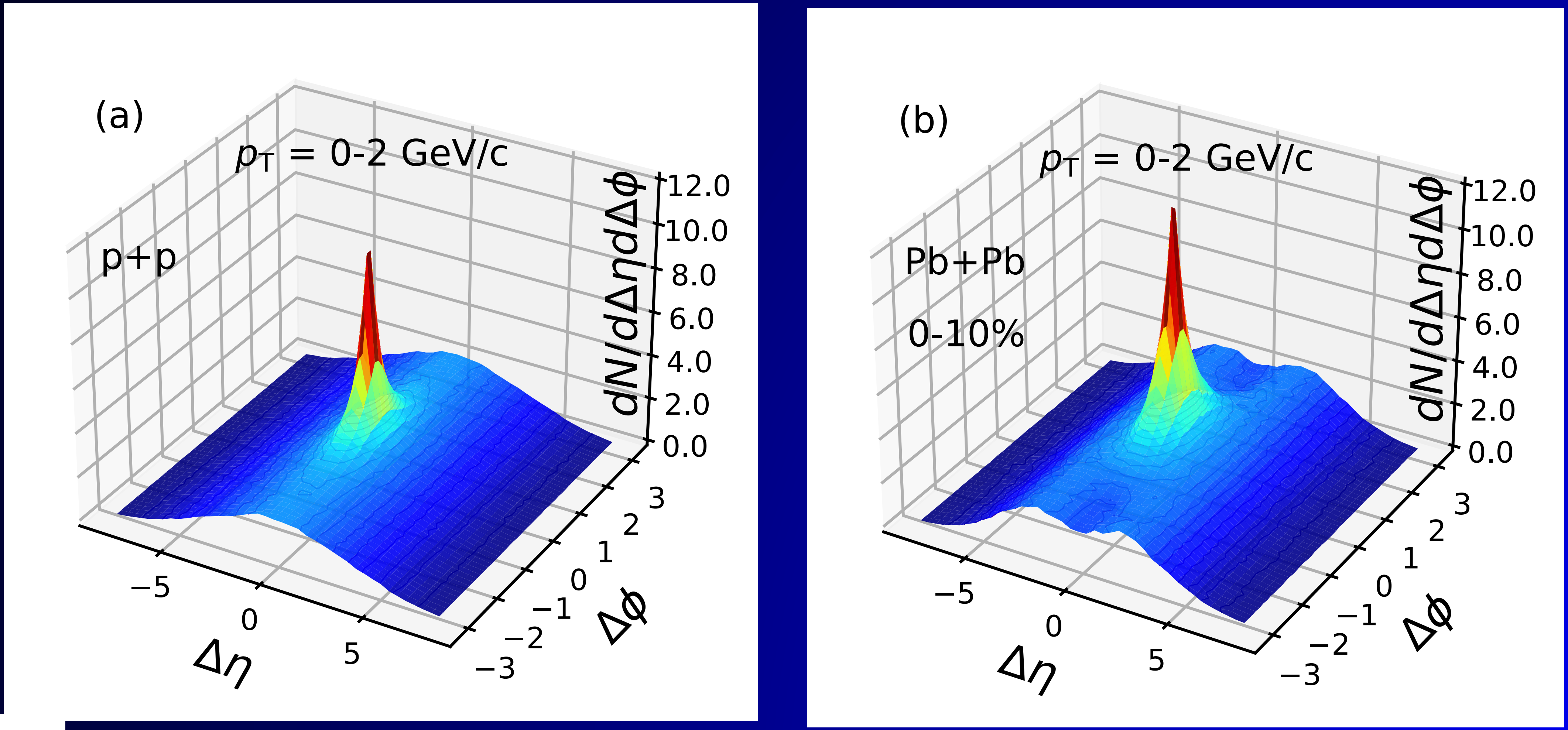
$$\frac{dN^{hZ}_{\text{MPI}}}{d\phi} = \frac{dN^{hZ}_{\text{mix}}}{d\phi} - \int_1^{\pi} \frac{d\phi}{\pi} \left(\frac{dN^{hZ}}{d\phi} - \frac{dN^{hZ}}{d\phi}\Big|_{\phi=1} \right)$$

3D structure of diffusion wake



3D structure of diffusion wake

Jet-hadron correlation in γ/jet events



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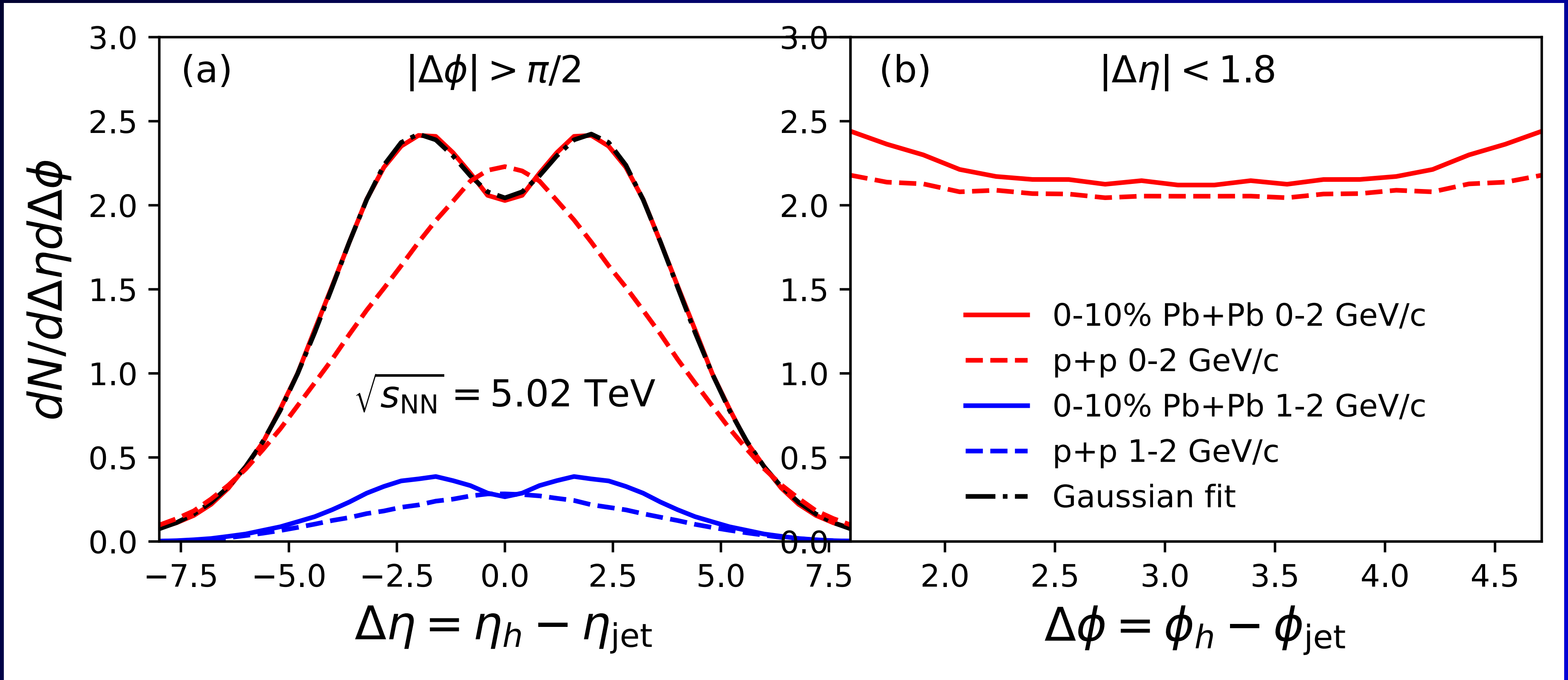
Double peak structure in η



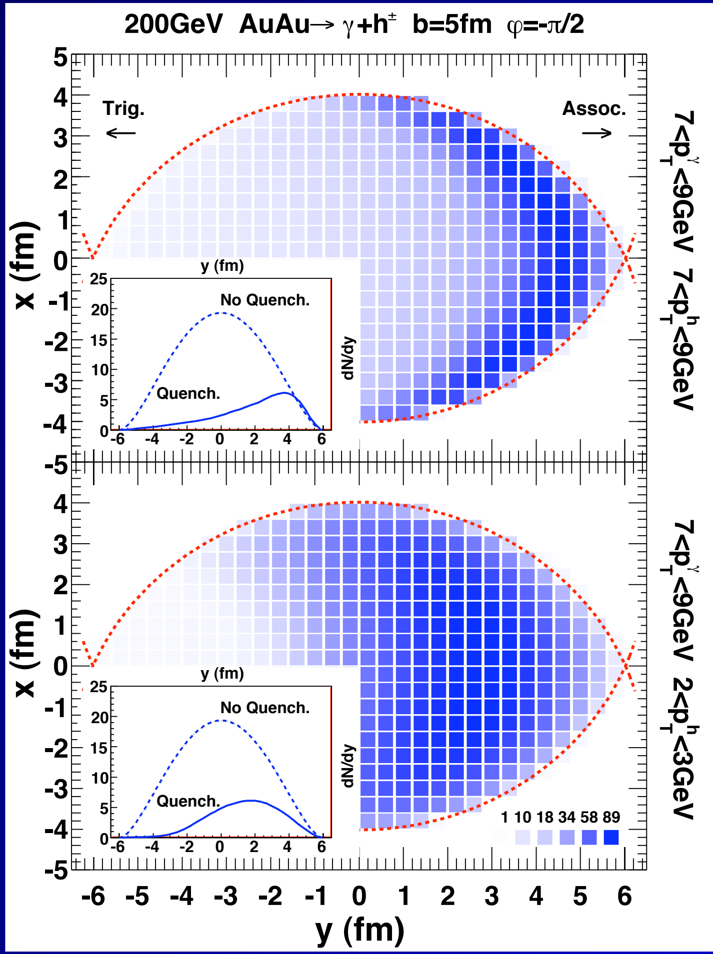
$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j F_3(\eta_j)(F_2(\Delta\eta, \eta_j) + F_1(\Delta\eta)),$$

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

Longitudinal jet tomography

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

length dependence of parton Energy loss



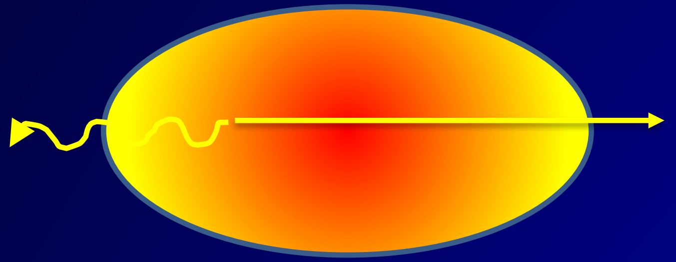
$p_T^h/p_T^\gamma \sim 1$

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

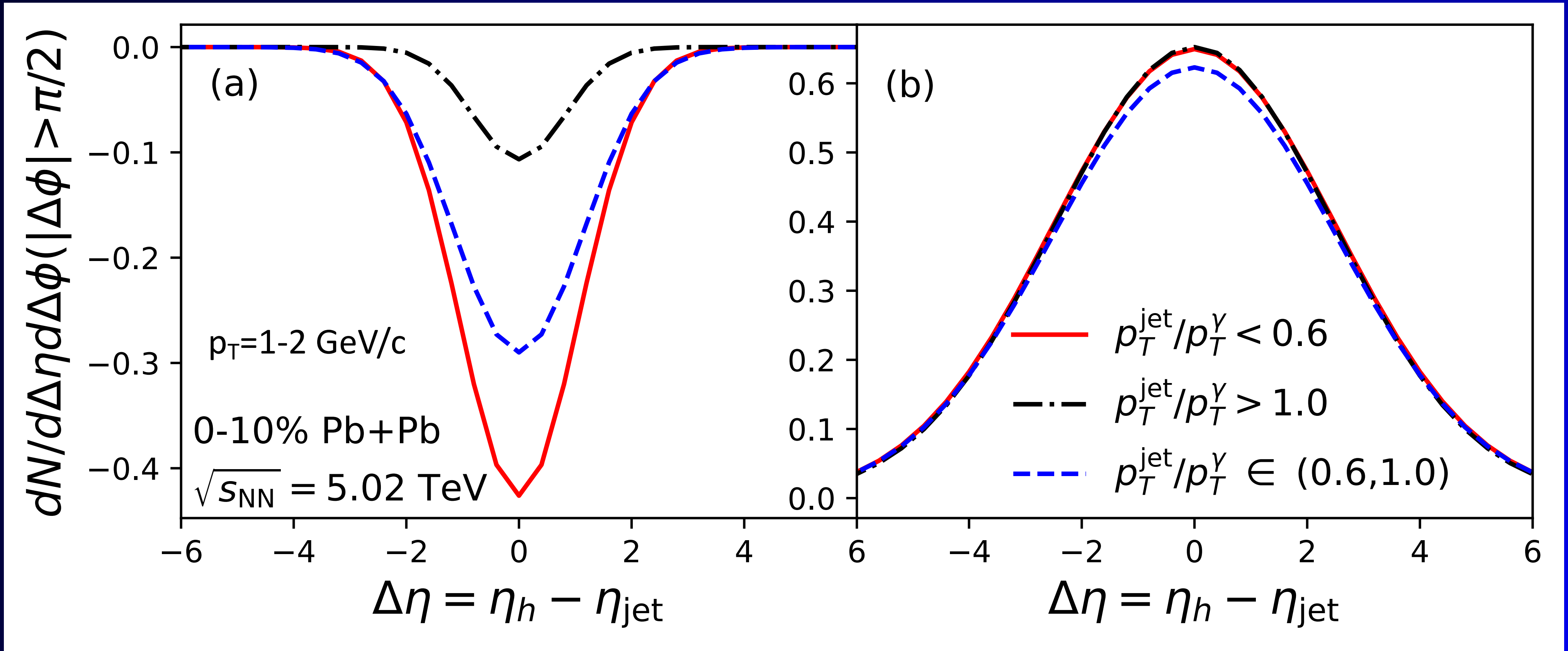
γ-jet asymmetry $x_{\gamma jet}=p_T^{jet}/p_T^\gamma$

Can be used to select propagation length <L>

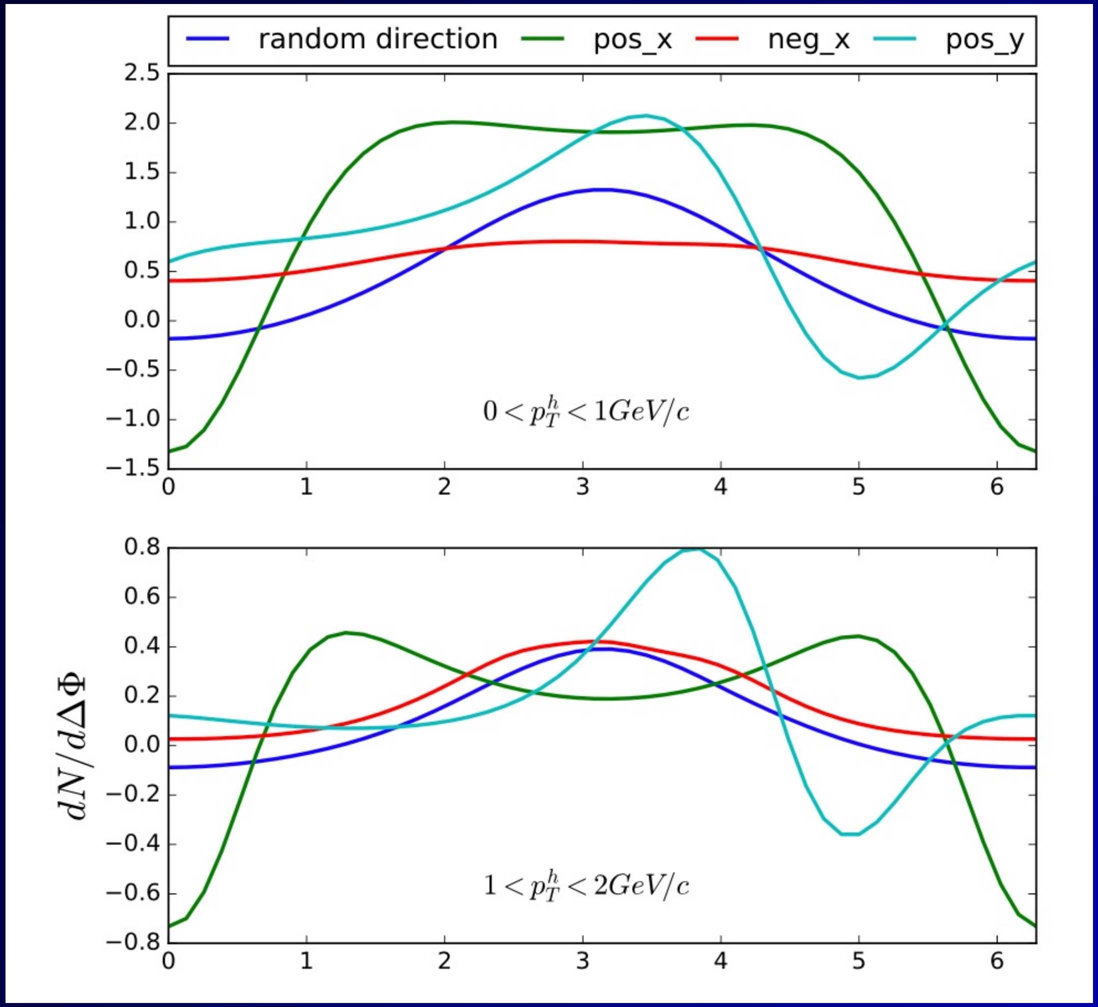
Diffusion wake and jet energy loss



p_T^{jet}/p_T^{γ} : proxy of jet energy loss

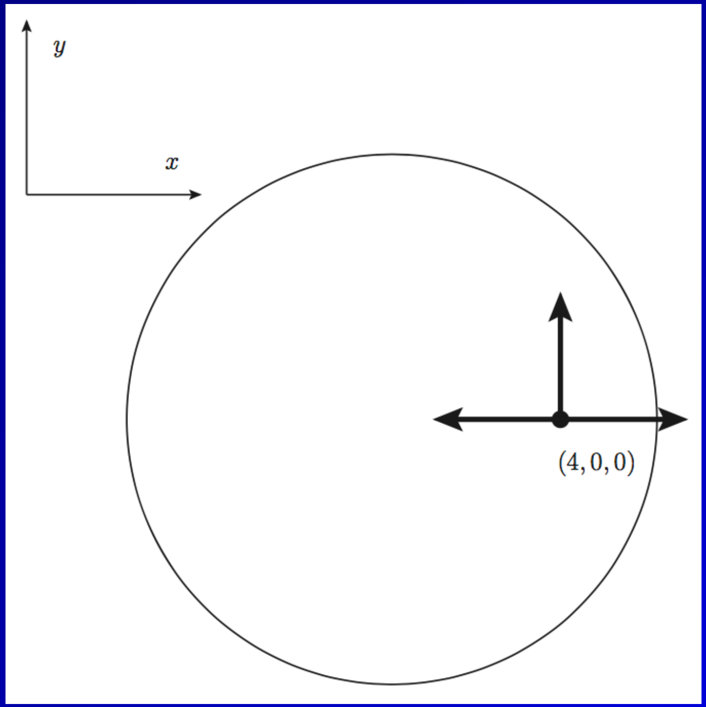


Initial position & azimuthal correlation



$\Delta\Phi$

γ-hadron correlation



W Chen & XNW (2018)

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

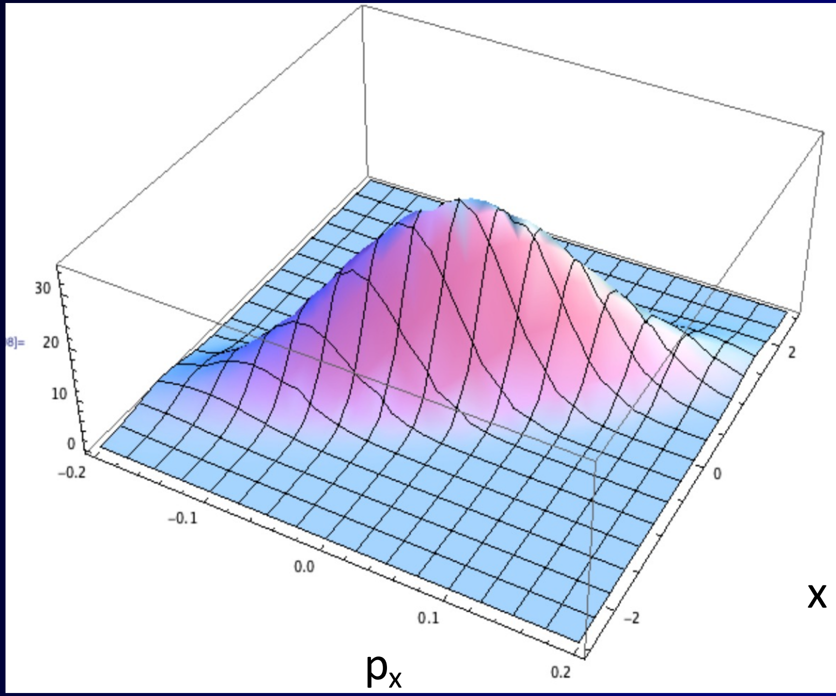
Tachibana, Shen & Majumder 2001.08321 (2020)

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



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

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

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

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

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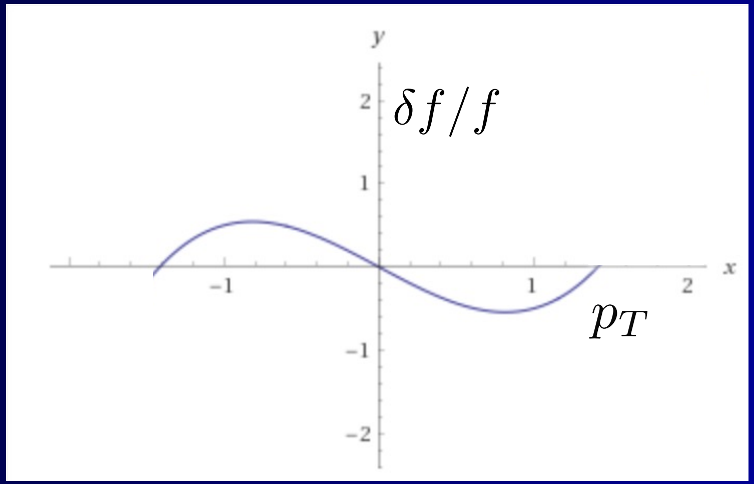
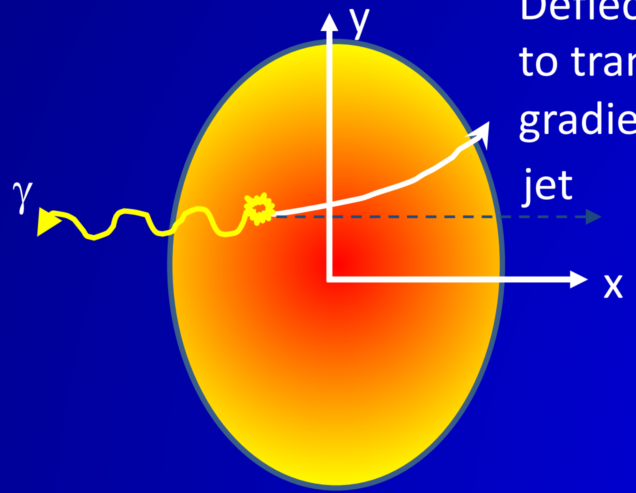
Drift-diffusion equation: non-uniform medium

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

Momentum asymmetry:

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

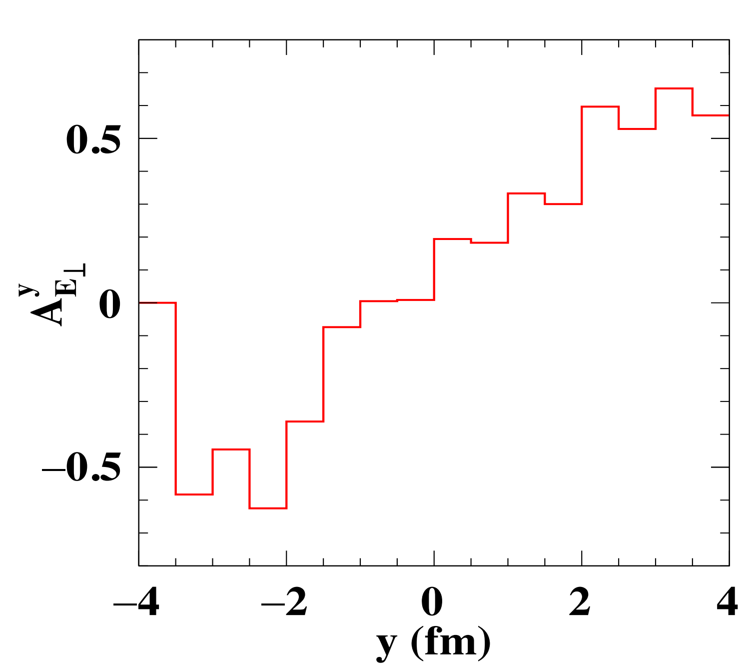


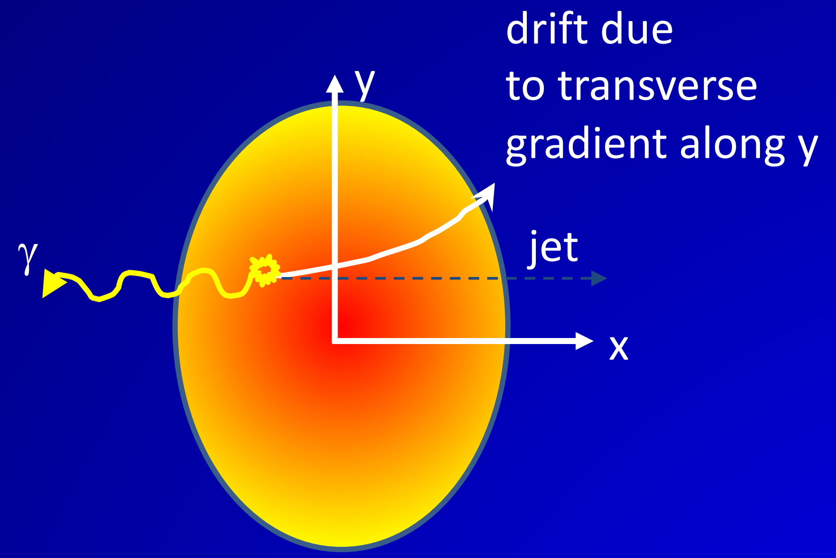


Transverse gradient tomography

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

(p_T>3 GeV/c)



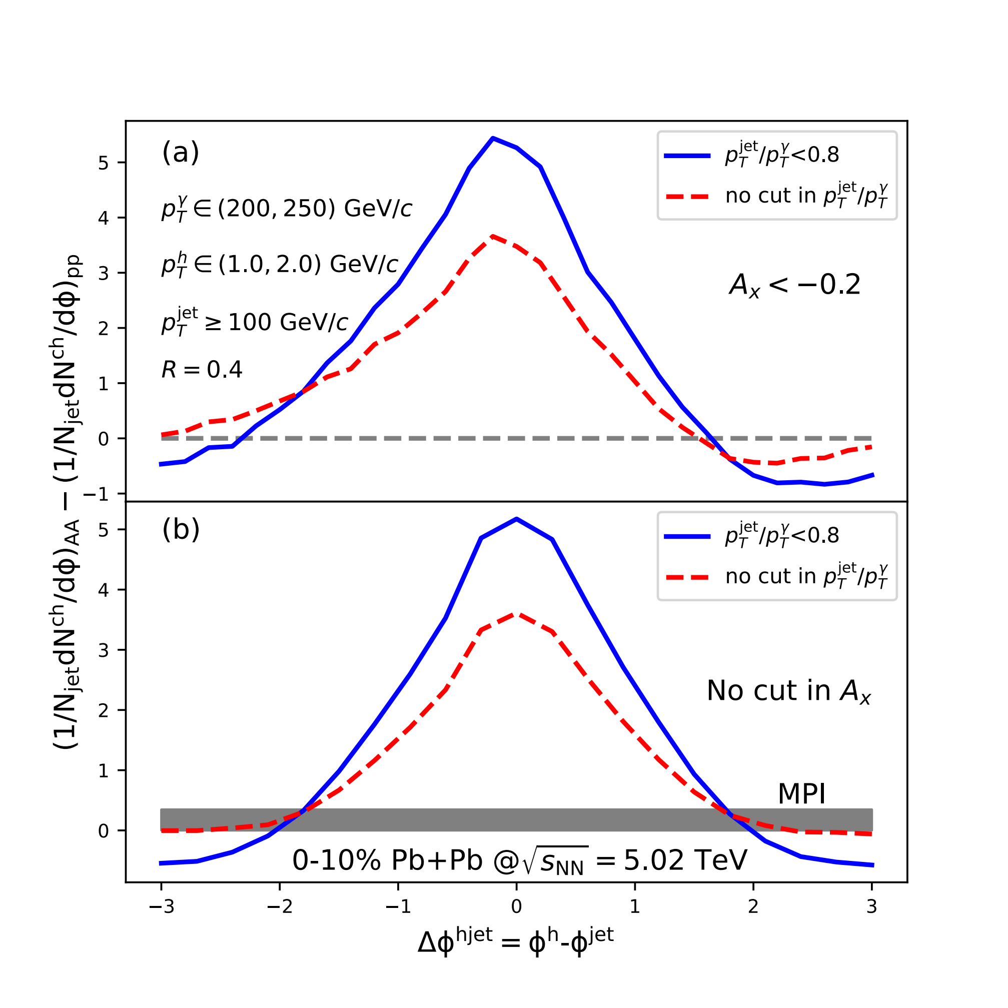


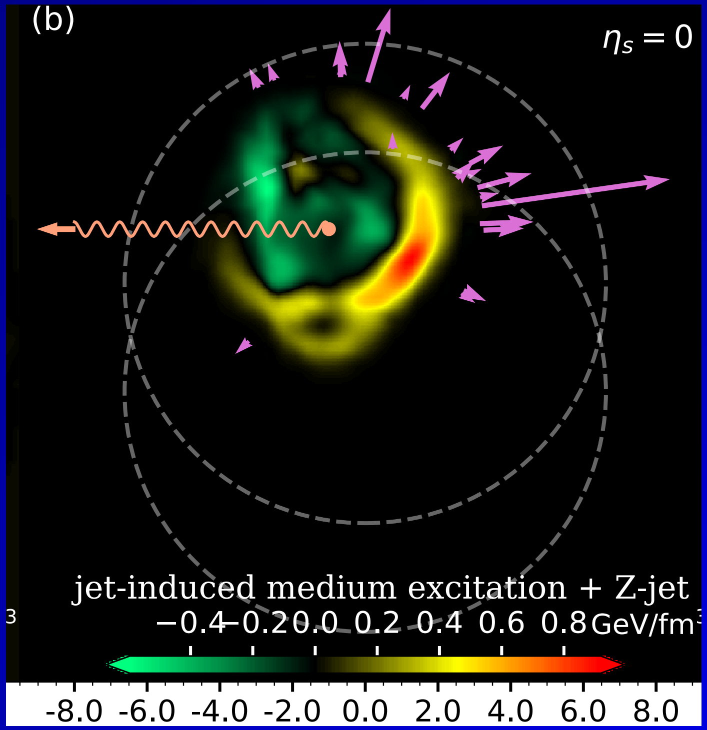
He, Pang & XNW, *Phys Rev Lett* 125 (2020) 12, 122301

Jet energy loss → propagation length → initial jet position in x: Longitudinal tomography

3D jet tomography

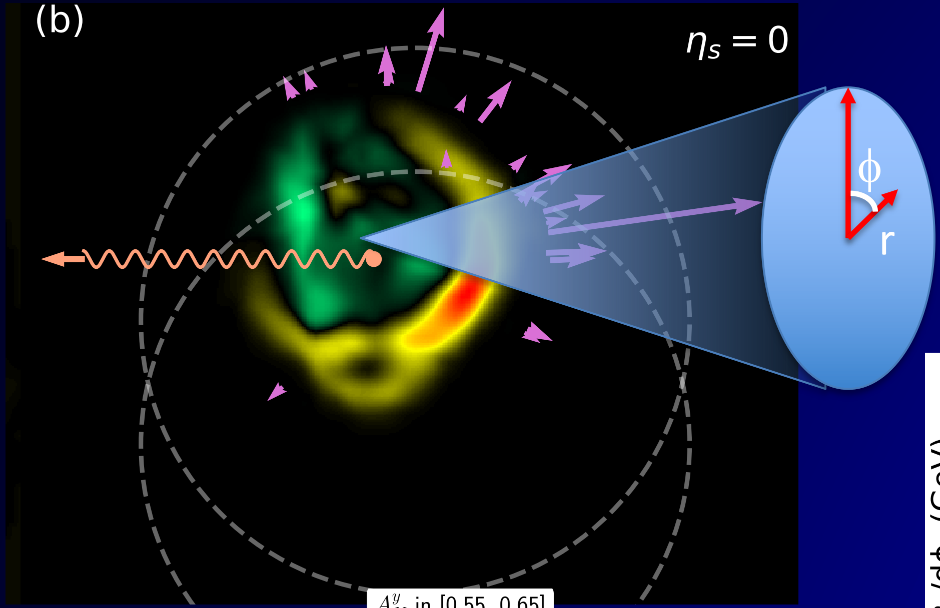
Enhancing the diffusion wake





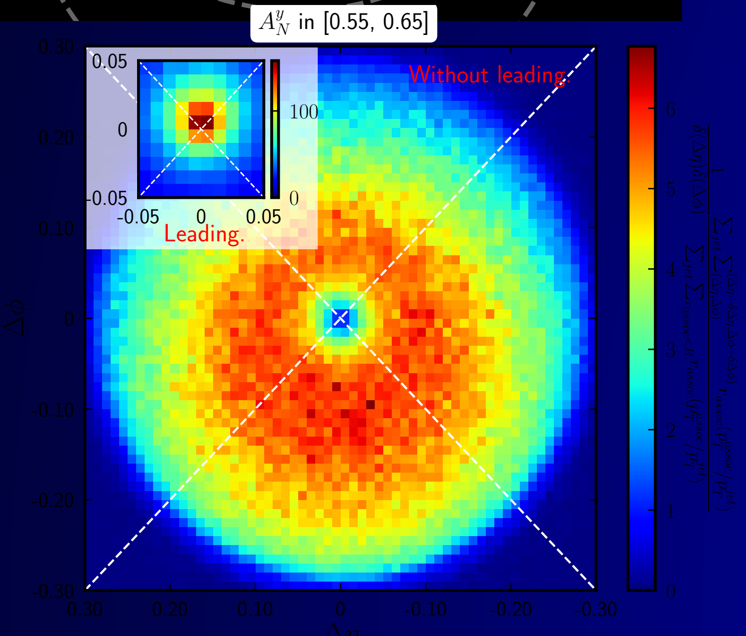
Chen, Yang, He, Ke, Pang and XNW, *Phys. Rev. Lett.* 127 (2021) 8, 082301

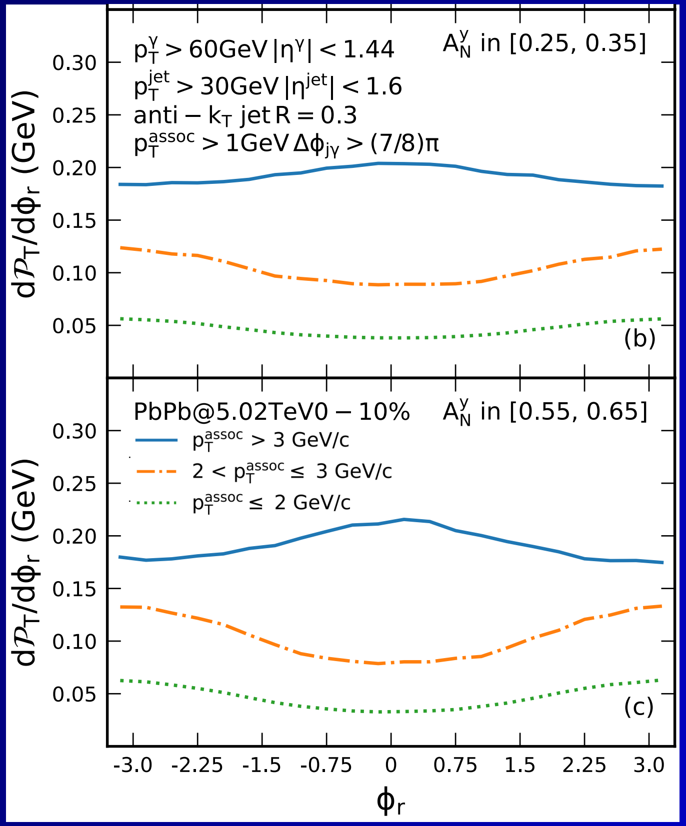
Asymmetric jet shape

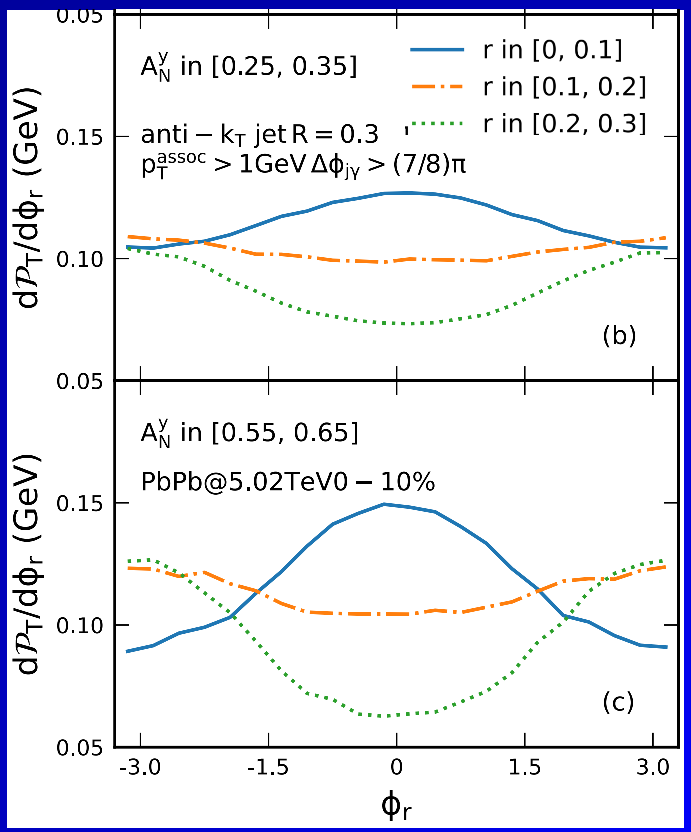


Energetic hadrons at the core of jet deflected away from center

Soft hadrons from medium response at large angle flow into center







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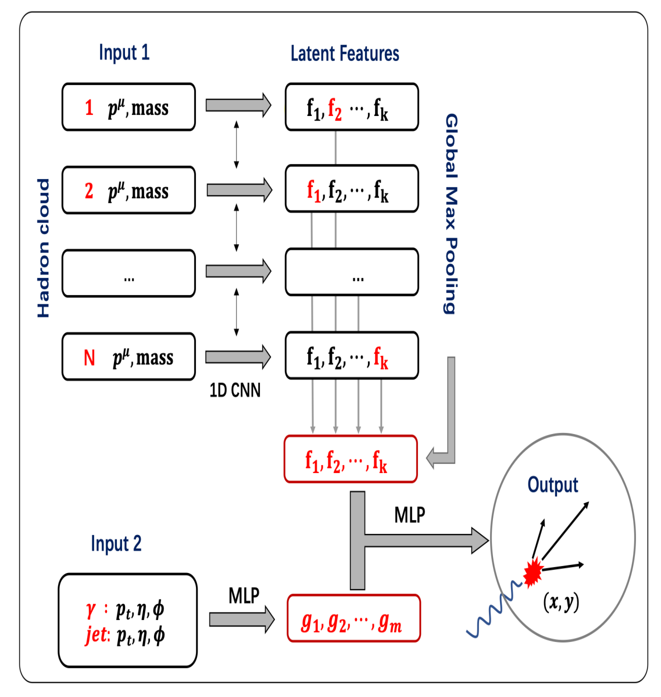
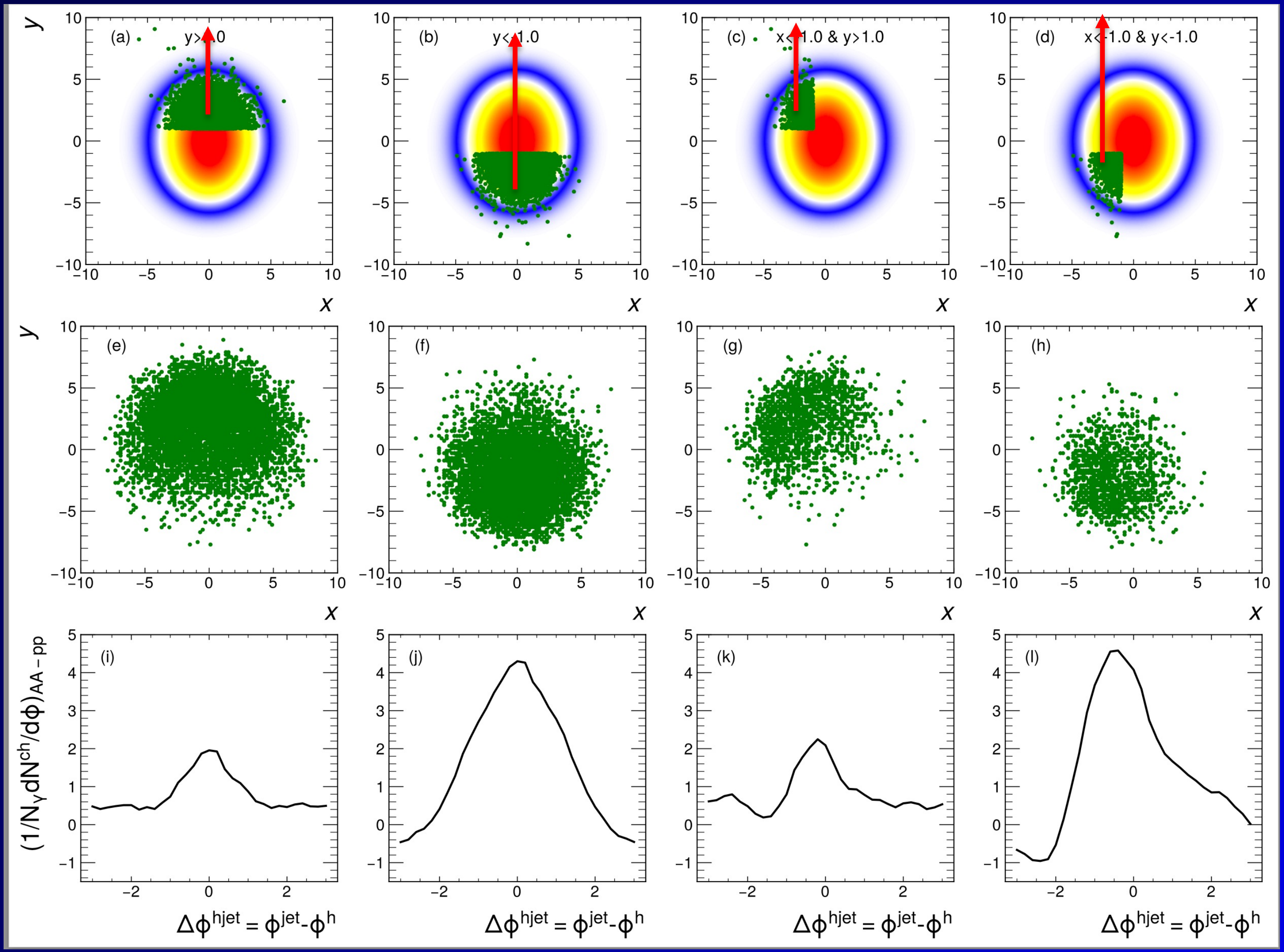
Deep learning assisted jet tomography

PCN (point cloud network)



Eur.Phys.J.C 83 (2023) 7, 652

Yang, He， Chen， Ke， Pang & XNW



DL network selection

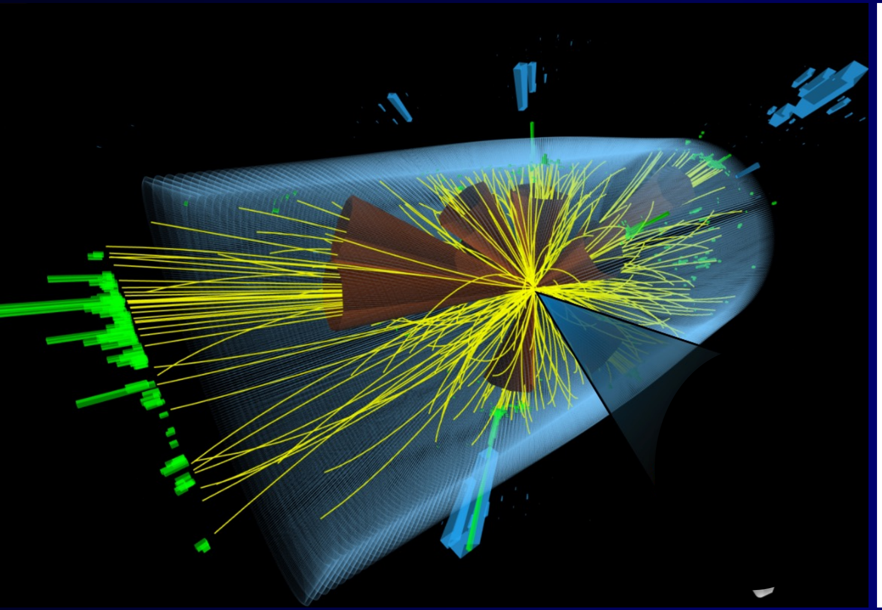
Actual distribution

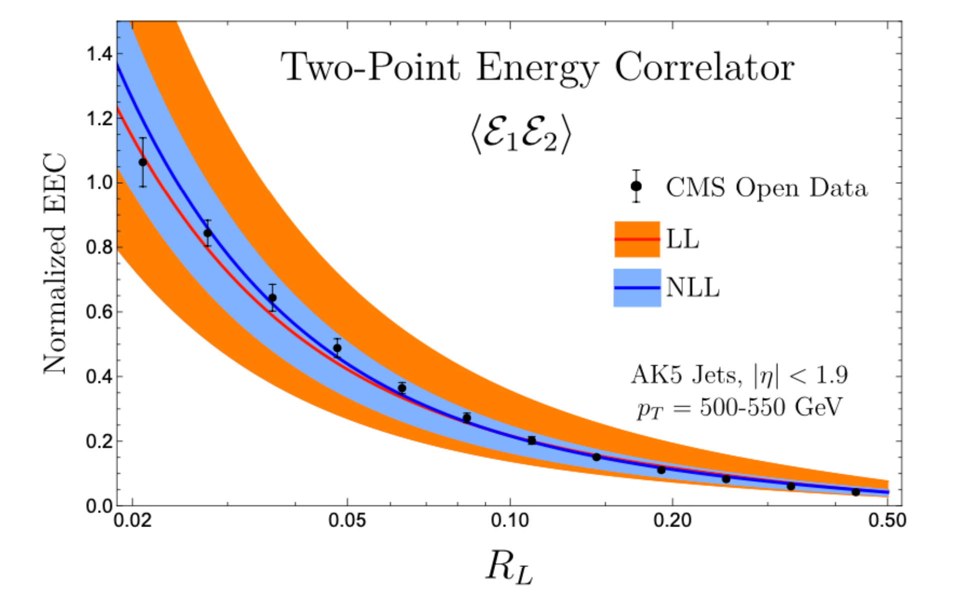
γ-soft hadron correlation

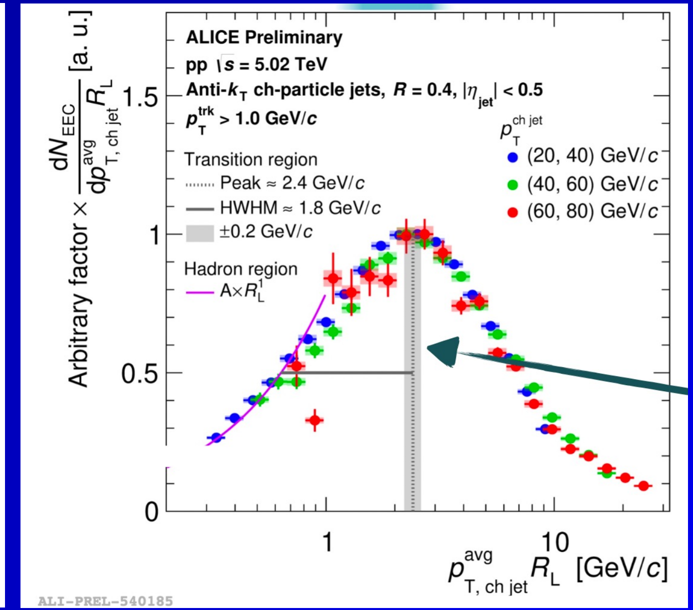
Energy-energy correlator (EEC)

A new jet substructure observable:

$$\frac{d\Sigma^{(n)}}{d\theta} = \frac{1}{\sigma}\sum_{i\neq j}\int d\vec{n}_{i,j}\,\frac{d\sigma_{ij}}{d\vec{n}_{i,j}}\,\frac{E_i^n E_j^n}{Q^{2n}}\,\delta(\vec{n}_1\cdot\vec{n}_2-\cos\theta)$$



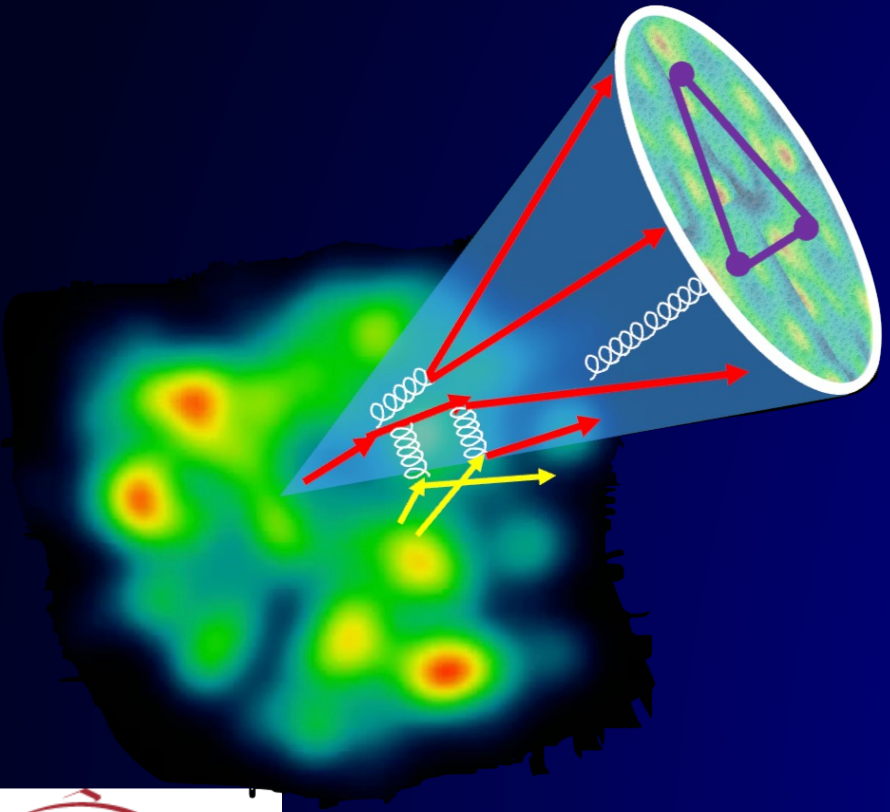


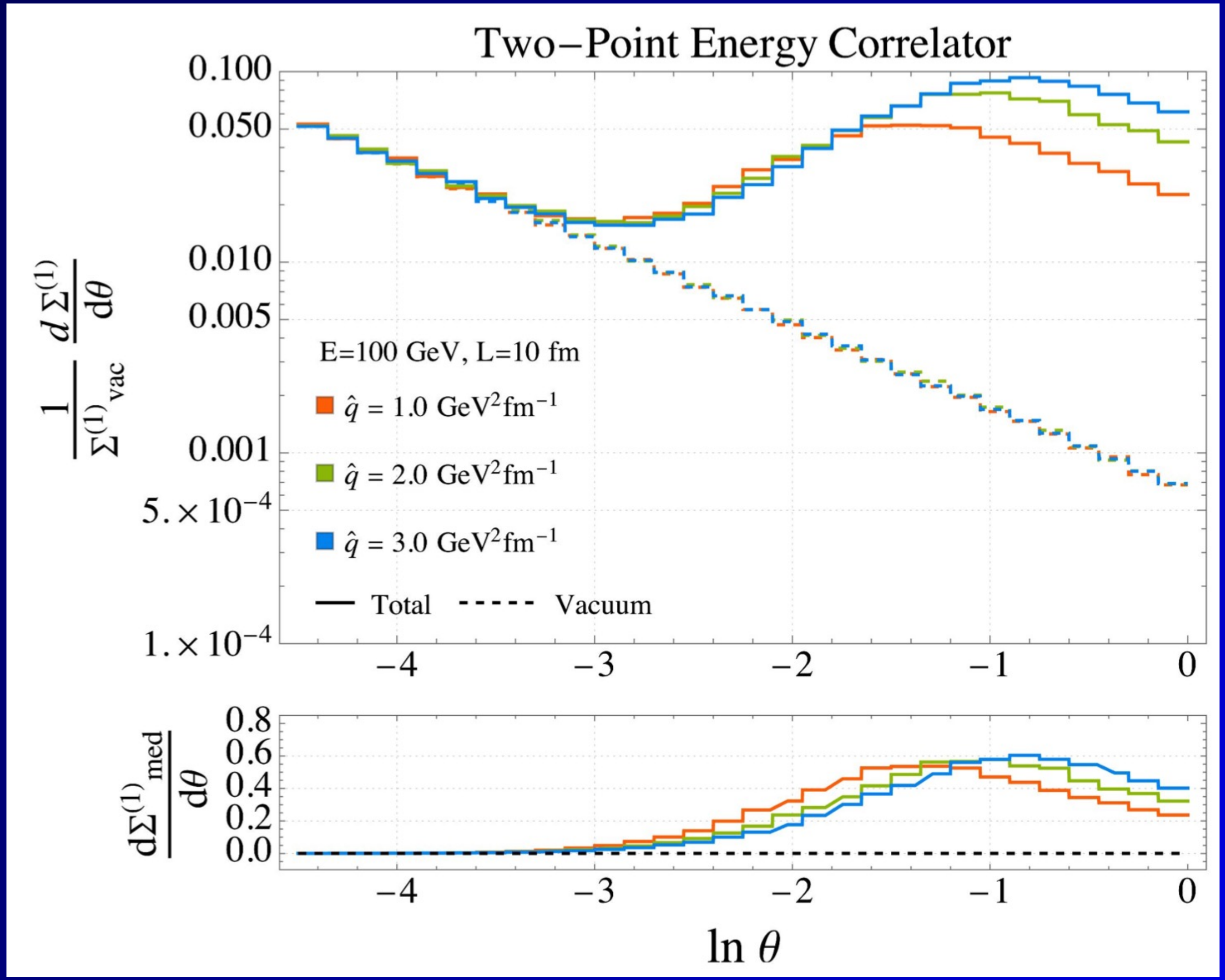


Moult, et al

Fan, QM23

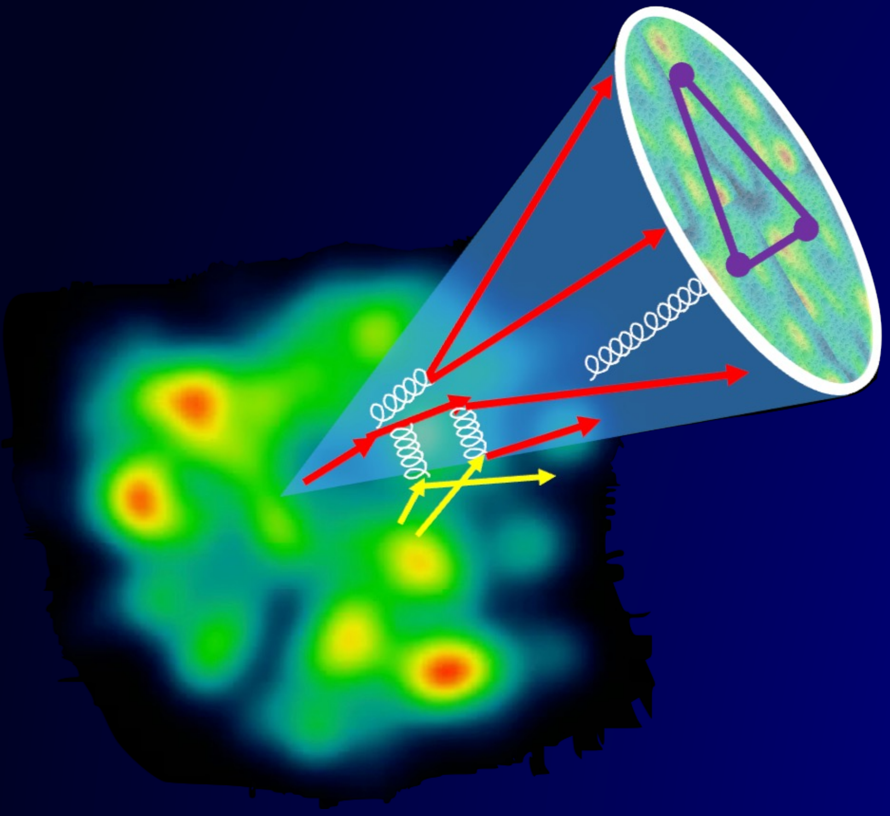
Resolving QGP scales with EEC





Andres, et al , 2209.11236

Resolving QGP scales with EEC



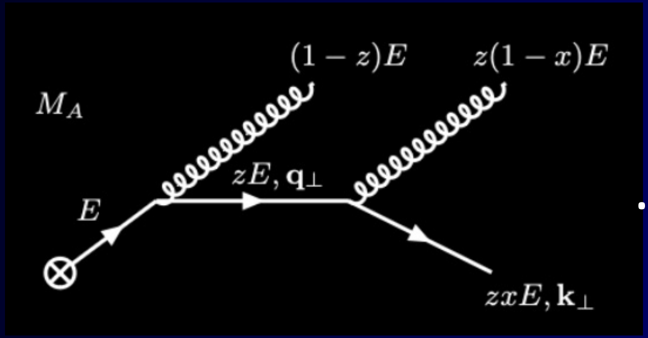
- Can EEC resolve the induced gluon emission in realistic heavy-ion collisions?
- Can EEC resolve recoil partons (medium response)?
- Can EEC resolve the angular scale of in-medium parton collisions

Jet EEC in Vacuum

LO emission in vacuum:

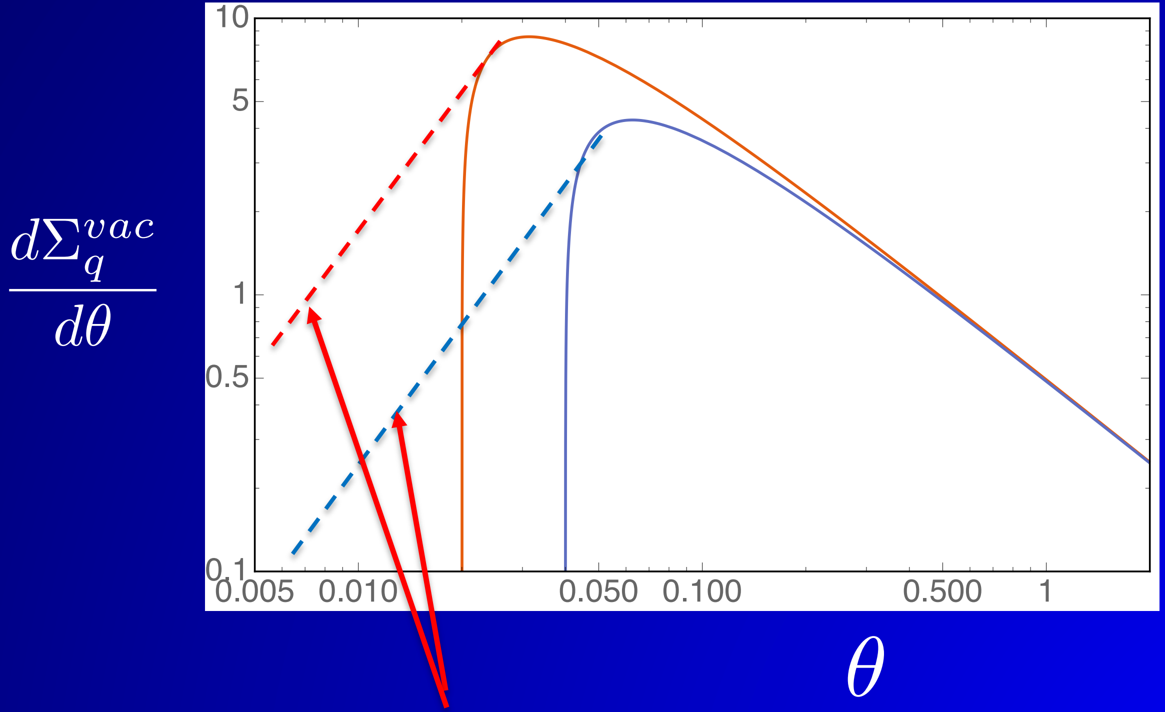
$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz\ z(1-z)P_{qg}(z) \int_{\mu_0^2}^{Q^2} \frac{d\ell_\perp^2}{\ell_\perp^2} \delta\left(\theta - \frac{\ell_\perp}{z(1-z)E}\right) \approx \frac{\alpha_s}{2\pi}\frac{C_F}{2\theta}\left(3 - \frac{2\mu_0}{E\theta}\right)\sqrt{1 - \frac{4\mu_0}{E\theta}}$$

Leading Log evolution:



....

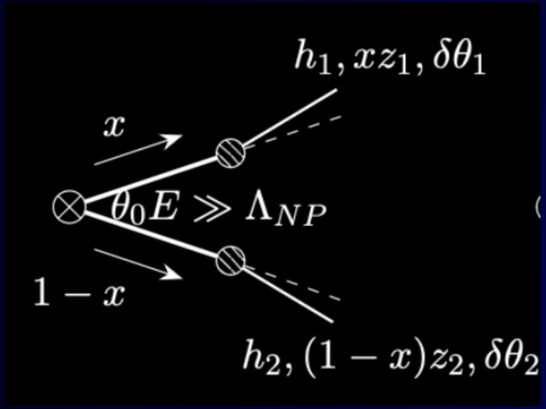
$$\frac{\partial \Sigma_q}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi}\left[\gamma_{qq}(3)\Sigma_q + \cdots\right]$$

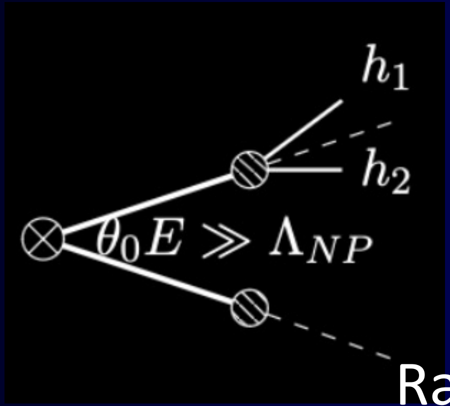


Non-leading log power corrections $\sim \theta$

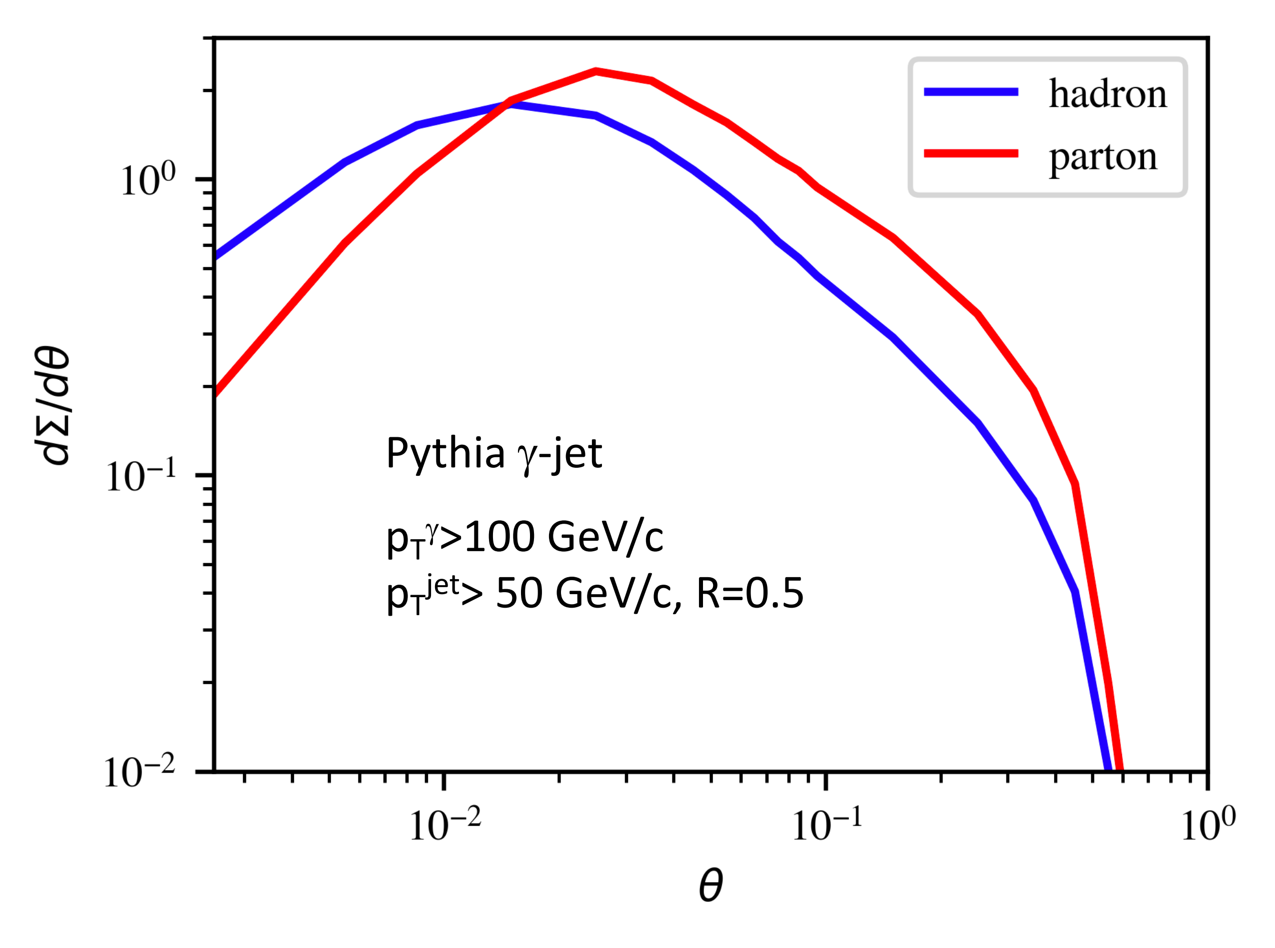
Uncorrelated emission at small angle

Effects of hadronization





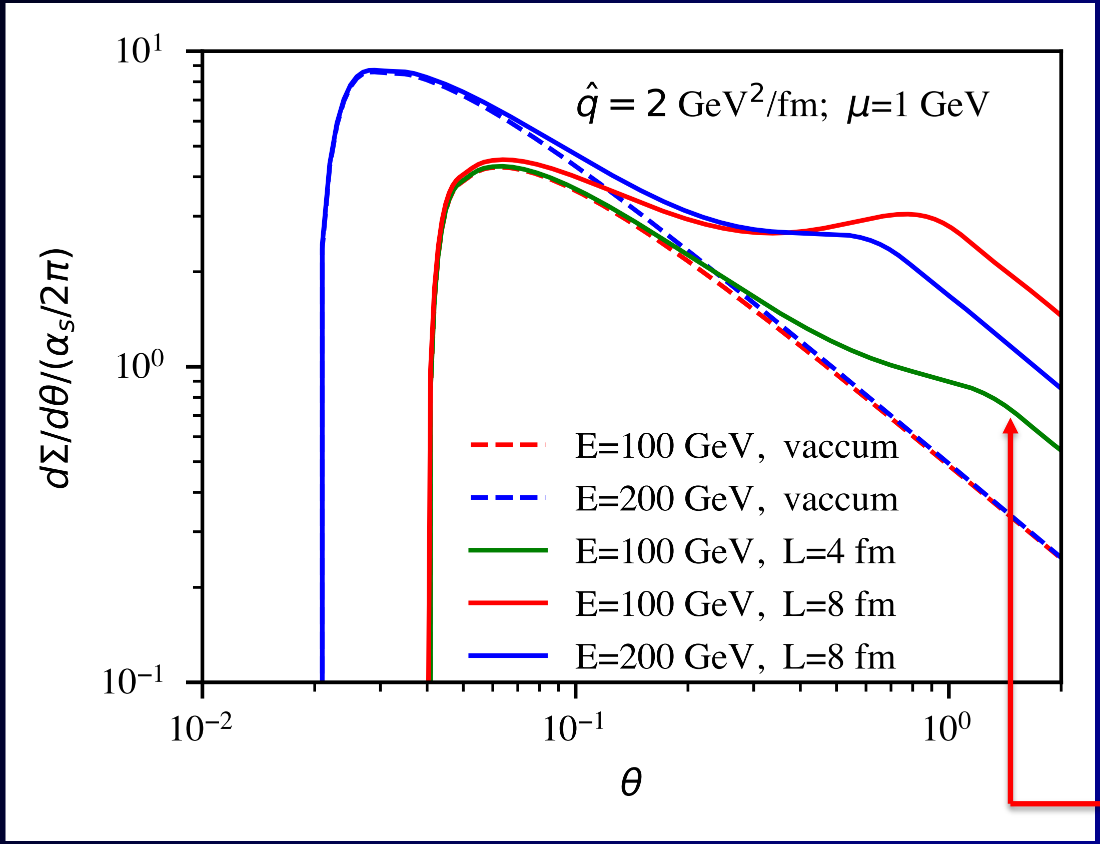
Random correlation at small angle

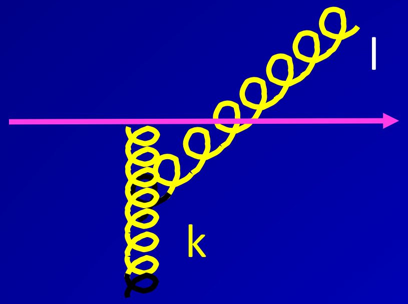


Power corrections at large angle

EEC from HT in single emission

$$\frac{d\Sigma_q^{\rm med}}{d\theta} = \frac{L^{5/2}\hat{q}_{HT}}{\pi\sqrt{E}}\frac{8\alpha_{\rm s}C_A}{(\sqrt{EL}\theta)^3}\int dz \frac{P_{qg}(z)}{z(1-z)}\left[1-\frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]$$





HT induced emission in a QGP brick:

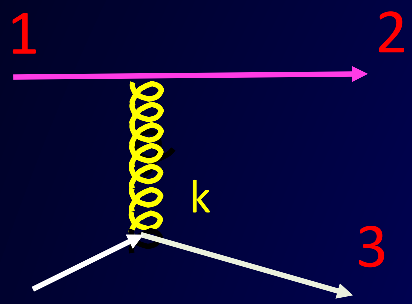
$$\frac{d\Sigma_q^{\rm med}}{d\theta} \approx \frac{L^3\hat{q}\alpha_{\rm s}C_A\theta}{64\pi}, \theta < \sqrt{8\pi/EL}$$

$$\frac{d\Sigma_q^{\rm med}}{d\theta} \approx \frac{L^2\hat{q}}{2E}\frac{\alpha_{\rm s}C_A}{\theta}, \theta > \sqrt{8\pi/EL}$$

Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

Contributions from medium response

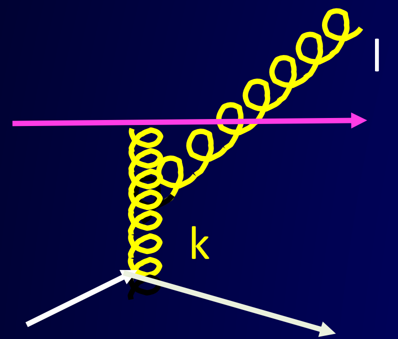
2→ 2 elastic collisions:

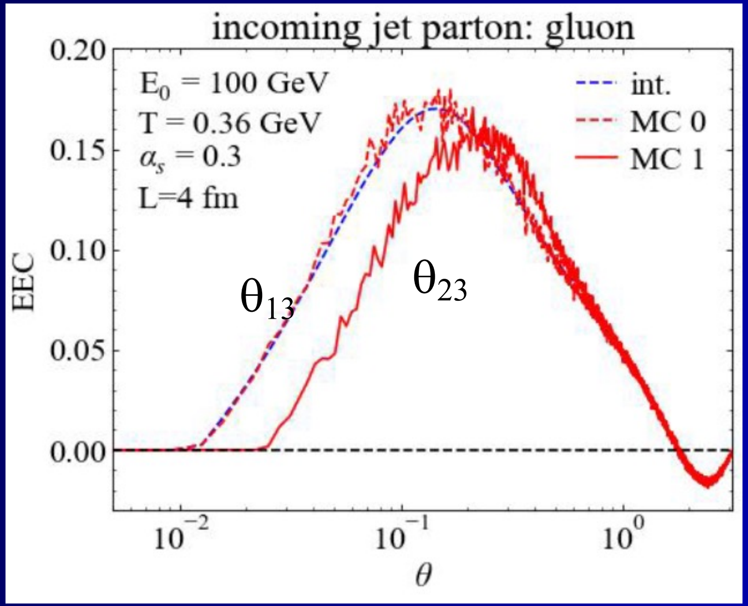


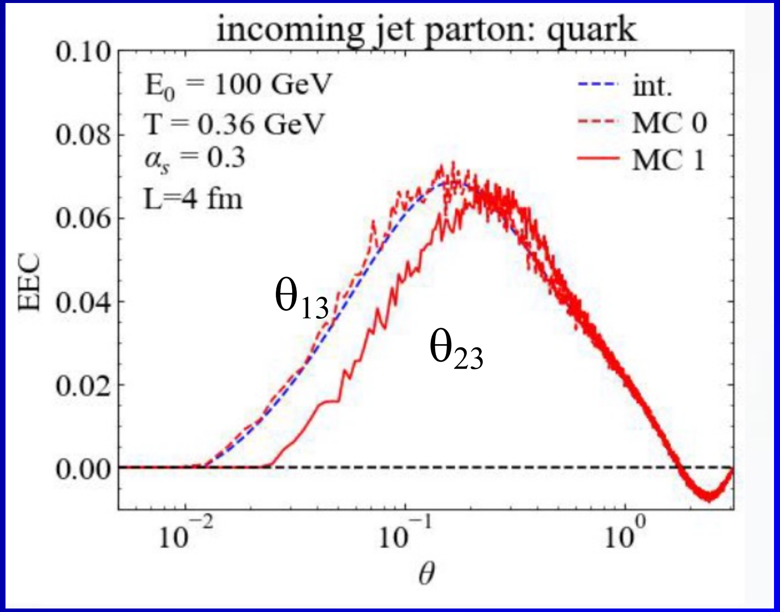
$$\frac{d\Sigma_a^{\rm med}}{d\theta} = \int dx d\vec{n}_{c,d}\delta(\vec{n}_c \cdot \vec{n}_d - \cos\theta) \sum_{b,(cd)} \int \prod_{i=b,c,d} d[p_i]$$
$$\times \frac{\gamma_b}{2E_a}\left[f_b(1\pm f_c)(1\pm f_d) - f_c(1\pm f_a)(1\pm f_b)\right]$$
$$\times \frac{E_c E_d}{E_a^2}(2\pi)^4\delta^4(p_a+p_b-p_c-p_d)\left|\mathcal{M}_{ab\to cd}\right|^2,$$

Both recoil and back-reaction ("negative partons")

2→ 3 inelastic collisions:







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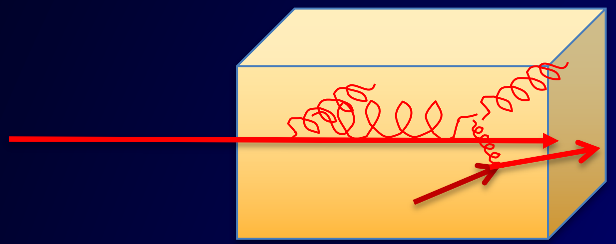
EEC of single parton in a QGP brick

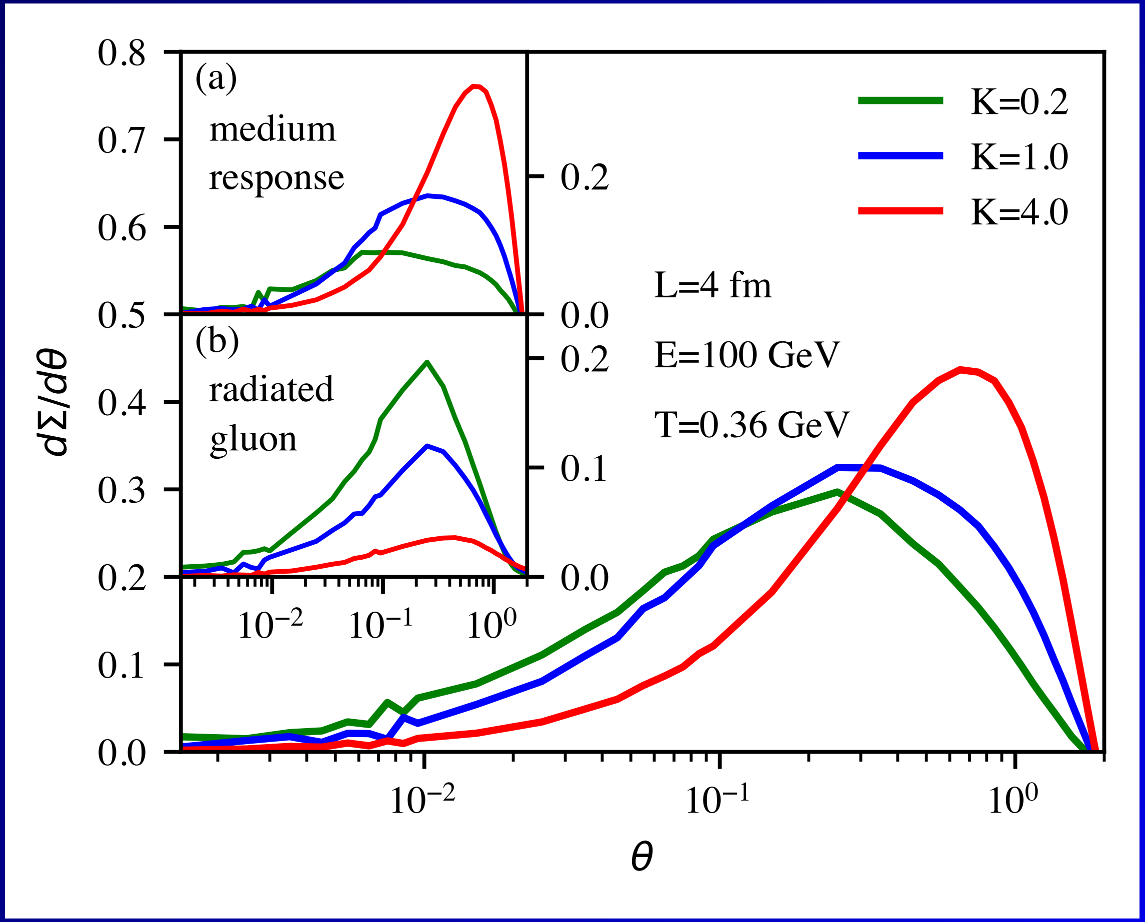
Single parton with multiple scattering in a brick in LBT



Debye mass:

$$\mu_D^2 = \frac{3}{2} K g^2 T^2$$

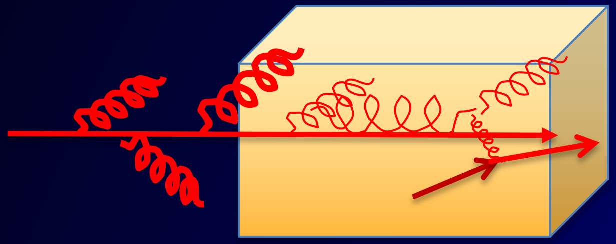
We vary only *K* in the sampling the transverse momentum transfer of 2→2 and kinematic limit of gluon bremsstrahlung. We however keep qhat and 2→2 rate unchanged.



Medium response (recoil + "negative" partons) Is (more) important

Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

EEC of a jet shower in a QGP brick

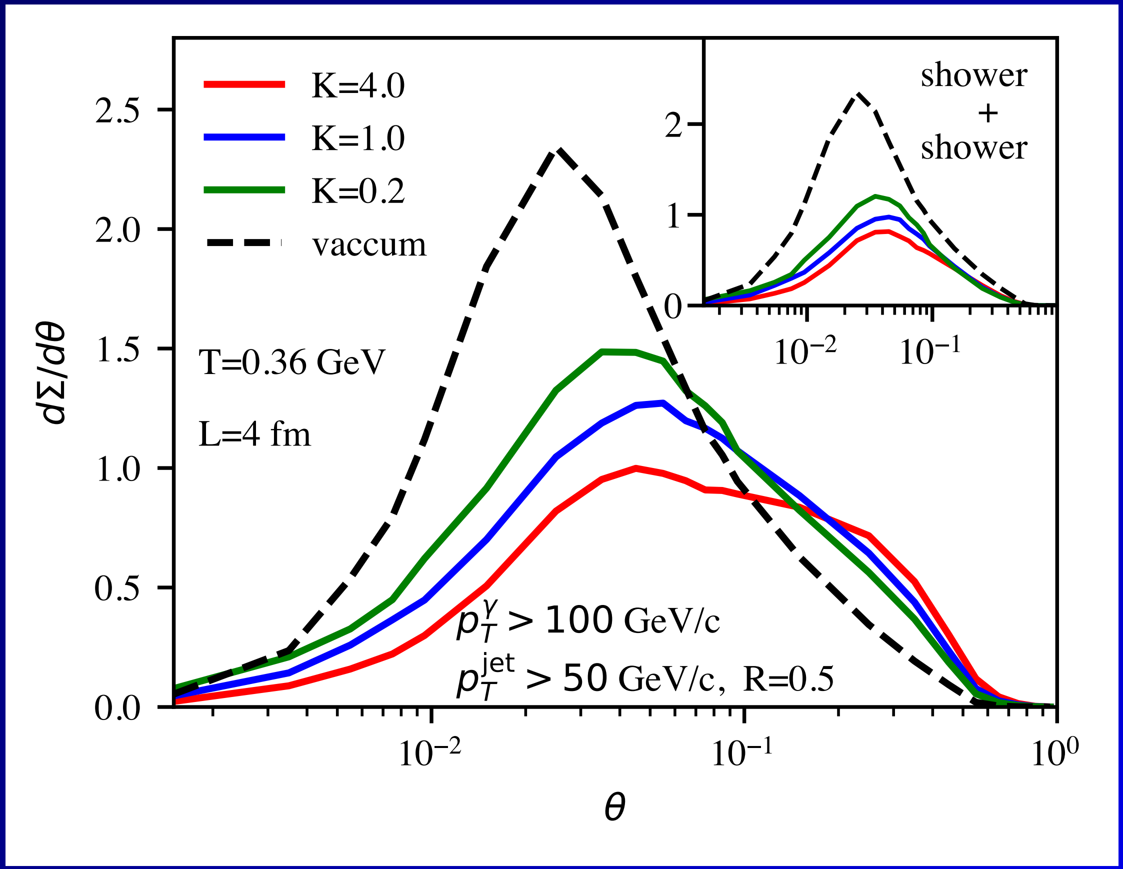


Initial γ-jet configurations generated from Pythia8

Energy loss and momentum broadening lead to suppression at small angles

Radiated gluon and medium response dominate at large angles

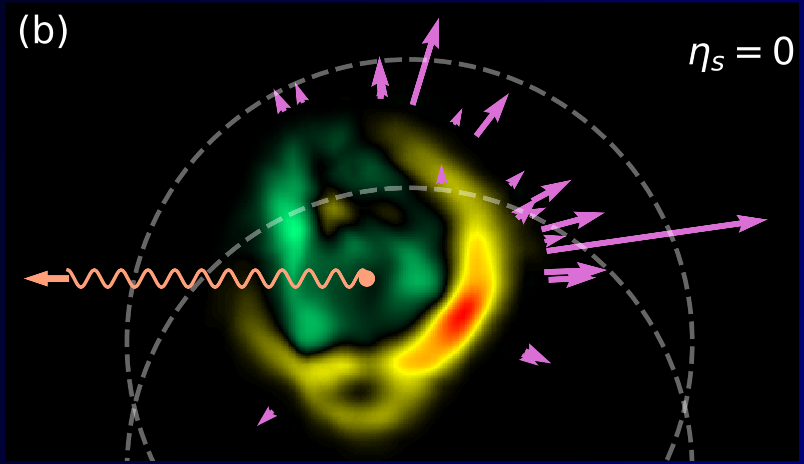
A jet shower in a brick in LBT



Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

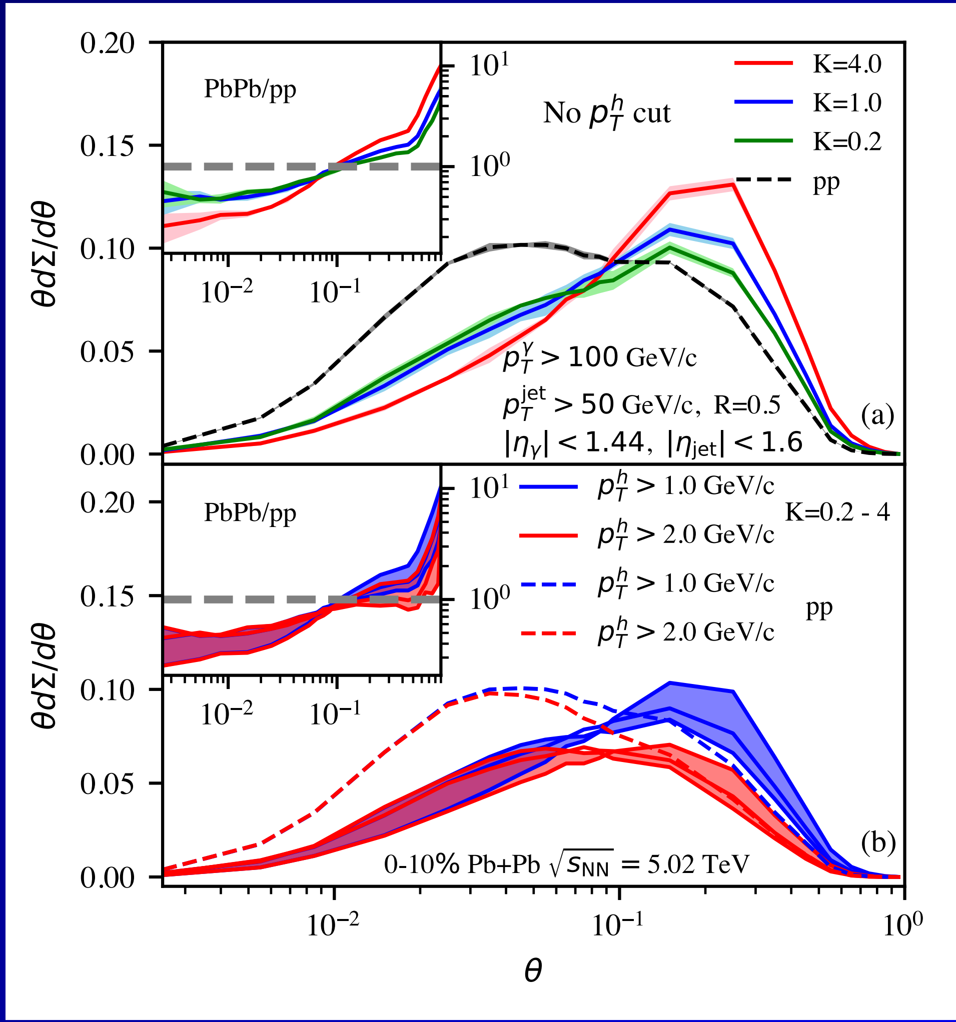
EEC of γ-jets in Pb+Pb Collisions

CoLBT simulations:



Enhancement at large angles by soft hadrons from radiated gluons and medium response, sensitive to pT cuts

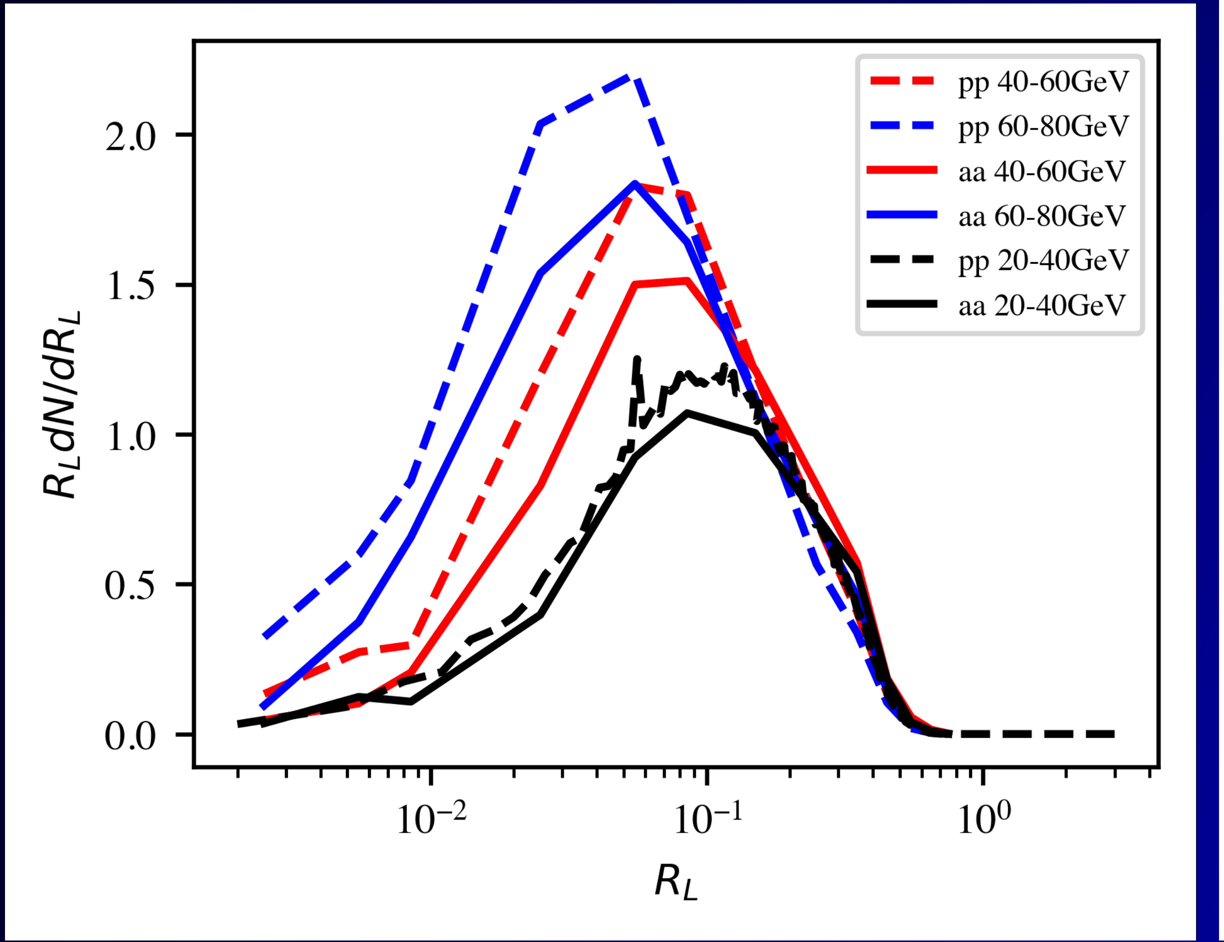
EEC by energetic hadrons from leading shower partons at small angles are suppressed, not affected by pT cuts



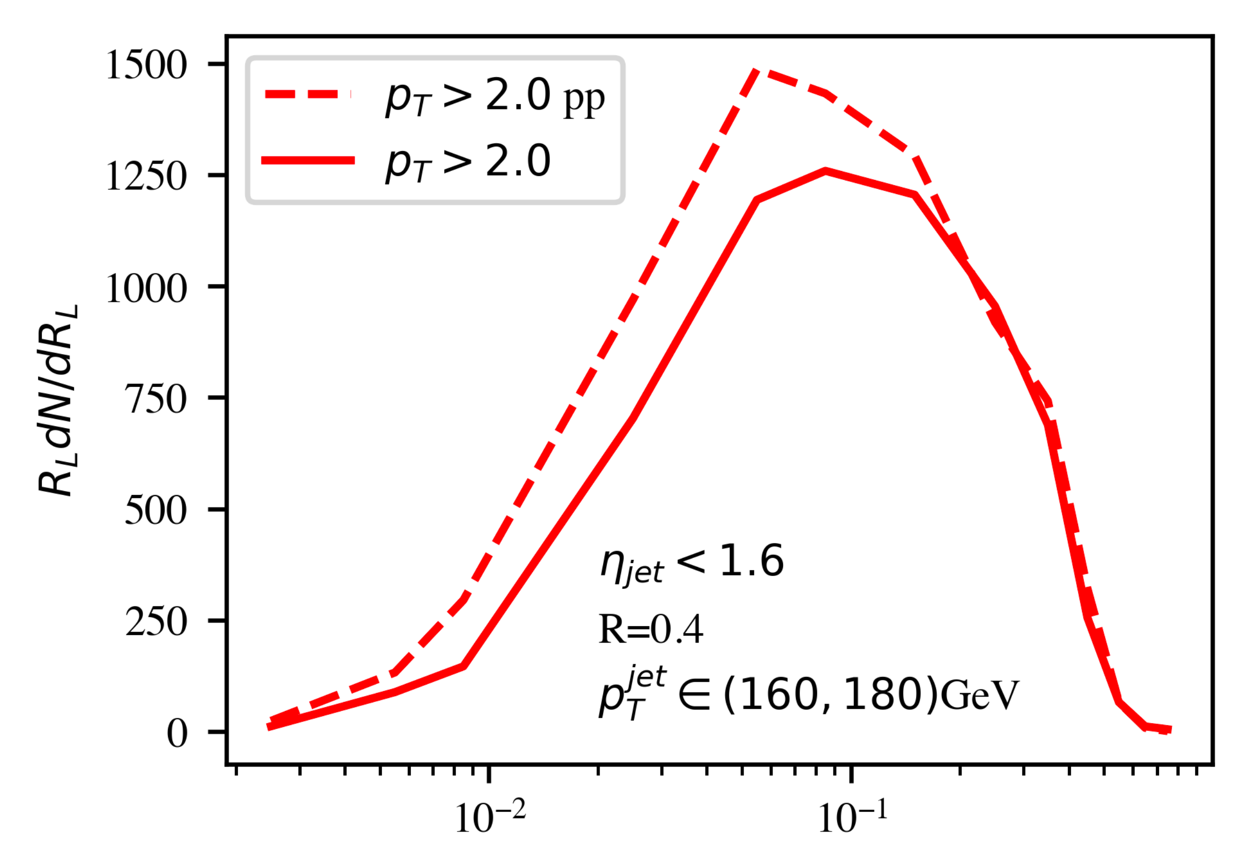
Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

EEC for single inclusive jets

Similar to EEC for γ-jets

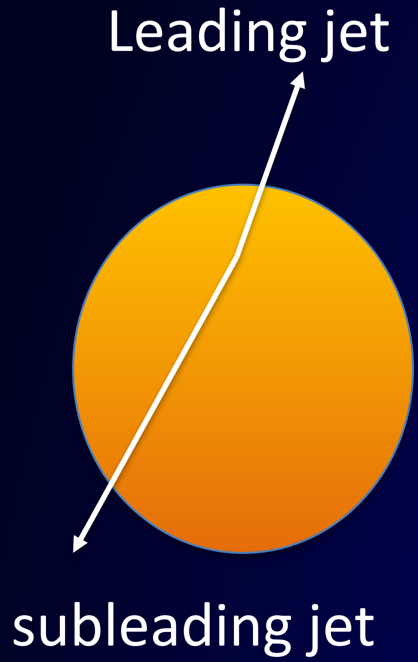


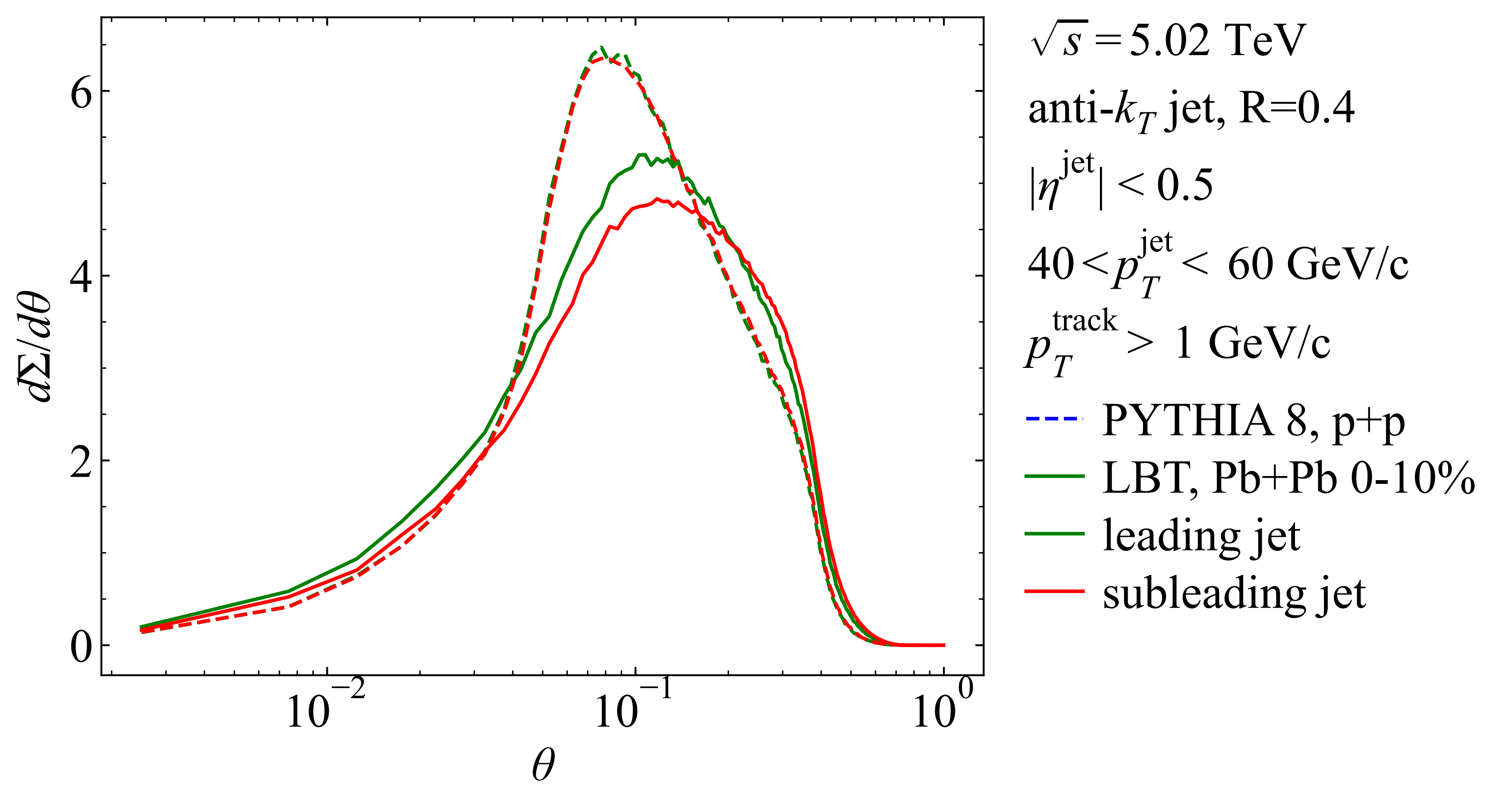
pT cut reduces enhancement from medium response



(not normalized by jet pT)

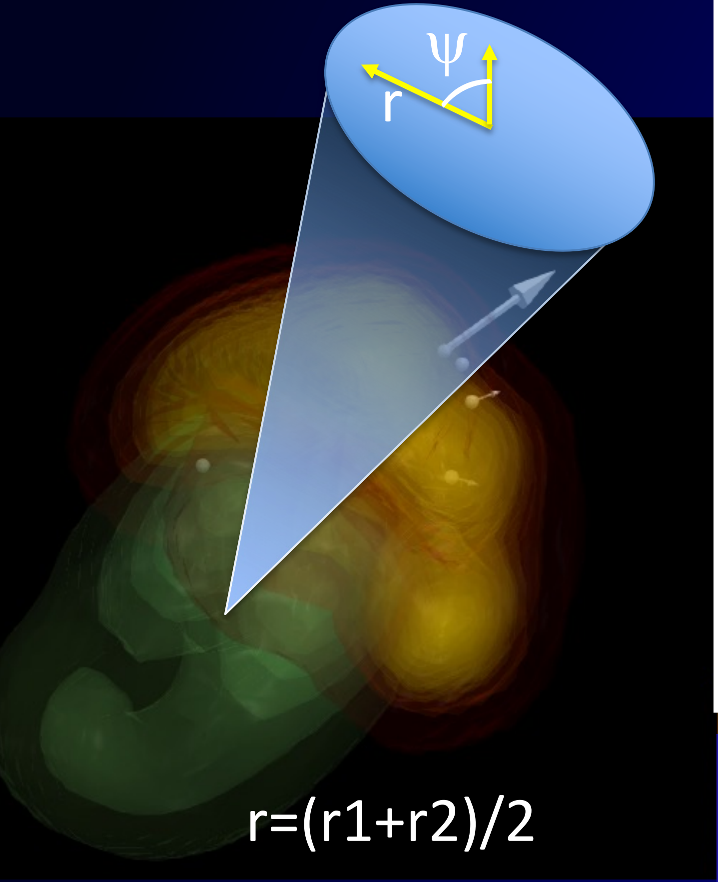
EEC of dijets



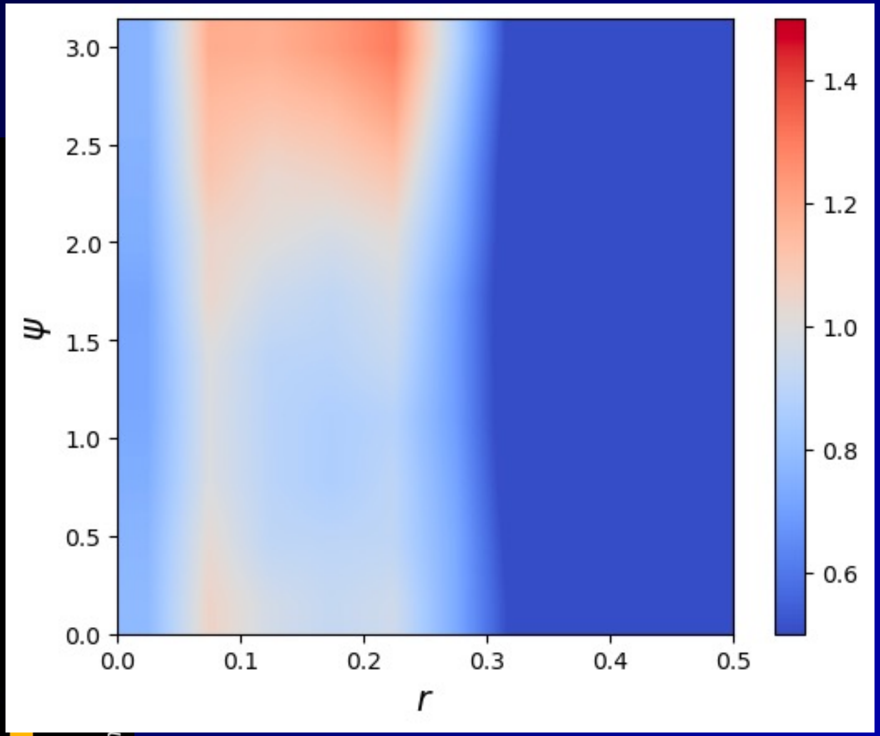


$EEC_{leading} - EEC_{subleading}$: robust measure of medium modification free of background

Seeing Mach-cone through 3p Azimuthal Correlation

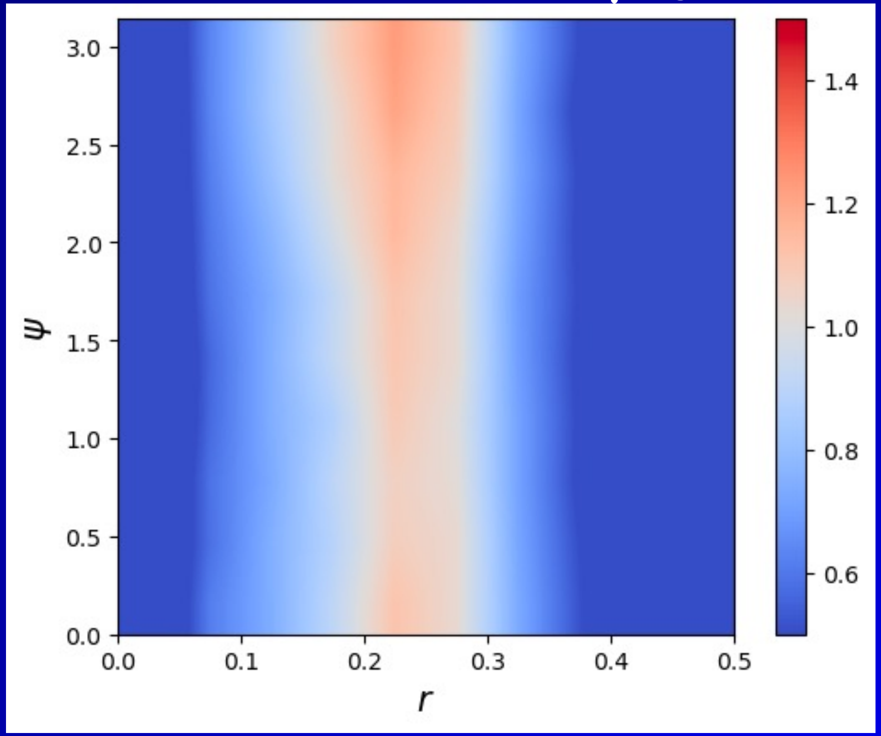


p+p (γ+jet) p_T>40 GeV/c



Back-to-back correlation due to momentum conservation of parton splitting

0-10%Pb+Pb (γ+jet)



Azimuthal uniform correlation due to medium-response: Mach-cone – sound velocity?

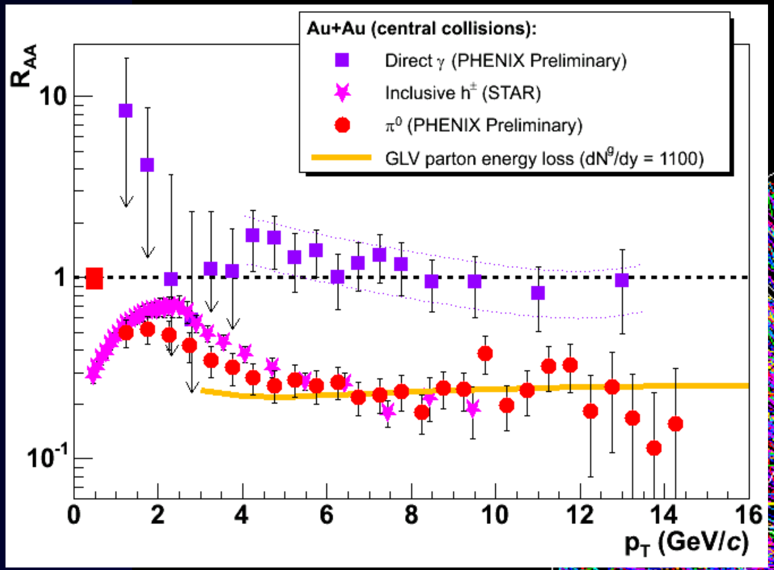
Summary 1

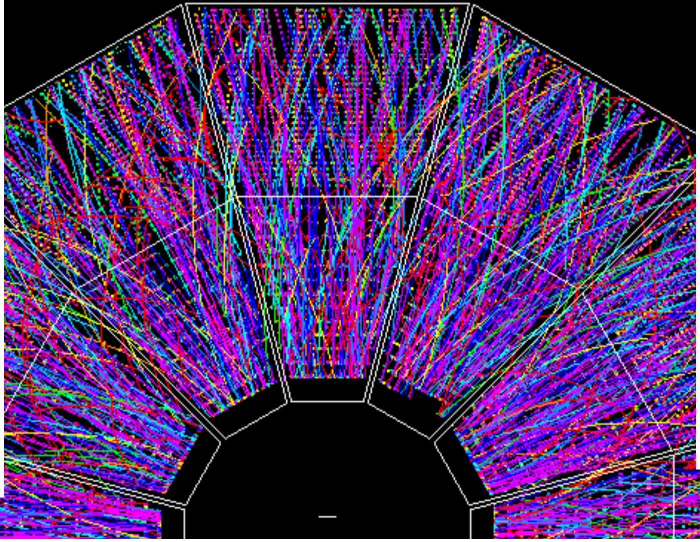
- Medium response reduces net jet energy loss
- Medium response leads to
  - enhancement of soft hadrons in jet direction
  - depletion of soft hadron on the away side
- Unique 3D structure of diffusion wake
- Use 2D jet tomography to reveal the angular structure of Mach-cone excitation
- Future studies: ML improved 2D tomography and constraint on EoS, transport coefficients

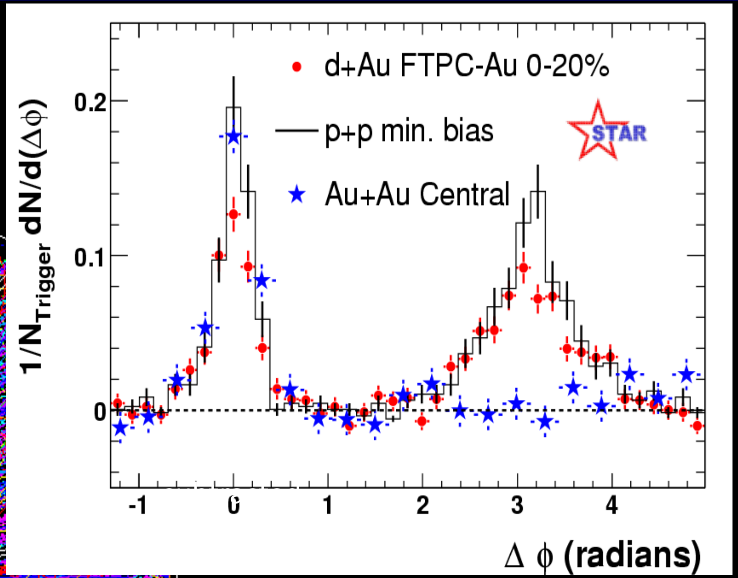
Summary 2

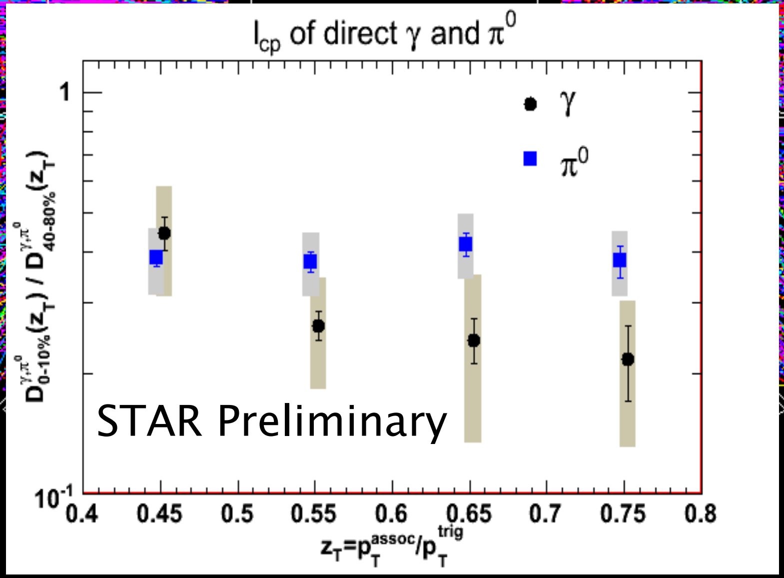
- First complete and realistic calculation of jet EEC in heavy-ion collisions
- Medium-response dominates enhancement of EEC at large angles
- Energy loss of leading jet shower partons leads to suppression of EEC at small angles
- Medium modification of EEC is sensitive to the angular scale of in-medium parton collisions
- Azimuthal dependence of EEC – imaging Mach-cone

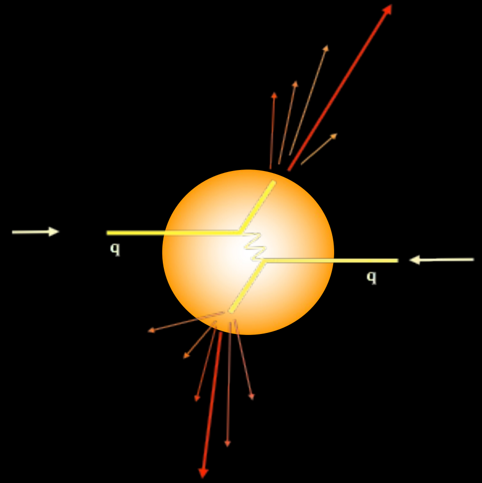
Jet Quenching phenomena at RHIC











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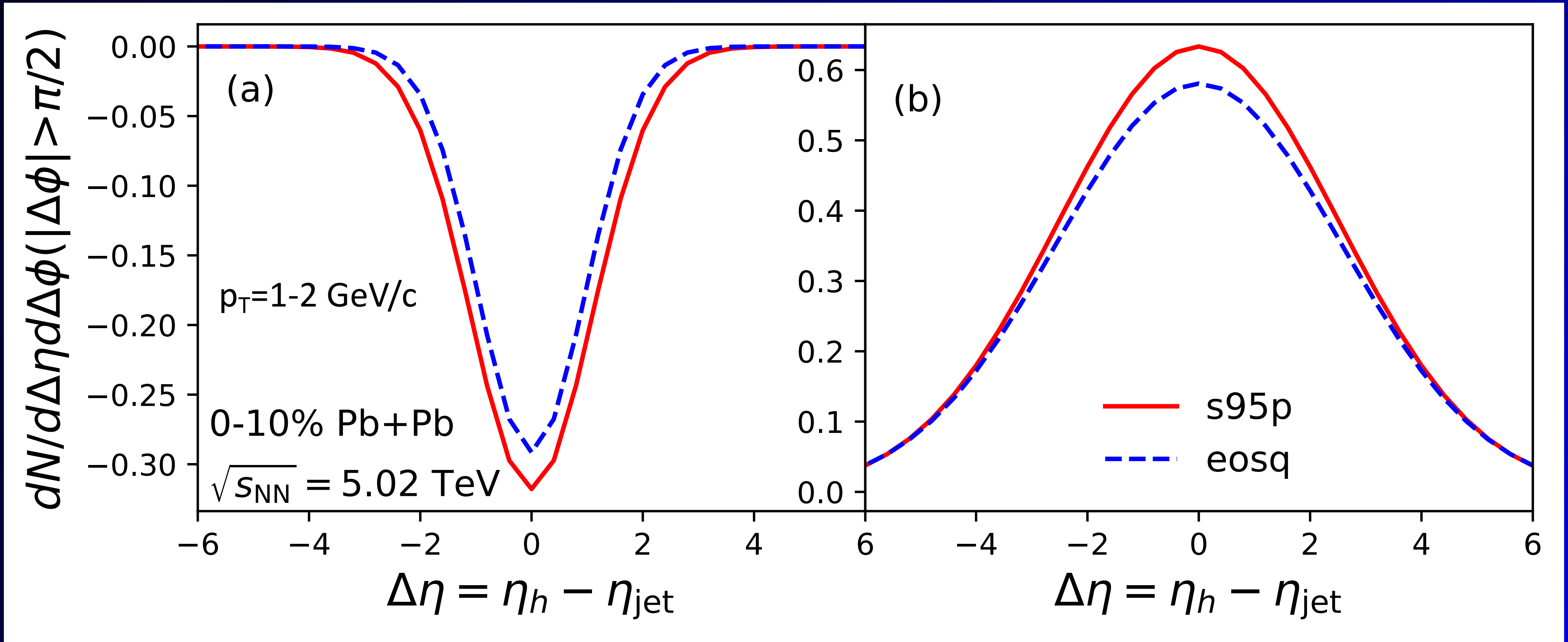
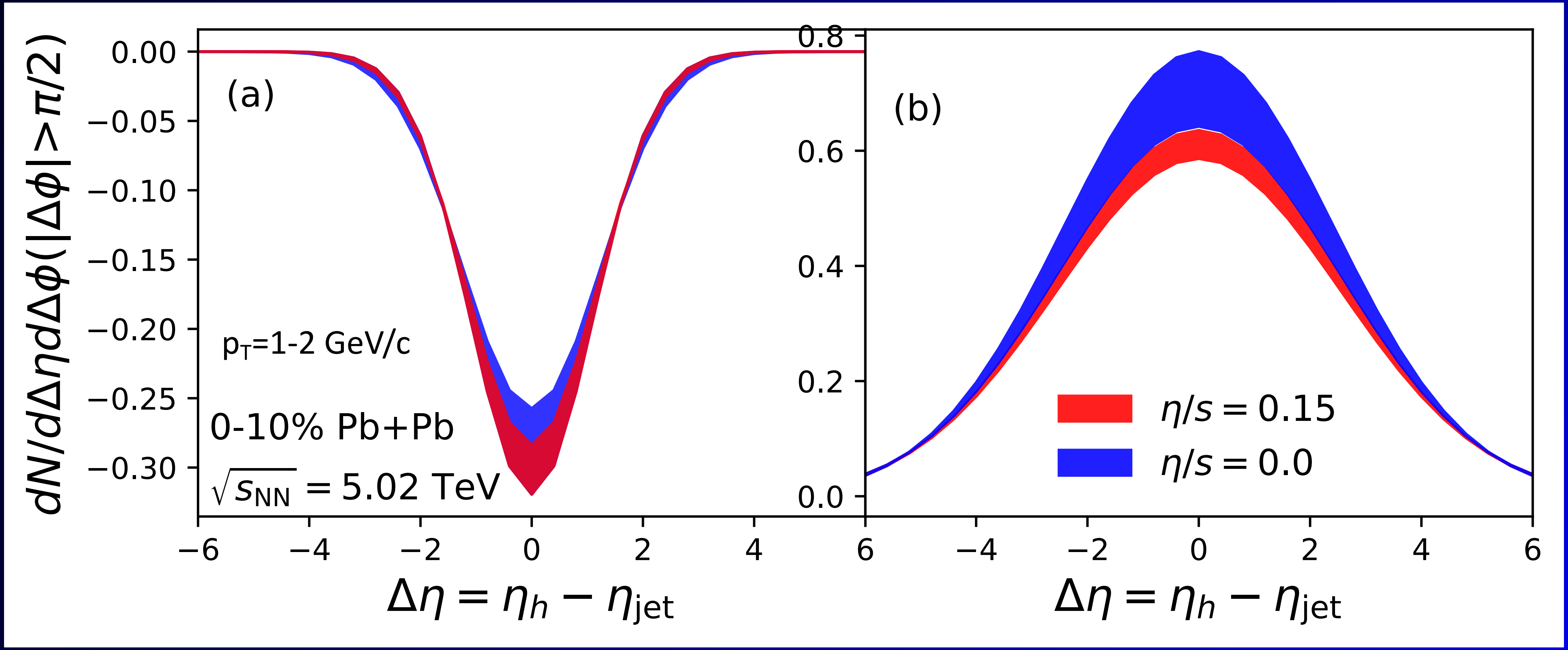
Diffusion wake and EoS

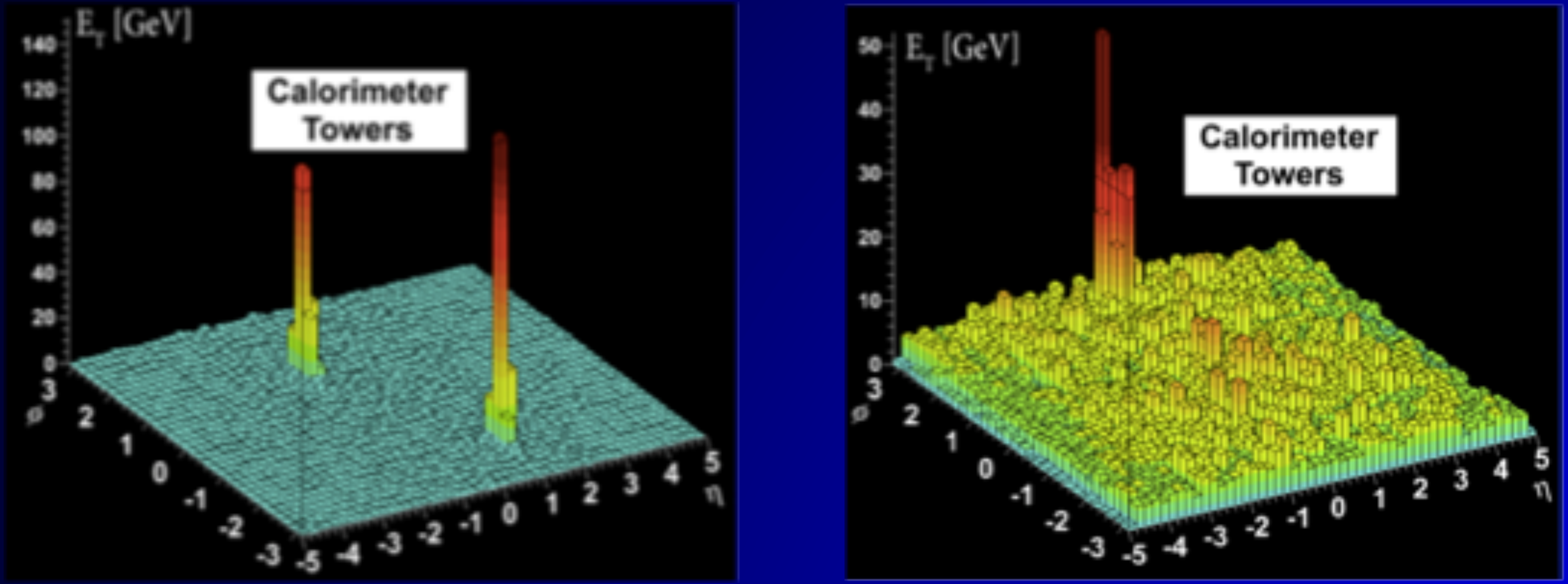


$$\langle c_s \rangle_{\rm eosq} > \langle c_s \rangle_{\rm s95p}$$

Diffusion wake and viscosity



Jet quenching at LHC



ATLAS jet events in p+p (left) and Pb+Pb (right) collisions