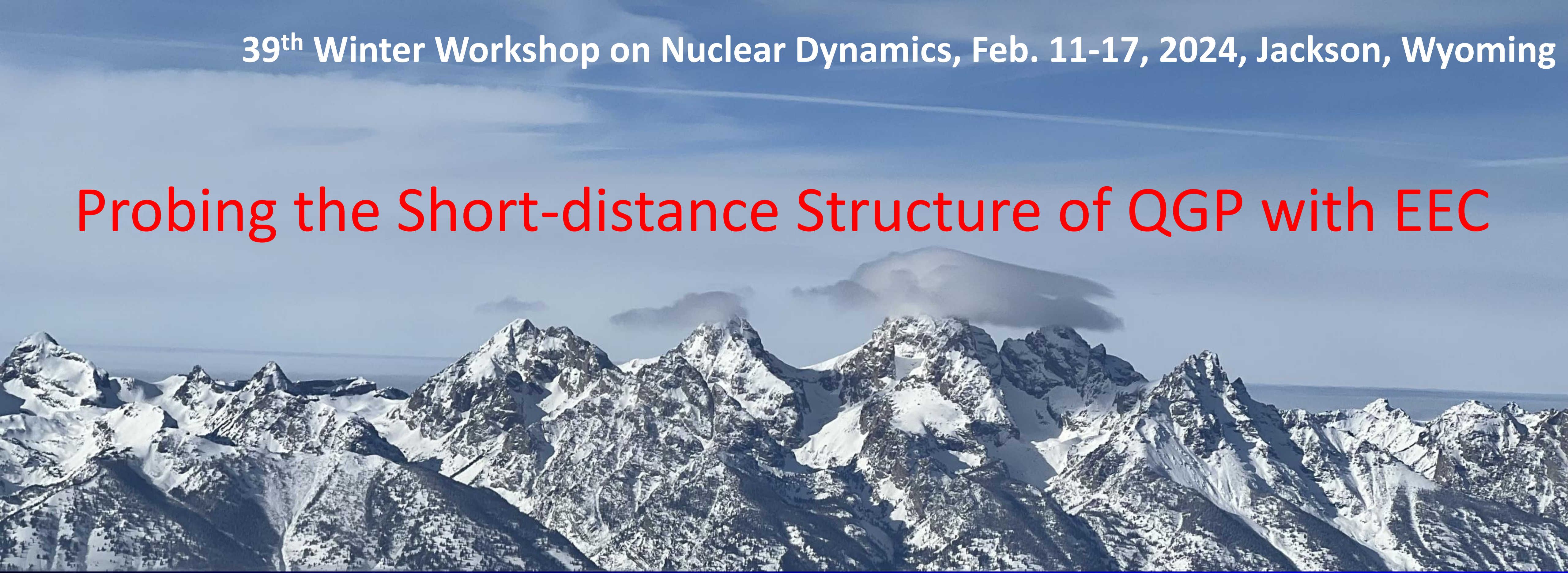
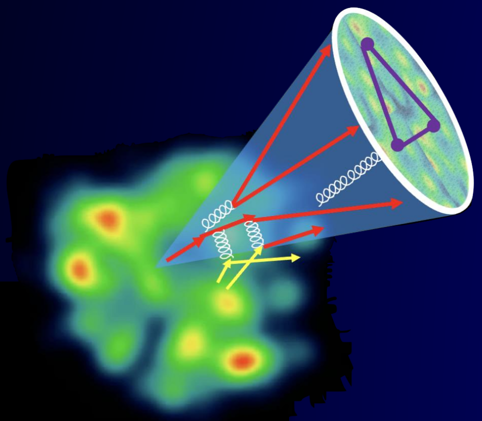


39th Winter Workshop on Nuclear Dynamics, Feb. 11-17, 2024, Jackson, Wyoming

Probing the Short-distance Structure of QGP with EEC



Xin-Nian Wang

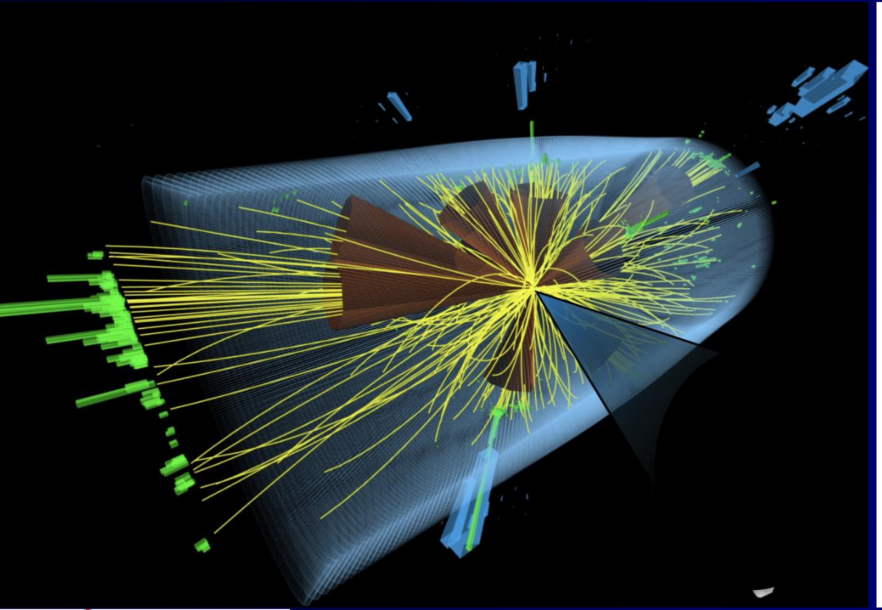
Lawrence Berkeley National Laboratory

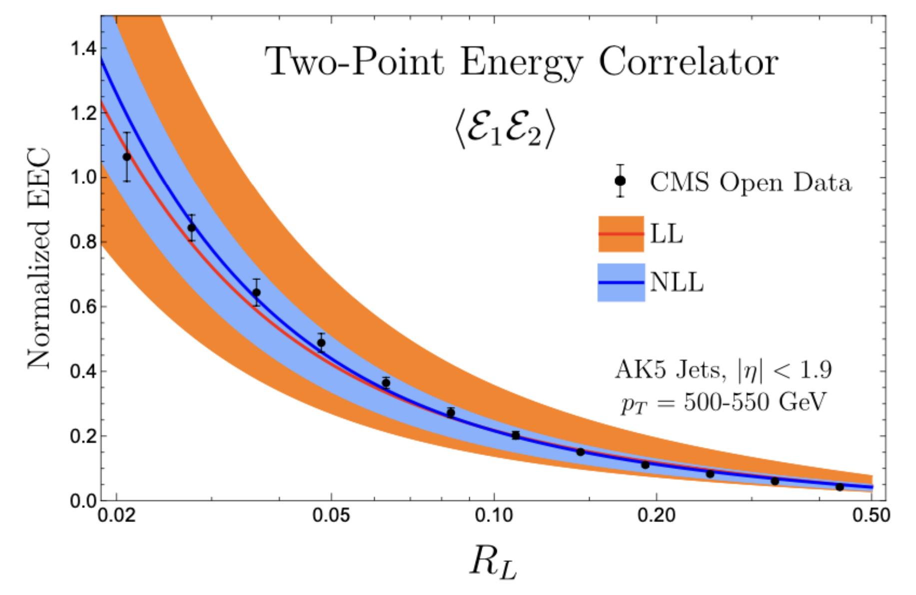
Collaborators: W. Ke, Y. He, I. Moult, Z. Yang and W. Zhao

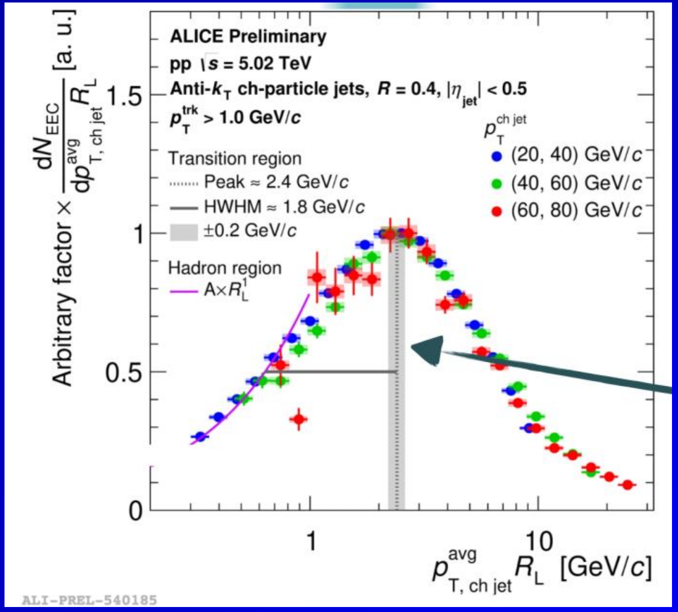
Energy-energy correlator (EEC)

A new jet substructure observable:

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



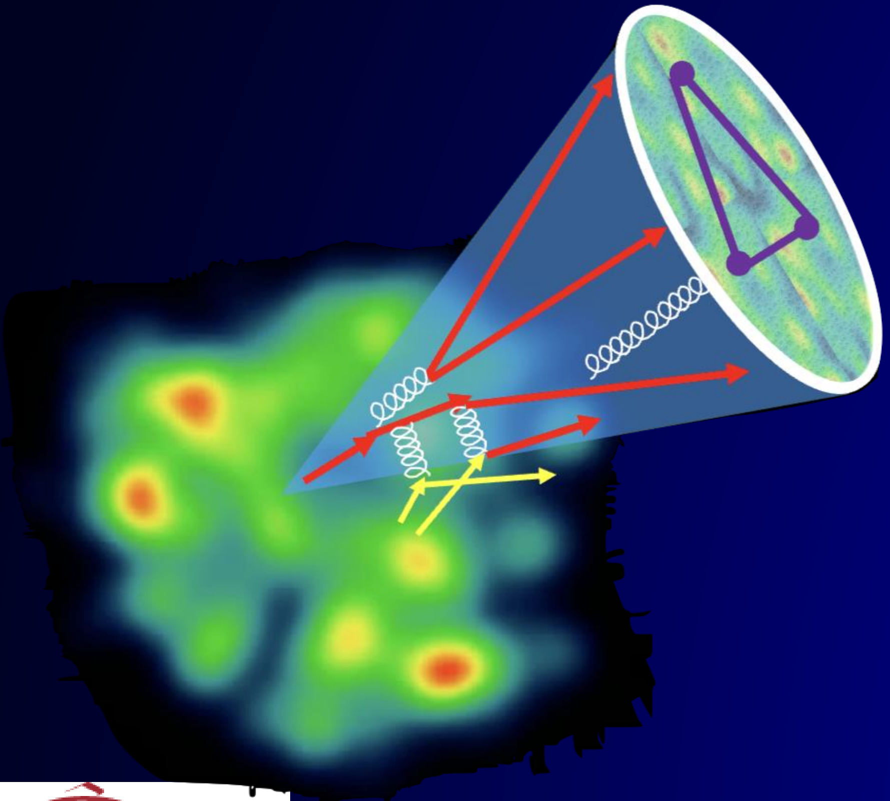


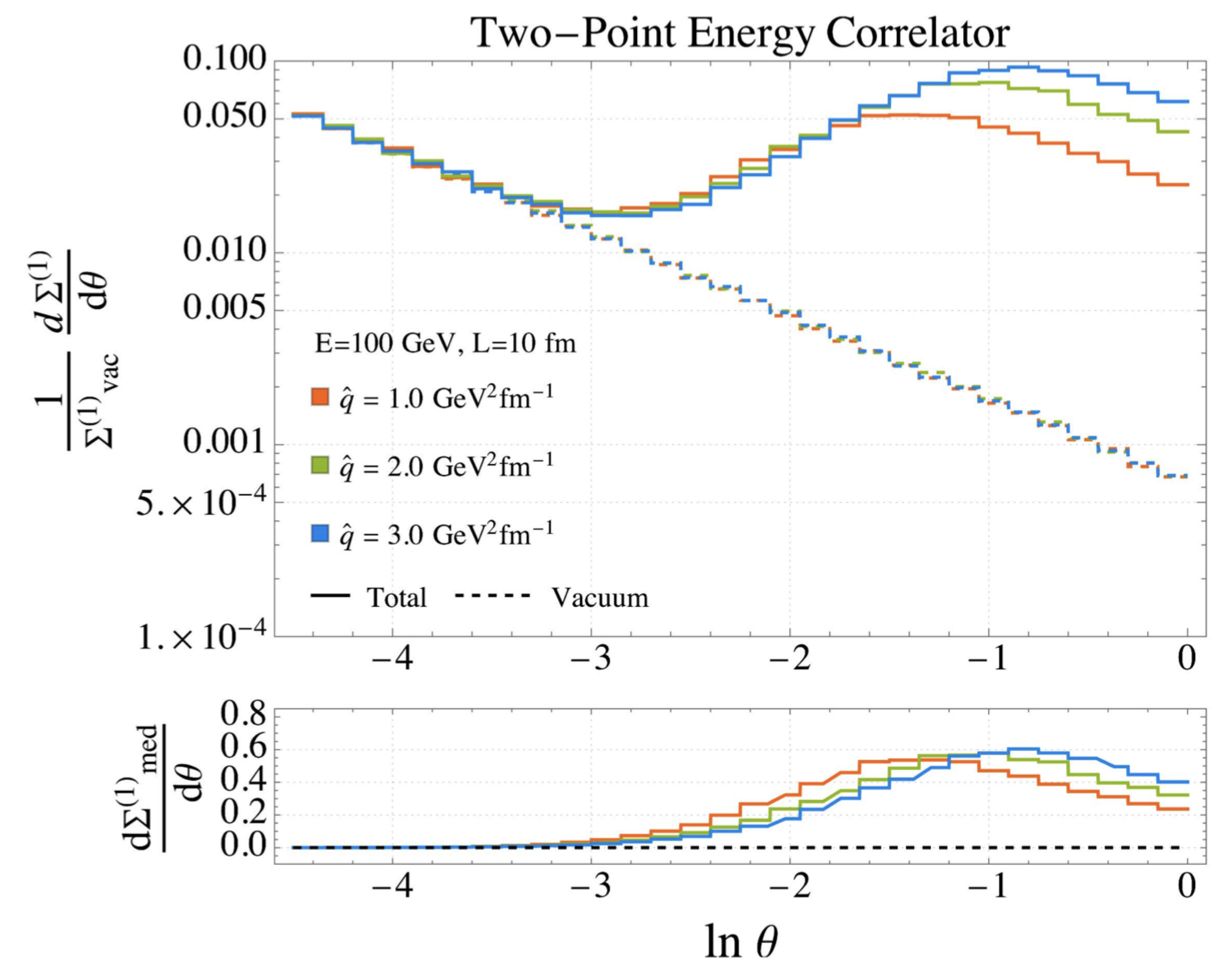


Moult, et al

Fan, QM23

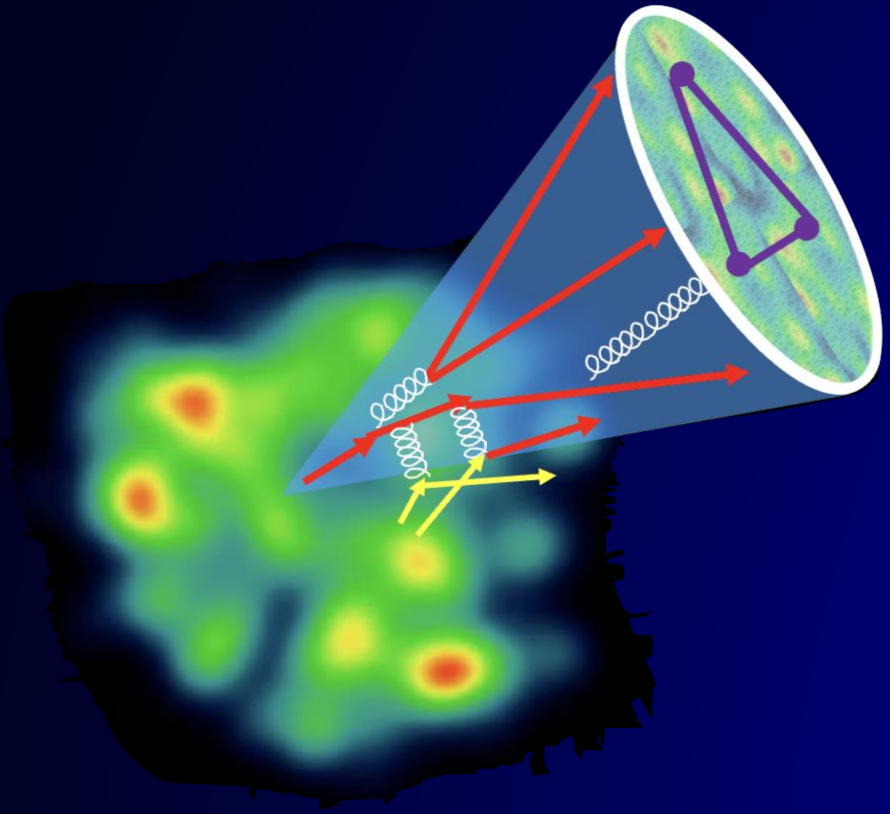
Resolving QGP scales with EEC





Andres, et al , 2209.11236

Resolving QGP scales with EEC



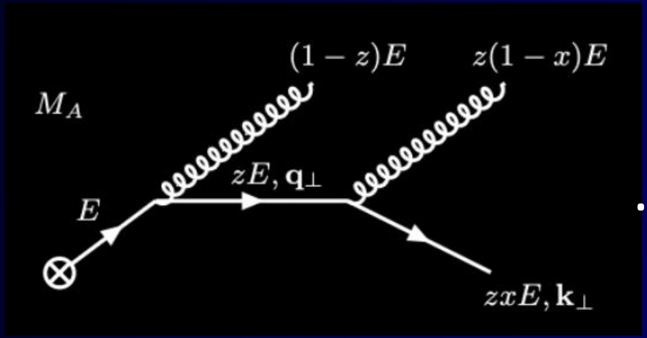
- Can EEC resolve the induced gluon emission in realistic heavy-ion collisions?
- Can EEC resolve recoil partons (medium response)?
- Can EEC resolve the angular scale of in-medium parton collisions

Jet EEC in Vacuum

LO emission in vacuum:

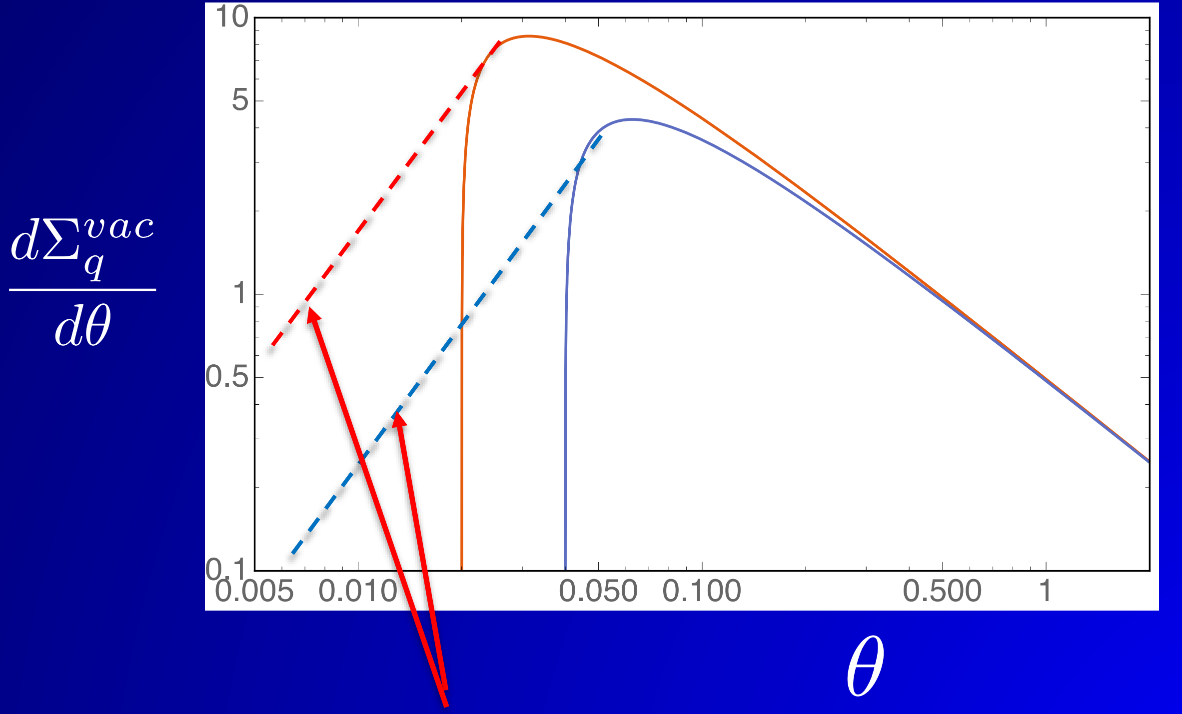
$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz\ z(1-z) P_{qg}(z) \int_{\mu_0^2}^{Q^2} \frac{d\ell_\perp^2}{\ell_\perp^2} \delta\left(\theta - \frac{\ell_\perp}{z(1-z)E}\right) \approx \frac{\alpha_s}{2\pi} \frac{C_F}{2\theta} \left(3 - \frac{2\mu_0}{E\theta}\right)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

Leading Log evolution:



....

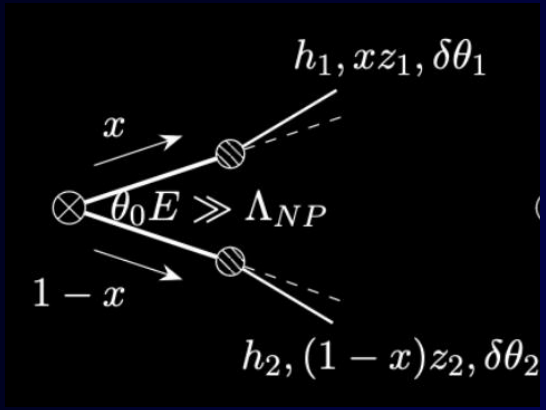
$$\frac{\partial \Sigma_q}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \left[\gamma_{qq}(3)\Sigma_q + \cdots\right]$$

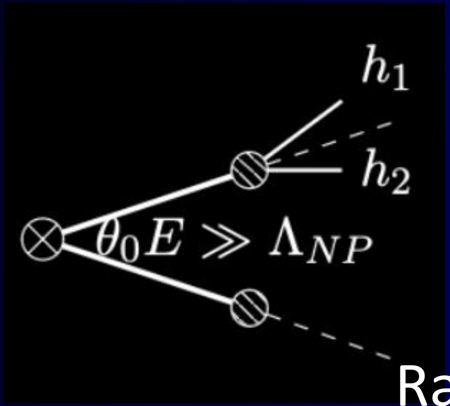


Non-leading log power corrections $\sim \theta$

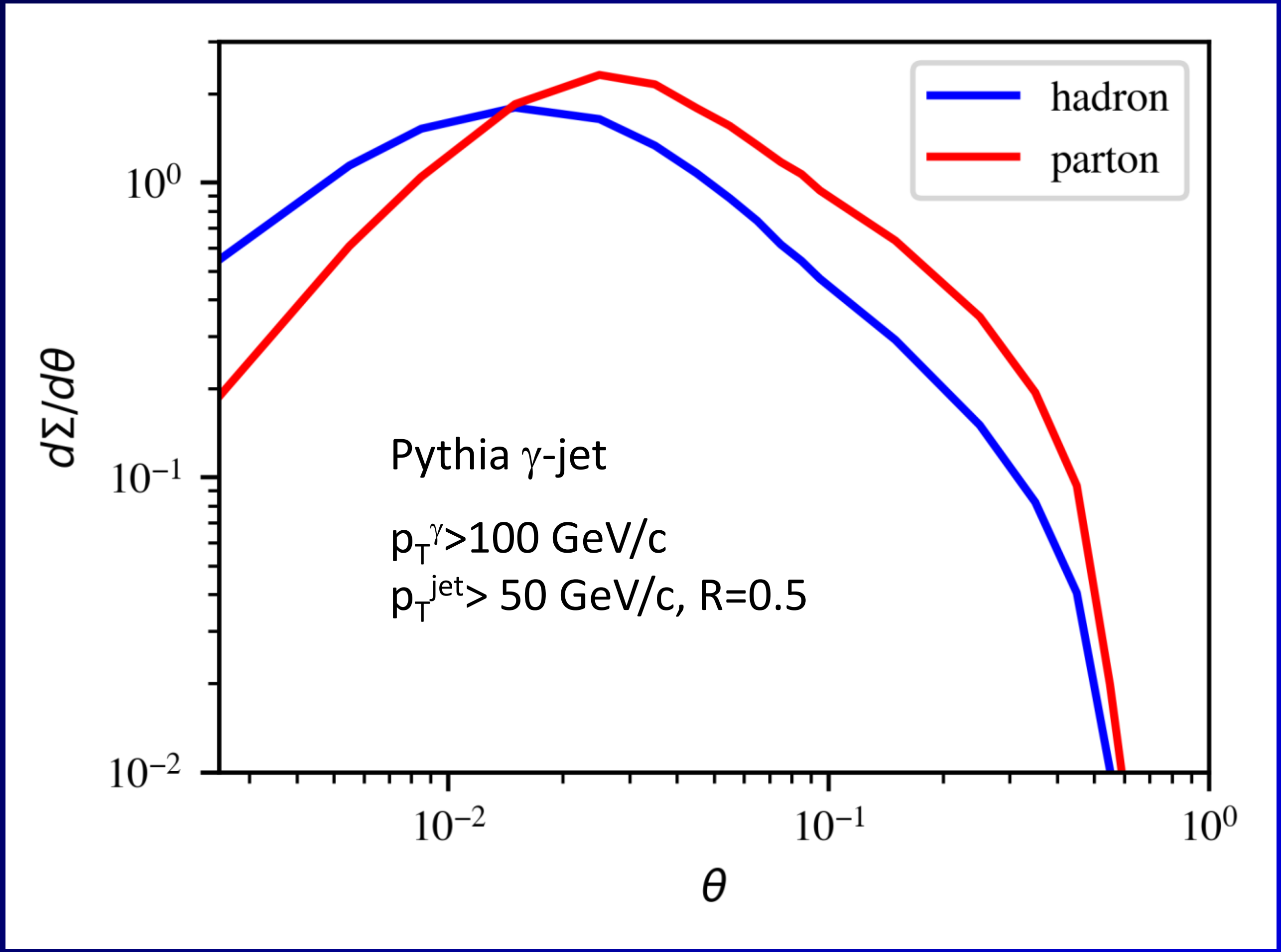
Uncorrelated emission at small angle

Effects of hadronization





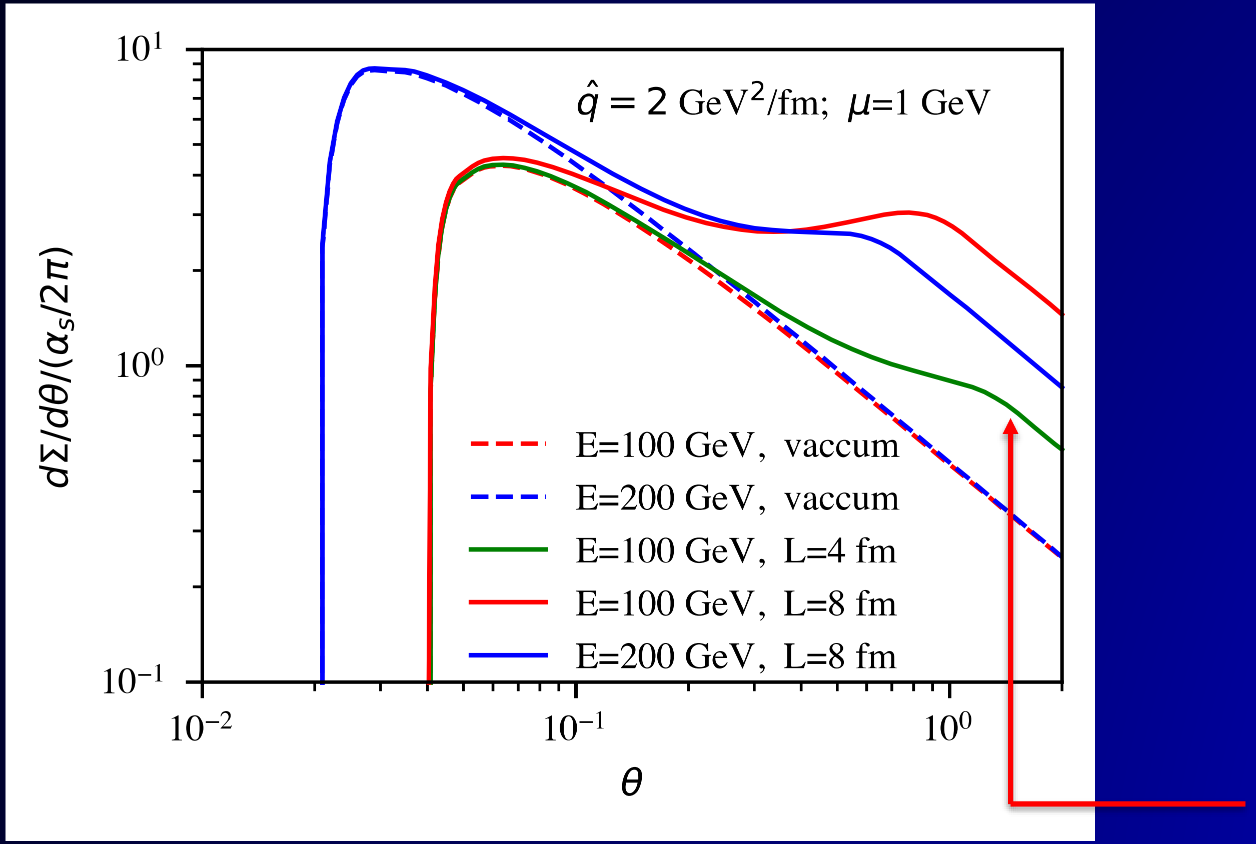
Random correlation at small angle

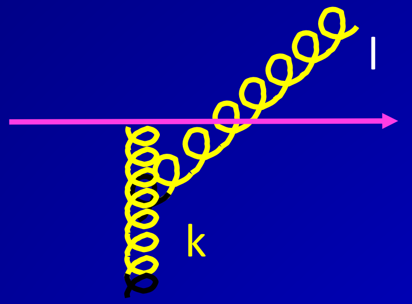


Power corrections at large angle

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:

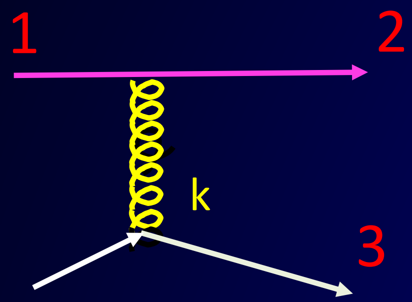
$$\frac{d\Sigma_q^{\rm med}}{d\theta} \approx \frac{L^3\hat{q}\alpha_{\rm s}C_A\theta}{64\pi}, \theta < \sqrt{8\pi/EL}$$

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

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

Contributions from medium response

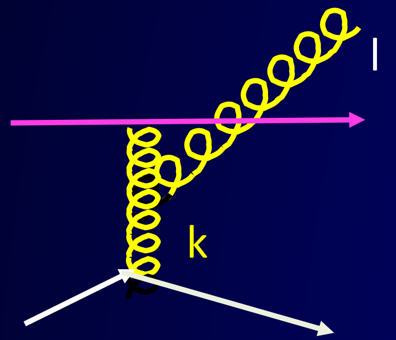
2→ 2 elastic collisions:

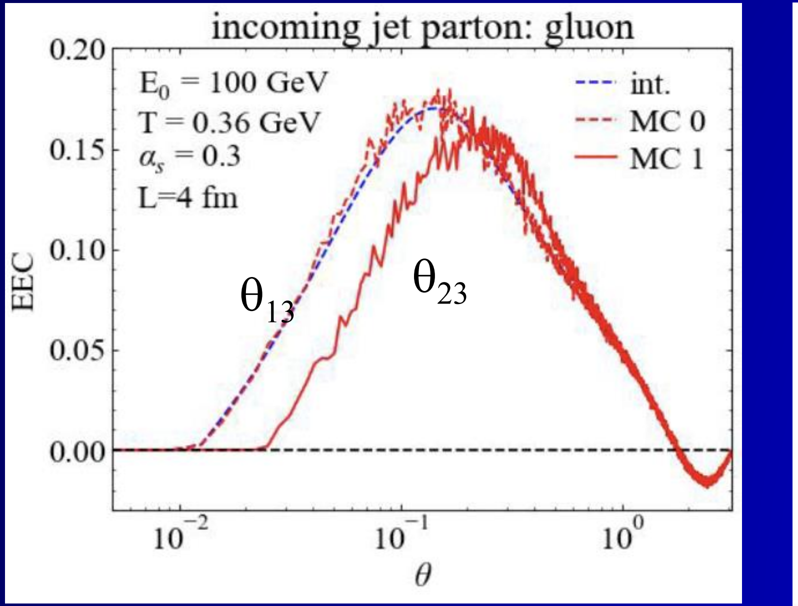


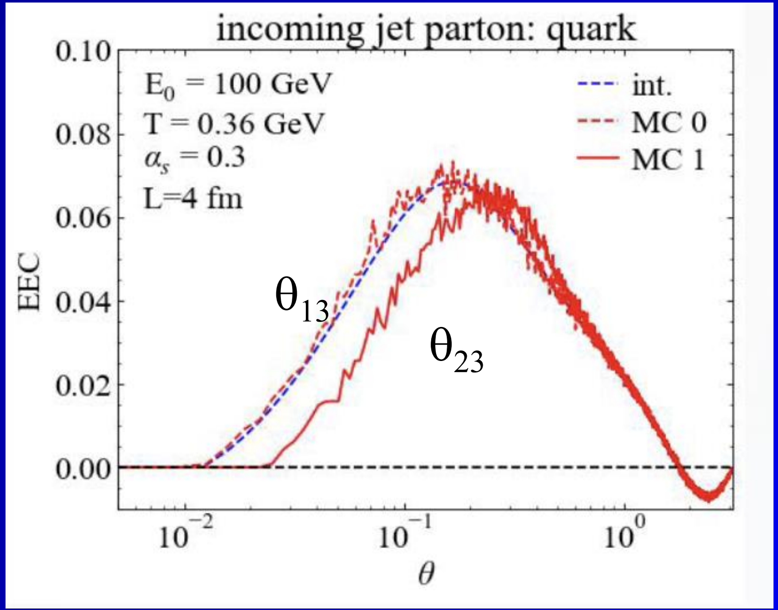
$$\frac{d\Sigma_a^{\rm med}}{d\theta} = \int dx d\vec{n}_{c,d} \delta(\vec{n}_c \cdot \vec{n}_d - \cos\theta) \sum_{b,(cd)} \int \prod_{i=b,c,d} d[p_i]$$
$$\times \frac{\gamma_b}{2E_a} [f_b(1 \pm f_c)(1 \pm f_d) - f_c(1 \pm f_a)(1 \pm f_b)]$$
$$\times \frac{E_c E_d}{E_a^2} (2\pi)^4 \delta^4(p_a + p_b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

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

2→ 3 inelastic collisions:







Linear Boltzmann Transport model

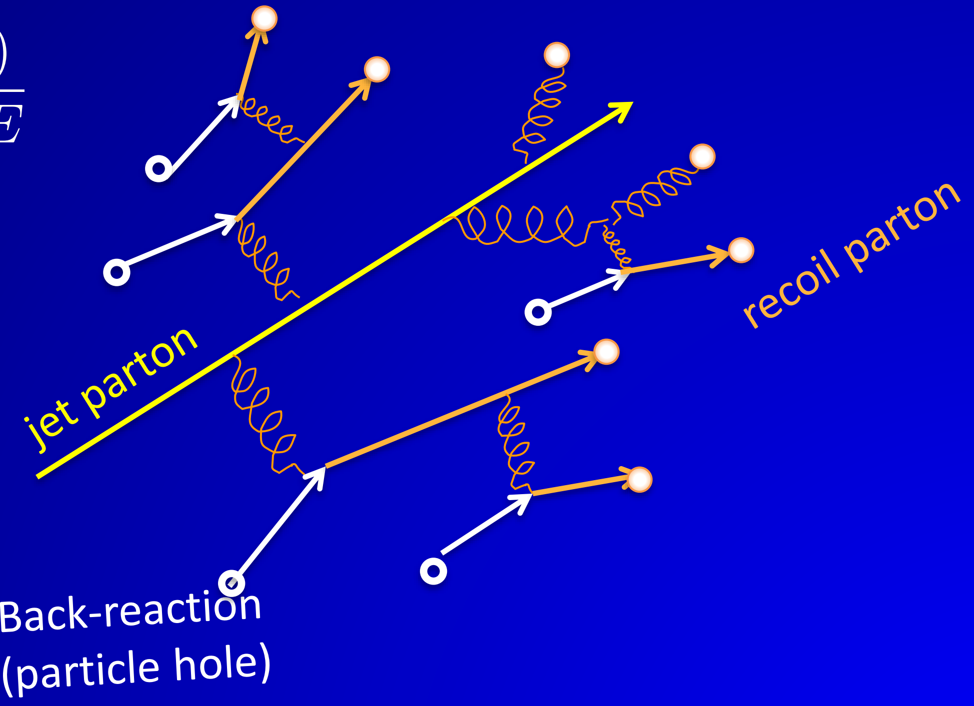
LBT: Linear Boltzmann Transport

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

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

CoLBT-hydro

(Coupled Linear Boltzmann Transport hydro)

Concurrent and coupled evolution of bulk medium and jet showers

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

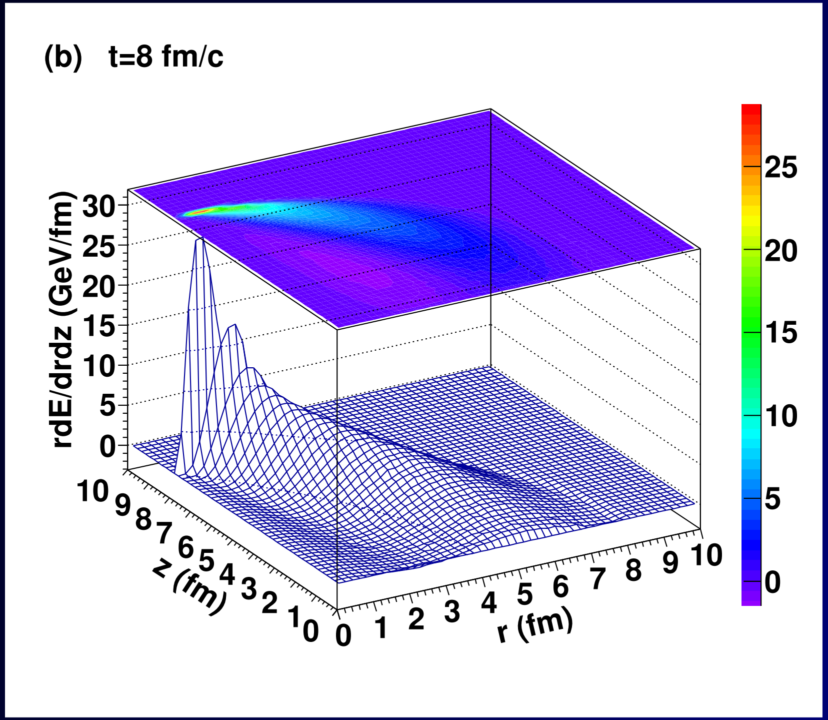
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

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

- 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

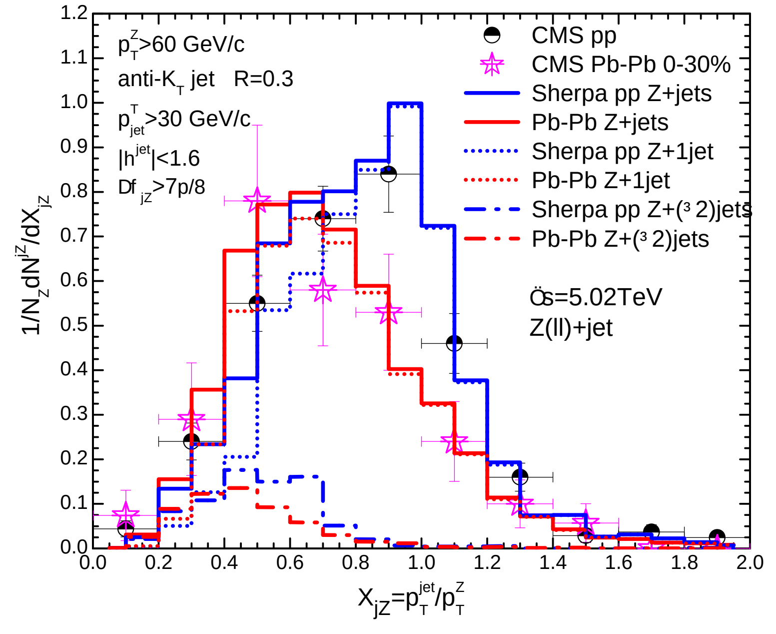
LBT & CoLBT: Jet-induced medium response



Energy transverse distribution of medium response in a static medium

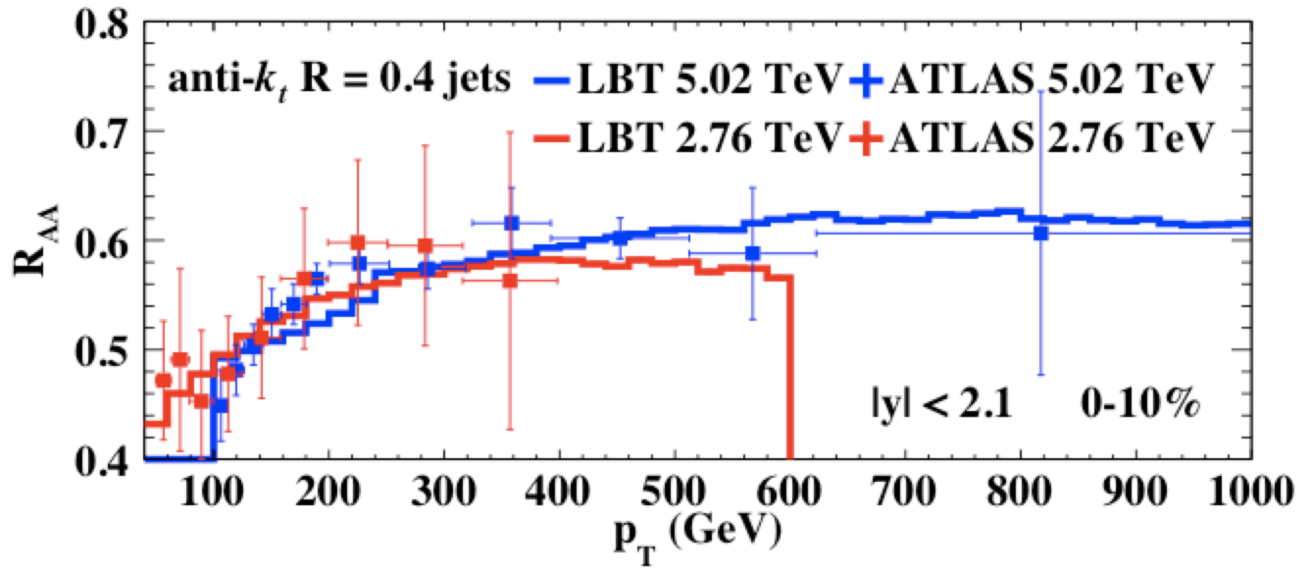
3D energy density distribution of the medium response induced by a γ-jet in a 0-10% Pb+Pb event

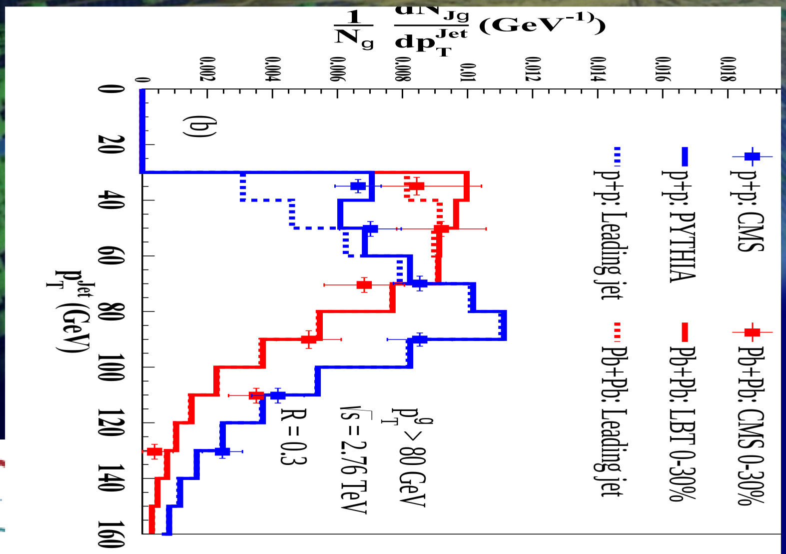
Jet suppression and medium response at LHC



Z-jet

Single inclusive jets





γ-jet

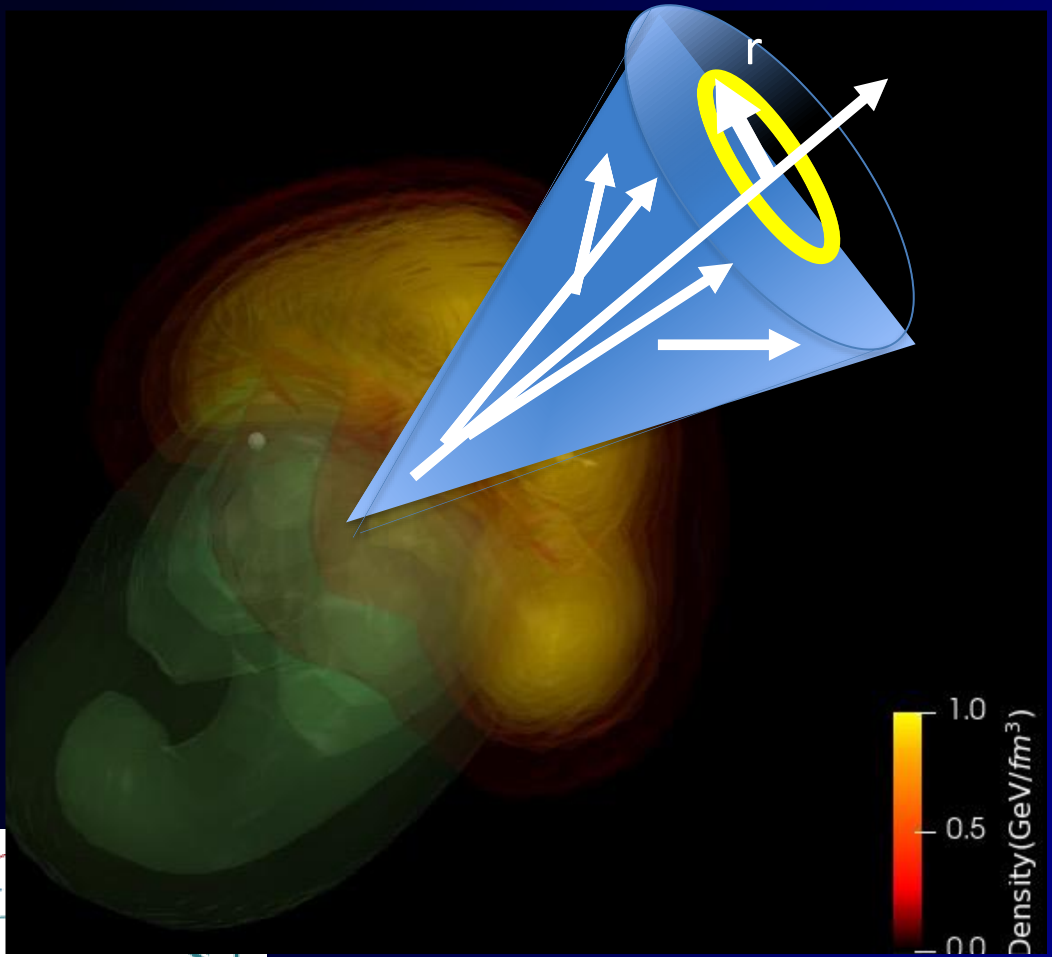
He, Cao, Chen, Luo, Pang & XNW 1809.02525

Zhang, Luo, XNW, Zhang, arXiv:1804.11041

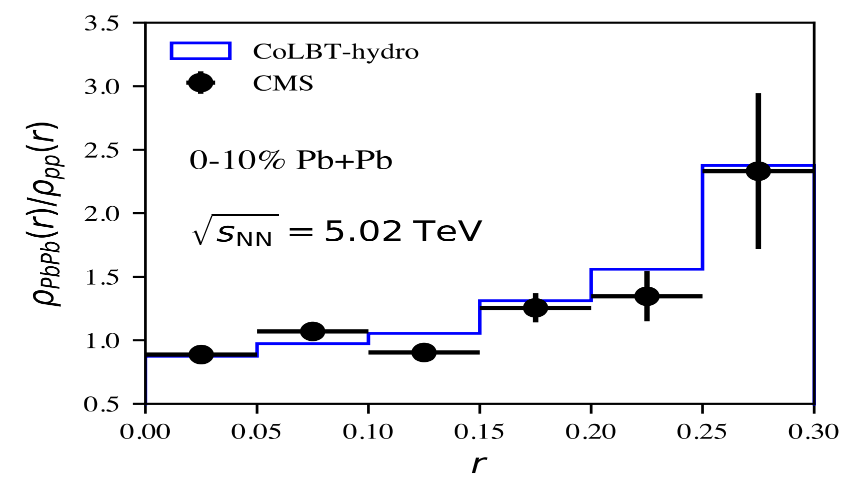
Luo, Cao, He & XNW, arXiv:1803.06785

Modification of jets and medium response

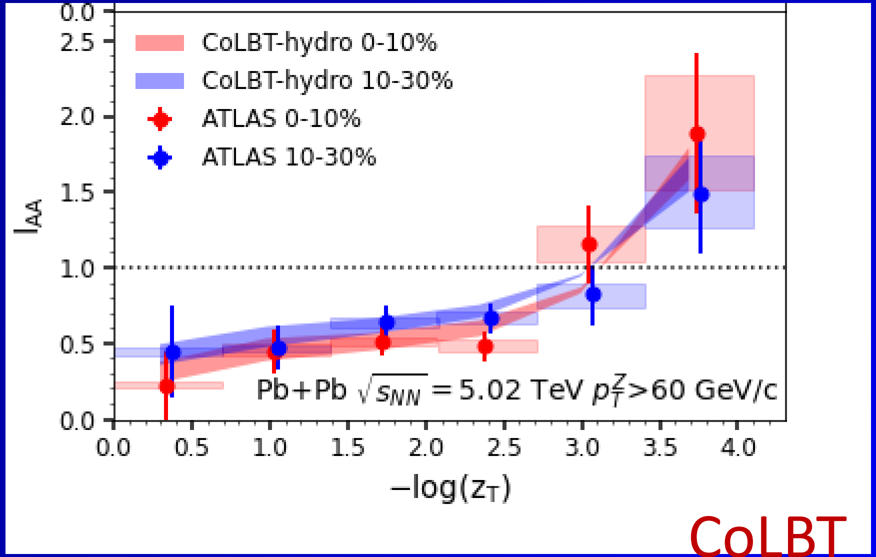
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{p_T^{jet}(r-\Delta r/2, r+\Delta r/2)}{p_T^{jet}(0,R)}$$



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



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



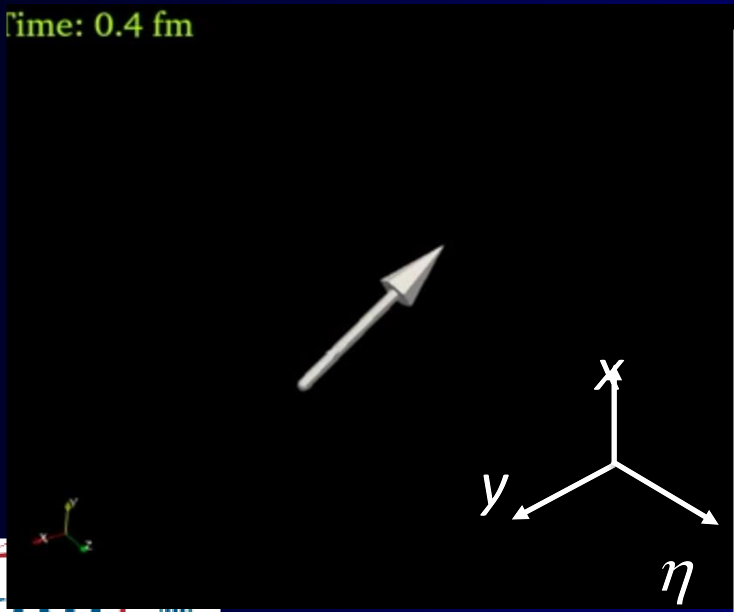
CoLBT

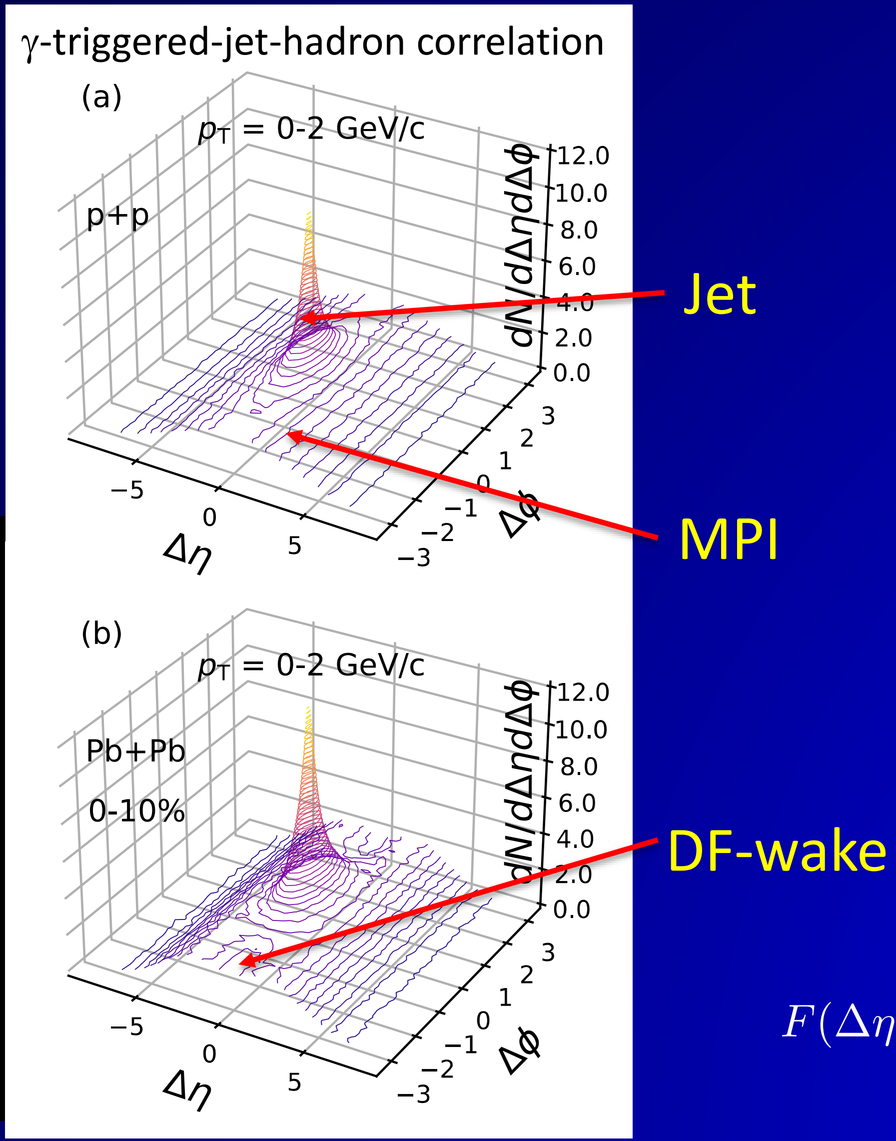
e-Print: 2101.05422

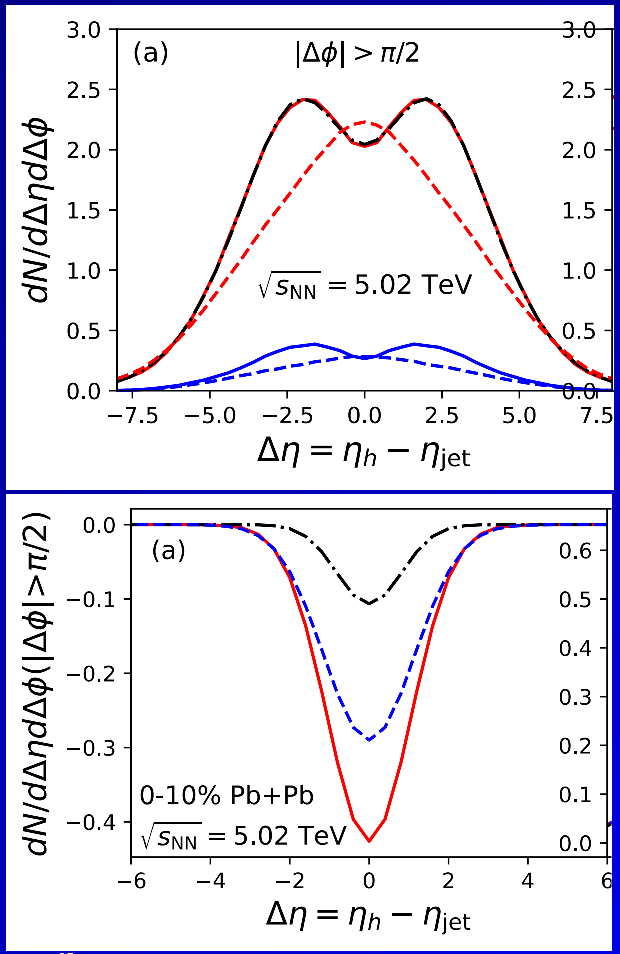
Search for jet-induced diffusion wake

Diffusion (DF) wake leads to depletion of soft hadron yield in the back of jet direction

Yang, Tan, Chen,Pang & XNW, *PRL,* 130 (2023) , 052301





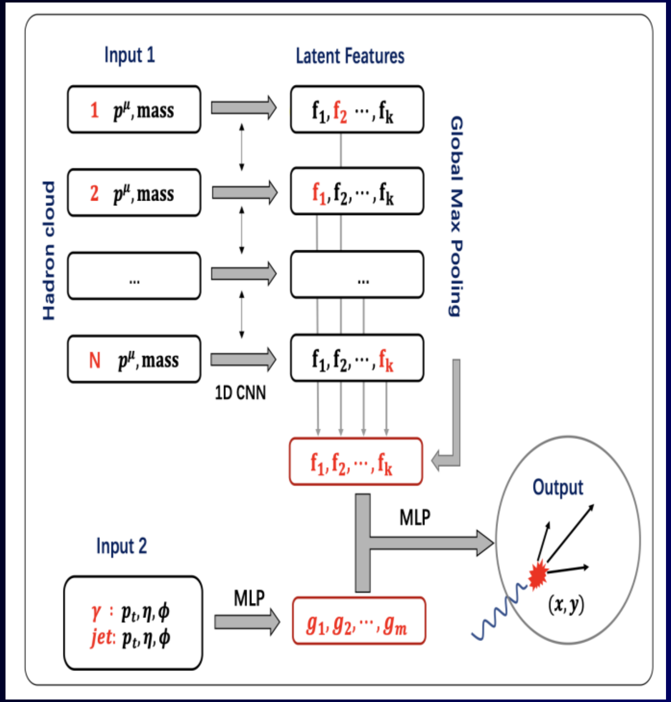


$$F(\Delta\eta) = \int_{\eta_{j1}}^{\eta_{j2}} d\eta_j \underset{\substack{\uparrow \\ \text{Jet-distr}}}{F_3(\eta_j)}(\underset{\substack{\uparrow \\ \text{MPI}}}{F_2(\Delta\eta,\eta_j)} + \underset{\substack{\uparrow \\ \text{DF-wake}}}{F_1(\Delta\eta)}),$$

s

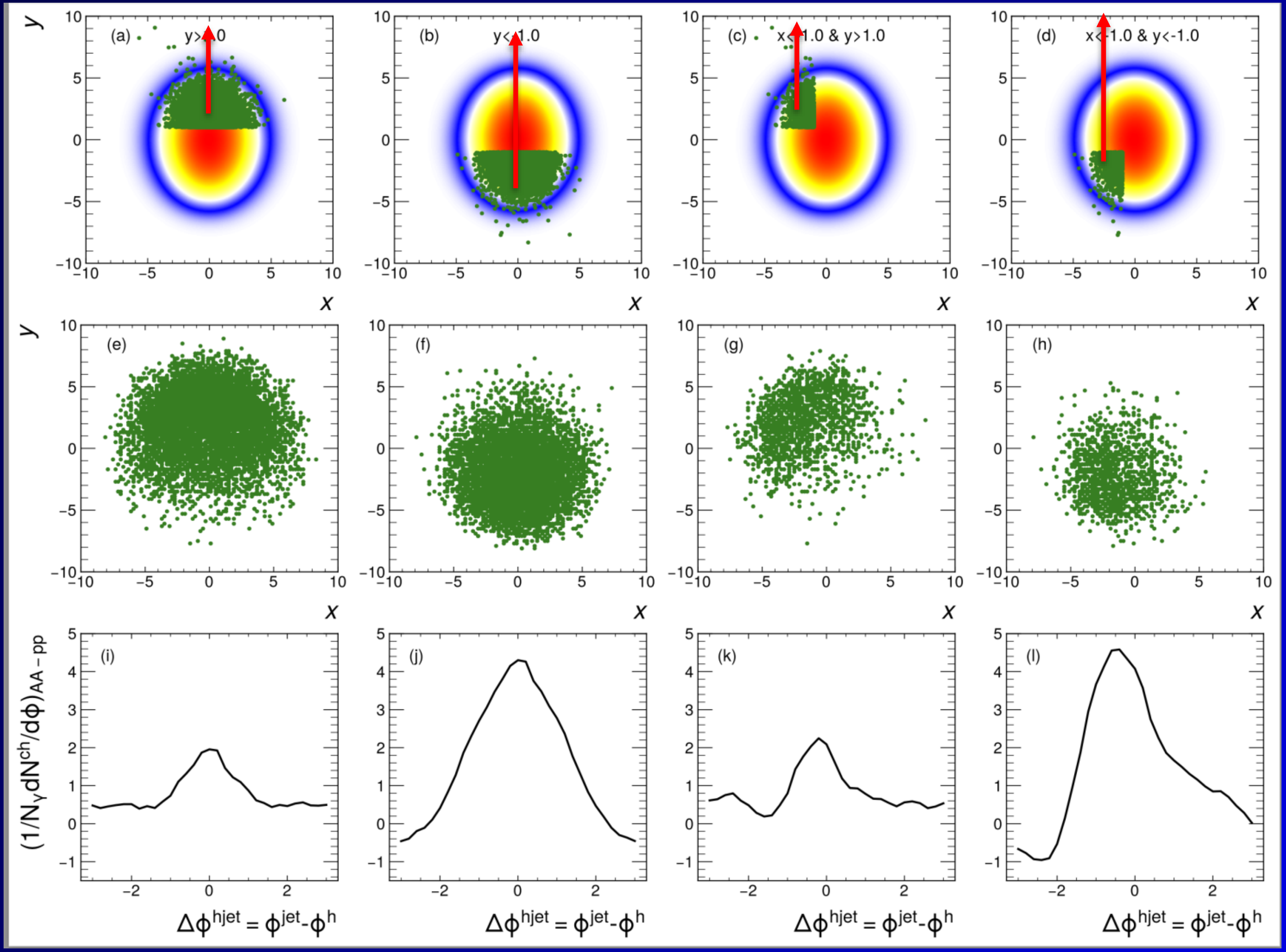
Deep learning assisted jet tomography

PCN (point cloud network)



e-Print: 2206.02393

Yang, He，Chen，Ke，Pang & XNW



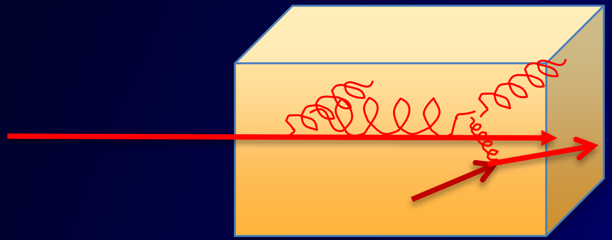
DL network selection

Actual distribution

γ-soft hadron correlation

EEC of single parton in a QGP brick

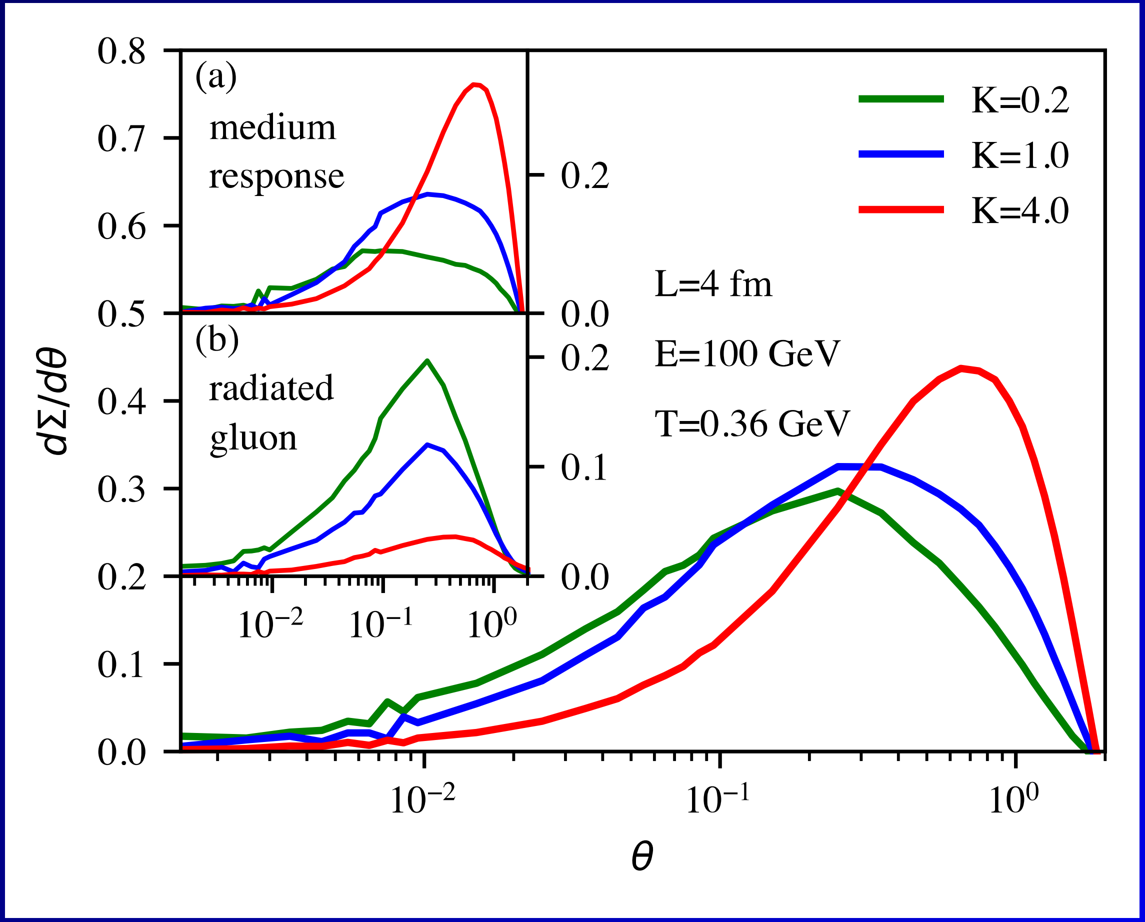
Single parton with multiple scattering in a brick in LBT



Debye mass:

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

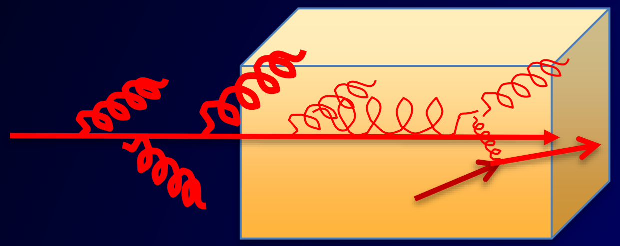
We vary only *K* in the sampling the transverse momentum transfer of 2→2 and kinematic limit of gluon bremsstrahlung. We however keep qhat and 2→2 rate unchanged.



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

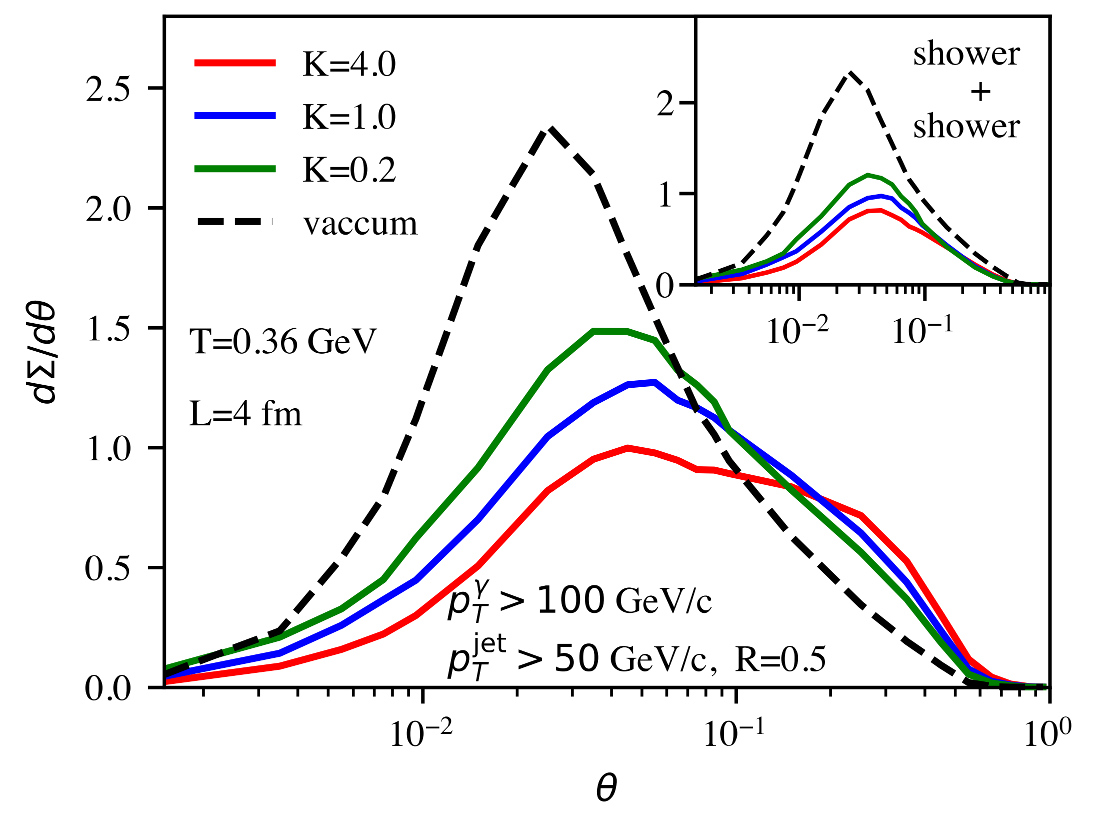


Initial γ-jet configurations generated from Pythia8

Energy loss and momentum broadening lead to suppression at small angles

Radiated gluon and medium response dominate at large angles

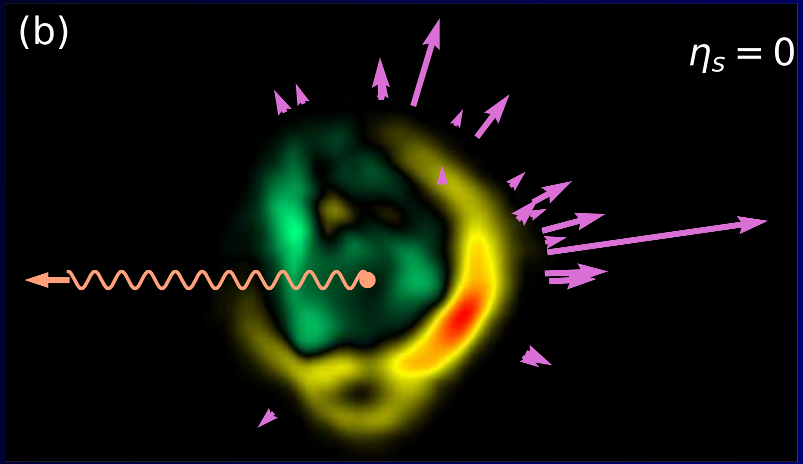
A jet shower in a brick in LBT



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

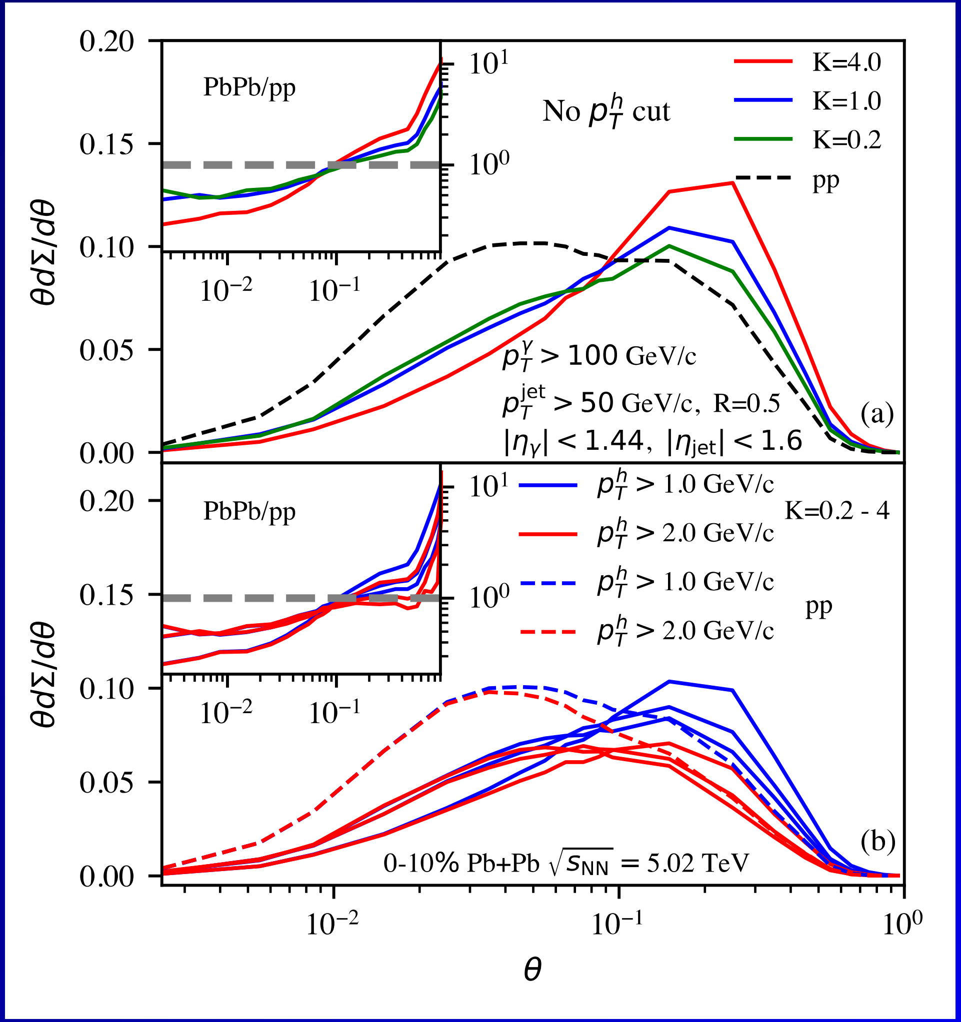
EEC of γ-jets in Pb+Pb Collisions

CoLBT simulations:



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

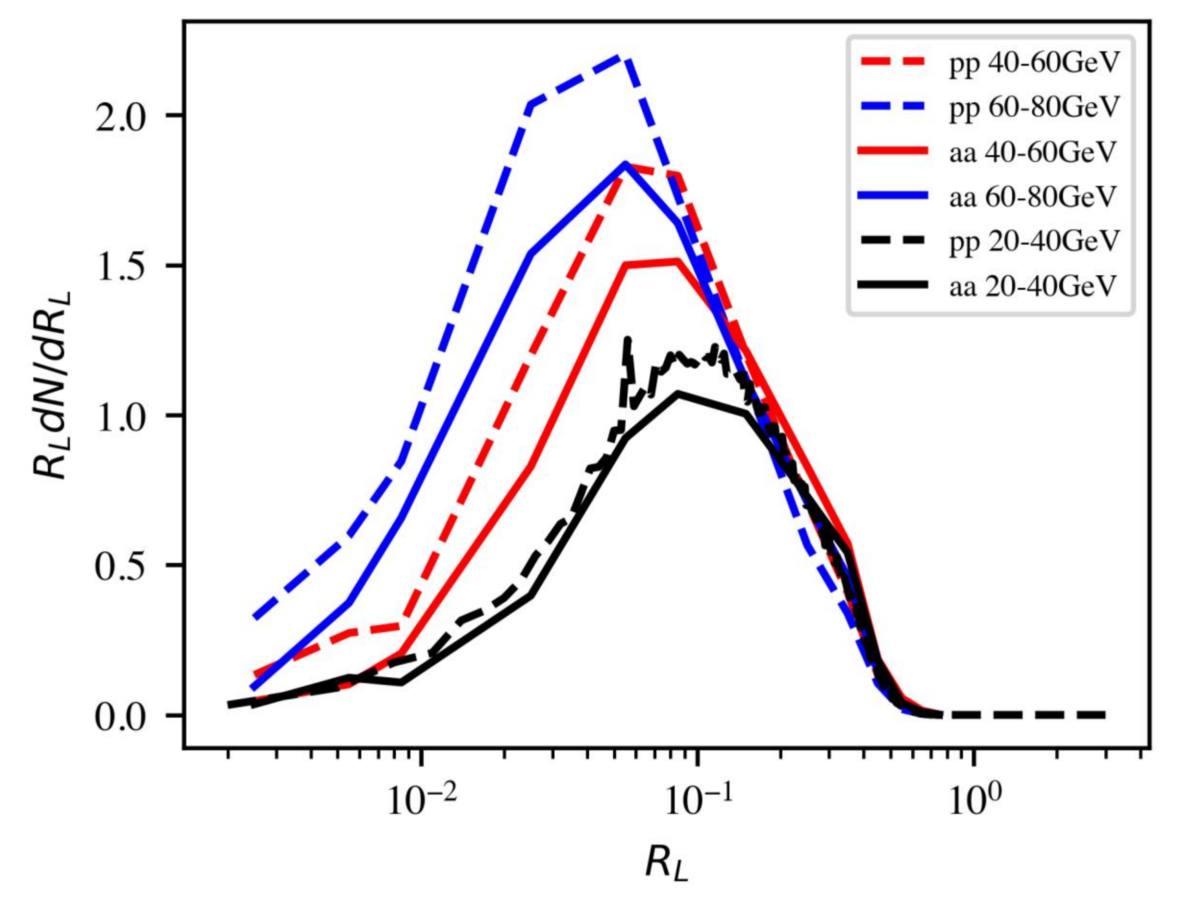
EEC by energetic hadrons from leading shower partons at small angles are suppressed, not affected by pT cuts



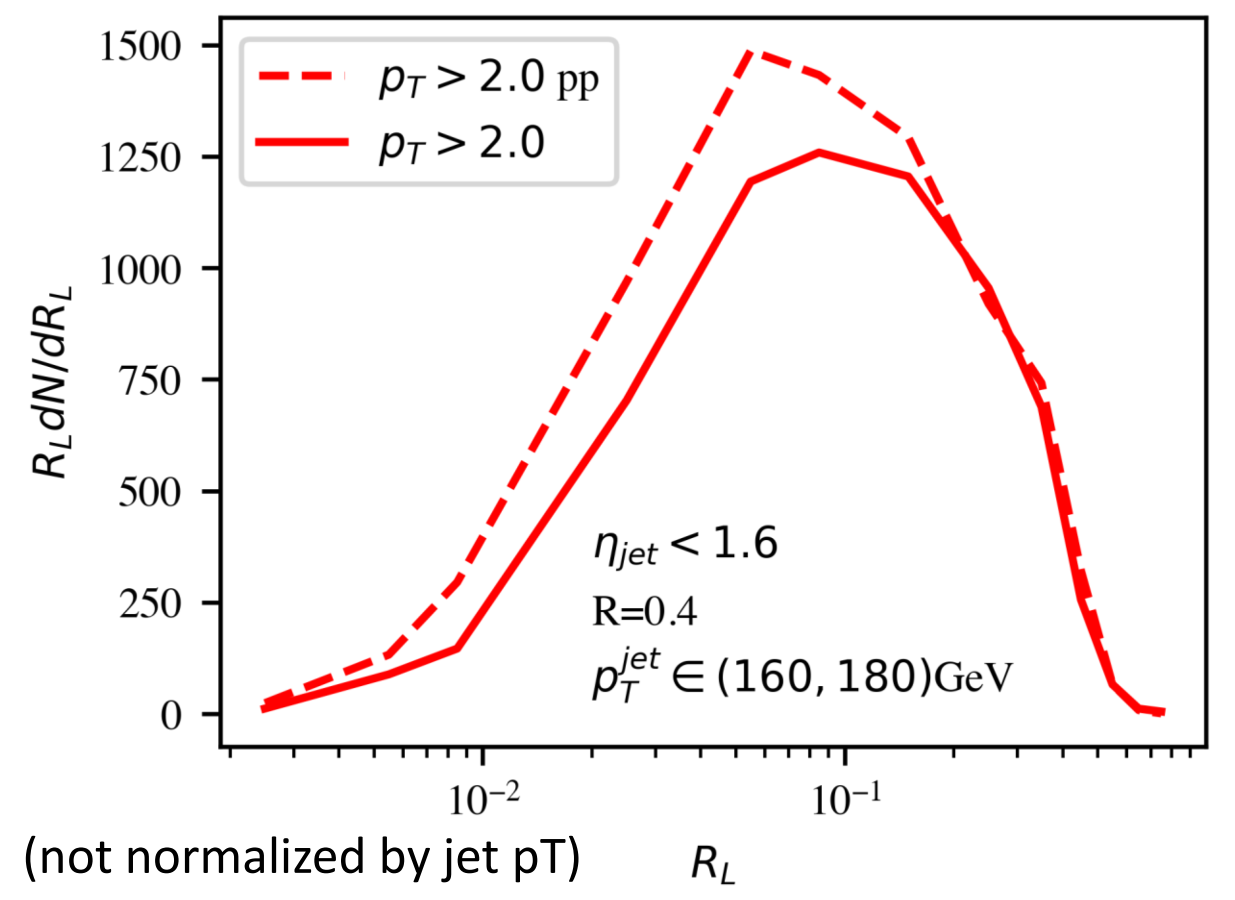
Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

EEC for single inclusive jets

Similar to EEC for γ-jets

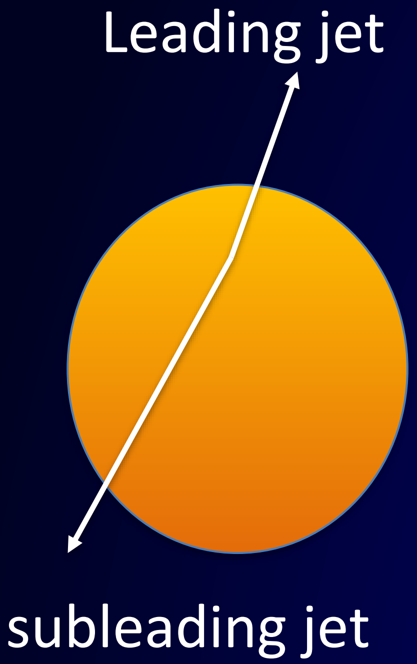


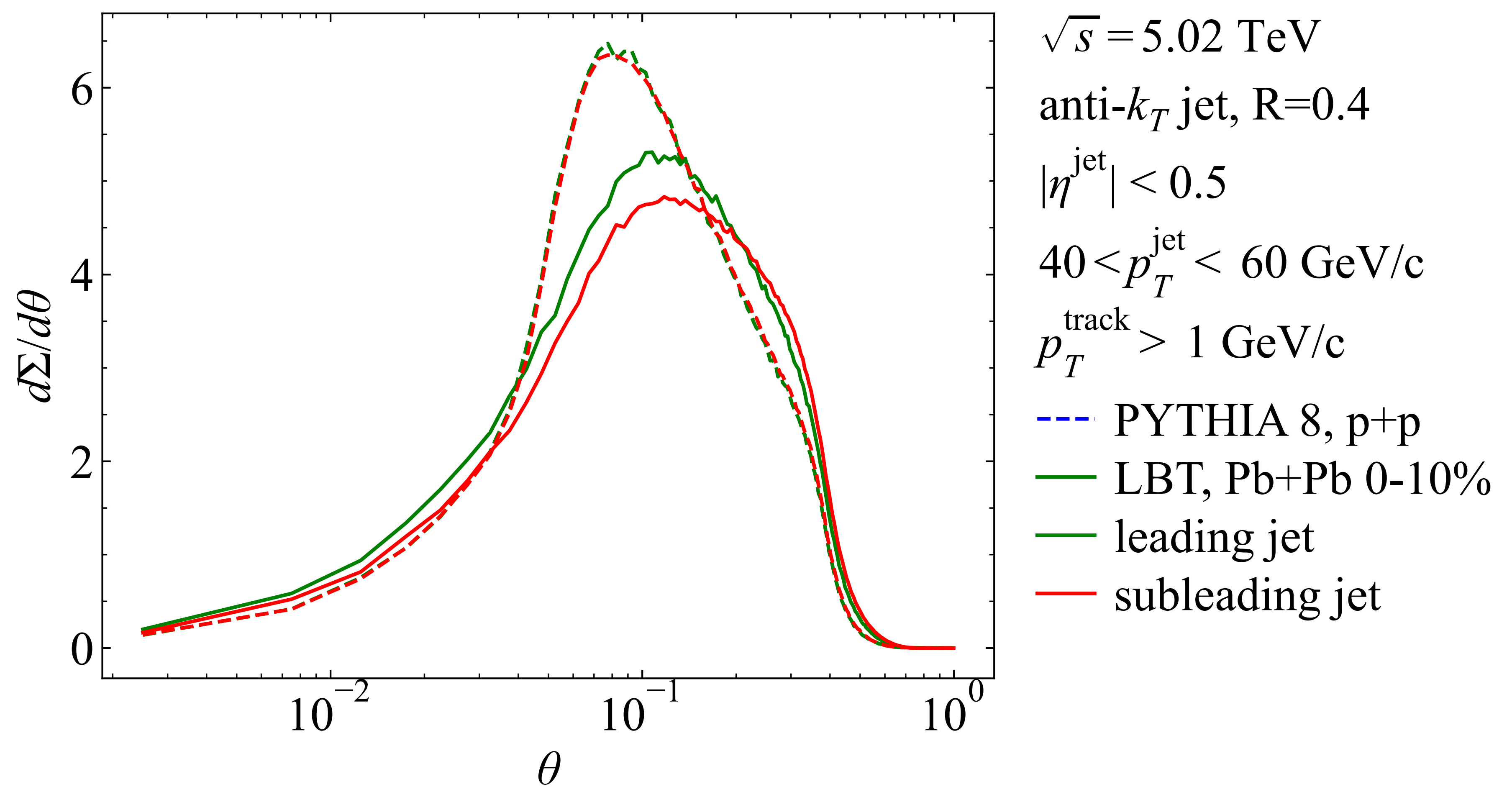
pT cut reduces enhancement from medium response



(not normalized by jet pT)

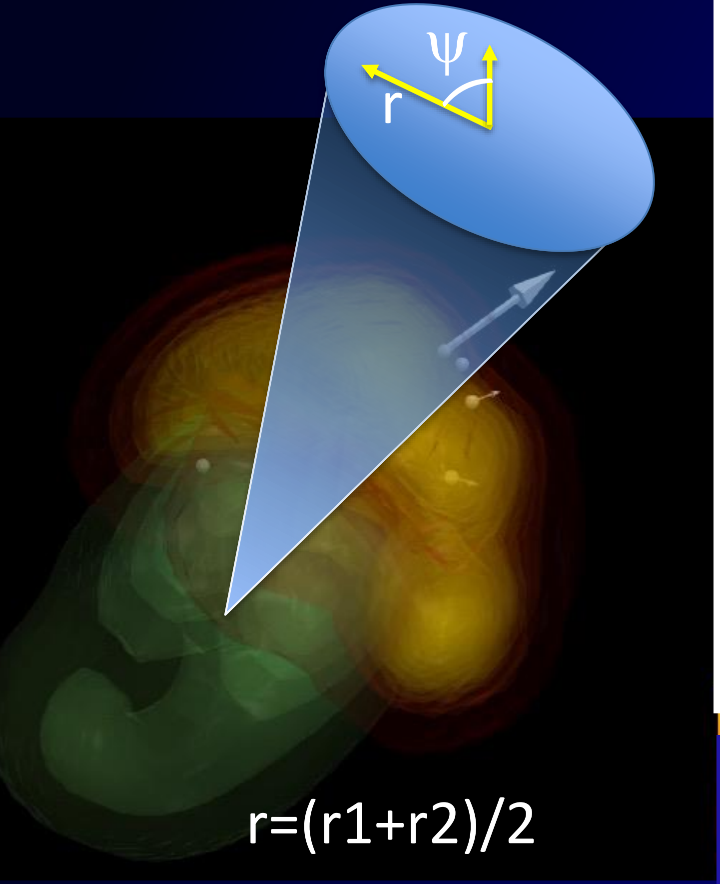
EEC of dijets





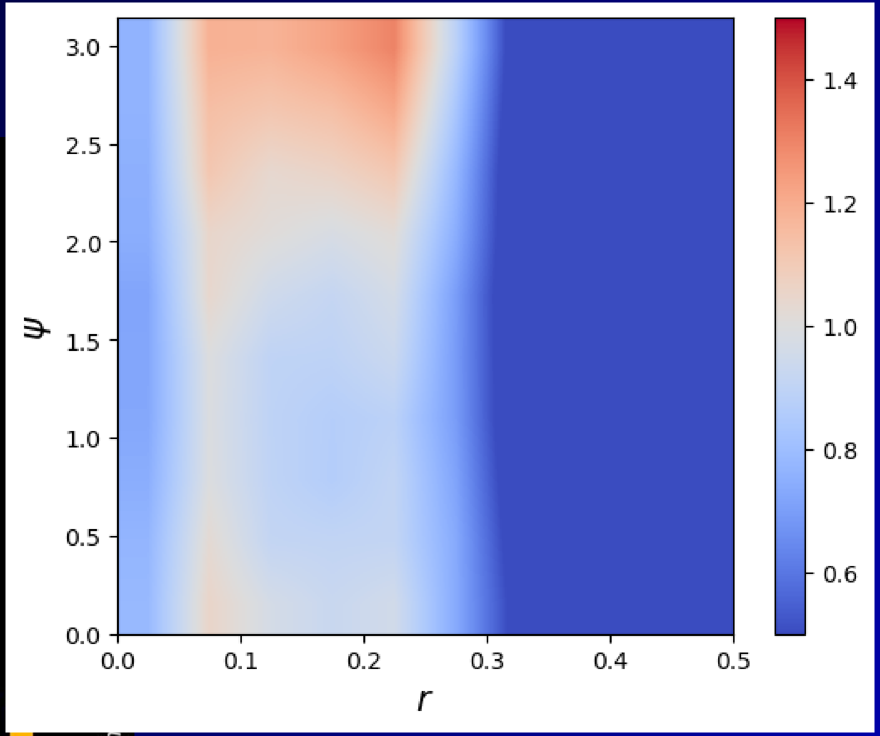
$\text{EEC}_{\text{leading}} - \text{EEC}_{\text{subleading}}$: robust measure of medium modification free of background

Seeing Mach-cone through 3p Azimuthal Correlation



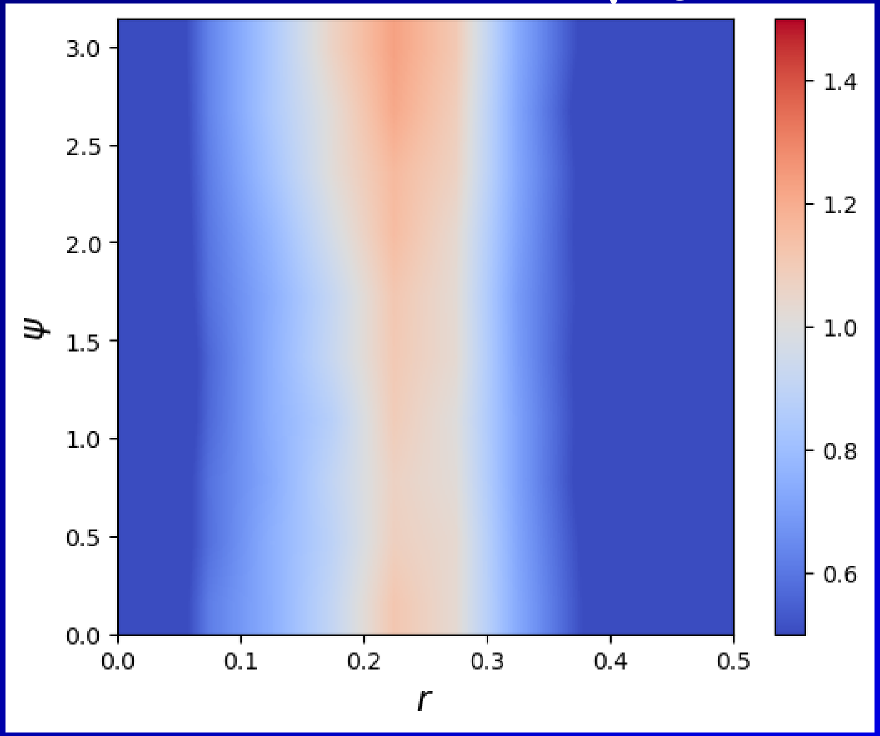
r=(r1+r2)/2

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)

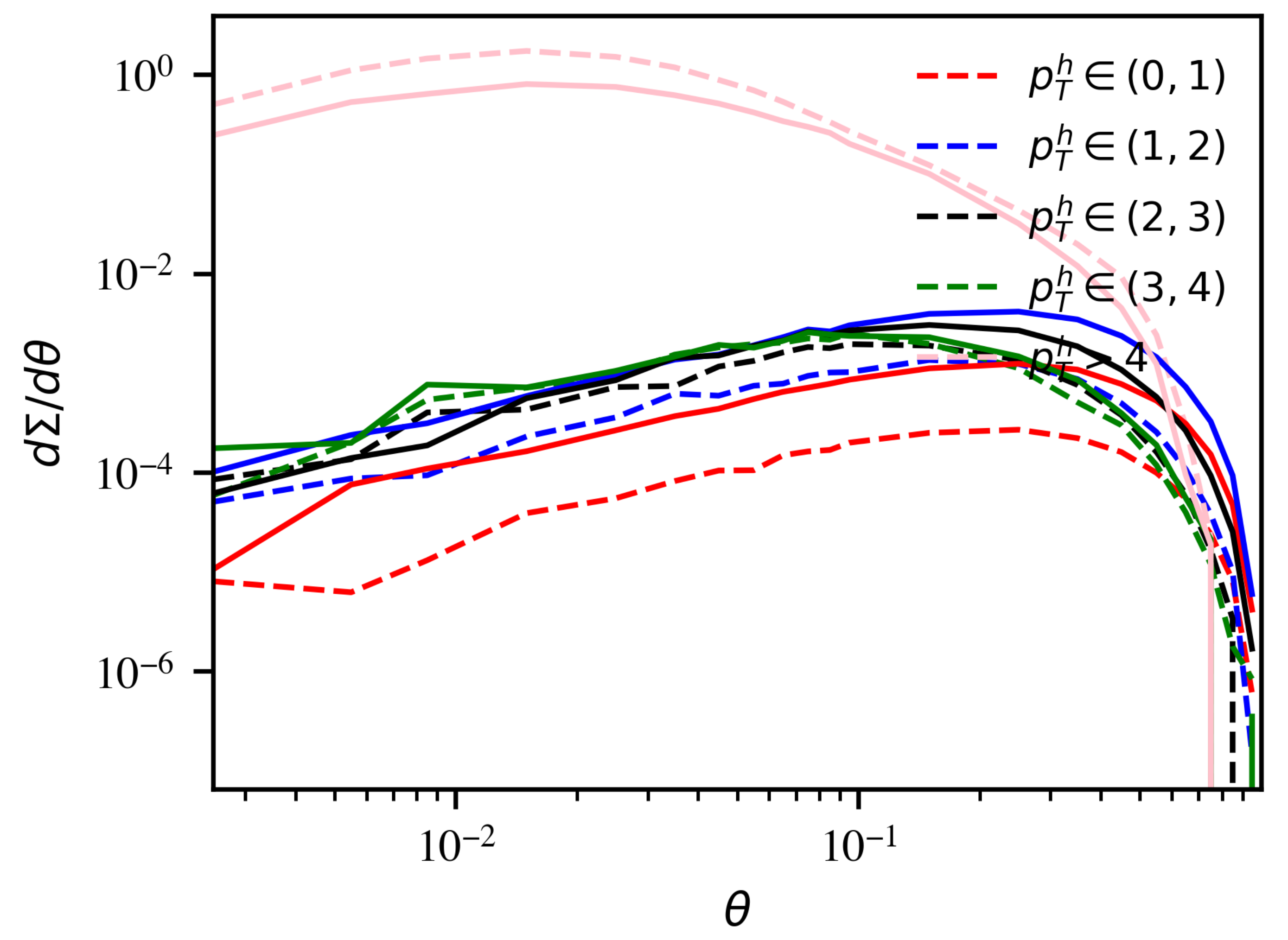


Azimuthal uniform correlation due to medium-response: Mach-cone – sound velocity?

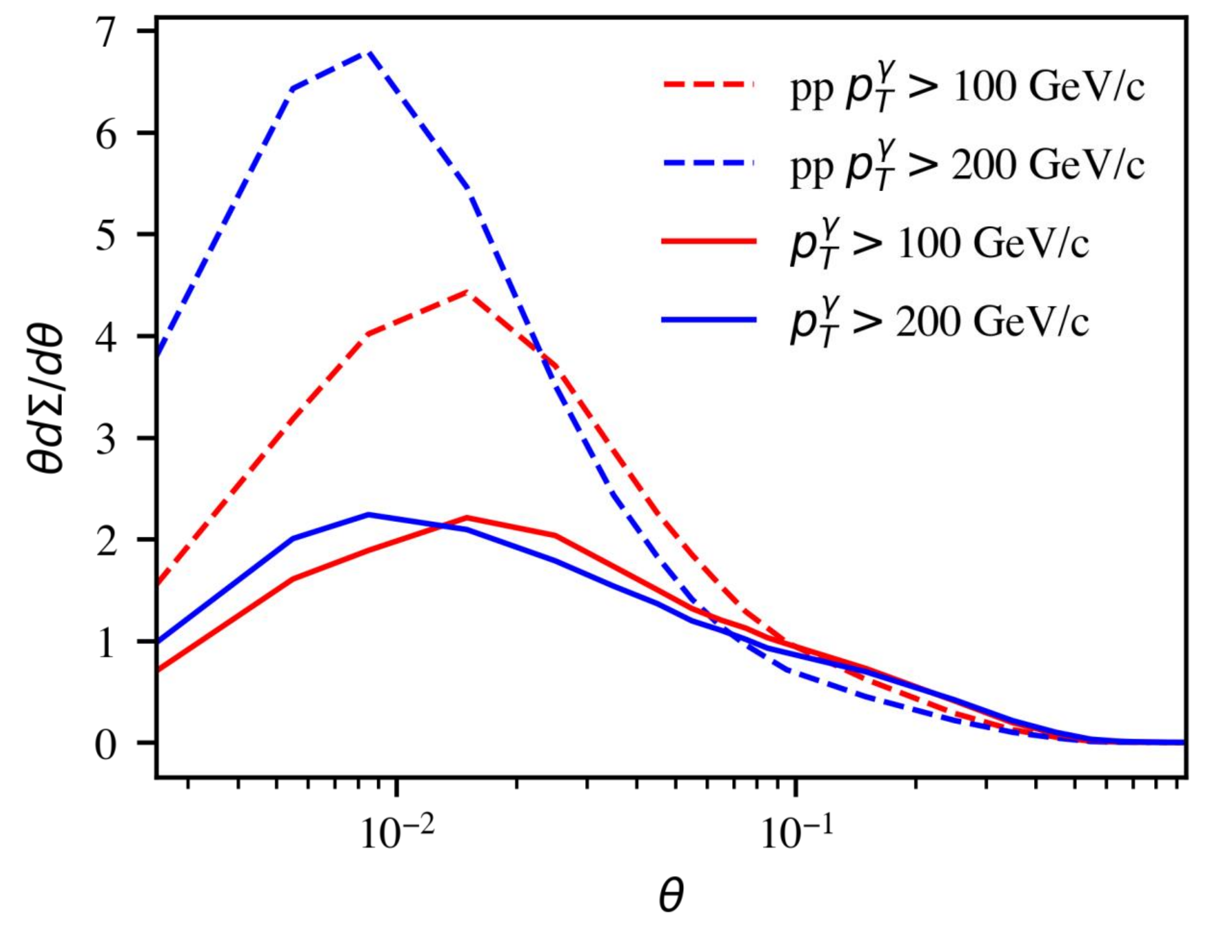
Summary

- 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

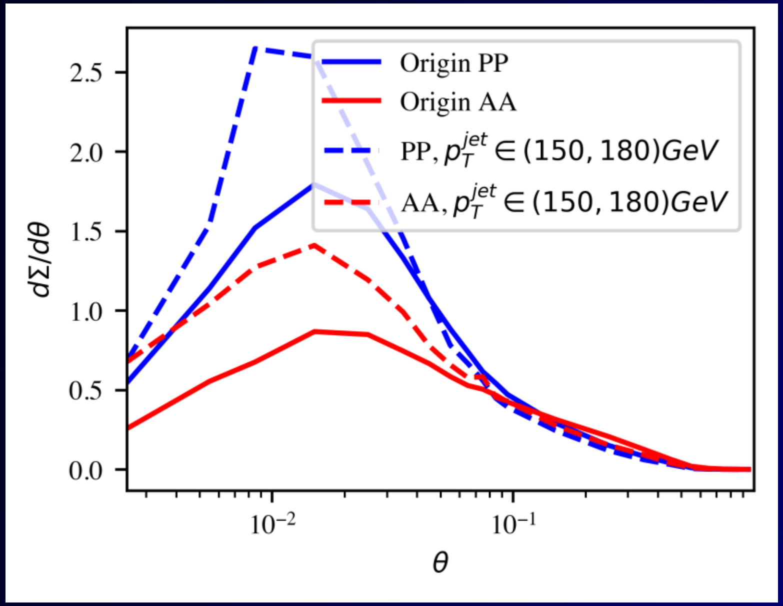
pT dependence of EEC

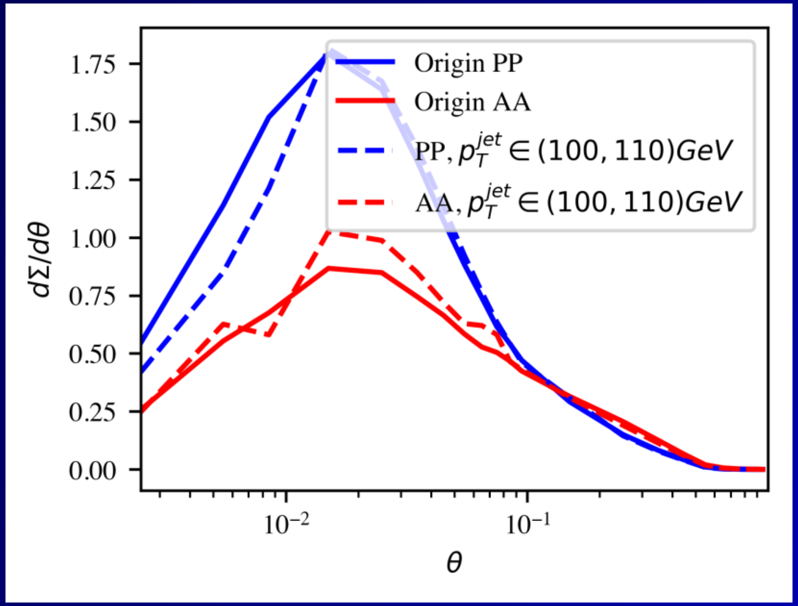


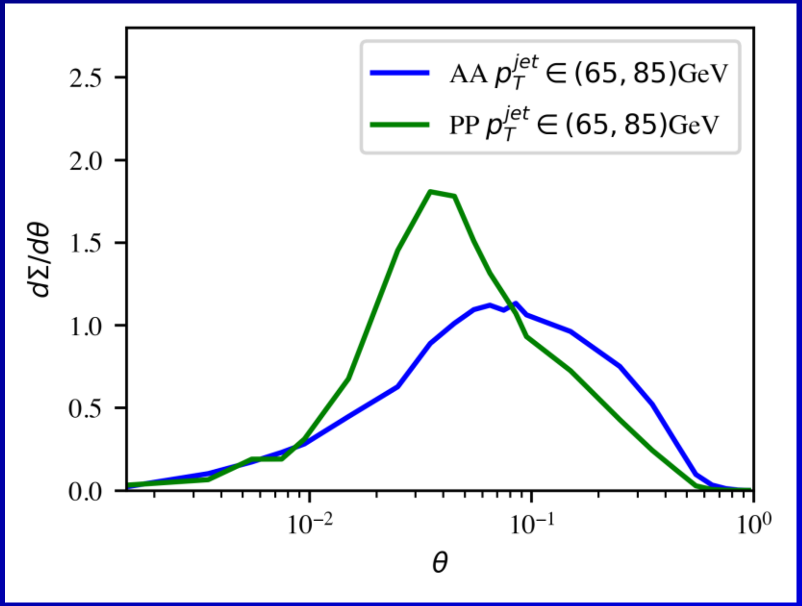
γ energy dependence



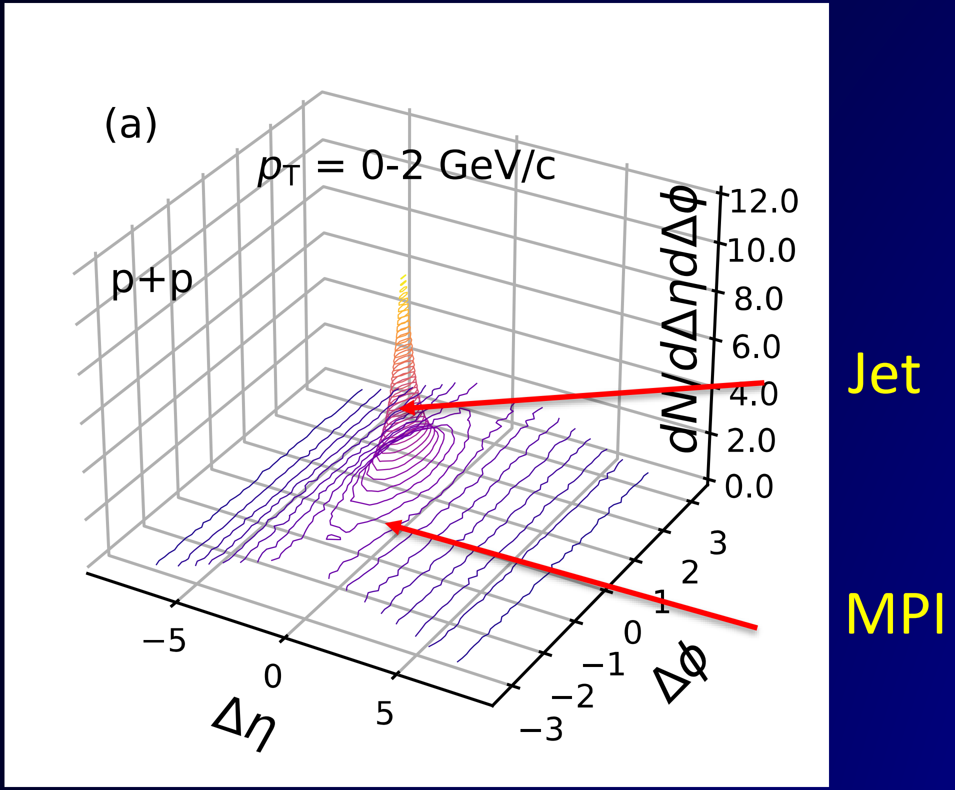
Jet energy dependence





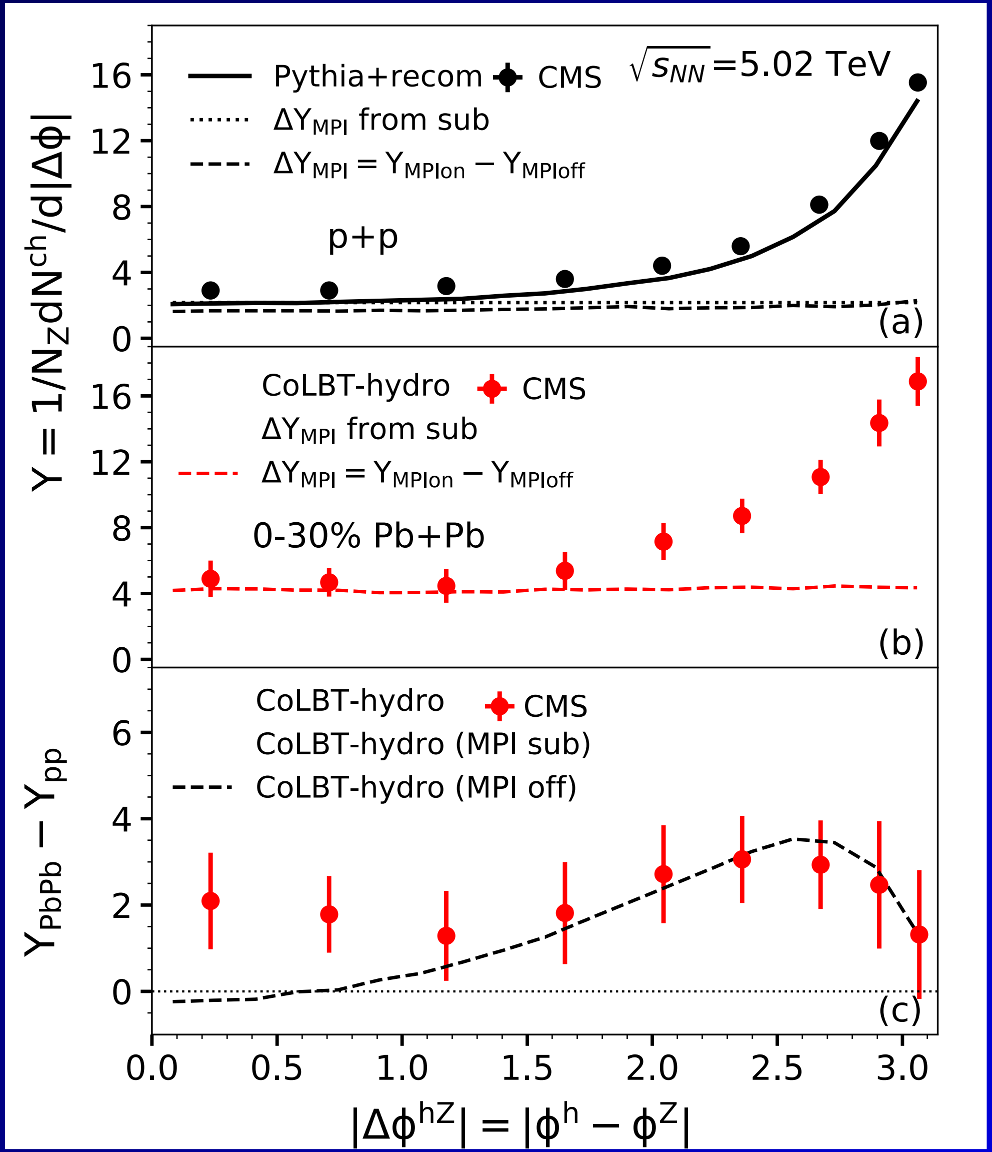


MPI subtraction in Z-hadron correlation



Mixed event subtraction

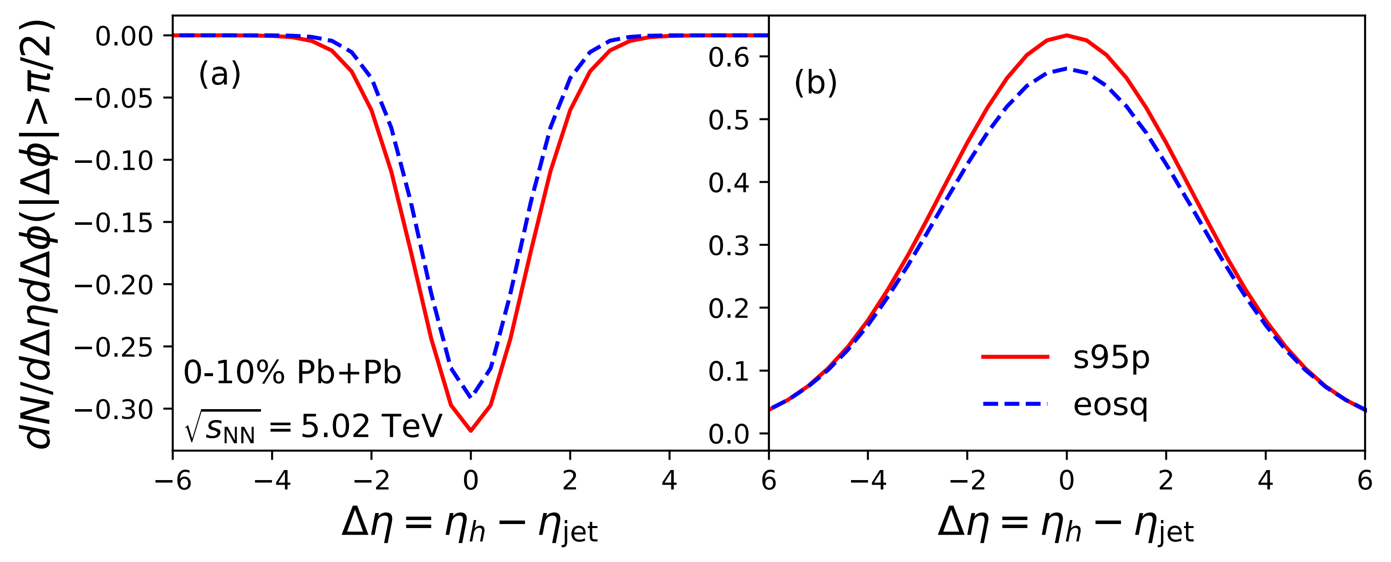
$$\frac{dN^{hZ}_{\rm MPI}}{d\phi} = \frac{dN^{hZ}_{\rm mix}}{d\phi} - \int_1^\pi \frac{d\phi}{\pi}\left(\frac{dN^{hZ}}{d\phi} - \frac{dN^{hZ}}{d\phi}|_{\phi=1}\right)$$



Medium modification of MPI: low pT enhancement and high pT suppression

No correlation with Z/γ-jet

Sensitivity to EoS and shear viscosity



eosq: first order

s95p: rapid crossover from LQCD

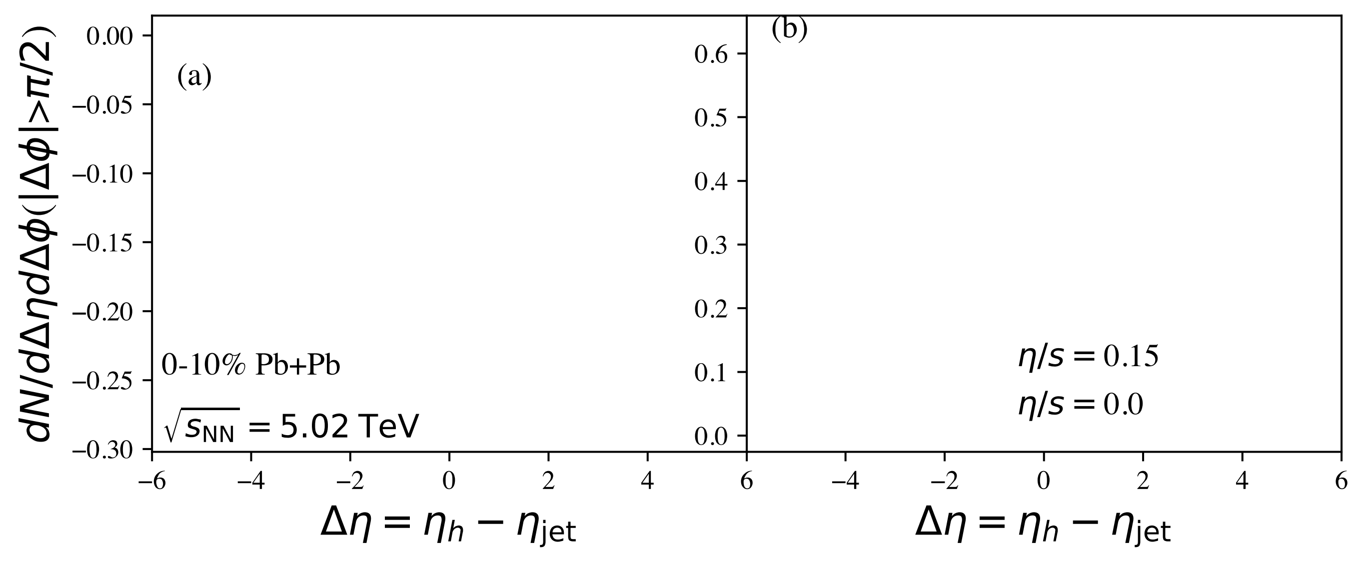
Larger effective c_s in eosq → :
larger Mach cone angle → shallower DF valley

Stronger radial flow → smaller soft MPI

Competition of:

η/s increase transverse flow → suppression of soft MPI and DF valley

Negative shear correction of longitudinal pressure → impede longitudinal expansion → increase MPI and DF valley

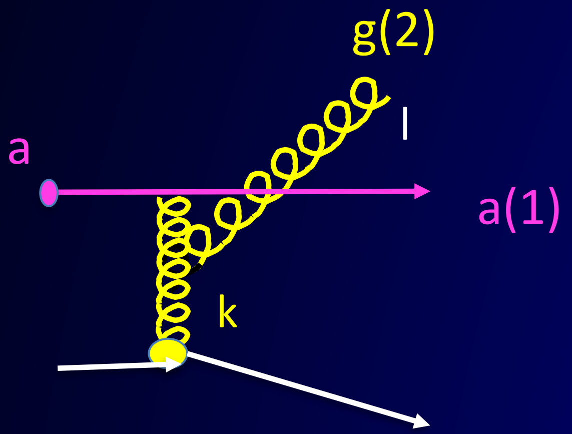


Gluon spectrum from single emission in GHT

Generalized HT induced emission in a QGP brick:

$$\tau_f = \frac{2z(1-z)E}{(\ell_\perp - \mathbf{k}_\perp)^\mathbf{2}}$$

$$\frac{dN_g^{a(\mathrm{GHT})}}{dz d\ell_\perp^2} = \frac{C_A C_2(R)}{N_c^2 - 1}\frac{\alpha_s}{2\pi}P_{ag}^{(0)}(z)\int dy \rho_A(y)\int_0^{Q^2} d^2\mathbf{k}_\perp \frac{\alpha_s \phi_g(x_g, \mathbf{k}_\perp^2)}{k_\perp^2}\frac{2\mathbf{k}_\perp \cdot \ell}{\ell_\perp^2(\ell_\perp - \mathbf{k}_\perp)^2}\left[1 - \cos\frac{y}{\tau_f}\right]$$



For small angle emission: $\ell_\perp \ll zE, |\mathbf{k}_\perp - \ell_\perp| \ll (\mathbf{1} - \mathbf{z})\mathbf{E}$

$$\theta_{12}^2 \approx 4\frac{(\ell_\perp - \mathbf{z}\mathbf{k}_\perp)^\mathbf{2}}{z^2(1-z)^2E^2} \approx 4\frac{(\ell_\perp - \mathbf{k}_\perp)^\mathbf{2}}{z^2(1-z)^2E^2}$$

Change of variable $\ell_\perp - \mathbf{k}_\perp \to \ell_\perp$

$$\theta_{12} \approx \frac{2\ell_\perp}{z(1-z)E} \qquad \tau_f = \frac{2z(1-z)E}{\ell_\perp^2} = \frac{8}{z(1-z)E\theta_{12}^2}$$

EEC in generalized high-twist

With a (GW) static potential model

$$\frac{\phi(0,\vec{k}_\perp)}{k_\perp^2} = C_2(T)\frac{4\alpha_{\rm s}}{(k_\perp^2+\mu_{\rm D}^2)^2}. \qquad \hat{q} = \int dk_\perp^2\,\phi(0,k_\perp) \approx \rho\,\frac{C_2(R)C_2(T)}{N_c^2-1}4\pi\alpha_s^2 \ln\frac{s^*}{4\mu_D^2}$$

$$\frac{d\Sigma_q^{\rm med}}{d\theta} = \frac{L^{5/2}}{\pi\sqrt{E}}\,\frac{\hat{q}}{\ln\frac{s^*}{4\mu_D^2}}\,\frac{8\alpha_{\rm s}C_A}{\theta\sqrt{EL}}\int dz\,\frac{z(1-z)P_{qg}(z)}{z^2(1-z)^2\theta^2EL+4\mu_D^2}\left[1-\frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]$$

For large angles $z^2(1-z)^2\theta^2EL \gg 4\mu_D^2$

Recover HT results:

$$\hat{q}_{HT} = \frac{\hat{q}}{\ln\frac{s^*}{4\mu_D^2}} \qquad \frac{d\Sigma_q^{\rm med}}{d\theta} = \frac{L^{5/2}\hat{q}_{HT}}{\pi\sqrt{E}}\,\frac{8\alpha_{\rm s}C_A}{(\sqrt{EL}\theta)^3}\int dz\,\frac{P_{qg}(z)}{z(1-z)}\left[1-\frac{\sin ELz(1-z)\theta^2/8}{ELz(1-z)\theta^2/8}\right]$$