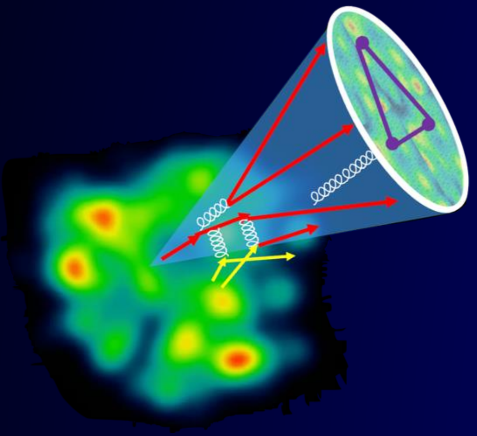
Galilieo Galilei Institute, March 24-27, 2025

Two kinds of correlations

Xin-Nian Wang

Central China Normal University



In collaboration with Y. He, W. Ke, I. Moult and Z. Yang, W. Zhao

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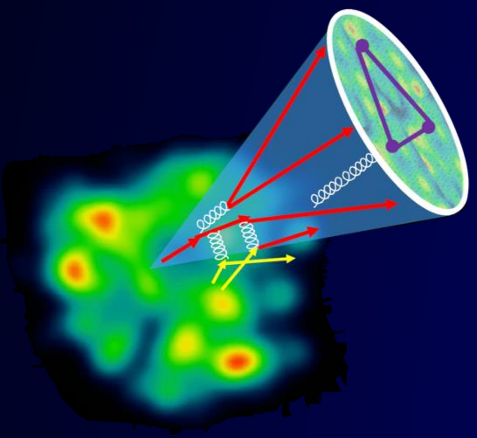
Galilieo Galilei Institute, March 24-27, 2025

Modification of EEC in cold and hot QCD medium

Xin-Nian Wang

Central China Normal University



In collaboration with Y. He, W. Ke, I. Moult and Z. Yang, W. Zhao

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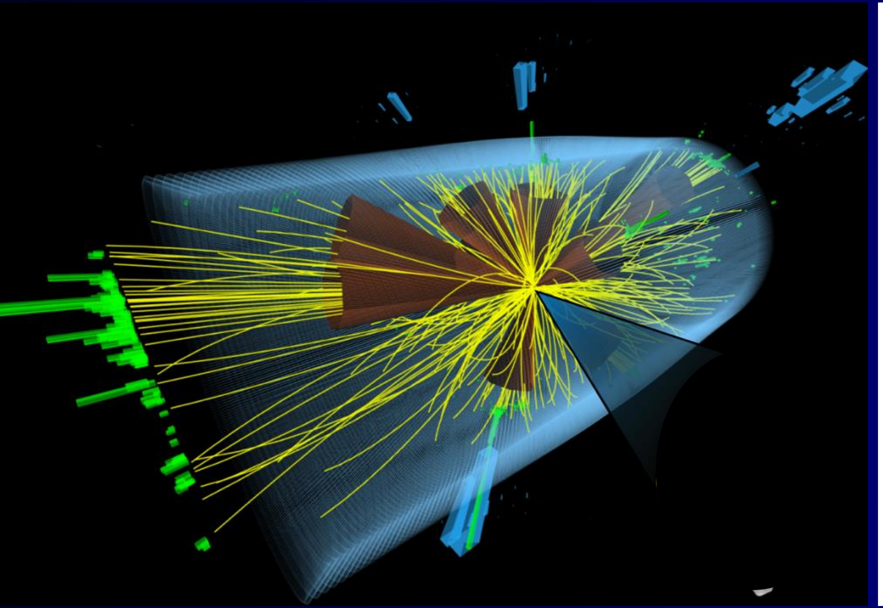
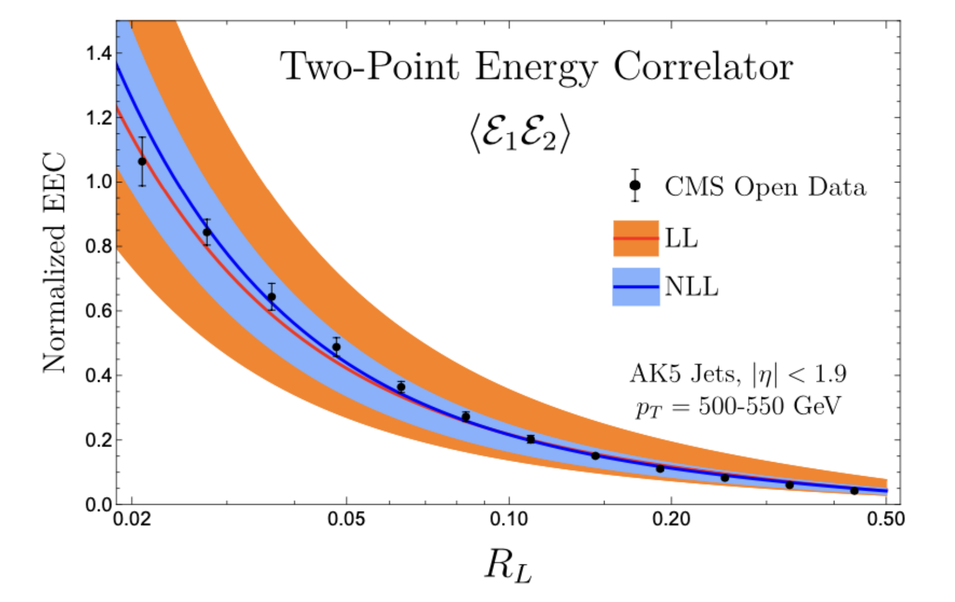
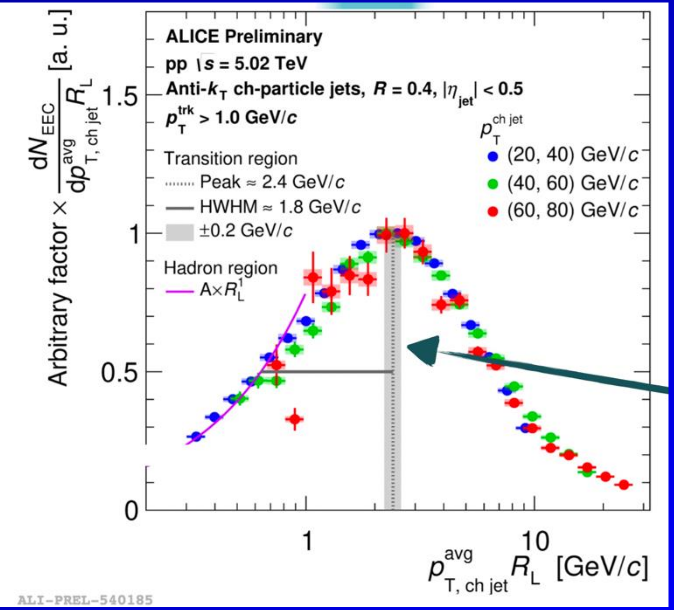
Energy-energy correlator (EEC)

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

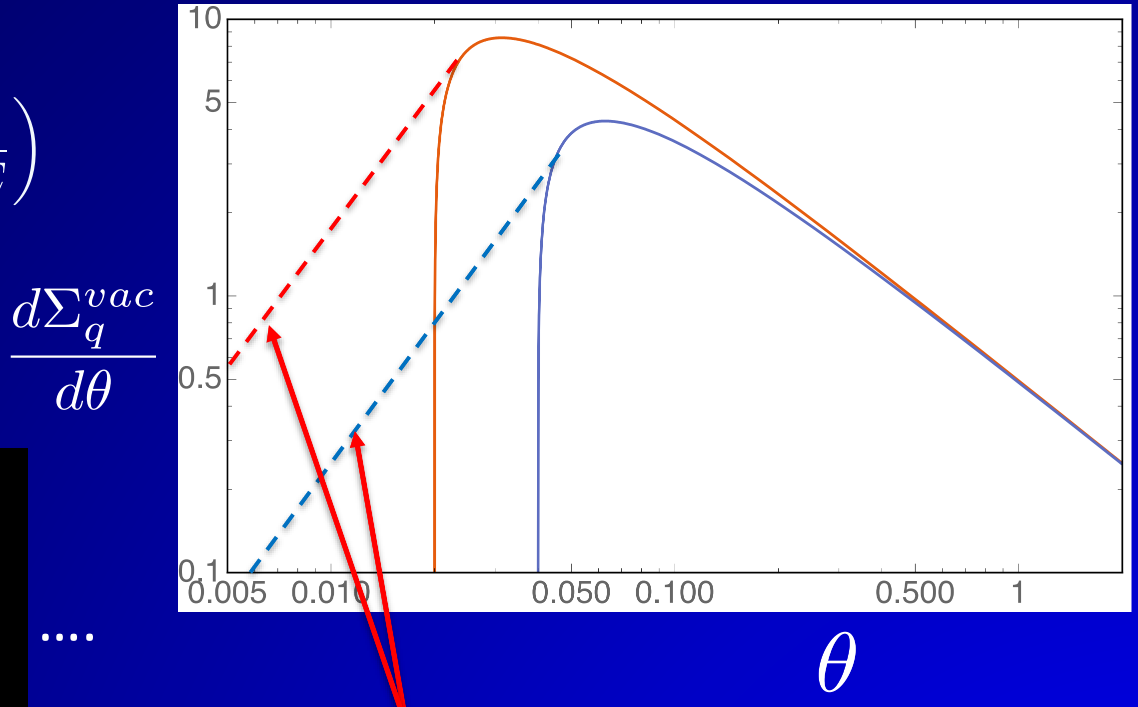
Fan, QM23

Jet EEC in Vacuum

LO emission:

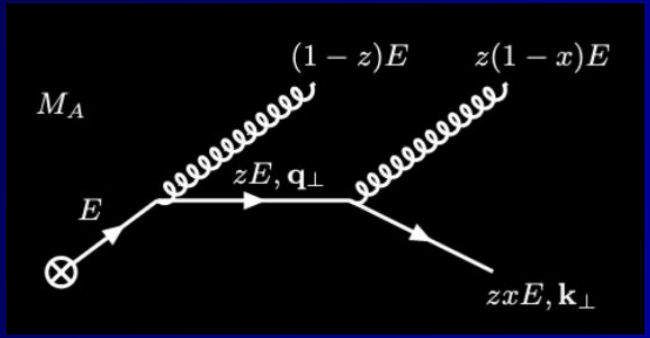
$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz\ z(1-z) P_{qg}(z) \int_{\mu_0^2}^{Q^2} \frac{d\ell_\perp^2}{\ell_\perp^2} \delta\left(\theta - \frac{\ell_\perp}{z(1-z)E}\right)$$

$$\approx \frac{\alpha_s}{2\pi} \frac{C_F}{2\theta} \left(3 - \frac{2\mu_0}{E\theta}\right) \sqrt{1 - \frac{4\mu_0}{E\theta}}$$



Uncorrelated emission at small angle

Leading Log evolution:



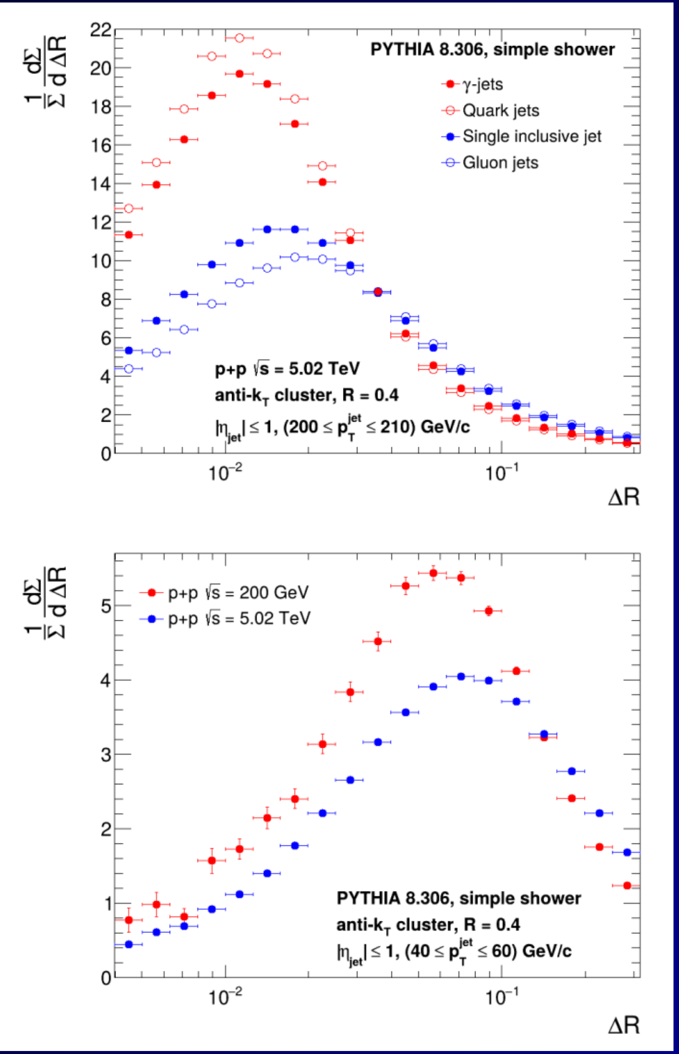
....

$$\frac{\partial}{\partial t}\begin{bmatrix}\Sigma_q \\ \Sigma_g\end{bmatrix} = \begin{bmatrix}\gamma_{qq}(3) & \gamma_{gq}(3) \\ 2N_f\gamma_{qg}(3) & \gamma_{gg}(3)\end{bmatrix}\begin{bmatrix}\Sigma_q \\ \Sigma_g\end{bmatrix}$$

Different EEC for quarks and gluons

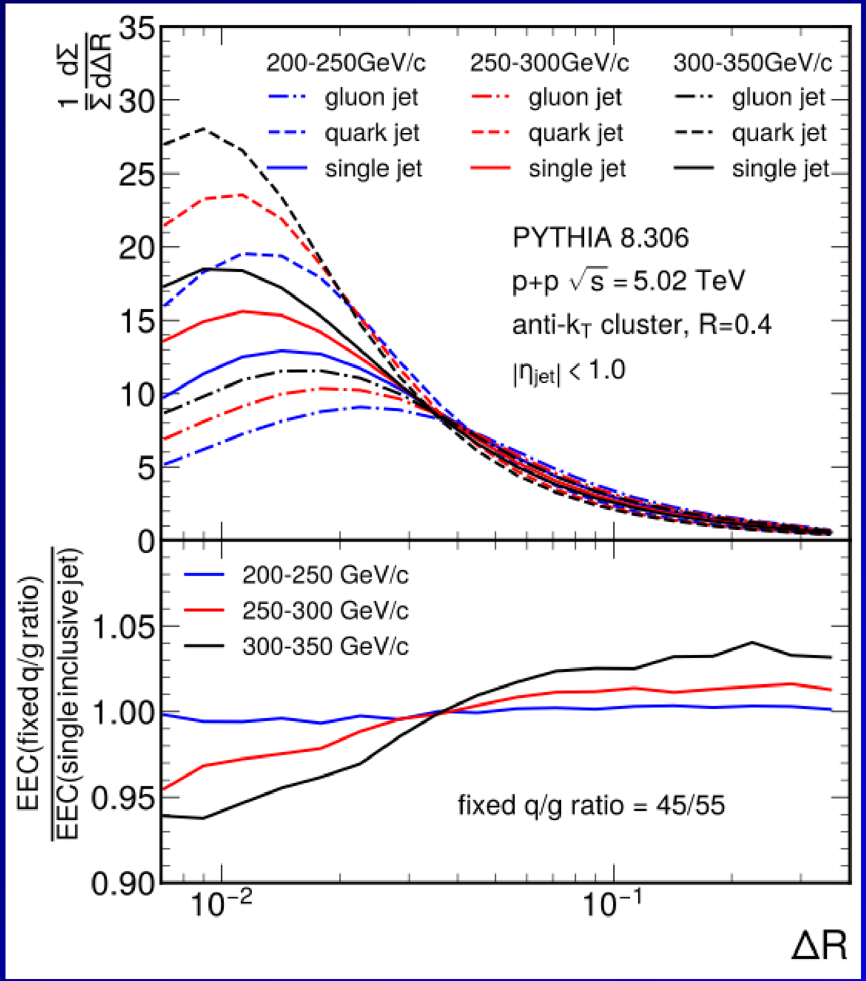
Consequences of flavor dependence of EEC

γ-jets vs. Single inclusive jets



$$x_T = \frac{2p_T^{\mathrm{jet}}}{\sqrt{s}}$$

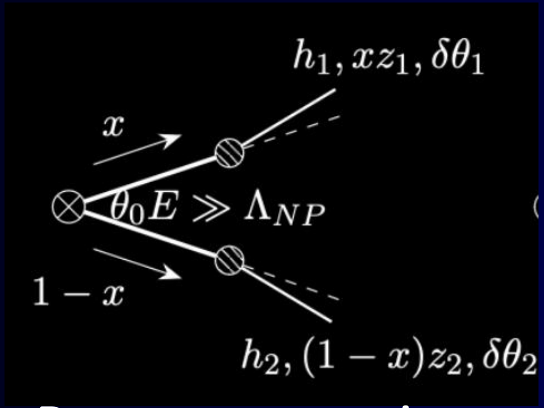
-dependence of EEC



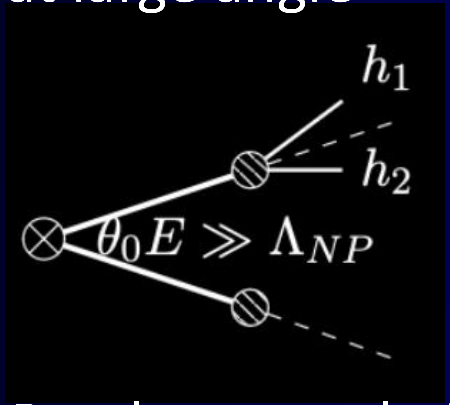
p_T – dependence of single inclusive jet EEC

L. Apolinari, Z. Yang, et al, 2502.11406

Effects of hadronization: TMD Fragmentation



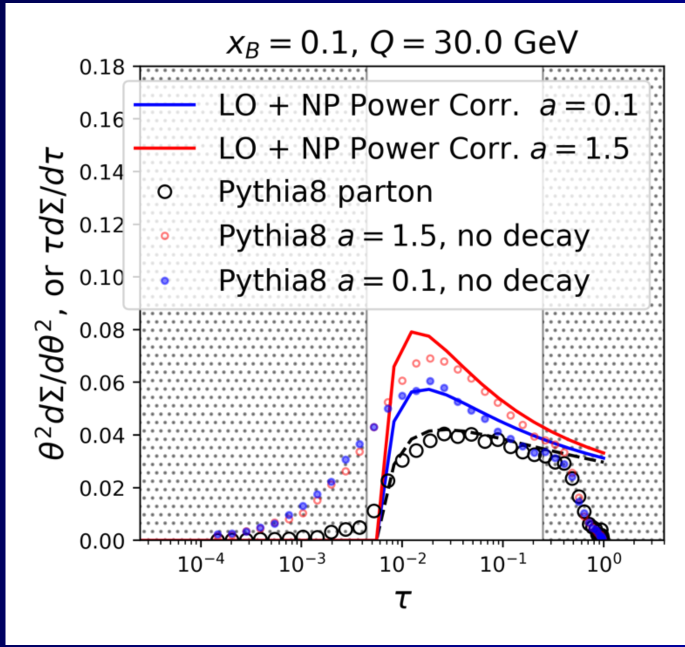
Power corrections at large angle

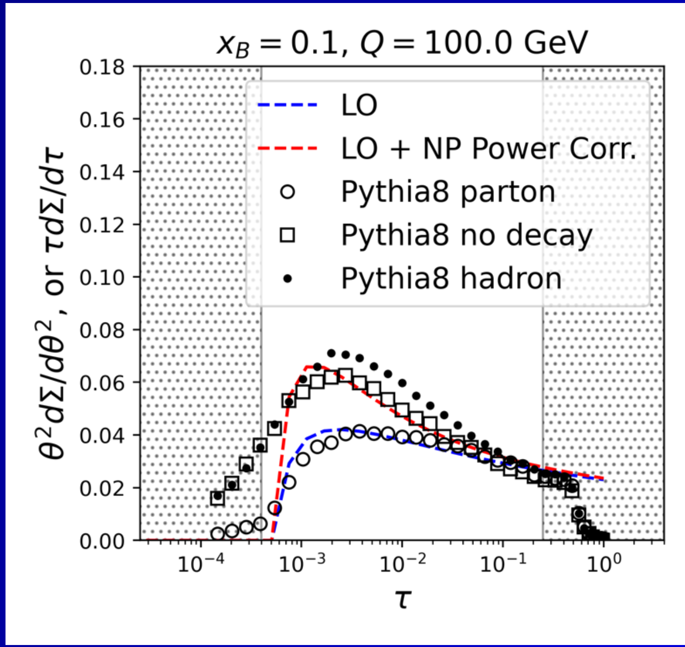


Random correlation at small angle

$$f_{h/i}(z_h, \mathbf{k}) = f_{h/i}(z_h)\frac{e^{-\mathbf{k}^2/2\sigma^2}}{2\pi\sigma^2} \qquad f_{h/i}(z_h) \propto \frac{(1-z)^a z^b}{z}$$

$$\frac{dN}{d\theta^2} = \frac{\alpha_s(\mu^2)C_F}{2\pi}\frac{3}{4}\left\{1 + \left[\frac{2\sigma^2}{\theta^2 E^2}\right]^{\frac{1}{2}}\frac{(1+a)\sqrt{\pi}}{3}\left[\log^2\frac{\mu^2}{\theta^2 E^2} + \mathcal{O}(\log\frac{\mu^2}{\theta^2 E^2})\right]\right\}$$

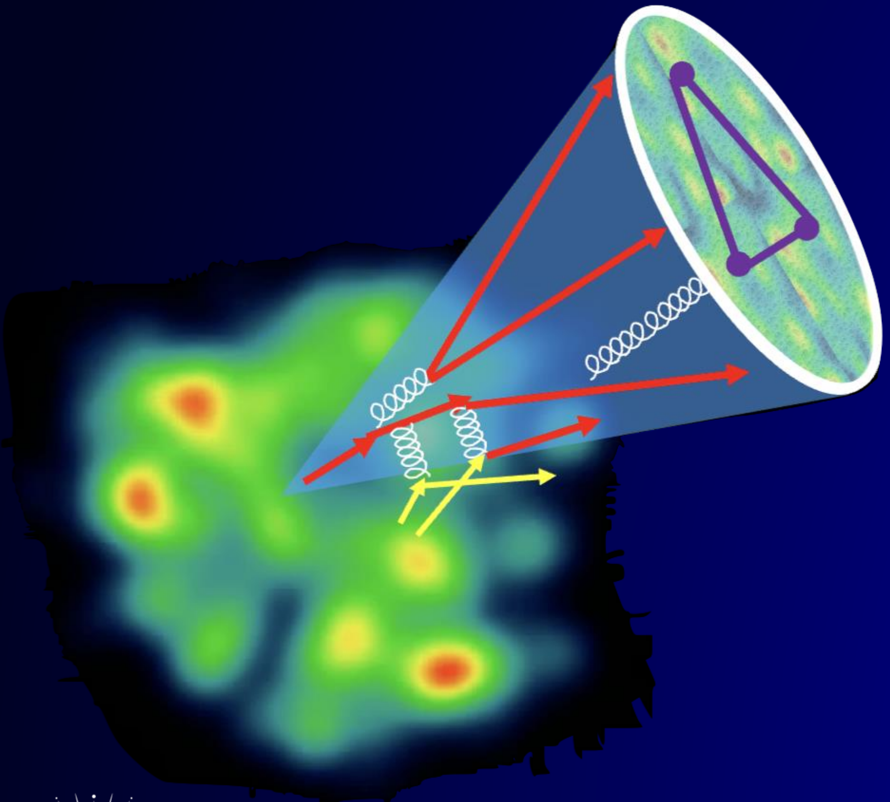


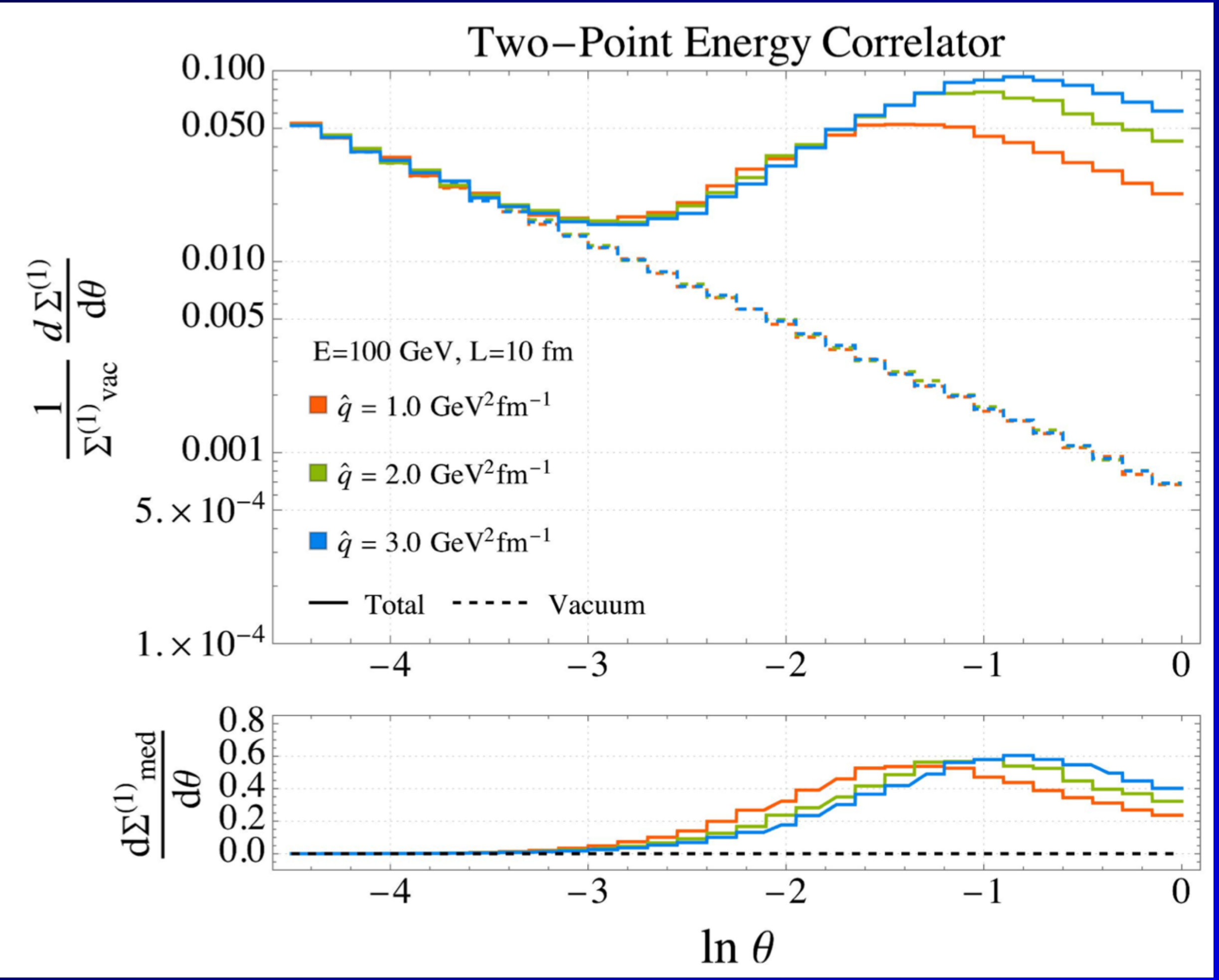


Y. Ke, XNW and W. Zhao in preparation

EEC should be sensitive to momentum broadening in medium

Resolving QGP scales with EEC





Andres, et al , *PRL* 130 (2023) 26, 262301 (2209.11236)

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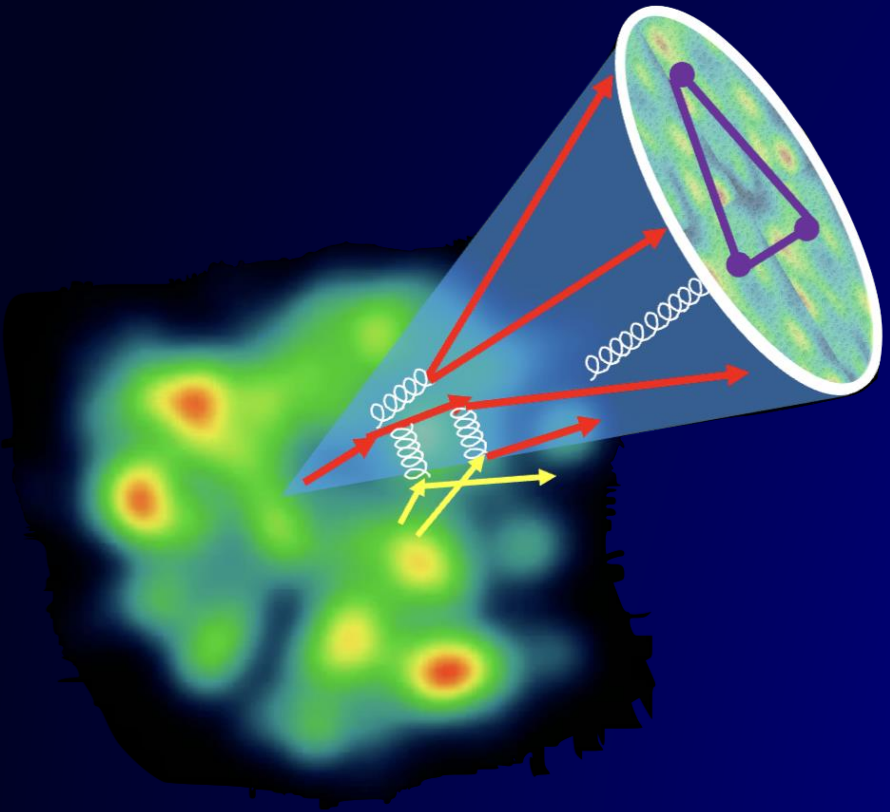
Resolving QGP scales with EEC

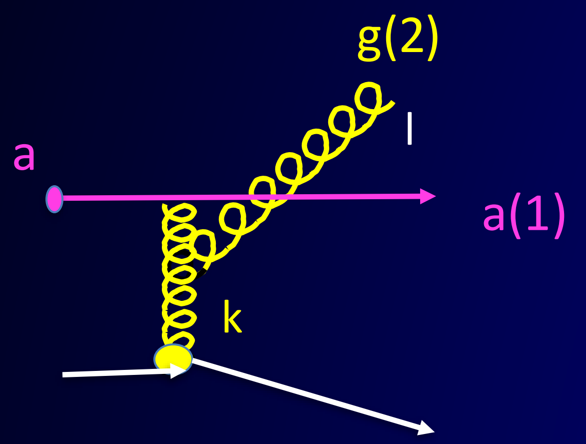


- Can EEC resolve the induced gluon emission in EIC and heavy-ion collisions?
- Can EEC resolve momentum broadening of leading partons and recoil partons (medium response)?
- Can EEC resolve the angular scale of in-medium parton collisions in EIC and heavy-ion collisions

Gluon spectrum from single emission in GHT

Generalized HT induced emission in a QCD brick medium:

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



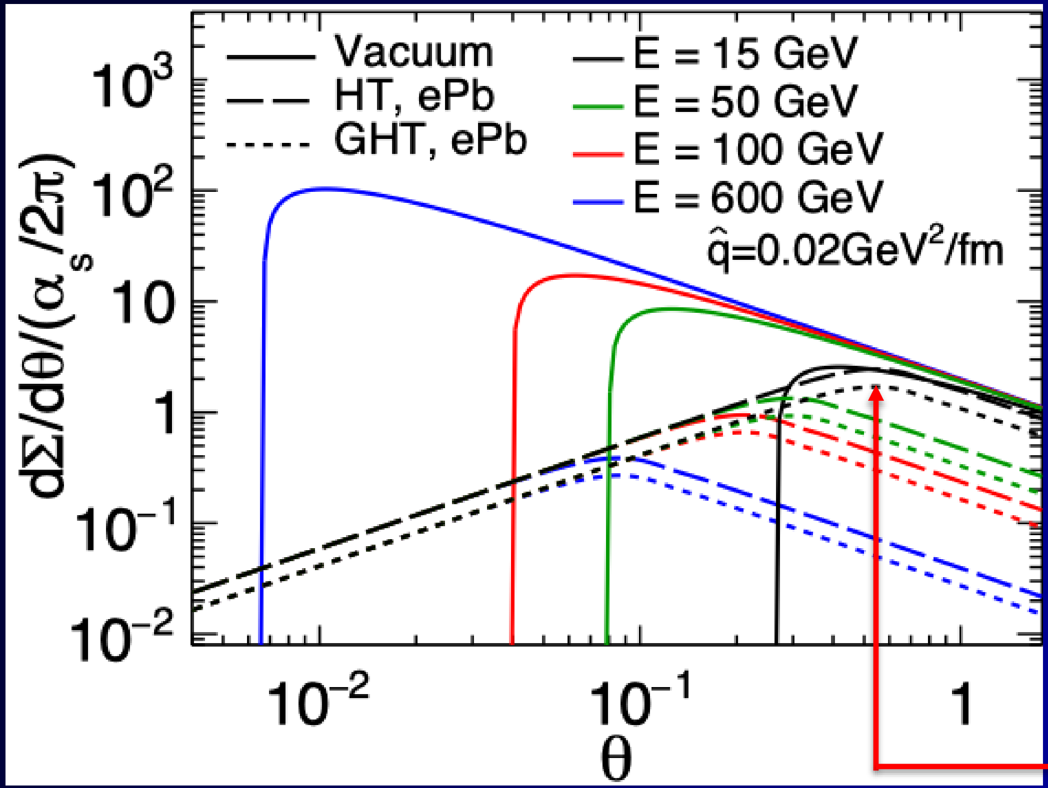
$$\alpha_s\phi_g(x_g,\mathbf{k}^2) = K\frac{(1-x_g)^n x_g^\lambda}{\mathbf{k}^2+Q_s^2}. \qquad \theta_{12}\approx\frac{2|\ell_\perp-\mathbf{k}_\perp|}{z(1-z)E} \qquad \tau_f=\frac{8}{z(1-z)E\theta_{12}^2}$$

$$\hat{q}_R=\int d^2k_\perp\frac{\alpha_s C_2(R)}{N_c^2-1}\rho_A\phi(x_g,\vec{k}_\perp)=\frac{\pi C_2(R)}{N_c^2-1}\rho_A K\ln\left(1+\frac{Q^2}{x_B Q_s^2}\right).$$

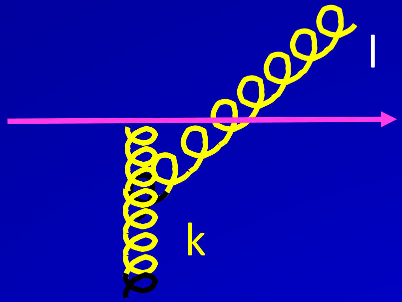
$$\frac{d\Sigma^{\mathrm{med}(\mathrm{GHT})}}{d\theta}\approx\frac{C_A\alpha_s L^-\hat{q}_R}{\pi q^{+2}\theta^3}\frac{8}{\ln\left(1+\frac{Q^2}{x_B Q_s^2}\right)}\int dz\frac{P_{qg}^{(0)}(z)}{z(1-z)}\left[1-\frac{\sin[z(1-z)q^+L^-\theta^2/8]}{z(1-z)q^+L^-\theta^2/8}\right].$$

EEC from single emission in e+Pb

$$\frac{d\Sigma^{\mathrm{med(GHT)}}}{d\theta} \approx \frac{C_A\alpha_s L^-\hat{q}_R}{\pi q^{+2}\theta^3}\frac{8}{\ln(1+\frac{Q^2}{x_B Q_s^2})}\int dz \frac{P_{qg}^{(0)}(z)}{z(1-z)}\left[1-\frac{\sin[z(1-z)q^+L^-\theta^2/8]}{z(1-z)q^+L^-\theta^2/8}\right].$$



$\hat{q}_F = 0.02\ \ \mathrm{GeV}^2/\mathrm{fm}$



GHT induced emission in e+Pb

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

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

Y. Ke, XNW and W. Zhao in preparation

eHIJING: electron Heavy Ion Jet Interaction Generator

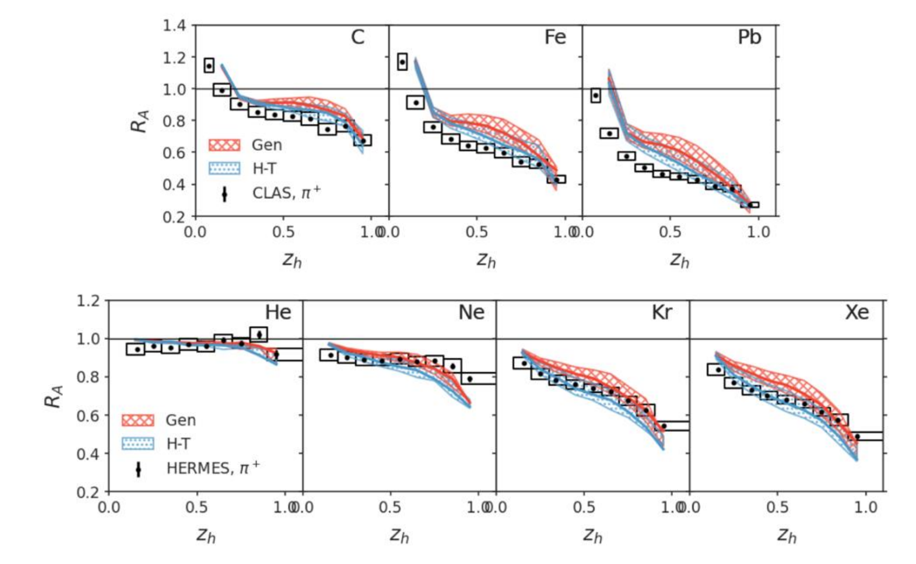
- Pythia for γ^*+N → jet shower processes
- Simple model for saturation in gluon TMD distribution
- Elastic scattering with TMD distr.
- Induced gluon emission
- Multi-scale evolution for multiple gluon emission
  – Q^2, Q_s^2, μ_0^2
- String hadronization

$$\alpha_s \phi_g(x_g, k_\perp^2, Q^2) = \frac{(1-x_g)^p x_g^\lambda}{q_\perp^2 + Q_s^2},$$

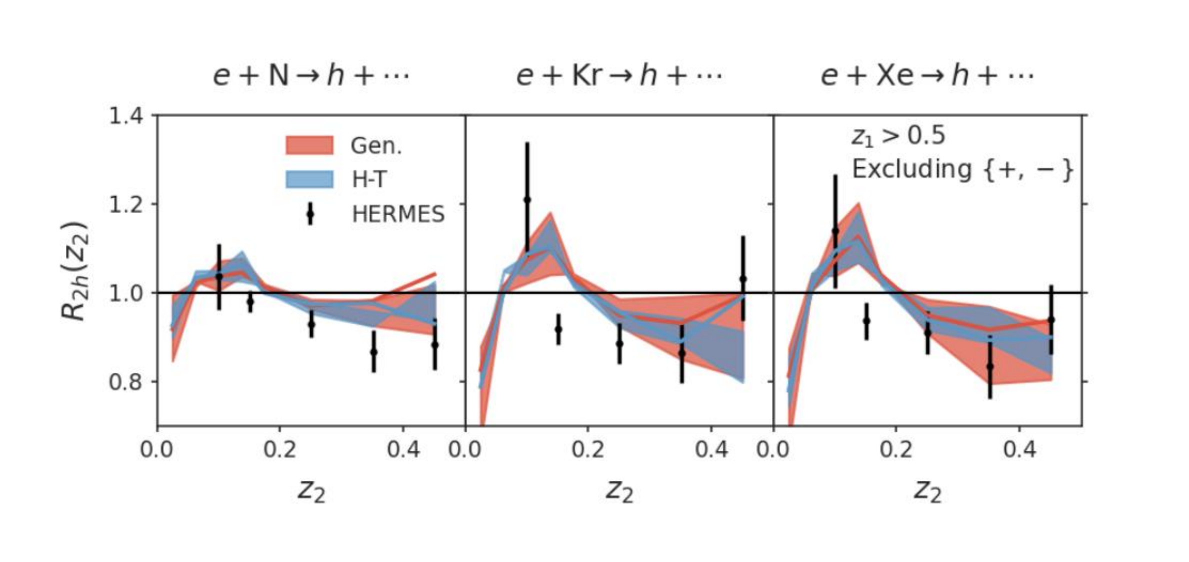
Ke, Zhang, Xing and XNW, Phys. Rev. D 110, 034001 (2024)

Modification of single and dihadron spectra in EIC

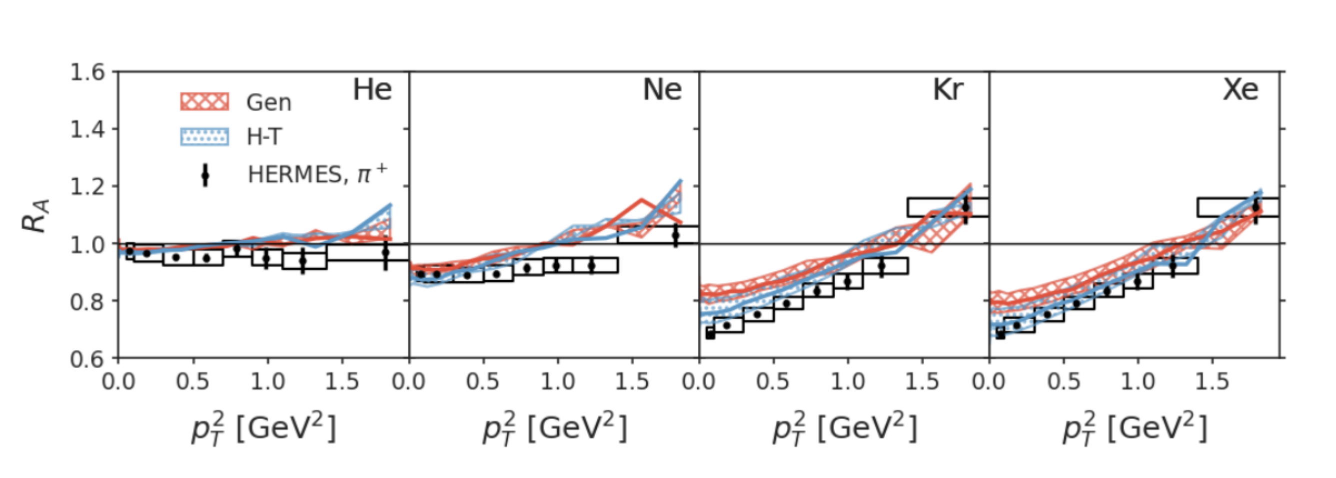
Leading hadron spectra



di-hadron spectra



Ke, Zhang, Xing and XNW, Phys. Rev. D 110, 034001 (2024)

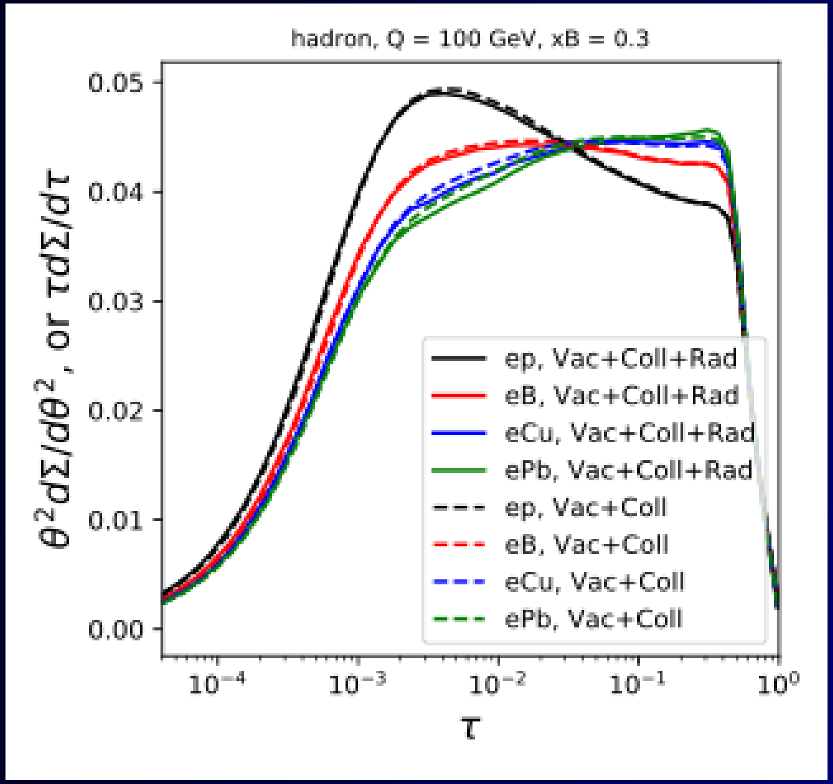


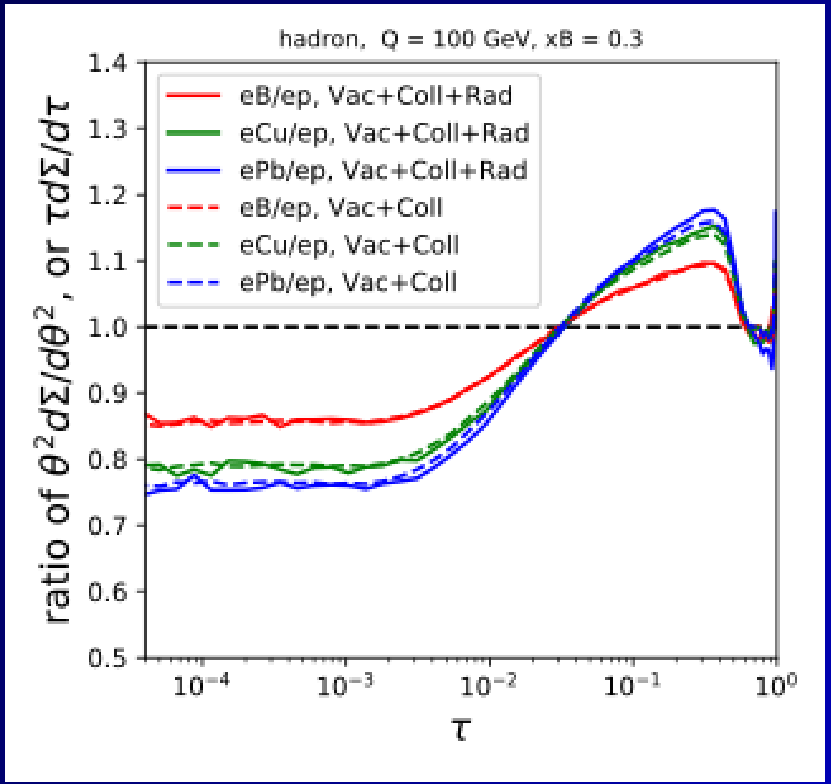
Leading hadron spectra

Medium modification of ECC in EIC

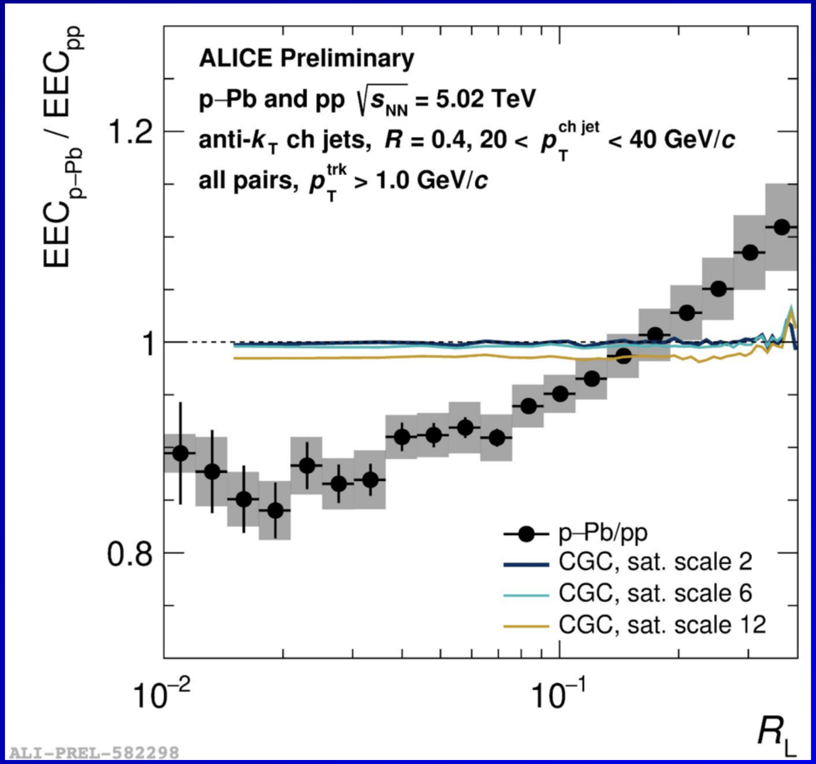
Modification mainly caused by momentum broadening

e+A





p + Pb

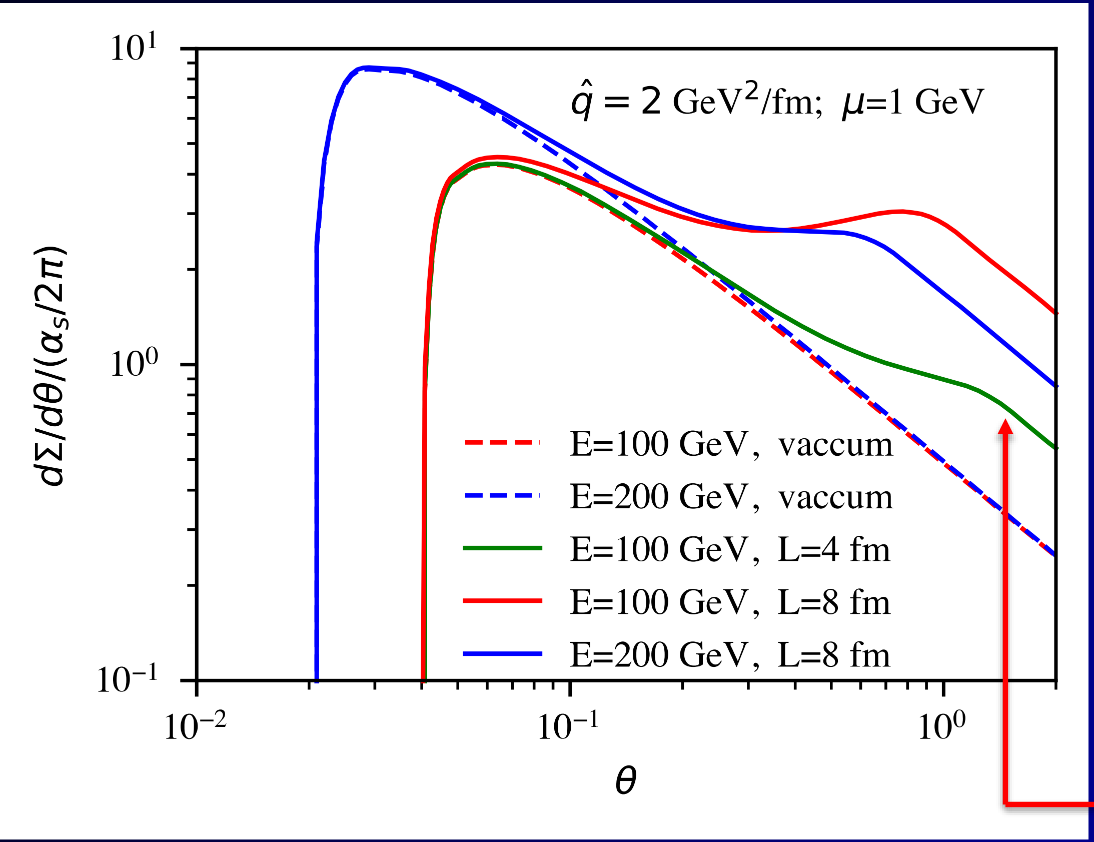


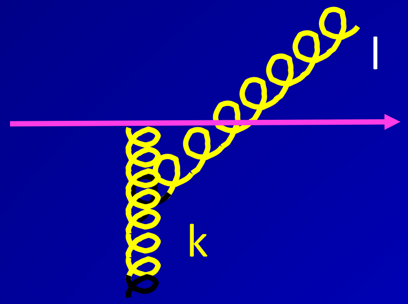
Y. Ke, XNW and W. Zhao in preparation

Nambrath for ALICE at HP2024

EEC from single emission in QGP

$$\frac{d\Sigma^{\rm med(GHT)}}{d\theta} \approx \frac{C_A\alpha_s L^- \hat{q}_R}{\pi q^{+2}\theta^3}\frac{8}{\ln(1+\frac{Q^2}{x_B Q_s^2})}\int dz \frac{P_{qg}^{(0)}(z)}{z(1-z)}\left[1-\frac{\sin[z(1-z)q^+L^-\theta^2/8]}{z(1-z)q^+L^-\theta^2/8}\right].$$





HT induced emission in a QGP brick:

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

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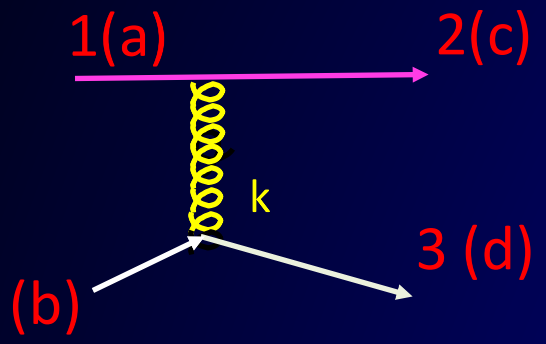
Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

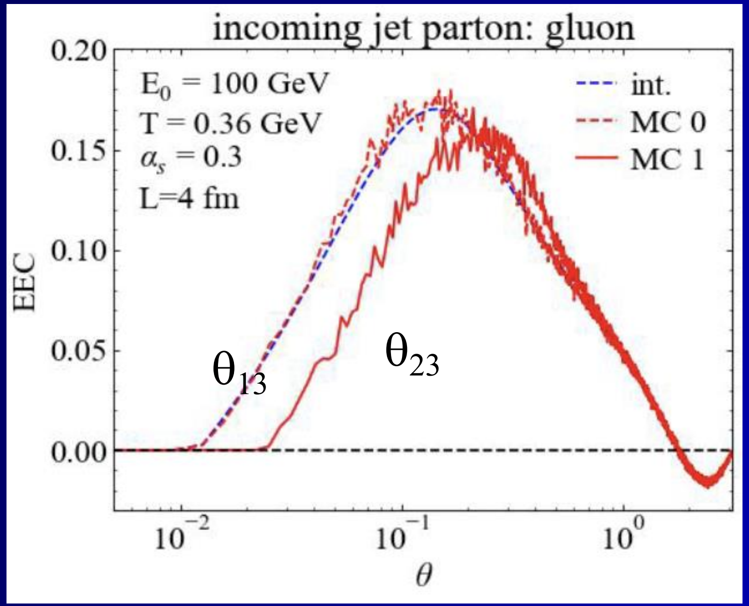
Contributions from medium response

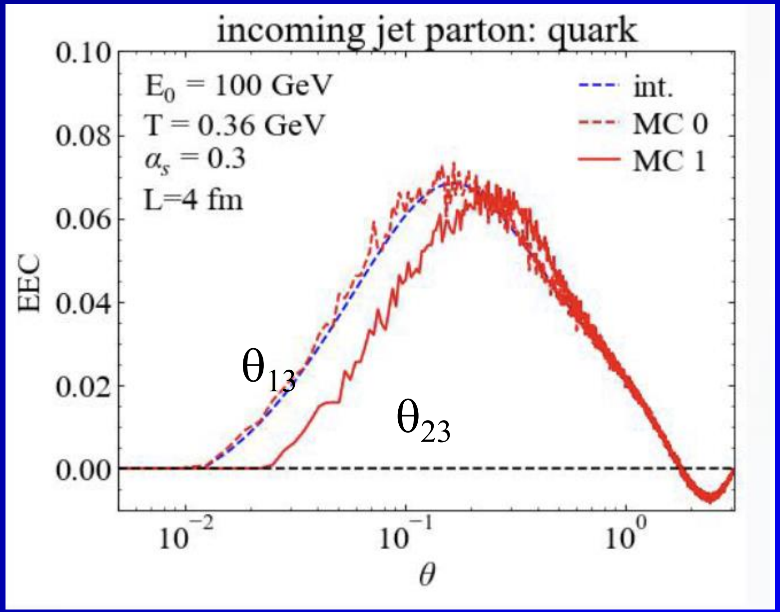
2→ 2 elastic collisions:

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

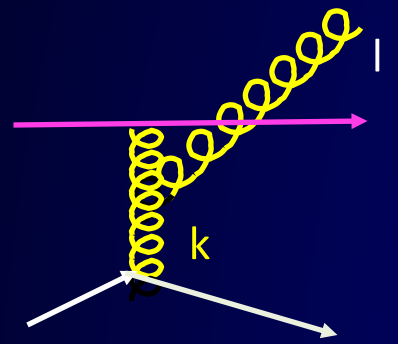


Both recoil and
back-reaction ("negative partons")



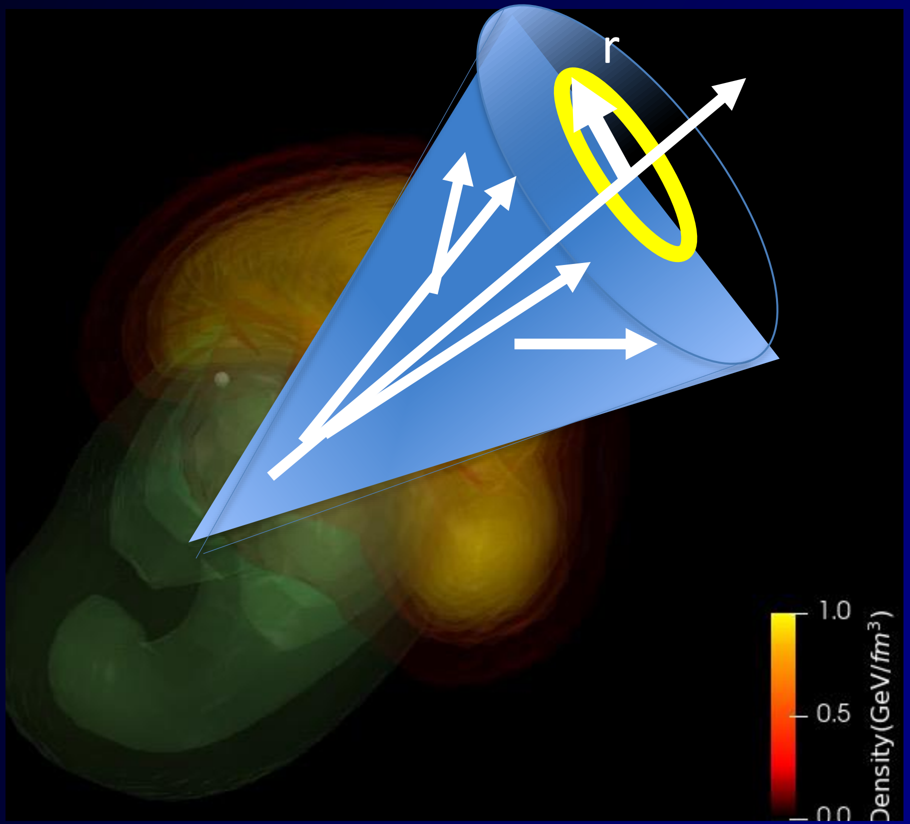


2→ 3 inelastic collisions:

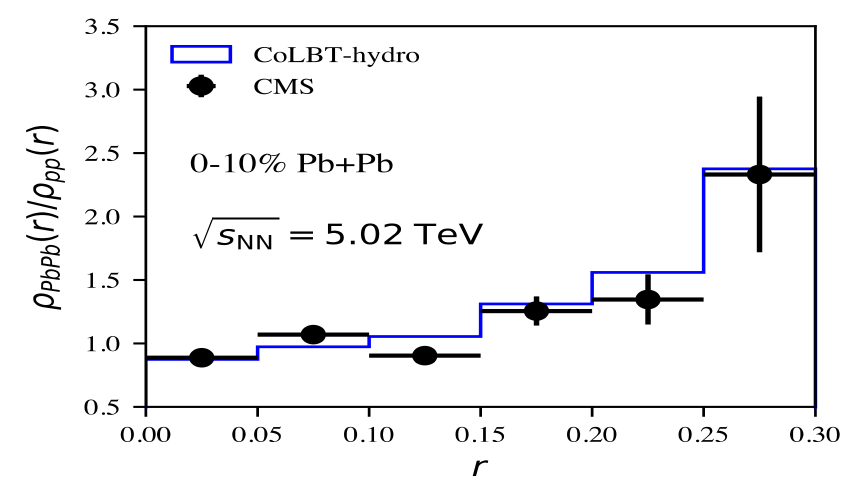


Modification of jets and medium response

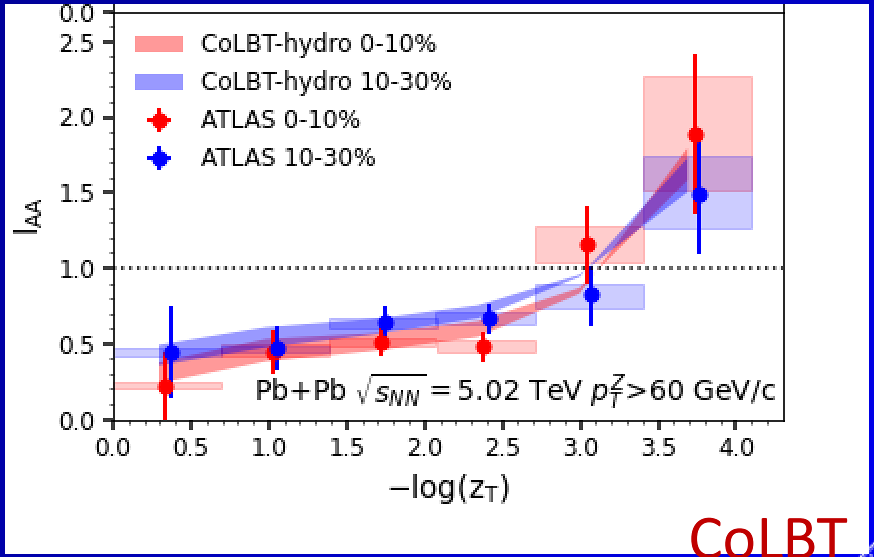
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N_{jet}}\sum_{jet}\frac{p_T^{jet}(r-\Delta r/2, r+\Delta r/2)}{p_T^{jet}(0,R)}$$



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



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

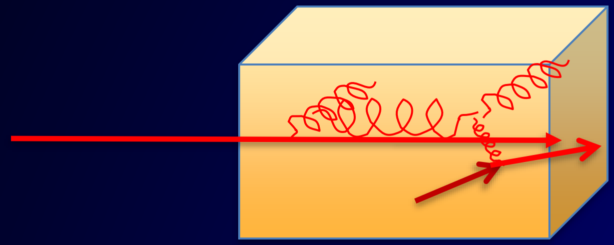


CoLBT

e-Print: 2101.05422

EEC of single parton in a QGP brick

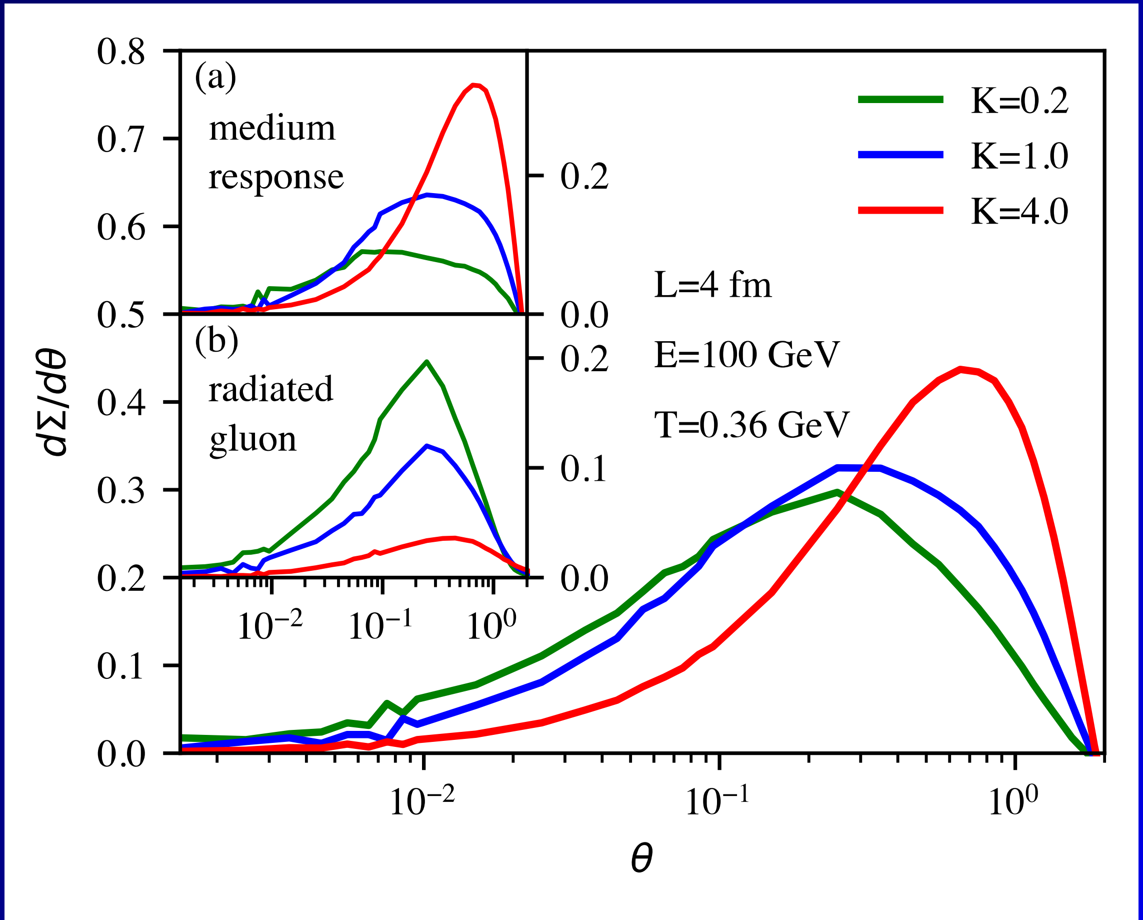
Single parton with multiple scattering in a brick in LBT



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

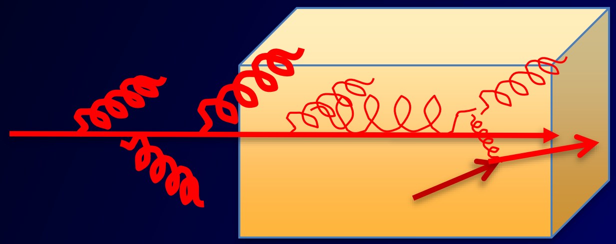
We vary only *K* in sampling the transverse momentum transfer of 2→2 and kinematic limit of gluon bremsstrahlung. We however keep qhat and 2→2 rate unchanged.

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

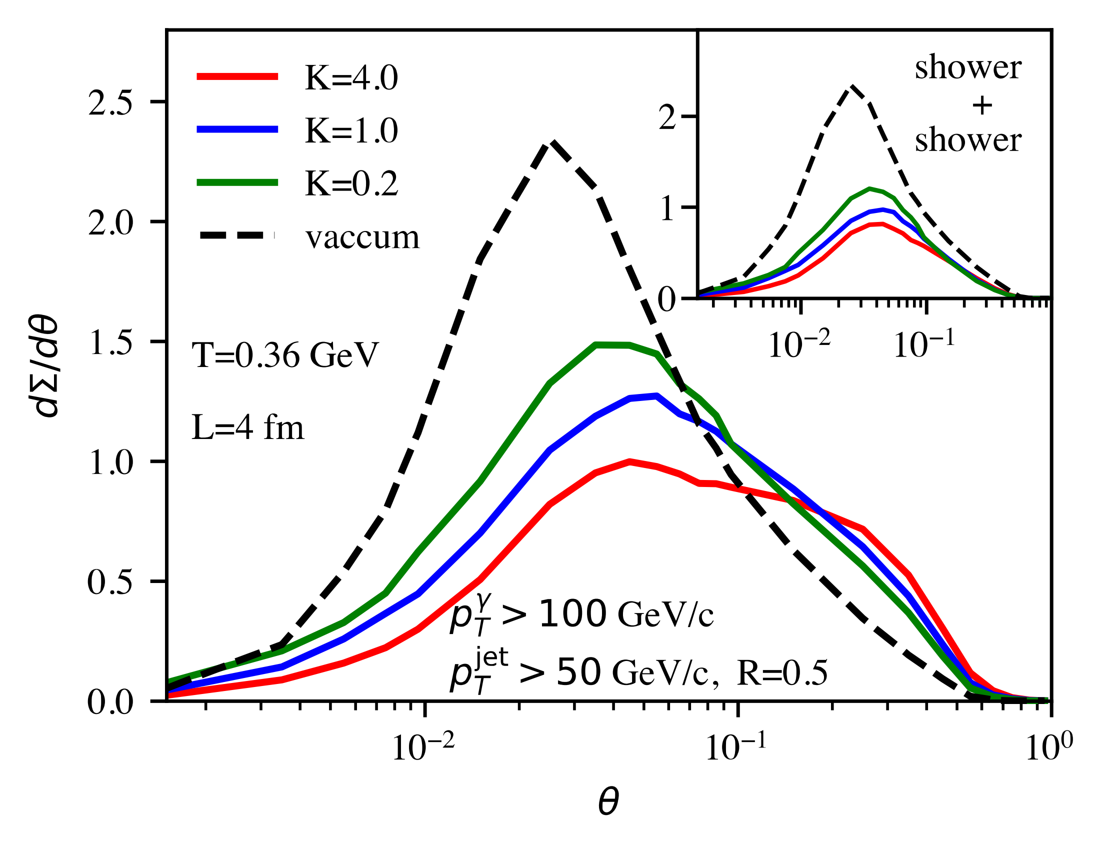


Initial γ-jet configurations generated from Pythia8

Energy loss and momentum broadening lead to suppression at small angles

Radiated gluon and medium response dominate at large angles

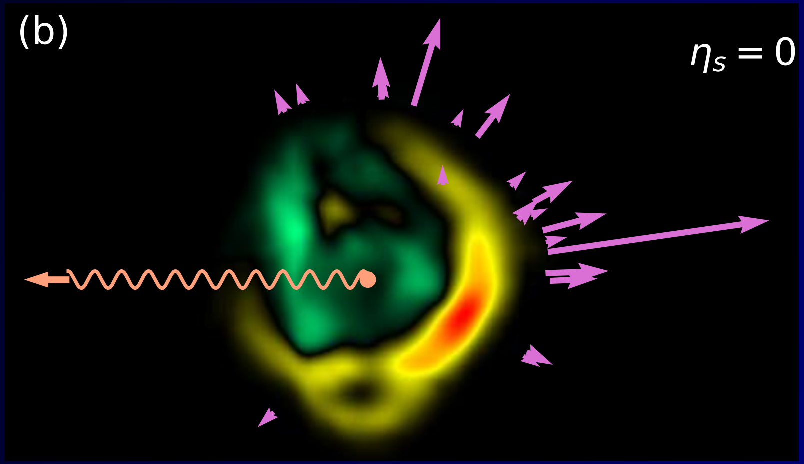
A jet shower in a brick in LBT



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

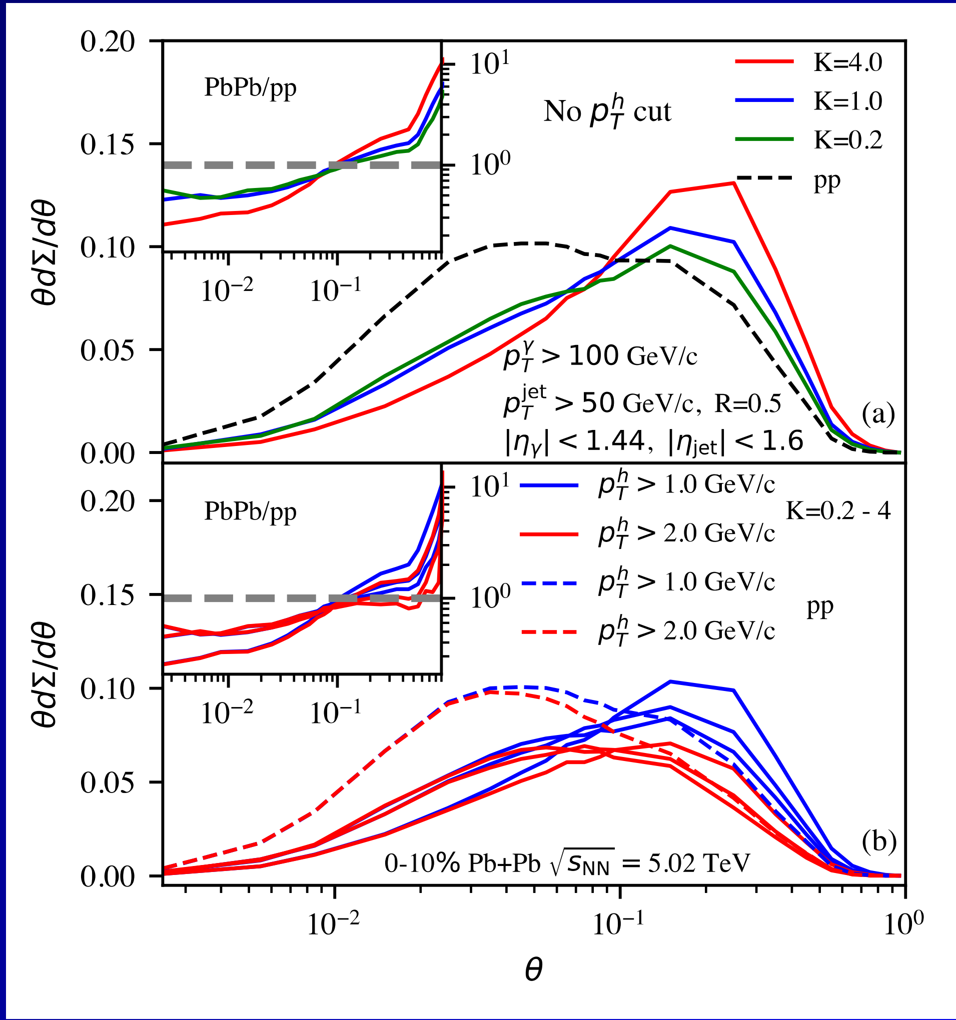
EEC of γ-jets in Pb+Pb Collisions

CoLBT simulations:



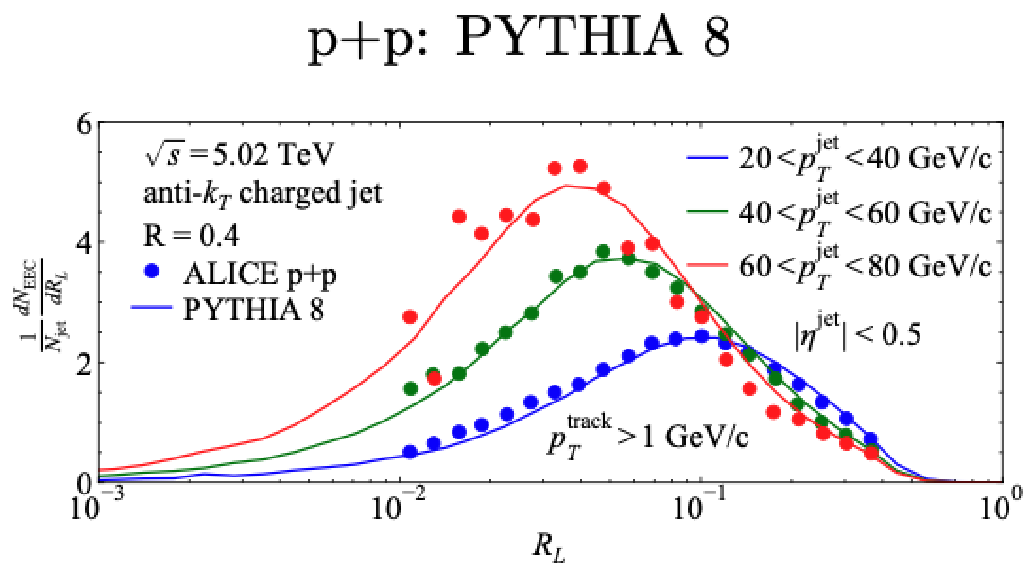
Enhancement at large angles by soft hadrons from radiated gluons and medium response, sensitive to pT cuts

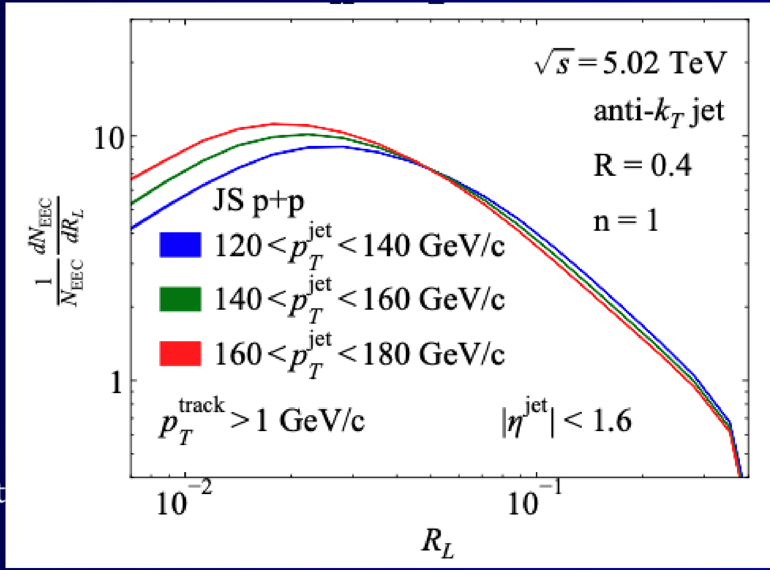
EEC by energetic hadrons from leading shower partons at small angles are suppressed, not affected by pT cuts



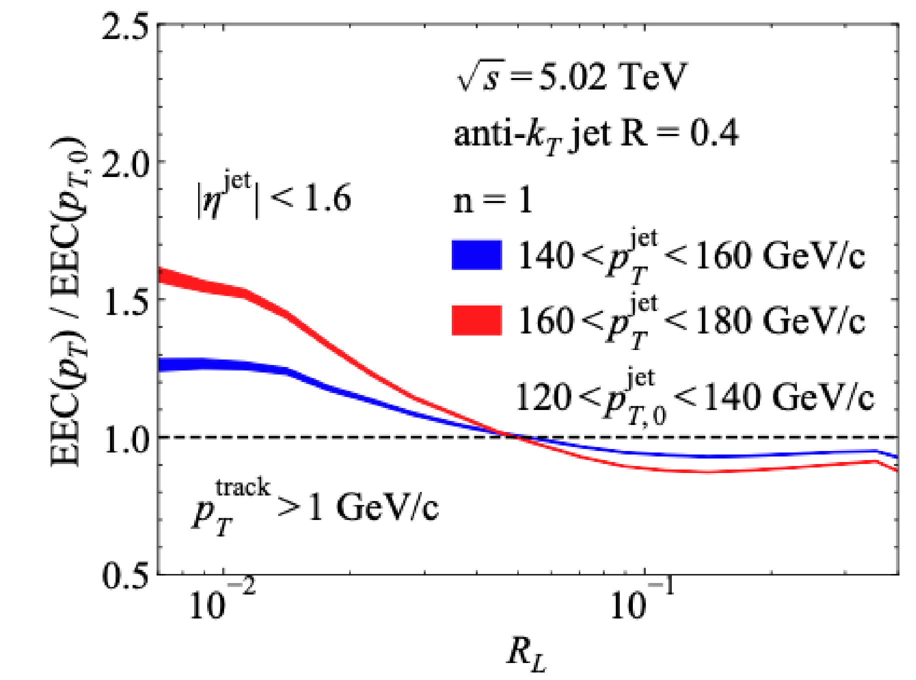
Yang, He, Moult & XNW, *PRL* 132 (2024) 1, 011901

EEC of Single inclusive jets





If 120 GeV jets come from vacuum fragmentation of jets with energy loss from initial 140 or 160 GeV

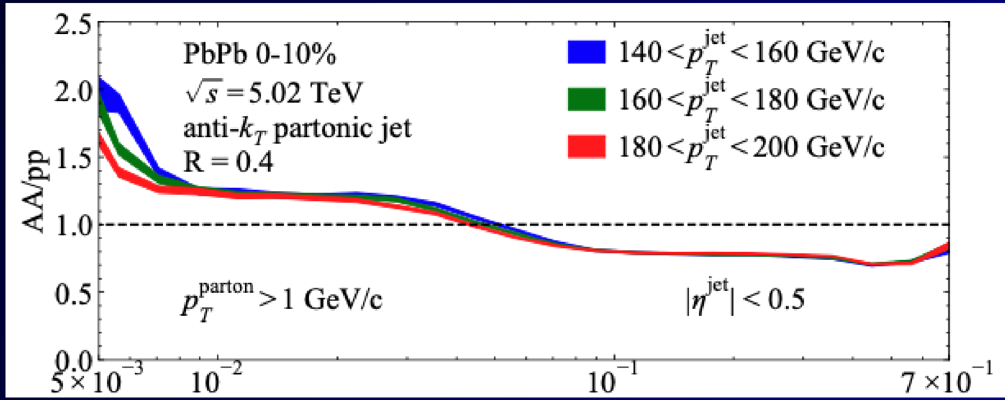


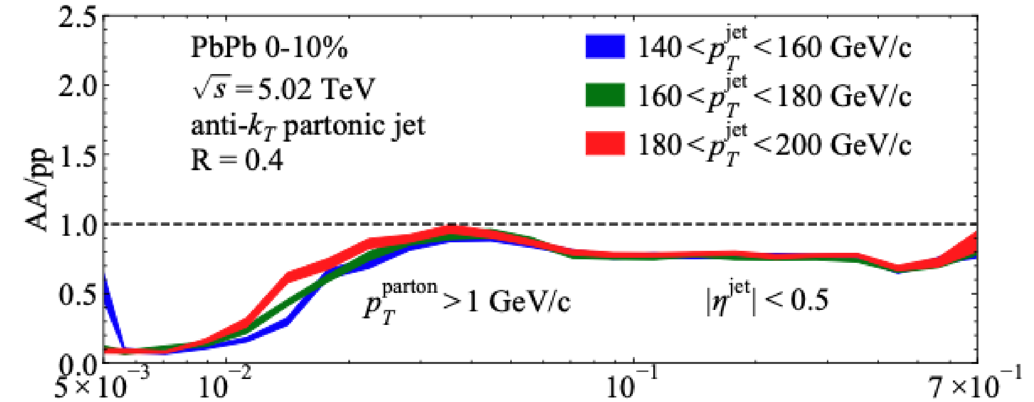
Enhancement due to jets with reduced energy?

With jet splitting outside medium

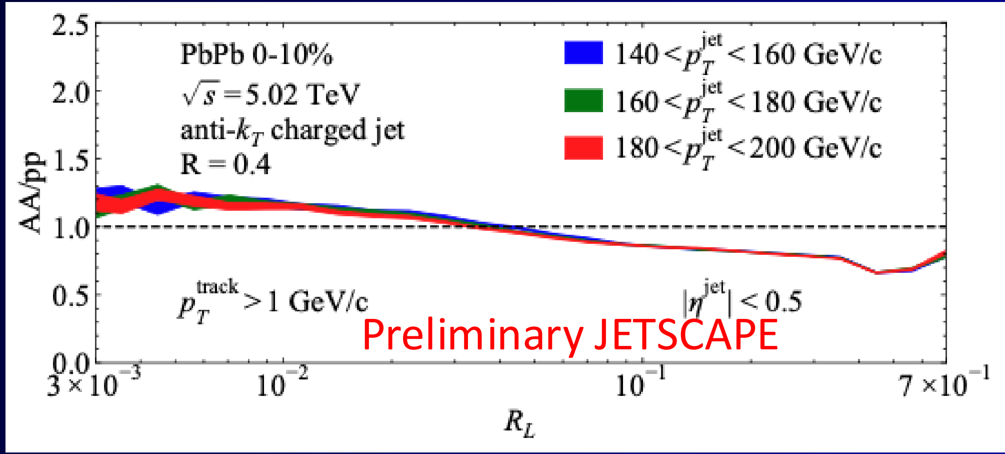
No jet splitting outside medium

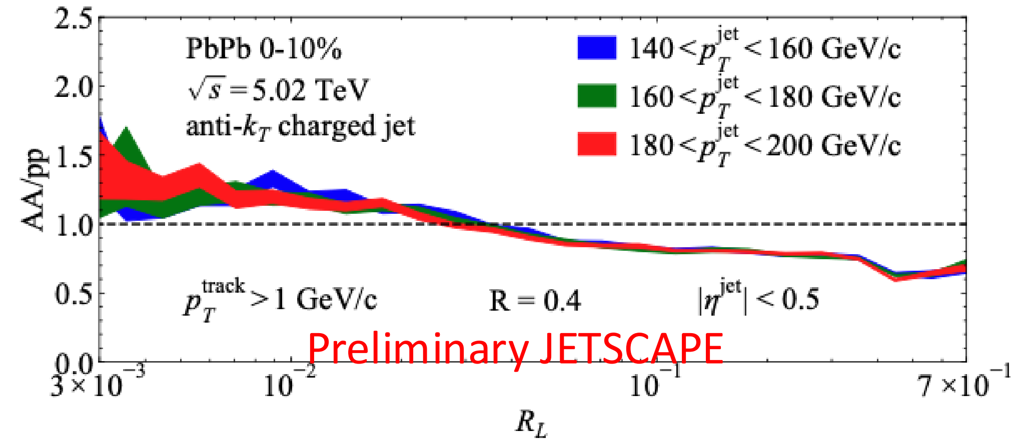
partons





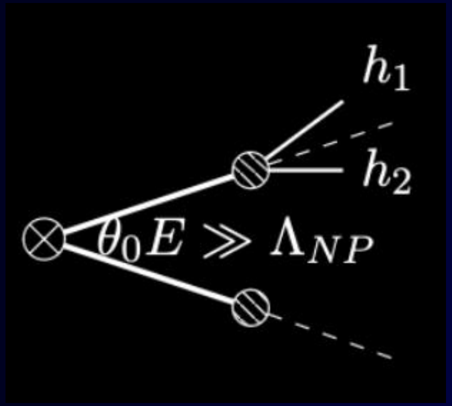
hadrons



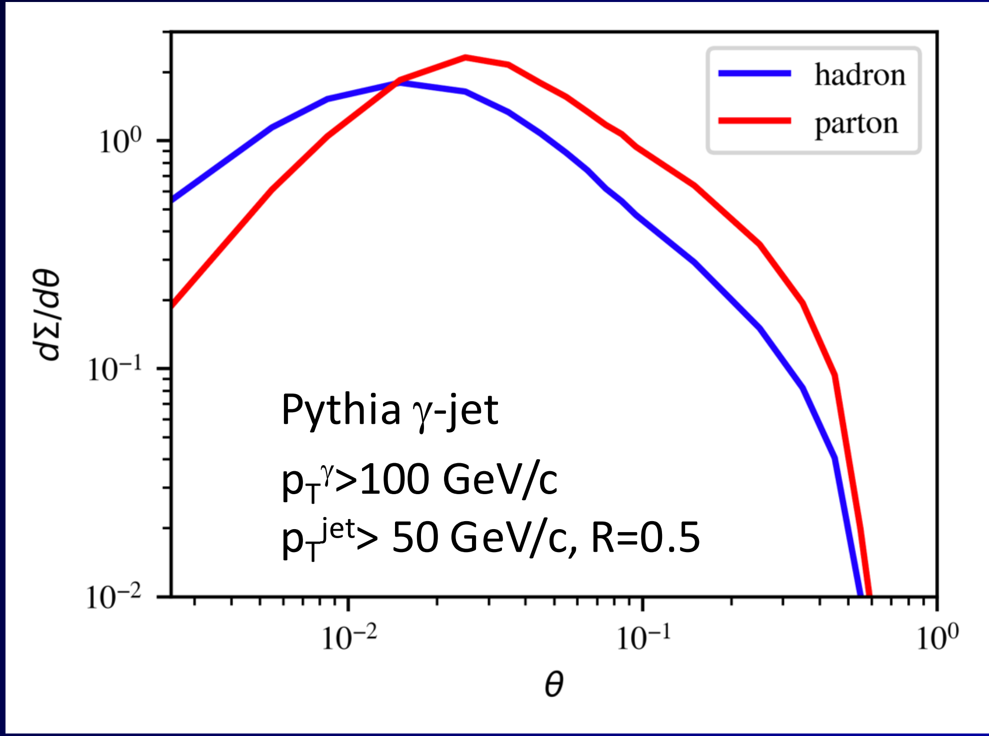


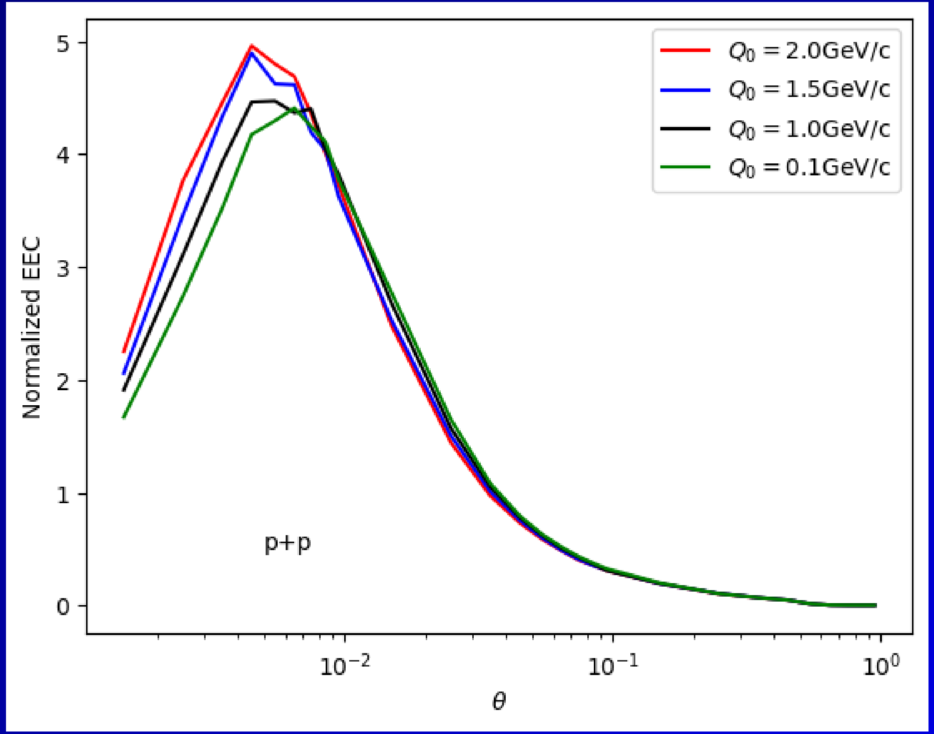
Effect of hadronization dominates at small angle !

Effects of hadronization



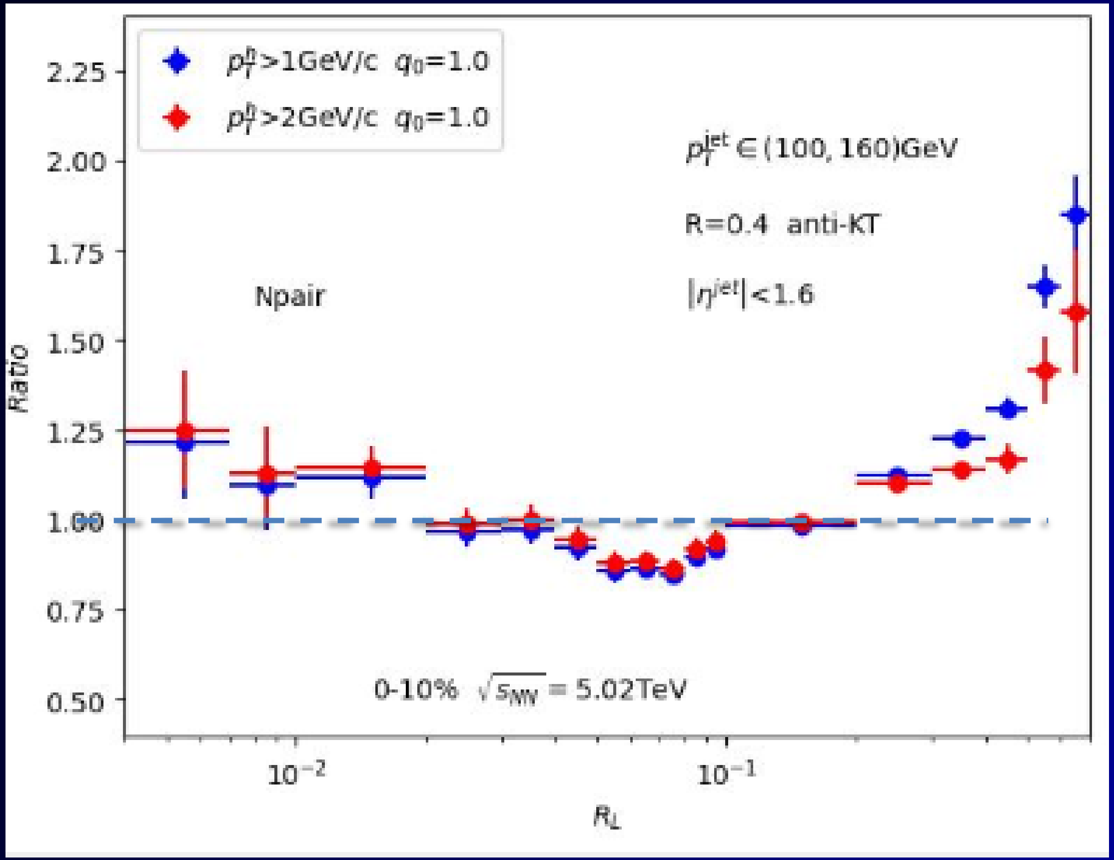
- Parton EEC at small angle due to random correlation
- Hadron EEC sensitive to hadronization

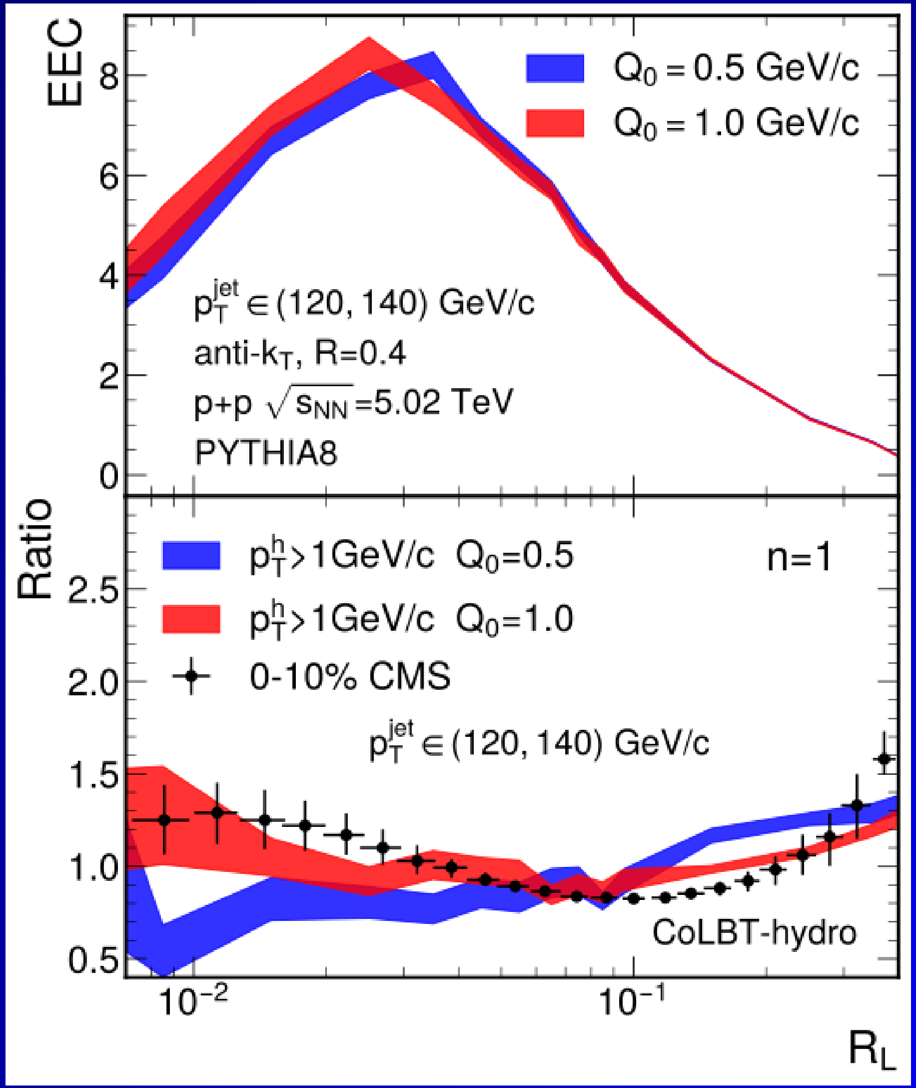




JETSCAPE: increase of the hadronization scale Q_0

Single jet EEC from CoLBT





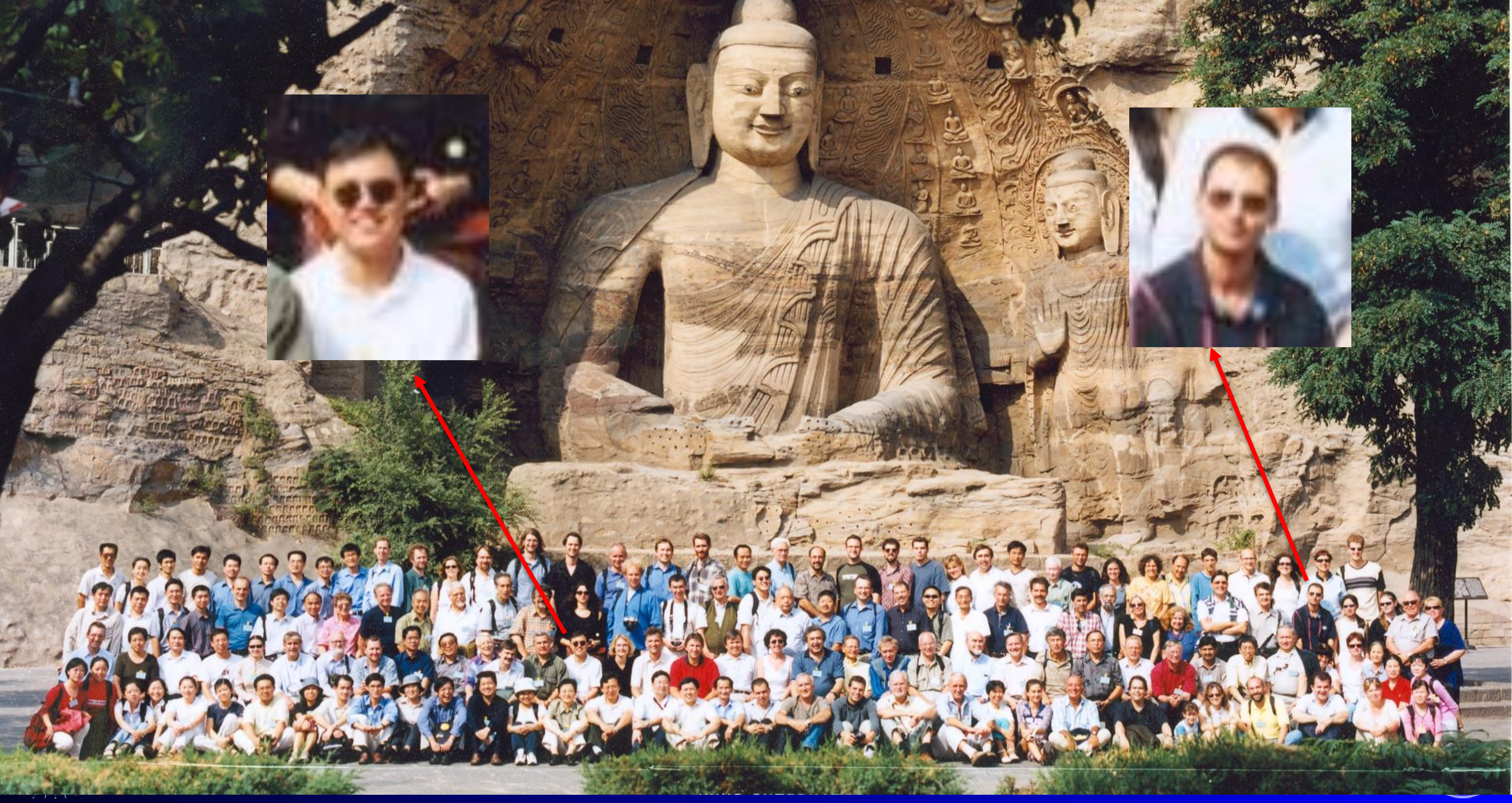
- Increased virtuality scale in medium leads to enhancement of EEC at small angle
- Medium response leads to enhancement at large angle R_L>0.3

Summary

- Medium modification of EEC in EIC by pt broadening
- Medium-response dominates enhancement of EEC at large angles in heavy-ion collisions which is sensitive to interaction scale in medium
- Increased parton scale in medium leads to enhancement of EEC at small anglee

My correlation with Edmond

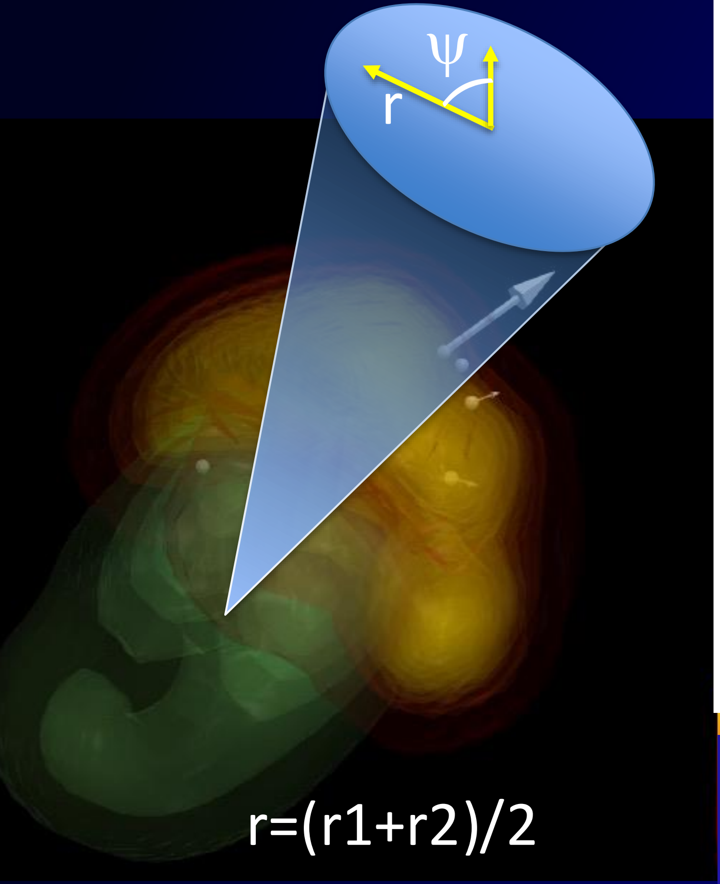
XXXI International Symposium on Multiparticle Dynamics, Datong, China, September 2001



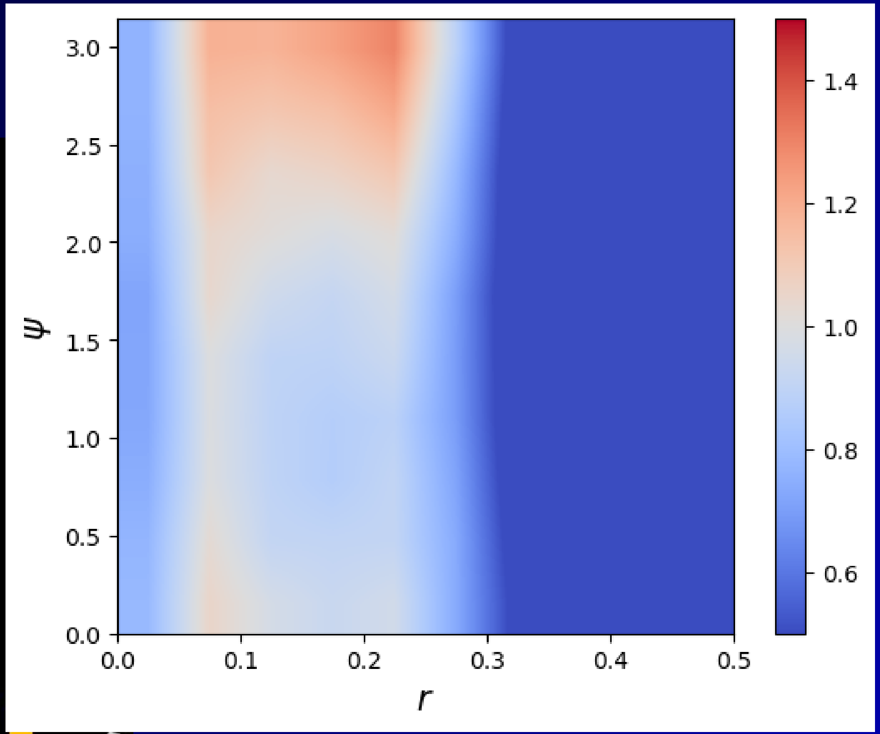
2022, Berkeley

Happy Birthday, Edmond!

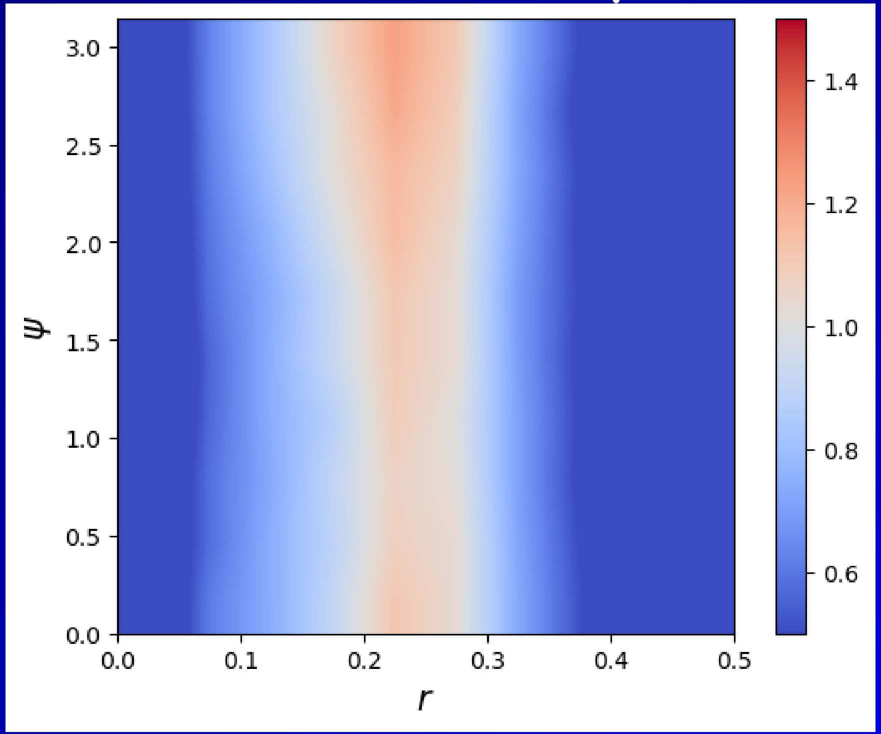
Seeing Mach-cone through 3p Azimuthal Correlation



p+p (γ+jet) p_T>40 GeV/c



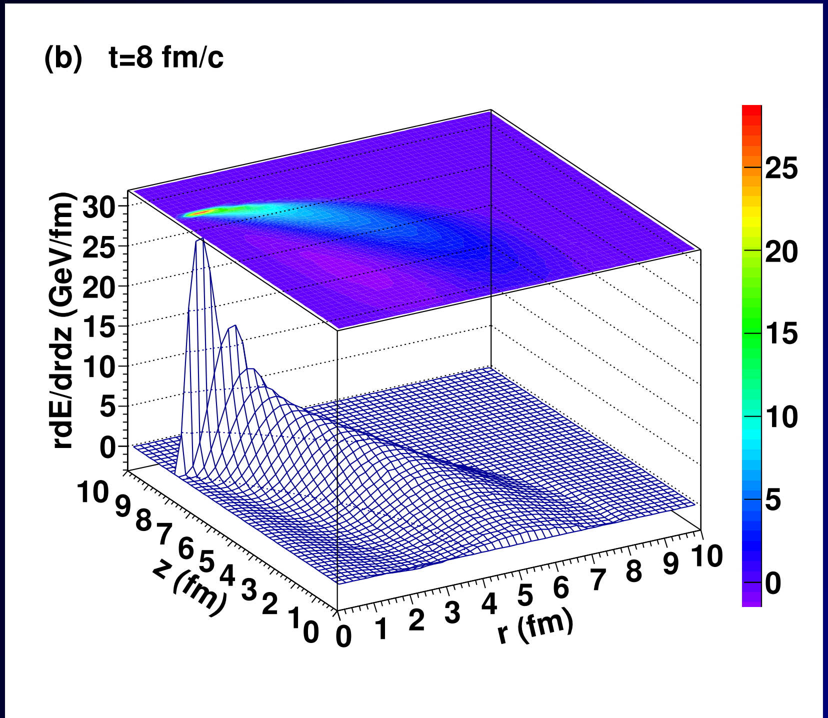
0-10%Pb+Pb (γ+jet)

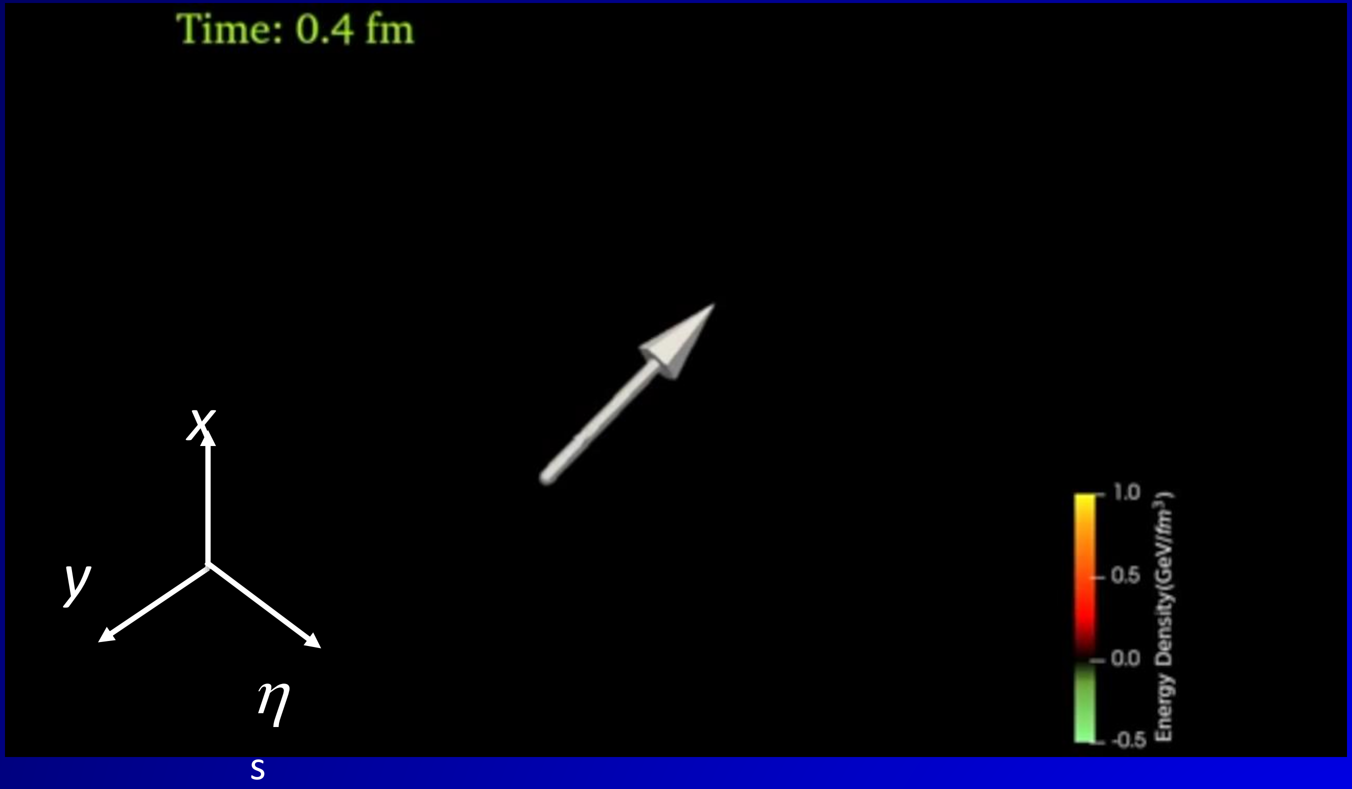


Back-to-back correlation due to momentum conservation of parton splitting

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

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

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Linear Boltzmann Transport model

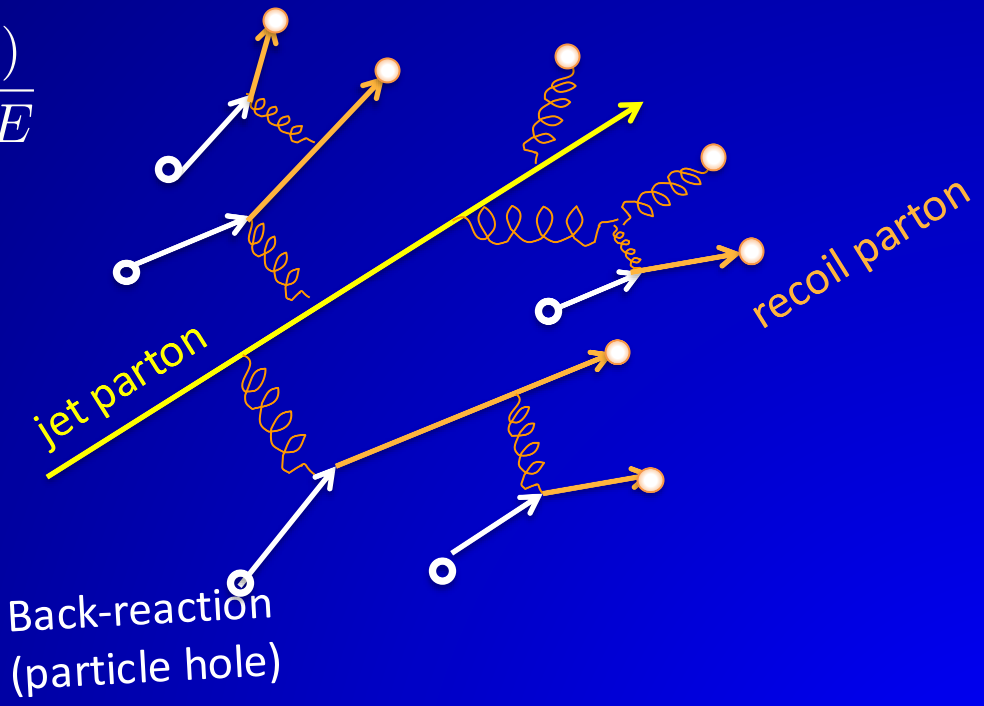
LBT: Linear Boltzmann Transport

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

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

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

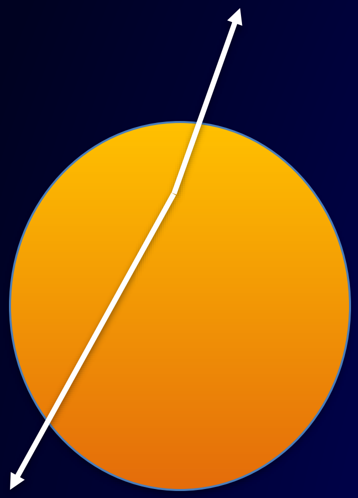
$$\partial_\mu T^{\mu\nu}(x) = j^\nu(x)$$

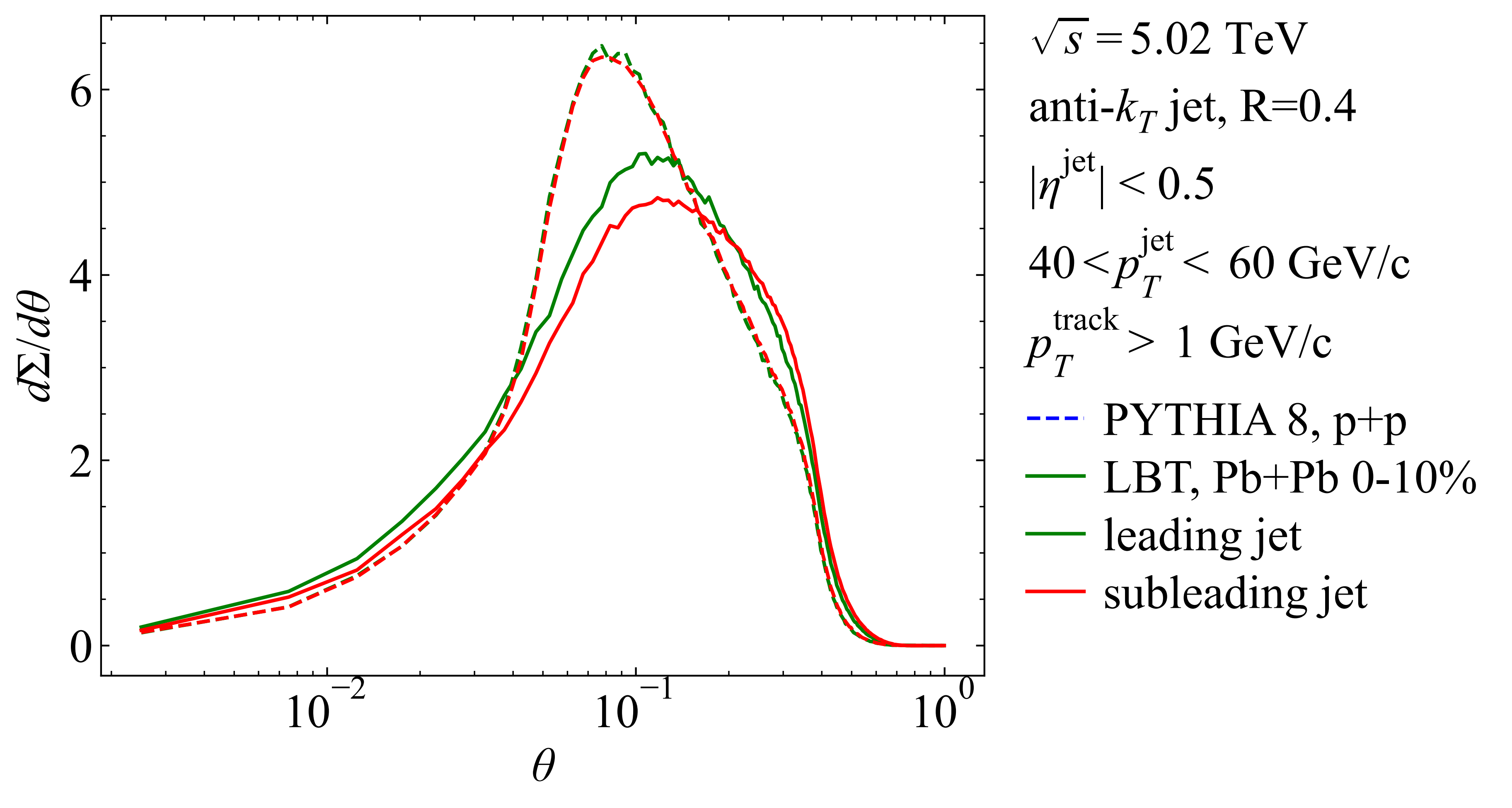
$$j^\nu(x) = \sum_i p_i^\nu \delta^{(4)}(x - x_i)\theta(p^0_{cut} - p \cdot u)$$

- 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

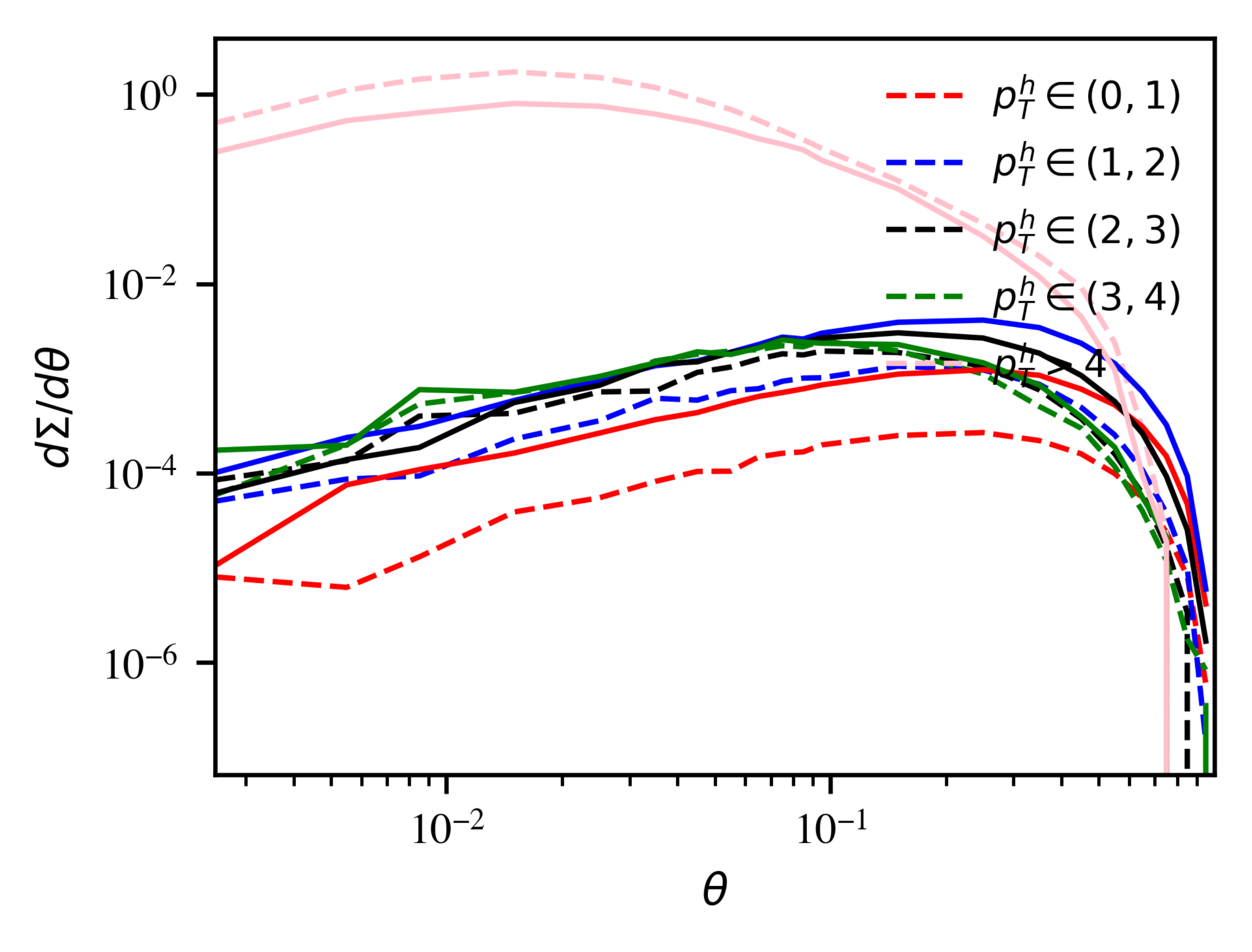
EEC of dijets





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

pT dependence of EEC



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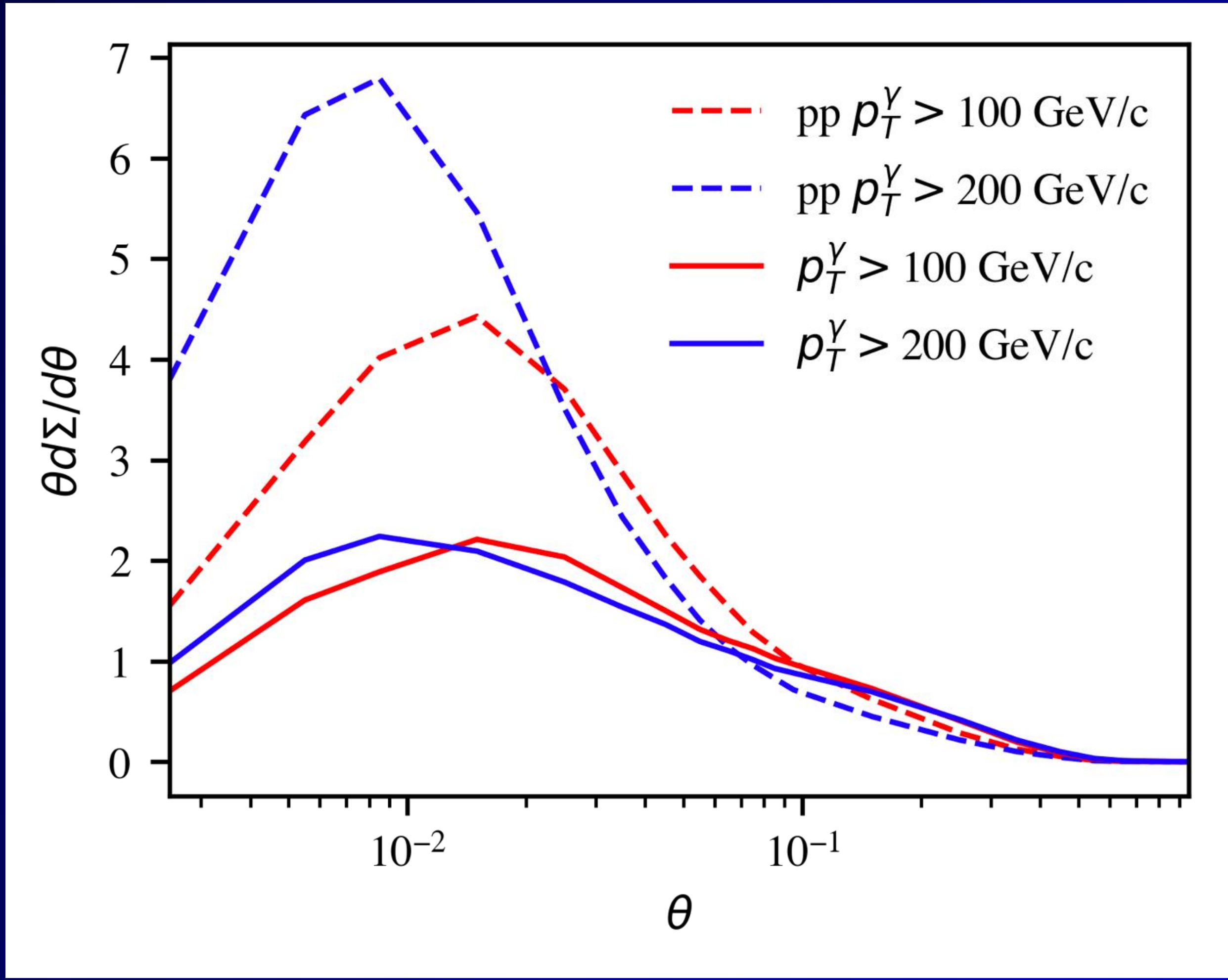
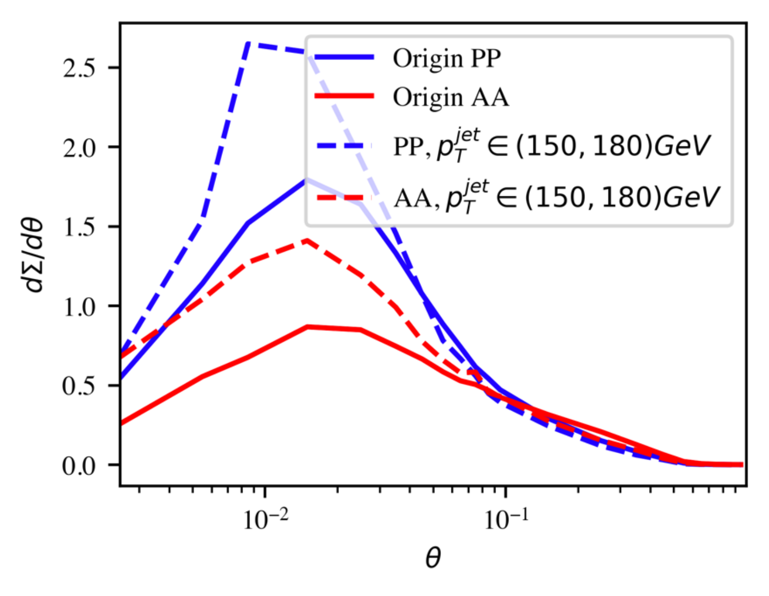
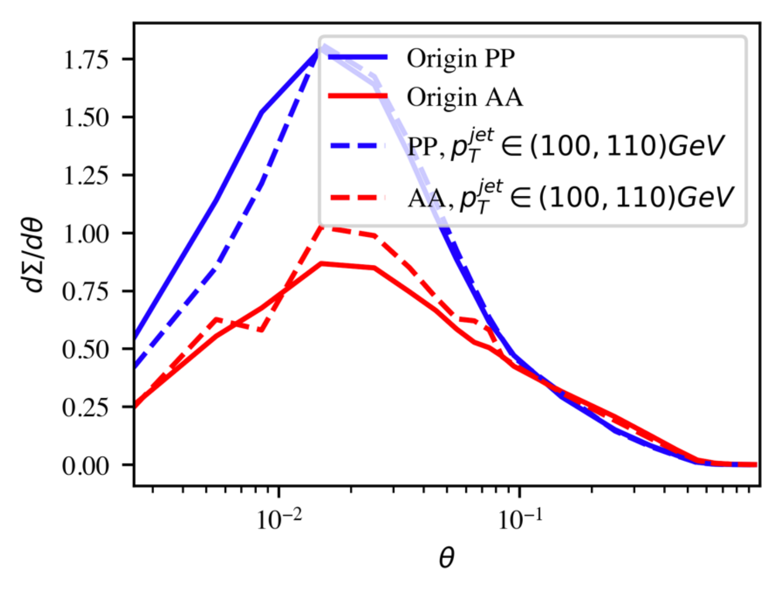
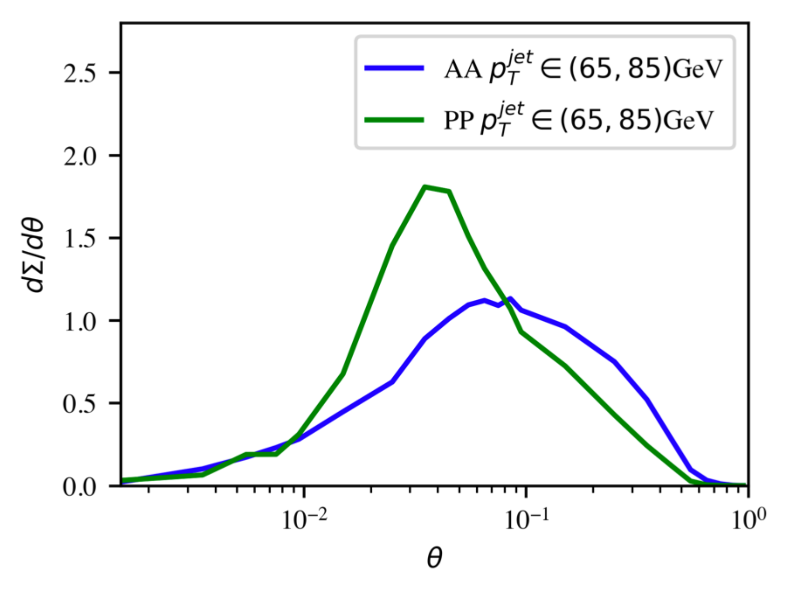
γ energy dependence



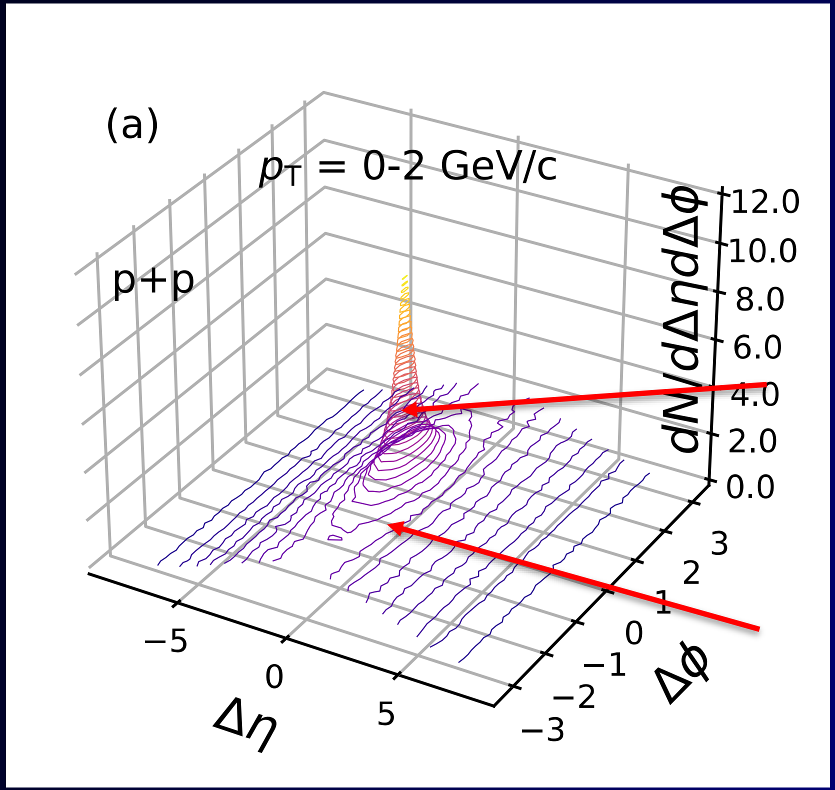
Jet energy dependence





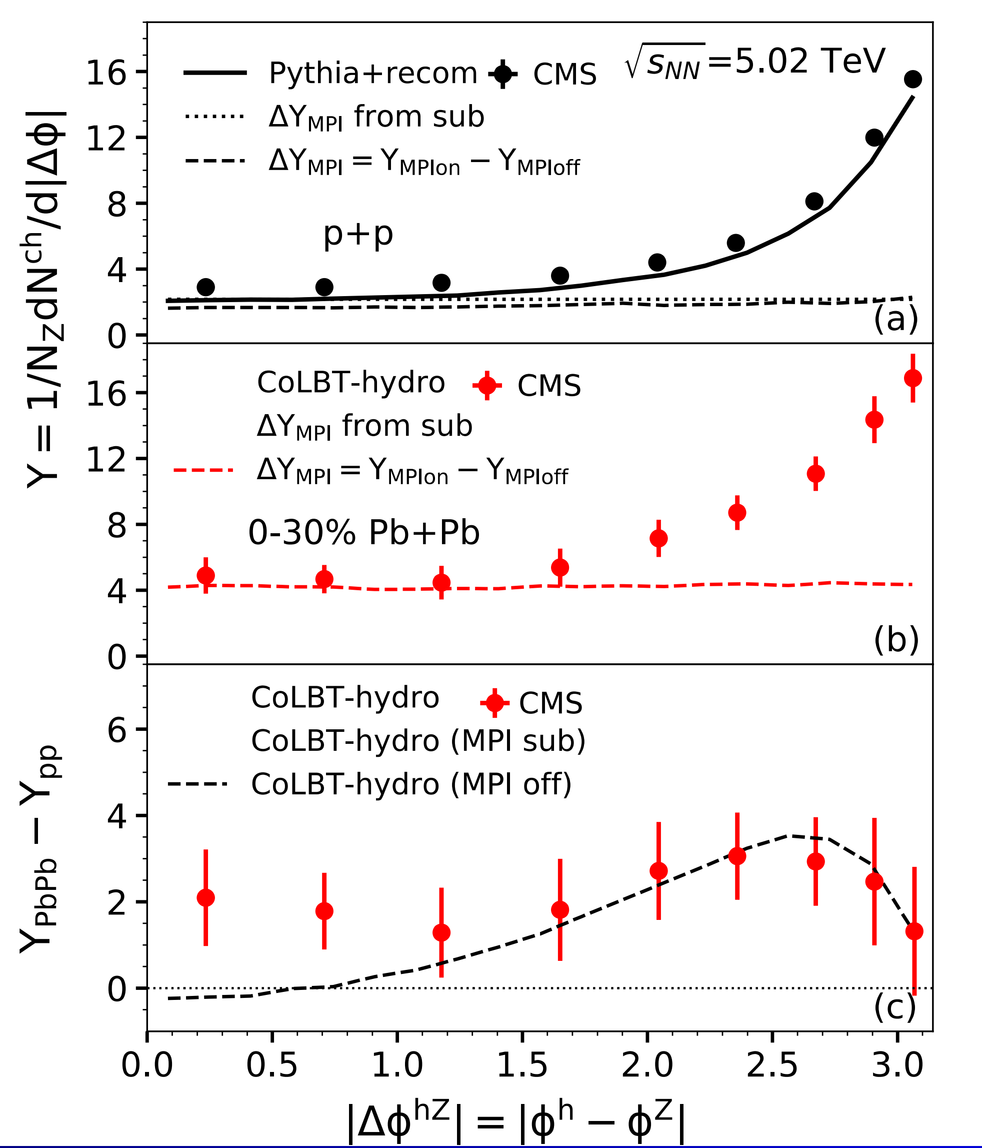


MPI subtraction in Z-hadron correlation



Mixed event subtraction

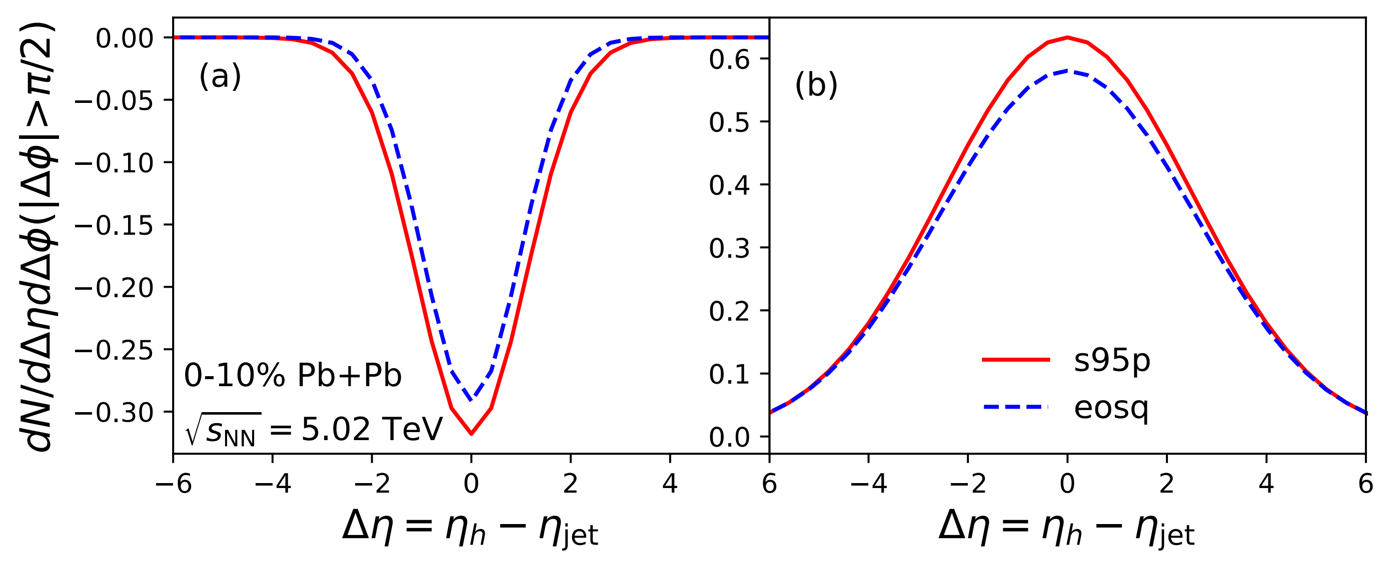
$$\frac{dN^{hZ}_{\mathrm{MPI}}}{d\phi} = \frac{dN^{hZ}_{\mathrm{mix}}}{d\phi} - \int_1^{\pi} \frac{d\phi}{\pi} \left(\frac{dN^{hZ}}{d\phi} - \frac{dN^{hZ}}{d\phi}\Big|_{\phi=1} \right)$$



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

No correlation with Z/γ-jet

Sensitivity to EoS and shear viscosity



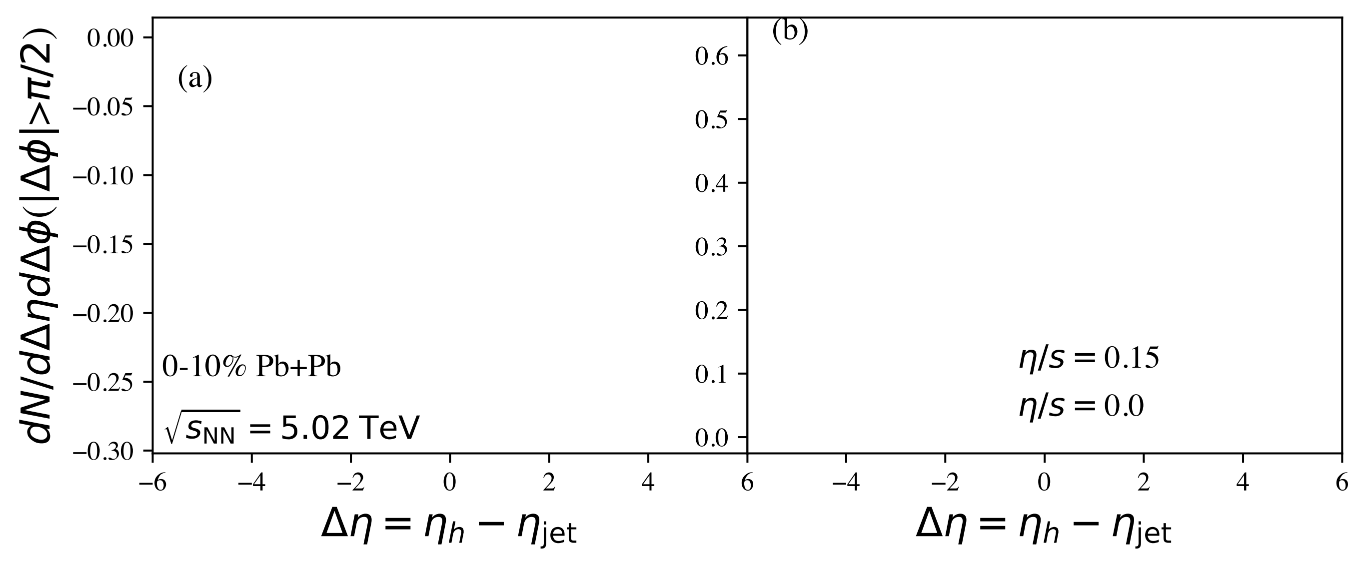
eosq: first order

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



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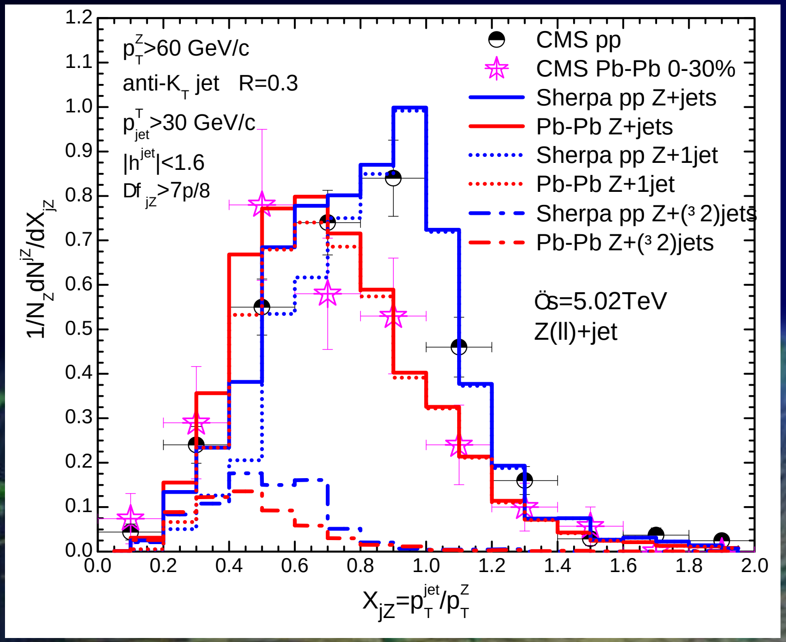
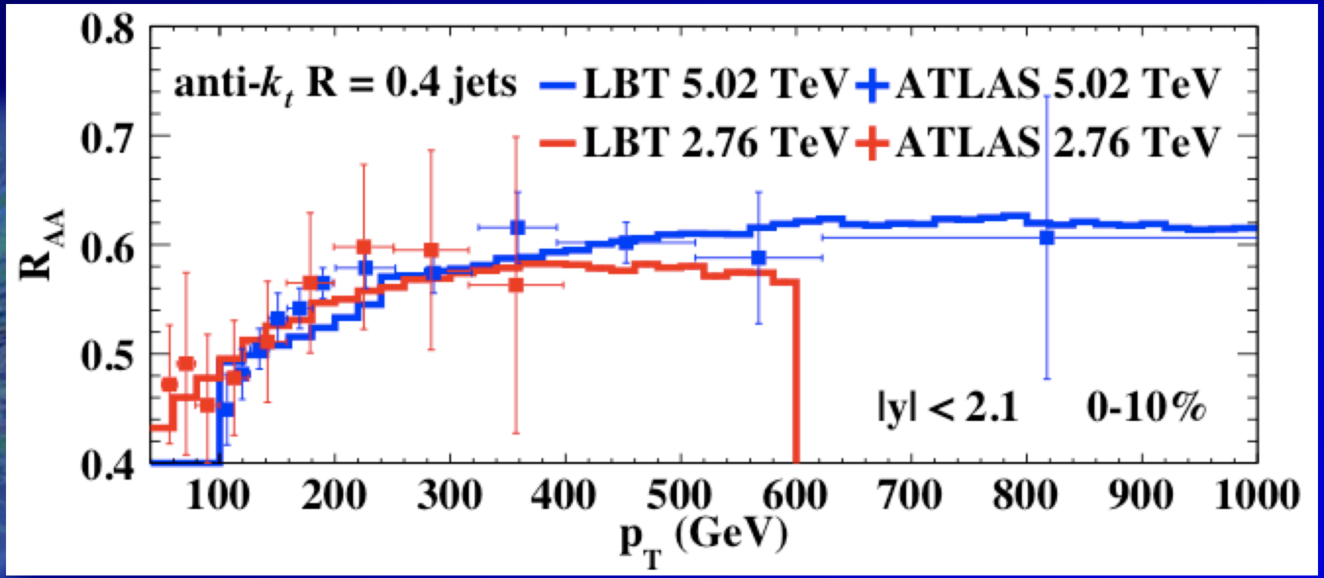
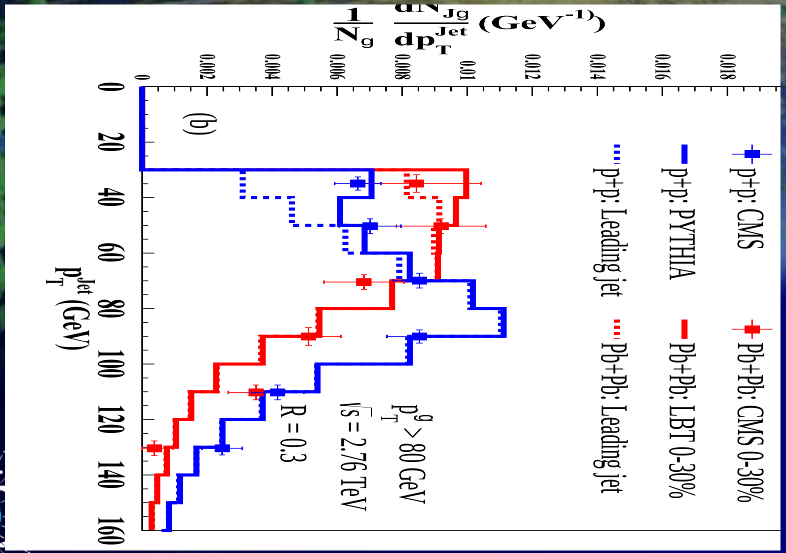
Jet suppression and medium response at LHC



Z-jet

Single inclusive jets





γ-jet

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

Zhang, Luo, XNW, Zhang, arXiv:1804.11041

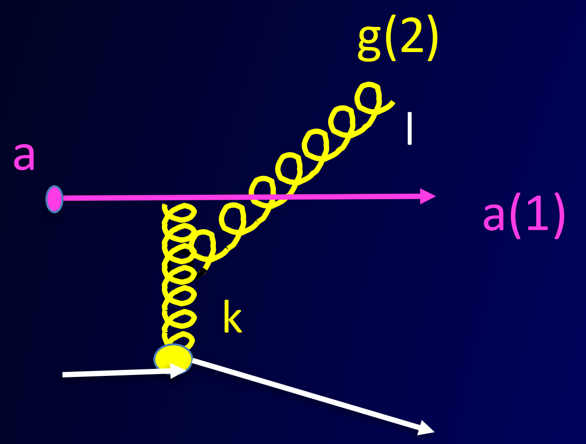
Luo, Cao, He & XNW, arXiv:1803.06785

Gluon spectrum from single emission in GHT

Generalized HT induced emission in a QGP brick:

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

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



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

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

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

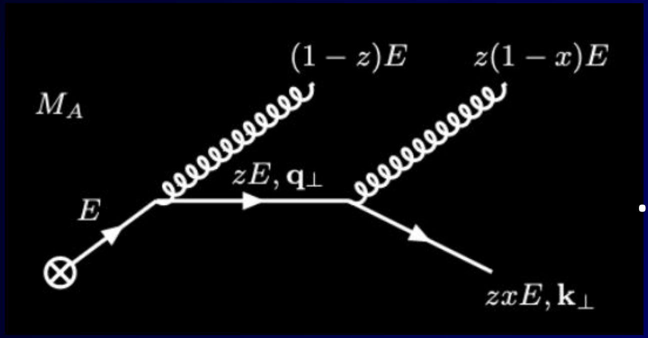
$$\theta_{12} \approx \frac{2\ell_\perp}{z(1-z)E} \qquad \tau_f = \frac{2z(1-z)E}{\ell_\perp^2} = \frac{8}{z(1-z)E\theta_{12}^2}$$

Jet EEC in Vacuum

LO emission in vacuum:

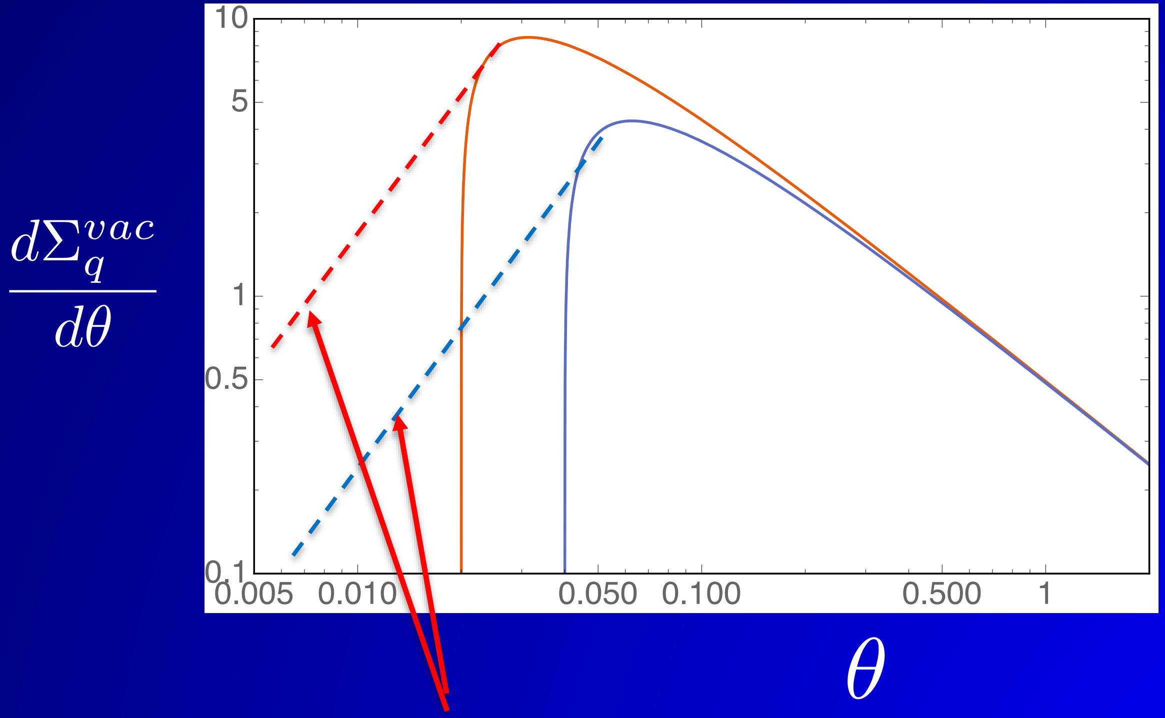
$$\frac{d\Sigma_q^{\rm vac}}{d\theta} \approx \frac{\alpha_s}{2\pi} C_F \int_0^1 dz \; z(1-z) P_{qg}(z) \int_{\mu_0^2}^{Q^2} \frac{d\ell_\perp^2}{\ell_\perp^2} \delta\left(\theta - \frac{\ell_\perp}{z(1-z)E}\right) \approx \frac{\alpha_s}{2\pi} \frac{C_F}{2\theta}\left(3 - \frac{2\mu_0}{E\theta}\right)\sqrt{1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

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

EEC in generalized high-twist

With a (GW) static potential model

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

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

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

Recover HT results:

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