Medium modification of the charge-weighted EEC in Pb+Pb collisions at 5.02 TeV

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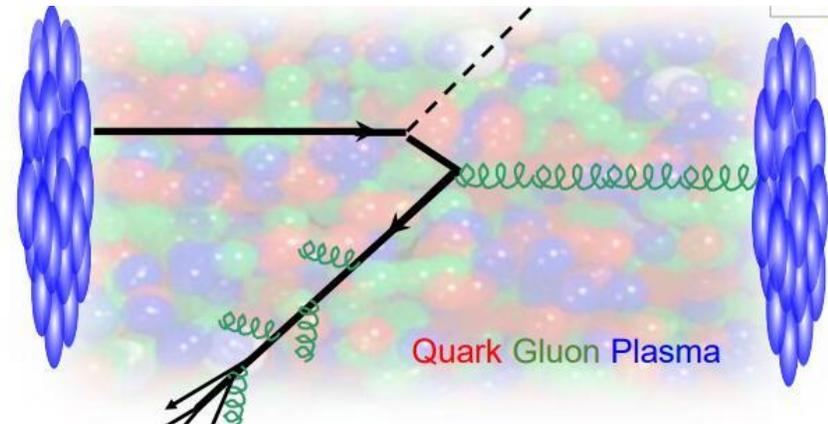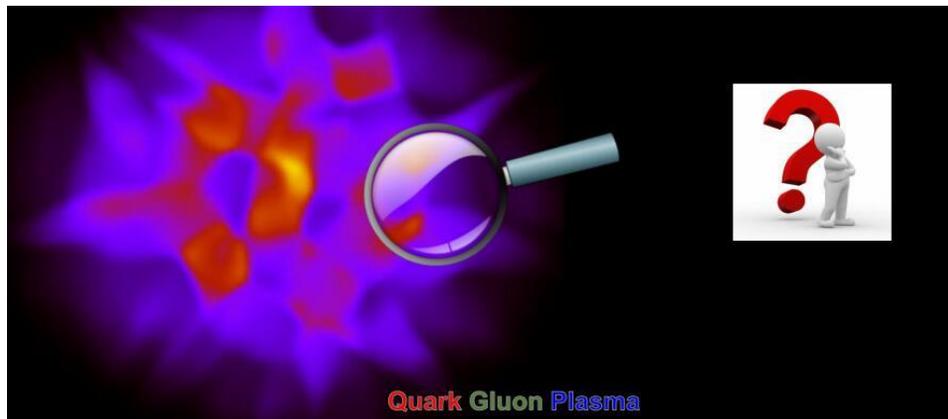
Based on: arXiv:2511.13495

JET AND HEAVY QUARK
JUST ASK QUESTIONS

Outline

☐   Motivation

☐   charge weighted EEC in pp and AA

☐   cEEC/EEC ratio in AA

☐   Summary

Motivation

Heavy-ion collisions: Quark Gluon Plasma

Jet quenching is one of the most powerfull hard probe to investigate QGP: parton energy loss, medium response.
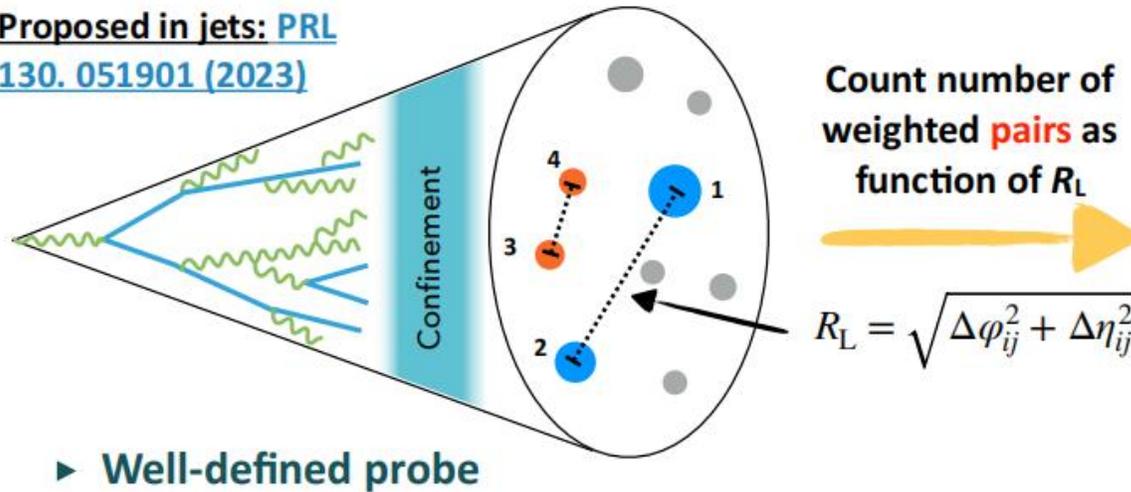
Jet substructure gives insight into the microscopic modification.

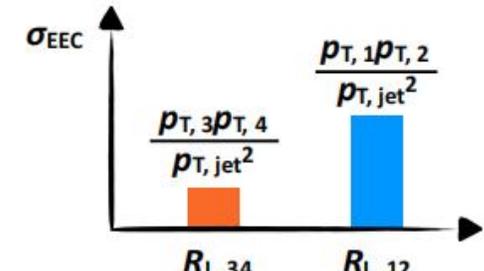Xin-Nian Wang, M.Gyulassy, PRL68(1992)1480

Motivation

Jet substructure: Energy-Energy Correlator

Proposed in jets: PRL 130. 051901 (2023)

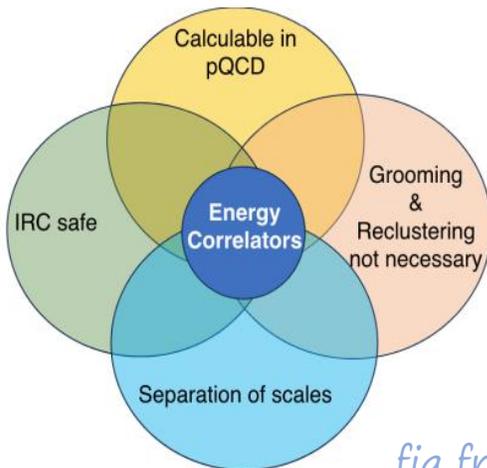Confinement

► **Well-defined probe**

$R_L = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$

Count number of weighted pairs as function of R_L

$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j}\int d\sigma(R'_L)\left(\frac{p_{T,i}\,p_{T,j}}{p_{T,jet}^2}\right)\delta(R'_L - R_{L,ij})$$

Energy weight

σ_{EEC}

$\dfrac{p_{T,3}p_{T,4}}{p_{T,jet}^2}$ $\dfrac{p_{T,1}p_{T,2}}{p_{T,jet}^2}$

$R_{L,34}$ $R_{L,12}$

Calculable in pQCD

IRC safe

Energy Correlators

Grooming & Reclustering not necessary

Separation of scales

Scaling: Different time scales of jet evolution imprinted in different angular scales

Simplicity: Soft contribution power suppressed by energy weight: no need for groomings

Control: Well understood pp baseline, medium modifications perturbatively calculable

fig from Ananya Rai

cEEC in pp collisions

charge weighted Energy-Energy Correlator:

$$Charge-weighted\ EEC = \frac{1}{N_{jet} \cdot \Delta R} \int_{R_L - \frac{1}{2}\Delta R}^{R_L + \frac{1}{2}\Delta R} \sum_{jets} \sum_{i,j} \frac{Q_i Q_j p_{T,i} p_{T,j}}{p_{T,jet}^2} \delta(R_L - R_{L,ij}) dR_L$$

$$= EEC_{Like} - EEC_{Opposite}$$

fig Andrew Tamis
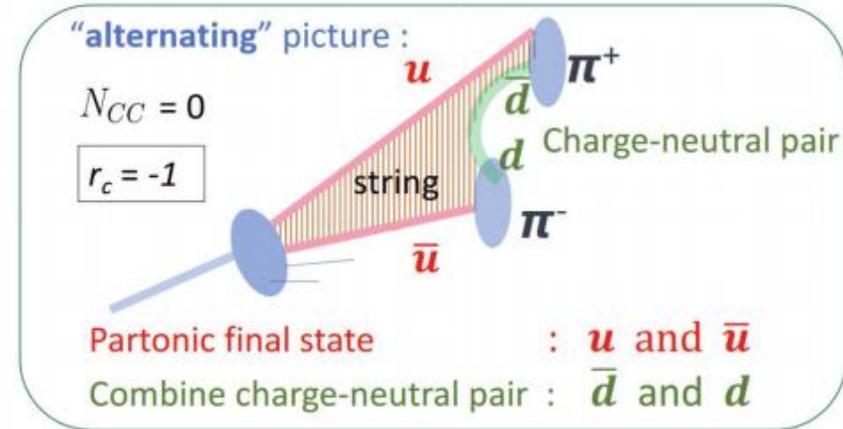
Figure: Mriganka Mouli Mondal

charge correlations modified by jet quenching?

charge weighted Energy-Energy Correlator:

$$Charge - weighted\ EEC = \frac{1}{N_{jet} \cdot \Delta R} \int_{R_L - \frac{1}{2}\Delta R}^{R_L + \frac{1}{2}\Delta R} \sum_{jets} \sum_{i,j} \frac{Q_i Q_j p_{T,i} p_{T,j}}{p_{T,jet}^2} \delta(R_L - R_{L,ij}) dR_L$$
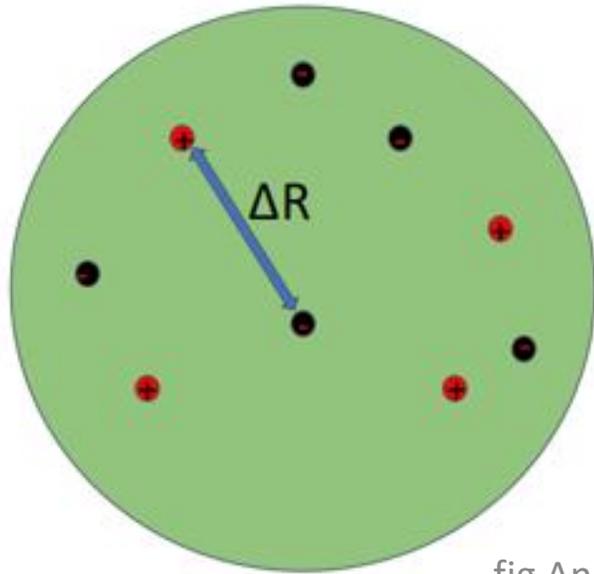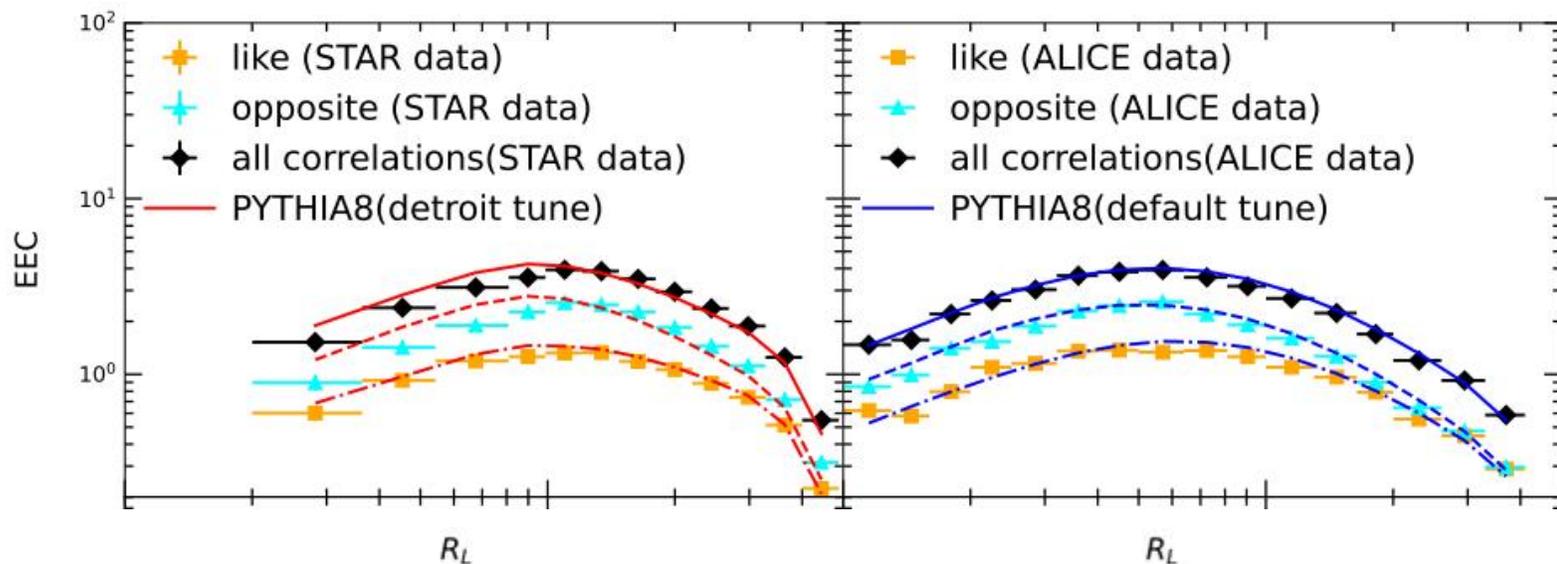
$$= EEC_{Like} - EEC_{Opposite}$$

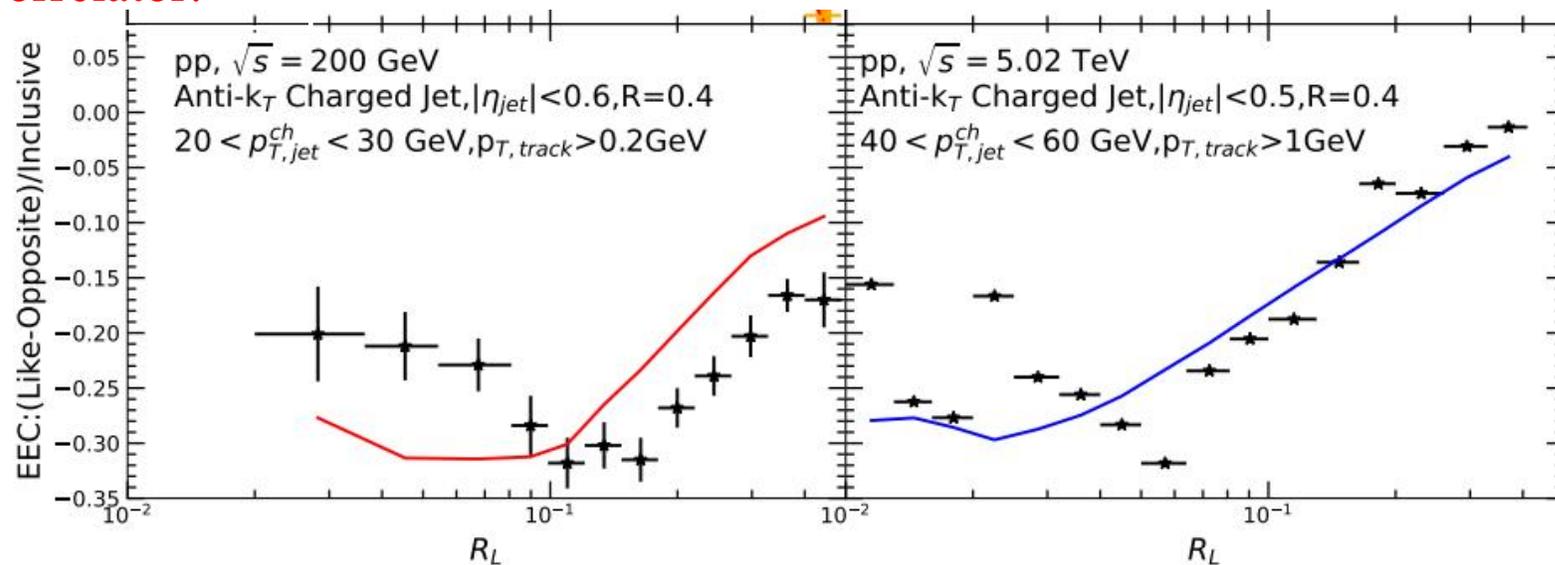B. E. Aboona et al. (STAR), Phys. Rev. Lett. 135, 111901 (2025), arXiv:2502.15925

fig Andrew Tamis

opposite-charge correlations are observed to be **stronger** than the like-charge correlations.

6

charge correlations: cEEC/EEC

charge weighted Energy-Energy Correlator:
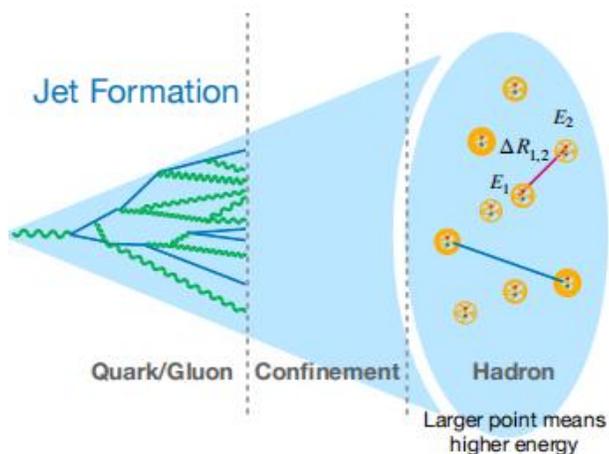
large-RL ➡ small-RL

1. cEEC/EEC ratio could characterizes the degree of charge correlations, (-1,1) , 0 an infinite thermal bath, like-charge and opposite-charge pairs are equal

2. from the large-RL toward small-RL, opposite-charge correlations strengthens relative to like-charge correlations.

jet quenching model: SHELL

☐ **radiative energy loss:** **Higher Twist**

$$\frac{\mathrm{d}N}{\mathrm{d}x\,\mathrm{d}k_\perp^2\,\mathrm{d}t} = \frac{2\alpha_s C_s P(x)\hat{q}}{\pi k_\perp^4}\sin^2\left(\frac{t-t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2+x^2M^2}\right)^4$$

☐ **collisional energy loss:** **Hard Thermal Loop**

$$\frac{dE}{dt} = \frac{\alpha_s C_s}{2}\mu_D^2\ln\left(\frac{\sqrt{ET}}{\mu_D}\right)$$

☐ **medium response:** **Hybrid Approach**

$$E\frac{\mathrm{d}\Delta N}{\mathrm{d}^3 p} = \frac{1}{32\pi}\frac{m_\mathrm{T}}{T^5}\cosh(y-y_j)\exp\left[-\frac{m_\mathrm{T}}{T}\cosh(y-y_j)\right]$$
$$\times\left\{p_T\Delta P_\mathrm{T}\cos(\phi-\phi_j)\right.$$
$$\left.+\frac{1}{3}m_\mathrm{T}\Delta M_\mathrm{T}\cosh(y-y_j)\right\},$$

Xiao-feng Guo , Xin-Nian Wang Phys. Rev. Lett. 85 (2000) 3591-3594
Ben-Wei Zhang , Xin-Nian Wang Phys. Rev. Lett. 93 (2004) 072301
A. Majumder, Phys.Rev. D85(2012)014023
W.T. Deng and X.N Wang, Phys.Rev.C 81(2010)024902
R. B. Neufeld Phys. Rev. D 83, 065012 (2011), arXiv:1011.4979
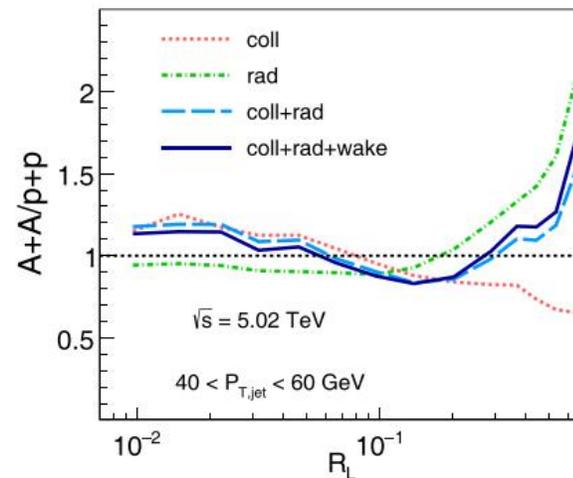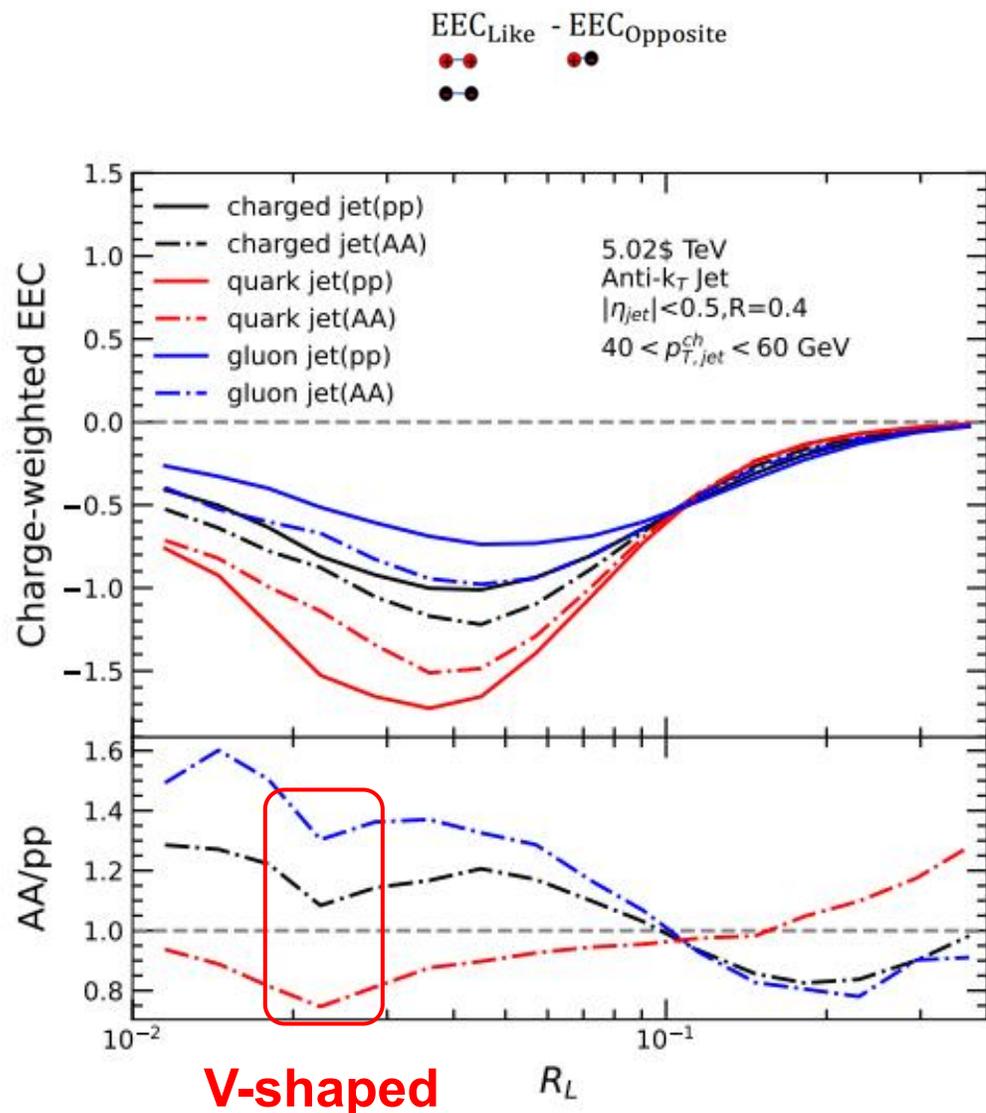
1. charge-weighted distribution of gluon-initiated jets lies closer to zero than quark-initiated jets.

2. their behavior of AA/pp ratios resembles the previously reported modification of the inclusive EEC.

3. in the small-RL region around R ≈ 0.02, we observe a characteristic **V-shaped** modification pattern.

charged weighted EEC in PbPb collisions:
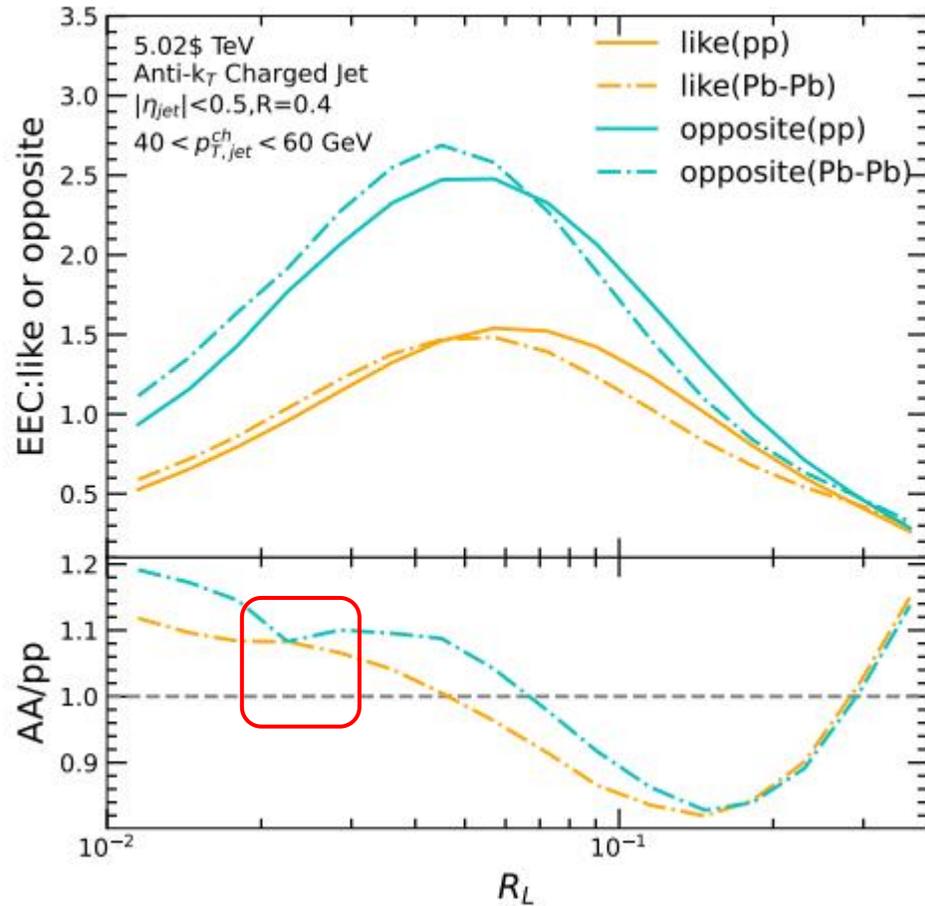
$EEC_{Like} - EEC_{Opposite}$

1. opposite-charge component exhibits a stronger enhancement in the transition and small RL region compared to the like-charge part;

2. V-shaped modification structure at the small RL is found exclusively in the opposite-charge component.
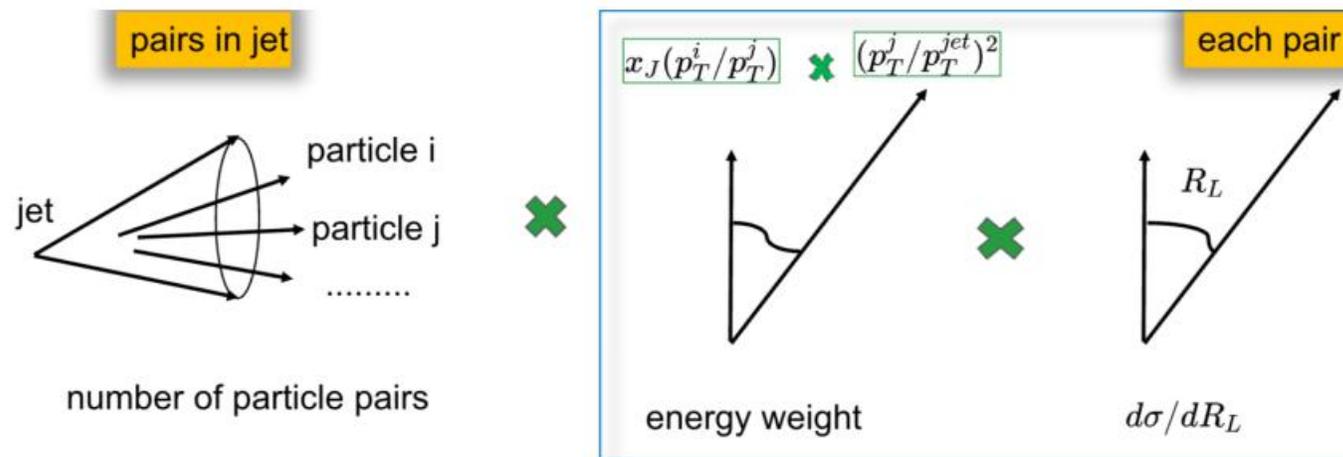
charged weighted EEC：component

Energy-Energy Correlator:

$$\Sigma_{\text{EEC}}(R_L) = \frac{1}{N_{\text{jet}} \cdot \Delta R} \int_{R_L - \frac{1}{2}\Delta R}^{R_L + \frac{1}{2}\Delta R} \sum_{\text{jets}} \sum_{i,j} \frac{p_{T,i} p_{T,j}}{p_{T,\text{jet}}^2} \delta(R_L' - R_{L,ij}) \, dR_L'$$

Normalized to jets

Energy weight

phenomenology understanding is needed!

pairs in jet

$x_J(p_T^i/p_T^j)$ ✖ $(p_T^j/p_T^{jet})^2$

each pair

jet — particle i

particle j

....

number of particle pairs
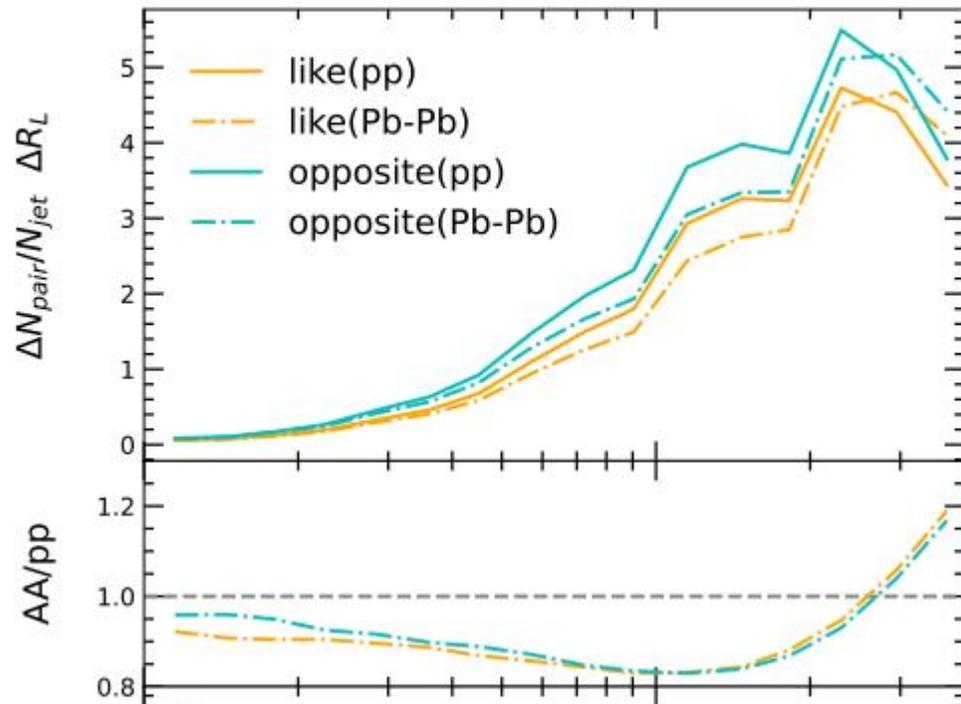
✖

energy weight ✖ $d\sigma/dR_L$

R_L

$$\Sigma_{\text{EEC}}(R_L) = \frac{N_{\text{pair}}^{\text{total}}}{N_{\text{jet}}^{\text{total}}} \cdot \frac{\Delta N_{\text{pair}}}{N_{\text{pair}}^{\text{total}} \Delta R}(R_L) \cdot \langle \text{weight} \rangle(R_L)$$

charged weighted EEC：component

charged weighted EEC in PbPb collisions:

$EEC_{Like} - EEC_{Opposite}$

1. in pp the number of opposite-charge pairs exceeds that of like-charge pairs across the entire RL range;

2. in AA the RL distributions of both types of hadron pairs shift toward larger RL;

3. the modification of opposite-charge pairs is slightly weaker than like-charge pairs.

charged weighted EEC：component

charged weighted EEC in PbPb collisions:

$$\frac{p_{T,i}p_{T,j}}{p_{T,\text{jet}}^2}$$
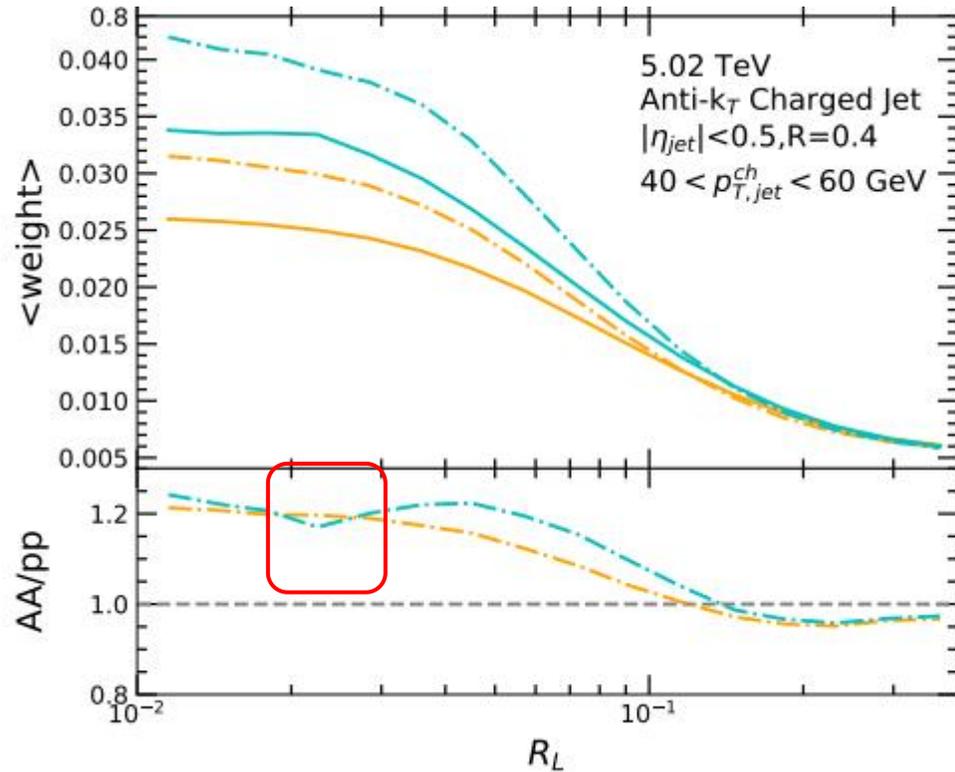
1. average energy weight of opposite-charge pairs is significantly larger than that of like-charge pairs;

2. the opposite-charge pairs exhibit a stronger enhancement at small RL compared to like-charge pairs;

3. characteristic V-shaped modification pattern emerges in the opposite-charge.

charge correlations: cEEC/EEC

charged weighted EEC in PbPb collisions:

$EEC_{Like} - EEC_{Opposite}$

5.02 TeV
Anti-k_T Jet
$|\eta_{jet}|<0.5, R=0.4$
$40 < p_{T,jet}^{ch} < 60$ GeV
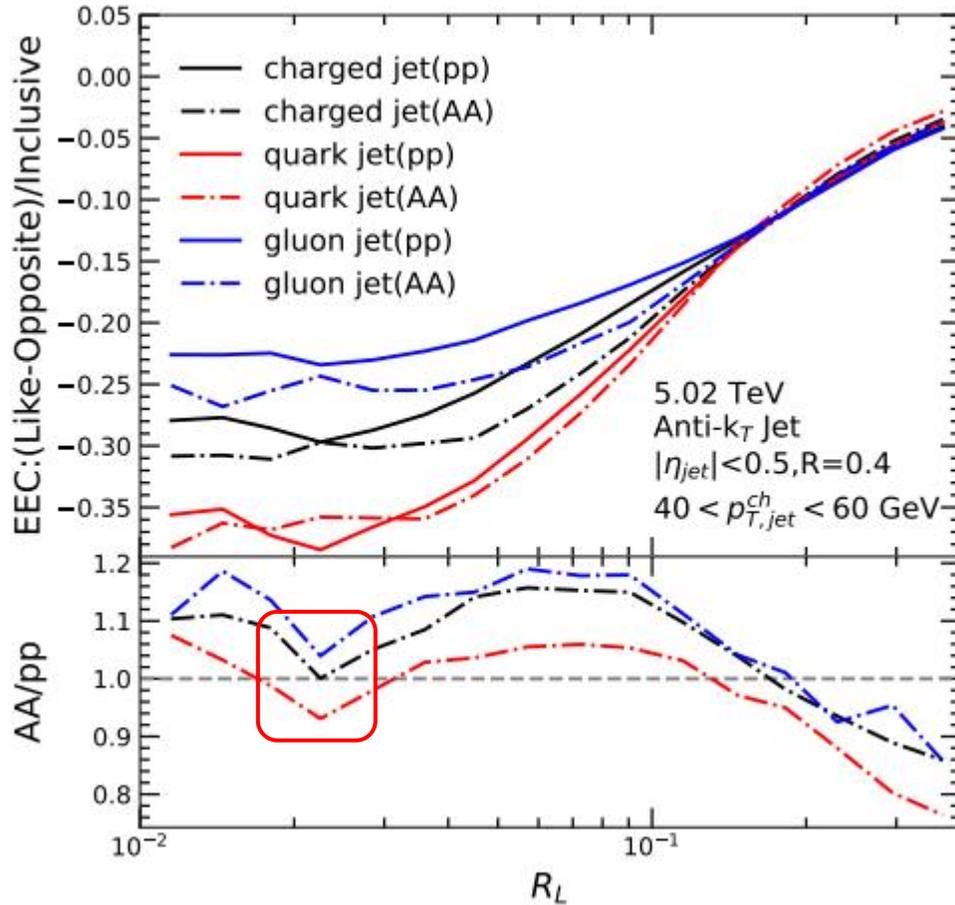
1. quark jets exhibit a quicker opposite-charge de-correlations at large RL, largest opposite-charge correlations at small RL;

2. The different modification patterns of quark jets from gluon jets in the charge-weighted EEC are canceled out;

3. V-shaped medium modification observed at the same RL position, independent of the jet initiator flavor.

charge correlations: cEEC/EEC

charged weighted EEC in PbPb collisions:
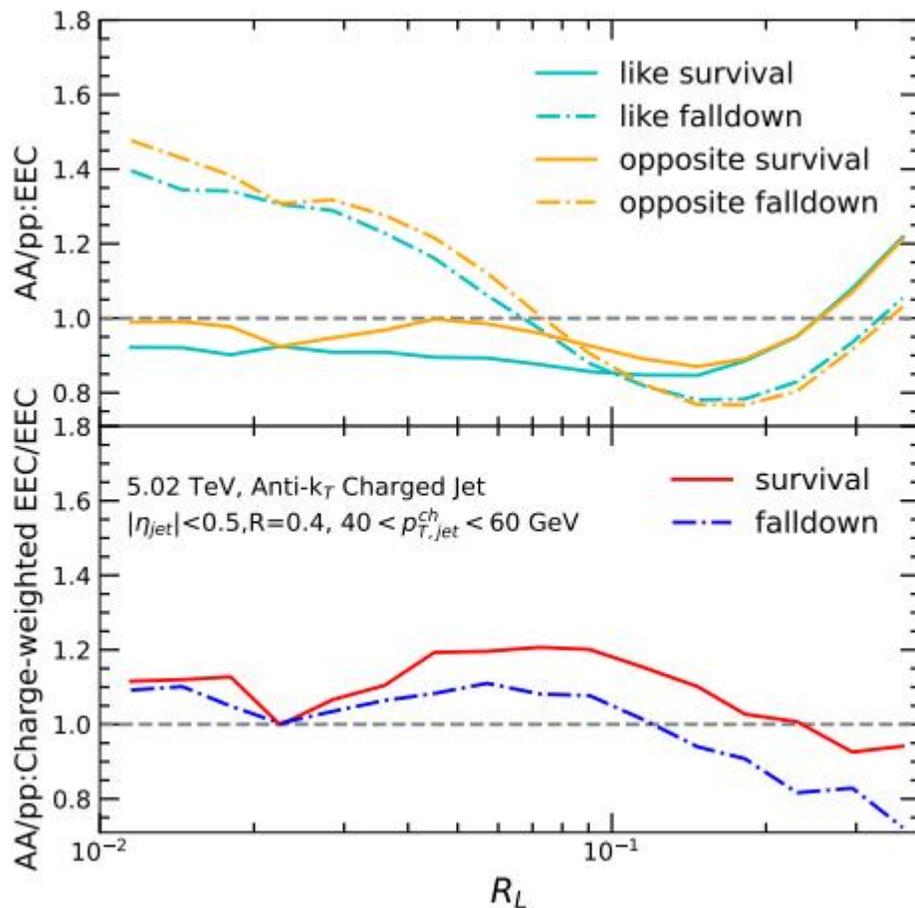
$EEC_{Like} - EEC_{Opposite}$

survived: $40 < p_{T,jet} < 60$ GeV in pp, remain   in A+A

fall-down: $p_{T,jet} > 60$ GeV in pp, fall into A+A

1. the overall behaviors of the survival and fall-down cases are qualitatively similar;

2. at large RL, the fall-down contribution induces a more rapid decorrelations;

3. enhancement of the charge correlations in the transition and small-RL region is unrelated to selection bias.

Summary

1. The behavior of AA/pp ratios(cEEC) of quark/gluon resembles the previously reported modification of the inclusive EEC;

2. opposite-charge component exhibits a stronger enhancement, V-shaped modification structure at the small RL is found exclusively in the opposite-charge component;

3. quark jets exhibit a quicker opposite-charge de-correlations at large RL, largest opposite-charge correlations at small RL;

4. Jet quenching enhances opposite-charge correlations at small angles while reducing it at large angles, resulting in a steeper RL dependence, a rapid de-correlated behavior with the increasing RL.

Thank you for your attantion !

Brownian motion
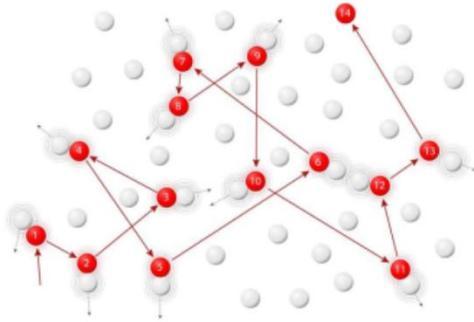
G.D. Moore and D. Teaney PRC 71 (2005) 064904; S. Cao, G.Y. Qin and S.A. Bass Phys.Rev. C88 (2013) 044907

- For heavy quark, $m_Q \gg T_{QGP}$, the modified discrete Langevin transport equations are used to describe the propagating of heavy quarks in the QGP.

$$\Delta \vec{x}(t + \Delta t) = \frac{\vec{p}(t)}{E} \Delta t \tag{1}$$

$$\Delta \vec{p}(t + \Delta t) = -\Gamma(p)\vec{p}\Delta t + \vec{\xi}(t)\Delta t - \vec{p}_g \tag{2}$$

The fluctuation-dissipation relation: $\kappa = 2ET\Gamma = \frac{2T^2}{D_s}$

Based on the LQCD calculation , D_s is fixed at $D_s(2\pi T) = 4$
A. Francis, O. Kaczmarek, M. Laine, T. Neuhaus and H. Ohno Phys.Rev. D92 (2015) no.11, 116003

The stochastic term $\xi(t)$ obeys Gaussian distribution :

$$W(\vec{\xi}(t)) = N \cdot \exp\left(\frac{\vec{\xi}^2(t)}{2\kappa}\right) \tag{3}$$

which leads to

$$\langle \xi_i(t) \rangle = 0 \tag{4}$$

$$\langle \xi_i(t)\xi_j(t') \rangle = \kappa \delta_{ij}(t - t') \tag{5}$$

- For light parton, the collisional energy loss is described by the calculation at Hard Thermal Loop (HTL) approximation:

R.B. Neufeld, Phys.Rev. D83 (2011) 065012; J. Huang, Z.B. Kang and I. Vitev, Phys.Lett. B726 (2013) 251-256

$$\frac{dE}{dz} = -\frac{\alpha_s C_i m_D^2}{2} \ln \frac{\sqrt{ET}}{m_D} \tag{6}$$

- Evolution of the bulk medium is produced by the iEBE-VISHNU hydro model.

C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz, Comput.Phys.Commun. 199 (2016) 61-85

backup：SHELL model

- For both heavy and light parton, the medium-induced gluon radiation is implemented based on the higher-twist approach.

X.f. Guo and X.N. Wang, Phys.Rev.Lett. 85 (2000) 3591-3594 ; B.W. Zhang, E. Wang and X. N. Wang, Phys.Rev.Lett. 93 (2004) 072301; A. Majumder, Phys.Rev. D85 (2012) 014023

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x) \hat{q}}{\pi k_\perp^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)\left(\frac{k_\perp^2}{k_\perp^2 + x^2 M^2}\right)^4 \quad (7)$$

$P(x)$ is the QCD splitting function in vacuum : W. T. Deng and X. N. Wang, Phys. Rev. C 81 (2010) 024902

$$P_{q \to qg}(x) = \frac{(1 + (1 - x)^2)(1 - x)}{x} \quad (8)$$

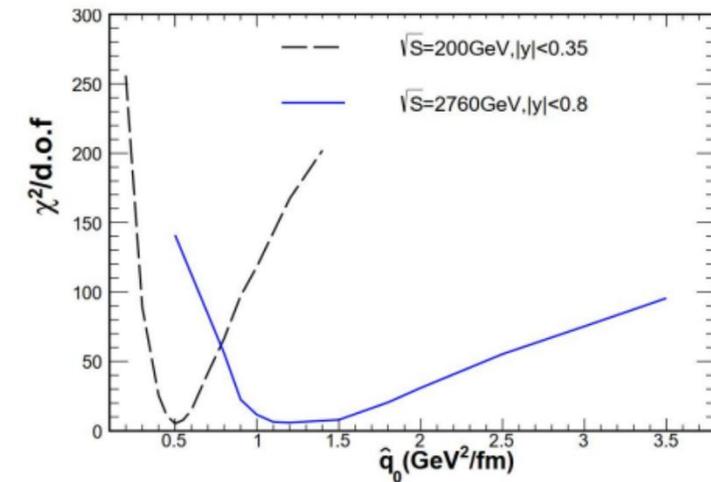$$P_{g \to gg}(x) = \frac{2(1 - x + x^2)^3}{x(1 - x)} \quad (9)$$

τ_f the gluon formation time :

$$\tau_f = \frac{2x E(1 - x)}{k_\perp^2 + x^2 M^2} \quad (10)$$

- $\hat{q}$ is the jet transport coefficient.

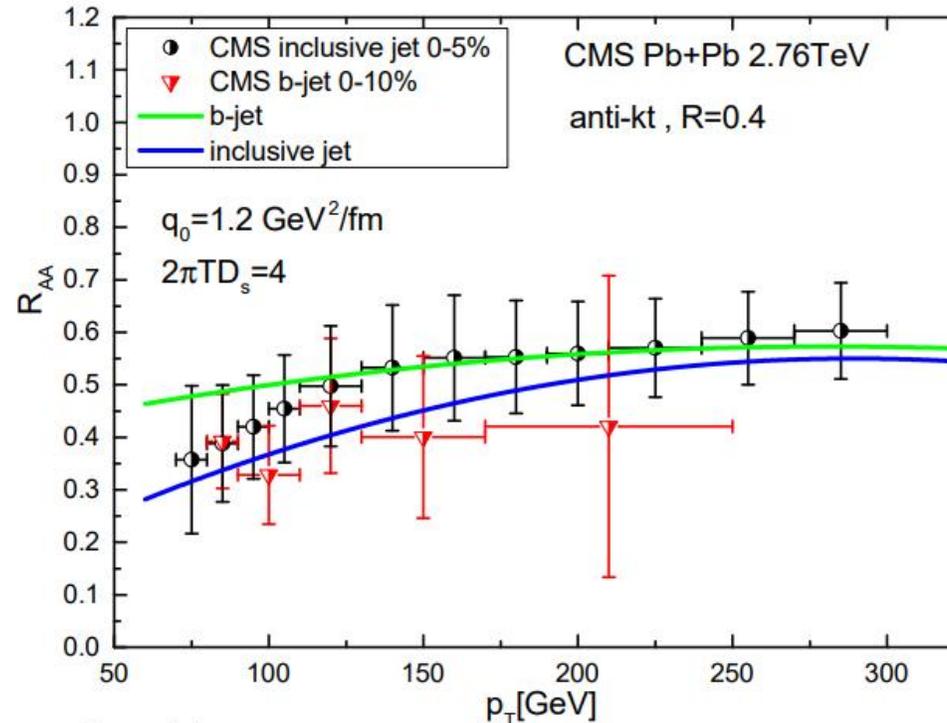X. F. Chen, C. Greiner, E. Wang, X.N. Wang and Z. Xu, Phys.Rev. C81 (2010) 064908

$$\hat{q} = \hat{q}_0 \left(\frac{T}{T_0}\right)^3 \frac{p^\mu u_\mu}{p^0} \quad (11)$$

G.Y. Ma, W. Dai, B.W. Zhang and E.K. Wang, Eur.Phys.J. C79 (2019) no.6, 518

$\hat{q}_0 \sim 0.5 \ \text{GeV}^2/\text{fm}$ in Au+Au 200 GeV

$\hat{q}_0 \sim 1.2 \ \text{GeV}^2/\text{fm}$ in Pb+Pb 2760 GeV

backup：SHELL model

- $R_{AA} = \frac{1}{\langle N_{bin} \rangle} \frac{dN^{AA}/dp_T^{\text{jet}}}{dN^{pp}/dp_T^{\text{jet}}}$ quantifies the suppression of jet yield in nucleus-nucleus collisions compared to p+p baseline.
- Comparable suppression of inclusive jet and b-jet measured by CMS collaboration, no clear mass effects of jet quenching observed in experiment.

W. Dai, S. Wang, S. L. Zhang, B. W. Zhang and E. Wang, CPC(2020), arXiv:1806.06332