南華大學
UNIVERSITY OF SOUTH CHINA

中国物理学会高能物理分会
第十二届全国会员代表大会暨学术年会

Jet quenching and EEC in heavy-ion collisions

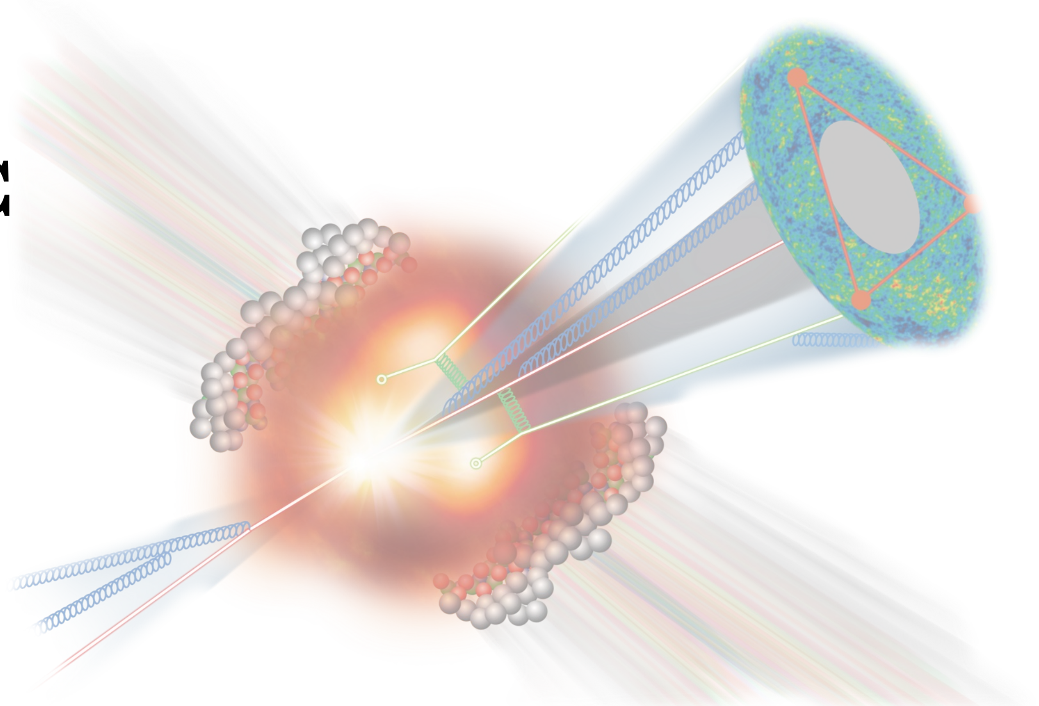
邢文静

南华大学

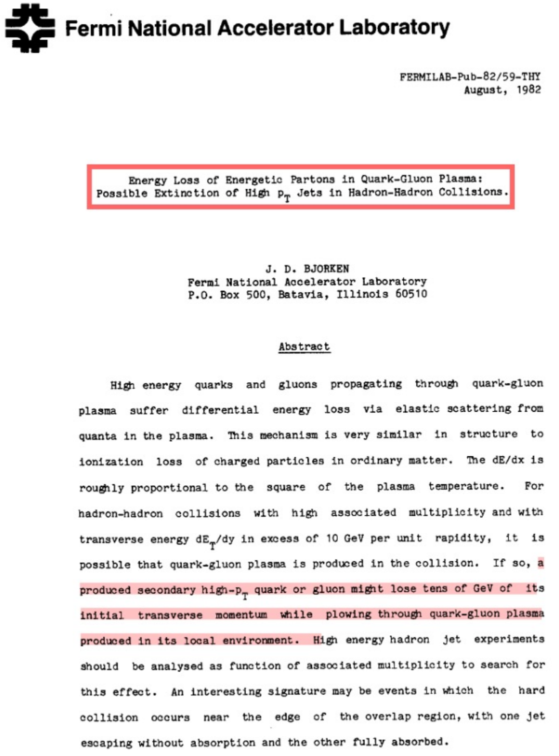
2026年7月13日-19日，广州

Outline

- ☐ Jet quenching in heavy-ion and light-ion collisions
- ☐ Flavor hierarchy of jet EEC in vacuum and QGP
- ☐ Genuine jet EEC
- ☐ Summary



Jet quenching in heavy-ion collisions


Fermi National Accelerator Laboratory

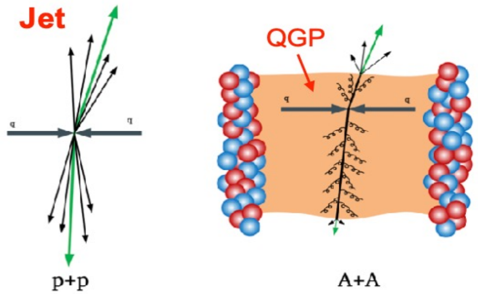
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

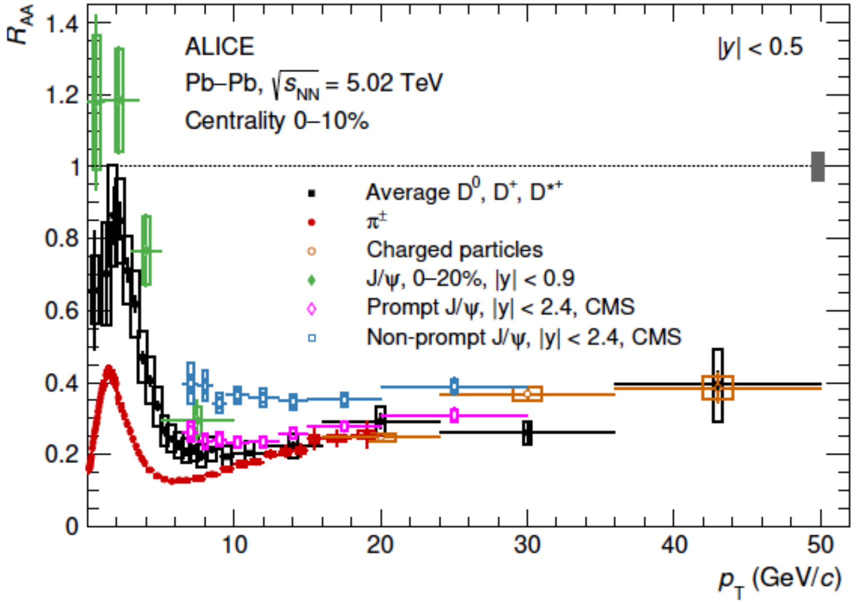
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



- Nuclear modification factor:

$$R_{AA}(p_T, y) = \frac{1}{N_{\rm coll}} \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

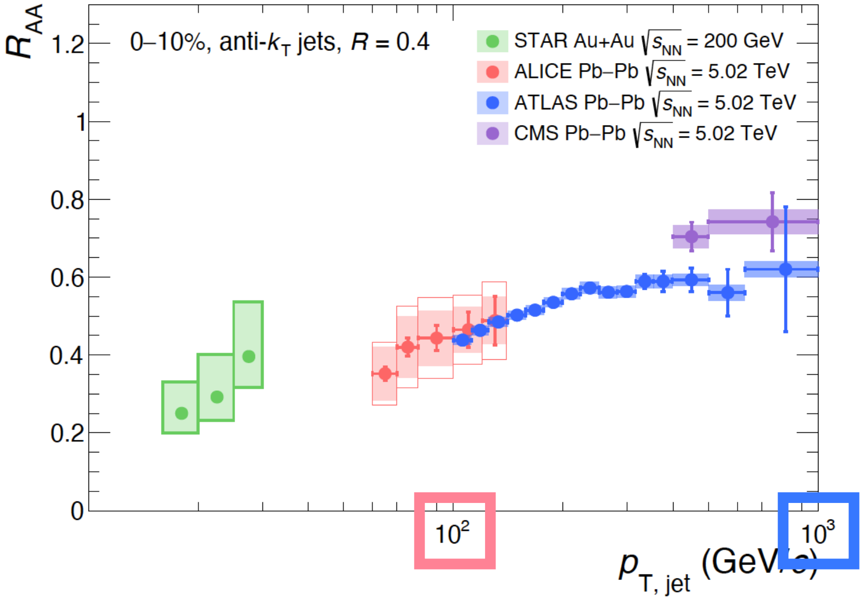


- **High p_T particles/jets lose enery in QGP medium.**

[Bjorjen, FERMILAB-PUB-82-059-THY (1982)]

- **Wang & Gylassy propose the first tool — RAA — for jet quenching studies.**

[Wang, Gyulassay, *Phys. Rev. Lett.* 68, 1480 (1992) ; Wang, *Phys. Rev. C* 58, 2321 (1998)]



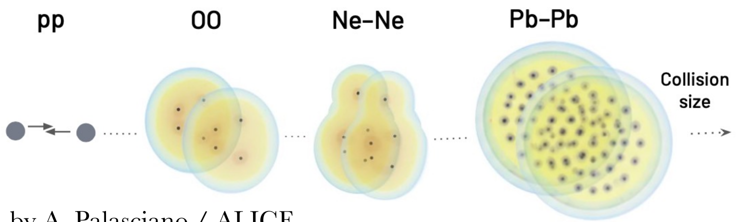
Single-hadron R_{AA} in OO collisions

New @ HP2026

[CMS: *Phys. Rev. Lett.* 136, 162301; arXiv:2602.21325]

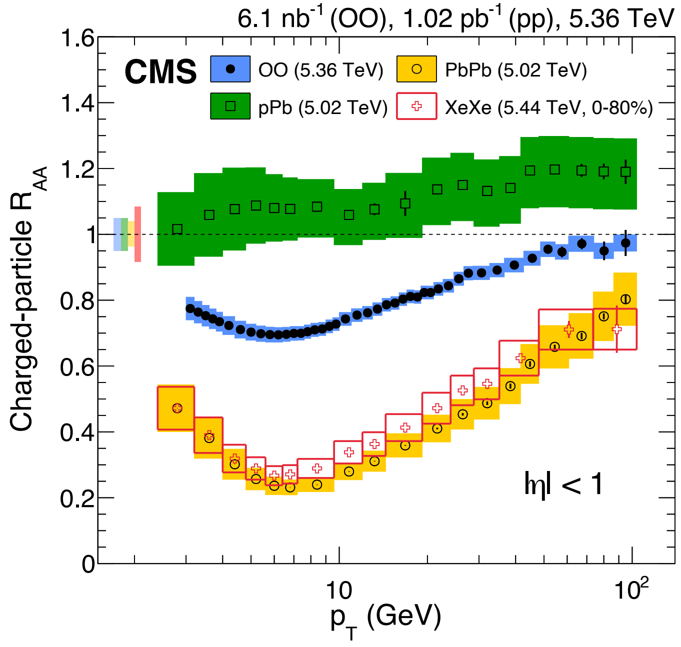
[ALICE: arXiv:2606.19967]

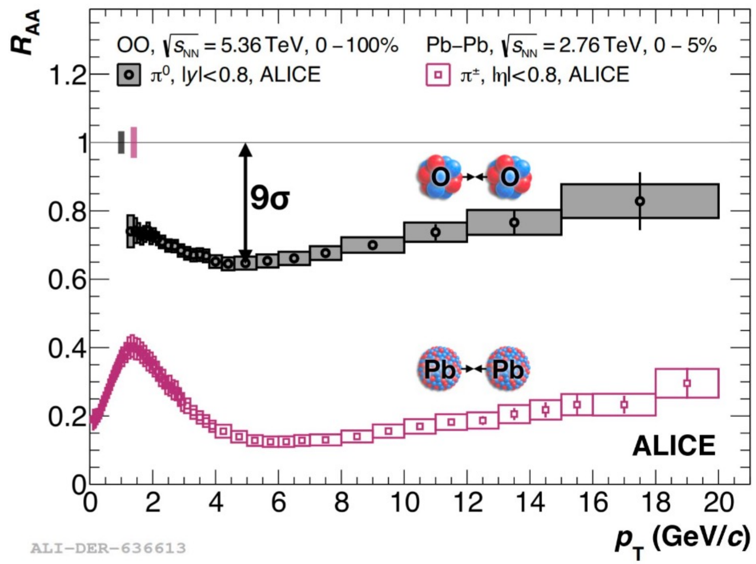
- **Probing the onset of energy loss effects in small system**

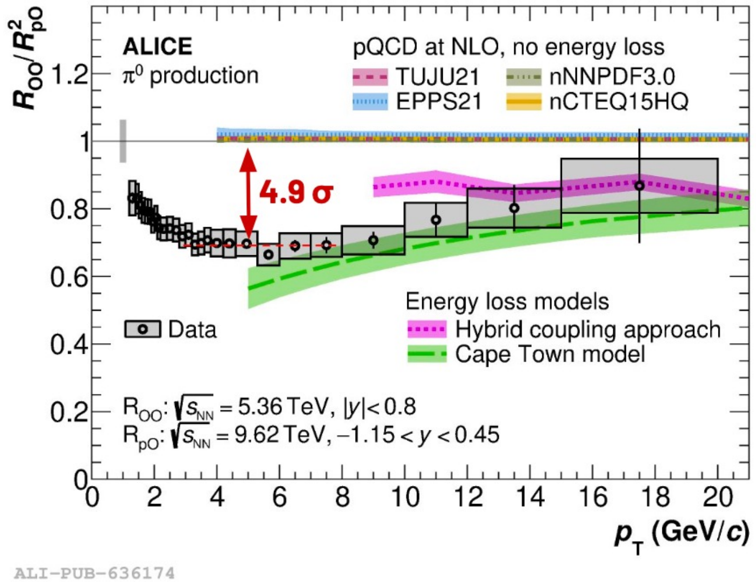


by A. Palasciano / ALICE

$$R_{AA} = \frac{1}{A^2}\frac{d\sigma_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

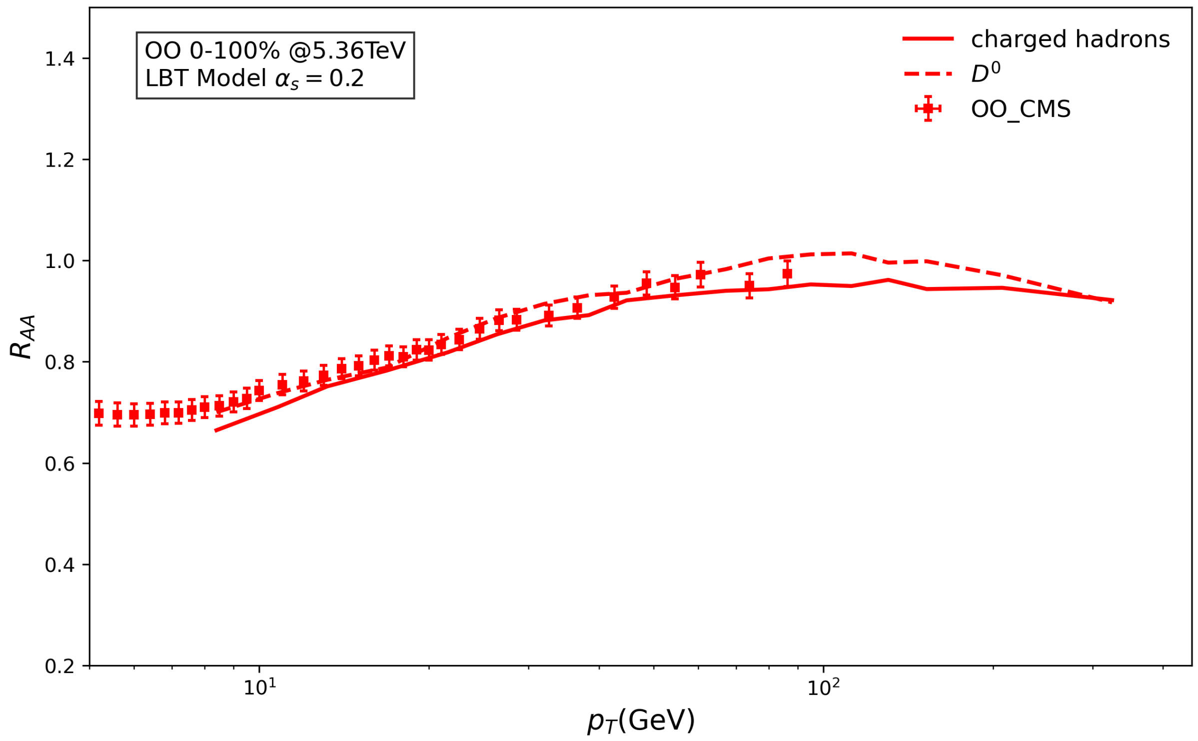


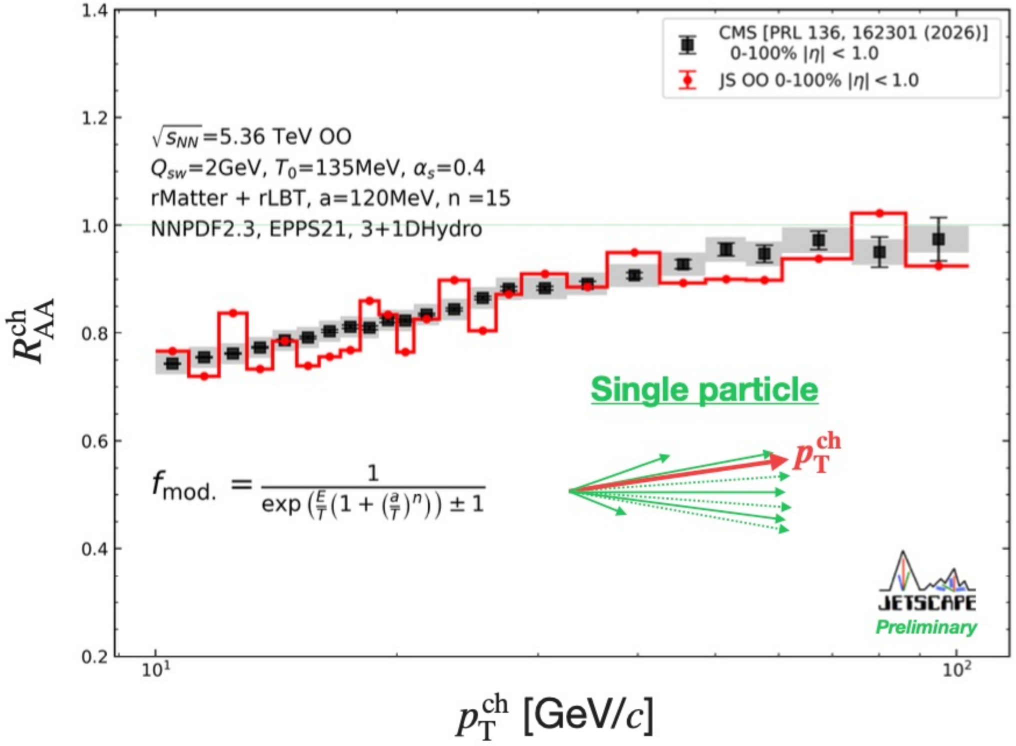




- **Significant suppression of single hadrons ($h^{\pm}$, π^0) in minimum-bias OO.**
- **R_{OO}/R^2_{pO} largely cancel CNM effect, providing strong evidence for parton energy loss in OO.**

Model calculations of high-p_T hadron R_{AA} in O-O





- **Nuclear suppression of high-p_T charged hadrons in light-ion collisions can be reproduced by LBT and JETSCAPE.**

[WJX, Cao, Qin, Xing, *Phys.Lett.B* 805 (2020) 135424]
[Majumder, Putschke, PRC 93, 054909 (2016), JETSCAPE, PRC96, 024909 (2017)]

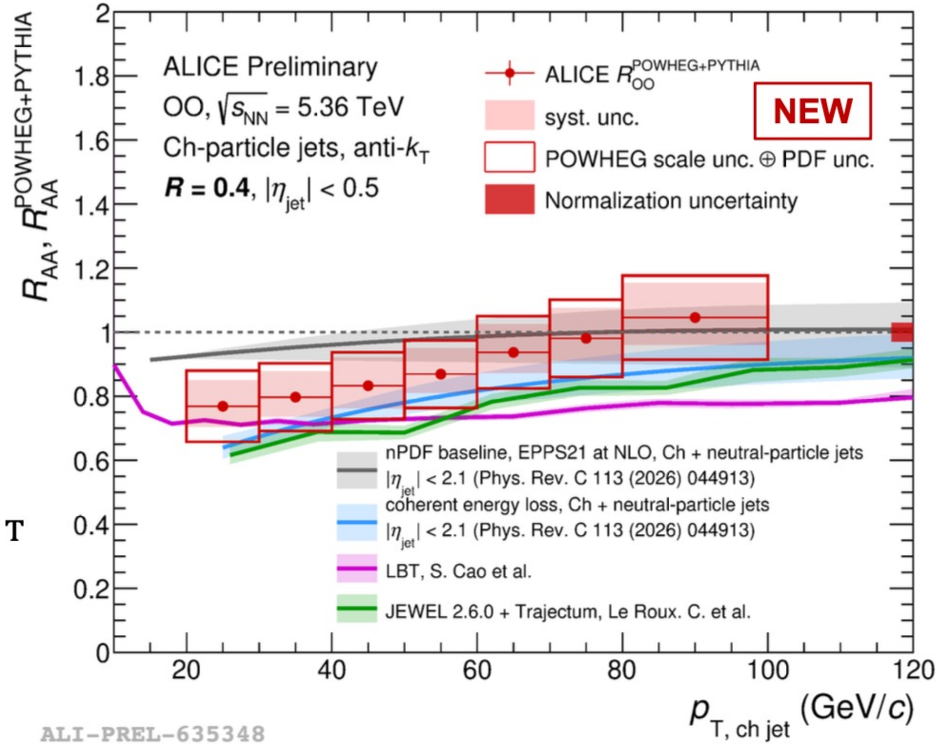
Jet R_{AA} in OO collisions

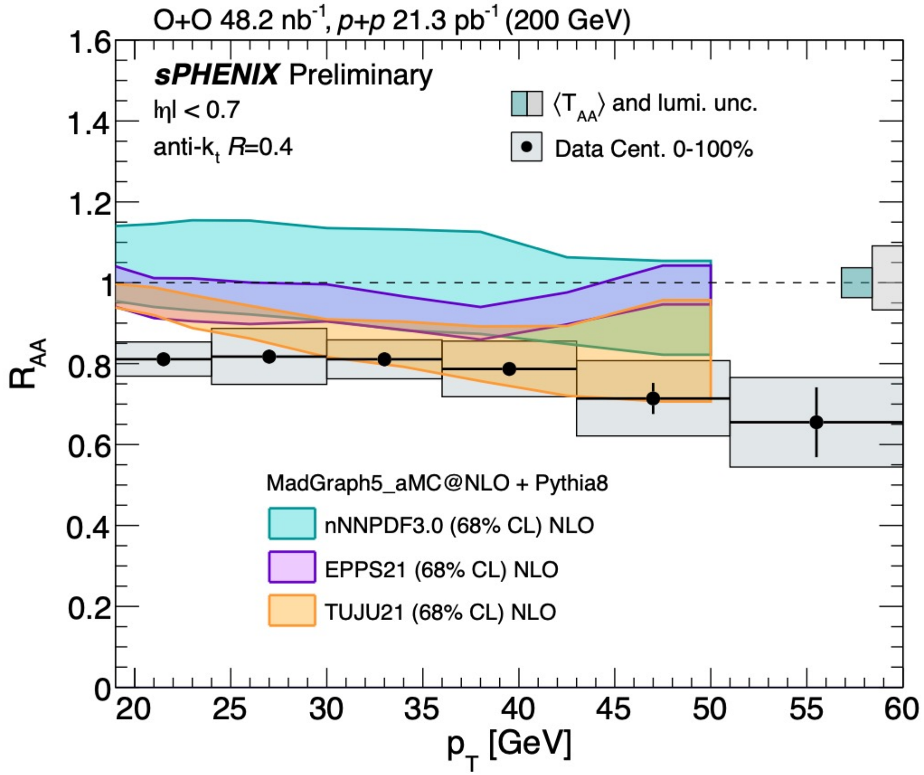
New @ HP2026

[ALICE: ALI –PREL-635348]

[sPHENIX: sPH-CONF-JET-2026-02]

- **Probing the onset of energy loss effects in small system**

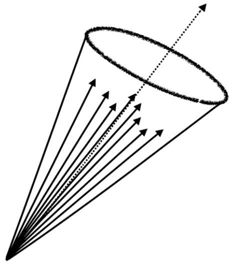


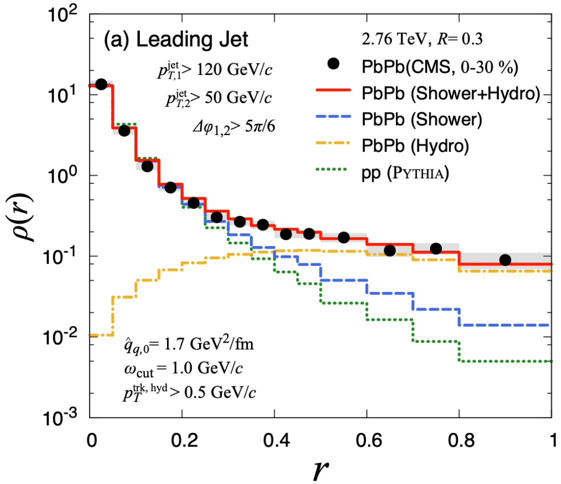


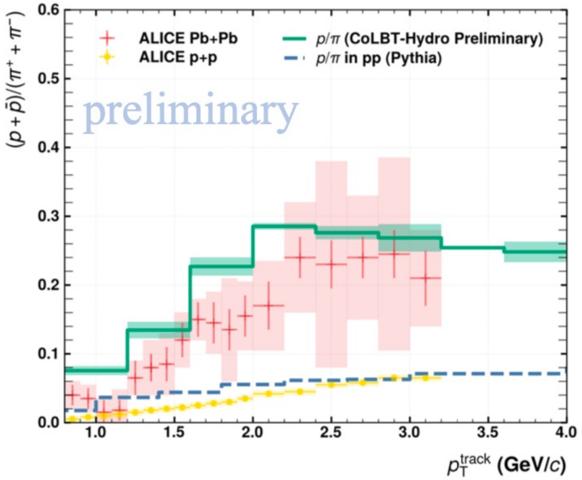
- **Jet suppression is suggestive, but current precision does not discriminate between CNM effect and parton energy loss scenarios.**
- **Hadron-hadron and hadron-jet correlation, γ-tagged hadron yields, Dijet imbalance also measured in OO, see C. Baldenegro's talk @HP26.**

Jet substructure probes jet-medium interactions across scales

☆ Particle distribution inside (& outside) the jet.



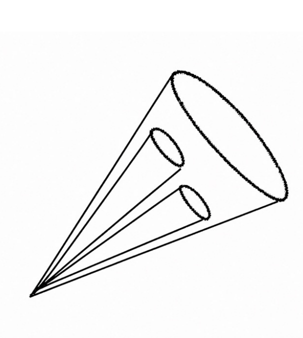


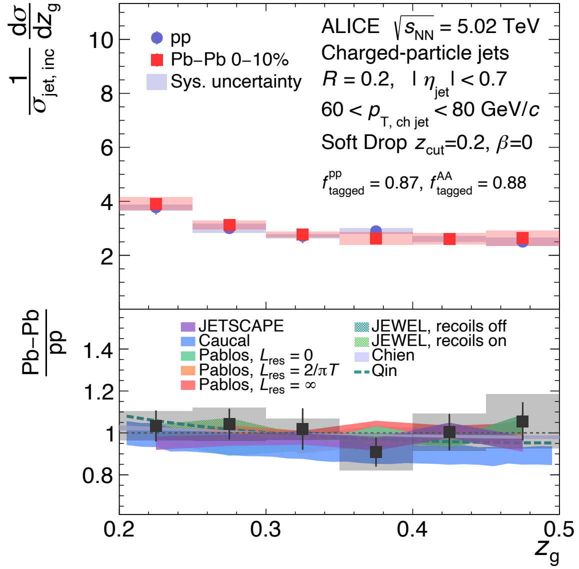


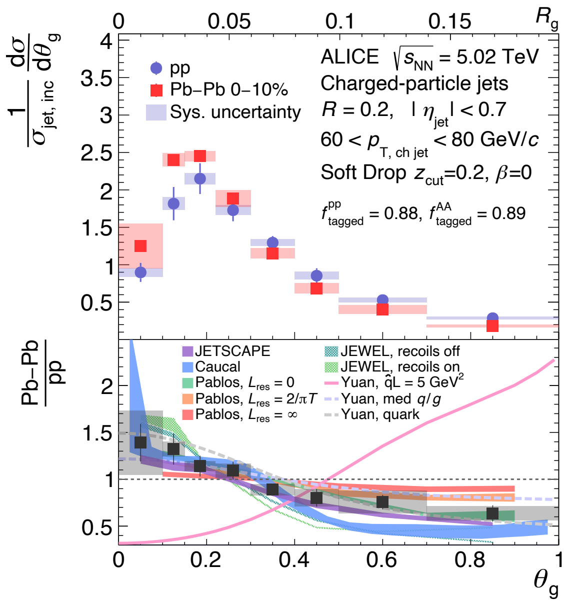
- **Jet momentum broadening**
- **Medium response (Soft, wide-angle)**

[Tachibana, Chang, Qin, *Phys.Rev.C* 95 (2017) 4, 044909; Yi, et al., in preparation]

☆ Particle/subjet correlations inside (& outside) the jet.



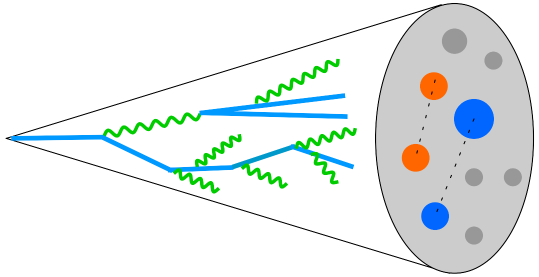




- **Medium-modified splittings,**
- **Medium resolving power**
- **Sensitivity to color coherence /decoherence.**

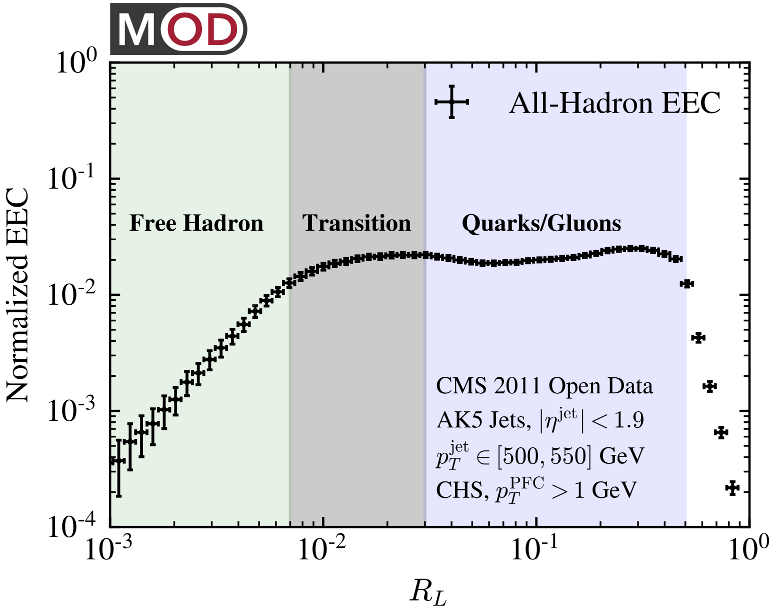
[ALICE, *Phys.Rev.Lett.* 128 (2022) 10, 102001; ATLAS, Phys. Rev. C 107 (2023)5, 054909]

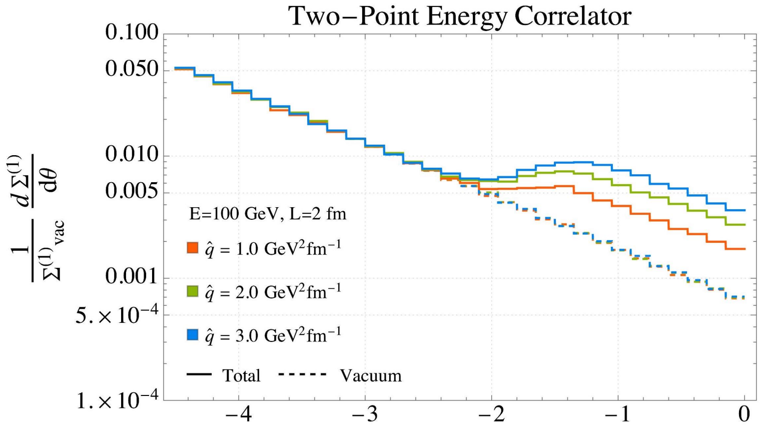
Jet energy-energy correlator (EEC)

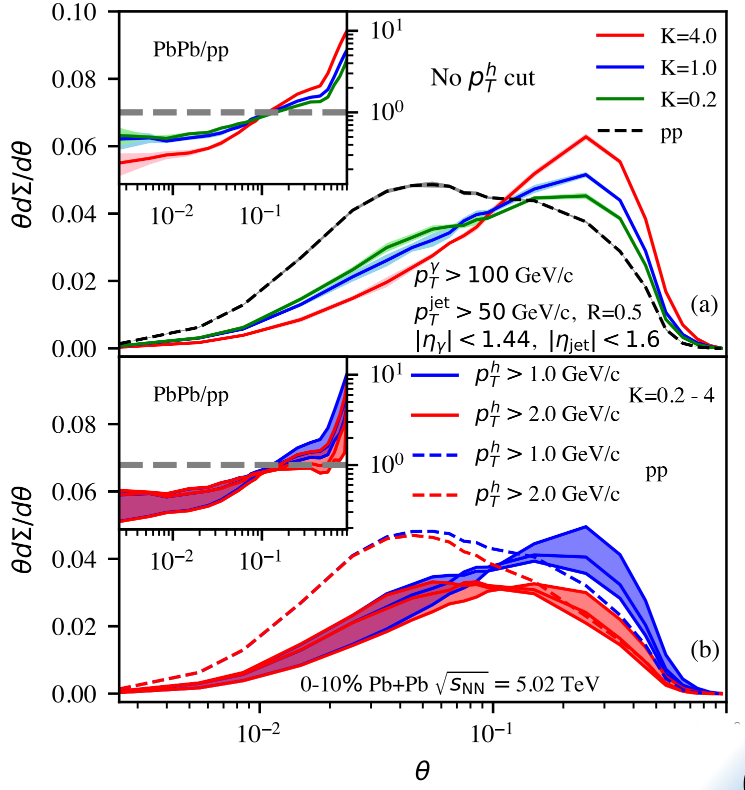


$$\frac{d\sigma_{\mathrm{EEC}}}{dR_L} = \int d\sigma(\Delta R_{ij}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^2} \delta(\Delta R_{ij} - R_L)$$

$$\Delta R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$



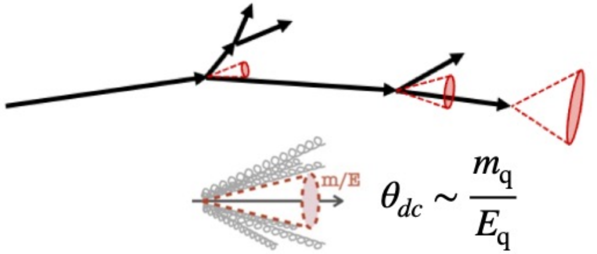


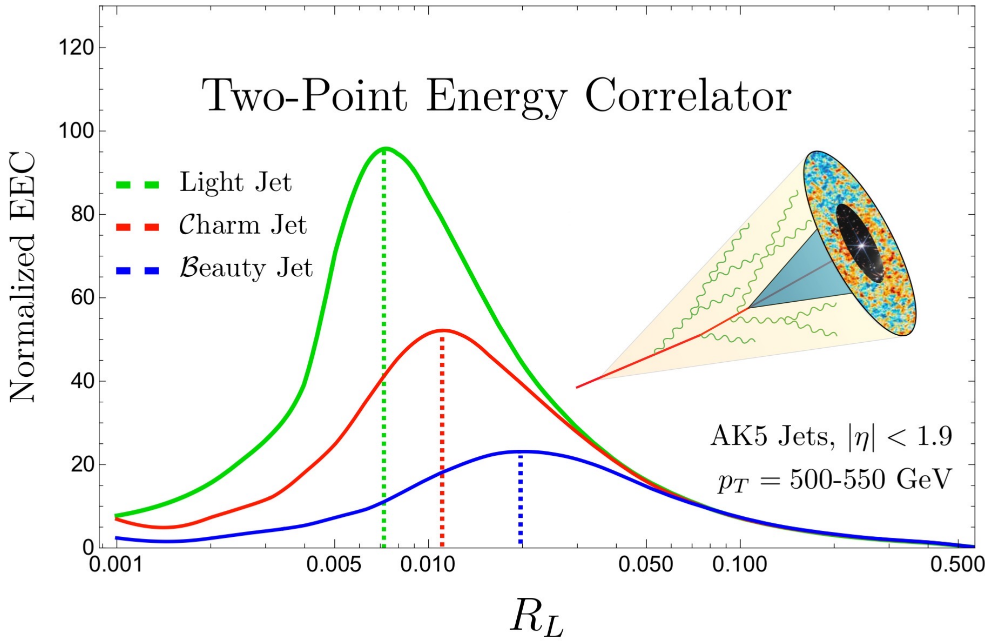


- Jet EEC is sensitive to various intrinsic or emergent scales.
- Jet EEC separates perturbative region from non-perturbative region by the confinement transition scale.
- Medium-modified jet EEC provides unique opportunity to probe jet-medium interaction mechanisms and QGP properties

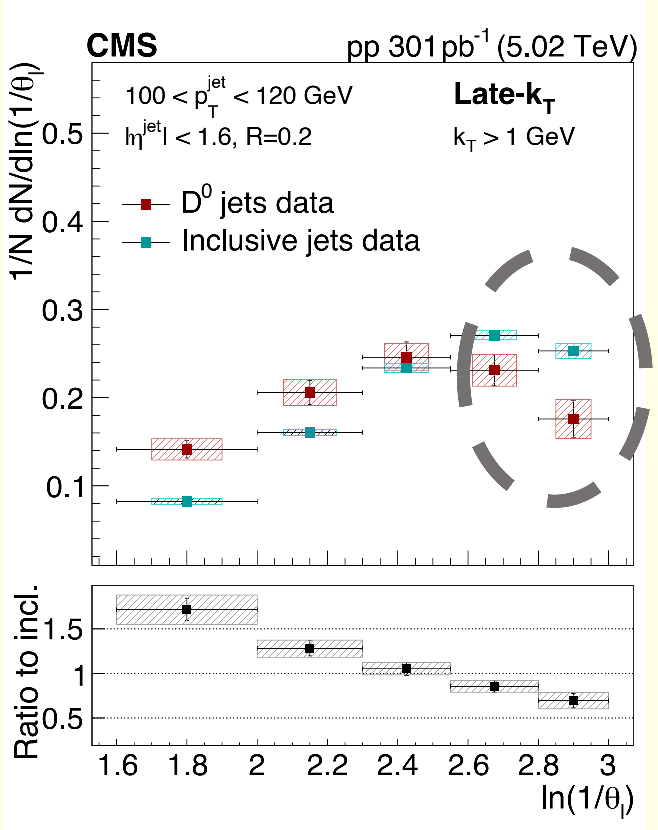
[Komiske, Moult, Thaler, Zhu, *Phys. Rev. Lett.* 130 (2023) 5, 05190; Yang, He, Moult, Wang, *Phys. Rev. Lett.* 132 (2024) 1, 11]

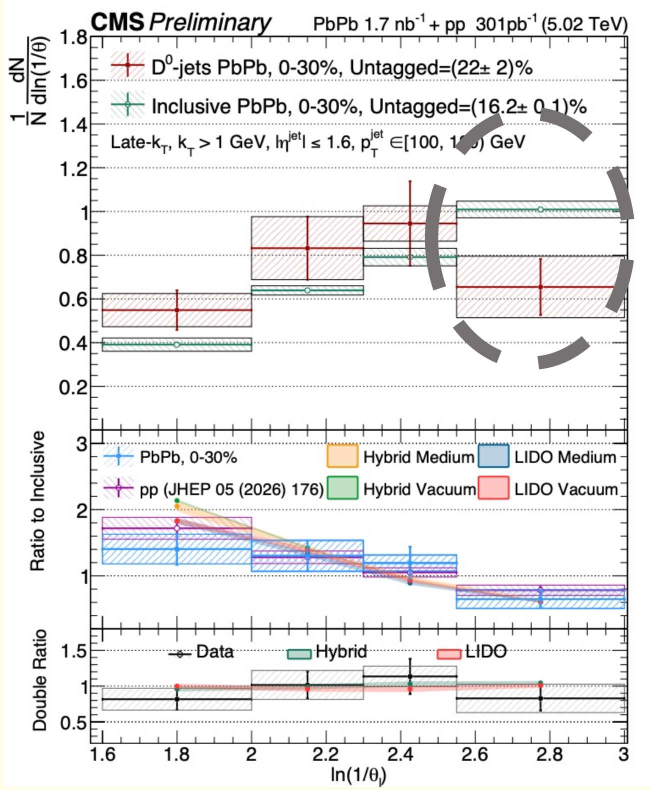
Jet EEC resolves heavy-quark mass





Charm's dead cone in pp and PbPb

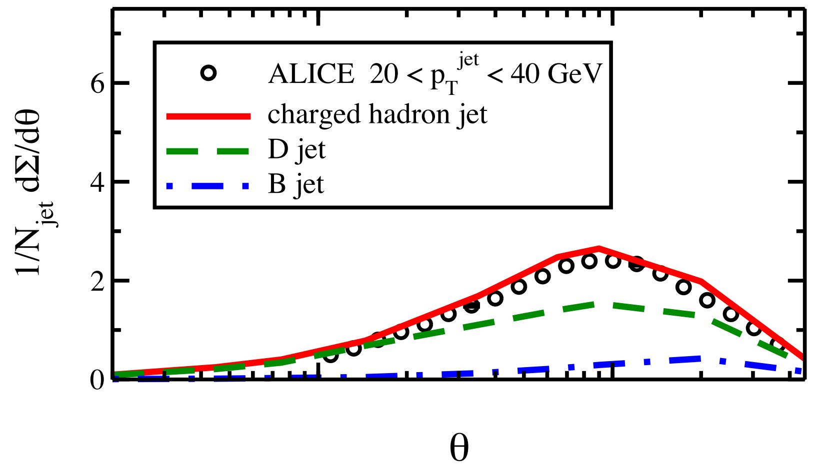




- Jet EEC serve as valuable tools to explore flavor (mass) dependence of parton splitting.
- First analysis of charm-quark's dead-cone in PbPb: medium-induced radiation does not fill the dead-cone.

[Craft, Lee, Mecaj, Moult, arXiv:2210.09311; CMS, JHEP 05 (2026) 176]

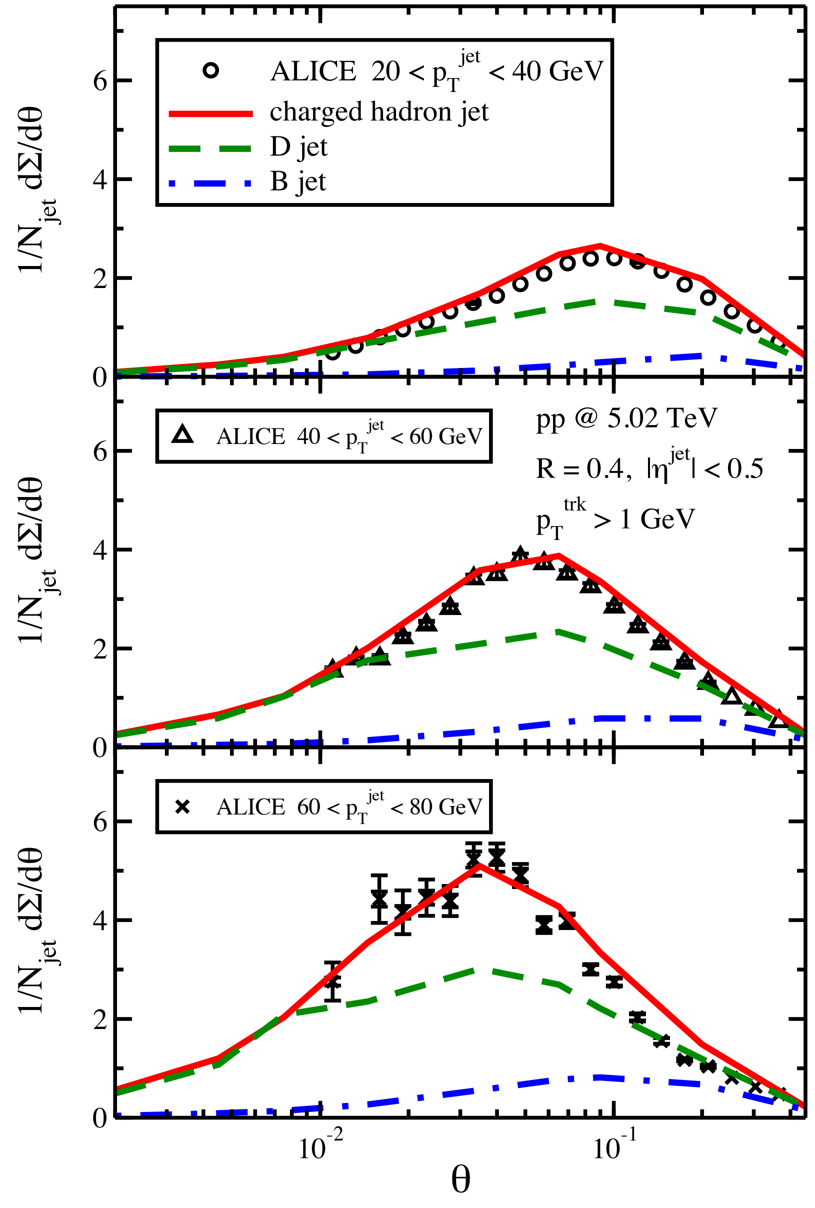
Light *vs.* heavy flavor jet EEC in pp



- **Jet in pp: Pythia 8 simulation**
- **Flavor (mass) dependence:**
  - Σ(charged jet) > Σ(D jet) > Σ(B jet)
  - θ^{peak}(charged jet) < θ^{peak}(D jet) < θ^{peak}(B jet)
- **Transition angle $\theta^{\mathrm{peak}} \sim \Lambda_{\mathrm{QCD}}/p_T^{\mathrm{jet}}(m_{\mathrm{Q}}/p_T^{\mathrm{jet}})$**

【WJX, Cao, Qin, Wang, *Phys.Rev.Lett.* 134 (2025) 5, 052301】

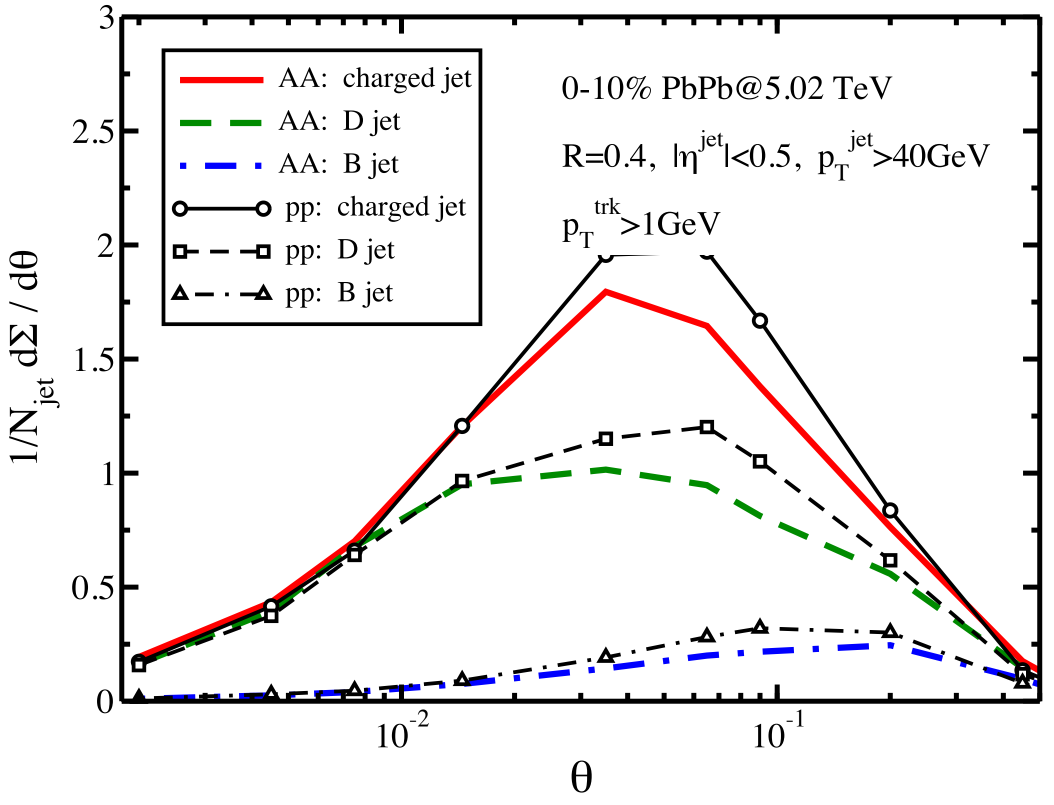
Light *vs.* heavy flavor jet EEC in pp

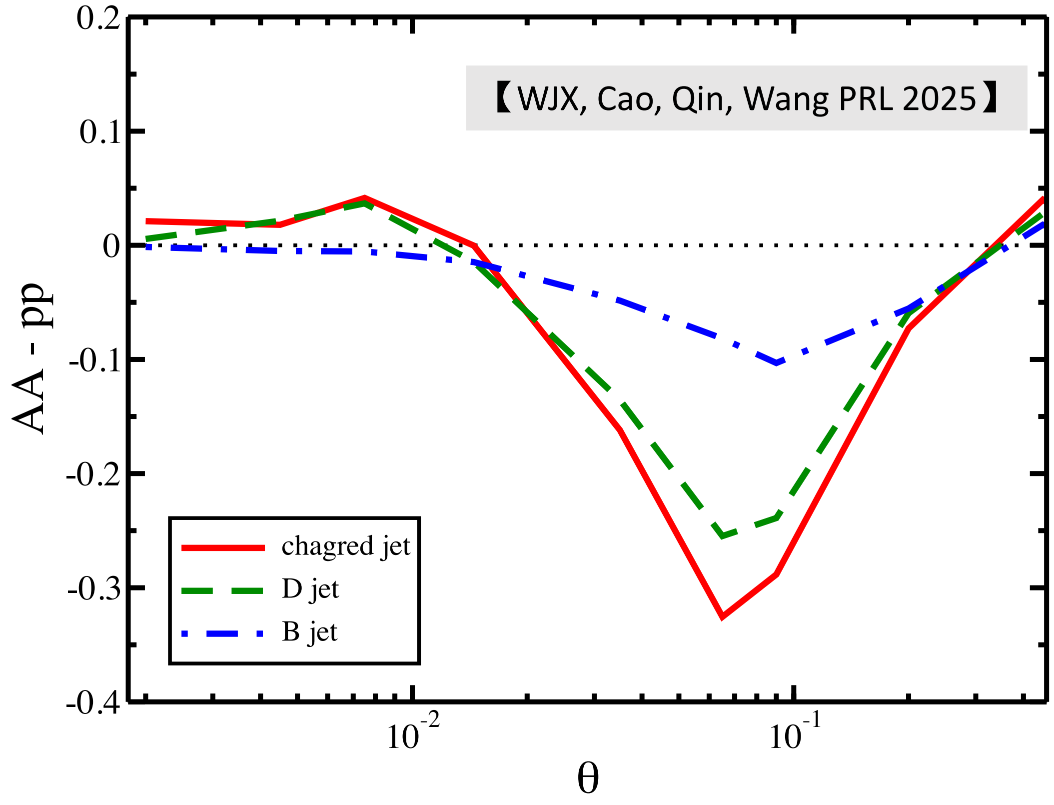


- **Jet in pp: Pythia 8 simulation**
- **Flavor (mass) dependence:**
  - Σ(charged jet) > Σ(D jet) > Σ(B jet)
  - θ^{peak}(charged jet) < θ^{peak}(D jet) < θ^{peak}(B jet)
- **Transition angle $\theta^{\text{peak}} \sim \Lambda_{\text{QCD}}/p_T^{\text{jet}}\,(m_{\text{Q}}/p_T^{\text{jet}})$**
- **Jet energy dependence:**
  - **Higher p_{T} jet peaks at smaller angle.**

【WJX, Cao, Qin, Wang, *Phys.Rev.Lett.* 134 (2025) 5, 052301】

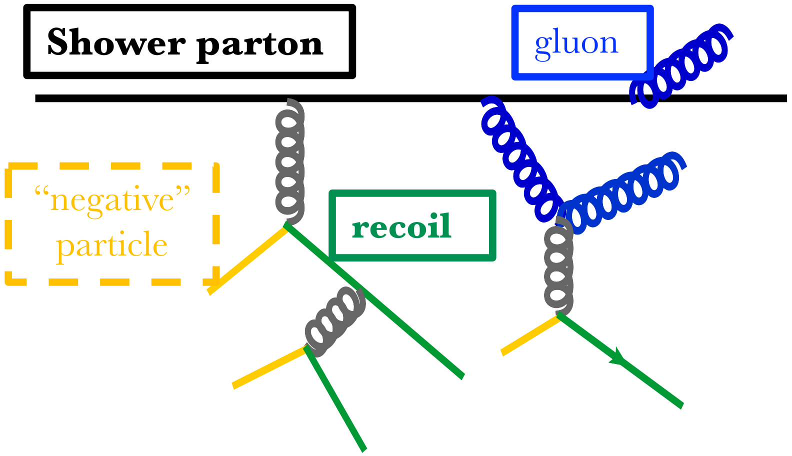
Light *vs.* heavy flavor jet EEC in Pb-Pb





- PYTHIA8 + LBT + CLvisc: jet transport in QGP
- **Flavor hierarchy of jet EEC is preserved in AA.**
- **General feature of nuclear modification (AA-pp): suppression at intermediate θ, enhancement at small θ (except for *B*-jet) and large θ.**

Different contributions to medium modification on EEC

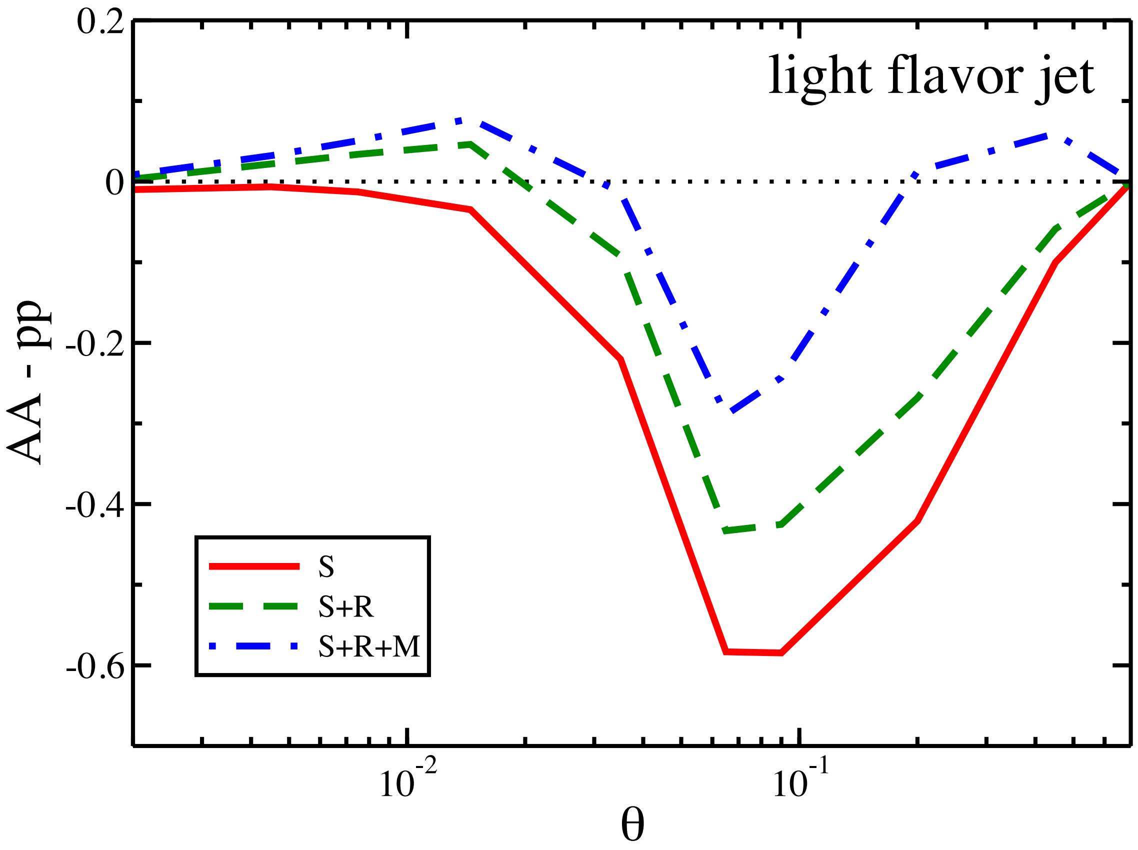


Pythia 8 + LBT in hydro

S: shower partons from Pythia

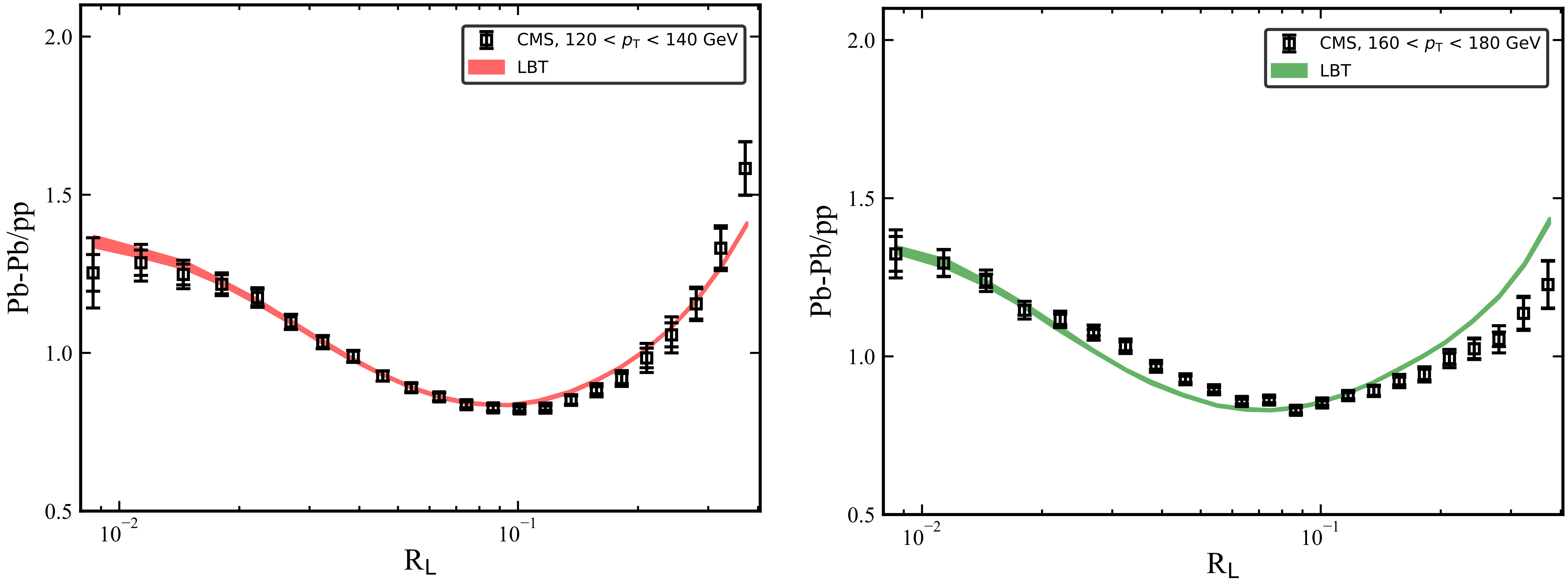
R: medium-induced radiated gluons

M: medium response



- **Jet energy loss causes suppression over entire θ region.**
- **Medium-induced gluon radiation enhances EEC at small θ.**
- **Medium response enhances EEC at large θ.**

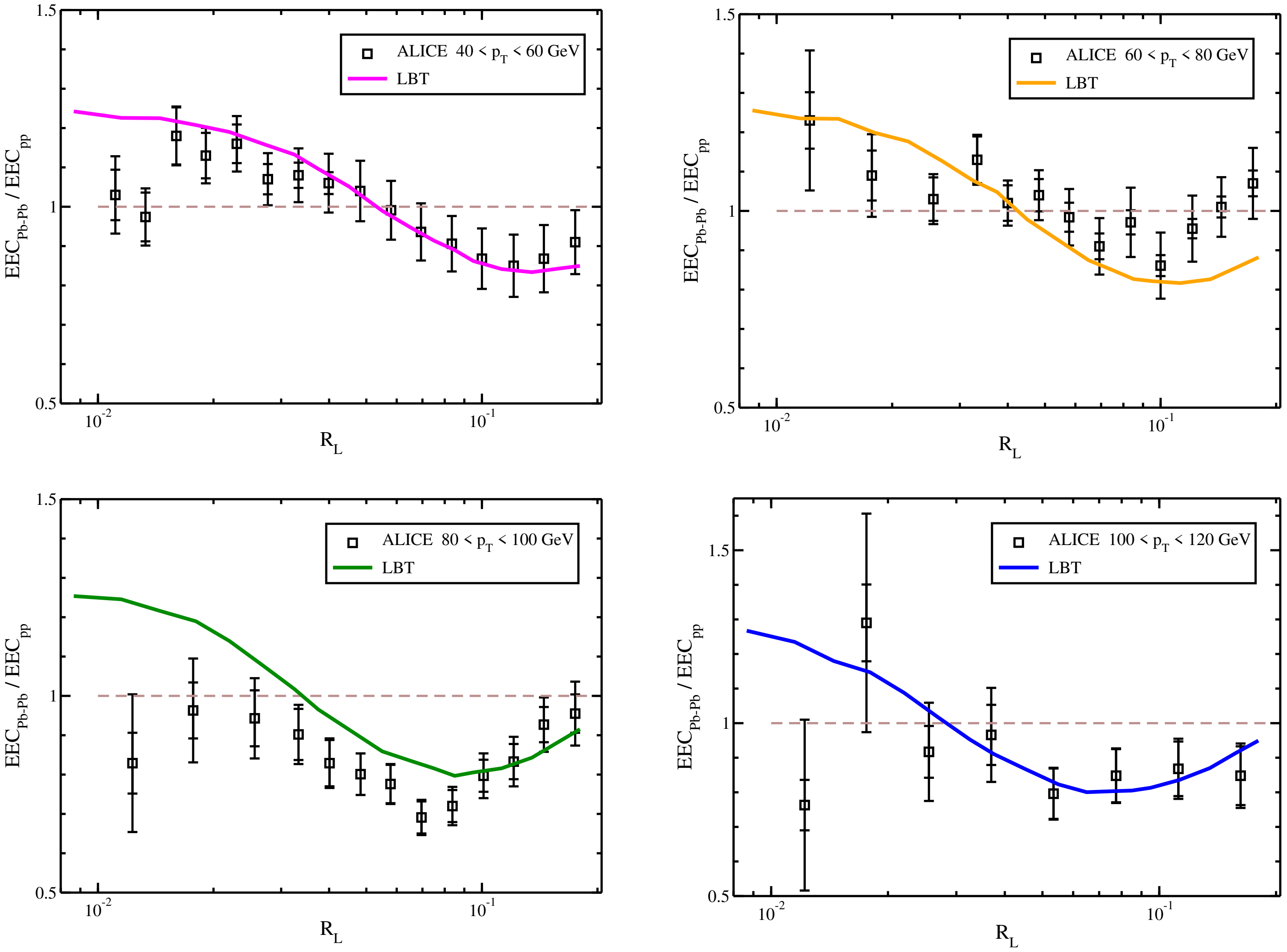
LBT *vs.* CMS data



[Dang, Cao, WJX, Qin, arXiv:2602.10395; WJX, Qin, Cao, in preparation]

- **When adjusting the scale of vacuum shower (in pythia) to Q_M=2GeV, LBT can describe the nuclear modification of jet EEC data measured by CMS.**

LBT *vs.* ALICE data

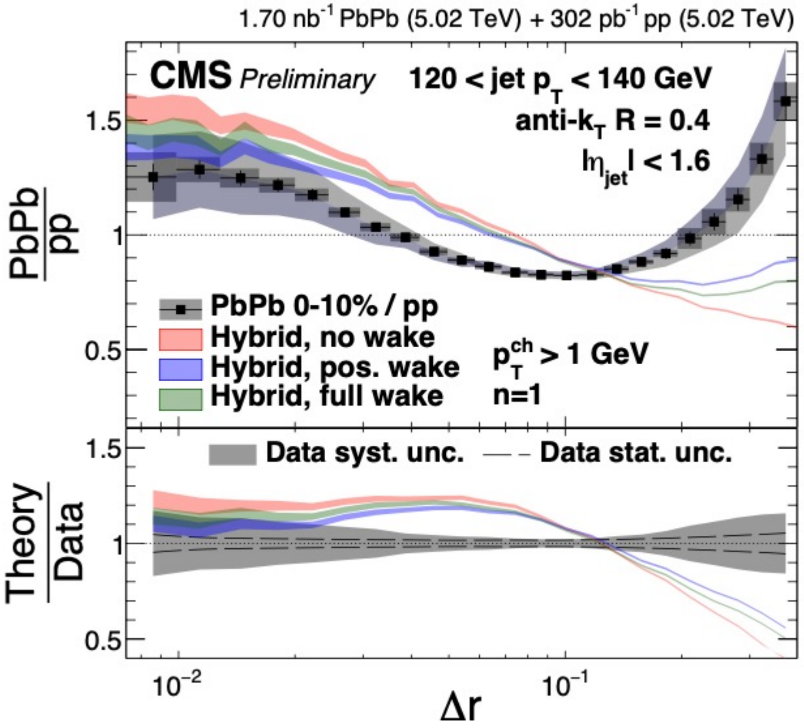


[WJX, Qin, Cao, in preparation]

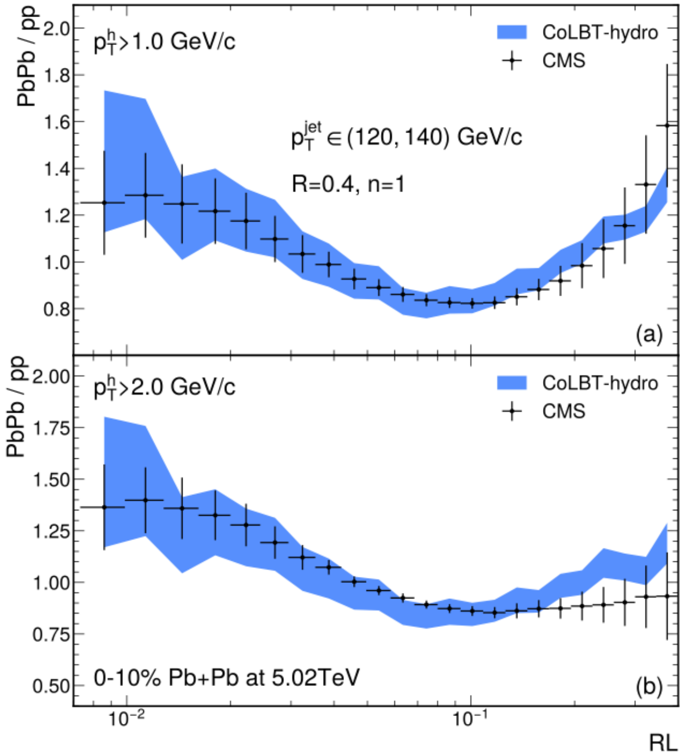
- **LBT can describe the nuclear modification of jet EEC measured by ALICE.**

EEC PbPb/pp ratio : model comparison

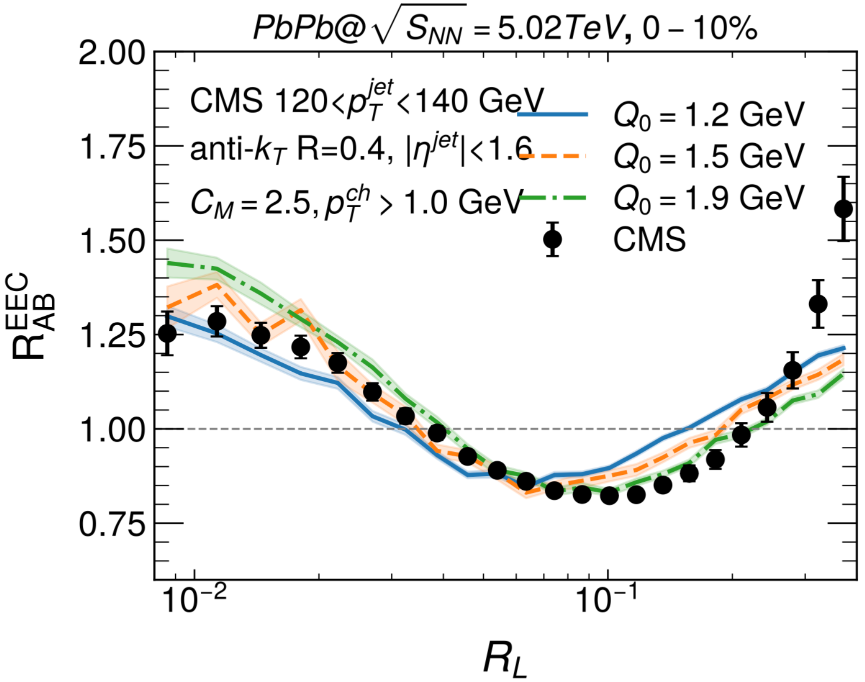
Hybrid model



CoLBT model



LIDO model



- **Hybrid model does not predict enough enhancement at large angle.**
- **CoLBT and LIDO can reproduce the structure of PbPb/pp ratio.**

Genuine jet EEC in vacuum

- **The full EECs inside jets:**

$$\frac{d\langle \mathrm{EEC}(\theta)\rangle_{\mathrm{full}}}{d^2\theta} = \frac{1}{N_{jet}}\sum_{jets\ \mathrm{J}}\sum_{i\neq j\in \mathrm{J}}\frac{E_iE_j}{E_J^2}\delta^{(2)}(\vec{\theta}-(\vec{\theta}_i-\vec{\theta}_j))$$

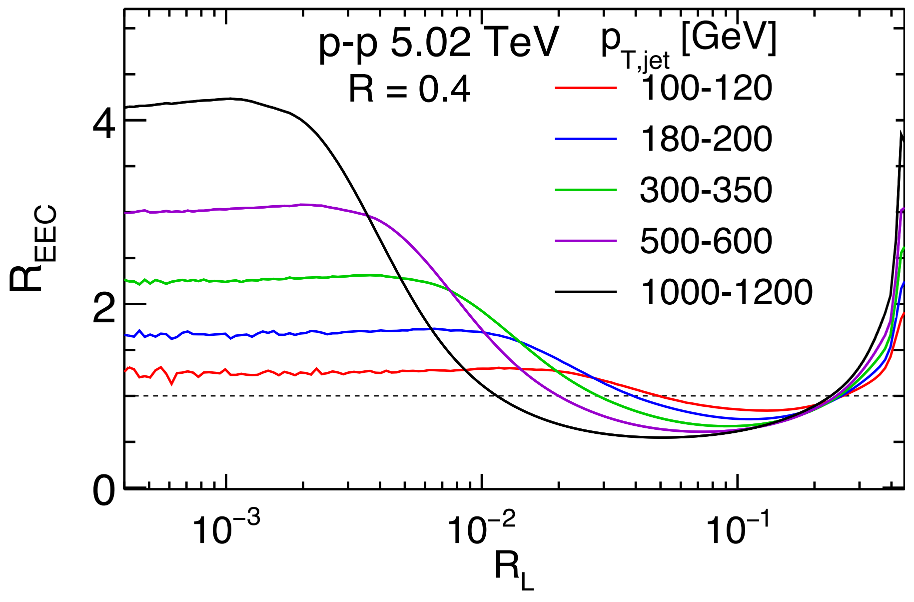
- **Trivial two particle distributions from single particle distributions:**

$$\frac{d}{d^2\theta}\langle \mathrm{EEC}(\theta)\rangle_{\mathrm{trivial}} = N_{\mathrm{trivial}}\int d^2\theta_1 d^2\theta \times \frac{d\langle \mathrm{E}(\theta_1)\rangle}{d^2\theta_1}\frac{d\langle \mathrm{E}(\theta_2)\rangle}{d^2\theta_2}\delta^{(2)}(\vec{\theta}-(\vec{\theta}_1-\vec{\theta}_2))$$

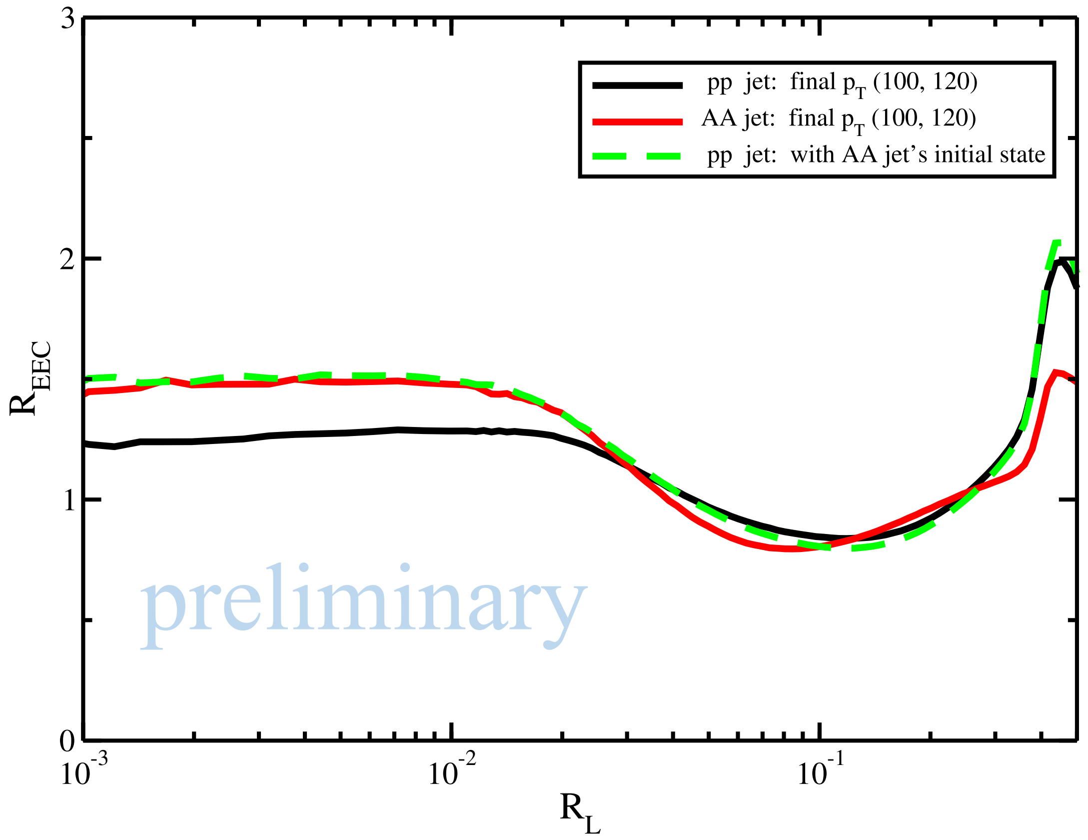
- **Genuine correlation:**

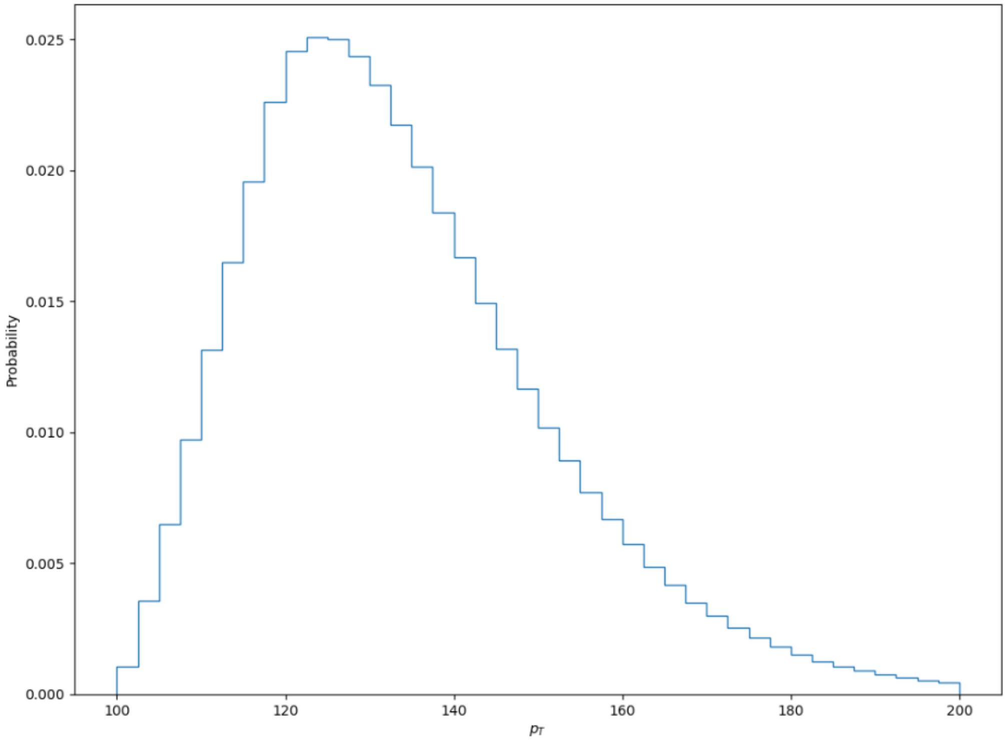
$$\mathcal{R}_{\mathrm{EEC}}(\theta) = \frac{d\langle \mathrm{EEC}(\theta)\rangle_{\mathrm{full}}}{d^2\theta}\Big/\frac{d\langle \mathrm{EEC}(\theta)\rangle_{\mathrm{trivial}}}{d^2\theta}$$

【Zhao, Koch, Yuan, arXiv:2507.18790】



Genuine jet EEC in QGP





- **Small R_L: selected p-p has the same platform as A-A, enabling quantitative extraction of the reduced jet p_T.**

- **Moderate and large R_L : selected p-p is the same as p-p.**

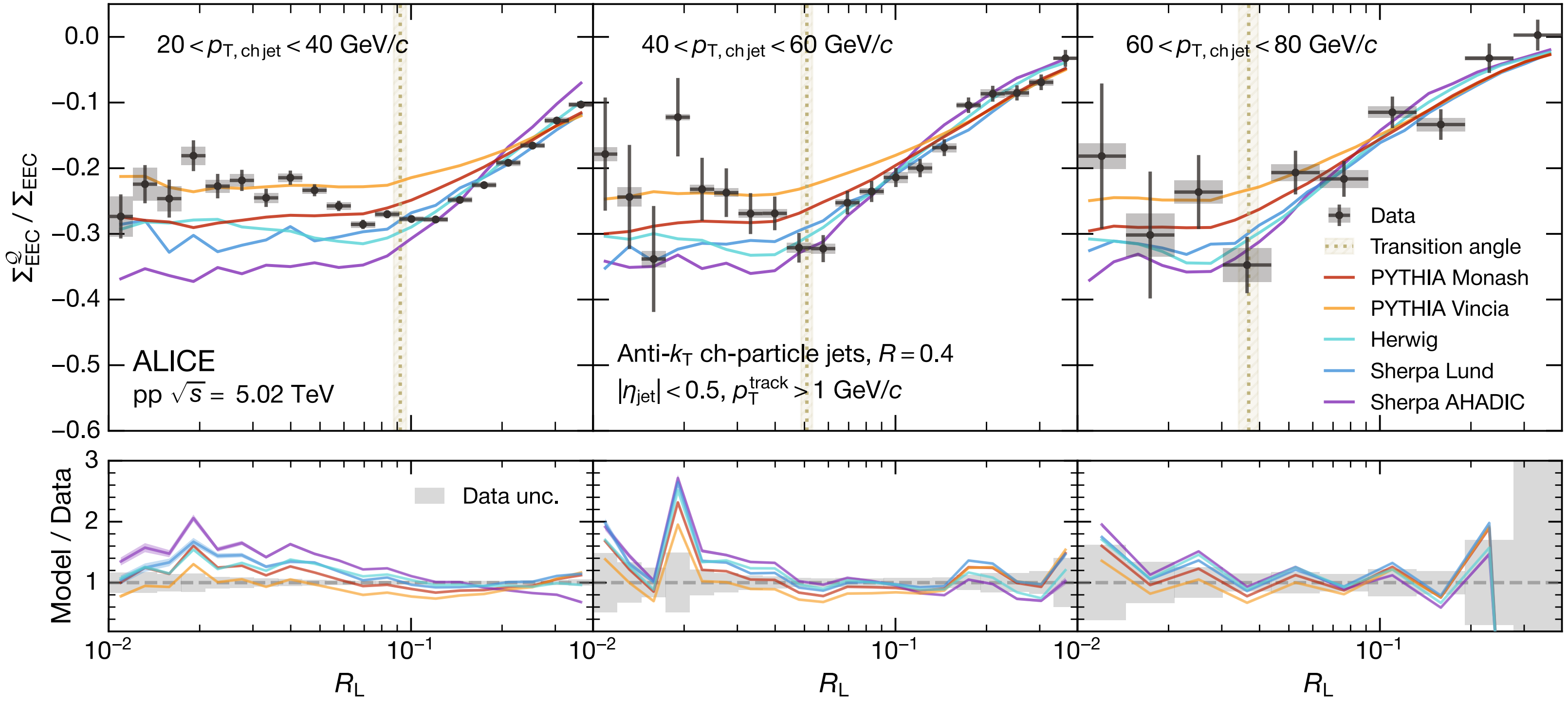
Charged jet EEC

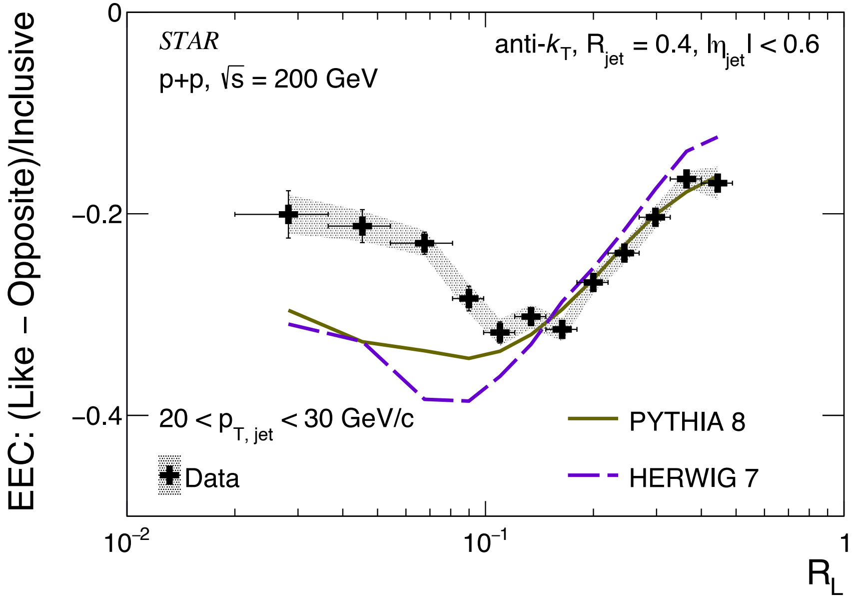
New @ HP2026

- **Charged EEC asymmetry:** $$\frac{\Sigma^{Q}_{\mathrm{EEC}}}{\Sigma_{\mathrm{EEC}}} = \frac{\Sigma^{++}_{\mathrm{EEC}} + \Sigma^{--}_{\mathrm{EEC}} - \Sigma^{+-}_{\mathrm{EEC}}}{\Sigma_{\mathrm{EEC}}}$$

[ALICE: arXiv:2606.18093]

[STAR: *Phys. Rev. Lett.* 135 (2025) 11, 111901]





- **Charged EECs effectively differentiate parton shower modeling and hadronization schemes.**

Summary

- Substantial suppression reported by CMS ($h^{\pm}$) and ALICE (π^0) provides strong evidence for parton energy loss in OO collisions.

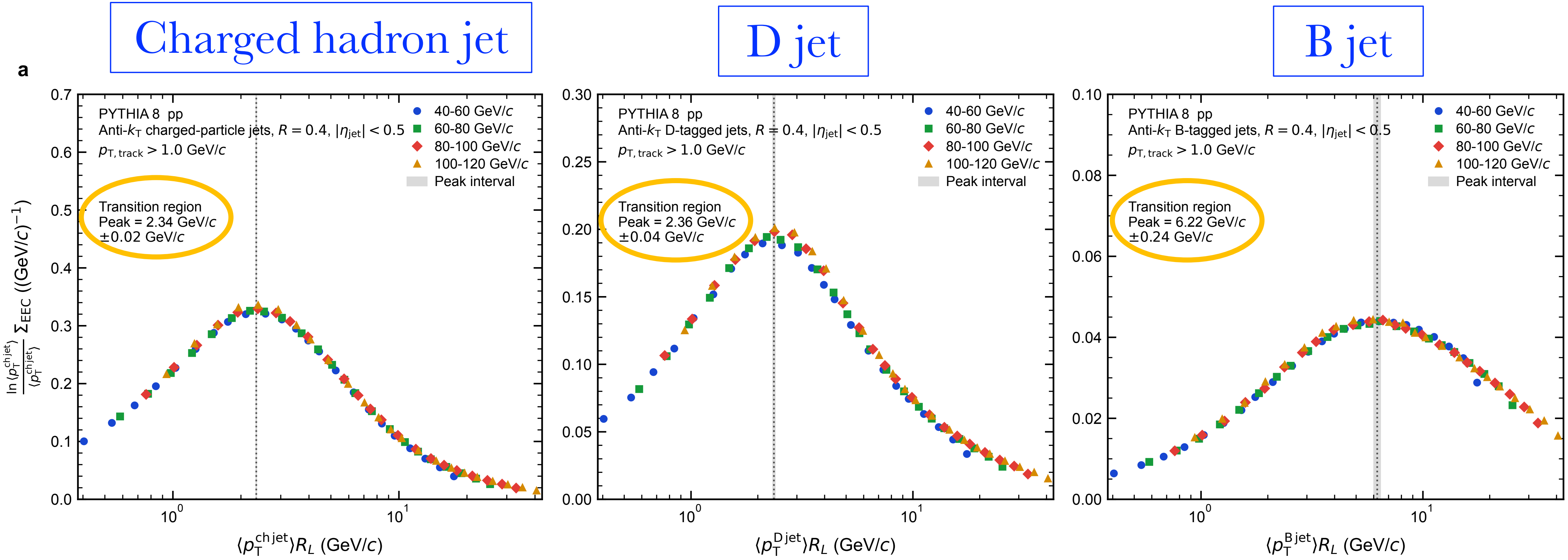
- Jet EEC provides a multi-scale tool to probe jet evolution and mechanisms in jet-medium interaction.

- Nuclear modification of jet EEC exhibits rich structure: suppression at intermediate angles, and enhancement at small and large angles, which can be explained by the interplay of mass effect, energy loss, medium-induced radiation and medium response.

- Genuine jet EEC has the capability to extract initial jet energy in AA collisions.

Thank You !

Light *vs.* heavy flavor jet EEC in pp



LBT model – elastic and inelastic scatterings

- **Boltzmann equation:**

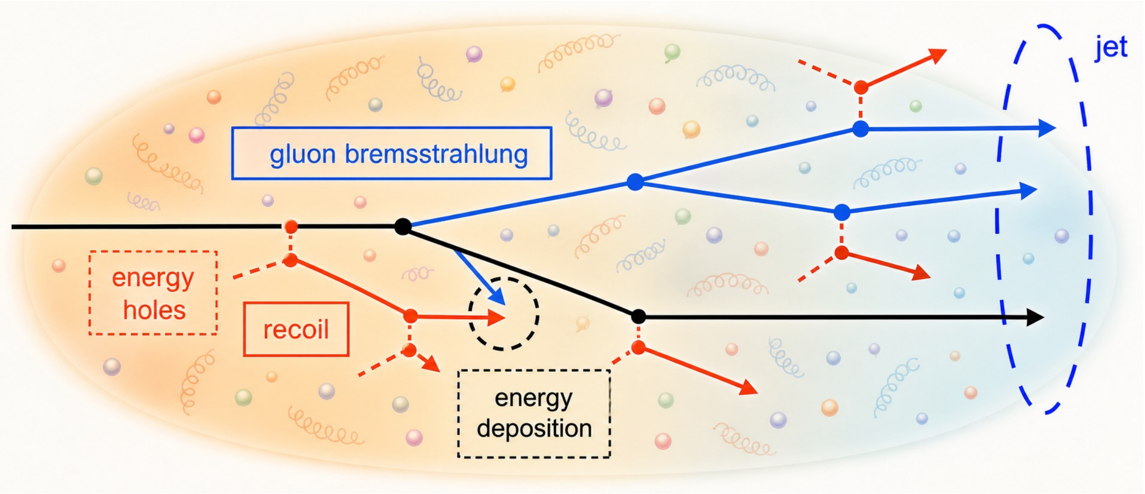
$$p_a \cdot \partial f_a = E_a \left[C^{\mathrm{el}}(f_a) + C^{\mathrm{inel}}(f_a)\right]$$

- **Elastic collisions:**

$$\Gamma_a^{\mathrm{el}}(E_a, T) = \sum_{b,(cd)} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} \frac{d^3 p_i}{E_i (2\pi)^3} f_b(E_b, T)$$
$$\times [1 \pm f_c(E_c, T)][1 \pm f_d(E_d, T)] S_2(\hat{s}, \hat{t}, \hat{u})$$
$$\times (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) |\mathcal{M}_{ab\to cd}|^2$$

- **Inelastic collisions:**

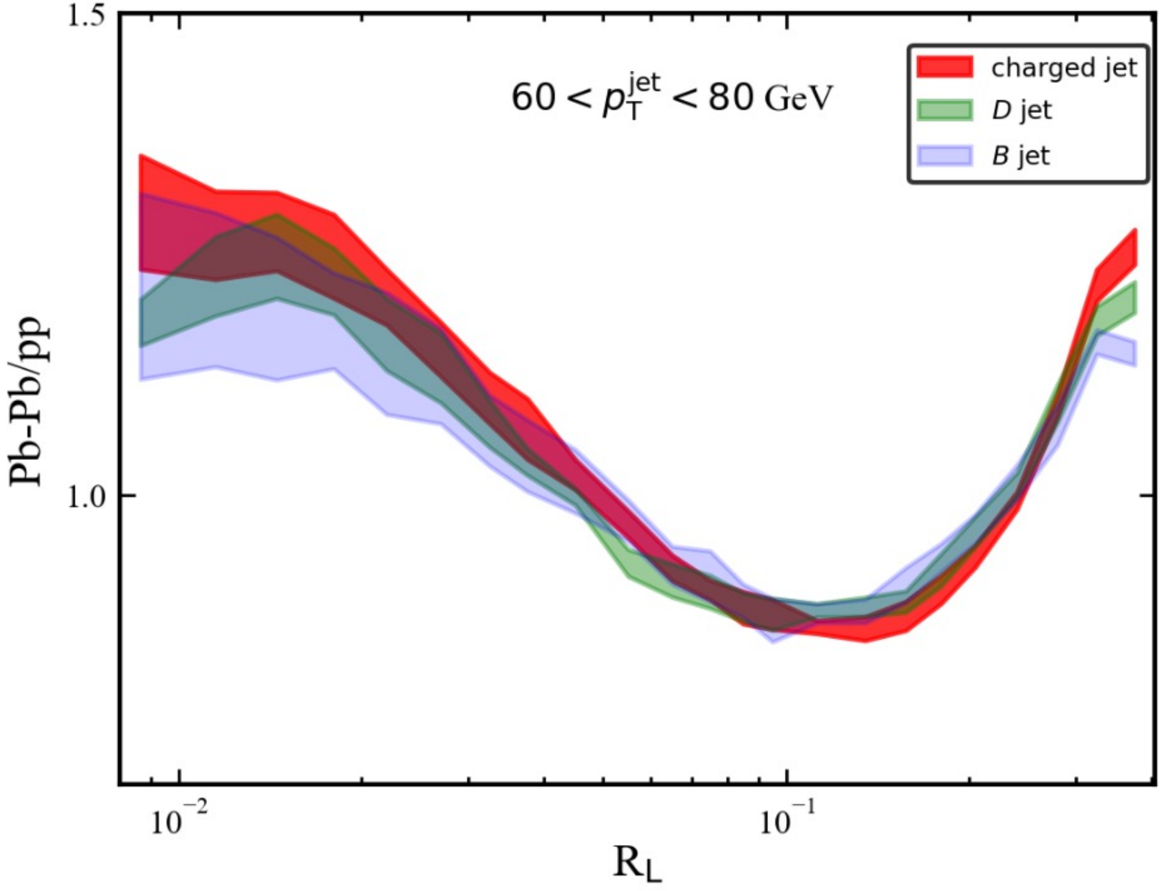
$$\Gamma_a^{\mathrm{inel}}(E_a, T, t) = \int dz dk_\perp^2 \frac{1}{1 + \delta^{ag}} \frac{dN_g^a}{dz dk_\perp^2 dt}$$

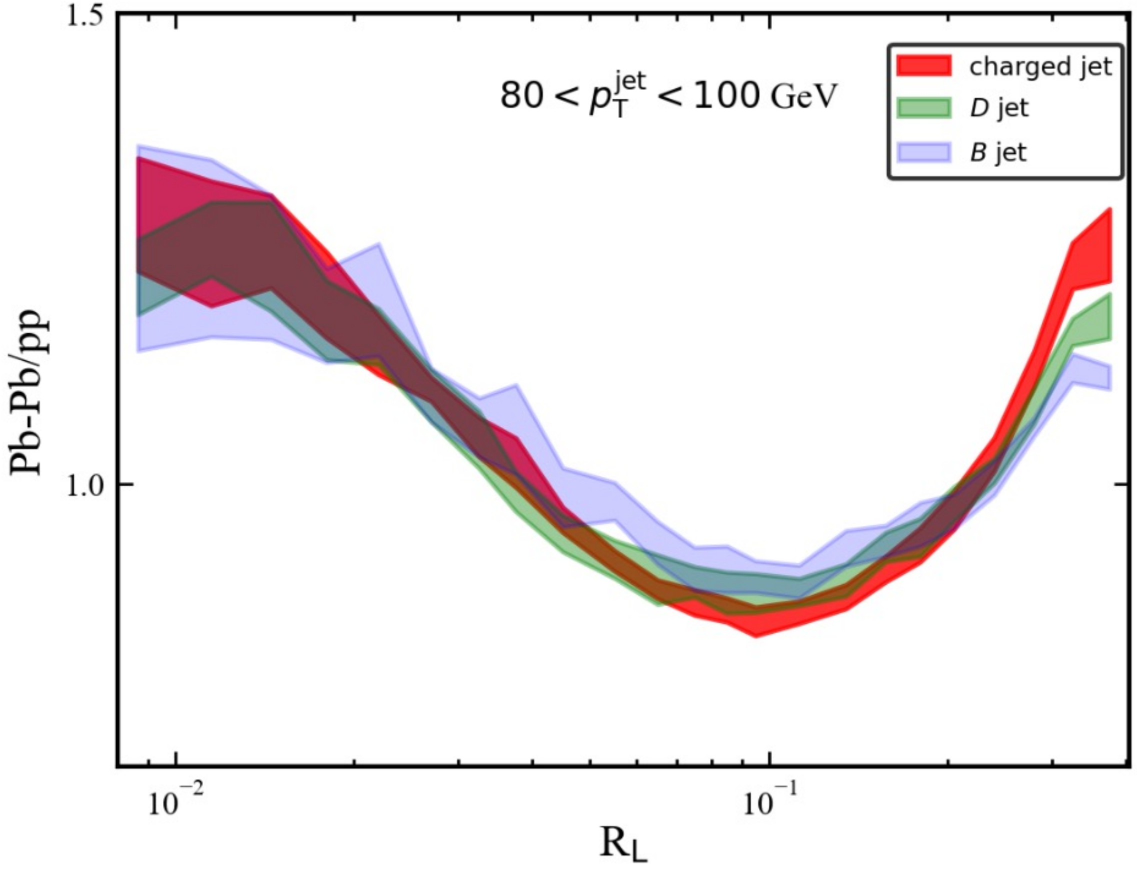


- **Thermal recoil + energy depletion → jet-induced medium response.**

[Wang, Zhu, *Phys. Rev. Lett.* 111 (2013) 6, 062301; He, Luo, Wang, Zhu, *Phys. Rev. C* 91 (2015) 054908; Cao, Luo, Qin, Wang, *Phys. Rev. C* 94 (2016) 1, 014909]

EEC PbPb/pp ratio from LBT model





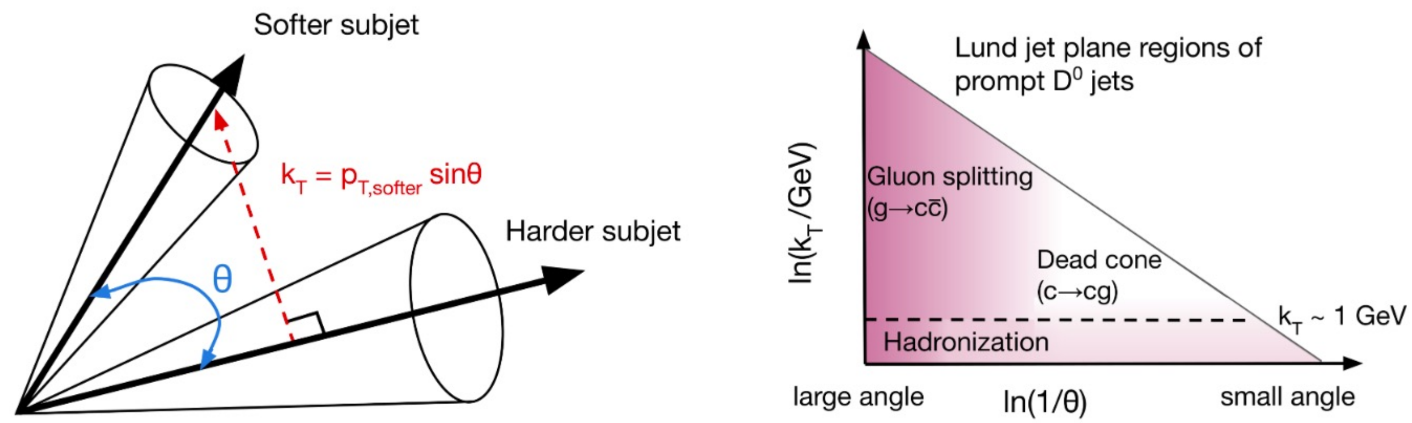


Figure 1. Schematic diagram of two subjets, with their splitting angle θ and the relative transverse momentum k_{T} of the softer subjet with respect to the harder subjet (left). Different Lund jet plane regions for charm quark jet showers (right), where the vertical axis is the logarithm of the relative momentum k_{T} of the emission and horizontal axis is the logarithm of the inverse of the angle between the emission and the emitter θ. The shading represents the density of emissions in the primary Lund jet plane for c quark jets.