首届喷注与重夸克物理研讨会

Flavor effects on jet quenching

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Flavor(mass) effects in jet shower

g-initiated jet

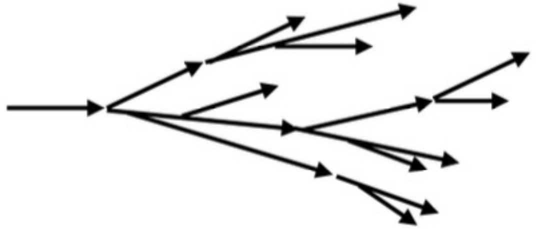
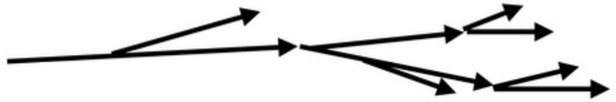


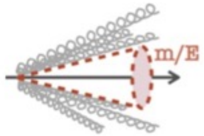
Illustration by P. Dhankher

q-initiated jet



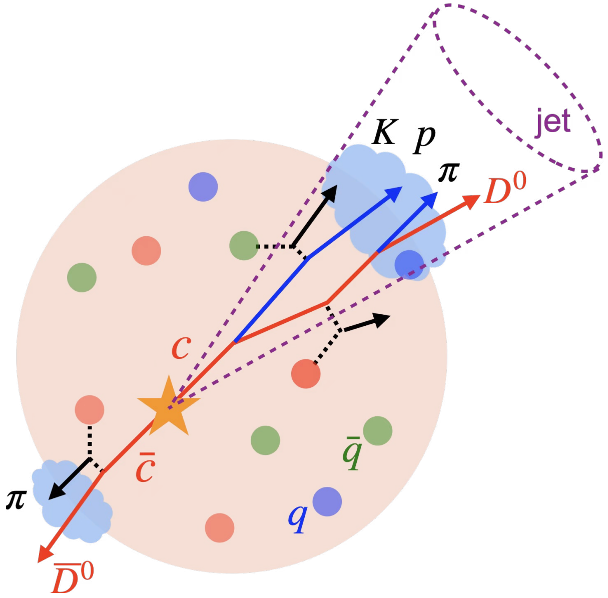
$$\frac{C_A}{C_F} = \frac{9}{4}$$

heavy-q-initiated jet

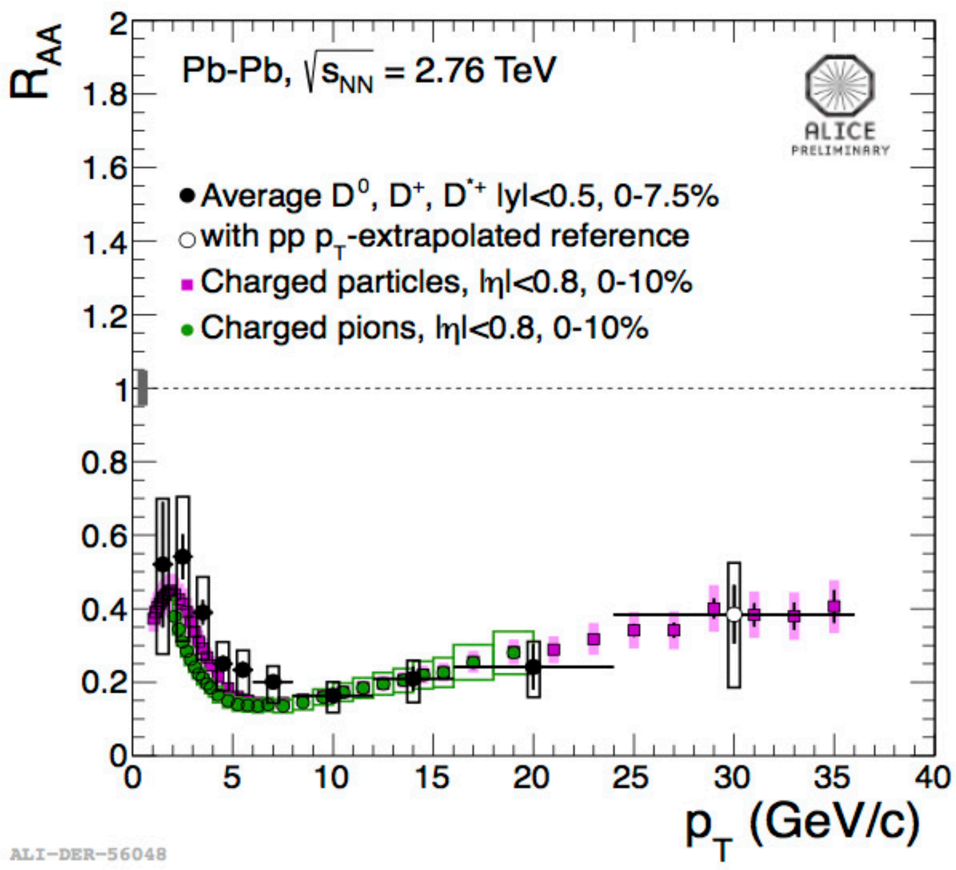


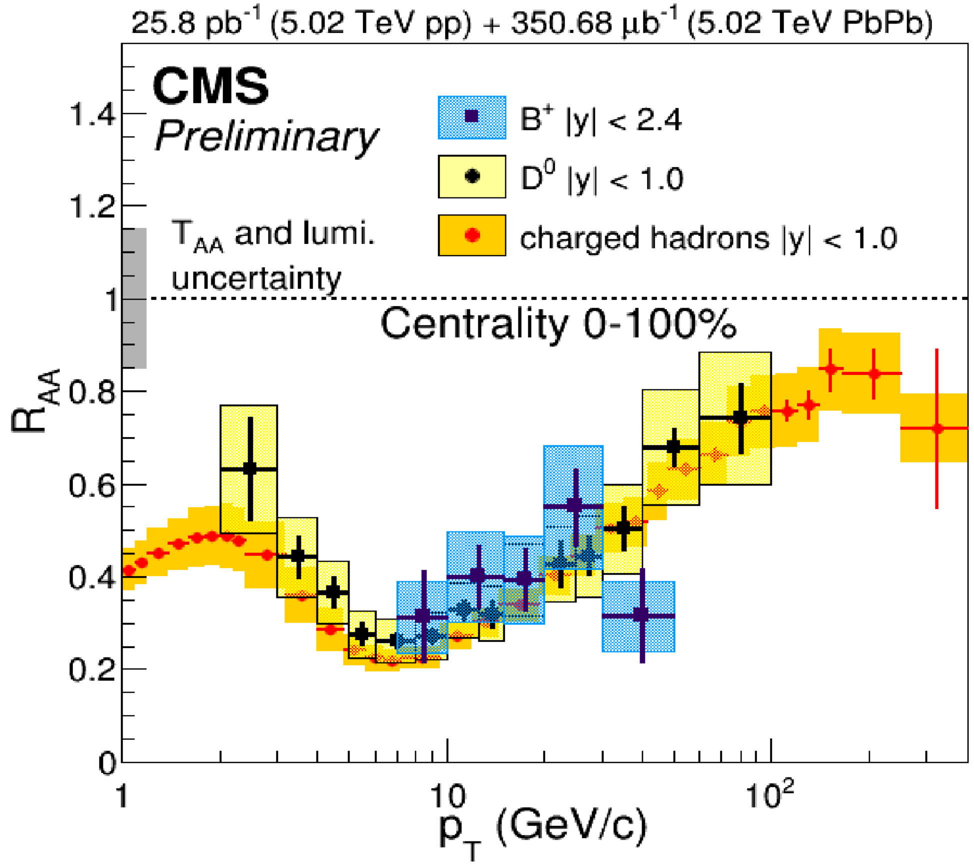
$$\theta_{dc} \sim \frac{m_q}{E_q}$$

- **Casimir-color factors: g-initiated showers have a broader and softer fragmentation profile than q-initiated showers.**
- **Mass (Dead-cone) effect: gluon emissions from massive quark are suppressed within a cone of $\theta_0 \sim m_Q/E$.**
- **Heavy-quark-tagged jets serve as key tools for studying the flavor dependence of parton splitting.**



Flavor hierarchy in single hadron R_{AA}



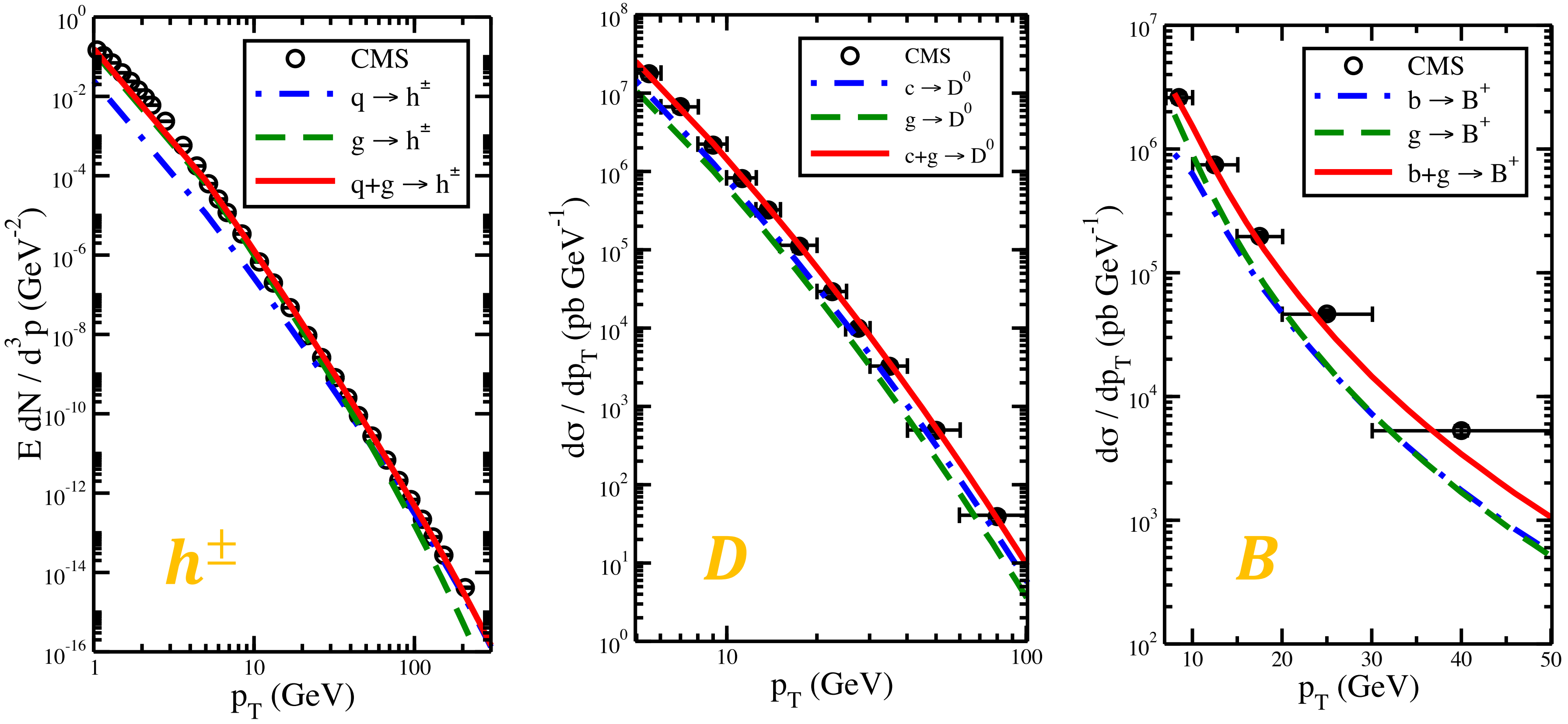


- **How to explain the observation of similar R_{AA} for D and $h^{\pm}$ at high p_T ?**
- **Constrain the flavor (mass) dependence of (leading-)parton energy loss.**

High-p_T hadron production in pp @NLO

$$d\sigma_{pp\to hX} = \sum_{abc} f_a \otimes f_b \otimes d\hat{\sigma}_{ab\to c} D_{h/c}$$

【WJX, Cao, Qin, Xing, PLB 2020】



- **Essential contribution from gluon fragmentation to hadron production.**
  - **dominates $h^{\pm}$ production up to 50 GeV.**
  - **Contributes to over 40% $D(B)$ up to 100 GeV.**

LBT model – elastic and inelastic scatterings

- **Boltzmann equation:**

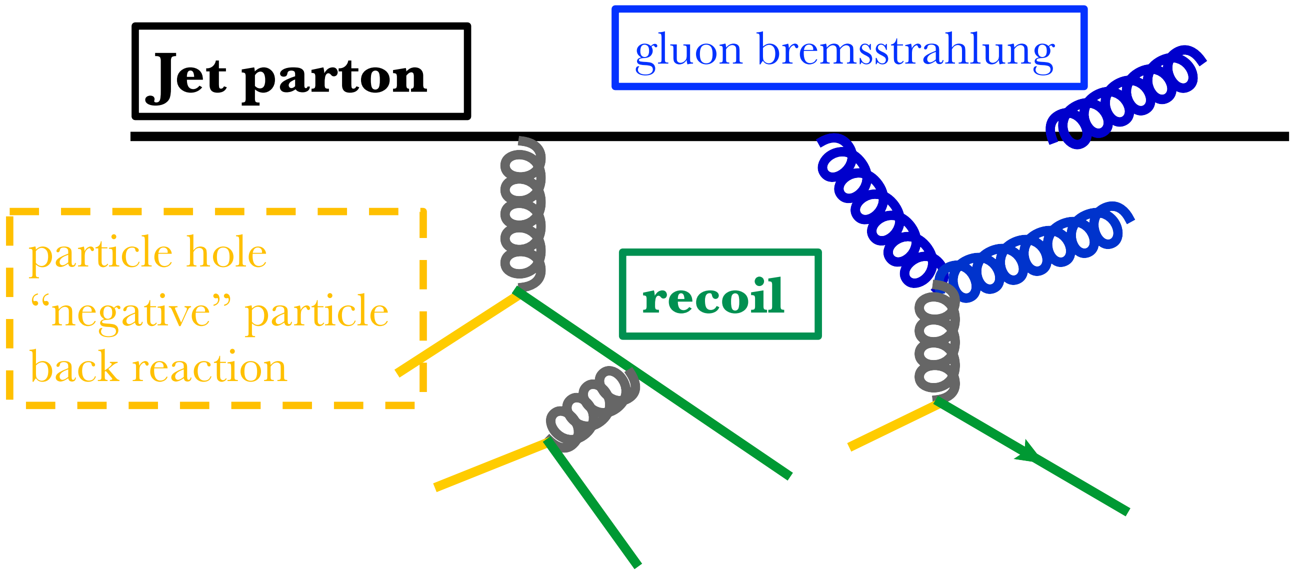
$$p_a \cdot \partial f_a = E_a \left[C^{\rm el}(f_a) + C^{\rm inel}(f_a)\right]$$

- **Elastic collisions:**

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

- **Inelastic collisions:**

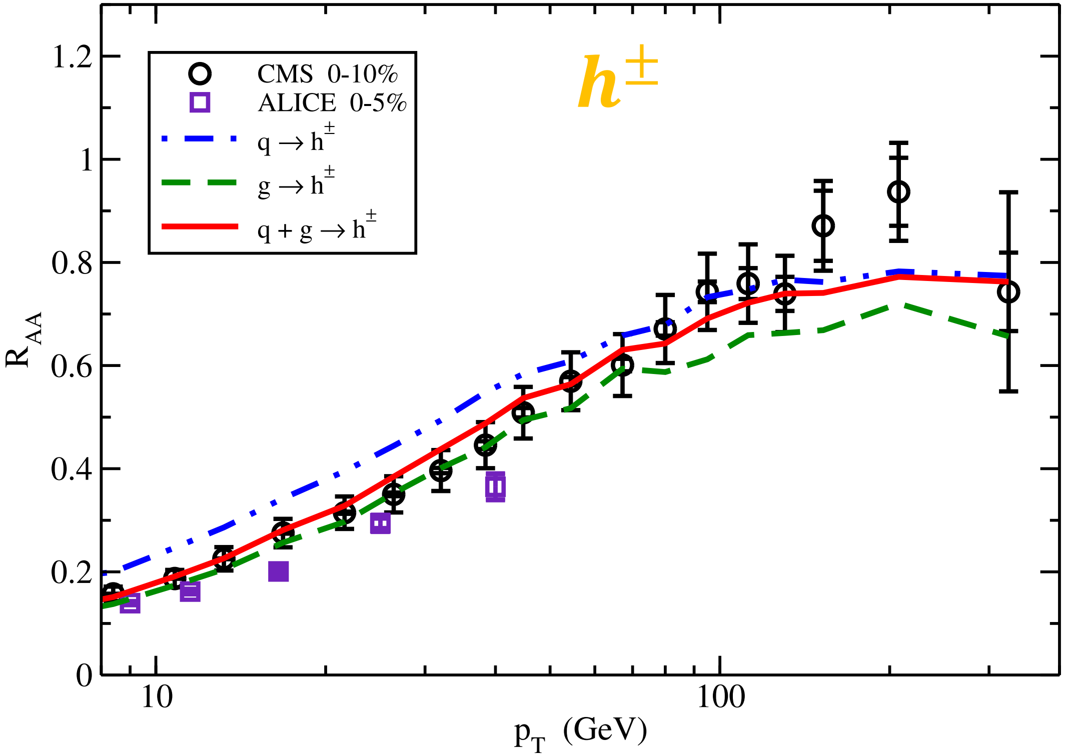
$$\Gamma_a^{\rm inel}(E_a, T, t) = \int dz dk_\perp^2 \frac{1}{1+\delta^{ag}} \frac{dN_g^a}{dz dk_\perp^2 dt}$$

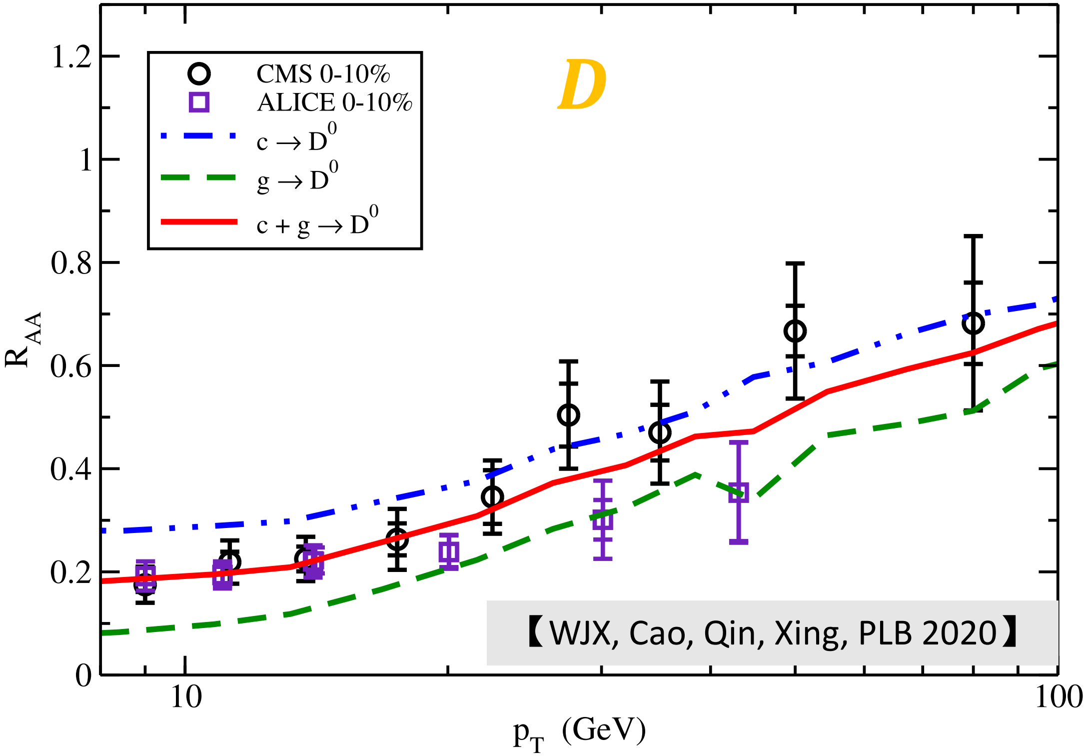


- **Describe jet partons, radiated gluons, recoil partons and "negative" partons within the same transport framework.**

High-p_T hadron suppression in central Pb-Pb collision

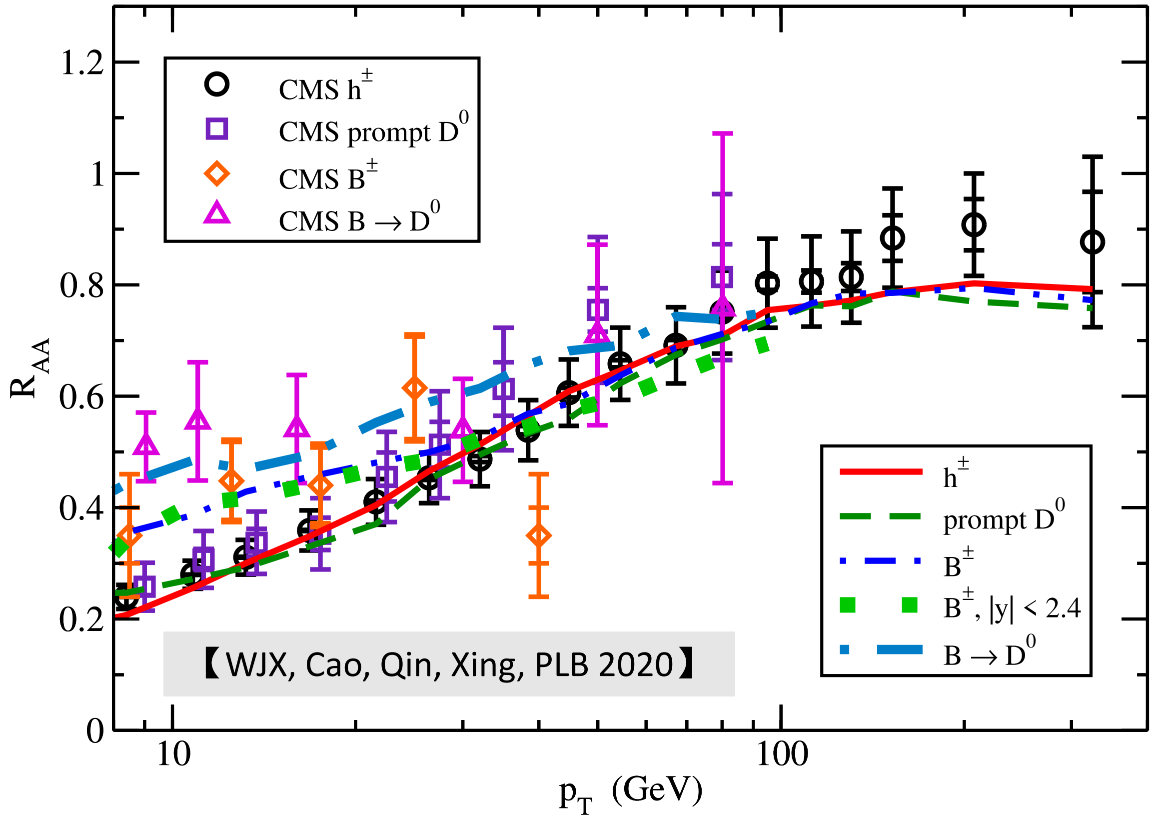
- A state-of-art jet quenching framework (NLO-pQCD + LBT + Hydrodynamics)





- **g-initiated hadron R_{AA} < q-initiated hadron R_{AA} [$\Delta E_g > \Delta E_{q/c}$].**
- $R_{AA}(c \to D) > R_{AA}(q \to h^{\pm})$ [$\Delta E_q > \Delta E_c$], $R_{AA}(g \to D) < R_{AA}(g \to h^{\pm})$ [different FFs],
  $\Rightarrow R_{AA}(D) \approx R_{AA}(h^{\pm})$.

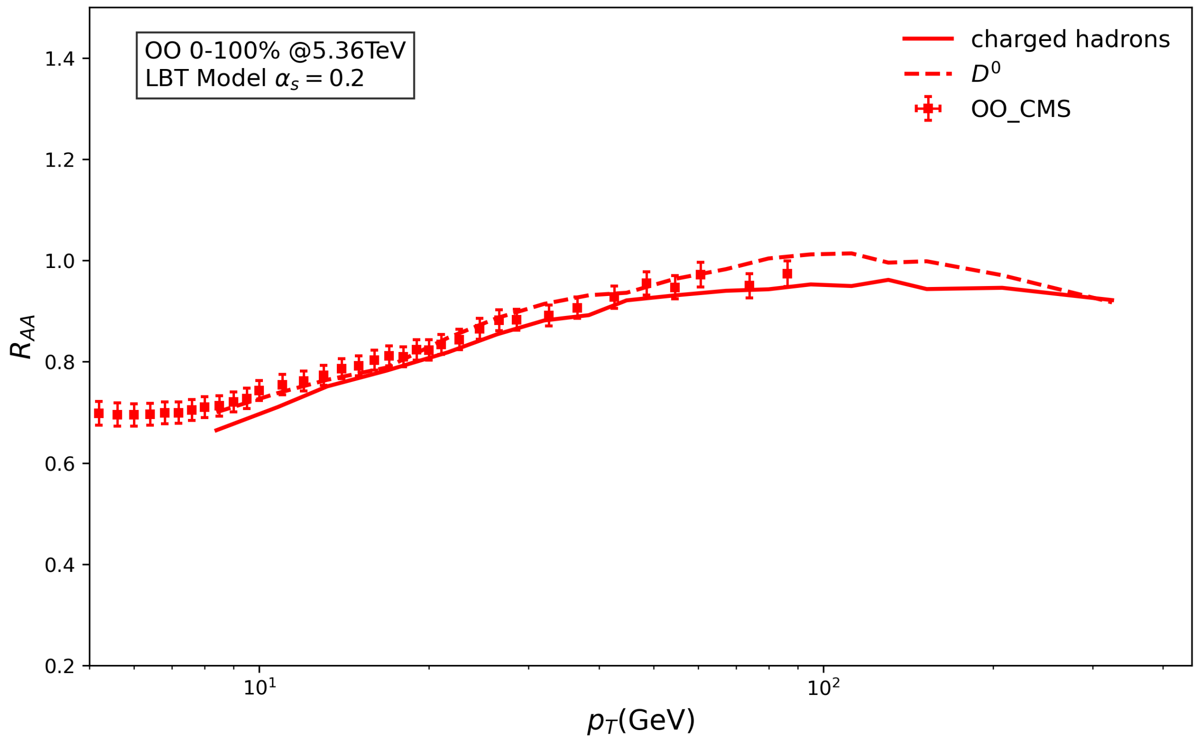
High-p_T hadron suppression in Pb-Pb collision

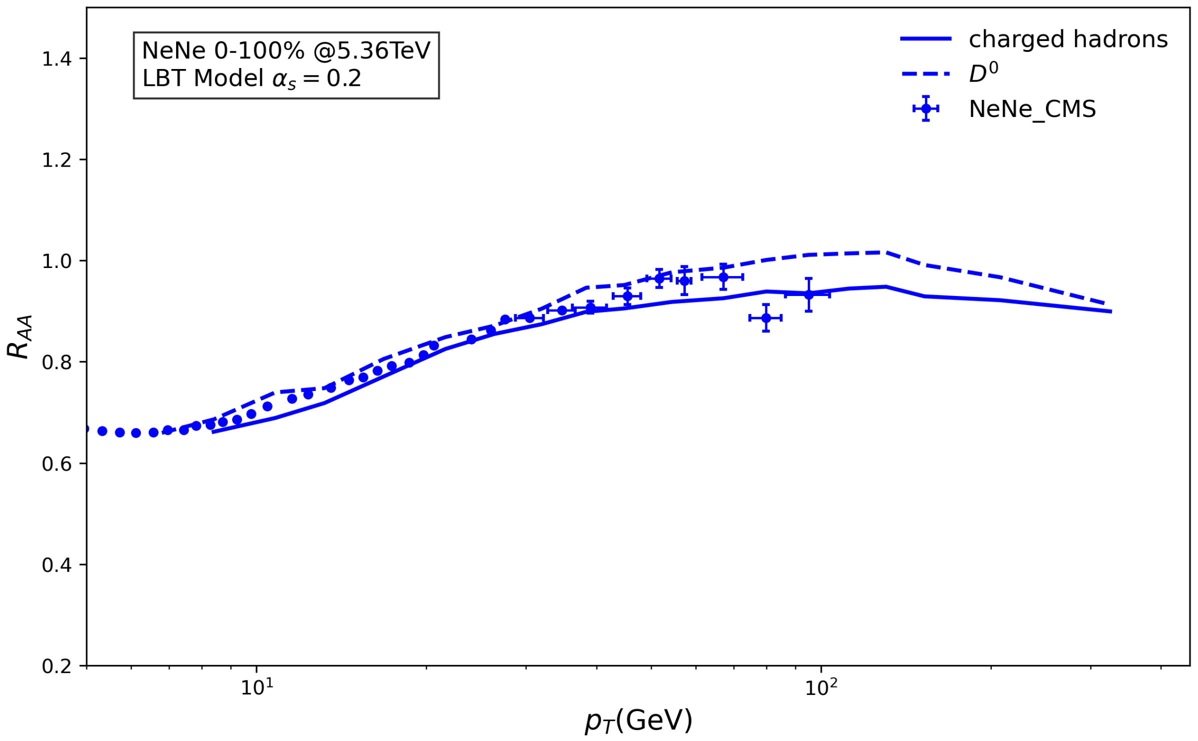


- **A simultaneous description of charged hadrons, *D* mesons, *B* mesons and *B*-decayed *D* mesons R_{AA}'s for $p_T > 8$ GeV.**

- **Predict similar R_{AA} for *B* mesons compared to charged hadrons and D mesons at $p_T >$ 30-40 GeV.**

High-p_T hadron suppression in O-O and Ne-Ne





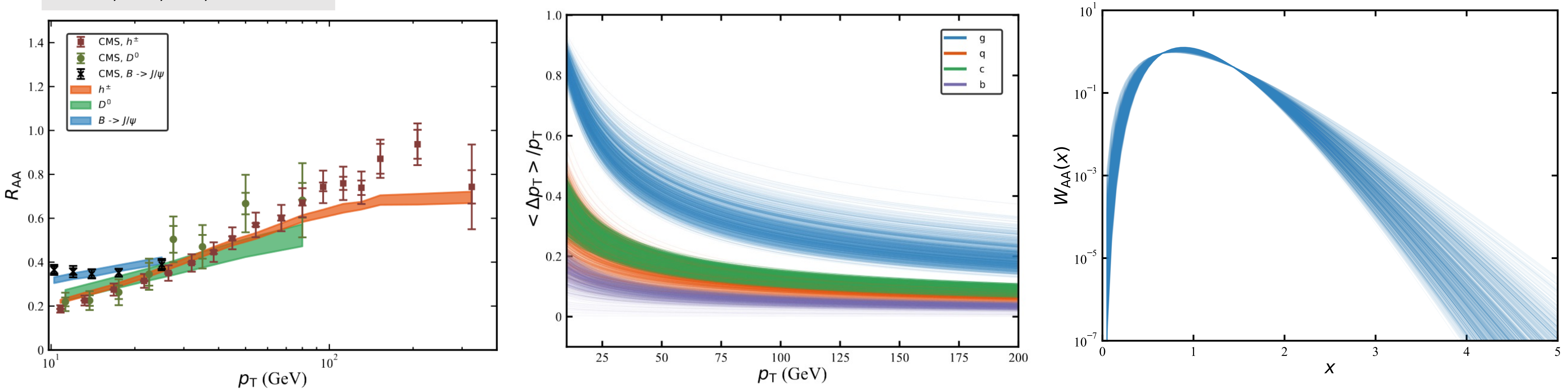
- **LBT model can reproduce the nuclear suppression of high-p_T charged hadrons in light-ion collisions.**

Parton energy loss from Bayesian analysis

$$\frac{1}{\langle N_{\rm coll}\rangle}\frac{d\sigma_{AA\to hX}}{dp_{\rm T}^h}=\sum_j\int dp_{\rm T}^j dx dz \frac{d\hat{\sigma}_{p'p'\to jX}}{dp_{\rm T}^j}(p_{\rm T}^j)W_{\rm AA}(x)D_{j\to h}(z)\delta(p_{\rm T}^h-z(p_{\rm T}^j-x\langle\Delta p_{\rm T}^j\rangle))$$

$$\langle\Delta p_{\rm T}^j\rangle = C_j\beta_g p_{\rm T}^{\gamma}\log(p_{\rm T}), \qquad W_{\rm AA}(x)=\frac{\alpha^\alpha x^{\alpha-1}e^{-\alpha}}{\Gamma(\alpha)}$$

【WJX, Cao, Qin, PLB 2024】



- $\langle\Delta \boldsymbol{E_g}\rangle > \langle\Delta \boldsymbol{E_q}\rangle \sim \langle\Delta \boldsymbol{E_c}\rangle > \langle\Delta \boldsymbol{E_b}\rangle$.
- **Direct extraction of flavor dependence of parton energy loss in QGP from data.**
- **Provides a stringent test of pQCD calculation in parton-medium interaction.**

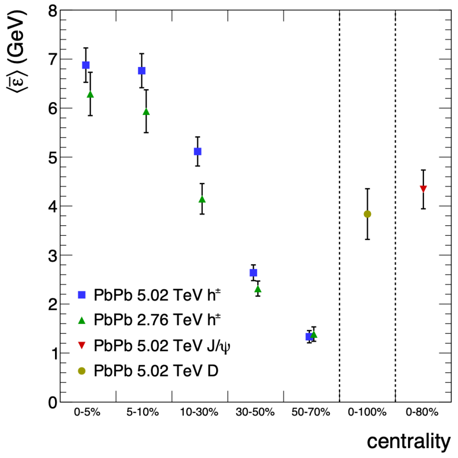
Other works on extracting parton energy loss

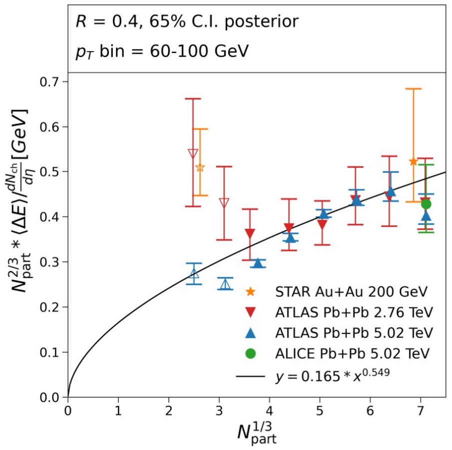
- **F. Arleo, PRL 2017.**
  – Take $W_{AA}(x)$ from BDMPS medium-induced gluon spectrum, and extract $\langle\Delta p_T\rangle$ R_{AA} data on $h^{\pm}$, D, J/ψ.

- **He, Pang and Wang, PRL 2019.**
  –Use a general ansatz of jet $W_{AA}(x)$, and extract flavor-averaged jet $\langle\Delta P_T\rangle$ and $W_{AA}(x)$ from R_{AA} data on single inclusive & γ-jets.

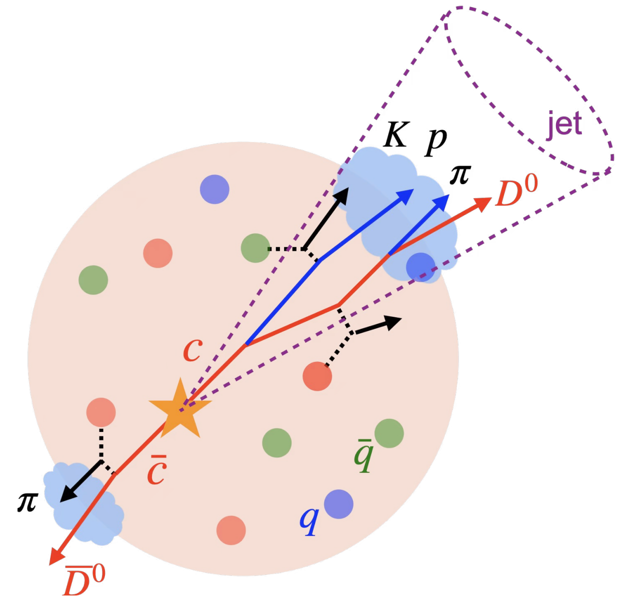
- **Wu, Ke and Wang, PRC 2023**
  – Extract L-dependence of jet $\langle\Delta P_T\rangle$ from R_{AA} data on single inclusive & γ-jets.

- **Zhang, Liao, Qin, Xing, Sci. Bull. 2023**
  – Extract gluon & charm quark $\langle\Delta p_T\rangle$ and $W_{AA}(x)$ from J/ψ R_{AA} data.





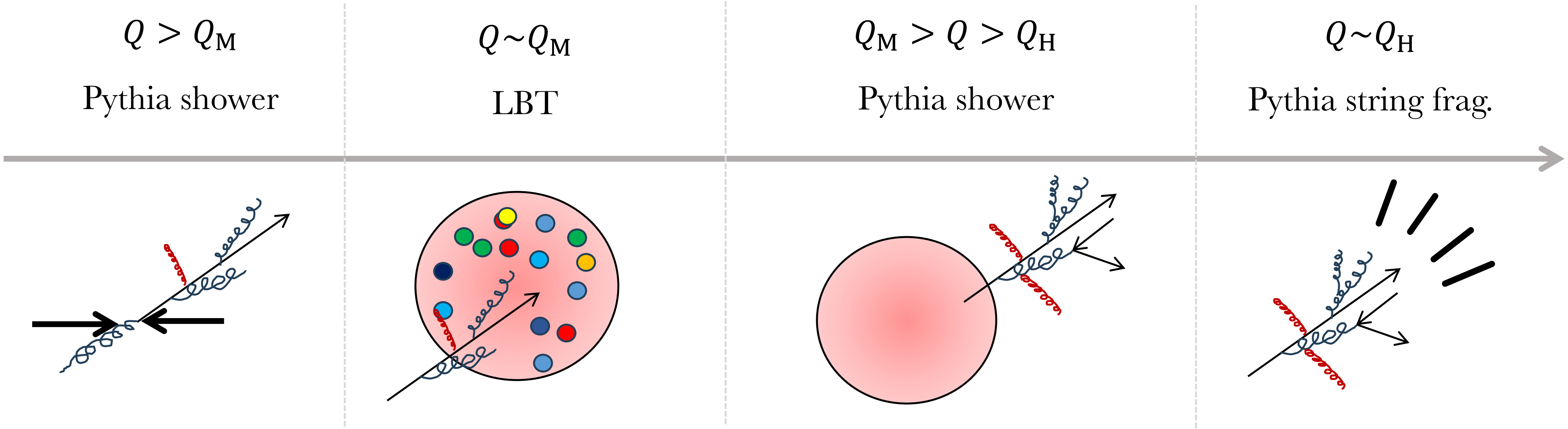
From leading hadron to jet/jet-substructure



- **Dead-cone effect on medium-induced radiation can be indirectly studied from the flavor hierarchy of leading hadron suppression in heavy-ion collisions.**

- **What else can jet/jet substructure tell us ?**

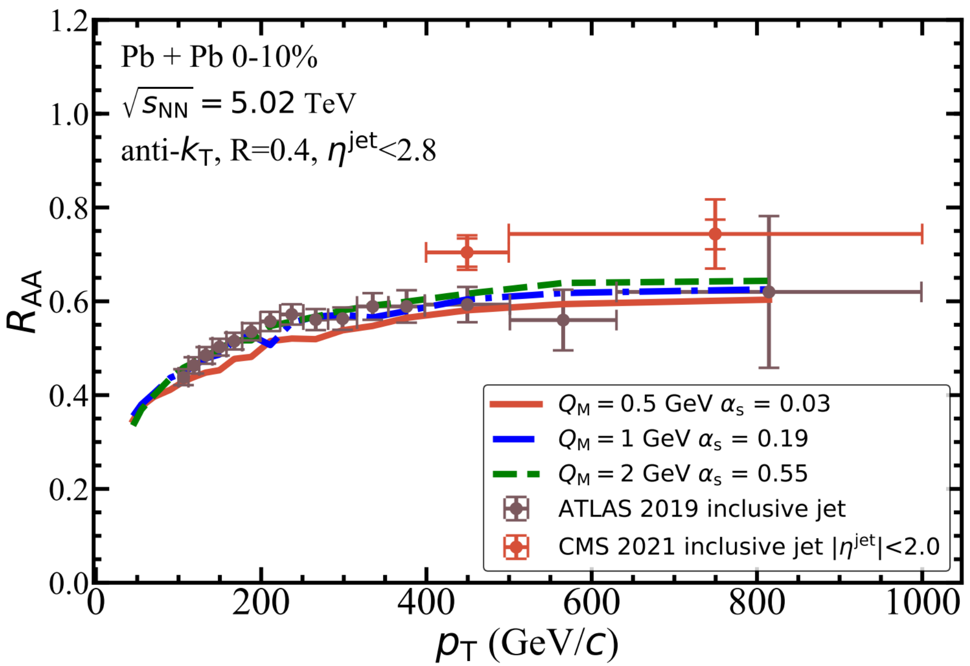
Jet quenching framework in QGP



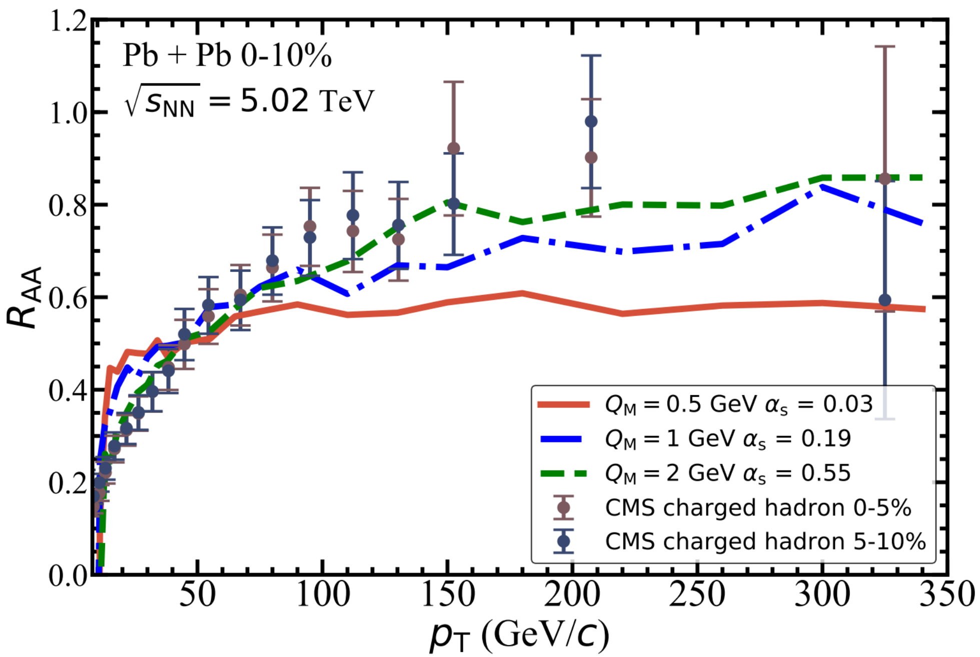
- Q_{M}: medium evolution scale
- Q_{H}: hadronization scale, ~ 0.5GeV

Q_M (medium scale) effect on jet & hadron R_{AA}

Inclusive jet :

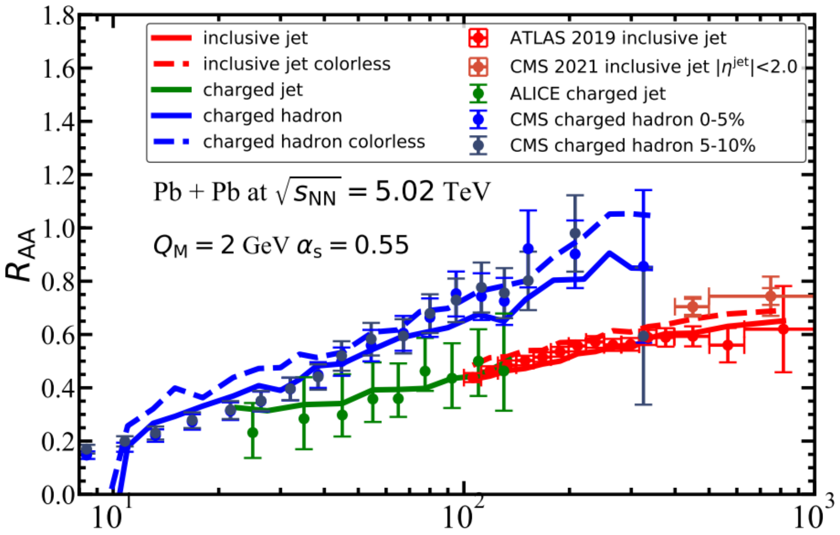


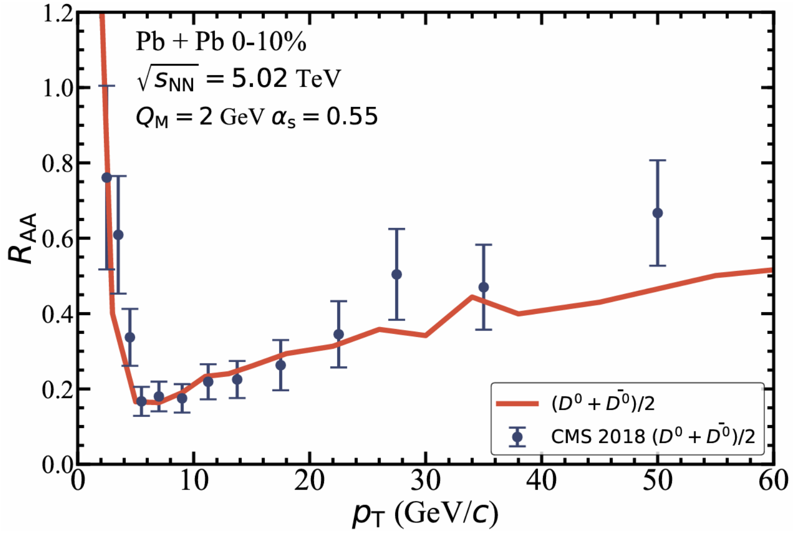
Charged hadron :

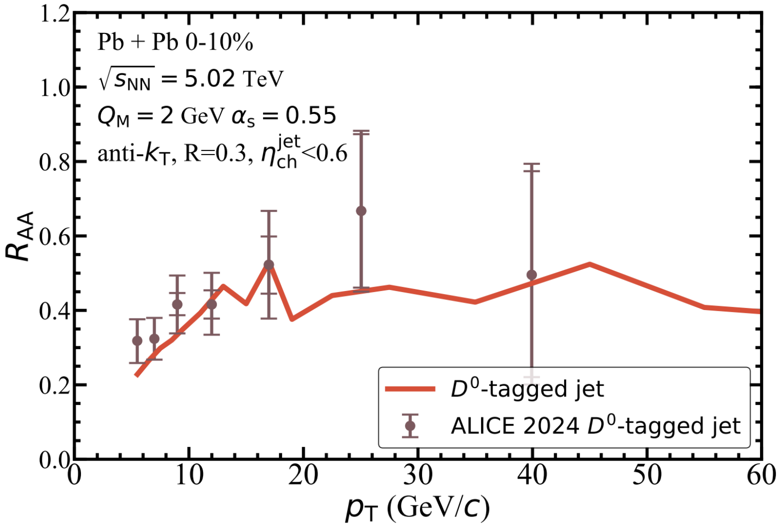


- **$Q_M = 2$ GeV provides a simultaneous description of jet and hadron R_{AA}.**
- **Setting larger Q_M enhances the energy loss of softer partons while leaves hard partons less affected.**

Light and heavy flavor jet & hadron R_{AA}







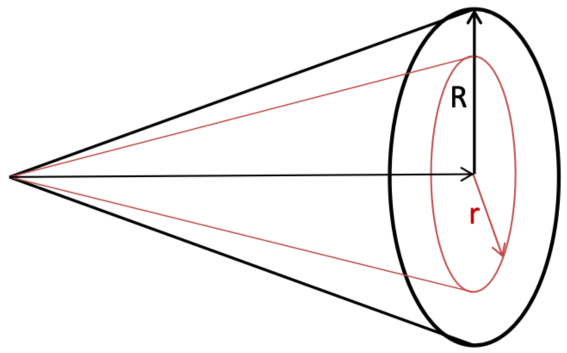
【Dang, et al, in preparation】

- **A simultaneous description of jet and hadron R_{AA} for both heavy and light flavors.**
- **Colorless hadronization approach — where strings are formed by connecting the particles that are closest in phase space — is used as an estimate of systematic errors.**

Jet shape

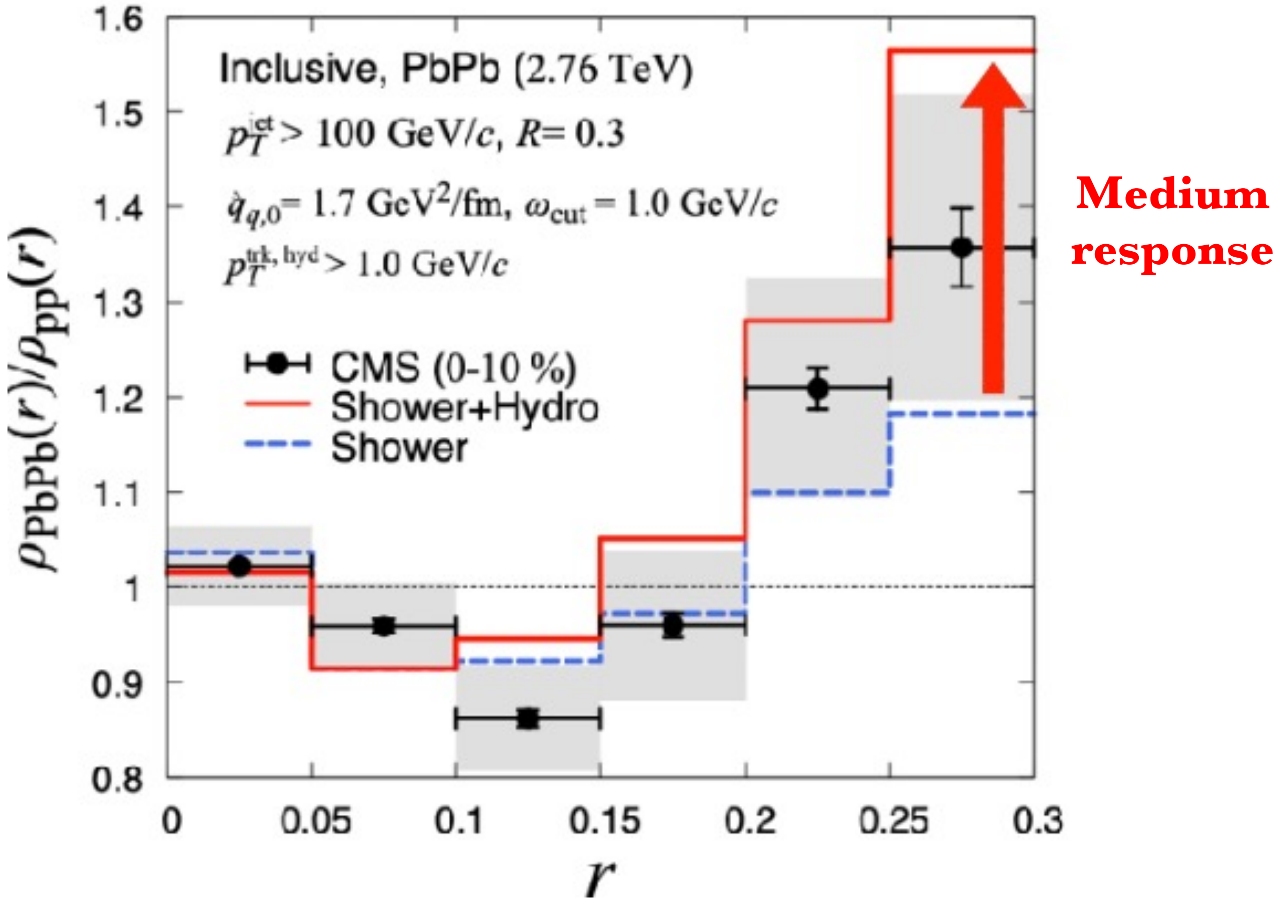
Tachibana, et al, PRC (2017)

p_T distribution of jet constituents along r :



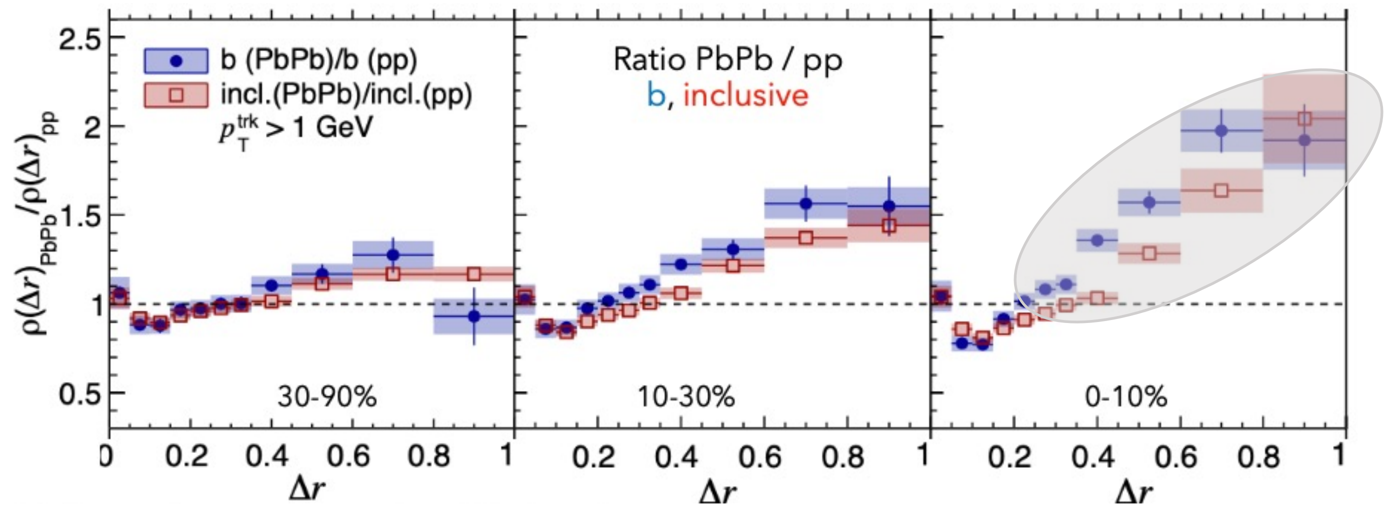
$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}}\frac{\sum_{\mathrm{trk}\in(r_a,r_b)} p_T^{\mathrm{trk}}}{\sum_{\mathrm{trk}} p_T^{\mathrm{tr}}}$$

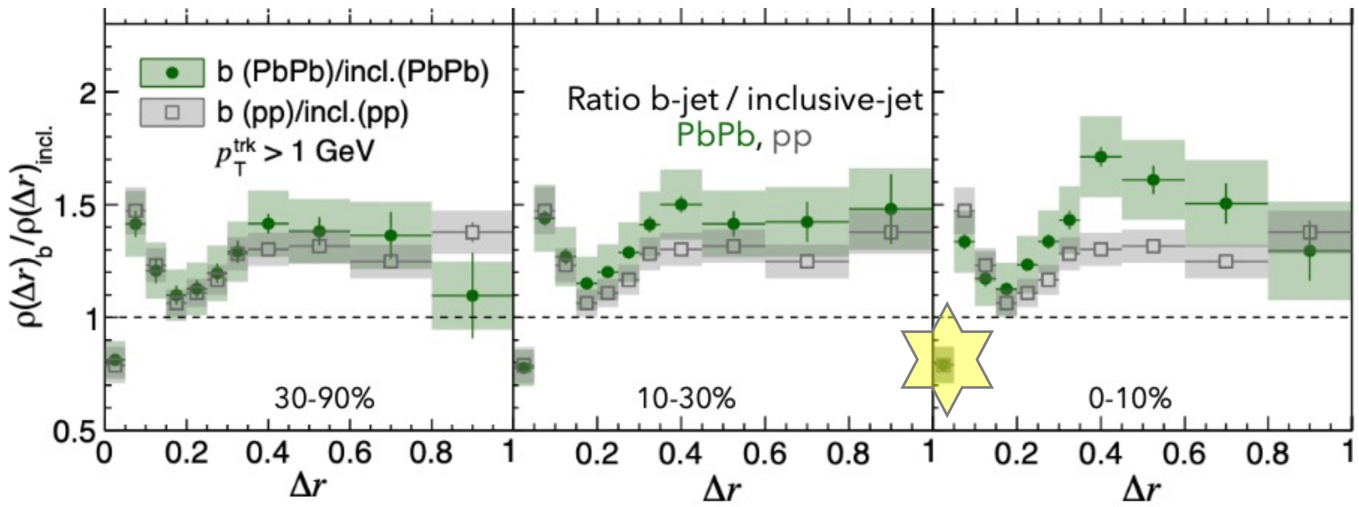
$$r = \sqrt{(\eta_{\mathrm{trk}} - \eta_{\mathrm{jet}})^2 + (\phi_{\mathrm{trk}} - \phi_{\mathrm{jet}})^2}$$



- **Medium response has a significant contribution to PbPb/pp ratio of jet shape at large r.**

Heavy and light flavor jet shape





【CMS, PLB (2023)】

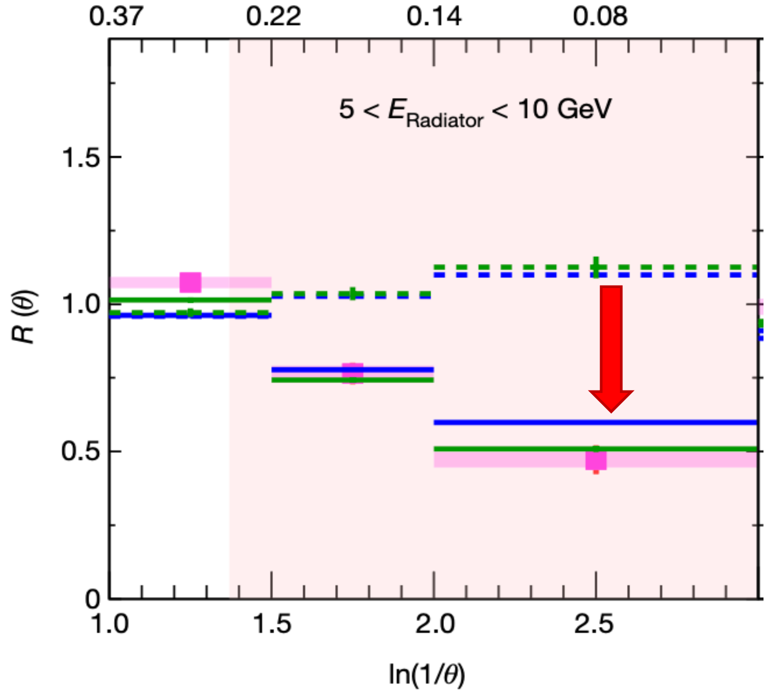
- **PbPb/pp ratio**
  - **Larger PbPb/pp ratio for b jets than for inclusive jets in the large-Δr region.**

- **b-jet/inclusive-jet ratio**
  - **A depletion is observed for $\Delta r \leq 0.05$, which indicates the dead-cone effect.**

Mass effect in parton splitting – dead-cone effect

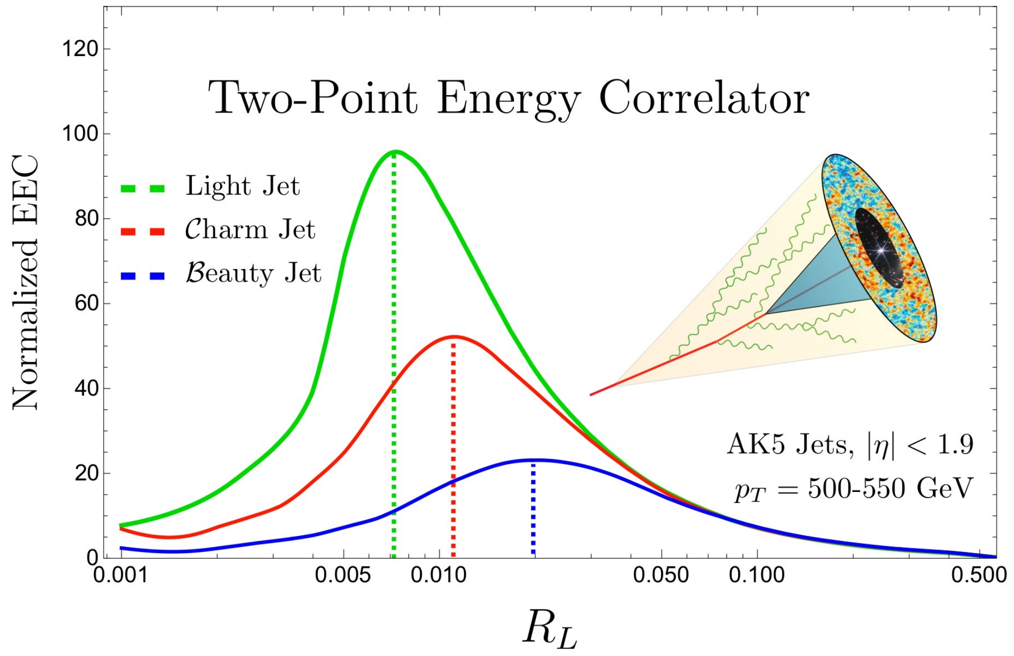
Splitting angle distribution

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}}\frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Big/ \frac{1}{N^{\text{inclusive jets}}}\frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)}$$

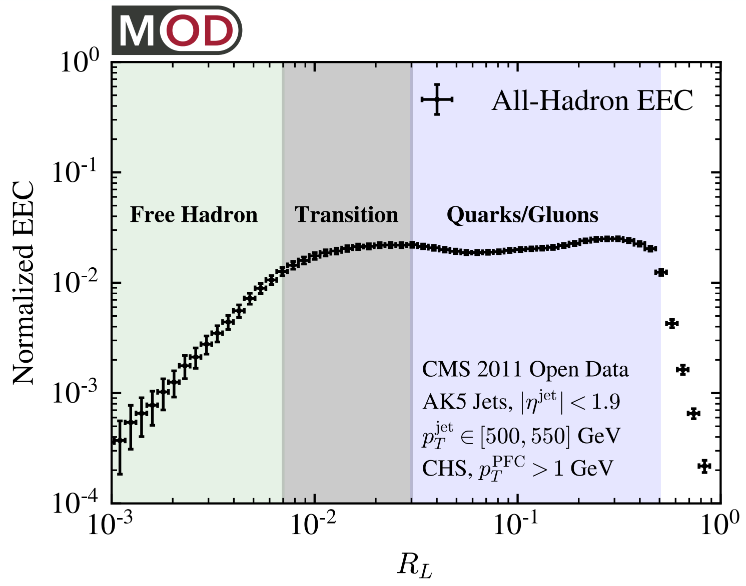


E-weighted angular distribution

$$\frac{d\Sigma_{\text{EEC}}}{dR_L} = \int d\sigma(\Delta R_{ij}) \frac{p_{\text{T},i} p_{\text{T},j}}{p^2_{\text{T,jet}}} \delta(\Delta R_{ij} - R_L), \qquad \Delta R_{ij} = \sqrt{\Delta\phi^2_{ij} + \Delta\eta^2_{ij}}$$

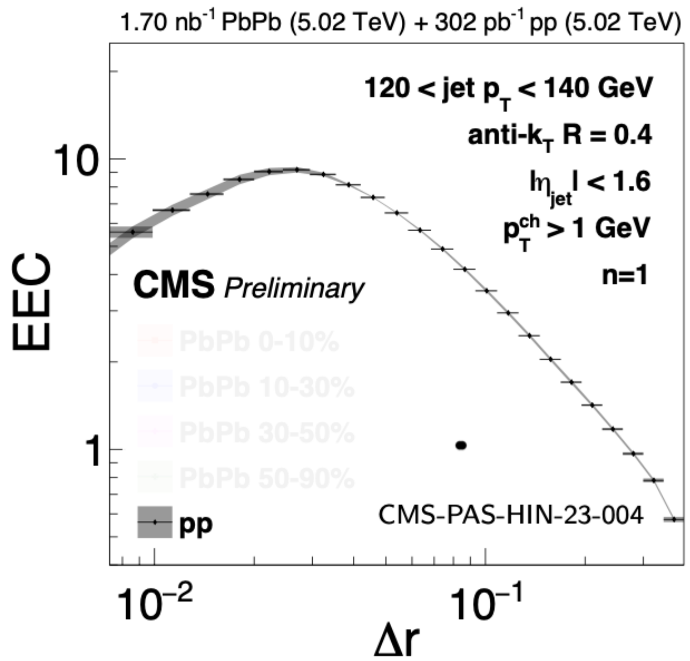


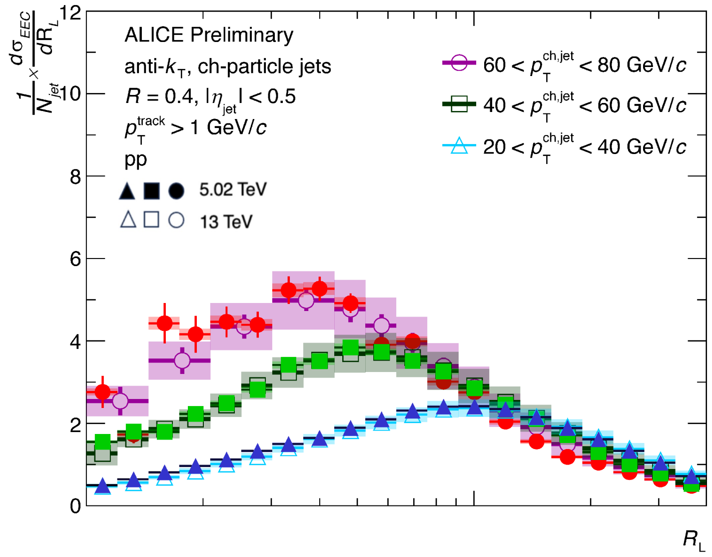
Jet EEC in pp

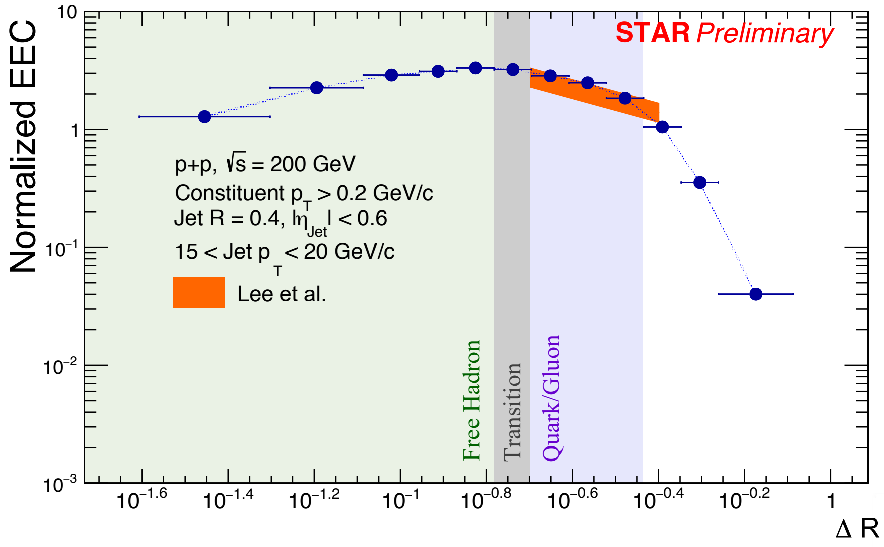


$$\frac{d\Sigma_{\mathrm{EEC}}}{dR_L} = \int d\sigma(\Delta R_{ij}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^2} \delta(\Delta R_{ij} - R_L), \qquad \Delta R_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$$

- Jet EEC is proposed in **PRL 130 (2023) 5, 051901**.
- Jet EEC separates pert. region and non-pert. region.
- Verified by experiments at RHIC and the LHC.

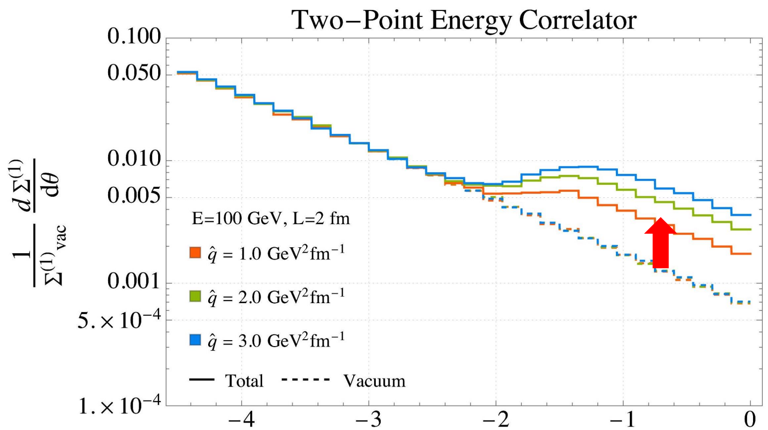


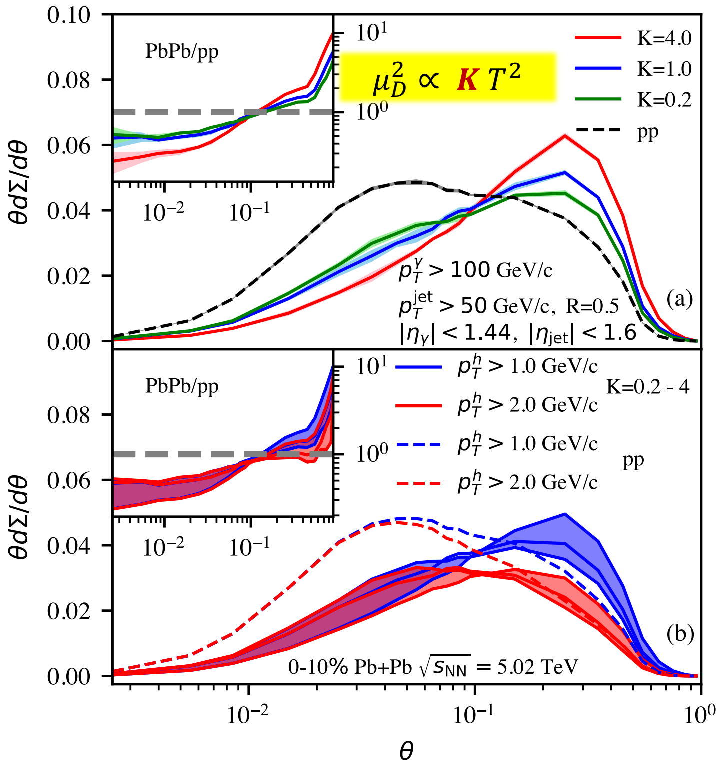


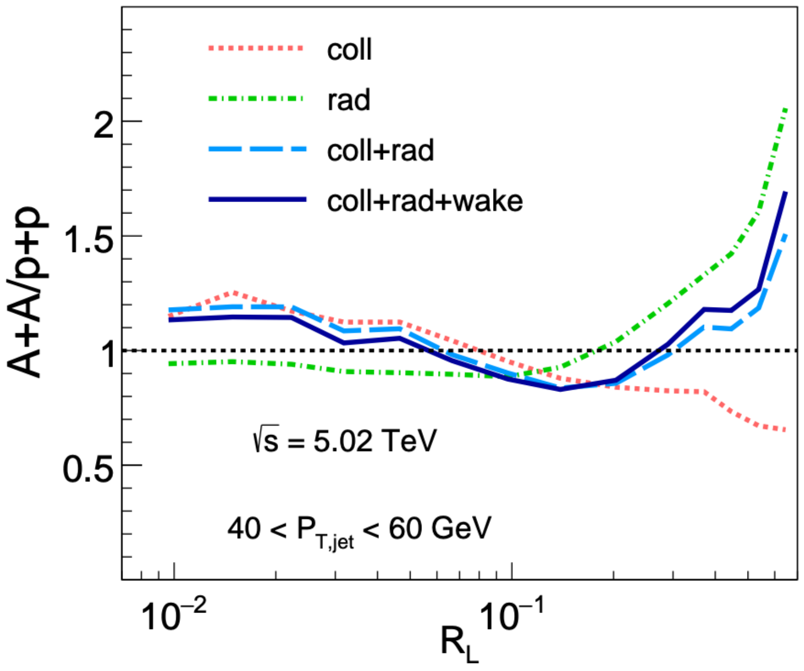


Jet EEC in heavy-ion collisions

- **Jet EECs imprints the scale of medium-induced radiation, medium screening mass, and jet-medium interaction mechanism.**

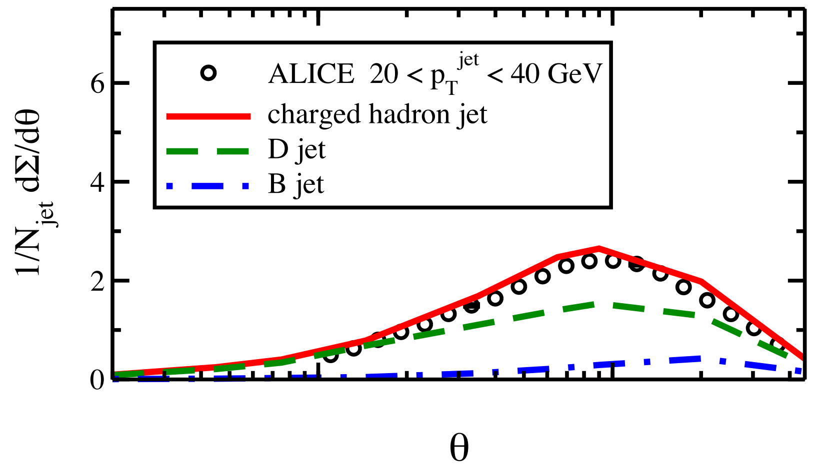






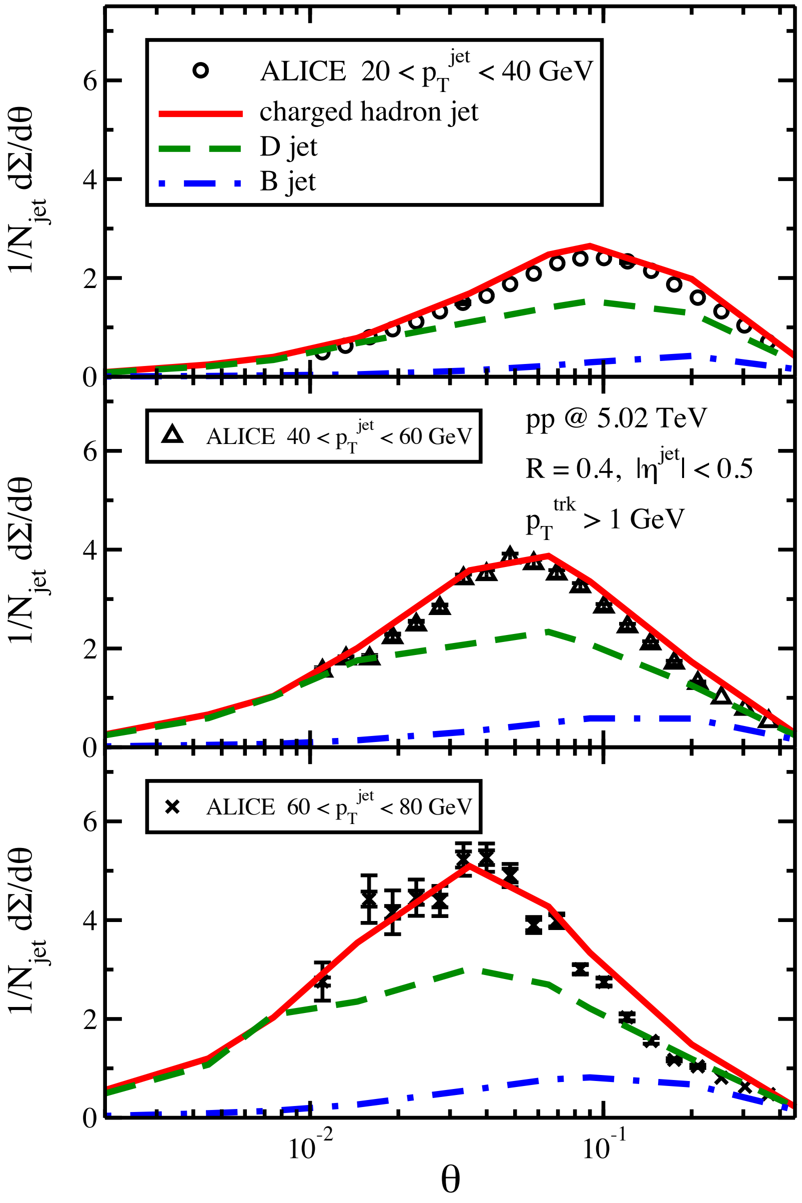
【Andres, et al., in PRL (2023)】
【Yang, et al., PRL (2024)】
【Chen, et al., arXiv:2409.13996】

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 $\theta^{\text{peak}} \sim \Lambda_{\text{QCD}}/p_T^{\text{jet}}\,(m_Q/p_T^{\text{jet}})$**

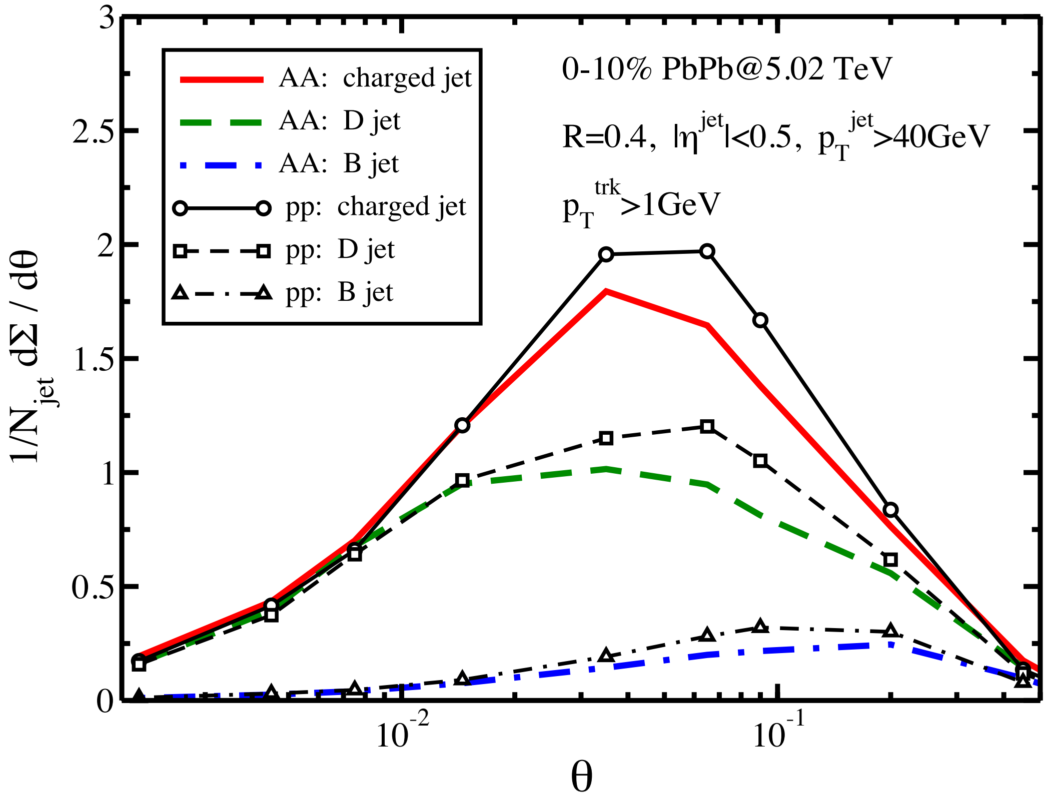
Light *vs.* heavy flavor jet EEC in pp

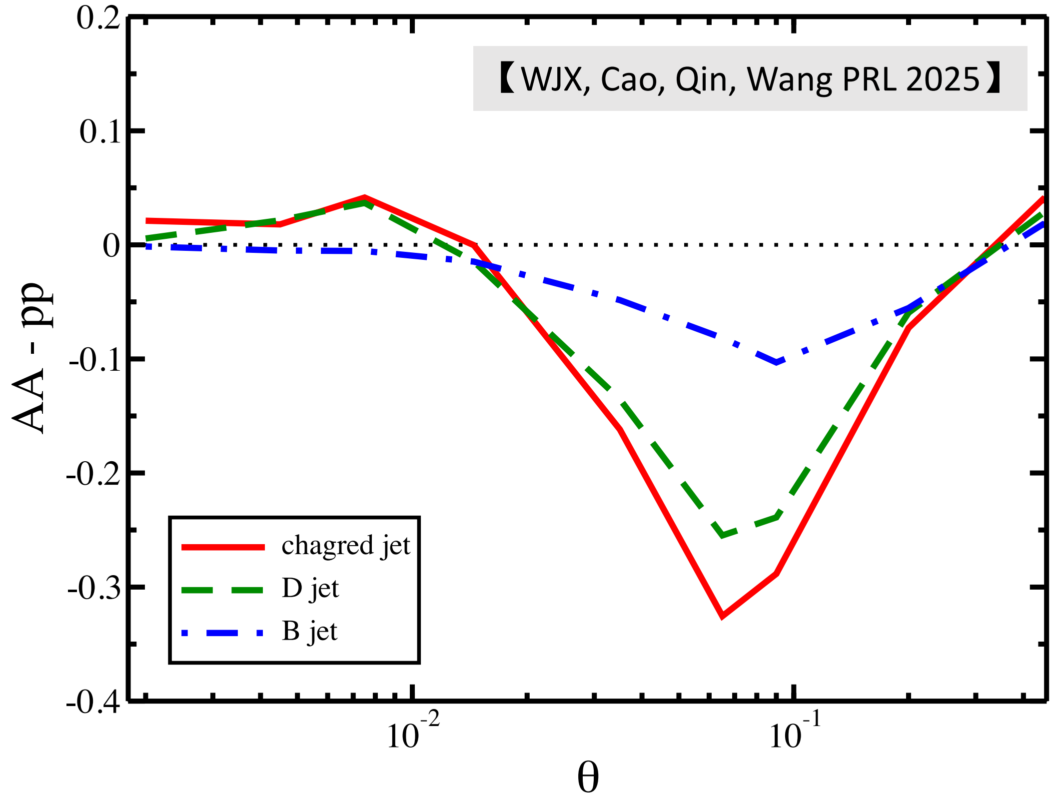


- **Jet in pp: Pythia 8 simulation**
- **Flavor (mass) dependence:**
  - Σ(charged jet) > Σ(D jet) > Σ(B jet)
  - θ^{peak}(charged jet) < θ^{peak}(D jet) < θ^{peak}(B jet)
- **Transition angle $\theta^{peak} \sim \Lambda_{QCD}/p_T^{jet}$ (m_Q/p_T^{jet})**
- **Jet energy dependence:**
  - **Higher p_{T}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

【WJX, Cao, Qin, Wang PRL 2025】

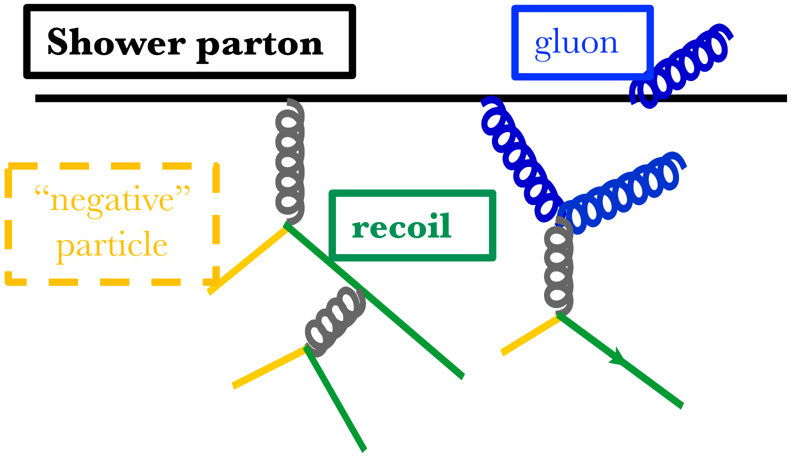
Light *vs.* heavy flavor jet EEC in Pb-Pb





- **Flavor hierarchy of jet EEC preserves in AA.**
- **General feature of nuclear modification (AA-pp): suppression at intemadiate *θ*, enhancement at small *θ* (except for *B*-jet) and large *θ*.**

Different contributions to medium modification on EEC

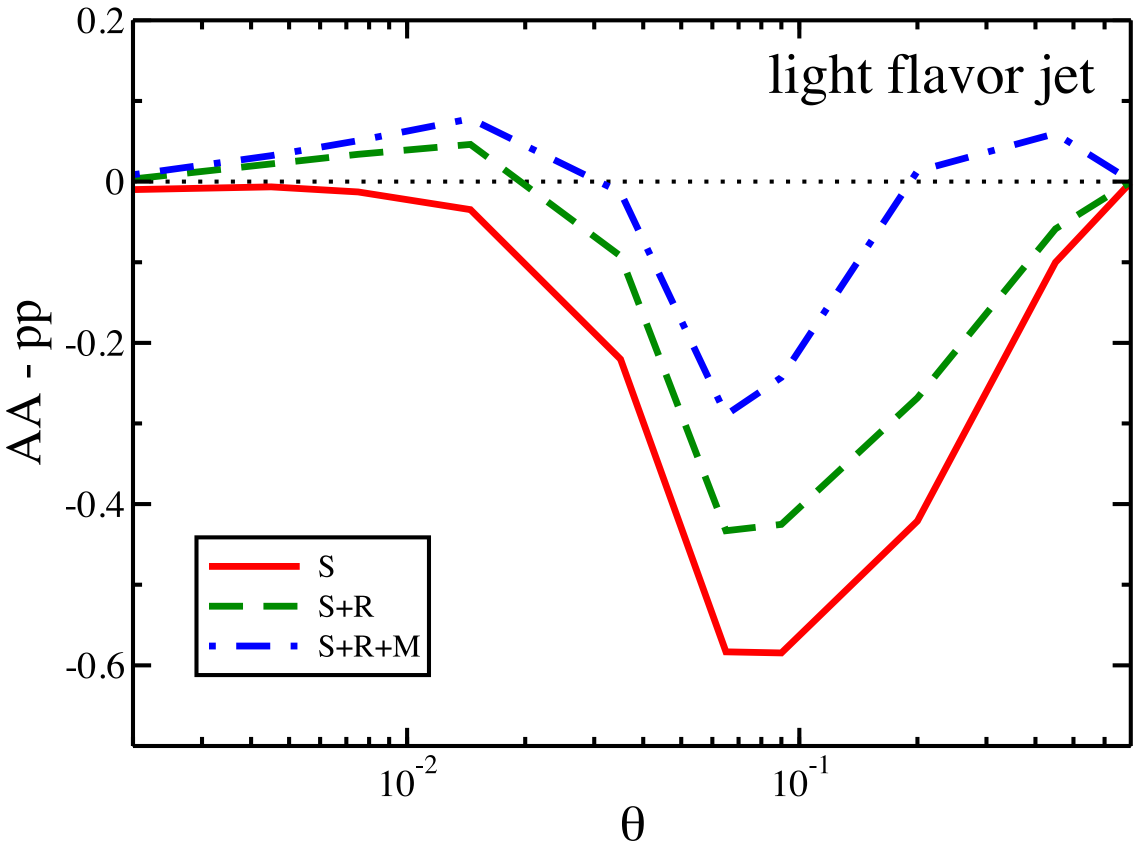


Pythia 8 + LBT in hydro

S: shower partons from Pythia

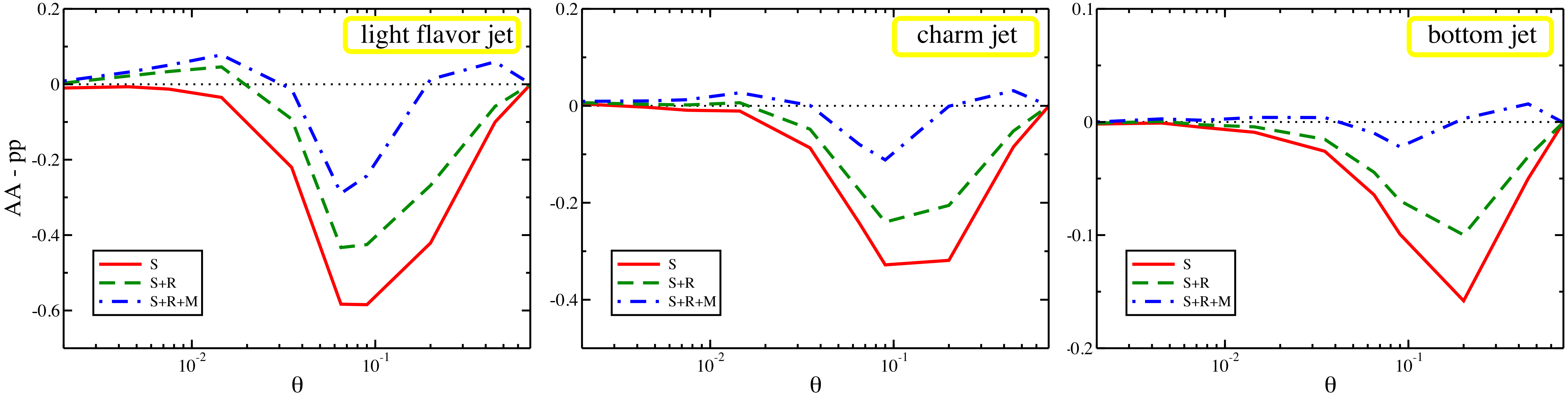
R: medium-induced radiated gluons

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.**

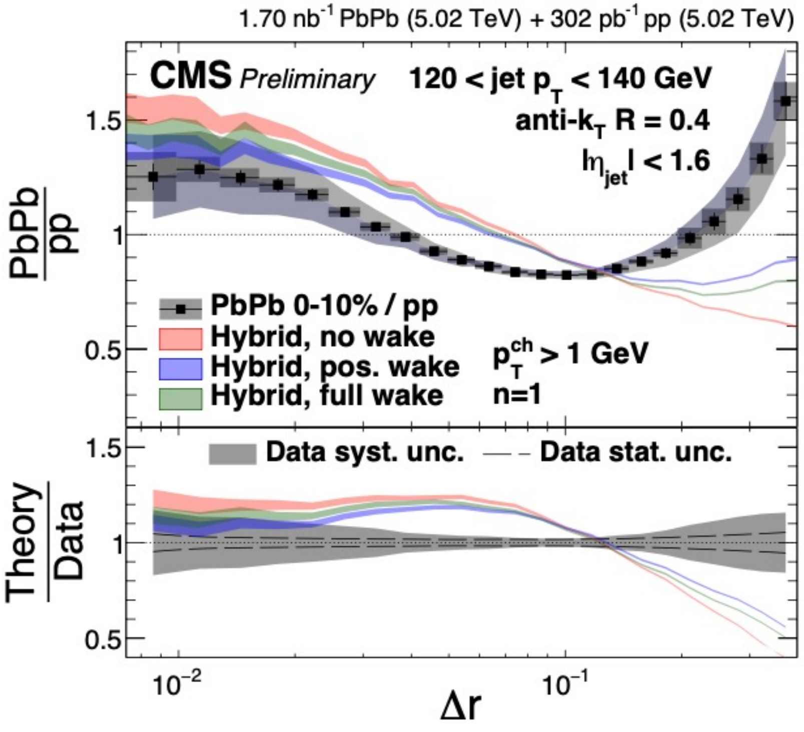
Mass effect on jet EEC modification



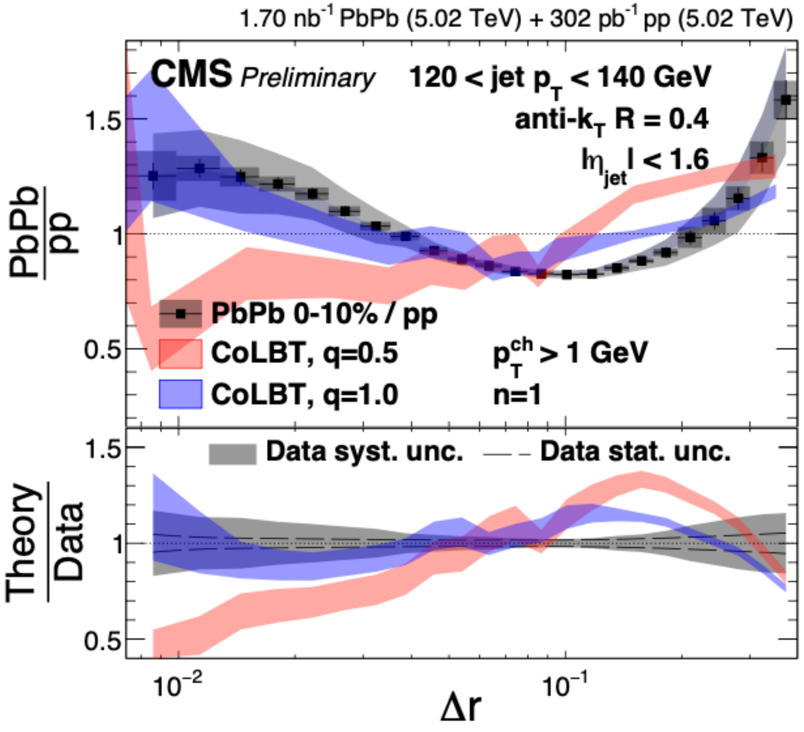
- **For heavy-quarks-tagged jets, both suppression and enhancement of EEC becomes weaker.**

Jet EEC: model comparison with PbPb/pp ratio

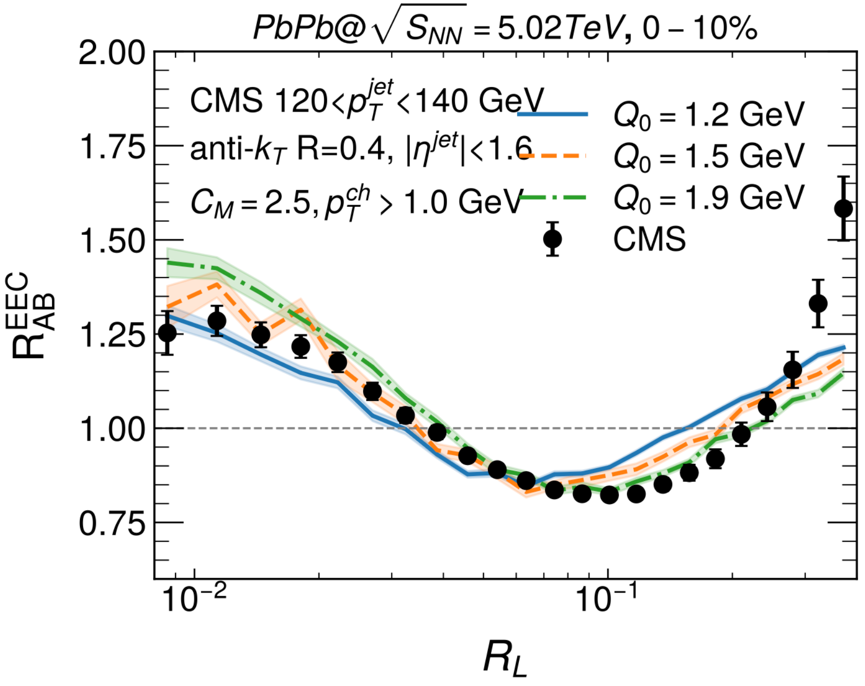
Hybrid model



CoLBT model

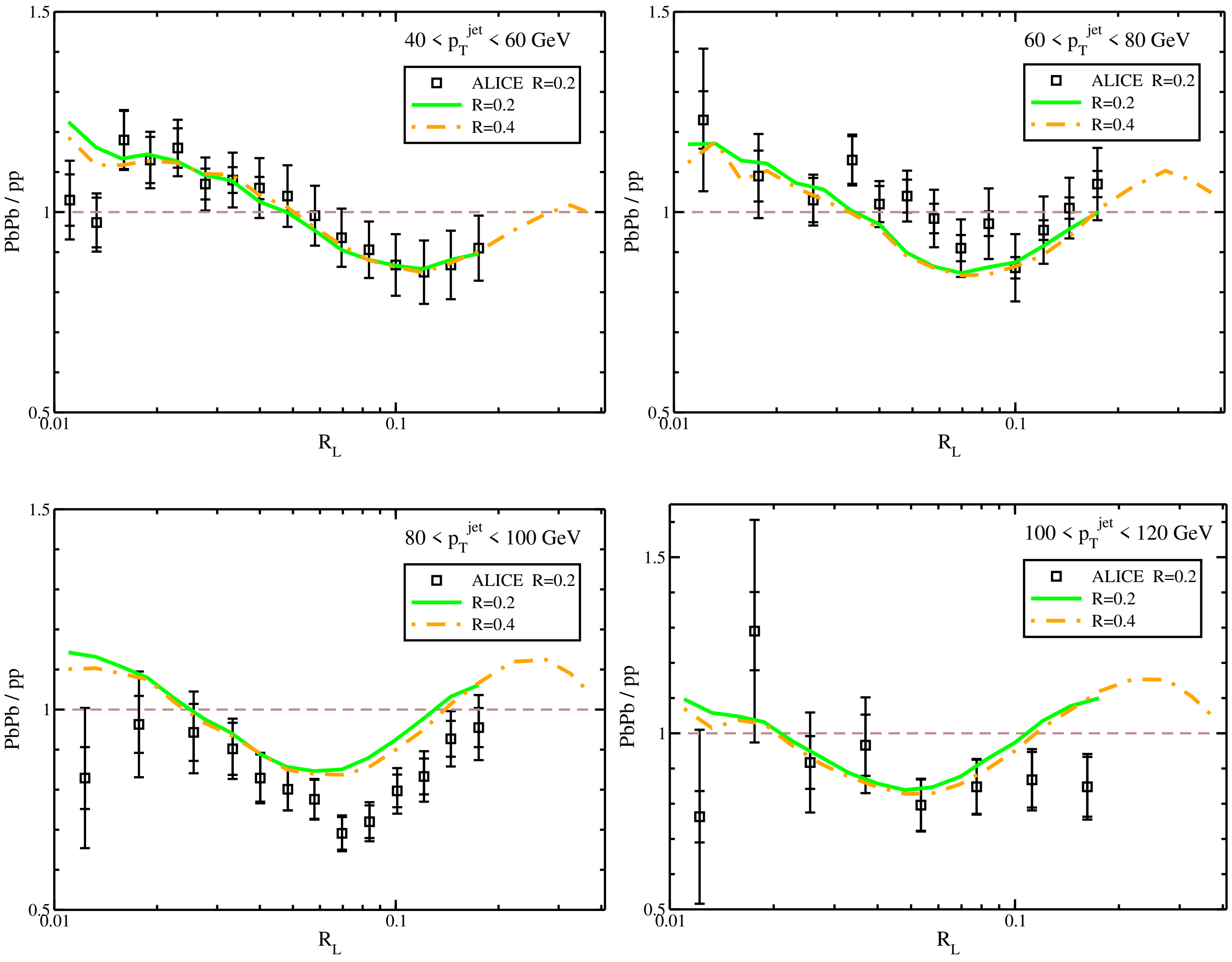


LIDO model



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

LBT *vs.* ALICE data

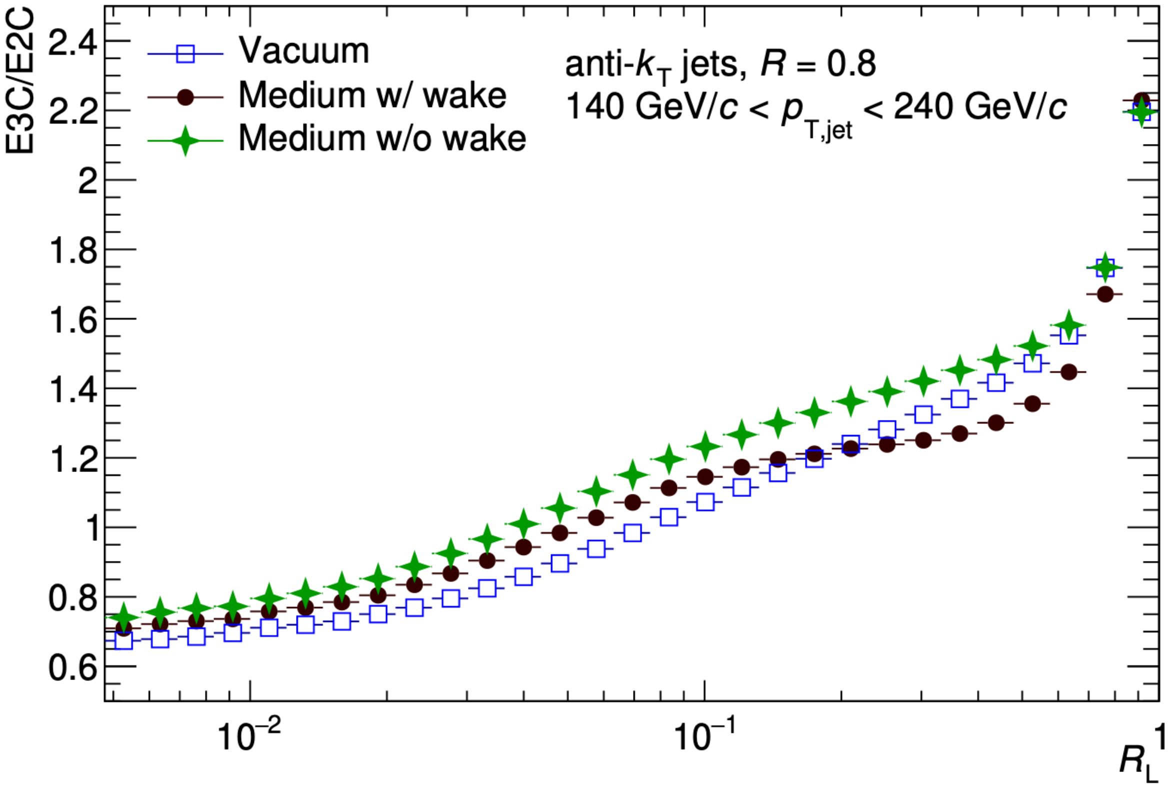


【ALICE: ALI-PREL-557542】

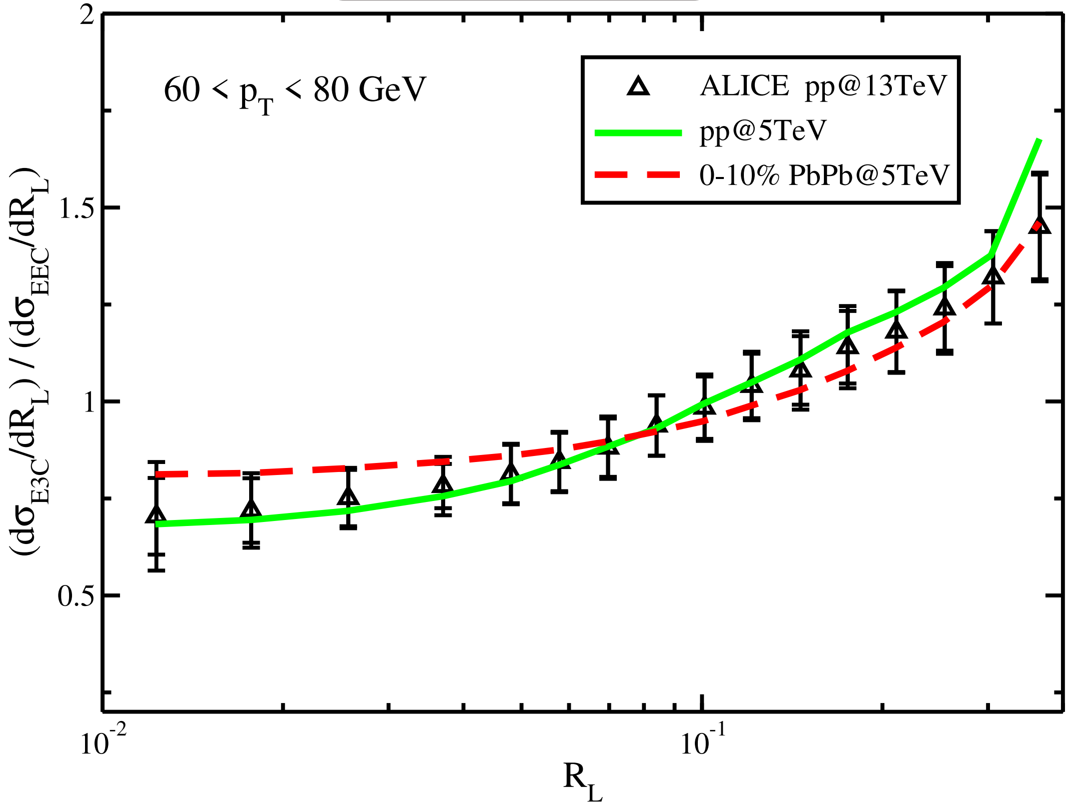
- **LBT describes the PbPb/pp ratio of jet EEC.**
- **LBT predicts a weak dependence of PbPb/pp ratio on jet cone size *R*.**

Extension to E3C/E2C

Hybrid model



LBT model



- **With medium response, both Hybrid and LBT model predict E3C/E2C get suppressed at large R_L.**
- **Can we use multi-particle correlation to probe dead-cone effect in medium?**

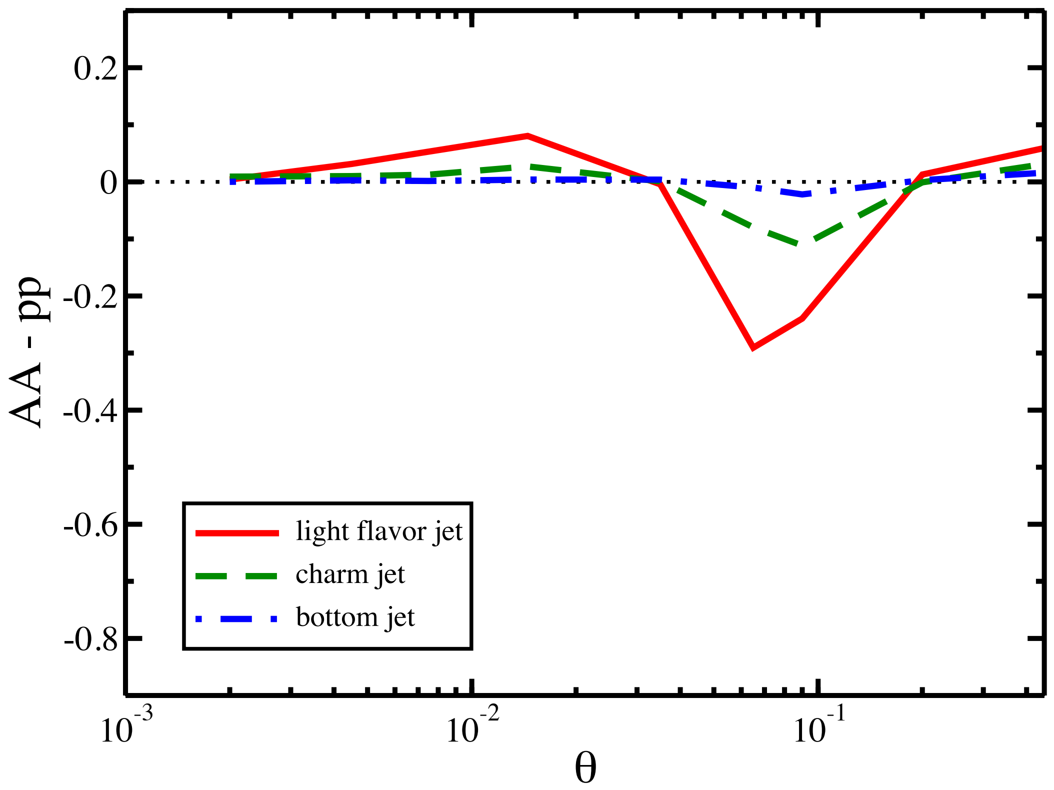
Summary

- **Mass effect on the nuclear modification of single hadrons:**
  - **By using a pQCD-based jet quenching model, we obtain a simultaneous description of R_{AA} for different flavor hadrons at p_T region in both heavy-ion and light-ion collisions.**
  - **Through a Bayesian analysis, we can extract averaged parton energy loss and the energy loss functions.**
- **Mass effect on the nuclear modification of jet and jet substructure:**
  - **A simultaneous description of jet and hadron R_{AA} for both heavy and light flavors.**
  - **The medium modification of inclusive 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.**
  - **The explorations on jet E3C is on-going …**

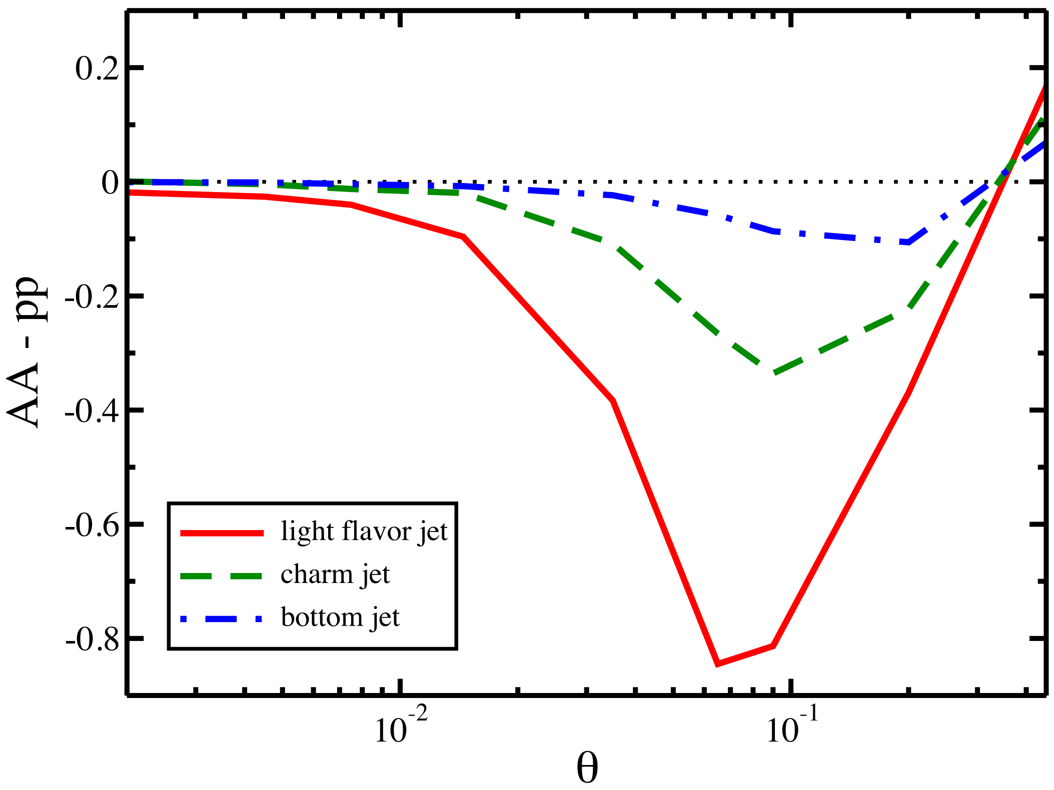
Thank You !

Effect of selection bias on jet EEC

p_T trigger in both pp and AA



p_T trigger only in pp
(no trigger bias in AA)



- **Selection bias contributes the enhancement of inclusive jet EEC: high energy jets tend to radiate more gluons, which facilitates the enhancement of EEC at small angle.**

Low to intermediate p_T heavy quark

- Use a parametrized Cornell-type potential to describe perturbative and non-perturbative interactions between HQs and QGP.

$$V(r) = V_{\rm Y}(r) + V_{\rm S}(r) = -\frac{4}{3}\alpha_s \frac{e^{-m_d r}}{r} - \frac{\sigma e^{-m_s r}}{m_s}$$

$$V(\vec{q}) = -\frac{4\pi\alpha_s C_F}{m_d^2 + |\vec{q}|^2} - \frac{8\pi\sigma}{(m_s^2 + |\vec{q}|^2)^2}$$

$$\alpha_s = 0.27,\ \sigma = 0.45\ \text{GeV}^2$$
$$m_d = 2T + 0.2\ \text{GeV}$$
$$m_s = \sqrt{0.1\ \text{GeV} \times T}$$

$$\begin{aligned} i\mathcal{M} &= \mathcal{M}_{\rm Y} + \mathcal{M}_{\rm S} \\ &= \overline{u}(p')\gamma^\mu u(p) V_{\rm Y}(\vec{q})\overline{u}(k')\gamma^\nu u(k) \\ &\quad + \overline{u}(p')u(p)V_{\rm S}(\vec{q})\overline{u}(k')u(k), \end{aligned}$$

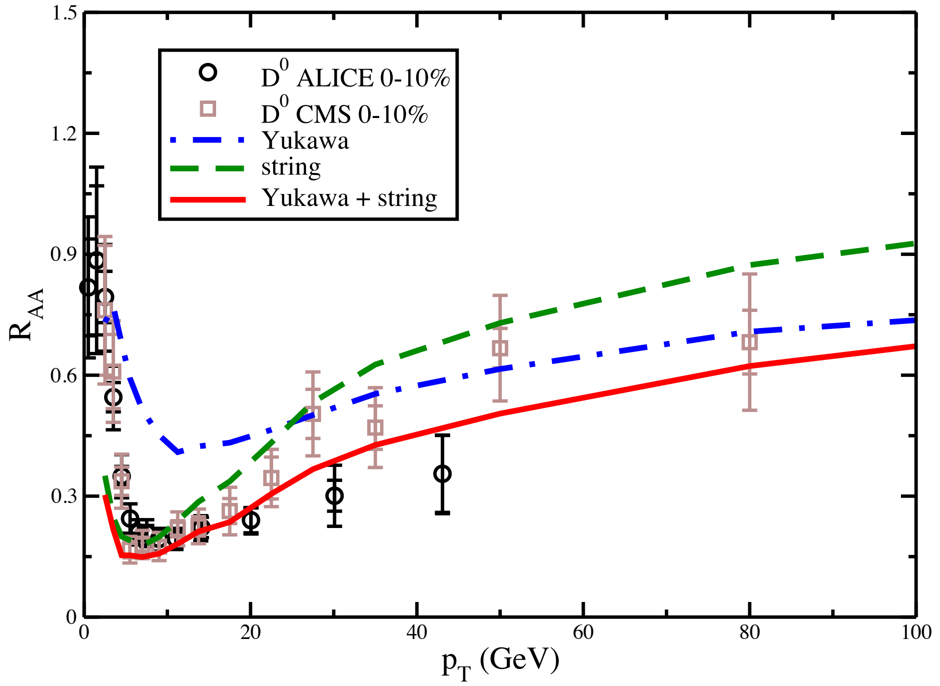
$$|\mathcal{M}_{\rm Qq}|^2 = \frac{64\pi^2\alpha_s^2}{9}\frac{(s-m_Q^2)^2 + (m_Q^2-u)^2 + 2m_Q^2 t}{(t-m_d^2)^2} + \frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t^2-4m_Q^2 t}{(t-m_s^2)^4},$$

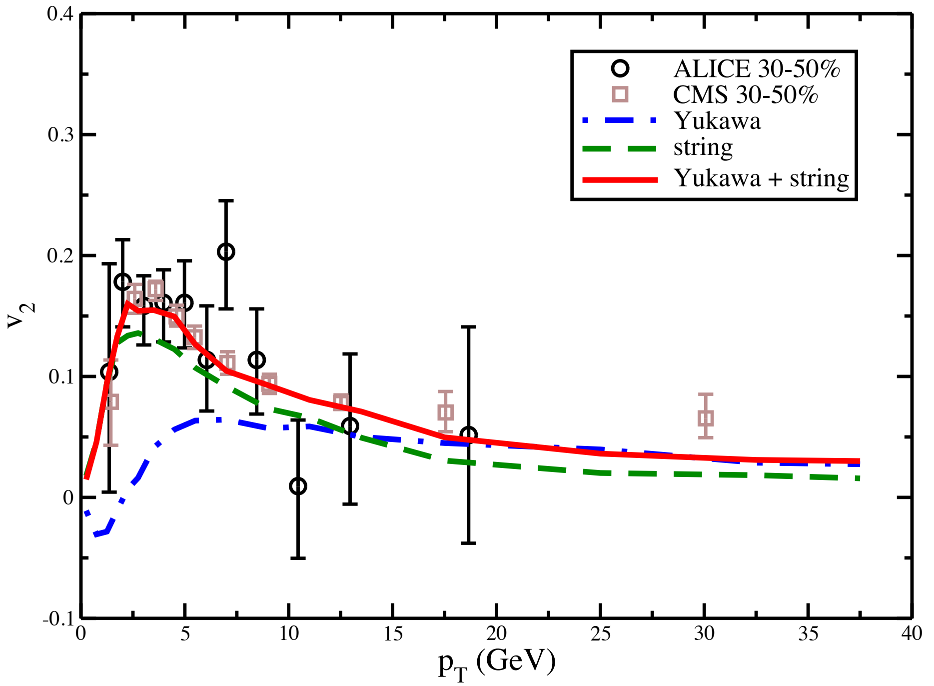
$$\begin{aligned} |\mathcal{M}_{Qg}|^2 = &\frac{64\pi^2\alpha_s^2}{9}\frac{(s-m_Q^2)(m_Q^2-u)+2m_Q^2(s+m_Q^2)}{(s-m_Q^2)^2} \\ &+ \frac{64\pi^2\alpha_s^2}{9}\frac{(s-m_Q^2)(m_Q^2-u)+2m_Q^2(u+m_Q^2)}{(u-m_Q^2)^2} \\ &+ 8\pi^2\alpha_s^2\frac{5m_Q^4+3m_Q^2 t-10m_Q^2 u+4t^2+5tu+5u^2}{(t-m_d^2)^2} \\ &+ 8\pi^2\alpha_s^2\frac{(m_Q^2-s)(m_Q^2-u)}{(t-m_d^2)^2} \\ &+ 16\pi^2\alpha_s^2\frac{3m_Q^4-3m_Q^2 s-m_Q^2 u+s^2}{(s-m_Q^2)(t-m_d^2)} \\ &+ \frac{16\pi^2\alpha_s^2}{9}\frac{m_Q^2(4m_Q^2-t)}{(s-m_Q^2)(m_Q^2-u)} \\ &+ 16\pi^2\alpha_s^2\frac{3m_Q^4-m_Q^2 s-3m_Q^2 u+u^2}{(t-m_d^2)(u-m_Q^2)} + \frac{C_A}{C_F}\frac{(8\pi\sigma)^2}{N_c^2-1}\frac{t^2-4m_Q^2 t}{(t-m_s^2)^4}. \end{aligned}$$

HQ dynamics at low energy & close to T_c is highly non-perturbative.
Include the contributions from long-range confining potential & short-range Yukawa potential.

Implementation of color potential interaction in LBT

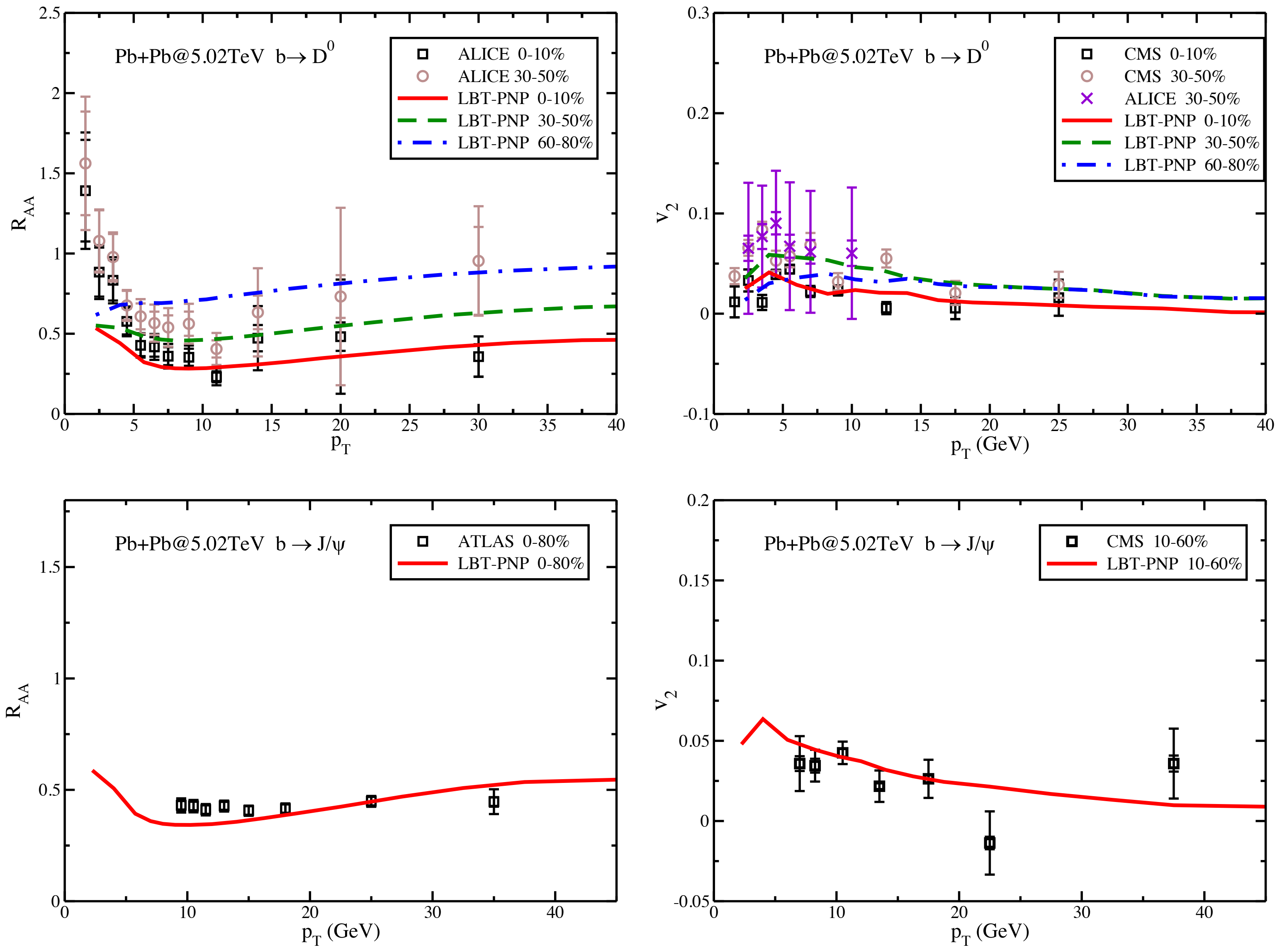
- **FONLL + LBT-PNP + hydrodynamics**



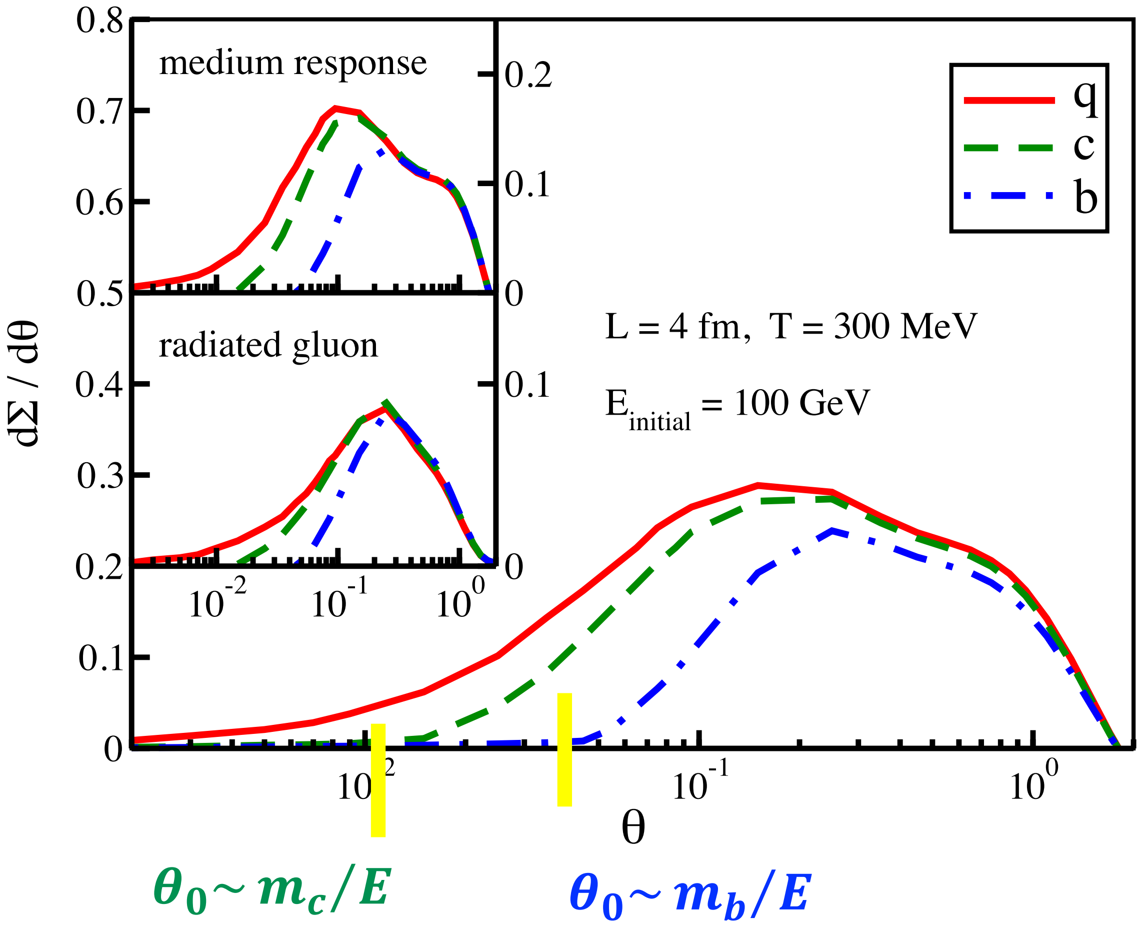


- **LBT-PNP model can simutaneously describe D meson R_{AA} & v_2 at RHIC & the LHC.**
- **Perturbative interaction dominates D meson R_{AA} and v_2 at high p_T, while non-perturbative interaction dominates at low p_T.**

Bottom quark dynamics within LBT-PNP

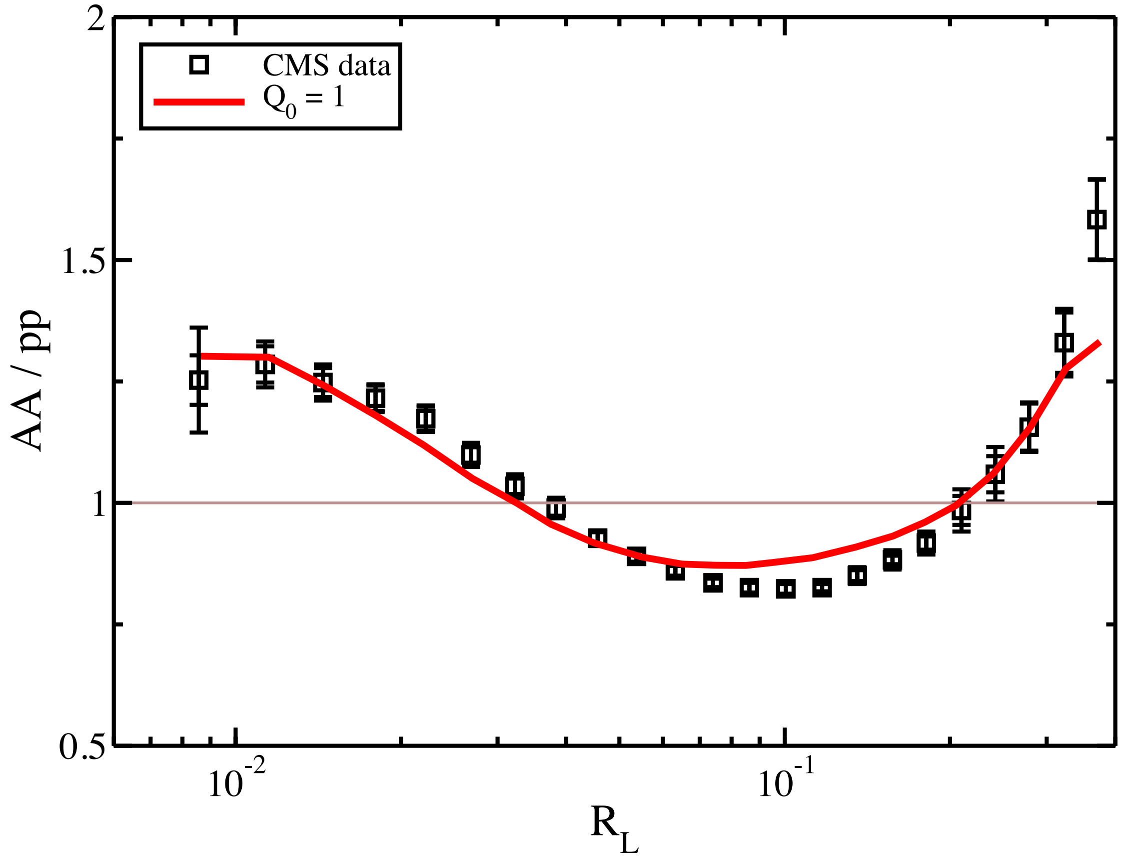


Medium response and medium-induced radiation to jet EEC



Flavor (mass) hierarchy in quark-jet EEC:

- **Σ(light jet) > Σ(charm jet) > Σ(bottom jet), this hierarchy maintains in the contribution from medium response and medium-induced radiation.**



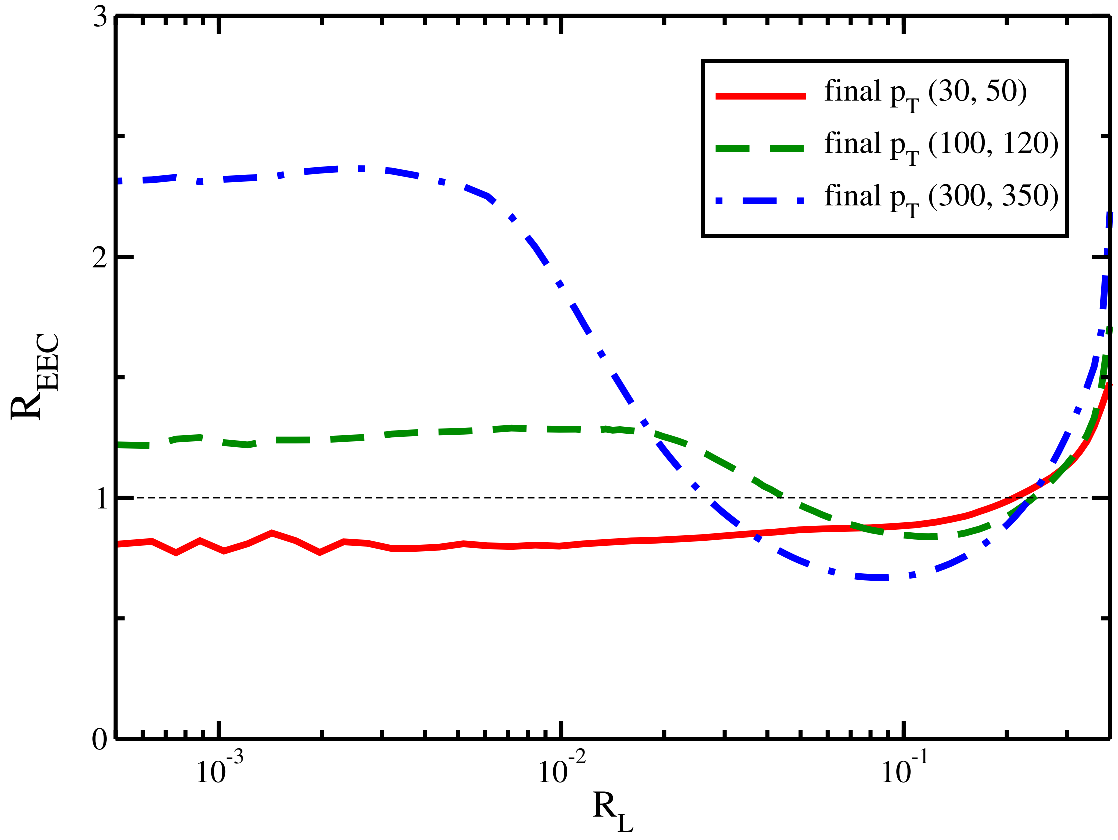
CMS data
Q0 = 1
AA / pp
R_L
2
1.5
1
0.5
10^-2
10^-1

Genuine particle correlation in jets

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

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

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



Genuine particle correlation in jets