Jet transport in relativistic nucleus-nucleus collisions

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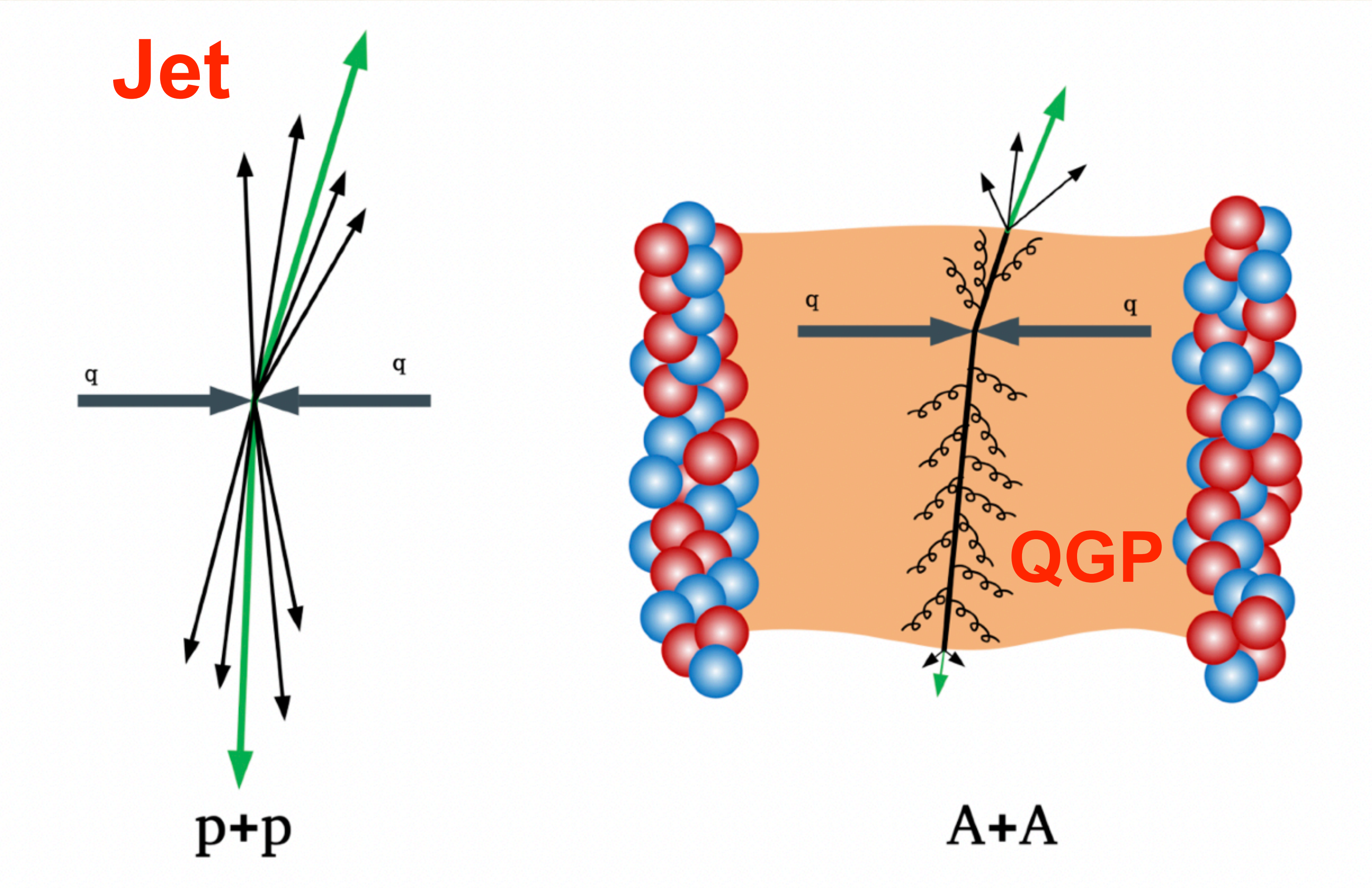
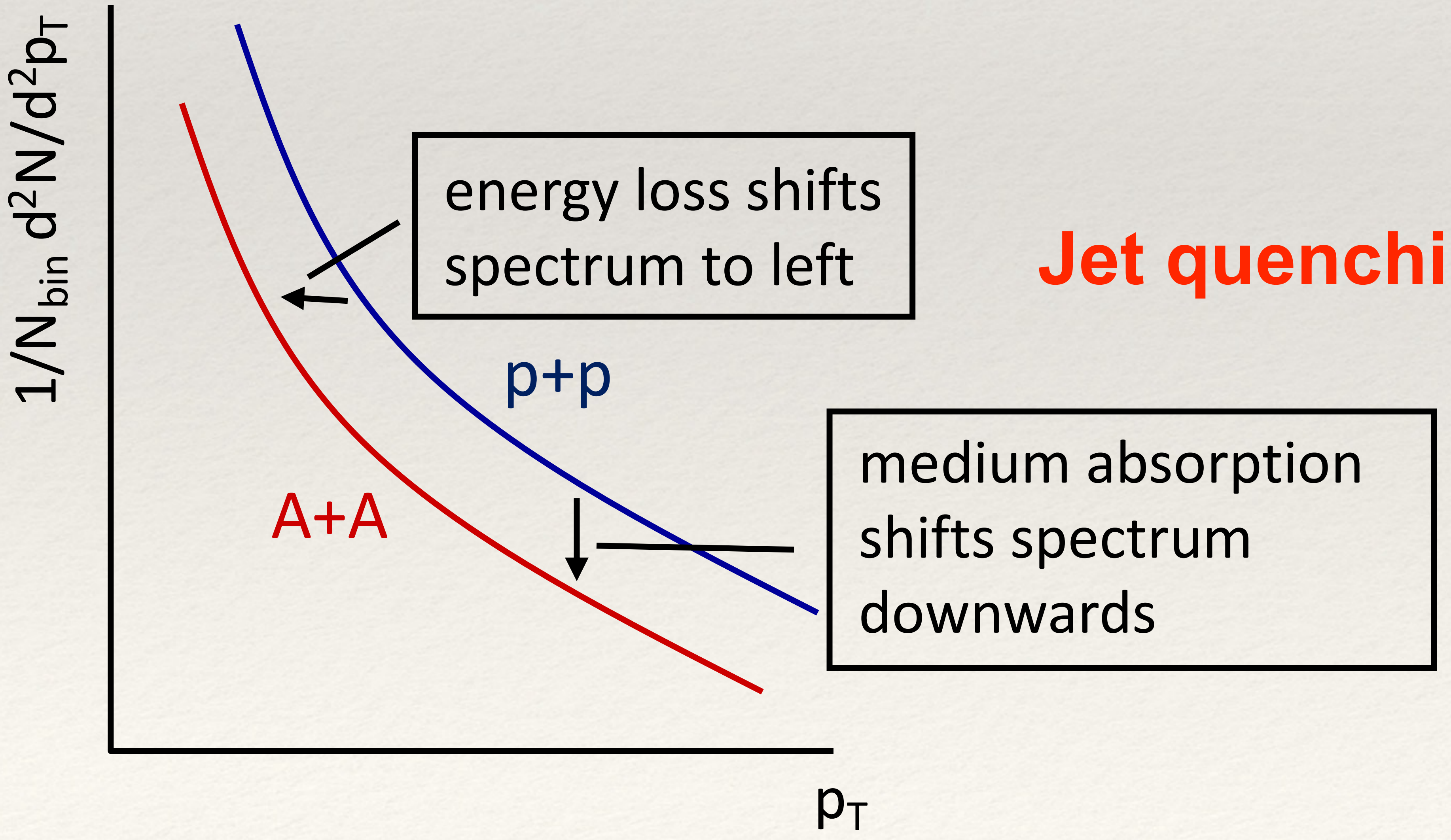
Jet quenching in high-energy nuclear collisions



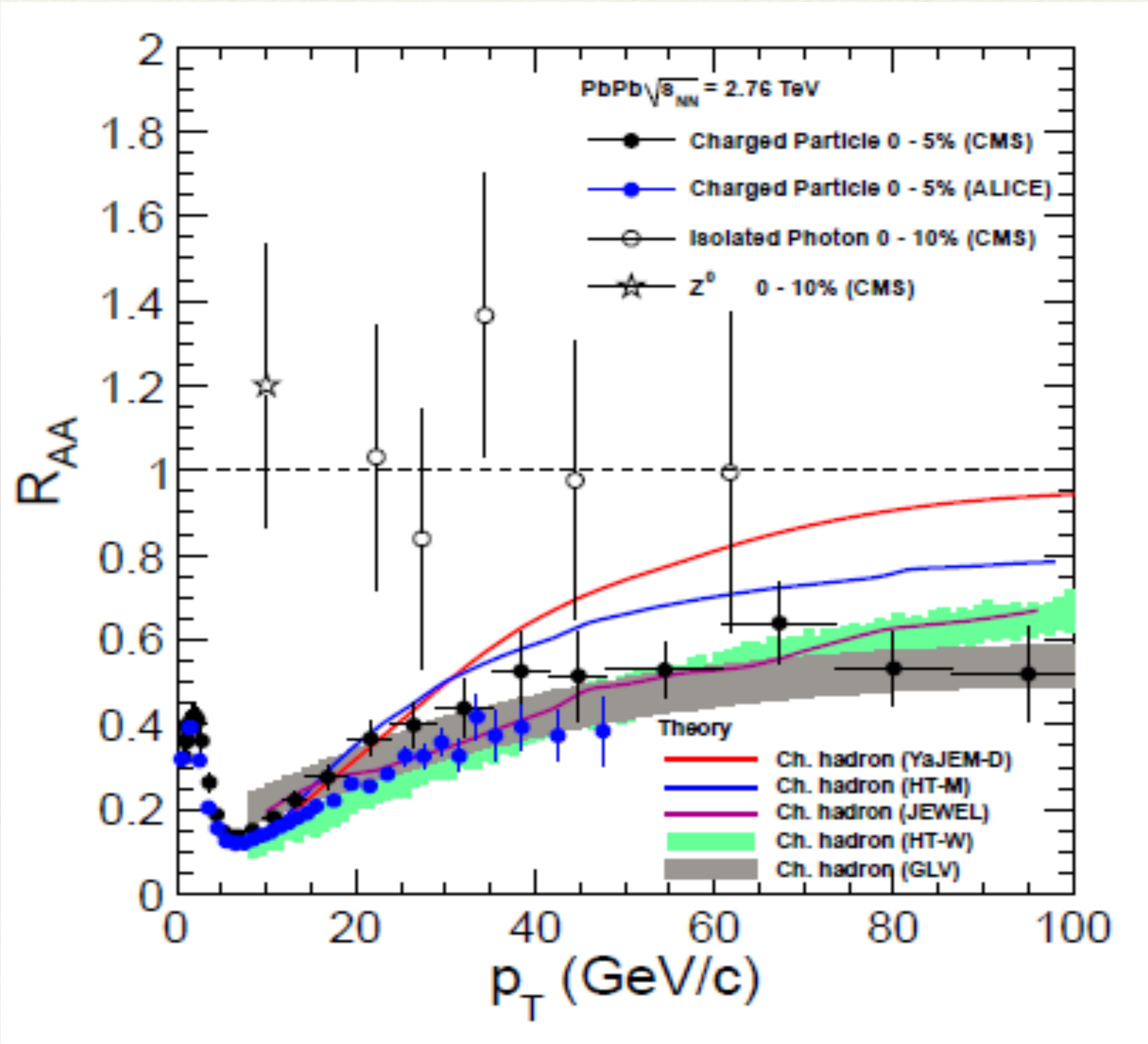
[by M. Rybar / ATLAS]



Jet quenching

Nuclear modification factor

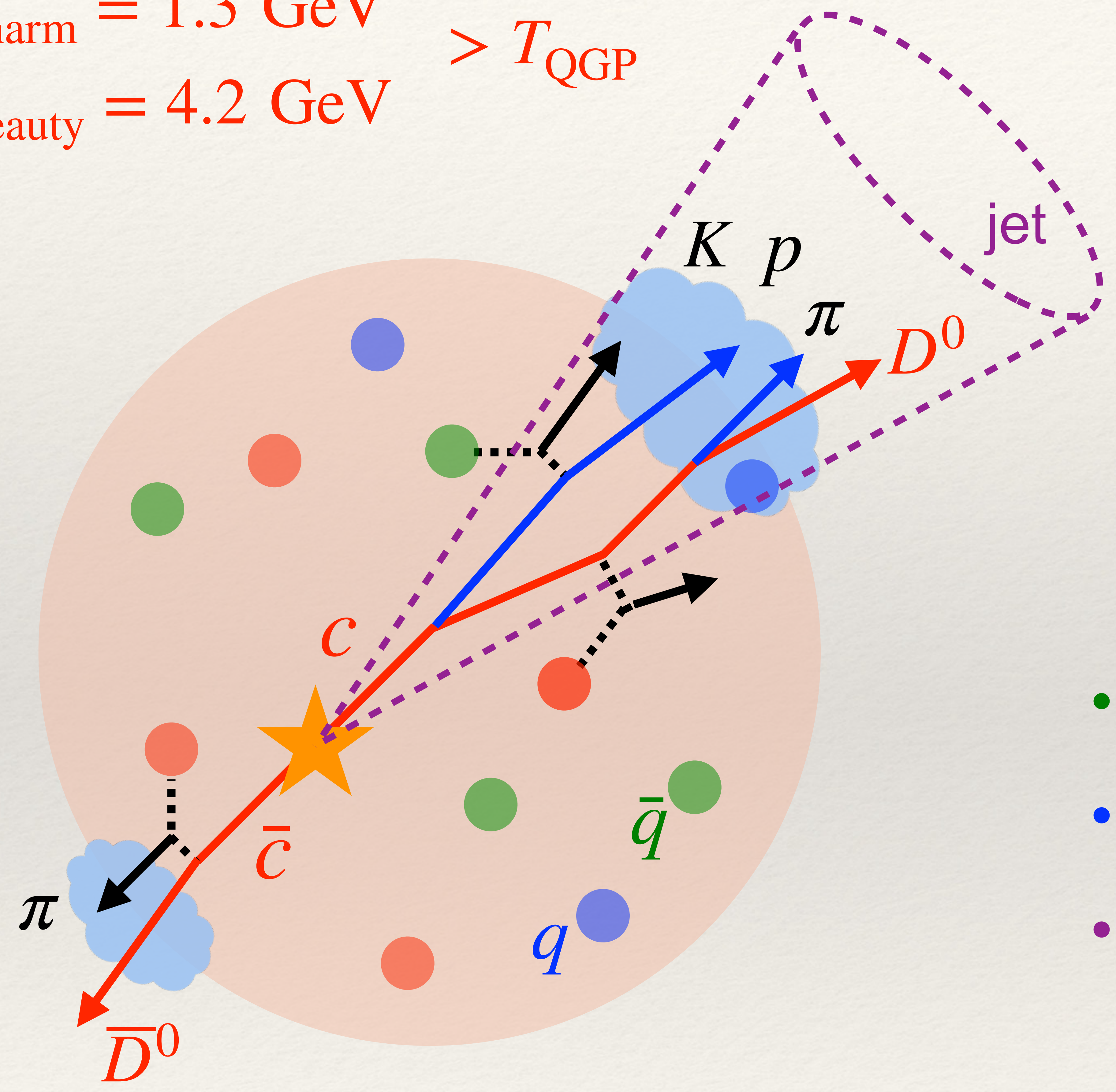
$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA} \rangle}$$



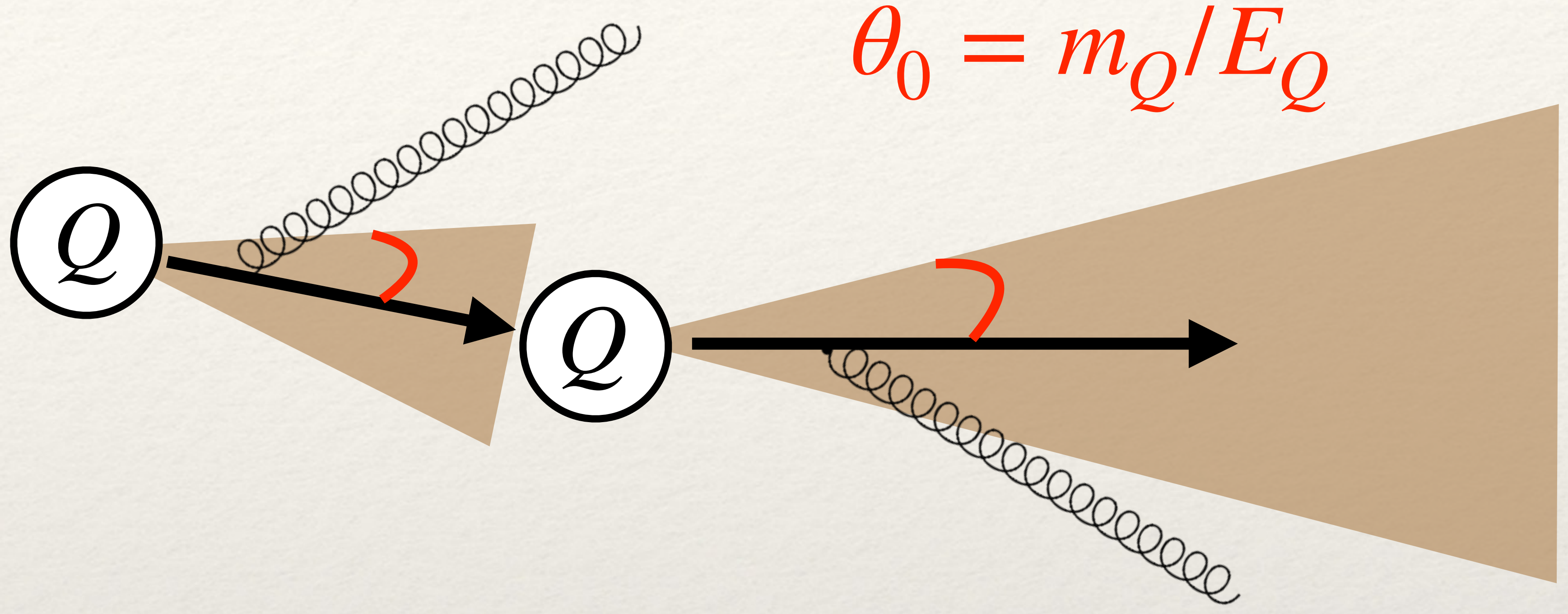
[Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)]

Jets tagged with heavy quarks

$m_{\text{charm}} = 1.3$ GeV
$m_{\text{beauty}} = 4.2$ GeV
$> T_{\text{QGP}}$



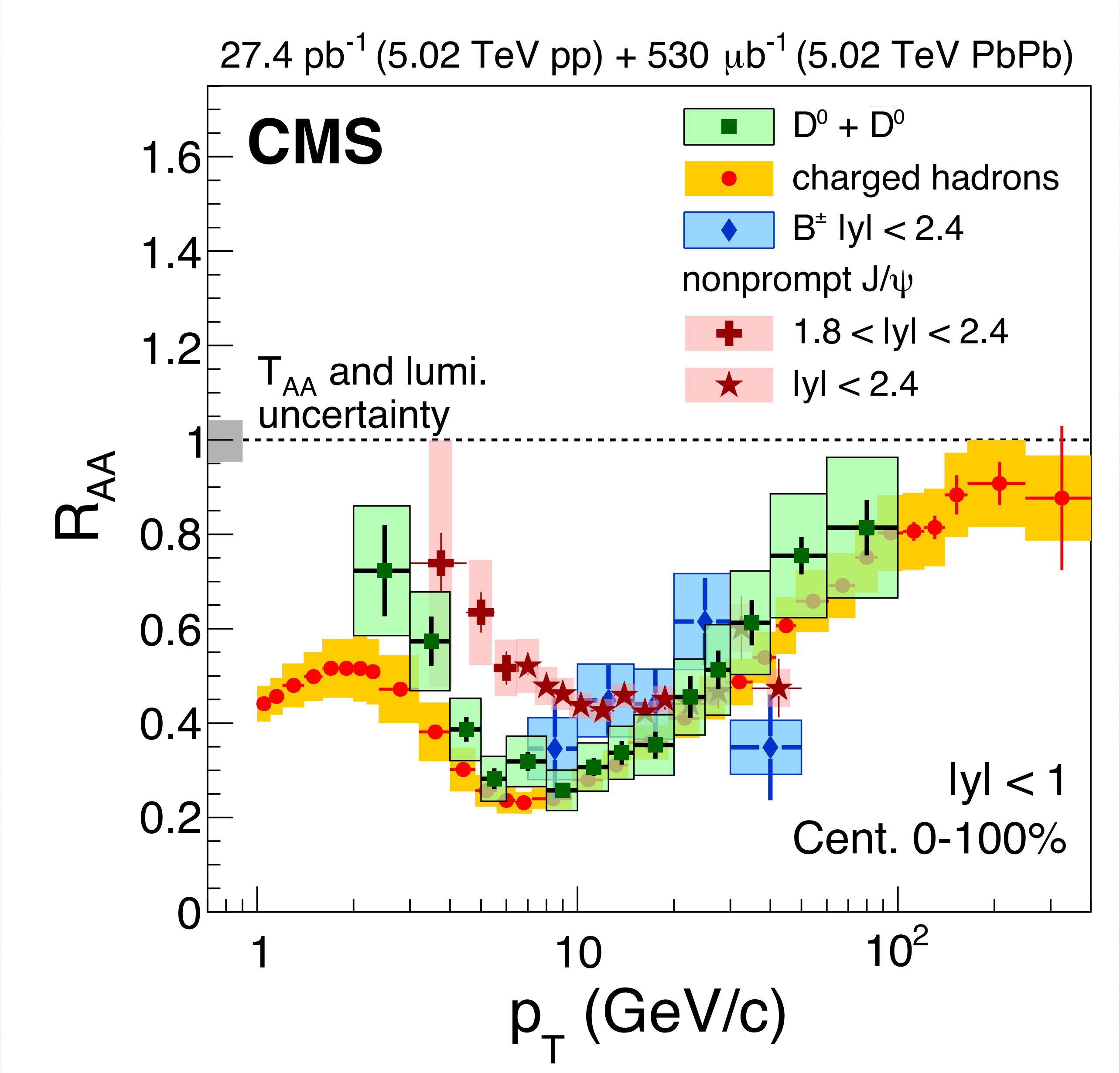
$\theta_0 = m_Q / E_Q$



- Produced from initial hard scatterings
- Serve as an ideal probe of the QGP properties
- Provide a unique opportunity for studying the flavor dependence of parton splitting (dead cone effect)

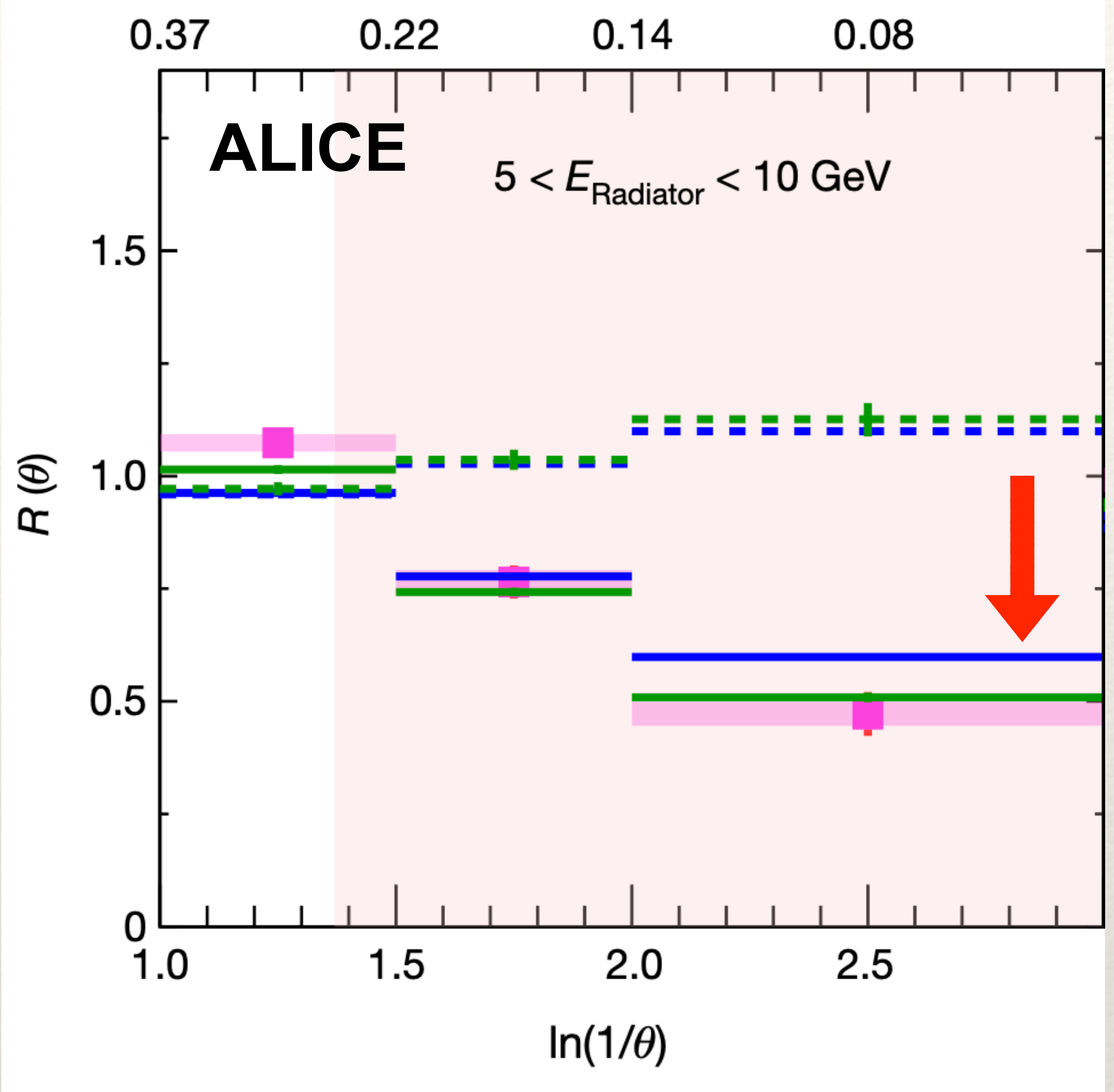
Searches for the flavor dependence of parton splitting

Hadron R_{AA} (parton energy loss)



Phys. Lett. B 782 (2018) 474-496

Distribution of splitting angles in *pp*



Nature 605 (2022) 7910

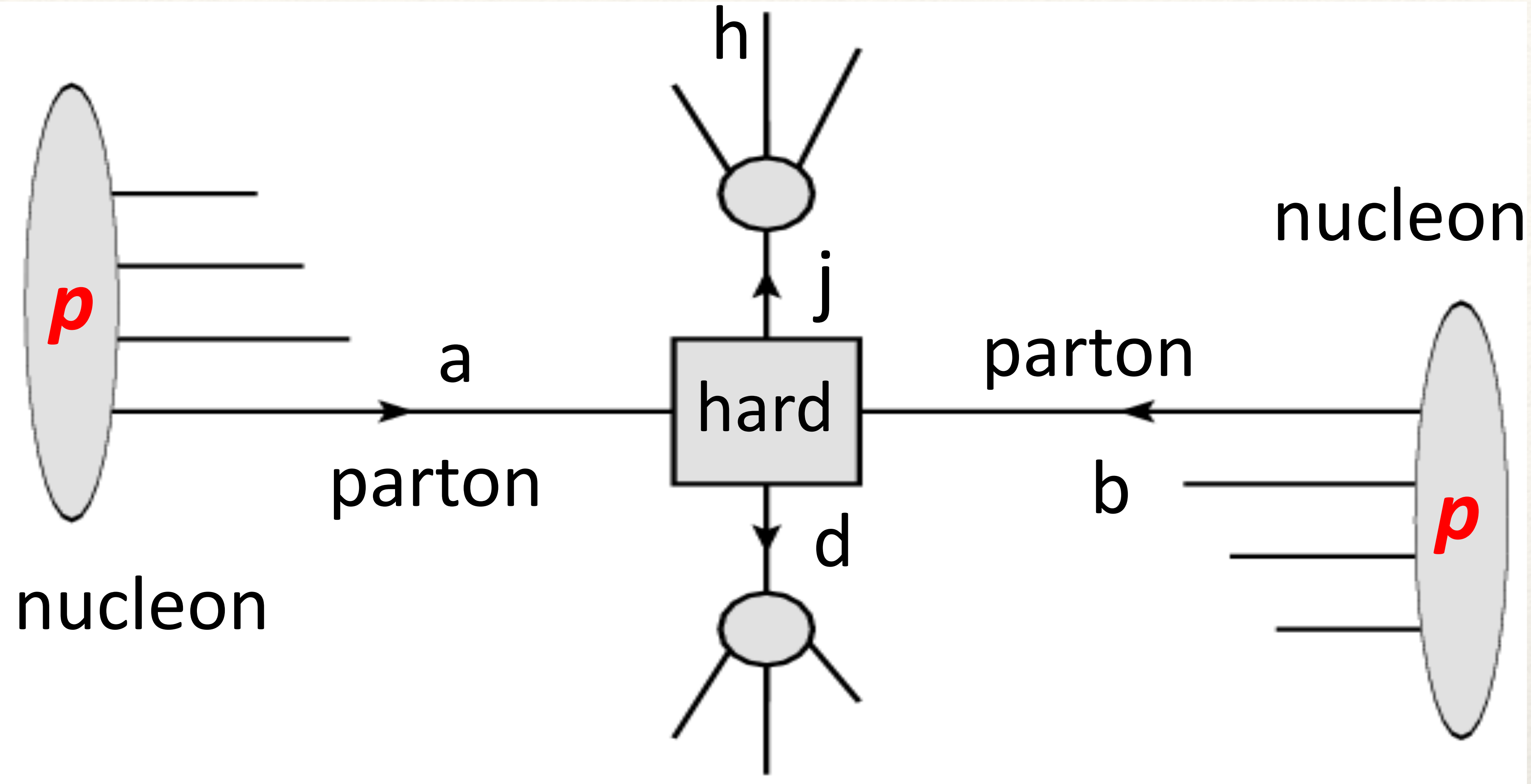
No clear separation between charged hadrons, *D*, and *B*, except at very low p_T

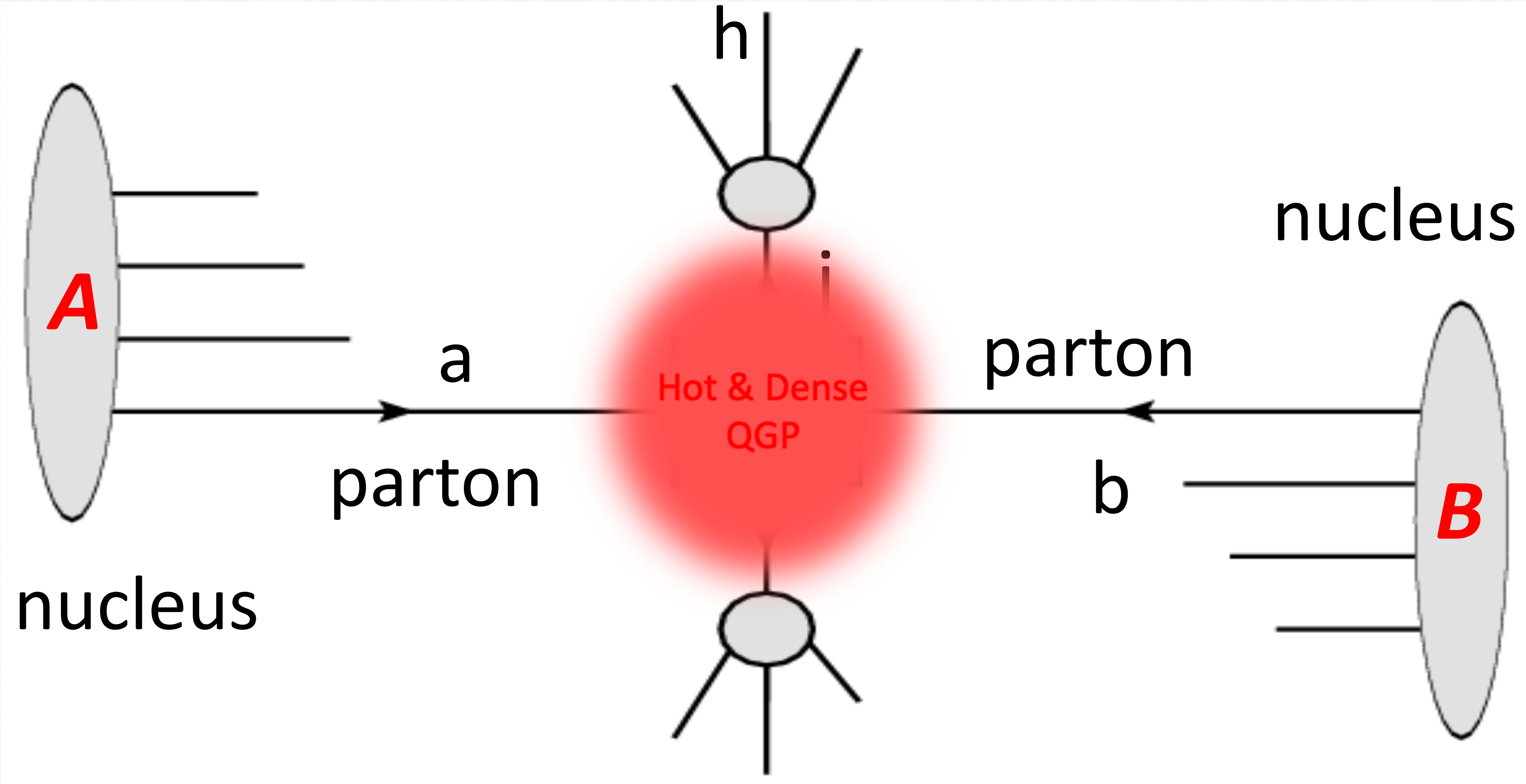
Clear suppression of splitting at small θ in *D*-jets *vs.* inclusive jets

Goals:

- Understand flavor hierarchies embedded in both hadrons and jets
- Use hadron and jet observables to probe the QGP properties

Theoretical framework of jet quenching





$$d\sigma_h = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

$$d\tilde{\sigma}_h = \sum_{abjd} f_{a/A} \otimes f_{b/B} \otimes d\sigma_{ab\to jd} \otimes \tilde{D}_{h/j}$$

- $f_{a/p}, f_{b/p} \to f_{a/A}, f_{b/B}$: cold nuclear matter (initial state) effect, e.g., shadowing, Cronin, … , measured in *pA* collisions
- $D_{h/j} \to \tilde{D}_{h/j}$: medium modified fragmentation function, hot nuclear matter (final state) effect
- Factorization assumption: $\tilde{D}_{h/j} = \sum_{j'} P_{j\to j'} \otimes D_{h/j'}$, nuclear modification of parton *j*

Parton transport inside the QGP

Linear Boltzmann Transport (LBT)

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\rm el} + \mathscr{C}_a^{\rm inel})$$

Parton transport inside the QGP

Linear Boltzmann Transport (LBT)

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\text{el}} + \mathscr{C}_a^{\text{inel}})$$

Elastic scattering ($ab \to cd$ **)**

$$\mathscr{C}_a^{\text{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab \to cd} \right|^2$$

$2 \to 2$ scattering matrices

Parton transport inside the QGP

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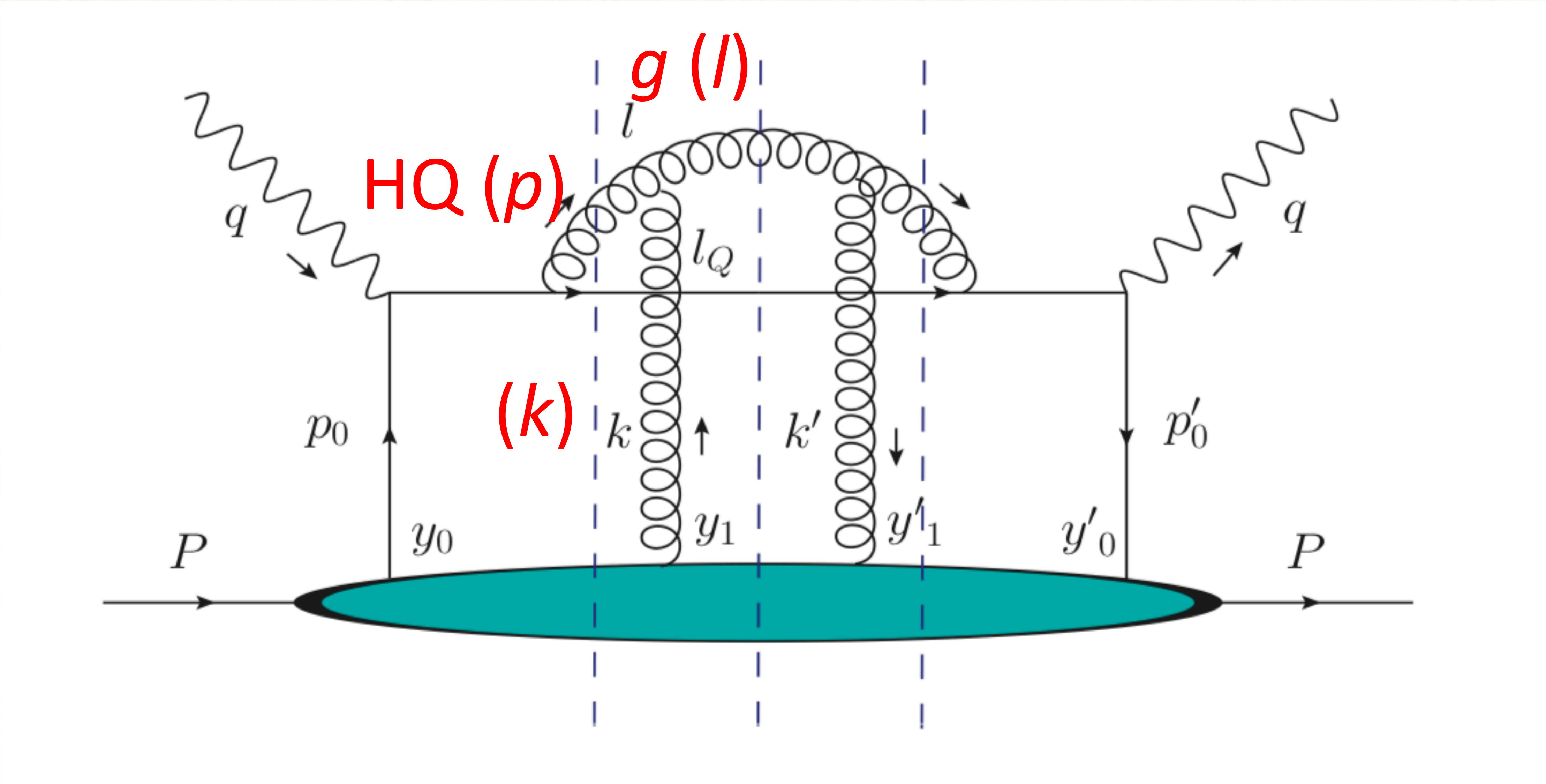
$2 \to 2$ scattering matrices

loss term: **scattering rate**
(for Monte-Carlo simulation)

$$\Gamma_a^{\text{el}}(\mathbf{p}_a, T) = \sum_{b,c,d} \frac{\gamma_b}{2E_a} \int \prod_{i=b,c,d} d[p_i] f_b \cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab\to cd} \right|^2$$

Inelastic scattering



Majumder PRD 85 (2012); Zhang, Wang and Wang, PRL 93 (2004)

- **Higher-twist formalism**: collinear expansion ($\langle k_\perp^2 \rangle \ll l_\perp^2 \ll Q^2$)

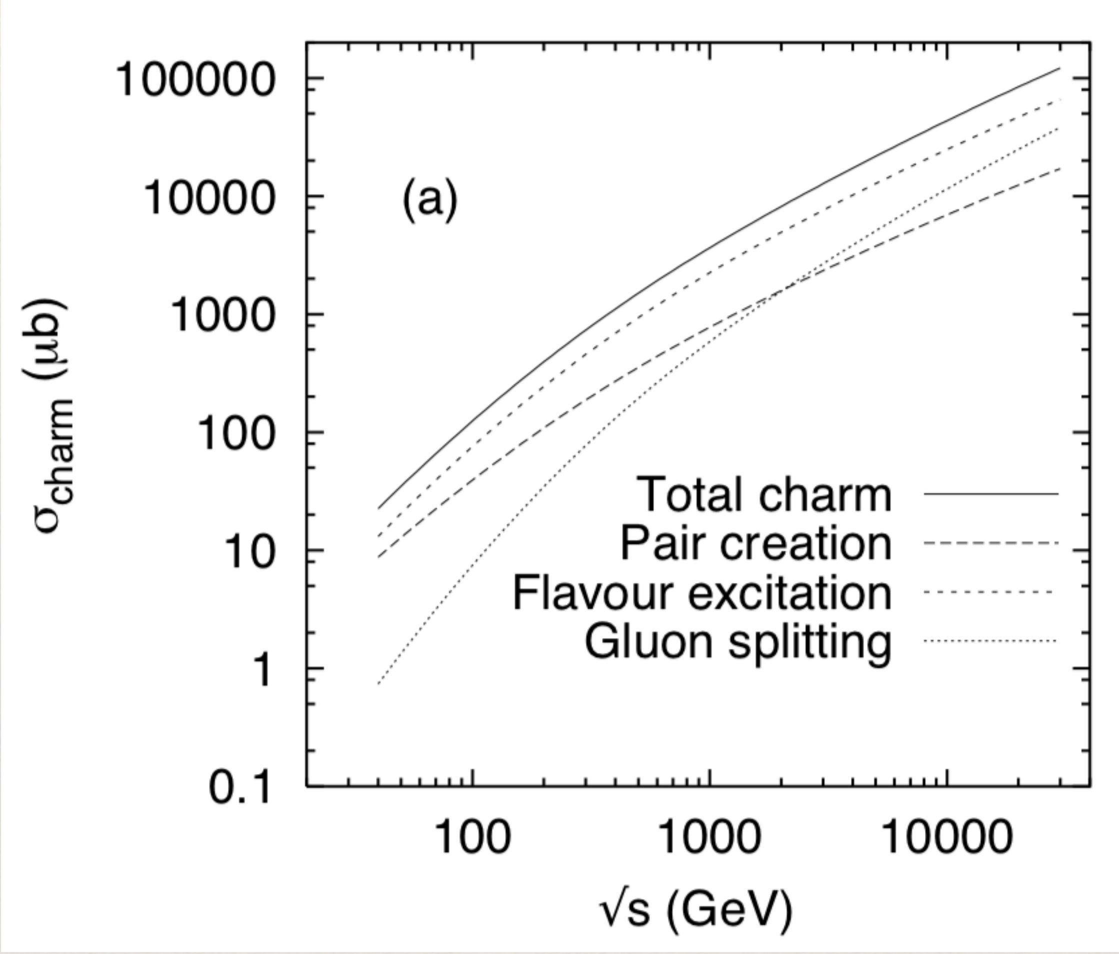
$$\frac{d\Gamma_a^{\rm inel}}{dz dl_\perp^2} = \frac{dN_g}{dz dl_\perp^2 dt} = \frac{6\alpha_s P(z) l_\perp^4 \hat{q}}{\pi(l_\perp^2 + z^2M^2)^4} \sin^2\left(\frac{t - t_i}{2\tau_f}\right)$$

- Medium information absorbed in $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$

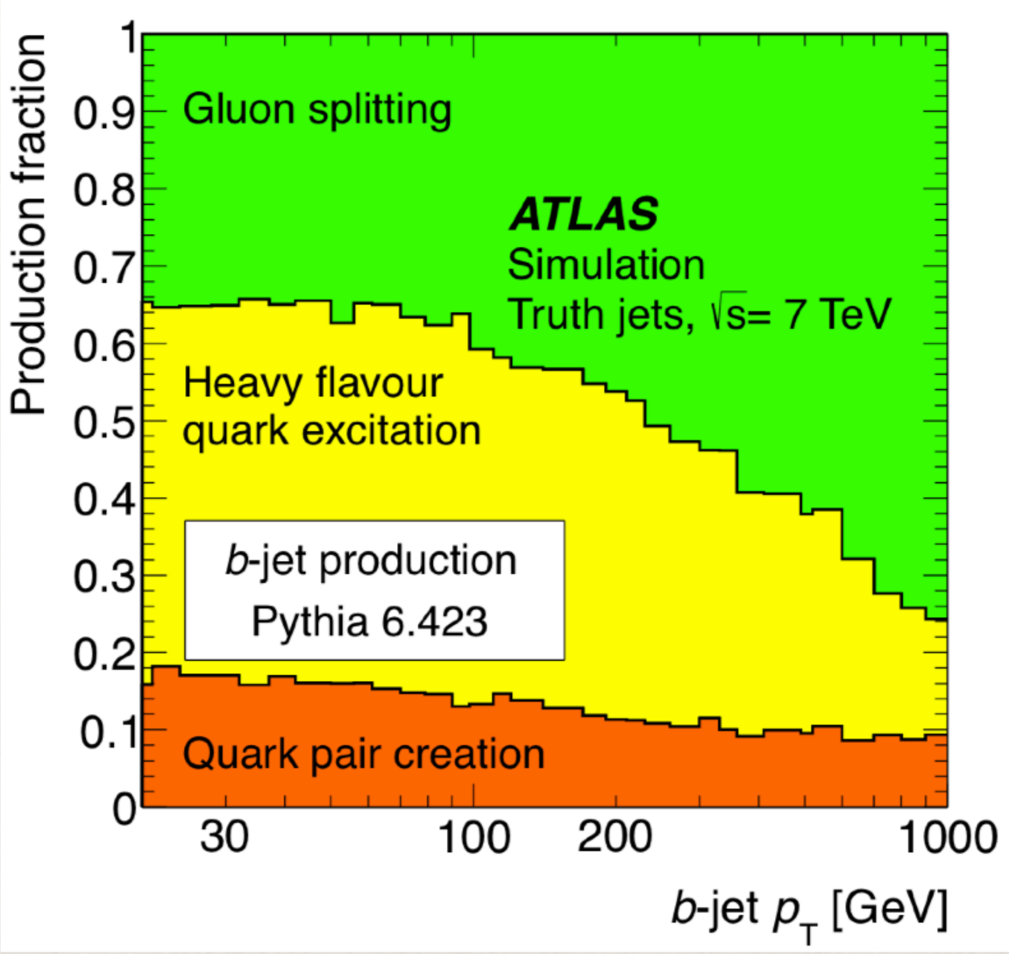
Flavor hierarchy of hadron suppression

- Hadron production in *pp* collisions: NLO production + fragmentation

NLO contribution to HQ production in Pythia simulation (gluon splitting)



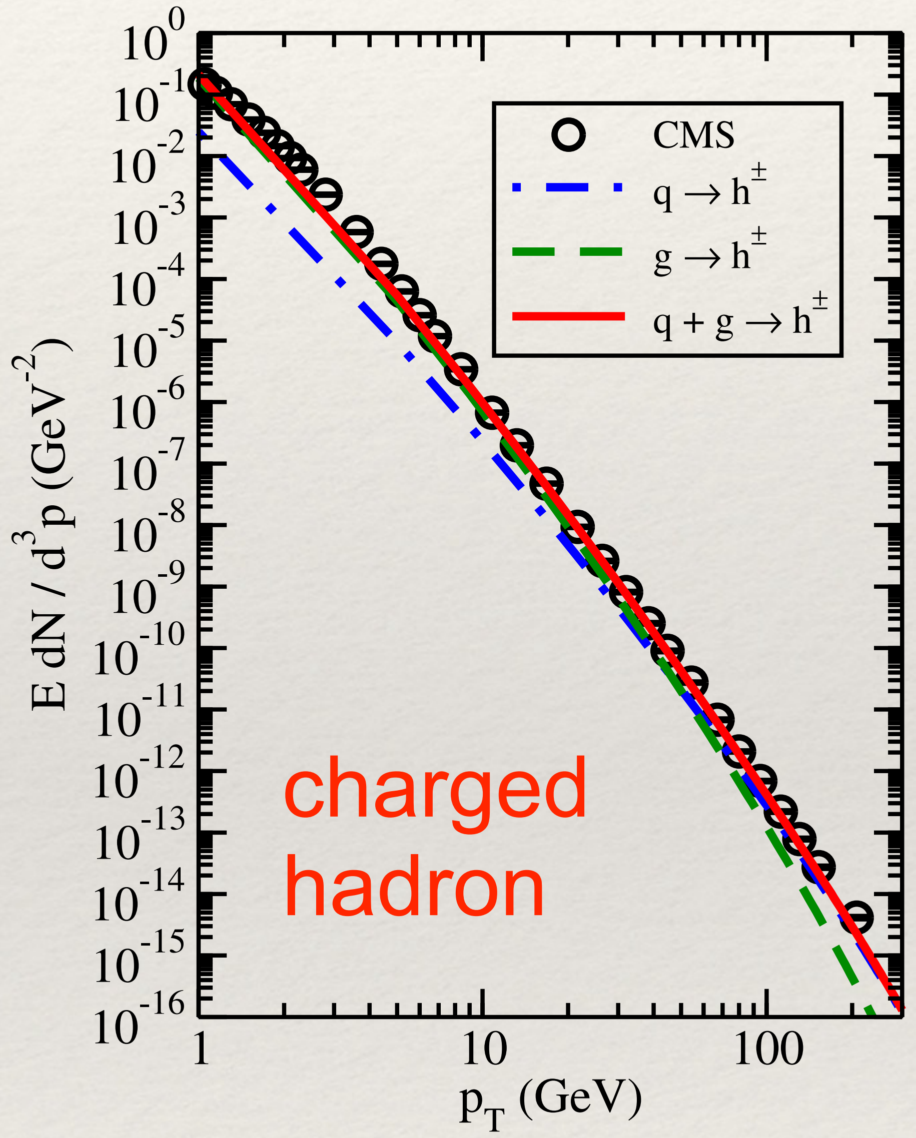
[Norrbin and Sjostrand, EPJC 17 (2000)]

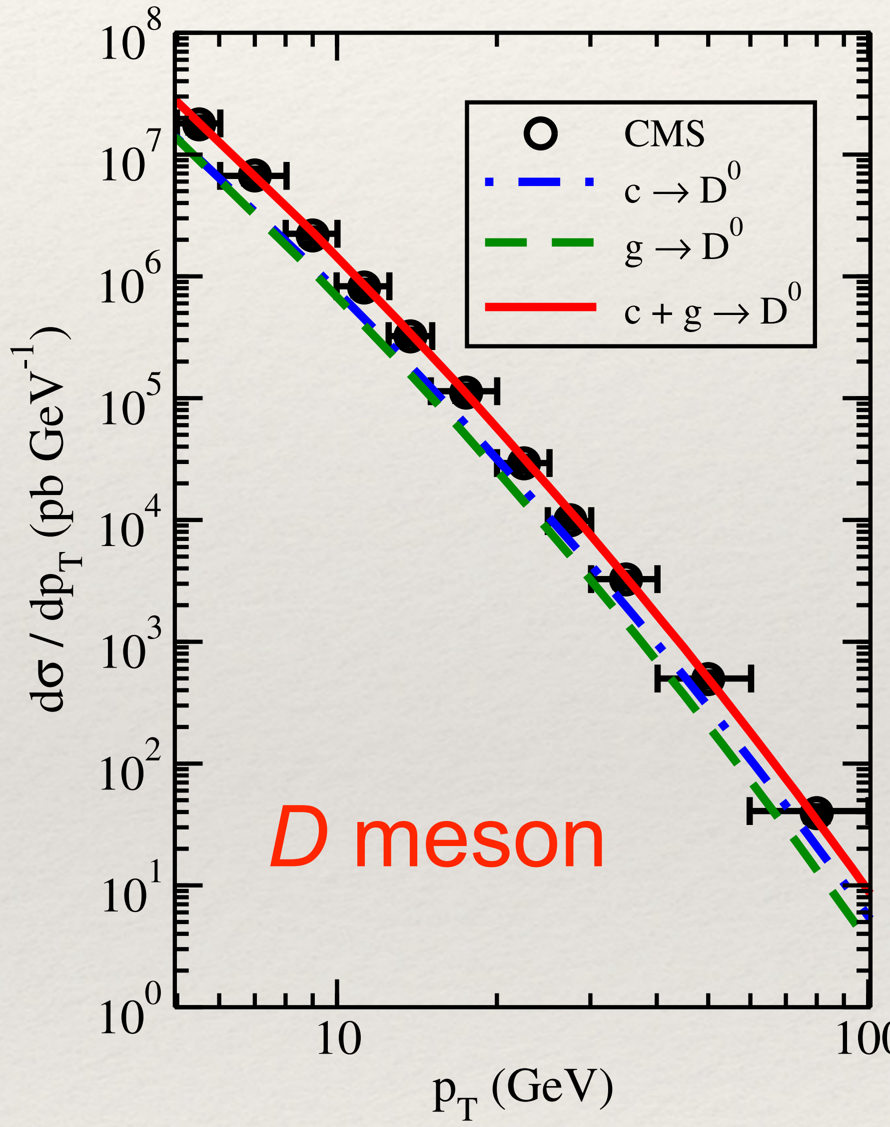


[ATLAS, EPJC 73 (2013)]

- NLO contribution increases with $\sqrt{s}$
- NLO contribution increases with *b*-jet p_T

Different NLO contributions to light and heavy flavor hadrons



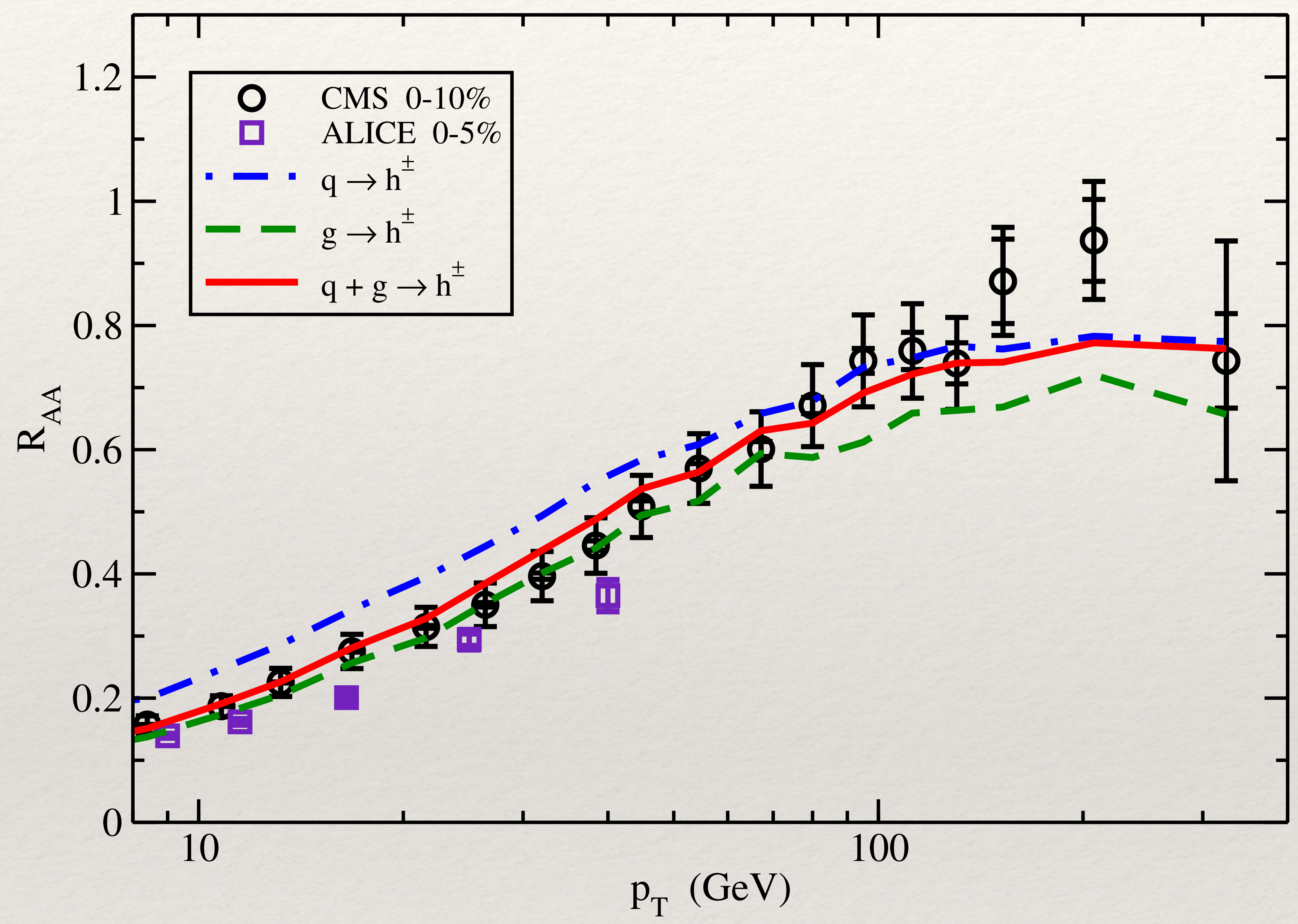


- dominates $h^{\pm}$ production up to 50 GeV
- contributes to over 40% *D* up to 100 GeV

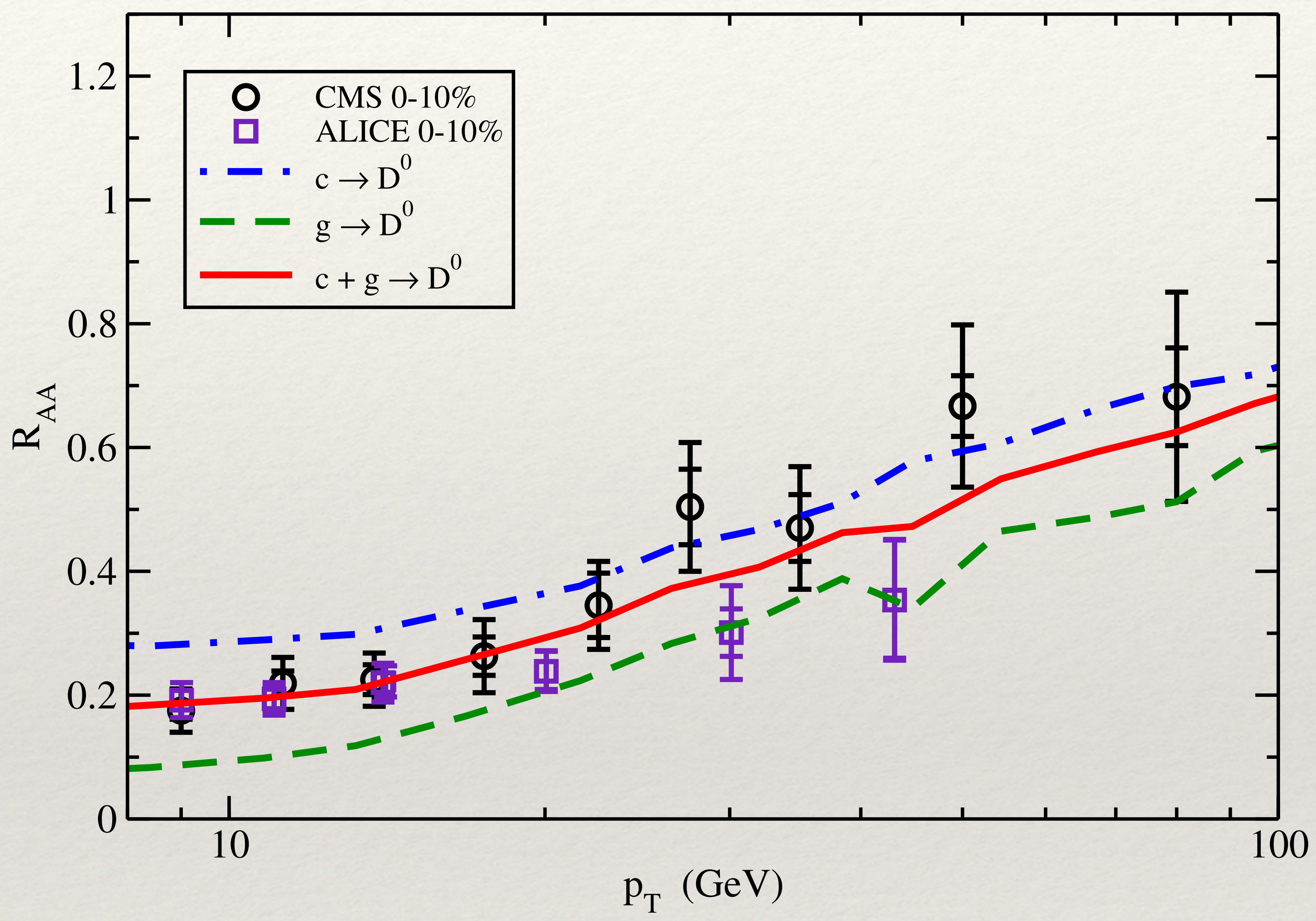
Flavor hierarchy of hadron suppression

NLO initial production and fragmentation + Boltzmann transport + hydrodynamic medium for QGP

charged hadron



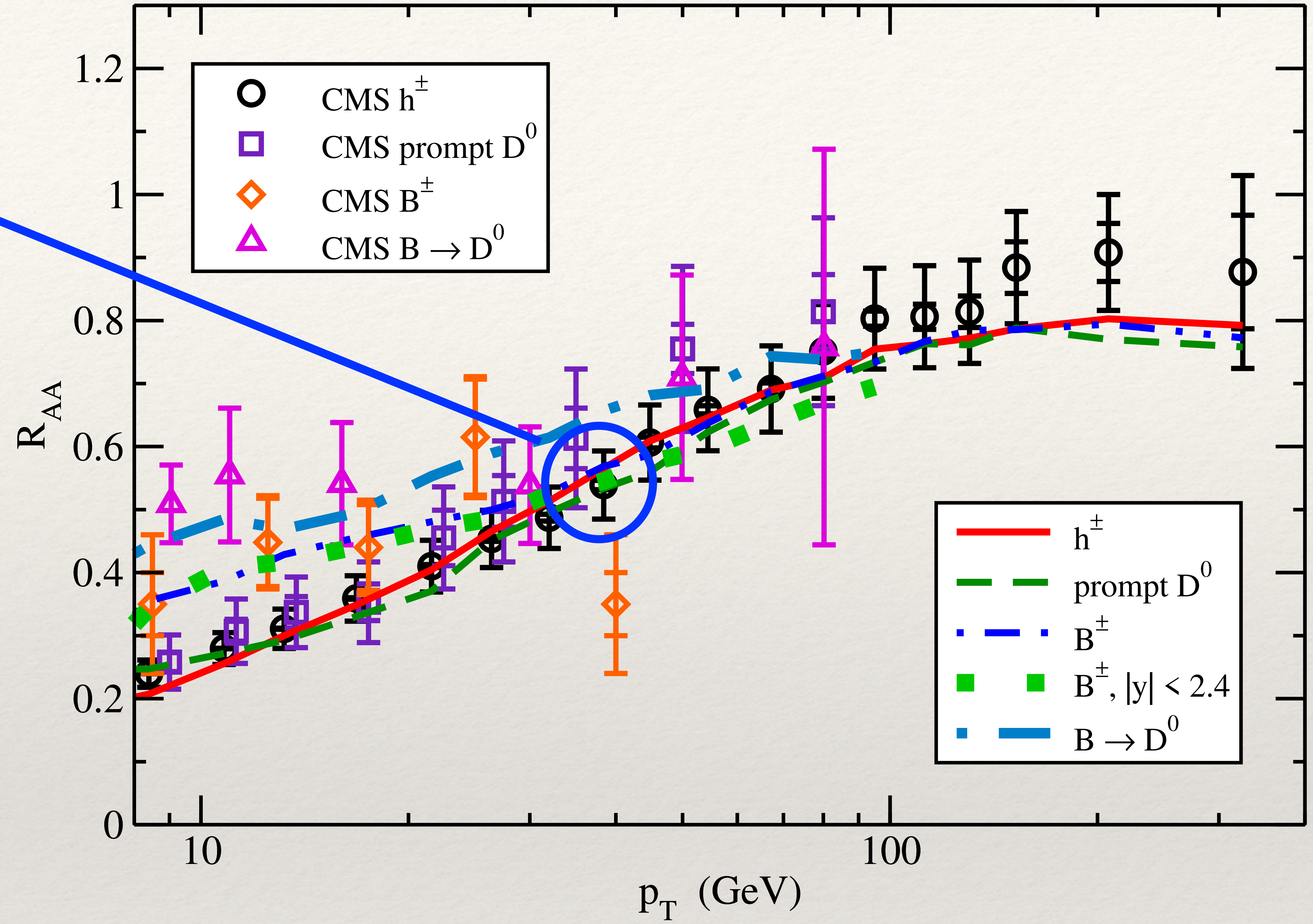
D meson



- *g*-initiated *h* & *D* R_{AA} < *q*-initiated *h* & *D* R_{AA} [$\Delta E_g > \Delta E_{q/c}$]
- R_{AA} (*c*->*D*) > R_{AA} (*q*->*h*) [$\Delta E_q > \Delta E_c$], R_{AA} (*g*->*D*) < R_{AA} (*g*->*h*) [different FFs] => R_{AA} (*h*) ≈ R_{AA} (*D*)
- Signature of flavor hierarchy of parton ΔE offset by NLO production/fragmentation in hadron R_{AA}

Flavor hierarchy of hadron suppression

Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



Xing, SC, Qin and Xing, Phys. Lett. B 805 (2020) 135424

- A simultaneous description of charged hadron, *D* meson, *B* meson, *B*-decay *D* meson R_{AA}'s starting from p_T ~ 8 GeV
- Predict R_{AA} separation between *B* and *h* / *D* below 40 GeV, but similar values above – **wait for confirmation from future precision measurement**

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Extraction of parton energy loss from hadron R_{AA}

NLO initial production and fragmentation + **Parametrized** parton energy loss inside the QGP

$$\frac{d\sigma_{AA\to hX}}{dp_T^h} = \sum_j \int_0^\infty dp_T^j \int_0^{\frac{p_T^j}{\langle \Delta p_T^j \rangle}} dx \int_0^1 dz \frac{d\hat{\sigma}_{p'p'\to jX}}{dp_T^j}(p_T^j) W_{AA}(x) D_{j\to h}(z) \delta\left[p_T^h - z\left(p_T^j - x\langle \Delta p_T^j \rangle\right)\right]$$

- Mean p_T loss: $\langle \Delta p_T^j \rangle = C_j \beta_g p_T^\gamma \log(p_T)$
  - β_g: overall magnitude for g
  - C_j: flavor dependence
  - γ: p_T dependence
- p_T loss distribution: $W_{AA}(x) = \frac{\alpha^\alpha x^{\alpha-1} e^{-\alpha x}}{\Gamma(\alpha)}$

$$x \equiv \Delta p_T / \langle \Delta p_T \rangle$$

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Bayesian calibration of parameter set $\boldsymbol{\theta}$

$$P(\boldsymbol{\theta}\,|\,\text{data}) \propto P(\text{data}\,|\,\boldsymbol{\theta})\, P(\boldsymbol{\theta})$$

posterior distribution — $P(\boldsymbol{\theta}\,|\,\text{data})$

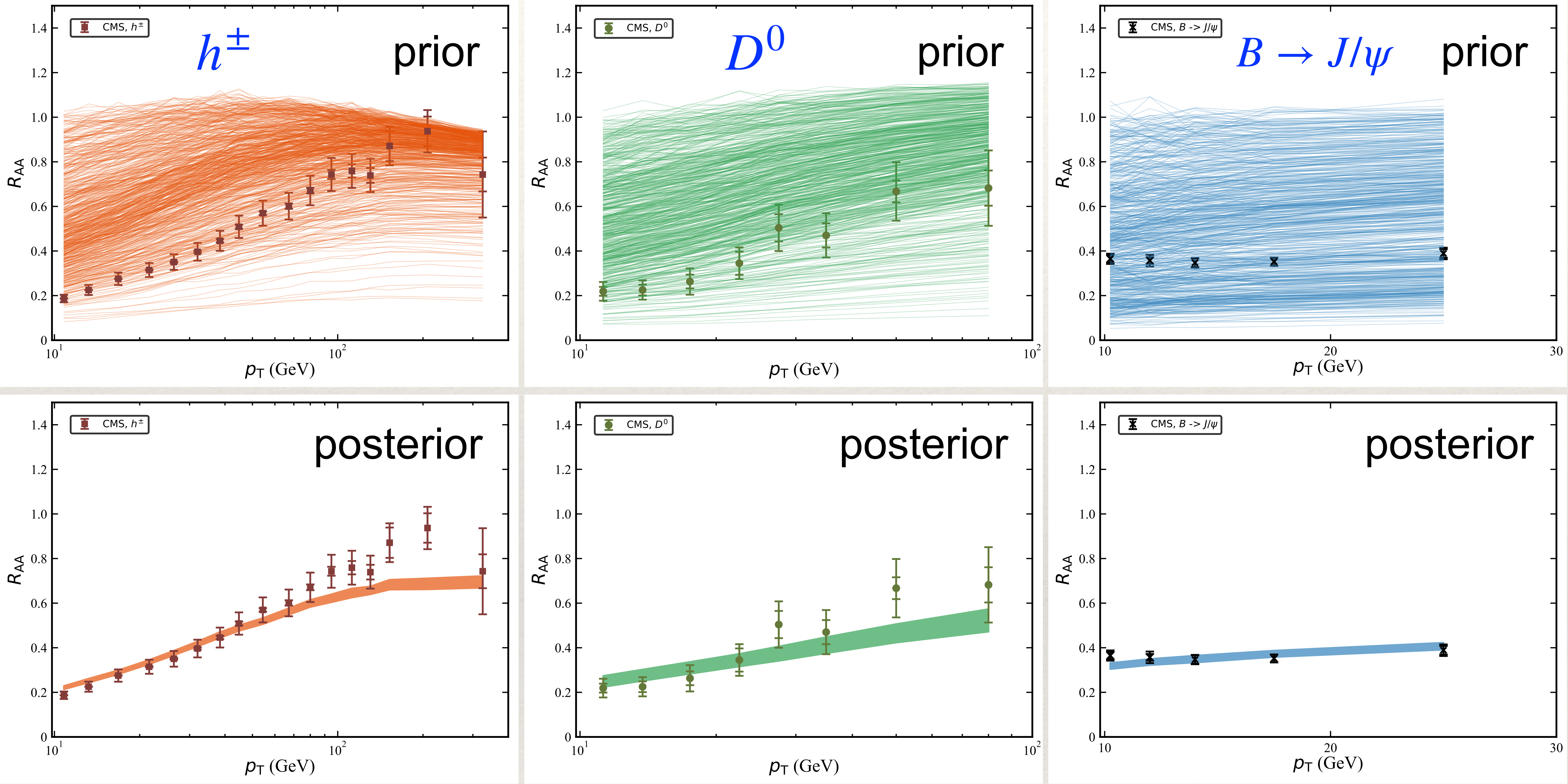
prior distribution — $P(\boldsymbol{\theta})$

model-to-data comparison — $P(\text{data}\,|\,\boldsymbol{\theta})$:

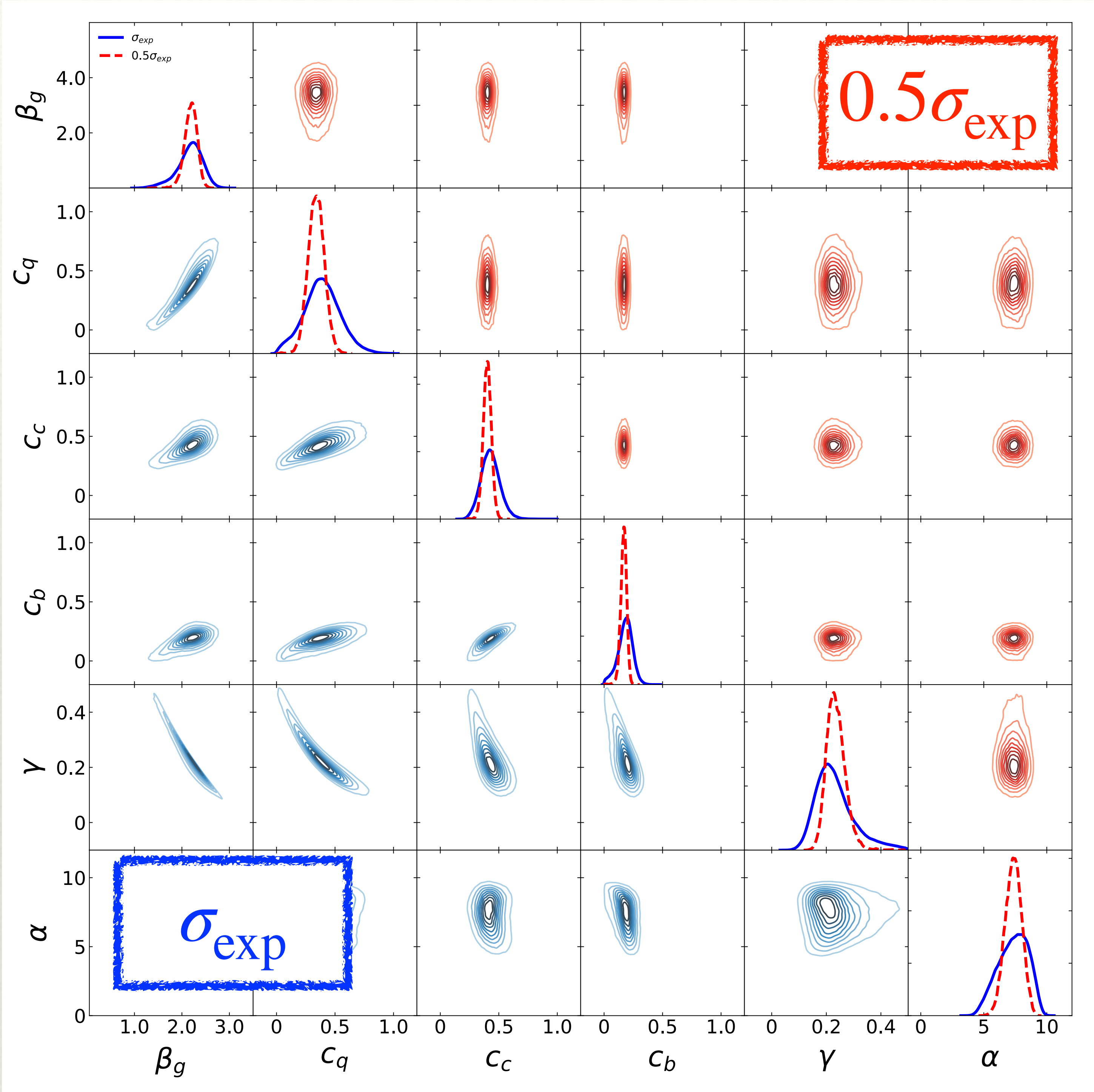
$$P(\text{data}\,|\,\boldsymbol{\theta}) = \prod_i e^{-\frac{\left[y_i(\boldsymbol{\theta}) - y_i^{\text{exp}}\right]^2}{2\sigma_i^2}}$$

Bayesian calibration

Calibration on $\boldsymbol{\theta} = (\beta_g, C_q, C_c, C_b, \gamma, \alpha)$



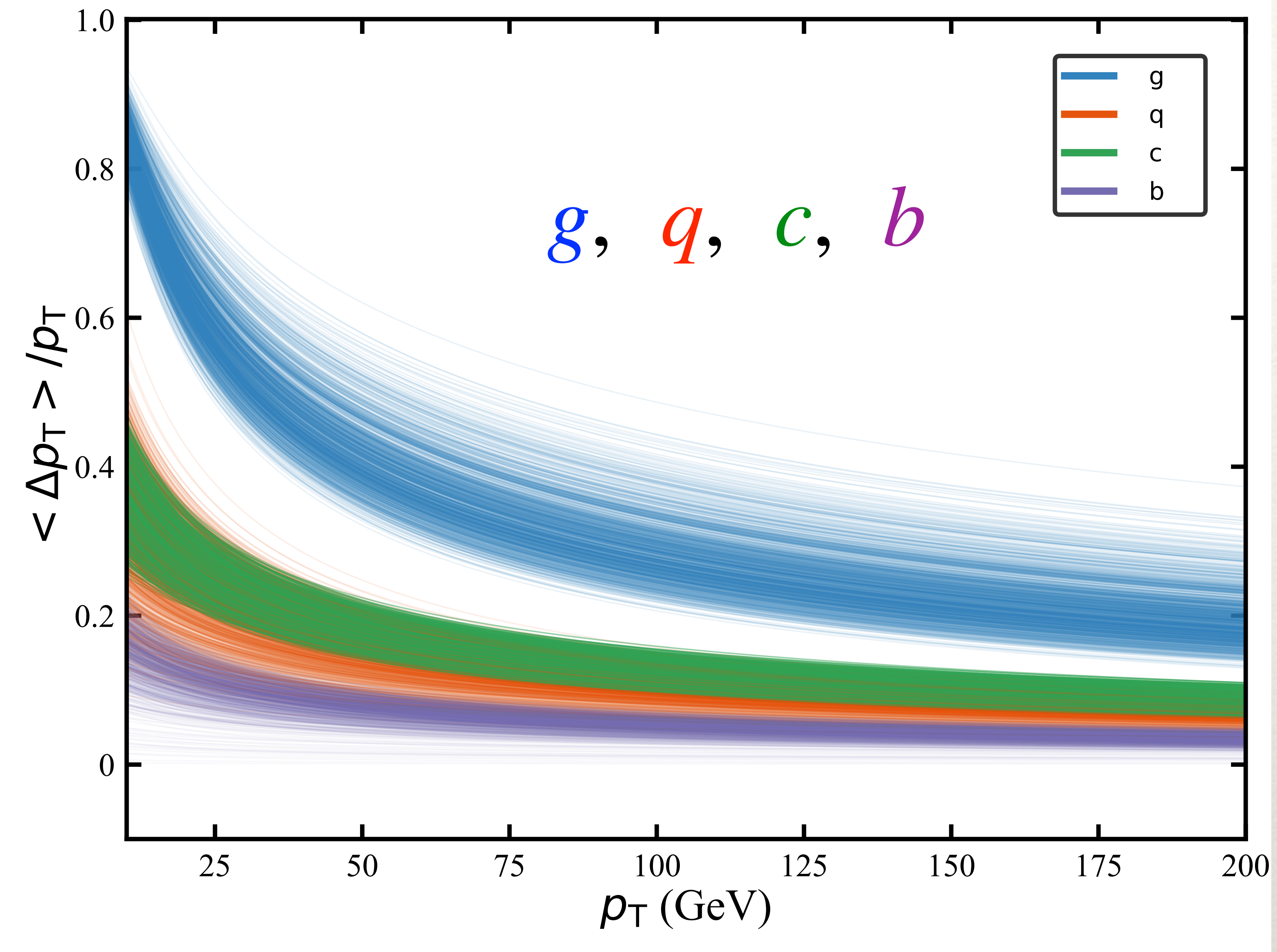
Posterior distribution of $\boldsymbol{\theta}$



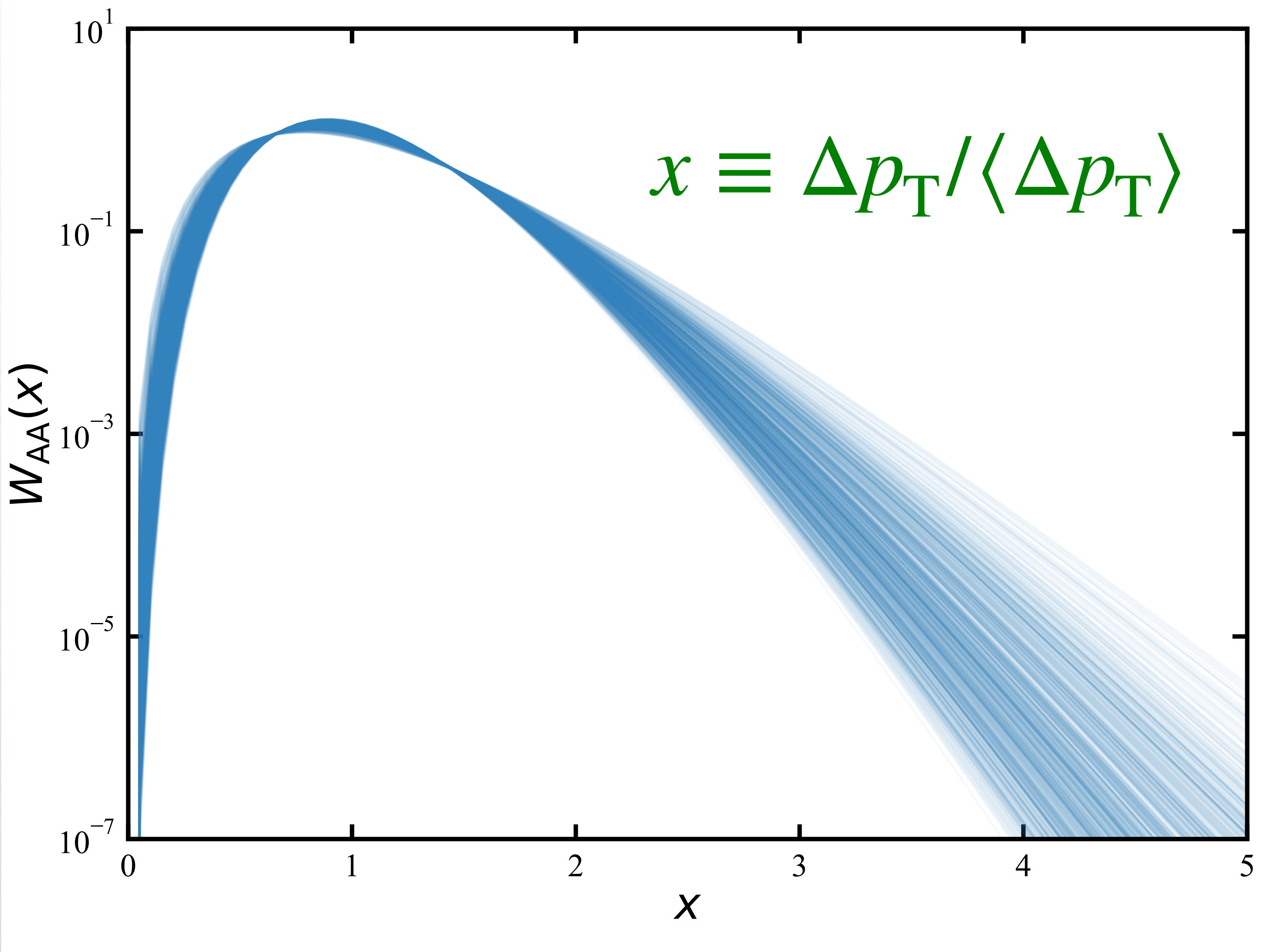
- A simultaneous calibration on the R_{AA} of charged hadrons, D mesons and B-decay J/ψ
- Halved experimental errors would provide tighter constraints on model parameters

Extraction of parton energy loss from hadron R_{AA}

Average energy loss



Energy loss distribution

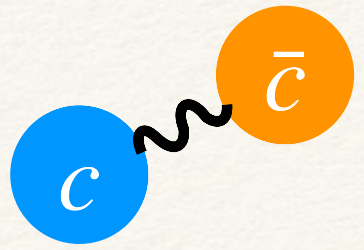


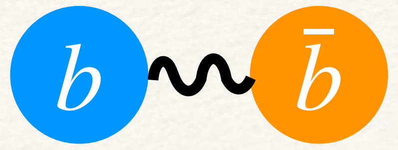
Xing, SC, Qin, Phys. Lett. B 850 (2024) 138523

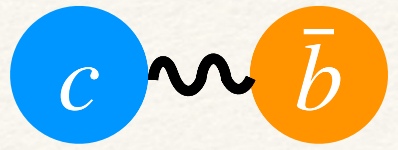
- $\Delta E_g > \Delta E_q \sim \Delta E_c > \Delta E_b$
- More stringent test on QCD calculation

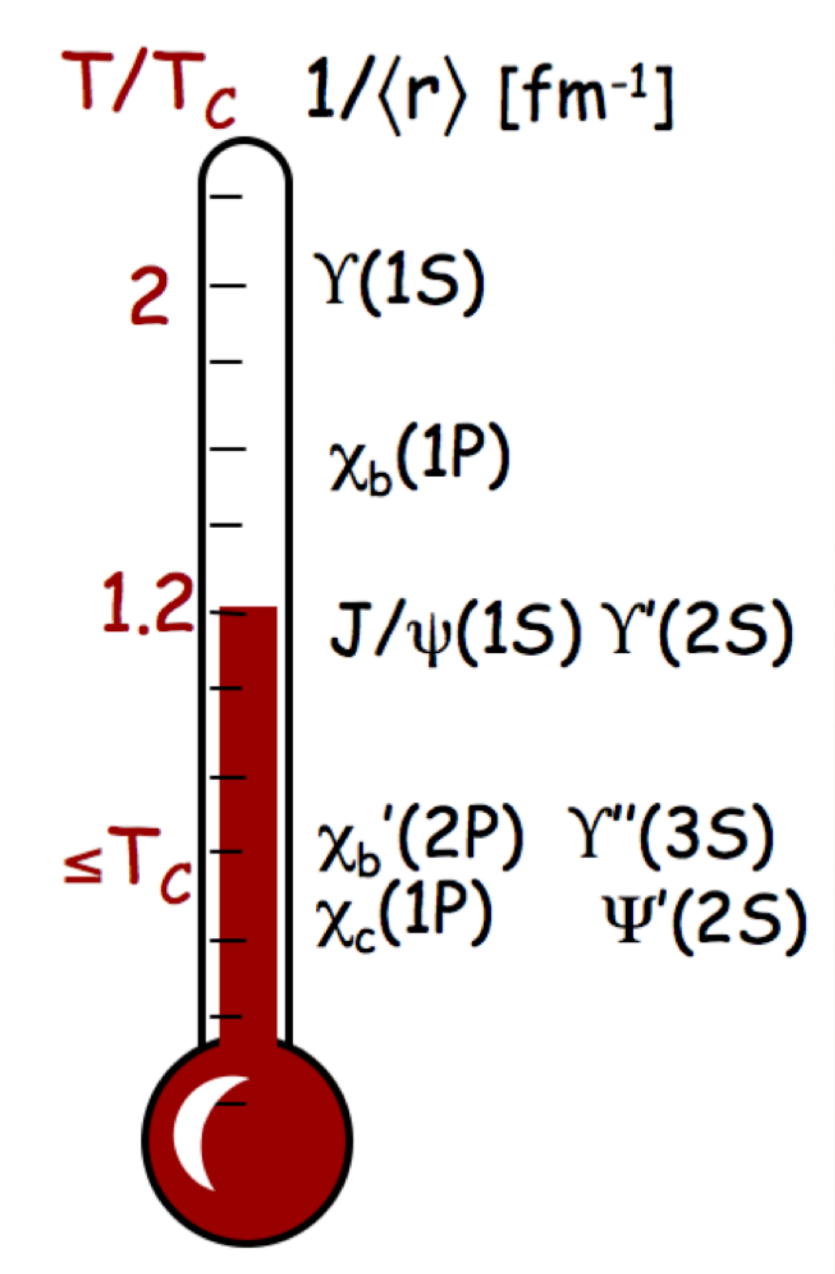
- Flavor hierarchy of parton energy loss is encoded in the hadron R_{AA} data
- No obvious hierarchy for the hadron R_{AA} data themselves, due to the interplay between parton energy loss and NLO production and fragmentation

From single-HQ hadrons to bound states of HQs

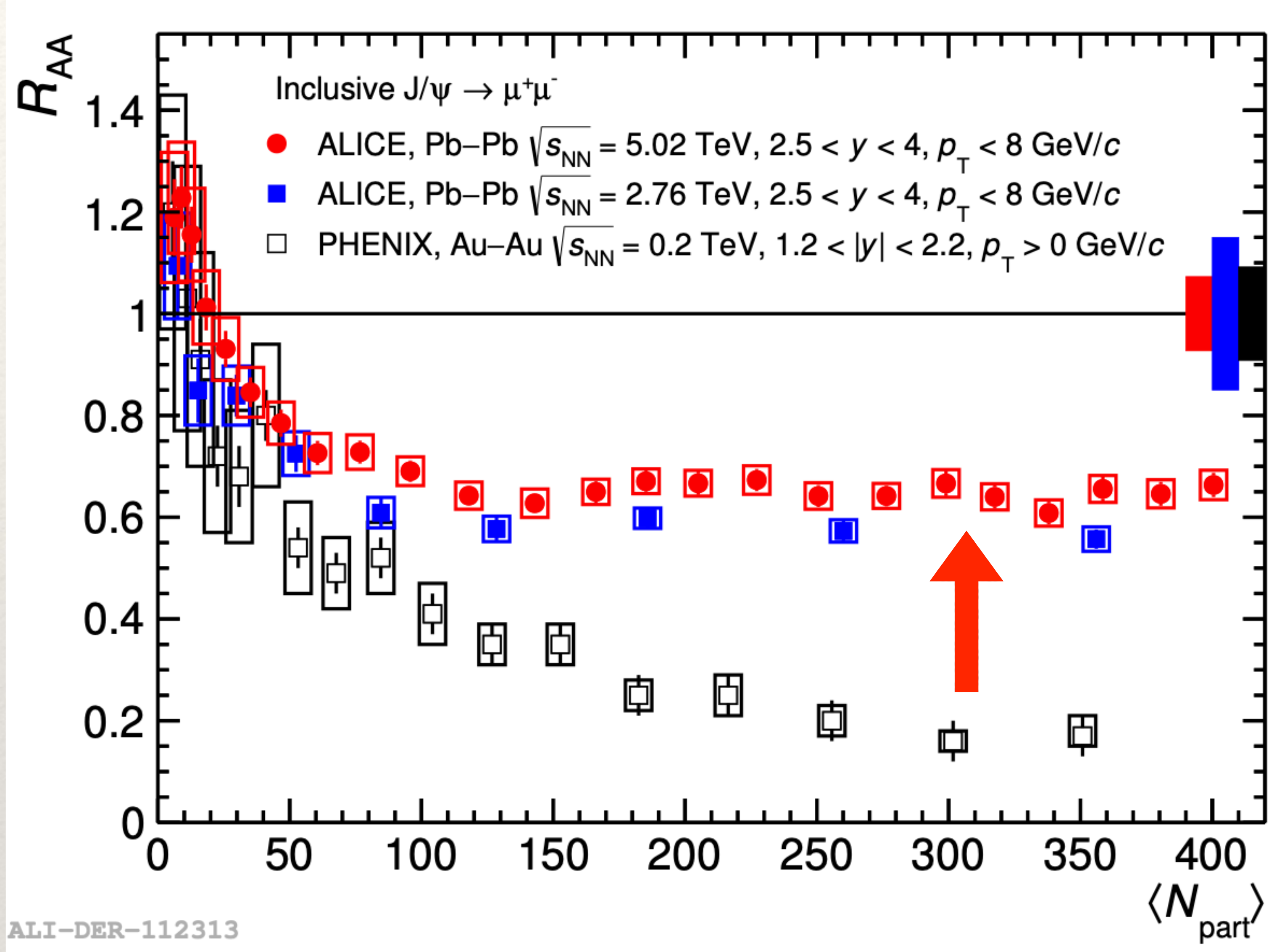




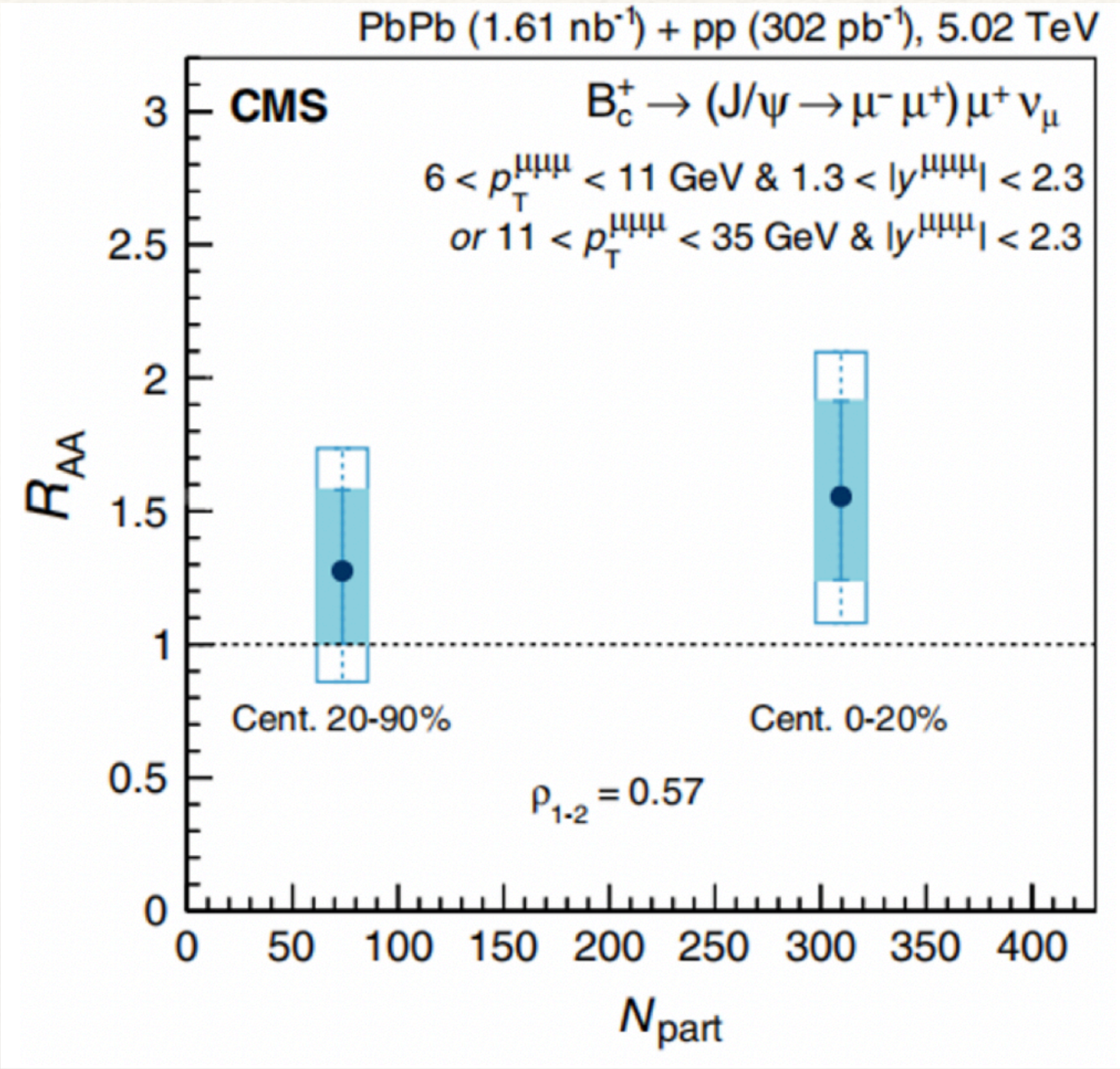




[Mocsy, EPJC 61 (2009) 705]



[Scomparin, NPA 967 (2017) 208]



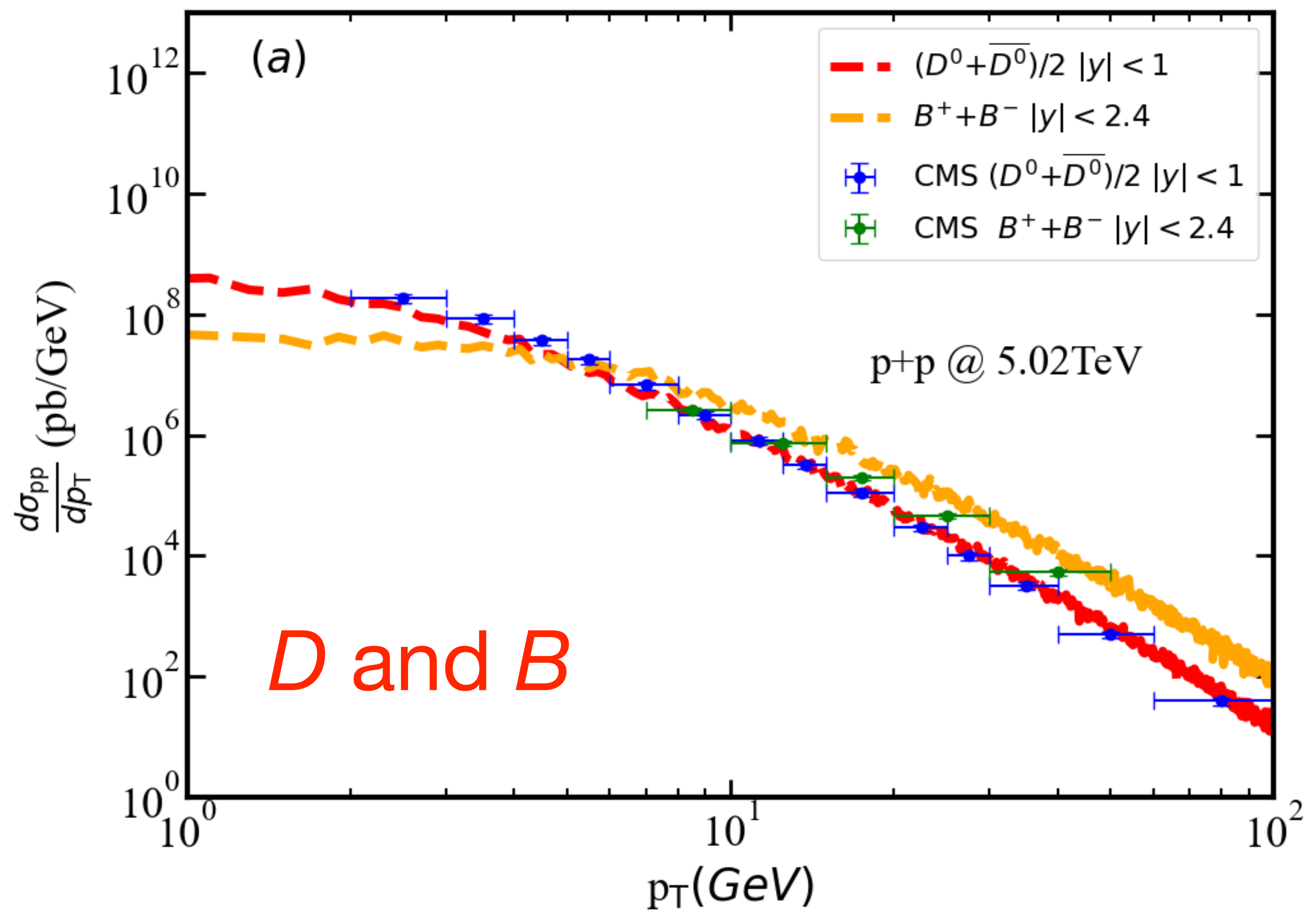
[CMS, PRL 128 (2022) 252301]

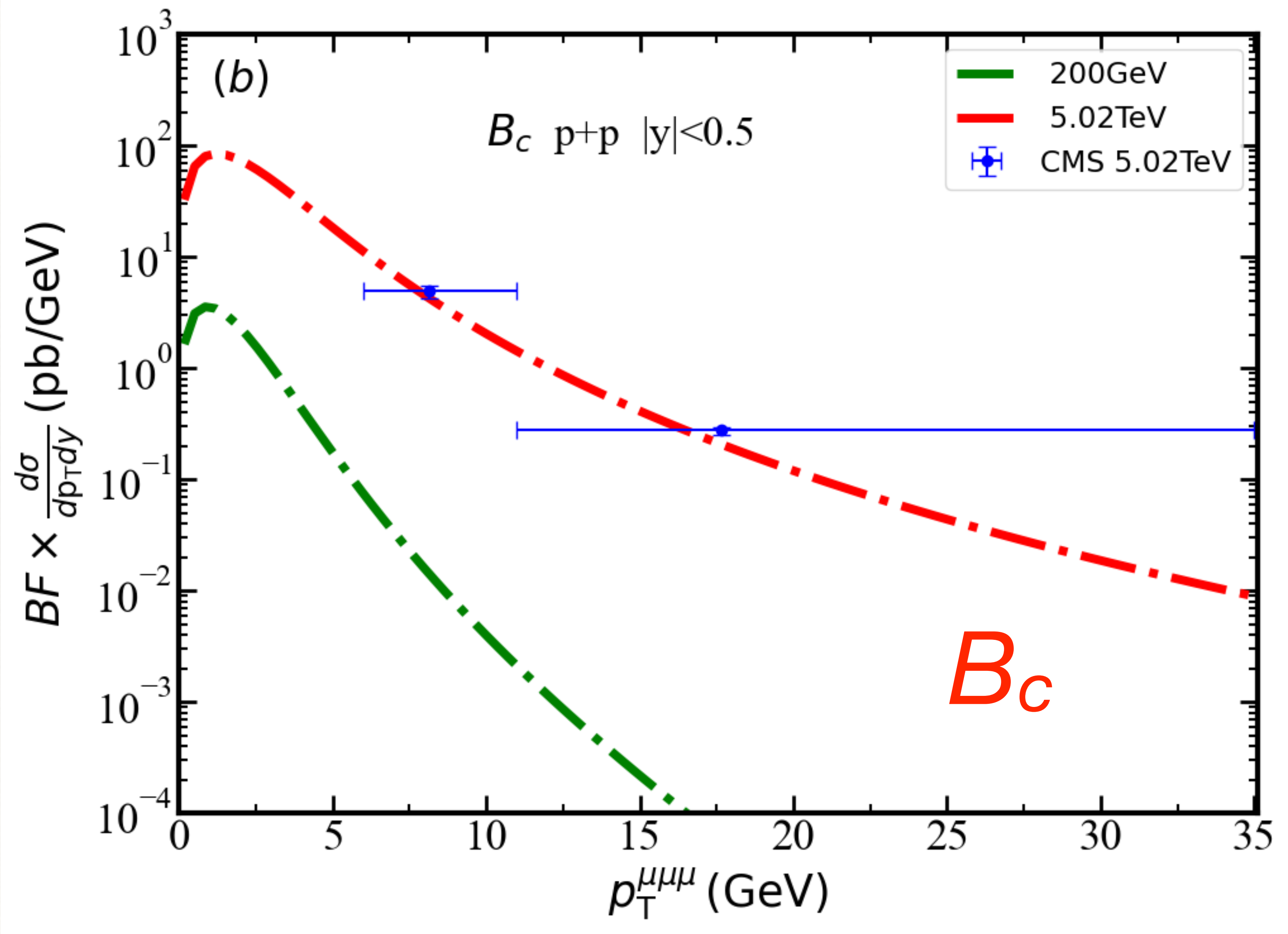
- Sequential melting of heavy quarkonia serves as a QGP thermometer
- Regeneration of heavy quarkonia is important at high heavy quark density
- Measurement on B_c mesons provides a new opportunity for studying heavy quarks

Initial production of B_c

- Initial charm and bottom quarks: FONLL
- *D* and *B* mesons in *pp*: *c*/*b* quark + Pythia fragmentation
- B_c in *pp*: *b* quark + fitted fragmentation function [Braaten, Cheung, Yuan, Phys. Rev. D 48 (1993) R5049]

$$D_{b\to B_c^-}(z) = N\frac{rz(1-z)^2}{[1-(1-r)z]^6}\left[6-18(1-2r)z+(21-74r+68r^2)z^2-2(1-r)(6-19r+18r^2)z^3+3(1-r)^2(1-2r+2r^2)z^4\right]$$





- NLO contribution not included in this calculation yet

Medium modification of B_c

- Dissociation (quasi-free dissociation picture): [Wu, Tang, He, Rapp, Phys. Rev. C 109 (2024) 014906]

$$\Gamma_{B_c}^{\text{disso}}(p) = \Gamma_c\left(\frac{m_c}{m_c+m_b}p\right) + \Gamma_b\left(\frac{m_b}{m_c+m_b}p\right)$$

$\Gamma_{c/b}$: Rate of scattering with $k^2 > \epsilon_b^2$

k: 4-momentum exchange, ϵ_b: binding energy of B_c

- Regeneration (coalescence of medium-modified *c* and *b* quarks):

$$\frac{d^3N_{B_c}(\vec{p})}{d^3p} = C_r g_{B_c} \int d^3p_c d^3p_{\bar{b}} \frac{d^3N_c(\vec{p}_c)}{d^3p_c}\frac{d^3N_{\bar{b}}(\vec{p}_b)}{d^3p_{\bar{b}}} W(\vec{k})\, \delta^{(3)}\left(\vec{p} - \vec{p}_c - \vec{p}_{\bar{b}}\right)$$

- ✴ $\sigma_{s/p}$ from $B_c(1S/P)$ radii
- ✴ C_r fit from N_{part} dependence of R_{AA}

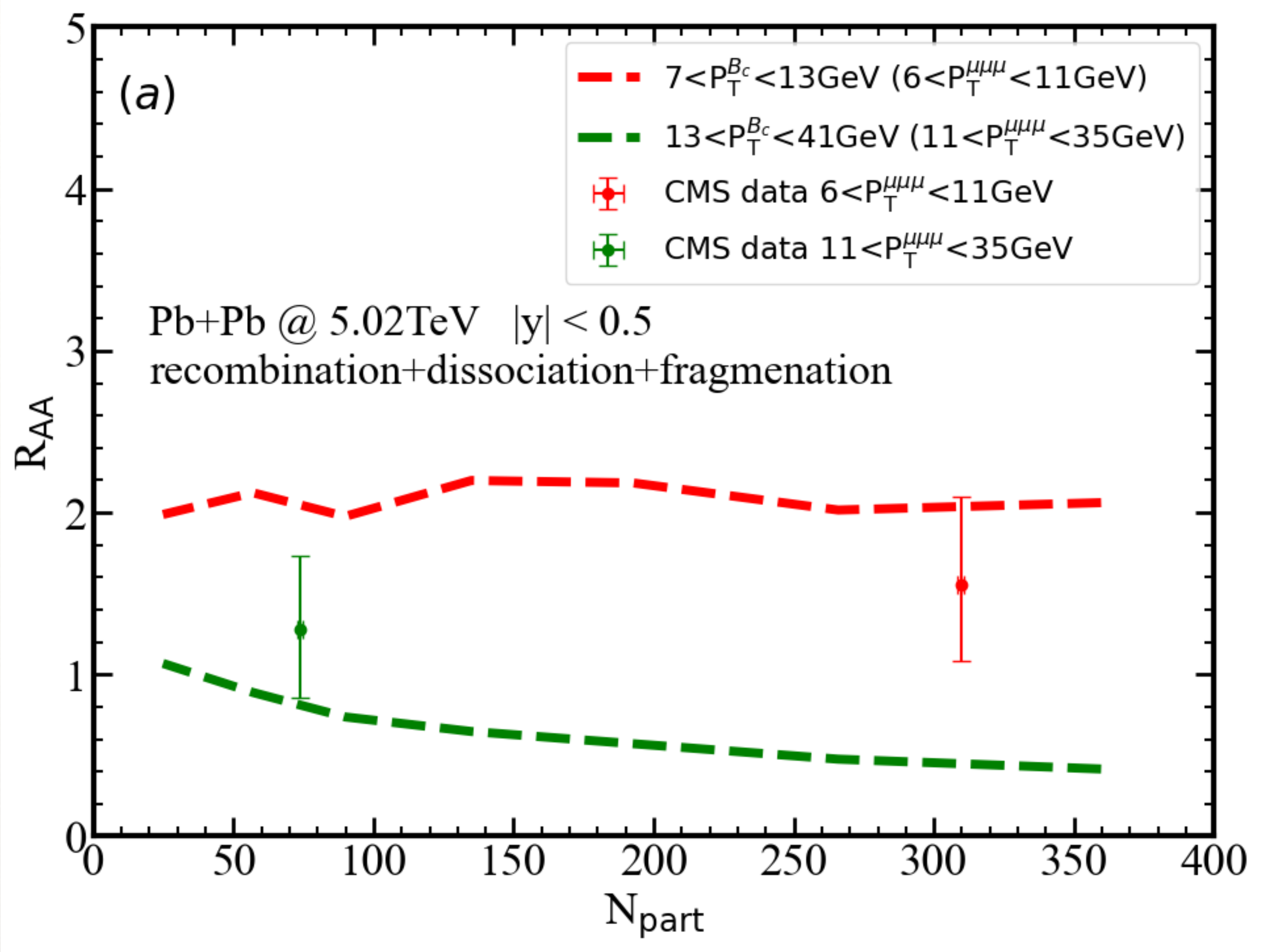
$$W_s(k) = \frac{(2\sqrt{\pi}\sigma_s)^3}{V} e^{-\sigma_s{}^2k^2} \qquad W_p(k) = \frac{(2\sqrt{\pi}\sigma_p)^3}{V}\frac{2}{3}\sigma_p{}^2k^2 e^{-\sigma_p{}^2k^2}$$

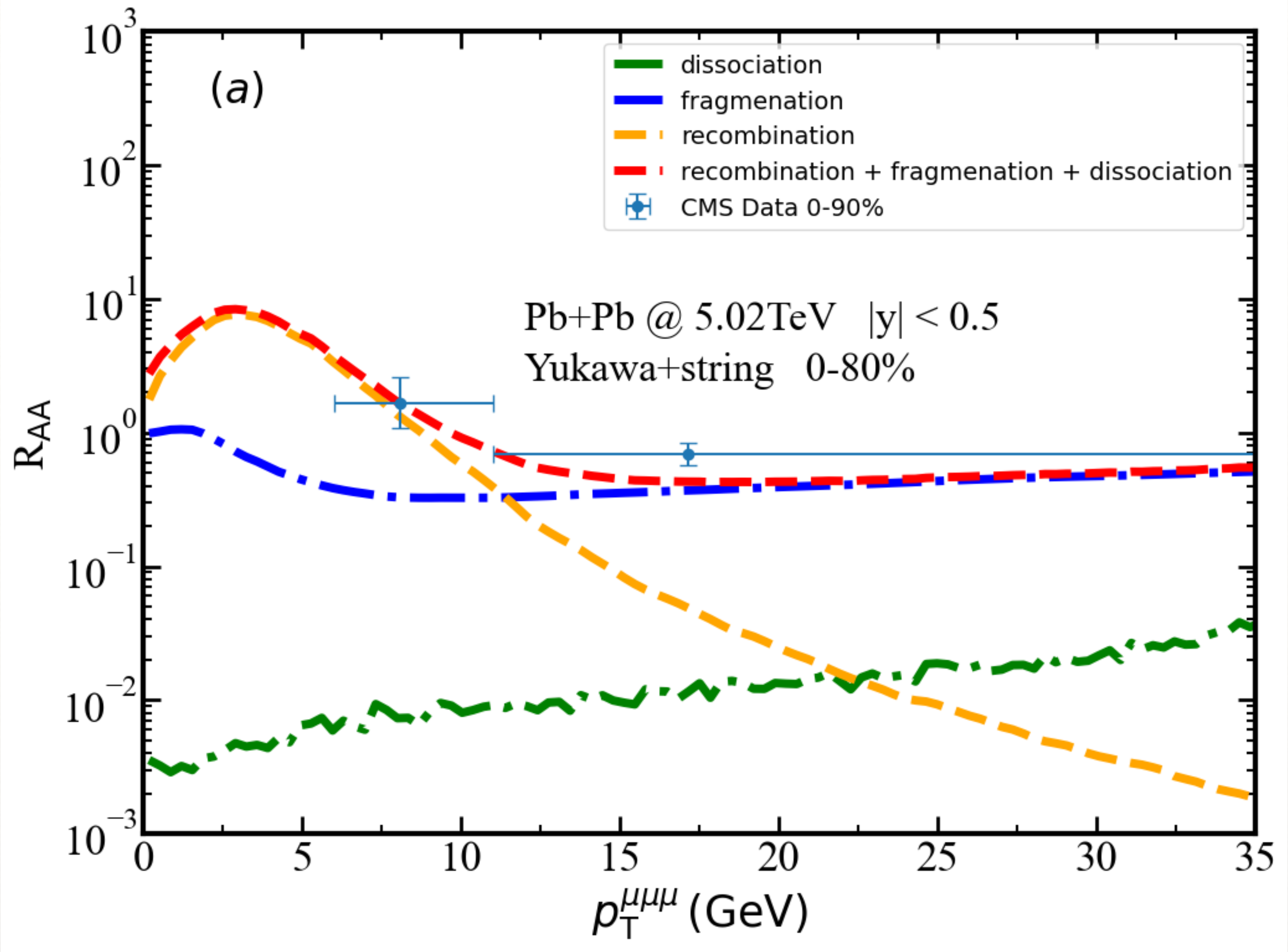
$B_c(1S)$ regenerated at T = 220 MeV, $B_c(1P)$ at T = 165 MeV

- Medium-modified fragmentation:

  Medium modified *b* quarks (at T = 165 MeV) + vacuum fragmentation function

Nuclear modification factor of B_c

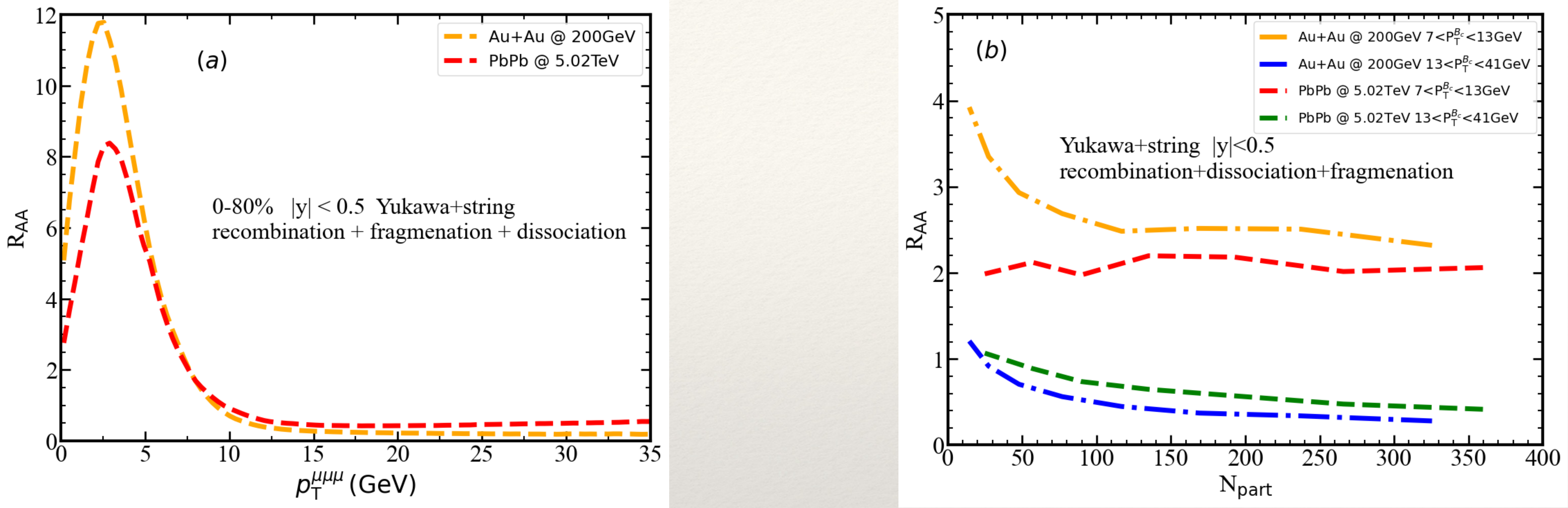




[Zhang, Xing, SC, Qin, in preparation]

- Coalescence probability increases with heavy quark density, decreases with the QGP volume → weak dependence on N_{part} (used to fix C_r in coalescence)
- Reasonable description of the p_T dependence of R_{AA}
- Little contribution from initially produced B_c, dominated by coalescence at low p_T, dominated by medium modified b-quark fragmentation at high p_T

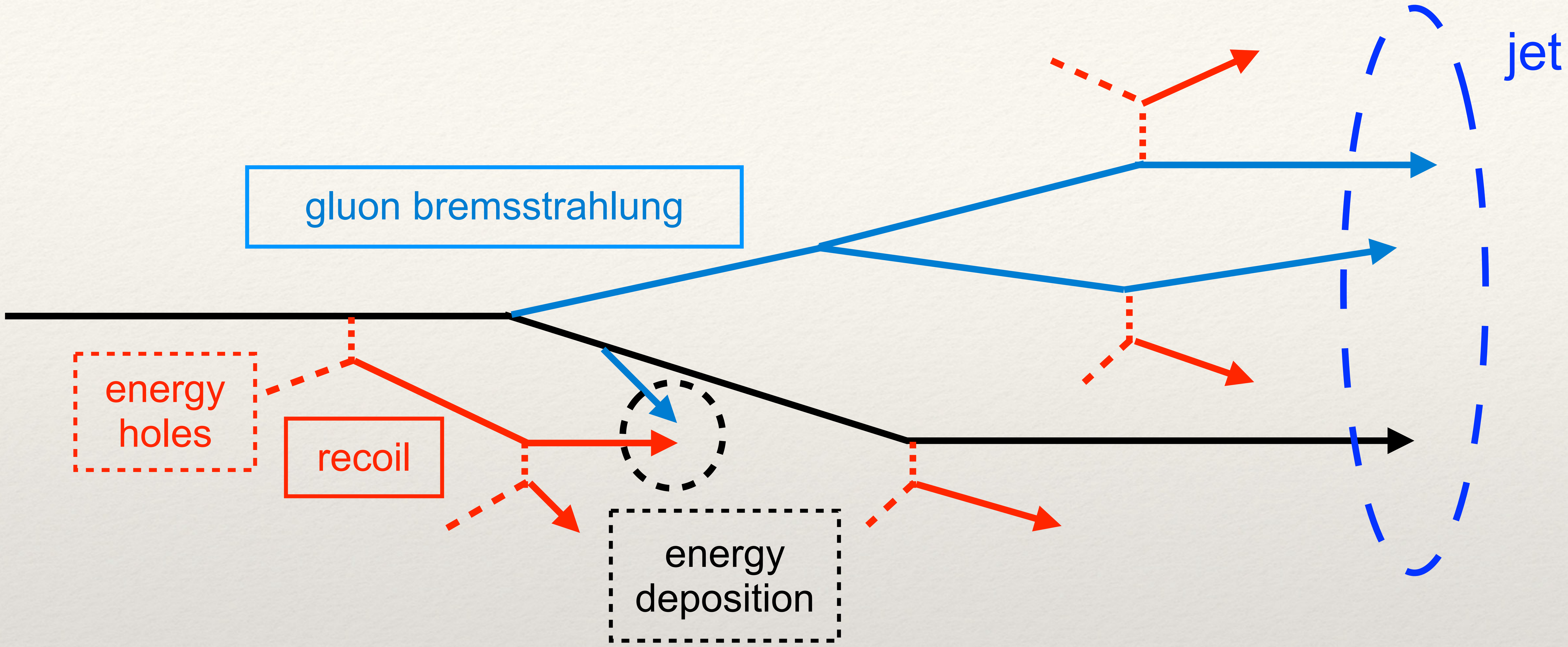
Predictions on R_{AA} of B_c at RHIC vs. LHC



[Zhang, Xing, SC, Qin, in preparation]

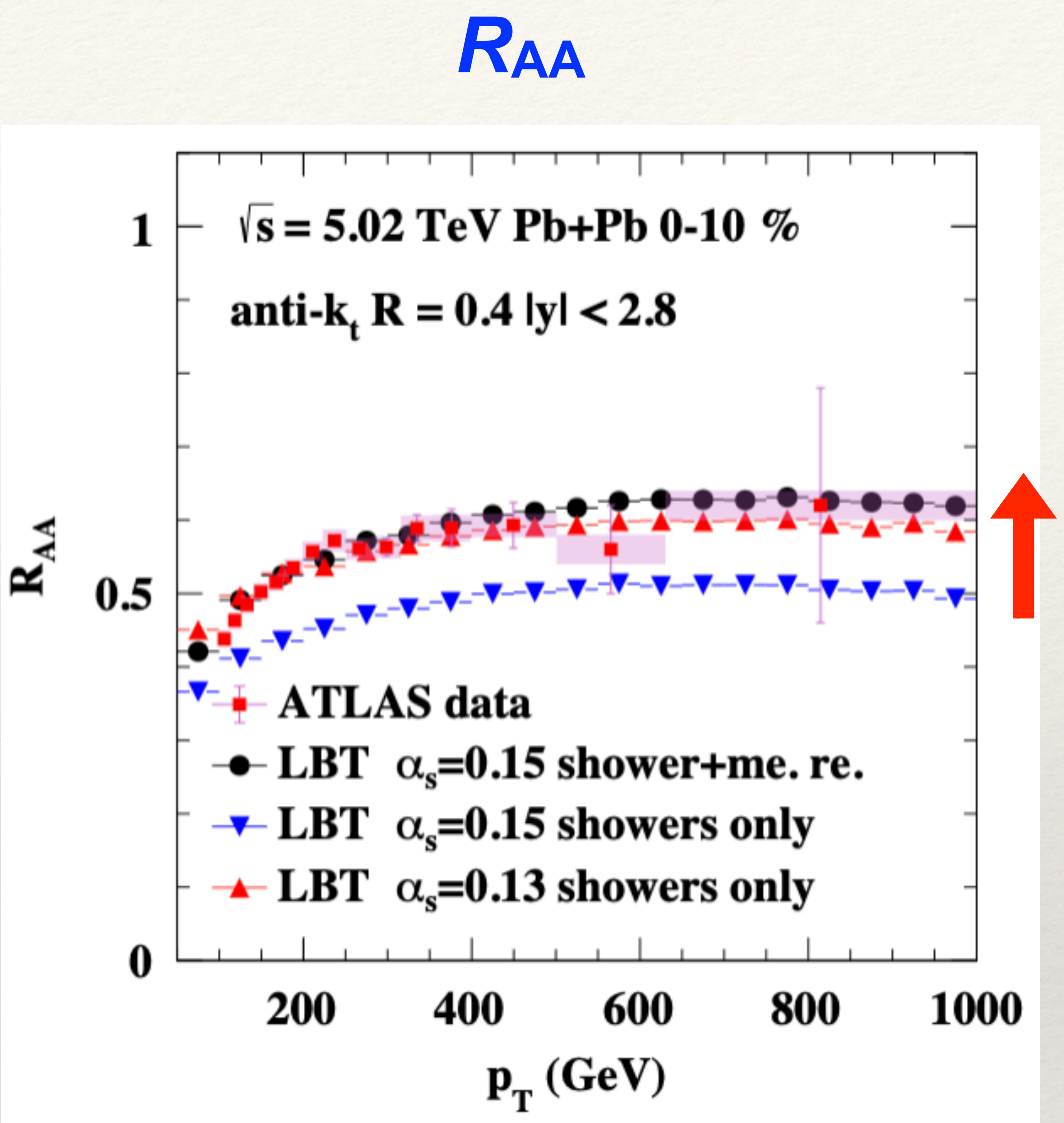
- RHIC > LHC at low p_T: dominated by coalescence (lower *pp* baseline and smaller V_{QGP} at RHIC)
- RHIC < LHC at high p_T: dominated by *b*-quark energy loss and fragmentation (softer *b*-quark spectrum at RHIC)
- Semi-analytical calculation at V (N_{part}) → 0 may not be reliable, will be improved by full MC

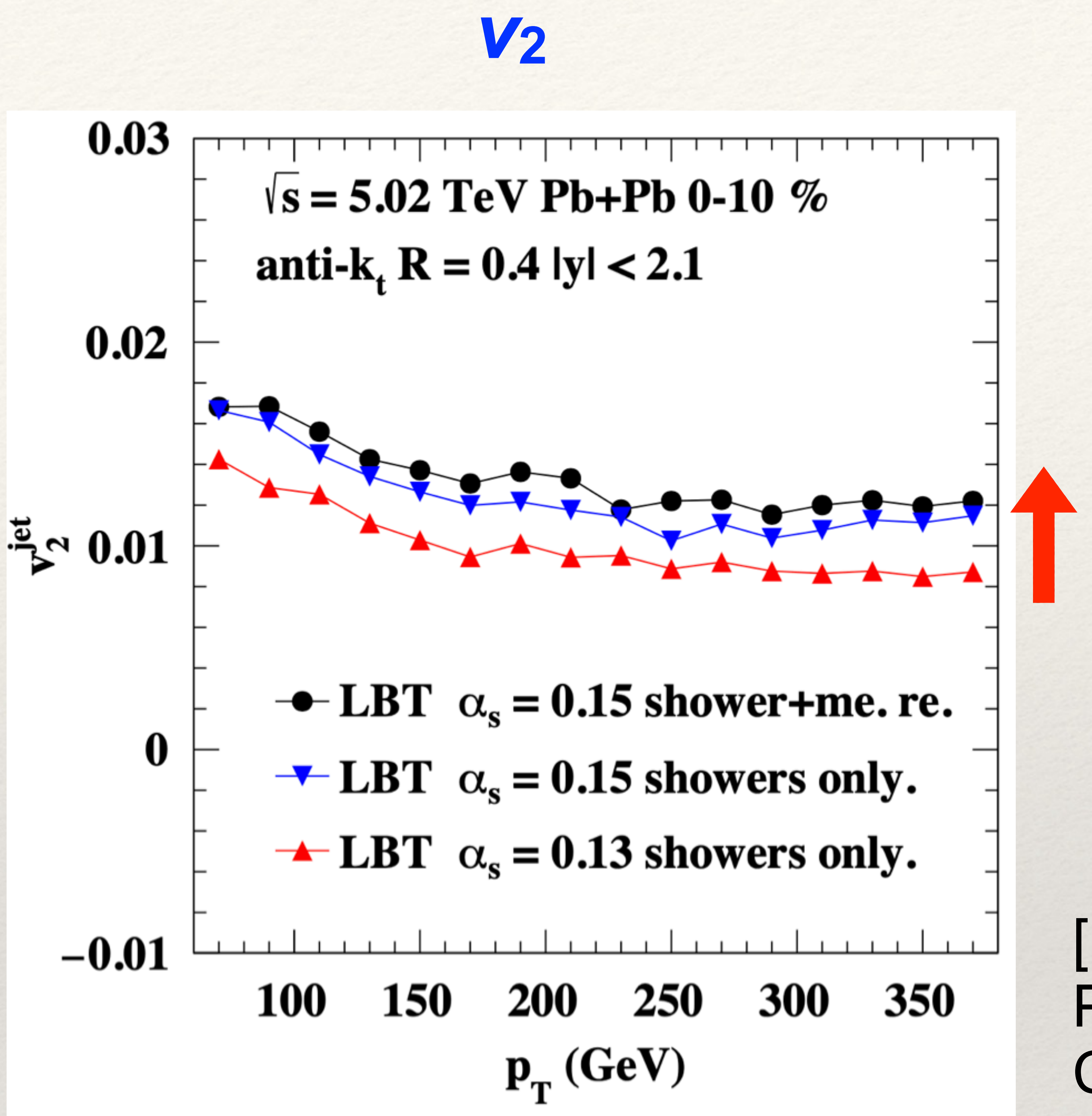
From hadrons to full jets



- Jet partons and medium background cannot be cleanly separated in reality
- Medium response (energy deposition + depletion) is naturally included in all jet observables
- Jet-medium interactions: medium modification of jets + medium response

Jet R_{AA} and v_2

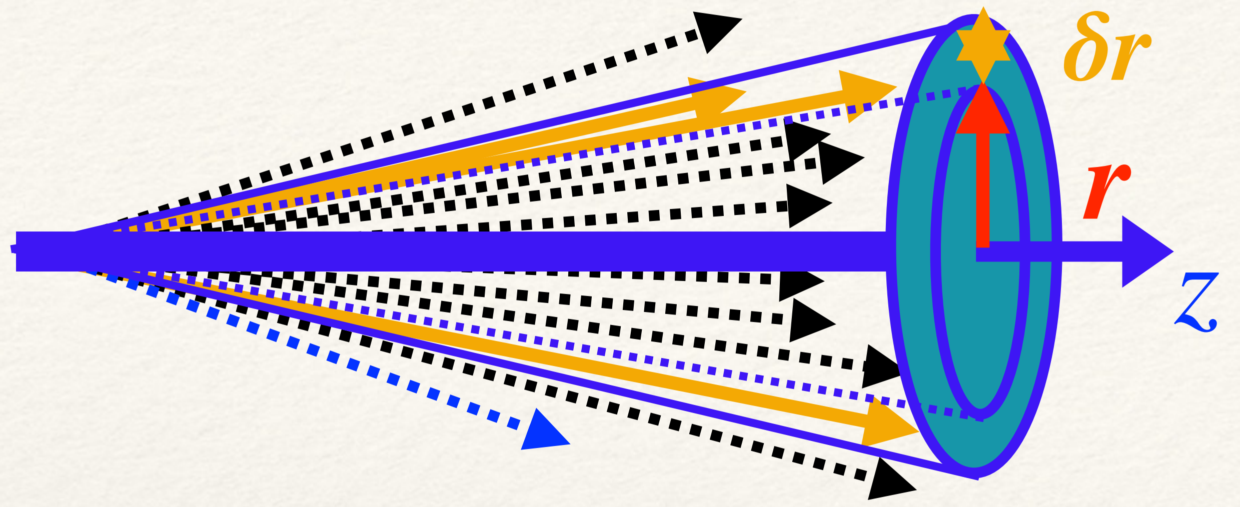




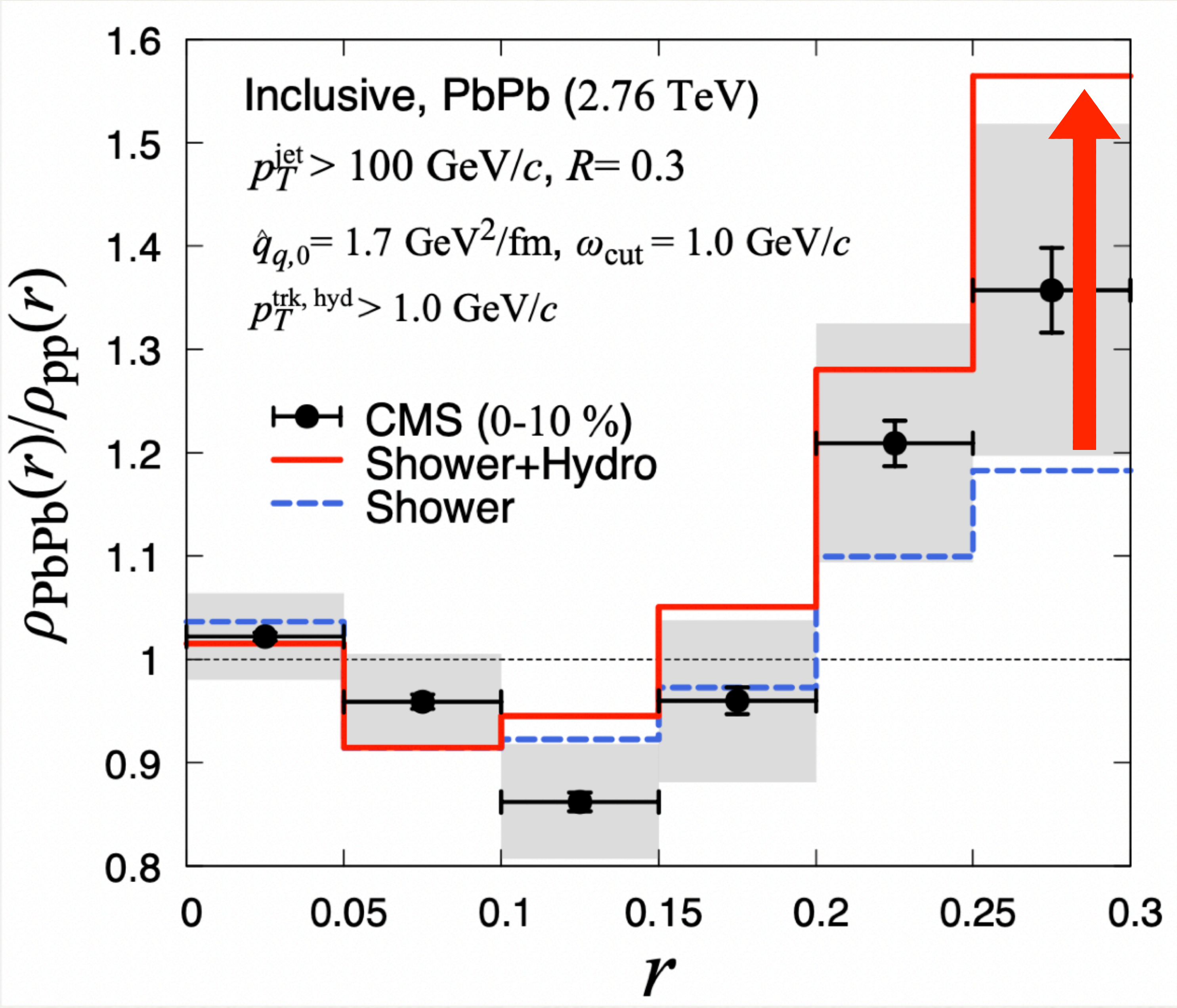
[He, Chen, Luo, SC, Pang, Wang, Phys. Rev. C 106 (2022) 044904]

- Including medium response reduces jet energy loss and thus increases the jet R_{AA}
- With R_{AA} fixed, including medium response (coupled to medium flow) increases the jet v_2

Jet substructure



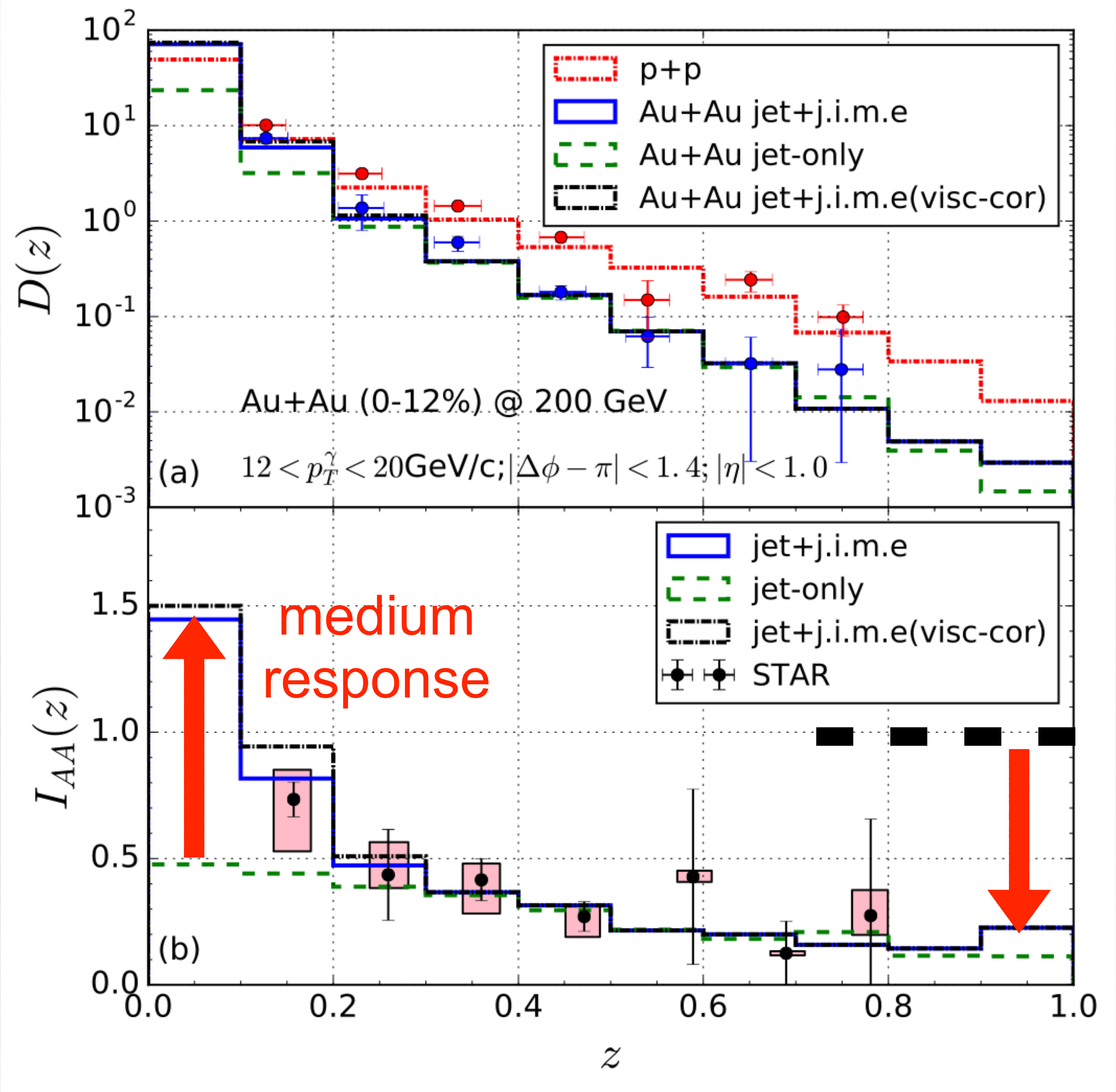
Transverse (r) distribution: jet shape



medium response

[Tachibana, Chang, Qin, Phys. Rev. C 95 (2017) 044909]

Longitudinal (z) distribution: jet fragmentation function

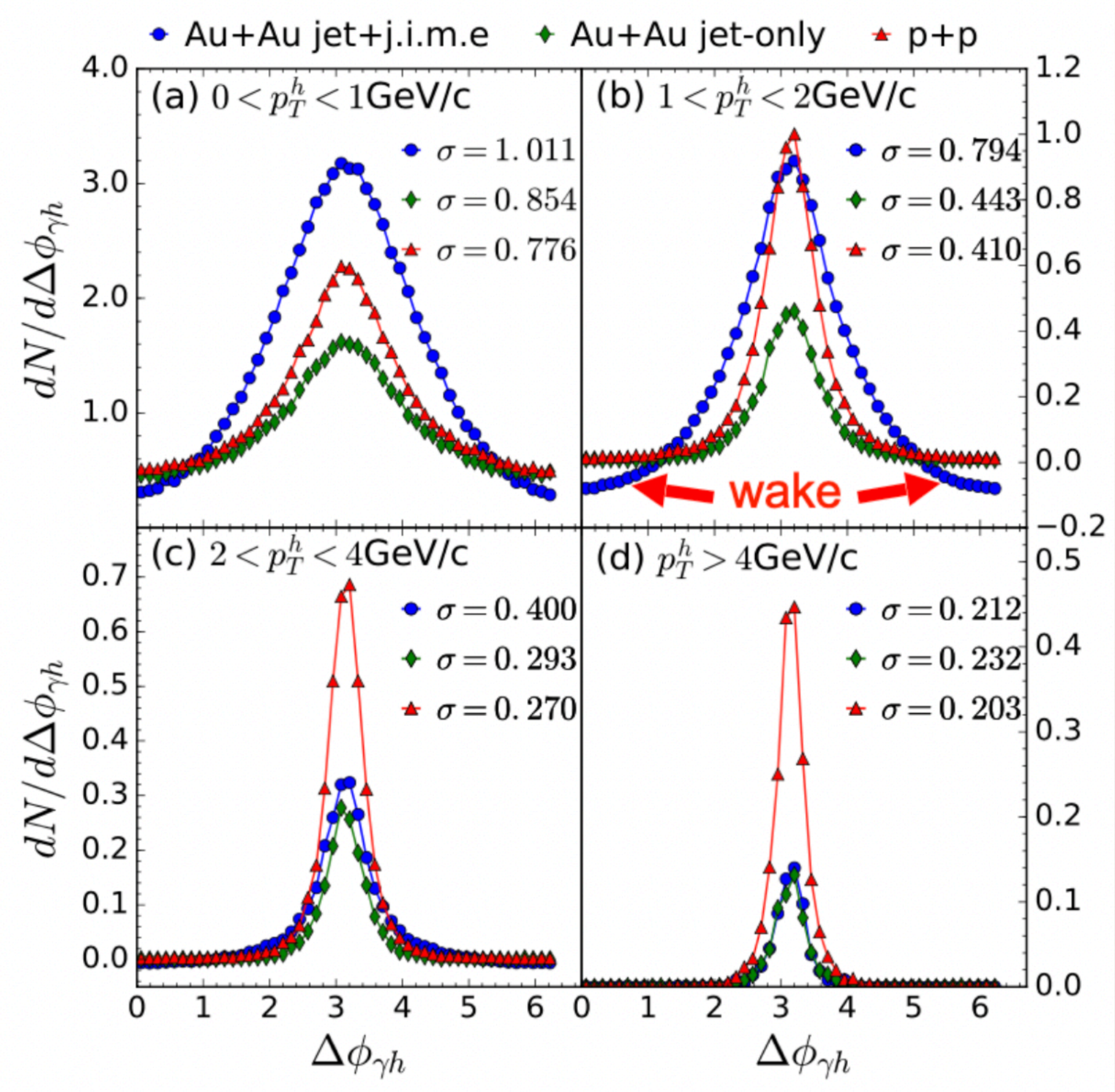


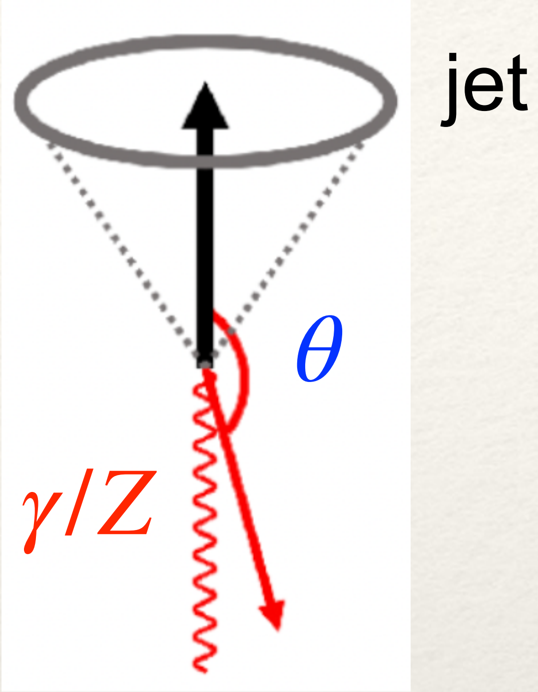
jet quenching

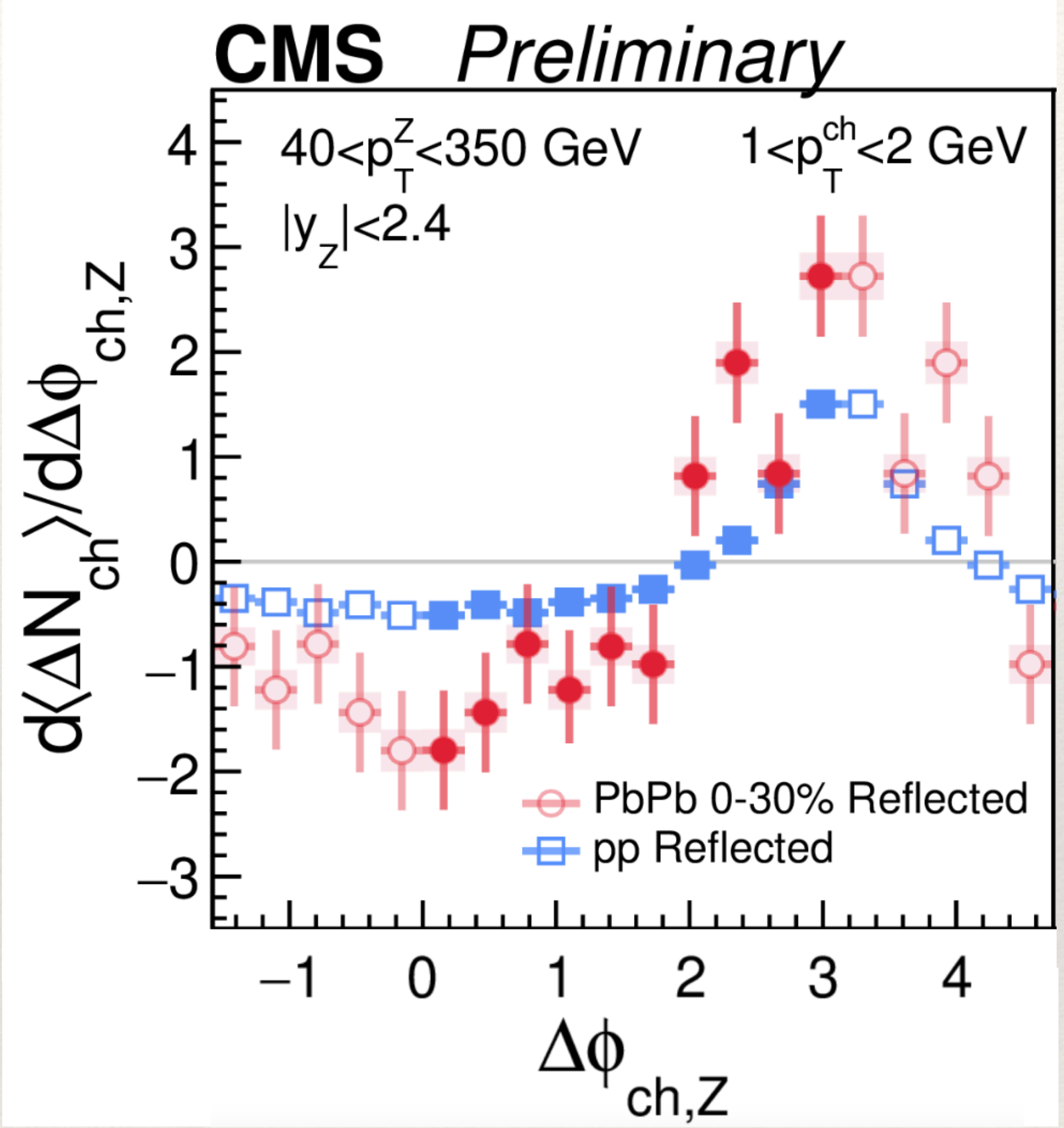
[Chen, SC, Luo, Pang, Wang, Phys. Lett. B 777 (2018) 86-90]

Search for unique signatures of medium response

Energy suppression in diffusion wake





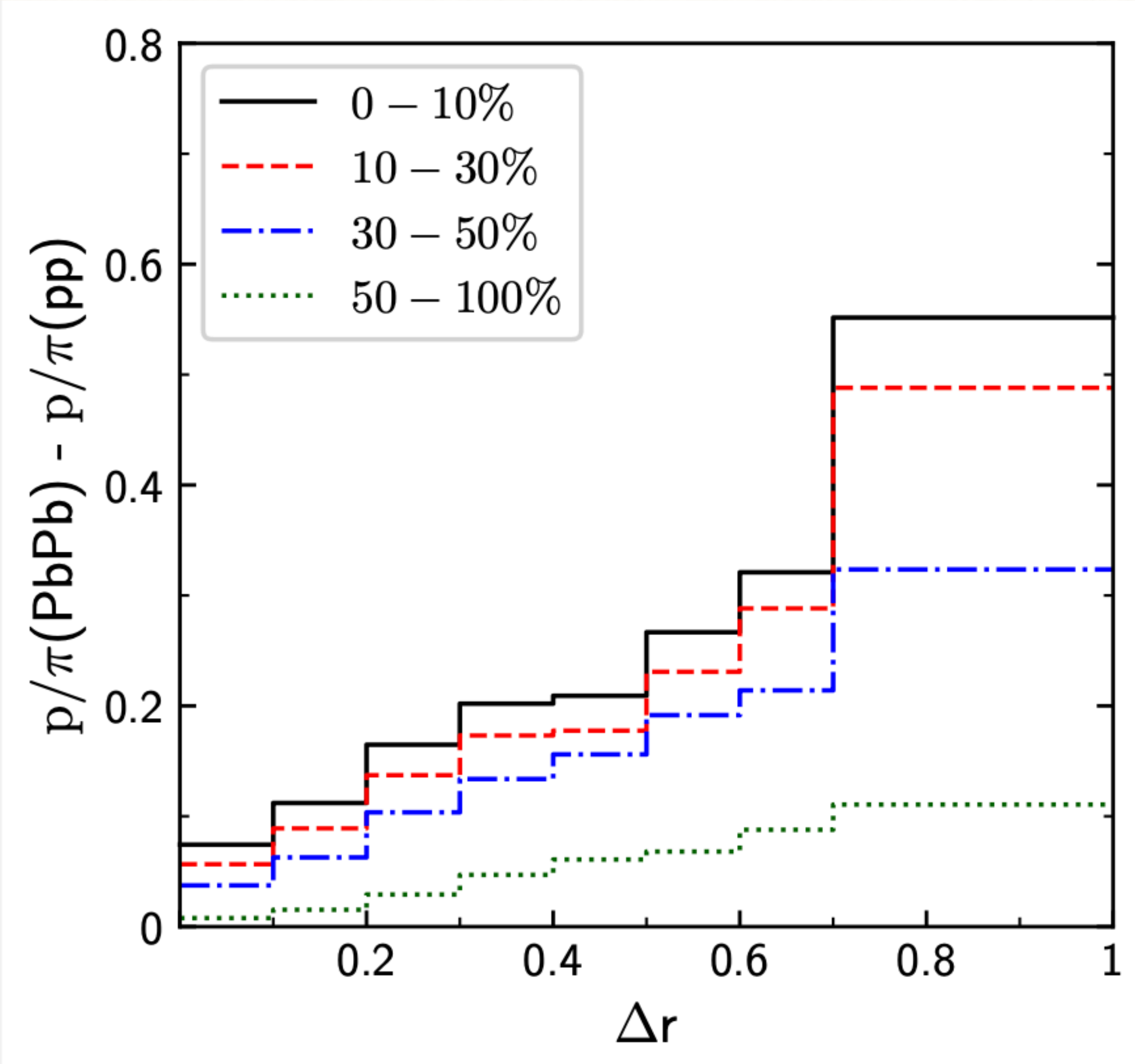


- Energy suppression predicted in the backward direction of jets at $1 < p_T^h < 2$ GeV [Chen, SC, Luo, Pang, Wang, PLB 777 (2018) 86, Yang, Luo, Chen, Pang, Wang, PRL 130 (2023) 052301]
- Confirmed by recent CMS data [CMS-PAS-HIN-23-006]

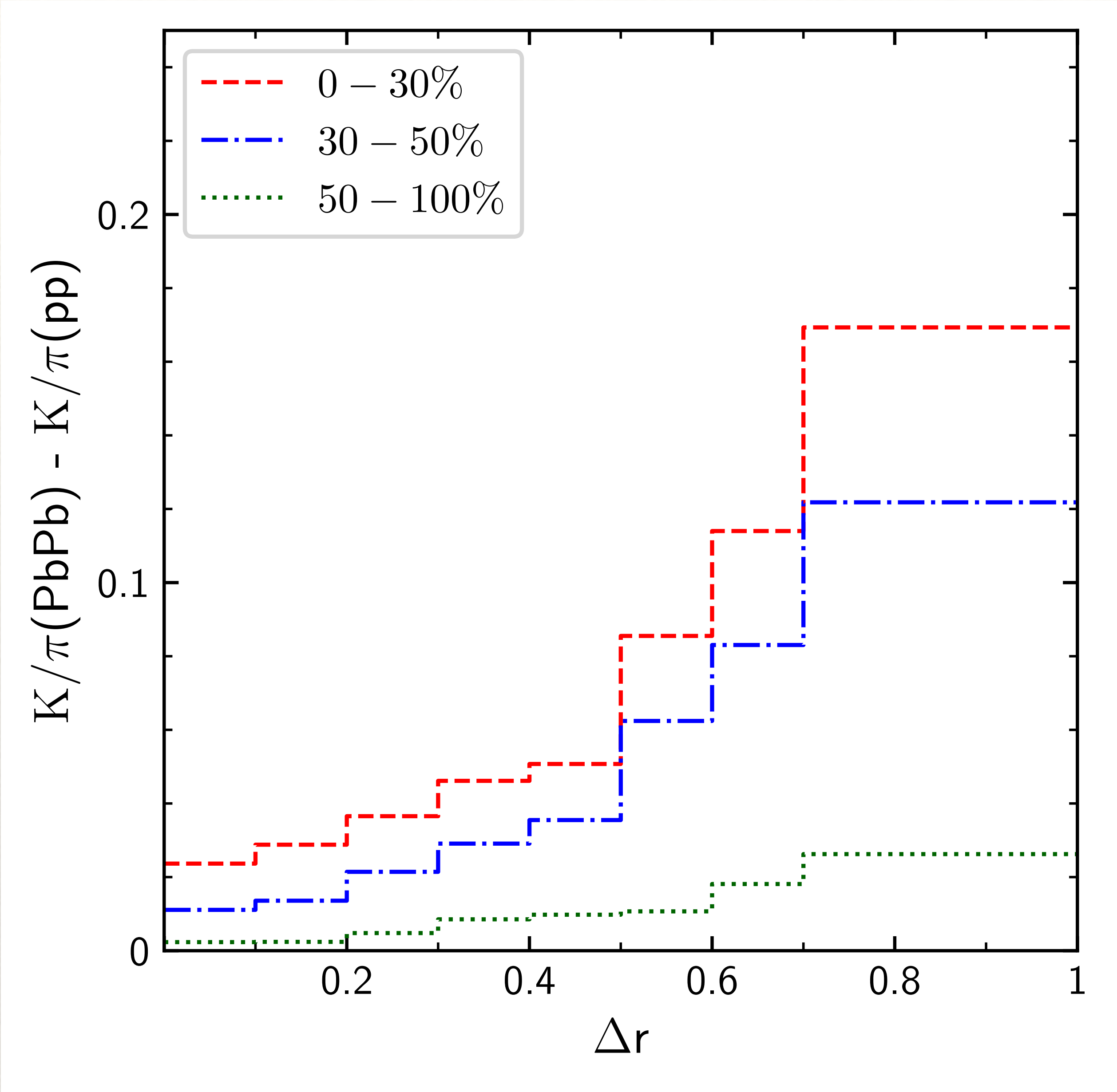
Search for unique signatures of medium response

Hadron chemistry around quenched jets

Baryon enhancement



Strangeness enhancement



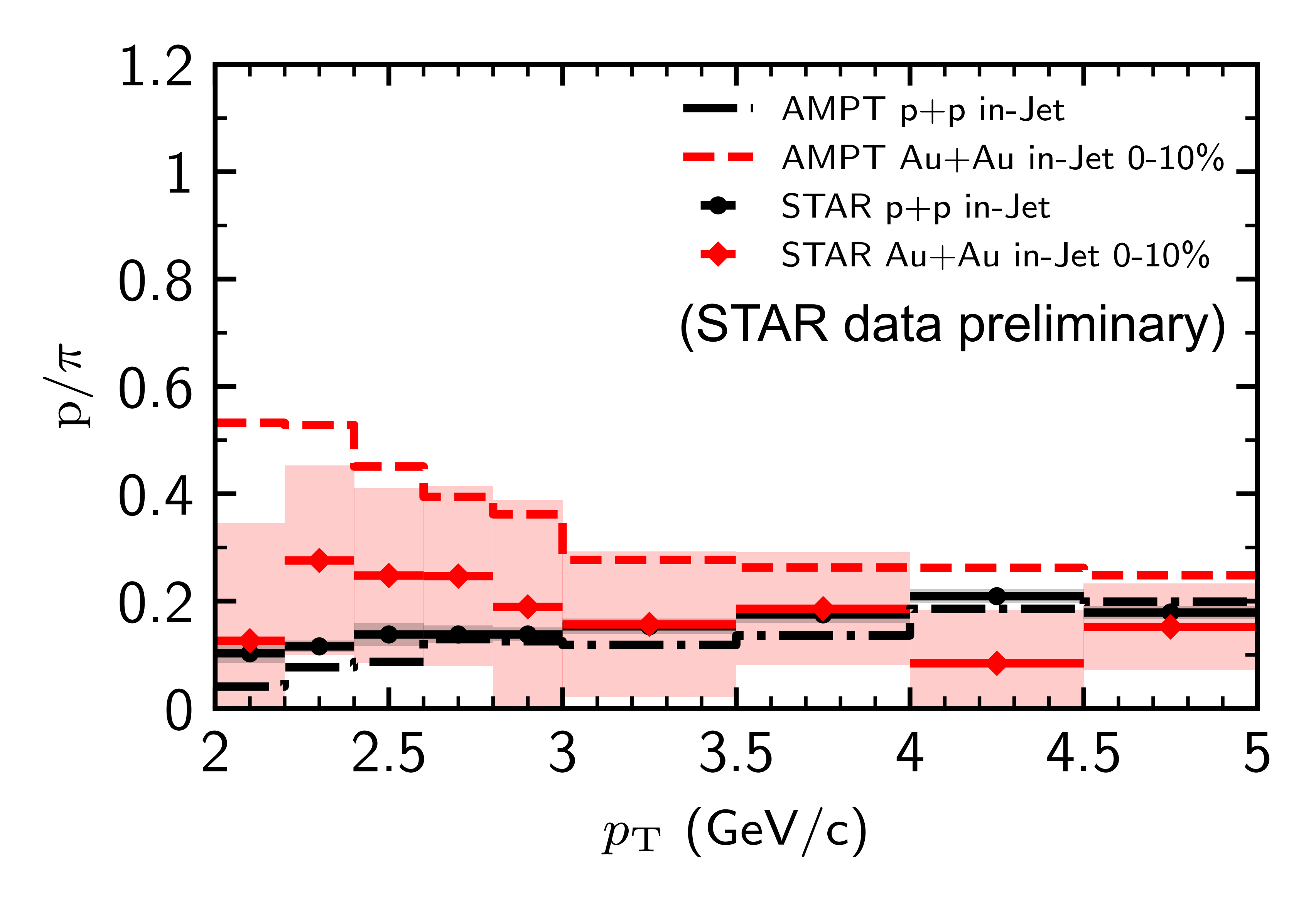
- Larger quark density and strangeness density in QGP than in vacuum jets
- Enhanced baryon-to-meson ratio and strangeness around jets in AA *vs*. *pp* collisions
- Stronger enhancement at larger distance from the jet axis

[Luo, Mao, Qin, Wang, Zhang, PLB 837 (2023) 137638; Chen, SC, Luo, Pang, Wang, NPA 1005 (2021) 121934]

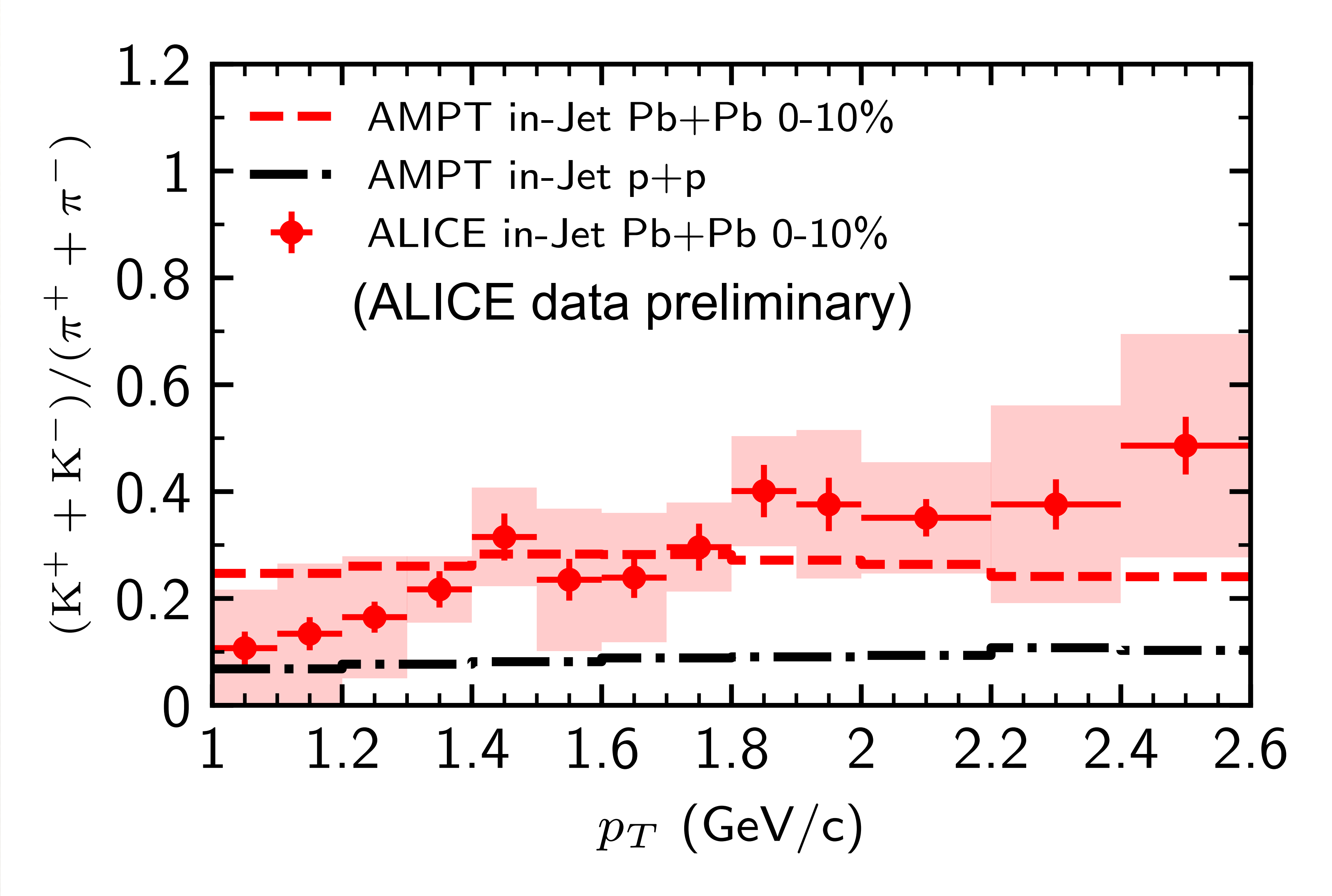
Search for unique signatures of medium response

Hadron chemistry around jets: comparison to experimental data

Baryon production at RHIC



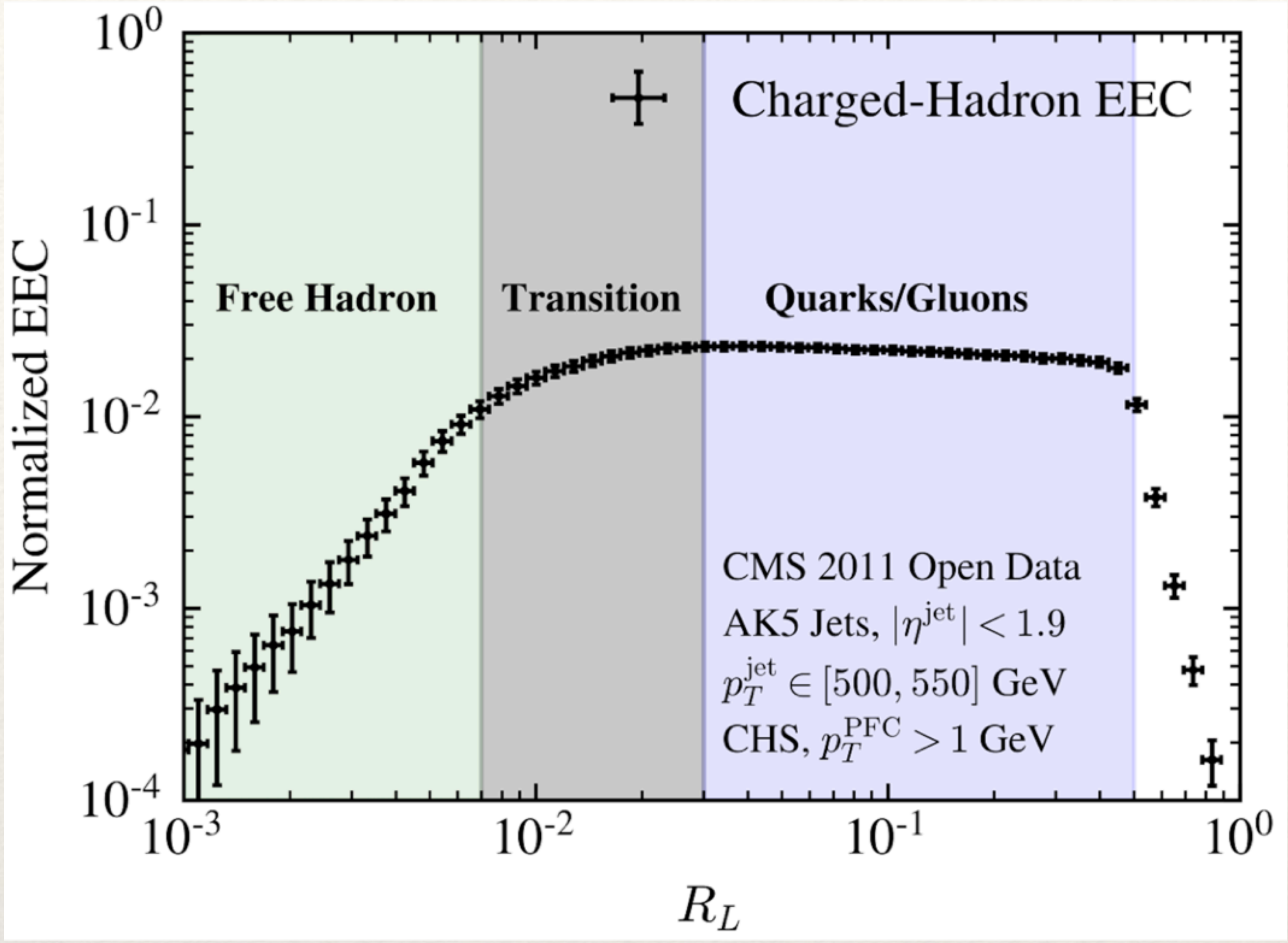
Strangeness production at LHC



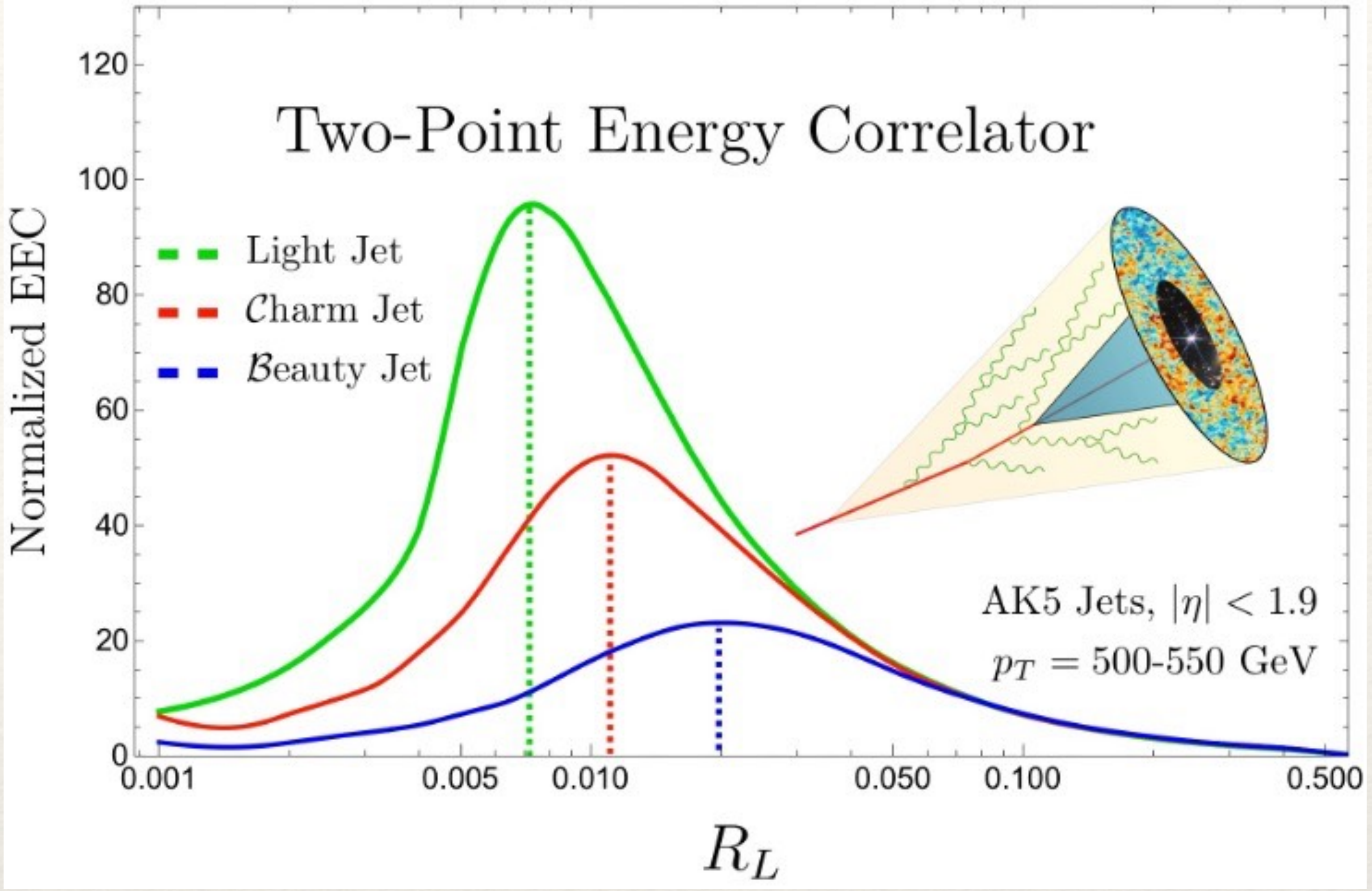
[Luo, SC, Qin, in preparation]

- Prediction on p/π enhancement in AuAu vs. *pp* collisions qualitatively agrees with the RHIC data
- Prediction on K/π ratio in PbPb collisions agrees with the LHC data (no data on *pp* yet)
- More precise experimental data and theoretical predictions are desired

A novel observable: energy-energy correlator (EEC)



[Komiske et. al., PRL 130 (2023) 051901]



[Craft et. al., arXiv:2210.09311]

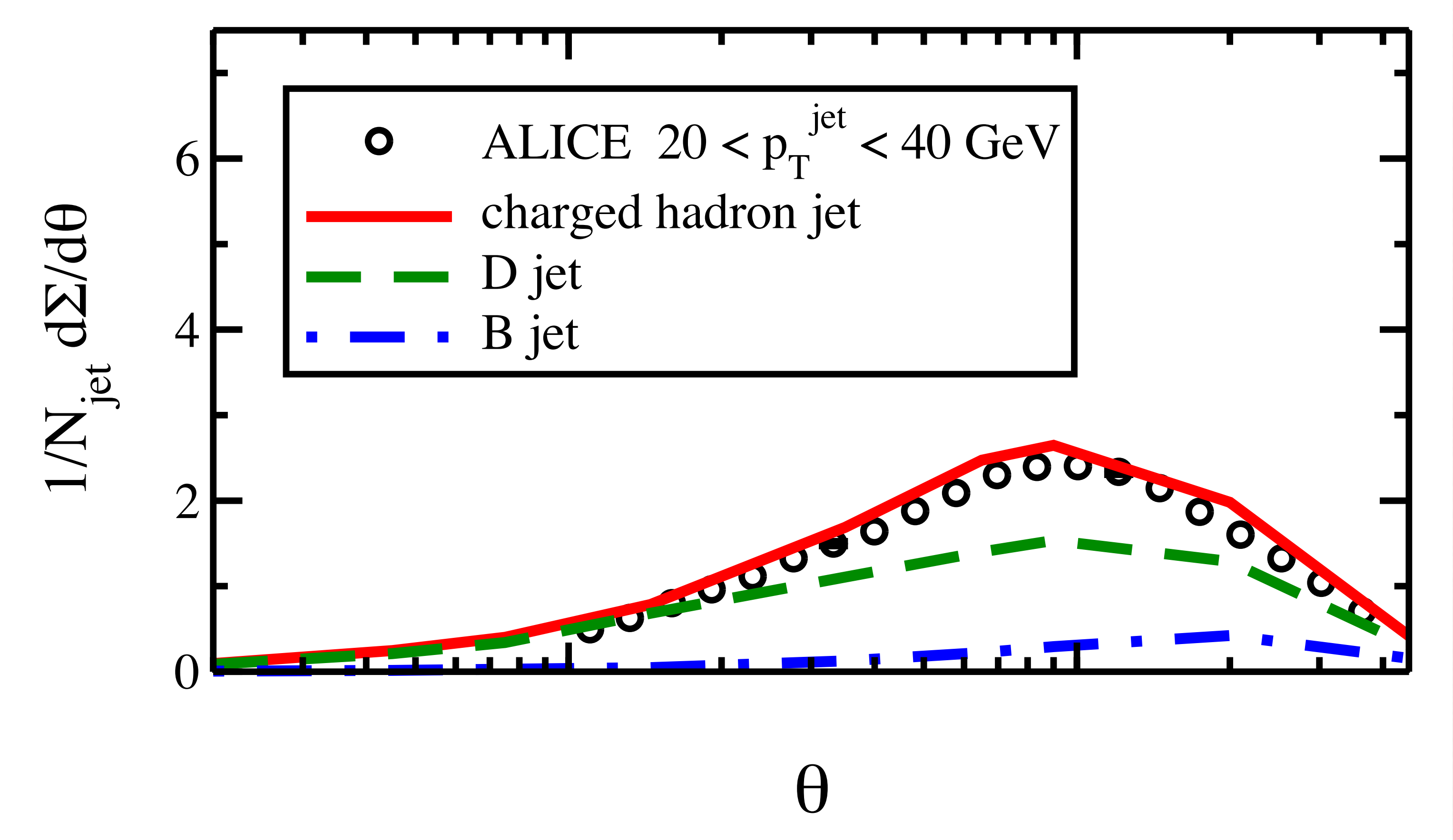
- EEC: $$\frac{d\Sigma}{dR_L} = \int d\vec{n}_1 d\vec{n}_2 \frac{\langle \mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2)\rangle}{Q^2}\delta(\Delta R_{12} - R_L)$$

  $\mathscr{E}$: energy flow in a given direction,

  $\Delta R_{12} = \sqrt{\Delta\phi_{12}^2 + \Delta\eta_{12}^2}$: relative angle, Q: hard scale

- EEC of jets presents a clear angular scale separation between perturbative and non-perturbative (e.g. hadronization) regions
- EEC can also reveal the flavor dependence of splitting angles of partons in *pp* collisions
- Implement a first realistic calculation on light and heavy flavor jet EEC in AA collisions

Light *vs.* heavy flavor jet EEC in *pp* collisions



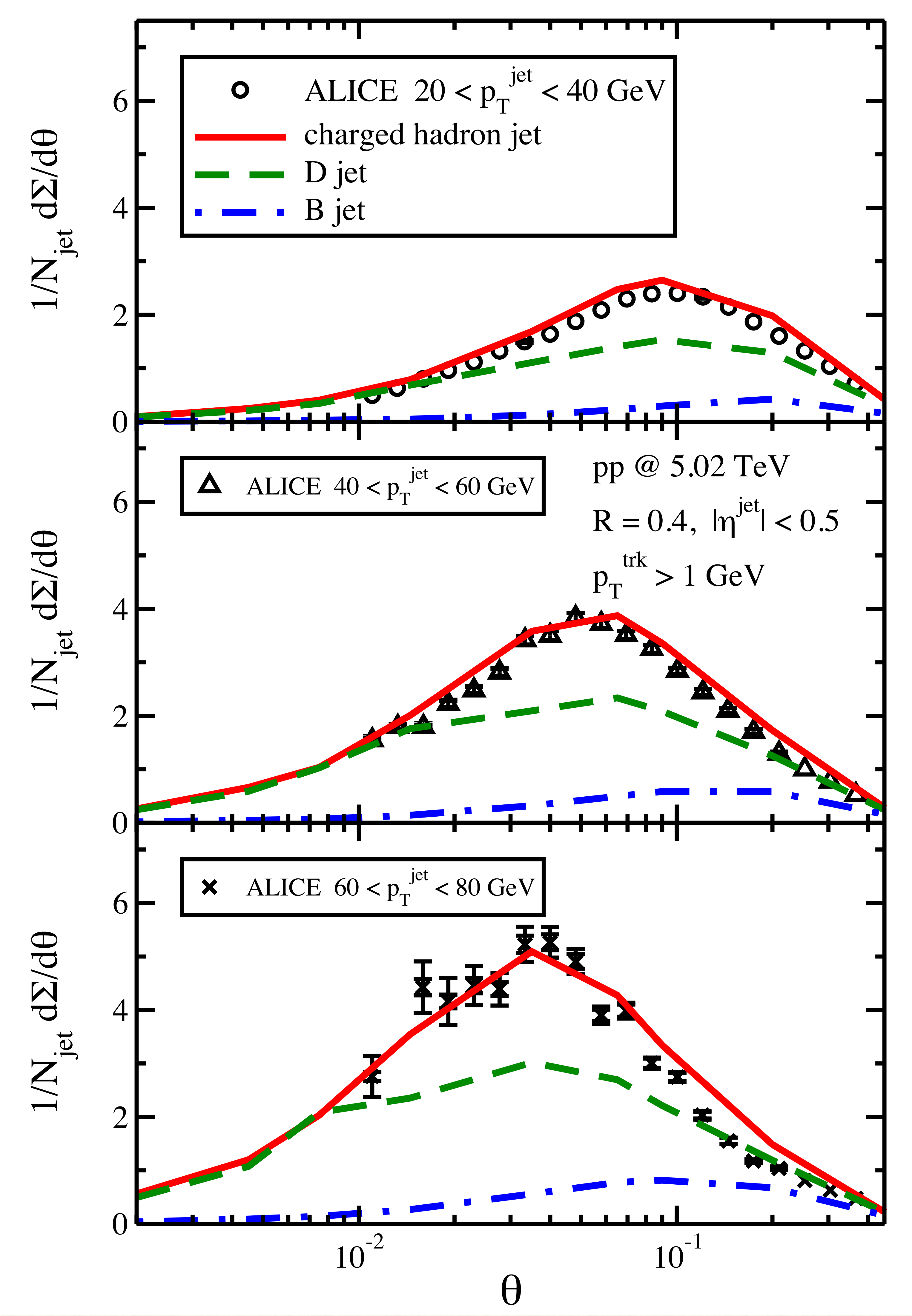
- Jet in *pp*: Pythia 8 simulation
- EEC analysis (*i*, *j* denote jet constituents)

$$\frac{d\Sigma(\theta)}{d\theta} = \frac{1}{\Delta\theta} \sum_{|\theta_{ij}-\theta|<\Delta\theta/2} \frac{p_{\mathrm{T},i}(\vec{n}_i)\, p_{\mathrm{T},j}(\vec{n}_j)}{p_{\mathrm{T,jet}}^2}$$

- Flavor (mass) dependence:
  - Overall magnitude: charged jet > *D*-jet > *B*-jet
  - Typical (peak) angle: charged jet < *D*-jet < *B*-jet

Suppression of splitting within $\theta_0 \sim m_Q/E_Q$ in vacuum

Light *vs.* heavy flavor jet EEC in *pp* collisions



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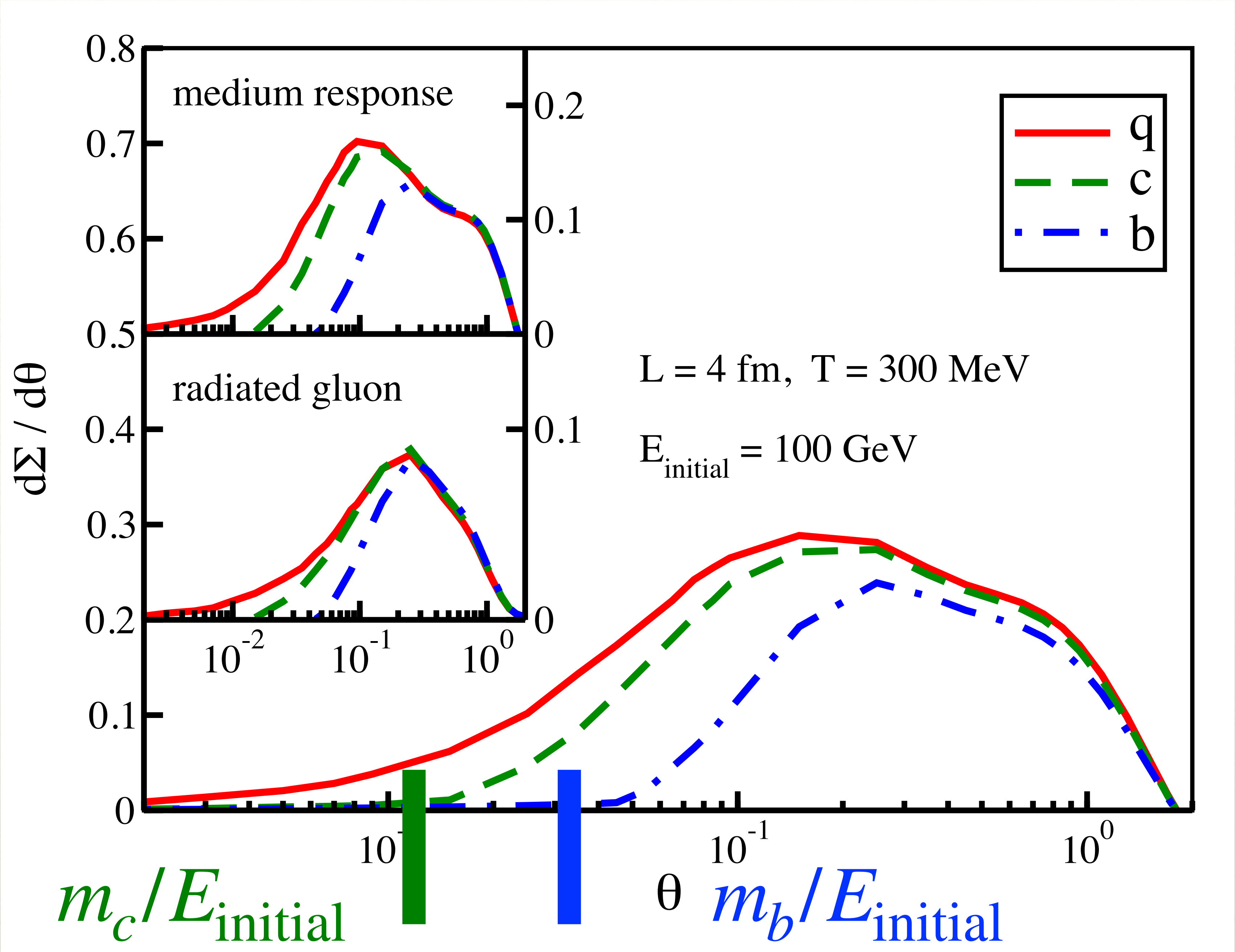
  Suppression of splitting within $\theta_0 \sim m_Q/E_Q$ in vacuum

- Jet energy dependence
  - Higher $p_T \rightarrow \Sigma$ peaks at smaller θ

  $p_T\theta_{peak}$ ~ transition scale between pert. and non-pert.

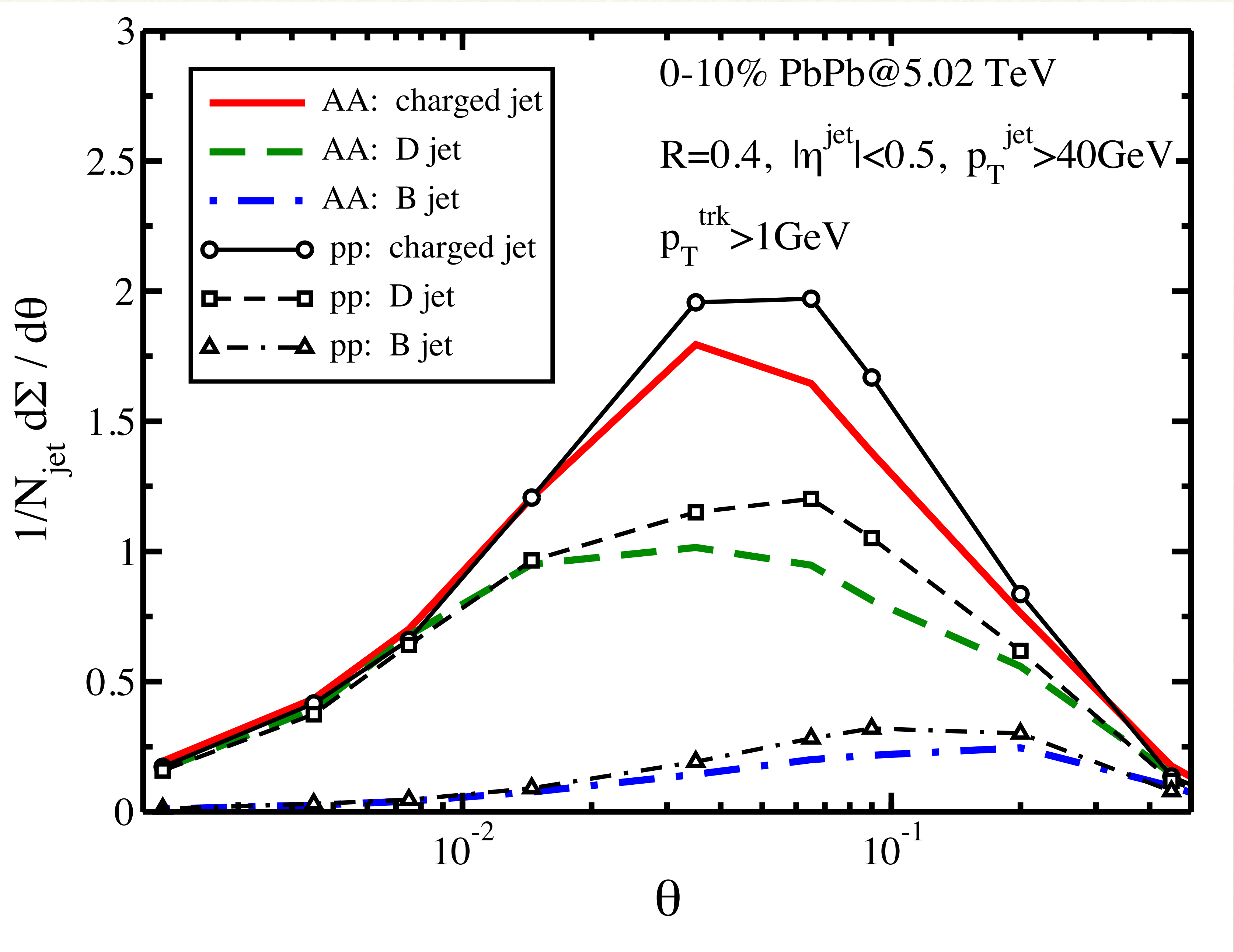
EEC of partons developed from a single quark

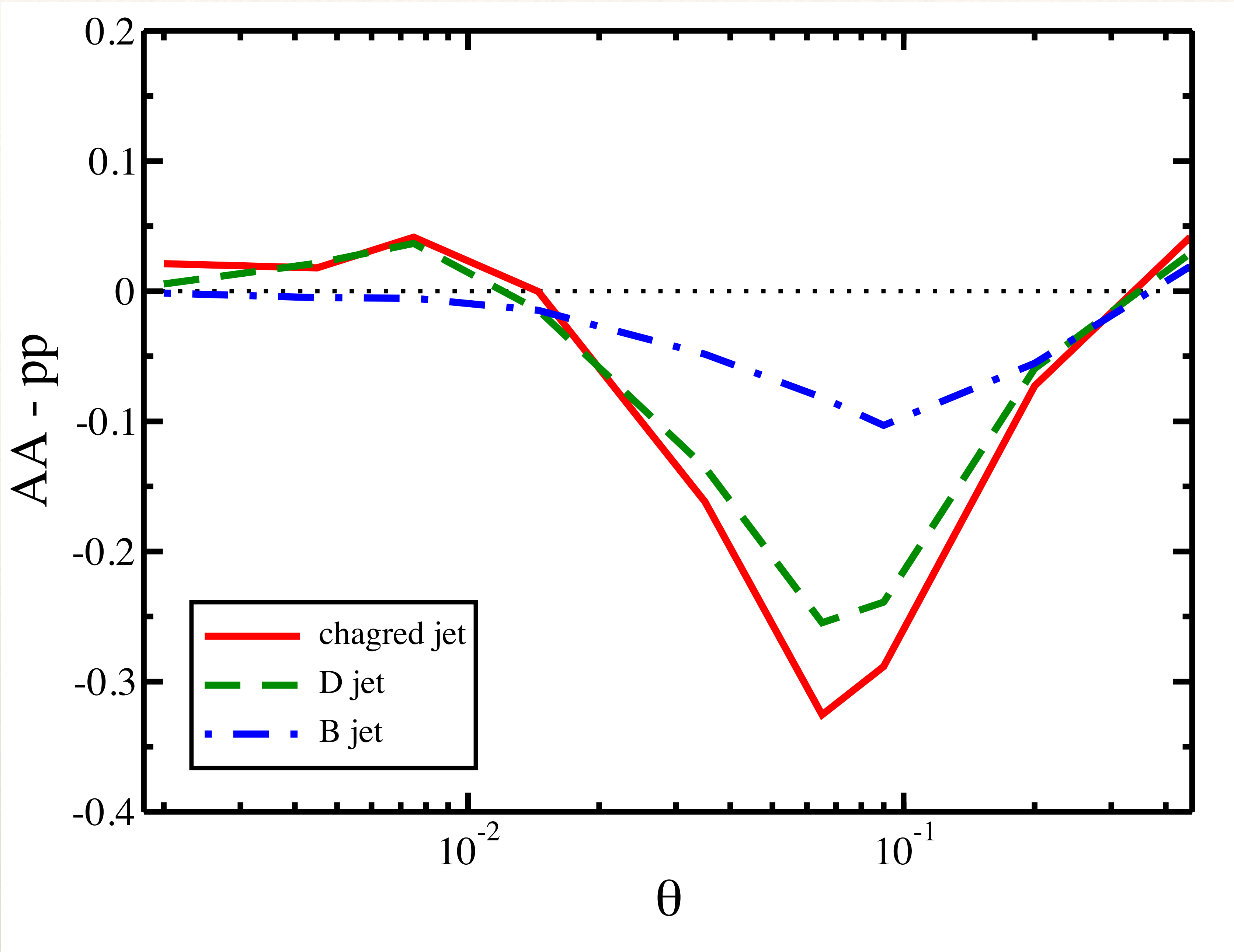


Xing, SC, Qin, Wang, arXiv:2409.12843

- Single quark → LBT + static medium → EEC of daughter partons
- Flavor (mass) hierarchy of EEC:
  - Magnitude: charged > *D* > *B*-jet; peak position: charged < *D* < *B*-jet (similar to vacuum jets)
  - Clear strong suppression of Σ below $\theta_0 \sim m_Q/E_{\text{initial}}$
- Contributions form medium response and gluon emission show similar hierarchies

Light *vs.* heavy flavor jet EEC in central PbPb collisions

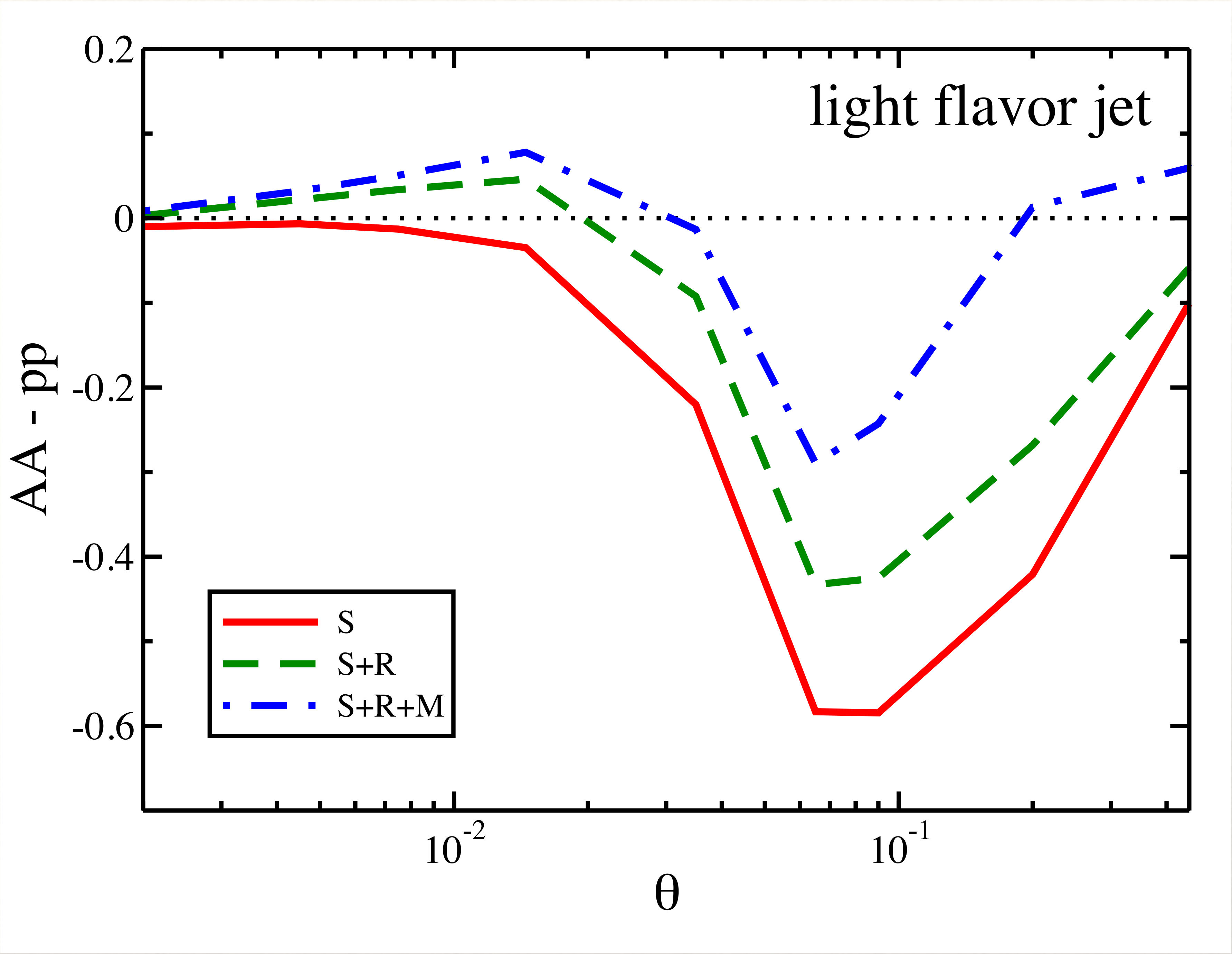




Nuclear modification (AA - *pp*) — Pythia + LBT in hydro

- General features: suppression at intermediate θ, enhancement at small θ (except for *B*-jet) and large θ
- Flavor hierarchy: weaker nuclear modification (both suppression and enhancement) for jets tagged with heavier mesons

Different contributions to medium modification on EEC



S: shower partons inherited from Pythia

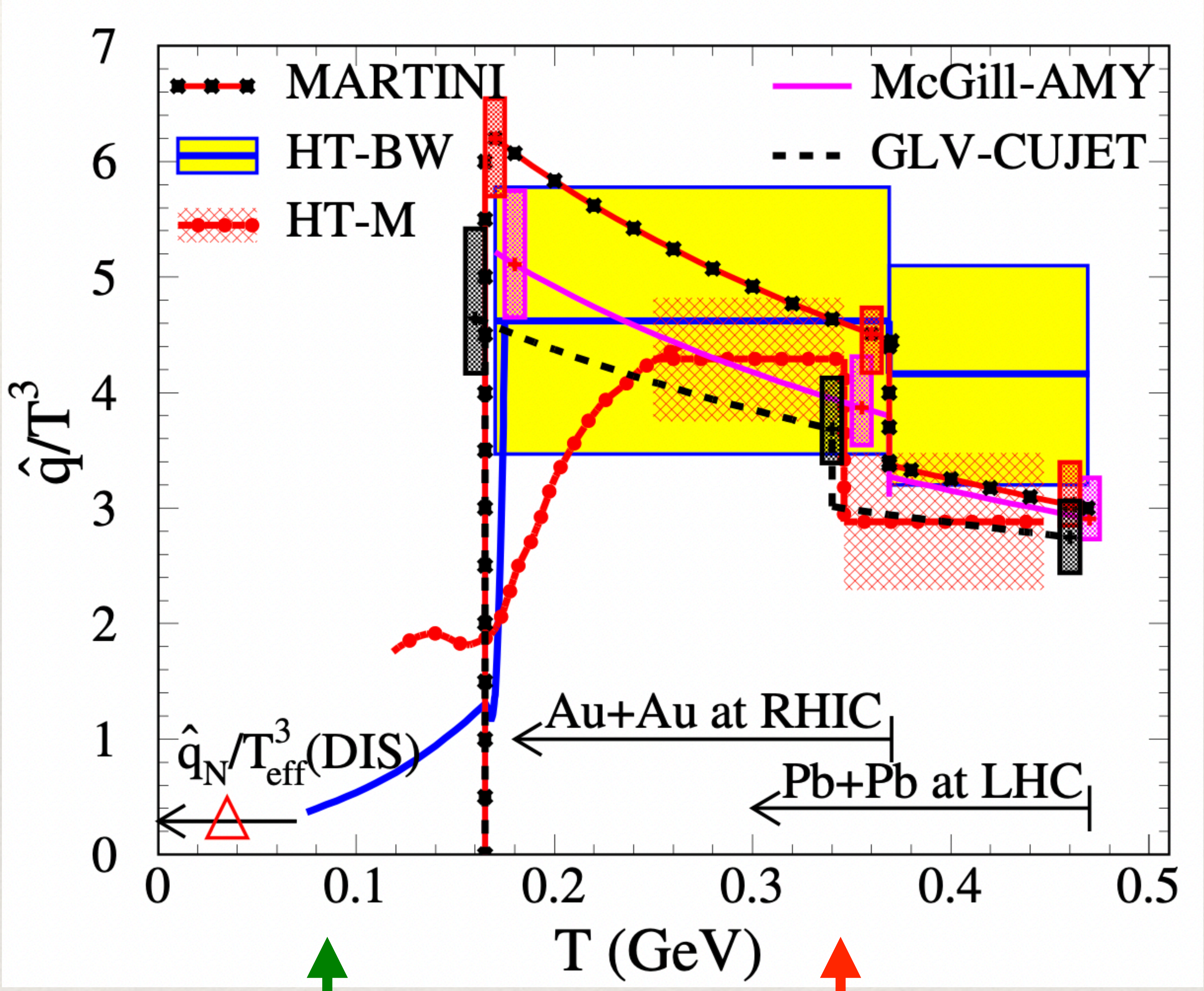
S+R: add medium-induced gluons

S+R+M: further add medium response

- Jet energy loss causes suppression over the entire θ region
- Medium-induced gluon emission enhances EEC at small θ
- Medium response enhances EEC at large θ

Constraints on jet transport coefficient inside the QGP

$$\hat{q} \equiv d\langle k_\perp^2 \rangle / dt \sim \langle F^{ai+}(0) F_i^{a+}(y^-) \rangle$$



nucleus ≪ QGP

[JET, Phys. Rev.C 90 (2014) 1, 014909]

- QGP is much more opaque than cold nuclear matter to jet propagation

- Recent developments on $\hat{q}$ extraction:

  Multistage jet evolution model with Bayesian analysis

  [JETSCAPE, Phys. Rev. C 104 (2021) 1, 024905]

  Information field based global interference

  [Xie et al., Phys. Rev. C 108 (2023) 1, L011901]

Probing the equation of state of the QGP

Transport

$$p_a \cdot \partial f_a(x_a, p_a) = E_a(\mathscr{C}_a^{\rm el} + \mathscr{C}_a^{\rm inel})$$

Thermal mass of partons

$$m_g^2 = \frac{1}{6}g^2\left[(N_c + \frac{1}{2}n_f)T^2 + \frac{N_c}{2\pi^2}\Sigma_q \mu_q^2\right]$$

$$m_{u,d}^2 = \frac{N_c^2 - 1}{8N_c}g^2\left[T^2 + \frac{\mu_{u,d}^2}{\pi^2}\right]$$

$$m_s^2 - m_{0s}^2 = \frac{N_c^2 - 1}{8N_c}g^2\left[T^2 + \frac{\mu_s^2}{\pi^2}\right]$$

Strong coupling strength

$g(E, T)$

Equation of state

$$P_{qp}(m_u, m_d, ..., T) = \Sigma_{i=u,d,s,g} d_i \int \frac{d^3p}{(2\pi)^3} \frac{|\vec{p}^2|}{3E_i(p)} f_i(p) - B(T)$$
$$= \Sigma_i P_{kin}^i(m_i, T) - B(T)$$

$$\epsilon = TdP(T)/dT - P(T), \qquad s = (\epsilon + P)/T$$

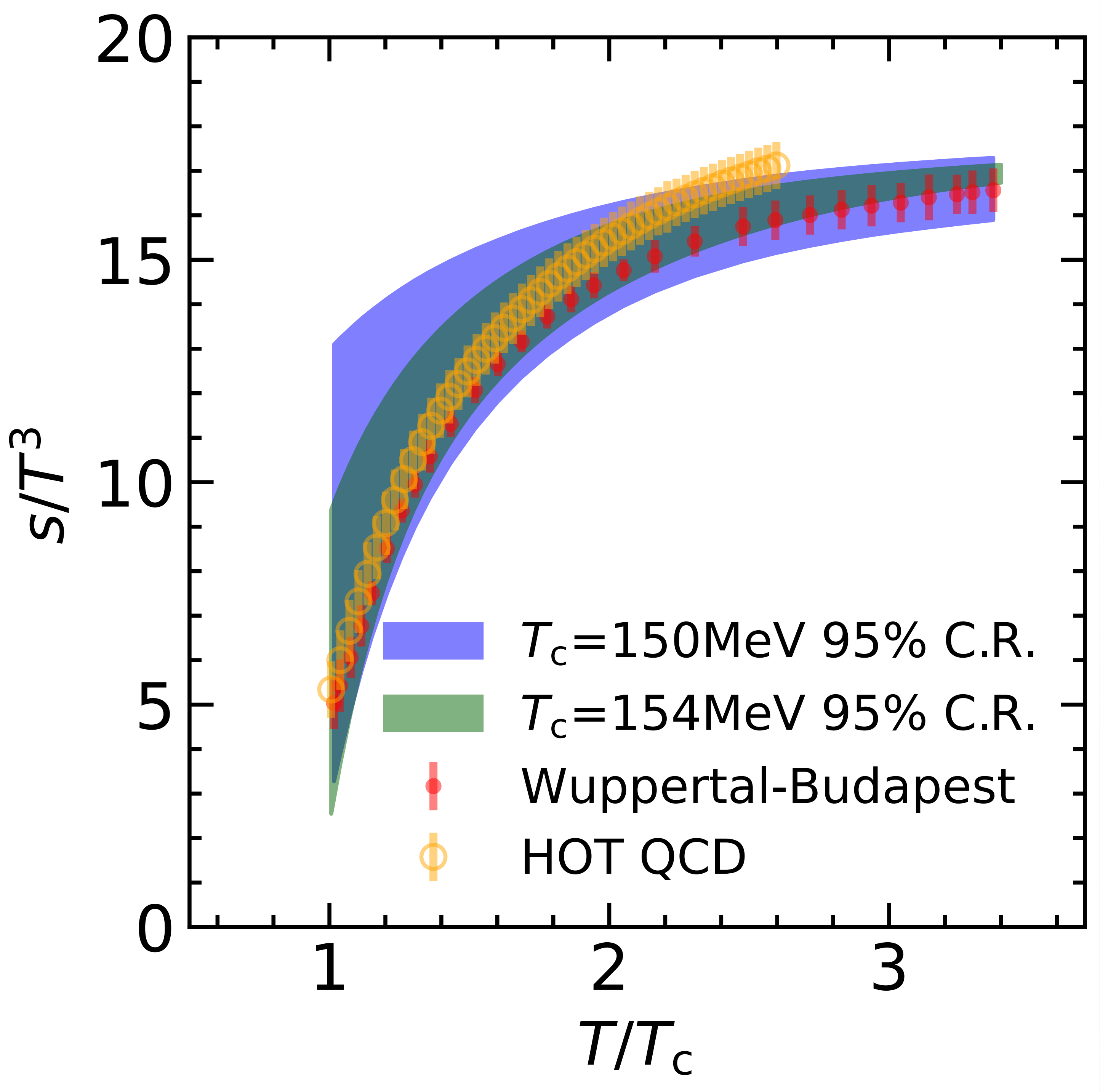
Strategy:

Fit g from comparing transport model to data

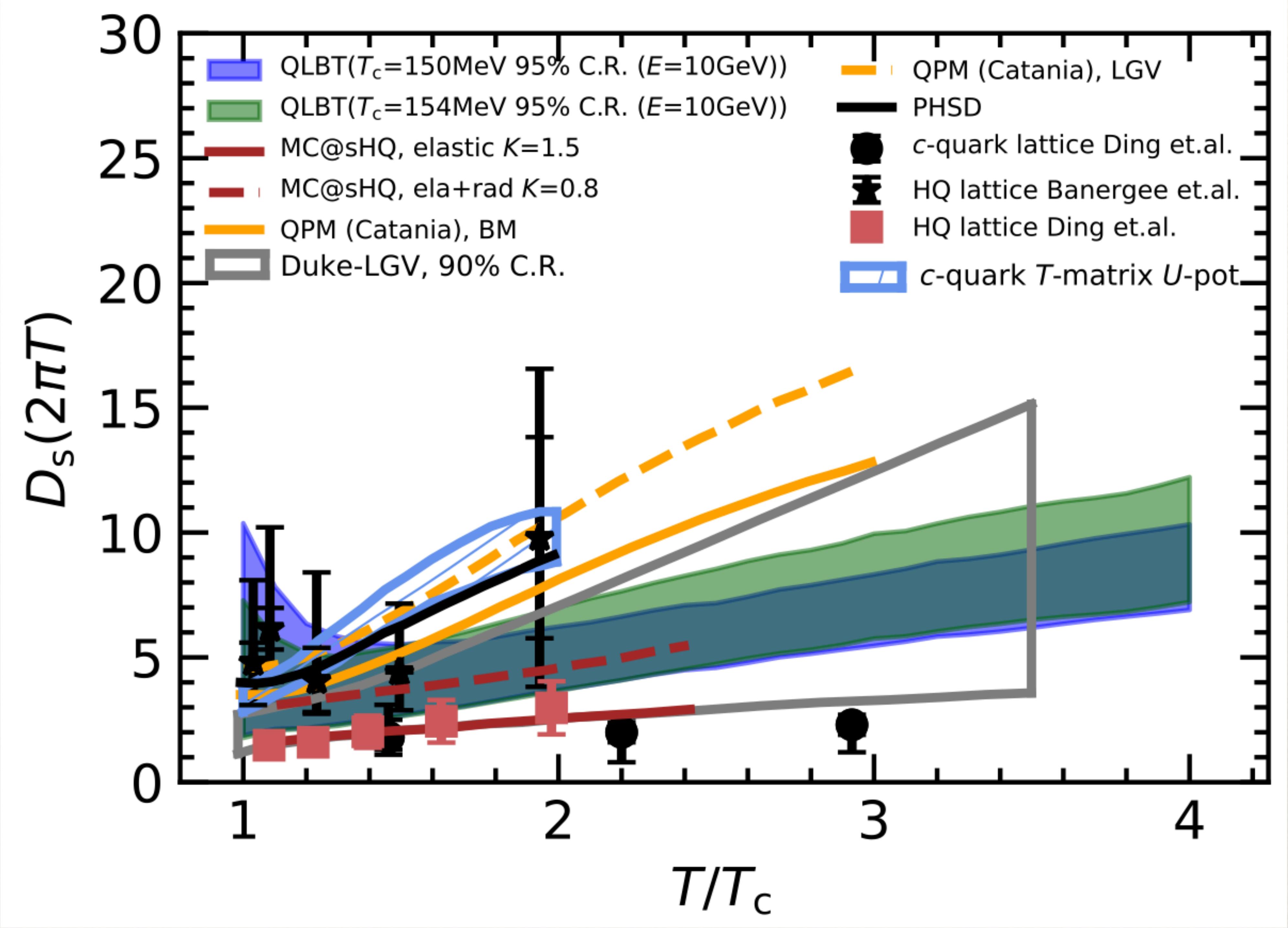
Calculate EoS from g

EoS of QGP and diffusion coefficient of heavy quarks

Equation of state



Diffusion coefficient



[Liu, Wu, SC, Qin, Wang, Phys. Lett. B 848 (2024) 138355]

- Agreement with the lattice data
- Simultaneous constraint on QGP properties and transport properties of hard probes

Summary

Transport study on nuclear modification of energetic hadrons and jets

- Flavor hierarchy of parton energy loss is encoded in the hadron R_{AA}, though not explicit due to the interplay between energy loss and NLO contributions
- The same transport model is extended to bound states of heavy quark pairs (B_c)
- The jet EEC is an excellent observable for studying the dead cone effect on parton splitting (magnitude and peak position of EEC) in *pp* and AA collisions
- Jet and heavy flavor observables can constrain various QGP properties

Thank you!