Jet Physics in Heavy-Ion Collisions

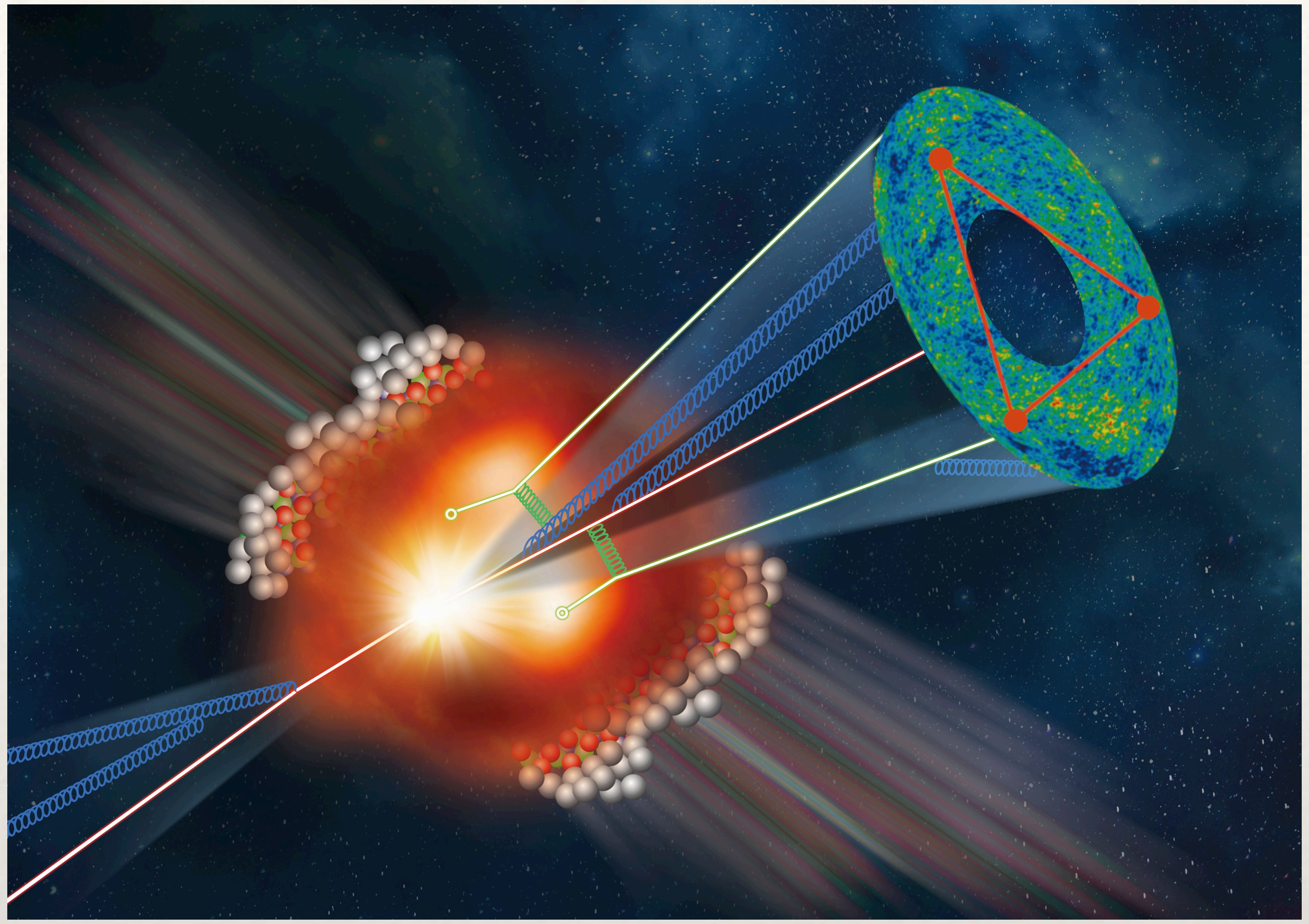
曹杉杉

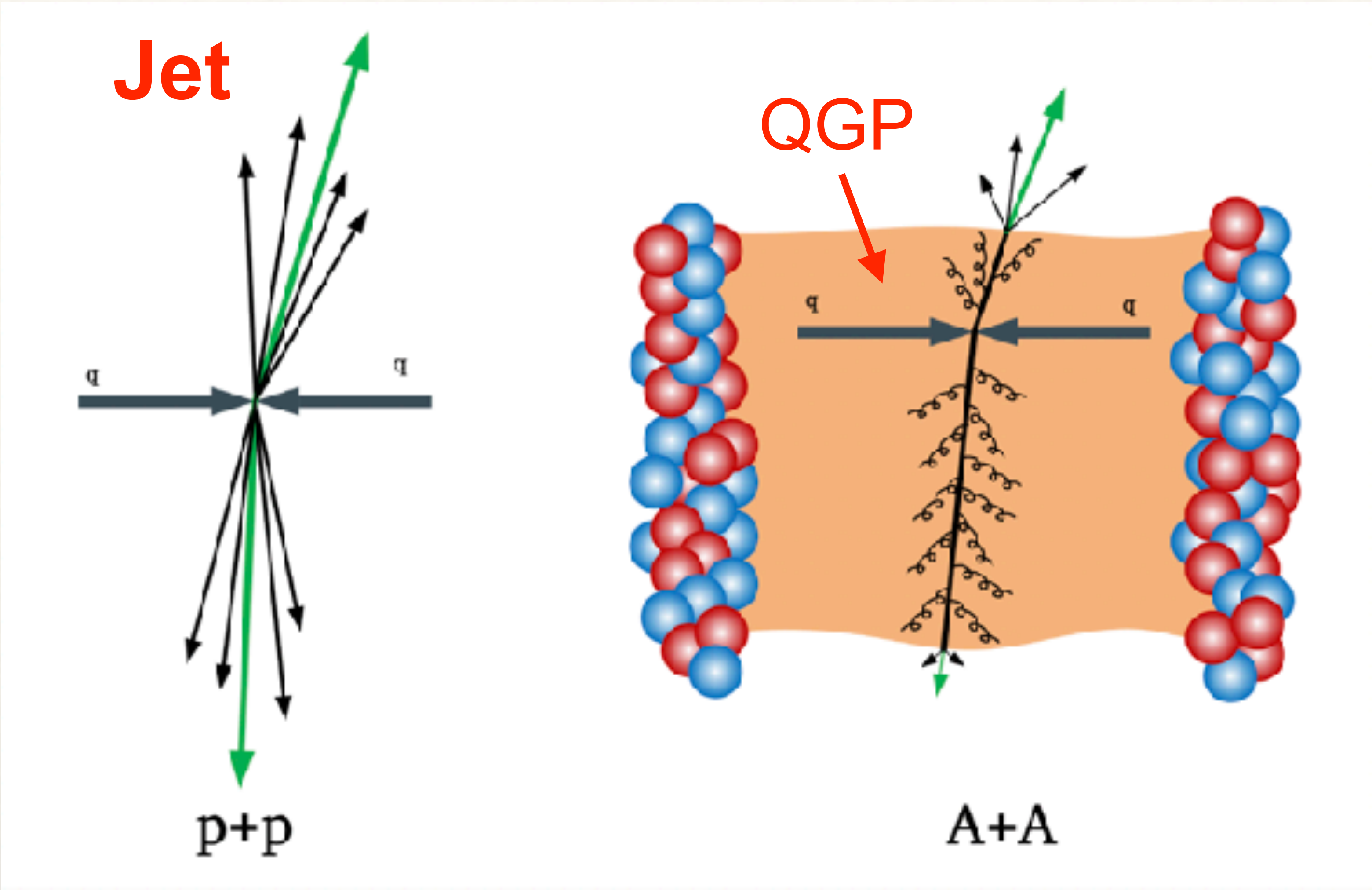
山东大学

2025年4月28日 上海

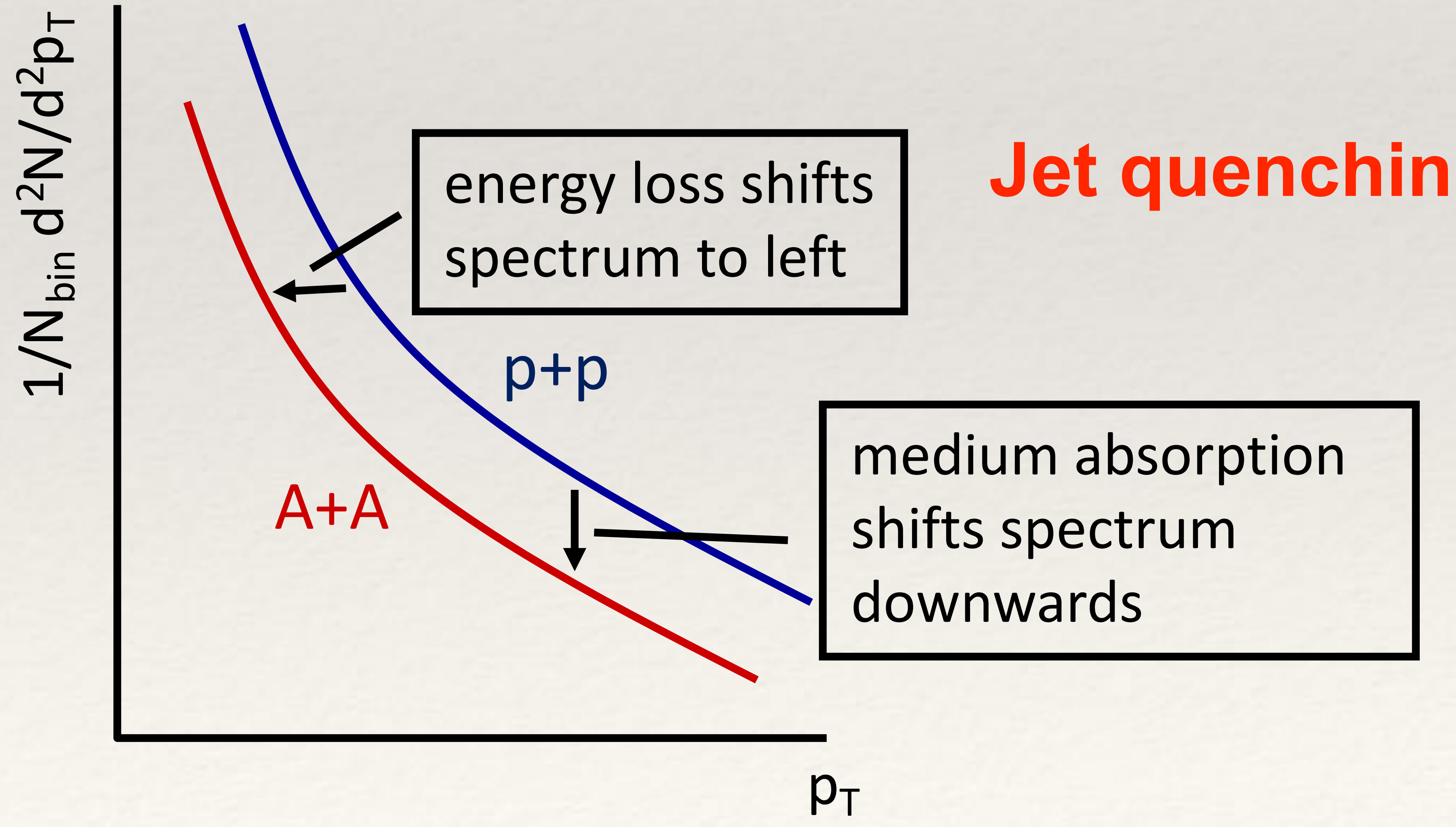
第二十届全国中高能核物理大会

Probing quark-gluon plasma (QGP) using jets





[by M. Rybar / ATLAS]



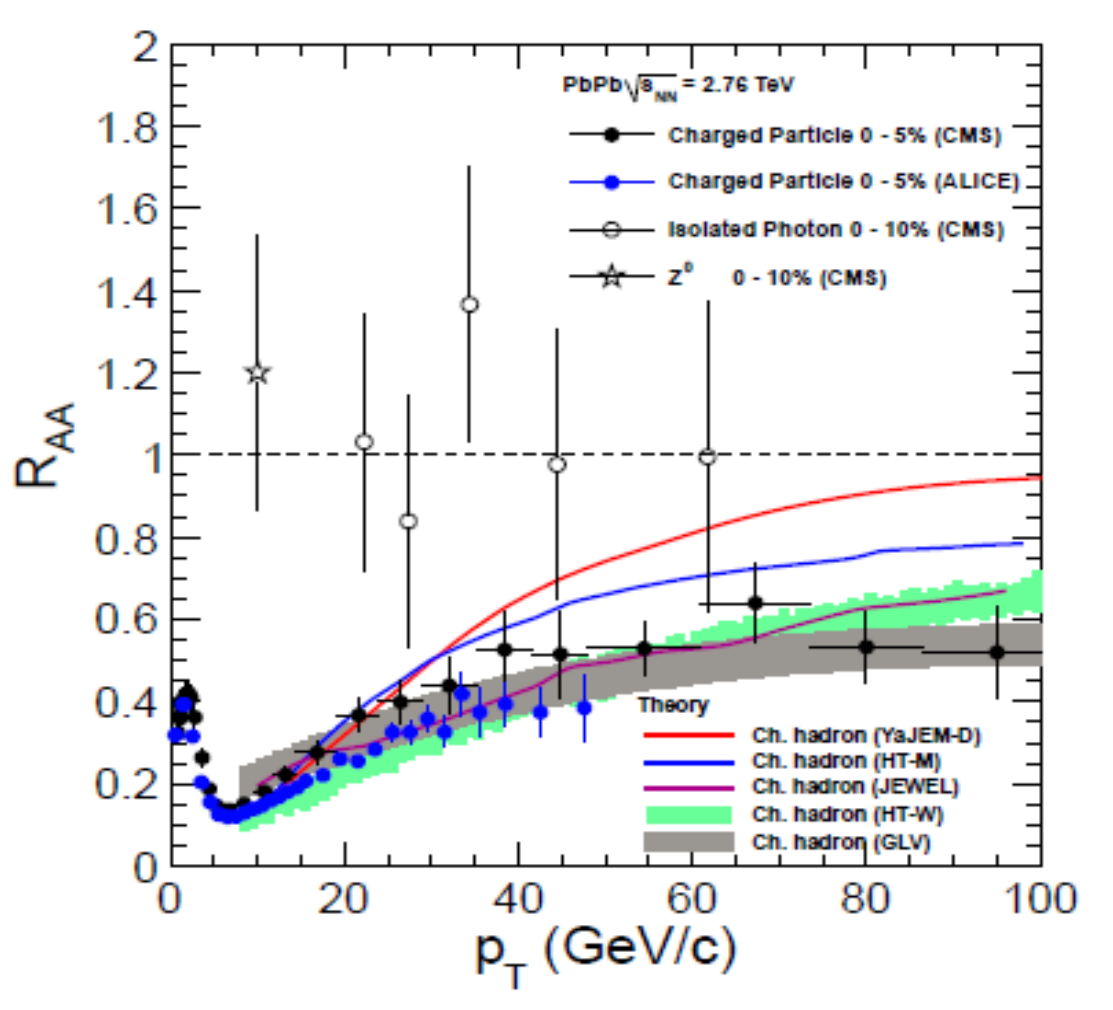
Jet quenching

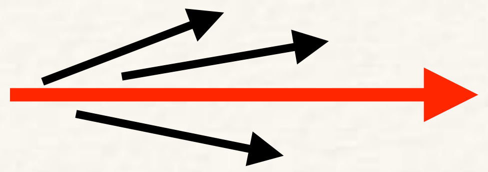
- Quantify QGP effects on jets by comparing jet spectra between *pp* and AA collisions
- Nuclear modification factor:

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{dN^{\mathrm{AA}}/dp_{\mathrm{T}}}{\langle N_{\mathrm{coll}}^{\mathrm{AA}} \rangle \times dN^{pp}/dp_{\mathrm{T}}}$$

What is a jet depends on how one defines a jet

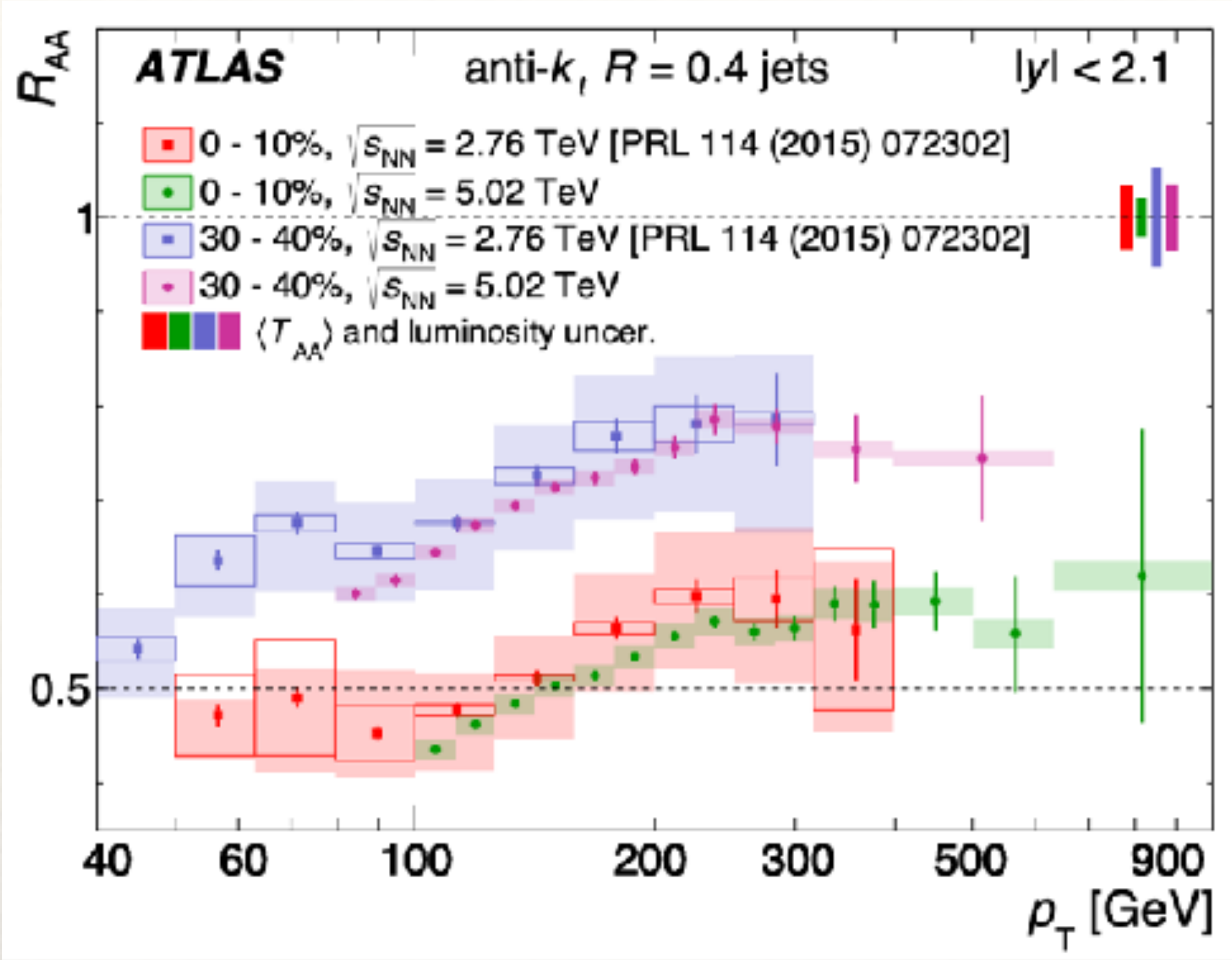
R_{AA} of single particles

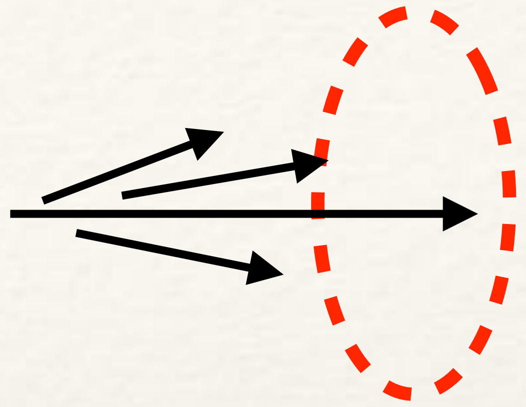




Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)

R_{AA} of full jets

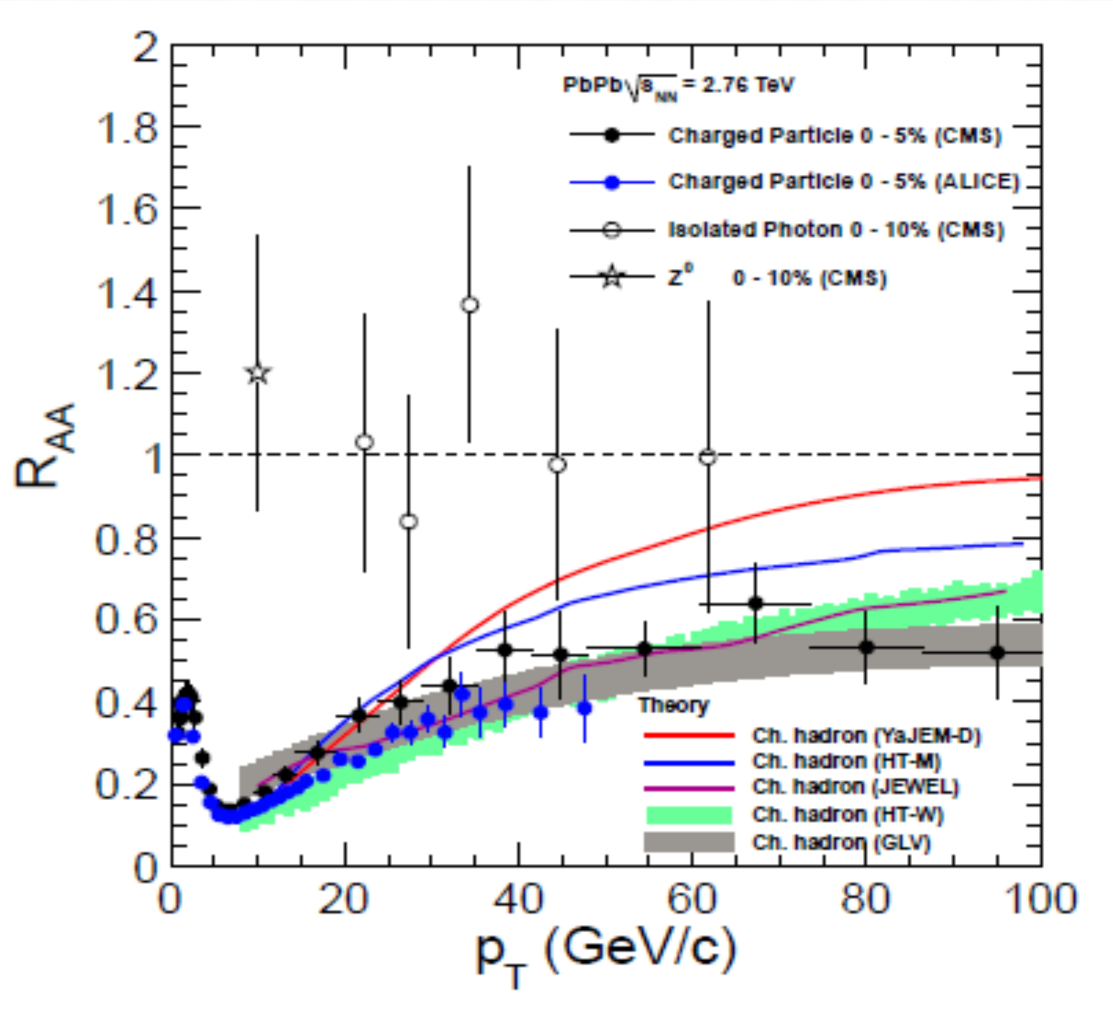


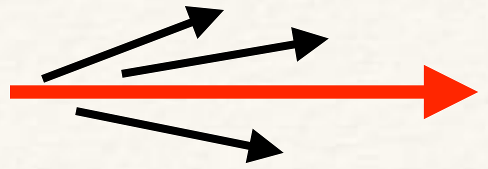


ATLAS, Phys. Lett. B 790 (2019) 108

What is a jet depends on how one defines a jet

R_{AA} of single particles





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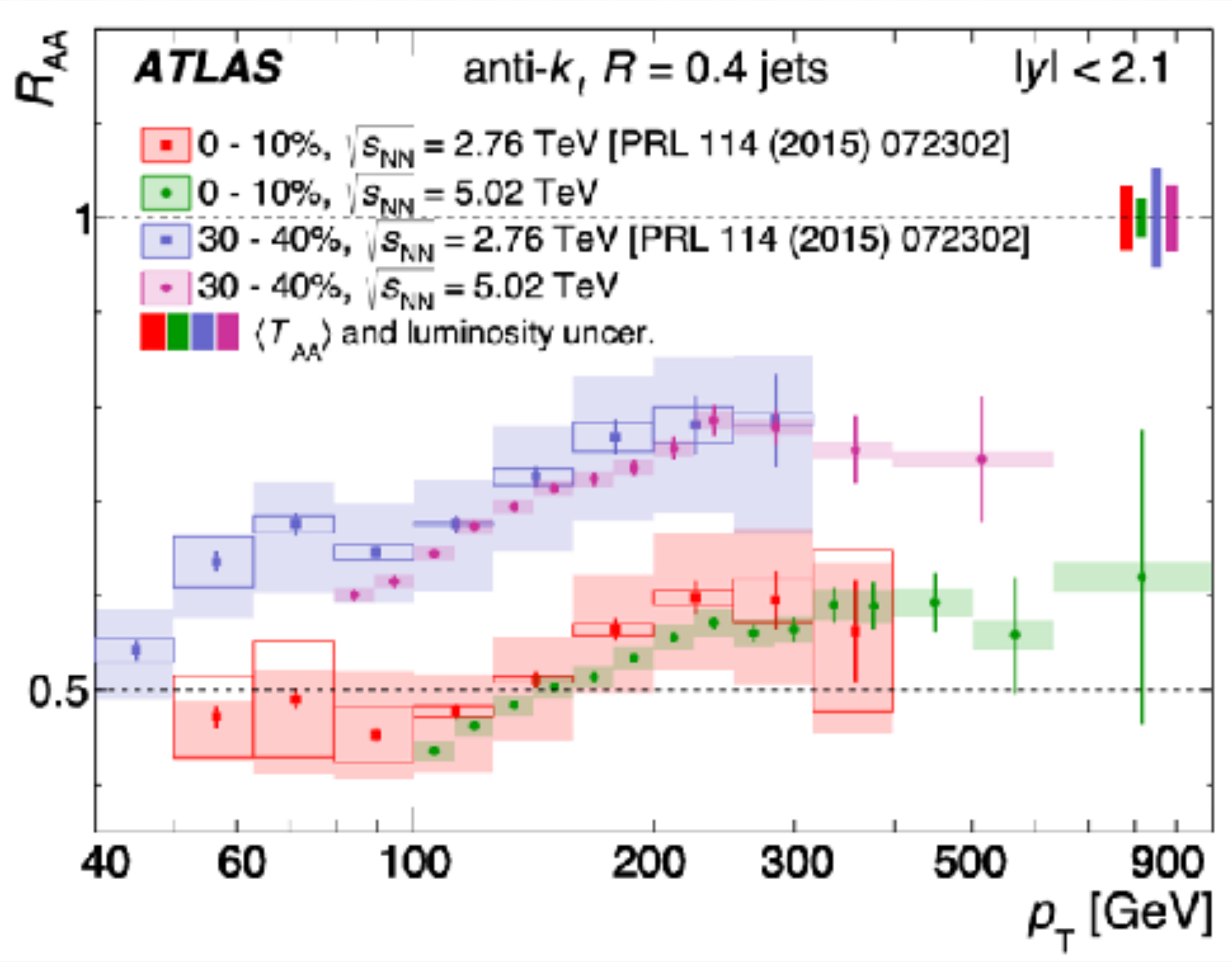
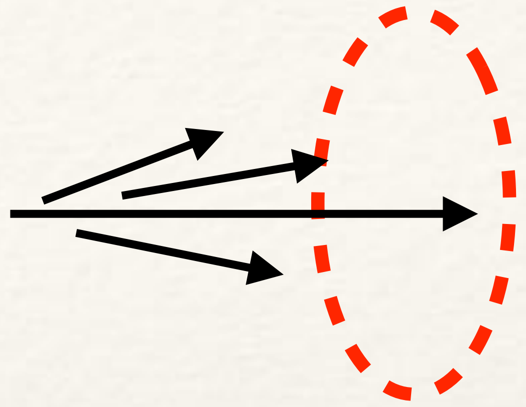
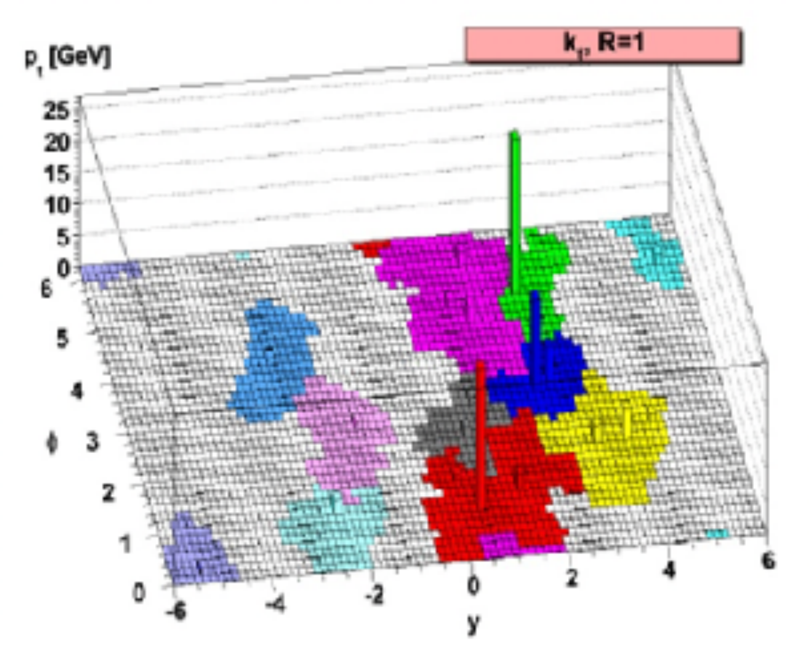
R_{AA} of full jets





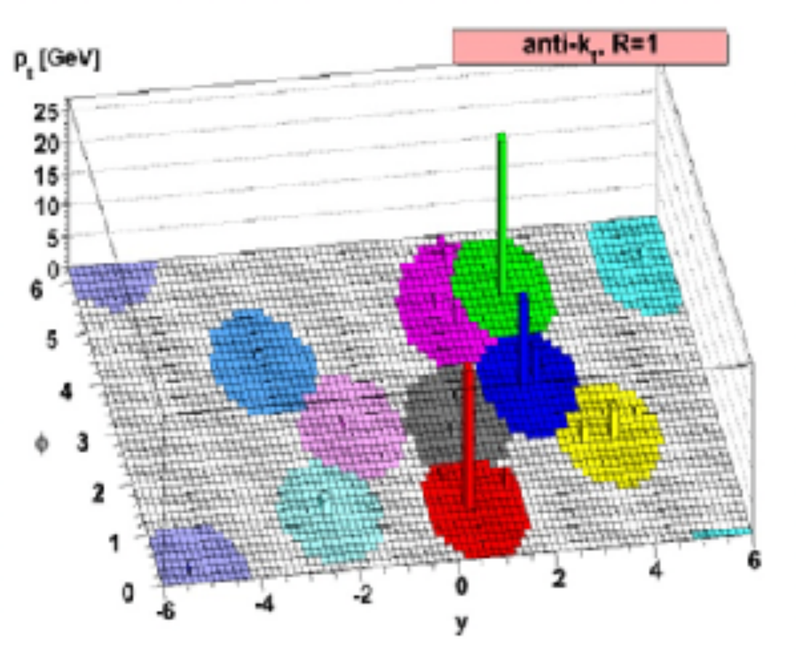
ATLAS, Phys. Lett. B 790 (2019) 108

- Different clustering algorithms developed for different purposes



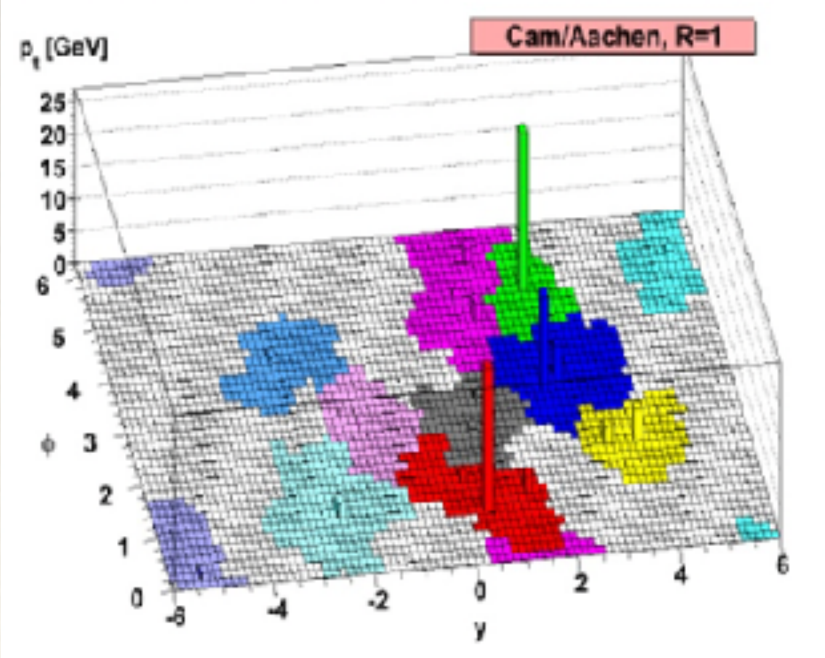
k_T algorithm

for estimating soft background



anti-k_T algorithm

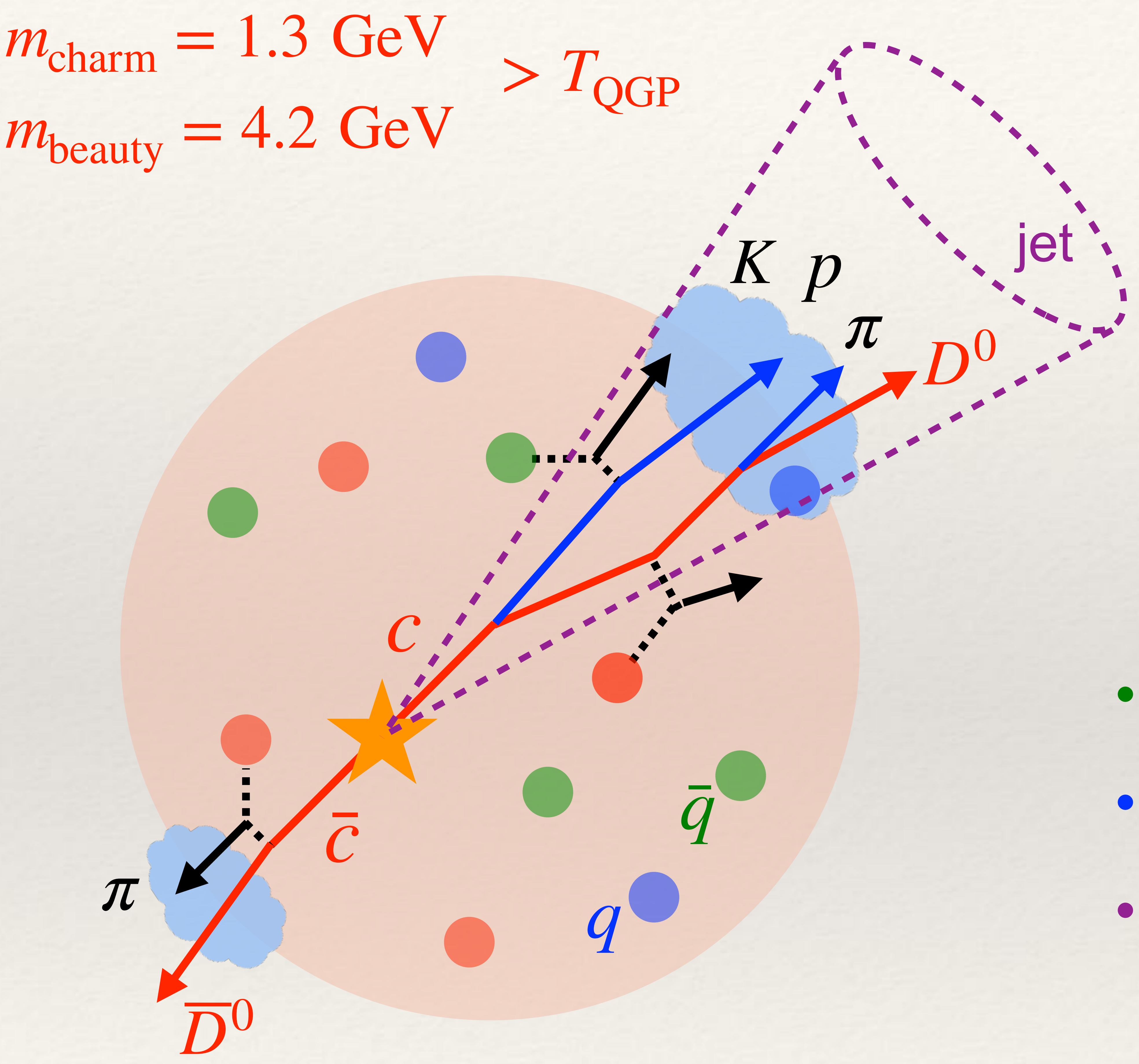
for identifying energetic jets

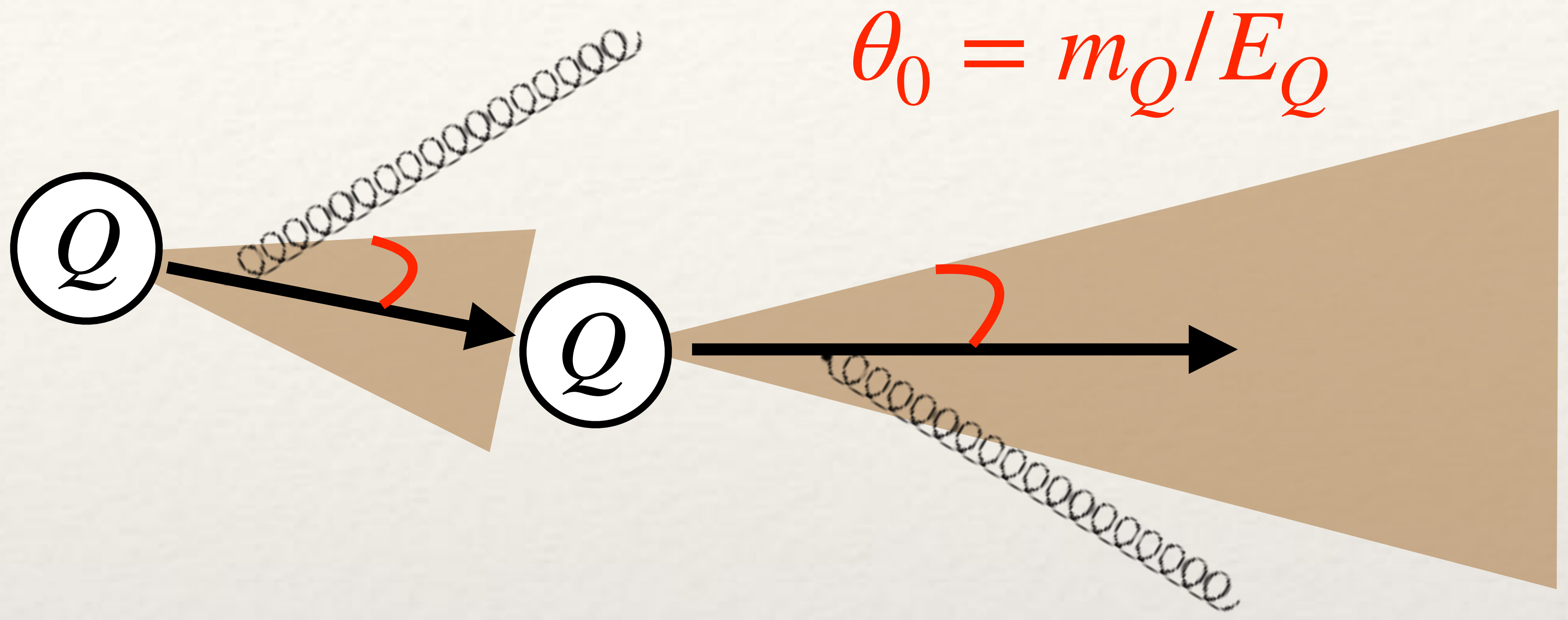


C/A algorithm

for identifying splitting angles

Jets tagged with heavy quarks

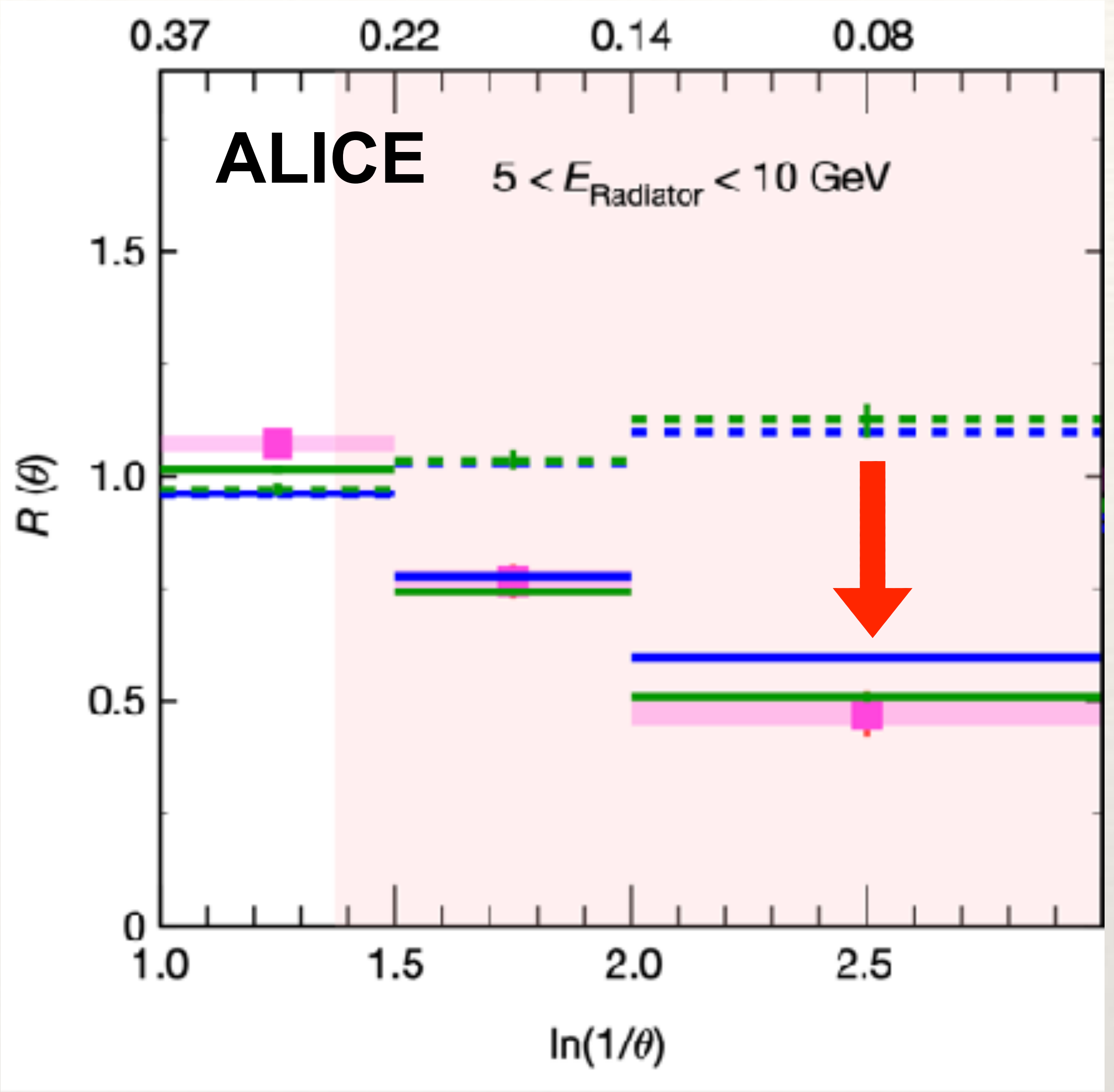




- Produced from initial hard scatterings
- Serve as an ideal probe of the QGP properties
- Provide a unique opportunity for studying the flavor dependence of parton splitting (dead cone effect)

Searches for the flavor dependence of parton splitting

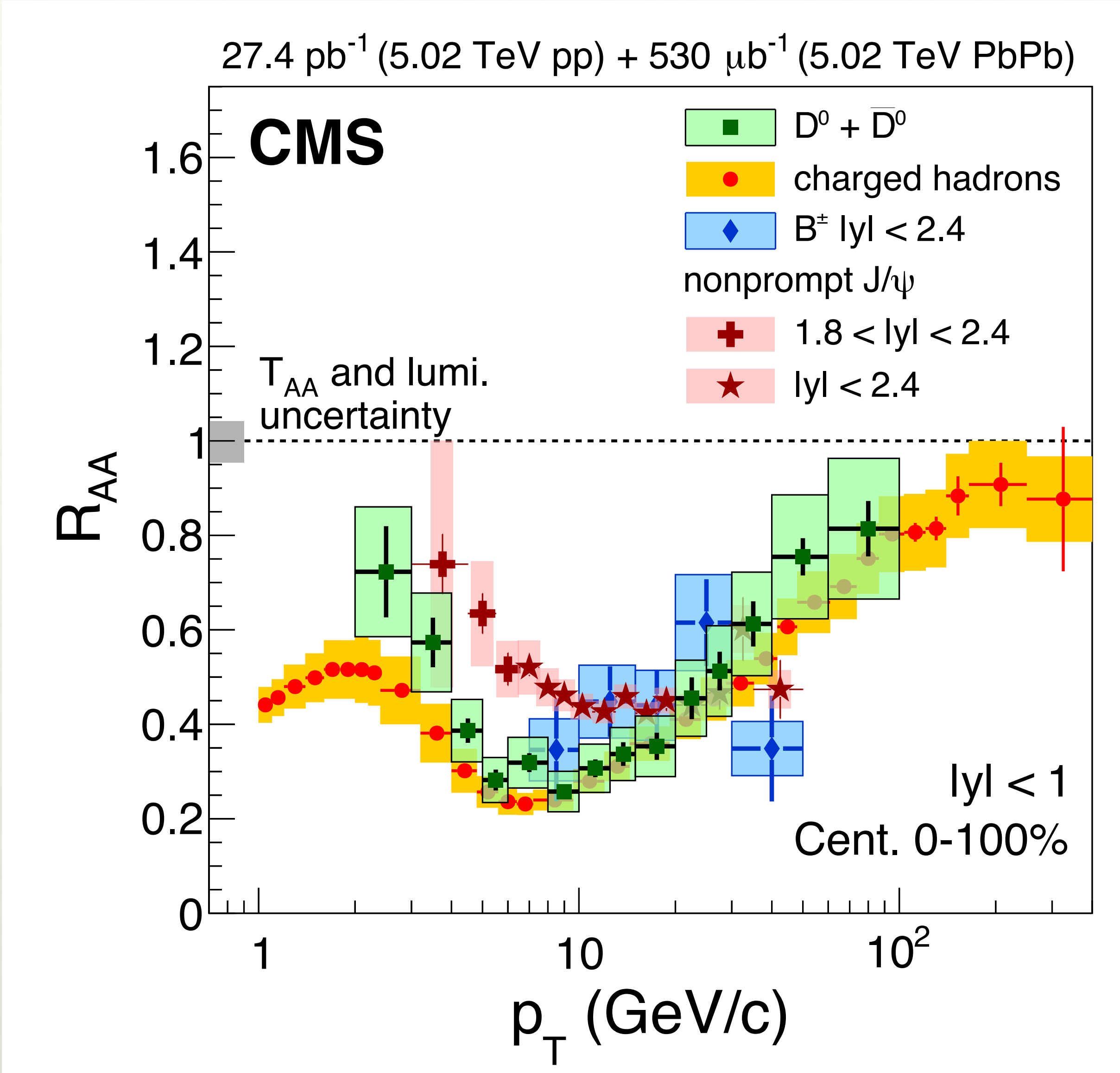
Distribution of splitting angles in *pp*



Nature 605 (2022) 7910

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

Hadron R_{AA} (parton energy loss)



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

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

Searches for the flavor dependence of parton splitting

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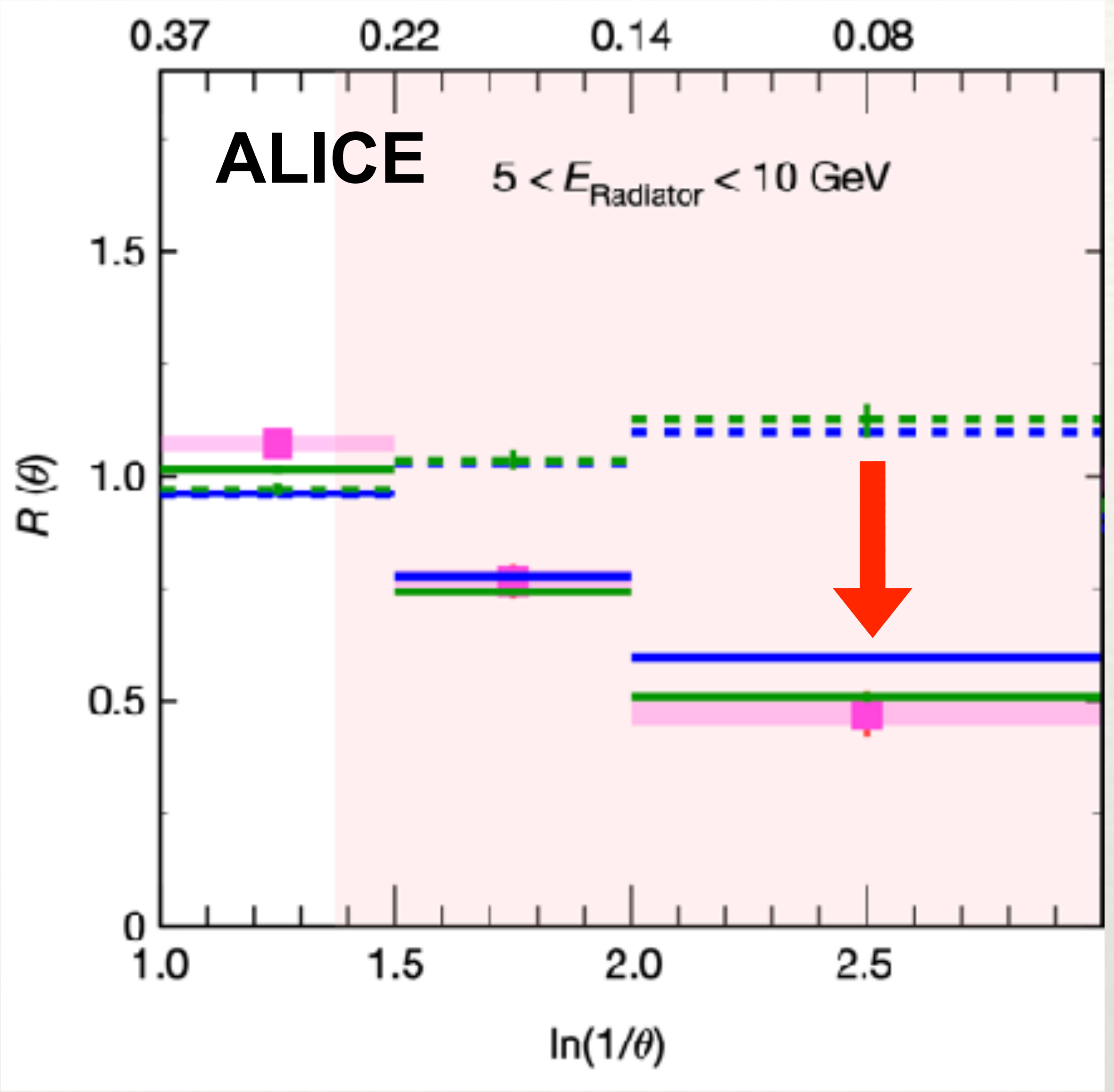

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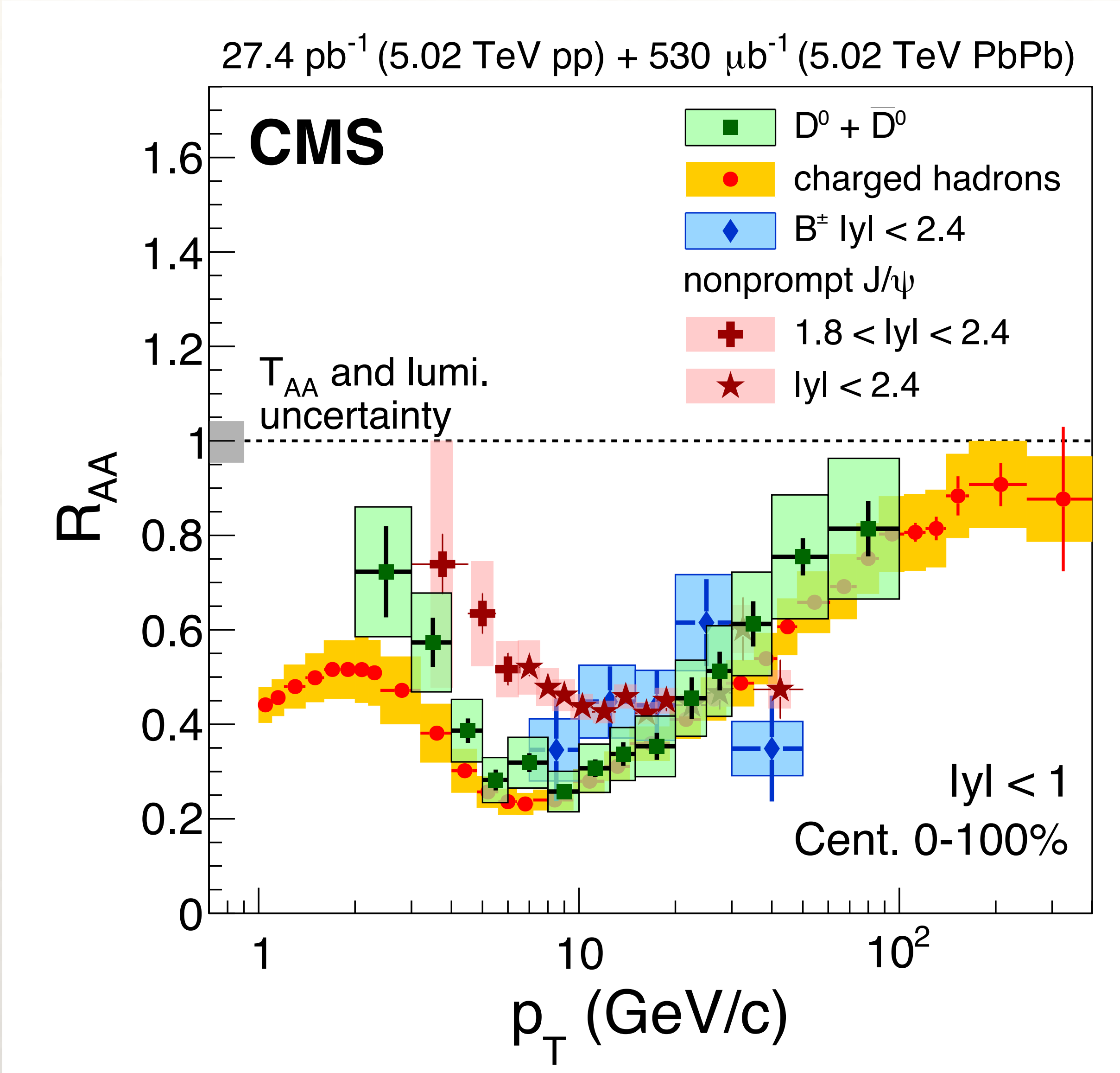

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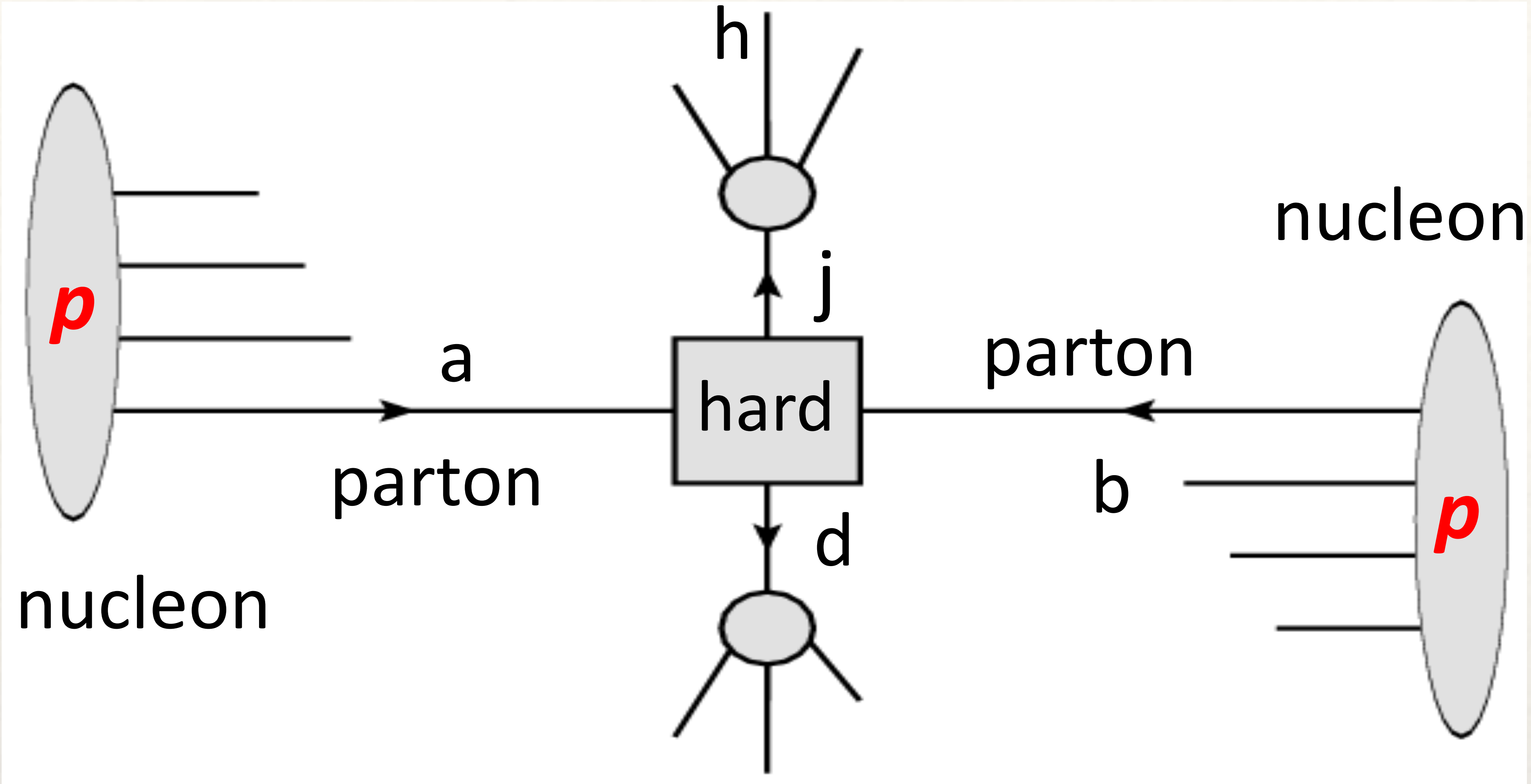
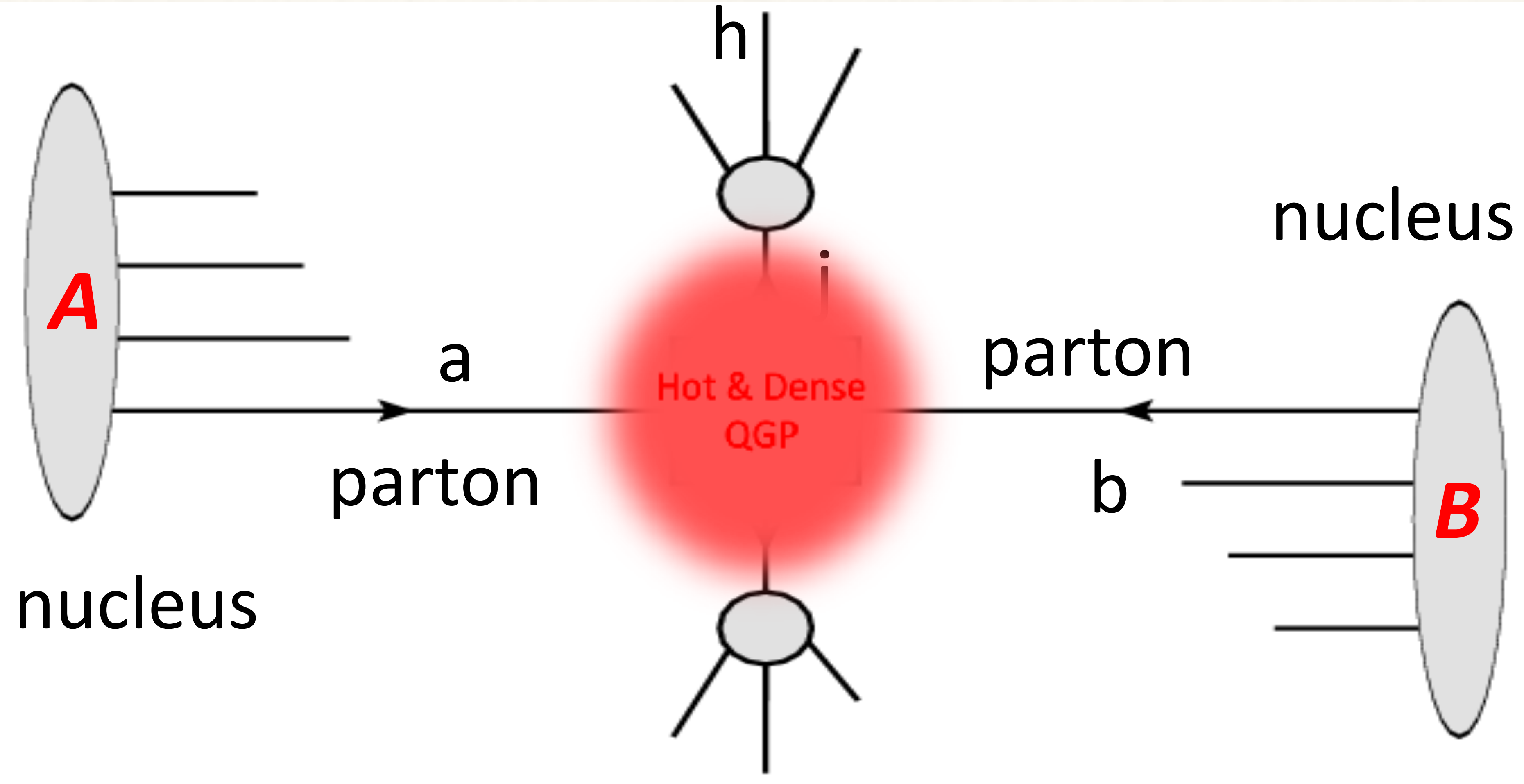
Goals:

- Consistently understand hadron and full jet observables
- Consistently understand light and heavy flavor jets
- Use jets to probe properties of the QGP

Theoretical framework of jet quenching





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

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

- $f_{a/p}, f_{b/p} \to f_{a/A}, f_{b/B}$: 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)

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

Parton transport inside the QGP

Linear Boltzmann Transport (LBT)

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

Elastic scattering ($ab \to cd$)

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

$2 \to 2$ scattering matrices

Parton transport inside the QGP

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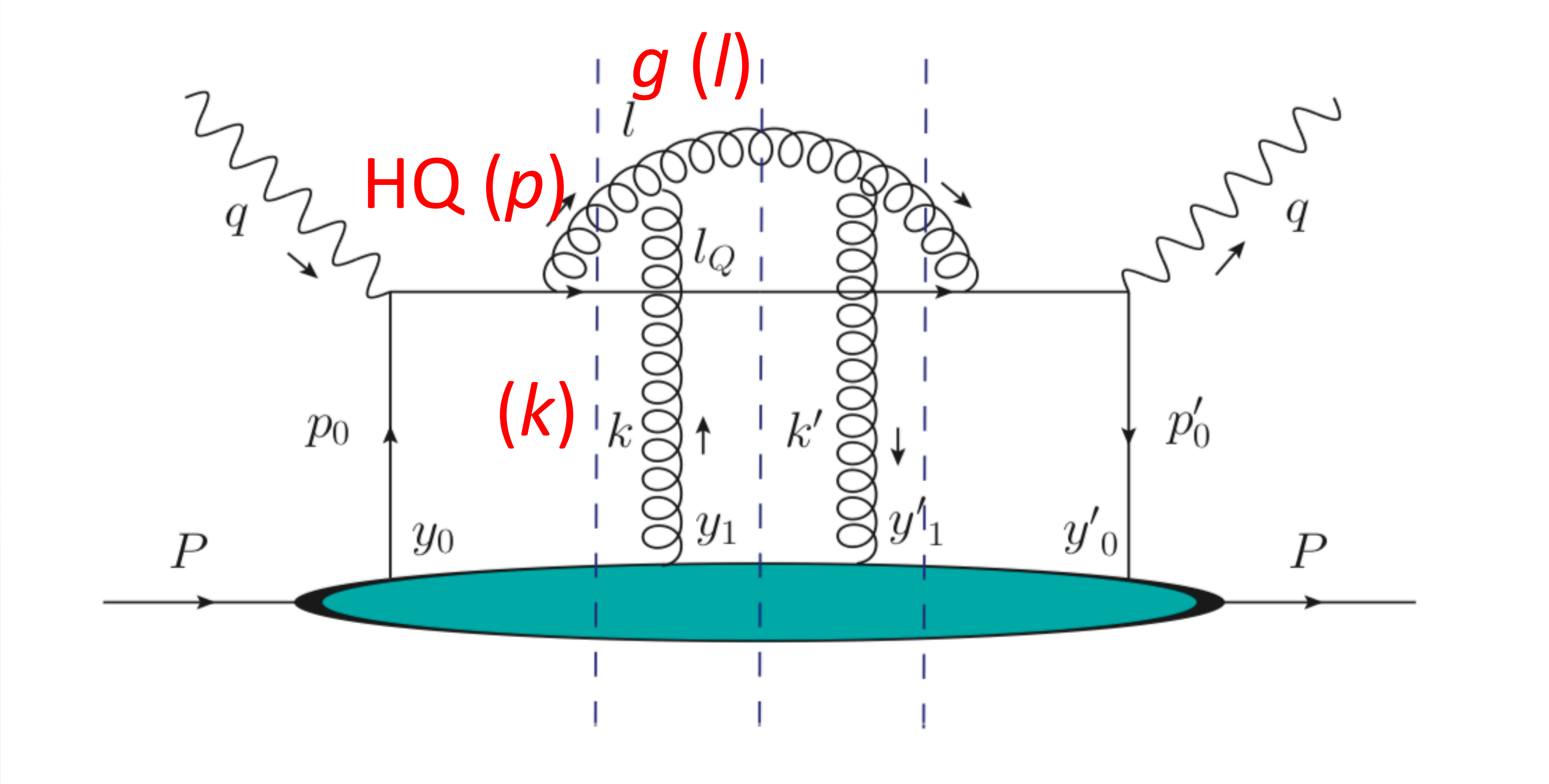
$2 \to 2$ scattering matrices

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 ($\langle k_\perp^2 \rangle \ll l_\perp^2 \ll Q^2$)

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

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

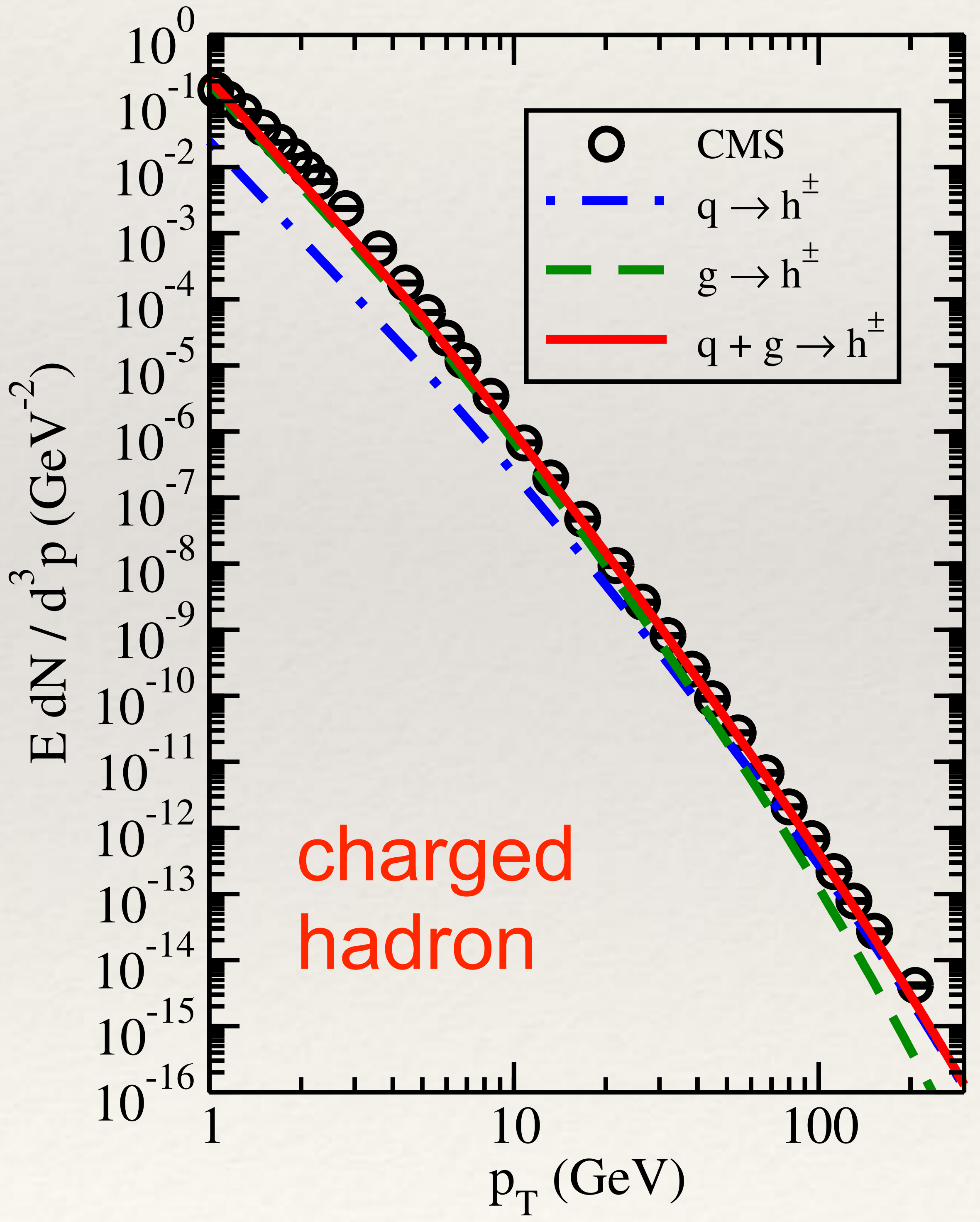
Flavor hierarchy in hadron suppression

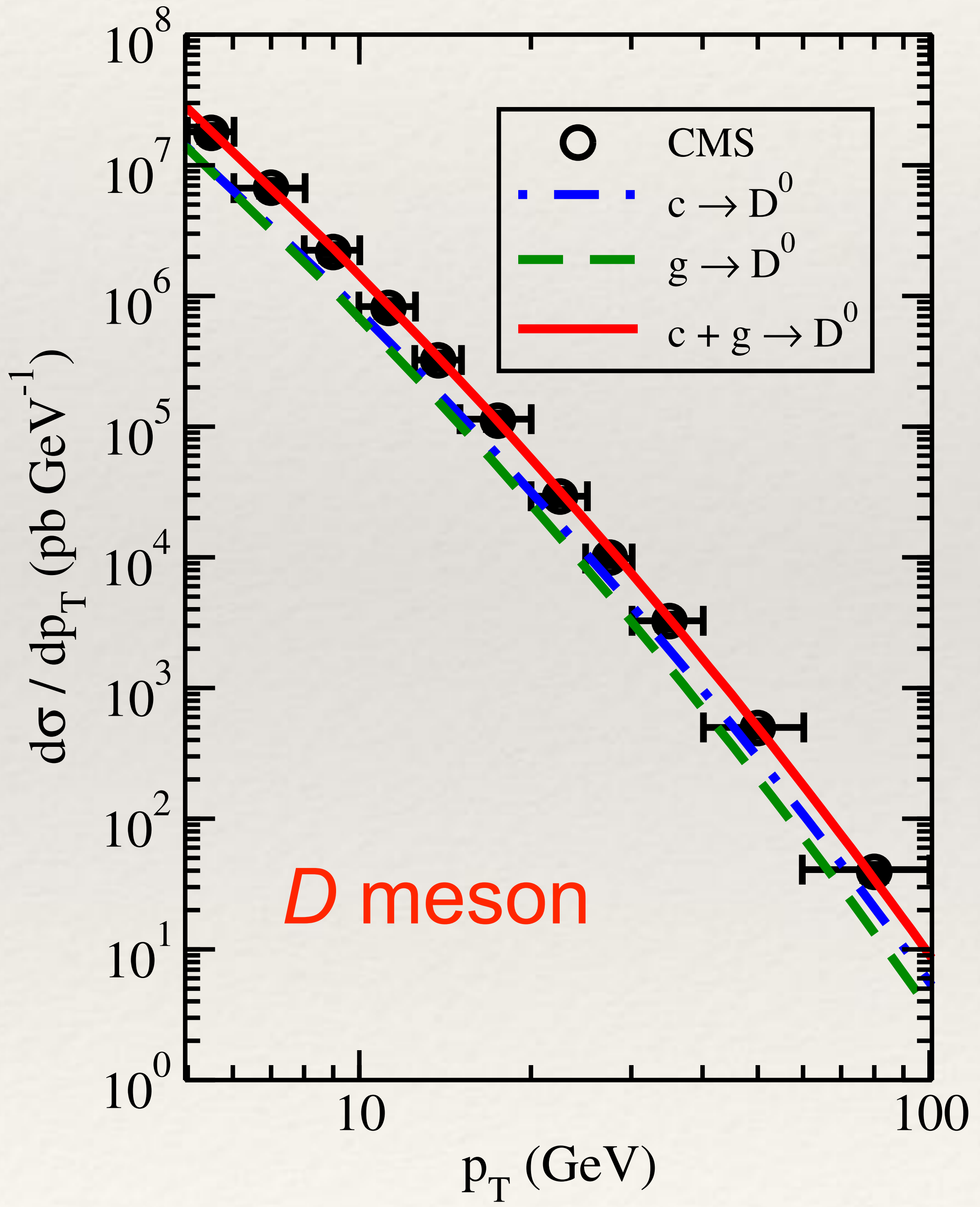
Perturbative calculation simultaneously describes the R_{AA} of light and heavy hadrons at high p_T

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

pp baseline within the NLO production + fragmentation framework

- Crucial contributions from the gluon fragmentation (or $g \to Q\bar{Q}$) process





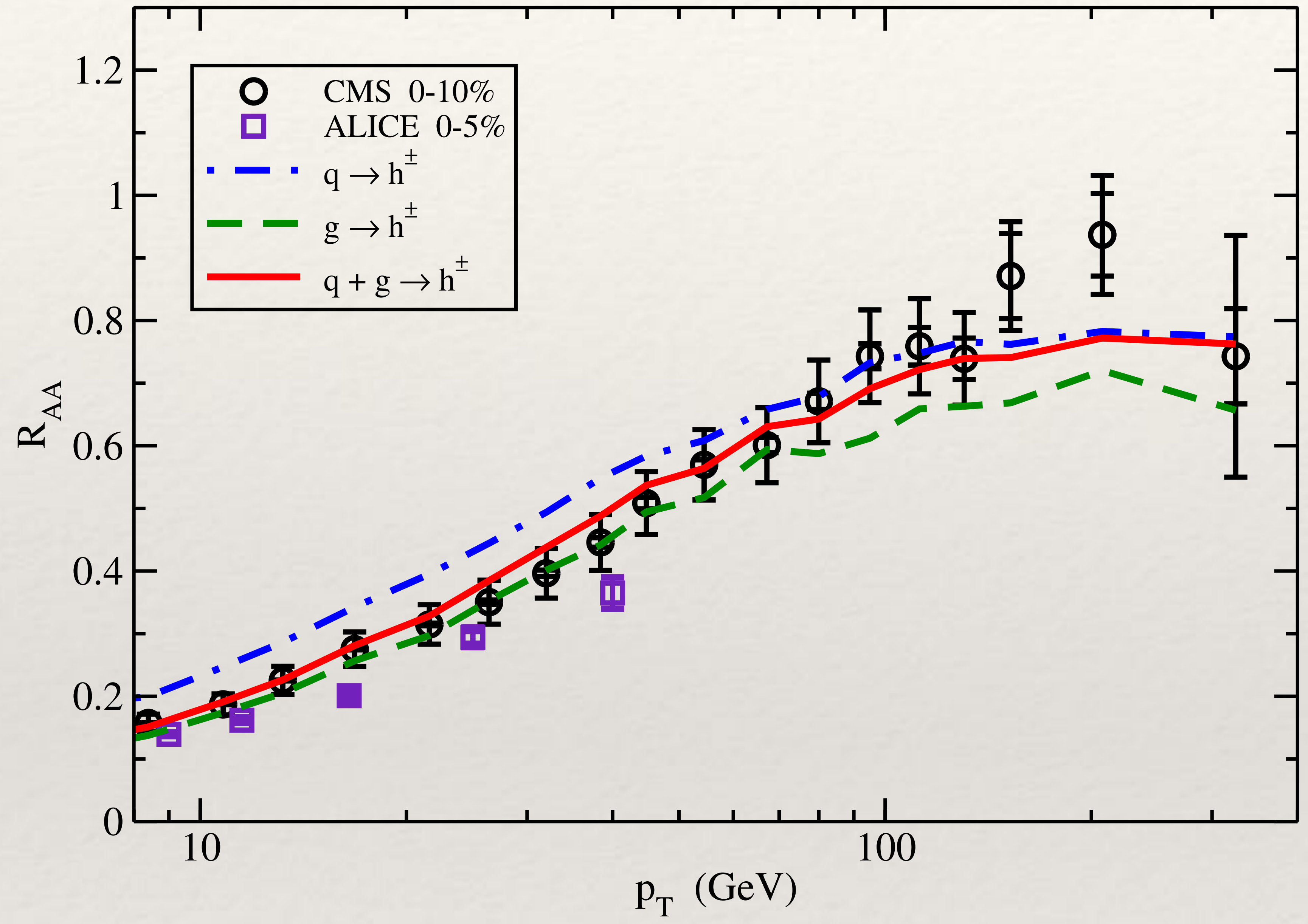
Gluon fragmentation

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

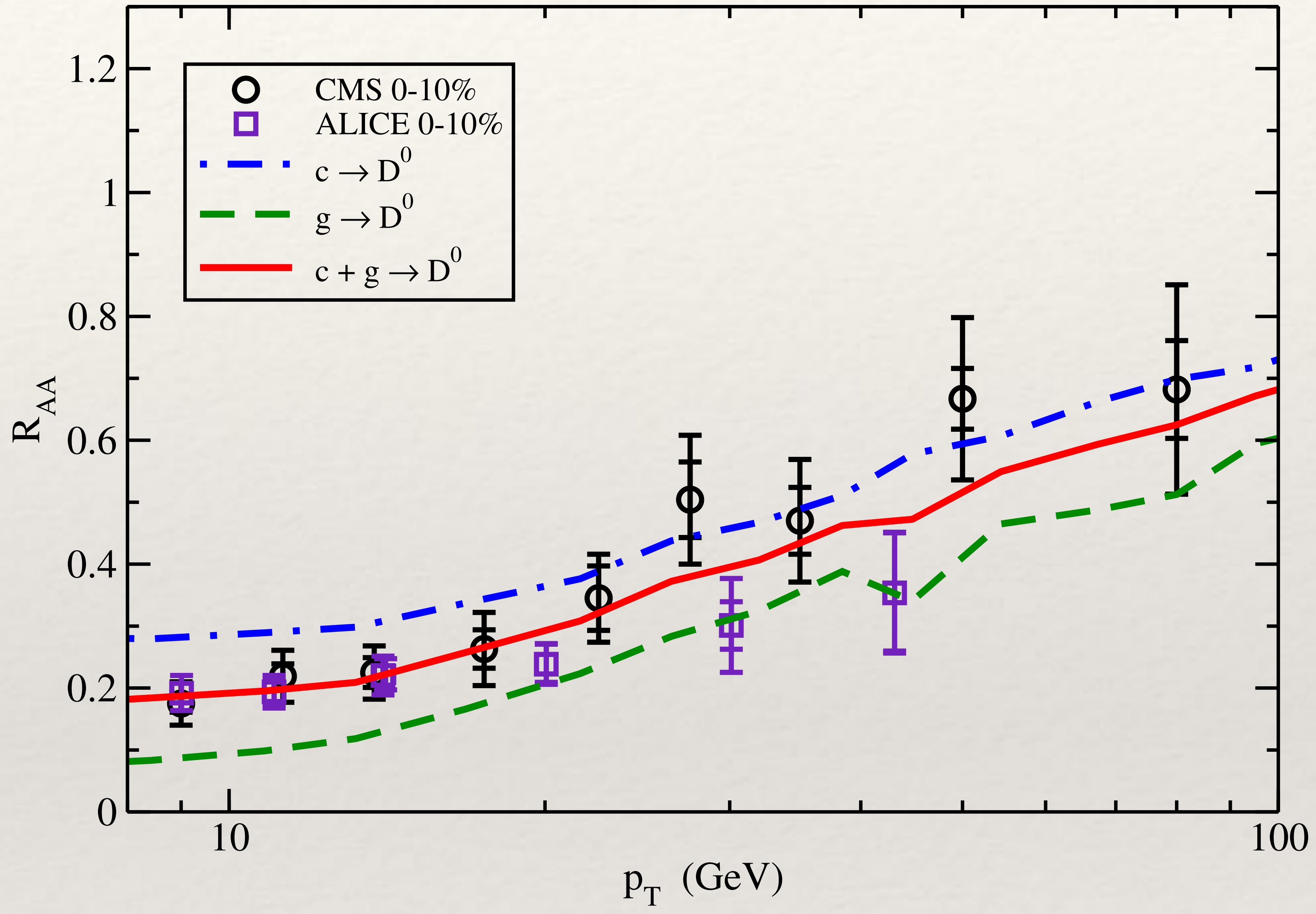
Flavor hierarchy in hadron suppression

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

charged hadron



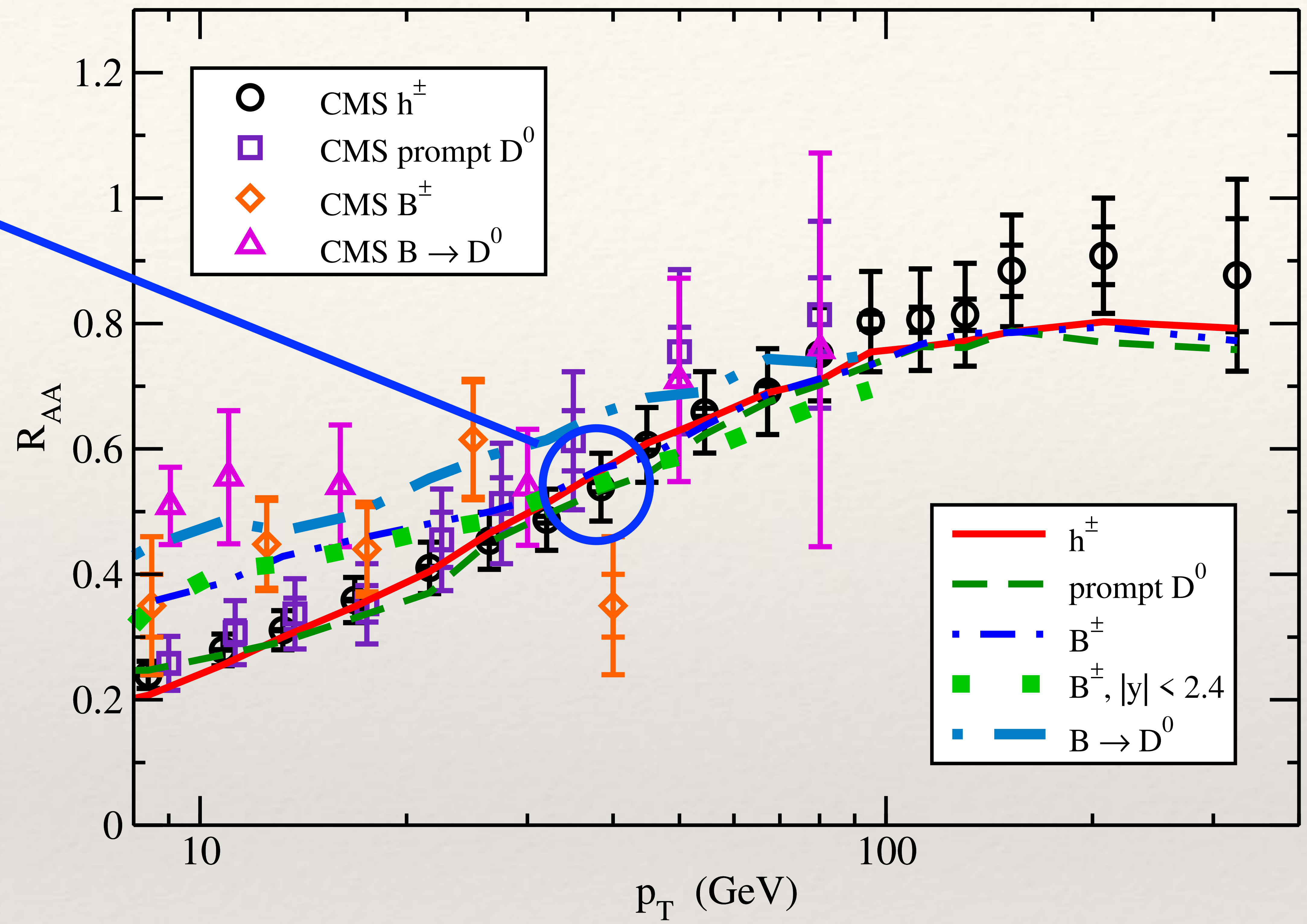
D meson



- *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 gluon production/fragmentation in hadron R_{AA}

Flavor hierarchy in hadron suppression

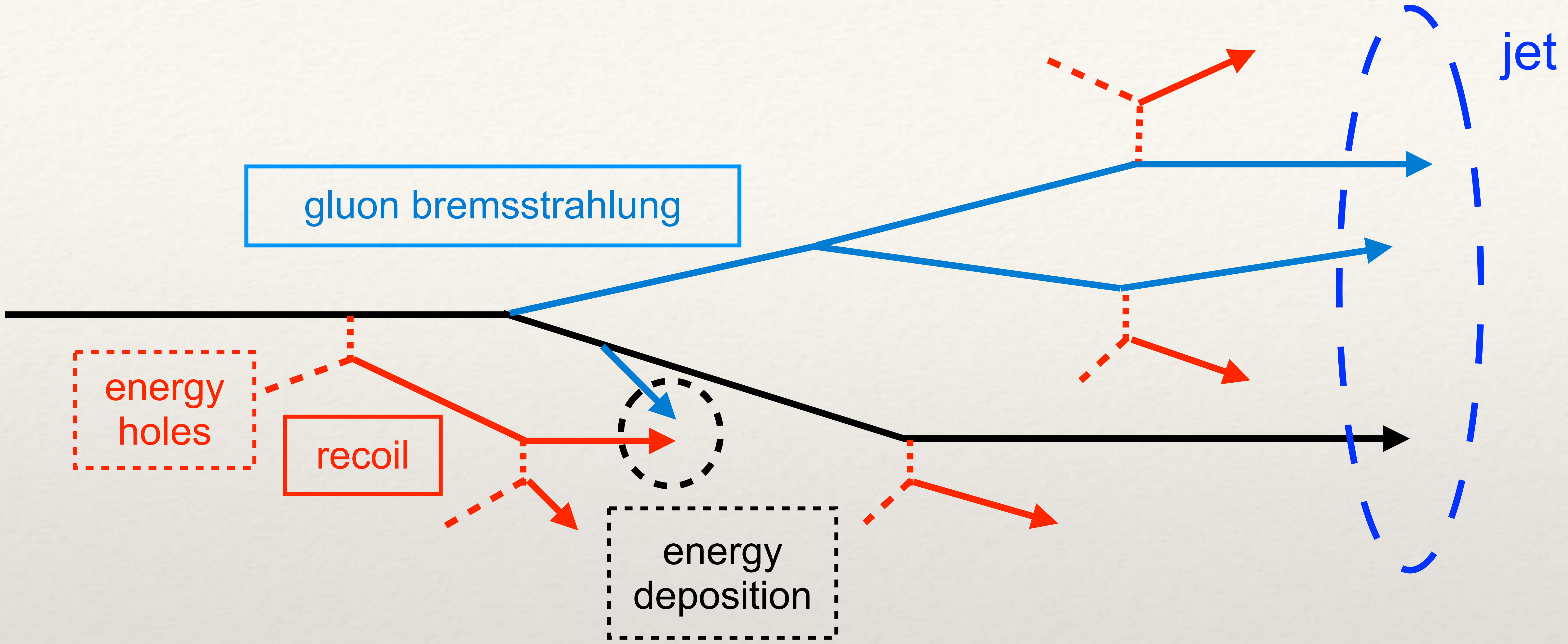
Merging of *D* and *B* R_{AA} at p_T ~ 40 GeV



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**

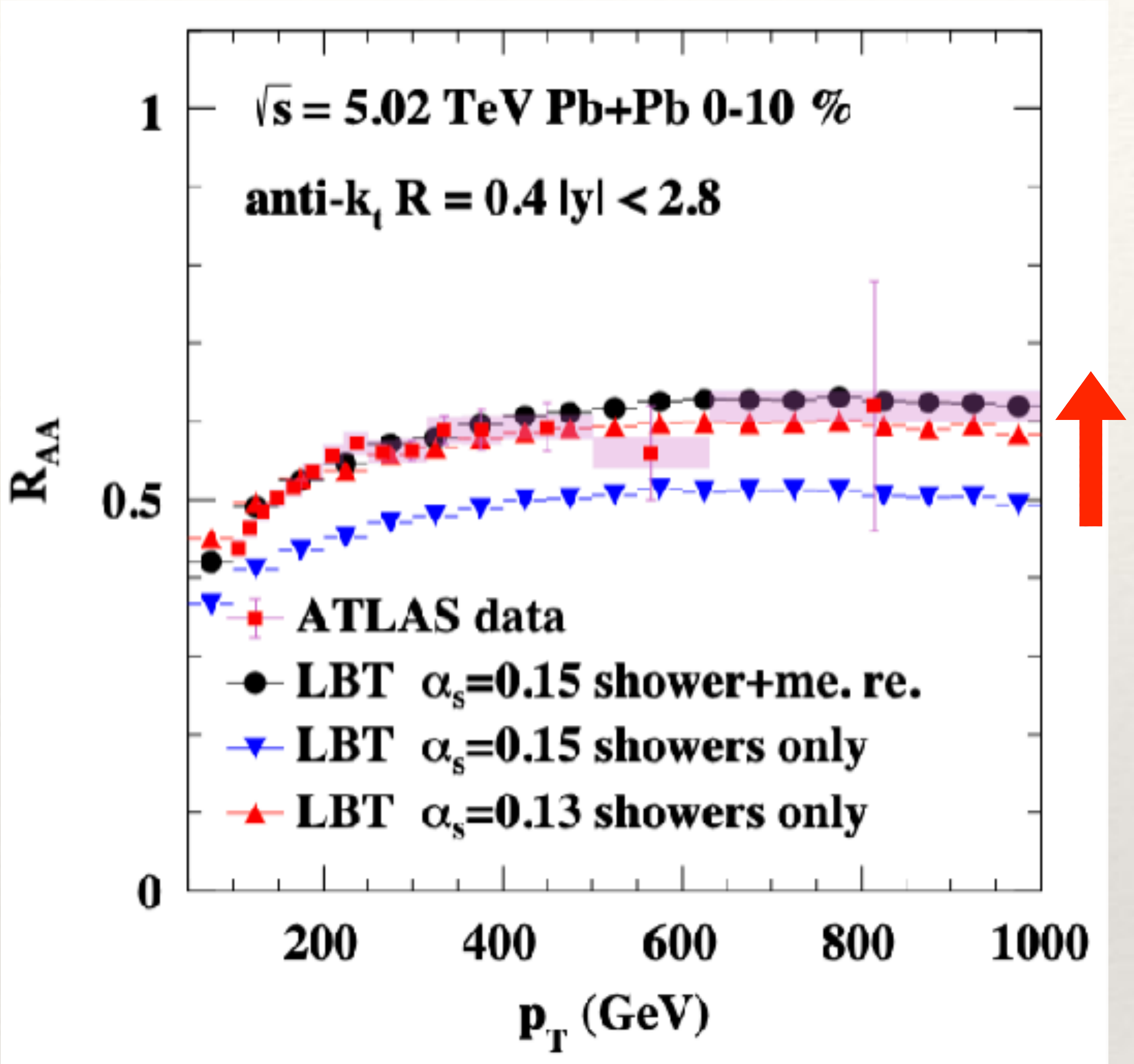
From hadrons to full jets



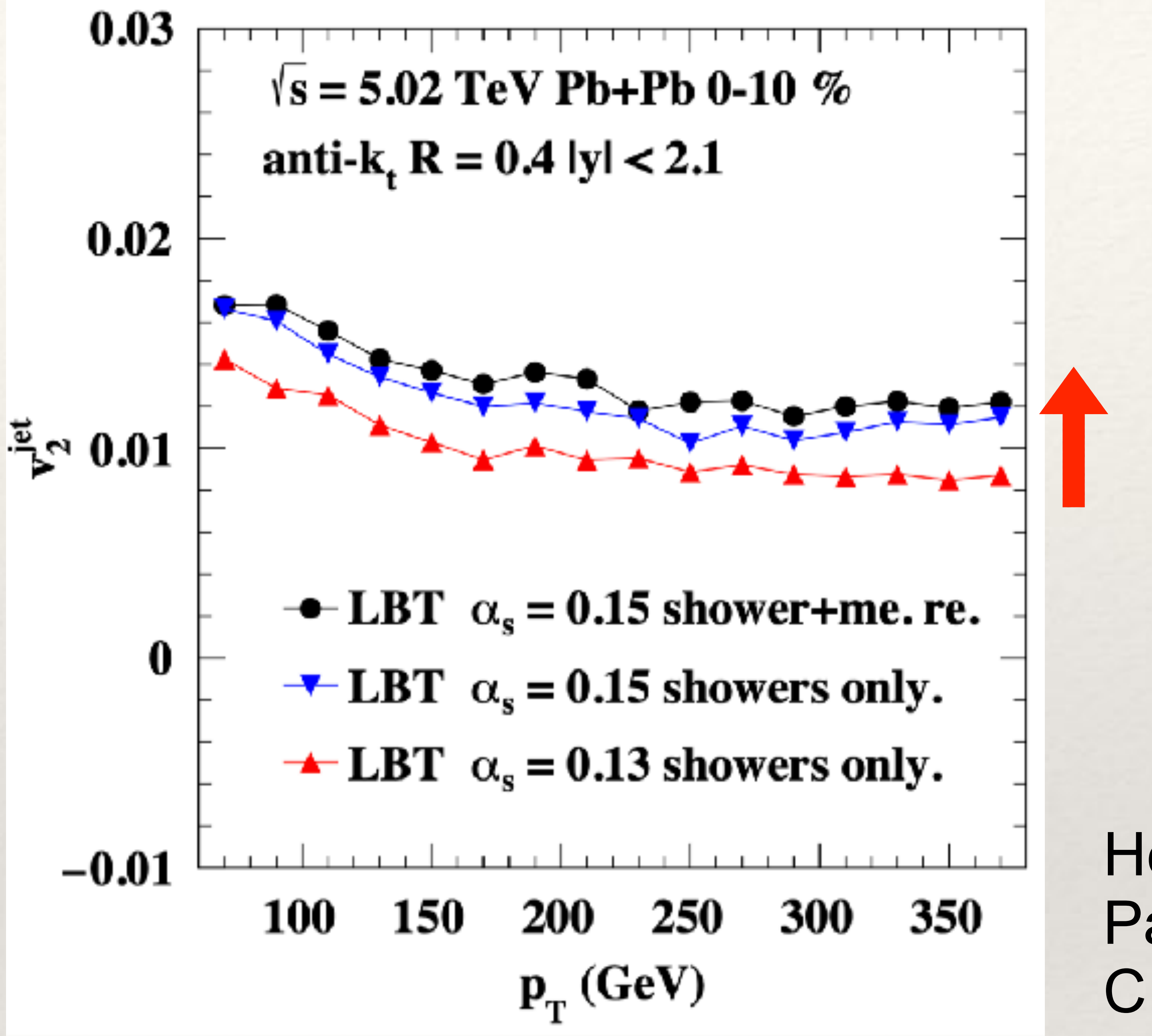
- Energy deposition + depletion → **jet-induced medium excitation (medium response)**
- Primordial jet partons and medium response cannot be cleanly separated for jet observables
- Jet-medium interactions: **medium modification of jets + medium response**

Jet R_{AA} and v_2

R_{AA}



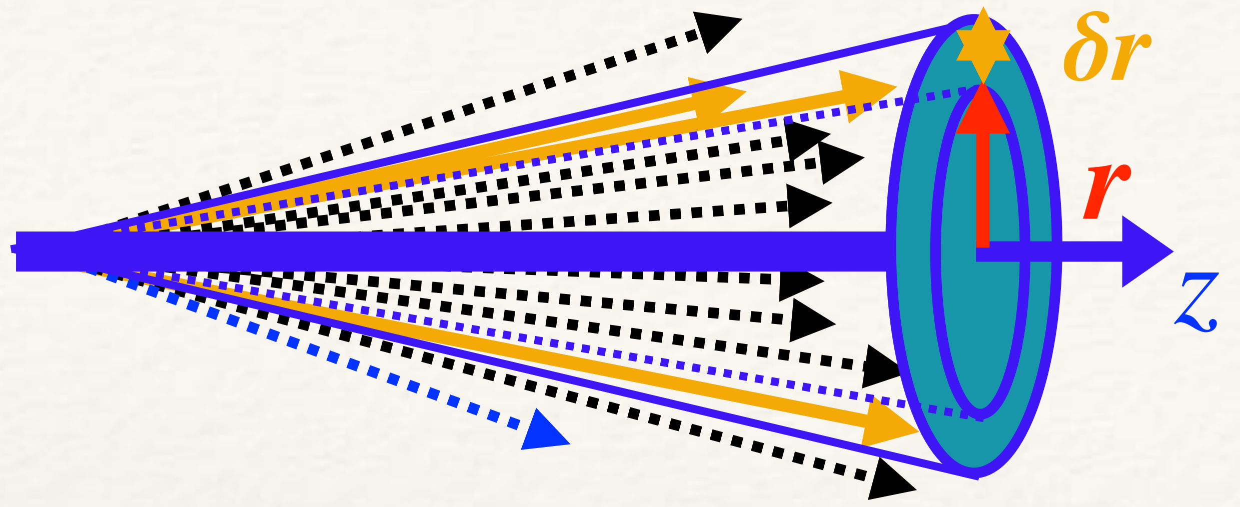
v_2



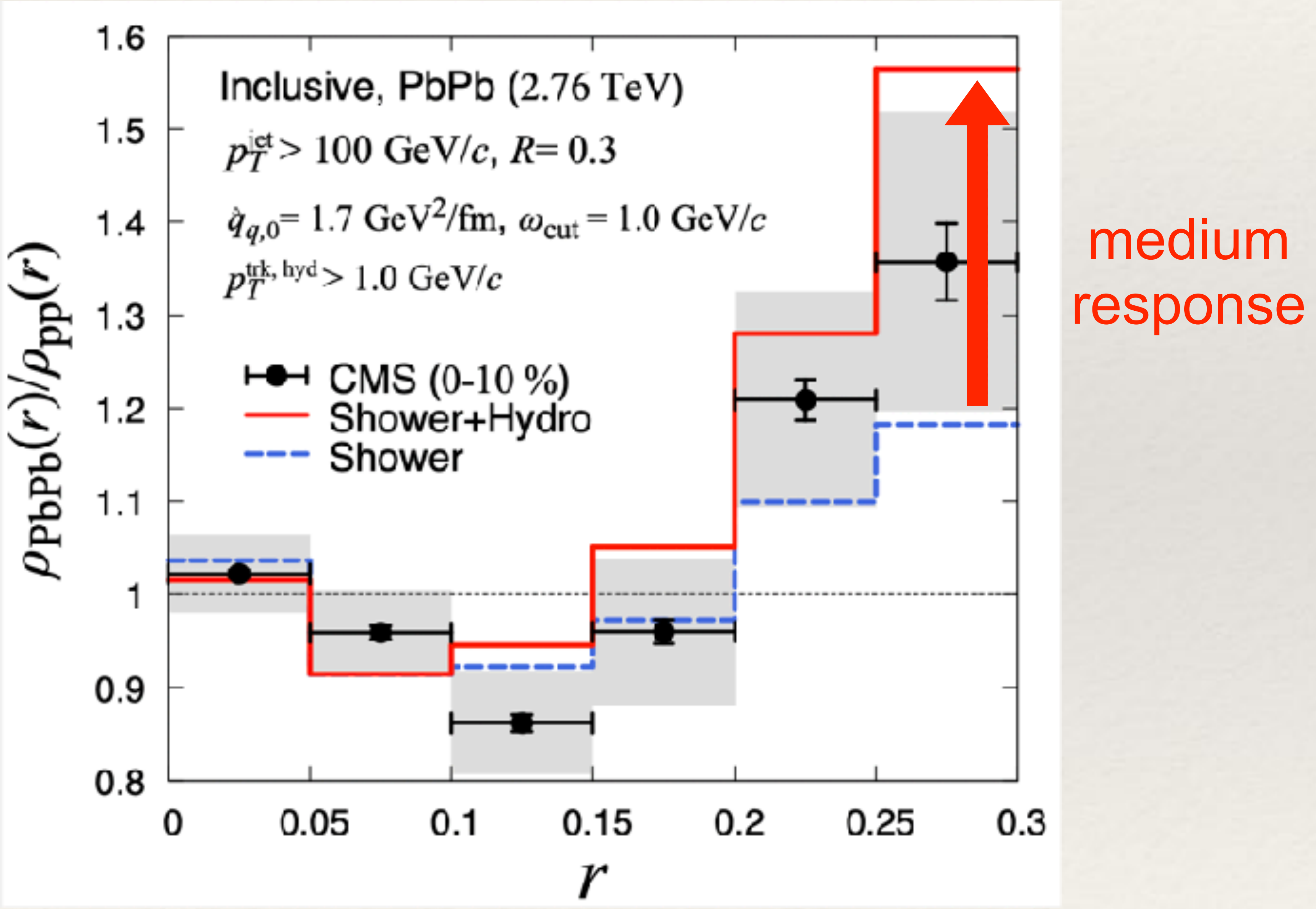
He, Chen, Luo, SC, Pang, Wang, Phys. Rev. C 106 (2022) 044904

- 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

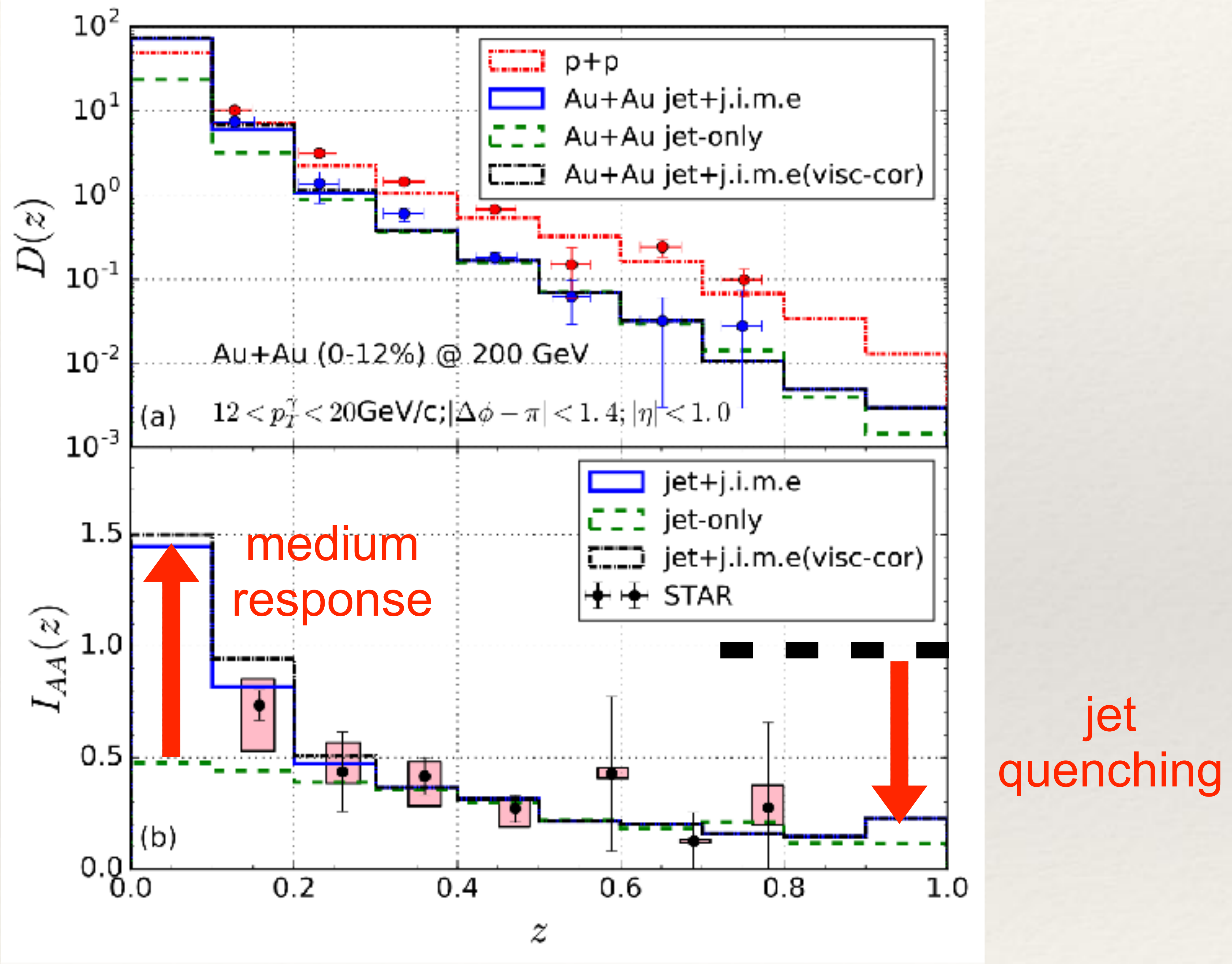


Transverse (r) distribution: jet shape



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

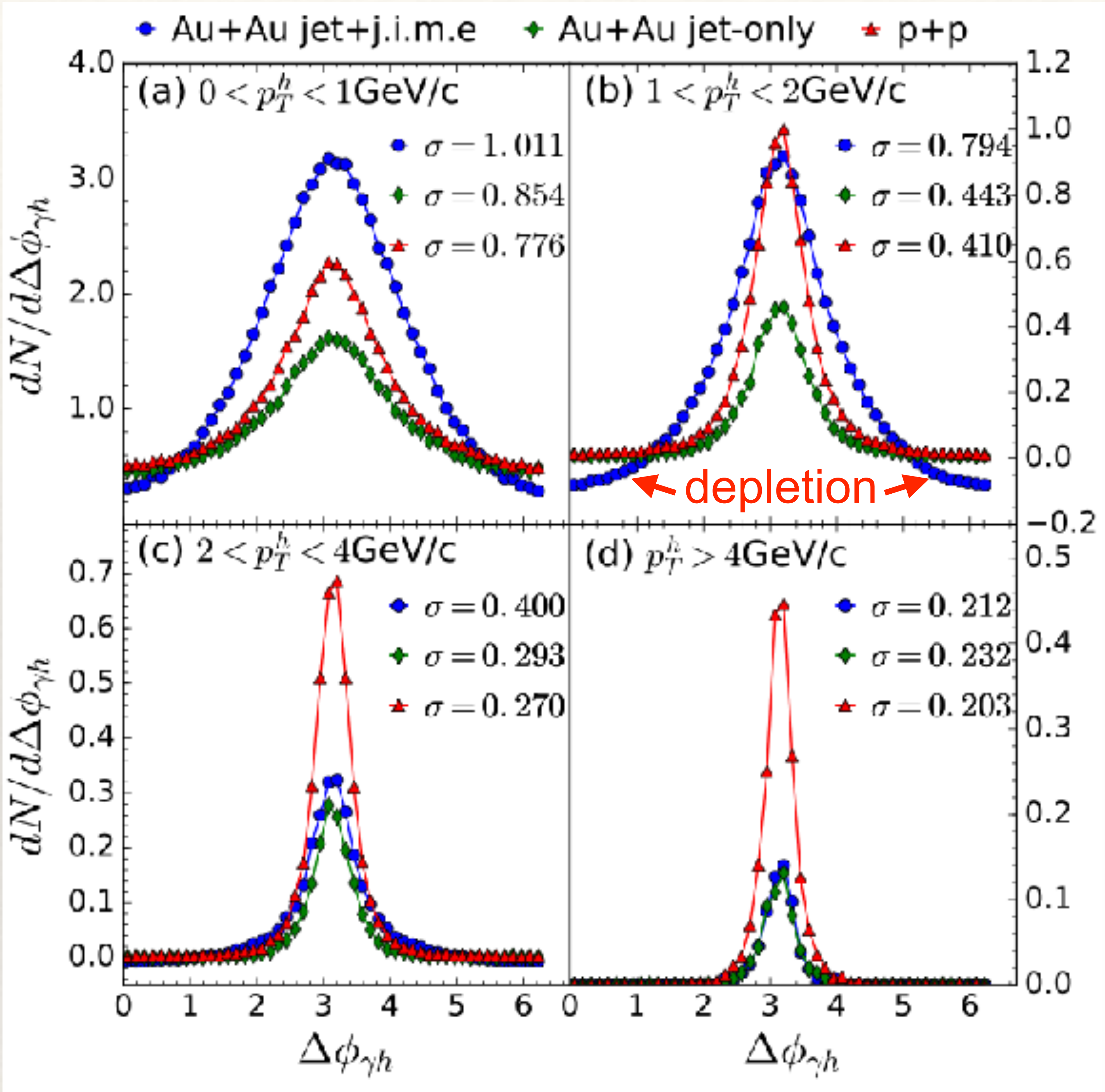
Longitudinal (z) distribution: jet fragmentation function

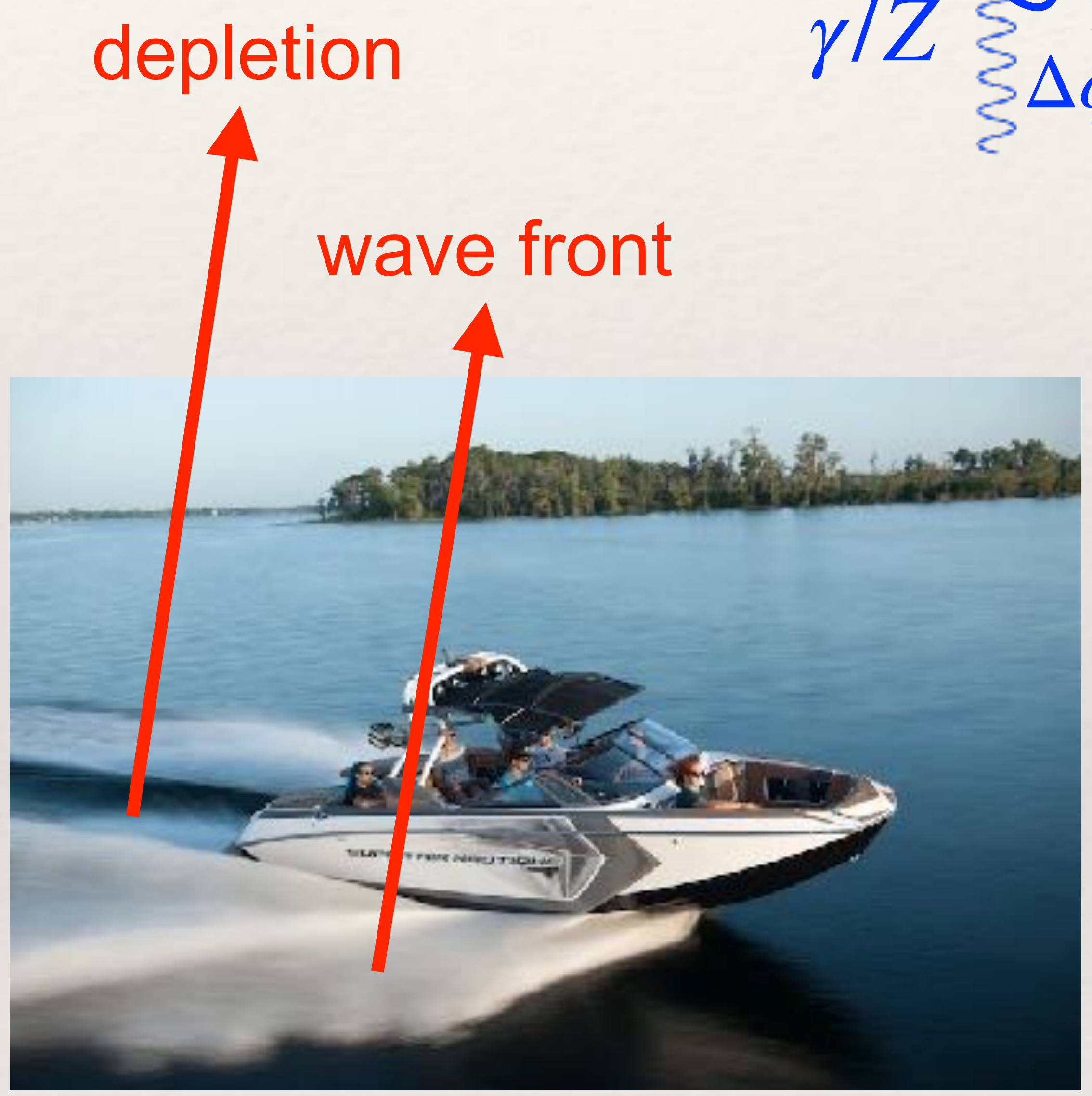


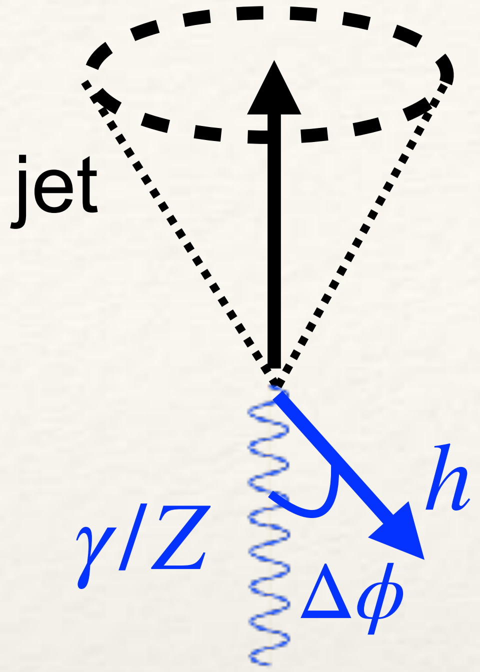
Chen, SC, Luo, Pang, Wang, Phys. Lett. B 777 (2018) 86-90

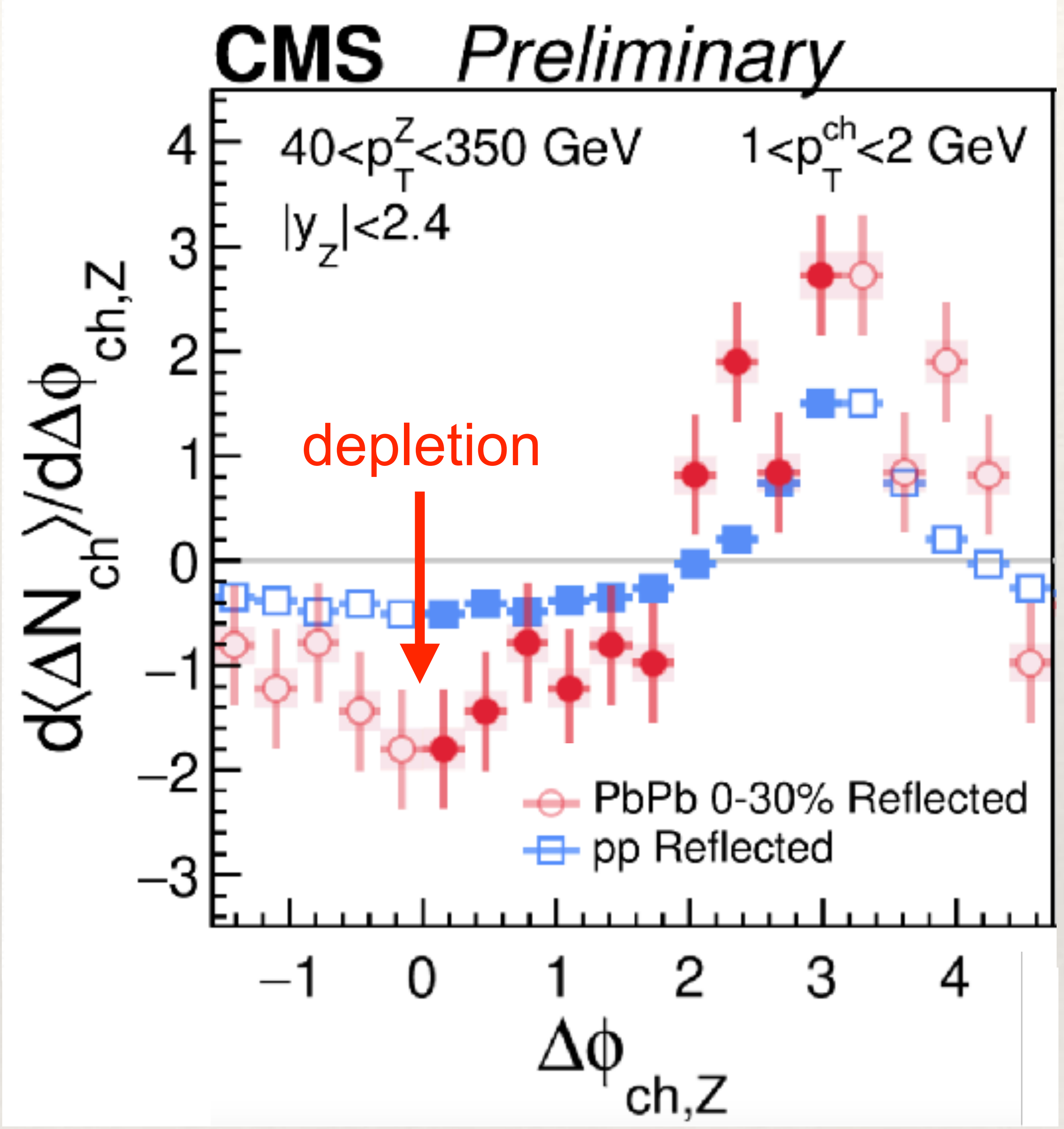
Search for unique signatures of medium response

Hadron suppression in diffusion wake









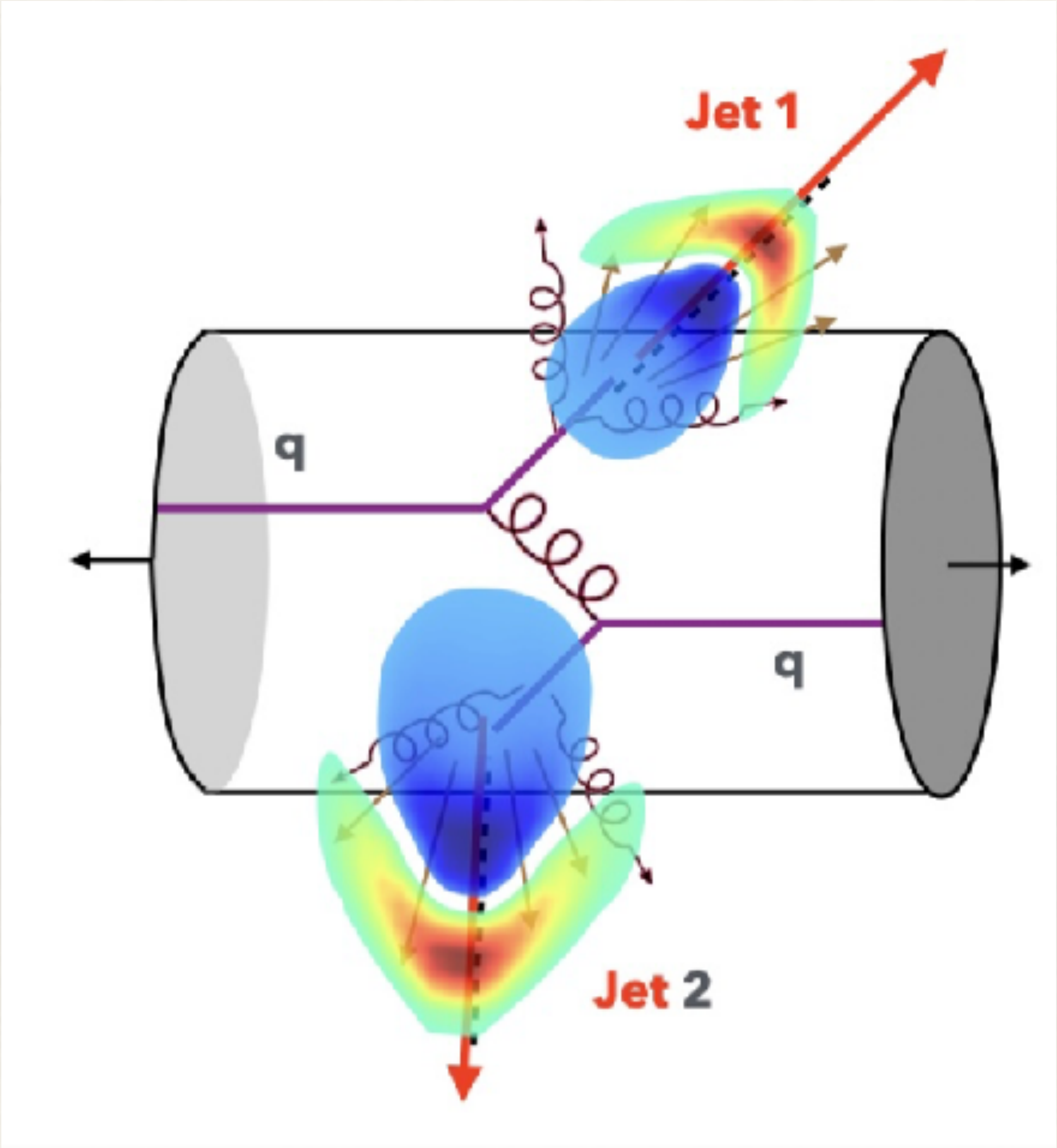
- Hadron suppression predicted in the backward direction of jets at $1 < p_T^h < 2$ GeV
  [Chen, SC, Luo, Pang, Wang, PLB 777 (2018) 86, Yang, Luo, Chen, Pang, Wang, PRL 130 (2023) 052301]
- Confirmed by recent CMS data [CMS-PAS-HIN-23-006]

New developments on searching for wake

- Extension from 2D (ϕ-plane) to 3D (η-ϕ) structure of wake

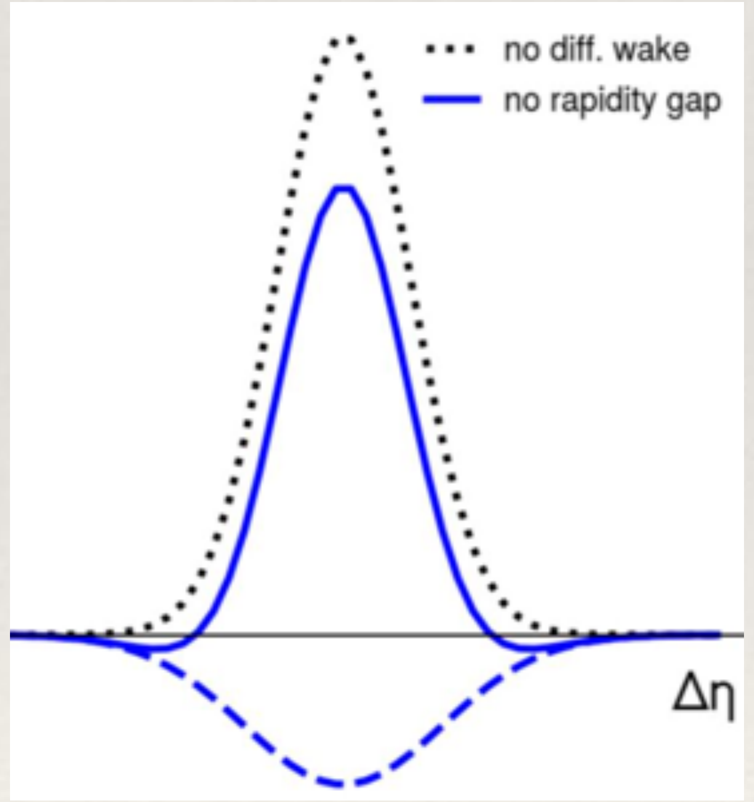
[Yang, Luo, Chen, Pang, Wang, Phys. Rev. Lett. 130 (2023) 5, 052301; Yang, Wang, arXiv: 2501.03419]

Example: interference between wave front and energy depletion in di-jet events

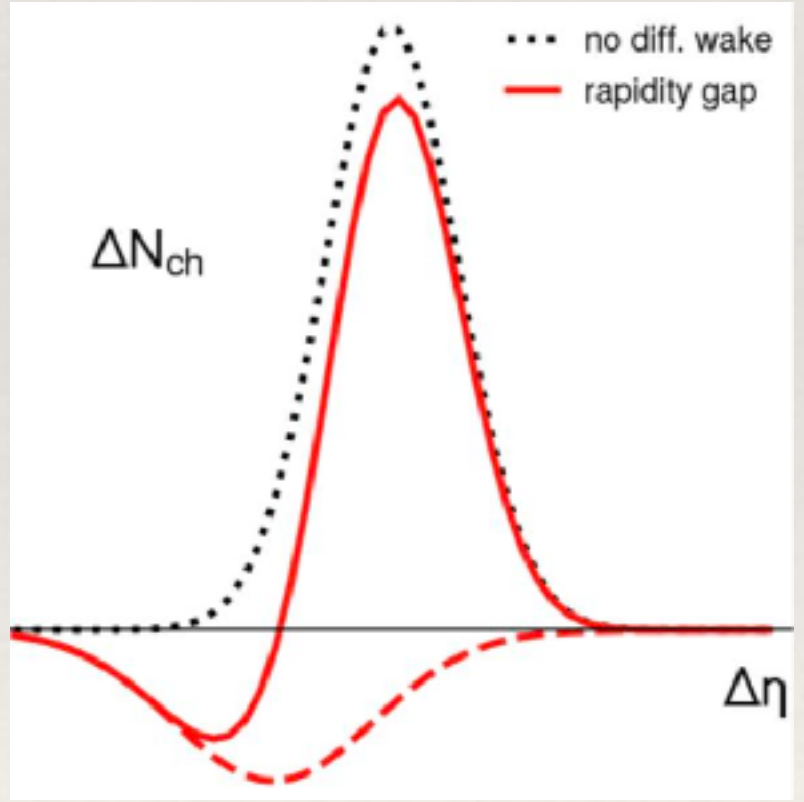


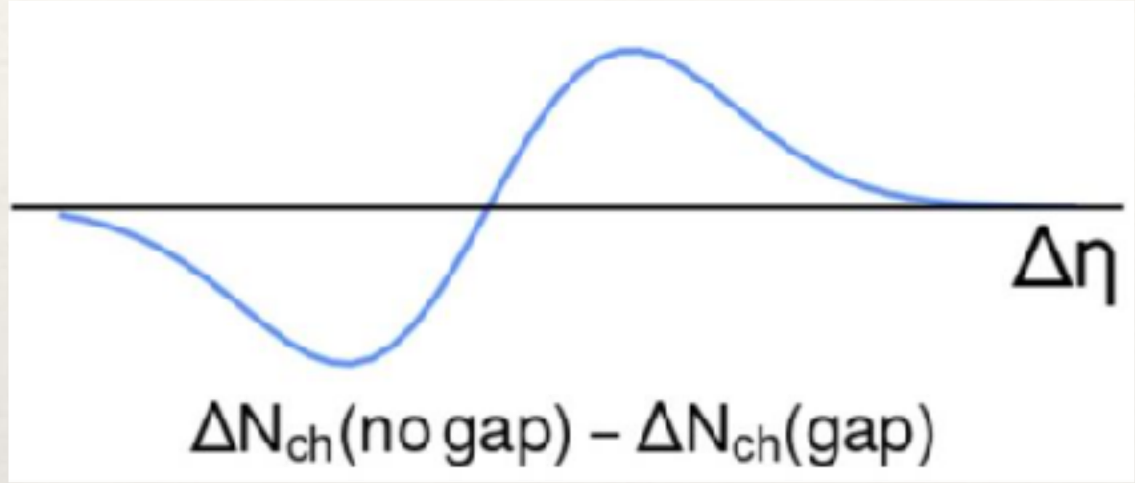
Hadron ($\Delta\eta$) distribution w.r.t. jet 1

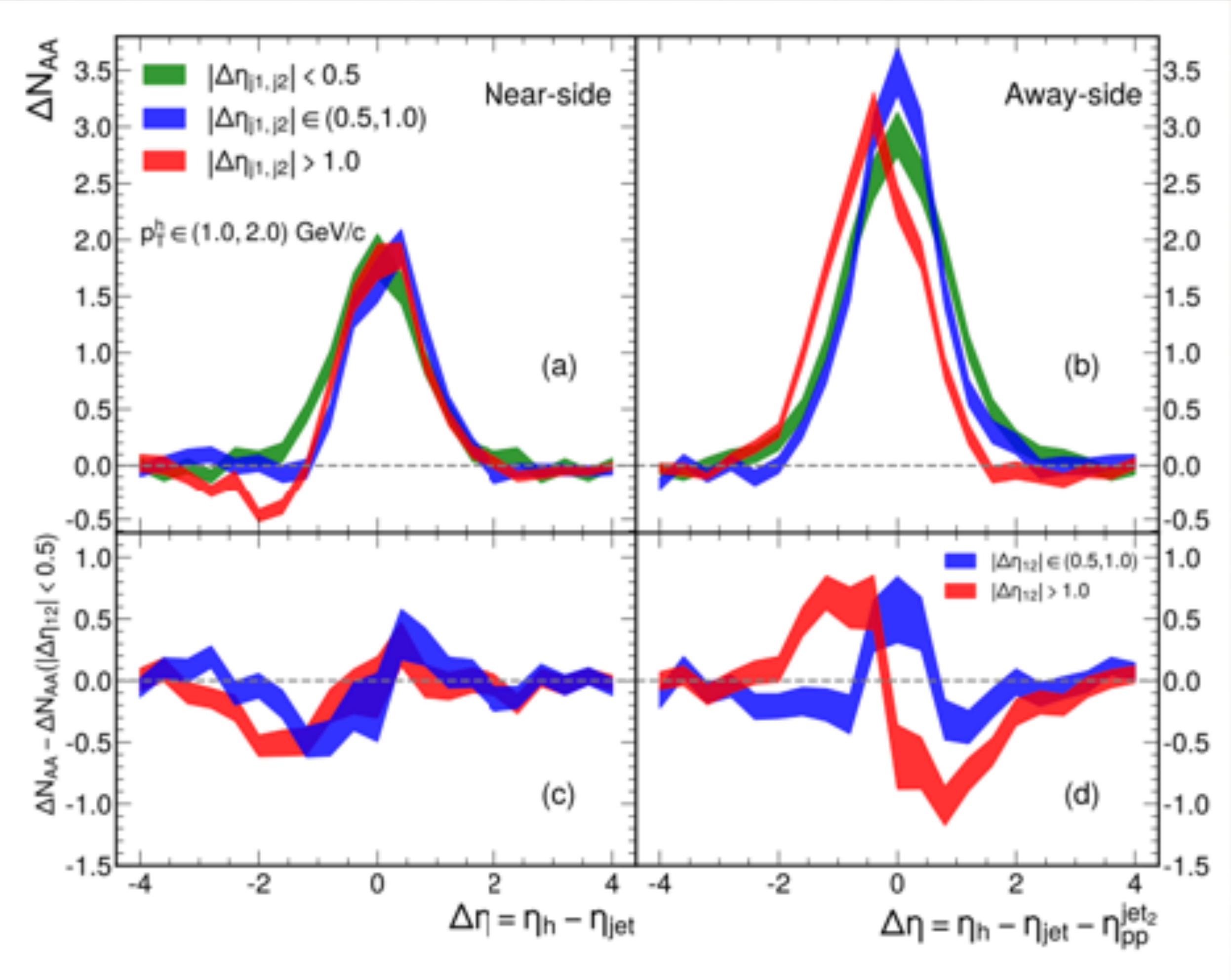
no rapidity gap between 1 and 2



with rapidity gap between 1 and 2







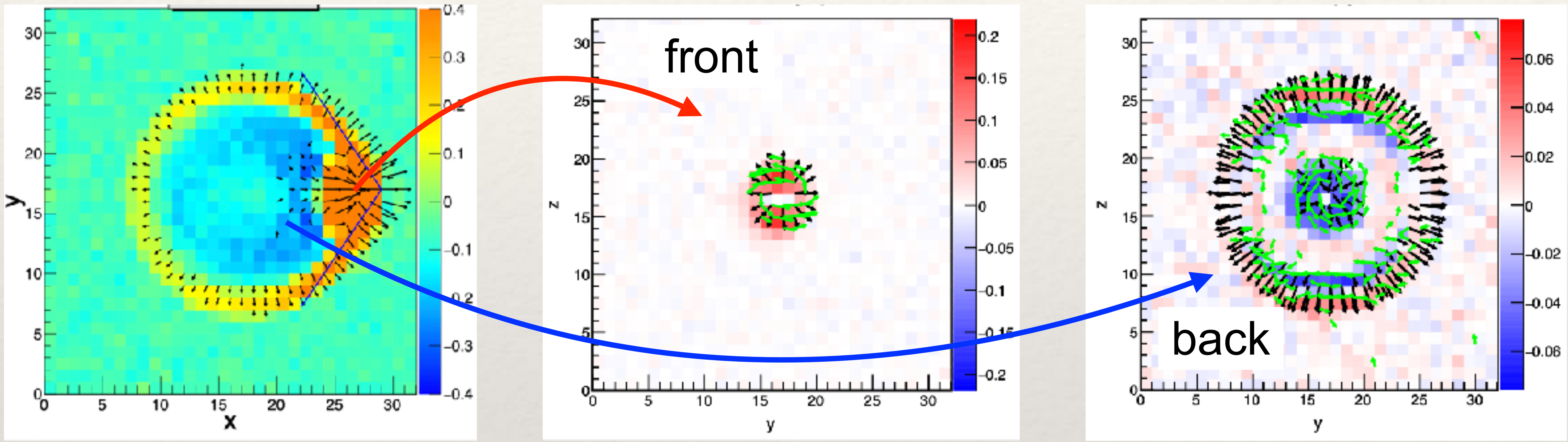
Rapidity asymmetry of hadron distribution w.r.t. the leading jet

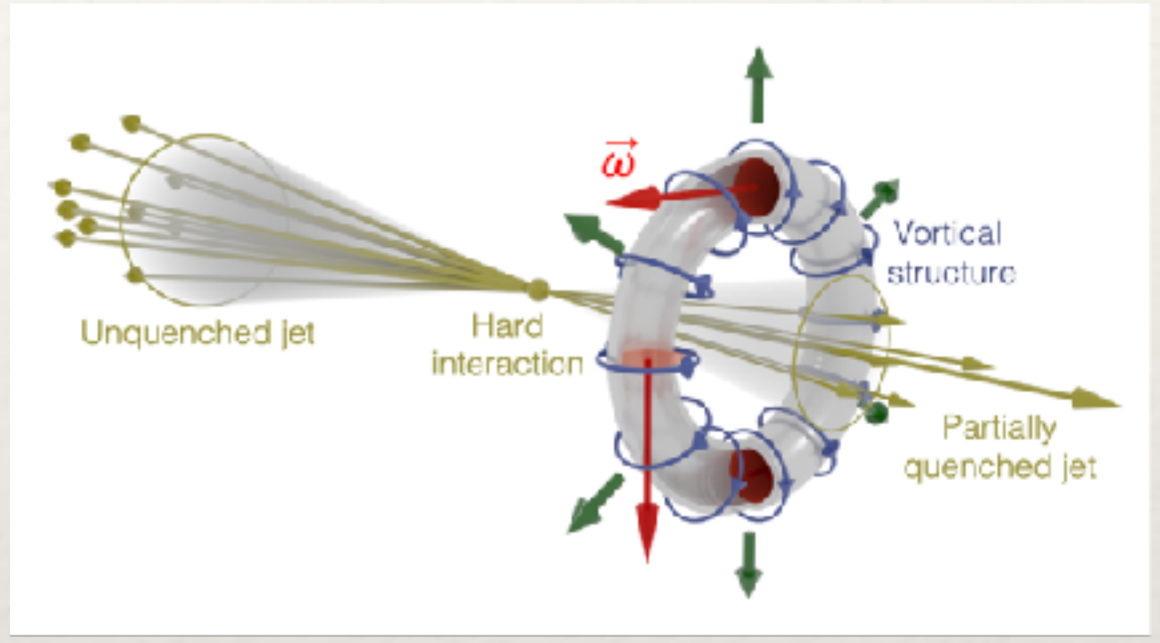
New developments on searching for wake

- From jet-transport-hydrodynamics simulation to ϕ^4 field simulation

Jian Deng's talk
4/26 5:00 pm

ϕ evolution with jet energy deposition: $\mathscr{L} = \frac{1}{2}\left(\partial_a \phi\right)^2 - \frac{g^2}{4!}\phi^4 + J\phi$



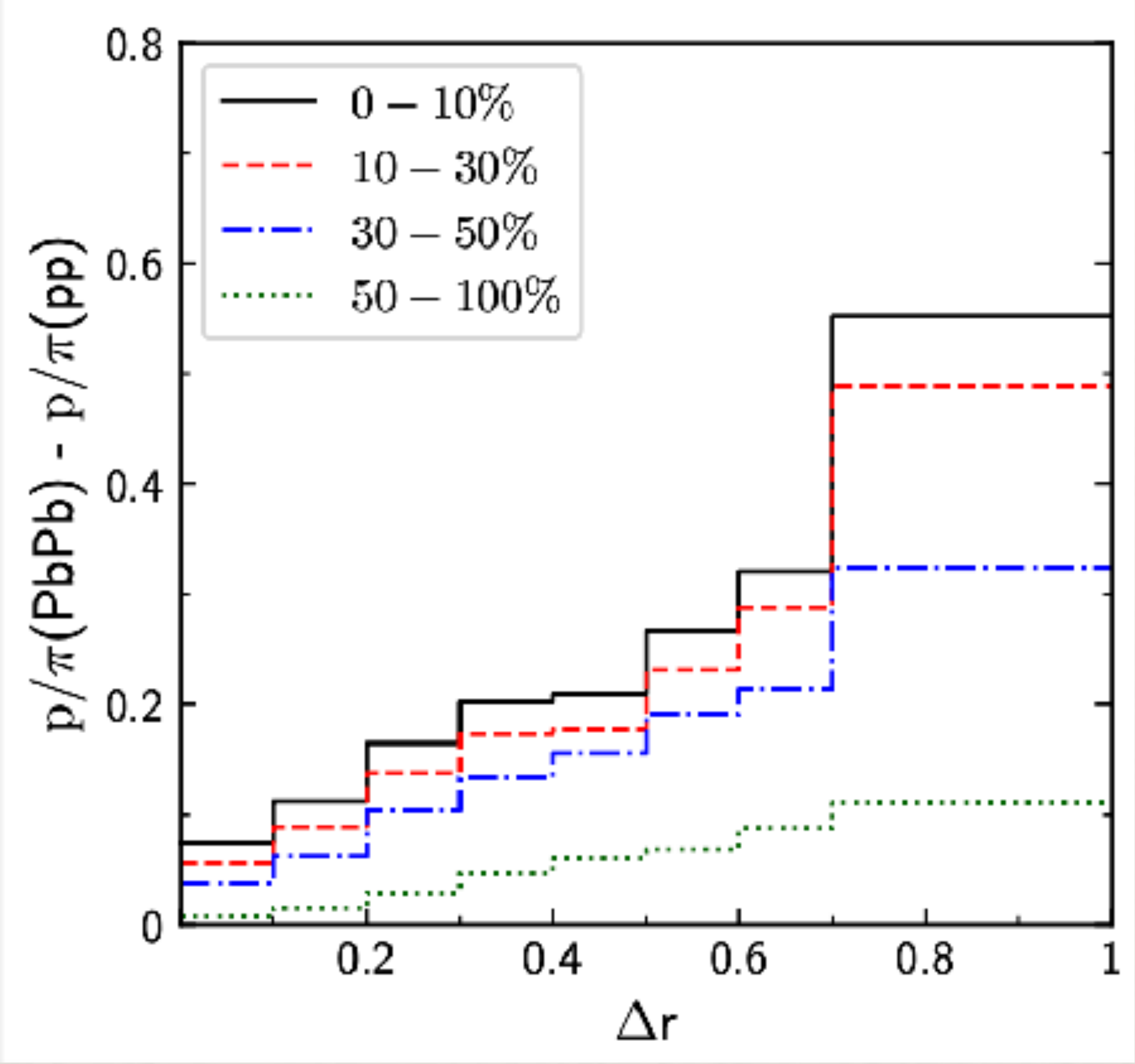


Cartoon from Serenone *et. al.*, PLB 820 (2021) 136500

- Jet energy deposition gradually approaches thermalization
- Mach cone structure for jet energy deposition
- Vortex ring structure: $\vec{\omega}$ parallel to $\vec{p}_{\rm jet} \times \vec{v}_{\rm med}$ in front, antiparallel in back (close to jet trajectory) $\rightarrow$ possible rich pattern for jet-induced QGP polarization

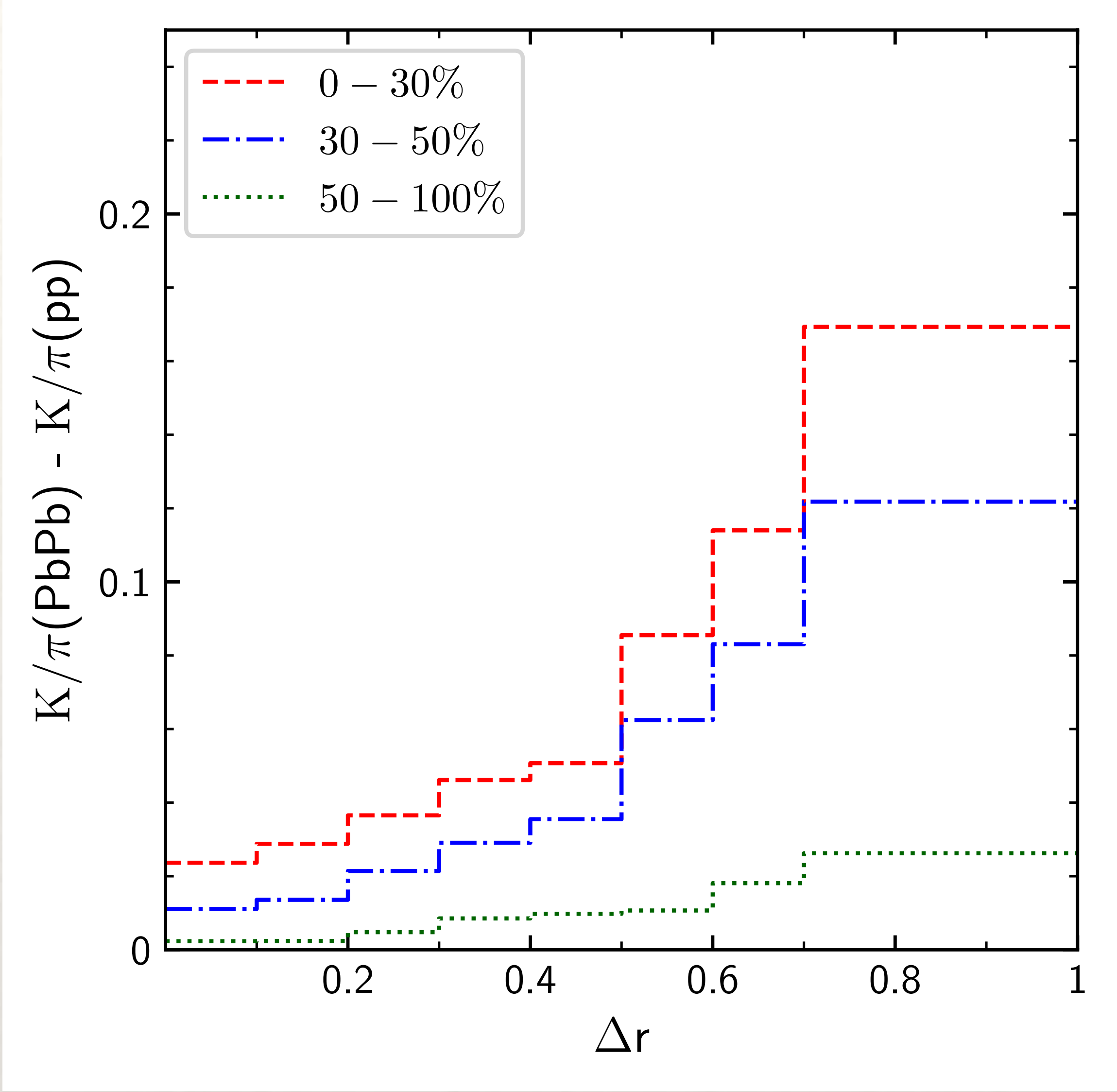
Hadron chemistry as a new signature of medium response

Baryon enhancement

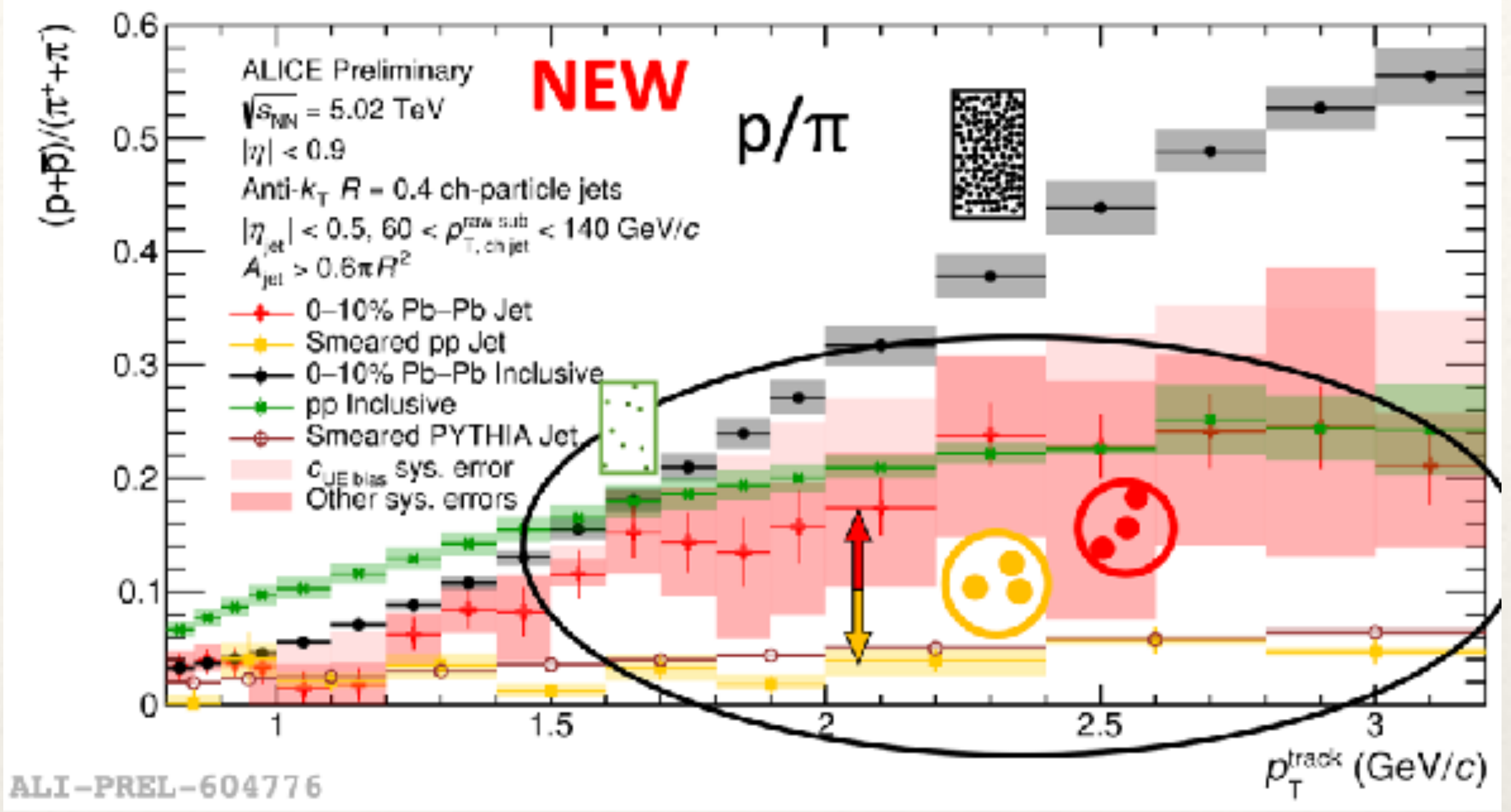


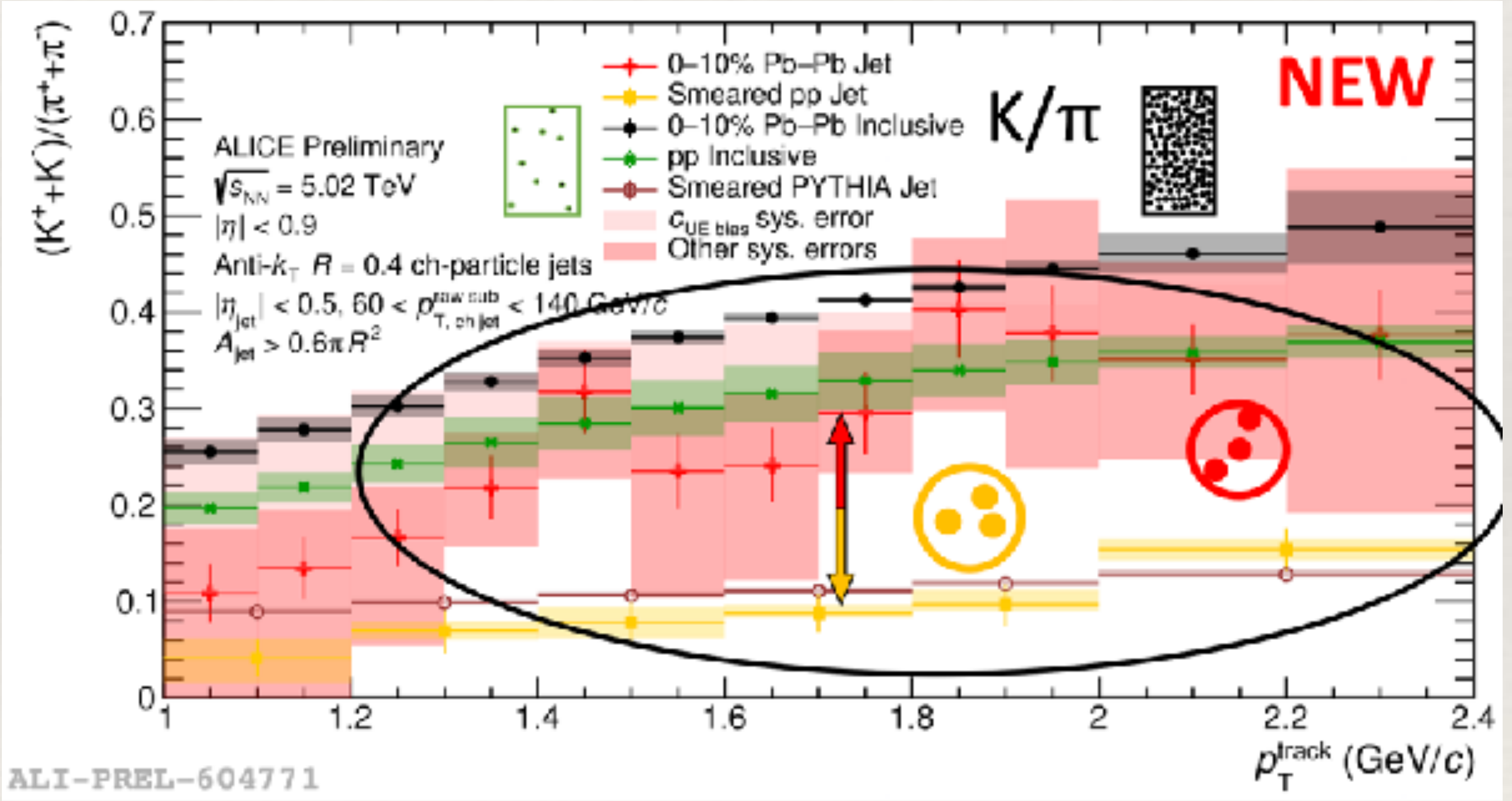
Luo, Mao, Qin, Wang, Zhang, PLB 837 (2023) 137638

Strangeness enhancement



Luo, SC, Qin, arXiv:2412.19283

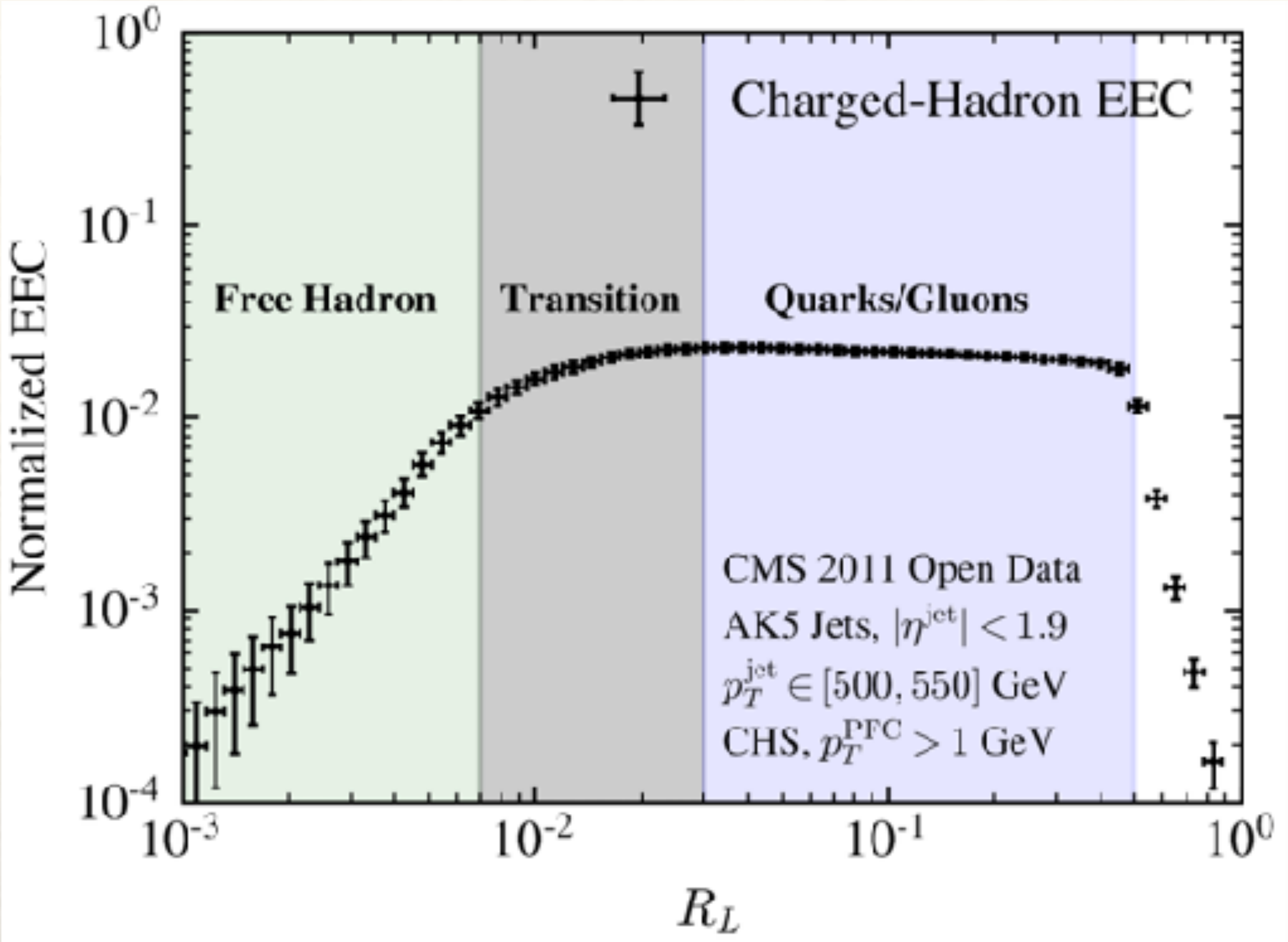




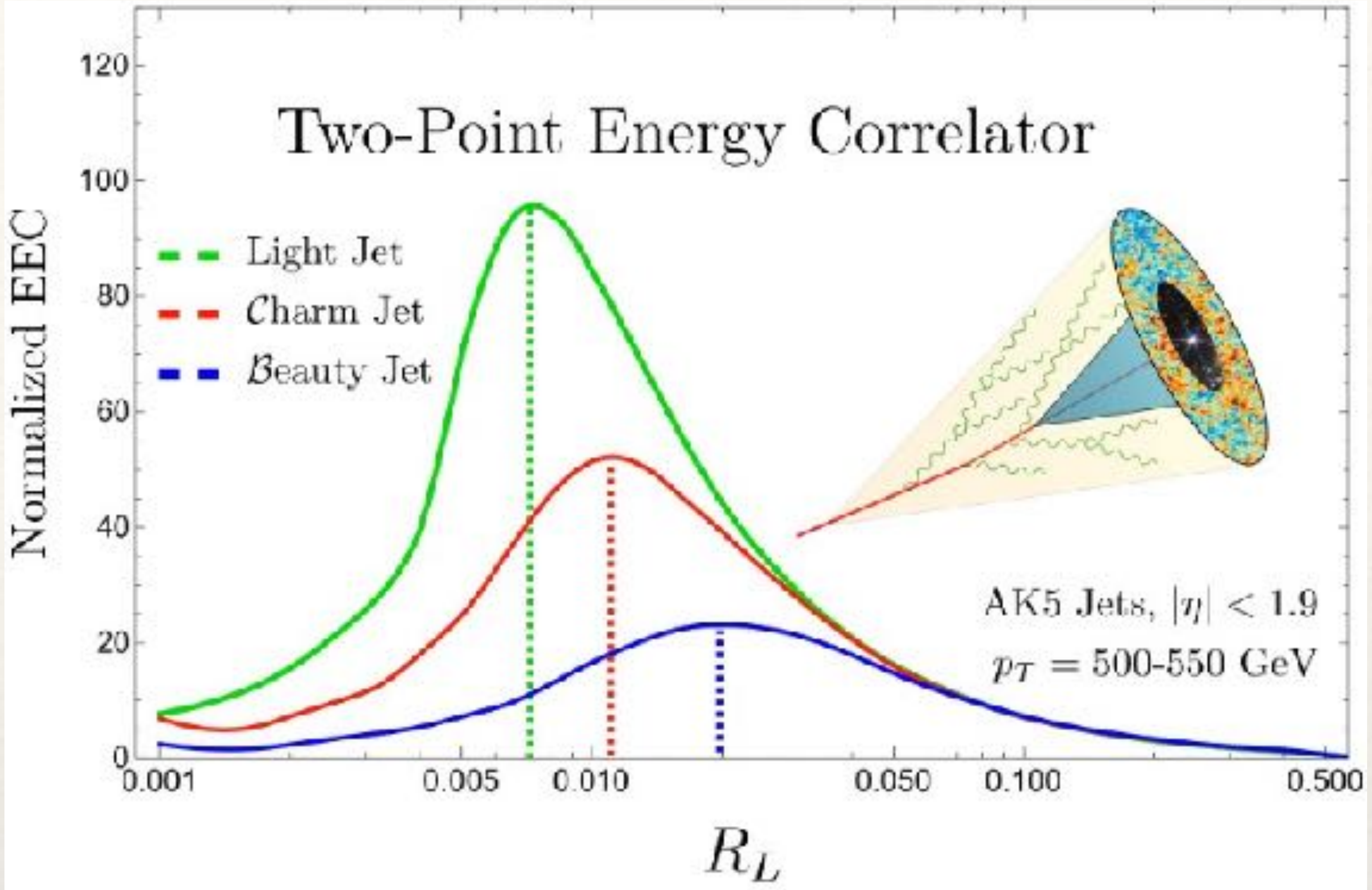
- Larger *q* and *s* densities in QGP than in vacuum jets
- Baryon and strangeness enhancement around jets in AA
- Stronger enhancement at larger distance from jet axis

- Confirmed by recent ALICE data
- Not seen in recent STAR data

A novel observable: energy-energy correlator (EEC)



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



[Craft et. al., arXiv:2210.09311]

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

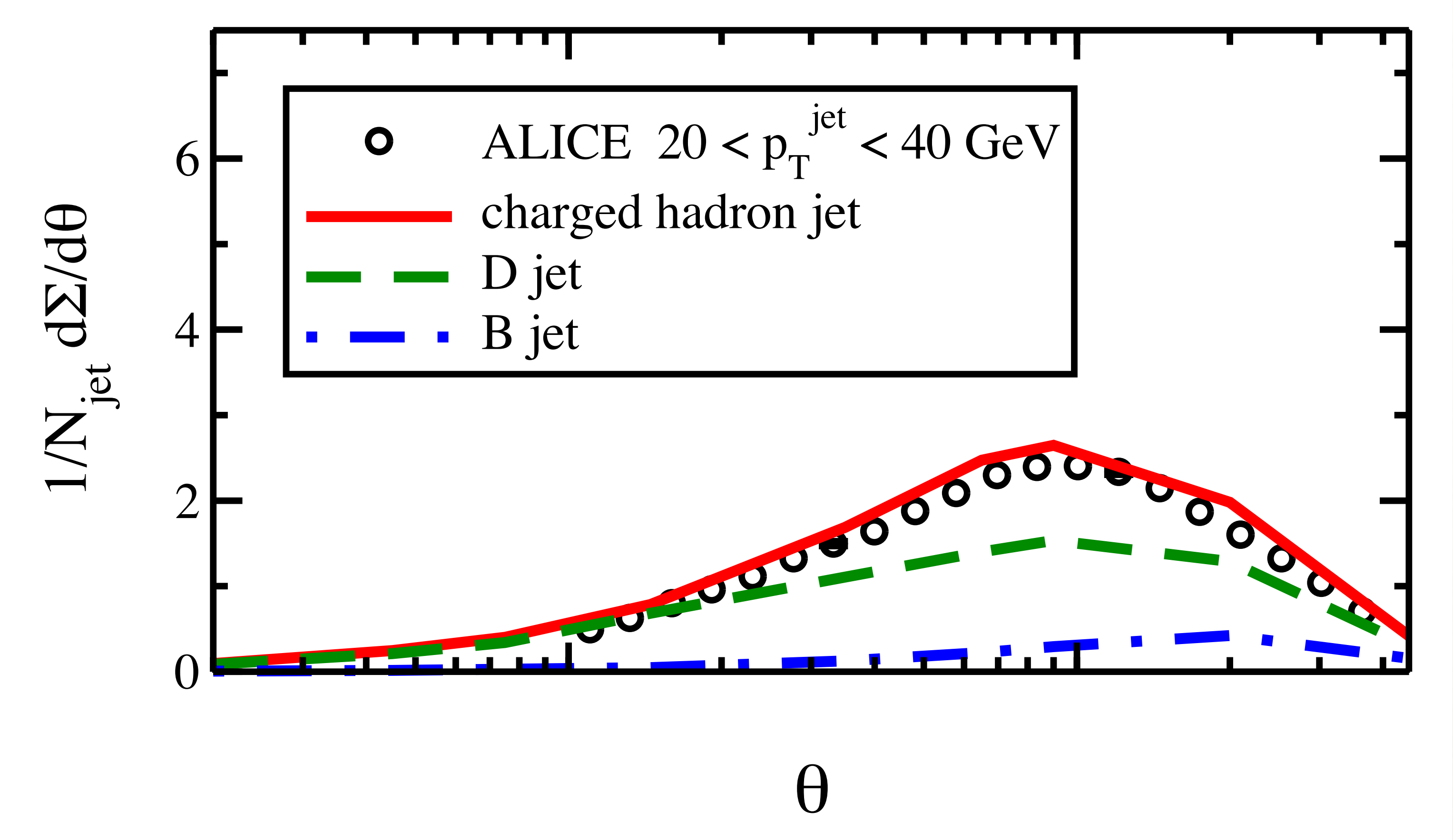
$\mathcal{E}$: energy flow in a given direction,

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

- Proposed by conformal theory, EEC(R_L) is scale independent at high energy limit
- Variation of EEC(R_L) indicates emergence of new scales: hadronization, QGP, quark mass …
- Implement a first realistic calculation on light and heavy flavor jet EEC in AA collisions

[Xing, SC, Qin, Wang, Phys. Rev. Lett. 134 (2025) 052301]

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



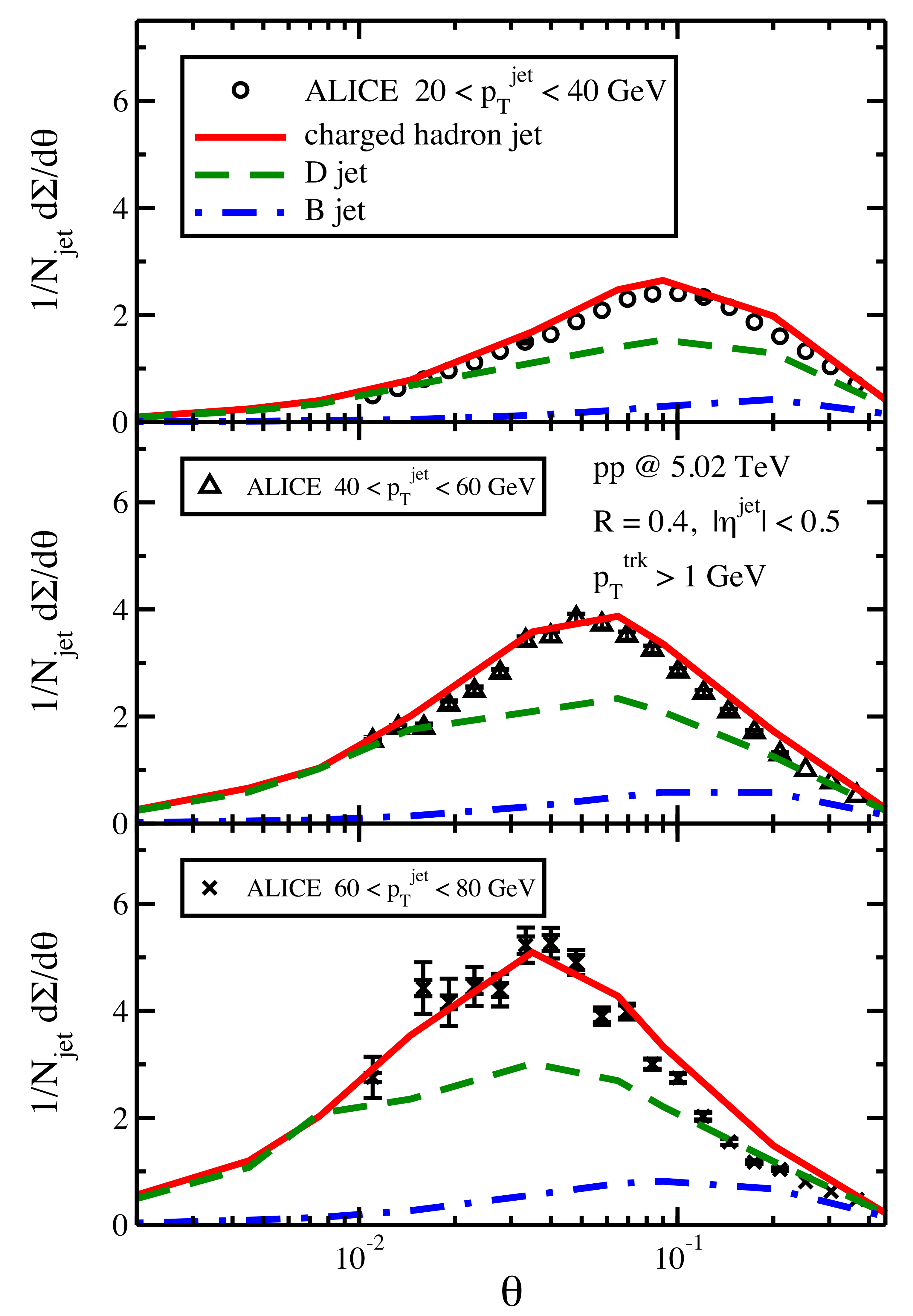
- Jet in *pp*: Pythia 8 simulation
- EEC analysis (*i*, *j* denote jet constituents)

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

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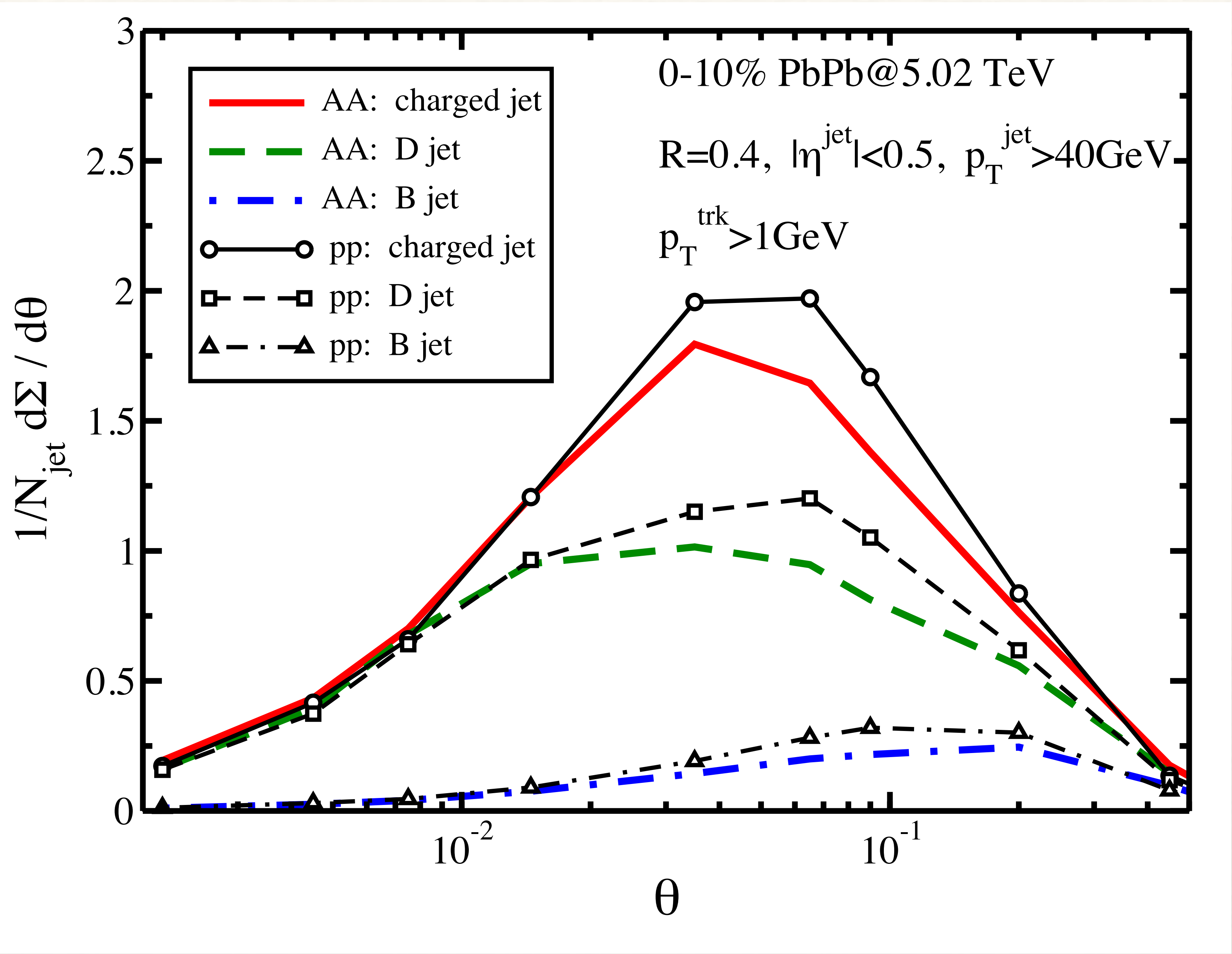
  - Overall magnitude: charged jet > *D*-jet > *B*-jet
  - Typical (peak) angle: charged jet < *D*-jet < *B*-jet

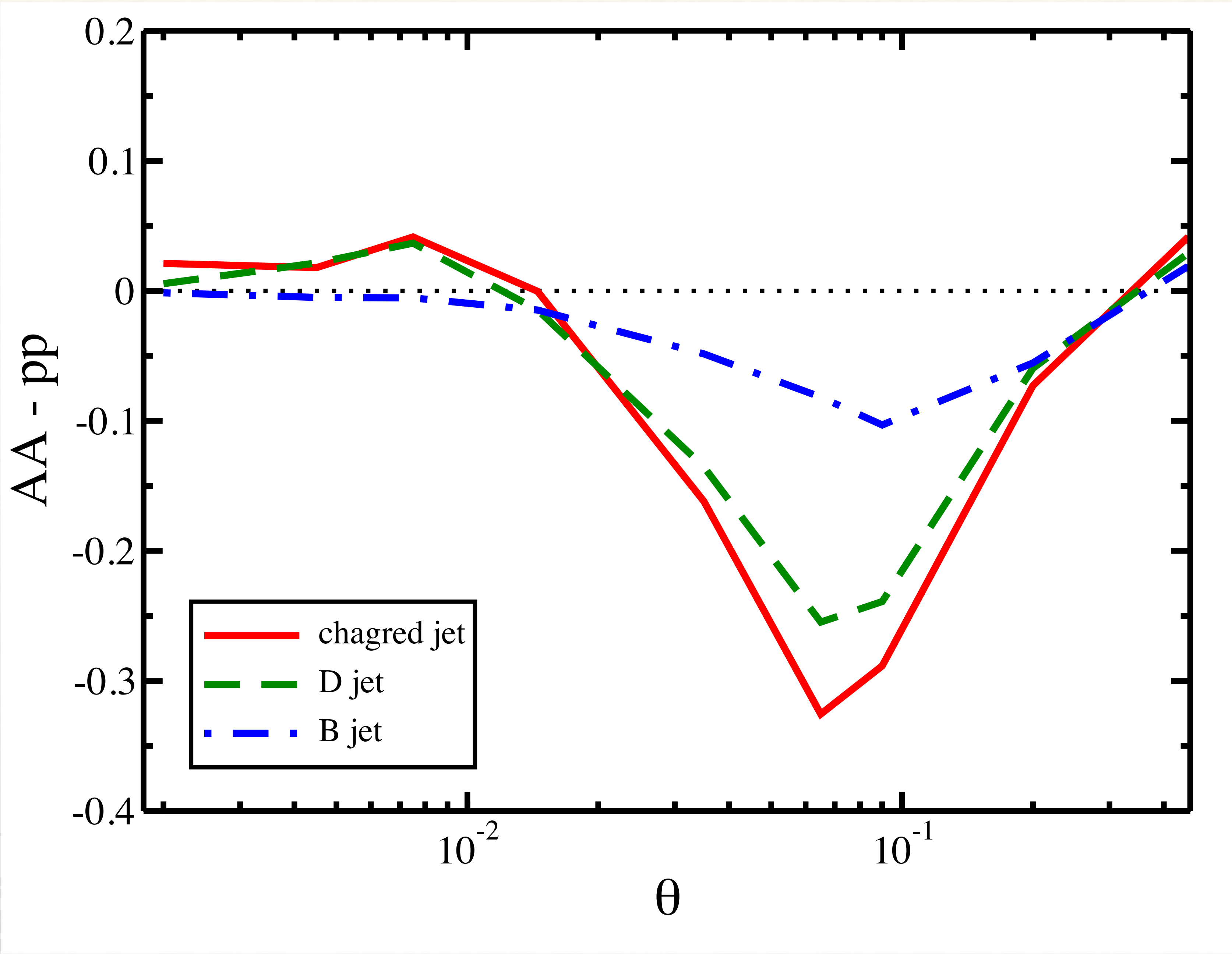
  Suppression of splitting within $\theta_0 \sim m_Q/E_Q$ in vacuum

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

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

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

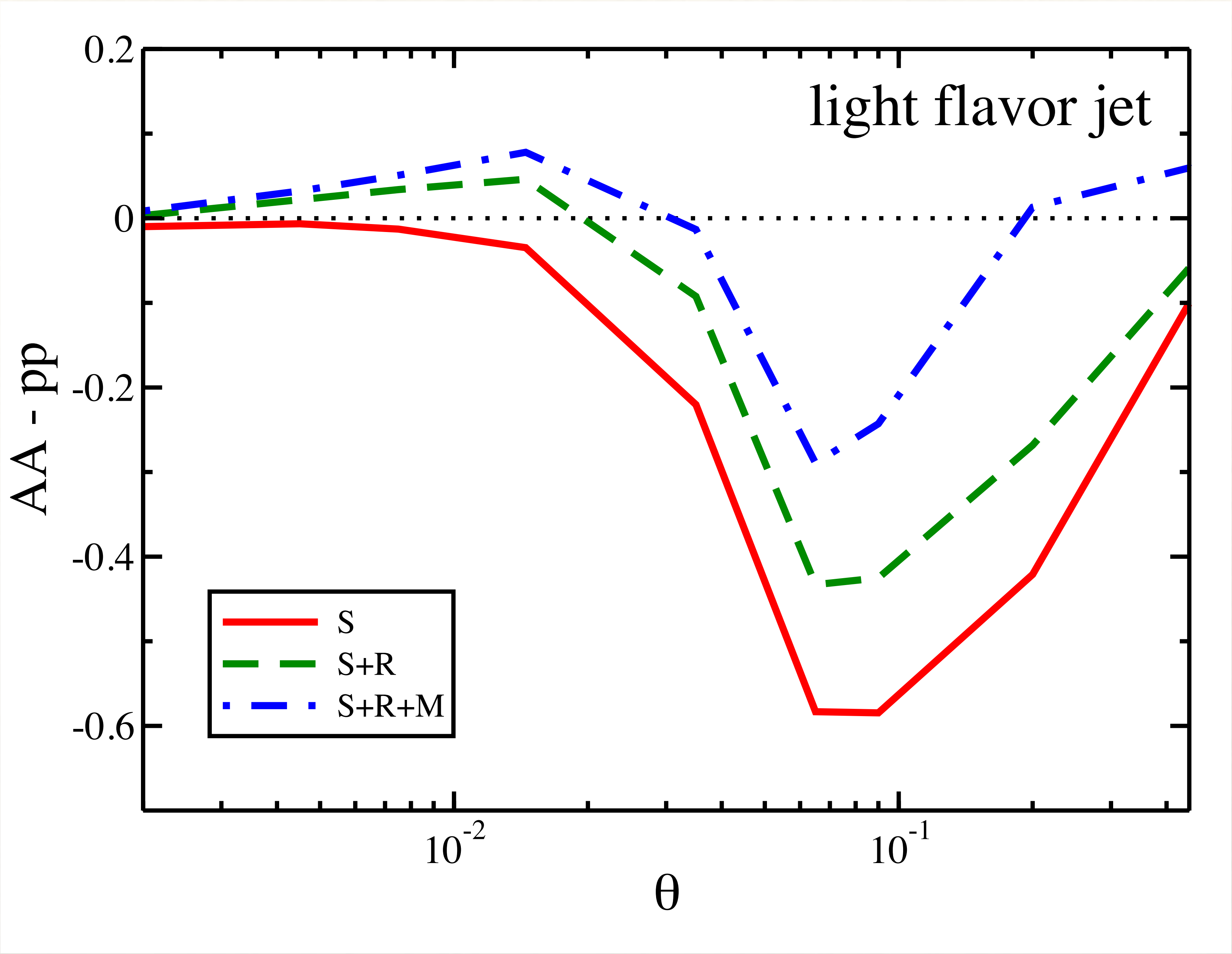




Full simulation — Pythia + LBT in hydro

- Flavor hierarchy of EEC preserves, though being modified, in AA collisions
- General features 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



S: shower partons inherited from Pythia

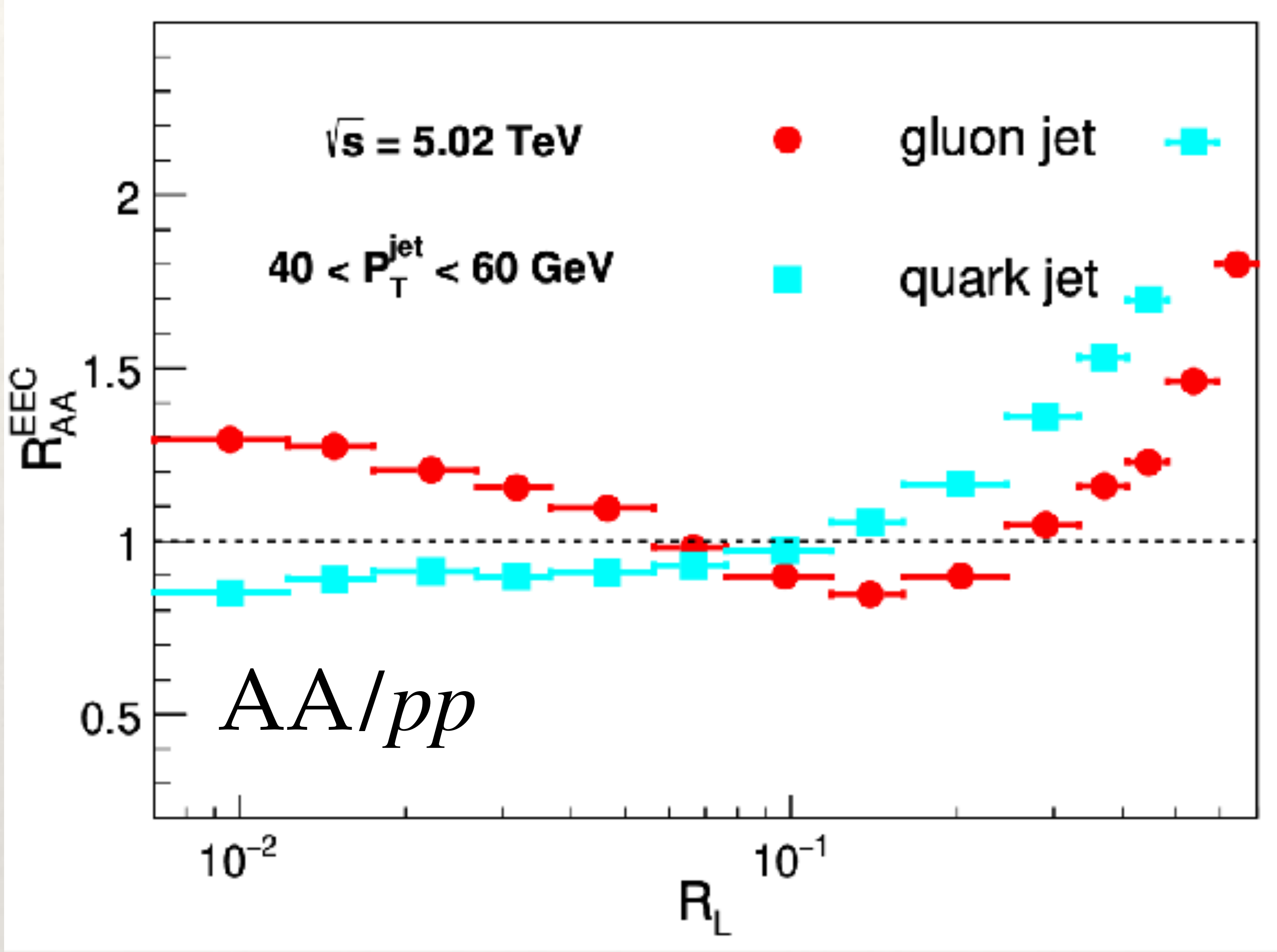
S+R: add medium-induced gluons

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

Further studies on EEC

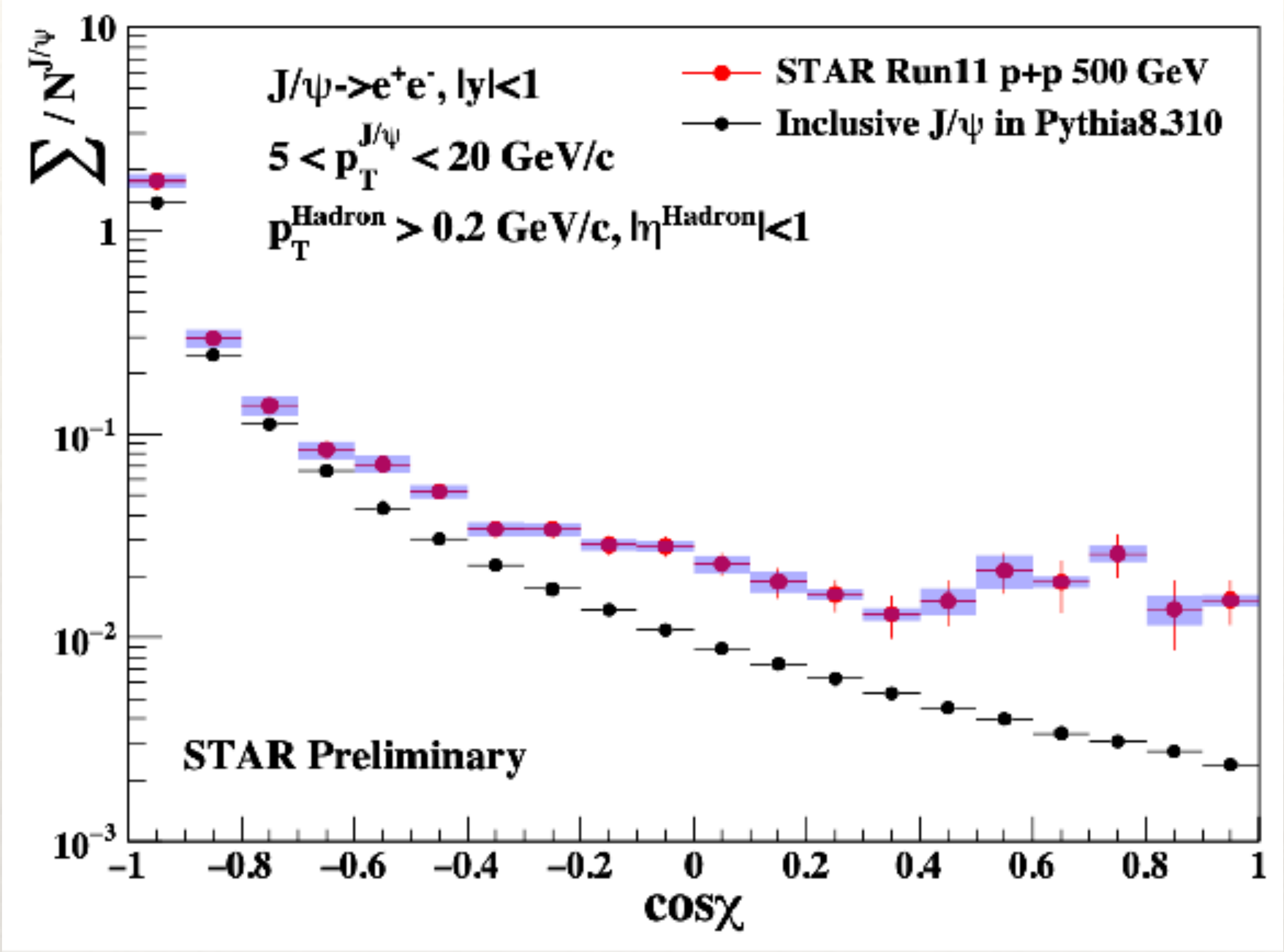
Discriminate quark and gluon jet quenching in AA collisions



[Chen, Shen, Xue, Dai, Zhang, Wang, arXiv:2409.13996]

- Can be tested by comparing between inclusive jets and γ-jets

Measurement of J/ψ energy correlator in *pp* collisions



[From STAR poster at Quark Matter 2025]

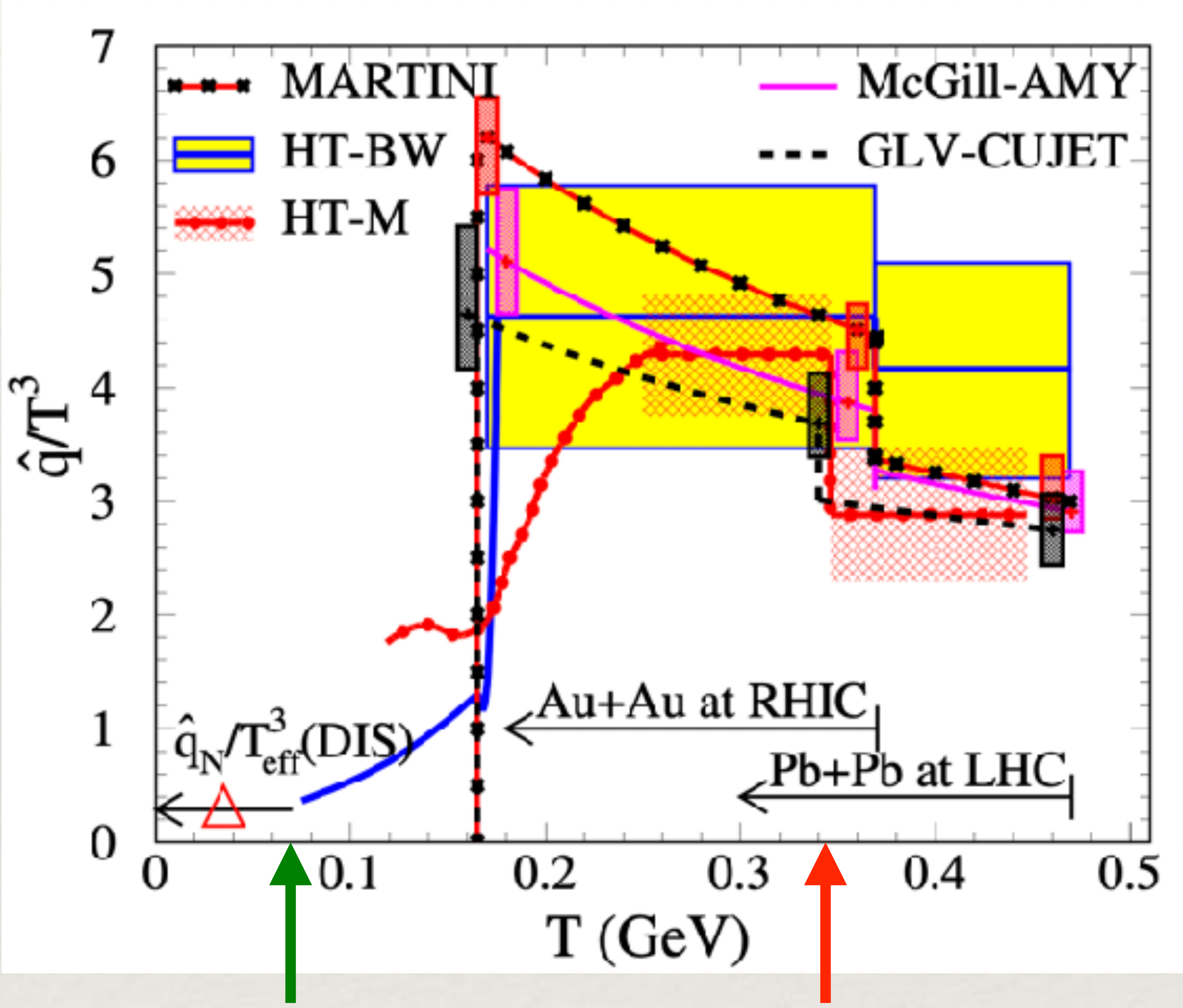
- May be used to probe the hadronization process of J/ψ, e.g., $c + \bar{c} \to J/\psi + g$

[Chen, Liu, Ma, Phy. Rev. Lett. 133 (2024) 191901]

Constraints on jet transport coefficient inside the QGP

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

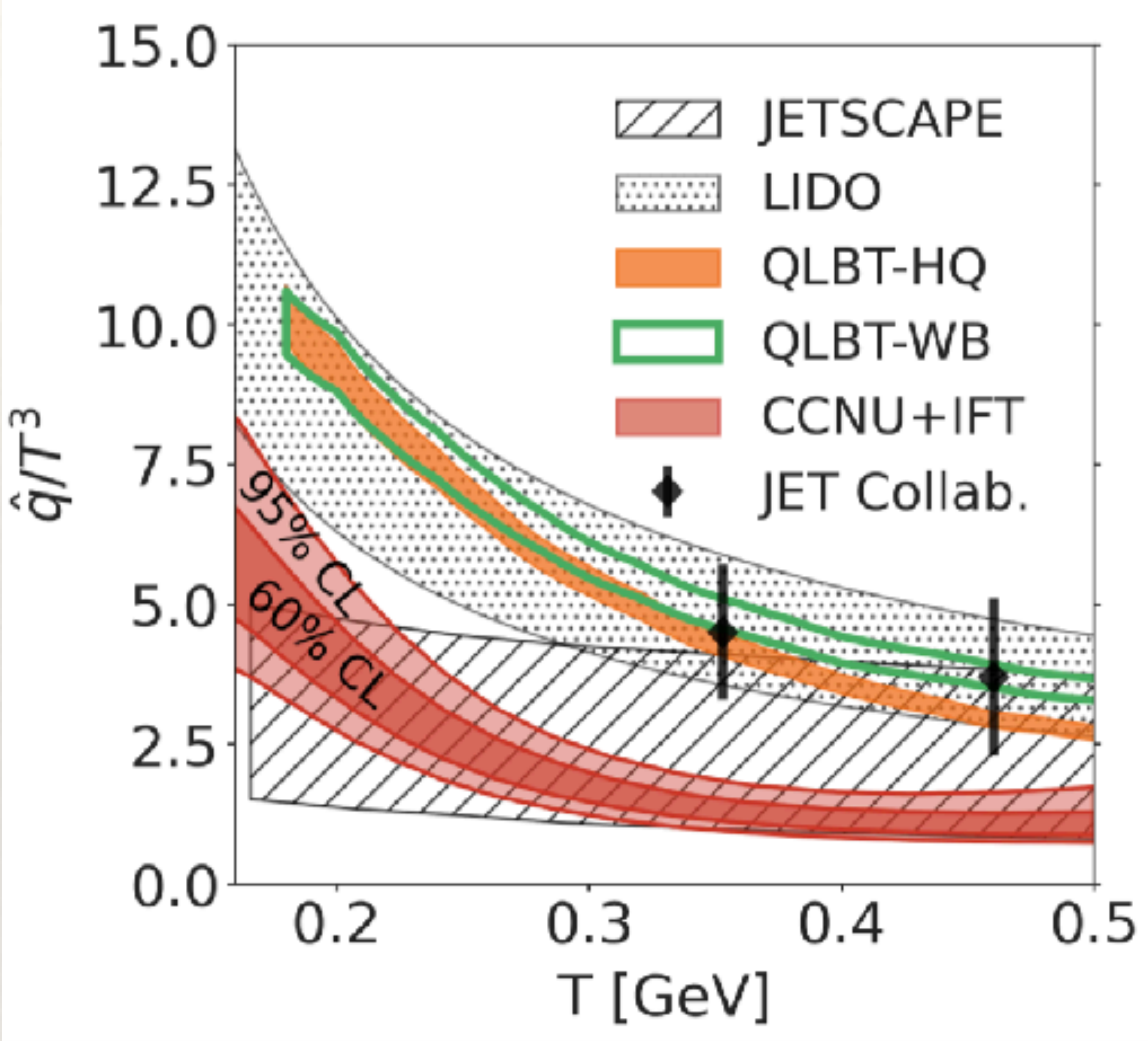
[JET, Phys. Rev. C 90 (2014) 1, 014909]



nucleus $\ll$ QGP

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

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



- Jet model improvement + Bayesian statistical analysis → temperature and jet energy dependences of $\hat{q}$

Probing the equation of state of the QGP

[F.-L. Liu, X.-Y. Wu, SC, G-Y. Qin, X.-N. Wang, Phys. Lett. B 848 (2024) 138355]

Transport

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

Thermal mass of partons

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

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

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

Strong coupling strength

$$g(E, T)$$

Equation of state

$$P_{\text{QPM}}(m_u, m_d, \ldots, T) = \sum_{i=u,d,s,g} d_i \int \frac{d^3p}{(2\pi)^3} \frac{|\vec{p}\,|^2}{3E_i(p)} f_i(p) - B(T)$$

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

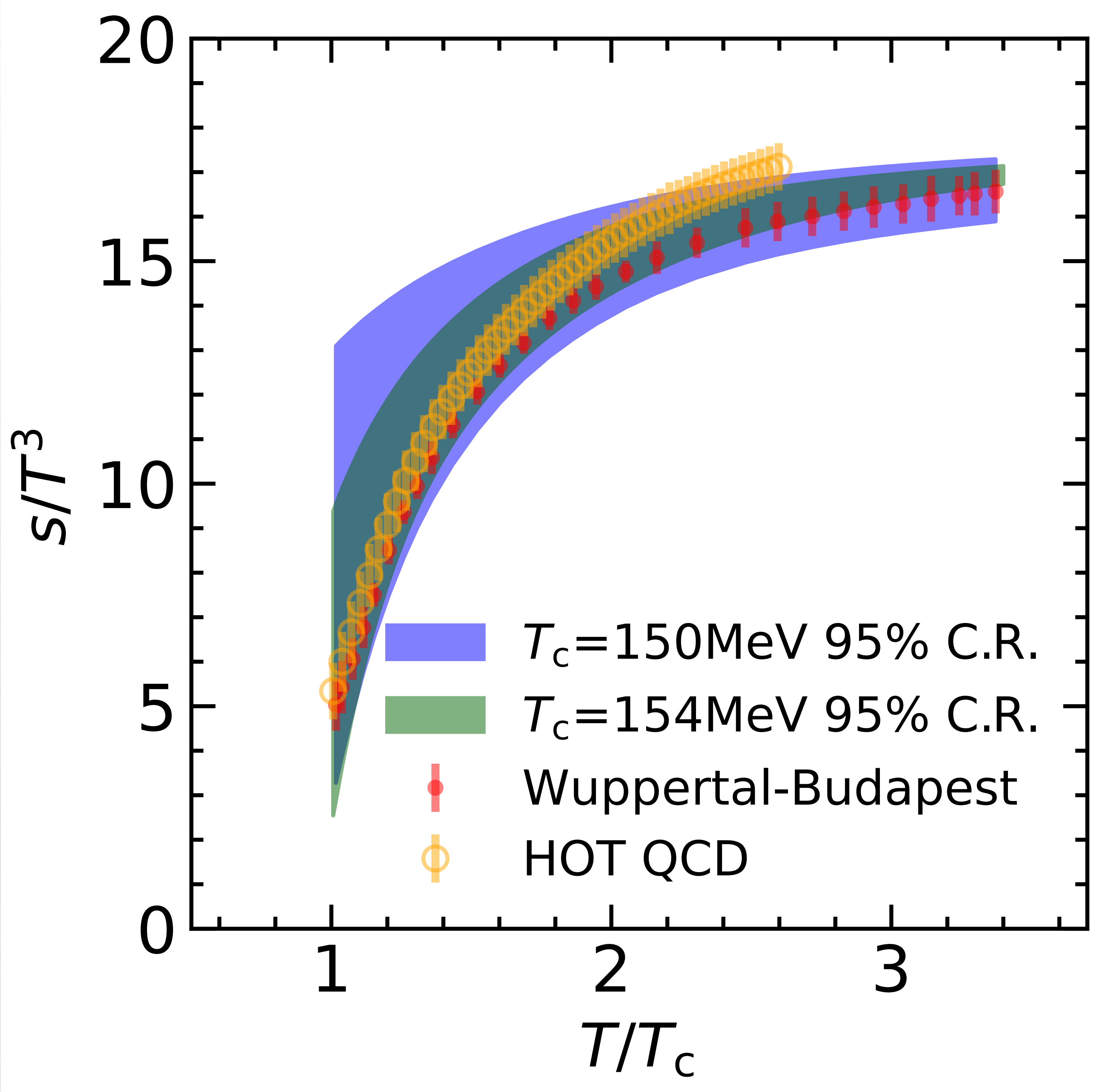
Strategy:

Fit g from comparing transport model to data

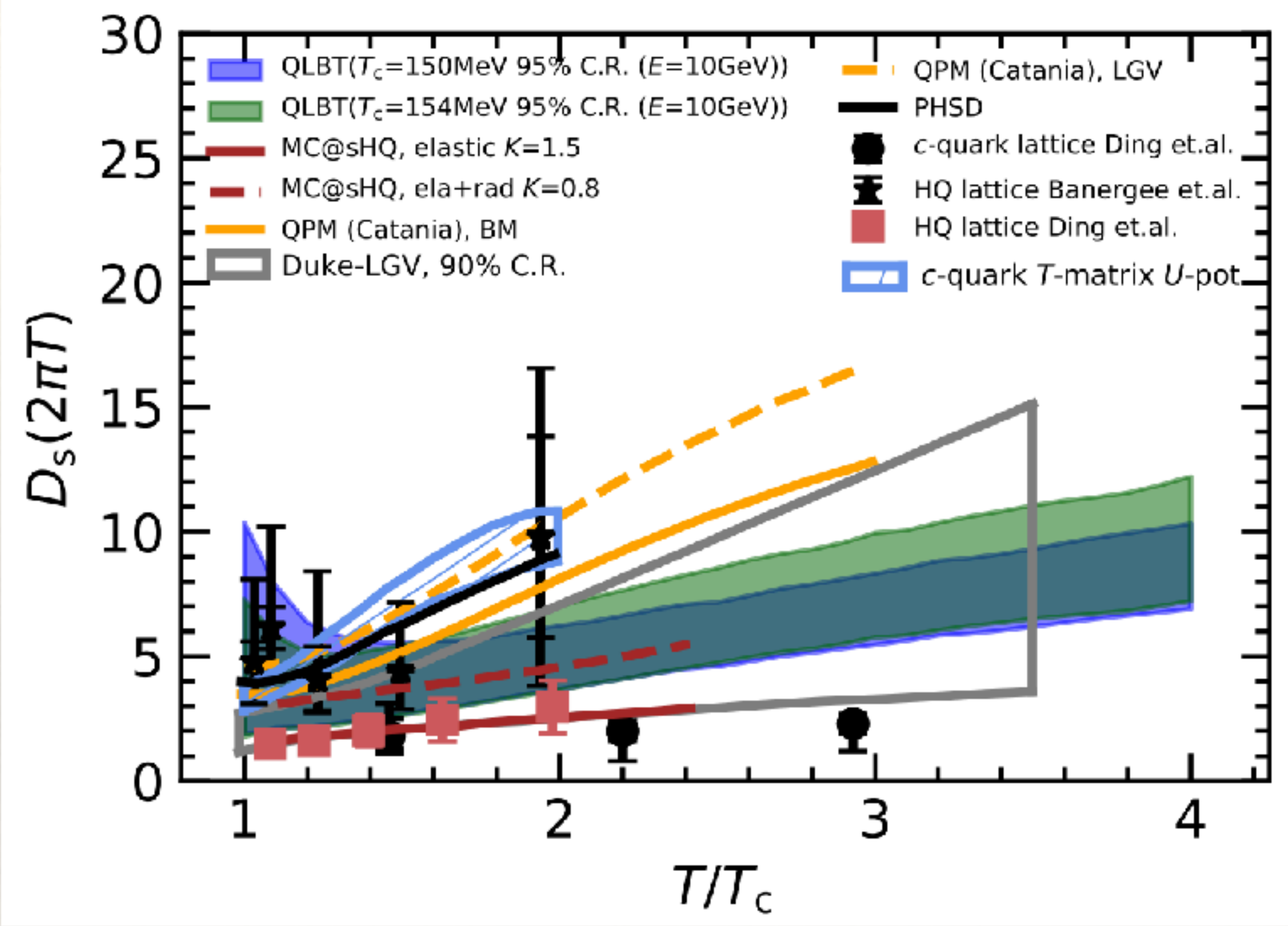
Calculate EoS from g

EoS of QGP and diffusion coefficient of heavy quarks

Equation of state



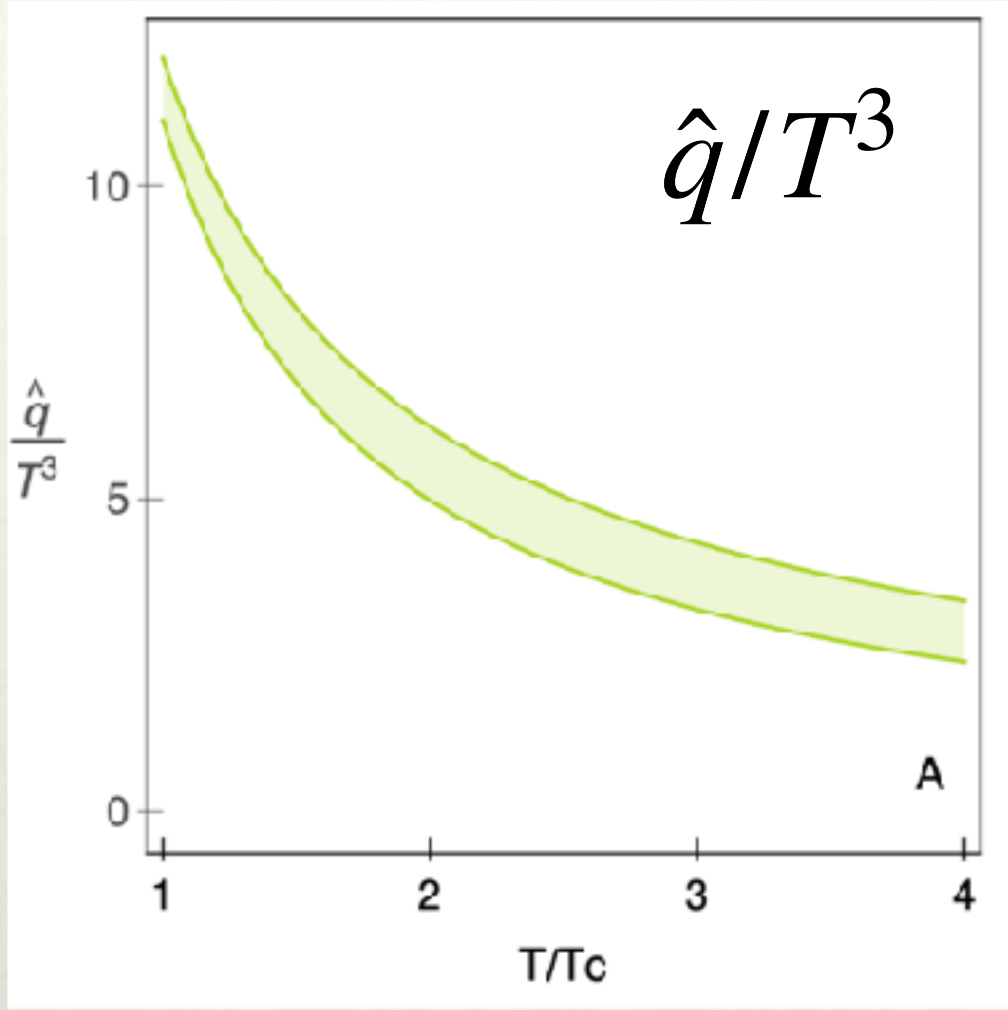
Diffusion coefficient



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

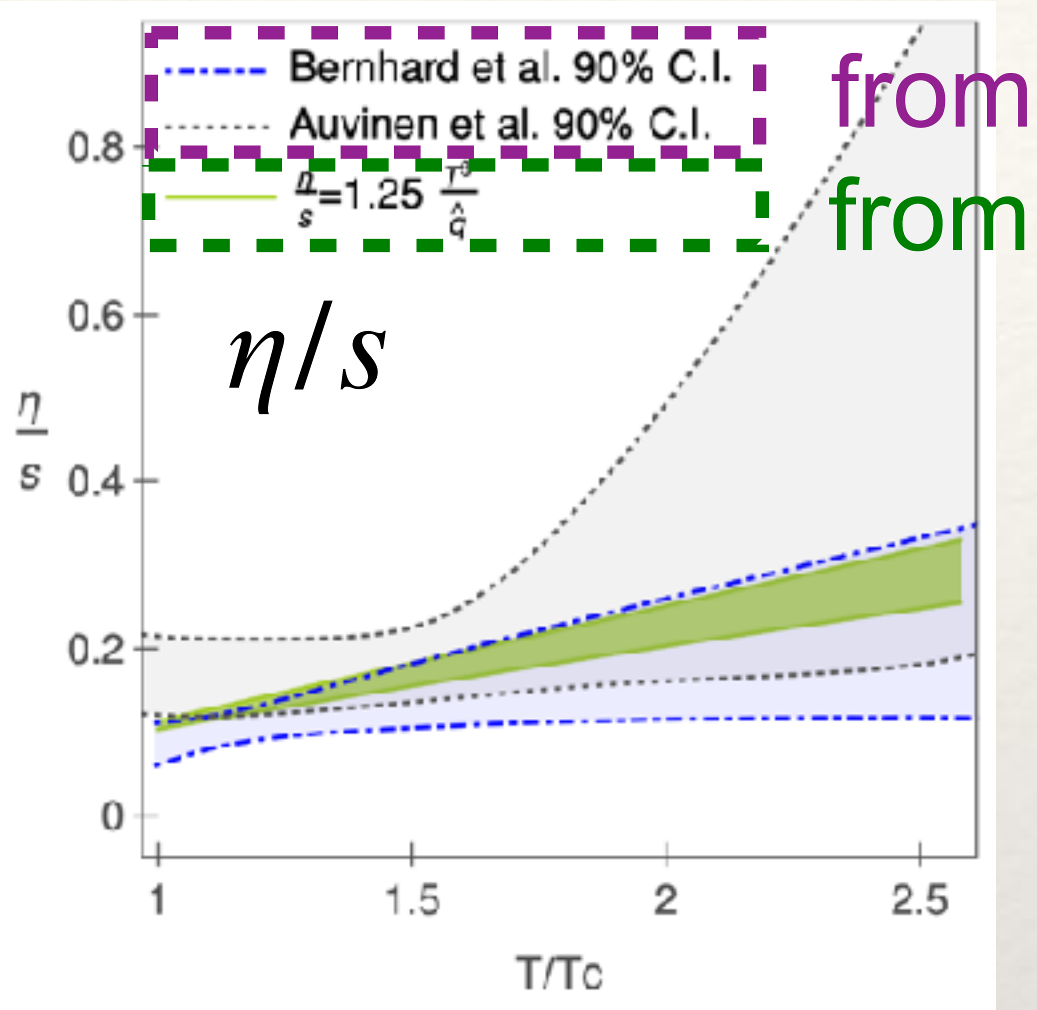
Probing the specific viscosity of the QGP

- Indirect constraint: convert $\hat{q}$ into η/s



$\eta/s \approx 1.25\, T^3/\hat{q}$

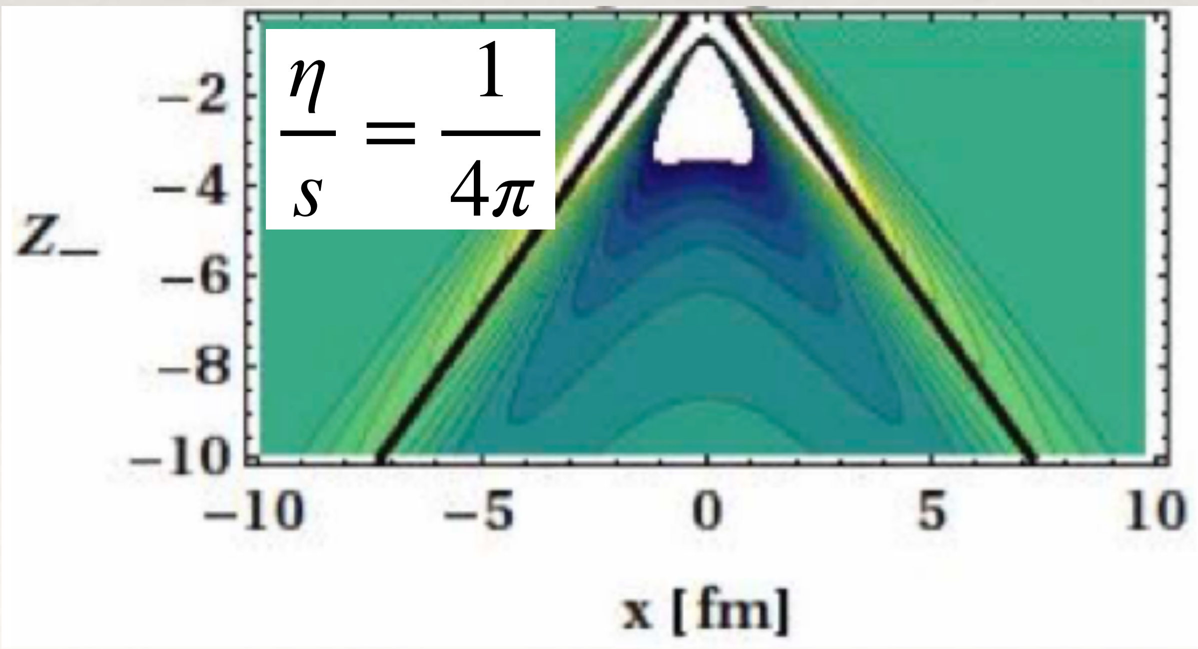
weak coupling calculation

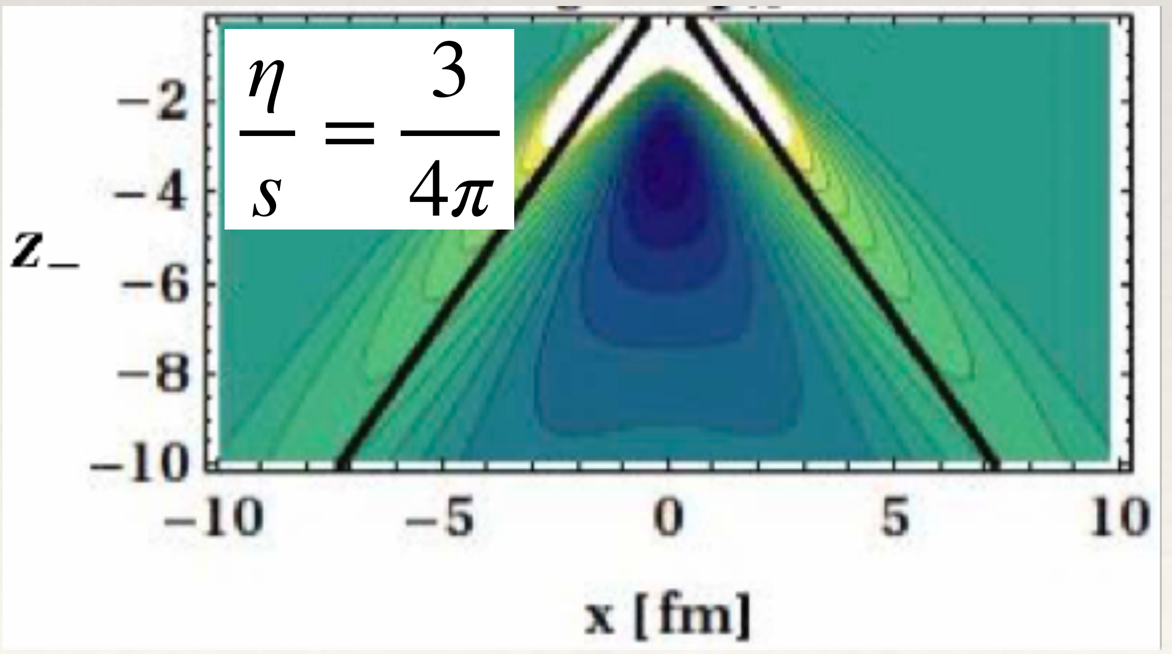


from hydro
from jet
} consistent

Karmakar et. al., Phys. Rev. C 108 (2023) 044907

- **Outlook**: constrain specific viscosity and speed of sound using medium response





Patterns of jet-induced Mach cone depends on η/s and c_s (EoS)

Neufeld, Phys. Rev. C 79 (2009) 054909

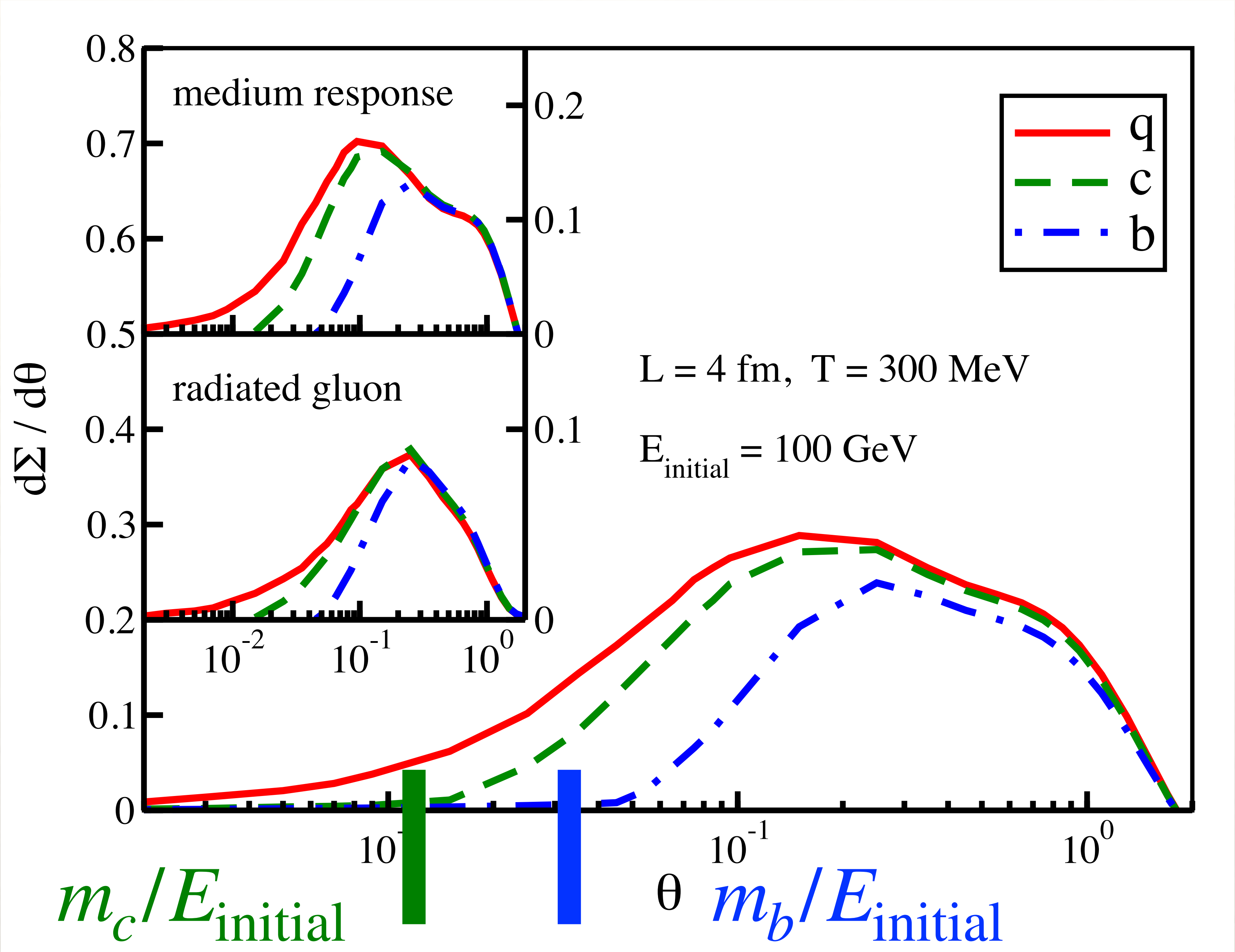
Summary

Probing strongly interacting matter using energetic hadrons and jets

- Perturbative calculation successfully describes hadron suppression at high p_T
- Jet-induced medium excitation is crucial for understanding full jet observables
- EEC is an excellent observable for studying flavor dependence of jet quenching
- Jet observables are used to constrain various QGP properties: $\hat{q}$, EoS, η/s ...

Thank you!

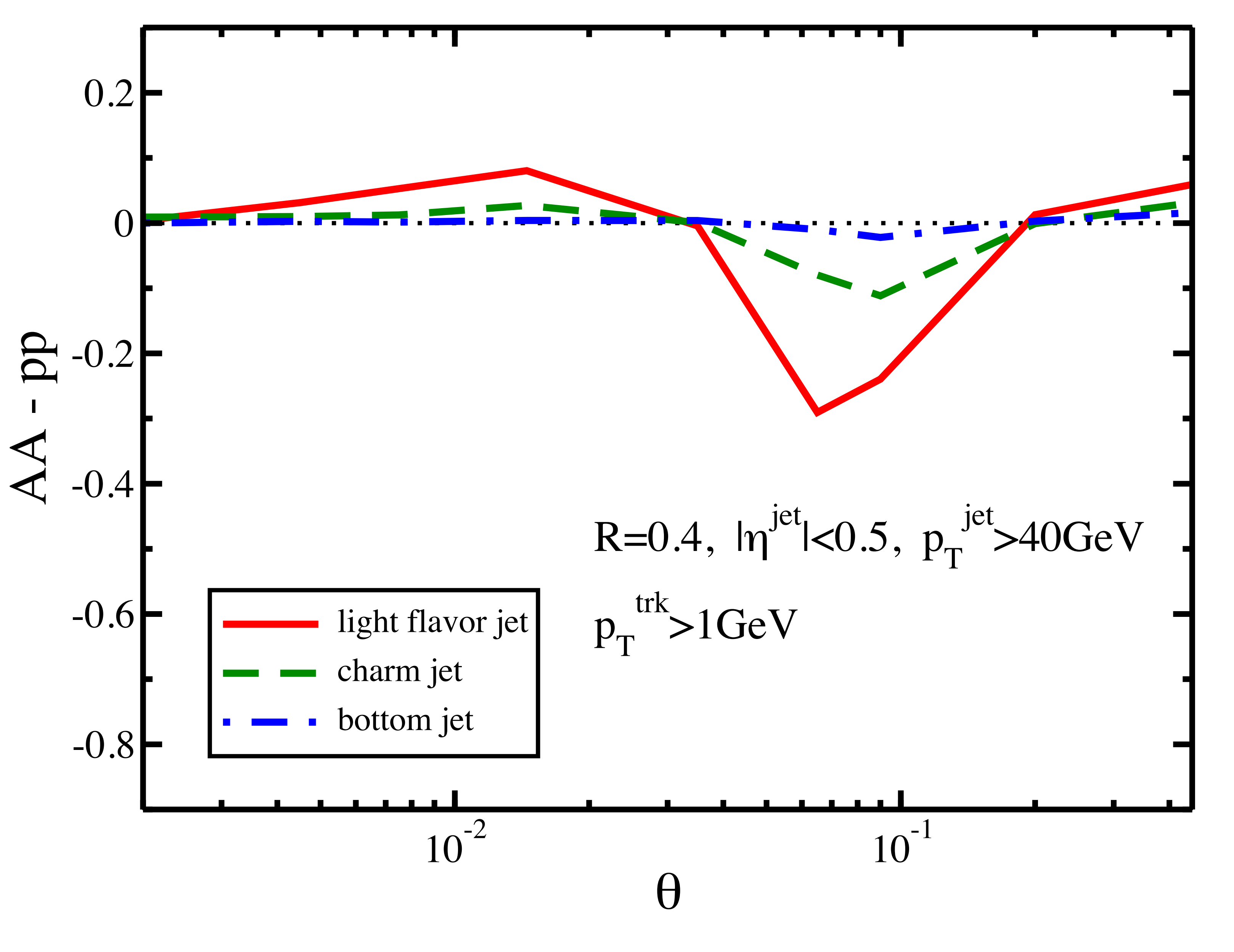
EEC of partons developed from a single quark



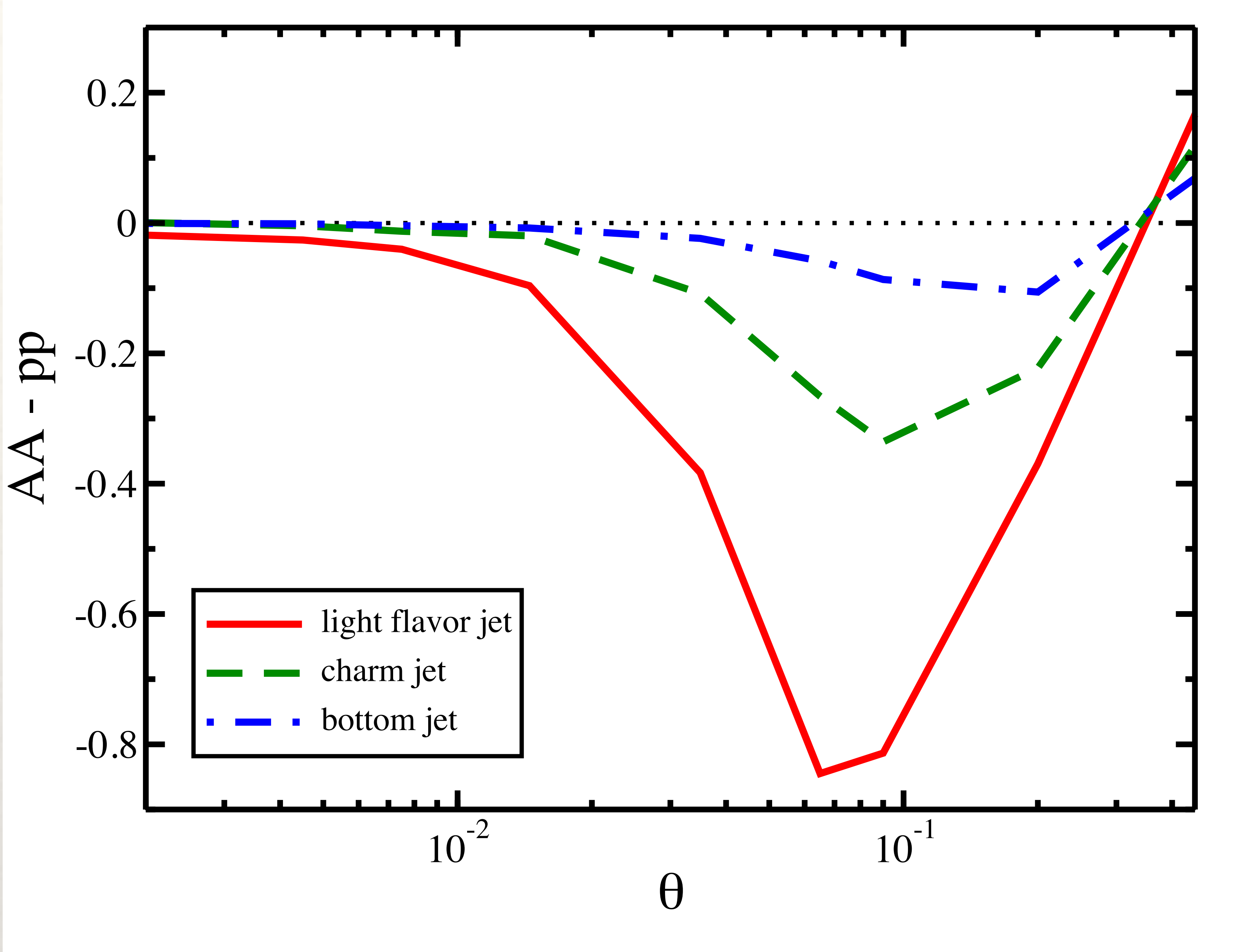
- Single quark → LBT + static medium → EEC of daughter partons
- Flavor (mass) hierarchy of EEC:
  - Magnitude: charged > *D* > *B*-jet; peak position: charged < *D* < *B*-jet (similar to vacuum jets)
  - Clear strong suppression of Σ below $\theta_0 \sim m_Q/E_{\text{initial}}$
- Contributions form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

Effects of trigger bias on the jet EEC

p_T trigger in both *pp* and AA



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



- AA jets with trigger bias originate from *pp* jets with higher p_T and initial virtuality scale

  → Stronger but narrower vacuum splittings

  → Enhances EEC at small θ, reduces the suppression/enhancement at intermediate/large θ

- Can be tested using γ-jets