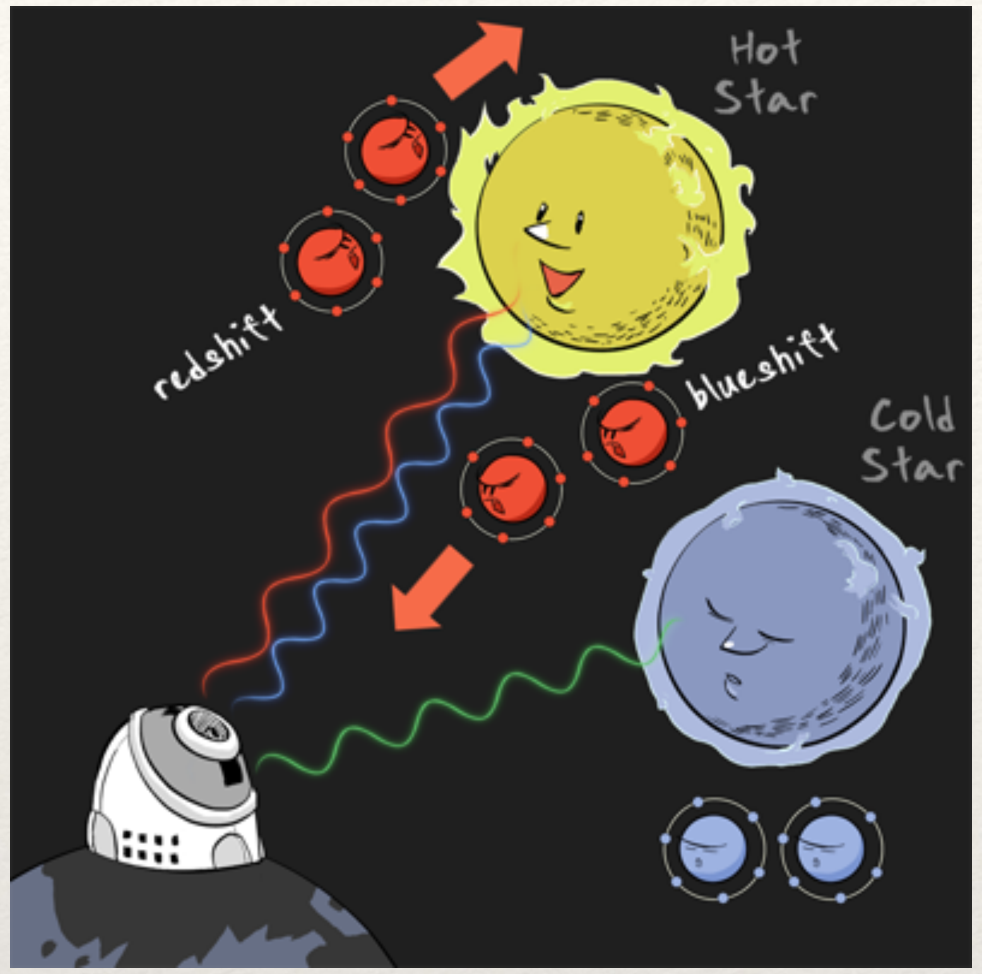
Unfolding the QGP properties with high-precision jets

曹杉杉

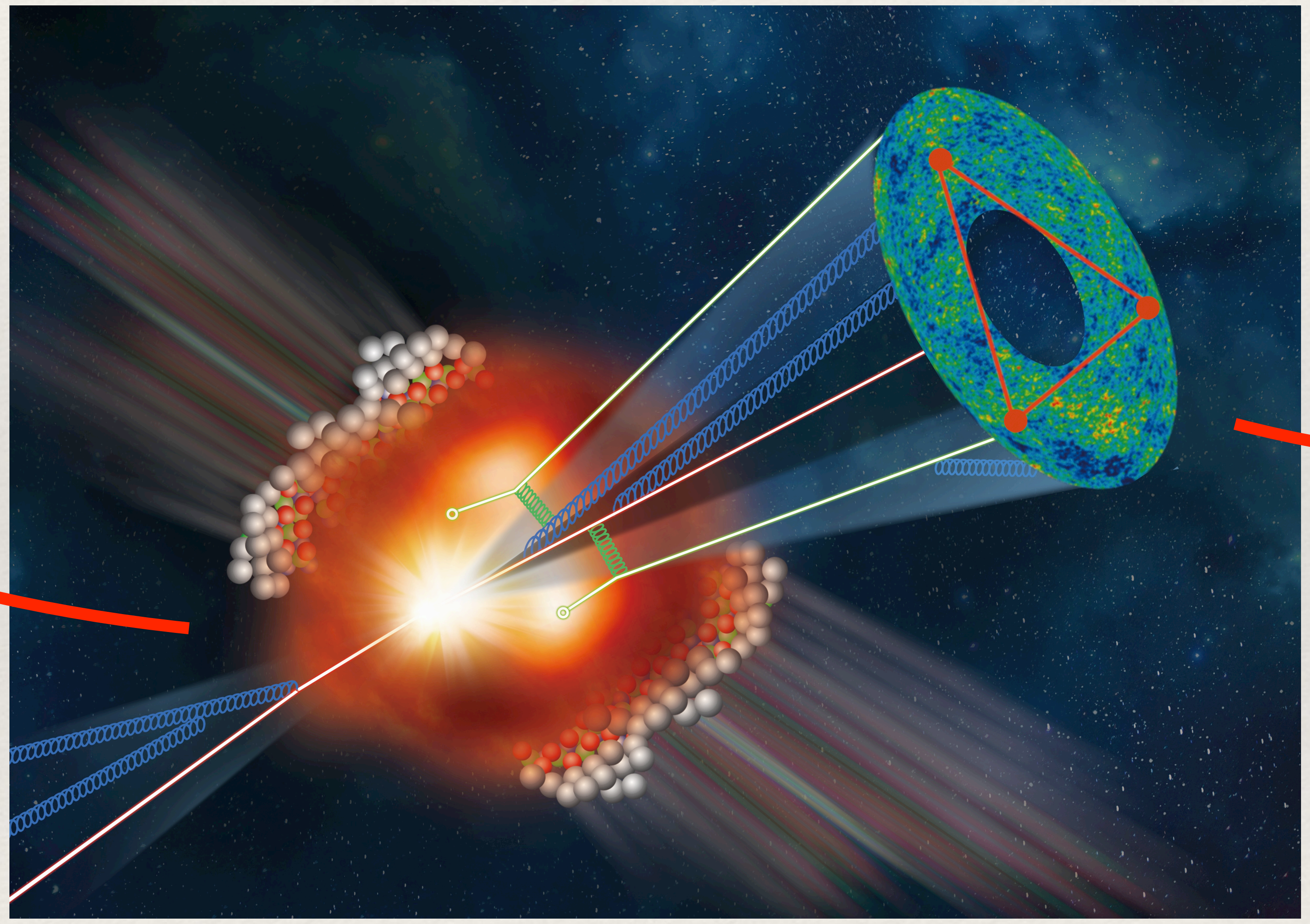
东南大学

极端条件下的QCD研讨会，烟台，2026年8月19日

Probing quark-gluon plasma (QGP) in heavy-ion collisions



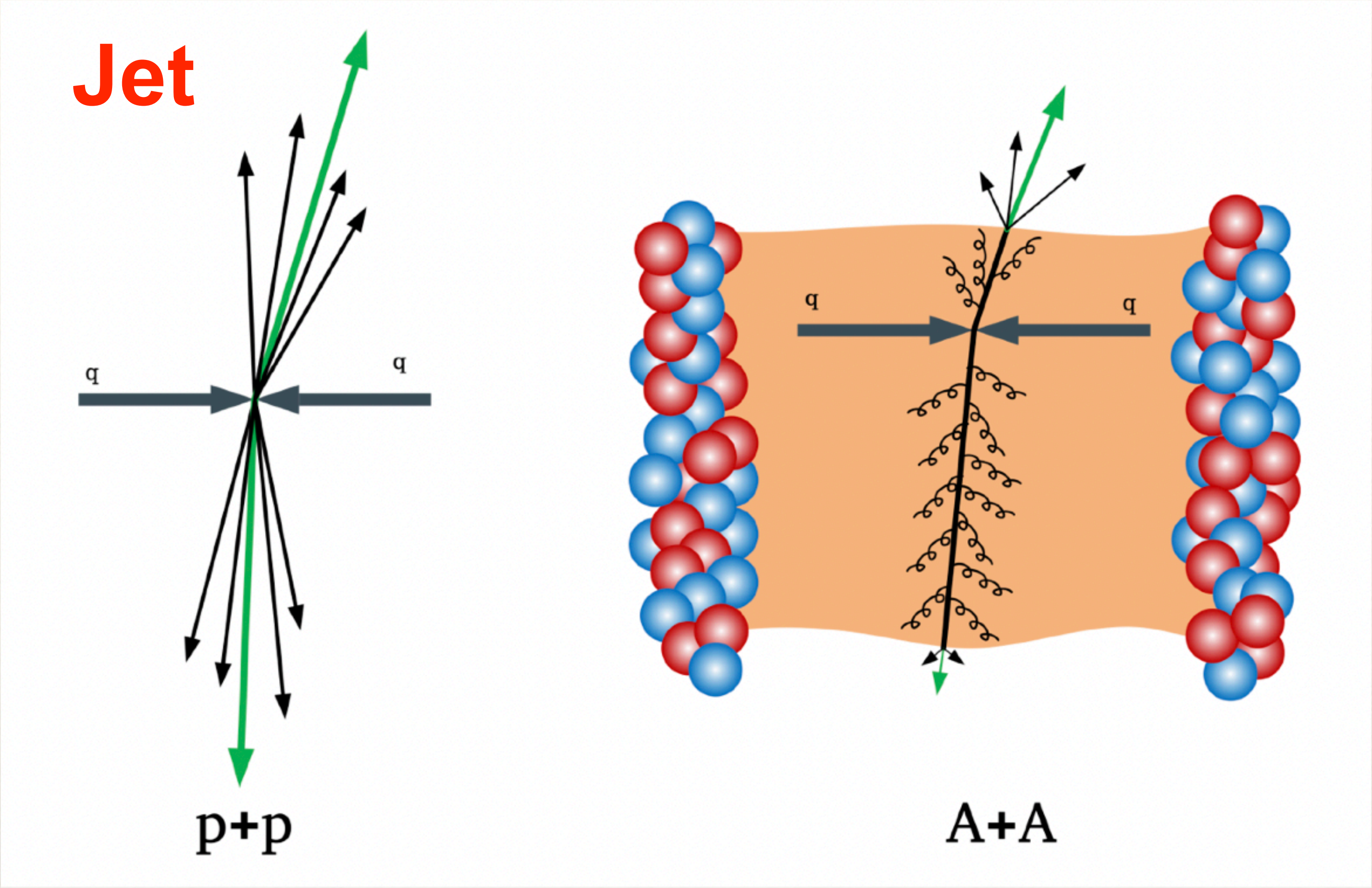
Thermal (**soft**)
particle emission



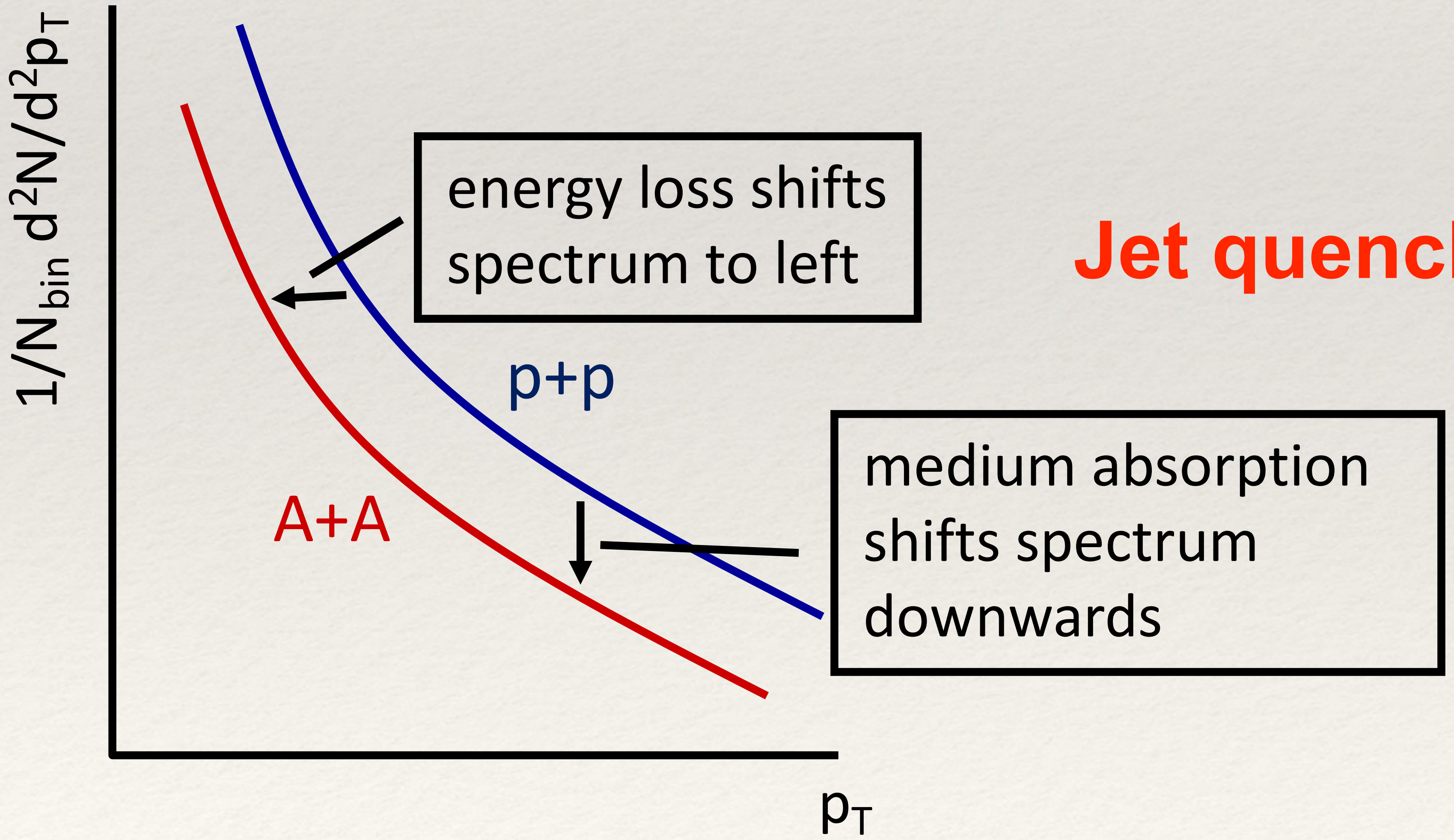
Energetic (**hard**)
particle tomography

Formation of color deconfined state of matter (QGP)
at extremely high temperature and high density

Nuclear modification of high-energy particles



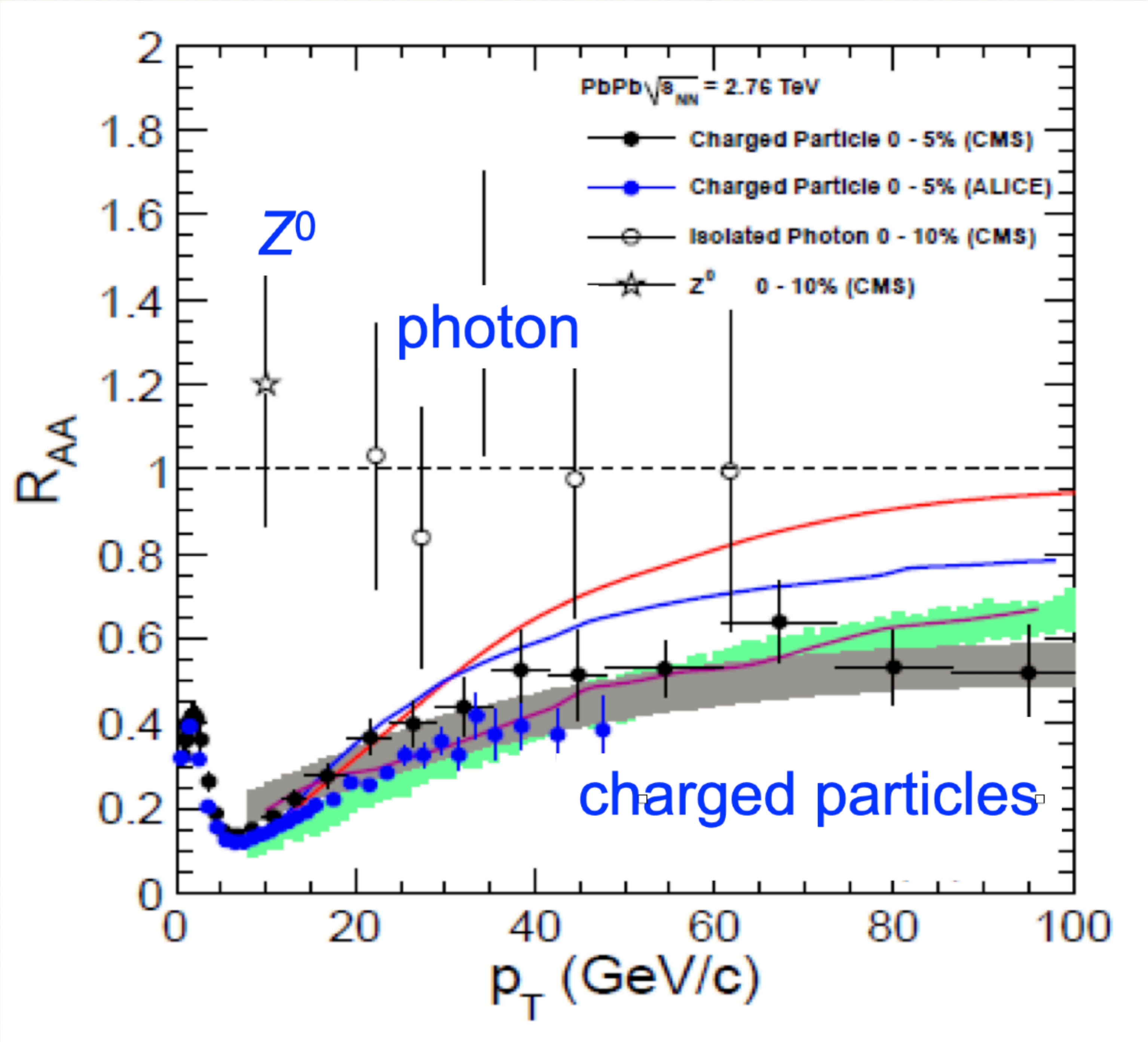
by M. Rybar / ATLAS



Jet quenching

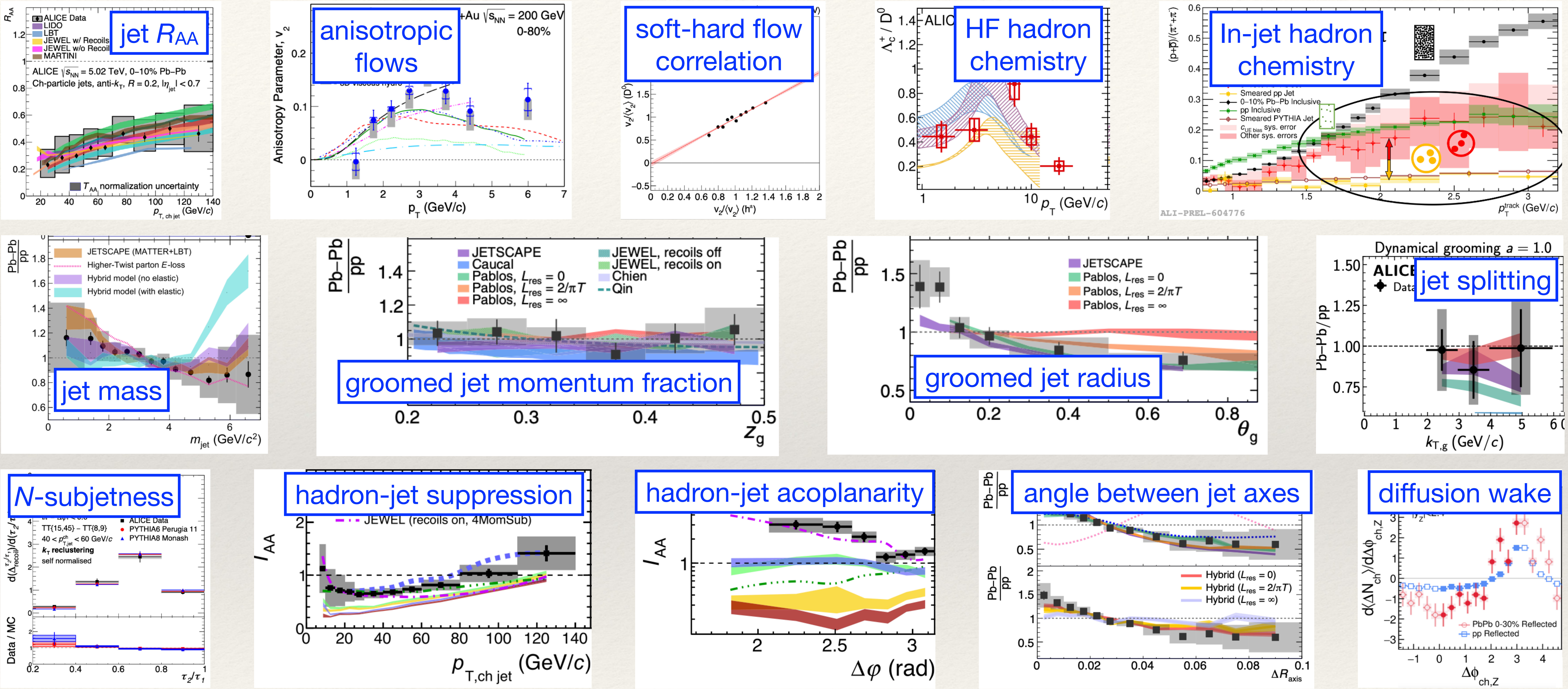
Nuclear modification factor

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}^{AA}\rangle \times dN^{pp}/dp_T}$$



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

A vast number of observables

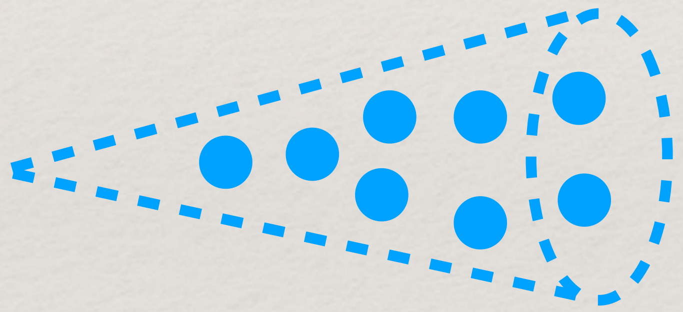


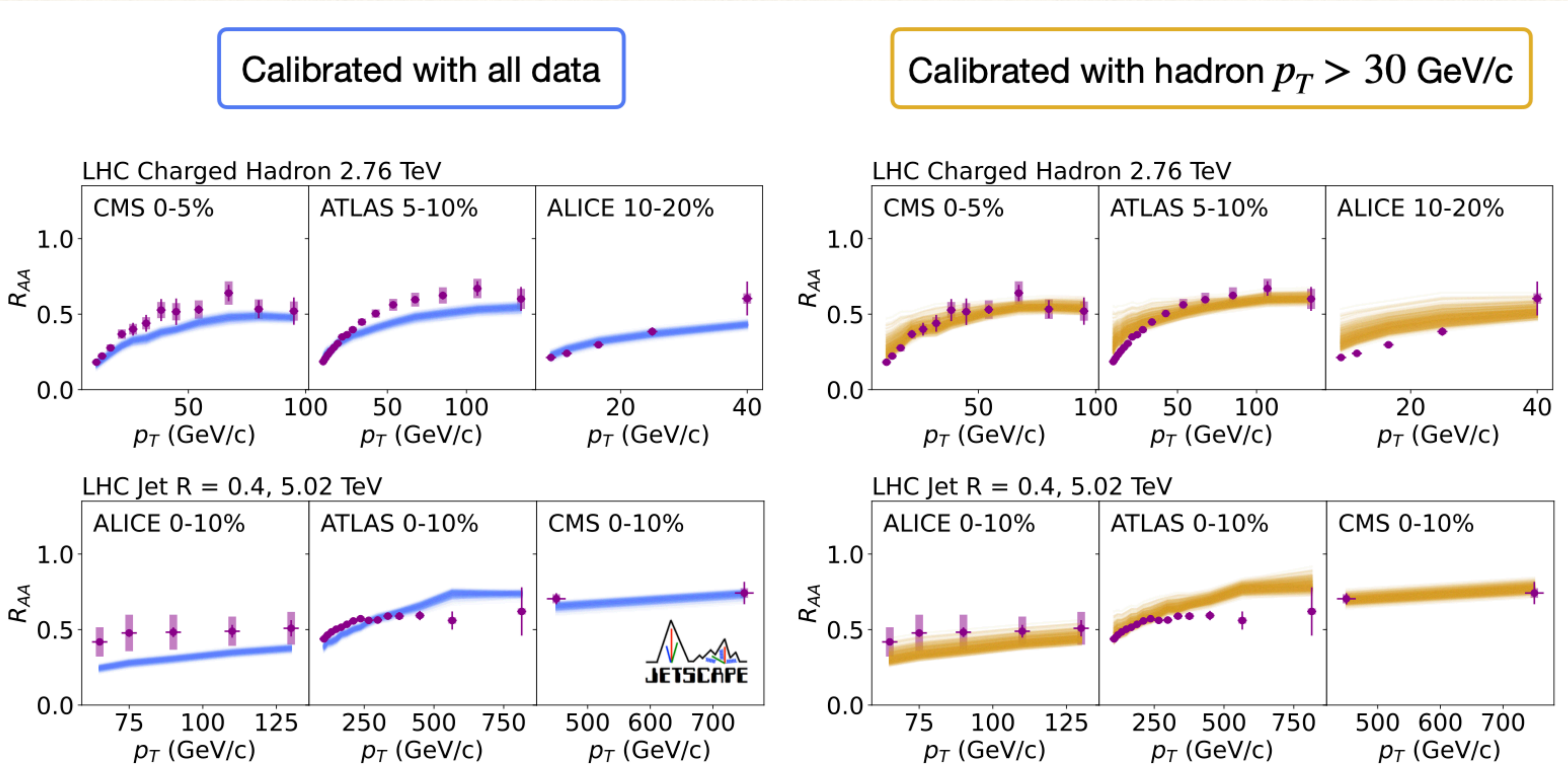
Offers multi-faceted insights into jet-medium interactions. But …

Have we precisely understood the simplest observable?

Single hadron

Full jet



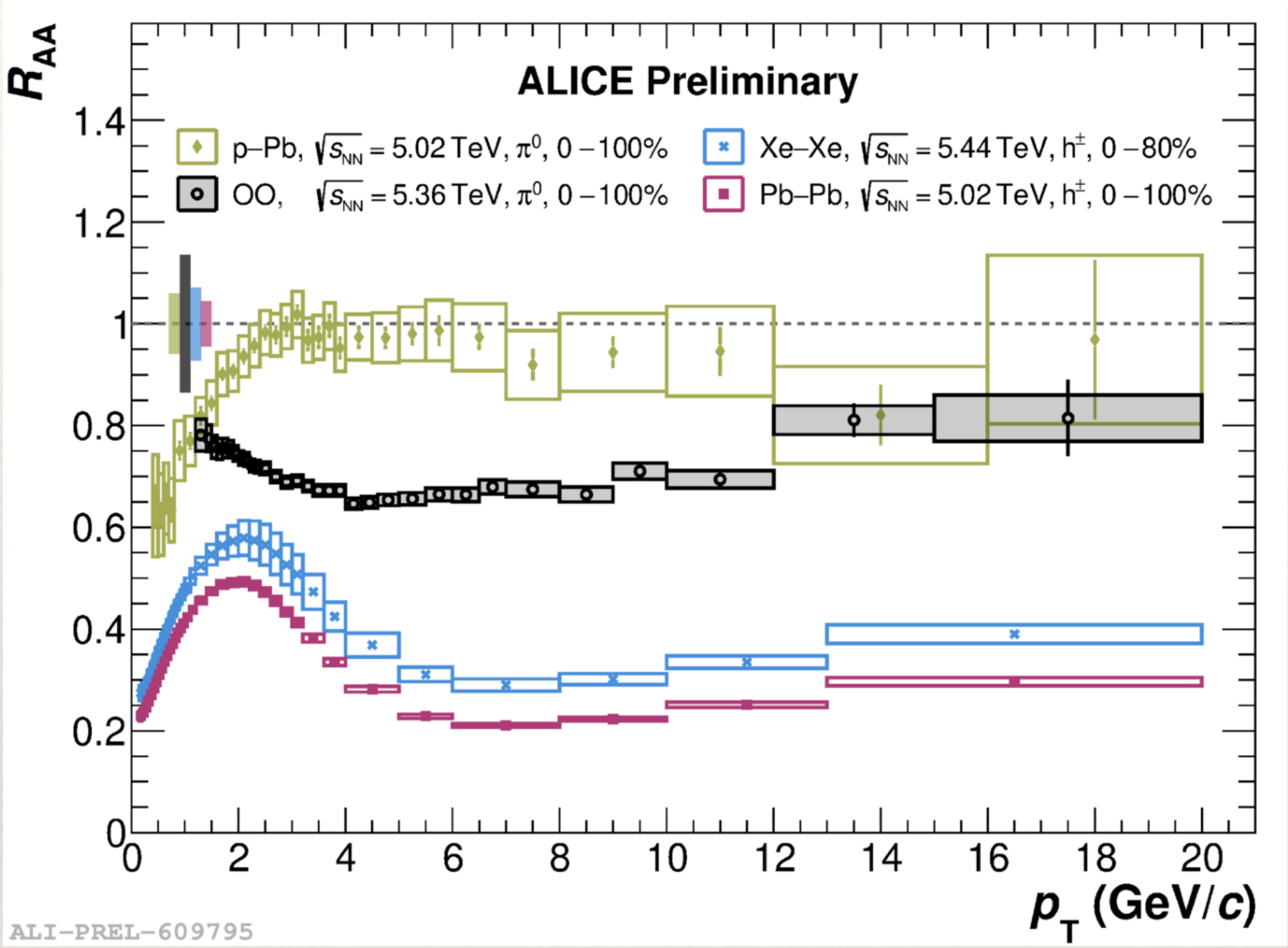


JETSCAPE, Phys. Rev. C 111 (2025) 054913

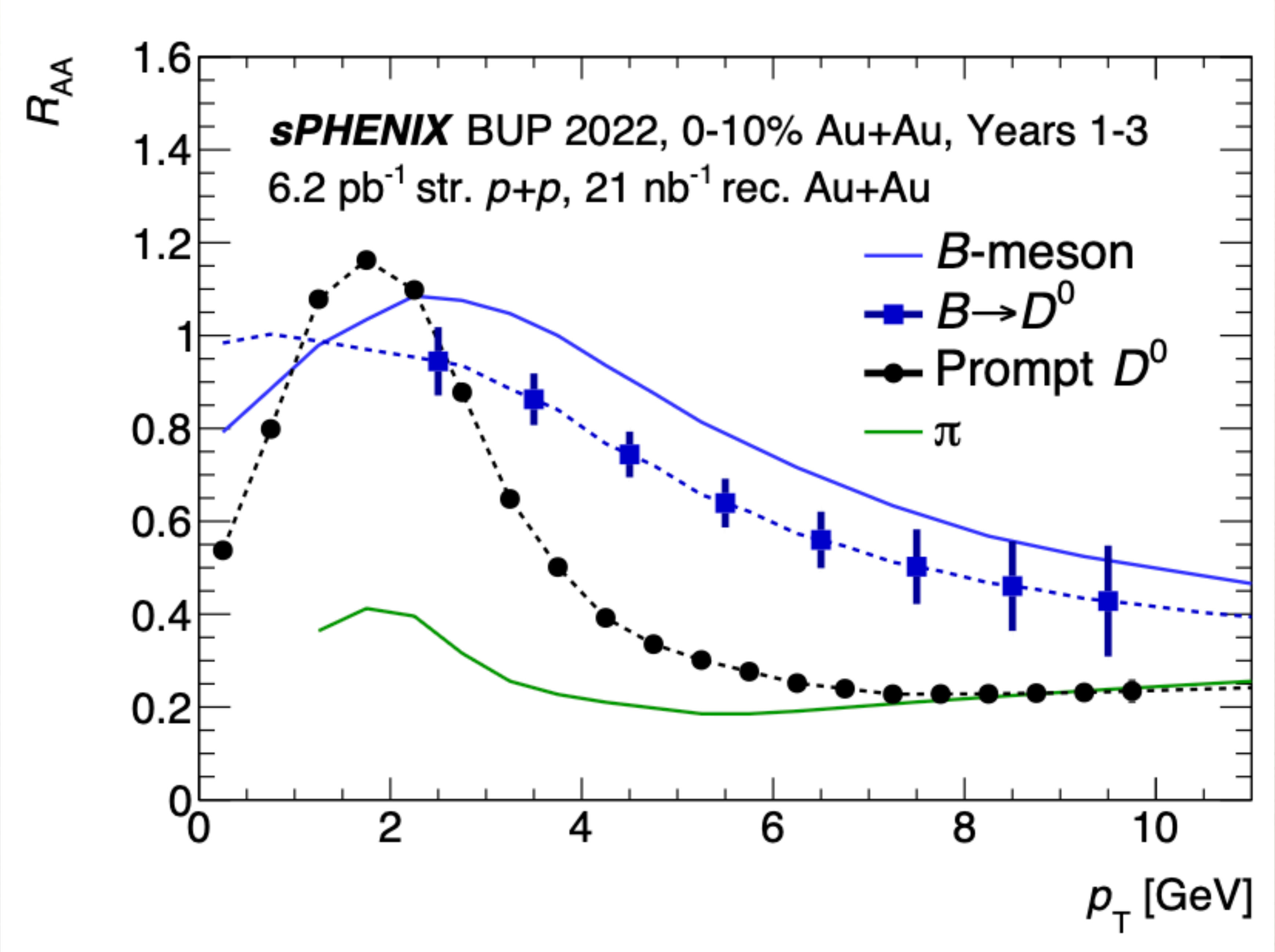
- Many theoretical models can quantitatively describe the R_{AA} of hadrons and jets ***separately***
- Few can describe them ***simultaneously*** even with a Bayesian calibration on model parameters

Current and upcoming high-precision data

ALICE data

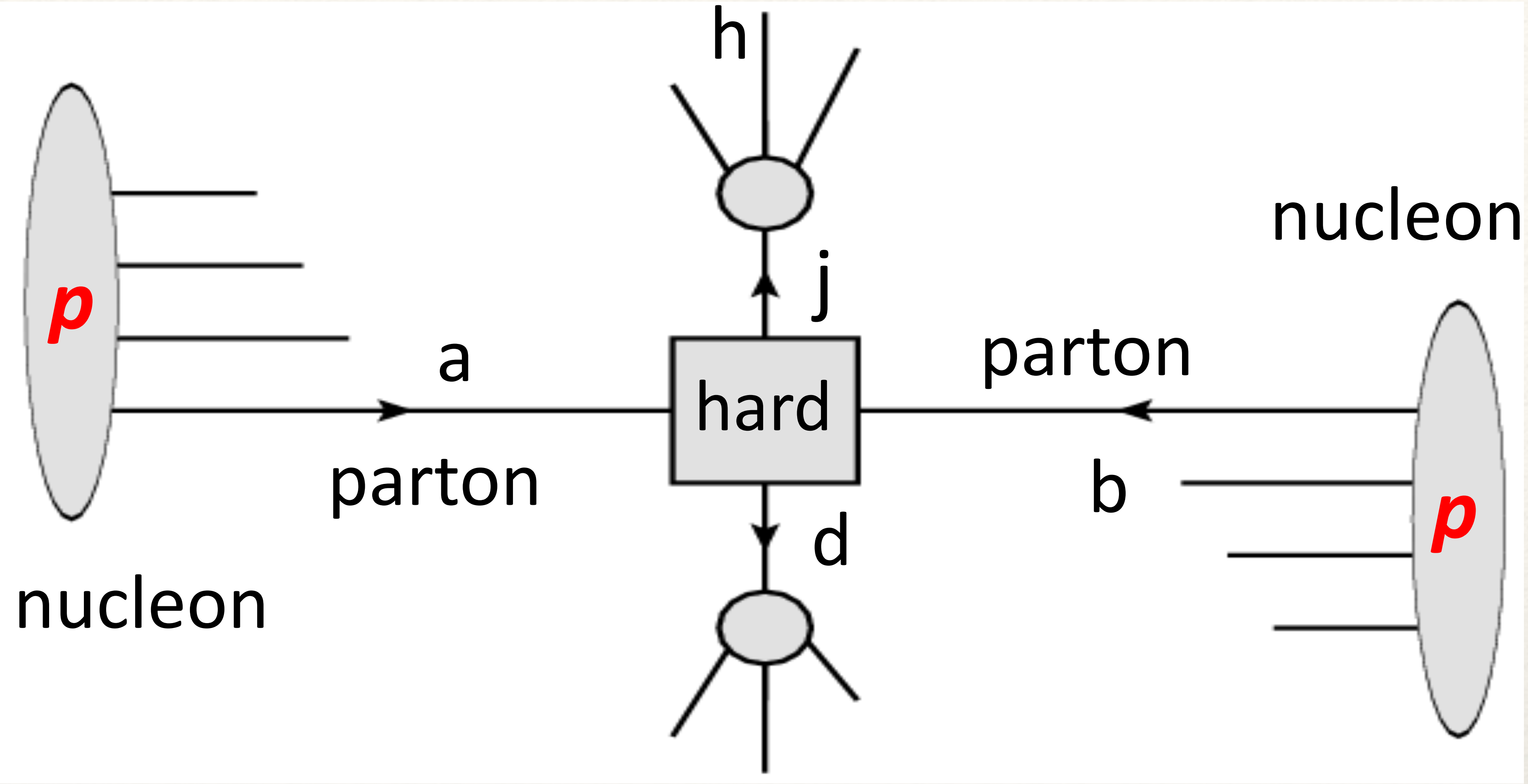


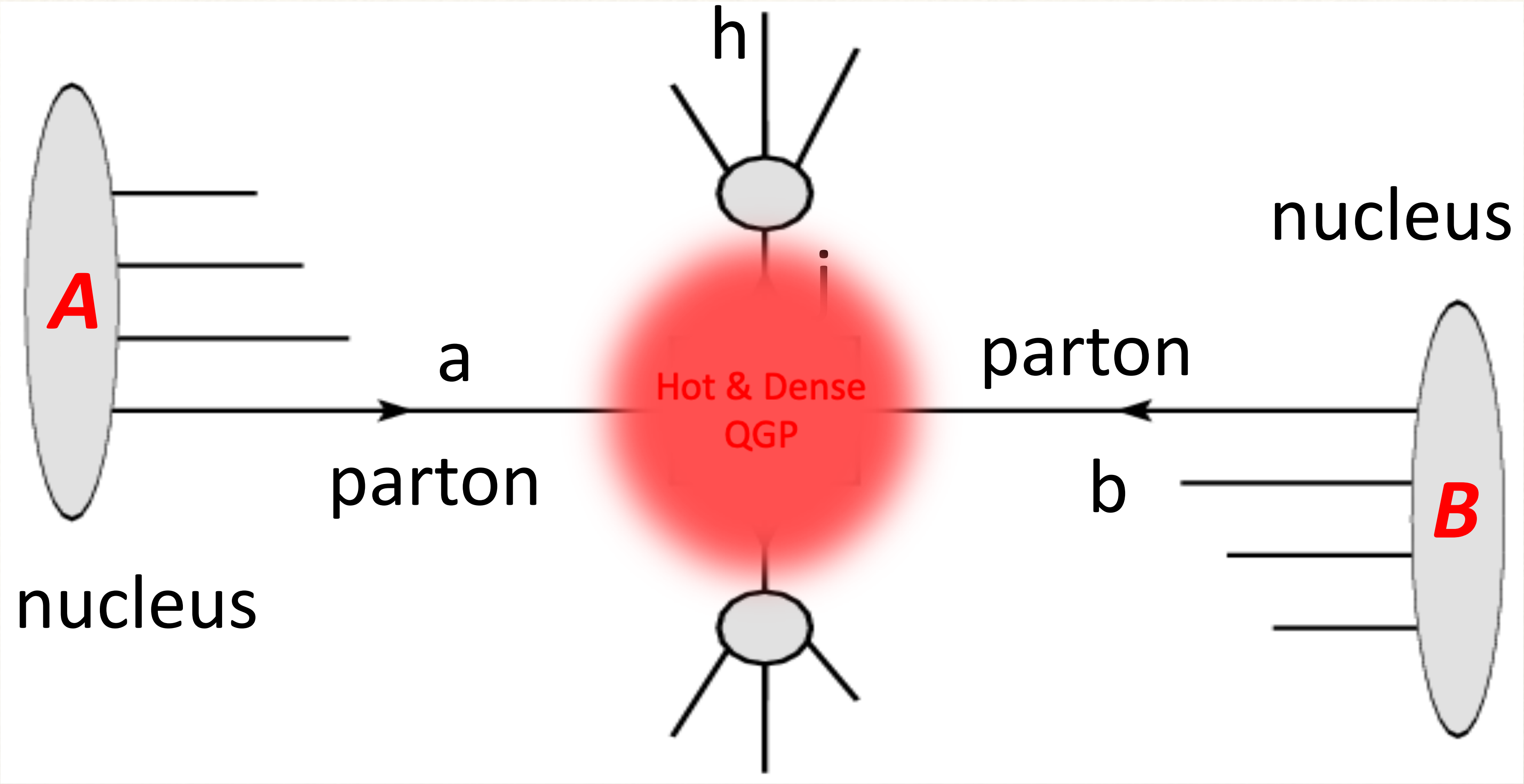
sPHENIX proposal



- Rising accuracy in jet quenching measurements
- Bottleneck of precise constraint on the QGP properties: jet models
- Goal of this talk: improve the precision of jet models for heavy-ion collisions

Theoretical framework of jet quenching





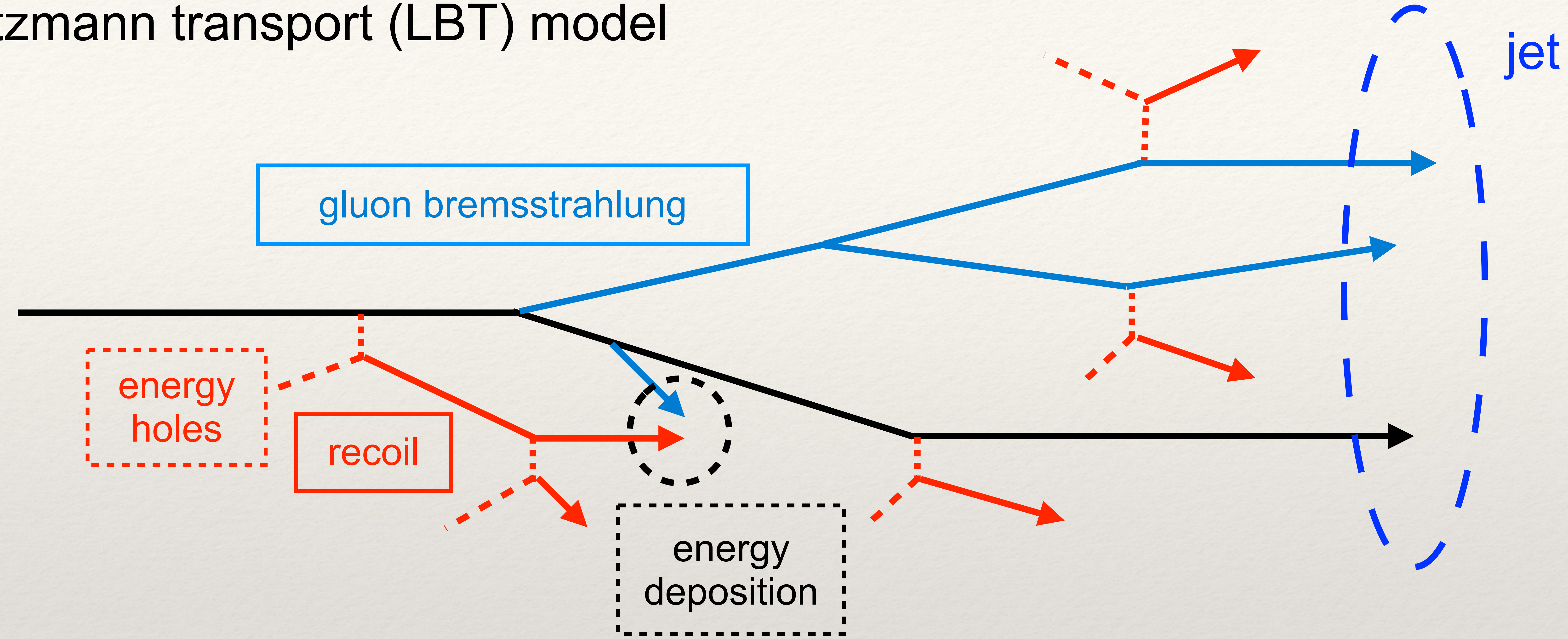
$$d\sigma_h = \sum_{abjd} f_{a/p} \otimes f_{b/p} \otimes d\sigma_{ab\to jd} \otimes D_{h/j}$$

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

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

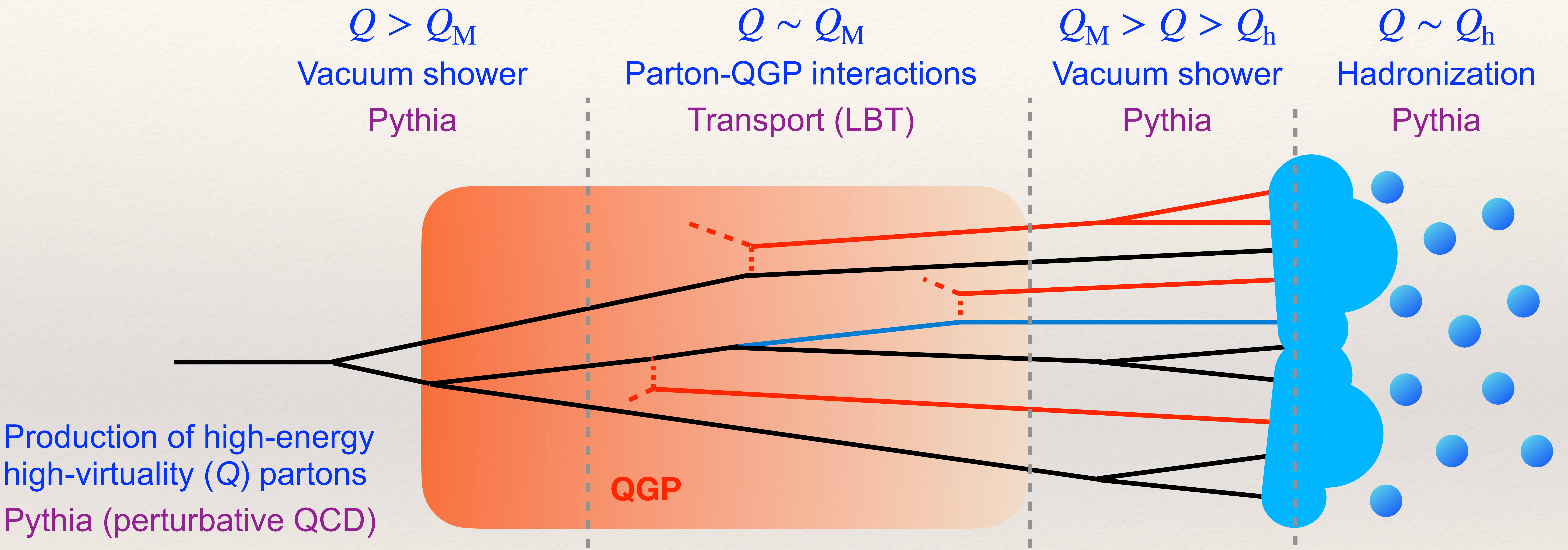
Parton-QGP interactions

Linear Boltzmann transport (LBT) model



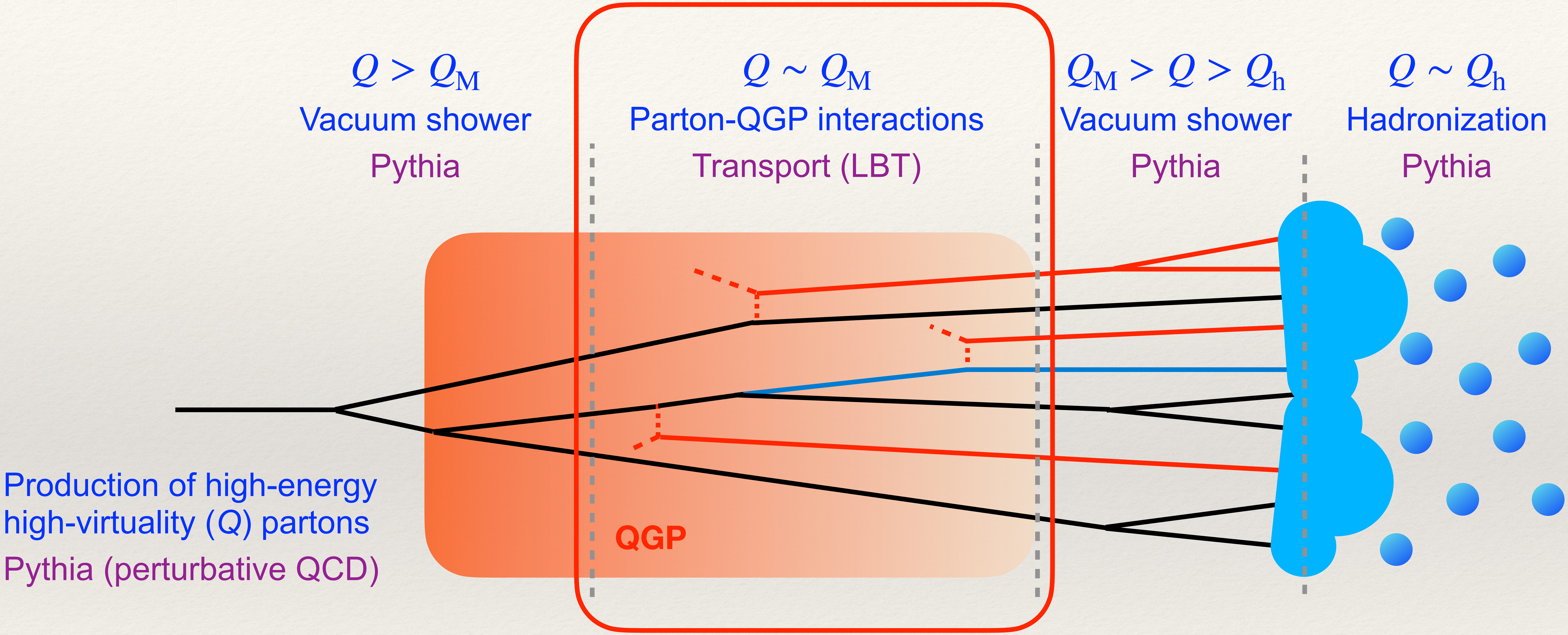
- Medium modification on jets: scattering, medium-induced gluon bremsstrahlung
- Jet modification on medium: energy deposition + depletion → **jet-induced medium excitation (medium response)**
- Jet-medium interactions: **medium modification of jets + medium response**

An improved framework for jet-QGP interactions



- **Old model**: $Q_M = Q_h = 0.5\ \mathrm{GeV}$; **New model**: $Q_M > Q_h$ can be varied

An improved framework for jet-QGP interactions



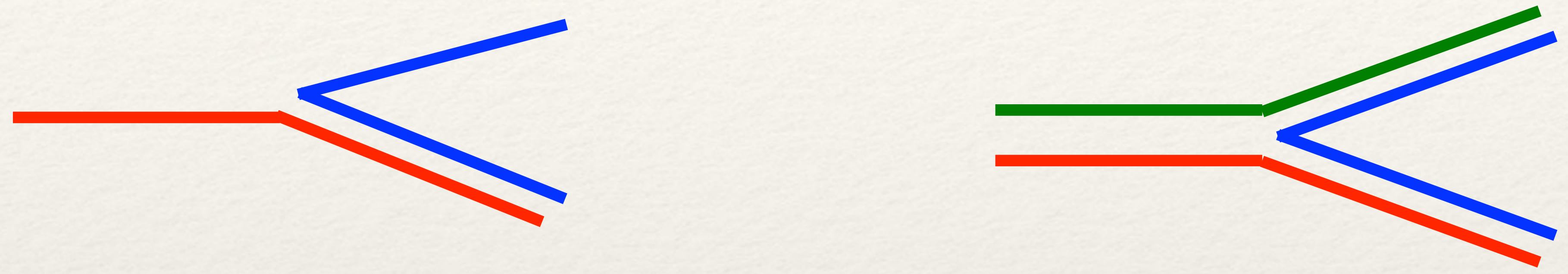
- **Old model**: $Q_M = Q_h = 0.5 \text{ GeV}$; **New model**: $Q_M > Q_h$ can be varied

Color schemes in elastic and inelastic scatterings

Technical challenge: color information required for partons transitioned from LBT back to Pythia

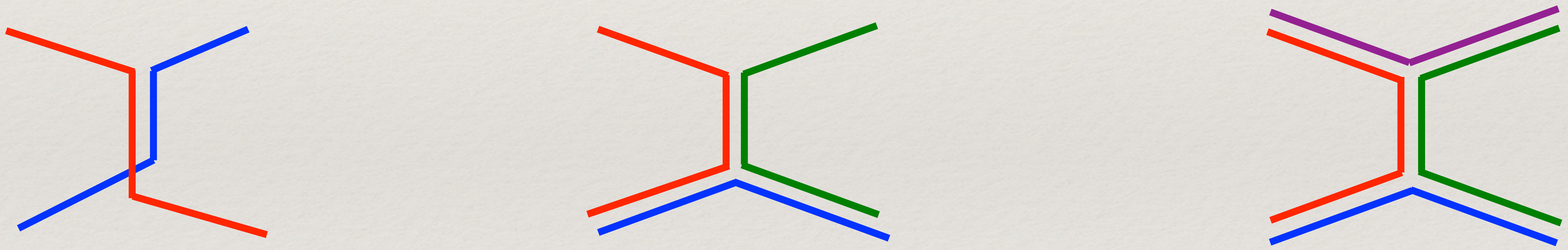
Parton splittings

$q \rightarrow qg$ $\qquad$ $g \rightarrow gg$



Jet-medium scatterings

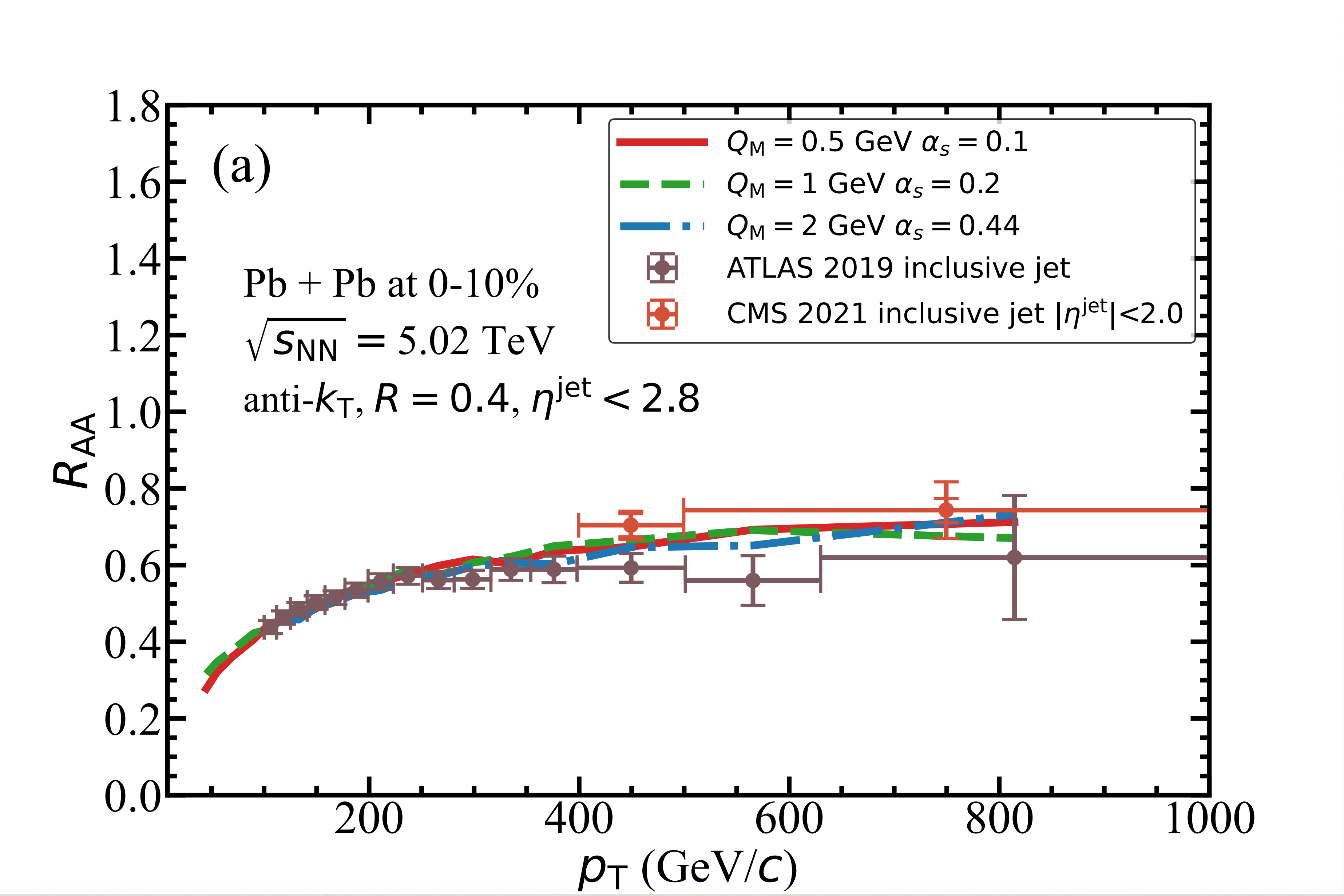
$qq \rightarrow qq$ $\qquad$ $qg \rightarrow qg$ $\qquad$ $gg \rightarrow gg$



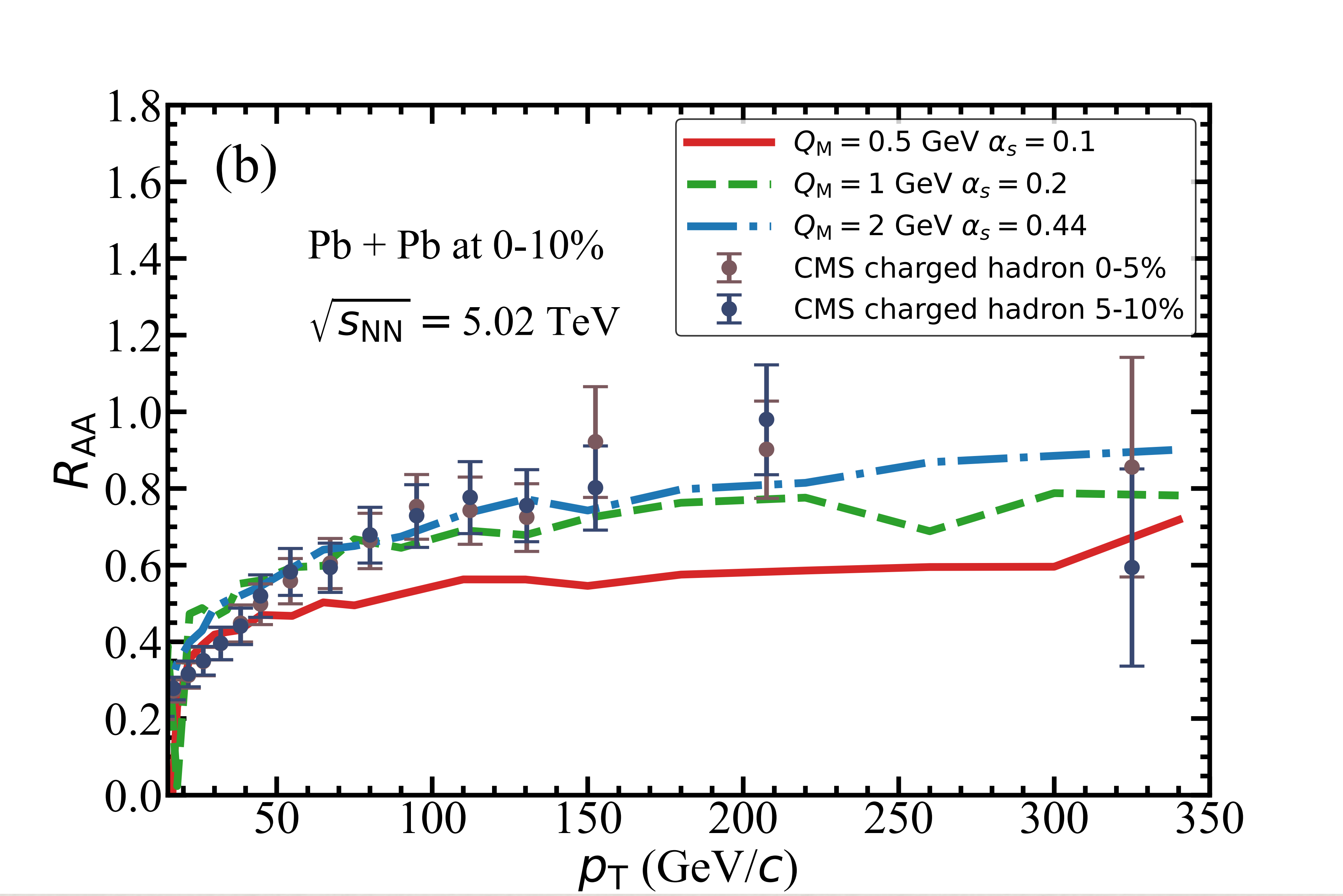
- Large N_c color scheme in Pythia, (color, anticolor), e.g., q (101, 0), $\bar{q}$ (0, 102), g (103, 104)
- Same color scheme for parton splitting processes
- Introduce color information for jet-medium scatterings

Effect of medium scale on jet *vs.* hadron R_{AA}

Inclusive jet



Charge hadron



Adjust α_s for the jet R_{AA} and examine the hadron R_{AA}

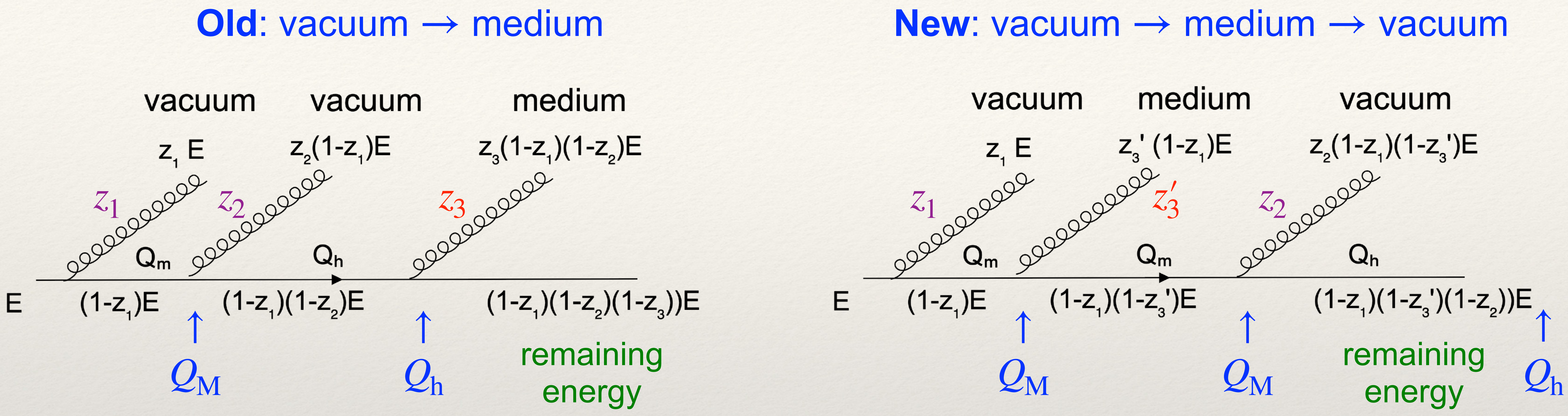
Observation:

- $Q_M \uparrow$ requires larger α_s to re-fit jet R_{AA}
- improves simultaneous jet and hadron descriptions

Implications:

- $Q_M \uparrow$ reduces jet and parton ΔE
- Stronger effects on partons than jets

Effect of medium scale on jet *vs.* hadron R_{AA}

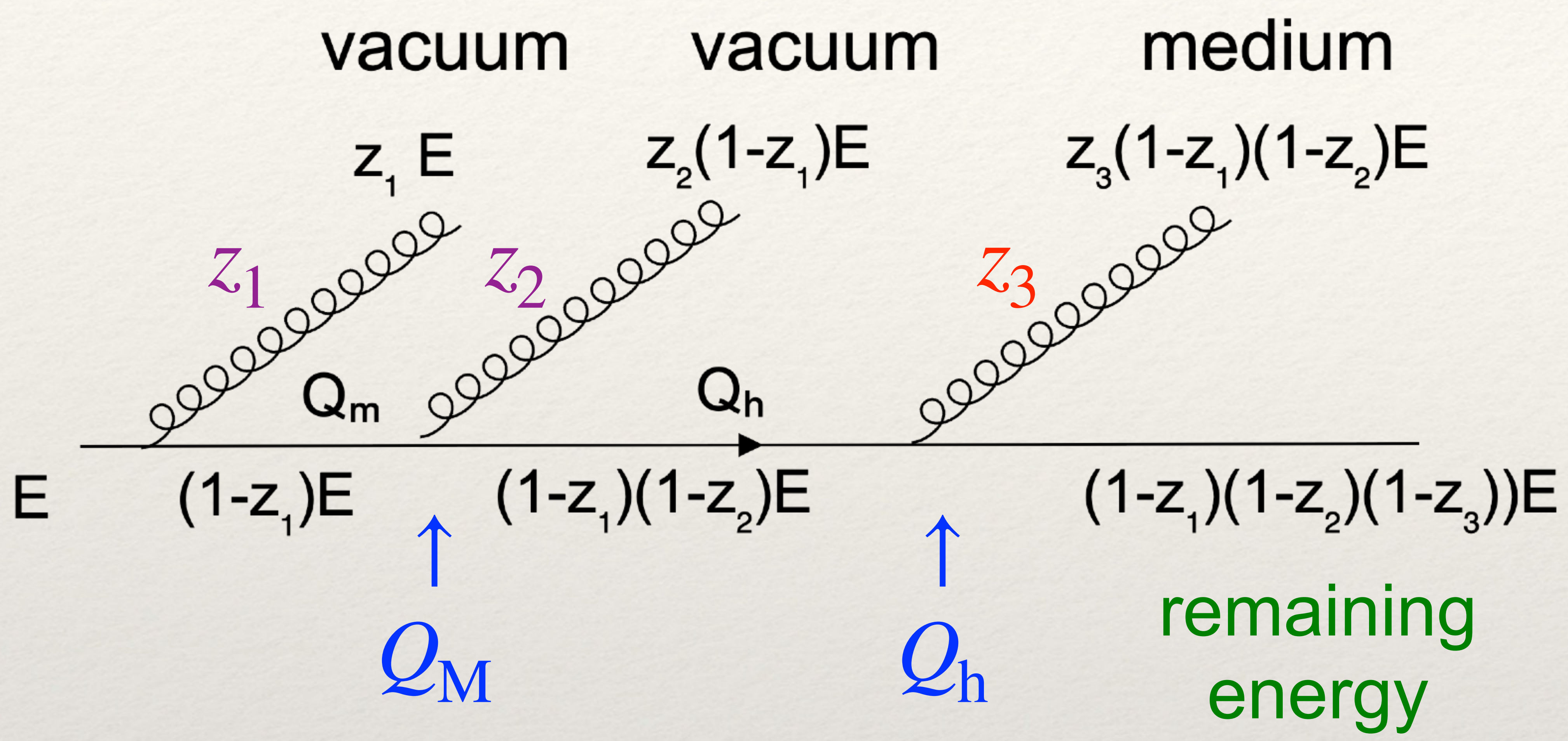


Why Δ*E* is reduced for both partons and jets in the new framework if α_s is fixed?

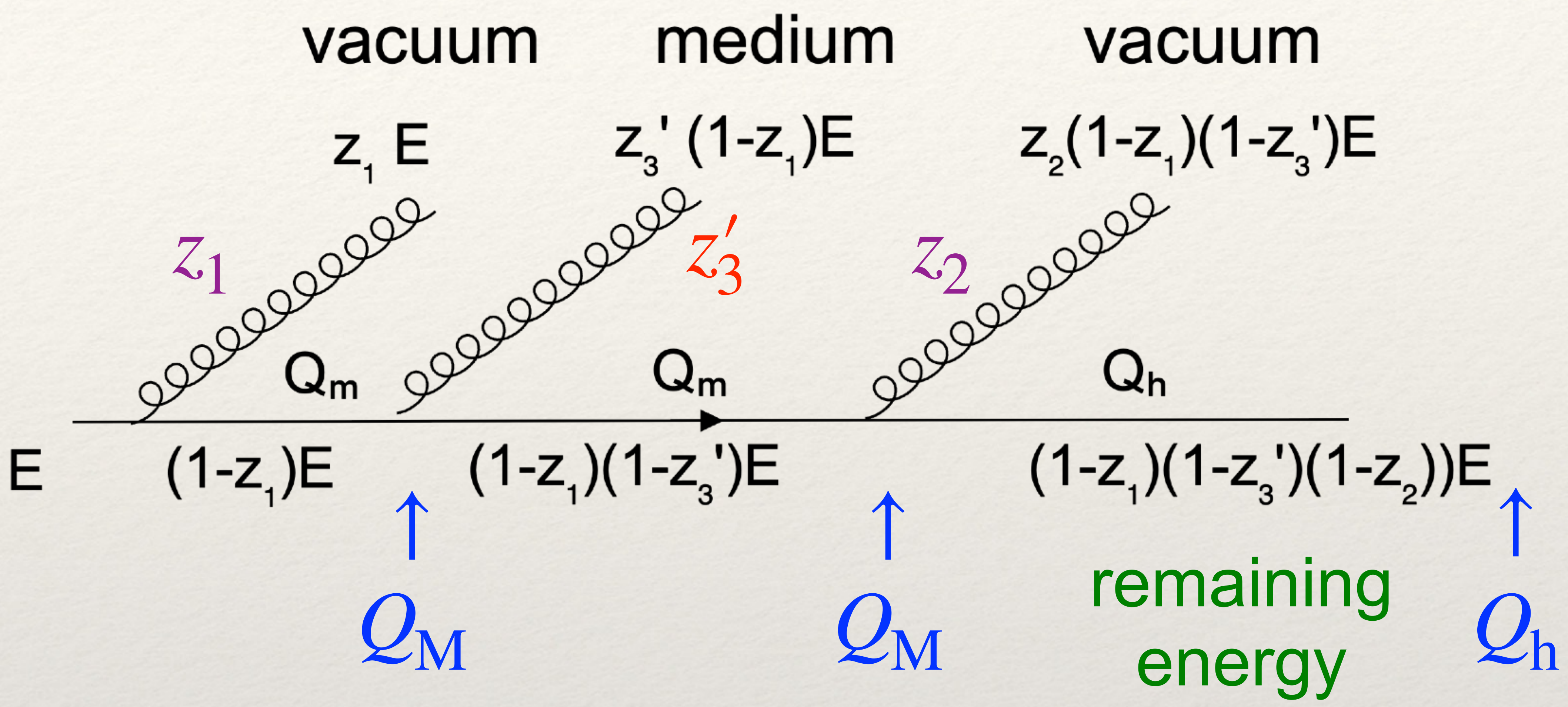
- *z* in parton splitting *P*(*z*) is *E*-independent in vacuum; Δ*E* is *E*-independent in medium
  → same z_1, z_2 between old and new, z_3 (old) > z_3' (new) → parton Δ*E*: old > new
- Number of partons entering medium: old > new → jet Δ*E*: old > new

Effect of medium scale on jet *vs.* hadron R_{AA}

Old: vacuum → medium



New: vacuum → medium → vacuum



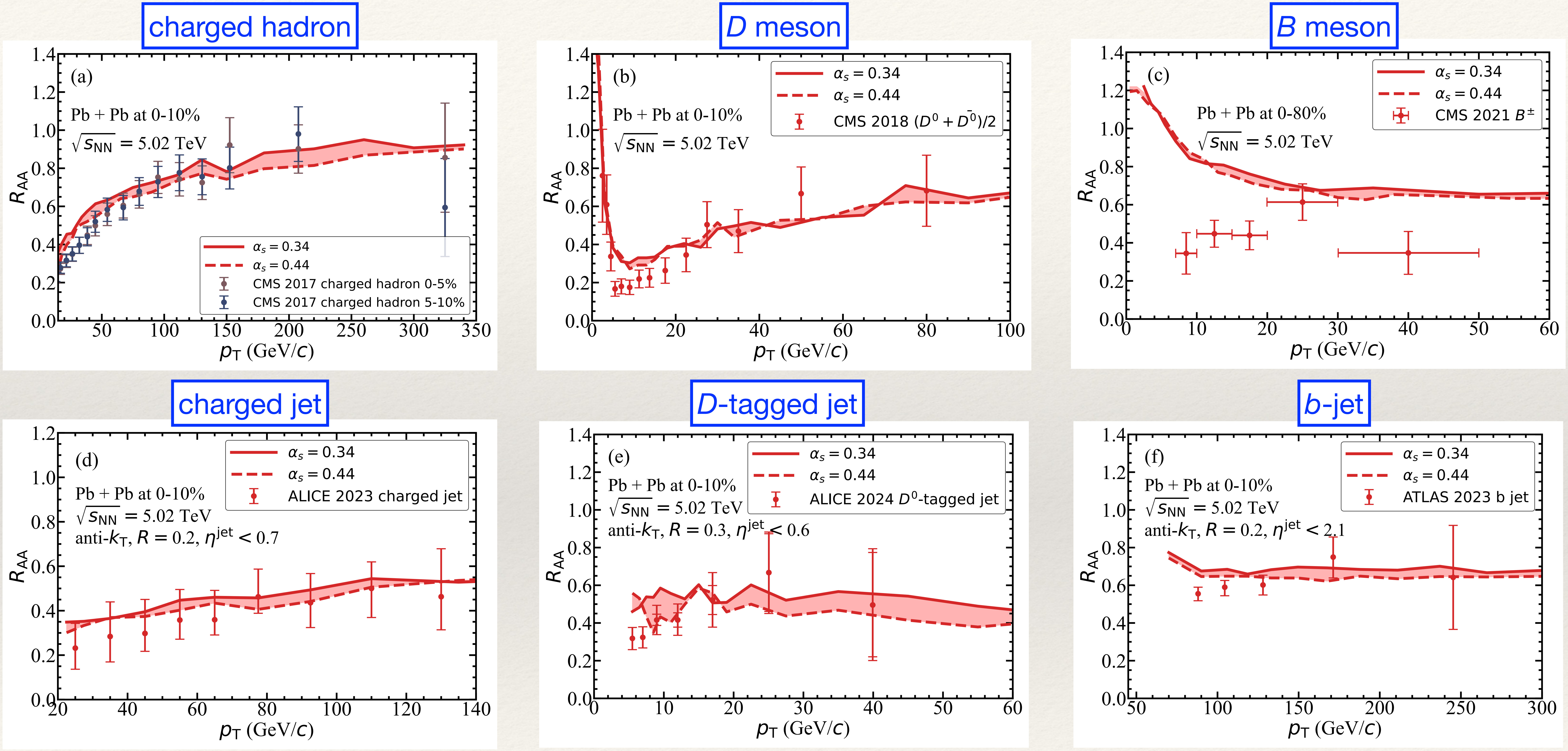
Why effect of Δ*E* reduction is more prominent for partons than for jets?

- Competing effect: starting jet-medium at higher *Q* extends interaction times → increases Δ*E*
- Larger impact on soft than hard partons ($\tau_f^{soft} > \tau_f^{hard}$ given Q)

→ Δ*E* enhancement: jets (soft + hard) > hadrons (hard)

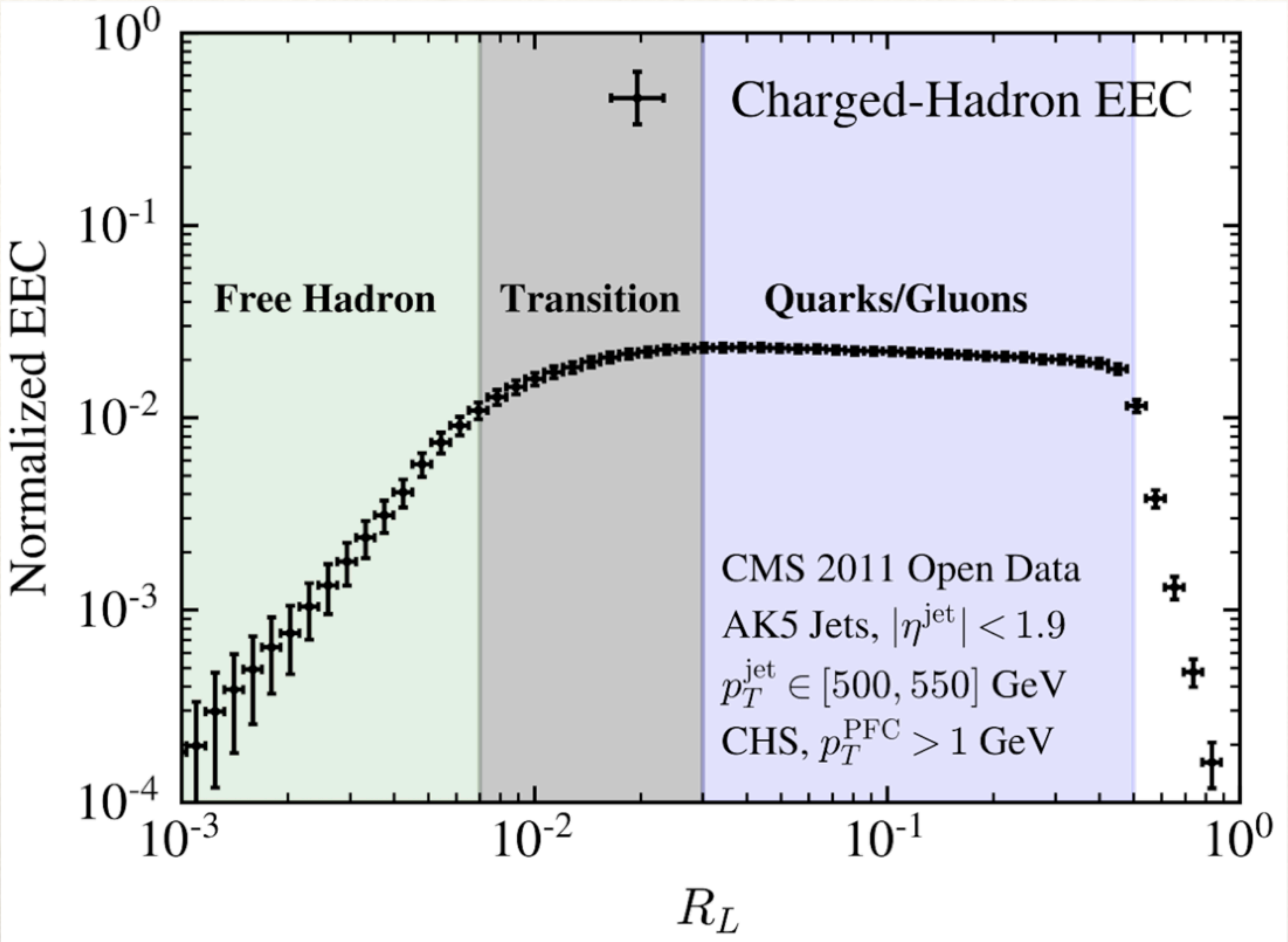
→ Raising Q_M in the new framework reduces hadron Δ*E* more than jet Δ*E* (preferred by data)

Hadrons and jets with different flavors

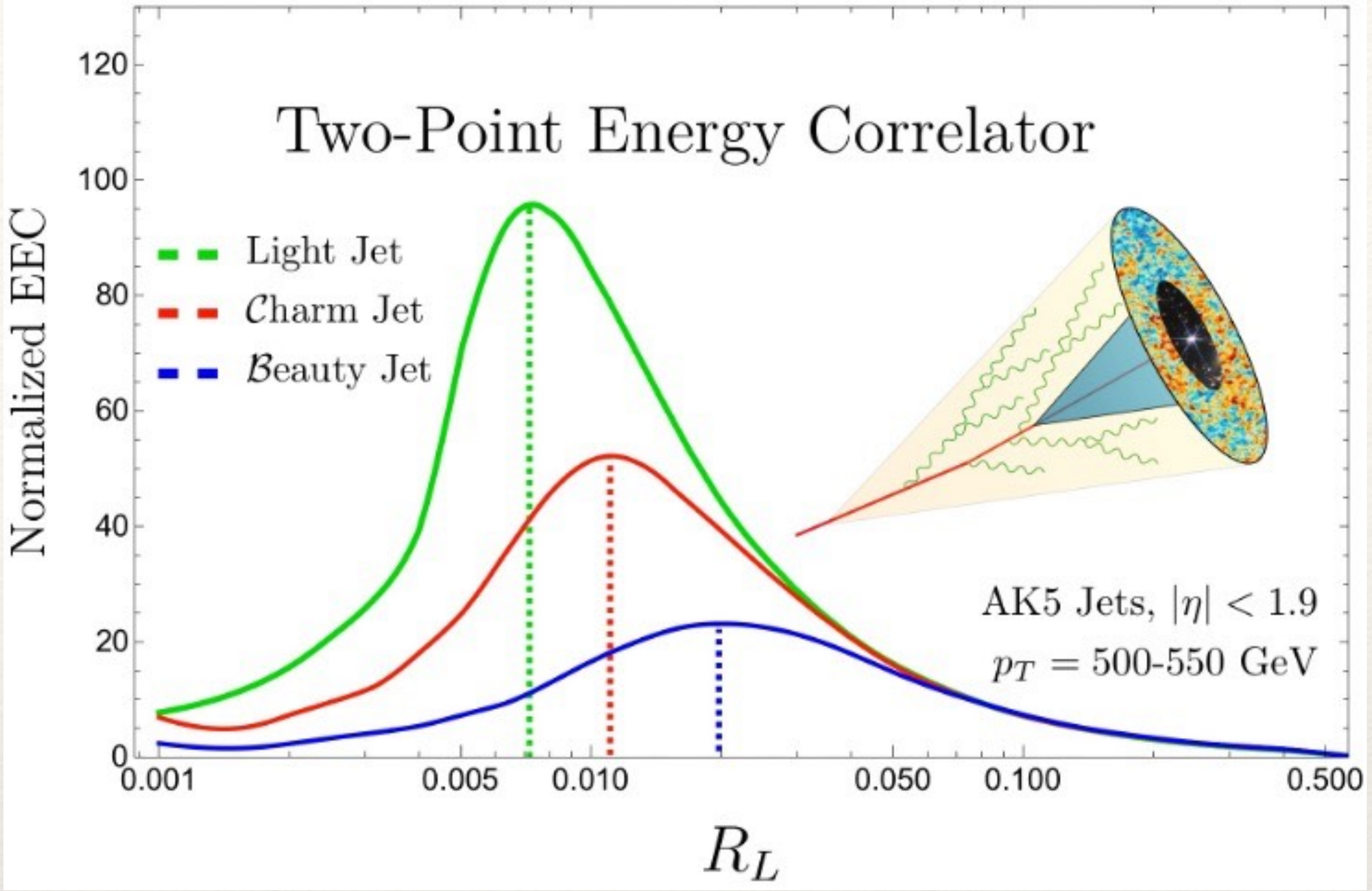


[Dang, SC, Xing, and Qin, Nucl. Sci. Tech. 37 (2026) 210]

Substructures of jets: energy-energy correlator (EEC)



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



[Craft et. al., PRD 114 (2026) L031501]

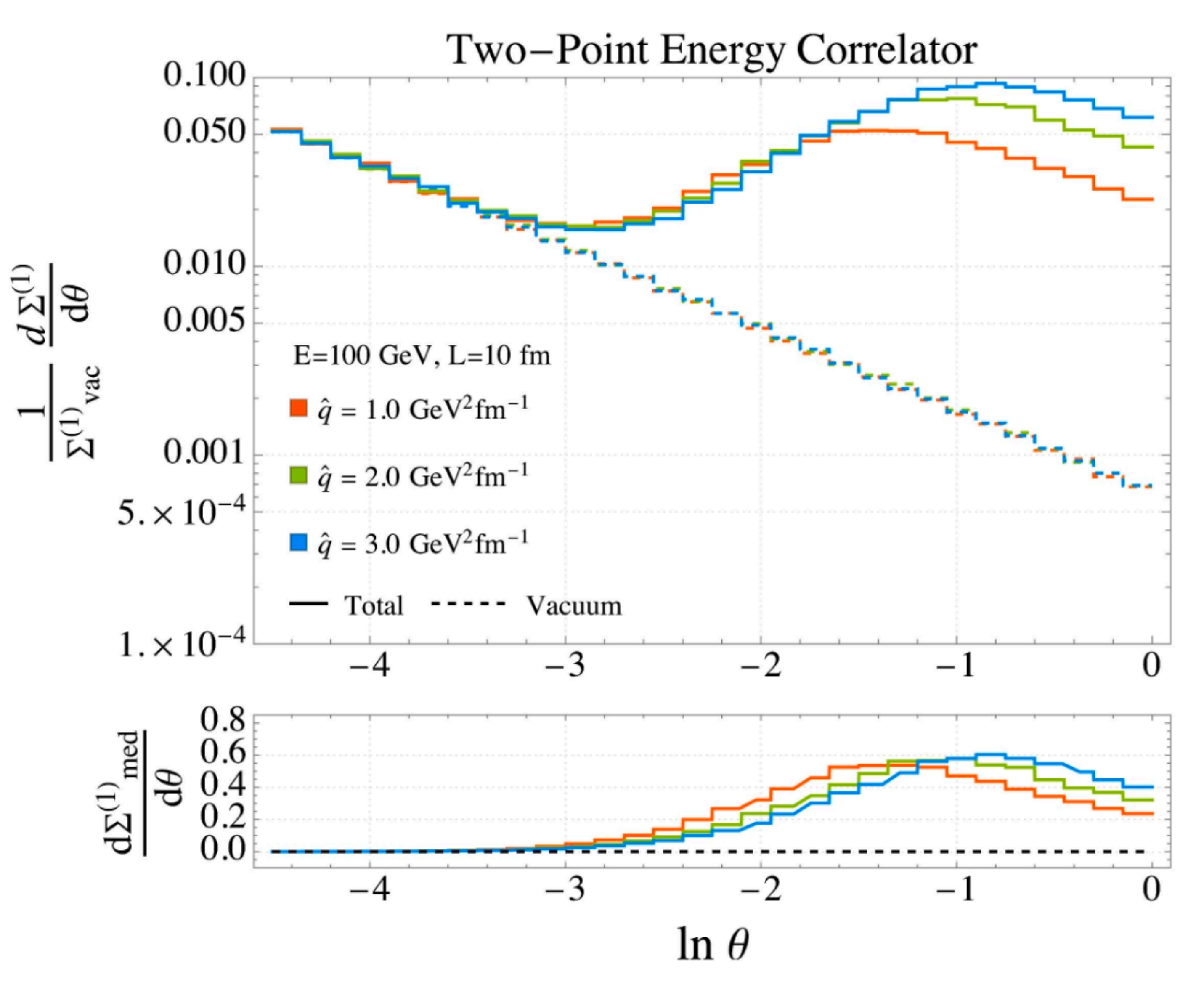
- EEC: $$\frac{d\Sigma}{dR_L} = \int d\vec{n}_1 d\vec{n}_2 \frac{\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle}{Q^2}\delta(\Delta R_{12} - R_L)$$

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

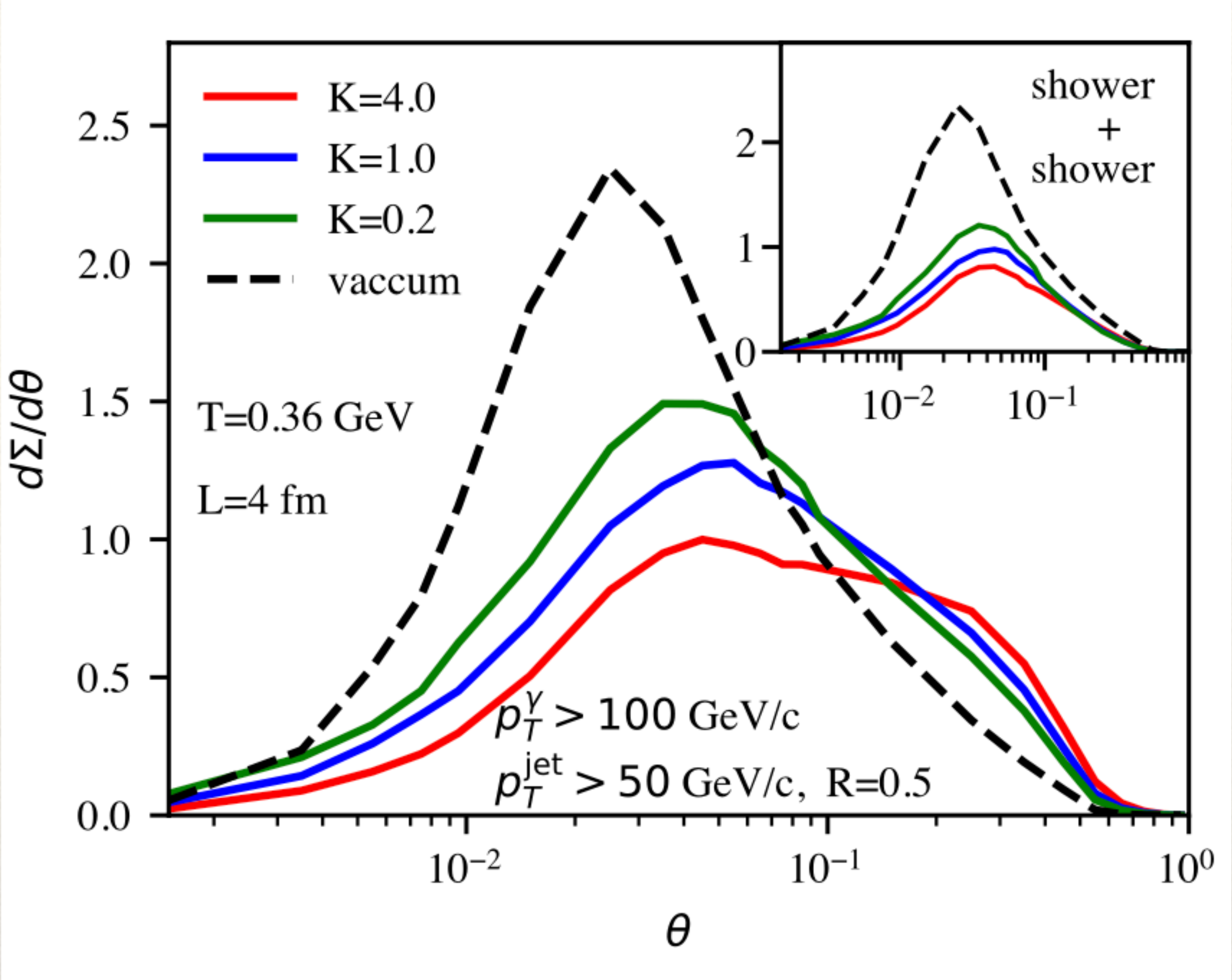
$\Delta R_{12} = \sqrt{\Delta\phi_{12}^2 + \Delta\eta_{12}^2}$: relative angle, Q: hard scale

- EEC of jets presents a clear angular scale separation between perturbative and non-perturbative (e.g. hadronization) regions in *pp* collisions
- EEC can also reveal the flavor dependence of splitting angles of partons in *pp* collisions

EEC in heavy-ion collisions



[Andres et. al., PRL 130 (2023) 262301]



[Yang, He, Moult, Wang, PRL 132 (2024) 011901]

- New scales emerge inside QGP
- $\tau_f^{vac} < L \;\rightarrow\; \theta > \theta_L \sim (EL)^{-1/2}$
  medium affects vacuum splitting
- $\tau_f^{med} < L \;\rightarrow\; \theta > \theta_c \sim (\hat{q}L^3)^{-1/2}$
  medium-induced splitting occurs

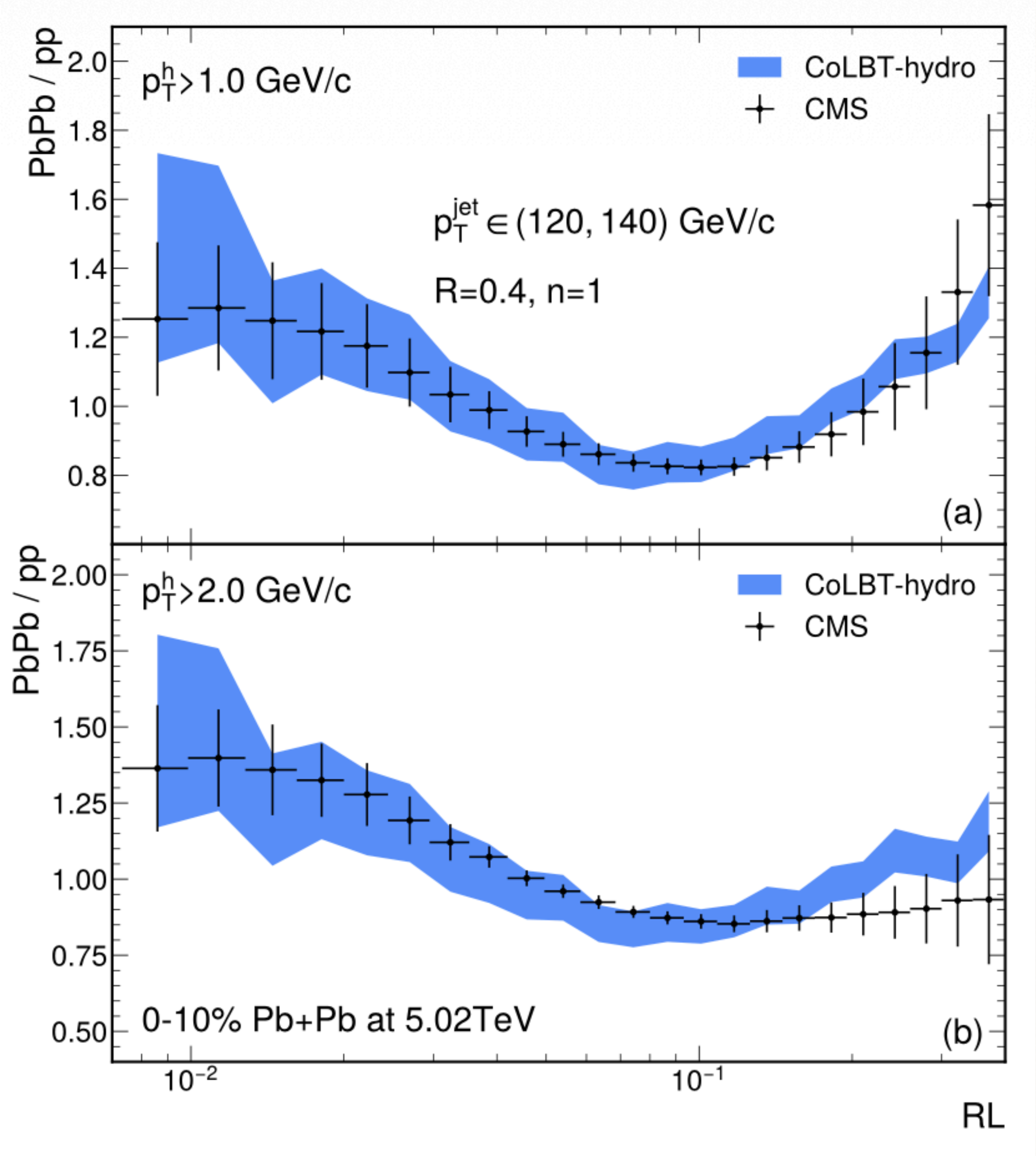
- Different features between analytical estimation and realistic simulation
- Sensitivity of EEC to short-distance structure of the QGP (μ_D quantified by K)
- Enhancement at large θ by medium response

Towards precise description of medium-modified EEC

Many studies on hot and cold nuclear matter effects

- Andres et. al., PRL 130 (2023) 262301
- Yang, He, Moult, Wang, PRL 132 (2024) 011901
- Xing, SC, Qin, Wang, PRL 134 (2025) 052301
- Andres et. al., PRL 134 (2025) 082303
- Barata, Kang, Lopez, Penttala, PRL 134 (2025) 251903
- Fu, Muller, Sirimanna, PRL 135 (2025) 112302
- Andres el. at., PRL 136 (2026) 122301
- Barata, Moult, Sadofyev, Silva, PRL 137 (2026) 052302

…



A quantitative description of the jet EEC in heavy-ion collisions has only been achieved very recently.

- By coupling the improved multi-stage LBT model into the CoLBT-hydro model.

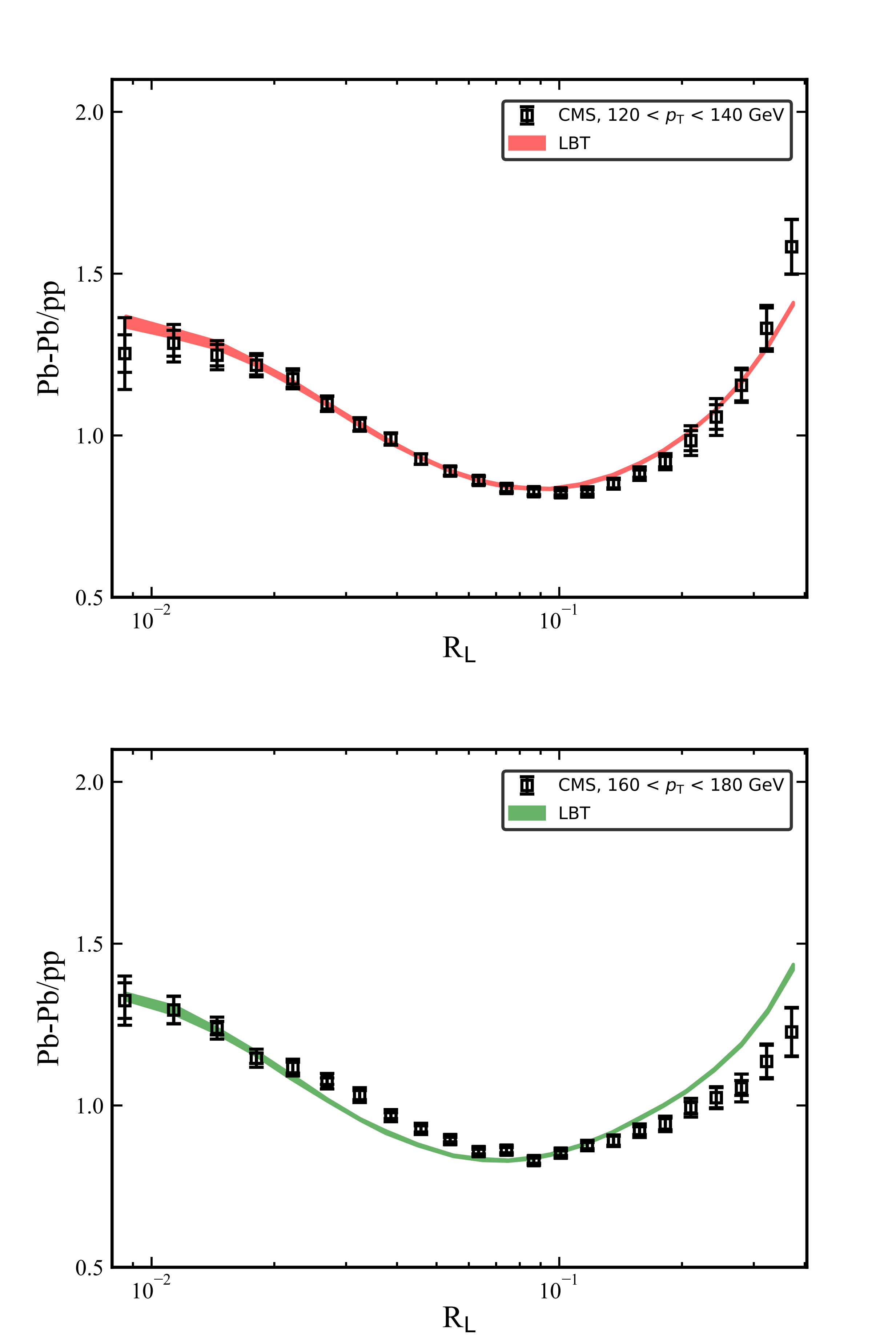
[Yang, Kunnawalkam Elayavalli, Wang, arXiv:2605.28788]

Description and prediction of the jet EEC in LBT

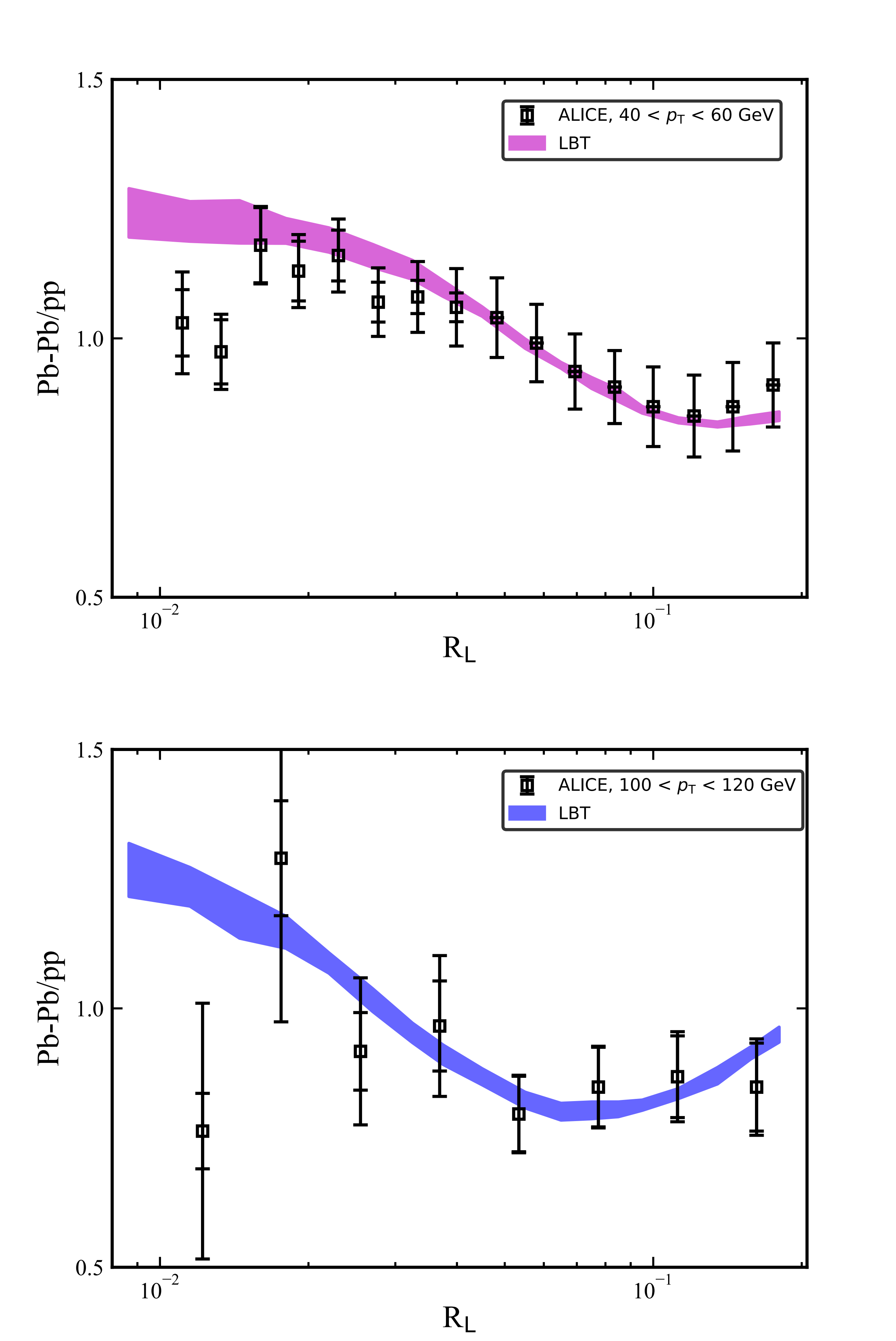
lower jet p_T

higher jet p_T

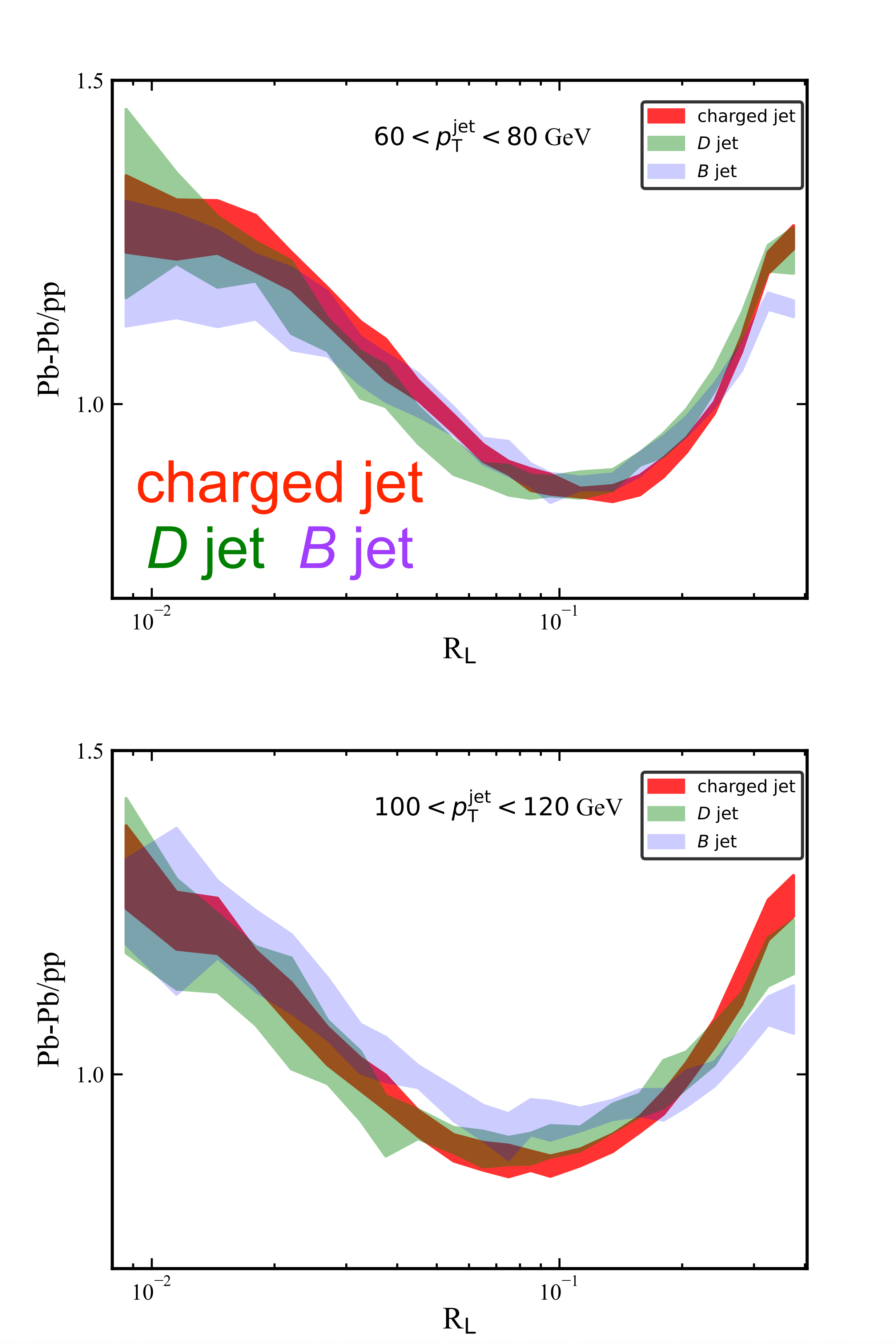
CMS charged jets



ALICE charged jets



Prediction for heavy-flavor jets

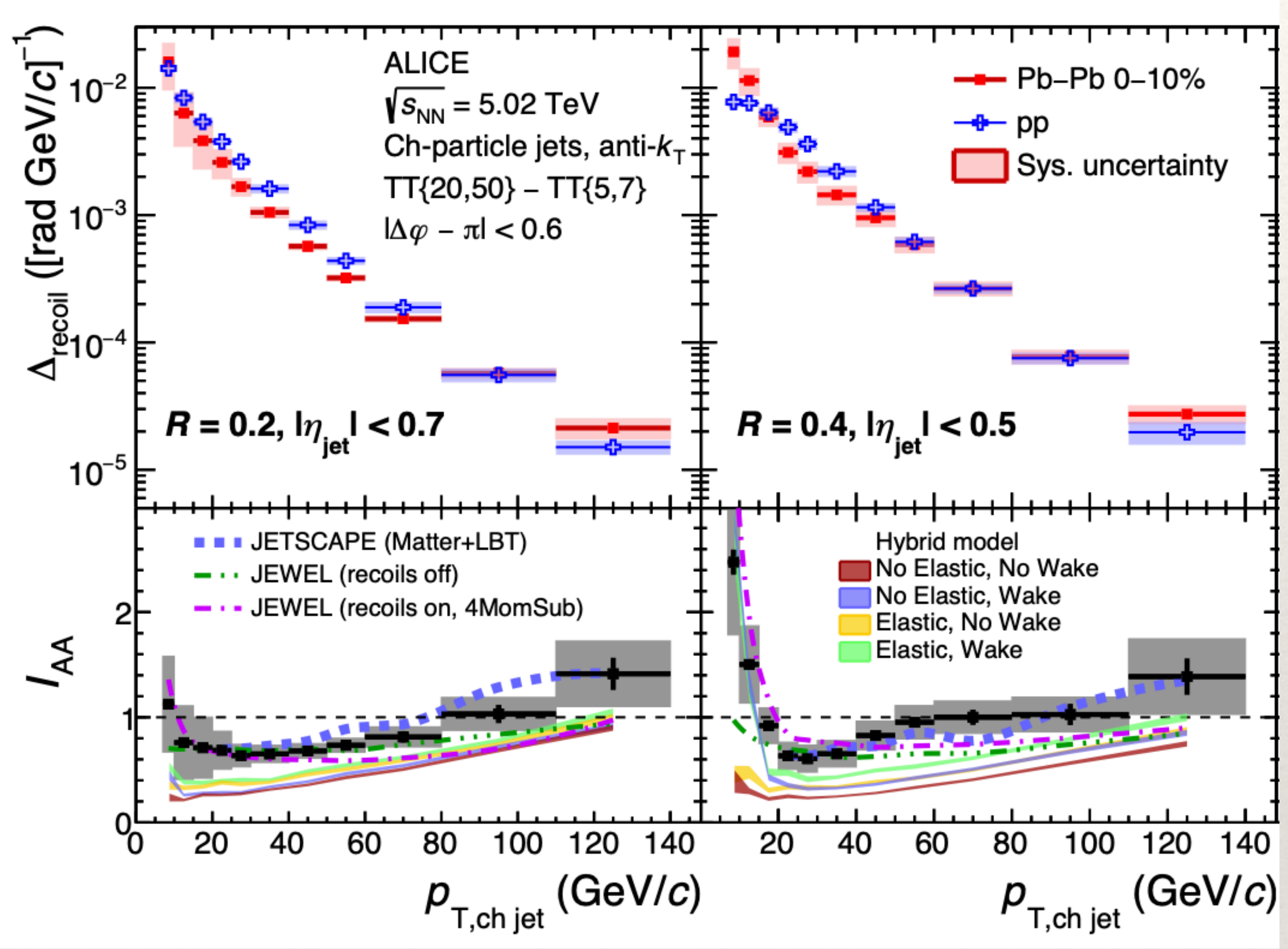


[Xing, SC, Qin, in preparation]

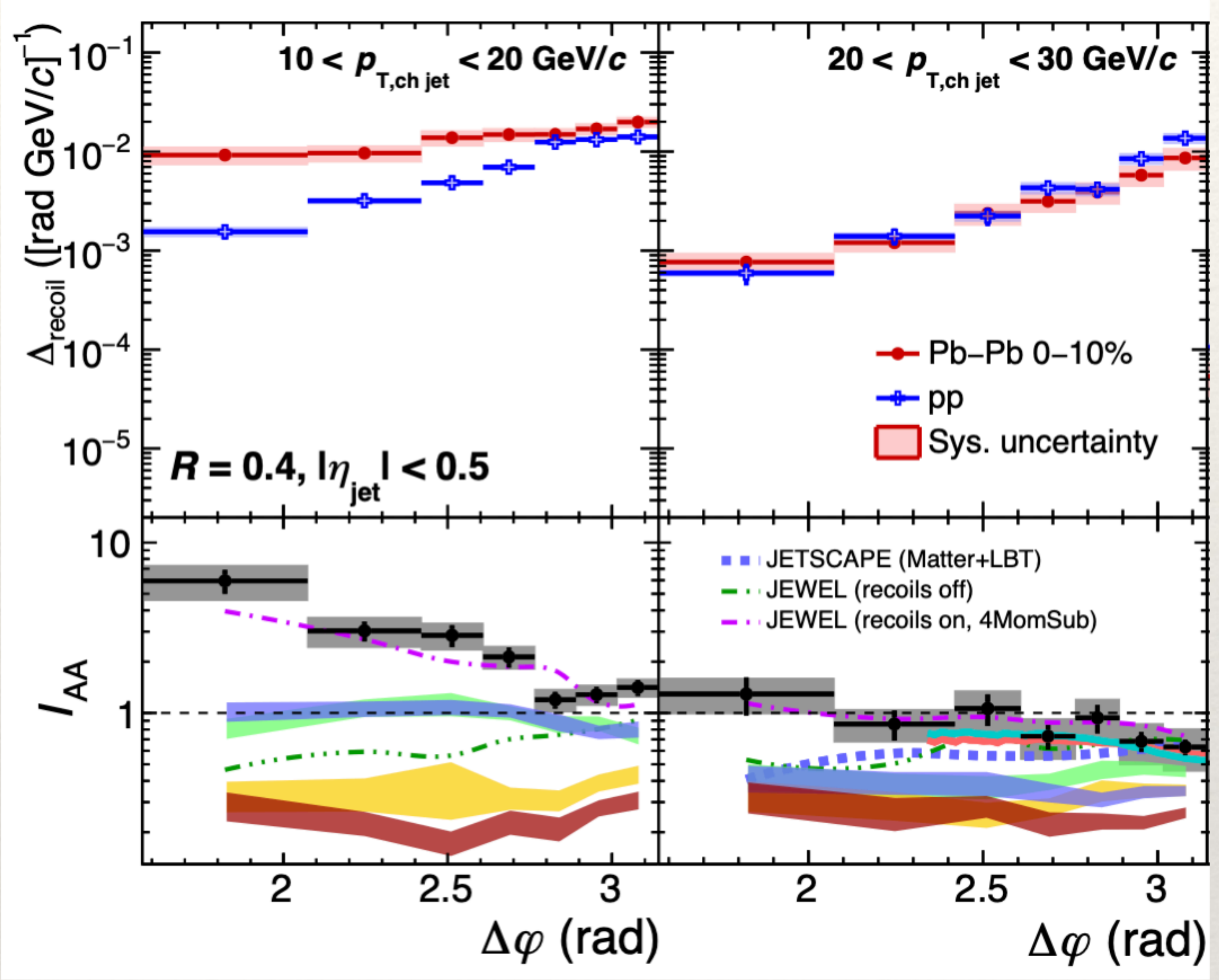
From hadrons and jets to hadron-triggered jets

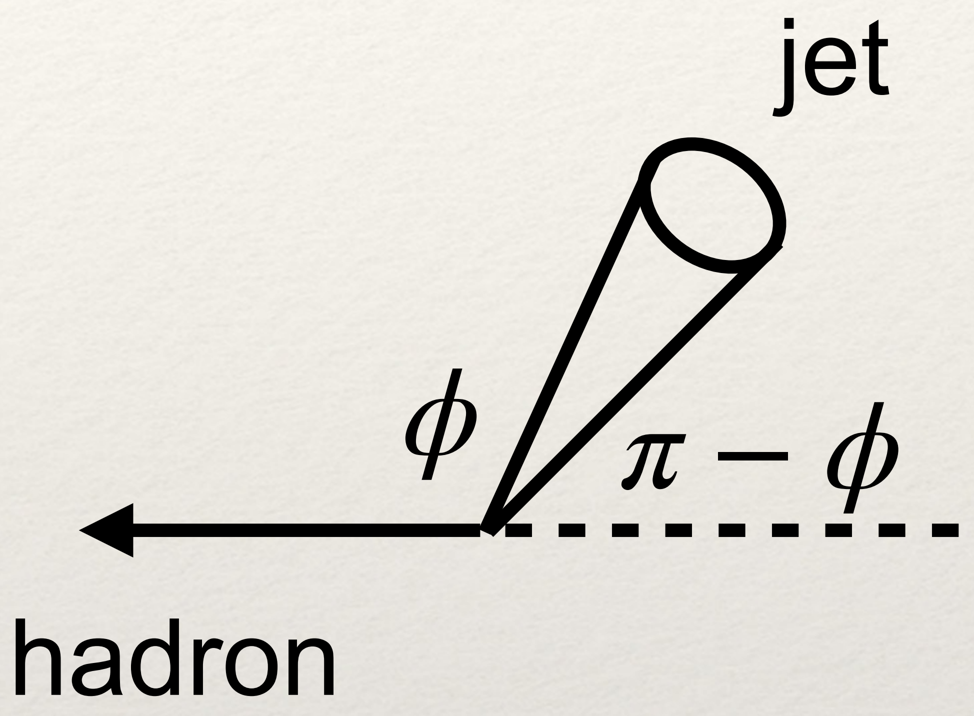
Puzzling observation of the *h*-jet I_{AA}

I_{AA} vs. $p_{T,\,\mathrm{jet}}$



I_{AA} vs. $\Delta\phi$

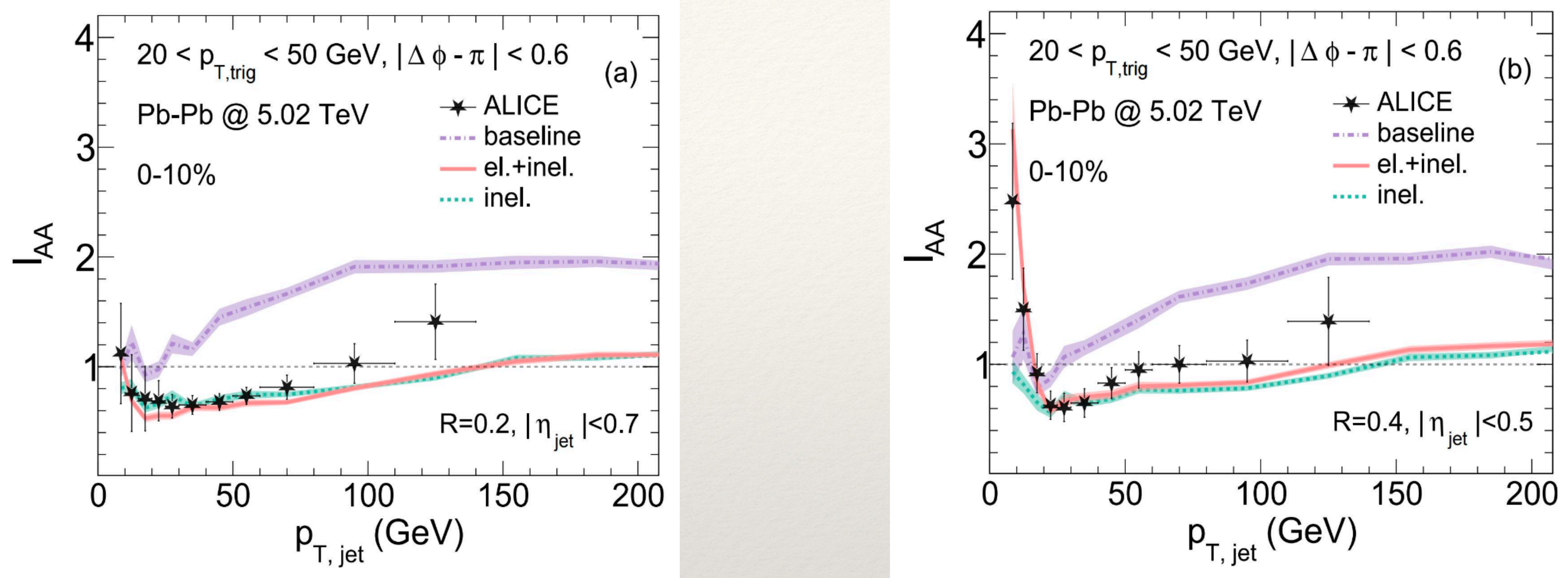




[ALICE, Phys. Rev. Lett. 133 (2024) 022301]

- No existing model can quantitatively describe both data
- No qualitative explanation of the enhancement at large $\pi - \phi$, and its disappearance for jets with small R or high p_T

Semi-inclusive hadron-triggered jets



[Jing, Dang, Zhang, He, SC, Yi, Wang, arXiv:2512.12715, accepted by PRL]

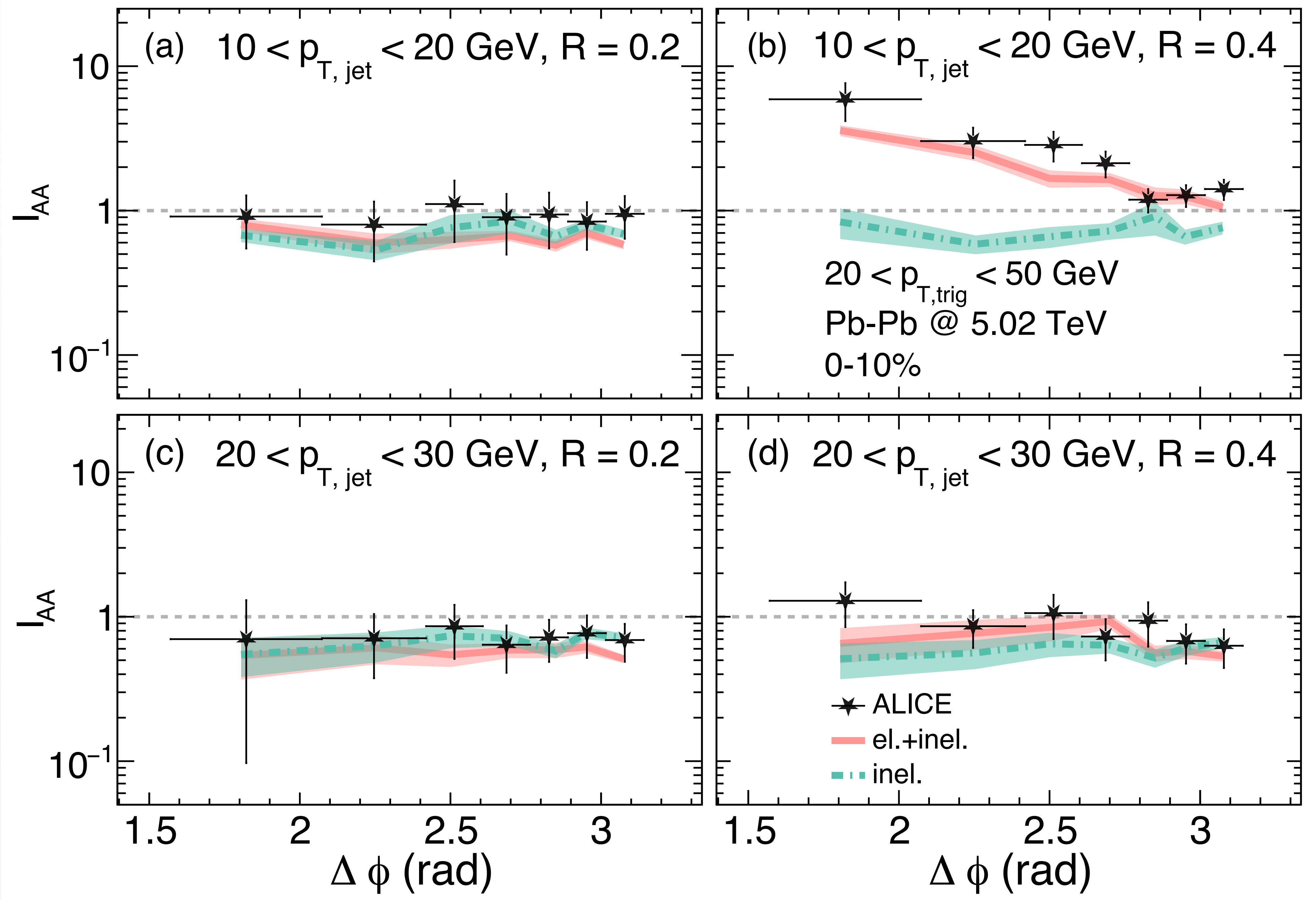
- Simultaneous description of hadron and jet is crucial for understanding hadron-triggered jets
- Enhancement at low $p_{\mathrm{T,jet}}$: medium response
- Enhancement at high $p_{\mathrm{T,jet}}$: enhancement of I_{AA} baseline by trigger bias

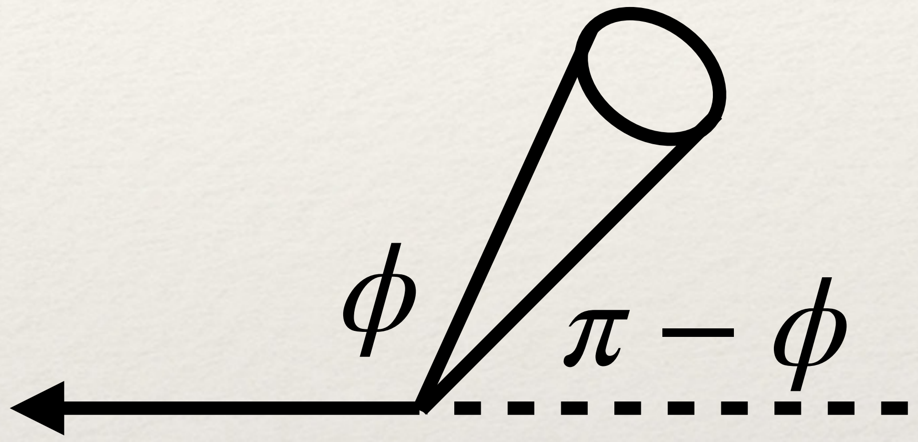
Acoplanarity of *h*-jets

$R = 0.2$ $R = 0.4$

$10 < p_{T,jet} < 20$ GeV

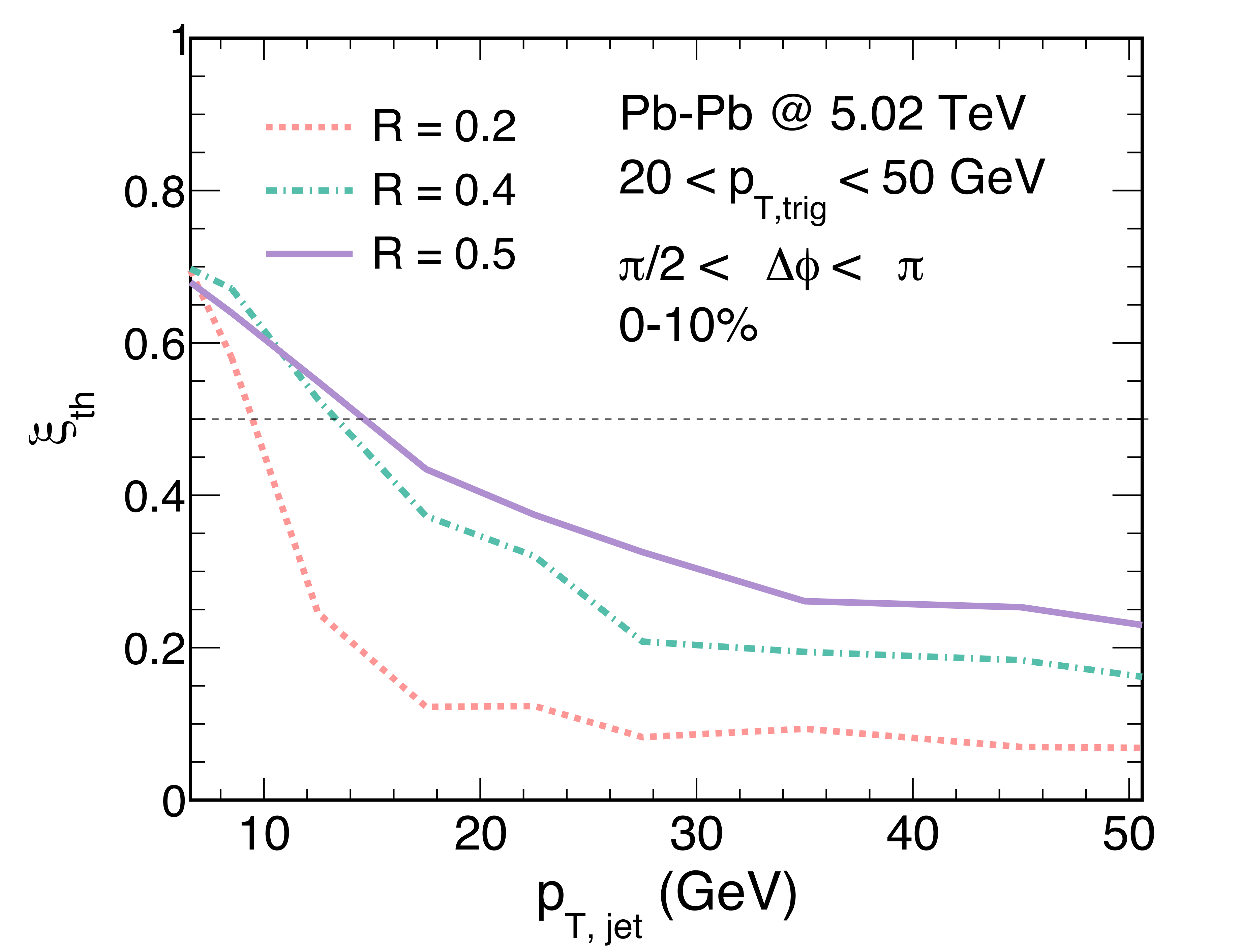
$10 < p_{T,jet} < 20$ GeV

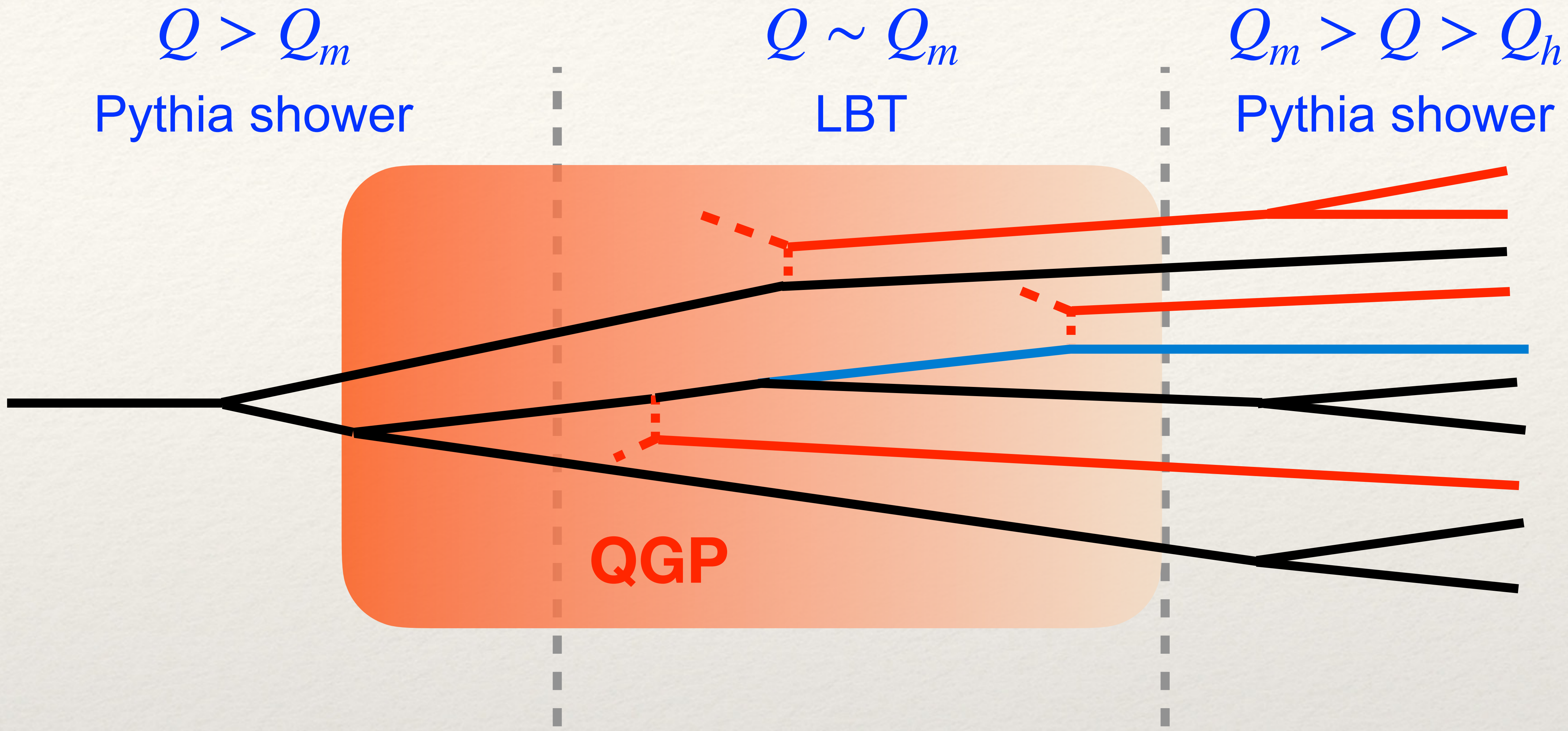




- Enhancement of I_{AA} at large $\pi - \phi$ for jets with large *R* and low $p_{T,jet}$, medium response.
- Enhancement disappears for small *R* or high $p_{T,jet}$. Why?

Thermal origin of the enhanced jet yields

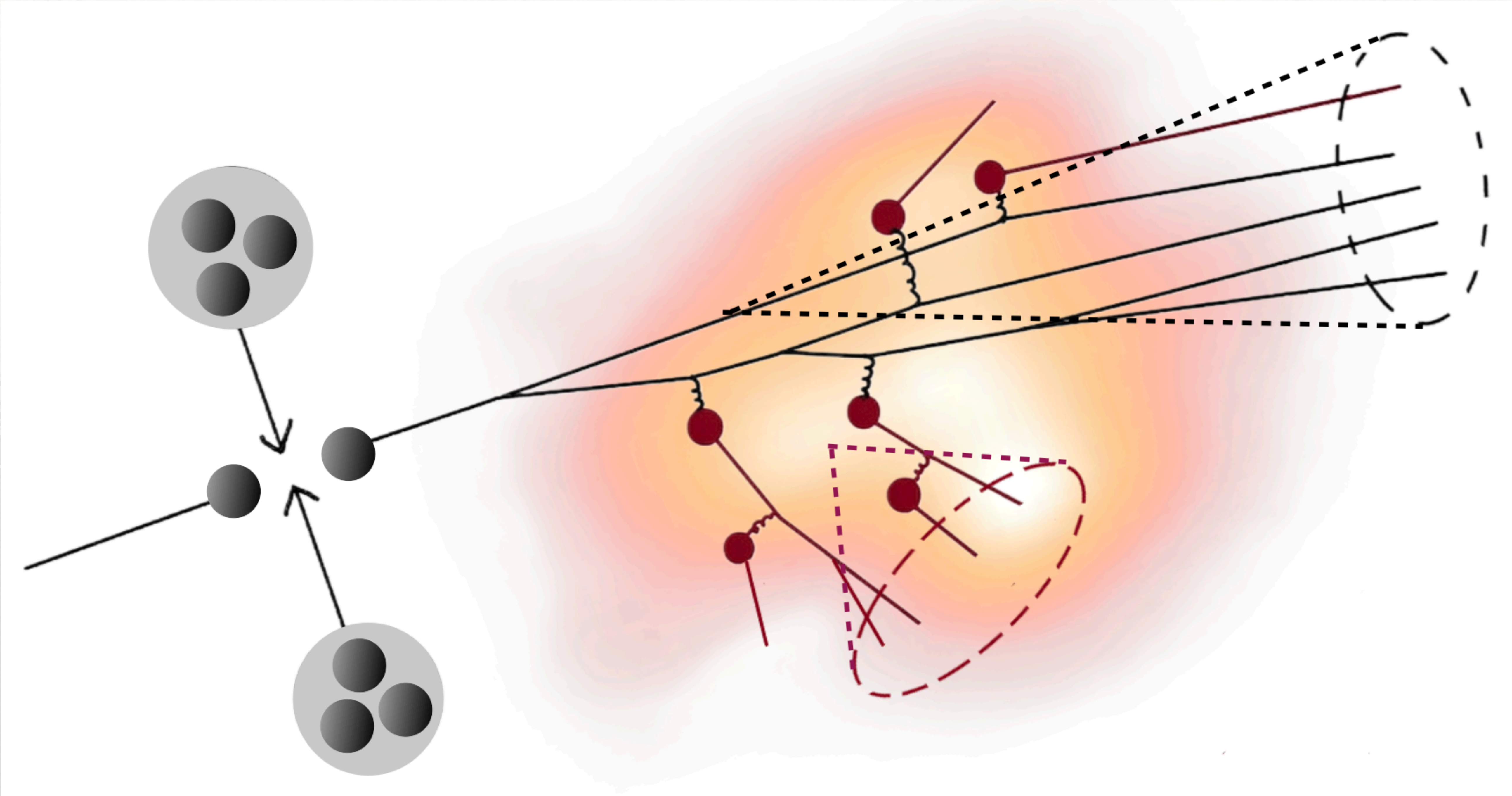




$$\xi_{\mathrm{th}} = \frac{|\vec{p}_{\mathrm{T}}^{\,\mathrm{recoil}} - \vec{p}_{\mathrm{T}}^{\,\mathrm{negative}}|}{|\vec{p}_{\mathrm{T}}^{\,\mathrm{recoil}} - \vec{p}_{\mathrm{T}}^{\,\mathrm{negative}}| + p_{\mathrm{T}}^{\mathrm{jet-shower}}}$$

- Large fraction of jet energy from thermal particles scattered out by hard jets
- More prominent thermal fraction for jets with lower $p_{\mathrm{T,jet}}$ and larger R

Emergence of "thermal recoil jets"



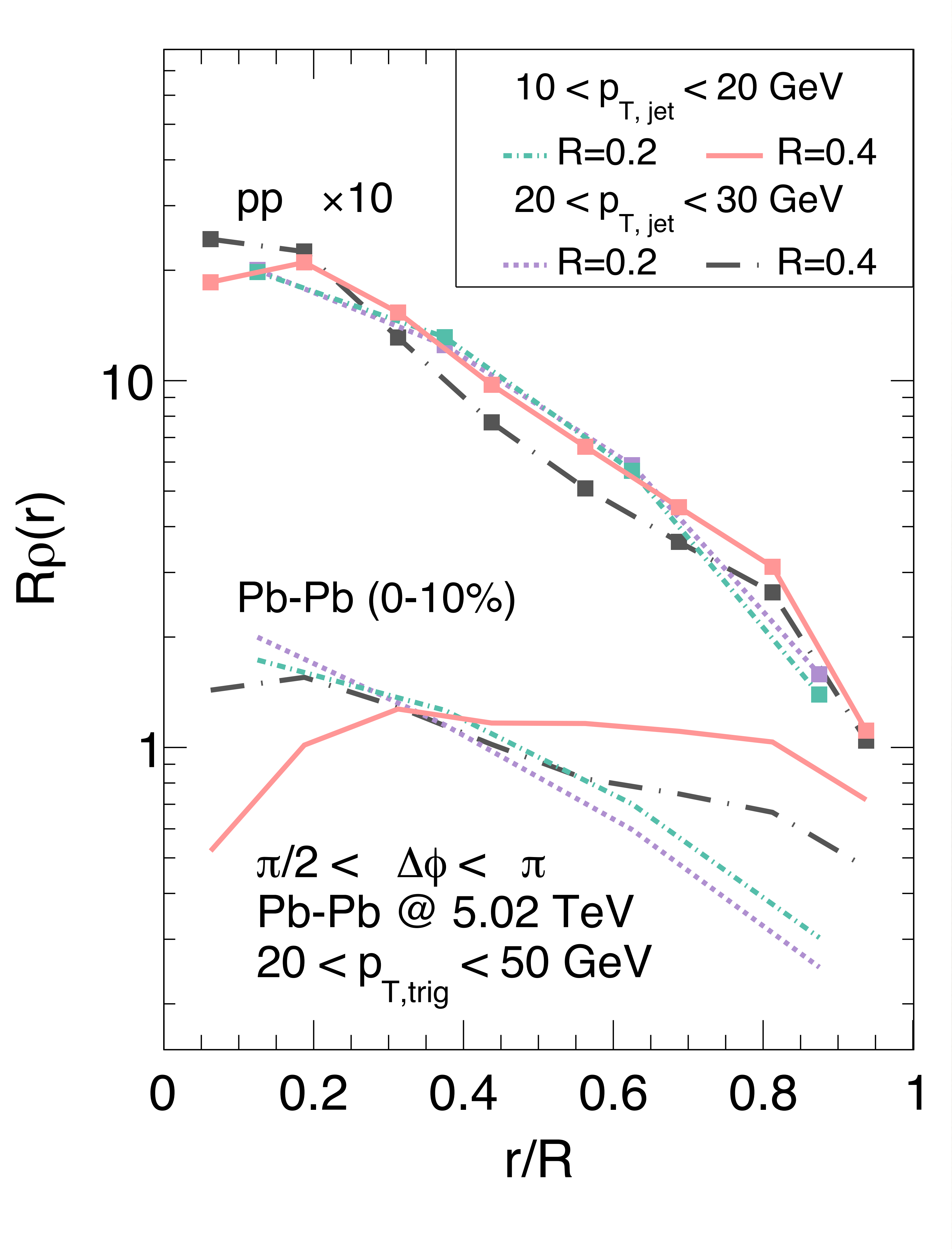
Hard jet

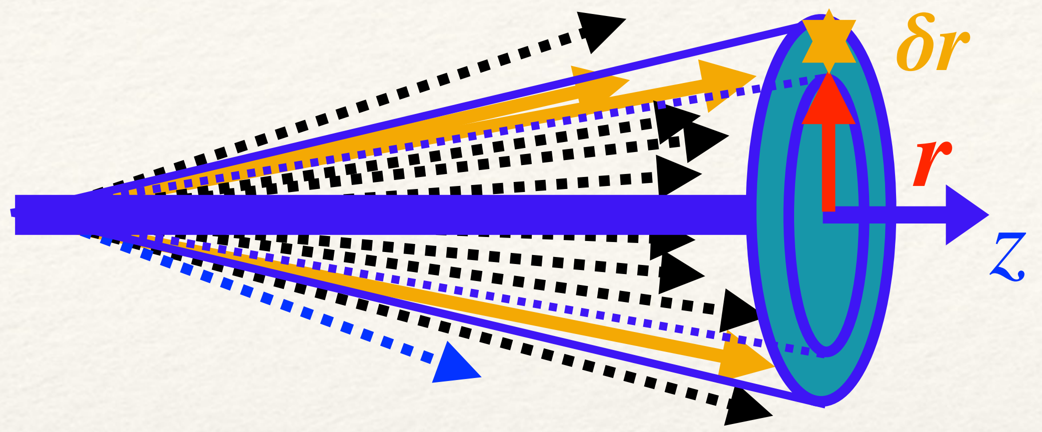
- Hard particles at the core, soft particles around

Thermal recoil jet

- Composed of soft particles sparsely distributed in the momentum space
- Require large R for reconstruction, only present at low jet p_T

Shapes of thermal recoil jets *vs.* hard jets





$$\rho(r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jet}\frac{\sum_{{\rm track}\in\left(r-\frac{\delta r}{2},\, r+\frac{\delta r}{2}\right)} p_{\rm T,track}}{p_{\rm T,jet}}$$

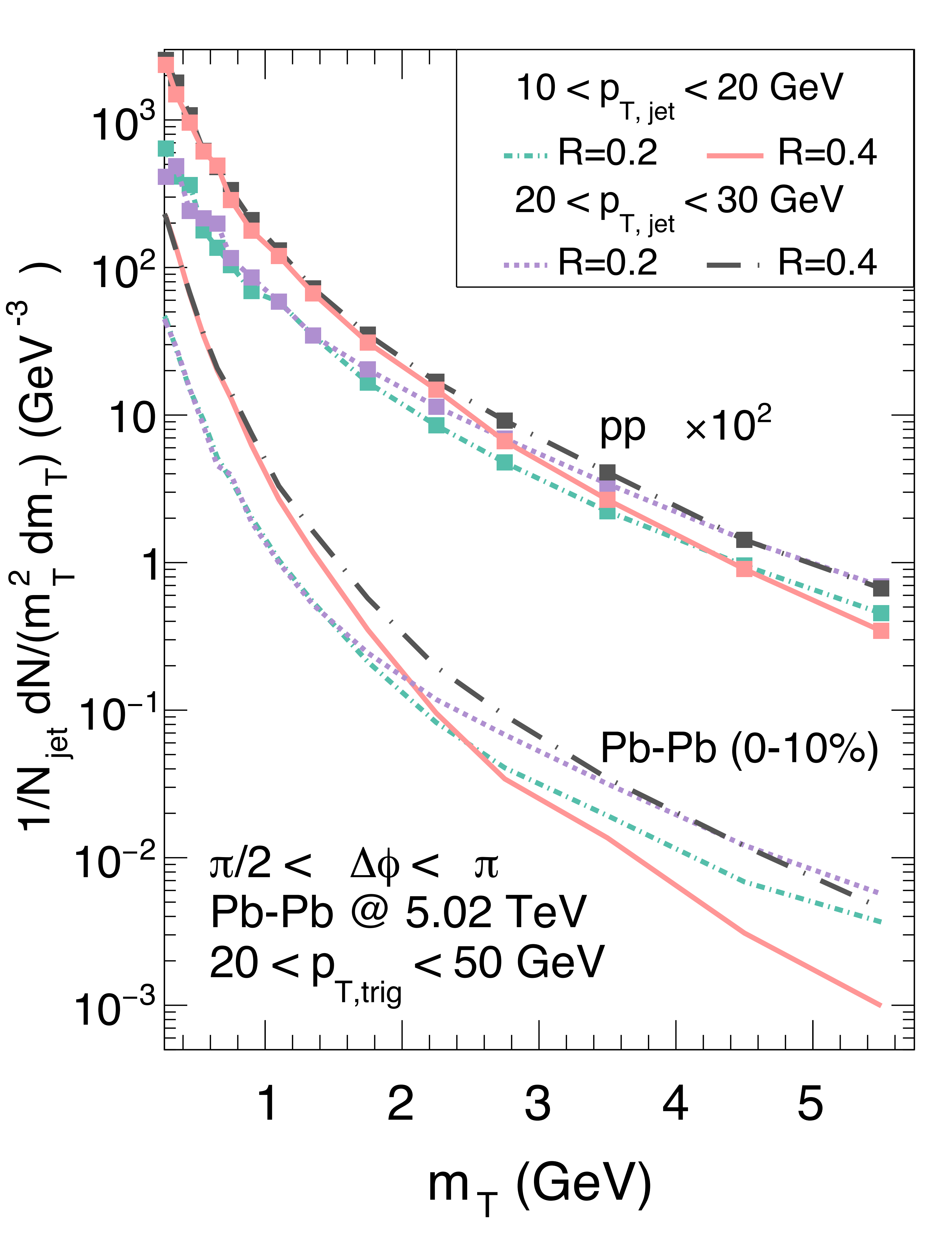
- Decreasing ρ with *r* for small cone-size (*R*) jet, similar to jets in *p*+*p* collisions

  — Feature of hard jet: energetic particles at jet core, soft particles at large *r*

- Increasing ρ with *r* for large *R* jet at low $p_{\rm T,jet}$

  — Feature of thermal recoil jet: soft particles sparsely distributed in the momentum space

m_T distributions of thermal recoil jets *vs.* hard jets

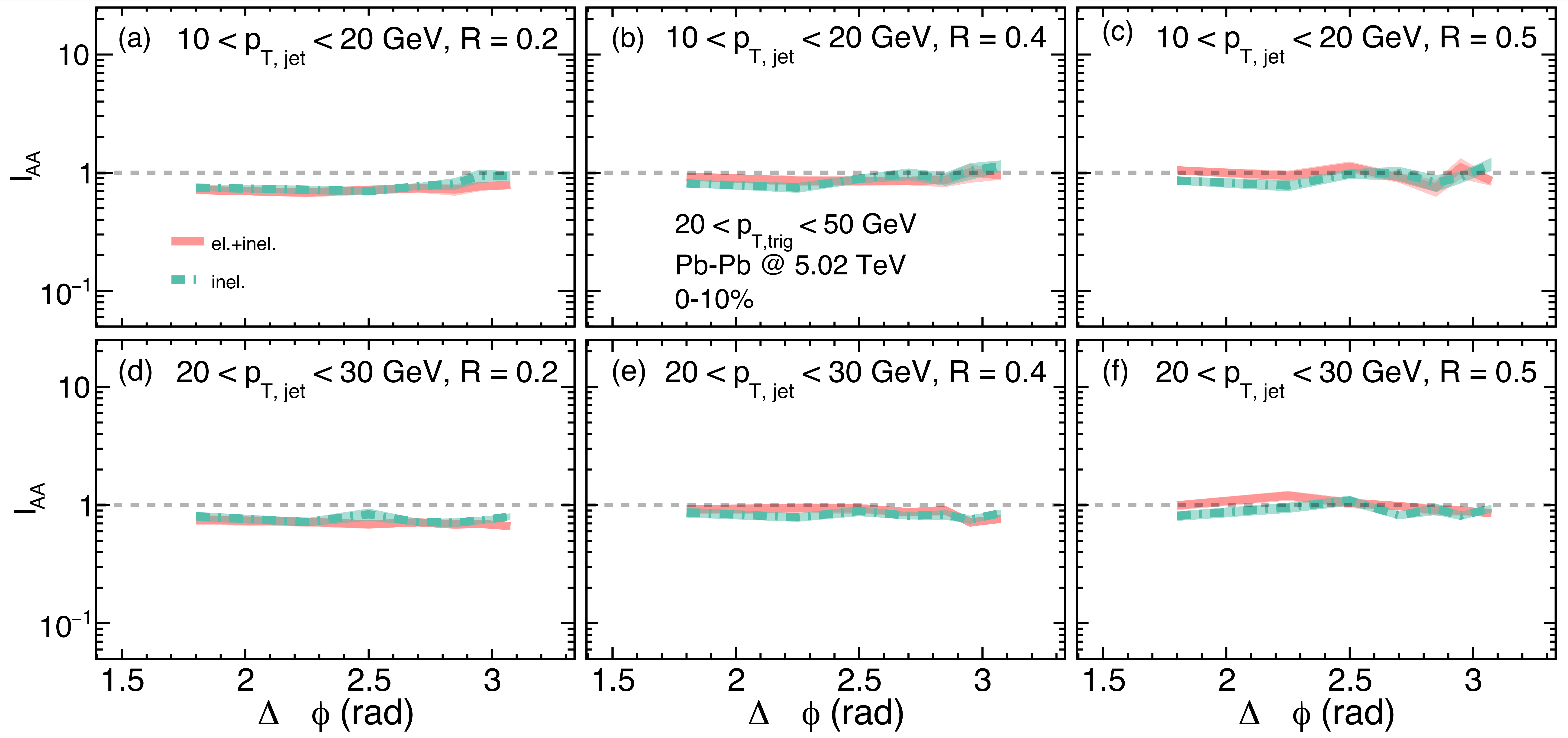


Thermal distribution:

$$\frac{1}{m_T^2}\frac{dN}{dm_T} \sim e^{-m_T/T_{\mathrm{eff}}}$$

- Power-law tail structures of m_T distributions of jet constituents at R = 0.2, similar to jets in p+p collisions
- Thermal-like distribution of jet constituents for R = 0.4 and $10 < p_{T,\mathrm{jet}} < 20$ GeV up to 2 GeV

Suppressing thermal recoil jets by heavy quark tags

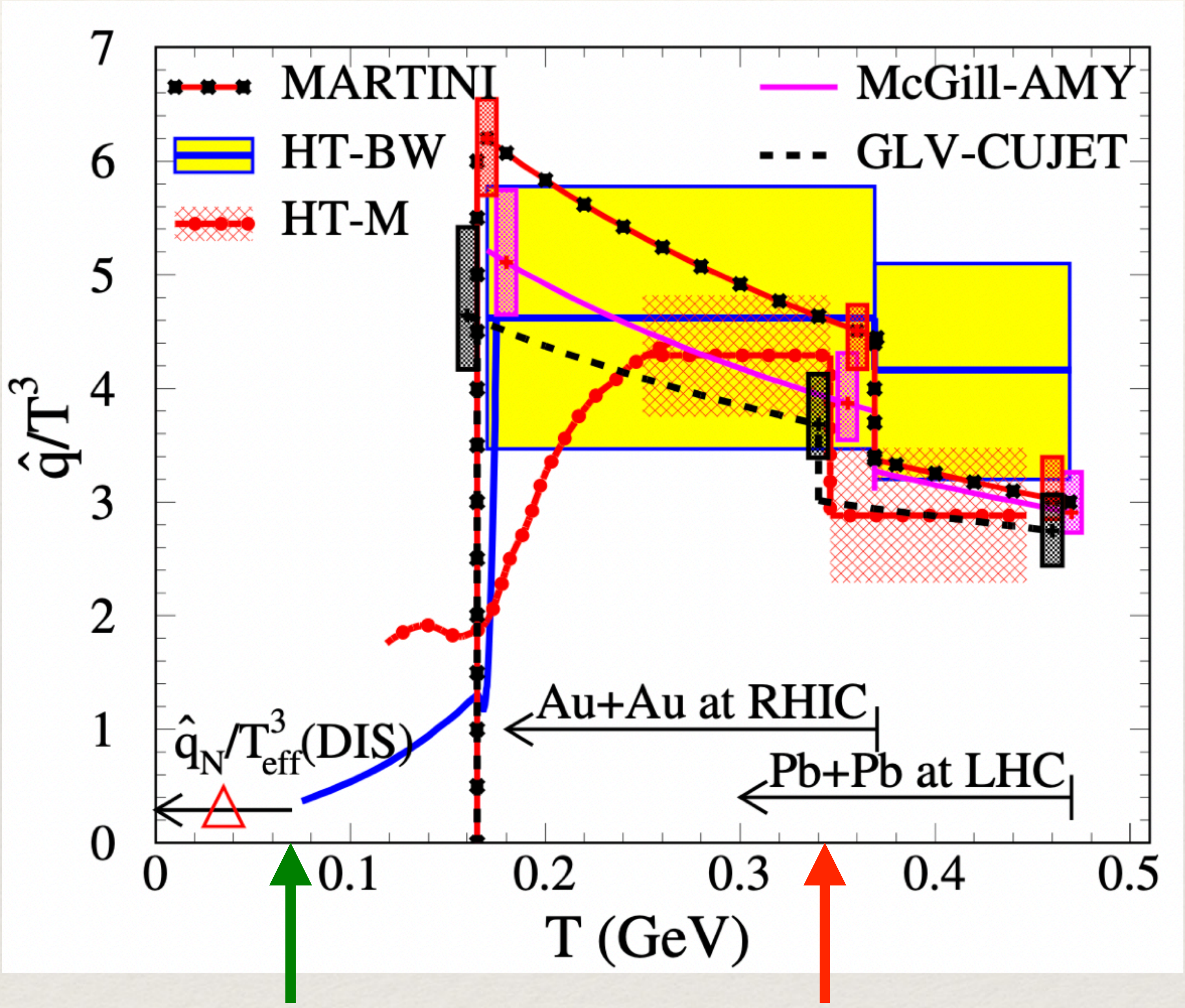


- Heavy quarks ($M_c = 1.3$ GeV $> T_{\mathrm{QGP}}$) are mainly produced by initial hard partonic scatterings
- The requirement for jets to contain heavy quarks filters out thermal recoil jets
- If confirmed, further support the concept of thermal recoil jet in *h*-jet acoplanarity enhancement

From studying jets to using jets to probe the QGP

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

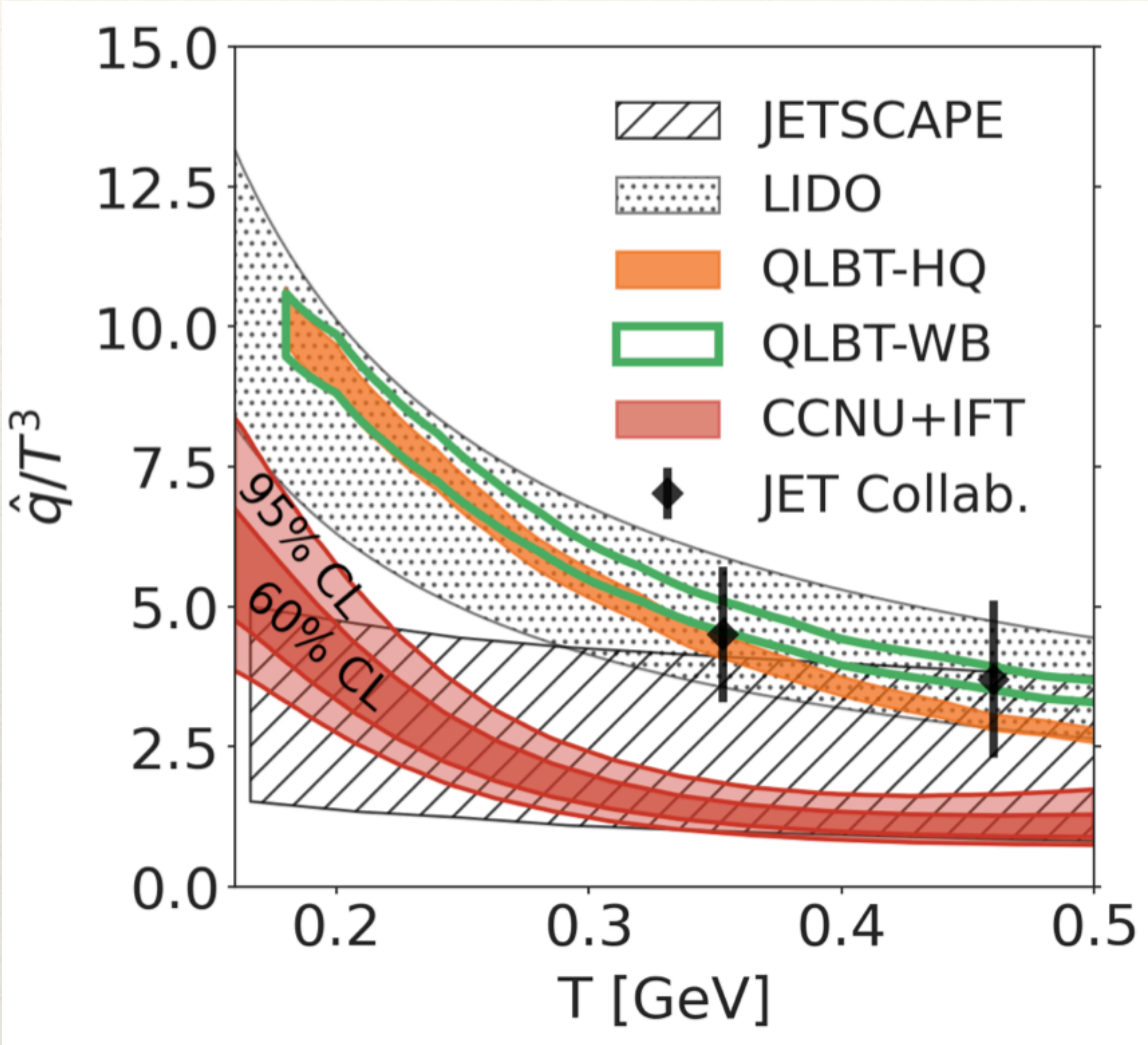
[JET, Phys. Rev. C 90 (2014) 1, 014909]



nucleus ≪ 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

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

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

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

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

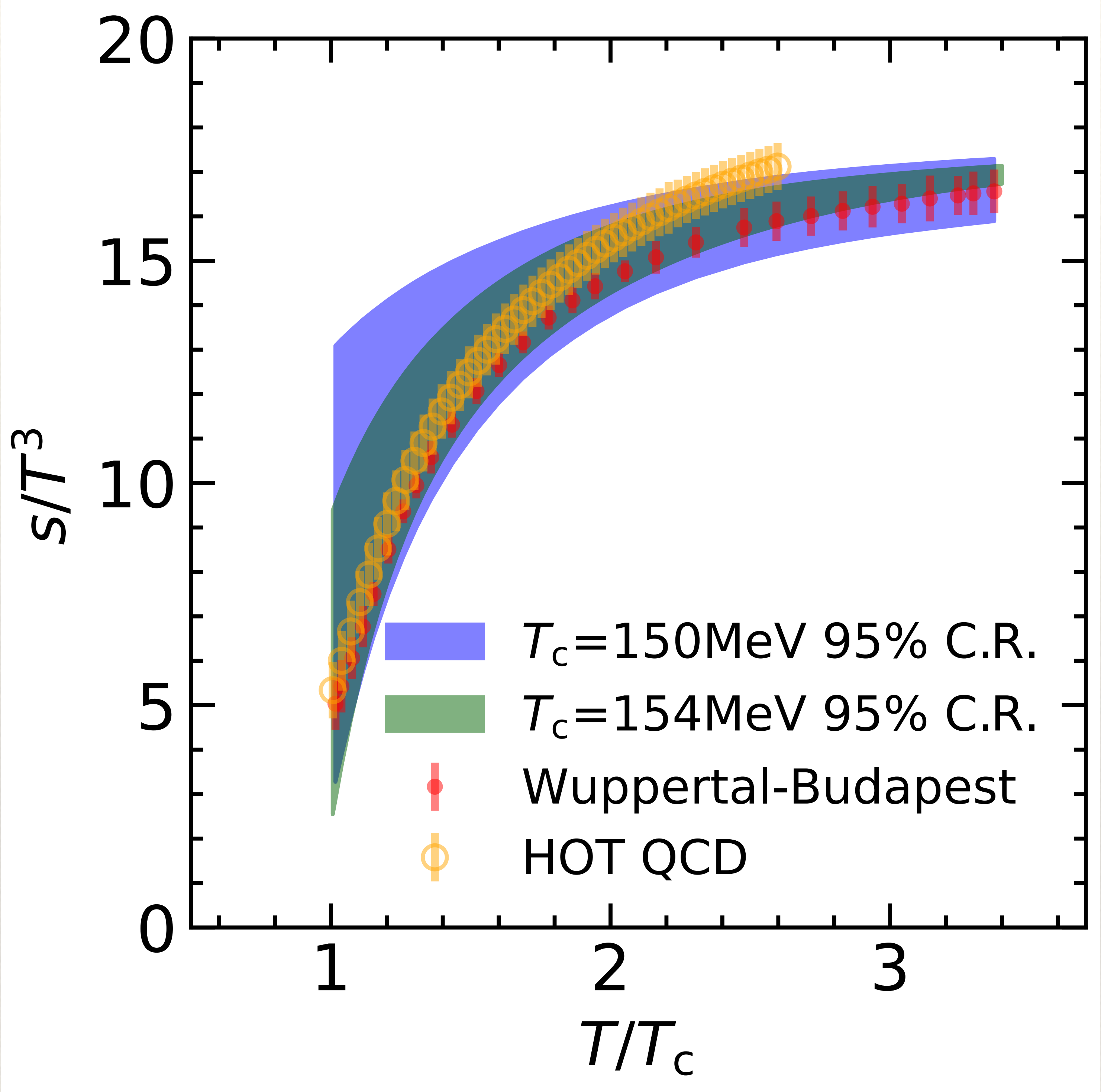
Strategy:

Fit g from comparing transport model to data

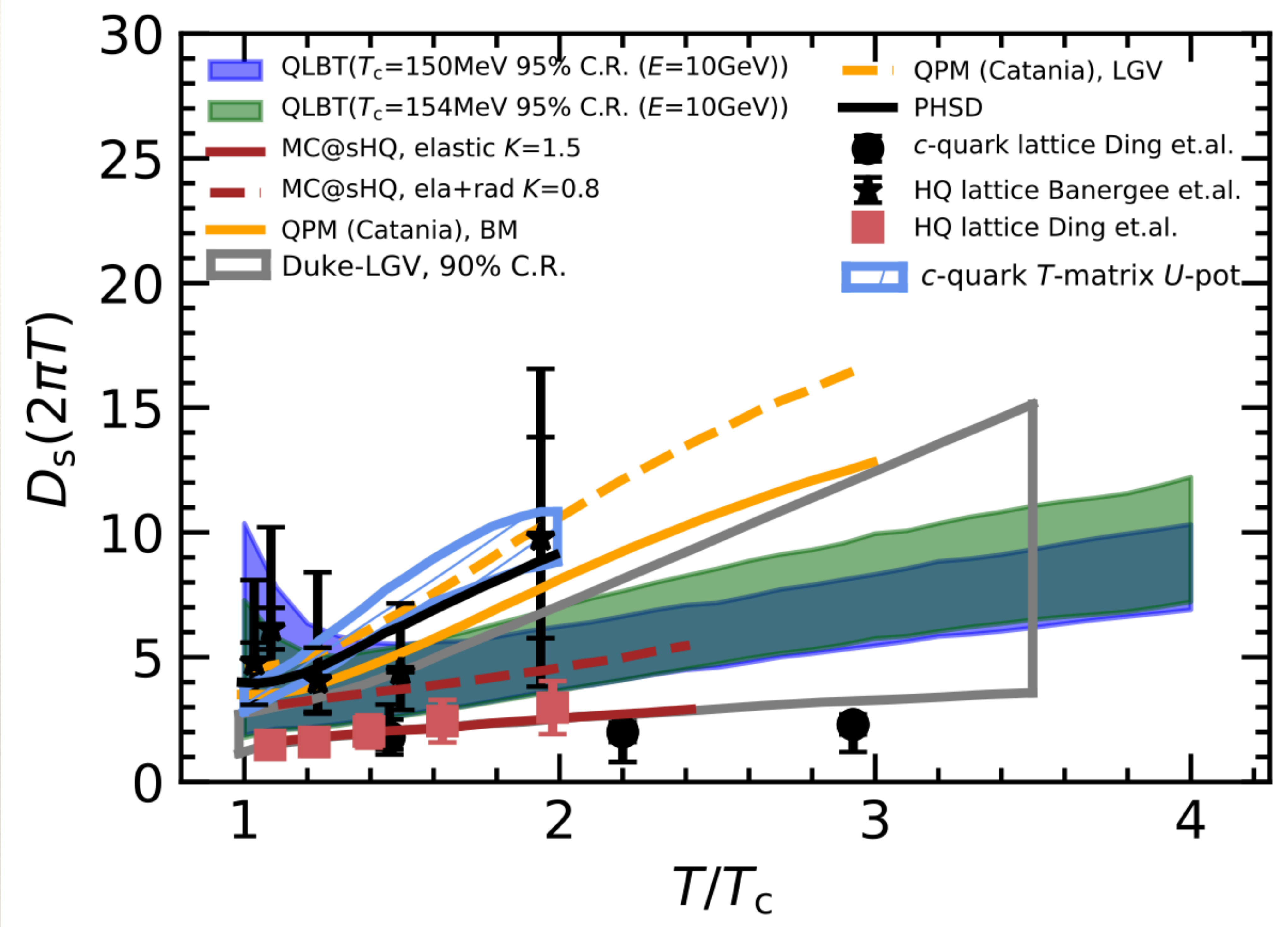
Calculate EoS from g

EoS of QGP and diffusion coefficient of heavy quarks

Equation of state

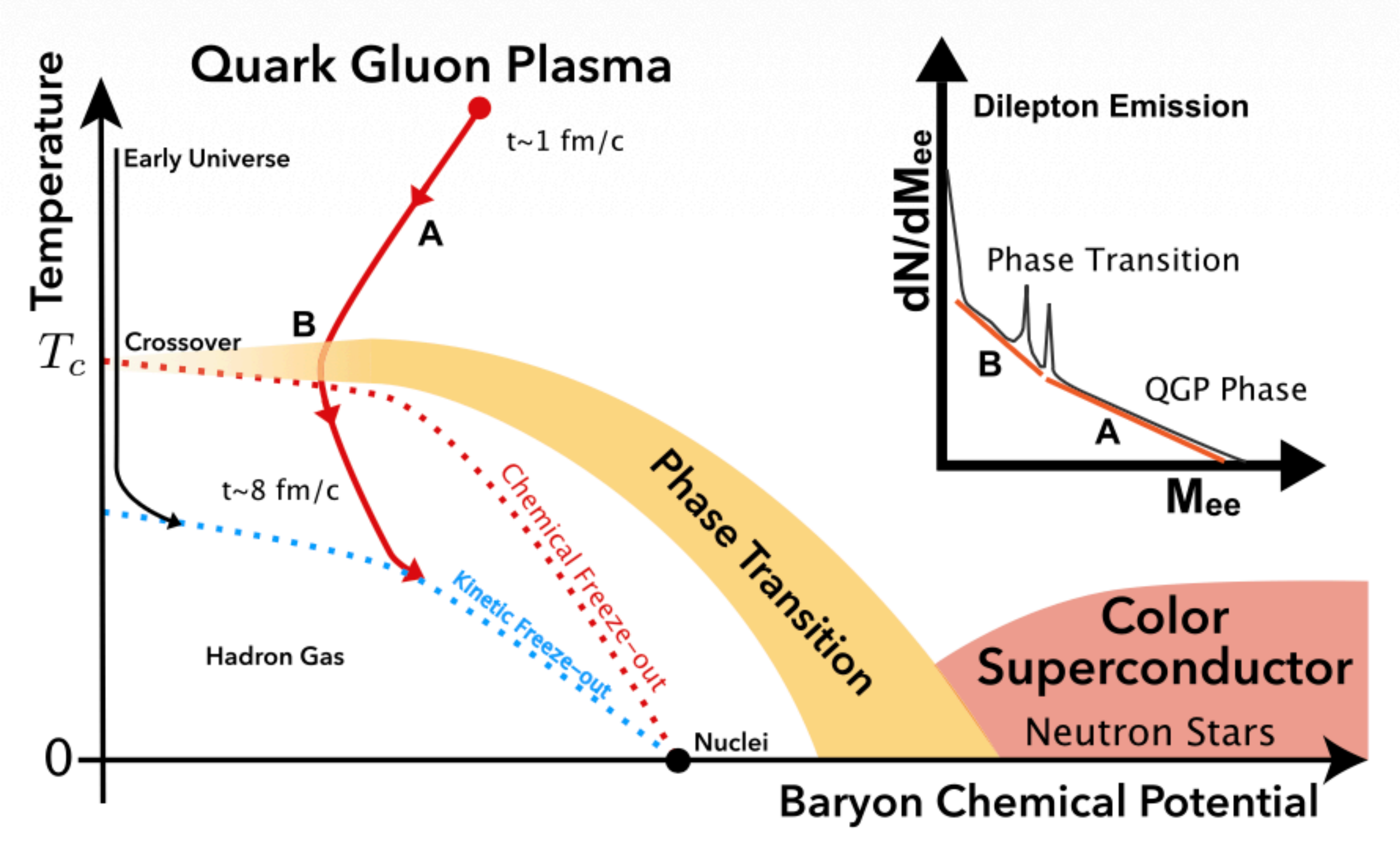


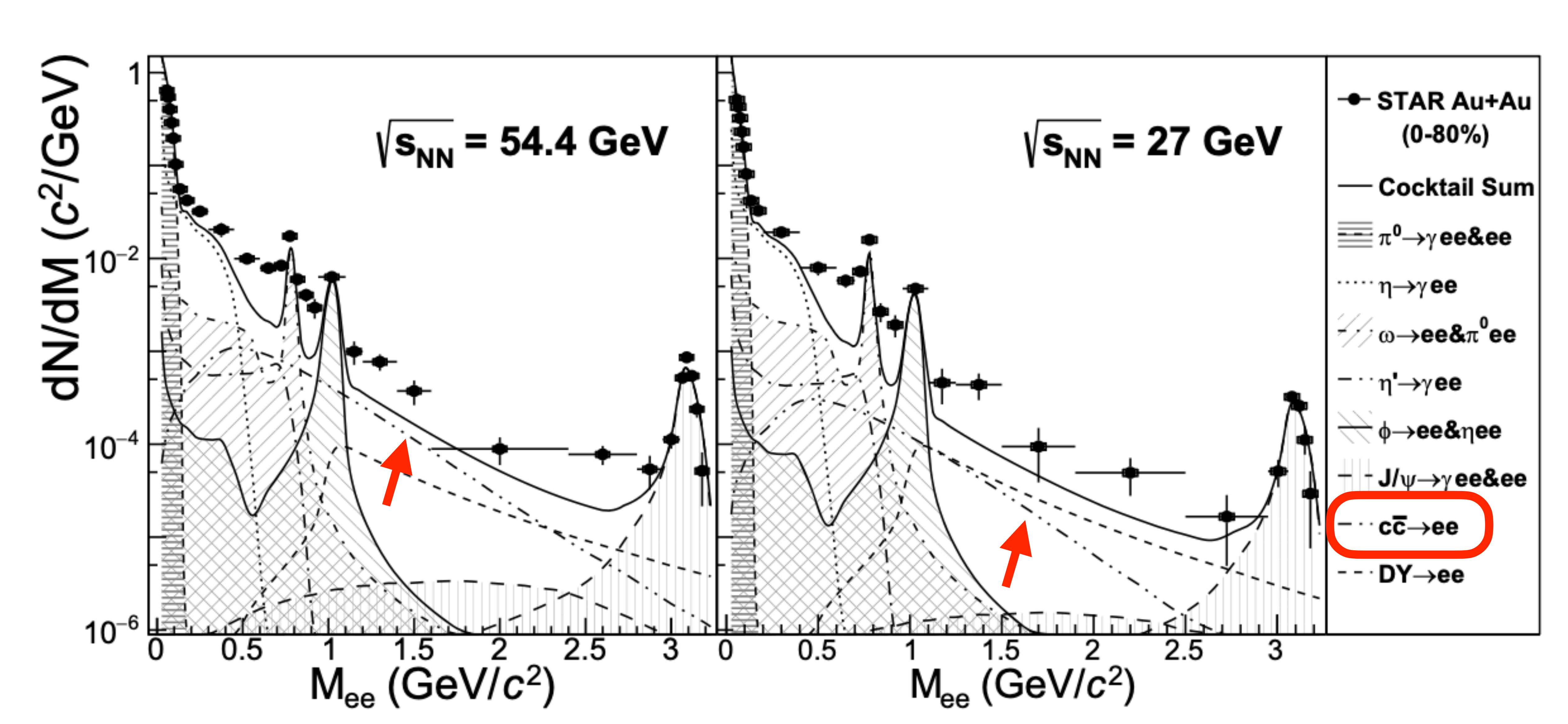
Diffusion coefficient



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

More precise constraint on the QGP temperature



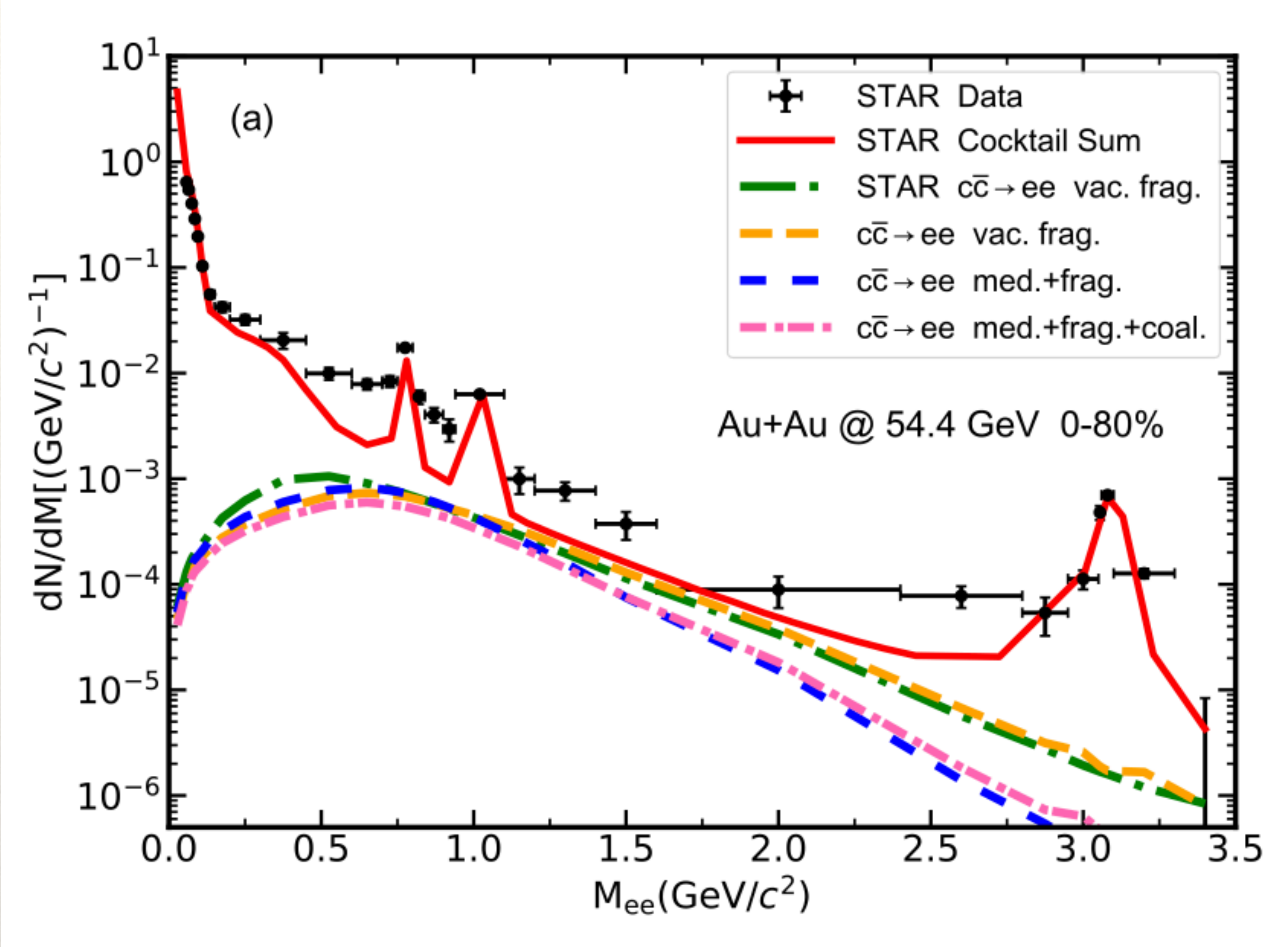


[STAR, Nature Commun. 16 (2025) 9098]

- Extracting the QGP temperature from the invariant mass spectrum of thermal dileptons
- A major background in the intermediate mass region: heavy quark decay ($c\bar{c} \to e^+e^-$)
- Current estimation of heavy quark background: Pythia + simple E shift and $\vec{p}$ randomization

  — Lack of realistic medium modification of heavy quarks

Systematic uncertainty of the extracted temperature



Au+Au @ 54.4 GeV

centrality	p+p (MeV)	frag (A+A) (MeV)	frag+recomb (A+A) (MeV)	Uncertainty (MeV)
0-10%	347±148	367±116	348±108	1-20
10-40%	263±61	292±55	280±52	17-29
0-80%	302±65	334±55	316±51	14-32
40-80%	286±73	306±64	296±63	10-20

RuRu+ZrZr @ 200 GeV

centrality	p+p (MeV)	frag (A+A) (MeV)	frag+recomb (A+A) (MeV)	Uncertainty (MeV)
0-10%	271±22	313±20	306±19	35-42
10-40%	313±15	351±15	340±13	27-38
0-80%	295±11	330±11	320±10	25-35
40-80%	333±18	357±18	345±17	12-24

[Zhang, Xing, SC, Qin, arXiv:2512.01592, accepted by Sci. China Phys. Mech. Astron.]

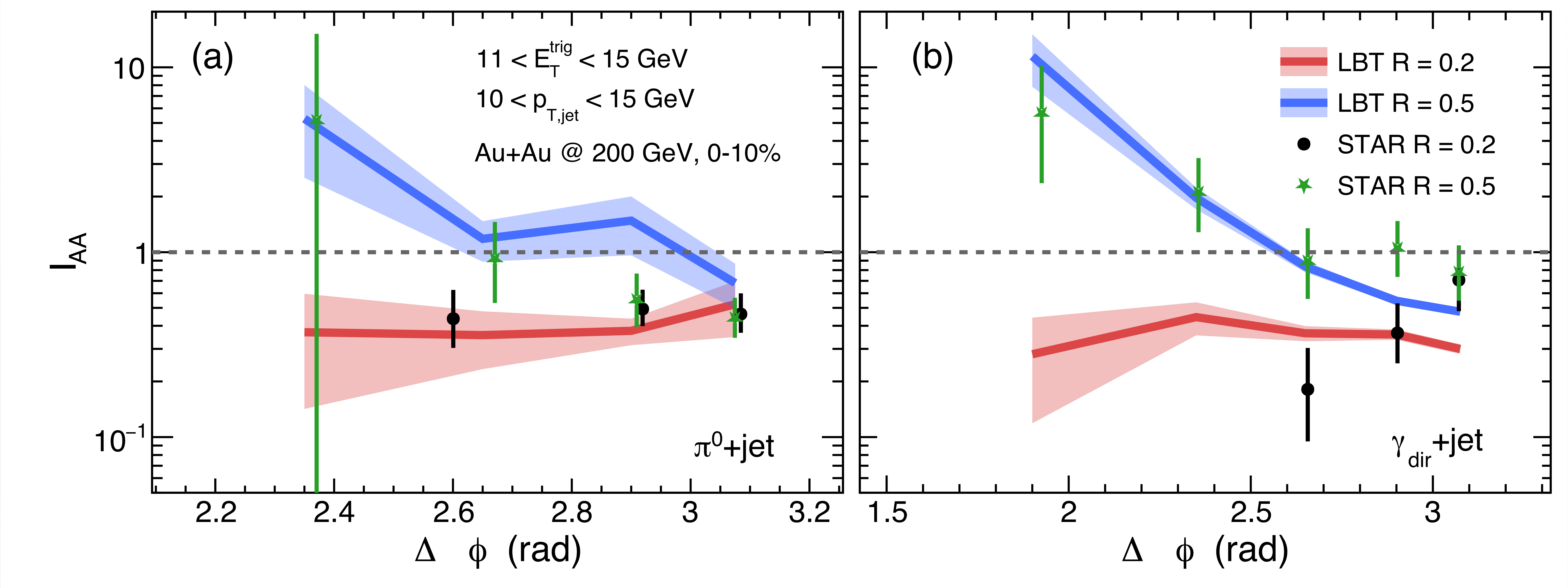
- Softening of the charm quark decay dilepton spectrum by medium modification
- Higher values of the extracted temperature compared to using Pythia in data analysis
- Mild effect for Au+Au @ 54.4 GeV, but non-negligible effect for Ru+Ru/Zr+Zr @ 200 GeV

Summary

- Developed a color-tracked multi-stage jet evolution model
  - Achieved a simultaneous description of hadron and jet suppression
  - Provided a quantitative description of the EEC of jets
  - Proposed the production of thermal recoil jets for understanding *h*-jet data
- Towards a more precise jet tomography of the QGP properties
  - Jet quenching parameter, equation of state, temperature, etc.

Thank you!

Backup: acoplanarity enhancement at RHIC



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 ($ab \rightarrow cd$)

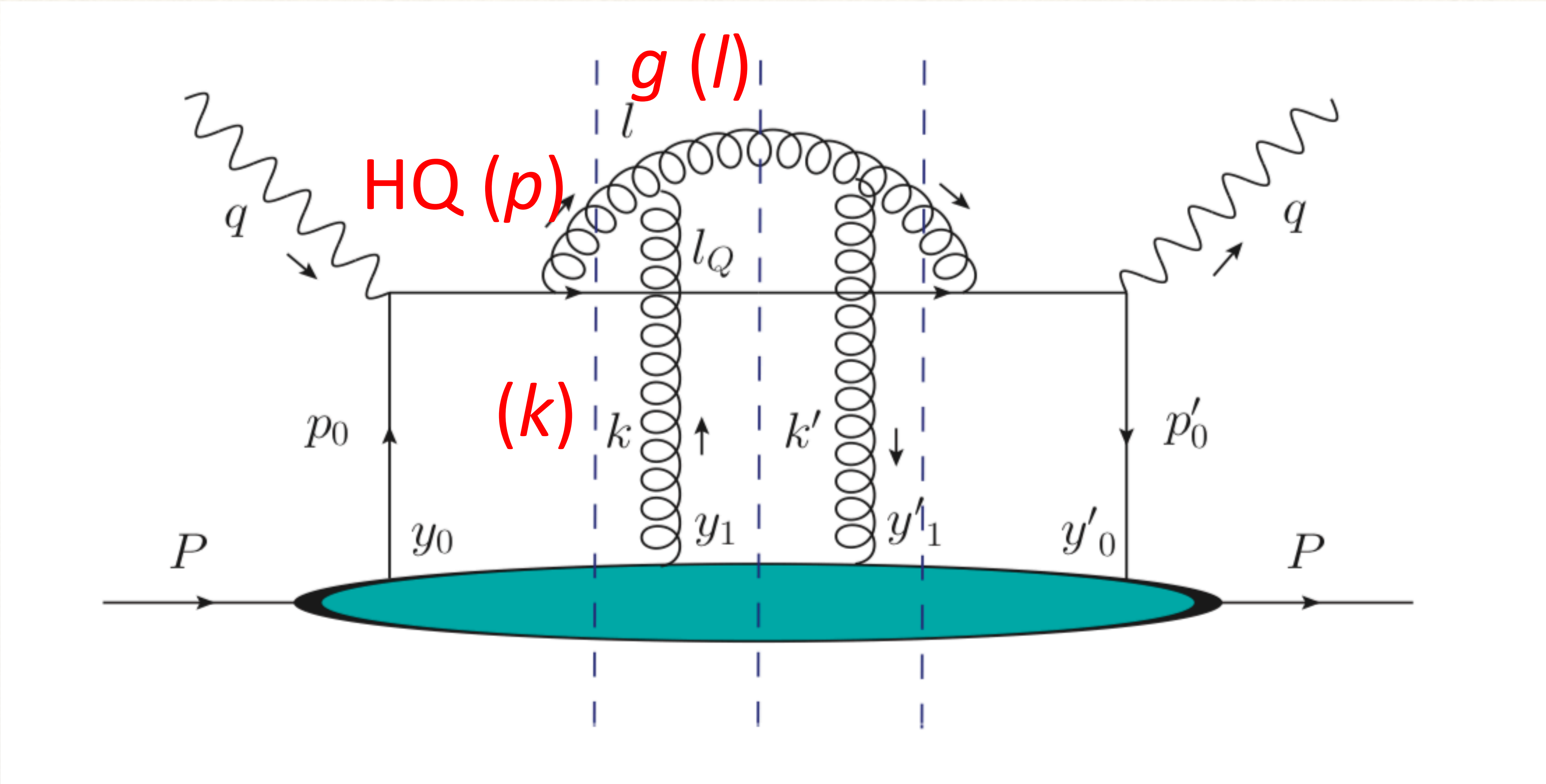
$$\mathscr{C}_a^{\text{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathscr{M}_{ab \rightarrow cd} \right|^2$$

$2 \rightarrow 2$ scattering matrices

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

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

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 $\hat{q} \equiv d\langle p_\perp^2 \rangle / dt$