Towards a more precise jet tomography of the QGP

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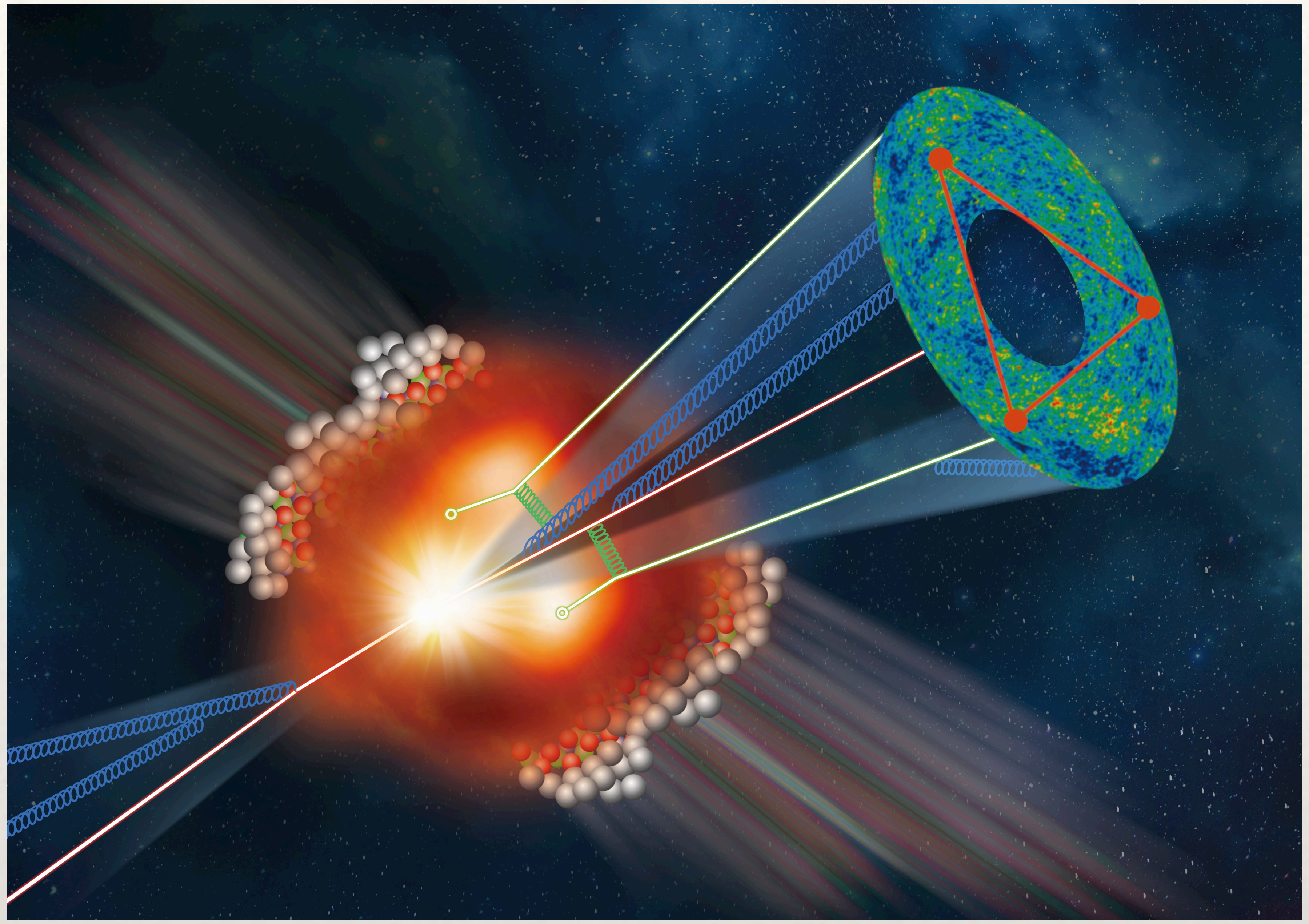
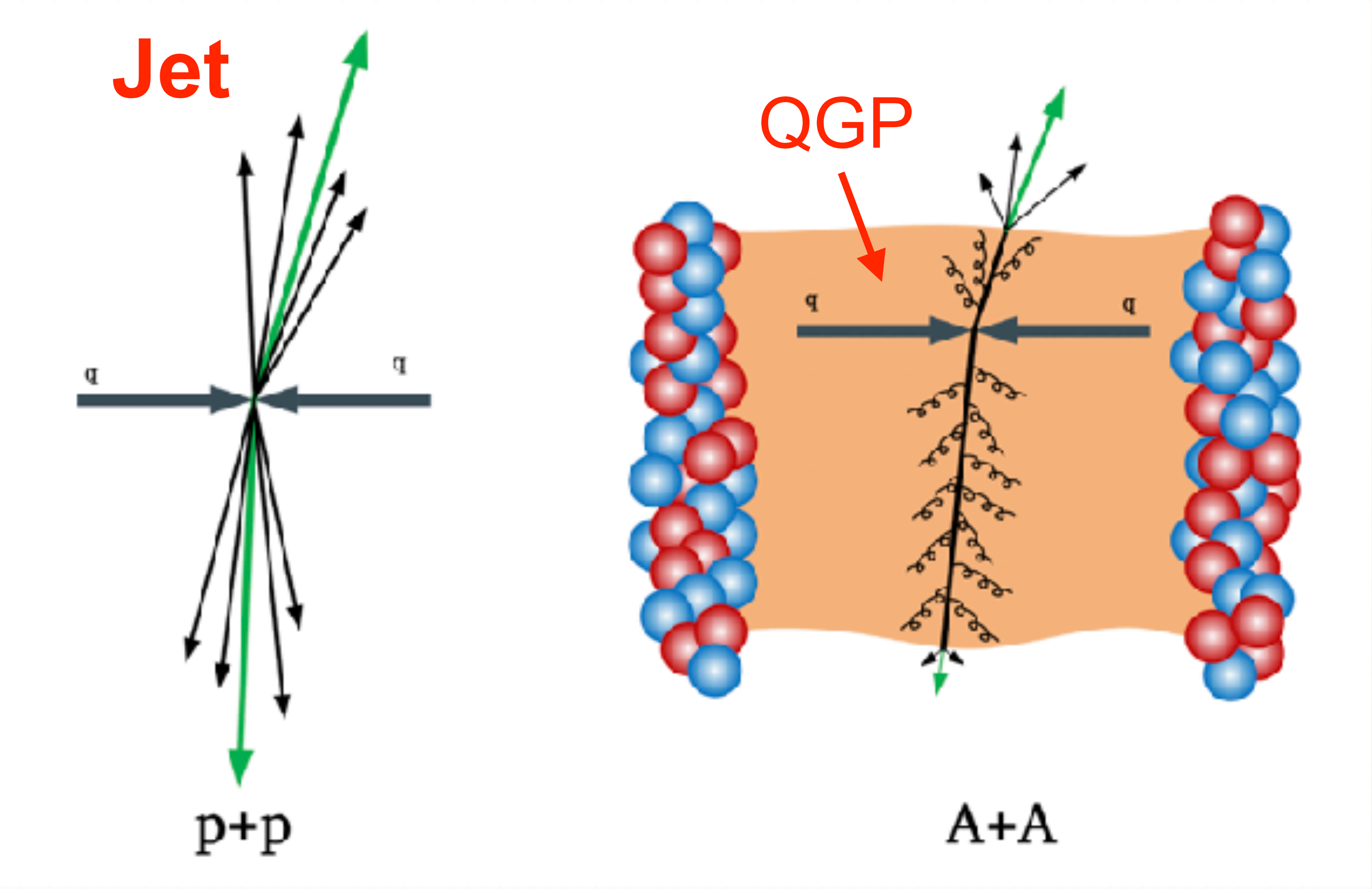
Based on arXiv:2602.10395, arXiv:2604.19288, arXiv:2512.12715

极端核物质前沿研讨会，宜昌，2026年4月27日

Probing quark-gluon plasma (QGP) using jets

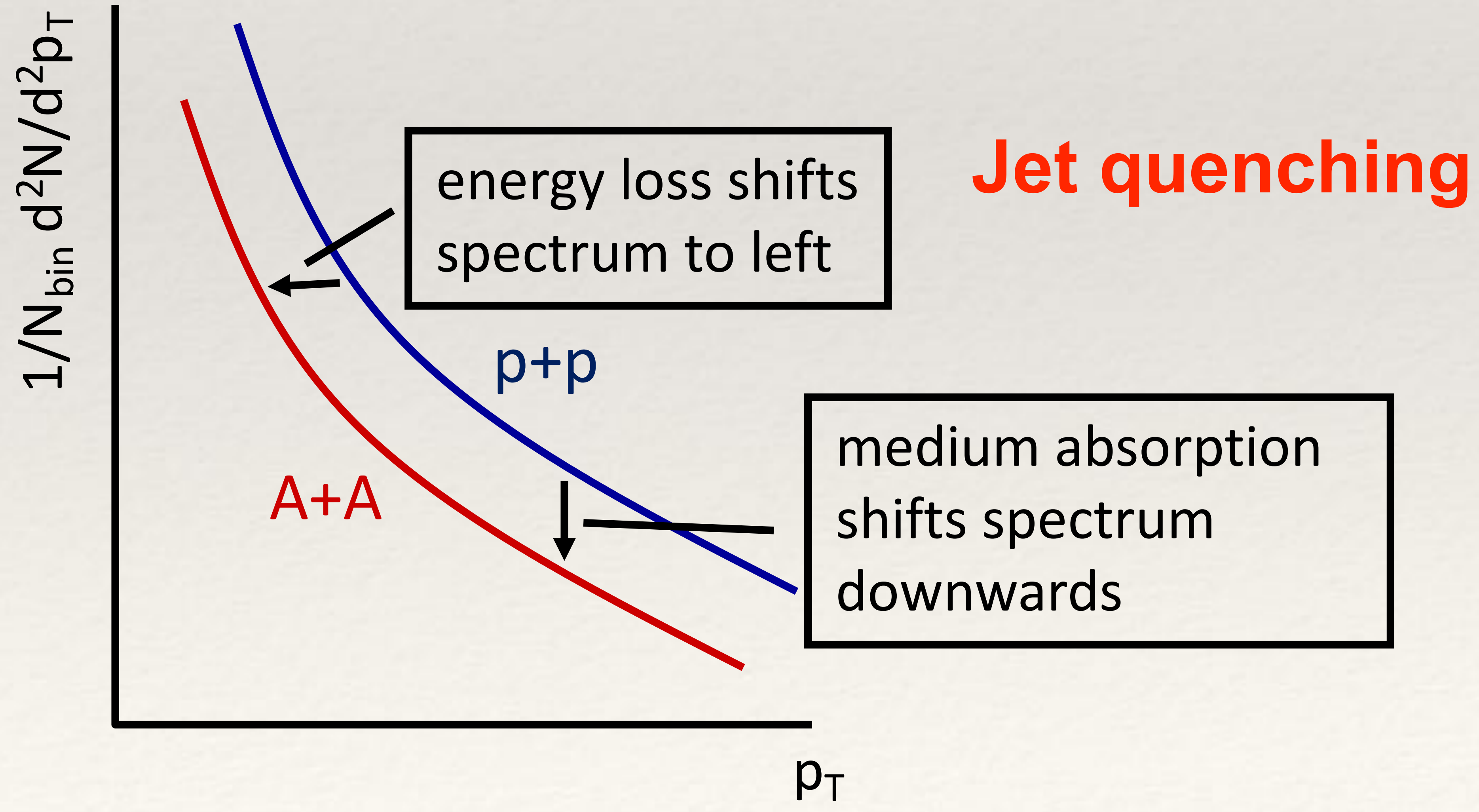




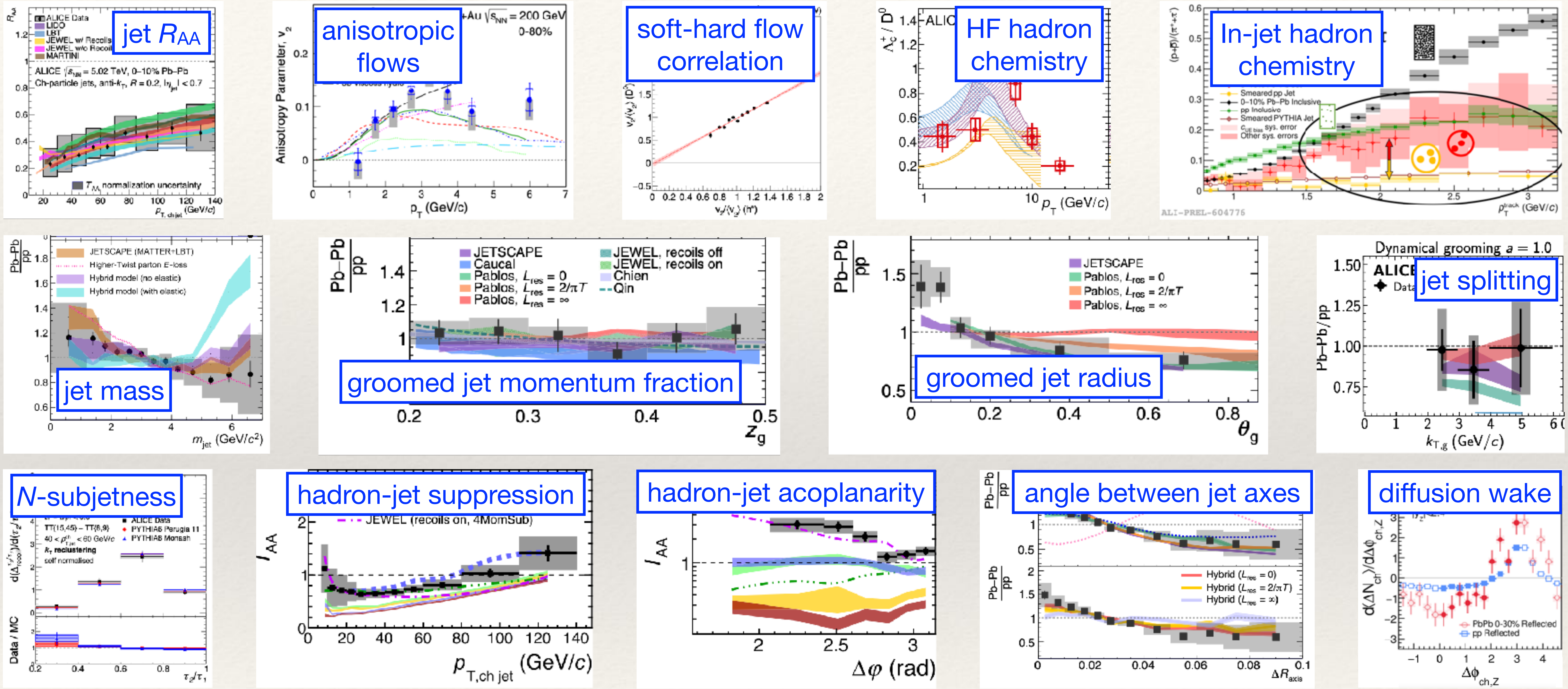
[by M. Rybar / ATLAS]

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

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

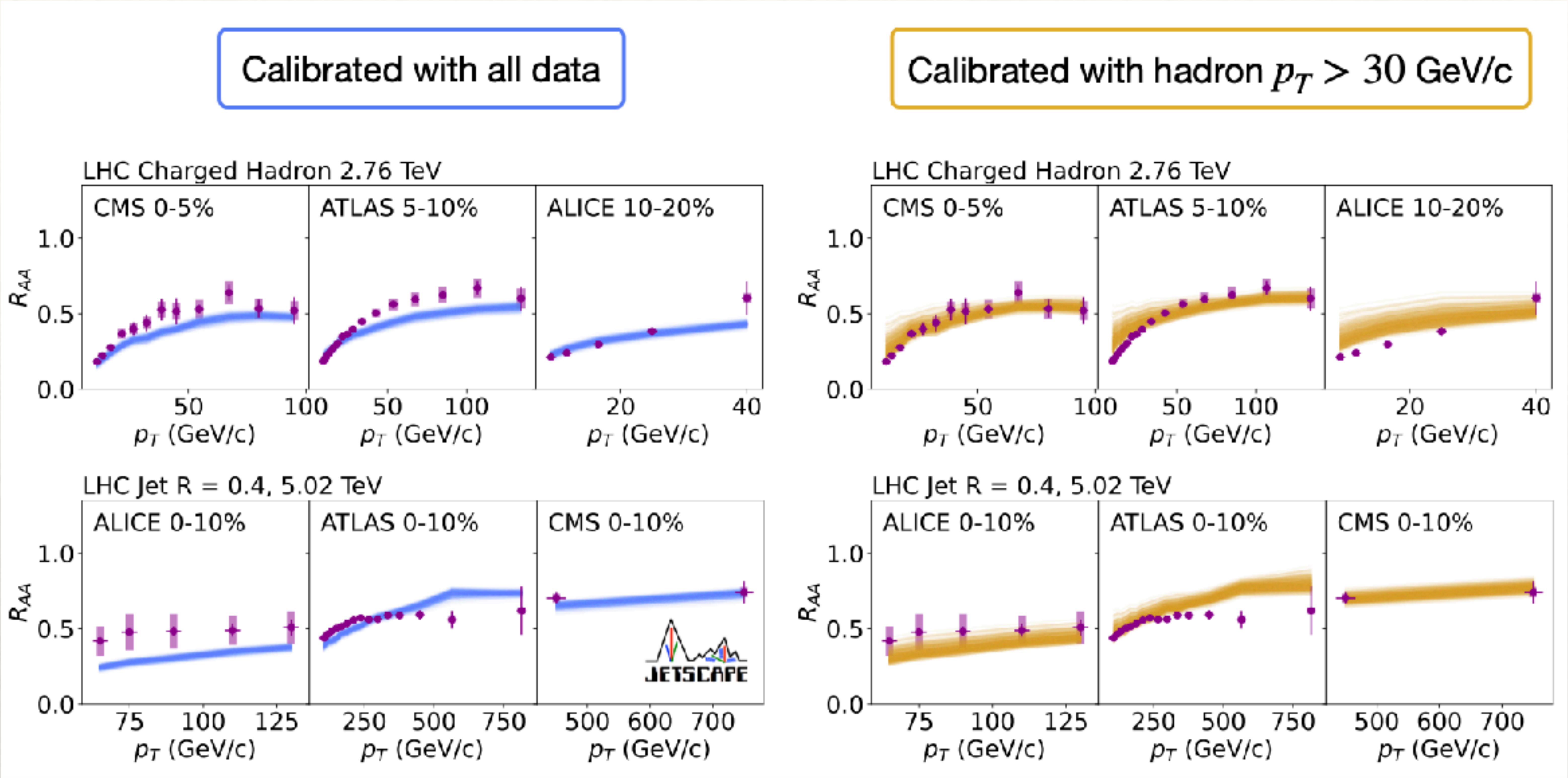


A vast number of observables



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

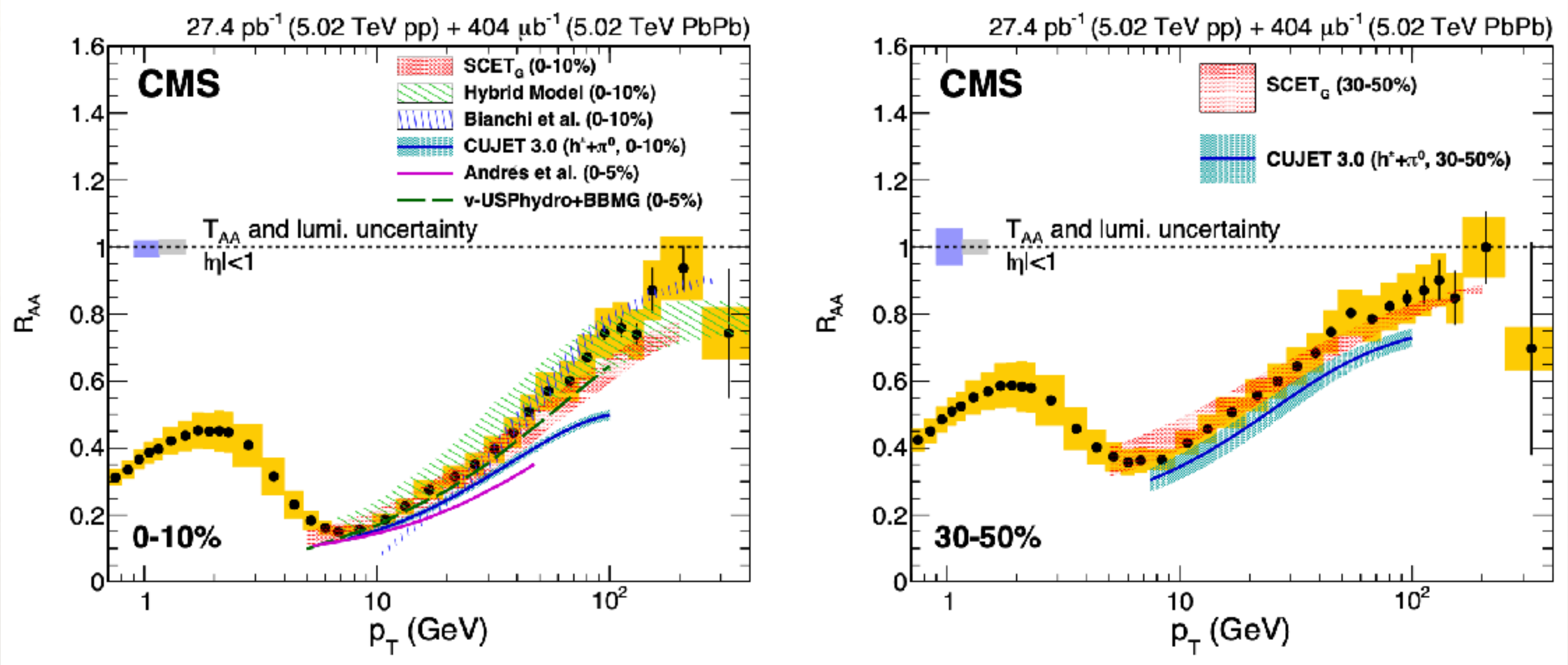
Have we precisely understood the simplest observable?



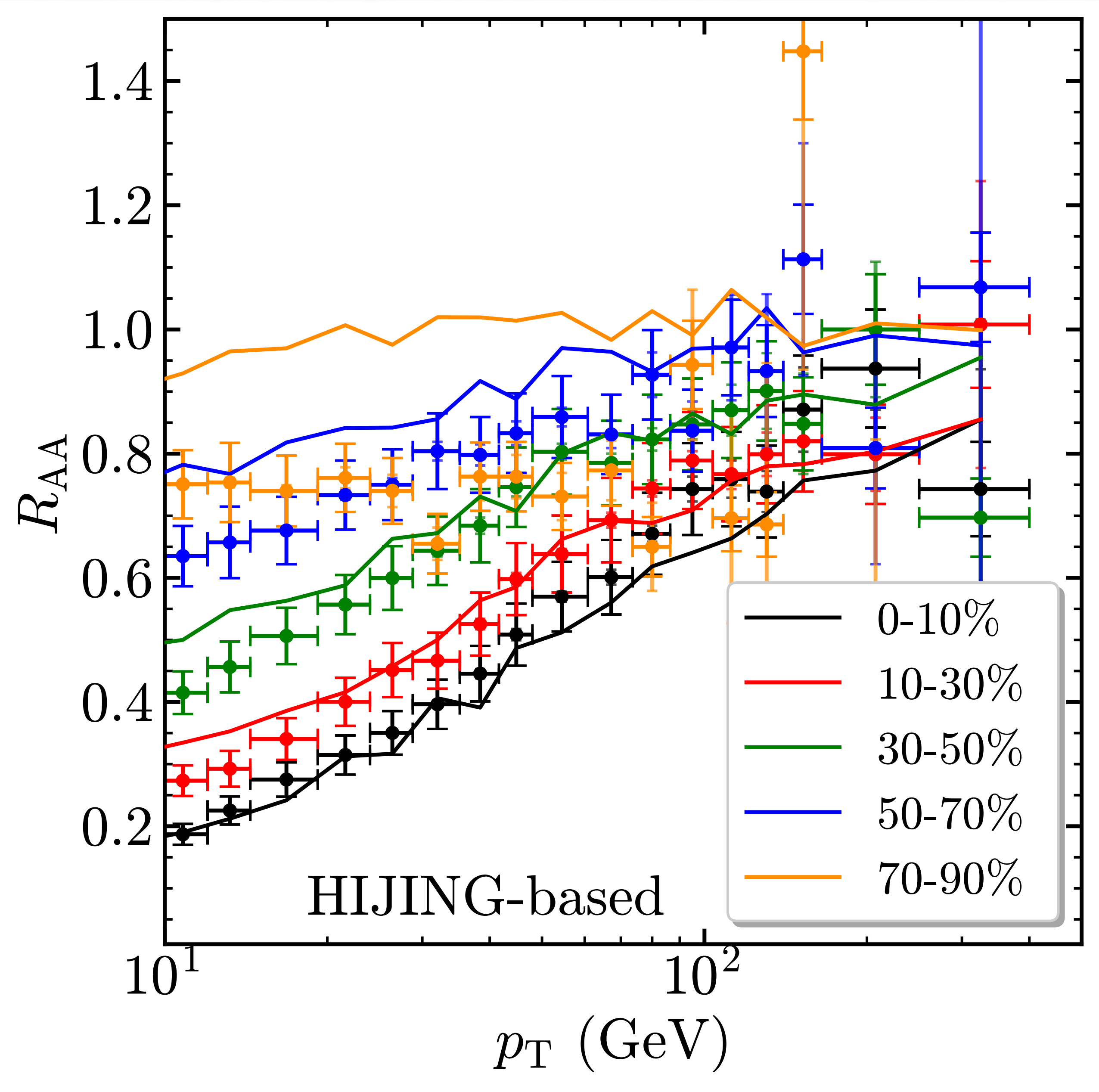
JETSCAPE, Phys. Rev. C 111 (2025) 054913

- 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

Centrality dependence of R_{AA}



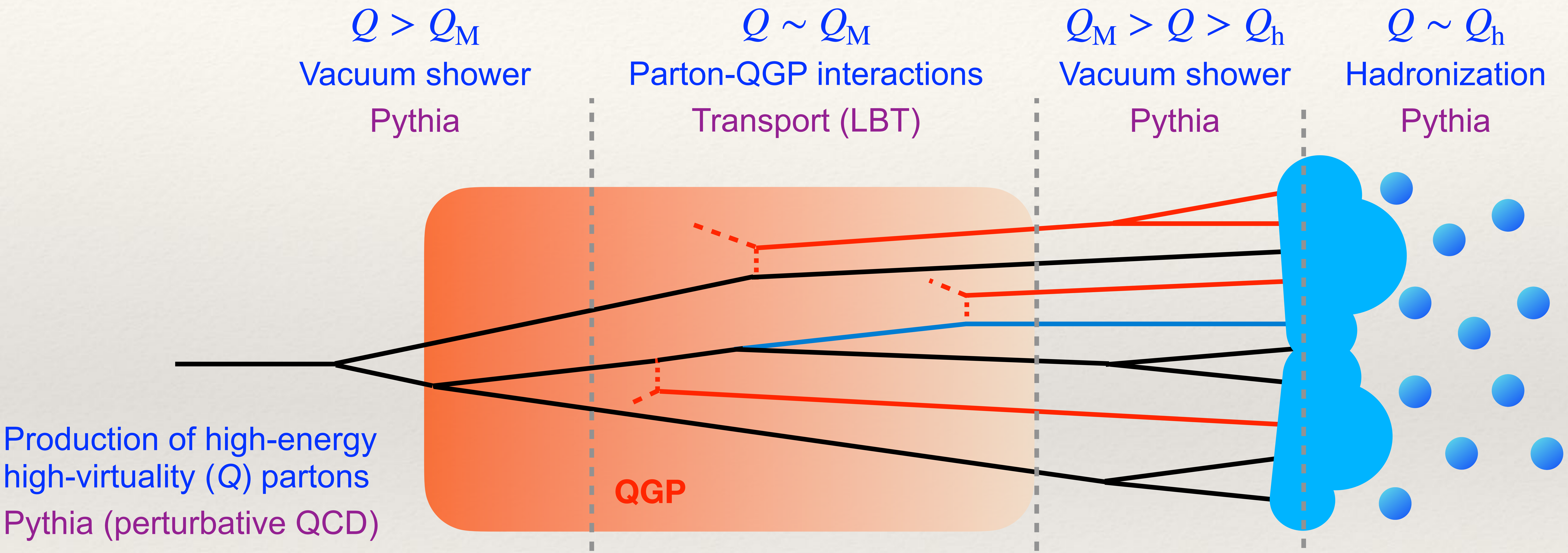
CMS, JHEP 04 (2017) 039



Sun, Dang, SC, arXiv:2604.19288

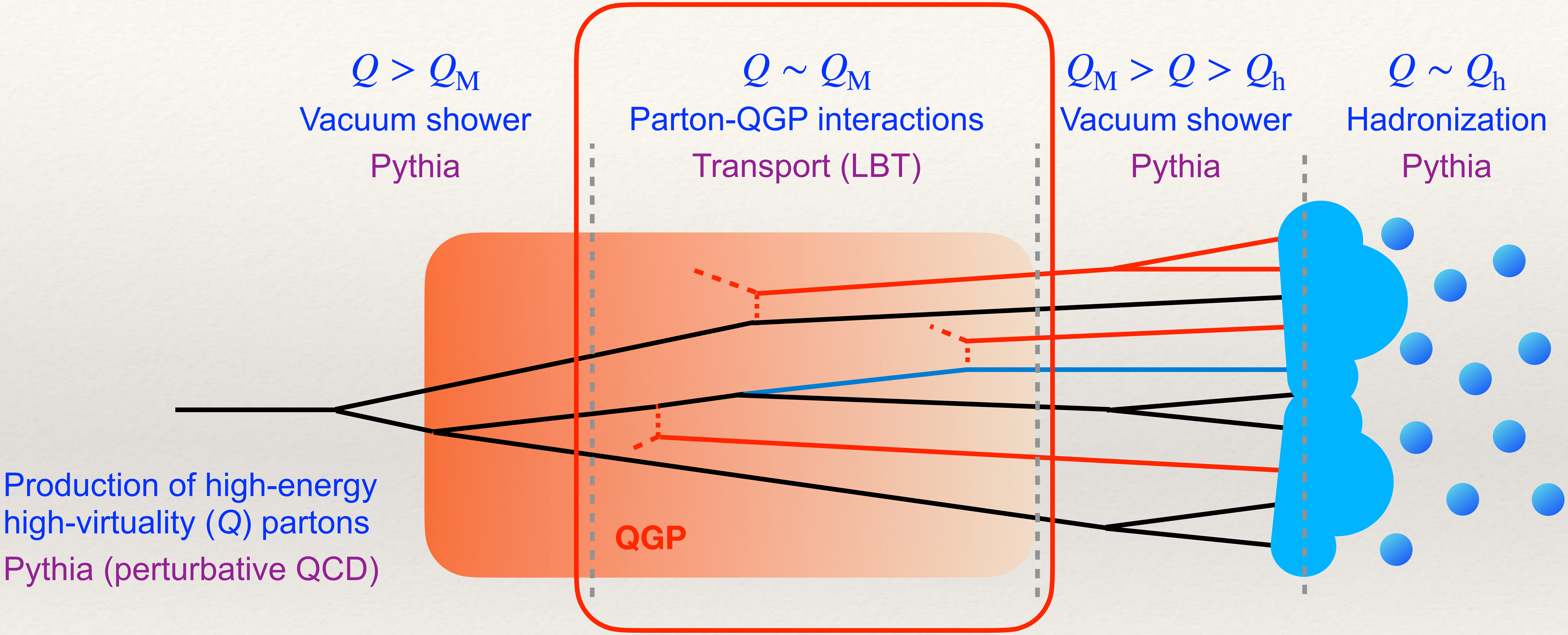
- Tension remains in simultaneous description of hadron R_{AA} from small to large centralities
- Fit R_{AA} in central collision → overestimate R_{AA} in peripheral collision
- Necessary to improve the precision of jet models for heavy-ion collisions — **Goal of this talk**

Monte-Carlo framework of jet-QGP interactions



- **Old model**: $Q_{\rm M} = Q_{\rm h} = 0.5$ GeV; **New model**: $Q_{\rm M} > Q_{\rm h}$ can be varied

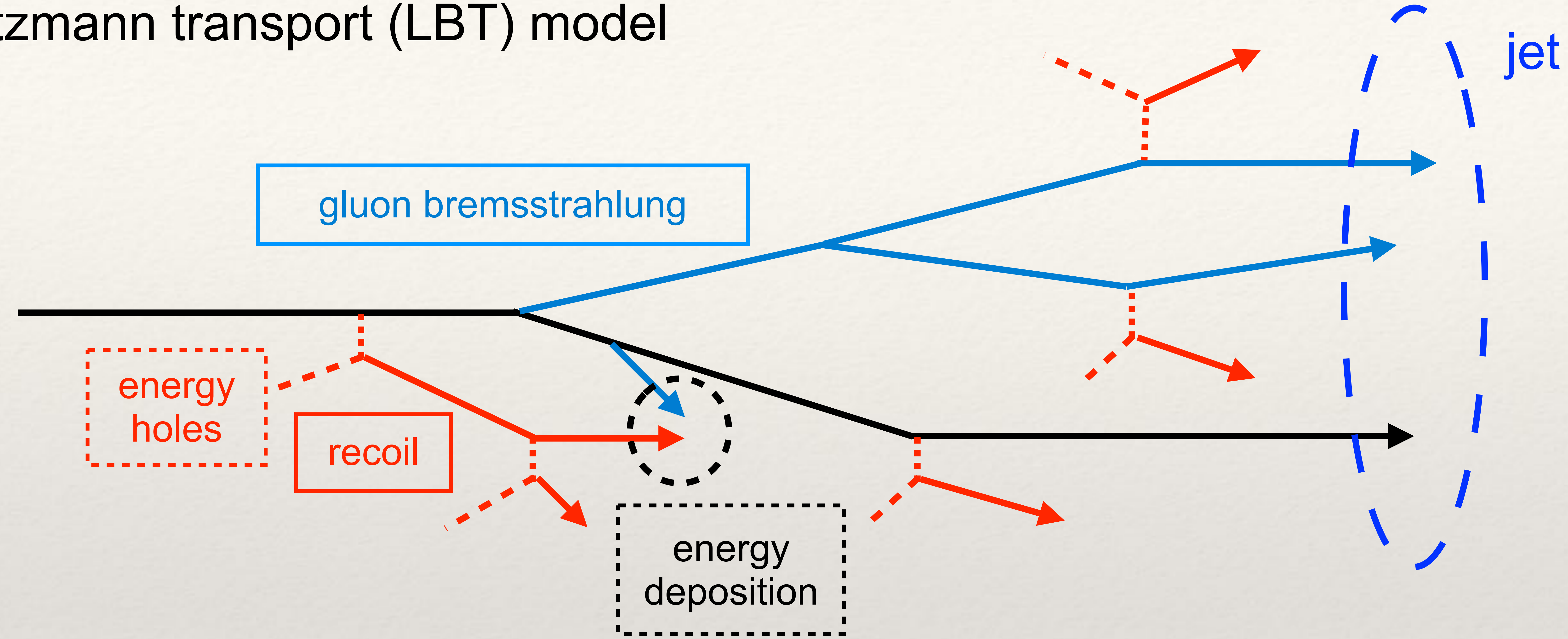
Monte-Carlo framework of jet-QGP interactions



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

Jet-QGP interactions

Linear Boltzmann transport (LBT) model



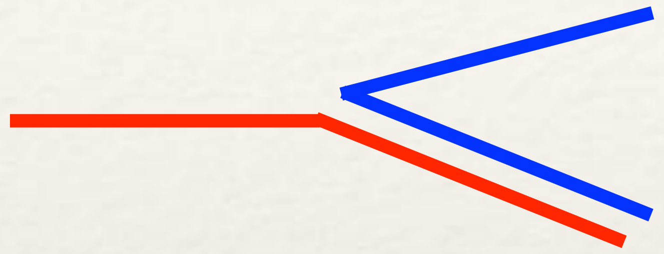
- Medium modification on jets: scattering, medium-induced gluon bremsstrahlung
- Jet modification on medium: energy deposition + depletion → **jet-induced medium excitation (medium response)**
- Jet-medium interactions: **medium modification of jets + medium response**

Color schemes in elastic and inelastic scatterings

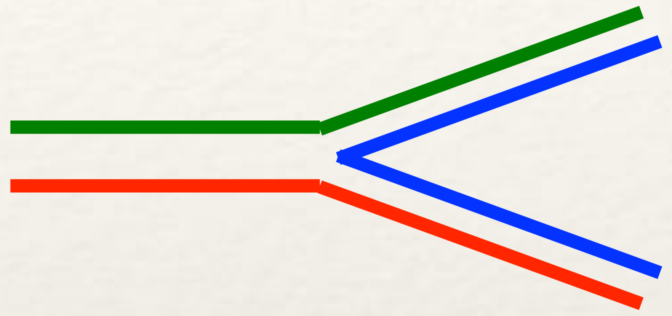
Technical challenge: color information required for partons transitioned from LBT back to Pythia

Parton splittings

$q \to qg$

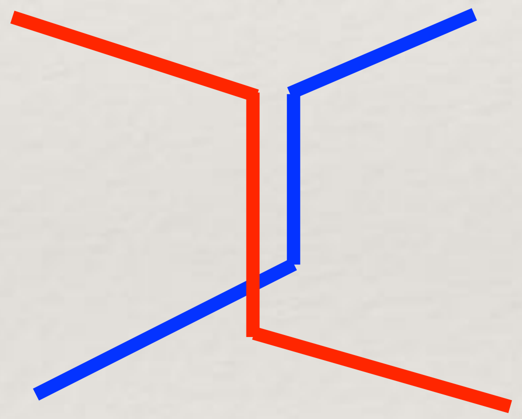


$g \to gg$

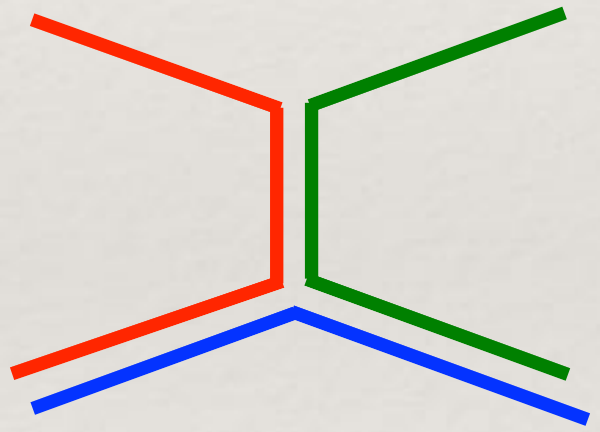


Jet-medium scatterings

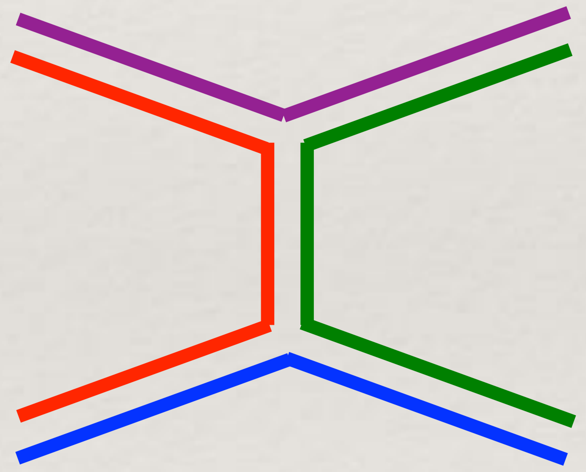
$qq \to qq$



$qg \to qg$



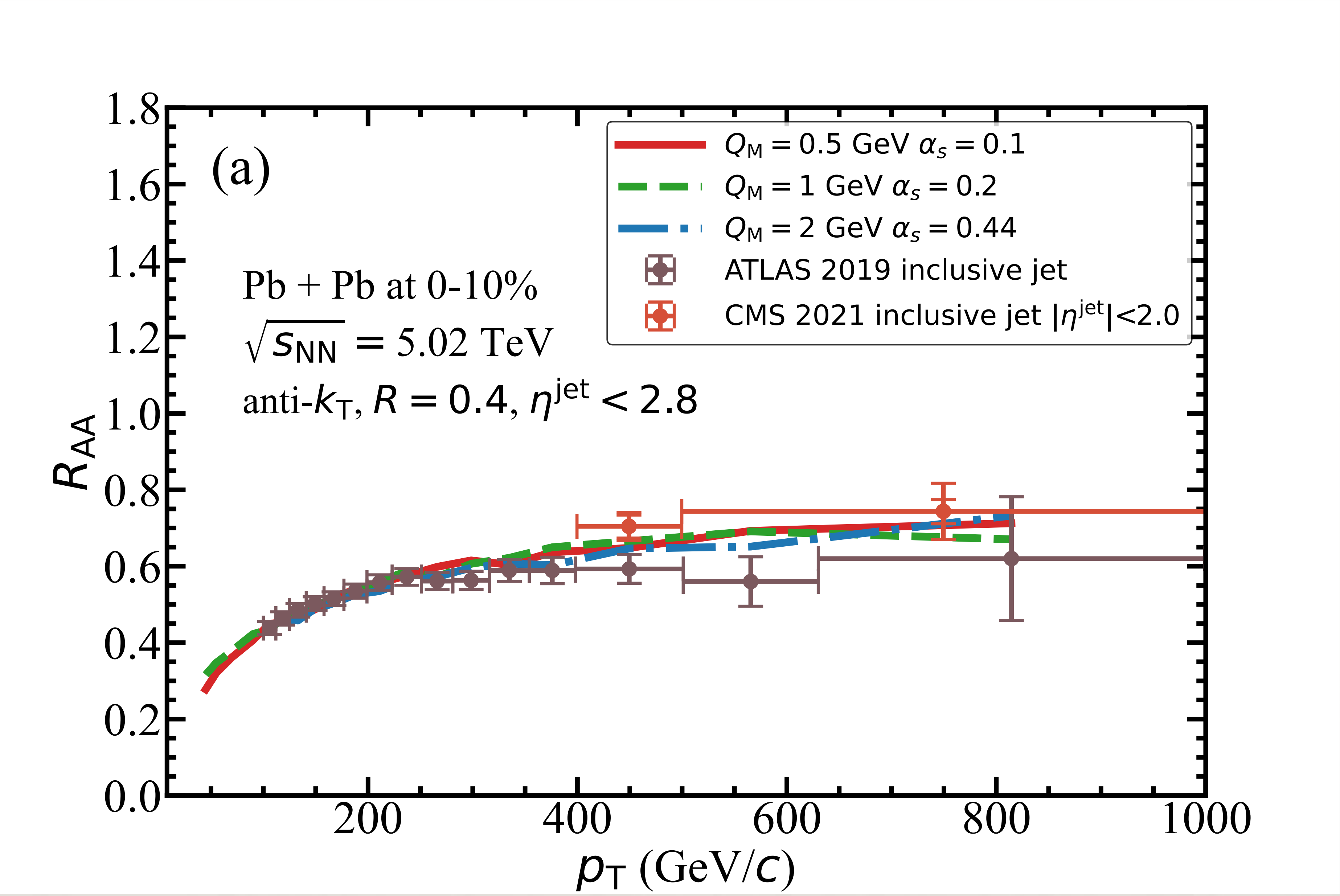
$gg \to gg$



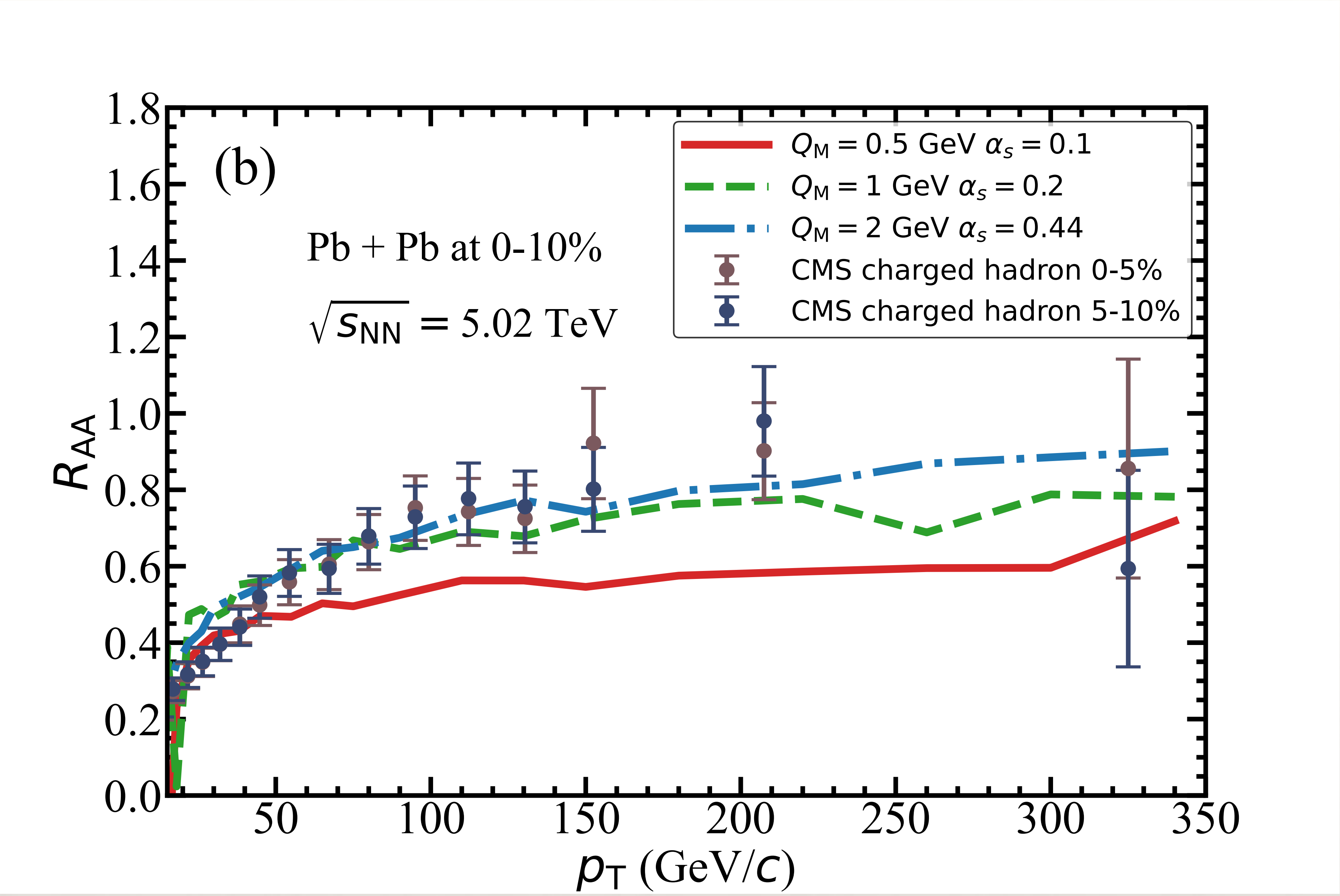
- Large N_c color scheme in Pythia, (color, anticolor), e.g., q (101, 0), $\bar{q}$ (0, 102), g (103, 104)
- Same color scheme for parton splitting processes
- Introduce color information for jet-medium scatterings

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:

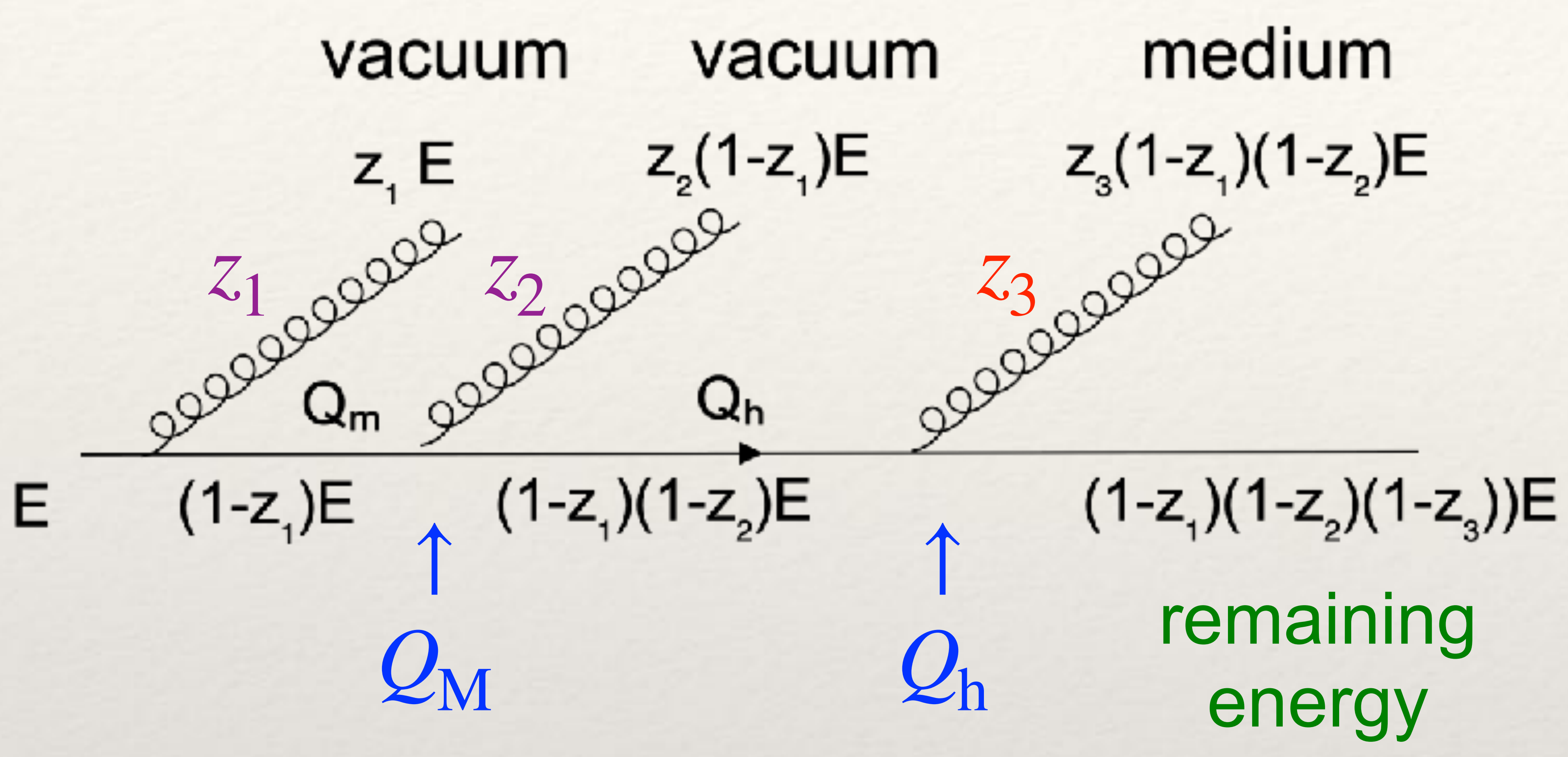
- $Q_M \uparrow$ requires larger α_s to re-fit jet R_{AA}
- improves simultaneous jet and hadron descriptions

Implications:

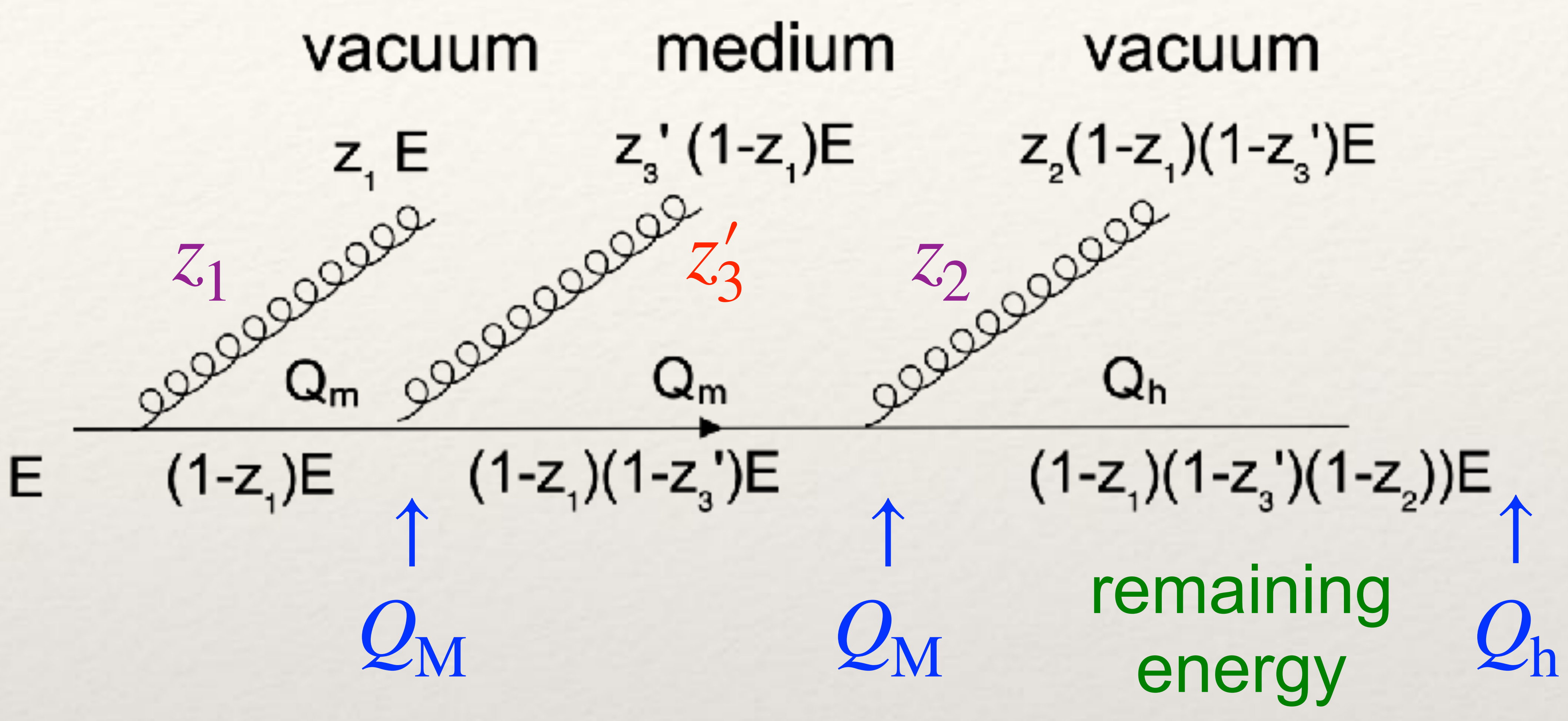
- $Q_M \uparrow$ reduces jet and parton ΔE
- Stronger effects on partons than jets

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

Old: vacuum → medium



New: vacuum → medium → vacuum

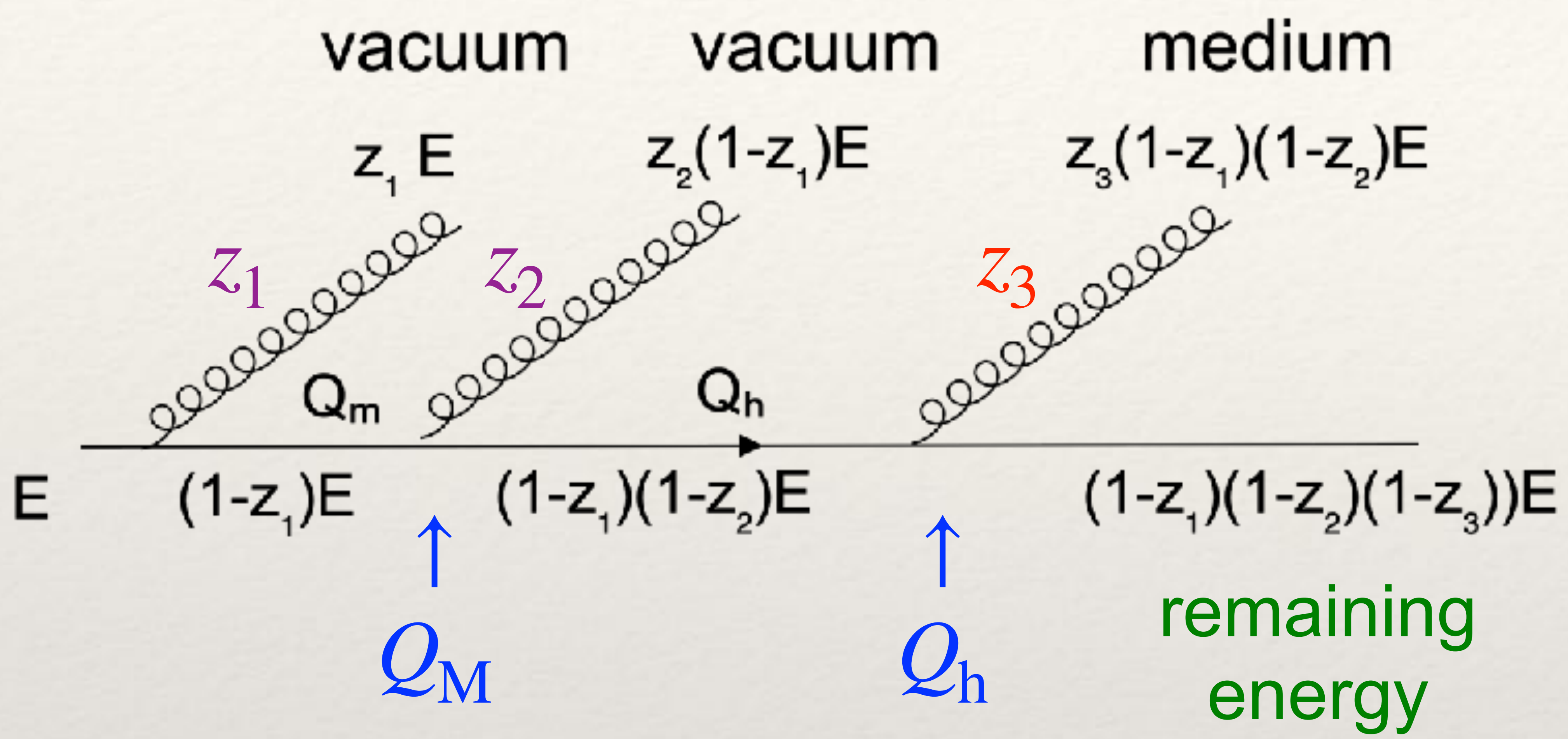


Why Δ*E* is reduced for both partons and jets in the new framework if α_s is fixed?

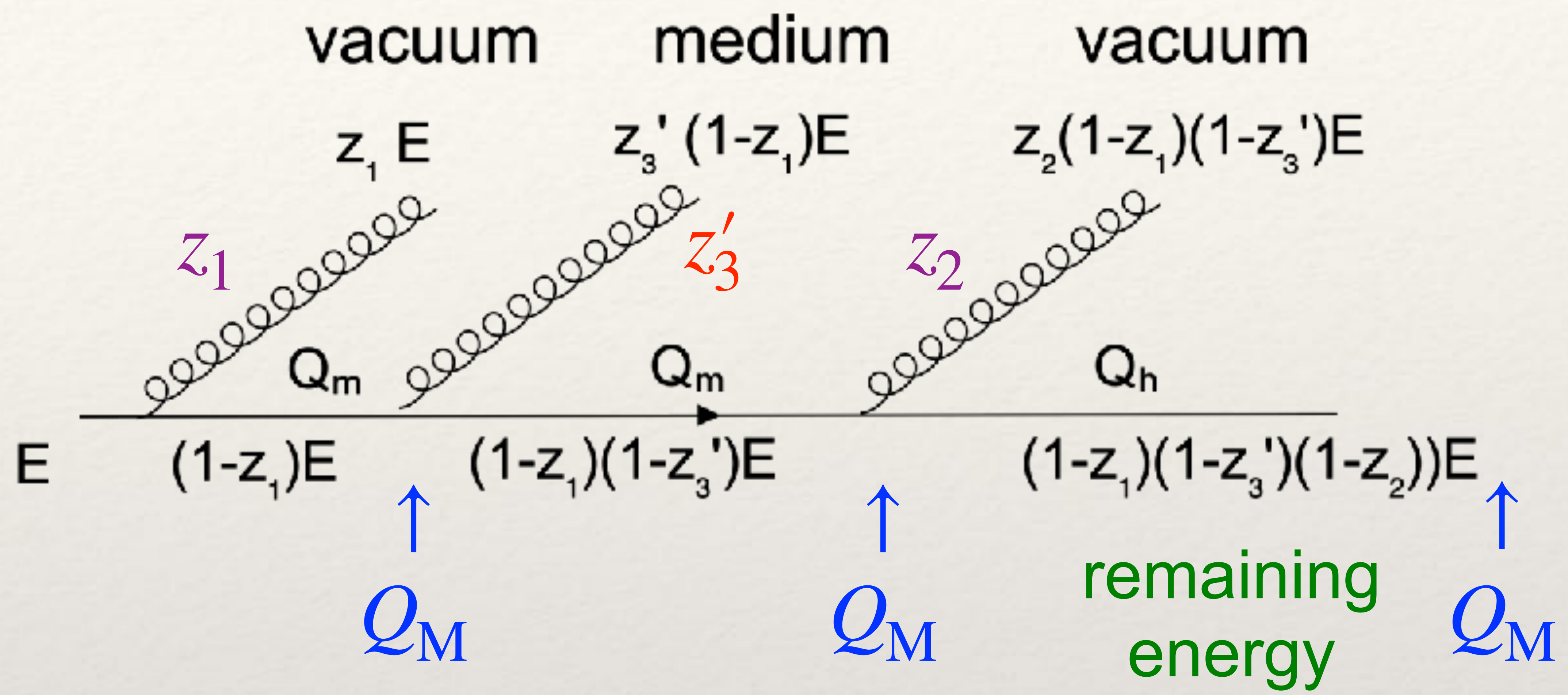
- *z* in parton splitting *P*(*z*) is *E*-independent in vacuum; Δ*E* is *E*-independent in medium → same z_1, z_2 between old and new, z_3 (old) > z_3' (new) → parton Δ*E*: old > new
- Number of partons entering medium: old > new → jet Δ*E*: old > new

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?

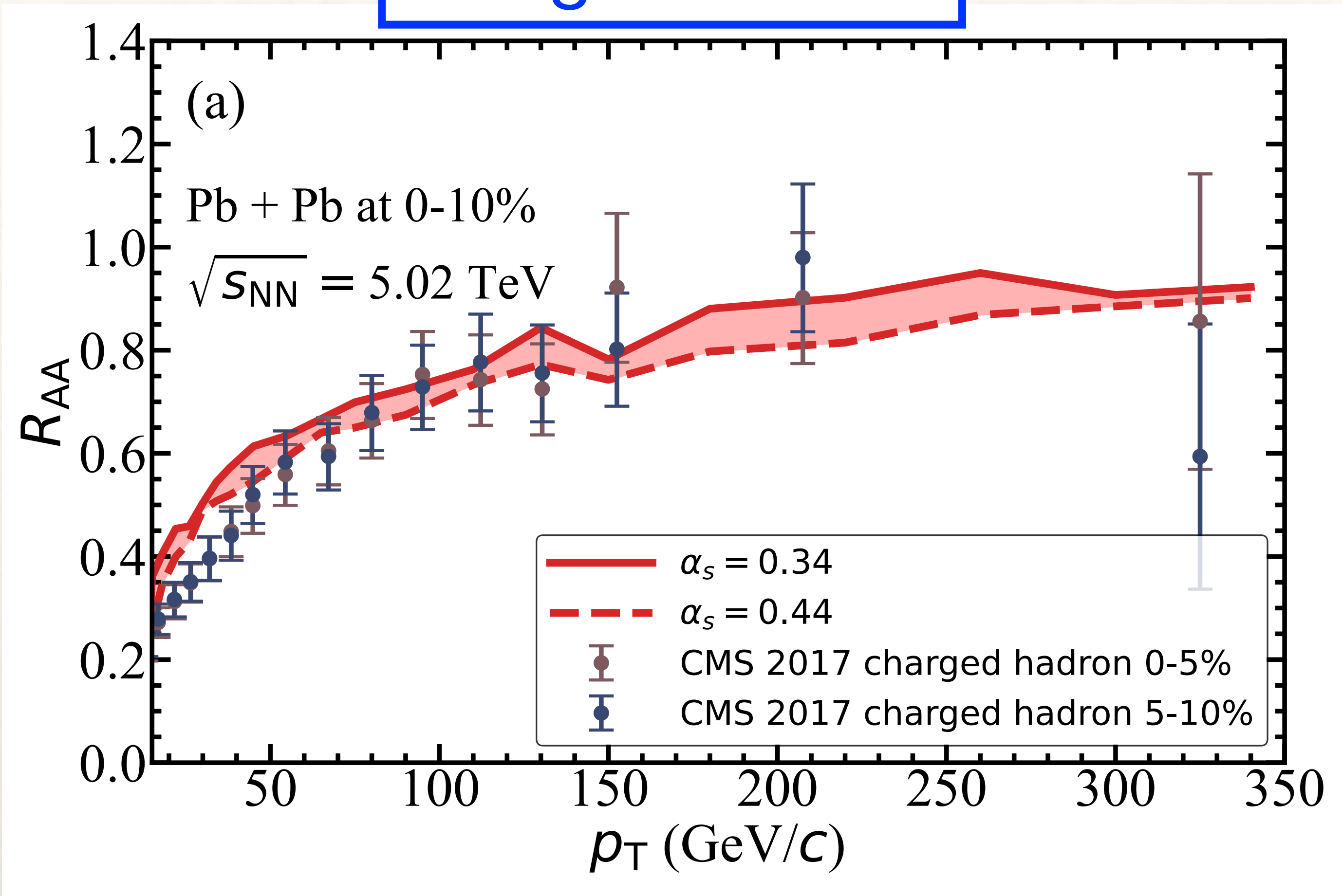
- Competing effect: starting jet-medium at higher *Q* extends interaction times → increases Δ*E*
- Larger impact on soft than hard partons ($\tau_f^{soft} > \tau_f^{hard}$ given Q)

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

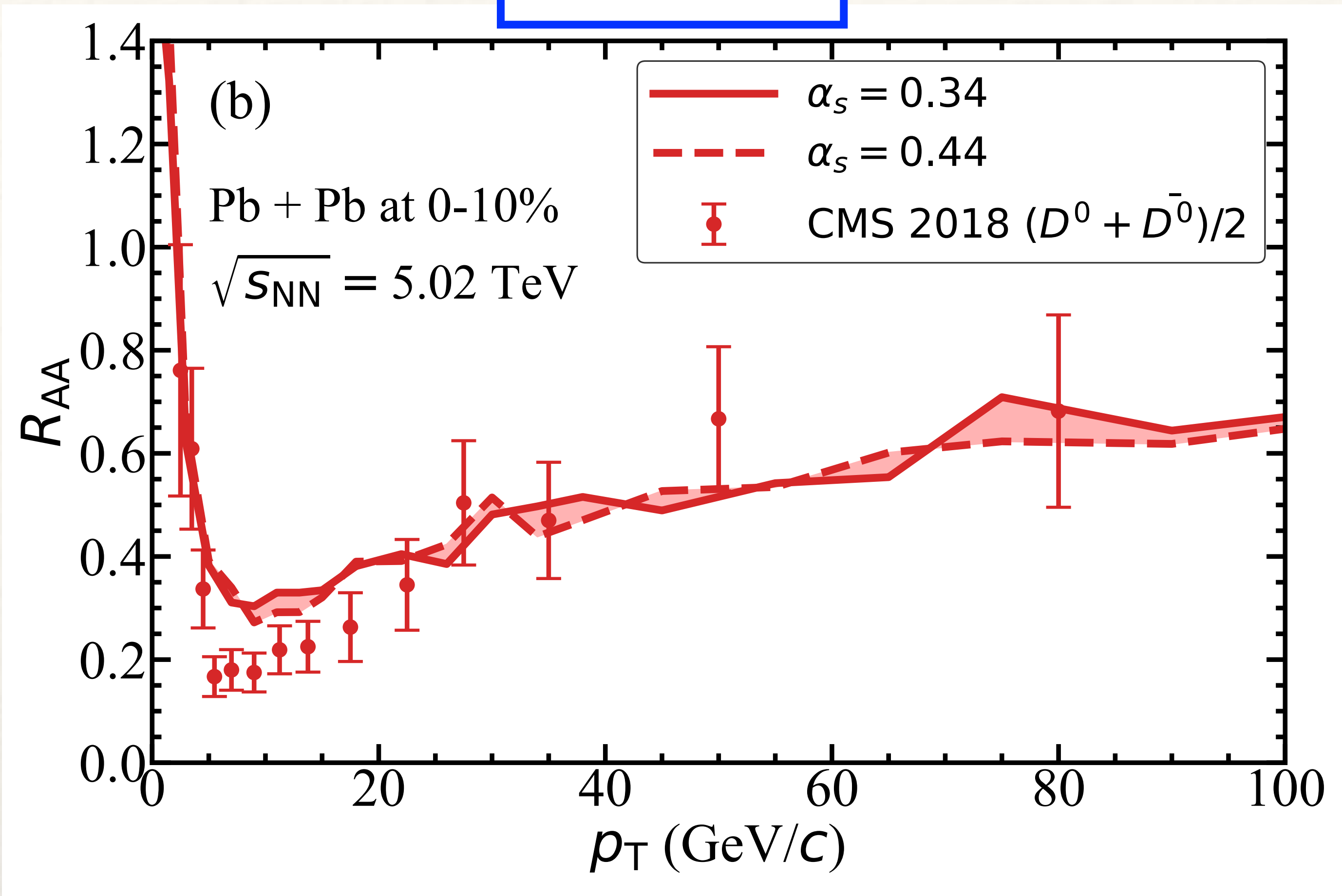
→ Raising Q_M in the new framework reduces hadron Δ*E* more than jet Δ*E* (preferred by data)

Hadrons and jets with different flavors

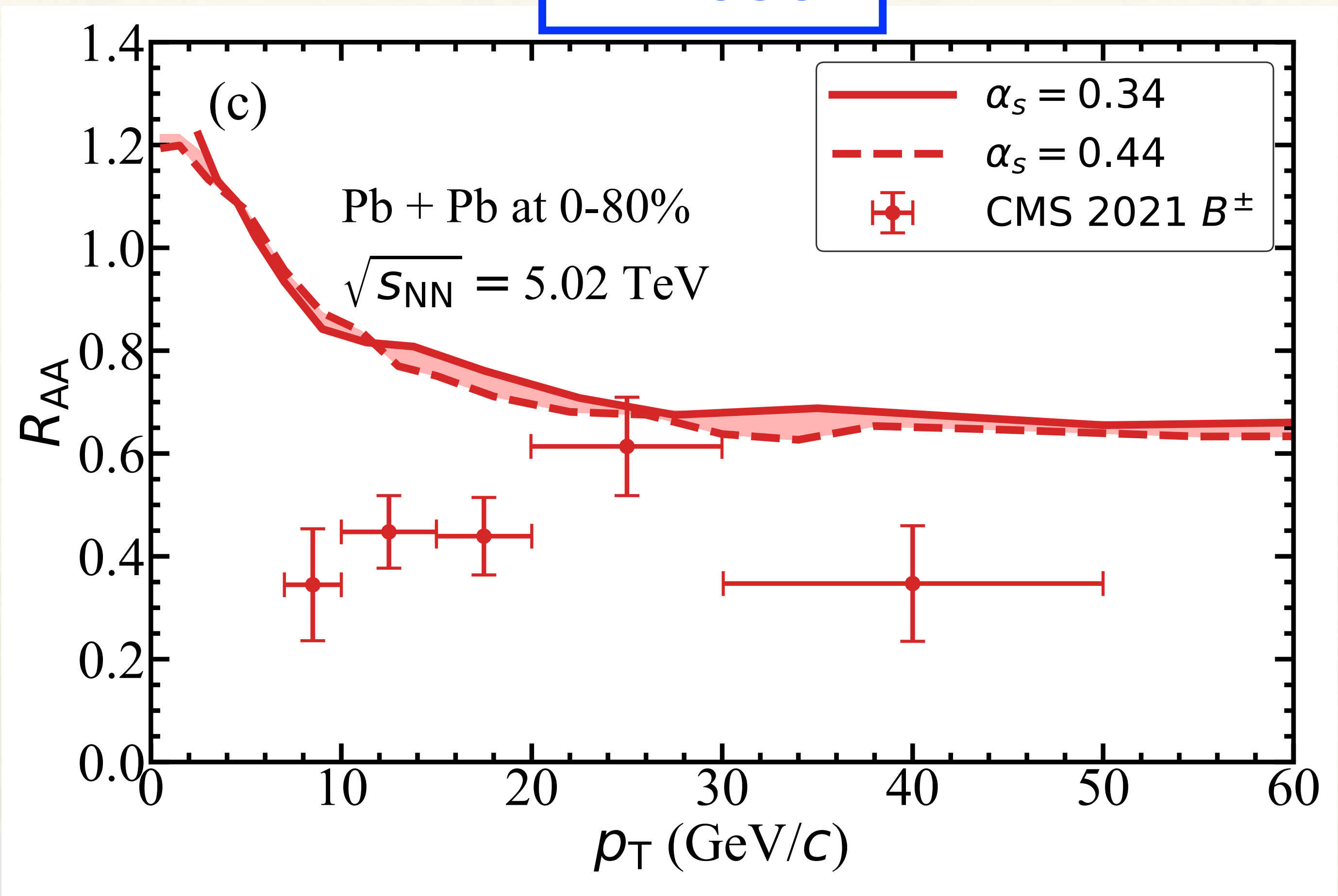
charged hadron



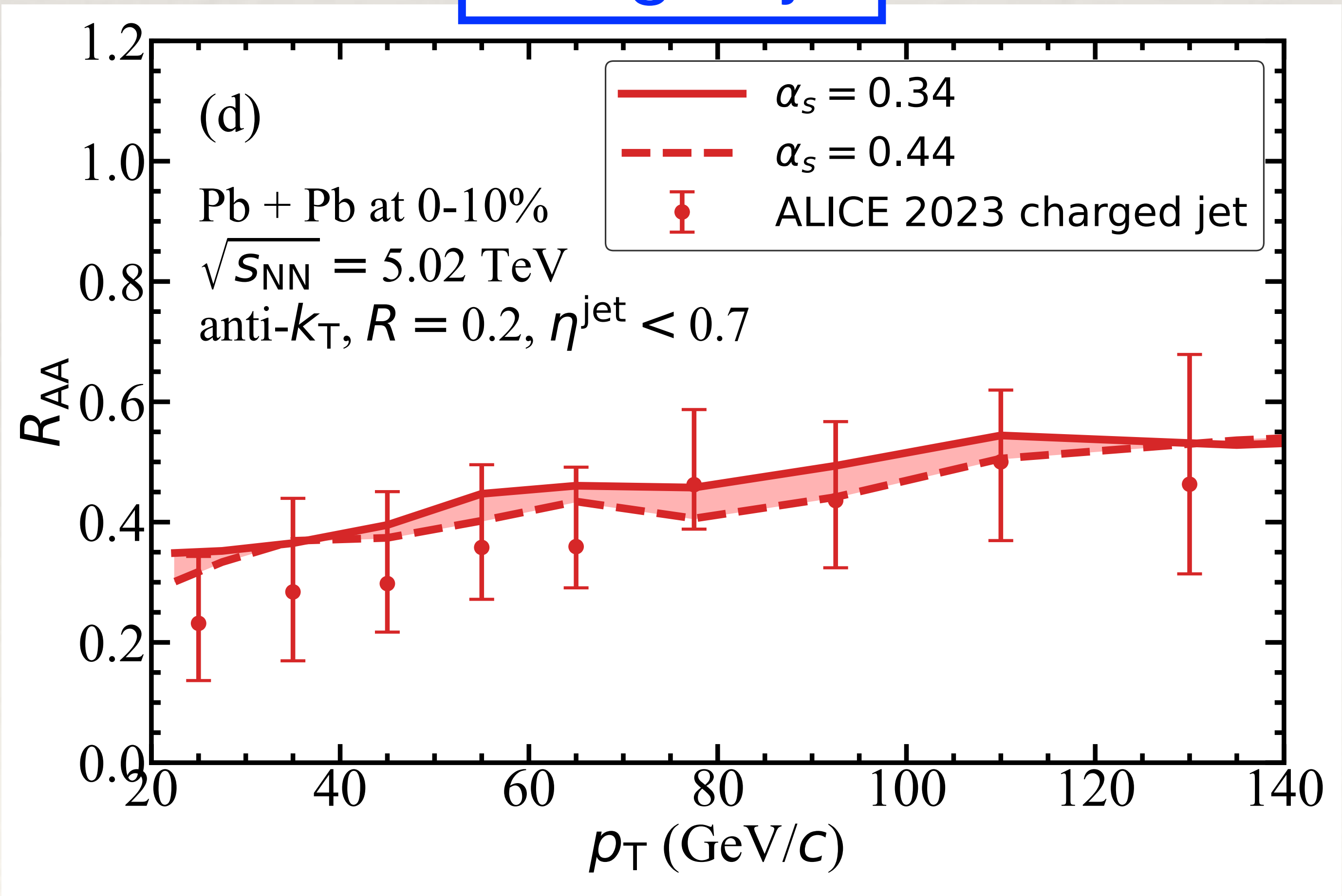
D meson



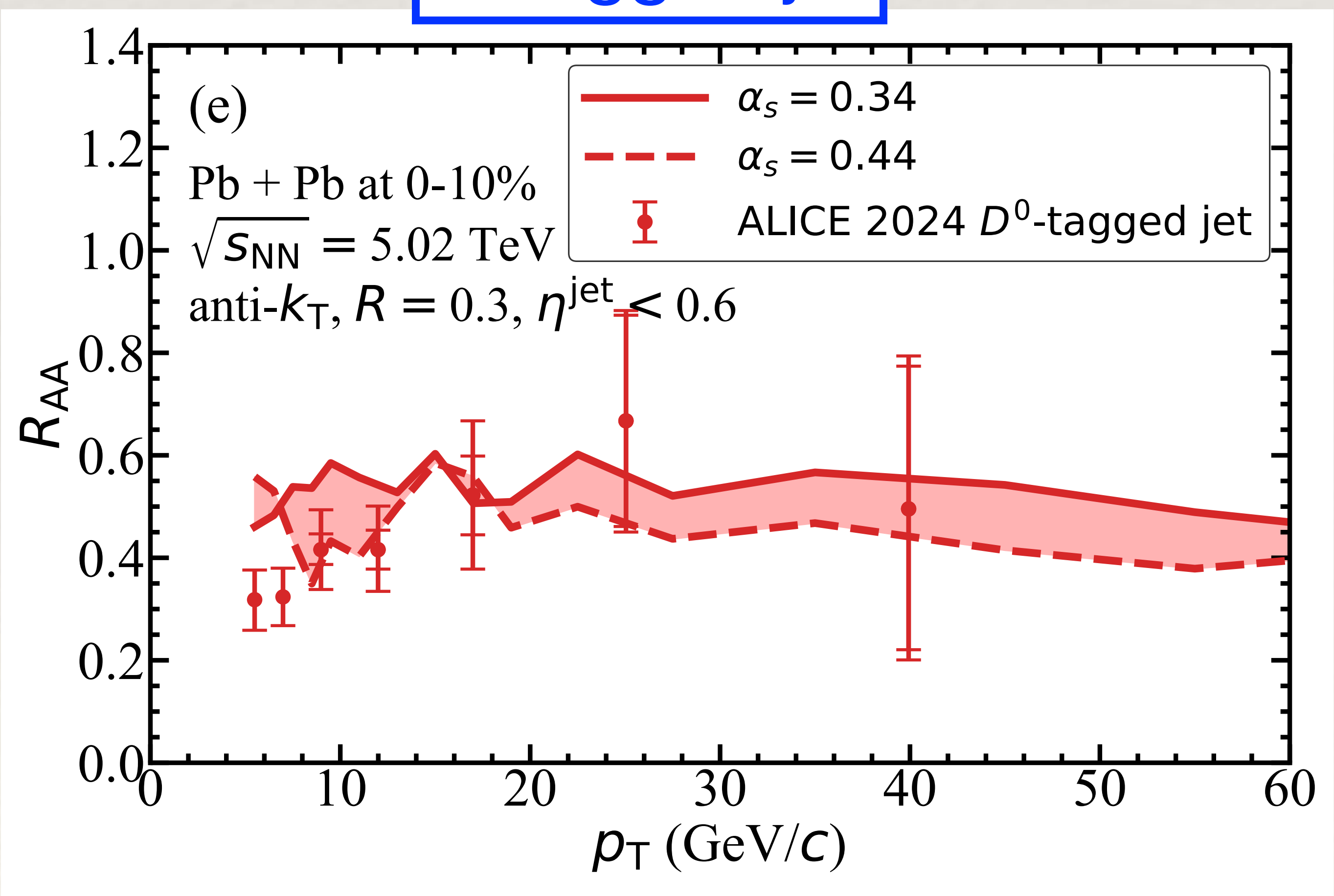
B meson



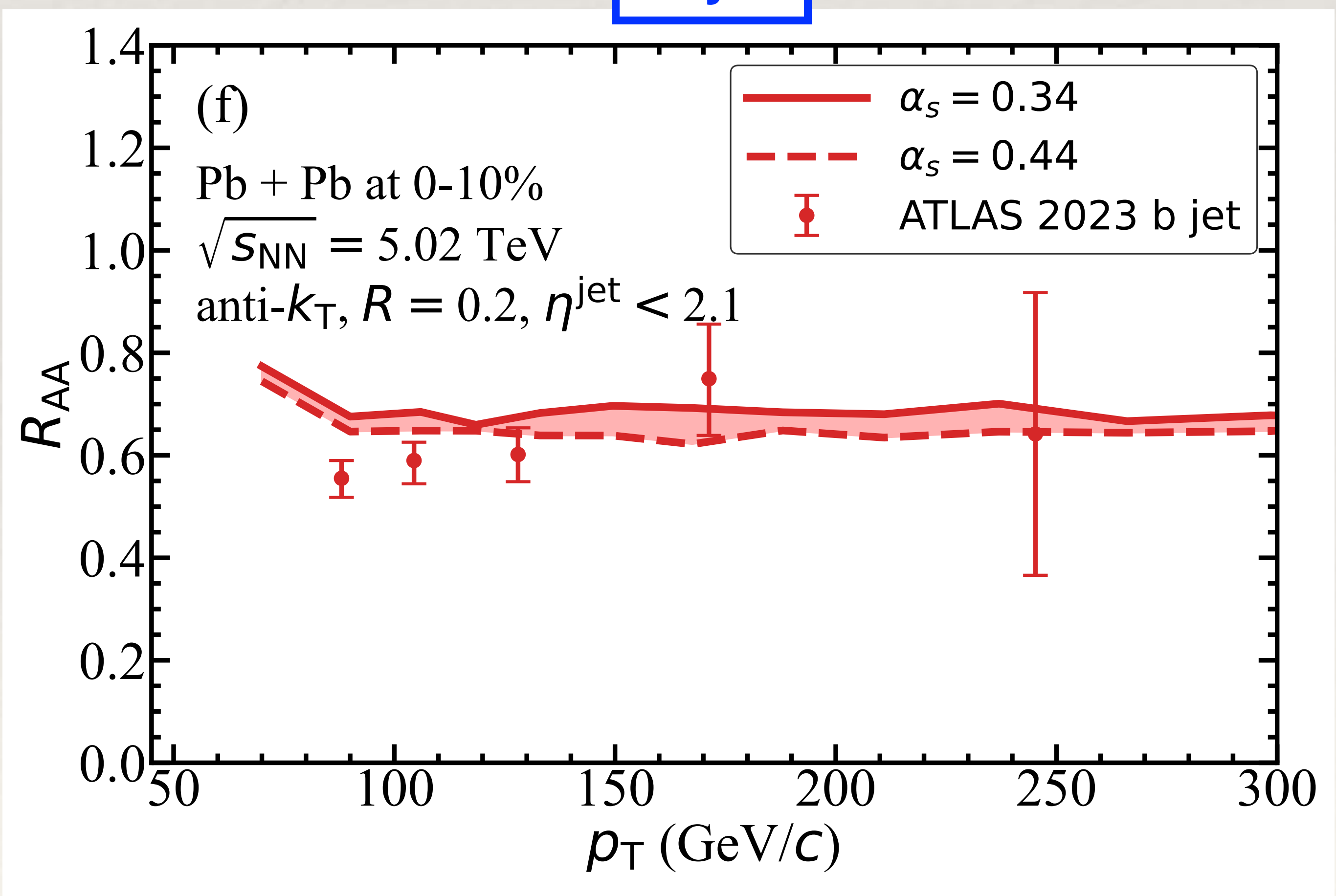
charged jet



D-tagged jet



b-jet



[Dang, SC, Xing, and Qin, arXiv: 2602.10395]

Centrality dependence of jet quenching

Revisit the definition of R_{AA}:

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{dN_{\mathrm{AA}}/dp_{\mathrm{T}}}{dN_{pp}/dp_{\mathrm{T}}}$$

$\langle N_{\mathrm{coll}} \rangle$: number of binary NN collisions

Centrality dependence of jet quenching

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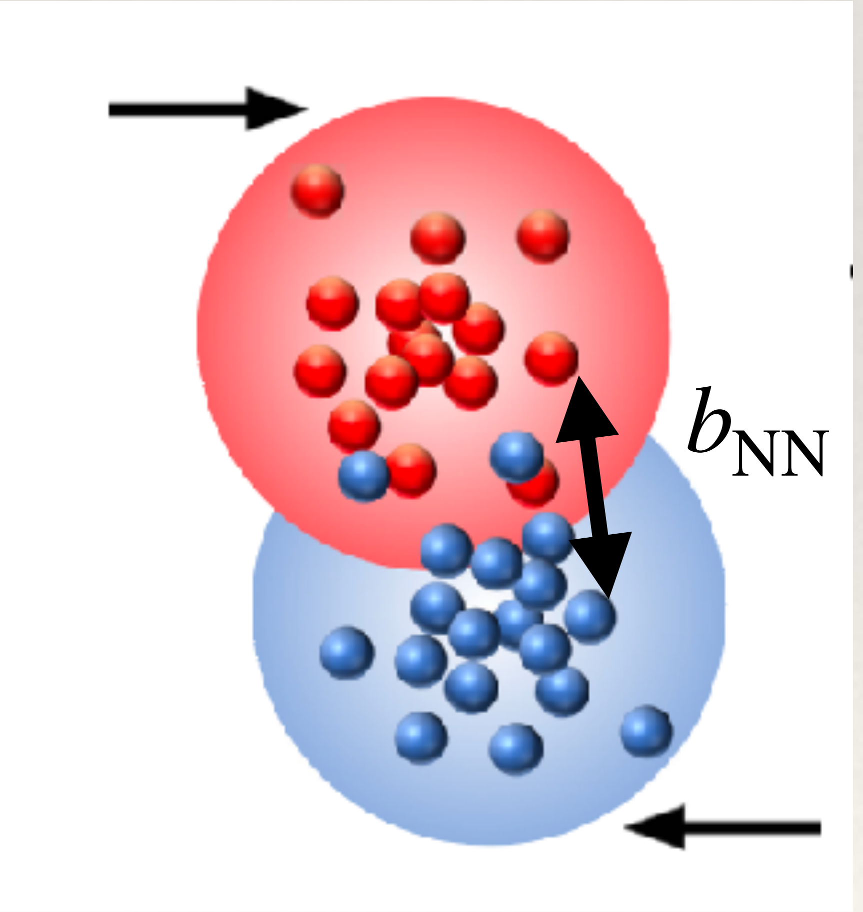
$\langle N_{coll} \rangle$: number of binary NN collisions

Underlying assumptions: without medium effect, 1 AA collision = $\langle N_{coll} \rangle$ *pp* collisions for jets

↓ require

Each binary NN collision in AA = one *pp* collision in jet production (hard partonic scatterings)

↓ require



NN collision does not depend on b_{NN}

$\langle b_{NN} \rangle$ in AA given centrality $\neq$ $\langle b_{NN} \rangle$ of unbiased *pp*

Centrality dependence of jet quenching

Revisit the definition of R_{AA}:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$

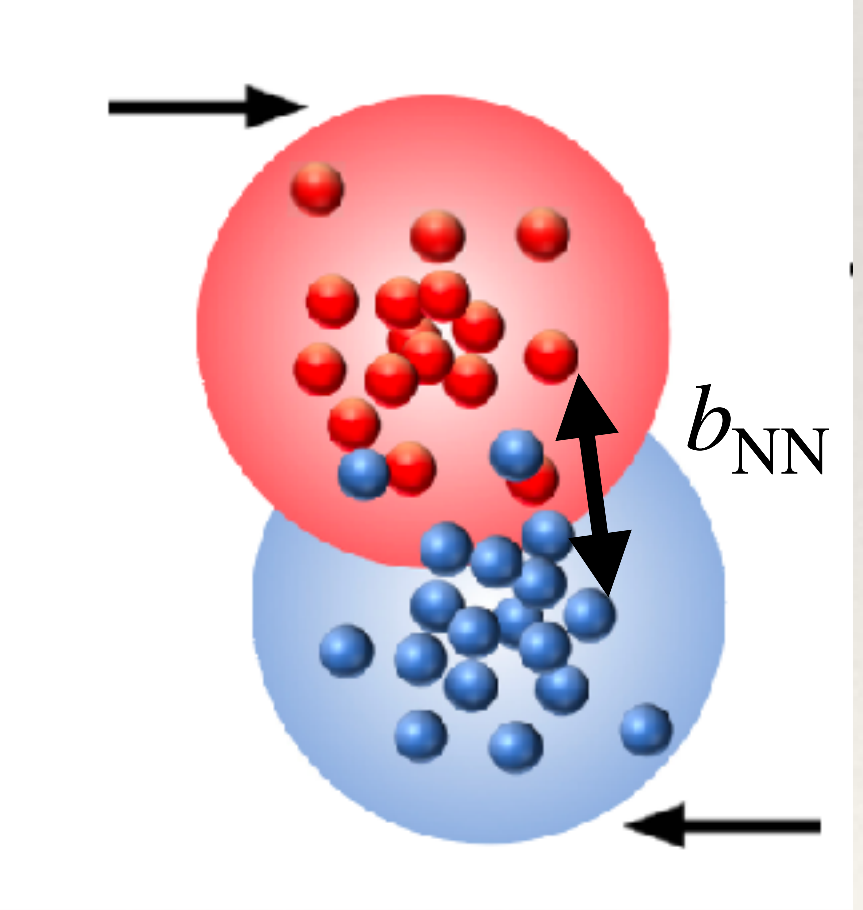
$\langle N_{coll} \rangle$: number of binary NN collisions

Underlying assumptions: without medium effect, 1 AA collision $= \langle N_{coll} \rangle$ *pp* collisions for jets

↓ require

Each binary NN collision in AA $=$ one *pp* collision in jet production (hard partonic scatterings)

↓ require



NN collision does not depend on b_{NN} (NOT true in reality)

$\langle b_{NN} \rangle$ in AA given centrality $\neq \langle b_{NN} \rangle$ of unbiased *pp*

1 AA collision $\neq \langle N_{coll} \rangle$ *pp* collisions even without medium effect

Geometric bias effect

Geometric bias factor

$$\frac{dN_{AA}}{dp_T} = \langle N_{coll} \rangle \frac{dN_{pp}}{dp_T} \otimes \text{med} \longrightarrow \frac{dN_{AA}}{dp_T} = \frac{\langle N_{AA}^{hard} \rangle}{\langle N_{NN}^{hard} \rangle} \frac{dN_{pp}}{dp_T} \otimes \text{med}$$

incorrect

correct

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{\langle N_{AA}^{hard} \rangle}{\langle N_{coll} \rangle \langle N_{NN}^{hard} \rangle} \frac{dN_{pp} \otimes \text{med}}{dN_{pp}}$$

experimental R_{AA} geometric bias factor theoretical R_{AA} (med effect)

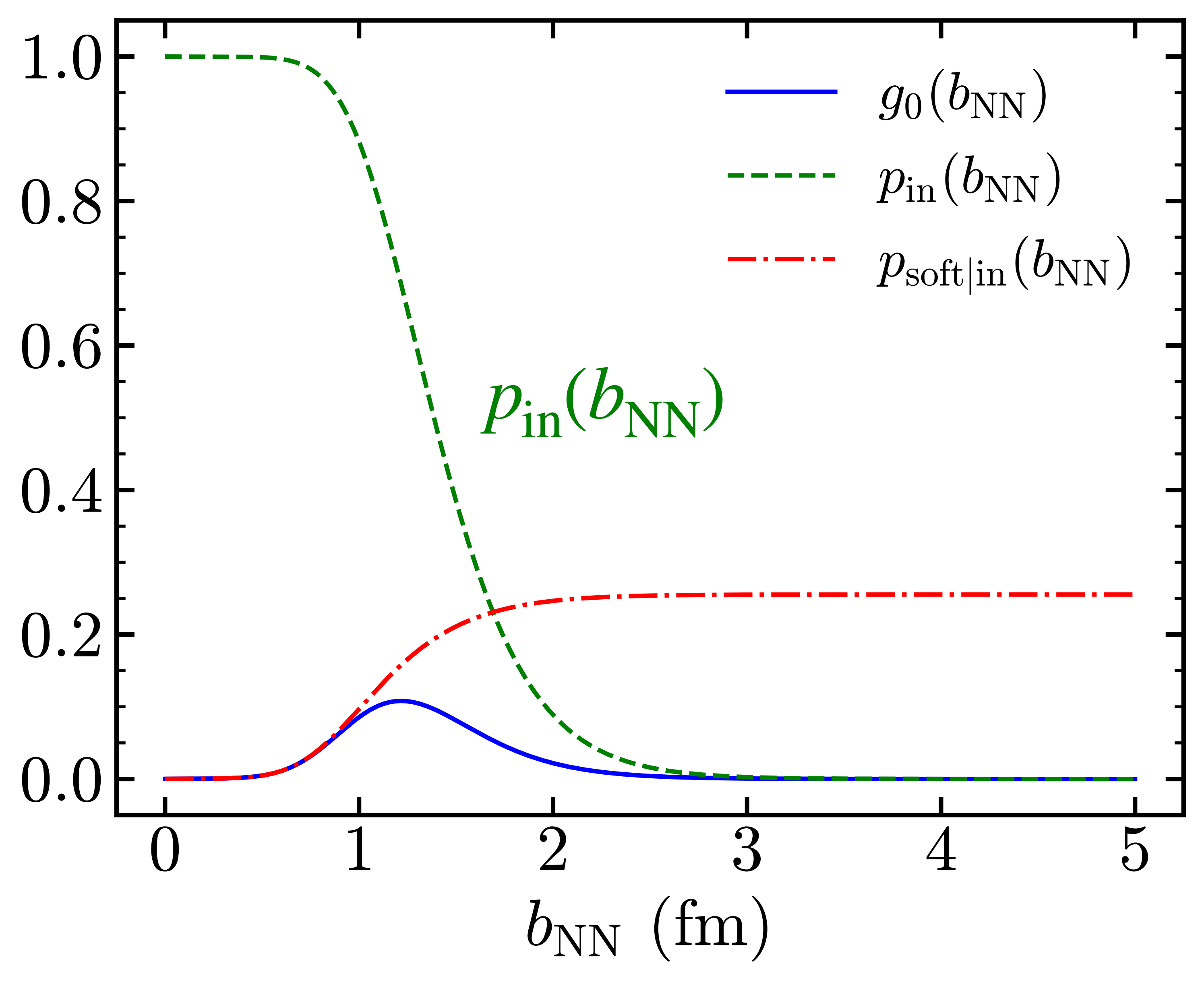
$$R_{AA} = R_{AA}^{bias} \times R_{AA}^{med}$$

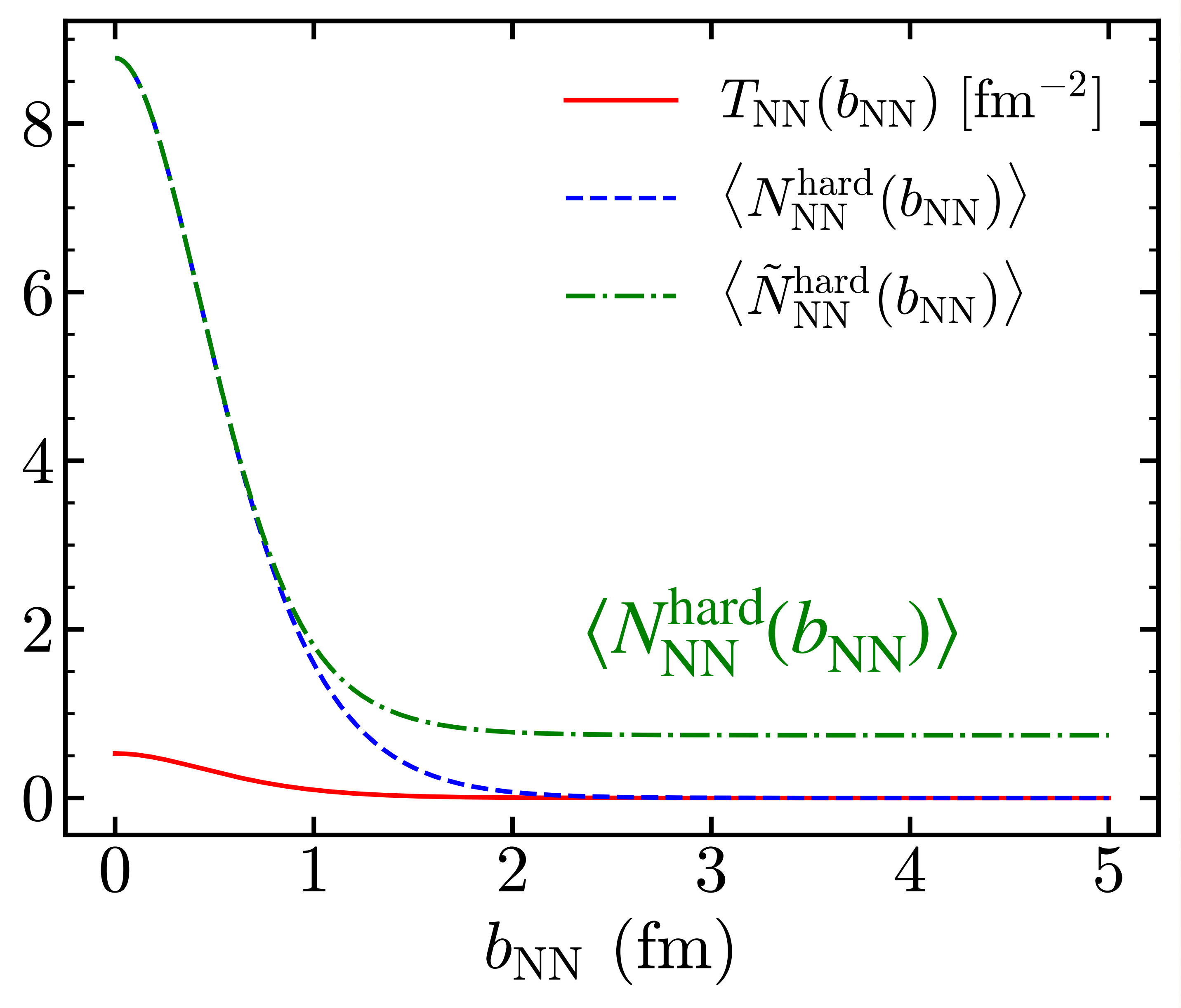
Standard Glauber *vs.* HIJING initial condition

Standard Glauber: binary (inelastic) collision happens when $b_{\rm NN} < \sqrt{\sigma_{\rm in}/\pi}$ (black disk)

one hard scattering per binary NN collision (no $b_{\rm NN}$ dependence)

HIJING: binary collision — $p_{\rm in}(b_{\rm NN})$, hard scattering number per binary NN collision — $\langle N_{\rm NN}^{\rm hard}(b_{\rm NN})\rangle$





Detailed calculations:

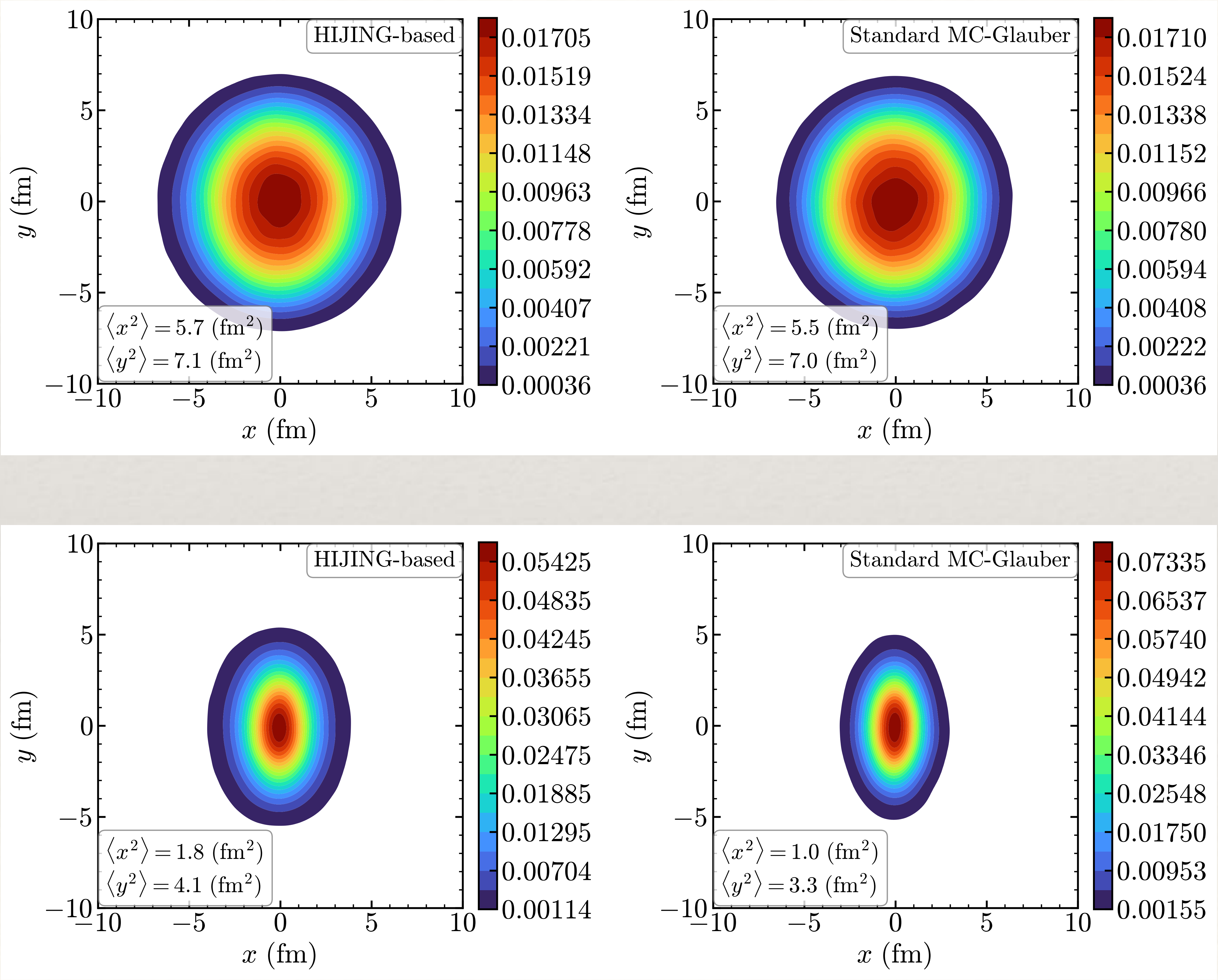
- Wang, PRD 43 (1991) 104
- Wang and Gyulassy, PRD 44 (1991) 3501
- Sun, Dang, SC, arXiv:2604.19288

Effects of b_{NN}-dependent $p_{\mathrm{in}}(b_{\mathrm{NN}})$ and $\langle N_{\mathrm{NN}}^{\mathrm{hard}}(b_{\mathrm{NN}})\rangle$

HIJING-based   Standard Glauber

0-10%

50-70%



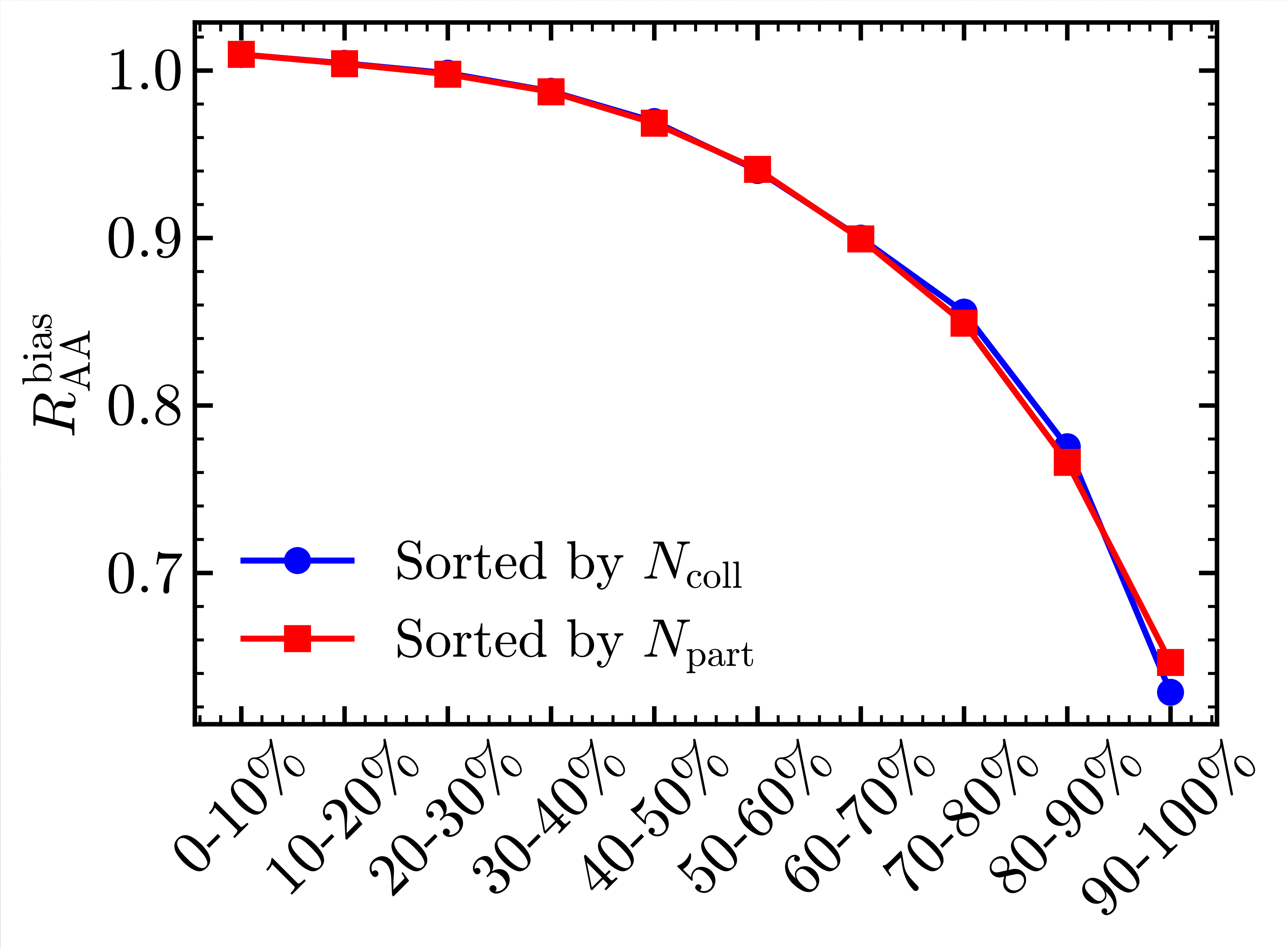
Distribution of jet production vertices

- Small difference in central collisions
- HIJING-based model gives more sparsely distributed jets in peripheral collisions — $b_{\mathrm{NN}} > \sqrt{\sigma_{\mathrm{in}}/\pi}$ can collide
- In principle: jet energy loss HIJING-based < Standard Glauber
- In reality: negligible difference due to weak energy loss in peripheral collisions

Effects of b_{NN}-dependent $p_{in}(b_{NN})$ and $\langle N_{NN}^{hard}(b_{NN})\rangle$

Geometric bias factor of R_{AA}:

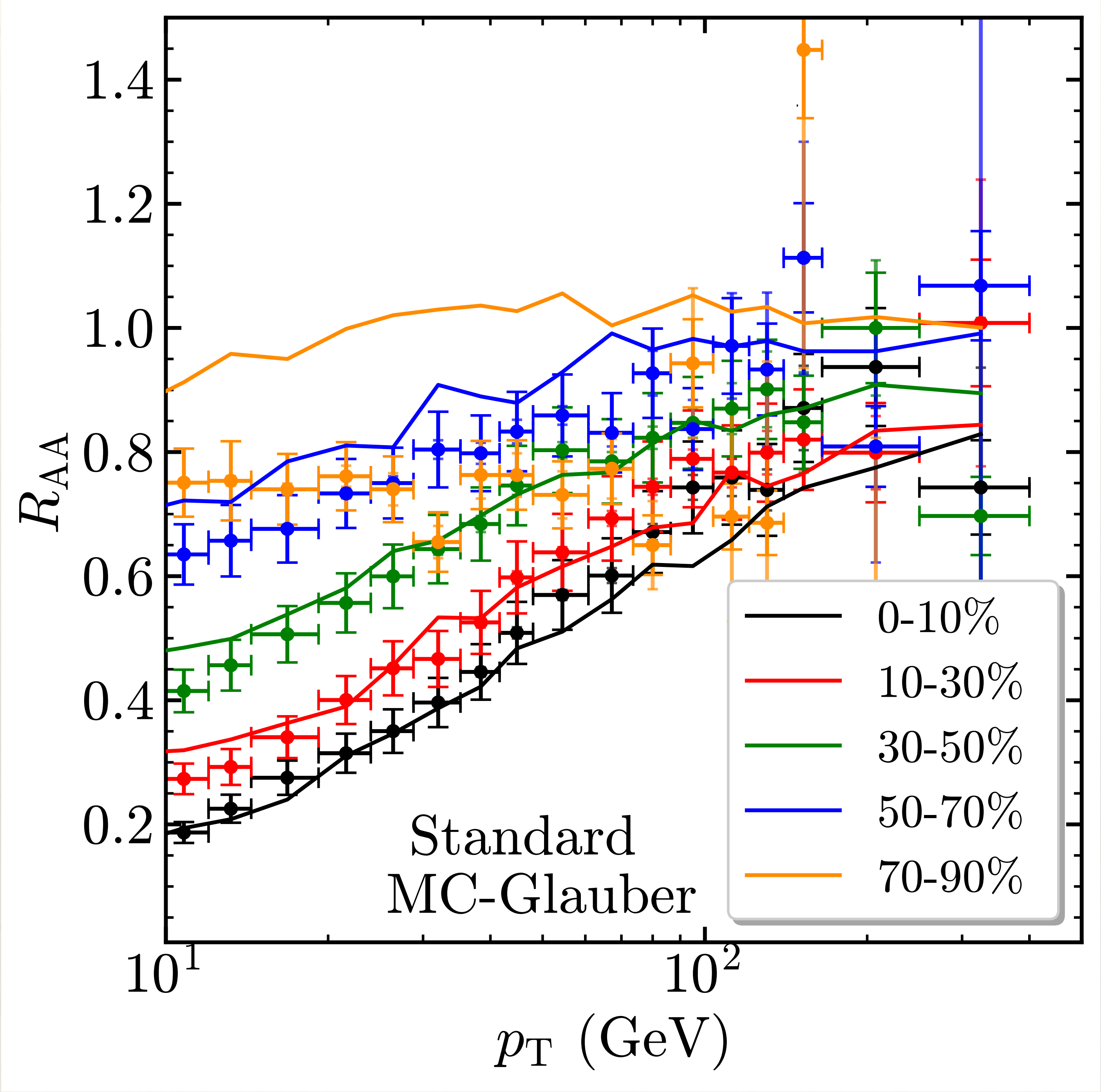
$$R_{AA}^{bias} = \frac{\langle N_{AA}^{hard}\rangle}{\langle N_{coll}\rangle\langle N_{NN}^{hard}\rangle}$$



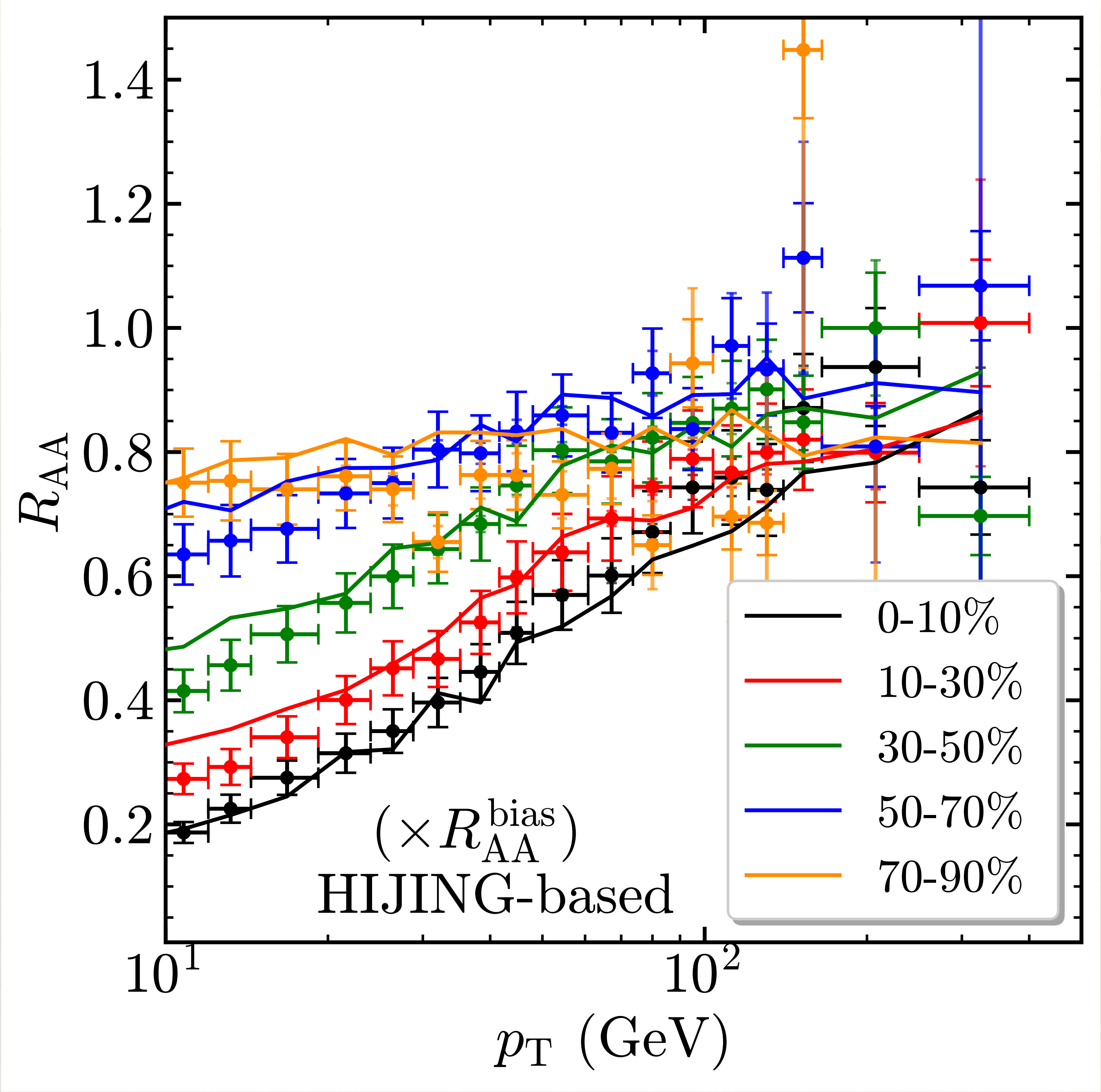
- Geometric bias effect: R_{AA} < 1 in peripheral collisions even in the absence of jet quenching
- Effect is larger than 5% beyond 50% centrality

Centrality dependence of the hadron R_{AA}

Standard Glauber initial condition



HIJING-based initial condition

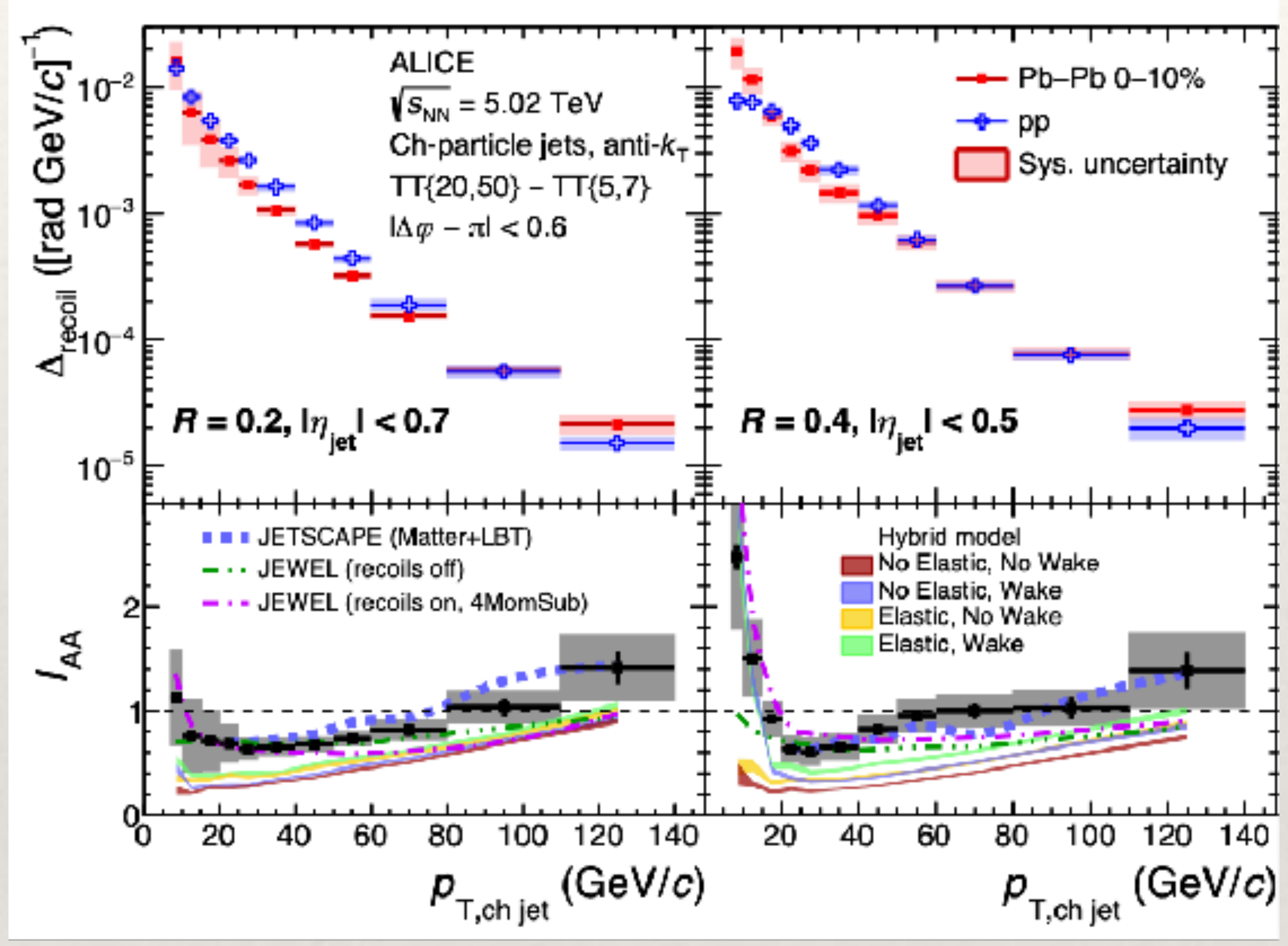


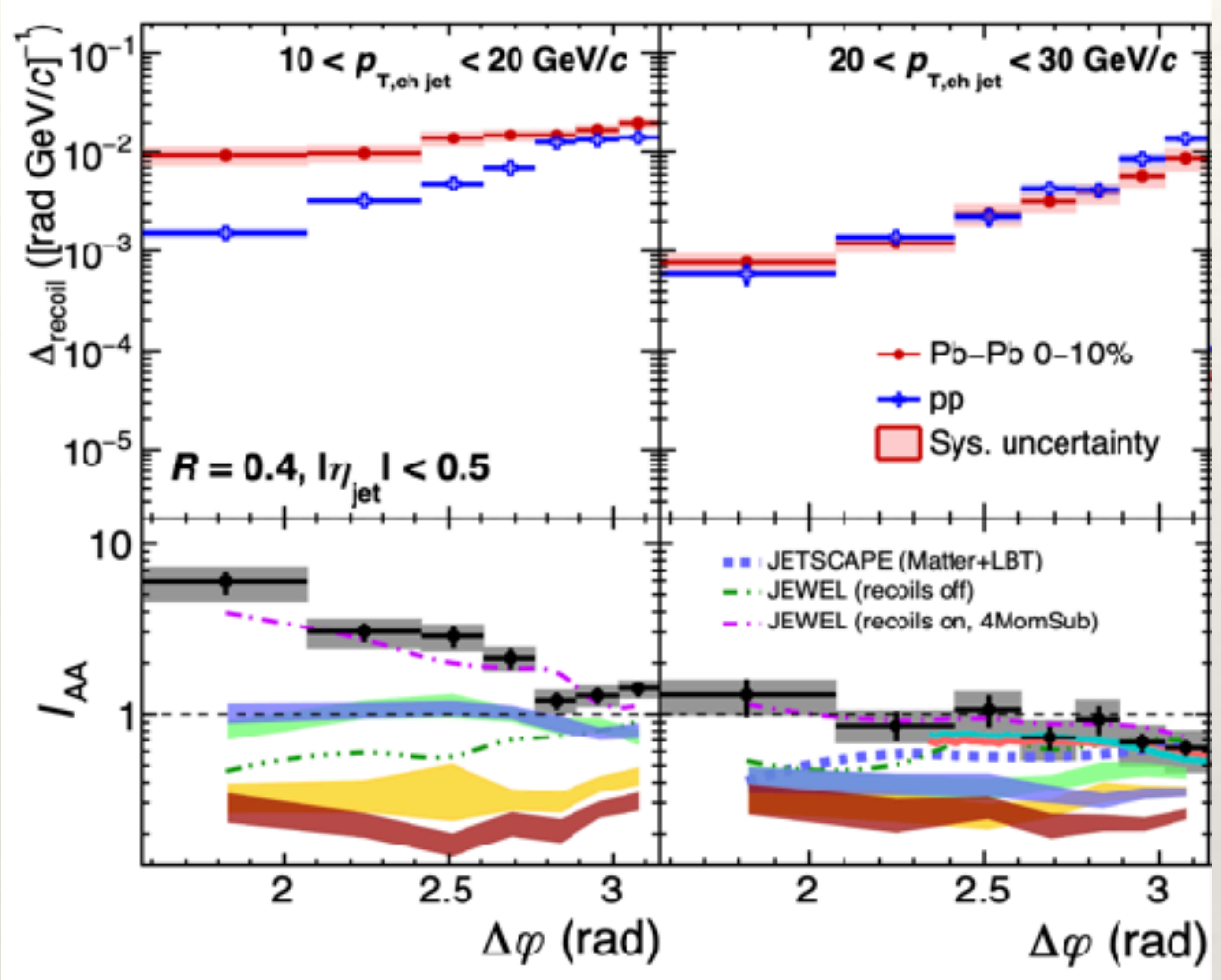
- Similar performance in central to mid-central collisions
- Significant improvement in peripheral collisions (over 50%)

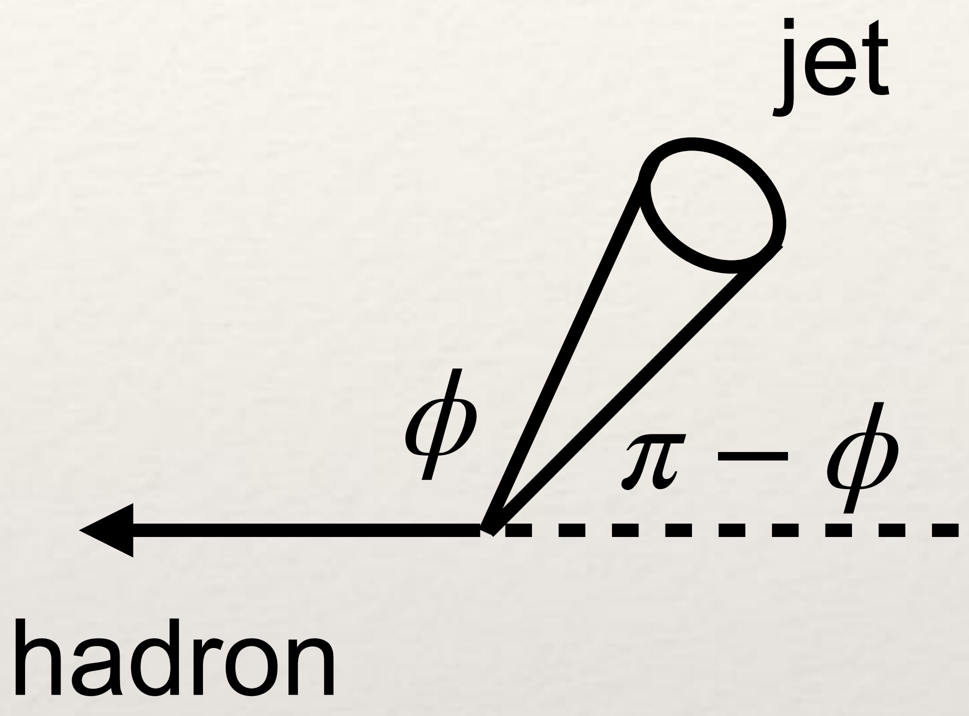
From hadrons and jets to hadron-triggered jets

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

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



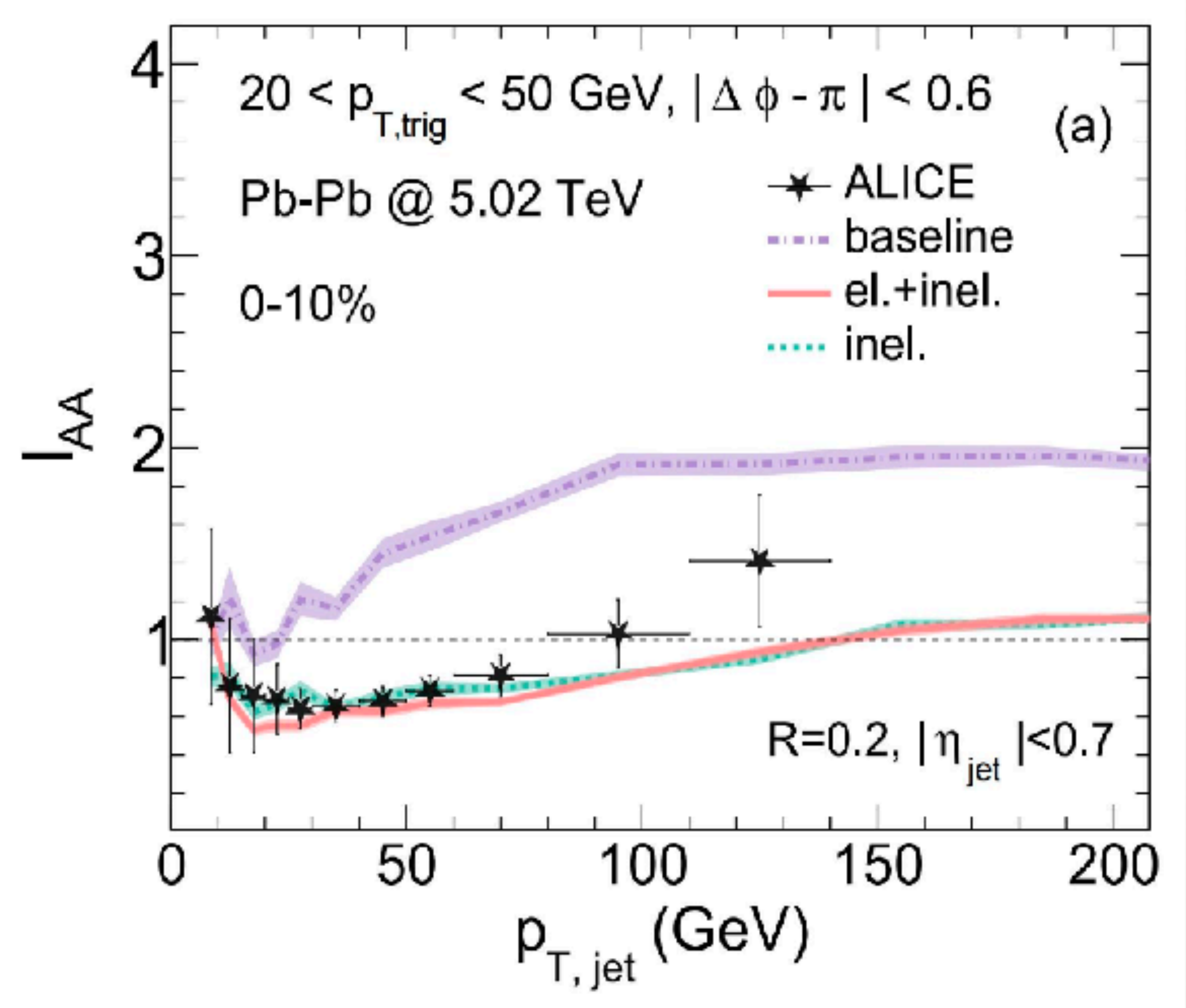


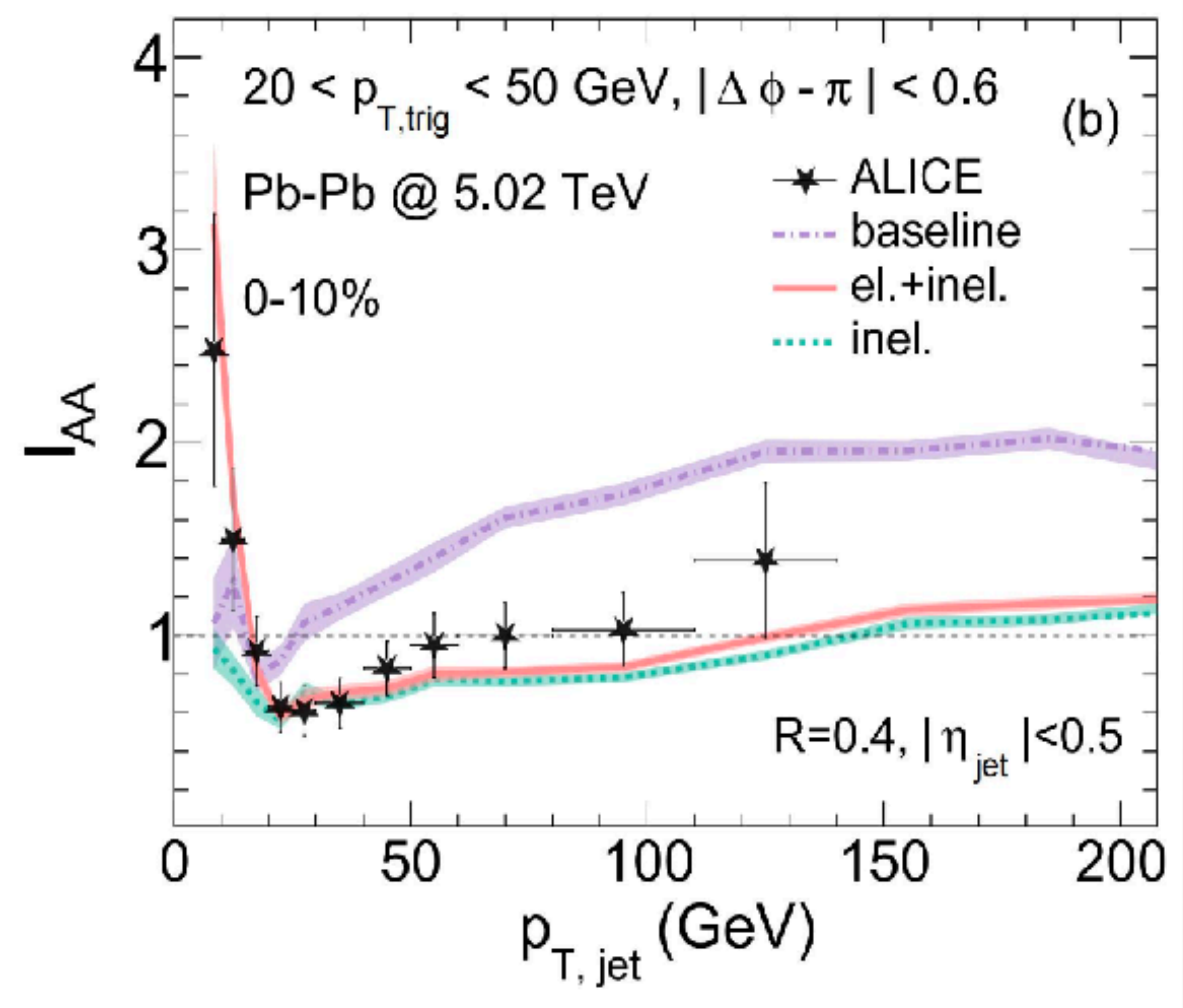


[ALICE, Phys. Rev. Lett. 133 (2024) 022301]

- 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, He, SC, Yi, Wang, arXiv:2512.12715]

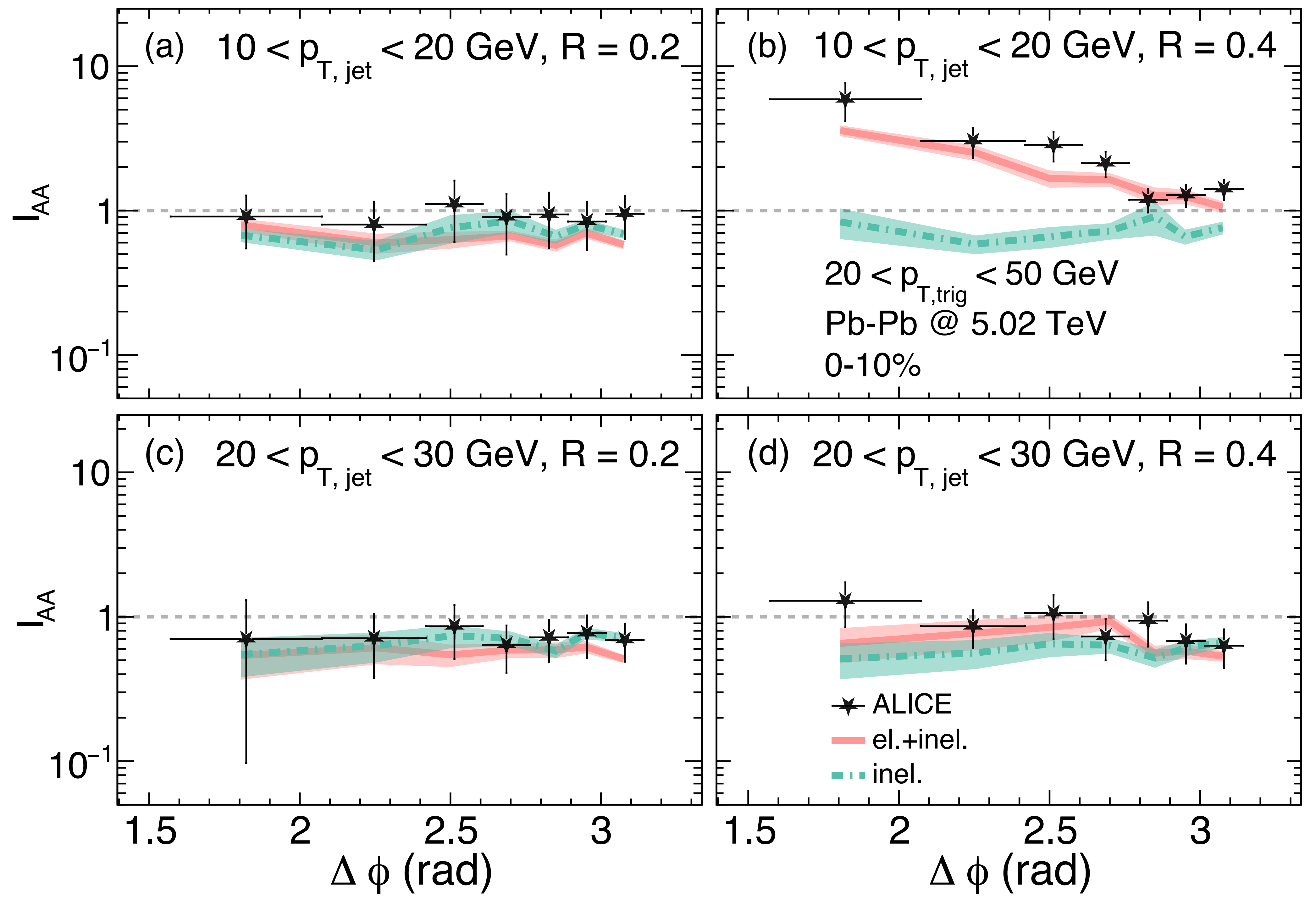
- Simultaneous description of hadron and jet is crucial for understanding hadron-triggered jets
- Enhancement at low $p_{\mathrm{T,jet}}$: medium response
- Enhancement at high $p_{\mathrm{T,jet}}$: enhancement of I_{AA} baseline by trigger bias

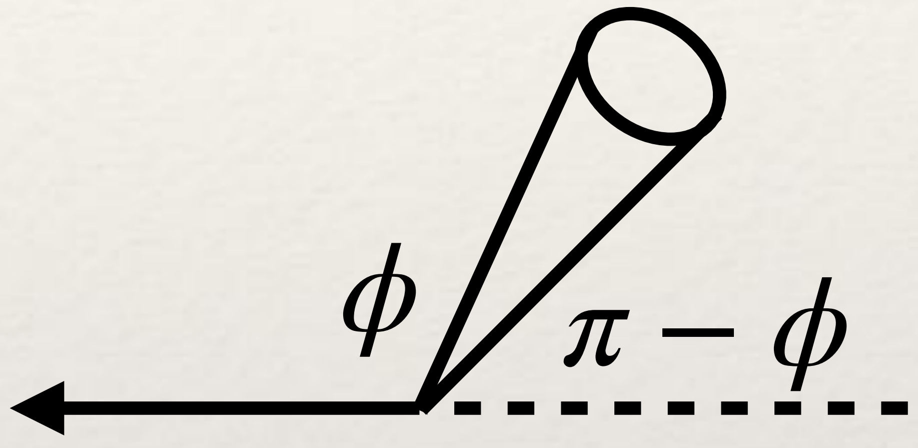
Acoplanarity of *h*-jets

$R = 0.2$ $R = 0.4$

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

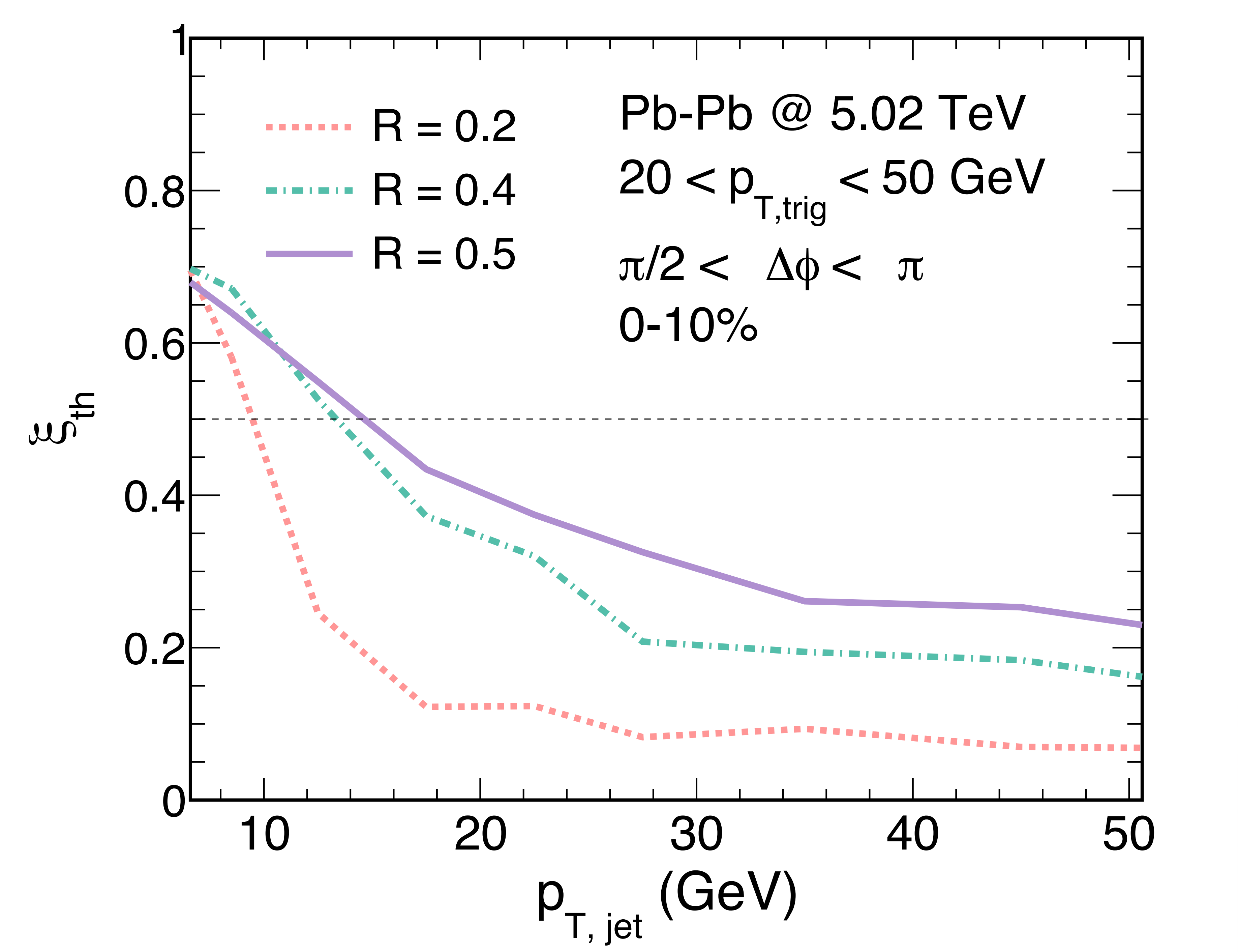
$10 < p_{\mathrm{T,jet}} < 20$ GeV

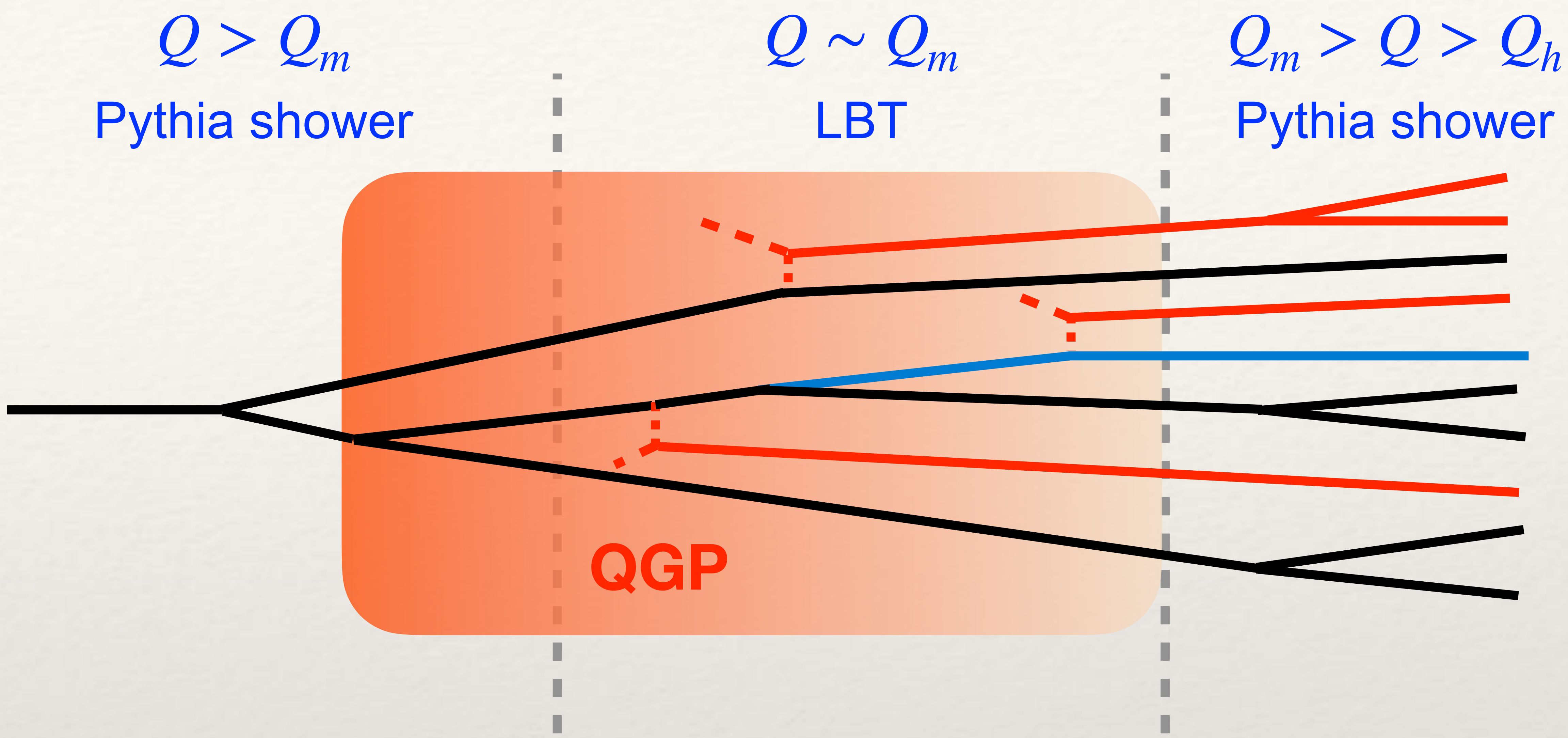




- Enhancement of I_{AA} at large $\pi - \phi$ for jets with large R and low $p_{\mathrm{T,jet}}$, medium response.
- Enhancement disappears for small R or high $p_{\mathrm{T,jet}}$. Why?

Thermal origin of the enhanced jet yields

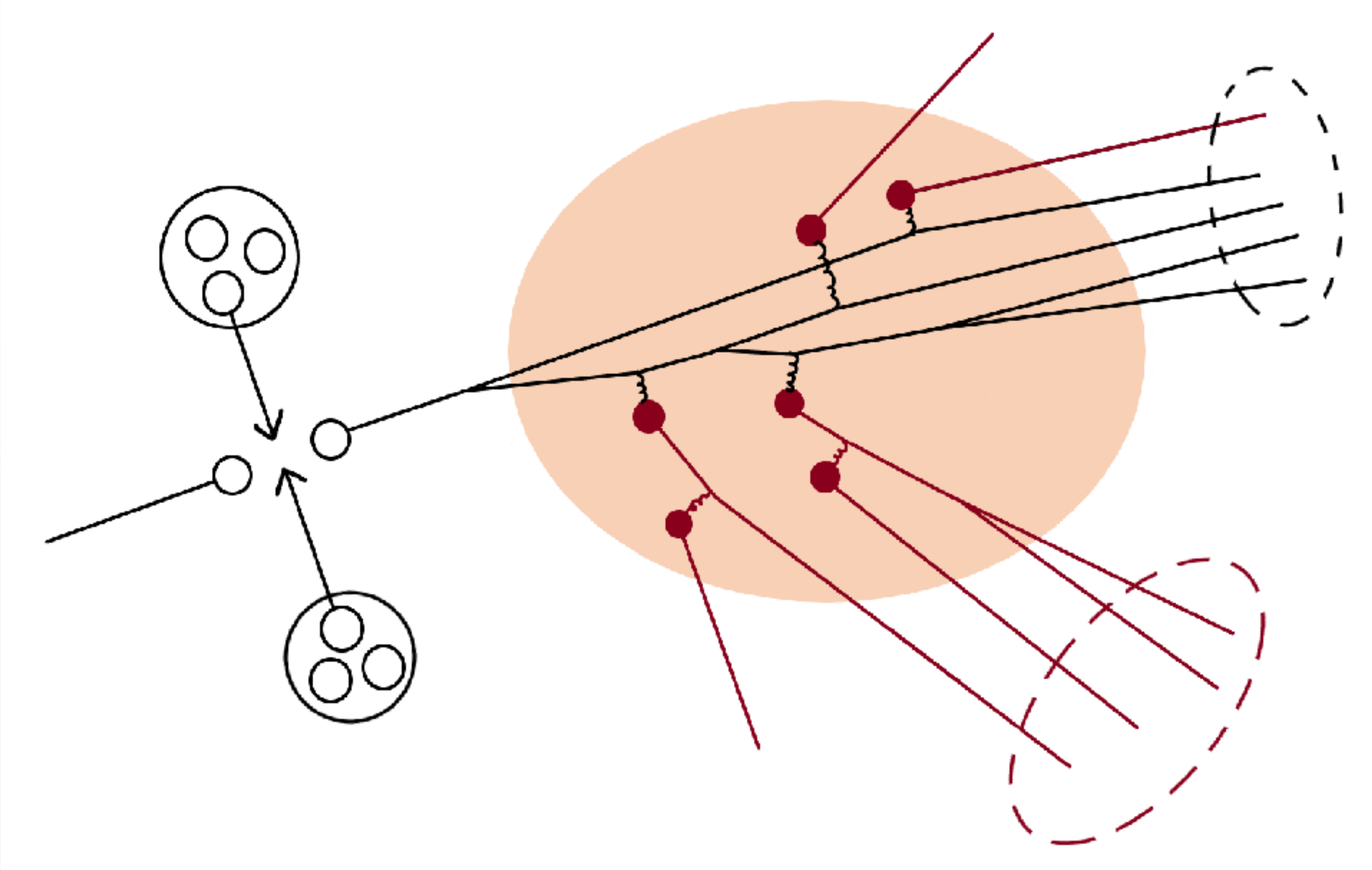




$$\xi_{\rm th} = \frac{|\vec{p}_{\rm T}^{\rm \,recoil} - \vec{p}_{\rm T}^{\rm \,negative}|}{|\vec{p}_{\rm T}^{\rm \,recoil} - \vec{p}_{\rm T}^{\rm \,negative}| + p_{\rm T}^{\rm jet-shower}}$$

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

Emergence of “thermal recoil jets”



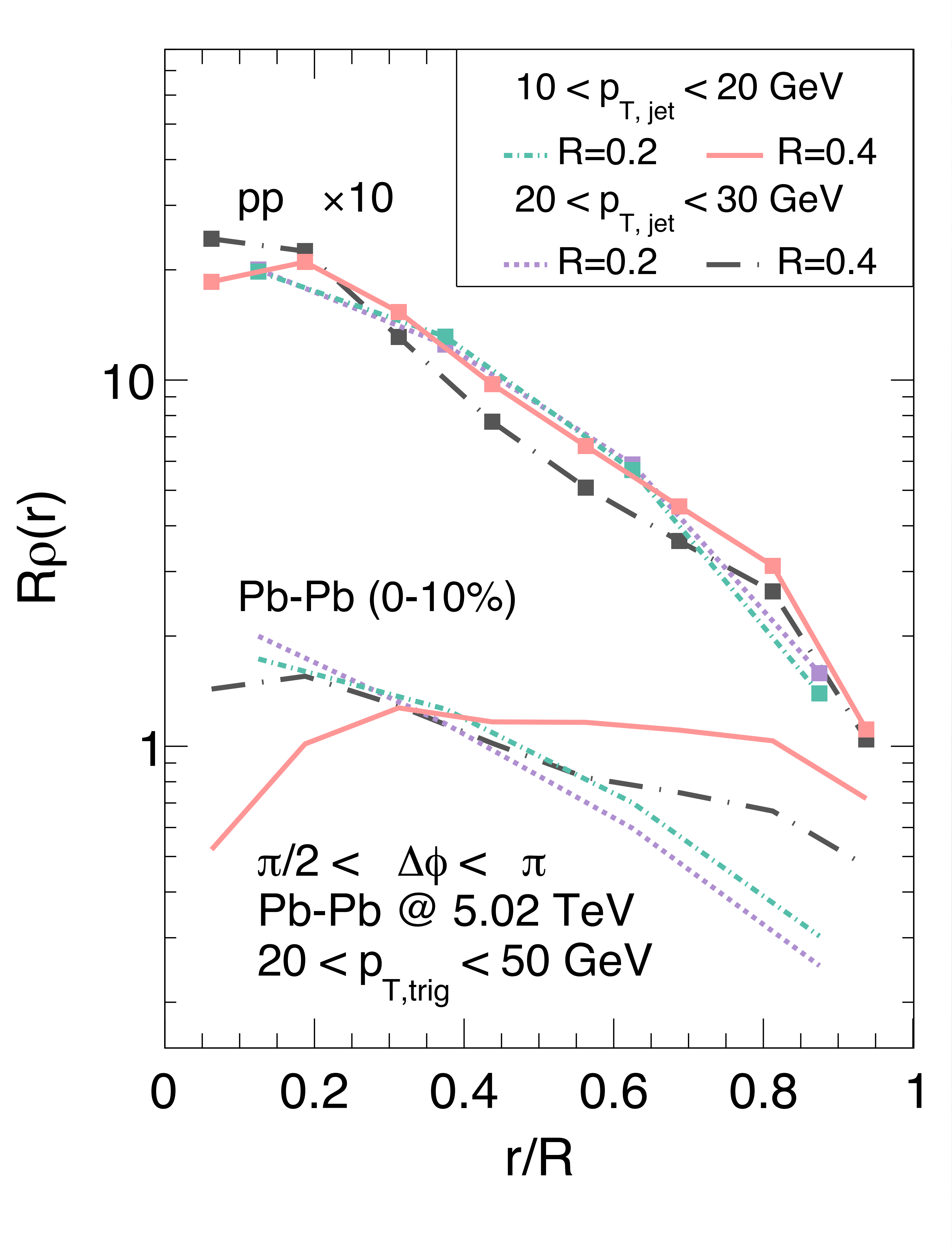
Hard jet

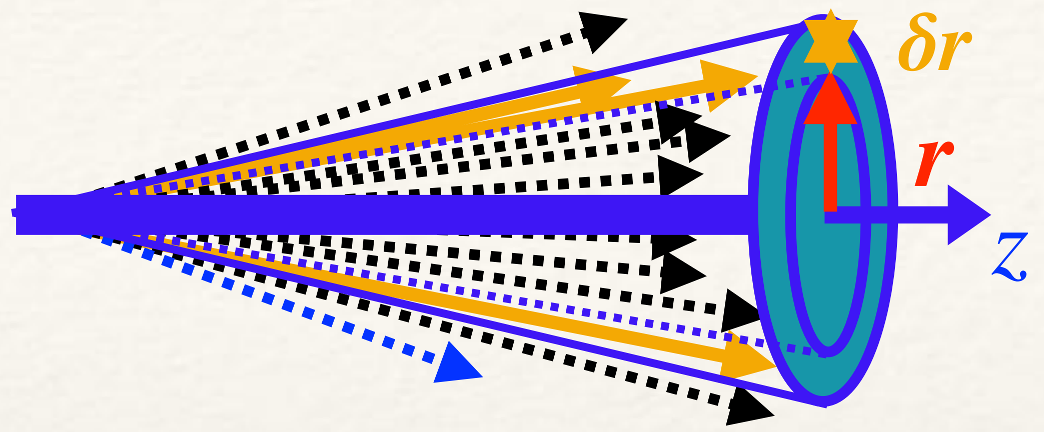
- Hard particles at the core, soft particles around

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





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

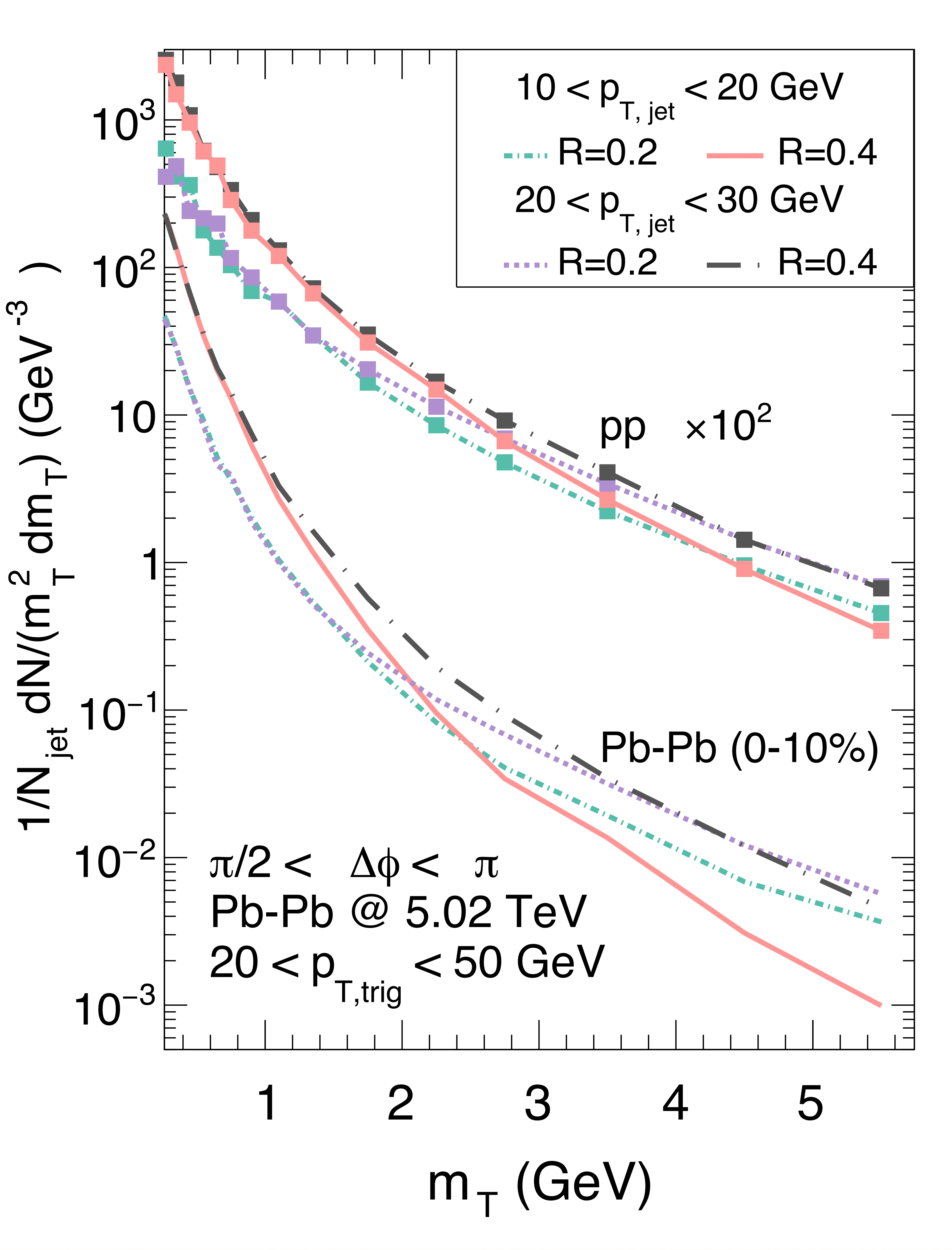
- Decreasing ρ with r for small cone-size (R) jet, similar to jets in p+p collisions

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

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

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

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



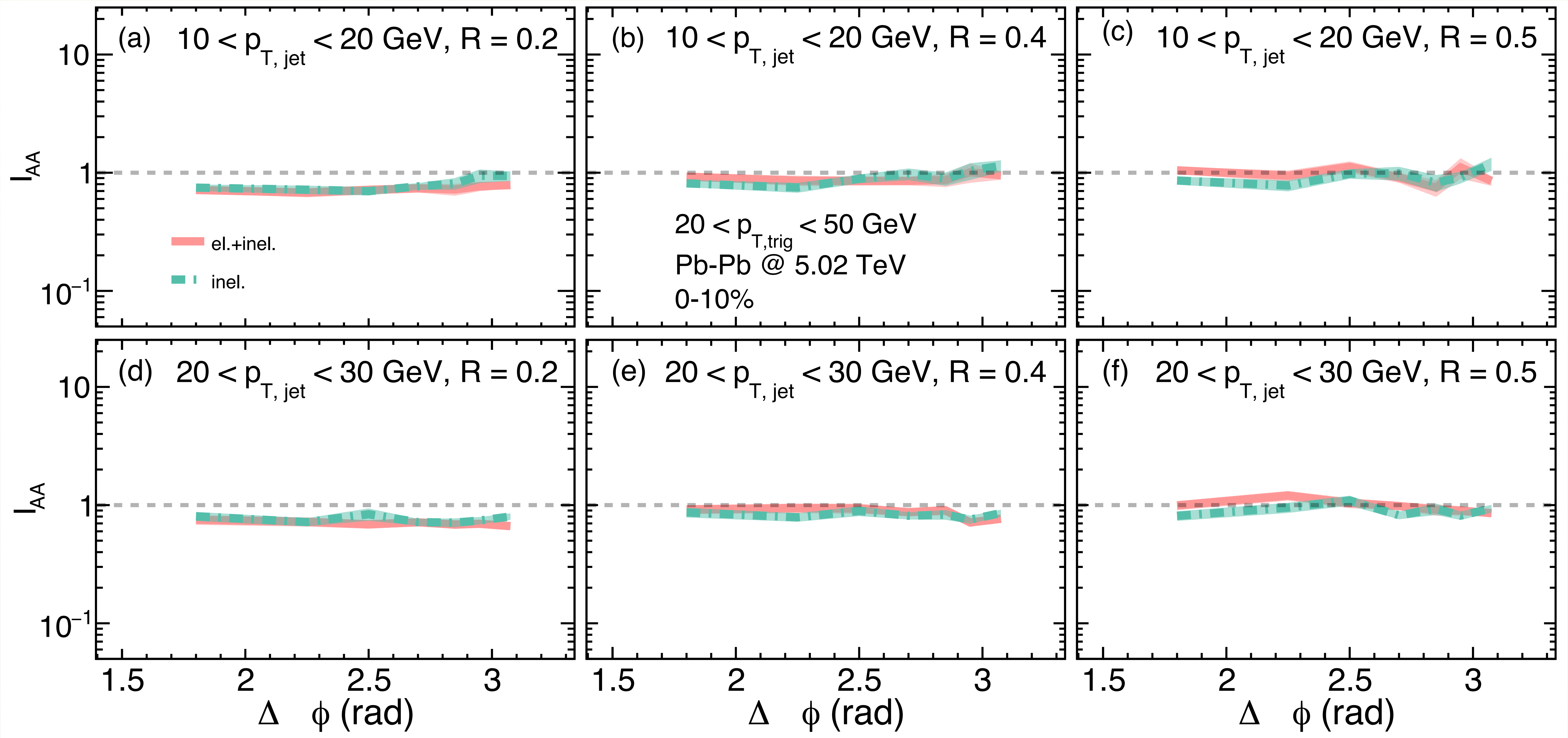
Thermal distribution:

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

- 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 $> T_{\rm QGP}$) 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

Summary

Precision improvements on jet quenching studies

- Developed a color-tracked multi-stage jet evolution model for a simultaneous description of hadron and jet suppression
- Introduced geometric bias for a better centrality dependence of jet quenching
- Proposed a novel jet production mechanism: thermal recoil jets

— naturally explains the p_T, R, $\Delta\phi$ dependencies of the hadron-jet I_{AA}

— can be straightforwardly tested by experiments

Thank you!

Backup: acoplanarity enhancement at RHIC