



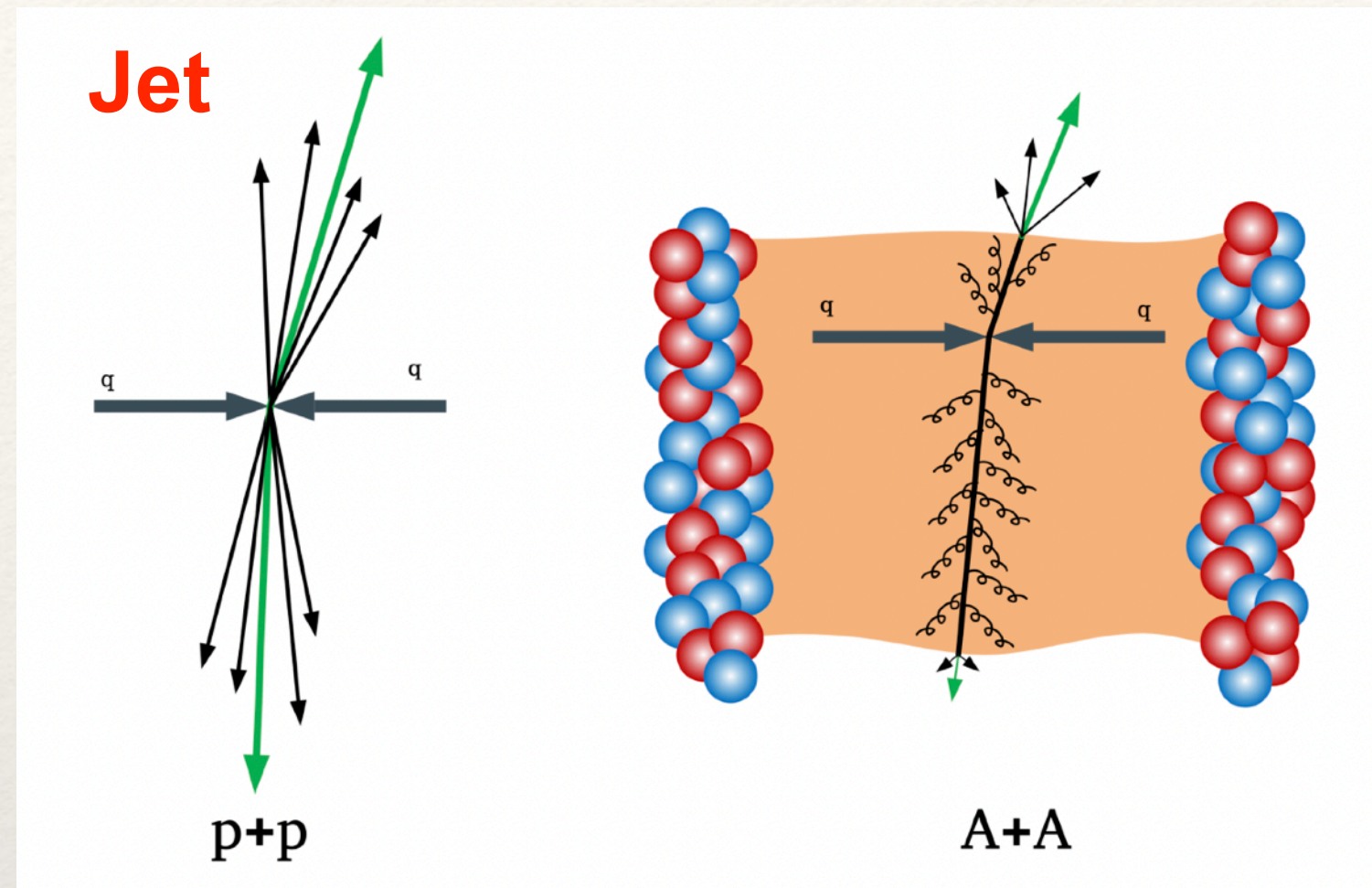
Understanding the hadron and photon triggered jet acoplanarity enhancement with thermal recoil jets

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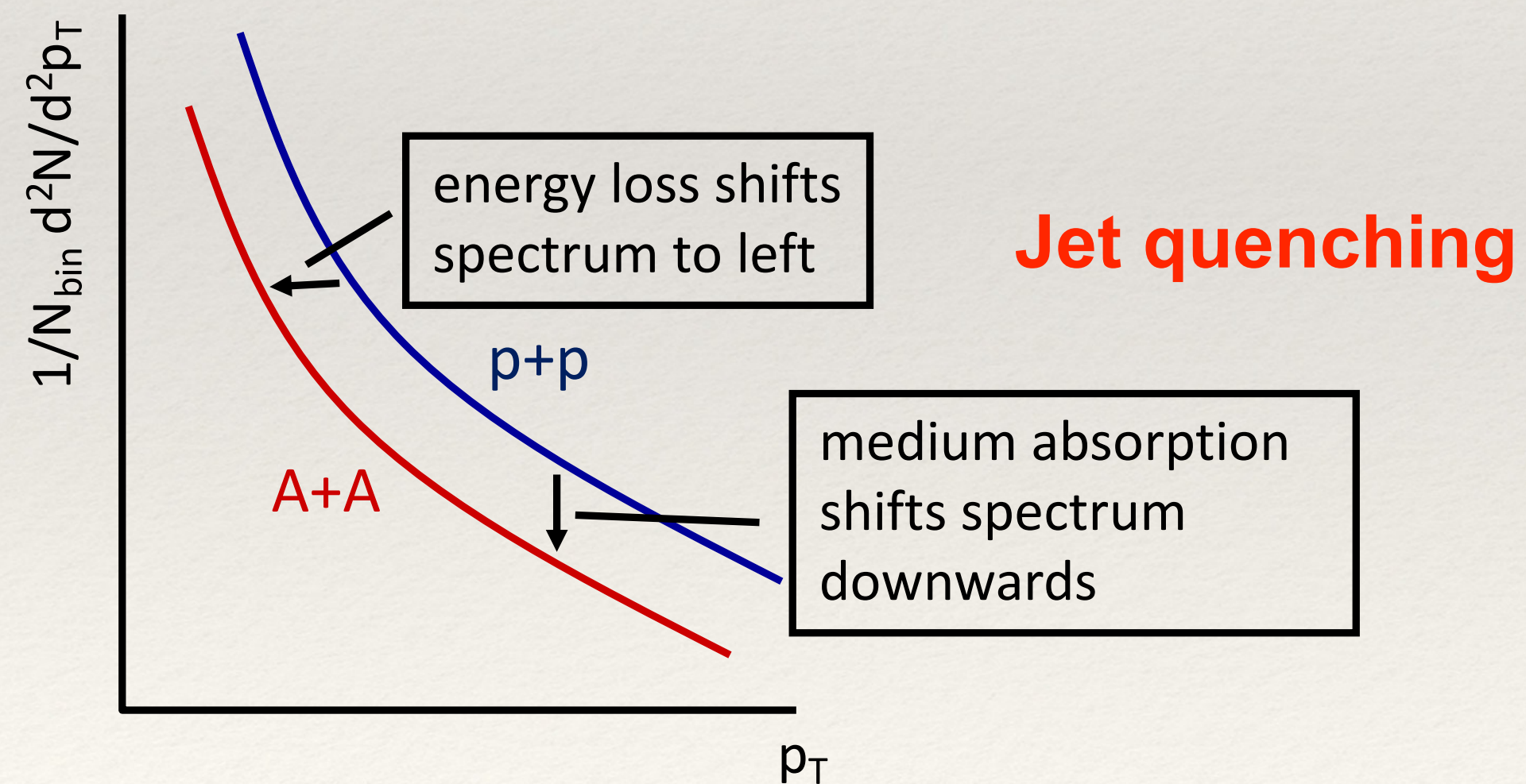
Phys. Rev. Lett. 137 (2026) 102301 and a longer article in preparation

HENPIC, October 8, 2026

Nuclear modification of high-energy particles

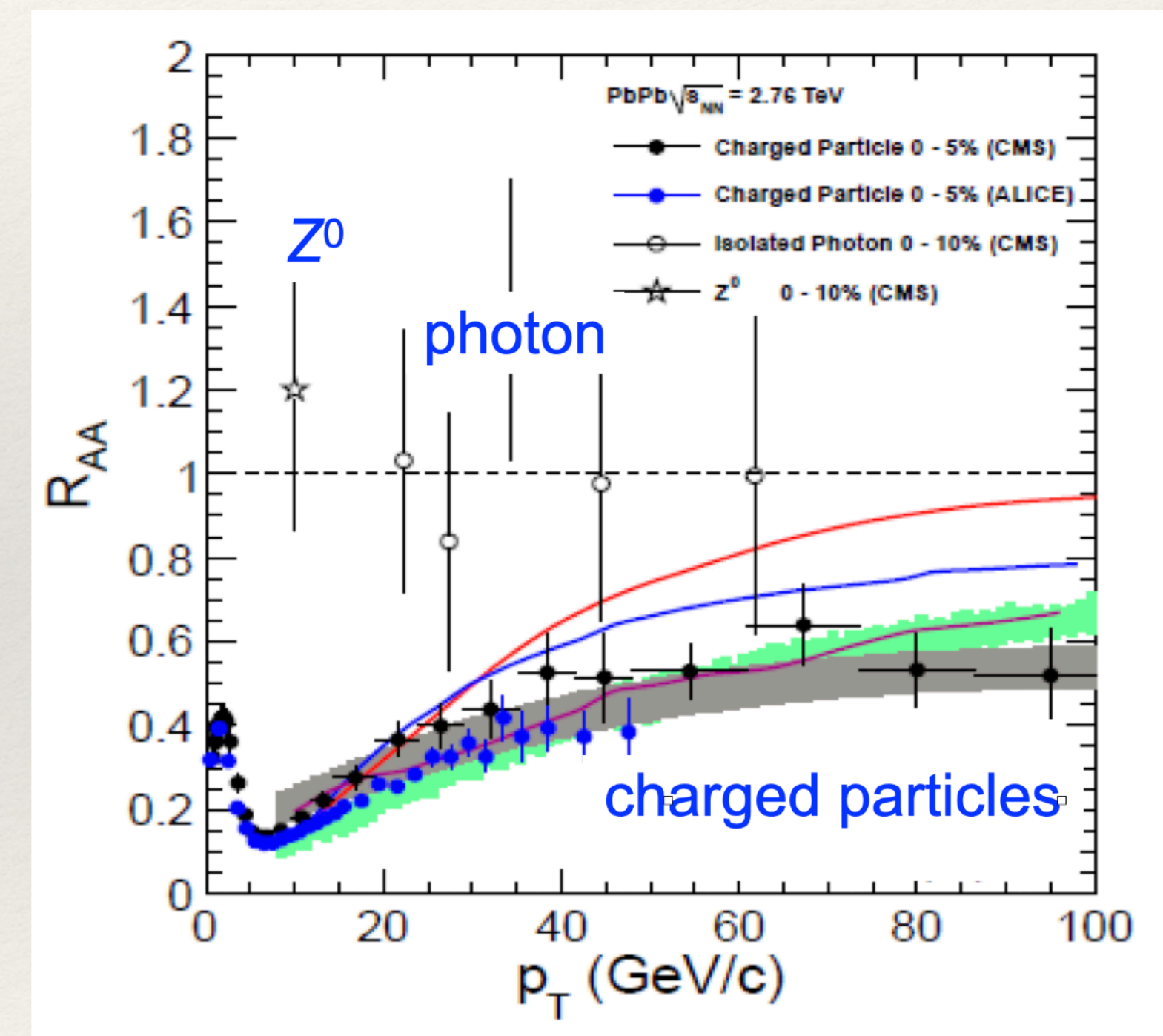


by M. Rybar / ATLAS



Nuclear modification factor

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



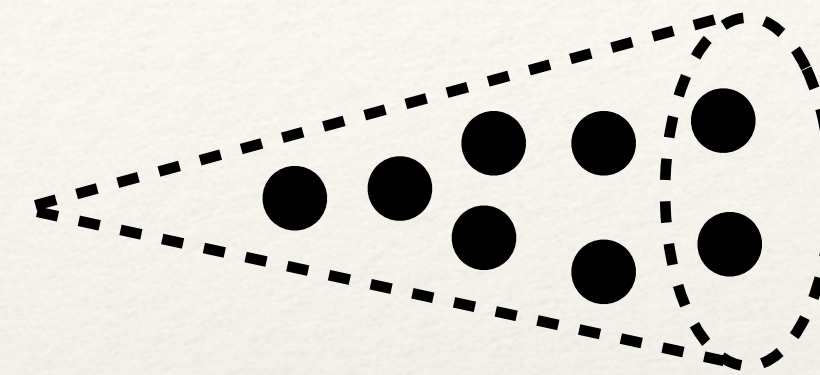
Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)

From single hadrons to full jets

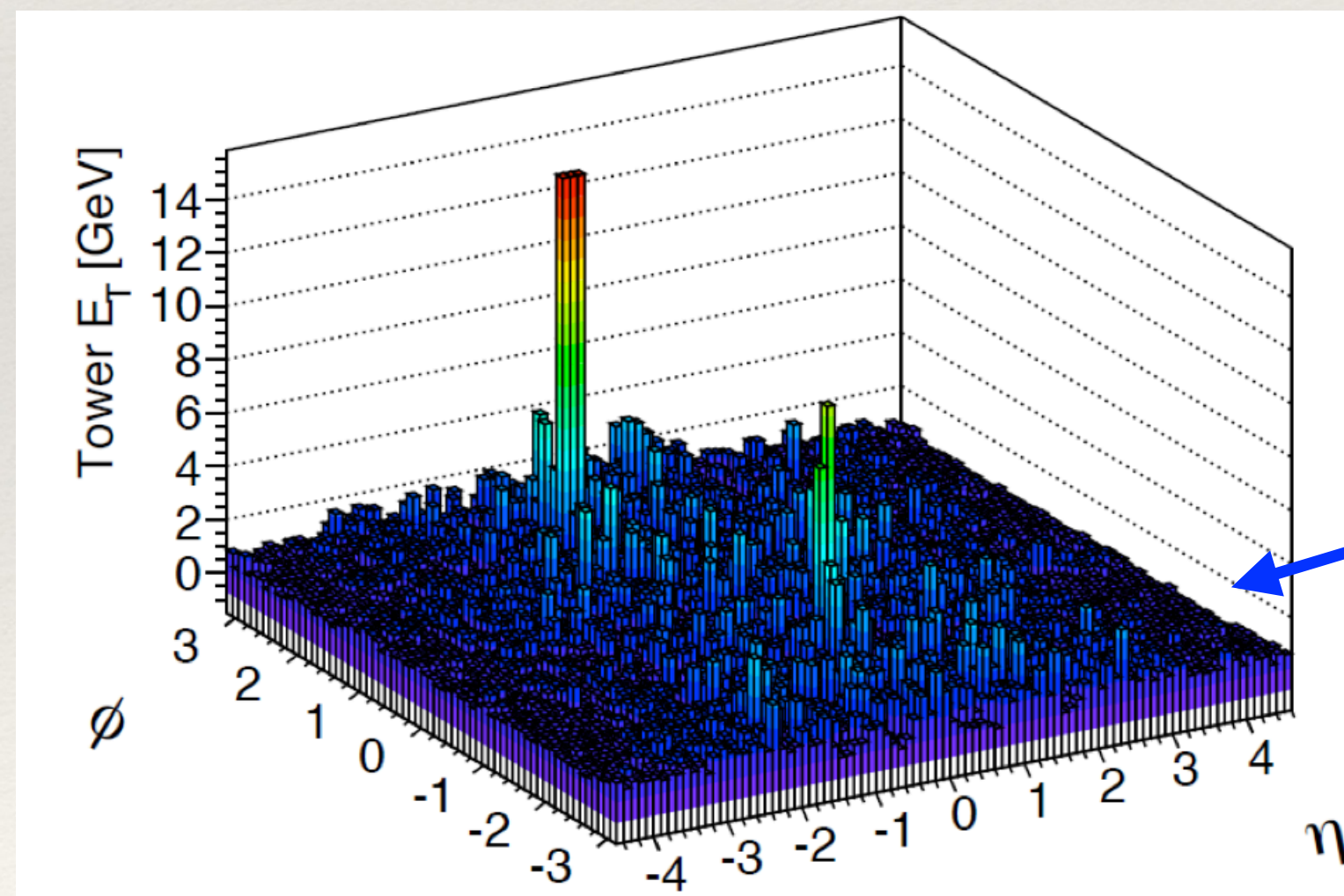
Single hadron



Full jet



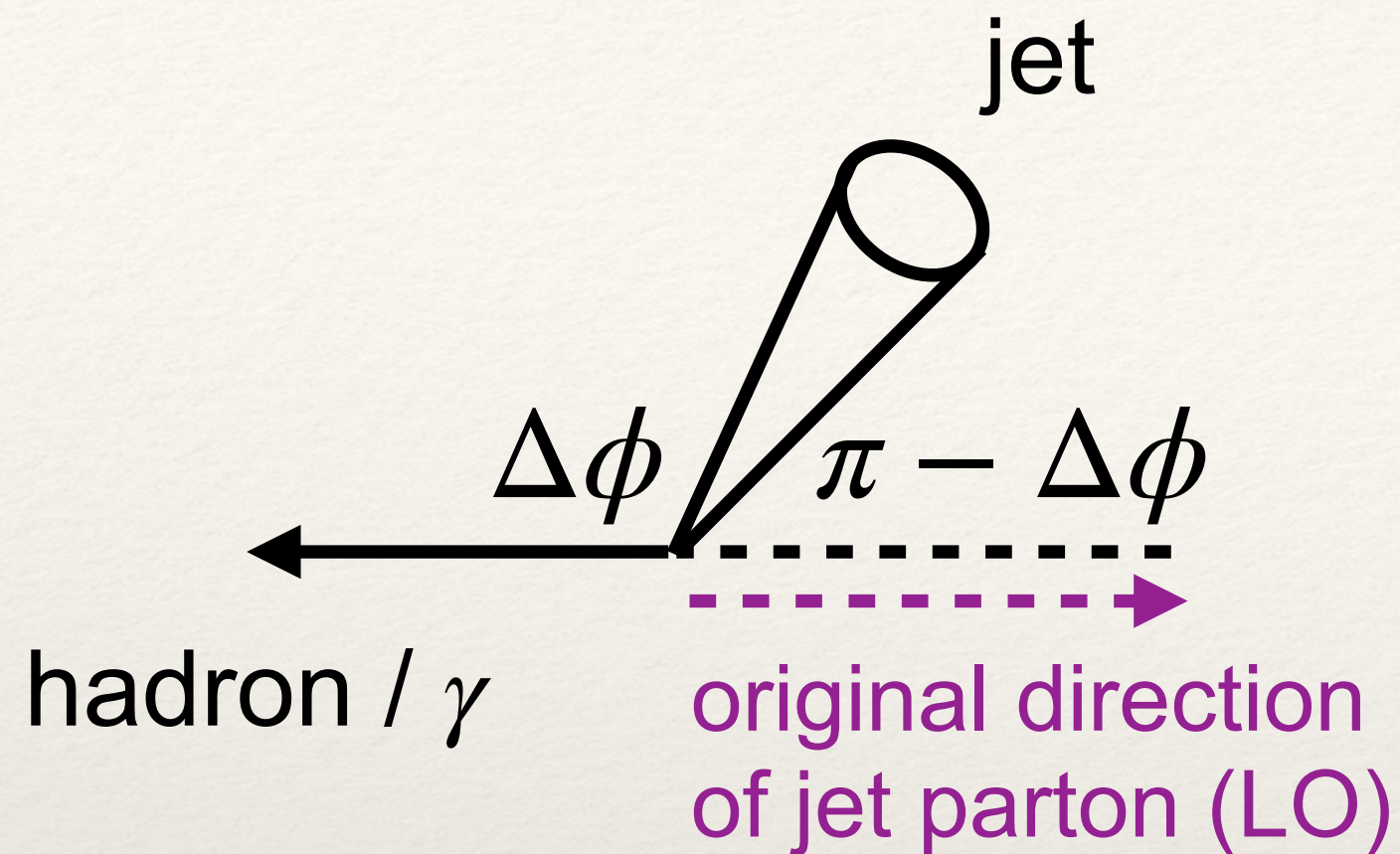
- Challenge in jet measurement in AA collisions



How to remove the QGP background in jet reconstruction?

Especially for jets with low transverse momentum (p_T) and large cone size (R)

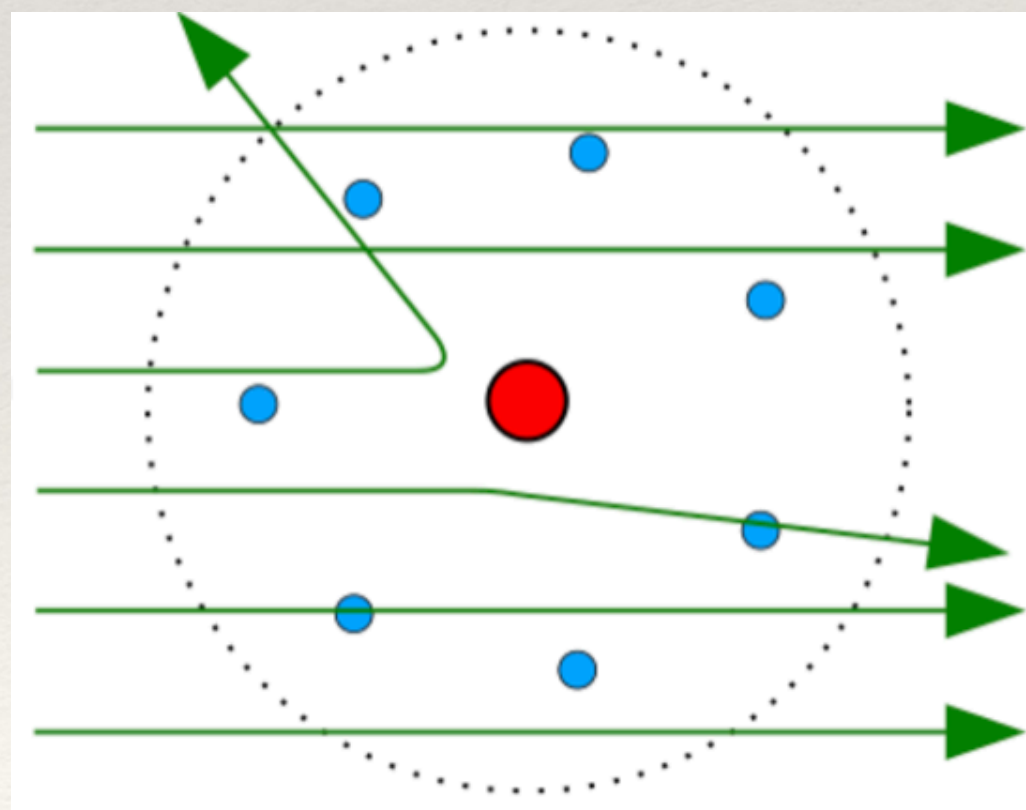
Semi-inclusive hadron or γ triggered jets



High p_T hadron/photon trigger

- enables to access low- p_T and large- R jets on its away side
- provides a reference for studying how energetic particles are deflected by medium (*acoplanarity*)

Large angle: power-law ($\sim 1/\phi^4$ for Coulomb)



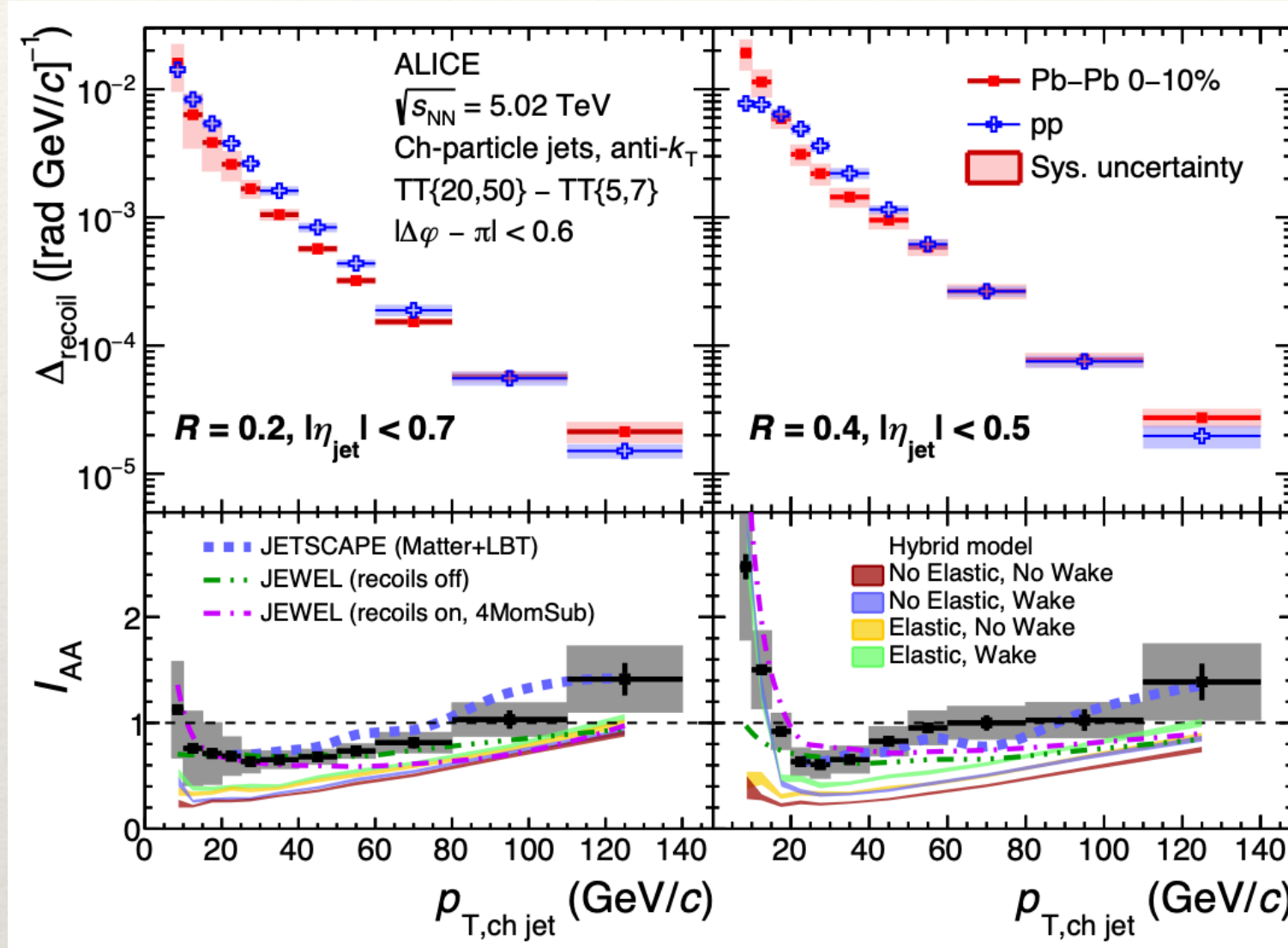
Forward: Gaussian from multiple soft scatterings

Search for Molière-like scatterings

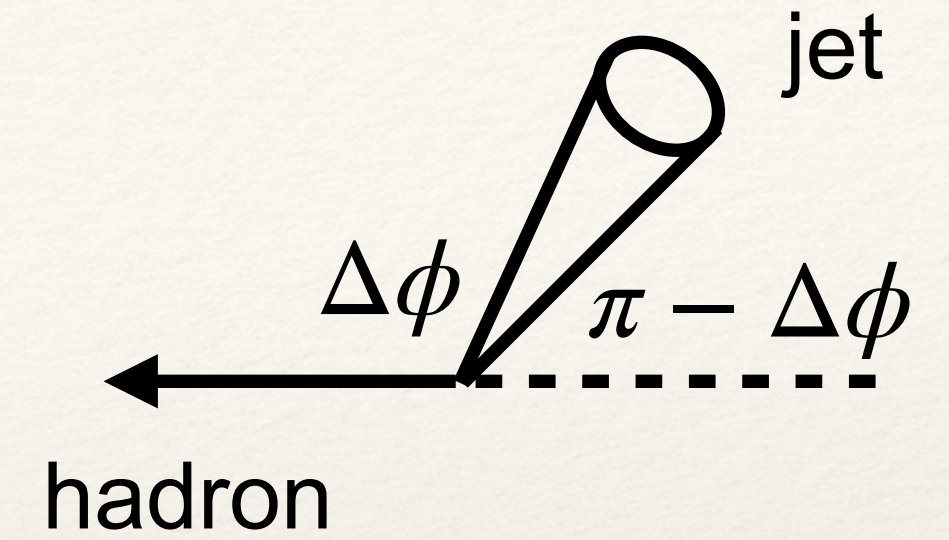
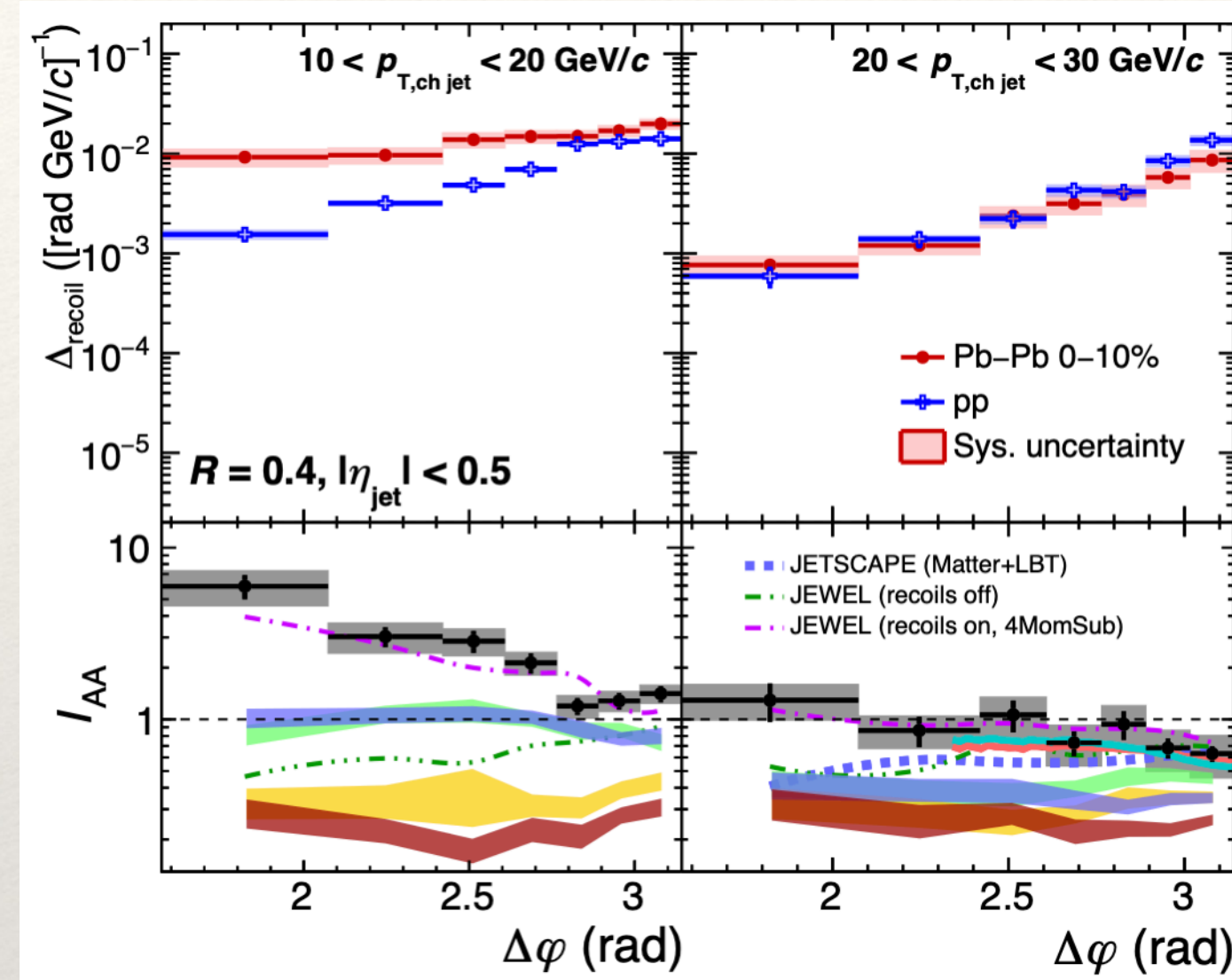
- Rutherford scatterings of QCD
- Quasi-particle structure of the QGP

Puzzling observation of the h -jet I_{AA}

I_{AA} VS. $p_{T, \text{jet}}$



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



ematic range, including low $p_{T, \text{jet}}$ and large R . A marked medium-induced **enhancement** in recoil jet acoplanarity is observed for the first time, but **only at low $p_{T, \text{jet}}$ for large R** ; this favors QGP wake effects or jet splitting as the underlying physical mechanism, and **disfavors large-angle jet scattering**.

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

- No existing model can quantitatively describe both data
- No intuitive explanation of the enhancement at large $\pi - \Delta\phi$, and its disappearance for jets with small R or high p_T
- Disfavor the origin of Molière-like scatterings

Linear Boltzmann transport (LBT) model

Boltzmann equation

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

Elastic scattering ($ab \rightarrow cd$)

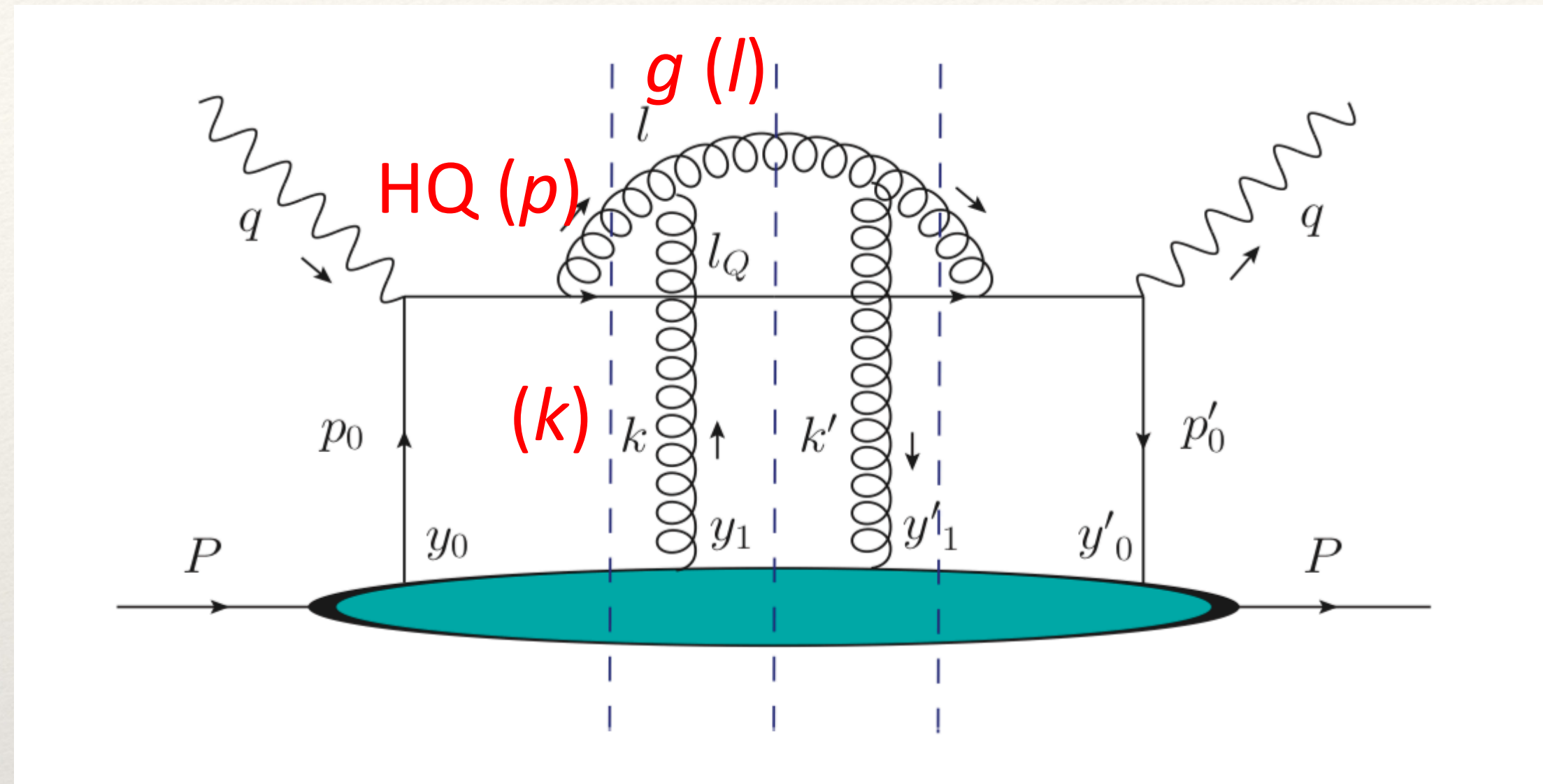
$$\mathcal{C}_a^{\text{el}} = \sum_{b,c,d} \int \prod_{i=b,c,d} \frac{d[p_i]}{2E_a} (\gamma_d f_c f_d - \gamma_b f_a f_b) \cdot (2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) \left| \mathcal{M}_{ab \rightarrow cd} \right|^2$$

2 → 2 scattering matrices

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

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

Inelastic scattering



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

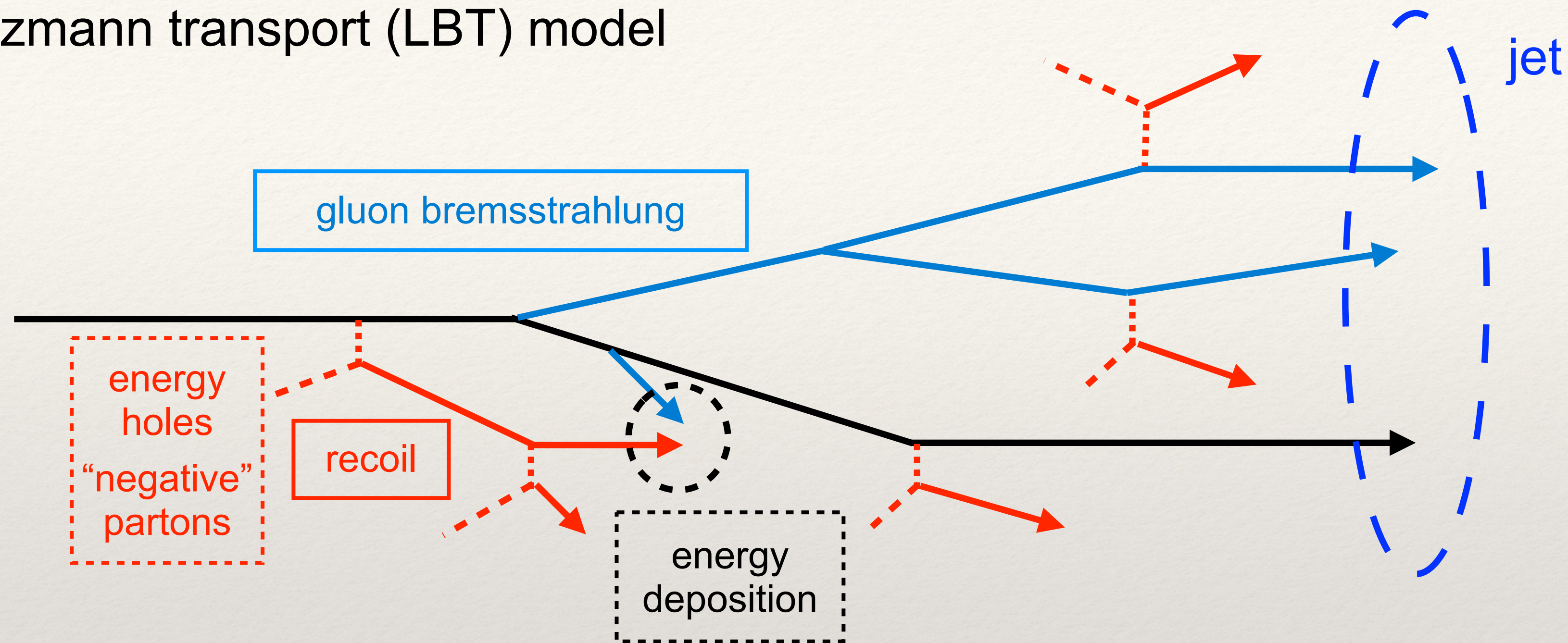
- **Higher-twist formalism:** collinear expansion ($\langle k_{\perp}^2 \rangle \ll l_{\perp}^2 \ll Q^2$)

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

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

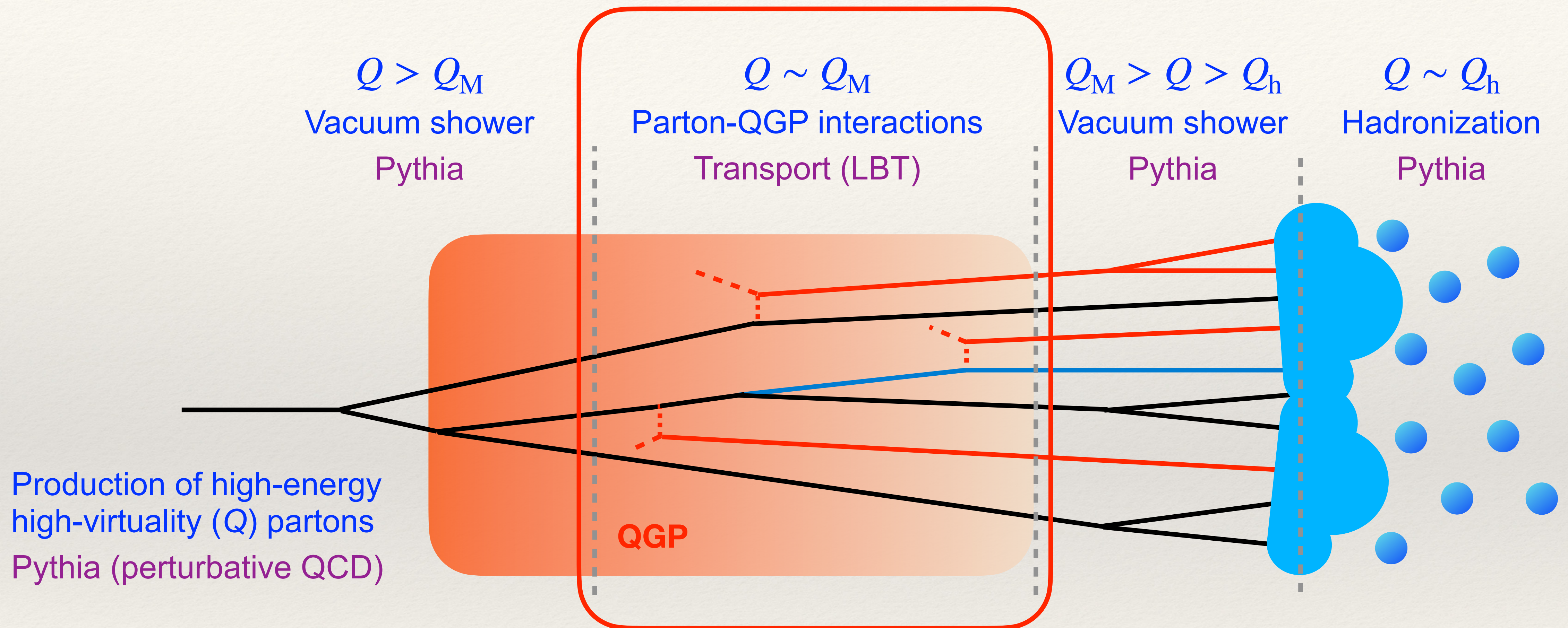
Parton-QGP interactions

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**

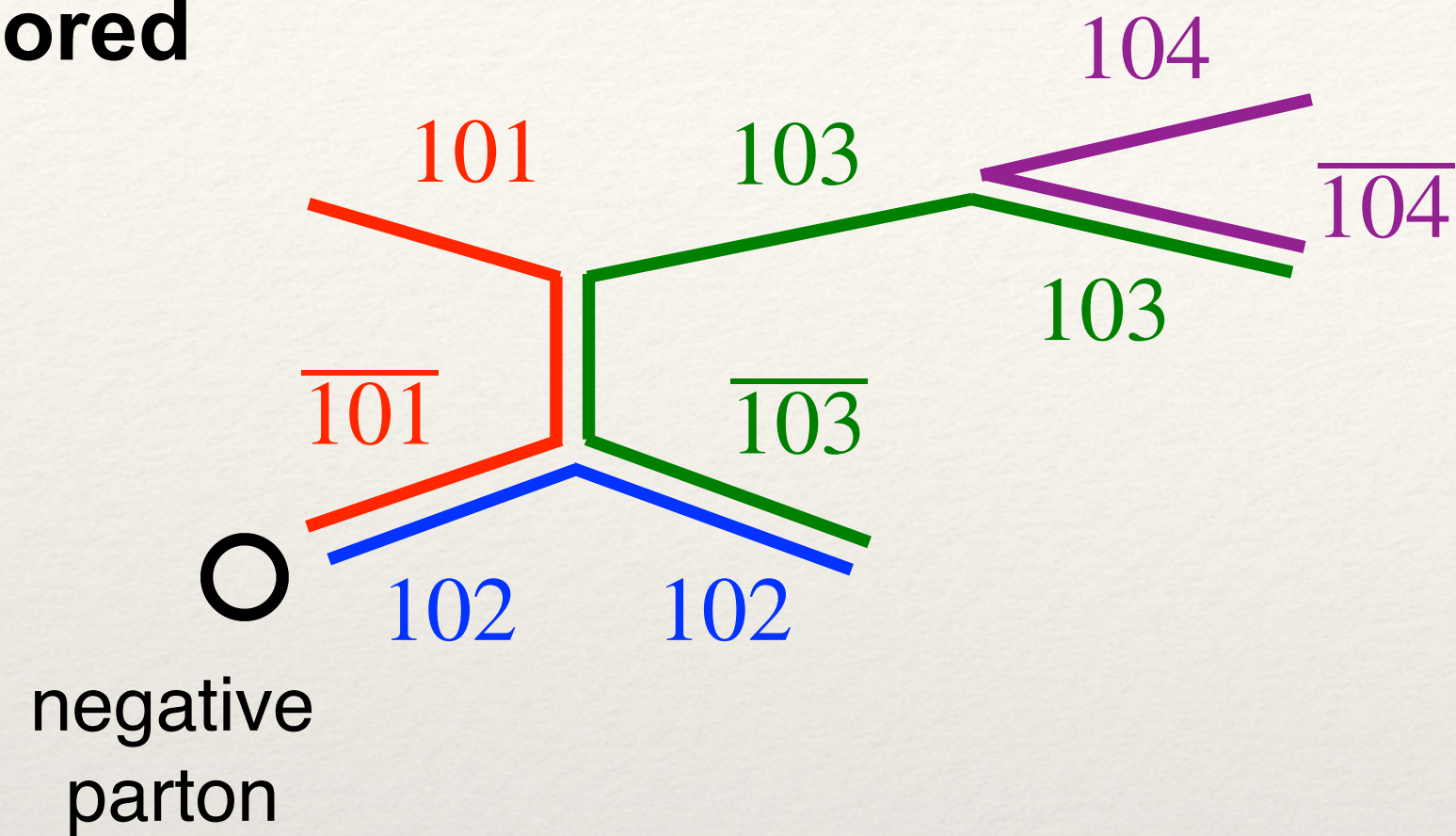
An improved framework for jet-QGP interactions



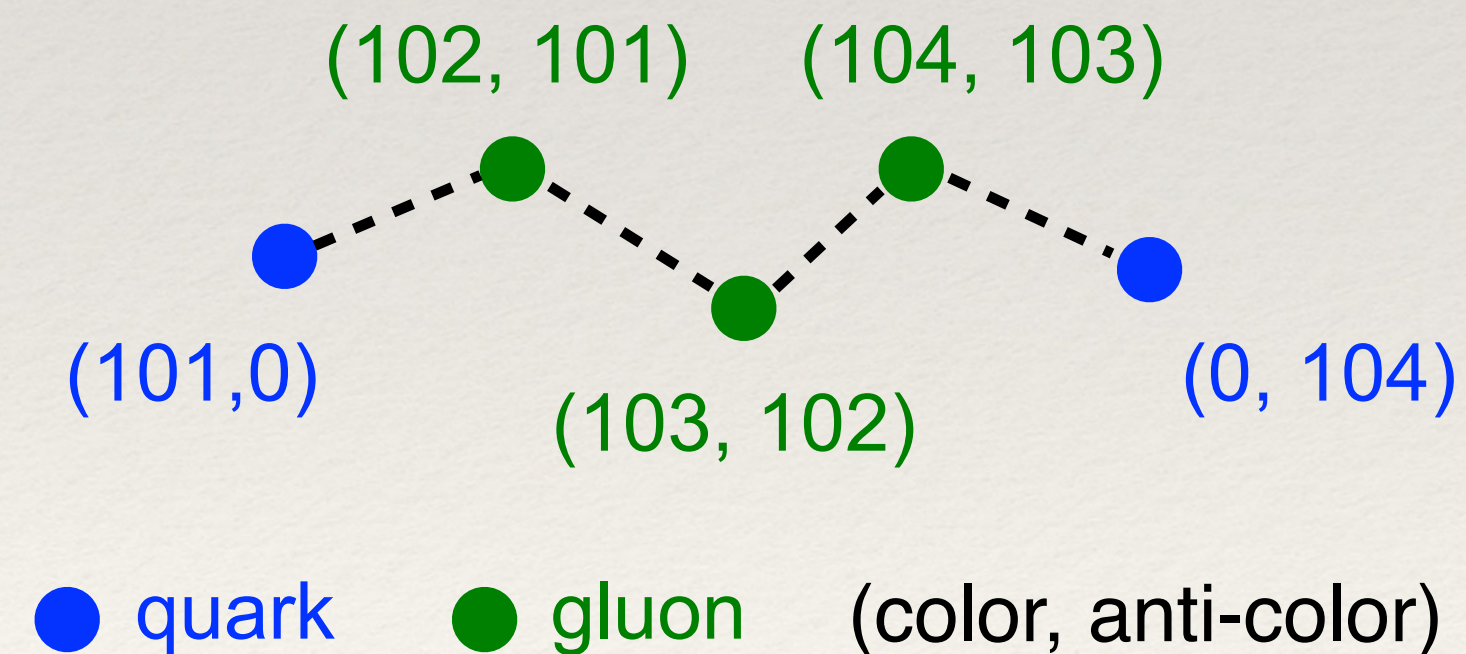
- **Old model:** $Q_M = Q_h = 0.5 \text{ GeV}$; **New model:** $Q_M > Q_h$ can be varied

Hadronization schemes

Colored



“Colorless”



Regular (positive) partons:

- Colored scheme: respect color flow information in parton-medium interactions [Dang, SC, Xing, and Qin, NST 37 (2026) 210]
- “Colorless” scheme: reconnect color strings for hadronization by minimizing parton distance in the (η, ϕ) space [JETSCAPE, PRC 102 (2020), 054906] [Zhao et. al., PRL 125 (2020) 072301]

← this work

Negative partons:

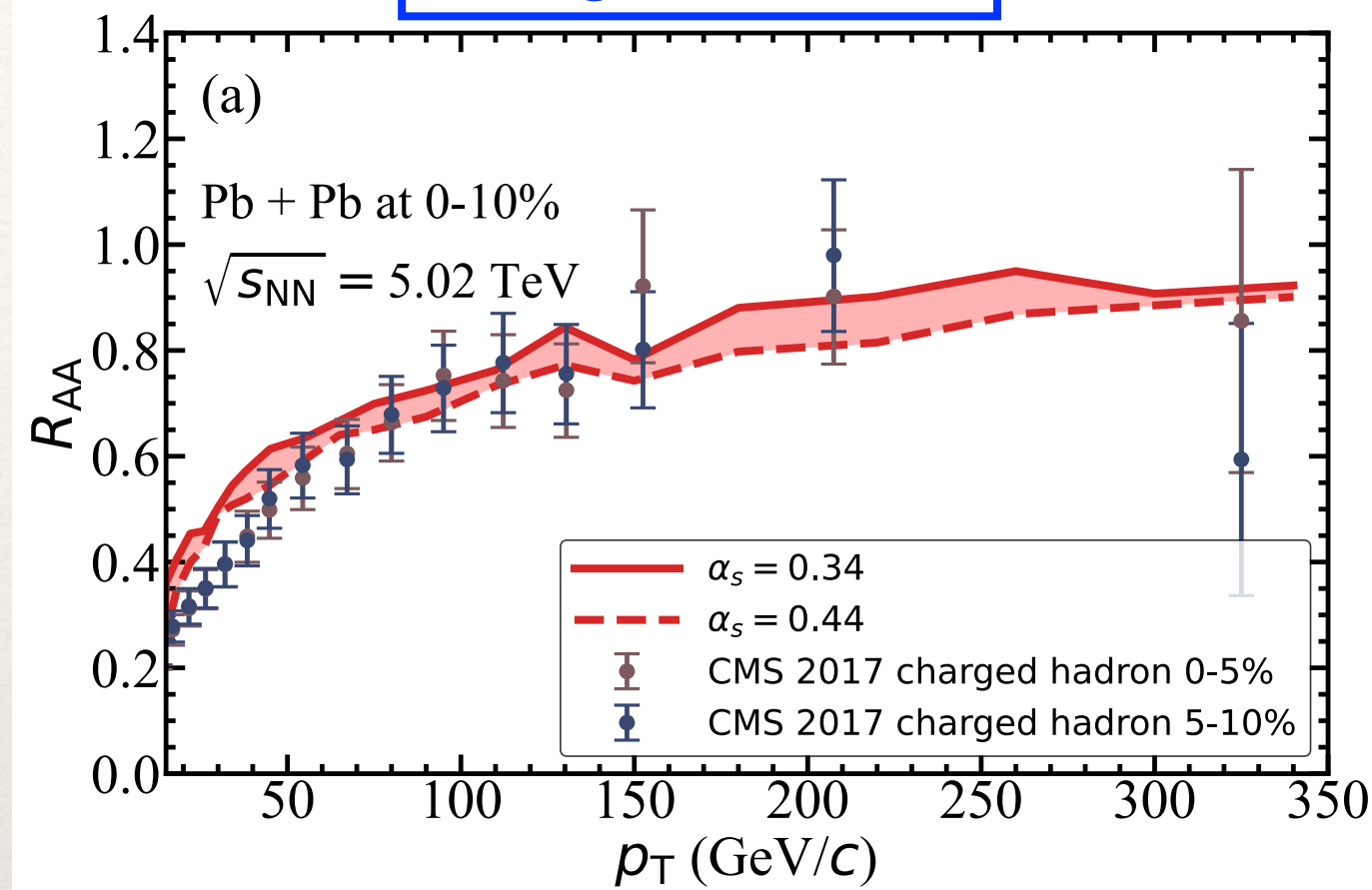
- “Colorless” scheme
- Thermal scheme: sample thermal hadrons up to total negative parton energy [Sun, Dang, SC, Universe 12 (2026) 5, 150]

← compared in this work

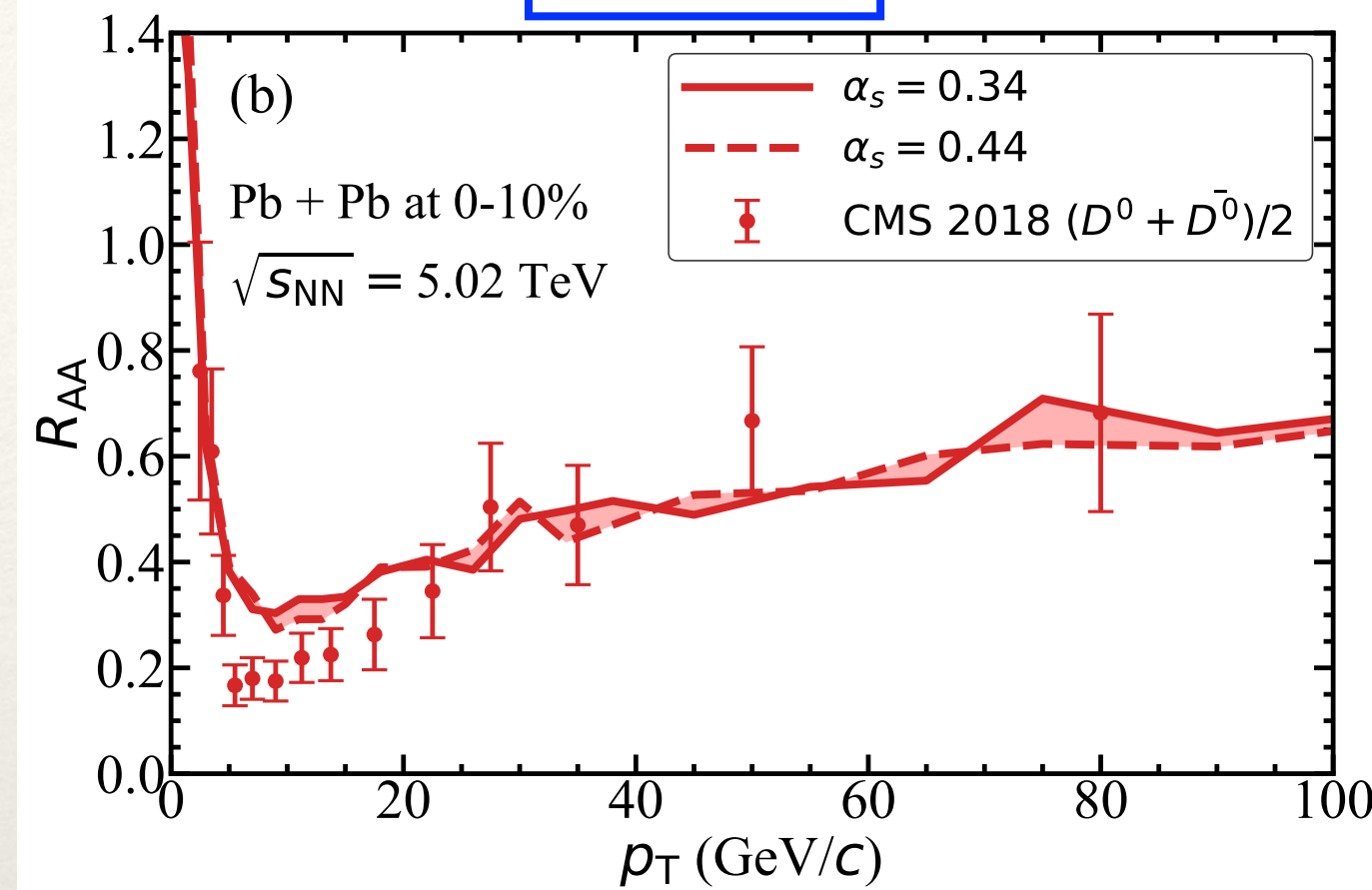


R_{AA} of hadrons and jets with different flavors

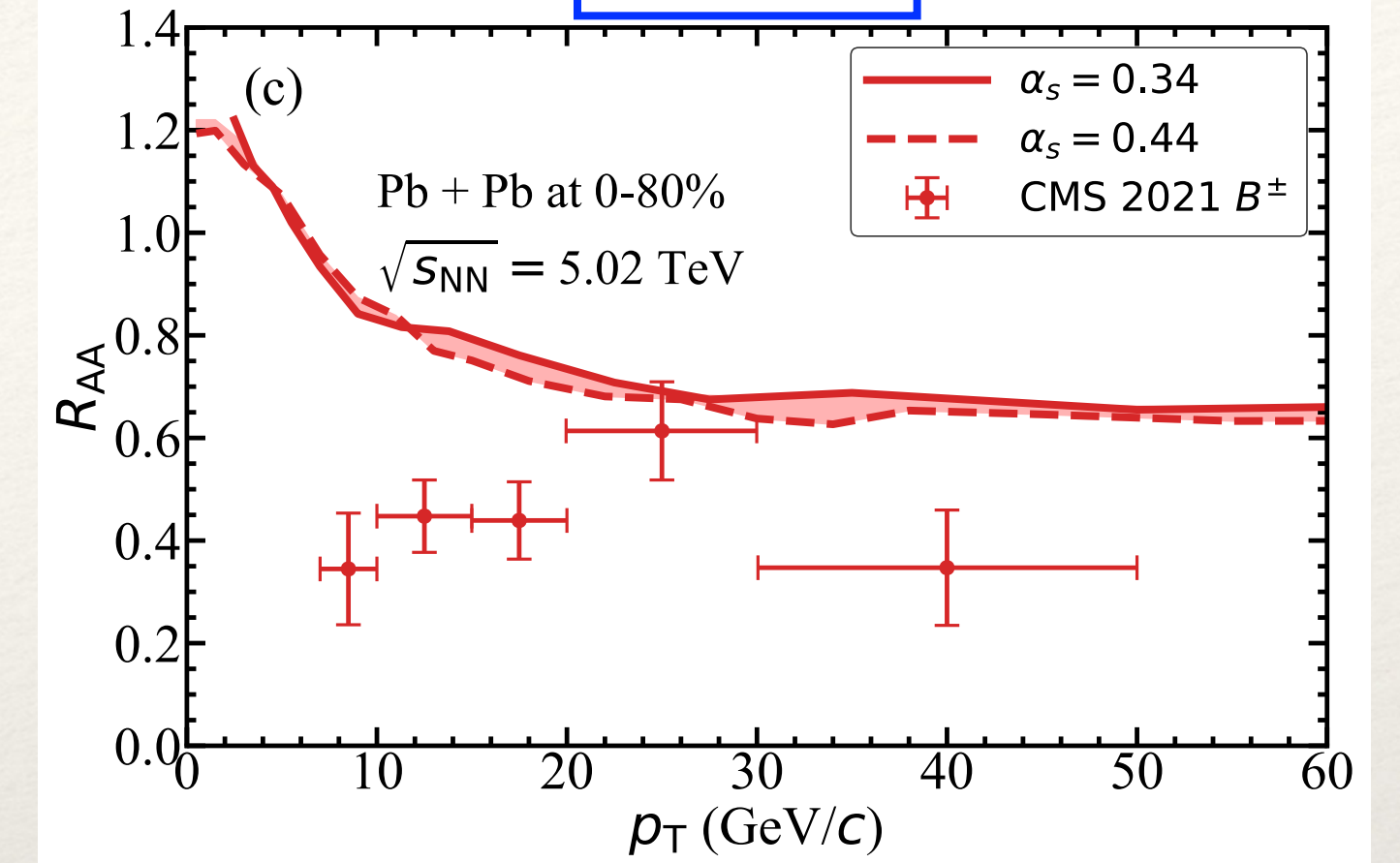
charged hadron



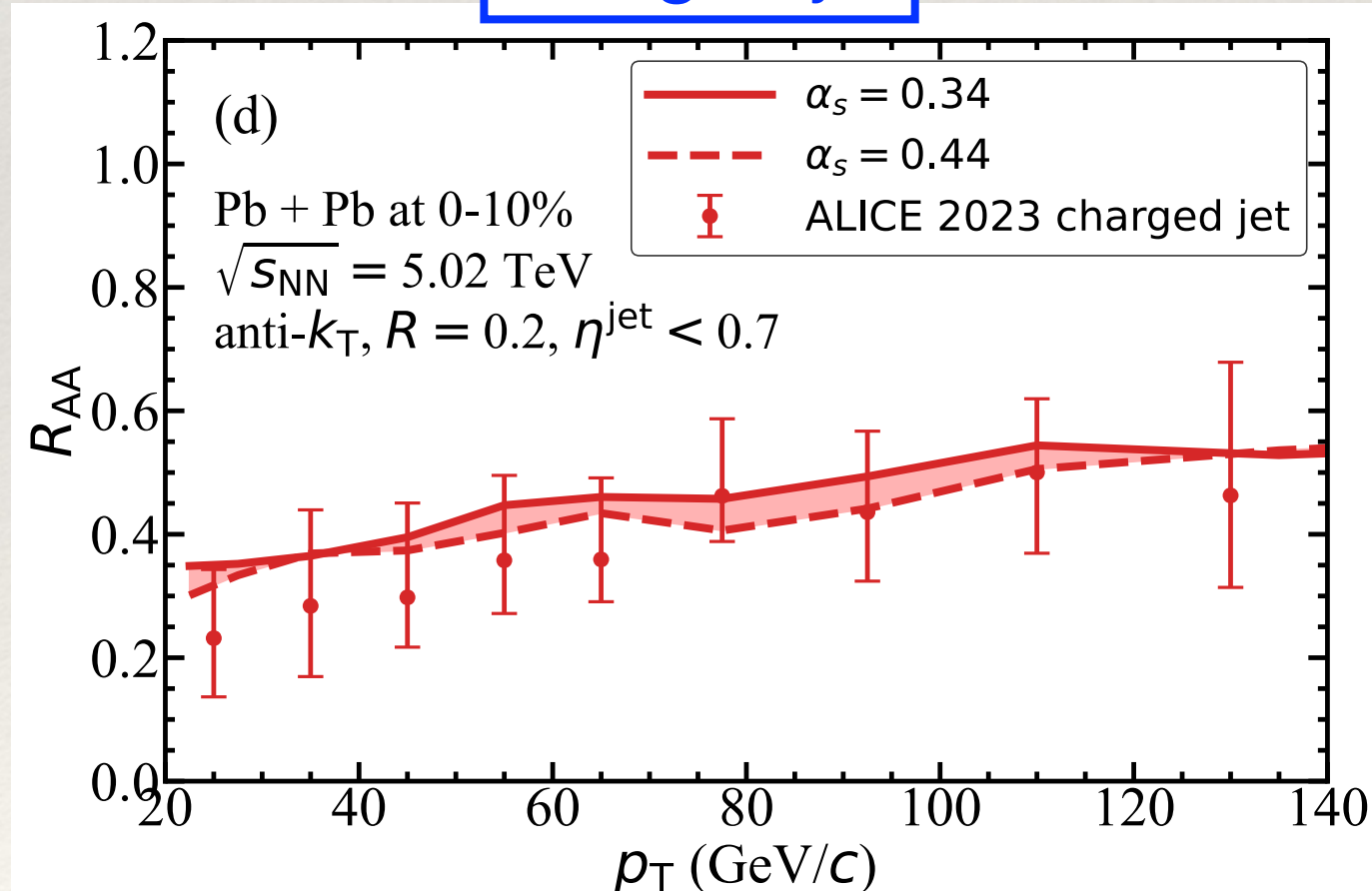
D meson



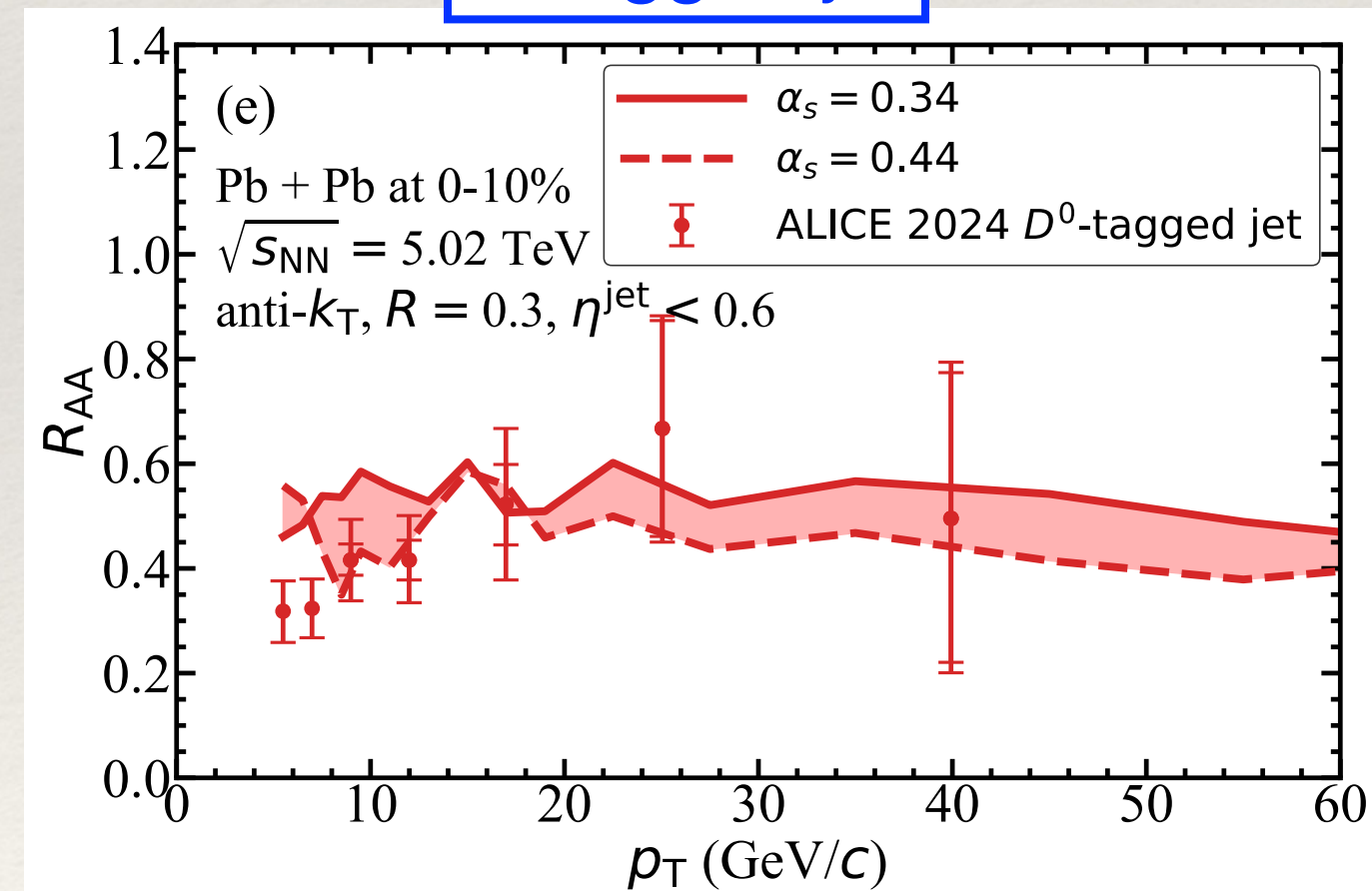
B meson



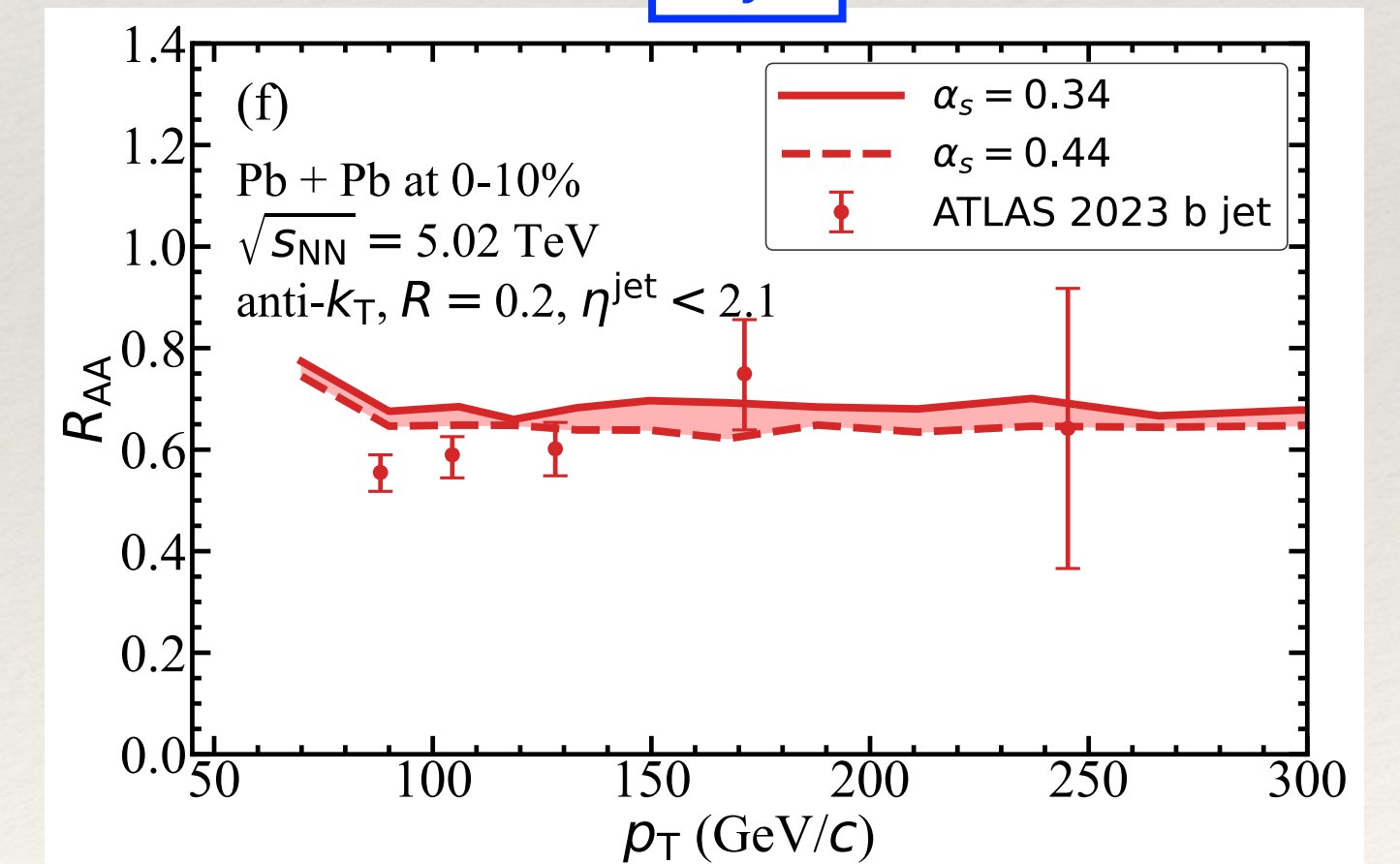
charged jet



D-tagged jet

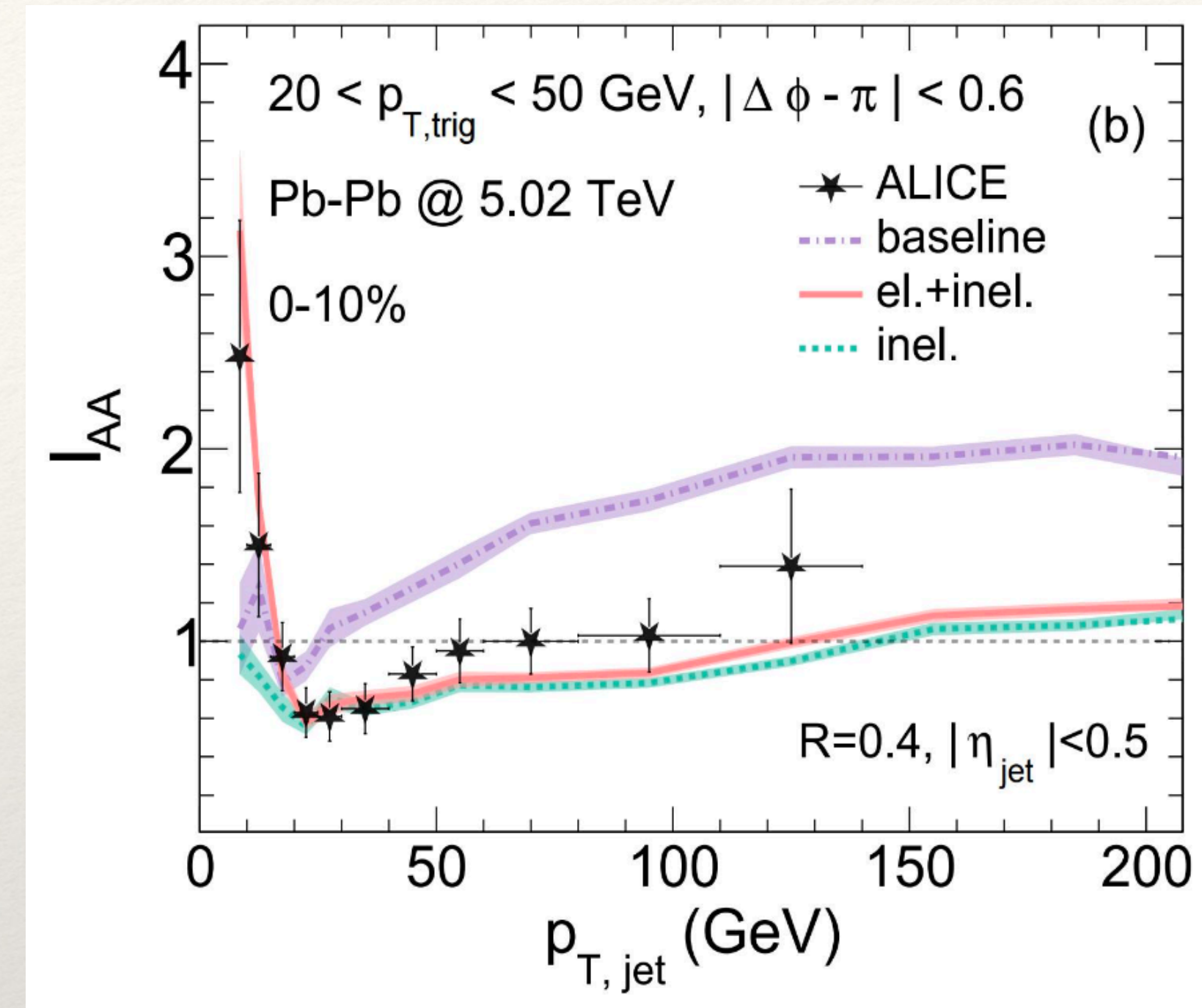
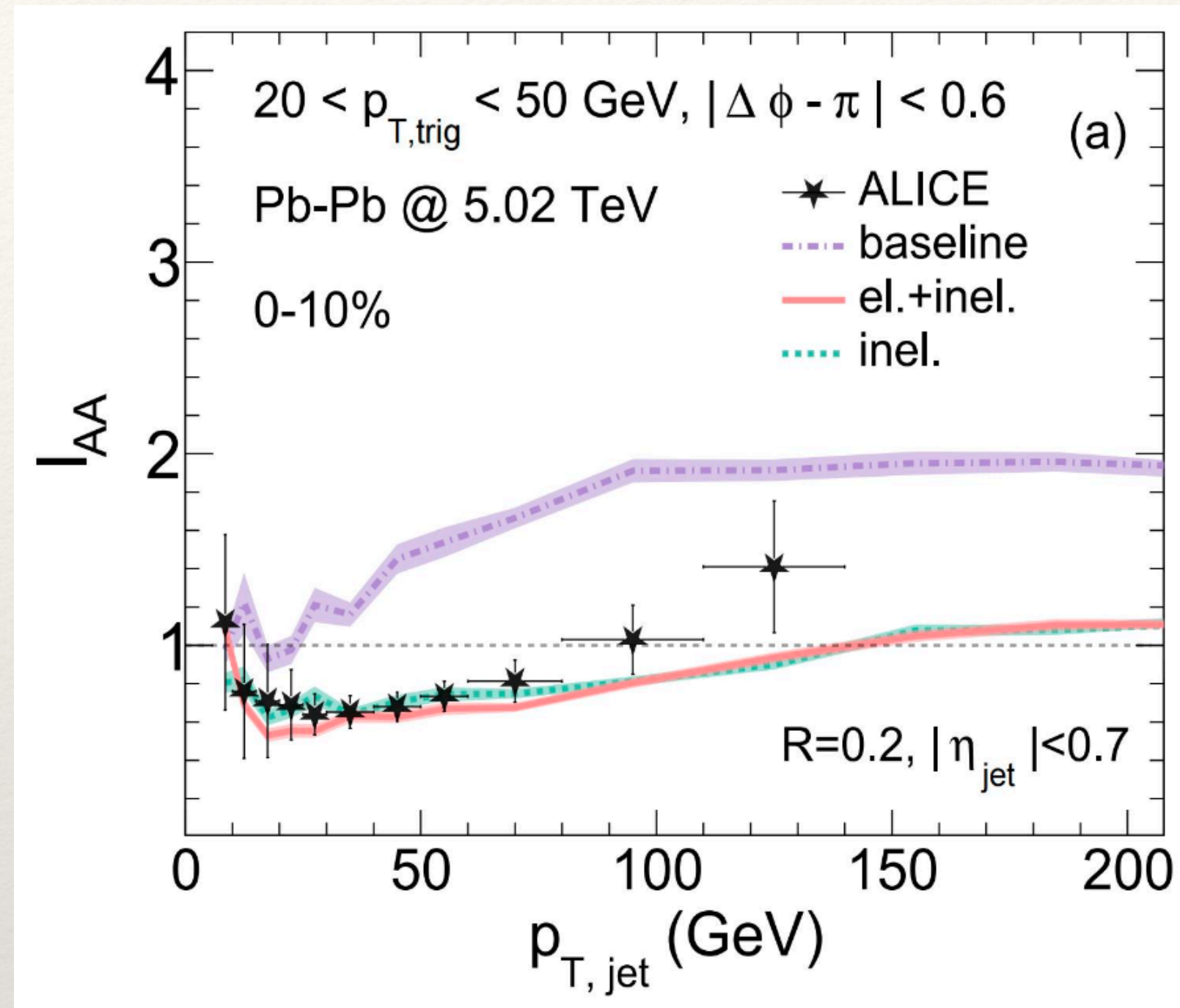


b-jet



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

Semi-inclusive hadron-triggered jets

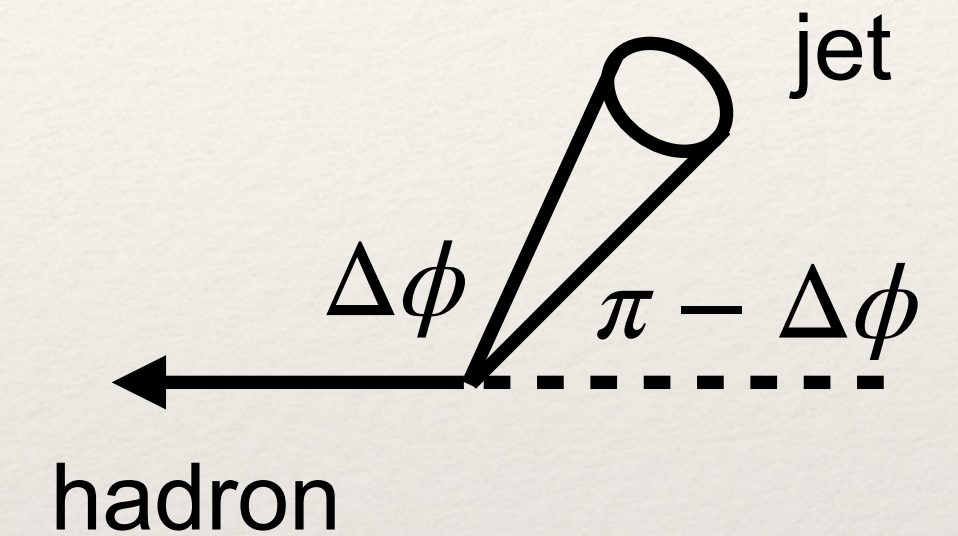
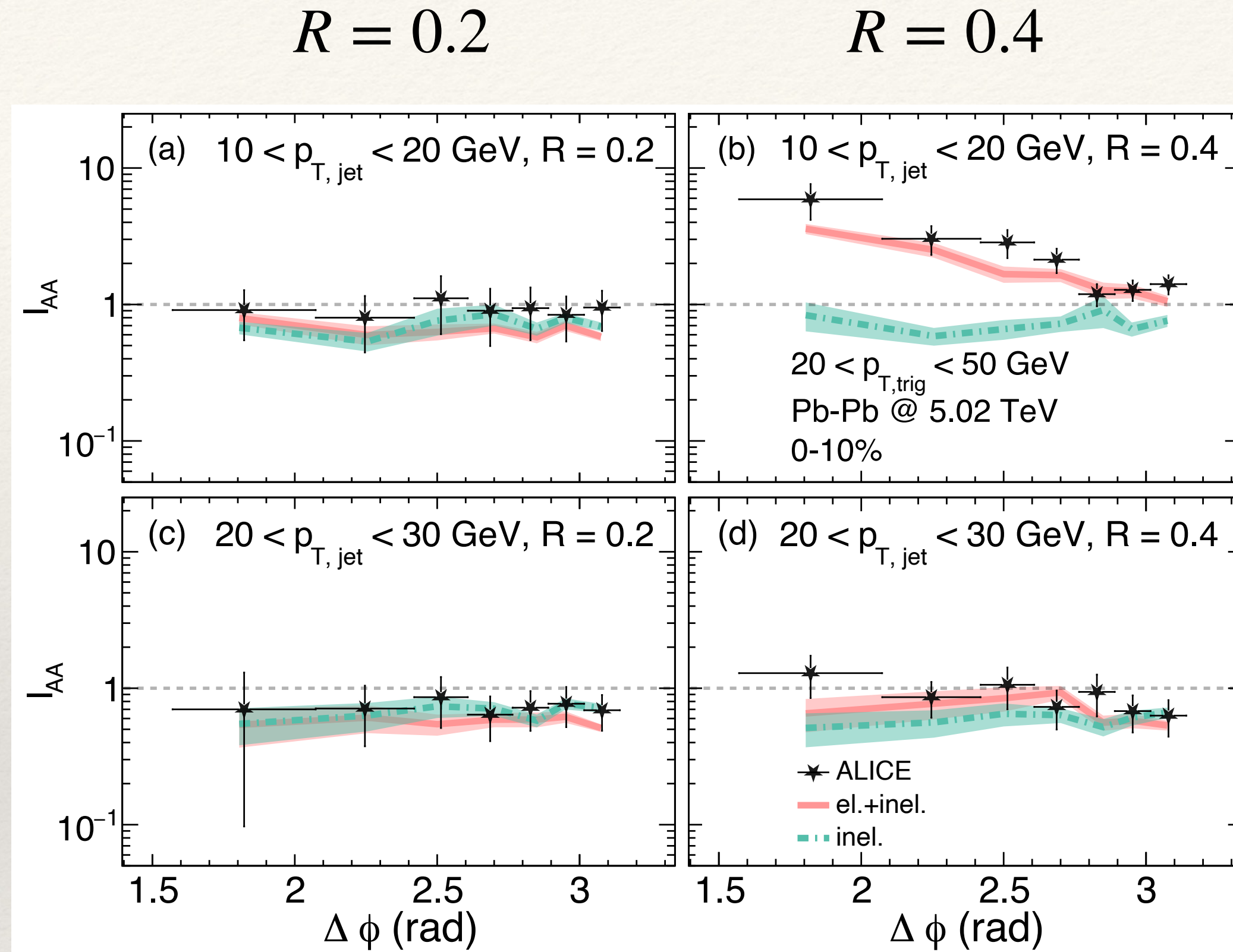


- Simultaneous description of hadron and jet is crucial for understanding hadron-triggered jets
- Enhancement at low $p_{T,jet}$: medium response
- Enhancement at high $p_{T,jet}$: enhancement of I_{AA} baseline by trigger bias (Will it disappear in γ -jet?)

Acoplanarity of h -jets

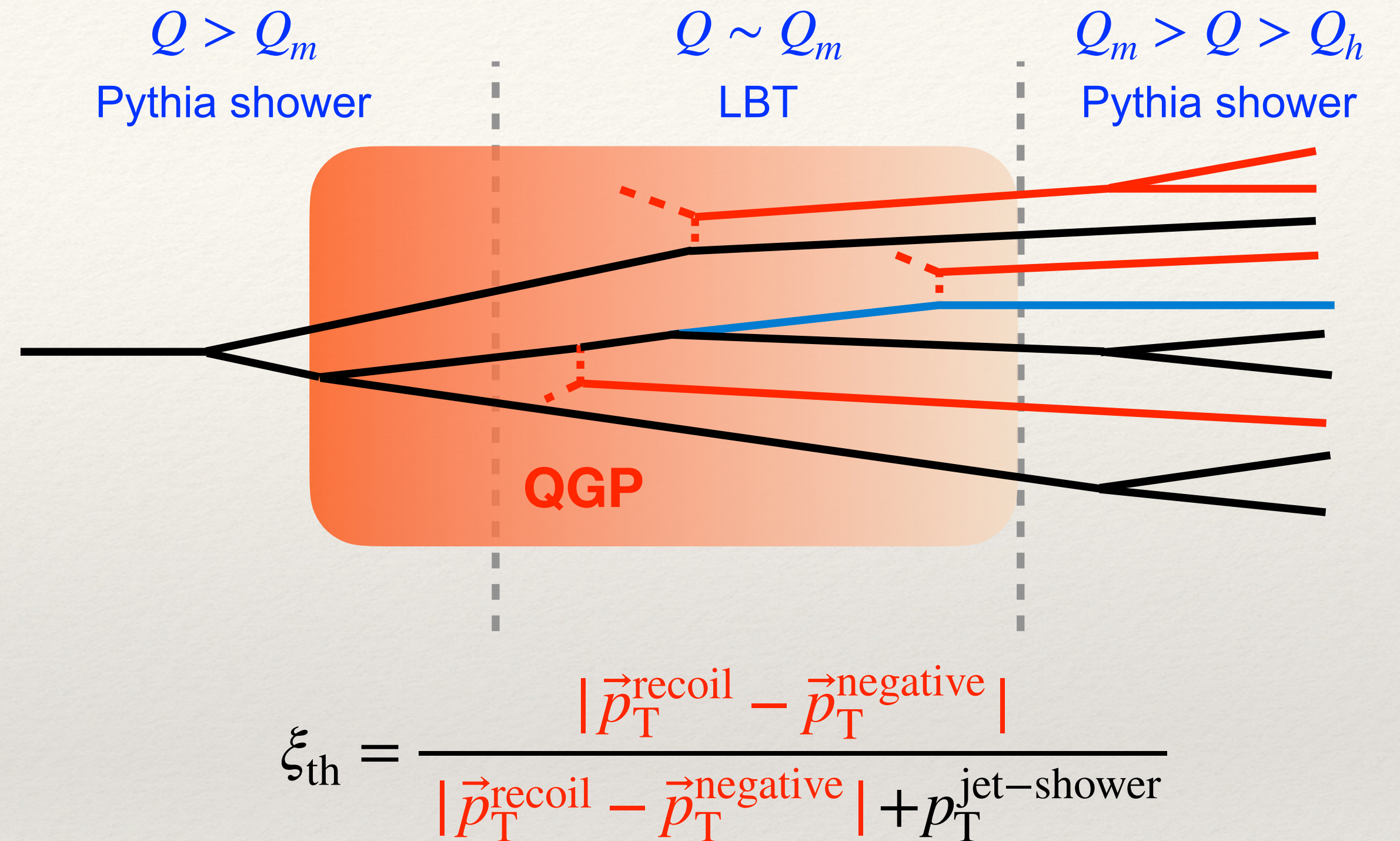
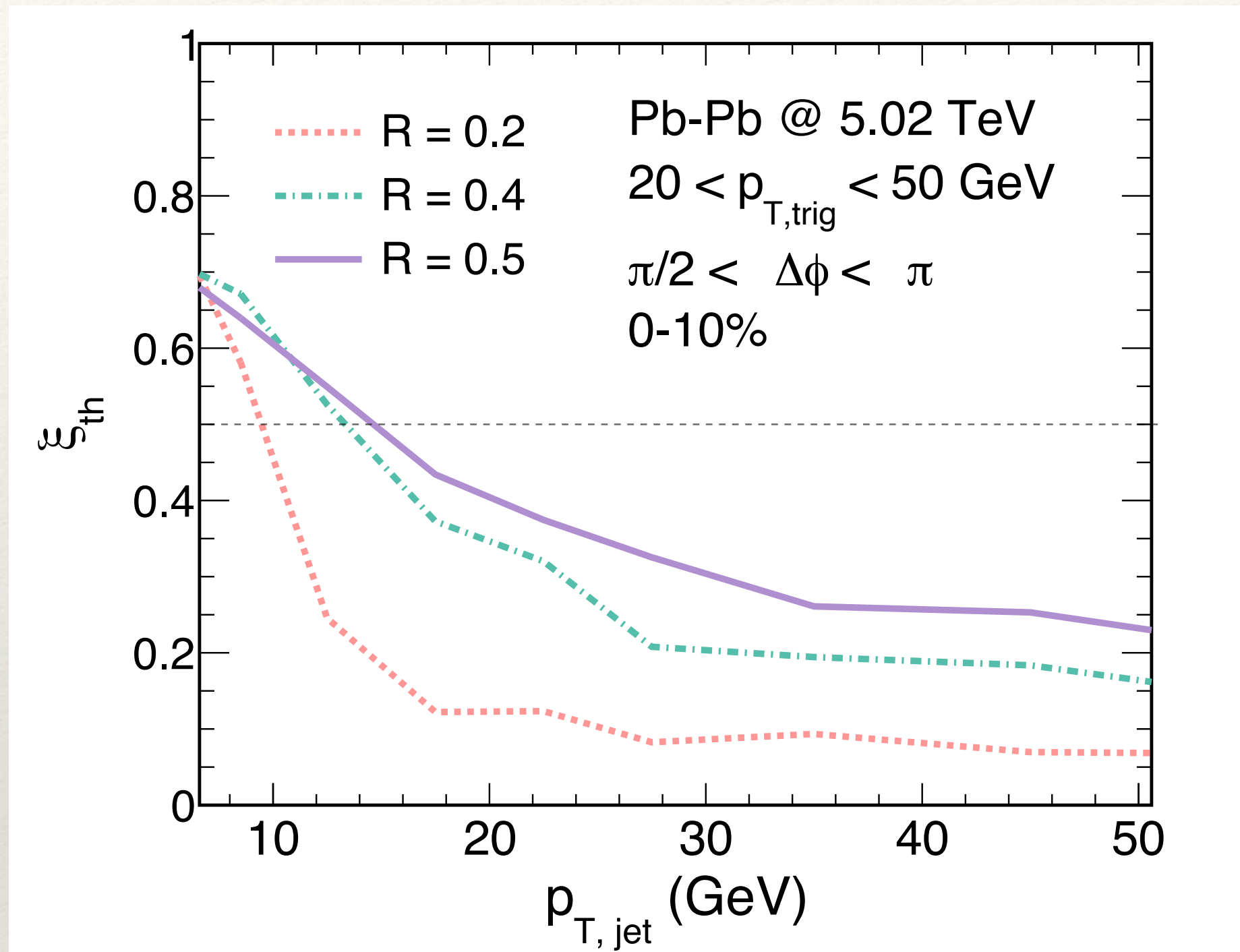
$10 < p_{T,\text{jet}} < 20 \text{ GeV}$

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



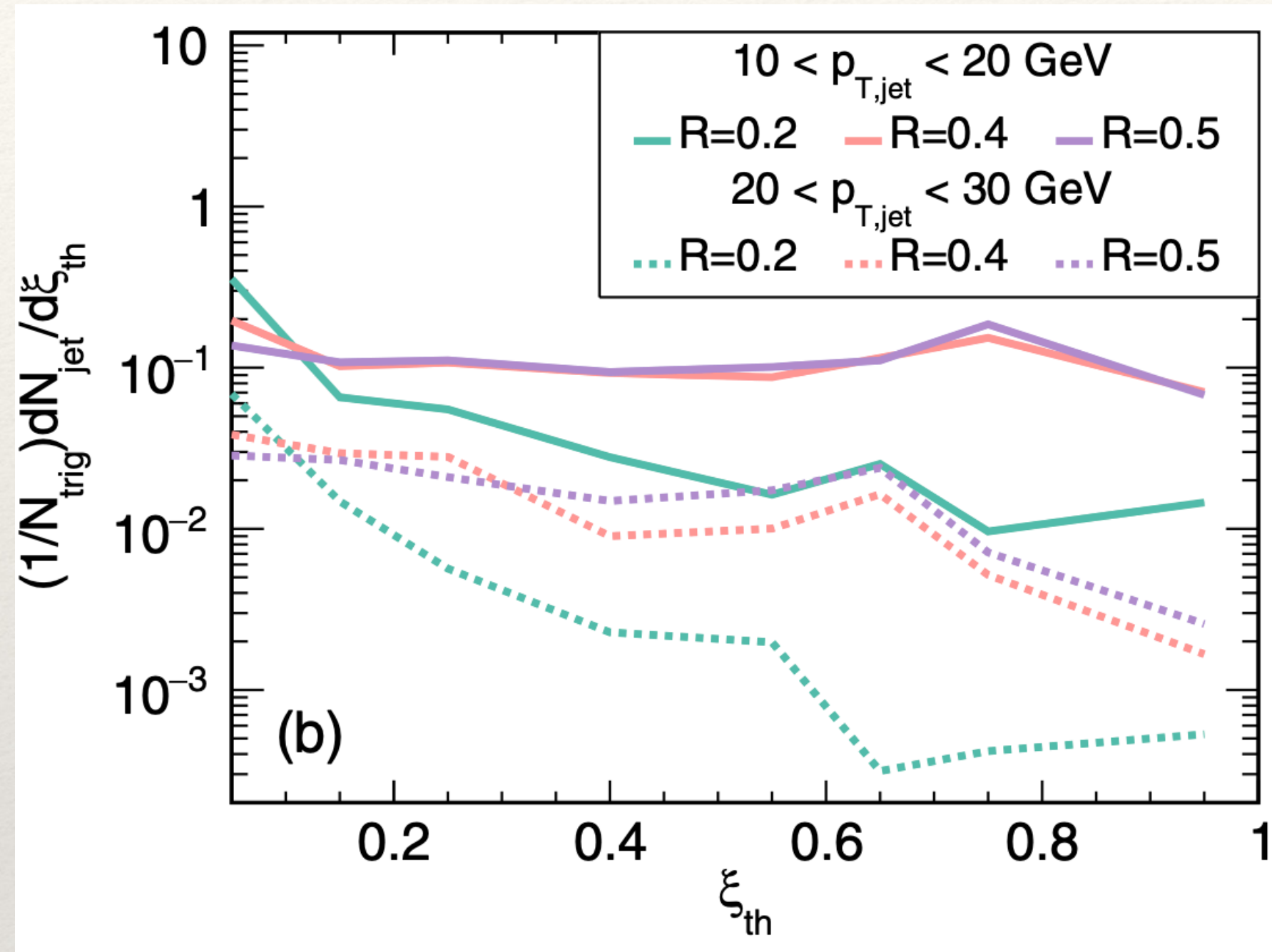
- Enhancement of I_{AA} at large $\pi - \phi$ for jets with large R and low $p_{T,\text{jet}}$, medium response.
- Enhancement disappears for small R or high $p_{T,\text{jet}}$. Why?

Thermal origin of the enhanced jet yields



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

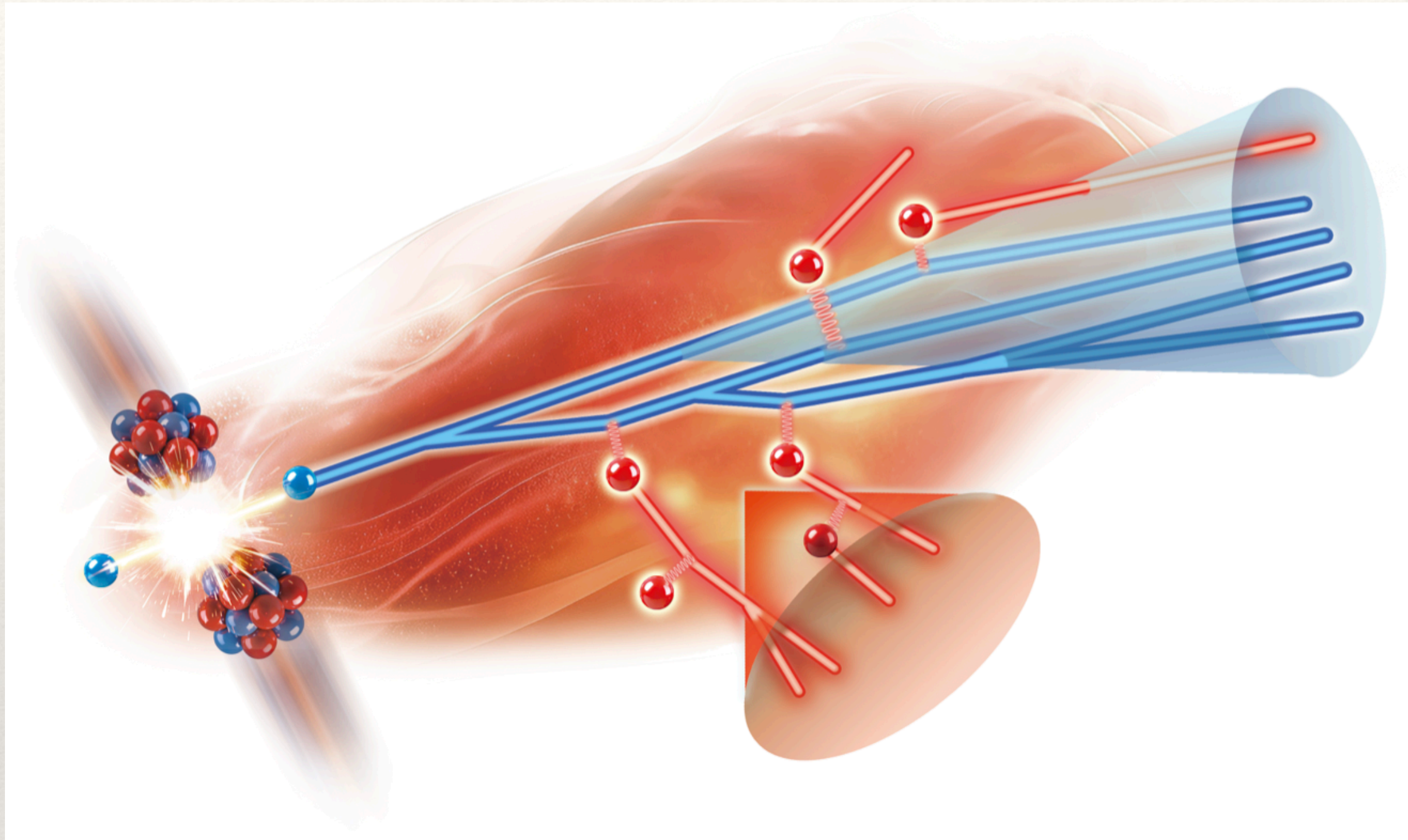
Probability distributions of ξ_{th}



$$\xi_{\text{th}} = \frac{|\vec{p}_T^{\text{recoil}} - \vec{p}_T^{\text{negative}}|}{|\vec{p}_T^{\text{recoil}} - \vec{p}_T^{\text{negative}}| + p_T^{\text{jet-shower}}}$$

- Jets with small R or large p_T are distributed mostly at small ξ_{th}
- Jets with large R and small p_T have peaks at large ξ_{th} , over 49% have $\xi_{\text{th}} > 0.5$, should not be considered as jets originating from initial hard partonic scatterings

Emergence of “thermal recoil jets”



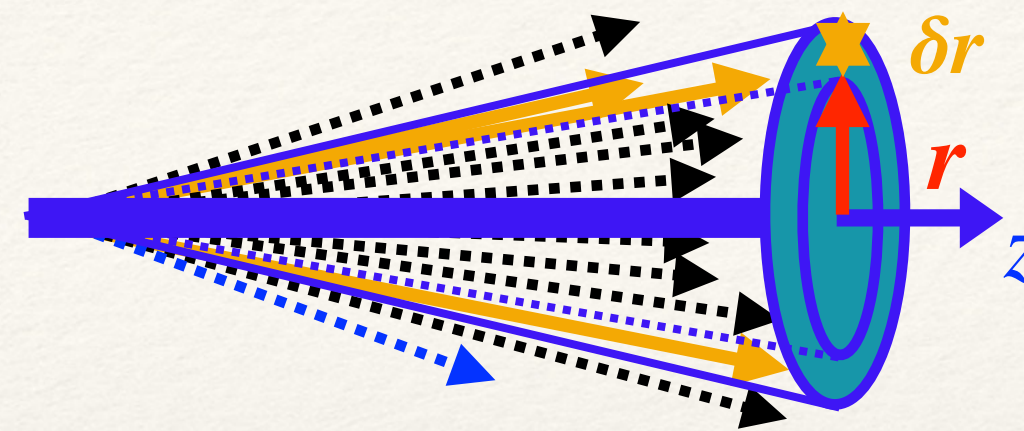
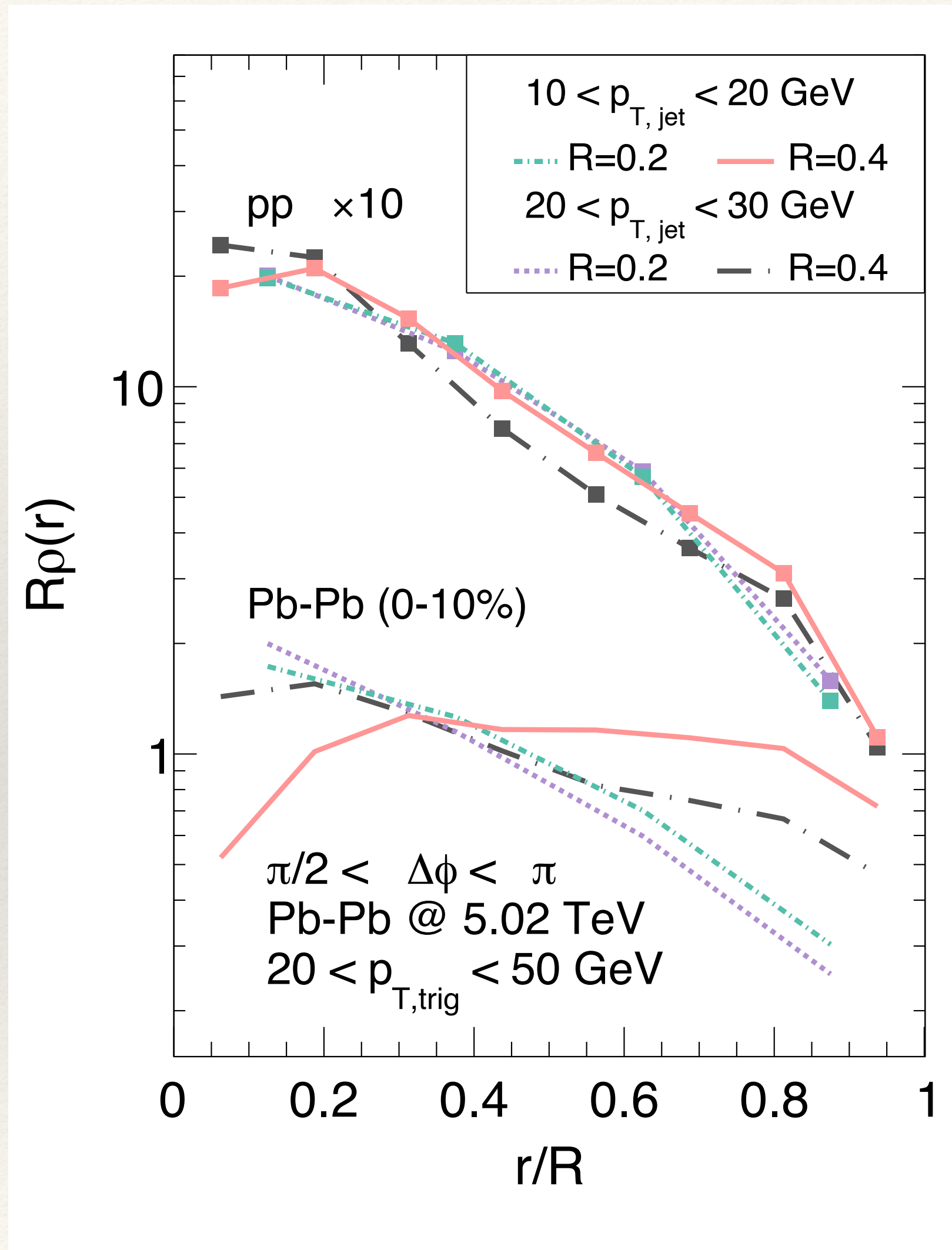
Hard jet

- 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

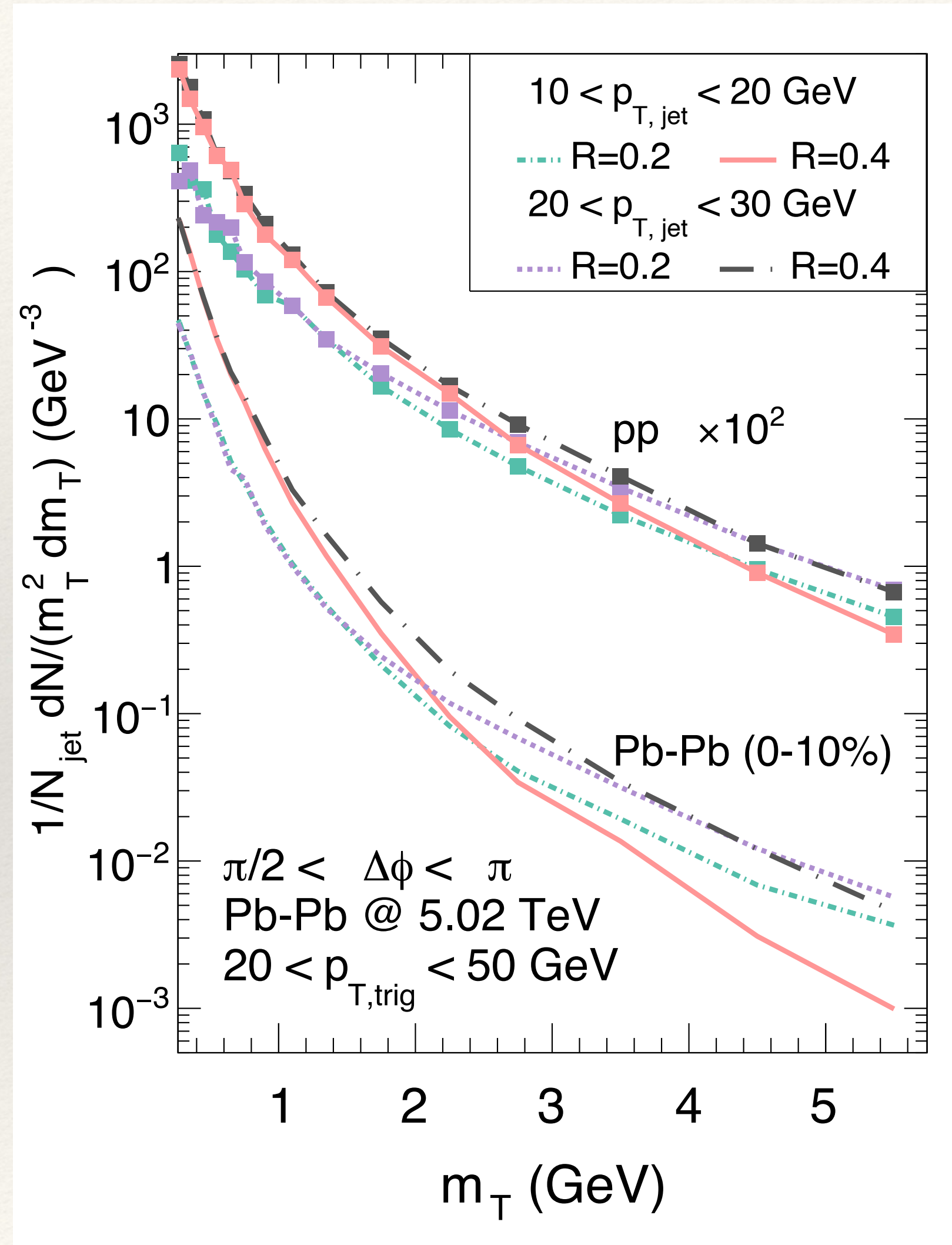
Shapes of thermal recoil jets vs. hard jets



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

- 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 $p_{T,jet}$
 - Feature of thermal recoil jet: soft particles sparsely distributed in the momentum space

m_T distributions of thermal recoil jets vs. hard jets

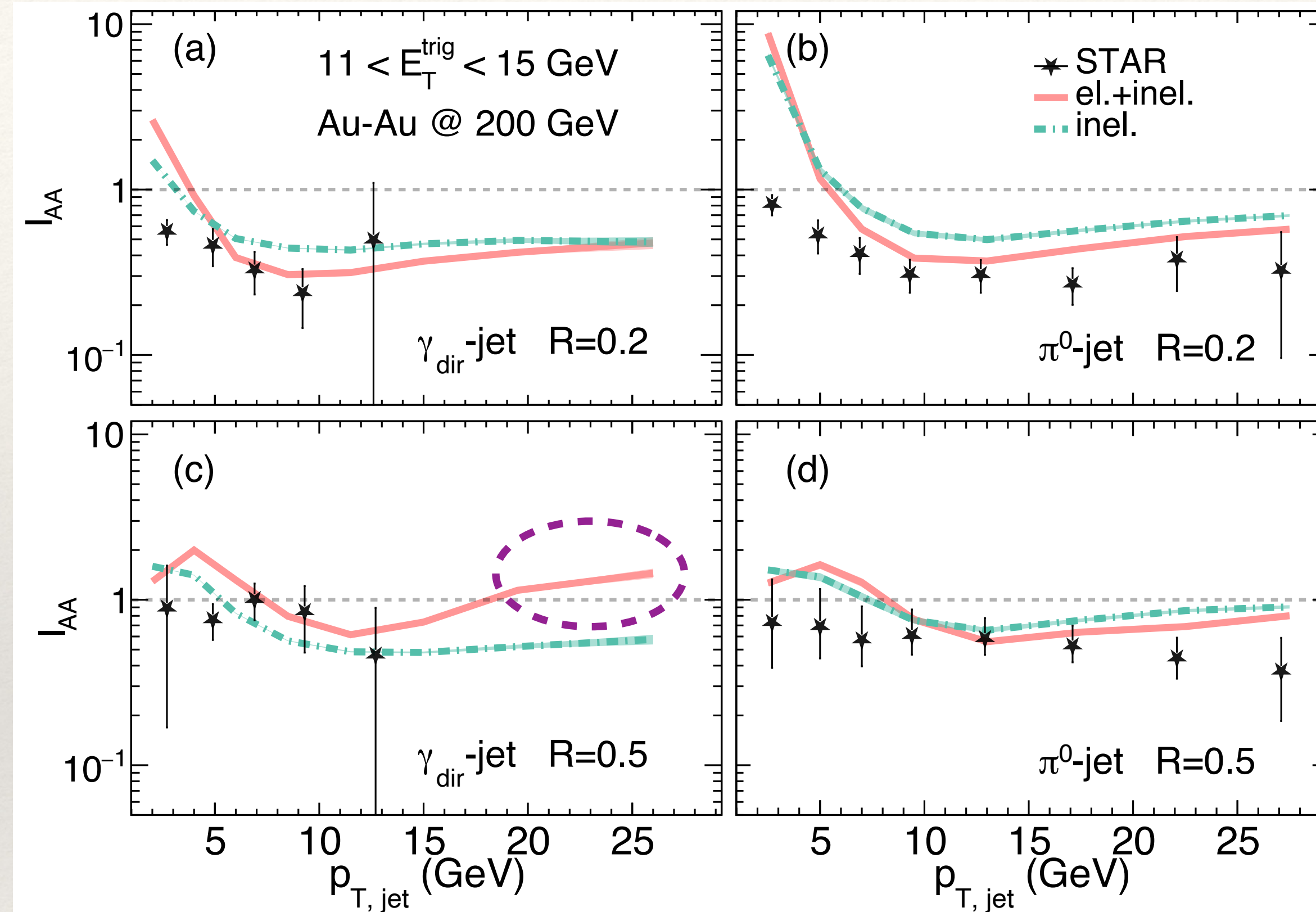


Thermal distribution:

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

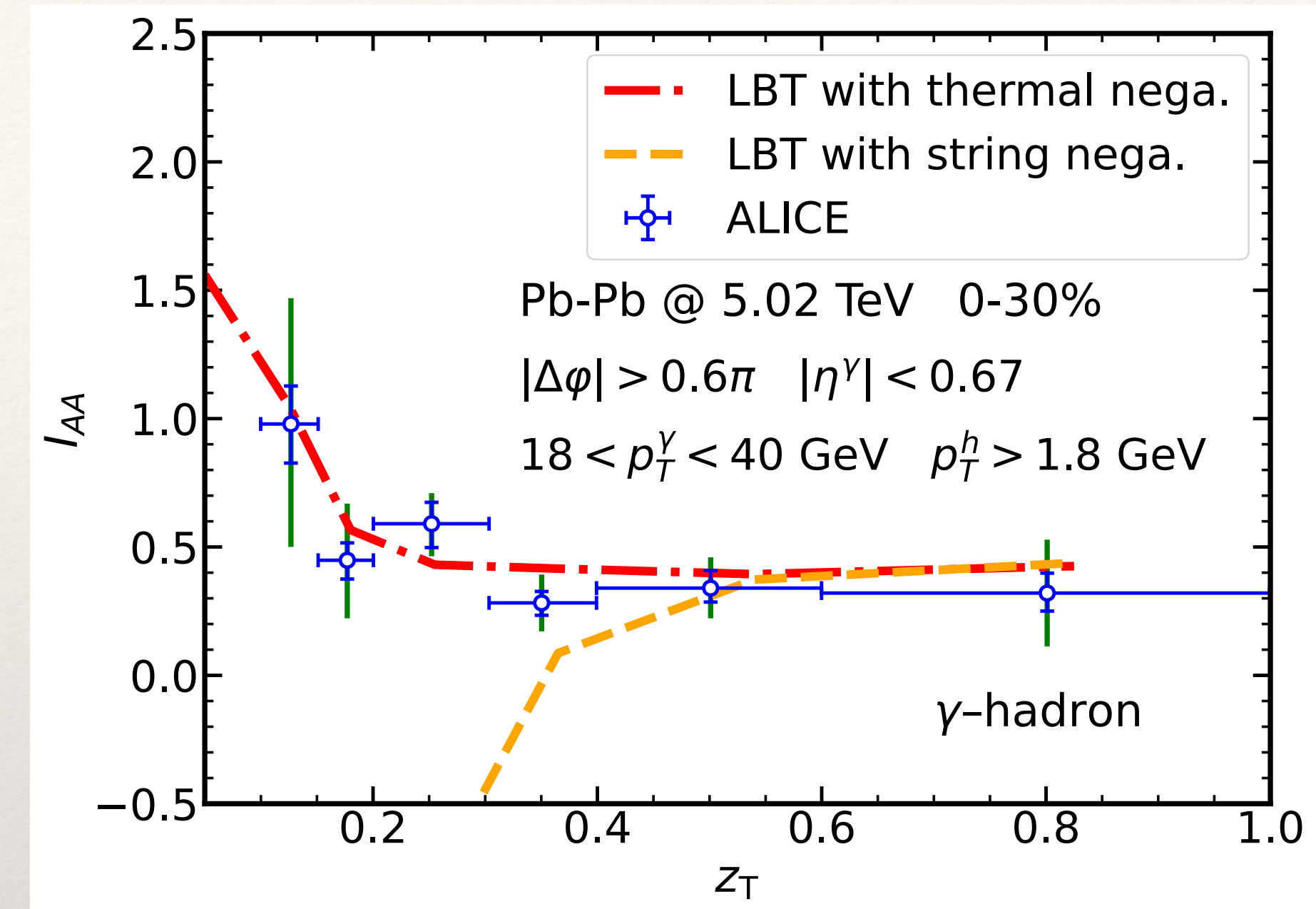
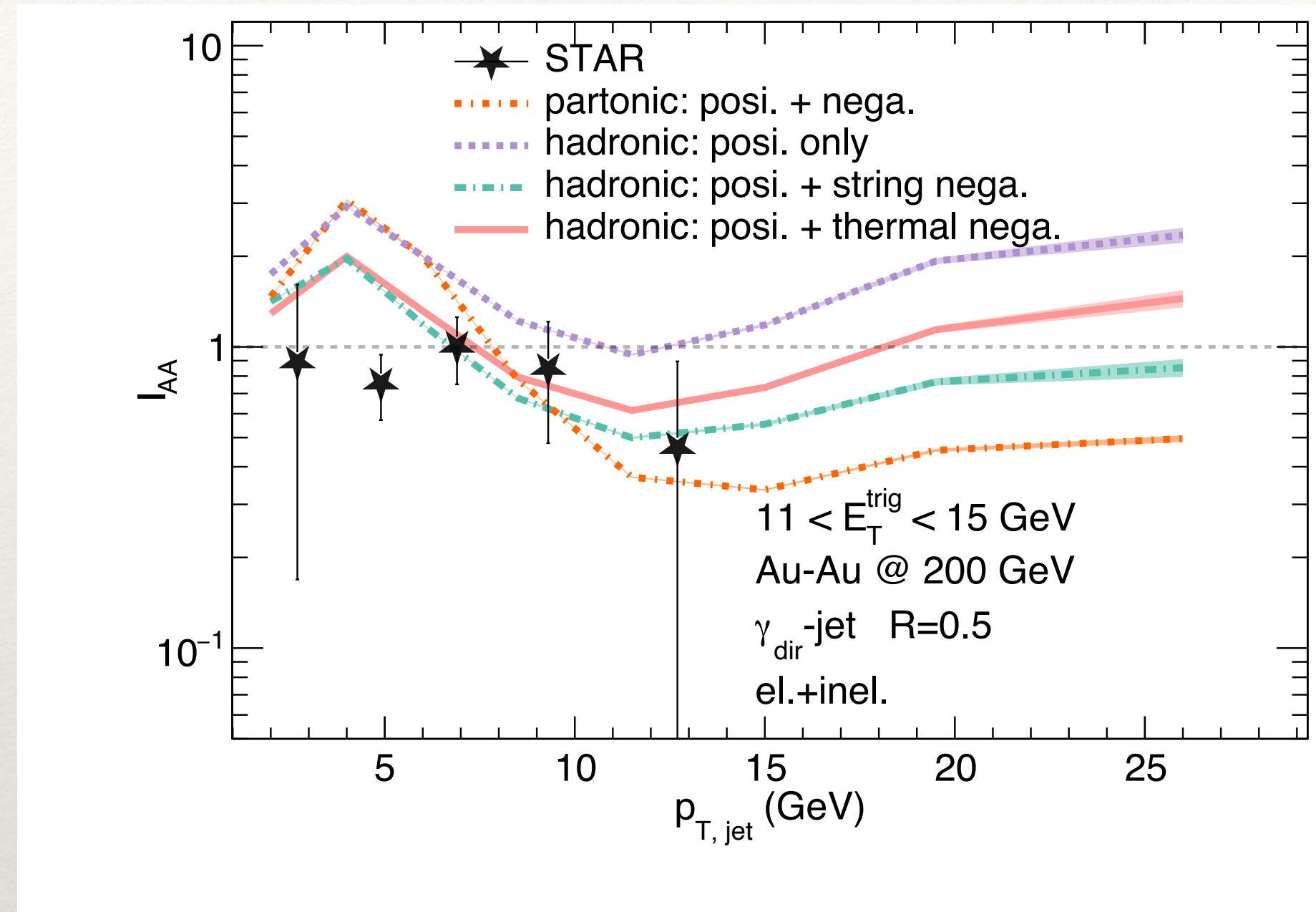
- Power-law tail structures of m_T distributions of jet constituents at $R = 0.2$, similar to jets in $p+p$ collisions
- Thermal-like distribution of jet constituents for $R = 0.4$ and $10 < p_{T,jet} < 20 \text{ GeV}$ up to 2 GeV

Nuclear modification of γ - and π^0 -jet at RHIC



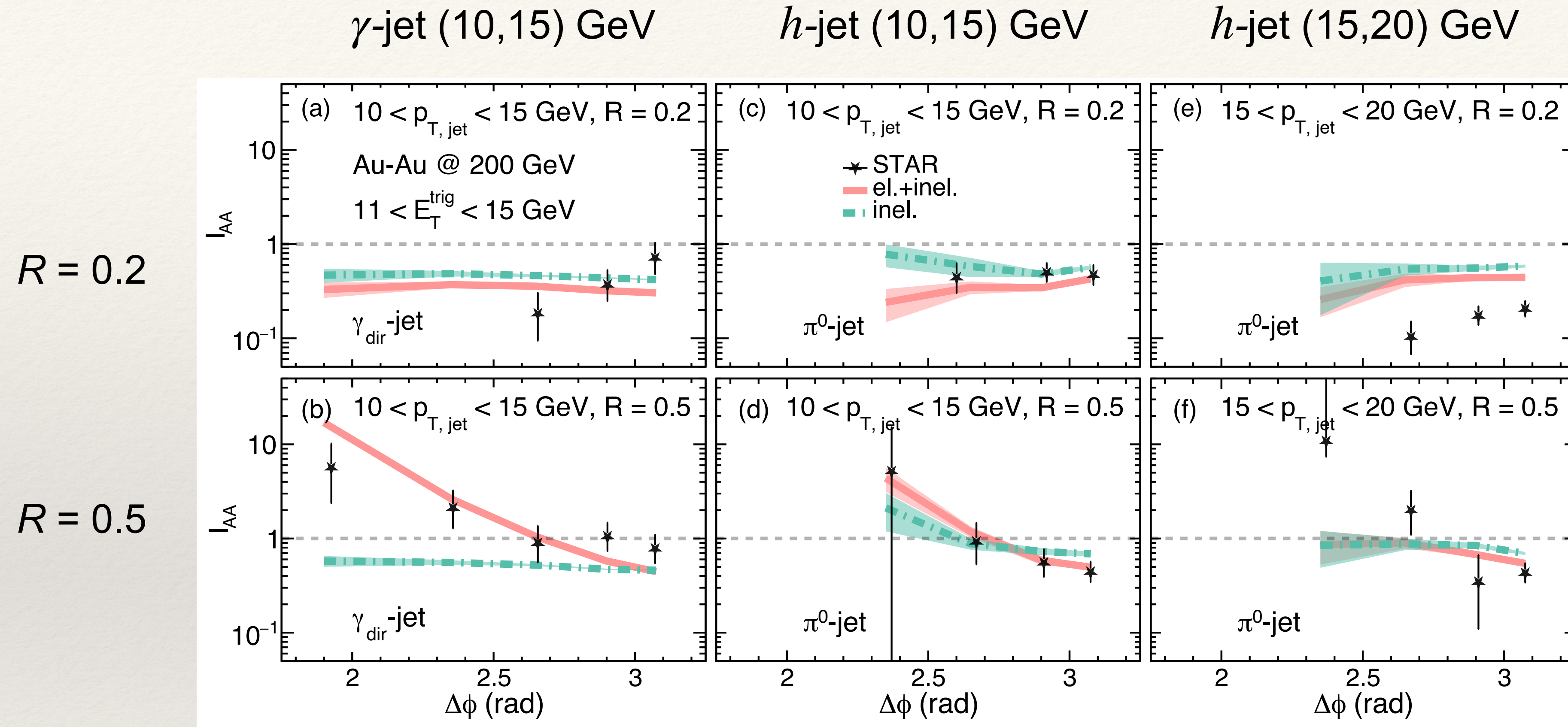
- In general agreement with the experimental data
- $I_{AA} > 1$ at high p_T for γ -jet, even in the absence of trigger bias

Effects of hadronization on γ -jet / hadron modification



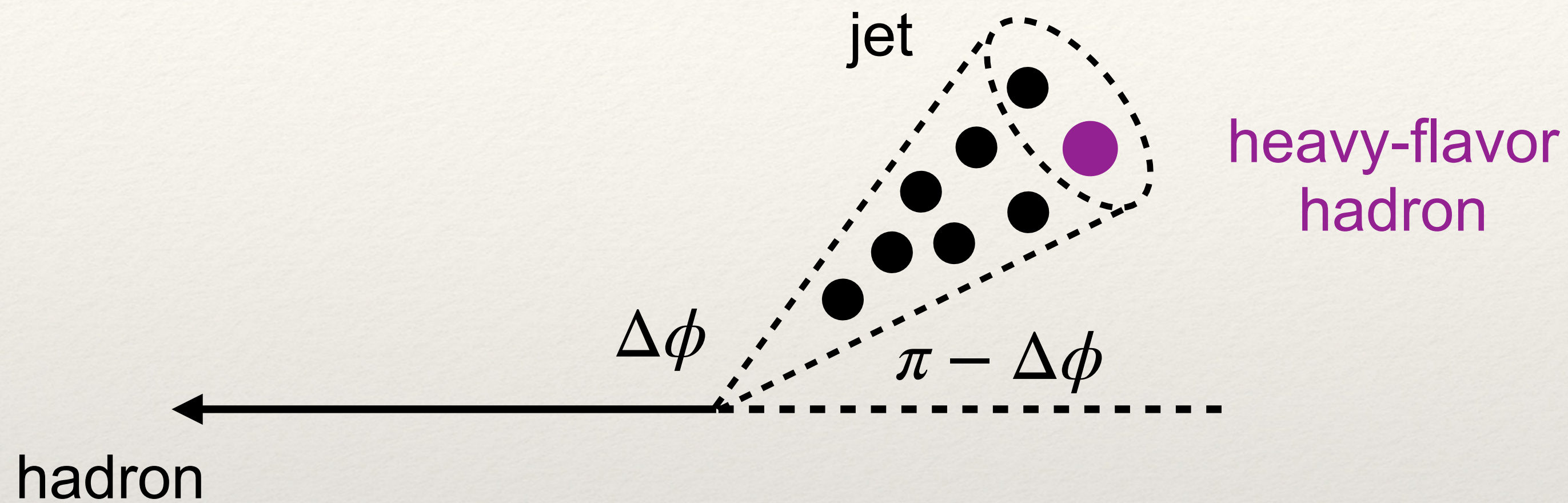
- $I_{AA} < 1$ at high p_T for partonic γ -jet
- String connection between shower partons and recoil partons causes $I_{AA} > 1$ for hadron jet
- $I_{AA} > 1$ or < 1 depends on the hadronization scheme of negative partons
- z_T distribution of γ -hadron prefers thermal over (colorless) string hadronization for negative partons

Acoplanarity of γ - and π^0 -jet at RHIC



- For both γ - and π^0 -jet within (10,15) GeV: suppression for small- R jet, enhancement at small $\Delta\phi$ for large- R jet
- Tension exists for π^0 -jet within (15,20) GeV

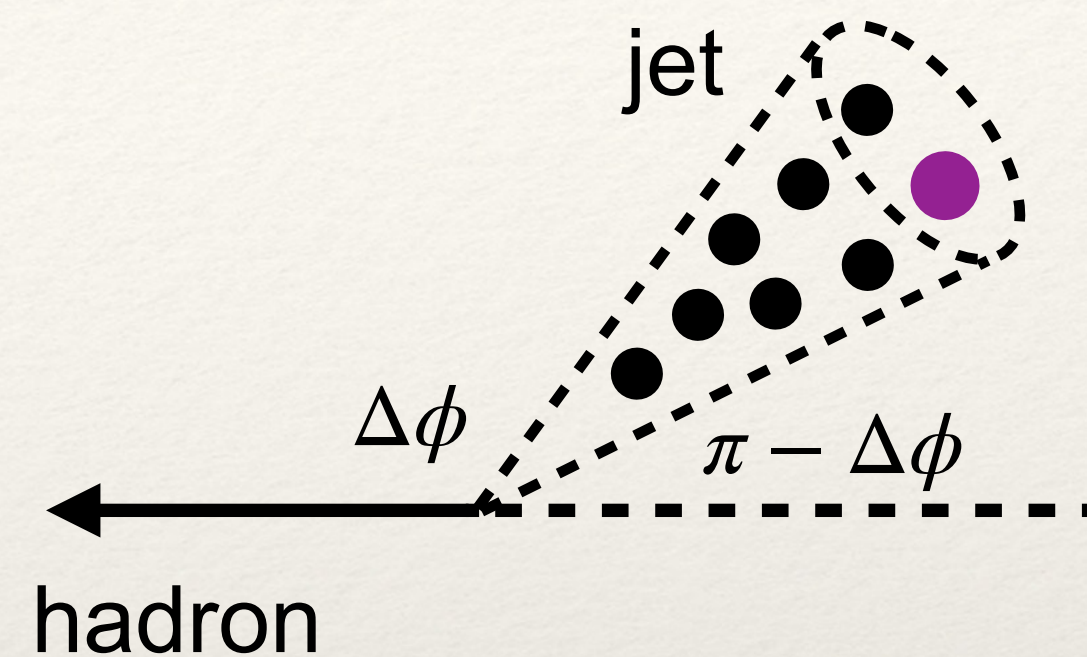
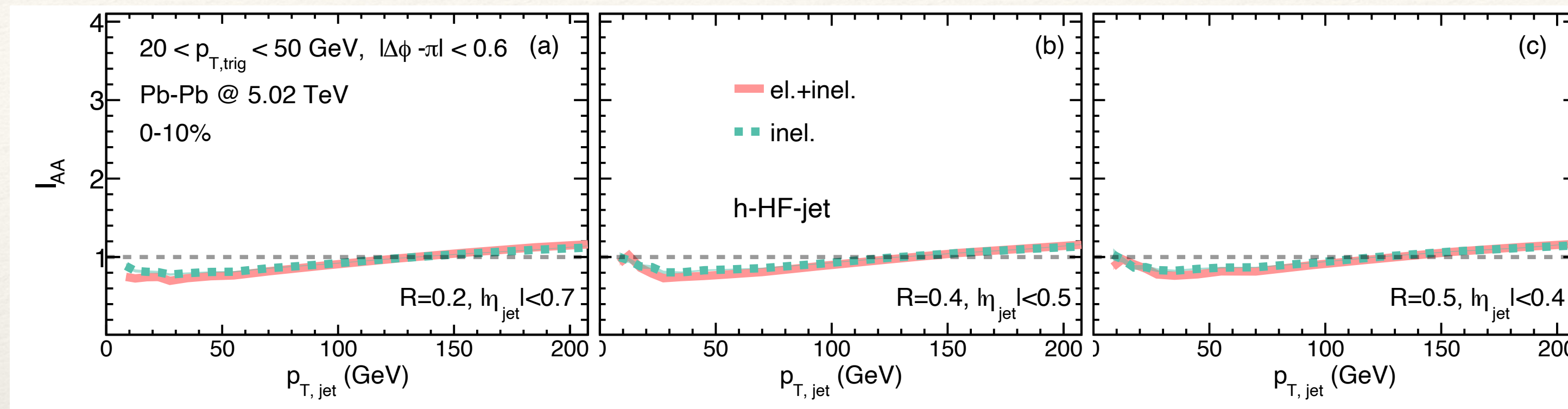
Suppressing thermal recoil jets by heavy quark tags



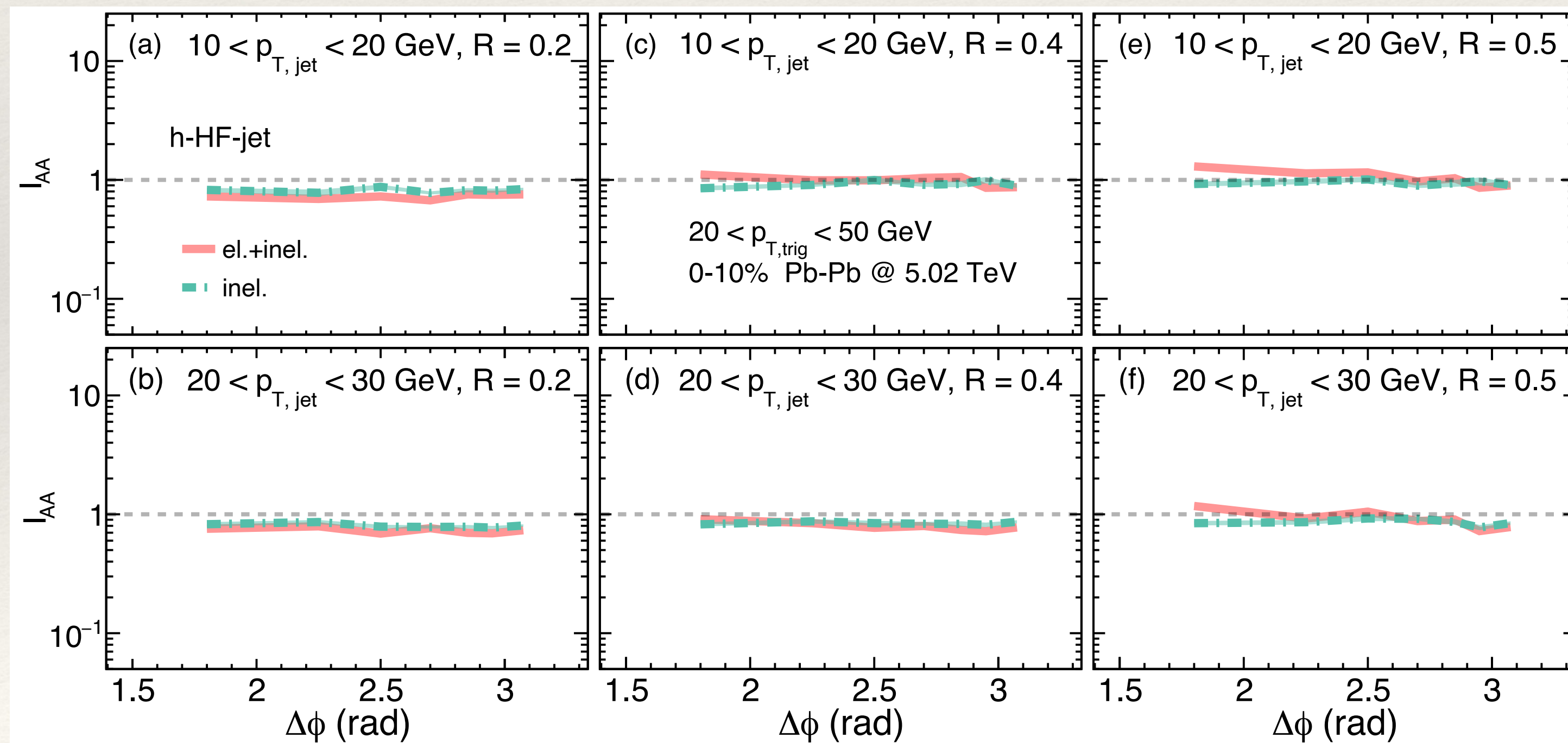
- Heavy quarks ($M_c = 1.3 \text{ GeV} > T_{\text{QGP}}$) are mainly produced by initial hard partonic scatterings
- The requirement for jets to contain heavy quarks suppresses thermal recoil jets
- Difference between light- and heavy-hadron jets will further support the concept of thermal recoil jet in h -jet acoplanarity enhancement

Nuclear modification of hadron triggered HF-jet I_{AA}

p_T dep.

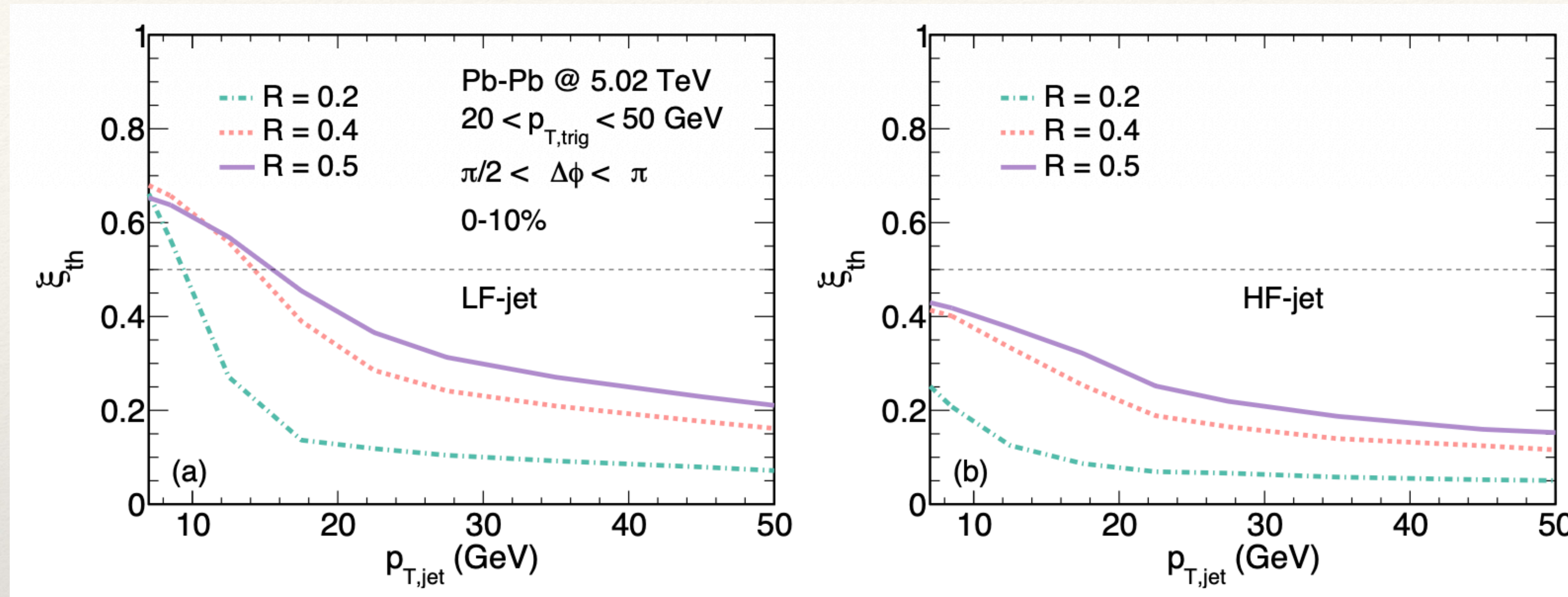


$\Delta\phi$ dep.



- Little enhancement at low p_T and small $\Delta\phi$
- Increasing contribution from recoil processes (el.+inel. vs. inel.) has little effect

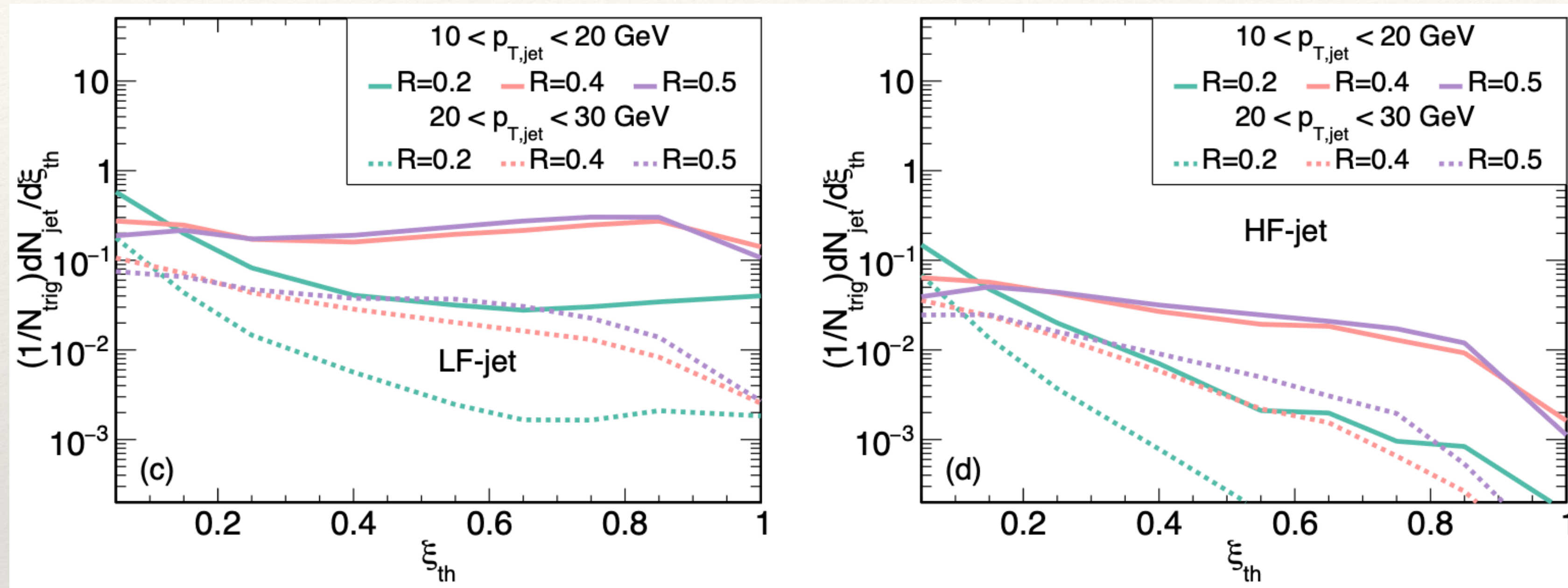
Comparison of average ξ_{th} between light and heavy flavor jets



$$\xi_{th} = \frac{|\vec{p}_T^{\text{recoil}} - \vec{p}_T^{\text{negative}}|}{|\vec{p}_T^{\text{recoil}} - \vec{p}_T^{\text{negative}}| + p_T^{\text{jet-shower}}}$$

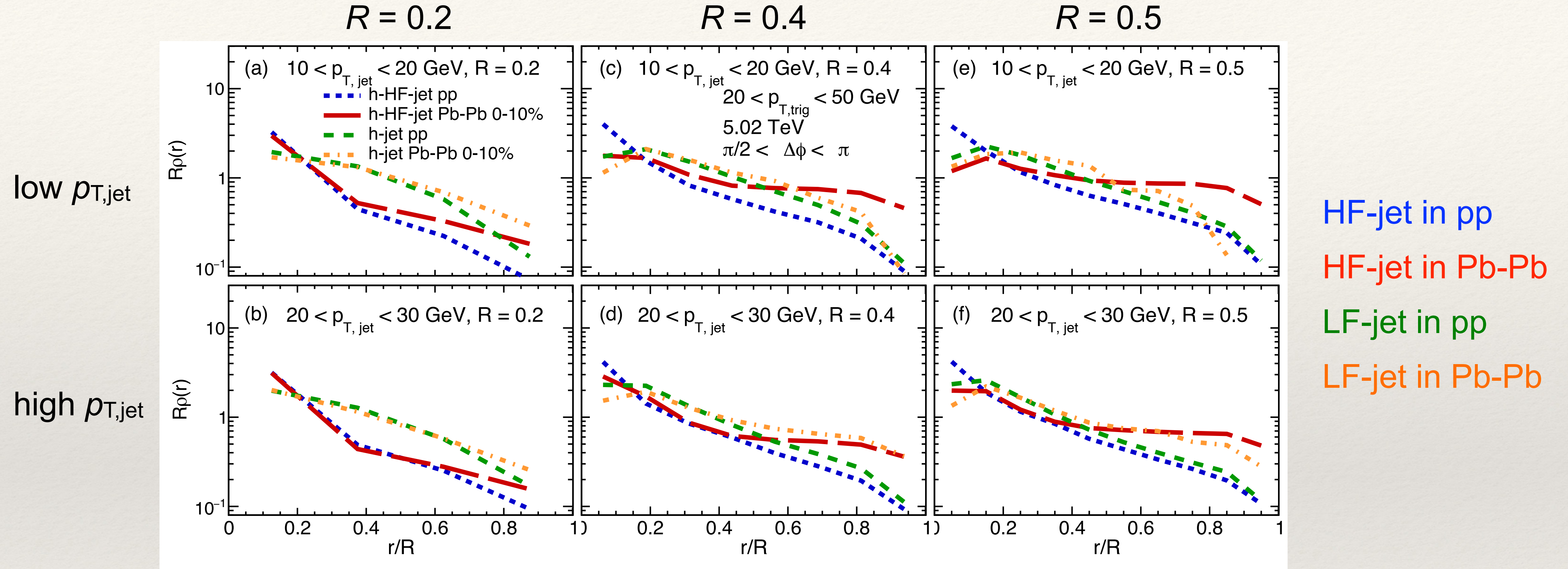
- Similar trend for hadron triggered LF-jet and HF-jet: larger ξ_{th} at smaller $p_{T,jet}$ and larger R
- HF-jets always have $\xi_{th} < 0.5$

Comparison of ξ_{th} distribution between LF- and HF-jets



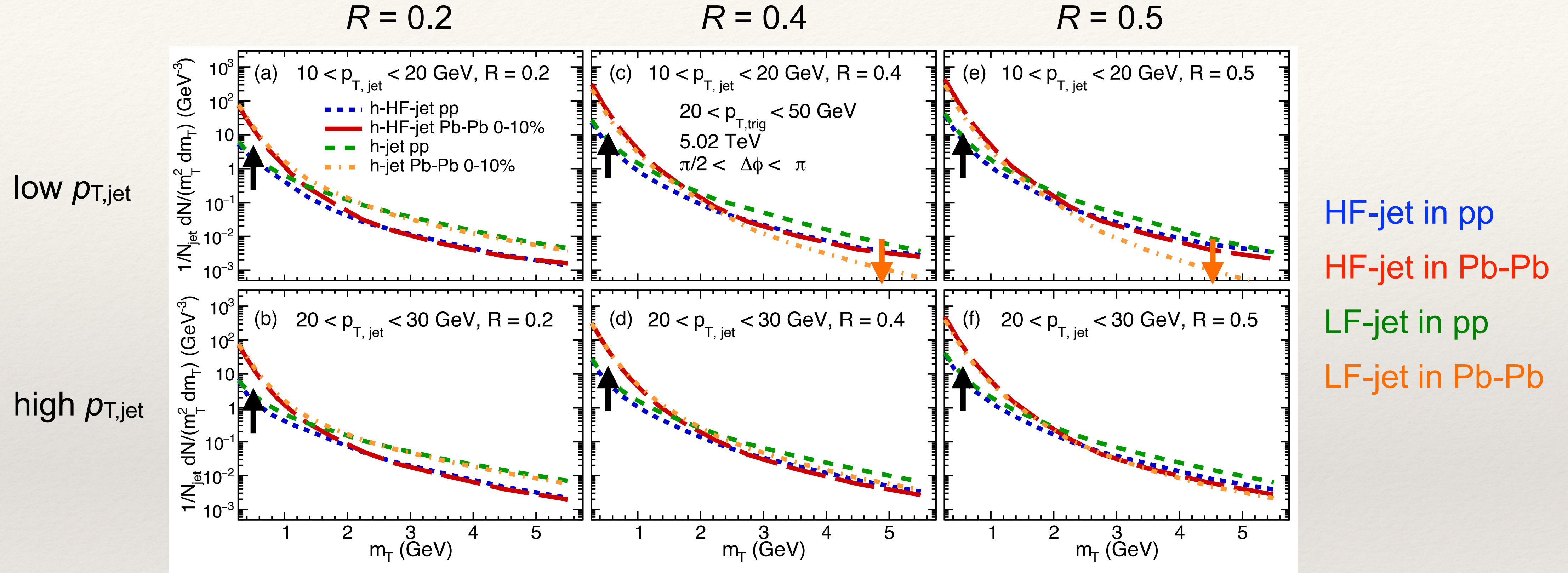
- Hadron triggered HF-jet is always dominated by jets with small ξ_{th}
- Thermal recoil jets (jets with large ξ_{th}) are significantly suppressed when HF-hadrons are required inside jets

Comparison of jet shape between LF- and HF-jets



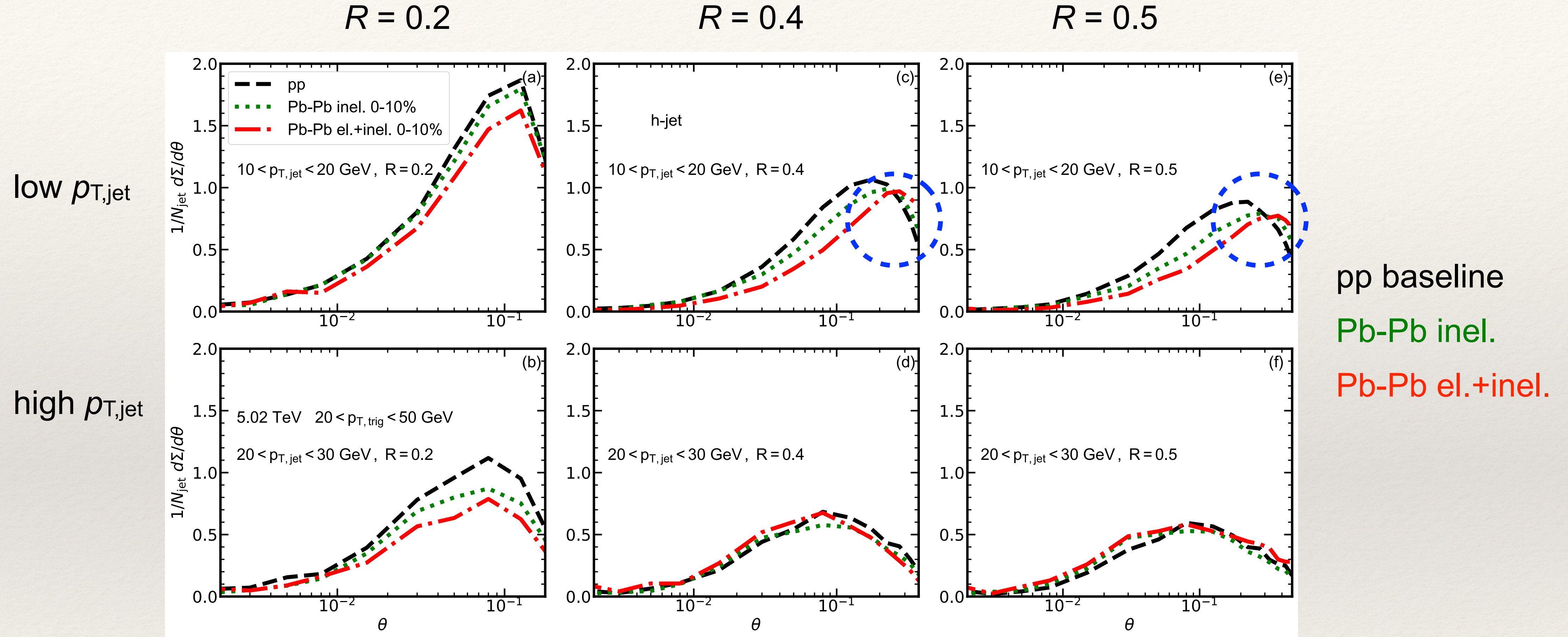
- Jets with small cone-size (R): hard core is un-modified, enhancement at large radii (r) in AA
- Jets with large R : suppression at small r , enhancement at large r (more prominent for low $p_{T,jet}$)
- No qualitative difference between LF- and HF-jets, probably due to their different shapes in pp

Comparison between particle spectra inside LF- and HF-jets



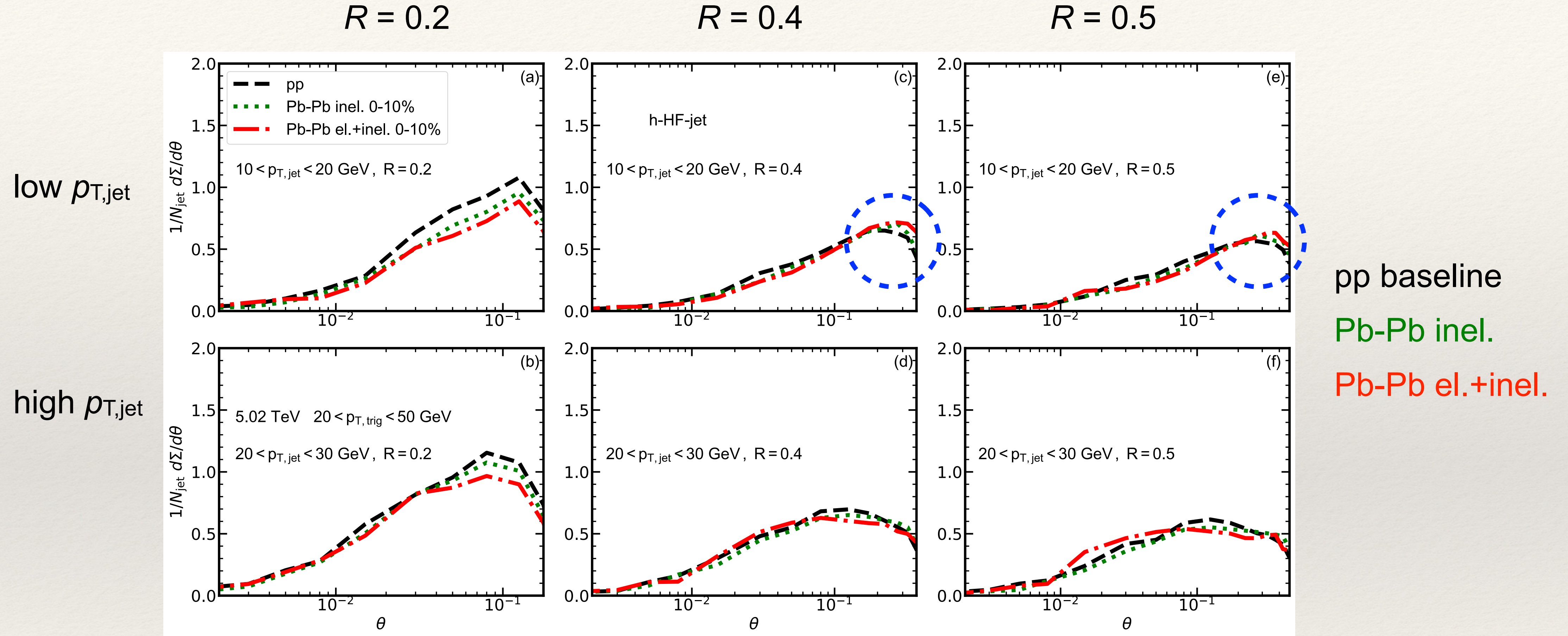
- Medium modified hard jets: strong enhancement at low m_T , minor suppression at high m_T
- Thermal recoil jets: strong enhancement at low m_T , strong suppression at high m_T
power $\rightarrow$ exponential spectra (prominent for low $p_{T,\text{jet}}$ and large- R LF-jets, not for HF-jets)

Energy-energy correlator of hadron triggered LF-jet



- Enhancement of the LF-jet EEC at large angle, from jet-induced medium excitation, only prominent for low $p_{T,jet}$ and large- R jets

Energy-energy correlator of hadron triggered HF-jet



- Much weaker EEC enhancement at large angle for HF-jets than for LF-jets

Summary

- Propose the emergence of thermal recoil jets in heavy-ion collisions, resulting from the energy deposition from hard jets inside the QGP
- Explain the acoplanarity enhancement of hadron and photon triggered light-flavor jets, observed solely for jets with low p_T and large R
- Predict unique features of jet shape, m_T distribution of jet constituents, and EEC of thermal recoil jets, and differences between light- and heavy-flavor jets, awaiting tests by future measurements

Thank. you!