



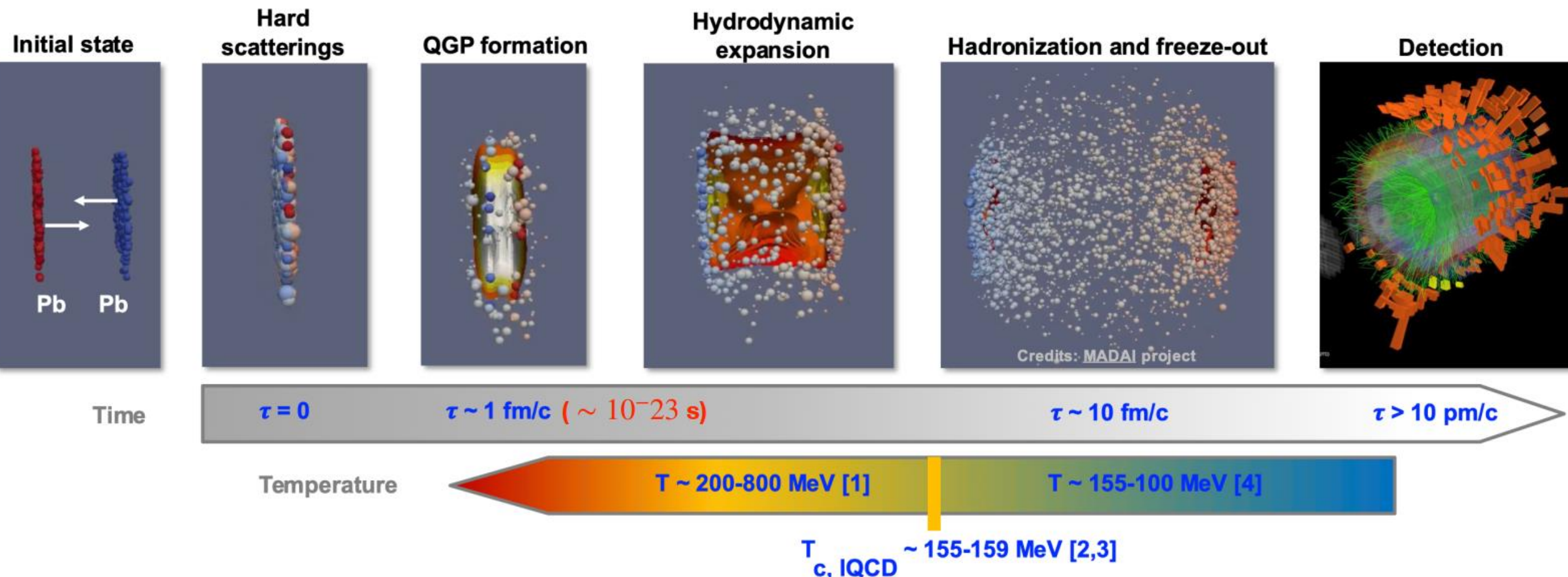
三峡大学
CHINA THREE GORGES UNIVERSITY

极端核物质前沿研讨会·宜昌

高能核碰撞中喷注子结构的介质诱导展宽

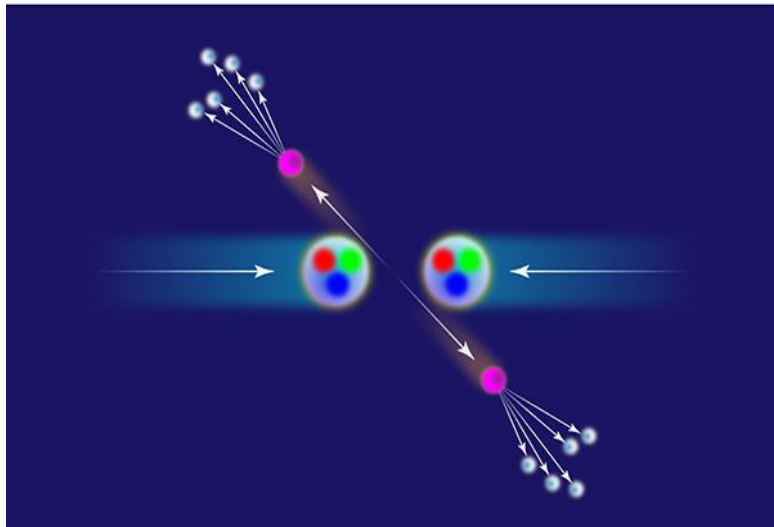
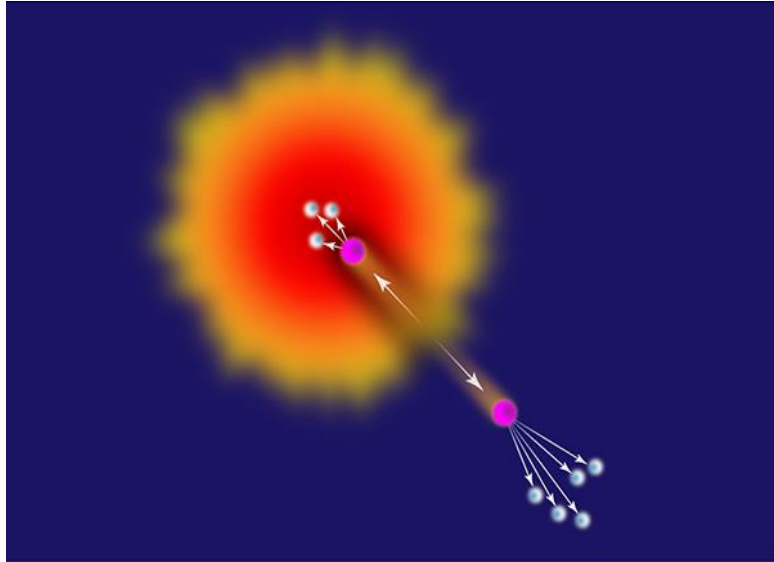
王洒
三峡大学数理学院
2026-04-27

Relativistic heavy ion collisions

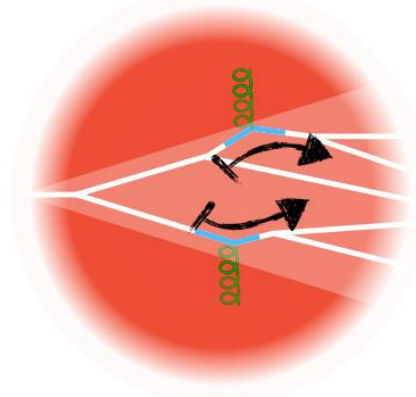


Ralf Averbeck, Quark Matter 2025

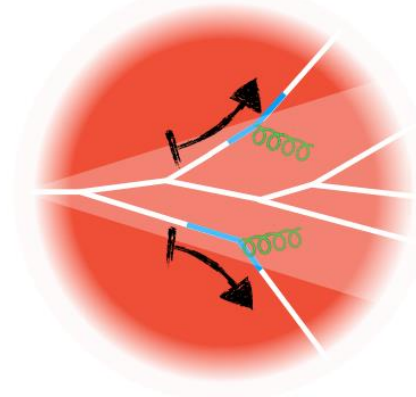
Jet quenching



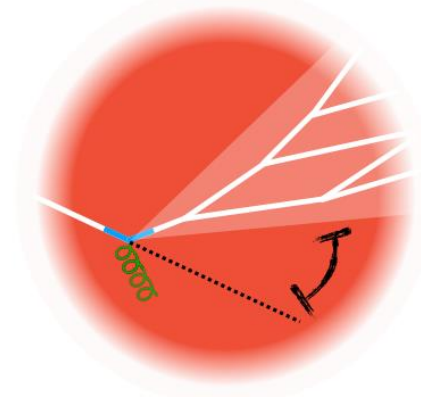
Substructure modification



Energy redistribution (“loss”)



Deflection

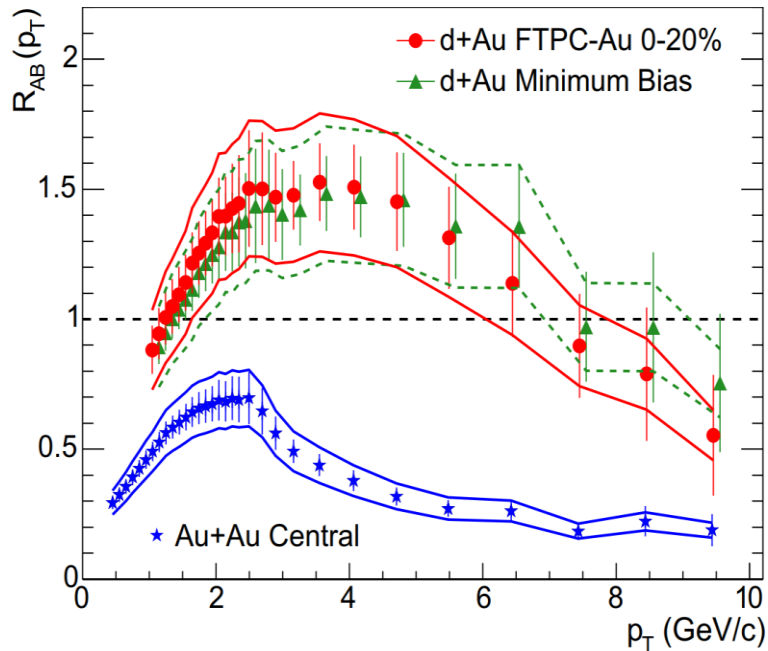


Jet transport coefficient : $\hat{q} = \frac{d\langle p_{\perp}^2 \rangle}{dt}$

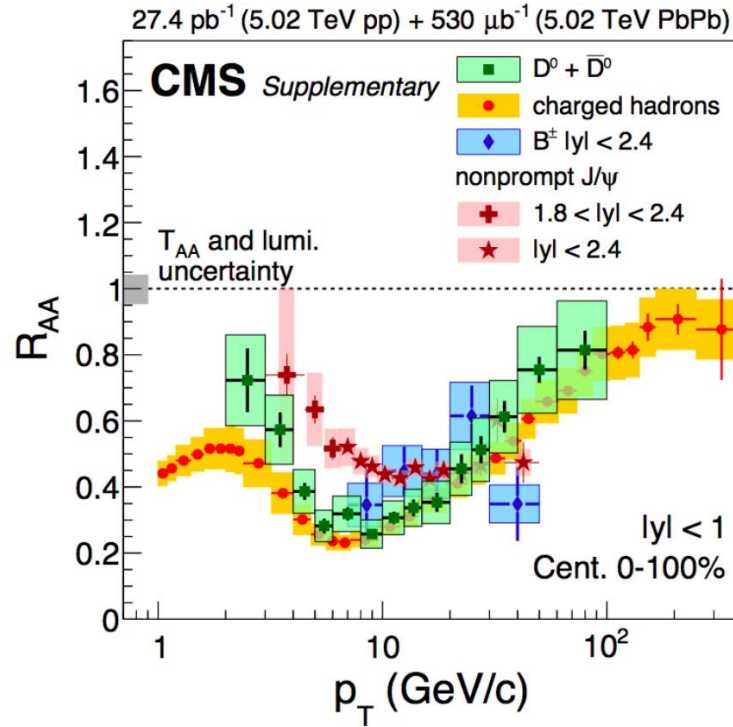
Energy loss : $\frac{dE}{dt}$

p_T -broadening : $\frac{dp_{\perp}}{dt}$

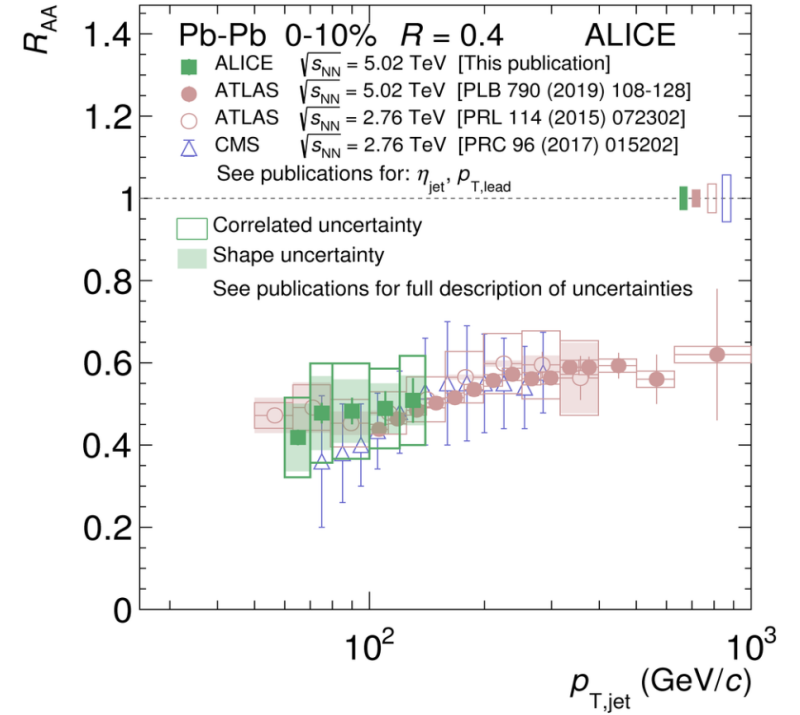
Yield suppression of high- p_T hadron and jet



STAR, PRL 91(2003)072304

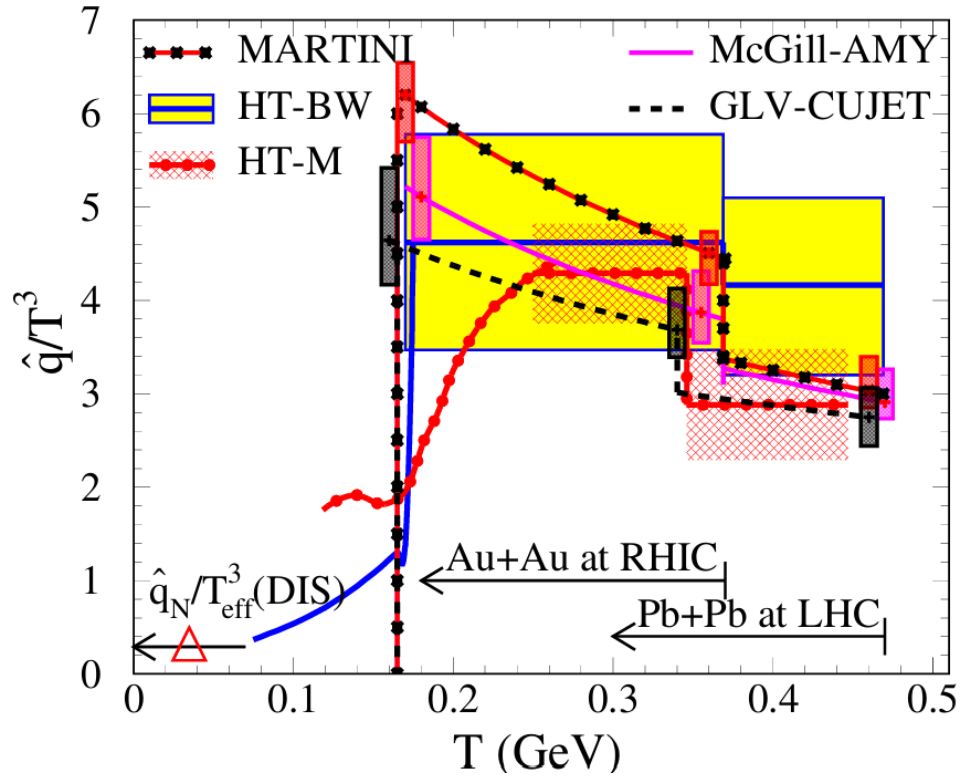
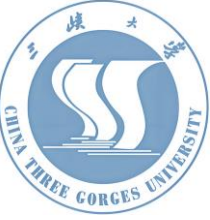


CMS, JHEP 04 (2017) 039
 CMS, PRC 96(2017) 015202
 CMS, PLB 782 (2018) 474

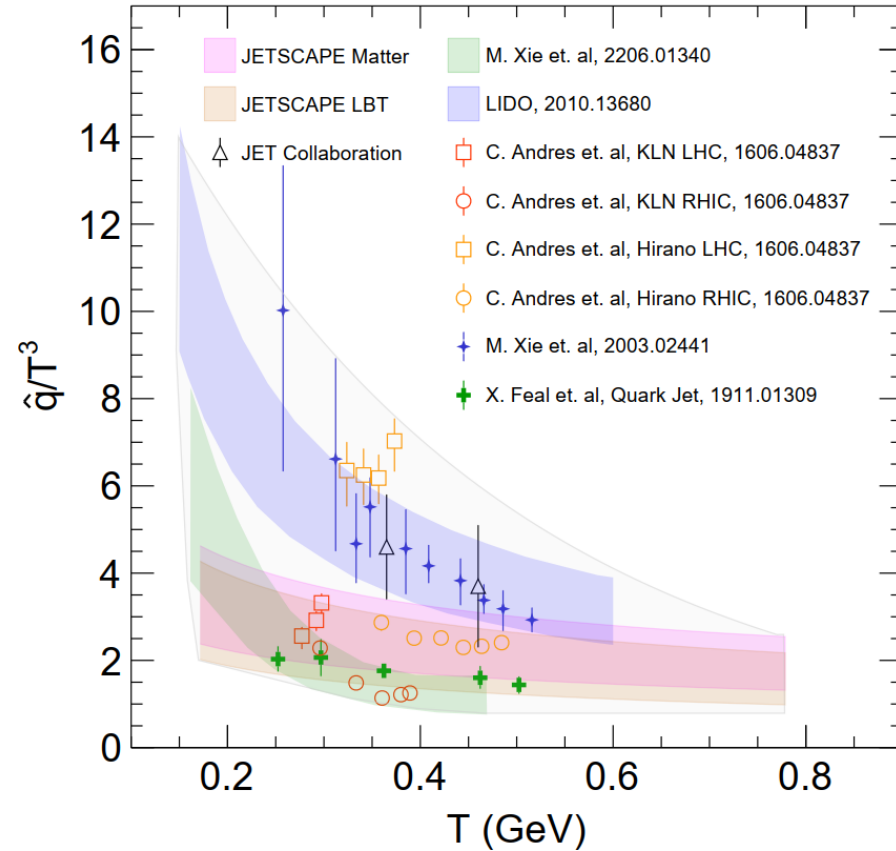


CMS, PRC 96(2017) 015202
 ATLAS, PRL 114 (2015) 072302
 ATLAS, PLB 790 (2019) 108-128

Jet transport coefficient



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



[Prog.Part.Nucl.Phys. 127 \(2022\) 103990](#)

Jet broadening in QGP

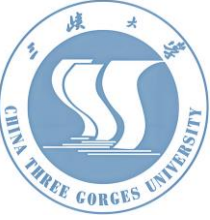
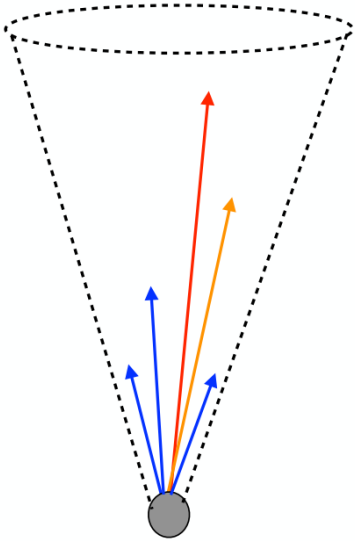
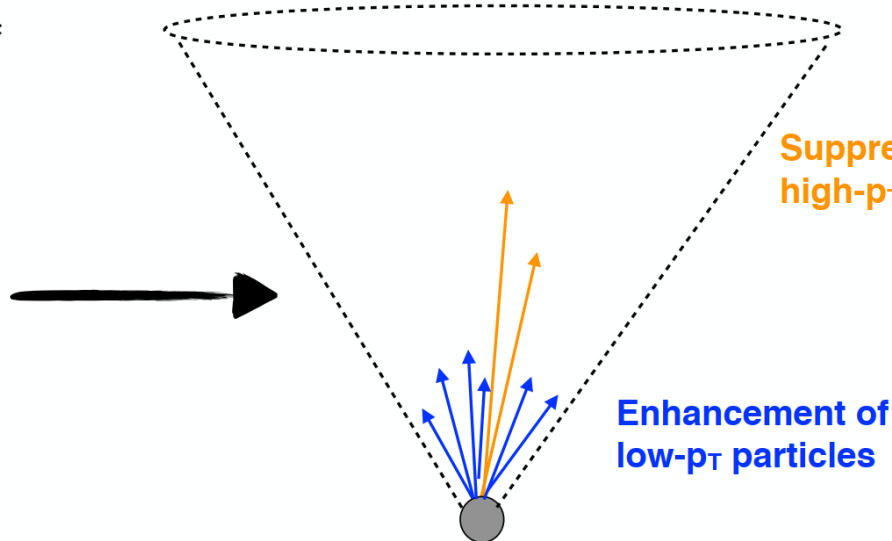


Image credit - Joern Putschke

Jet in vacuum



Jet in medium

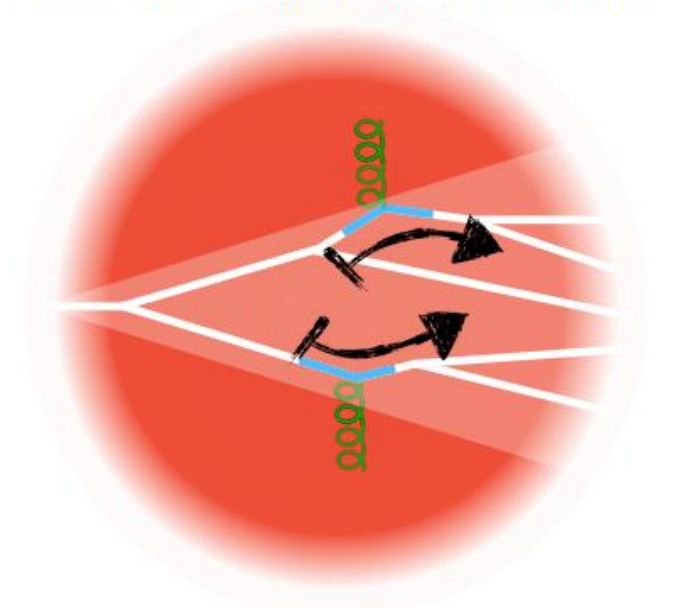


Jet broadening

Suppression of high- p_T particles

Enhancement of low- p_T particles

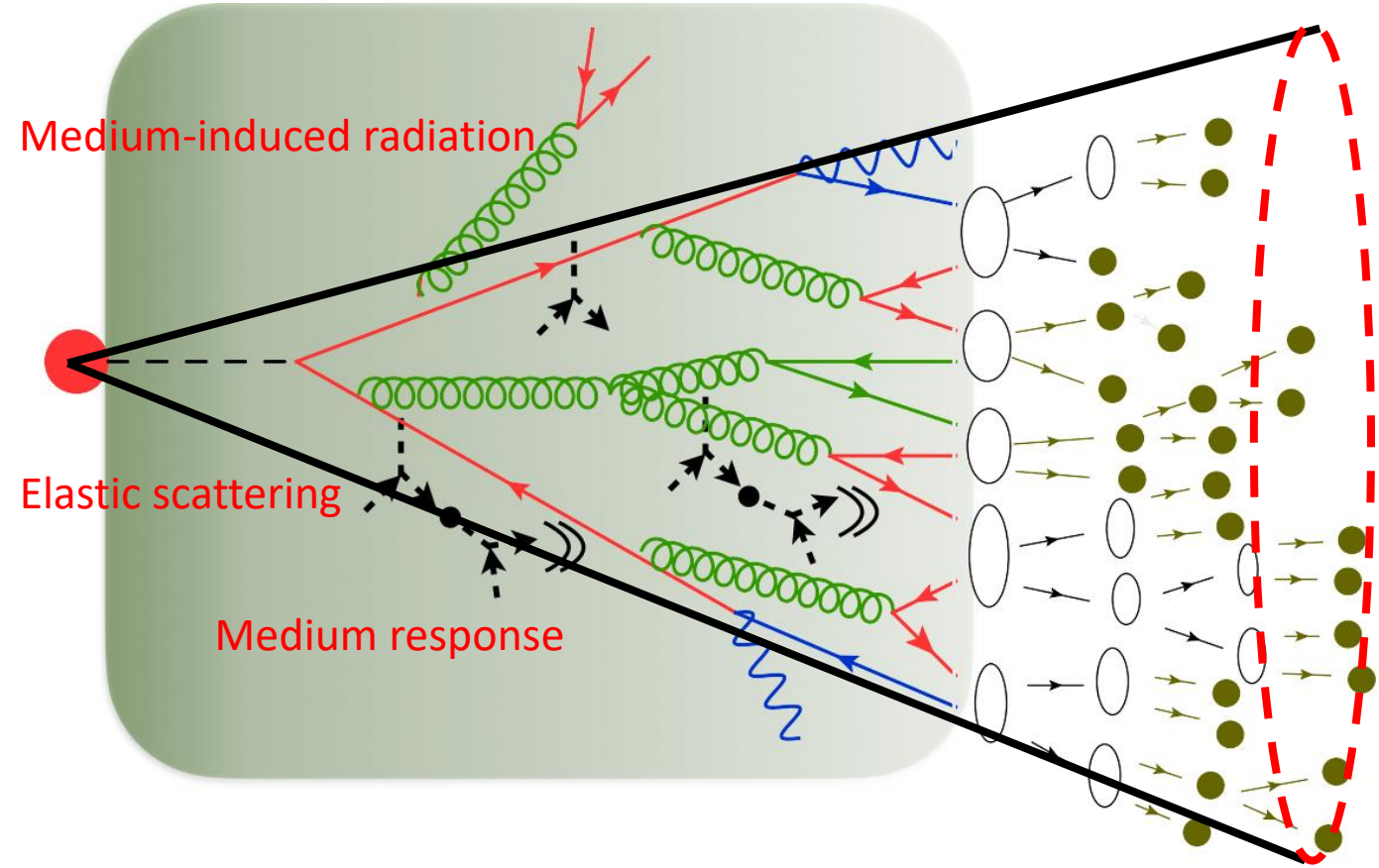
Substructure modification



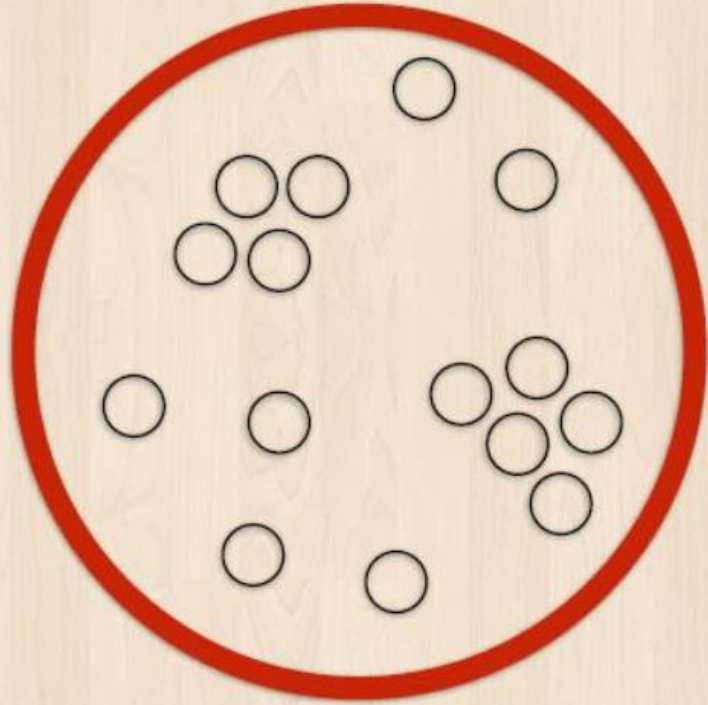
What can we learn from jet broadening?



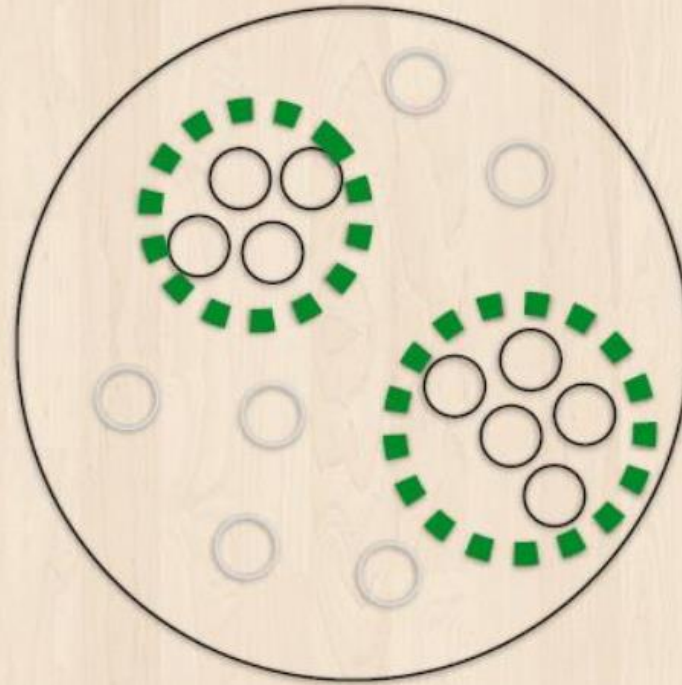
- Underlying partonic energy loss mechanism: **coll. Vs rad., $\hat{q}(T, p)$** ...
- Mass/flavor dependence of jet quenching: **dead cone, C_A/C_F** ...
- Phase structure of quark-gluon plasma: **large-angle scattering, quasi-particle, resolution length**...



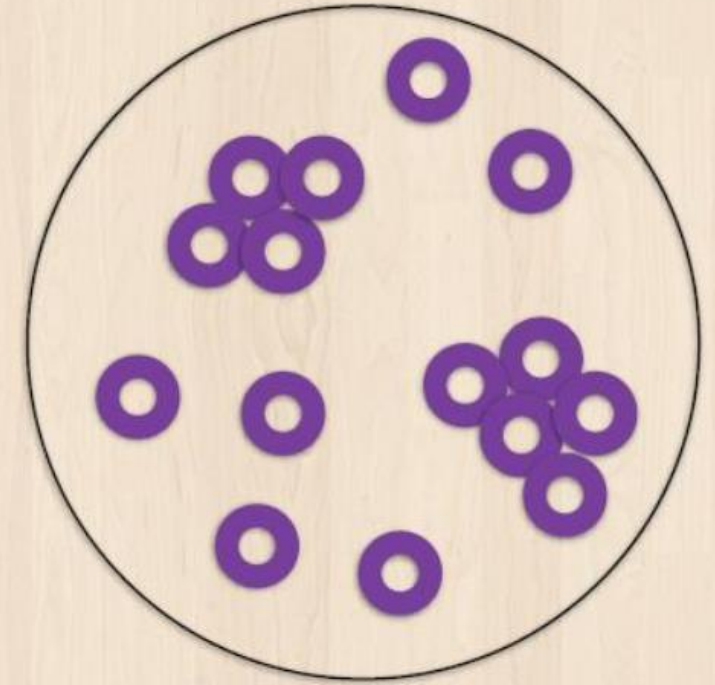
The current focus: jet substructure



Full jet



Large structure



Constituent

Yield suppression R_{AA}/I_{AA}
Angular correlation $\Delta\phi$

Groomed radius r_g
Momentum sharing z_g

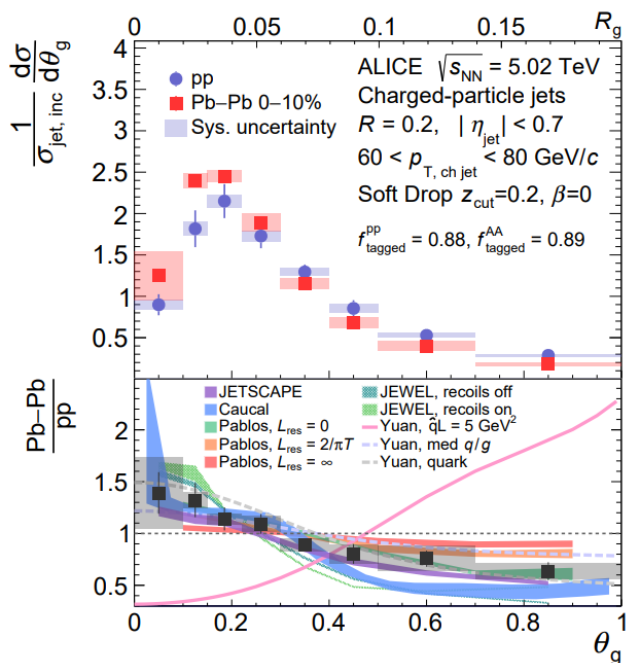
Jet angularity λ_β^κ
EEC

Probing broadening of jet substructures



Groomed radius

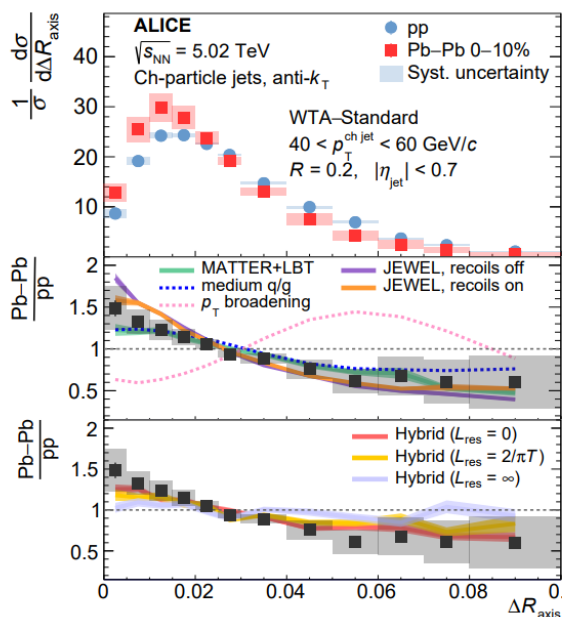
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R} \right)^\beta$$



ALICE, PRL(2022)

Angle between jet axis

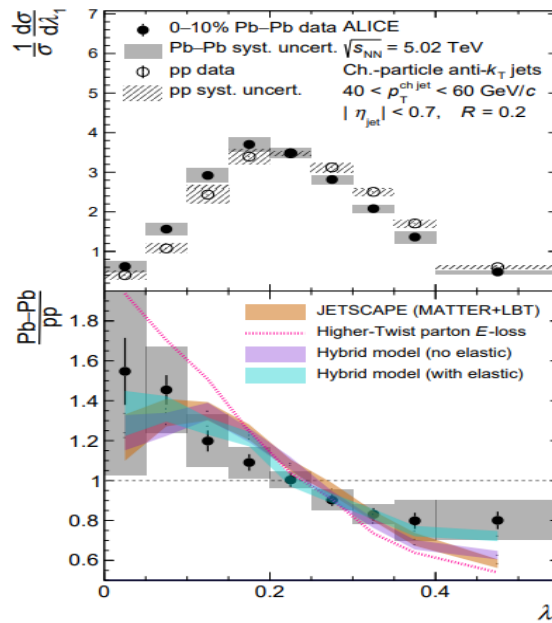
$$\Delta R_{\text{axis}}^{a-b} = \sqrt{(y_{\text{axis}}^a - y_{\text{axis}}^b)^2 + (\phi_{\text{axis}}^a - \phi_{\text{axis}}^b)^2}$$



ALICE, PRC(2026)

Jet angularity

$$\lambda_\alpha^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}} \right)^\kappa \left(\frac{\Delta R_i}{R} \right)^\alpha$$

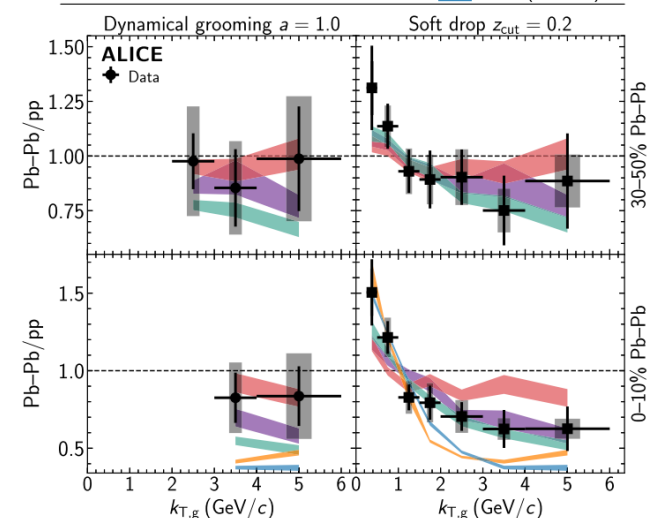


ALICE, PLB(2025)

Relative p_T between subjets

$$k_{T,g} = p_{T,2} \cdot \sin R_g$$

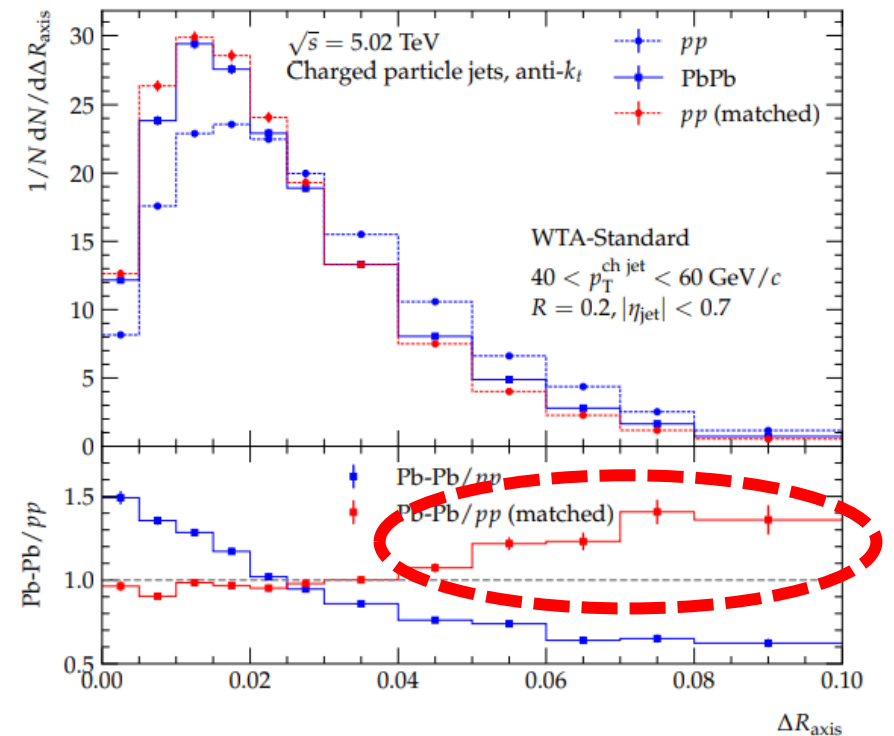
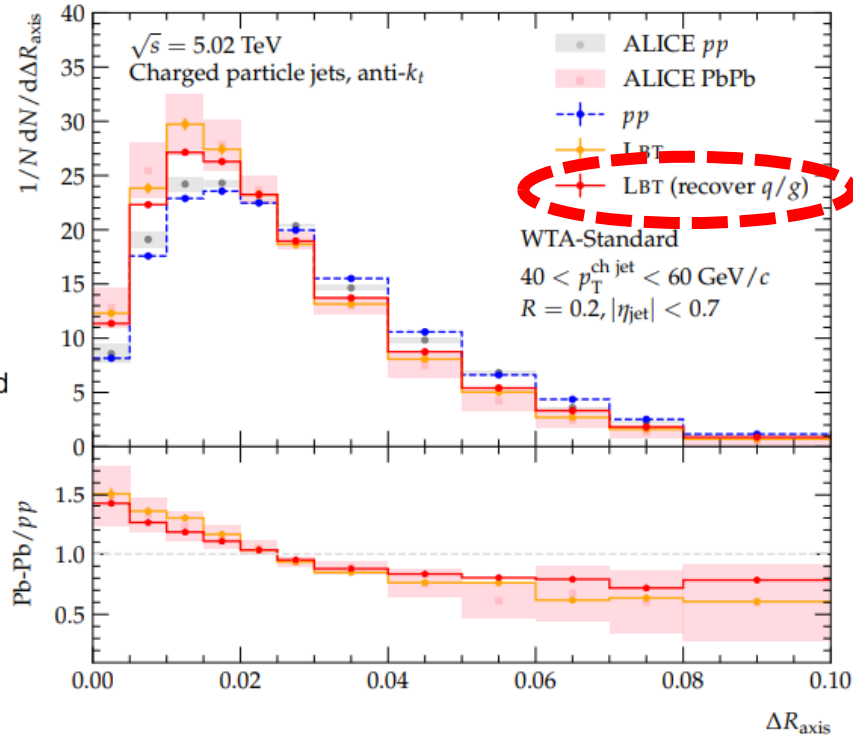
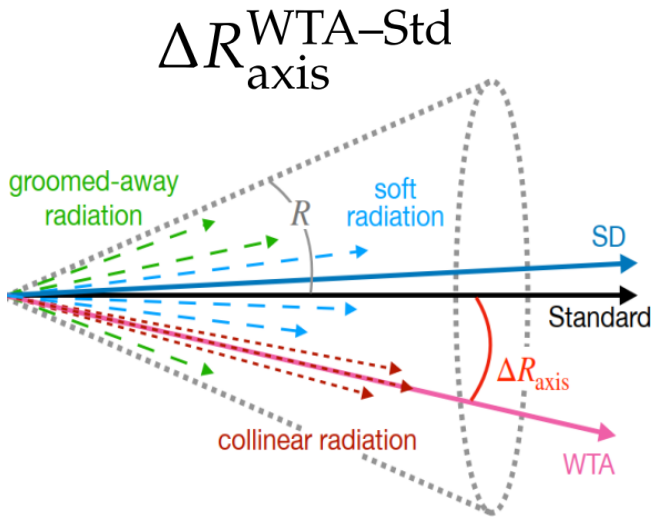
0-10%, 30-50% Pb-Pb, pp $\sqrt{s_{\text{NN}}} = 5.02$ TeV
 Anti- k_T ch-particle jets, $R = 0.2$, $|\eta_{\text{jet}}| < 0.7$
 $60 < p_{T,\text{ch jet}} < 80$ GeV/c



ALICE, PRL(2025)

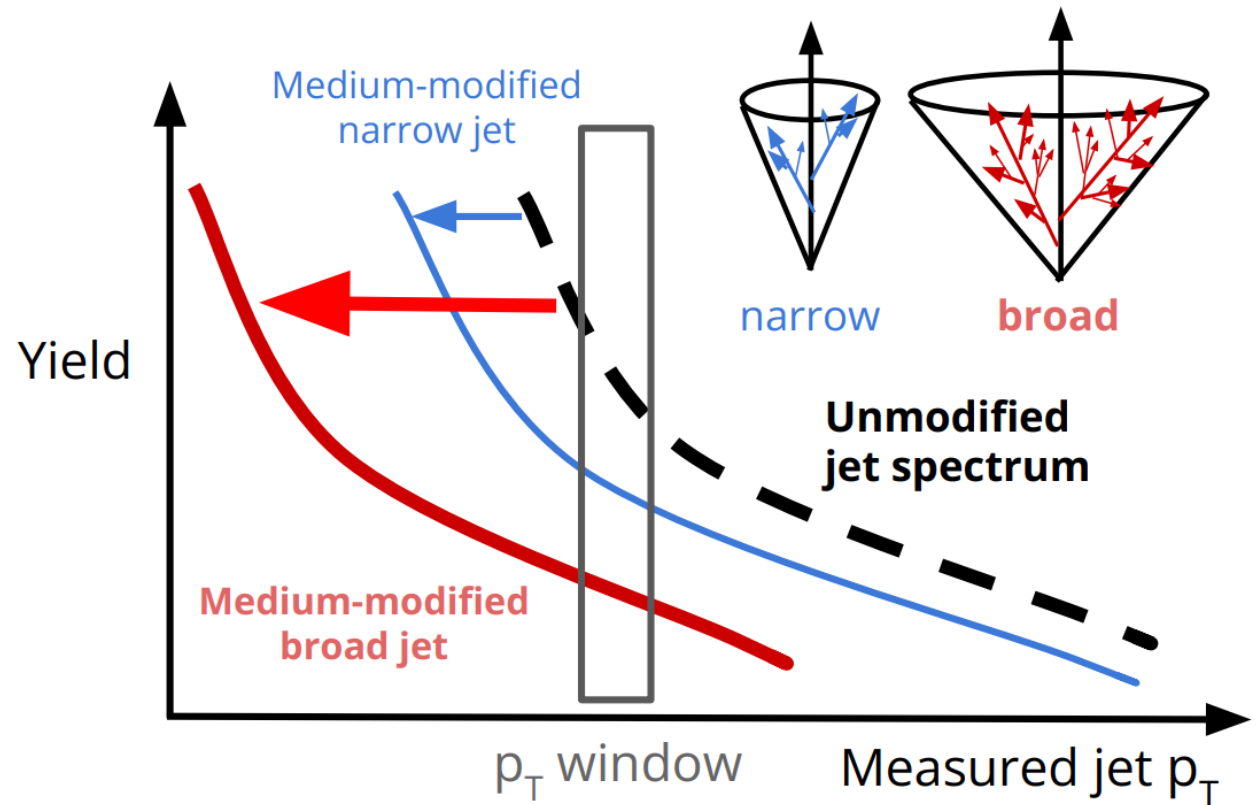
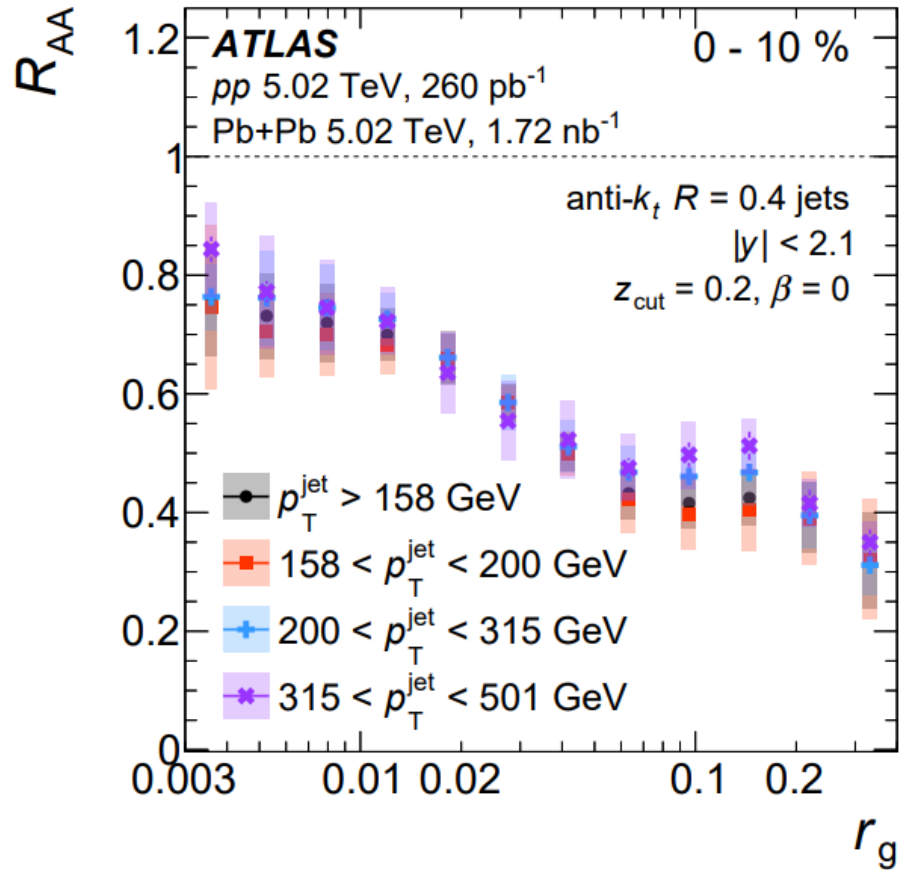
Narrowing instead of broadening observed in experiment!

Why jet narrowing observed?



- The q/g -jet fraction change may not significantly influence the modification pattern of ΔR_{axis} .
- A biased comparison between $p+p$ and $A+A$ conceals the actual jet-broadening effect in the experimental measurements.

Biased comparison between pp and AA

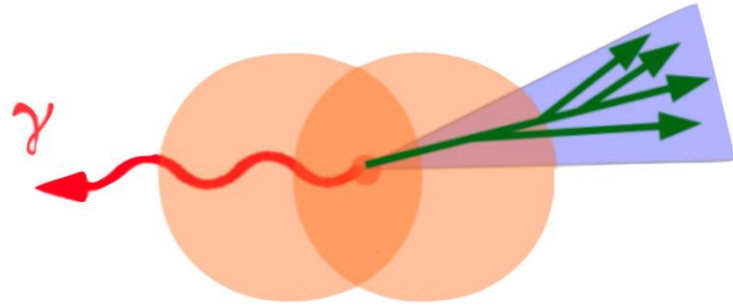


[ATLAS, Phys.Rev.C 107 \(2023\) 5, 054909](#)

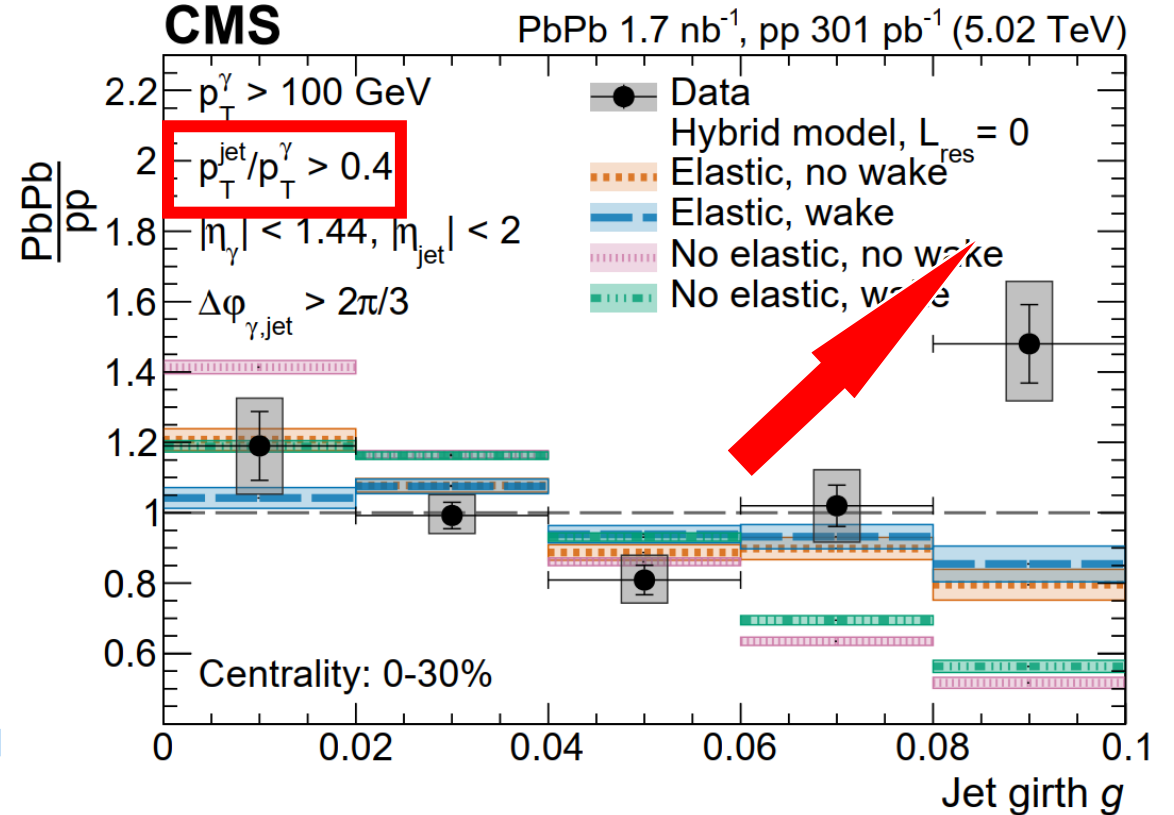
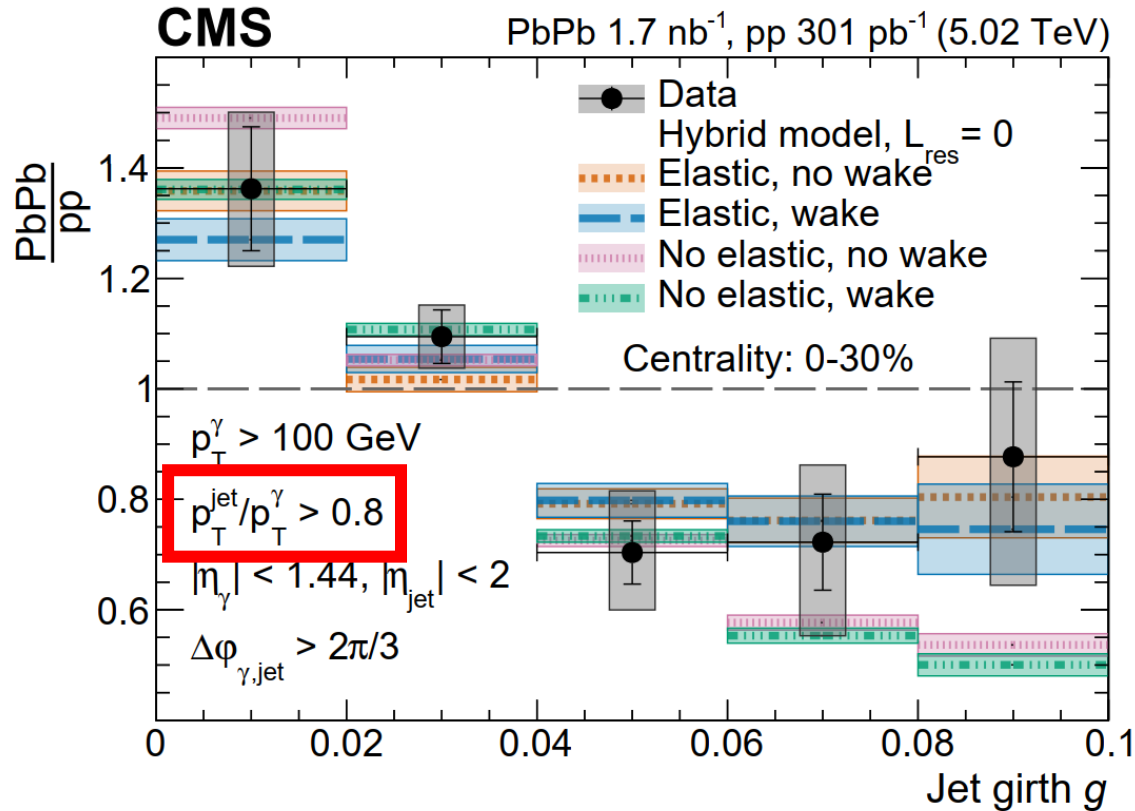
Due to energy loss in QGP, effectively quenched jets may be less likely to pass the p_T selection threshold in A+A collisions, while some jets with insufficient quenching may still survive.

Medium-modified substructure of photon-tagged jets

$$\lambda_\alpha^\kappa \equiv \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}} \right)^\kappa \left(\frac{\Delta R_i}{R} \right)^\alpha$$



CMS, Phys.Lett.B 861 (2025) 139088



➤ Signal of jet substructure broadening observed for jets with lower energy threshold in Pb+Pb collisions.

Simulating Heavy and Light quark jet Energy Loss



Collisional energy loss: pQCD@HTL

$$\frac{dE_{\text{coll}}}{dL} = -\frac{C_i}{4} \left(1 + \frac{N_f}{6}\right) \alpha_s(ET) g_s^2(\alpha_s^{\text{eff}}) T^2 \times \ln\left(\frac{q_{\text{max}}}{q_{\text{min}}}\right) \left(\frac{1}{v} - \frac{1-v^2}{2v^2} \ln\frac{1+v}{1-v}\right)$$

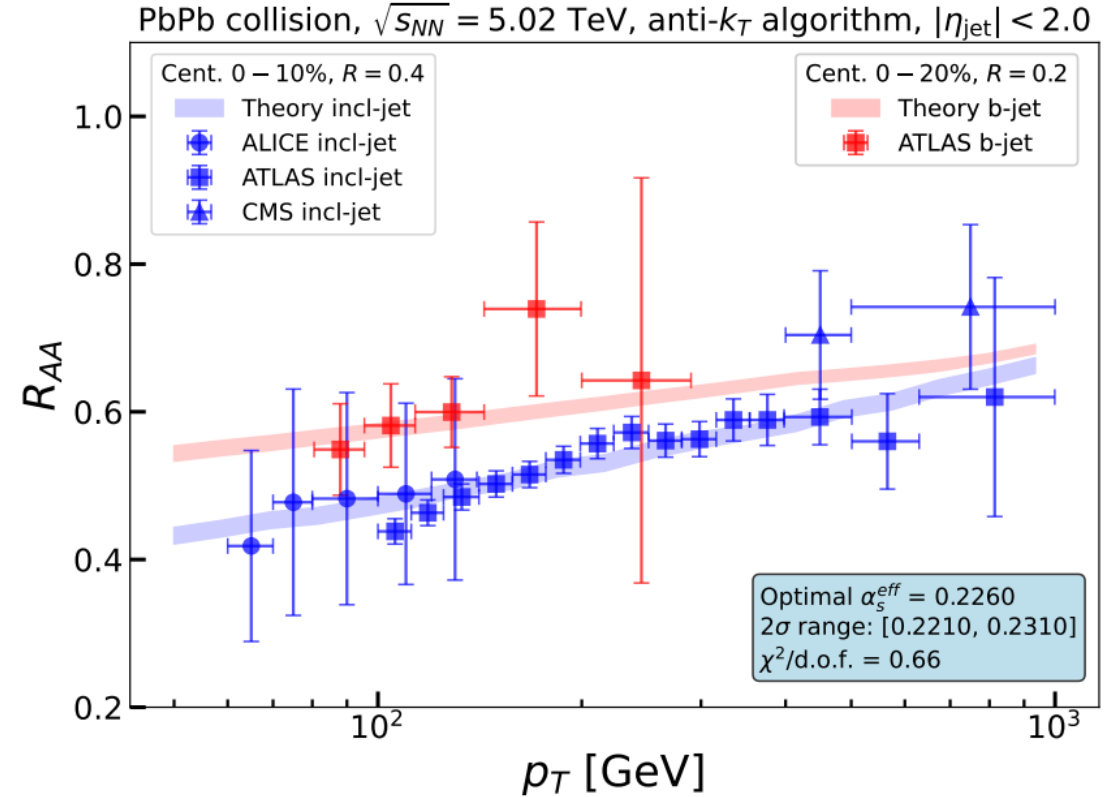
Radiative energy loss: Higher-Twist formalism

$$\frac{dN}{dx dk_{\perp}^2 dt} = \frac{2\alpha_s C_s P(x) \hat{q}}{\pi k_{\perp}^4} \sin^2\left(\frac{t-t_i}{2\tau_f}\right) \left(\frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2}\right)^4$$

$$\hat{q} = C_i \frac{42\zeta(3)}{\pi} \alpha_s(\mu^2) \alpha_s^{\text{eff}} T^3 \ln\left[\frac{cET}{4m_D^2}\right]$$

Medium response: Perturbed Hydrodynamic Wake

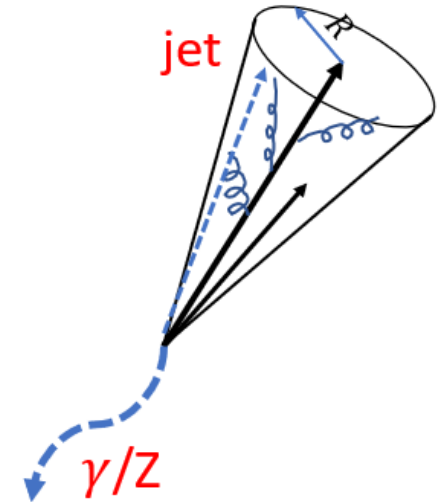
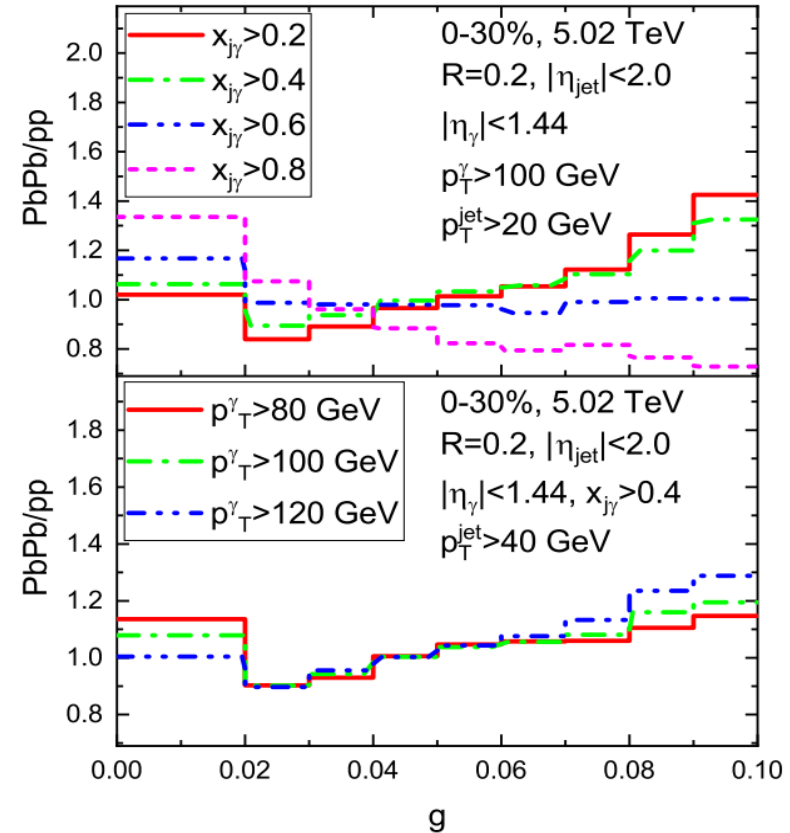
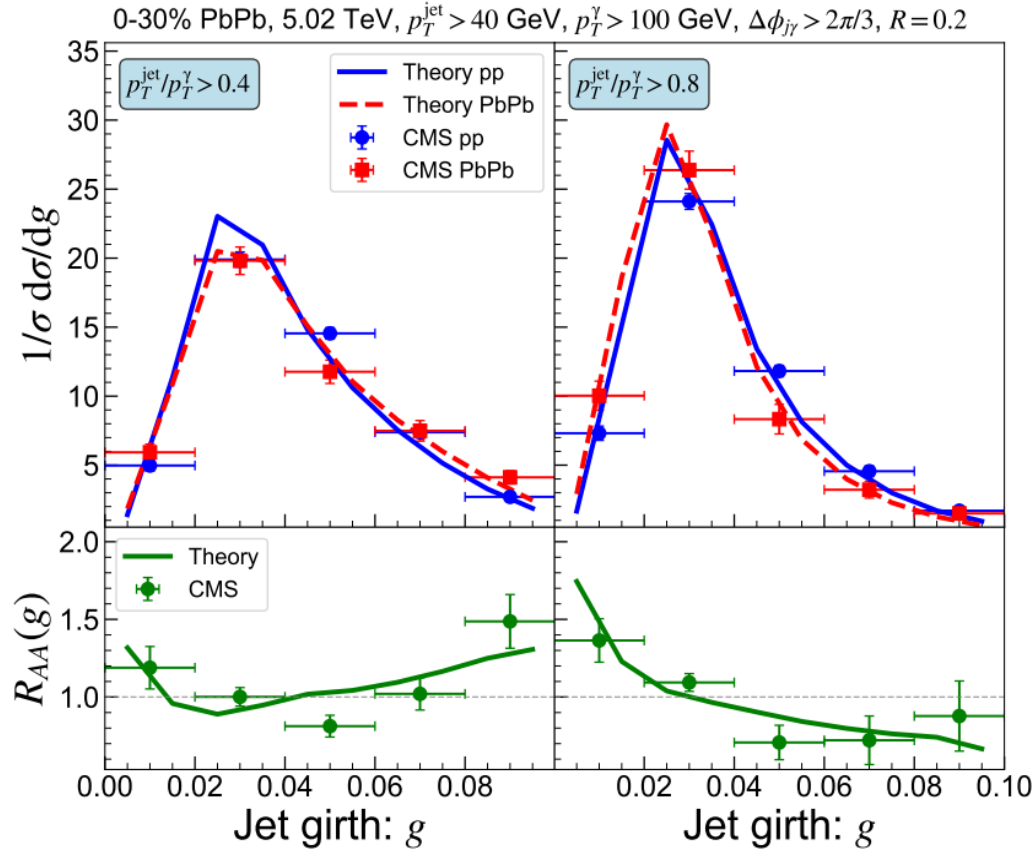
$$E \frac{d\Delta N}{d^3p} = \frac{m_T}{32\pi T^5} \cosh(\Delta y) \exp\left[-\frac{m_T}{T} \cosh(\Delta y)\right] \times \left\{ p_T \Delta P_{\perp} \cos(\Delta\phi) + \frac{1}{3} m_T \Delta M_T \cosh(\Delta y) \right\}$$



[Phys.Rev.D 44 \(1991\) 9, R2625](#)
[Phys.Rev.D 77 \(2008\) 114017](#)
[Phys.Rev.C 82 \(2010\) 024906](#)
[JHEP 03 \(2017\) 135](#)

[Phys. Rev. Lett. 85 \(2000\) 3591](#)
[Nucl. Phys. A 720, 429-451 \(2003\)](#)
[Phys. Rev. Lett. 93 \(2004\) 072301](#)
[Phys.Rev.C 94 \(2016\) 1, 014909](#)

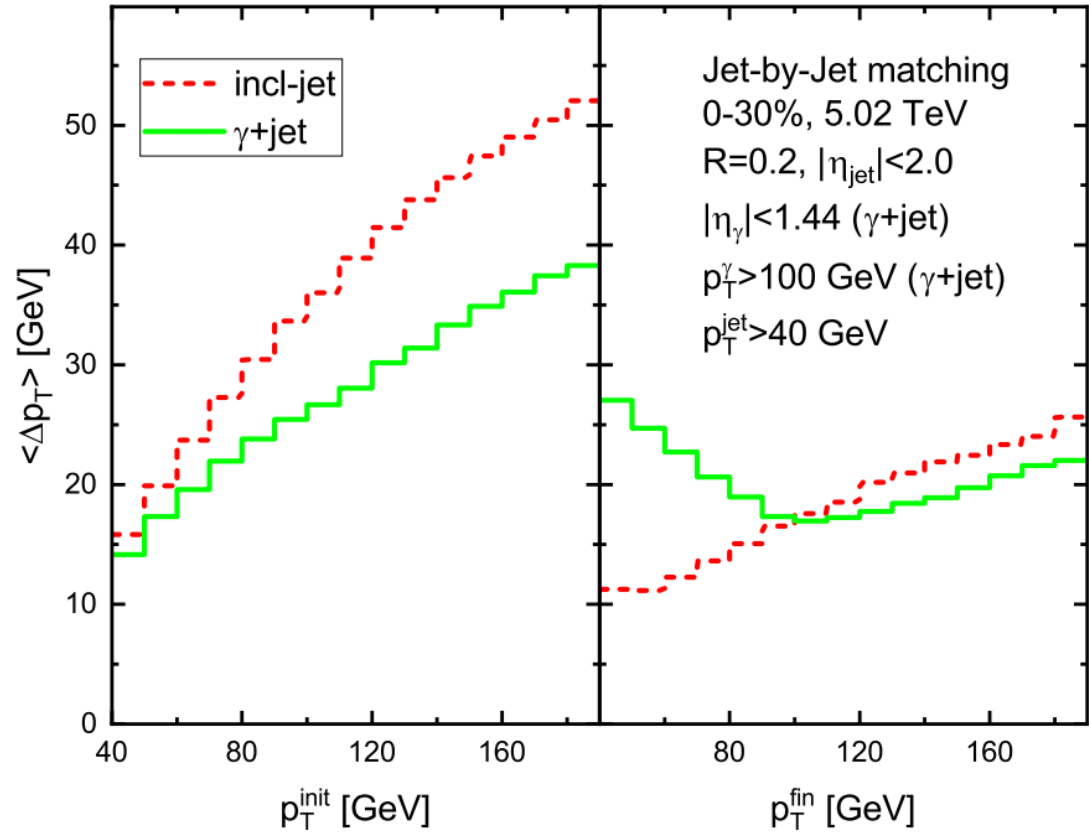
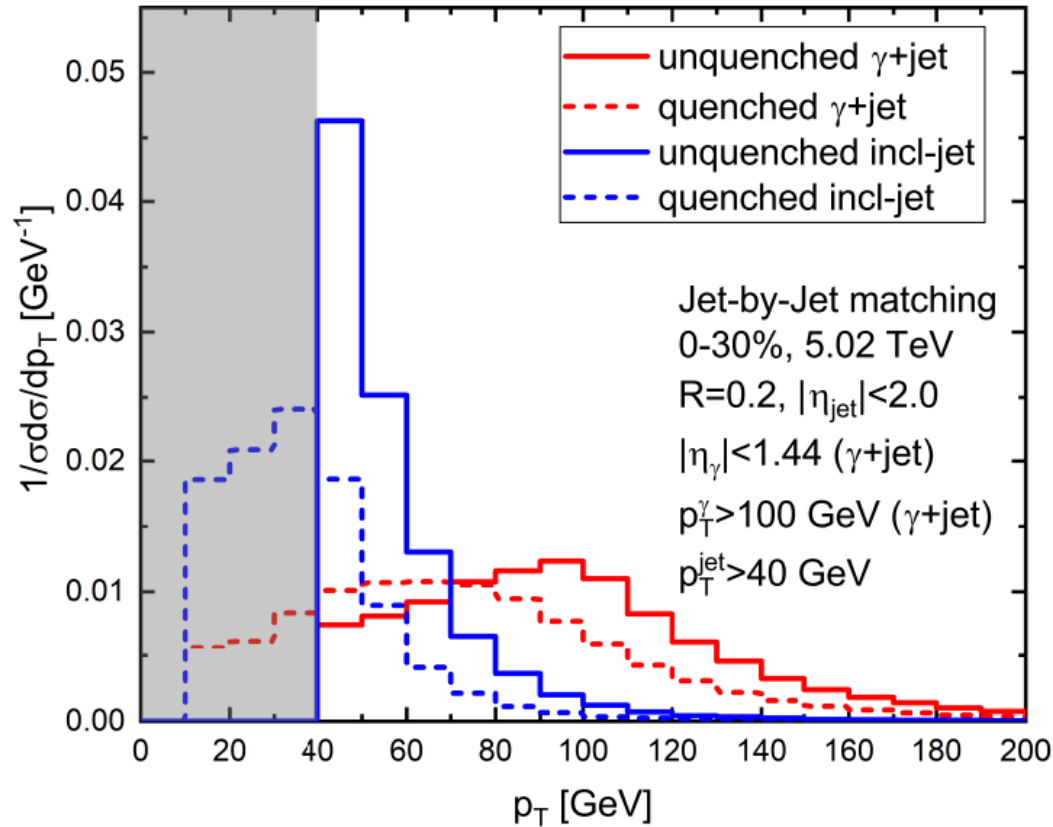
Theoretical calculation vs. experimental data



$$x_{j\gamma} = \frac{p_T^{\text{jet}}}{p_T^\gamma}$$

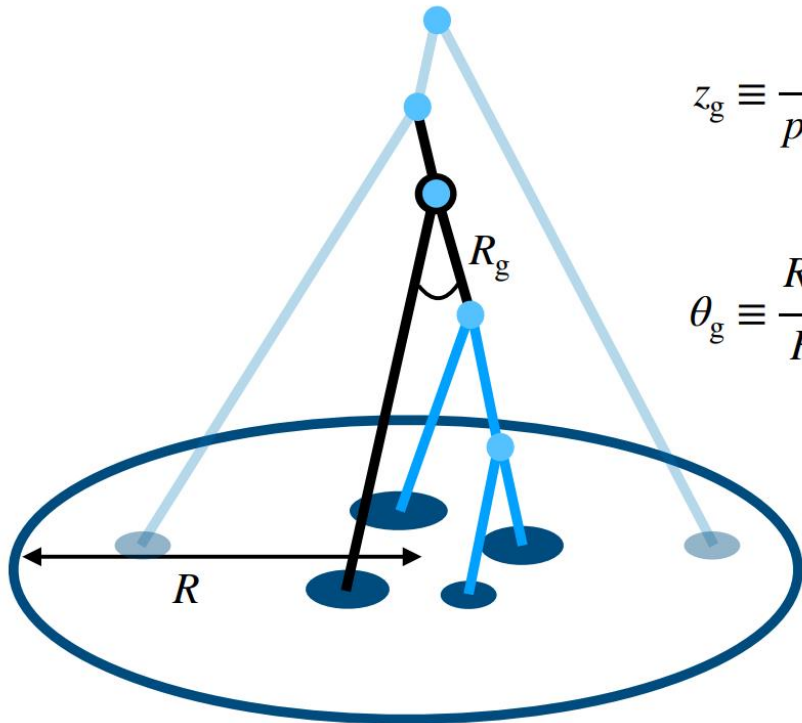
- Theoretical calculations of jet girth modification pattern are consistent with CMS data, show a clear p_T threshold dependence of modification pattern.

Advantages of $\gamma + \text{jet}$ to capture jet broadening



- $\gamma + \text{jet}$ reduces selection bias and can effectively select jets sufficiently quenched, which is crucial to capture the jet angular broadening.

Jet grooming: suppress non-perturbative effects



$$z_g \equiv \frac{p_{T,\text{subleading}}}{p_{T,\text{leading}} + p_{T,\text{subleading}}}$$

$$\theta_g \equiv \frac{R_g}{R} \equiv \frac{\sqrt{\Delta y^2 + \Delta \phi^2}}{R}$$

Soft-Drop Grooming (SDG):

Set an energy threshold and control the angular weighting for subjects to scan the clustering tree until a suitable pair is found.

$$z > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R} \right)^\beta \quad \text{JHEP 05 (2014) 146}$$

Dynamical Grooming (DyG):

Defines a “hardness” variable κ and dynamically searches for the two subjects that maximize κ .

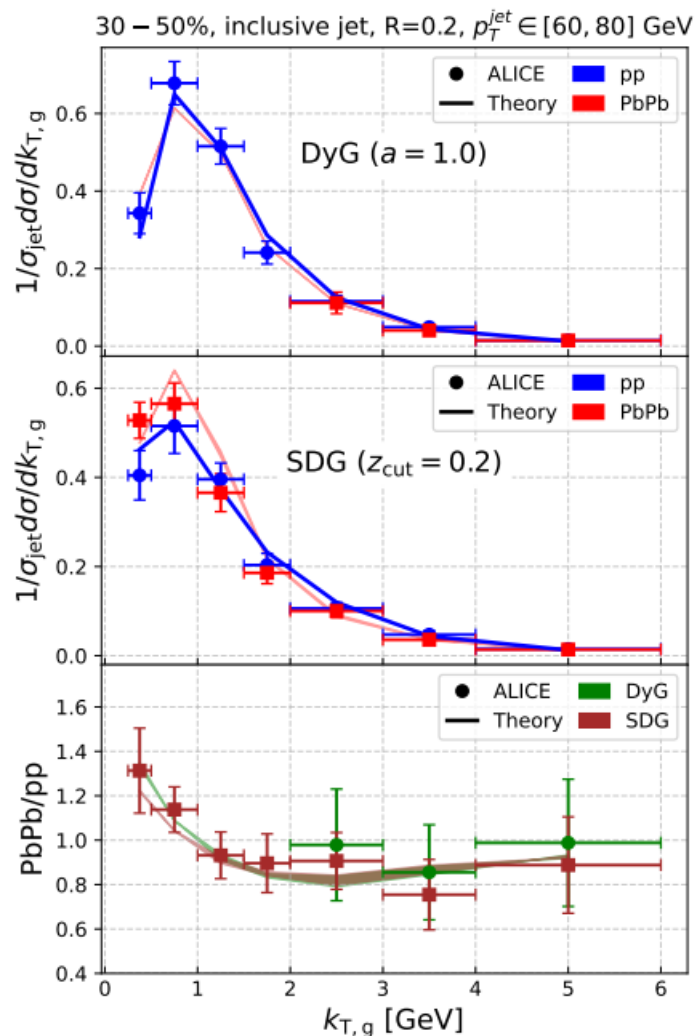
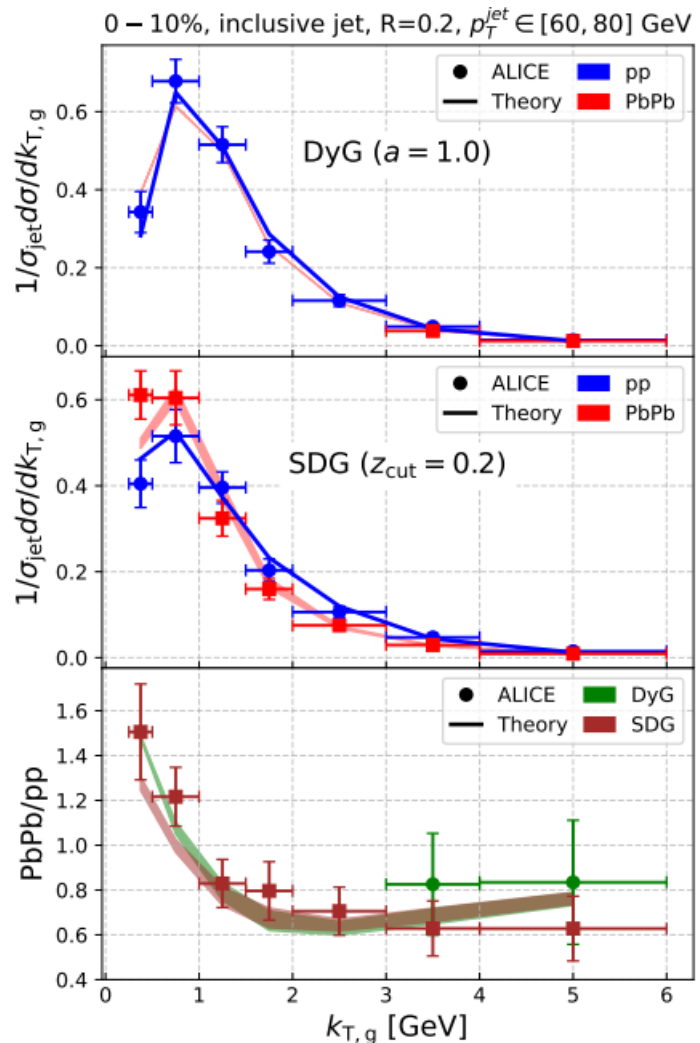
$$\kappa = z(1 - z)p_{T,\text{split}} \left(\frac{\Delta R_{12}}{R} \right)^a$$

PRD 101 (2020) 3

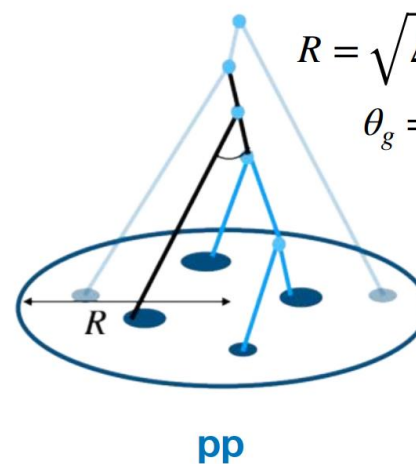
$$\text{Anti-} k_T : d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \xrightarrow{\text{decluster}} \text{C/A: } d_{ij} = \frac{\Delta R_{ij}^2}{R^2}$$

- Grooming techniques remove the soft, wide-angle radiation, reducing the impact of non-perturbative contributions and preserving the characteristic of hard splitting.

Relative transverse momentum between subjects

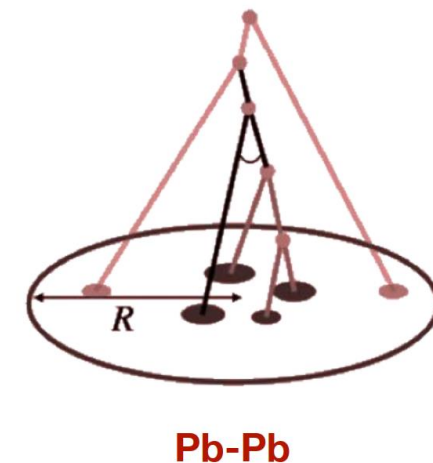


$$k_{T,g} = p_{T,2} \cdot \sin R_g$$

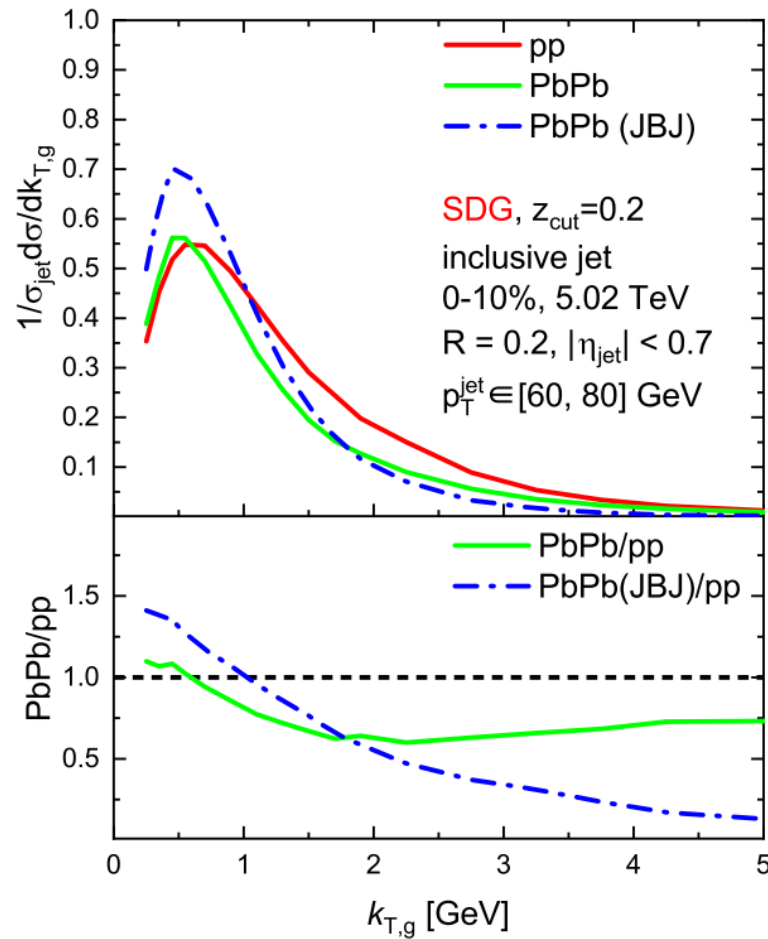
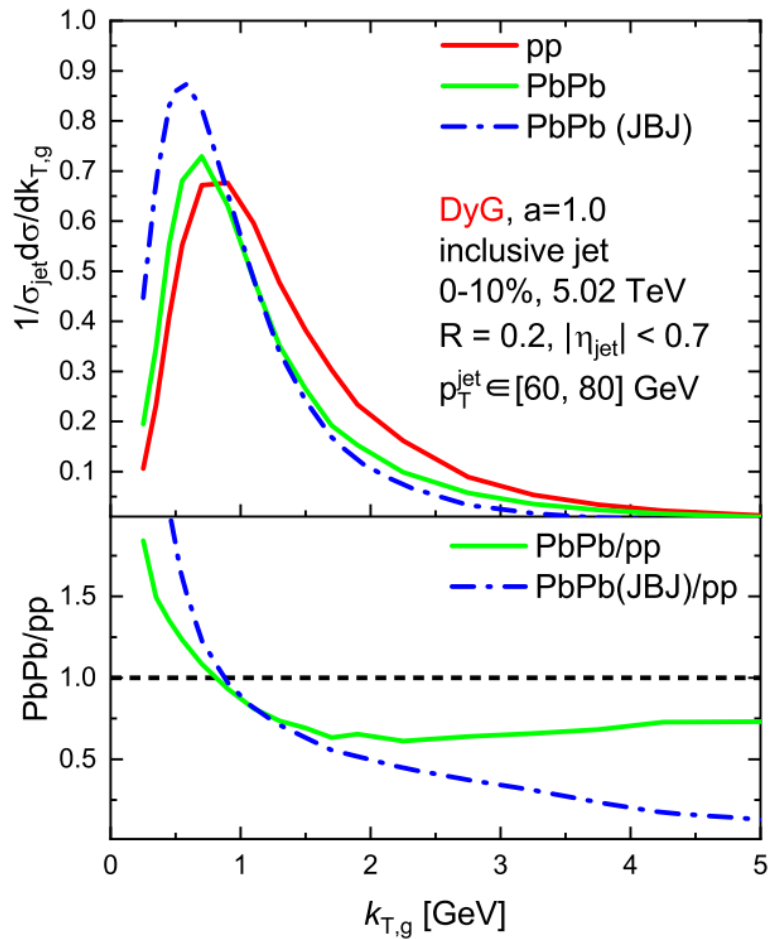


$$R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$$

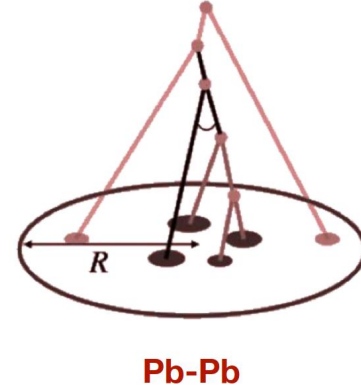
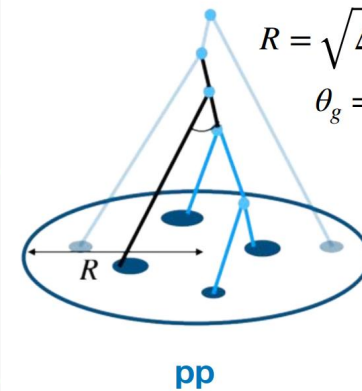
$$\theta_g = R_g/R$$



Relative transverse momentum between subjects

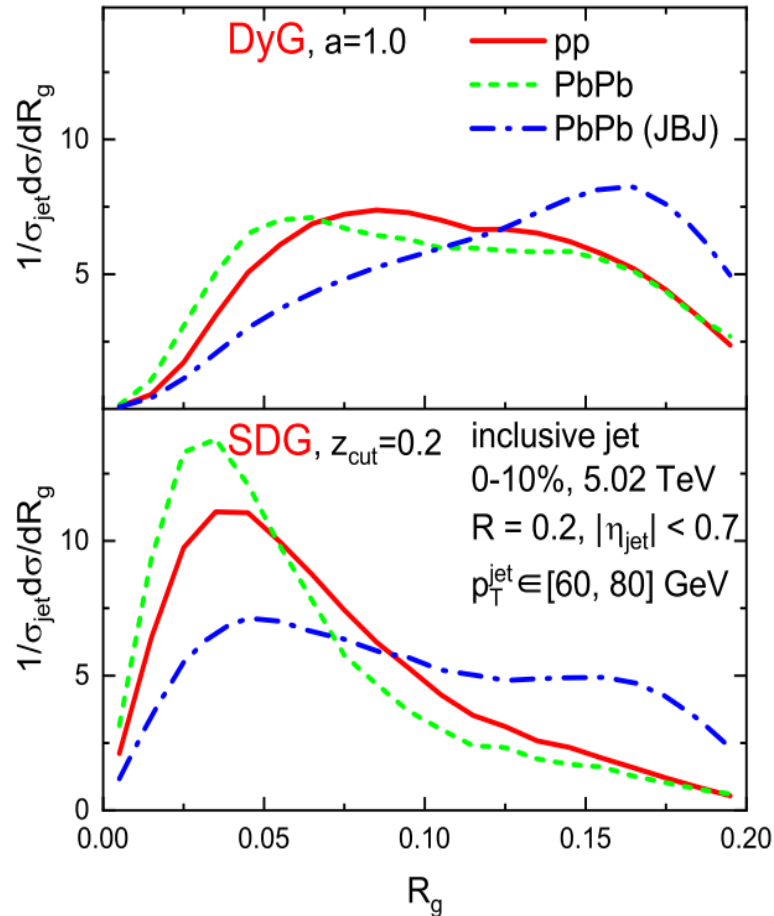
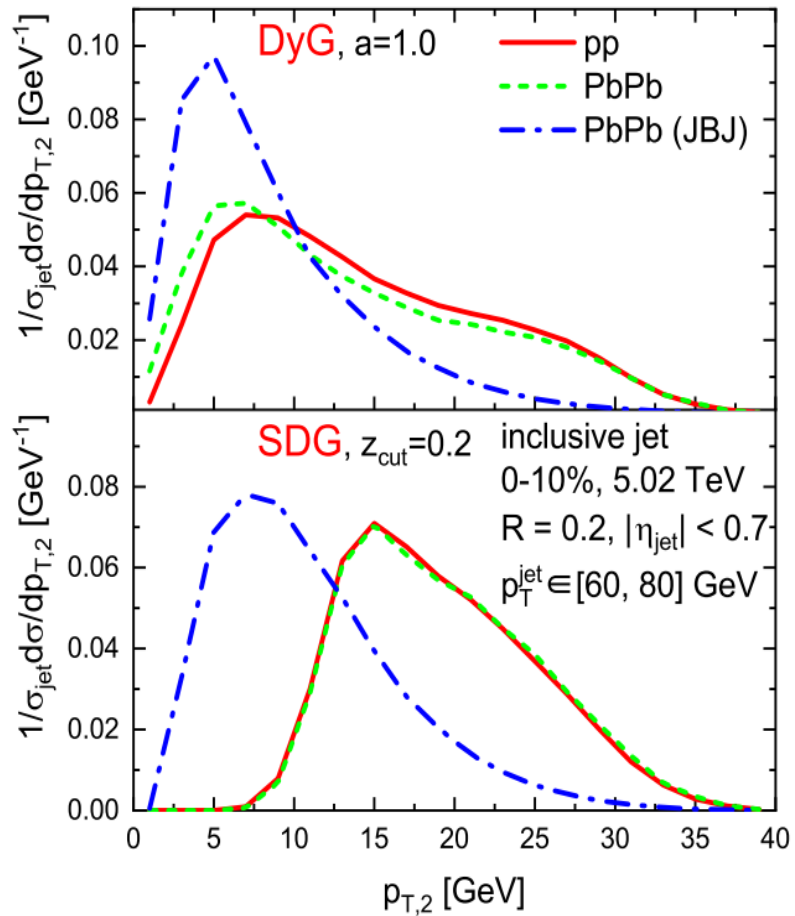


$$k_{T,g} = p_{T,2} \cdot \sin R_g$$

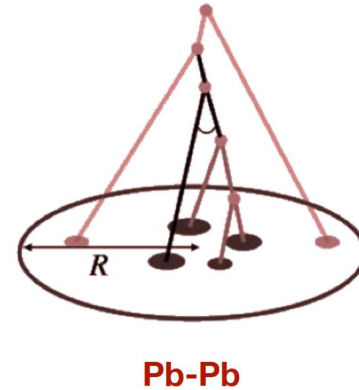
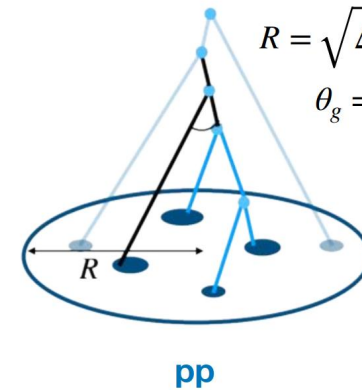


- $\gamma + \text{jet}$ reduces selection bias and can effectively select jets sufficiently quenched, which is crucial to capture the jet angular broadening.

Relative transverse momentum between subjects

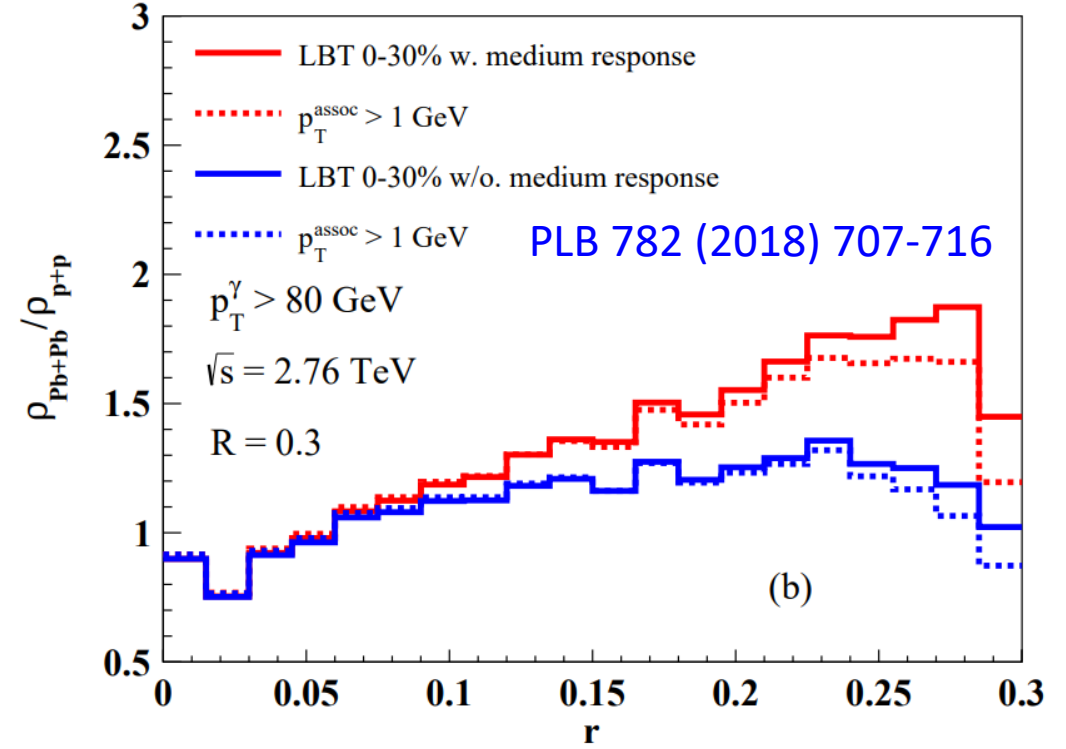
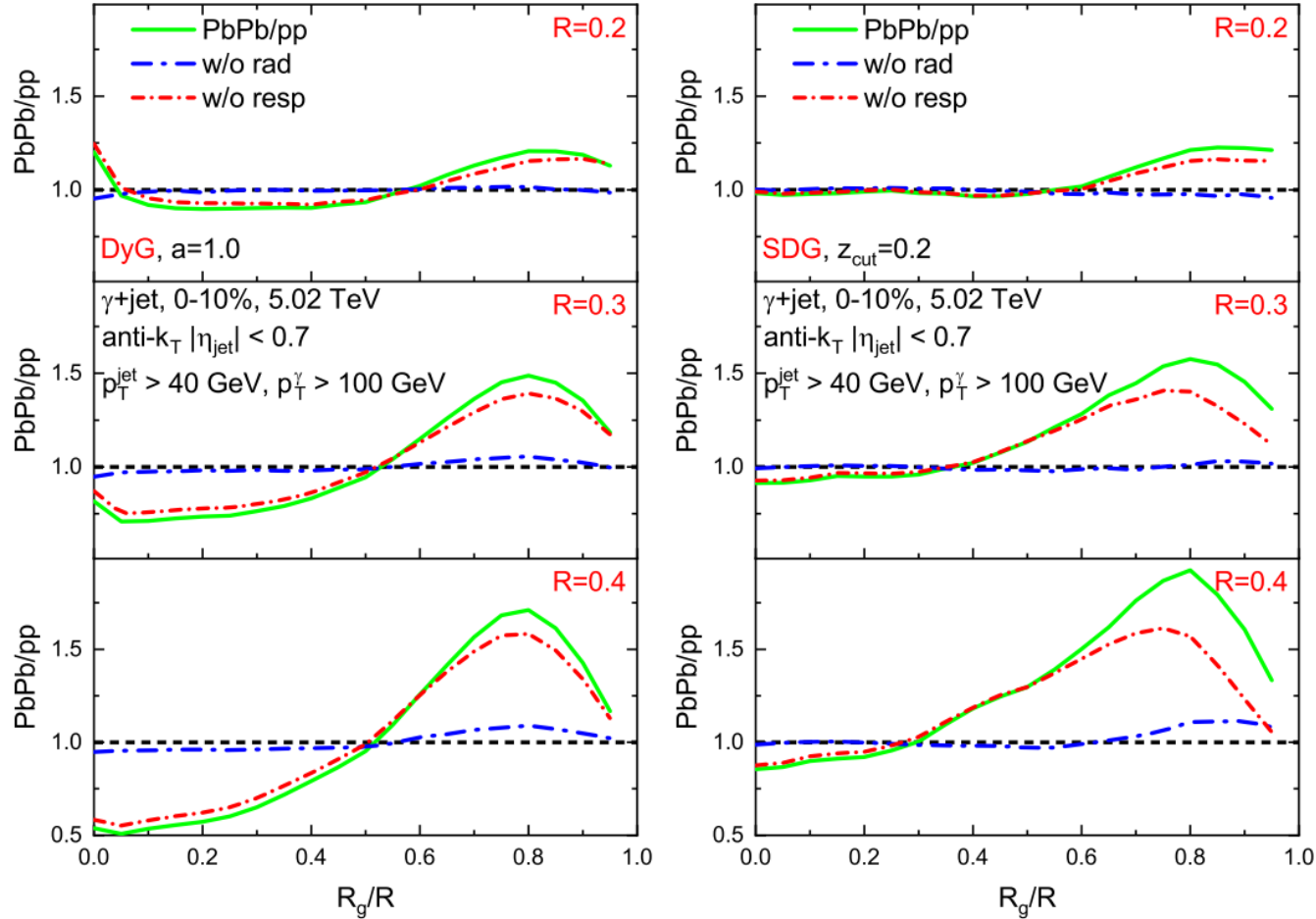


$$k_{T,g} = p_{T,2} \cdot \sin R_g$$



- γ + jet reduces selection bias and can effectively select jets sufficiently quenched, which is crucial to capture the jet angular broadening.

Groomed jet radius



$$\rho(r) = \frac{1}{\Delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \frac{p_T^{\text{jet}}(r - \Delta r/2, r + \Delta r/2)}{p_T^{\text{jet}}(0, R)}$$

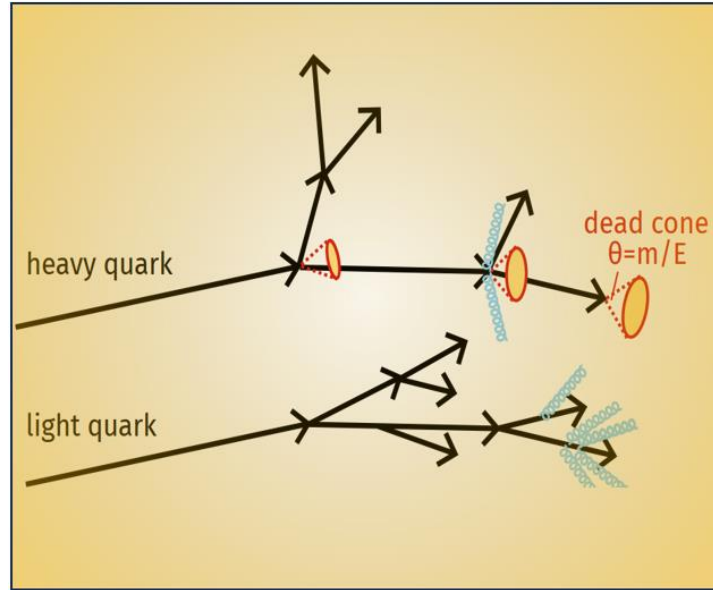
➤ γ + jet reduces selection bias and can effectively select jets sufficiently quenched, which is crucial to capture the jet angular broadening.

Flavor/mass dependence for jet broadening?



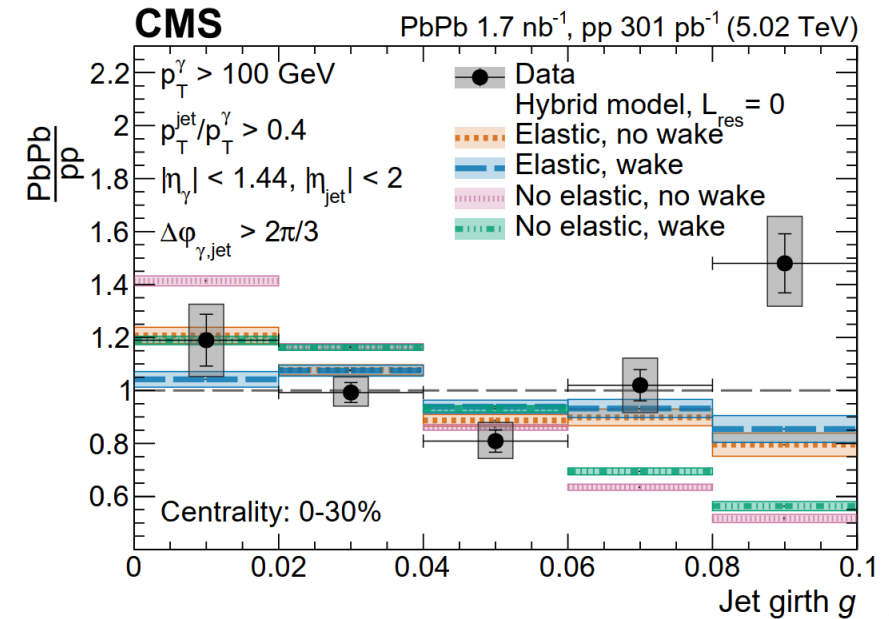
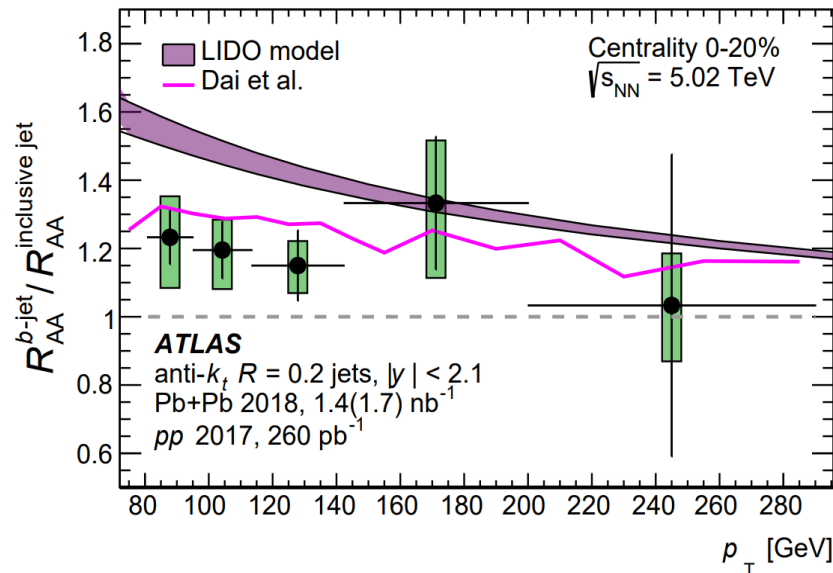
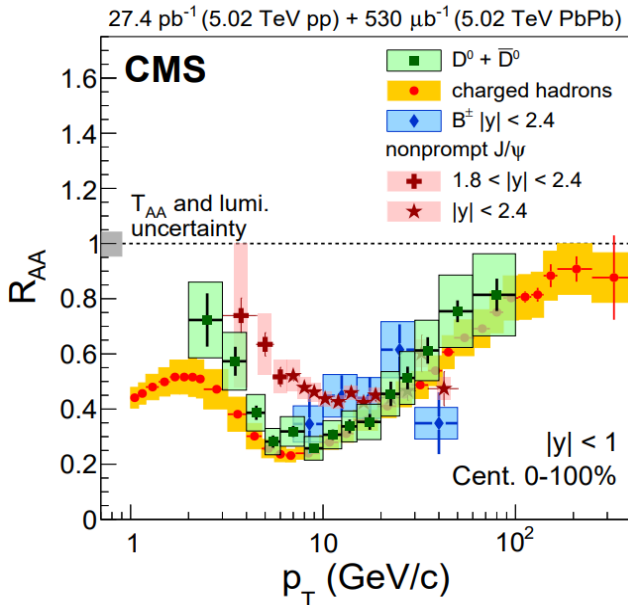
Energy loss : $\frac{dE}{dt}$

[ALICE, PLB \(2018\)](#)
[CMS, PRL \(2017\)](#)
[ATLAS, EPJC\(2023\)](#)



p_T -broadening : $\frac{dp_{\perp}}{dt}$

[CMS, PLB \(2025\)](#)

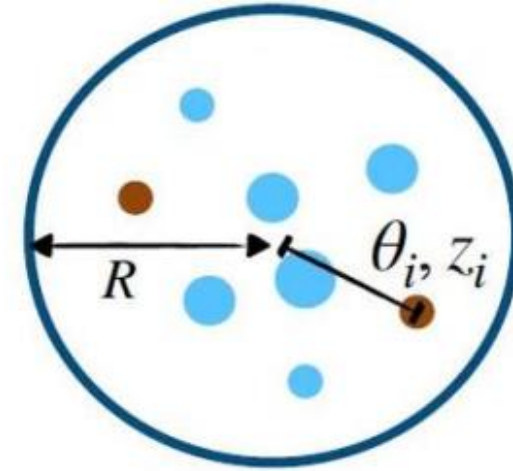


Generalized jet angularity



Angularity:

$$\lambda_{\beta}^{\kappa} = \sum_{i \in \text{jet}} \left(\frac{p_{T,i}}{p_{T,\text{jet}}} \right)^{\kappa} \left(\frac{\Delta R_{\text{jet},i}}{R_{\text{jet}}} \right)^{\beta} = \sum_{i \in \text{jet}} z_i^{\kappa} \theta_i^{\beta}$$



z_i : momentum fraction carried by jet constituents.

θ_i : scaled angular distance between jet constituents and jet axis.

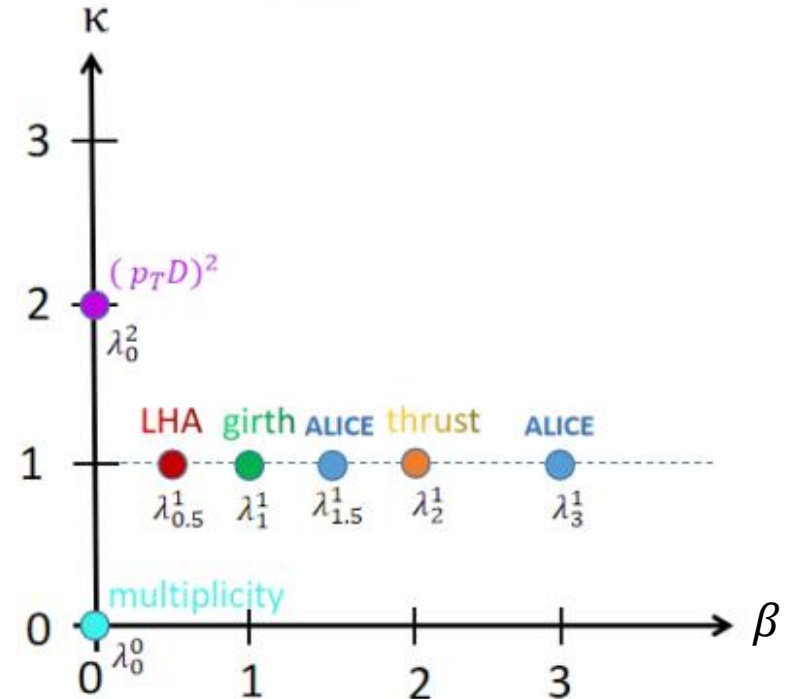
Jet angularities (κ, β)

$(0, 0)$: jet multiplicity

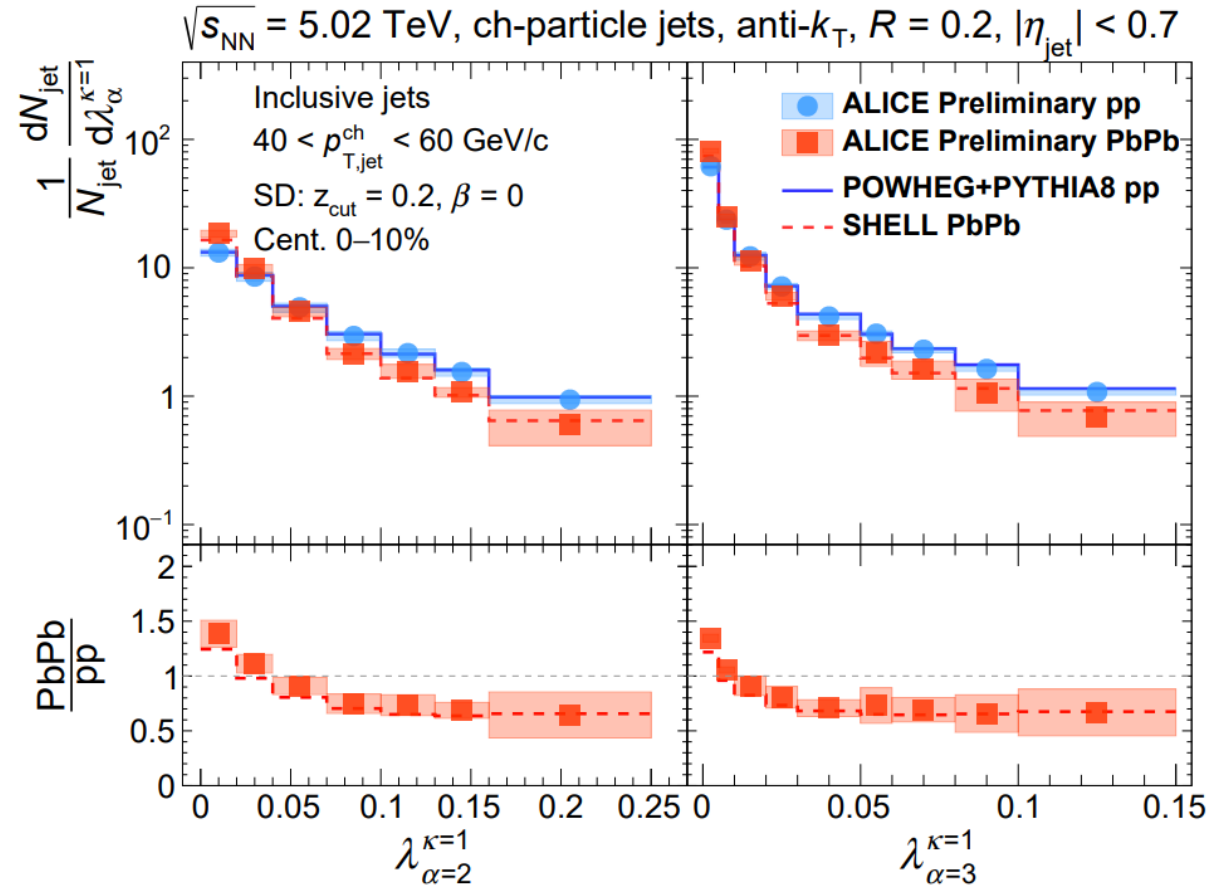
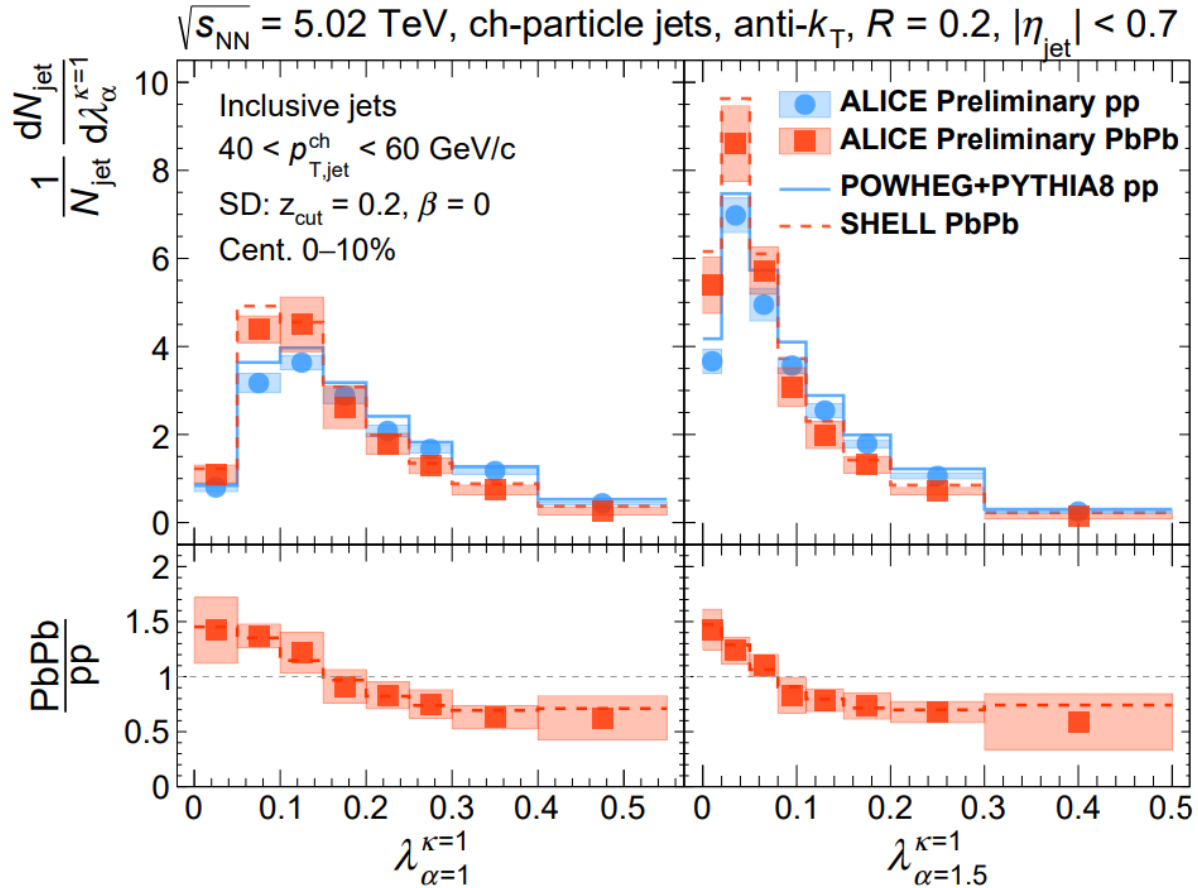
$(1, 1)$: jet girth

$(1, 2)$: jet mass

$(2, 0)$: jet $p_T D$

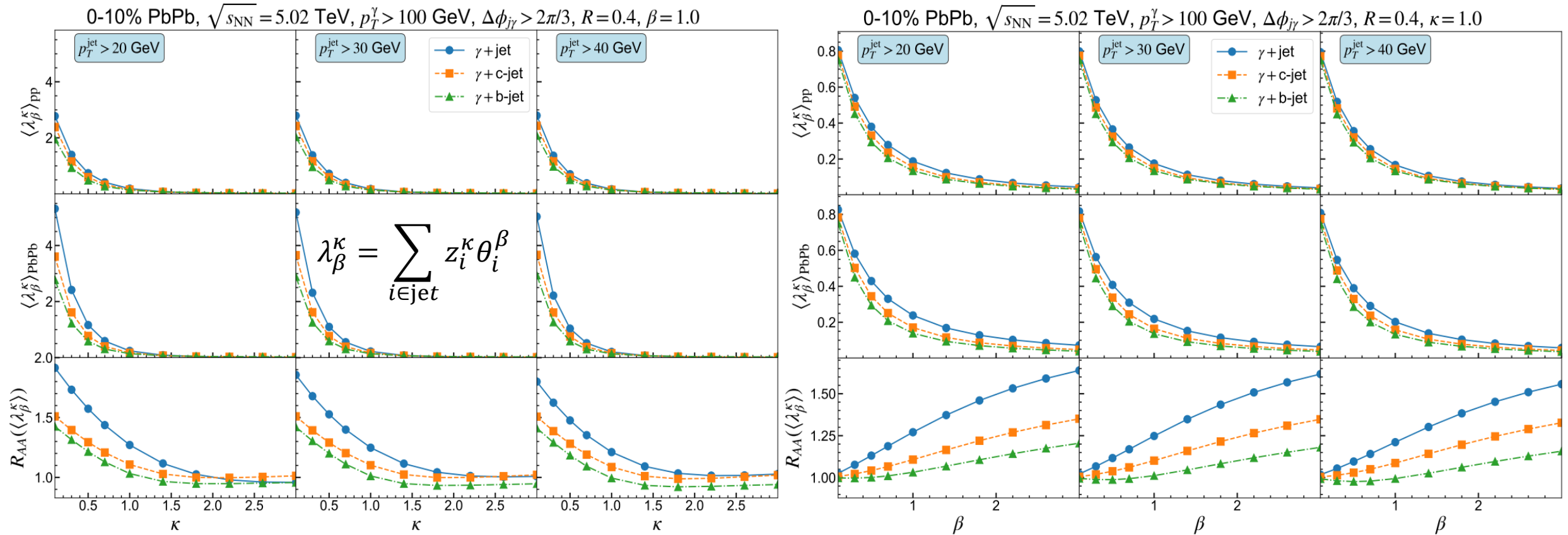


Jet angularity modification of inclusive jet



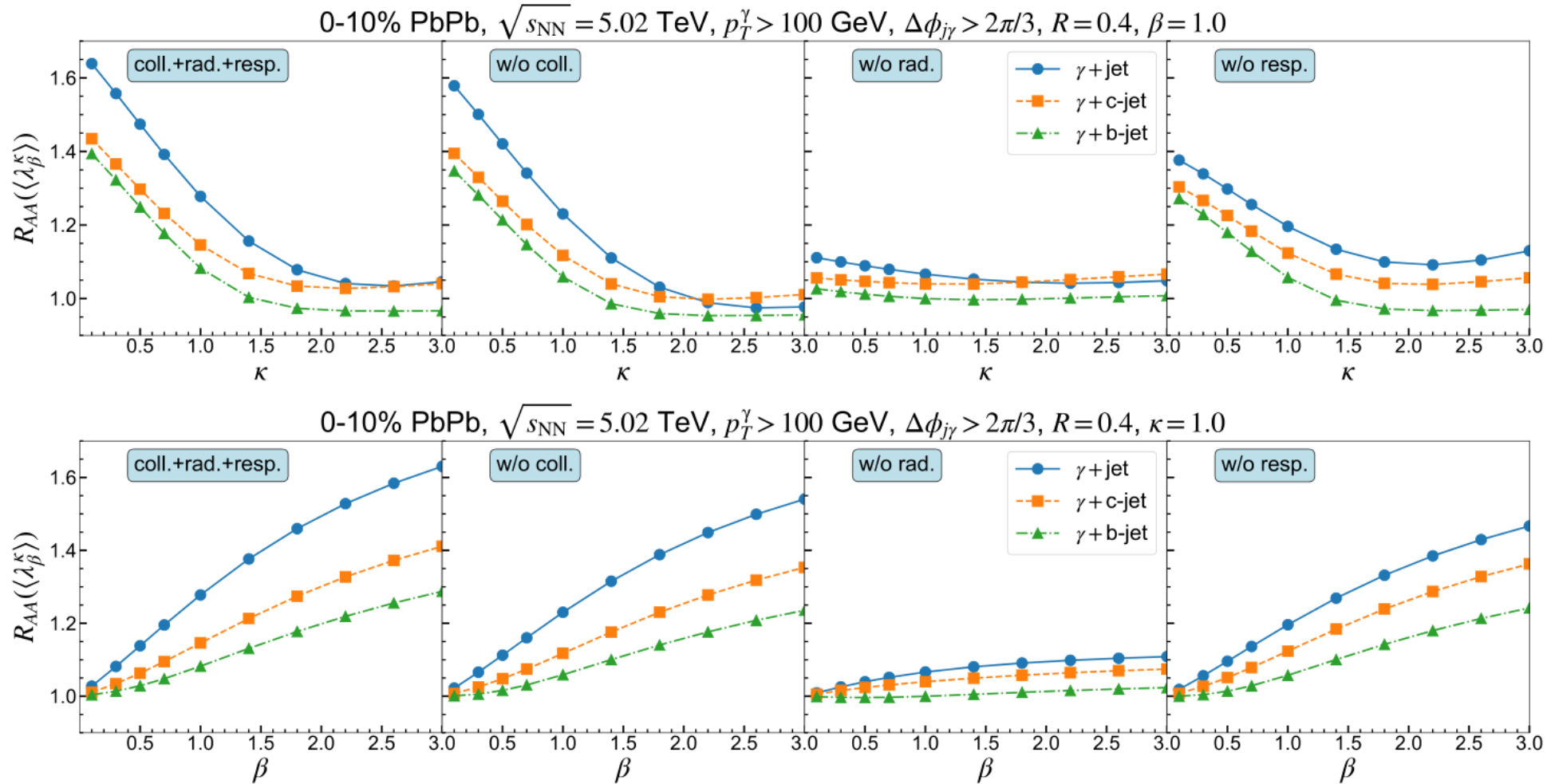
Y Li, S Chen, W Kong, S W, BW Zhang, Chin.Phys.Lett. 42 (2025) 1, 011201

Mass-dependent jet angularity modification



- A clear mass-ordered broadening of jet angularity in heavy-ion collisions.
- $\langle \lambda_\beta^\kappa \rangle$ show different sensitivities to the variations of (κ, β) for light and heavy quark jets.

Mass-dependent jet angularity modification

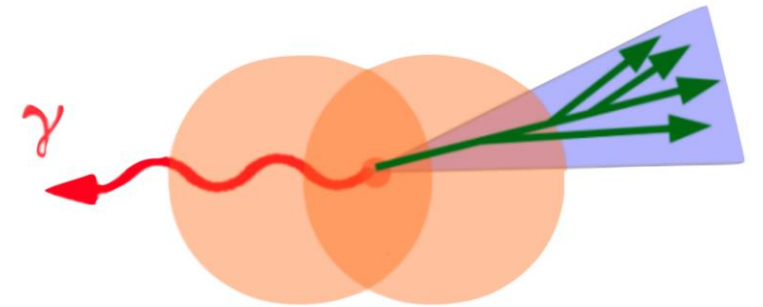


- Medium-induced gluon radiation plays a critical role in the angularity broadening.
- A promising method to test the “dead cone” effect of heavy quarks in nucleus-nucleus collisions.

Summary and outlook



- γ +jet mitigates selection bias and effectively selects jets sufficiently quenched.
- Jet substructure observables in γ +jet events exhibit clear angular broadening, demonstrating sensitivity to the underlying jet–QGP interaction mechanisms.
- We confirm a mass-ordered broadening of angularity in heavy-ion collisions, new perspective on jet–QGP interaction mechanisms and mass effects (“dead cone” effect).
- Search for substructure observables sensitive to large angle scattering (quasi-particles).
- Jet substructure broadening in small systems (critical size).



Thank you