The 16th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT2025・Guilin)

Jet broadening and selection bias in high-energy nuclear collisions

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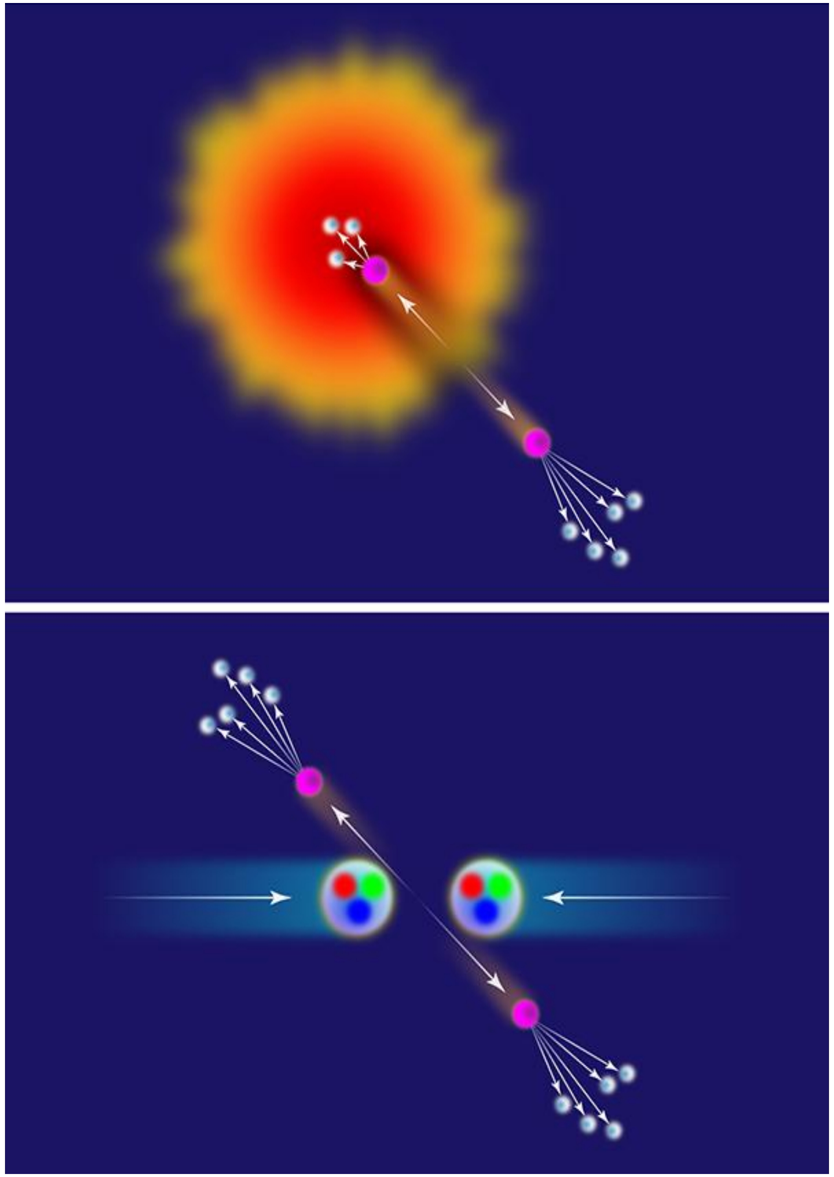
Outline

1. Background and motivation
2. Theoretical framework
3. Jet angular broadening in A+A collisions
4. Summary and outlook

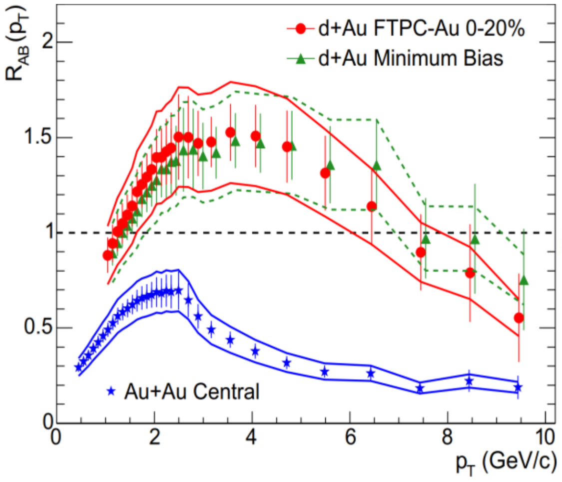
Jet quenching

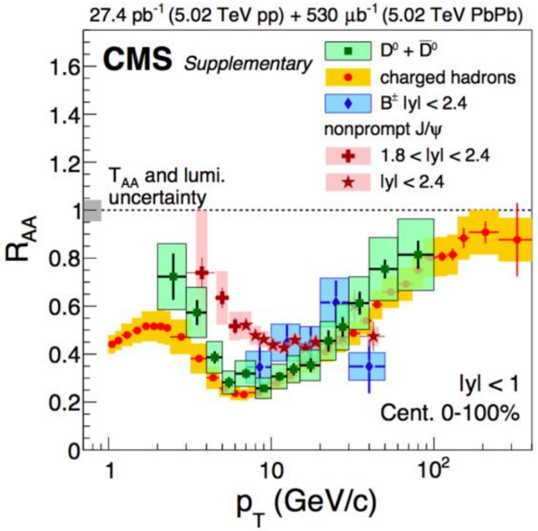


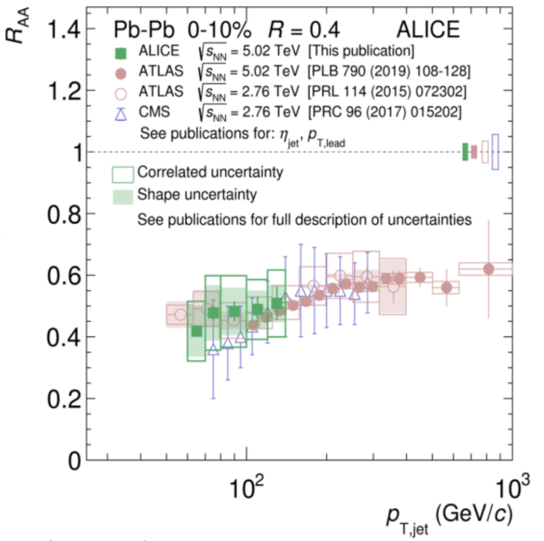
Jet transport coefficient : $\hat{q} = \frac{\mathrm{d}\langle p_\perp^2 \rangle}{dt}$

Energy loss : $\frac{\mathrm{d}E}{dt}$

p_T-broadening : $\frac{\mathrm{d}p_\perp}{dt}$



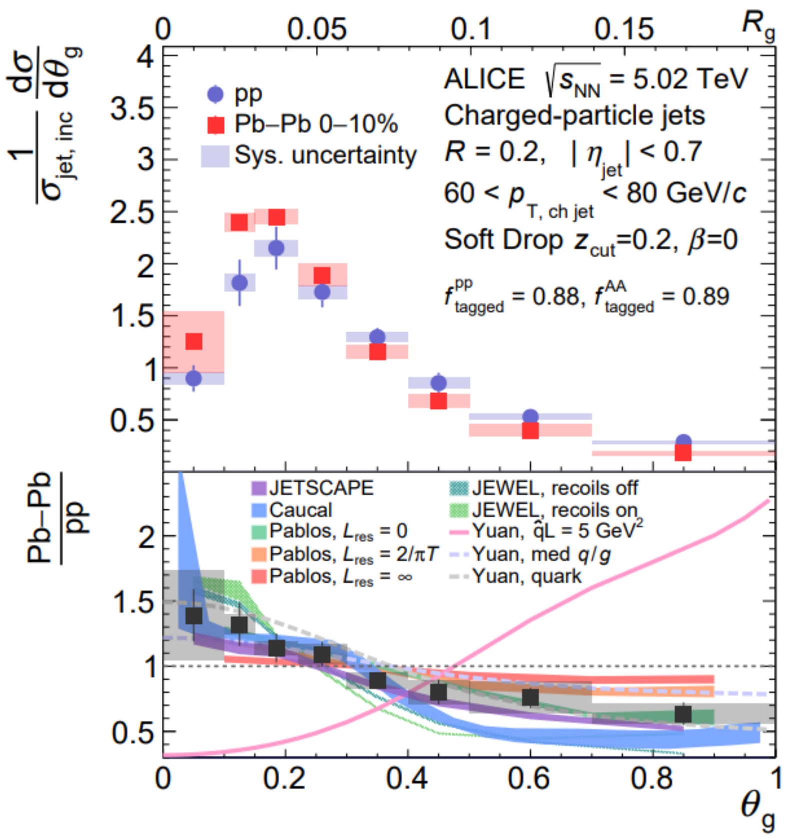




STAR, PRL 91(2003)072304
CMS, PRL 119 (2017) 152301
ATLAS, PLB 790 (2019) 108-128
ATLAS, PRL 114 (2015) 072302
CMS, JHEP 04 (2017) 039
CMS, PLB 782 (2018) 474
CMS, PRC 96(2017) 015202

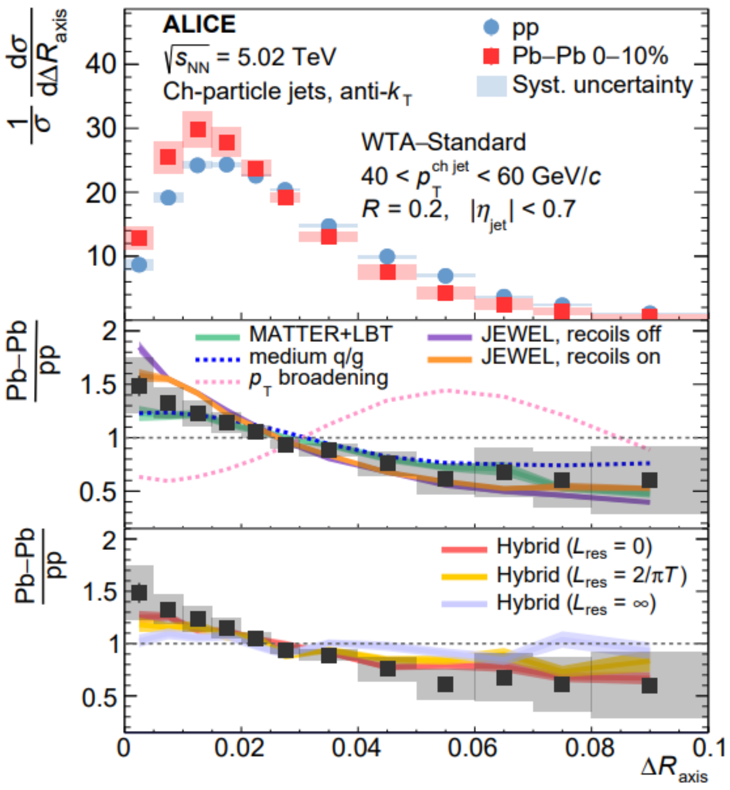
Probing intra-broadening by jet substructures

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



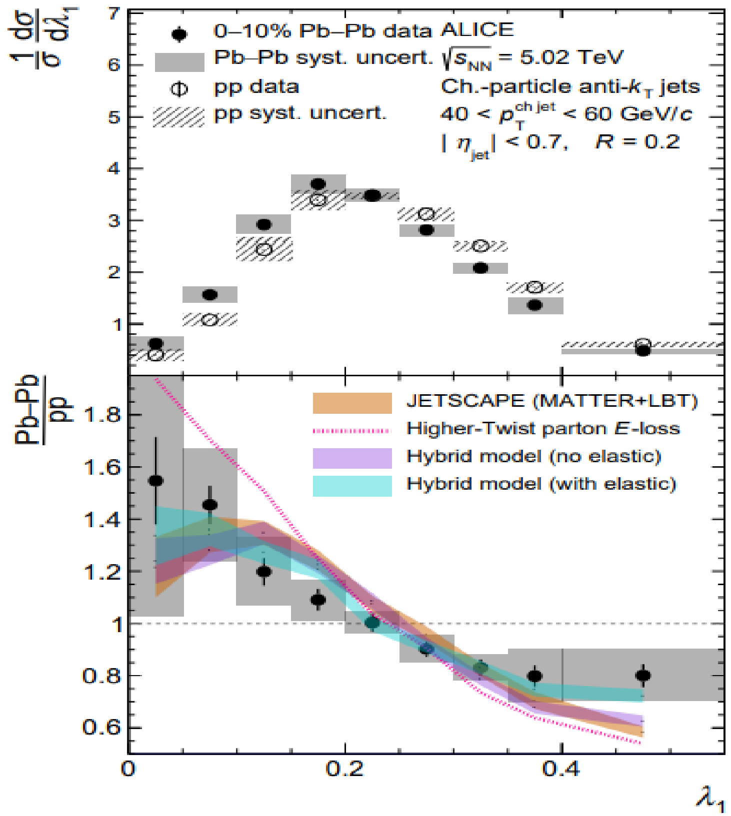
[ALICE, PRL(2022)](#)

$$\Delta R^{a-b}_{\mathrm{axis}} = \sqrt{(y^{a}_{\mathrm{axis}} - y^{b}_{\mathrm{axis}})^2 + (\phi^{a}_{\mathrm{axis}} - \phi^{b}_{\mathrm{axis}})^2}$$



[ALICE, 2303.13347](#)

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

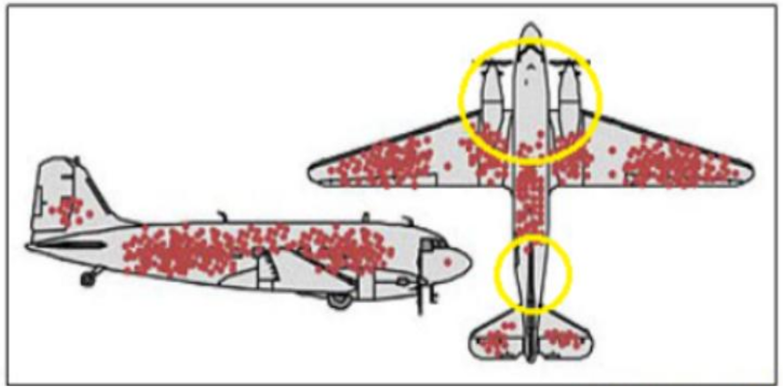


[ALICE, PLB(2025)](#)

Narrowing instead broadening observed in experiment!

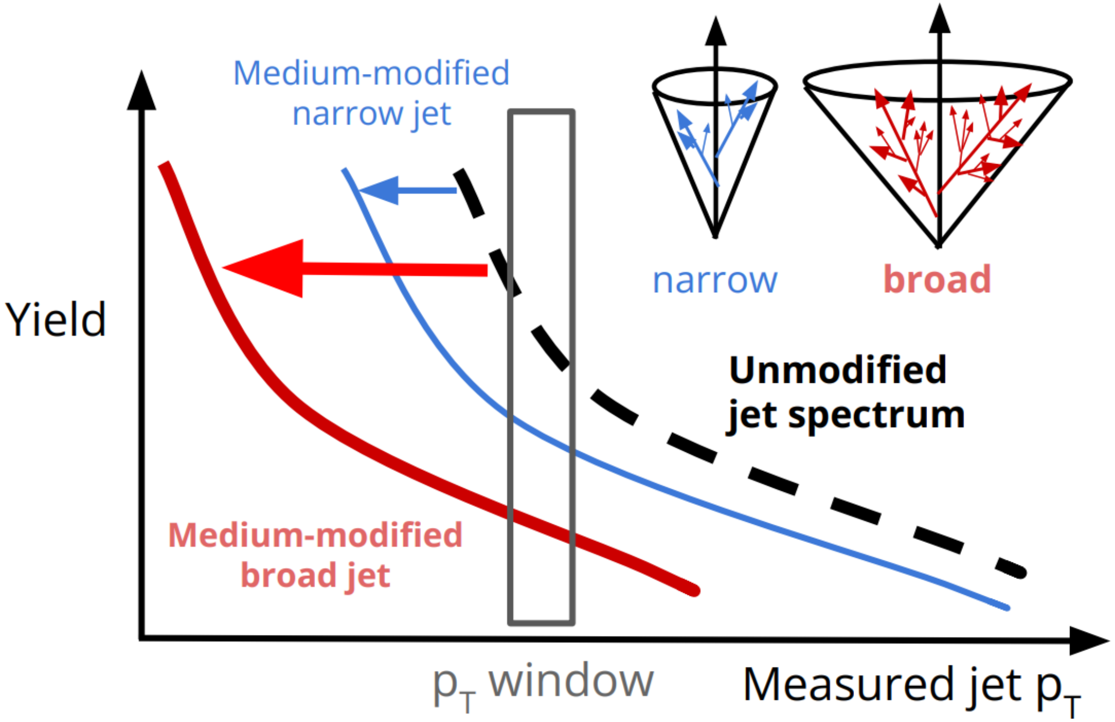
Selection bias in jet quenching

Survival bias



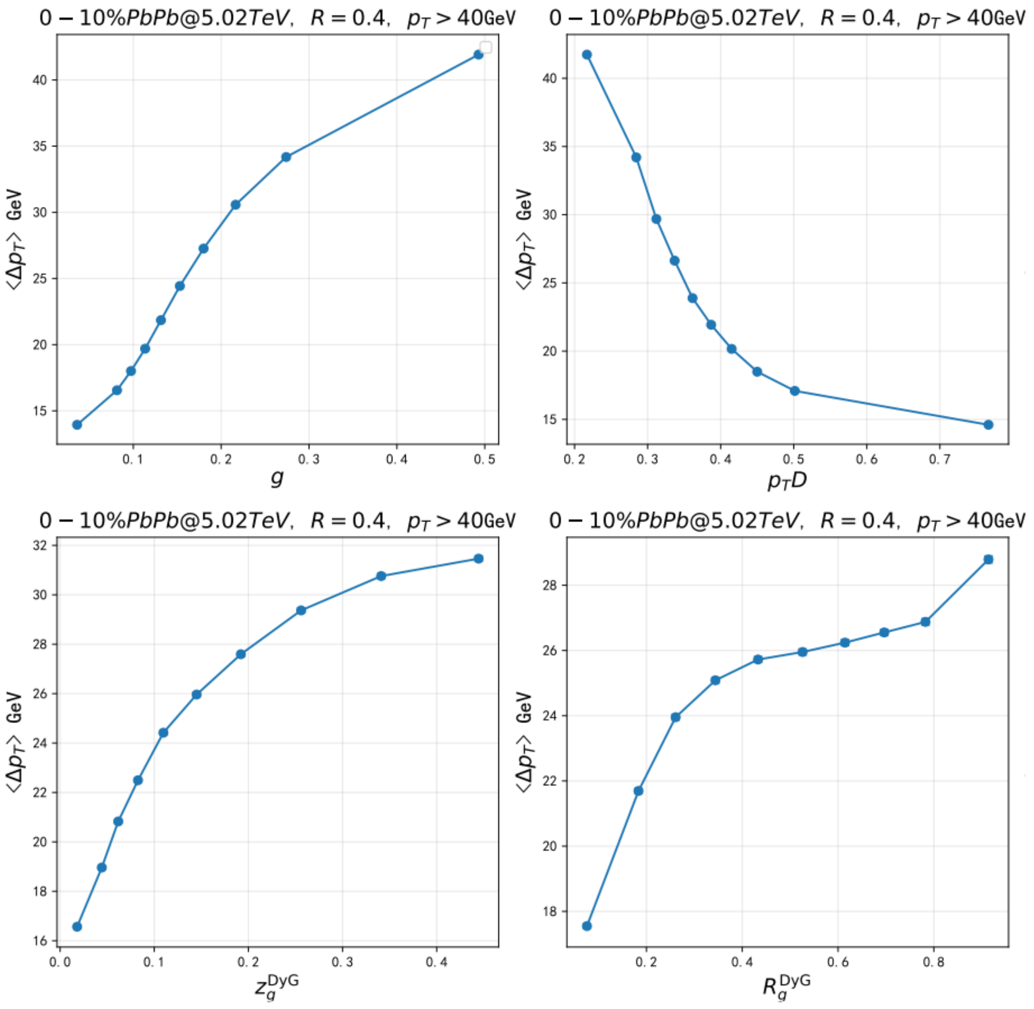
Abraham Wald (1902-1950)

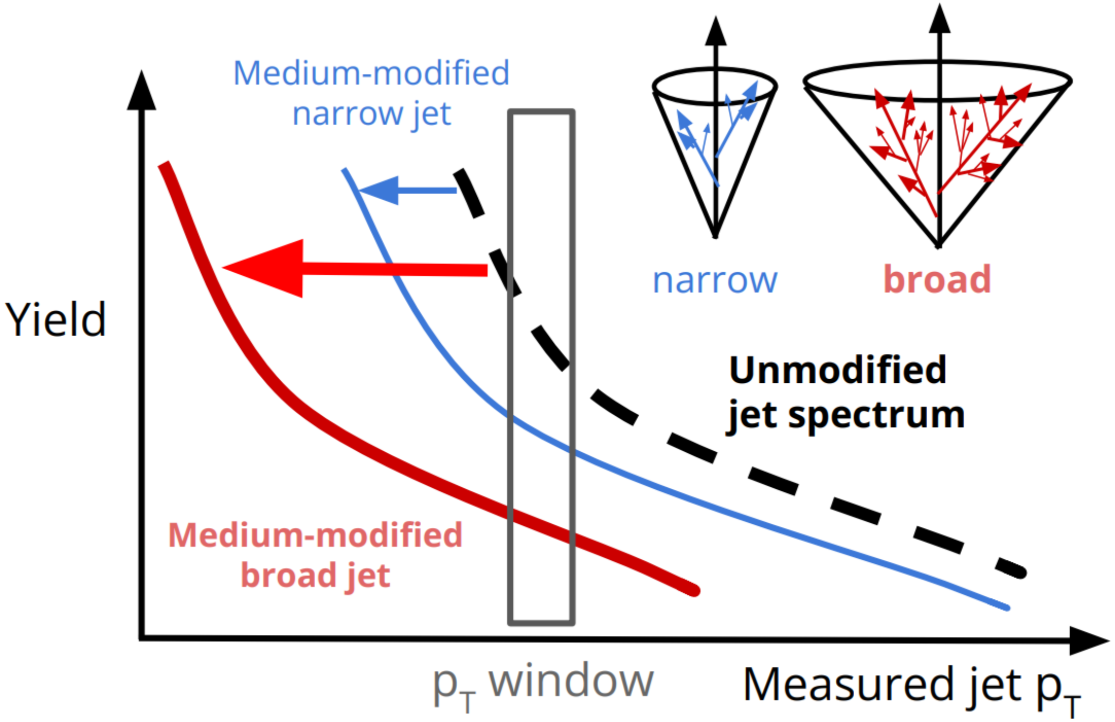
Gentlemen, you need to put more armour-plate where the holes aren't because that's where the holes were on the airplanes that didn't return - Abraham Wald 1942.



[CMS, PLB(2025)]

Selection bias in jet quenching



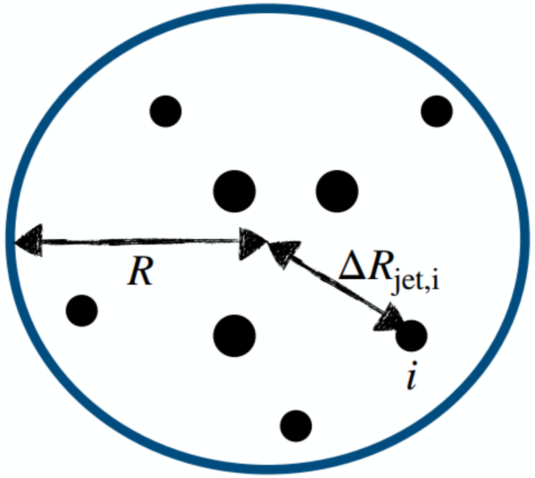


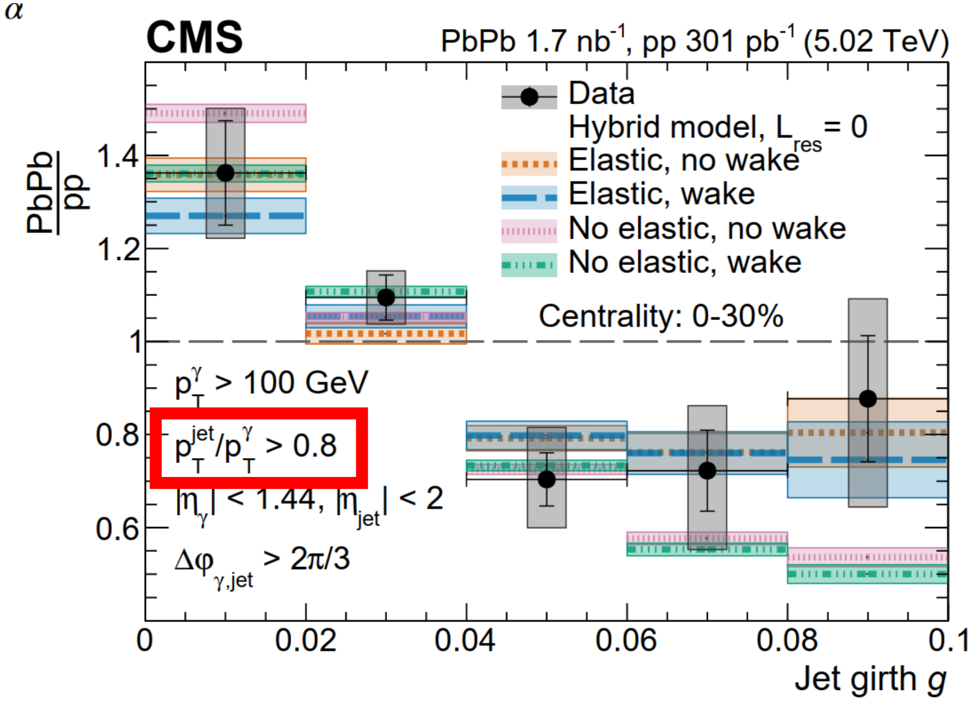
CMS, PLB(2025)

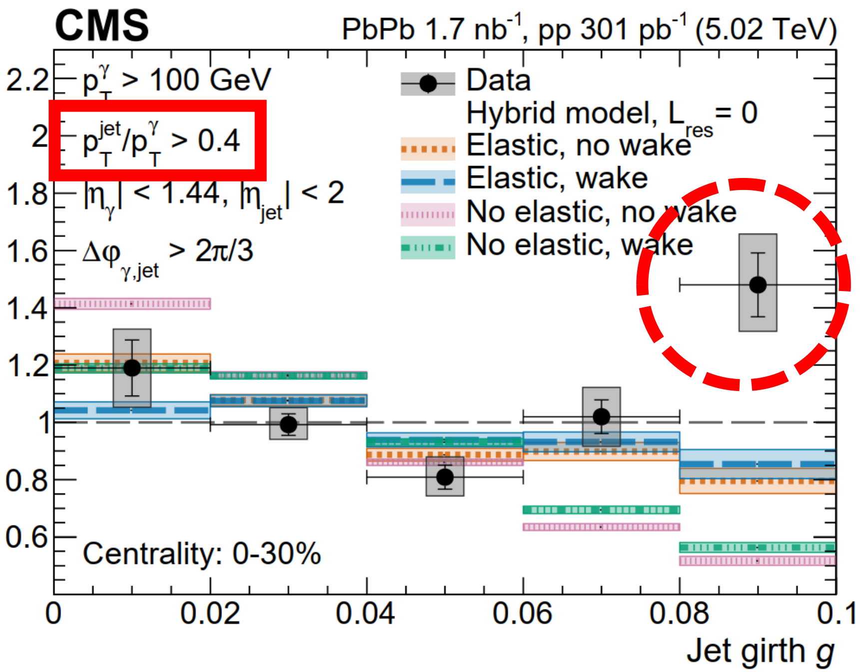
- Due to the energy loss in the QGP, the effectively quenched jets may have a lower probability of passing the p_T selection threshold in A+A collisions, while the one with insufficient quenching survives.

Angularity of photon-tagged jet (γ−jet) in Pb+Pb

$$\lambda_\alpha^\kappa = \sum_{i\in jet} \left(\frac{p_{\mathrm{T,i}}}{p_{\mathrm{T,jet}}}\right)^\kappa \left(\frac{\Delta R_{\mathrm{jet,i}}}{R}\right)^\alpha$$







CMS, PLB(2025)

- How does p_T balance of γ−jet influence the modification patterns of jet girth in Pb+Pb collisions ?
- Why are the girth modification patterns of inclusive jet and γ−jet different in the same collision system ?

SHELL transport model for jet evolution in HICs

- Medium-induced gluon radiation: Higher-Twist formalism

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

$$P_{q\to qg}(x) = \frac{(1-x)(1+(1-x)^2)}{x}$$

$$P_{g\to gg}(x) = \frac{2(1-x+x^2)^3}{x(1-x)}$$

$$\hat{q}(\tau,\vec{r}) = q_0 \frac{\rho^{QGP}(\tau,\vec{r})}{\rho^{QGP}(\tau_0,0)} \frac{p^\mu u_\mu}{p^0}$$

Phys. Rev. Lett. 85 (2000) 3591
Nucl. Phys. A 720, 429-451 (2003)
Phys. Rev. Lett. 93 (2004) 072301
Nucl. Phys. A 757 (2005) 493
Phys. Rev. D 85 (2012) 014023

- Elastic energy loss at the Hard-Thermal-Loop approximation:

$$\frac{dE}{dL} = -\frac{\alpha_s C_s \mu_D^2}{2} ln\frac{\sqrt{ET}}{\mu_D}$$

Phys. Rev. D 83 (2011) 065012
Phys. Lett. B 726 (2013) 251

- Medium response with the Cooper-Frye formula at the perturbed freeze-out hypersurface :

$$E\frac{dN}{d^3p} = \frac{1}{(2\pi)^3}\int d\sigma^\mu p_\mu f(u^\mu p_\mu, \delta u^i, \delta T)$$

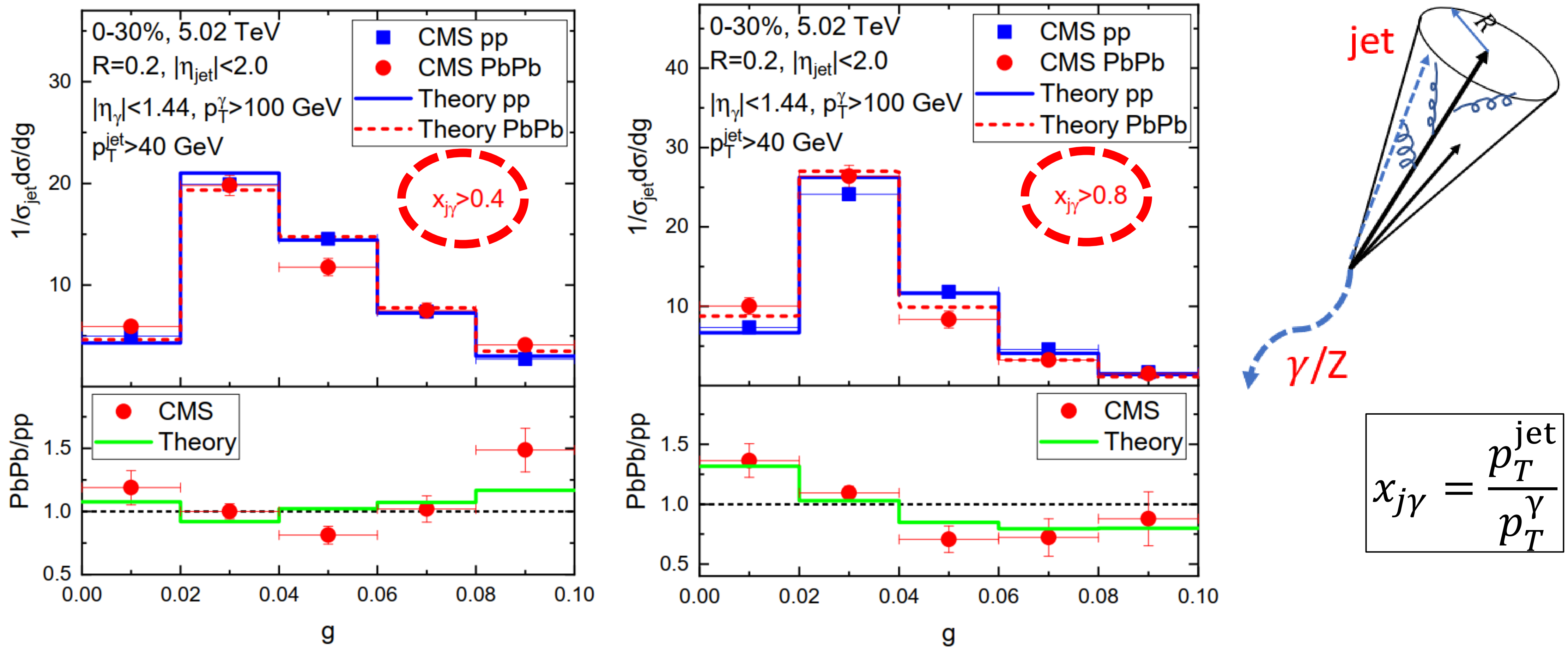
$$f(u^\mu p_\mu, \delta u^i, \delta T) = \exp\left[-\frac{u^\mu p_\mu}{T} + \frac{u^\mu p_\mu}{T^2}\delta T + \frac{p_\perp^i}{T}\delta u_\perp^i\right]$$

$$\Delta P_\perp^i = w\,\tau \int d^2x_\perp\, d\eta\, \delta u_\perp^i \qquad \Delta S = \frac{s\,\tau}{c_s^2}\int d\eta\, d^2x_\perp \frac{\delta T}{T}$$

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

Jorge Casalderrey-Solana et al. JHEP(2017)

Theoretical calculations of γ–jet girth modification

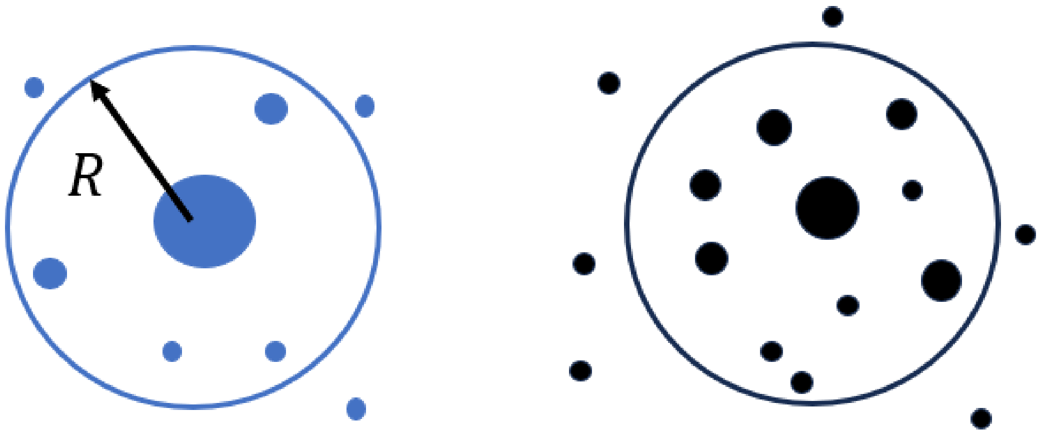


$$x_{j\gamma} = \frac{p_T^{\rm jet}}{p_T^{\gamma}}$$

S. Wang, Y. Li, J.-W. Kang, B.-W. Zhang, arXiv:2408.10924

Quantify the influence of selection bias

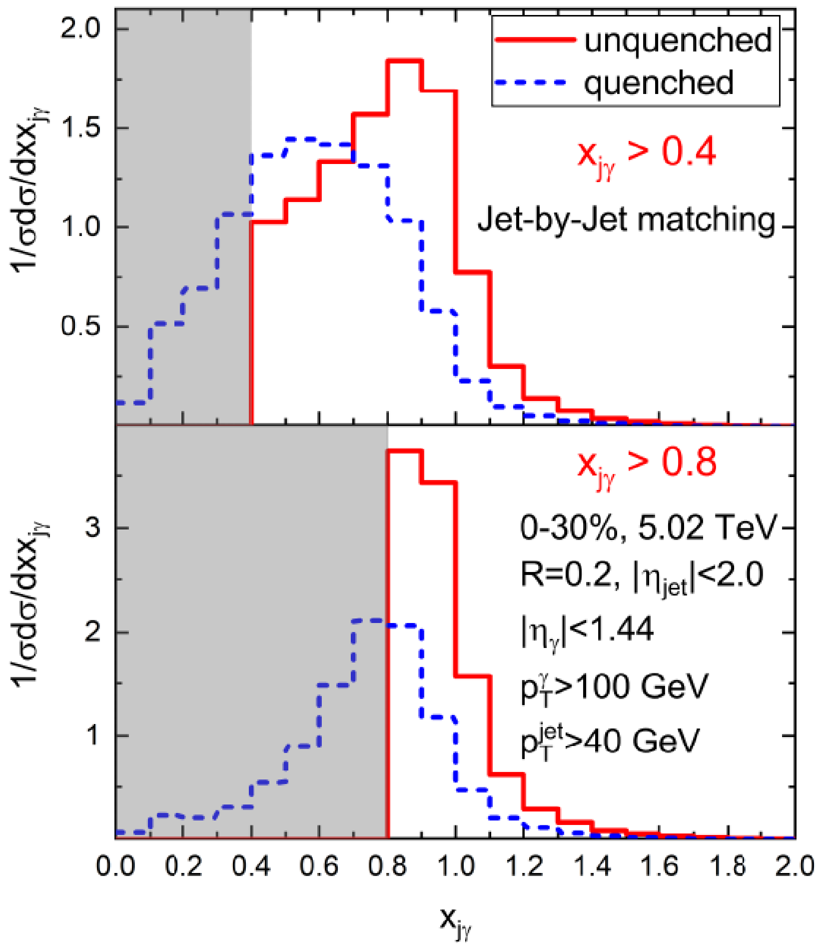
Jet-by-jet (JBJ) matching



Before quenching

After quenching

$x_{j\gamma}$	$x_{j\gamma}$>0.4	$x_{j\gamma}$>0.8
Survival rate	76.1%	41.6%



- Using lower $x_{j\gamma}$ threshold will include more jets with sufficient quenching in Pb+Pb collisions, which finally leads to broader modification of γ−jet girth relative to p+p as observed in the CMS measurement.

Quantify the influence of selection bias

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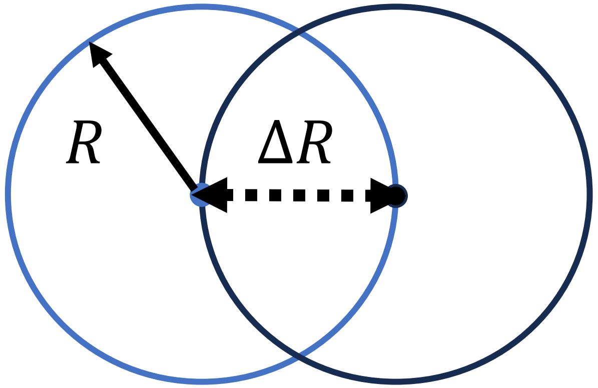

$\boxed{\Delta R < R}$

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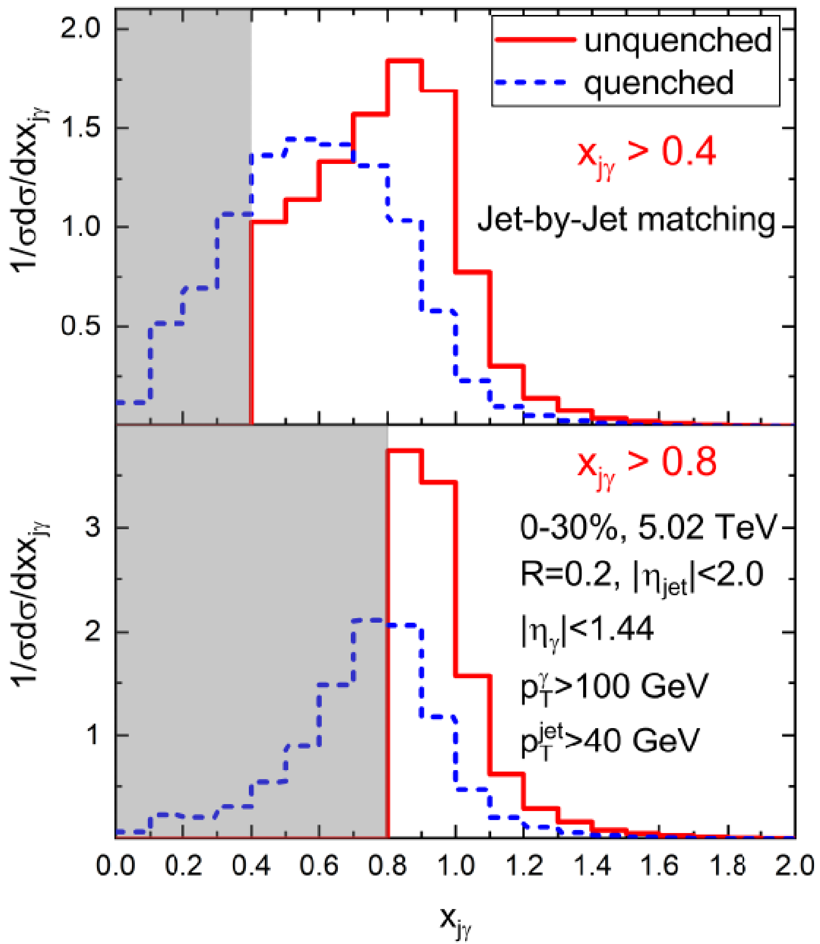

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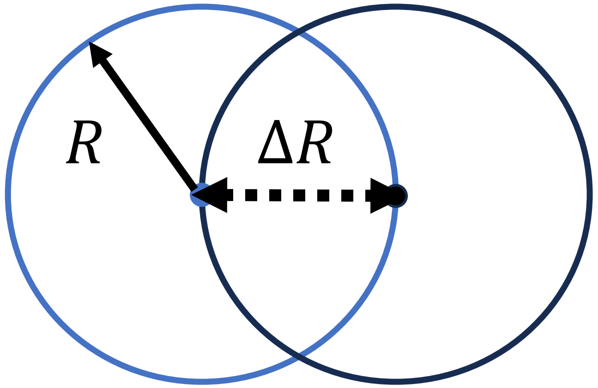

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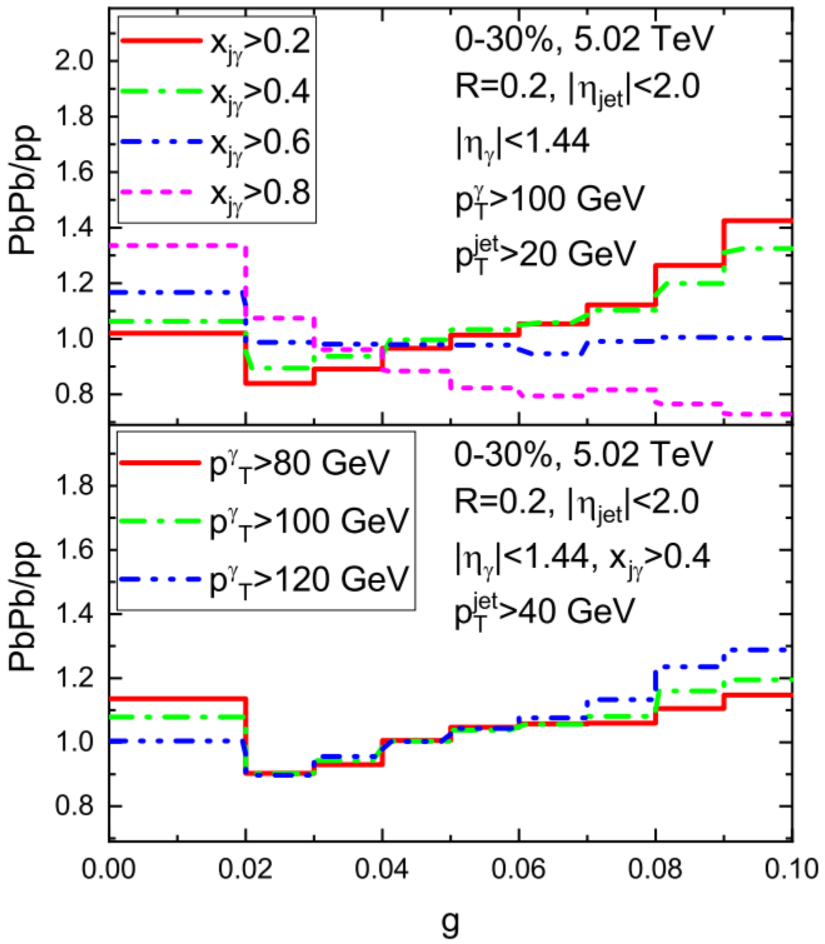

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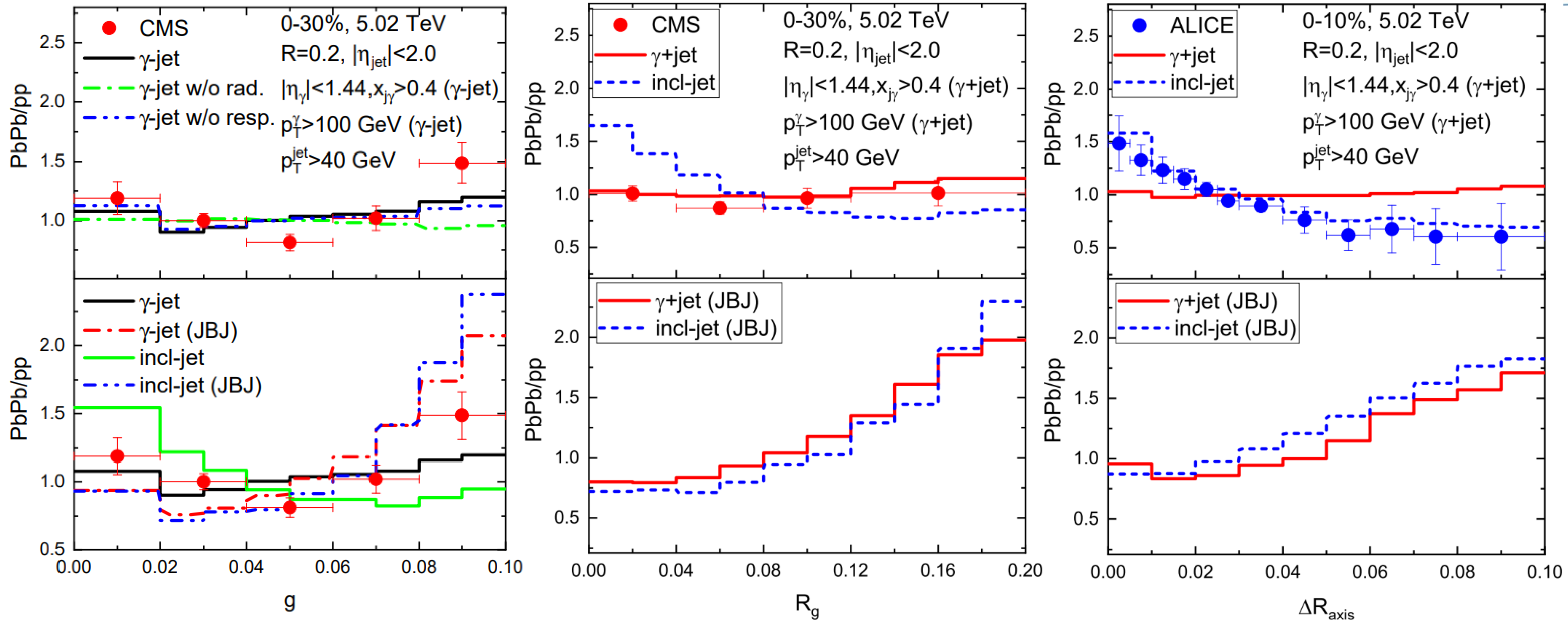
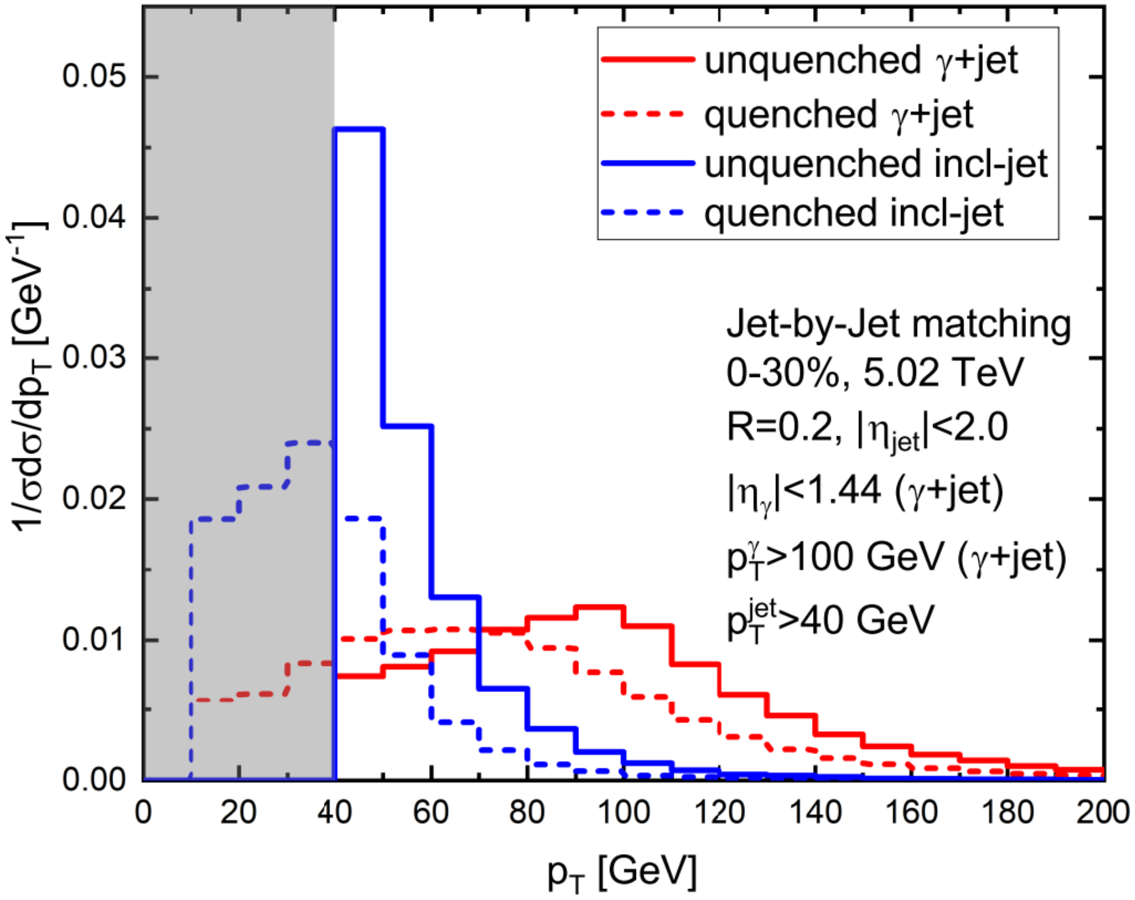
Substructure modification of inclusive jet and γ–jet



- The medium modification is very moderate without considering the gluon radiation.
- The medium response slightly enhances the modification at the region of larger girth.

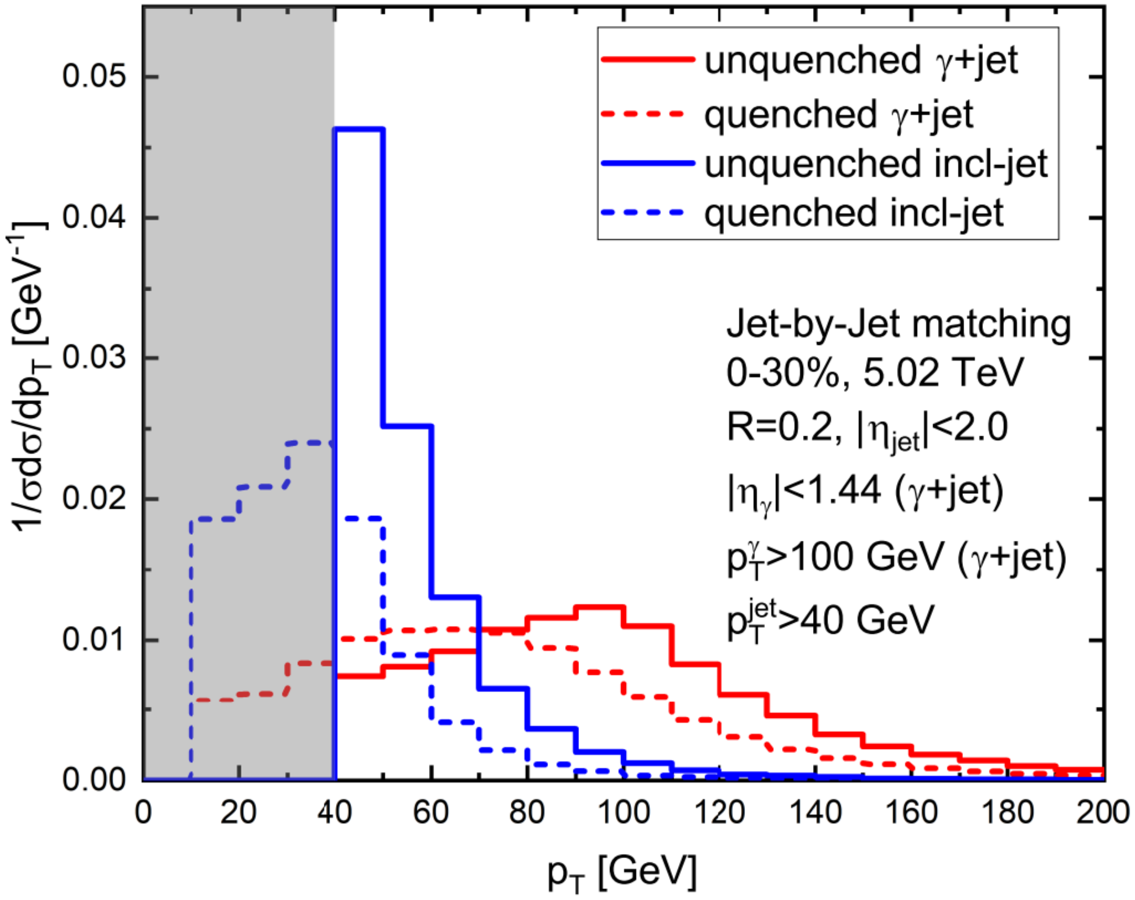
Selection bias for inclusive jet and γ–jet

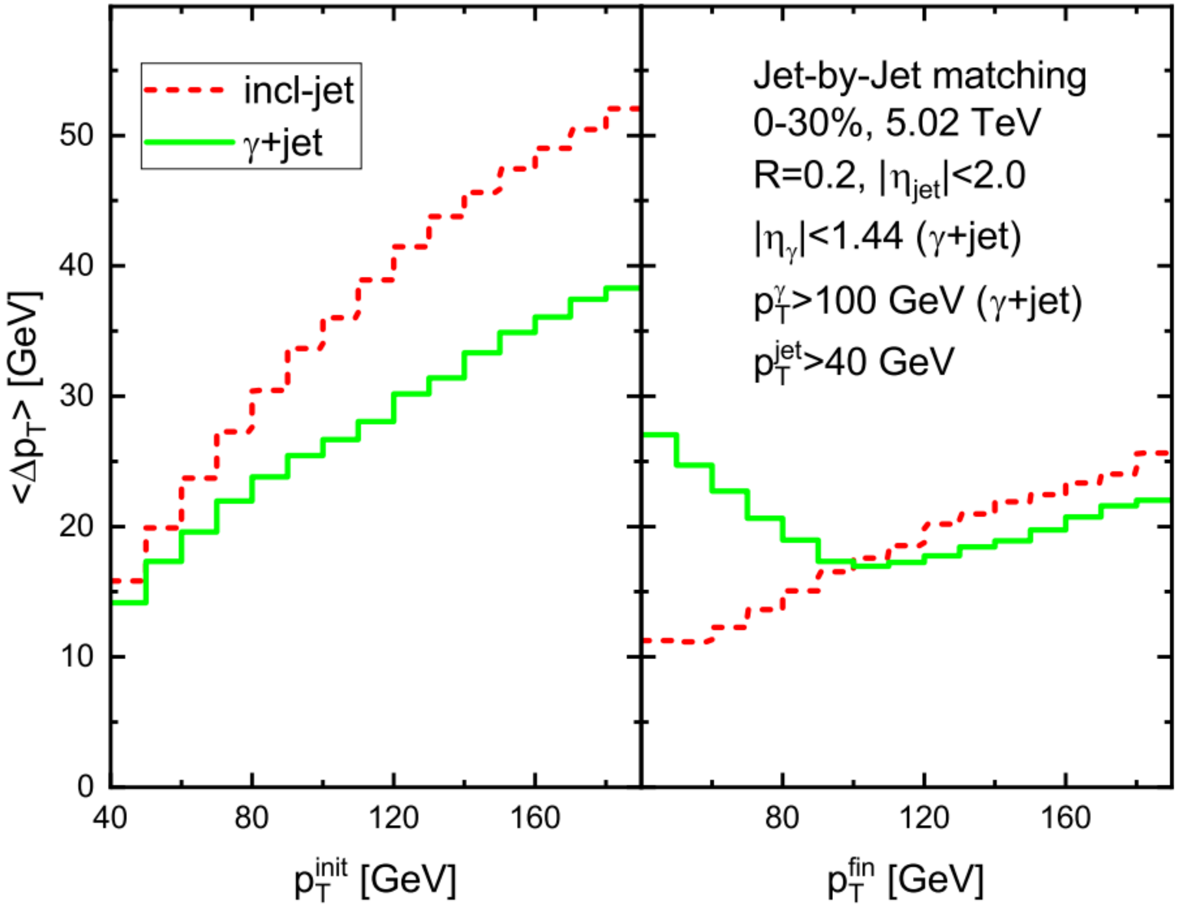


- The inclusive jet is initially distributed mostly near the selection cut (40 GeV), while γ–jet over a wider region with a peak near the trigged photon p_T .
- The unique p_T spectra of the latter thus give a much lower probability of jets falling below the cut after quenching
- The inclusive jet contains considerable fractions of both quark- and gluon-jet, may lose more energy and has a lower survival rate.

	incl-jet	γ-jet
Survival rate	36.6%	79.7%

Jet energy loss for inclusive jet and γ–jet





- For fixed initial p_T, inclusive jet loses more energy than γ–jet, the latter is a quark-jet dominant sample.
- For jets with the same final p_T, γ–jet suffers more sufficient quenching than inclusive jet at p_T < 100 GeV.

Summary

- Revealing the connection between selection bias and jet kinematics when choosing different $x_{j\gamma}$ cuts.
- γ-jet provides significant advantages to reduce the selection bias and can effectively collect jets sufficiently quenched compared to the inclusive jet.

Thank you