Probing medium-induced jet splitting in heavy-ion collisions

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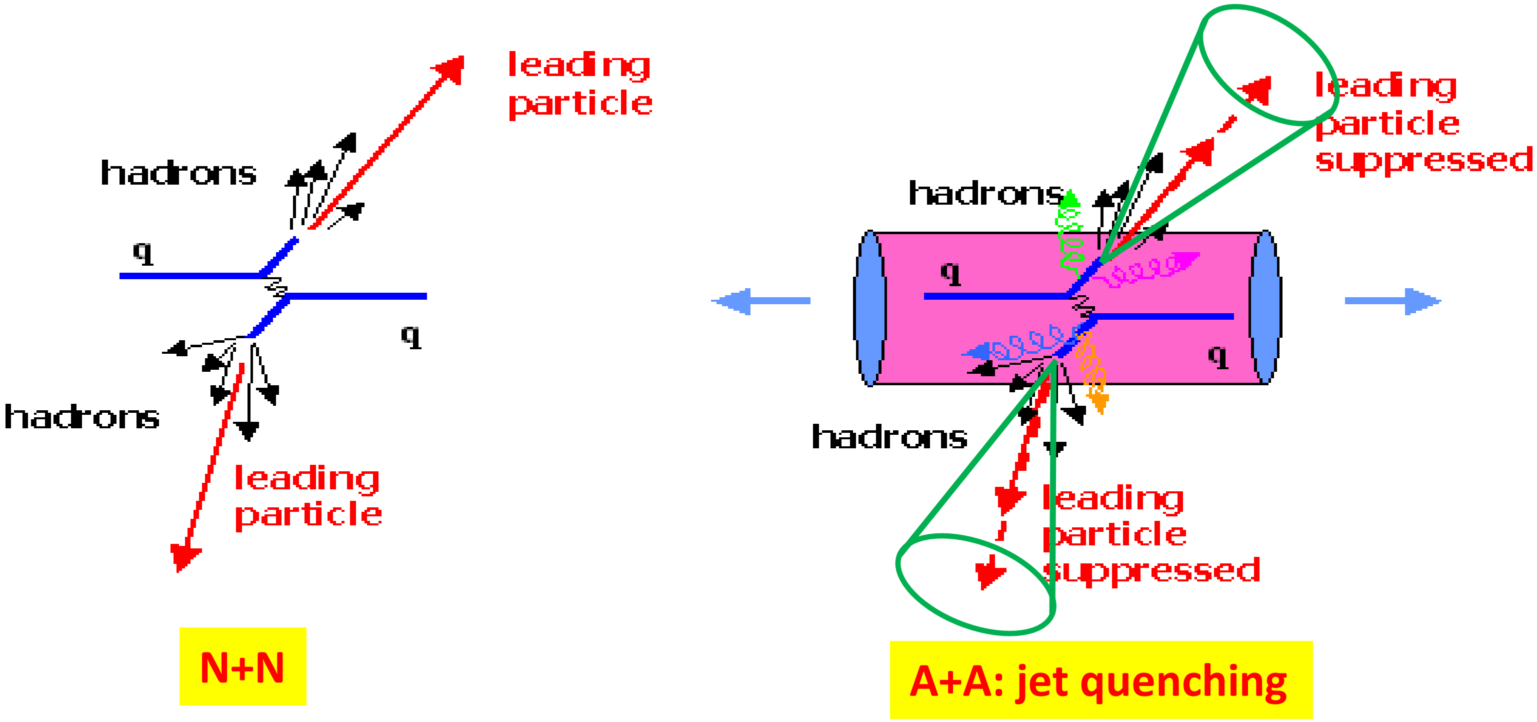
N.B. Chang, S. Cao, GYQ, Phys.Lett. B781 (2018) 423-432

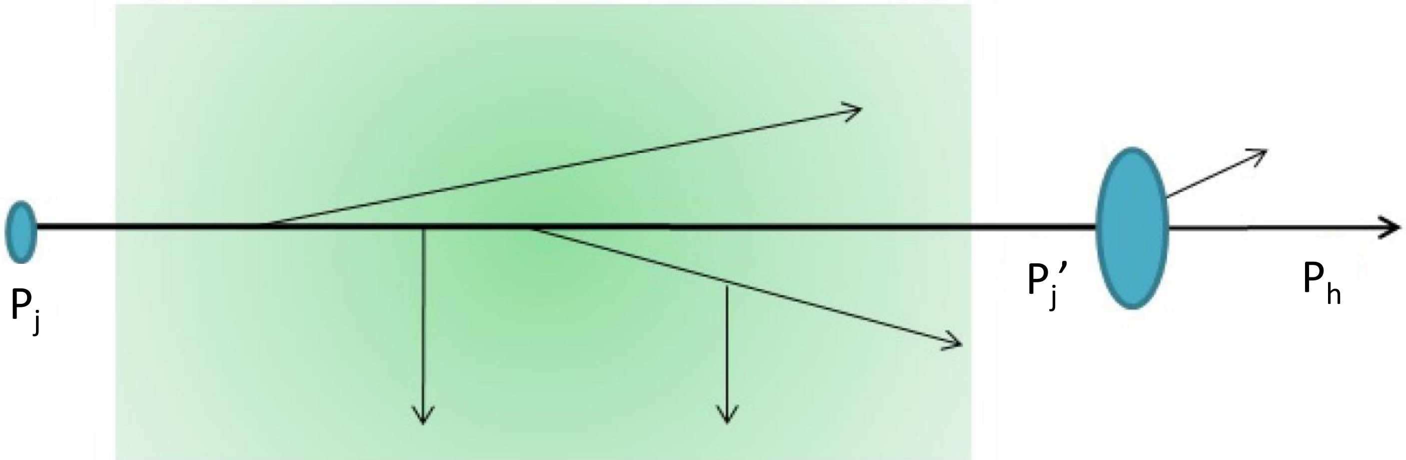
Jets are hard probes of QGP



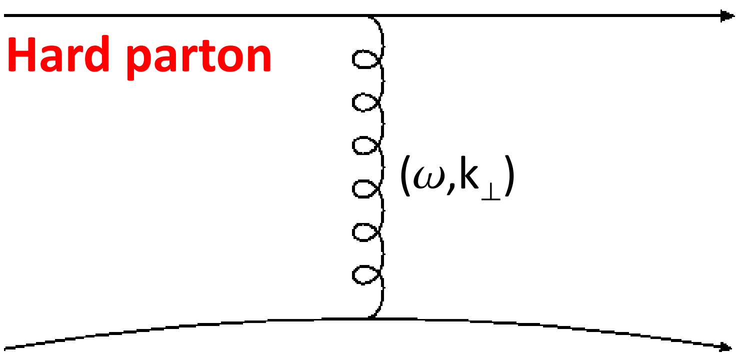
Jets (and **jet-medium interaction, jet quenching**) provide valuable tools to probe hot & dense QGP in relativistic heavy-ion collisions (at RHIC & LHC):

(1) parton energy loss, (2) modification of jet substructure

Elastic and inelastic interactions

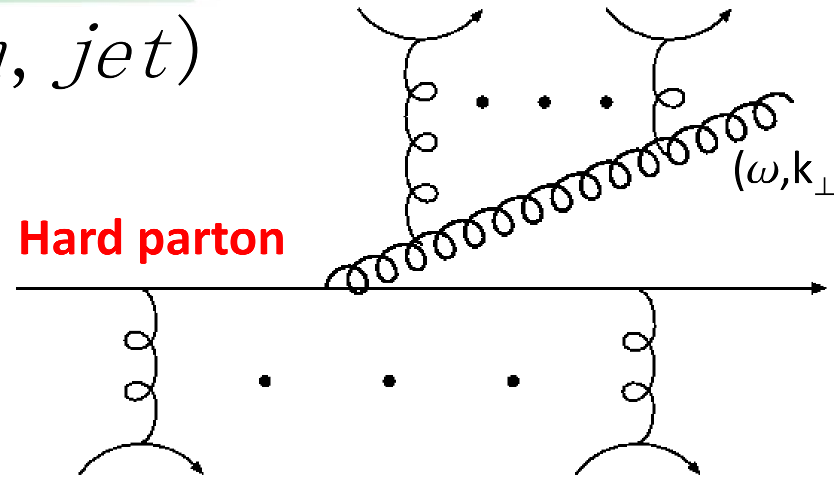


$$P_{j\to j'}(medium,\ jet)$$



Elastic (collisional)

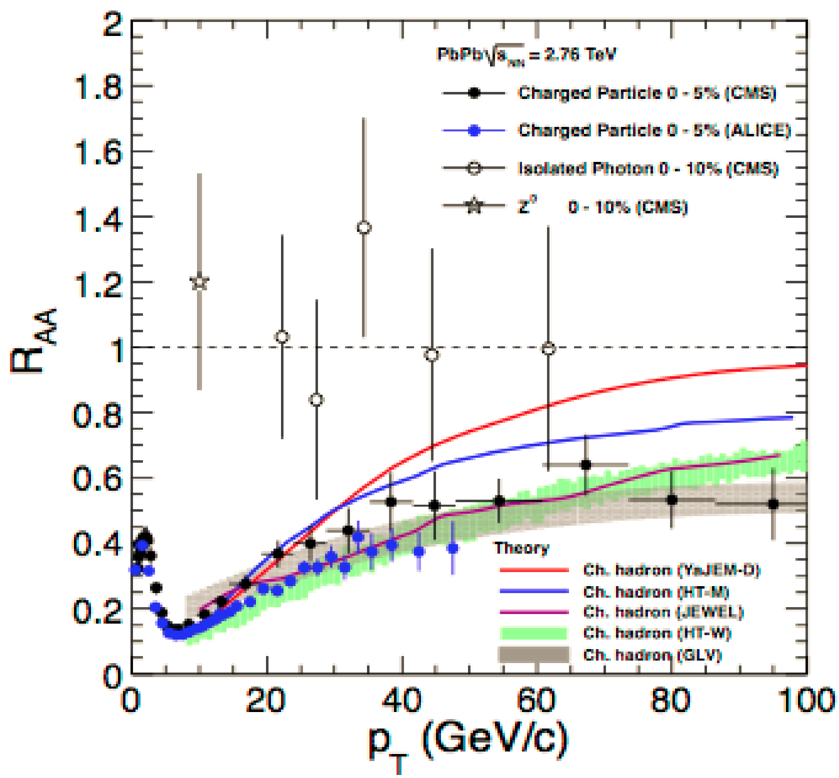
$$\frac{d\Gamma_{coll}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

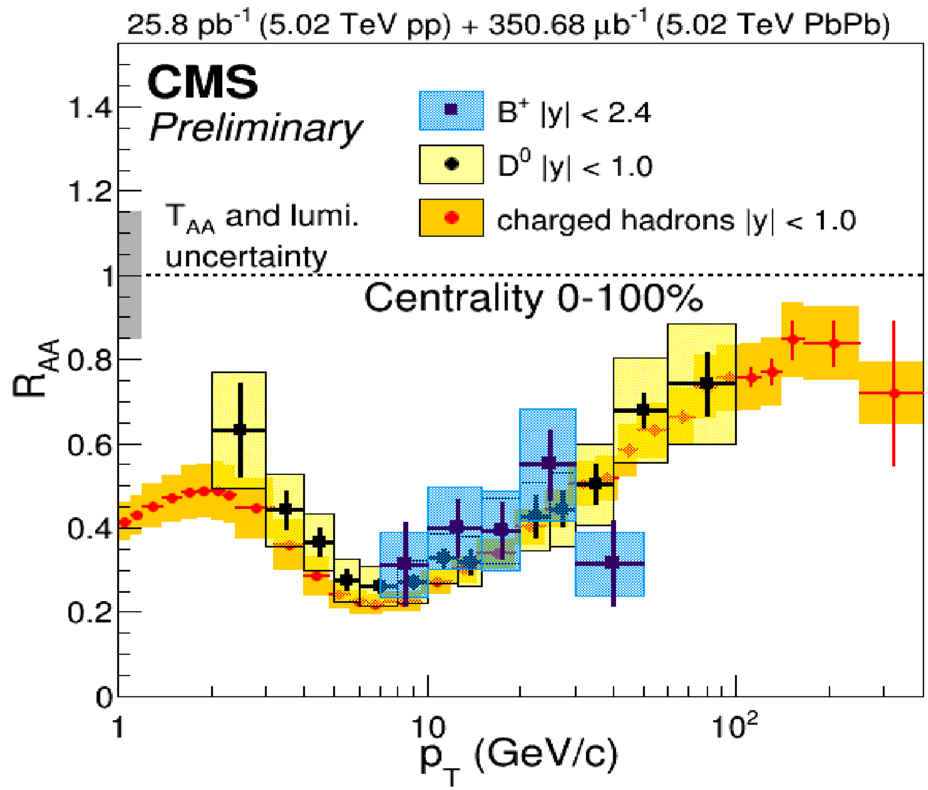


Inelastic (radiative)

$$\frac{d\Gamma_{rad}}{d\omega dk_\perp^2 dt}(T, E, \ldots) = ?$$

Nuclear modifications of large p_T hadrons

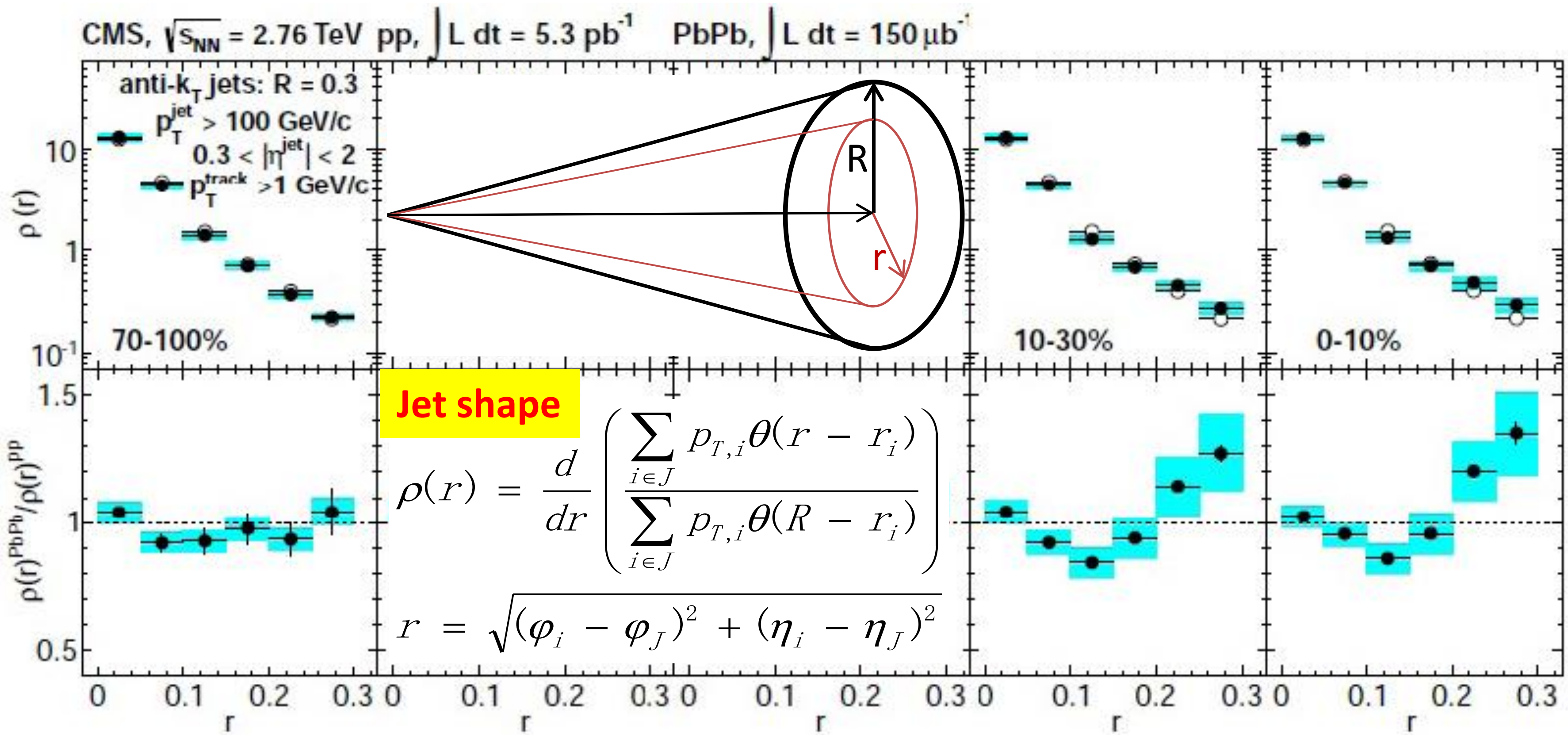




$$R_{AA} = \frac{1}{N_{\rm coll}} \frac{dN^{AA} / d^2 p_T dy}{dN^{pp} / d^2 p_T dy}$$

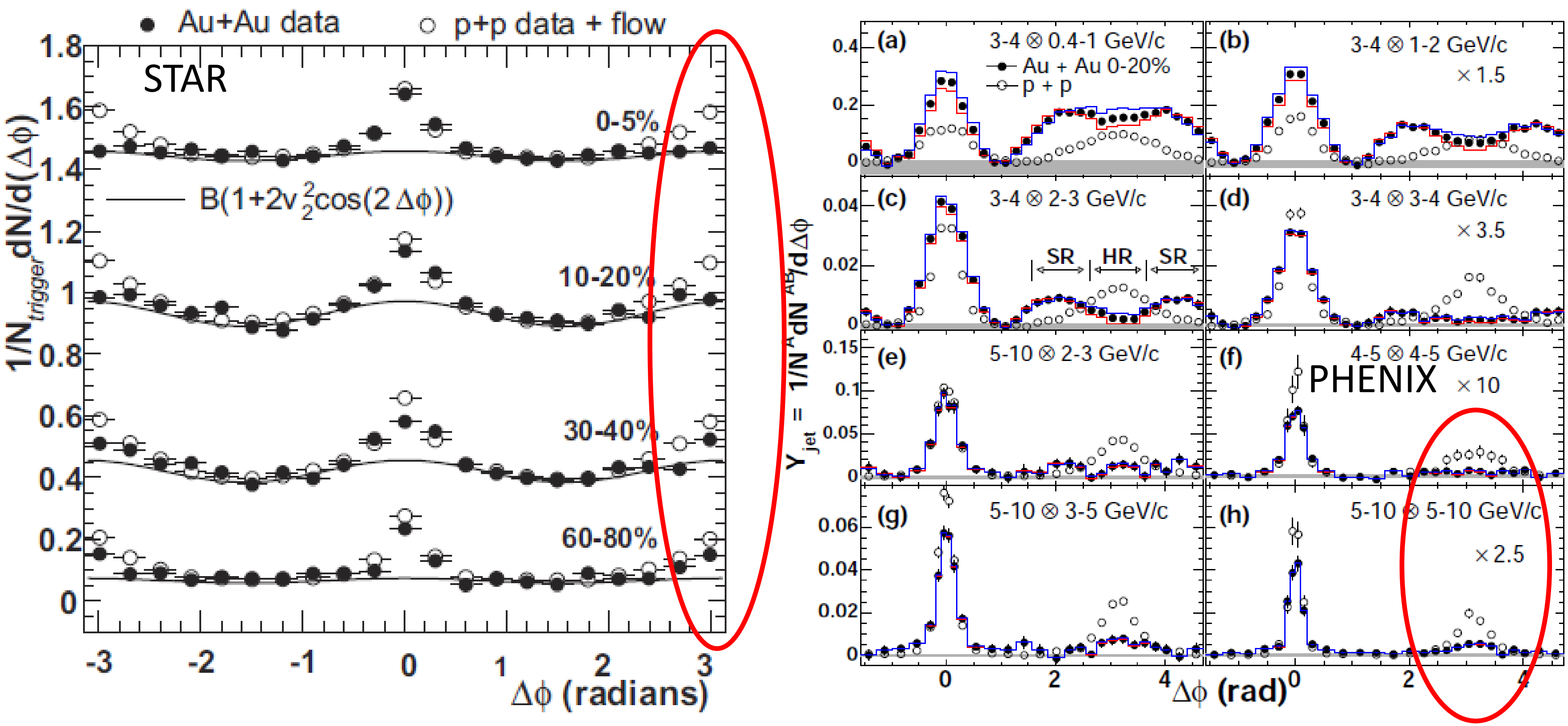
Color & flavor dependences of parton energy loss: $\Delta E_g > \Delta E_{uds} > \Delta E_c > \Delta E_b$?

Jet substructure (e.g., jet shape)



- **The observed enhancement at large r** is consistent with jet broadening (& medium-induced radiation)
- The soft outer part of the jet is easier to modify, while changing the inner hard cone is more difficult

Jet-related correlations



Both per-trigger yield and the shape of the angular distribution are modified by QGP

Medium-induced jet splitting

- Medium-induced jet splitting function (emission rate) is one of the central quantities in jet quenching studies.
- It controls both the amount of radiative energy loss and the detailed substructure of the full jets
- It enters into many phenomenological studies, e.g.,
  - Transport model:

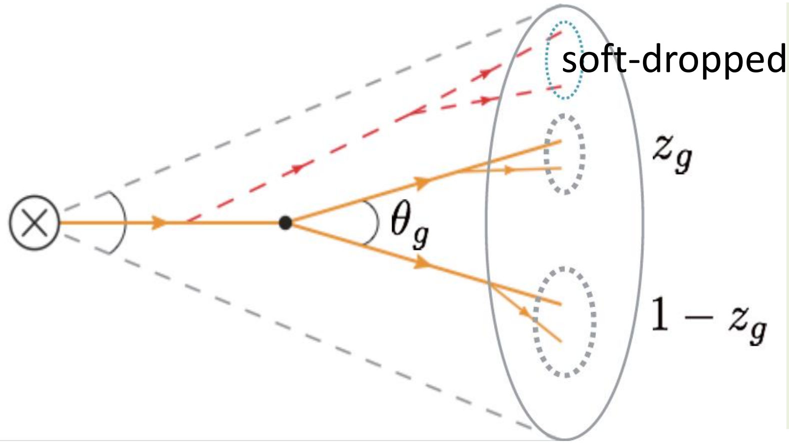
$$\langle N_g \rangle = \Gamma_g \Delta t = \Delta t \int dx dl_\perp^2 \frac{dN_g}{dx dl_\perp^2 dt} \qquad P_{inel} = 1 - e^{-\langle N_g \rangle}$$

  - Medium-modified DGLAP evolution:

$$\frac{\partial \tilde{D}_i(z, Q^2, E)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \sum_j \int \frac{dy}{y} [P_{i\to j}^{vac}(y) + \Delta P_{i\to j}^{med}(y, E)] \tilde{D}_j(z, Q^2, yE)$$

- However, many jet quenching observables (e.g., R_{AA}, I_{AA}, jet shape, etc.) only probe medium-induced jet splitting indirectly
- Direct tools to probe jet splitting function & its medium modification?

Jet grooming via soft drop declustering



- **Idea:** recursively removes soft wide-angle radiation from a jet
- **Experimental implementation:** re-cluster anti-k_T jet with Cambridge/Aachen (C/A) algorithm, then de-cluster the angular-ordered C/A tree by dropping soft branches

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

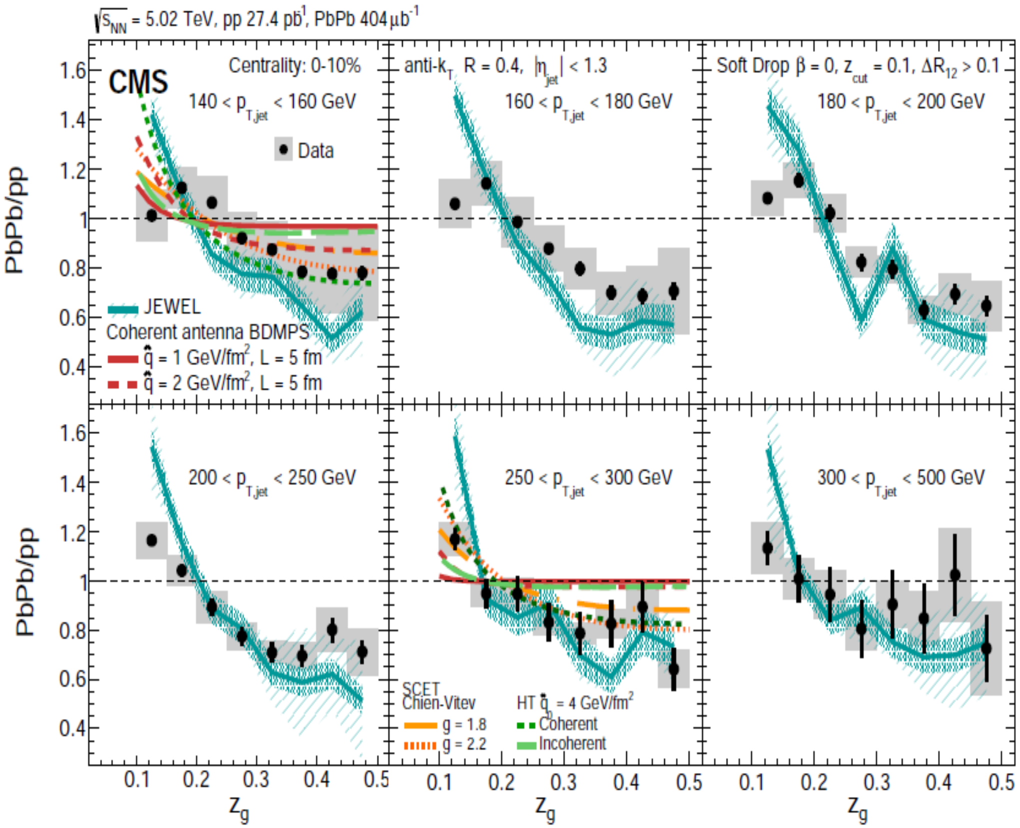
$$z > z_{cut}\theta^{\beta} = z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$$

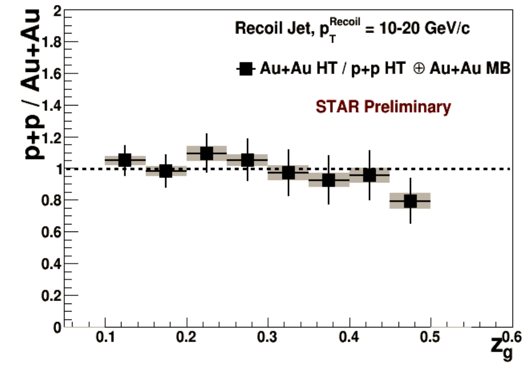
$$p(z_g) = \frac{1}{N_{jet}}\frac{dN}{dz_g}$$

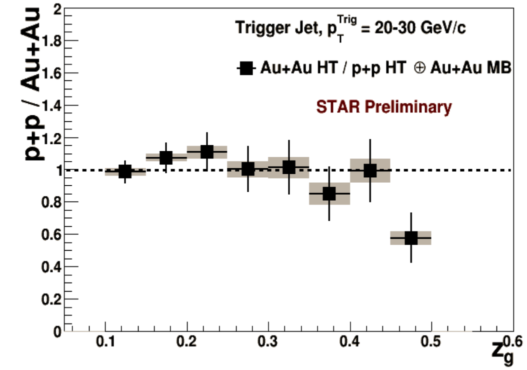
Butterworth, Davison, Rubin,Salam, PRL (2008)
Larkoski, Marzani, Soyez, Thaler, JHEP (2014)
Larkoski, Marzani, Thaler, PRD (2015)

- z_g is the momentum fraction carried by the subleading subjet in the groomed jet
- The splitting function $p(z_g)$ for soft dropped jets encodes the momentum sharing fraction for the hardest splitting/branching (a direct probe to jet splitting function)

CMS & STAR results (jet energy dependence)







- CMS: smaller (larger) modification for increasing (decreasing) jet energies
- STAR: no significant modification of groomed jet splitting (z_g distribution for soft dropped jets) in Au+Au collisions as compared to pp collisions

Chien, Vitev, PRL 2017; Mehtar-Tani, Tywoniuk, JHEP 2017; Chang, Cao, GYQ, PLB 2018; Elayavalli, Zapp, JHEP 2017; Tripathee, Xue, Larkoski, Marzani, Thaler, PRD 2017; Milhano, Wiedemann, Zapp, PLB 2018; Lapidus, Oliver, arXiv:1711.00897; Li and Vitev, arXiv:1801.00008; Chien, Elayavalli, arXiv:1803.03589

Framework

$$\mathcal{P}_i(x,k_\perp^2) = \mathcal{P}_i^{\rm vac}(x,k_\perp^2) + \mathcal{P}_i^{\rm med}(x,k_\perp^2)$$

$$p_i(z_g) = \frac{\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(z_g,k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(z_g,k_\perp^2)\right]}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(x,k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(x,k_\perp^2)\right]}$$

Larkoski, Marzani, Thaler, PRD (2015); Chien, Vitev, PRL 2017

Here we take higher-twist jet energy loss formalism:

$$\mathcal{P}_i^{\rm med}(x,k_\perp^2) = \frac{2C_A\alpha_s}{\pi k_\perp^4}\mathcal{P}_i^{\rm vac}(x)\int dt\hat{q}_i(t)\sin^2\left(\frac{t}{2\tau_f}\right)$$

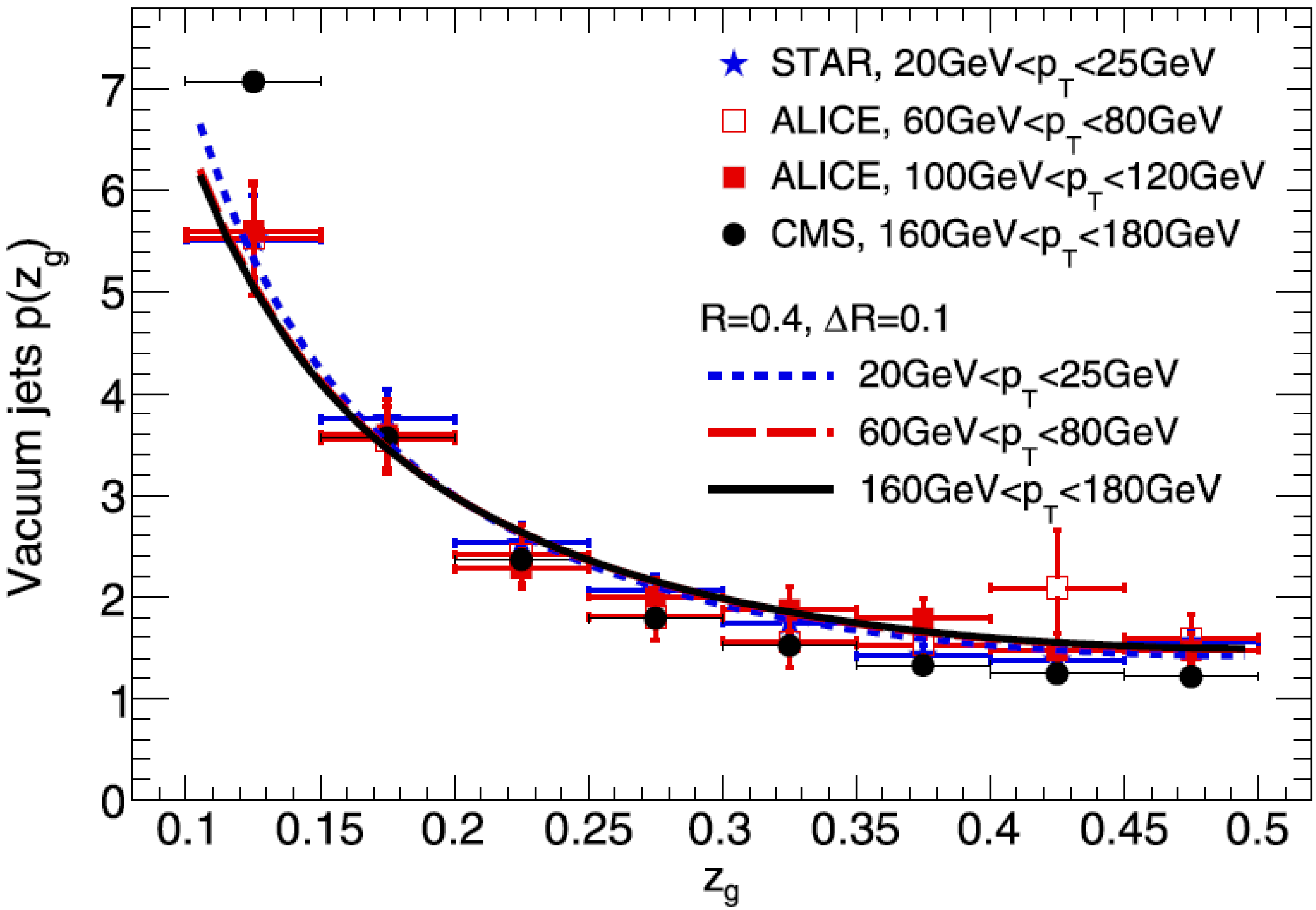
Guo, Wang, PRL 2000, Majumder, PRD 2012

Jet splitting function in medium is expected to be steeper than in vacuum

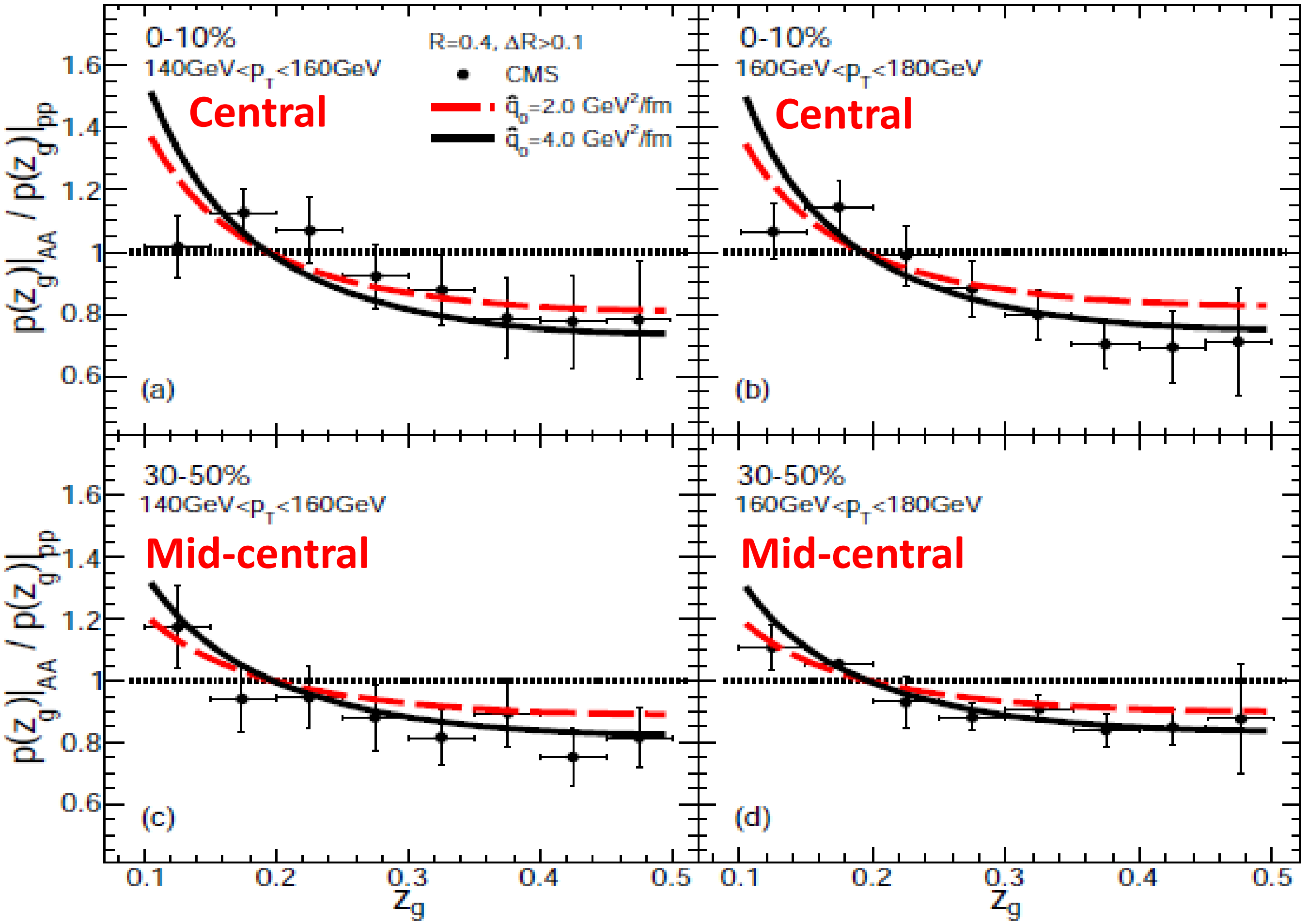
Incorporate the out-of-cone energy loss of the jet as follows:

$$p^{\rm obs}(z_g) = \frac{1}{\sigma_{\rm total}}\sum_{j=q,g}\int d^2X\mathcal{P}(\vec{X})\int_{p_{\rm T,1}^{\rm ini}=p_{\rm T,1}^{\rm obs}+\Delta E_1}^{p_{\rm T,2}^{\rm ini}=p_{\rm T,2}^{\rm obs}+\Delta E_2} dp_{\rm T}^{\rm ini}\frac{d\sigma_j}{dp_{\rm T}^{\rm ini}}p_j(z_g|p_{\rm T}^{\rm ini})$$

Jet splitting function in vacuum

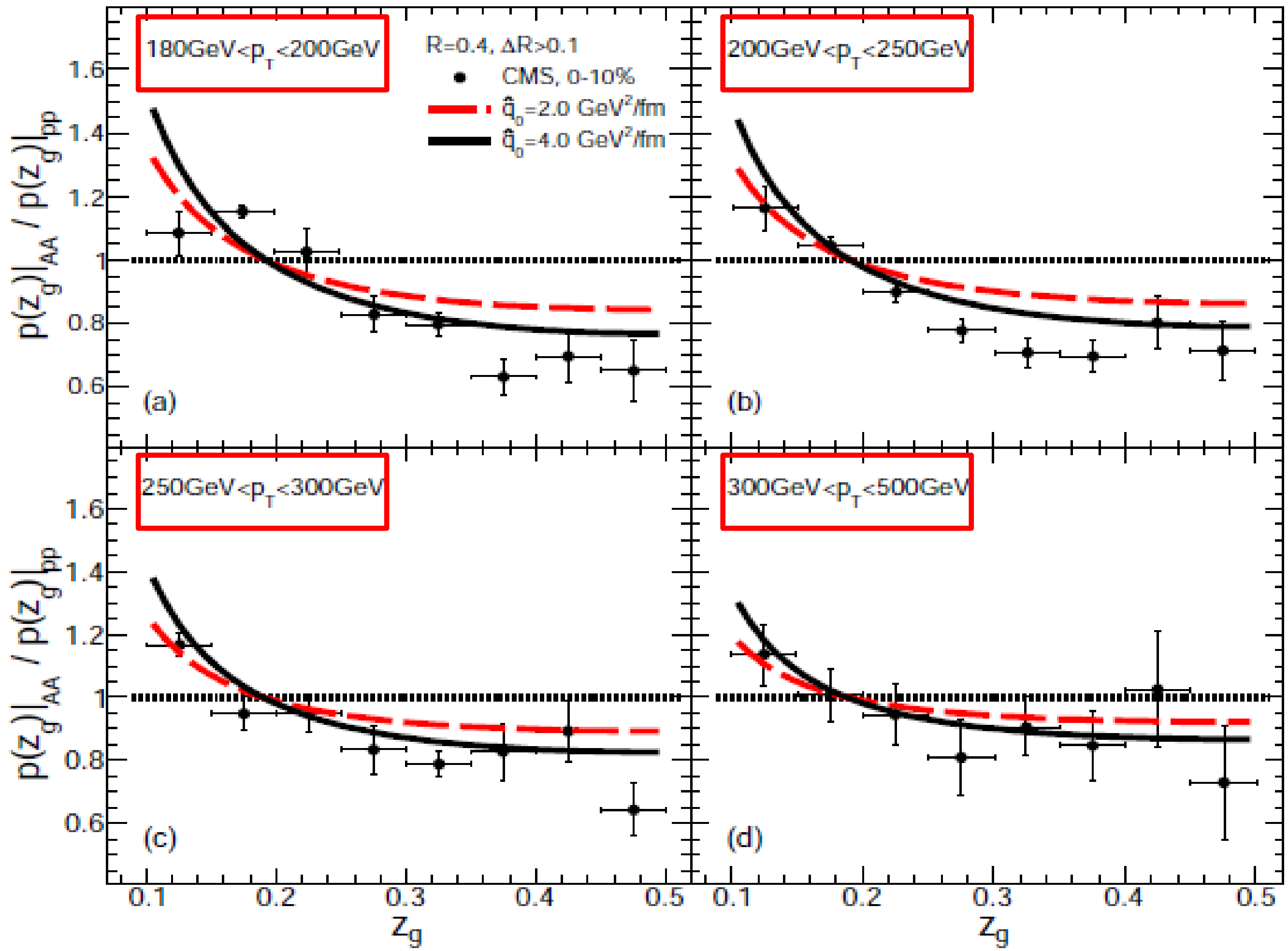


Jet splitting function in AA @LHC: centrality dependence



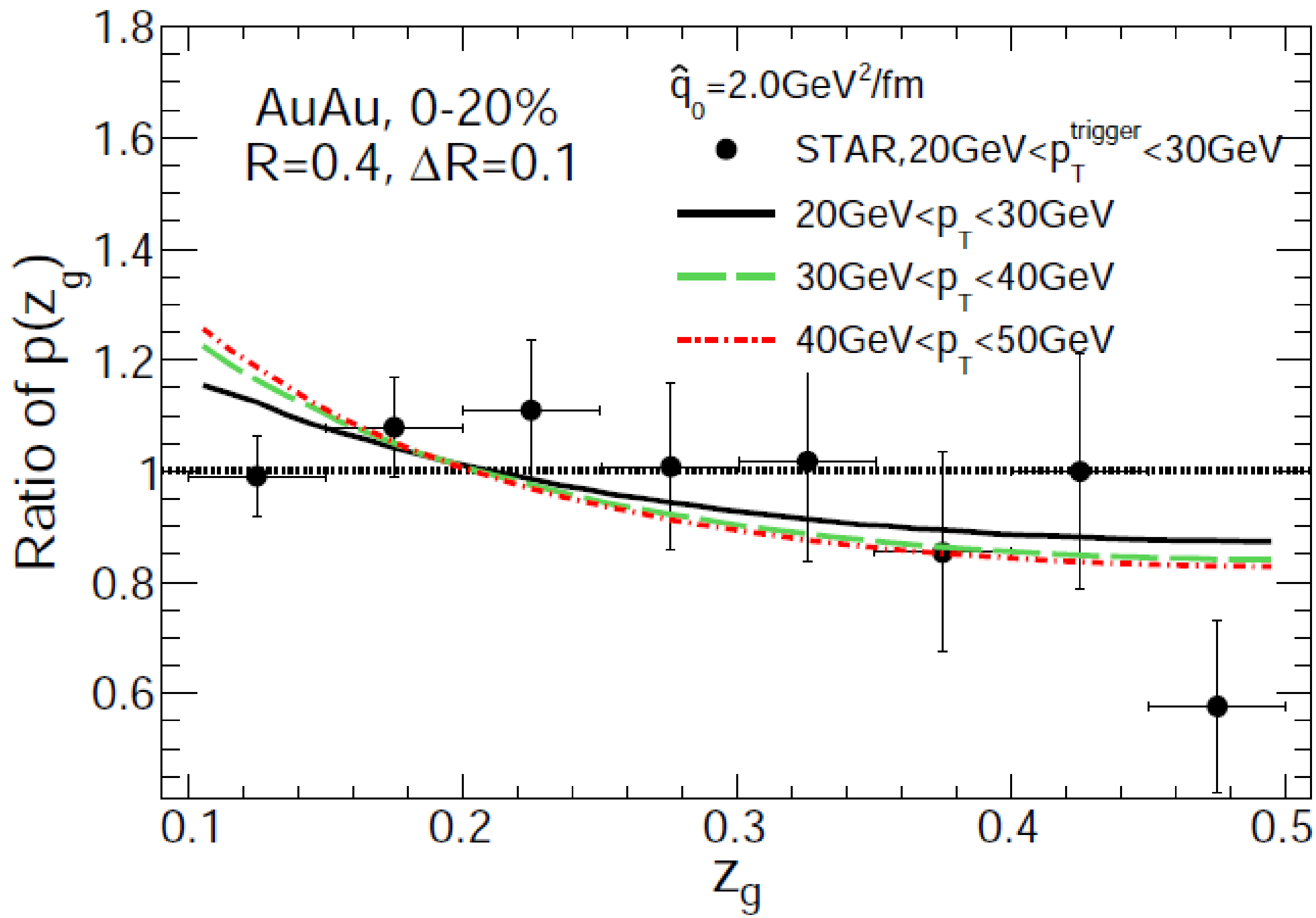
More jet-medium interaction, **steeper** splitting function for soft dropped jet

Jet splitting function in AA @LHC: jet energy dependence



CMS: **larger (smaller)** jet energy, **less (more)** nuclear modification effect on soft dropped jet splitting function

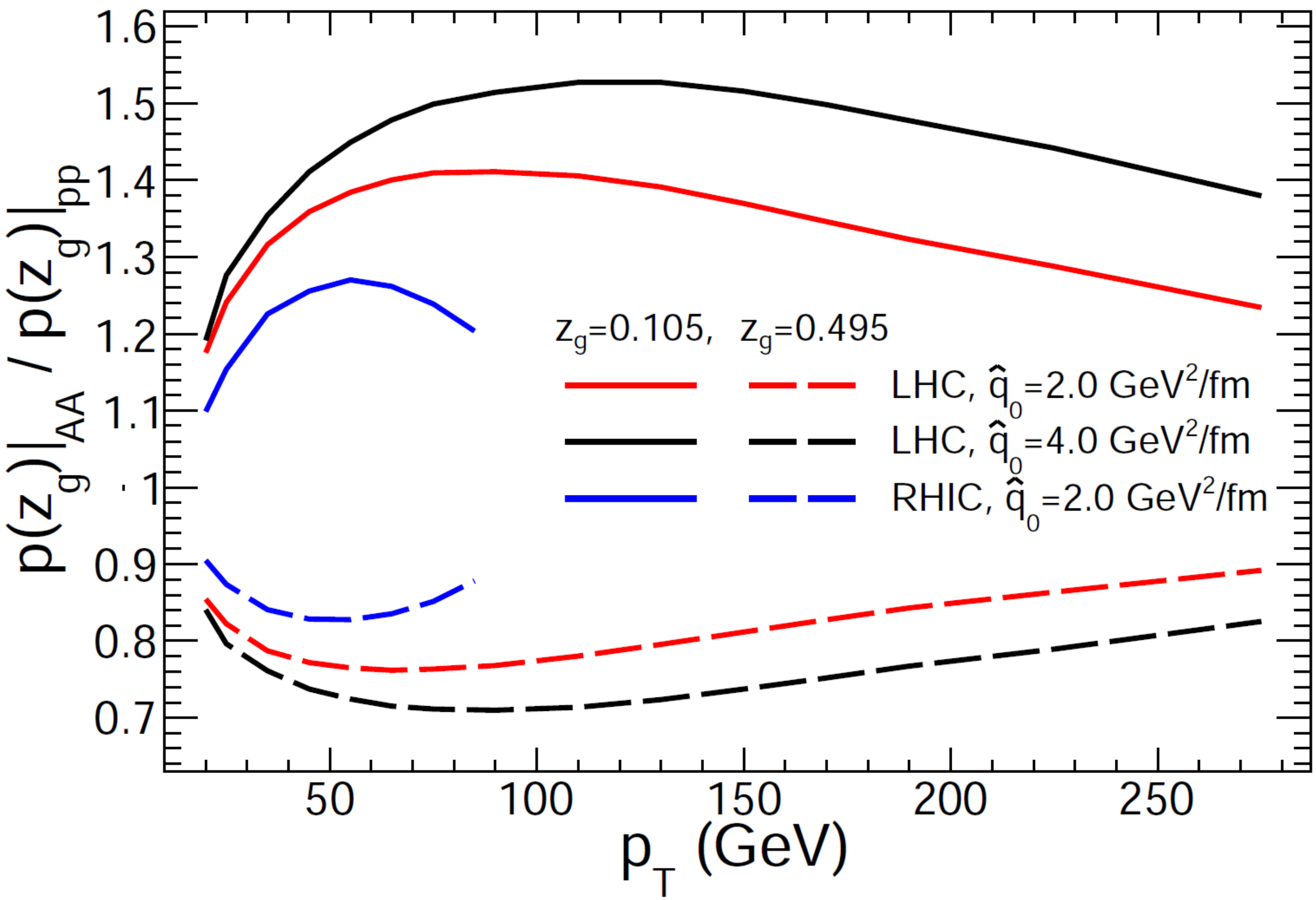
Jet splitting function in AA @RHIC



- RHIC: **smaller** jet energies, **less** nuclear modification
- CMS: **smaller** jet energies, **more** nuclear modification

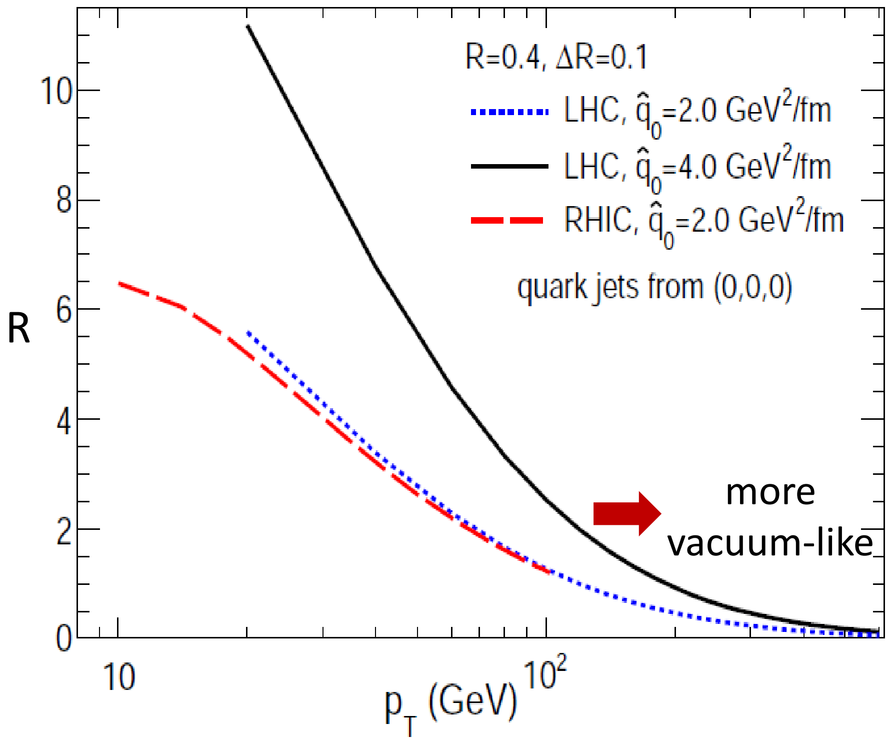
=> Non-monotonic jet energy dependence for $p(z_g)$ modification

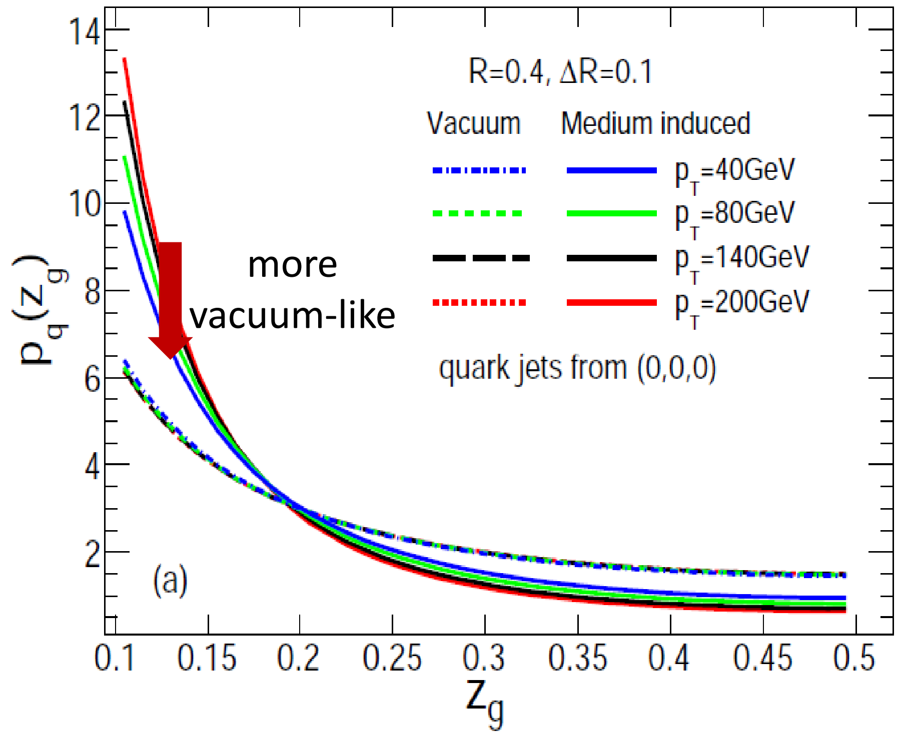
Jet energy dependence for $R[p(z_g)]$



Non-monotonic jet energy dependence for the nuclear modification of $p(z_g)$

Jet energy dependence: two competing factors





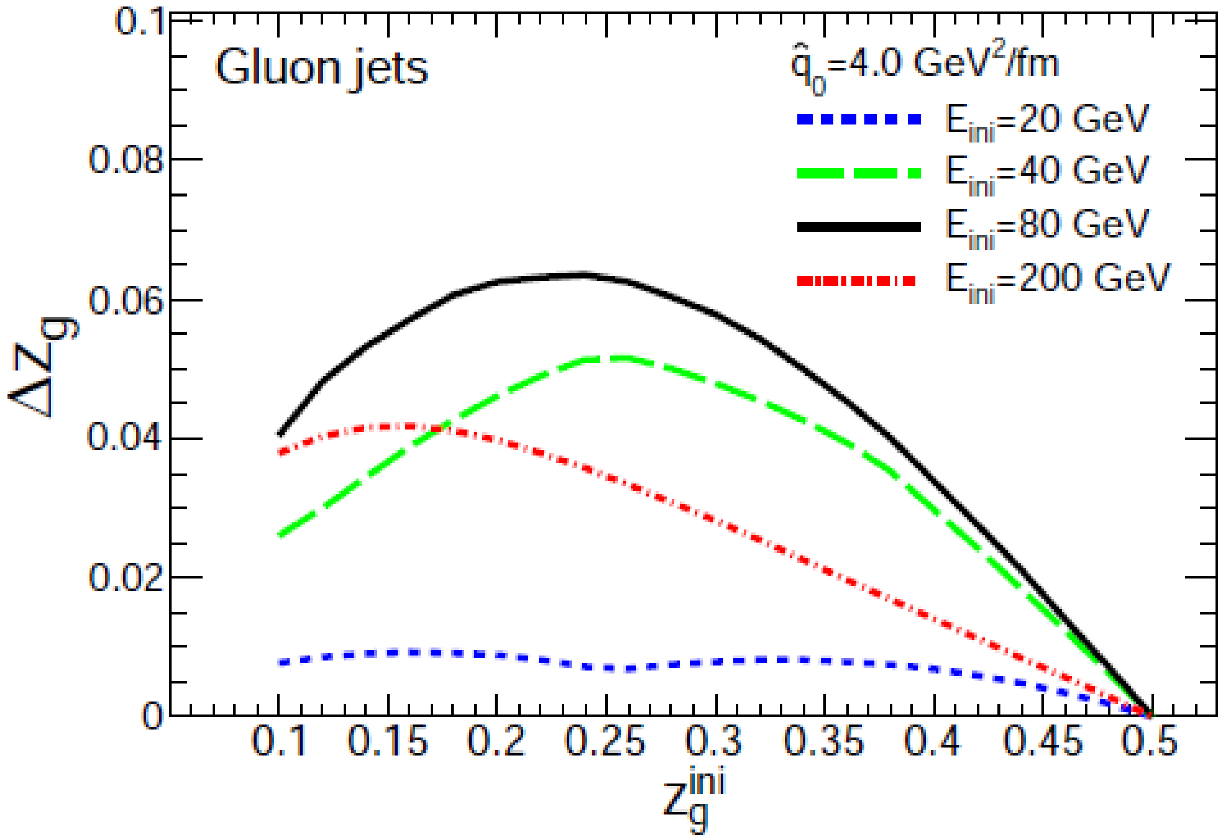
$$p_i(z_g) = \frac{\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(z_g, k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(z_g, k_\perp^2)\right]}{\int_{z_{cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \left[\overline{\mathcal{P}}_i^{\rm vac}(x, k_\perp^2) + \overline{\mathcal{P}}_i^{\rm med}(x, k_\perp^2)\right]}$$

$$\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \overline{\mathcal{P}}_i^{\rm med}(x, k_\perp^2) \to \begin{cases} 1/x\,, & \text{small } E \\ 1/x^3\,, & \text{large } E \end{cases}$$

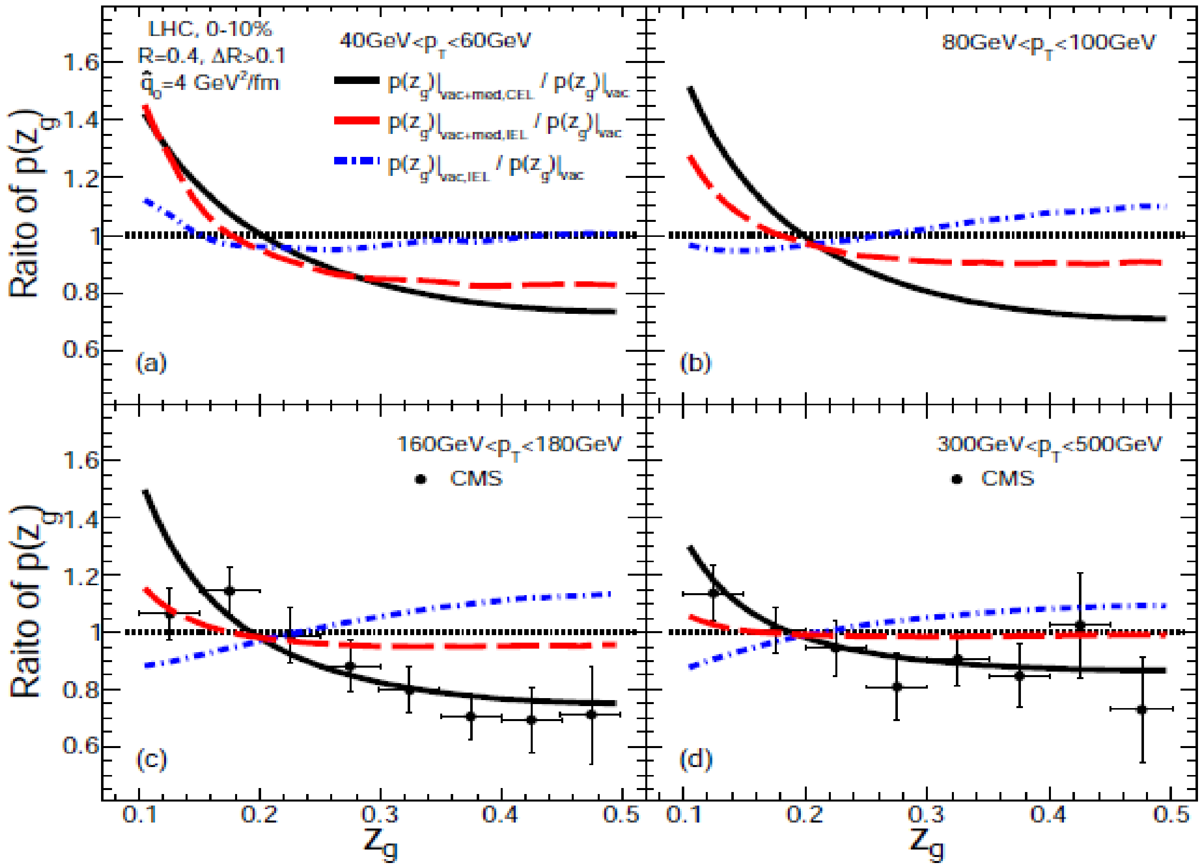
With **smaller** jet energies, the medium-induced contribution is **increasing**, but the medium-induced part of the splitting function is **flatter**

Medium-modified splitting or energy loss effect?

$$z_g^{ini} = z_1, z_2 = 1 - z_1, \frac{z_1'}{z_2'} < \frac{z_1}{z_2}, z_g^{fin} = \frac{z_1'}{z_1'+z_2'} \leq z_g^{ini}$$



Medium-modified splitting or energy loss effect?



Three scenarios

(1): MM-splitting + CEL

(2): MM-splitting + IEL

(3): V-splitting + IEL

Additional medium-induced splitting with coherent energy loss for subjets is favored by the observed p(zg) modification data

Casalderrey-Solana, Iancu, JHEP 2011; Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, PLB 2013; Mehtar-Tani, Tywoniuk, JHEP 2017

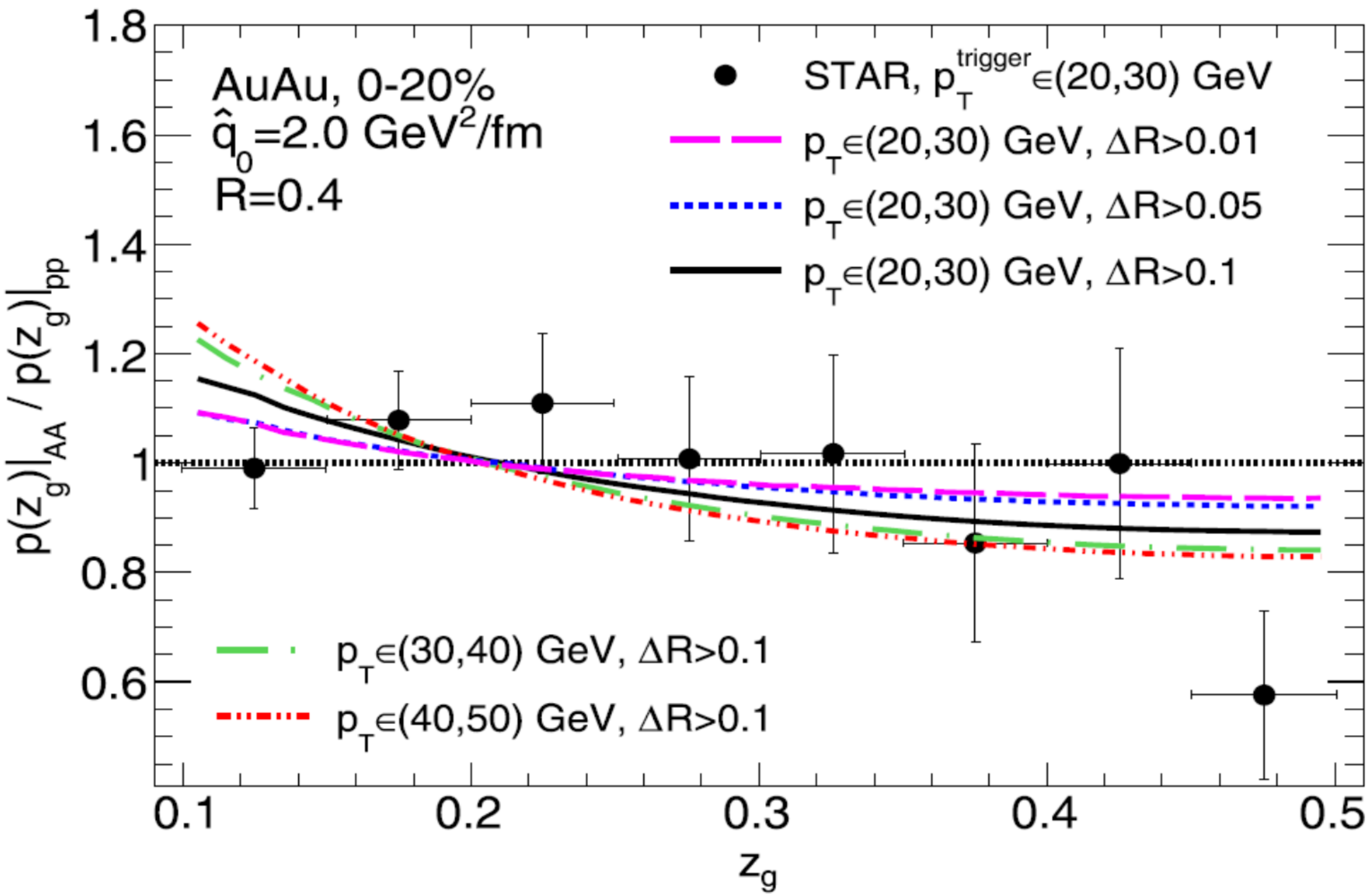
Summary

- Groomed jets provide a direct tool to probe jet splitting function & its medium modification in heavy-ion collisions

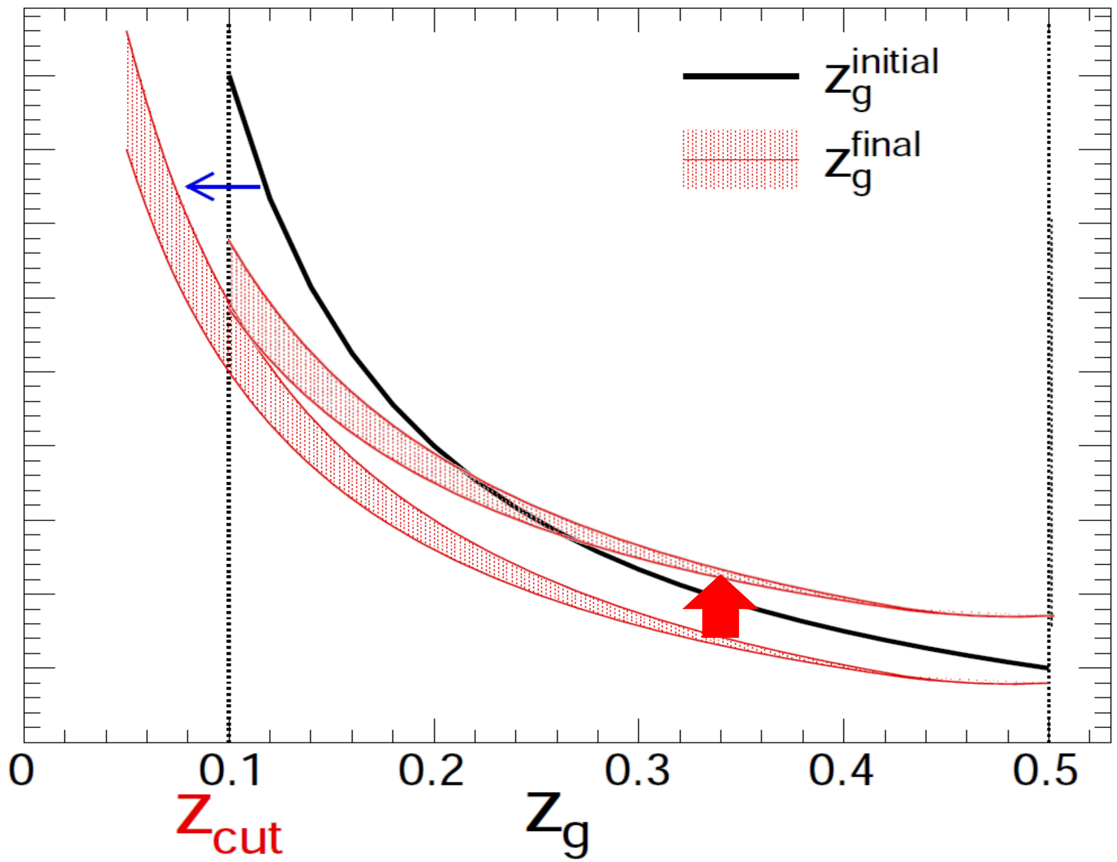
- The nuclear modification of groomed jet splitting is studied using higher-twist formalism
  - Non-monotonic dependence on jet energy is obtained for $R_{AA}[p(z_g)]$
  - STAR & CMS data on $R_{AA}[p(z_g)]$ favor additional medium-induced splitting with coherent E loss for subjets

- Future: lower jet energies at the LHC & larger jet energies at RHIC, various angular separations between two subjets

Jet splitting function in AA @RHIC



Independent energy loss for two subjets



$$z_g^{ini} = z_1, z_2 = 1 - z_1, \frac{z_1'}{z_2'} < \frac{z_1}{z_2}, z_g^{fin} = \frac{z_1'}{z_1'+z_2'} \leq z_g^{ini}$$

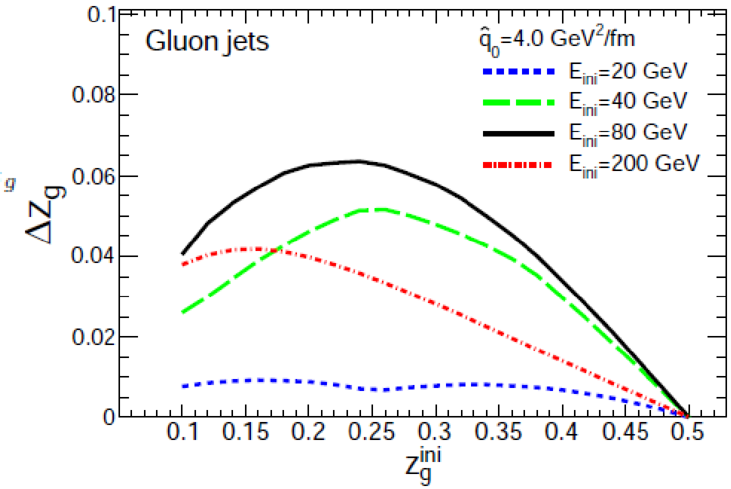
Independent energy loss for two subjets

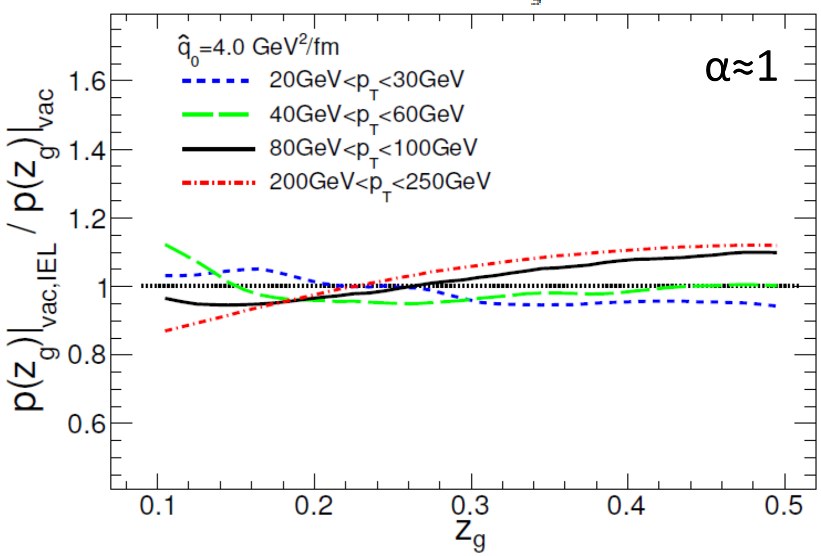
$$dN^{\rm ini}/dz_g^{\rm ini} \sim 1/(z_g^{\rm ini})^\alpha$$

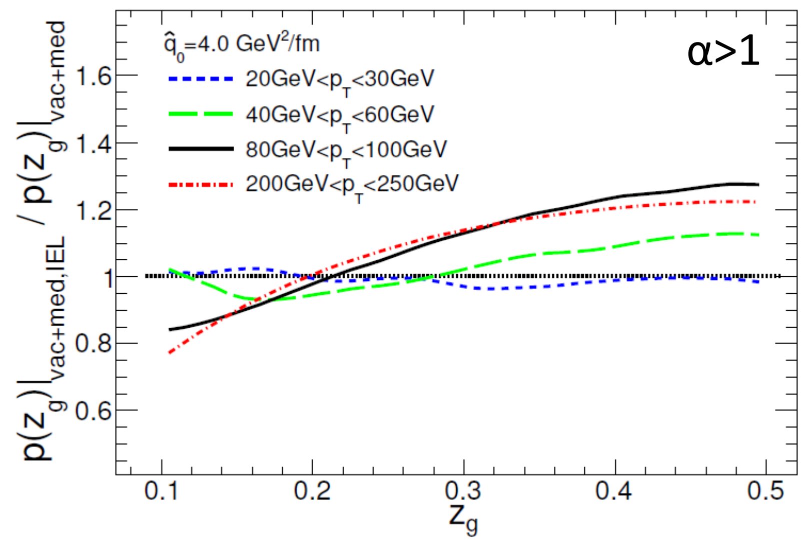
$$\frac{dN^{\rm fin}}{dz_g^{\rm fin}} = \int d\Delta z_g P(\Delta z_g|z_g^{\rm ini}) \left.\frac{dN^{\rm ini}}{dz_g^{\rm ini}}\right|_{z_g^{\rm ini}=z_g^{\rm fin}+\Delta z_g}$$

$$\frac{dN^{\rm fin}}{dz_g^{\rm fin}} \approx \frac{1}{|\mathcal{J}|}\frac{1}{(z_g^{\rm fin})^\alpha}\left(1-\alpha\frac{\Delta z_g}{z_g^{\rm fin}}+\cdots\right)$$

$$p^{\rm fin}(z_g^{\rm fin}) = \frac{\frac{dN^{\rm fin}}{dz_g^{\rm fin}}}{\int_{z_{\rm cut}}^{1/2} dz_g^{\rm fin}\frac{dN^{\rm fin}}{dz_g^{\rm fin}}}$$







How $p(z_g)$ is modified depends on the slope of $p(z_g)$ and the details of z_g shift.

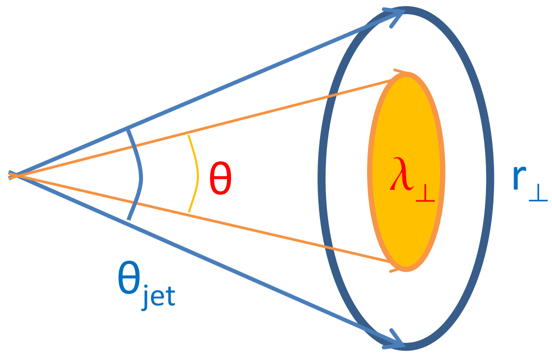
Coherence or decoherence

- Consider a qq^{bar} antenna emitting system with a transverse size $r_\perp = \theta_{jet} L$
- Gluon with energy $(\omega, k_\perp)$ emitted at angle $\theta = k_\perp/\omega$ has wavelength $\lambda_\perp = 1/k_\perp$

- Vacuum:
  - In-cone emission ($\lambda_\perp < r_\perp$): independent emission by each quark
  - Out-of-cone emission ($\lambda_\perp > r_\perp$): coherent emission by qq^{bar} system
- Medium:
  - If medium color field varies over $r_\perp$, then q and q^{bar} lose their color coherence
  - Jet-medium interaction destroys the color coherence
  - De-coherence parameter

$$\Delta_{med} = 1 - \exp\left(-\frac{1}{12}\frac{r_\perp^2}{\lambda_\perp^2}\right) = 1 - \exp\left(-\frac{1}{12}\theta_{jet}{}^2 \hat{q} L^3\right)$$

- Massive antenna: a heavy-quark gluon antenna loses coherence faster than a light-quark gluon antenna (lose more energy loss) (Calvo, Moldes, Salgado, arXiv:1403.4892)



Armesto, Ma, Mehtar-Tani, Salgado, Tywoniuk, 2011; Iancu, Casalderray-Solana 2011; Blaizot, Dominguez, Iancu, Mehtar-Tani, 2012; Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk, PLB 2013