Probing jet splitting and energy loss via groomed jets in relativistic heavy-ion collisions

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In collaboration with Shanshan Cao and Guang-You Qin
Based on PLB.781,423

Outline

- Motivation and Framework
- Jet energy dependence for the nuclear modification of groomed jet splitting function ?
- Coherent or incoherent subjet energy loss ?
- Summary and Outlook

Why study groomed jet substructures

- In jet quenching studies, medium-modified splitting functions are key quantities.
- They enter into many phenomenological studies (I_{AA}, R_{AA}, *jet shape, jet fragmentation function*.....) in various ways, e.g.,

DGLAP evolution for parton fragmentation function:

$$\frac{\partial \tilde{D}(z,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\int_z^1 \frac{dy}{y}\Big(P^{vac}(y) + P^{med}(y)\Big)\tilde{D}\Big(\frac{z}{y},Q^2\Big)$$

Transport model (scattering rate):

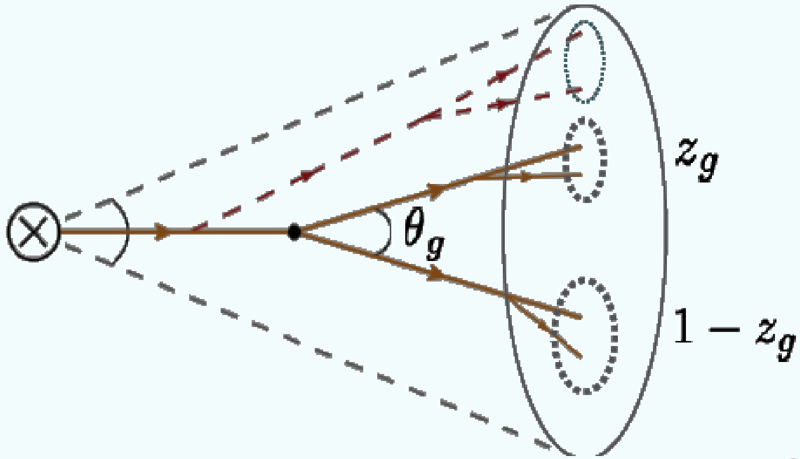
$$\Gamma^{\rm inel} = \langle N_g\rangle(E,T,t,\Delta t)/\Delta t = \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2\, dt}$$

- These phenomenological jet quenching studies can only indirectly probe splitting functions.
- We would like to have a direct probe of splitting functions.

Softdrop jet grooming algorithm

Anti-kT jet is re-clustered with Cambridge/Aachen (CA)

Then decluster the angular-ordered CA tree, Drop soft branches



$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \equiv z_g > z_{\text{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

CMS: $z_{cut} = 0.1, \beta$=0, $\Delta R \geq 0.1$

STAR: $z_{cut} = 0.1, \beta$=0

Butterworth, Davison, Rubin and Salam,Phys.Rev.Lett. 100 (2008) 242001

Larkoski, Marzani, Soyez and Thaler, JHEP1405(2014)146,PRD91,111501(2015)

Chien and Vitev, Phys.Rev.let,119,112301(2017); Li and Vitev, arXiv:1801.00008.

Mehtar-Tani and Tywoniuk, JHEP 1704, 125 (2017)

Kunnawalkam Elayavalli and Zapp, JHEP 1707, 141 (2017)

Tripathee, Xue, Larkoski, Marzani and Thaler, Phys. Rev.D96, 074003 (2017)

Chang, Cao and Qin, Phys.Lett,B781,423(2018)

Milhano, Wiedemann and Zapp, Phys. Lett. B779, 409 (2018)

Lapidus and Oliver, arXiv:1711.00897. Chien and Kunnawalkam Elayavalli, arXiv:1803.03589

Framework

Calculate p(z_g) based on paron splitting function

$$p_i(z_g) = \frac{\int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \, \overline{P}_i(z_g, k_\perp^2)}{\int_{z_{\rm cut}}^{1/2} dx \int_{k_\Delta^2}^{k_R^2} dk_\perp^2 \, \overline{P}_i(x, k_\perp^2)}$$

$$\overline{P}_i(x, k_\perp^2) = \sum_{j,l} \left[P_{i\to j,l}(x, k_\perp^2) + P_{i\to j,l}(1-x, k_\perp^2) \right]$$

Larkoski, Marzani, Thaler, Phys. Rev. D91,111501 (2015); Y.-T. Chien and I. Vitev, Phys.Rev.let,119,112301

Paron splitting function is modified by medium

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

$$P_i^{\rm med}(x, k_\perp^2) = \frac{2\alpha_s}{\pi k_\perp^4} P_i^{\rm vac}(x) \int d\tau \hat{q}_g(\tau) \sin^2\left(\frac{\tau}{2\tau_f}\right)$$

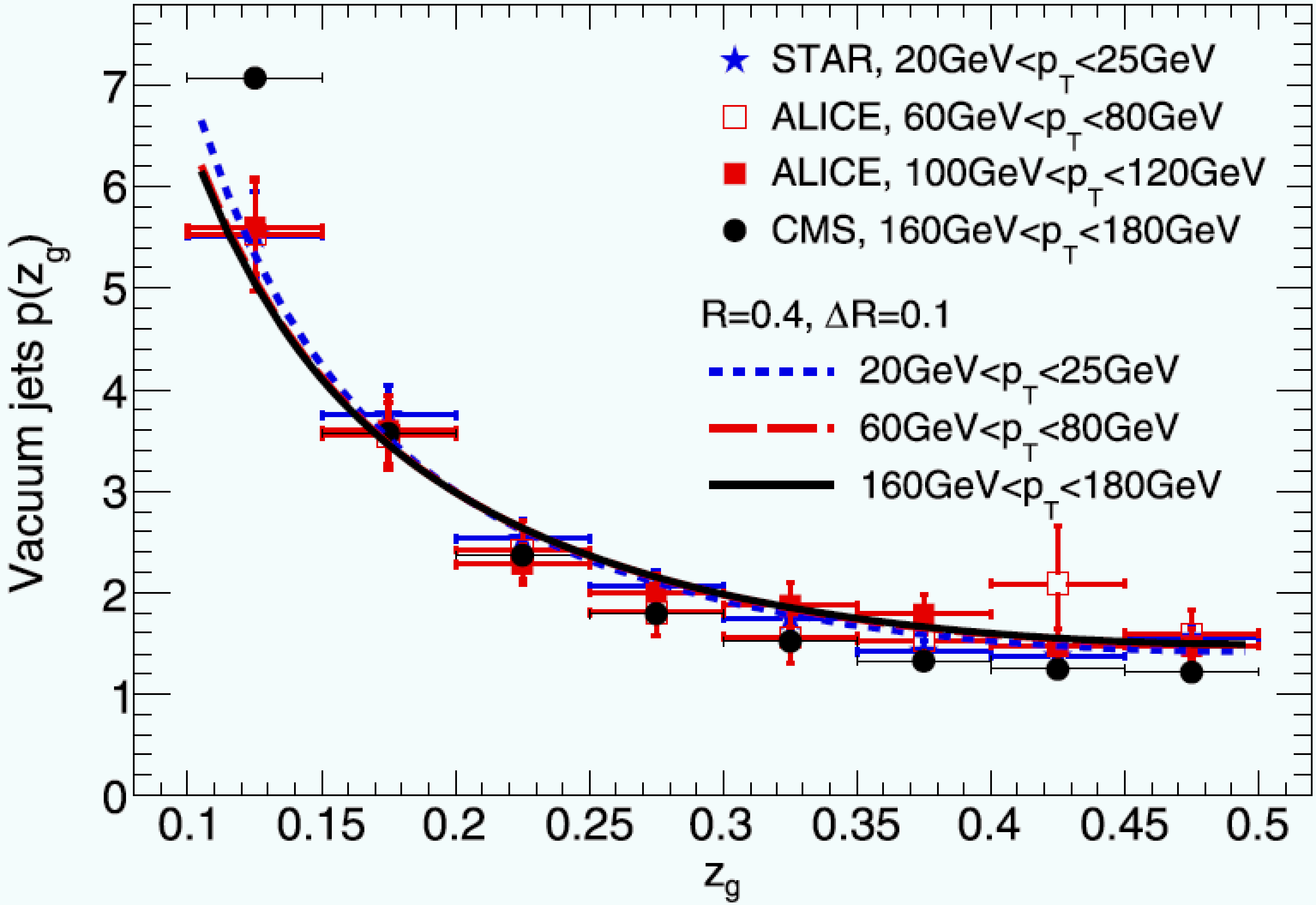
X.N. Wang and X.F. Guo,Nucl.Phys.A696, 788(2001)
A. Majumder, Phys.Rev.D85,014023 (2012)

Convolute with cross section and consider energy loss

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

$$\Delta E = \int dx dk_\perp^2 (xE) \overline{P}^{\rm med}(x, k_\perp^2) \theta(\frac{1}{2} - x) \theta(k_\perp - k_R)$$

Jet splitting function in vacuum

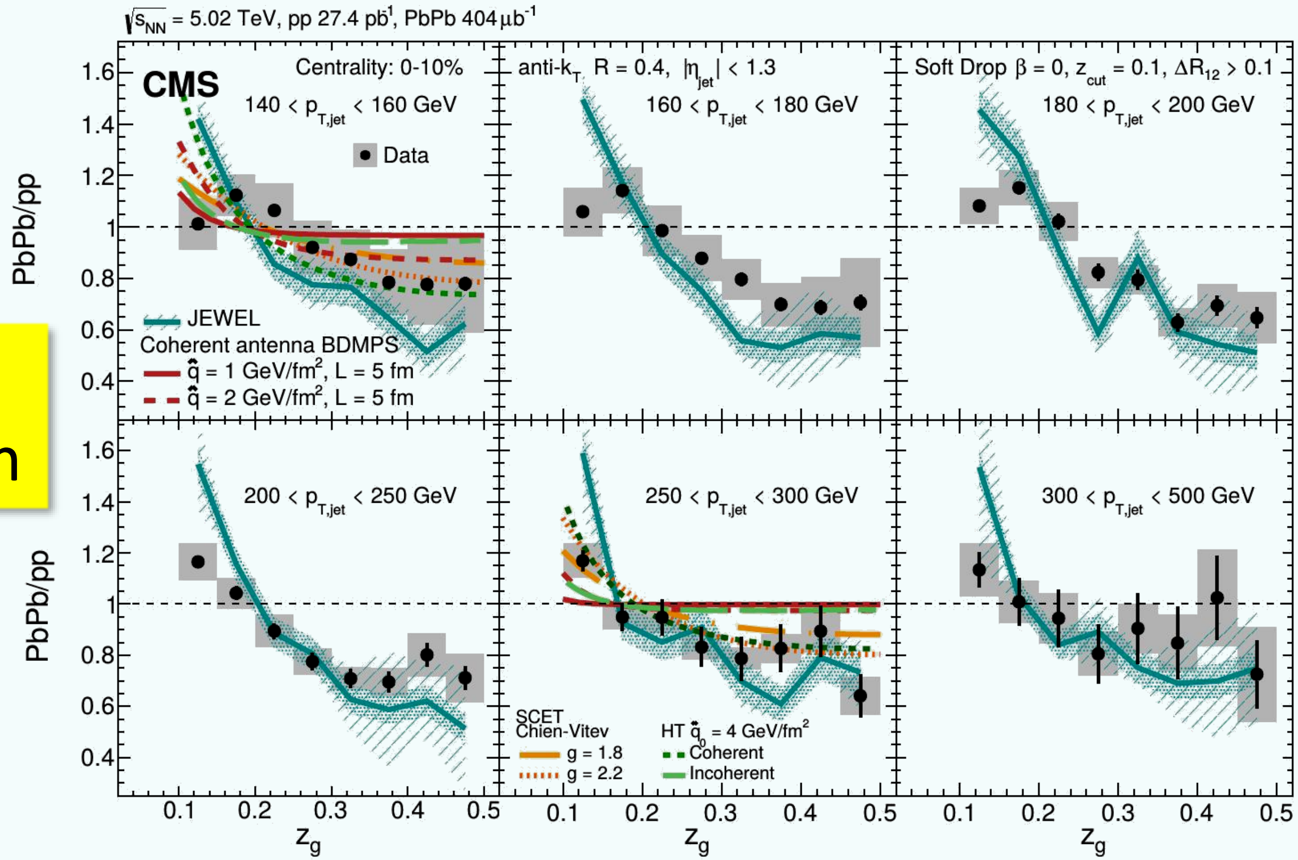


Vacuum jet splitting function has little p_T dependence.

p_T dependence of the nuclear modification

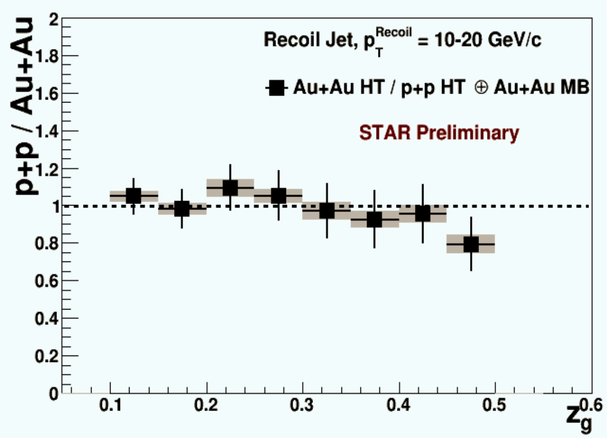
$$R_{p(z_g)} = \frac{p(z_g)\,|_{AA}}{p(z_g)\,|_{pp}}$$

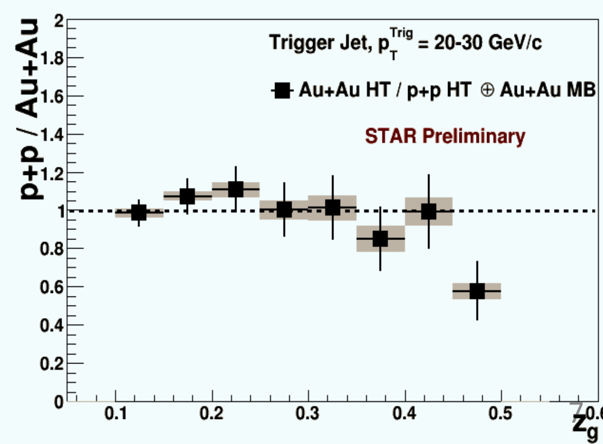
CMS, PRL.120,142302



lower jet p_T ,
stronger modification

Kolja Kauder for STAR
Nucl.Phys.A967,516

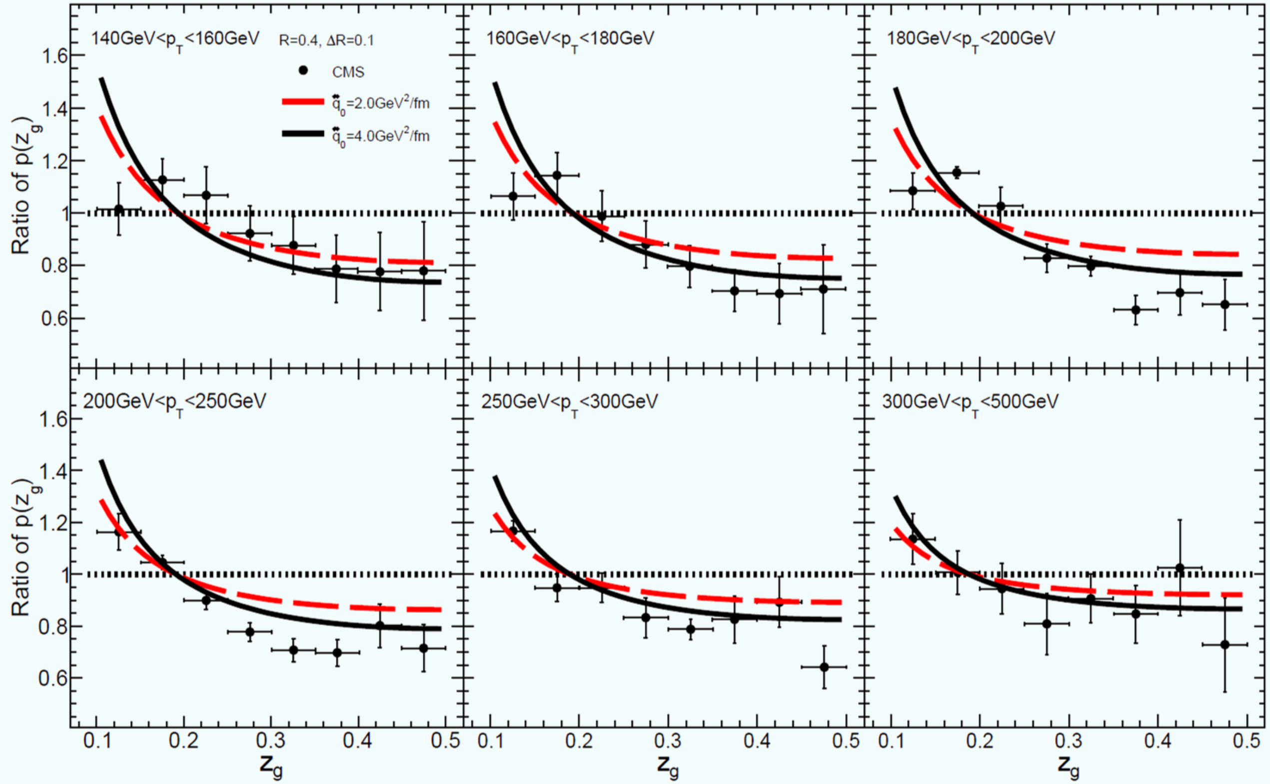


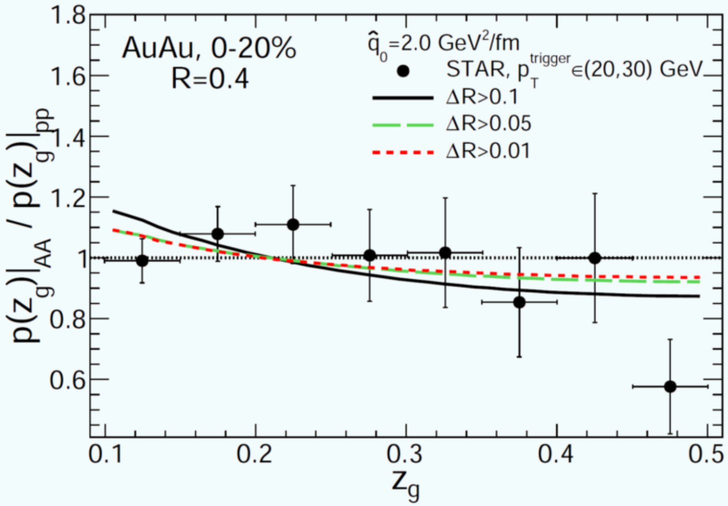


small jet p_T ,
little modification

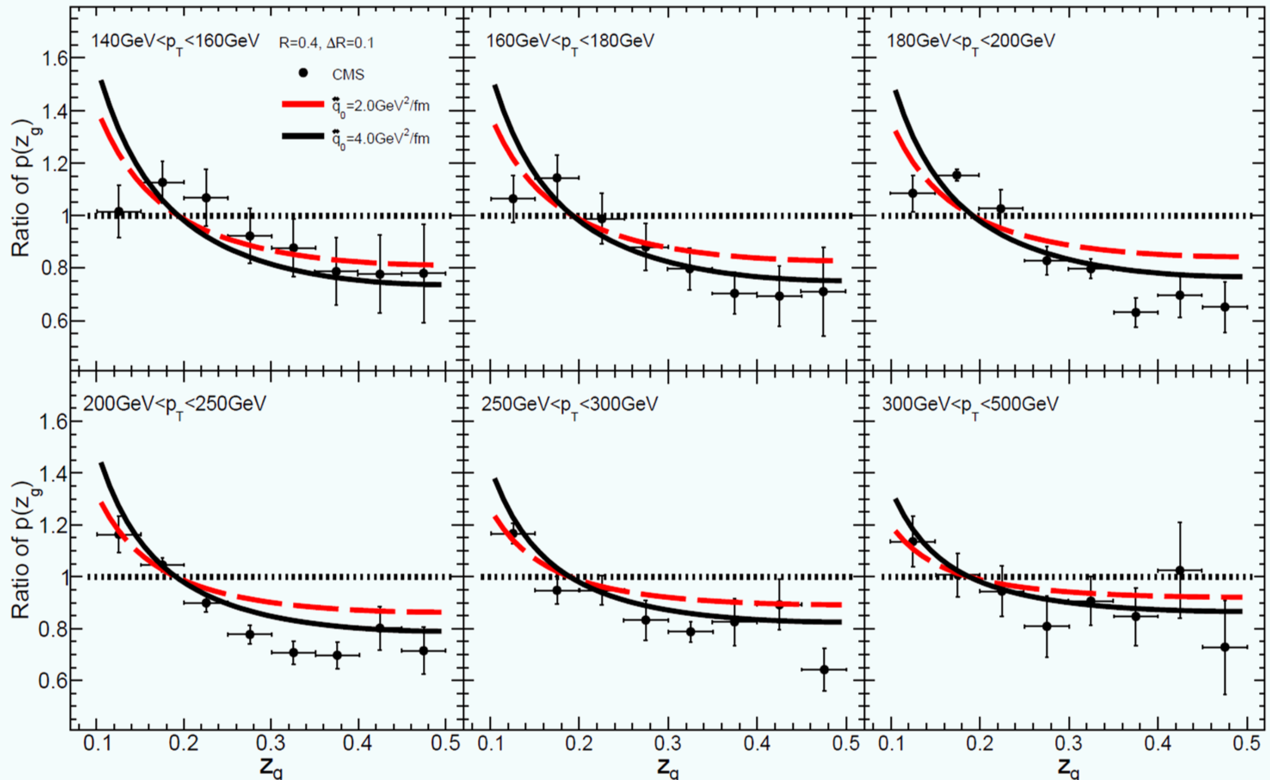
Comparison with CMS and STAR data

larger jet p_T
less modification





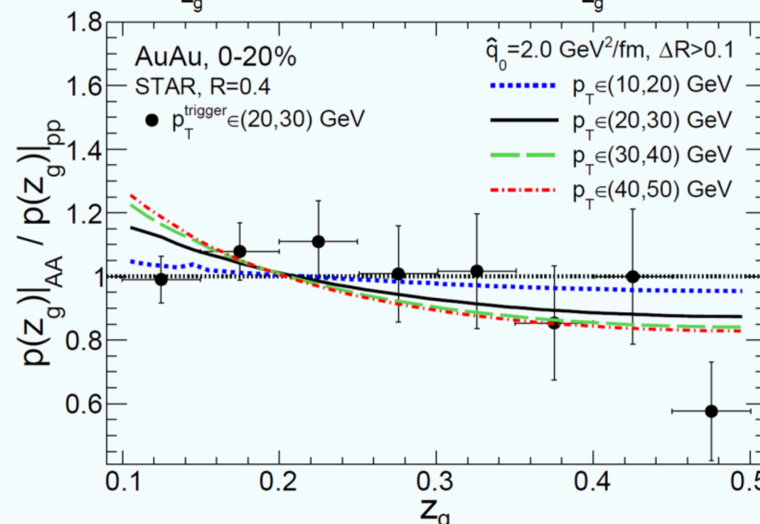
Comparison with CMS and STAR data



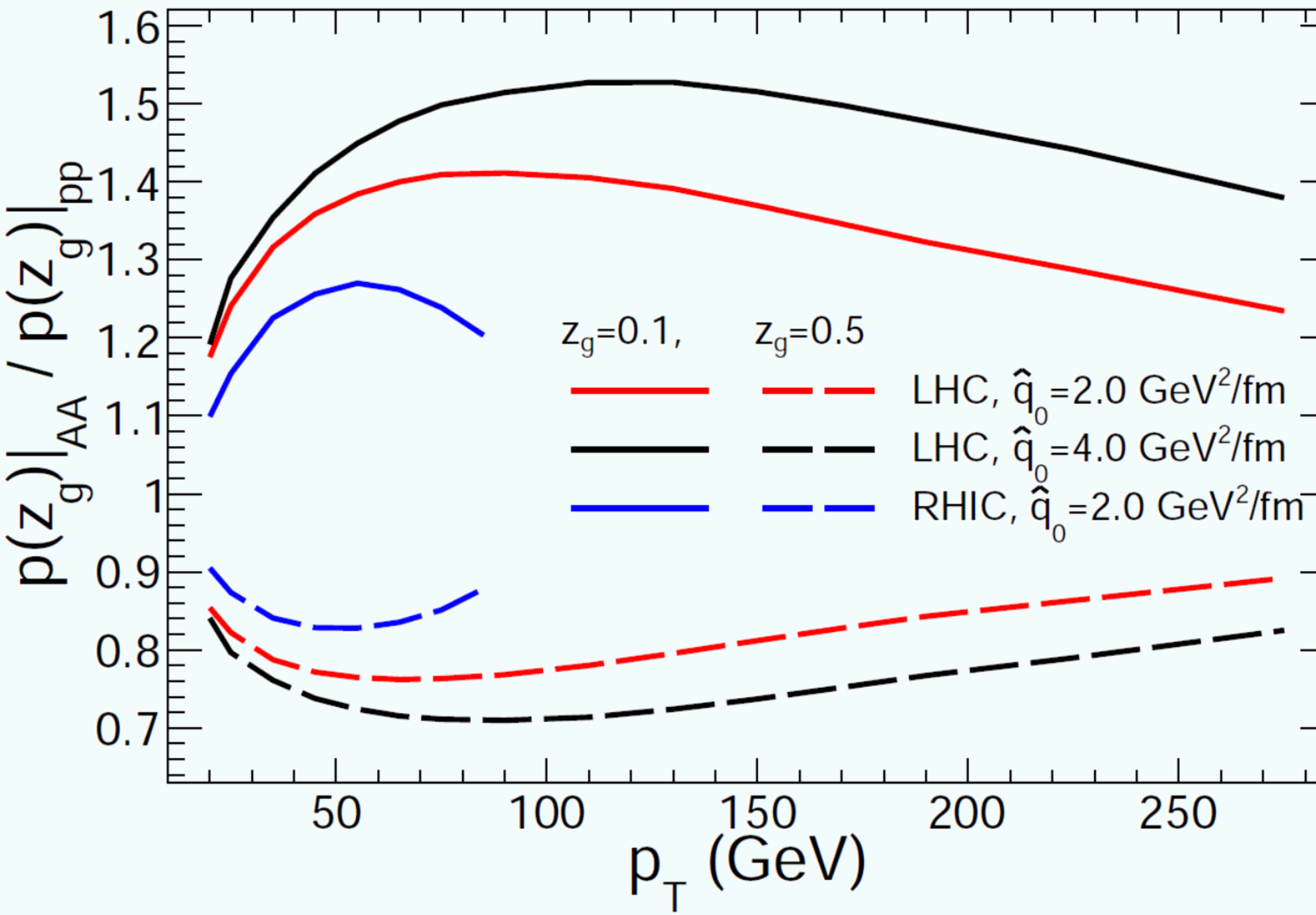
larger jet p_T
less modification

Non-monotonic jet p_T dependence!

larger jet p_T
larger modification



Non-monotonic jet energy dependence



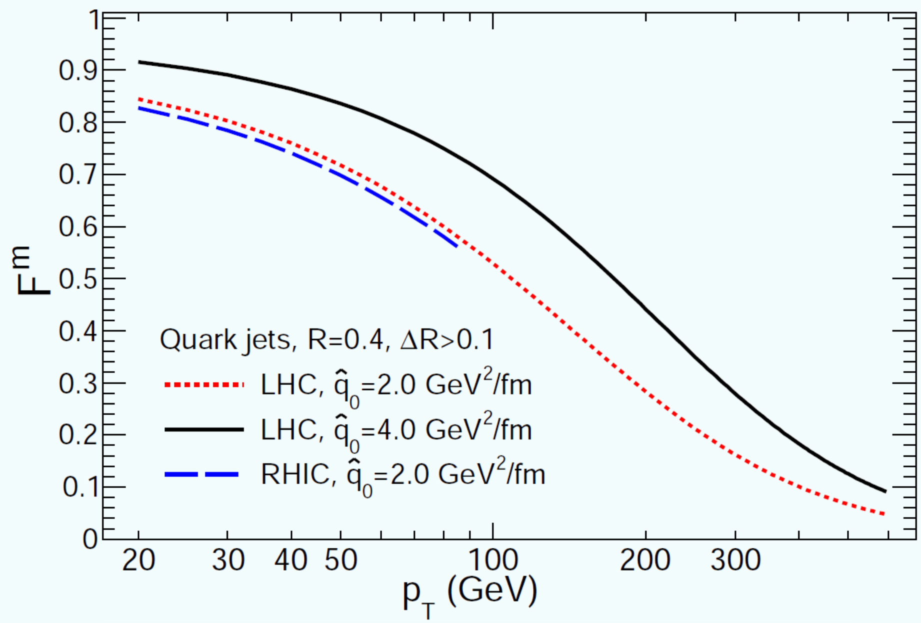
R_{AA} for $p(z_g)$ at endpoints z_g=0.1 and z_g=0.5

Origin of Non-monotonic jet energy dependence

$$P_i(x,k_\perp^2) = P_i^{\text{vac}}(x,k_\perp^2) + P_i^{\text{med}}(x,k_\perp^2)$$

Weight

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



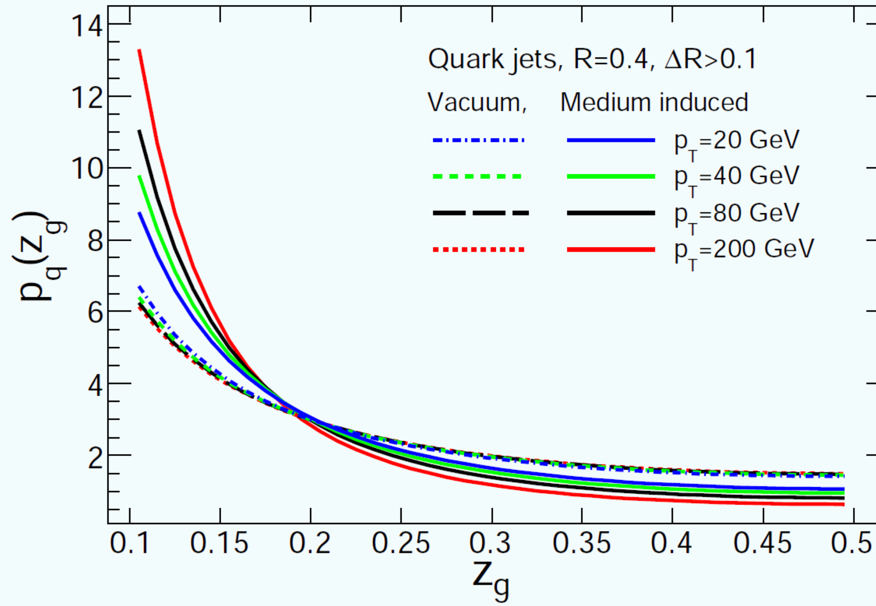
p_T decreases,

more $p^{med}(x)$ vs. $p^{vac}(x)$.

Explain p_T dep. of CMS

***x* behavior**

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

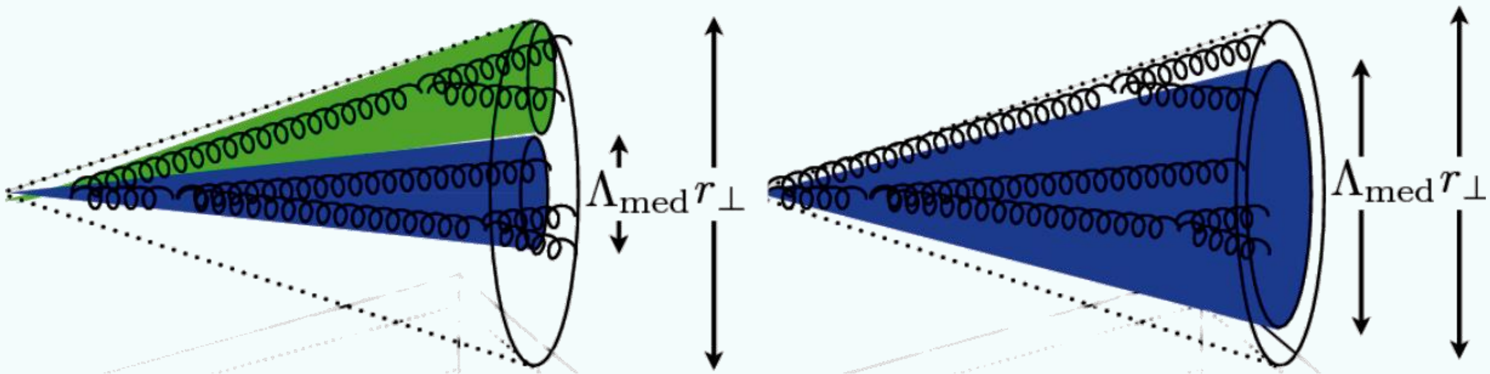


p_T decreases,

$p^{med}(x)$ closer to $p^{vac}(x)$.

Explain p_T dep. of STAR

Coherent vs. incoherent energy loss of subjet?



By Casalderrey-Solana, Mehtar-Tani, Salgado and Tywoniuk, *Phys. Lett. B* ***725*** (2013) 357

Transverse separation: $r_\perp = \theta\tau_f = \theta\frac{2Ex(1-x)}{k_\perp^2}$

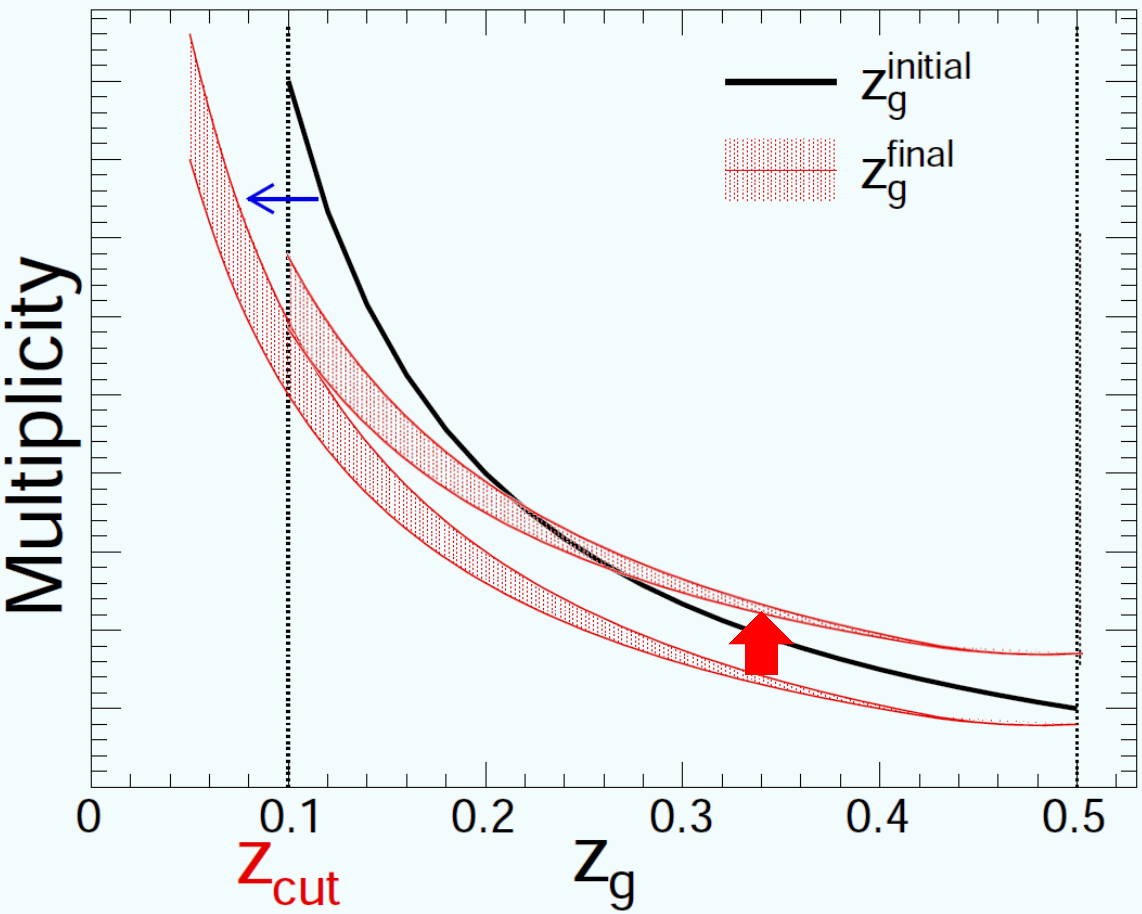
Transverse wavelength: $\lambda_\perp = \frac{1}{k_\perp} = \frac{1}{2Ex(1-x)tan(\frac{\theta}{2})}$

Medium resolution scale: $\Lambda_{med} = \frac{1}{\sqrt{\hat{q}L}}$

Coherent: $r_\perp < \lambda_\perp , \Lambda_{med}$

Casalderrey-Solana and Iancu, JHEP 1108, 015 (2011)
Mehtar-Tani, Salgado and Tywoniuk, Phys. Lett. B707, 156 (2012)
Casalderrey-Solana, Mehtar-Tani, Salgado and Tywoniuk, *Phys. Lett. B* ***725*** (2013) 357
Mehtar-Tani and Tywoniuk, JHEP 1704, 125 (2017) ….

Effect of the incoherent energy loss (IEL)



Larger energy,
less energy loss fraction.
IEL reduces Z_g:

$$z_1 \equiv z_g^{ini}\ ,\ z_2 = 1 - z_1$$

IEL: $\frac{z_1'}{z_1} < \frac{z_2'}{z_2}$

$$z_g^{fin} = \frac{z_1'}{z_1' + z_2'} \leq z_g^{ini}$$

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

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

Effect of the incoherent energy loss (IEL)

$$\frac{dN^i(z_g^i)}{dz_g^i} = \frac{1}{(z_g^i)^\alpha}\,; \quad \Delta z_g(z_g^i) = z_g^i - z_g^f$$

$$\frac{dN^f(z_g^f)}{dz_g^f} \approx \frac{1}{(z_g^f)^\alpha}\left(1-\alpha\frac{\Delta z_g(z_g^i)}{z_g^f}\right)\left(1+\frac{d\Delta z_g(z_g^i)}{dz_g^i}\right)$$

$\frac{\Delta z_g}{z_g}$ large at small z_g, small at large z_g.

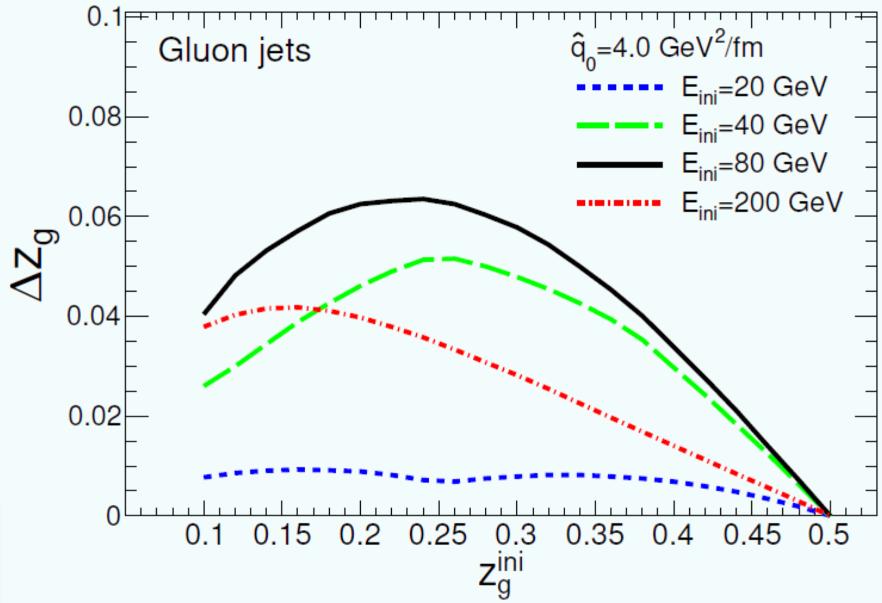
→ increases with z_g

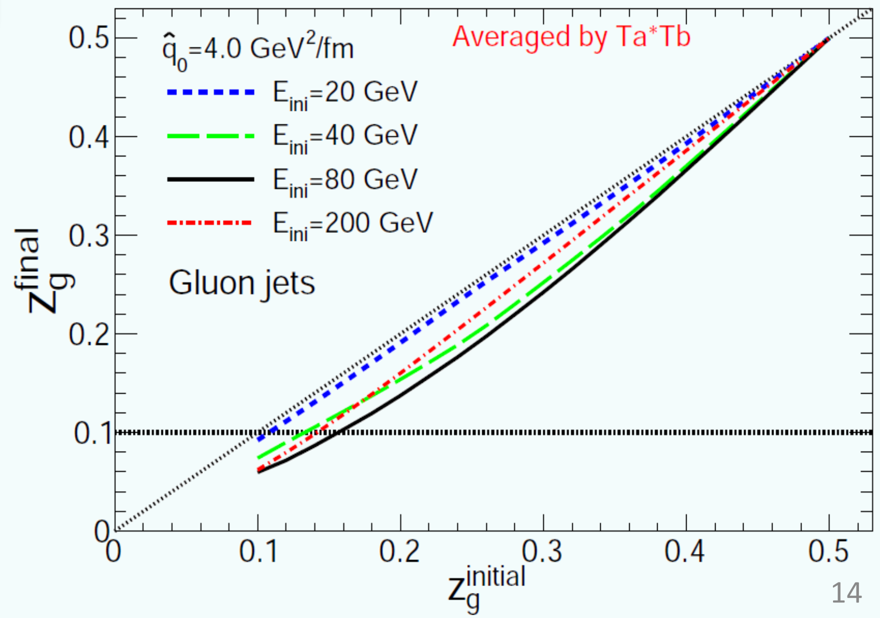
→ flattens $p(z_g)$

$\frac{d\Delta z_g}{dz_g}$ plus at small z_g, minus at large z_g.

→ decreases with z_g

→ steepens $p(z_g)$





Effect of the incoherent energy loss (IEL)

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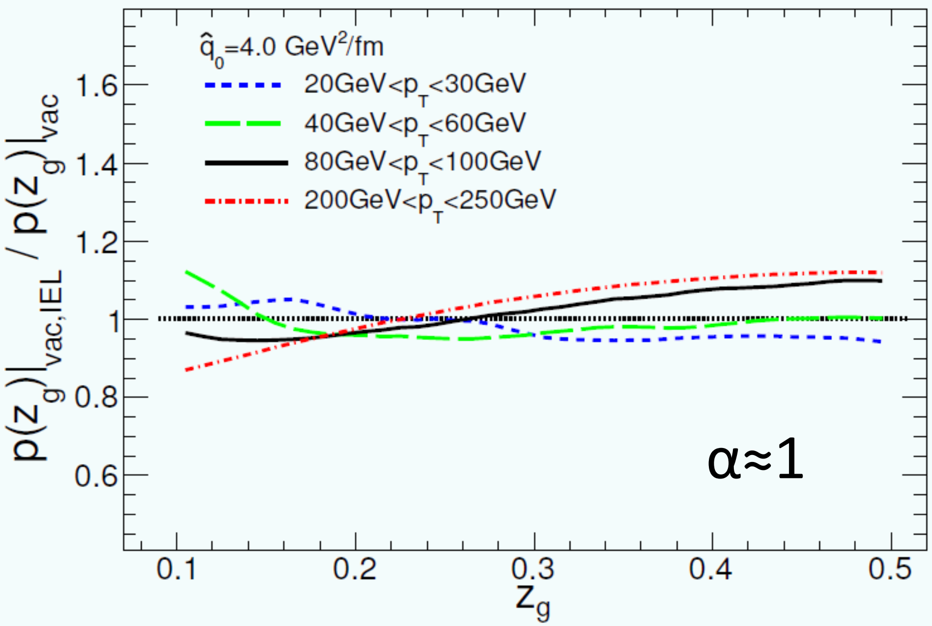
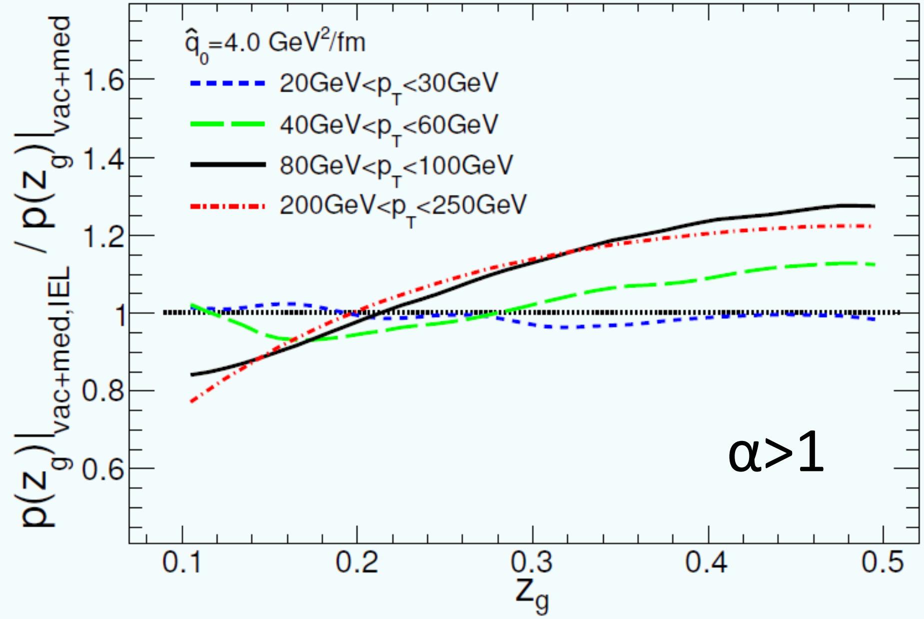
$$\frac{dN^f(z_g^f)}{dz_g^f} \approx \frac{1}{(z_g^f)^\alpha}\underline{\left(1 - \alpha\frac{\Delta z_g(z_g^i)}{z_g^f}\right)}\,\underline{\left(1 + \frac{d\Delta z_g(z_g^i)}{dz_g^i}\right)}$$

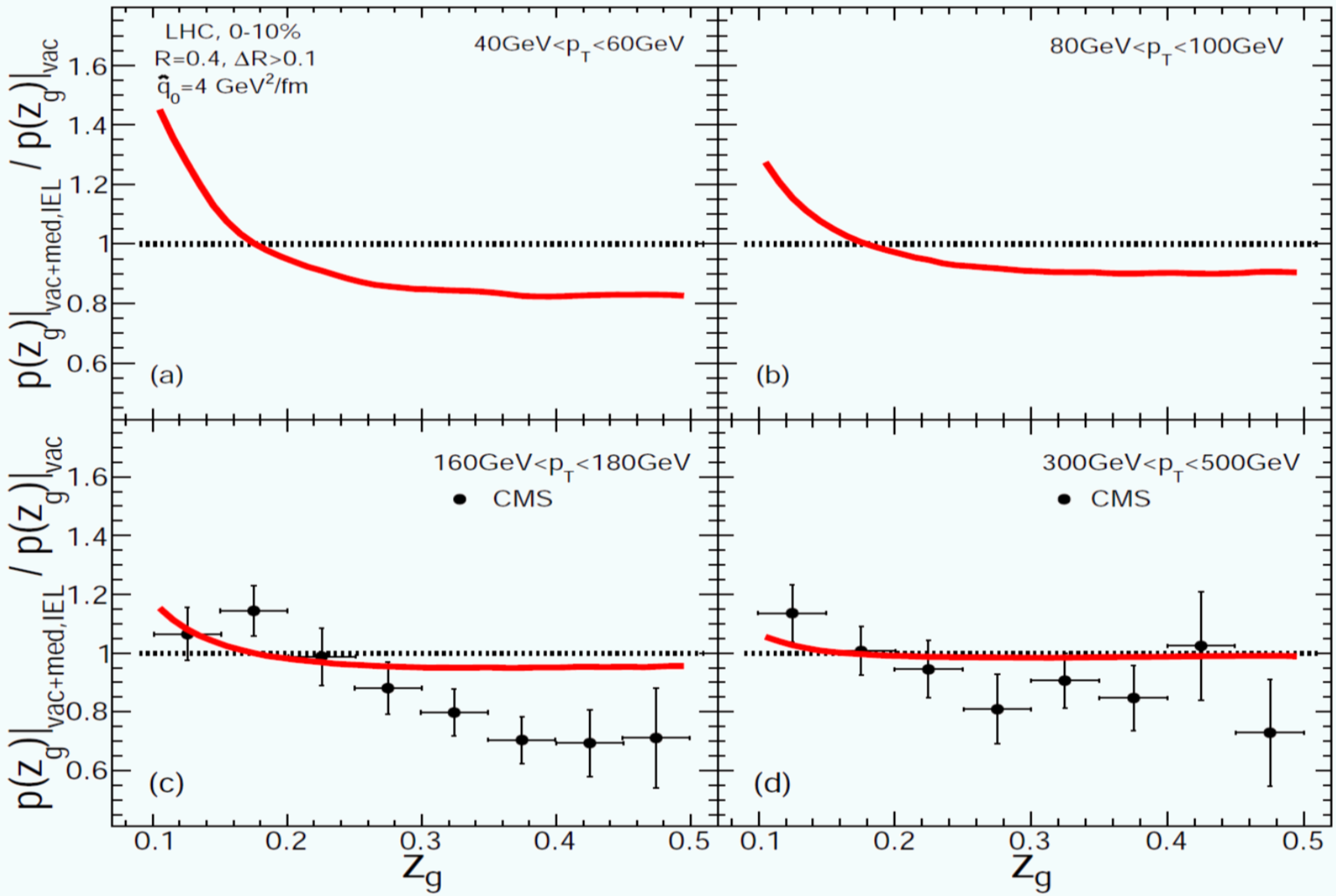
flattens $p(z_g)$ | steepens $p(z_g)$





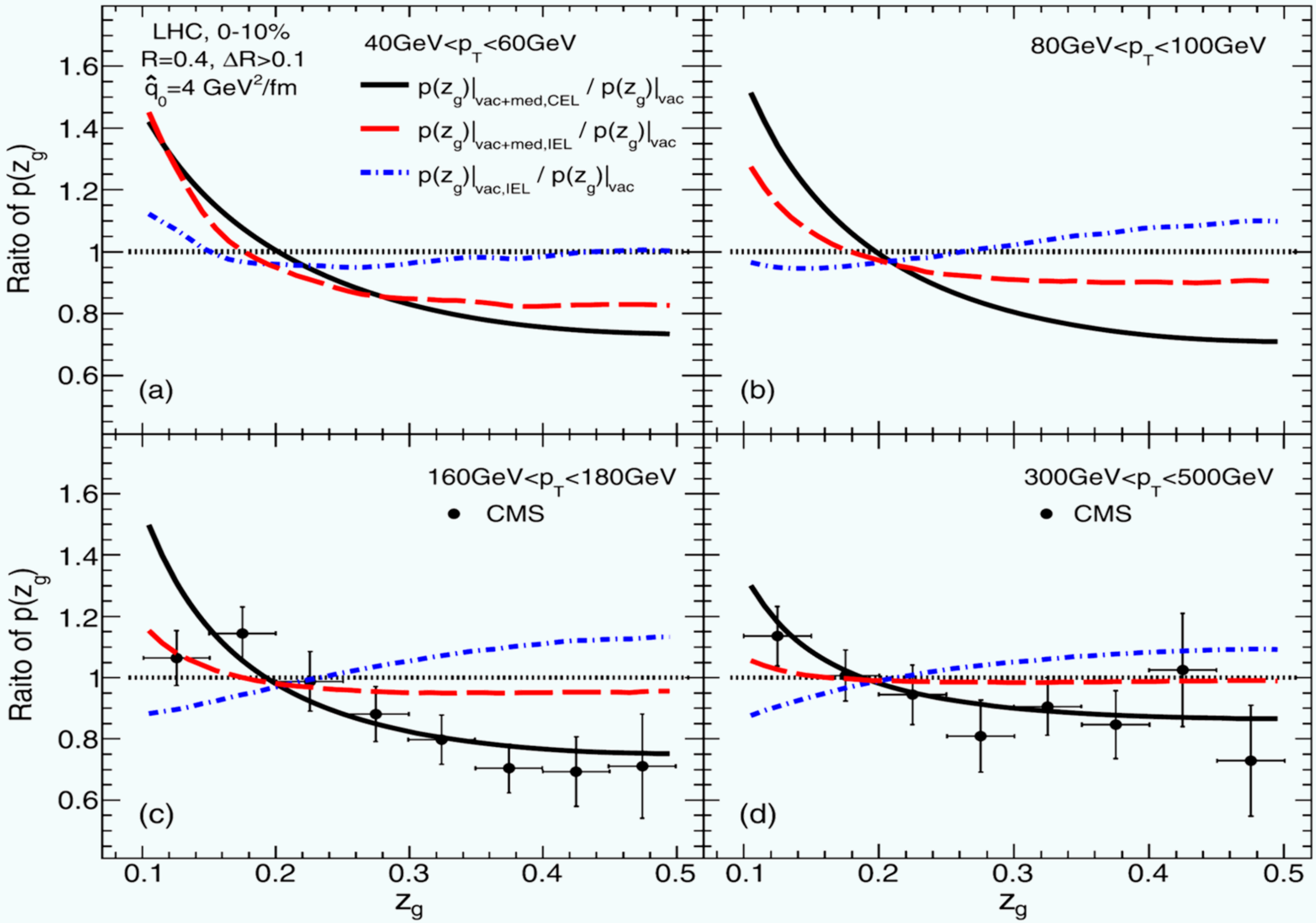
Flattening factor dominates, larger α, larger modification.

Effect of the incoherent energy loss (IEL)



With IEL, the non-monotonic jet p_T dependence disappears, and the CMS data can't be described.

Coherent vs. incoherent energy loss



Only CEL can describe current experimental data.

Summary and outlook

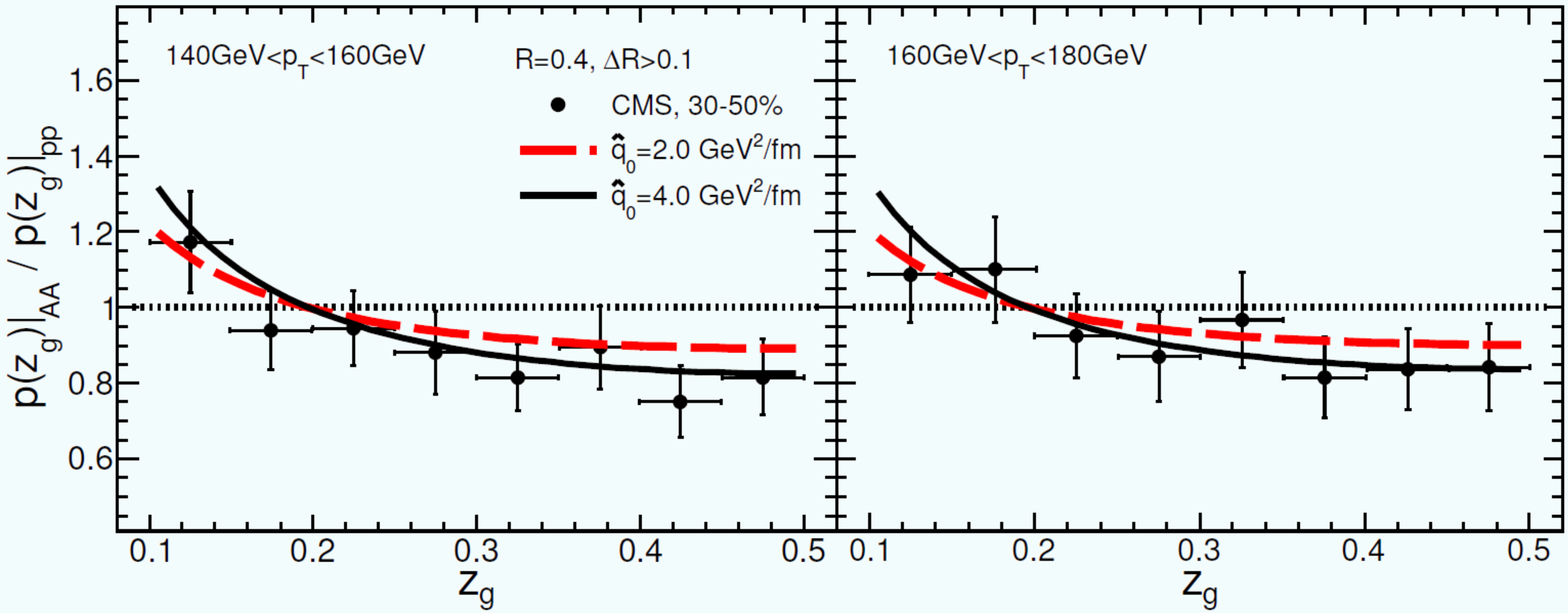
- We study the nuclear modification of groomed jet splitting function using higher-twist jet energy loss formula.
- Nuclear modification of jet splitting function depend on jet p_T non-monotonically.
- Within current kinematics, CMS and STAR data favor coherent energy loss picture.

➢ Further measurements with wider p_T range at RHIC and the LHC, and with varying angular separation and jet cone size can test our finding.

Thanks for your attention!

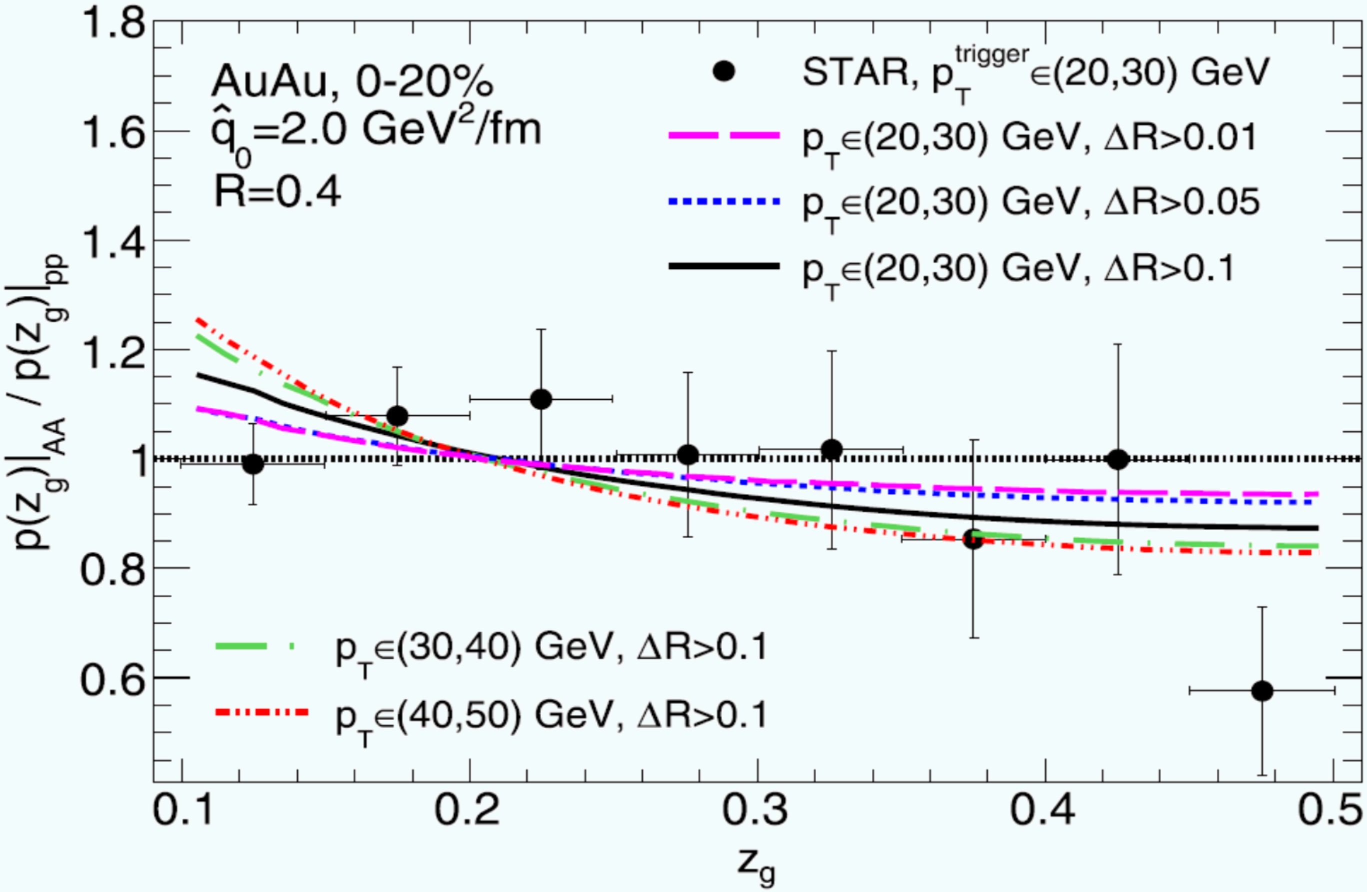
Backup

Comparison with CMS data of mid-central collision



$$R_{p(z_g)} = \frac{p(z_g)\ |_{\mathrm{AA}}}{p(z_g)\ |_{\mathrm{pp}}}$$

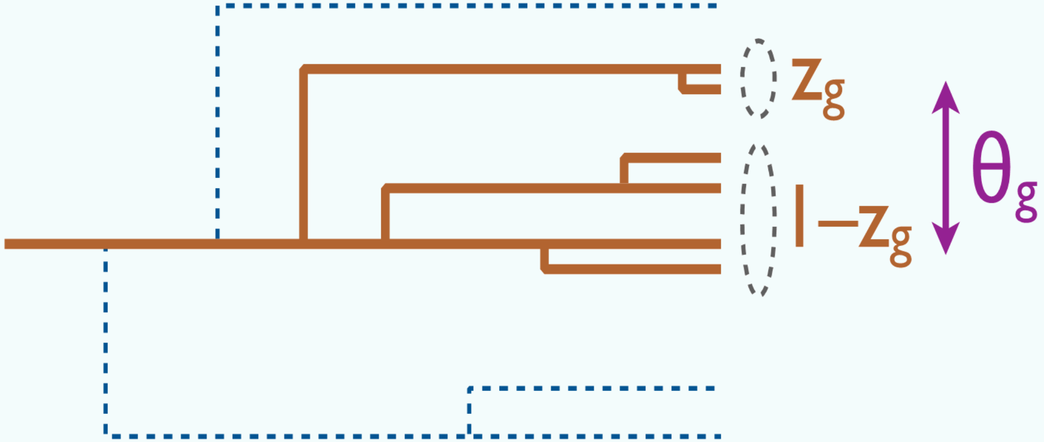
Comparison with STAR data



There are non-monotonic jet energy dependence both in experimental data and in theory!

$$
\begin{aligned}
\mathcal{P}^{vac}_{q\to qg} &= \frac{\alpha_s(\mu)}{\pi} C_F \frac{1+(1-x)^2}{x} \frac{1}{k_\perp}\,, \\
\mathcal{P}^{vac}_{q\to gq} &= \mathcal{P}^{vac}_{q\to qg}(x \to 1-x)\,, \\
\mathcal{P}^{vac}_{g\to q\bar{q}} &= \frac{\alpha_s(\mu)}{\pi} T_F n_f \left[x^2 + (1-x)^2\right] \frac{1}{k_\perp}\,, \\
\mathcal{P}^{vac}_{g\to gg} &= \frac{\alpha_s(\mu)}{\pi} C_A \left[\frac{1-x}{x} + \frac{x}{1-x} + x(1-x)\right] \frac{1}{k_\perp}
\end{aligned}
$$

$$
p(z_g) = \frac{1}{N_{\mathrm{evt}}} \frac{dN_{\mathrm{evt}}}{dz_g}
$$



Effect of the incoherent energy loss (IEL)

$$\frac{dN^f(z_g^f)}{dz_g^f} = \frac{1}{(z_g^i)^\alpha}\frac{dz_g^i}{dz_g^f} = \frac{1}{\left(z_g^f + \Delta z_g(z_g^i)\right)^\alpha}\frac{dz_g^i}{dz_g^f} \approx \underbrace{\frac{1}{(z_g^f)^\alpha}\left(1-\alpha\frac{\Delta z_g(z_g^i)}{z_g^f}\right)}_{} \underbrace{\frac{1}{1-\frac{d\Delta z_g(z_g^i)}{dz_g^i}}}_{}$$

z_g shift → increases with z_g → flattens $p(z_g)$

Jacobian → decreases with z_g → steepens $p(z_g)$