Probing medium-induced jet splitting and energy loss in heavy-ion collisions

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arXiv:1707.03767

Outline

- Motivation and Framework
- Non-monotonic jet energy dependence of the nuclear modification to jet splitting function
- Effect of coherent vs. incoherent energy loss
- Summary and Outlook

Why to study groomed jet substructures

- Theory calculations (e.g. higher twist) provides medium-modified splitting functions in heavy-ion collisions
- Phenomenological studies [JETSCAPE talk on Wednesday] put these splitting functions in either ***DGLAP evolution equation*** or ***rate equation of transport models*** and calculate R_{AA}, v_2 etc and compare to data.

DGLAP evolution for parton fragmentation function:

$$\frac{\partial}{\partial Q^2} D(z, Q^2) = \frac{\alpha_s}{2\pi} \frac{1}{Q^2} \int_z^1 \frac{dy}{y} P(y) D\left(\frac{z}{y}, Q^2\right)$$

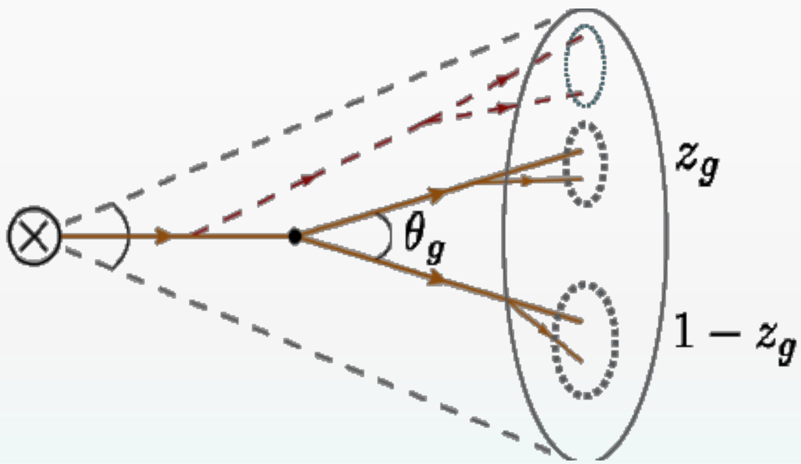
Transport model (scattering rate):

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

- **Indirect test** of theory calculation of the splitting functions.

Softdrop jet grooming algorithm

Anti-k_T jet is clustered with Cambridge/Aachen (CA)
Then decluster the angular-ordered CA tree
Drop soft branches

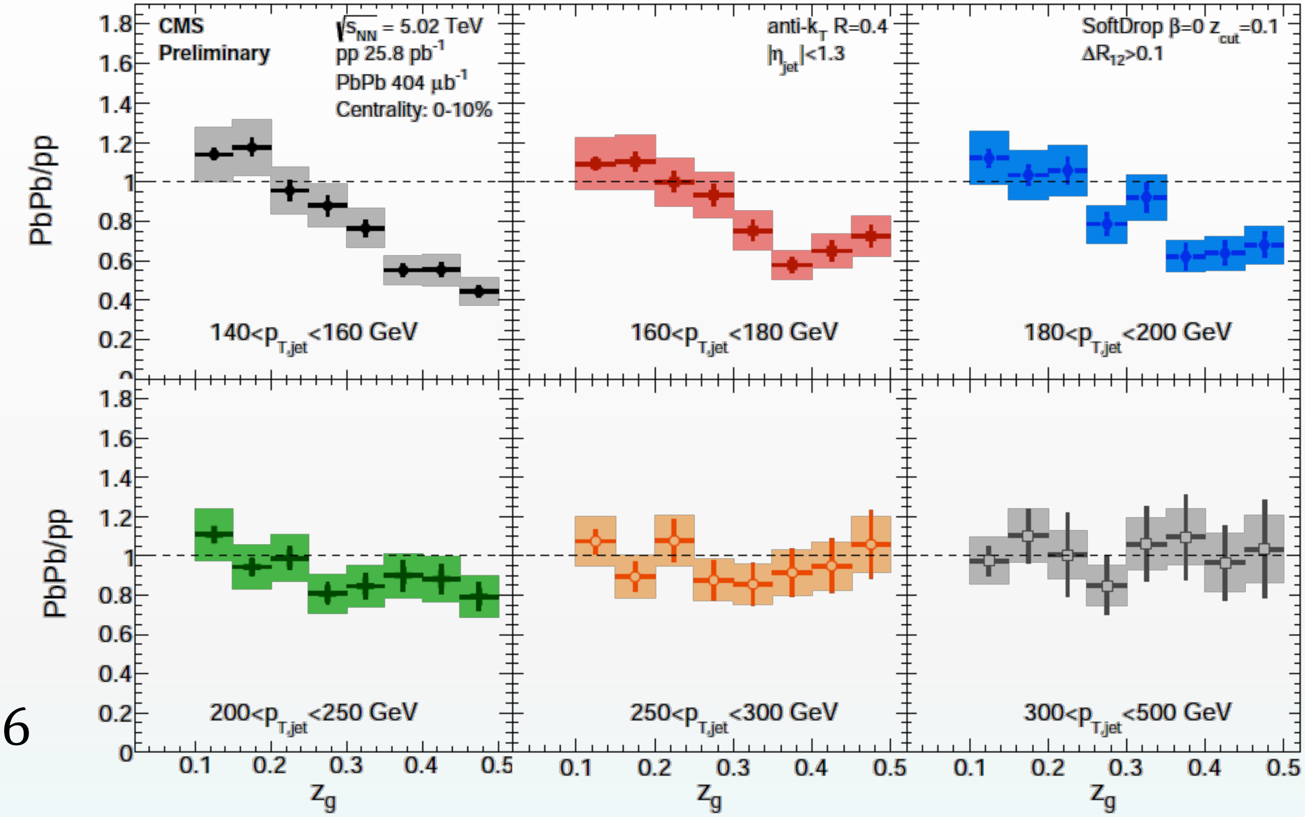


$$\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \equiv z_g > z_{\mathrm{cut}} \left(\frac{\Delta R}{R}\right)^{\beta}$$

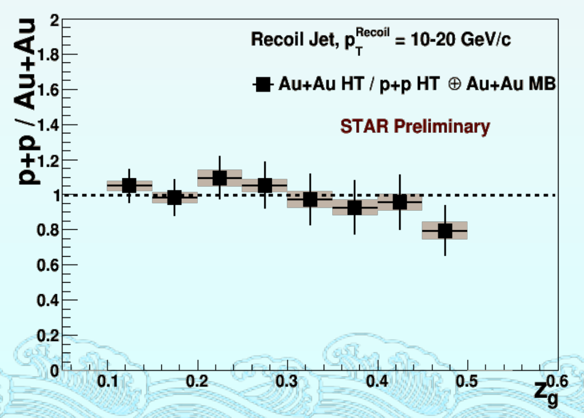
Larkoski, Marzani, Thaler, Phys. Rev. D91,111501 (2015)
Soft Drop: JHEP 1405 (2014) 146

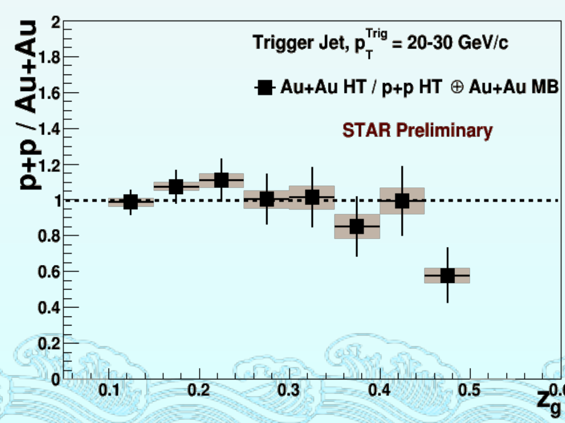
"Puzzle" in CMS vs. STAR measurements

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



CMS-PAS-HIN-16-006





Kolja Kauder for STAR
arXiv:1703.10933

Framework of theoretical calculation

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

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

Larkoski, Marzani, Thaler, Phys. Rev. D91,111501 (2015); Y.-T. Chien and I. Vitev arXiv:1608.07283

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

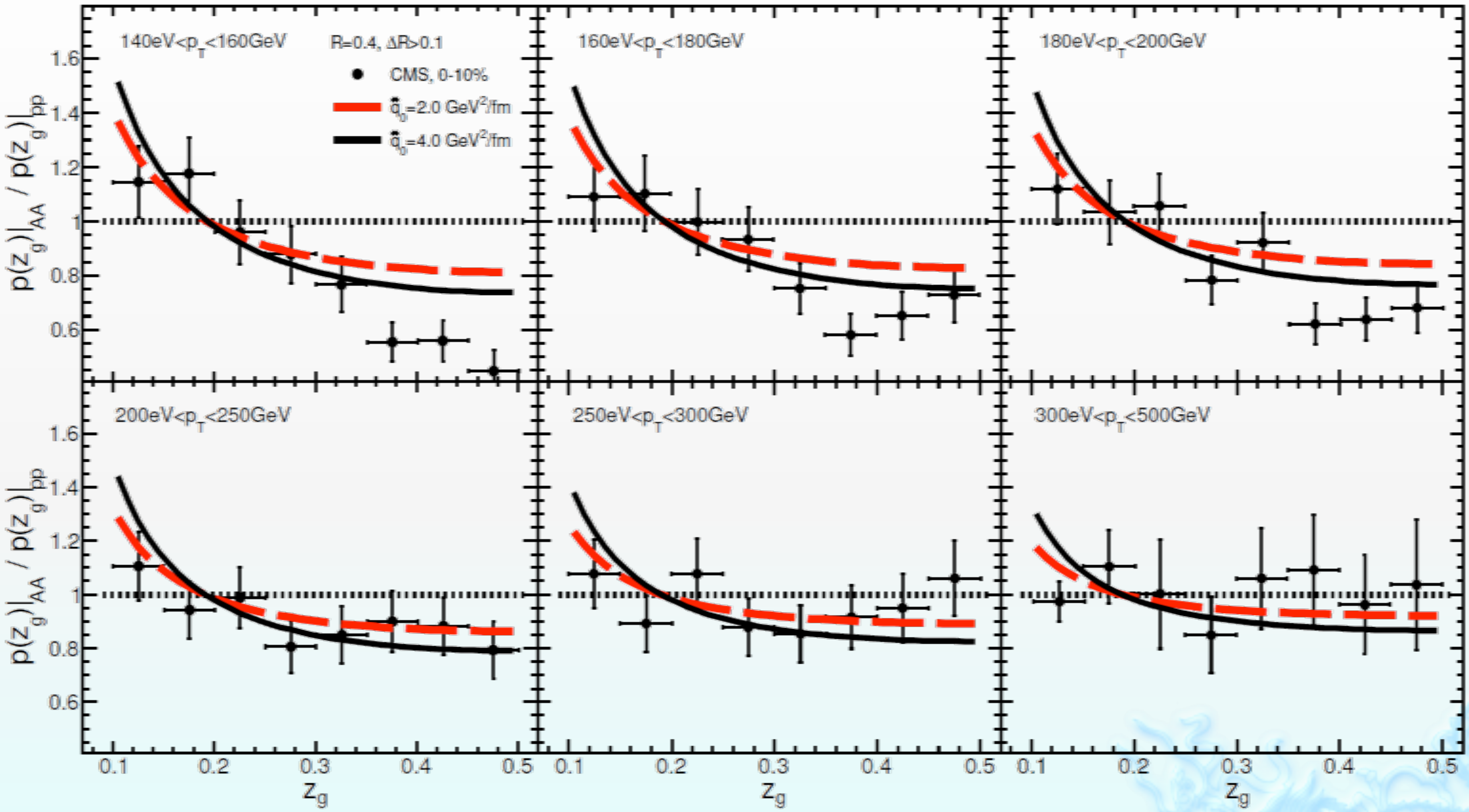
$$P_i^{\rm med}(x, k_\perp^2) = \frac{2\alpha_s}{\pi k_\perp^4} P_i^{\rm vac}(x) \int d\tau \hat{q}_g(\tau) \sin^2\left(\frac{\tau}{2\tau_f}\right)$$

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

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

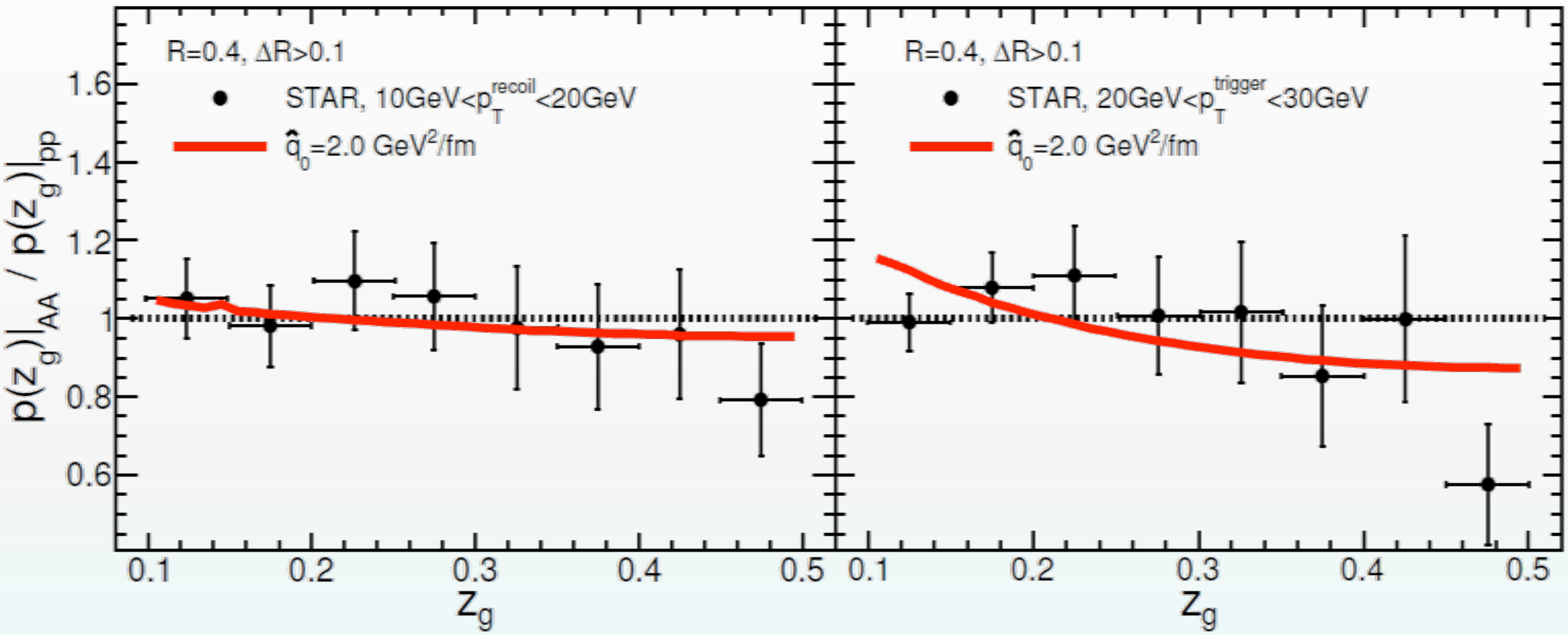
$$\Delta E = \int dx dk_\perp^2 (xE) \overline{P}^{\rm med}(x, k_\perp^2) \theta(\frac{1}{2} - x) \theta(k_\perp - k_R)$$

Comparison with CMS data



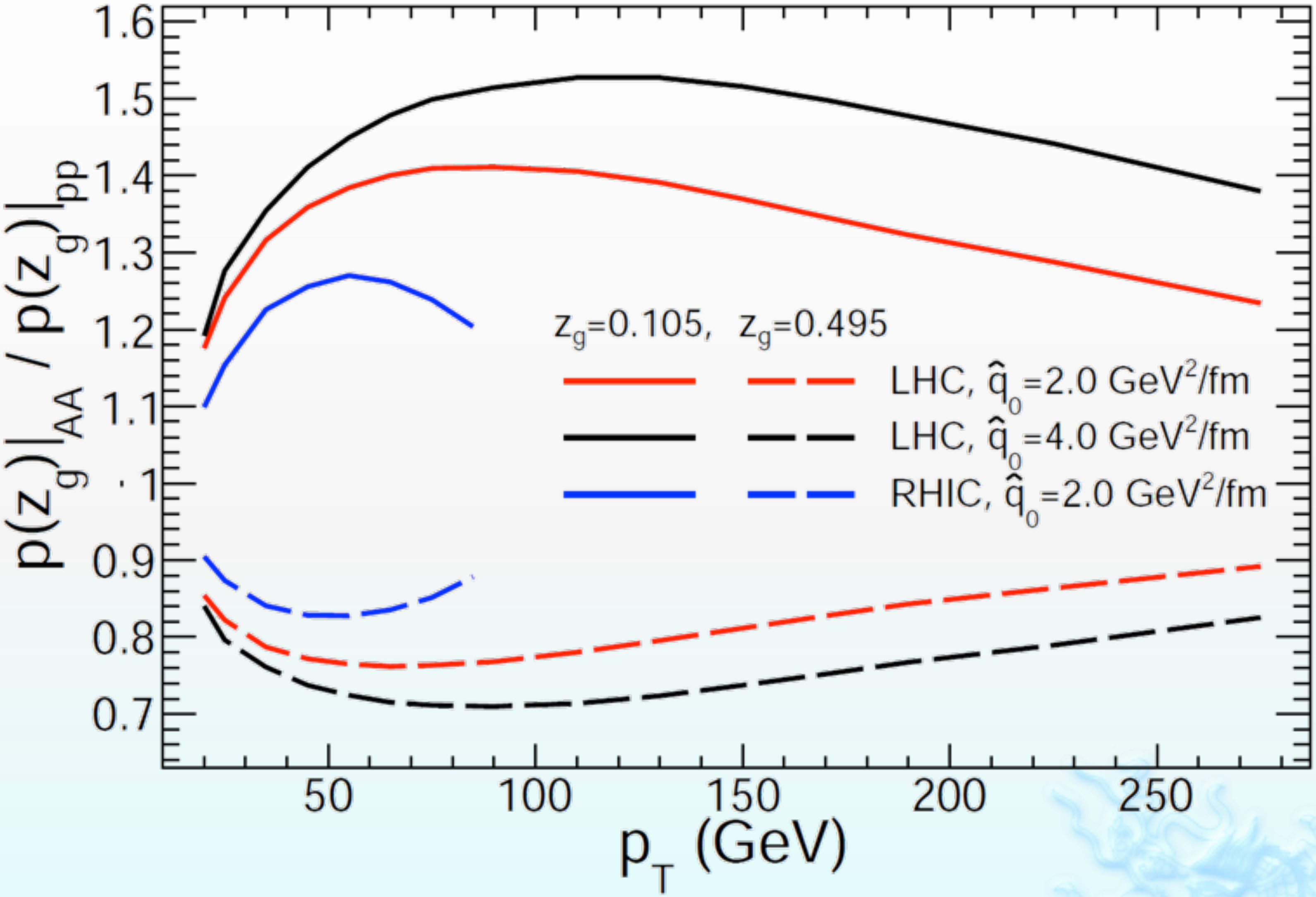
$$R_{p(z_g)} = \frac{p(z_g)\ |_{\mathrm{AA}}}{p(z_g)\ |_{\mathrm{pp}}}$$

Comparison with STAR data



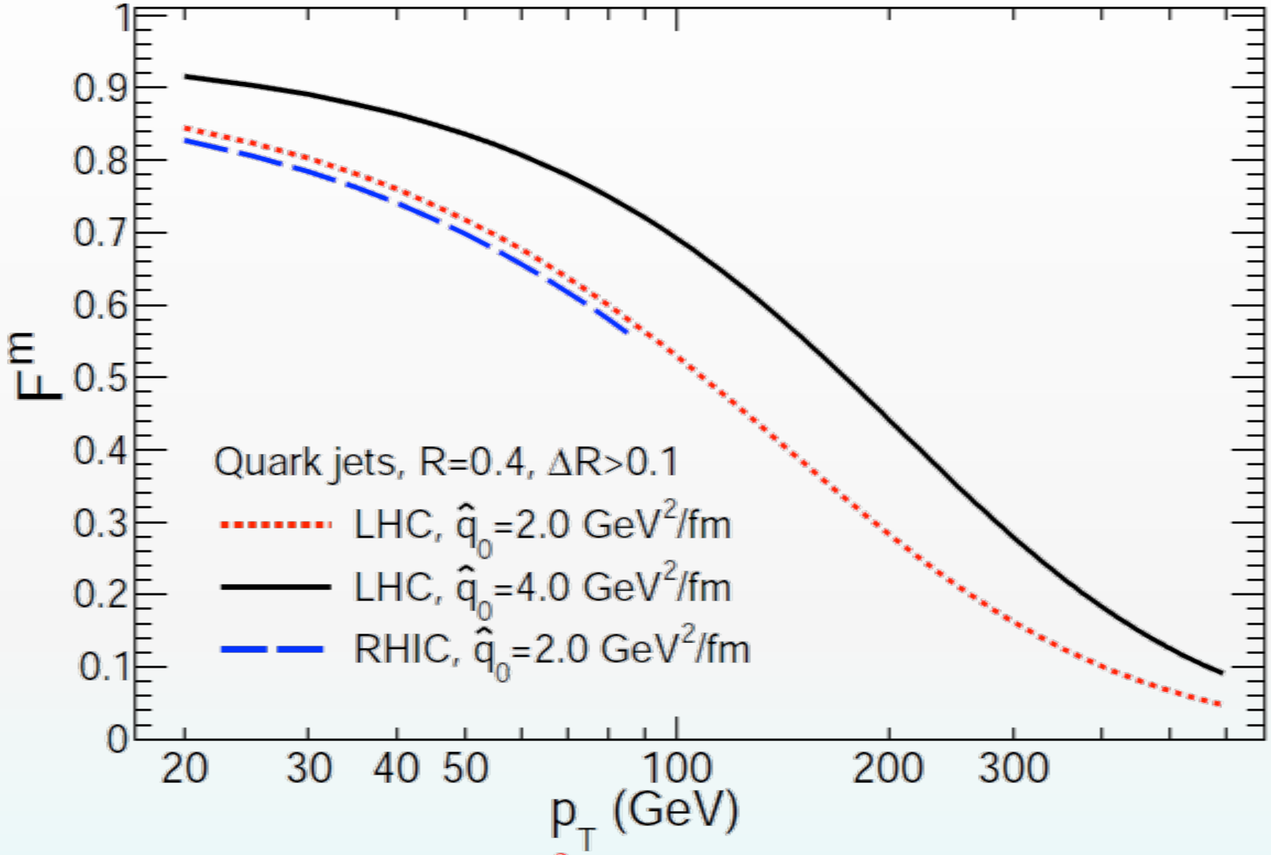
There are non-monotonic jet energy dependence both in experimental data and in theory!

Prediction of the energy dependence



Endpoints of the nuclear modification factor.

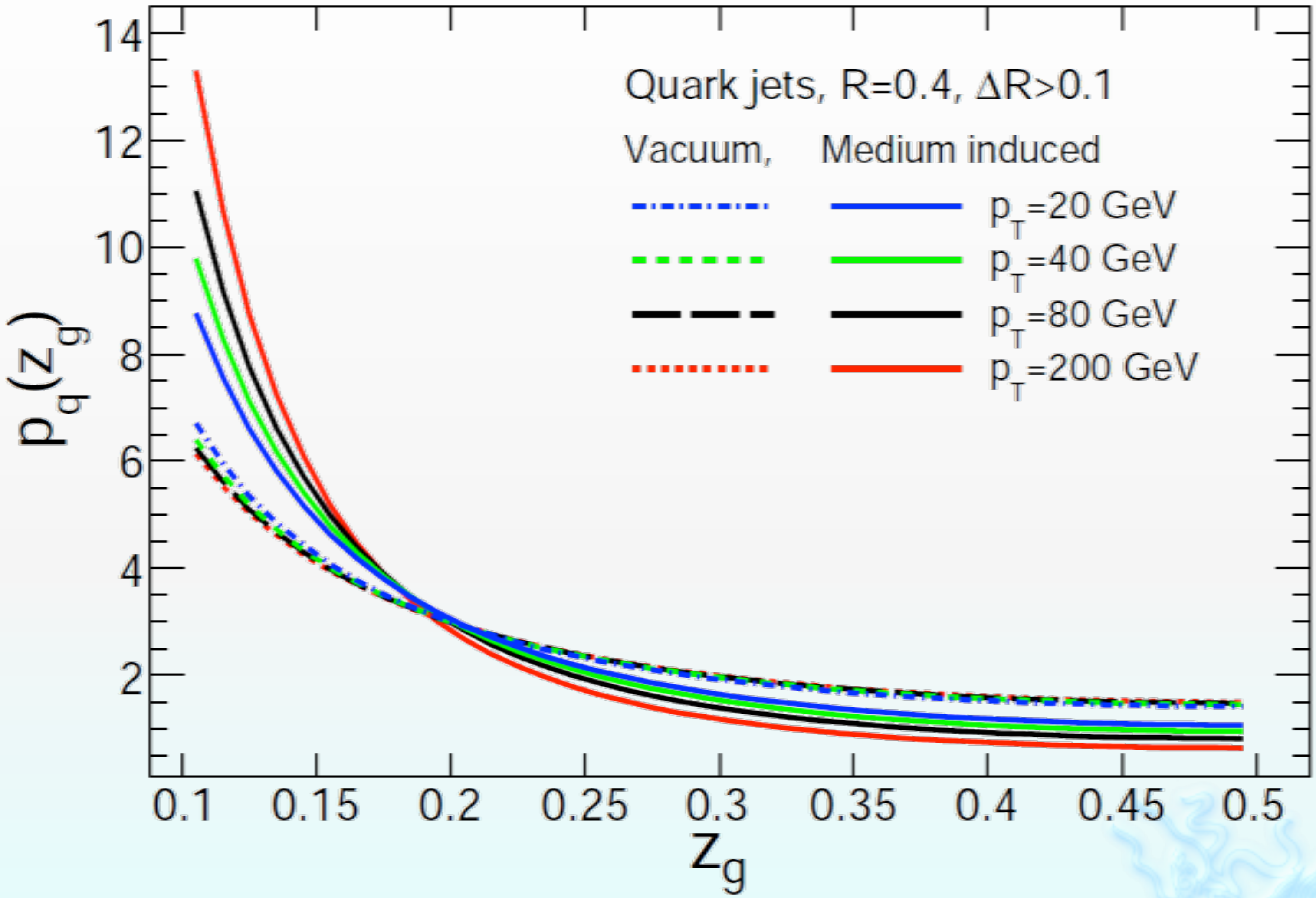
Source of the Non-monotonic behavior: I



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

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

Source of the Non-monotonic behavior: II



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

Probing coherent vs. incoherent energy loss of subjets

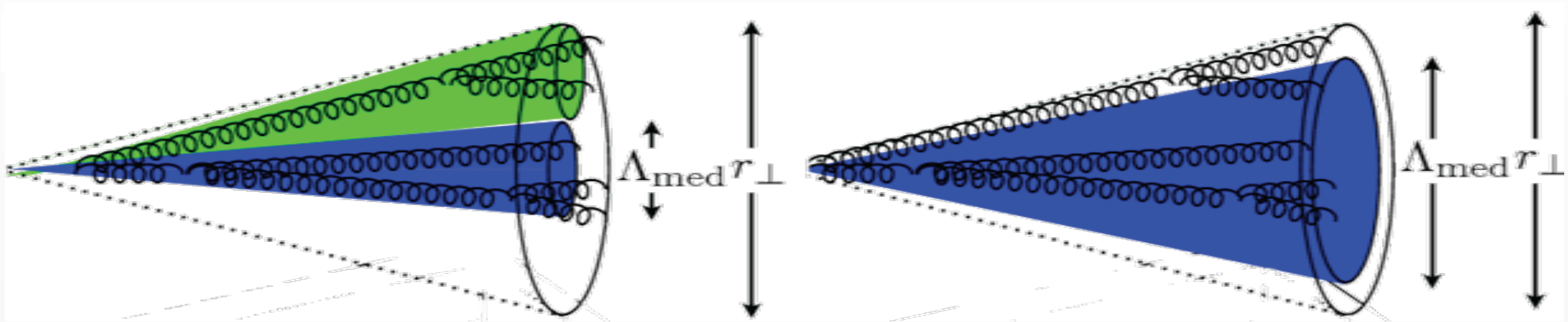


Figure taken from *Phys. Lett. B* ***725*** (2013) 357–360

Transverse separation:

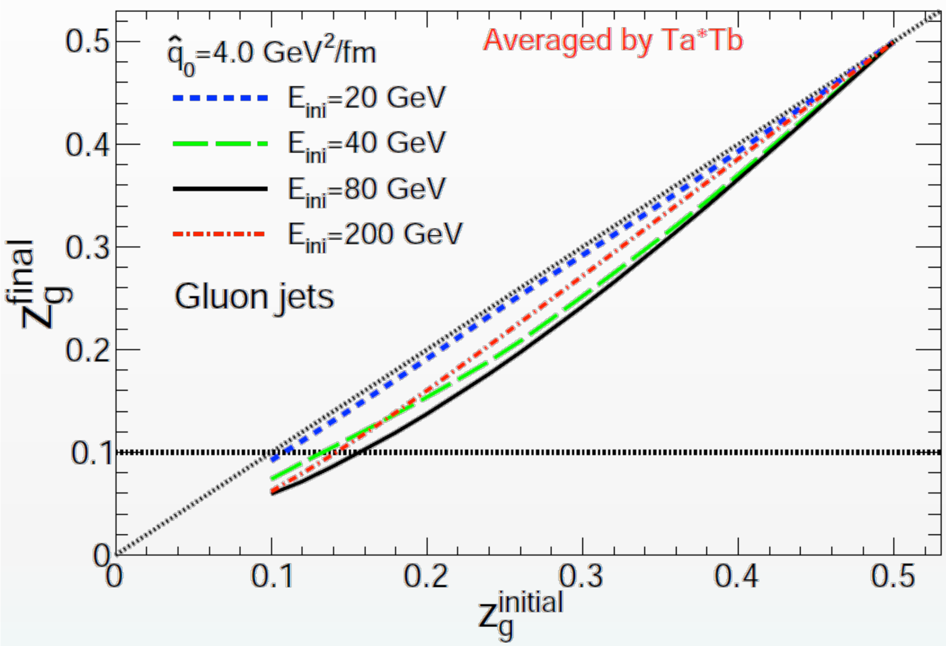
$$r_\perp = \theta\tau_f = \theta\frac{2Ex(1-x)}{k_\perp^2} = \theta\frac{1}{2Ex(1-x)tan(\frac{\theta}{2})^2}$$

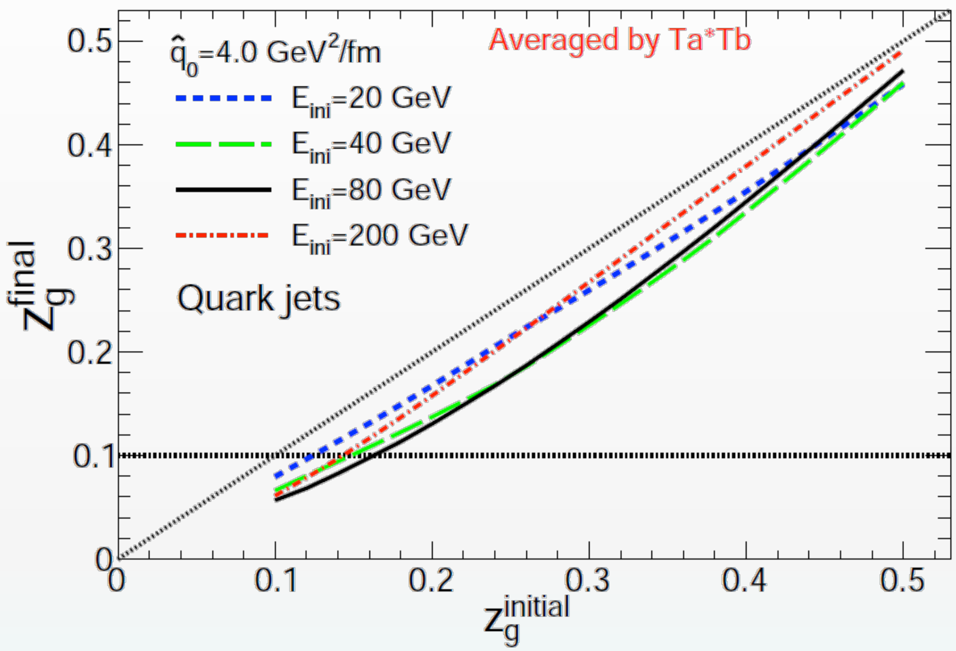
Transverse wavelength:

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

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

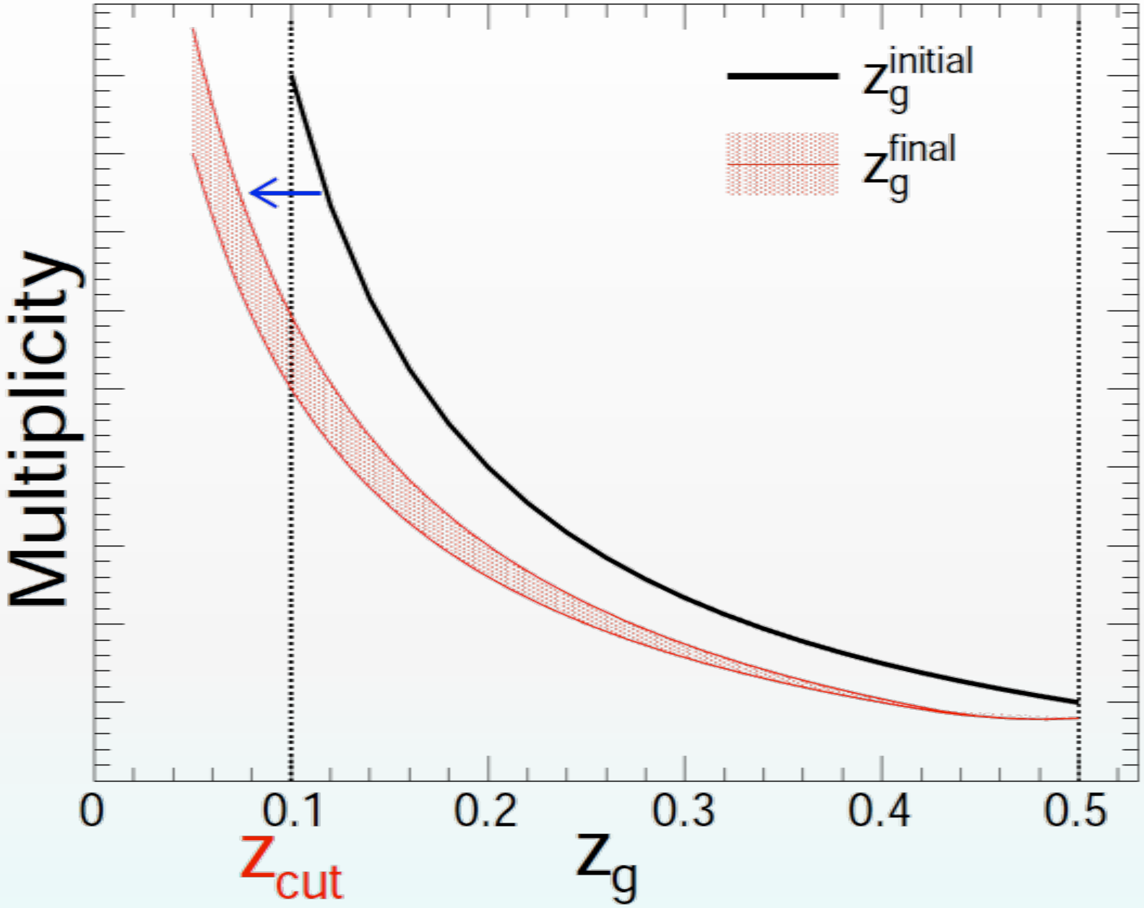
Effect of the incoherent energy loss





- Within HT, parton with larger energy loses smaller fractional energy through the medium.
- Z_g shifts to smaller value due to subjets incoherent energy loss.

Effect of the incoherent energy loss

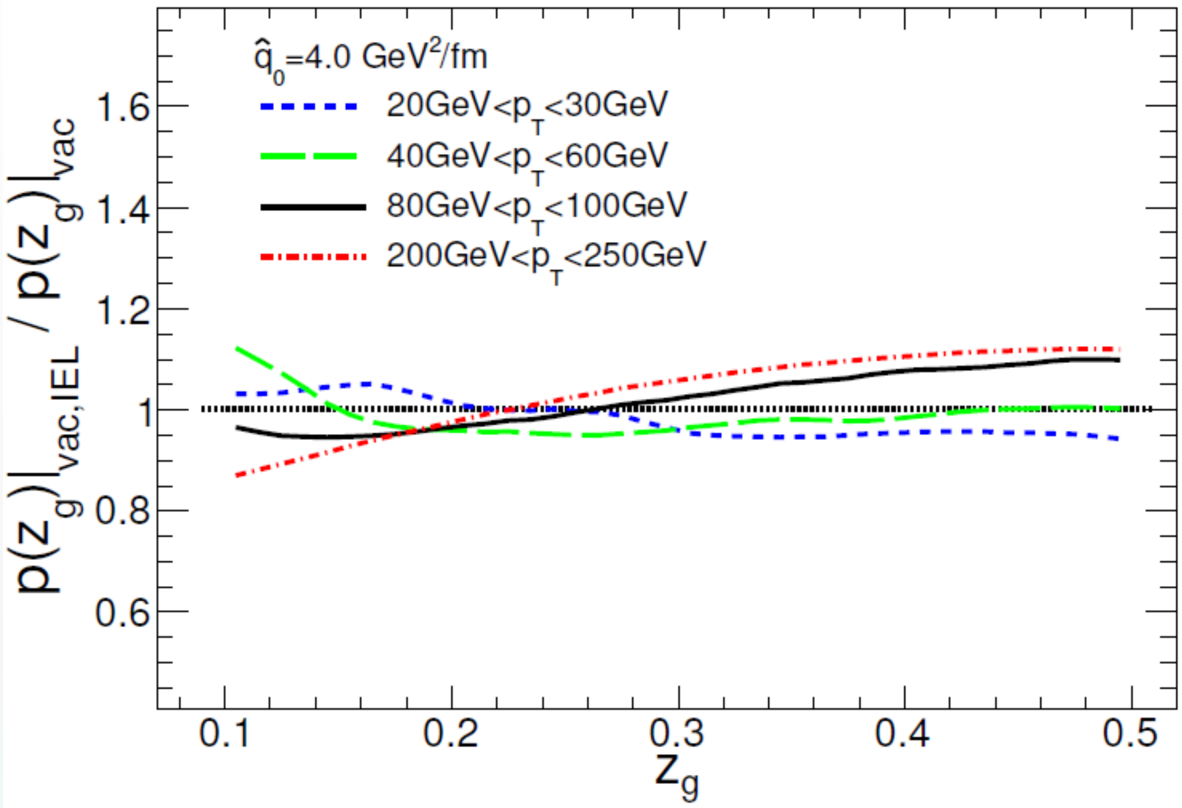


The z_g distribution is always self-normalized.

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

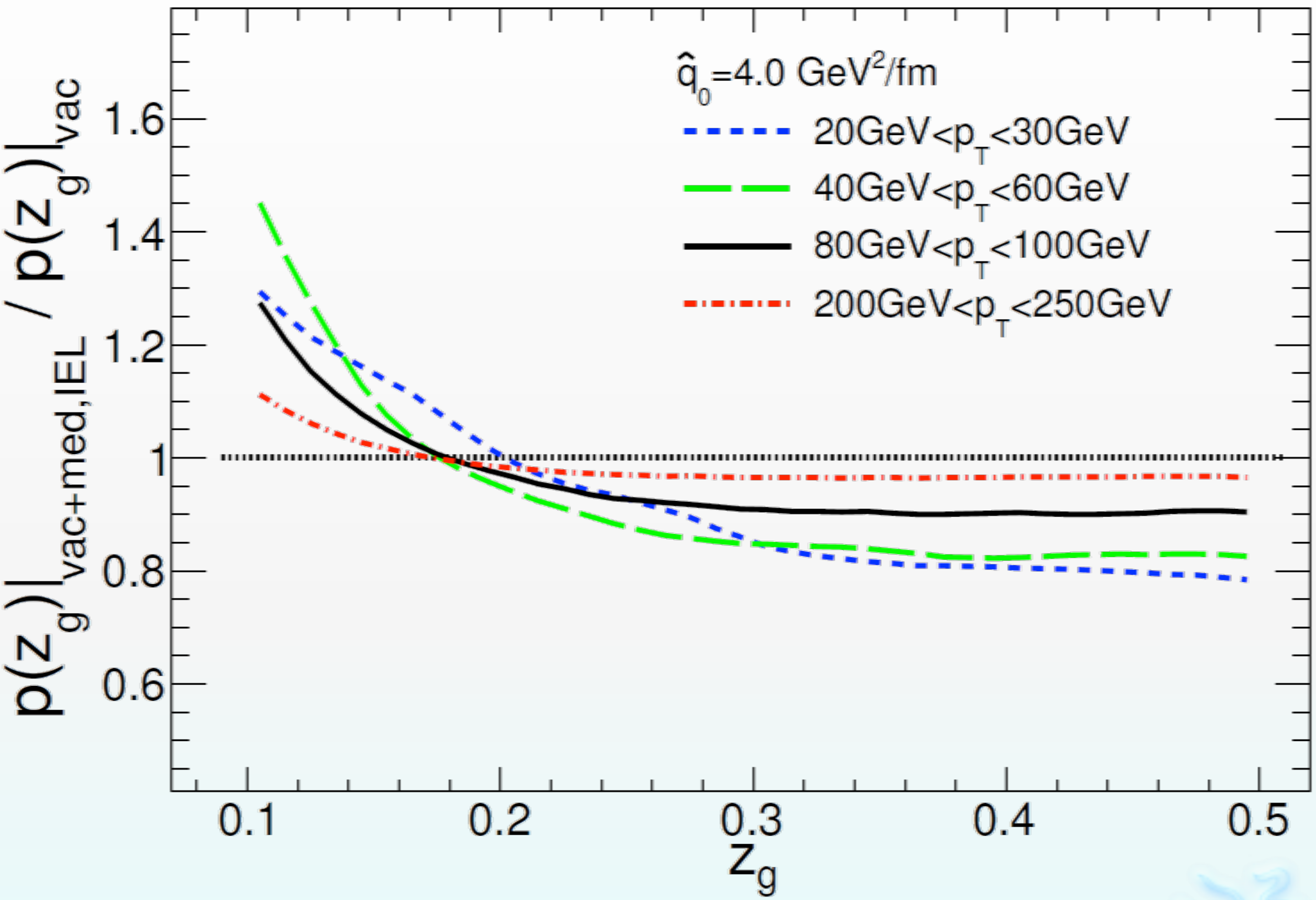
Z_g shifts to smaller value due to subjets incoherent energy loss. But $p(Z_g)$ at small Z_g is not necessarily enhanced. The shape of $p(Z_g)$ can be flattened instead.

Effect of the incoherent eLoss on vac P(z)



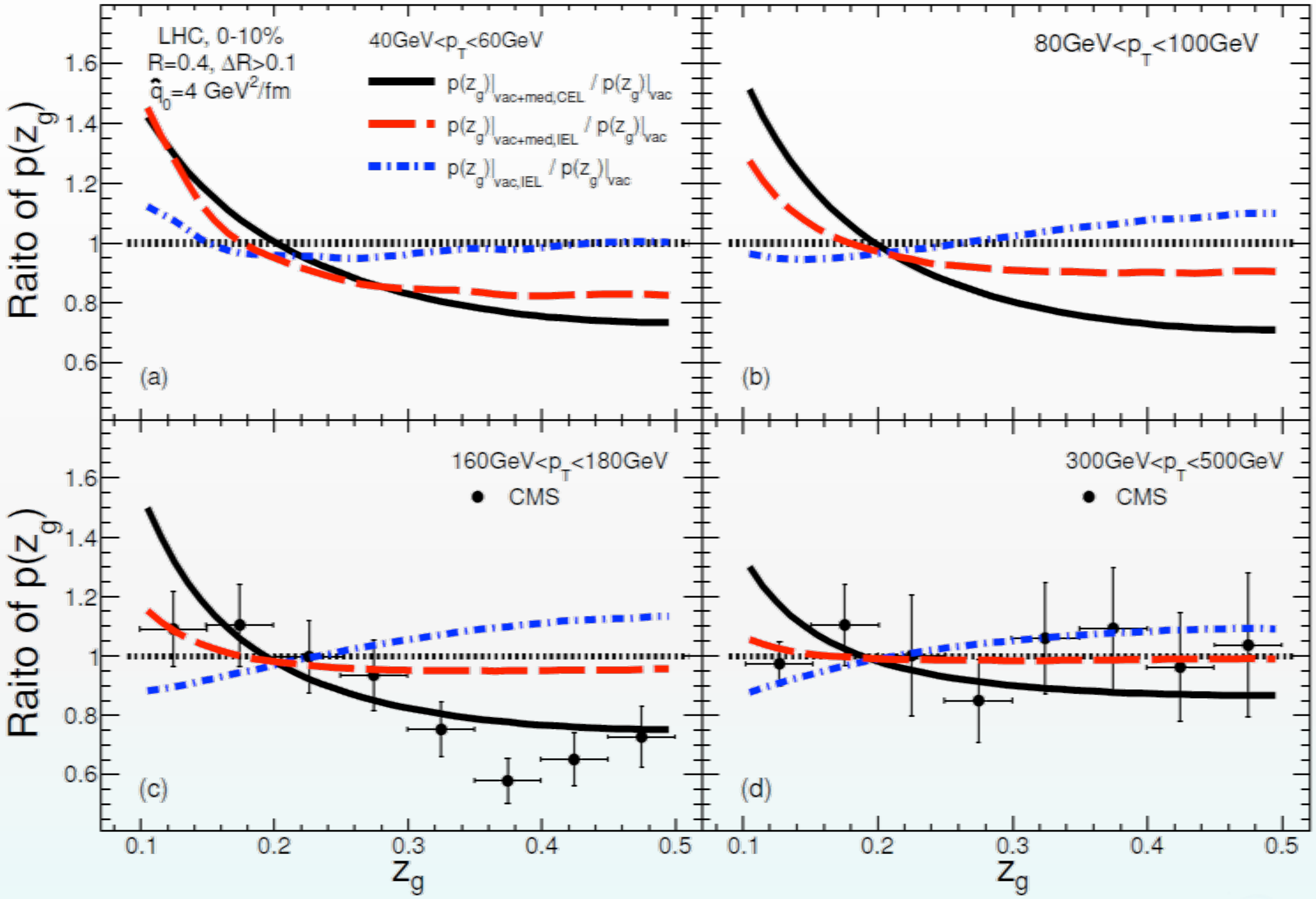
Applying IEL effect (z_g shift effect) on the pure vacuum splitting function leads to an enhancement of the medium modification factor at large z_g.

Effect of the incoherent energy loss



Applying IEL on medium-modified splitting, the non-monotonic behavior disappears .

Effect of the incoherent energy loss



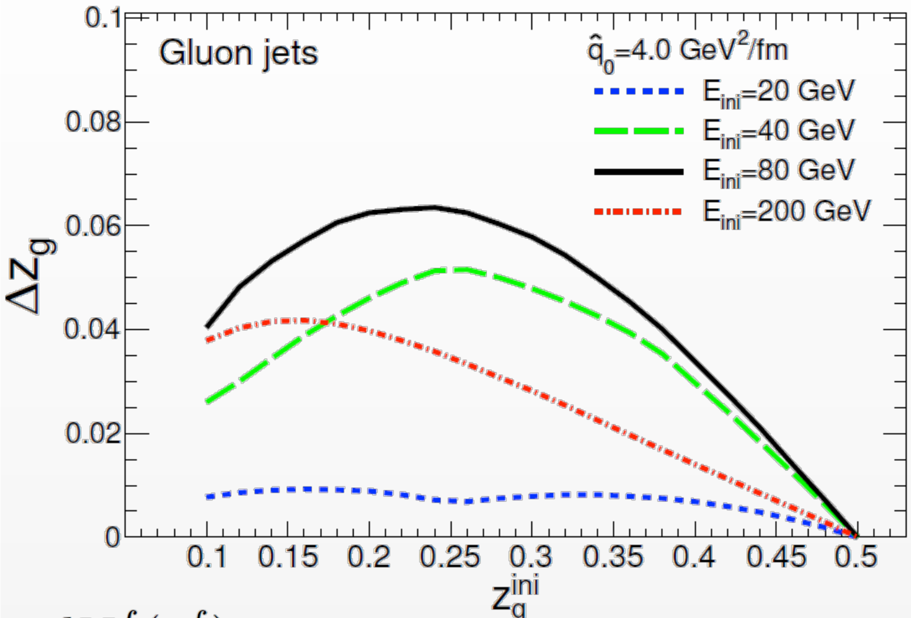
- Experimental data favor the CEL picture.
- One should interpret this conclusion with care: IEL vs. CEL depends on the jet energy, and the choice of R and ΔR.

Summary and outlook

- Two factors of the medium induced splitting function render the non-monotonic nuclear modification to the groomed jet splitting function.
- Measurements with wider p_T range at RHIC and the LHC can test our finding.
- CMS and STAR data favor coherent energy loss picture (within current kinematics)
- Measurements with varying the jet cone size and the angular separation between the two subjets can detect the effect of incoherent energy loss.

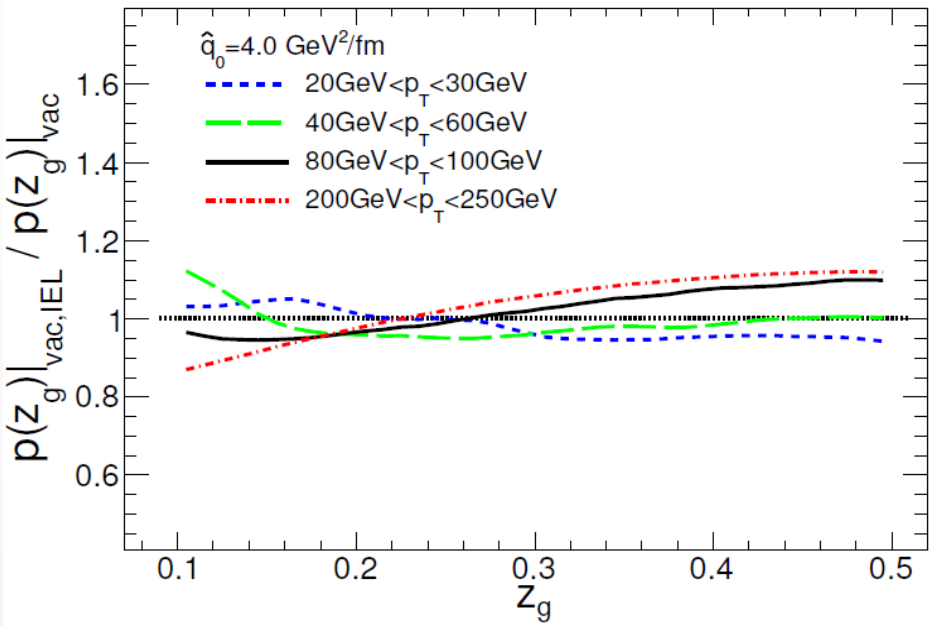
Backup

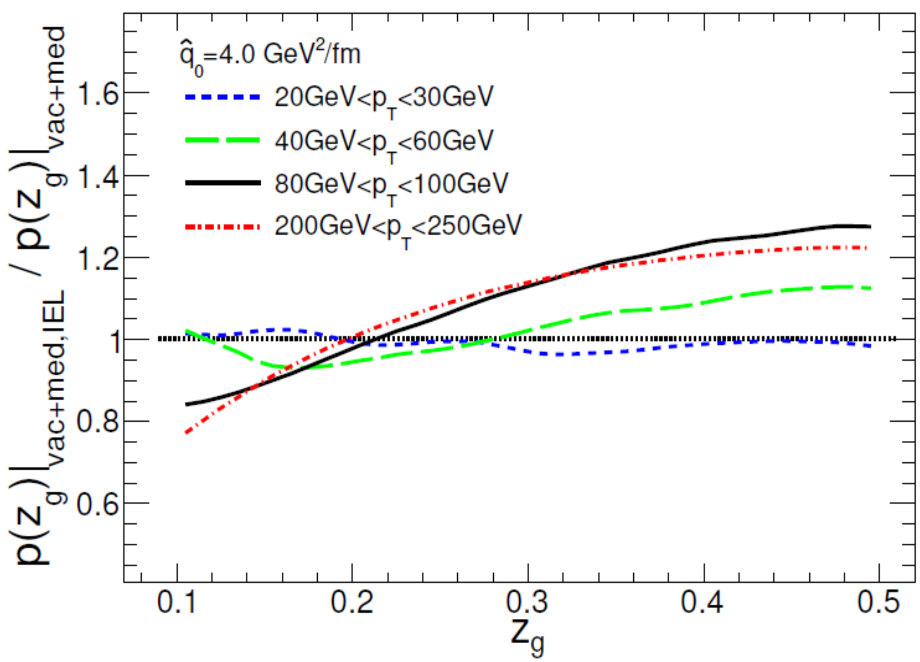
Effect of the incoherent energy loss



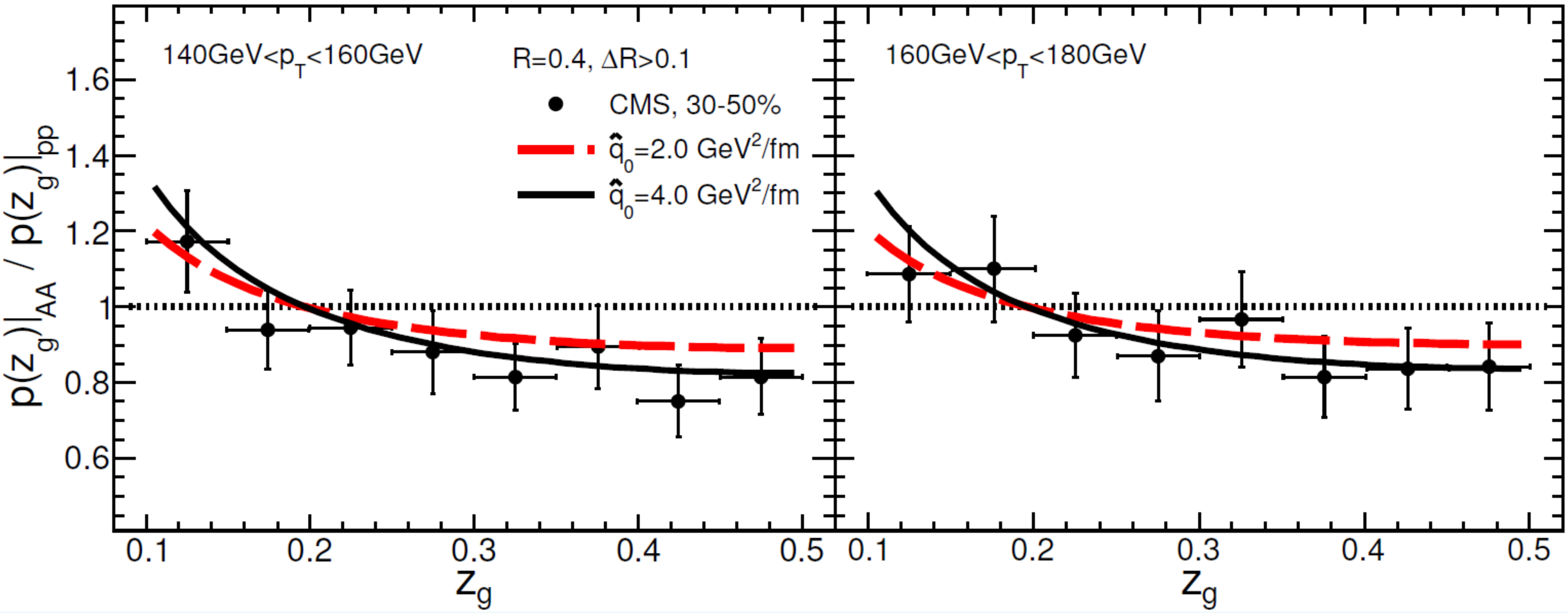
$$\frac{dN^f(z_g^f)}{dz_g^f} = \frac{1}{(z_g^i)^\alpha}\frac{dz_g^i}{dz_g^f}\, p(Zg) = \frac{1}{\left(z_g^f + \Delta z_g(z_g^i)\right)^\alpha}\frac{dz_g^i}{dz_g^f} \approx \frac{1}{(z_g^f)^\alpha}\left(1 - \alpha\frac{\Delta z_g(z_g^i)}{z_g^f}\right)\frac{1}{1 - \frac{d\Delta z_g(z_g^i)}{dz_g^i}}$$

Zg shift flattens p(Zg), Jacobian steepens





Comparison with CMS data of mid-central collision



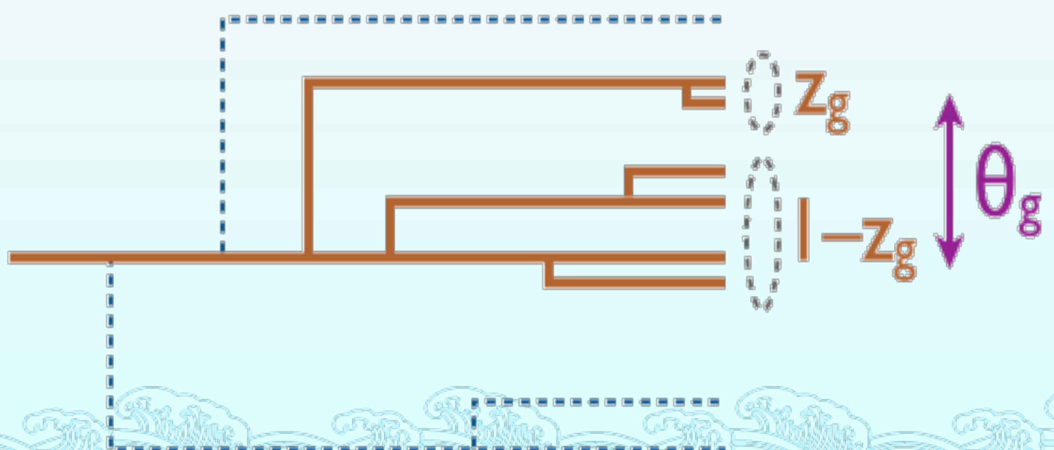
$$\mathcal{P}^{vac}_{q\to qg} = \frac{\alpha_s(\mu)}{\pi} C_F \frac{1+(1-x)^2}{x} \frac{1}{k_\perp},$$

$$\mathcal{P}^{vac}_{q\to gq} = \mathcal{P}^{vac}_{q\to qg}(x \to 1-x),$$

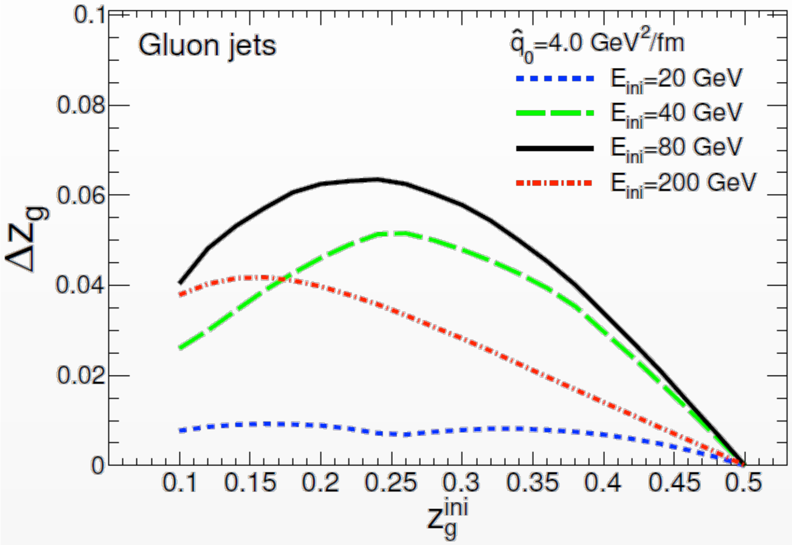
$$\mathcal{P}^{vac}_{g\to q\bar{q}} = \frac{\alpha_s(\mu)}{\pi} T_F n_f \left[x^2 + (1-x)^2\right] \frac{1}{k_\perp},$$

$$\mathcal{P}^{vac}_{g\to gg} = \frac{\alpha_s(\mu)}{\pi} C_A \left[\frac{1-x}{x} + \frac{x}{1-x} + x(1-x)\right] \frac{1}{k_\perp}$$

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



Effect of the incoherent energy loss



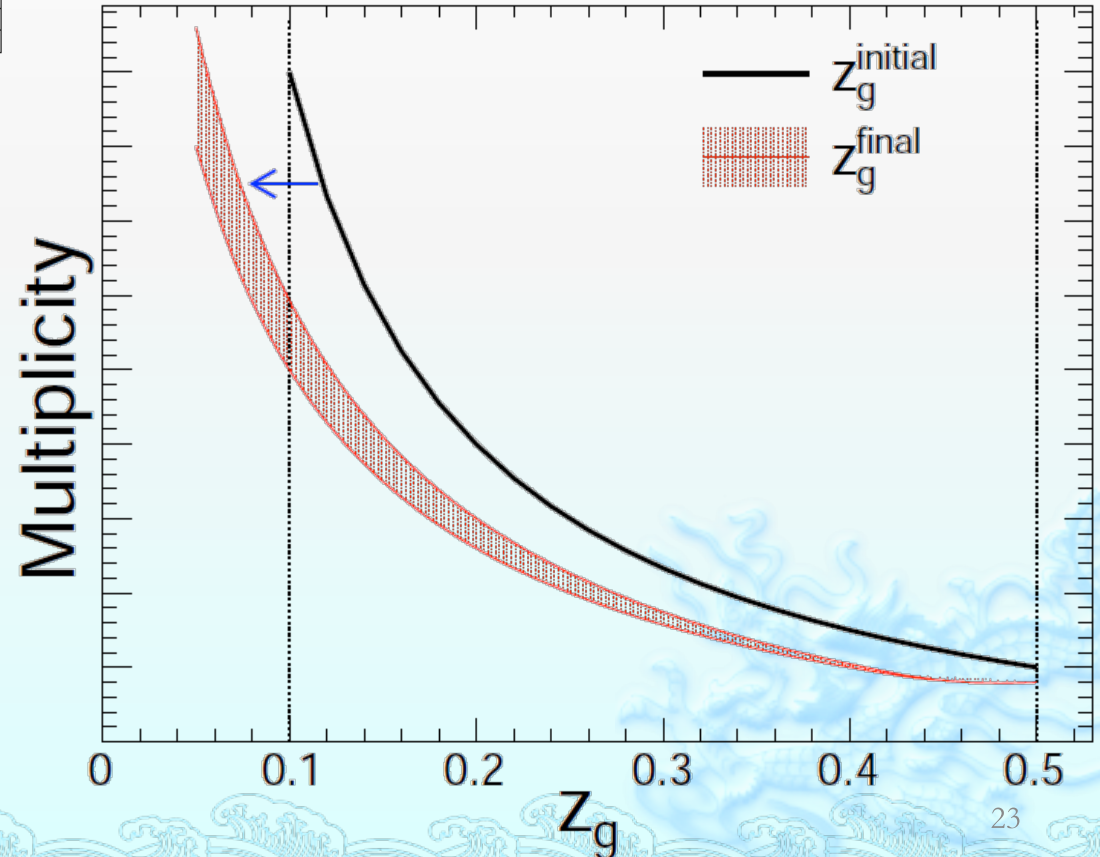
Zg shift flattens p(Zg),
Jacobian steepens p(Zg)

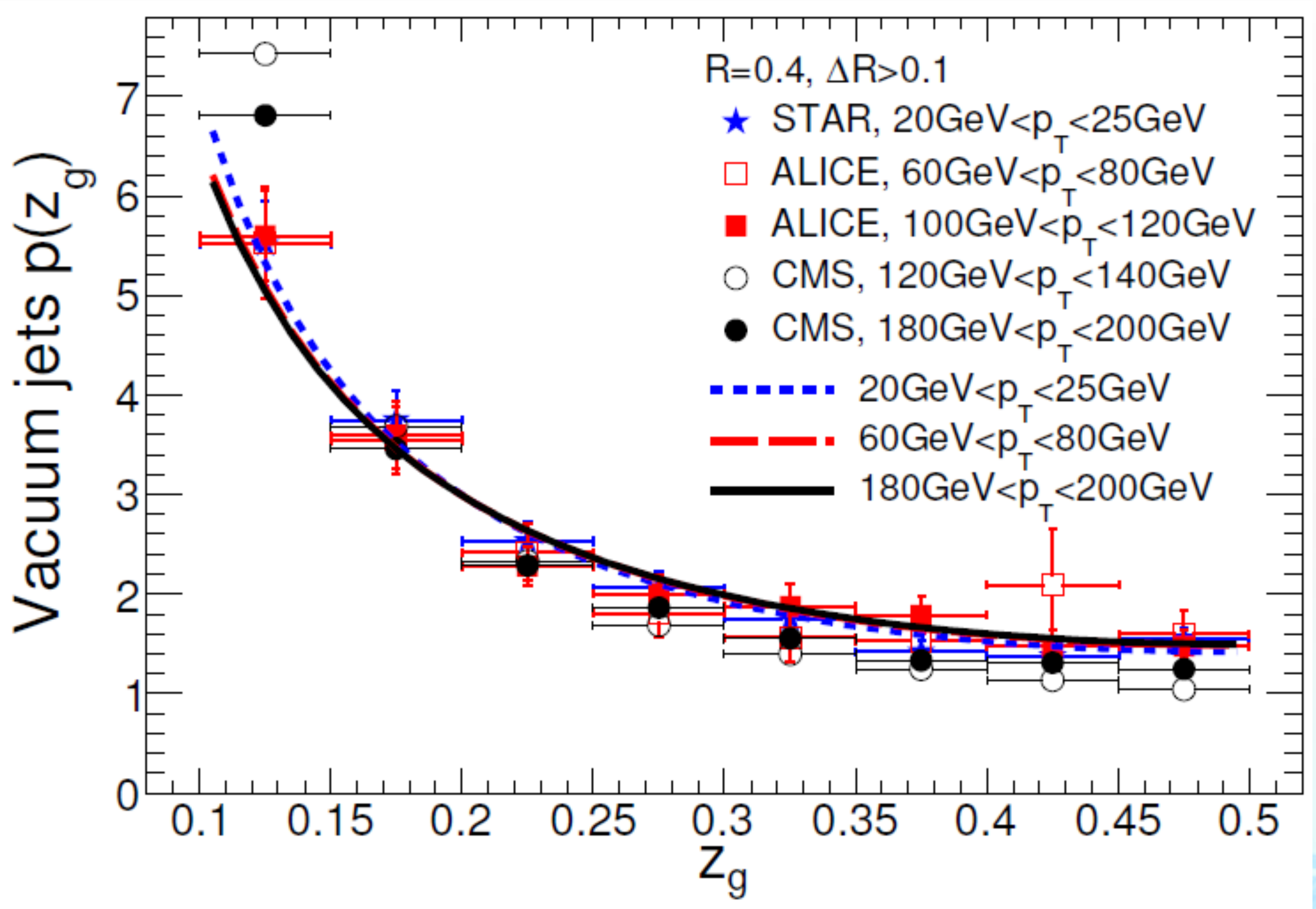
$$\frac{dN^f(z_g^f)}{dz_g^f}$$

$$= \frac{1}{(z_g^i)^\alpha}\frac{dz_g^i}{dz_g^f}$$

$$= \frac{1}{\left(z_g^f + \Delta z_g(z_g^i)\right)^\alpha}\frac{dz_g^i}{dz_g^f}$$

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





R=0.4, ΔR>0.1
STAR, 20GeV<p_T<25GeV
ALICE, 60GeV<p_T<80GeV
ALICE, 100GeV<p_T<120GeV
CMS, 120GeV<p_T<140GeV
CMS, 180GeV<p_T<200GeV
20GeV<p_T<25GeV
60GeV<p_T<80GeV
180GeV<p_T<200GeV
Vacuum jets p(z_g)
z_g
0
1
2
3
4
5
6
7
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5