Deciphering the z_g distribution in heavy ion collisions

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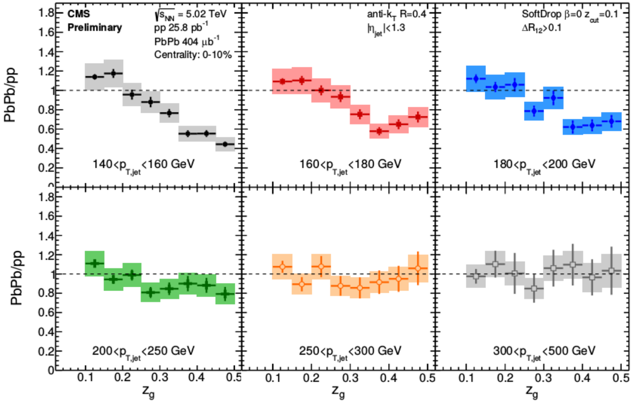
Introduction

- I will focus mainly on the z_g distribution because this allows for comparisons with results from pQCD.

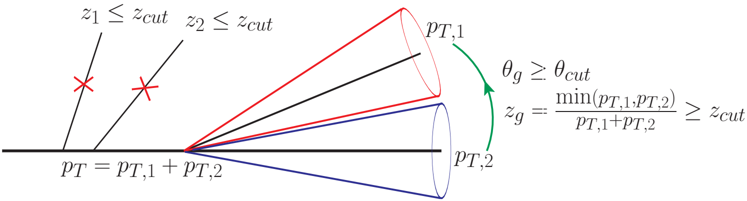
- How to understand from first principles these measurements ?
  CMS Collab. PAS HIN-16-006



z_g distribution in a nutshell

- Jets are first defined with anti-k_T.
- All final particles in **one** jet are reclustered with Cambridge/Aachen to impose physical angular ordering.
- A SoftDrop declustering is used the find the first two subjets satisfying $z_g \geq z_{\text{cut}}$. The angle of branching is called θ_g.

  Larkoski, Marzani, Soyez, Thaler, 2014
- One can also impose a minimal angle between the two subjets $\theta_g \geq \theta_{\text{cut}}$.



pQCD calculation in the vacuum

- Sudakov form factor $\Delta(R, \theta_g)$: probability to have no branching between R and θ_g with $z \geq z_{\text{cut}}$.

$$\Delta_i(R, \theta_g) = \exp\left(- \int_{\theta_g}^{R} d\theta \int_{z_{\text{cut}}}^{1/2} dz \mathcal{P}_i(z, \theta)\right)$$

$$\mathcal{P}_i(z, \theta) = \frac{2C_i}{\pi} \frac{\alpha_s(z p_T \theta)}{\theta} \bar{P}_i(z)$$

- The probability density $p_i(z_g)$ to have a given value of z_g is

$$p_i(z_g) = \mathcal{N} \Theta(z_g - z_{\text{cut}}) \int_{\theta_{\text{cut}}}^{R} d\theta_g \Delta_i(R, \theta_g) \mathcal{P}_i(z_g, \theta_g)$$

Jet evolution in a dense QCD medium

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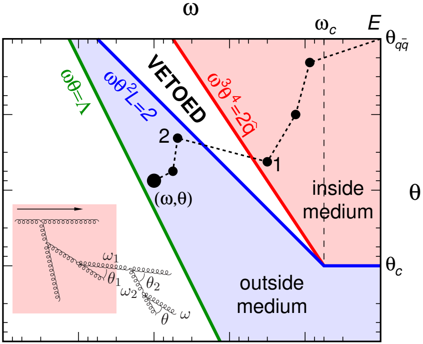
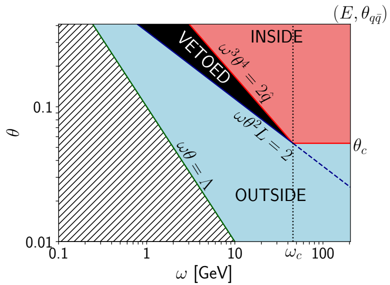
- The evolution of a jet **factorizes** into three steps:
  - one **angular ordered** *vacuum-like shower* inside the medium ,
  - *medium-induced showers* triggered by previous sources;
  - finally, a *vacuum-like shower* outside the medium.
  - Vetoed region for VLEs: essential for the factorization of VLEs from MIEs.

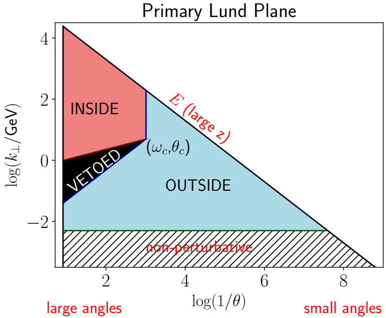


- $\omega_c = \frac{1}{2}\hat{q}L^2$
- $\theta_c = \frac{2}{\sqrt{\hat{q}L^3}}$

Primary Lund plane - Definition

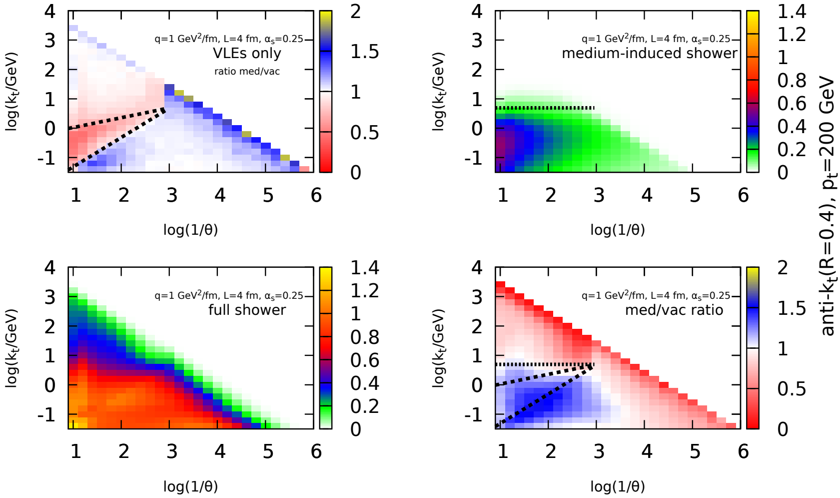
- Density of primary emissions with a given $k_T = \omega\theta$ and $1/\theta$.
  (see e.g. Dreyer, Salam, Soyez, 2018)



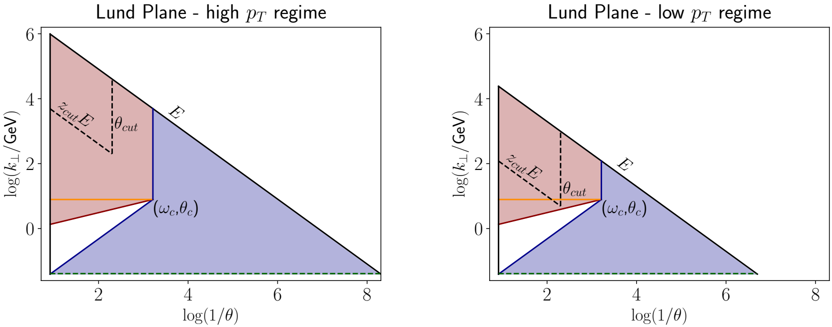


Primary Lund planes (from MC calculations)

- New scale for the medium-induced shower: $k_T = Q_s \equiv \sqrt{\hat{q}L}$.



Two regimes: "high p_T" and "low p_T"



z_g-distribution for "**monochromatic**" gluon jets in the regimes:

- "High p_T": $z_{\text{cut}} p_T \geq \omega_c$ and $\theta_{\text{cut}} \geq \theta_c$. Medium induced emission can **not** be selected by SoftDrop.
- "Low p_T": $z_{\text{cut}} p_T \leq \omega_c$ and $\theta_{\text{cut}} \geq \theta_c$. Medium induced emissions **might** be selected by SoftDrop. Mehtar-Tani, Tywoniuk, 2016
- In the current LHC data, $\theta_{\text{cut}} = 0.1$ whereas in our set-up $\theta_c \leq 0.05$

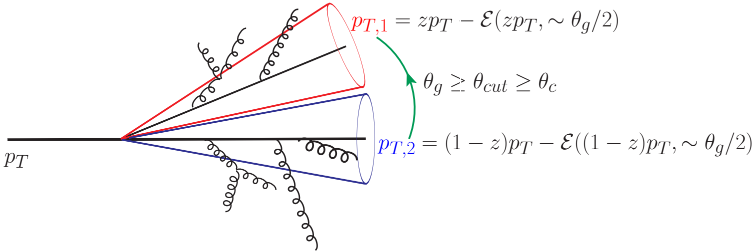
High p_T regime: incoherent energy loss

- In the high pT regime, the only leading medium effect is the incoherent energy loss of the two subjets via medium-induced radiation.

- Incoherent energy loss because we chose $\theta_g \geq \theta_{\text{cut}} \geq \theta_c$.

  Mehtar-Tani, Salgado, Tywoniuk, 2010-1 ; Casalderrey-Solana, Iancu, 2011

- Let us call $\mathcal{E}(p_{T,1}, R_1)$ the energy loss by a subjet.



High p_T regime: pQCD calculation

- Vacuum:

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_{\text{cut}}) \int_{\theta_{\text{cut}}}^{R} d\theta_g \Delta_i(R, \theta_g) \mathcal{P}_i(z_g, \theta_g)$$

$$\Delta_i(R, \theta_g) = \exp\left(- \int_{\theta_g}^{R} d\theta \int_0^{1/2} dz \mathcal{P}_i(z, \theta) \Theta(z - z_{\text{cut}}) \right)$$

High p_T regime: pQCD calculation

- Vacuum: z is the physical splitting fraction.

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_{\text{cut}}) \int_0^1 dz \int_{\theta_{\text{cut}}}^R d\theta_g \Delta_i(R, \theta_g) \mathcal{P}_i(z, \theta_g) \delta(z - z_g)$$

$$\Delta_i(R, \theta_g) = \exp\left(- \int_{\theta_g}^R d\theta \int_0^{1/2} dz \mathcal{P}_i(z, \theta) \Theta(z - z_{\text{cut}}) \right)$$

High p_T regime: pQCD calculation

- With the medium:

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_{\text{cut}}) \int_0^1 dz \int_{\theta_{\text{cut}}}^R d\theta_g \Delta_i(R, \theta_g)\mathcal{P}_i(z, \theta_g)\delta(Z_g(z, \theta_g) - z_g)$$

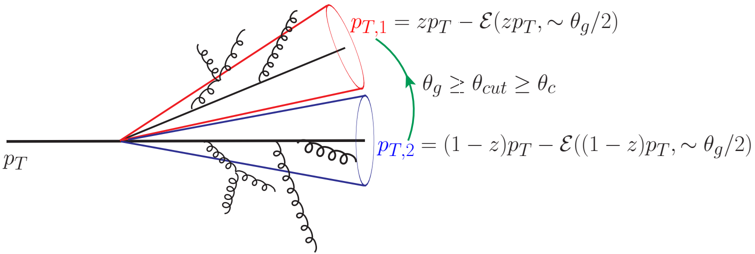
High p_T regime: pQCD calculation

- With the medium:

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_{\rm cut}) \int_0^1 dz \int_{\theta_{\rm cut}}^R d\theta_g \Delta_i(R,\theta_g)\mathcal{P}_i(z,\theta_g)\delta(Z_g(z,\theta_g) - z_g)$$

$$\Delta_i(R,\theta_g) = \exp\left(- \int_{\theta_g}^R d\theta \int_0^{1/2} dz \mathcal{P}_i(z,\theta)\Theta(Z_g(z,\theta) - z_{\rm cut})\right)$$

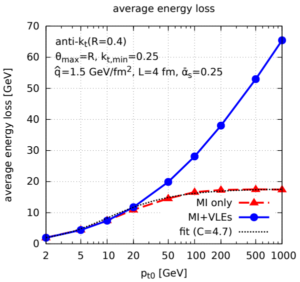
$$Z_g(z,\theta) = \frac{\min(zp_T - \mathcal{E}(zp_T,\theta_g), (1-z)p_T - \mathcal{E}((1-z)p_T,\theta_g))}{p_T - \mathcal{E}(zp_T,\theta_g) - \mathcal{E}((1-z)p_T,\theta_g)}$$

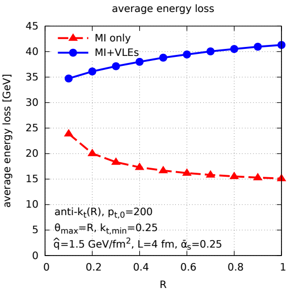


The energy loss function $\mathcal{E}(p_T, R)$

The importance of the "in-medium" multiplicity of VLEs

- For $p_T \gg \omega_{br} \equiv \bar{\alpha}_s{}^2\omega_c$, partonic energy loss via MIEs is constant.
- For jets with VLEs and MIEs, the energy loss increases because of the VLEs multiplicity **inside** the medium.

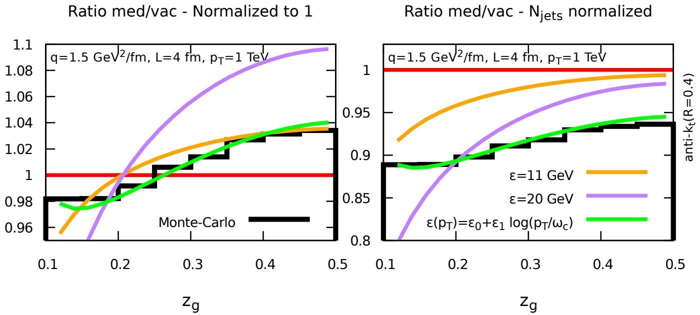




- Analytical estimations: DL and single emission approximation,

$$\mathcal{E}(p_T, \theta_g) \propto \omega_{br} \int_0^{p_T} d\omega \int_{\theta_c}^{R} d\theta \frac{d^2N}{d\omega d\theta} \Theta_{in}$$

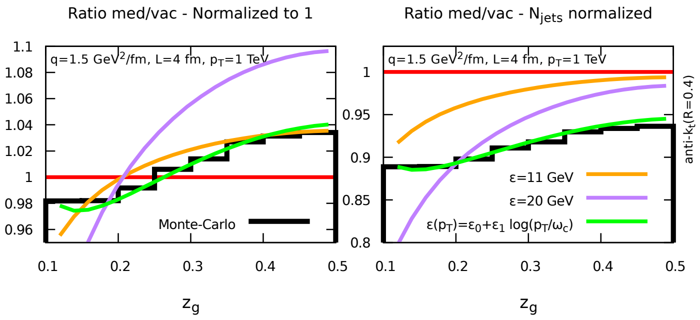
High p_T regime: analytical and MC results



Comments

- p_T dependence of energy loss coming from VLEs leading to an increase in the number of sources.
- This p_T dependence is important to achieve a good analytic description of both ways of normalizing z_g.

High p_T regime: analytical and MC results



Comments

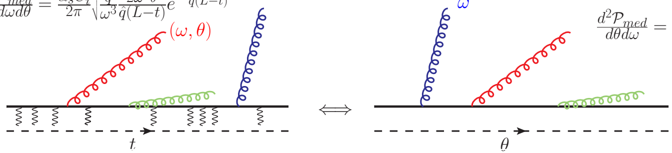
- The effects of the incoherent energy loss on z_g have also been discussed in Mehtar-Tani, Tywoniuk, 2016 & Chang, Cao, Qin, 2018
- These papers refers to relatively low p_T. Indeed, even in that regime, this mechanism represents an ingredient of the full physical scenario.

Low p_T regime: medium induced emissions

Purely medium-induced shower - z_g distribution

- For MIEs, the evolution variable is the emission time, **not** the angle.
- Primary emissions dominate the intrajet activity in the kinematics of interest since $z_{\rm cut} p_T \gg \omega_{br} \equiv \bar{\alpha}_s^2 \omega_c$. Blaizot, Iancu, Mehtar-Tani, 2013
- For such emissions, one can build a fictitious angular ordering that mimics C/A declustering.

$$\frac{d^3\mathcal{P}_{med}}{dt\,d\omega\,d\theta} = \frac{\alpha_s C_i}{2\pi}\sqrt{\frac{\hat{q}}{\omega^3}}\frac{2\omega^2\theta}{\hat{q}(L-t)}e^{-\frac{\omega^2\theta^2}{\hat{q}(L-t)}}$$



$$\frac{d^2\mathcal{P}_{med}}{d\theta\,d\omega} = \frac{\alpha_s C_i}{\pi}\sqrt{\frac{2\omega_c}{\omega^3}}\frac{2\theta\omega^2}{Q_s^2}\Gamma(0, \frac{\omega^2\theta^2}{Q_s^2})$$

$$p_{\rm i,med}(z_g) = \mathcal{N}\Theta(z_g - z_{\rm cut})\int_{\theta_{\rm cut}}^{R} d\theta_g \Delta_{\rm i,med}(R,\theta_g)\mathcal{P}_{\rm i,med}(z_g,\theta_g)$$

$$\Delta_{\rm i,med}(R,\theta_g) = \exp\left(-\int_{\theta_g}^{R} d\theta \int_0^{1/2} dz\,\mathcal{P}_{\rm i,med}(z,\theta)\Theta(z - z_{\rm cut})\right)$$

Low p_T regime: full parton shower

- The z_g distribution taking into account both VLEs and MIEs is:

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_c)\int_{\theta_{\text{cut}}}^{R} d\theta_g \Delta_i^{\text{vac}}(R,\theta_g)\Delta_i^{\text{med}}(R,\theta_g)$$
$$\times \int_0^{1/2} dz\Big(\mathcal{P}_i^{\text{vac}}(z,\theta_g)\delta(Z_g^{\text{vac}} - z_g) + \mathcal{P}_i^{\text{med}}(z,\theta_g)\delta(Z_g^{\text{med}} - z_g)\Big)$$

Low p_T regime: full parton shower

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$$\times \int_0^{1/2} dz \left(\mathcal{P}_i^{\text{vac}}(z,\theta_g)\delta(Z_g^{\text{vac}} - z_g) + \mathcal{P}_i^{\text{med}}(z,\theta_g)\delta(Z_g^{\text{med}} - z_g)\right)$$

- Incoherent energy loss for the 2 sub-jets emerging from either a hard vacuum-like splitting, or a hard medium-induced one.
- But the respective values for the energy loss are different.
- **However the story is not over !**

Low p_T regime: full parton shower

- The z_g distribution taking into account both VLEs and MIEs is:

$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_c)\int_{\theta_{\rm cut}}^{R} d\theta_g \Delta_i^{\rm vac}(R,\theta_g)\Delta_i^{\rm med}(R,\theta_g)$$
$$\times \int_0^{1/2} dz\Big(\mathcal{P}_i^{\rm vac}(z,\theta_g)\delta(Z_g^{\rm vac} - z_g) + \mathcal{P}_i^{\rm med}(z,\theta_g)\delta(Z_g^{\rm med} - z_g)\Big)$$

- A MI branching can be emitted by any of the partonic sources created via VLEs inside such that $\omega \geq z p_T$ and $\theta_c \leq \theta \leq \theta_g$.

Low p_T regime: full parton shower

- The formula with all the important physical ingredients is

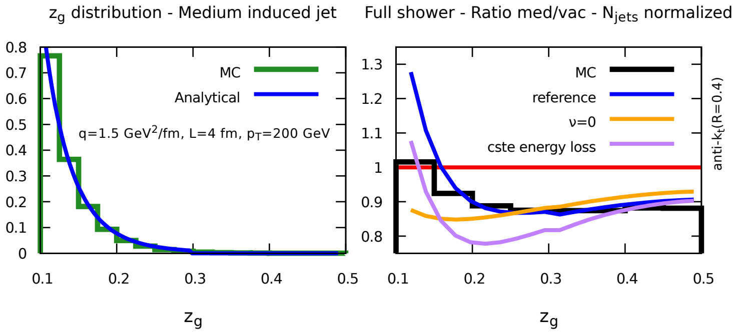
$$p_i(z_g) = \mathcal{N}\Theta(z_g - z_c)\int_{\theta_{\text{cut}}}^{R} d\theta_g \Delta_i^{\text{vac}}(R,\theta_g)\Delta_i^{\text{med}}(R,\theta_g)$$
$$\times \int_0^{1/2} dz\Big(\mathcal{P}_i^{\text{vac}}(z,\theta_g)\delta(Z_g^{\text{vac}} - z_g) + (1+\nu)\mathcal{P}_i^{\text{med}}(z,\theta_g)\delta(Z_g^{\text{med}} - z_g)\Big)$$

- A MI branching can be emitted by any of the partonic sources created via VLEs inside such that $\omega \geq z p_T$ and $\theta_c \leq \theta \leq \theta_g$.
- The probability $\mathcal{P}_i^{\text{med}}(z,\theta_g)$ is enhanced by a factor $1+\nu$ with

$$\nu = \int_{z p_T}^{p_T} d\omega \int_{\theta_c}^{\theta_g} d\theta \frac{d^2 N}{d\omega d\theta}\Theta_{in}$$

and the Sudakov $\Delta_i^{\text{med}}(R,\theta_g)$ suppressed accordingly.

Low p_T regime: analytical and MC results

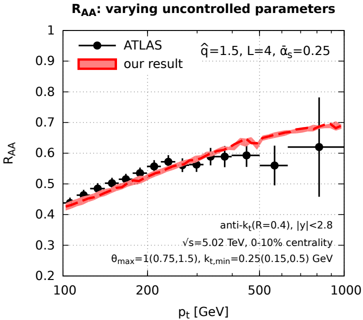


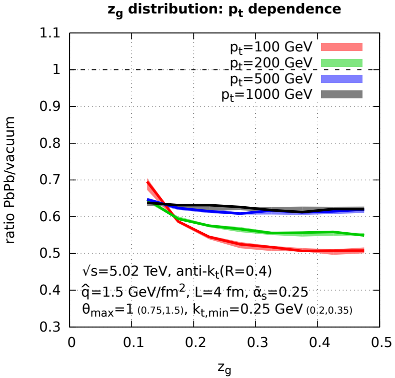
Comments

- For curve "reference", ν is overestimated in the DLA approximation: $\nu = \bar{\alpha}_s \log(1/z) \log(\theta_g/\theta_c)$.
- Curve "cste energy loss": taking a constant energy loss for vacuum-like subjets does not reproduce the flat behavior at large z_g.

Full MC results with initial jet cross section

- So far, only "monochromatic" initial jet cross section.
- The normalization factor for z_g distributions is sensitive to the steeply falling spectrum.
- N.B. Change of the global shape around $p_T \simeq 500$ GeV $\sim \omega_c / z_{\text{cut}}$.

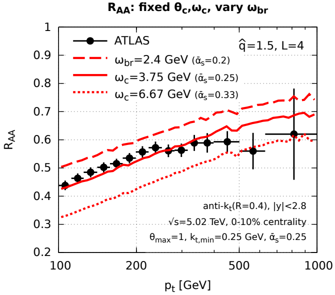


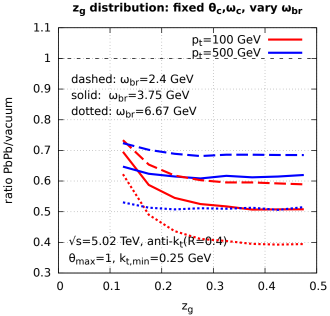


z_g distributions for realistic initial jet cross section

Variation with ω_{br} (fixed ω_c and θ_c)

- ω_{br} is the scale controlling the energy loss and the BDMPS-Z rate.
- R_{AA} decreases when ω_{br} increases.
- High-p_T z_g distribution: global normalization decreases when ω_{br} increases.
- Low-p_T z_g distribution: peak increases when ω_{br} increases.





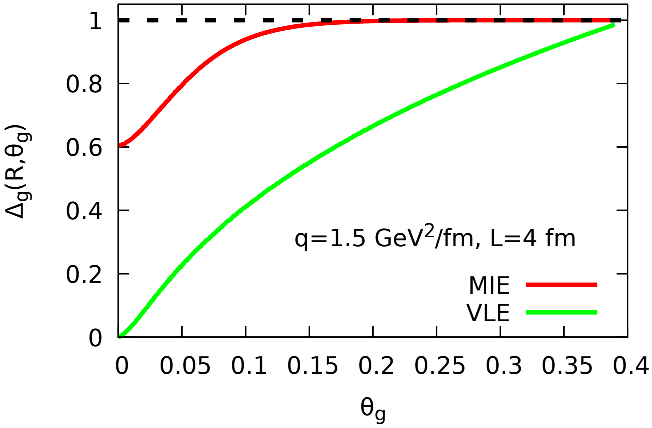
Conclusion

Take-home messages

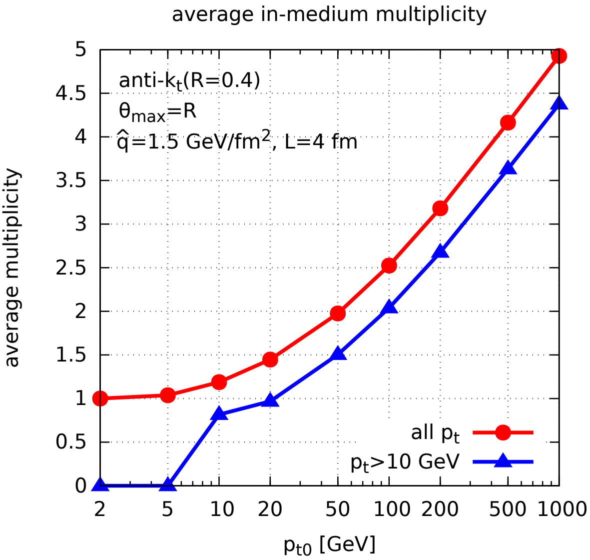
- Recall: the phase-space constraint refers to the VLEs.
- First phase space effect: the z_g distribution in the high $p_T \gg \omega_c/z_{\text{cut}}$ and low $p_T \ll \omega_c/z_{\text{cut}}$ regime cannot be explained without the in-medium multiplicity of VLEs which introduces a p_T dependence of the energy loss.
- We predict a change of behavior of the nuclear modification factor for the z_g distribution around $p_T \sim \omega_c/z_{\text{cut}}$.
- Second phase space effect: the z_g distribution in the low p_T regime is affected by the in-medium multiplicity of VLEs that enhances the probability to have a MIE selected by SoftDrop.

THANK YOU !

Back-up - Sudakov form factors



Back-up - In-medium VLEs multiplicity



Back-up - Transition low p_T/high p_T