Can jet quenching constrain the evolution history of parton showers?

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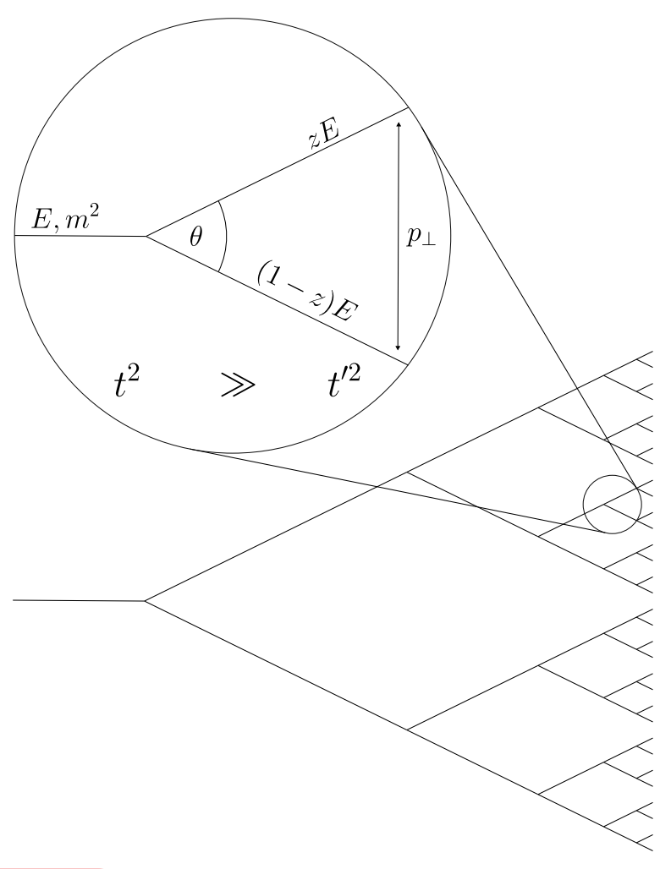
1. The “space-time” Picture of Jets



- Parton showers evolve by decreasing an **arbitrary energy scale t** via iterated splittings:
  - Virtual ordering (PYTHIA6): $t = m$;
  - Transverse ordering (PYTHIA8): $t = p_\perp$;
  - Angular ordering (HERWIG): $t = E\theta$;
  - Formation time ordering: $t = t_{\mathrm{f}}^{-1}$.
- Different orderings lead to different formation times, varying the applied quenching.

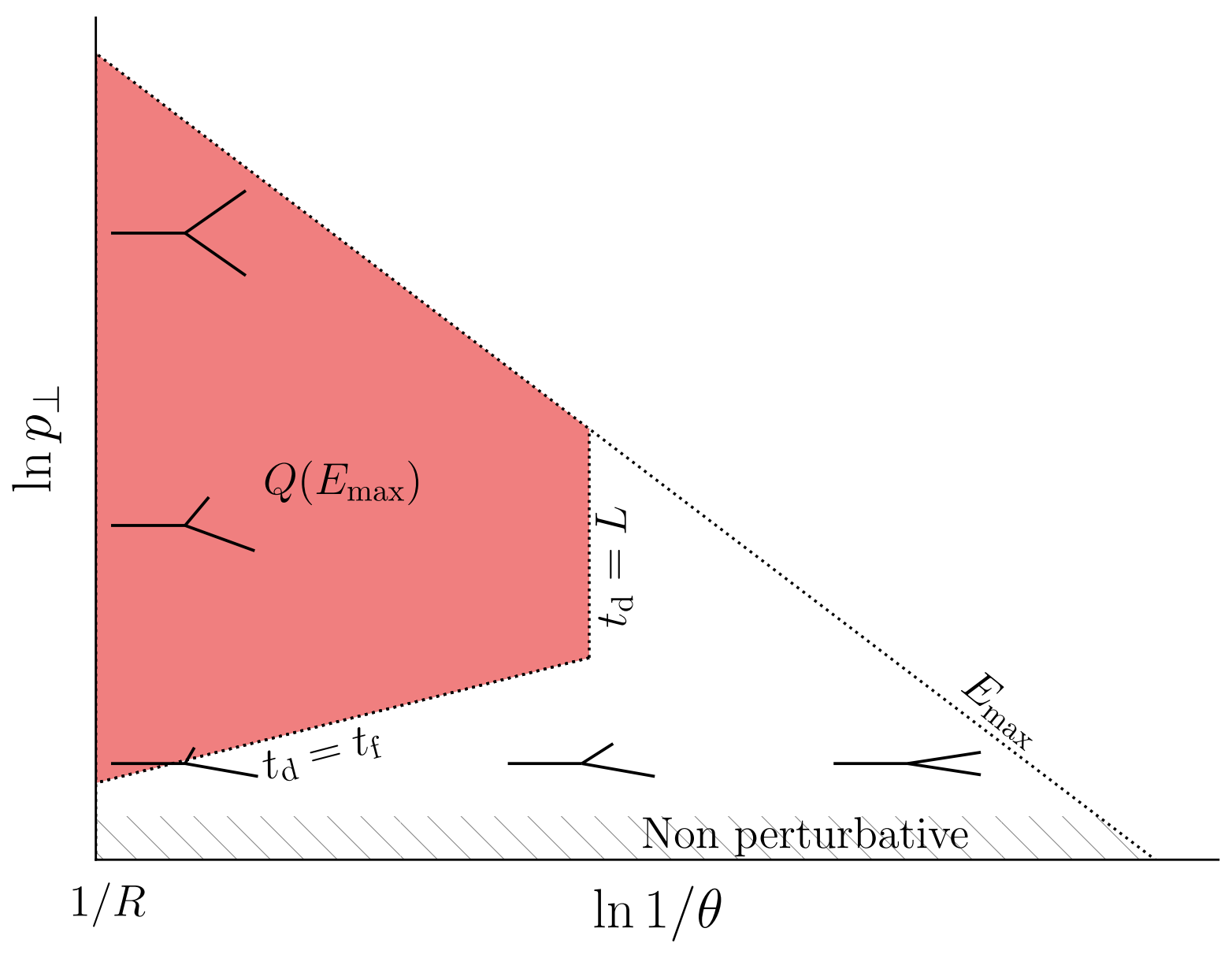
How much does jet quenching depend on t?

2. Quenched Parton Showers

The momentum radiated out of the jet cone is described by the quenching factor Q of each parton, resulting for n particles [1]

$$\frac{\mathrm{d}^n\sigma_{\mathrm{med}}(p_{\mathrm{jet}})}{\mathrm{d}p_1\cdot\ldots\cdot\mathrm{d}p_n} = Q^n(p_{\mathrm{jet}})\,\frac{\mathrm{d}^n\sigma_{\mathrm{vac}}(p_{\mathrm{jet}})}{\mathrm{d}p_1\cdot\ldots\cdot\mathrm{d}p_n}\,, \tag{1}$$

assuming that all branchings are affected by energy loss. However, a **branch is quenched only if the medium resolves its color** [2]. This takes time t_{d}, thus the branching formation has to be long enough, and placed inside the medium $t_{\mathrm{d}} < t_{\mathrm{f}} < L$. This implies a separation of time-scales of vacuum and medium-induced processes. The branches and the **quenched region** are illustrated on the Lund plane below.



Quenching is implemented by the following procedure (see Fig. 1.):

1. Generate a vacuum jet.
2. Count the splittings inside the region and forbid jump-backs.
3. Reweight the whole jet by the quenching factor (extracted from data).

Comparing with analytic

The no emission probability (Sudakov [3]) for a primary emission is

$$\Delta_{\mathrm{med}}(R) = \exp\left[-\int^R \mathrm{d}\theta \int \mathrm{d}z\, P(\theta,z)\,\left(Q^2\,\Theta^{\mathrm{in}}_{\mathrm{med}} + \Theta^{\mathrm{out}}_{\mathrm{med}}\right)\right]\,, \tag{2}$$

where the splitting kernel with $P(z)$ splitting function is

$$P(\theta,z) = \frac{1}{\theta}\frac{\alpha_s}{\pi}\,P(z)\,\Theta(p_\perp - p_{\perp,\min})\,, \tag{3}$$

where $p_{\perp,\min}$ is the shower stopping criteria.

4. Conclusions

- Implement quenching in multi-parton observables via reweighting.
- Develop Monte Carlo and analytical techniques.
- Study the role of the choice of ordering variable t.
- θ ordering results more splittings, but less quenching, due to a nontrivial interplay of of t and $\alpha_s(p_\perp)$.
- Multiplicity created at low scales affects jet quenching observables!
- Different orderings have sensitivity to IR and medium physics!

References

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[1] R. Baier, Y. L. Dokshitzer, A. H. Mueller and D. Schiff, JHEP **0109**, 033 (2001).
[2] Y. Mehtar-Tani and K. Tywoniuk, Phys. Rev. D**98**, 051501 (2018).
[3] Y. L. Dokshitzer et al. “Basics of perturbative QCD,” Ed. Frontieres (1991).

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3. Results

We implemented parton showers with quenching and different orderings to study the t dependence of quenching.

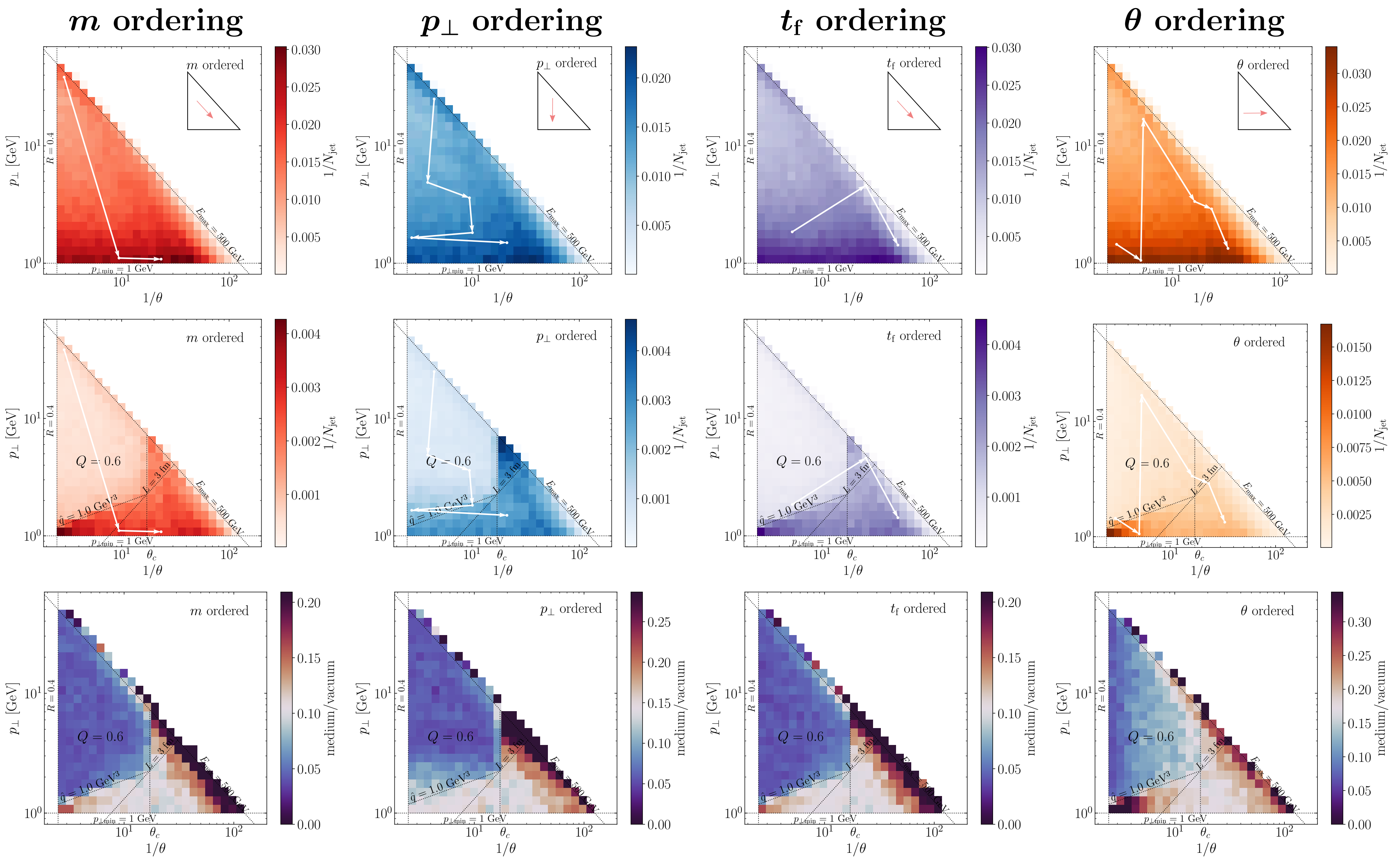


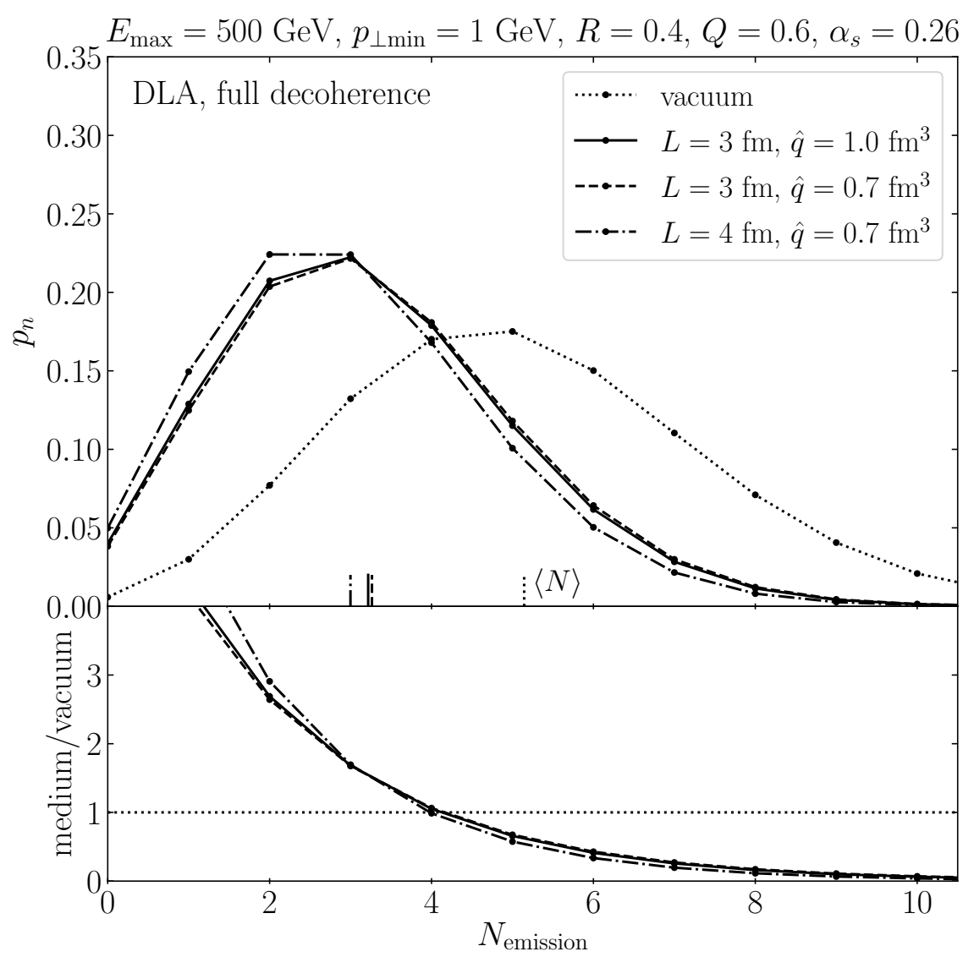
Fig. 1. *Up:* primary Lund plane of vacuum jets with different orderings. The patterns are similarly driven by $\alpha_s(p_\perp)$, but individual jets (illustrated by paths) are ordered differently. *Middle:* after reweighting the vacuum jets, the quenched region is clearly suppressed, but the paths do not change. *Down:* medium to vacuum ratio is not 1 due to quenching (like R_{AA}). Ordering in θ presents the least quenching due to having fewer branches inside the quenched region. The patterns differ due to the forbidden jump-backs.

Multiplicity Puzzle

The multiplicity of primary emissions follows the Poisson distribution,

$$P_n(R) = \frac{\Delta_{\mathrm{med}}(R)}{n!}\,[-\ln(\Delta_{\mathrm{med}}(R))]^n\,, \tag{4}$$

where the average is proportional to the area of the Lund plane. By quenching, the effective size decreases, resulting in fewer emissions, shown on the right up to double logarithmic approximation (DLA). Quenching strongly suppresses multiplicity - also presented on Fig. 2. for different showers.



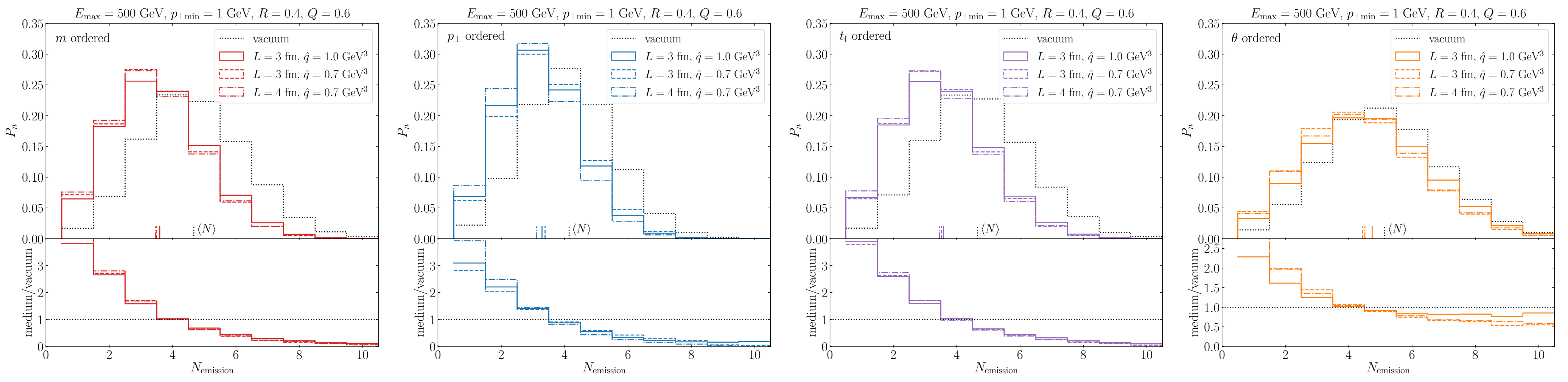


Fig. 2: The vacuum and quenched shower multiplicity of primary emissions with different orderings. In total, θ ordering results the most emissions.

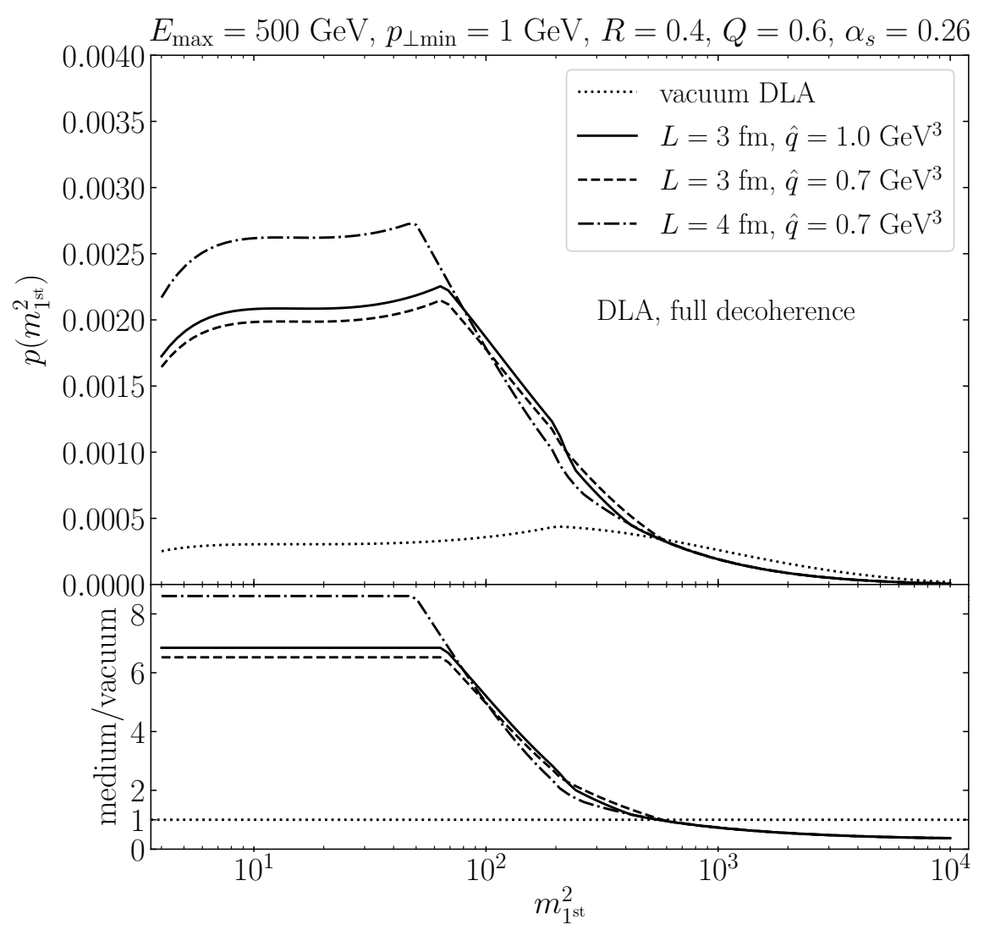
- θ ordering has the most emissions and the least quenching (Fig. 1.).
- More splittings $\neq$ bigger quenching, if they are not resolved by the medium.
  The controversy is caused by a nontrivial interplay of the evolution variable and running $\alpha_s(p_\perp)$.
- Multiplicity created at low scales affects jet quenching observables!

Mass distribution

The mass of the first splitting inside the jet strongly varies for different orderings. In case of mass ordering, it trivially corresponds to the probability of the first splitting. Using the no emission probability

$$p(m^2) = \frac{\mathrm{d}}{\mathrm{d}m^2}\,\Delta_{\mathrm{med,g}}(m^2)\,, \tag{5}$$

it suppresses big masses due to quenching above θ_c, shown on the right up to DLA. It has a good agreement with the m ordered shower, see below. The showers on Fig 3. show slightly different distributions, indicating sensitivity of different orderings to IR and medium physics!



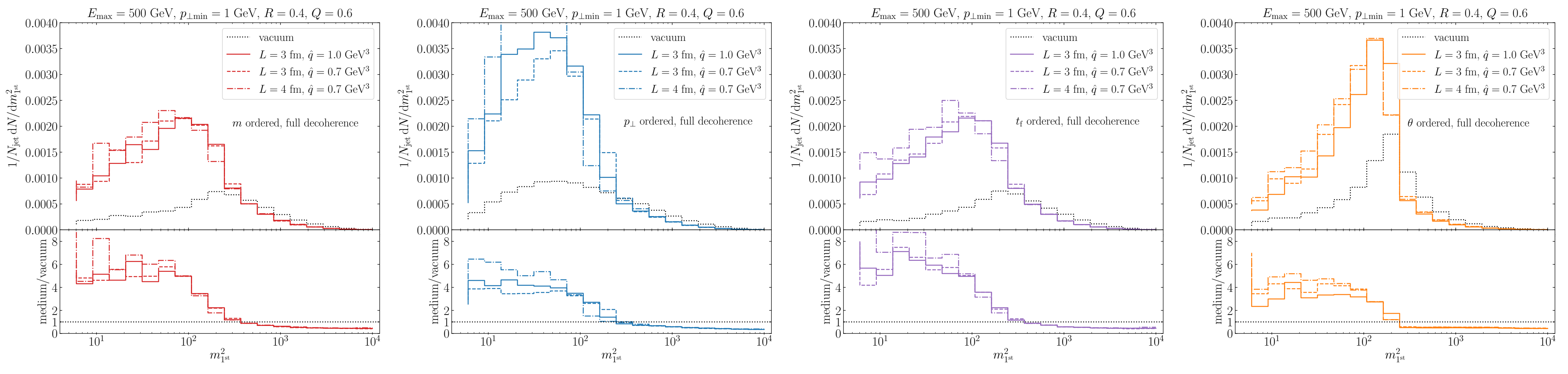


Fig. 3: The mass of the first splitting inside the jet for different quenched showers and their ratio to vacuum. Suppression is highly sensitive to θ_c coherence angle ($t_{\mathrm{d}} = L$).