Exploring Parton Showers in the presence of an extended QCD medium

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In collaboration with:

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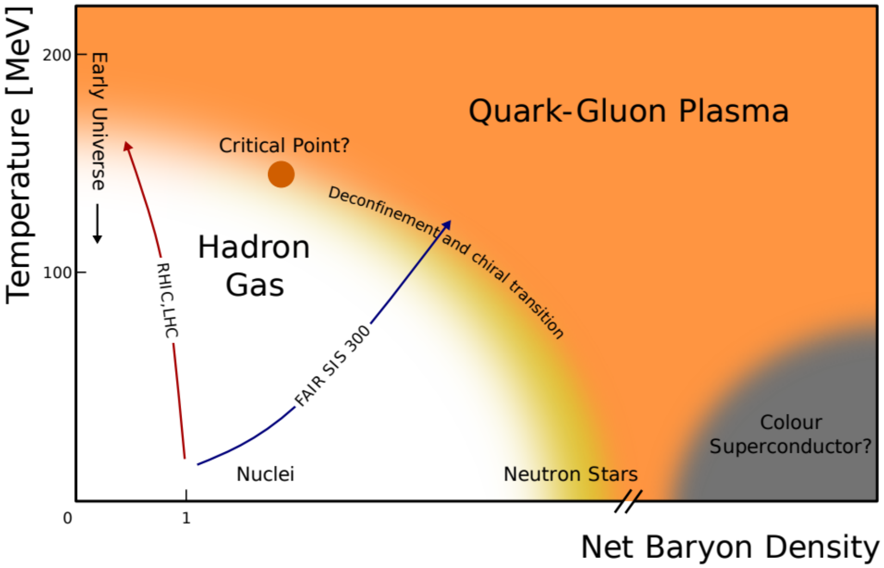
Fourth Joint Workshop IGFAE / LIP

Why we study heavy ion collisions

- **Quantum matter in extreme conditions:** explore the QCD phase diagram
- **Collectivity:** emergent behaviour from fundamental d.o.f.
- **Cosmology:** the QGP filled the early universe



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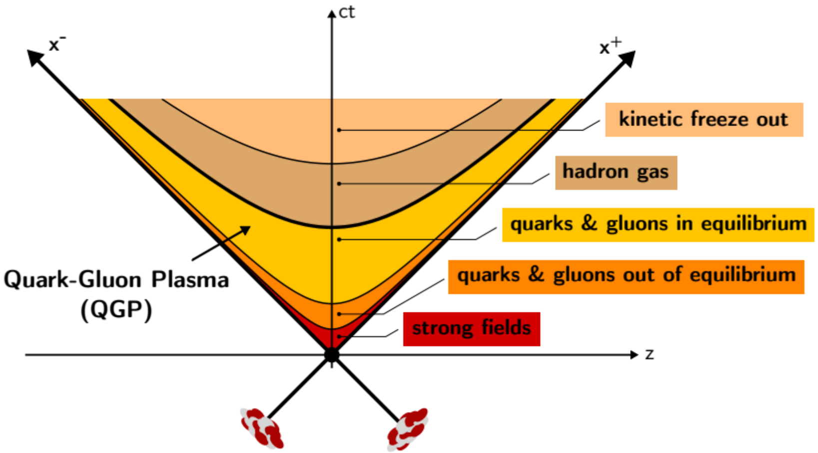
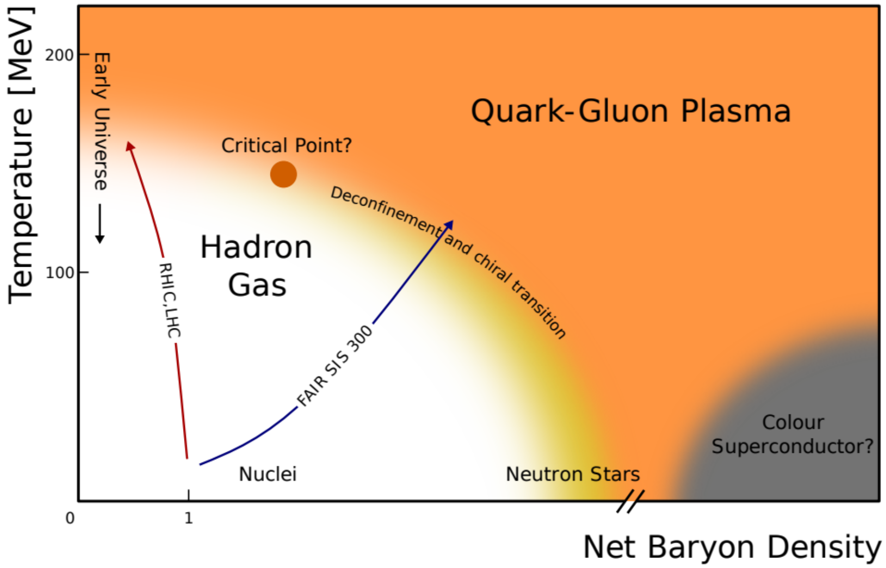


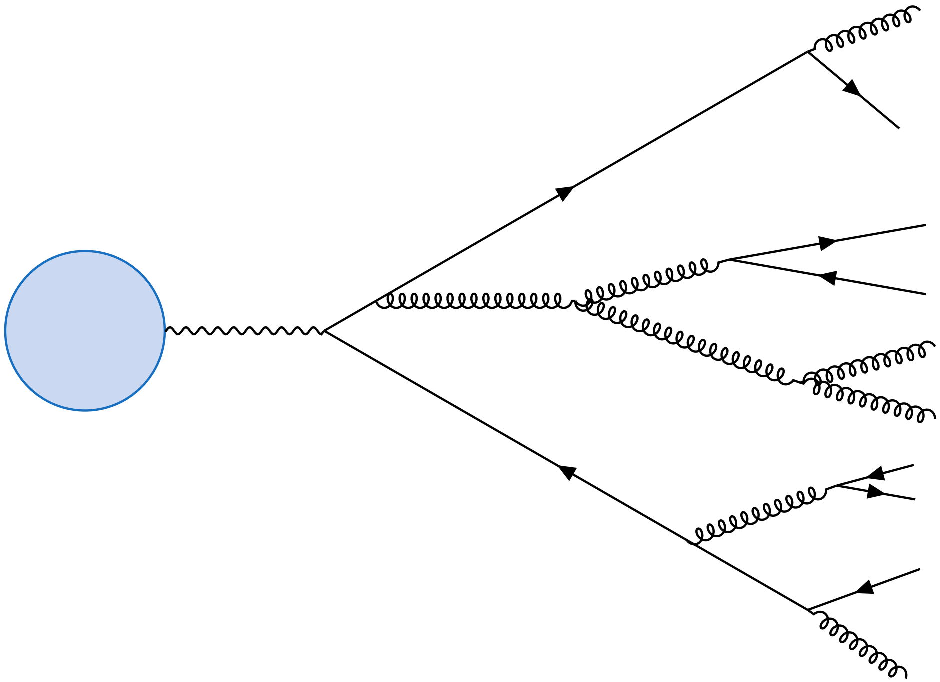


Main challenge: the QGP is extremely short lived (~10^{-24} s)

One approach: Probe it with (high-momentum) particles produced in the collision!

Probing the QGP with parton cascades

Hard partons radiate until the hadronisation scale →
Parton cascades provide a multi-scale object



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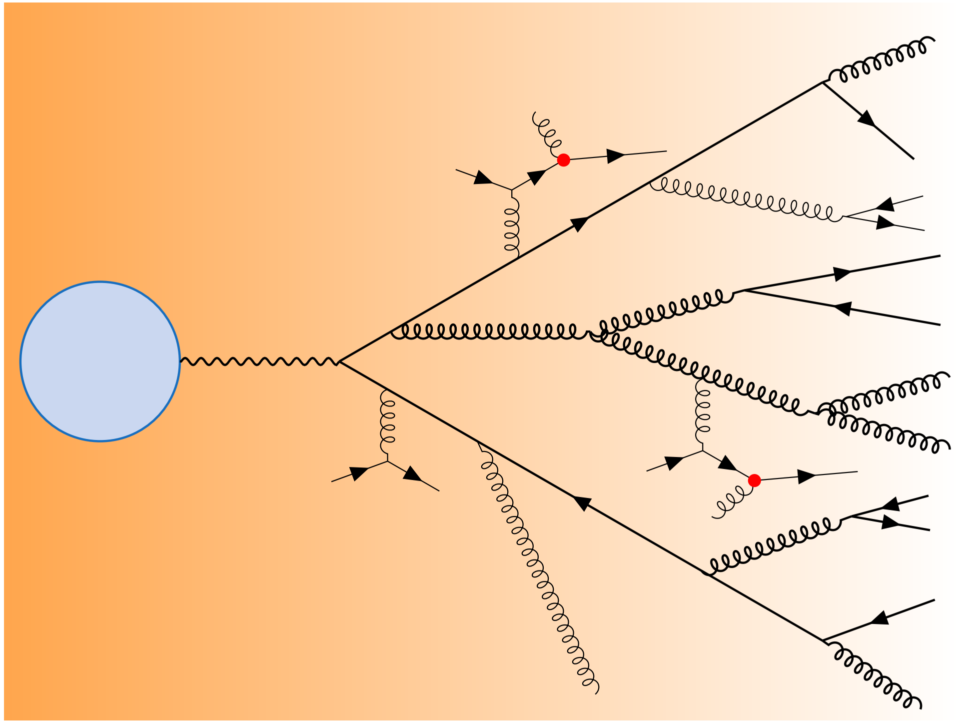

In-medium cascades require an interface with the evolving medium → This encodes the QGP evolution!

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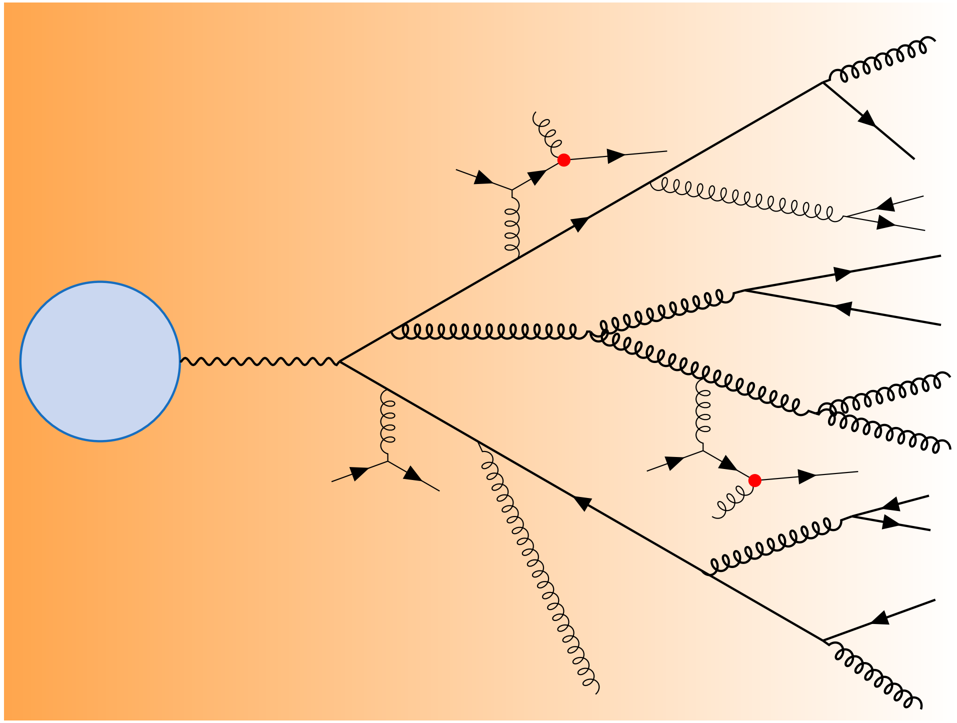

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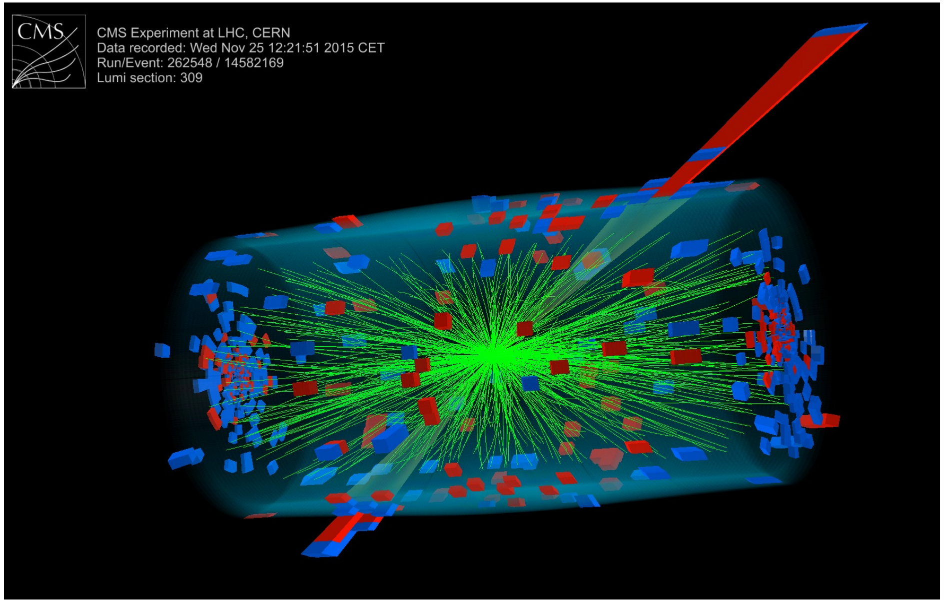
Experimental objects: jets
Different jets suffer different energy loss



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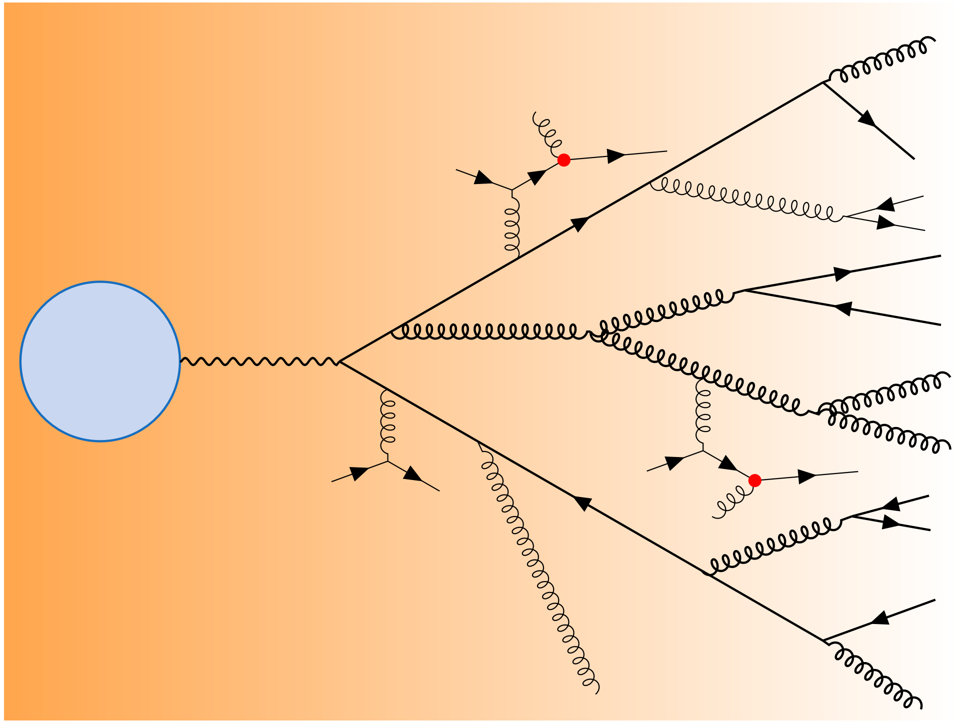

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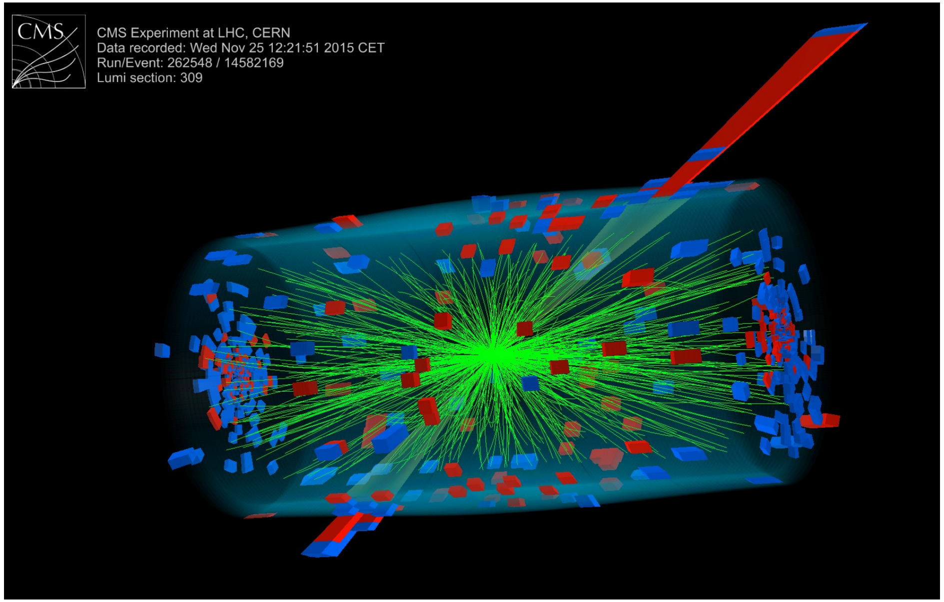
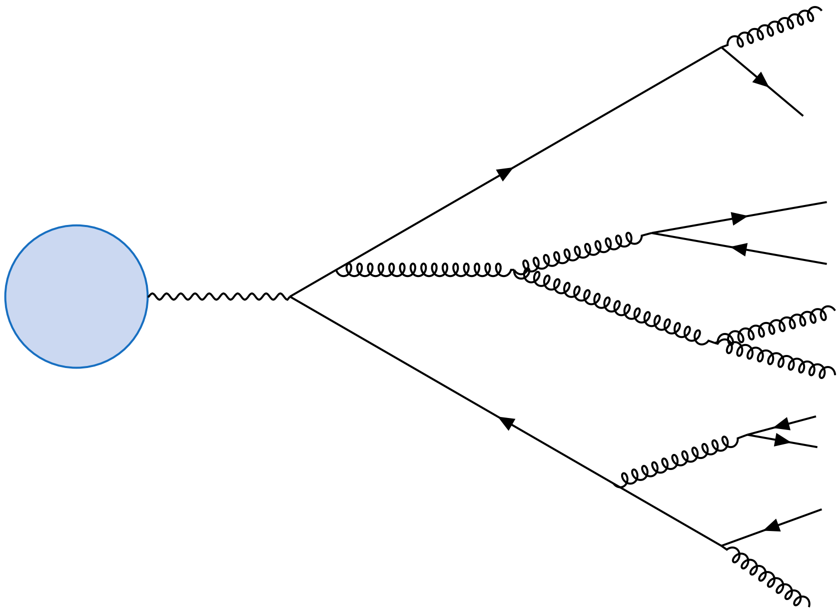


Are the medium modifications sensitive to the vacuum evolution?

First, a look at vacuum showers

Parton Cascades vs Jets

Parton Cascade: Sequence of QCD splittings, defined in perturbation theory → Can be sampled numerically



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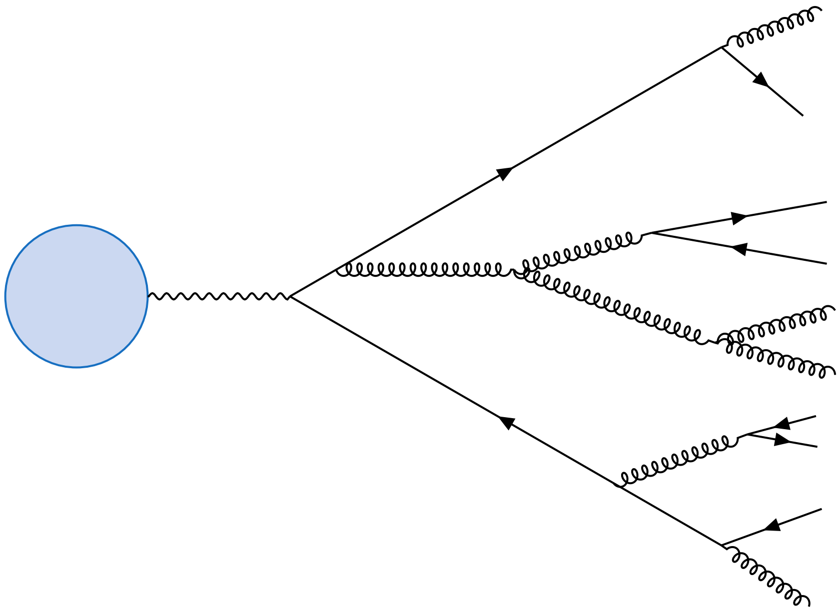
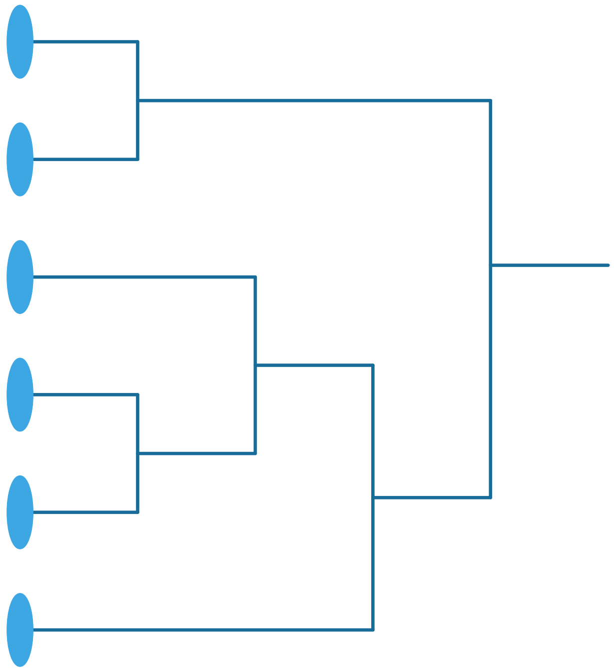


<u>Jet:</u> Sequence of hadron clusterings, according to some (arbitrary) definition → Proxy for initial parton



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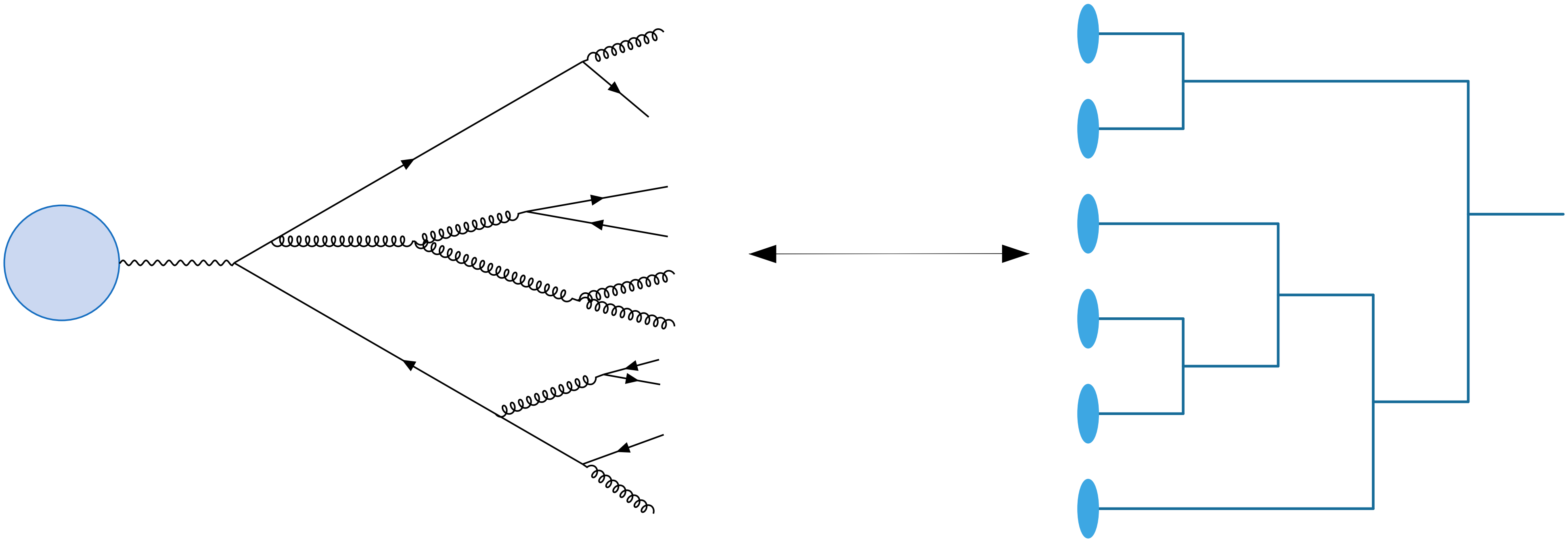
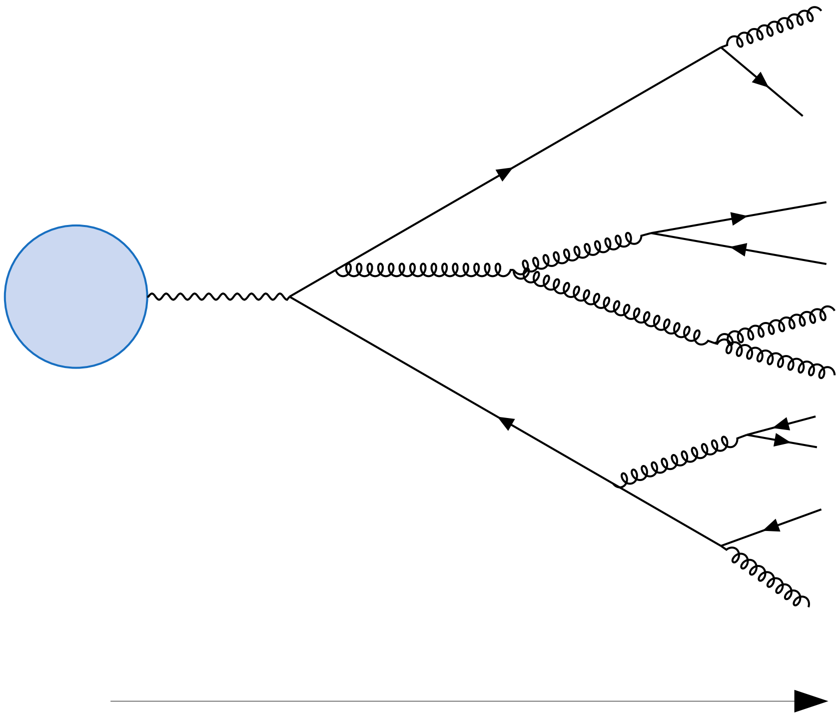


For appropriate definitions jet structure coincides with the cascade ordering

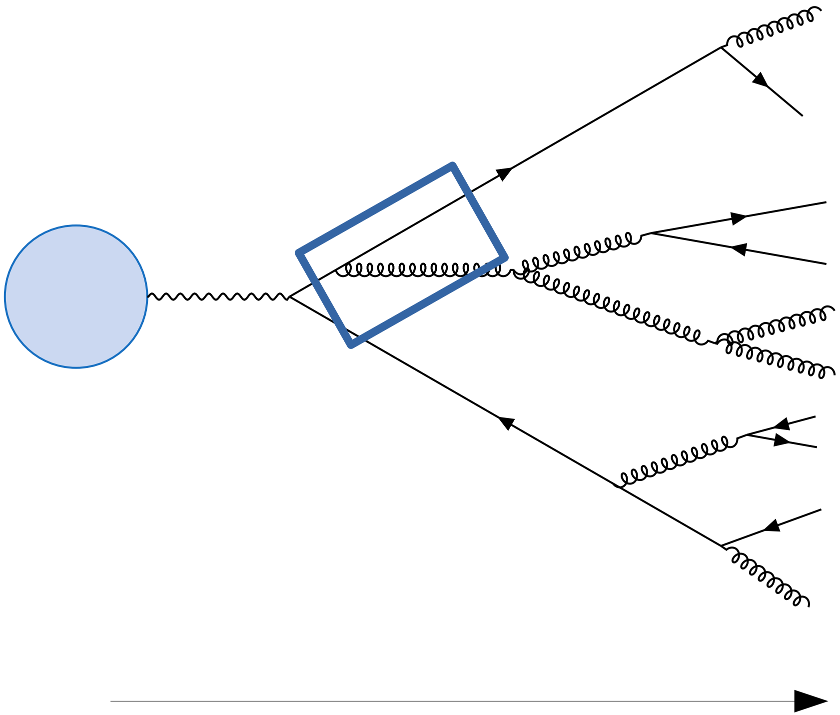
How to build a parton shower



Splittings with decreasing scale μ

How to build a parton shower

<u>Building blocks:</u> QCD splittings



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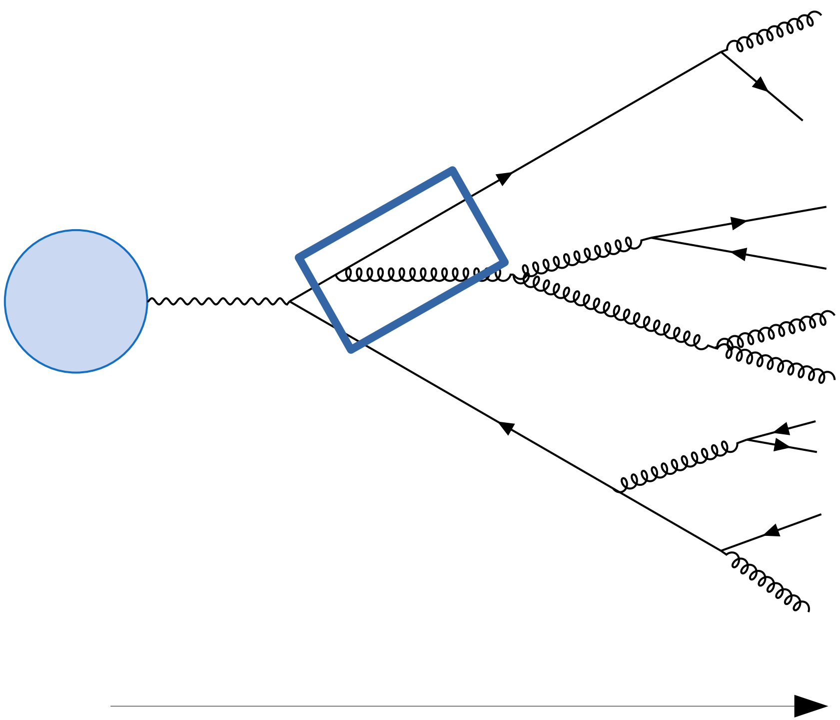
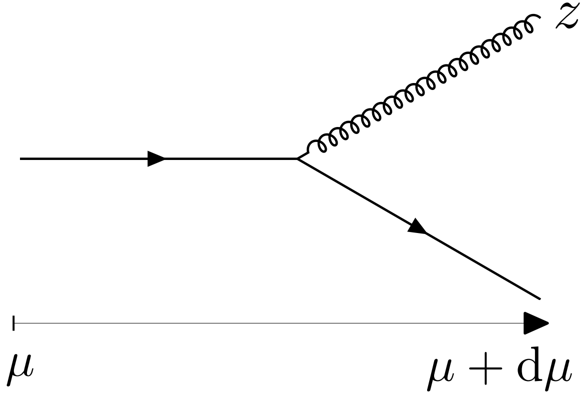


Splittings with decreasing scale μ

Splitting probability given by pQCD:



$$\sim \frac{\alpha\, C_\mathrm{F}}{\pi} \frac{\mathrm{d}\mu}{\mu} \frac{\mathrm{d}z}{z}$$

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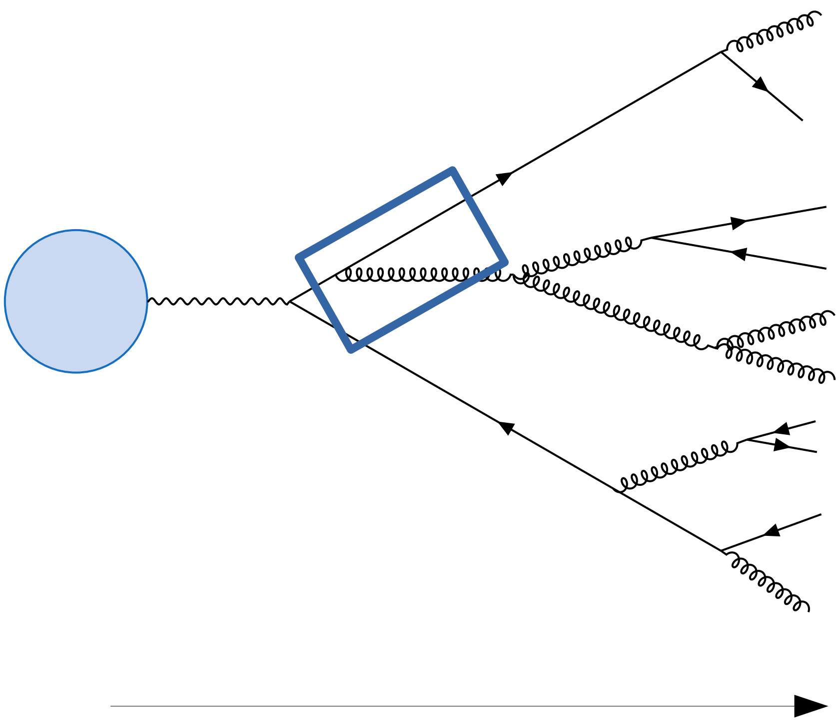

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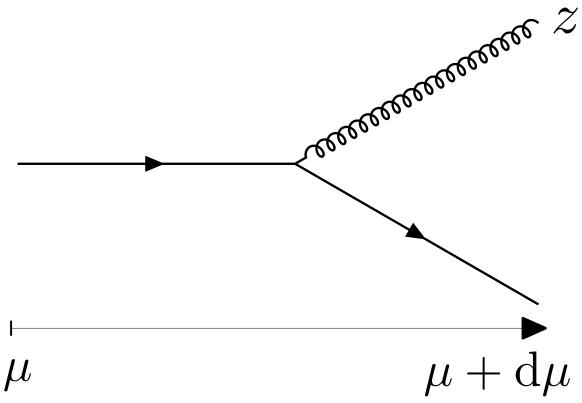

$$\sim \frac{\alpha\, C_{\mathrm{F}}}{\pi} \frac{\mathrm{d}\mu}{\mu} \frac{\mathrm{d}z}{z}$$

Probability of not emitting until some scale s :

$$\Delta(s_{\mathrm{prev}}, s) = \exp\left\{ -\frac{\alpha C_R}{\pi} \int_{s}^{s_{\mathrm{prev}}} \frac{\mathrm{d}\mu}{\mu} \int_{z_{\mathrm{cut}}(\mu)}^{1} \frac{\mathrm{d}z}{z} \right\}$$

Yields the next emission scale s, given the previous scale s_{prev}

Building differently ordered cascades

No-emission probability:

$$\Delta(s_{\mathrm{prev}}, s) = \exp\left\{-\frac{\alpha C_R}{\pi}\int_s^{s_{\mathrm{prev}}}\frac{\mathrm{d}\mu}{\mu}\int_{z_{\mathrm{cut}}(\mu)}^1\frac{\mathrm{d}z}{z}\right\}$$

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Interpretations for the scale:

$$s \to t_{\mathrm{form}}^{-1} = \frac{|\boldsymbol{\ell}|^2}{2p^+ z(1-z)}$$

(Formation time)

$$s \to \tilde{m}^2 = 2p^+ t_{\mathrm{f}}^{-1}$$

(Virtuality)

$$s \to \tilde{\theta}^2 = \frac{|\boldsymbol{\ell}|^2}{(p^+)^2[z(1-z)]^2}$$

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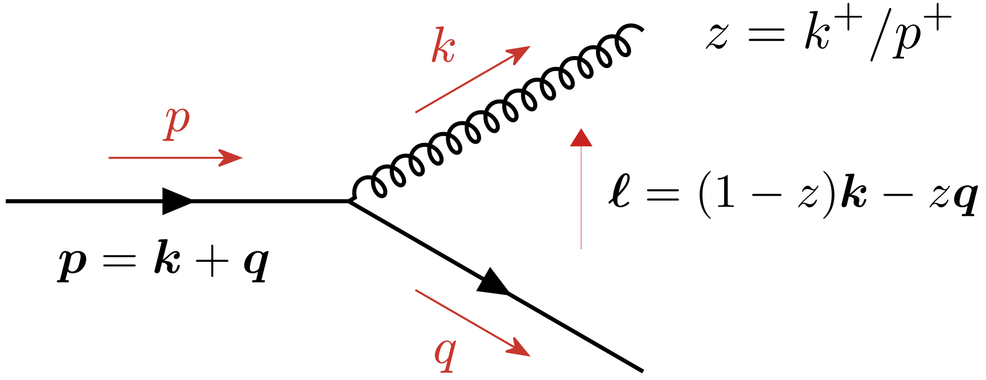

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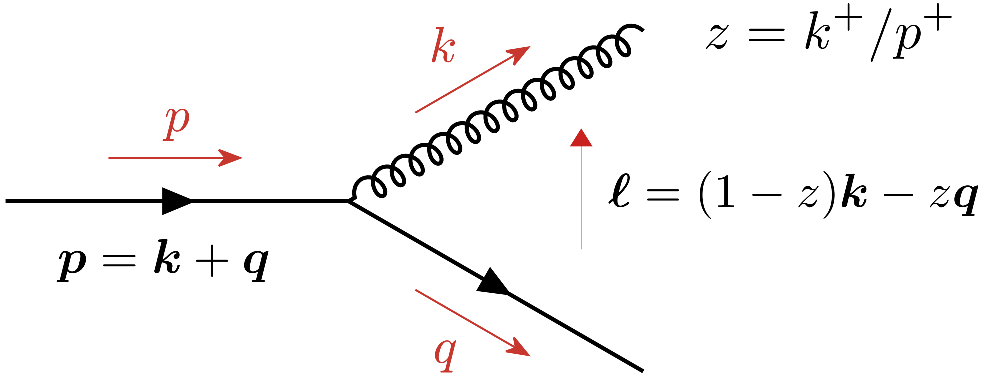

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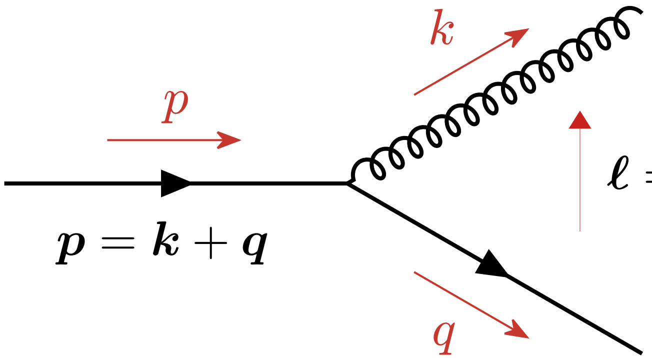

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$$\boldsymbol{\ell} = (1-z)\boldsymbol{k} - z\boldsymbol{q}$$

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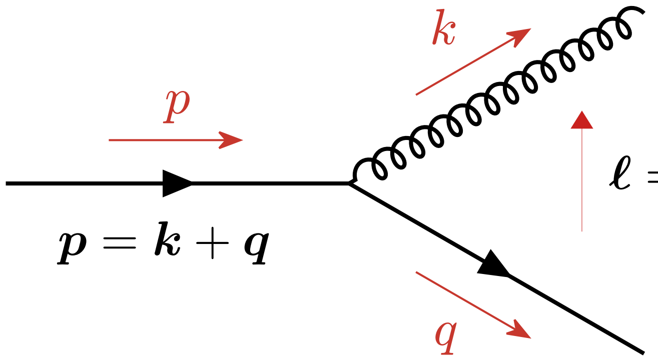

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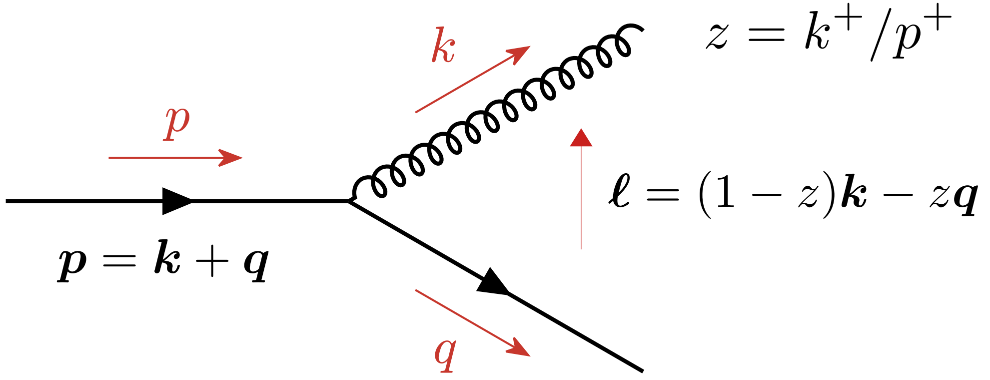

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Ensure that $|\boldsymbol{\ell}|^2 > k_{\text{had}}^2$

Parton Shower Details

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- Splittings happen above some hadronization scale $|\boldsymbol{\ell}|^2 > k_{\text{had}}^2$
  - Can be rewritten as a condition $z > z_{\text{cut}}$
- Initialization condition: $t_{\text{form}}^{-1} < p^+$

E.g. Formation time:

$$z_{\text{cut}} = \frac{k_{\text{had}}^2}{2p^+ t_{\text{form}}^{-1}}$$

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- To avoid large angles: $\tilde{\theta} < 2\sqrt{2}$

Opening angle:

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Determining Splitting Kinematics

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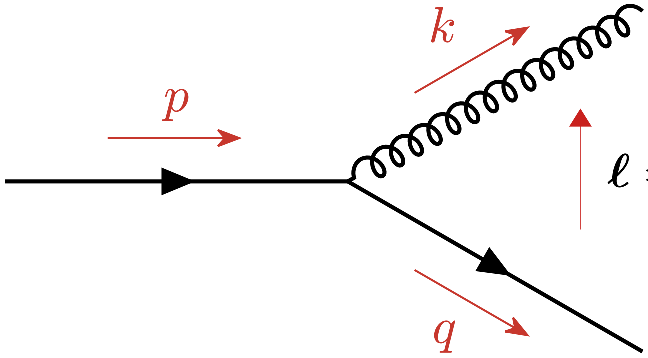

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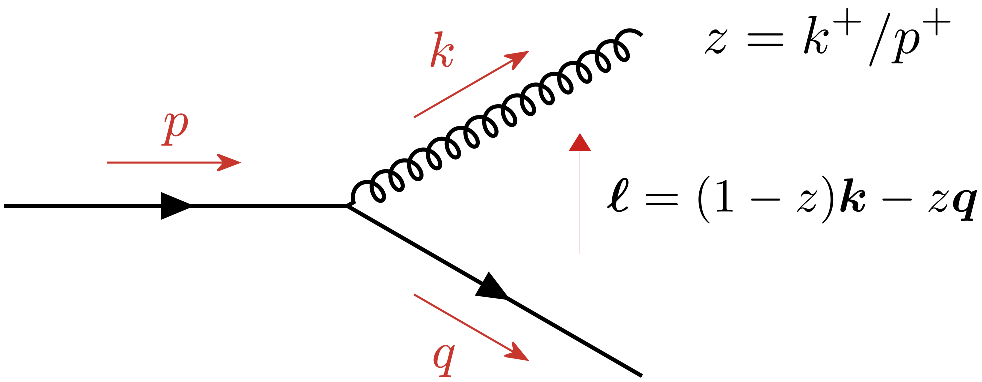

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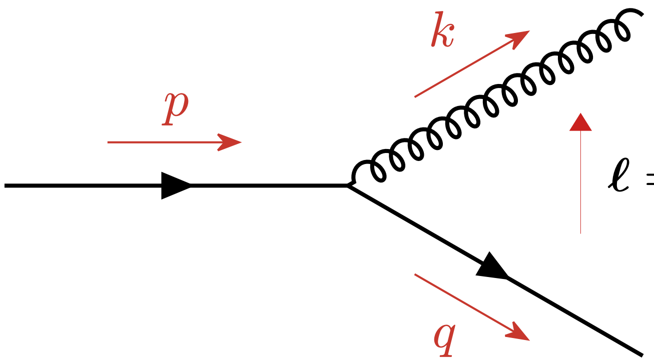

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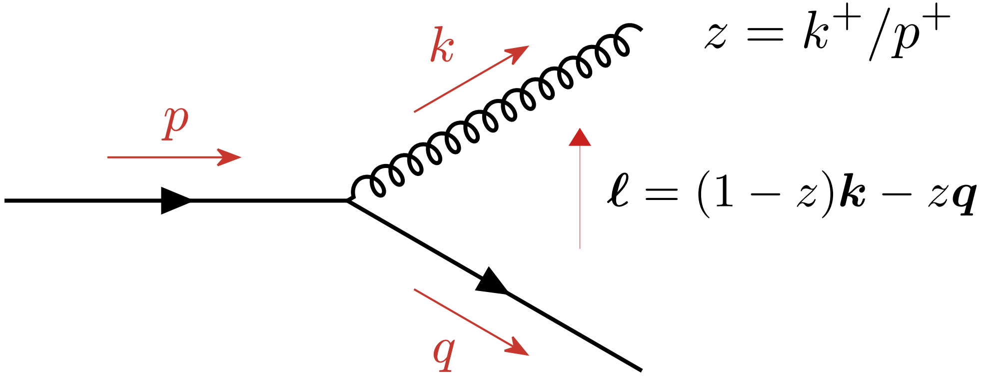

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$$\boldsymbol{\ell} = (1-z)\boldsymbol{k} - z\boldsymbol{q}$$
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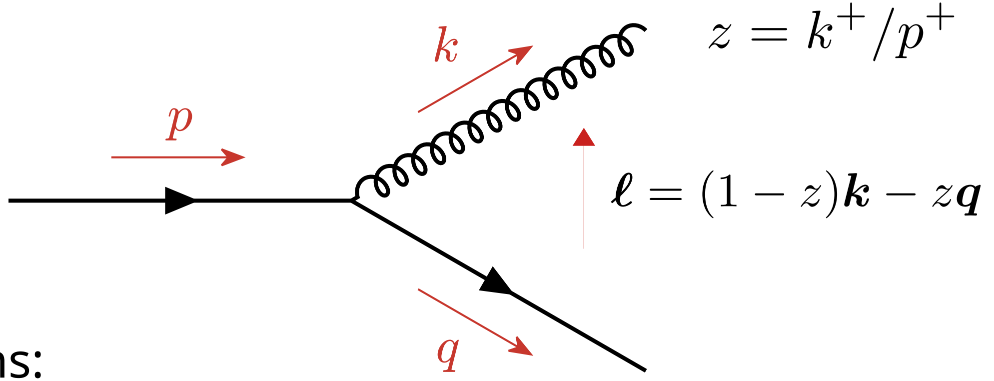

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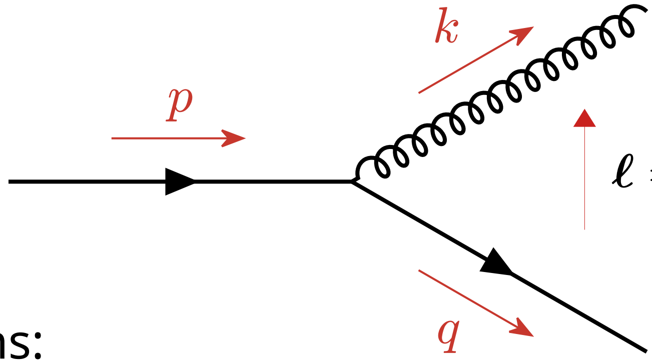
$$\boldsymbol{p} = \boldsymbol{k} + \boldsymbol{q} \qquad \boldsymbol{q} = -\boldsymbol{\ell} + (1-z)\boldsymbol{p}$$



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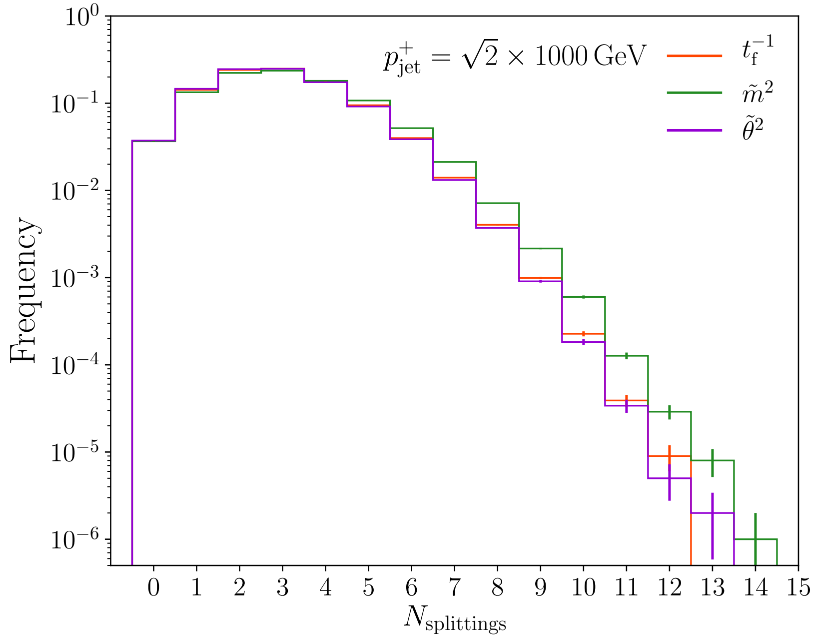
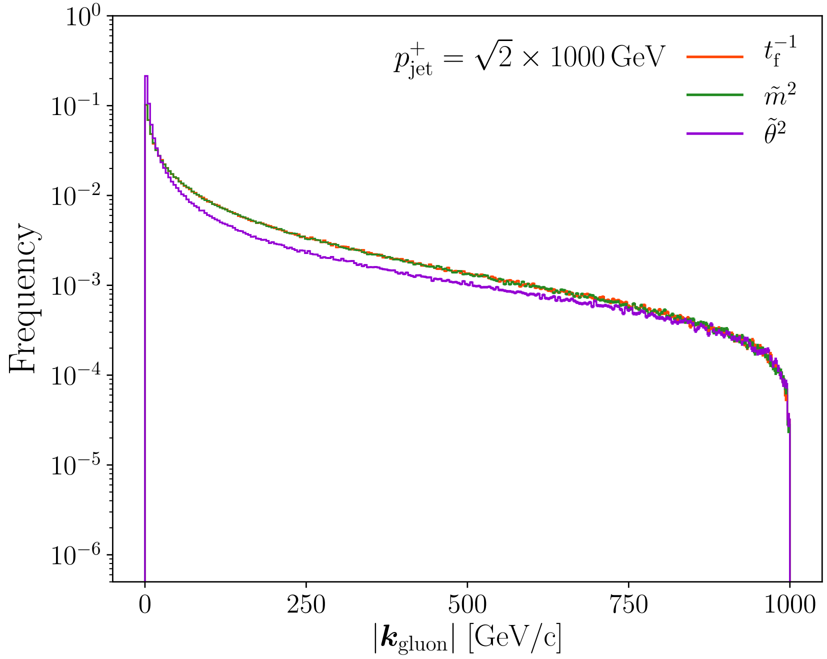
Differences in ordering choices

Splittings along the quark branch





Different orderings → Different phase-space for allowed splittings

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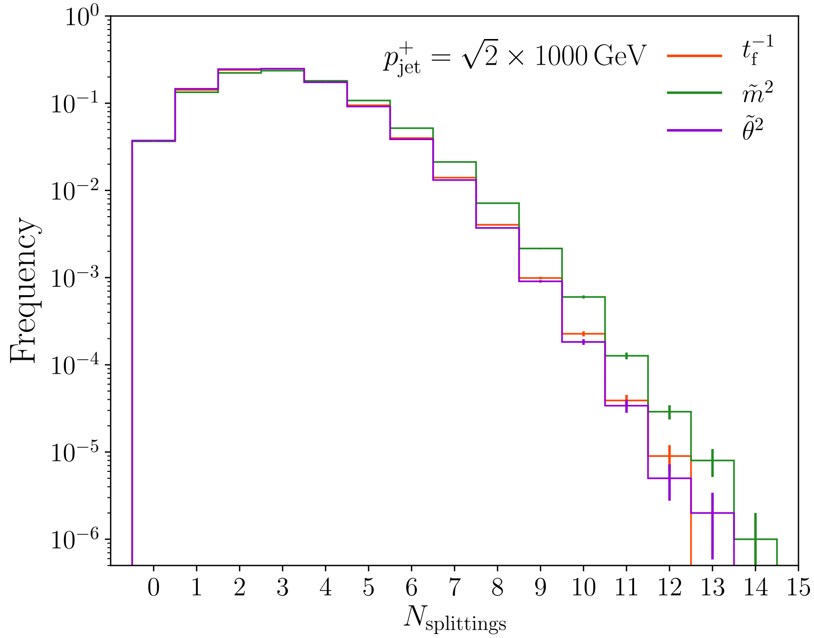

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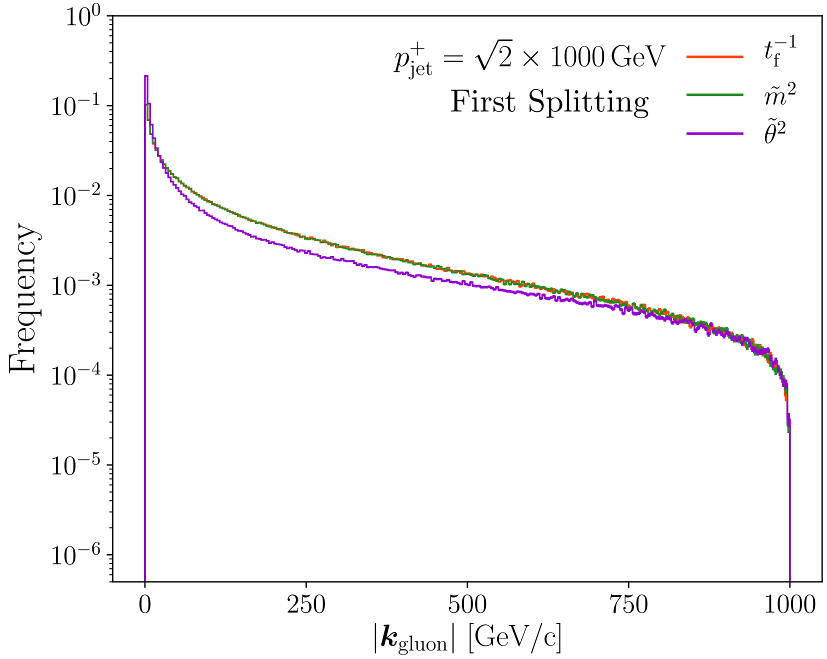
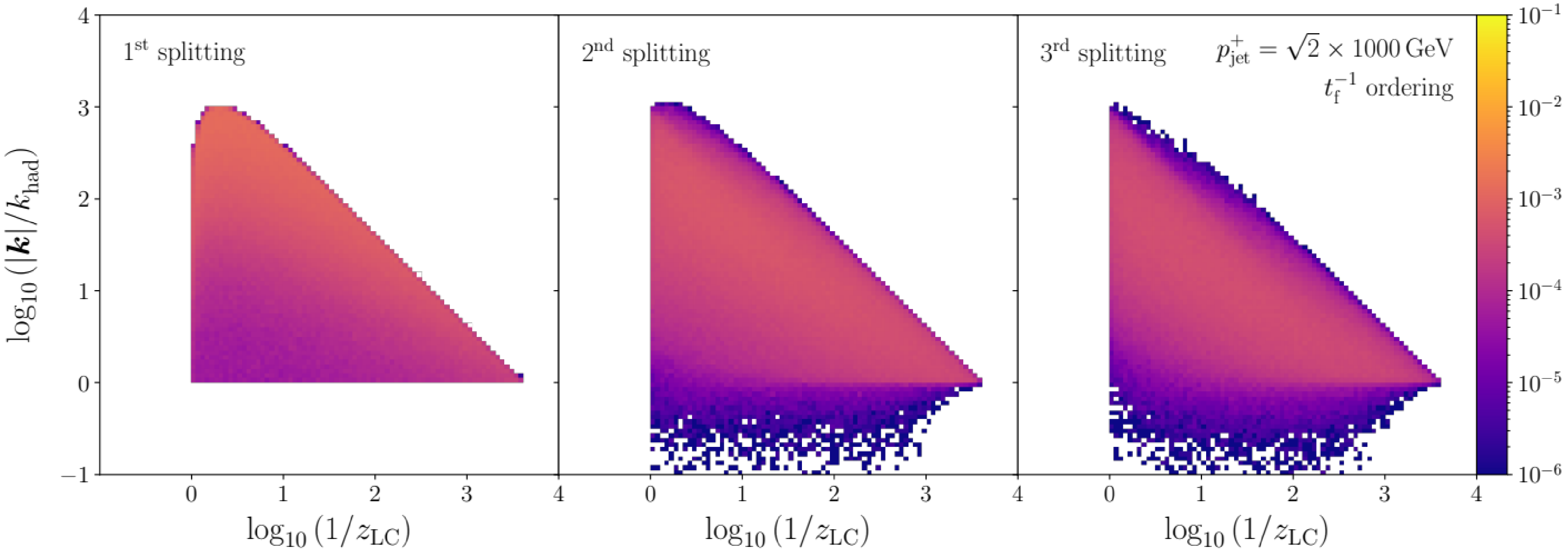
Transverse momentum of 1st splitting



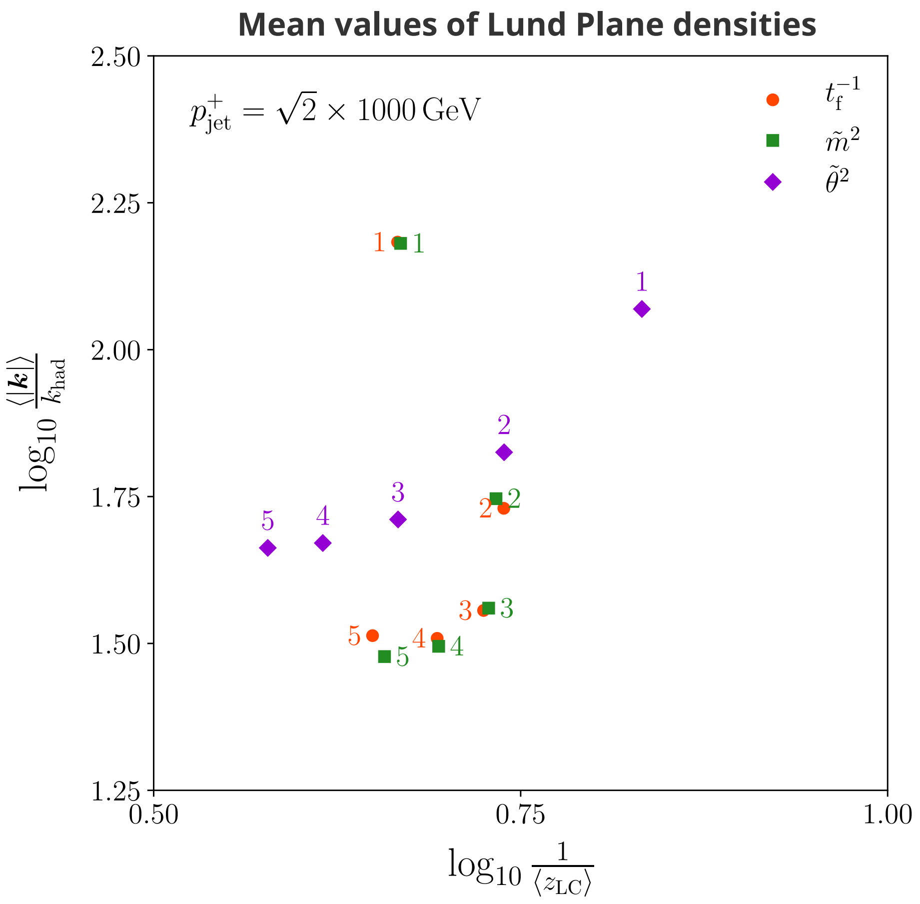
Transverse momentum distribution follows $\frac{\mathrm{d}|\boldsymbol{k}|^2}{|\boldsymbol{k}|^2}$

Lund Plane Densities



Shower evolution: Transverse momentum decreases, momentum fraction increases.

Lund Plane Trajectories



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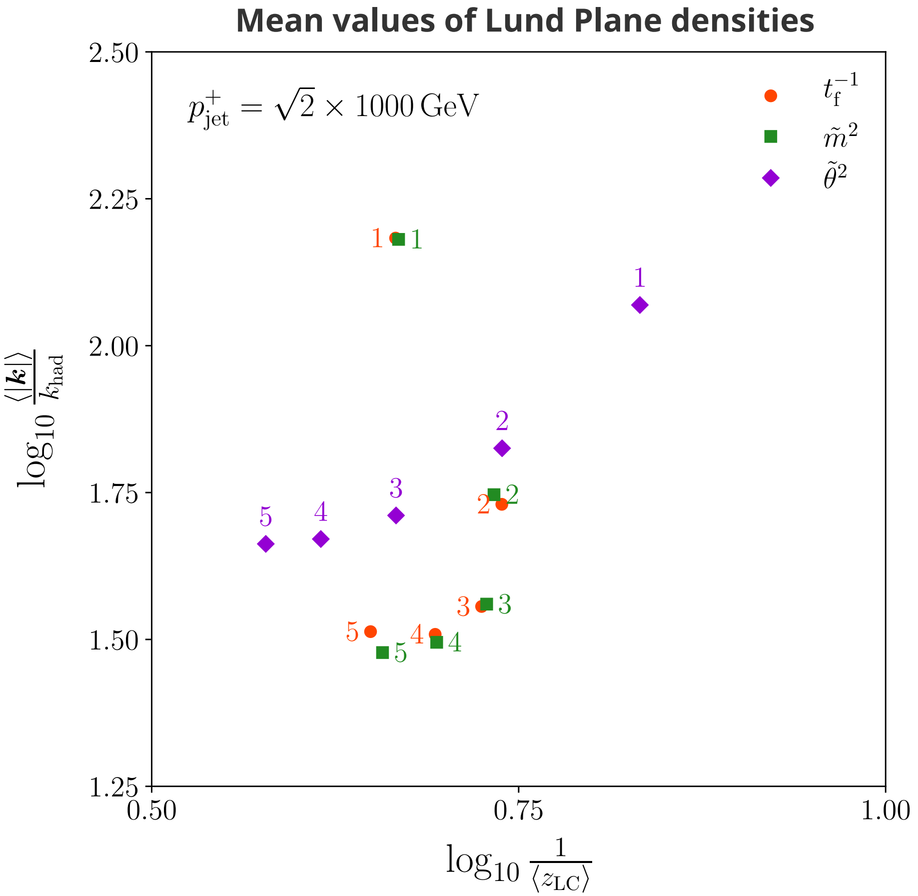
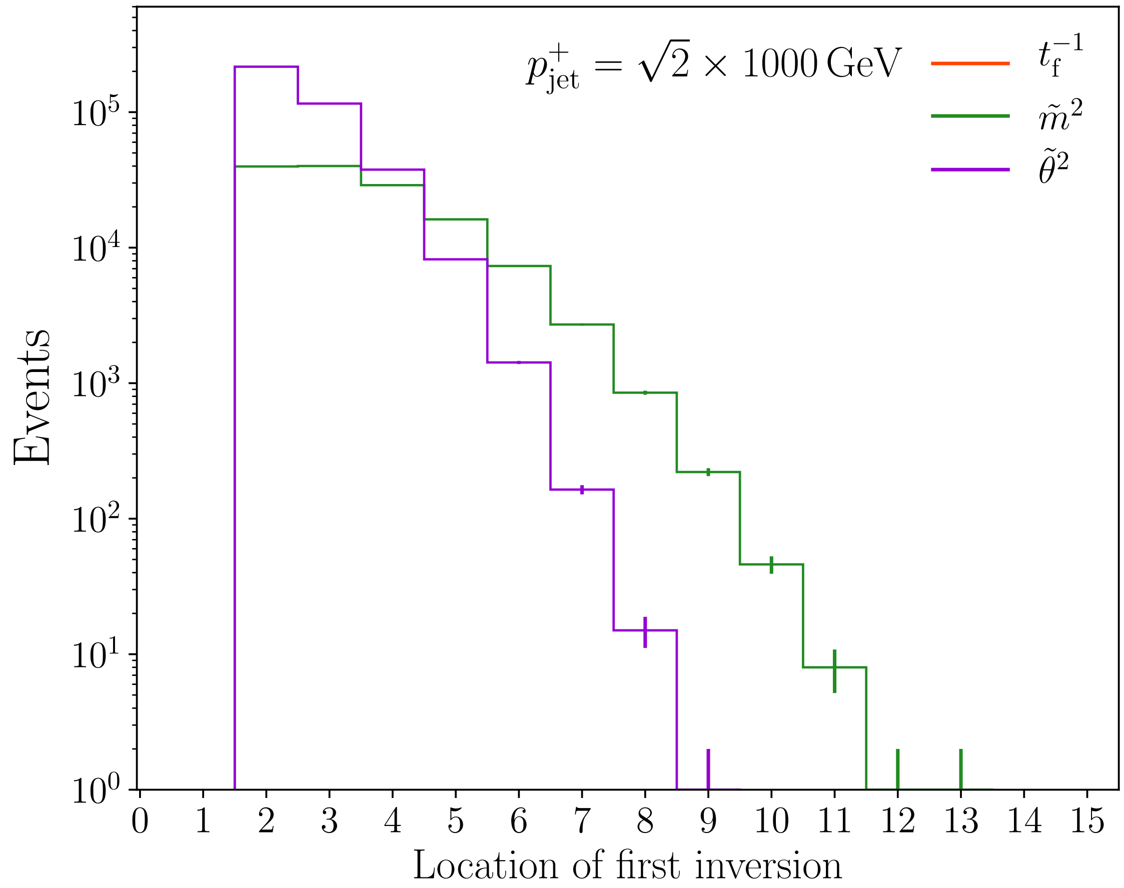


Differences between phase-space trajectories

Formation Time Inversions



Formation Time Inversions:

Splittings with a formation time shorter that their immediate predecessor.

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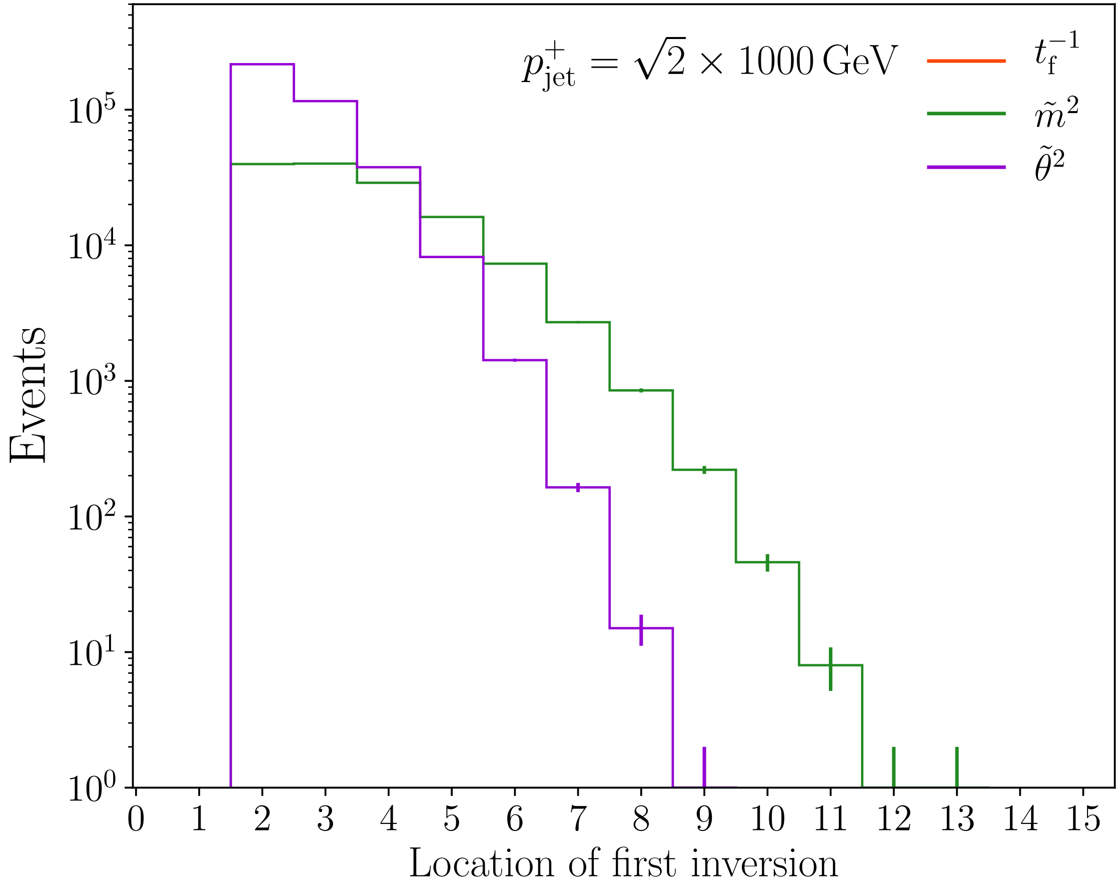


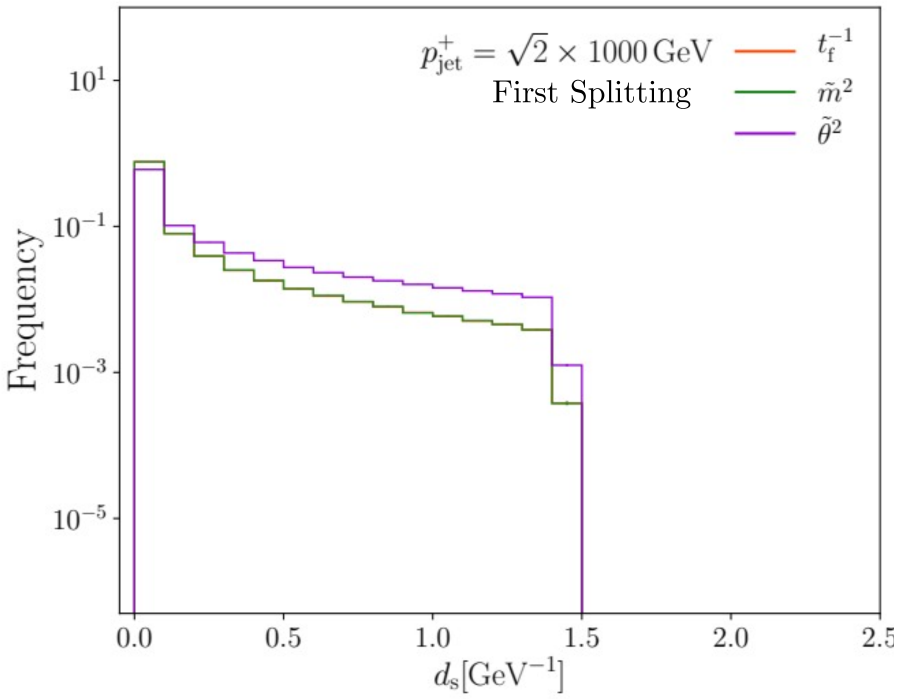
Formation Time Inversions:

Splittings with a formation time shorter that their immediate predecessor.

Does this discrepancy translate into differences in quenching magnitude?

Let’s look at jet quenching!

Simple (Pseudo-)Quenching Models



- Consider distance between daughters: $\mathrm{d}_s = \sqrt{\frac{t_{\rm form}}{k^+}}$
- **A <u>simplistic</u> model:**
  - Eliminate event if $d_s > d_{\rm coh} = \frac{1}{\sqrt{\hat{q}L}}$ **(Decoherence)**

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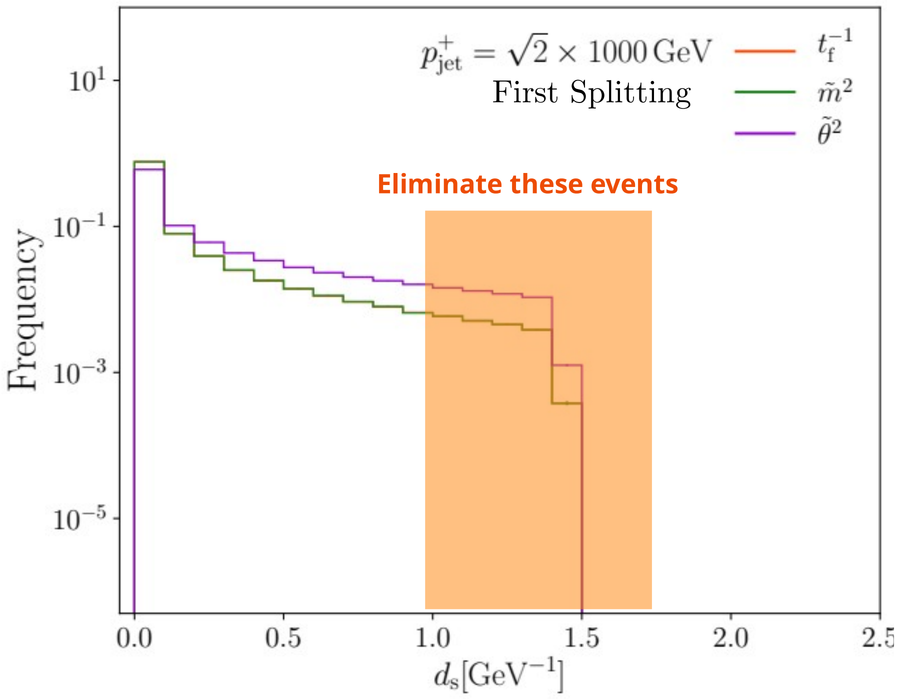

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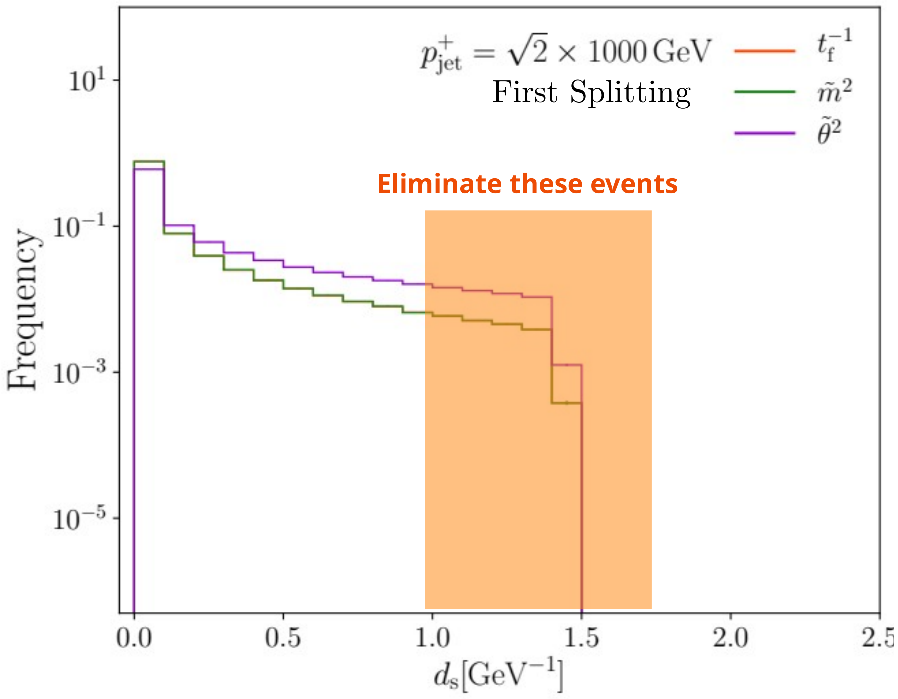

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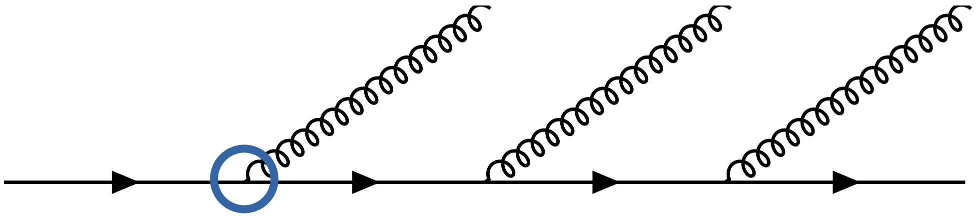

- Option 1: Apply only to first splitting

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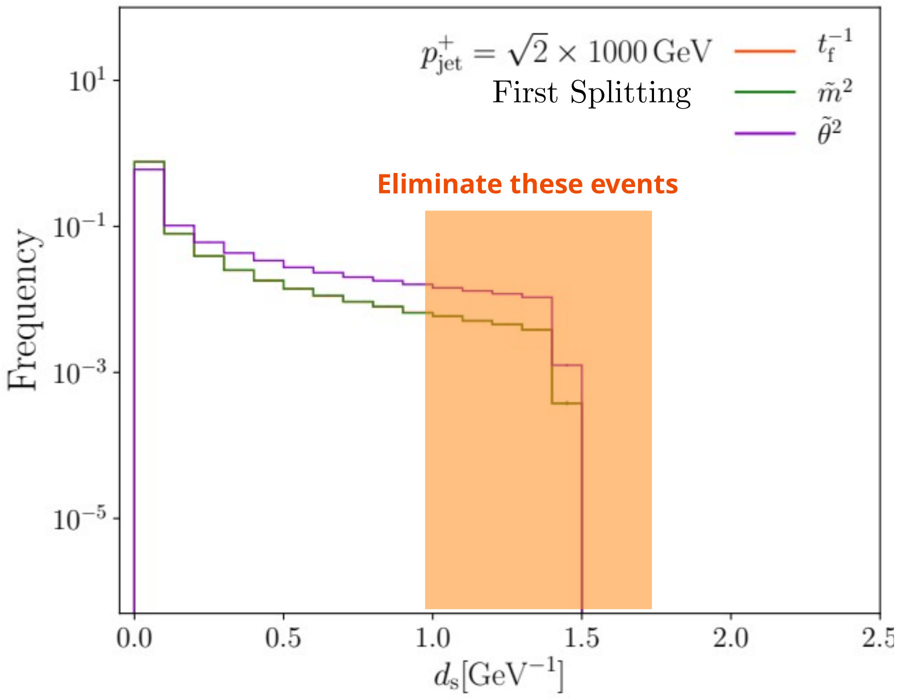

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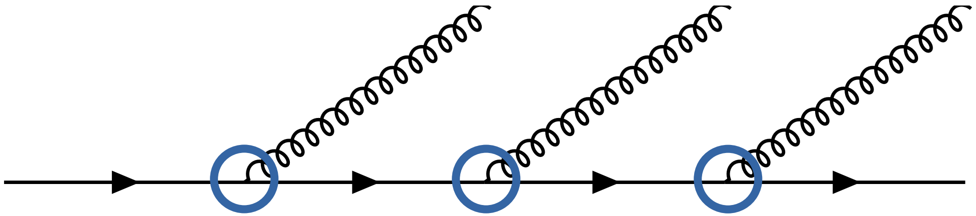

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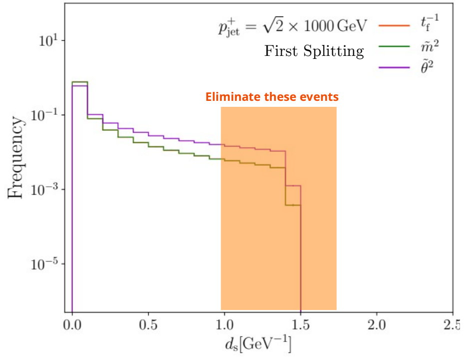

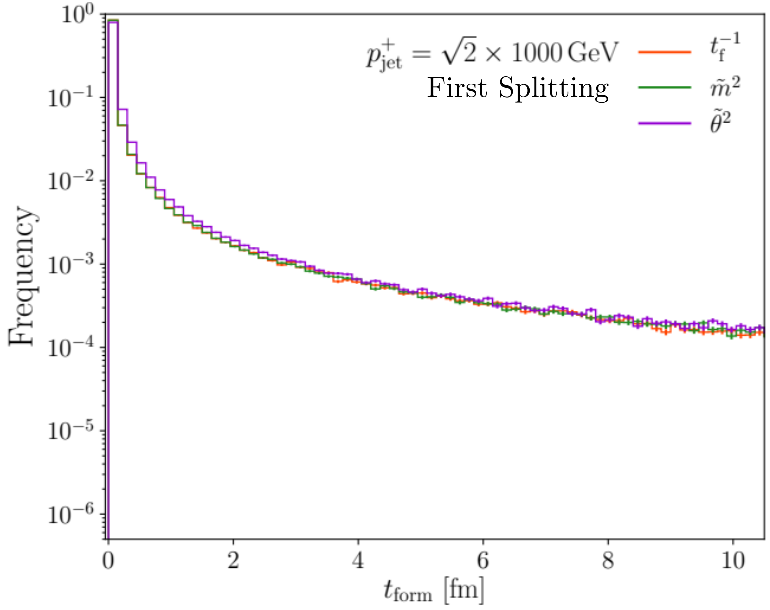

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- **A <u>slightly</u> less simplistic model:**
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  - And if $t_{\rm form} < L$

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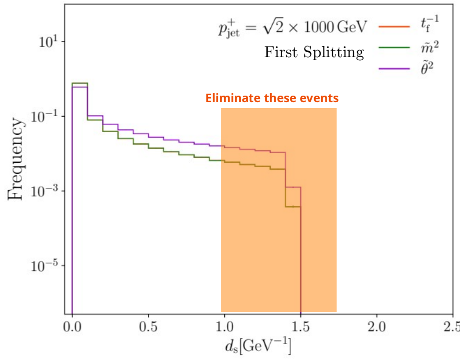

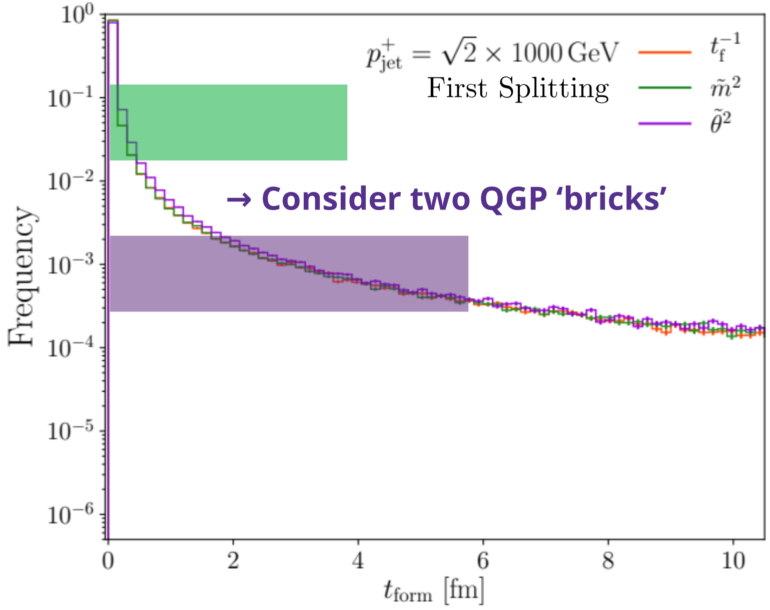

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Influence of the first splitting on quenching

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Apply quenching condition to the entire quark branch

Quantifies importance of ordering scale

Summary

- We have created a toy Parton Shower Monte Carlo:
  - To explore differences between ordering variables
  - Aiming at a framework for time-ordered, medium-induced emissions
- Choice of vacuum ordering → Sensitivity to quenching at differential timescales
  - Model does not account for medium dilution, differential energy loss
  - Only implements vacuum emissions **[Medium-induced emissions needed]**
- Is jet quenching sensitive to the ordering of vacuum-like emissions?
  - Suggested by this simple model. **[Work in Progress]**

Thank you!

Acknowledgements

LIP

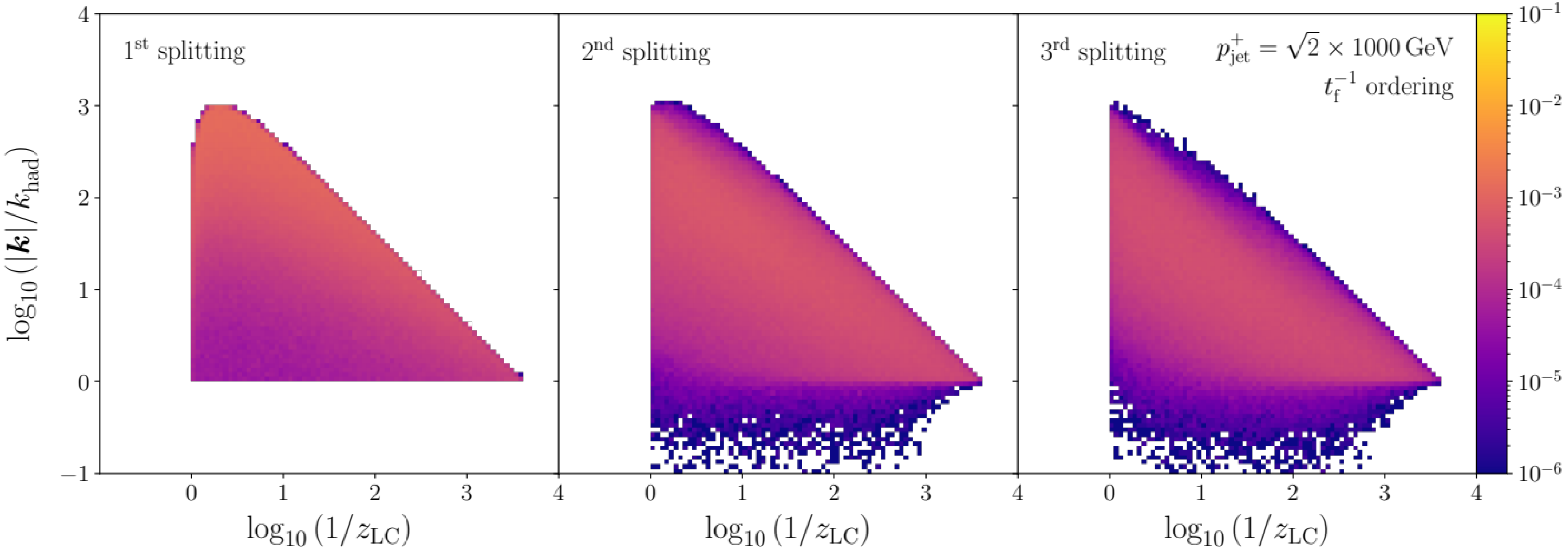
fct
Fundação para a Ciência e a Tecnologia

TÉCNICO LISBOA

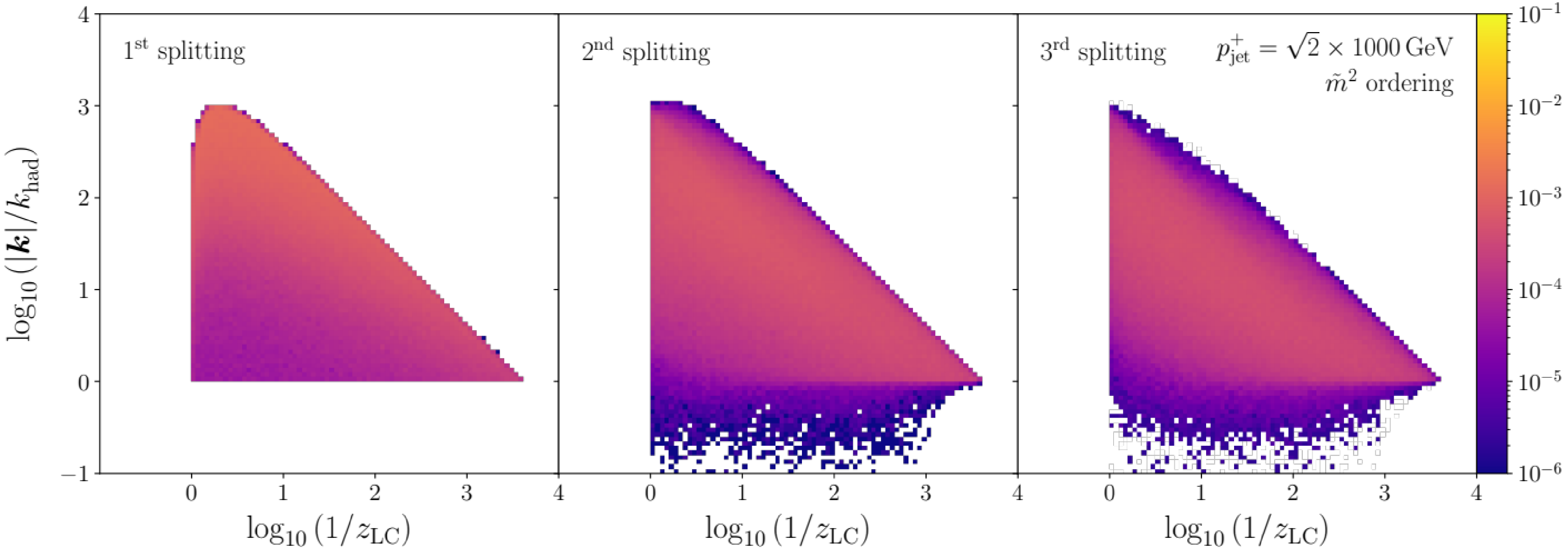
REPÚBLICA PORTUGUESA

Backup Slides

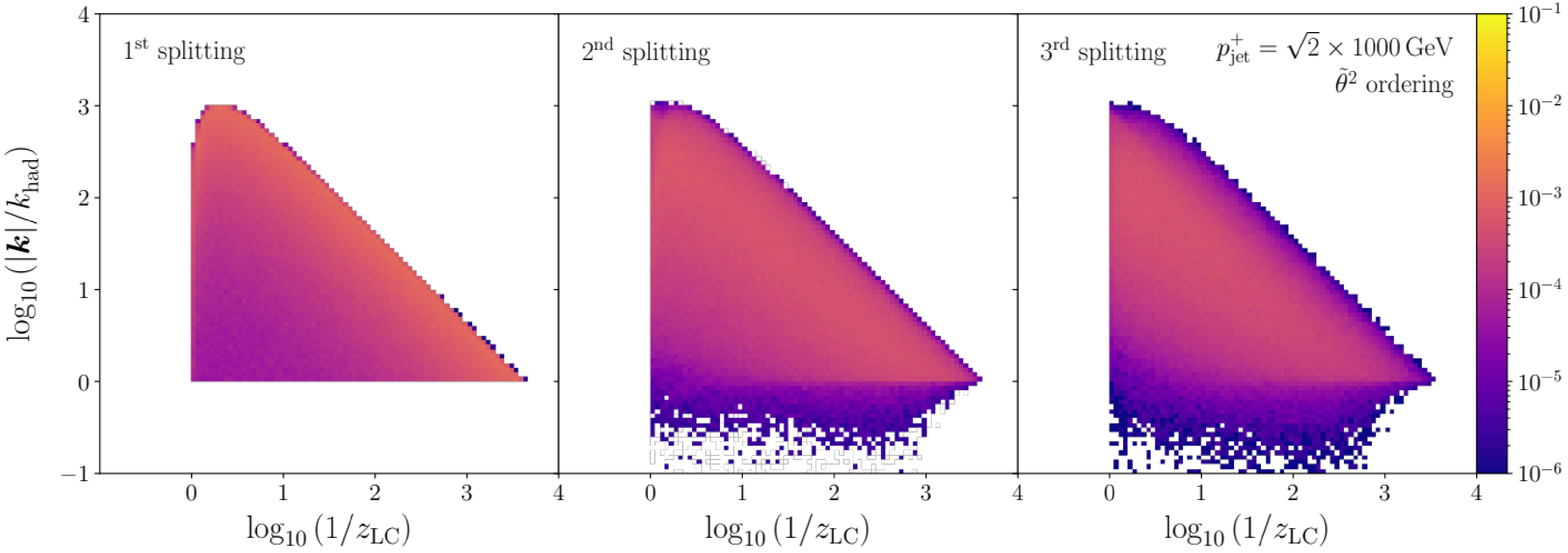
Lund Plane Densities – Time ordering



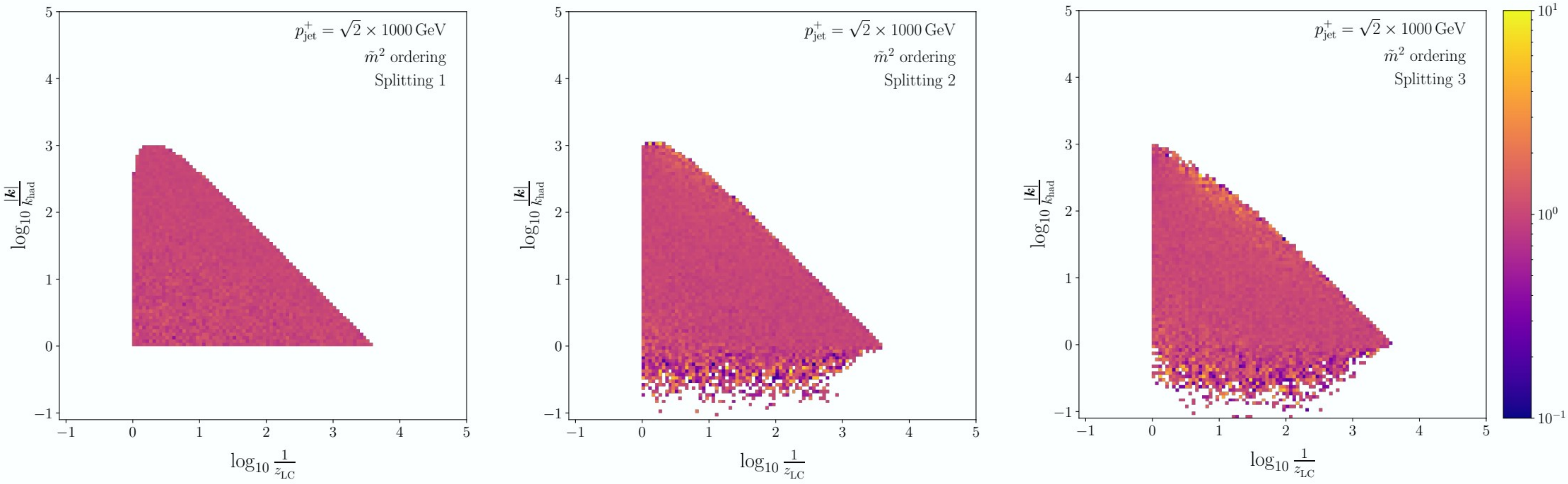
Lund Plane Densities – Virtuality ordering



Lund Plane Densities – Angular ordering



Lund Density Ratio – Mass / Formation Time



All Events

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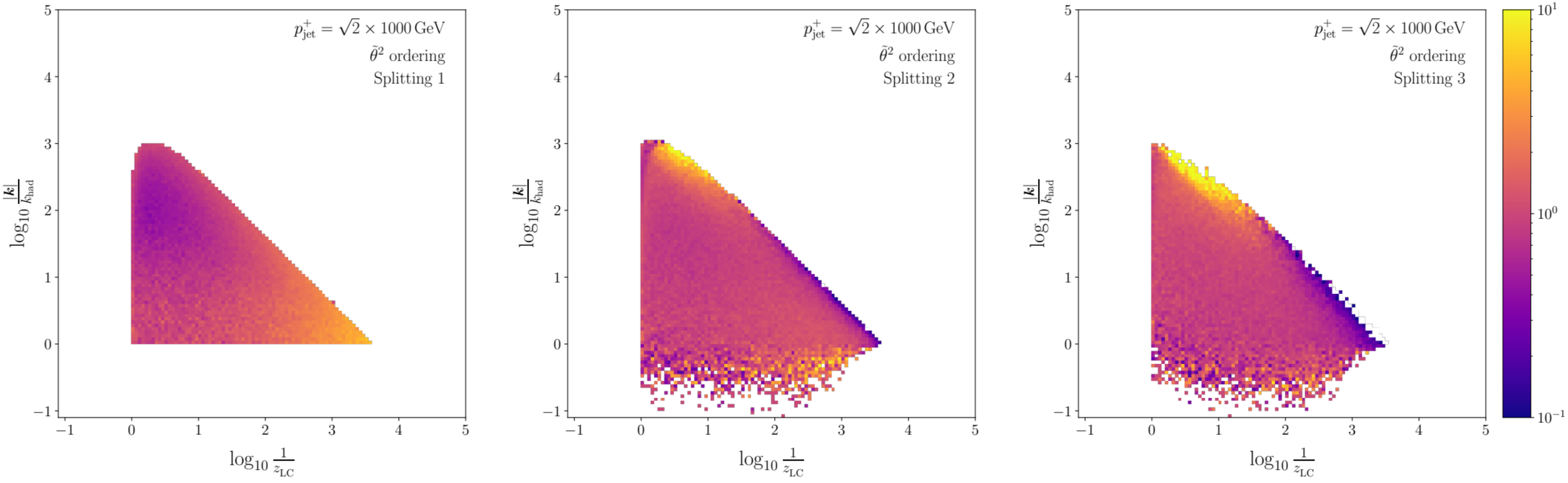

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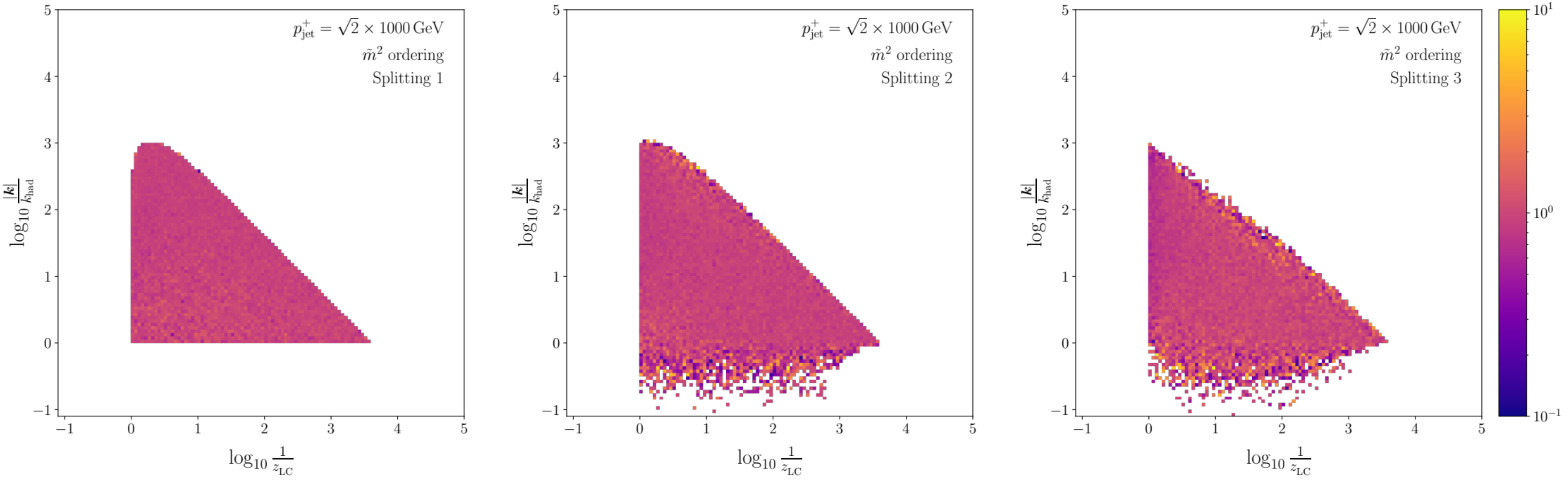

Events with at least 3 quark splittings

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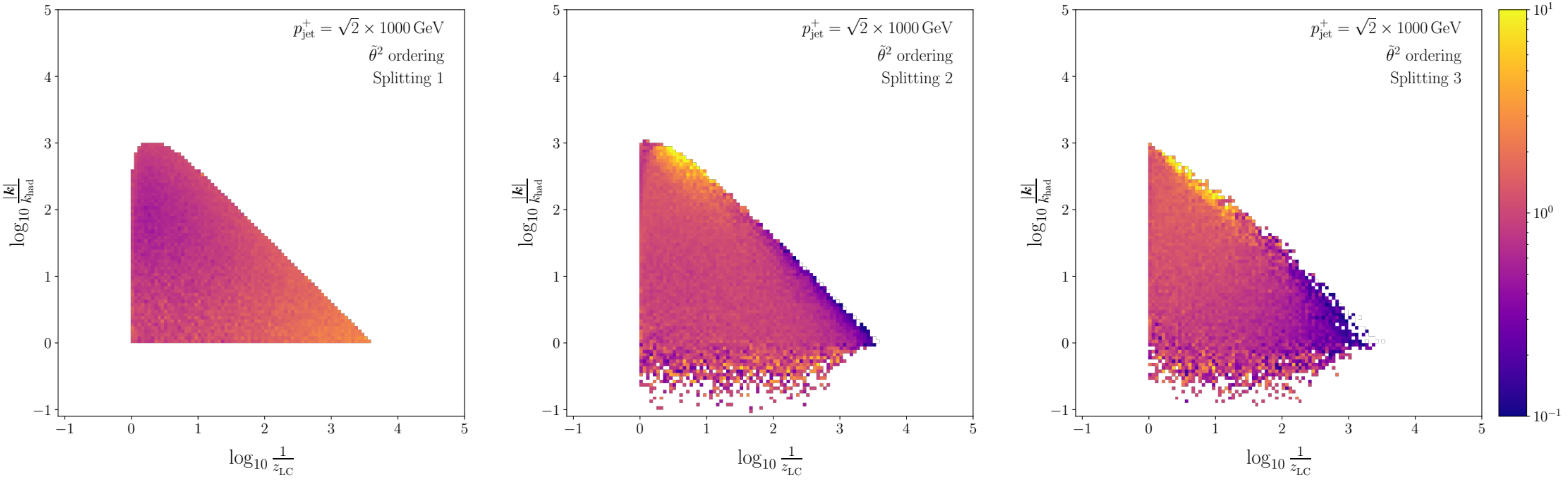

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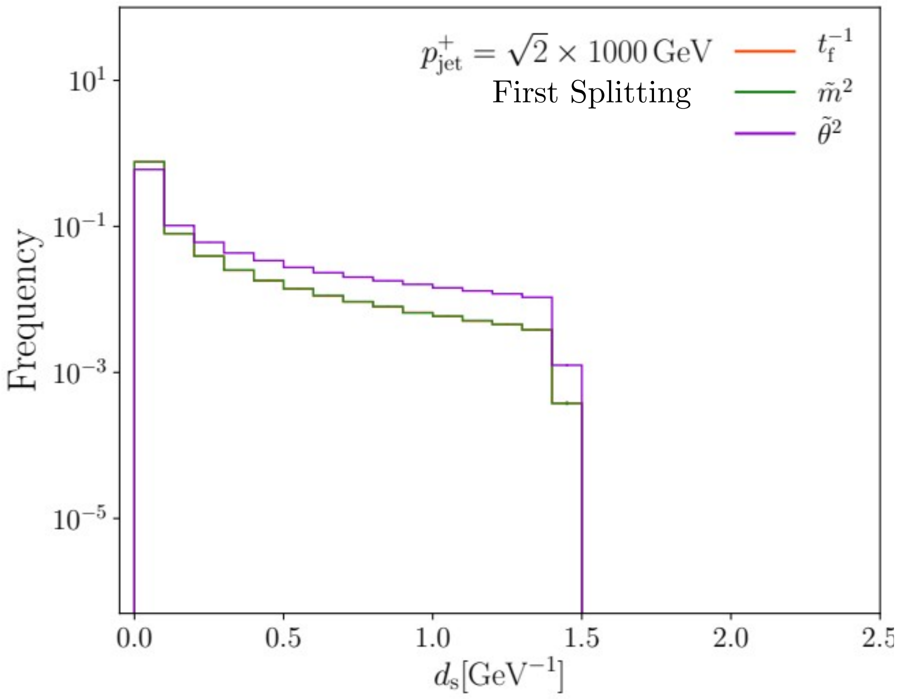

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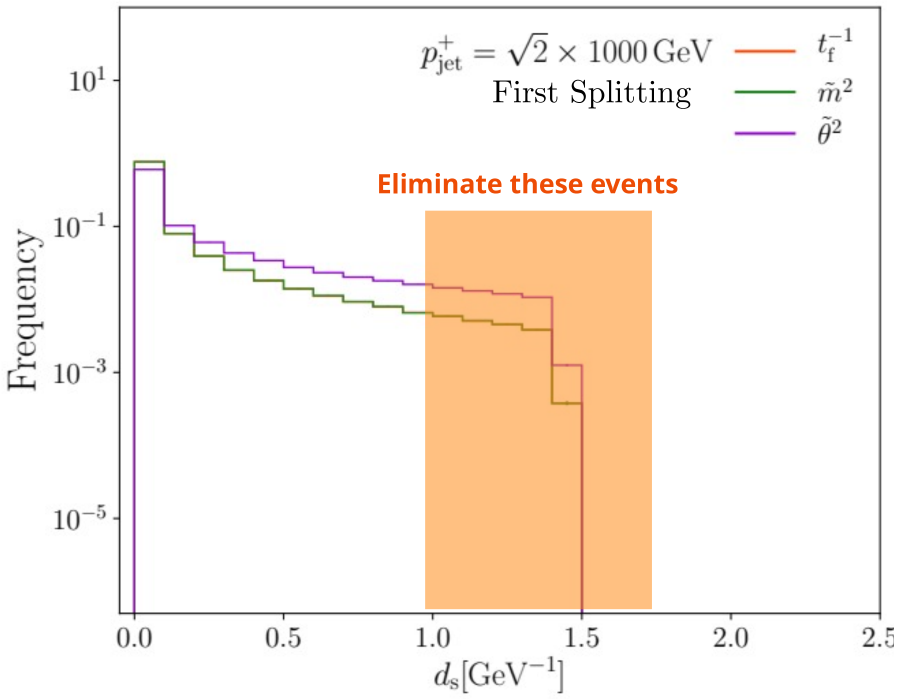

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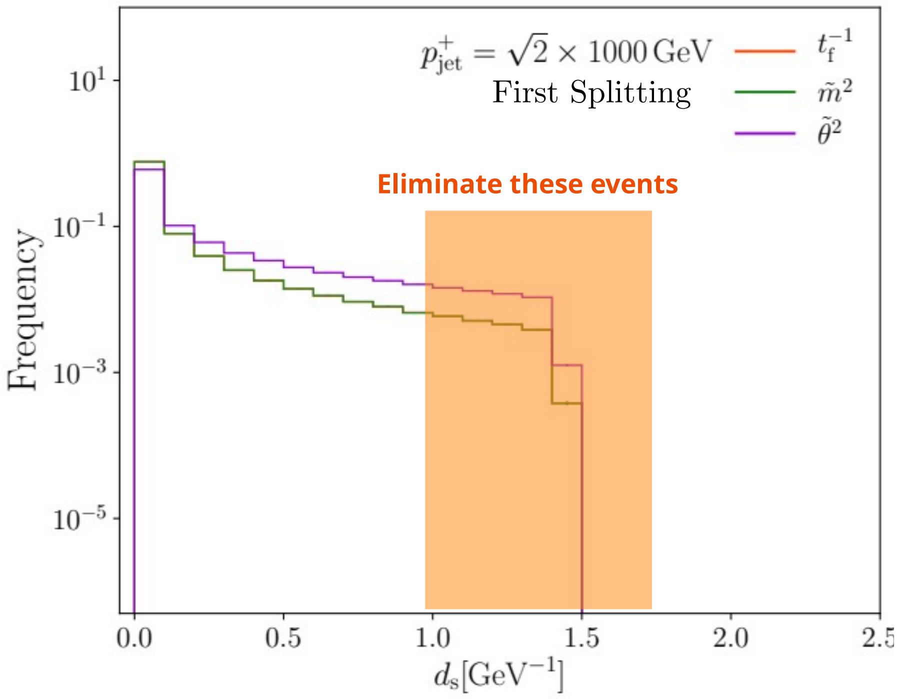

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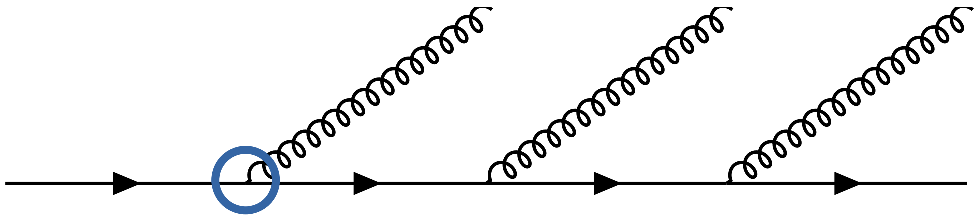

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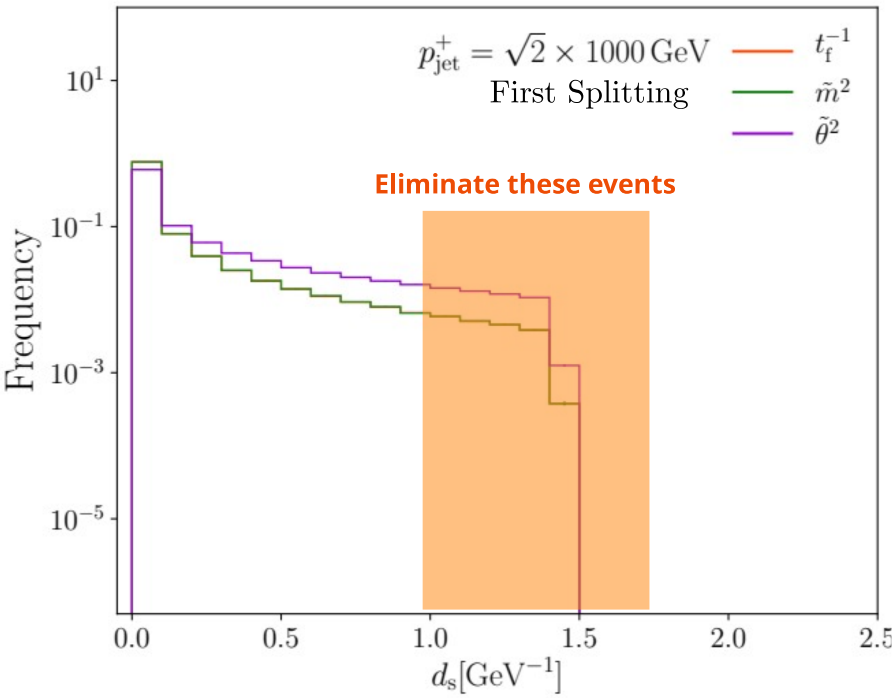

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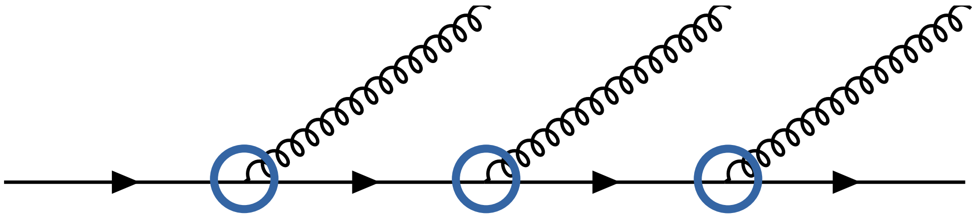

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Quenched events in simple model

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$\tilde{\theta}^2$	8.0 %	12.5 %	18.2 %

Apply quenching condition to the first splitting

L [fm]	4		6
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t_{f}^{-1}	11.0 %	18.0 %	28.1 %
$\tilde{m}^2$	11.8 %	19.3 %	29.9 %
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Apply quenching condition to the entire quark branch