Parton cascades at DLA: the role of the evolution variable

André Cordeiro

In collaboration with:

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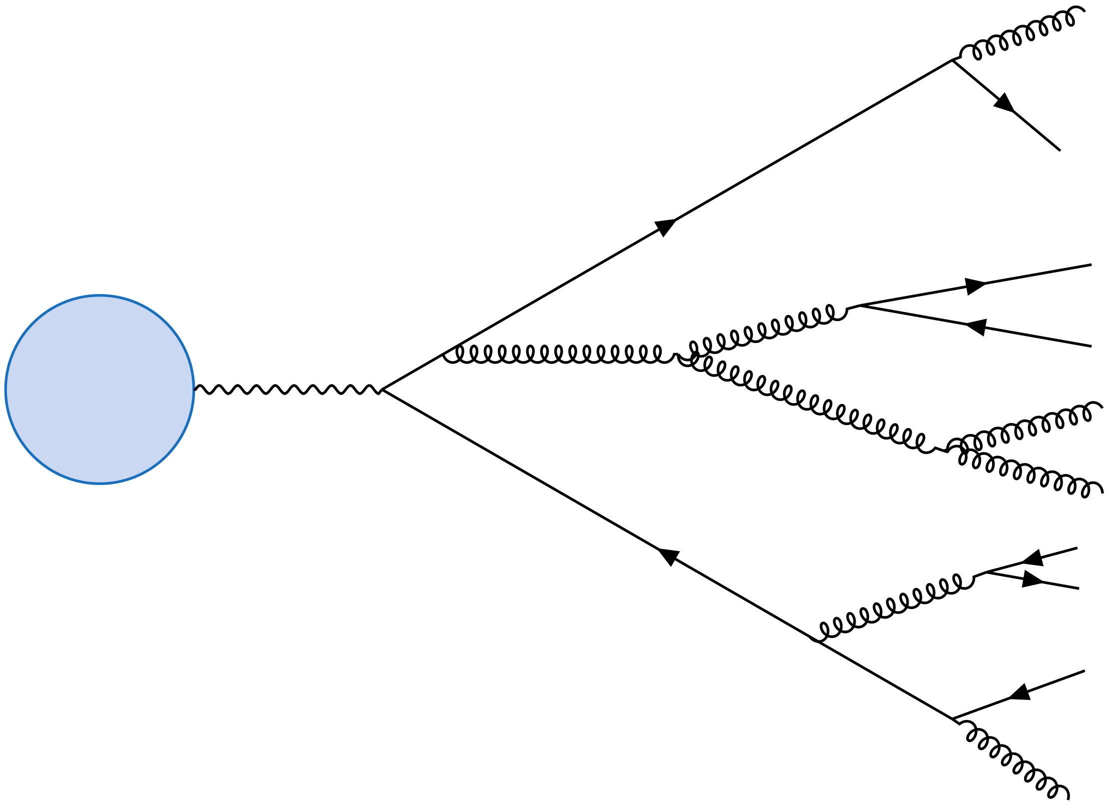
Fabio Dominguez, Guilherme Milhano

LIP

TÉCNICO LISBOA

New jet quenching tools to explore equilibrium and non-equilibrium dynamics in heavy-ion collisions
12–16 February 2024

Parton Showers in a Coloured Medium



- Hard partons radiate until the hadronisation scale → <u>Multi-scale object</u>

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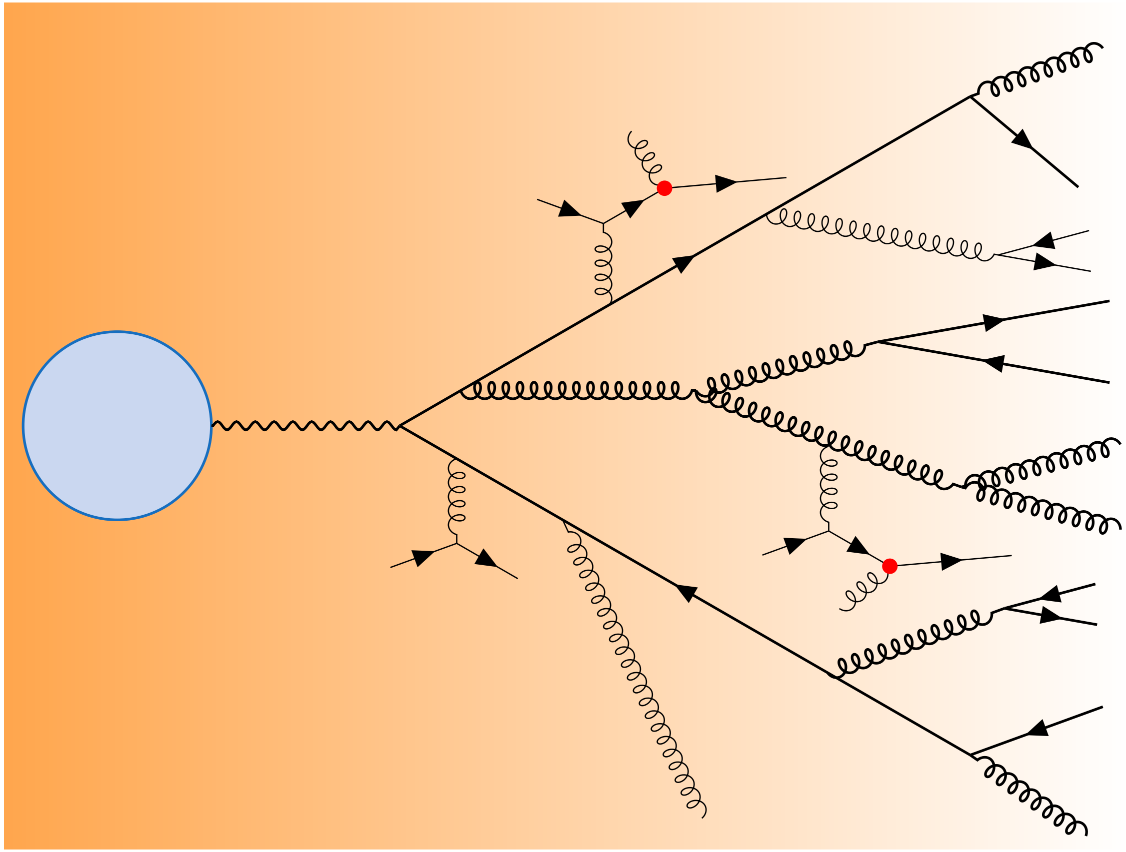

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- Time-ordered picture needed for medium interface with the cascade

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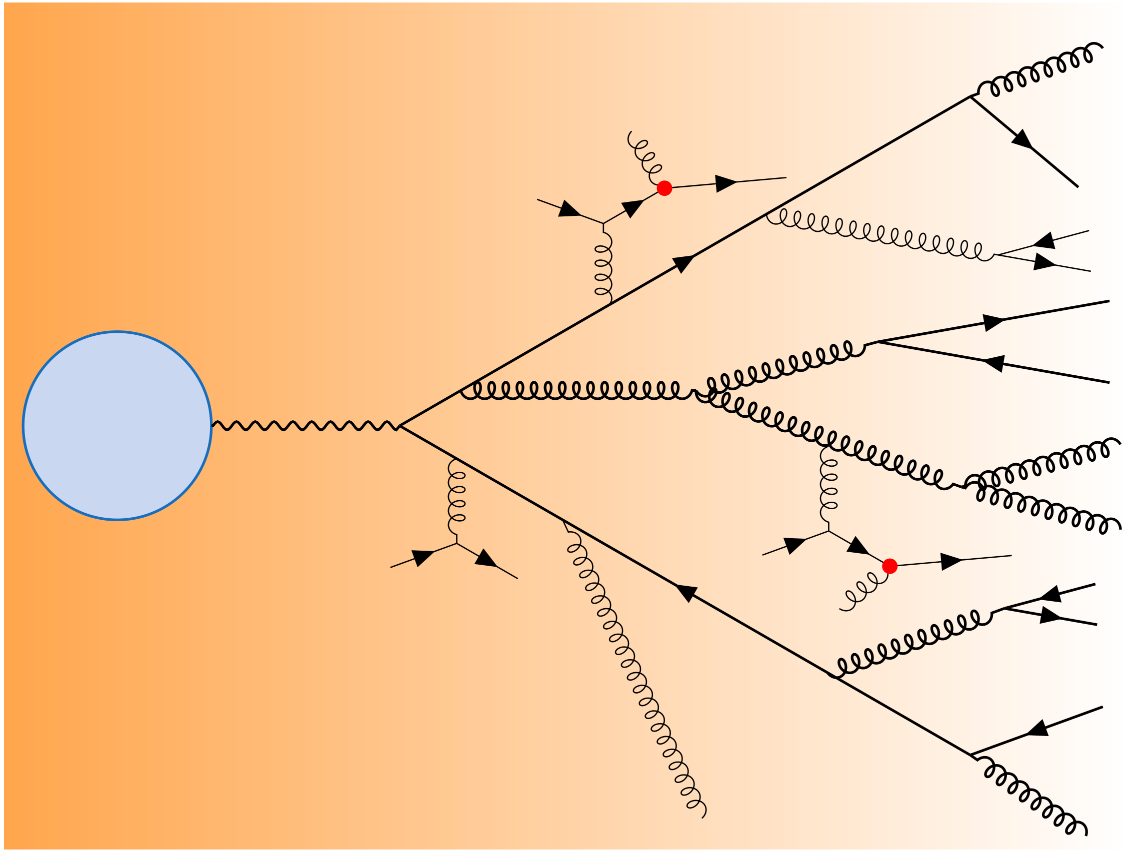

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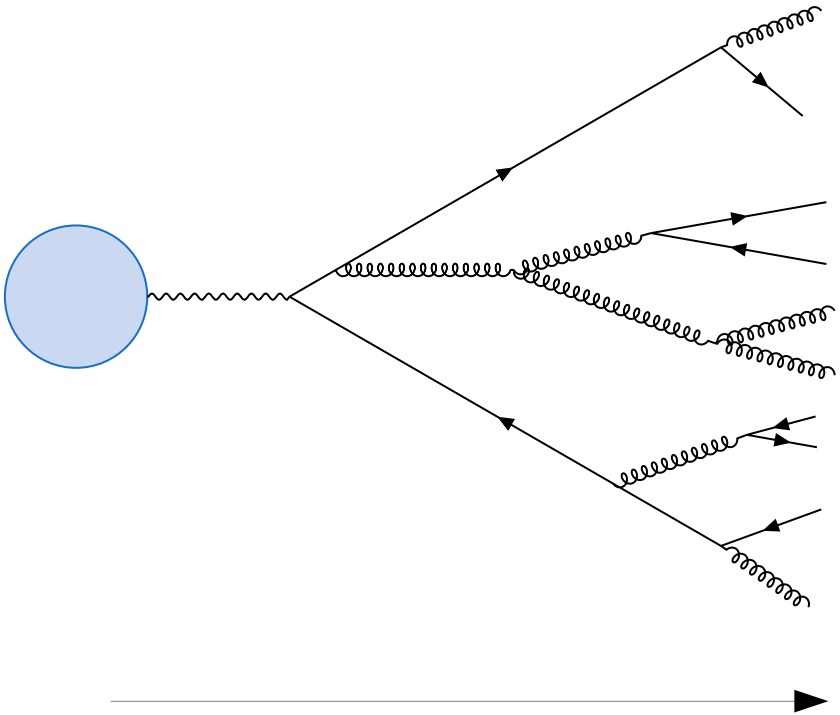
Is jet quenching sensitive to the ordering of vacuum-like splittings?

First, a look at vacuum (proton-proton) showers

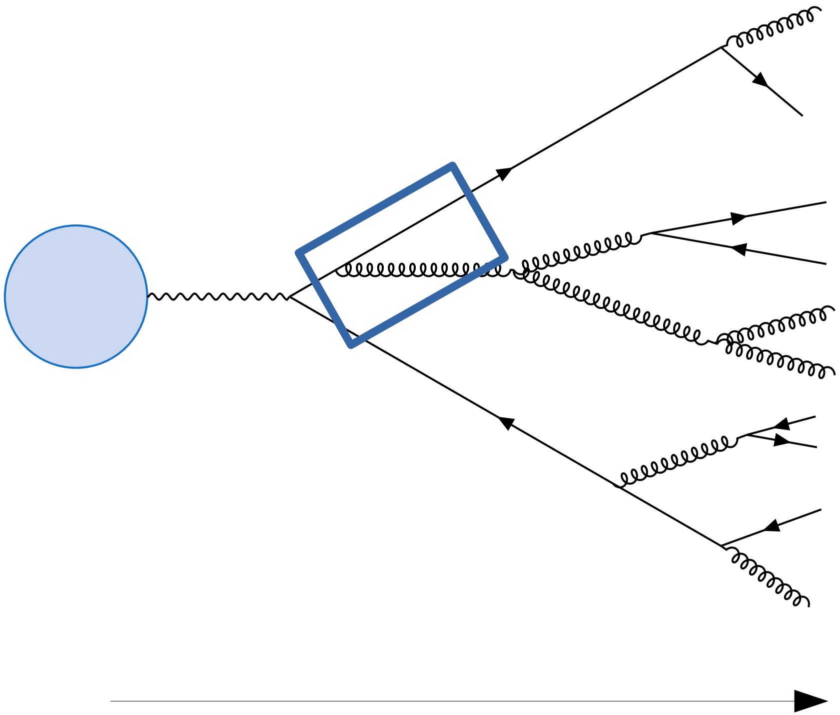
How to build a parton shower



Splittings with decreasing scale μ

How to build a parton shower

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



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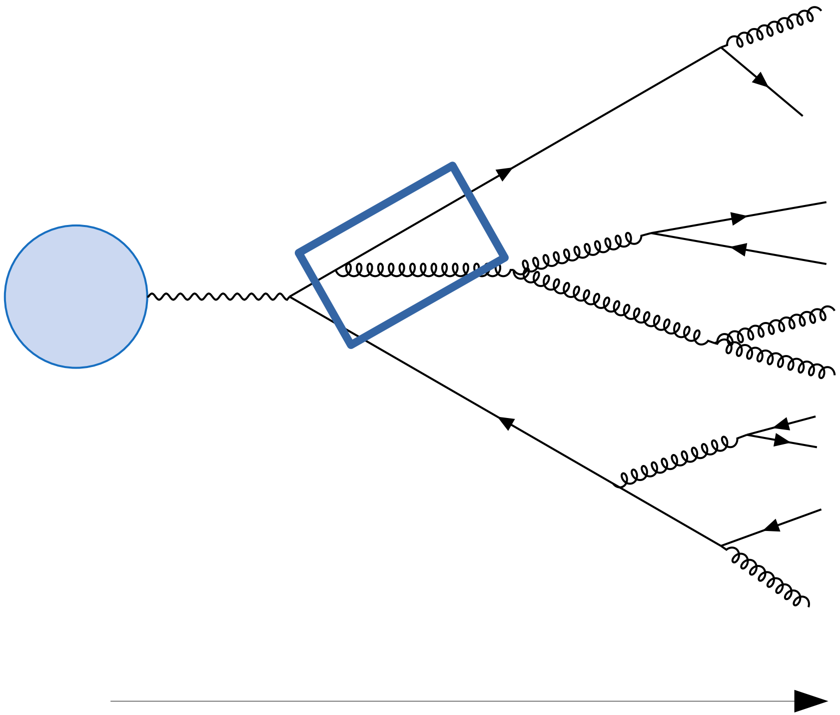
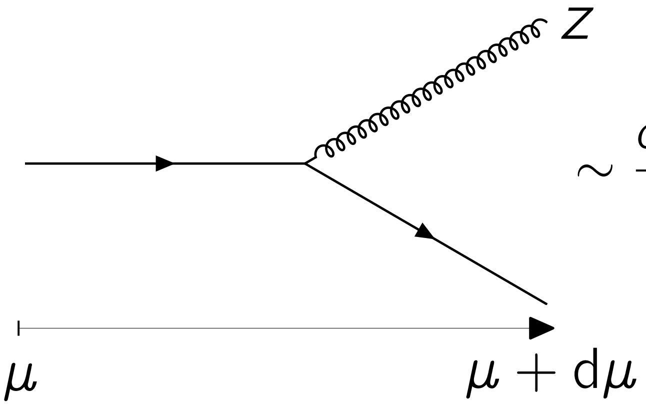


Splittings with decreasing scale μ

Splitting probability given by pQCD:



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

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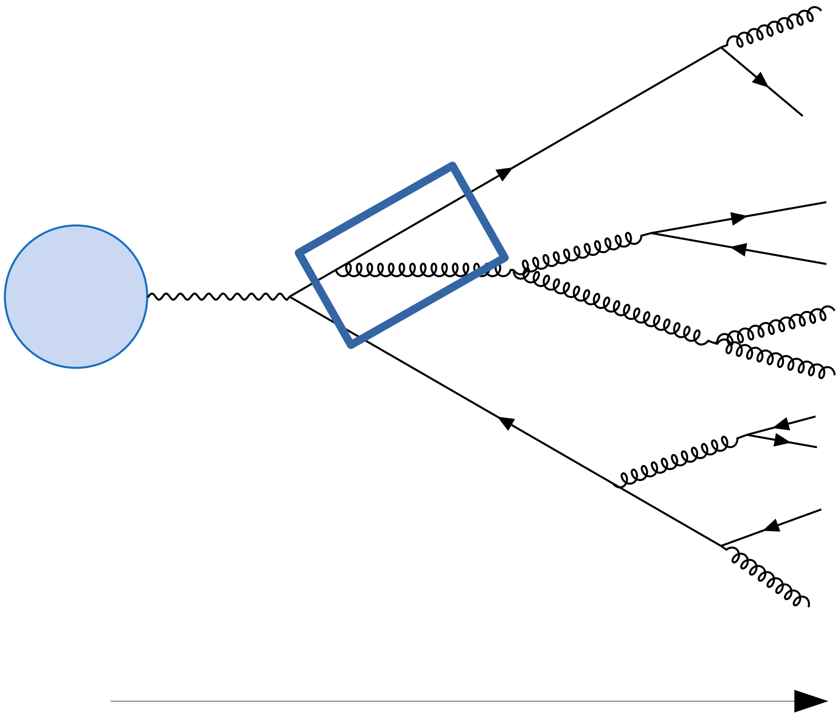

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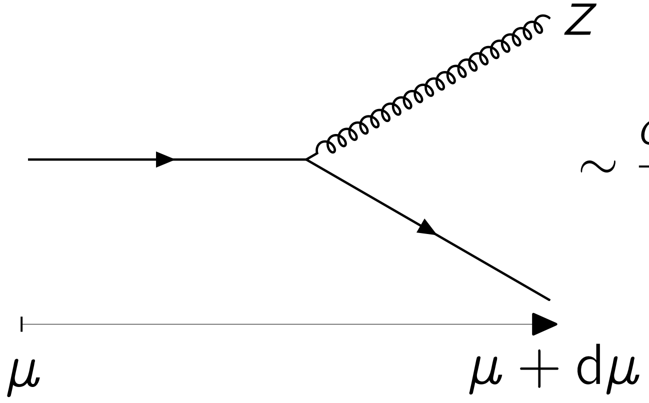

$$\sim \frac{\alpha\, C_F}{\pi} \frac{\mathrm{d}\mu}{\mu} \frac{\mathrm{d}z}{z}$$

Probability of not emitting until some scale s **:**

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

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

Building differently ordered cascades

No-emission probability:

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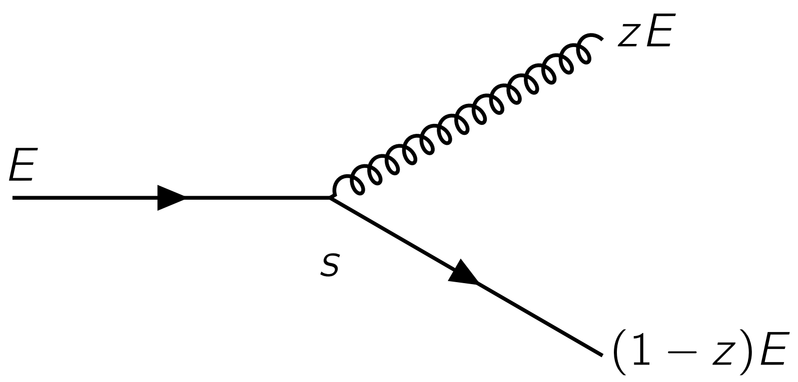
Splitting variables:



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Interpretations for the scale:

$$s \to p^2 = \frac{|\boldsymbol{p}_{\rm rel}|^2}{z(1-z)}$$

(Virtuality)

$$s \to t_{\rm form}^{-1} = \frac{p^2}{E} = \frac{|\boldsymbol{p}_{\rm rel}|^2}{E z(1-z)}$$

(Formation time)

$$s \to \zeta = \frac{p^2}{E^2 z(1-z)} = \left(\frac{|\boldsymbol{p}_{\rm rel}|}{E\, z(1-z)}\right)^2$$

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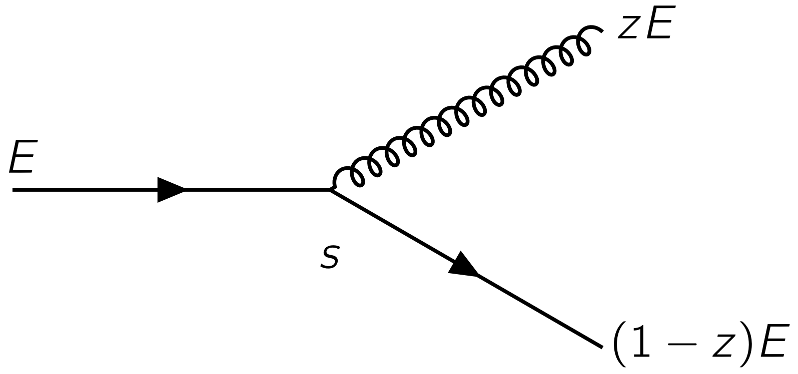

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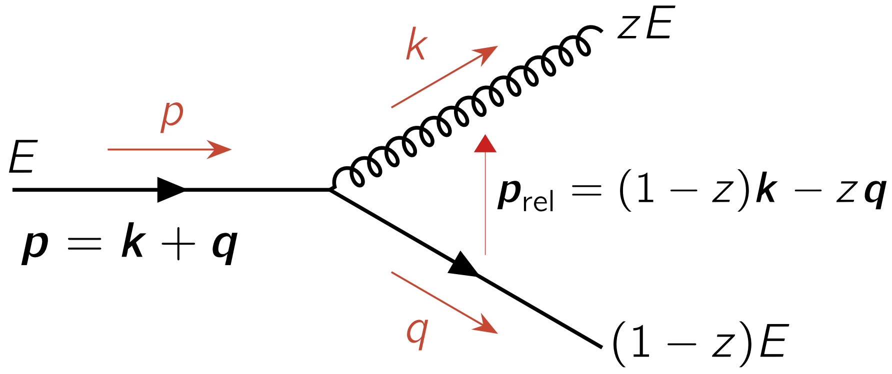
To generate a splitting:



1. Sample a scale from $\Delta(s_{\rm prev}, s)$
2. Sample a fraction from $\hat{P}(z) \propto 1/z$

Ensure that $|\boldsymbol{p}_{\rm rel}|^2 > \Lambda^2$

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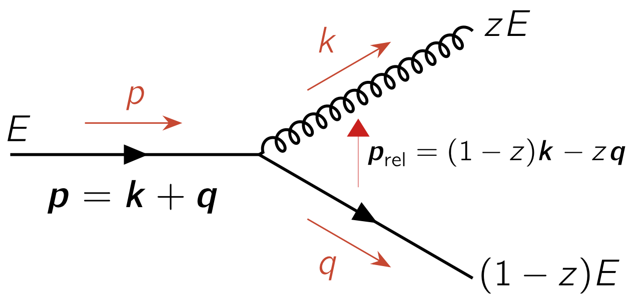

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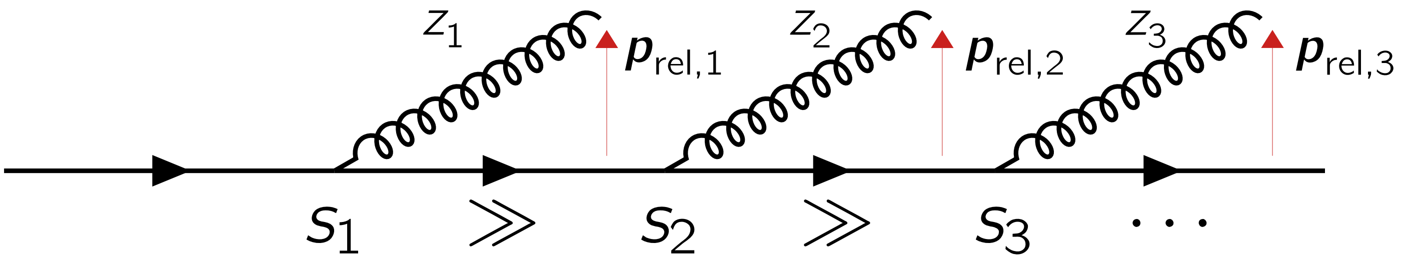
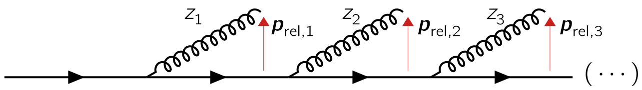


This results in the strong ordering of scales

Parton Shower Details



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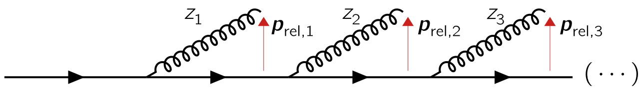

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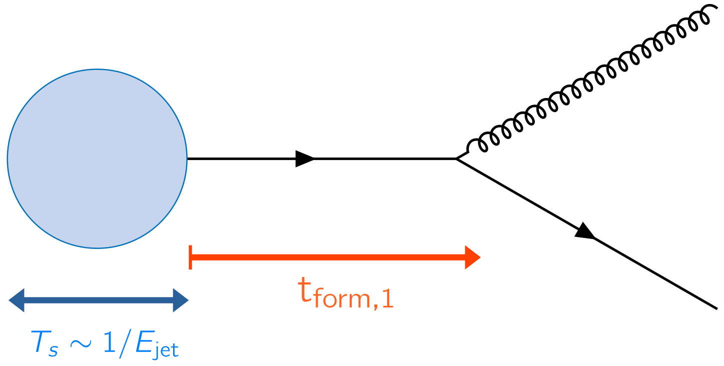
- Splittings must happen above an hadronisation scale: $|\boldsymbol{p}_{\text{rel}}|^2 > \Lambda^2$
  - This provides a **soft cutoff:** $z > z_{\text{cut}}(s)$

    e.g.: Formation time ordering $|\boldsymbol{p}_{\text{rel}}|^2 > \Lambda^2 \Longleftrightarrow z(1-z) > \dfrac{\Lambda^2}{t_{\text{form}}^{-1} E}$

- Initialisation condition for the shower: $t_{\text{form}}^{-1} < E$



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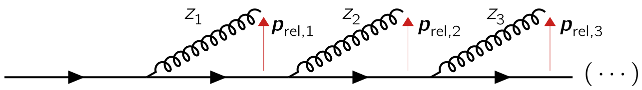

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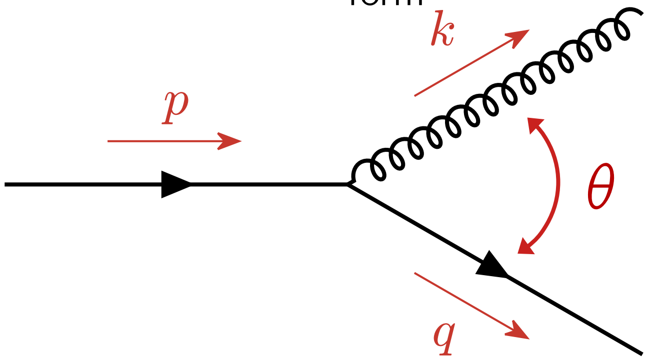
  - For consistency between orderings: $\zeta < 4 \Longrightarrow |\boldsymbol{p}_{\mathrm{rel}}| < \frac{E}{2}$

    (Enforced via retrials)

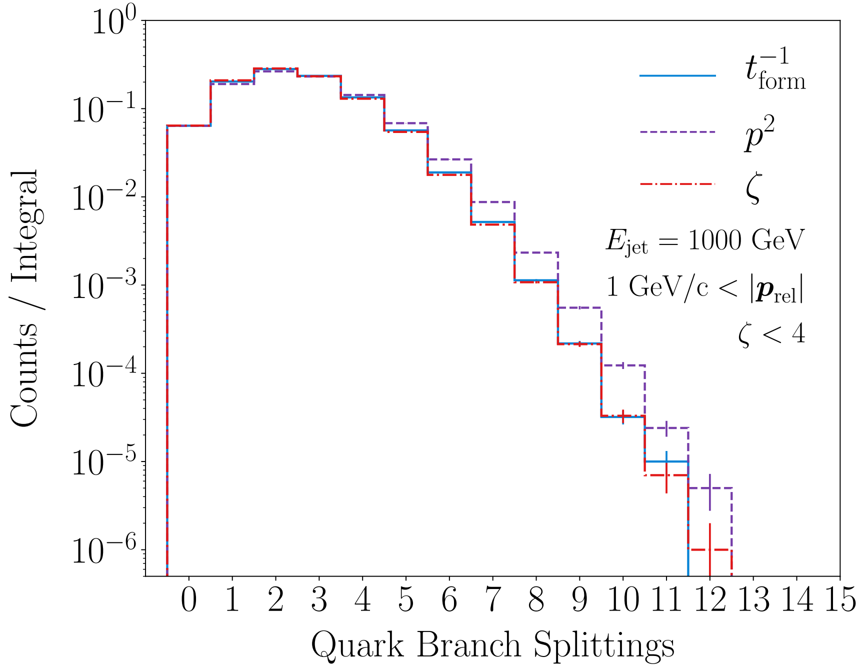


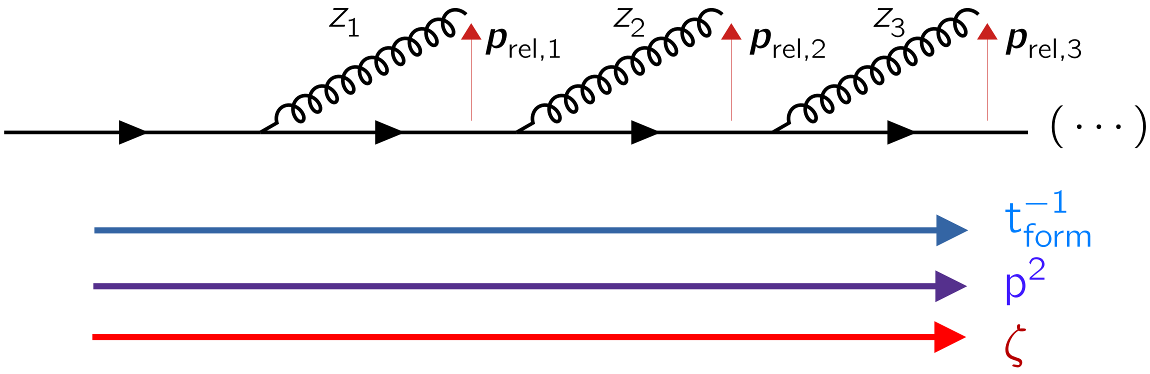
Massless Limit : $\zeta \simeq 2(1-\cos\theta)$

Results (Work in Progress)

Differences in Ordering Choices

Splittings along the quark branch

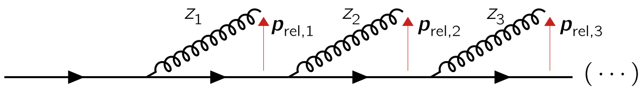




<u>The strictly decreasing scale is different for the three algorithms</u>

Different orderings → Different phase-space for allowed splittings

Differences in Ordering Choices



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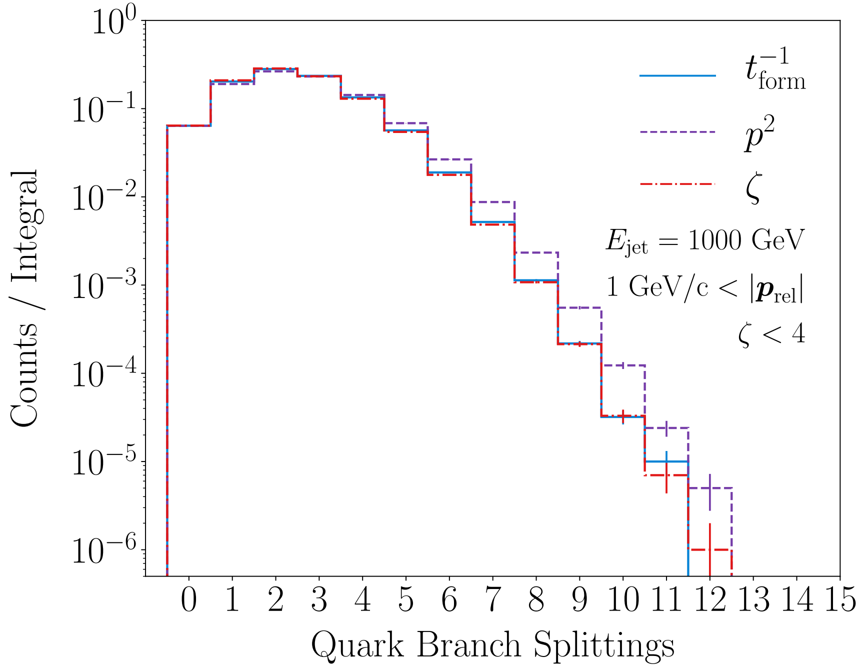
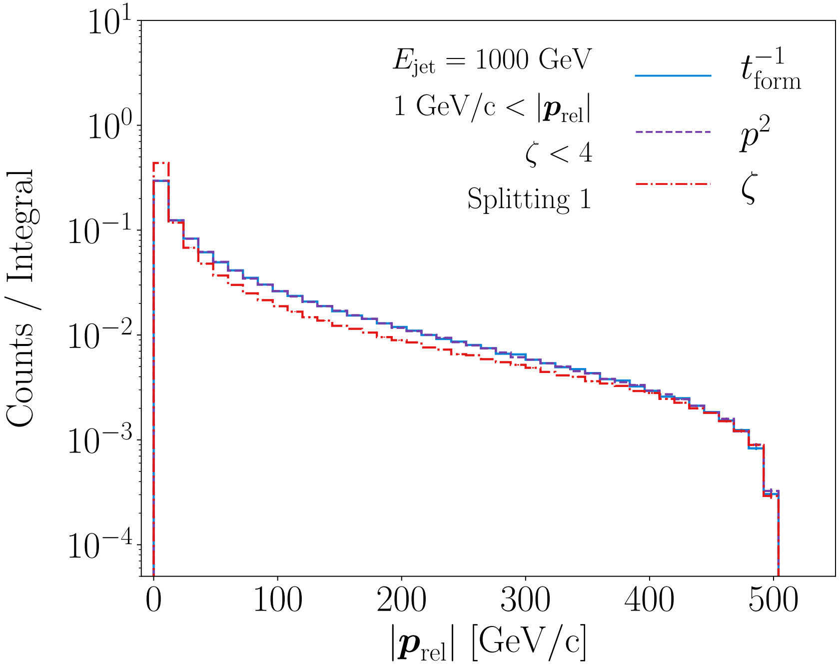


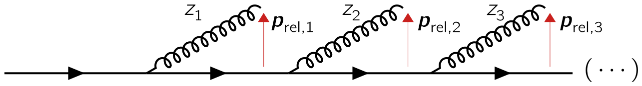
Different orderings → Different phase-space for allowed splittings

Relative transverse momentum (1st splitting)



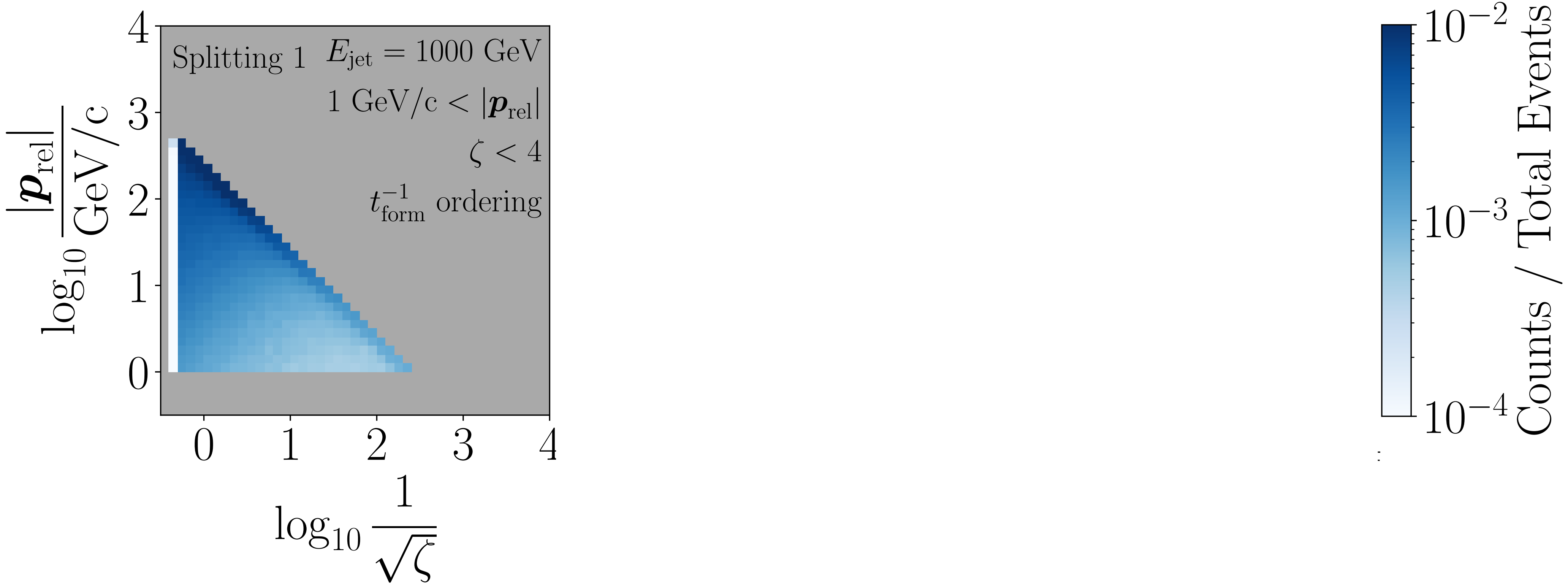
Transverse momentum distributions follow $\frac{\mathrm{d}\boldsymbol{p}_{\text{rel}}^2}{\boldsymbol{p}_{\text{rel}}^2}$

Lund Plane Densities



Consider the shower evolution along the quark branch:

*Exaggerated scale



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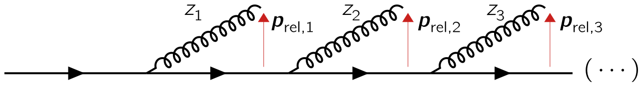

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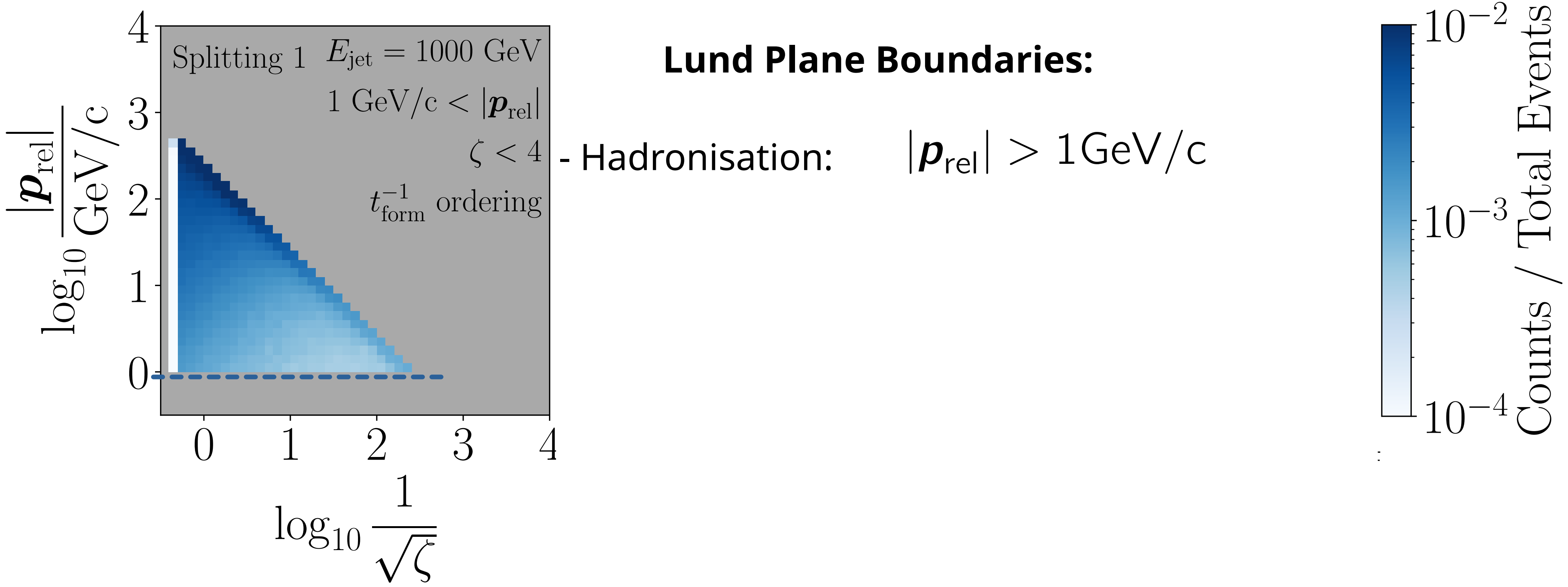

Lund Plane Boundaries:

- Hadronisation: $|\boldsymbol{p}_{\rm rel}| > 1{\rm GeV/c}$

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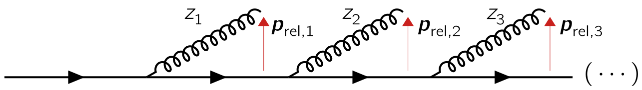

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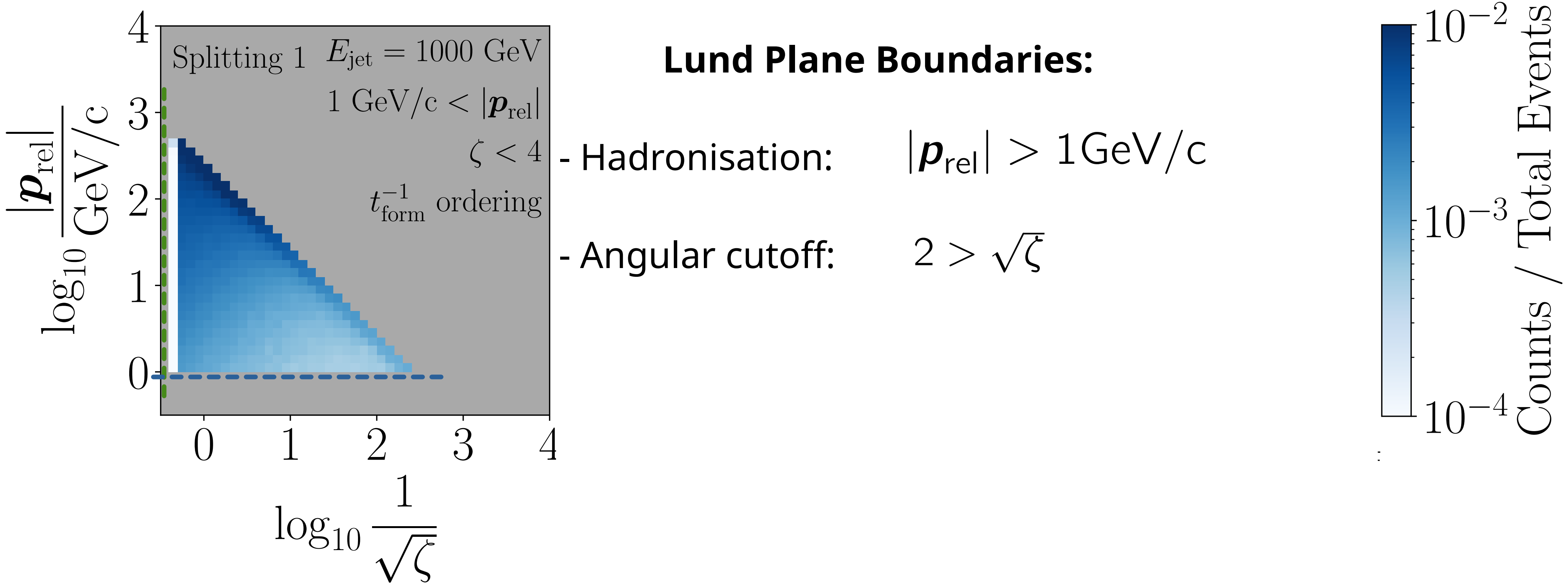

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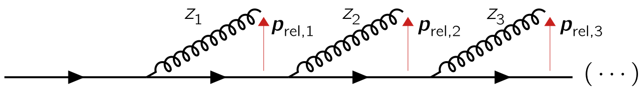

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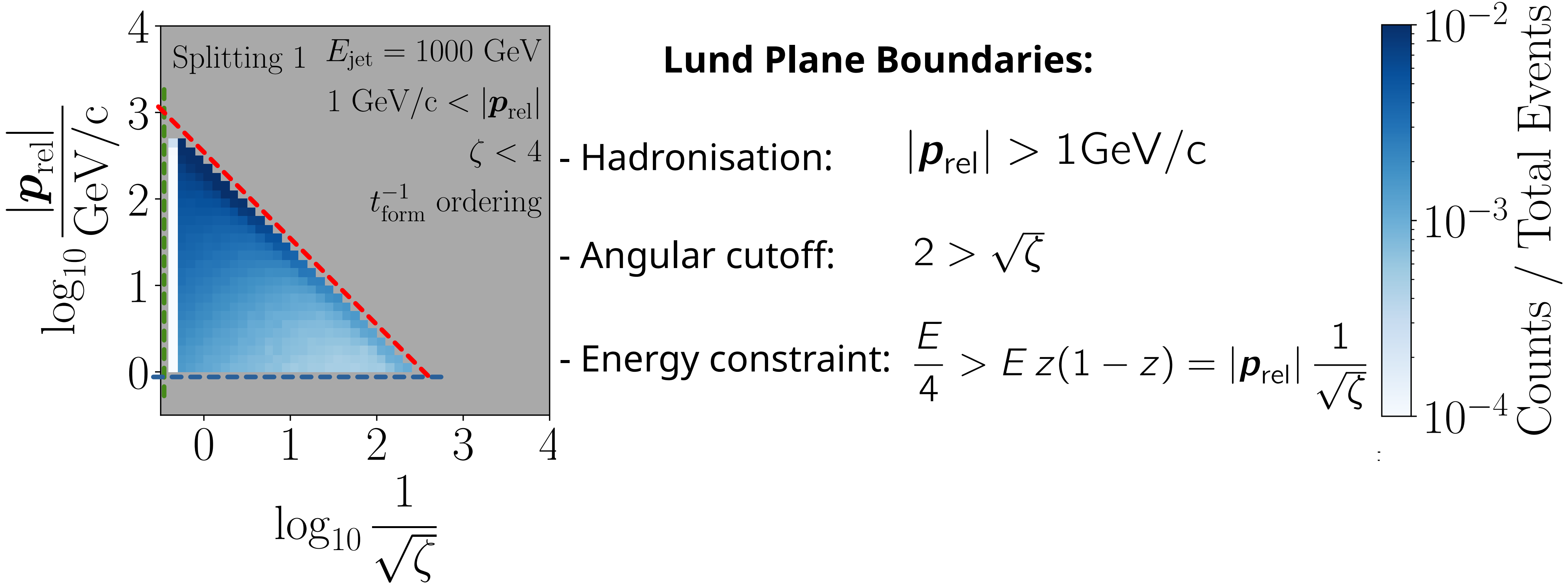

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Shower evolution: Both transverse momentum and angle <u>decrease.</u>

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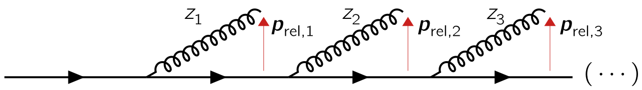

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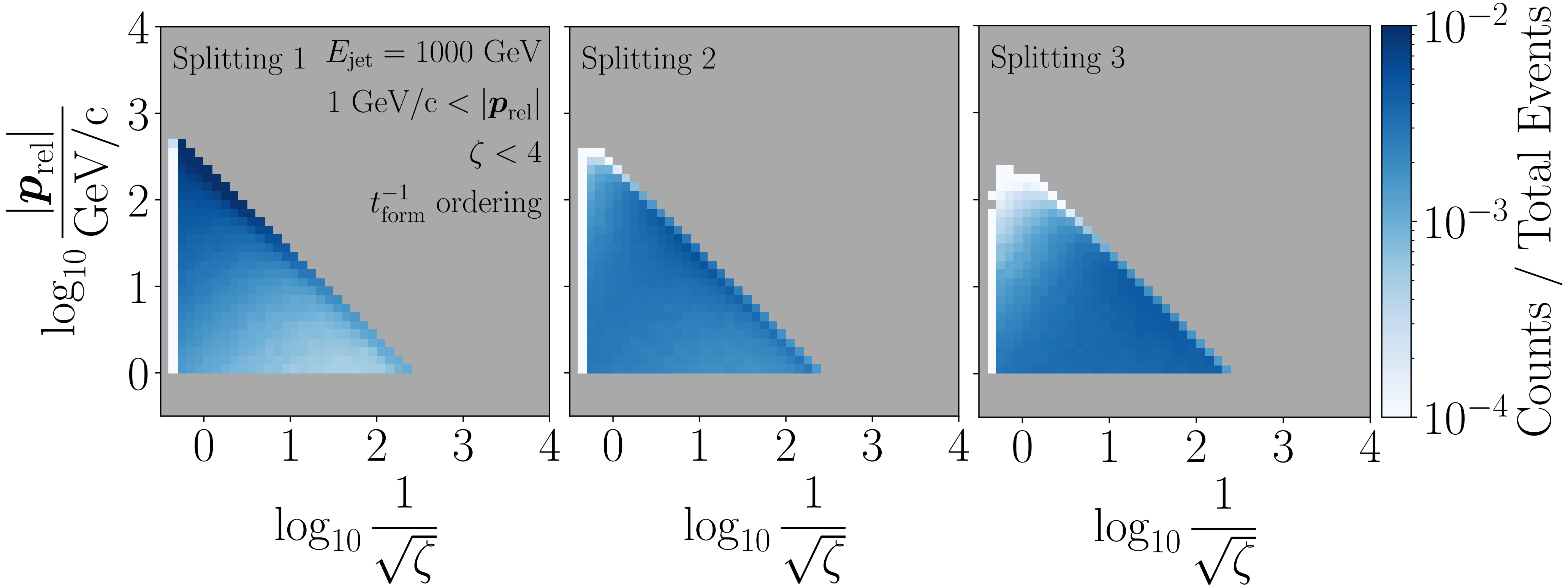

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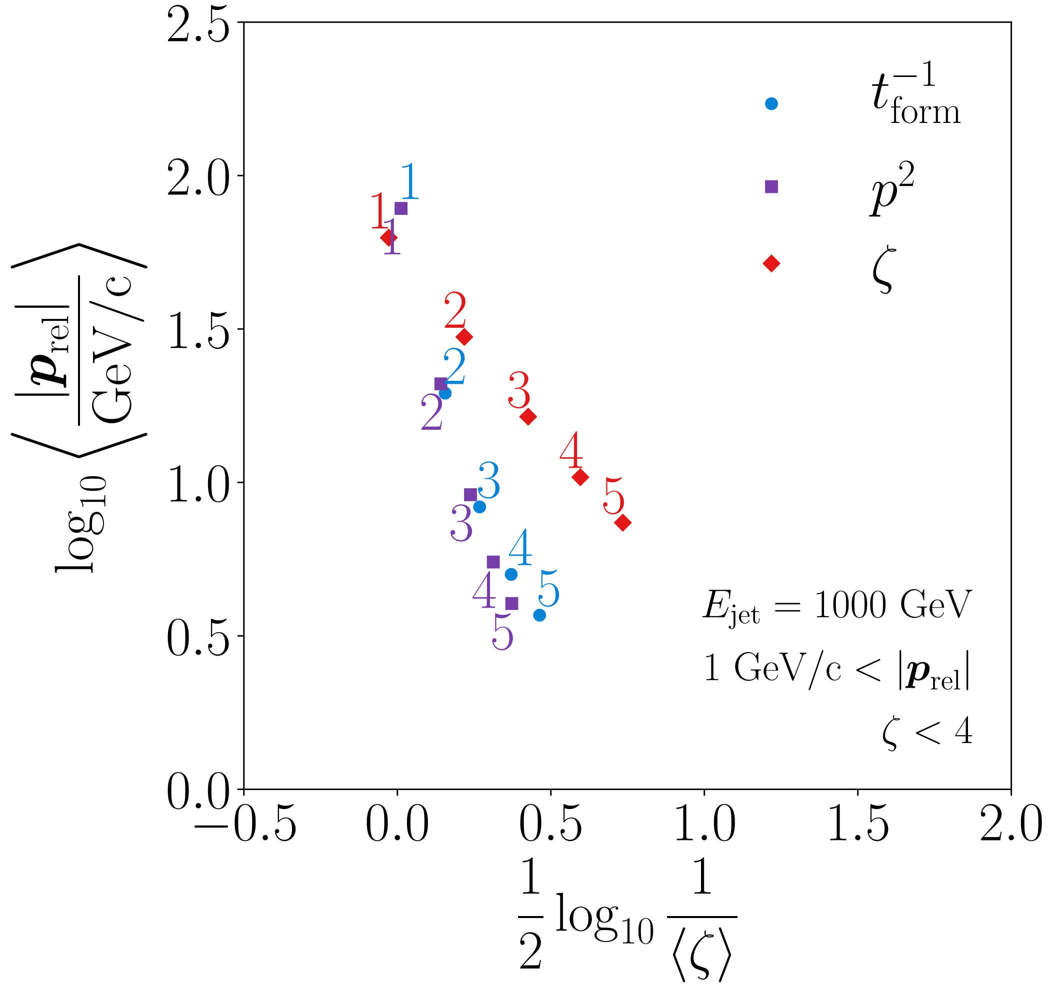
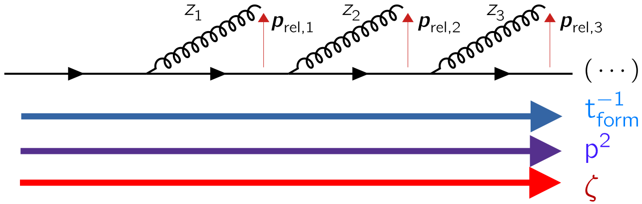
Lund Plane Trajectories



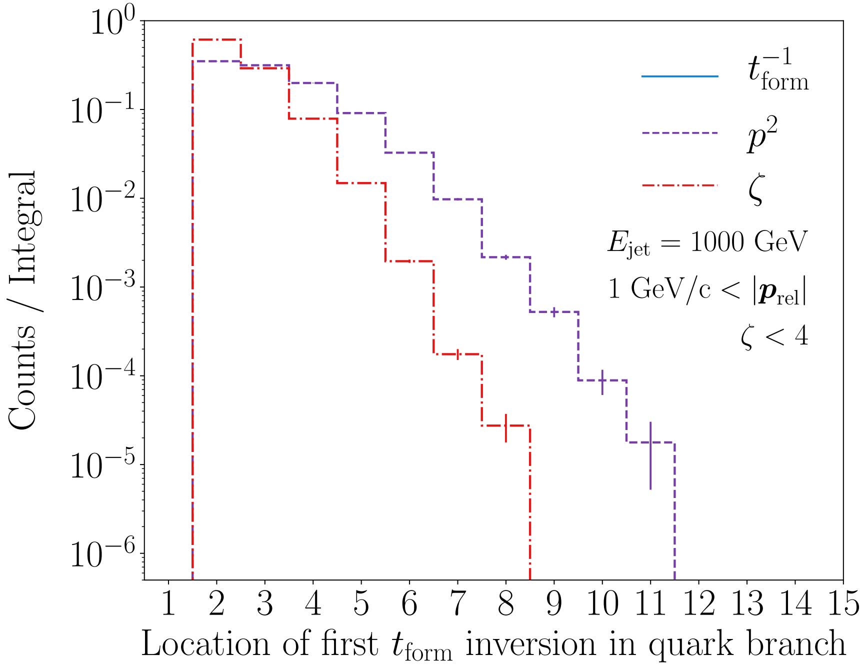


Differences between phase-space trajectories

→ Uncertainty at DLA Accuracy

Inversions in Kinematic Variables

(~ 30% Events with time inversions)



Formation Time Inversions:

Splittings with a formation time shorter that their immediate predecessor.

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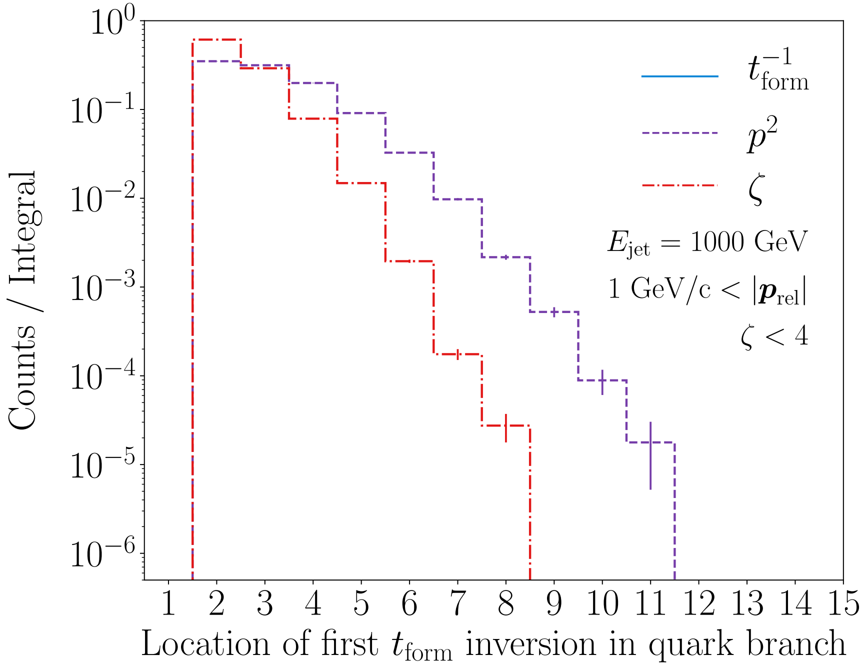

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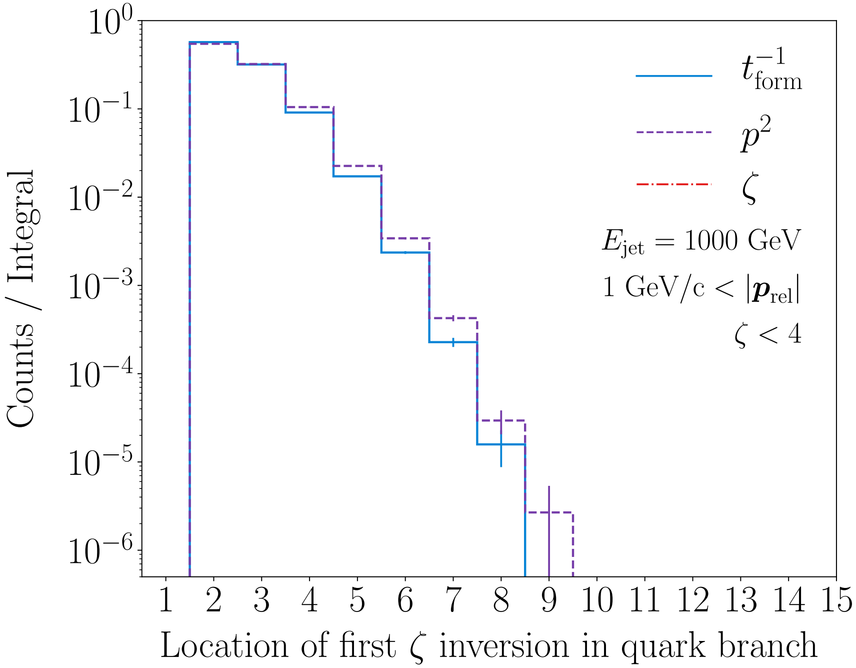

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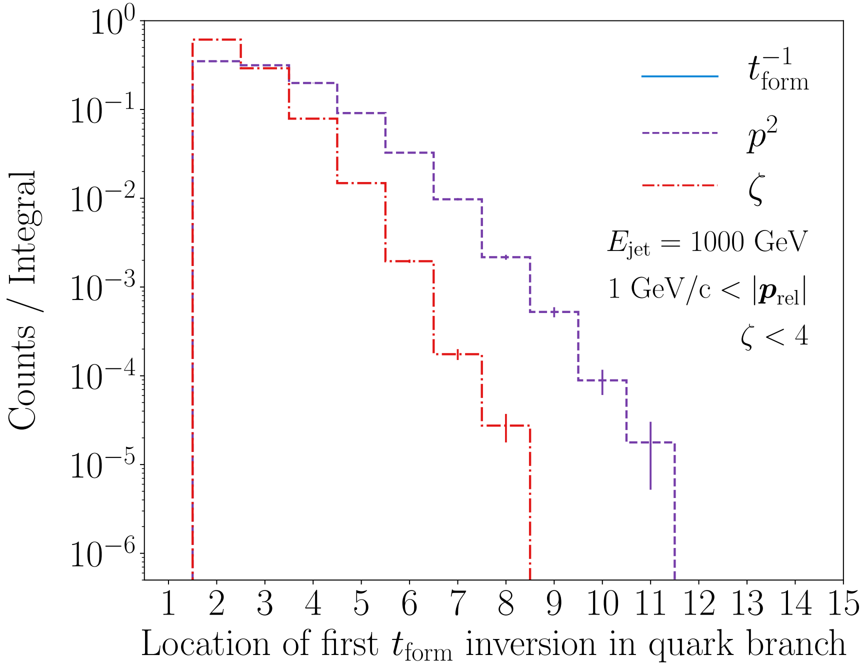

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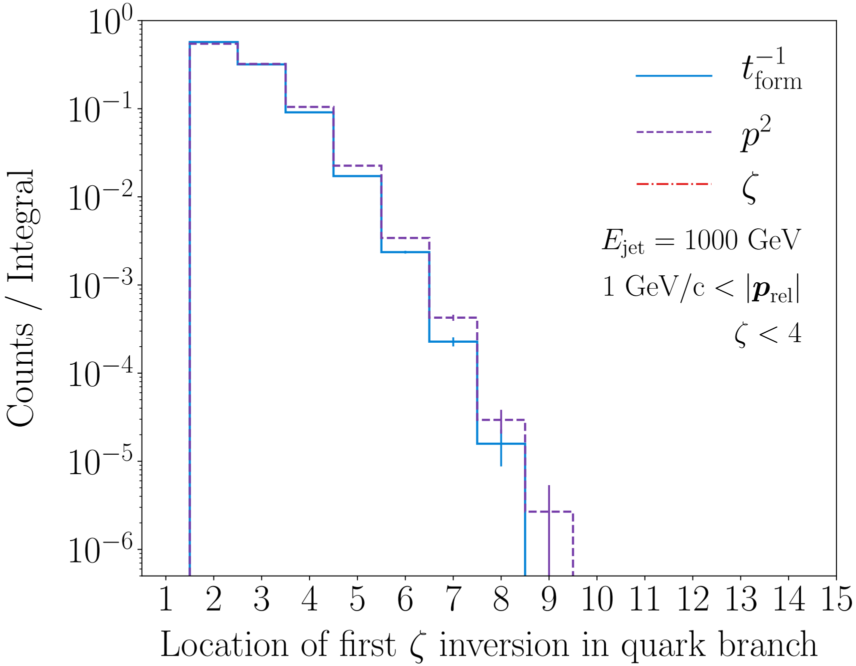


Angular inversions

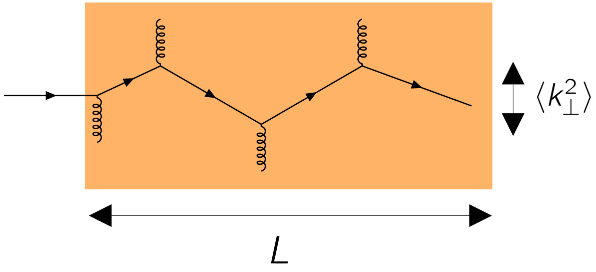
Can this discrepancy translate into differences in quenching magnitude?

Now, a simple jet quenching model!

Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
Casalderrey-Solana, Iancu :: JHEP 08 (2011) 015

Choosing a quenching condition

(Tywoniuk, Wed 14:00)



Medium parameters (for a simple model):

– Medium length: L

– Transport coefficient: $\hat{q} \sim \frac{\langle k_\perp^2 \rangle}{\lambda}$

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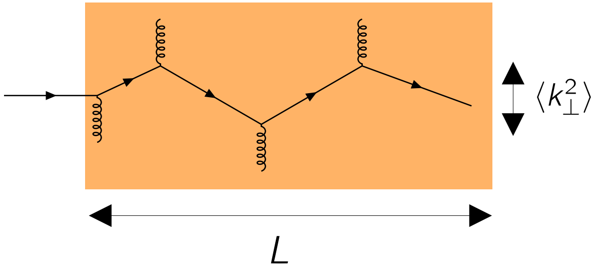

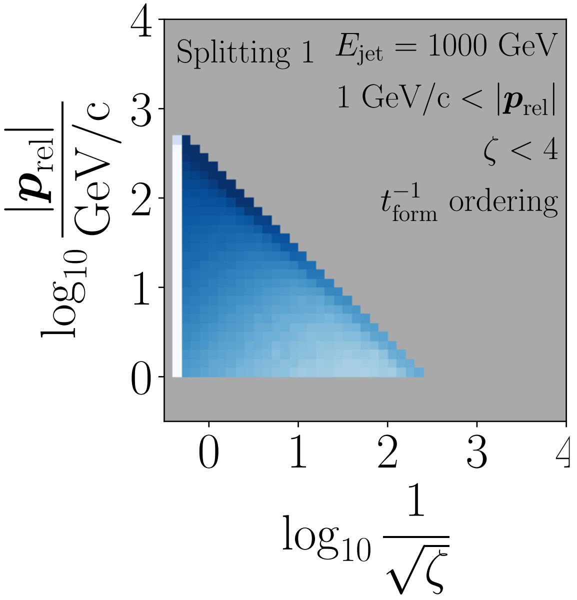

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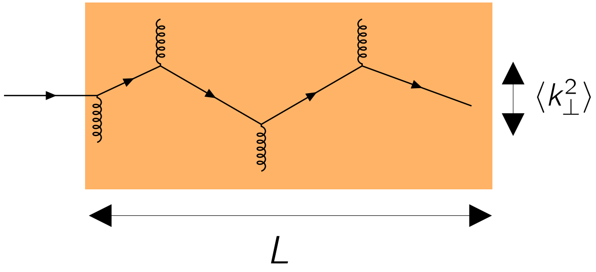

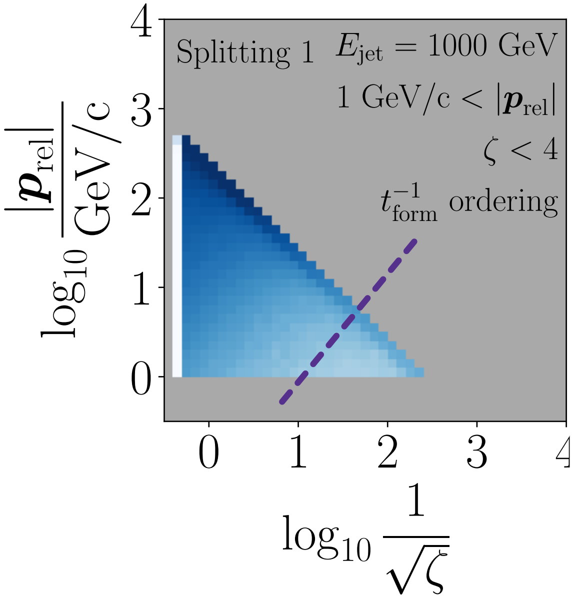

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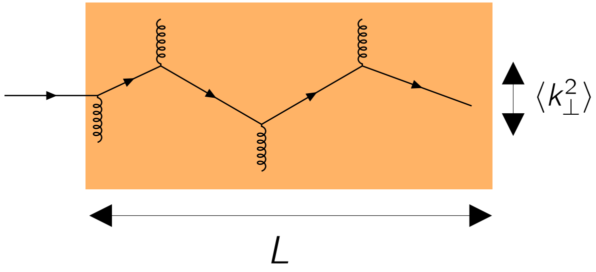

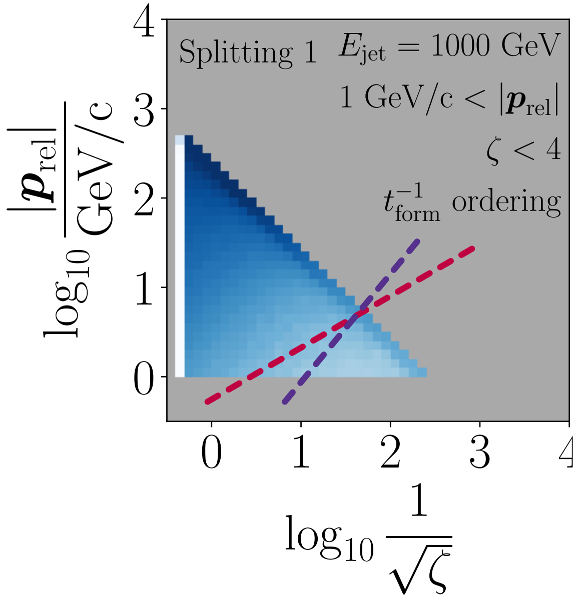

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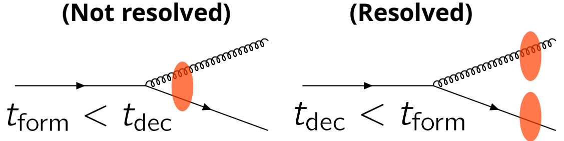
- Splitting transverse momentum is below medium scale:

$$|\boldsymbol{p}_{\rm rel}|^2 < \hat{q}\, t_{\rm form} \iff \underbrace{(\hat{q}\zeta)^{-1/3}}_{t_{\rm dec}} < t_{\rm form}$$

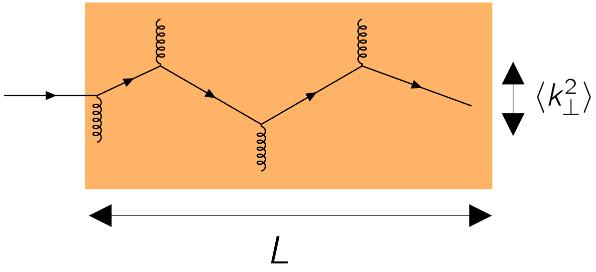
Medium resolves splittings on the (de)coherence time scale
→ Daughters lose energy individually



Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
Casalderrey-Solana, Iancu :: JHEP 08 (2011) 015

Choosing a quenching condition

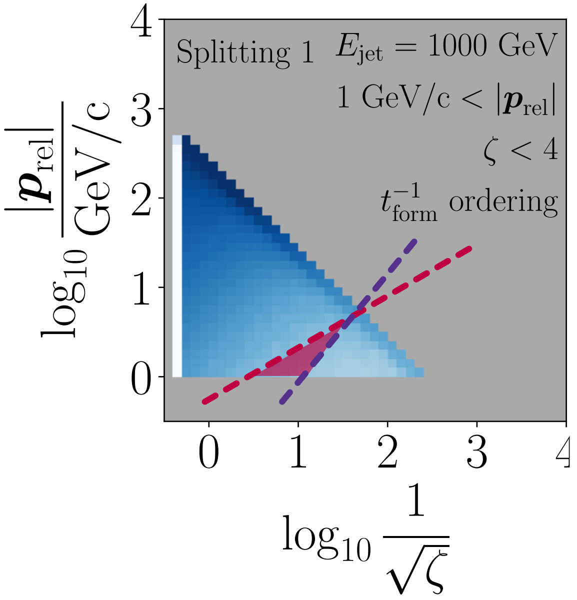
(Tywoniuk, Wed 14:00)



Medium parameters (for a simple model):

– Medium length: L

– Transport coefficient: $\hat{q} \sim \dfrac{\langle k_\perp^2 \rangle}{\lambda}$



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Eliminate events within this area:

$$\mathcal{P}_{\rm quench} = \Theta(L > t_{\rm form} > t_{\rm dec})$$

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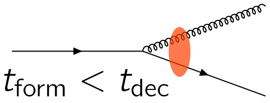
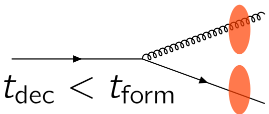
(Not resolved)



(Resolved)



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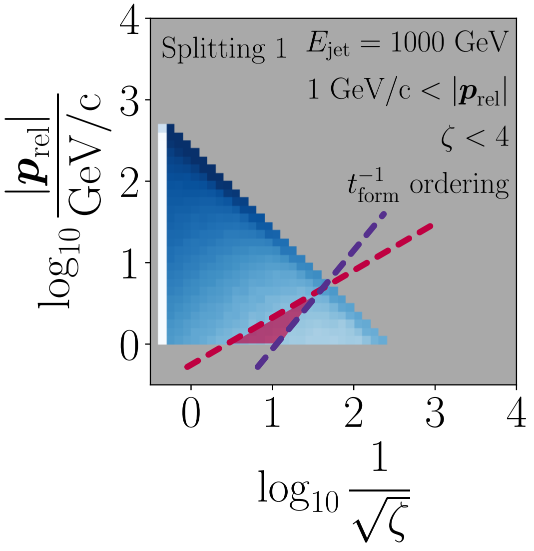

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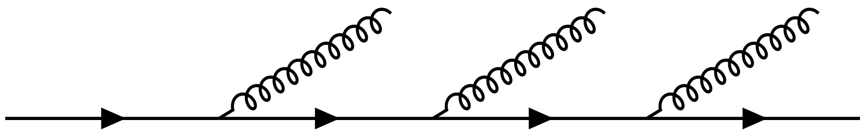

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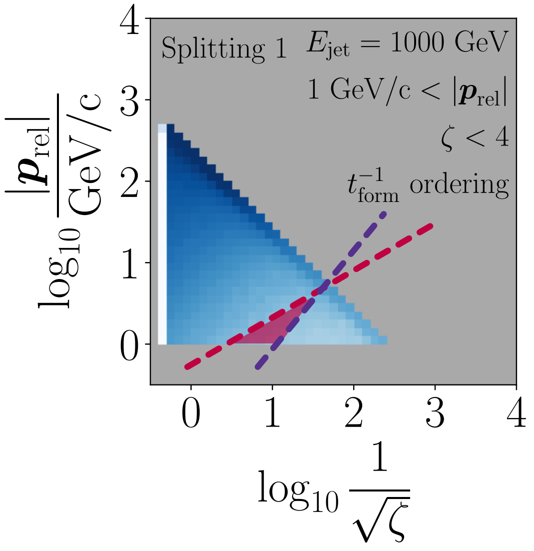

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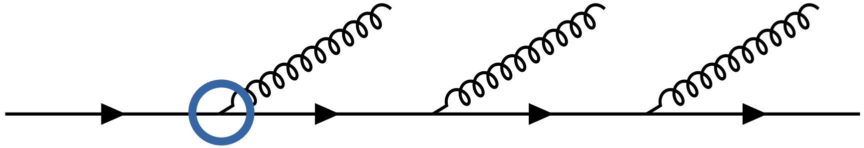
Two implementations:



- Option 1: Apply only to first splitting

Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
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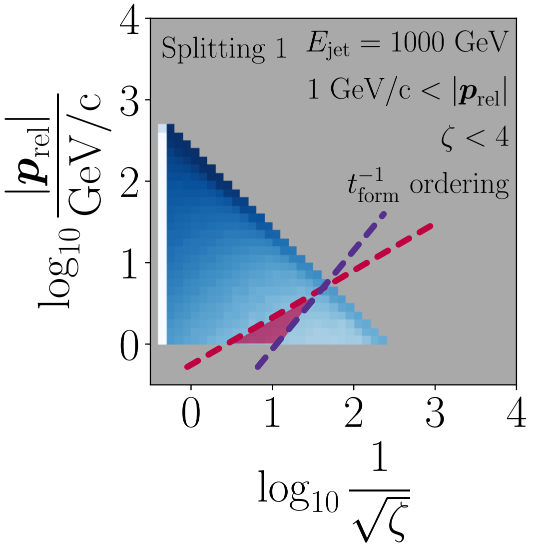
Choosing a quenching condition



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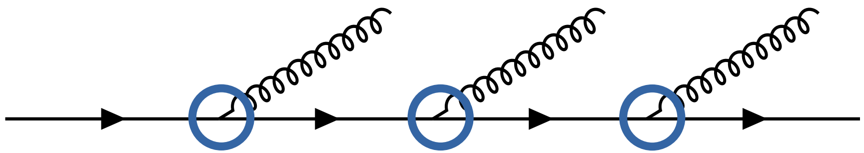

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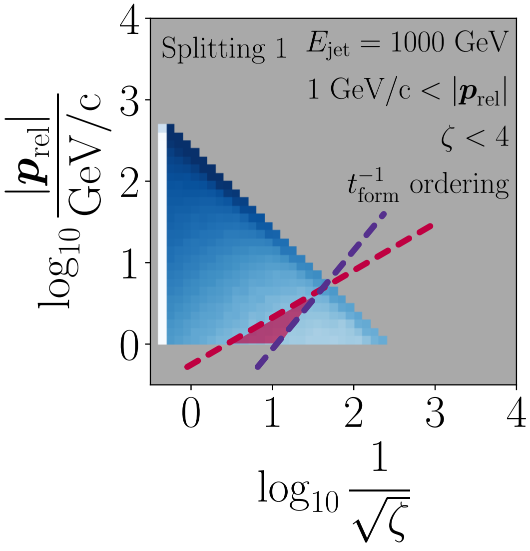
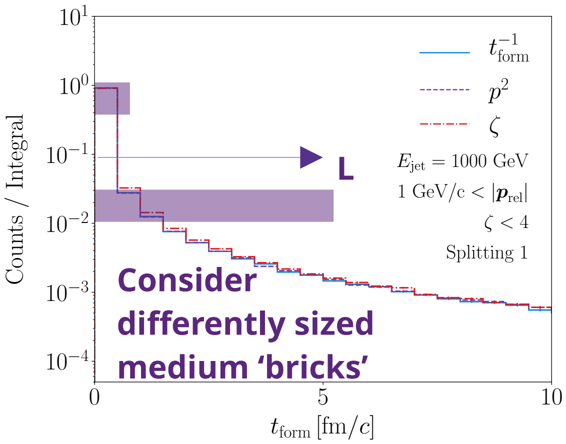
Choosing a quenching condition





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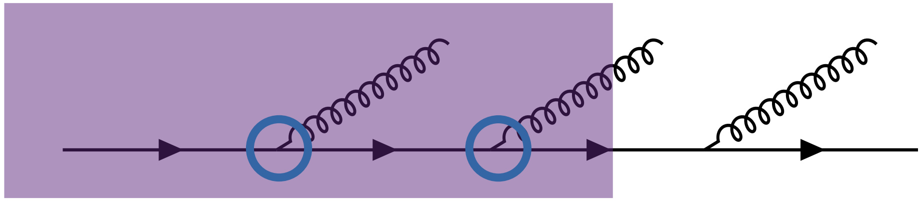

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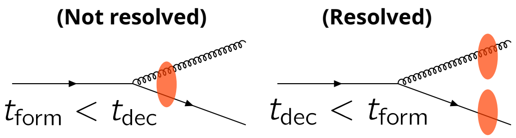
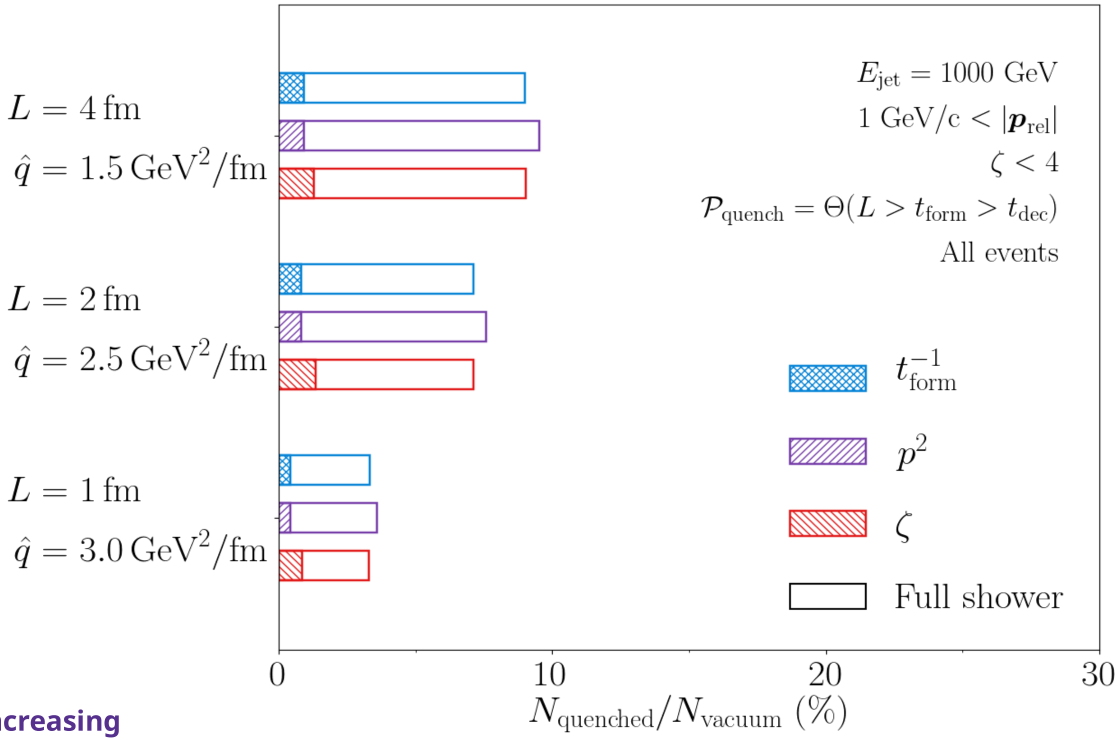
Fraction of Quenched Events



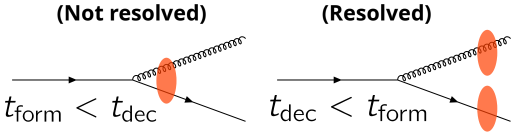
$$\mathcal{P}_{\text{quench}} = \Theta(L > t_{\text{form}} > t_{\text{dec}})$$

Percentage of events eliminated by the quenching condition



Increasing quenching effects

Fraction of Quenched Events



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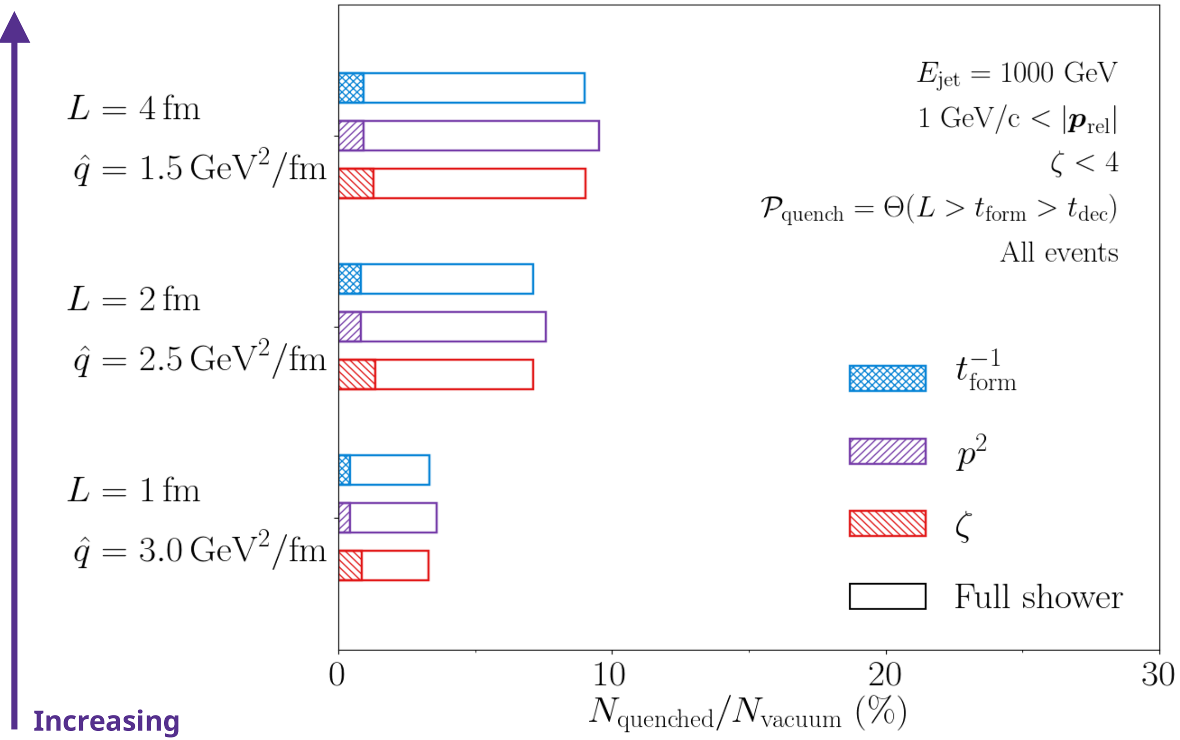
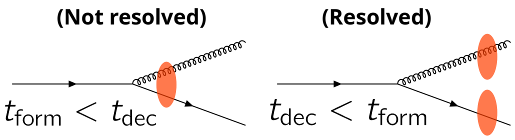


Increasing quenching effects

Applying conditon to the first splitting → Significant differences in quenching between algorithms

Differences are **seem to remain (for larger L)** when applying the condition to the full quark branch.

Fraction of Quenched Events



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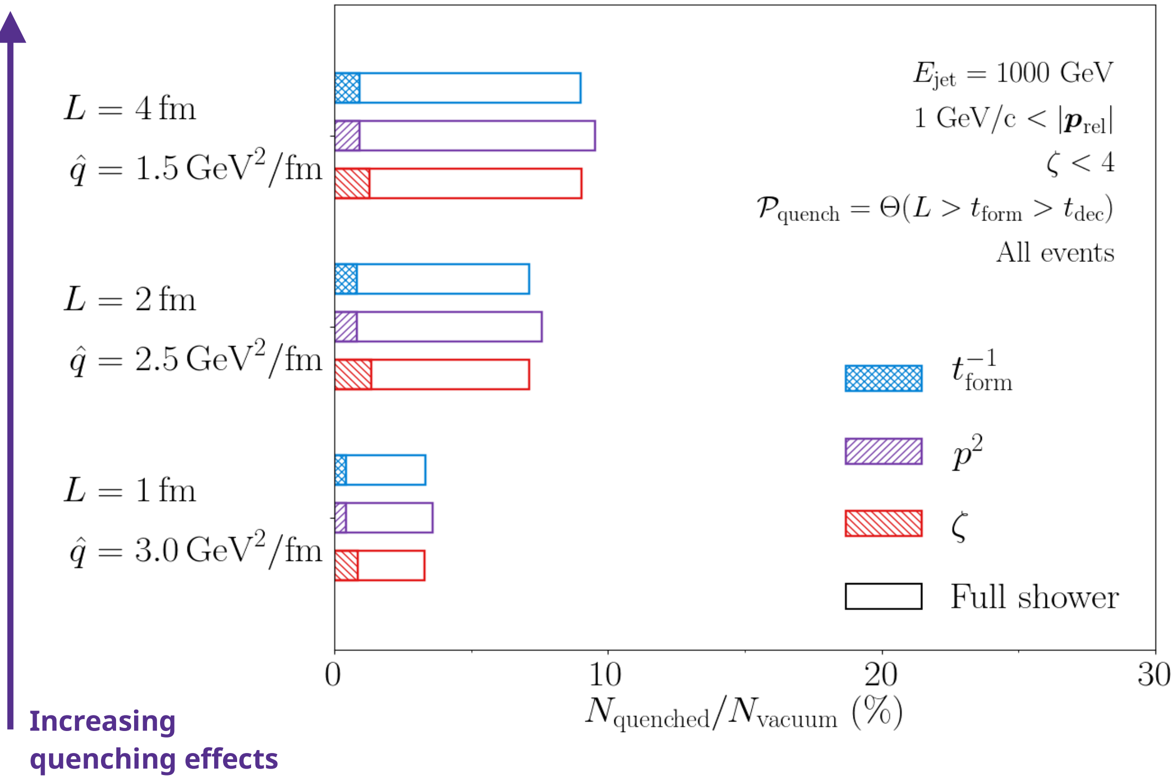

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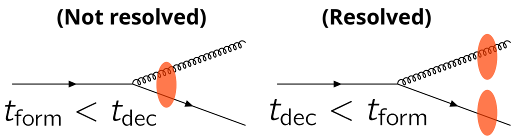
<u>**What role do time-inversions play in these quenching differences?**</u>

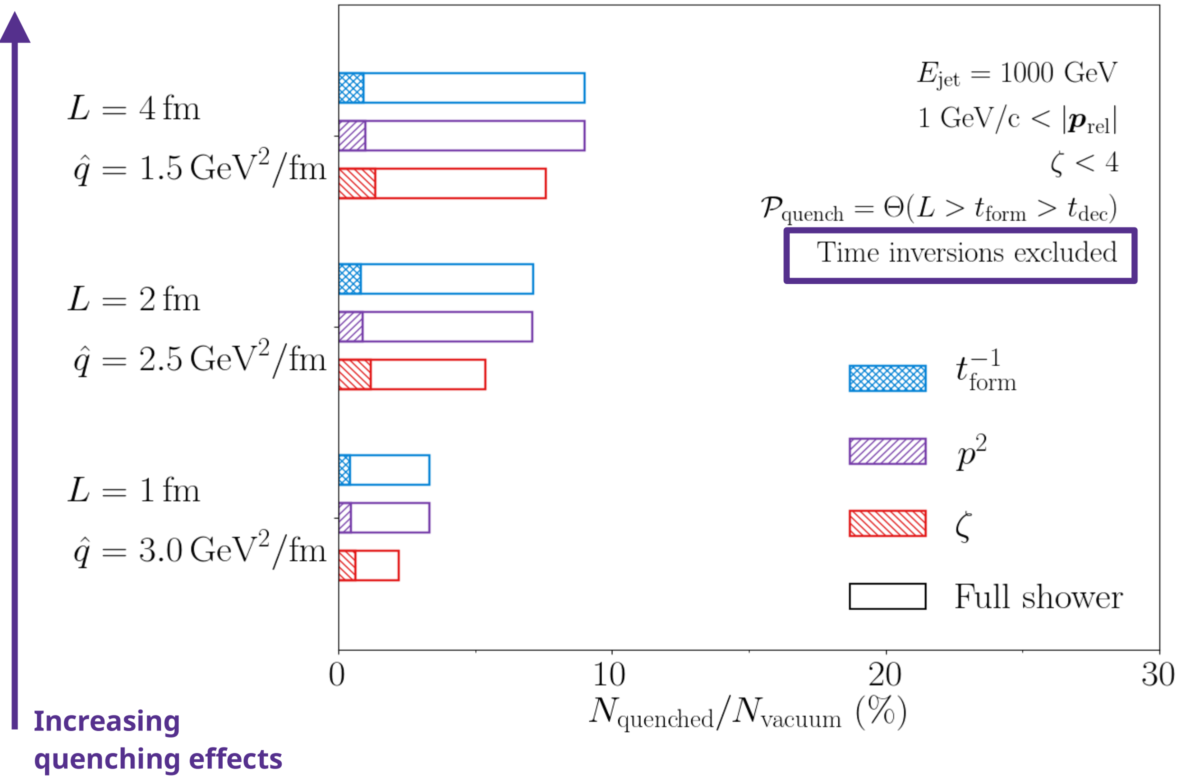
Fraction of Quenched Events



$\mathcal{P}_{quench} = \Theta(L > t_{form} > t_{dec})$

Discarding time-inverted events from the samples:

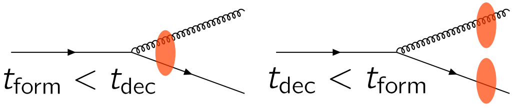
(Ad-hoc 'cut')



*** All events with at least one time-inverted splitting are removed before applying the quenching model

Fraction of Quenched Events

(Not resolved) (Resolved)



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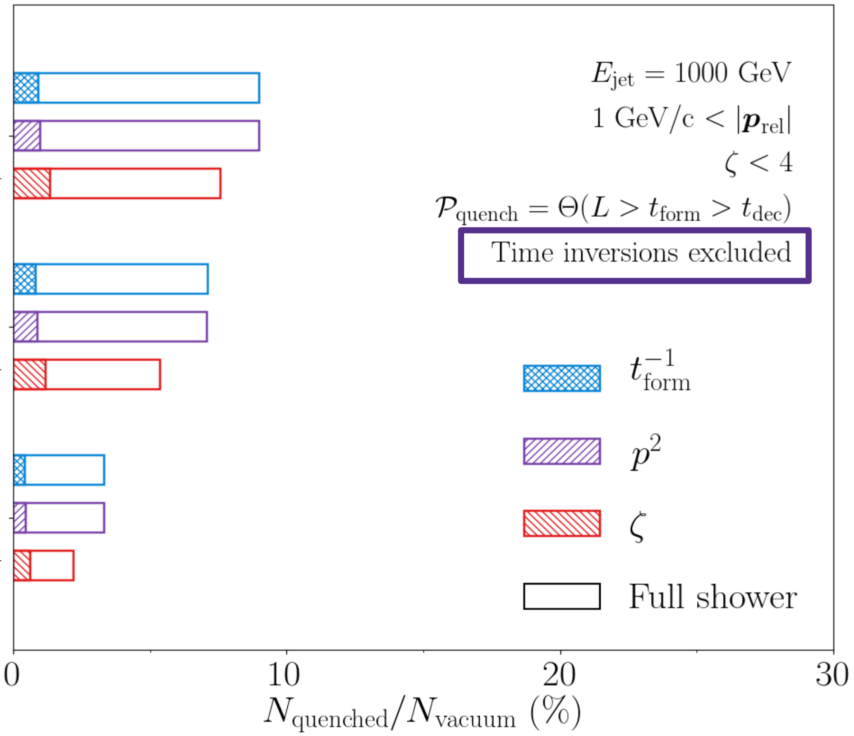

Increasing quenching effects

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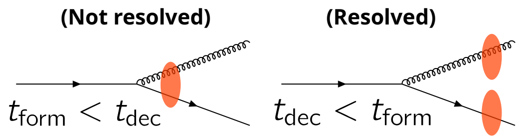
For angular ordered showers:

$\Rightarrow \zeta$ strictly decreasing

$\Rightarrow t_{dec}$ strictly increasing

$\Rightarrow$ No time inversions → less quenched phase-space

Fraction of Quenched Events



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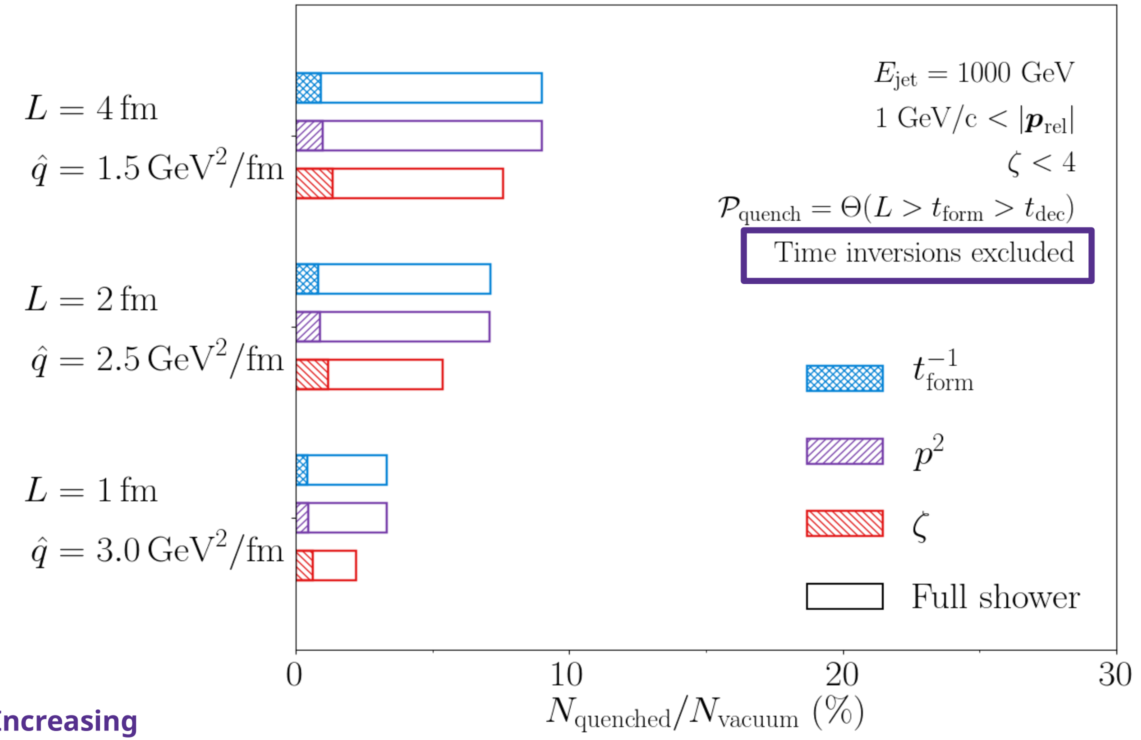

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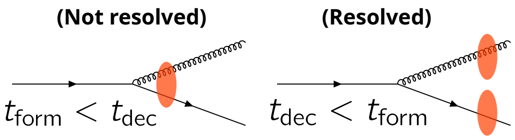
This is only one way of preventing inversions!

Fraction of Quenched Events



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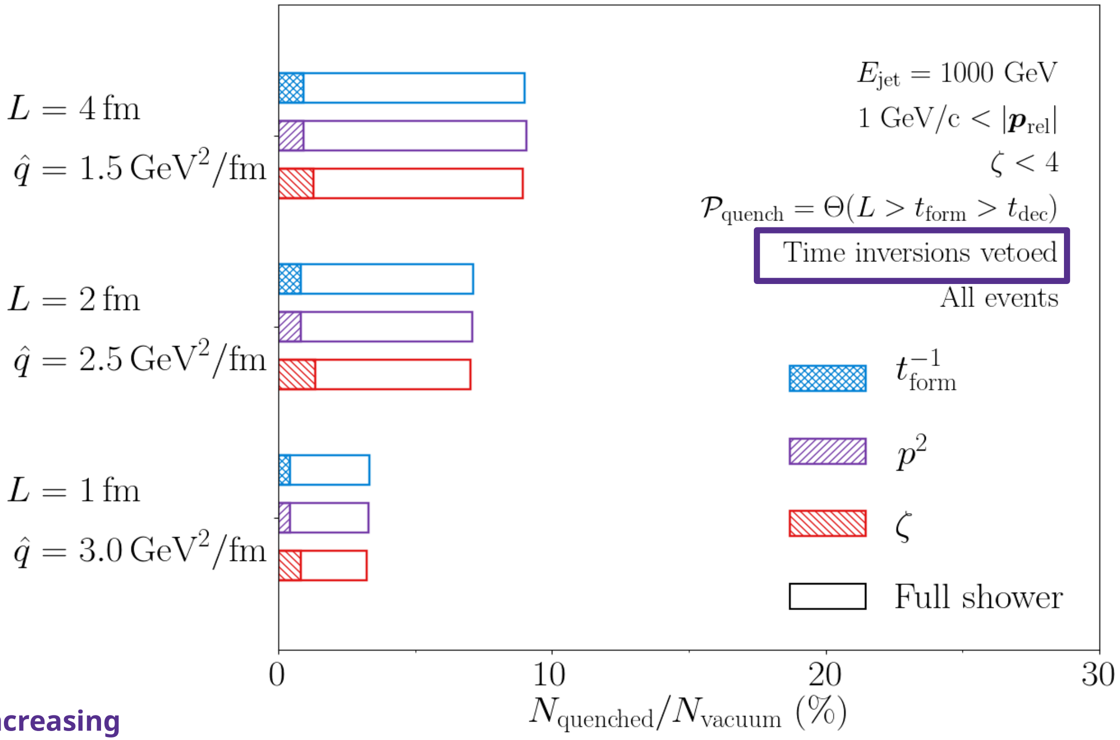
Vetoing the time-inversions by retrial:

(Phase-space is adjusted splitting by splitting)



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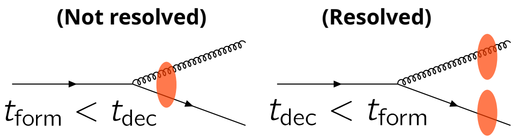
Fraction of Quenched Events



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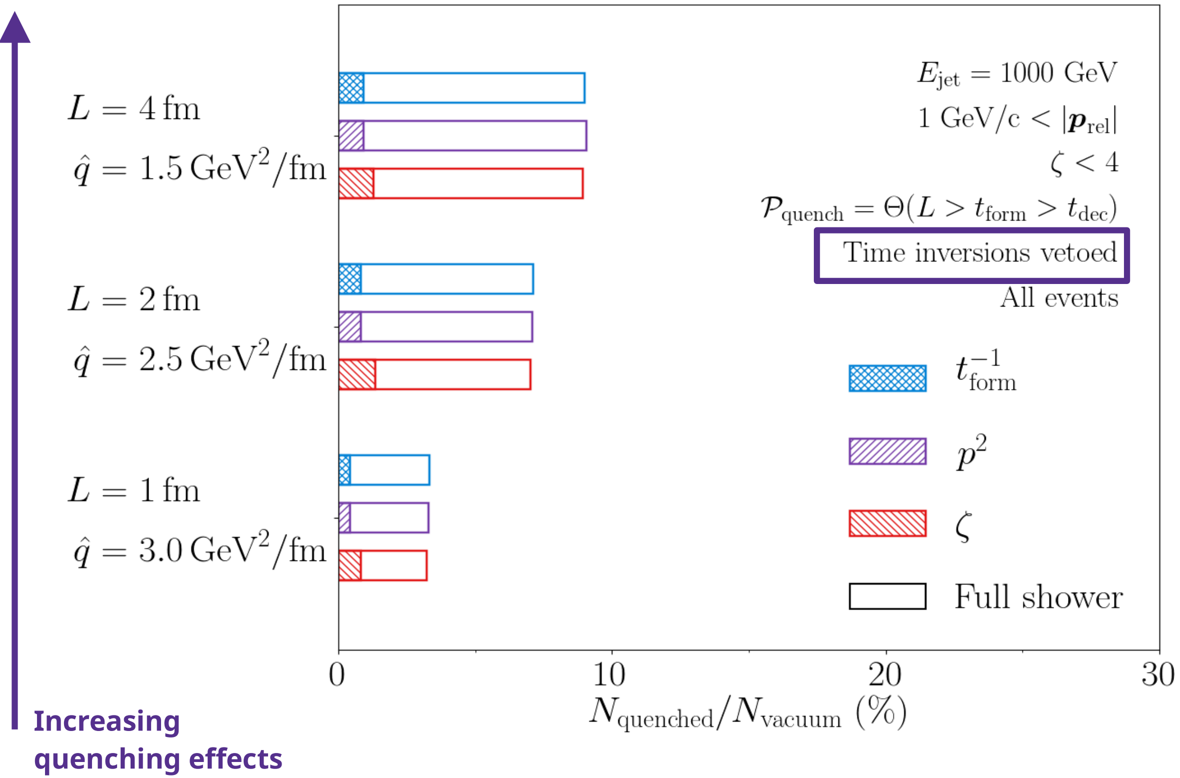

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Fraction of quenched events remains levelled across algorithms for the 'Full Branch' condition

<u>Warning:</u> Phase-space altered splitting-by-splitting

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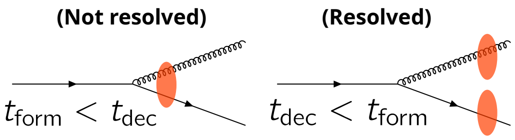

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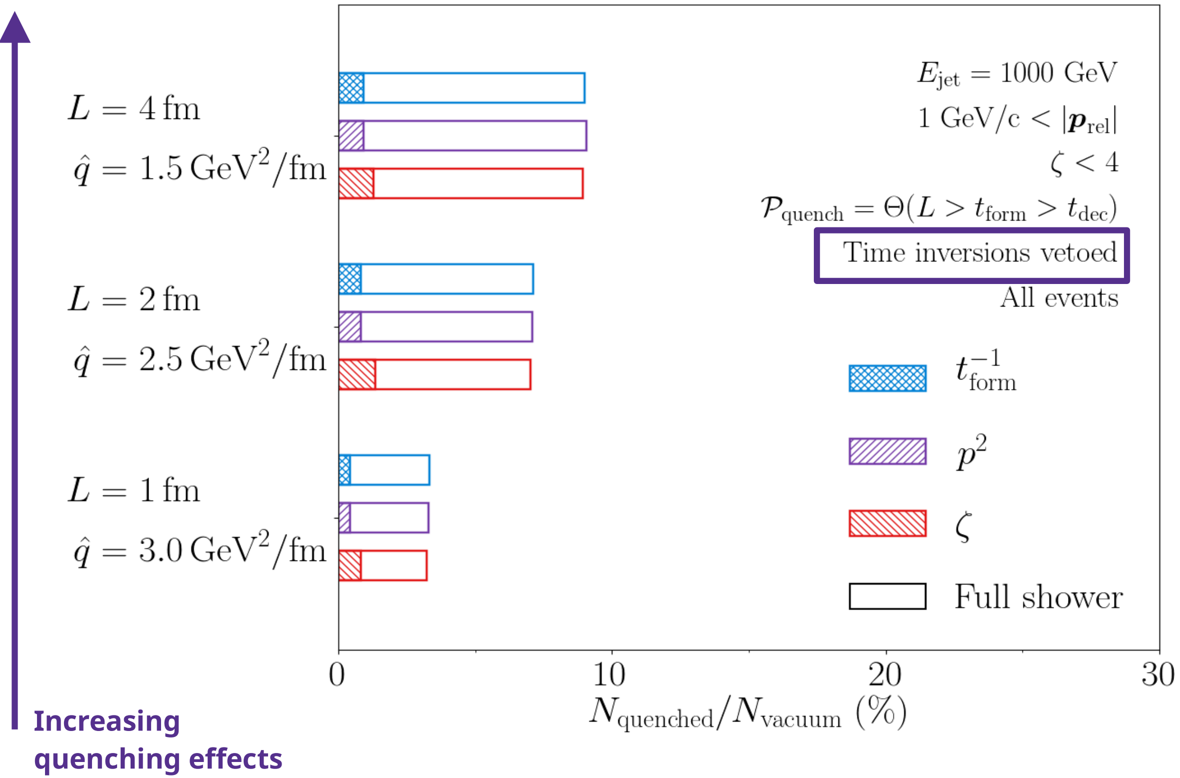

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The implementation details of the jet interface with a time-evolving medium are crucial!

Summary

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Thanks!

Acknowledgements

LIP

TÉCNICO LISBOA

erc
European Research Council
Established by the European Commission

STRONG 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

IGFAE
Instituto Galego de Física de Altas Enerxías

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

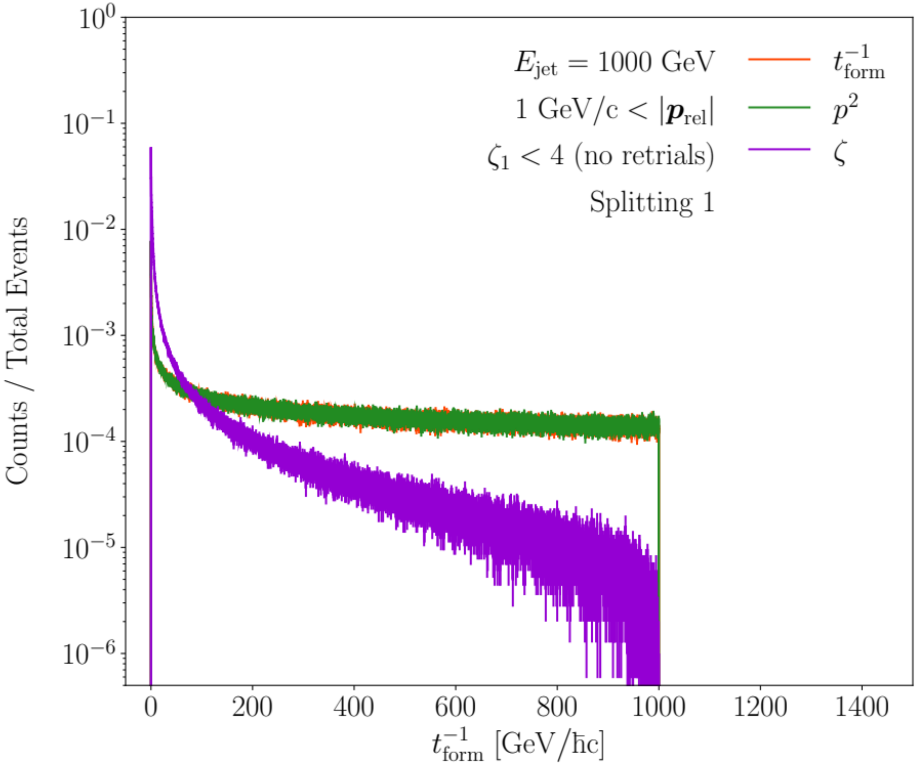
XUNTA DE GALICIA

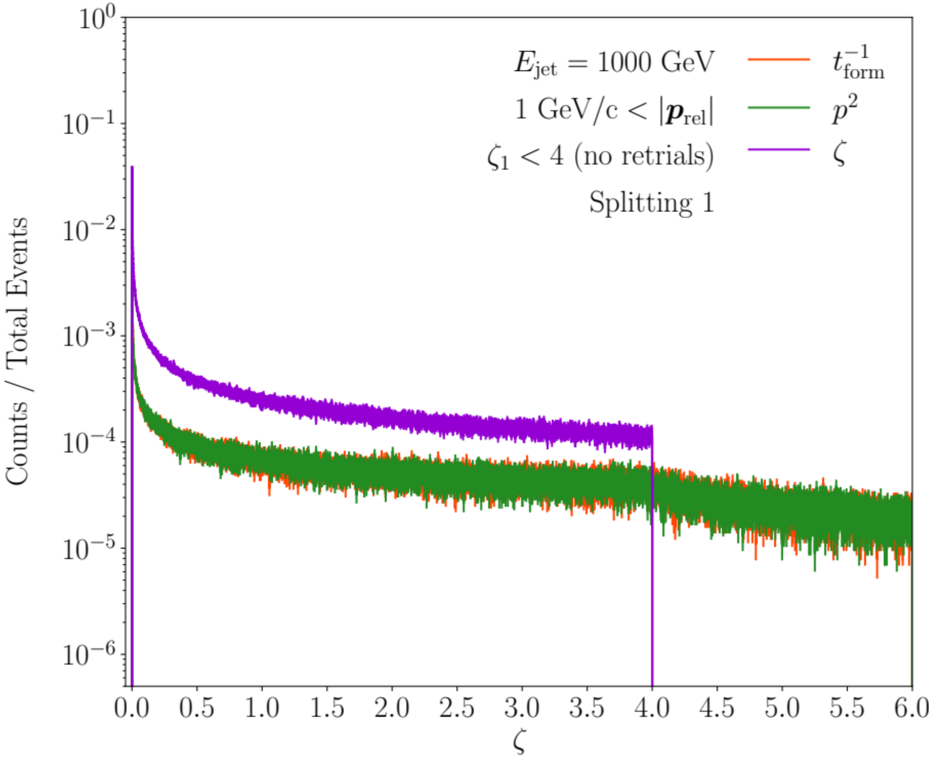
fct
Fundação para a Ciência e a Tecnologia

REPÚBLICA PORTUGUESA

Backup Slides

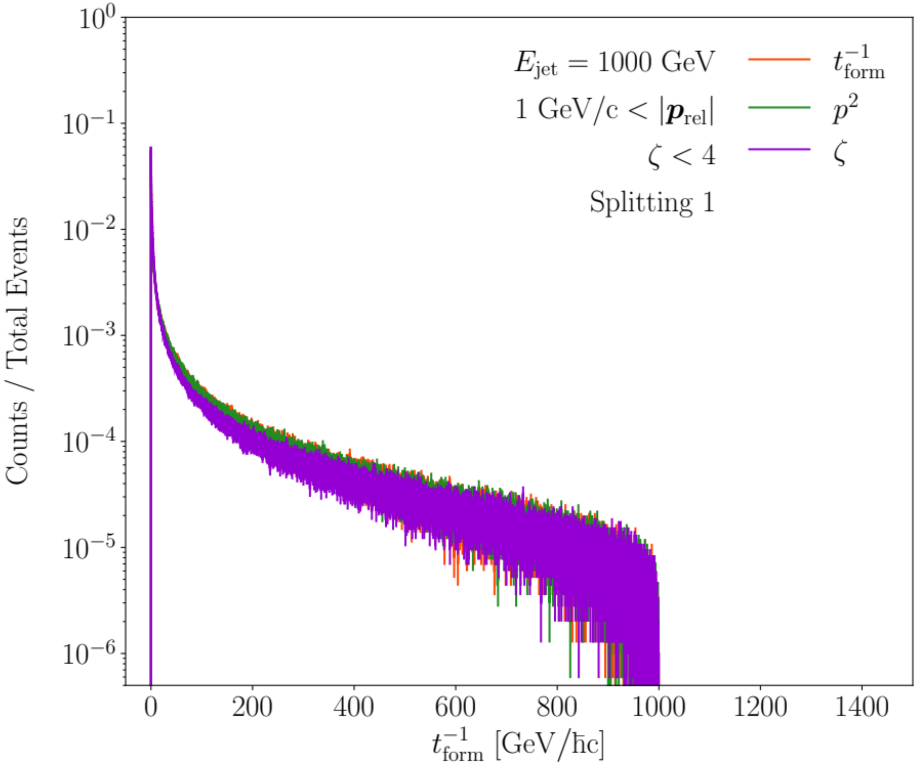
Without the consistency condition

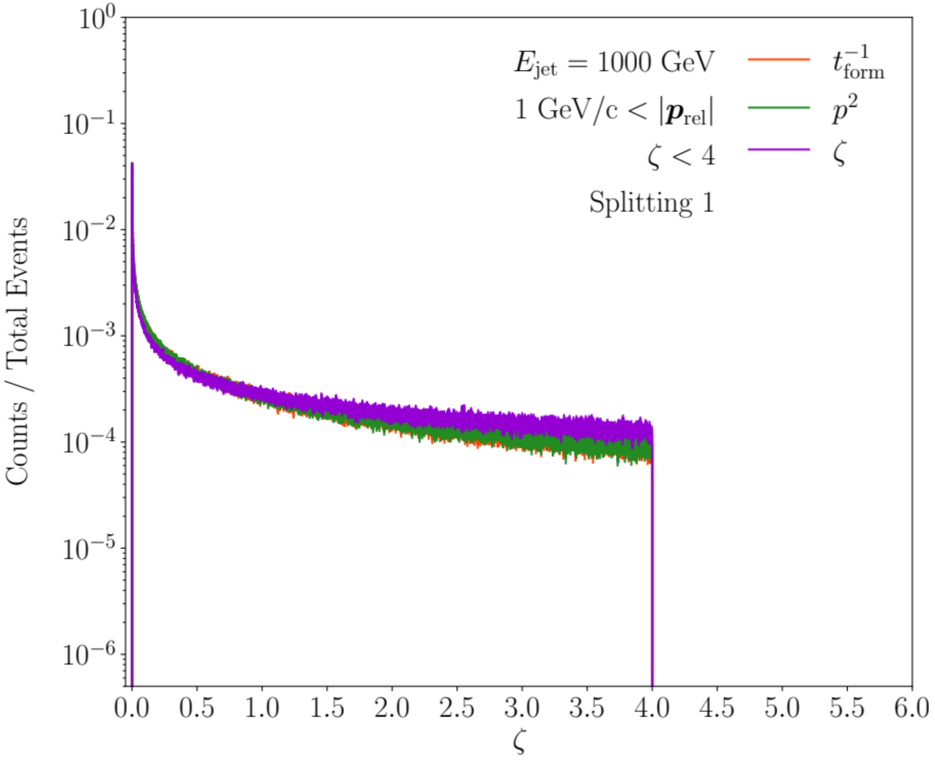




If the condition ζ < 4 is used simply to initialise the angular shower, the time and angle distributions do not behave consistently across algorithms

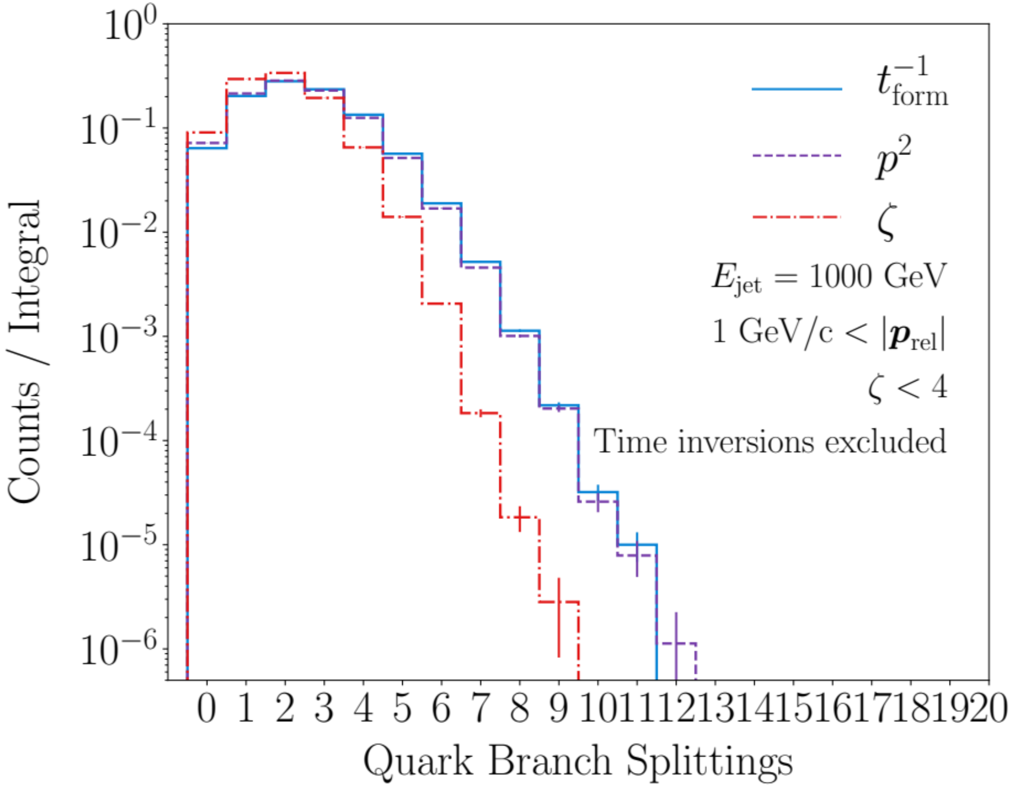
With the consistency condition

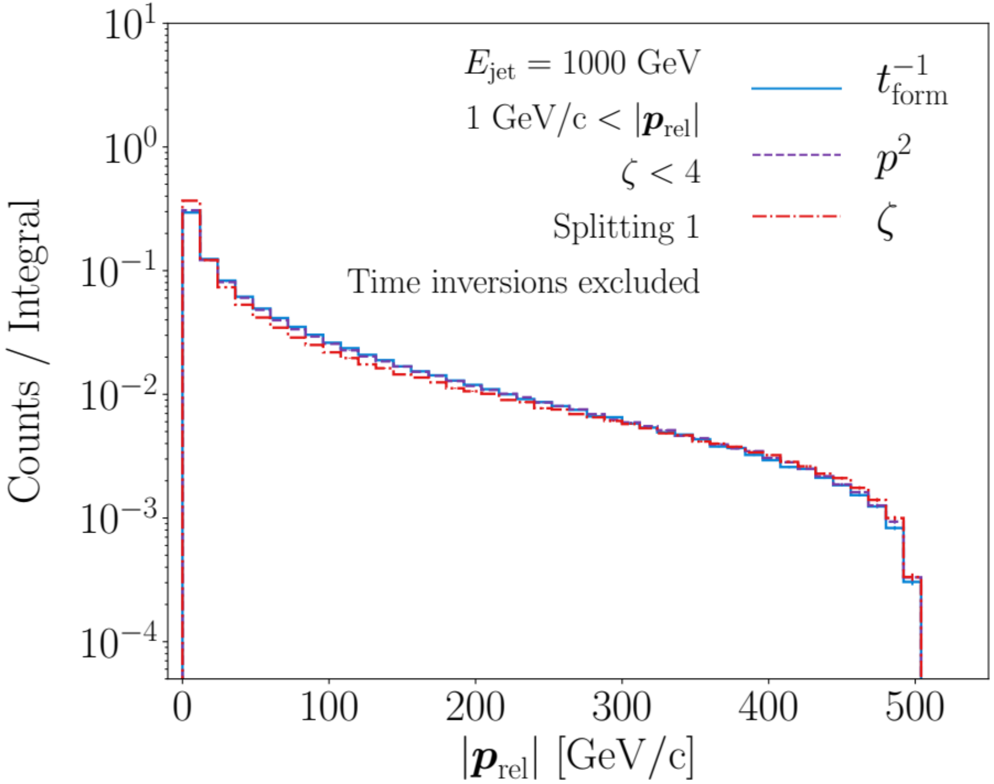




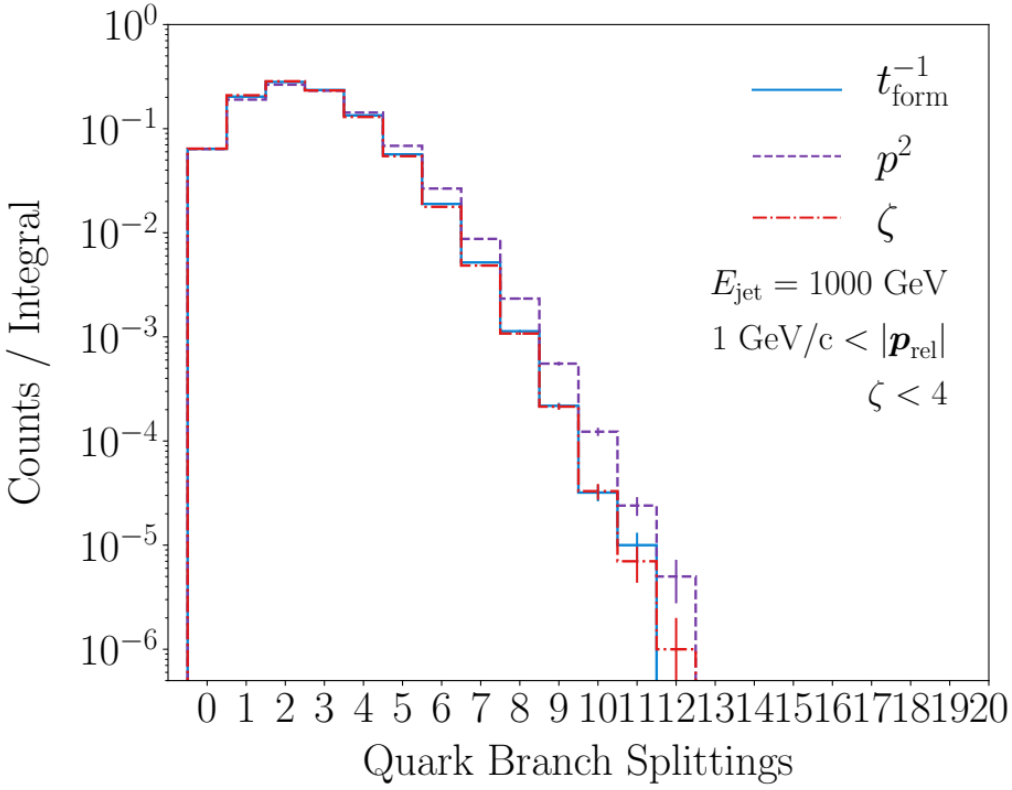
When the condition ζ < 4 is used as a veto for all emissions, the distributions become consistent.

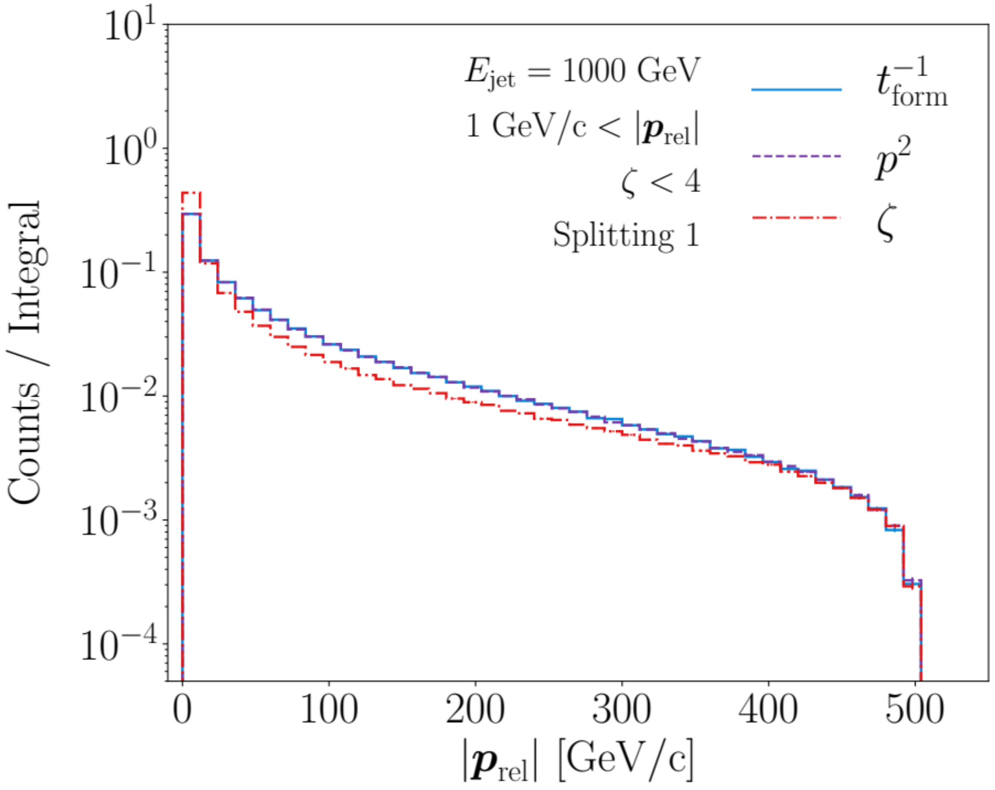
Excluding time inversions – 1D Distributions



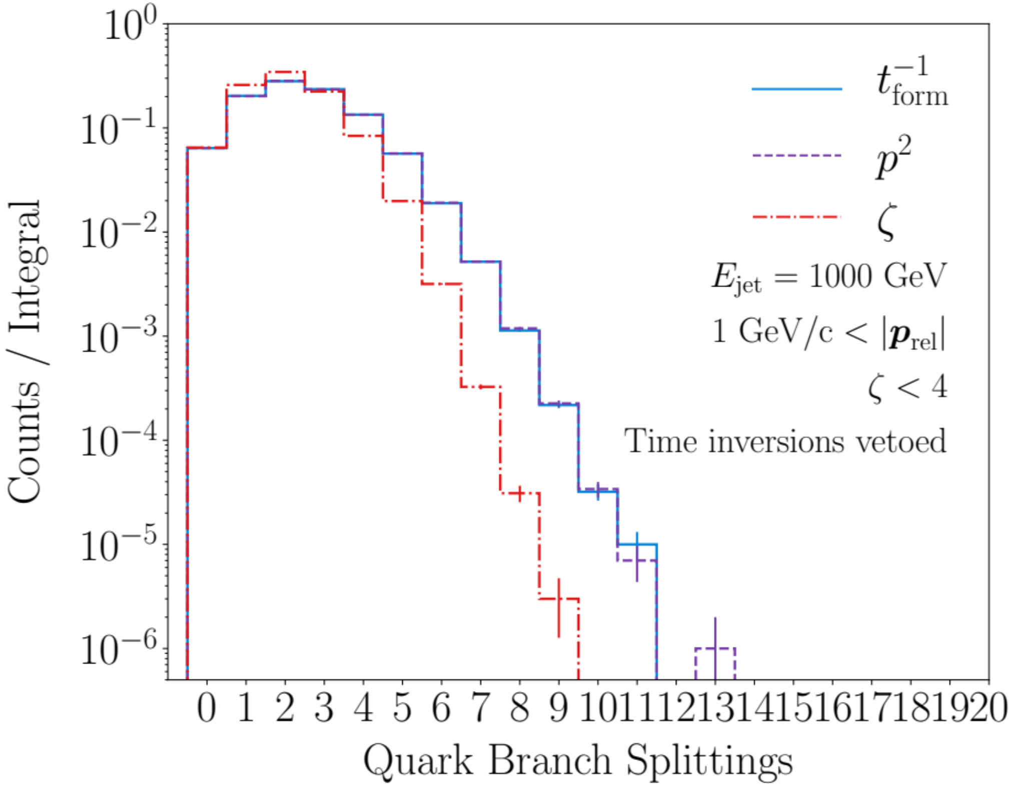


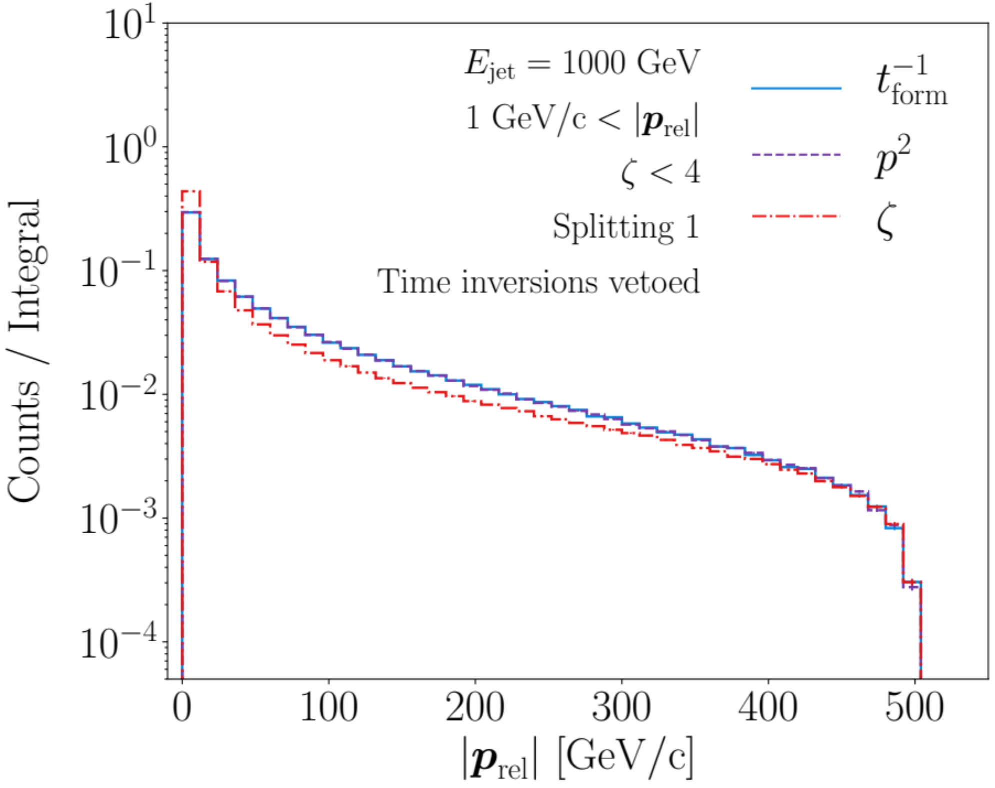
Inclusive Sample – 1D Distributions





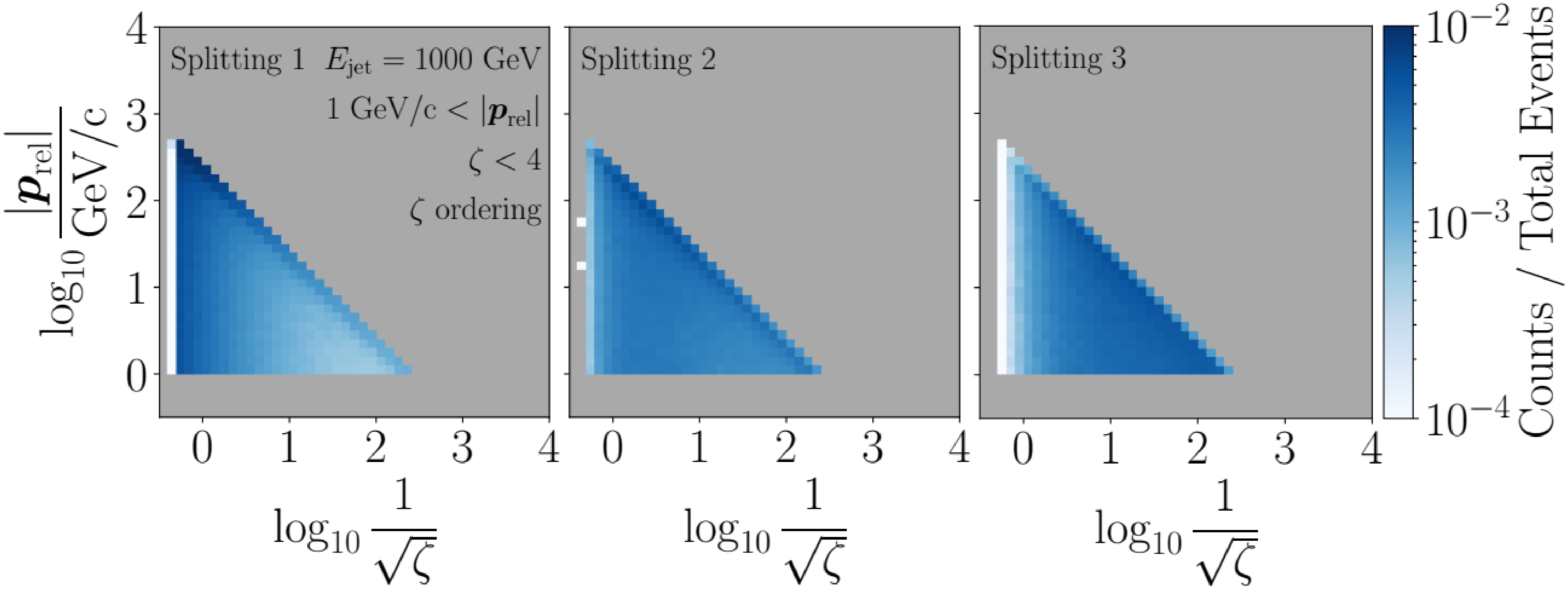
Vetoing time inversions – 1D Distributions





Inclusive Sample – Lund Planes

<u>*Ordered in angle</u>



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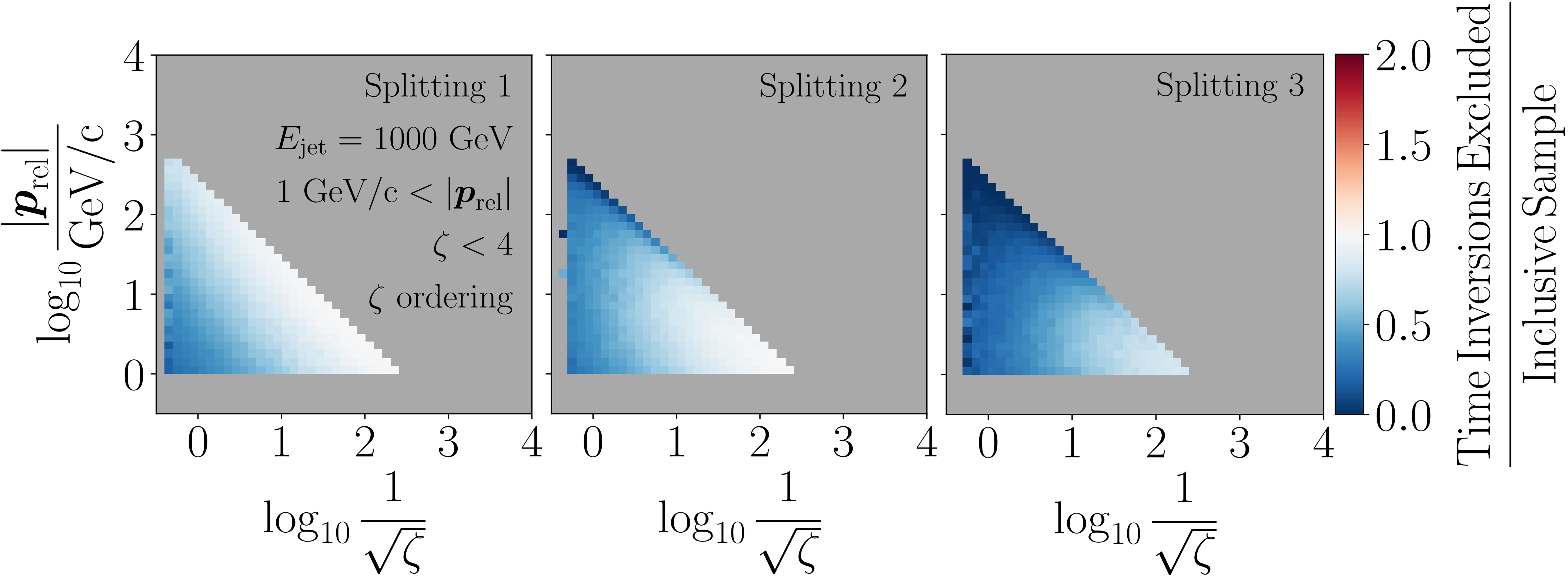

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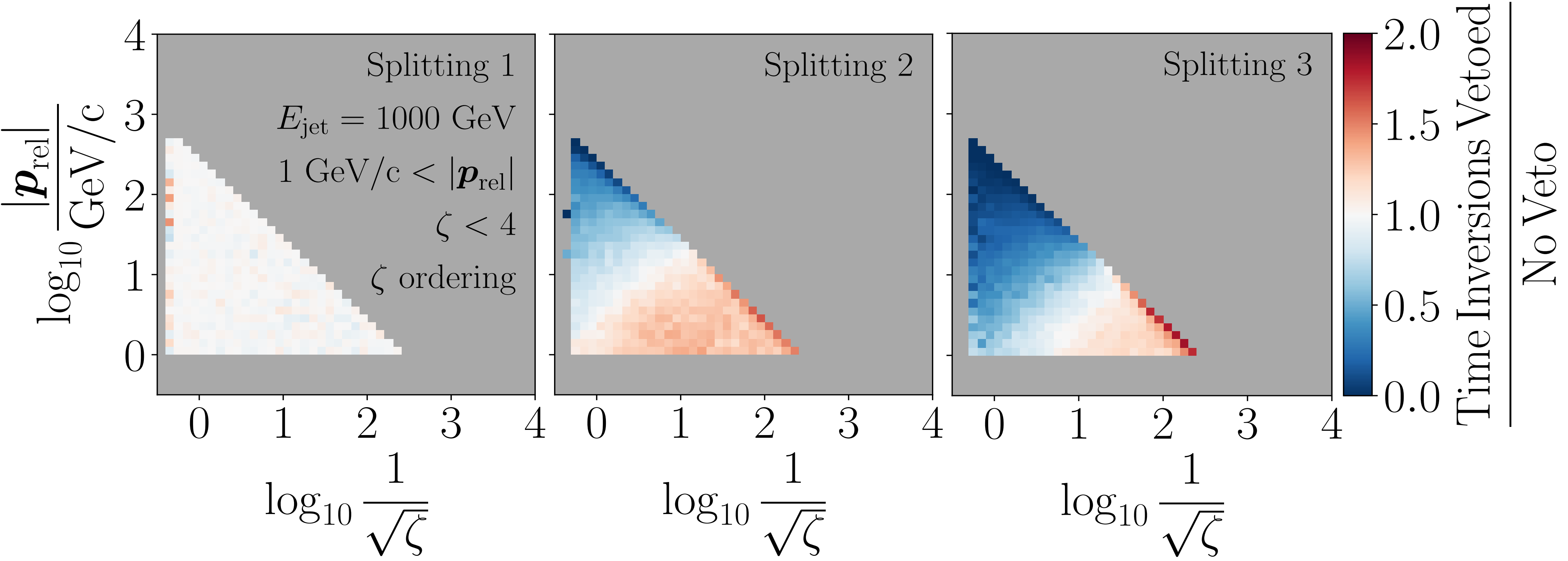
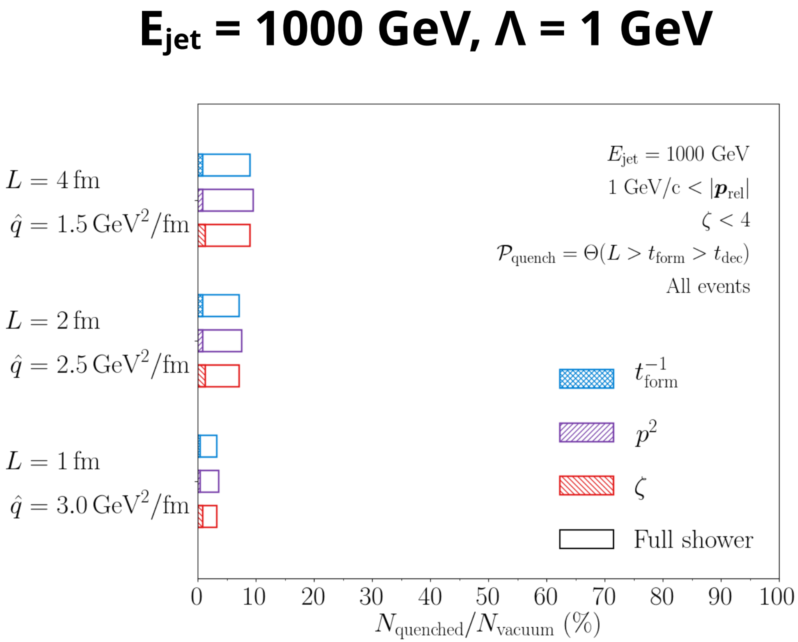
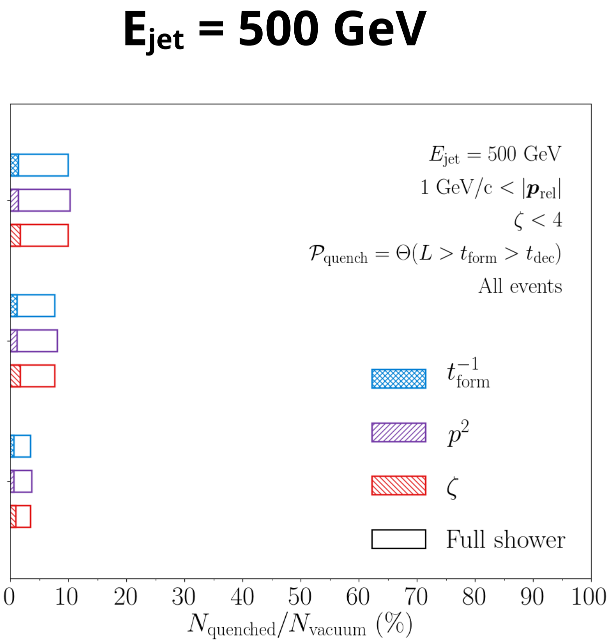
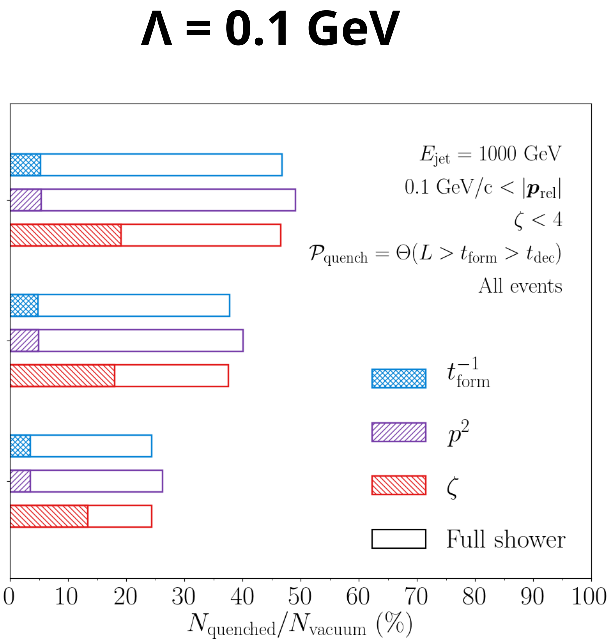


Quenching Weights





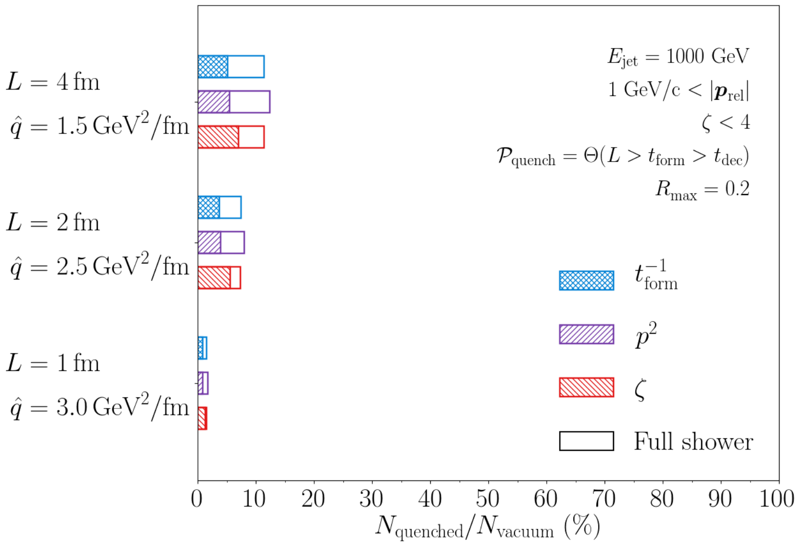


An apparent dependence on the hadronisation cutoff and initial jet energy

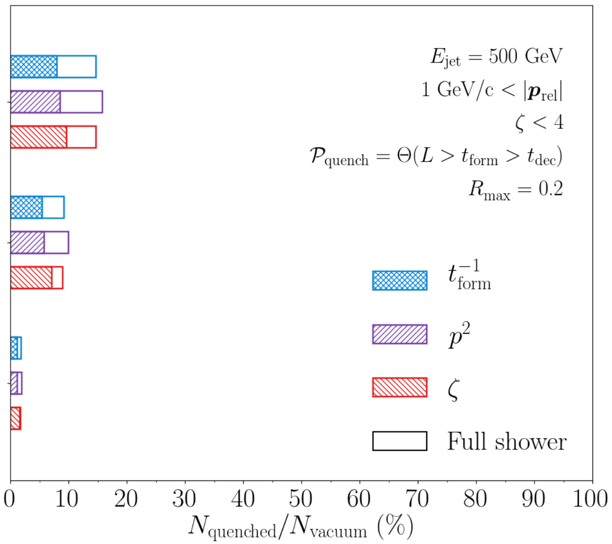
Very Preliminary!

Quenching Weights – Radius Cut

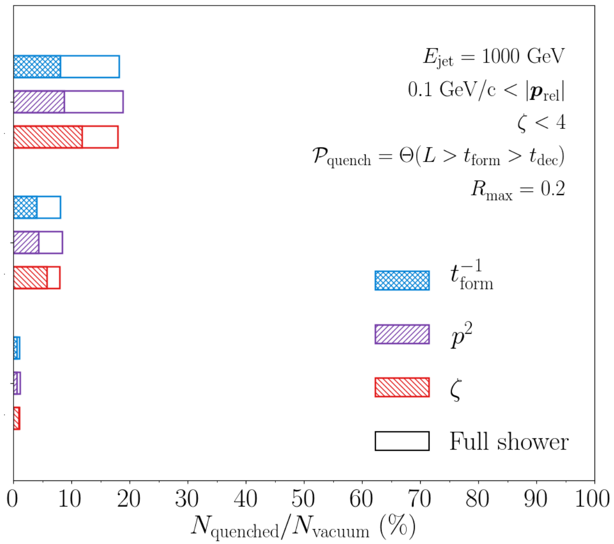
E_{jet} = 1000 GeV, Λ = 1 GeV



E_{jet} = 500 GeV



Λ = 0.1 GeV



Cut all events whose quark branch has a splitting wider than R_{max} = 0.2
- This defines the new vacuum sample, and the quenching model is applied on top of this cut

An aggressive cut, but it returns independence of E_{jet} and Λ.