Parton cascades at DLA: the role of the evolution variable

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In collaboration with:

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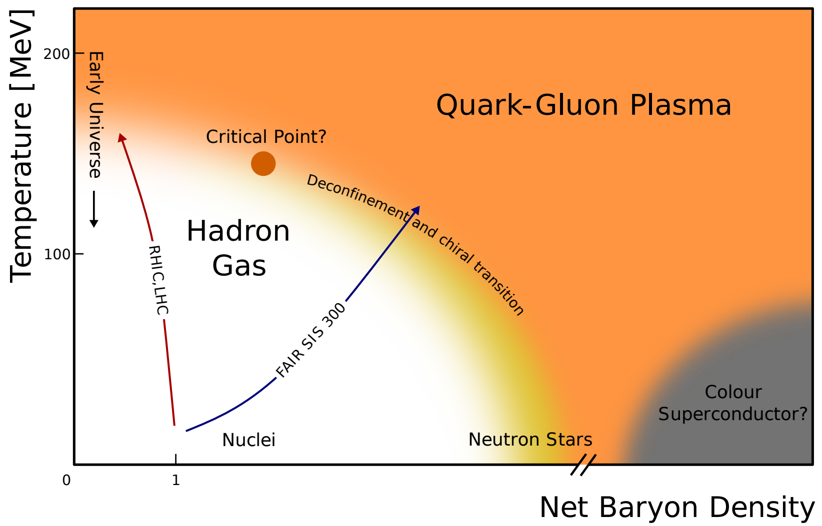
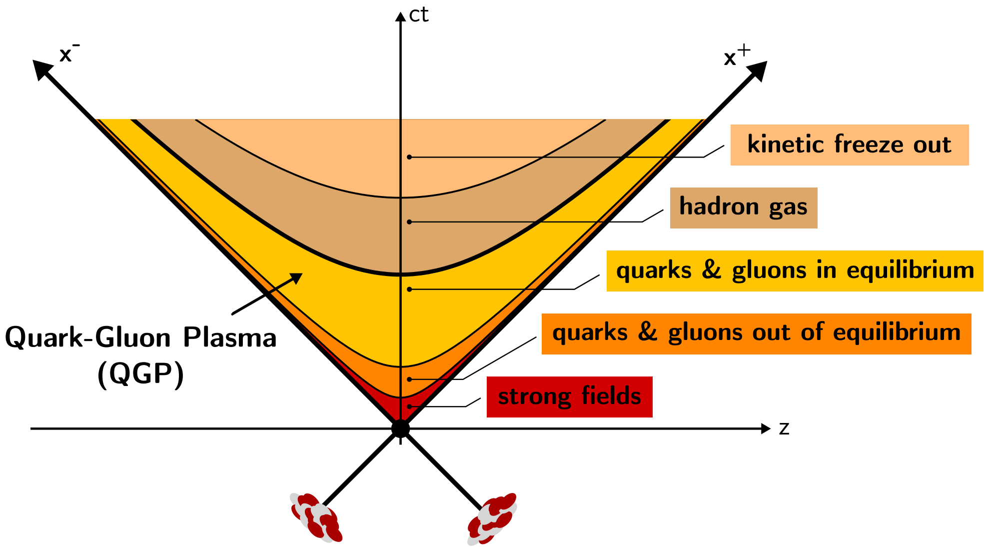
Excited QCD Workshop, 19th January 2024

Heavy Ion Collisions

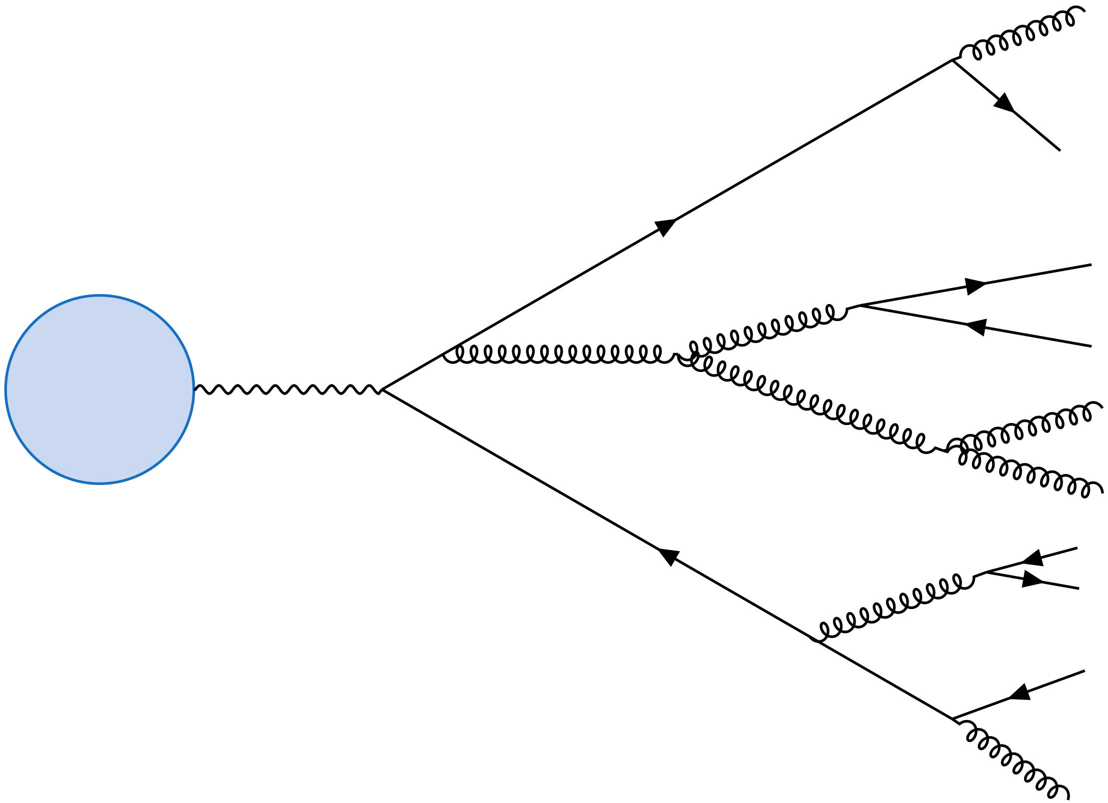


Heavy Ion collisions are valuable as a laboratory to study the QCD phase diagram

The spacetime evolution of QCD matter covers a wide range of time/energy scales



Parton Showers in a Coloured Medium



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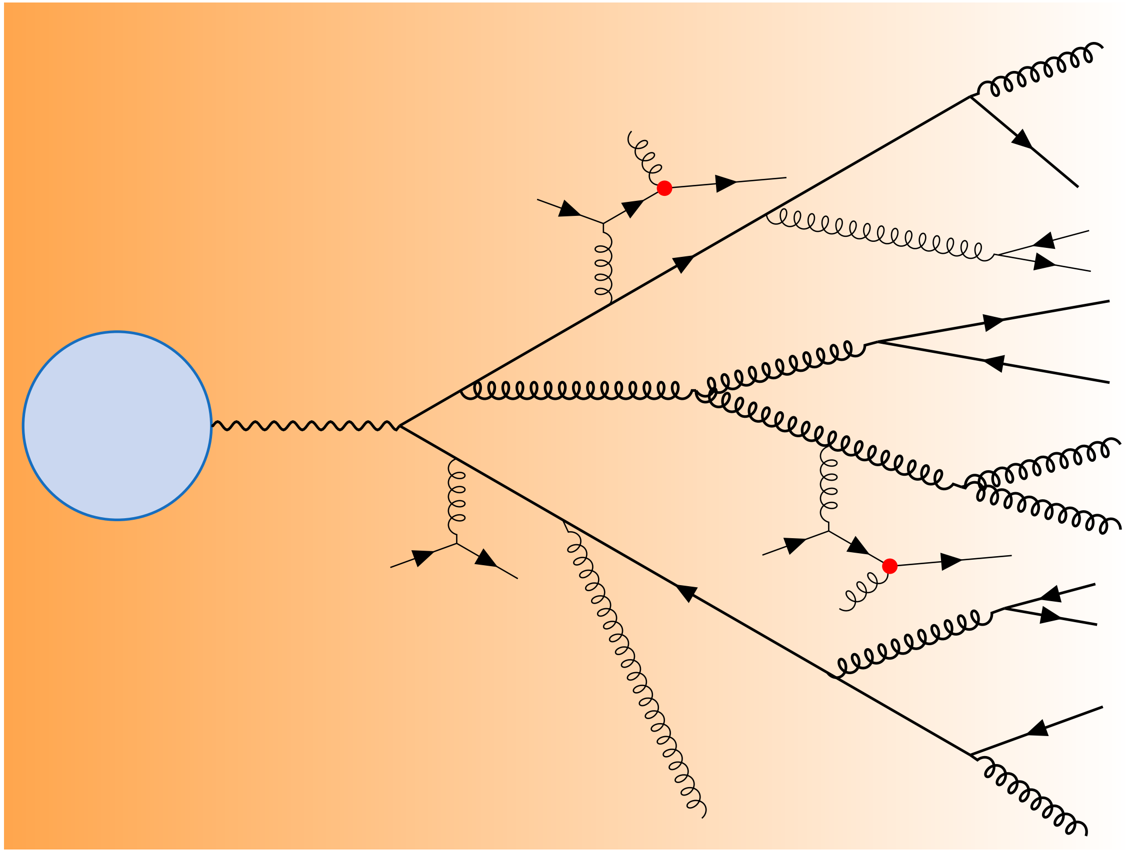

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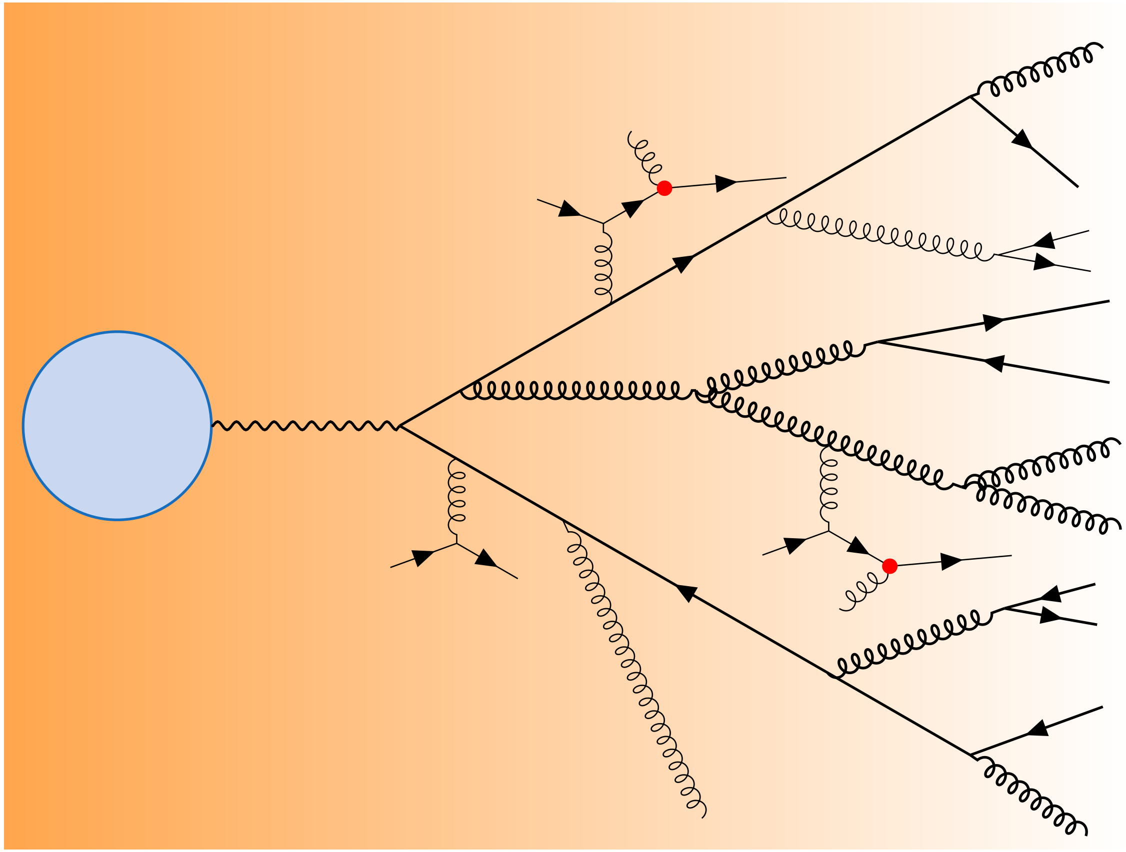

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- Time-ordered picture needed for medium interface with the cascade

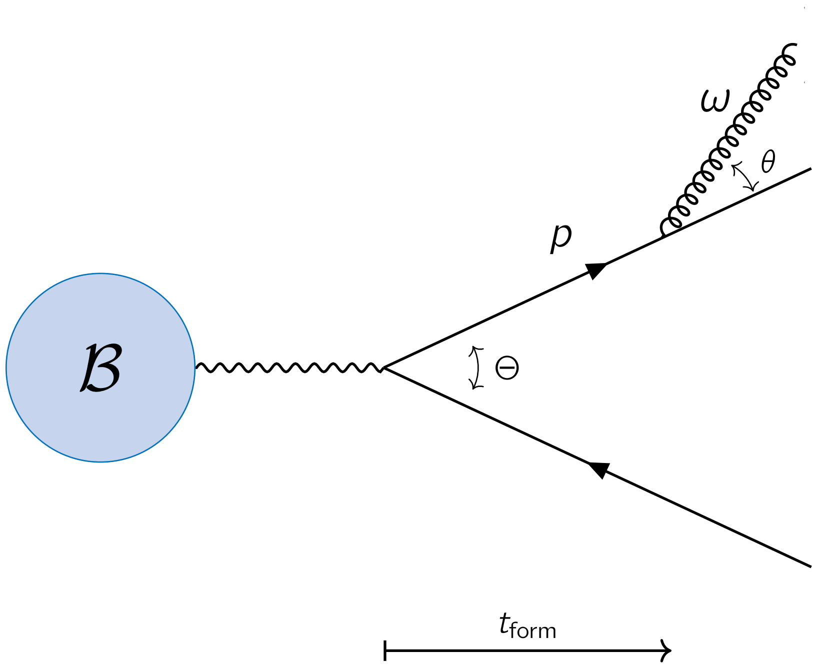
Is jet quenching sensitive to the ordering of vacuum-like splittings?

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

QCD Vacuum Splittings

Estimate some scales:

- Formation time: $t_{\text{form}} \propto \frac{1}{m}\frac{E}{m} \sim \frac{E}{p^2} \sim \frac{1}{\omega\theta^2}$



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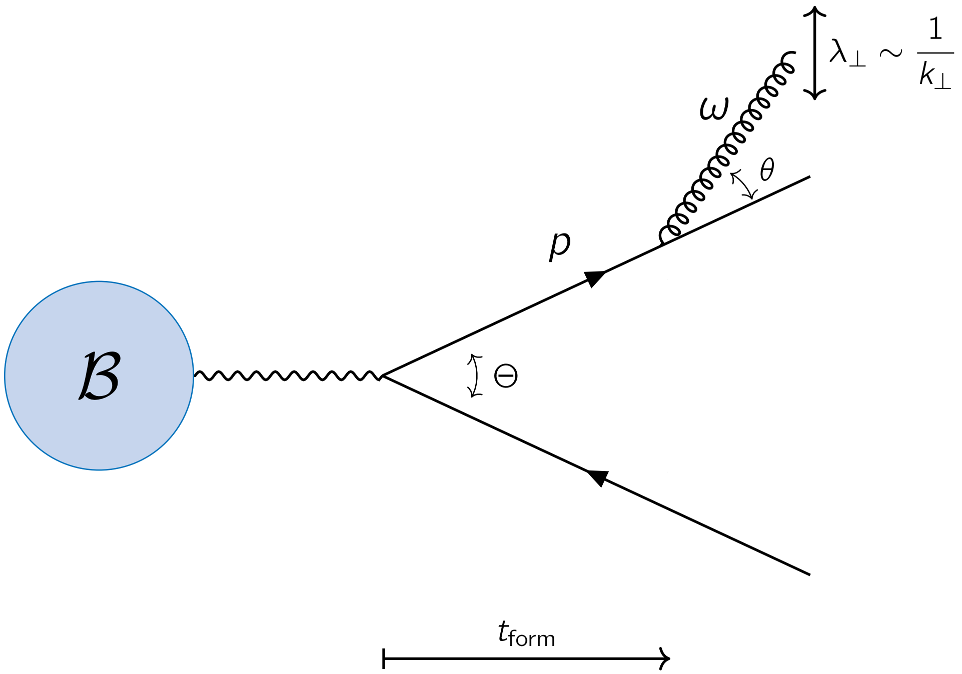

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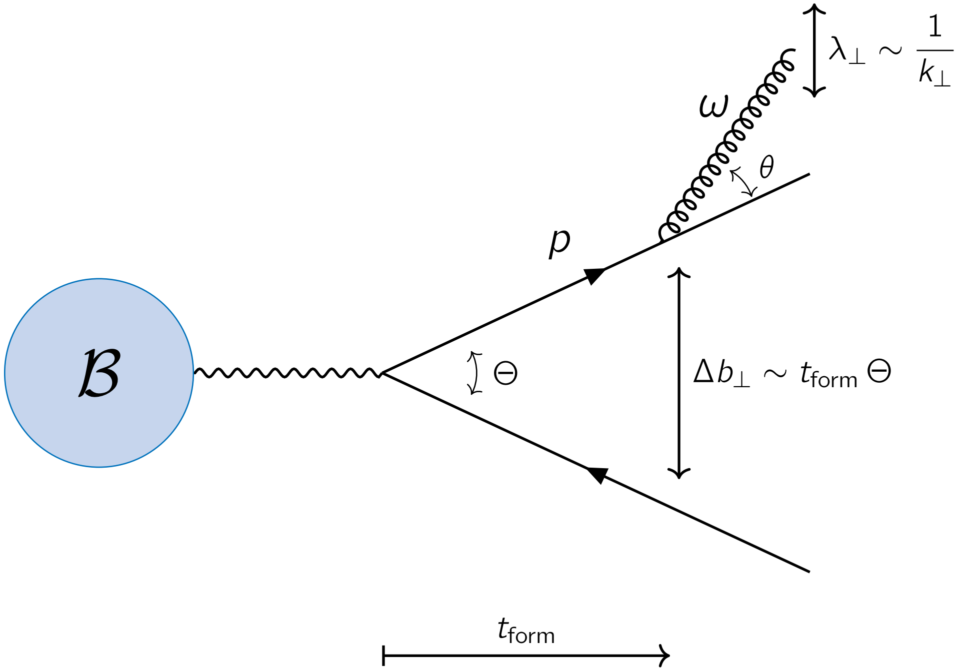

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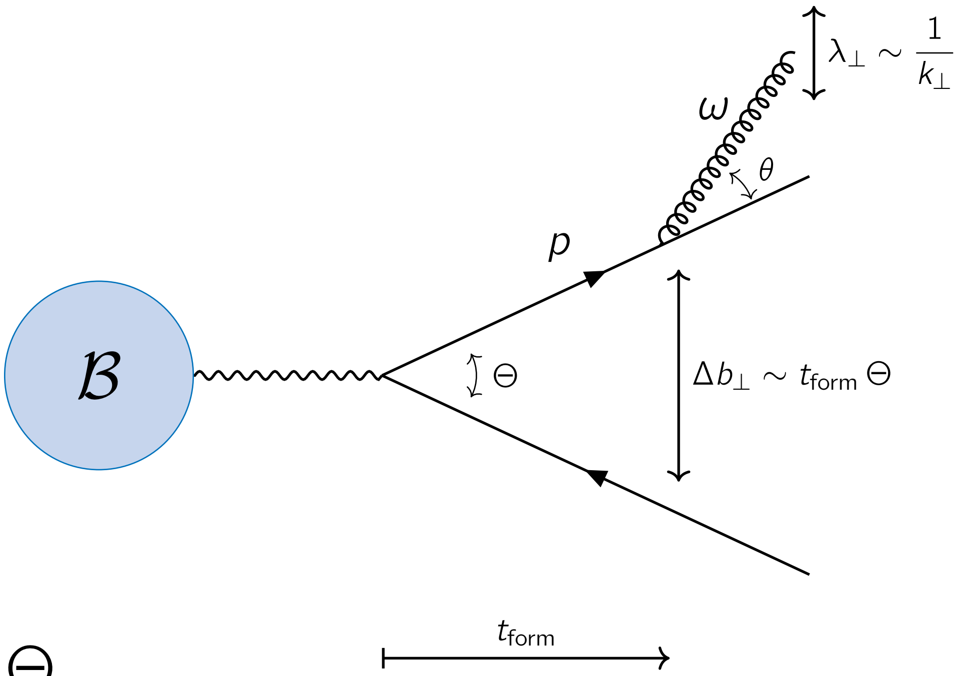

For an antenna: $\lambda_\perp < \Delta b_\perp \iff \theta < \Theta$

*** Larger λ_T**
→ Gluon cannot resolve the antenna legs
→ Emission by the antenna as a whole
→ Singlets cannot radiate

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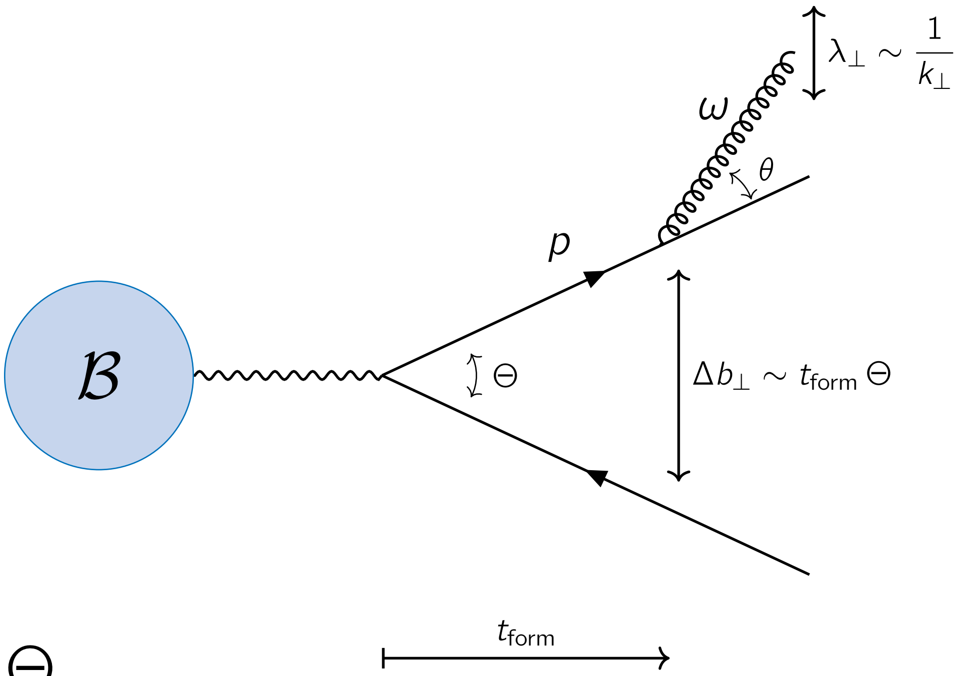

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This is the <u>angular ordering</u> property of vacuum splittings → Showers are collimated

QCD Vacuum Splittings

*Can be generalised to non-singlets & mutiple emissions

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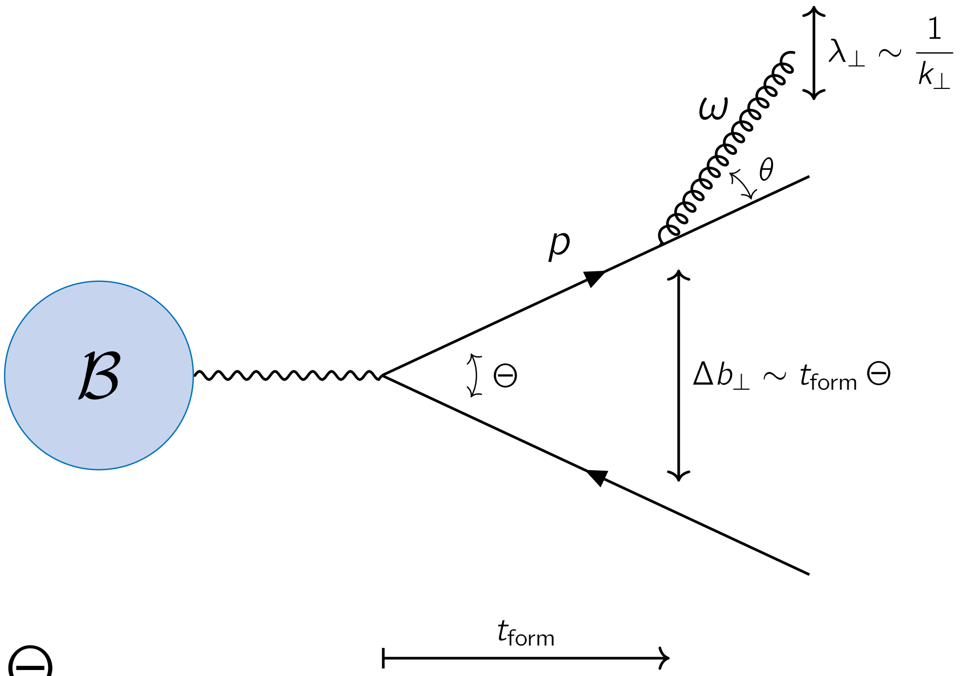

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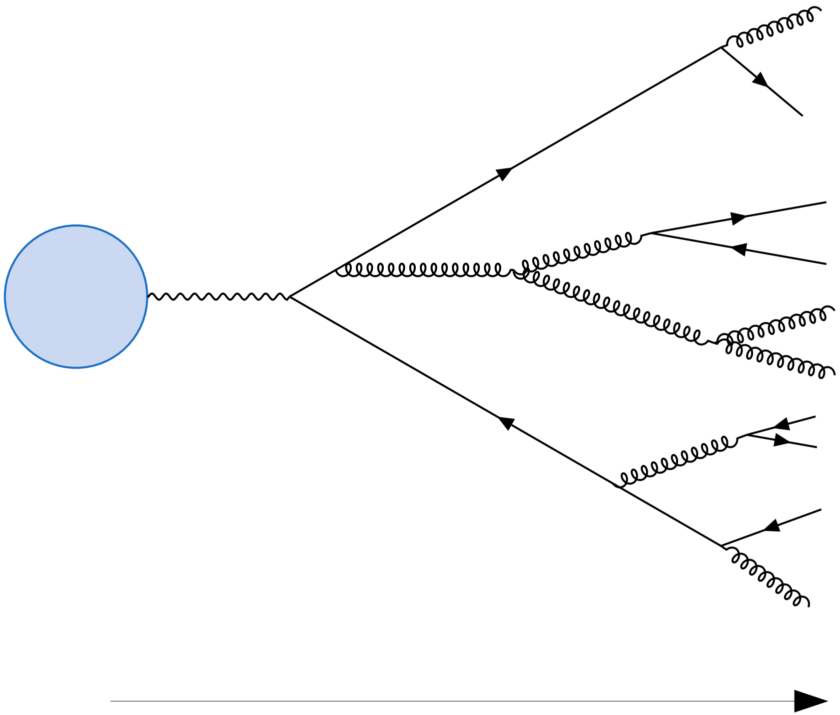
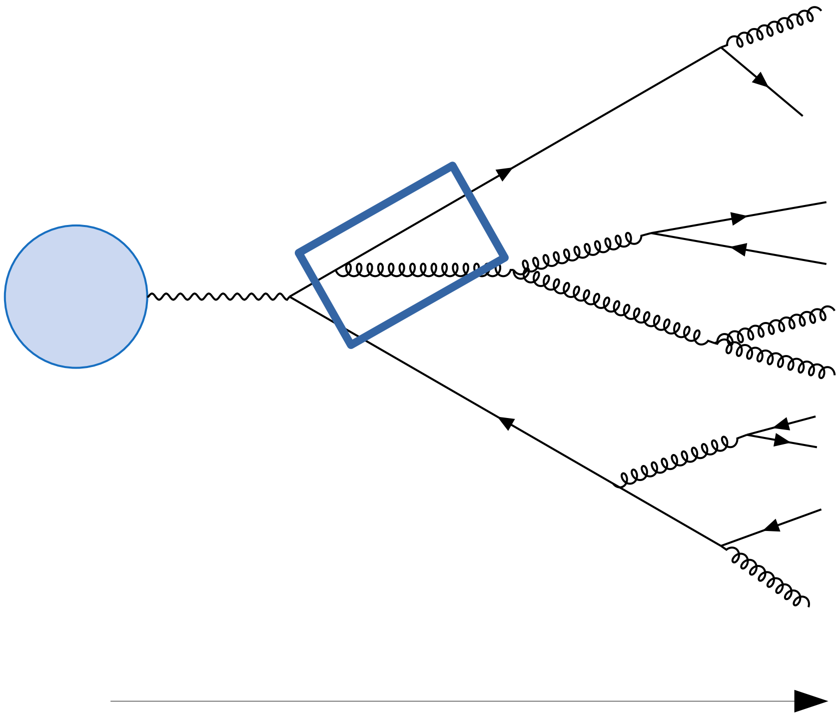
How to build a parton shower



Splittings with decreasing scale μ

How to build a parton shower

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



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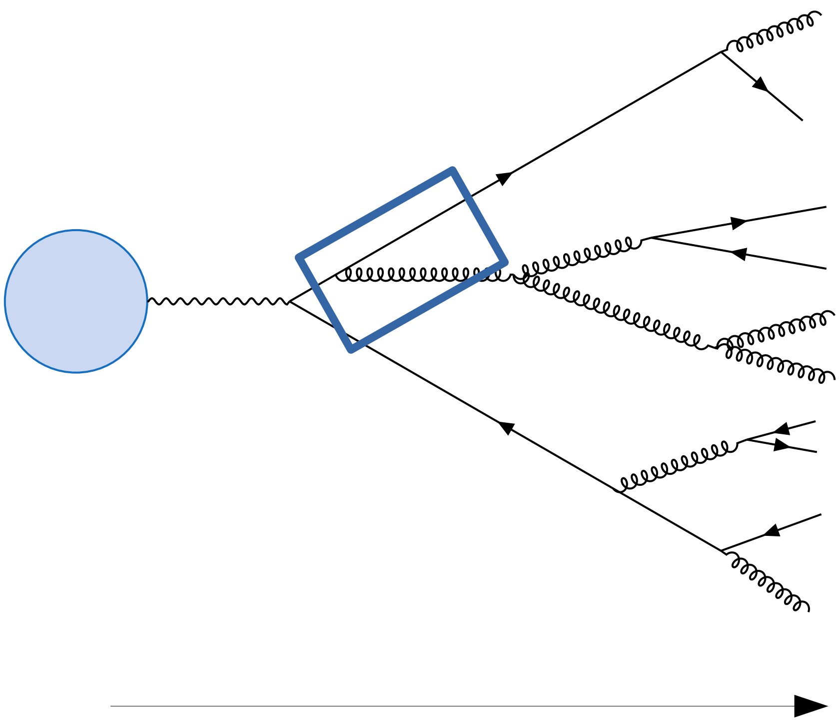
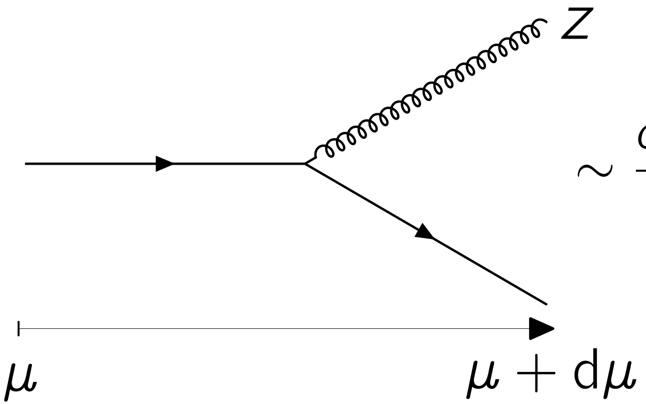


Splittings with decreasing scale μ

Splitting probability given by pQCD:



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

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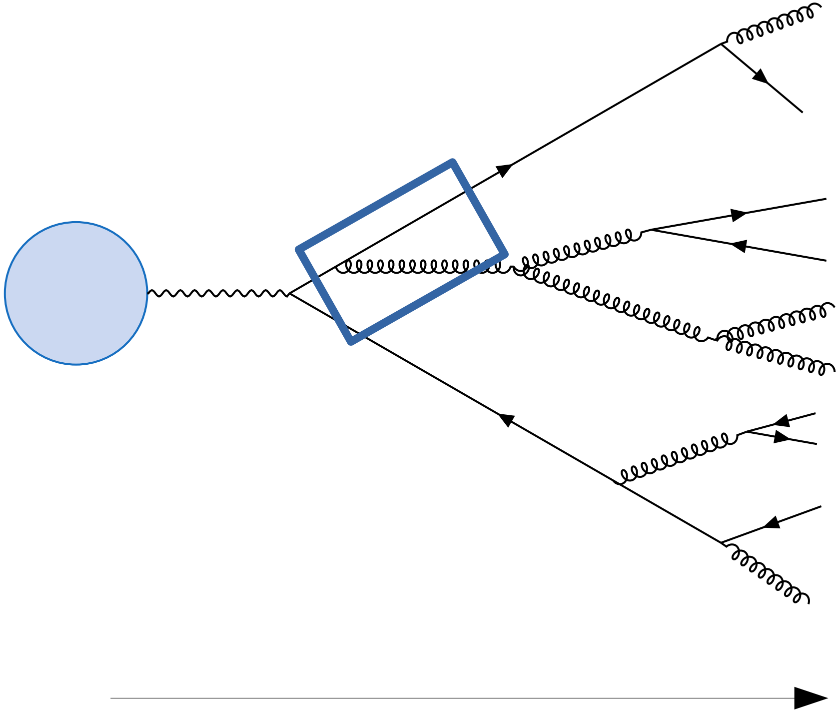

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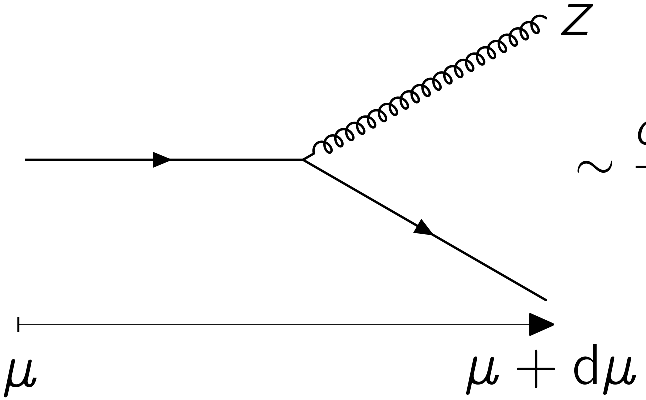

$$\sim \frac{\alpha\, C_F}{\pi} \frac{\mathrm{d}\mu}{\mu} \frac{\mathrm{d}z}{z}$$

Probability of not emitting until some scale s :

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

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

Building differently ordered cascades

No-emission probability:

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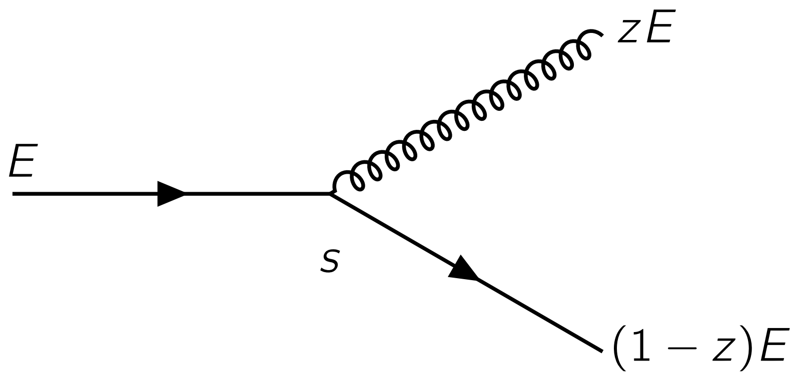
Splitting variables:



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Interpretations for the scale:

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

(Virtuality)

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

(Formation time)

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

(Angle)

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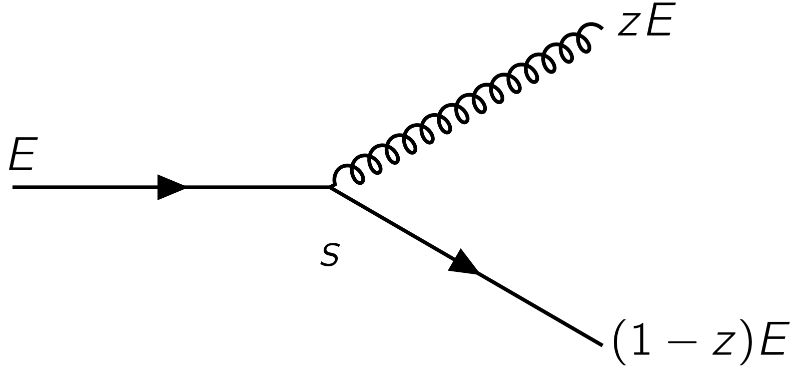

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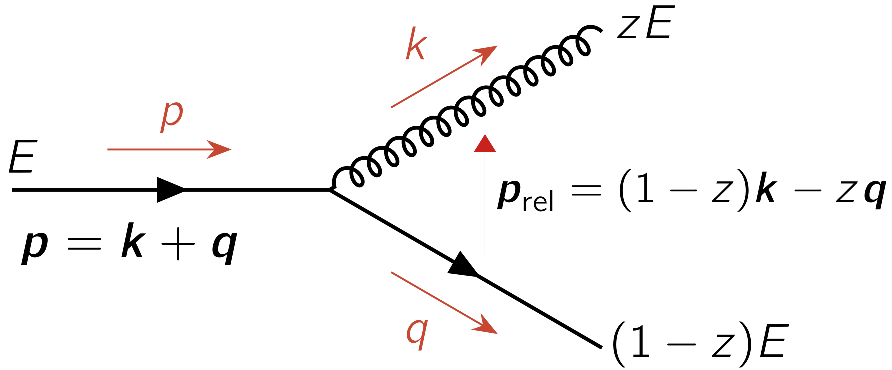
To generate a splitting:



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

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

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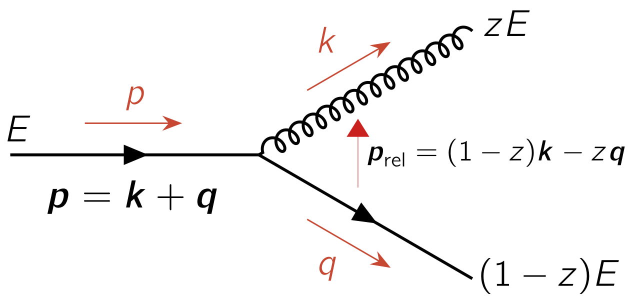

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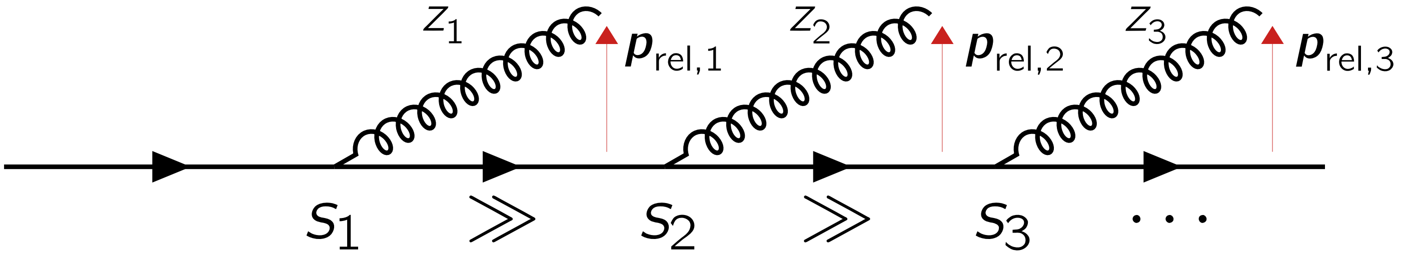
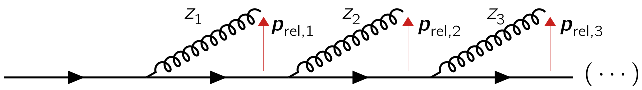


This results in the strong ordering of scales

Parton Shower Details



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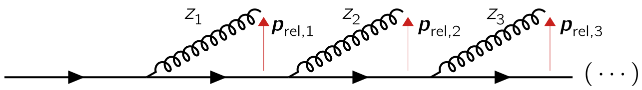

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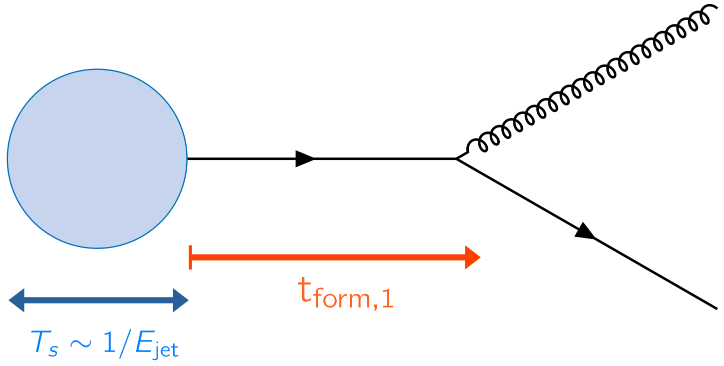
- Splittings must happen above an hadronisation scale: $|\boldsymbol{p}_{\mathrm{rel}}|^2 > \Lambda^2$
  - This provides a **soft cutoff:** $z > z_{\mathrm{cut}}(s)$

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

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



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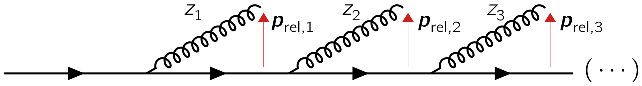

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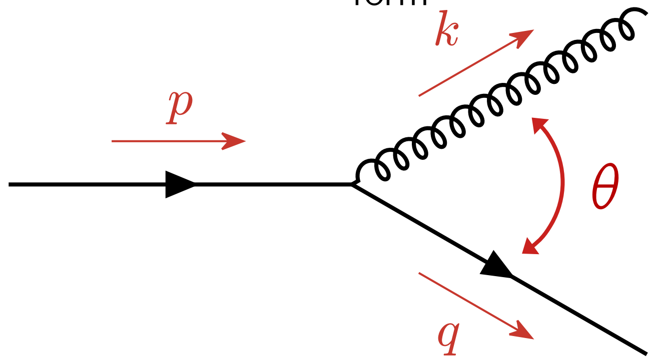
  - For consistency between orderings: $\zeta < 4 \Longrightarrow |\boldsymbol{p}_{\text{rel}}| < \frac{E}{2}$

    (Enforced via retrials)

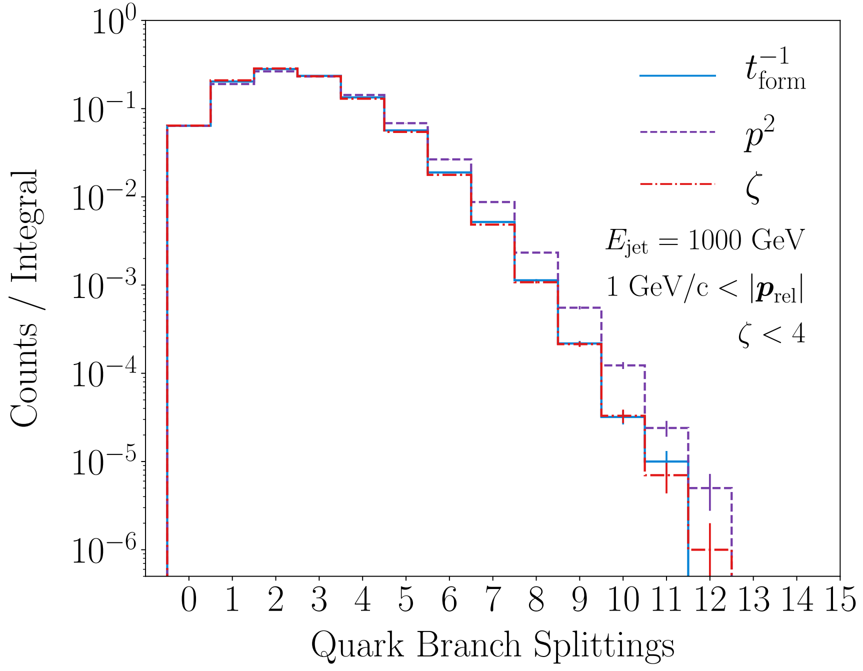


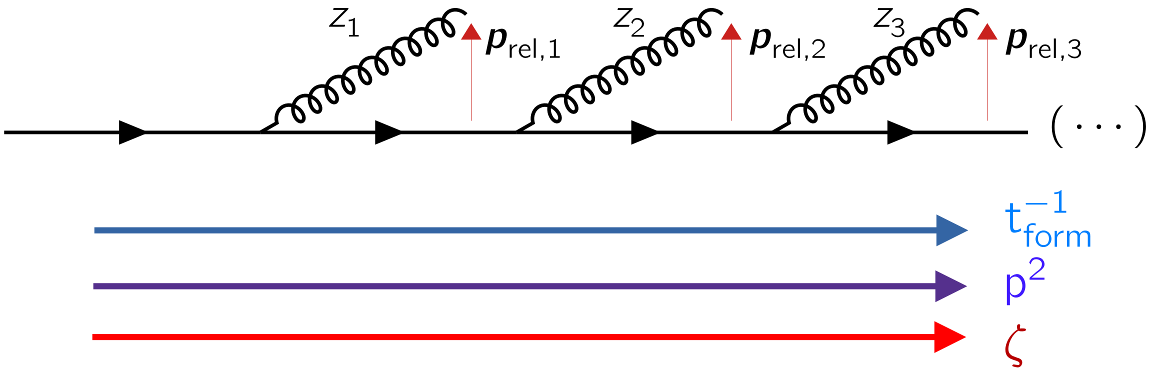
Massless Limit : $\zeta \simeq 2(1-\cos\theta)$

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

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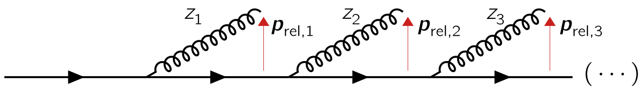

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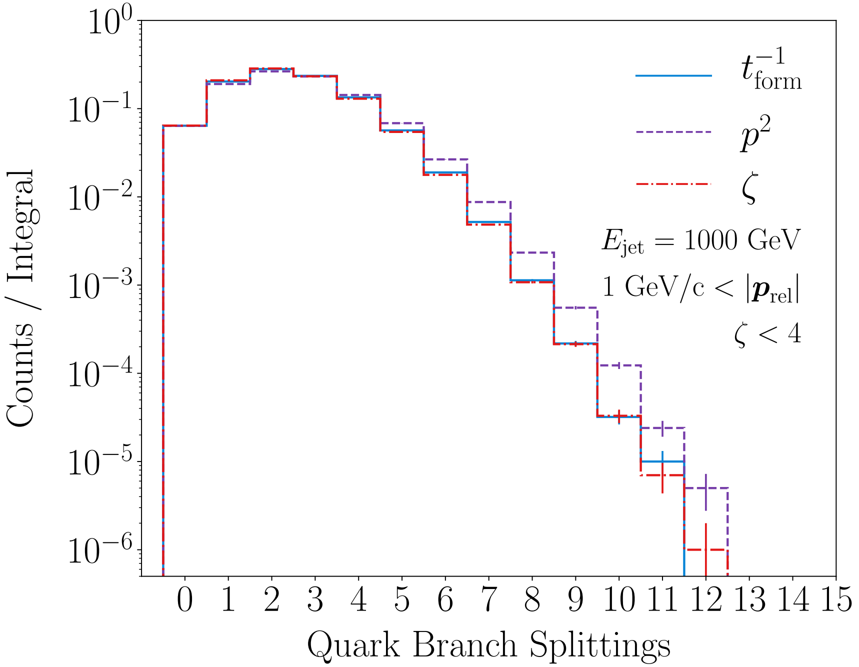

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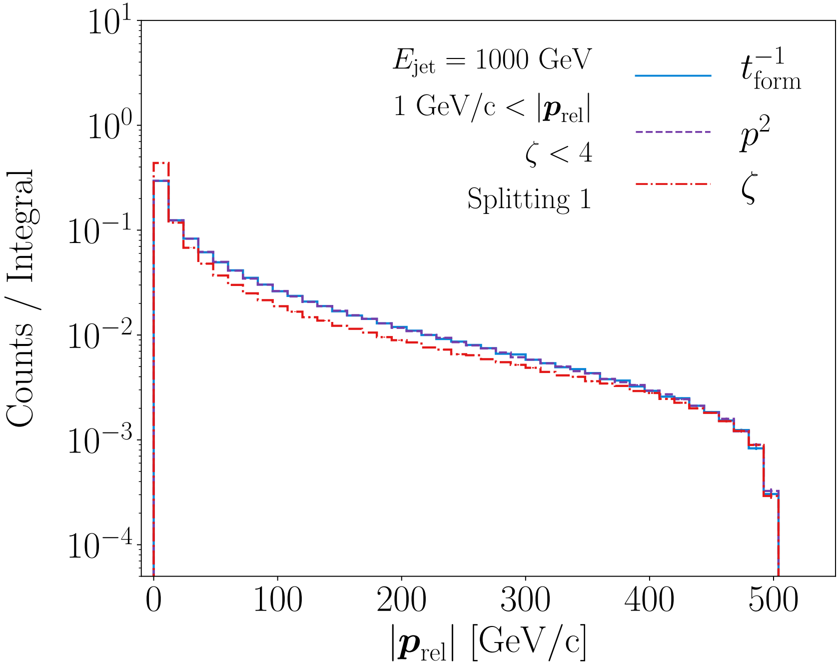
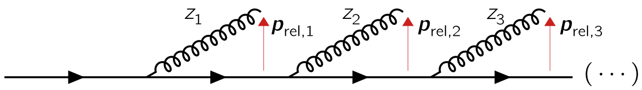
Relative transverse momentum (1st splitting)



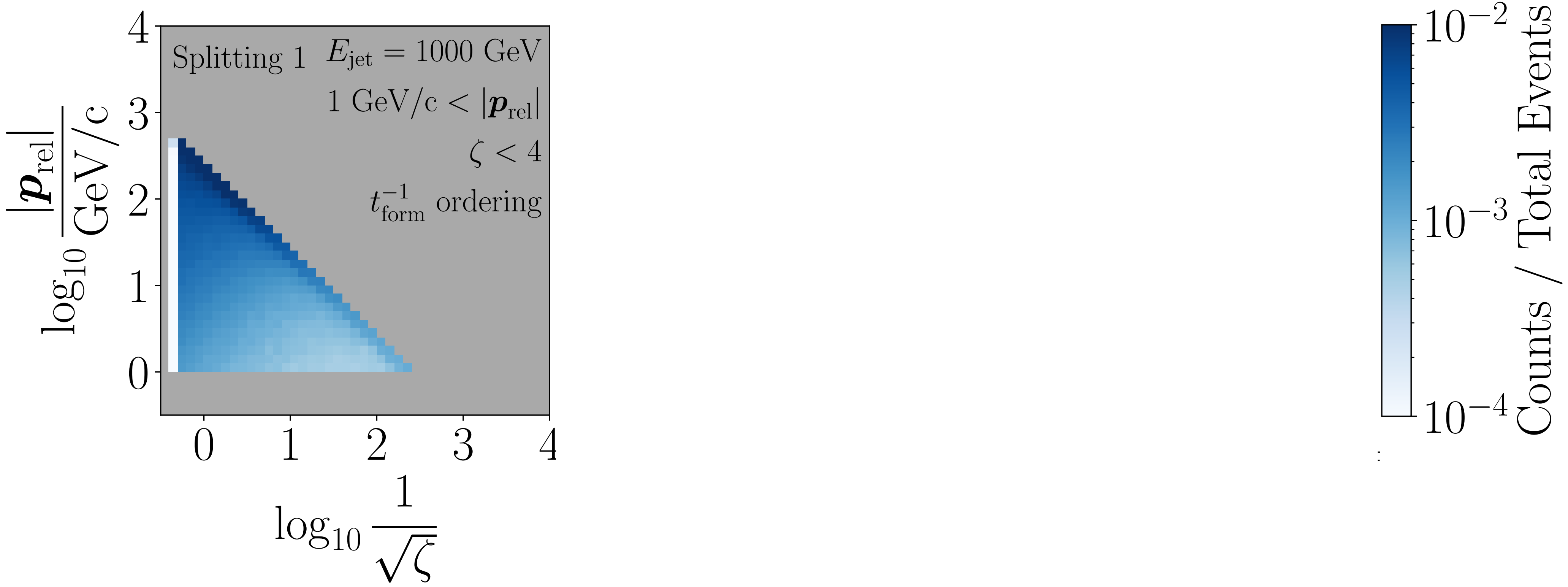
Transverse momentum distributions follow $\frac{\mathrm{d}\boldsymbol{p}_{rel}^2}{\boldsymbol{p}_{rel}^2}$

Lund Plane Densities



*Exaggerated scale

Consider the shower evolution <u>along the quark branch</u>:



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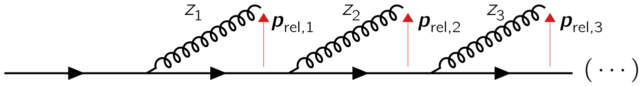

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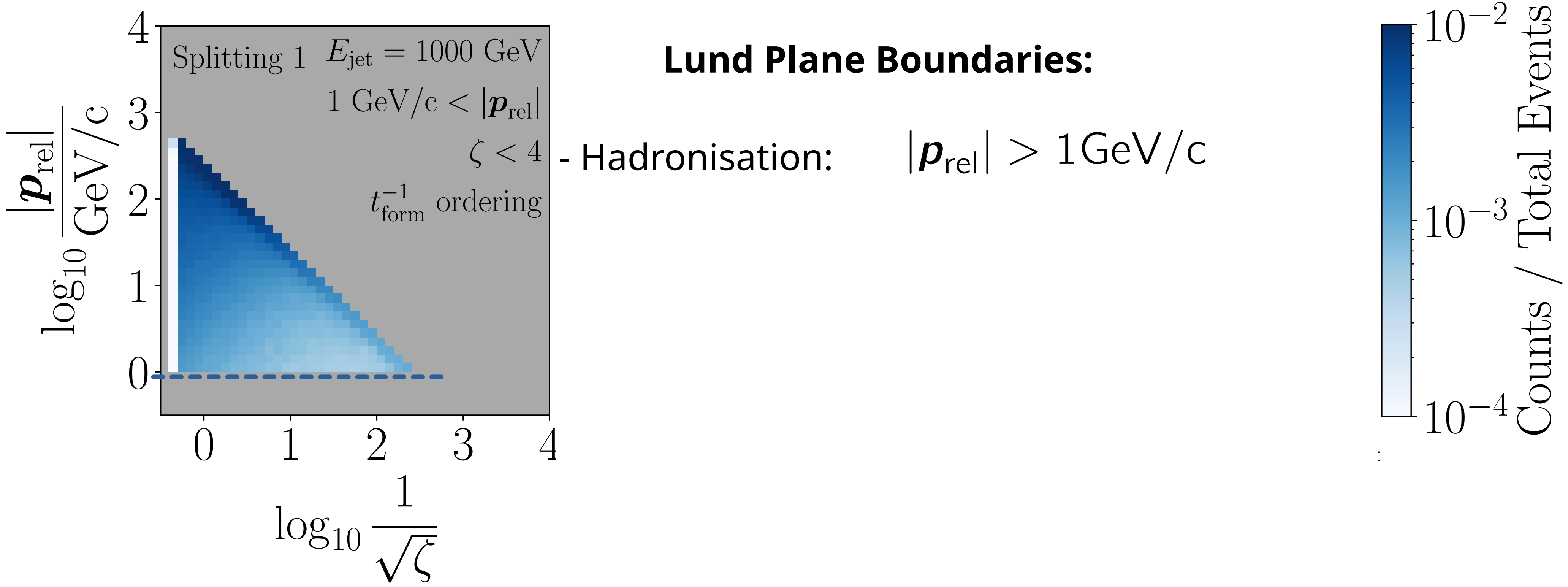

Lund Plane Boundaries:

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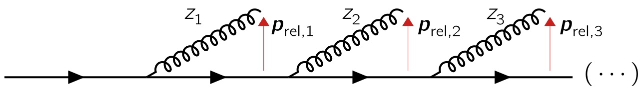

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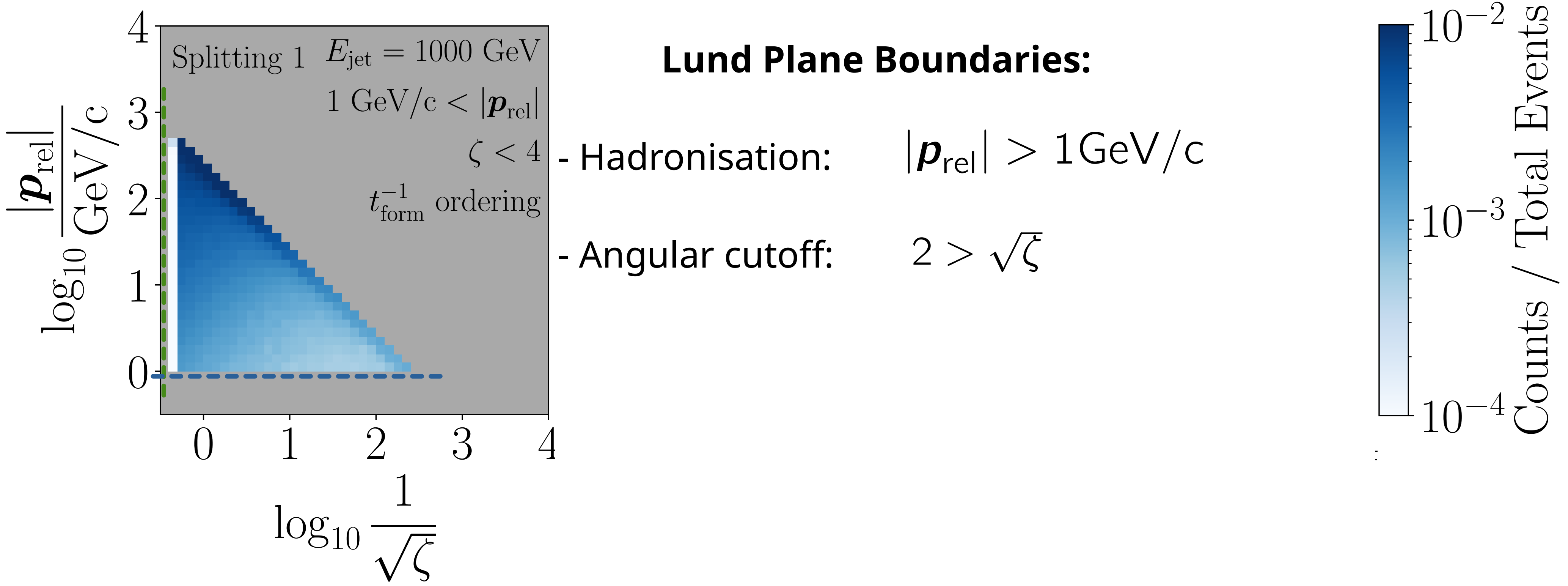

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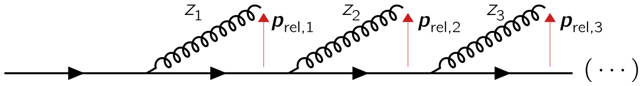

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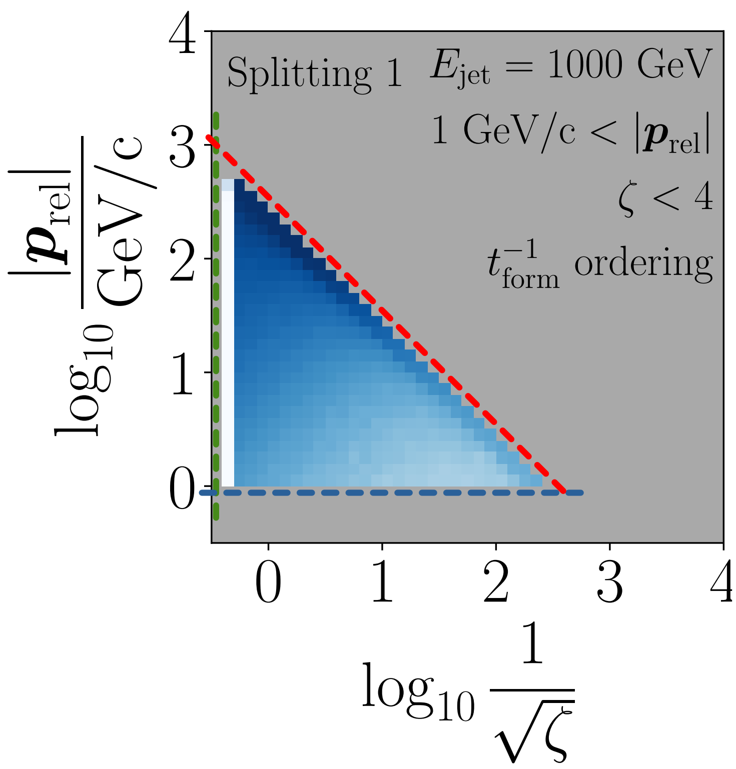

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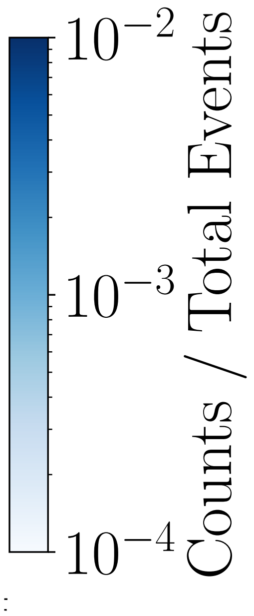

Shower evolution: Both transverse momentum and angle decrease.

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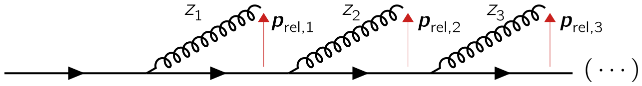

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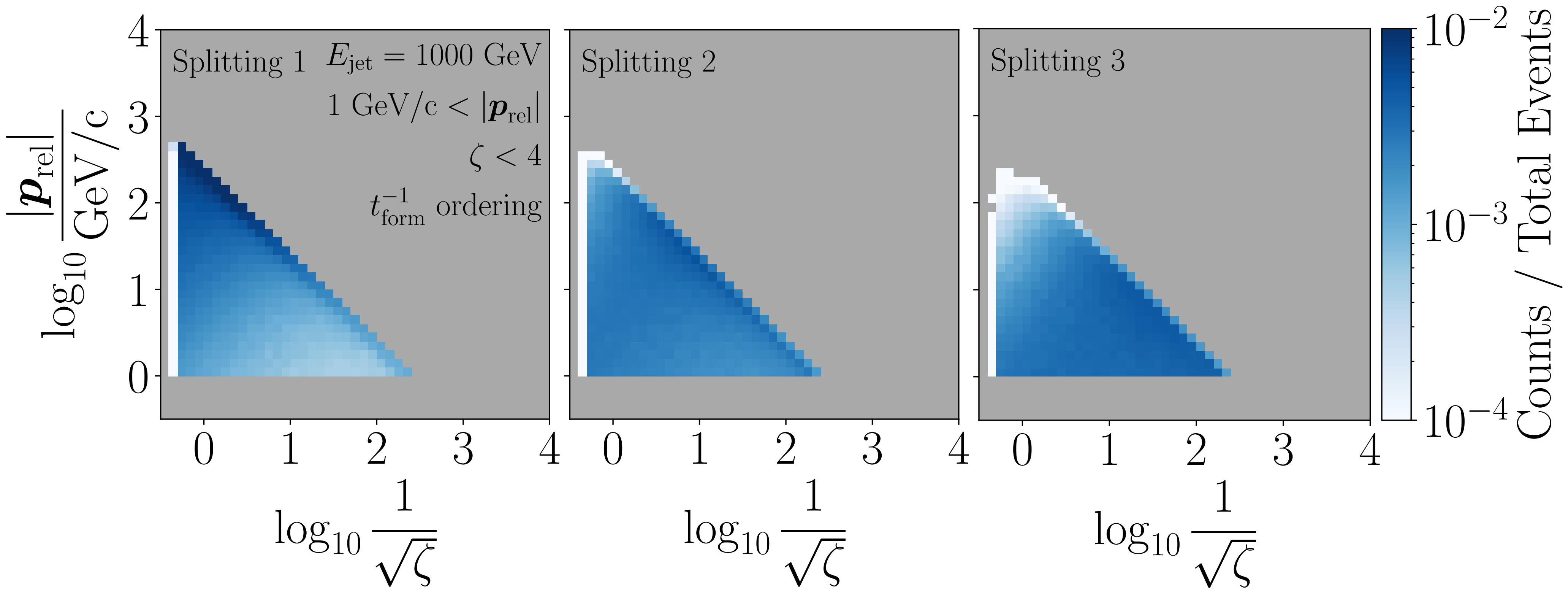

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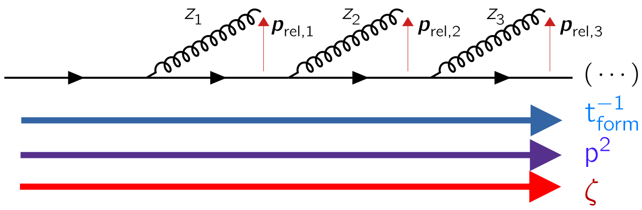
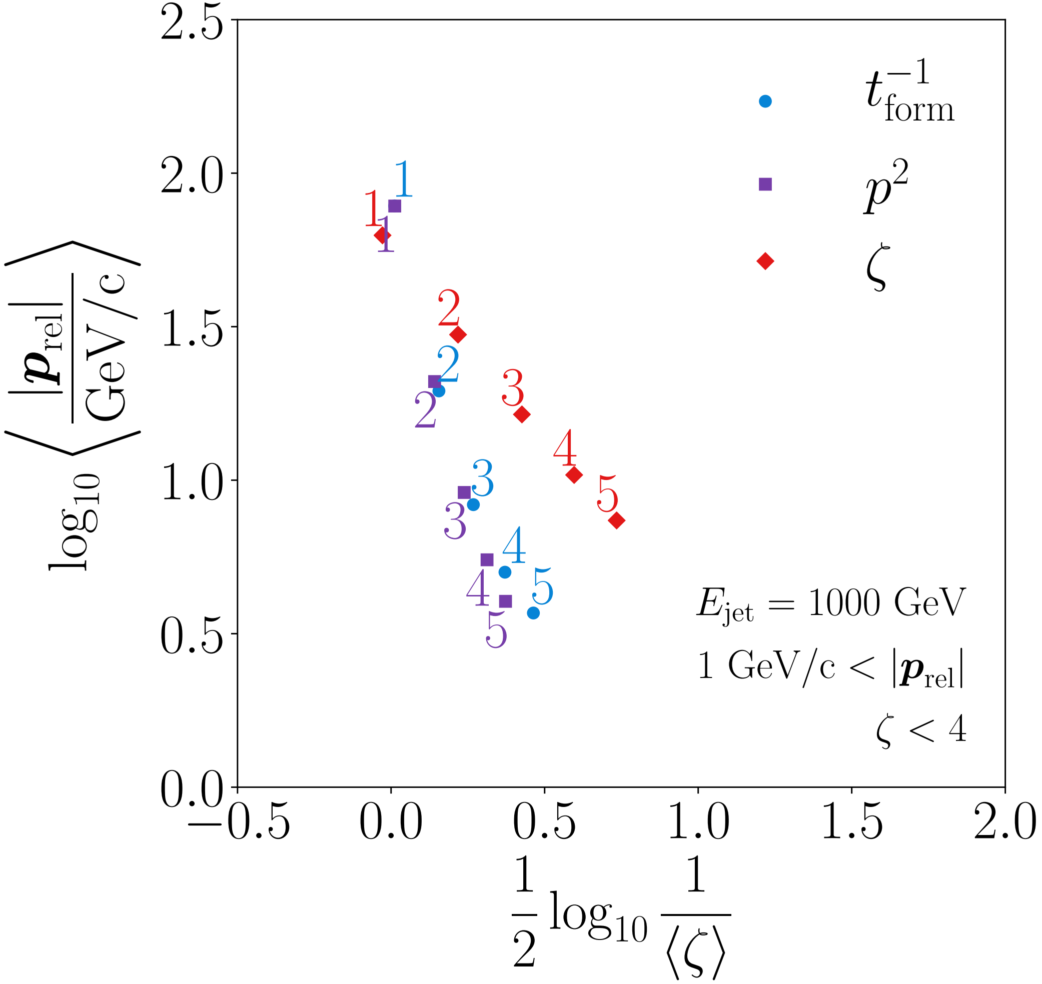
Lund Plane Trajectories



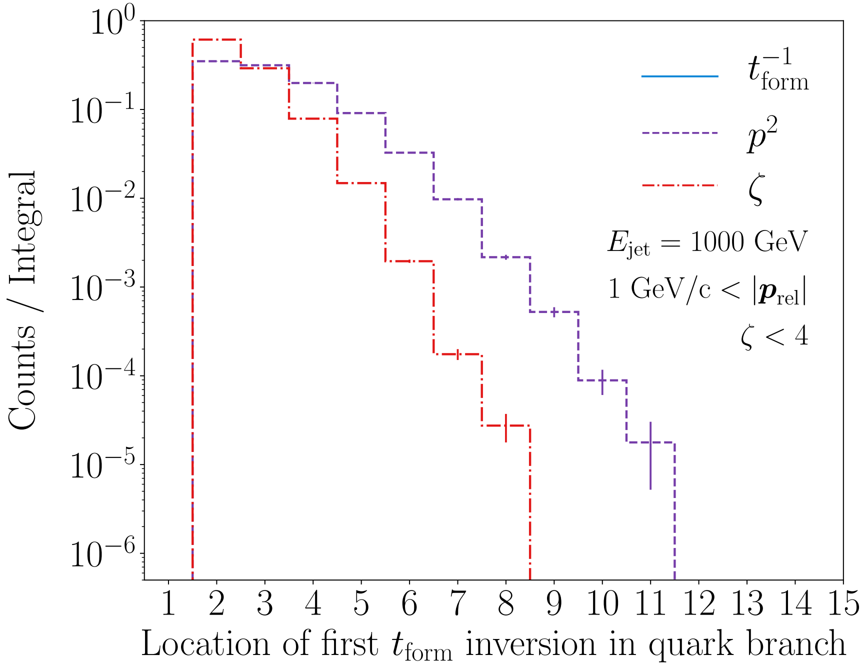


Differences between phase-space trajectories

→ 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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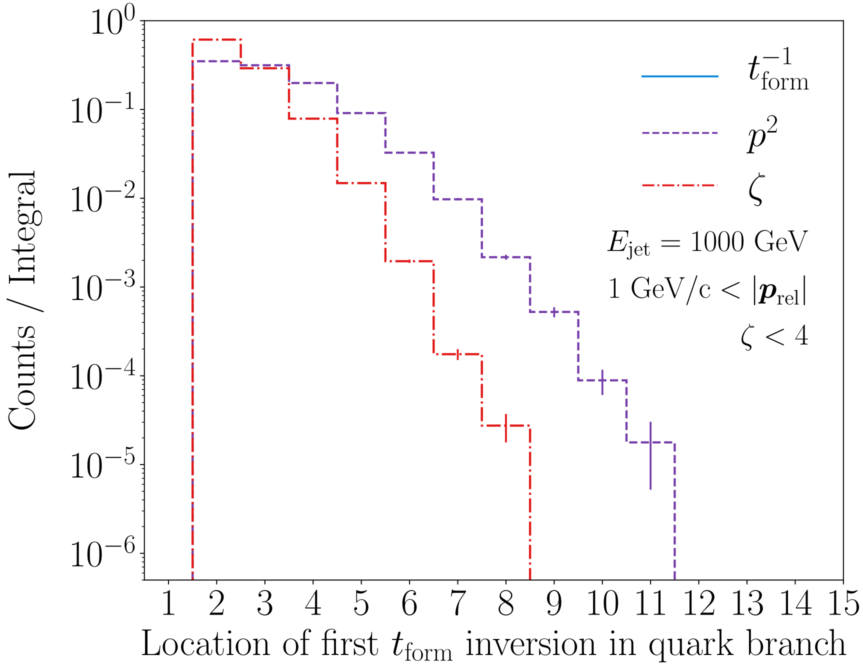

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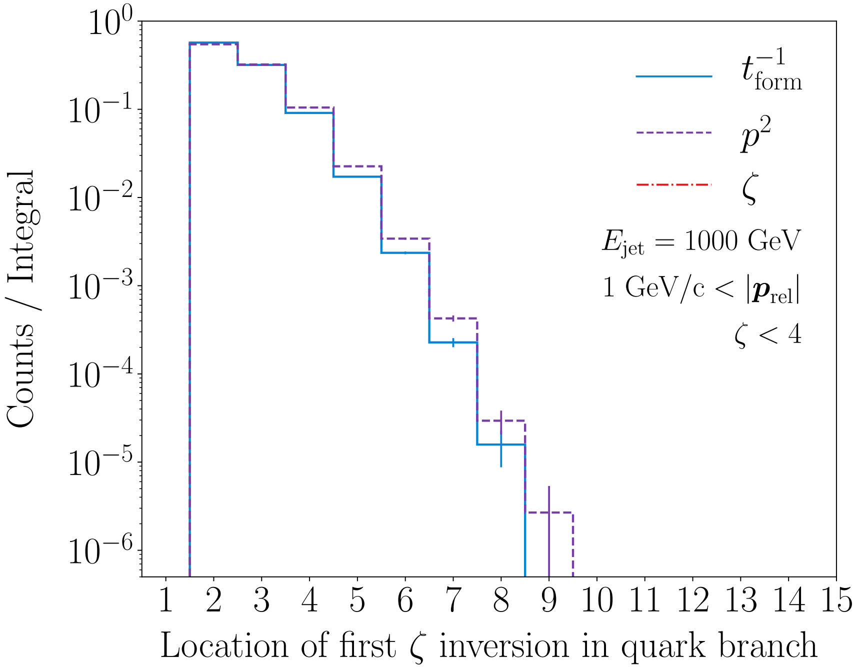

Angular inversions

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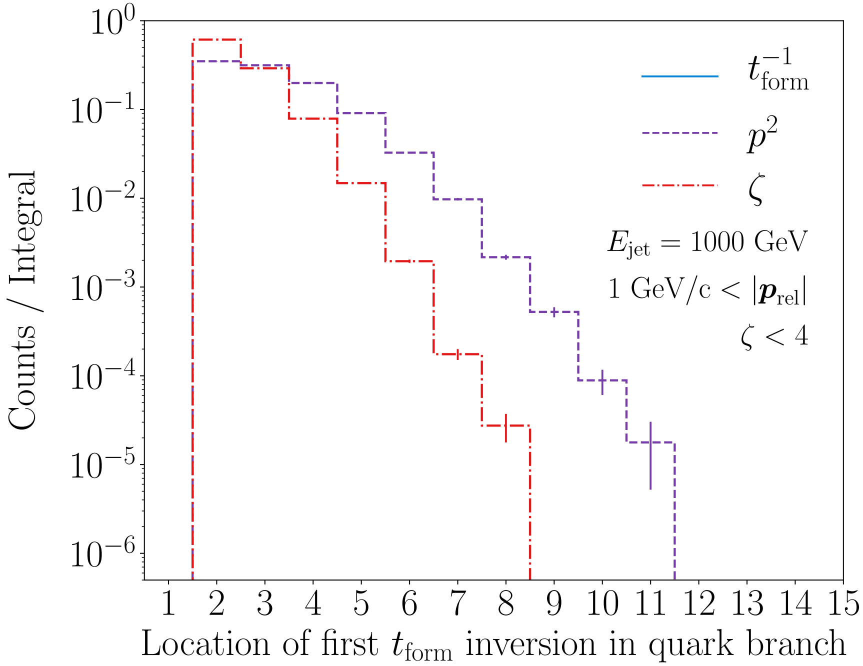

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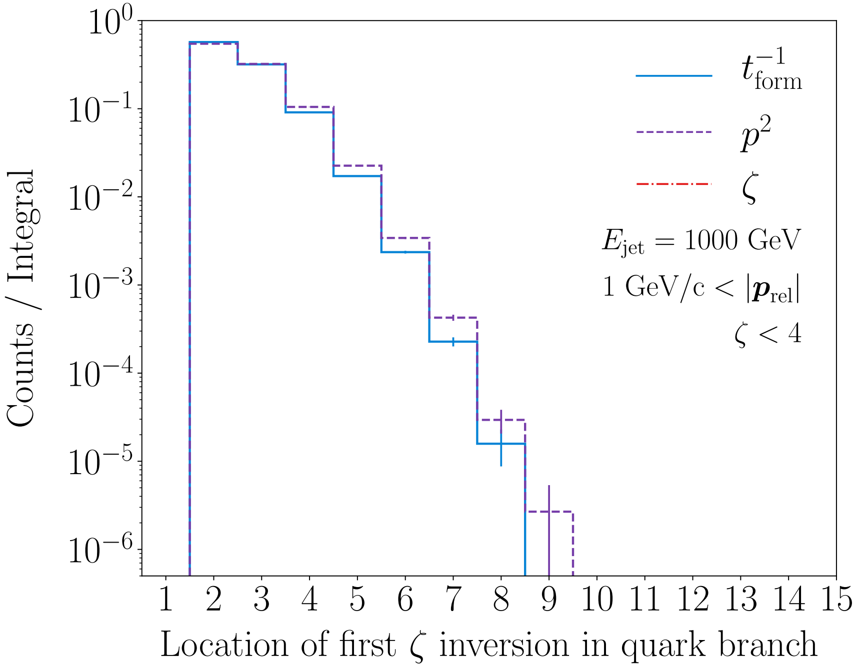
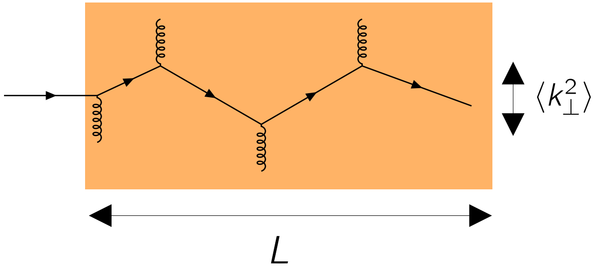


Angular inversions

Can this discrepancy translate into differences in quenching magnitude?

Now, a simple jet quenching model!

Choosing a quenching condition



Medium parameters (for a simple model):

- Medium length: L
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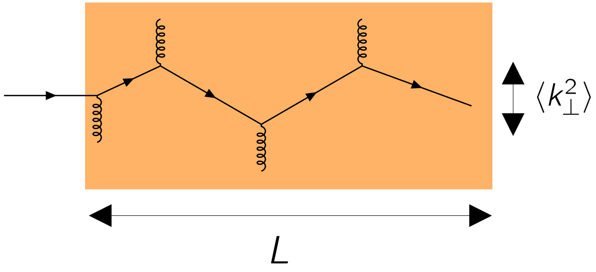
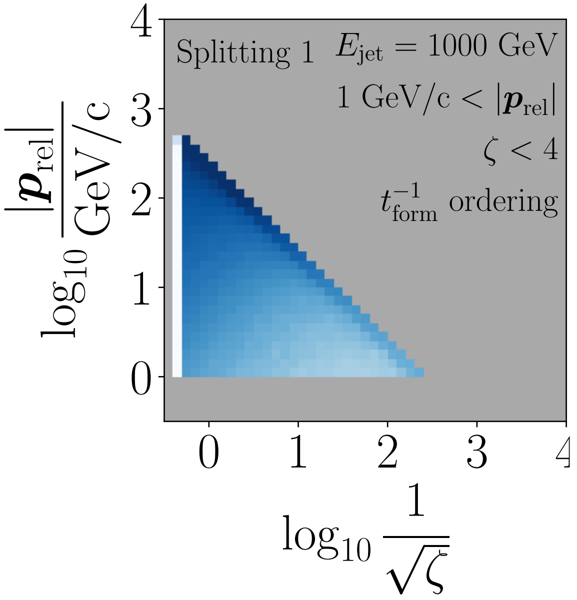
Choosing a quenching condition





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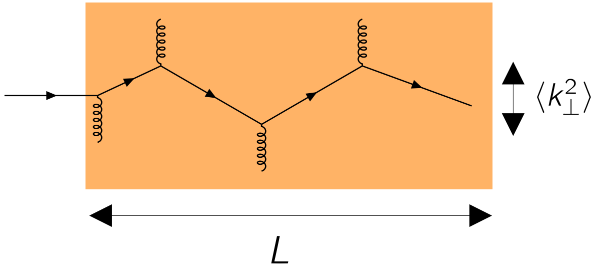
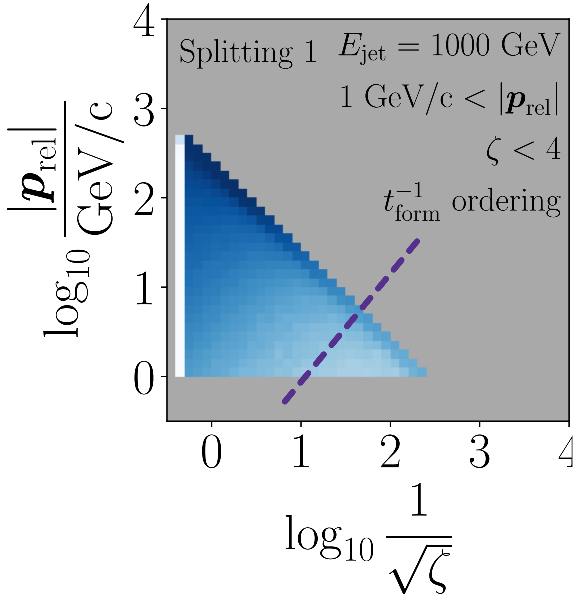
Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
Casalderrey-Solana, Iancu :: JHEP 08 (2011) 015

Choosing a quenching condition





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Eliminate event if

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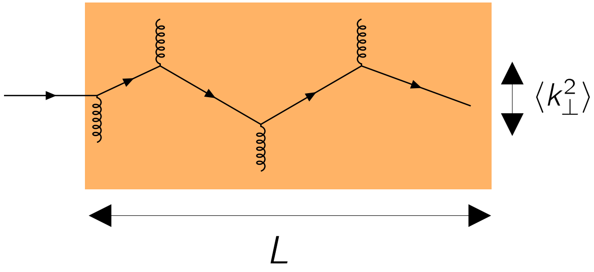

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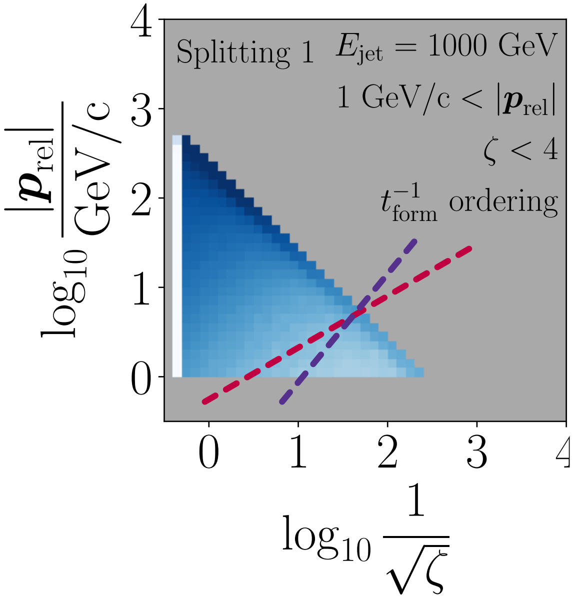

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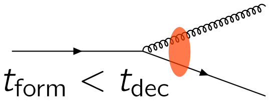
– Splitting transverse momentum is below medium scale:

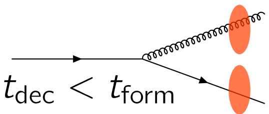
$$|\boldsymbol{p}_{\text{rel}}|^2 < \hat{q}\, t_{\text{form}} \Longleftrightarrow \underbrace{(\hat{q}\zeta)^{-1/3}}_{t_{\text{dec}}} < t_{\text{form}}$$

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

(Not resolved)



(Resolved)



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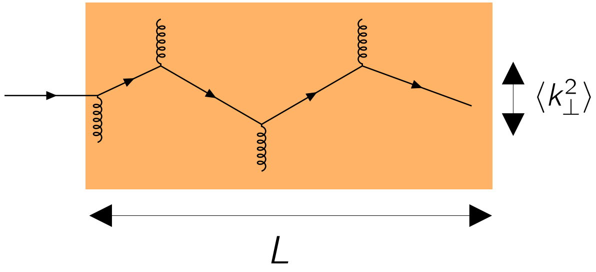

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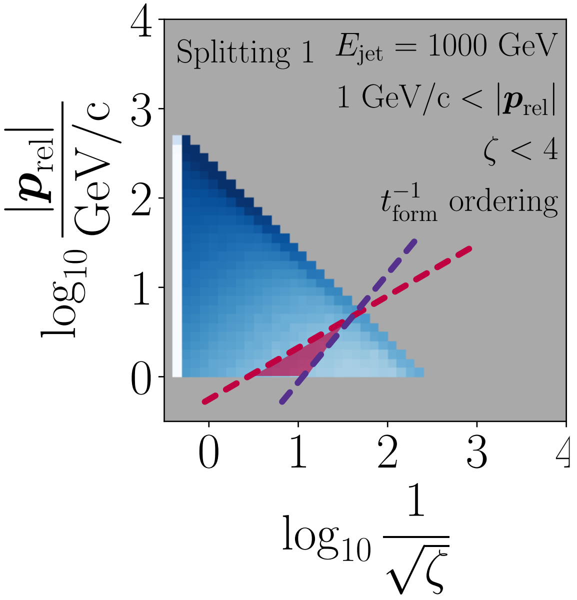
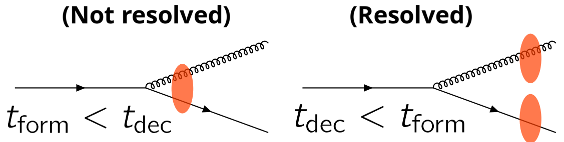


Eliminate events within this area:

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

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



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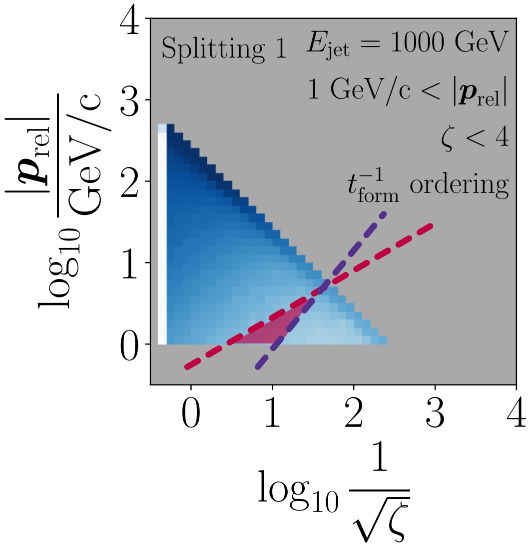

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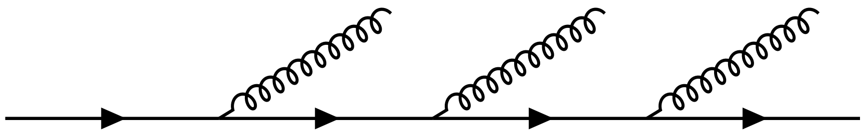

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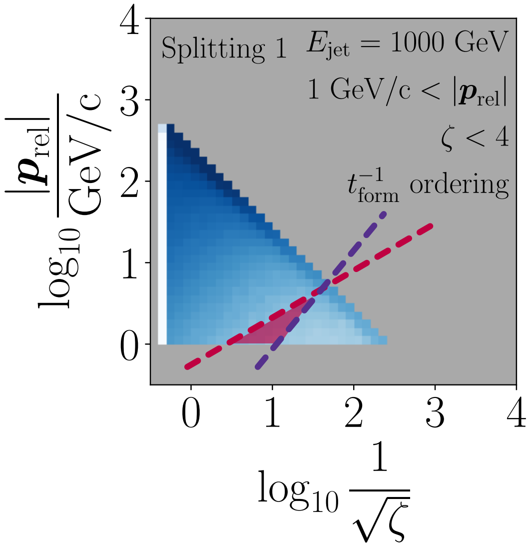

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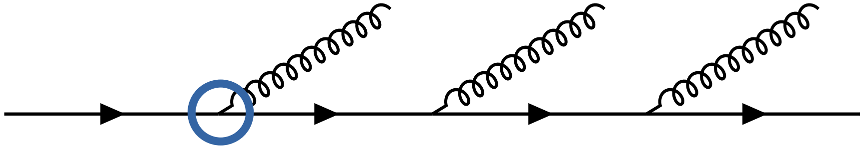

- Option 1: Apply only to first splitting

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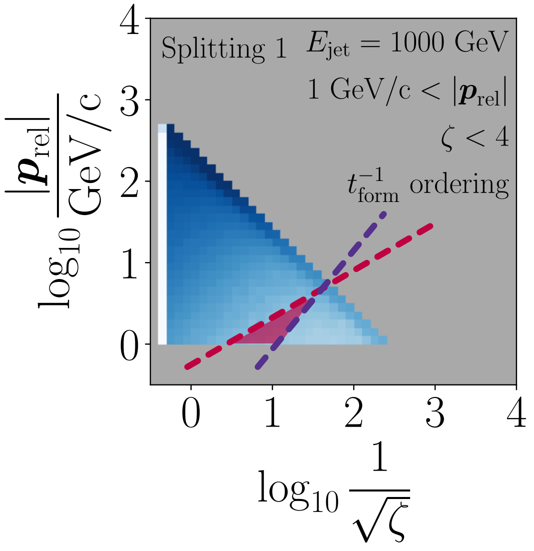

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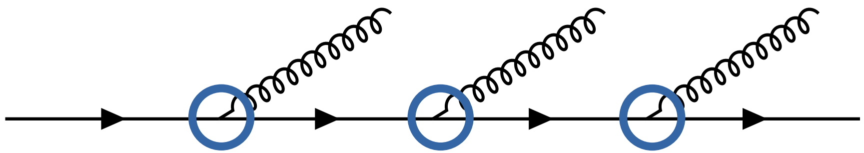

- Option 1: Apply only to first splitting
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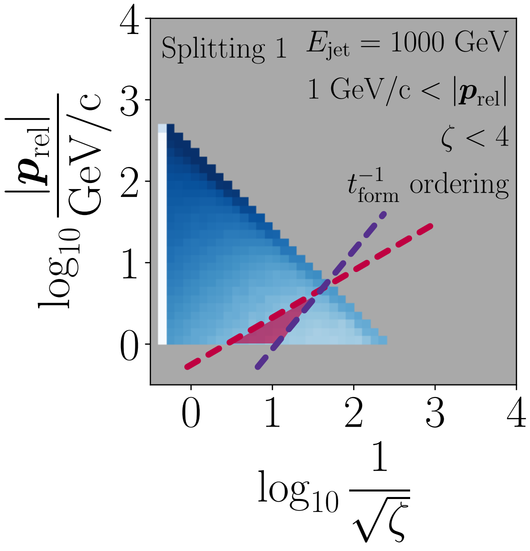

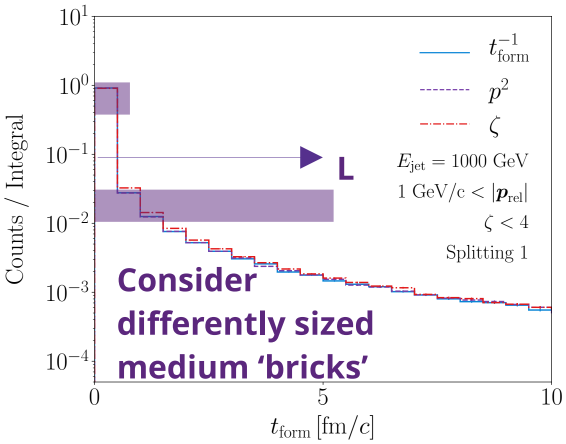

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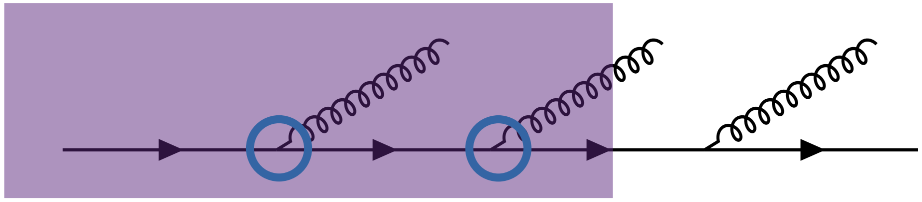

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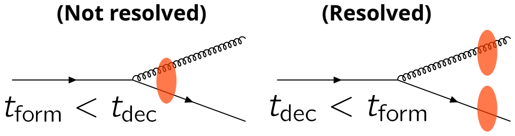
Fraction of Quenched Events



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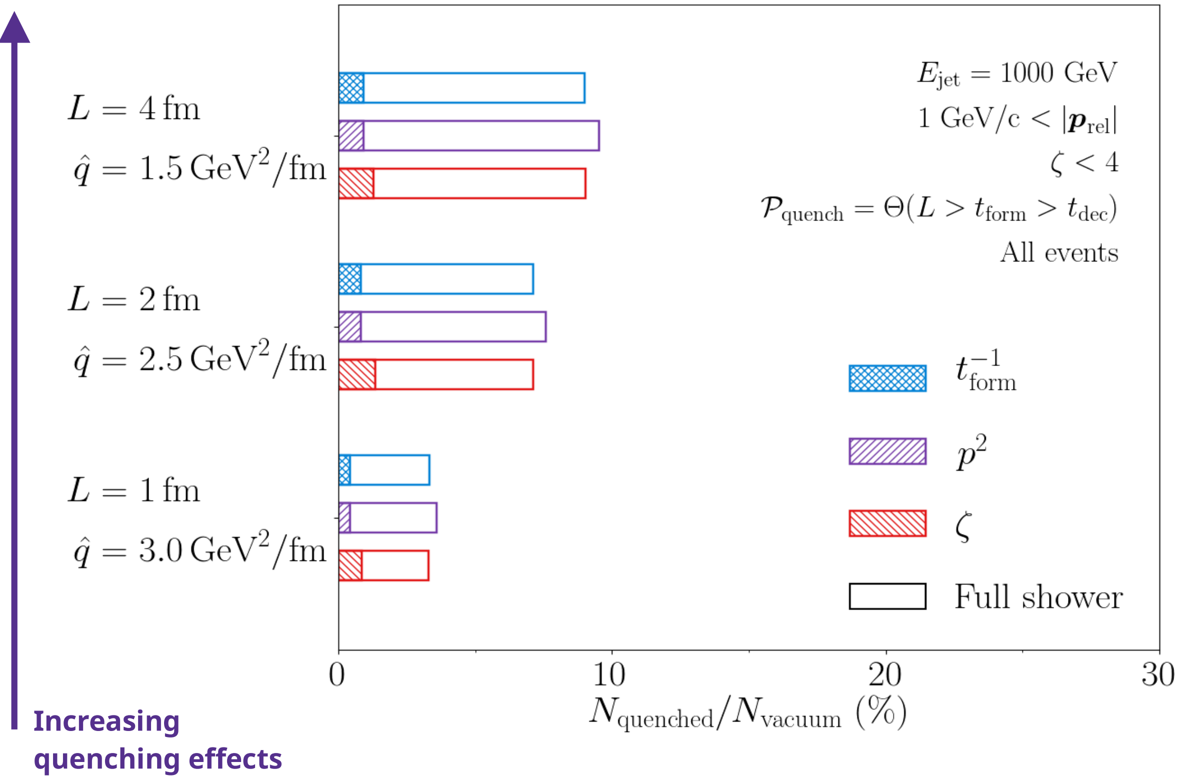
Percentage of events eliminated by the quenching condition



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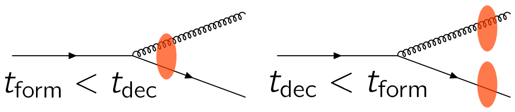

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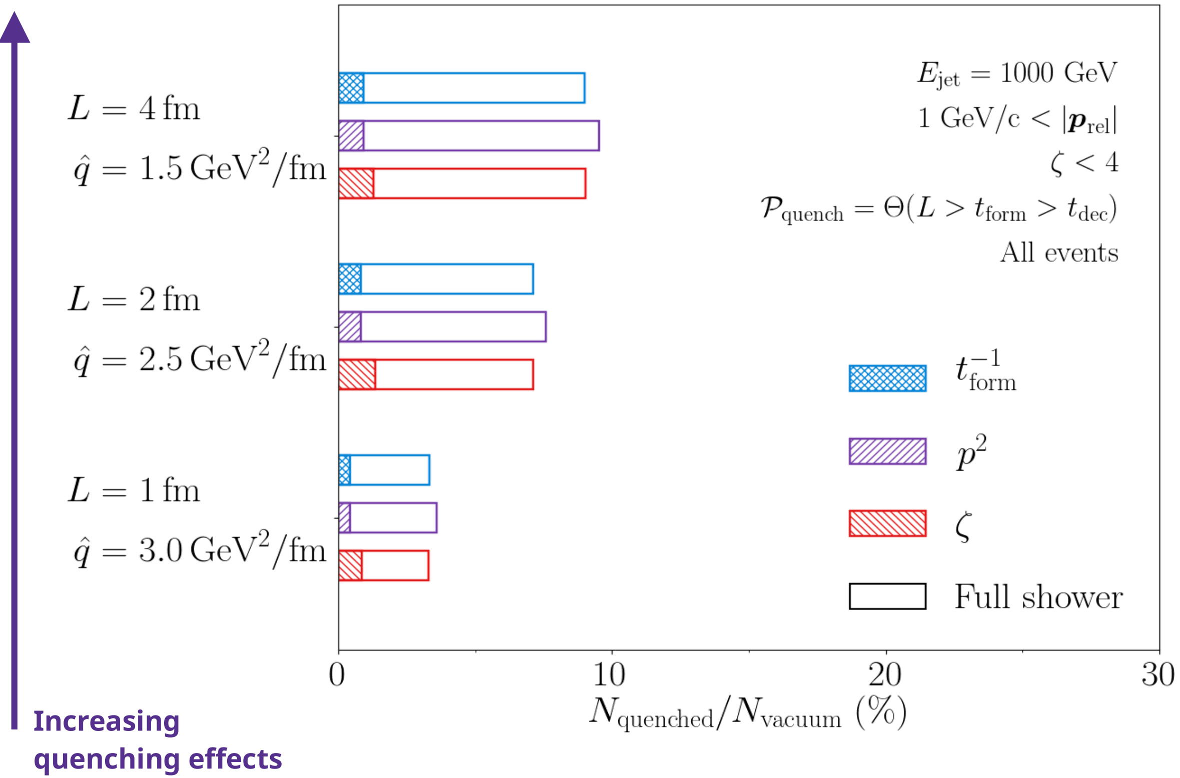

Applying conditon to the first splitting → Significant differences in quenching between algorithms

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

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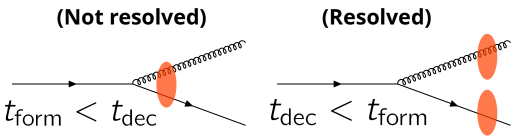

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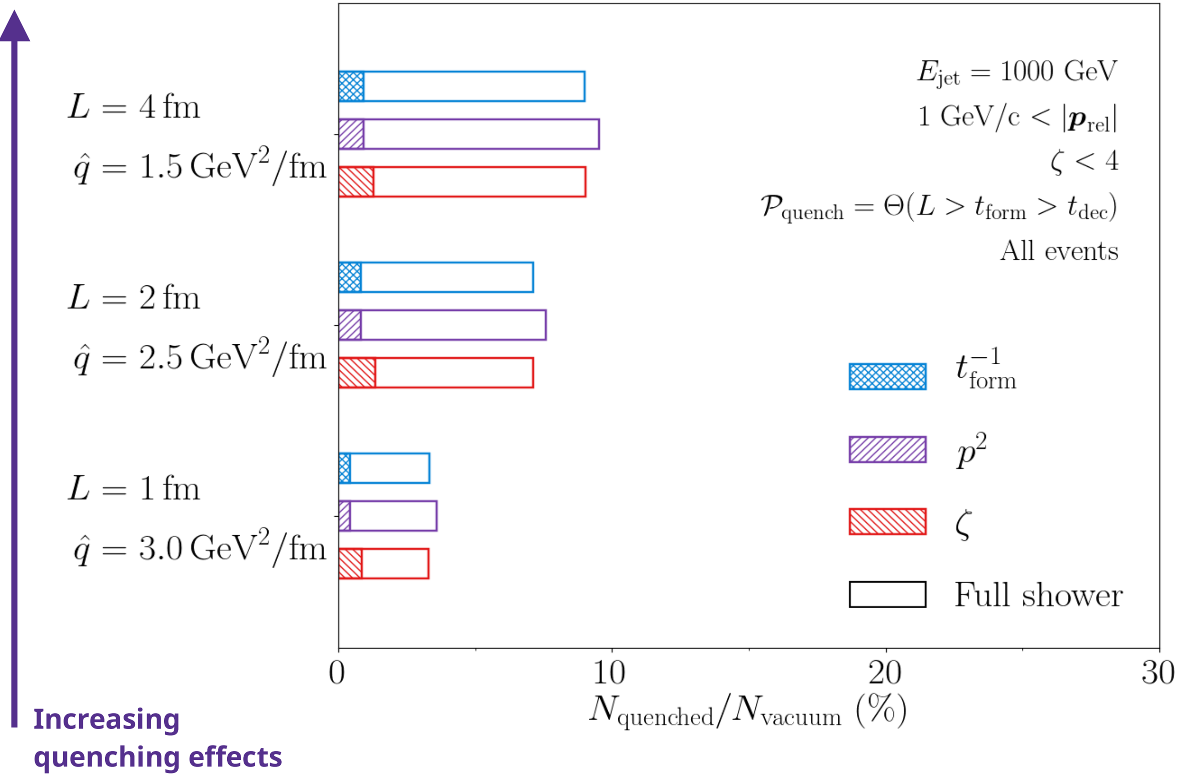

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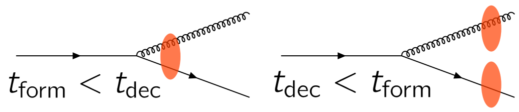
<u>What role do time-inversions play in these quenching differences?</u>

Fraction of Quenched Events



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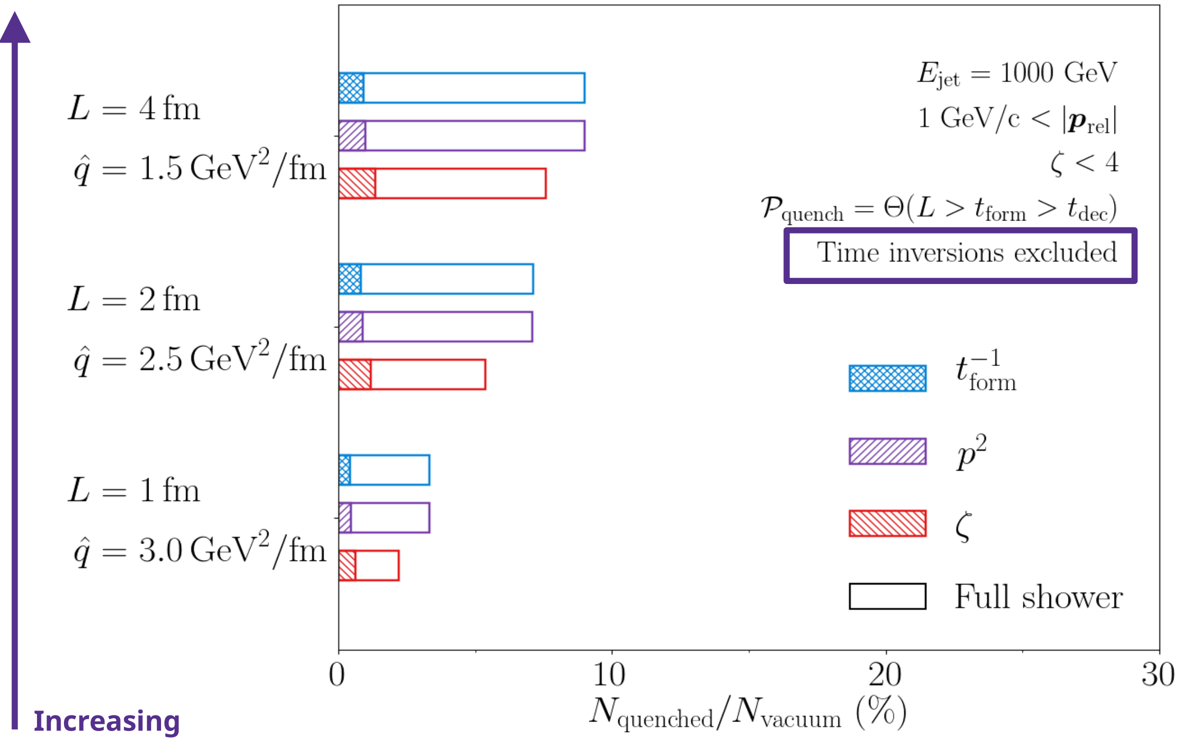
Discarding time-inverted events from the samples:

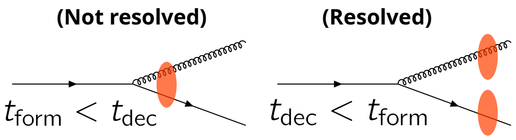
(Ad-hoc ‘cut’)



Increasing quenching effects

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

Fraction of Quenched Events



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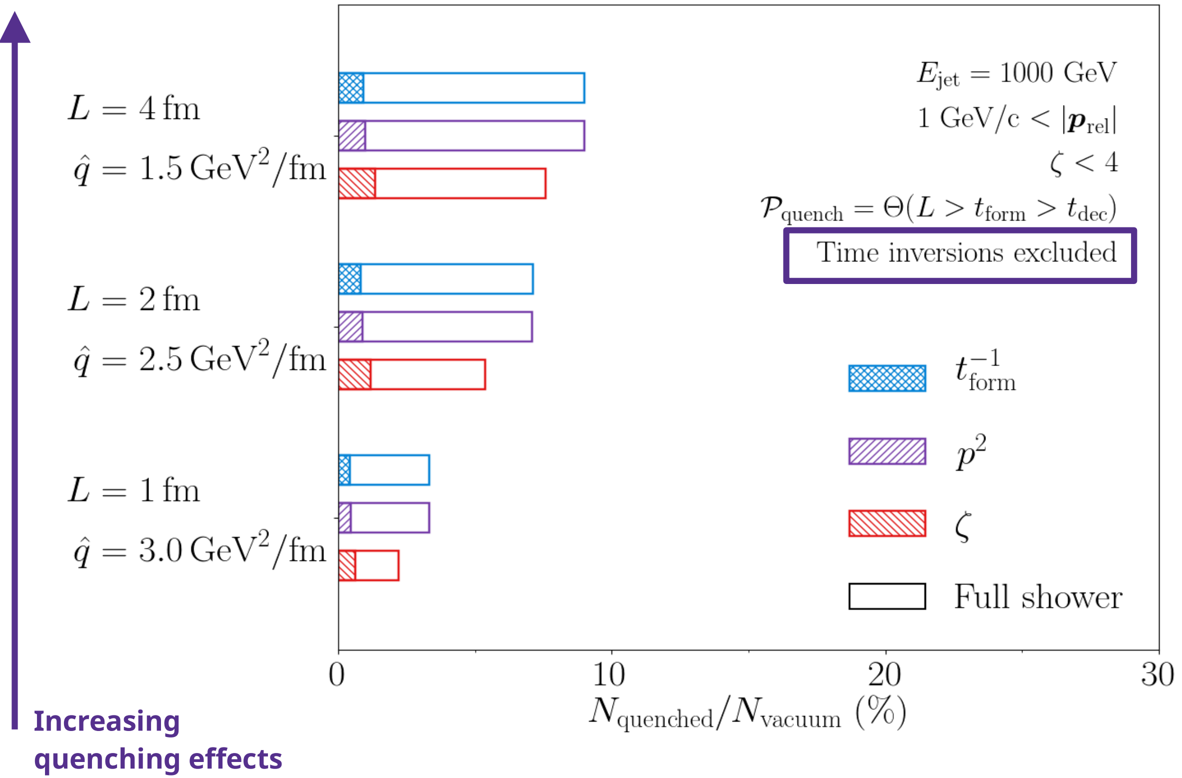

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$\Rightarrow \zeta$ strictly decreasing

$\Rightarrow t_{\text{dec}}$ strictly increasing

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

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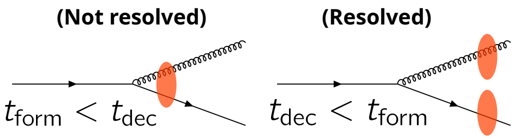

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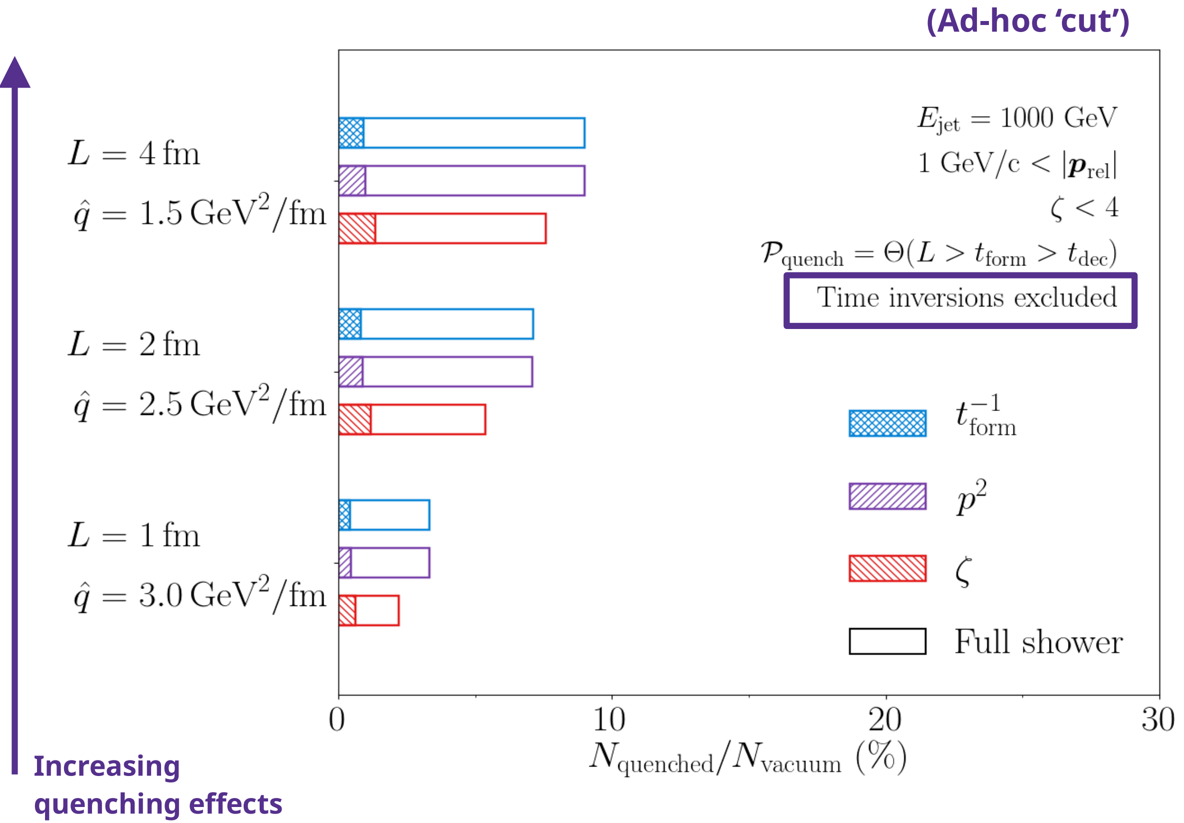

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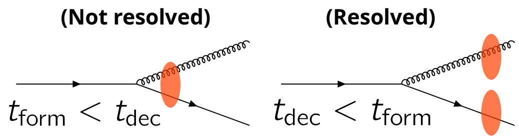
This is only one way of preventing inversions!

Fraction of Quenched Events



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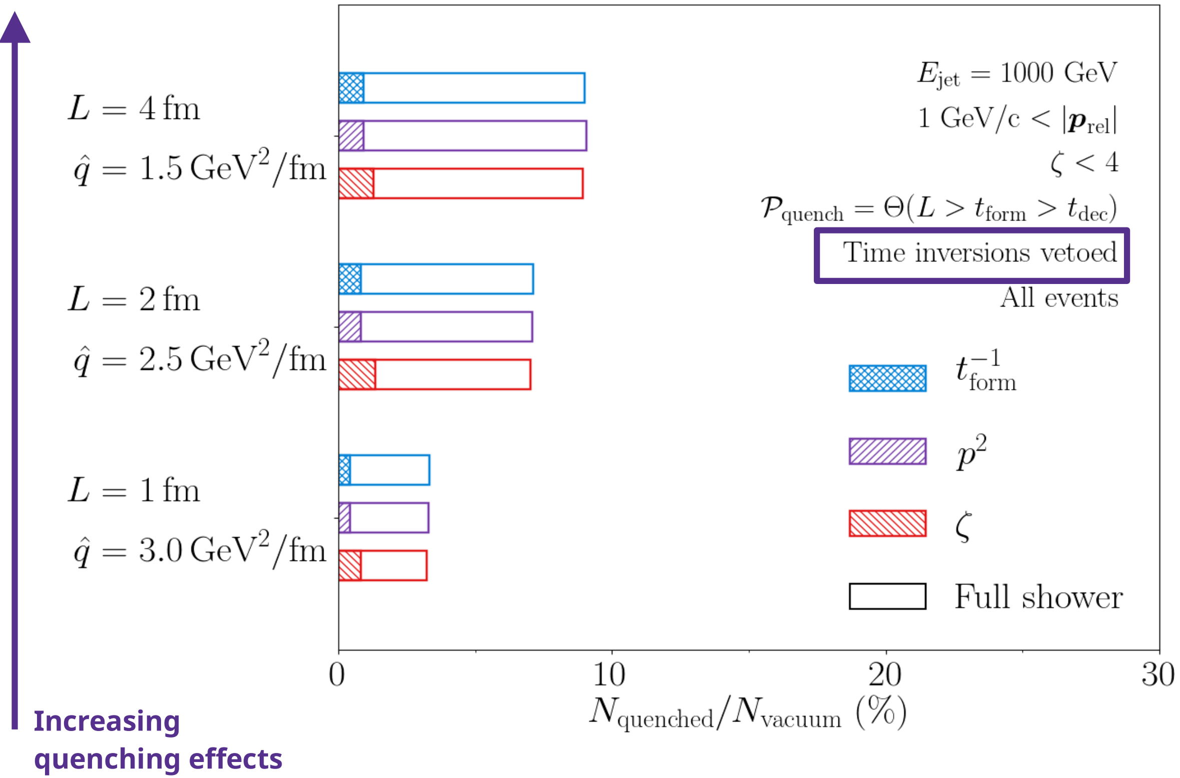
Vetoing the time-inversions by retrial:

(Phase-space is adjusted splitting by splitting)



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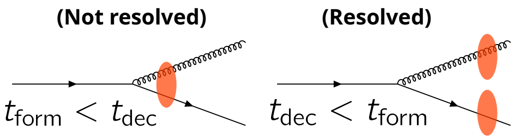

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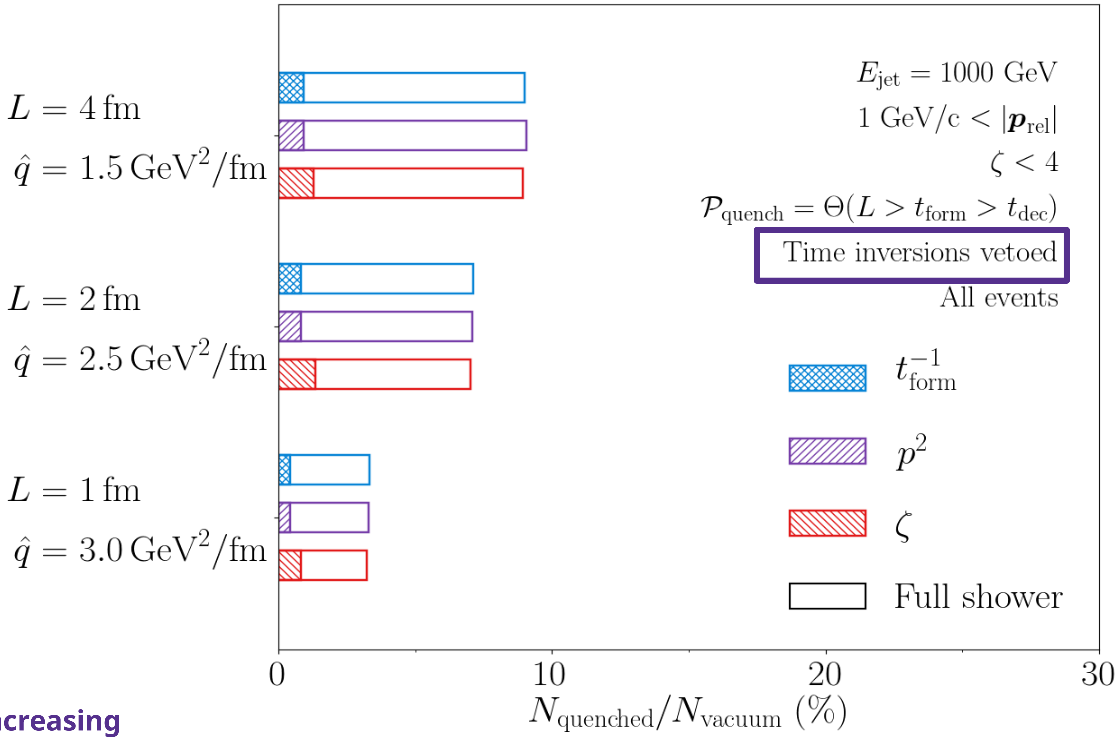

Increasing quenching effects

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

Warning: Phase-space altered splitting-by-splitting

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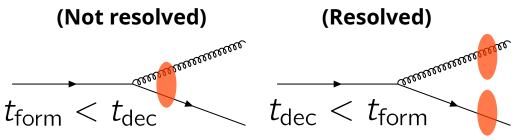

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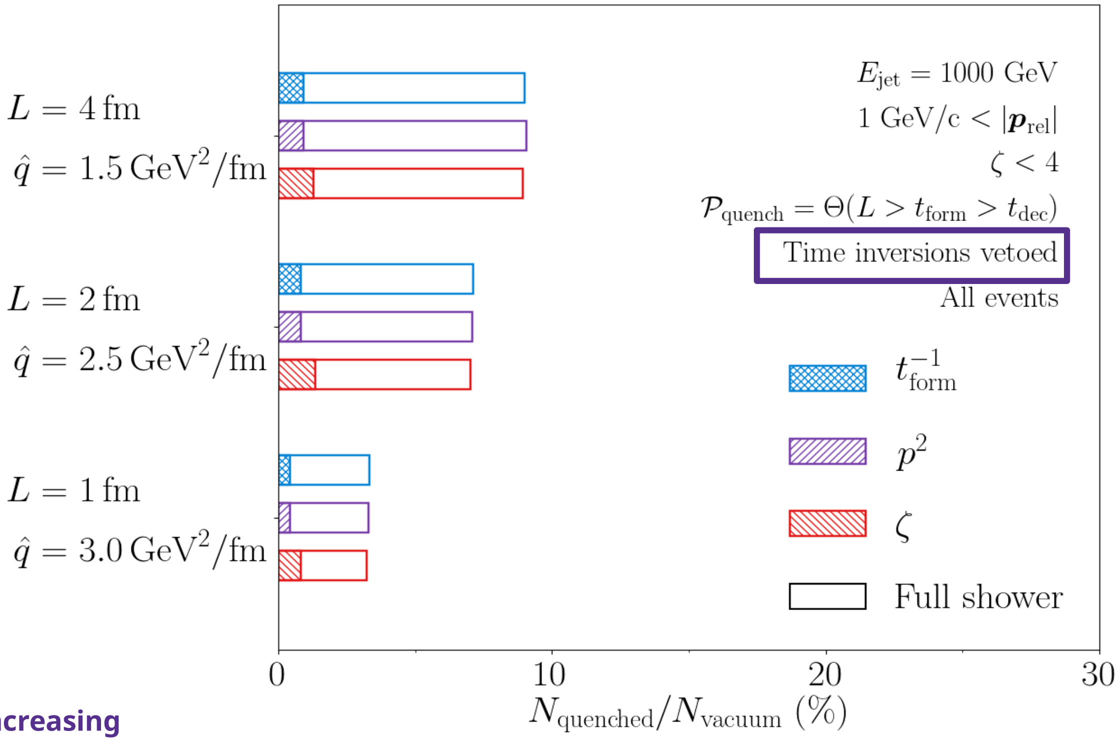

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The implementation details of the jet interface with a time-evolving medium are crucial!

Summary

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- **A toy Monte Carlo parton shower was developed:**
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Thanks!

Acknowledgements

LIP

fct

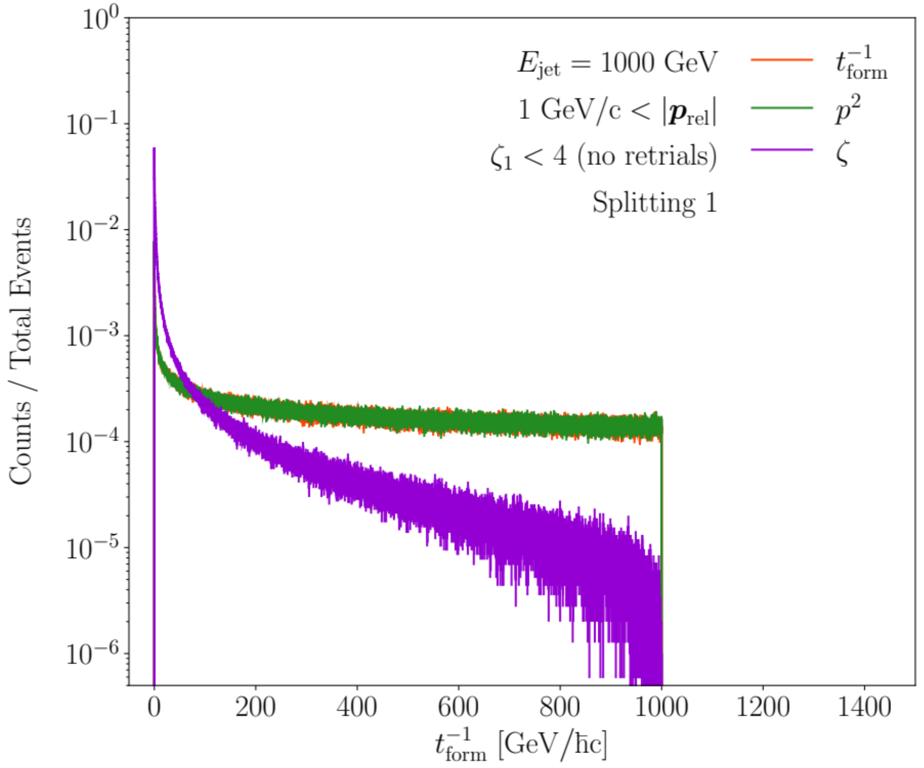
Fundação
para a Ciência
e a Tecnologia

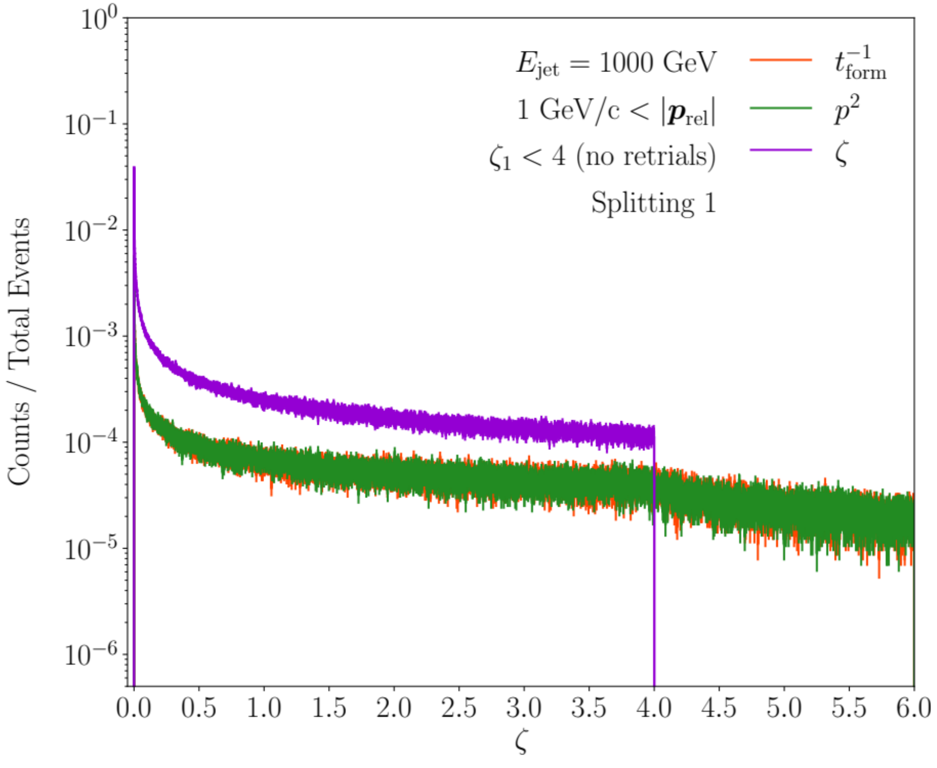
TÉCNICO
LISBOA

REPÚBLICA
PORTUGUESA

Backup Slides

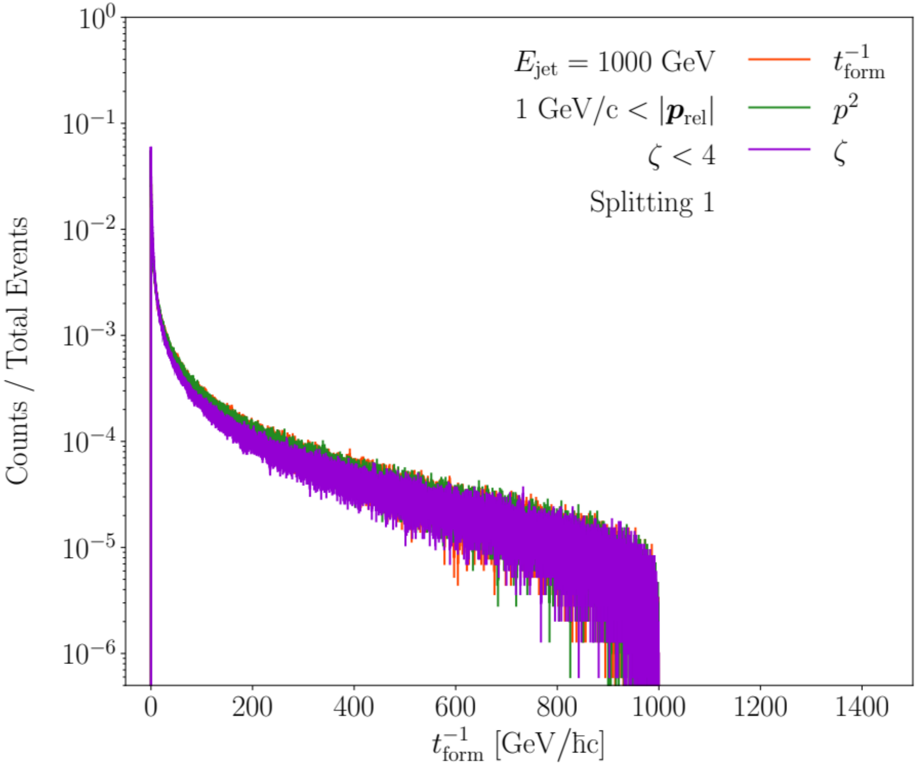
Without the consistency condition

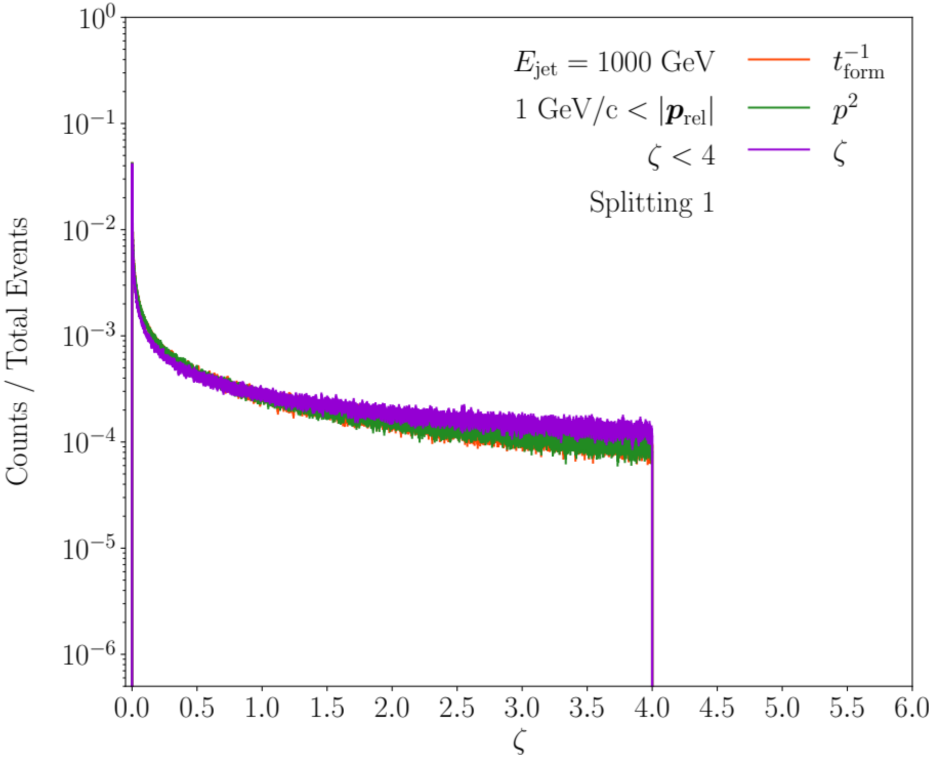




If the condition $\zeta < 4$ is used simply to initialise the angular shower, the time and angle distributions do not behave consistently across algorithms

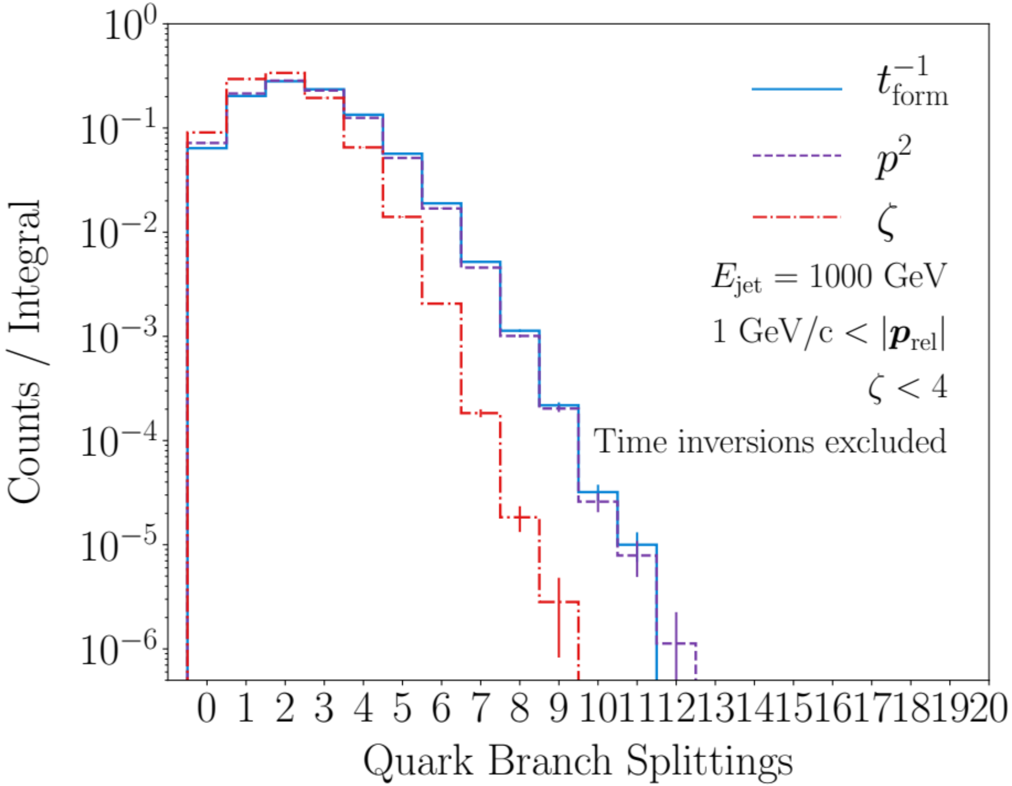
With the consistency condition

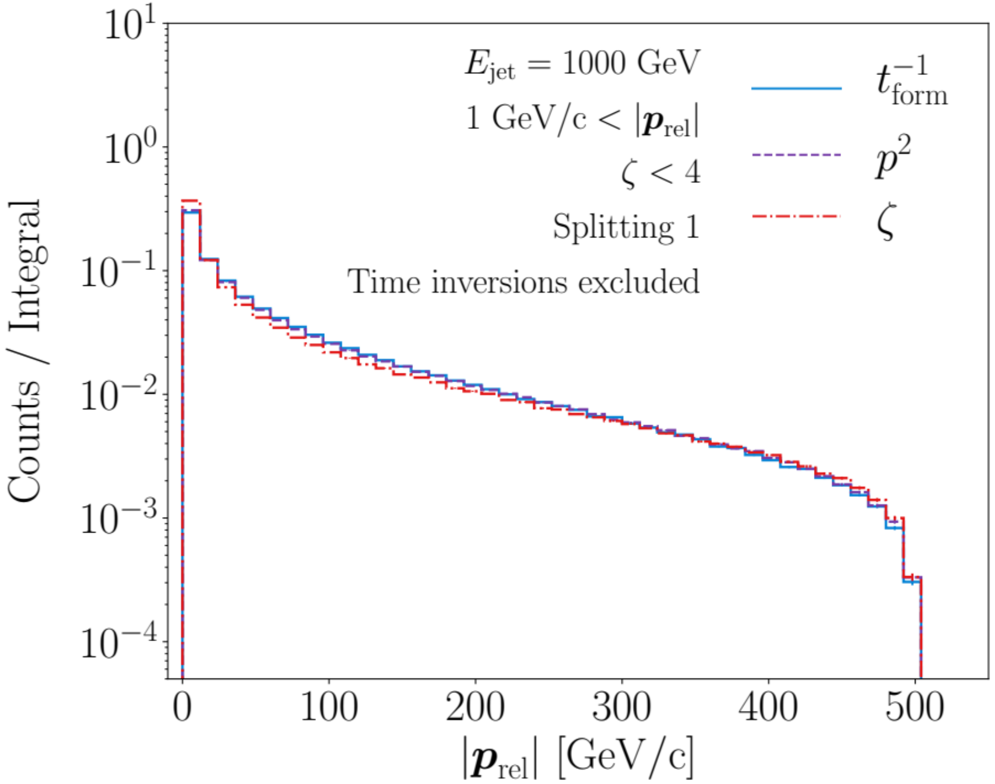




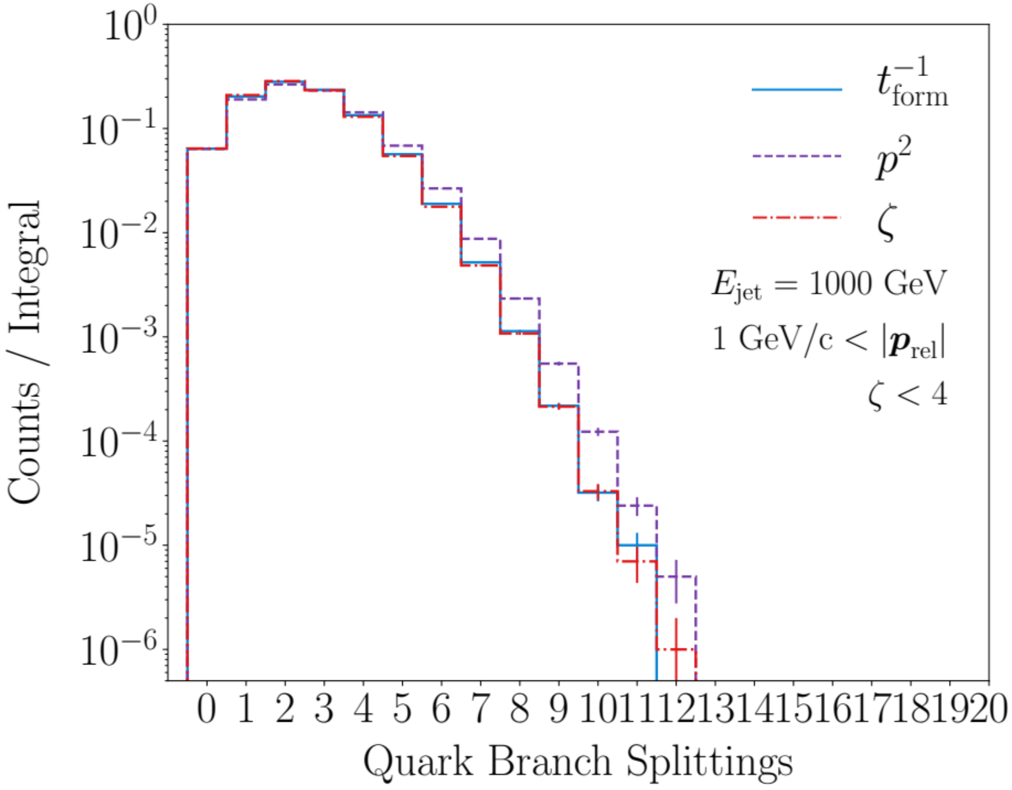
When the condition ζ < 4 is used as a veto for all emissions, the distributions become consistent.

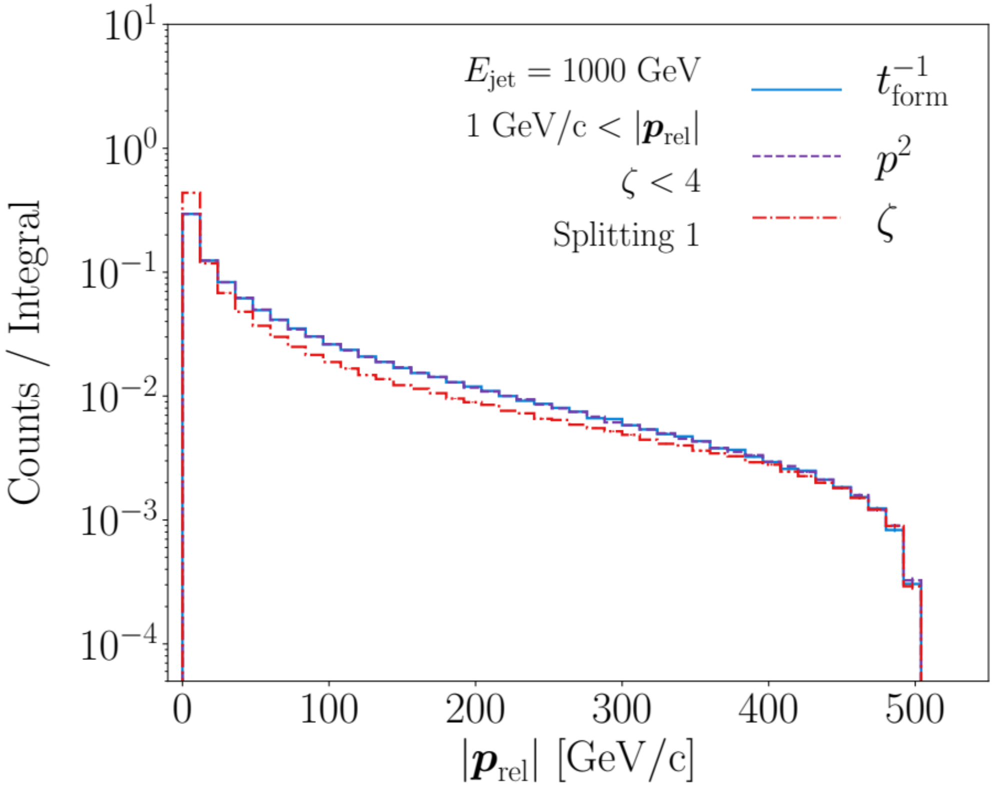
Excluding time inversions – 1D Distributions



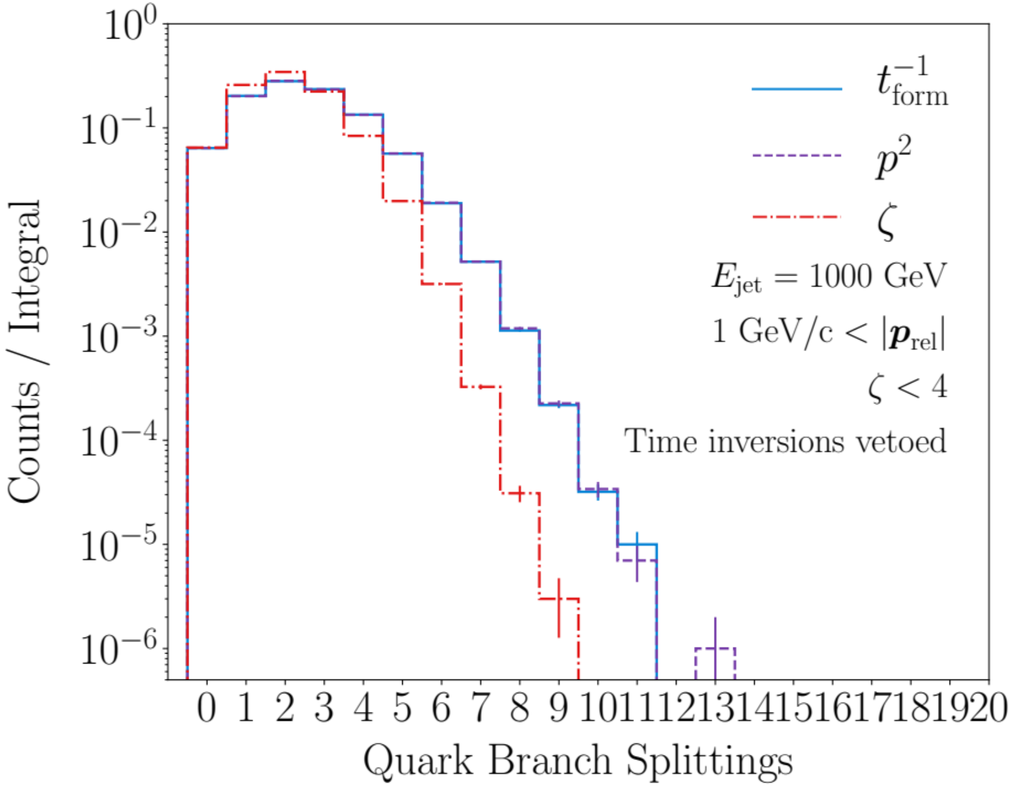


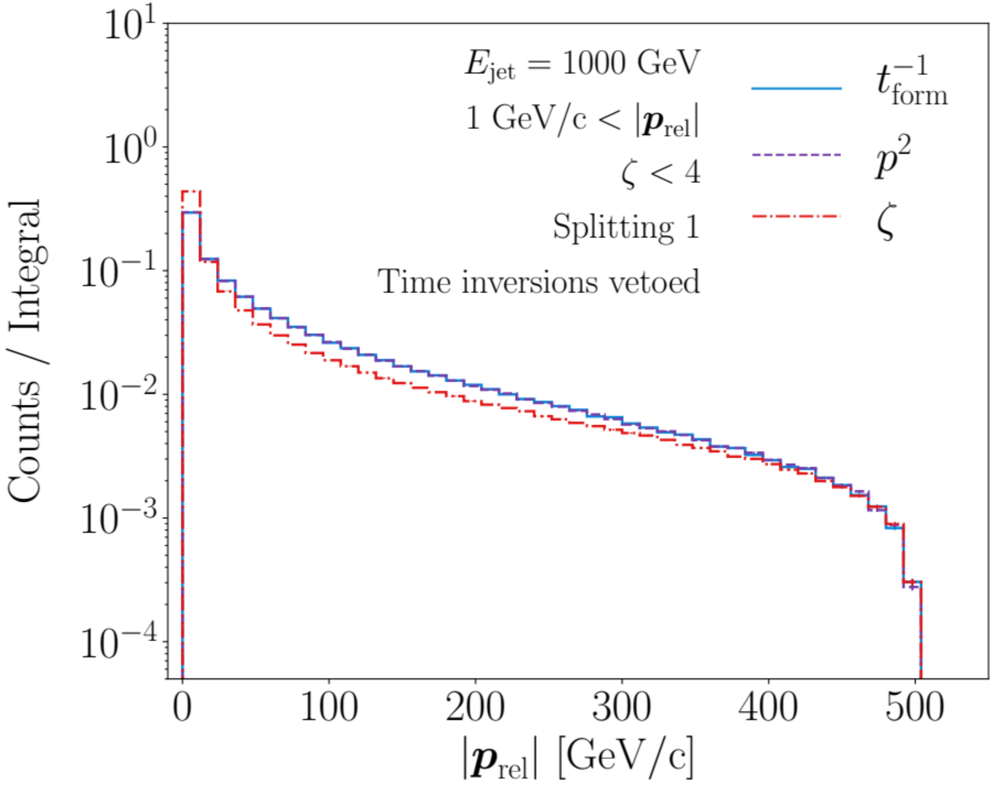
Inclusive Sample – 1D Distributions





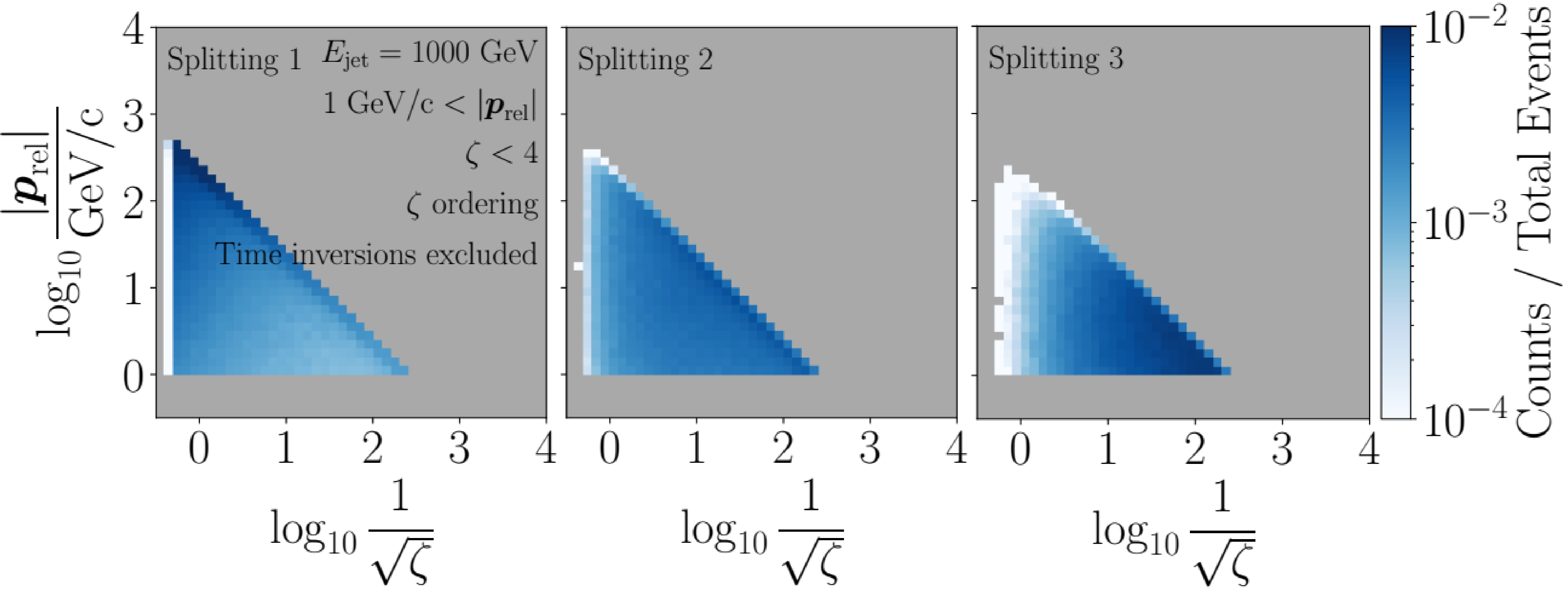
Vetoing time inversions – 1D Distributions





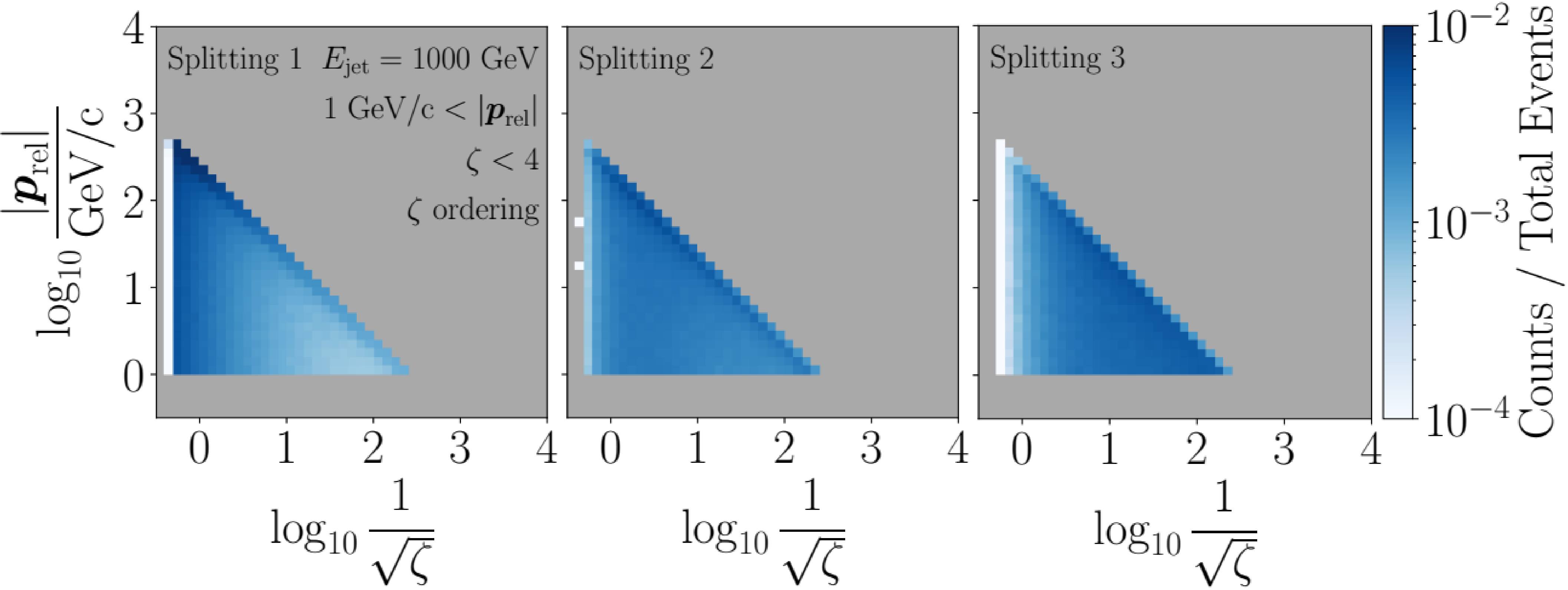
Excluding time inversions – Lund Planes

***Ordered in angle**



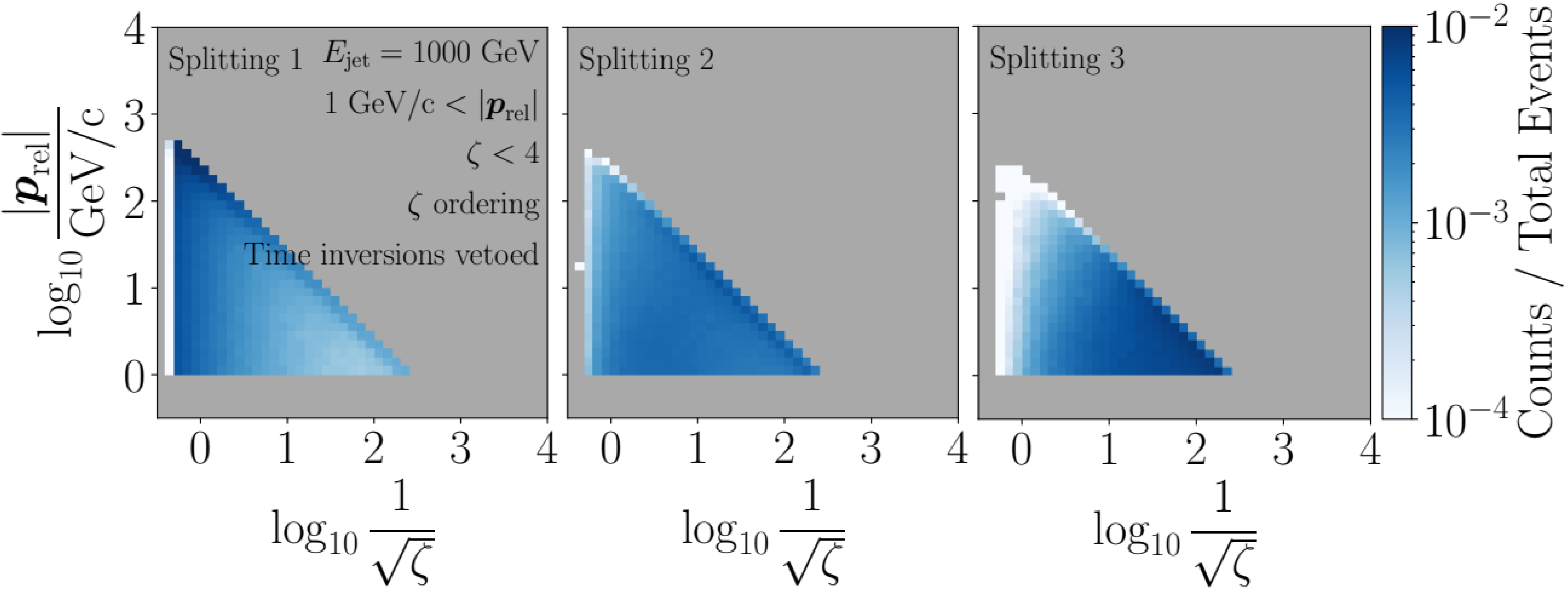
Inclusive Sample – Lund Planes

***Ordered in angle**



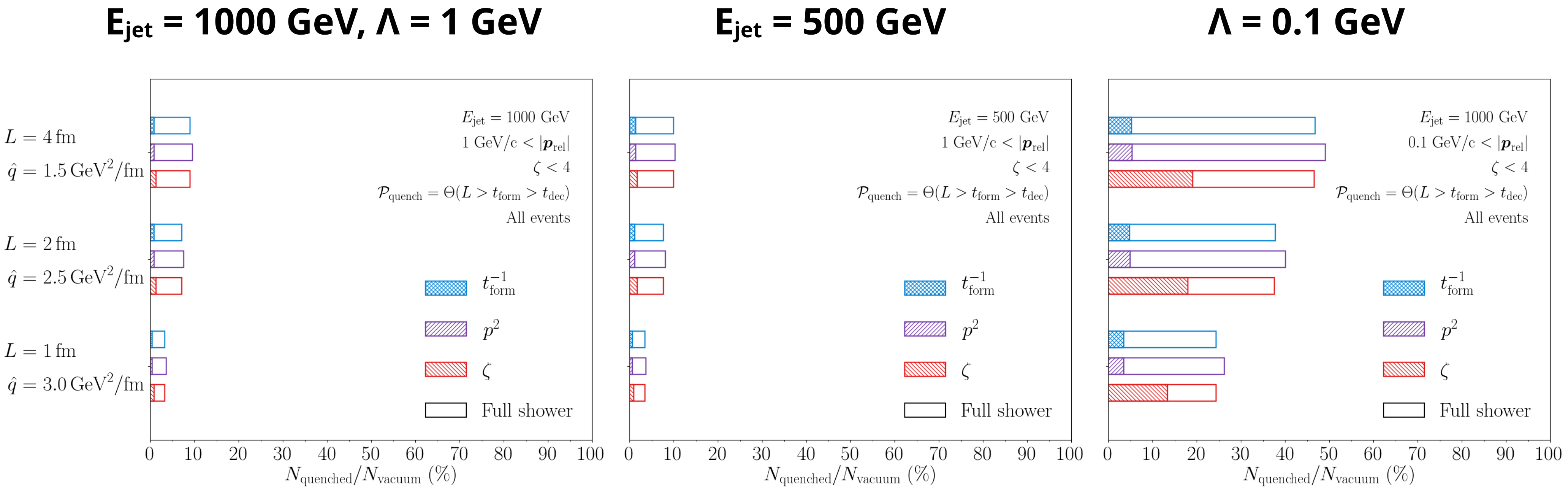
Vetoing time inversions – Lund Planes

<u>*Ordered in angle</u>



Very Preliminary!

Quenching Weights

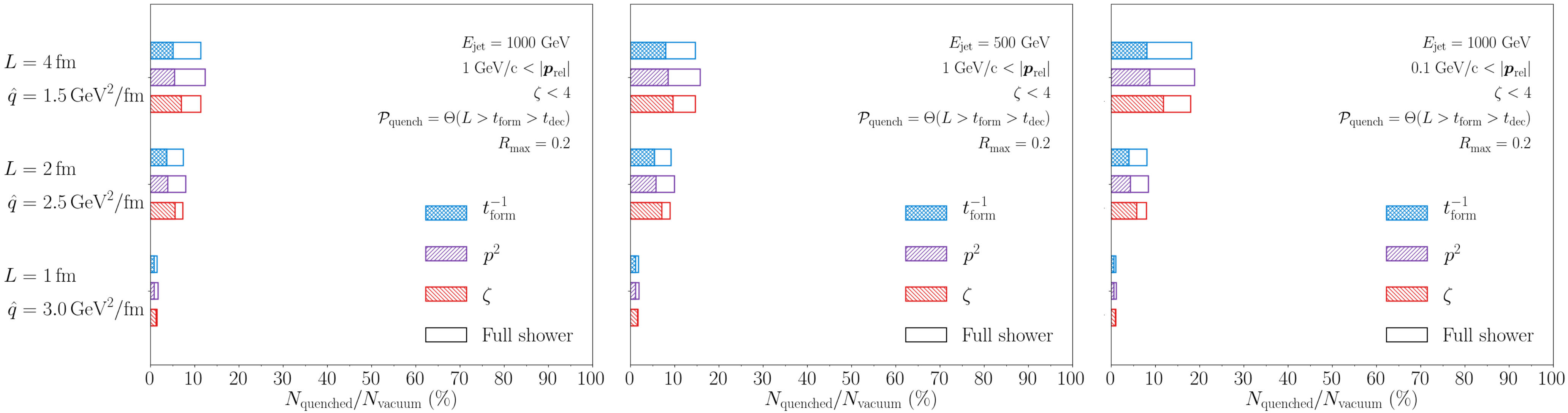


An apparent dependence on the hadronisation cutoff and initial jet energy

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

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