Parton Showers for Heavy Ion Collisions

André Cordeiro

Supervisors: Liliana Apolinário, Néstor Armesto, José Guilherme Milhano

Based on: arxiv:2409.13536 (with Carlota Andres, Fabio Dominguez)

LIP

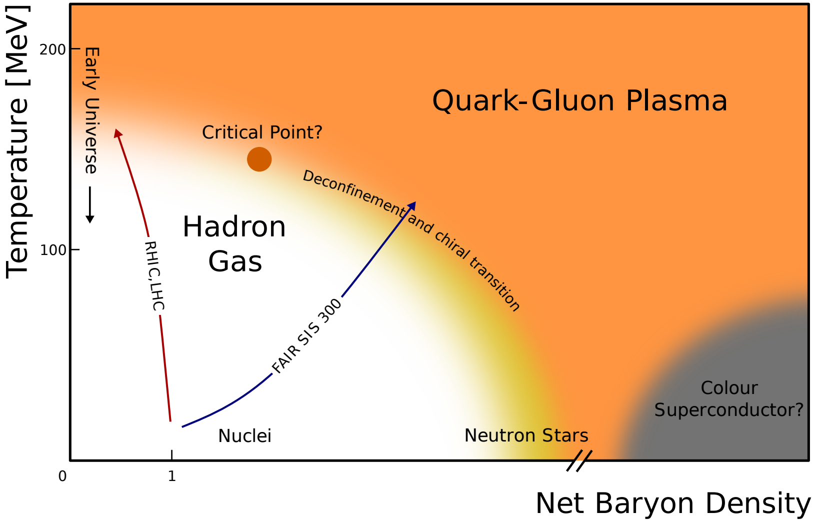
TÉCNICO LISBOA

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

8th LIP/IDPASC PhD Students Workshop

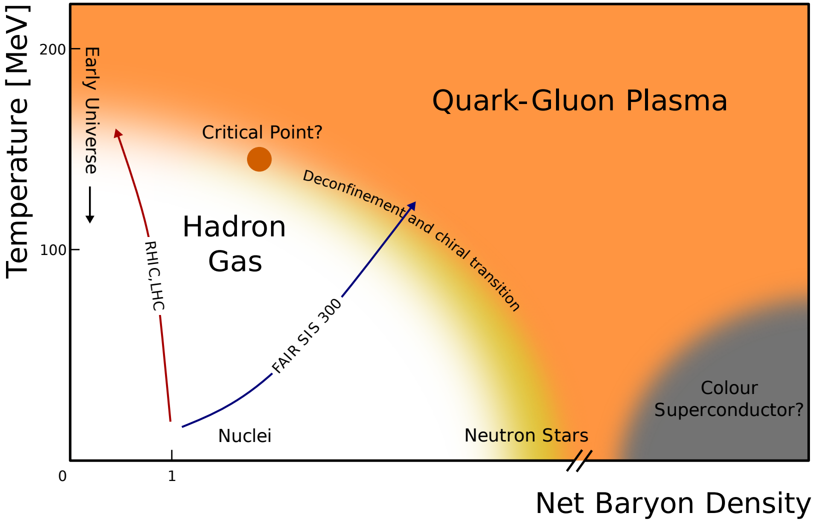
16–17 October 2024

Why we study Heavy Ion Collisions

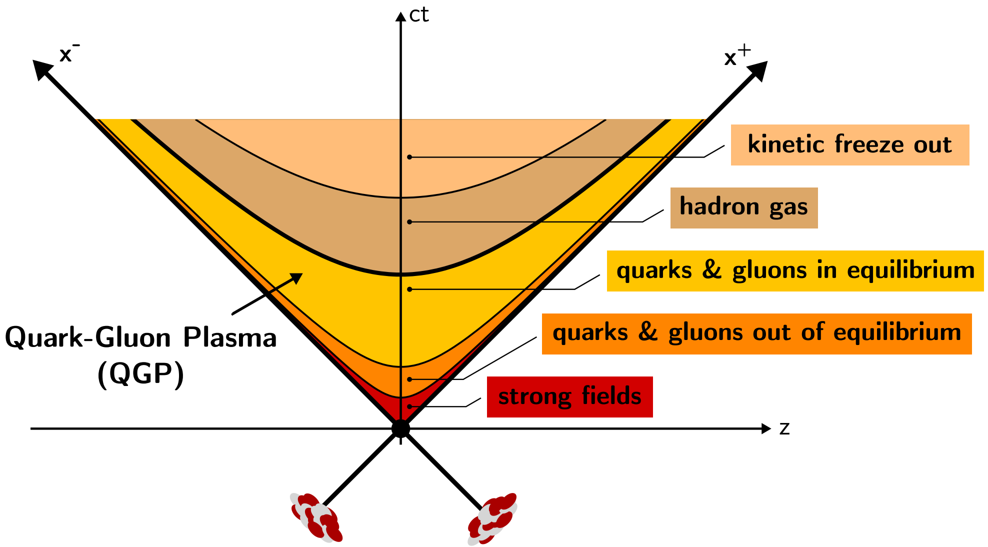


- **Quantum Matter:** explore the QCD phase diagram
- **Collectivity:** emergent behaviour from fundamental d.o.f.
- **Cosmology:** the QGP filled the early universe

Why we study Heavy Ion Collisions

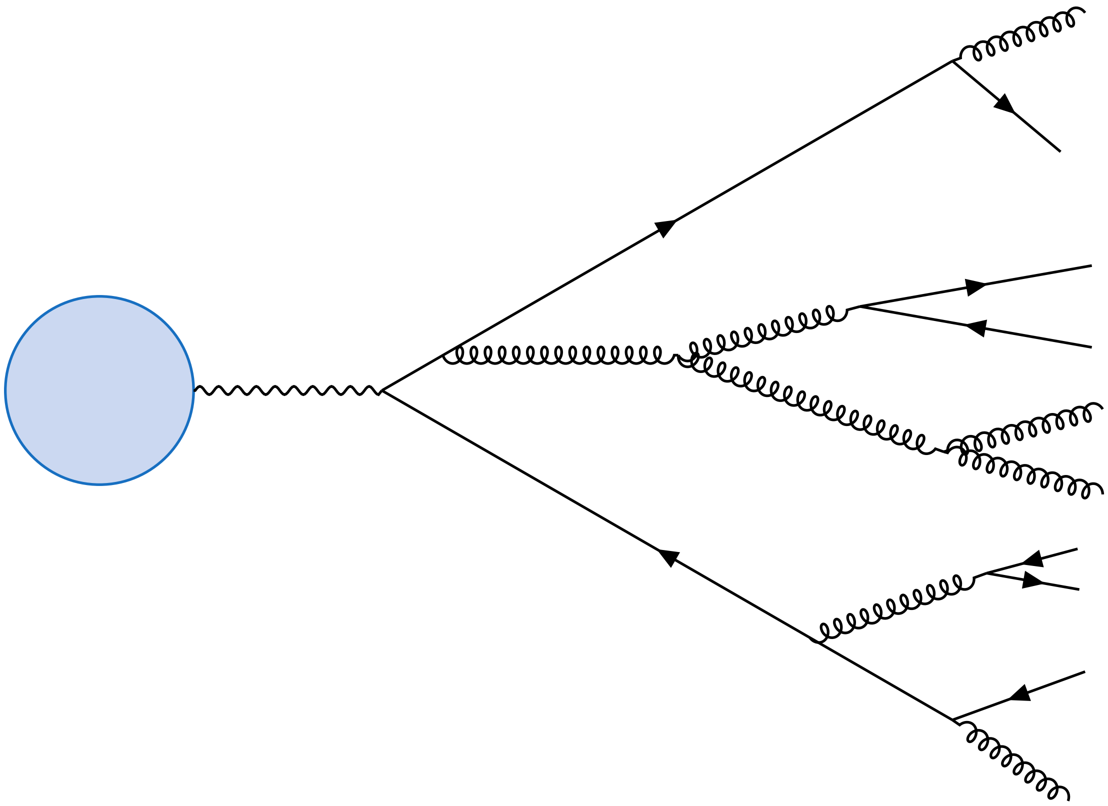


- **Quantum Matter:** explore the QCD phase diagram
- **Collectivity:** emergent behaviour from fundamental d.o.f.
- **Cosmology:** the QGP filled the early universe



Main Challenge: Very short lifetime (10^{-24} s) over wide range of scales

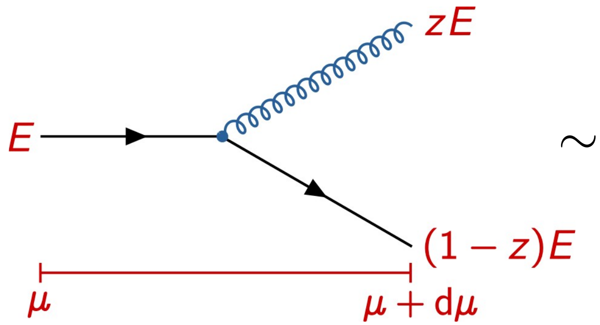
Solution: Probe medium with (high-energy) particles produced in the collision!



Parton Cascades
(in vacuum)

How to build a Parton Shower

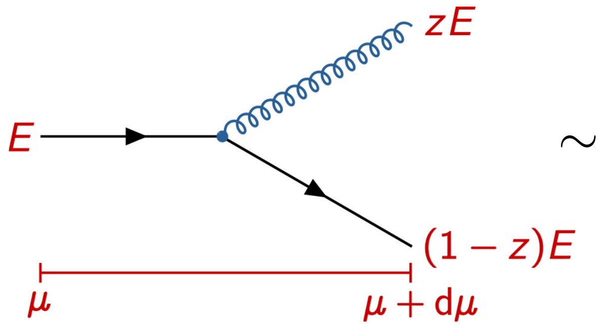
At each scale interval, a splitting may happen:



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

How to build a Parton Shower

At each scale interval, a splitting may happen:



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

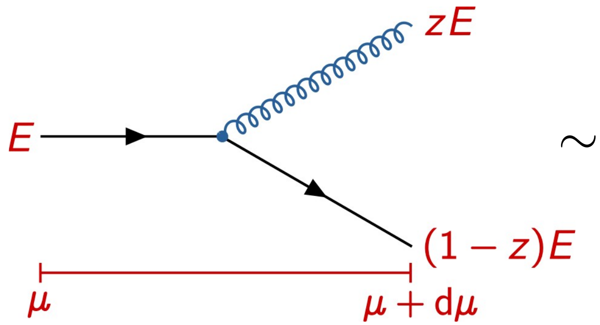
Like radioactive decay: Compute probability of next emission

Probability of no-emission: $$\Delta(s_{\text{prev}}, s) = \exp\left\{ -\frac{\alpha C_R}{\pi} \int_s^{s_{\text{prev}}} \frac{d\mu}{\mu} \int_{z_{\text{cut}}(\mu)}^{1} \frac{dz}{z} \right\}$$

Phase space depends on splitting scale

How to build a Parton Shower

At each scale interval, a splitting may happen:



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

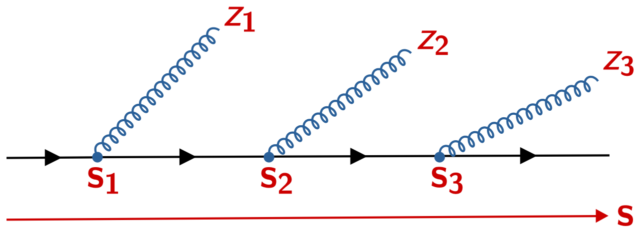
Like radioactive decay: Compute probability of next emission

Probability of no-emission: $$\Delta(s_{\text{prev}}, s) = \exp\left\{ -\frac{\alpha C_R}{\pi} \int_s^{s_{\text{prev}}} \frac{d\mu}{\mu} \int_{z_{\text{cut}}(\mu)}^{1} \frac{dz}{z} \right\}$$

Phase space depends on splitting scale

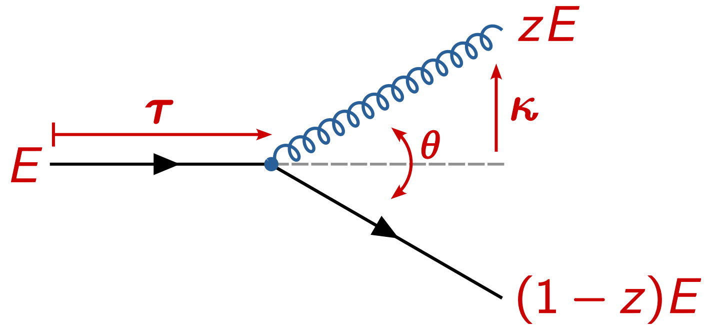
Generate cascade by sampling this probability

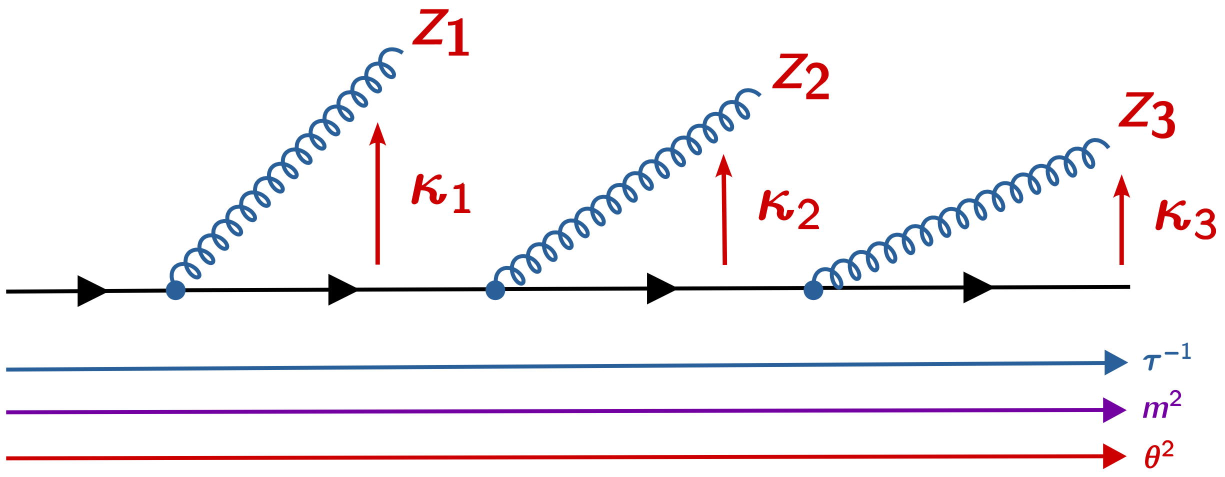
But first, choose an ordering!



Kinematics provide the scales

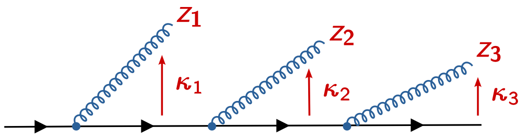
- Invariant mass $m^2 = \dfrac{\kappa^2}{Ez(1-z)}$
- Formation time $\tau = E/m^2$
- Opening angle $\theta = \dfrac{\kappa}{Ez(1-z)}$



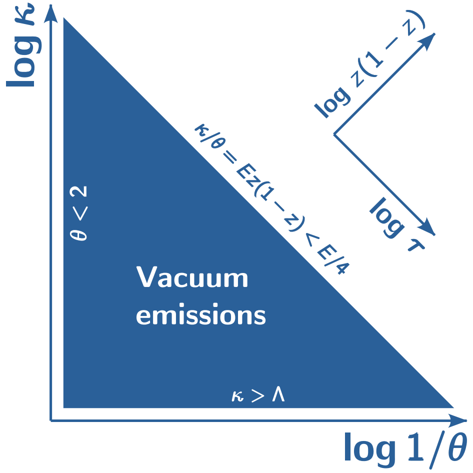


How does the choice of ordering impact the outcome of Parton Showers?

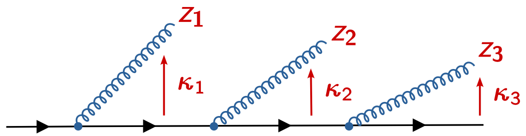
Lund Planes



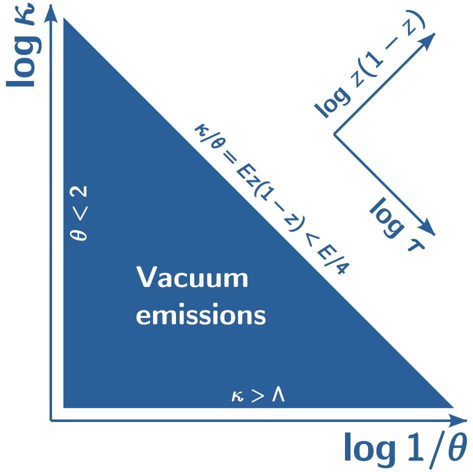
Visualise each splitting in a 2D phase-space: The Lund Plane



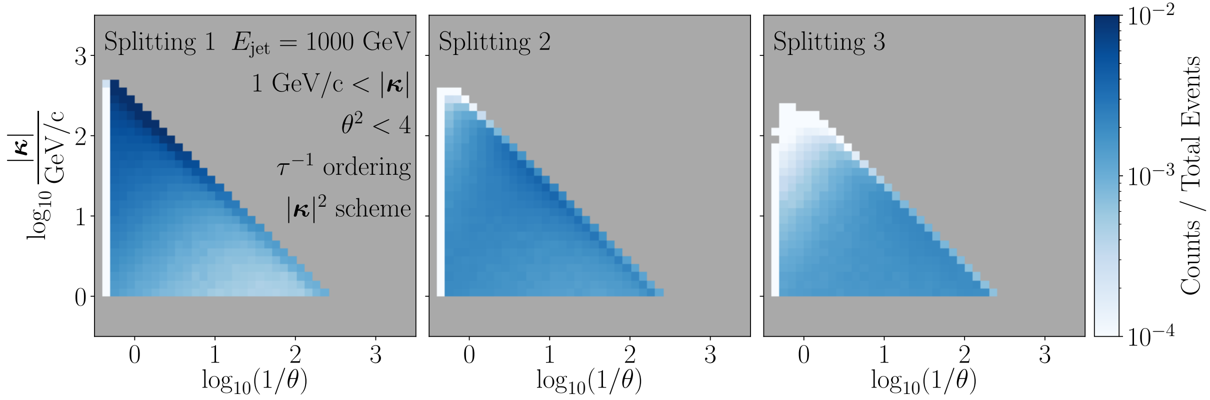
Lund Planes



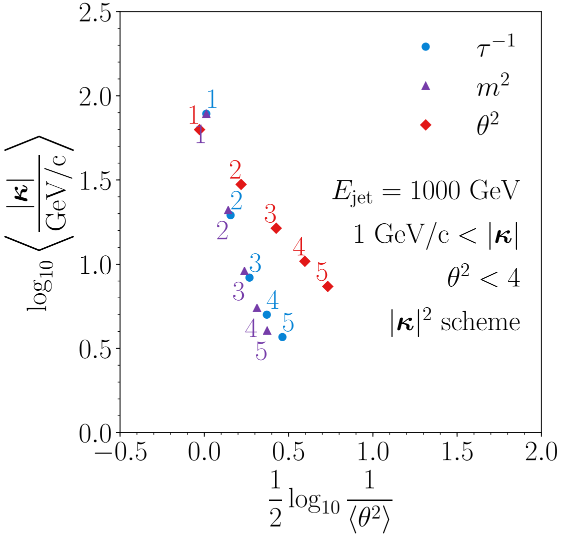
Visualise each splitting in a 2D phase-space: The Lund Plane



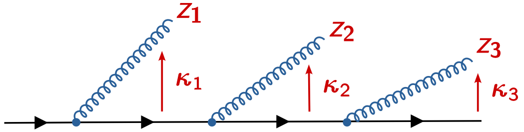
Non constant density



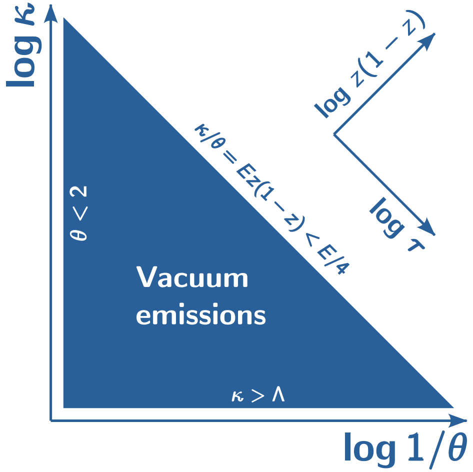
Average for each splitting density → Lund plane trajectories



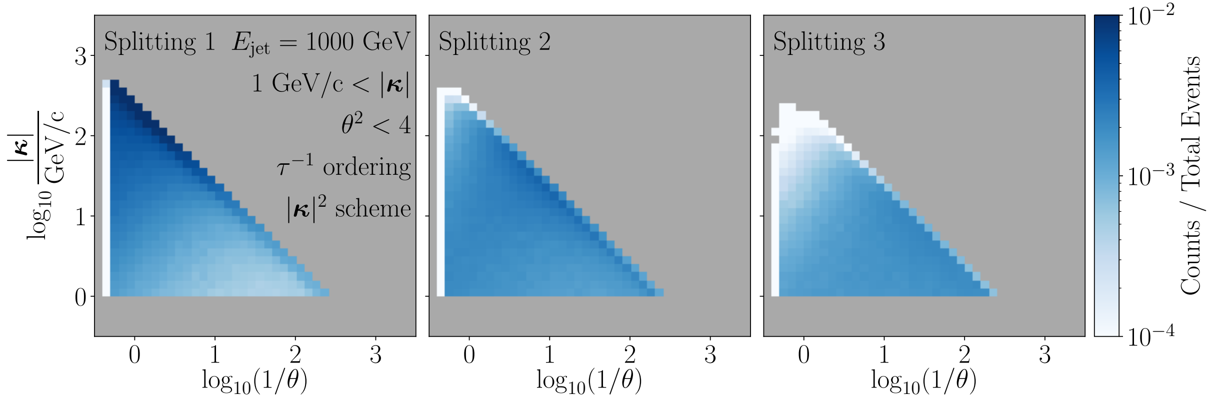
Lund Planes



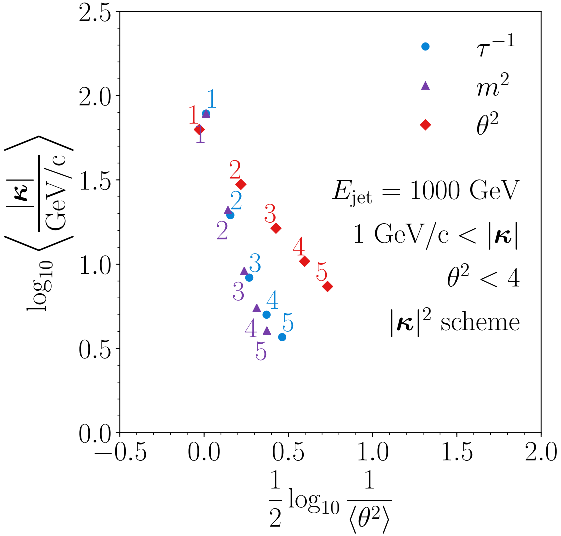
Visualise each splitting in a 2D phase-space: The Lund Plane



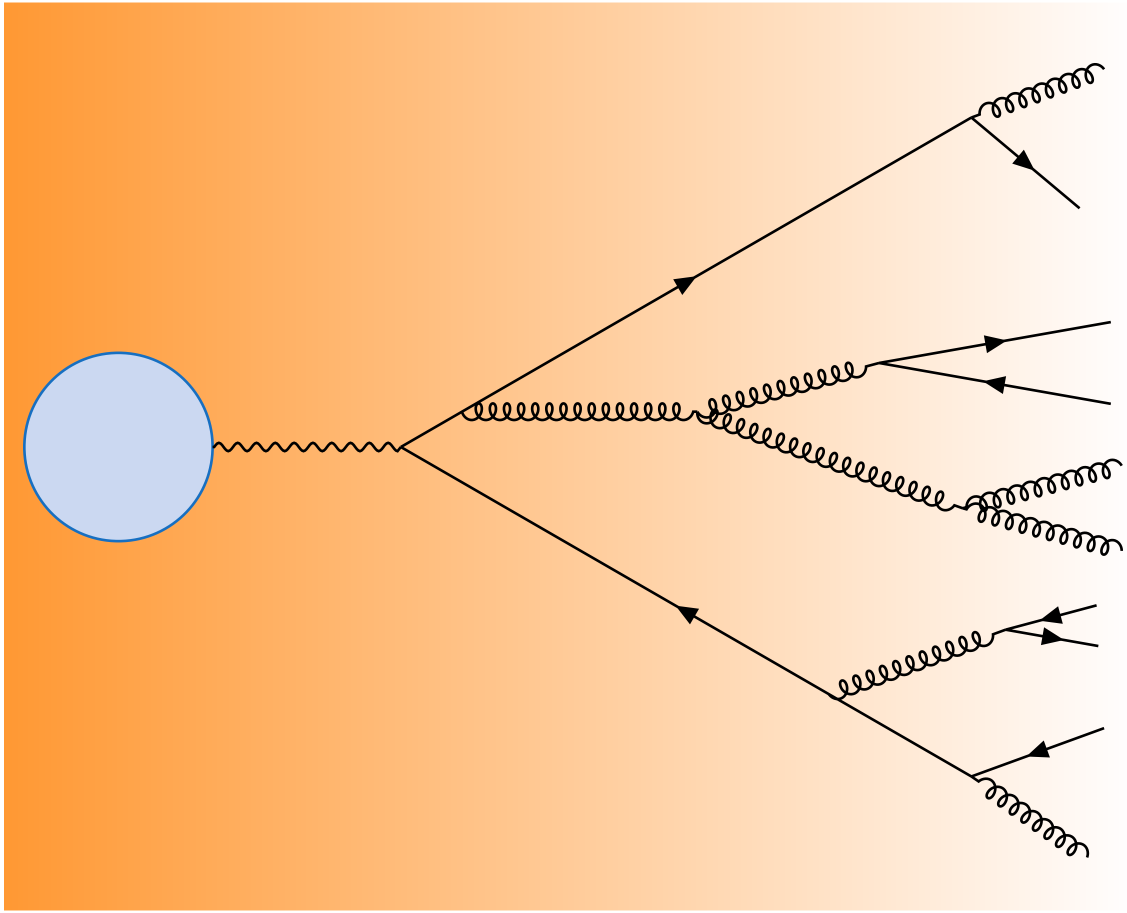
Non constant density



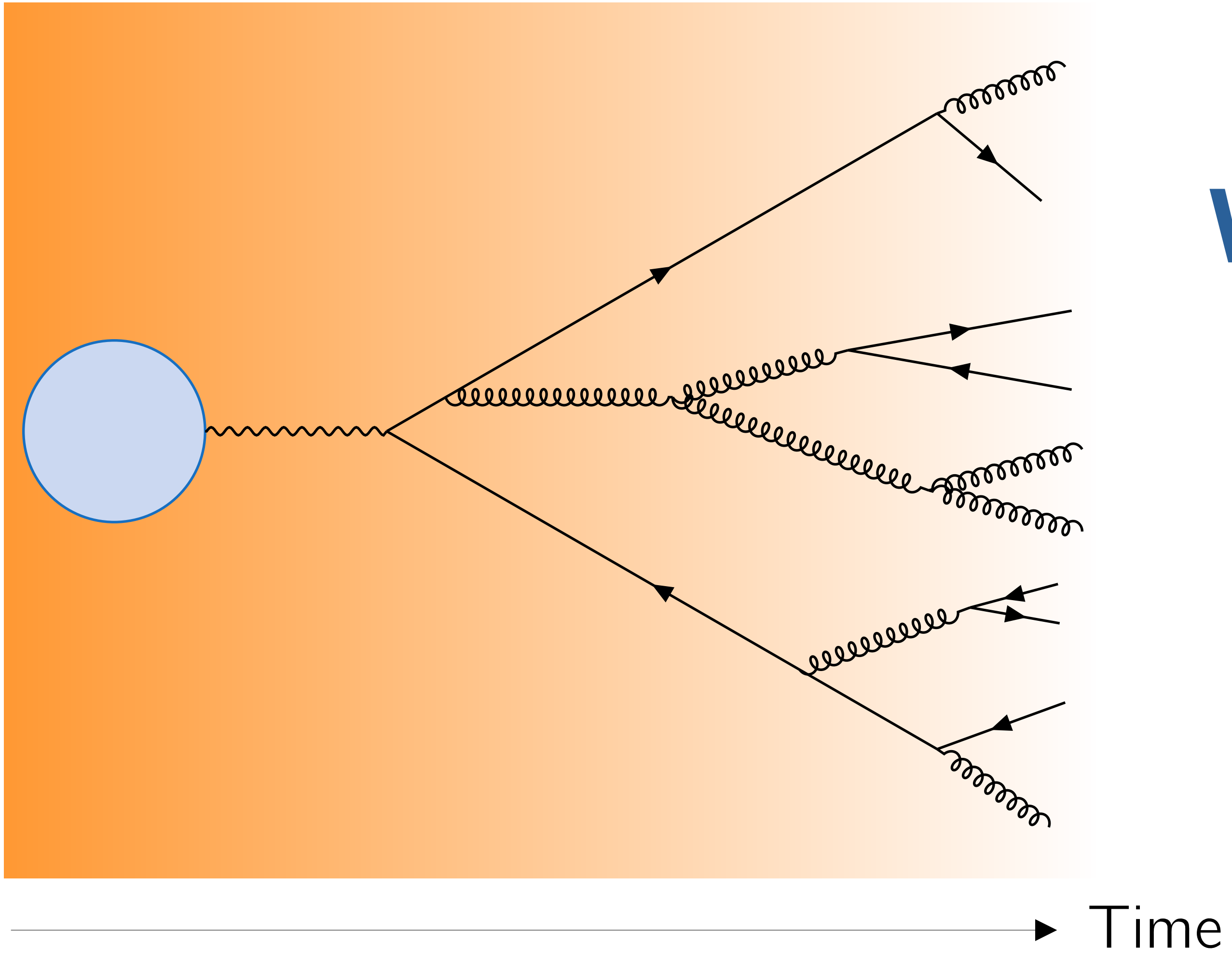
Average for each splitting density → Lund plane trajectories



Different orderings → Different shower evolution!



What happens in a medium?



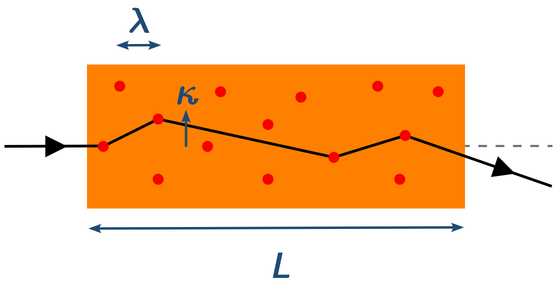
What happens in a medium?

First, we need a space-time picture for the shower!

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

Simple Quenching Model

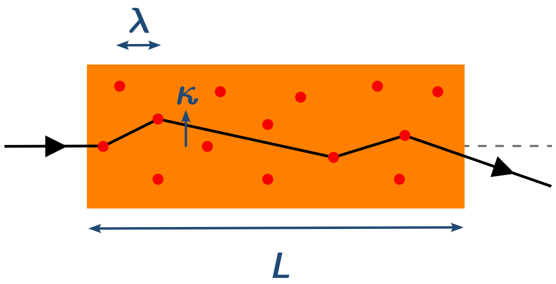
Medium as a 'brick' that deflects partons: $\hat{q} \sim \langle \kappa^2_{\rm acc} \rangle / \lambda$



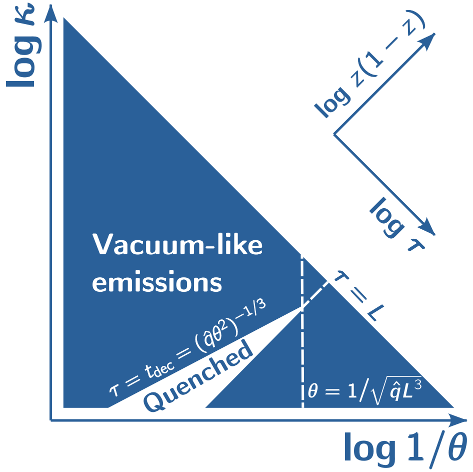
Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
Casalderrey-Solana, Iancu :: JHEP 08 (2011) 015

Simple Quenching Model

Medium as a 'brick' that deflects partons: $\hat{q} \sim \langle \kappa^2_{\rm acc} \rangle / \lambda$



Phase-space for quenched splittings:



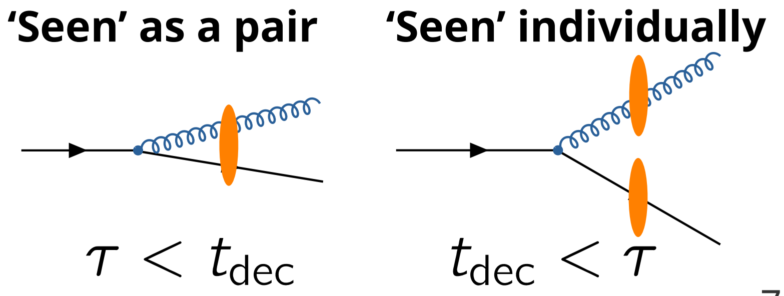
- Splitting transverse momentum below medium scale:

$$\kappa^2 < \hat{q}\tau \Leftrightarrow t_{\rm dec}(\theta) < \tau$$

- Splitting inside medium:

$$\tau < L$$

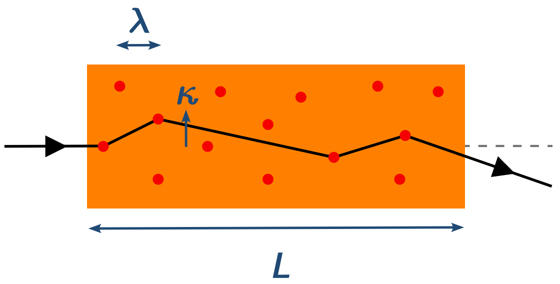
τ provides the space-time picture!

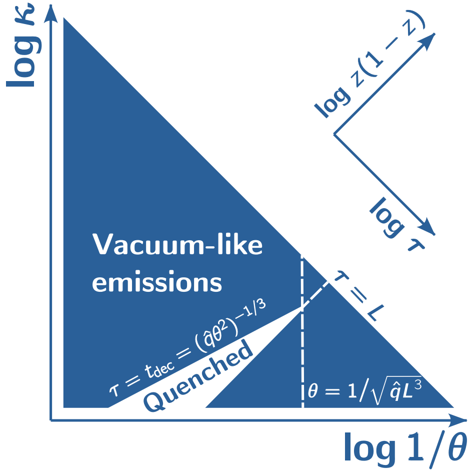


Mehtar-Tani, Salgado, Tywoniuk :: Phys.Rev.Lett. 106 (2011)
Casalderrey-Solana, Iancu :: JHEP 08 (2011) 015

Simple Quenching Model

Medium as a ‘brick’ that deflects partons: $\hat{q} \sim \langle \kappa^2_{\rm acc} \rangle / \lambda$





Phase-space for quenched splittings:

- Splitting transverse momentum below medium scale:

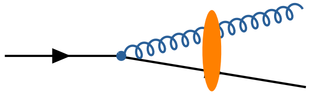
$$\kappa^2 < \hat{q}\tau \Leftrightarrow t_{\rm dec}(\theta) < \tau$$

- Splitting inside medium:

$$\tau < L$$

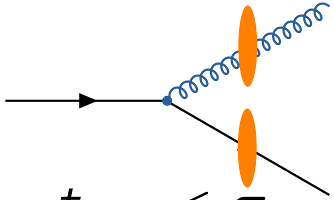
τ provides the space-time picture!

‘Seen’ as a pair



$\tau < t_{\rm dec}$

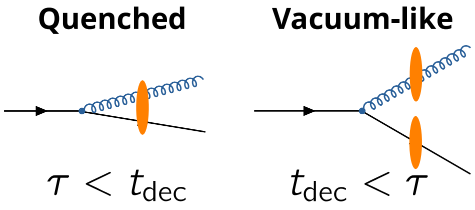
‘Seen’ individually



$t_{\rm dec} < \tau$

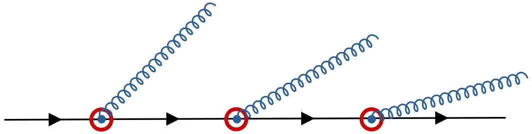
How does this affect our parton showers?

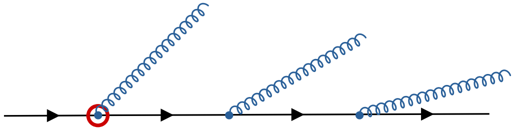
Quenching and Parton Showers



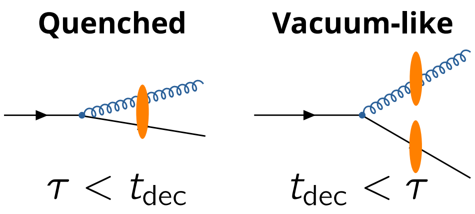
Look for splittings where $t_{dec} < \tau < L$

We can check: *** Simplistic Approach (!)**

- The full quark branch 

- Only the first splitting 

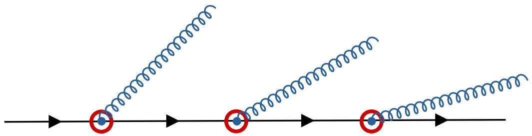
Quenching and Parton Showers



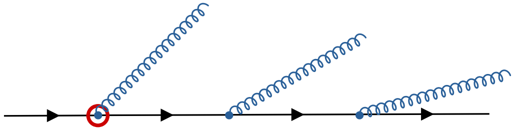
Look for splittings where $t_{\text{dec}} < \tau < L$

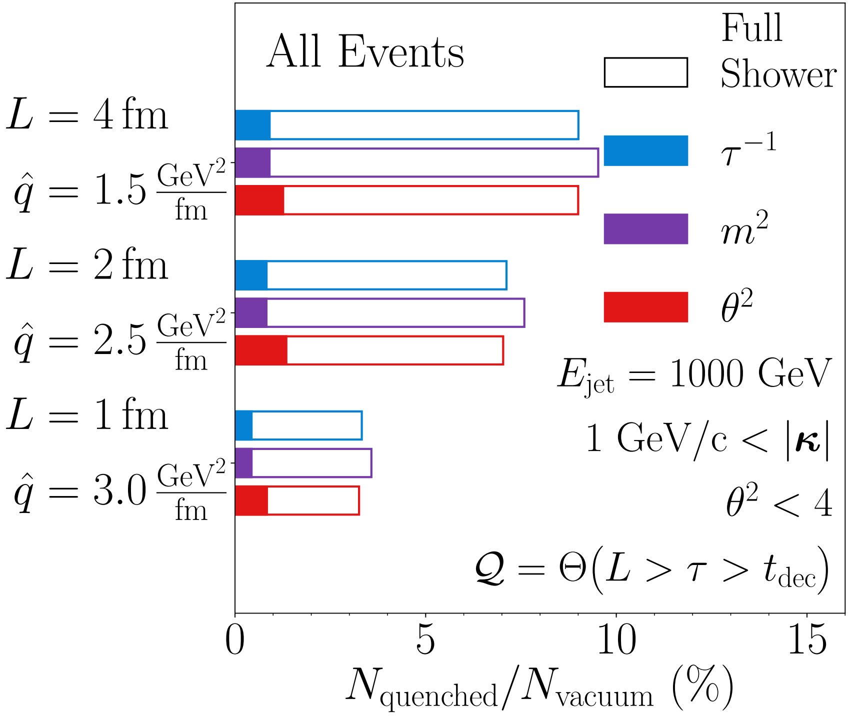
We can check: * Simplistic Approach (!)

- The full quark branch (Empty bars)

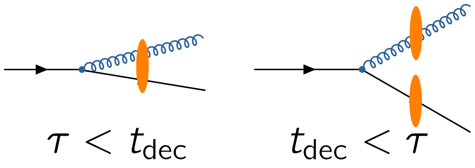


- Only the first splitting (Full bars)





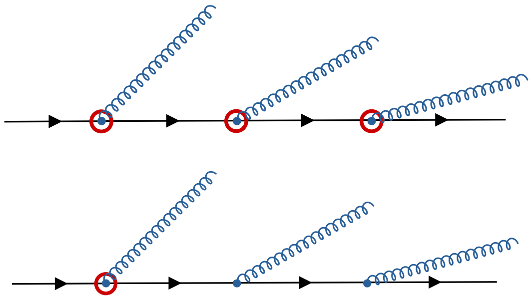
Quenching and Parton Showers



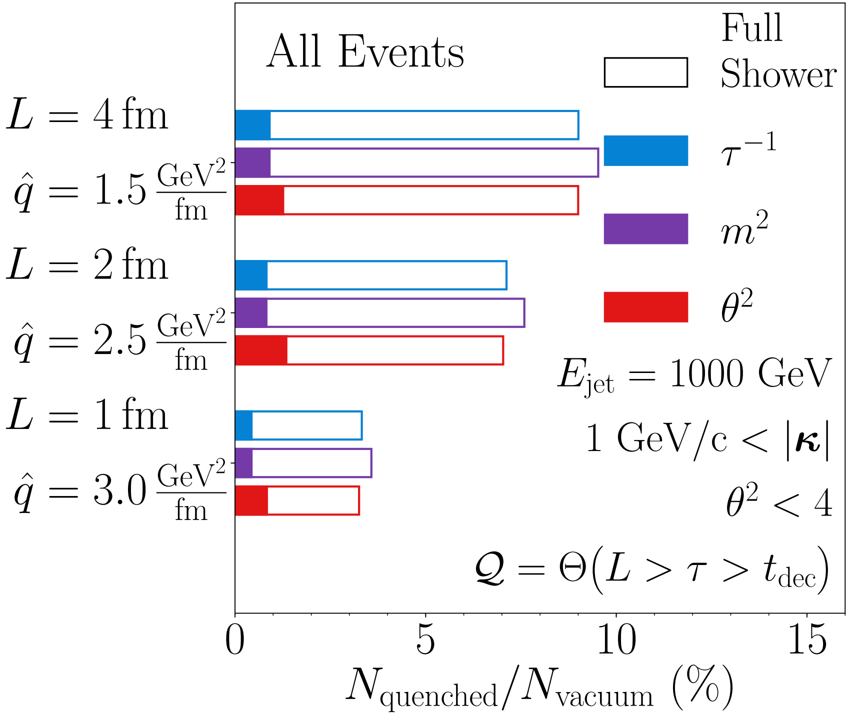
Look for splittings where $t_{\rm dec} < \tau < L$

We can check: *** Simplistic Approach (!)**

- The full quark branch **(Empty bars)**
- Only the first splitting **(Full bars)**

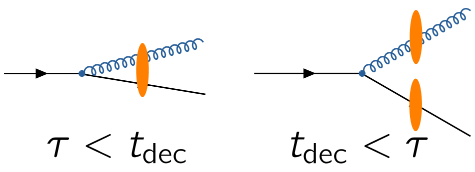


Angular ordered showers see more quenching



**** Robust under control of:**
- Time ordering violations
- Jet radius

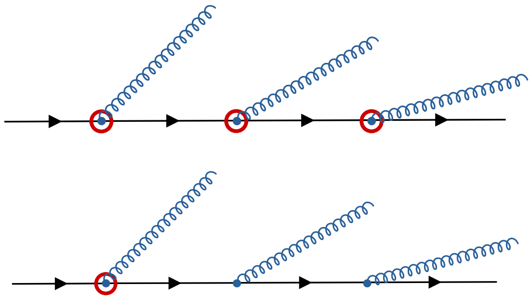
Quenching and Parton Showers



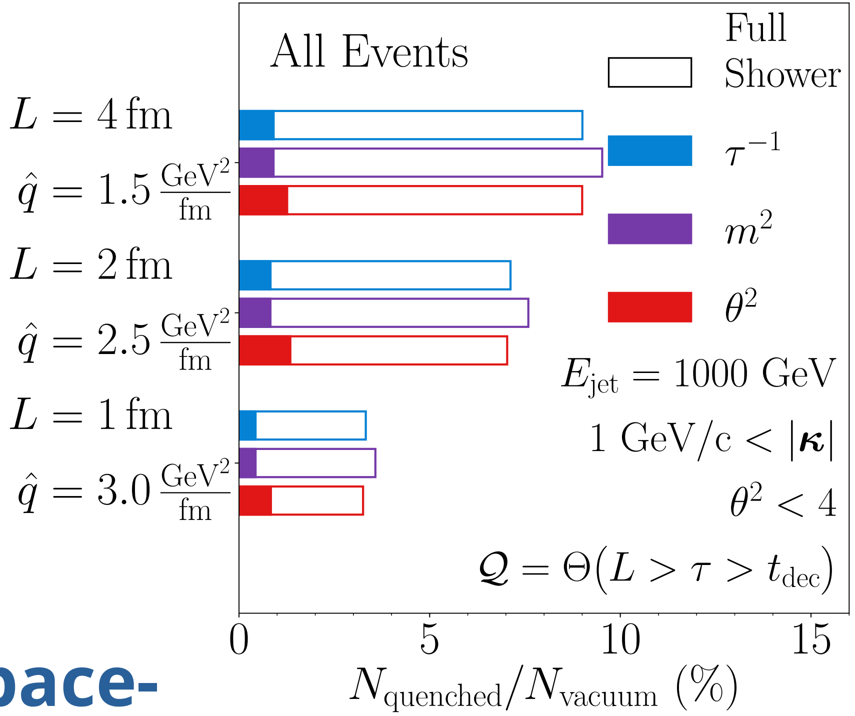
Look for splittings where $t_{\rm dec} < \tau < L$

We can check: *** Simplistic Approach (!)**

- The full quark branch **(Empty bars)**
- Only the first splitting **(Full bars)**



Angular ordered showers see more quenching



Ordering impacts the cascade's space-time structure → Influences Jet Quenching

**** Robust under control of:**
- Time ordering violations
- Jet radius

Summary

The Quark Gluon Plasma can be probed by high-energy partons and their radiation pattern

This requires a space-time picture of a Parton Shower → Choice of ordering prescription is non-trivial

A full coordinate space description is needed!

More details: arXiv:2409.13536

Thanks!

Acknowledgements

LIP

TÉCNICO LISBOA

fct Fundação para a Ciência e a Tecnologia

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IGFAE INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS 25 1999 2024

REPÚBLICA PORTUGUESA

erc European Research Council
Established by the European Commission

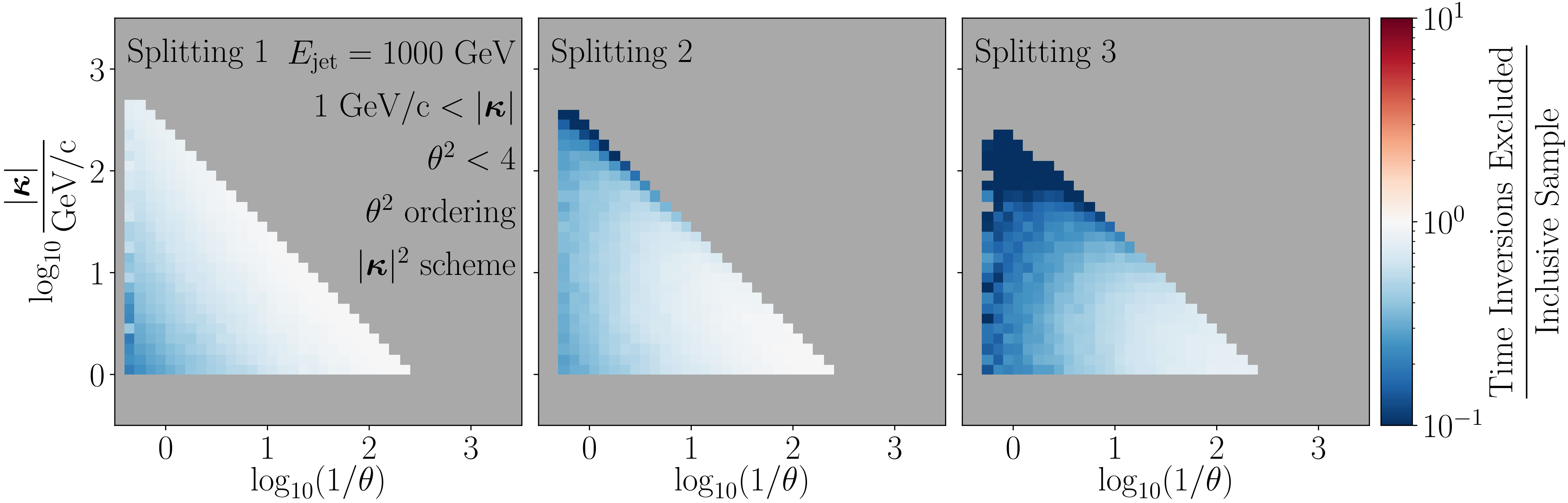
STRONG 2020

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

Backup Slides

Excluding time inversions – Lund Planes

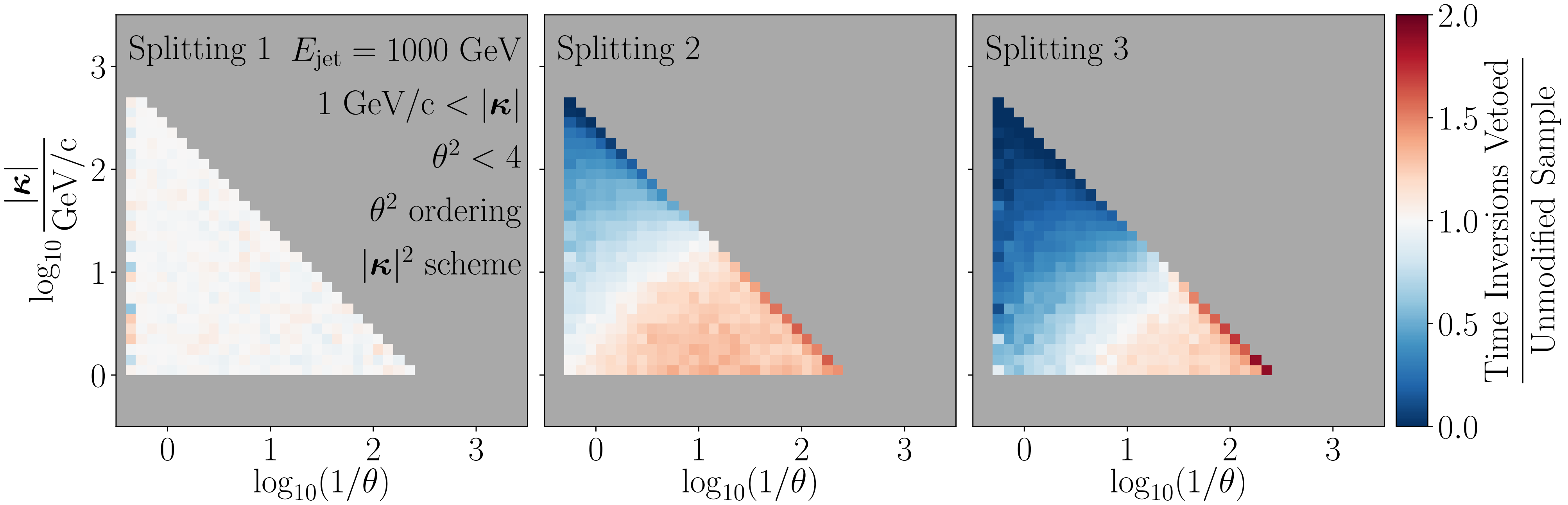
***Ordered in angle**



Excluding all events with at least one time inversion in quark branch

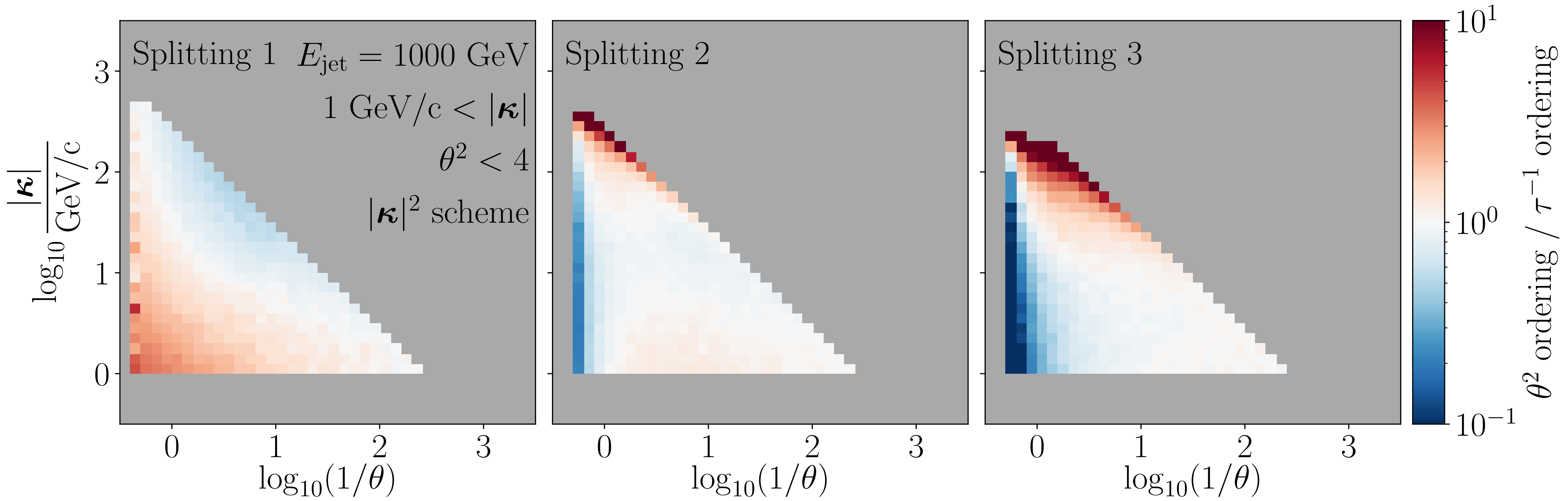
Vetoing time inversions – Lund Planes

***Ordered in angle**



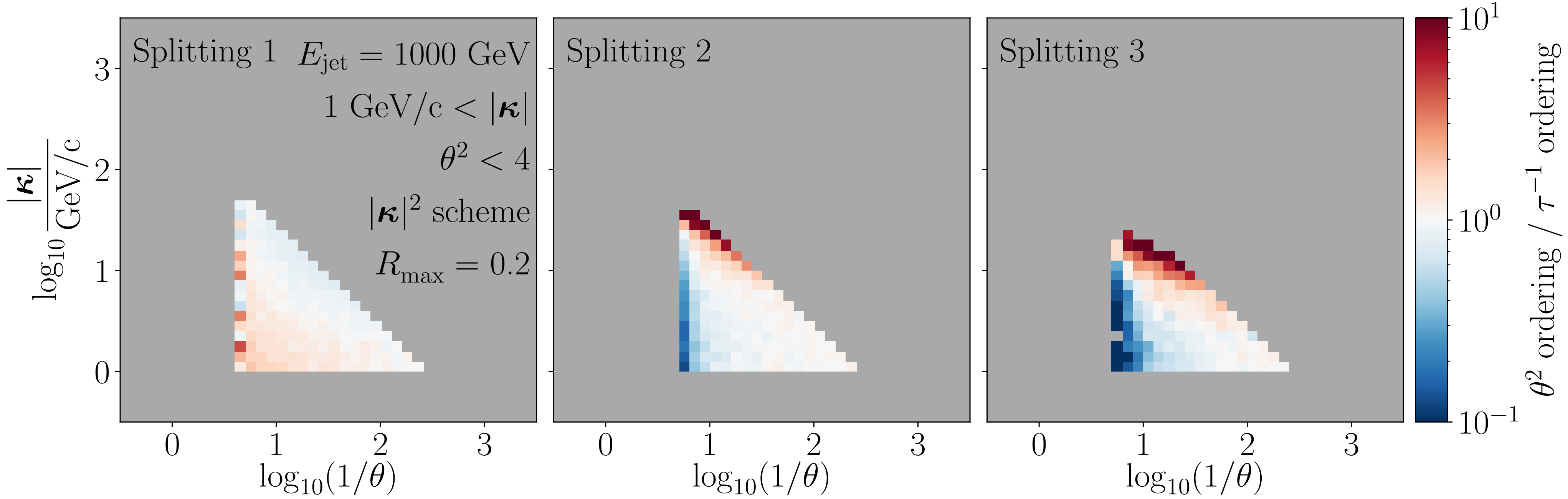
Preventing time inversions at generation level (by retrial)

Algorithm Ratios



Ratio between time and angular ordered samples

Controlling for Jet Radius – Algorithm Ratios



When restricting sample to angles under 0.2, Lund densities scale uniformly

Quenching Weights and Vetos