Exploring the time axis within medium-modified jets

Pablo Guerrero Rodríguez [a]

In collaboration with Liliana Apolinario [a] and Korinna Zapp [b]

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"NEW JET QUENCHING TOOLS" WORKSHOP

ECT*, Trento (Italy)

[a] *Laboratório de Instrumentação e Física Experimental de Partículas (LIP)*

[b] *Department of Astronomy and Theoretical Physics, Lund University*

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Jet quenching as a tool for QGP tomography

- *Can we use jets to access the time structure of the Quark Gluon Plasma?*
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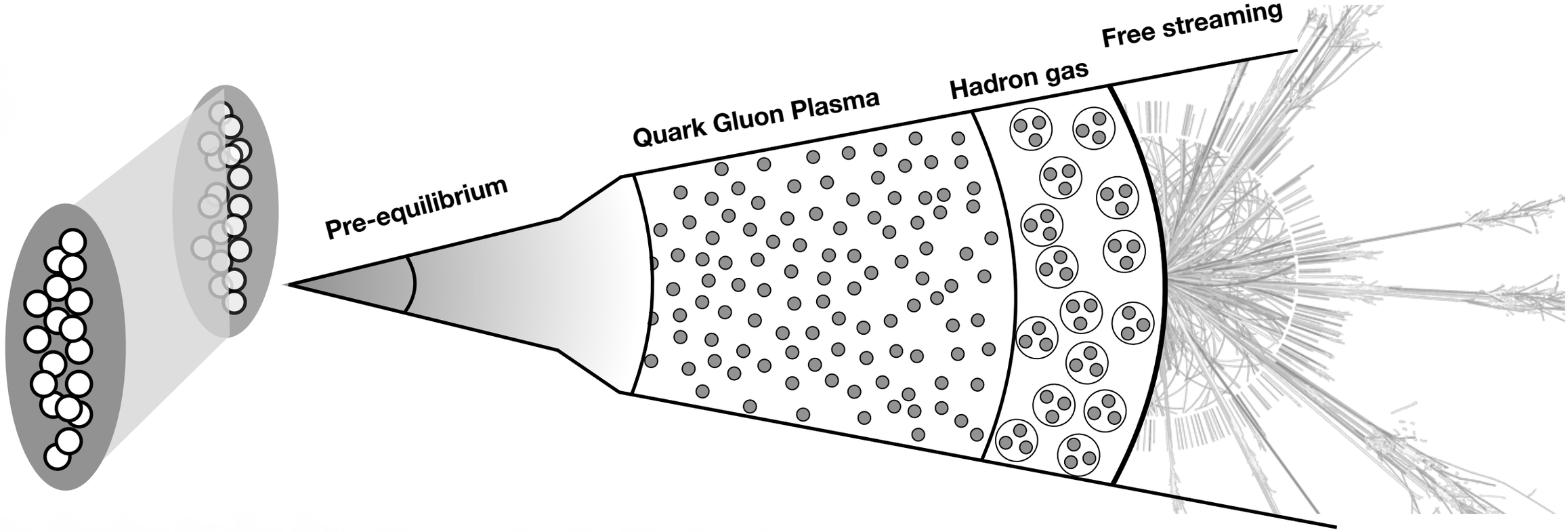

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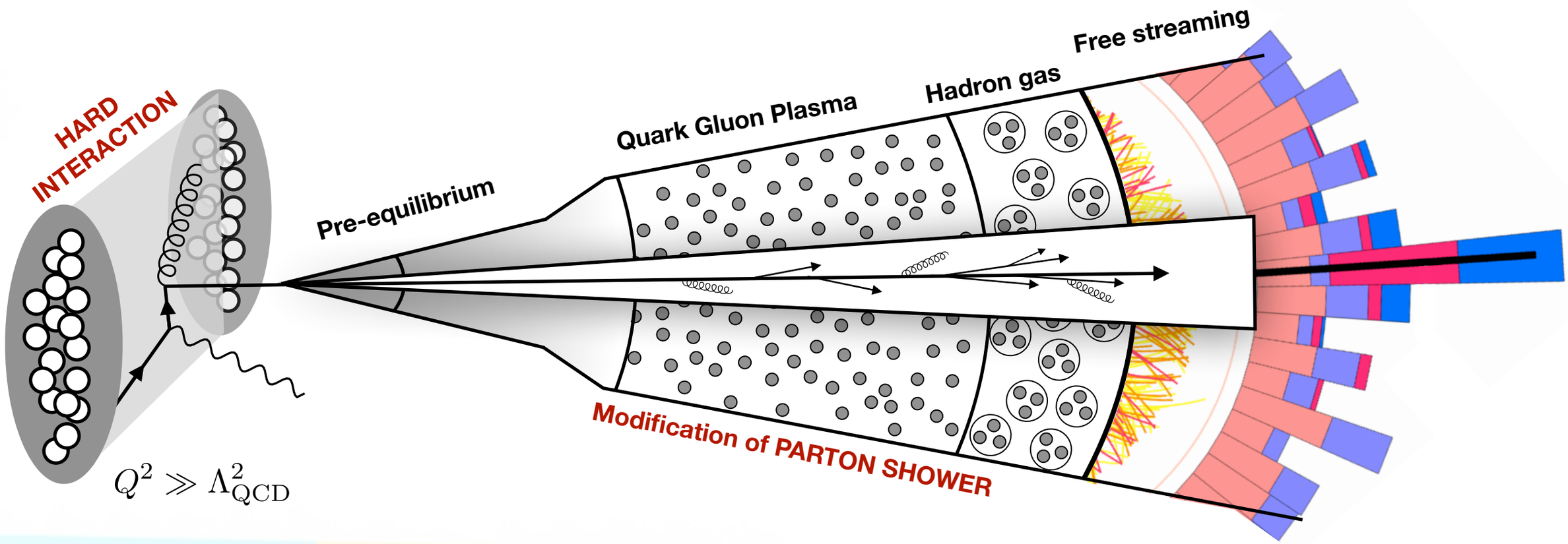

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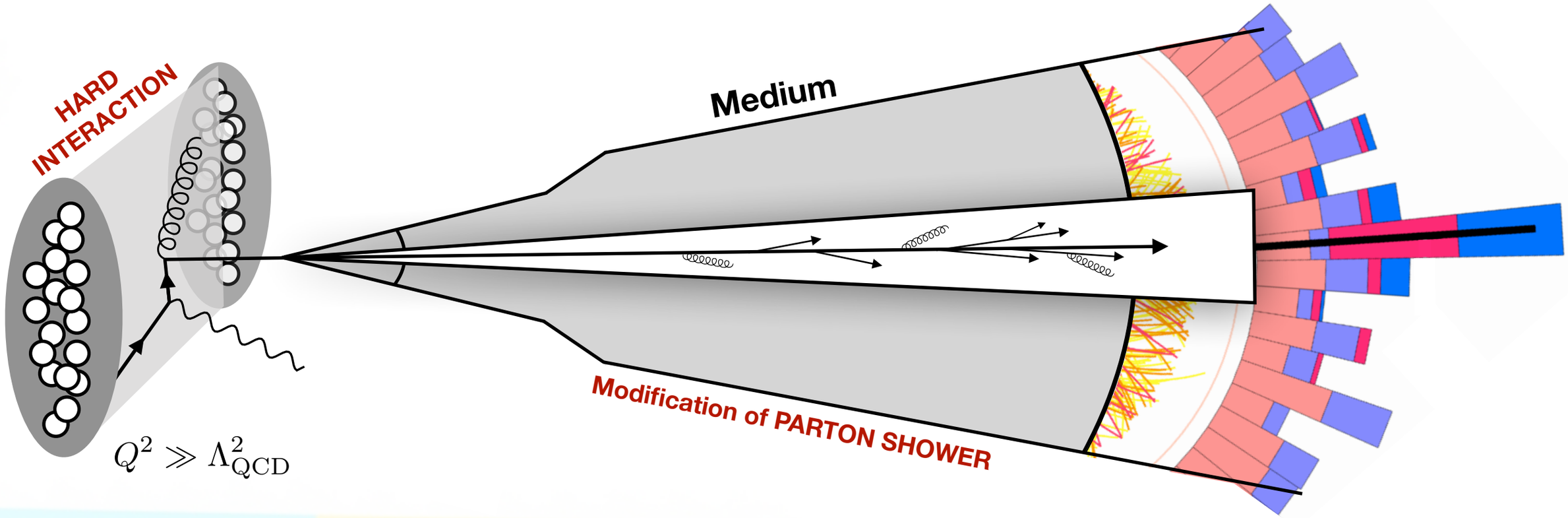

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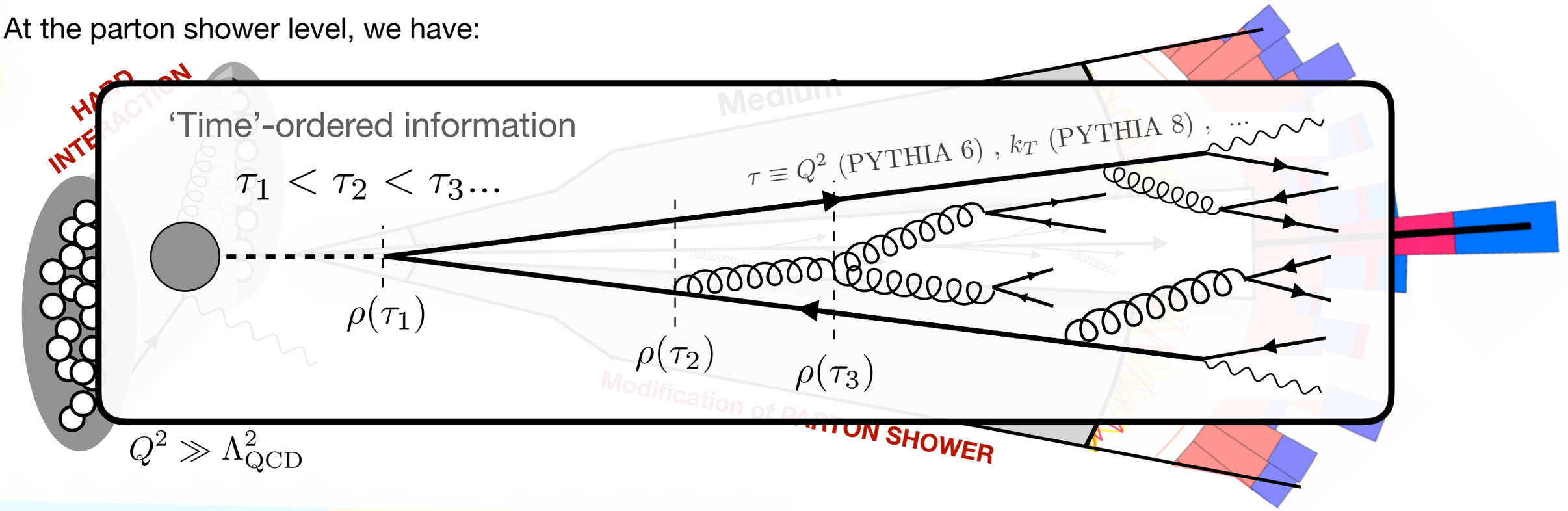

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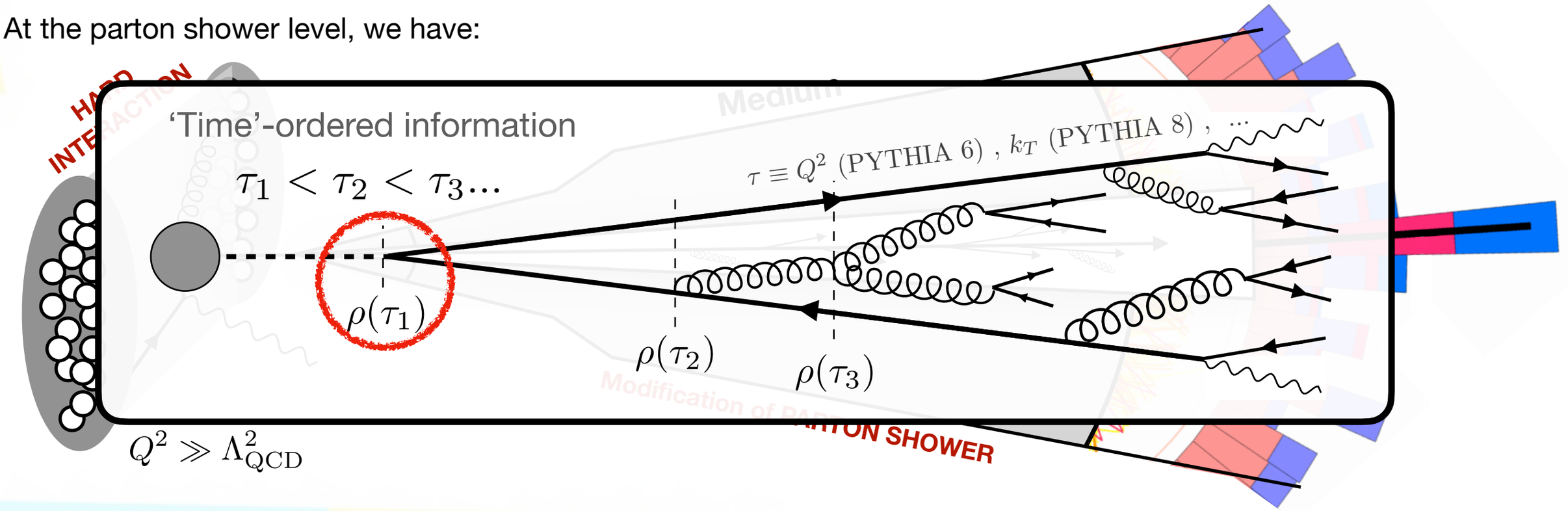

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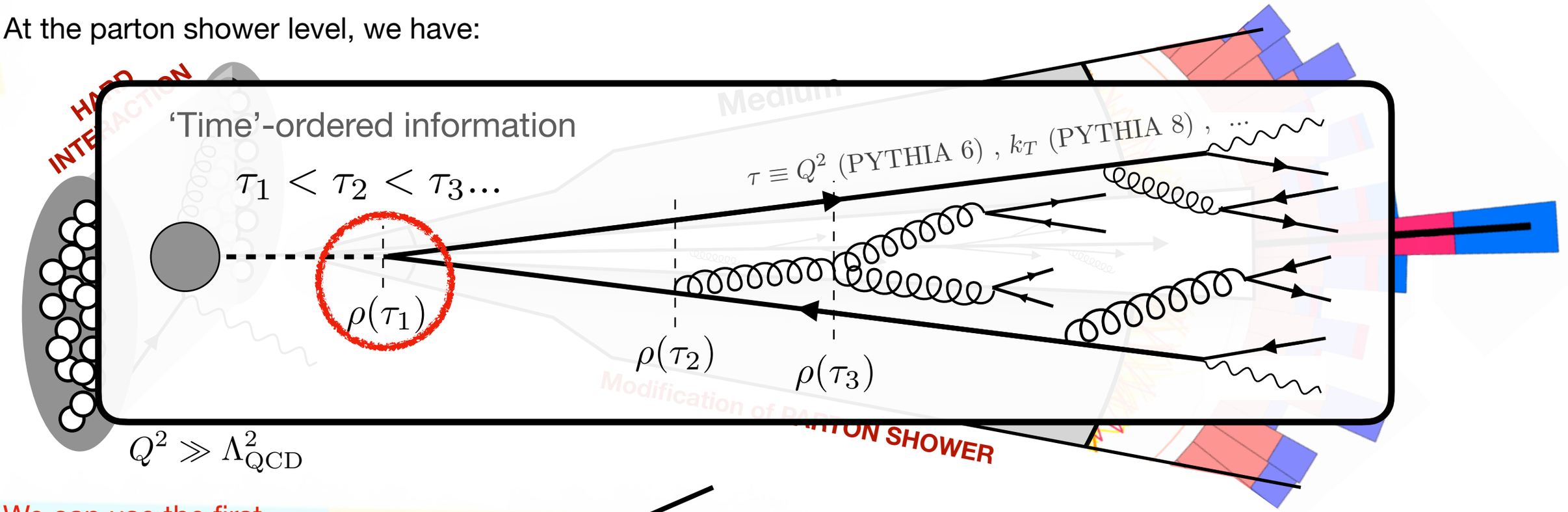

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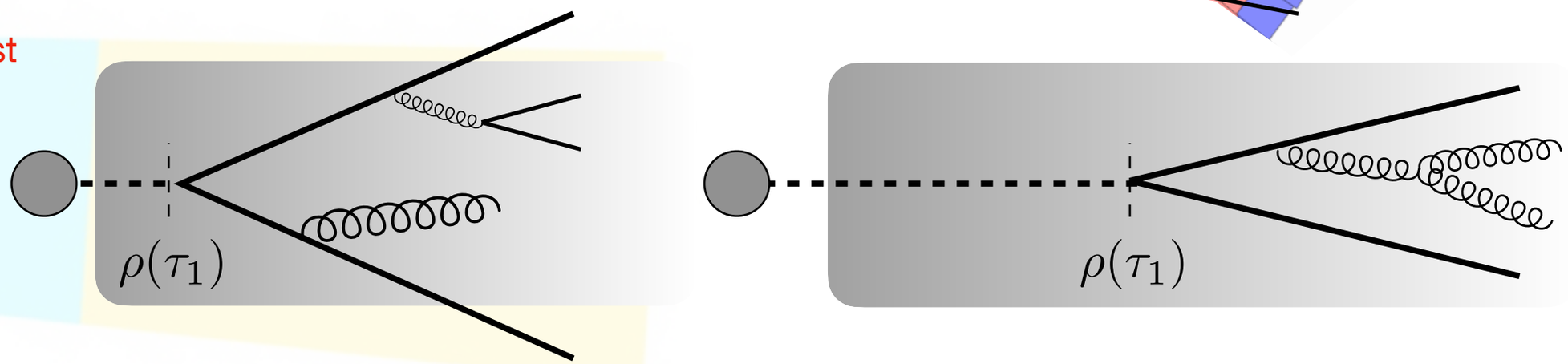

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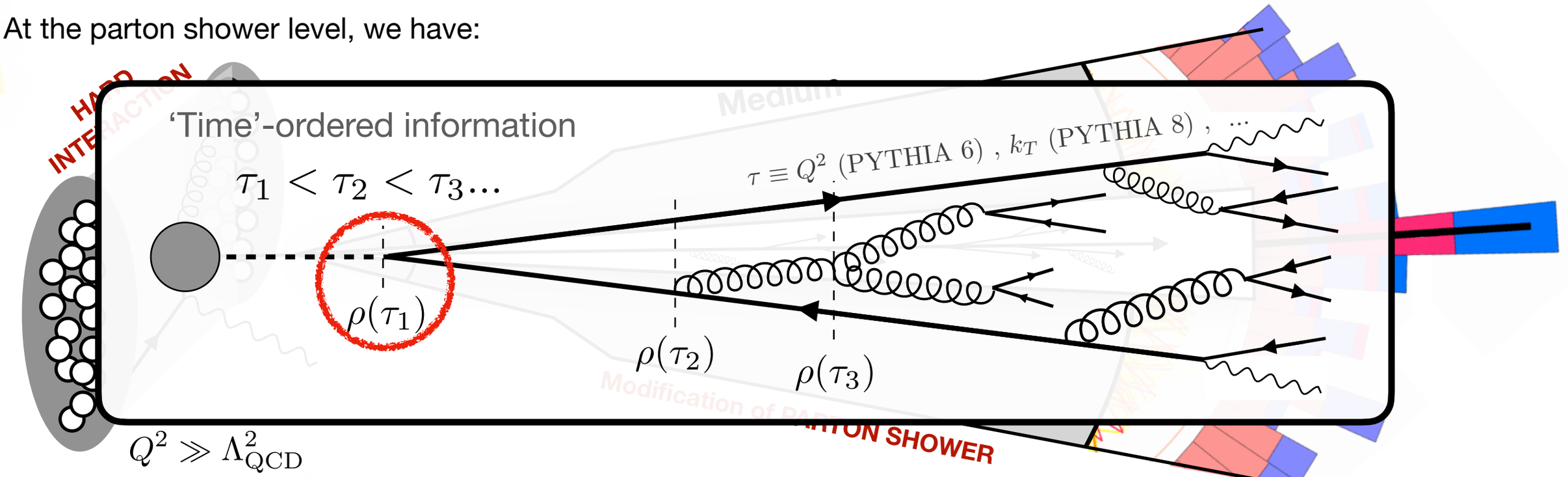

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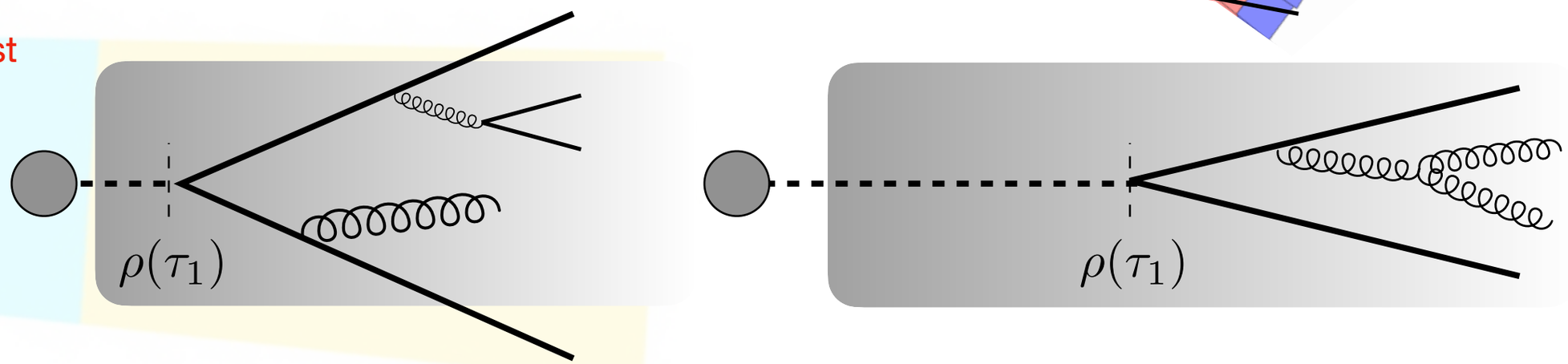

- *BUT how can we access this information?*

Jet clustering

- ➡ We want to extract information from the internal structure of jets
- *So, how do we make a jet?*

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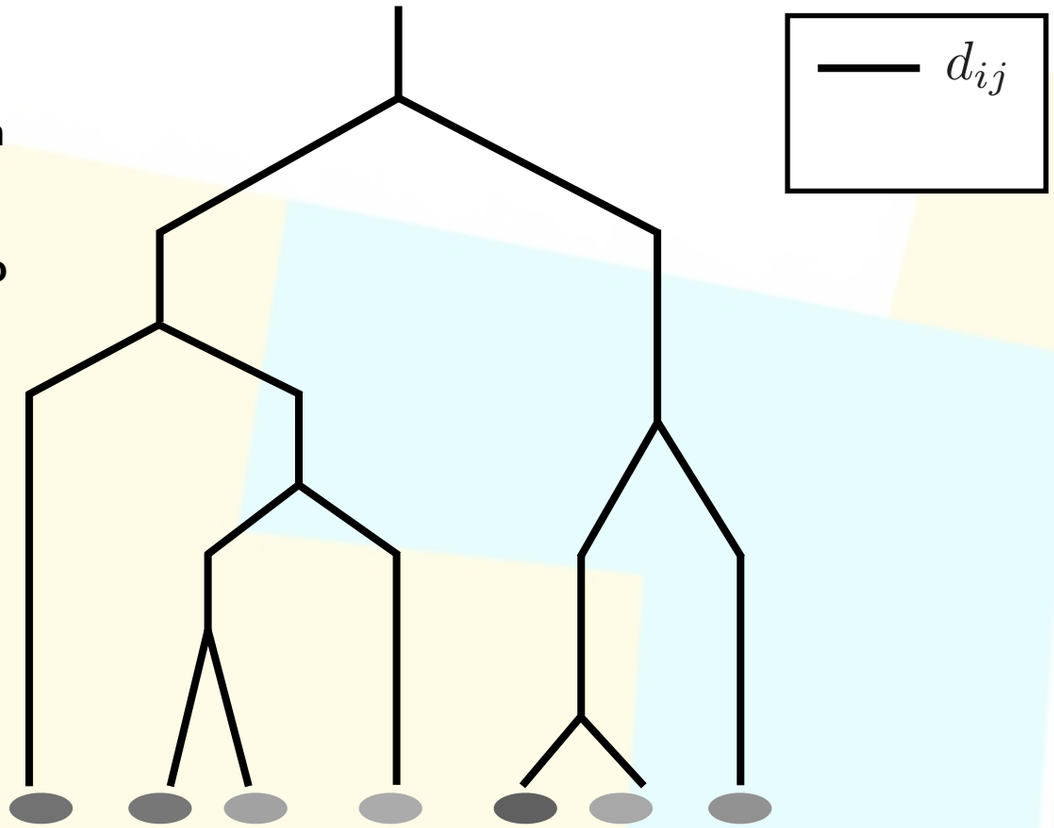
● *So, how do we make a jet?*

Sequential combination of particles ordered according to some user-defined distance measure d_{ij}



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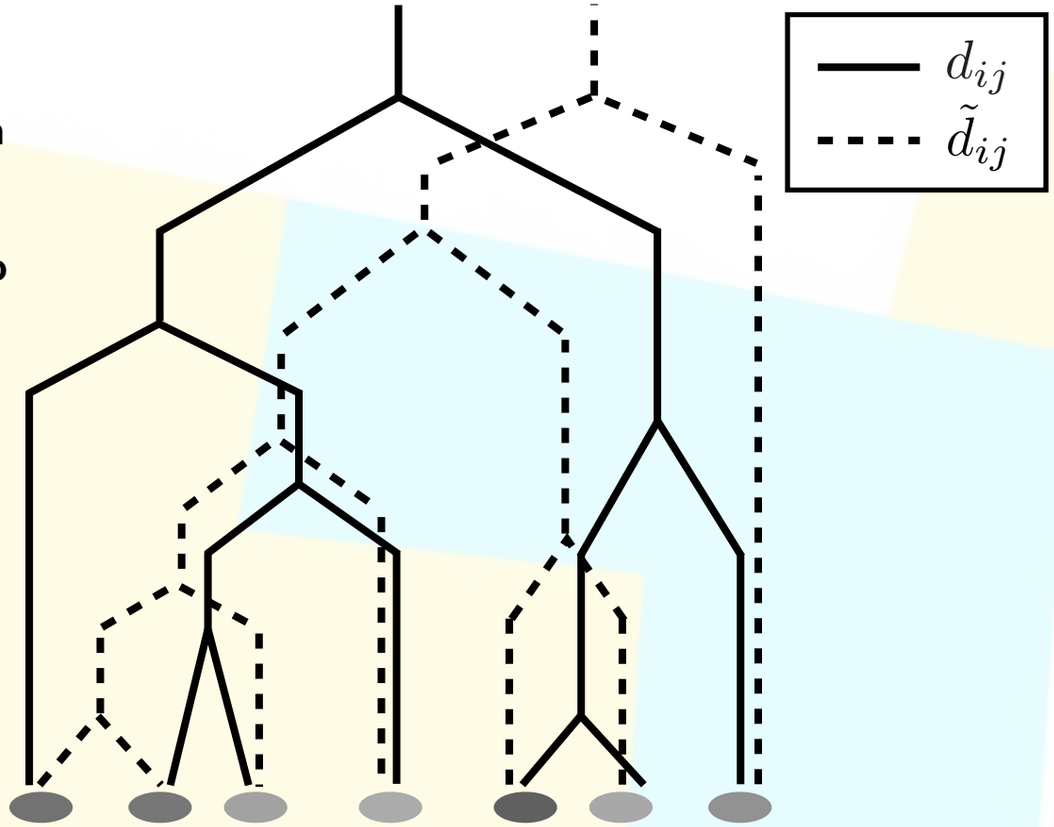

Cartoon courtesy of K. Zapp

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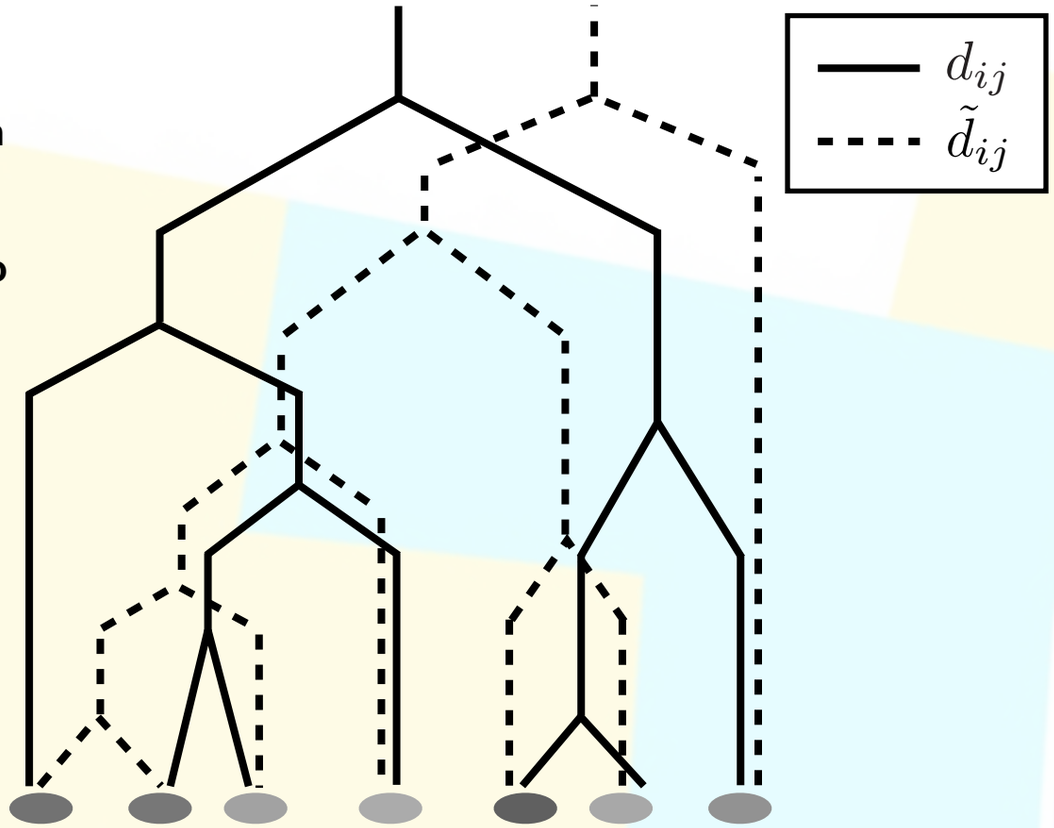

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➡ We use the **generalized** k_t **algorithm**

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \text{ , with } \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

$$p = 0 \longrightarrow \text{C/A}$$
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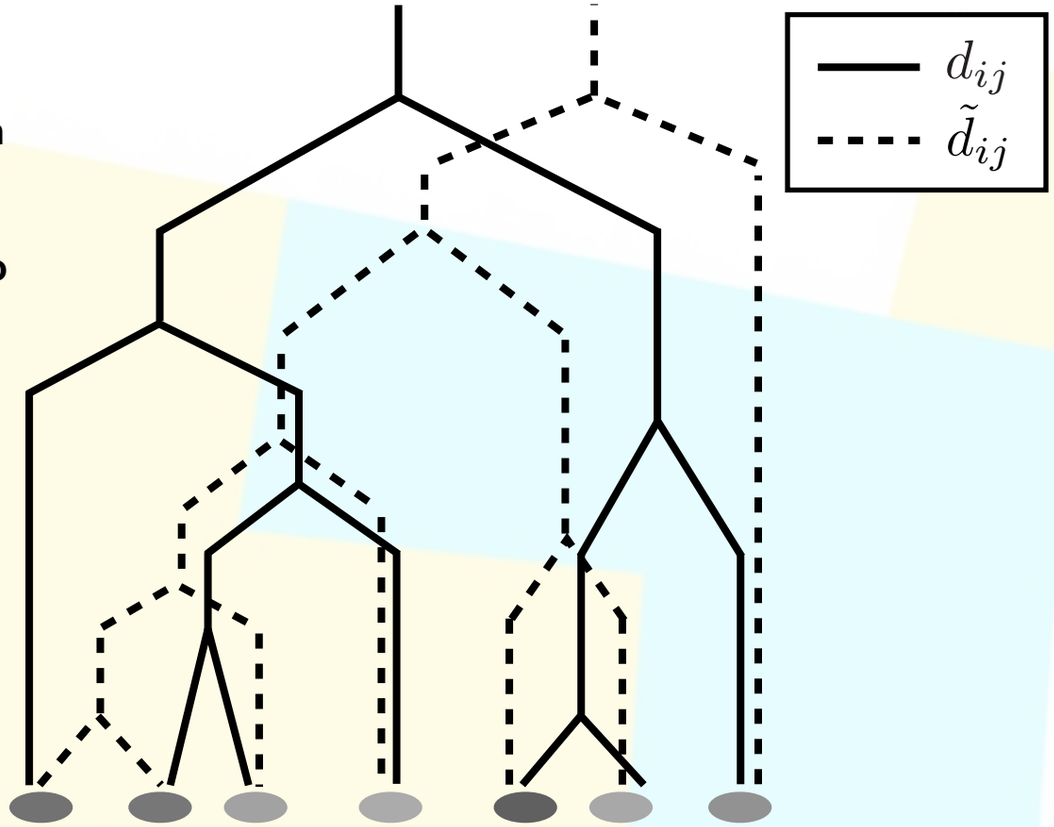

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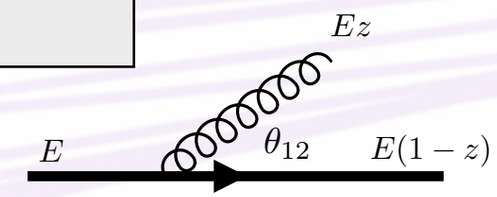
$$\begin{aligned} p = 0 &\longrightarrow \text{C/A} \\ p = -1 &\longrightarrow \text{Anti-}k_t \\ p = 1 &\longrightarrow k_t \\ p = 0.5 &\longrightarrow \tau \end{aligned}$$

➡ We propose using $p = 0.5$. With this setup:

$$d_{ij} \sim p_{T,i}\theta^2 \sim \frac{1}{\tau_{\text{form}}} \text{ , with } \tau_{\text{form}} \approx \frac{E}{Q^2} \overset{\text{(High energy limit)}}{\approx} \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$



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● *So, how do we make a jet?* Can we relate them to parton showers?

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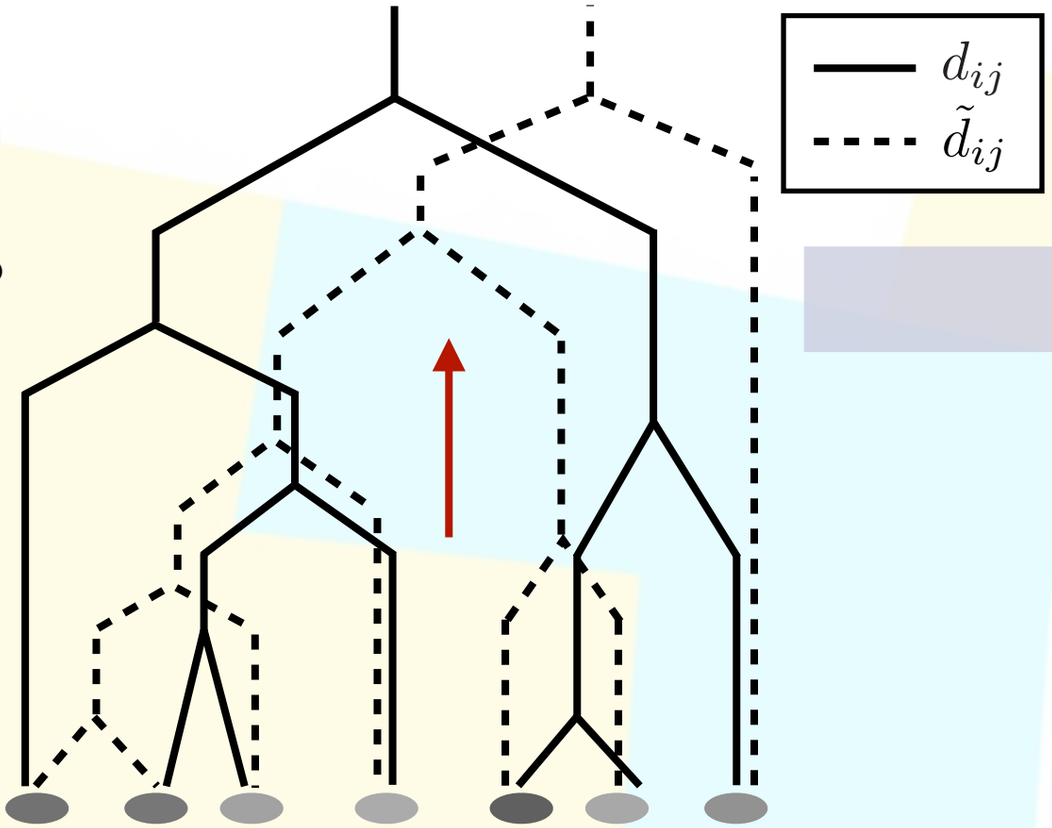

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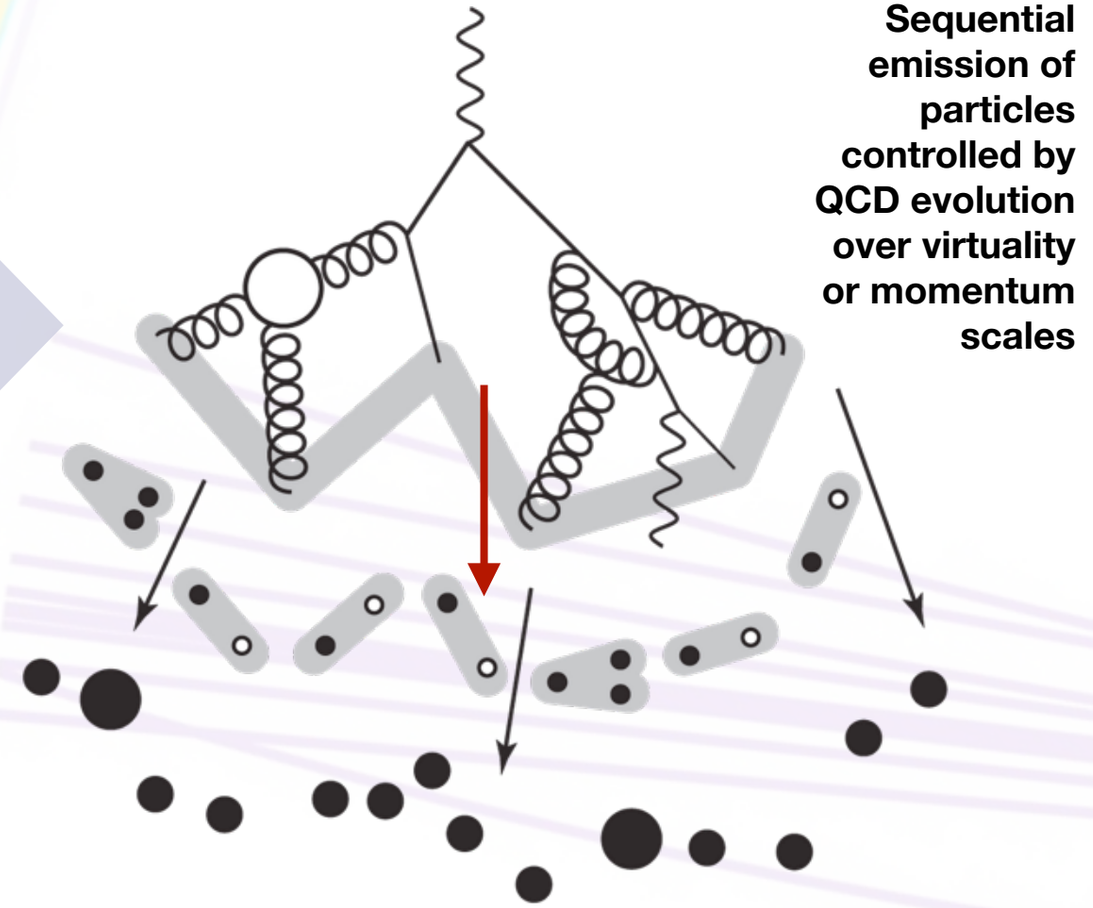

Sequential emission of particles controlled by QCD evolution over virtuality or momentum scales

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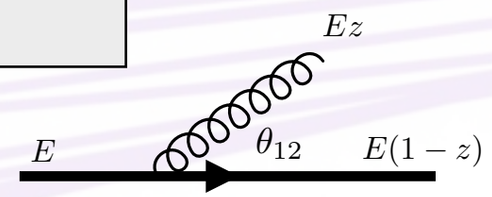

➡ **We can use the clustering history of the jet to reconstruct the parton shower splitting by splitting**

Jet unclustering with the τ-algorithm

L. Apolinário, A.Cordeiro, K. Zapp, Eur. Phys. J. C 81 (2021) 6, 561

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1) Identify jets applying anti-kt algorithm (p=-1)

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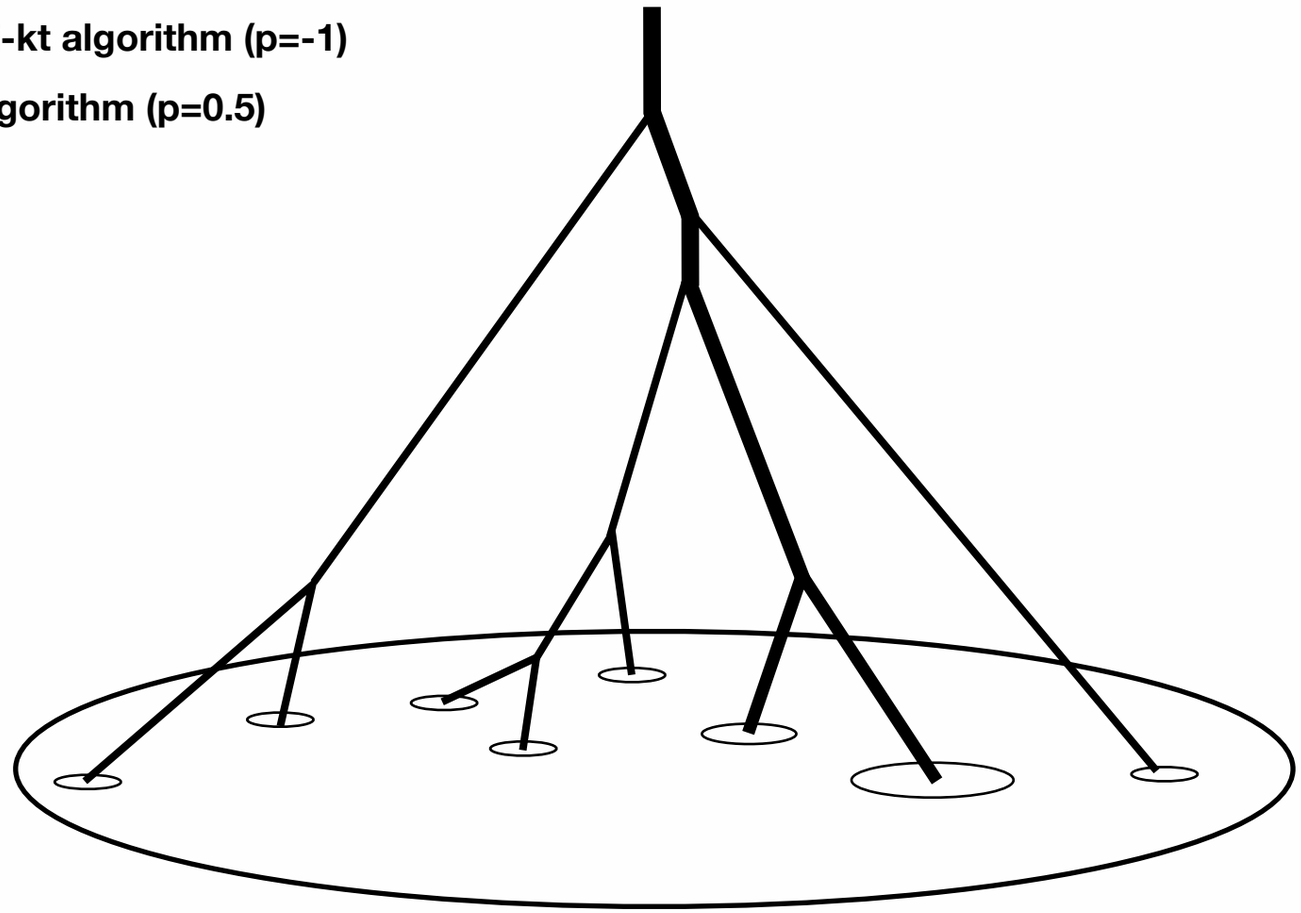

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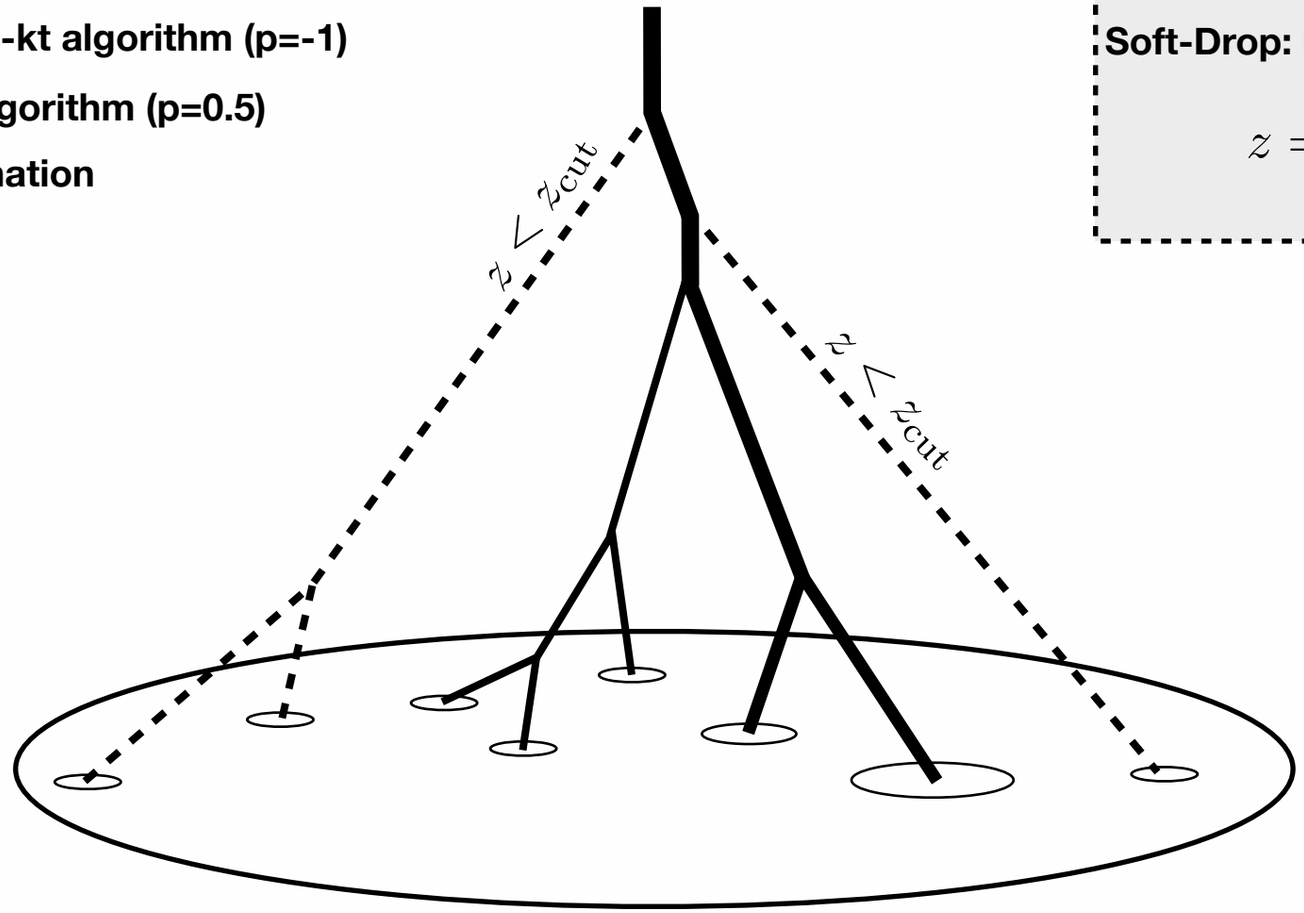

Soft-Drop: Remove emissions that don't satisfy

$$z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\rm cut}$$

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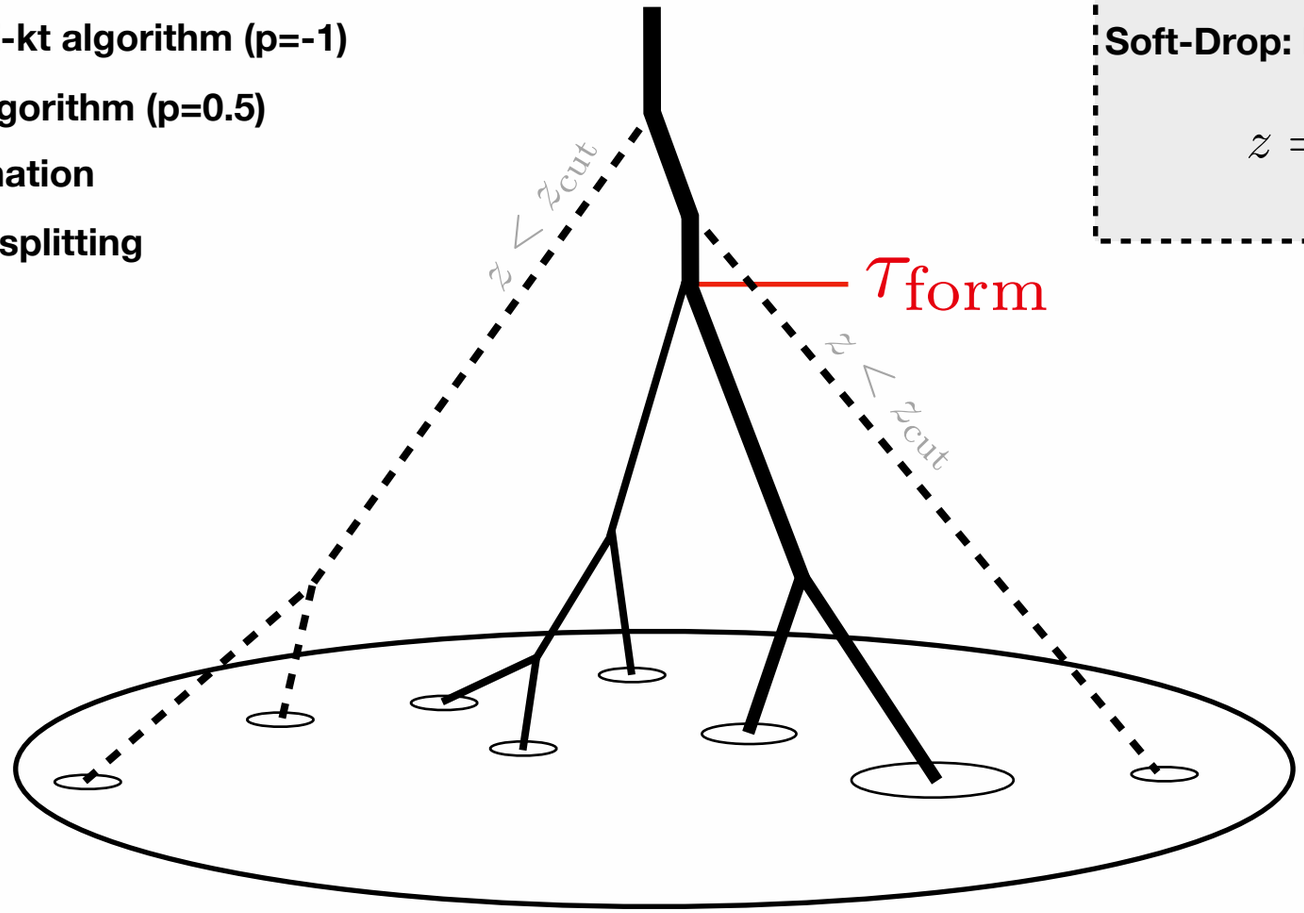

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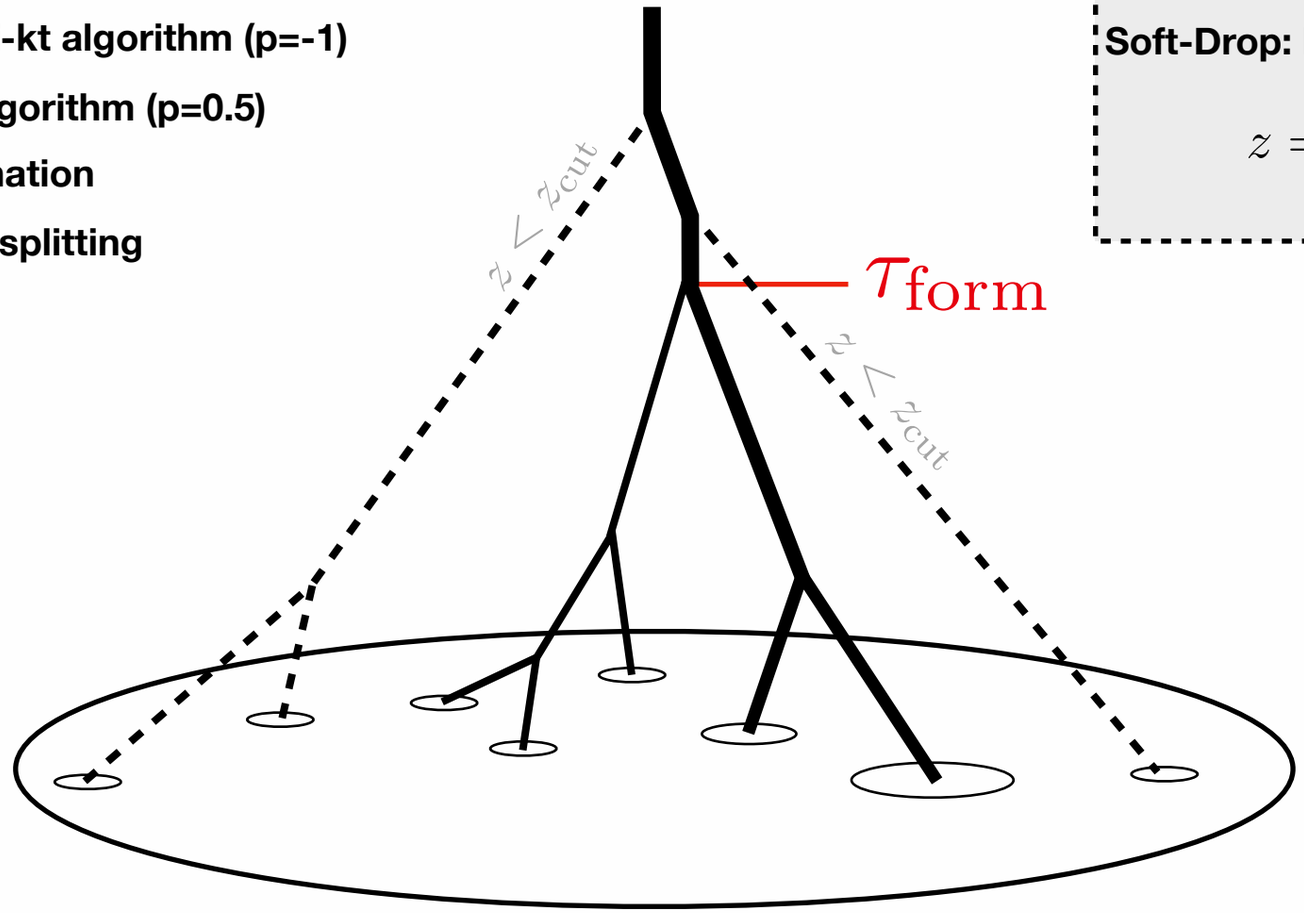

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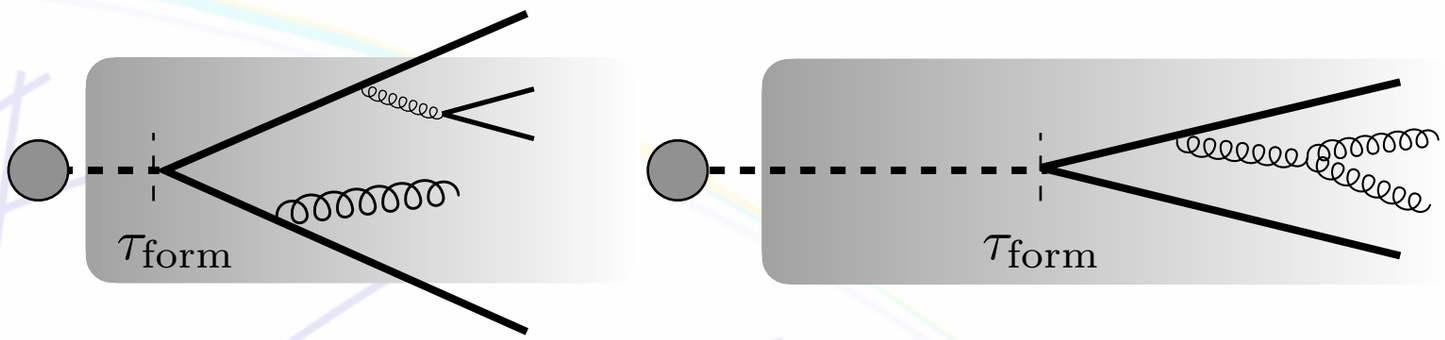

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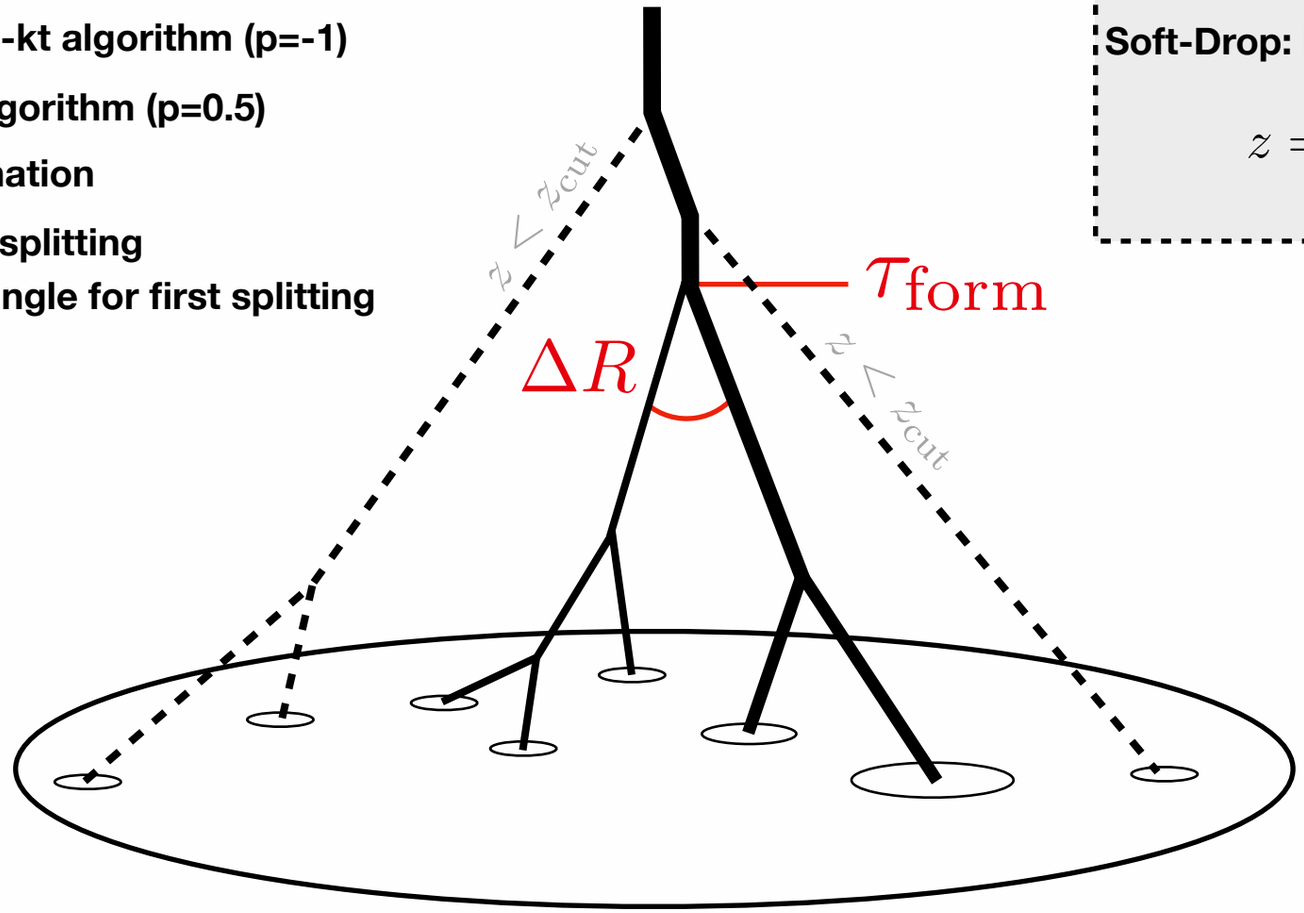

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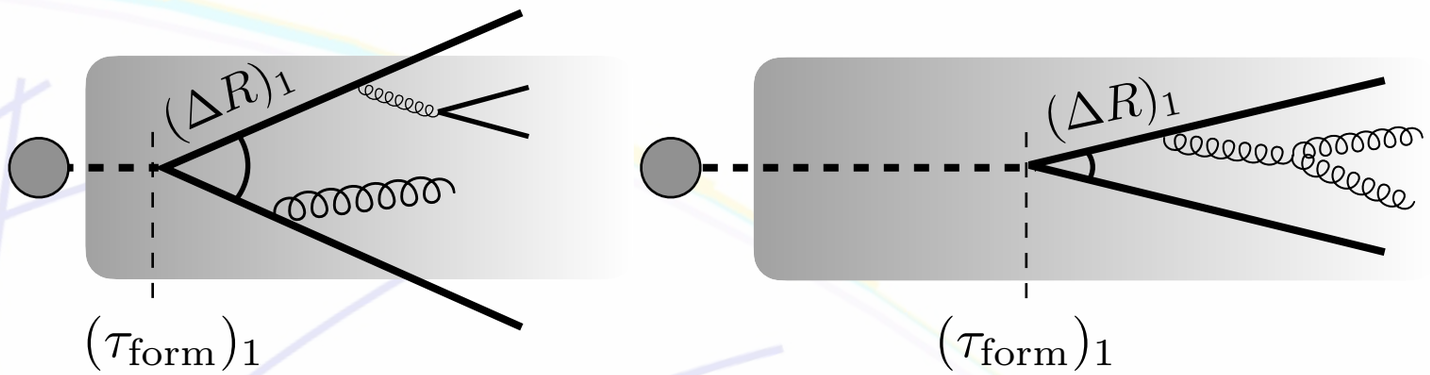

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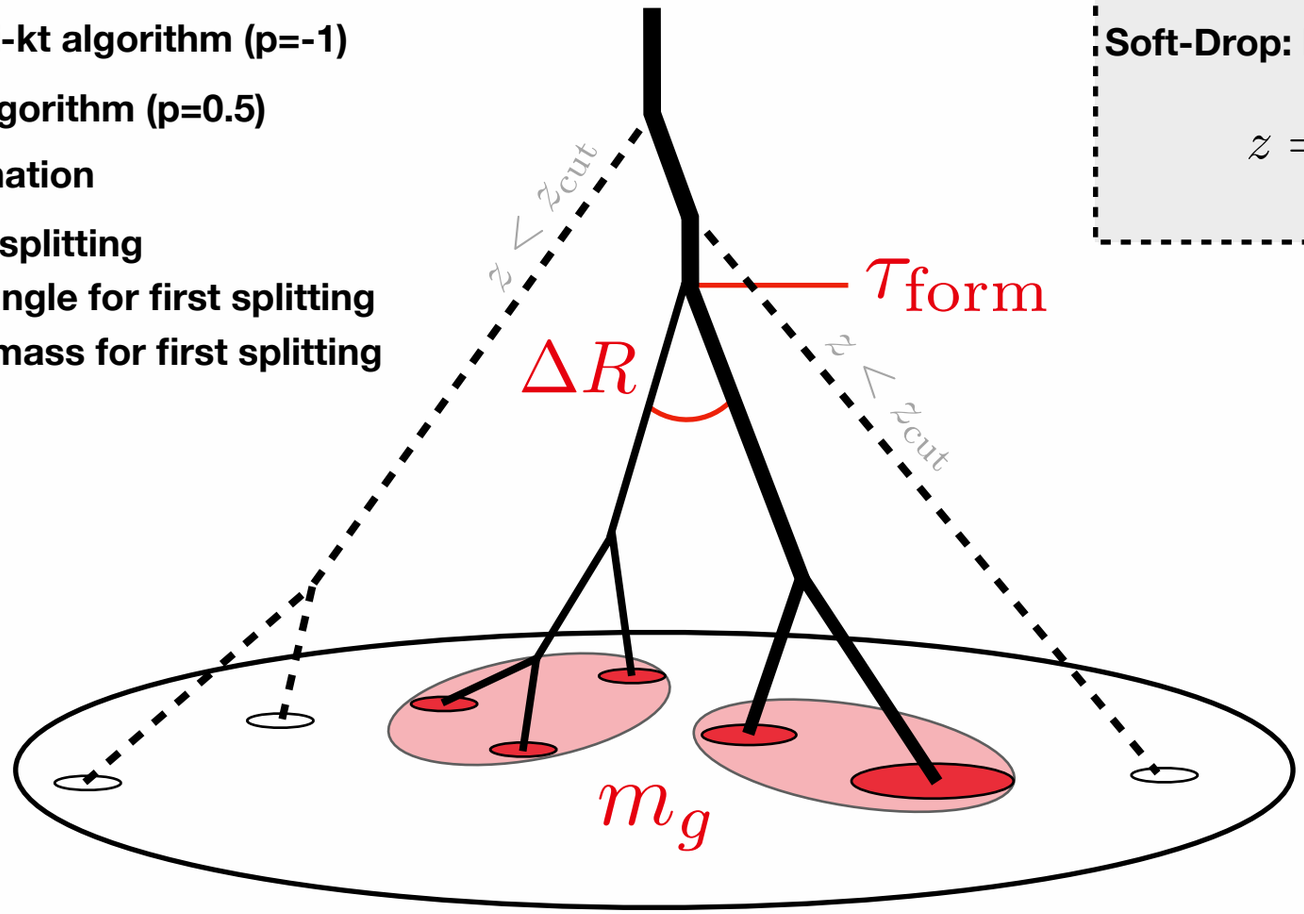

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We work with the groomed mass normalized by the (ungroomed) jet transverse momentum

$$\rho_g \equiv m_g / p_{T,j}$$

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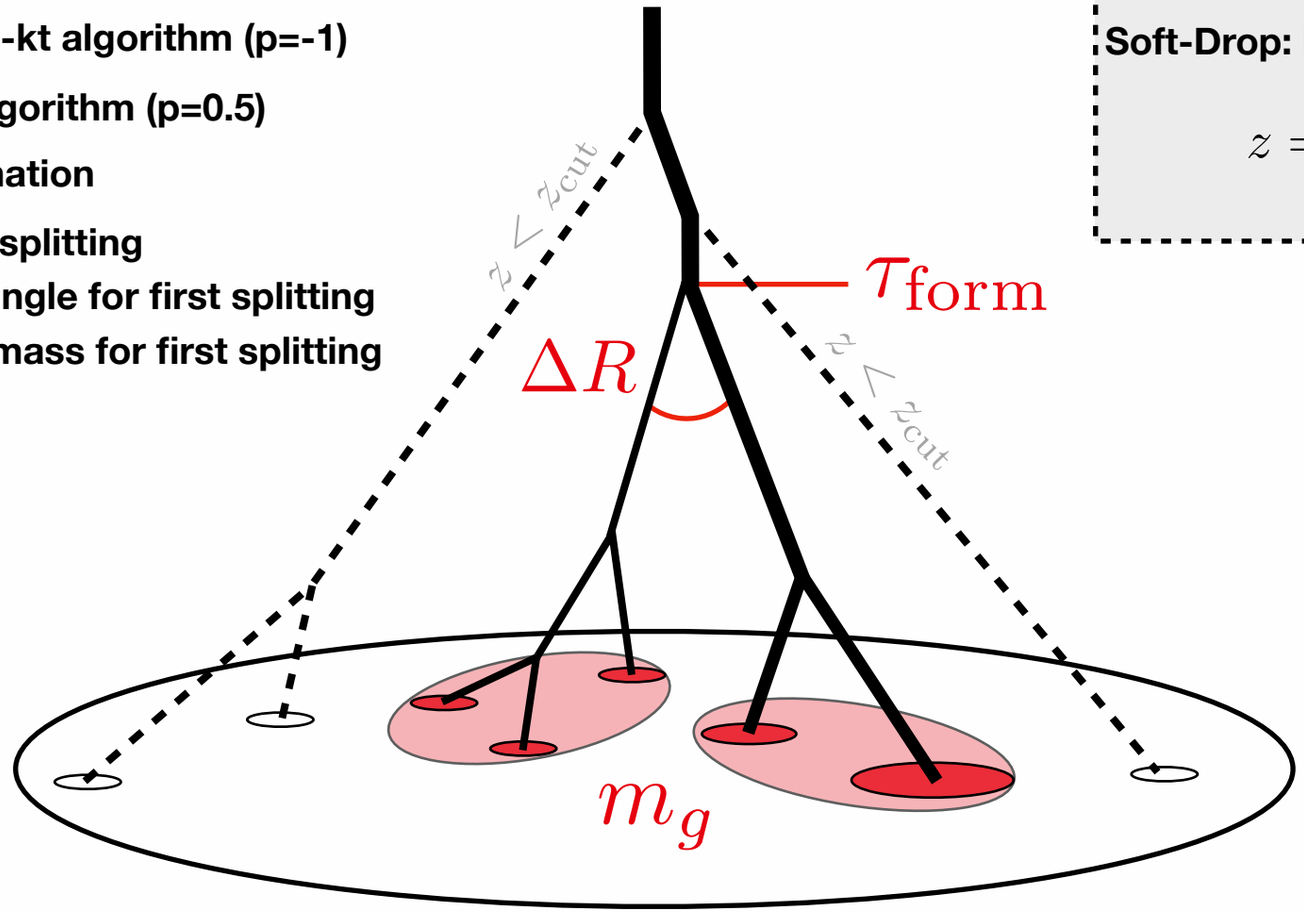

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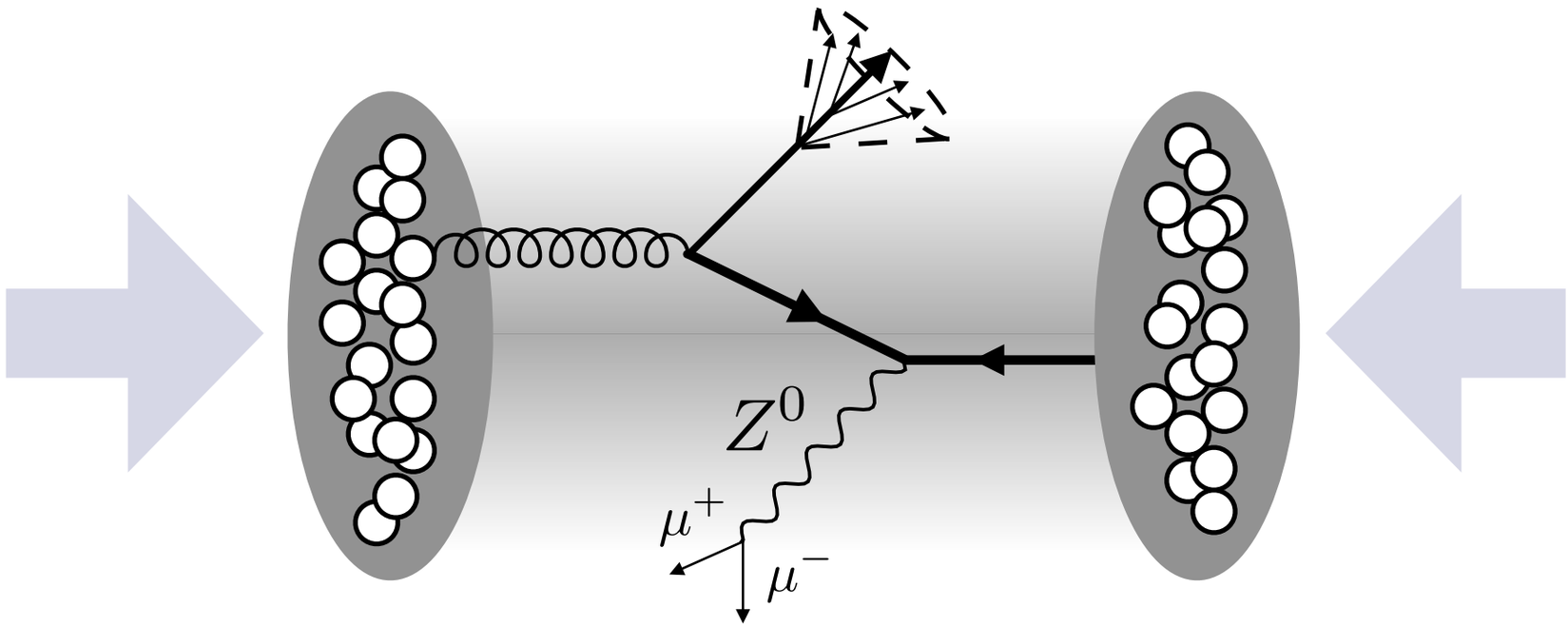
- *Are these variables related to energy loss in heavy ion collisions?*

Energy loss in an evolving QCD medium

- We focus on **Z-jet events**: a clean and well calibrated environment for energy loss studies
- The **momentum imbalance** $x_{jZ} = P_{j\perp}/P_{Z\perp}$ provides an estimate for the **energy loss** of the jet within the medium



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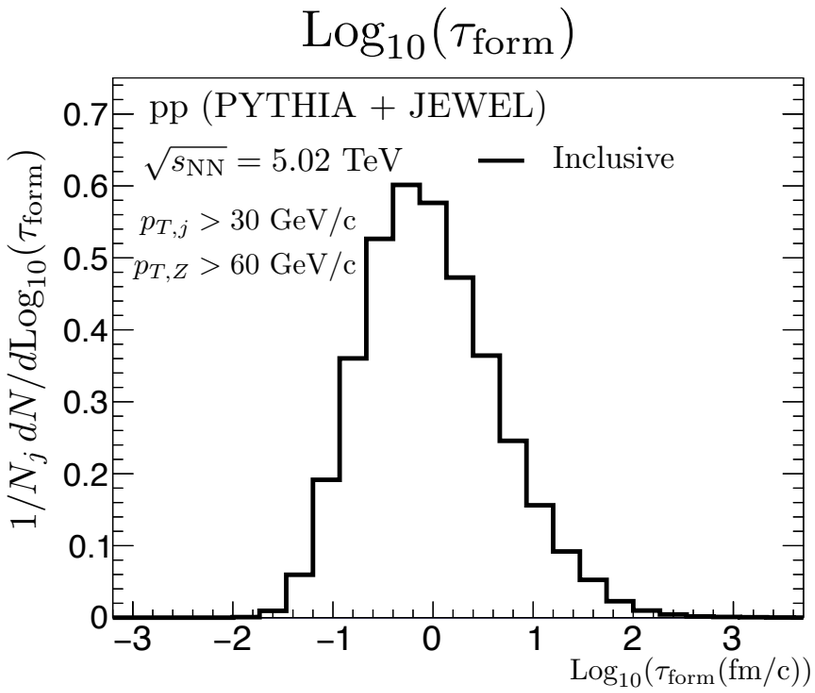

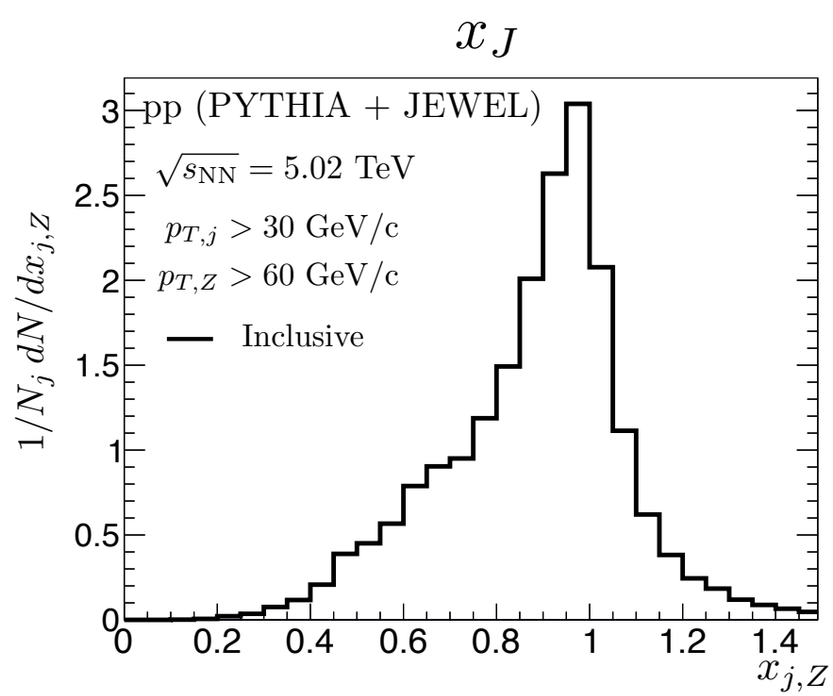

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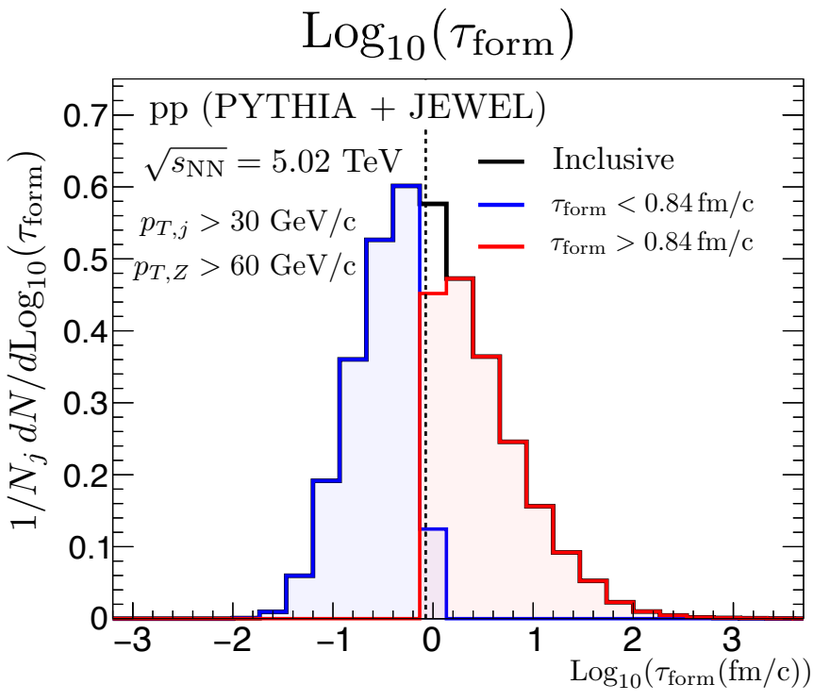

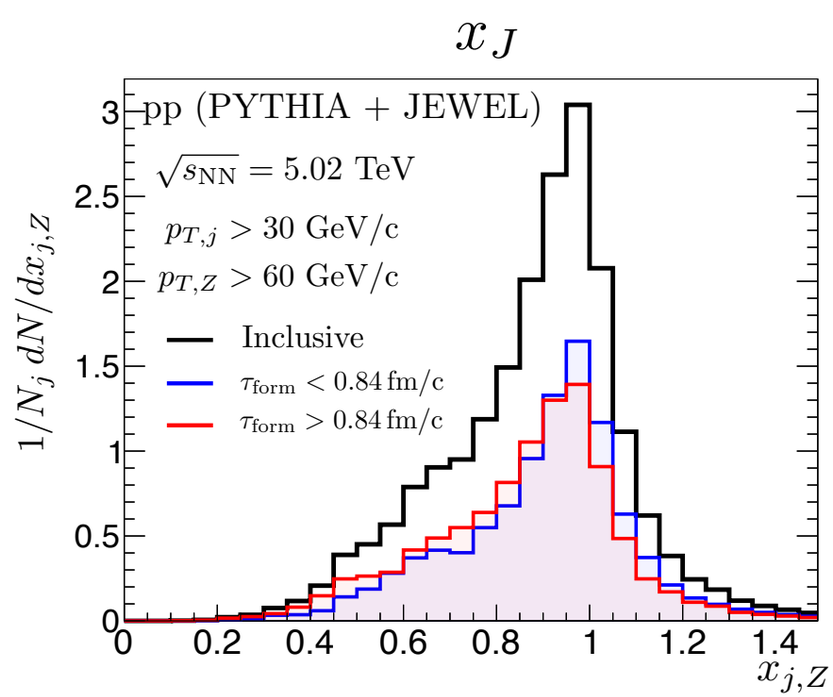

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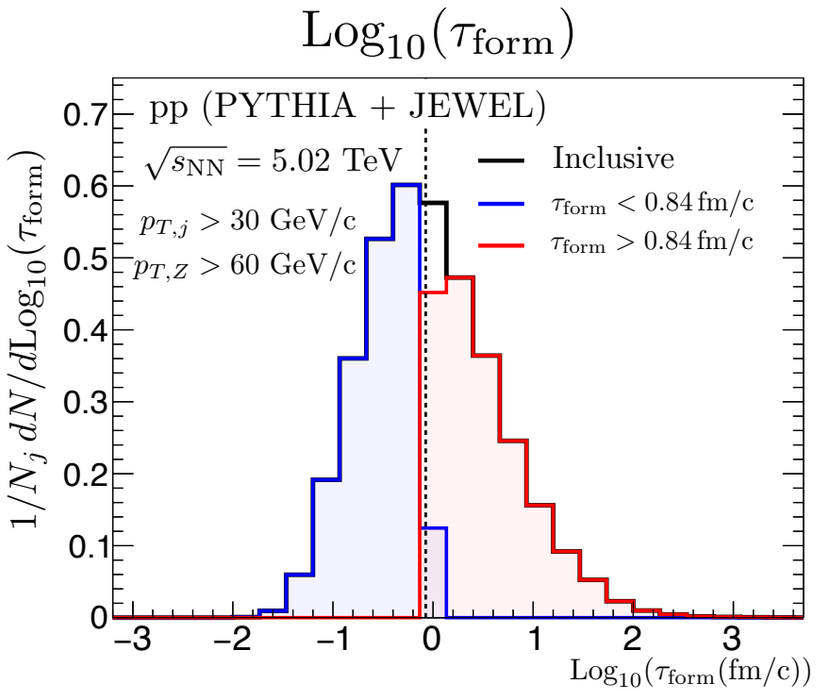
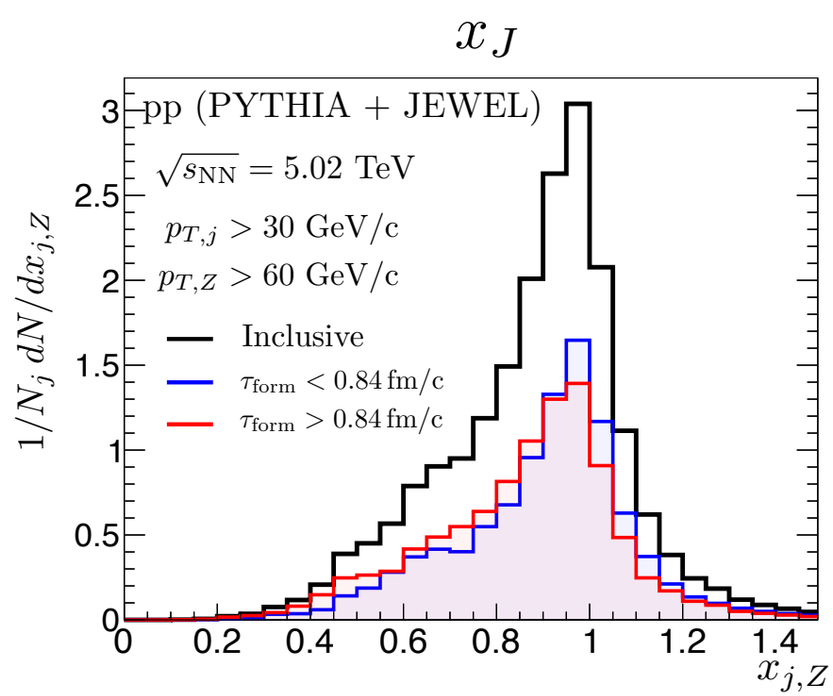
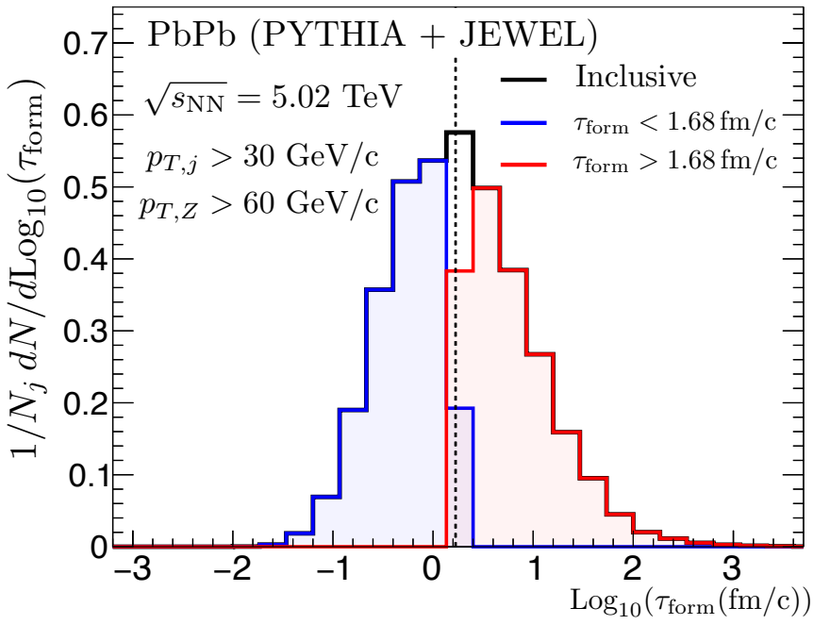
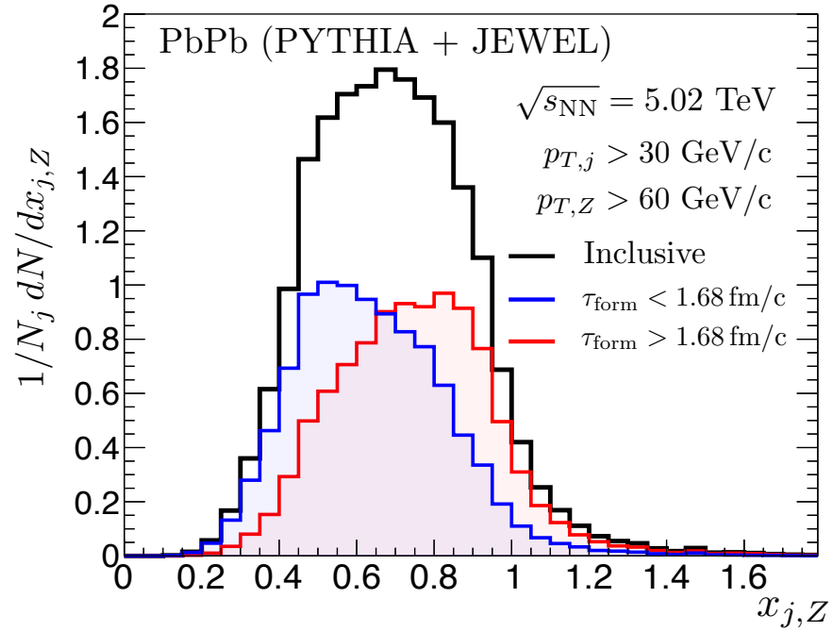




PbPb



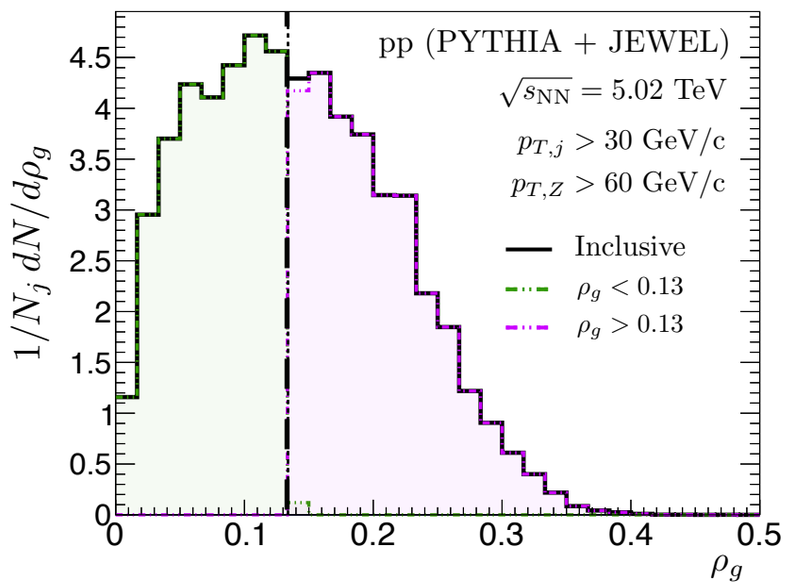


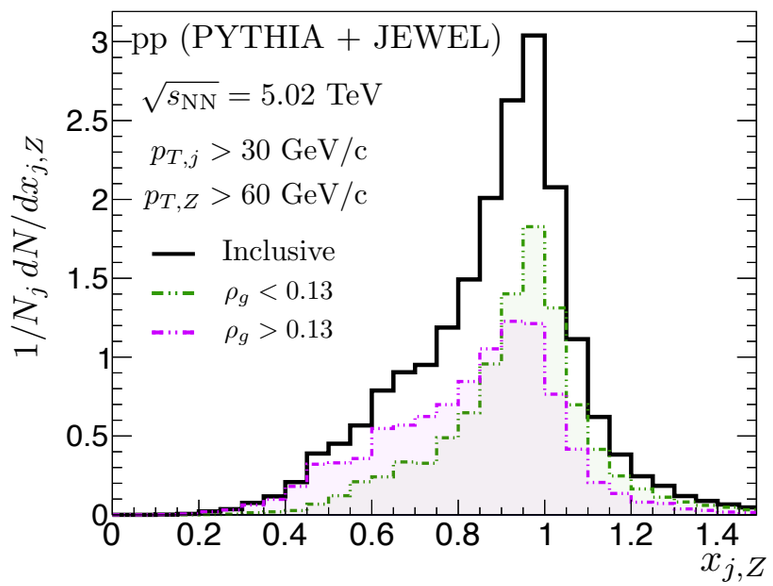
- Our early/late jet selection on τ_{form} allows to evaluate ΔE

Energy loss in an evolving QCD medium (revisited)

- We can repeat the exercise with almost identical results:

pp





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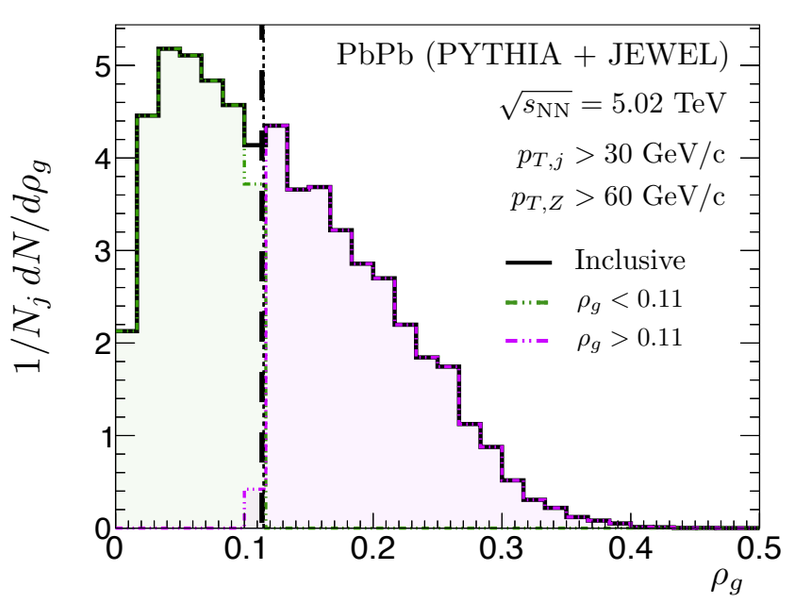

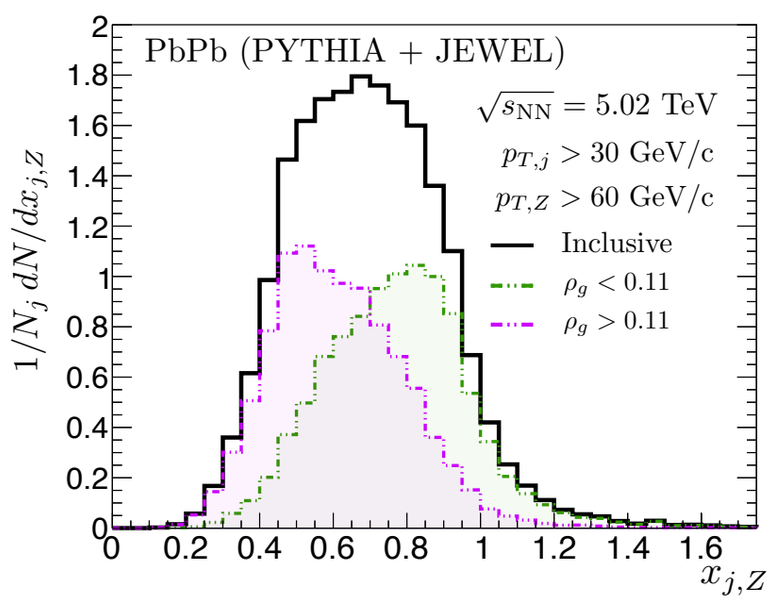

Energy loss in an evolving QCD medium (revisited)

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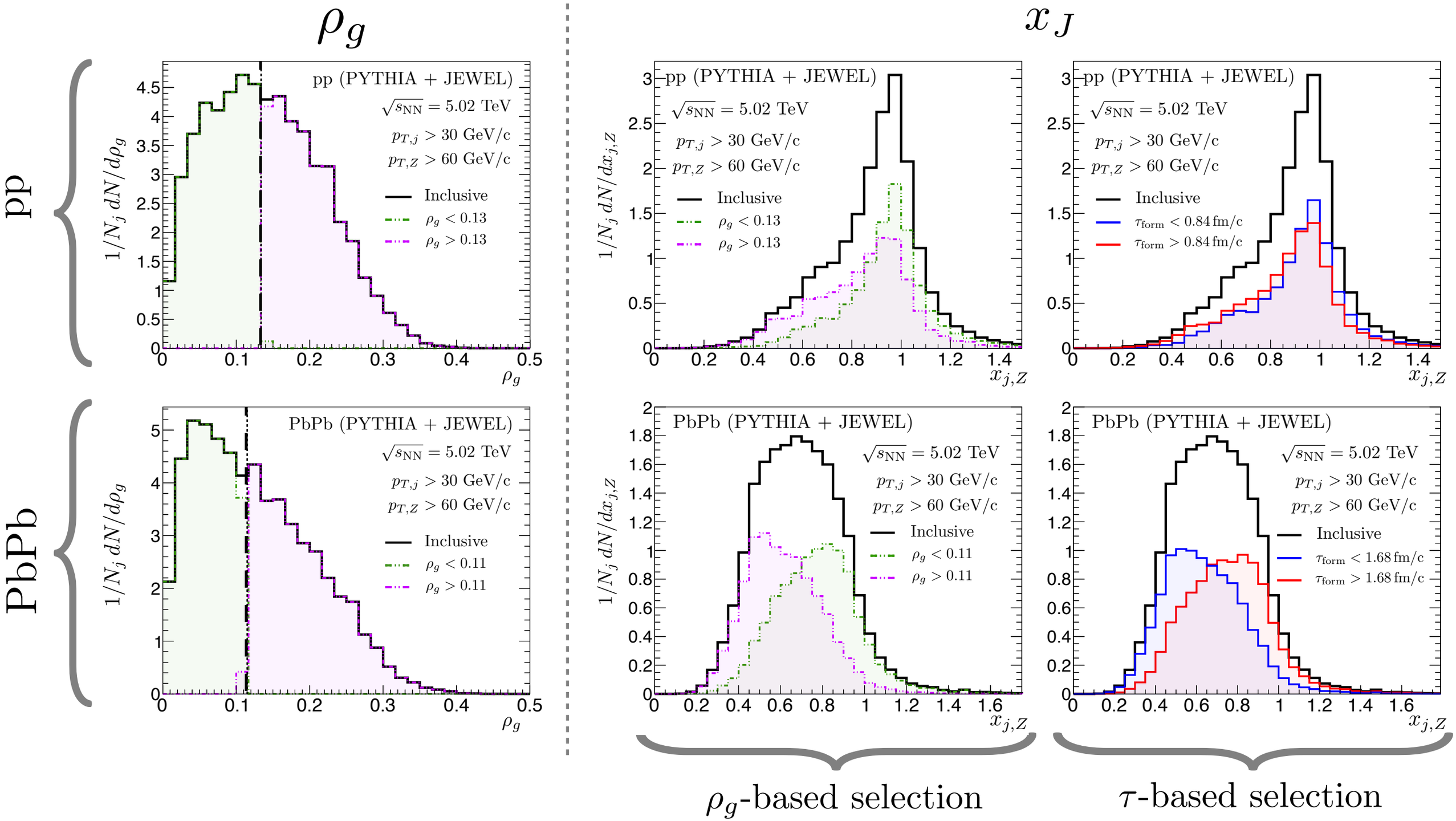

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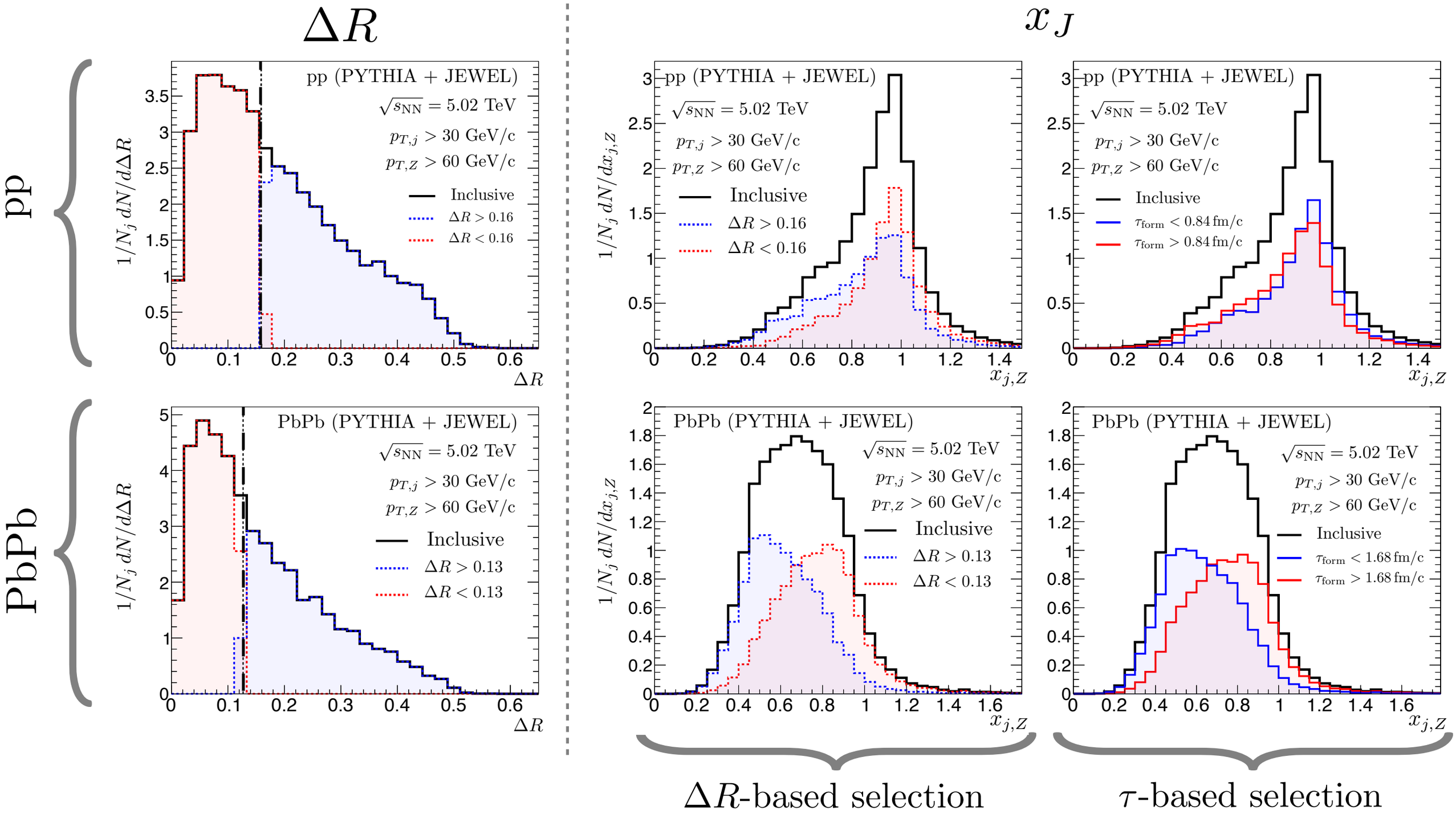
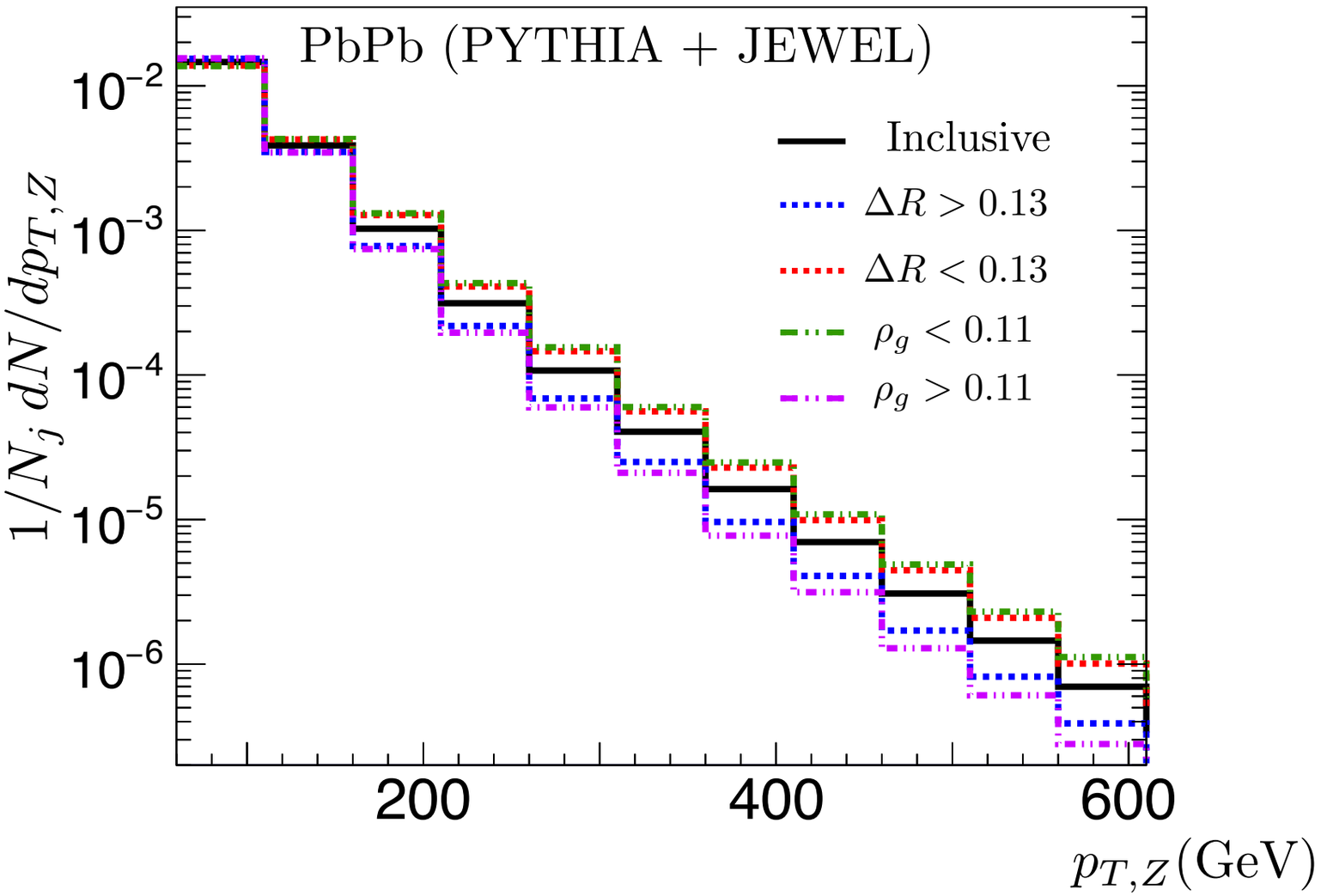


- *Same jet selection as with $\tau_{\rm form}$?*

Bias comparison

- Selecting in terms of τ_{form} minimizes the distorsion of the initial p_t spectra of our samples
- **This is essential to compute ΔE!**



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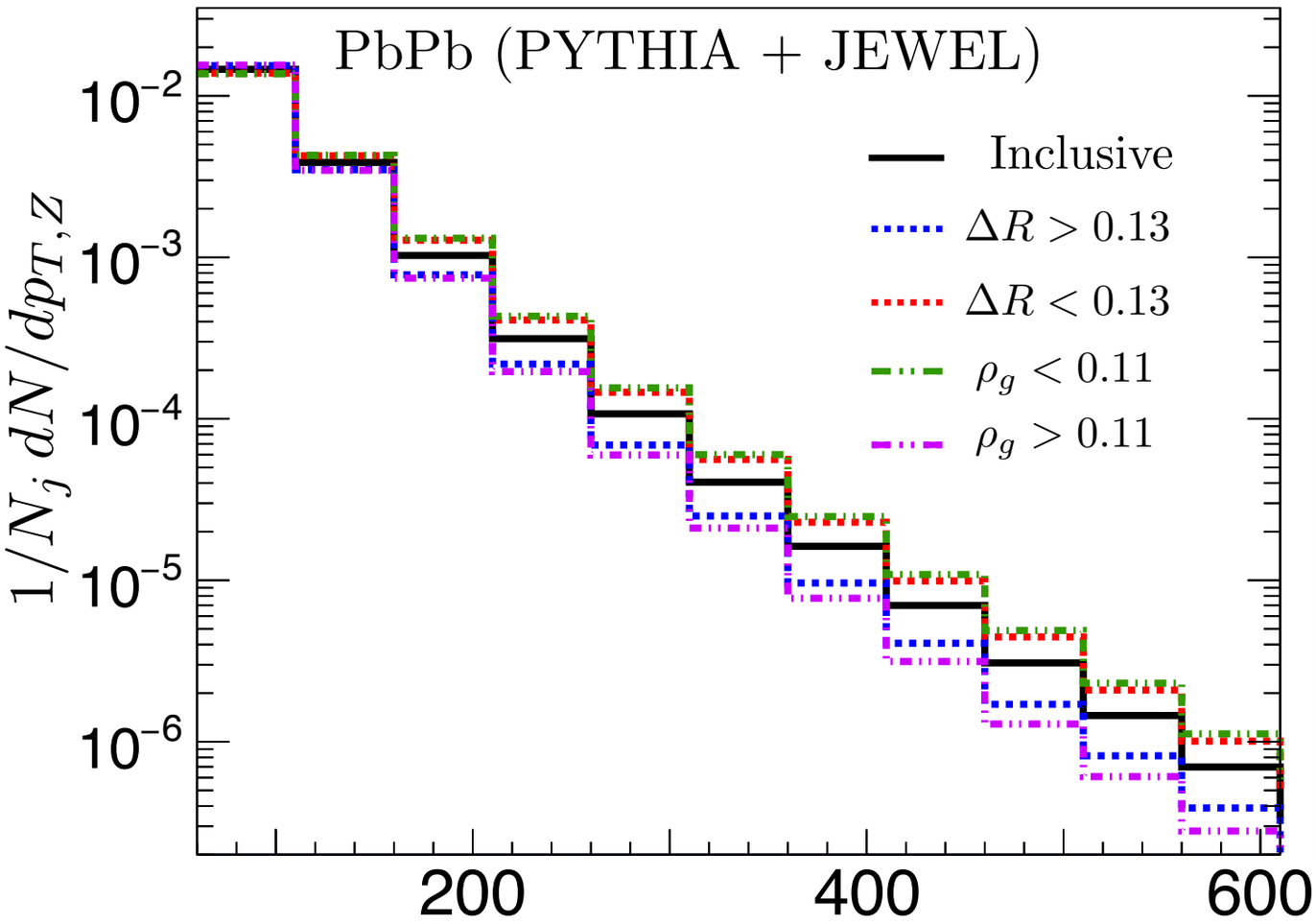
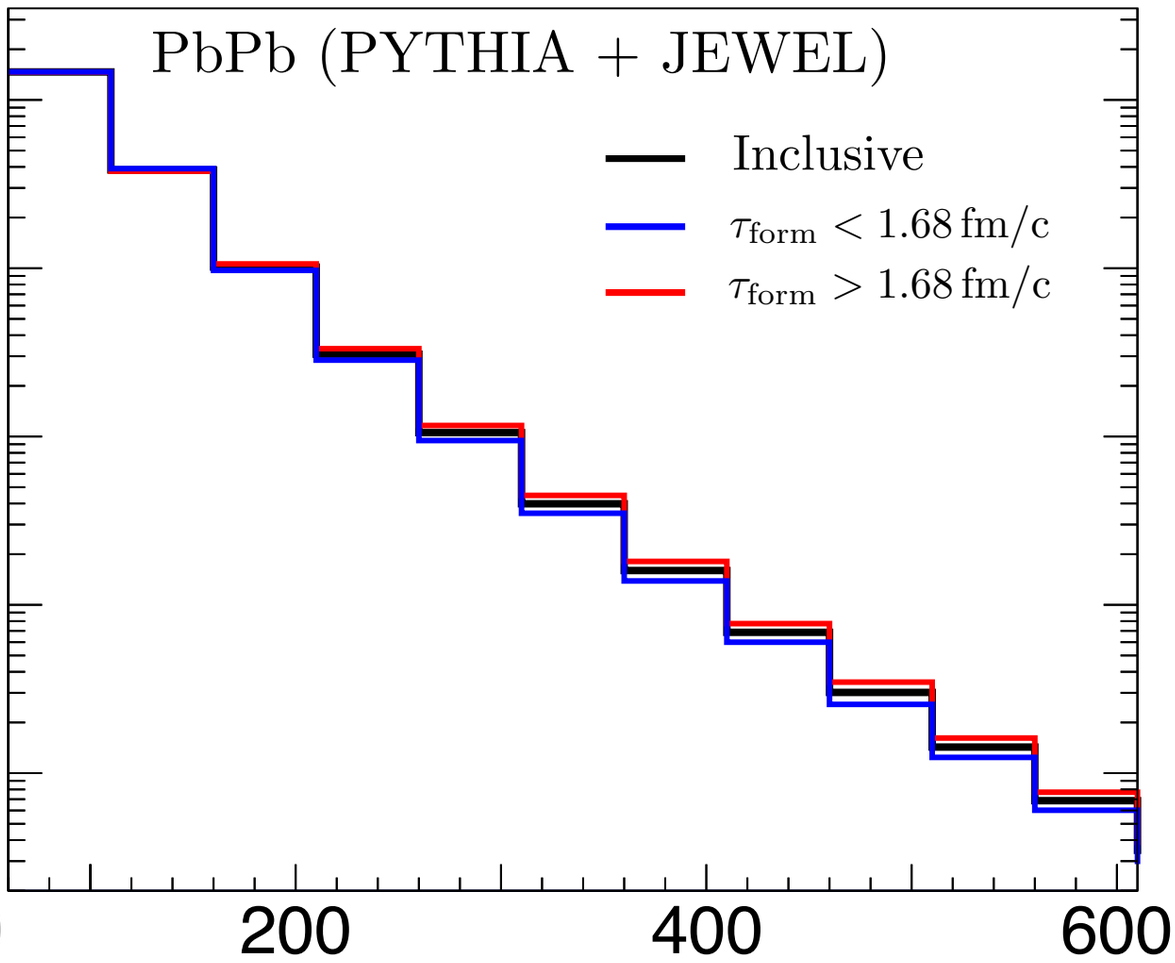
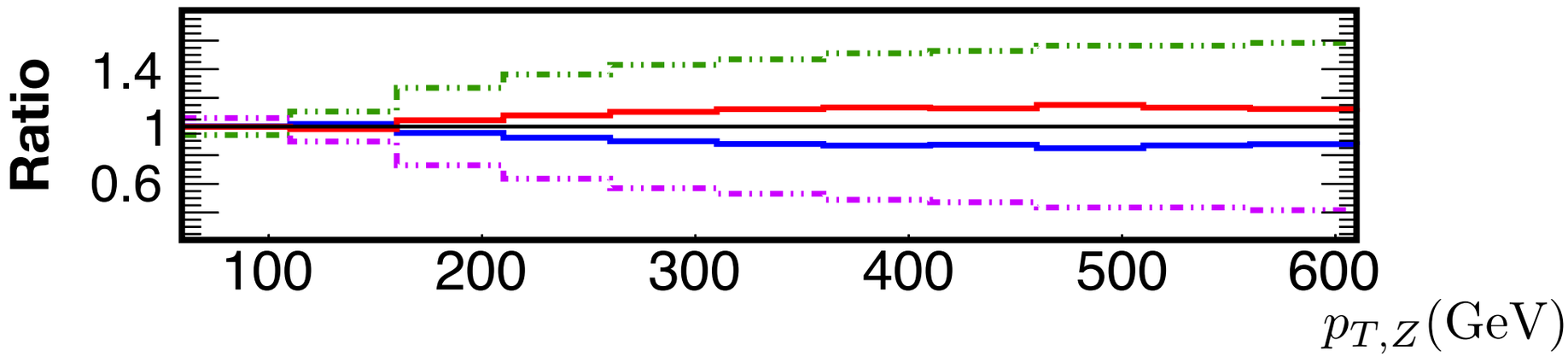
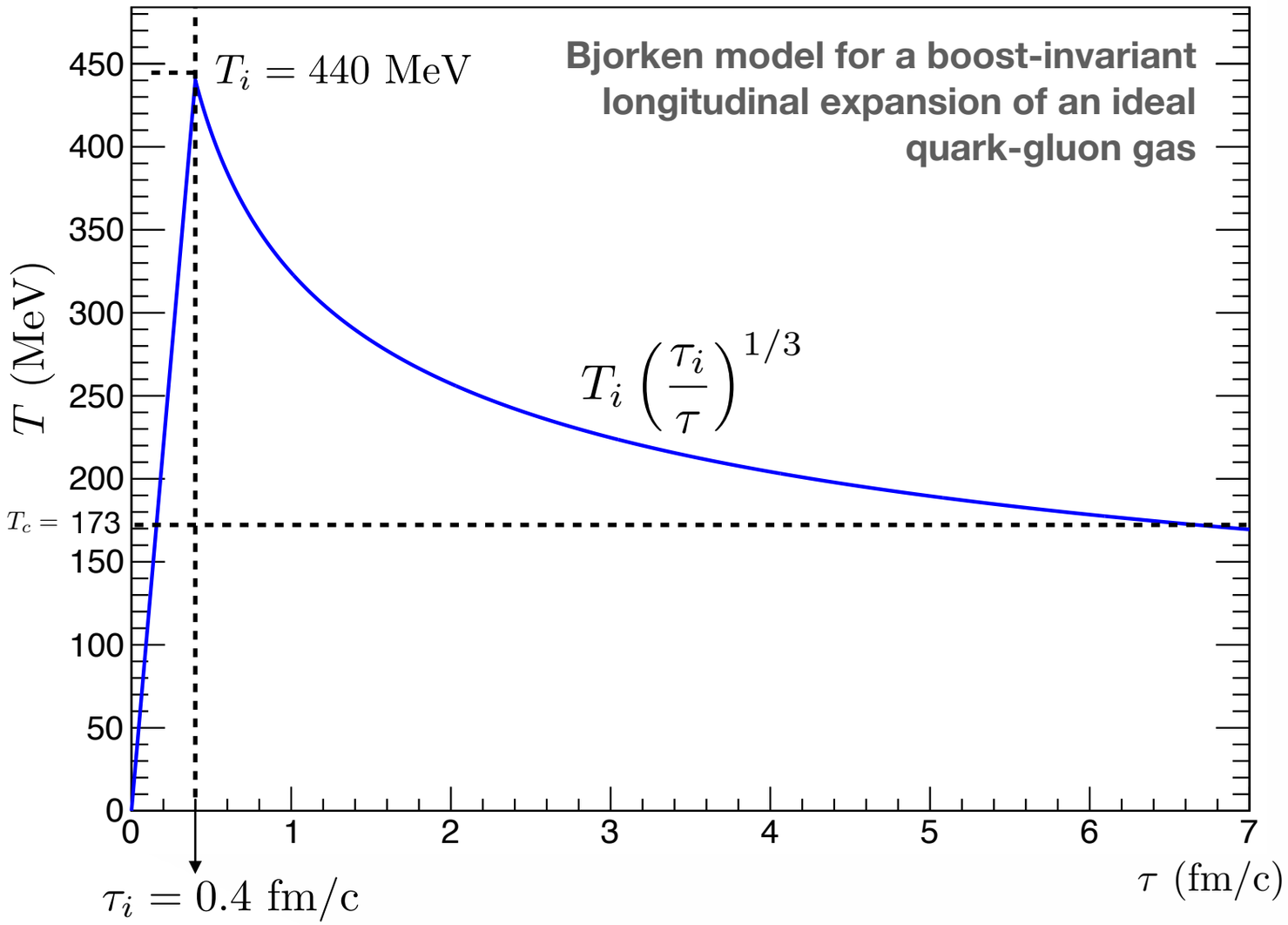






QGP Tomography

- *So, finally: can we use jets to access the time structure of the Quark Gluon Plasma?*
  - ➡ The medium simulated in JEWEL looks like this:



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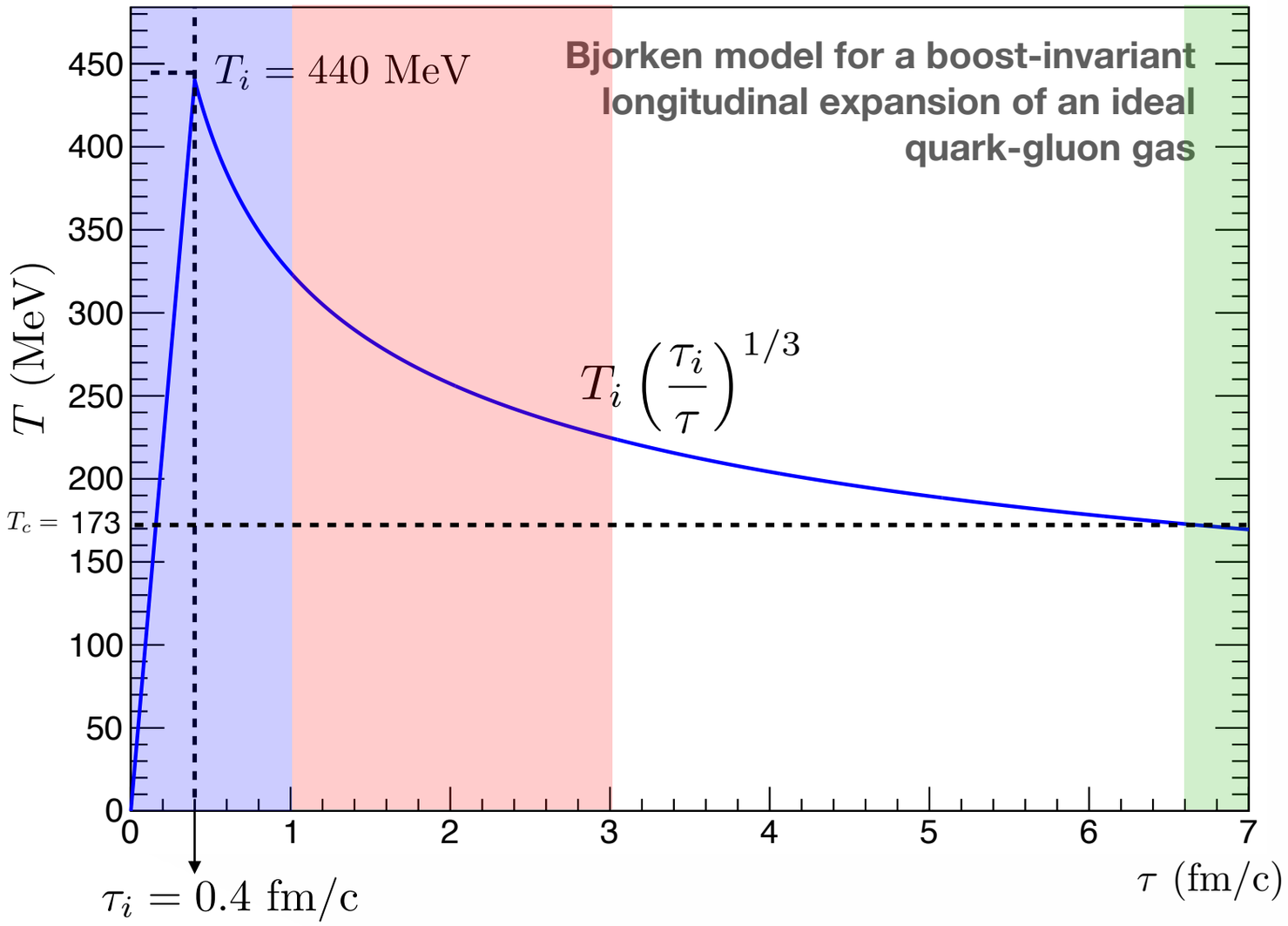

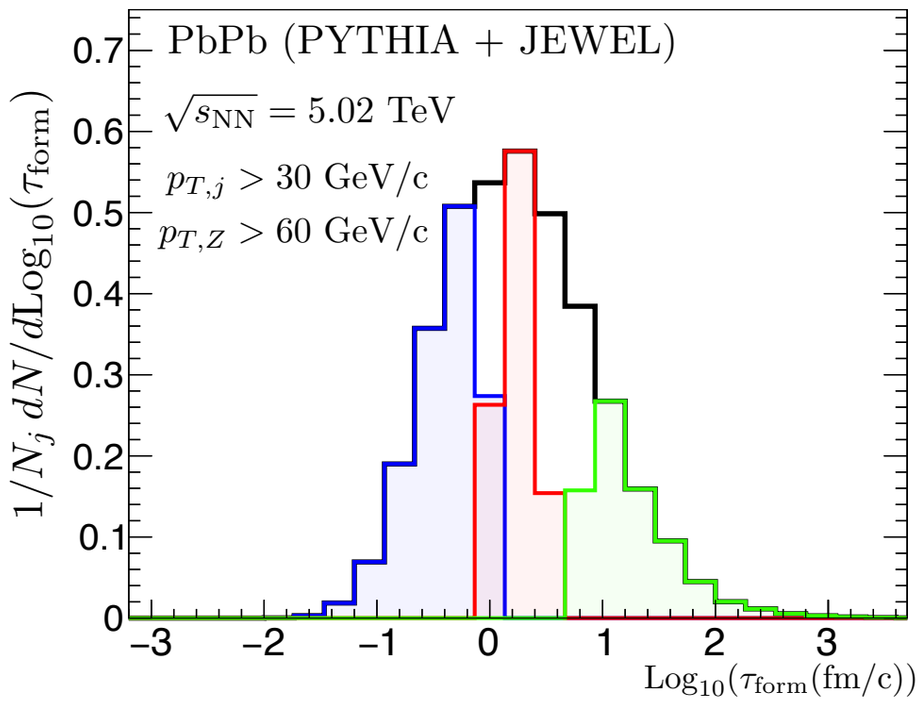

➡ Let us define the following evolution stages:

- **Pre-equilibrium/Early stage** $(\tau < 1$ fm/c$)$
- **QGP expansion** $(1 < \tau < 3$ fm/c$)$
- **Vacuum** $(\tau > 6.6$ fm/c$)$

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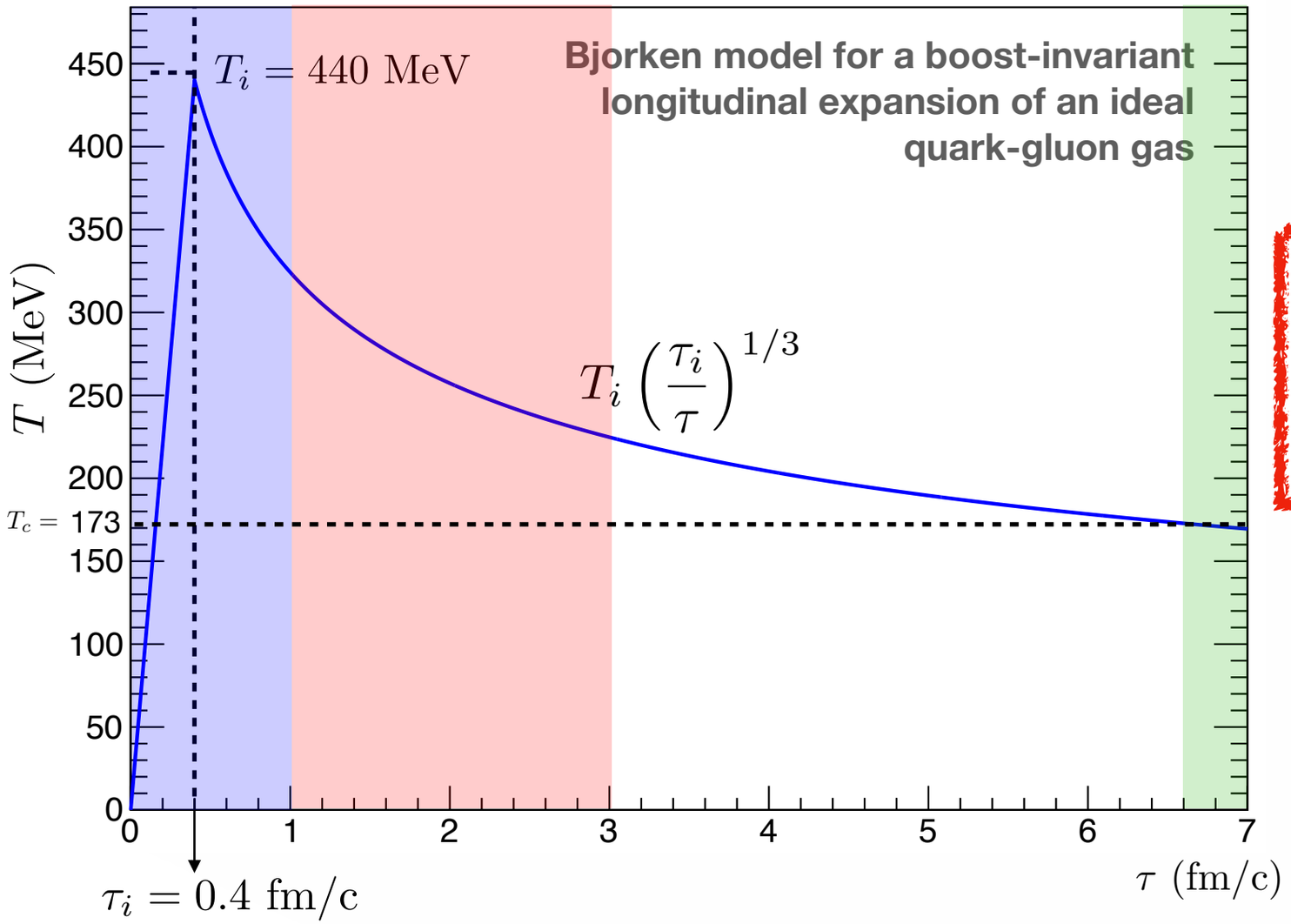
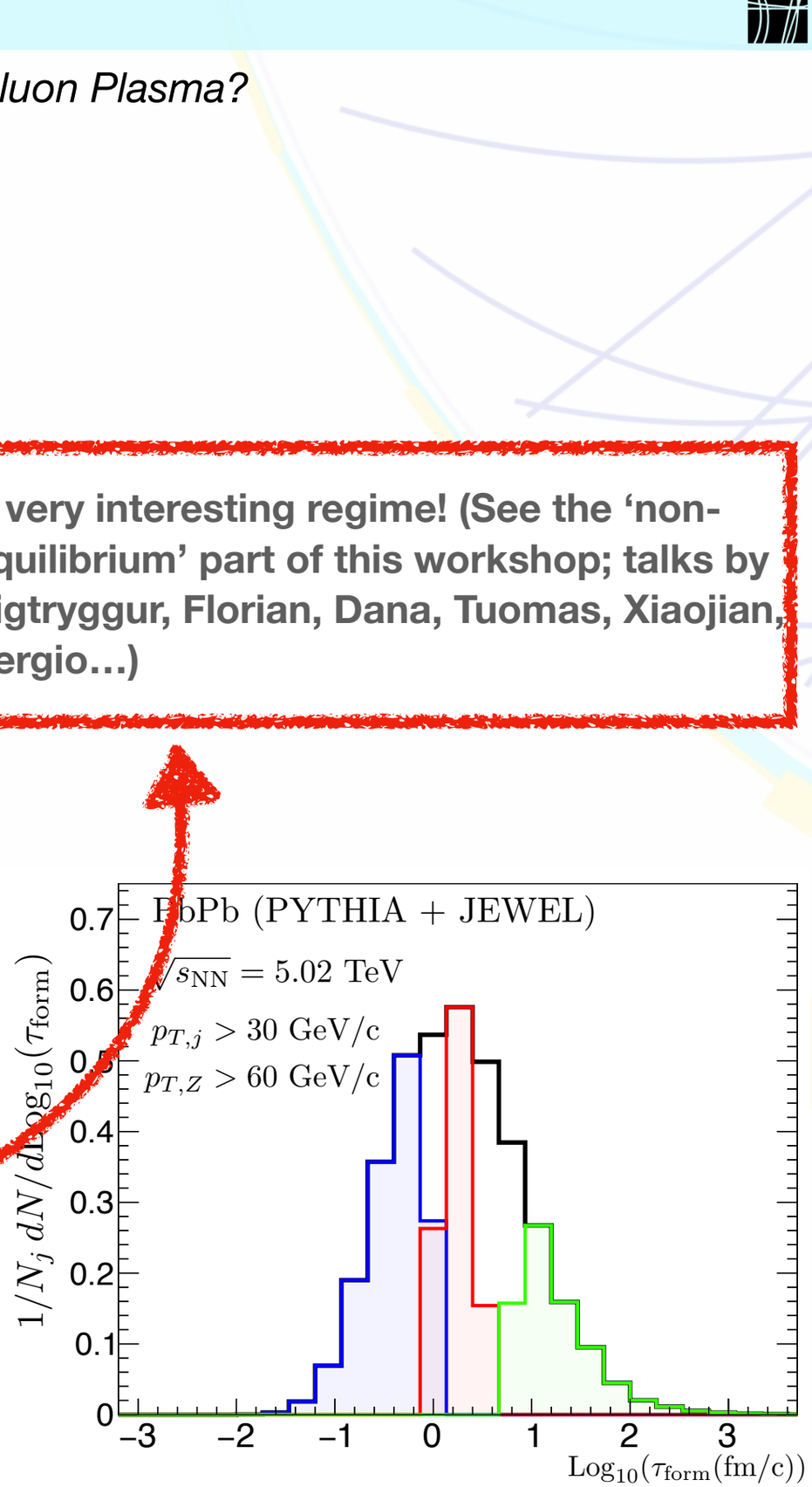


A very interesting regime! (See the 'non-equilibrium' part of this workshop; talks by Sigtryggur, Florian, Dana, Tuomas, Xiaojian, Sergio…)



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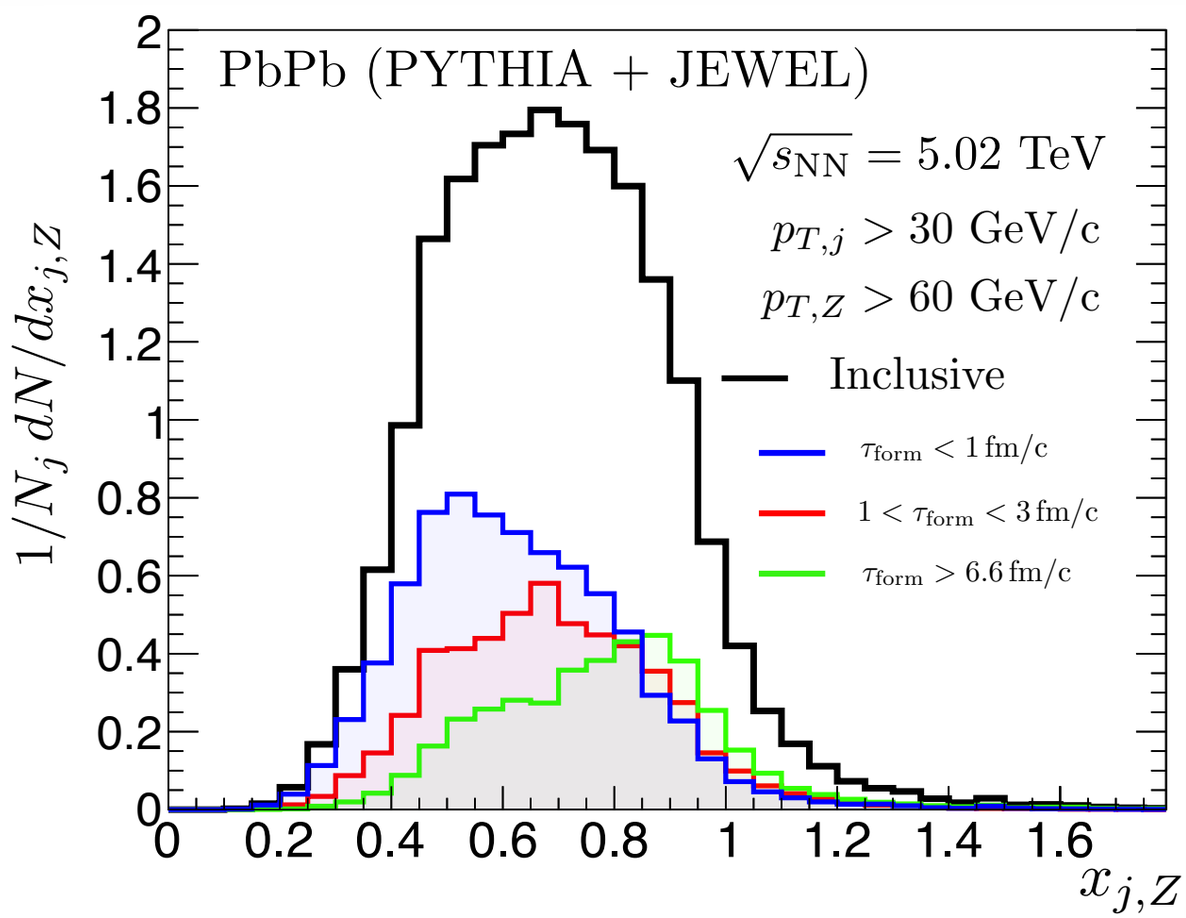
QGP Tomography

➡ We obtain the following results for the x_{jZ} distributions:



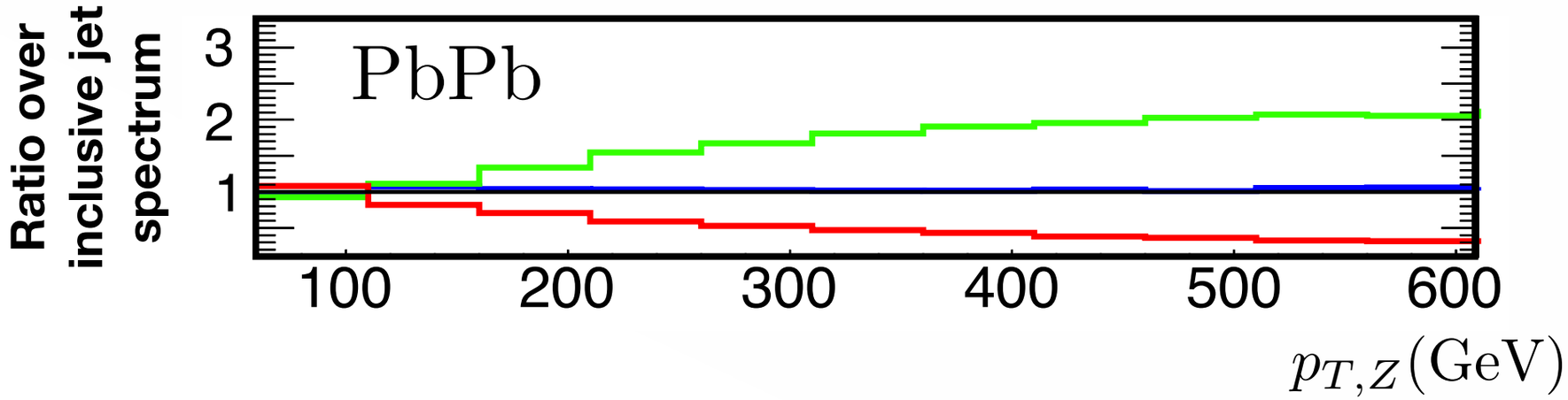
Mean values:

$\bar{x}_j \sim 0.6$

$\bar{x}_j \sim 0.7$

$\bar{x}_j \sim 0.8$

➡ With the corresponding ratios over the inclusive $p_{T,Z}$ distributions:



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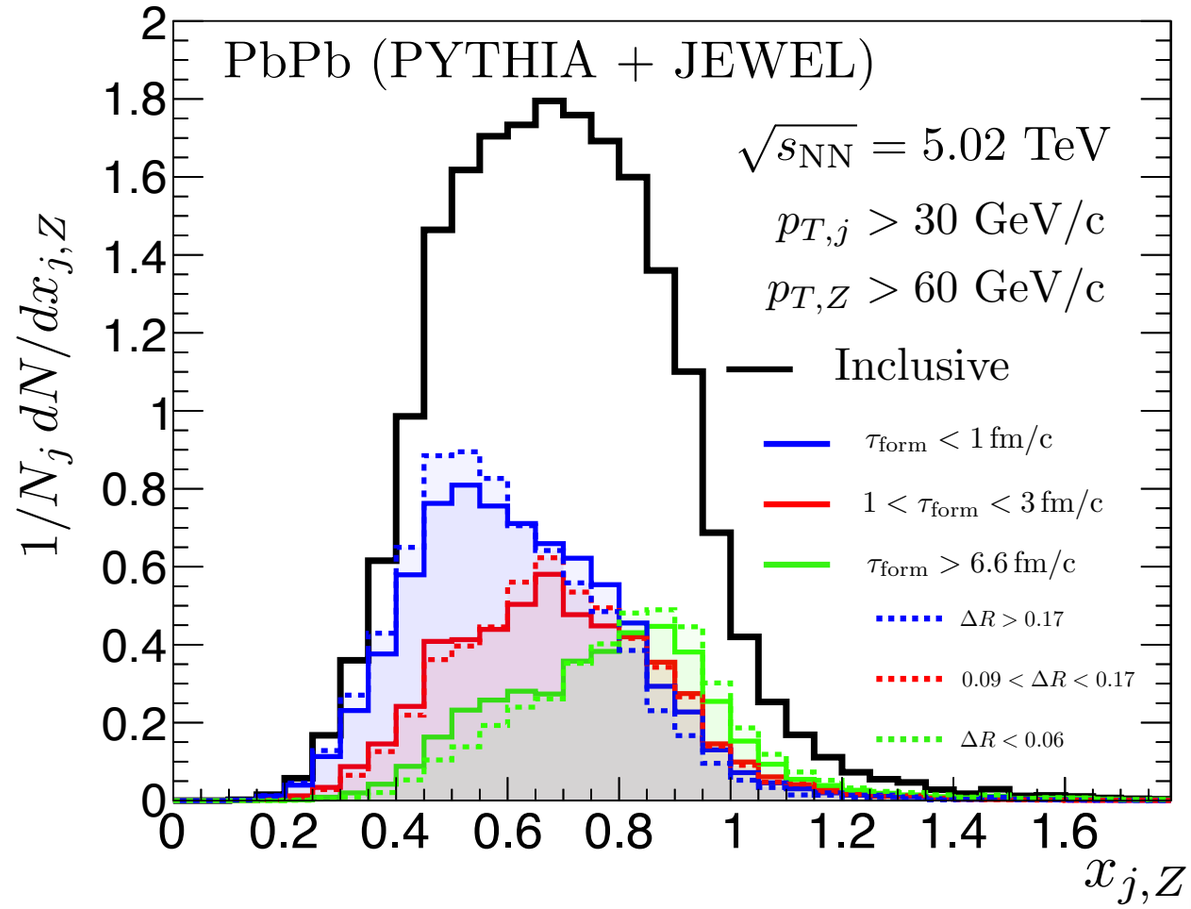

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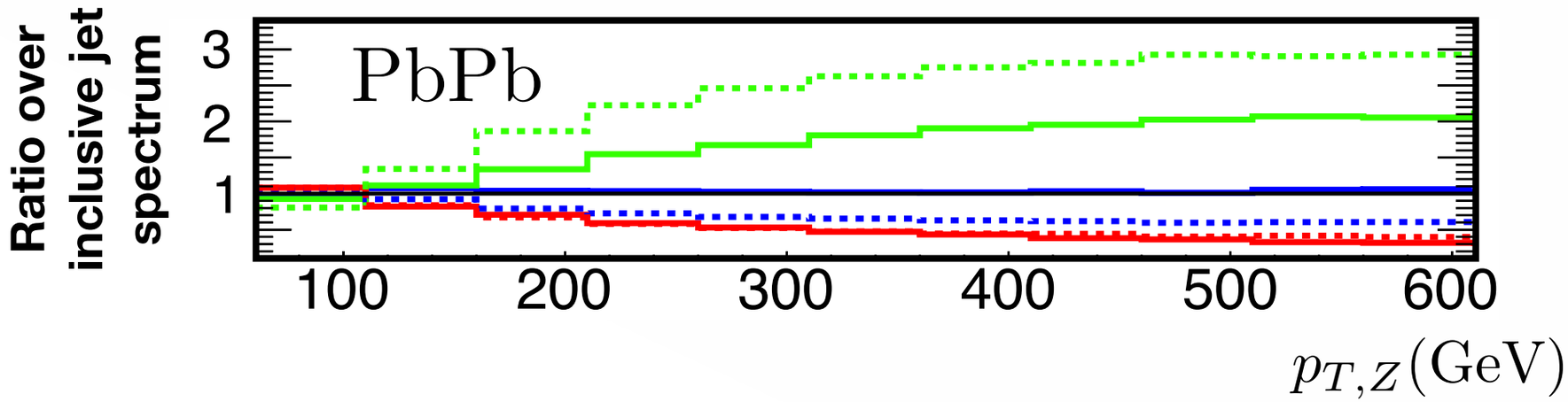
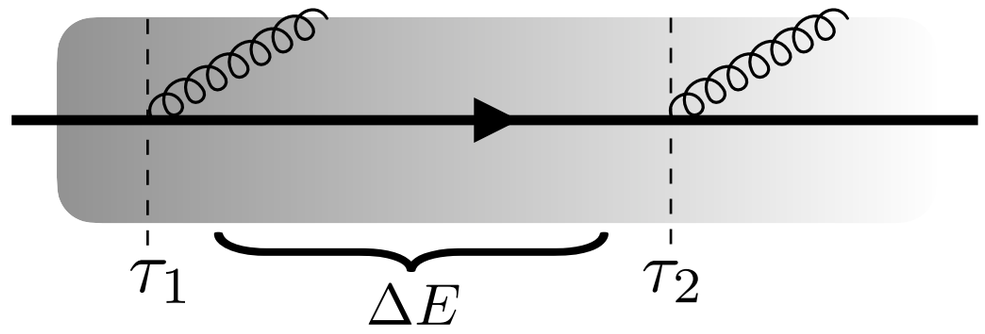


Second splitting

- *Can we use subsequent splittings of the shower to make differential measurements?*

➡ Necessary in order to relate energy loss to path length within the medium



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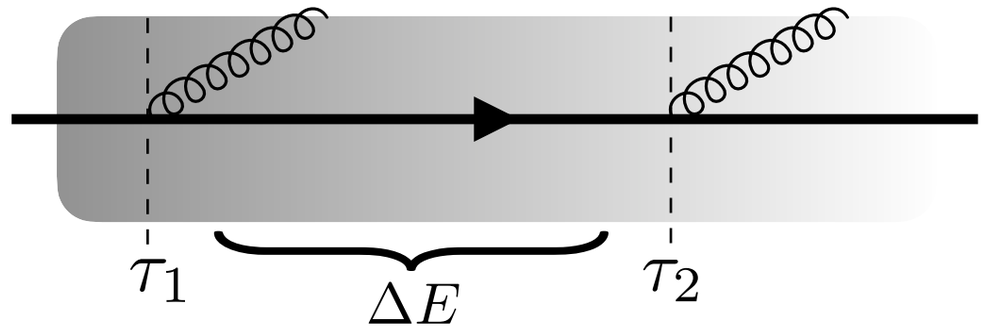
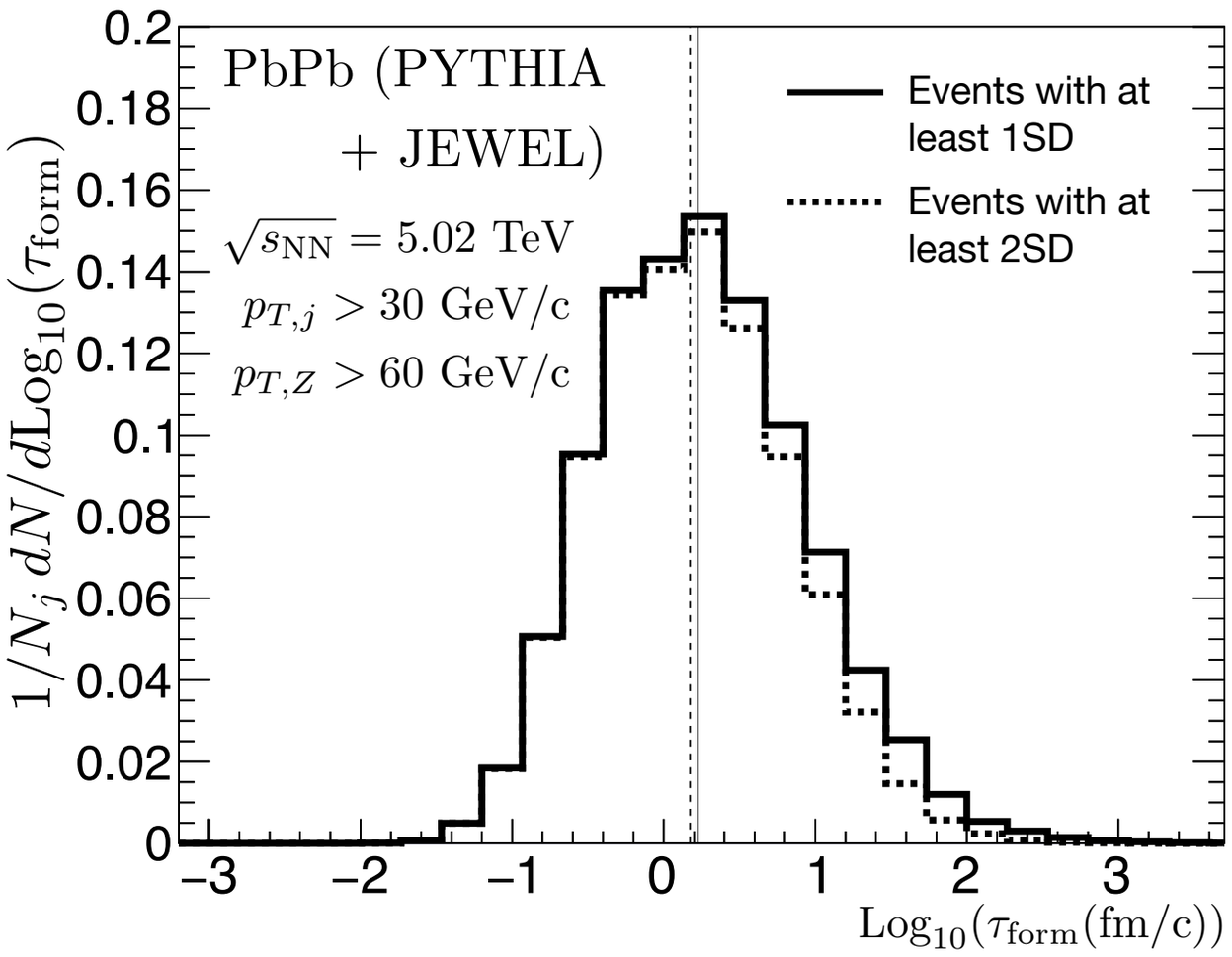
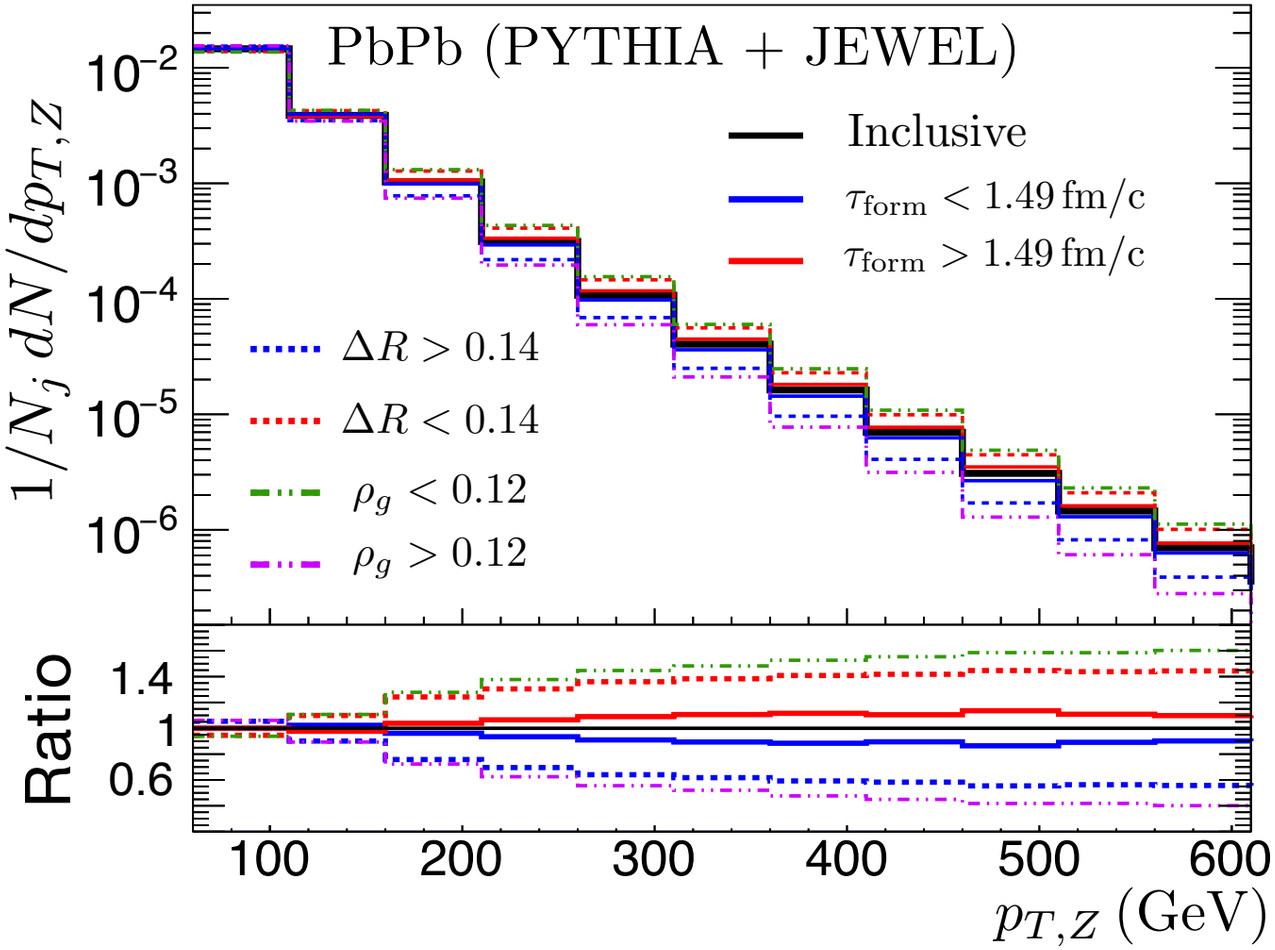


➡ Demanding at least two SD-approved emissions: **we bias our sample towards jets that fragment more**





Summary, future prospects

- We use the tau-algorithm to extract the formation time corresponding to the first splitting of the parton showers
- This information allows to classify jets according to sensitivity to medium interactions
- We checked that $\tau_{\rm form}(p_{T,i}, \Delta E)$ (unlike $\Delta R(p_{T,i}, \Delta E)$ or $\rho_g(p_{T,i}, \Delta E)$)

arXiv:2401.14229

- To-do list:
  - ➡ Include medium response (JEWEL 2.4.0 available!)
  - ➡ Check performance of $\tau_{\rm form}$ -based binning with other jet substructure observables (for example, z_g, jet radial profile, etc.)
  - ➡ Can we make the association $\tau_{\rm form} \longrightarrow \tau_{\rm medium}$?
  - ➡ Can we use subsequent splittings of the shower to estimate differential properties?
  - ➡ ...

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  - ➡ ...

Thank you for your attention

LIP

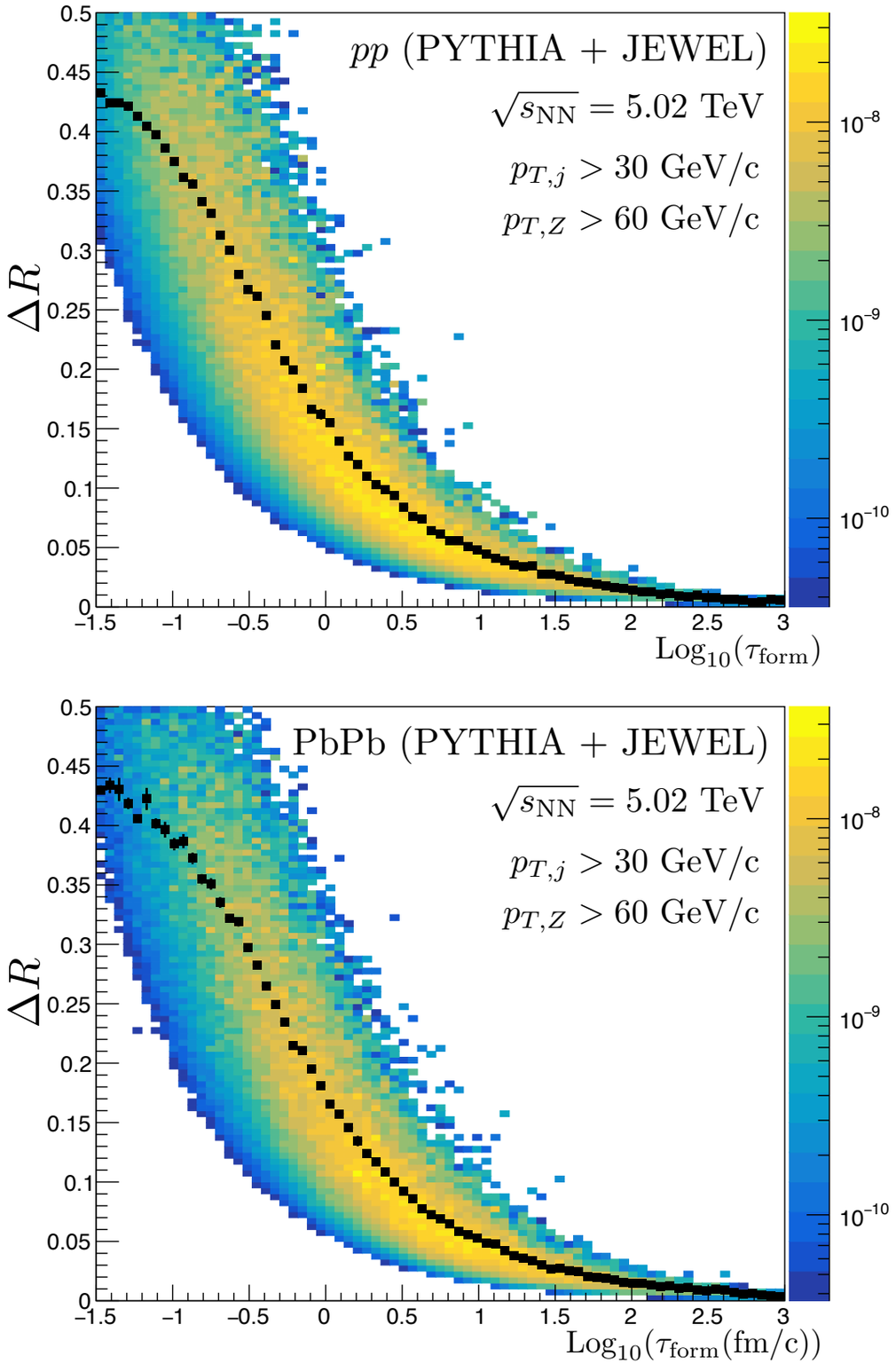
fct Fundação para a Ciência e a Tecnologia

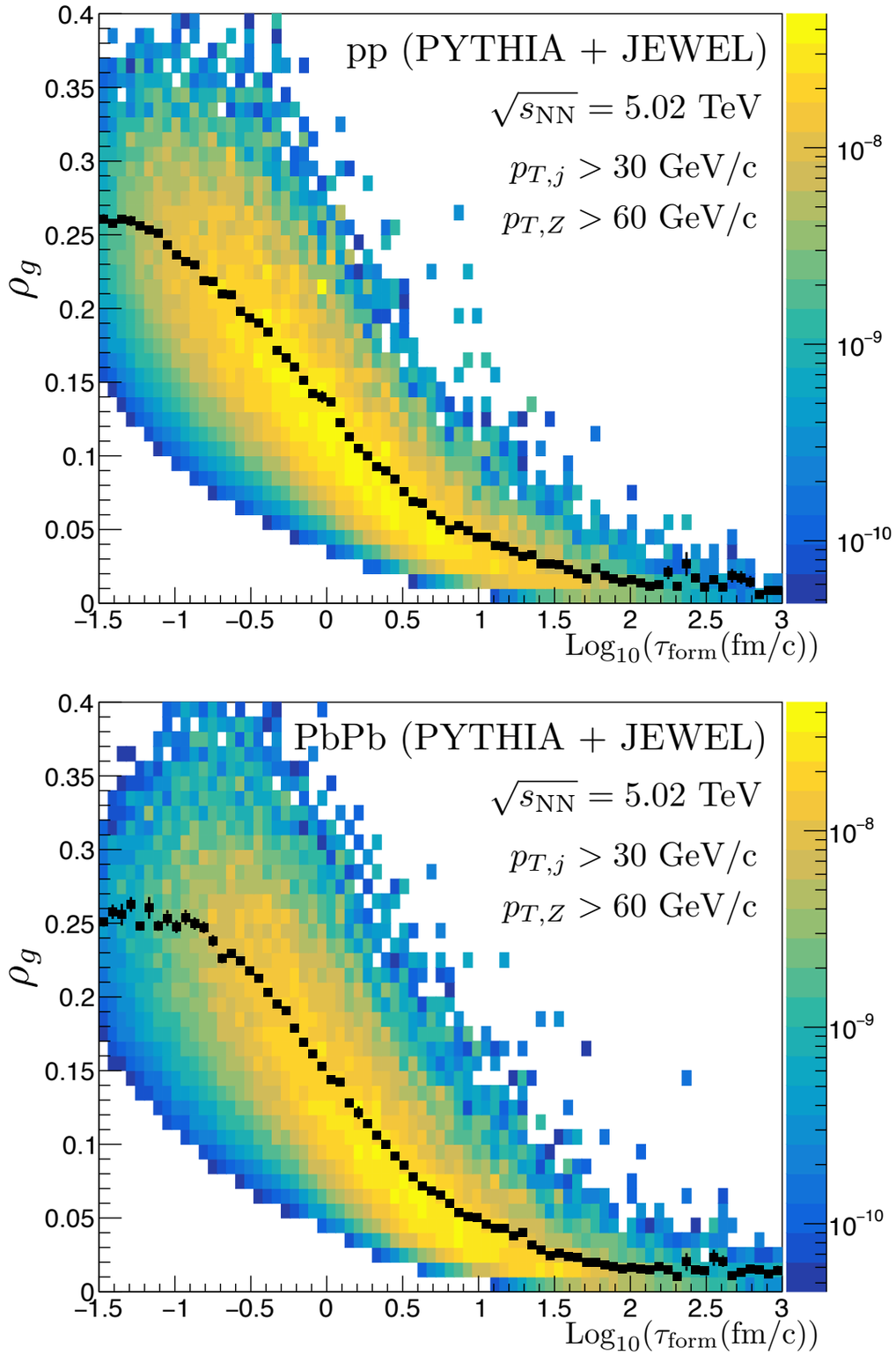
STRONG 2020

erc European Research Council Established by the European Commission

Back-up: Correlations

- The following correlations are observed in our datasets:

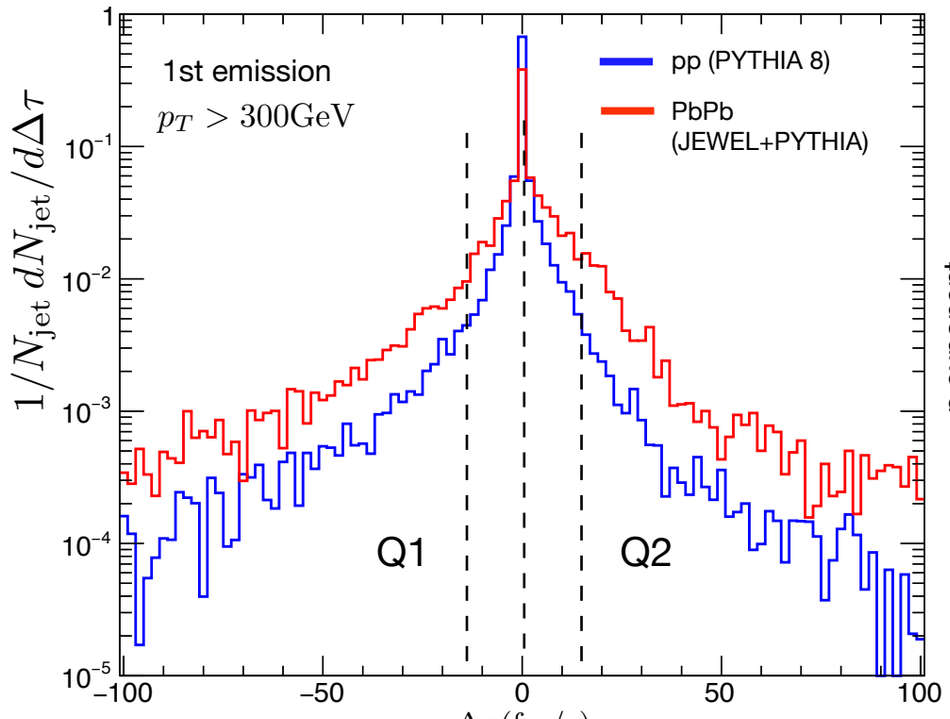


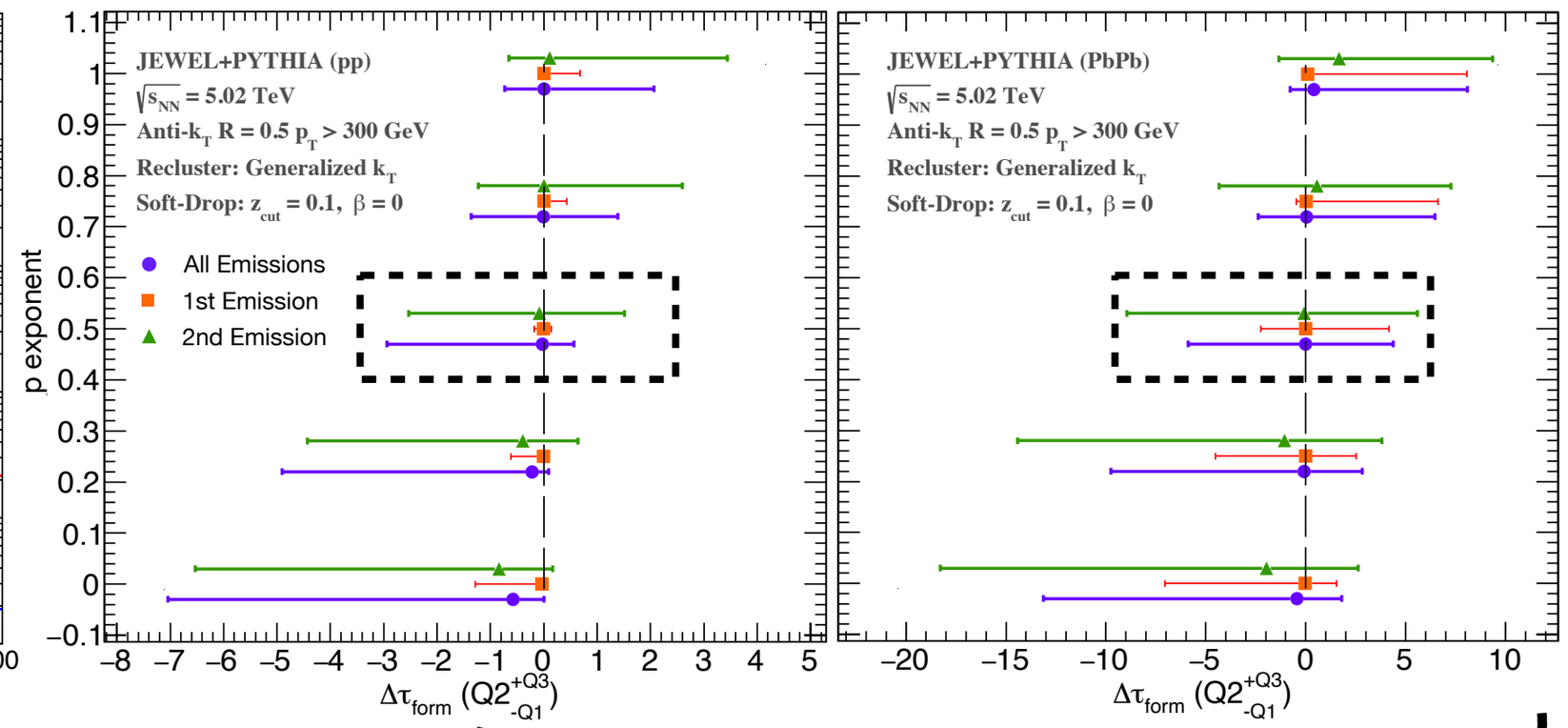


Back-up: Effectiveness of proxy

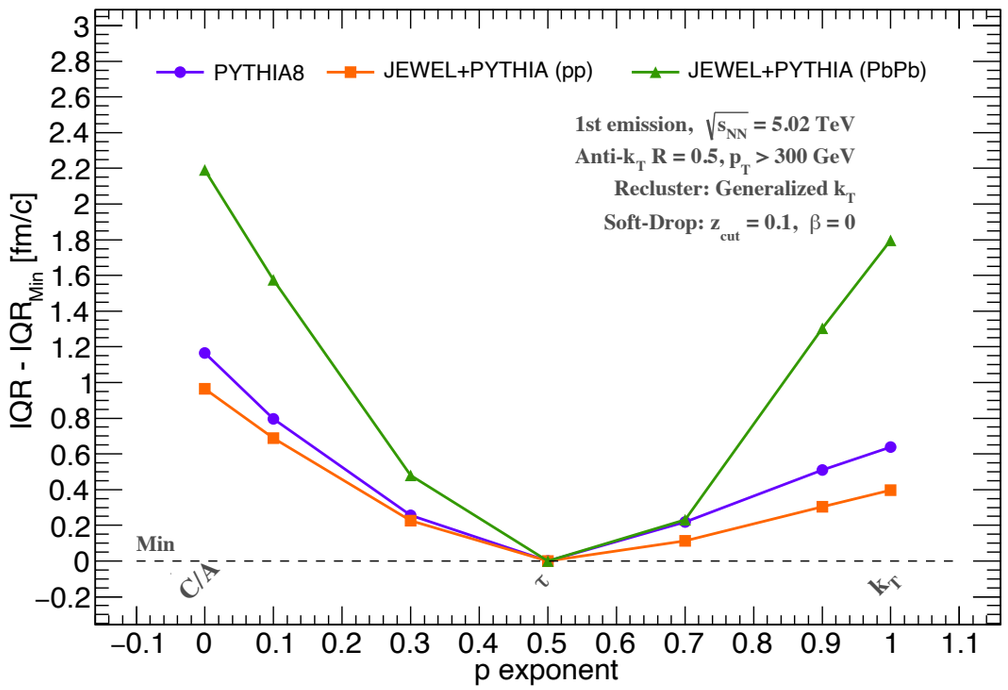
L. Apolinário, A.Cordeiro, K. Zapp, Eur. Phys. J. C 81 (2021) 6, 561

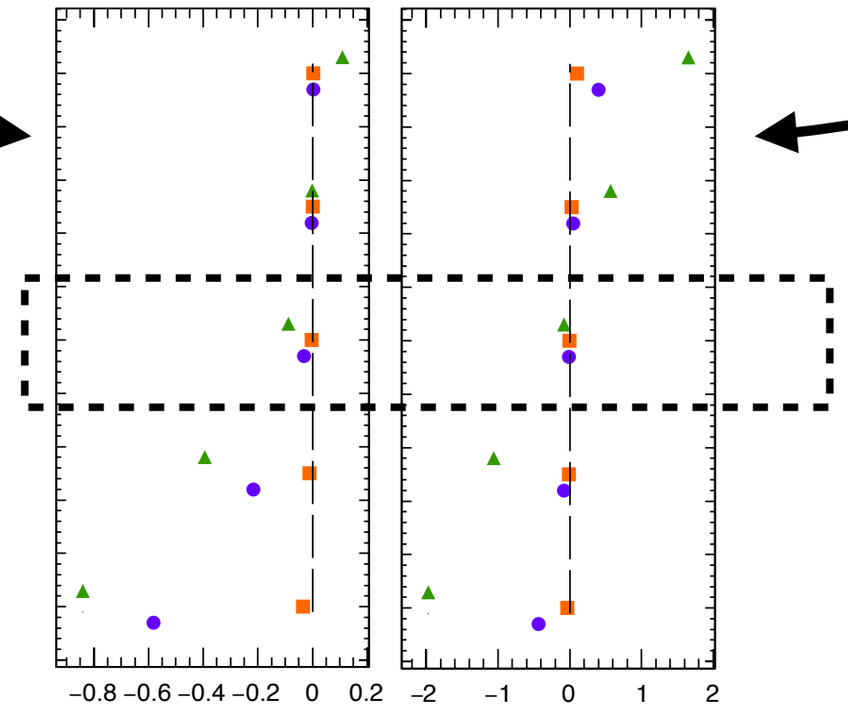
- We want to quantify the correlation between the values of τ_{form} obtained through unclustering and those extracted from MonteCarlo-generated **di-jet events**. We look at $\Delta\tau = \tau_{\mathrm{form}}^{\mathrm{MC}} - \tau_{\mathrm{form}}^{\mathrm{Unclustering}}$ distributions:





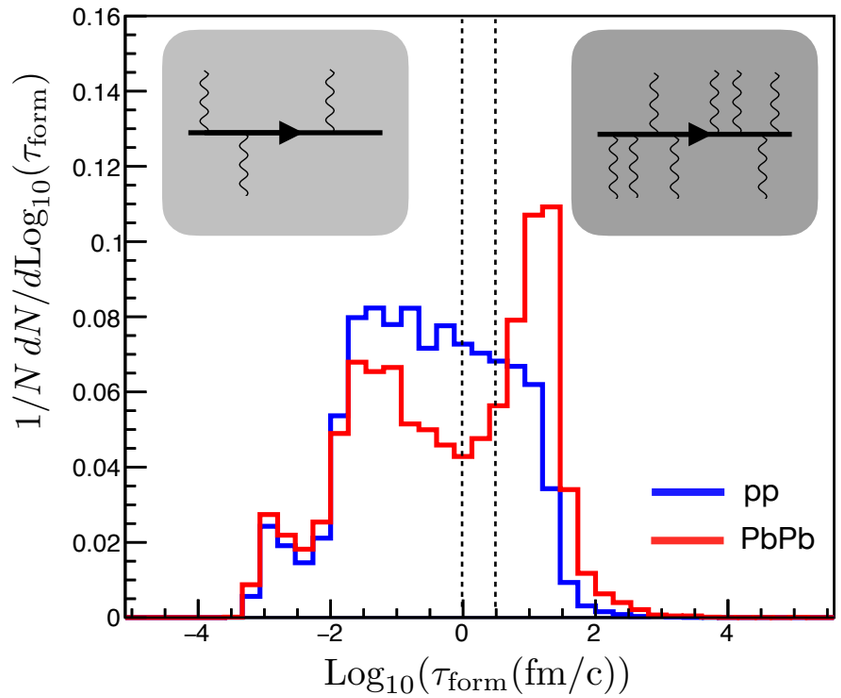
- We compare for different algorithms and different parton showers:



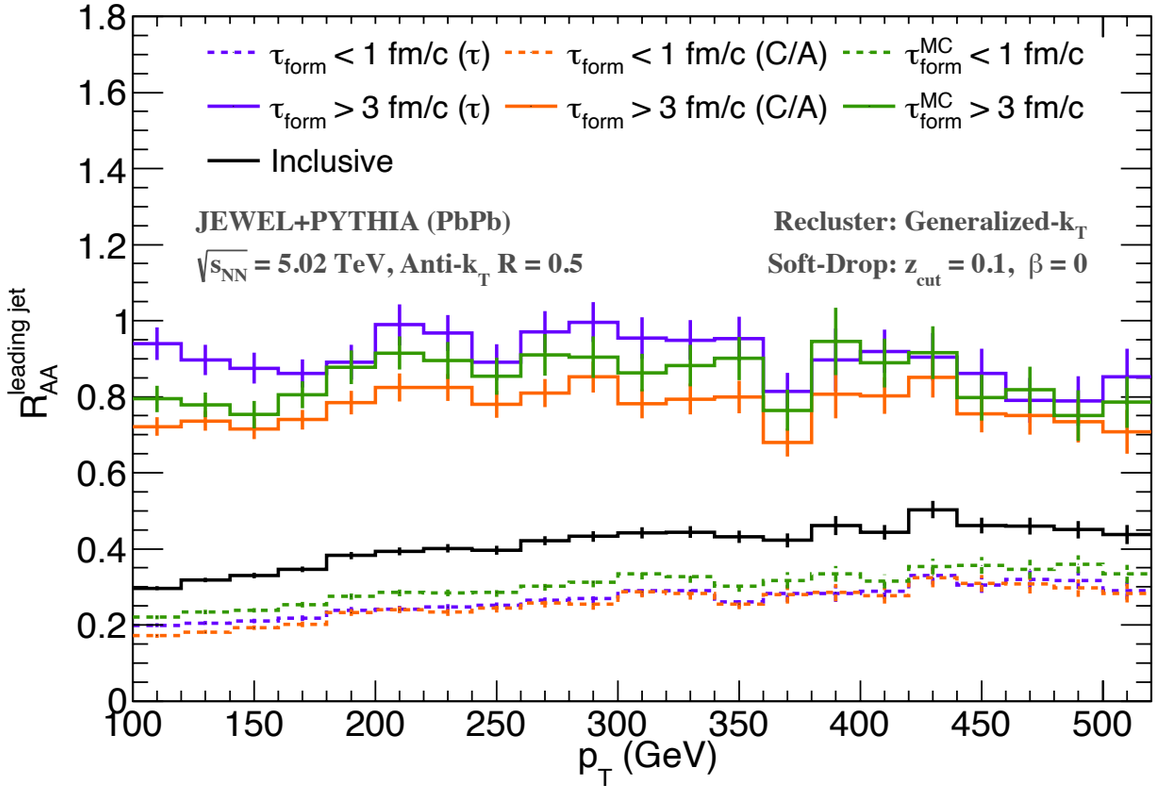


Back-up: The τ -algorithm (more)

- We define two populations according to the value of $\tau_{\mathrm{form}}^{\mathrm{Unclustering}}$ for the first splitting:
  - ✳ **Early jets** (first 1 fm/c) ⟶ **Strongly modified**
  - ✳ **Late jets** (after 3 fm/c) ⟶ **Weakly modified**



- We compute the **nuclear modification factor** for each population:



$$R_{\mathrm{AB}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{dN/dp_T|_{\mathrm{A+B}}}{dN/dp_T|_{\mathrm{p+p}}}$$

⟶ **Weakly modified**

⟶ **Strongly modified**

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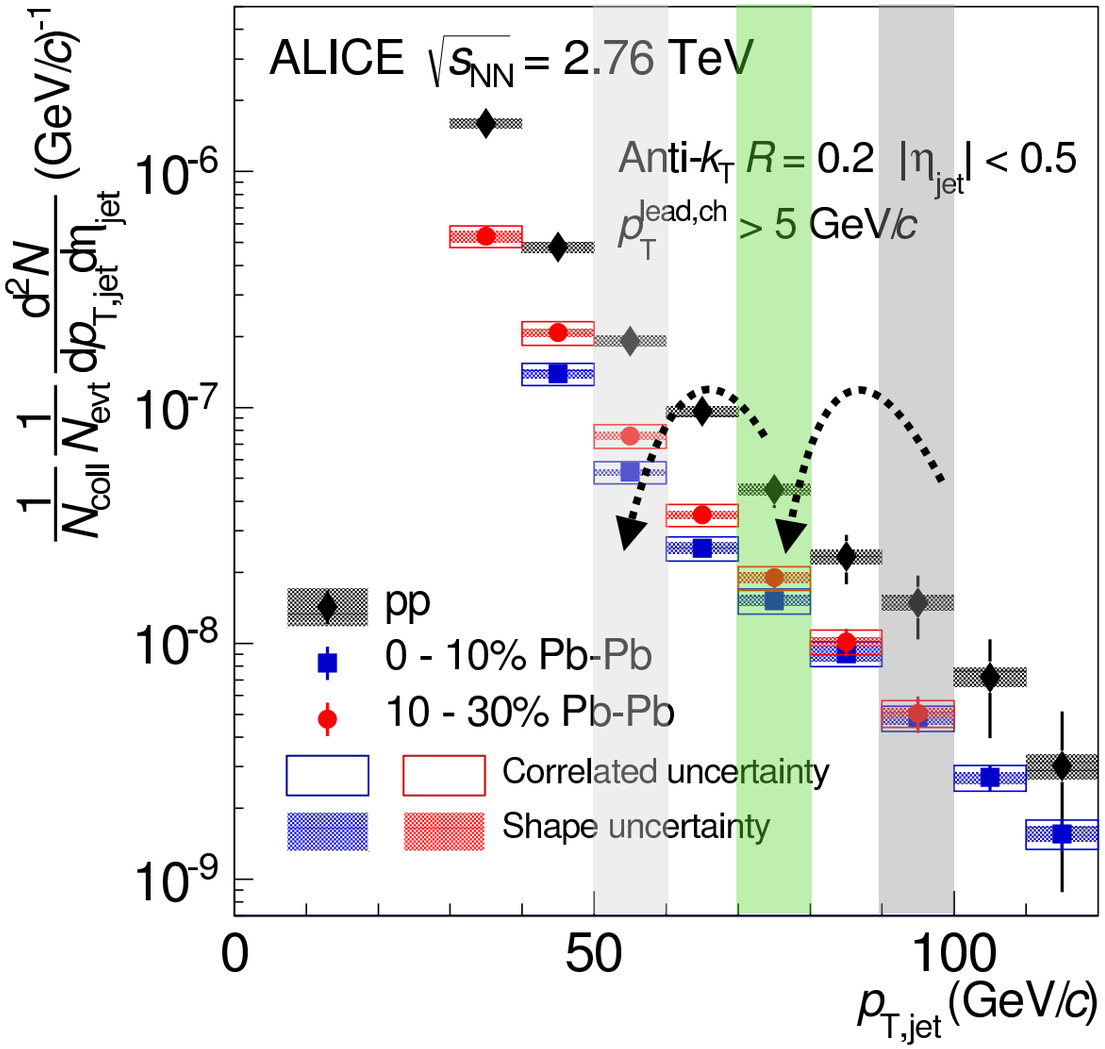
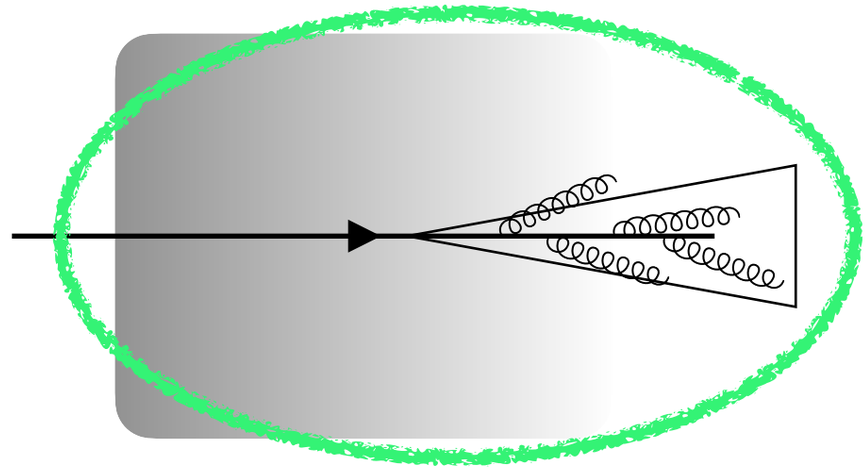
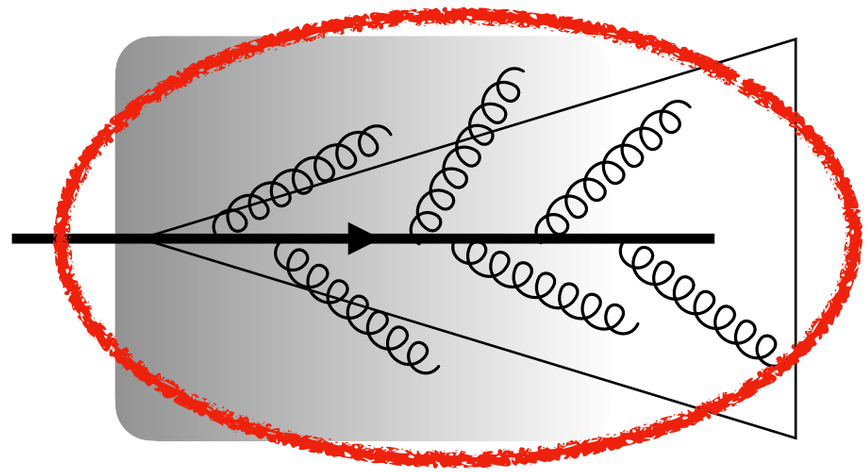
Back-up: selection bias

- We want to apply the τ-algorithm to study **energy loss**
- In general, energy loss is difficult to quantify because of **selection bias**





Dominant contribution for a given pt bin



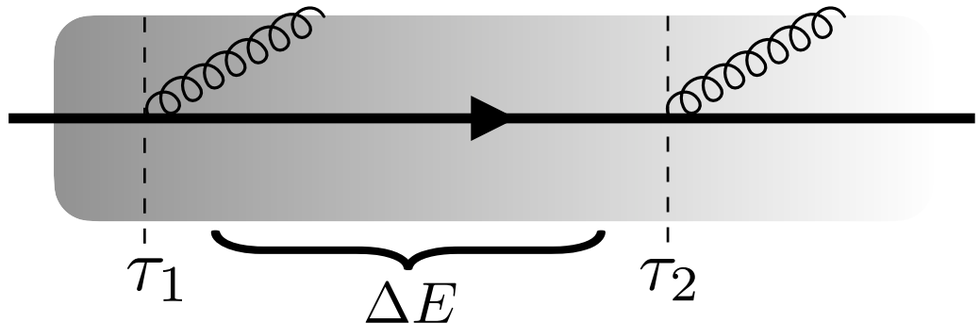
Highly quenched jets from higher pt bins: pt-suppressed contribution

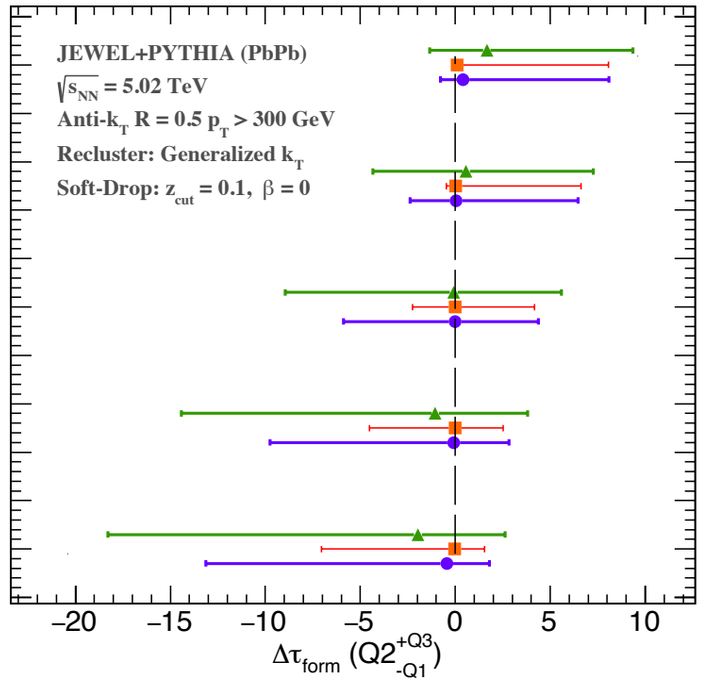
- When we select jets according to $p_{t,\mathrm{jet}}$, we are biased towards **weakly quenched jets**
- **Will we induce a similar bias when selecting jets according to τ ? Difficult to tell with di-jet events**

ALICE collaboration, Phys. Lett. B 746 (2015) 1

Back-up: With regard to the second splitting

- Necessary in order to relate **energy loss to path length within the medium**





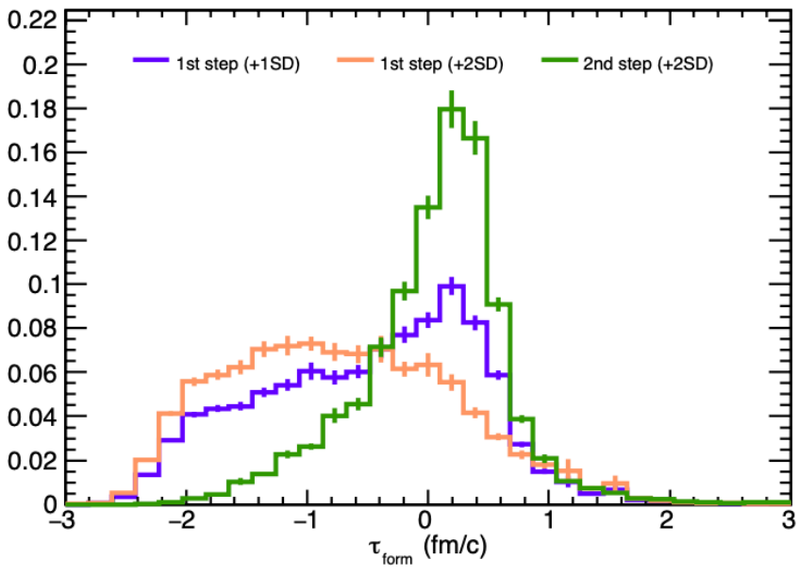
- But the IQR for the second step is significantly larger

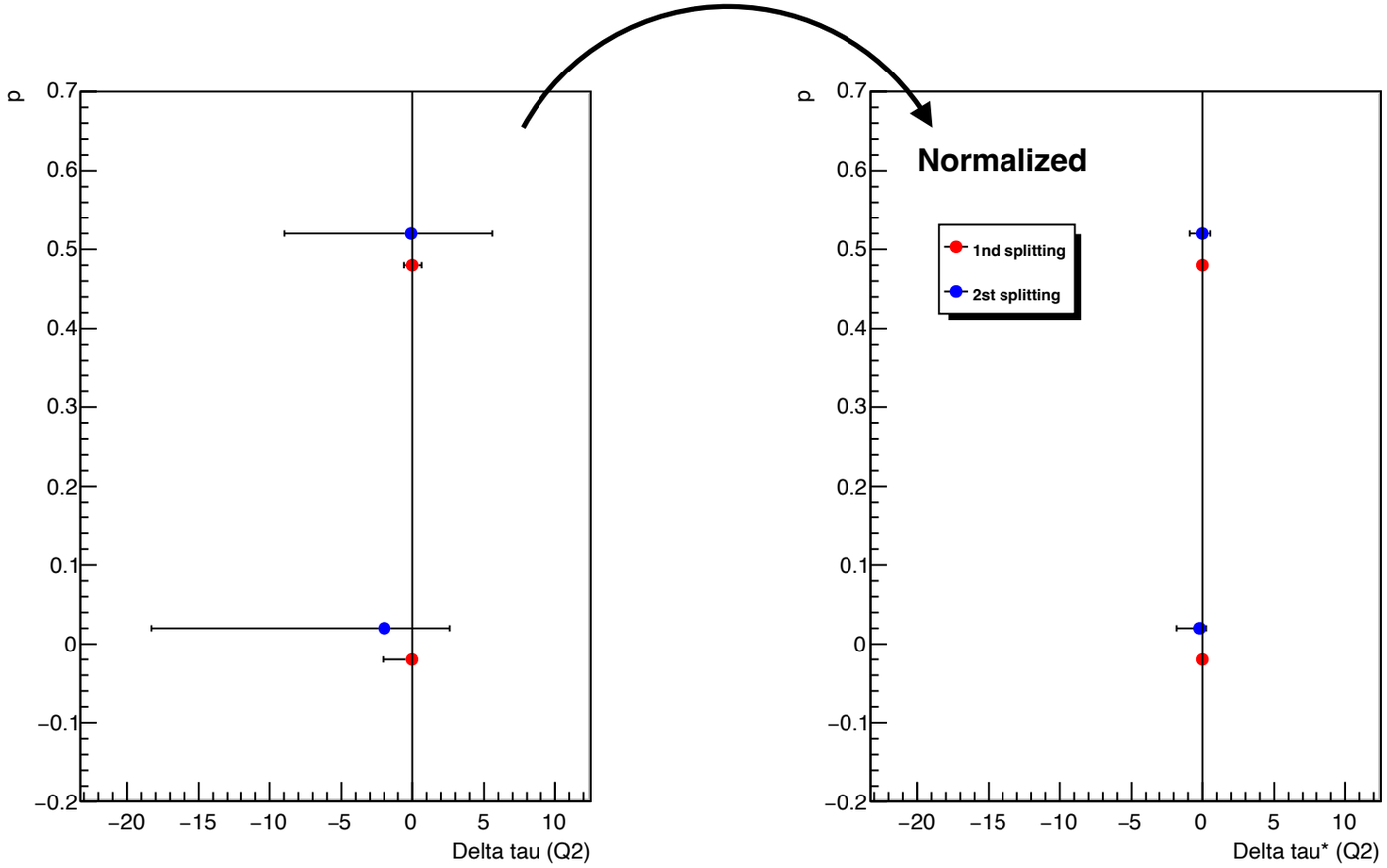
  ✳ However, so is $\tau_{\rm form}$!

  ✳ How about using the *relative* IQR?

  This seems to do the trick, but…

- By looking at jets with at least two splittings, we are introducing new biases





Back-up: What about the dispersion of the distributions?

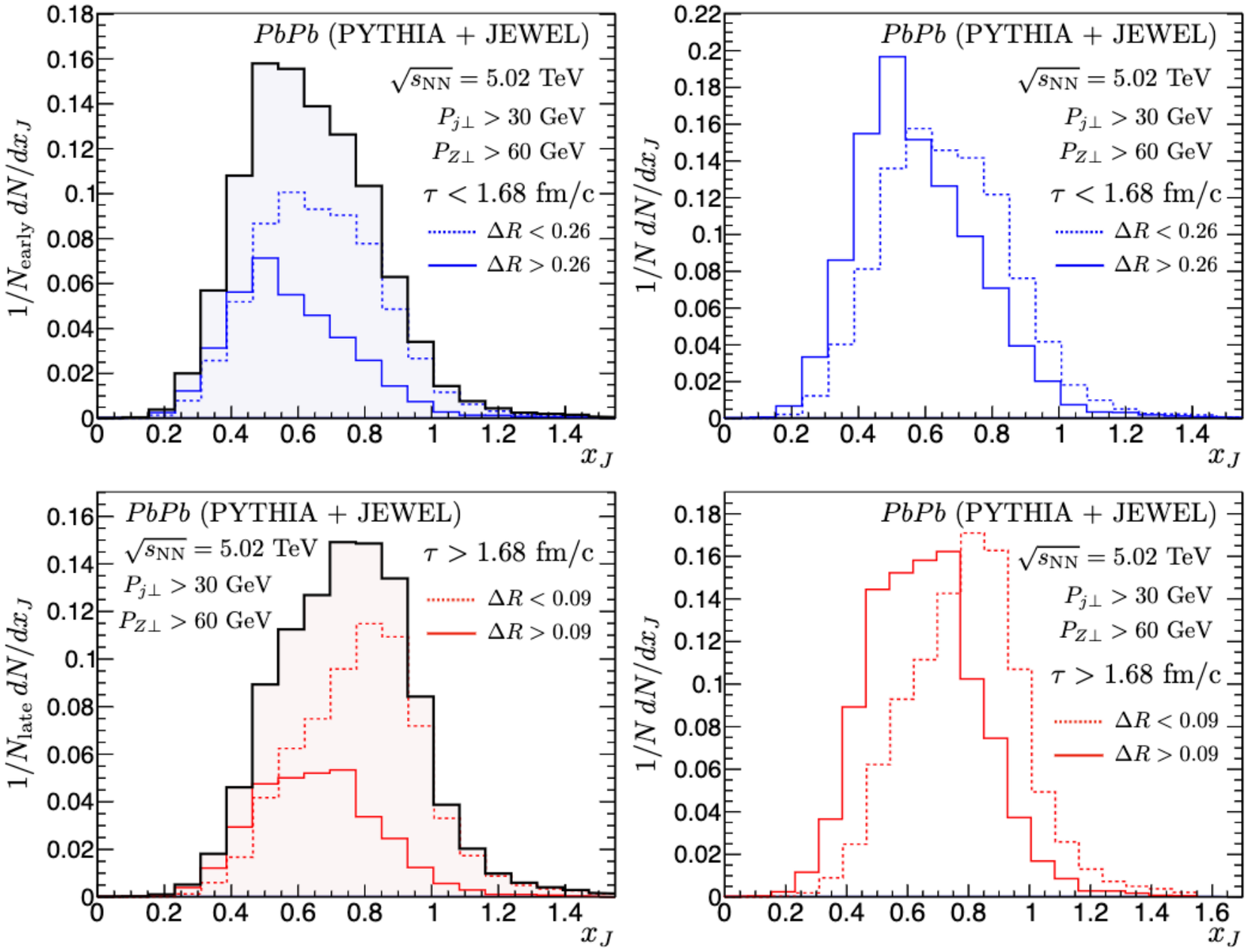


FIG. 2: Comparison of x_{jZ} distributions for narrow (full colored lines) and wide (dashed lines) subsamples taken from the early (top) and late (bottom) PbPb jet selections. The distributions in the left panels are normalized to the size of the corresponding parent jet samples, represented as full black lines above color-shaded areas (note that these same distributions were shown previously in the left bottom plot of Fig.1). In the right panels we display the narrow and wide subsamples only, each normalized to unity.