Deciphering Jet Quenching Effects Using Novel Analysis Tools

A comprehensive study

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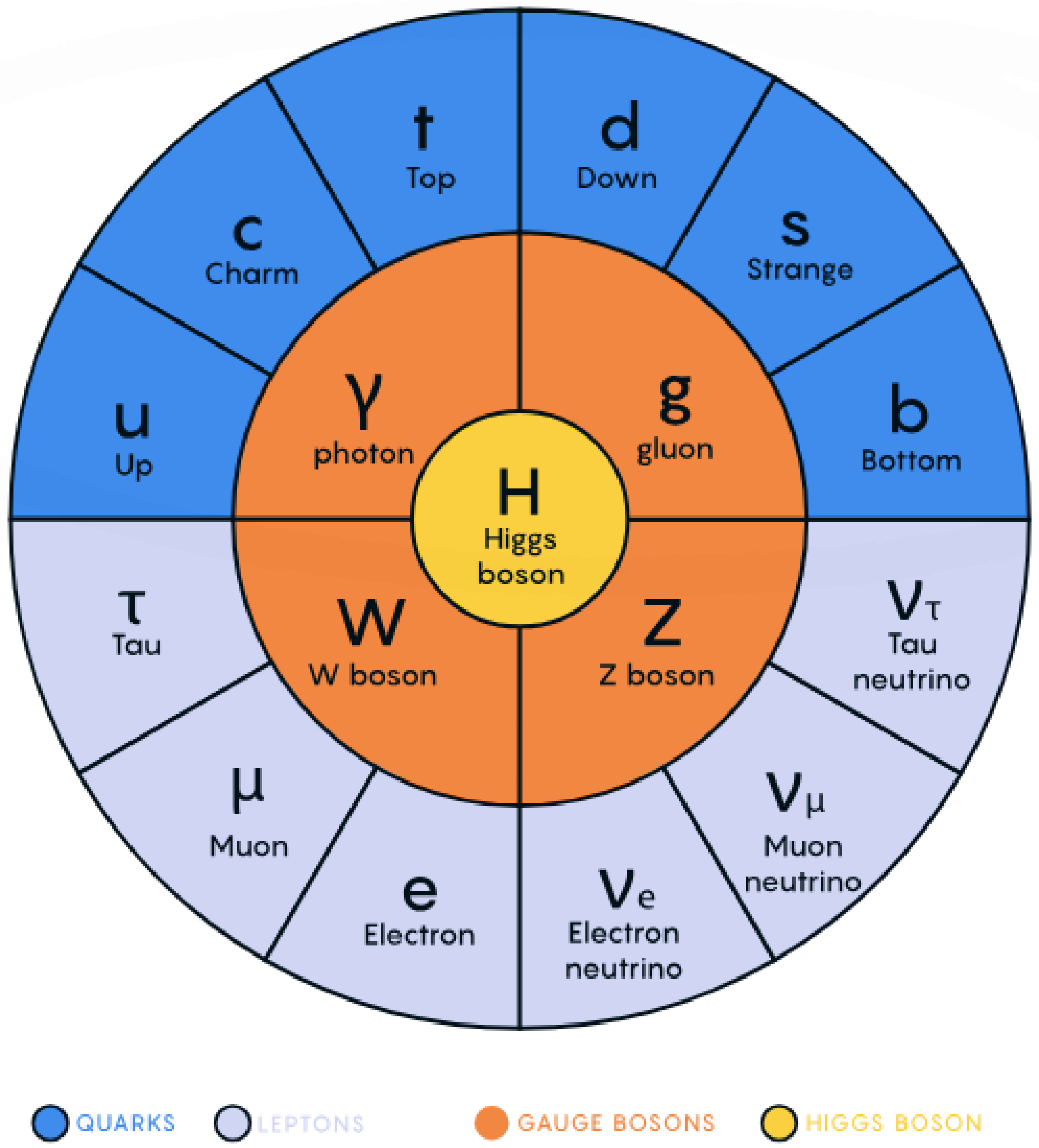
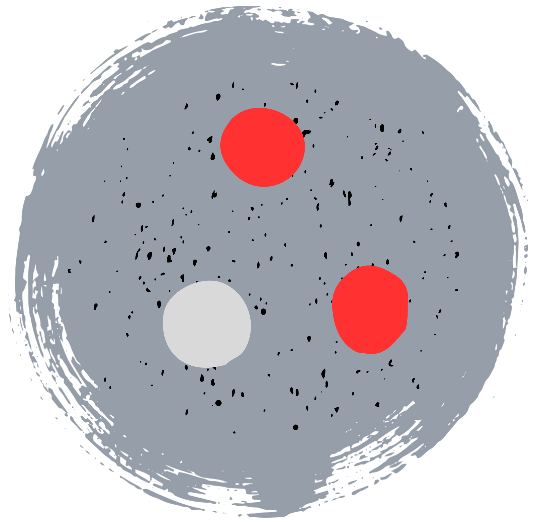
PRESENTED BY
Jay Nesbitt

Quantum Chromodynamics (QCD)

QCD governs the strong coupling sector of the Standard Model.



Proton



In any high energy collision involving hadrons, quarks and gluons (partons) will scatter, forming:

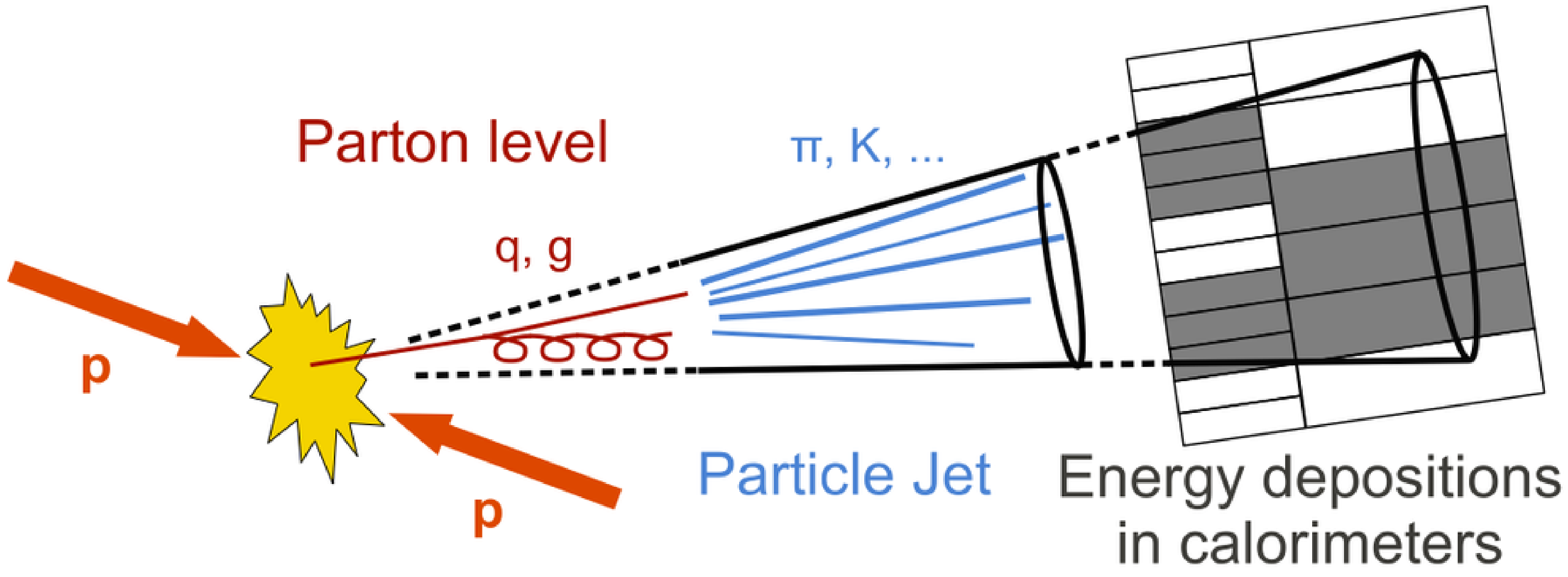
a jet!

What is a Jet?

For all (sort of) intensive purposes and in no way an exhaustive definition of a jet is a:

"**Collimated spray of particles** produced by high pT parton..."

https://cms.cern/news/jets-cms-and-determination-their-energy-scale



A more insightful definition (for our explicit purposes) is to **think of jets as mathematical objects constructed by an algorithm**: these algorithms create said objects to match the energy signatures in the calorimeters while obeying QCD rules.

$$d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p}) \frac{\Delta R_{ij}}{R}$$

$$\Delta R_{ij} = \sqrt{(\phi_i - \phi_j)^2 + (y_i - y_j)^2}$$

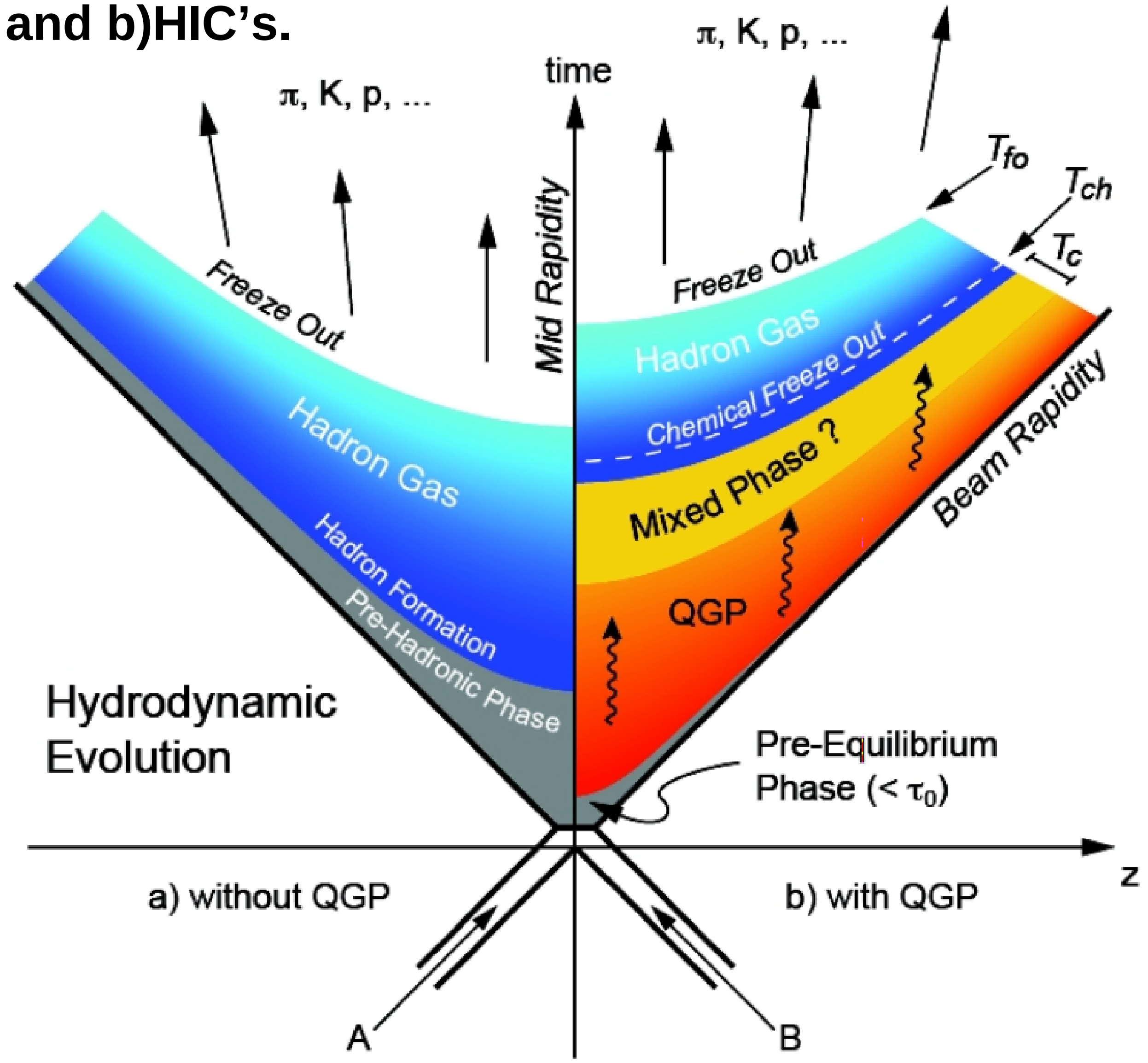
Jets in Heavy-Ion Collisions (HIC's)

https://particlesandfriends.wordpress.com/2016/10/14/evolution-of-collisions-and-qgp/

Minkowski Diagram of a) proton-proton collisions and b)HIC's.

Could not observe pre-hadronic phase in the past. With the help of HIC's, this is now (indirectly) possible!

HIC's produce a colour singlet-permitting state colloquially named 'quark soup'. This state is known as Quark-Gluon Plasma (**QGP**).



Medium-induced modification of a jet's cross section and structure is called **jet quenching**.

Side by side, we can observe how the QGP affects our final states: this can be achieved through analysing jet quenching!

Let's dive deeper...

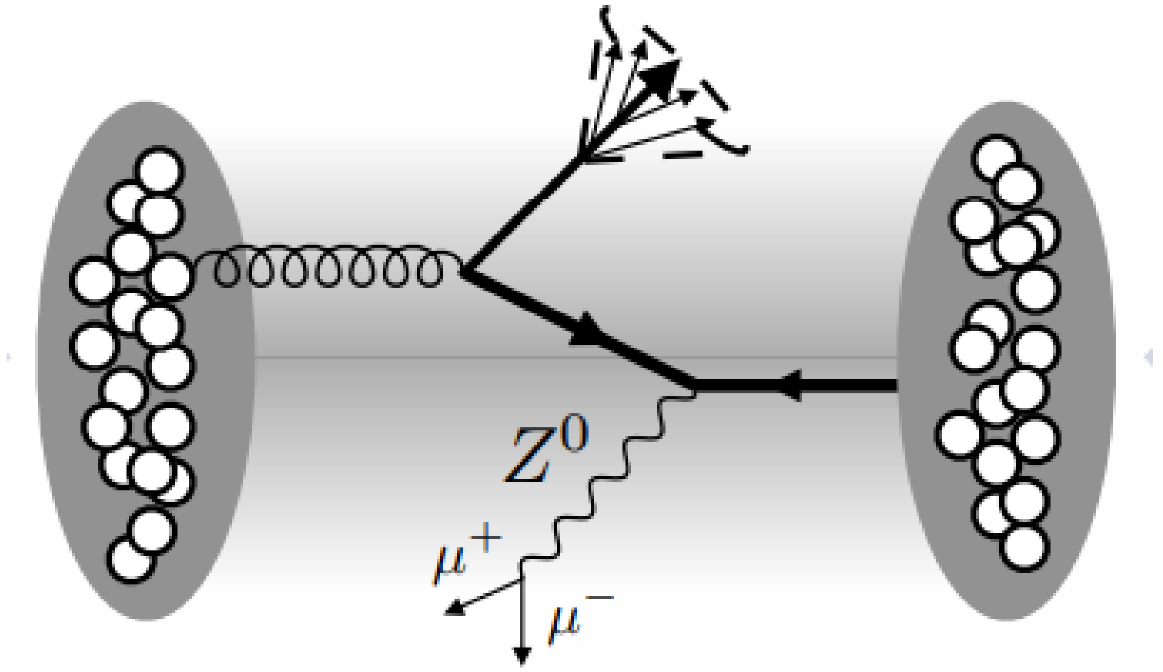
HARD SCATTER → **QGP EXPANSION** → **HADRONISATION** → **DETECTION**

How can we use Jet Quenching?

QGP observables evolve with time: modeled by complex hydrodynamics.

How can these changes in state be quantified?

Answer: use a time proxy as an estimate for the hydrodynamical expansion of QGP: **formation time**.



Formulating Formation Time

Extended Uncertainty Principle

$$\Delta E \Delta t \geq \frac{\hbar}{2} \longrightarrow \tau_{form} \approx \frac{E}{m^2}$$

Lorentz boost + Natural Units

$$E_1 = Ez$$
$$E_2 = E(1-z)$$

$$1 - \cos\theta \rightarrow \frac{\theta^2}{2}$$

$$m^2 = (p_1 + p_2)^2 \approx 2E_1E_2(1-\cos\theta) \approx 2E^2z(1-z)(1-\cos\theta) \approx E^2z\theta^2$$

Soft-collinear limit:

$$\tau_{\text{form}} \approx \frac{E}{m^2} \approx \frac{1}{2Ez(1-z)(1-\cos\theta)} \approx \frac{1}{zE\theta^2}$$

From https://arxiv.org/pdf/2012.02199.pdf (Liliana Apolinário, André Cordeiro, Korinna Zapp)

$$d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p})\frac{\Delta R_{ij}}{R} \xrightarrow{p=0.5} d_{ij} \approx \frac{1}{\tau_{\text{form}}}$$

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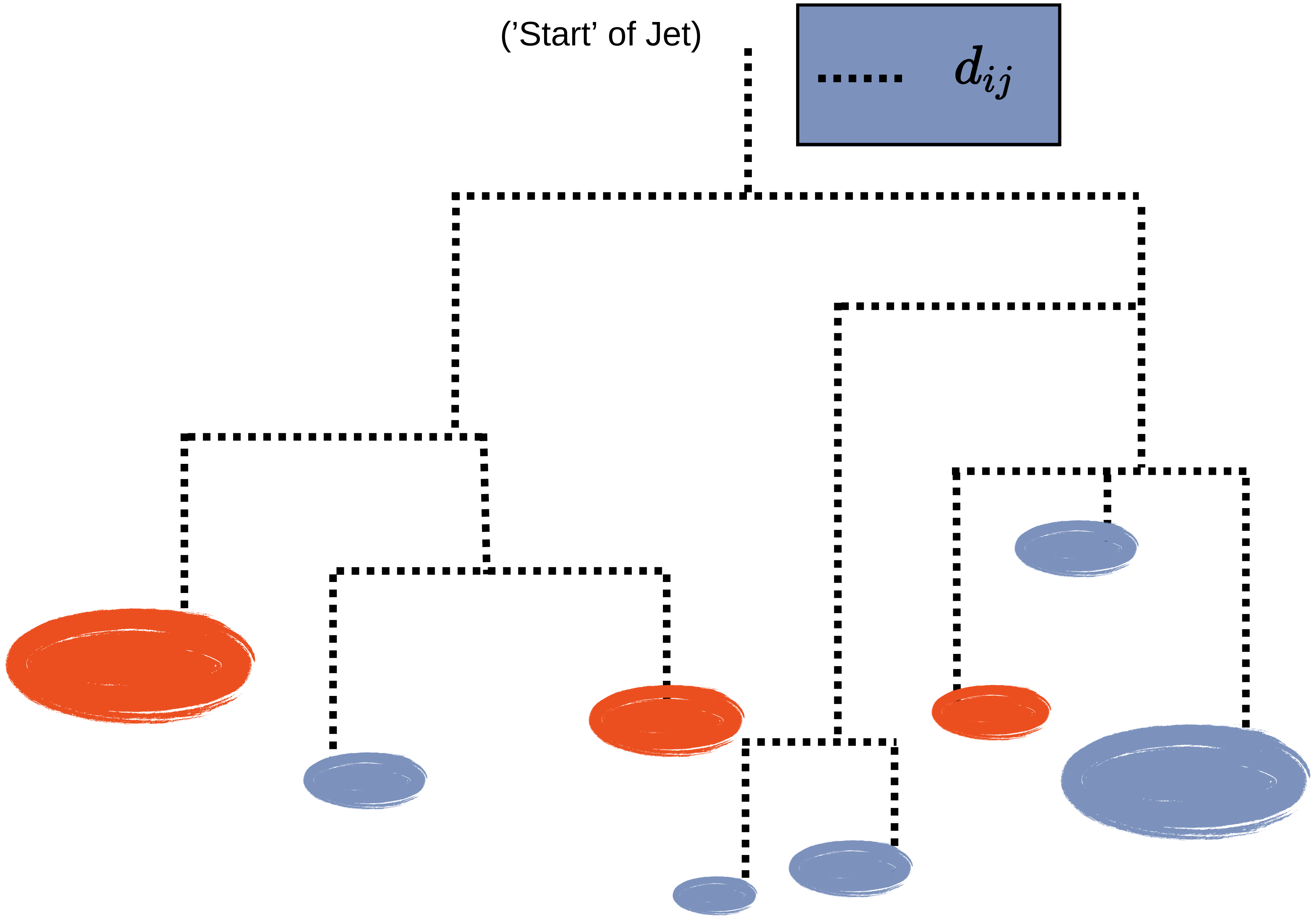
$$\ldots \tau_{\rm form} \approx m \approx \Delta R \text{ ?}$$

Hard Process

('Start' of Jet)



Can we use formation time as a proxy for physical time, to cluster jets based on the distance measure derived here?

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Methodology: Event Selection

Simulating Events: **PYTHIA8** used for vacuum (**pp**) events and **JEWEL** for **PbPb** collisions.

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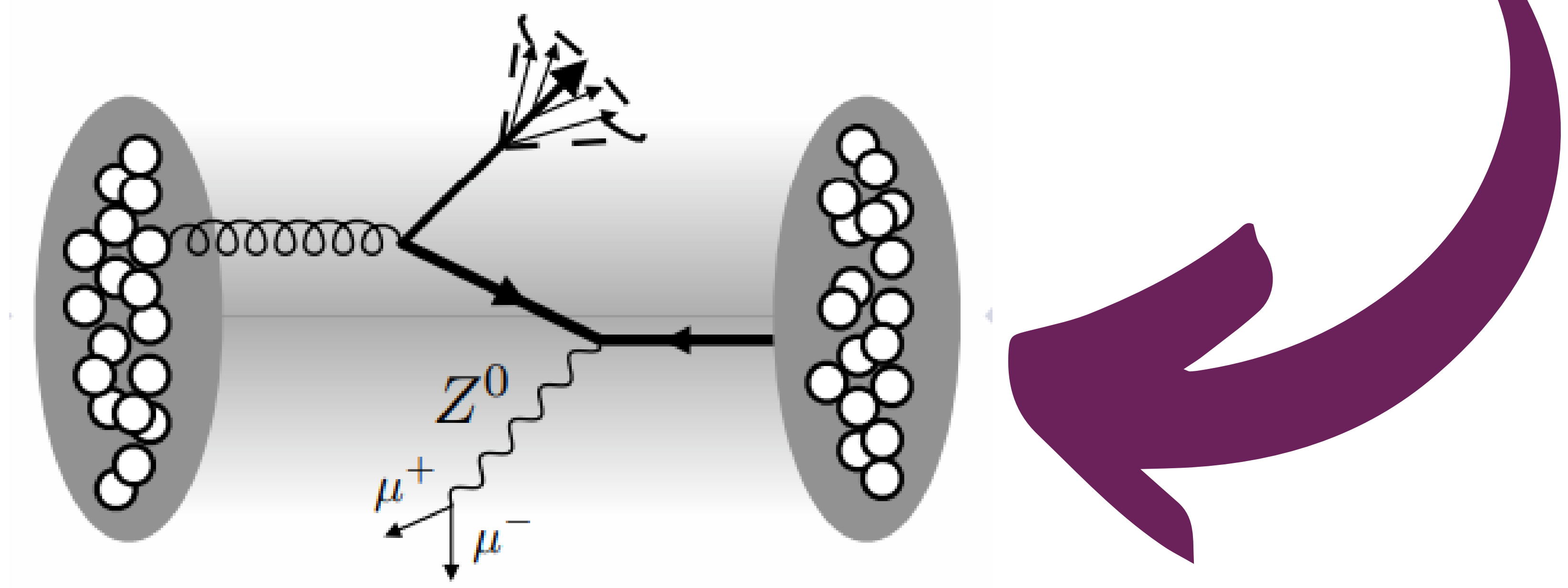

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Selection Cuts

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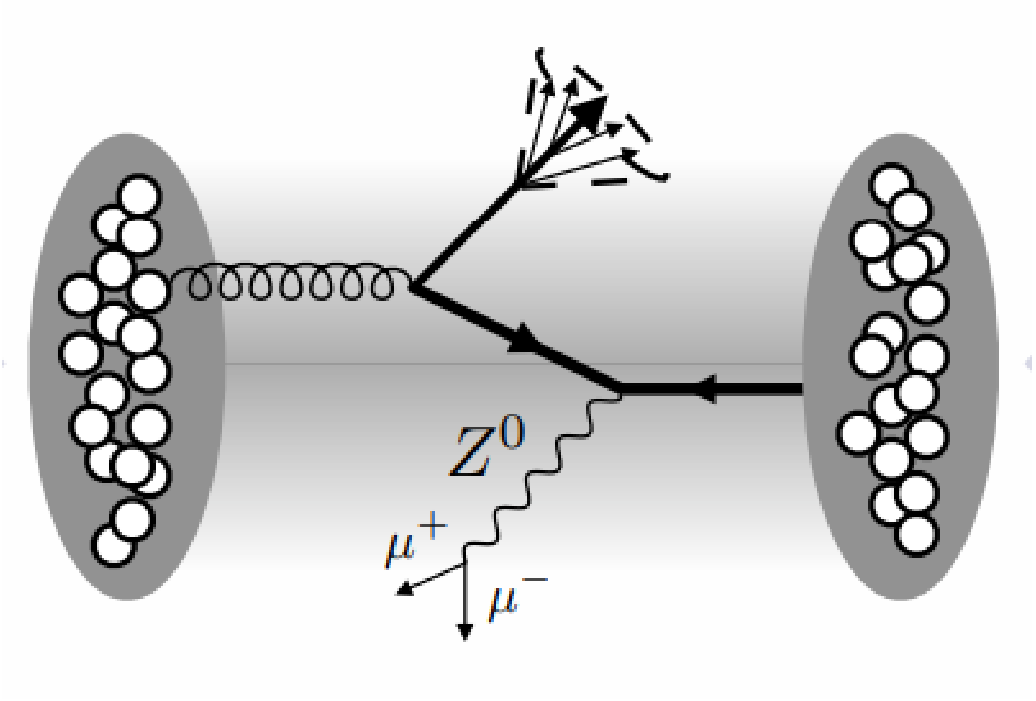

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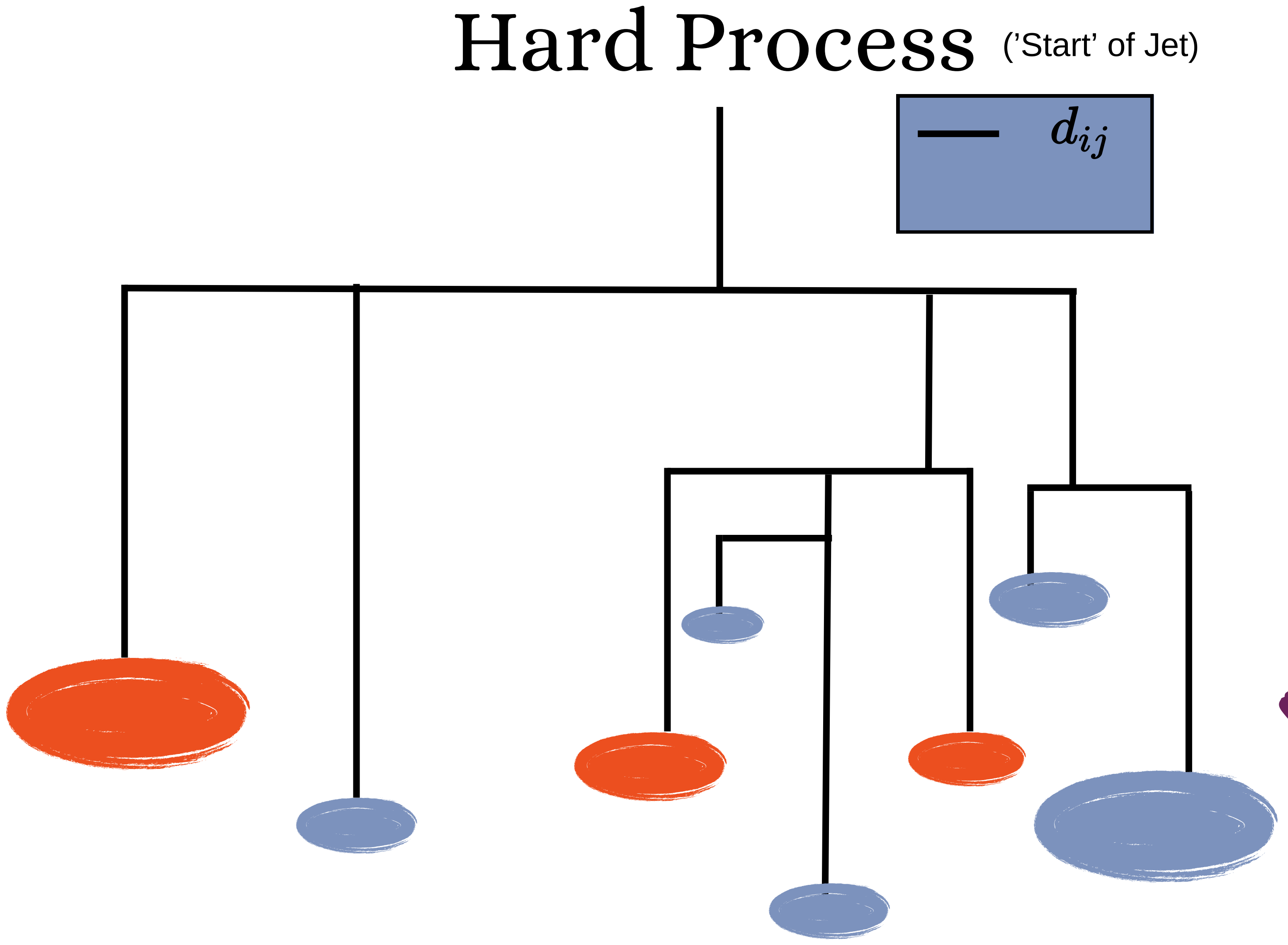
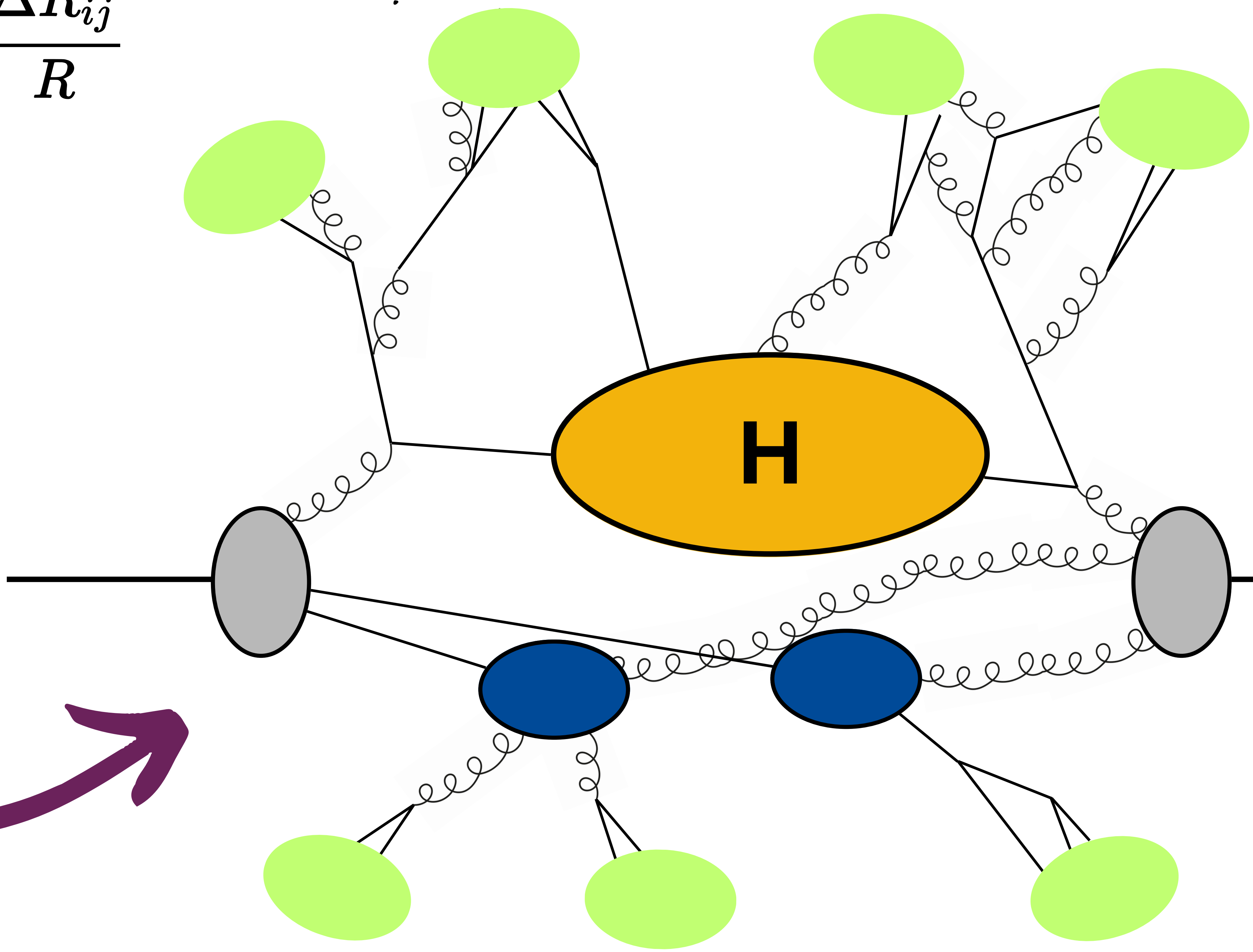
Methodology: Generalised kT-Algorithm

Experiment

Theory (Parton Shower)

$$d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p})\frac{\Delta R_{ij}}{R}$$





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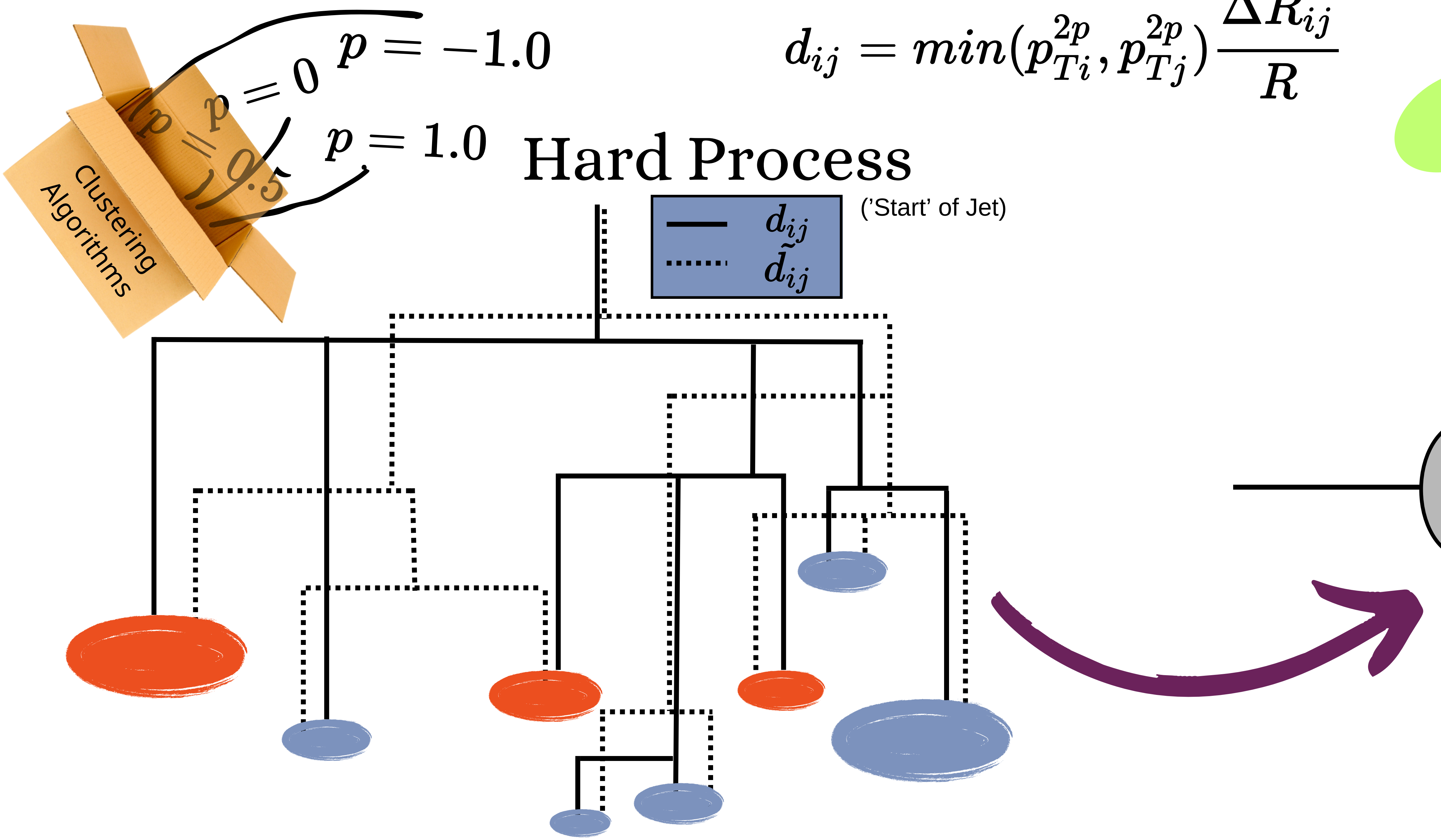

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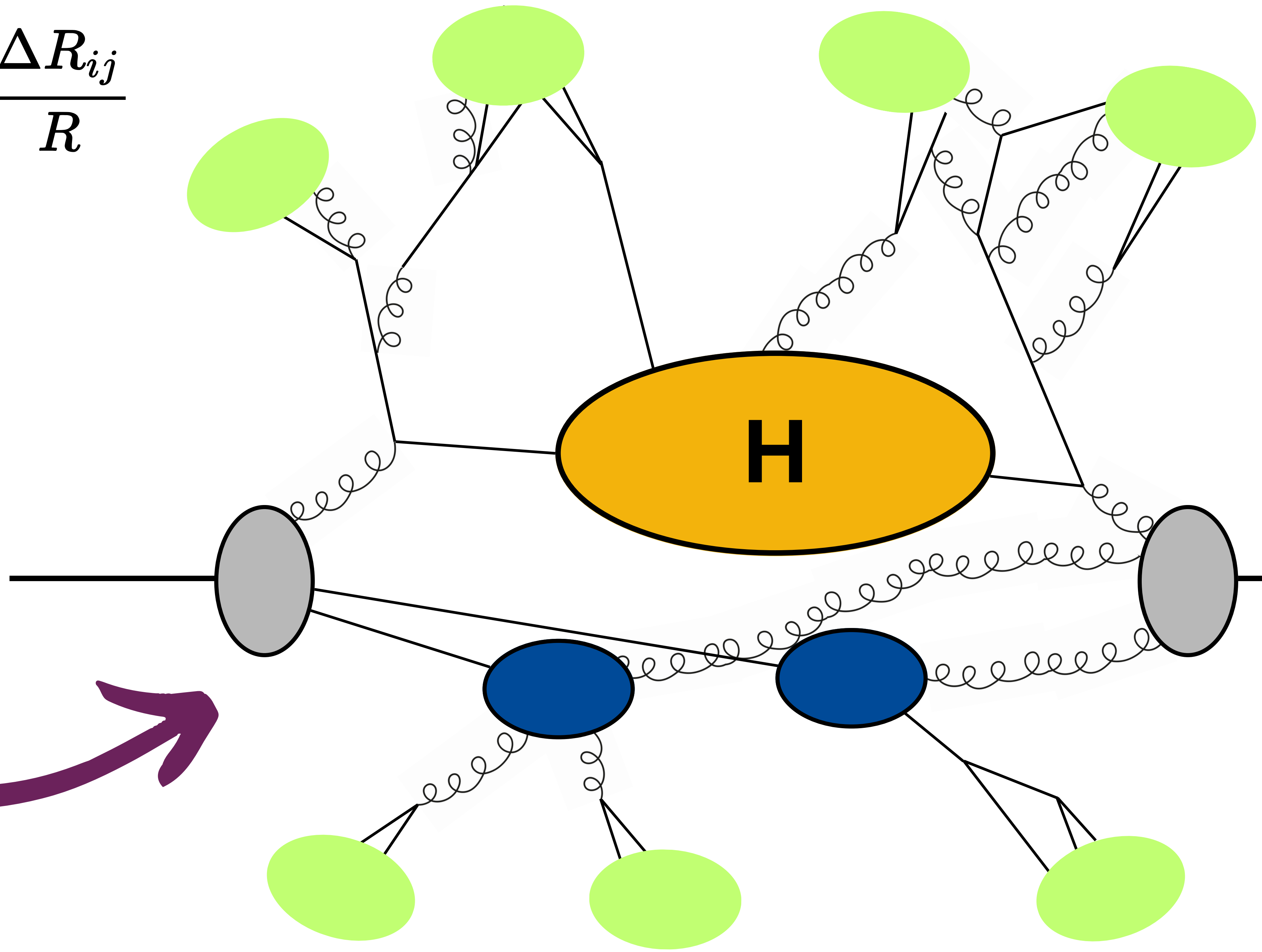

We can choose either procedure to describe jets in PS: choose p=0.5 as our algorithm.

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Results

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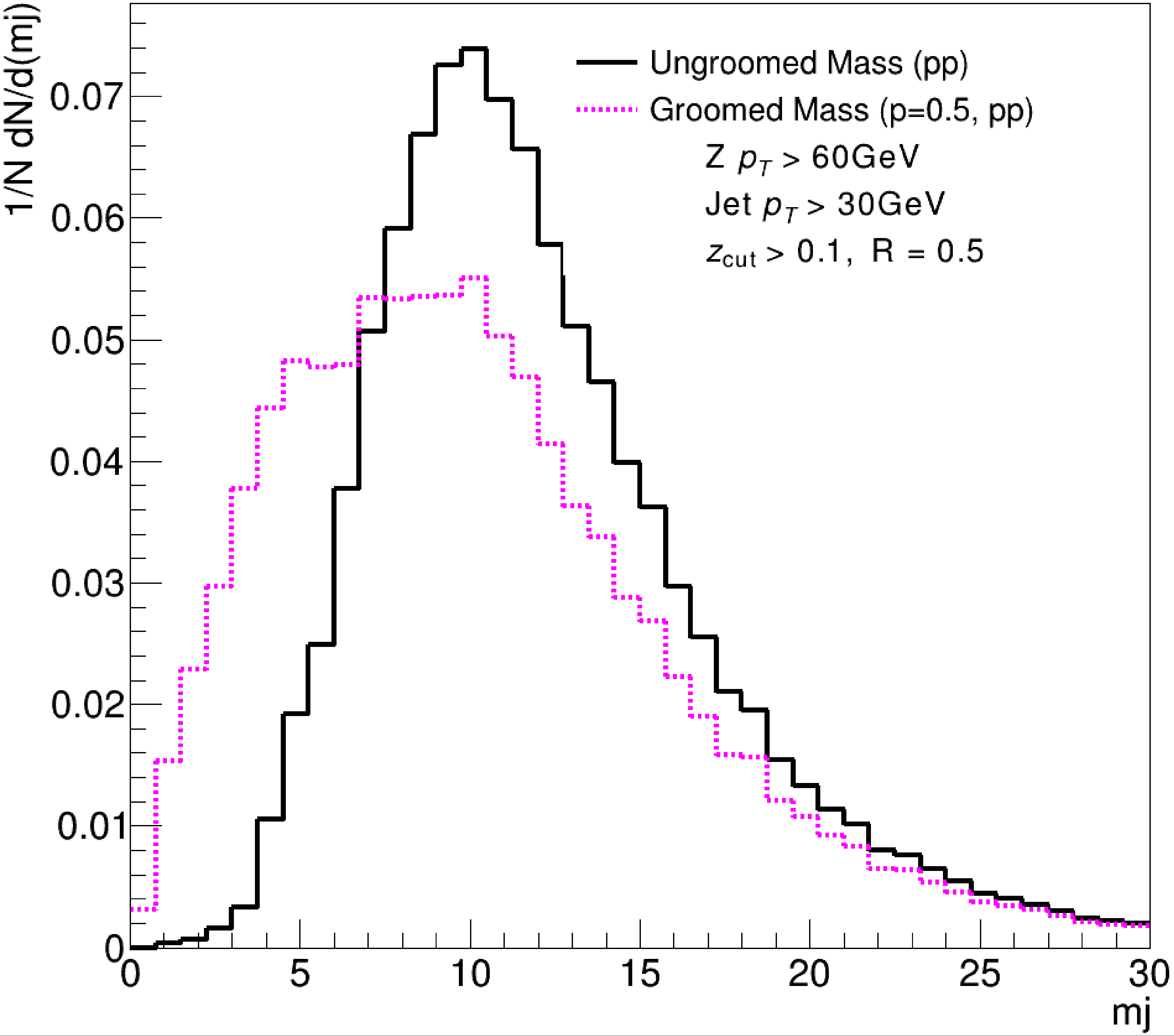
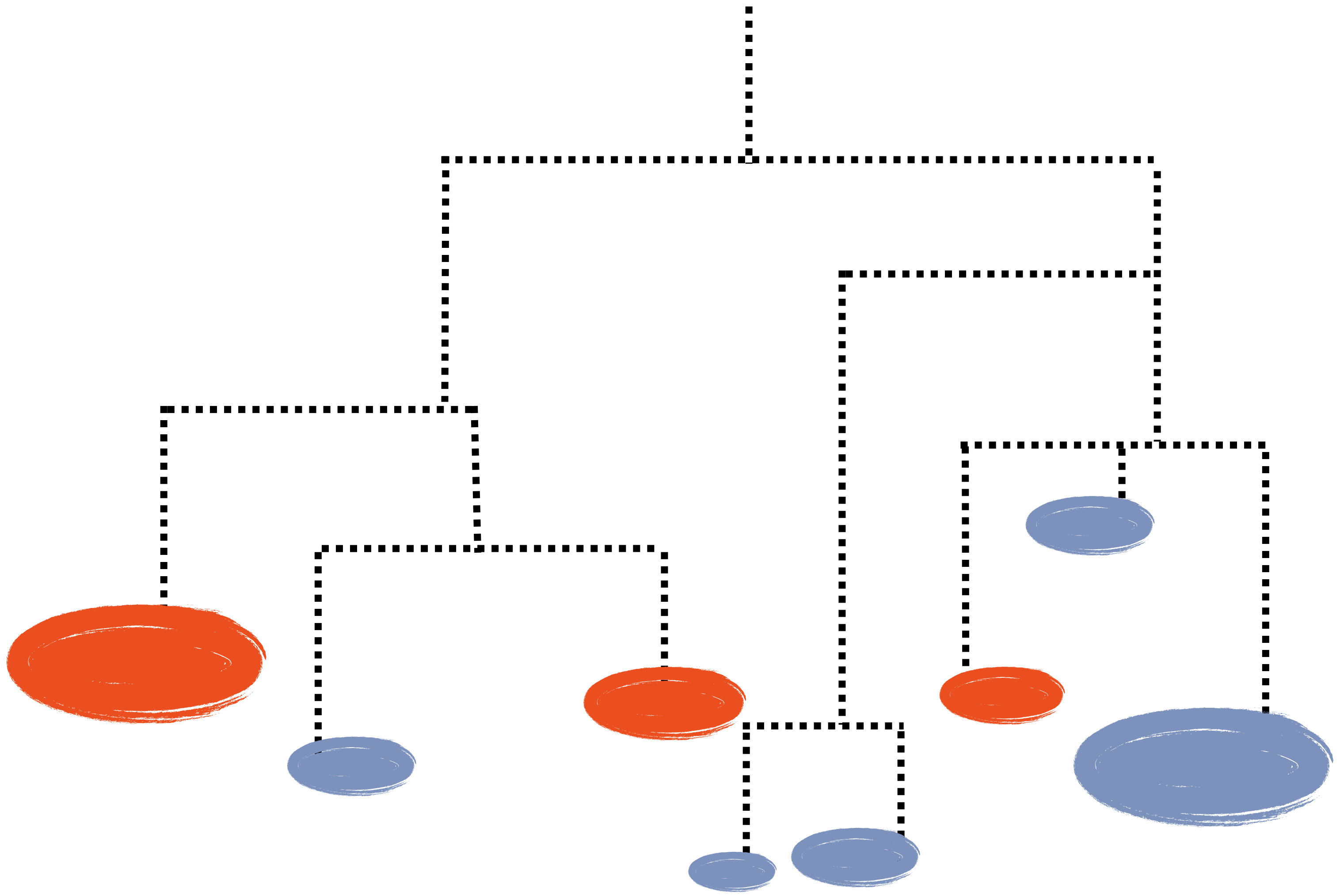
Grooming, SoftDrop and Jet Mass



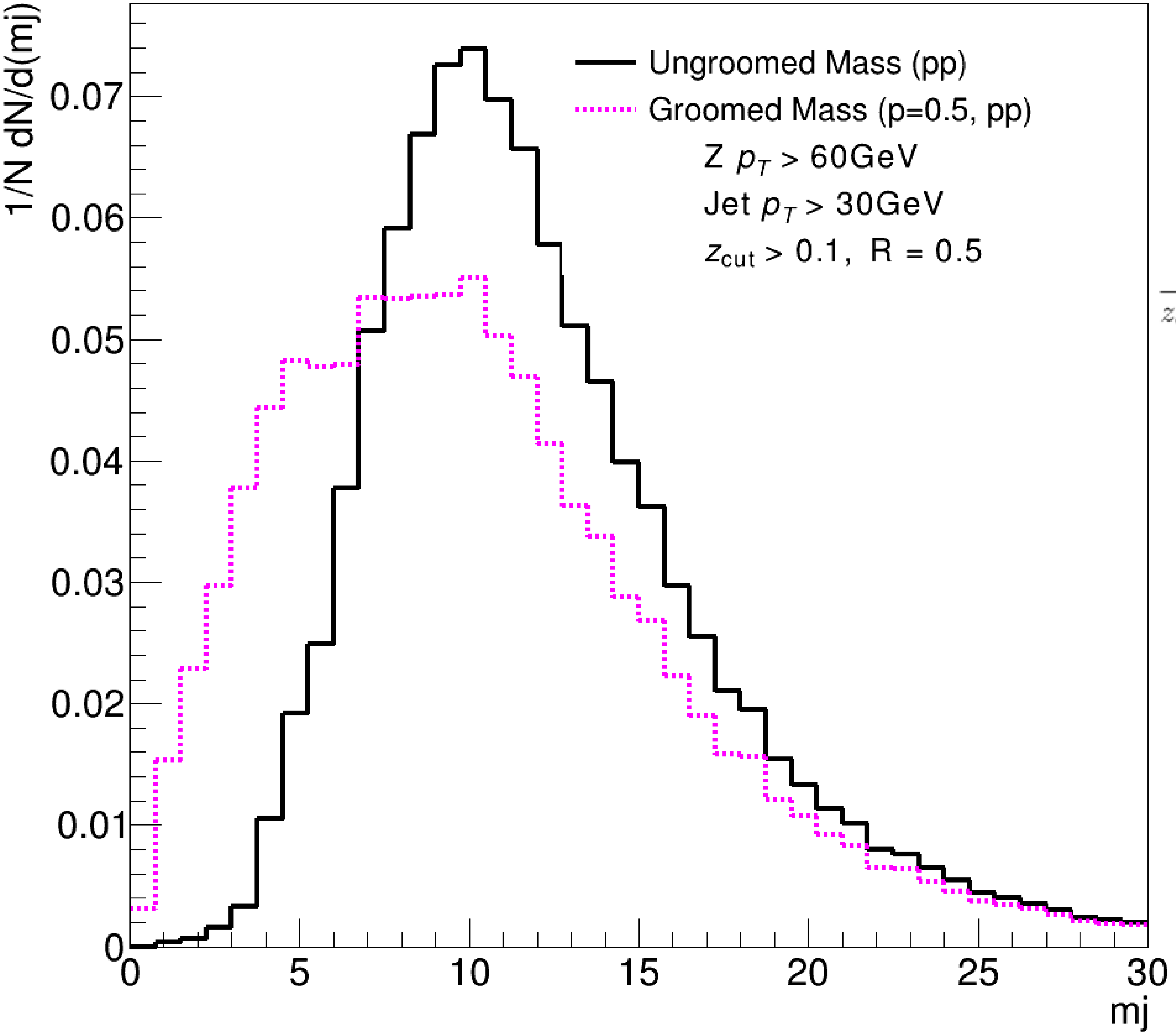


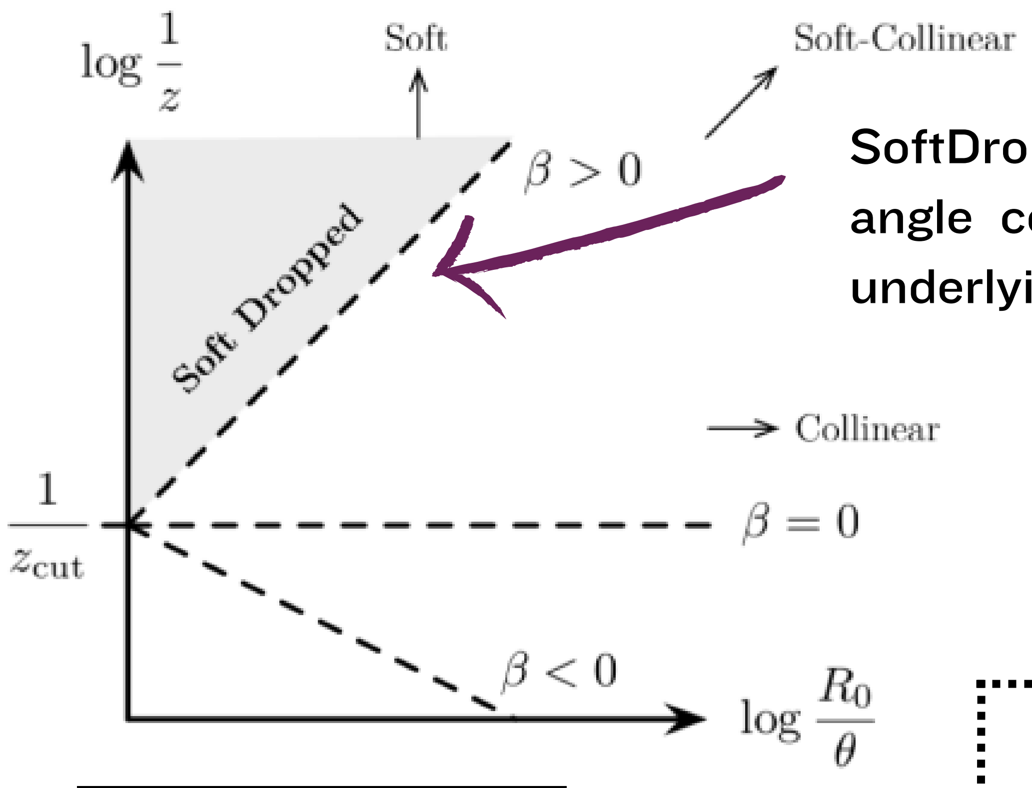
Reclustering schematic, no SoftDrop

Vacuum (pp)

Grooming, SoftDrop and Jet Mass

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta}$$

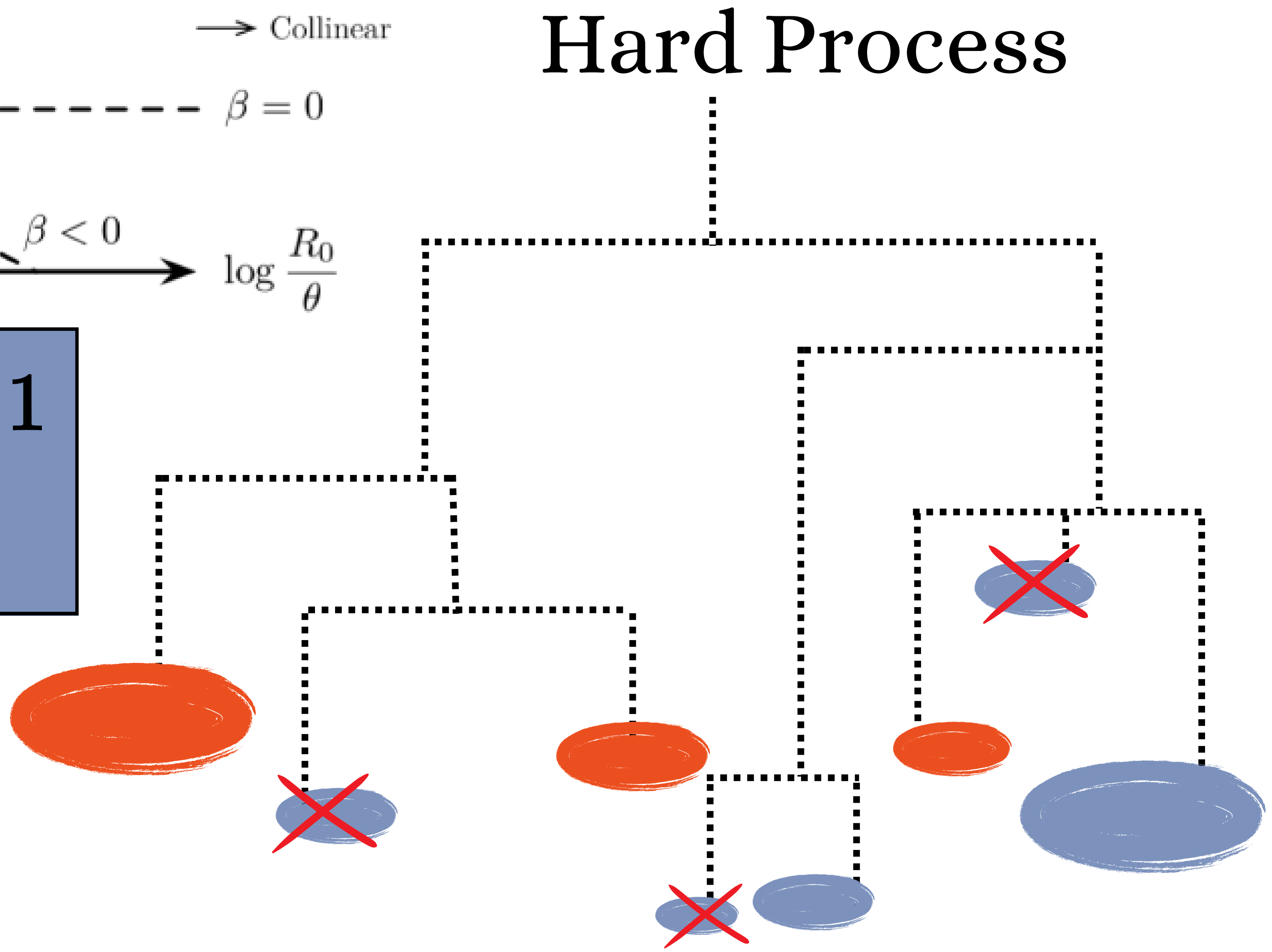




SoftDrop condition: eliminates soft, large angle contamination from uncorrelated underlying events.

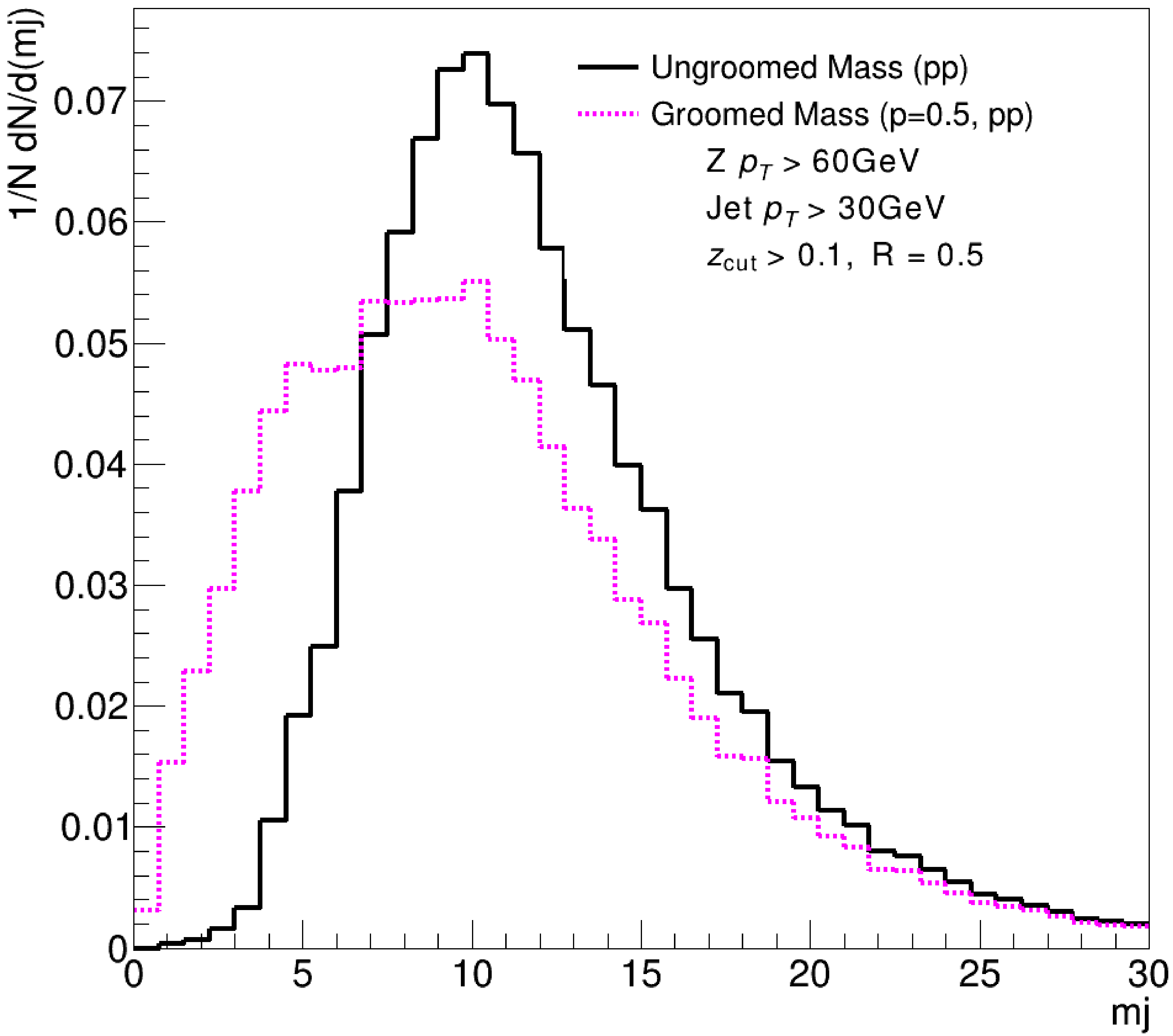
$z_{\text{cut}} = 0.1$

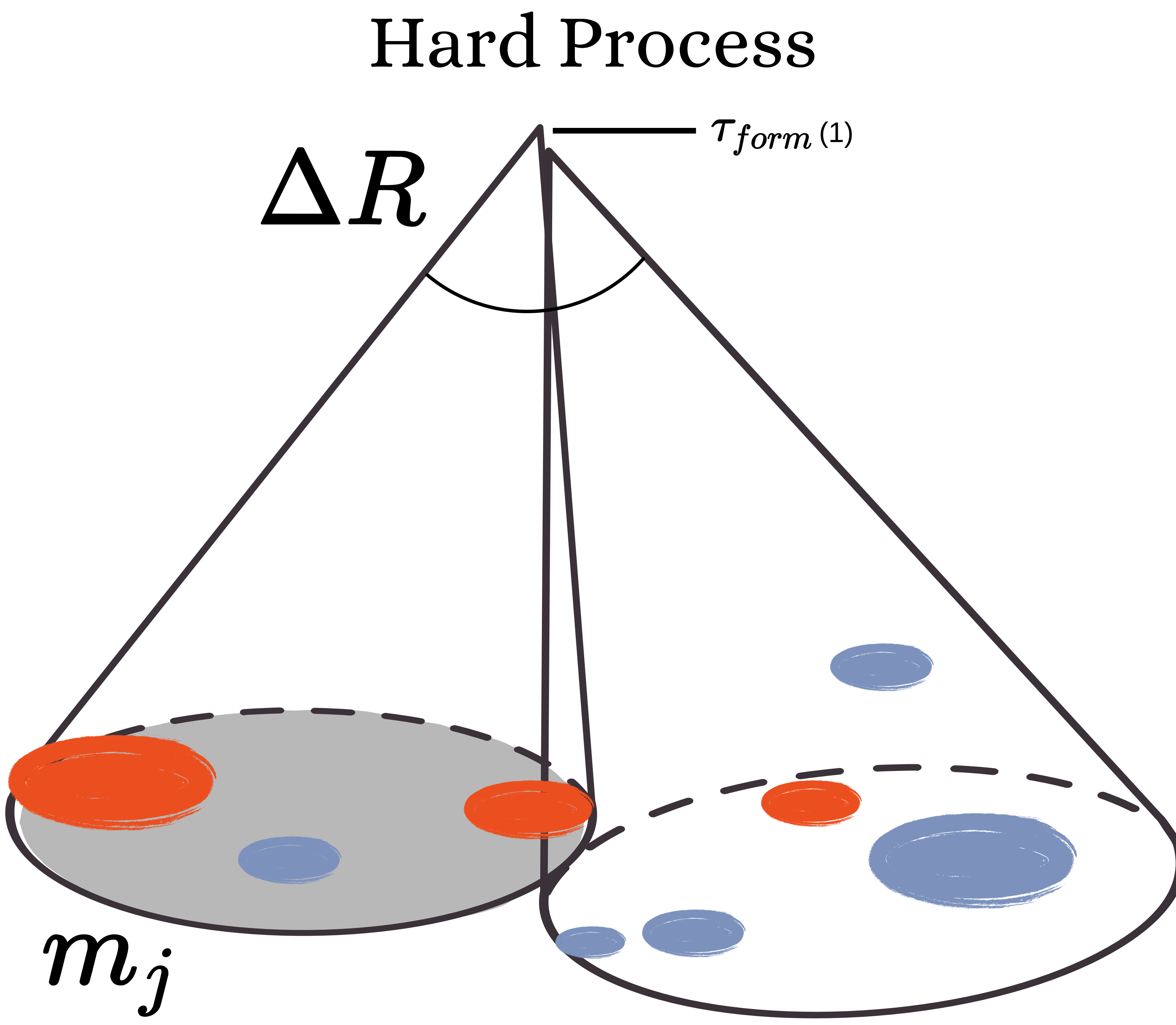
$\beta = 0$



Reclustering schematic, SoftDrop applied

Grooming, SoftDrop and Jet Mass





Conical schematic, no SoftDrop

Grooming, SoftDrop and Jet Mass

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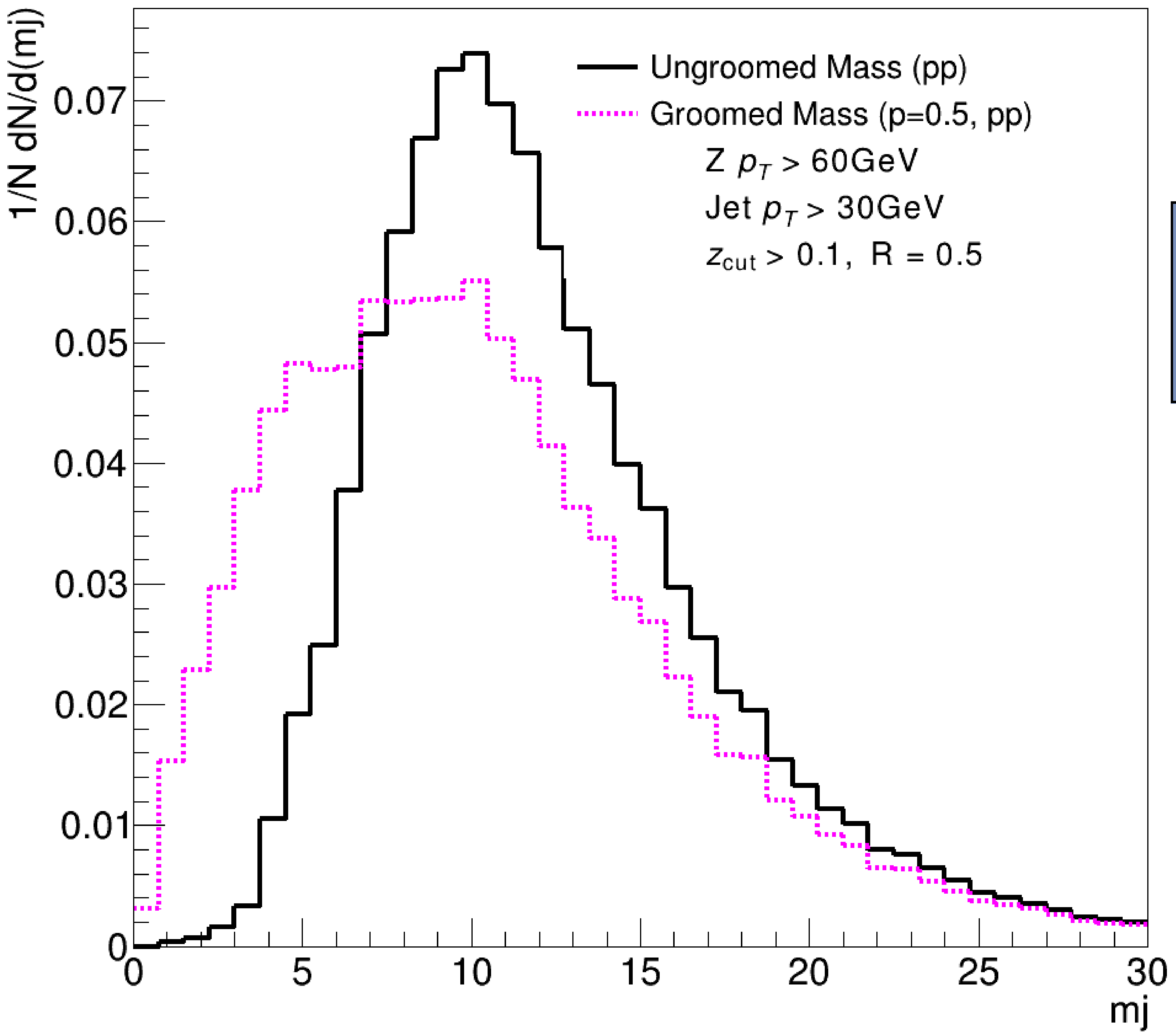
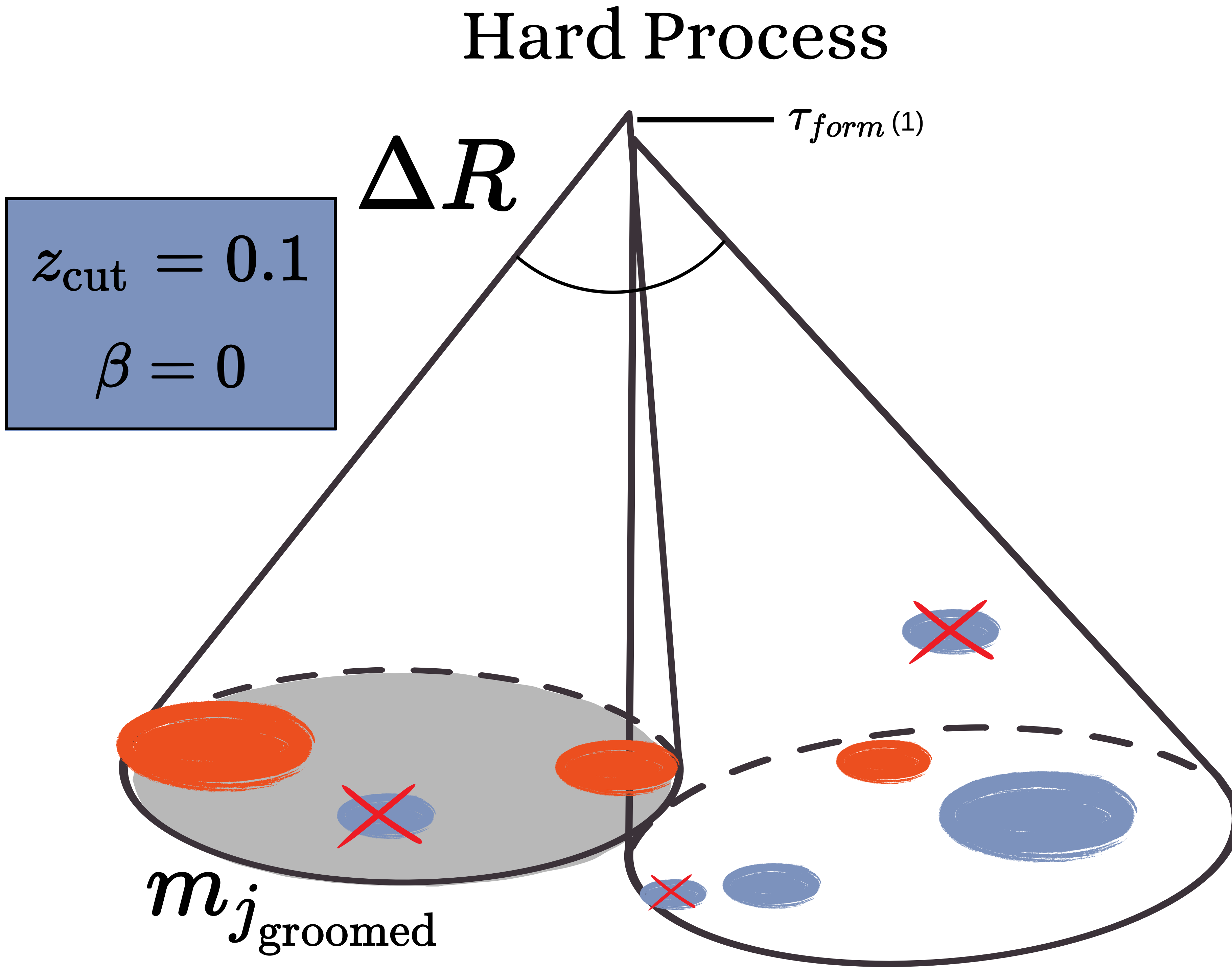


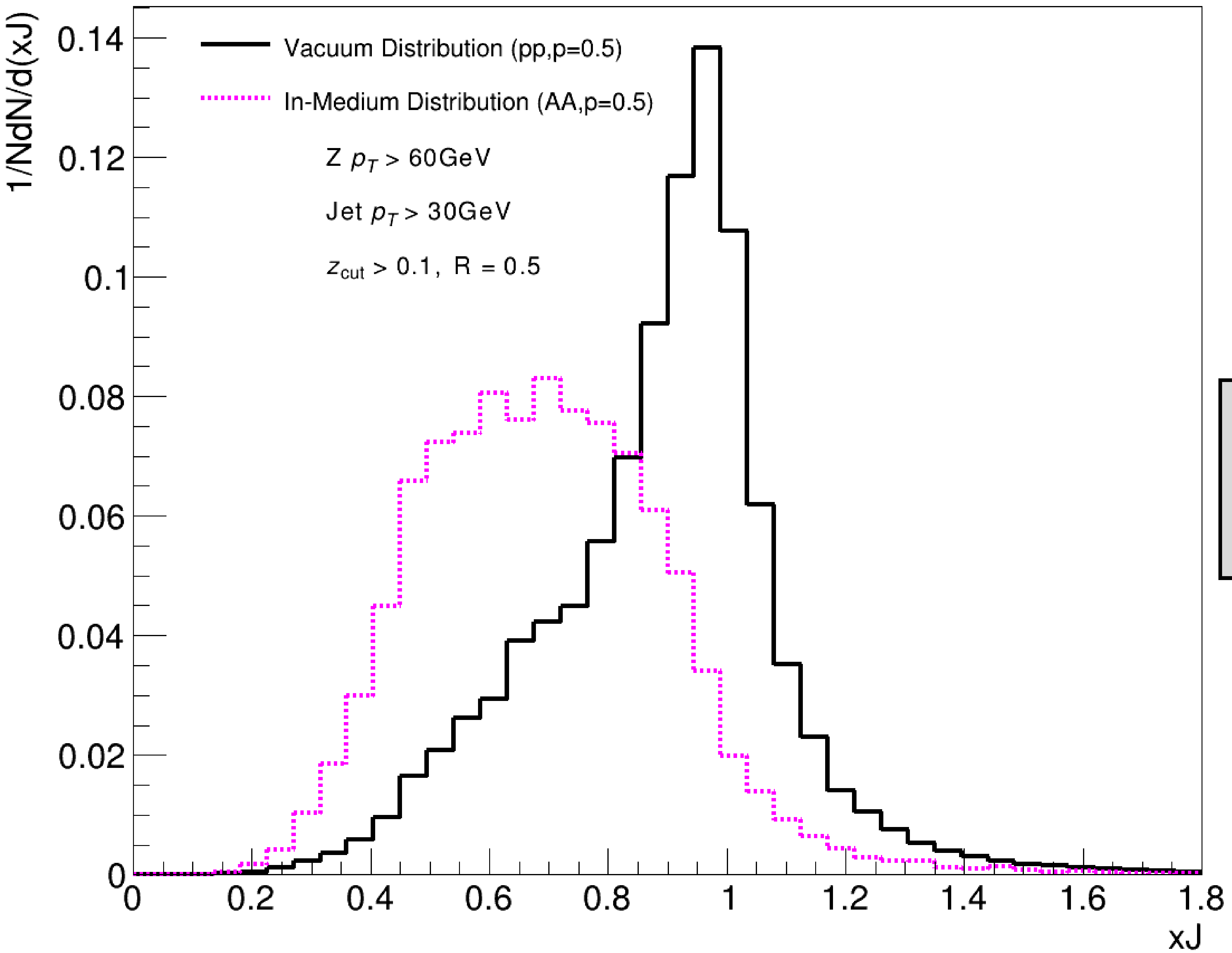


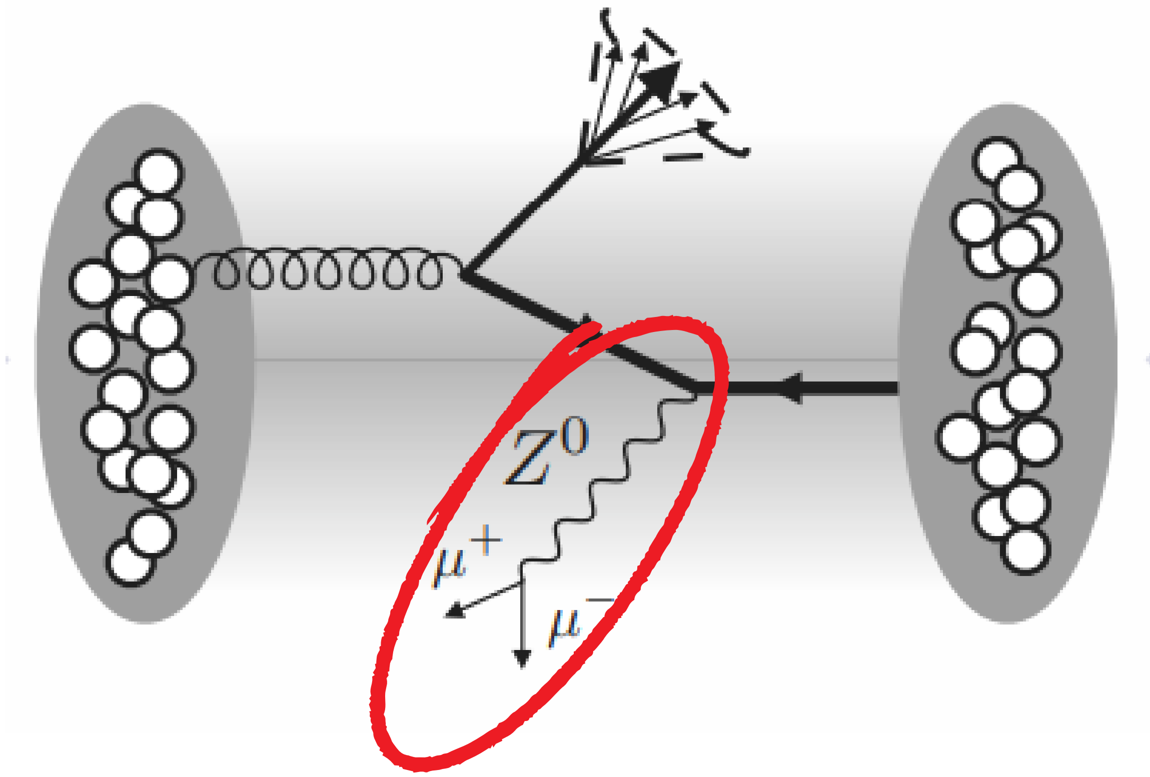
Conical schematic, SoftDrop applied

Vacuum (pp)

Comparing Momentum Imbalance Spectra

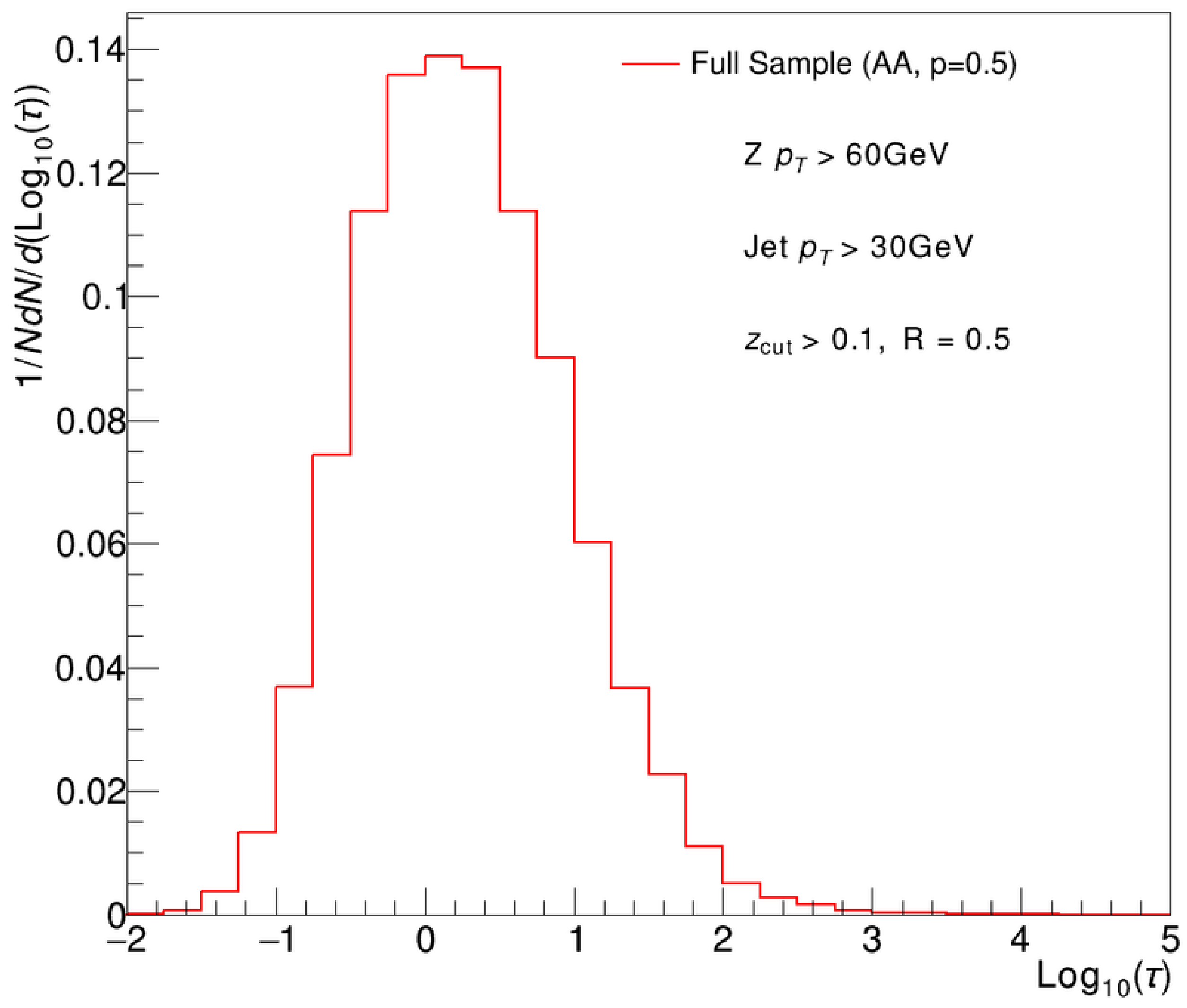
$$x_{jZ} = p_{j_\perp} / p_{Z_\perp}$$



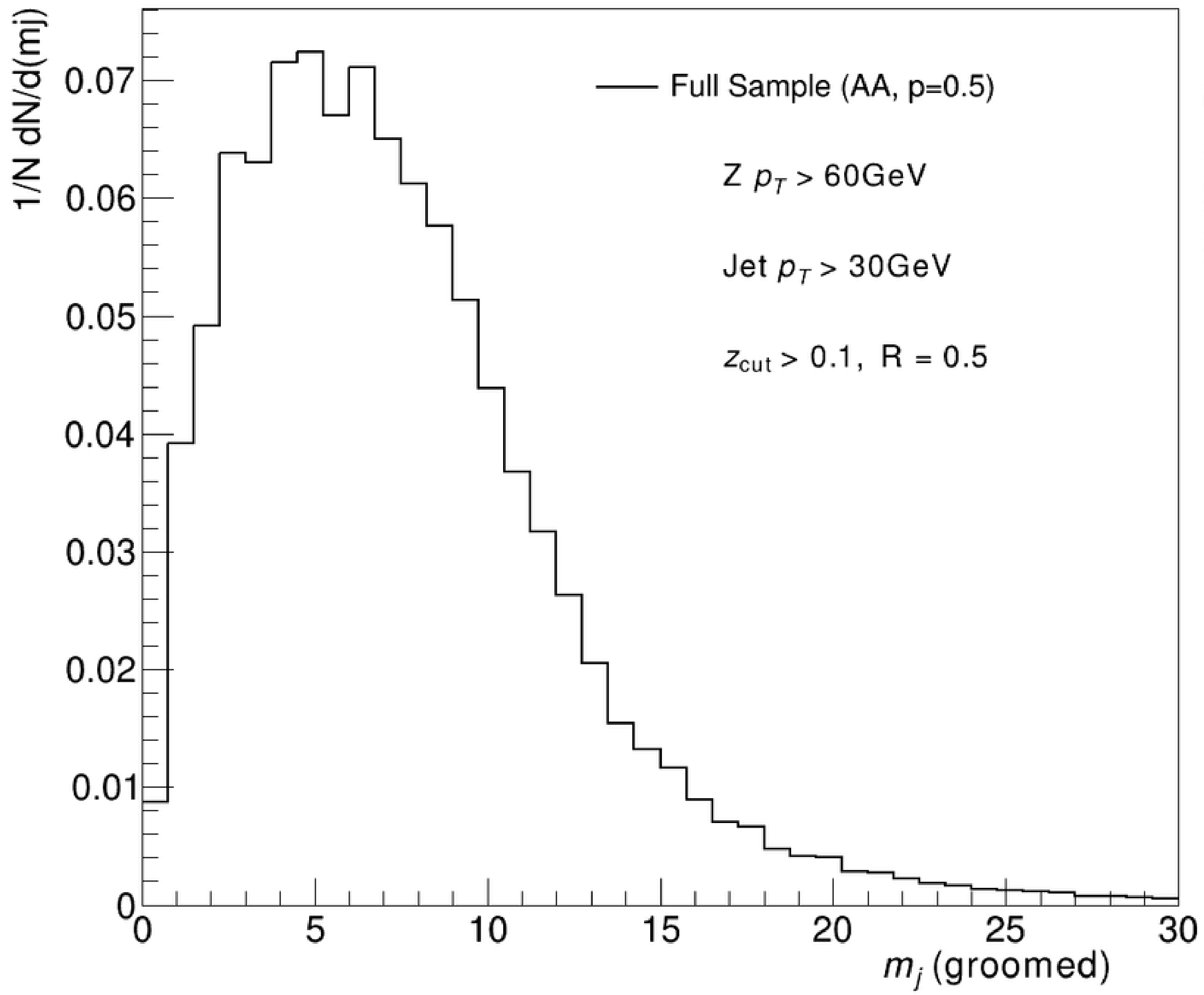


The 'Golden Channel' provides a clear example of medium-induced effects: jet quenching!

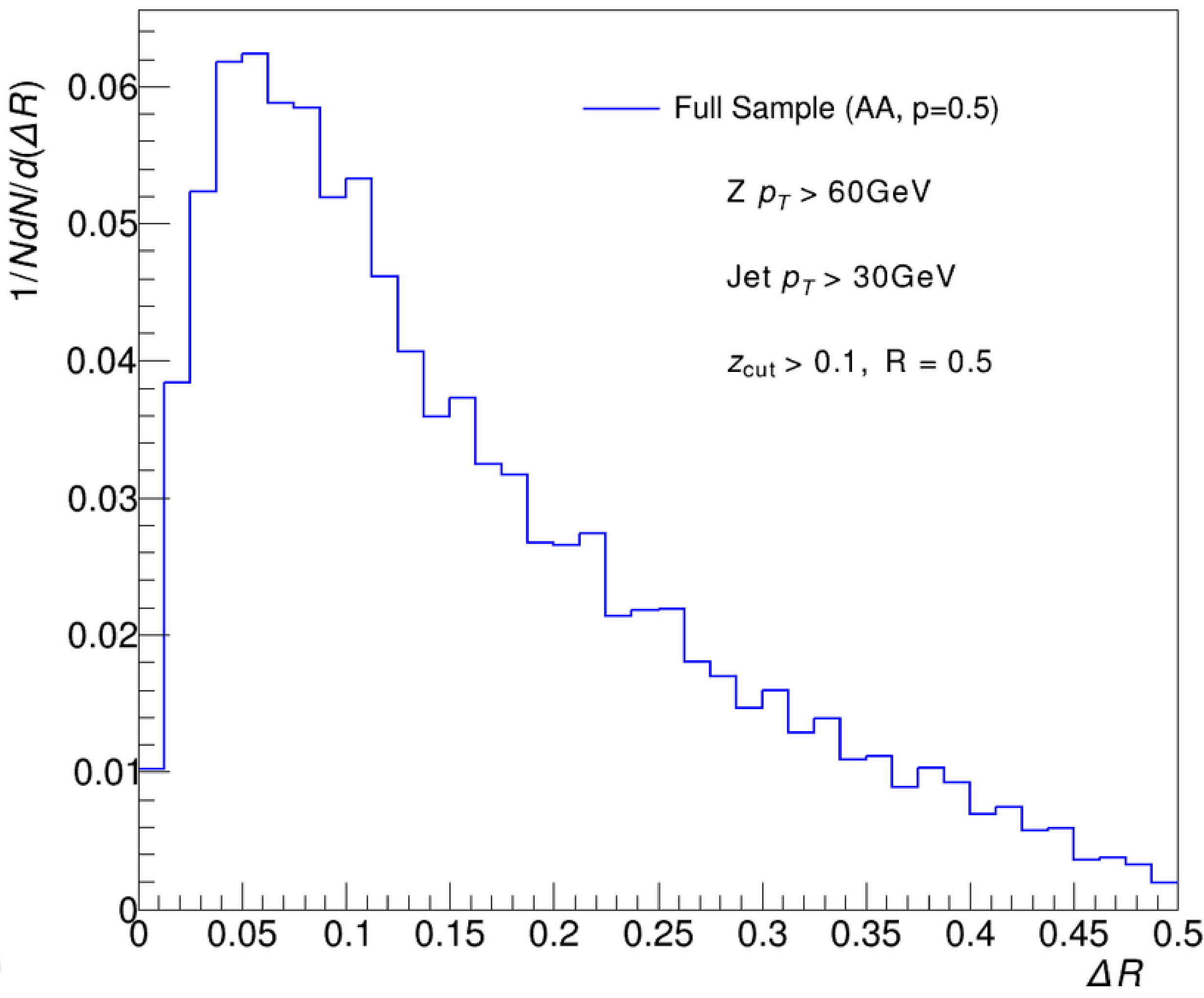
Kinematic Variables of Interest



τ_{form}



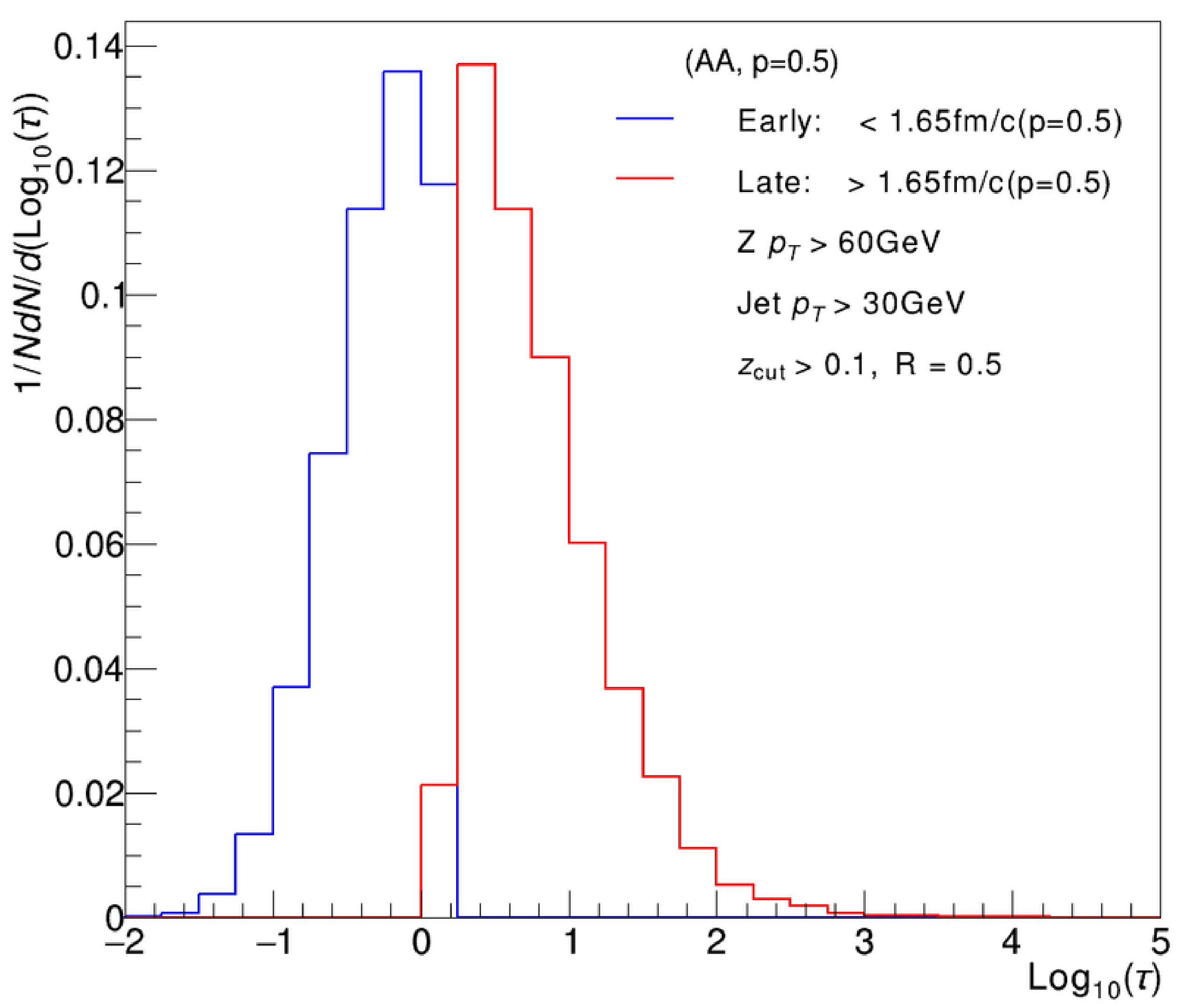
$m_{j_{\text{groomed}}}$



ΔR

Kinematic Variables of Interest

Splitting the selected kinematic variables by their **median** can highlight whether the same selection of jets is chosen by each variable based on the following distributions:



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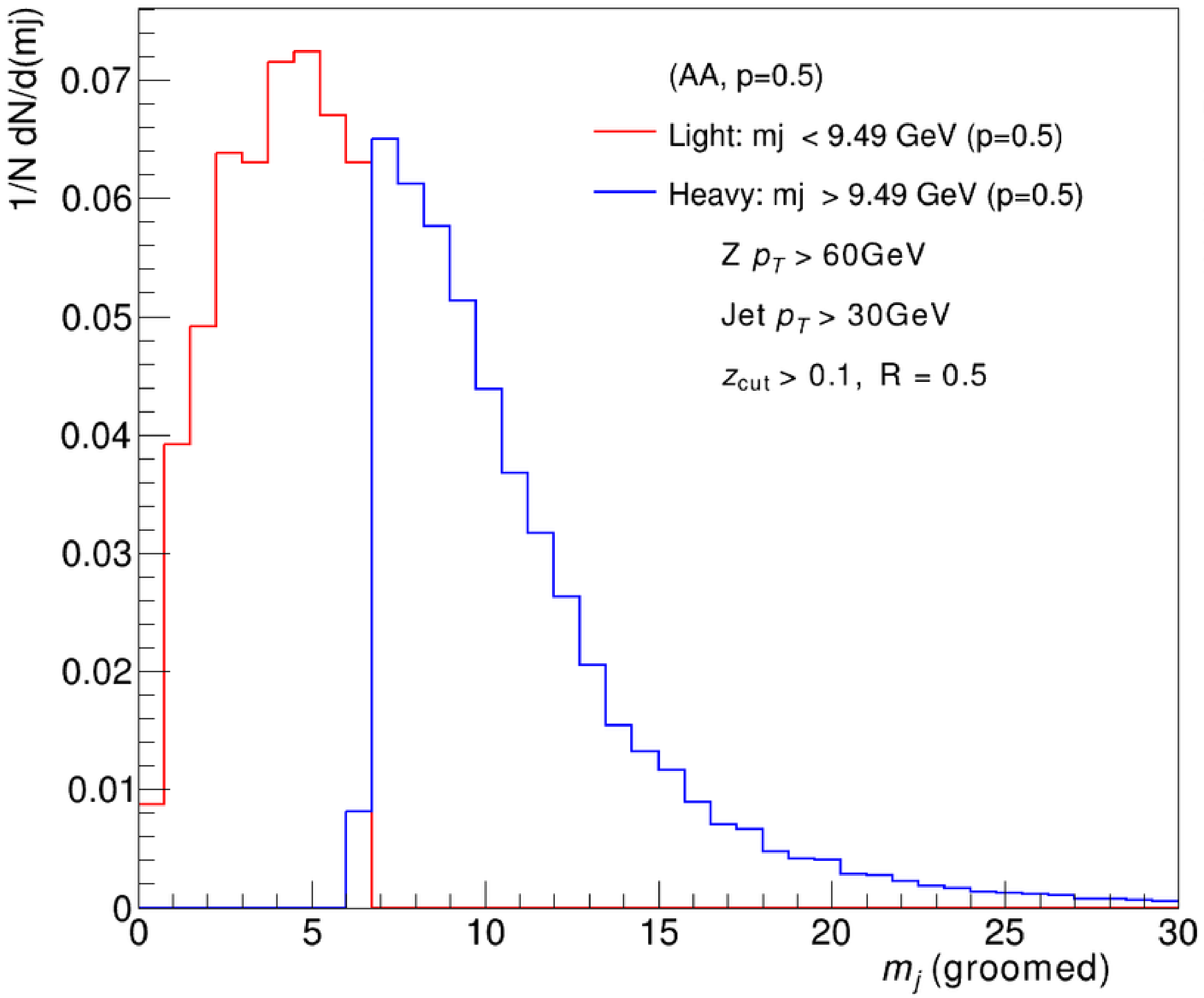

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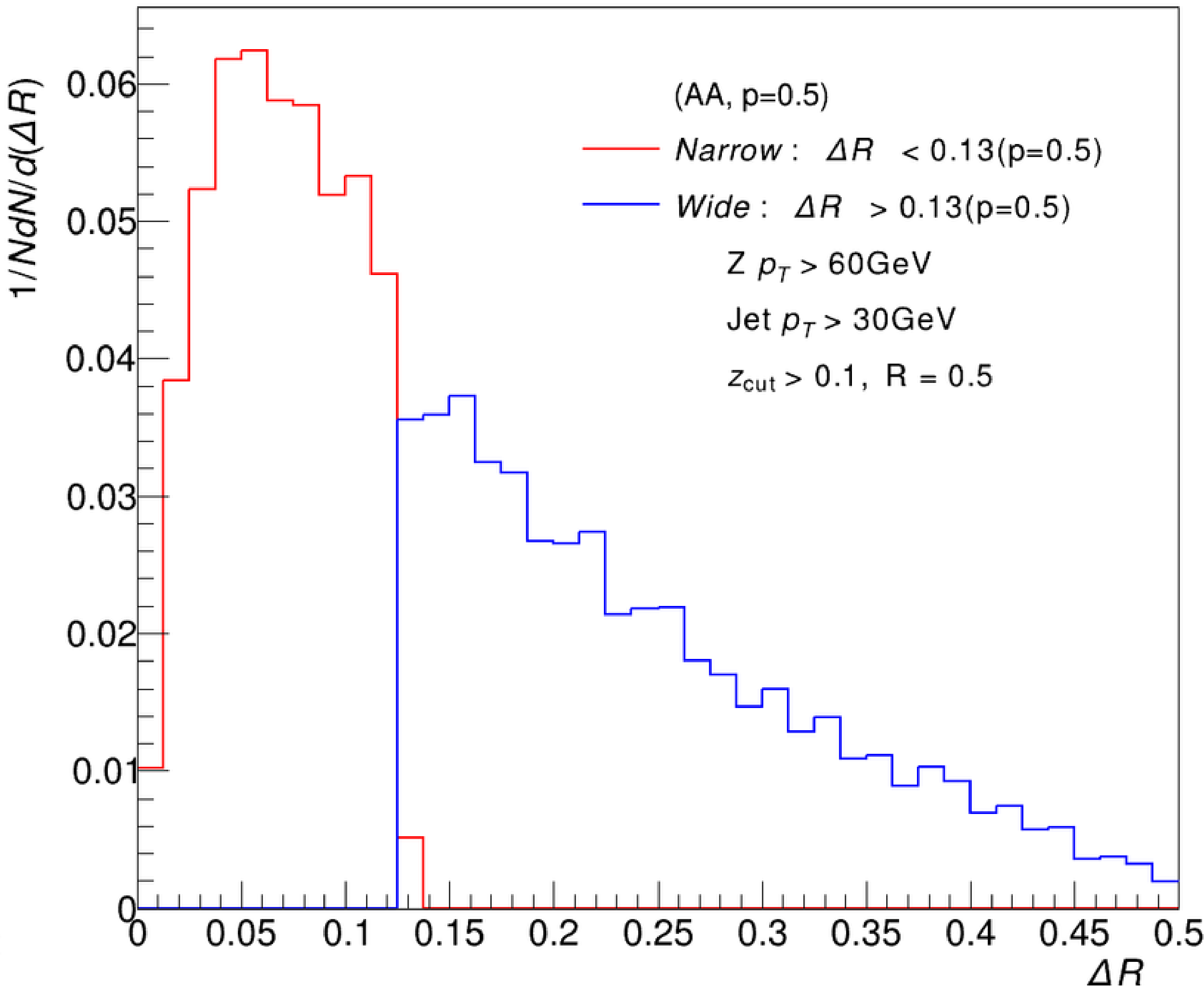
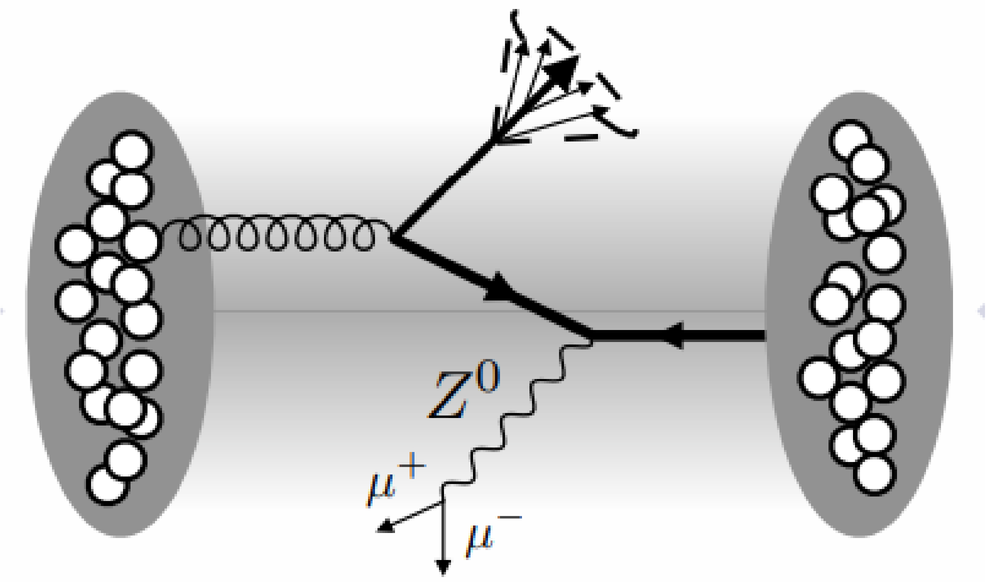


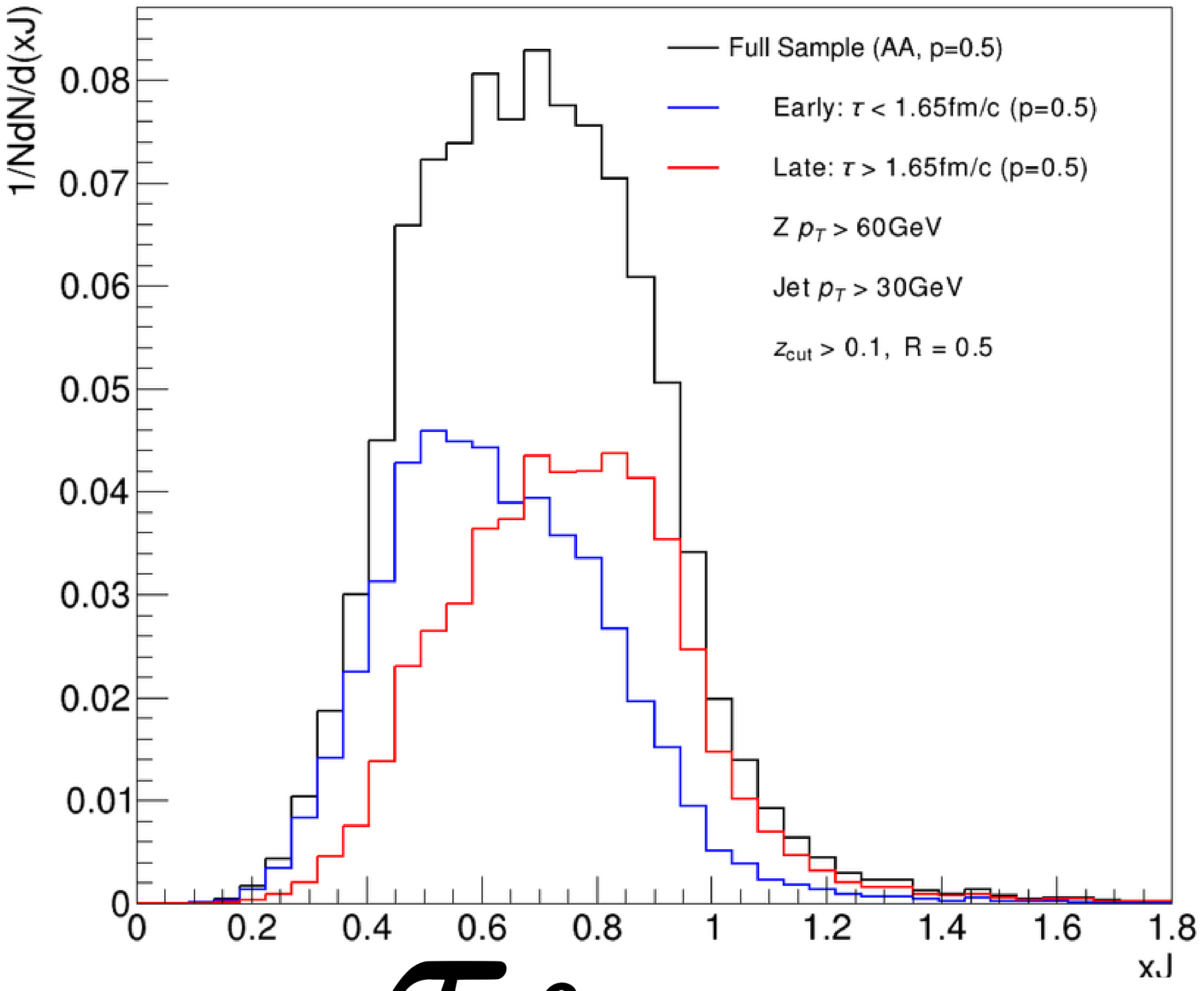
ΔR

Momentum Imbalance Spectra Splittings

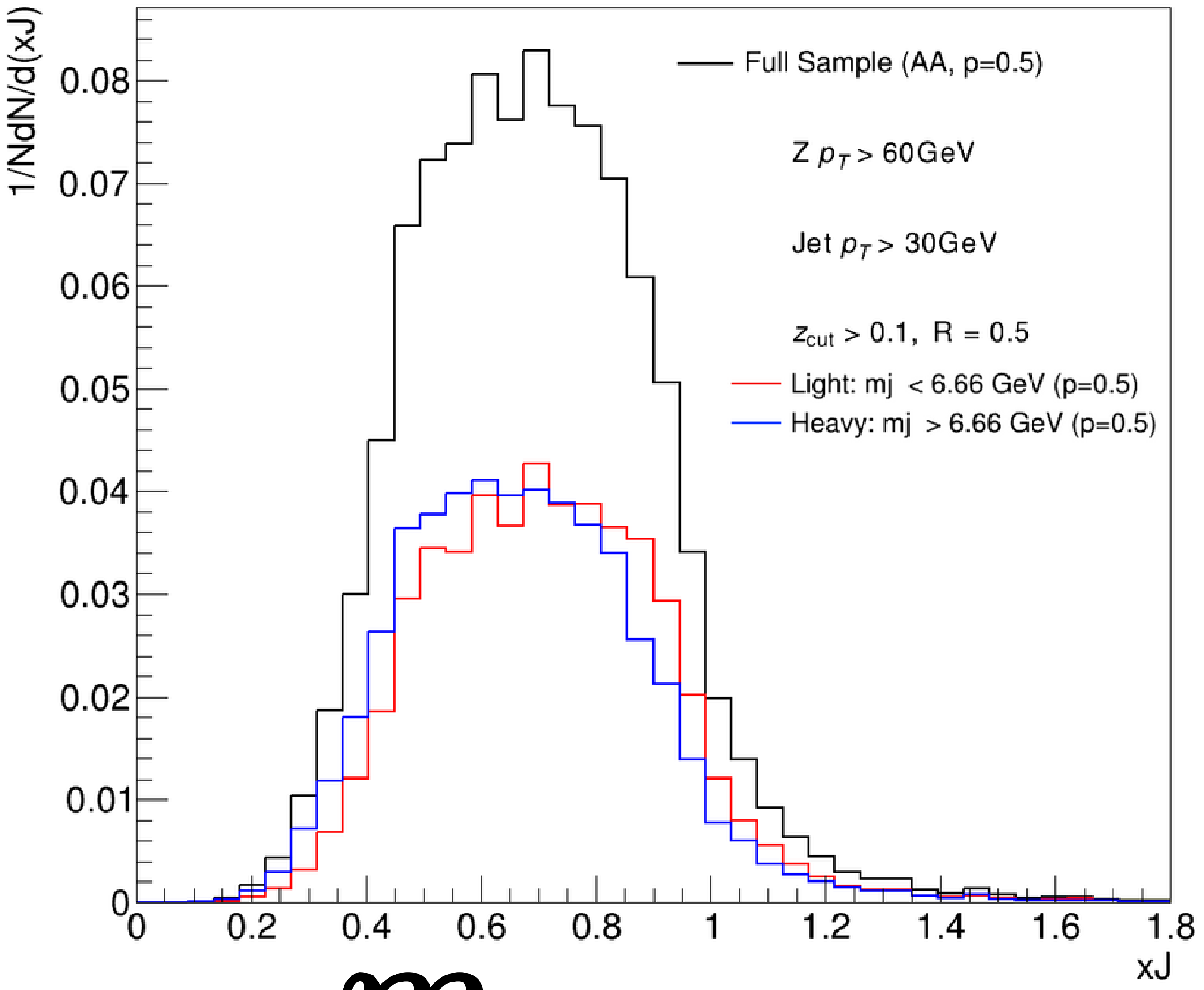
Groomed jet mass median splitting does **NOT** select the same sample of jets as formation time, nor opening angle.

Data suggests that these **correlated variables are physically different!**

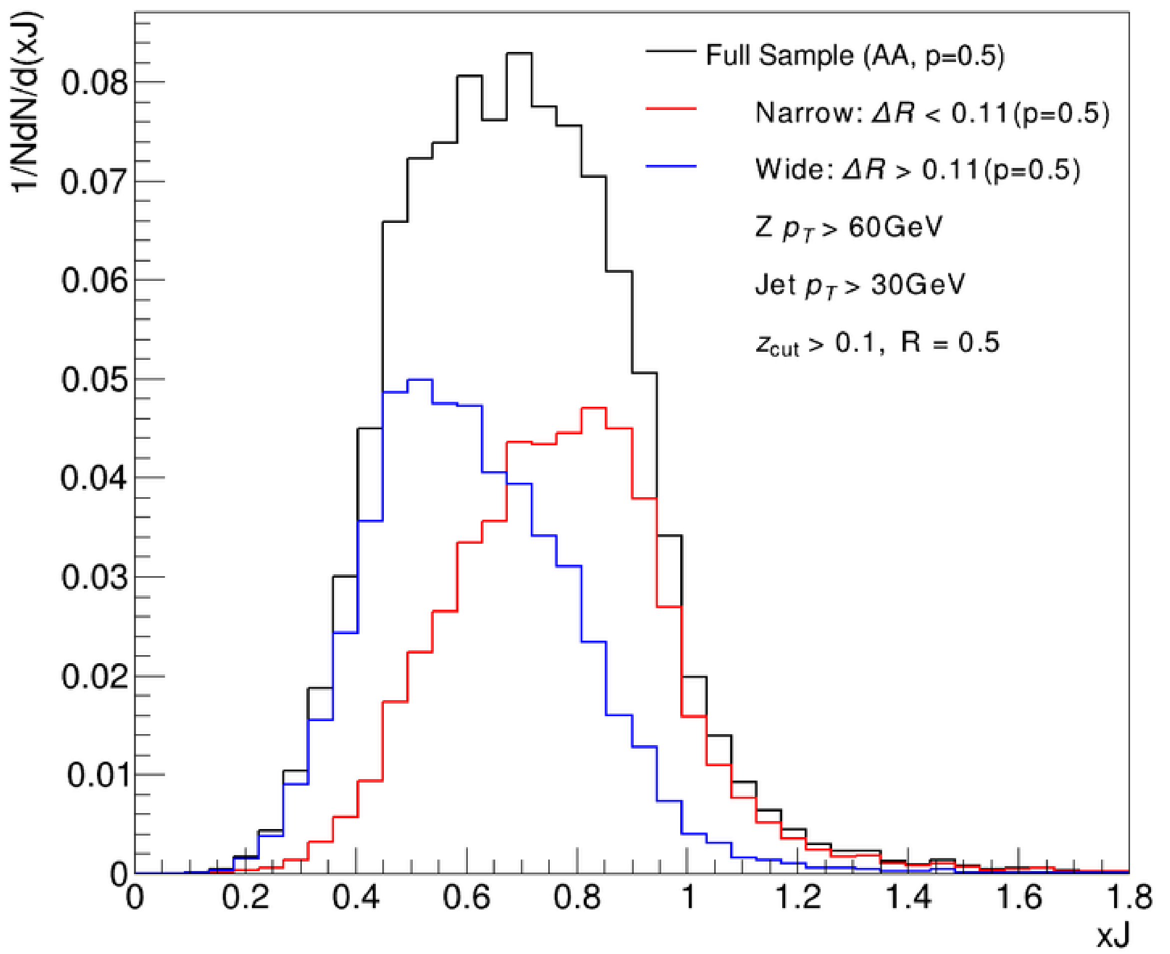




τ_{form}

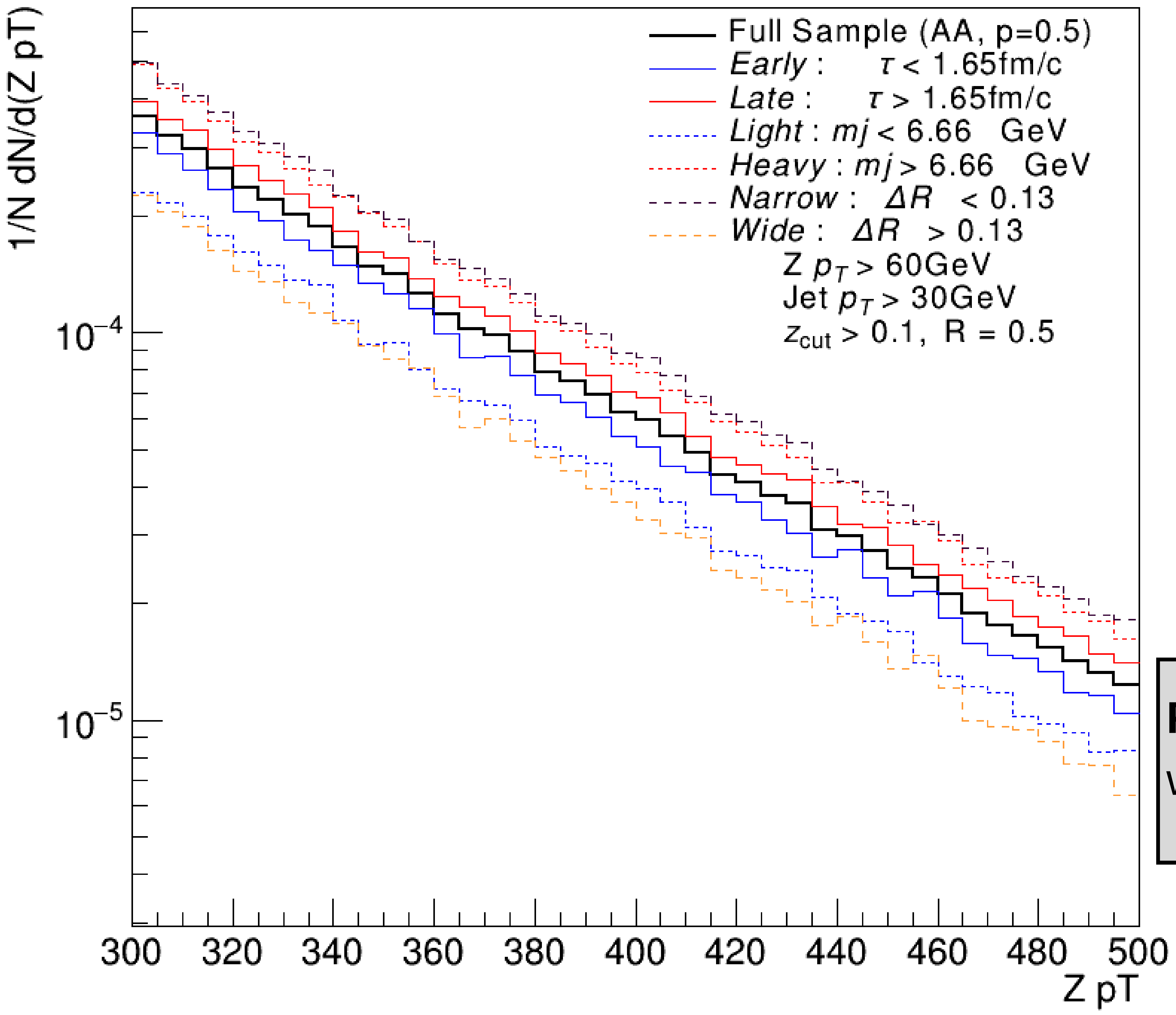


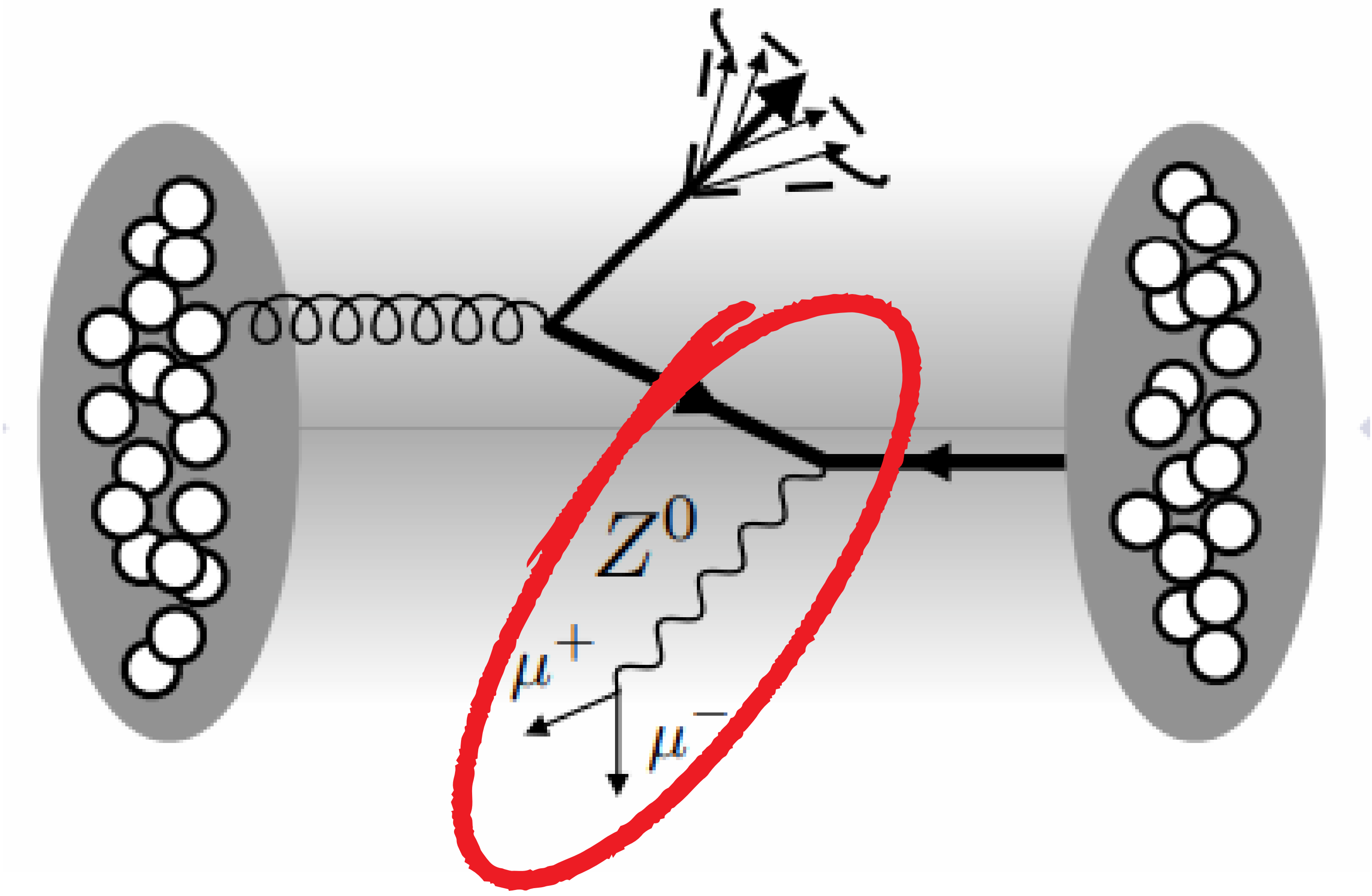
$m_{j_{\text{groomed}}}$



ΔR

Selection Bias Assessment:





Formation time is consistently the least biasing variable with respect to the Z boson momentum spectrum.

Summary

- Formation time algorithm consistently allows for a **reduction in selection bias during analyses**. Overall a strong candidate for future studies in the explored phase space.
- Groomed jet mass splitting corresponds to a **different selection of jets to formation time or opening angle**, as highlighted by the momentum imbalance spectra.
- Procedure was repeated for manual momentum fraction z cut = 0.1,0.2,0.05,0.0. Similar analyses were applied to R=1.0 datasets, as well as a repeat analysis for both radii with respect to momentum splitting. All data supports **formation time as the most promising candidate for future QGP probing**.

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Fin.

Scan Me!

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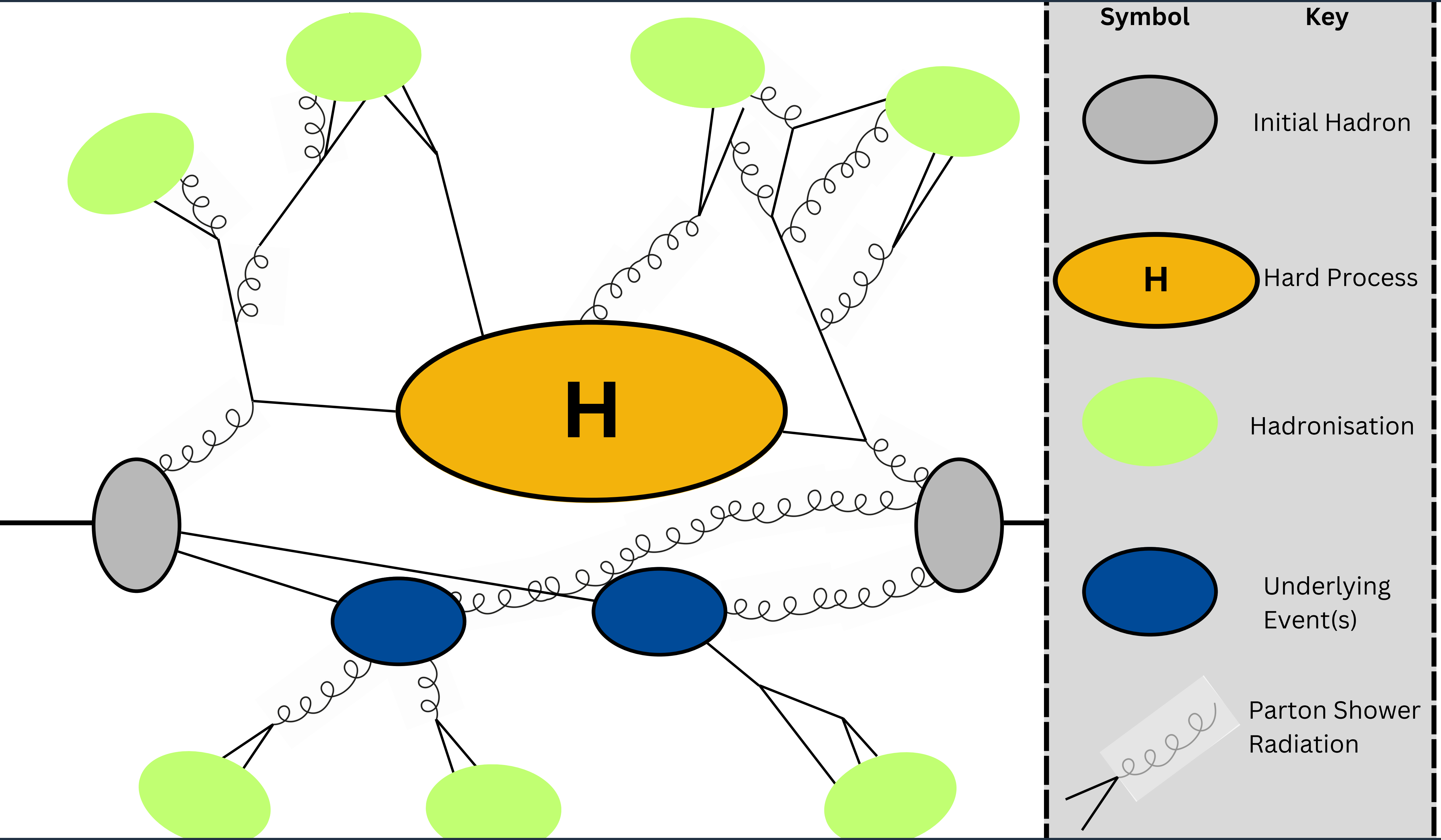
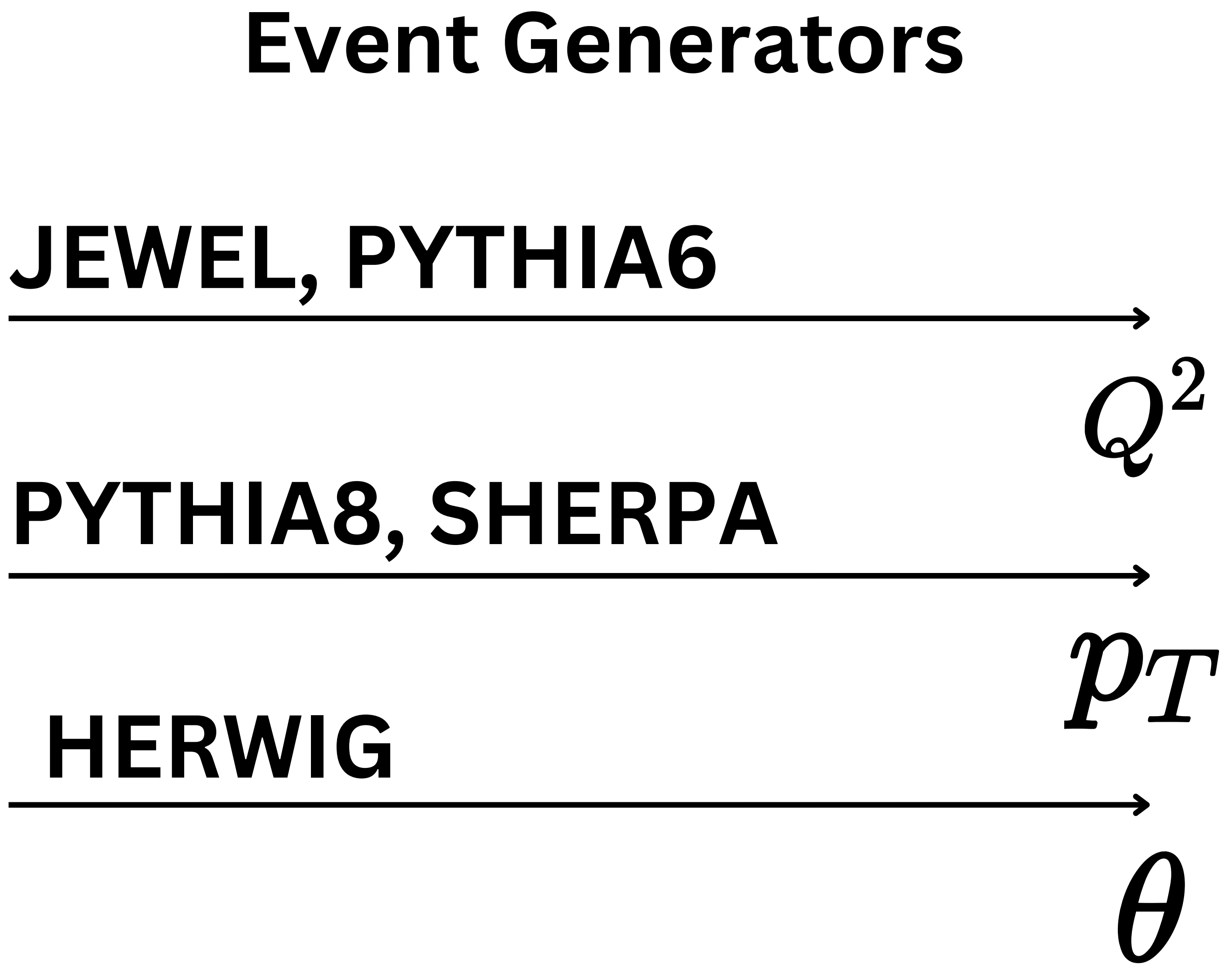
Backup Slides

Parton Showers

- LO QCD-led Simulations.
- Computationally extensive.
- Easy to simulate BSM physics via parameter tweaks.



In typical parton shower algorithms, the main approximation is collinear or soft splitting.



Clustering Algorithms Extended

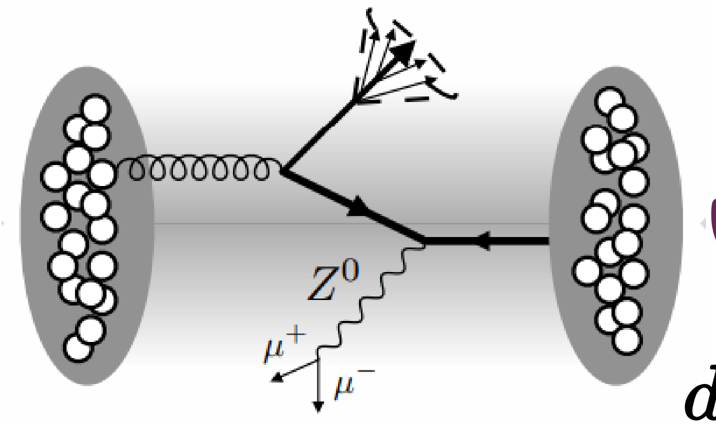
- **Anti-kT (p=-1)**, behaves as an idealised cone algorithm: creates perfectly conical jets for well separated, hard jets (ΔR > 2R, p>>Q).
- For a hard particle, 1, and a soft particle, i, the angular separation clusters i into 1 without any significant uncertainty.
- Used overwhelmingly often for clustering due to conical output.

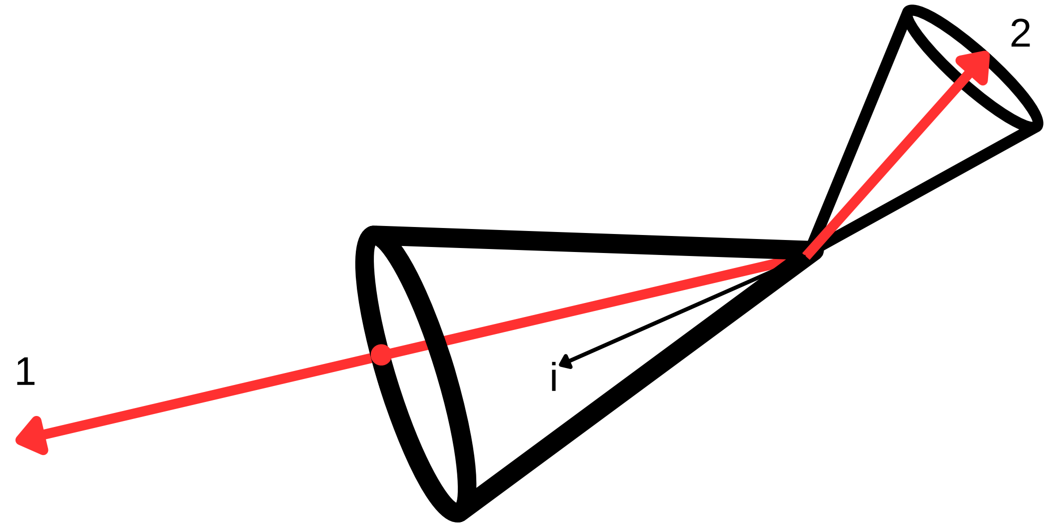
<u>Selection Cuts</u>

$$p_{T_j} > 30 \text{ GeV}$$
$$p_{T_Z} > 60 \text{ GeV}$$
$$z_{\text{cut}} = 0.1$$
$$\beta = 0$$
$$|\eta_{\text{jet}}| < 1.6$$
$$\Delta\phi > \frac{7\pi}{8}$$
$$R = 0.5$$

Event Generators used: **PYTHIA8** to compare experimental jets to those produced in vacuum (**pp**), and a version of **JEWEL** containing parton shower history for **PbPb** collisions

Data is taken from the Z+jet channel, which provides the **best experimental signature for energy loss purposes**, including a **strong estimate for the initial jet momentum**.





Hard, well-separated jets

$$d_{ij} = \min\left(\frac{1}{p_{Ti}^2}, \frac{1}{p_{Tj}^2}\right)\frac{\Delta R_{ij}}{R} \longrightarrow d_{1i} = \min\left(\frac{1}{p_{T1}^2}, \frac{1}{p_{Ti}^2}\right)\frac{\Delta R_{1i}}{R}$$

Declustering Framework Comparison

$$d_{ij} = min(p_{Ti}^{2p}, p_{Tj}^{2p})\frac{\Delta R_{ij}}{R}$$

C/A (p=0) $d_{ij} = \frac{\Delta R_{ij}}{R}$	τ_{form} (p=0.5) $d_{ij} \approx p_{Ti}\theta^2 \approx \frac{1}{\tau_{\text{form}}}$ *
• Fits QCD description of vacuum very well due to angular ordering. • Works as the methodological inverse of the HERWIG MC generator. • Extensive applications across the field in pp collisions. • Anti-angular ordering introduced in HIC's diminishes resourcefulness.	• Quantum mechanical variable representing formation time: used as proxy. • Formation time is the inverse of the computed distance measure, anti-angular ordering introduced in HIC's is treated by *. • Newly proposed algorithm; current studies are currently less rigorous than it's predecessors.

$$\text{Soft-collinear limit: } \tau_{form} \approx \frac{E}{Q^2} \approx \frac{1}{2Ez(1-\cos\theta_{12})}$$

Relates nicely to virtuality

Tools for Tomography... (De)Clustering!

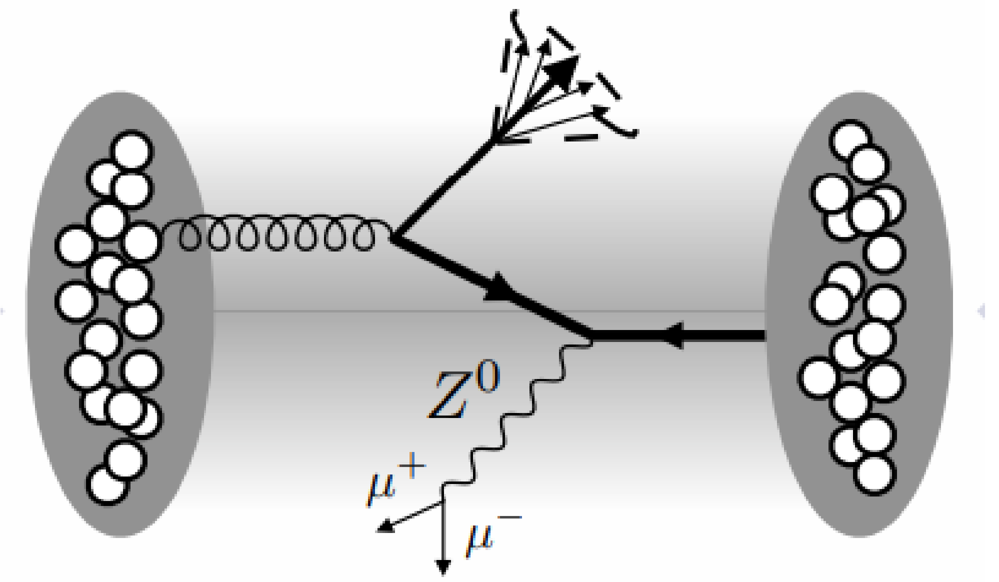
How do we use jet clustering to see 'under the bonnet'?

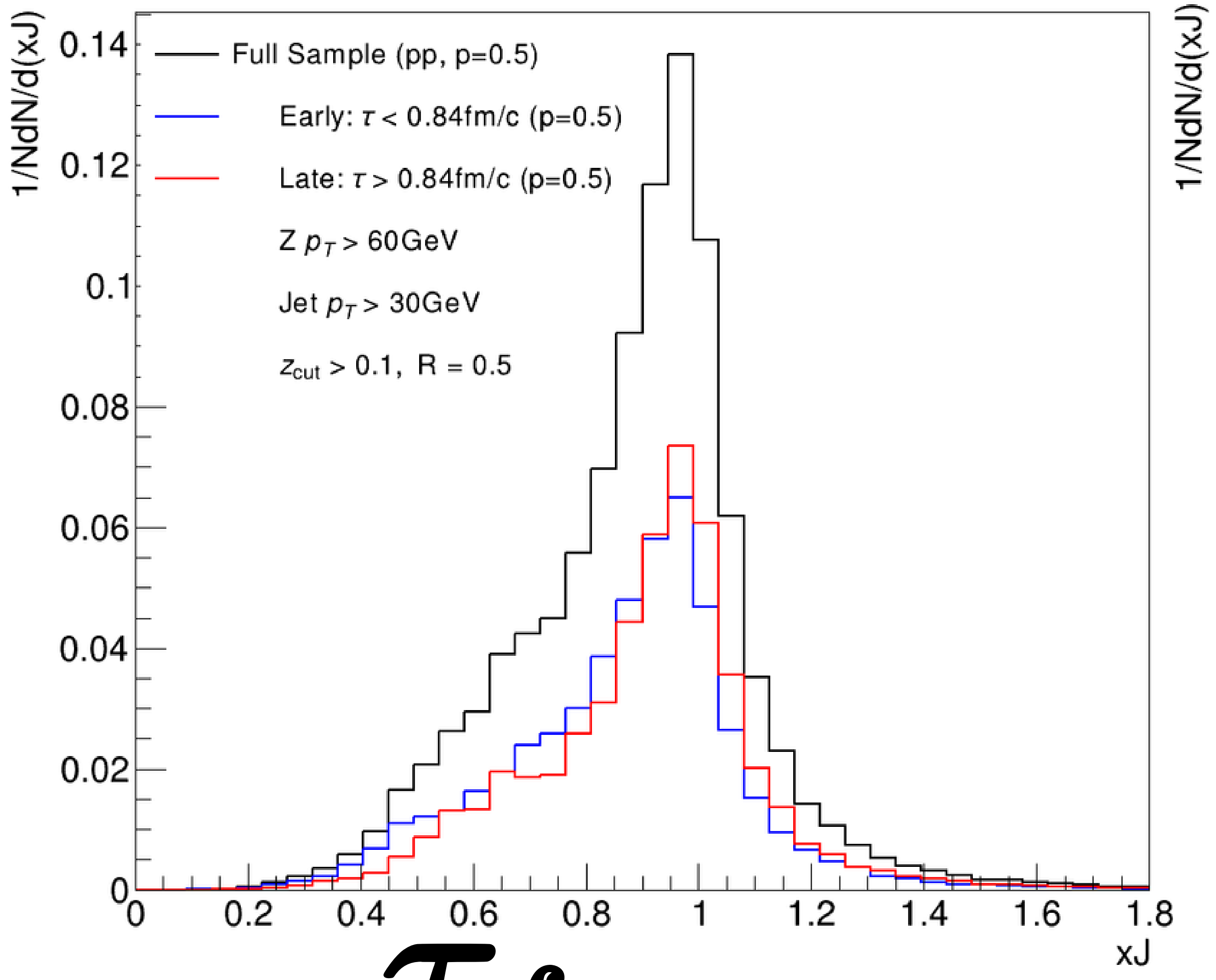
2008: Revival of jet substructure:

- List of pseudo-jets with kinematic variables; calculate d_{ij}, , d_{iB}.
- Compare & combine: merge particles with the smallest d_{ij}, or if d_{iB} is the smallest, classify pseudo-jet as a jet.
- Iterate for all particles until all have been collected into jets. Now we have a sequential history of combinations (clustering).

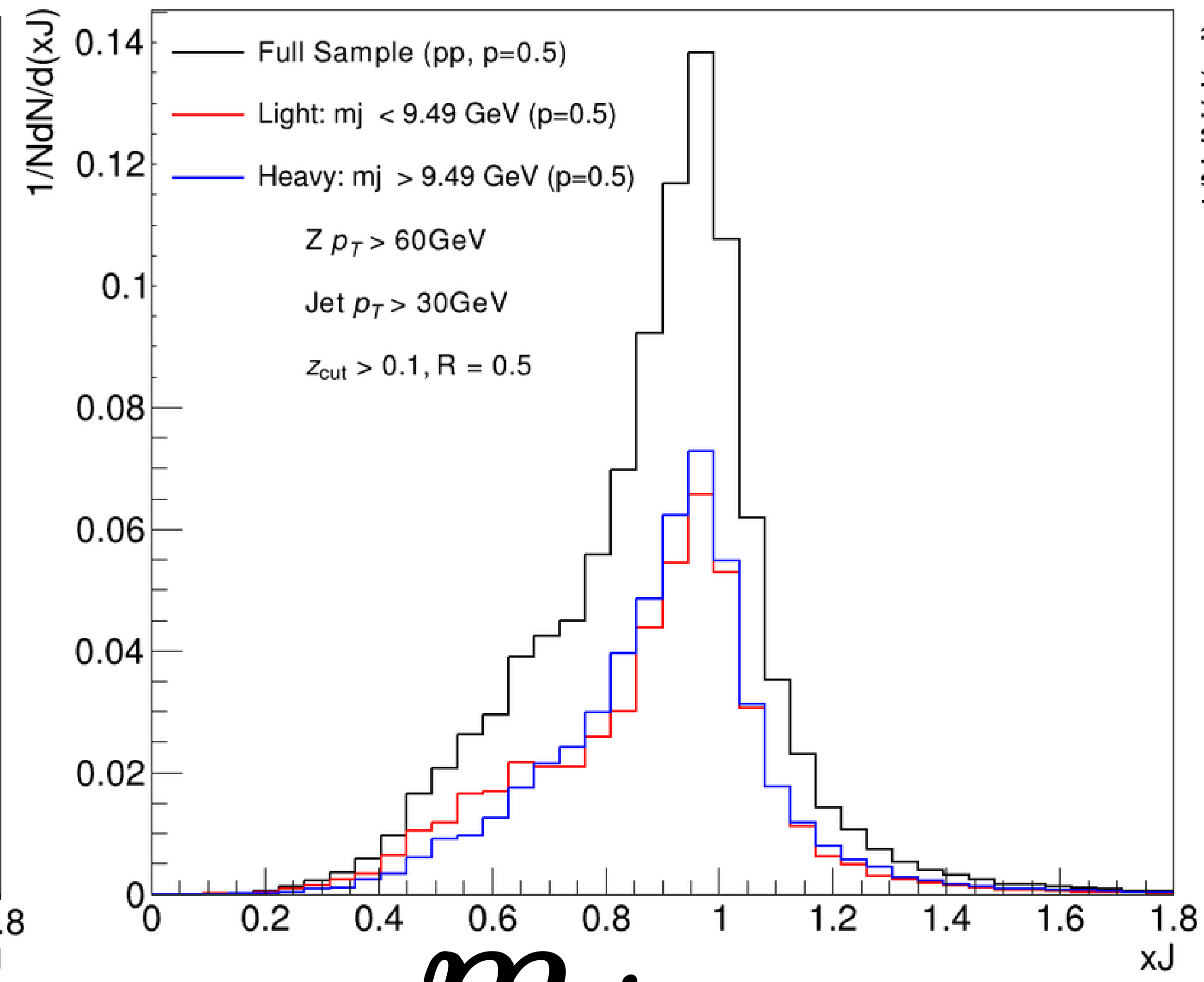
xJ: what about Vacuum?

Very similar distributions regardless of splitting variable: the kinematic variables of interest are sensitive to medium-induced effects in.

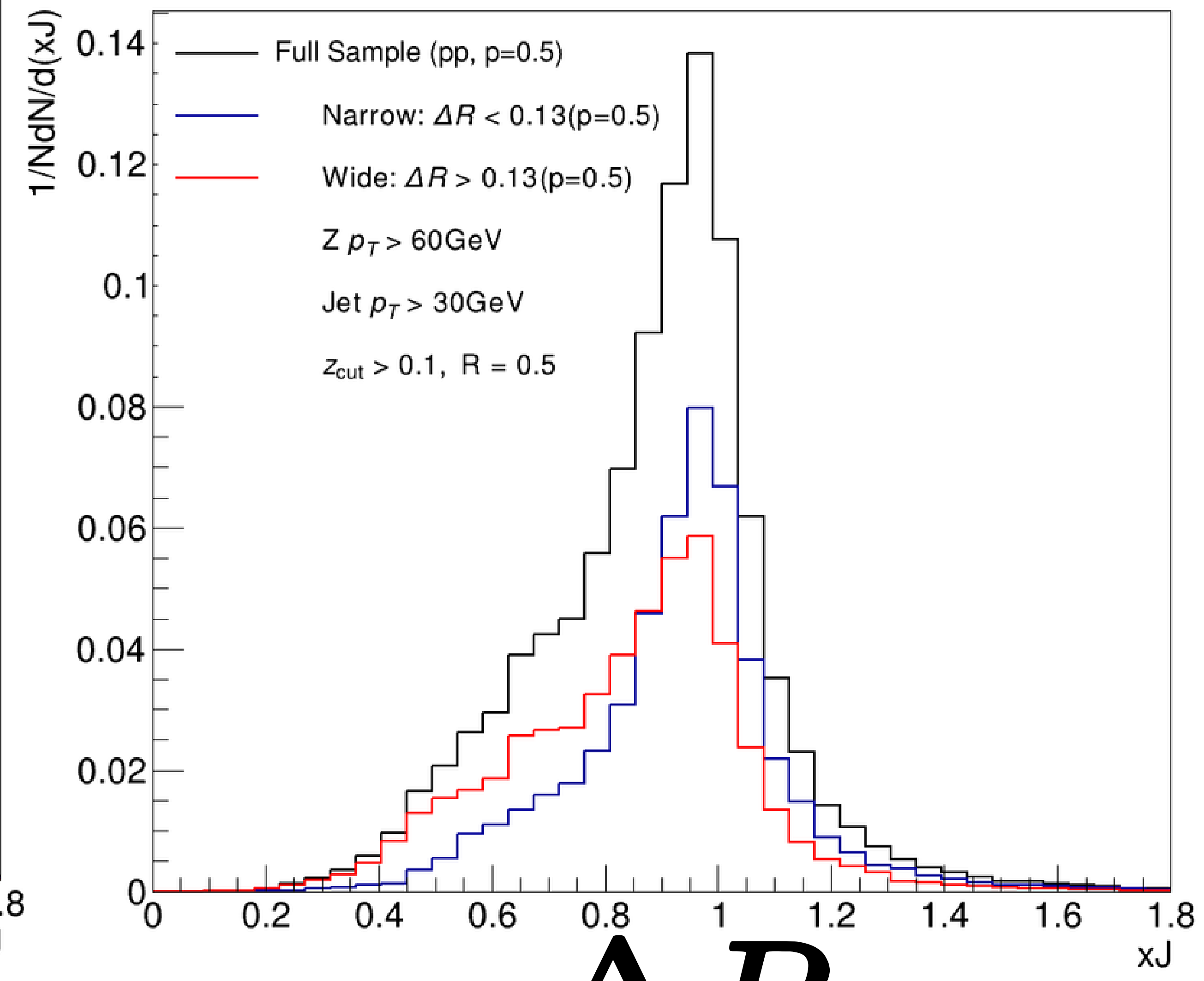




τ_{form}

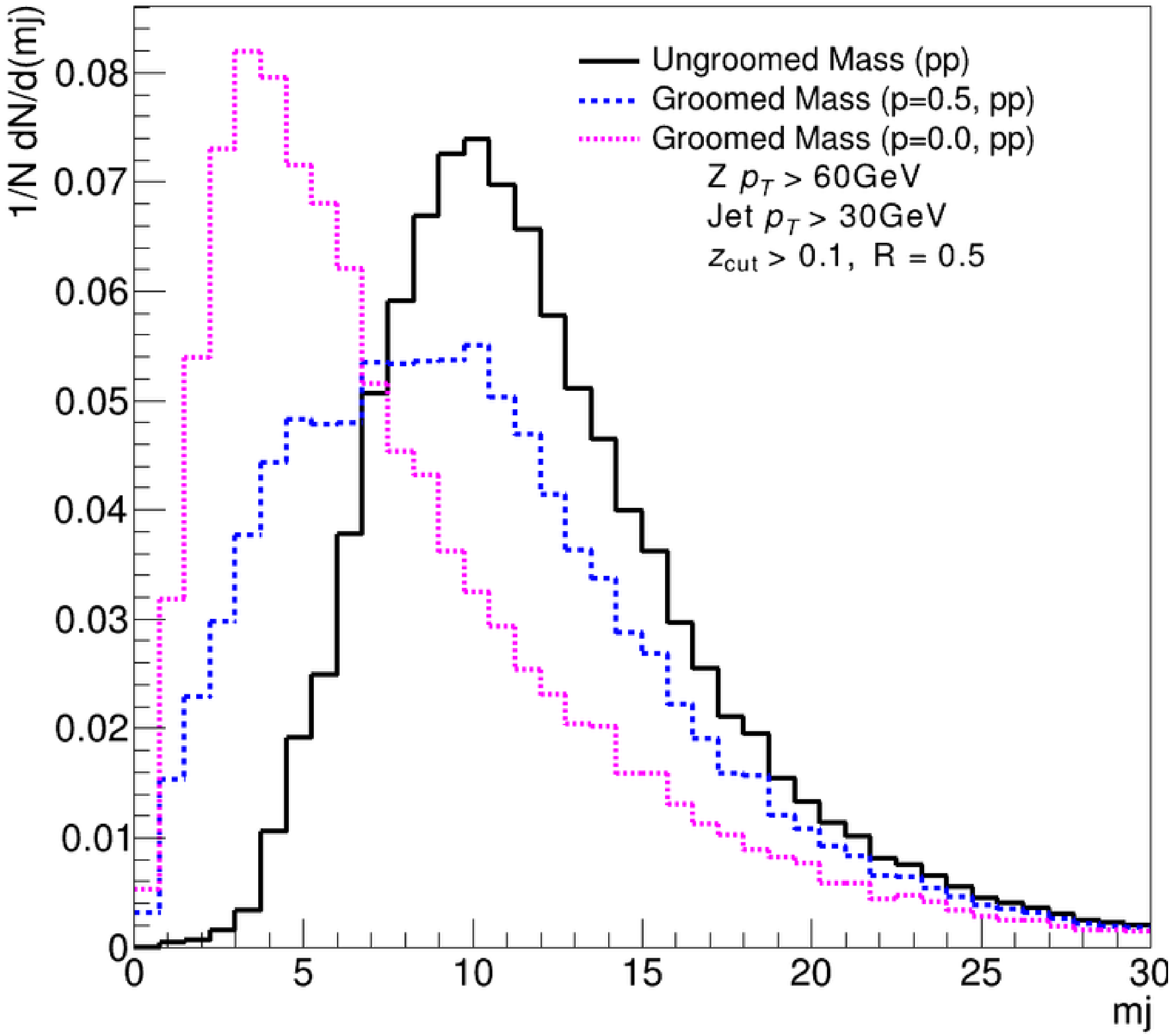


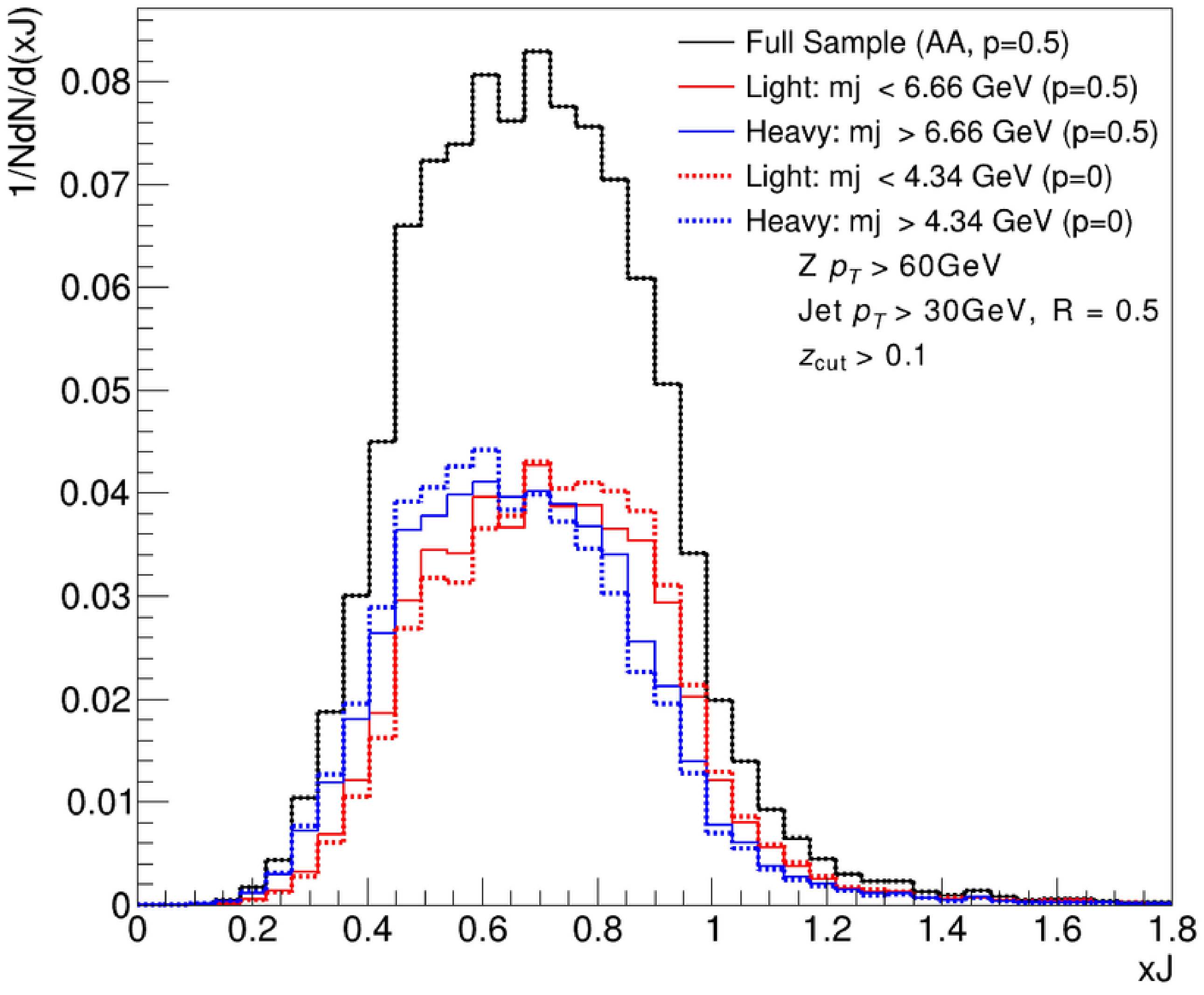
$m_{j_{\text{groomed}}}$

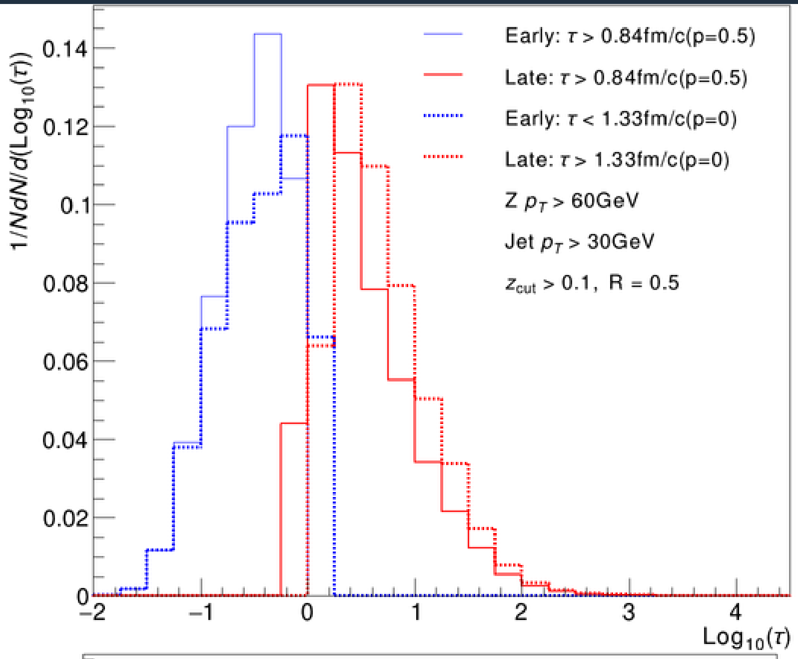


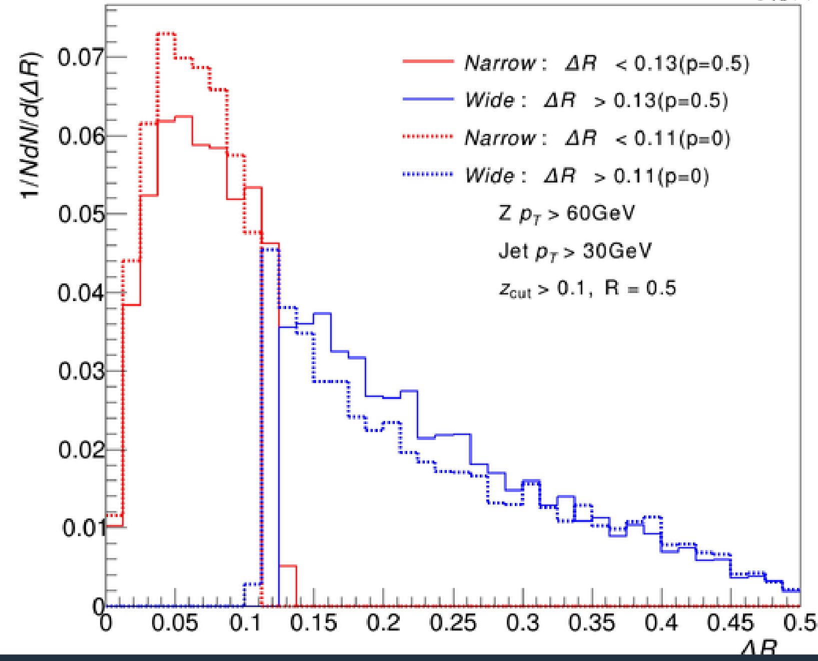
ΔR

What about C/A?









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