Time reclustering for jet quenching

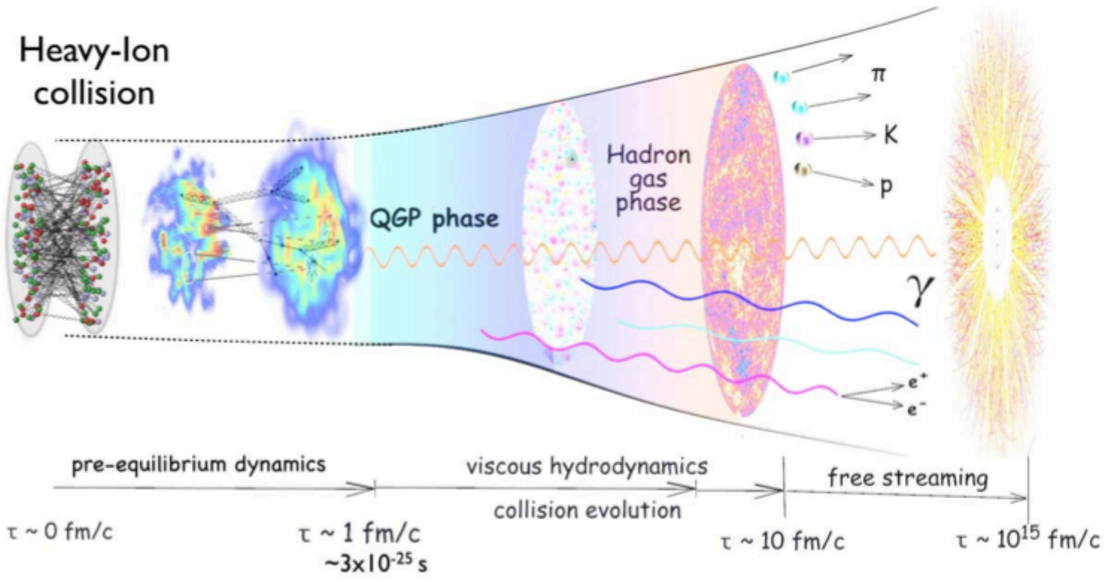
Liliana Apolinário

In collaboration with A. Cordeiro, P. Rodriguez and K. Zapp

QGP: a fast expanding medium

- What is the information that we get?
  - Integrated result of the whole medium (fast) evolution
    - However there is a strong time-dependence of the medium properties (expansion and cooling of the system)

[talks: Carlota, Souvik, Andrey, João]

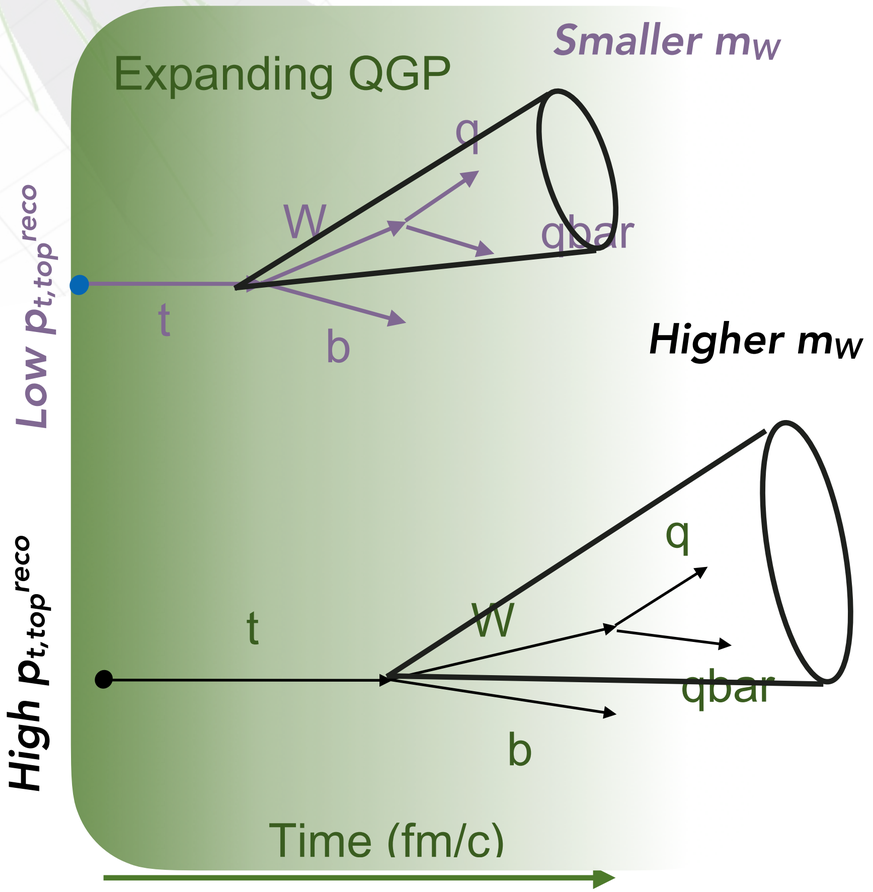


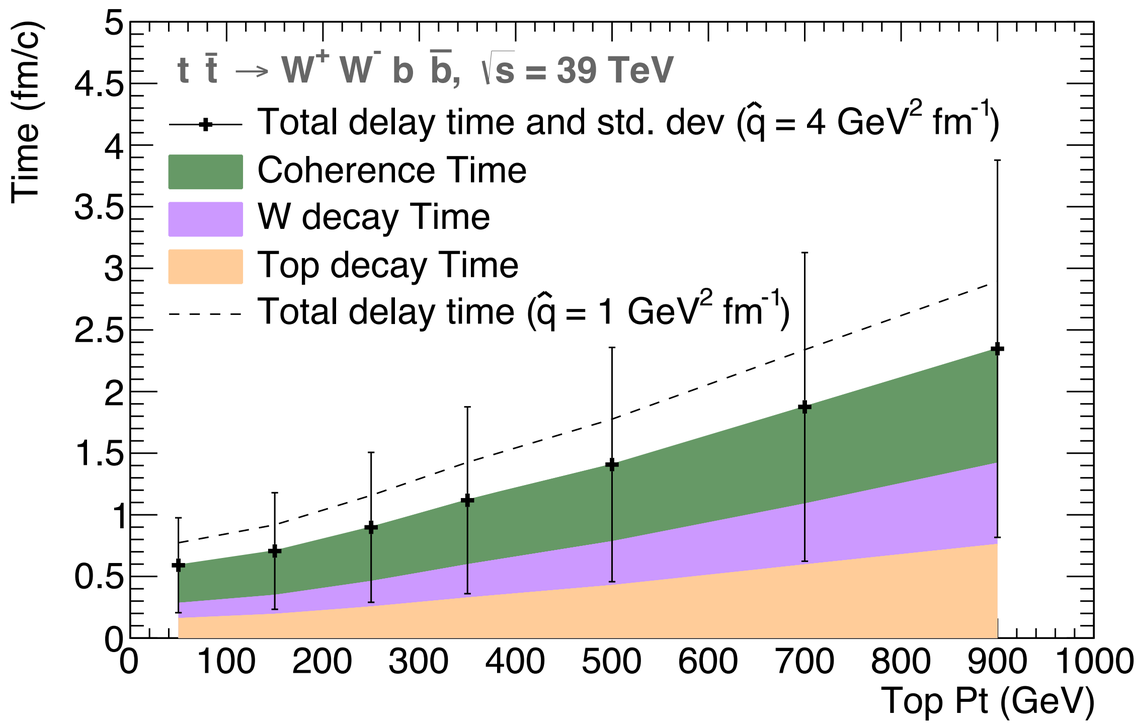
Can hard probes be able to probe different structures of the QGP?

Sensitivity to QGP timescales

[LA, Milhano, Salam, Salgado (19)]

- Reconstructed hadronic W boson jet mass:





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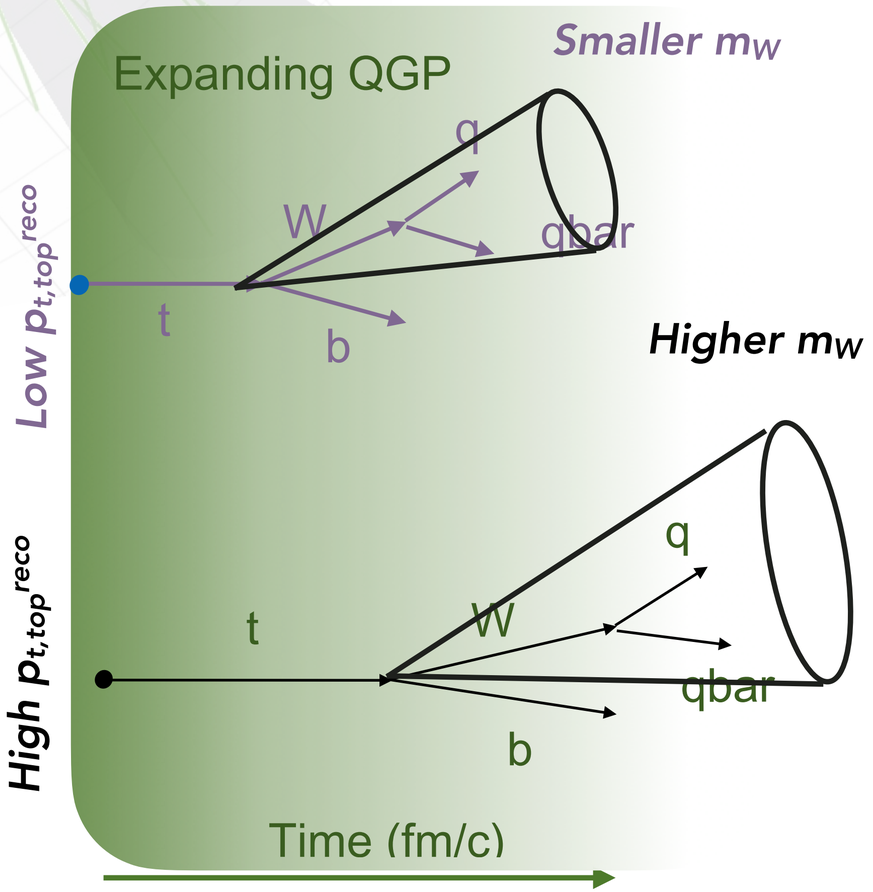
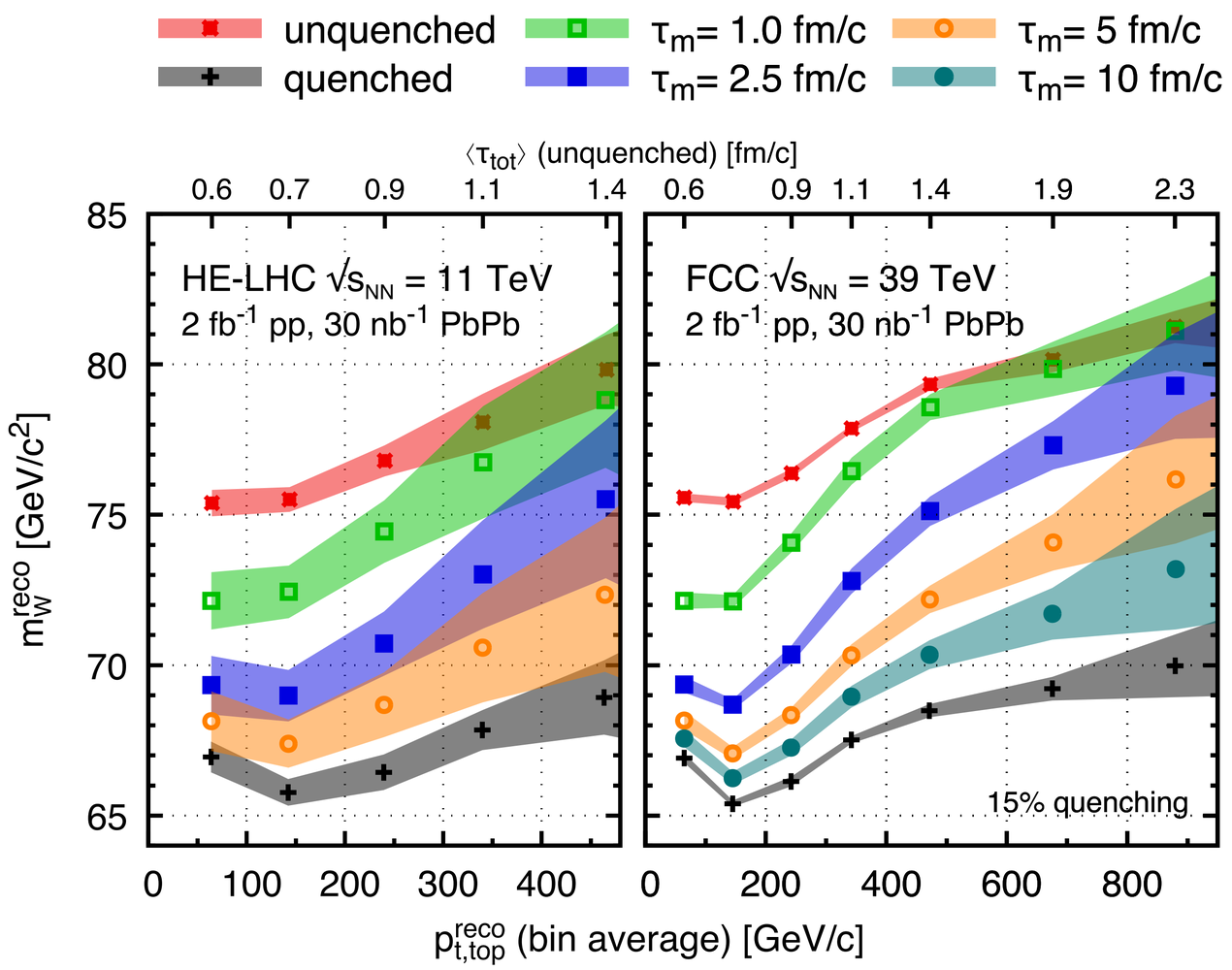


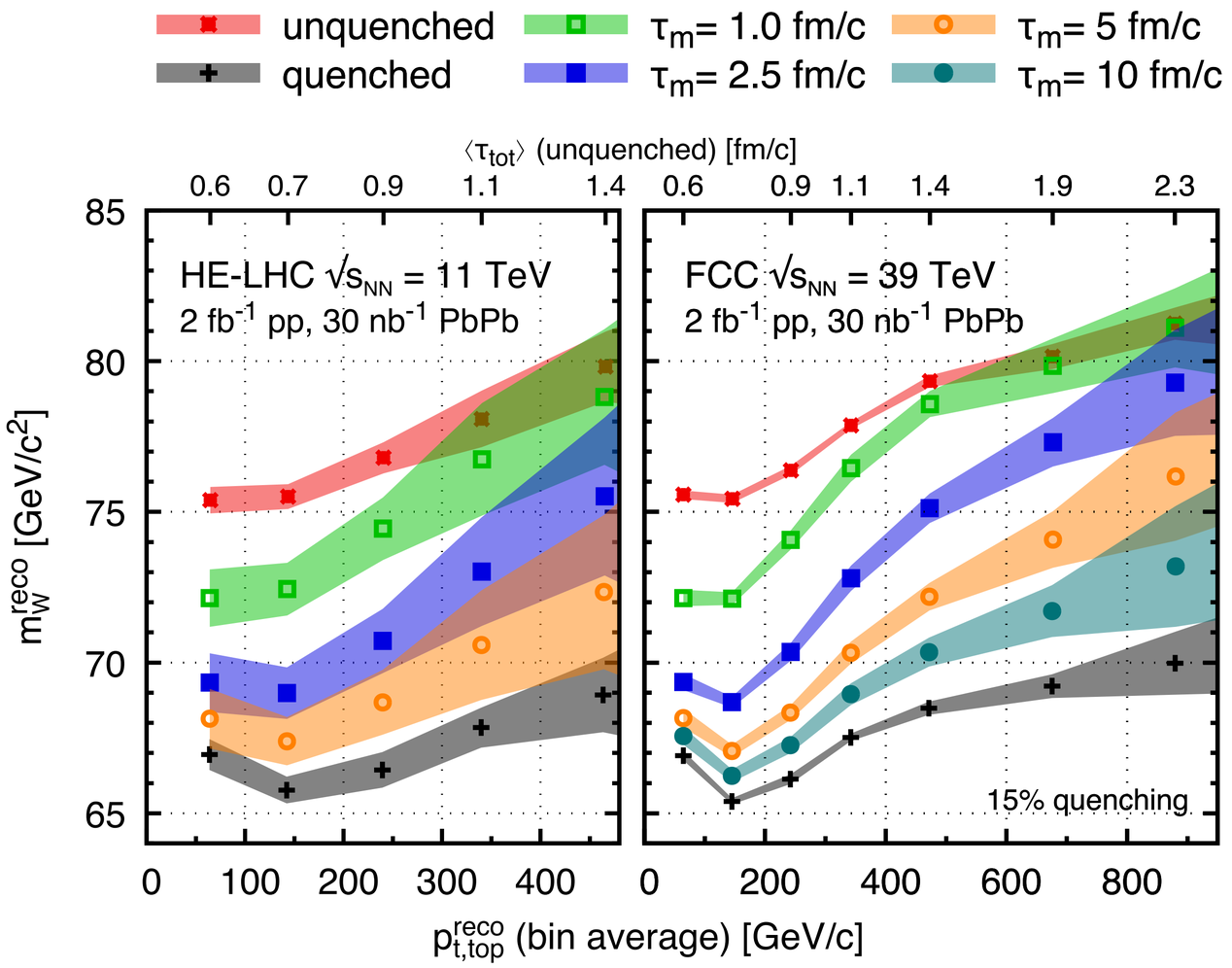


@ FCC: Full QGP tomography!

Sensitivity to QGP timescales

[LA, Milhano, Salam, Salgado (19)]

- Tops can be used as probes of the QGP time structure
  - Limited by statistics at current LHC energies
- How about jets?



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[Gen-kT (FastJet): Cacciari et al (2012)]

Jets

- What are jets?

From: K. Zapp (21)

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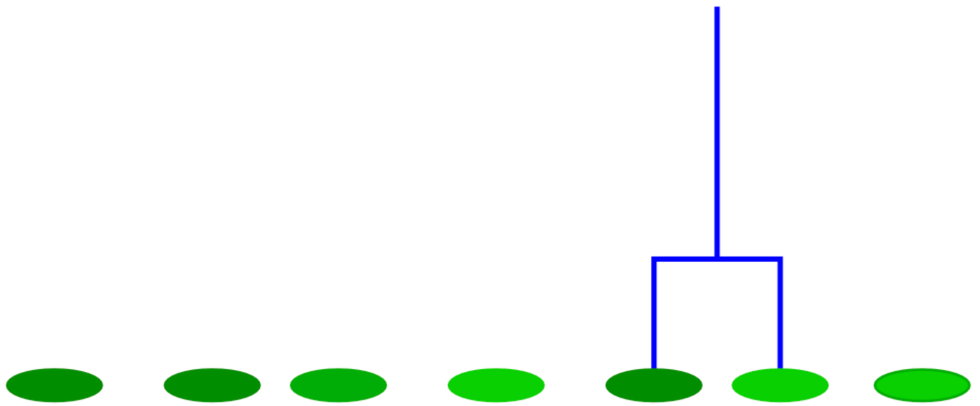
  - Clustering of final state particles



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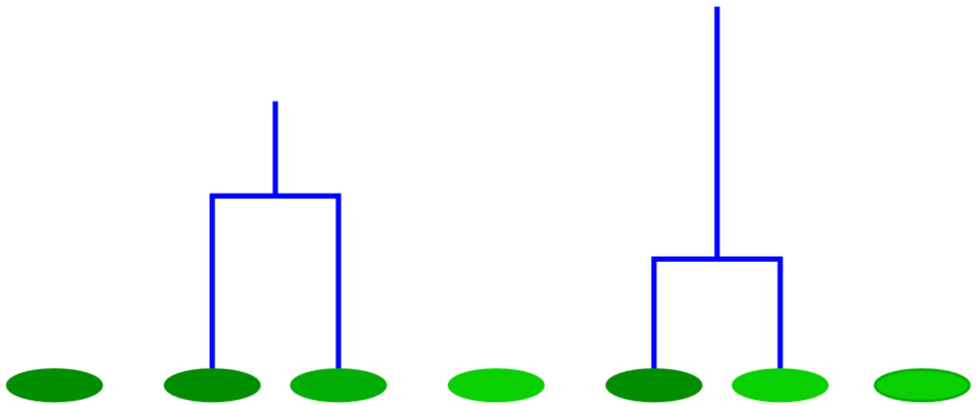

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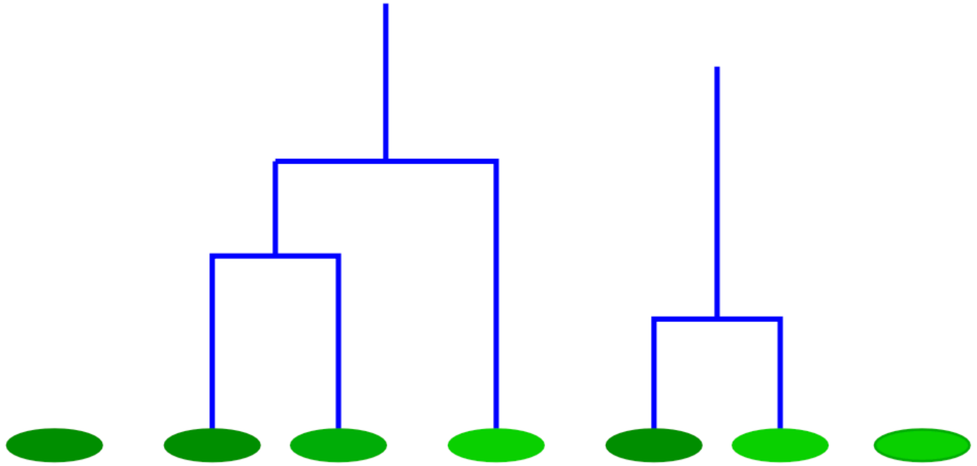

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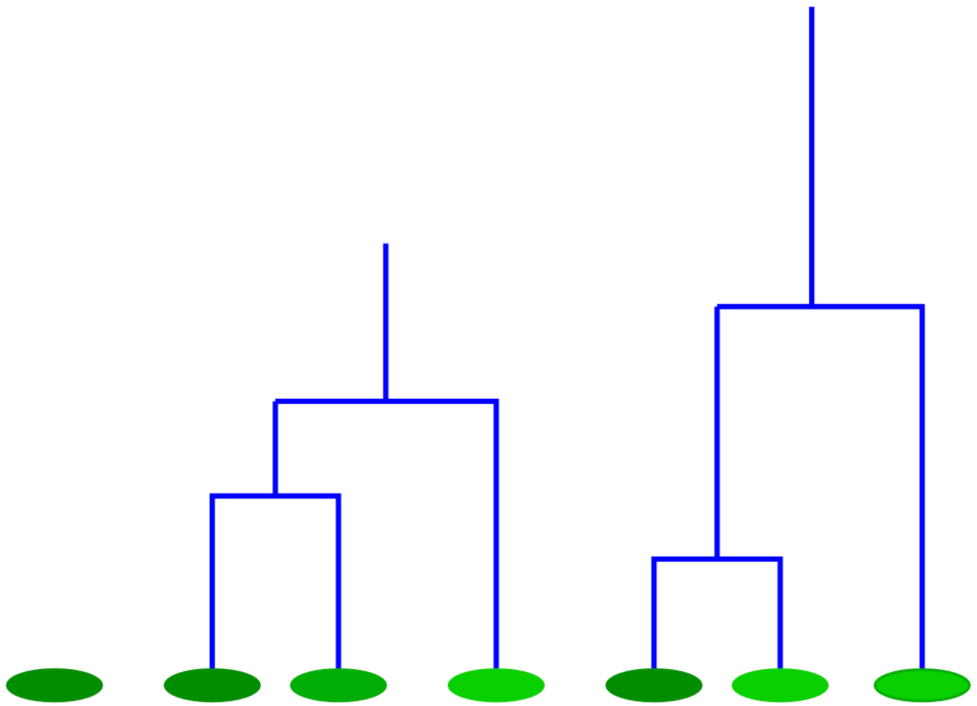

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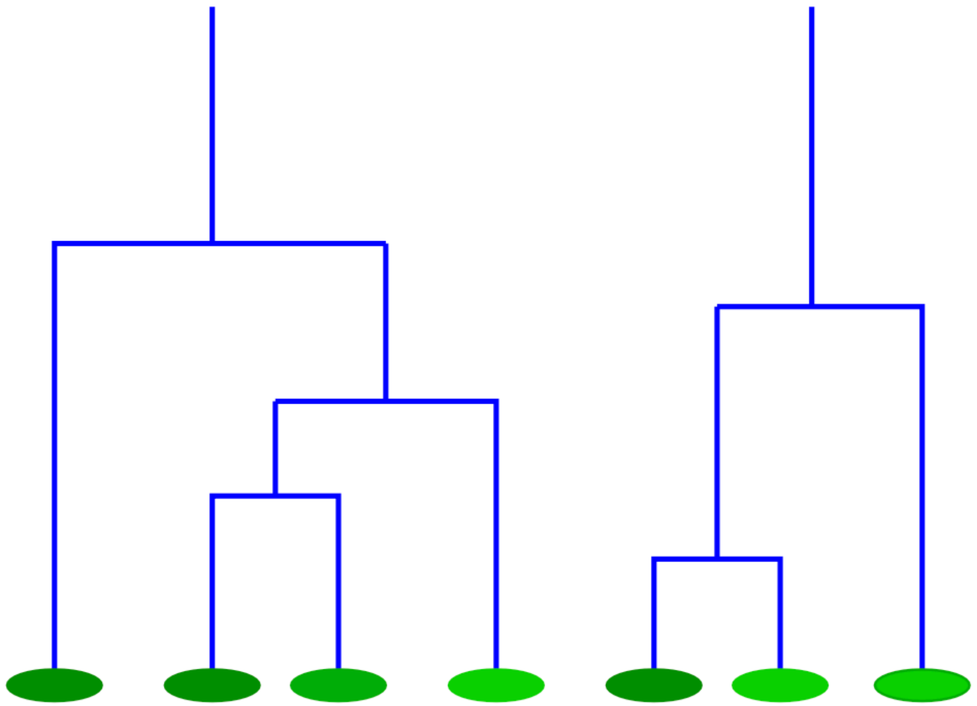

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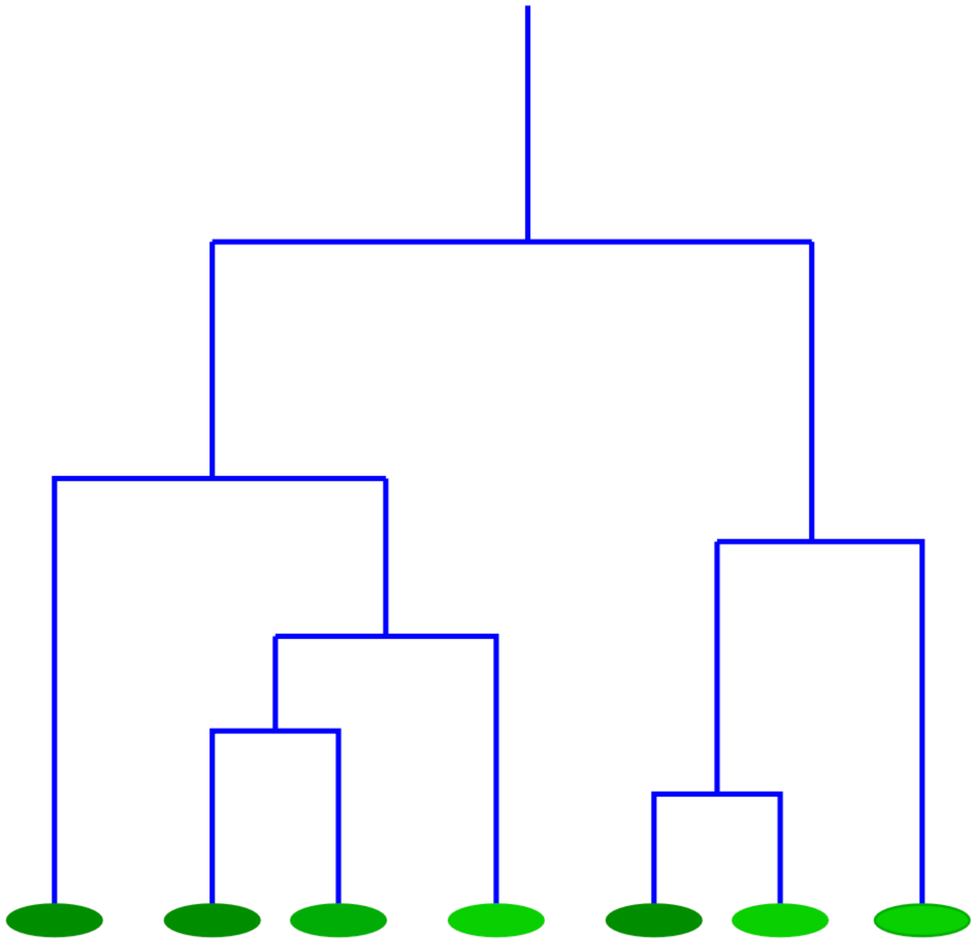

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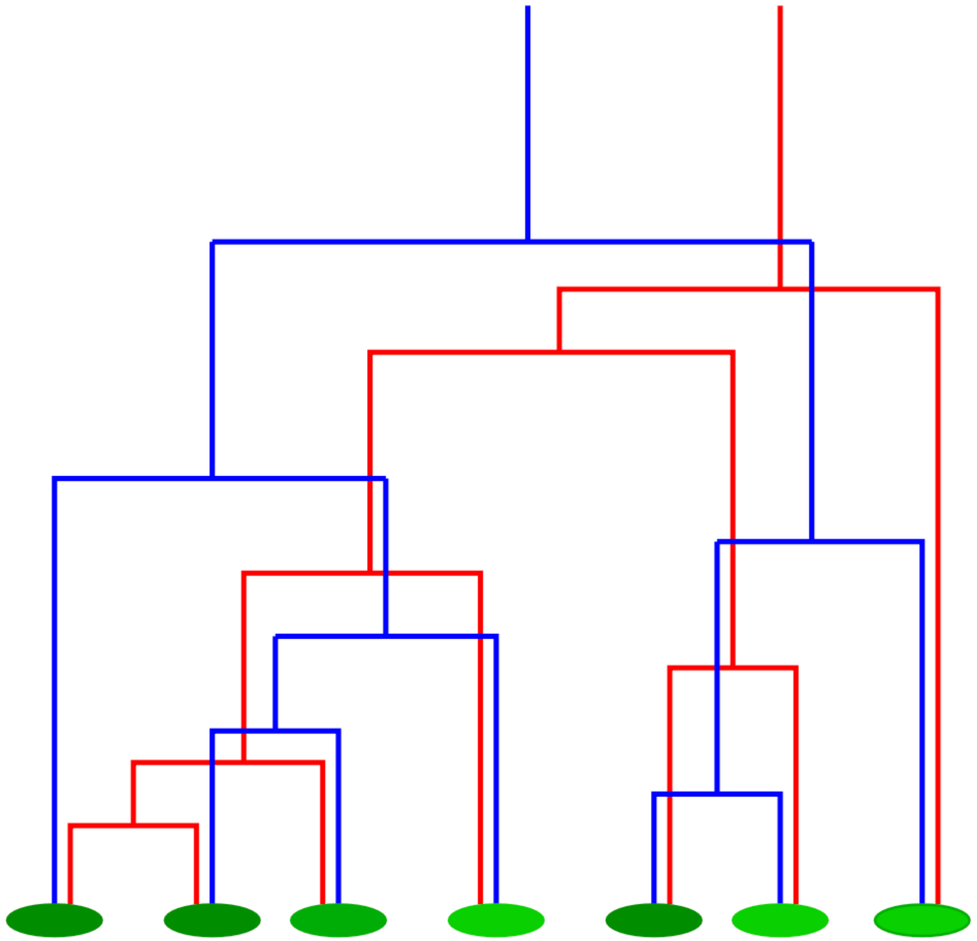

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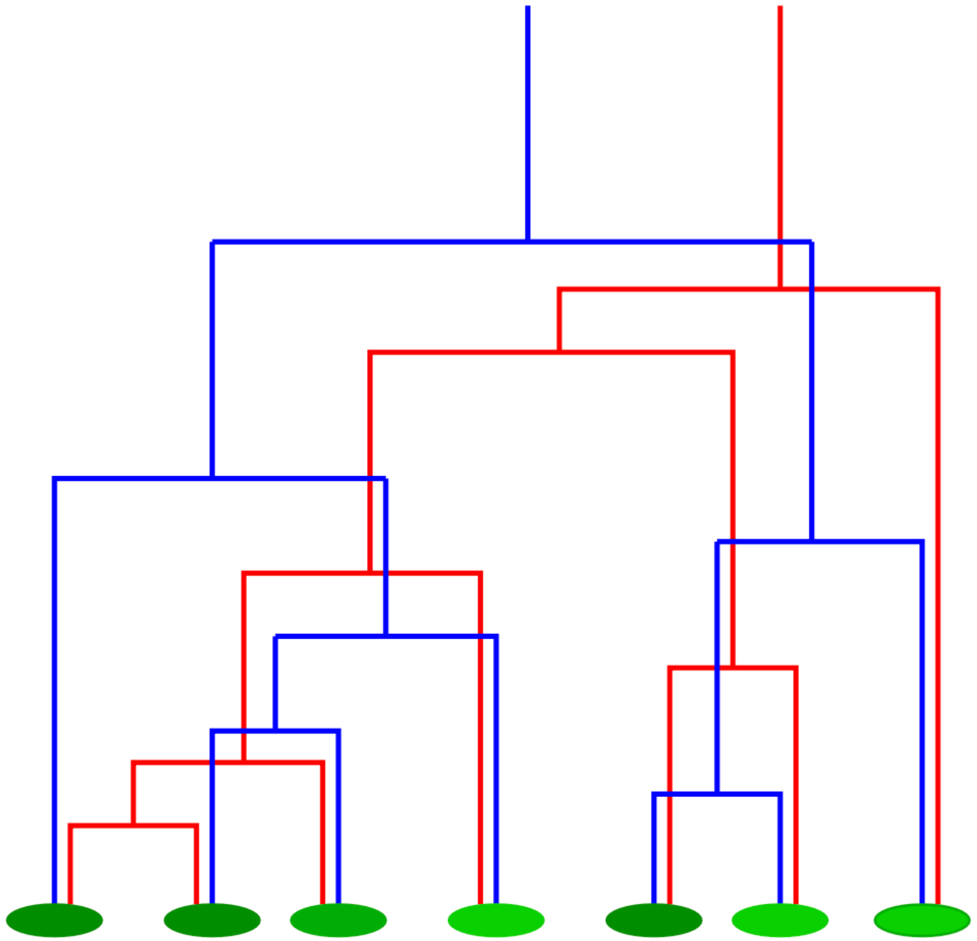
Iterative distance between 2 pseudo-jets

Generalized-k_T family:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{t,i}^{2p}$$

p = 0: Cambridge/Aachen
p = 1: k_T
p = -1: Anti-k_T



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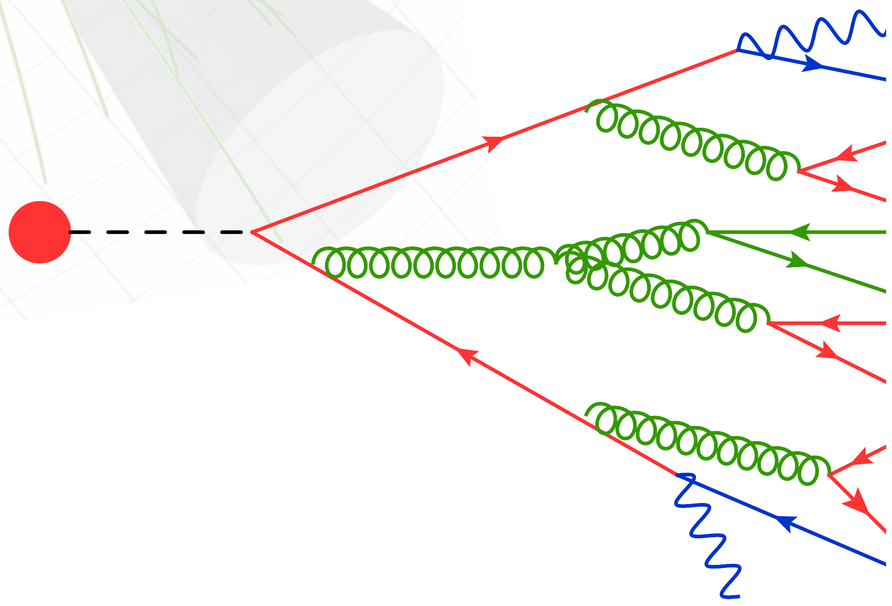
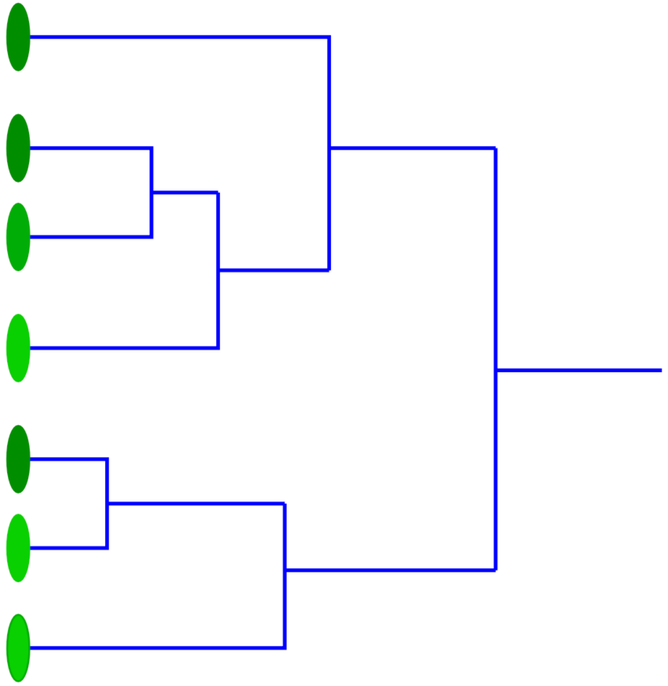
Jets and Parton Showers

Parton Shower



Jet



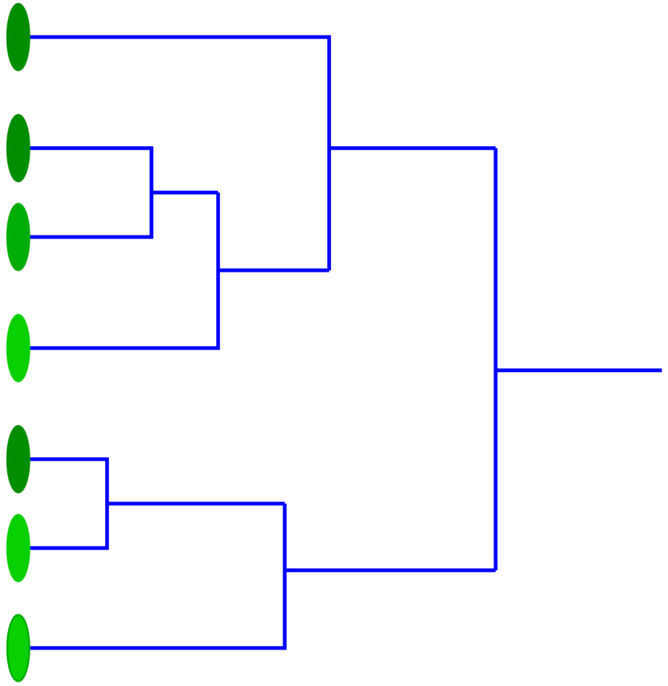
Ordering in vacuum parton shower?
To LL accuracy, all (virtuality, k_T,…) equivalent

Medium-modified jets

Parton Shower

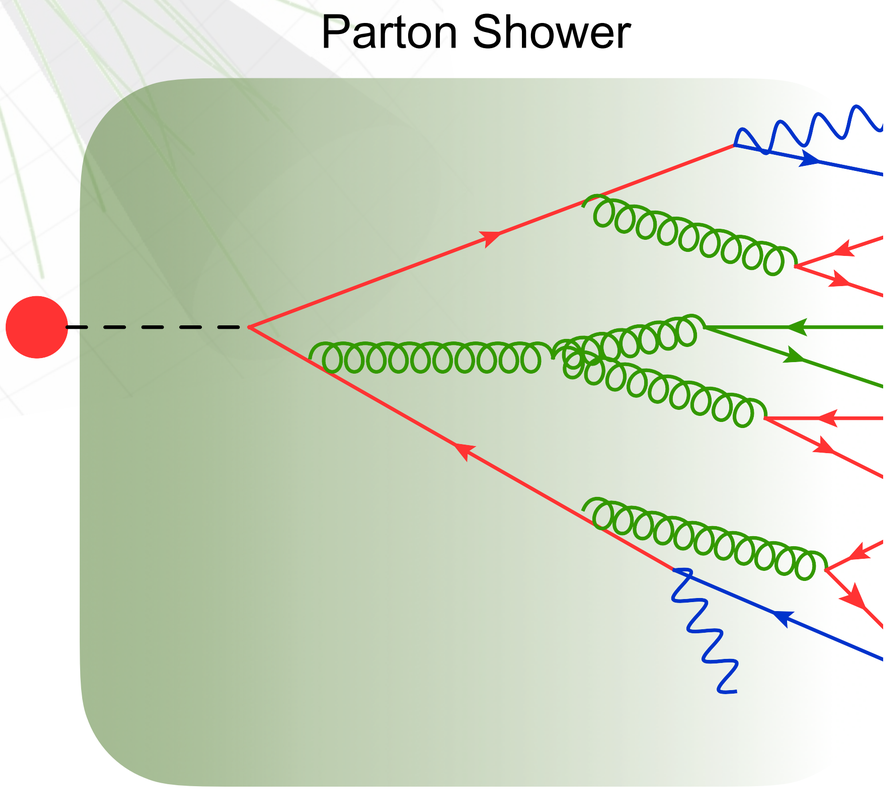
Expanding Medium

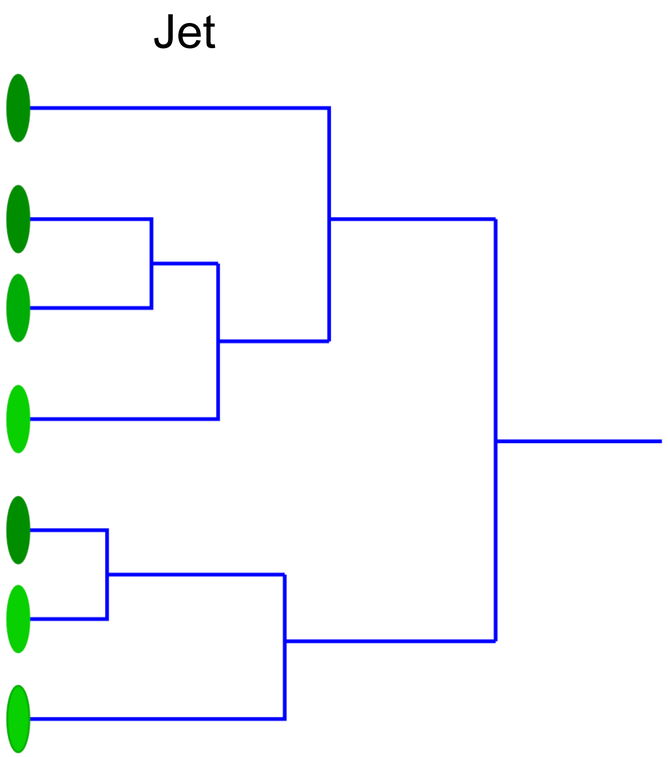
Jet



In-medium radiation will depend on local QGP parameters

Medium-modified jets





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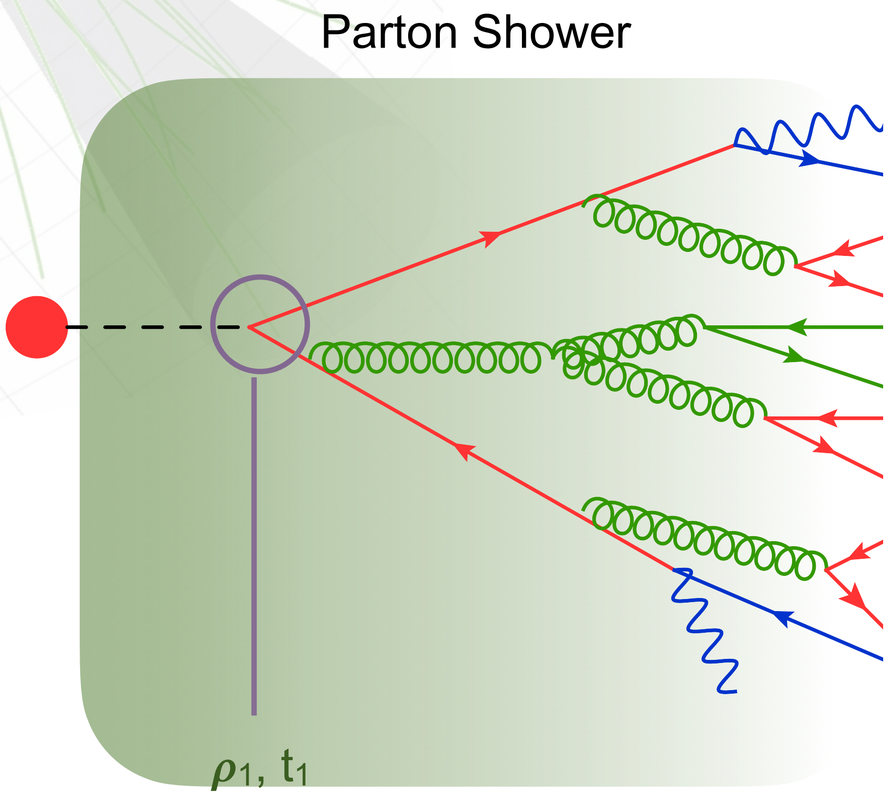

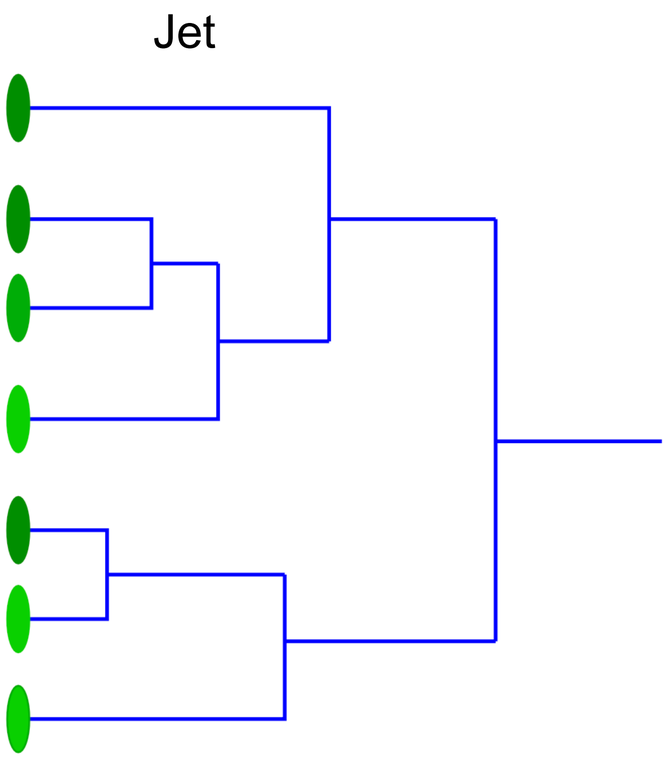

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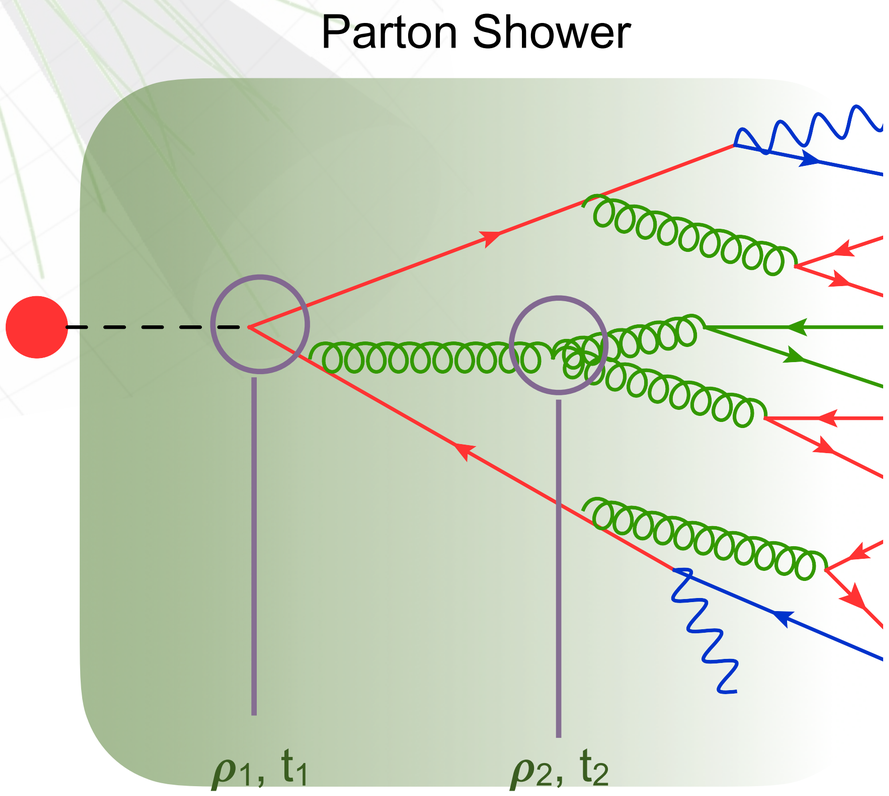

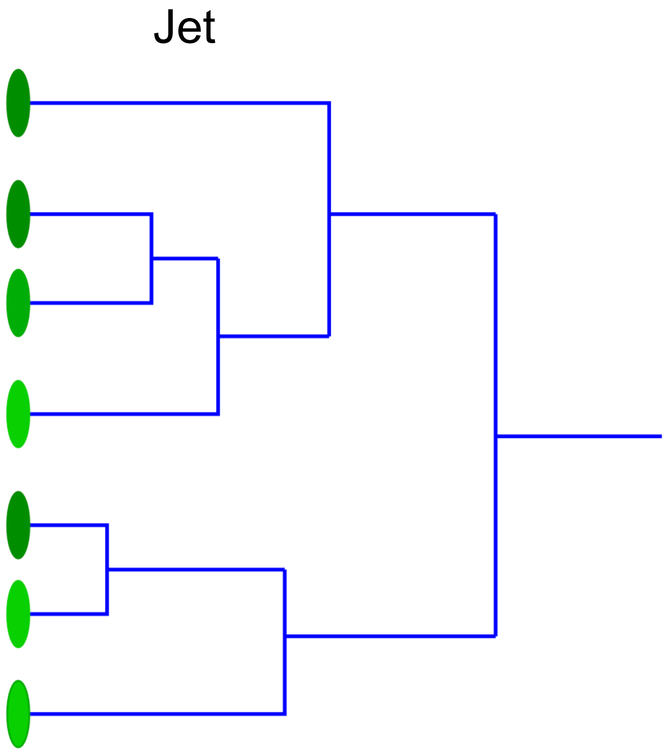

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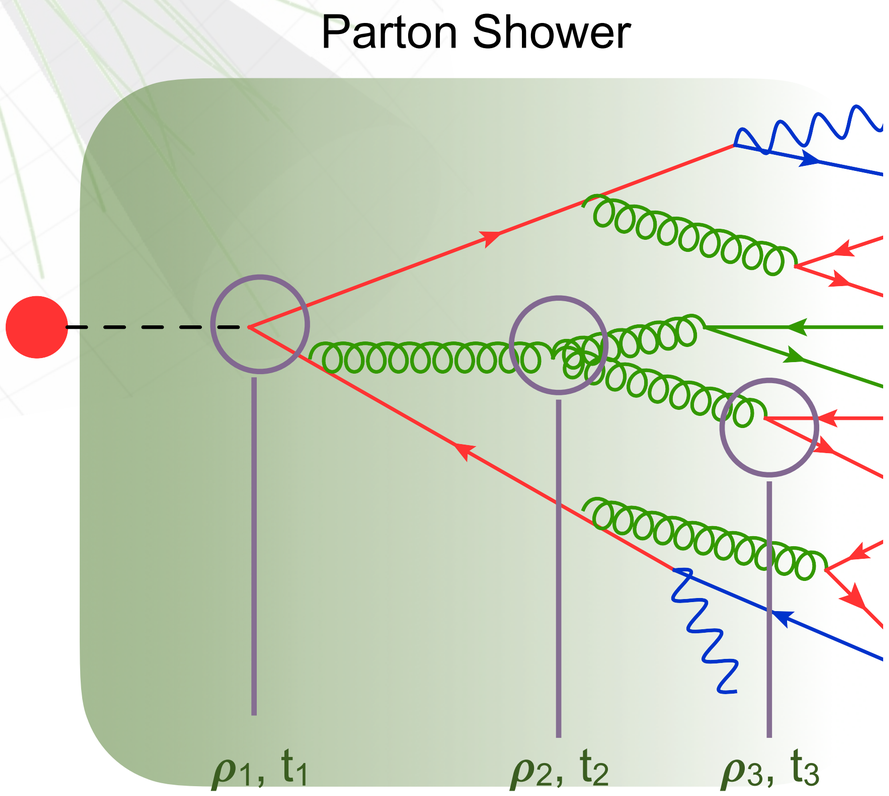

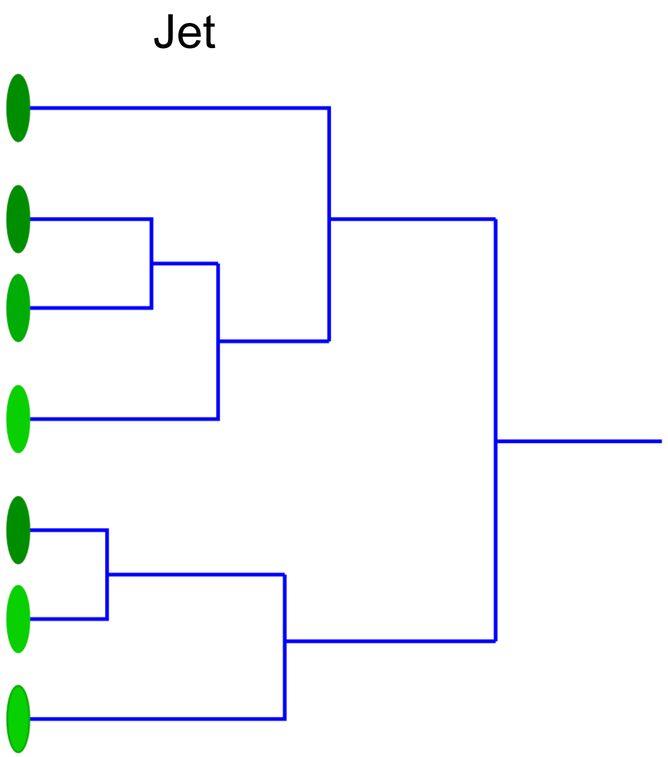

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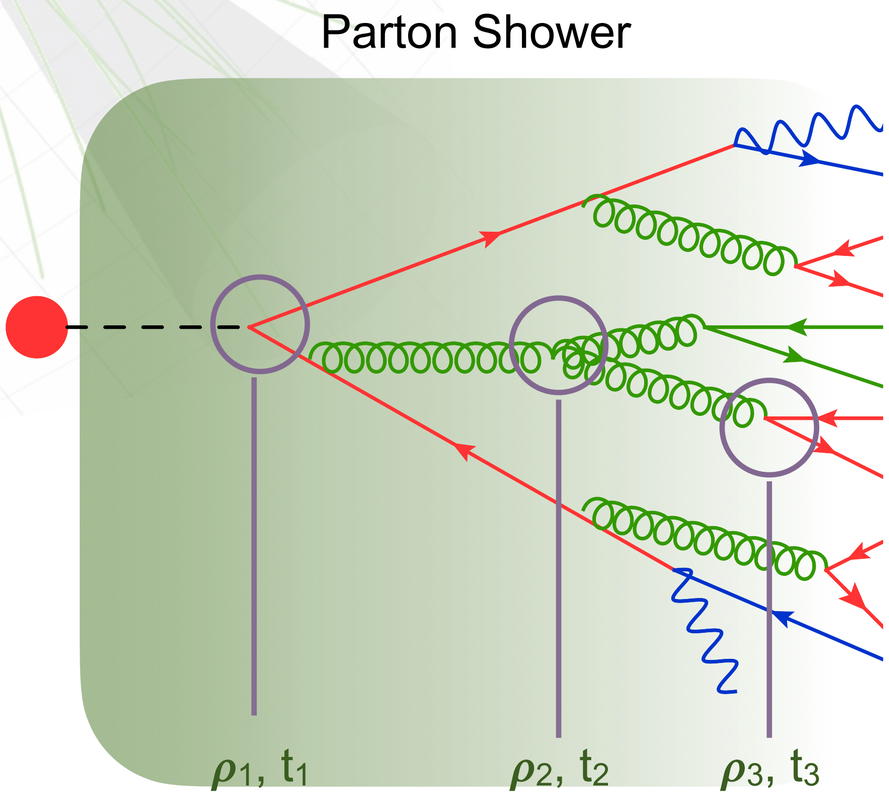

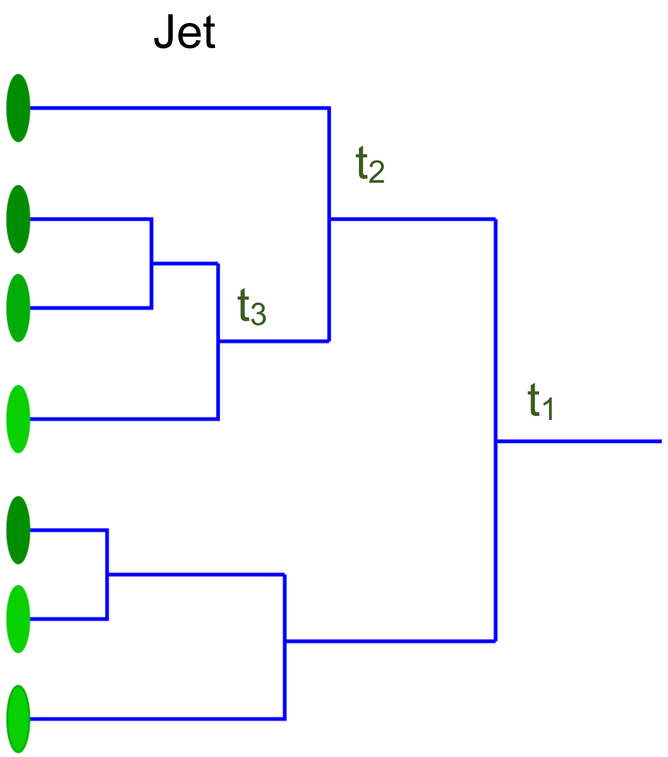

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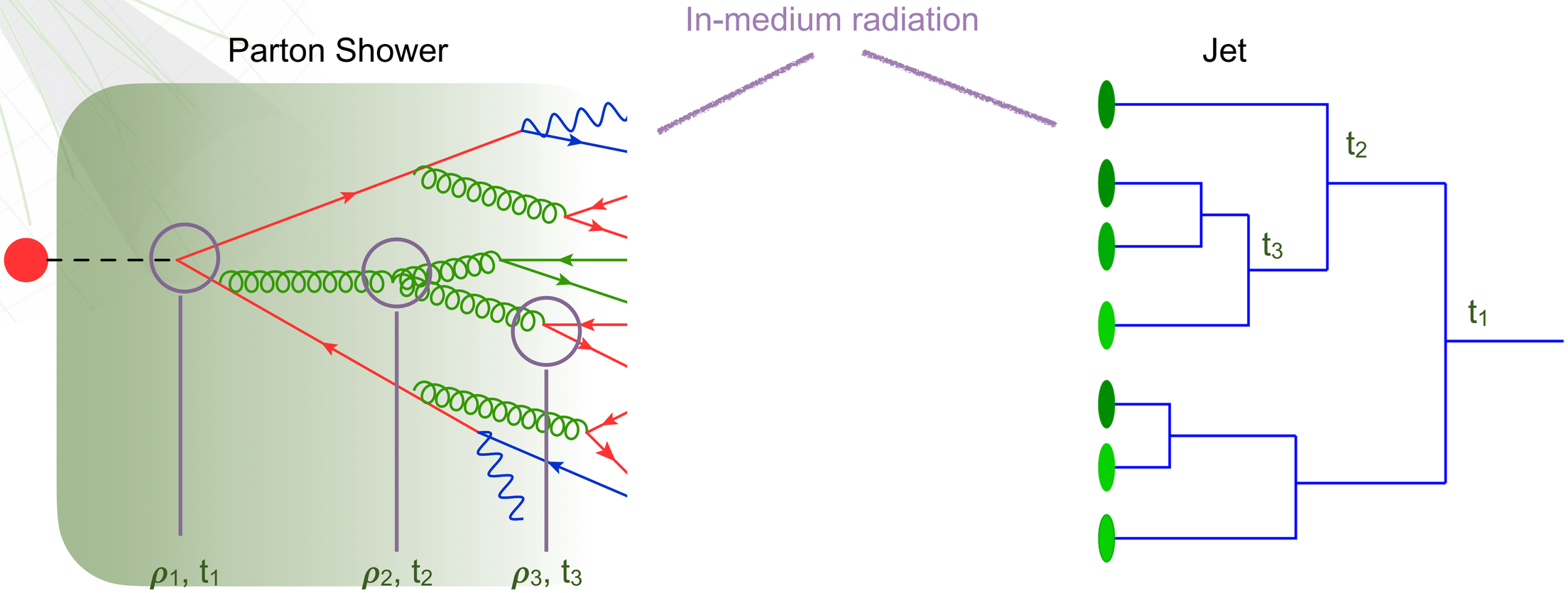


$\theta_1 >> \theta_2 >> \theta_3 \ldots \quad \mapsto \quad t_1 >> t_2 >> t_3 \ldots$

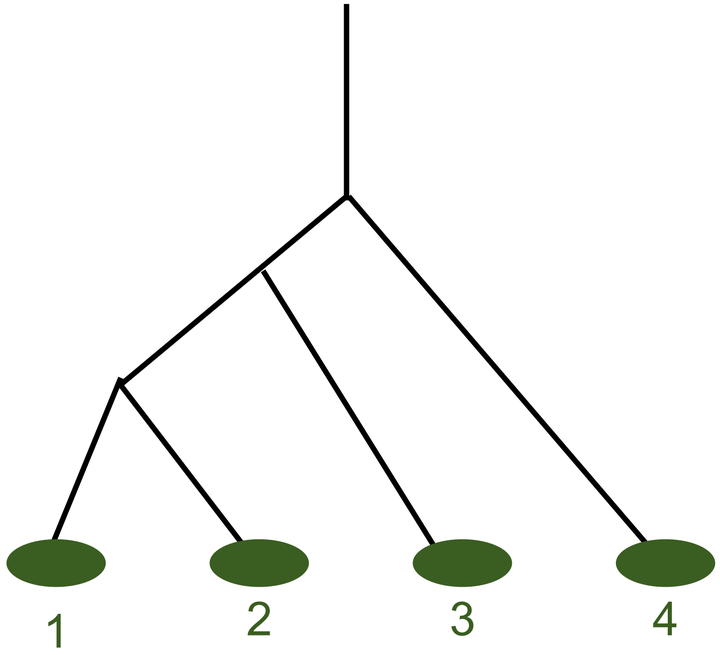
(Vacuum) $\mapsto$ (QGP)

The τ algorithm

- Generalised kt family of (reclustering) jet algorithms:

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2} \qquad d_{iB} = p_{t,i}^{2p}$$

p = 0 (C/A)
⋮
0.5 (τ)
⋮
1 (k_T)



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- $\boxed{0.5\ (\tau)}$
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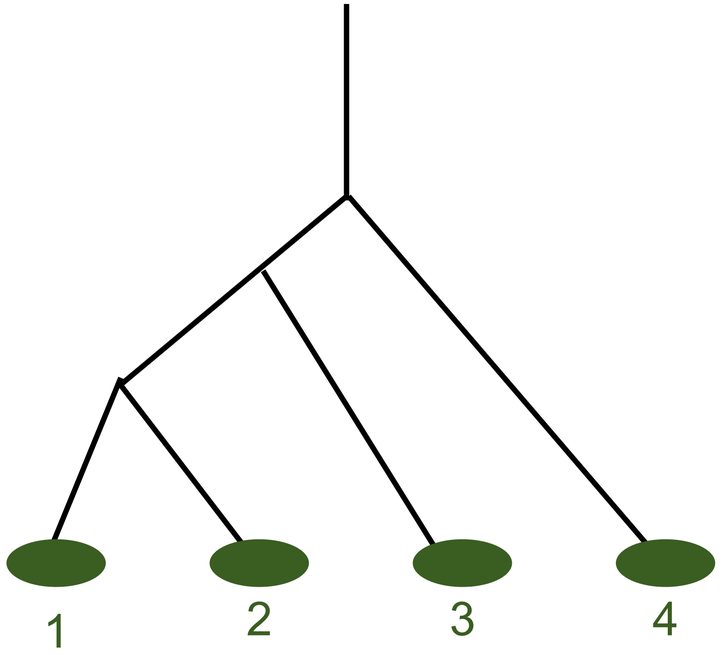
$$d_{ij} \sim p_{T,i} \frac{\Delta R_{ij}^2}{R^2} \sim p_T \theta^2 \sim \frac{1}{\tau_{form}}$$

$$\tau_{form} \approx \frac{E}{Q^2} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$



[PYTHIA 8: Sjostrand et al (2006)]

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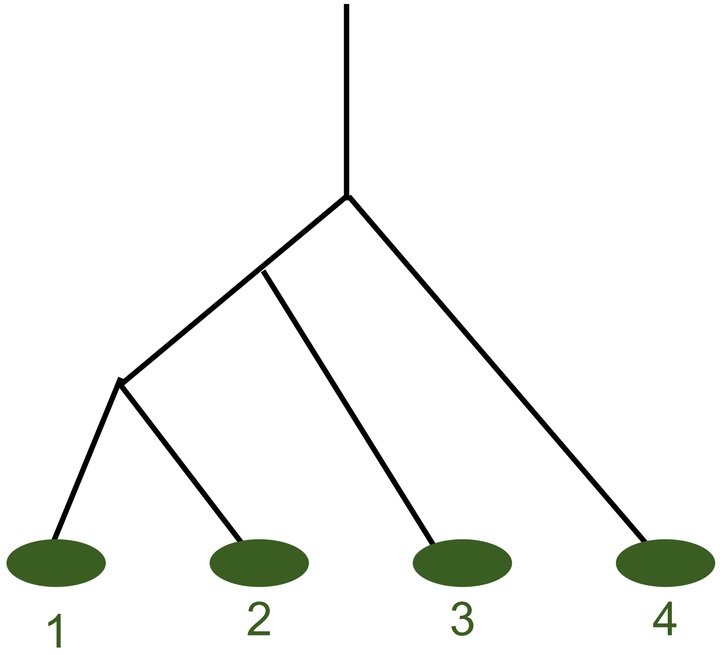

Vacuum: PYTHIA 8 (k_T ordered)

[PYTHIA 8: Sjostrand et al (2006)]
[JEWEL: Zapp (2014)]

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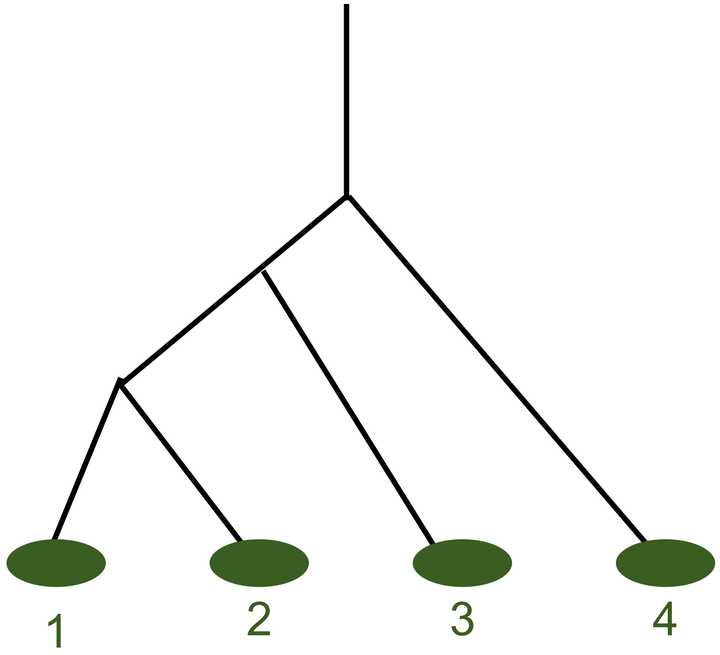

Vacuum: PYTHIA 8 (k_T ordered)

Vacuum: JEWEL (~PYTHIA 6, Q^2 ordered)

The τ algorithm

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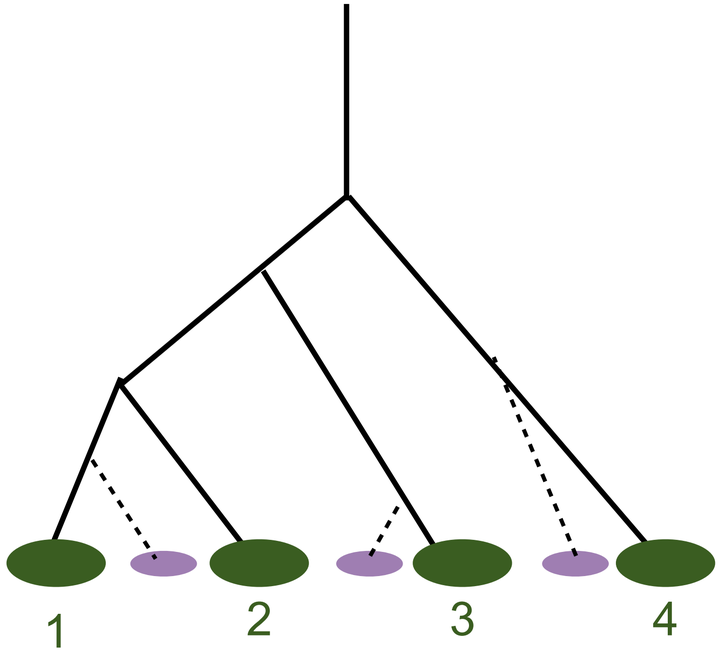


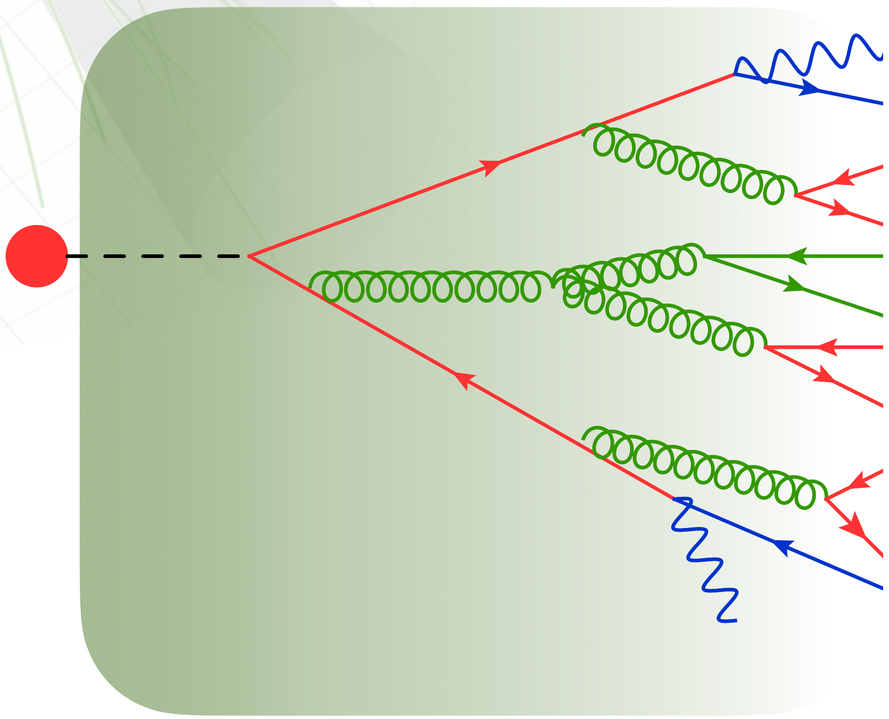
Vacuum: PYTHIA 8 (k_T ordered)

Vacuum: JEWEL (~PYTHIA 6, Q^2 ordered)

Medium: JEWEL (Q^2 ordered + τ veto)

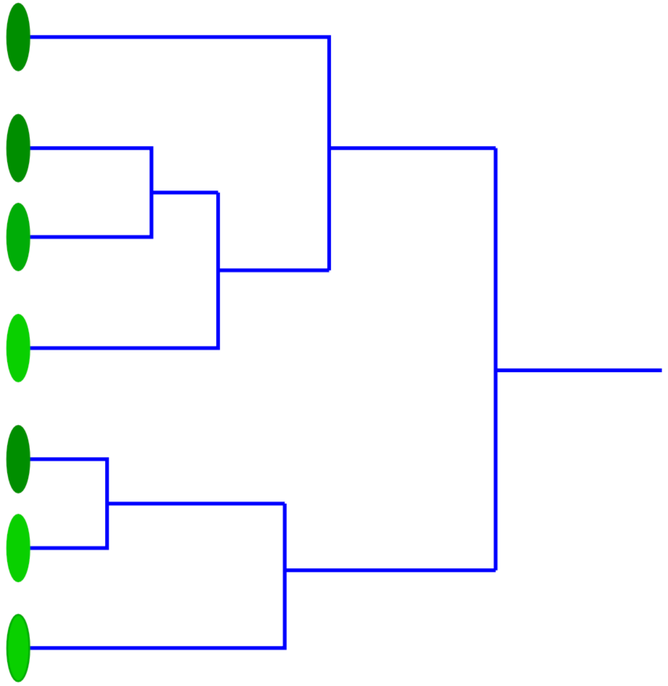
Proxy for τ_{form}

Parton Shower



$\tau_{form}^{PartonShower}$

Jet



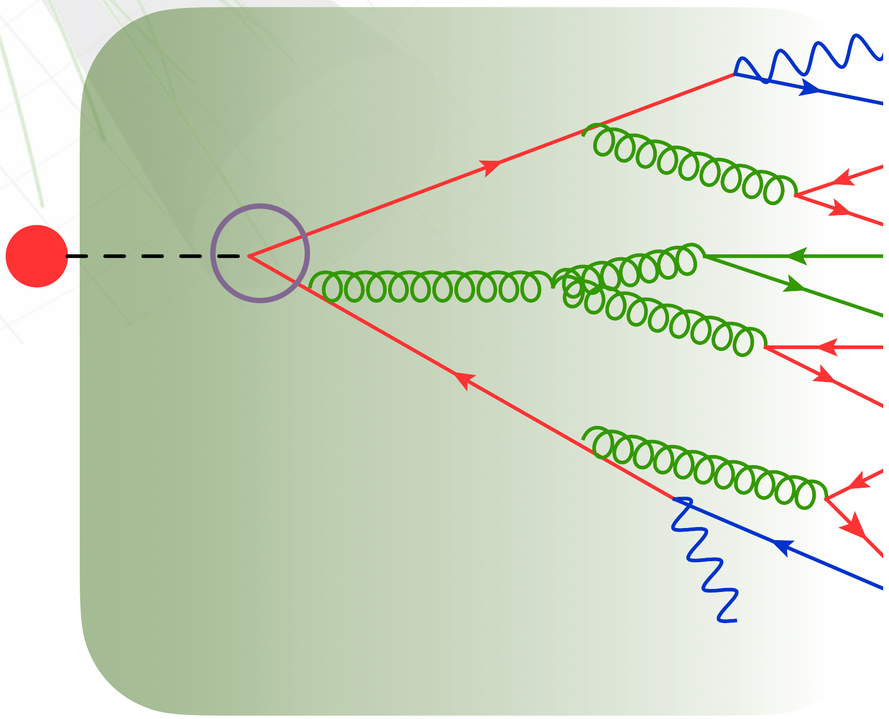
$\tau_{form}^{Uncluster}$

Measure correlation using τ_{form}

$$\tau_{form} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$

Proxy for τ_{form}

Parton Shower



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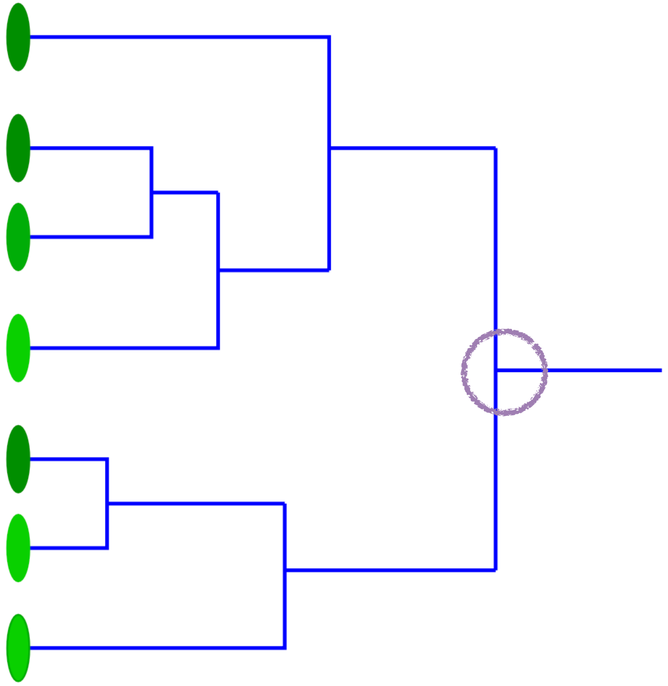

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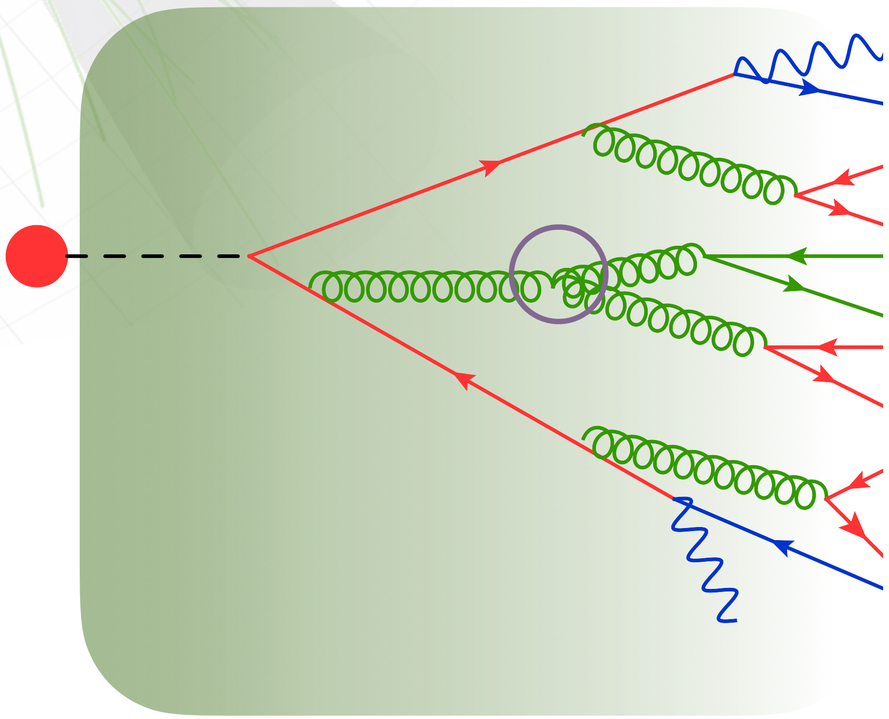
Proxy for τ_{form}

Parton Shower



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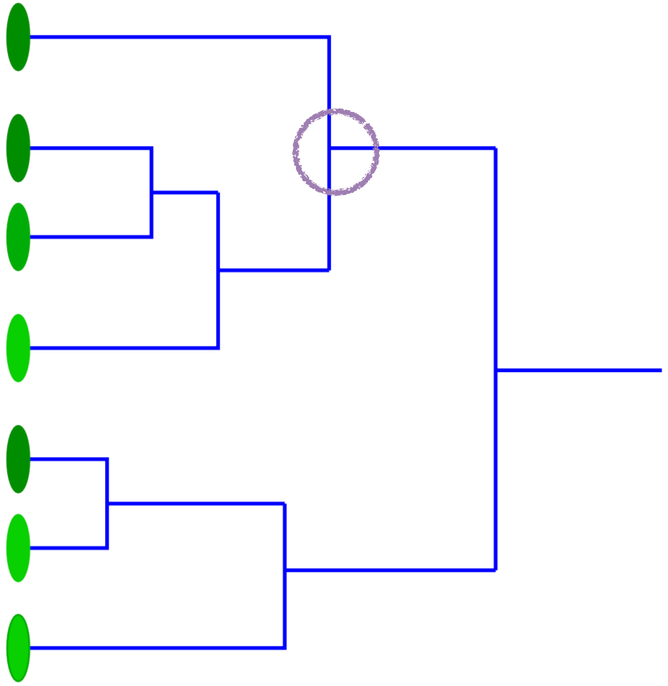

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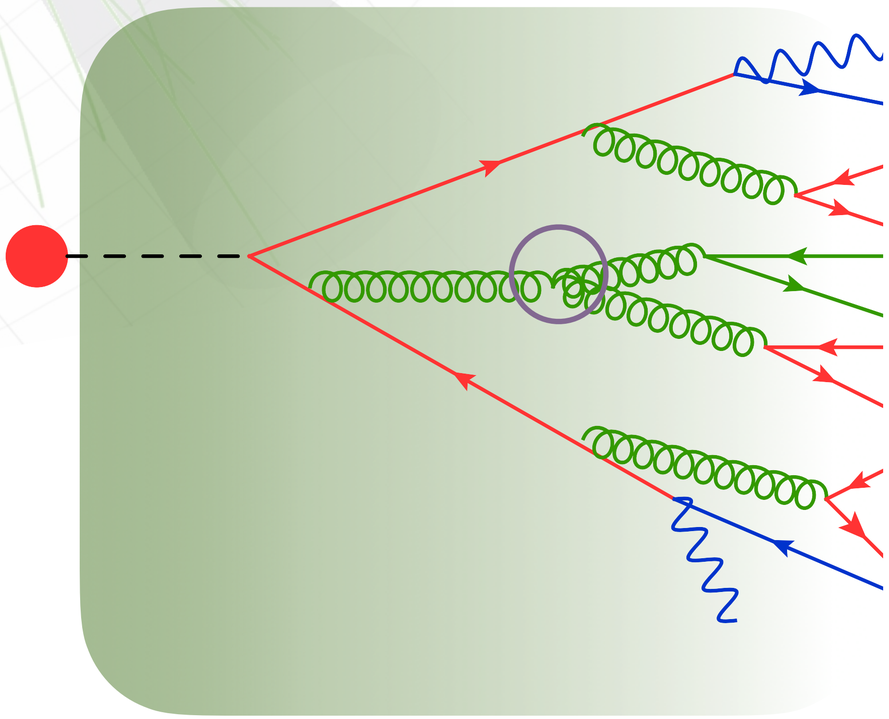

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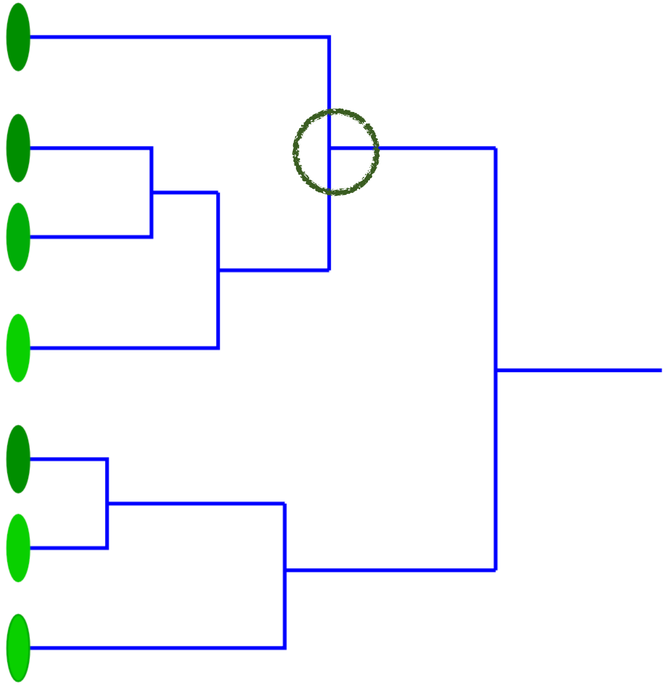
Jet



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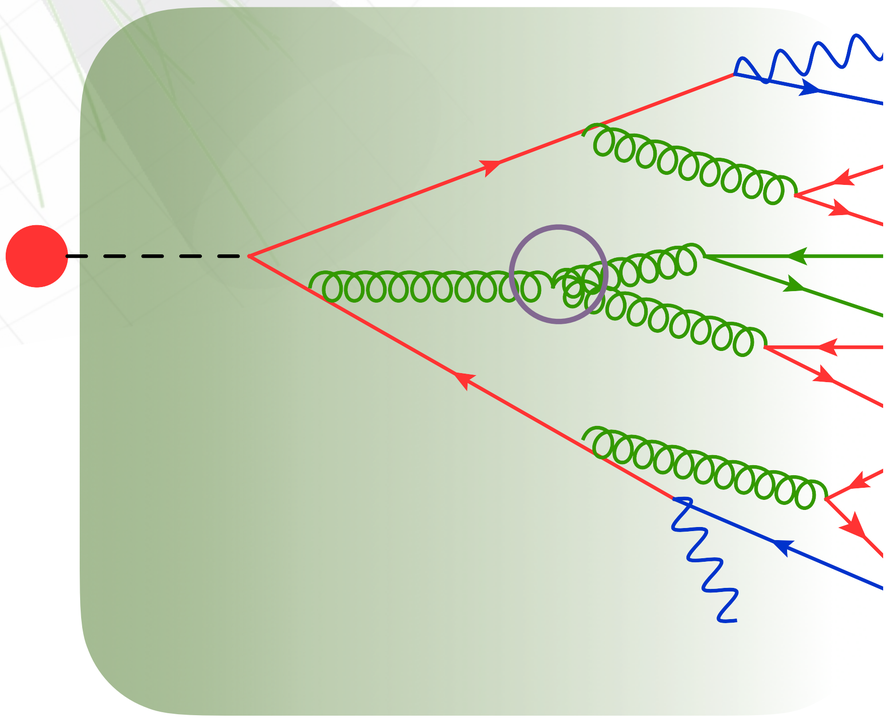
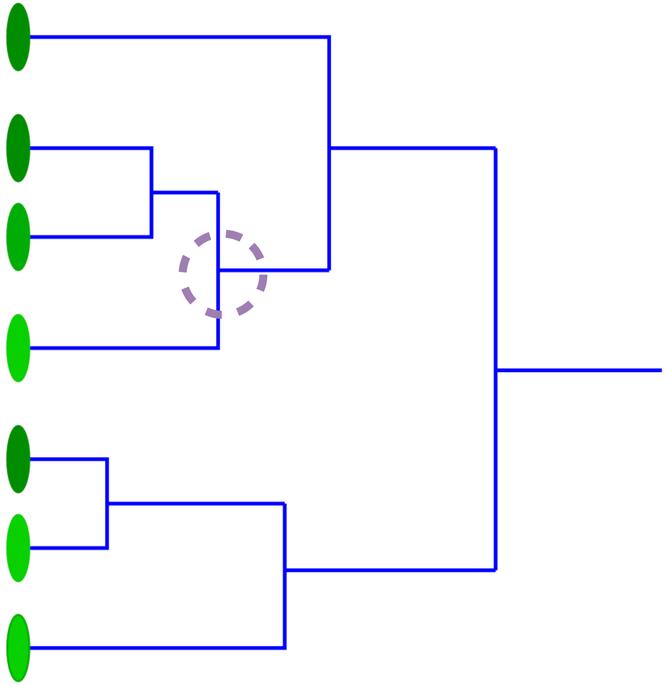
Proxy for τ_{form}

Parton Shower



$\tau_{form}^{PartonShower}$

Jet



$\tau_{form}^{Uncluster}$

Measure correlation using τ_{form}

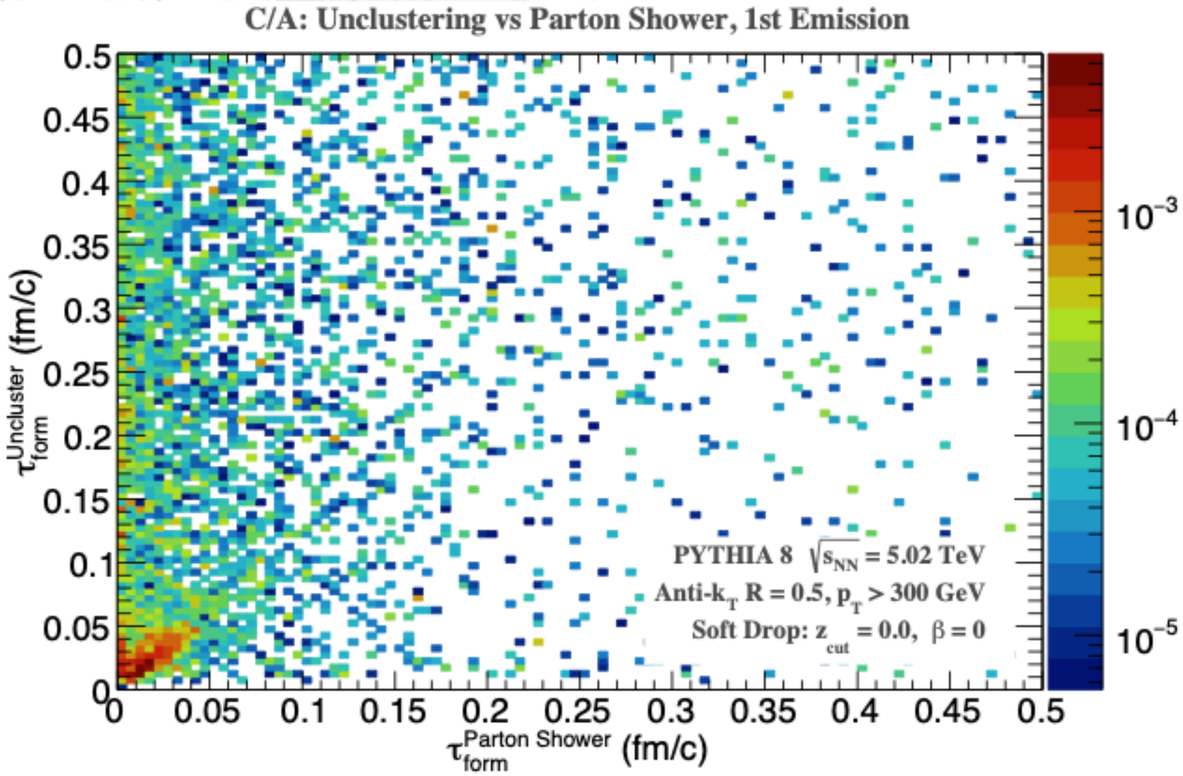
$$\tau_{form} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$

Correlation (no grooming)

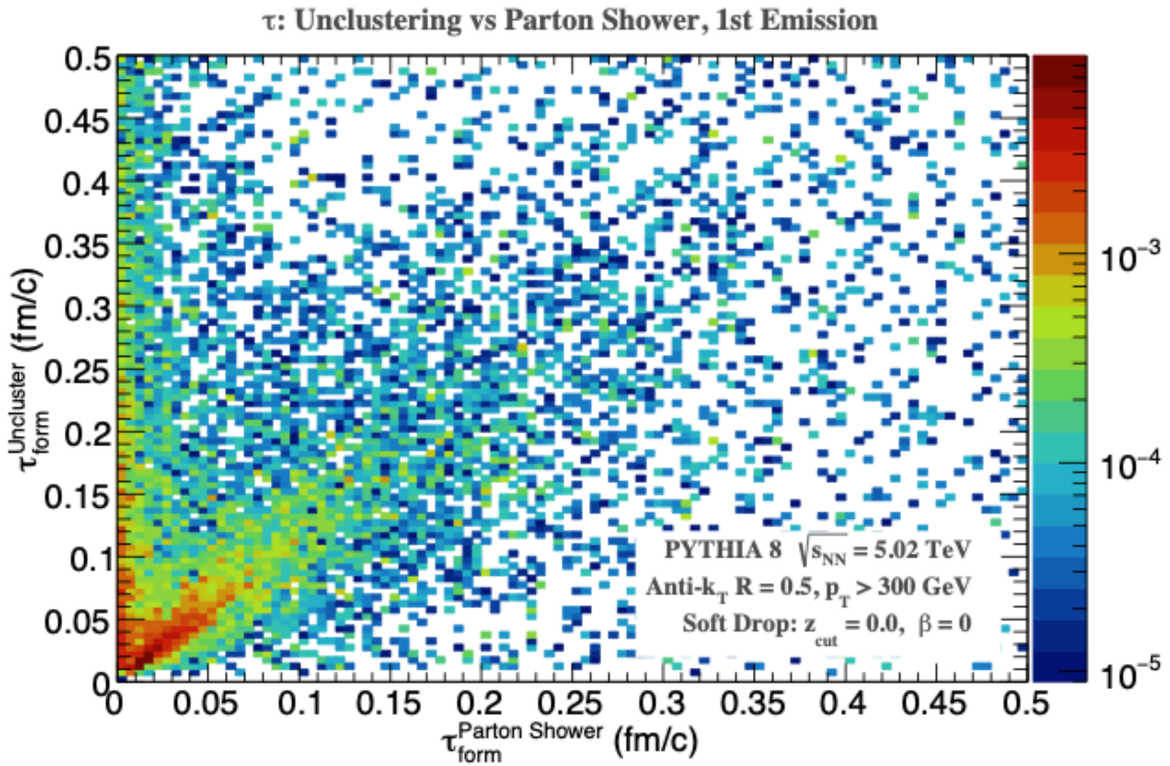
[LA, Cordeiro, Zapp (21)]

- Correlation MC-truth vs Unclustering:

C/A



τ



[talks: Marta, Adam]

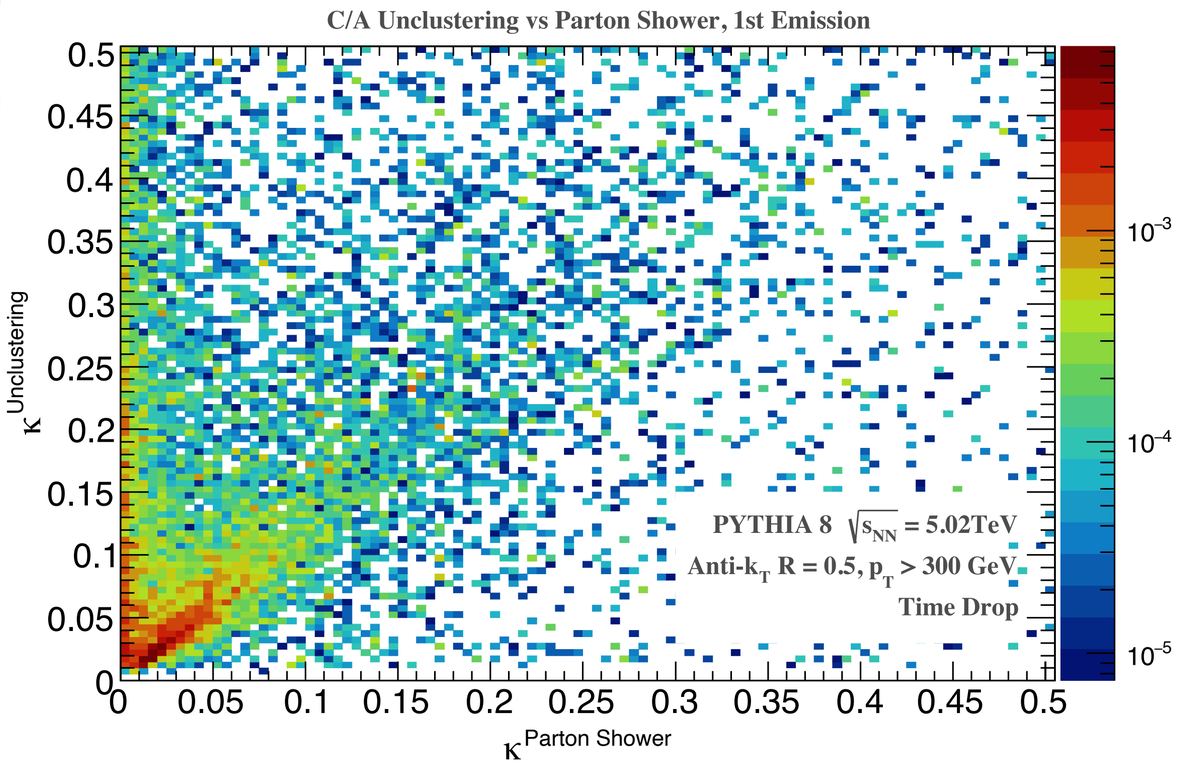
Grooming

[Larkoski, Marzani, Soyez, Thaler (14)]
[Mehtar-Tani, Soto-Ontoso, Tywoniuk (20)]

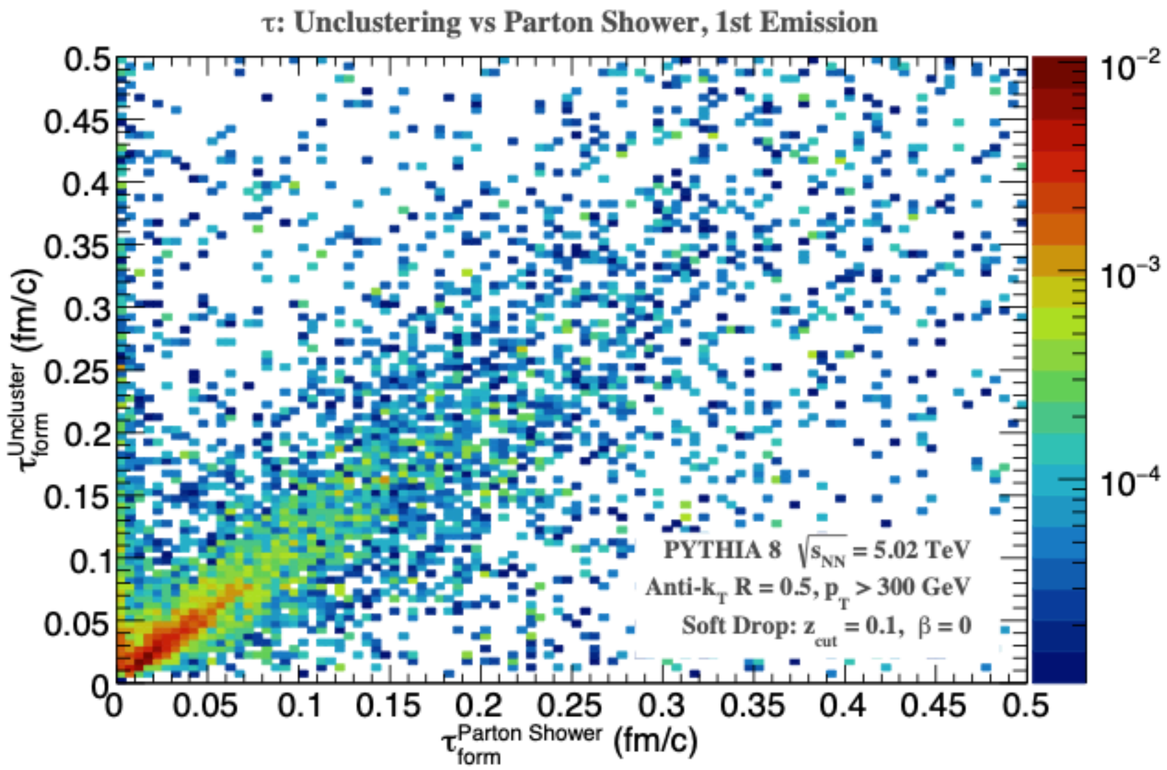
- Testing several types of grooming:

Cleaning soft fragments improves correlation

C/A + TimeDrop (a=2)

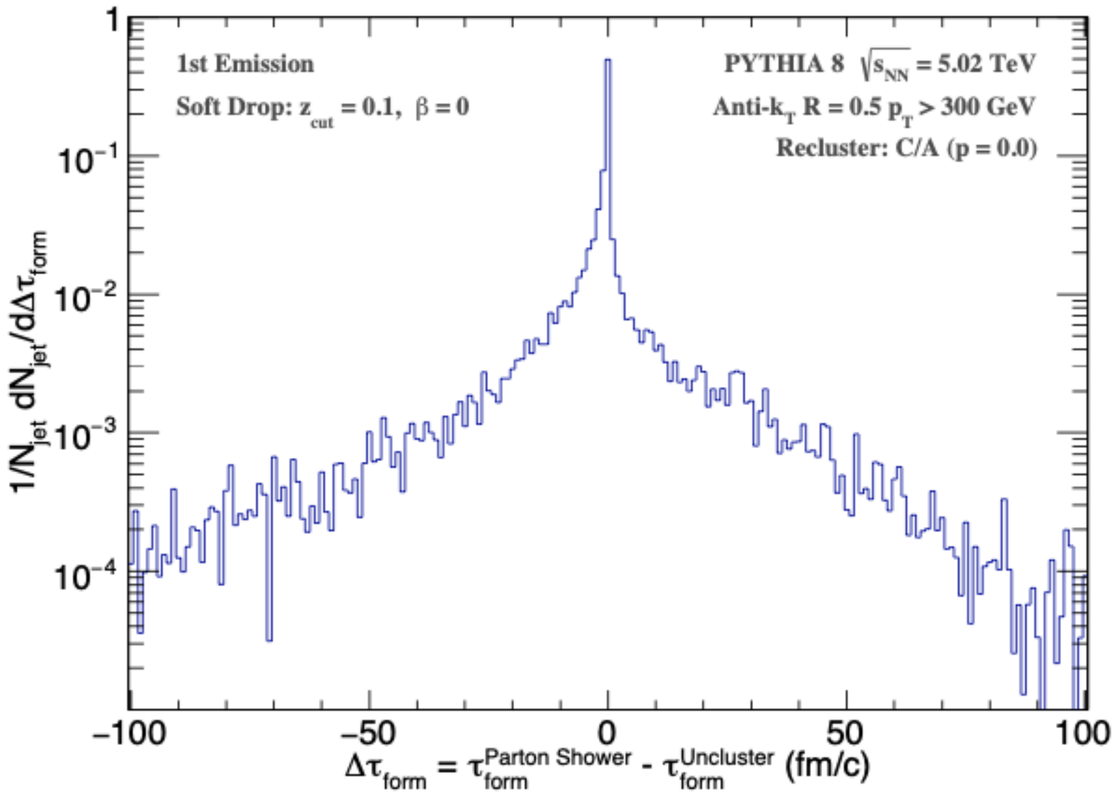


τ + Soft-drop (z_{cut}=0.1)



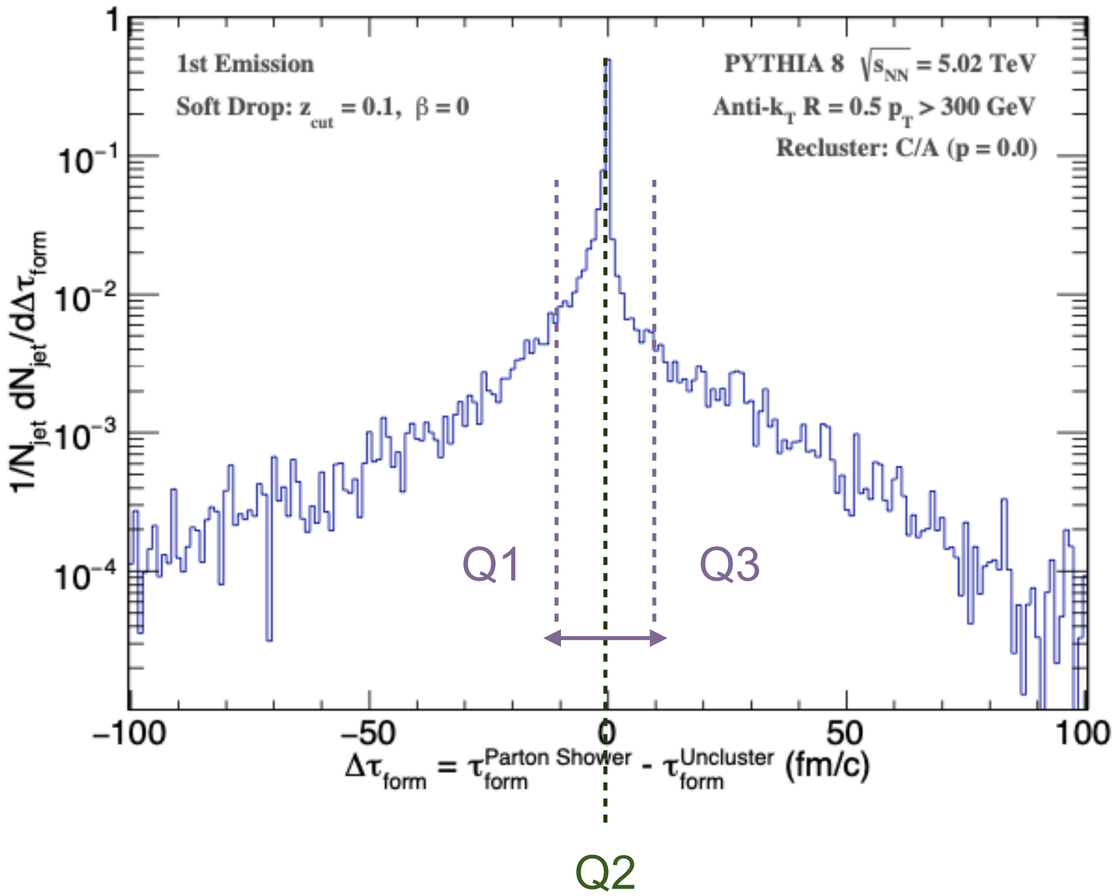
Correlation

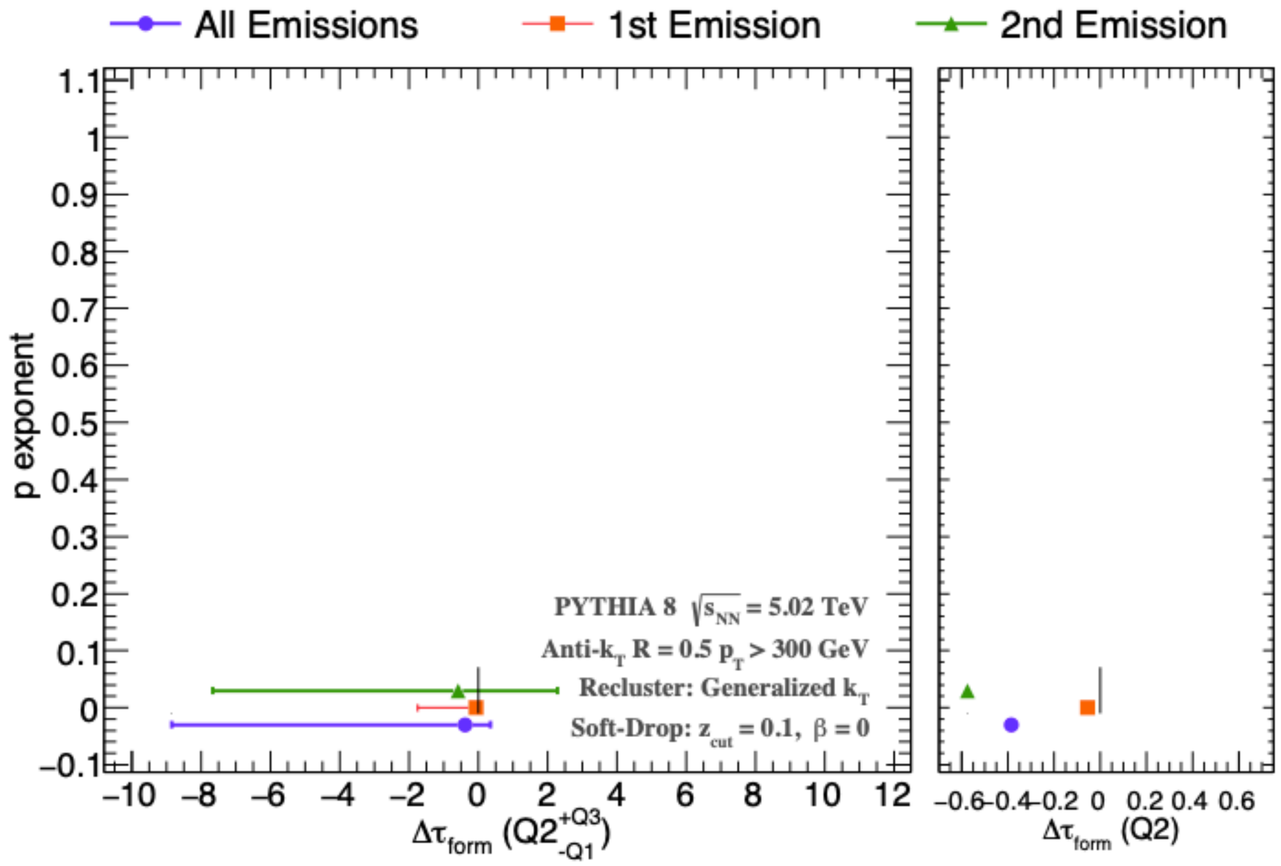
- Using the difference between the two formation times: $\Delta\tau = \tau_{form}^{Parton\ Shower} - \tau_{form}^{Unclustering}$



Correlation

- Using the difference between the two formation times: $\Delta\tau = \tau_{form}^{Parton\ Shower} - \tau_{form}^{Unclustering}$





Correlation

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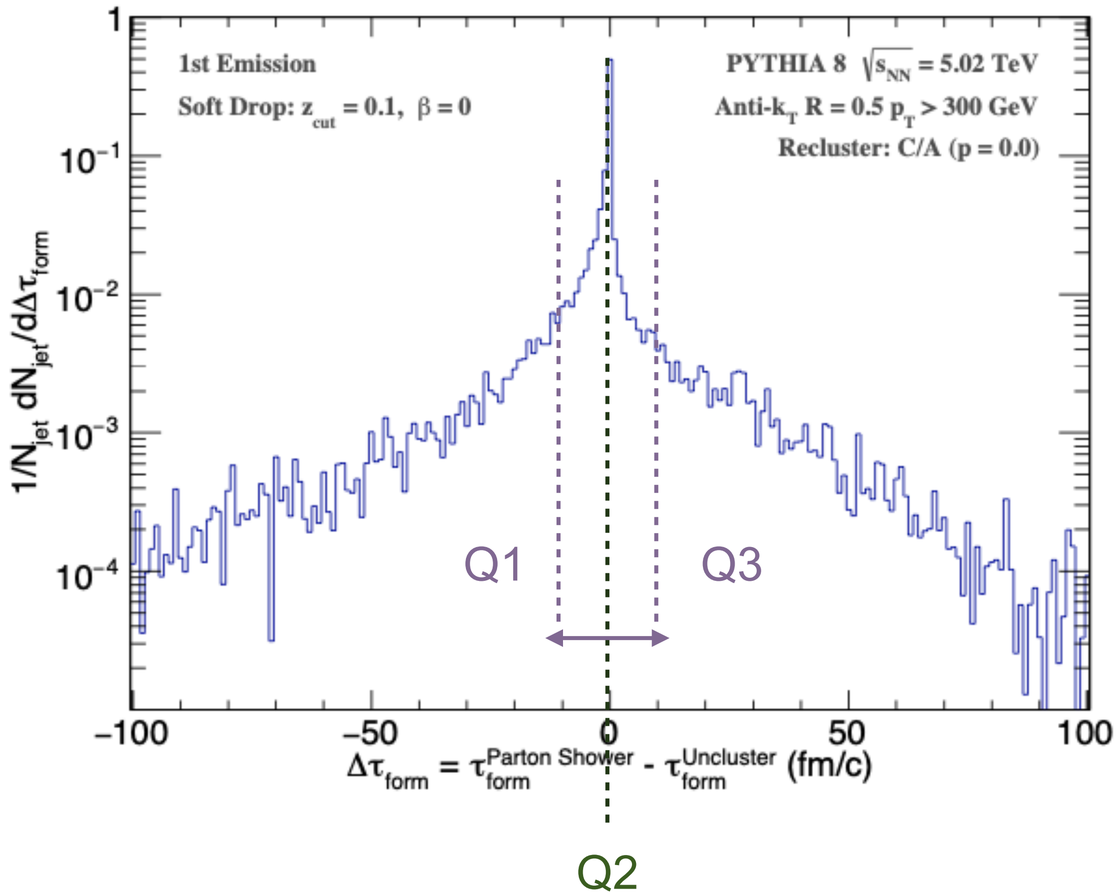
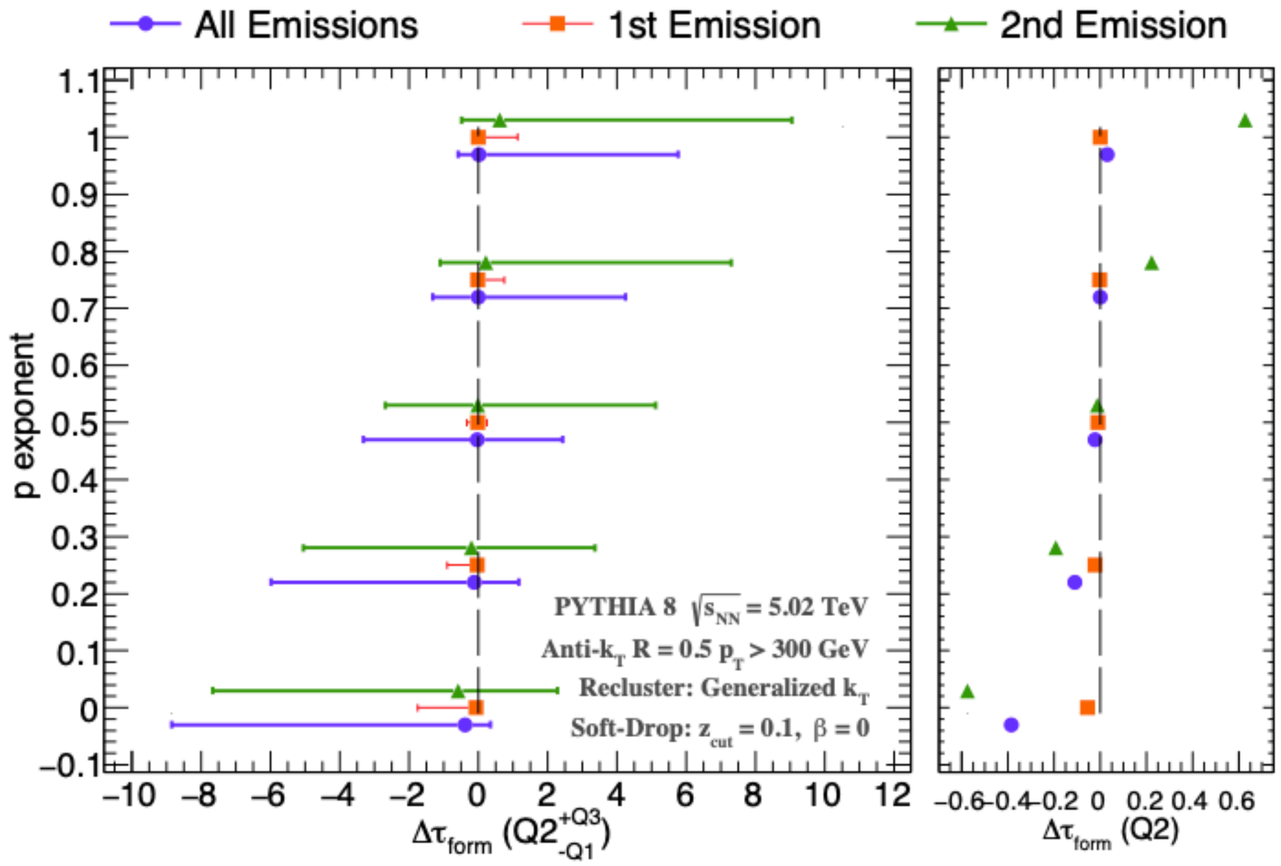
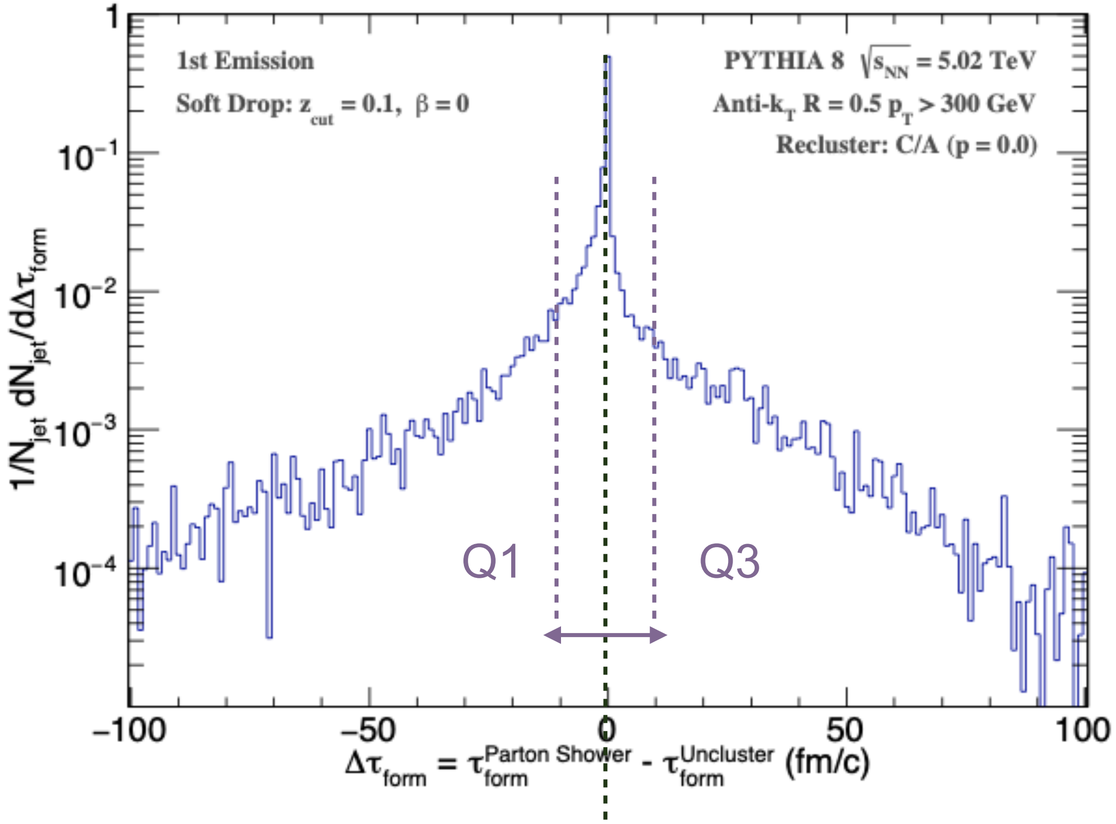
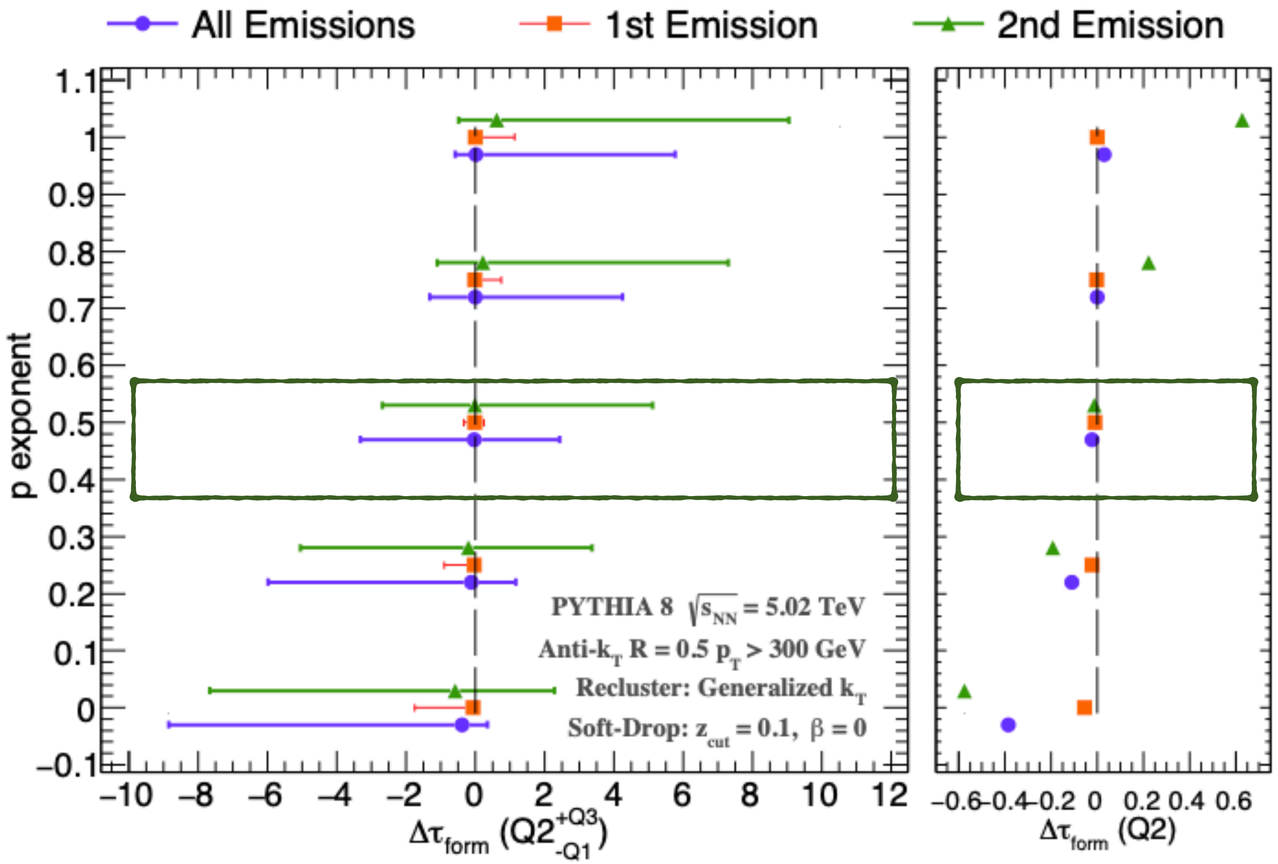




Correlation

- Using the difference between the two formation times: $\Delta\tau = \tau_{form}^{Parton\ Shower} - \tau_{form}^{Unclustering}$

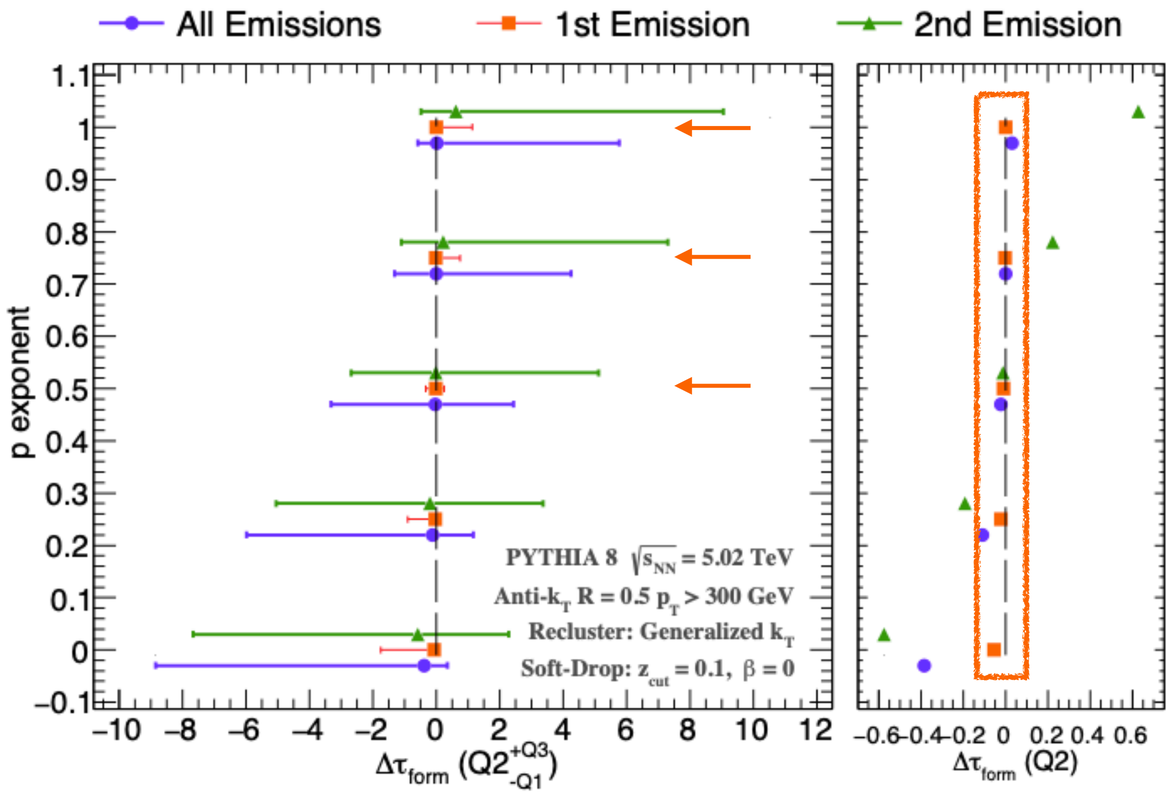




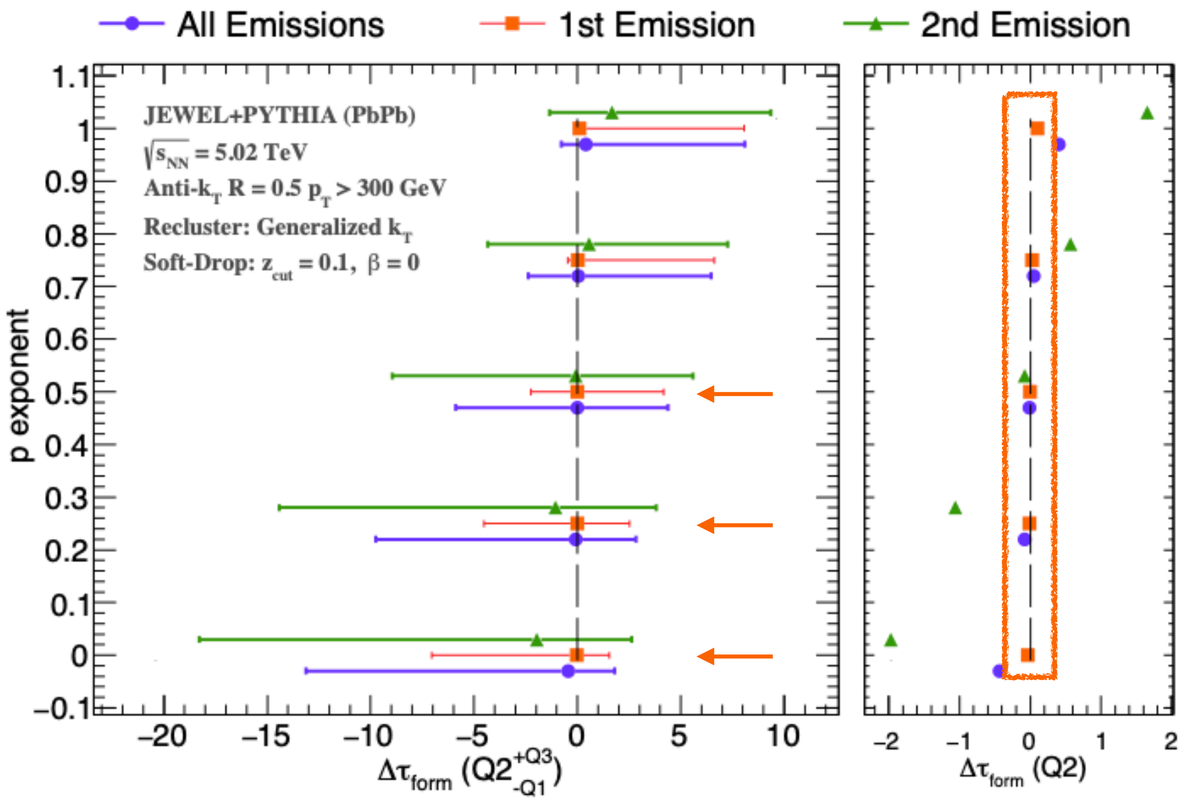
τ-algorithm: better overall performance

Vacuum vs Medium

$\Delta\tau$ distribution (vacuum quartiles):



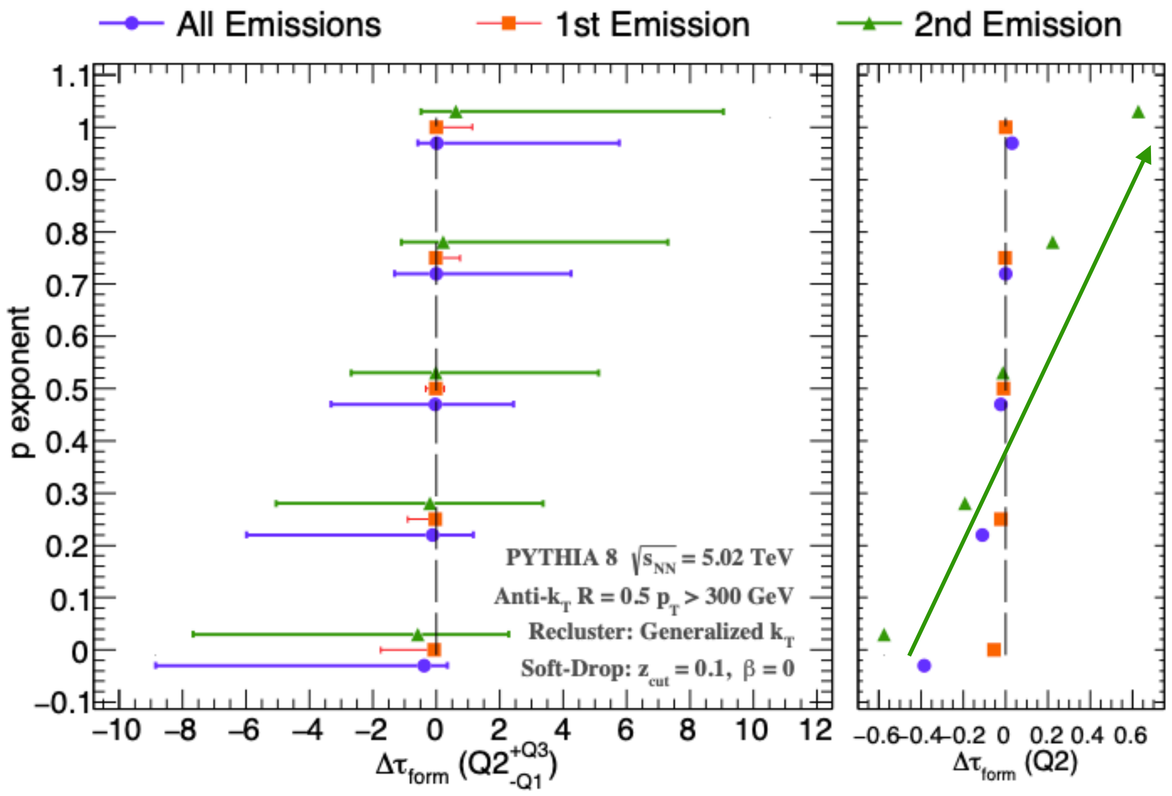
$\Delta\tau$ distribution (in-medium quartiles):



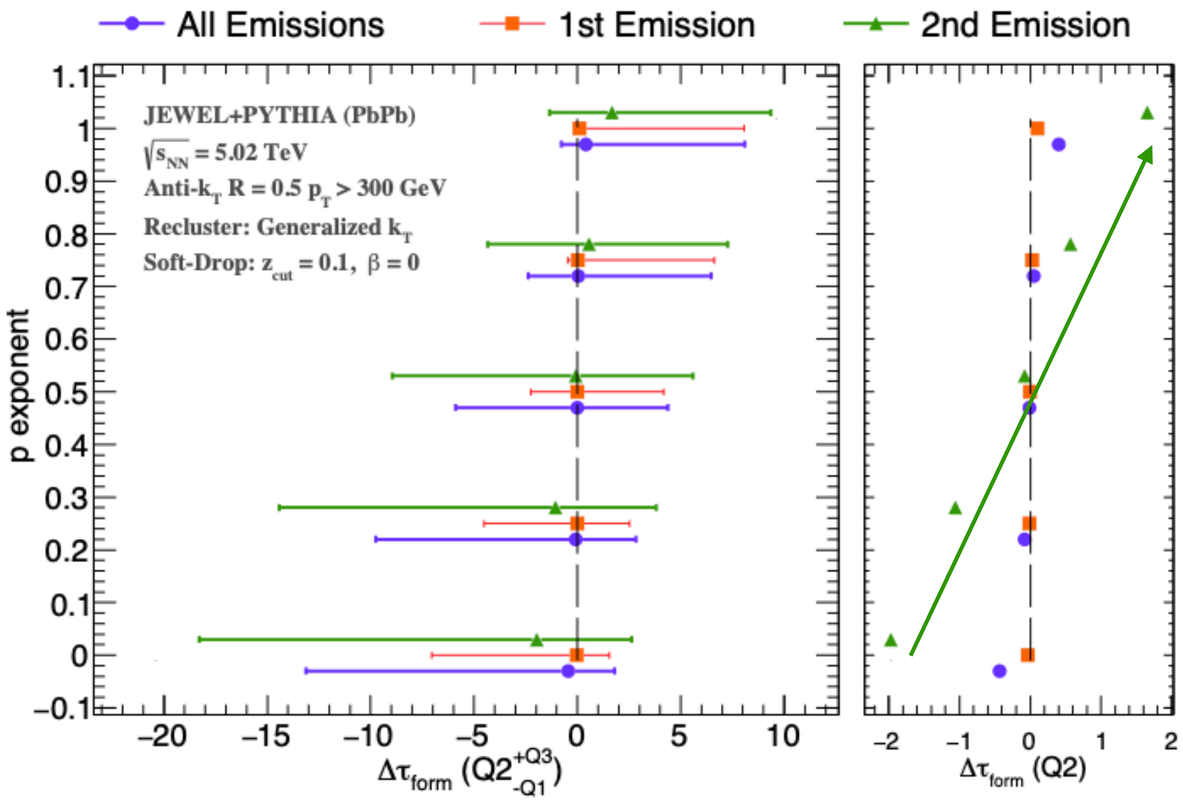
1st emission (with SD) has always median (Q2) centred at 0 (change in IQR)

Vacuum vs Medium

$\Delta\tau$ distribution (vacuum quartiles):



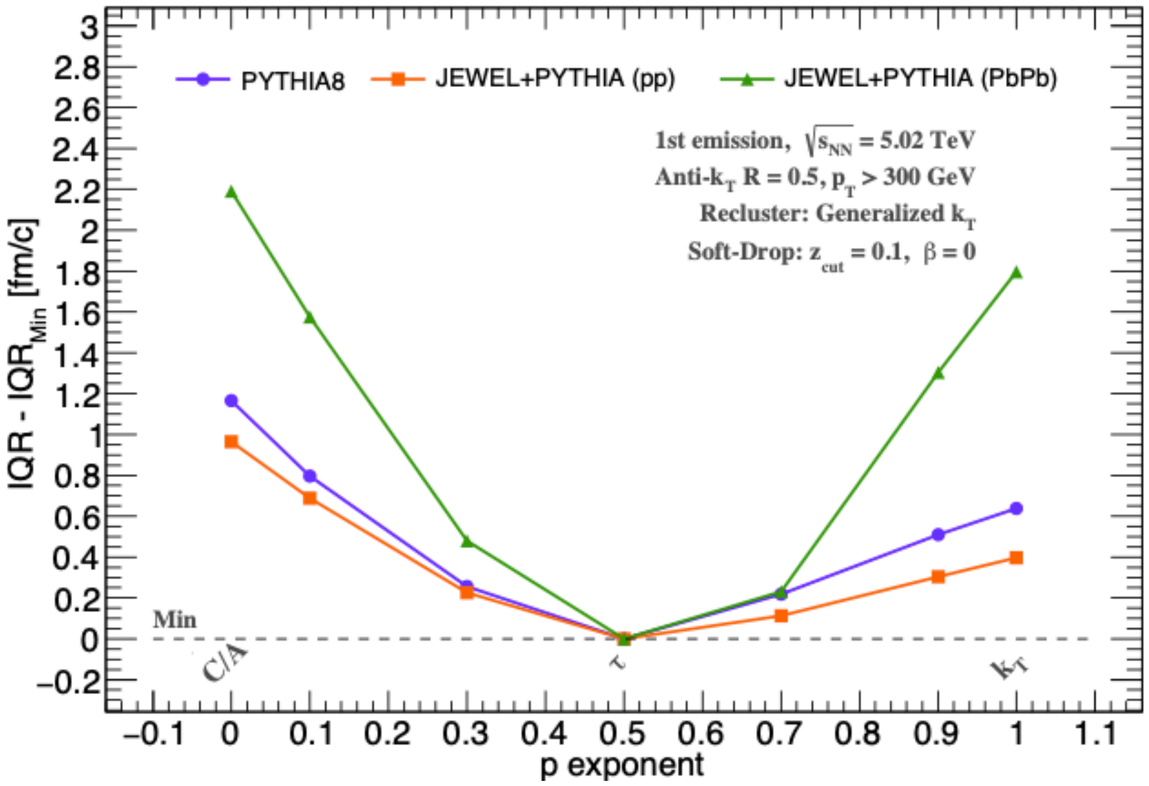
$\Delta\tau$ distribution (in-medium quartiles):



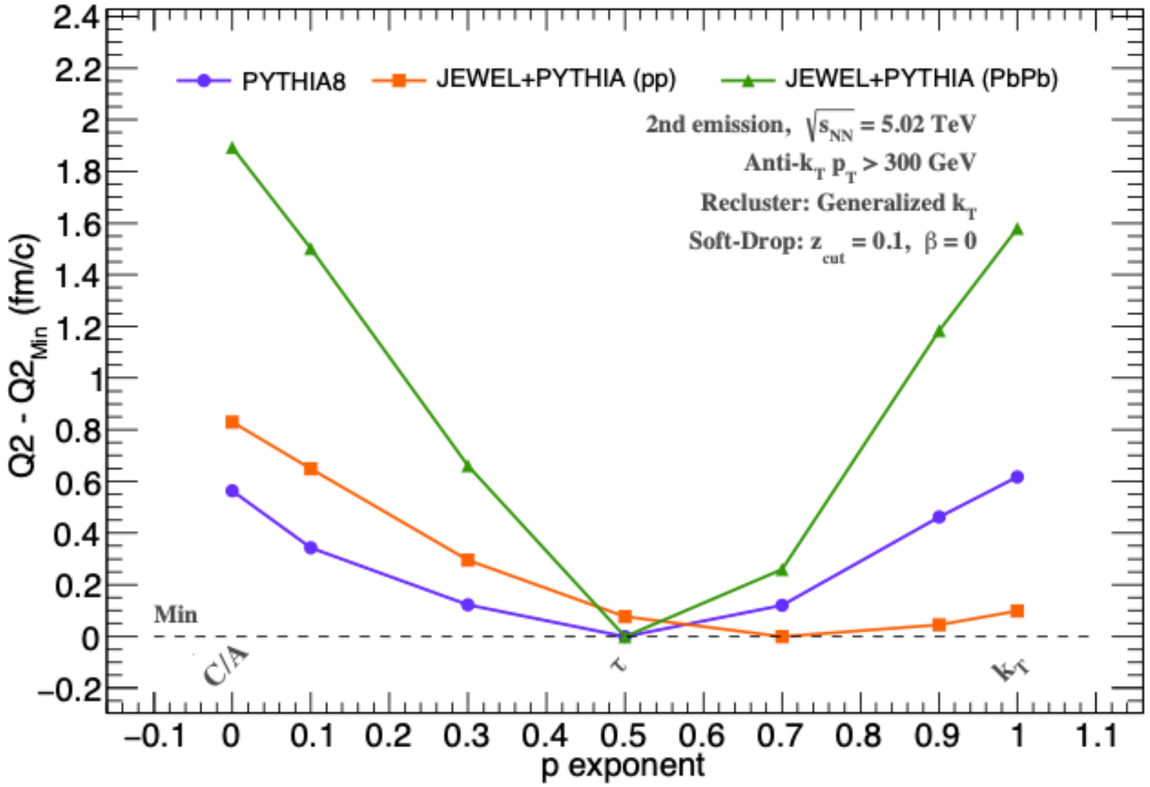
Shift in the median (Q2) of 2nd emission

Algorithms Comparison

1st emission/unclustering step (IQR)



2nd emission/unclustering step (Q2)



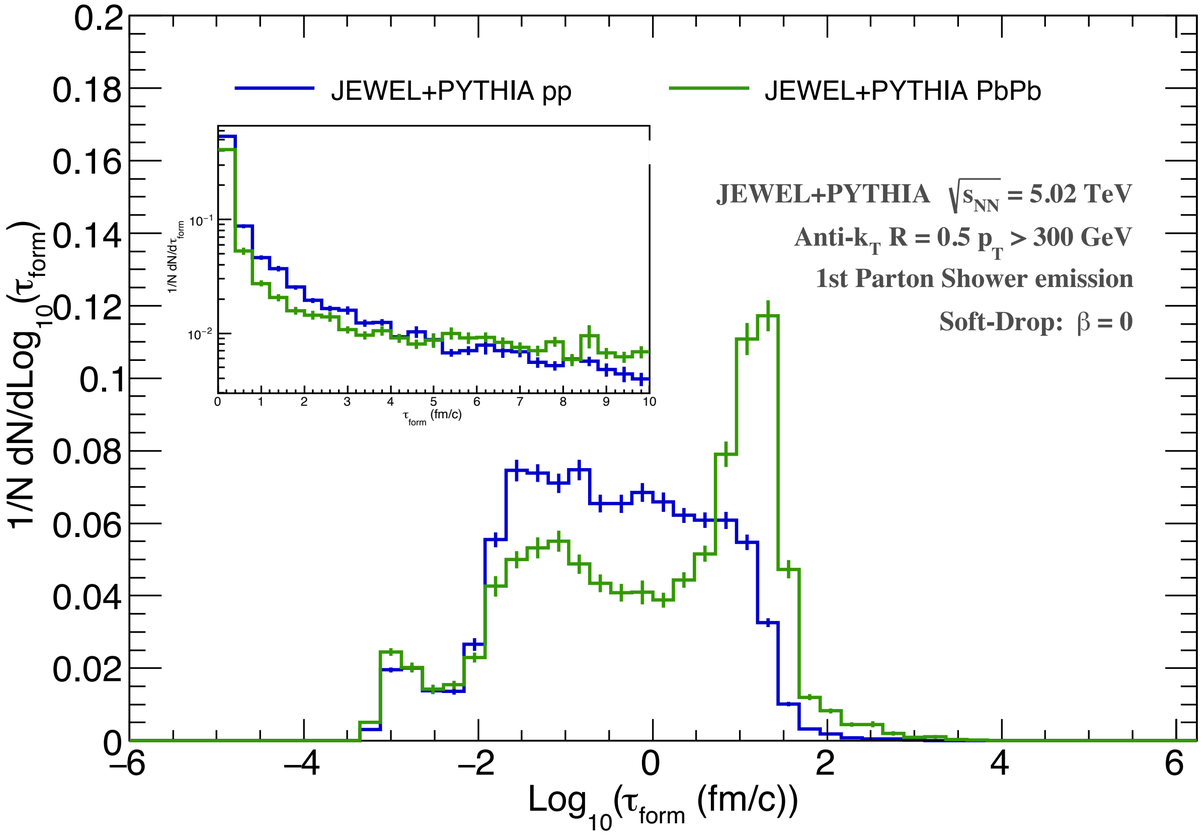
Absolute differences w.r.t to minimum value

Available timescales

R = 0.5, $p_{T,jet}$ > 300 GeV

- Focus on first emission:
  - What are the τ_{form} available?
  - Is it modified by the medium?

Harder fragmentation ⇔ Longer τ



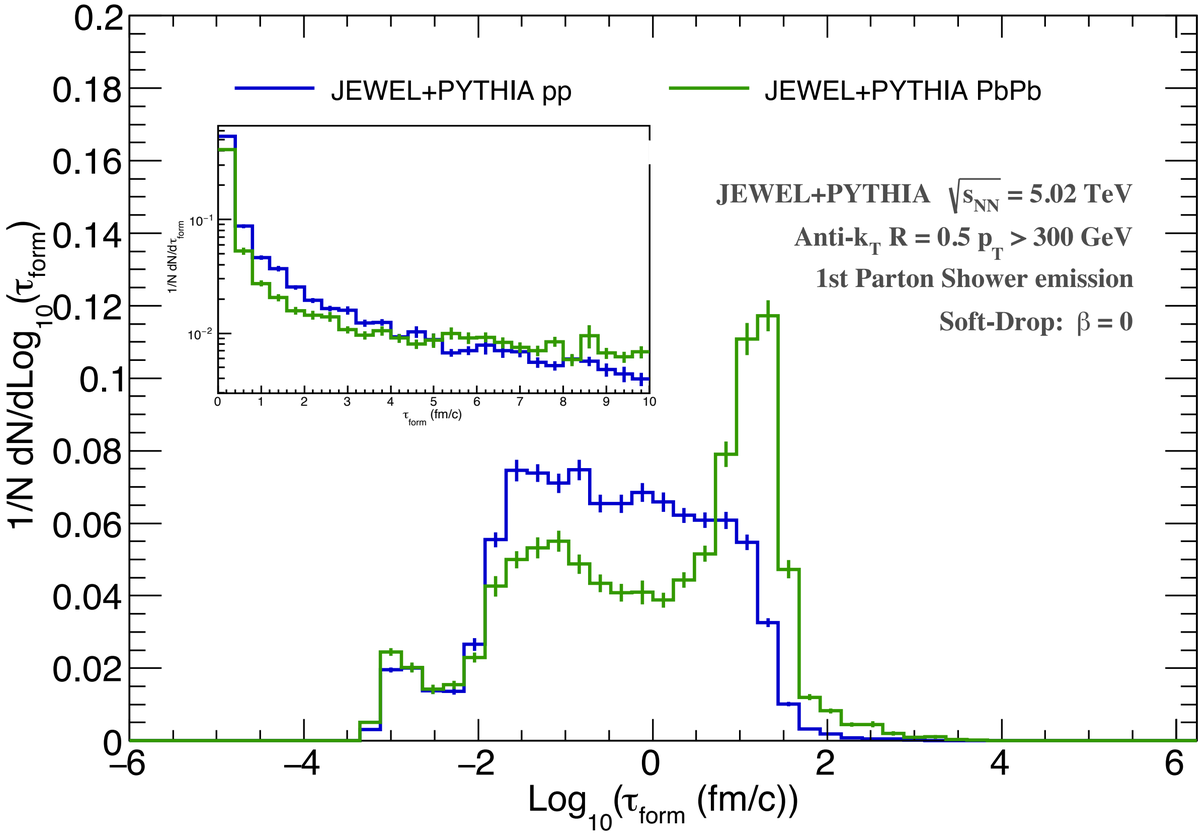
Available timescales

R = 0.5, $p_{T,jet}$ > 300 GeV

- Focus on first emission:
  - What are the τ_{form} available?
  - Is it modified by the medium?

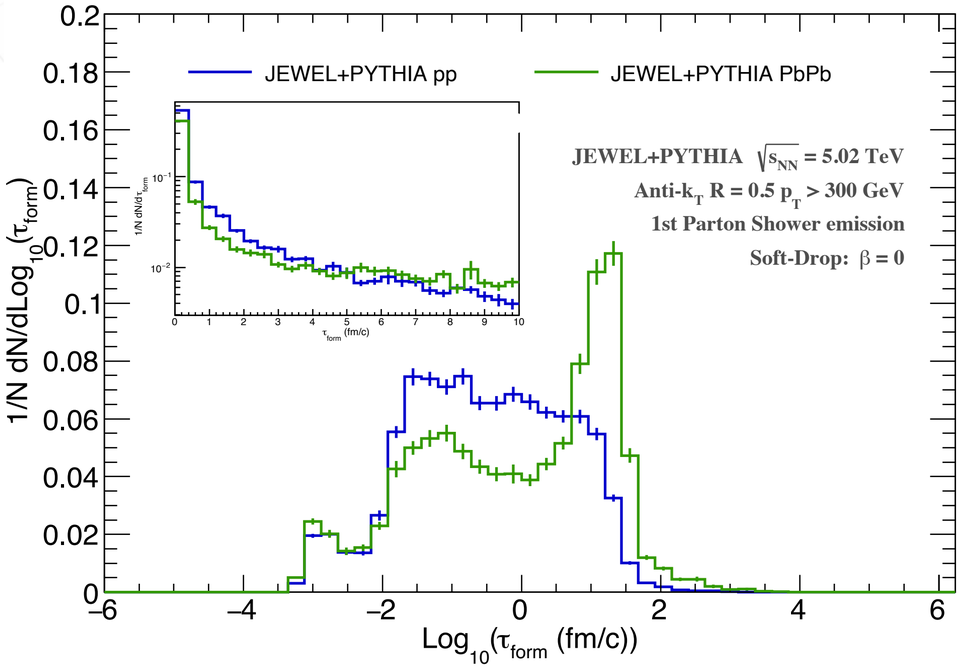
Harder fragmentation ⇔ Longer τ

⇔ Survive more to in-medium jets



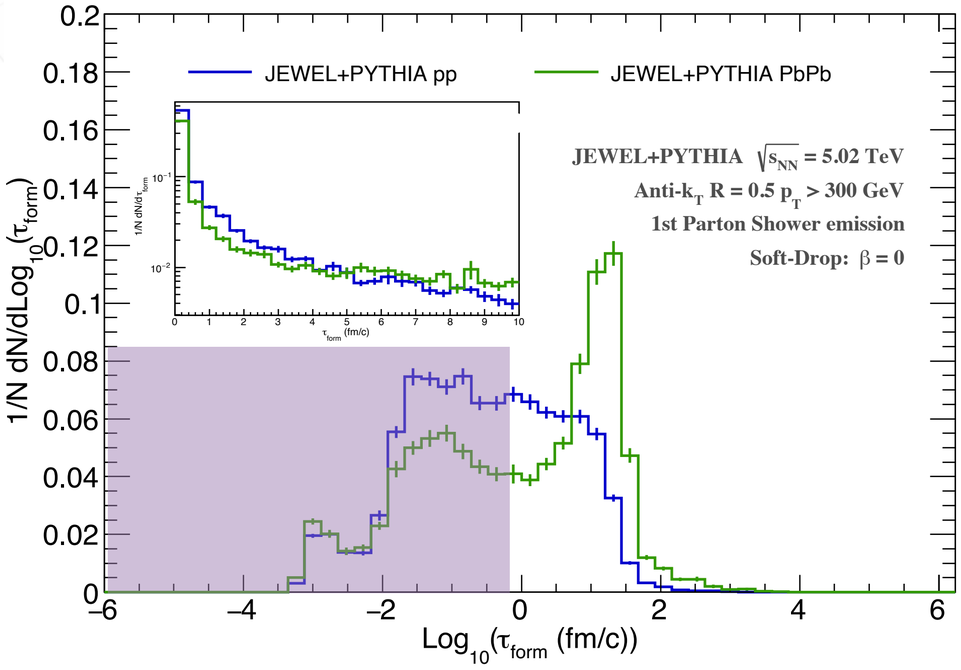
Example application: $R_{AA}^{\text{lead jet}}$

- Easily select two classes of jets:



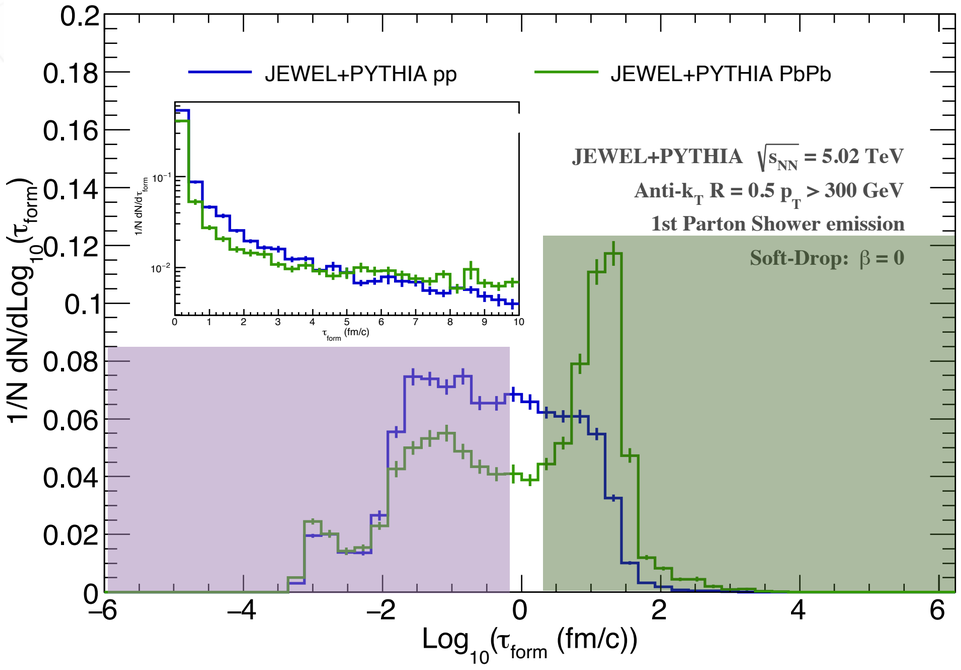
Example application: $R_{AA}^{\text{lead jet}}$

- Easily select two classes of jets:
  - "early" jets: τ_1 < 1 fm/c (strongly modified)

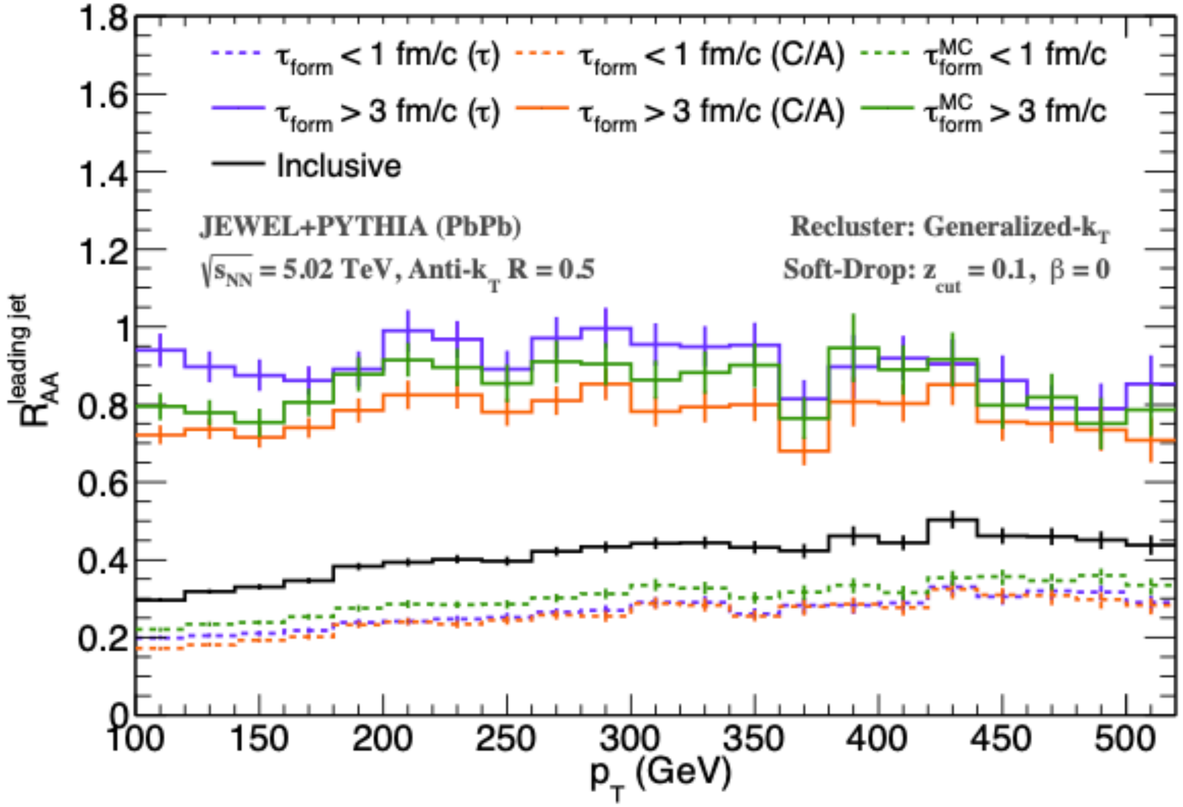


Example application: $R_{AA}^{\text{lead jet}}$

- Easily select two classes of jets:
  - "early" jets: τ_1 < 1 fm/c (strongly modified)
  - "late" jets: τ_1 > 3 fm/c (weakly modified)



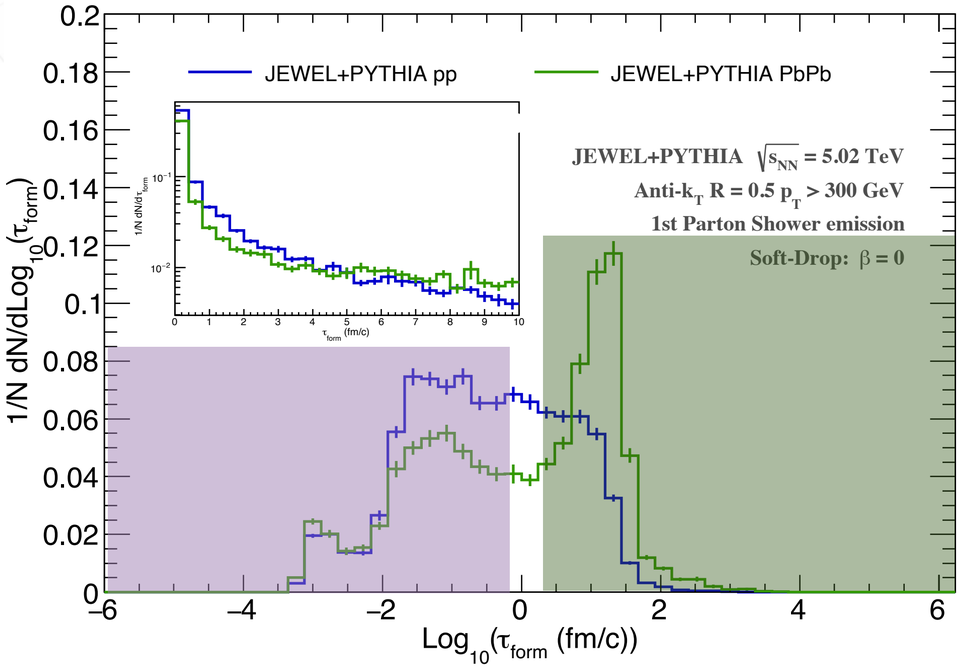
Previous results



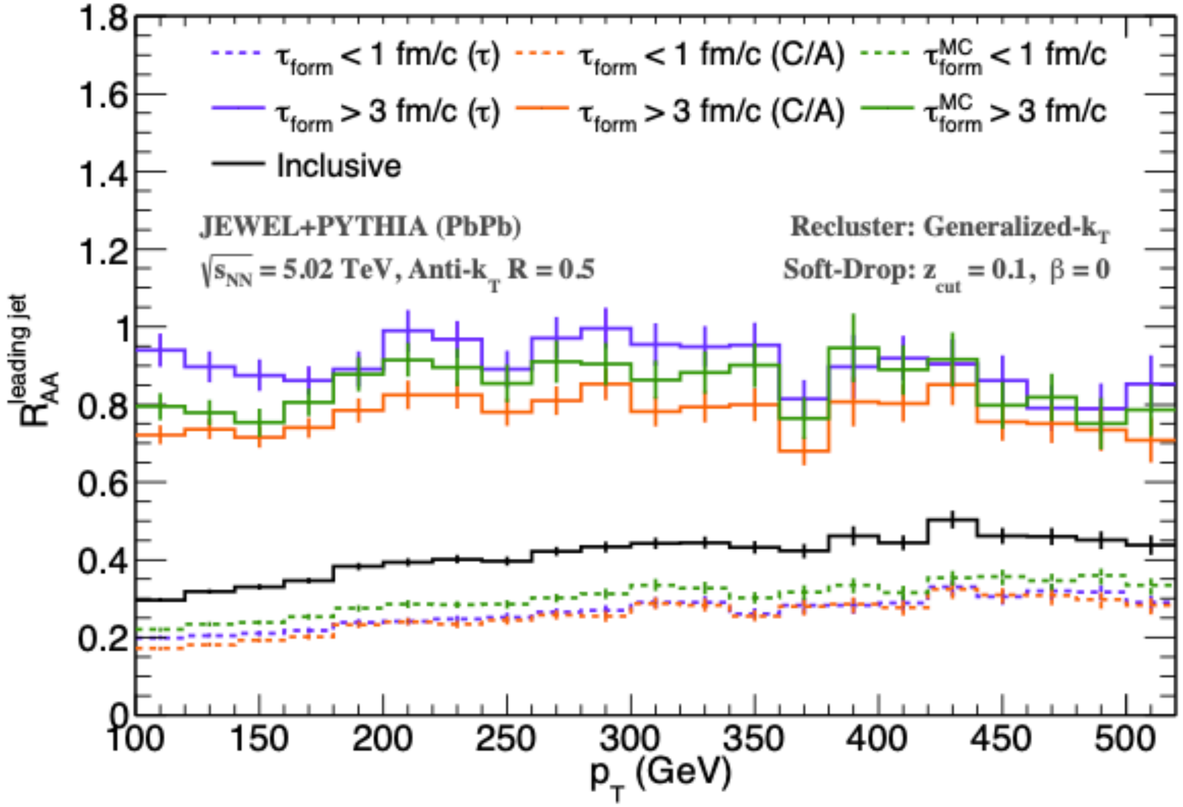
Example application: $R_{AA}^{\text{lead jet}}$

[talks on jet quenching selection: Laura, Raymond, Mateusz]

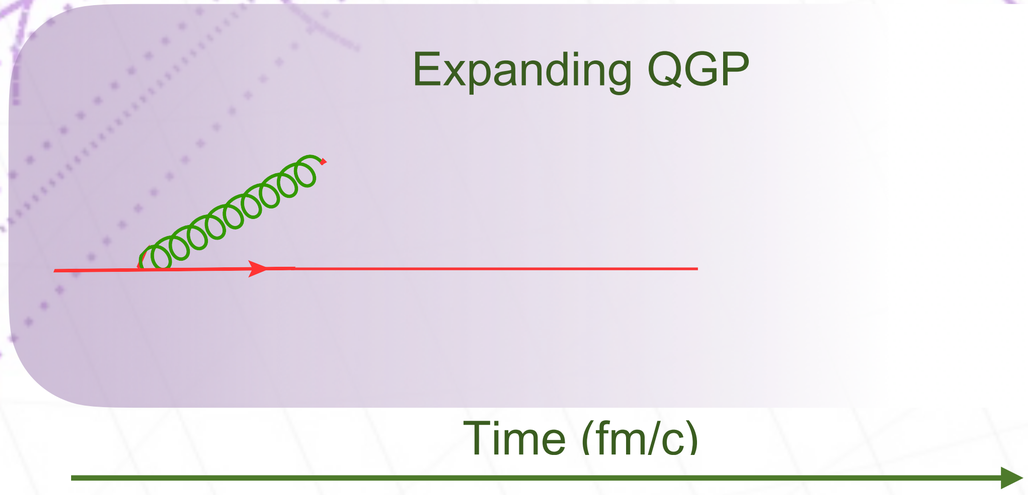
- Easily select two classes of jets:
  - "early" jets: τ_1 < 1 fm/c (strongly modified)
  - "late" jets: τ_1 > 3 fm/c (weakly modified)



Previous results

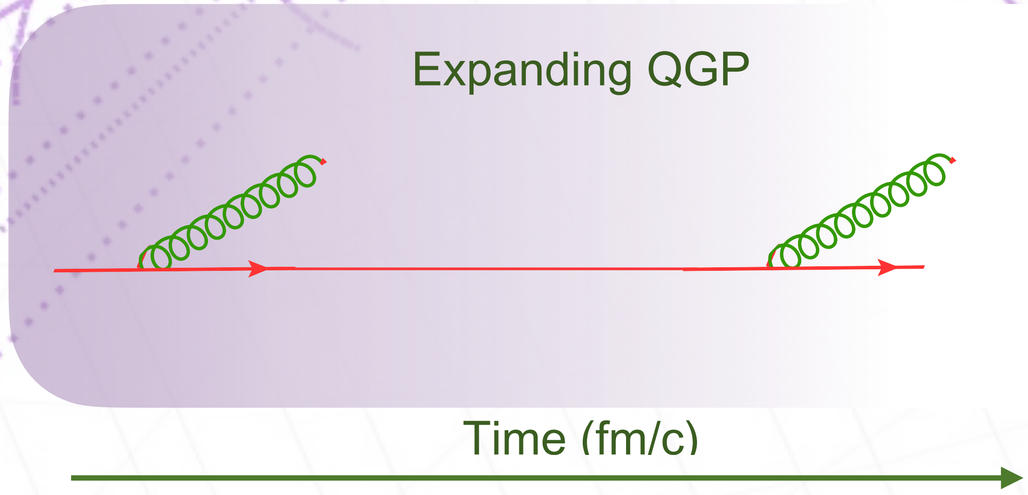


1st unclustering: ✓



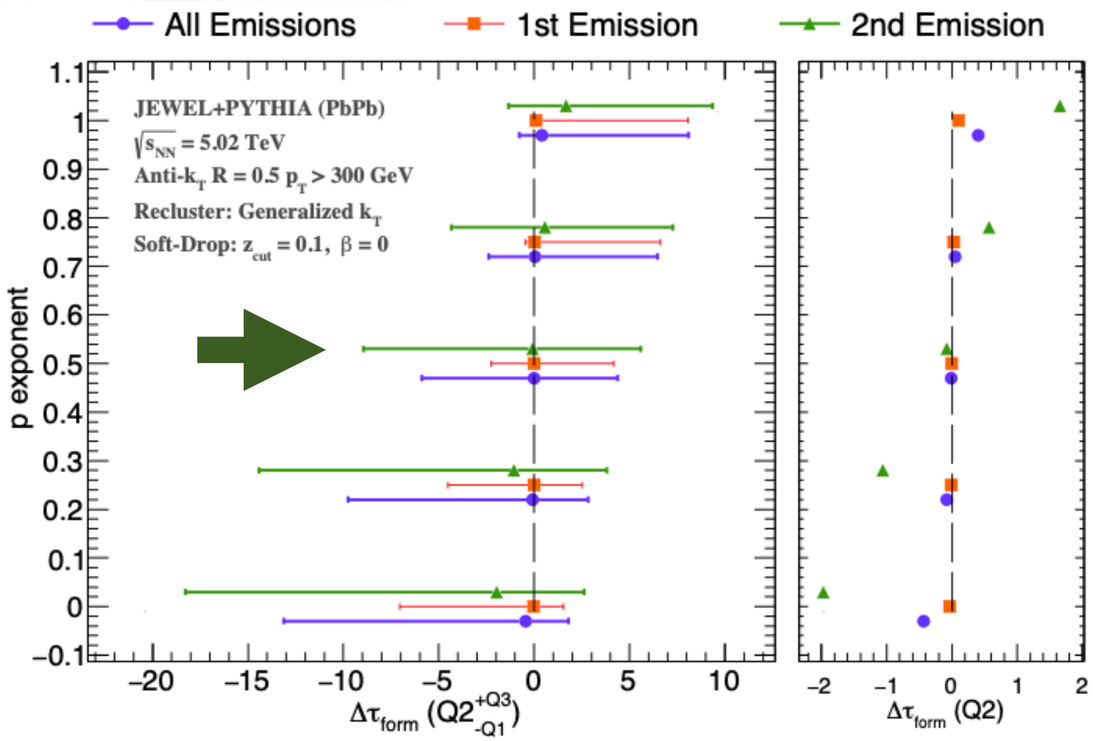
1st unclustering: ✓

Can we go further?
(2nd unclustering)



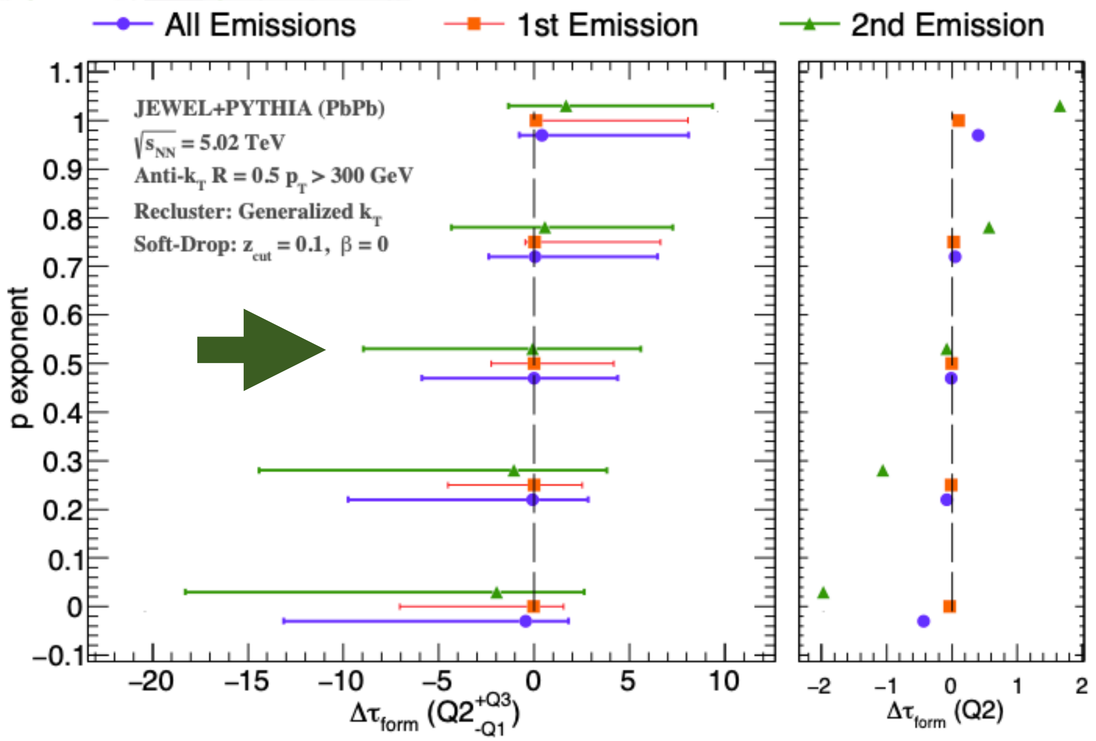
1st vs 2nd Unclustering Step

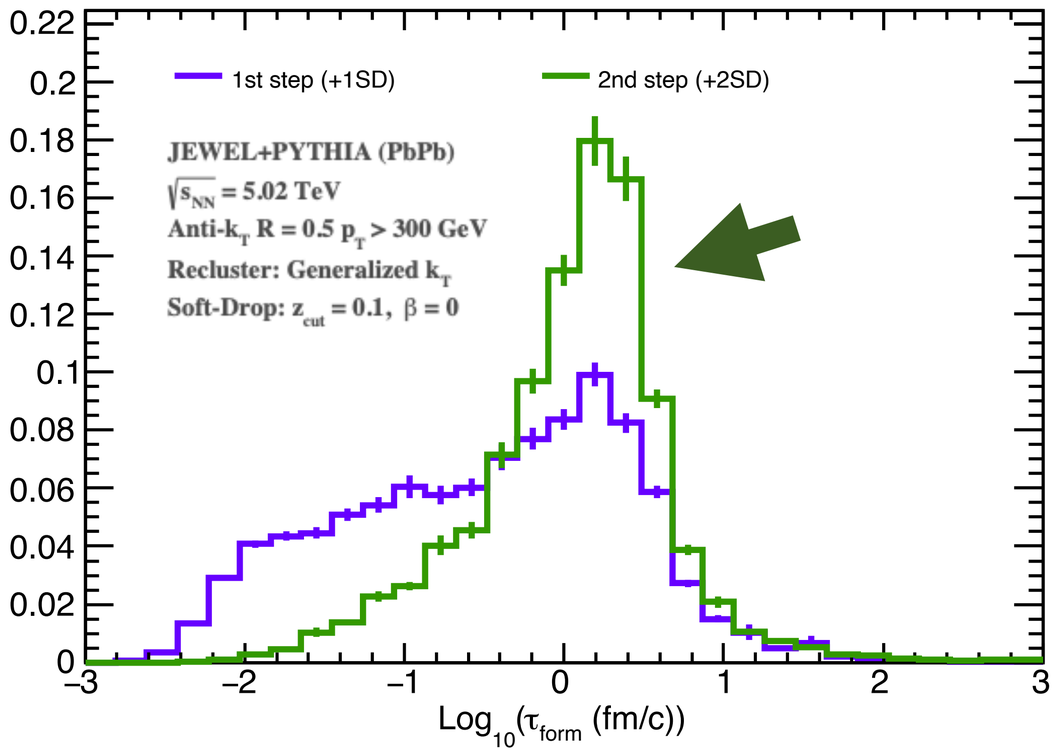
- Uncertainty on 2nd unclustering step is larger…



1st vs 2nd Unclustering Step

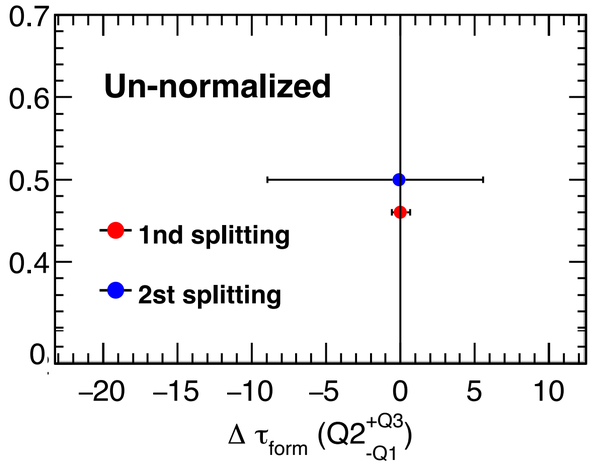
- Uncertainty on 2nd unclustering step is larger…
  - But τ_{form}-distribution is also displaced towards larger values

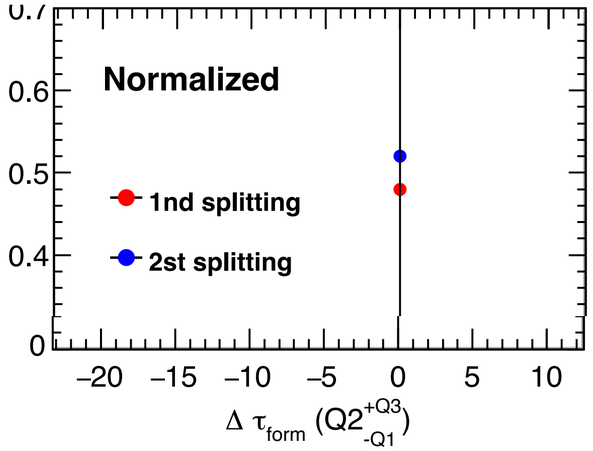




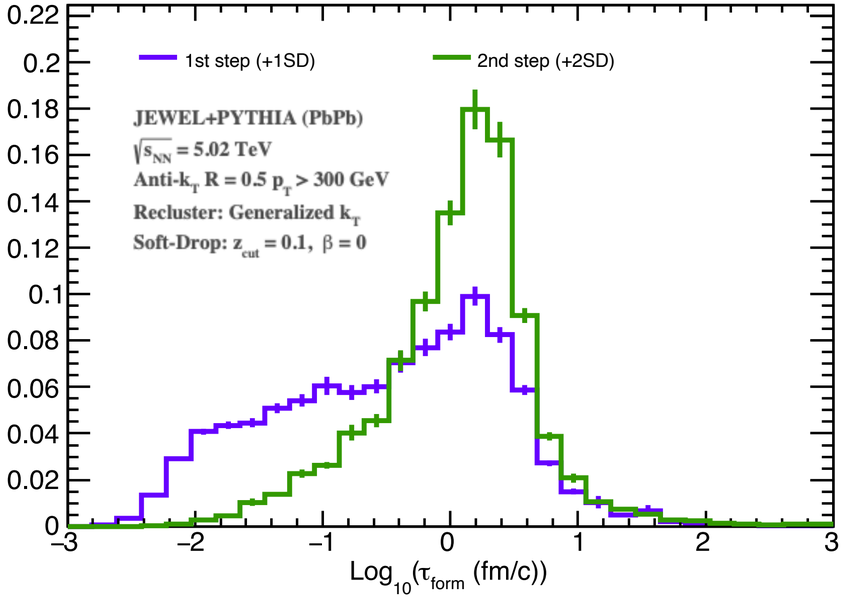
Normalised IQR

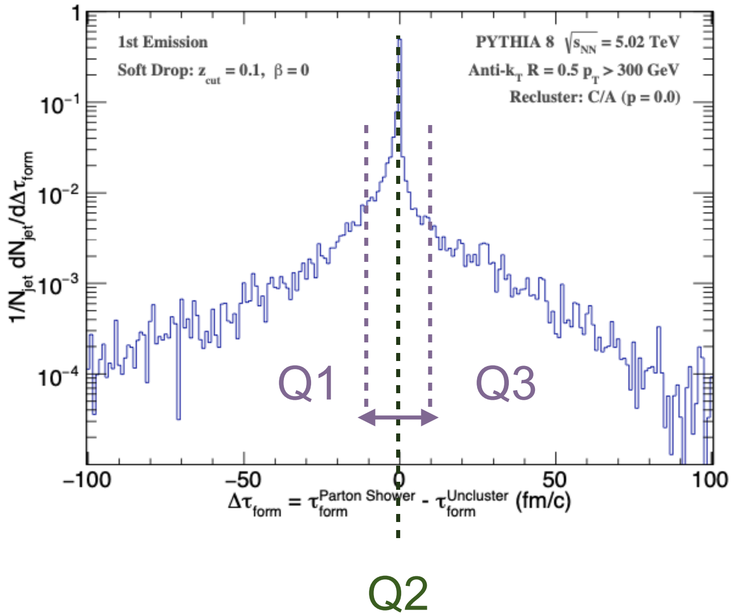
- Formation time gets logarithmic larger at each unclustering step
  - Normalising by the average <τ_{form}>:





<τ_2> obtained from: $e^{-t/<\tau 2>}$





Normalised IQR

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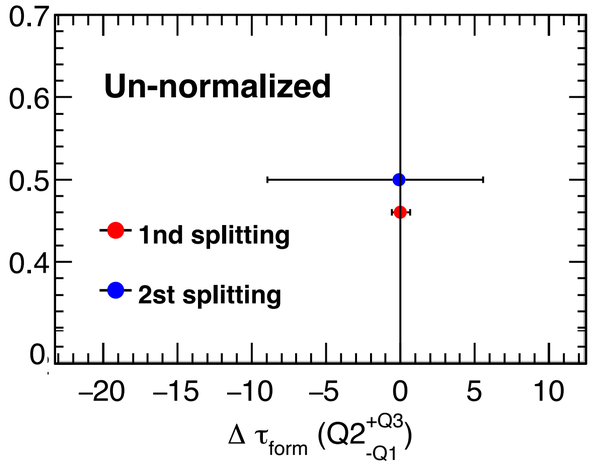
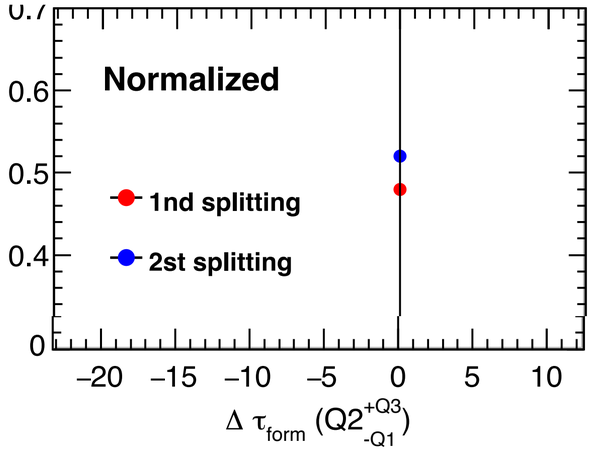
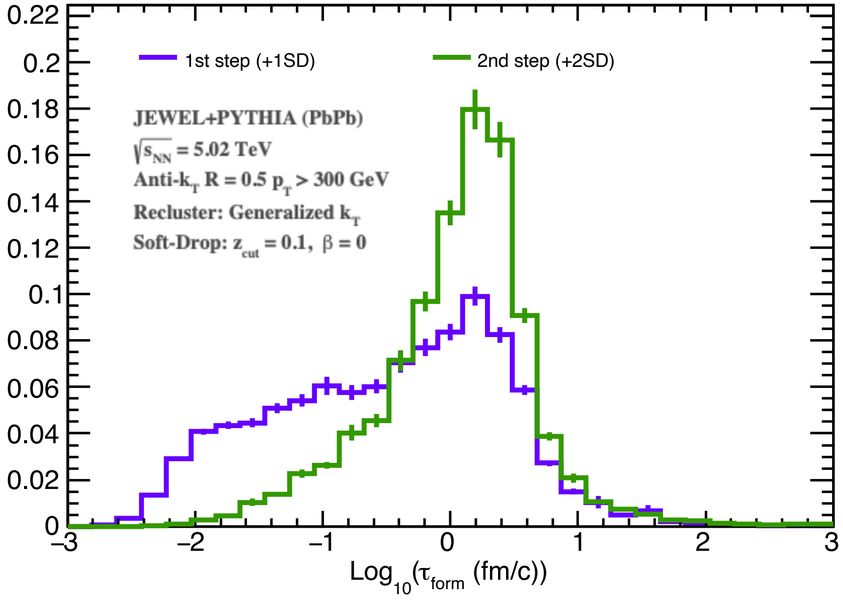
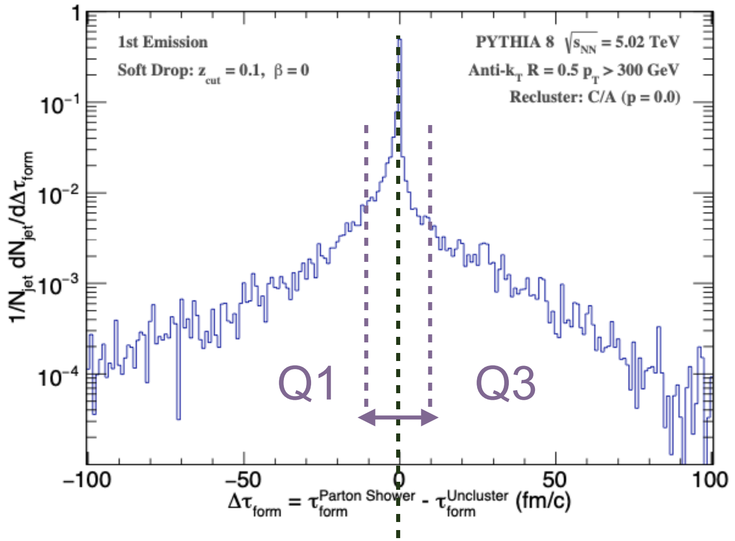




<τ_2> obtained from: $e^{-t/<\tau 2>}$



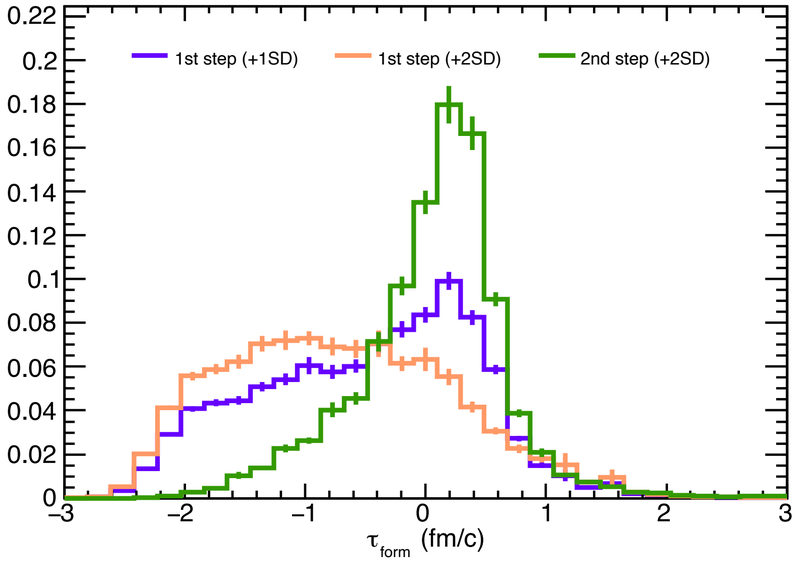


Q2

Relative IQR for 2nd unclustering still looks manageable

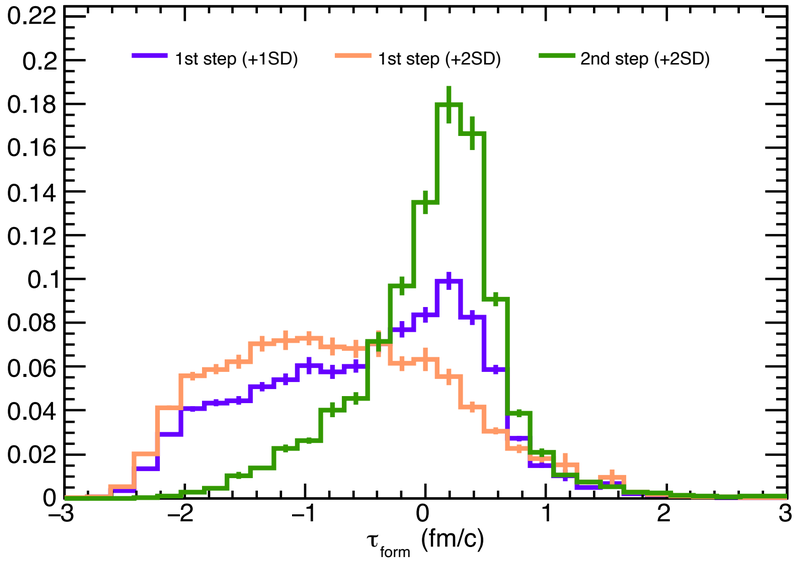
But…

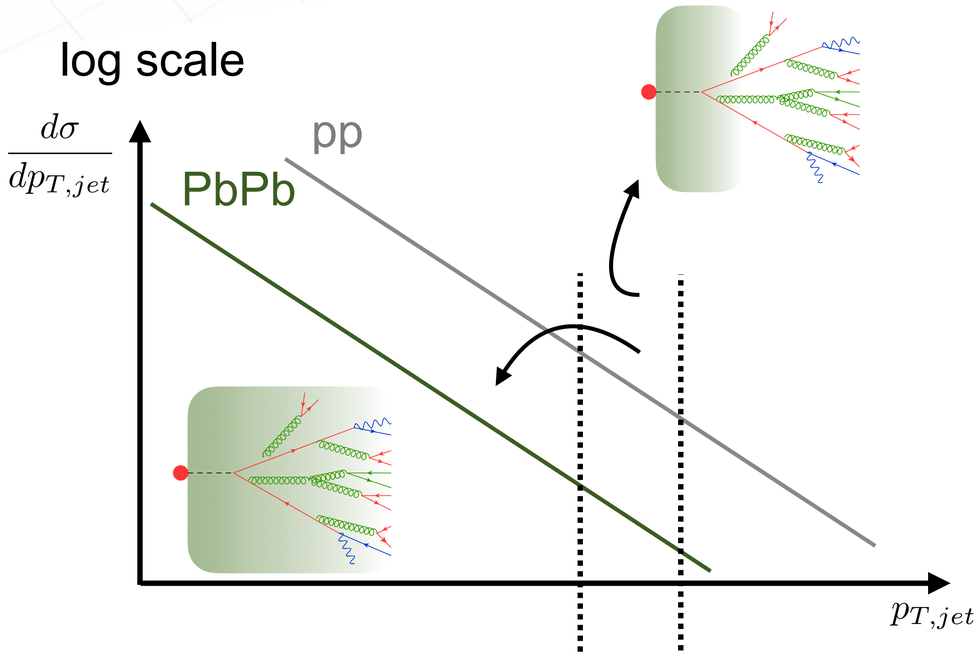
- There are several biases one needs to consider…
  - Phase space restrictions…

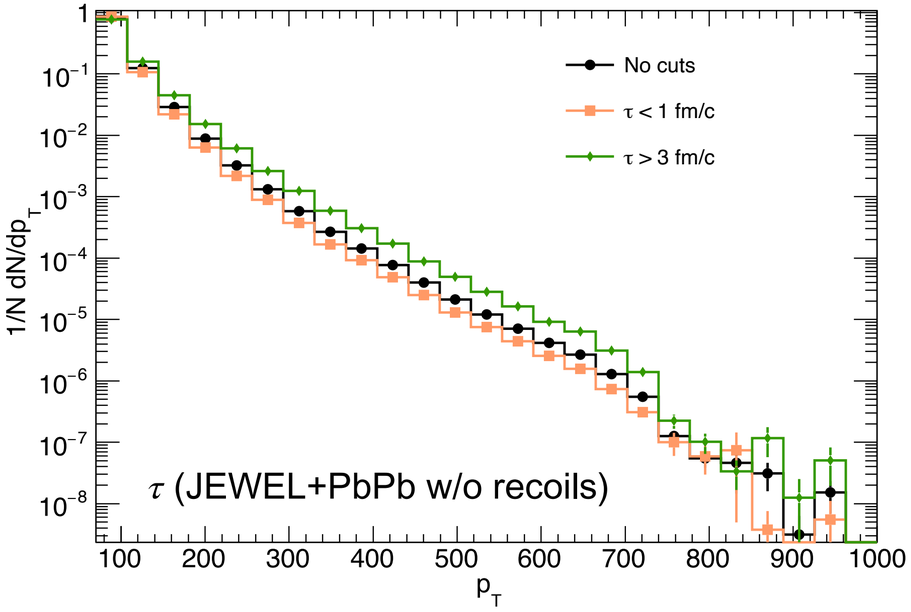


But…

- There are several biases one needs to consider…
  - Phase space restrictions…
  - Jet-pT/Flavour selection…

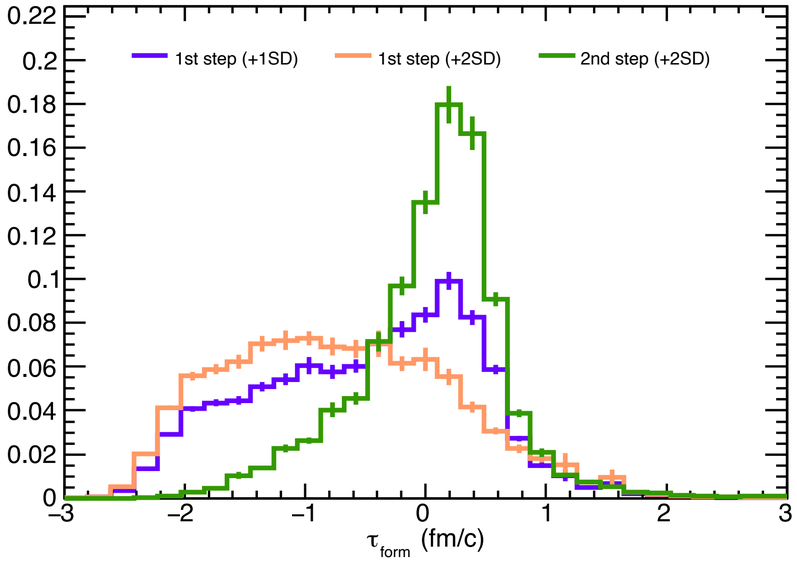


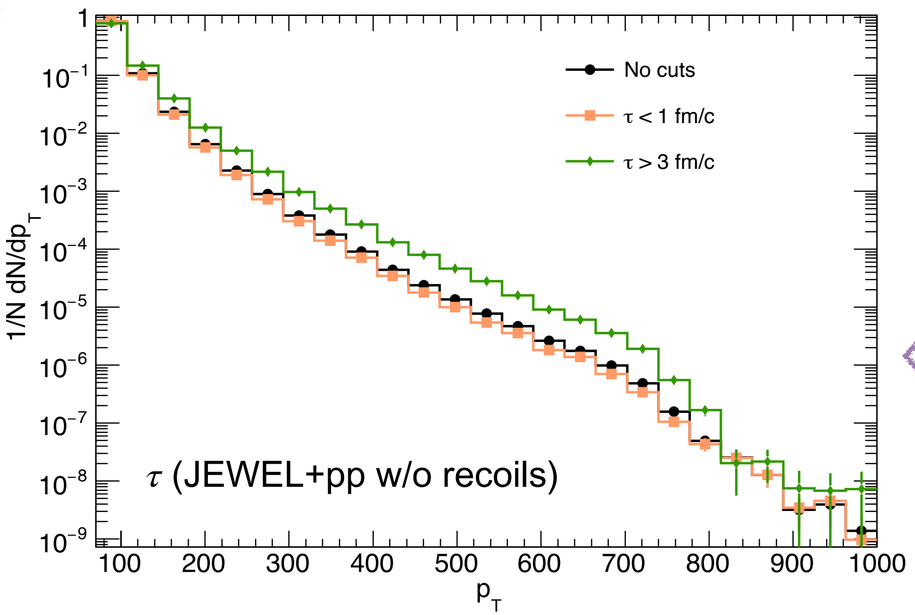




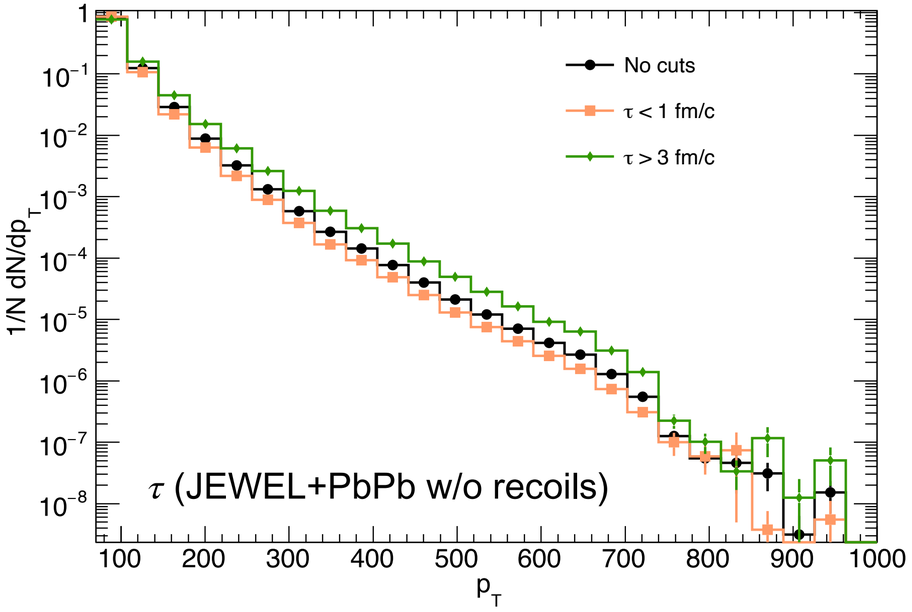
But…

- There are several biases one needs to consider…
  - Phase space restrictions…
  - Jet-pT/Flavour selection… different in pp and PbPb…



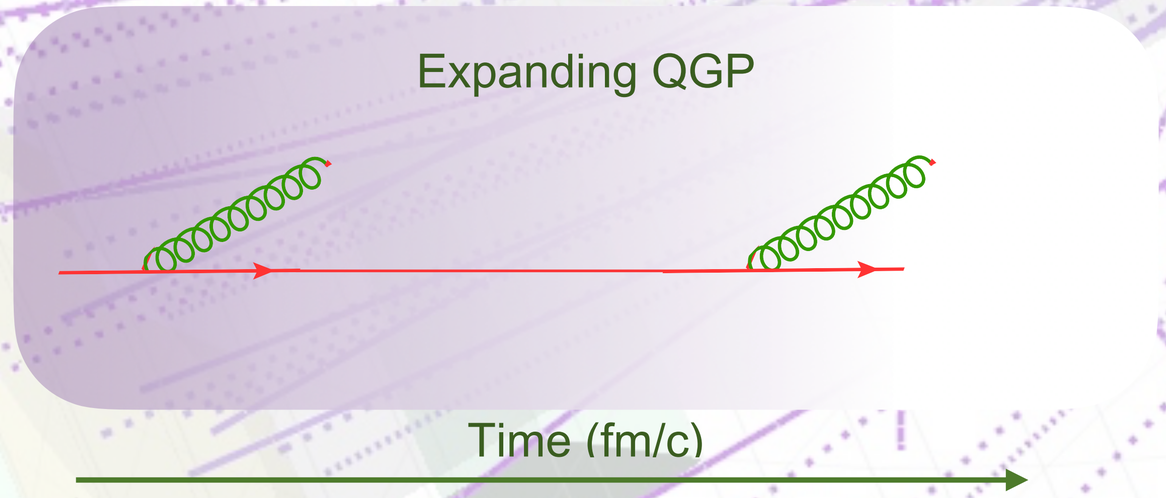


???

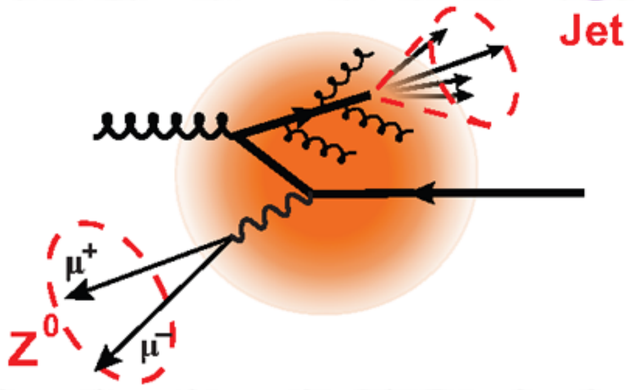


2nd unclustering: ?

Need a more calibrated setup:

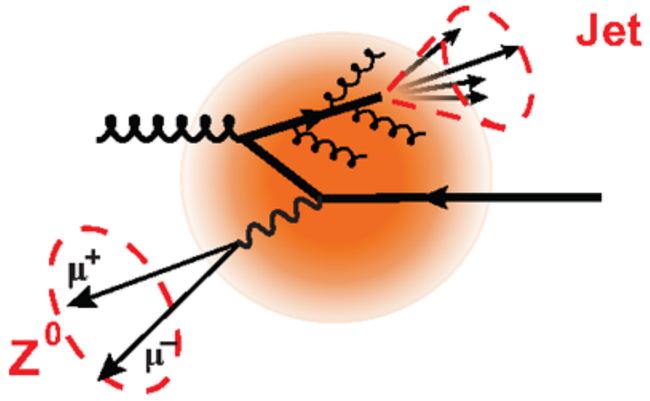


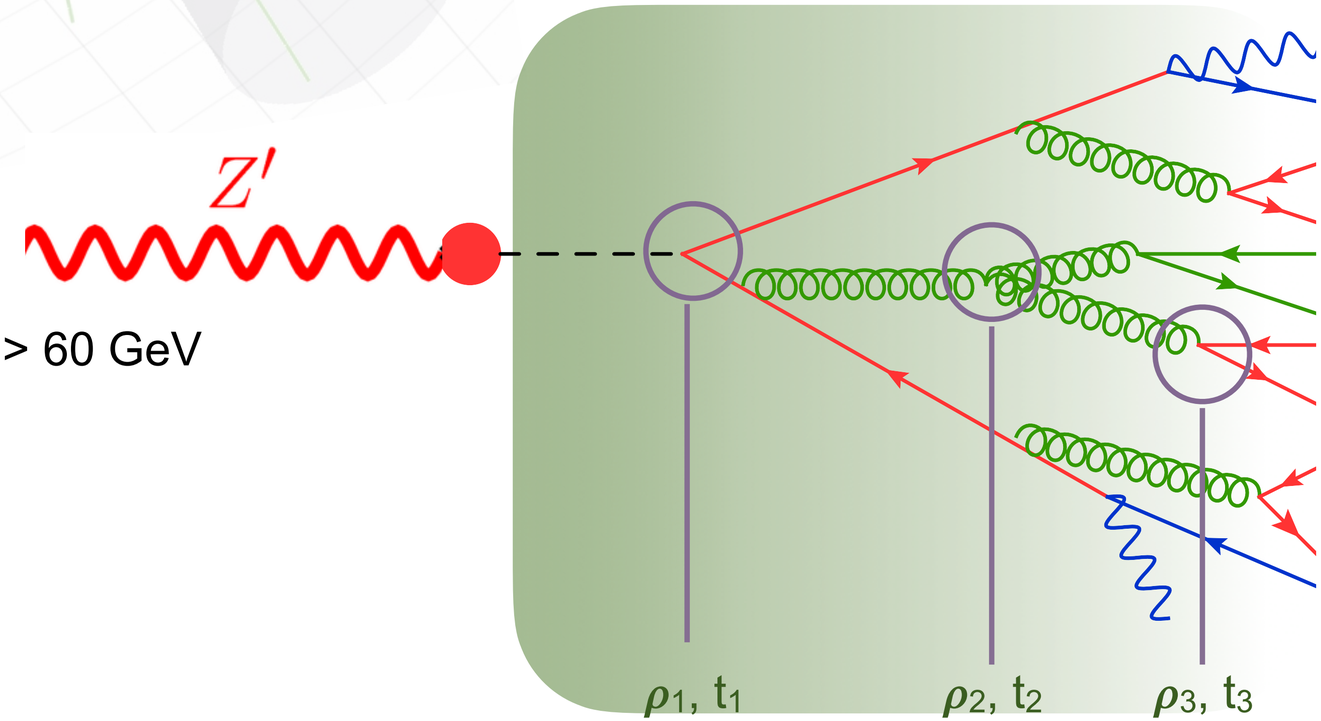
Dijets ⇒ Z+jet



From di-jets to Z+jet events

- More calibrated results: boson + (quark) jet
  - Recoiling jet R = 0.5, $p_{T,Z}$ > 60 GeV, p_{Tjet} > 30 GeV





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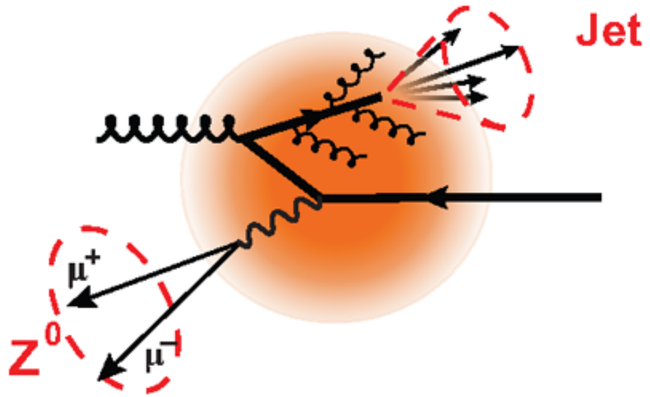
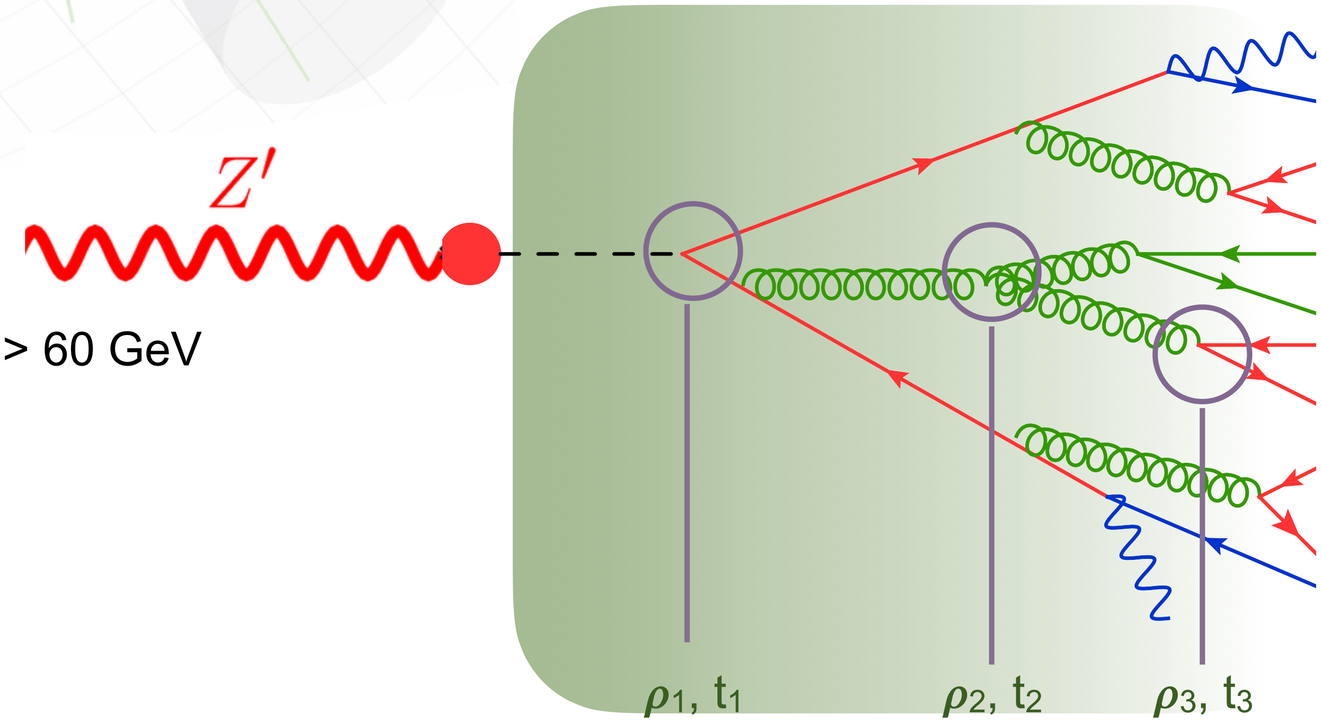
  - Recoiling jet R = 0.5, $p_{T,Z}$ > 60 GeV, p_{Tjet} > 30 GeV





$p_{T,Z}$ > 60 GeV

$$d_{ij} \sim p_{T,i}\frac{\Delta R_{ij}^2}{R^2} \sim p_T\theta^2 \sim \frac{1}{\tau_{form}}$$

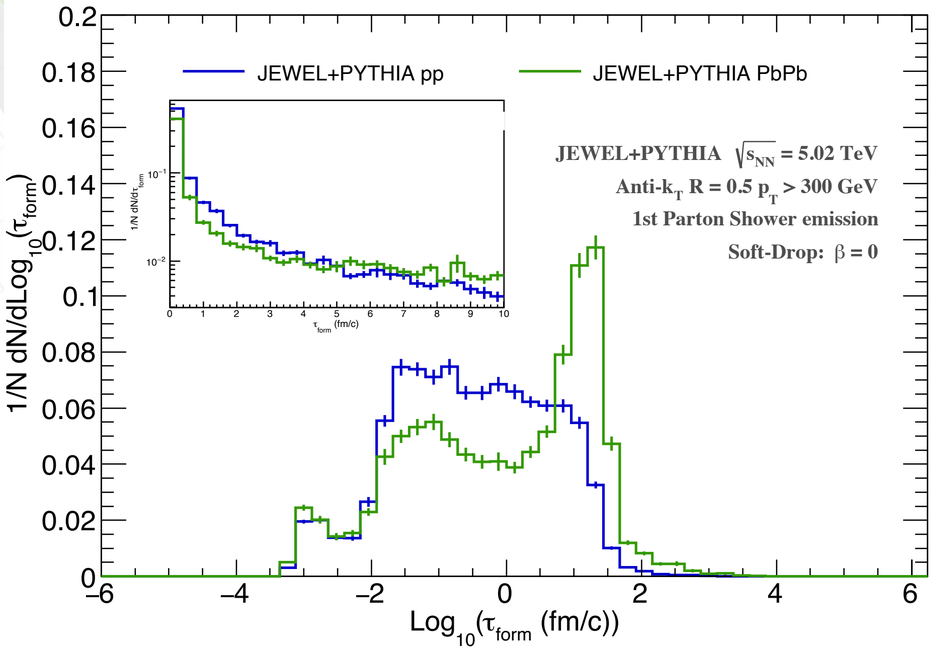
$$\tau_{form} \approx \frac{E}{Q^2} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$

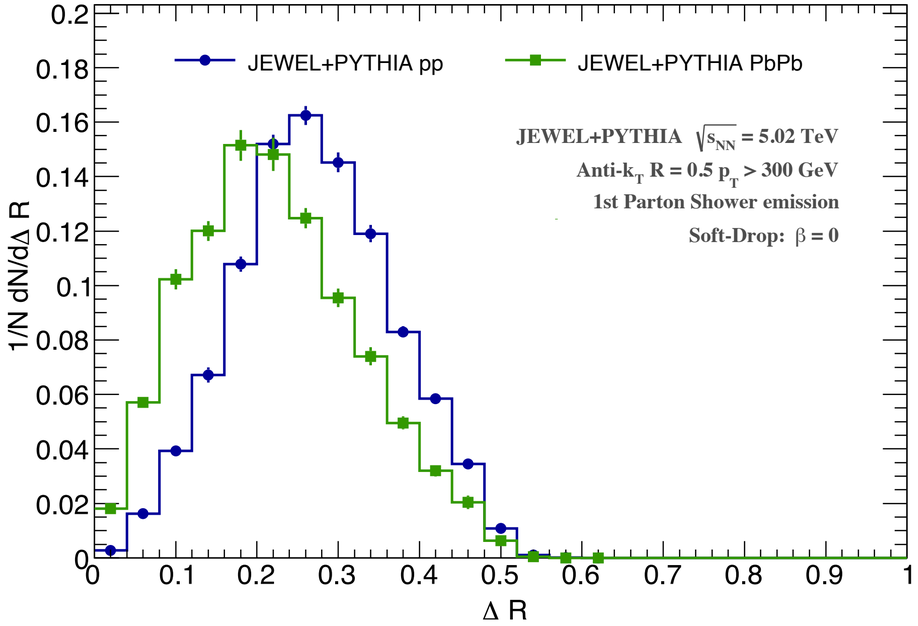
$\tau_{form} = \tau_{form}(\Delta R, z)$

Kinematic cut?

ΔR vs τ_{form}

- Selecting on ΔR vs selecting on τ_{form}:





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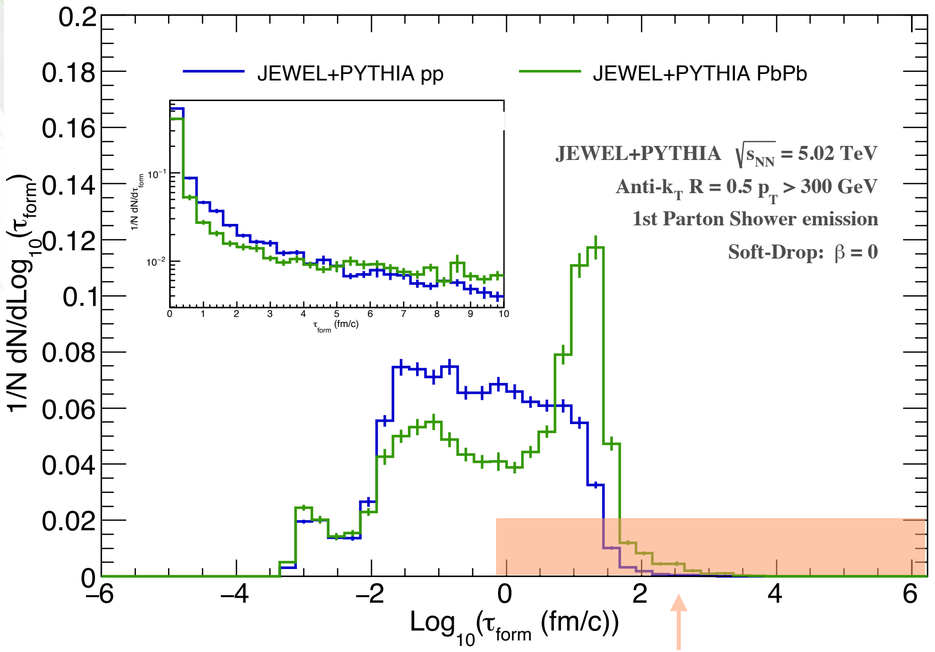
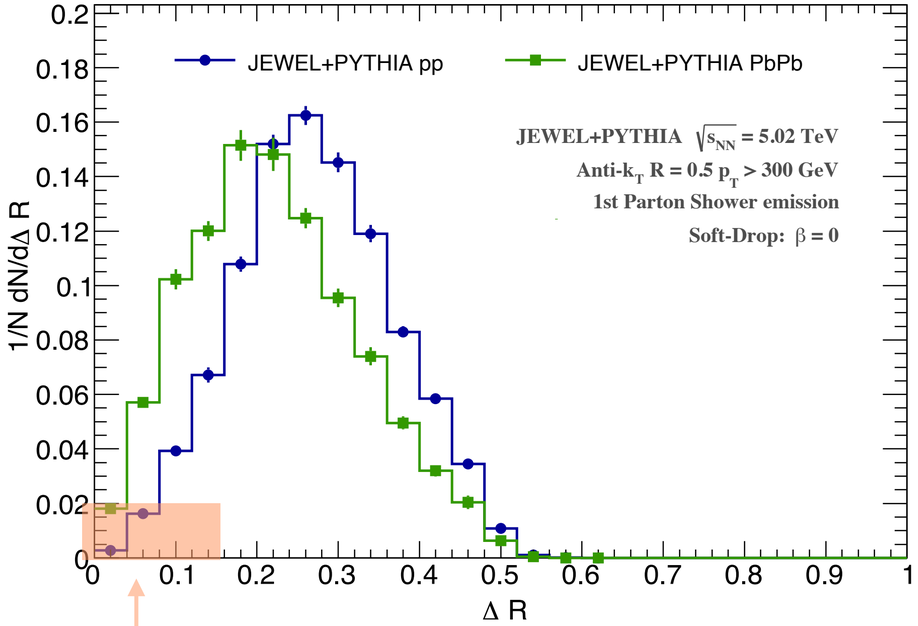
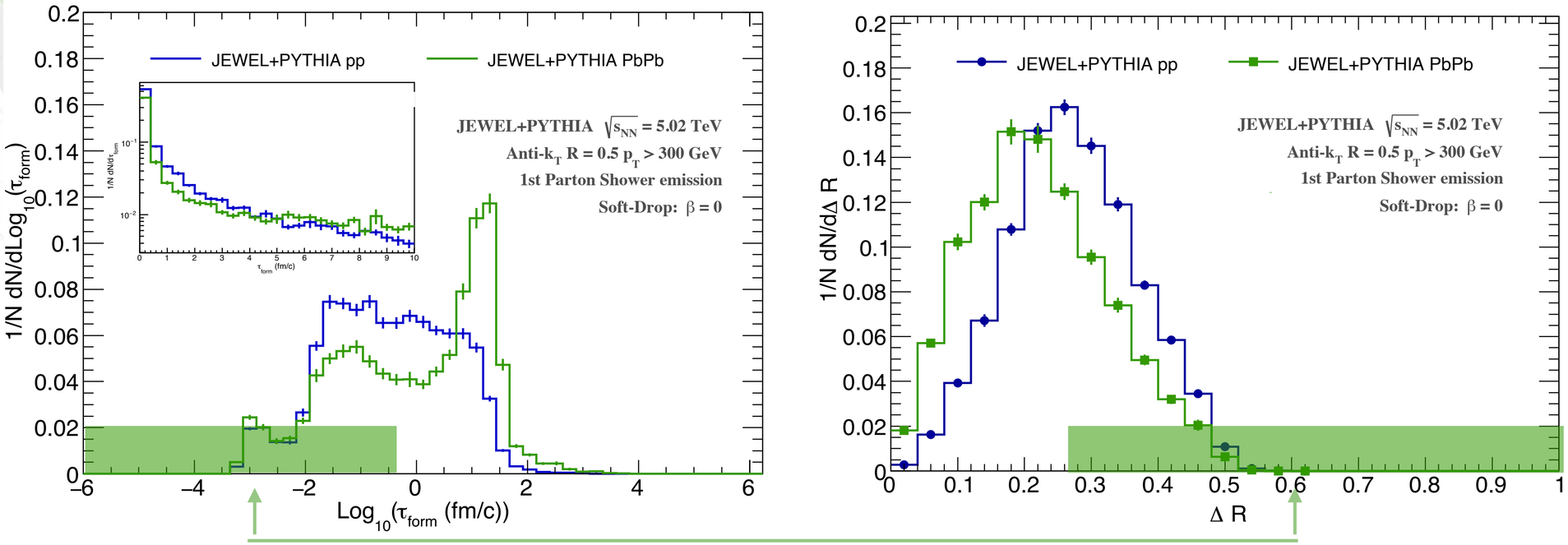




Harder fragmentation ⇔ Longer τ ⇔ Smaller ΔR

ΔR vs τ_{form}

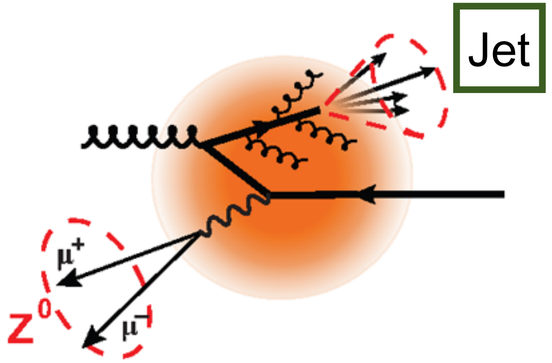
- Selecting on ΔR vs selecting on τ_{form}:



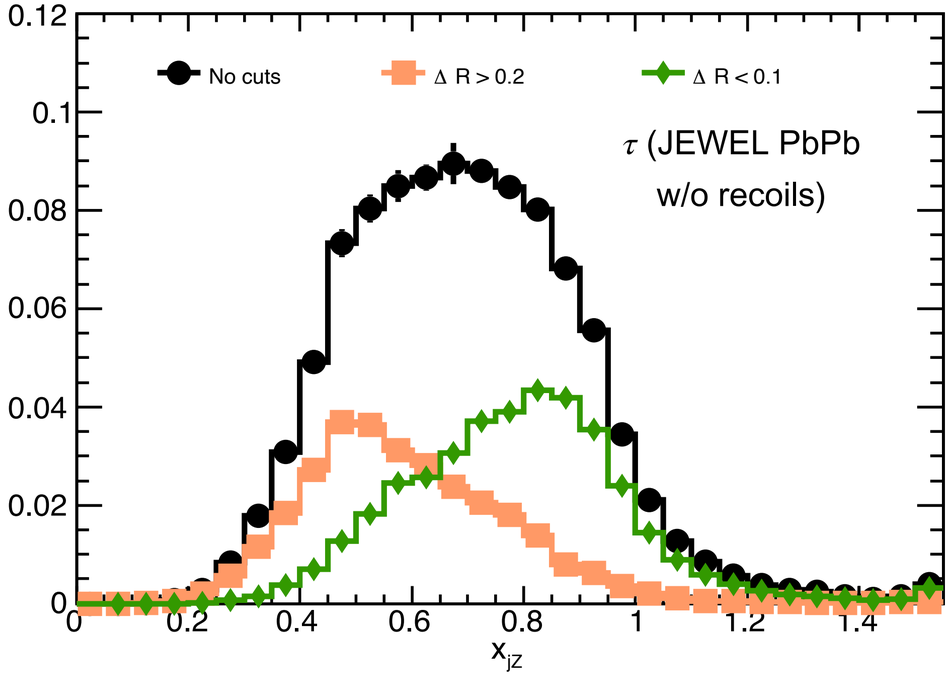
Softer fragmentation ⇔ Smaller τ ⇔ Larger ΔR

ΔR vs τ_{form}

- Selecting jets based on ΔR or τ_{form}? Will we select the same jet sample?

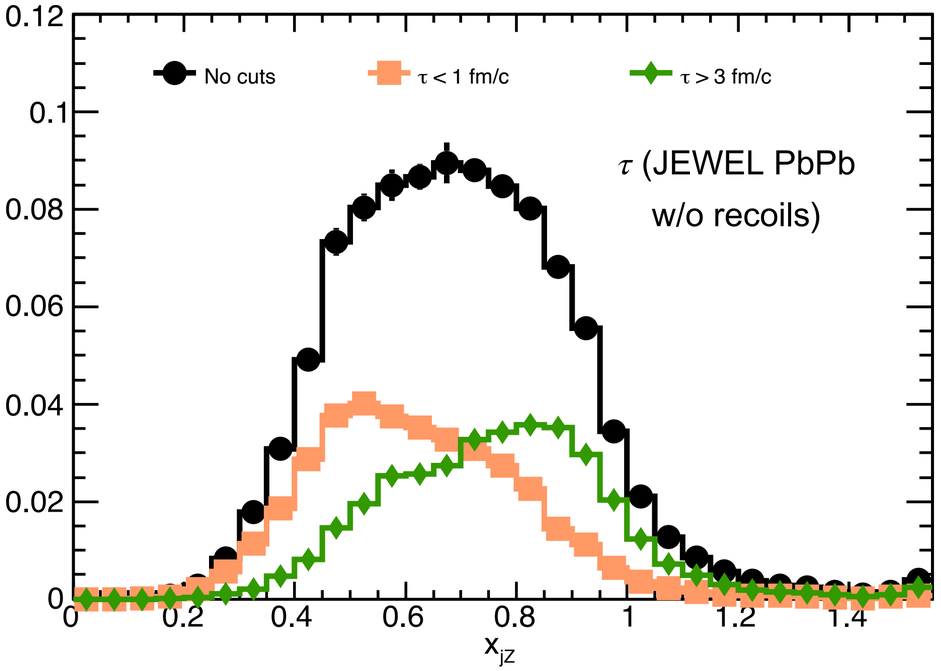


ΔR bins



Identical jet distributions…

τ_{form} bins



ΔR vs τ_{form}

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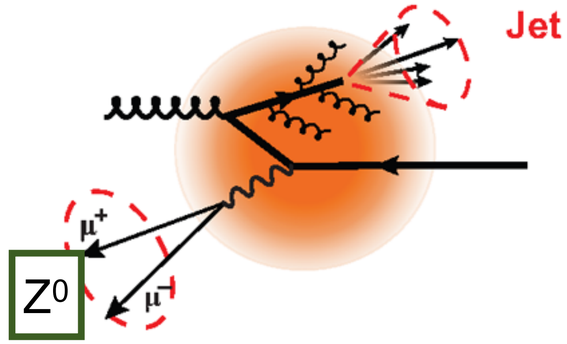
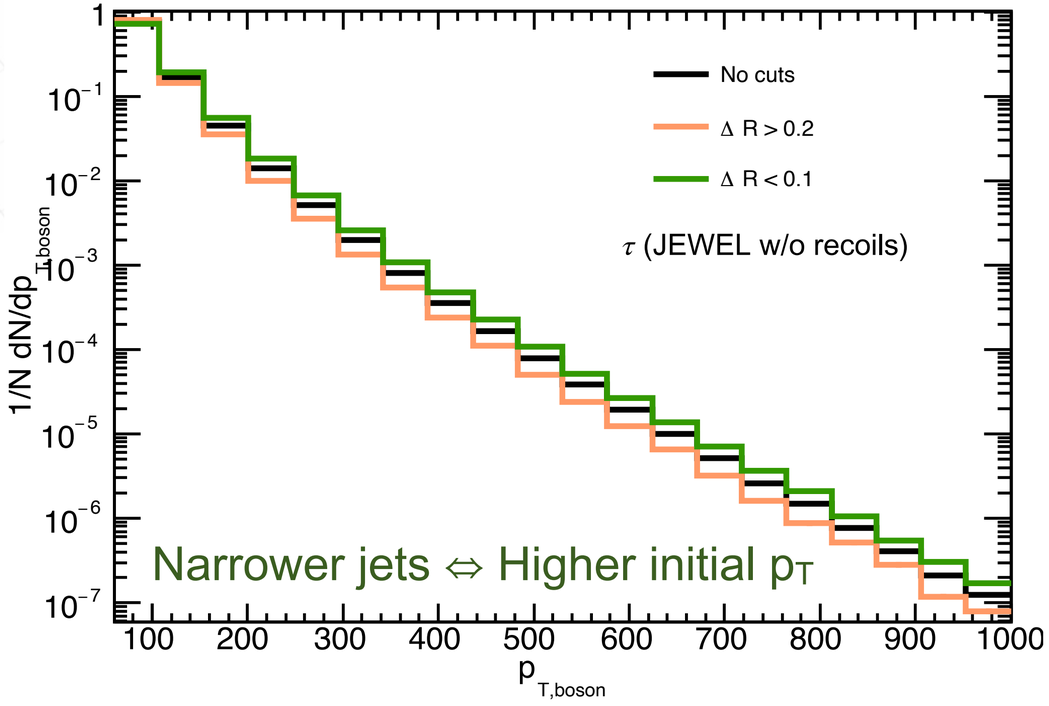


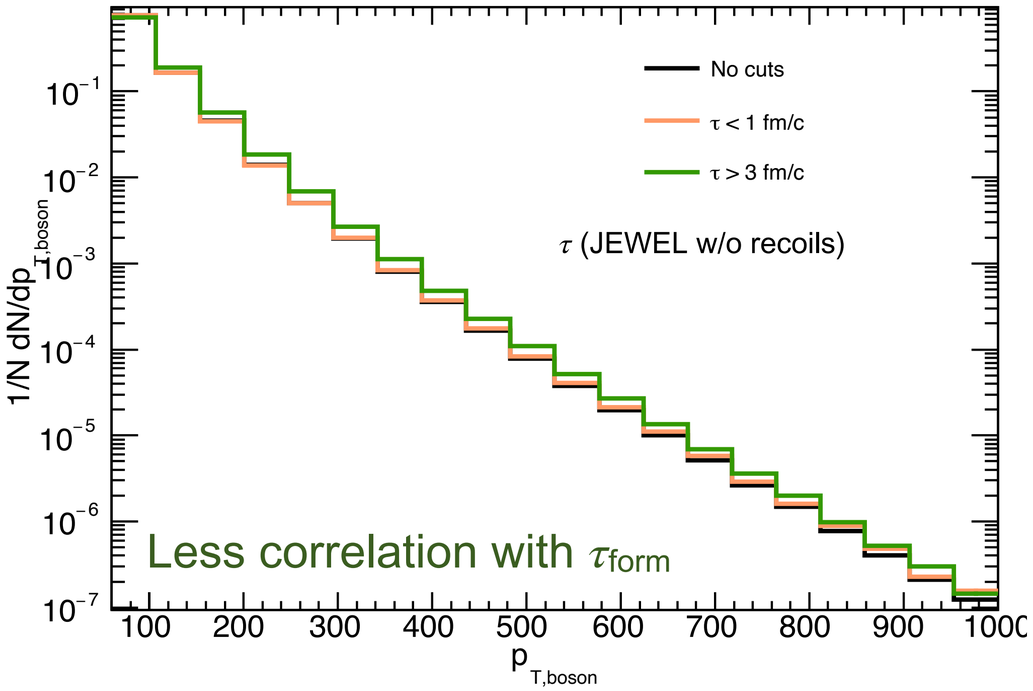
ΔR bins



Narrower jets ⇔ Higher initial p_T

But different initial p_T!

τ_{form} bins



Less correlation with τ_{form}

ΔR vs τ_{form}

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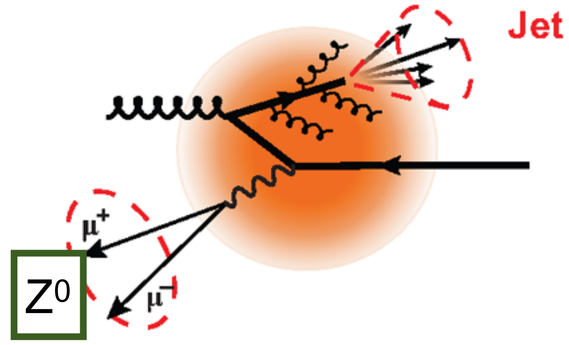
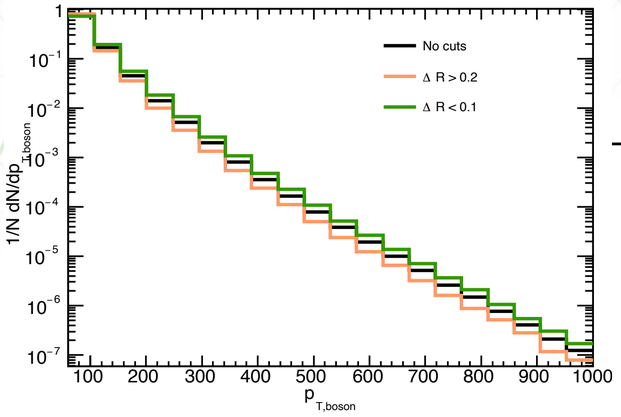
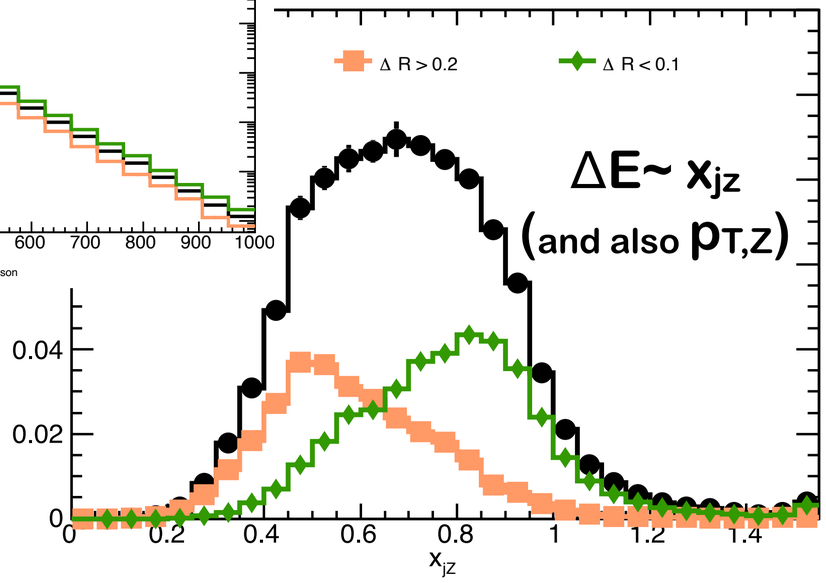


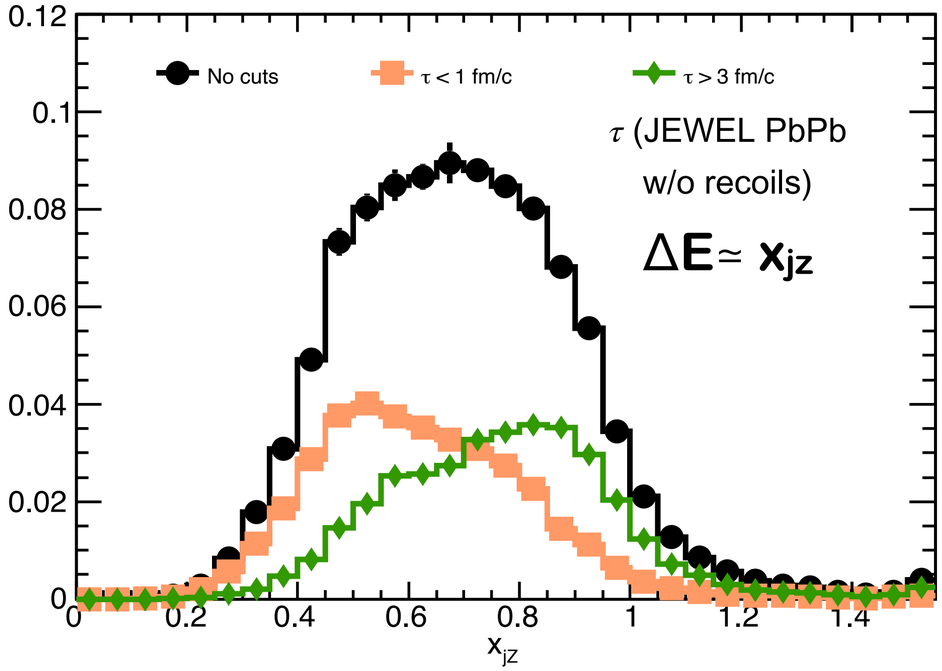
ΔR bins

ΔR !=τ_{form}



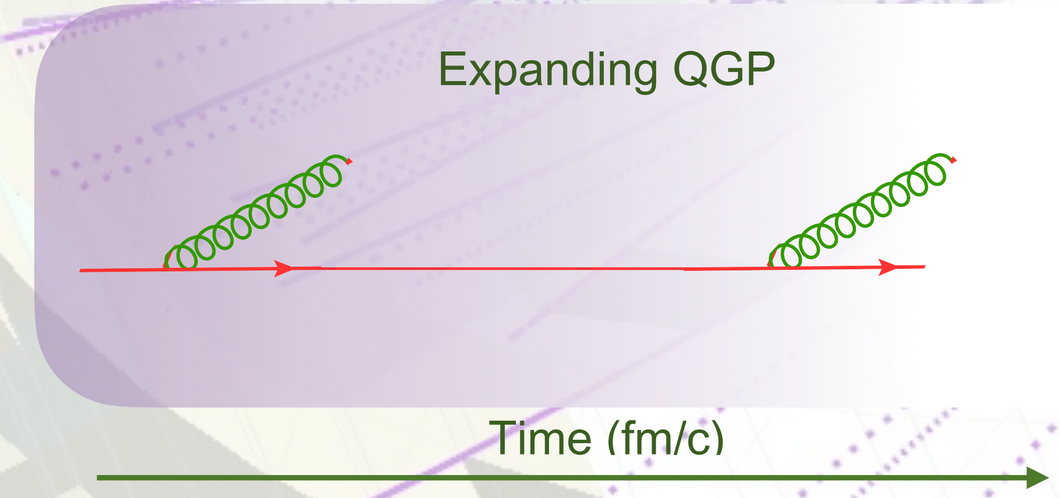


τ_{form} bins

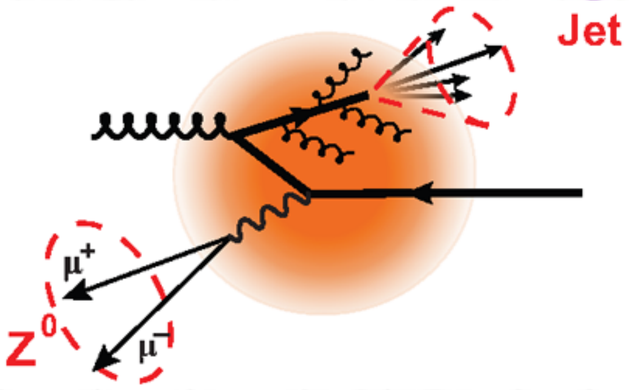


2nd unclustering:

Selection on τ_{form}: allows to evaluate ΔE in a $\Delta\tau$

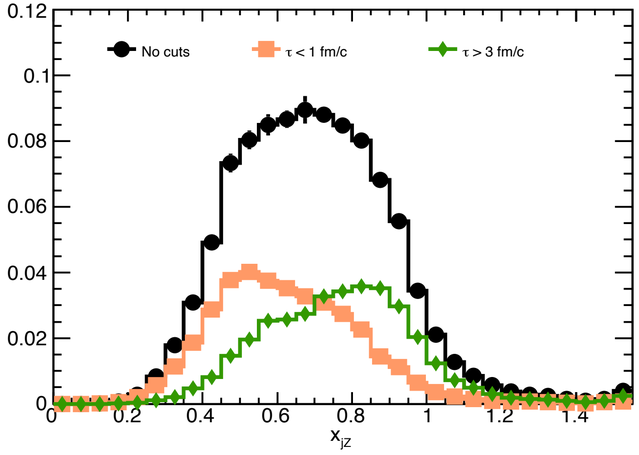


Z+jet



Summary

- New jet scale $\tau_{\mathbf{form}}$ allows to:
  - Select quenched jets without biasing initial p_T (accurate evaluation of energy loss)
  - 1st and 2nd unclustering steps with identical relative τ_{form} resolution
    - $\Delta E = \Delta E\ (\tau_{form})$? (On-going…)



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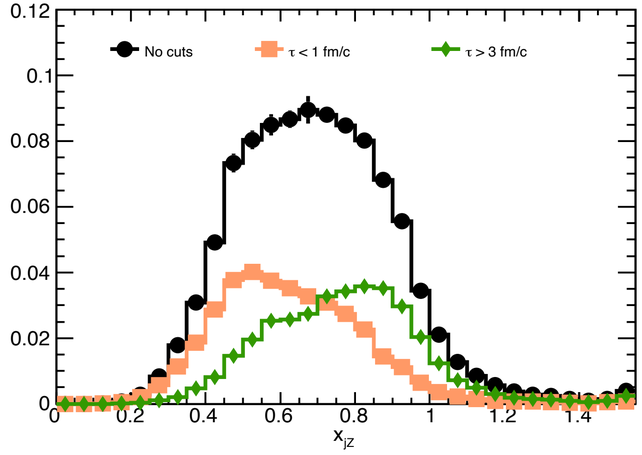

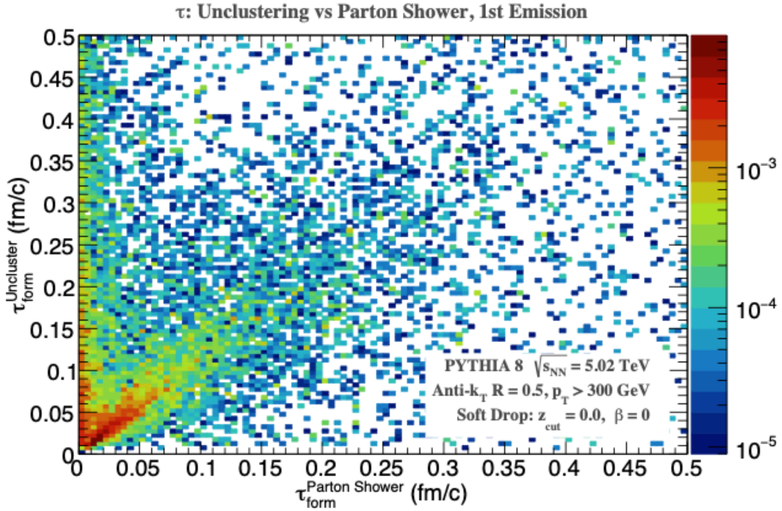

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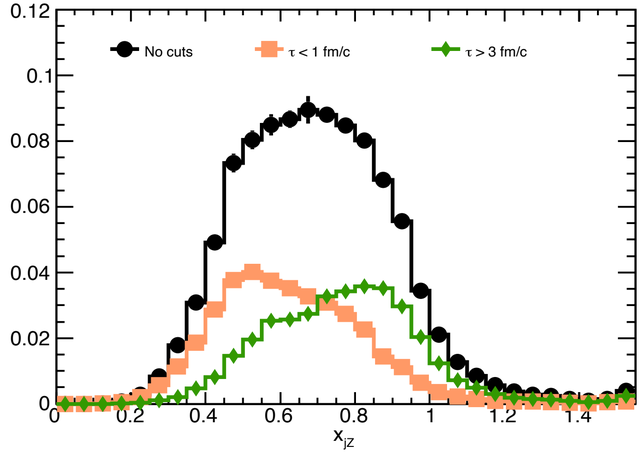
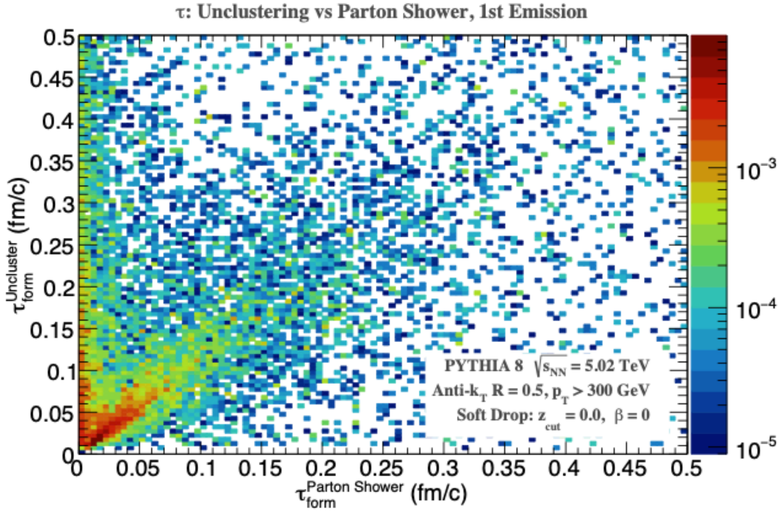




Acknowledgments

REPÚBLICA PORTUGUESA

FCT
Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA

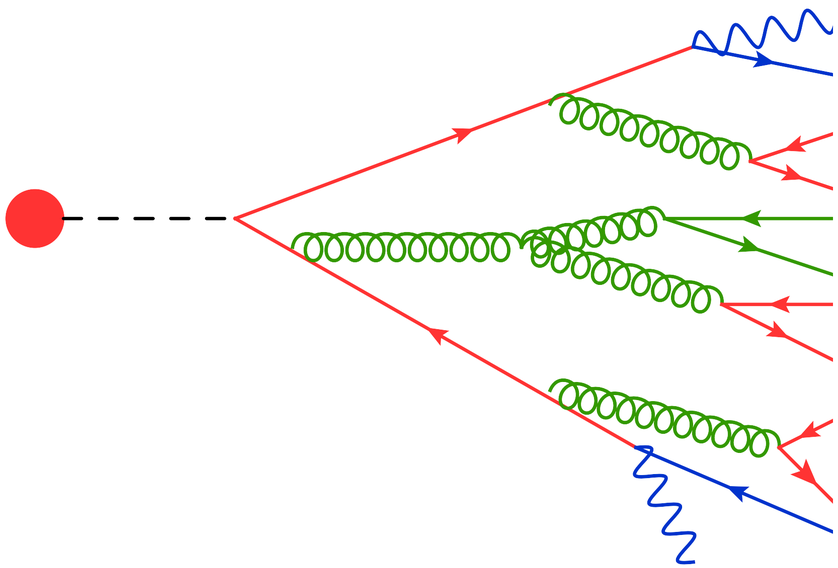
LIP

TÉCNICO LISBOA

Backup slides

Jets in the QGP

- What happens when a high momentum particle travels through the QGP?



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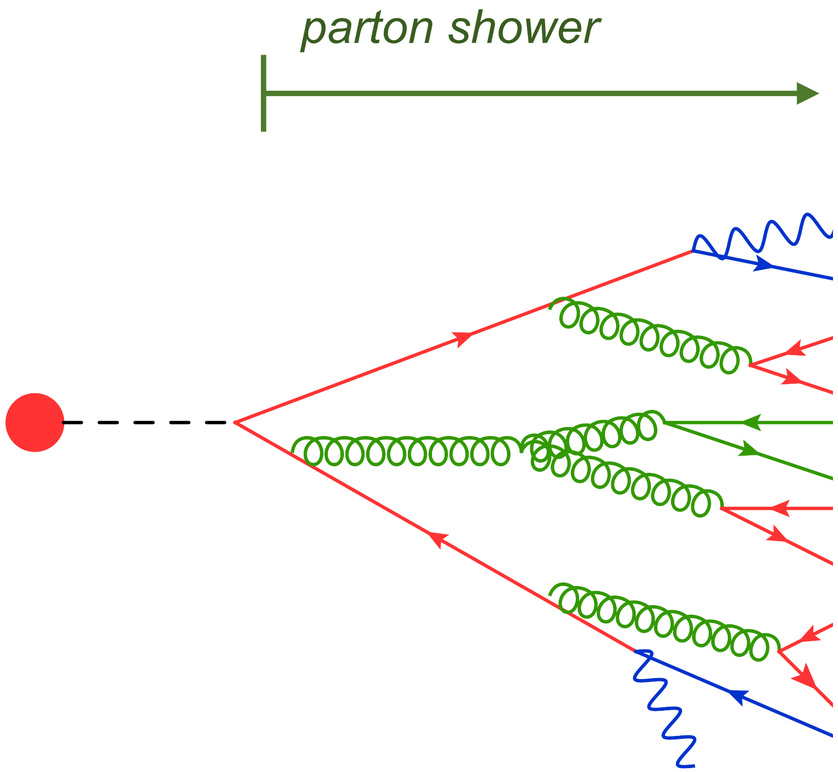

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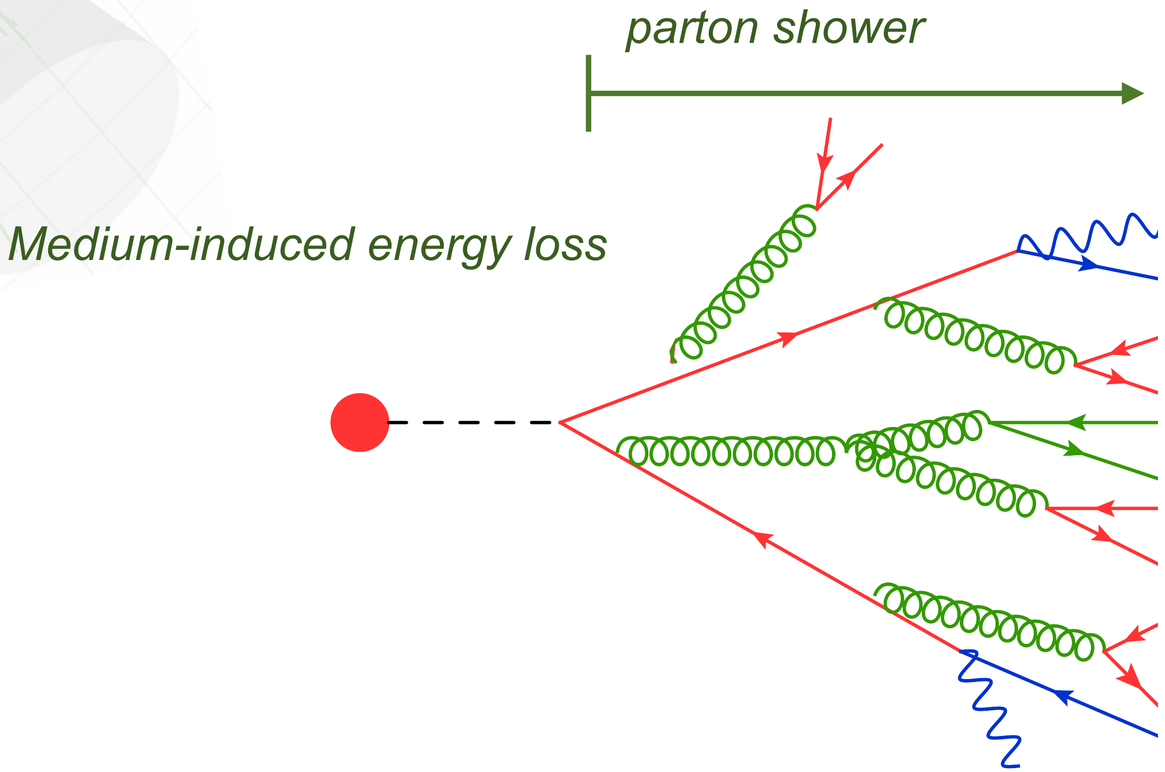

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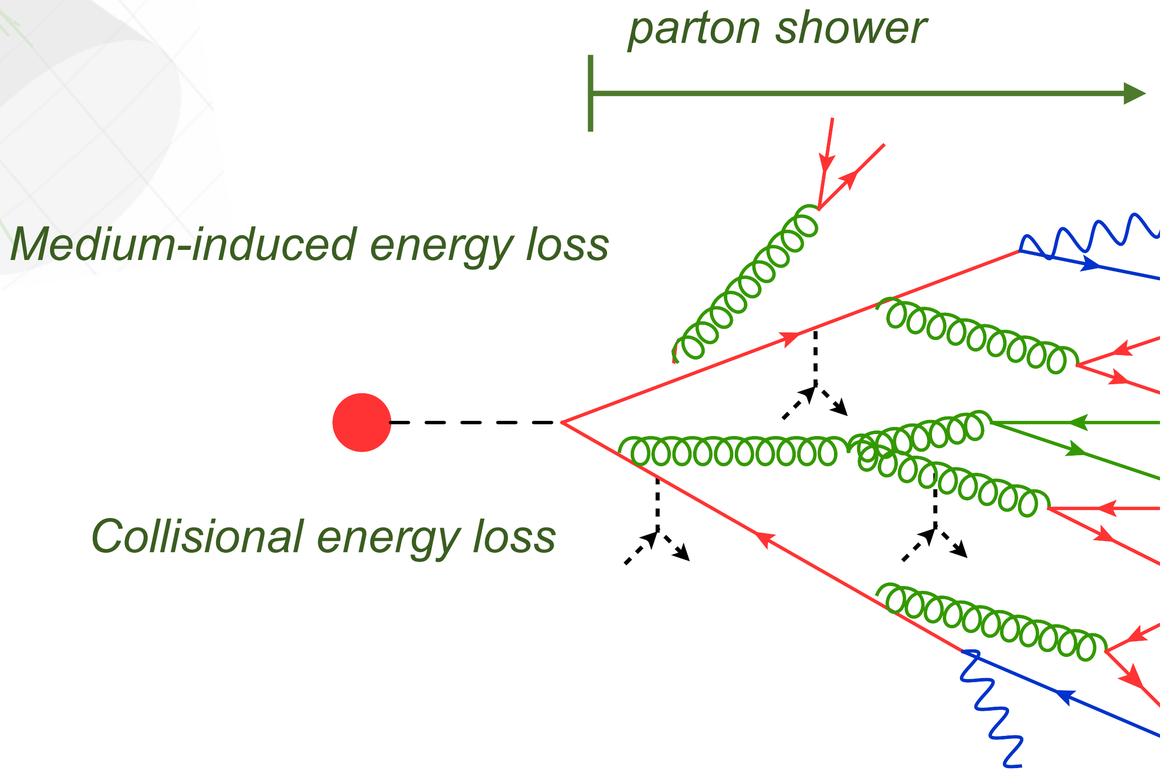

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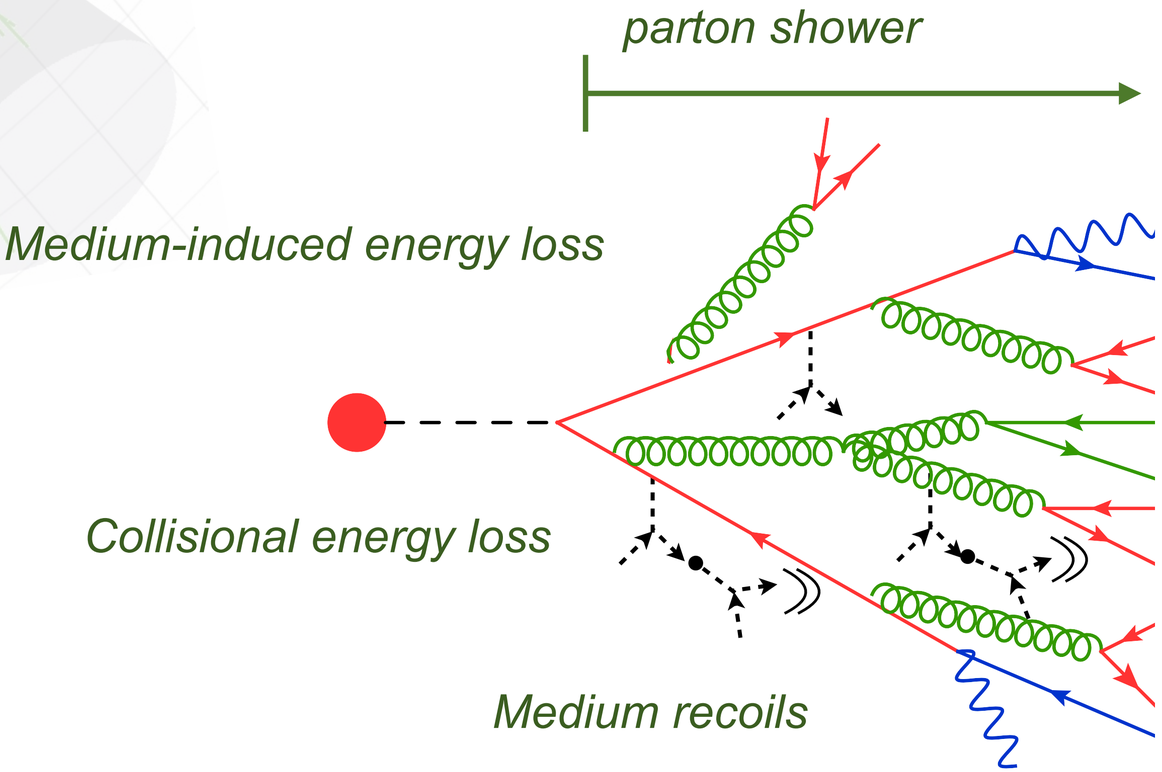

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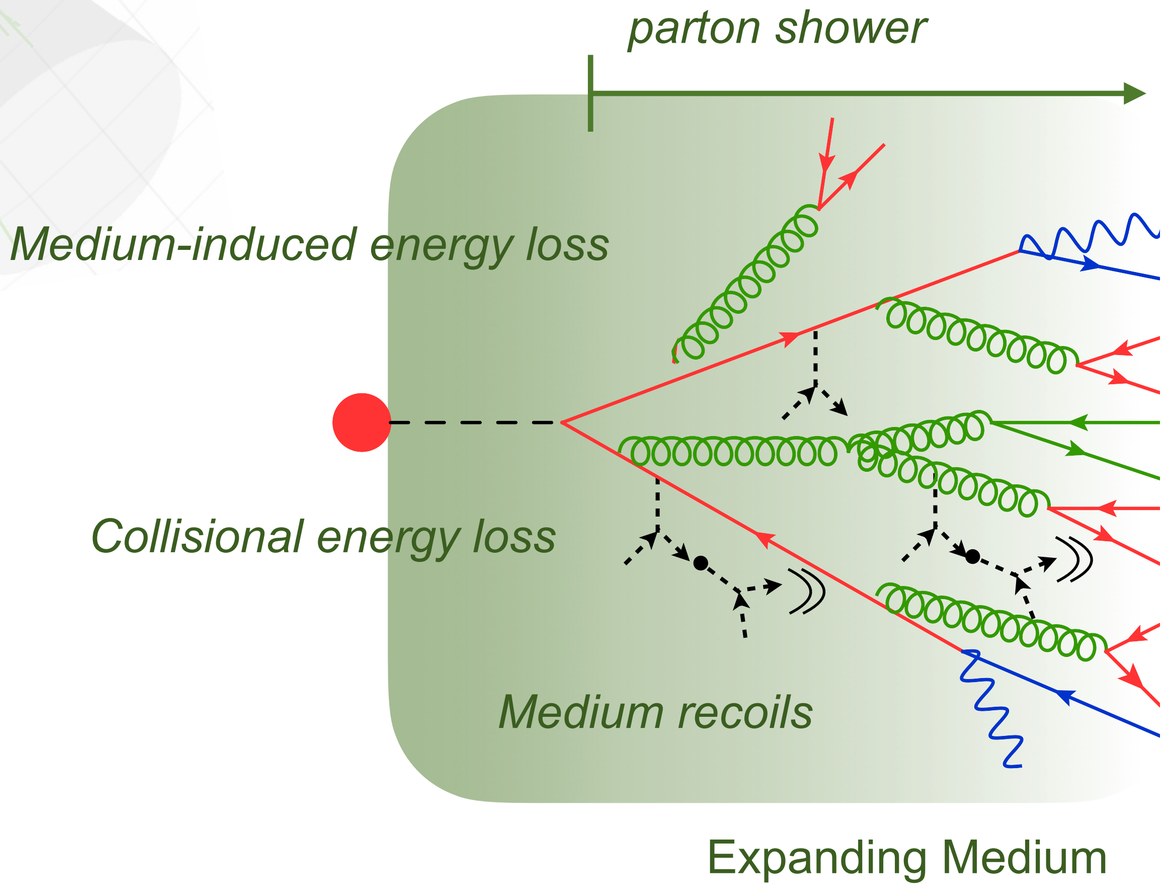

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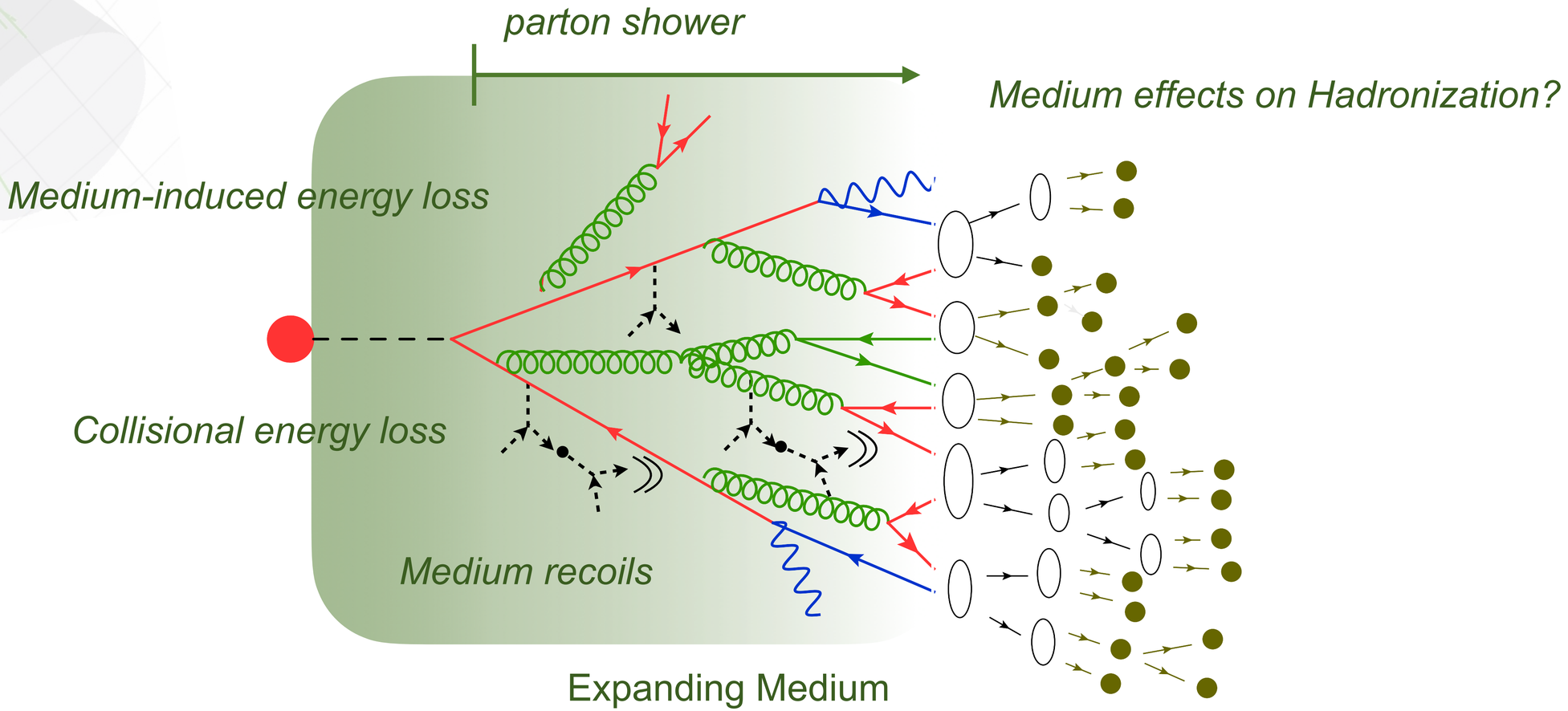

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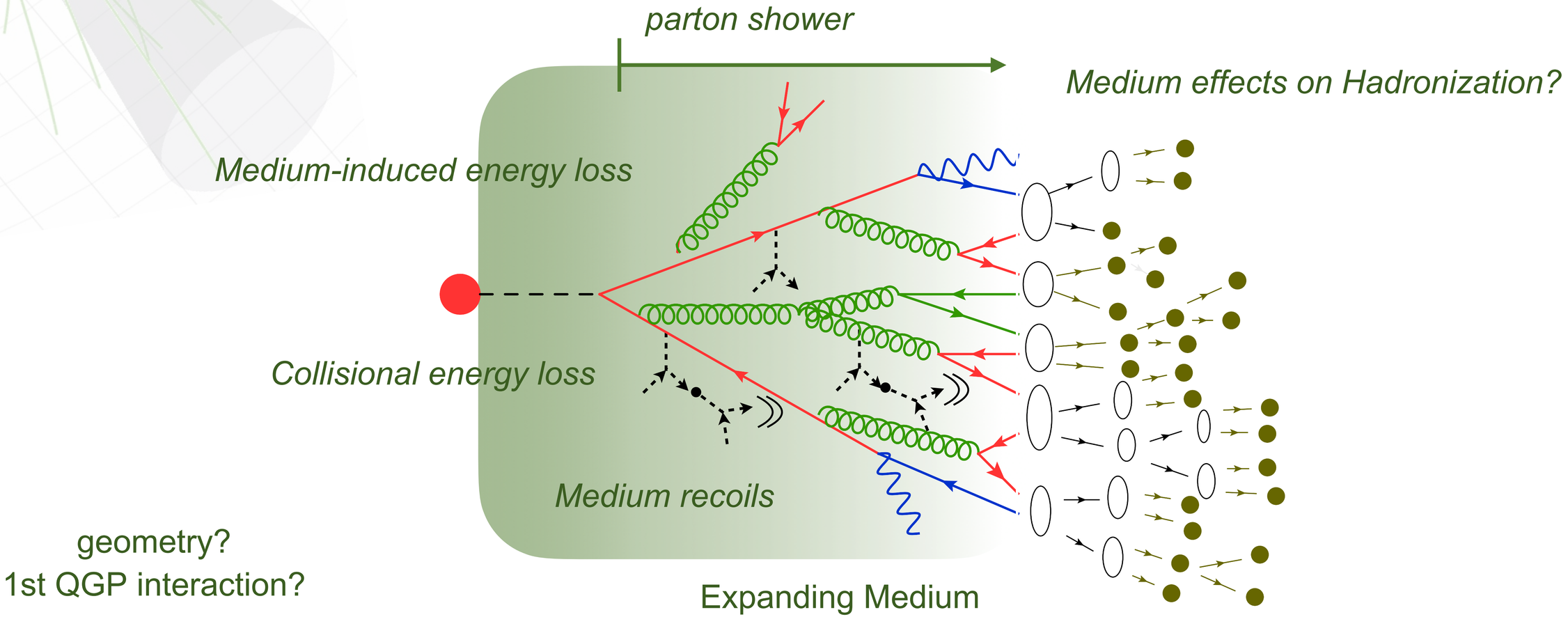
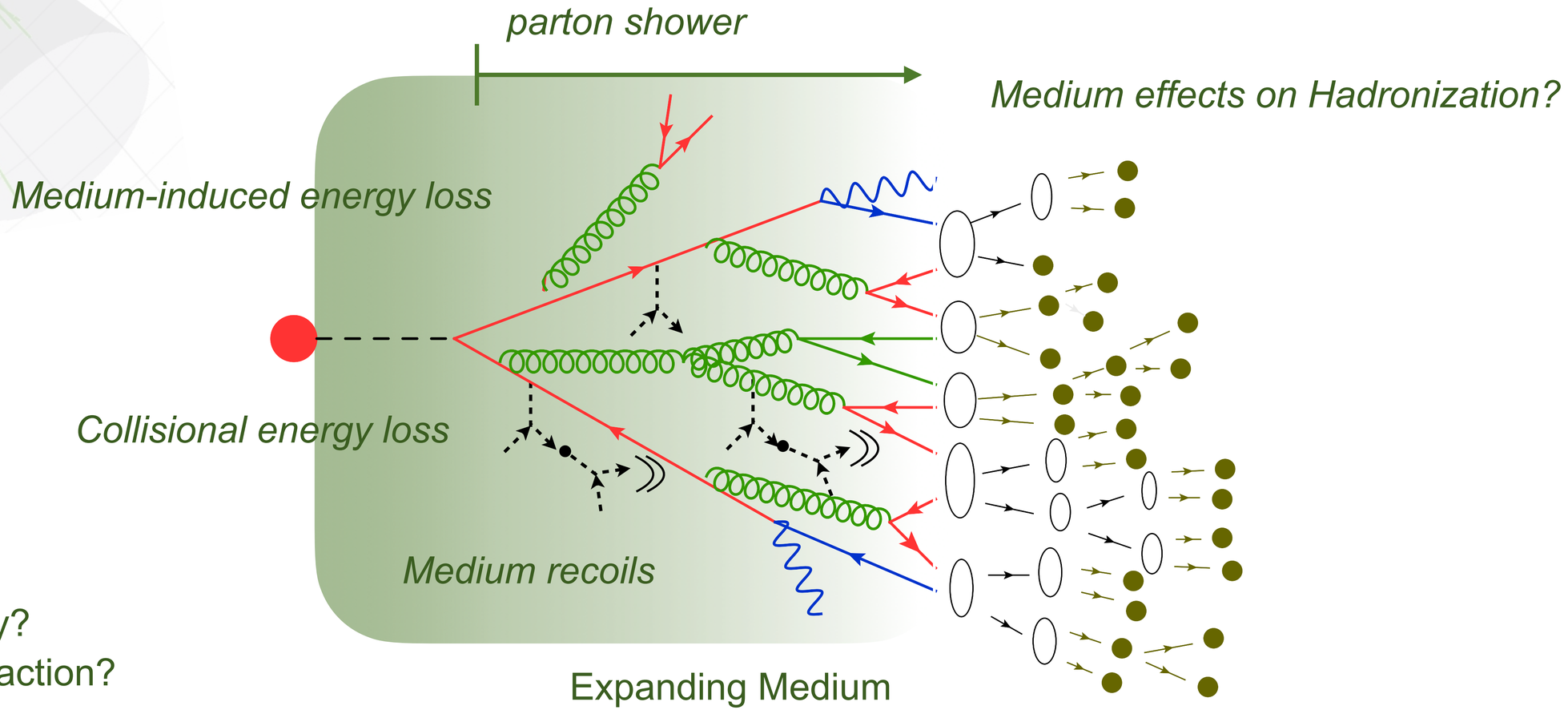


Jets in the QGP

Several unknowns!

- What happens when a high momentum particle travels through the QGP?

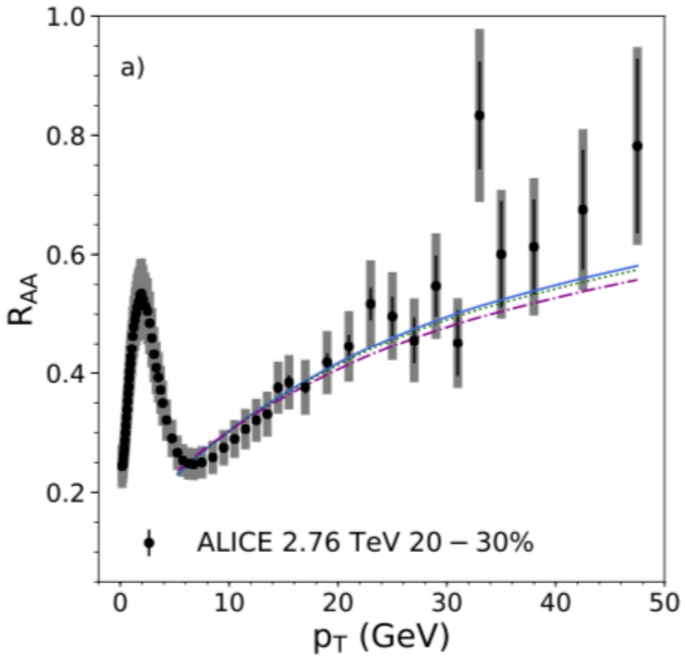


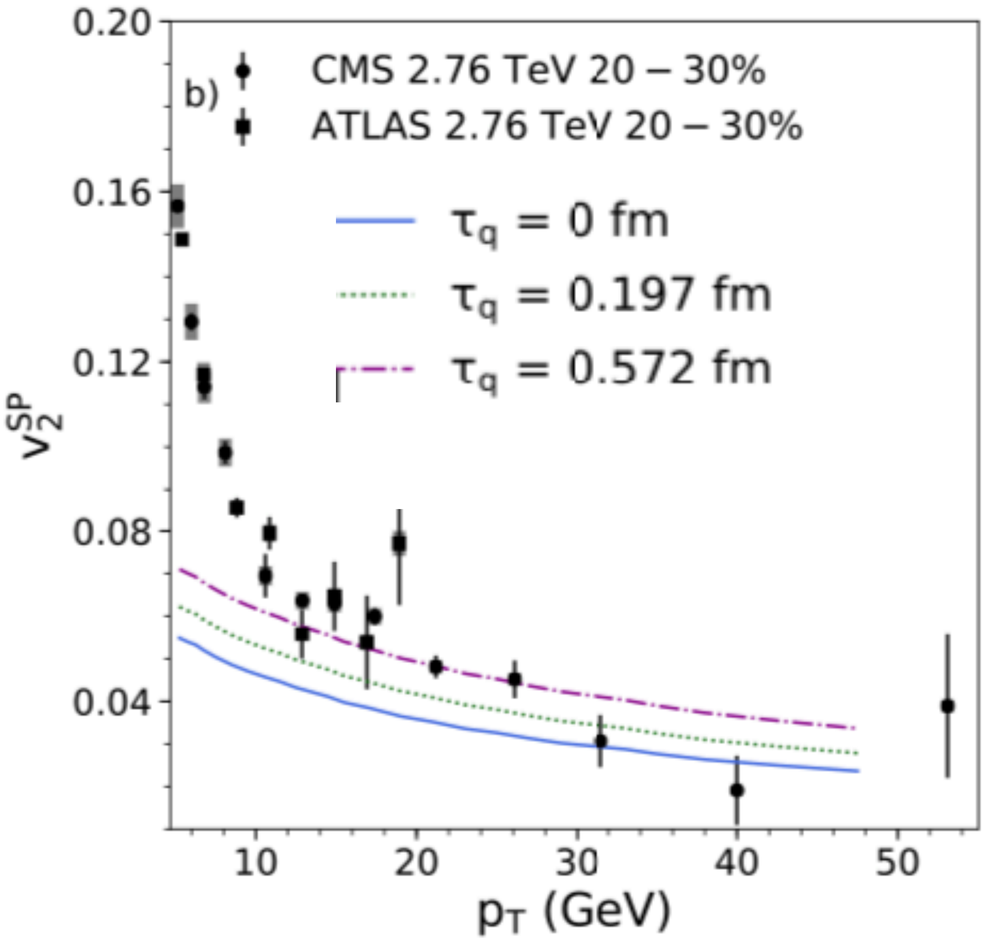
geometry?
1st QGP interaction?

Sensitivity to early times?

- A description of high-p_T anisotropic flow needs both hard and soft sectors:
  - Framework to change quenching during early stages (based on quenching weights)

[Andrés et al (19)]





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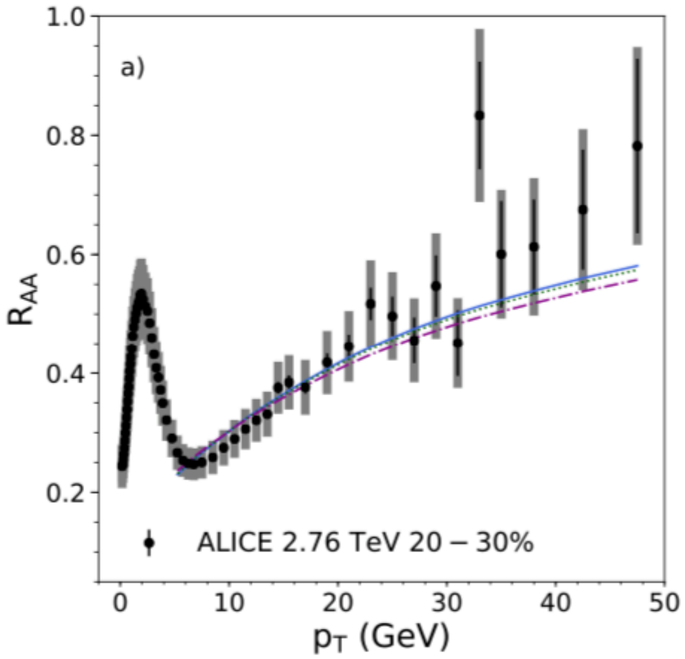
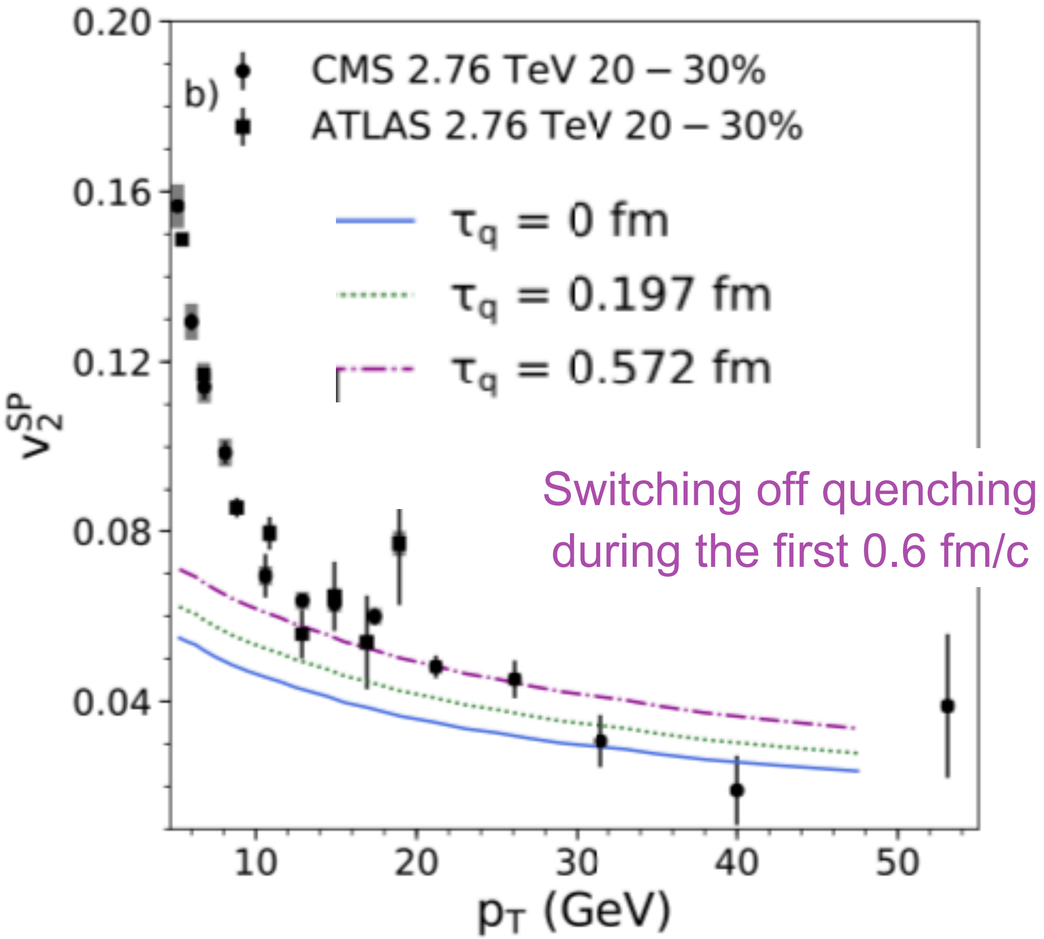




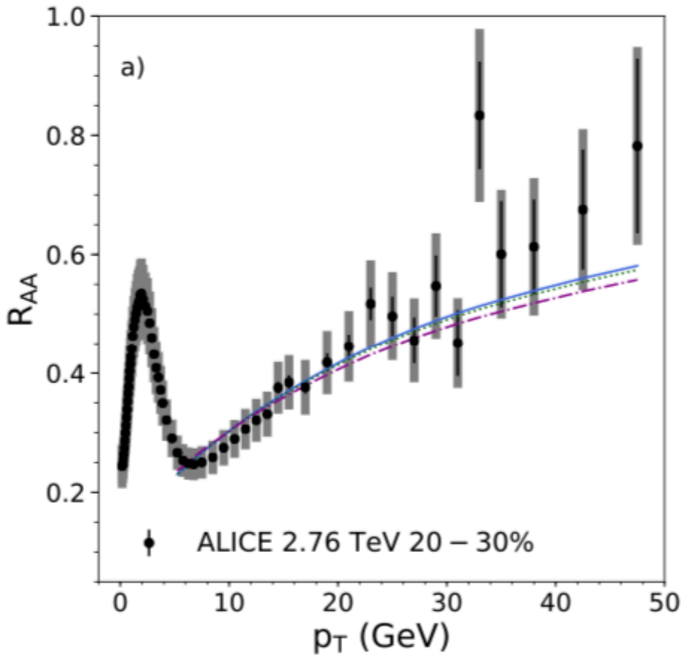
Switching off quenching during the first 0.6 fm/c

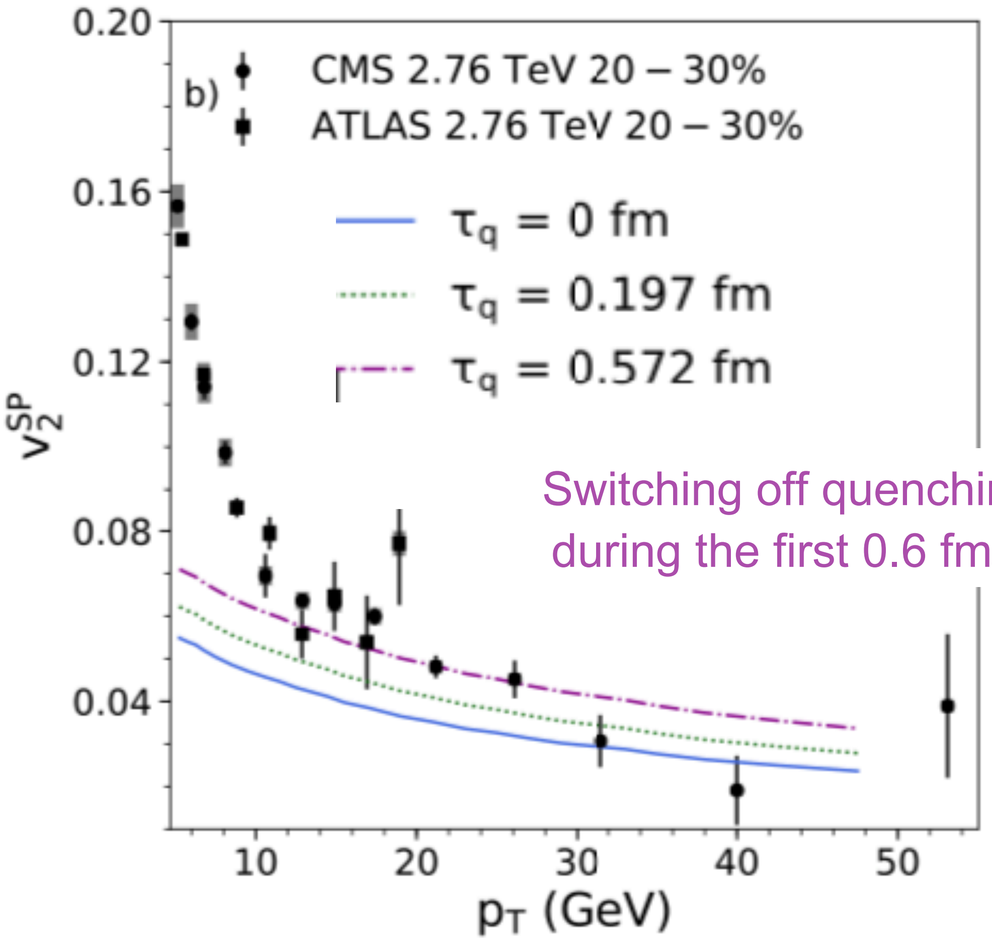
Sensitivity to early times?

- A description of high-p_T anisotropic flow needs both hard and soft sectors:
  - Framework to change quenching during early stages (based on quenching weights)

[Andrés et al (19)]

Potential to constrain the dynamics of the initial stages of the evolution



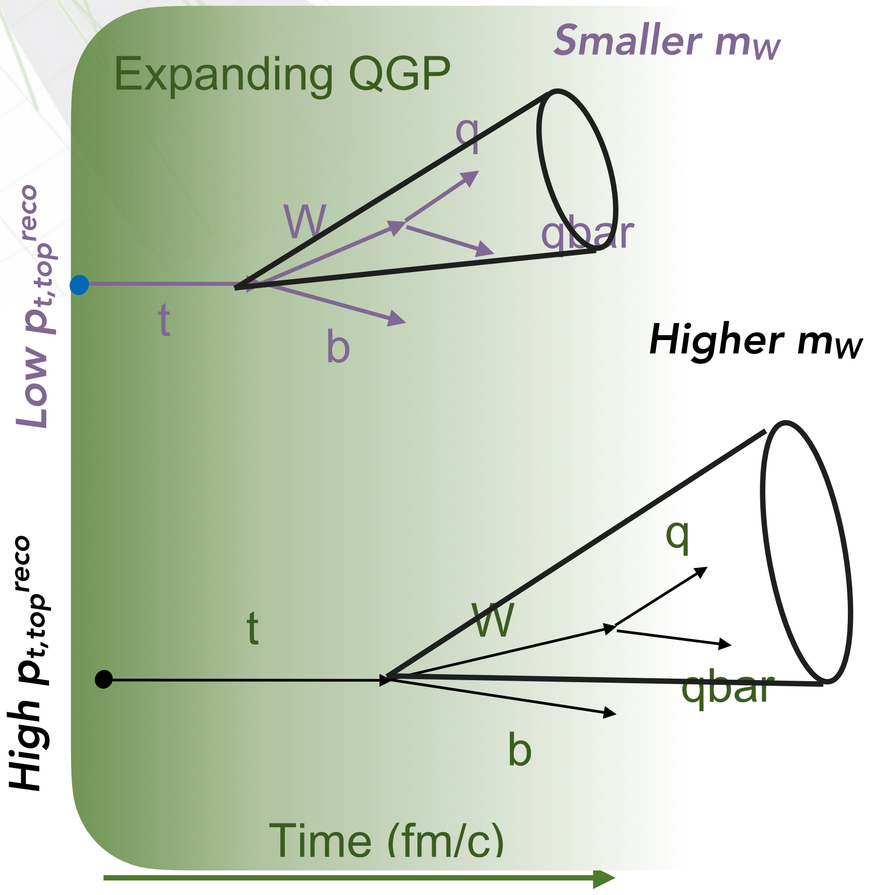


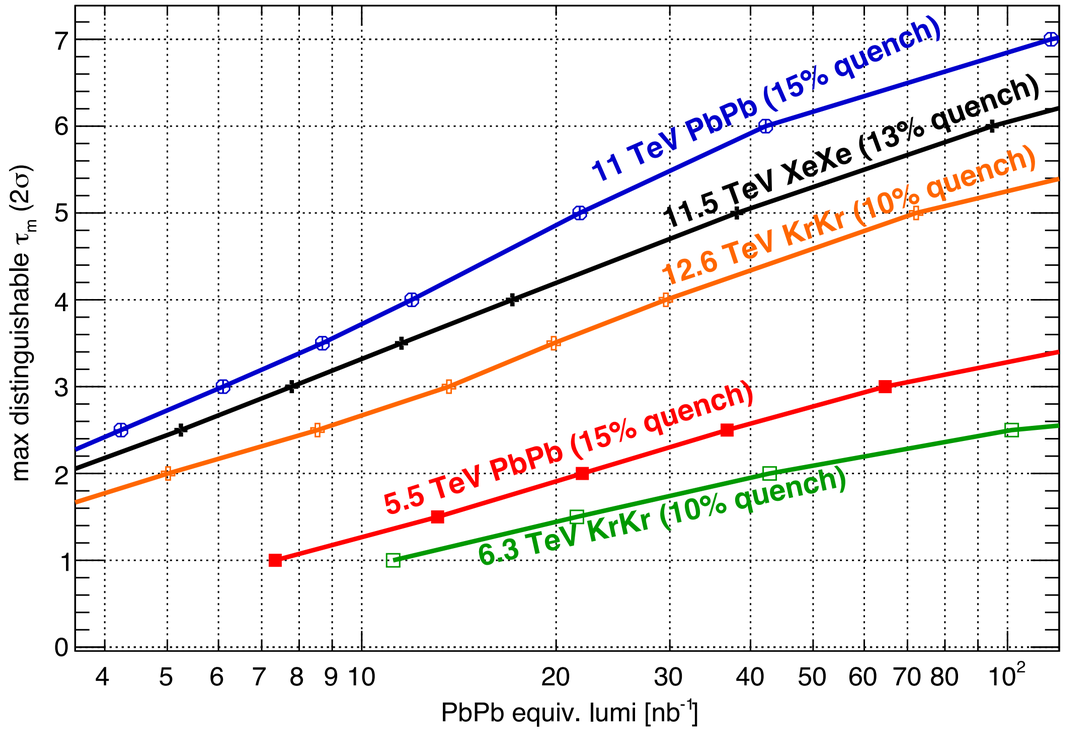
Switching off quenching during the first 0.6 fm/c

Sensitivity to later times?

[Citron et al (19)]

- Reconstructed hadronic W boson jet mass:





@ LHC: limited sensitivity (identify long vs short lived scenarios)

Sensitivity to different timescales:

Sensitivity to different timescales:

- Early dynamics ✓

Sensitivity to different timescales:

- Early dynamics ✓
- Late dynamics ✓

Sensitivity to different timescales:

- Early dynamics ✓
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- Anything else … ?

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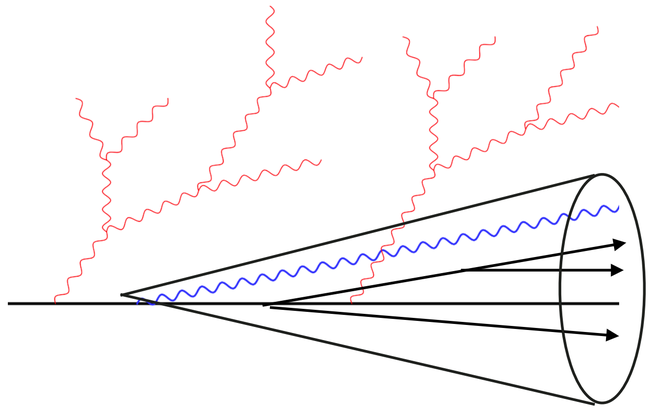
Jets are multi-scale objects!



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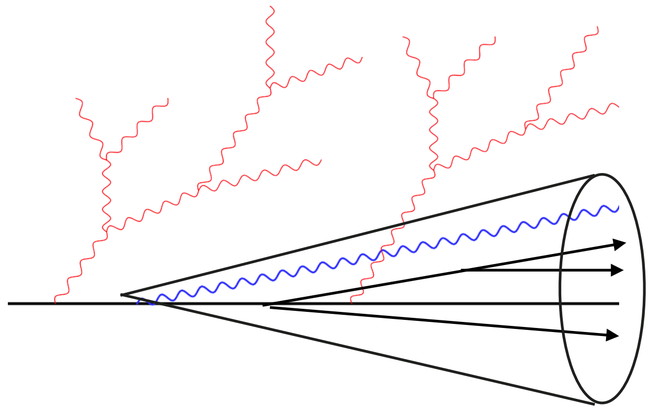


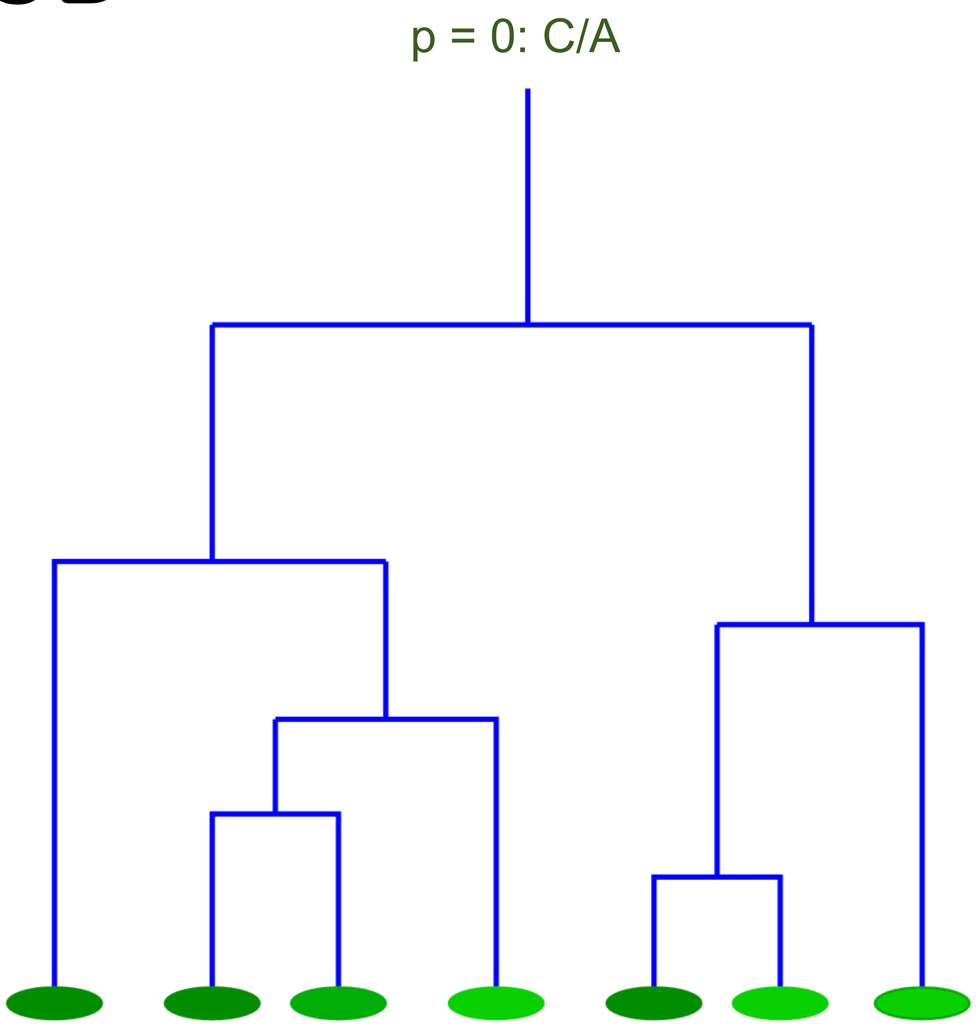
High momentum particles (typically from vacuum-like parton shower)

"Semi-hard" & Soft medium-induced radiation

Soft jet-induced medium response

Jets and QCD

- C/A

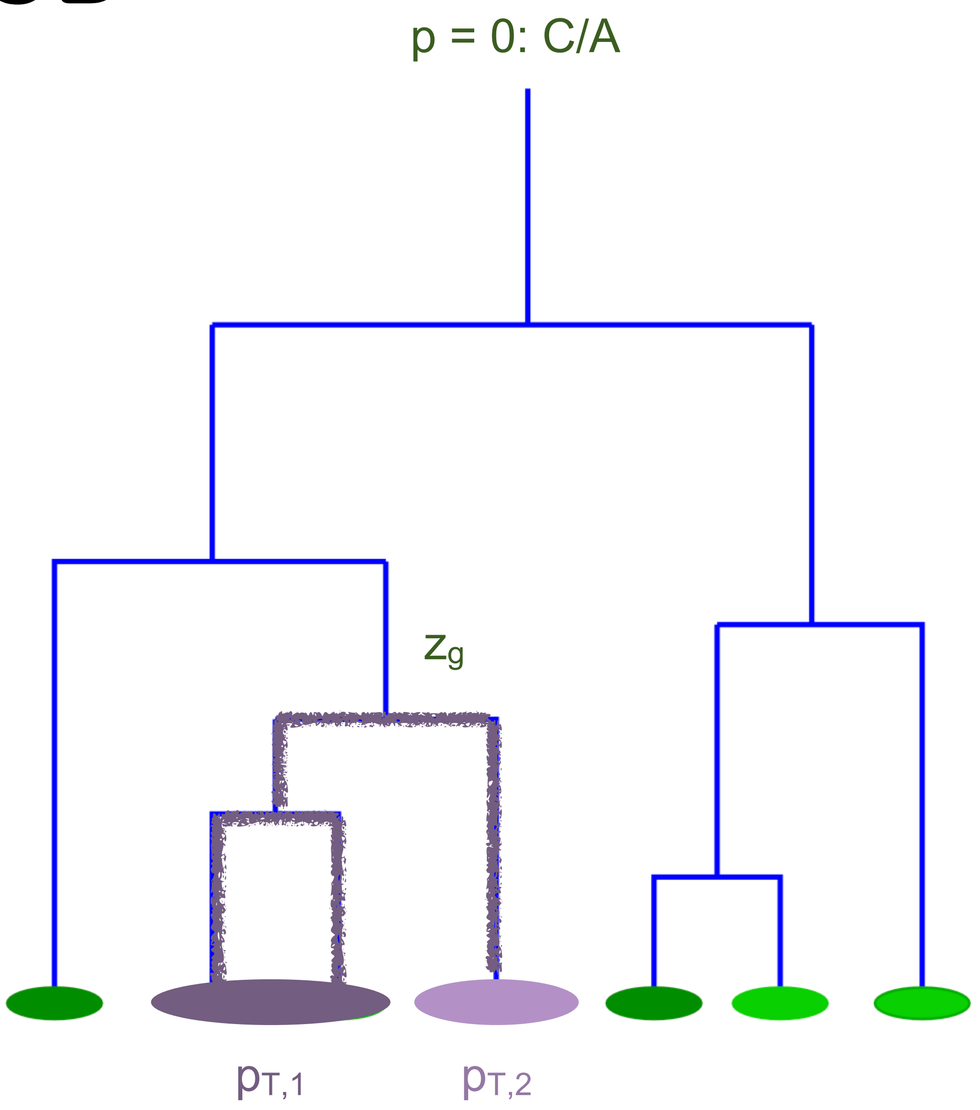


Jets and QCD

- C/A + Soft drop

  [Larkoski, Marzani, Soyez, Thaler (2014)]
  [Larkoski, Marzani, Thaler (2015)]

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} \quad \text{when} \quad \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_{12}}{R_0} \right)^{\beta}$$



Jets and QCD

- C/A + Soft drop = Jet splitting function

  [Larkoski, Marzani, Soyez, Thaler (2014)]
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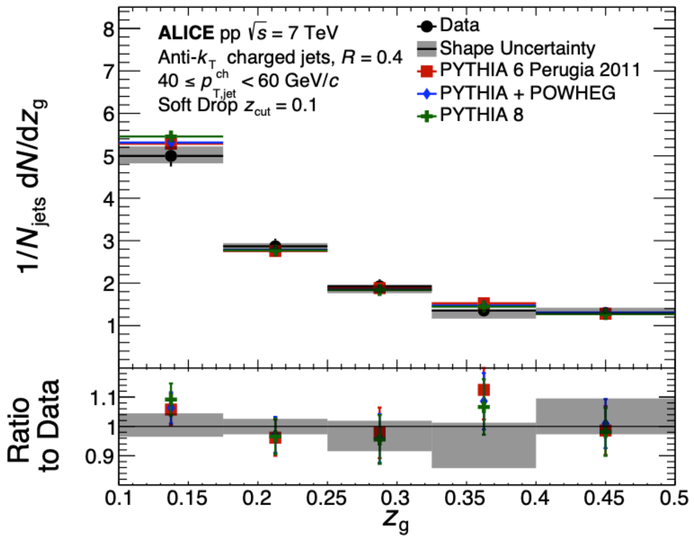
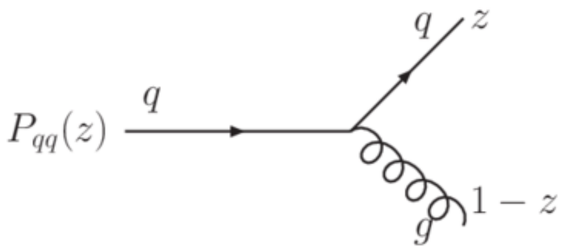
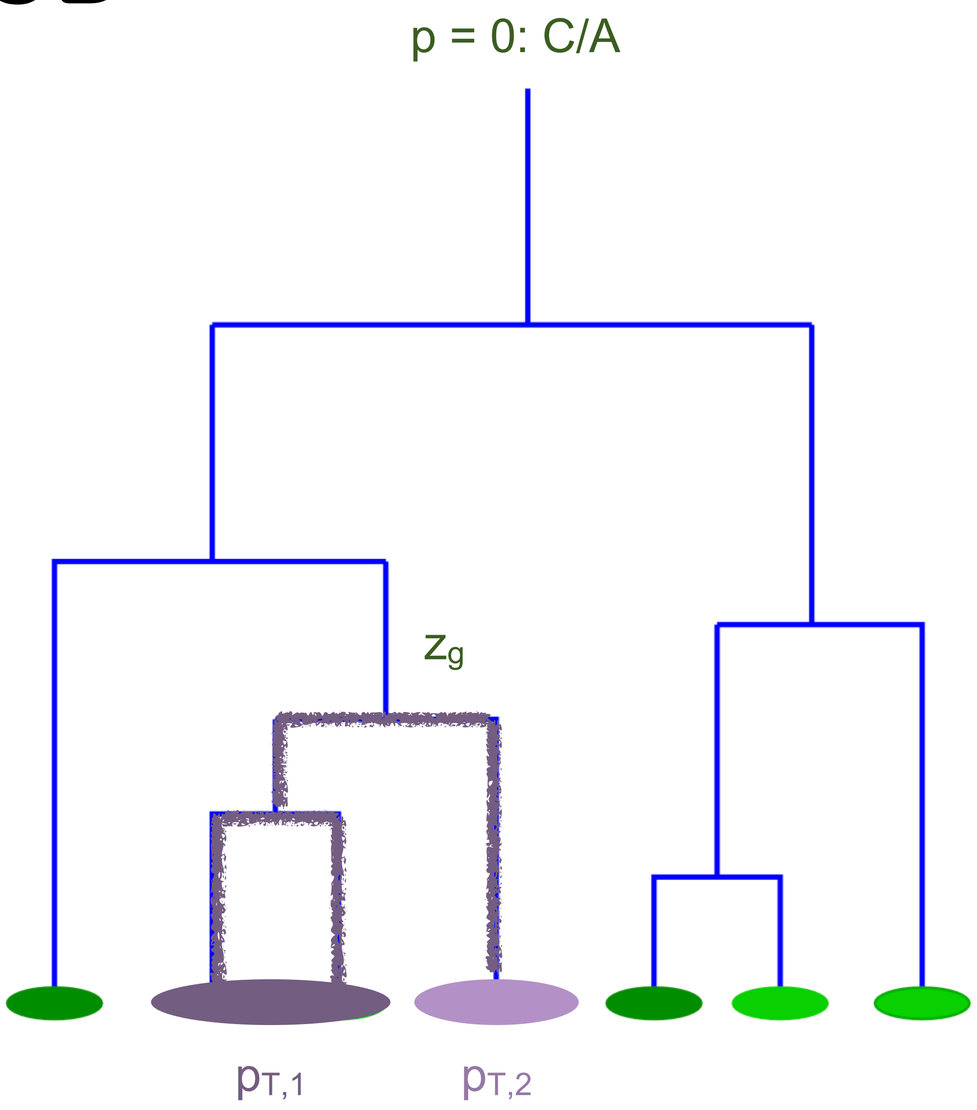


[ALICE PLB 802 (2020) 135227]



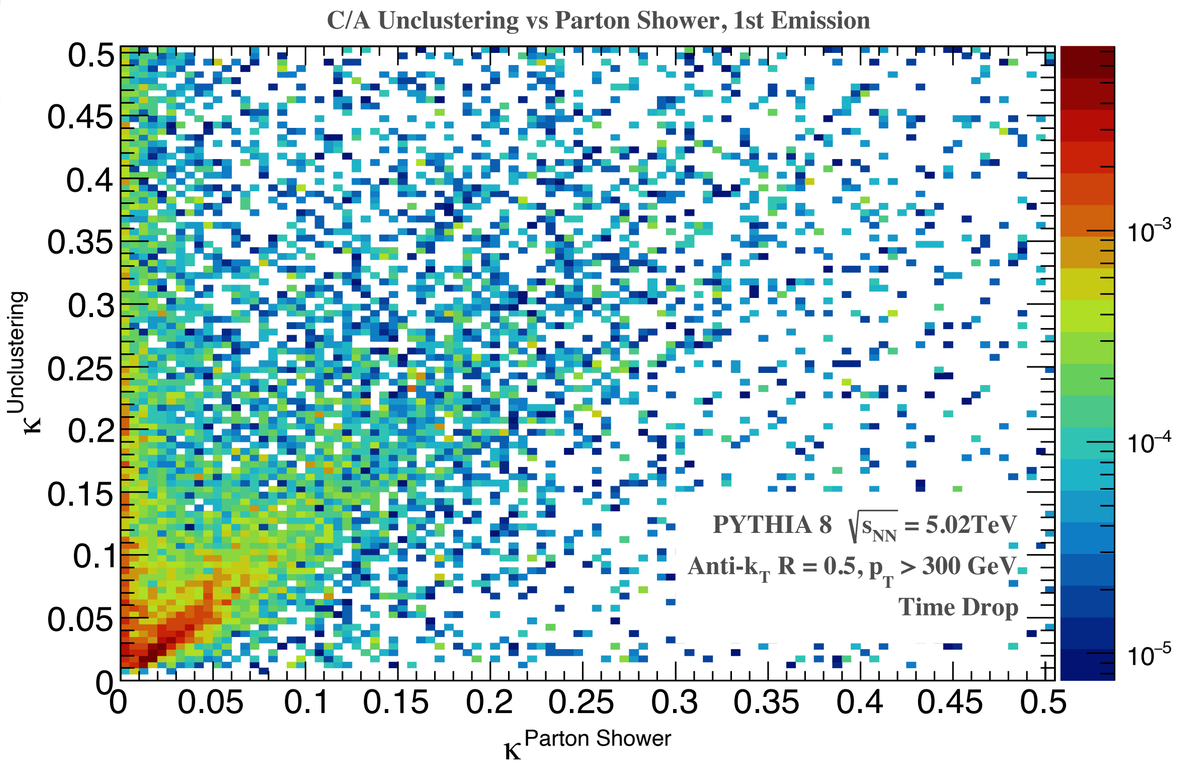


[Larkoski, Marzani, Soyez, Thaler (14)]
[Mehtar-Tani, Soto-Ontoso, Tywoniuk (20)]

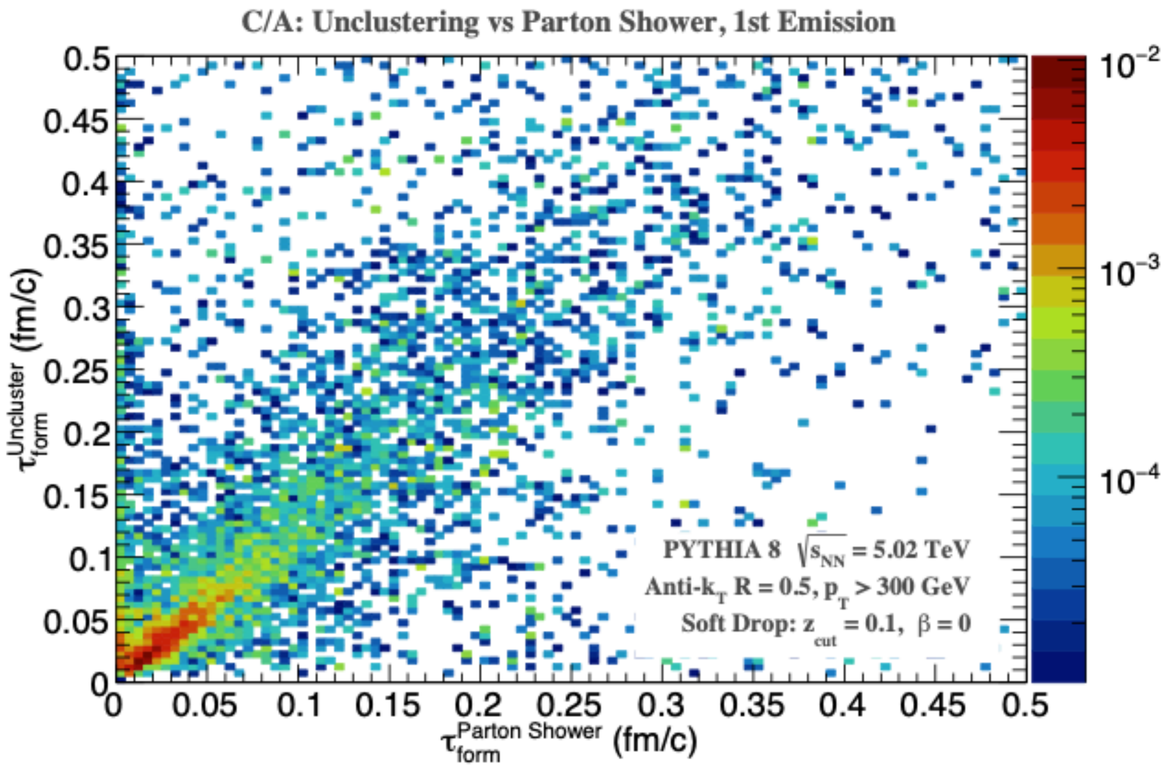
Grooming

- Testing several types of grooming:

TimeDrop (a=2)



Soft-drop (z_{cut}=0.1)



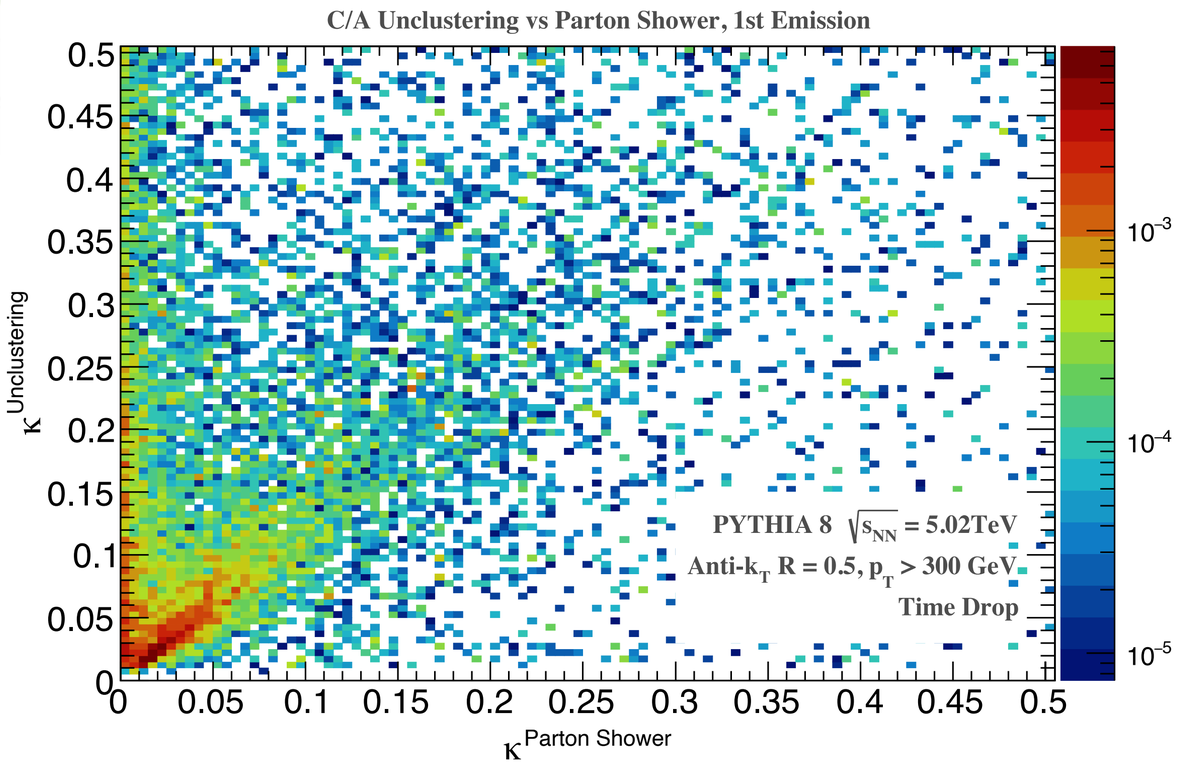
[Larkoski, Marzani, Soyez, Thaler (14)]
[Mehtar-Tani, Soto-Ontoso, Tywoniuk (20)]

Grooming

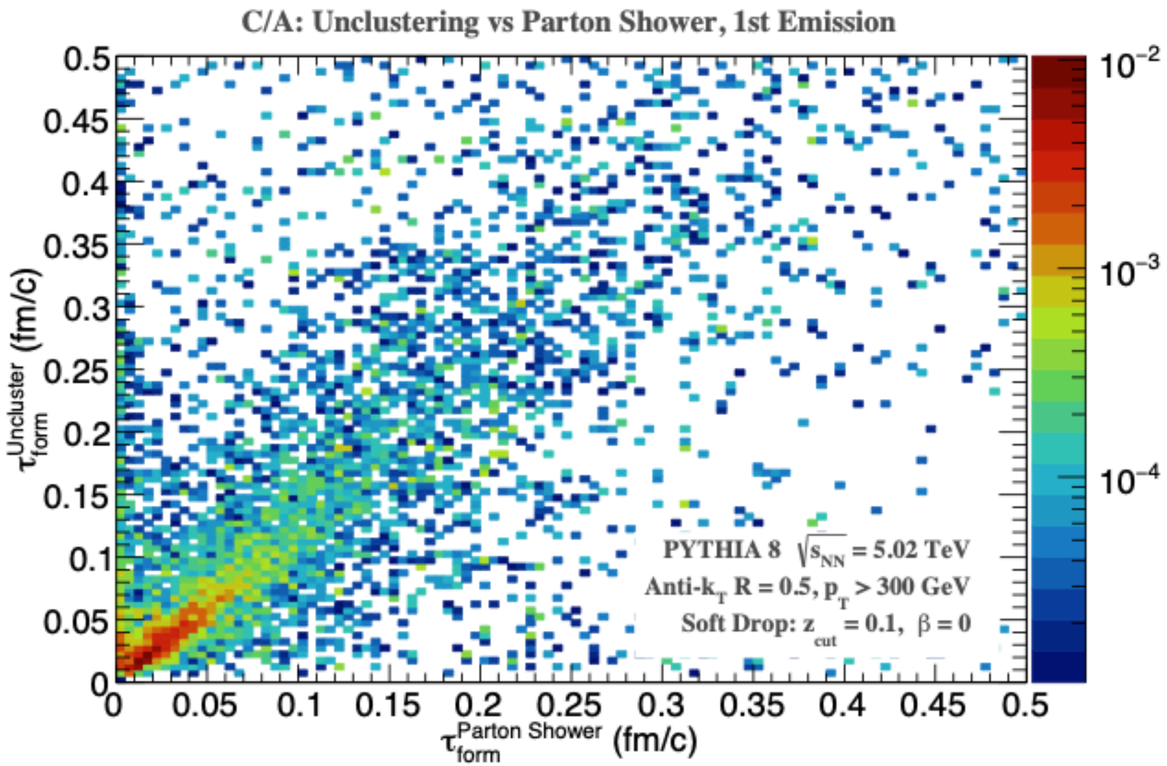
- Testing several types of grooming:

Cleaning soft fragments improves correlation

TimeDrop (a=2)



Soft-drop (z_{cut}=0.1)

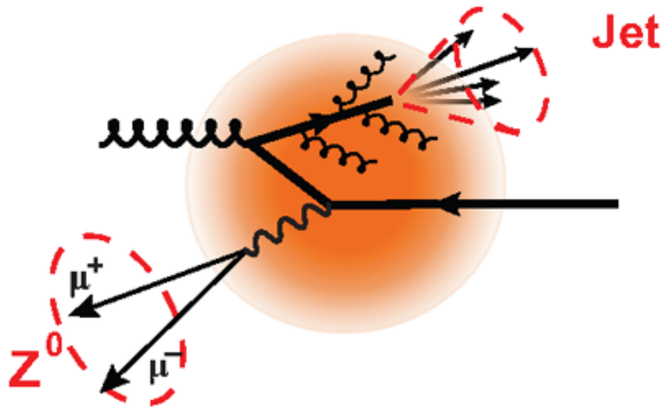


Testing ground

- Z+Jet events
  - Leptonic decay of Z boson

    Choose “cleanest” channel as a first setting
  - Recoiling jet
    - R = 0.5
    - p_T > 300 GeV
    - |η| < 1

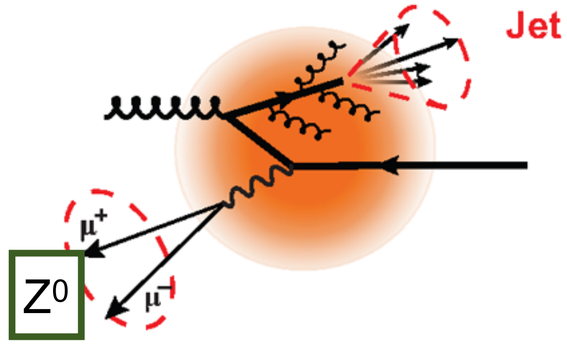
$$\tau_{form} \approx \frac{1}{2Ez(1-z)(1-\cos\theta_{12})}$$



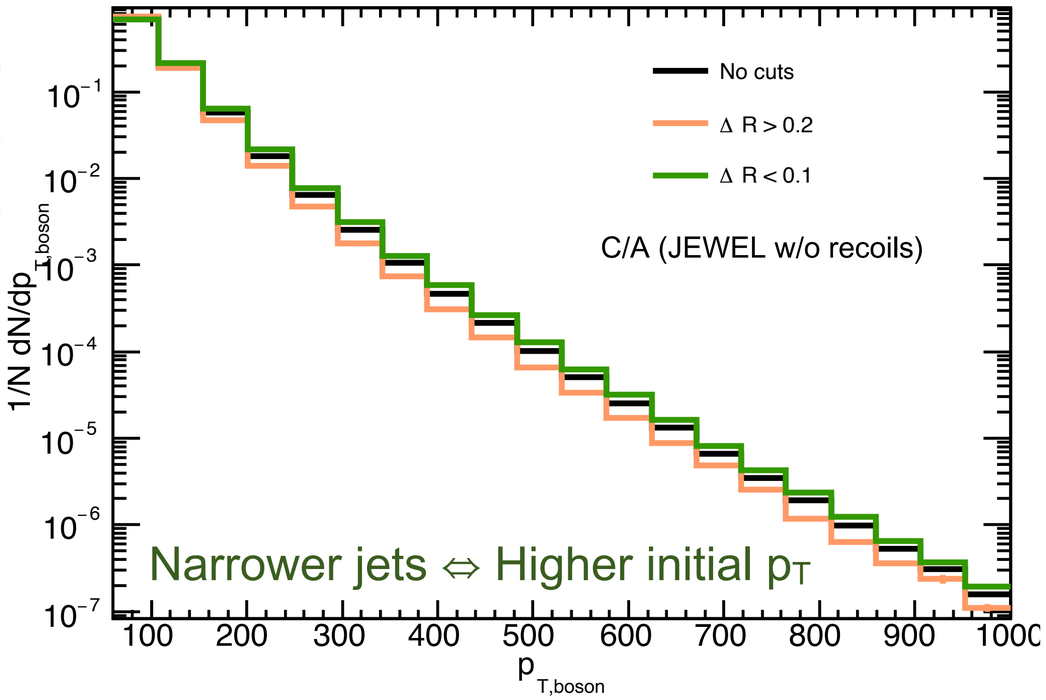
All done at hadron level

ΔR vs τ_{form}

- Selecting jets based on ΔR or τ_{form}? Will we select the same jet sample?



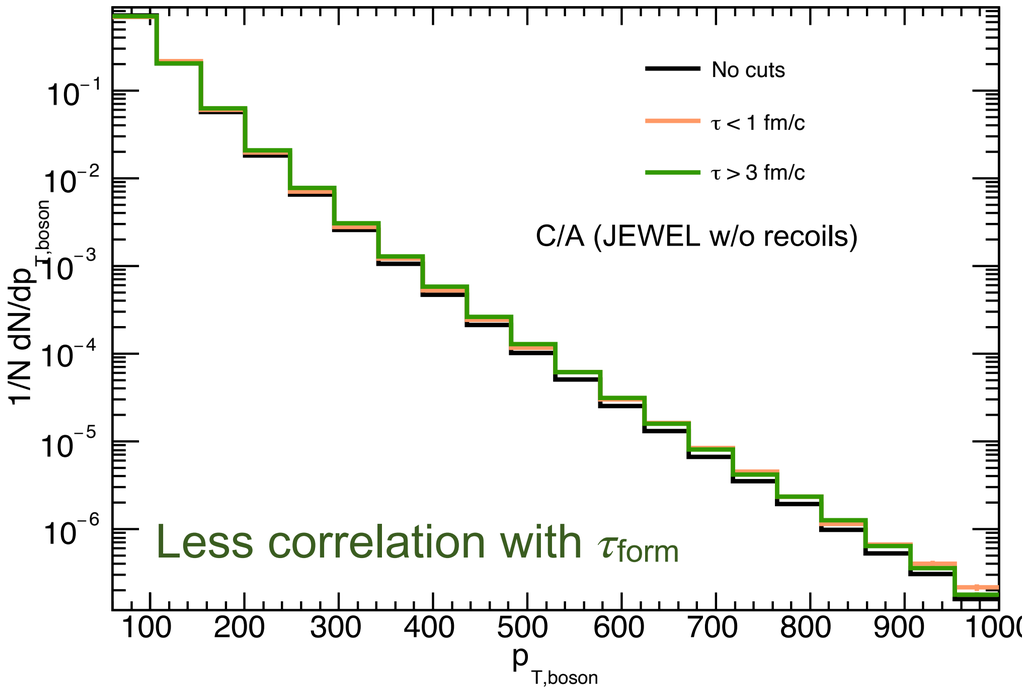
ΔR bins



Narrower jets ⇔ Higher initial p_T

But different initial p_T!

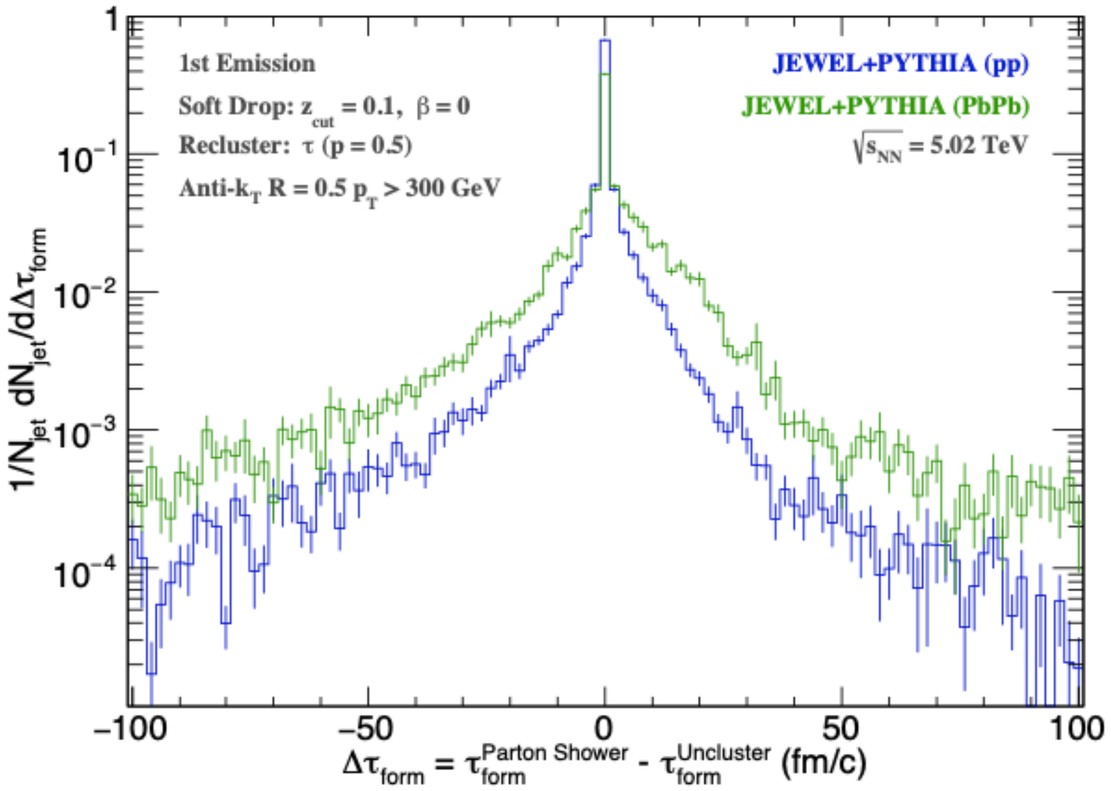
τ_{form} bins



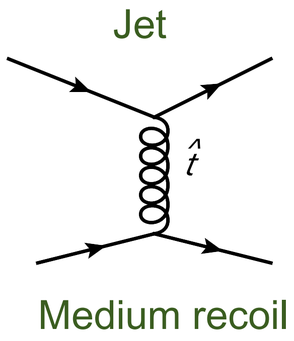
Less correlation with τ_{form}

Vacuum vs Medium

$\Delta\tau$ distribution (τ algorithm):



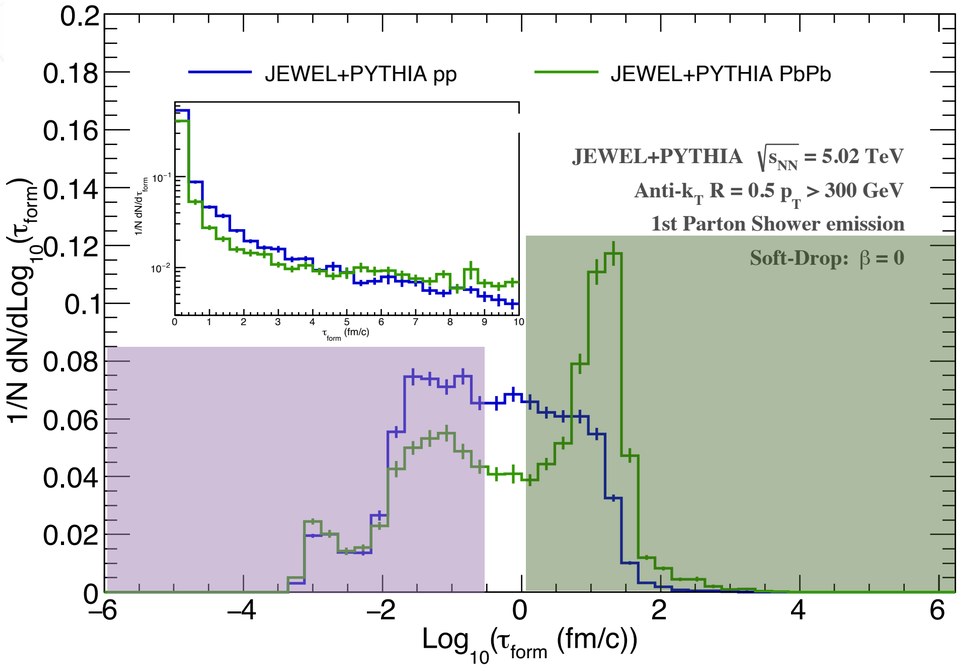
In-medium scatterings deteriorate resolution…



Shift in transverse momentum due to elastic scatterings
(Shift in reconstructed τ_{form})

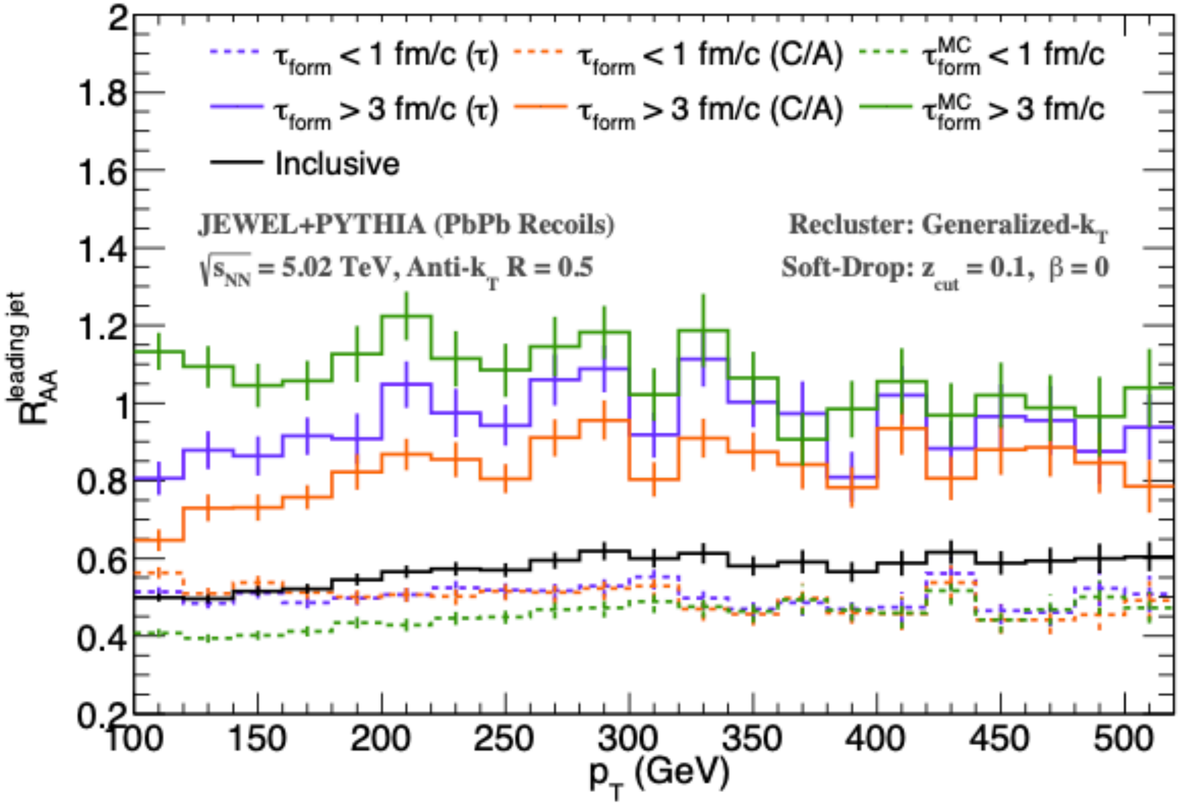
Example application: $R_{AA}^{lead\ jet}$

- Easily select two classes of jets:
  - "early" jets: τ_1 < 1 fm/c (strongly modified)
  - "late" jets: τ_1 > 3 fm/c (weakly modified)



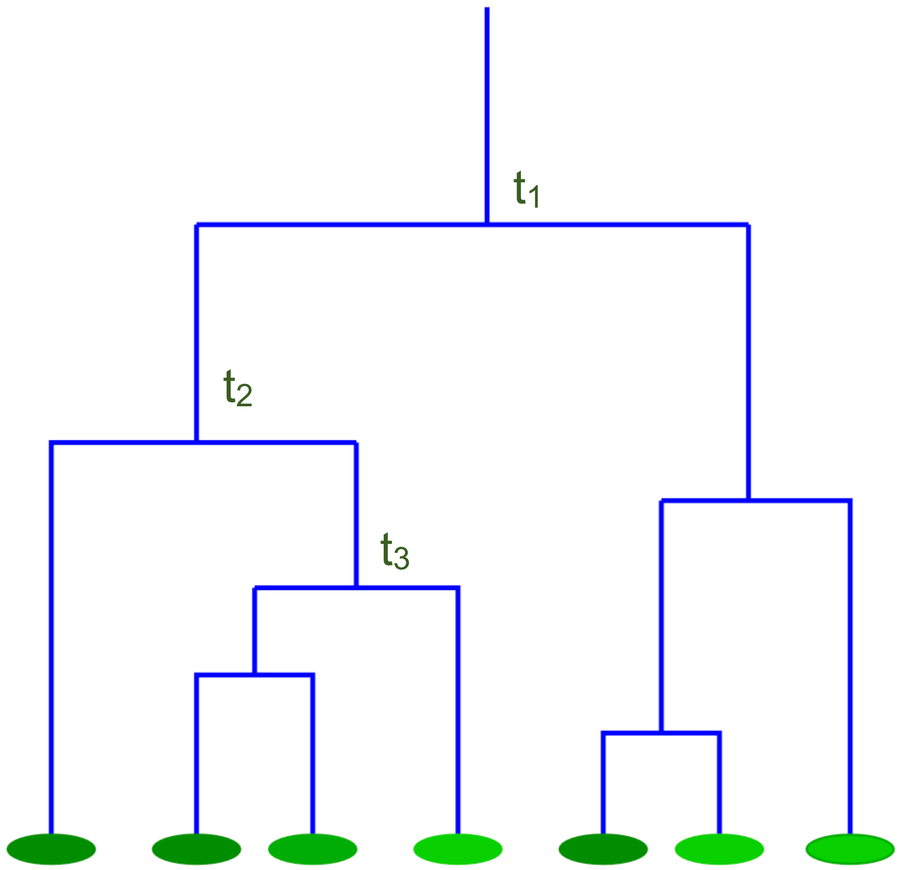
Previous results

With recoils



Looking to the shortest τ_{form}

- Even with soft-drop, emissions/unclustering steps might not be ordered in τ_{form}



Looking to the shortest τ_{form}

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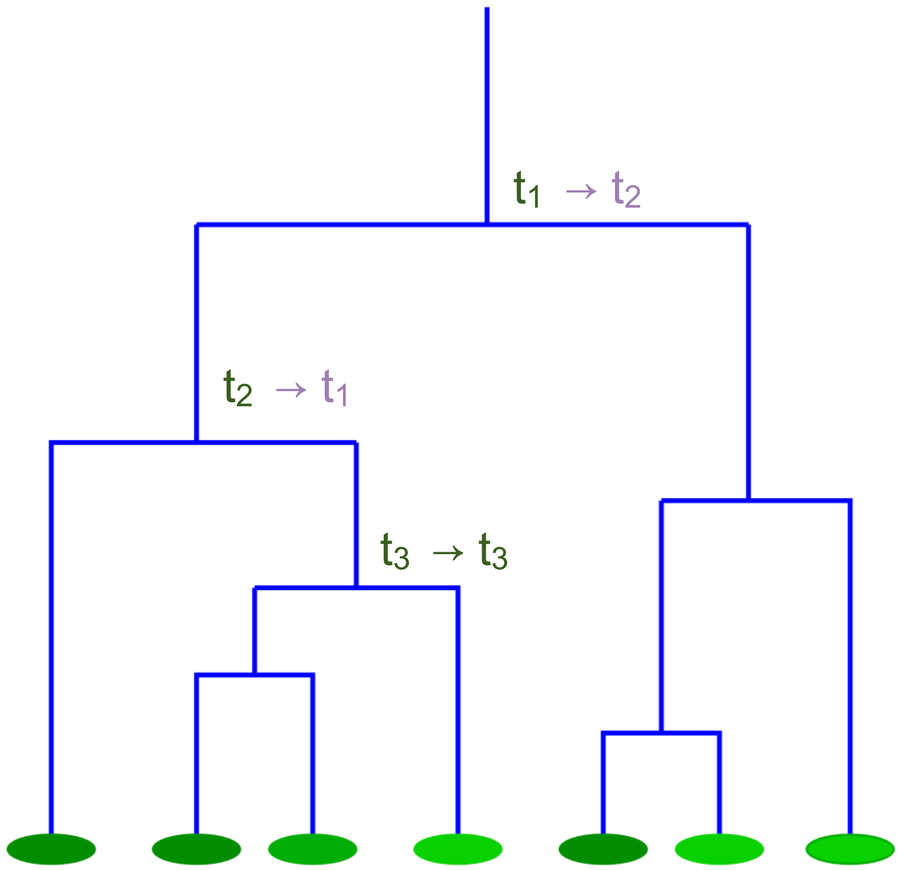
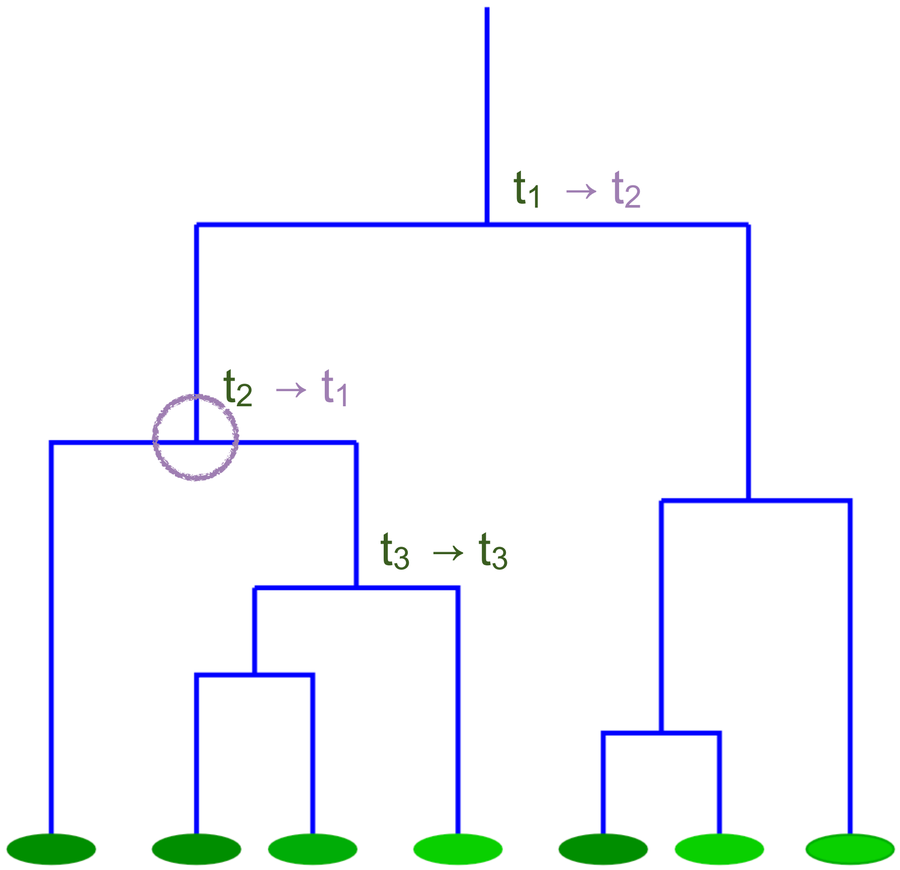


Looking to the shortest τ_{form}

- Even with soft-drop, emissions/unclustering steps might not be ordered in τ_{form}
- From leading branch, select the one with the shortest τ_{form}

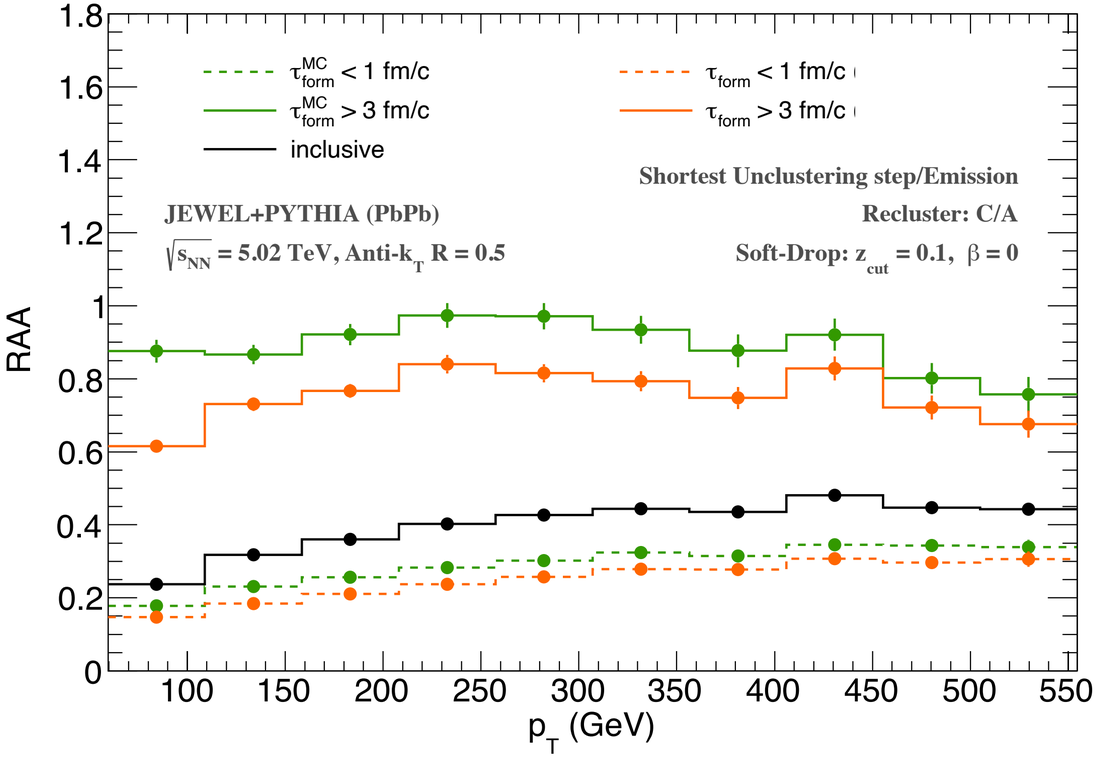


Looking to the shortest τ_{form}

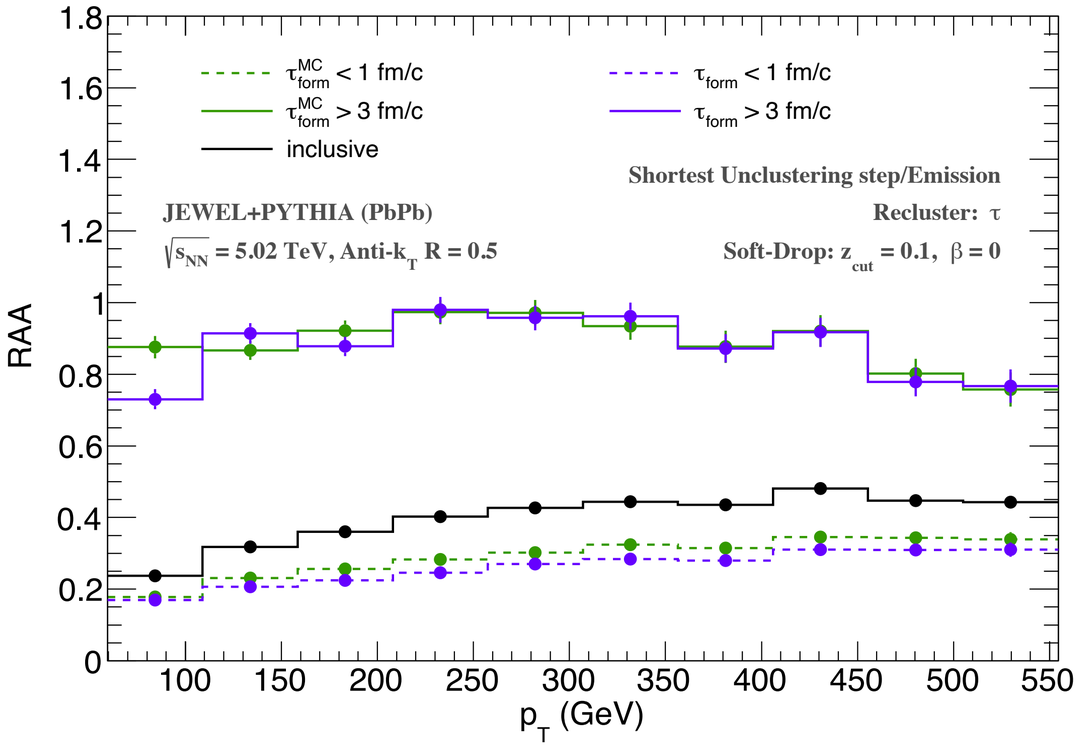
Even τ can yield a fraction unordered emissions…

- Even with soft-drop, emissions/unclustering steps might not be ordered in τ_{form}
- From leading branch, select the one with the shortest τ_{form}

C/A (p = 0.0)



τ (p = 0.5)



Time-drop vs Soft-drop

- How about other grooming settings?

Soft-drop

[Larkoski, Marzani, Soyez, Thaler (2014)]
[Larkoski, Marzani, Thaler (2015)]

C/A re-clustered jet

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

$$\text{when} \quad \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{R_{12}}{R_0} \right)^{\beta}$$

Time-drop vs Soft-drop

- How about other grooming settings?

Time-drop

[Metar-Tani, Soto-Ontoso, Tywoniuk (2020)]

C/A re-clustered jet

$$\kappa^{(a)} = \frac{1}{p_{\mathrm{T}}} \max_{i \in \mathrm{C/A\ seq.}} \left[z_i (1 - z_i)\, p_{\mathrm{T},i} \left(\frac{\theta_i}{R} \right)^a \right]$$

a = 2: $t_{\mathrm{f}}^{-1} \sim \kappa^{(2)} p_{\mathrm{T}}.$

Soft-drop

[Larkoski, Marzani, Soyez, Thaler (2014)]
[Larkoski, Marzani, Thaler (2015)]

C/A re-clustered jet

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$

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