Jetography in Heavy Ion Collisions

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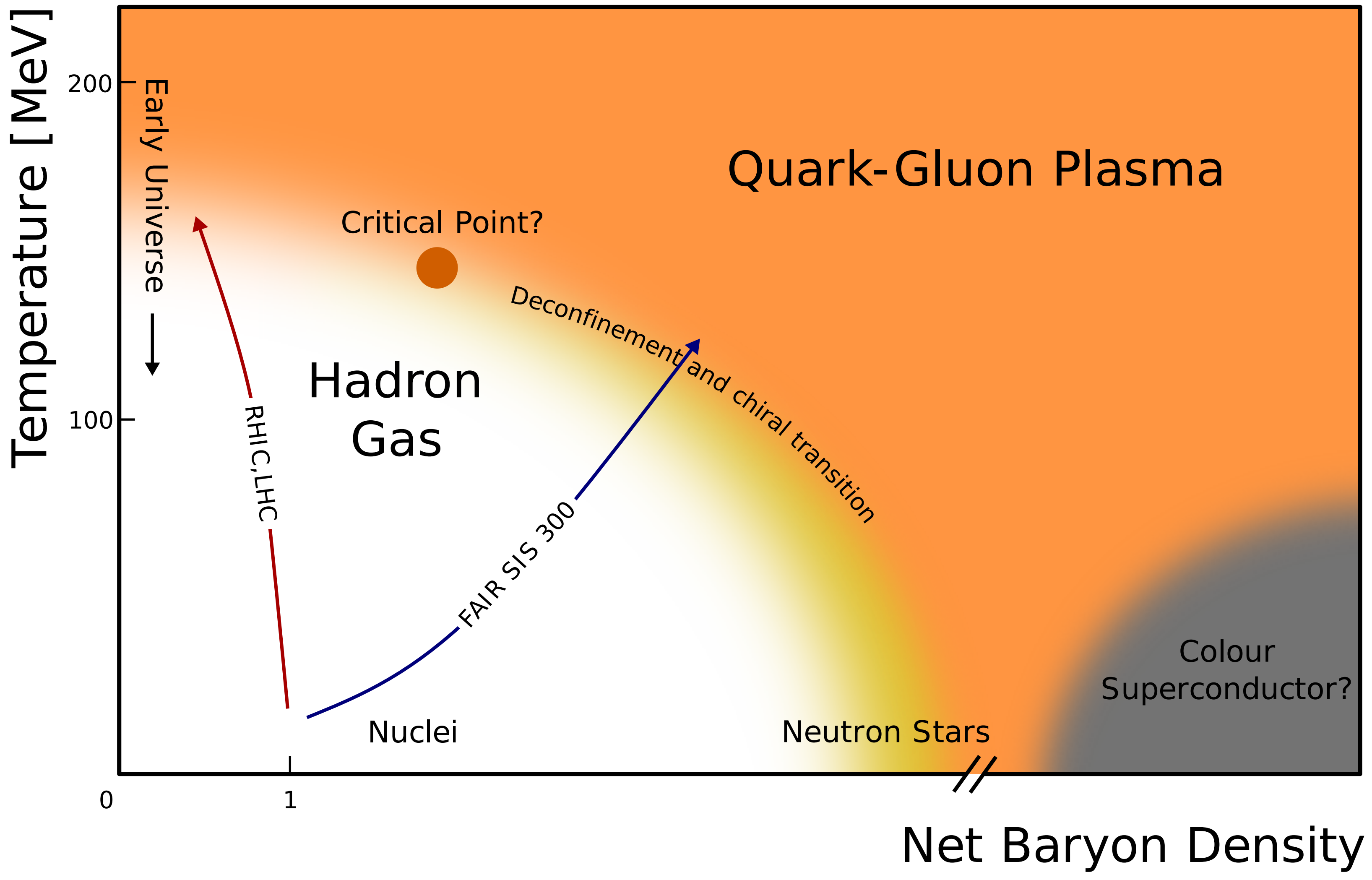
Why we study heavy ion collisions

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



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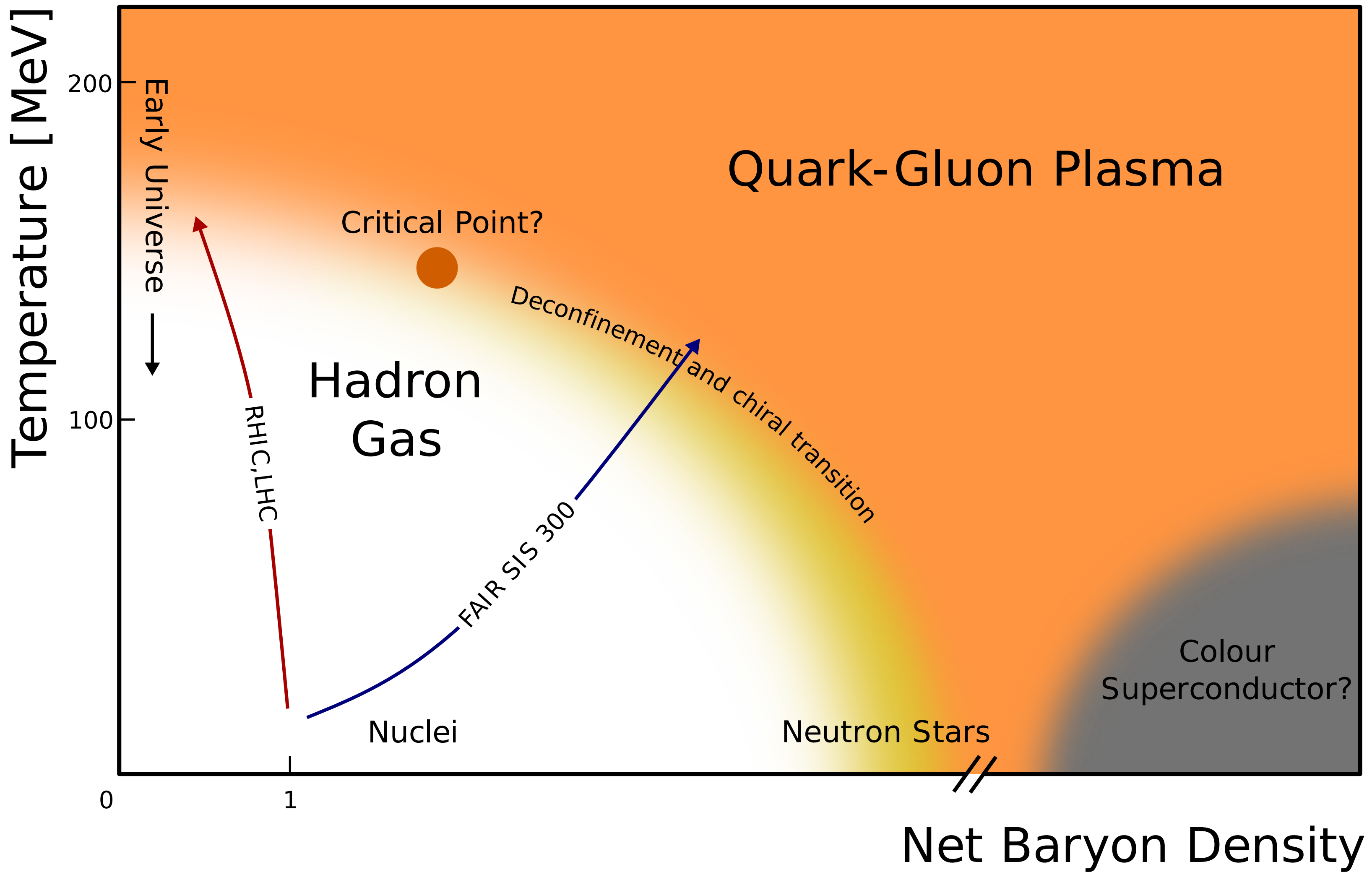

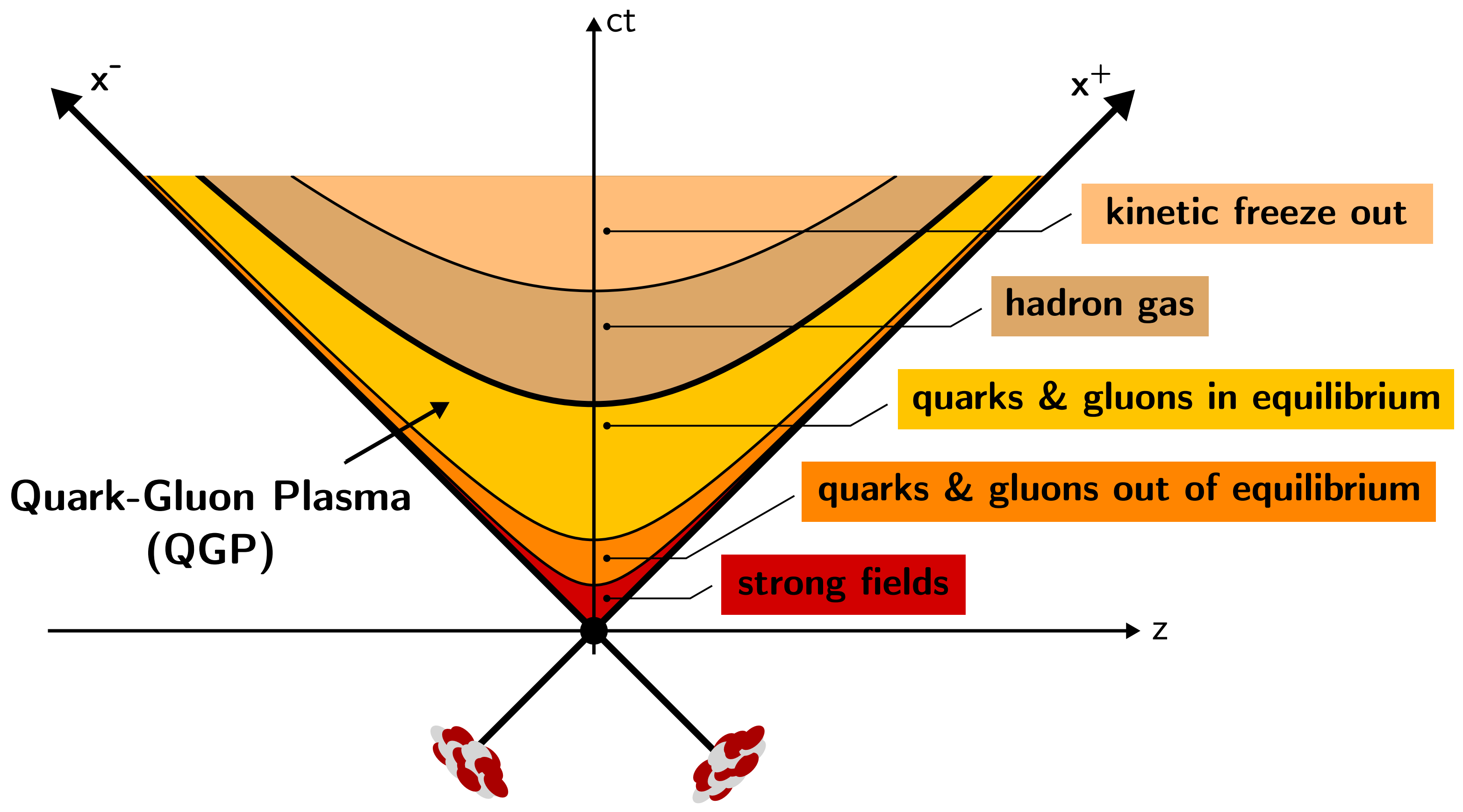

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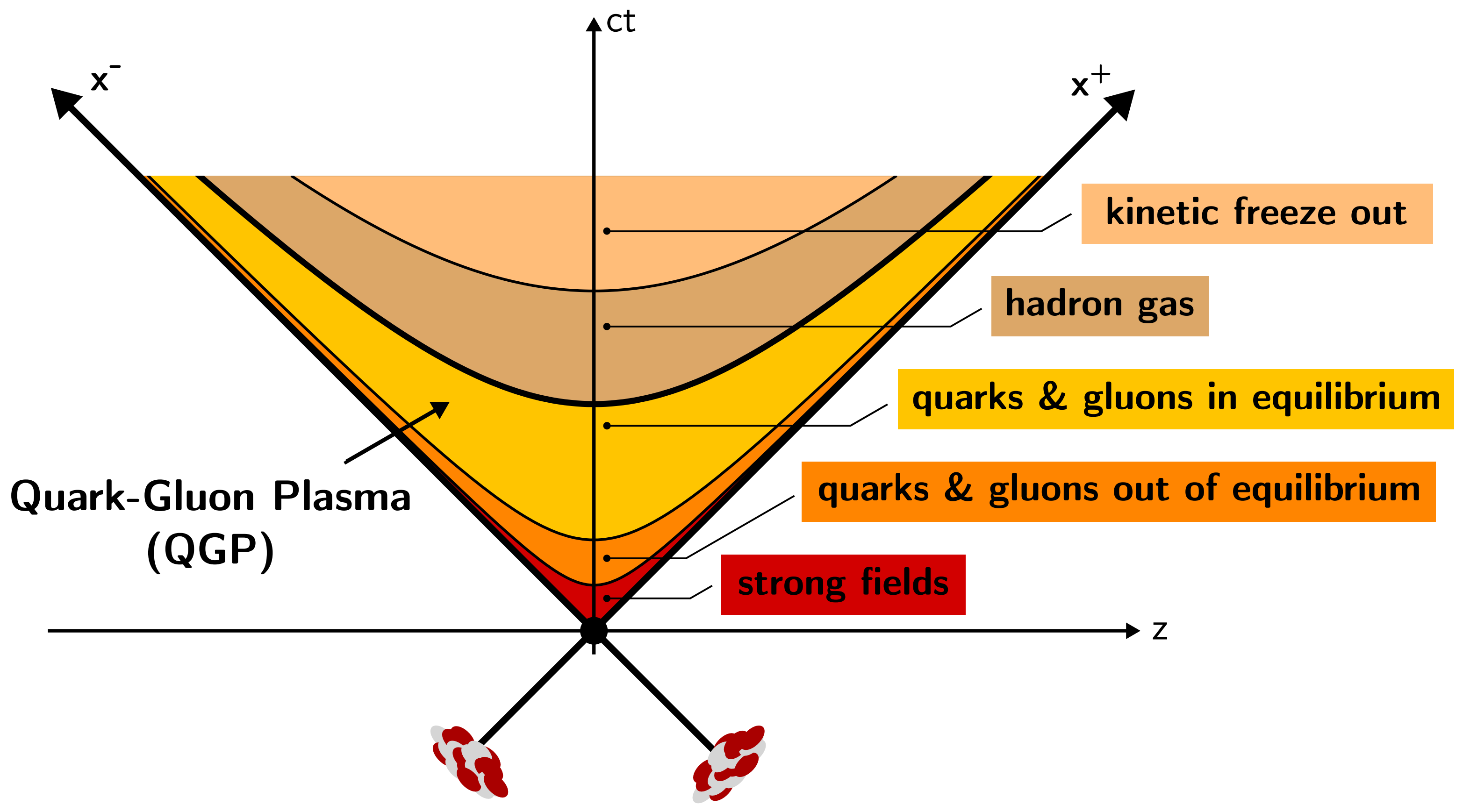
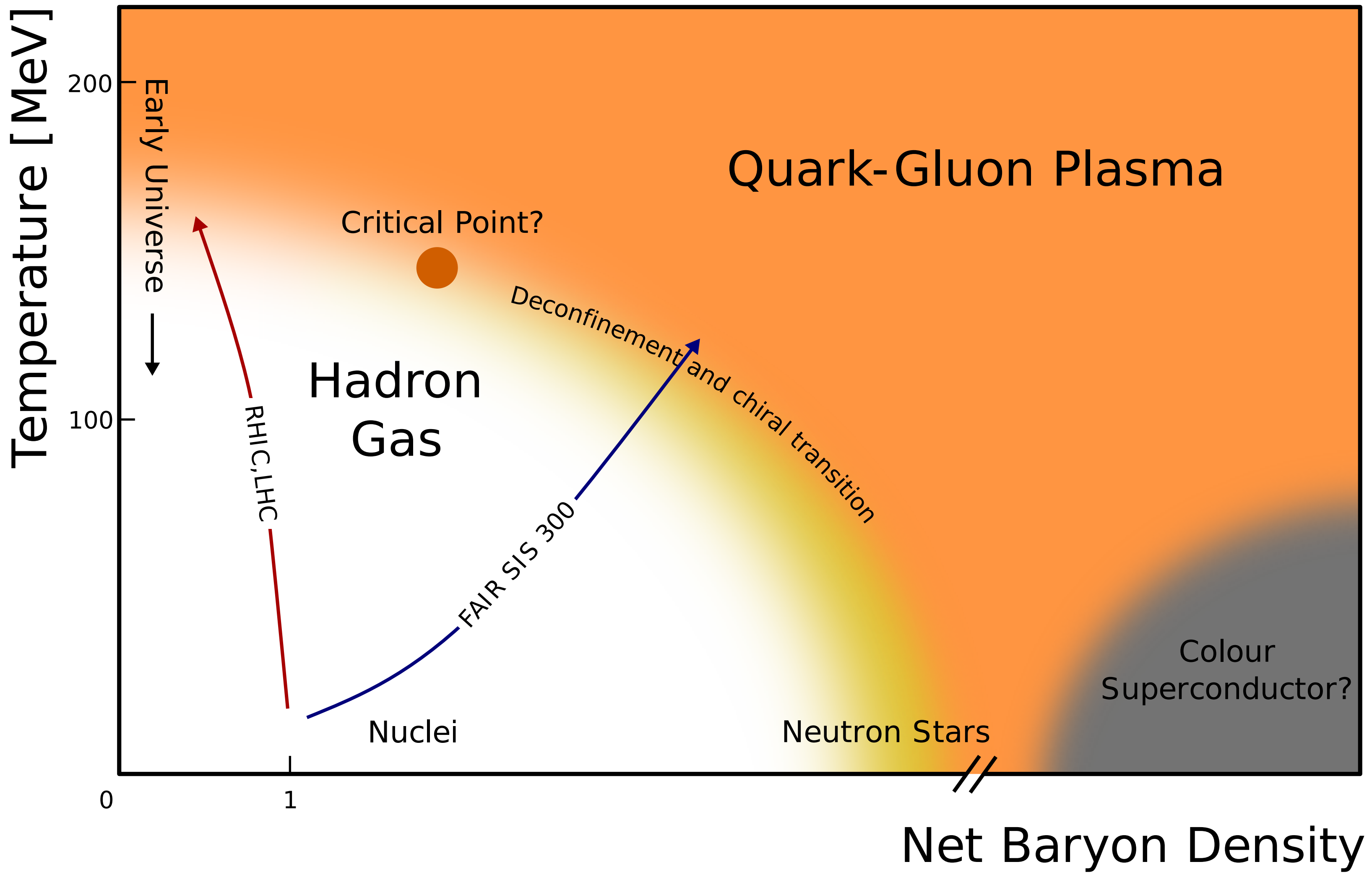


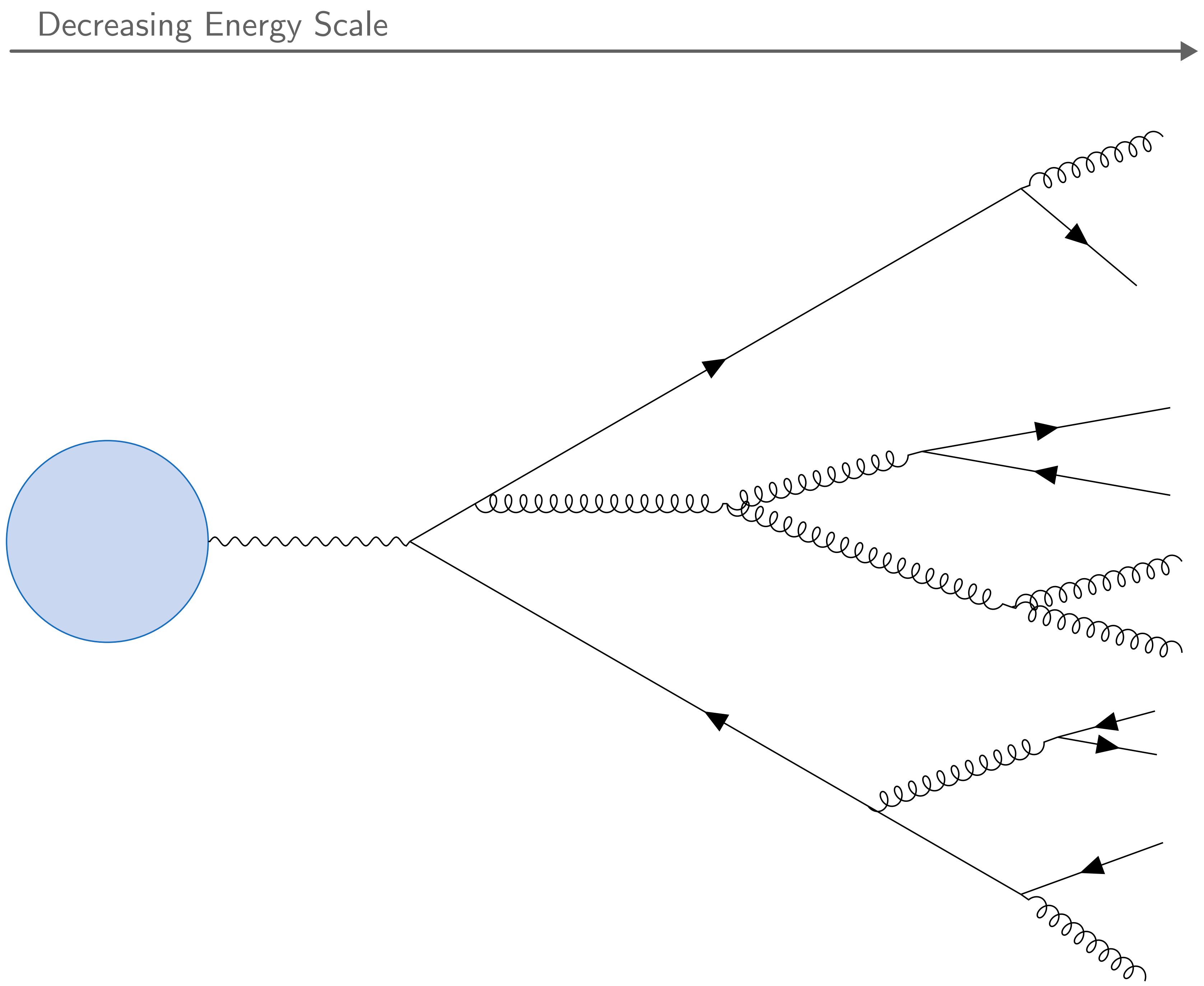


Main Challenge: **the QGP is extremely short lived (10^{-24} s)**

Solution: **Probe it with (high-momentum) particles produced concurrently with the collision!**

Jets as probes of the Quark-Gluon Plasma

Particles created during the collision radiate until the hadronisation scale: This is a multi-scale object!



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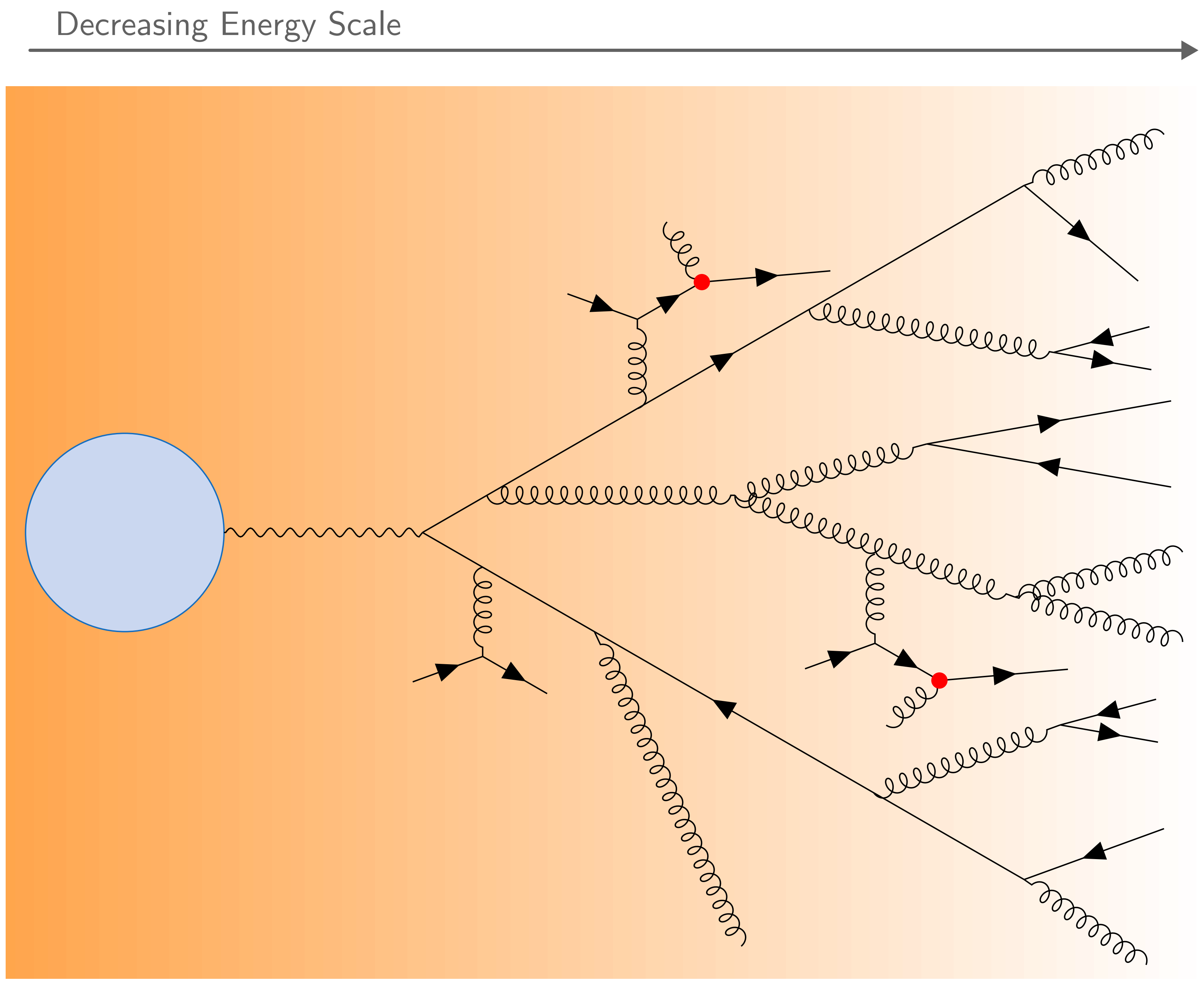

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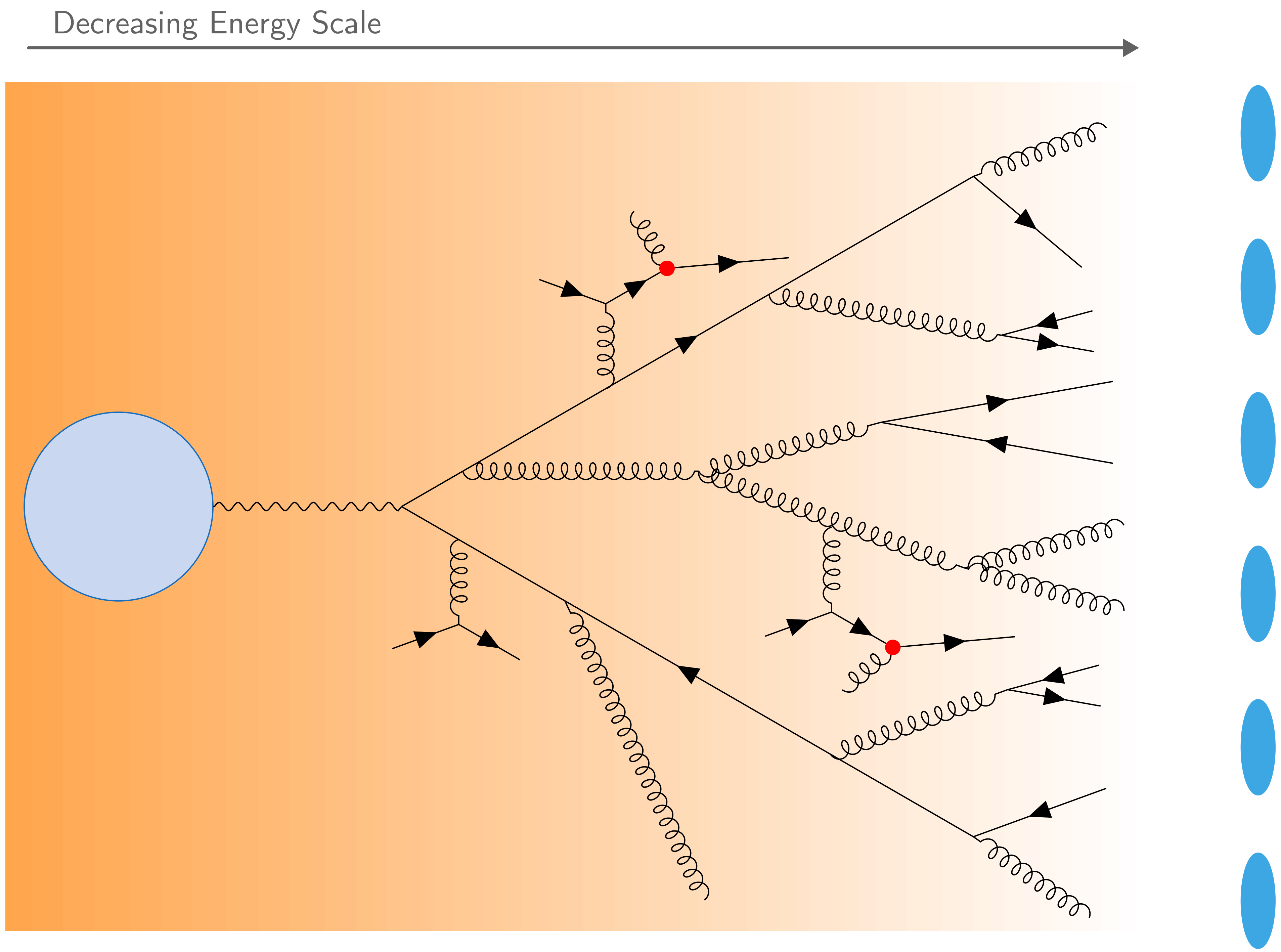

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Experimental access is restricted to final state hadrons

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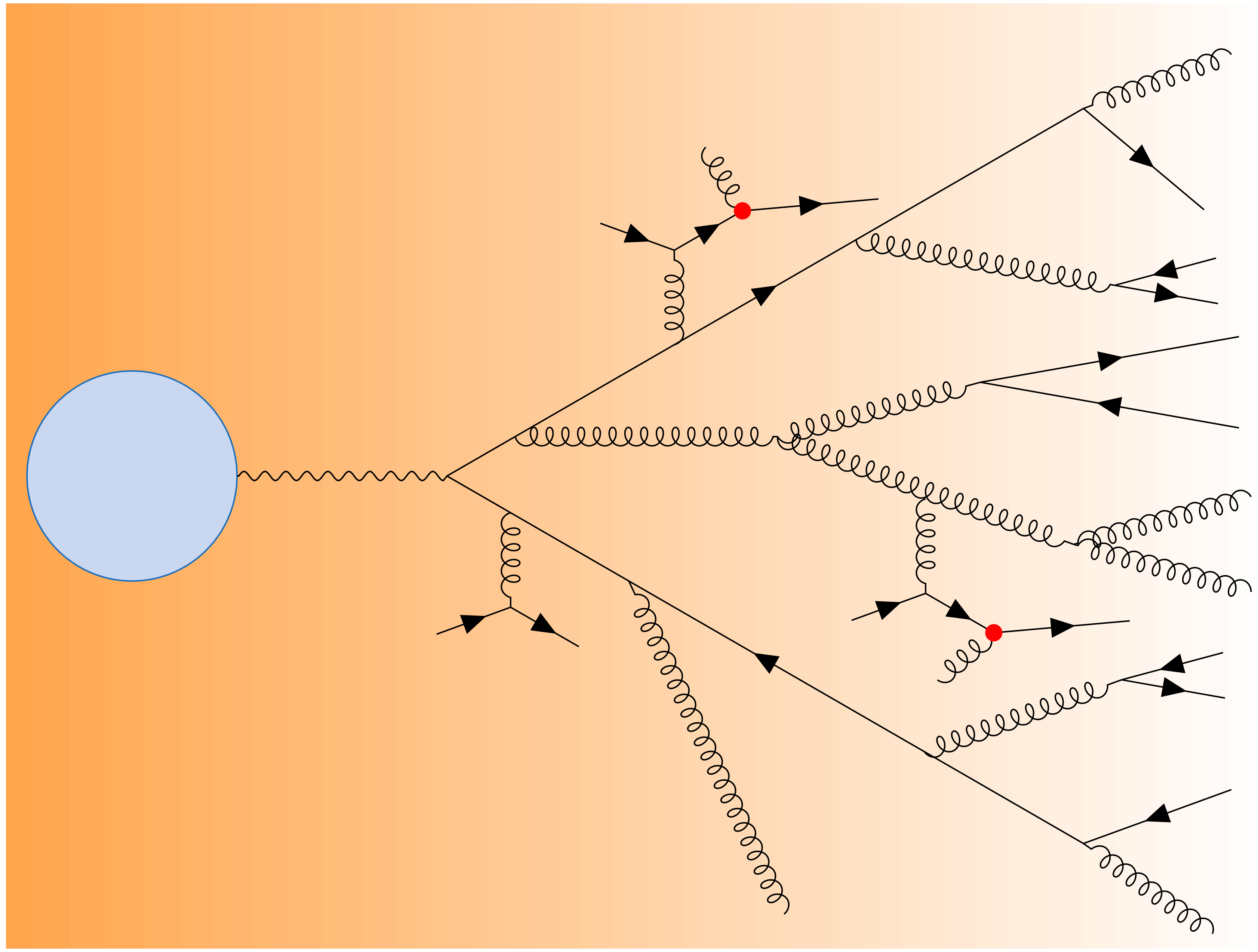
Decreasing Energy Scale



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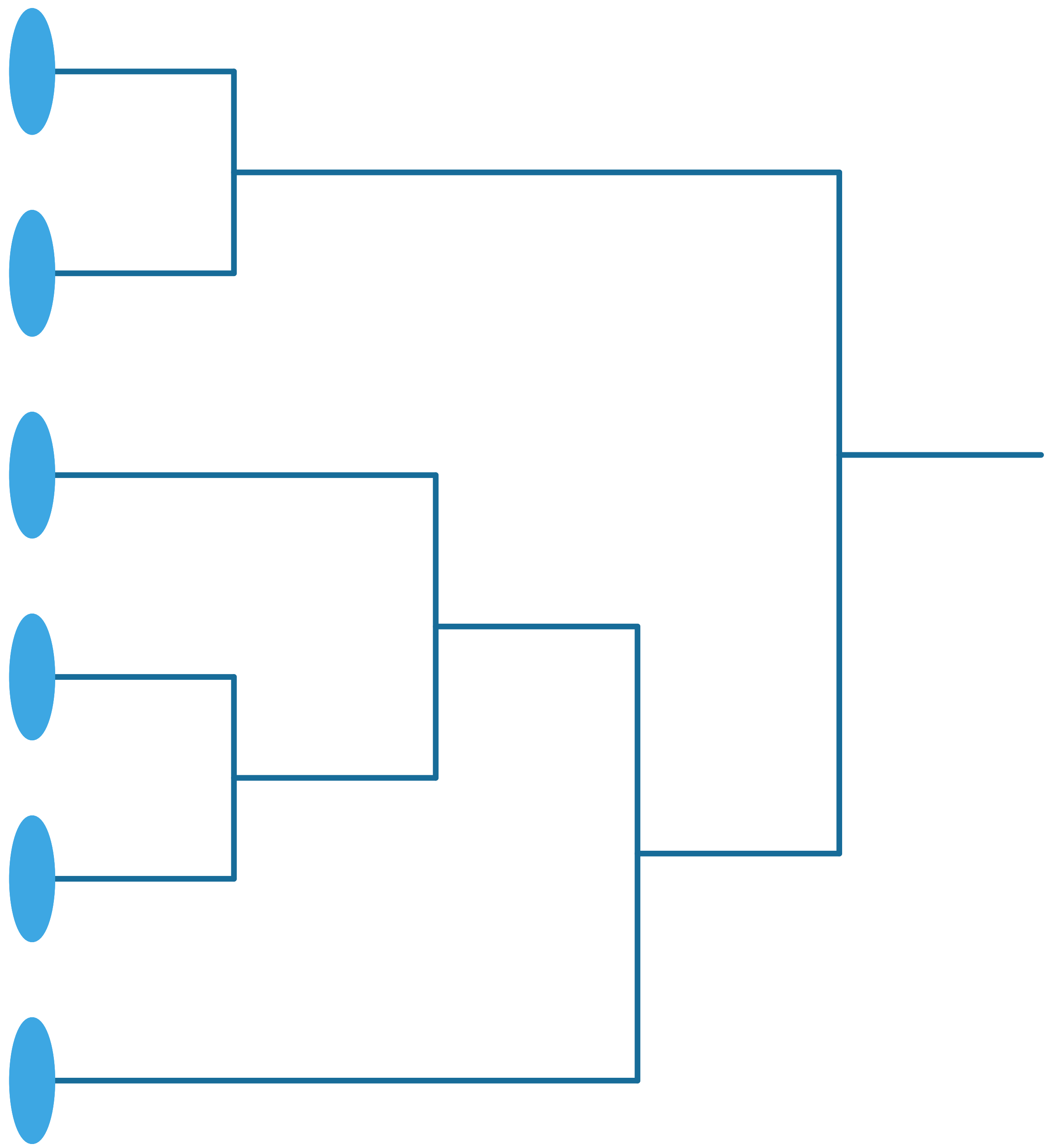

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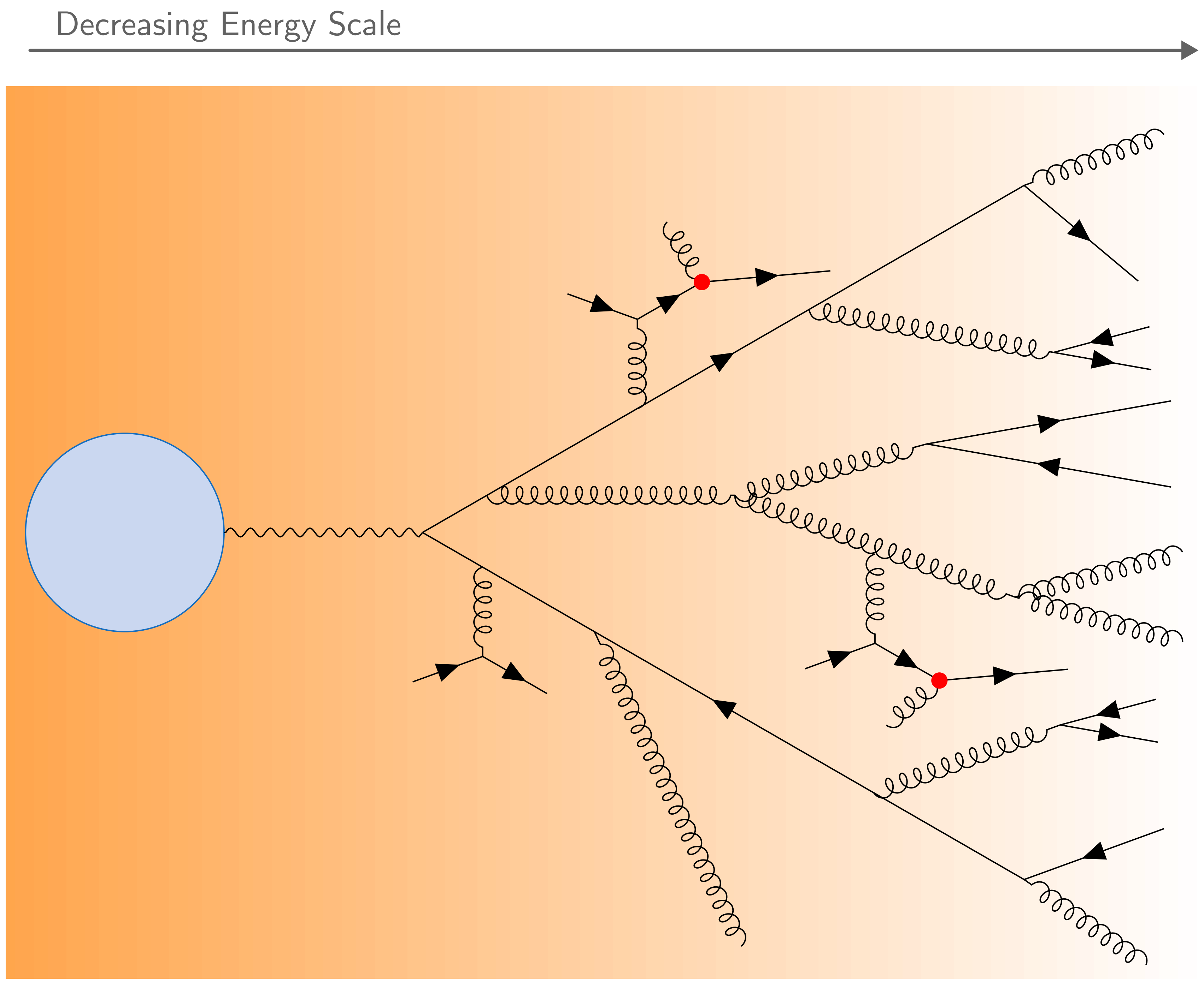

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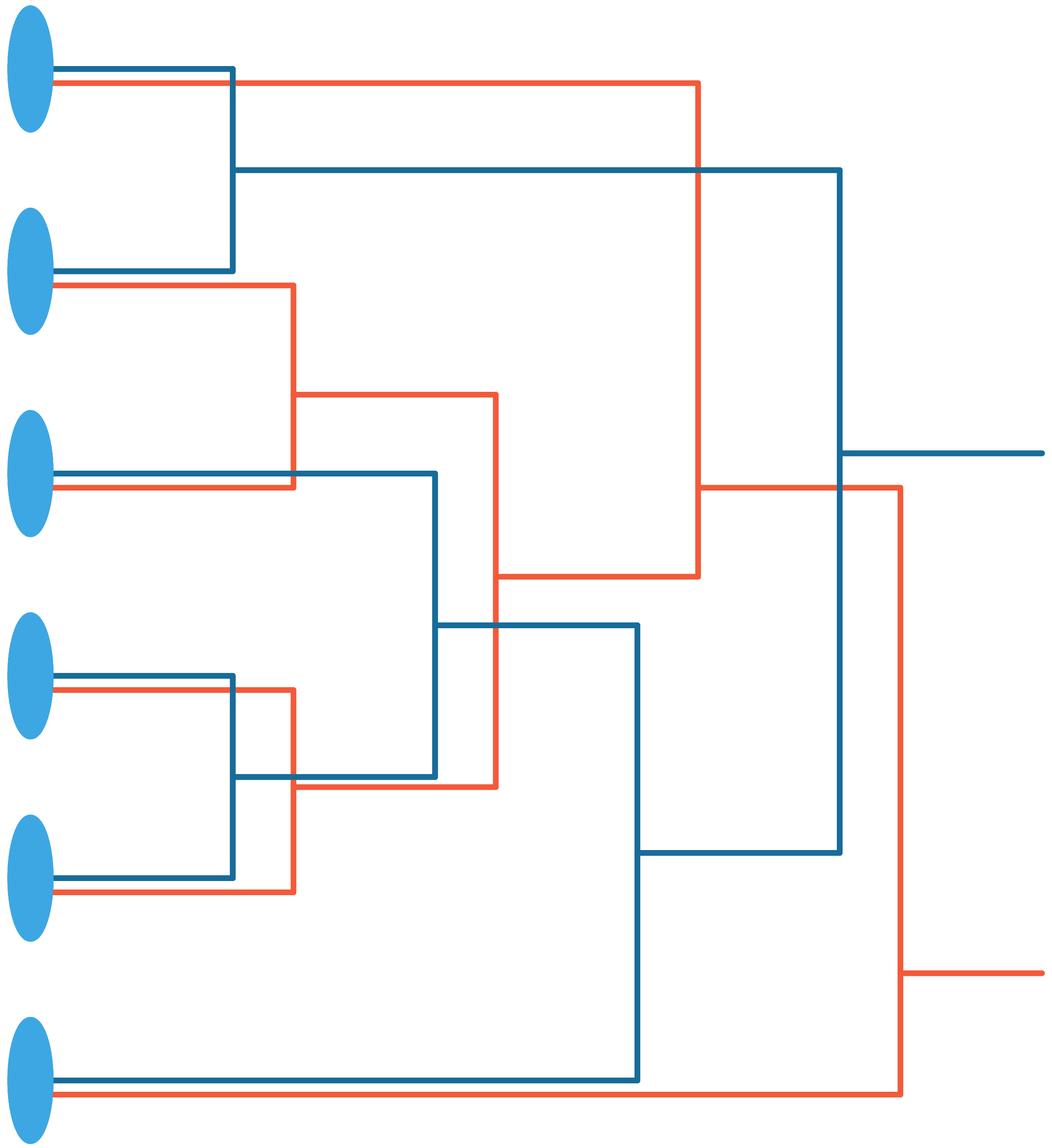
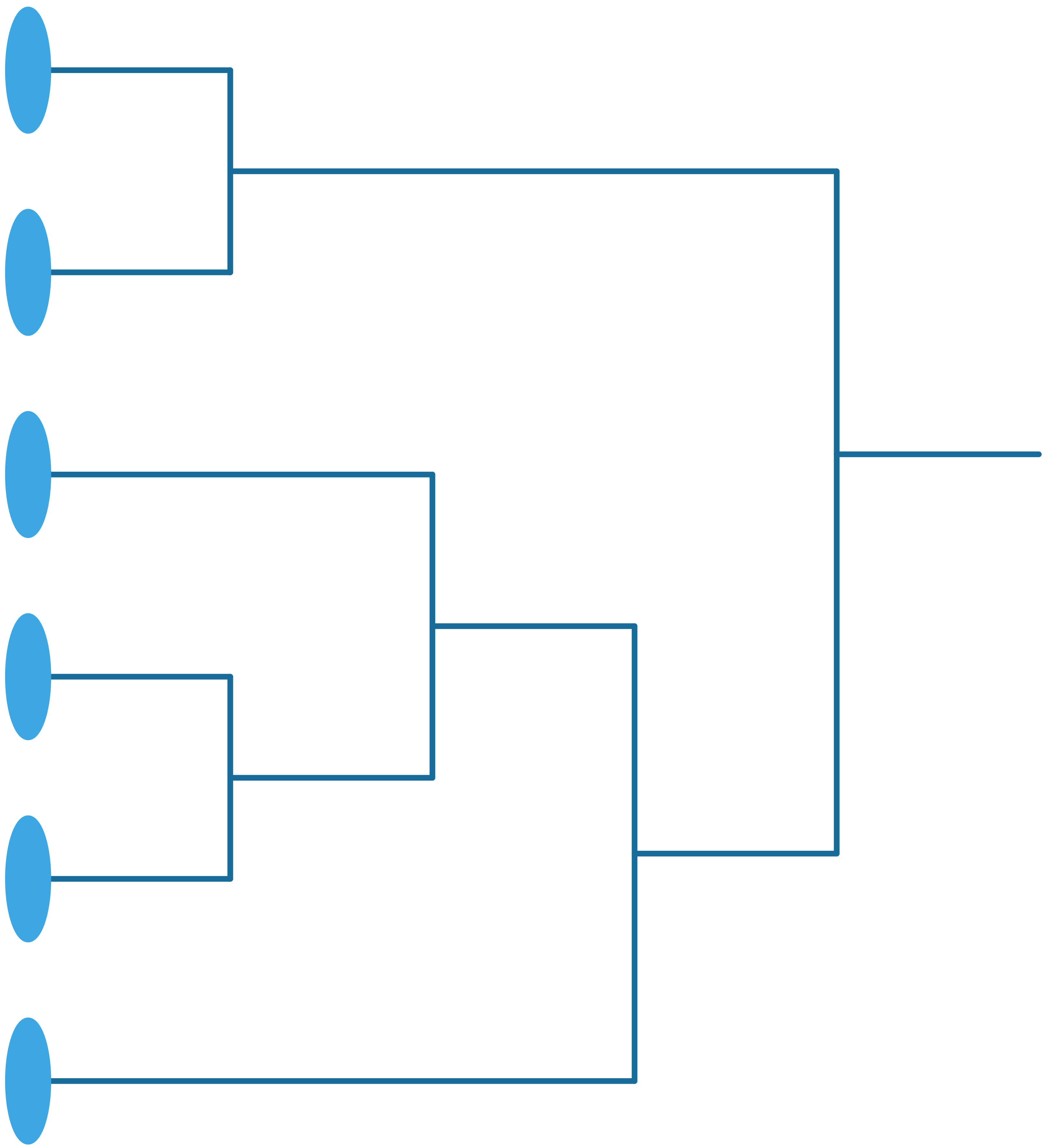


Solution: Cluster them pairwise into jets

<u>Note: The jet definition is always ambiguous!</u>

We begin by focusing on the jets

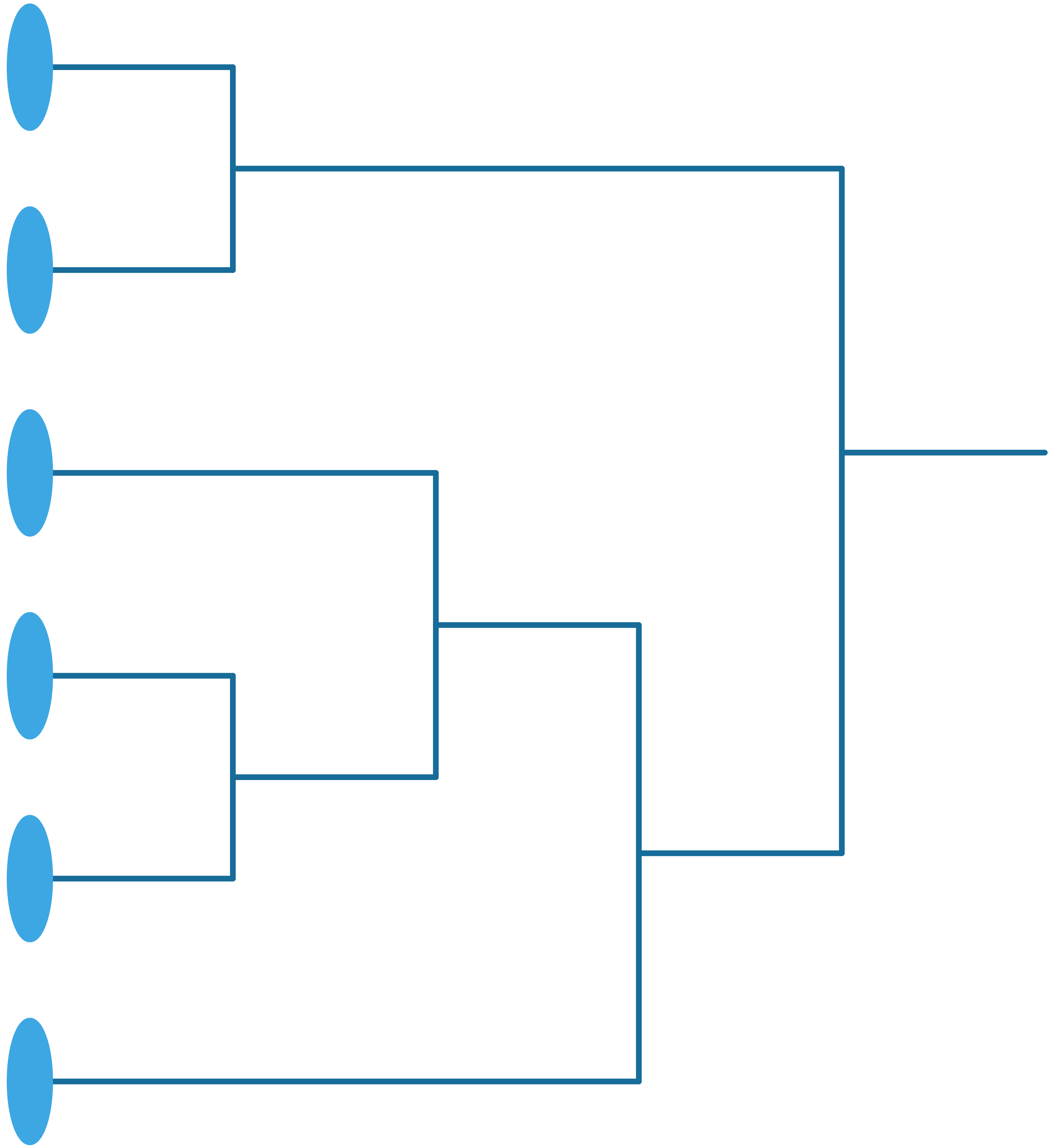


Jet definitions: Clustering algorithms

Sequential algorithms: minimise distance between pairs

- Use the generalised-k_T measure:

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



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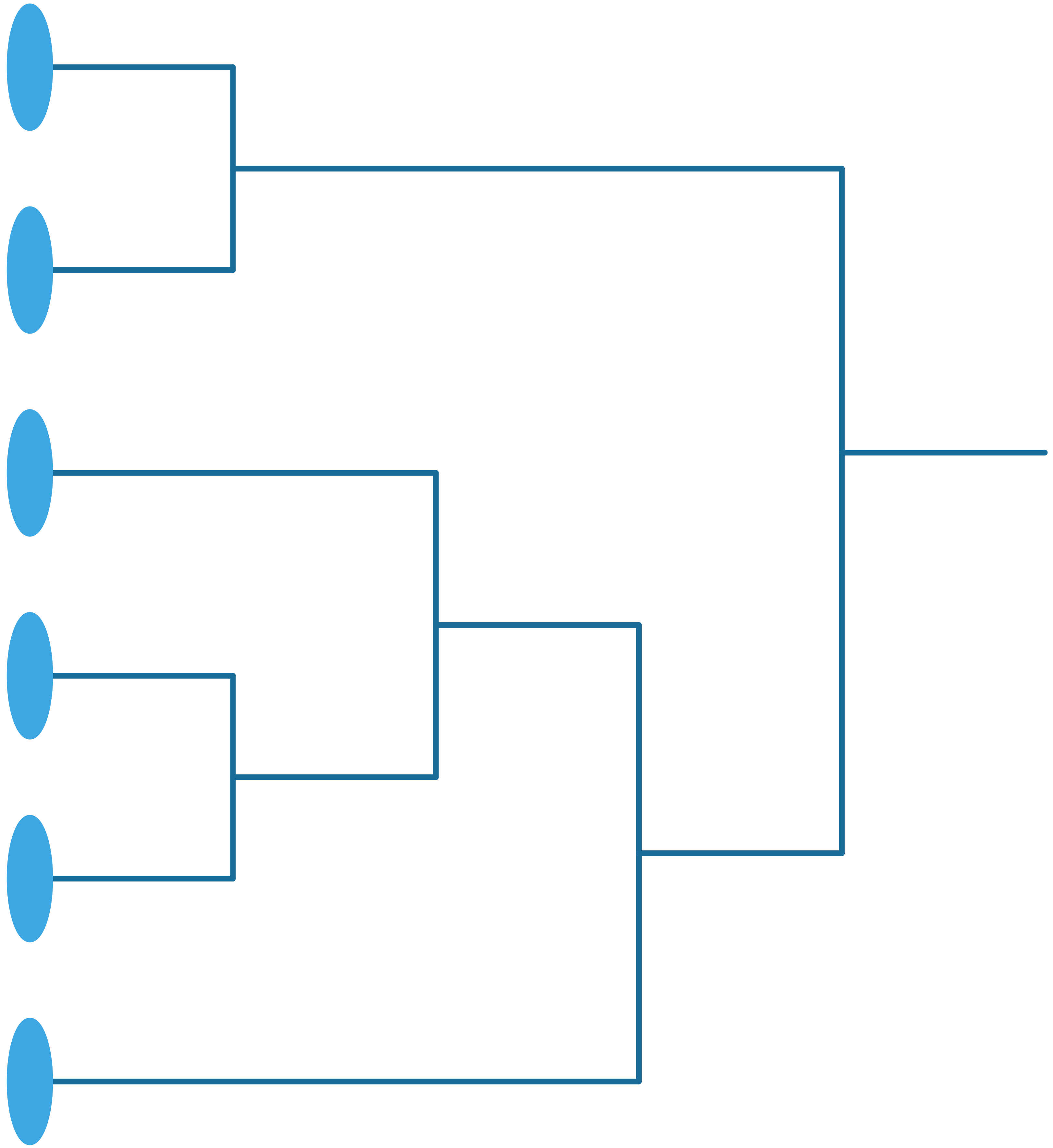
$p = -1$ Anti-k_T : Tags hard partons

$p = 0$ Cambridge/Aachen (C/A) : Angular ordering



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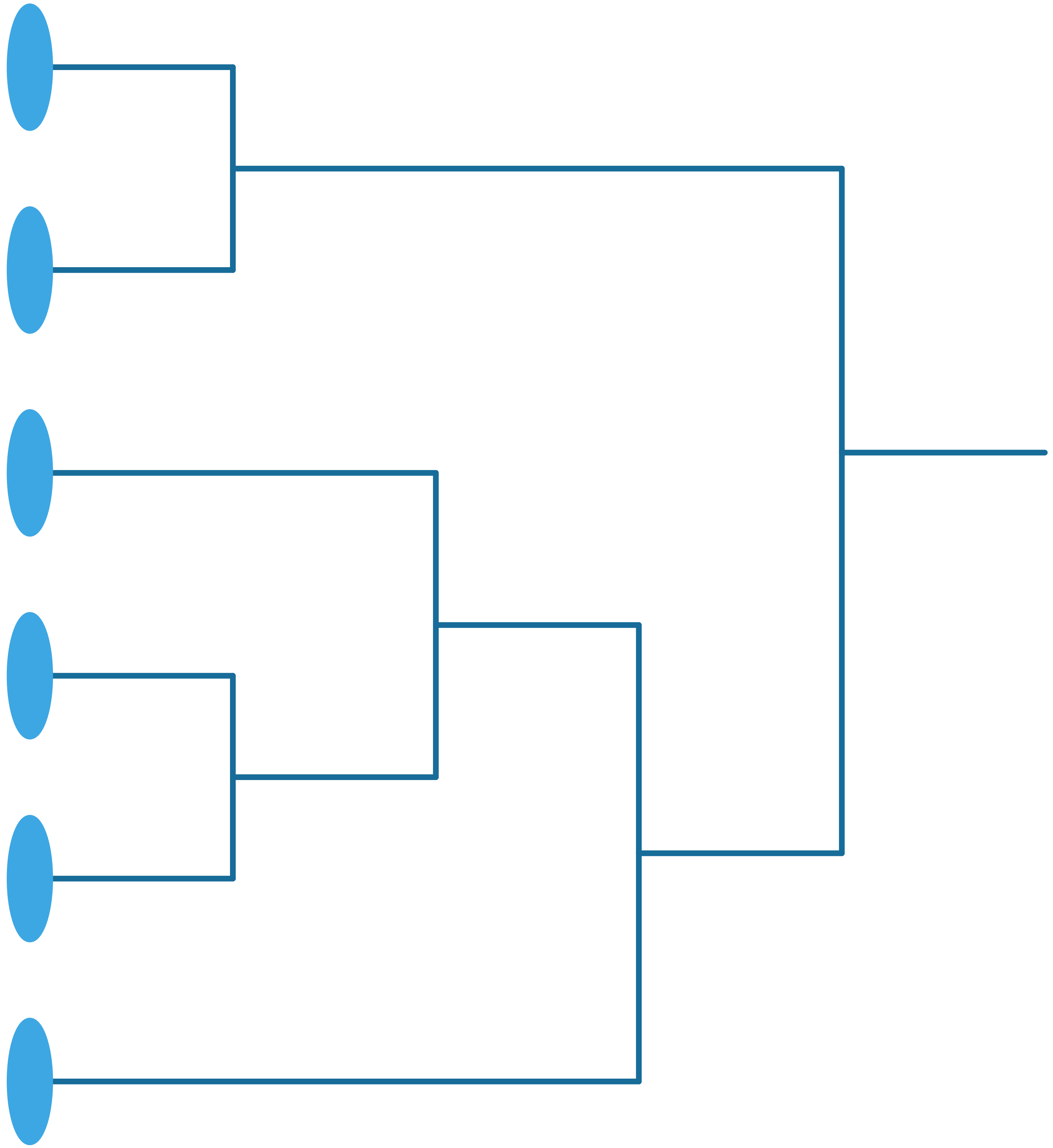

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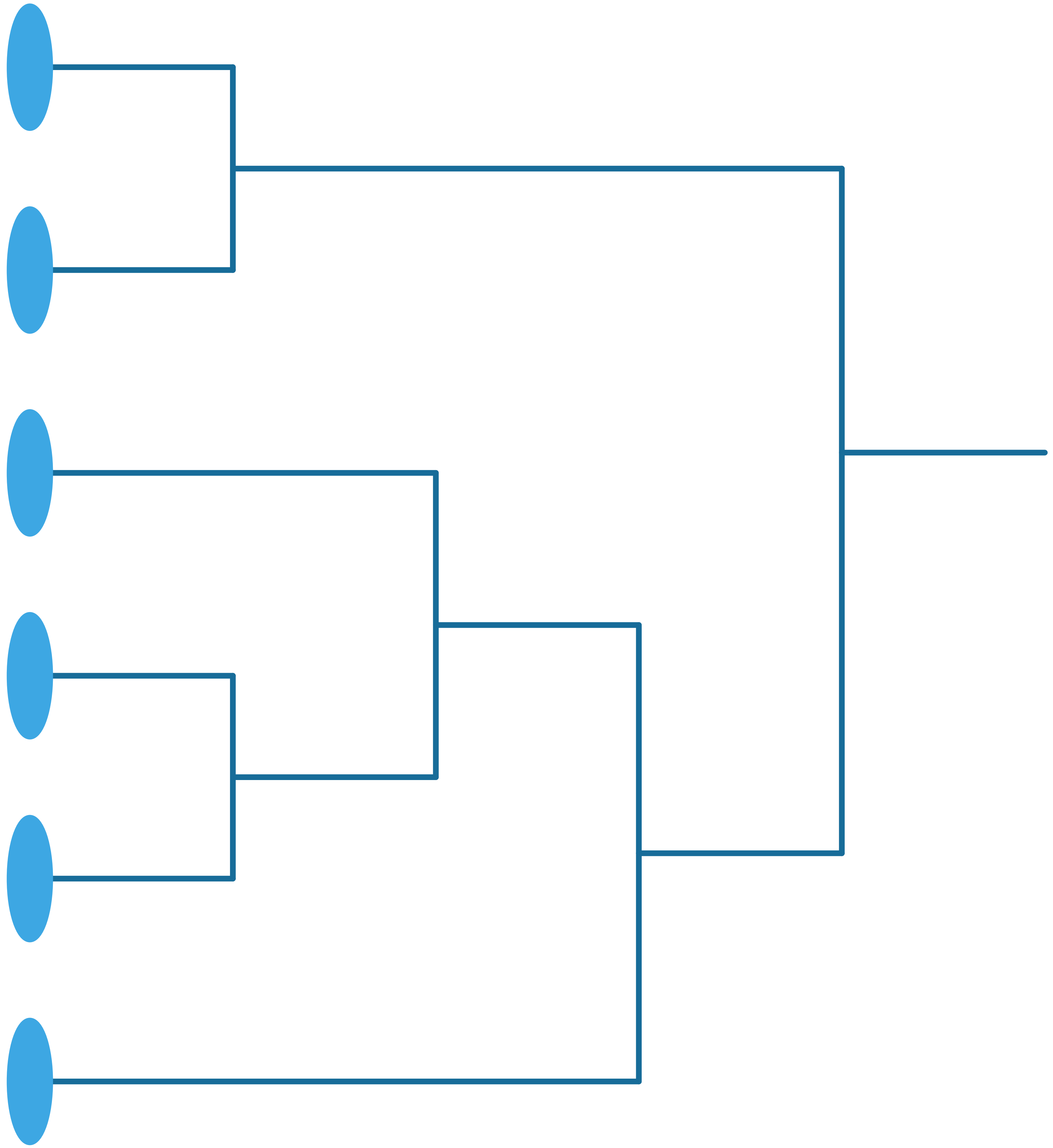
Clusters jets according to splitting formation time!

This is the τ algorithm



τ algorithm: Jet quenching classifier

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]

- Consider the jet formation time (1st splitting):
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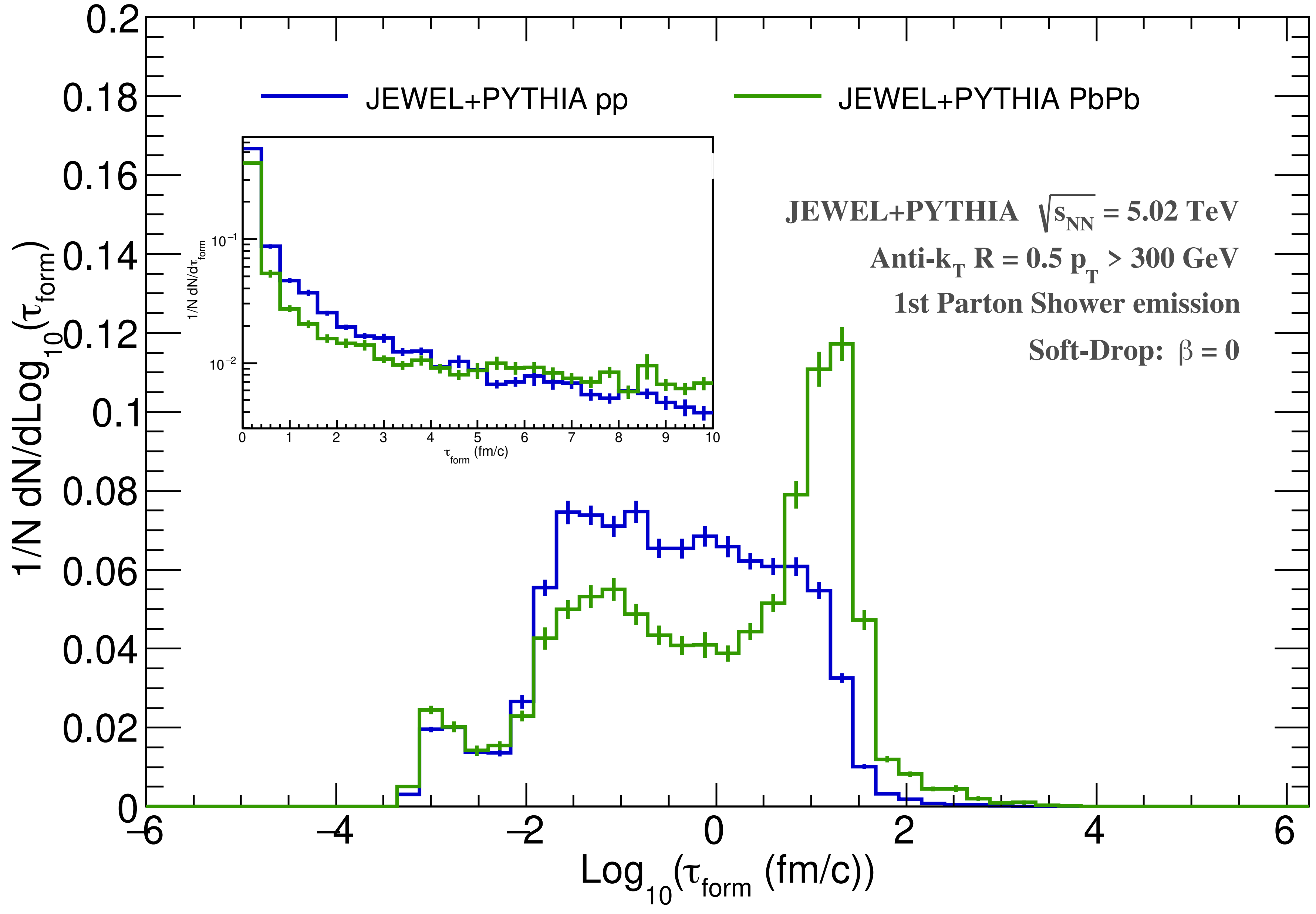

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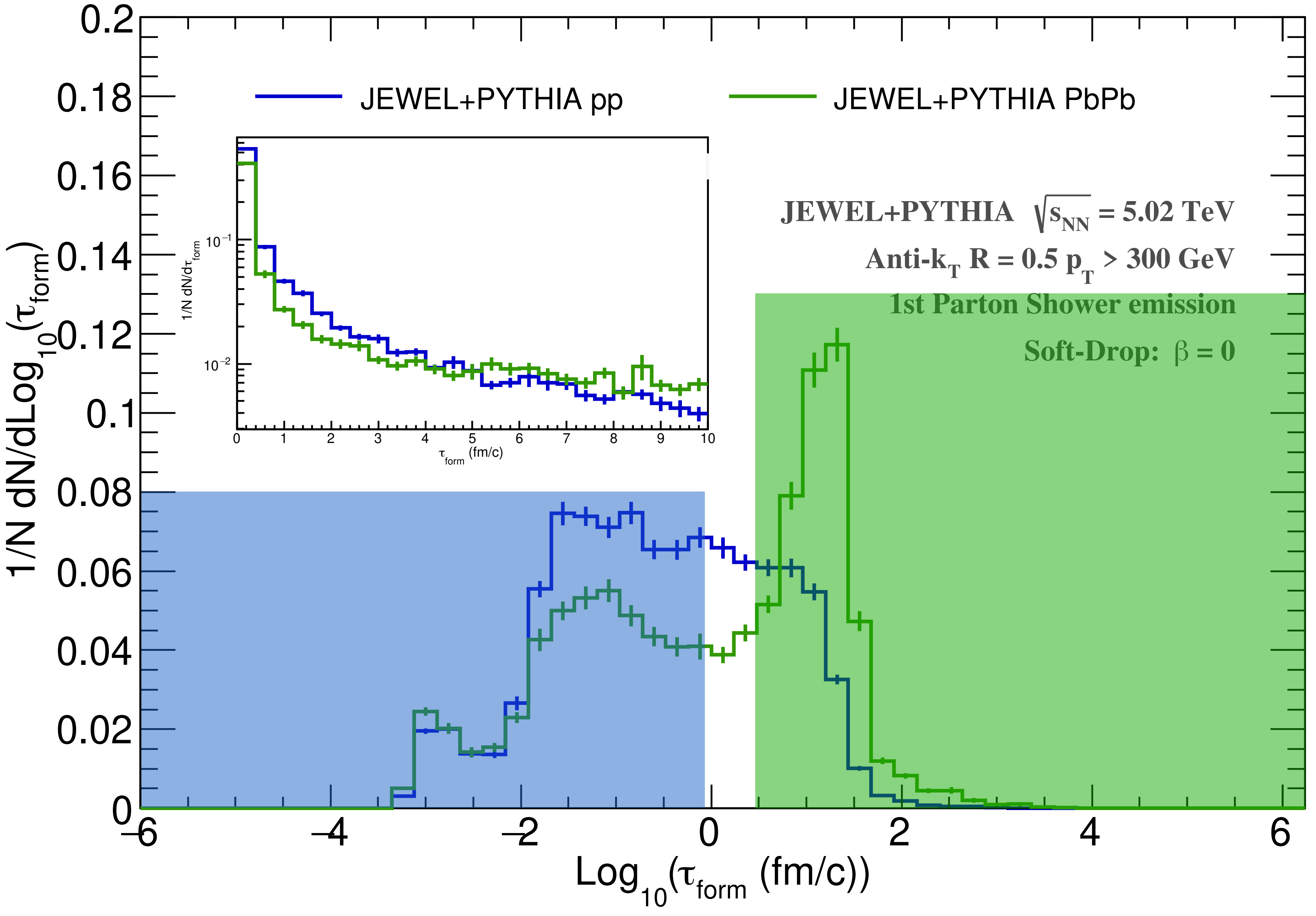

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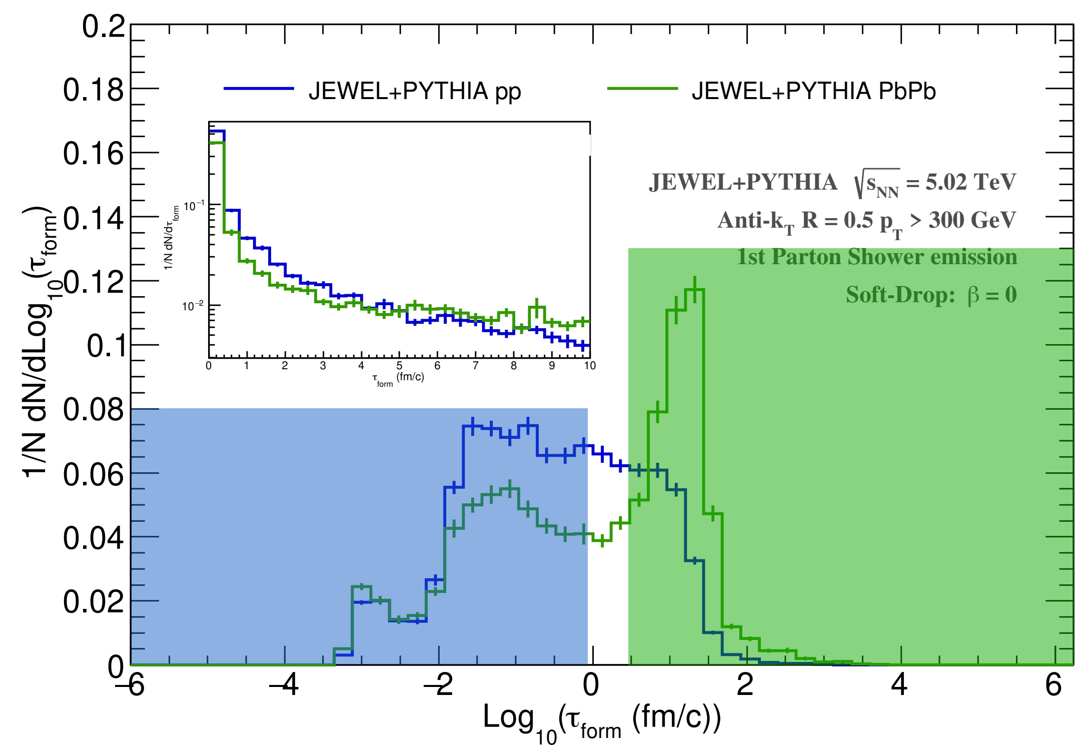
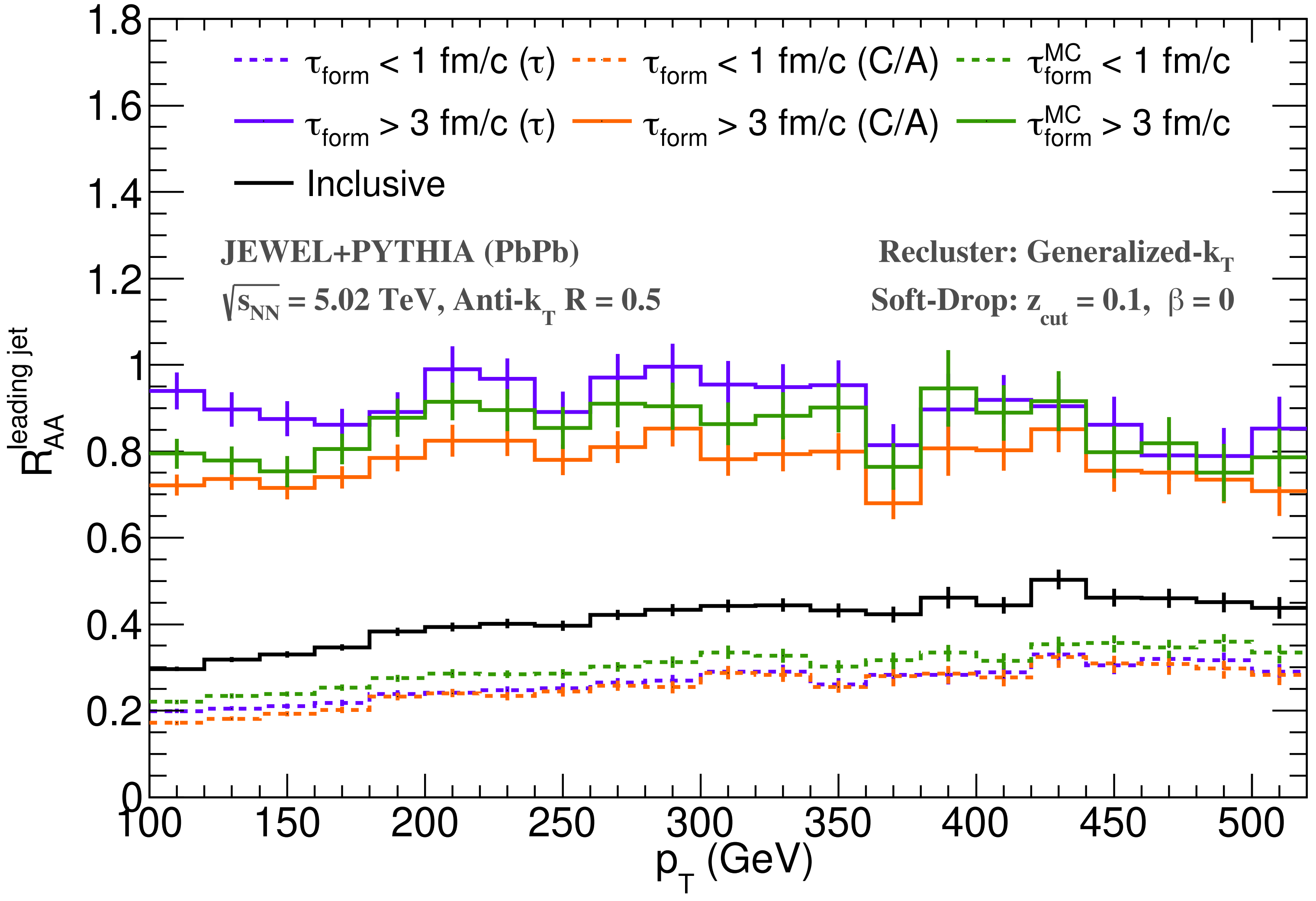
    - $R_{AA} \approx 1$ (almost no suppression)

$$R_{\mathrm{AA}}(p_t) = \frac{1/N_{\mathrm{evt}}^{\mathrm{AA}}\ \mathrm{d}N_{\mathrm{jets}}^{\mathrm{AA}}/\mathrm{d}p_t}{1/N_{\mathrm{evt}}^{\mathrm{pp}}\ \mathrm{d}N_{\mathrm{jets}}^{\mathrm{pp}}/\mathrm{d}p_t}$$





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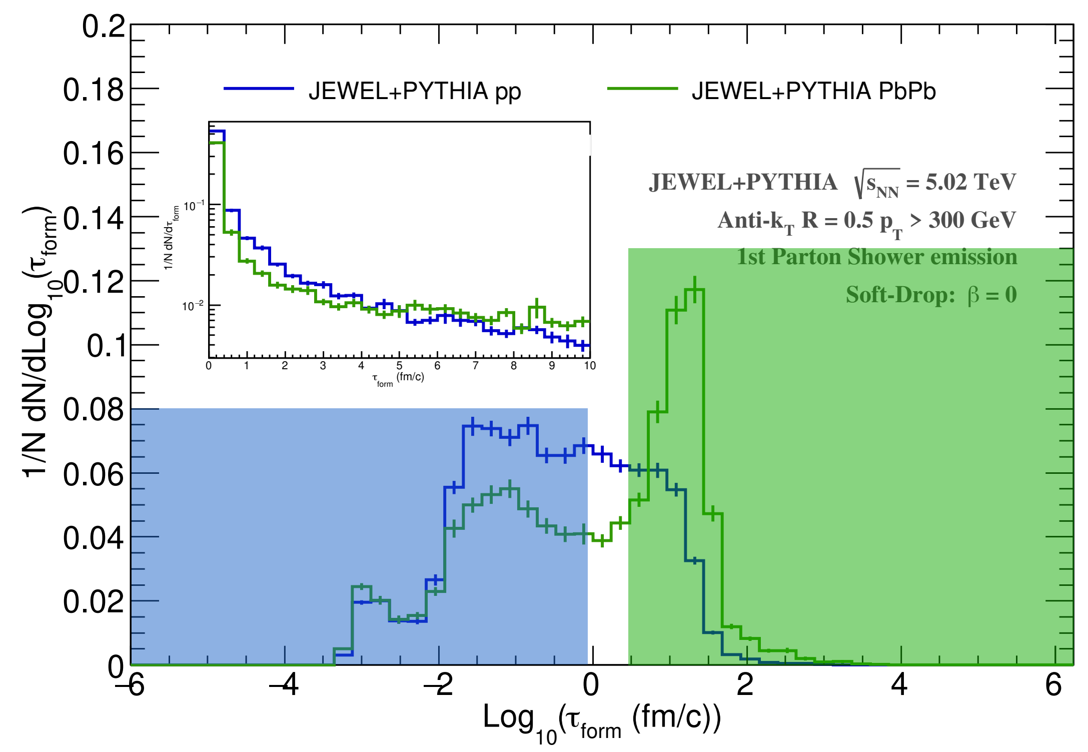

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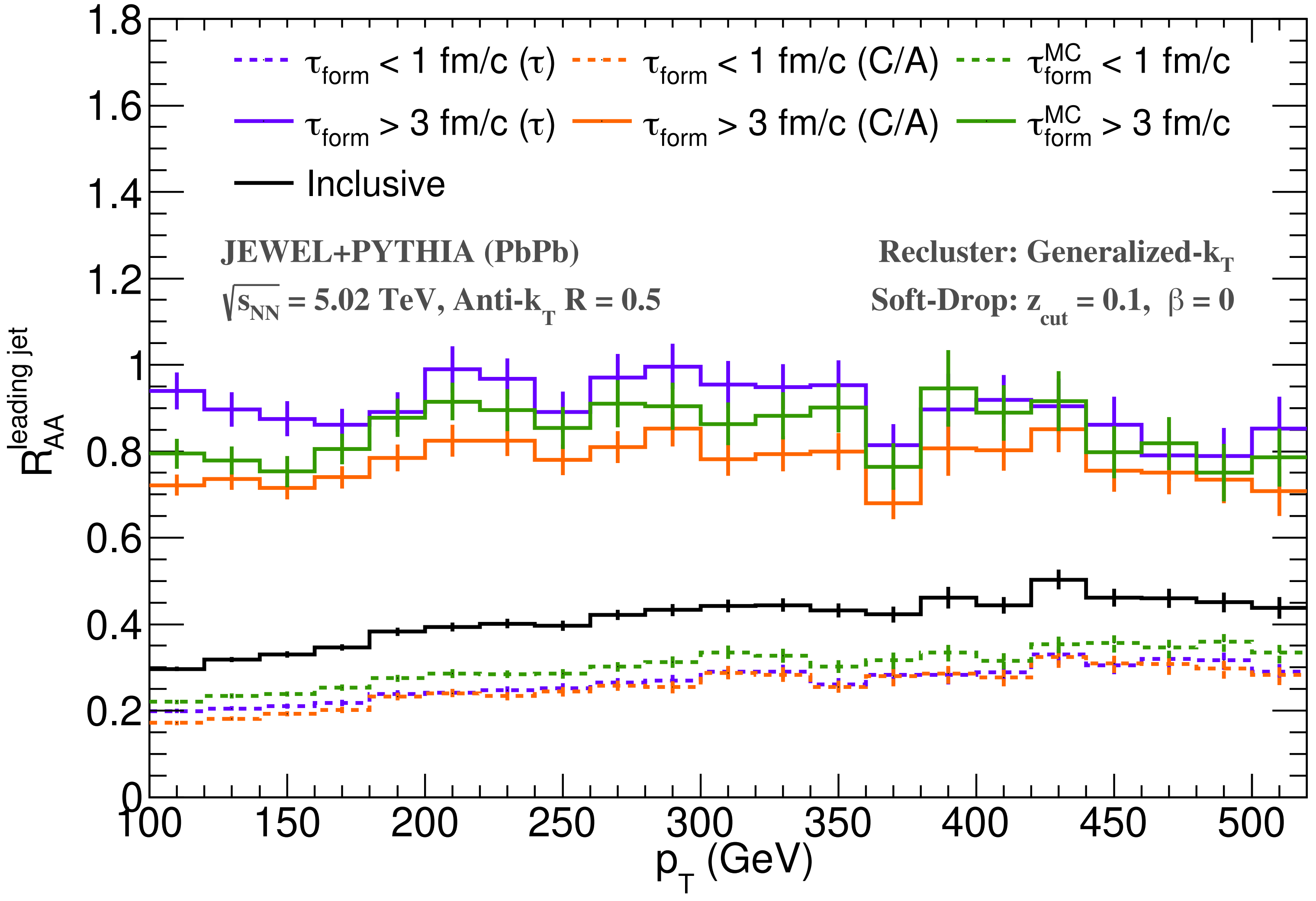
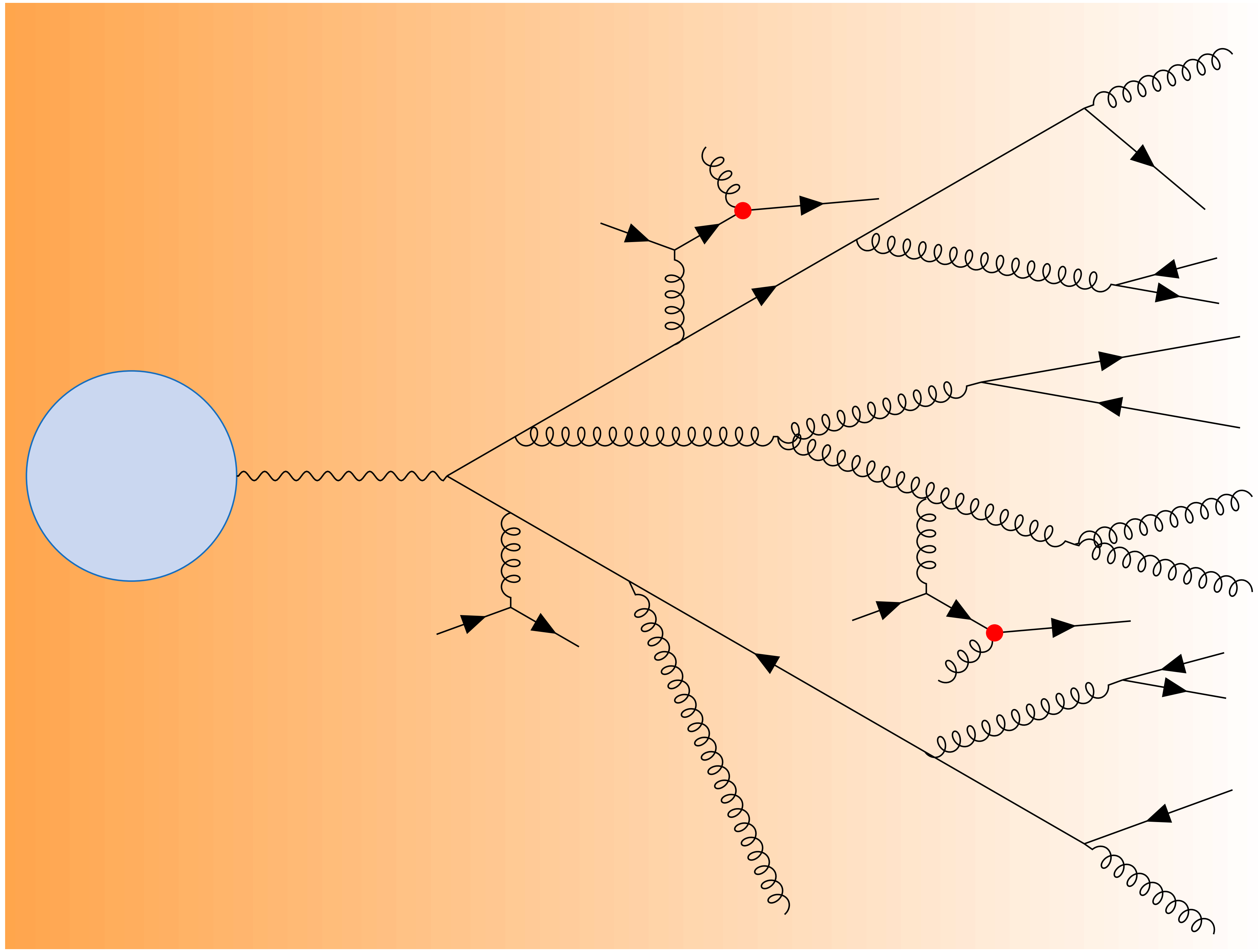
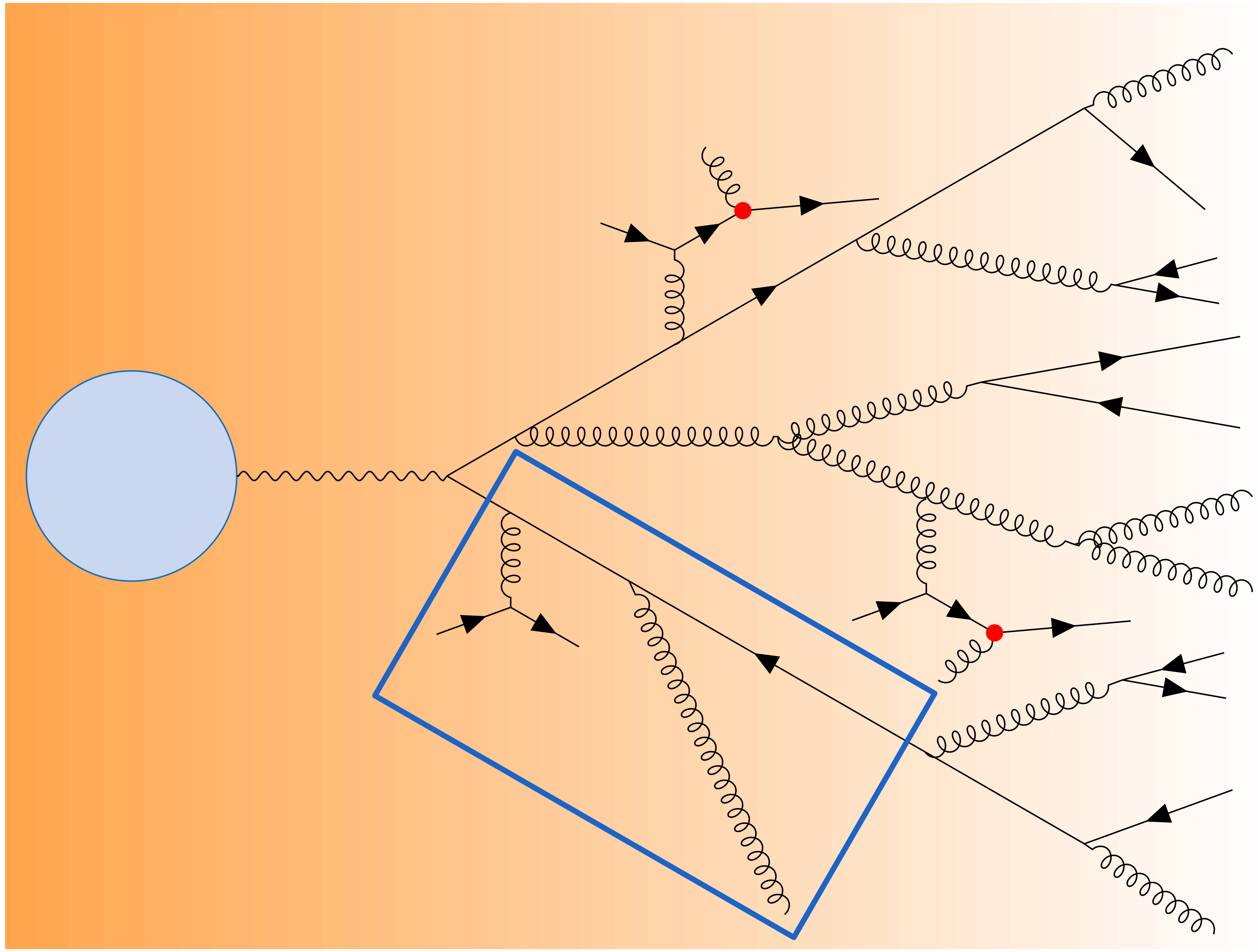


A jet quenching classifier:

Important step towards a tomographic analysis of the QGP!



Next, consider the parton cascade



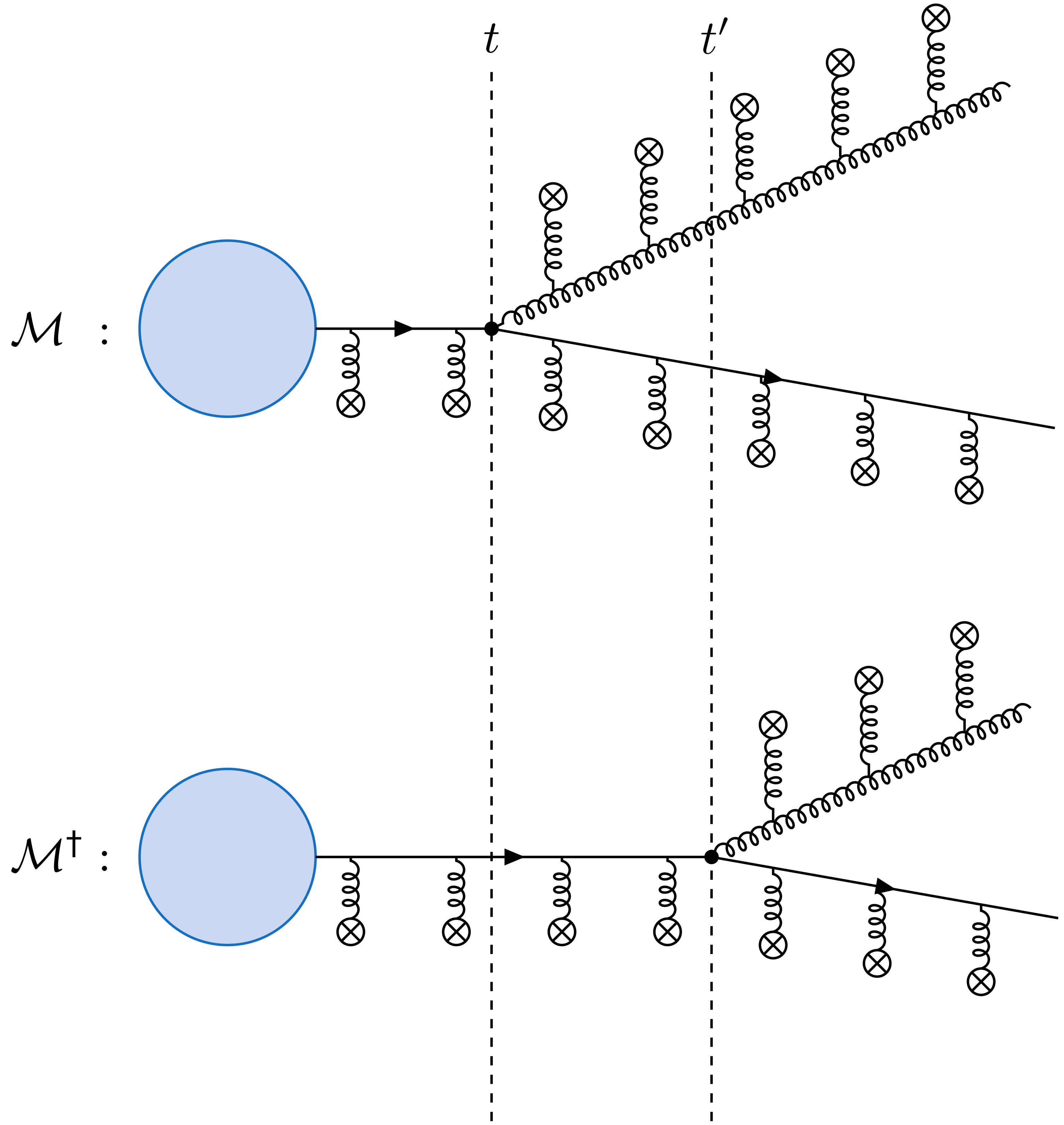
The building blocks

Next, consider the parton cascade

Medium-modified gluon emission

[On-going work...]

Three distinct regions for $|\mathcal{M}|^2$:



Medium-modified gluon emission

[On-going work...]

- **The gluon emission spectrum:**

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega \mathrm{d}^2\boldsymbol{k}} = \frac{\alpha_s C_F}{(2\pi)^2\omega^2} \, 2\mathrm{Re} \int_0^\infty \mathrm{d}t' \int_0^{t'} \mathrm{d}t \int_{\boldsymbol{q},\boldsymbol{p}} \boldsymbol{p} \cdot \boldsymbol{q} \, \mathcal{K}(t', \boldsymbol{q}; t, \boldsymbol{p}) \, \mathcal{P}(\infty, \boldsymbol{k}; t', \boldsymbol{q})$$

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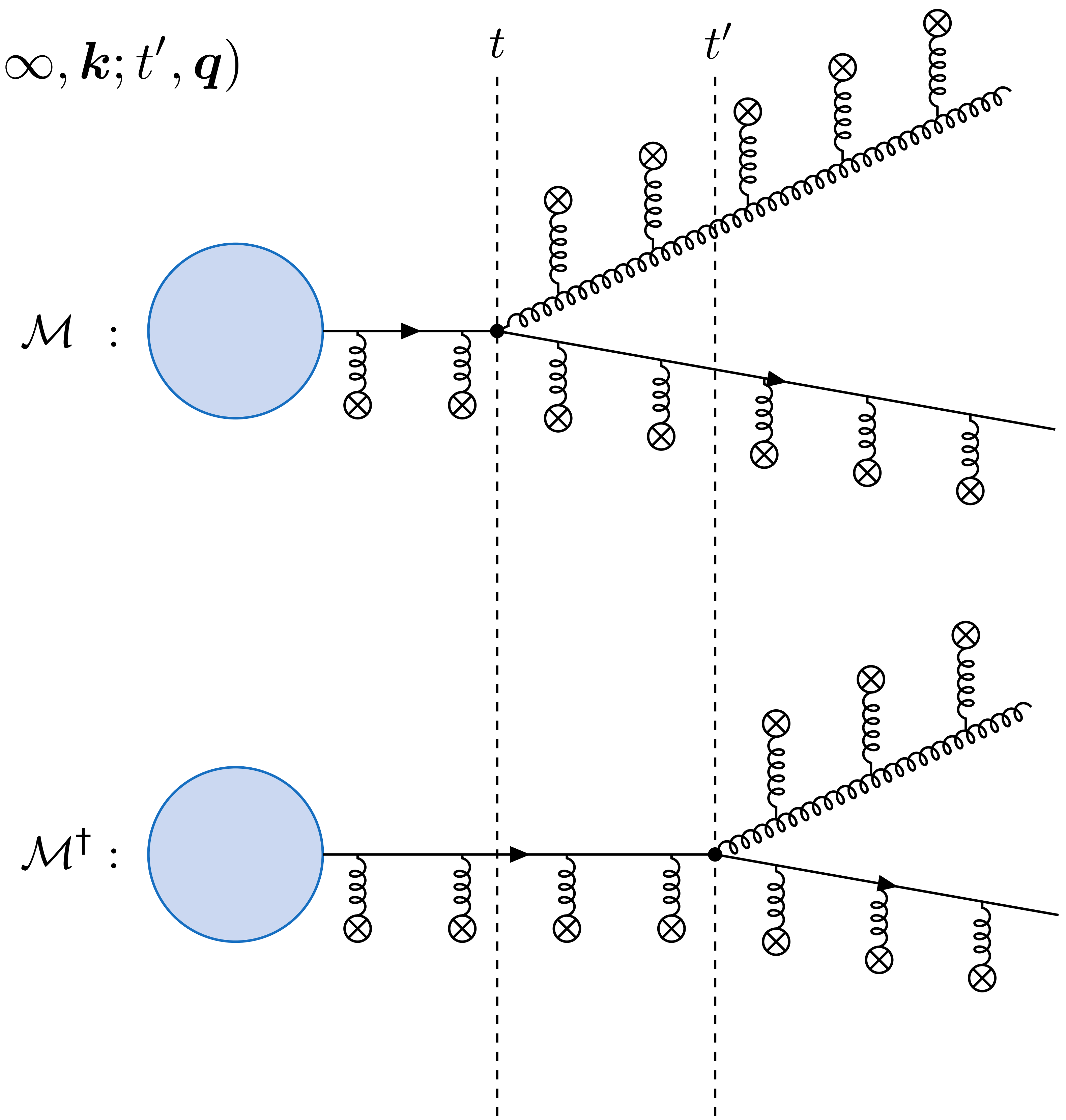

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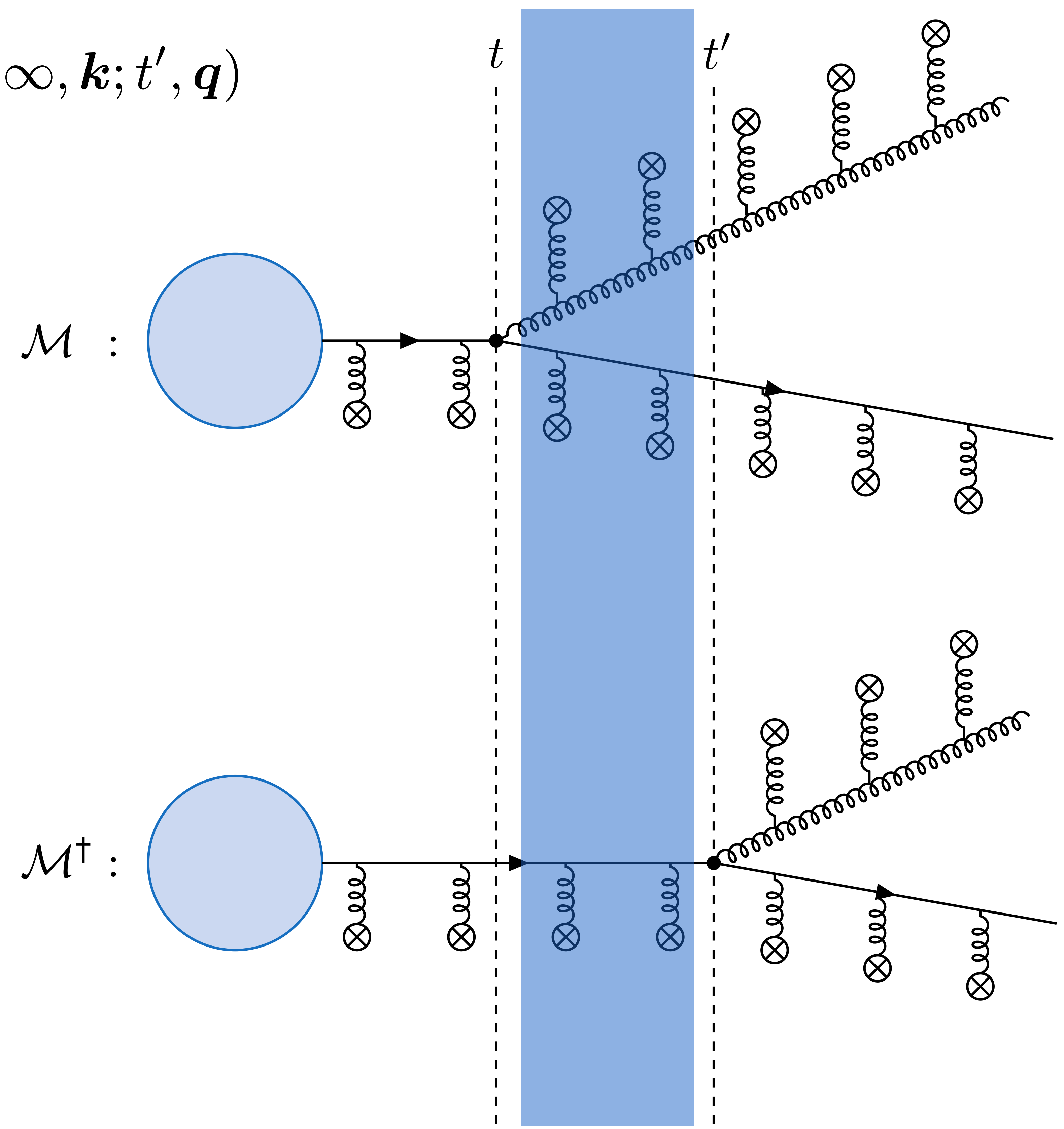

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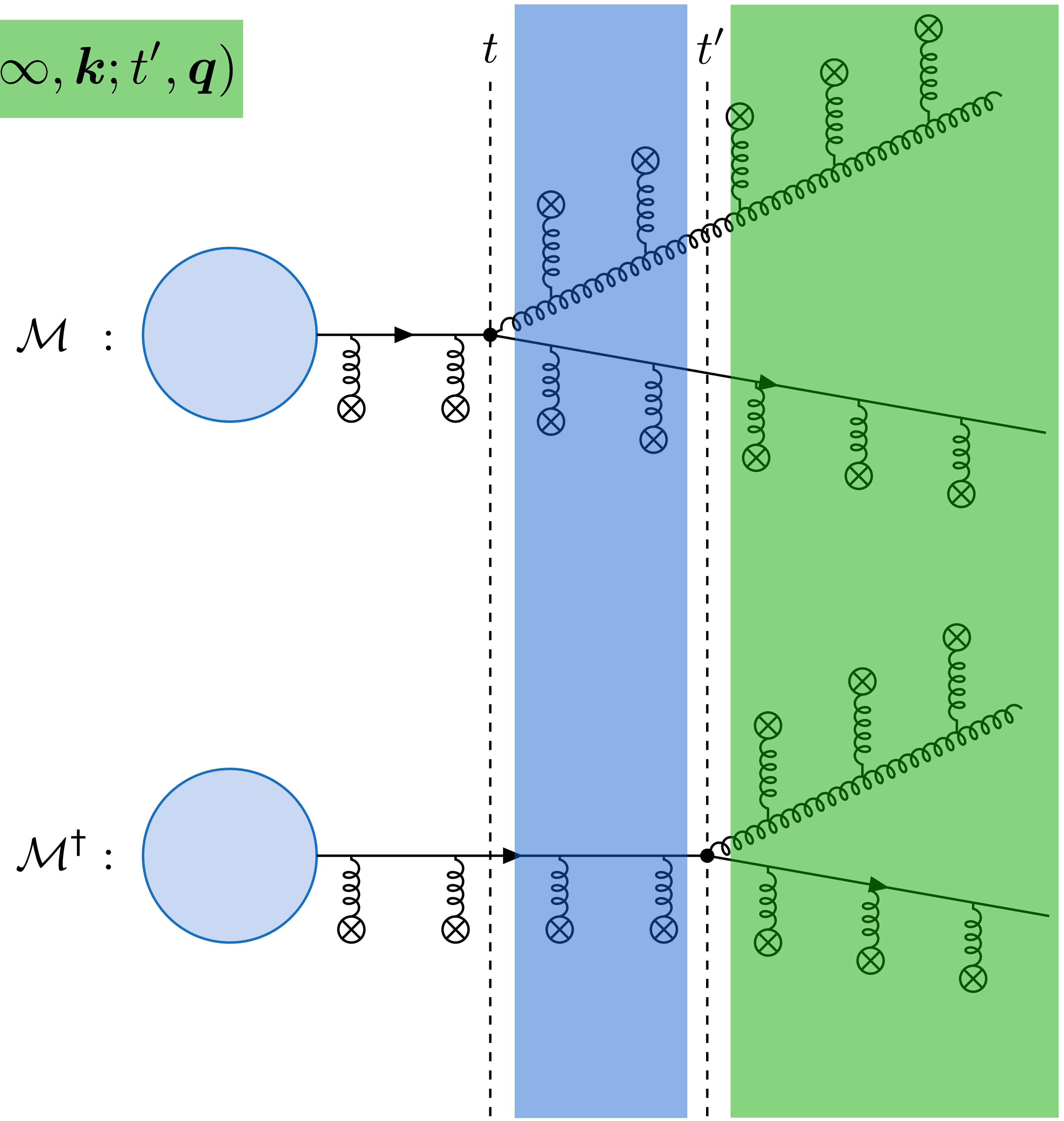

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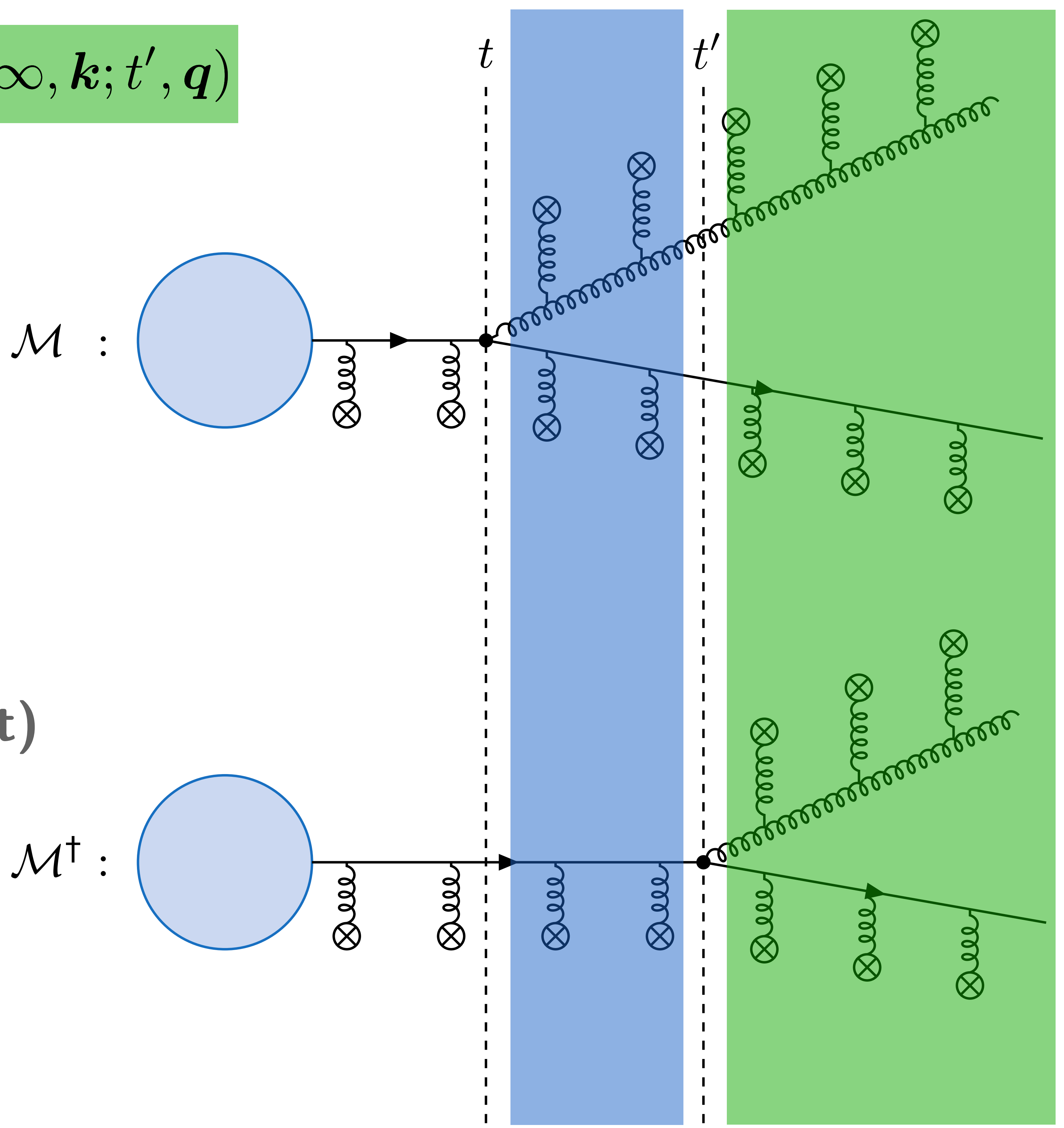

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Lifting these restrictions is a crucial step in improving our theoretical description of in-medium cascades

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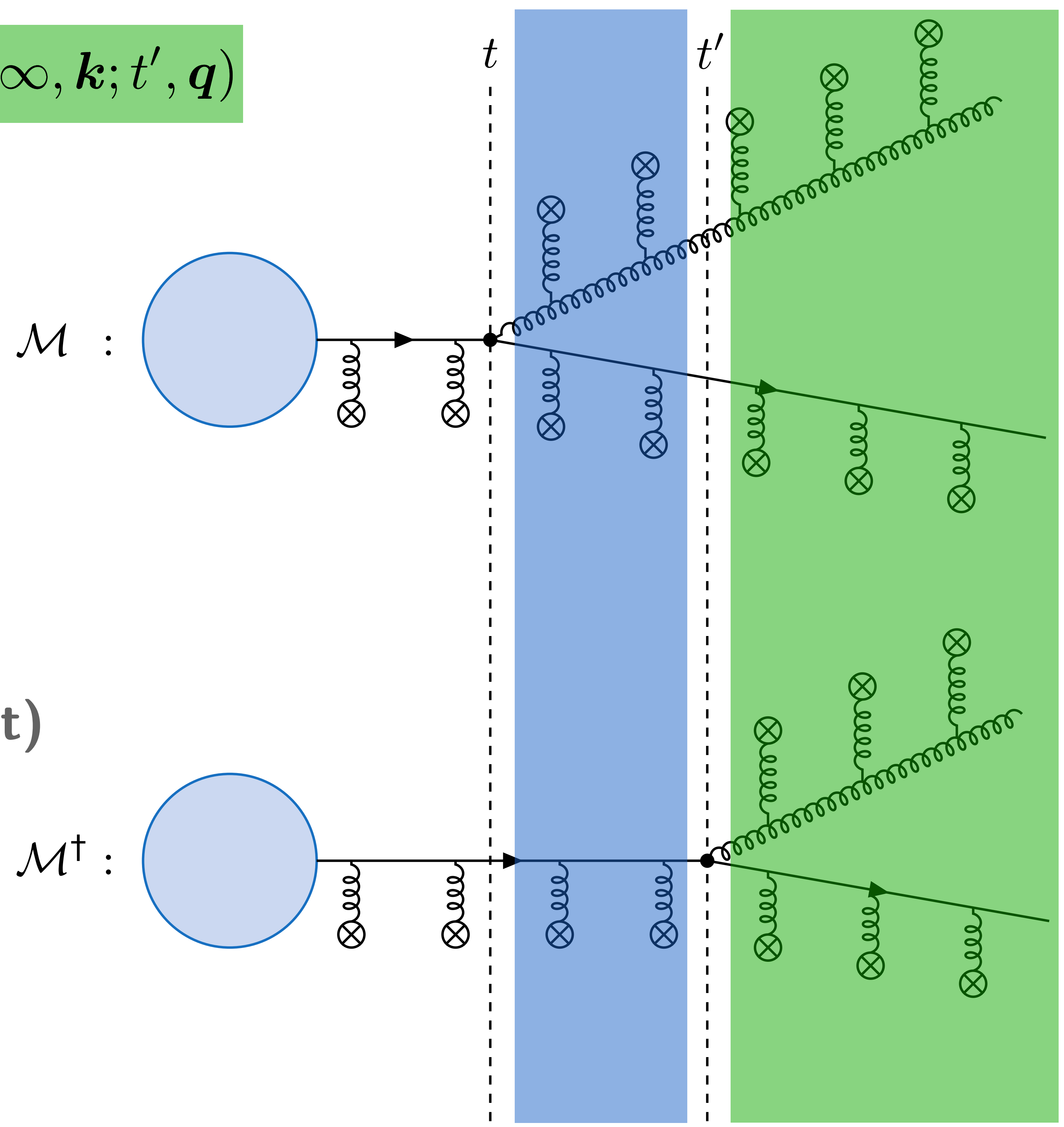

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- By carefully clustering jets, we can estimate their formation times!
    - This is a <u>quenching classifier</u> - an important step towards QGP tomography!

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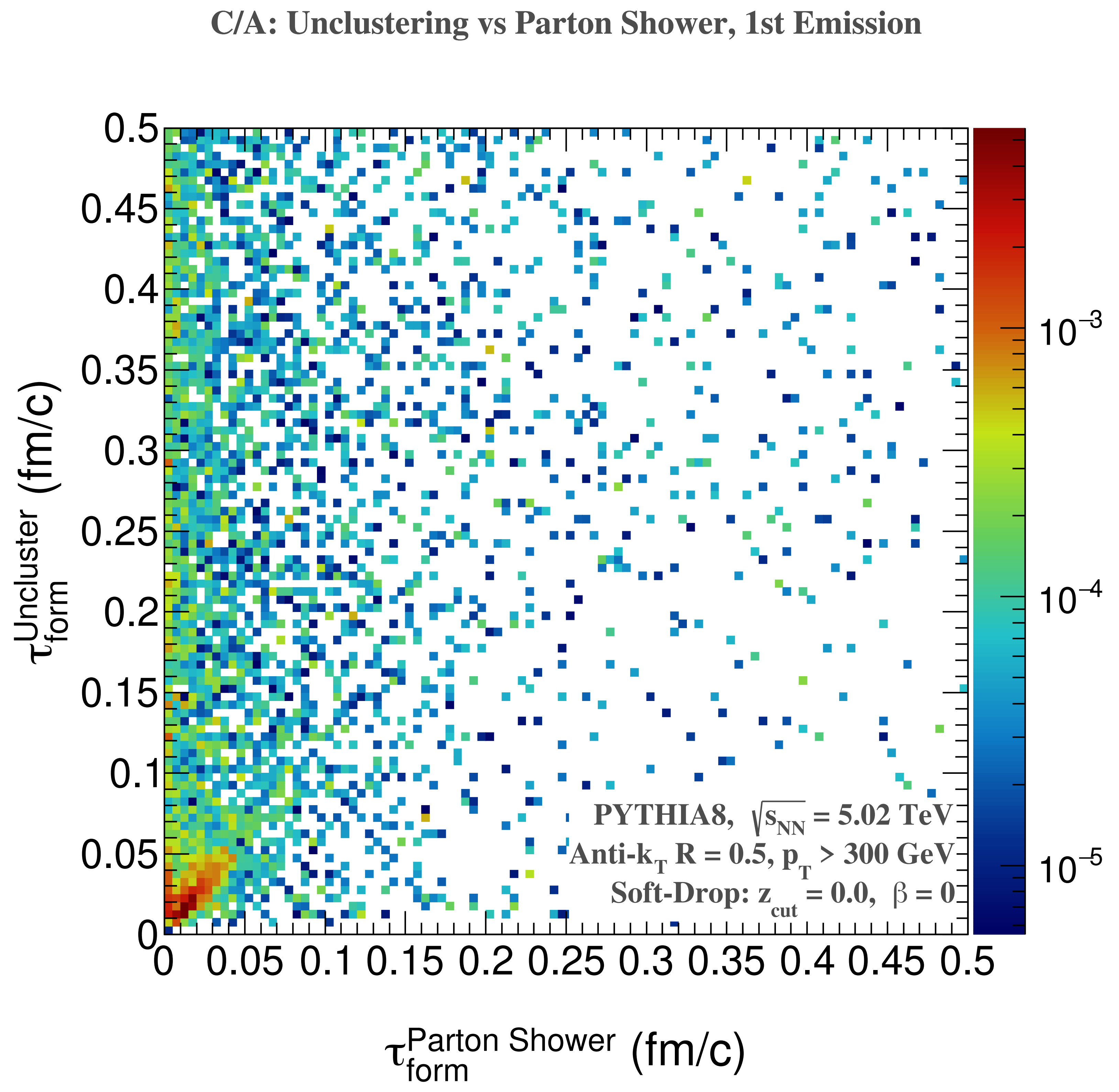
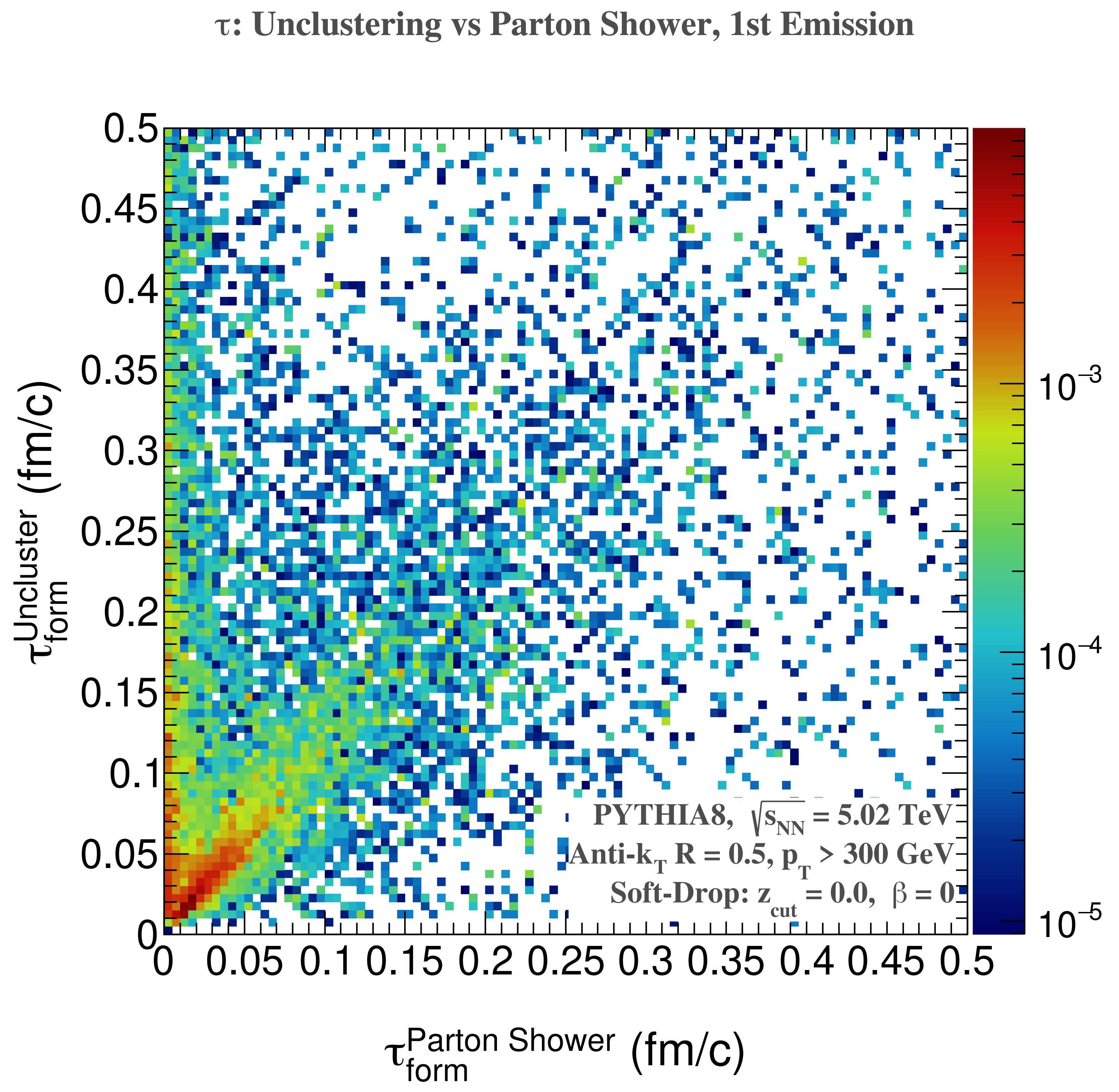
- The theoretical description of in-medium parton cascades must be extended:
    - To time-dependent media.
    - Beyond the soft limit.

Thank you!

Jet-Shower Correlation

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]



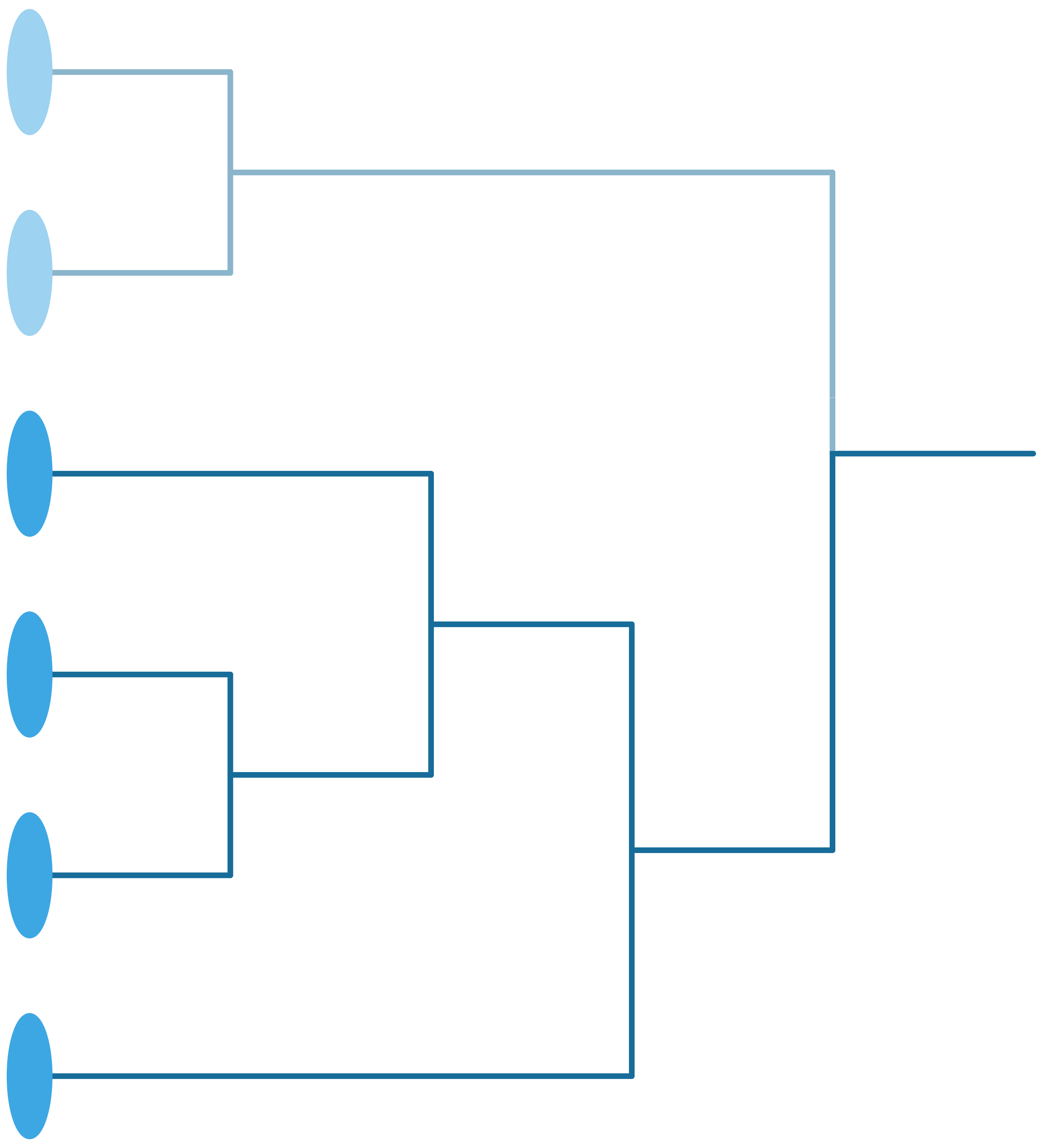


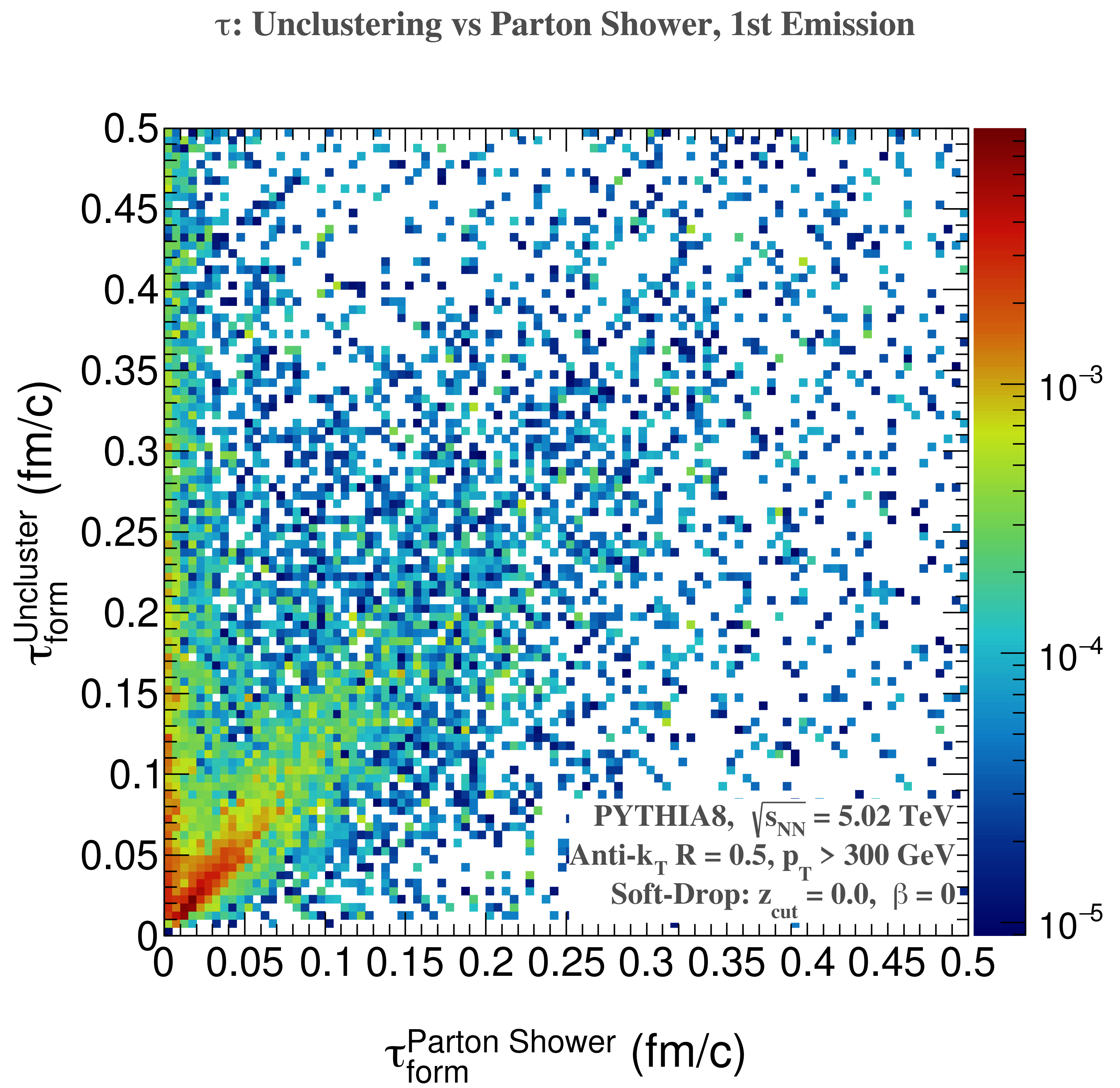
Diagonal: True Correlation

Vertical Band: Emissions outside jet cone

Jet-Shower Correlation

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]



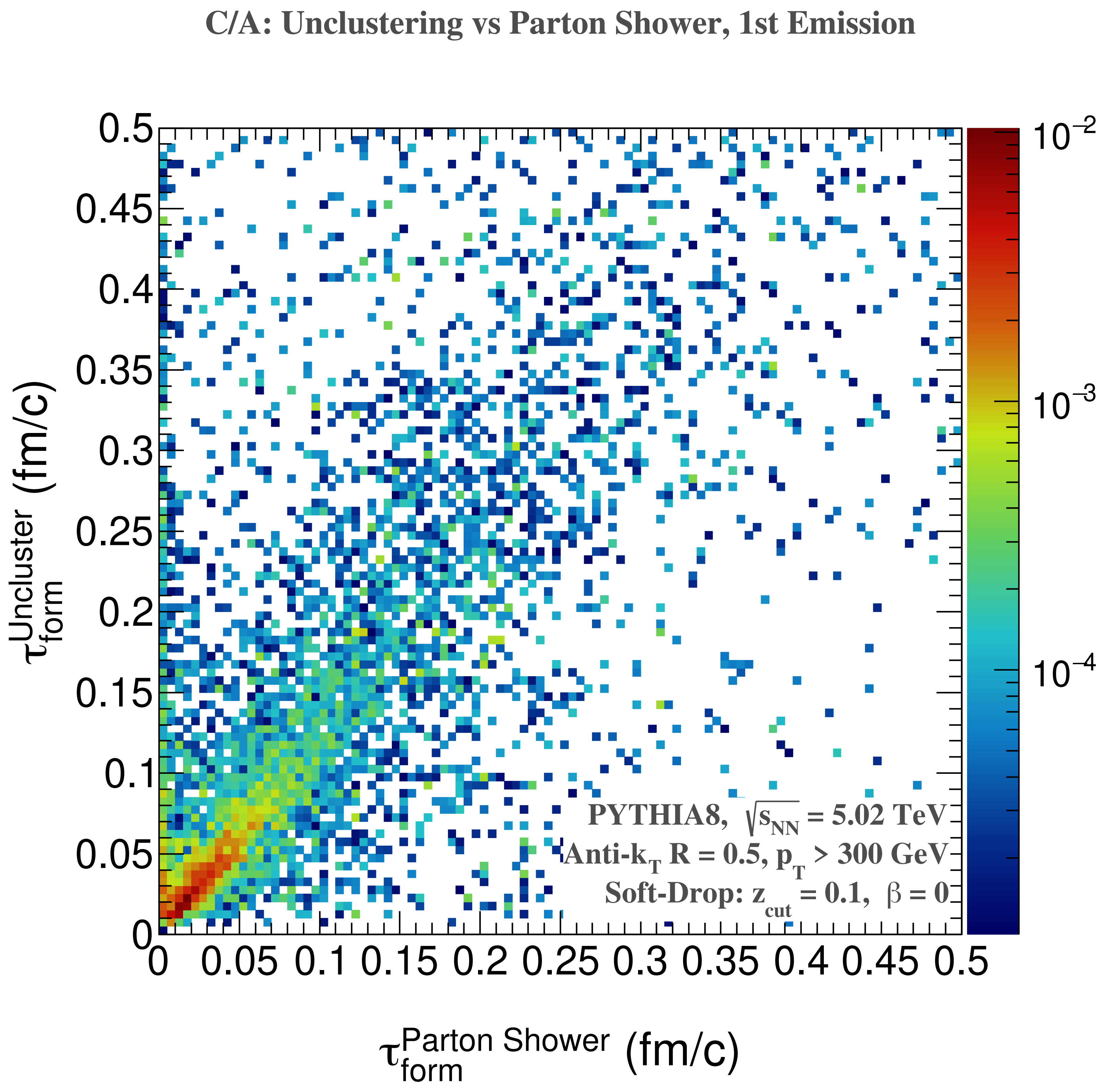


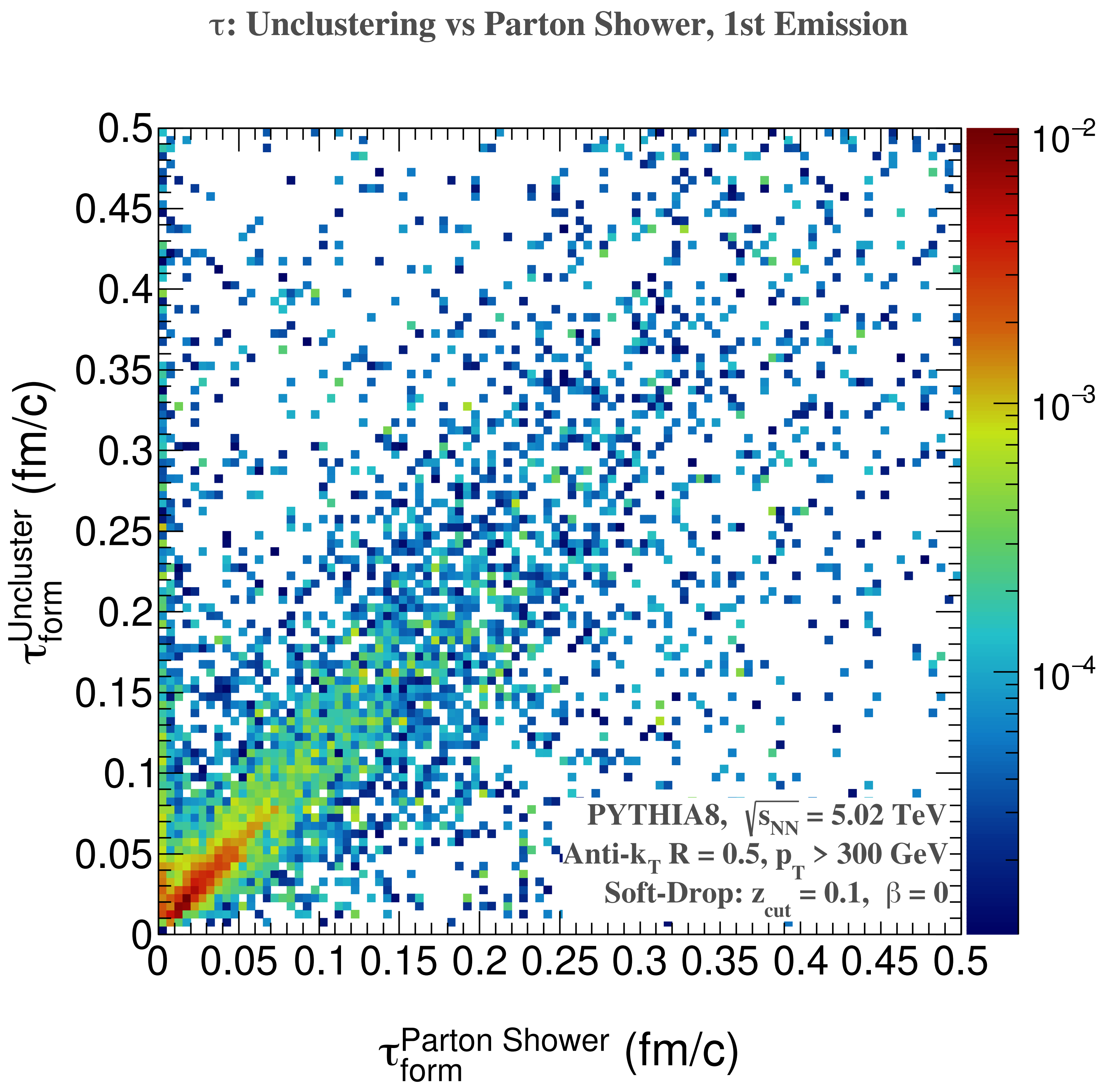
SoftDrop **grooming**: Keep only those splittings with

$$z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\mathrm{cut}} = 0.1$$

Jet-Shower Correlation - Groomed jets

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]





Jet grooming improves the correlation considerably!

τ algorithm: Estimating τ_{form}

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]

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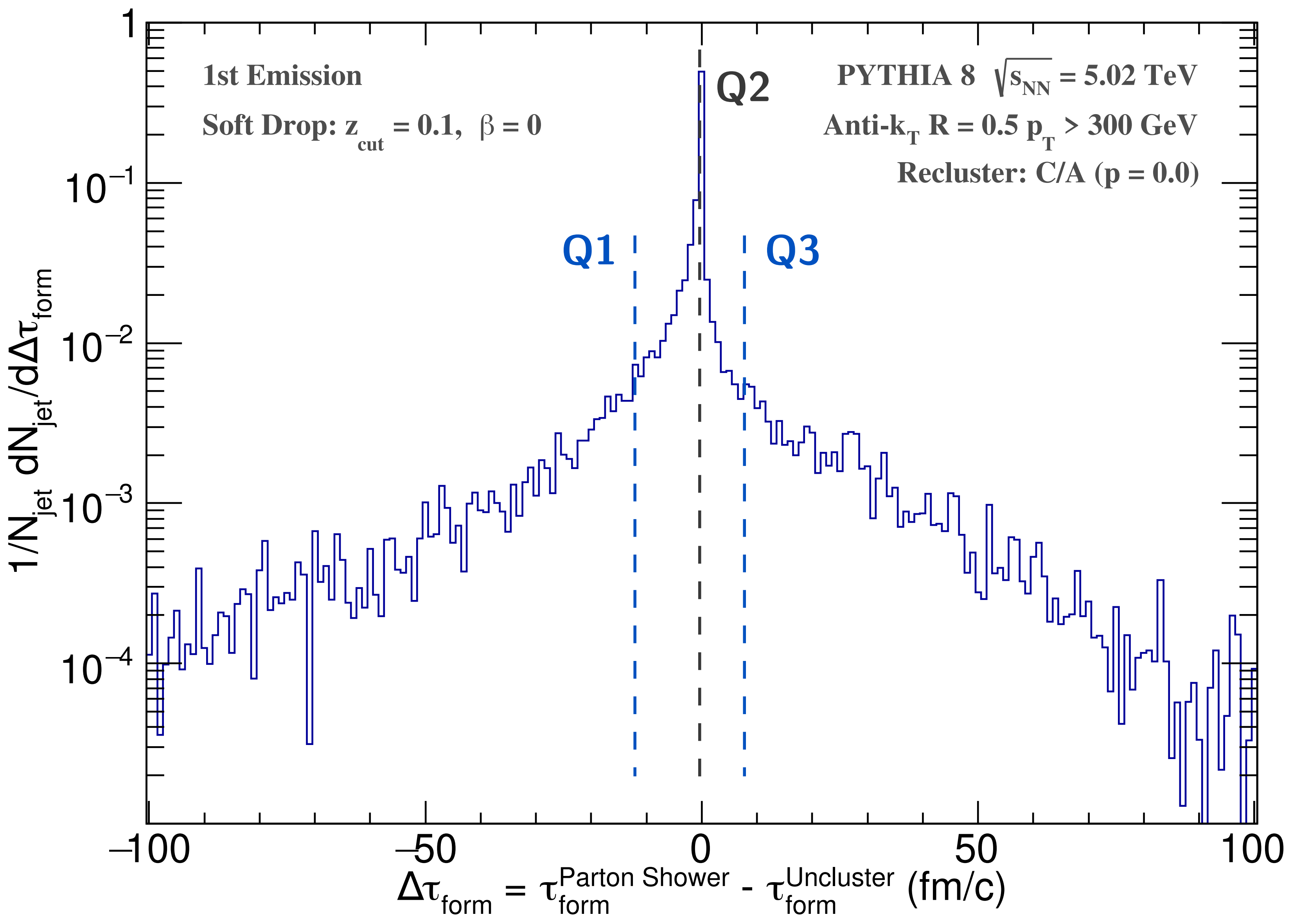

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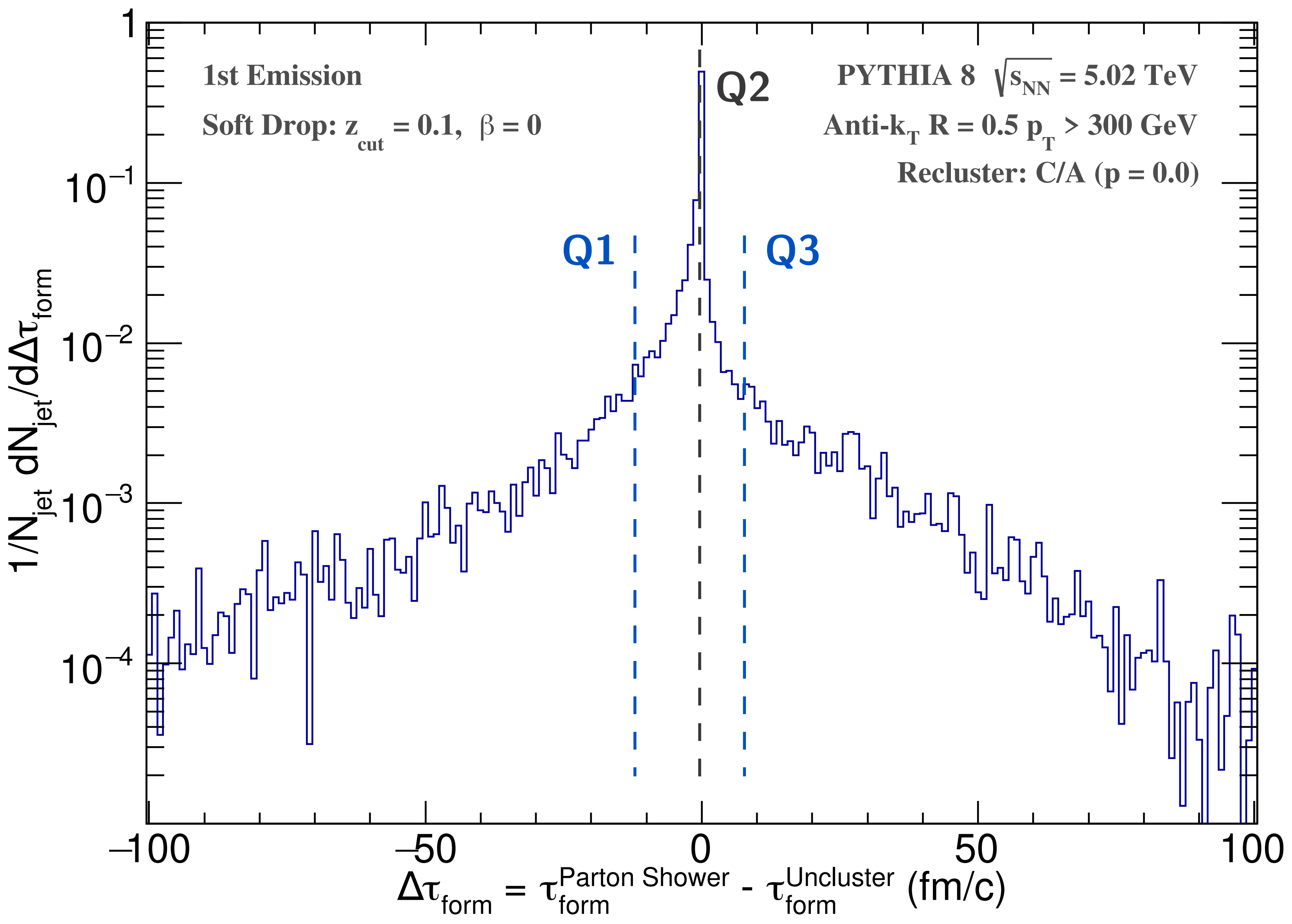

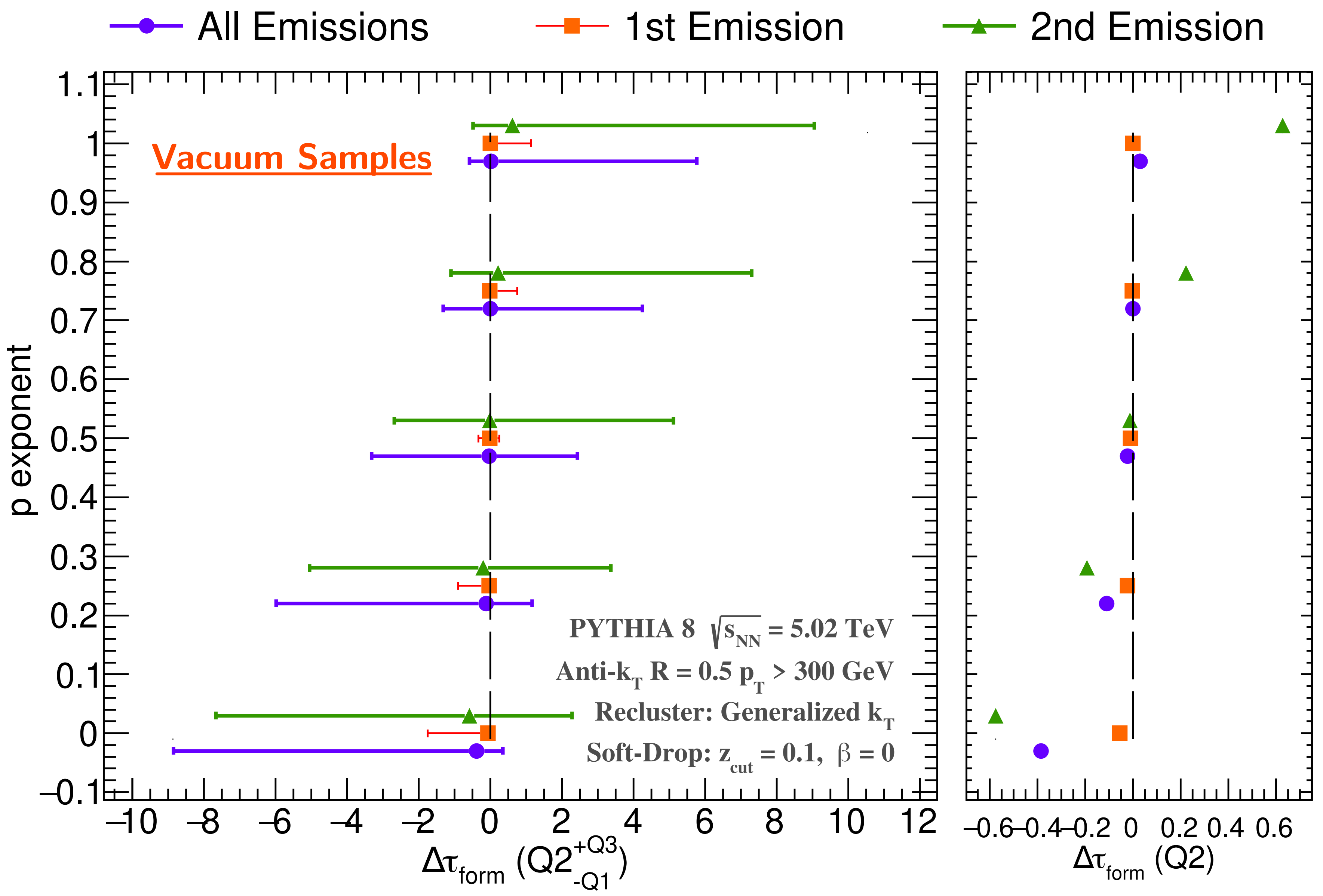

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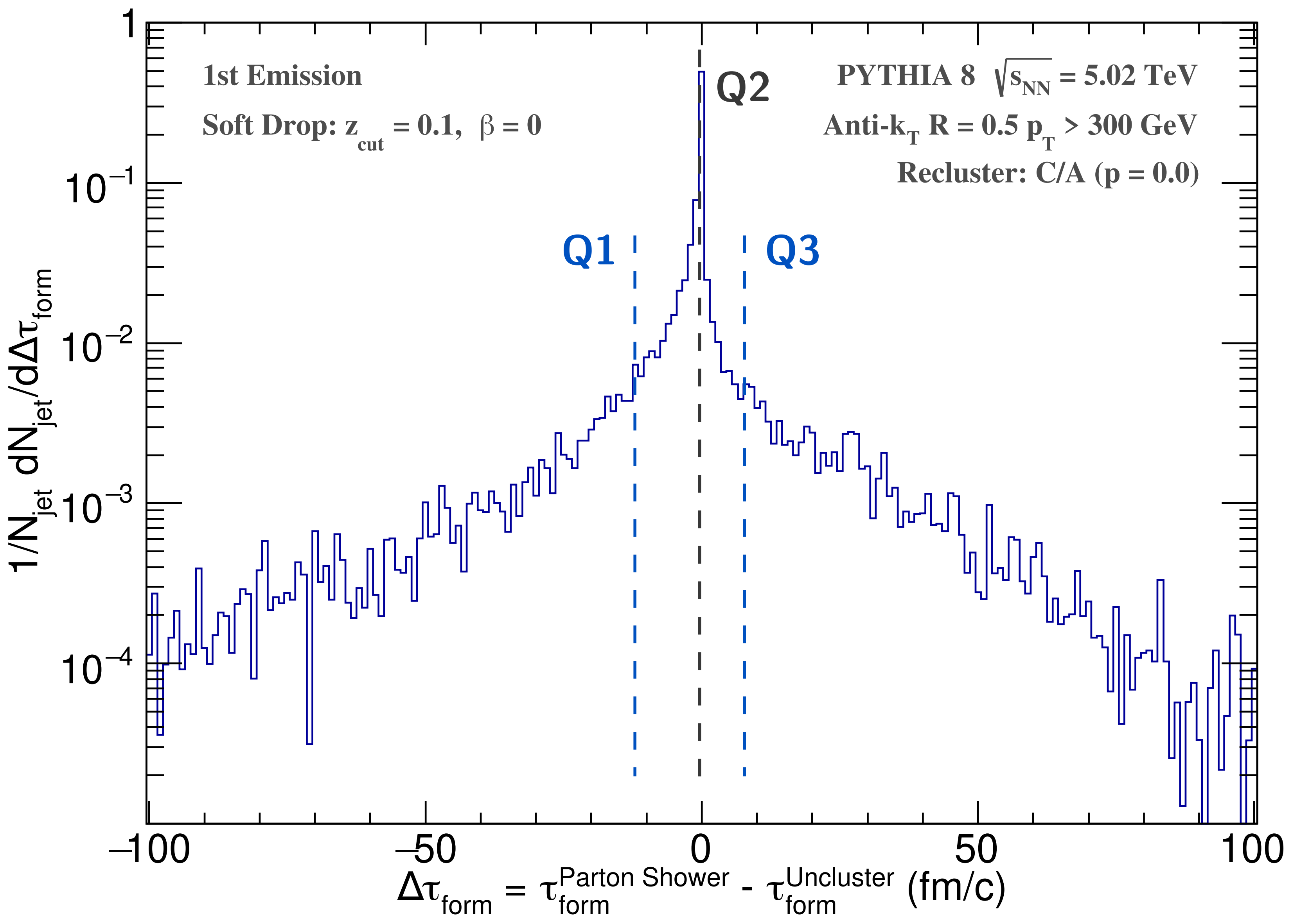
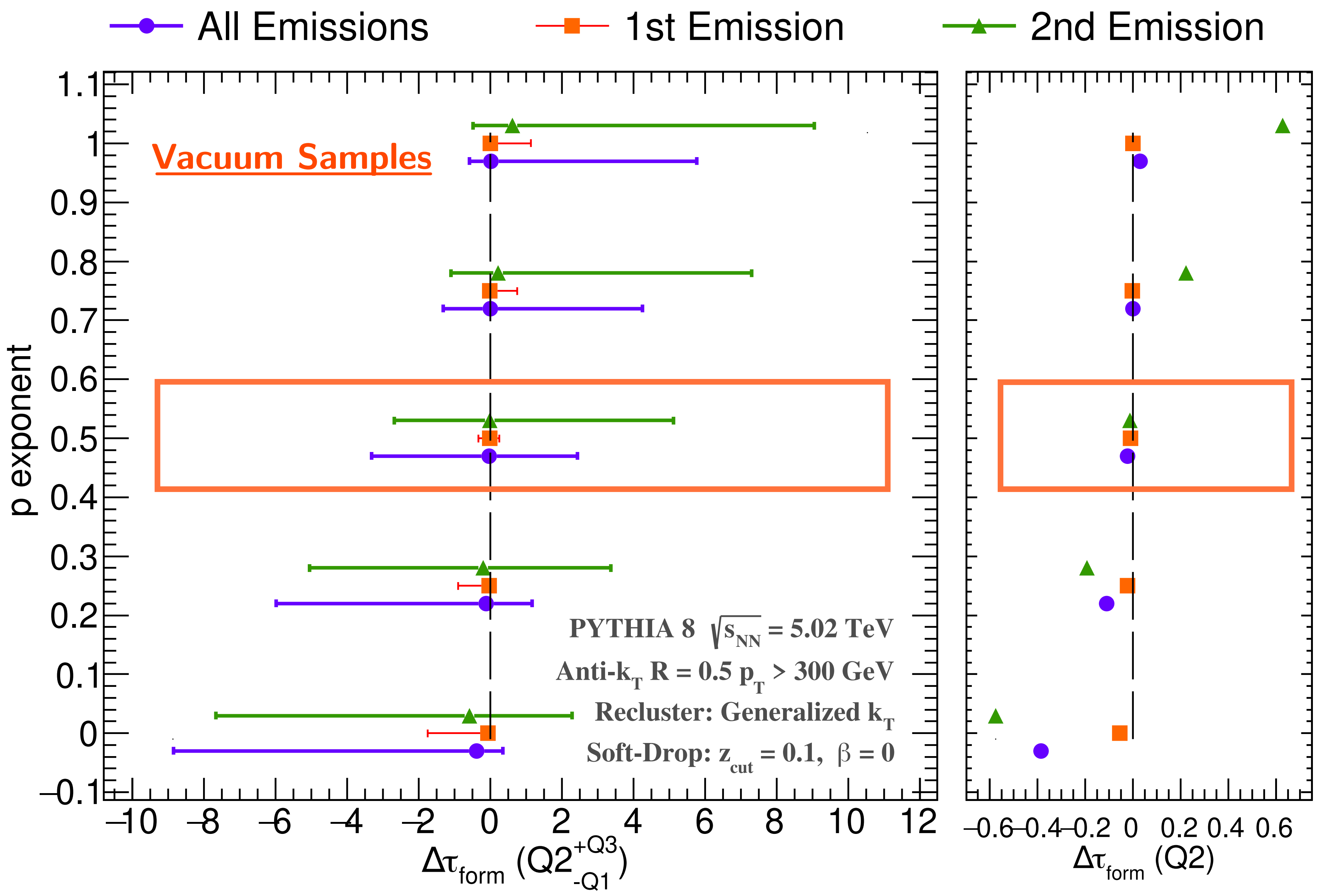
- **Correlation between parton shower and unclustering:** $\Delta\tau_{\text{form}} = \tau_{\text{form}}^{\text{Parton Shower}} - \tau_{\text{form}}^{\text{Unclustering}}$



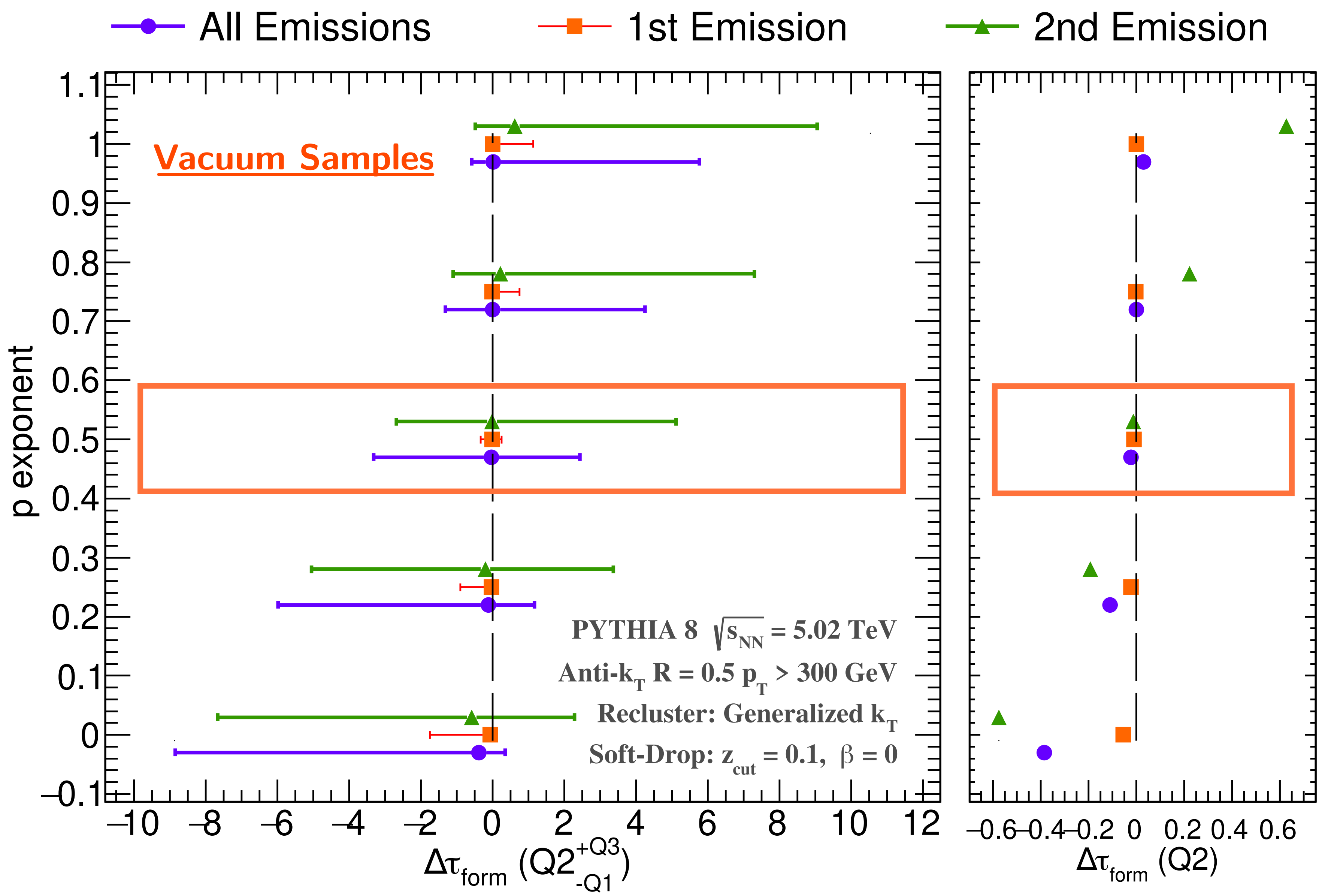


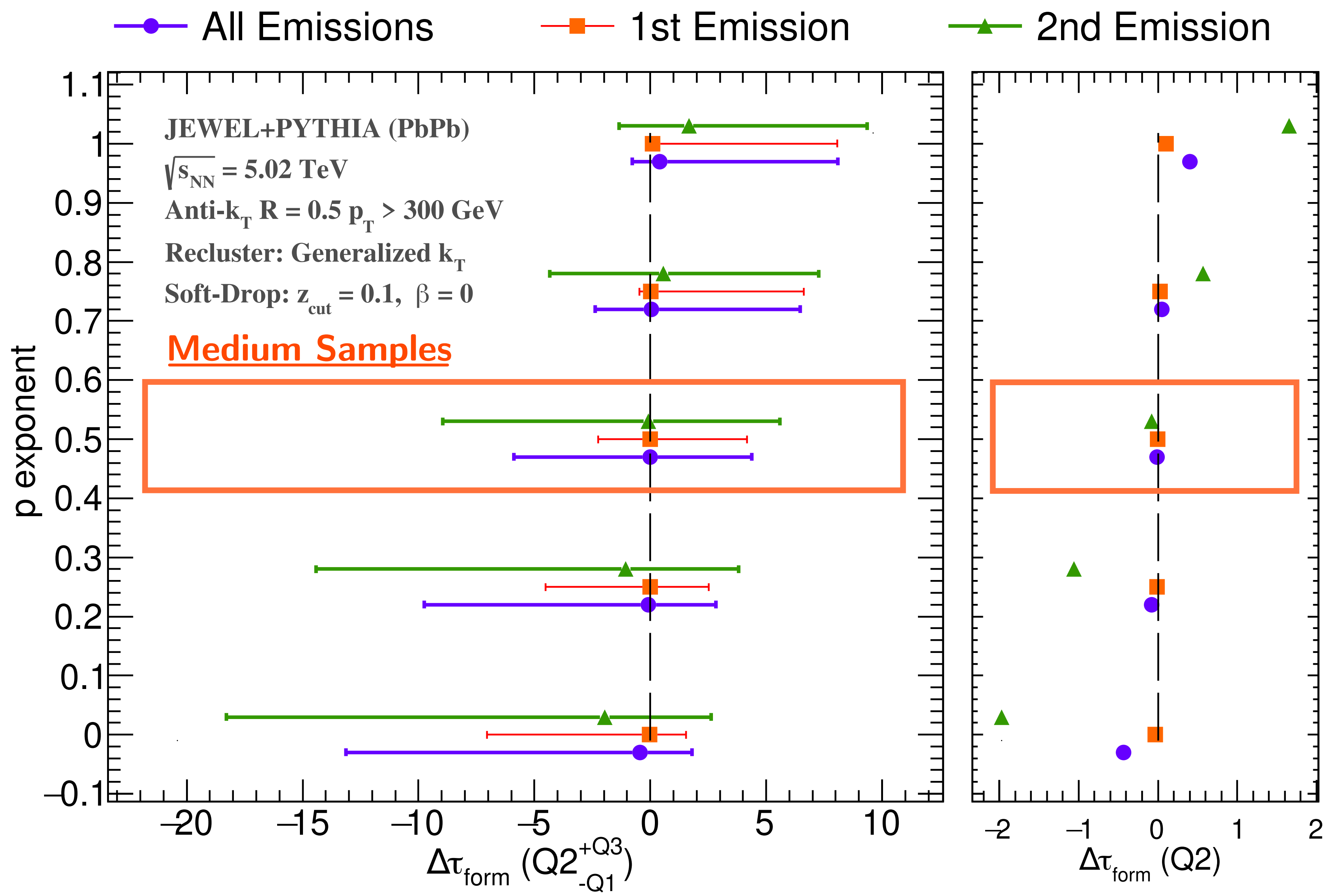
Characterise it by the median and quartiles

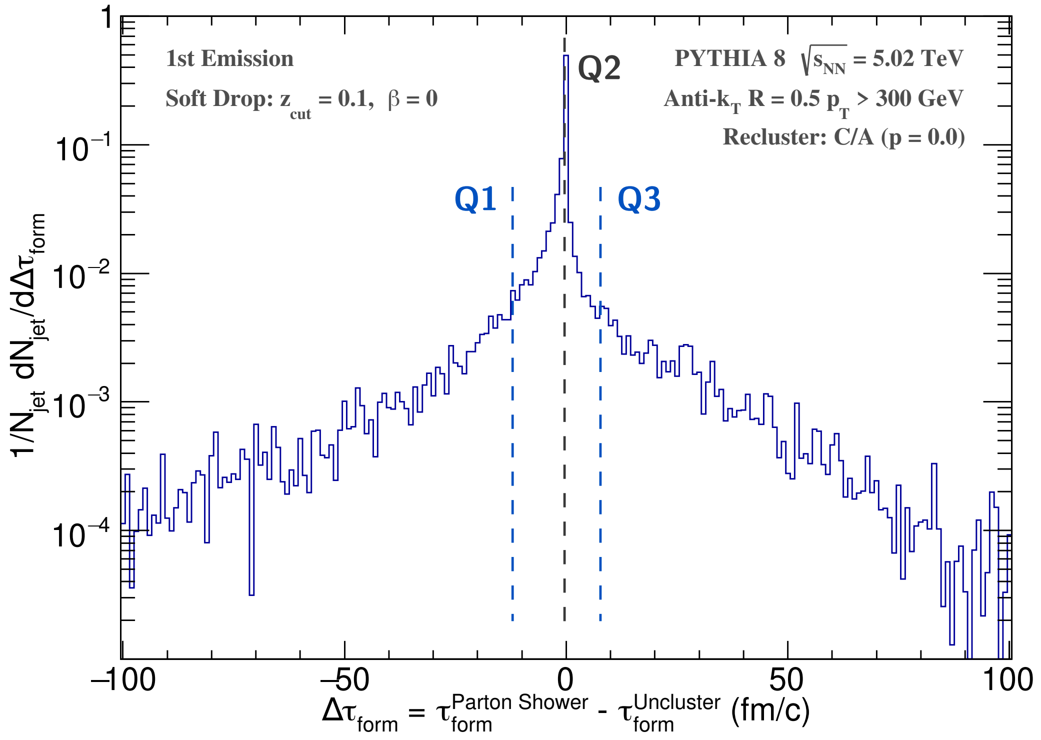
An unbiased estimator of formation time!

$\Delta\tau_{form}$: Vacuum vs Medium samples

[Apolinário, Cordeiro, Zapp :: EPJC 81, 561 (2021)]







$$\Delta\tau_{\text{form}} = \tau_{\text{form}}^{\text{Parton Shower}} - \tau_{\text{form}}^{\text{Unclustering}}$$

p=0.5 yields the most centred, symmetric distributions.

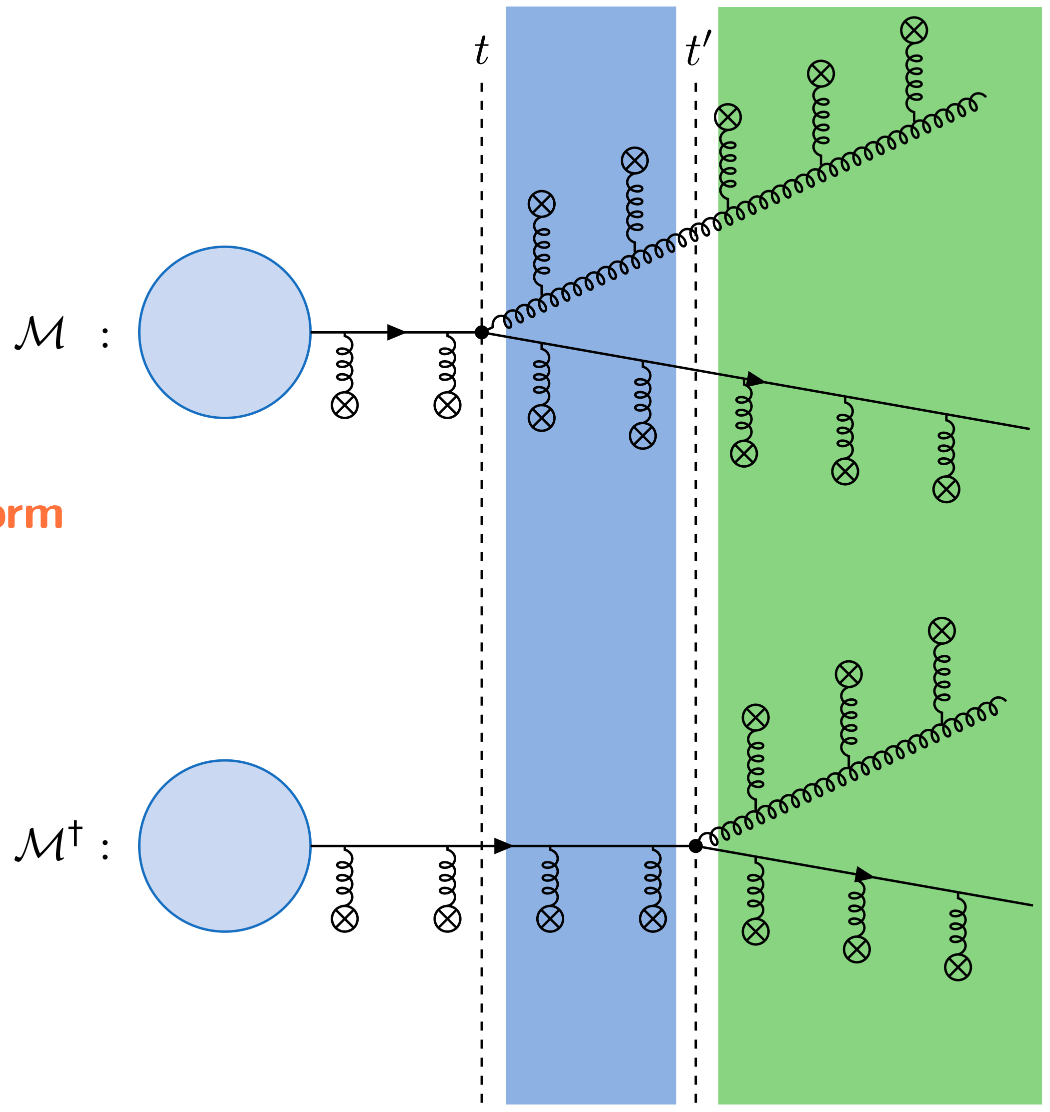
The τ algorithm provides an unbiased estimator of the jet formation time

Dyson-Schwinger equations

[Andrés, Apolinário, Dominguez :: JHEP 2020, 114 (2020)]
[On-going work...]

Emission Kernel Broadening Factor

$$\omega \frac{dI}{d\omega d^2\boldsymbol{k}} = \frac{\alpha_s C_F}{(2\pi)^2\omega^2} 2\mathrm{Re}\int_0^\infty dt' \int_0^{t'} dt \int_{\boldsymbol{q},\boldsymbol{p}} \boldsymbol{p}\cdot\boldsymbol{q}\, \mathcal{K}(t',\boldsymbol{q};t,\boldsymbol{p})\, \mathcal{P}(\infty,\boldsymbol{k};t',\boldsymbol{q})$$



- **Emission kernel**

Path integral (complicates numerical treatment)

Scattering potential, complicated functional form

$$\mathcal{K}(t',\boldsymbol{q};t,\boldsymbol{p}) = \int_{\boldsymbol{x},\boldsymbol{y}} e^{-i(\boldsymbol{y}\cdot\boldsymbol{q}-\boldsymbol{x}\cdot\boldsymbol{p})} \int_{\boldsymbol{r}(t)=\boldsymbol{x}}^{\boldsymbol{r}(t')=\boldsymbol{y}} \mathcal{D}\boldsymbol{r}(t) \exp\left\{\int_t^{t'} ds \left(\frac{i\omega}{2}\dot{\boldsymbol{r}}^2 - \frac{1}{2}n(s)\sigma(\boldsymbol{r})\right)\right\}$$

- **Broadening factor**

$$\mathcal{P}(t'',\boldsymbol{k};t,\boldsymbol{q}) = \int_{\boldsymbol{z}} e^{-i\boldsymbol{z}\cdot(\boldsymbol{q}-\boldsymbol{p})} \exp\left\{-\frac{1}{2}\int_{t'}^{t''} ds\, n(s)\sigma(\boldsymbol{r})\right\}$$

The collision rate (Coulomb-like at large q)

$$\sigma(\boldsymbol{r}) = \int_{\boldsymbol{q}} V(\boldsymbol{q})\left(1-e^{i\boldsymbol{q}\cdot\boldsymbol{r}}\right)$$

- **Evaluation can be simplified by using Dyson-Schwinger type equations:**

$$\mathcal{K}(t',\boldsymbol{q};t,\boldsymbol{p}) = (2\pi)^2\delta^{(2)}(\boldsymbol{q}-\boldsymbol{p})e^{-i\frac{\boldsymbol{p}^2}{2\omega}(t'-t)} - \frac{1}{2}\int_t^{t'} ds\, n(s)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{q}-\boldsymbol{k}')e^{-i\frac{\boldsymbol{q}^2}{2\omega}(t'-s)}\mathcal{K}(s,\boldsymbol{k}';t,\boldsymbol{p})$$

$$\mathcal{P}(t'',\boldsymbol{k};t',\boldsymbol{q}) = (2\pi)^2\delta^{(2)}(\boldsymbol{k}-\boldsymbol{q}) - \frac{1}{2}\int_{t'}^{t''} ds\, n(s)\int_{\boldsymbol{k}'} \sigma(\boldsymbol{k}'-\boldsymbol{q})\mathcal{P}(t'',\boldsymbol{k};s,\boldsymbol{k}')$$

Can this be extended to time-dependent potentials, beyond the soft limit?