Transitioning from pQCD to npQCD within Jets

Raghav Kunnawalkam Elayavalli (they/them) [Vanderbilt]
Nuno Olavo and Liliana Apolinário [LIP]
Based on 2212.11846 and in-progress

Hard Probes @ Aschaffenburg Germany, March 28th 2023

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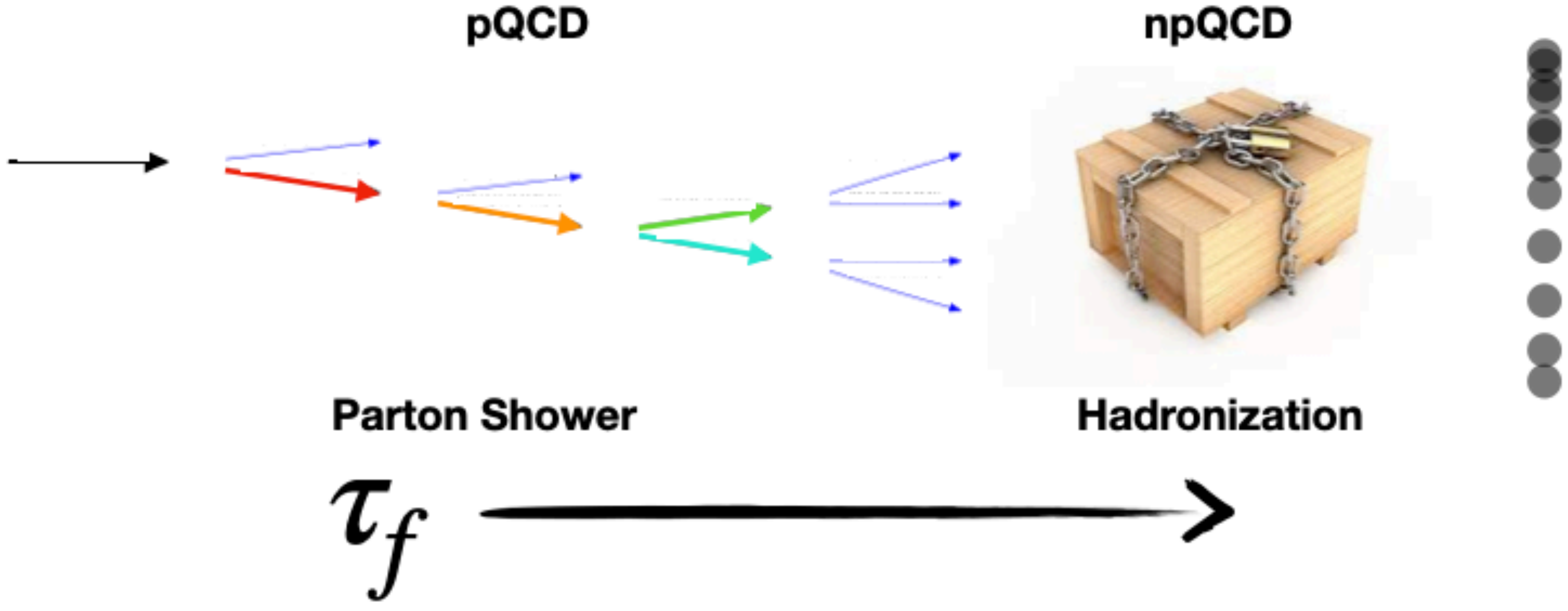
Motivation

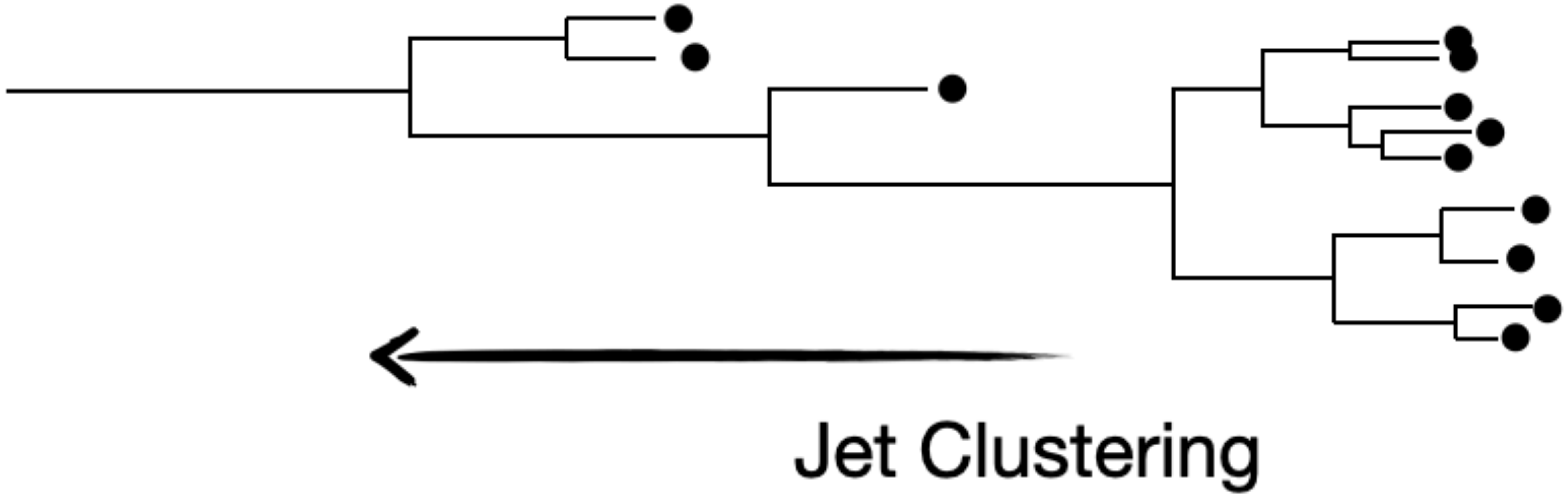
Splittings

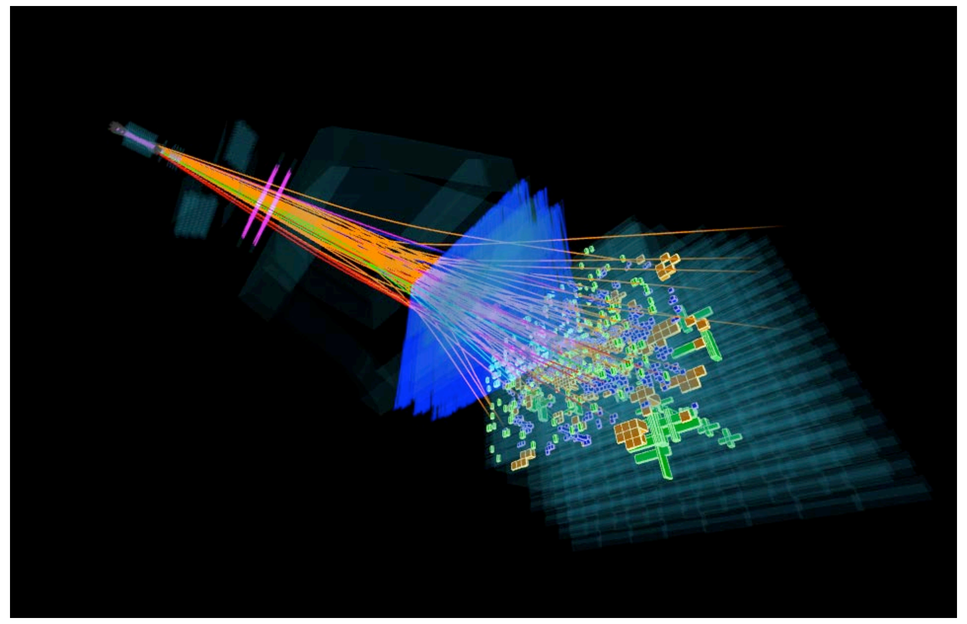
npQCD-ish

Conclusions

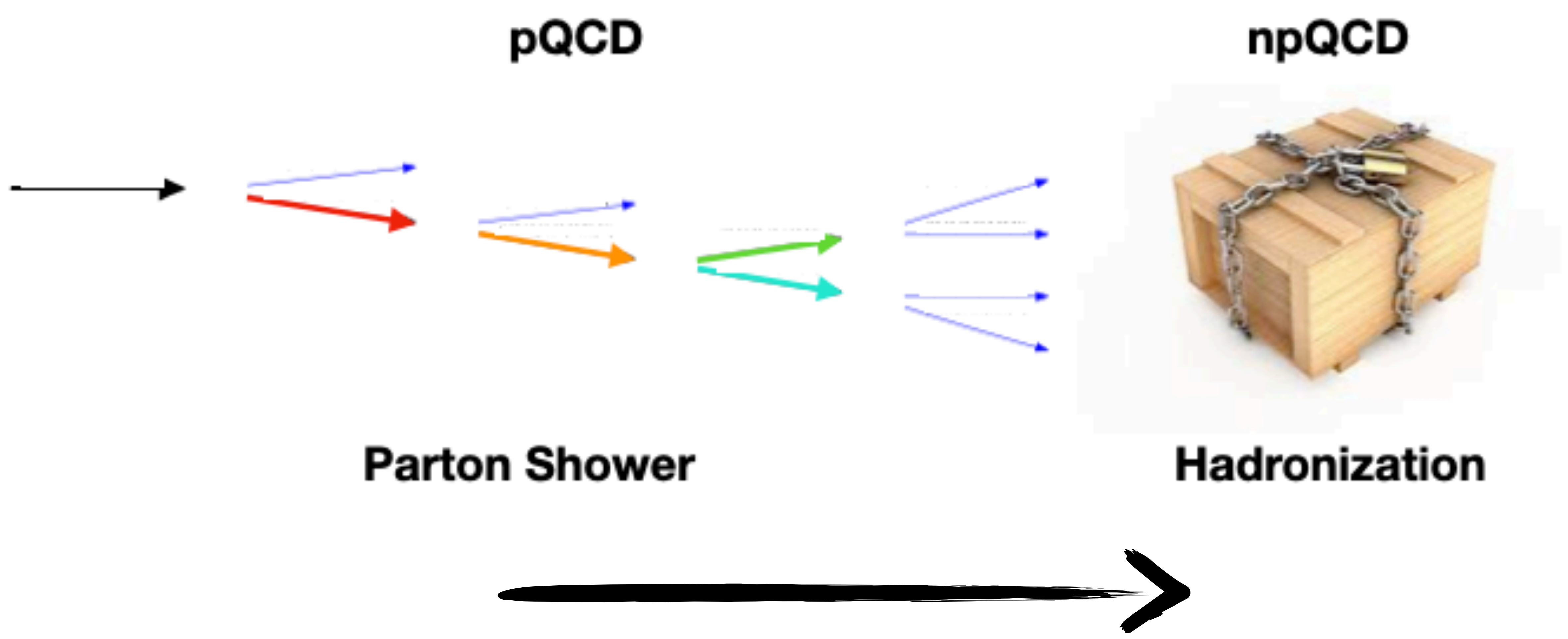
Conceptual picture of jets

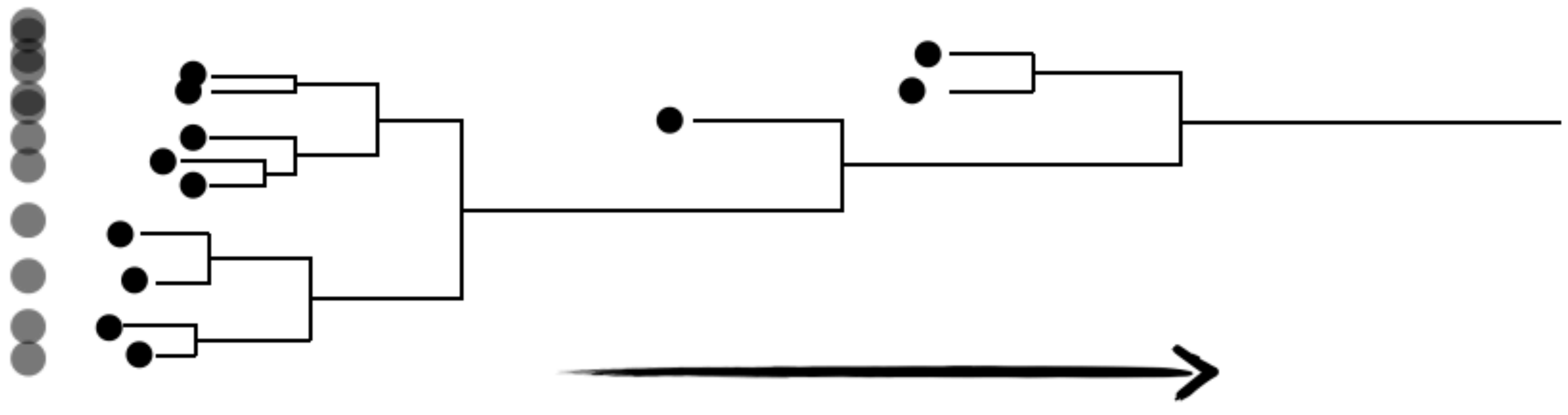






What do we want?





- Quantify the phenomenological structure of splittings or branchings within the jet clustering tree
- Identify a method by which we can quantify the transition from pQCD-like behavior to dominance of npQCD effects - O(1) effects from Alba Ontoso's plenary talk

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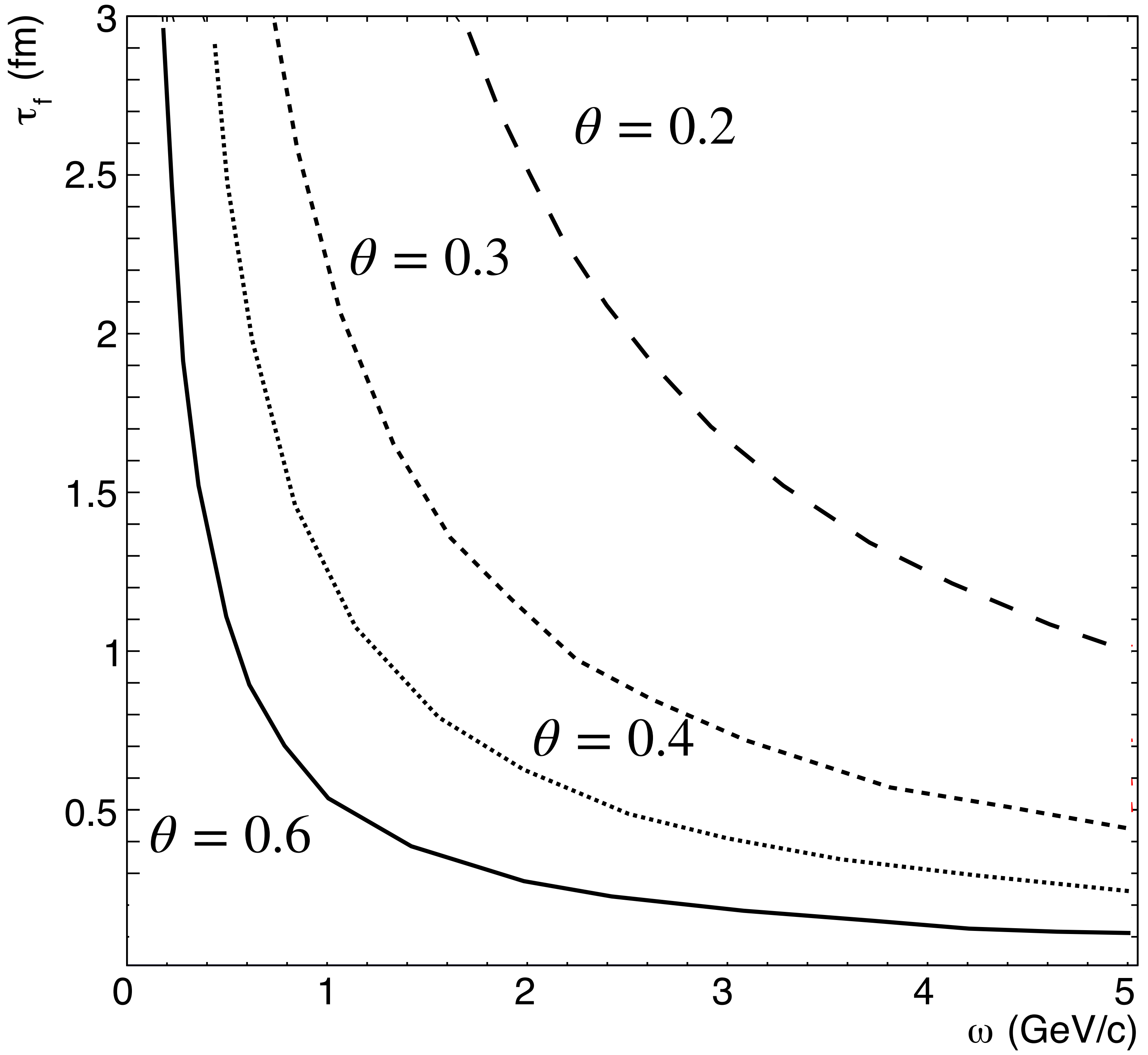
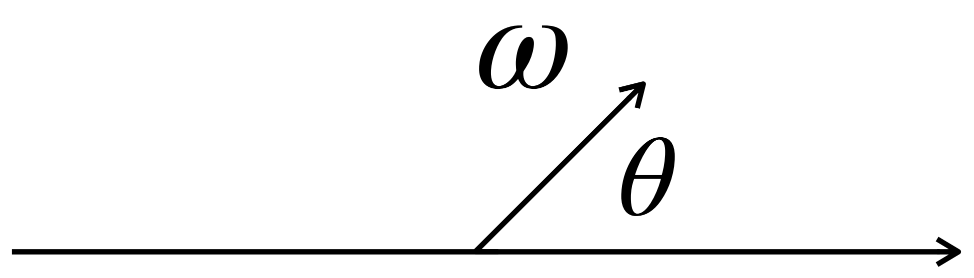
Splittings in theory

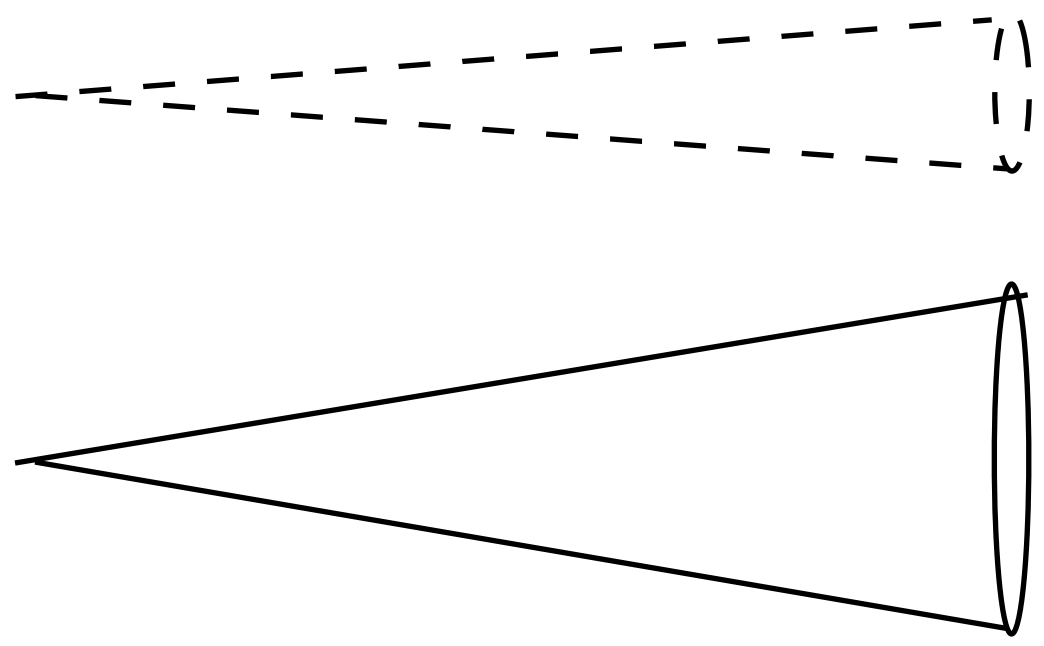


DGLAP Functions!



$$\tau_f^{vac} \cong \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega}$$

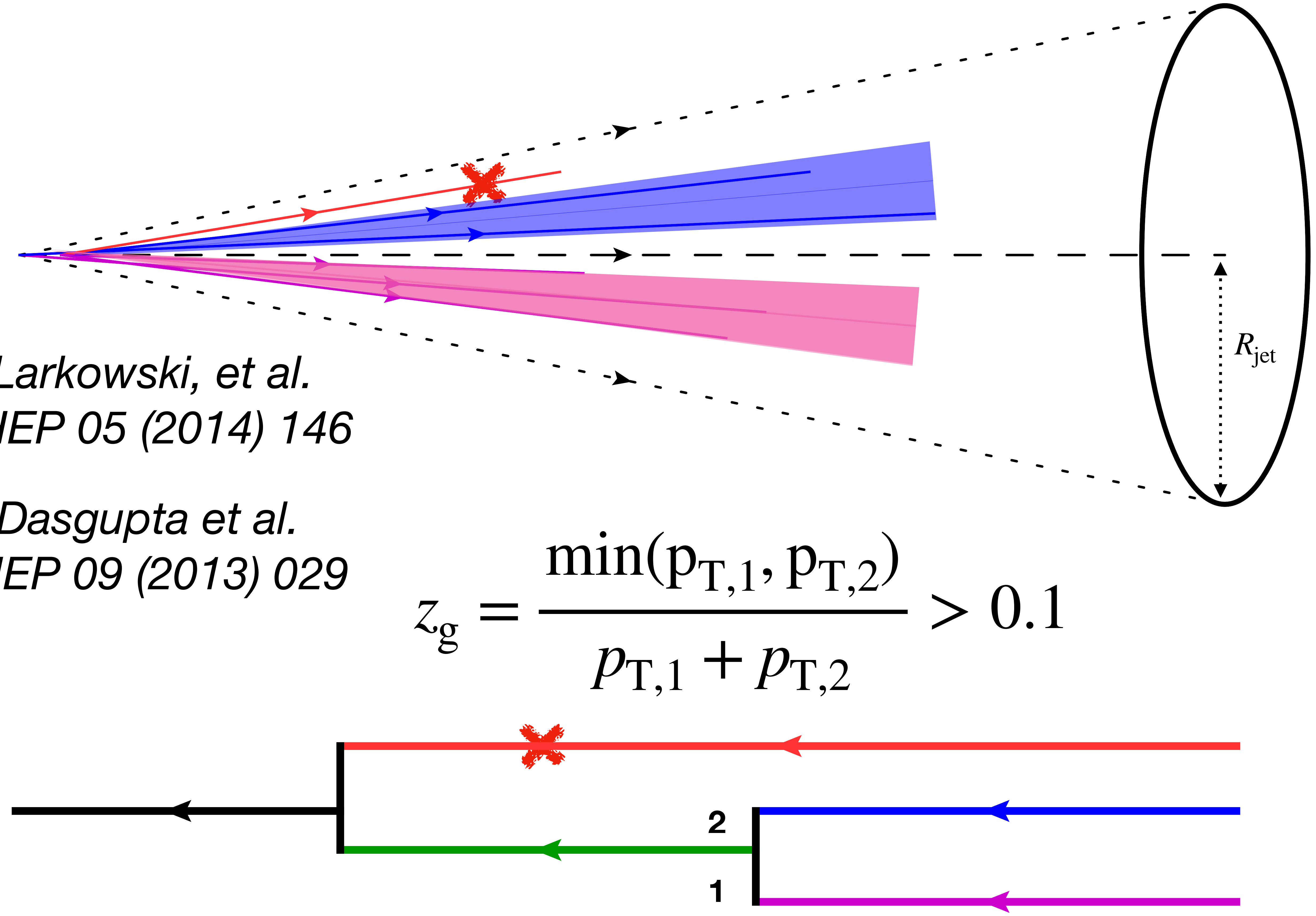
Narrow emission - late time



wide emission - early time

- Two fundamental scales involved in jet evolution - opening angle and energy
- Narrow emissions occur at later times
- Early time emissions correspond to wider angle
- At fixed emission energy - angle of emission determines the time scale!

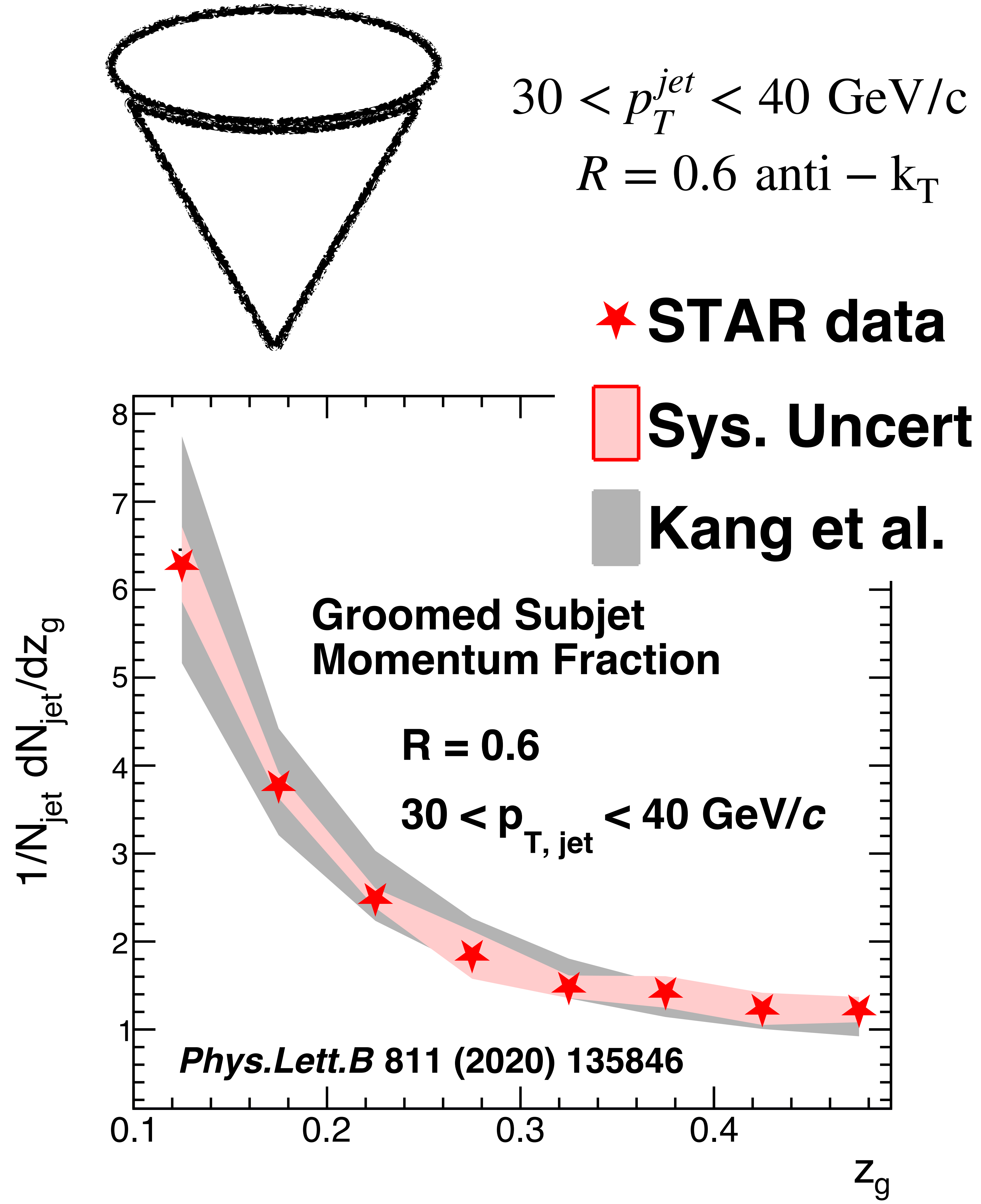
How do we know this is true?



Larkowski, et al.
JHEP 05 (2014) 146

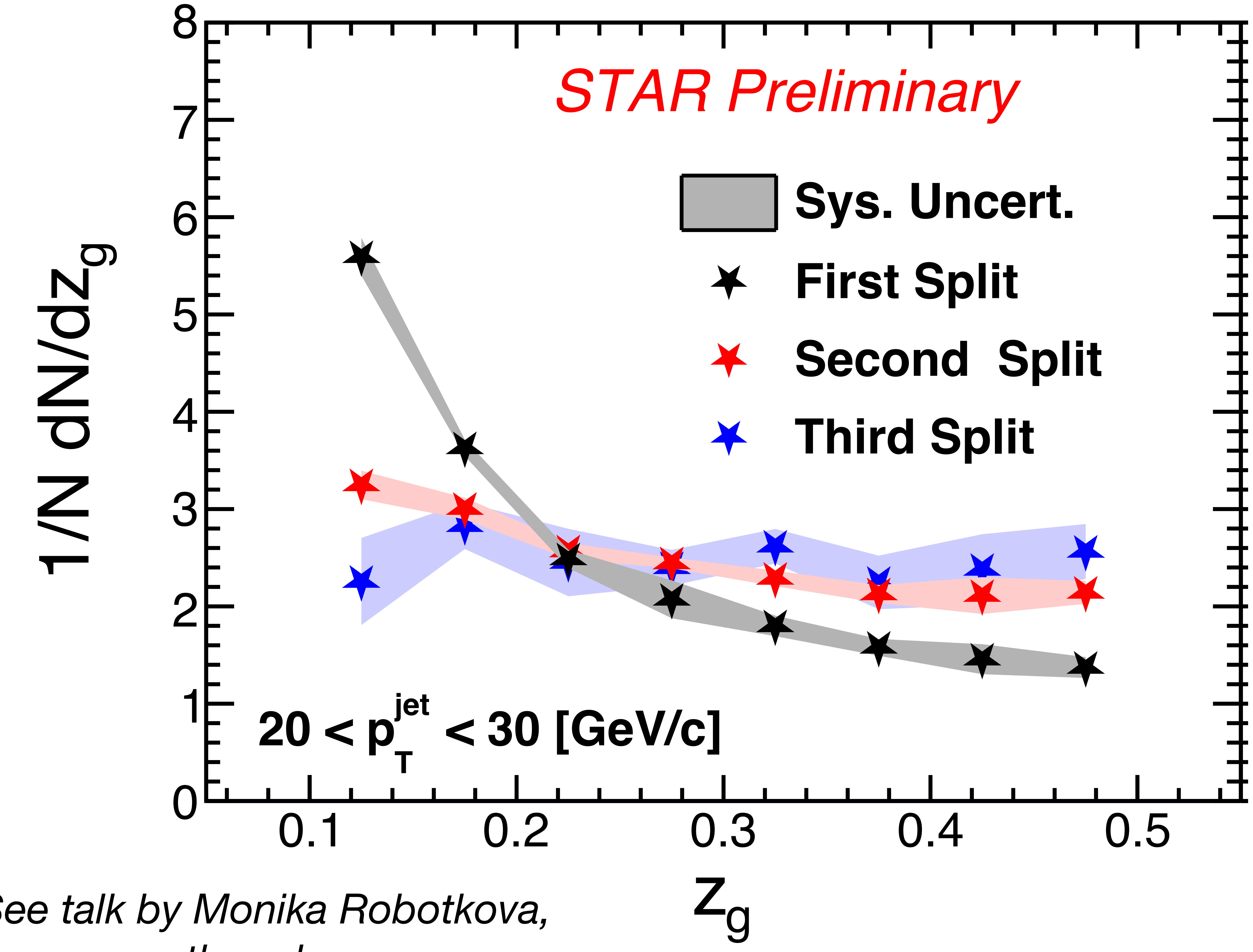
Dasgupta et al.
JHEP 09 (2013) 029

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$



First SoftDrop splittings can be described by pQCD

We know it has to break!

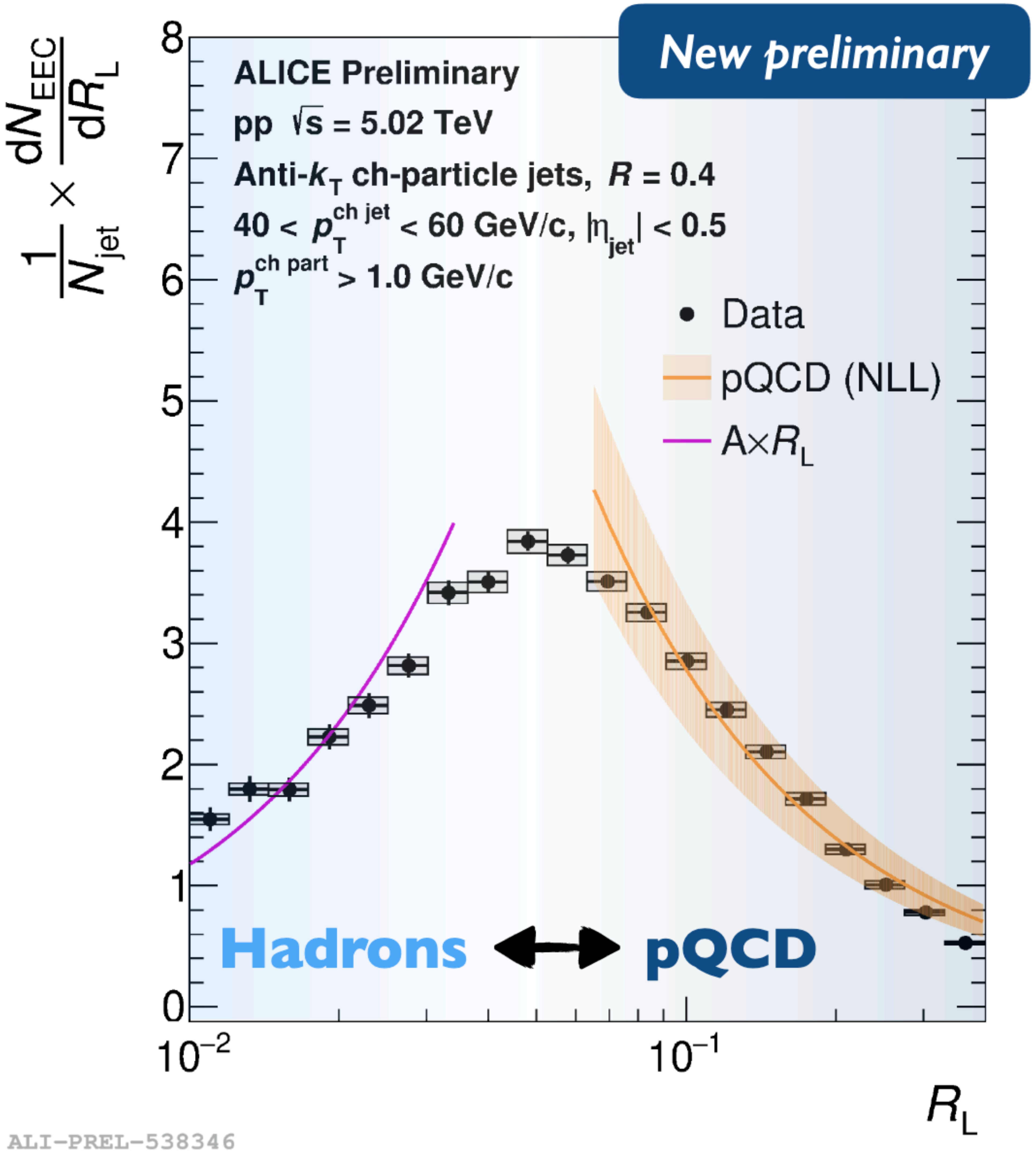


See talk by Monika Robotkova, thursday

- Flat z_g distribution and smaller $\langle R_g \rangle$ for the third split, where we observe collinear emissions
- At some point within the clustering tree (directly observed at RHIC, but will also be true at the LHC), we need to move away from pQCD
- **When is that?**

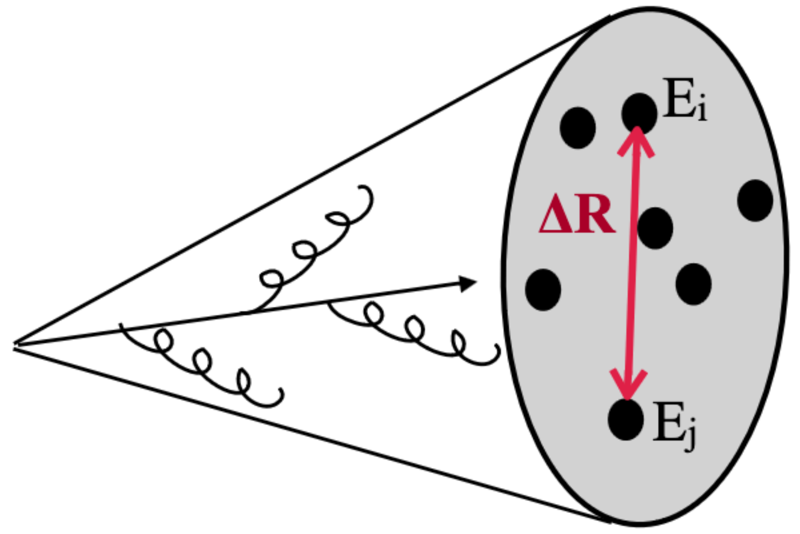
Another evidence for transition

See talk by Reynier Cruz-Torres, Tuesday

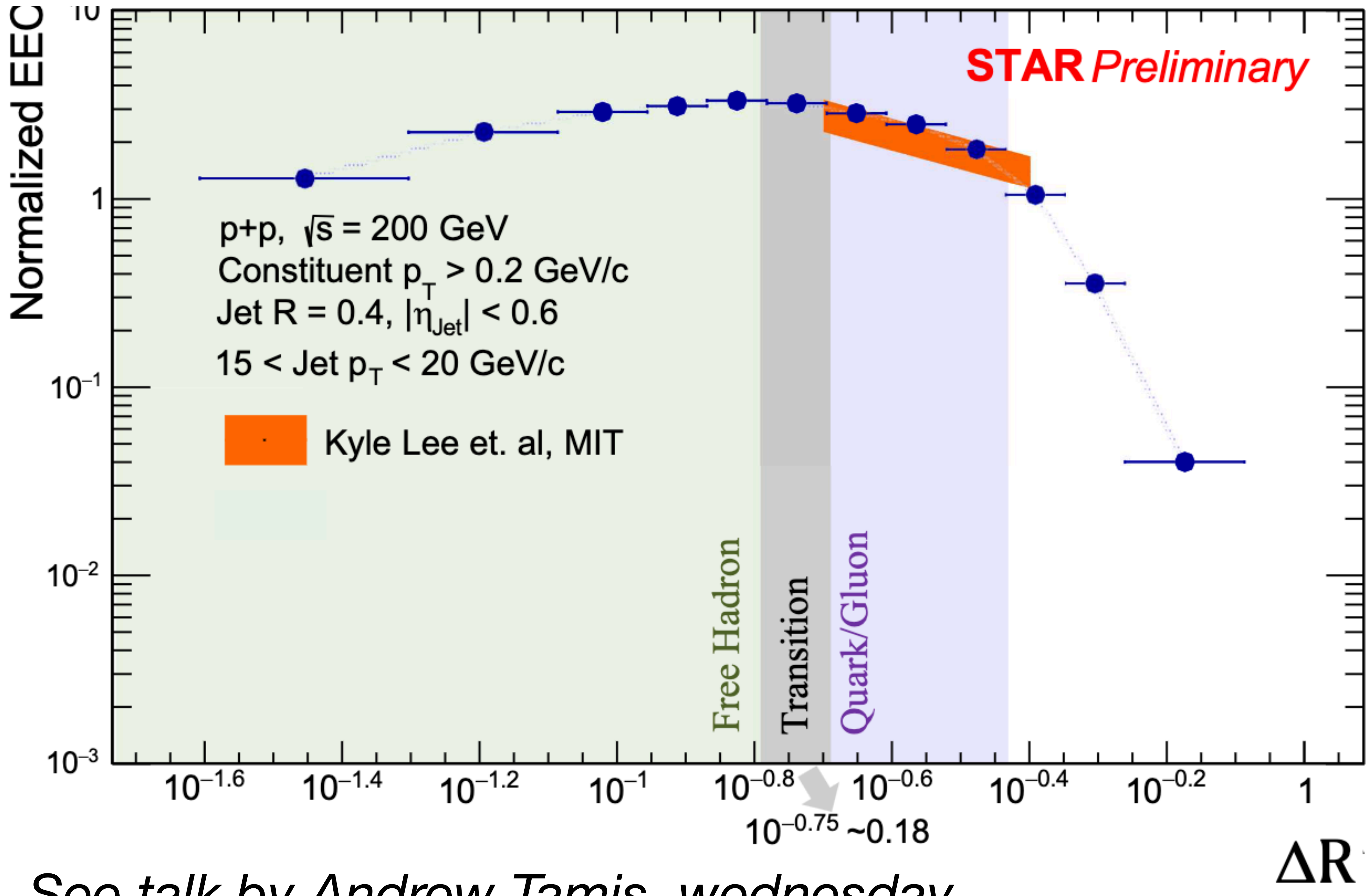


"field theory faces reality"

arXiv:2205.03414 , 2209.11236



- Transition indicated as a function of the opening angle - which we know is related to the time scale!



See talk by Andrew Tamis, wednesday

What is the formation time?

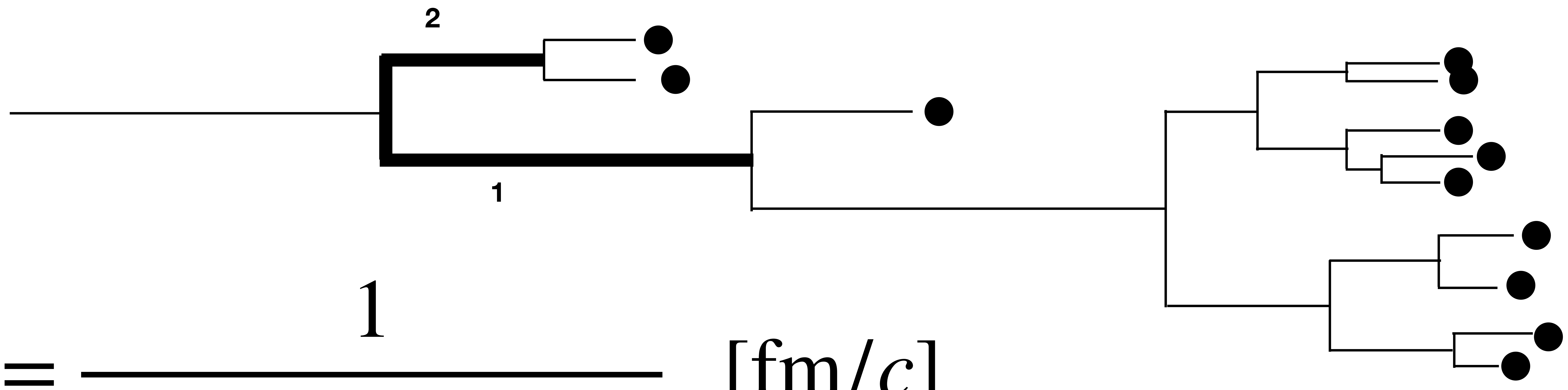
$$z = \frac{\min(\mathrm{p}_{\mathrm{T},1}, \mathrm{p}_{\mathrm{T},2})}{p_{T,1} + p_{T,2}}$$

$$E = E_1 + E_2$$

Chien et. al. 2109.15318

$$\theta = \Delta R(1,2)$$

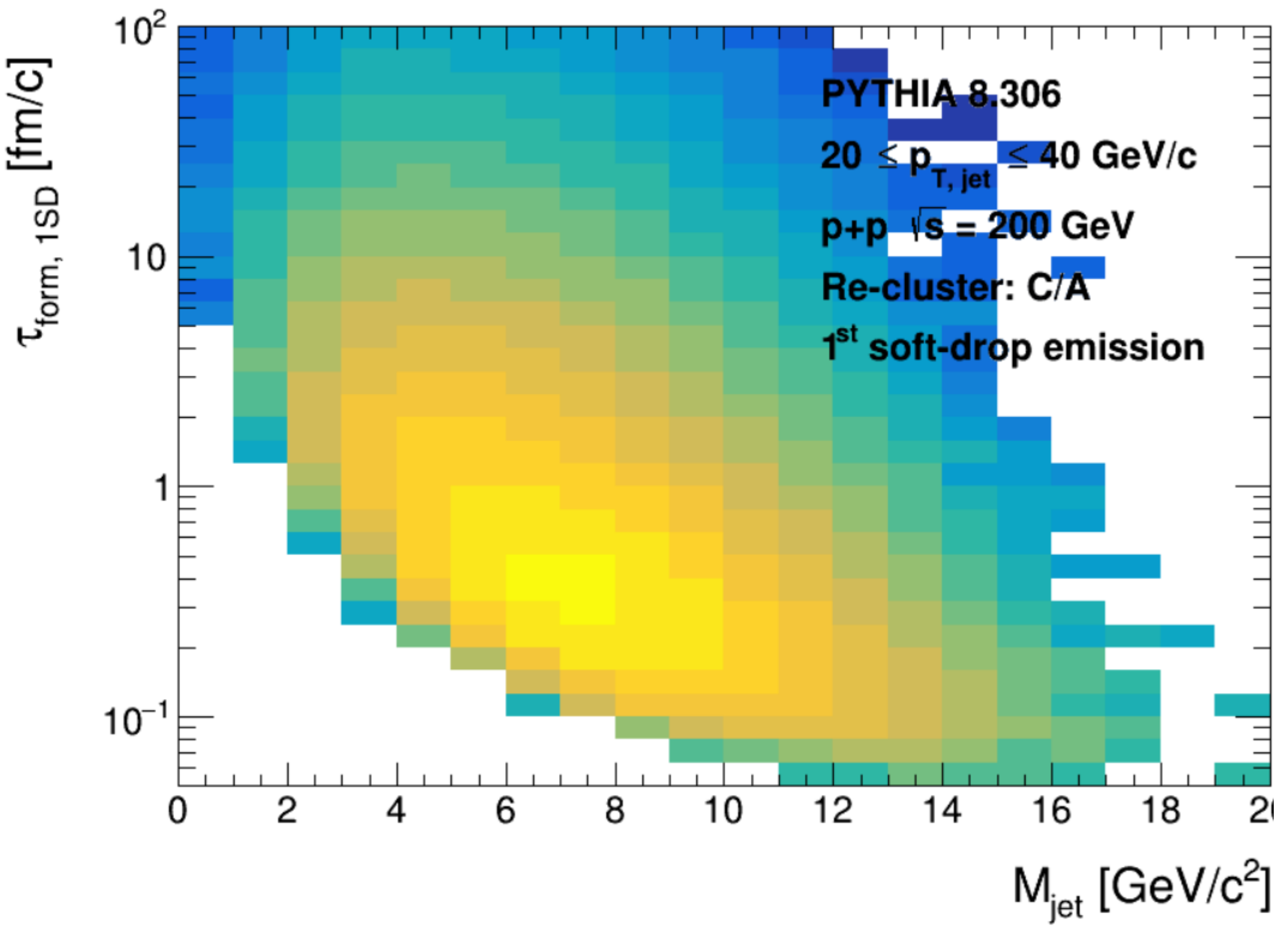
Apolinario et al. Eur. Phys. J. C 81 (2021) 6, 561

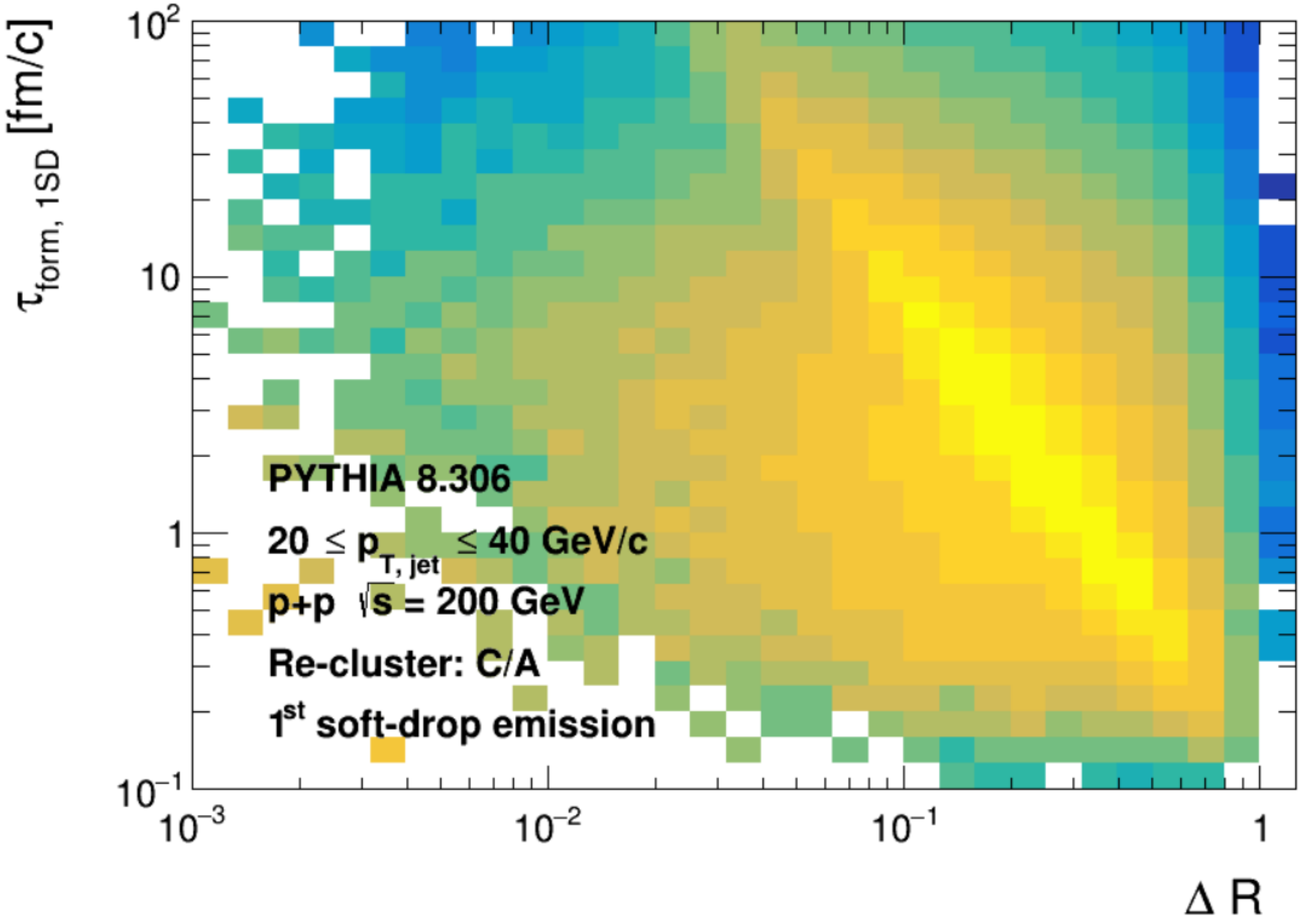


$$\tau_f = \frac{1}{z \cdot (1 - z) \cdot \theta^2 \cdot E} \quad [\mathrm{fm}/c]$$

QCD inspired formation time for any two objects to be treated independently

How to think about the time observable

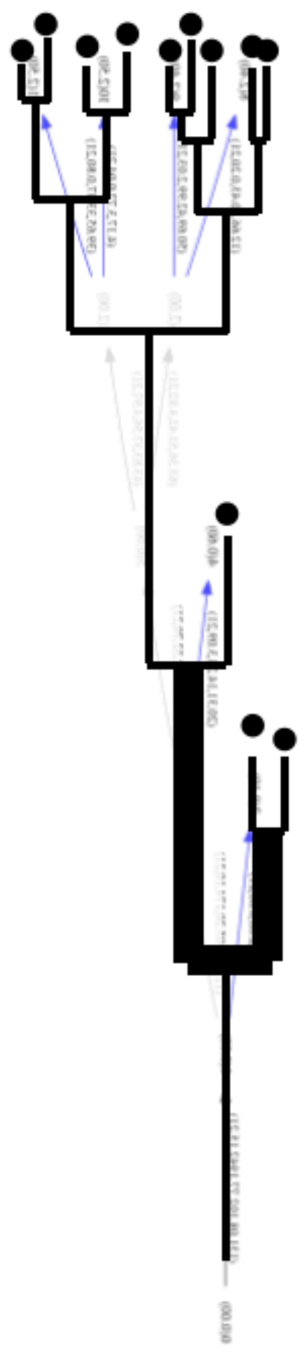


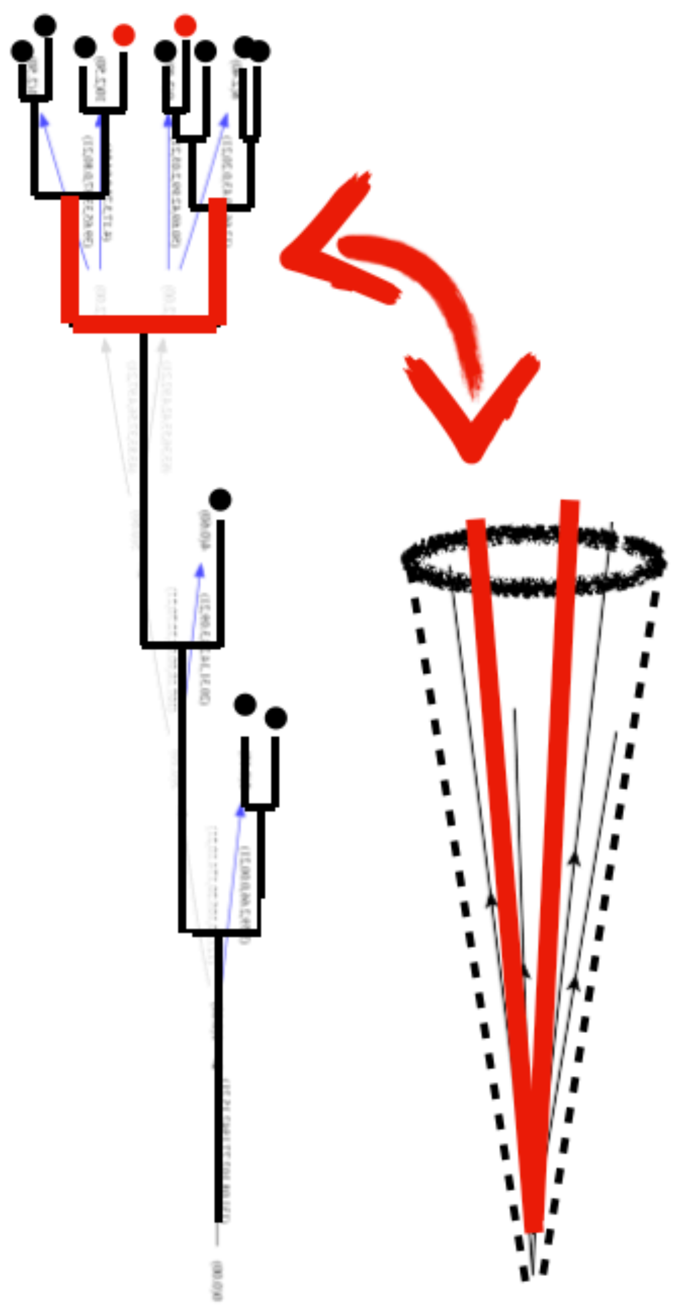


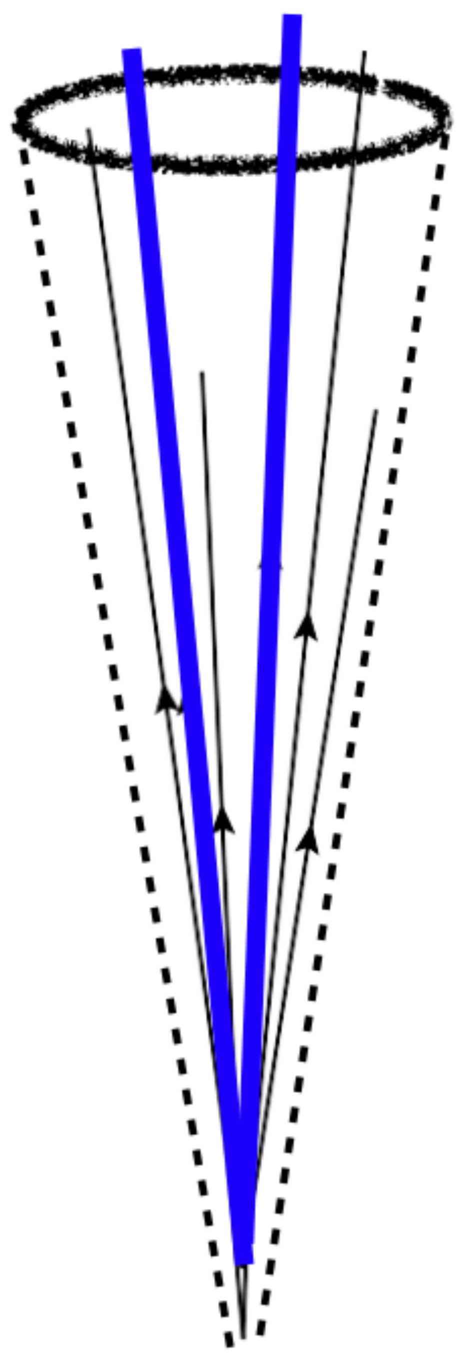
Large mass - early time - larger opening angle - large virtuality
Allows a selection of jets based on space-time structure

Lets identify splittings within jets

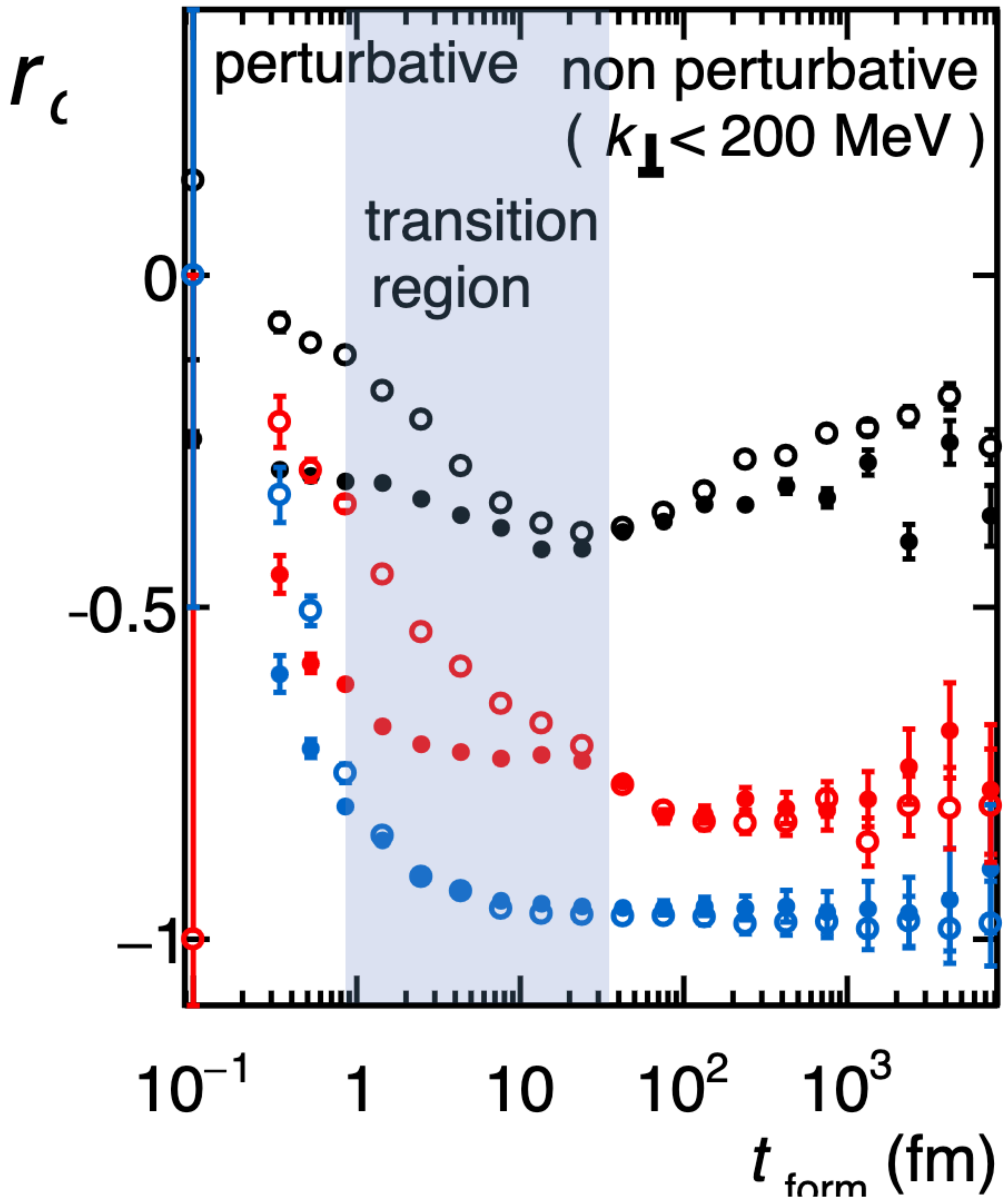
- SoftDrop first split τ_f
- SoftDrop split resolving the two leading charged particles
- Leading and subleading ch-particle τ_f







Why look at the formation time and charged particles

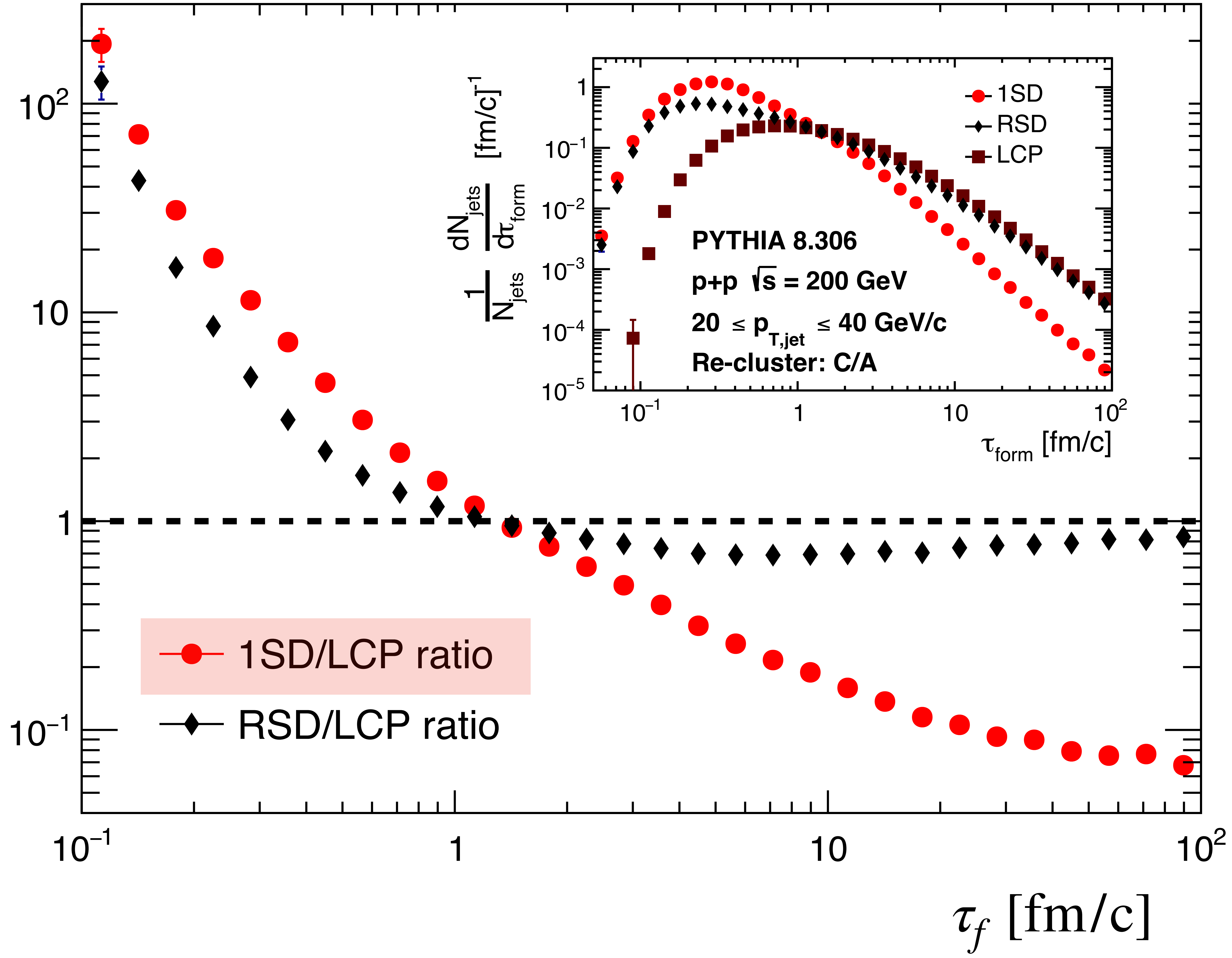


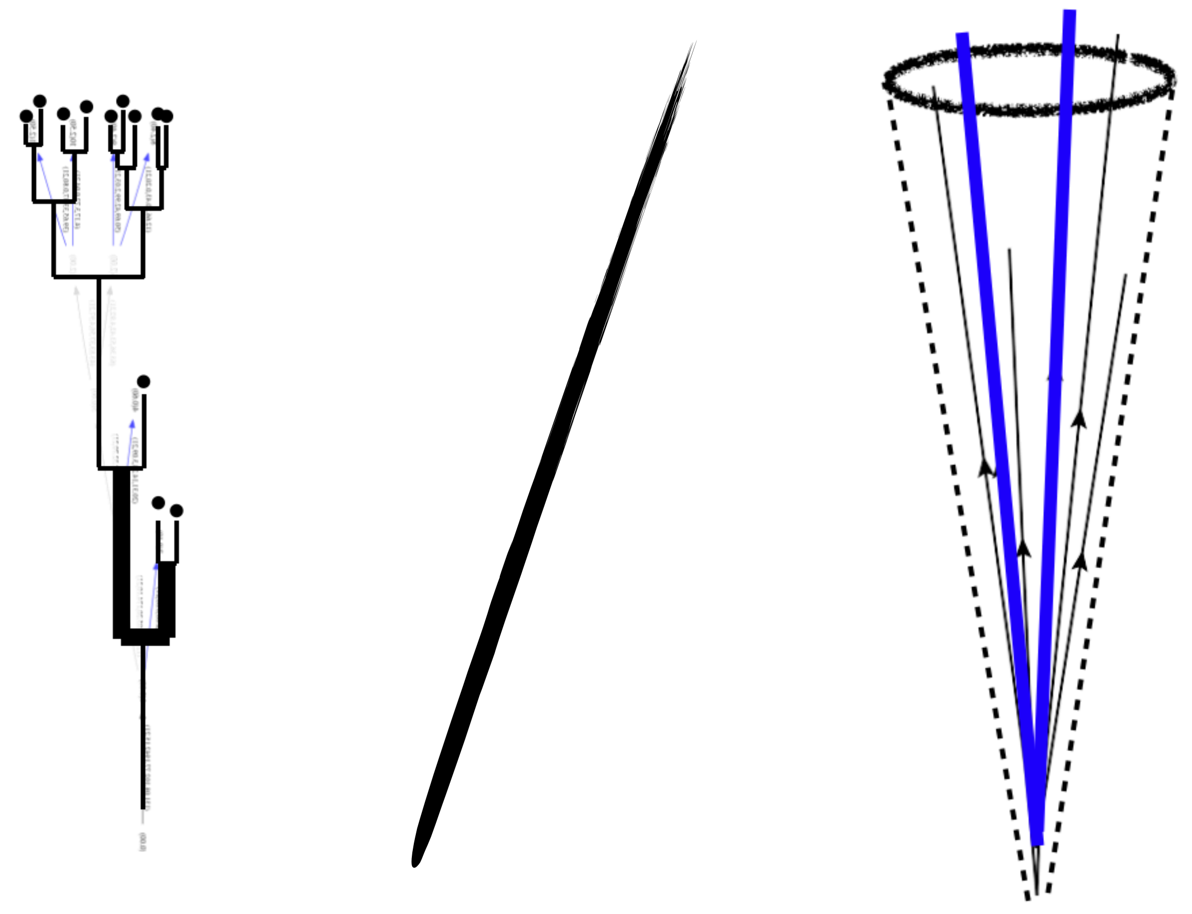
- Recent studies also show its usefulness from the theoretical POV on isolating regions where calculations are valid
- Fuzzy area, but overall one can separate out **'mostly' perturbative** and **'mostly' non-perturbative** regions based on formation time

$$r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 \overline{h_2}}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 \overline{h_2}}/dX}\,.$$

Y-T Chien, A Deshpande, M Mondal, G Sterman
arXiv: 2109.15318

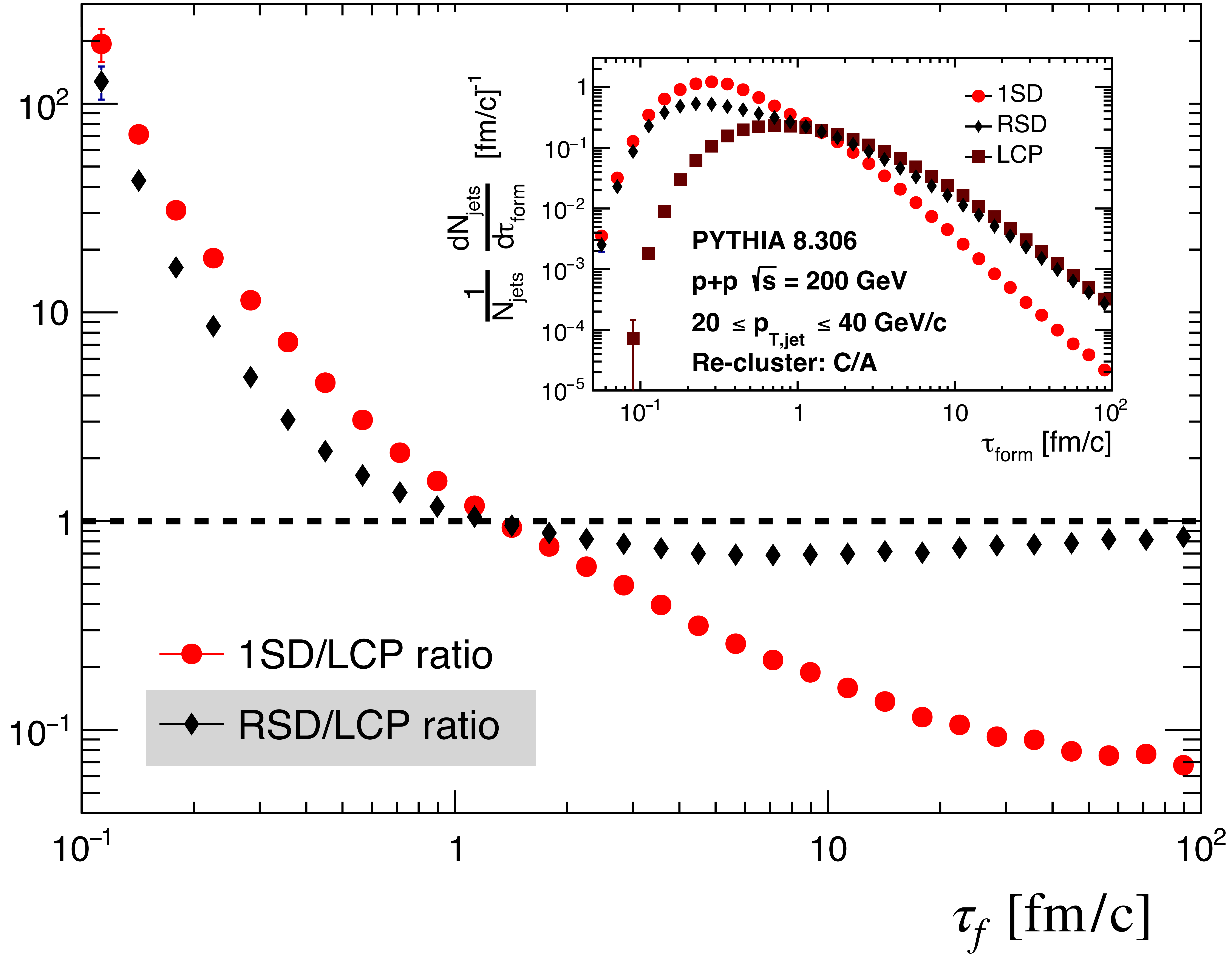
Start with the formation times

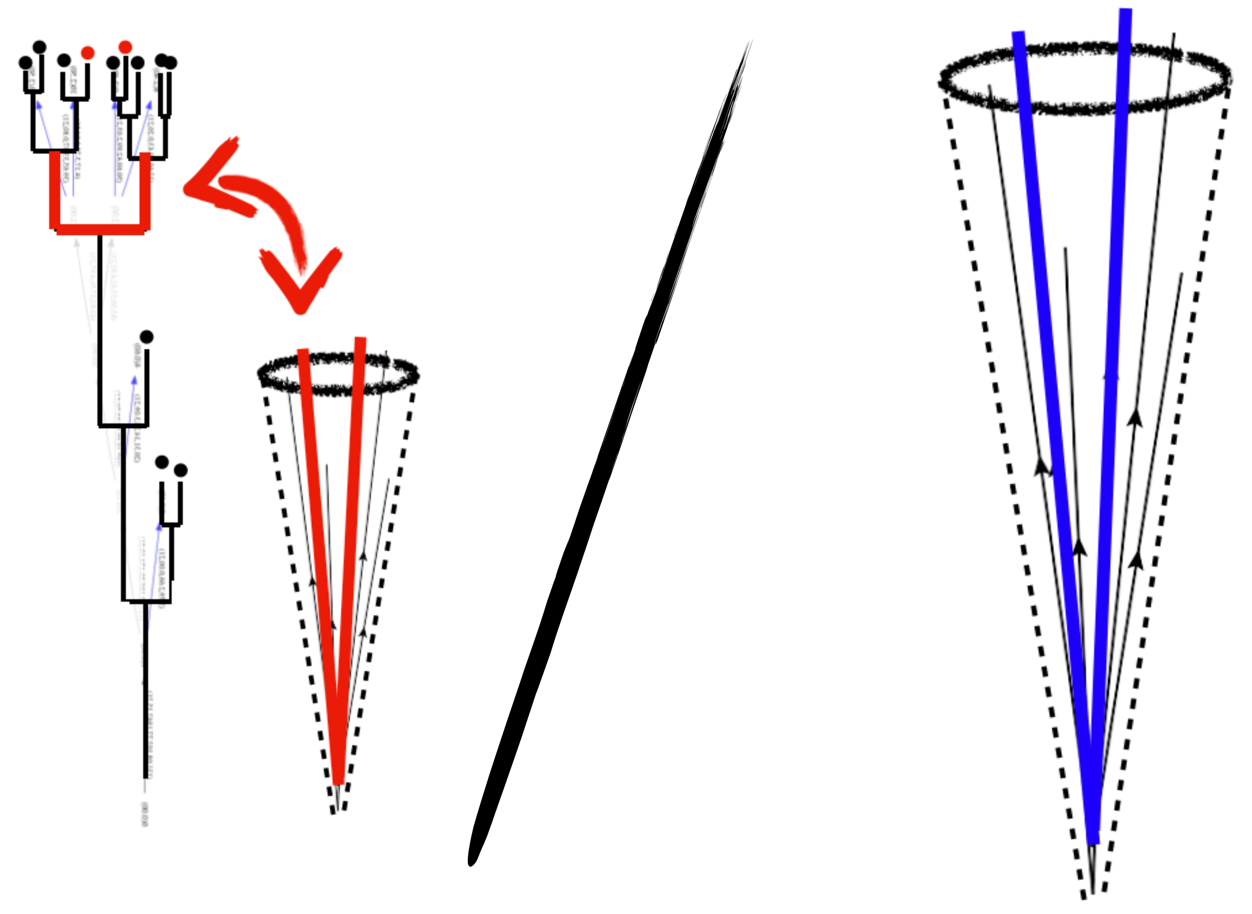




- 1SD splittings are predominantly early time and do not follow the shape the LCP

Start with the formation times





- 1SD splittings are predominantly early time and do not follow the shape the LCP
- RSD shows the characteristic shape at early time and follows the LCP at later times

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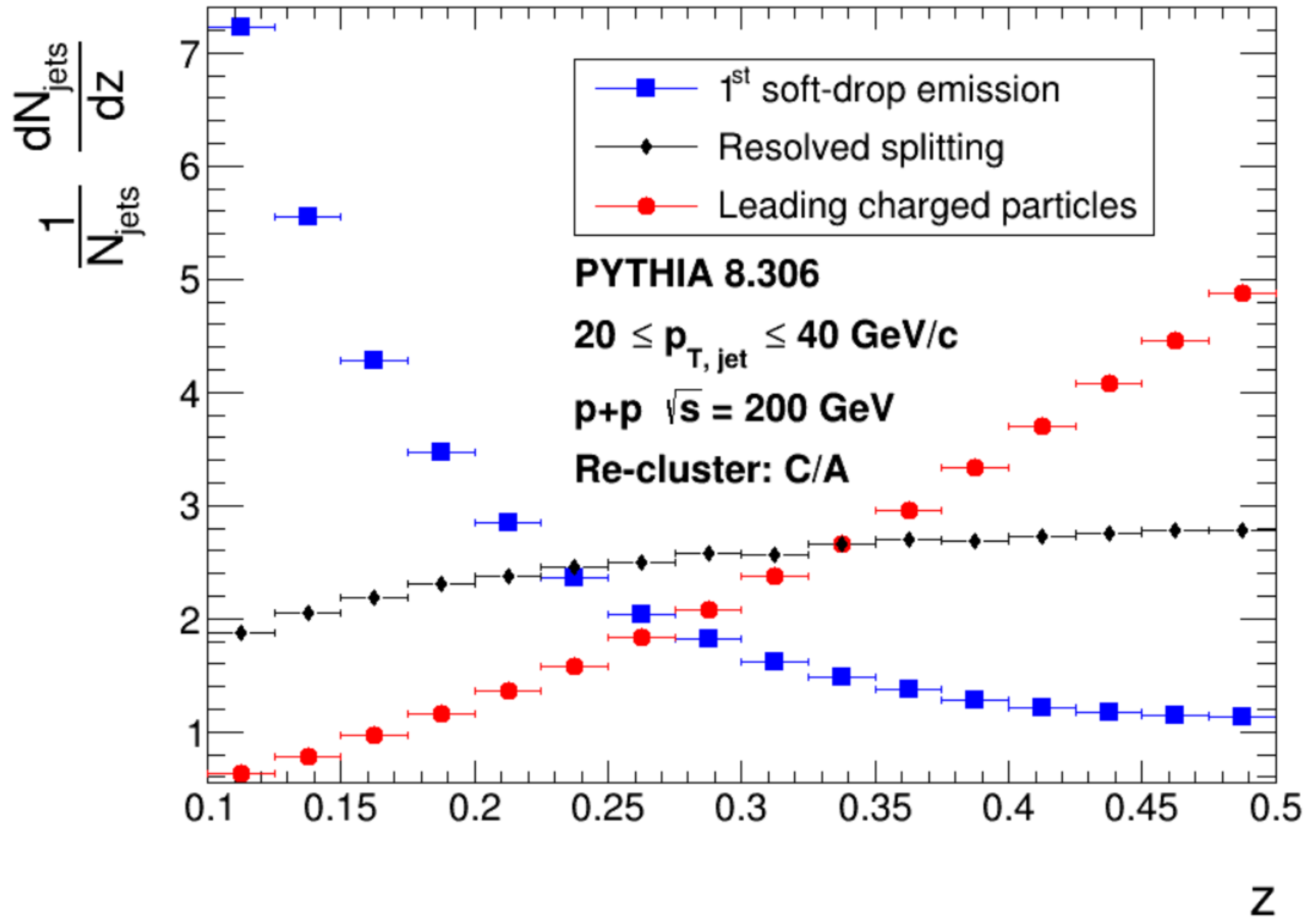
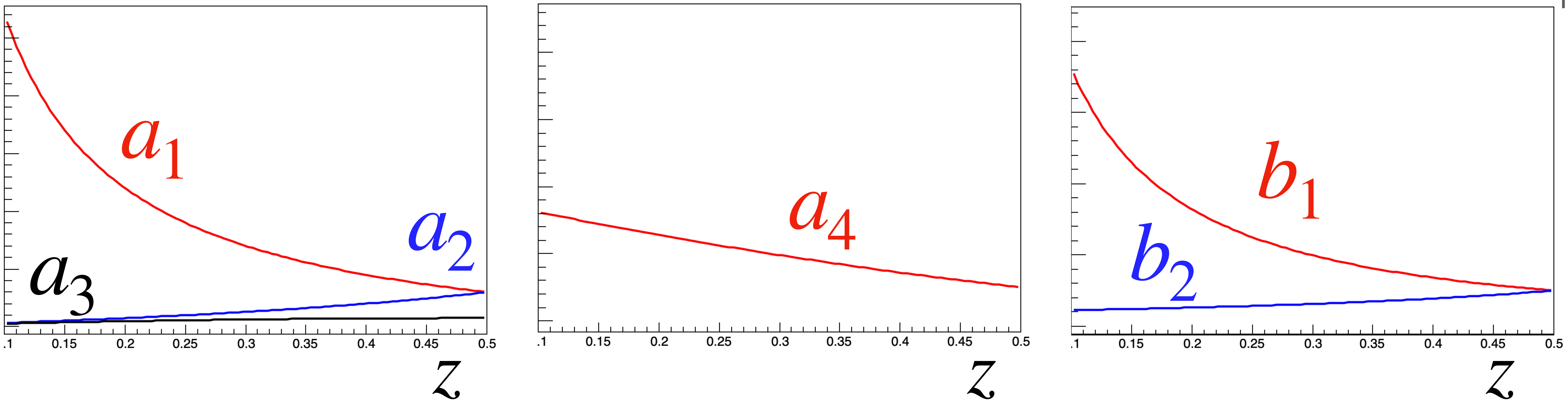
Lets quantify the splitting shapes



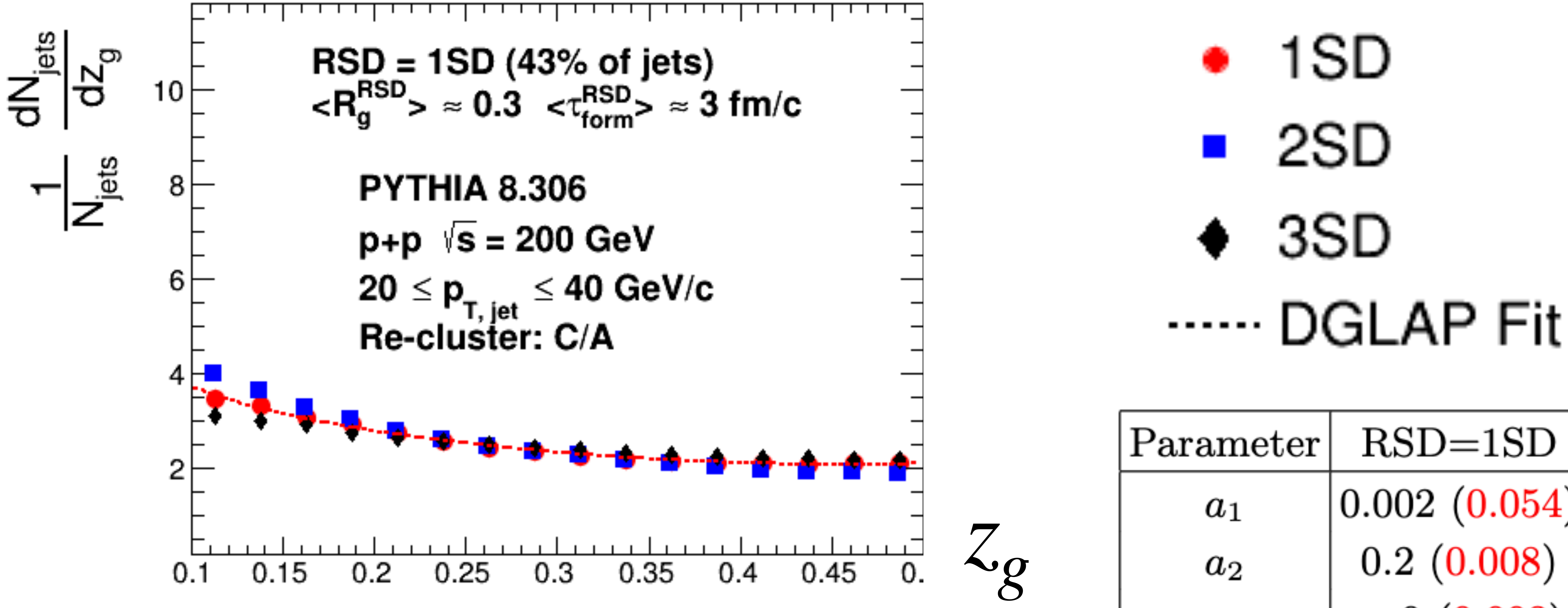
- We would nominally expect the following ordering 1SD -> RSD -> LCP
- 1SD is a steeply falling distribution reminiscent of DGLAP leading order
- LCP is significantly peaked at larger values
- RSD is somewhere in the middle



$$P_{gg}(z) = 2C_A \left(a_1 \frac{1-z}{z} + a_2 \frac{z}{1-z} + a_3 z(1-z) \right) ,$$

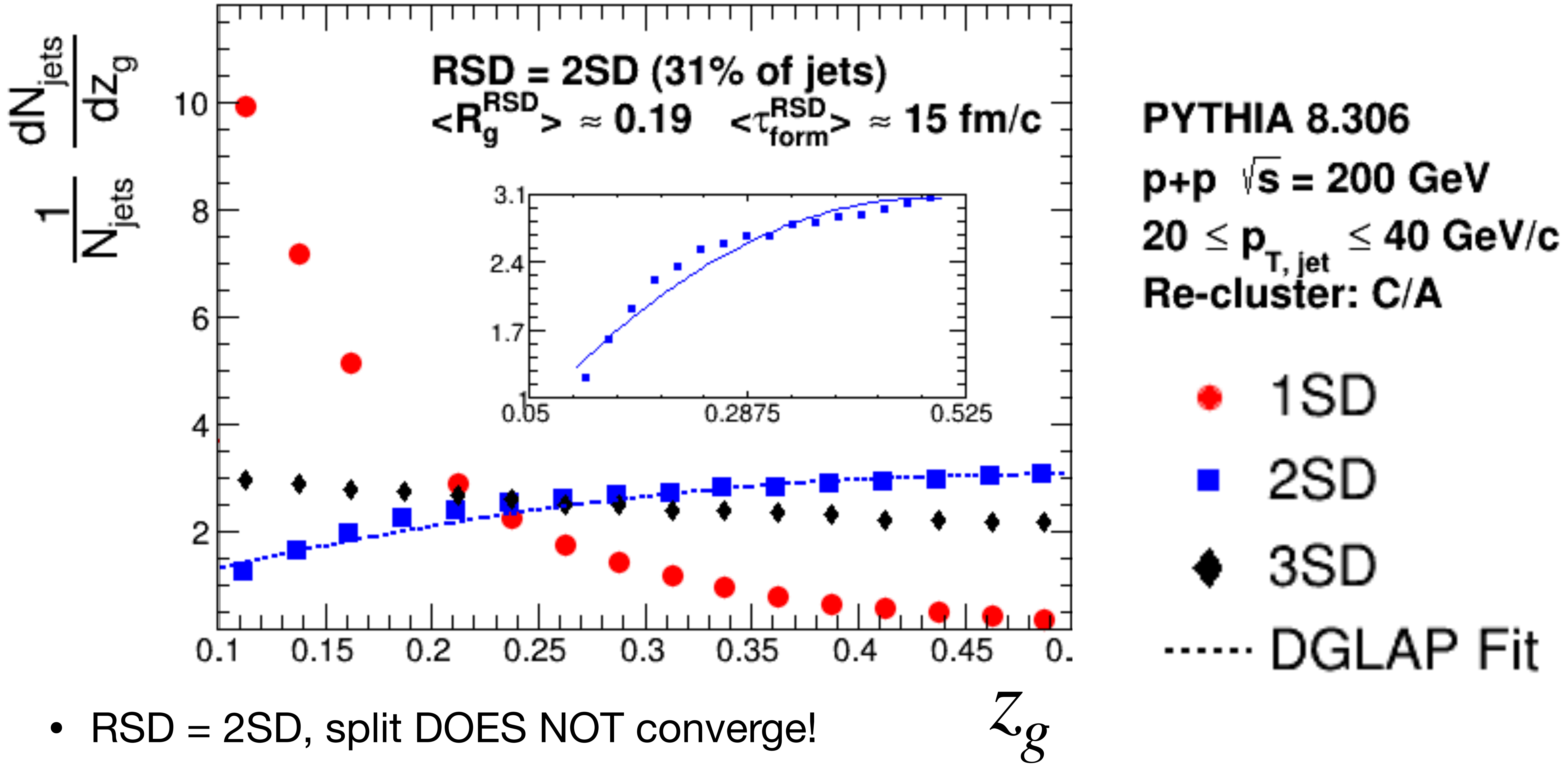
$$P_{qg}(z) = T_R a_4 \left(z^2 + (1-z)^2 \right) ,$$

$$P_{gq}(z) = C_F b_1 \left(\frac{1+(1-z)^2}{z} \right) = b_2 P_{qq}(1-z) .$$



Parameter	RSD=1SD
a_1	0.002 (0.054)
a_2	0.2 (0.008)
a_3	~ 0 (0.003)
a_4	3.17 ($\sim$0)
b_1	0.05 (0.166)
b_2	~ 0 (0.043)

- Multi-parameter simultaneous fit converges for when RSD = 1SD - with unreasonable weights!



- RSD = 2SD, split DOES NOT converge!
  Shape of this z_g is definitely not perturbative

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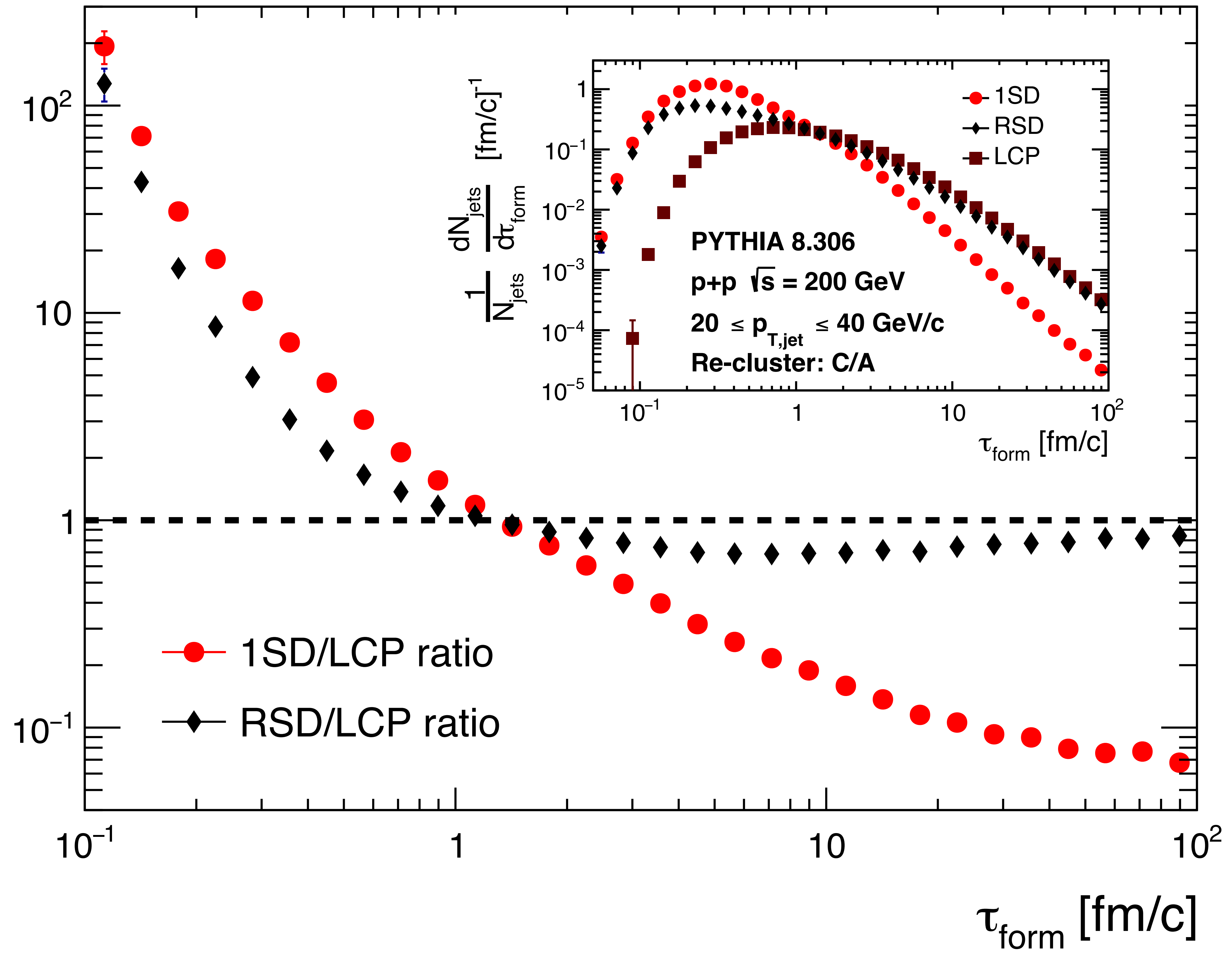
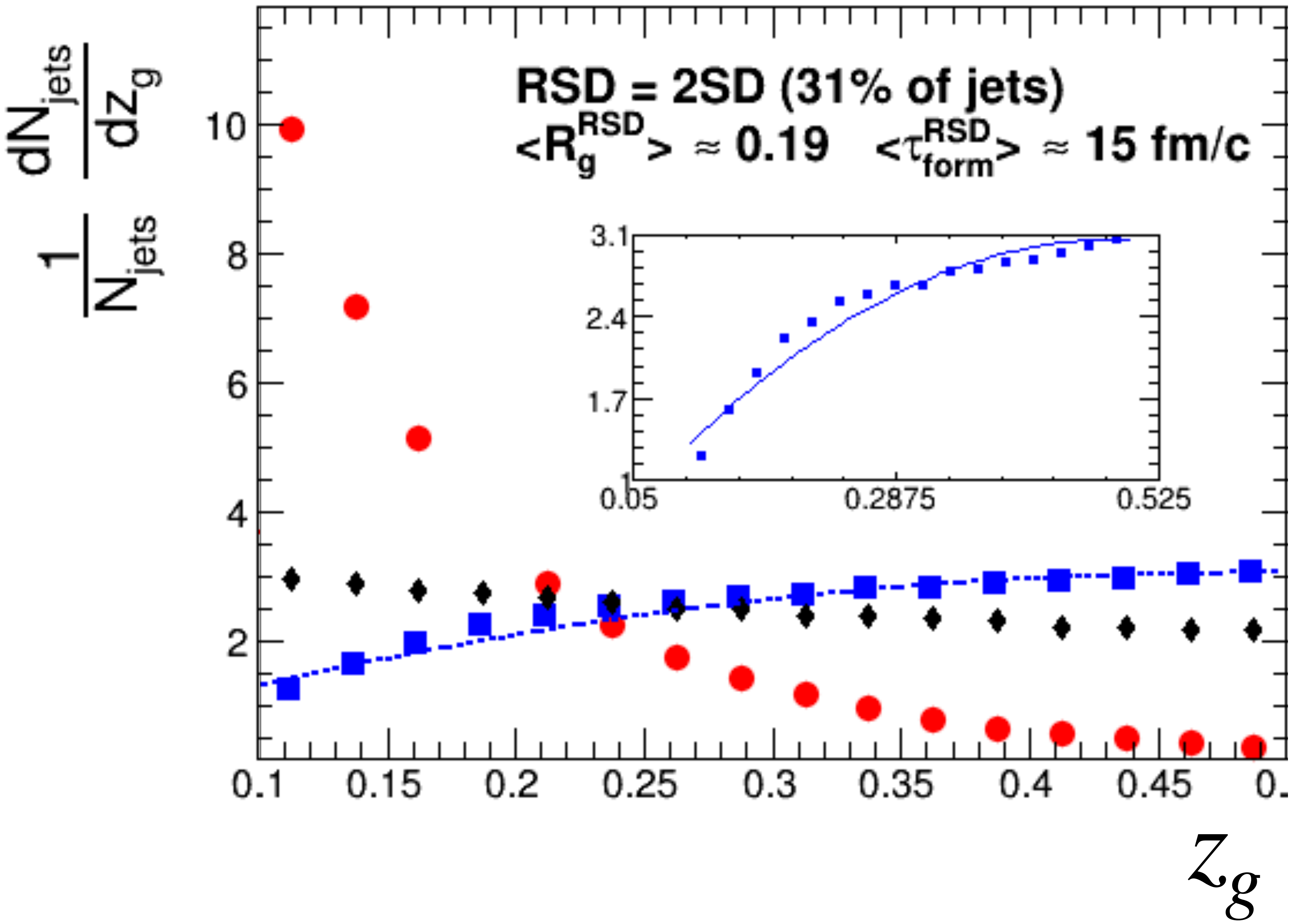


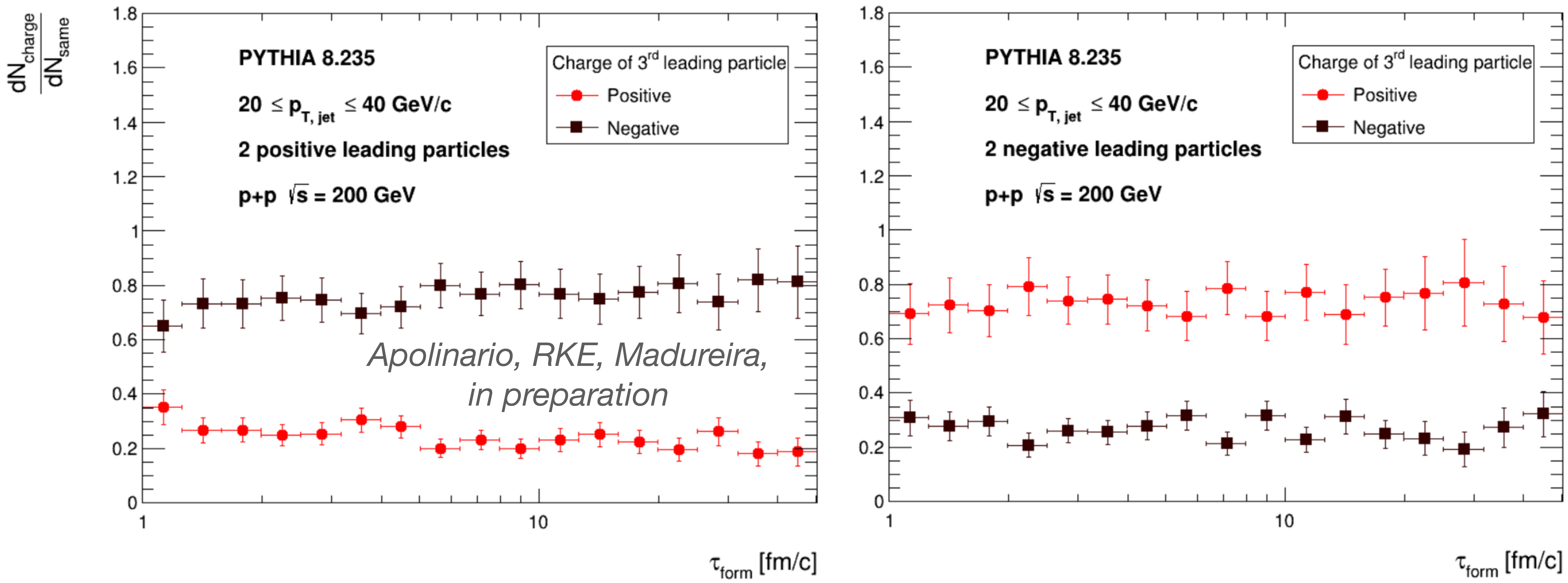


- Associating a **timescale to jet evolution** via the formation time highlights its usefulness from very early time pQCD dynamics to late time npQCD mechanics and hadronization

- **Resolved splittings potentially straddles the transition regime** - leading charged particle selection will make this free of background contribution in heavy ions!

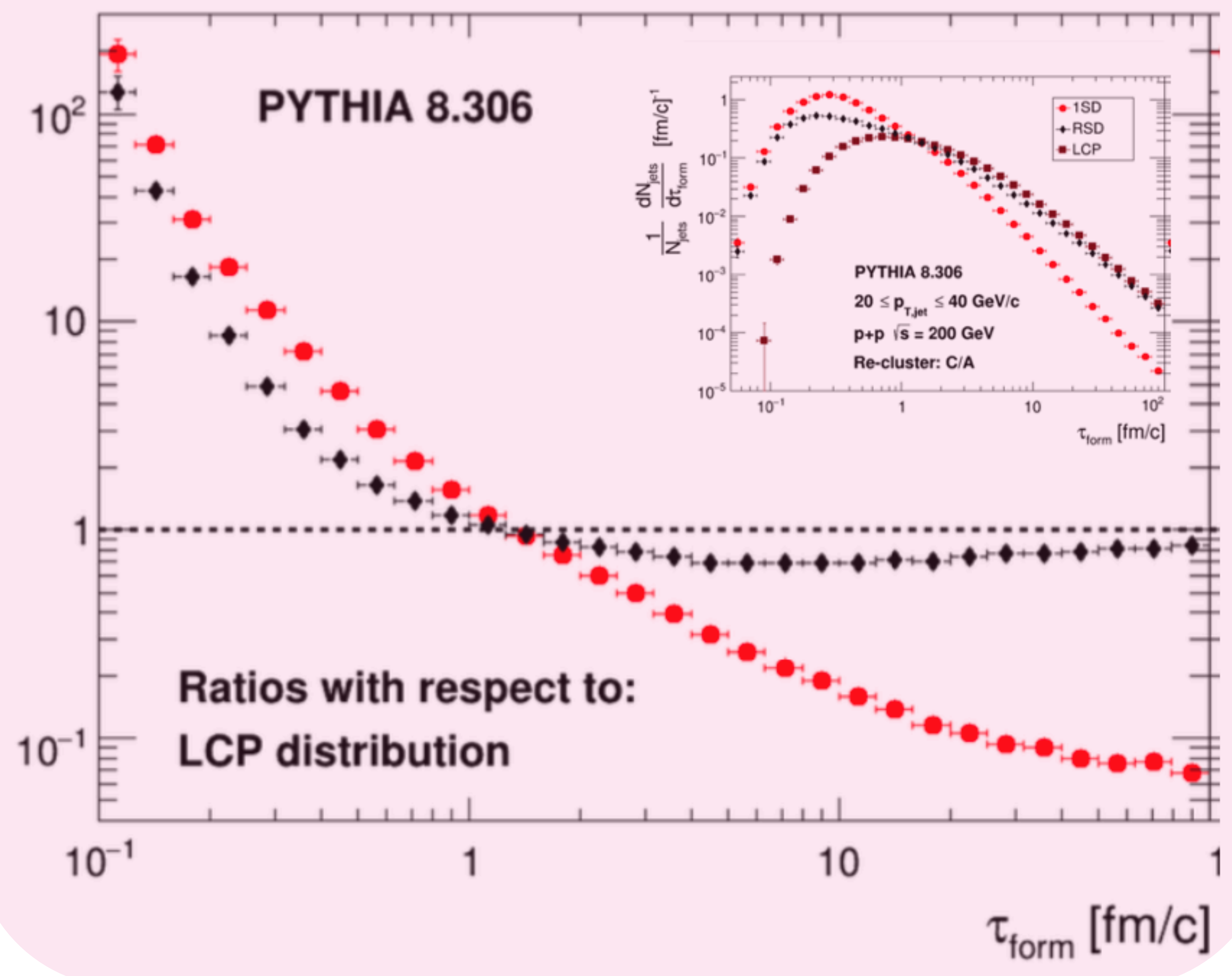
Bonus Slides

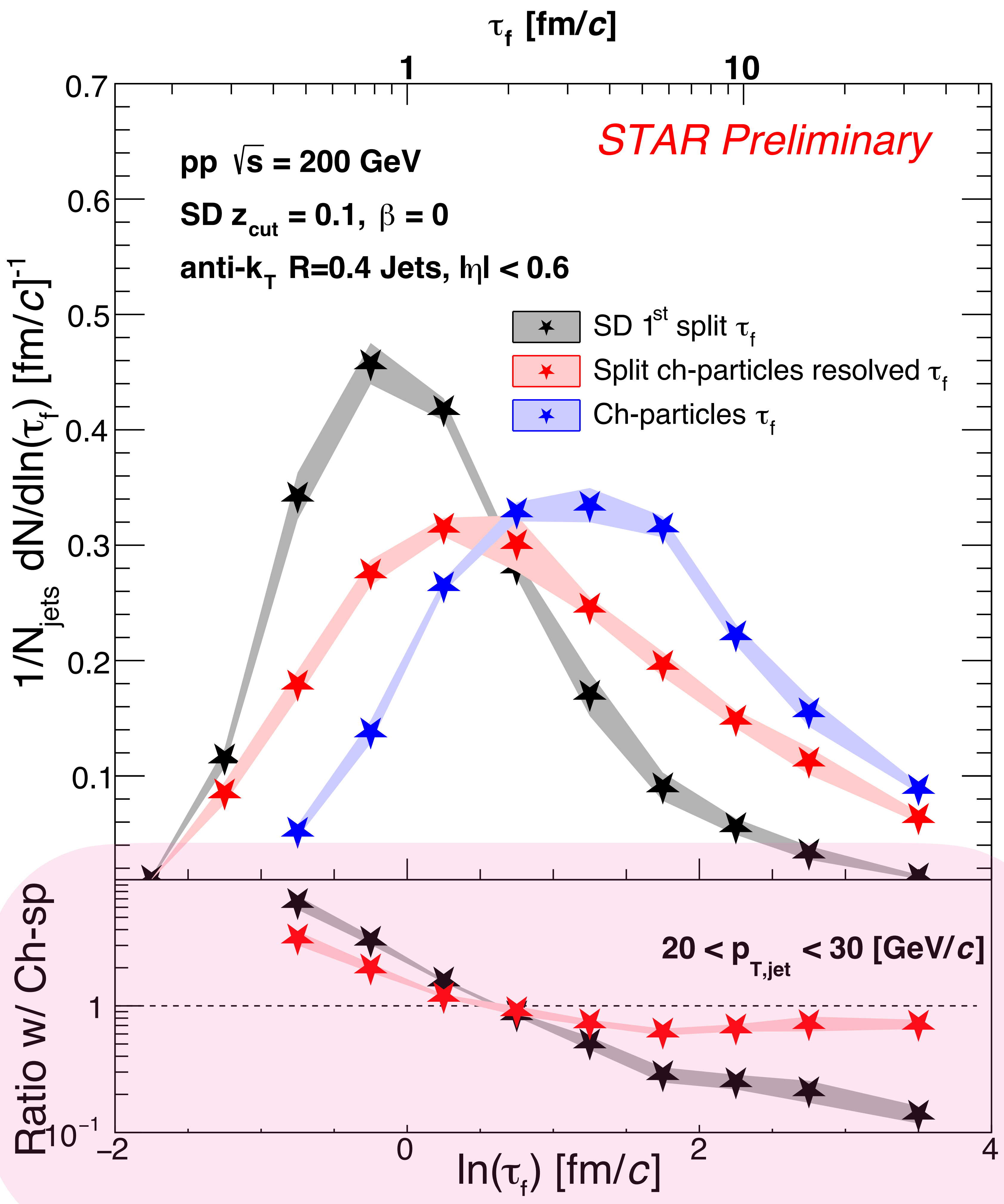
Extending towards correlations



- One example of ongoing studies with charged correlation - Like-sign leading particles
- Significant split in the formation times for 3rd particle to be opposite sign - quantitative categorizing of charge conservation in jets vs time
- Emerging as a new avenue thats complementary to jet substructure focused on understanding hadronization mechanisms

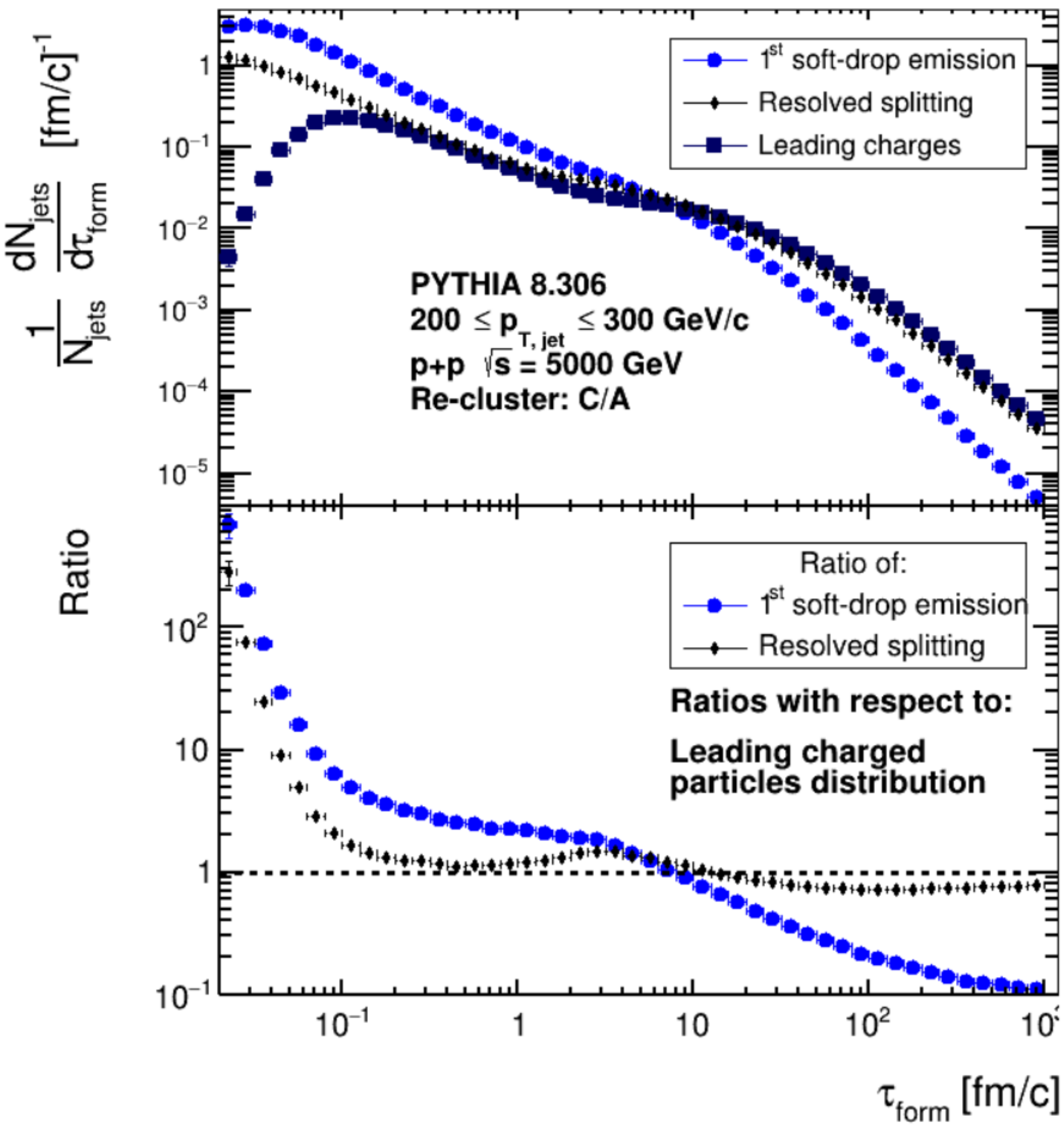
Already followed up in experiment





- Similar structure - will be very exciting to see this at the LHC

At the LHC



- Selecting on the formation time - sculpts your mass distribution
- Later time is almost exclusively larger mass - allows for selecting early time dynamics