Wright Laboratory

Jet substructure and hadronization with STAR

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For the STAR Collaboration

2nd Workshop on Jets for 3D Imaging at the EIC

Center for Frontiers in Nuclear Science Workshop series

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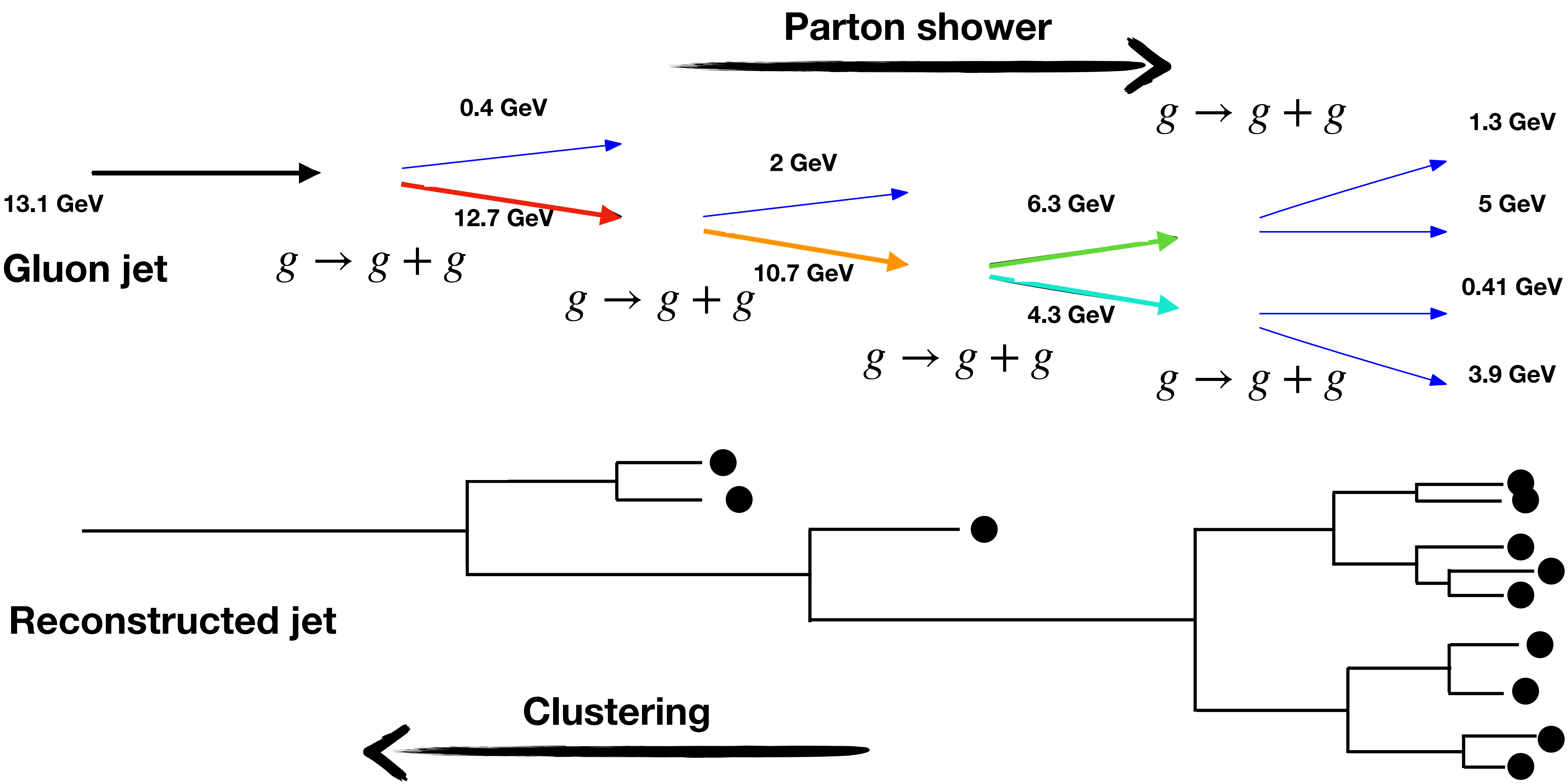
STAR

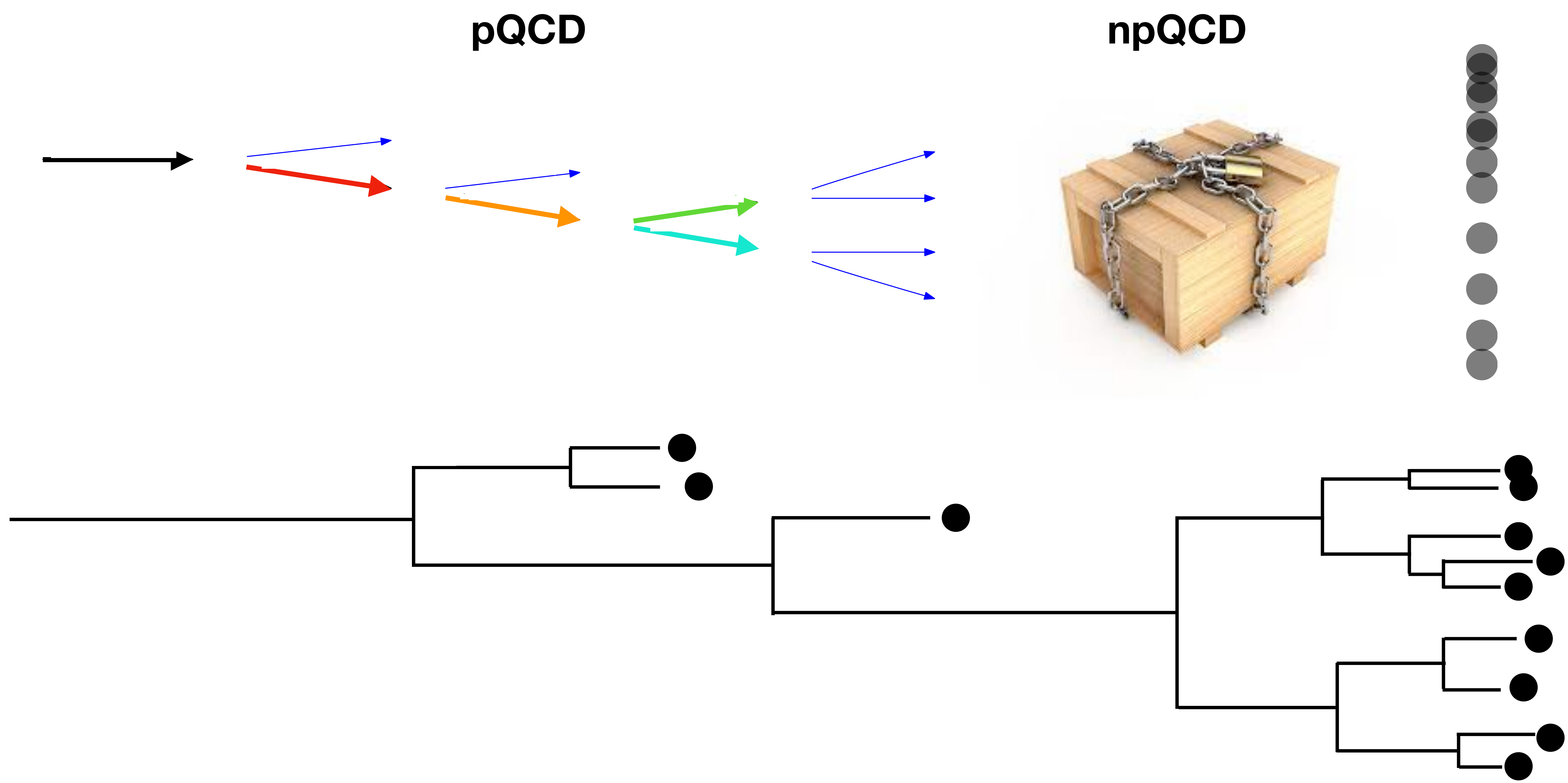
What do we want to measure?

We want to translate an intrinsic (and unmeasurable) parton shower to experimentally accessible observable(s)

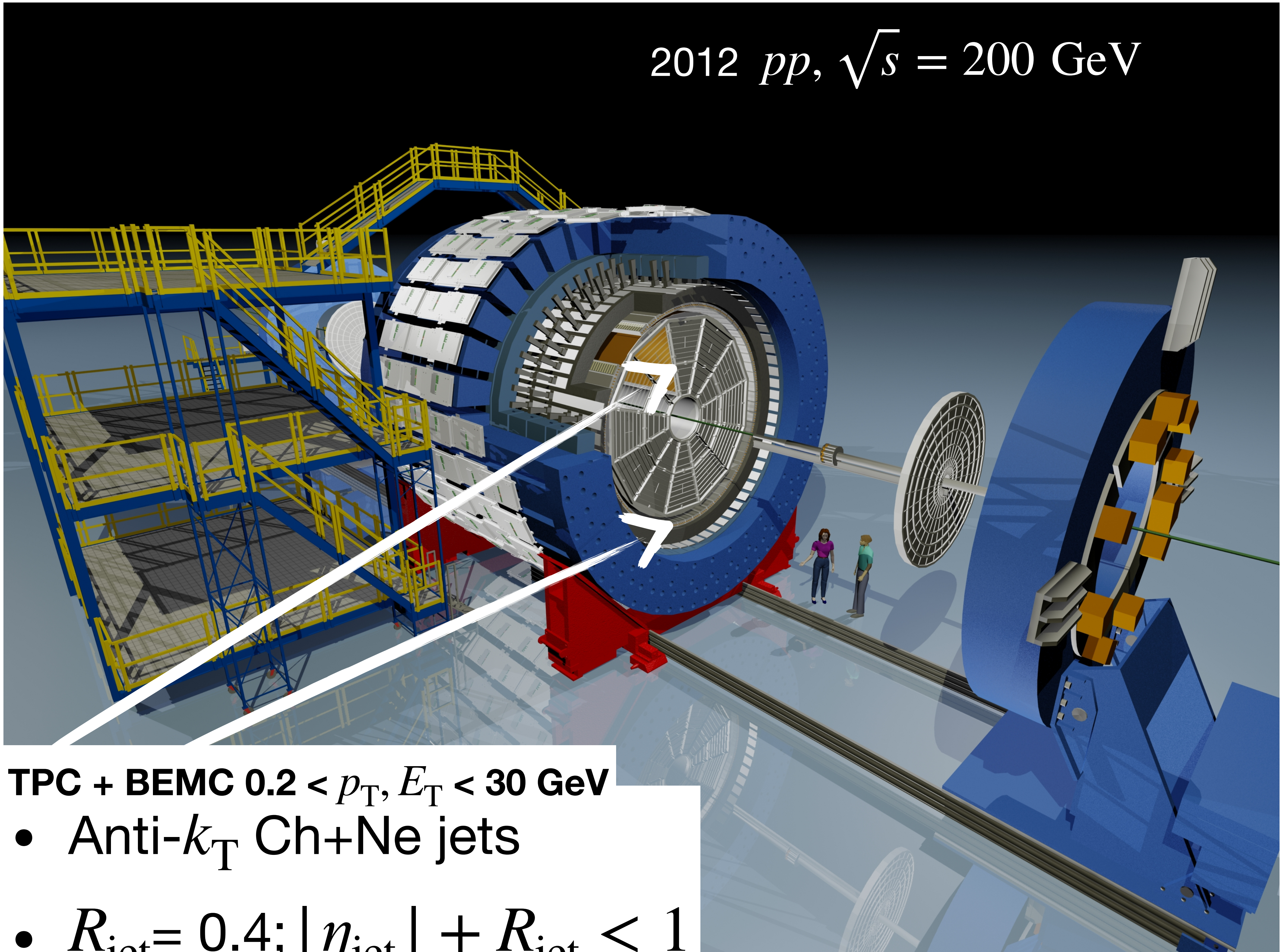


What do we want to measure?

Isolate regions of phase-space within jet evolution that are sensitive to pQCD vs npQCD



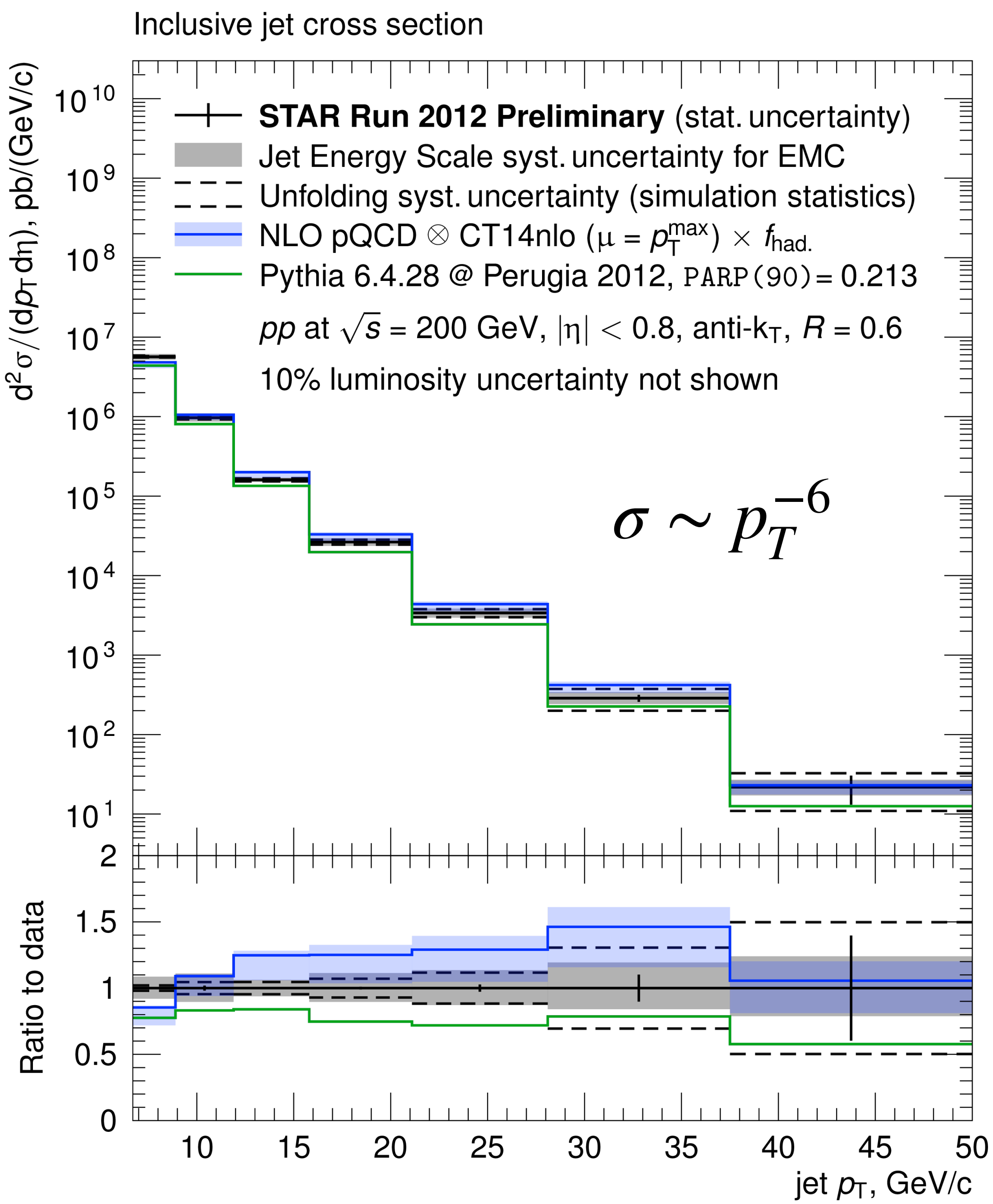
Jet reconstruction at STAR

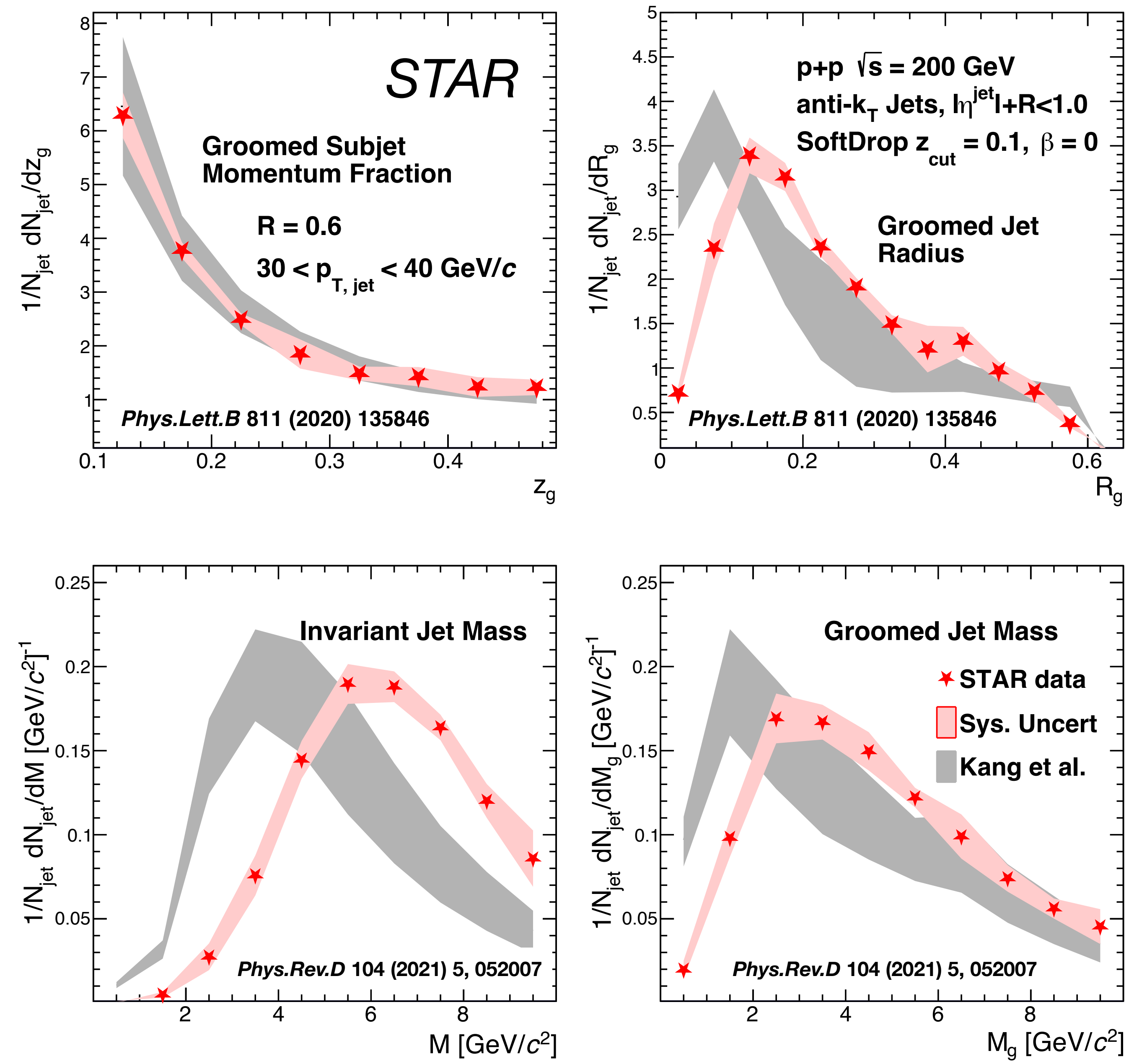


TPC + BEMC 0.2 < $p_{\mathrm{T}}, E_{\mathrm{T}}$ < 30 GeV

- Anti-k_{T} Ch+Ne jets
- R_{jet}= 0.4; $|\eta_{\mathrm{jet}}| + R_{\mathrm{jet}} < 1$

Jets in pp $\sqrt{s} = 200$ GeV





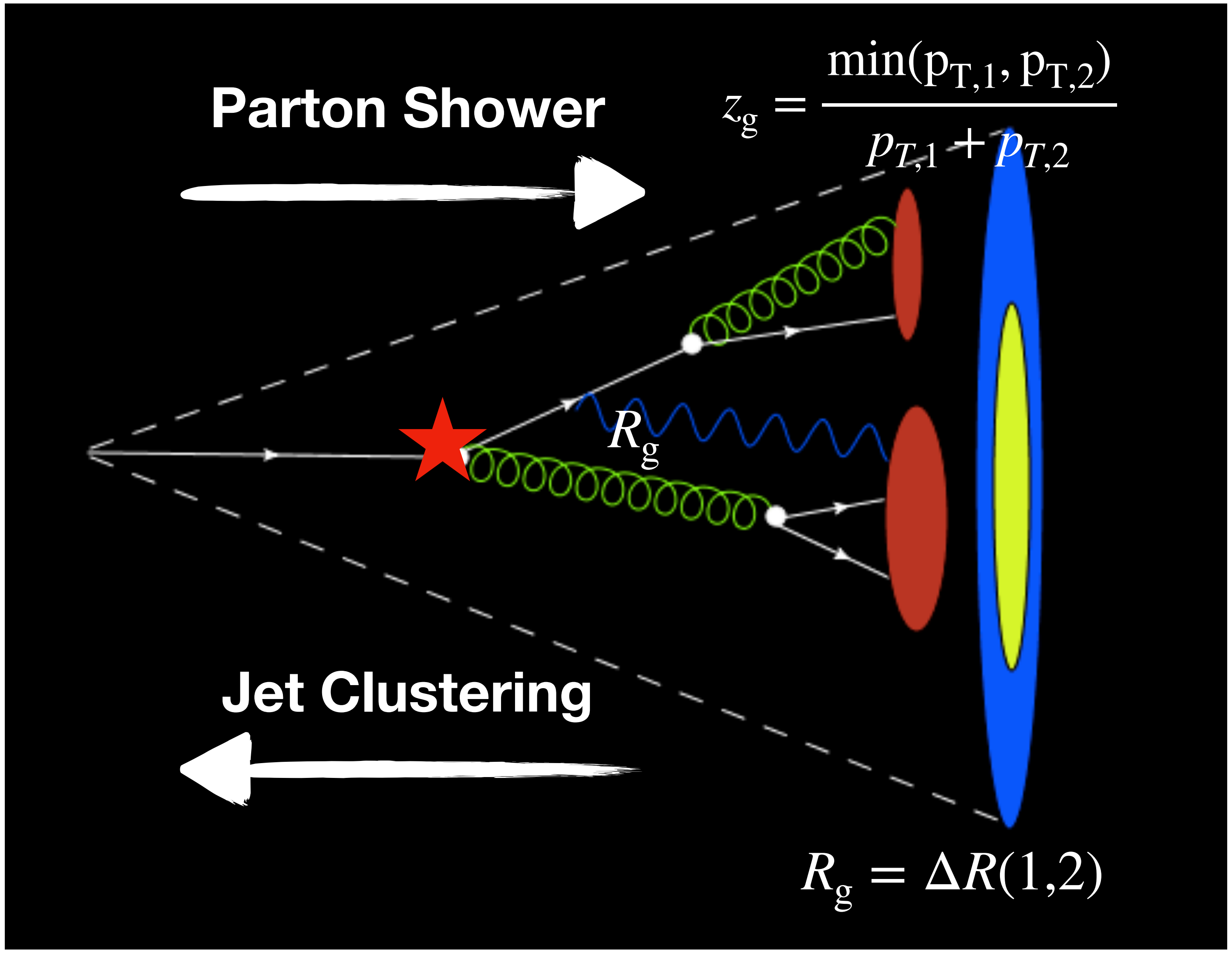
Unique population of jets with varied substructure

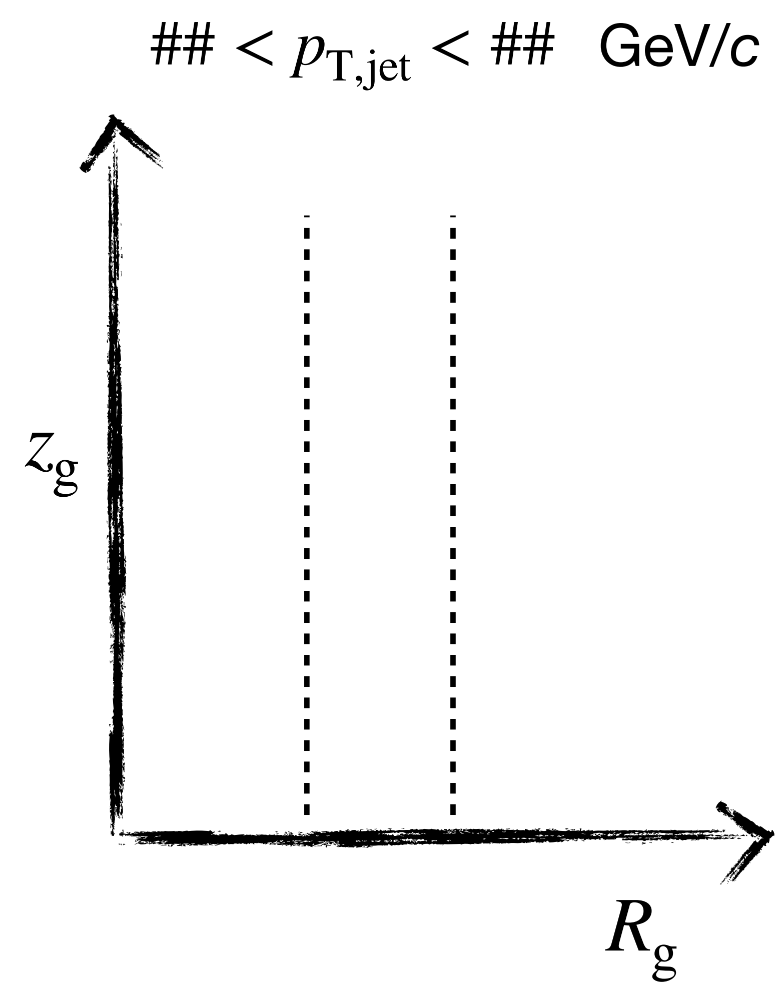
Scales extend from jet $p_T \rightarrow \Lambda_{QCD}$ (similar to the EIC)

Correlations between substructure observables at the first split

Evolution of the splitting observables as we travel along the jet shower

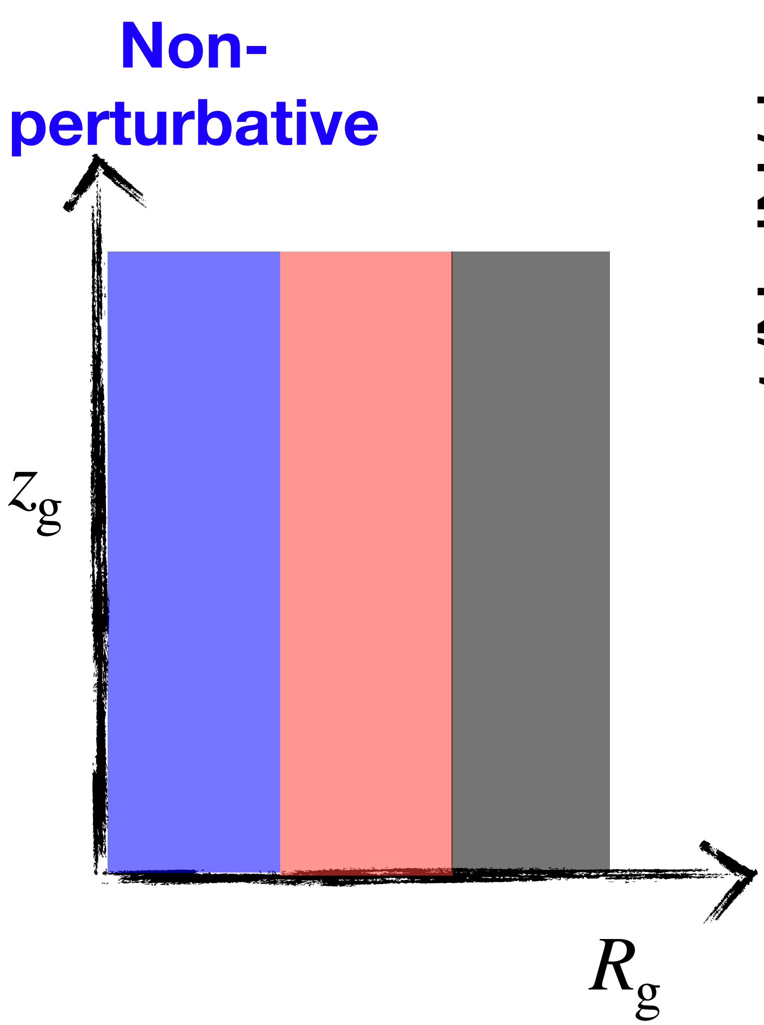
Formation time connecting jet splitting and charged particles in the jet



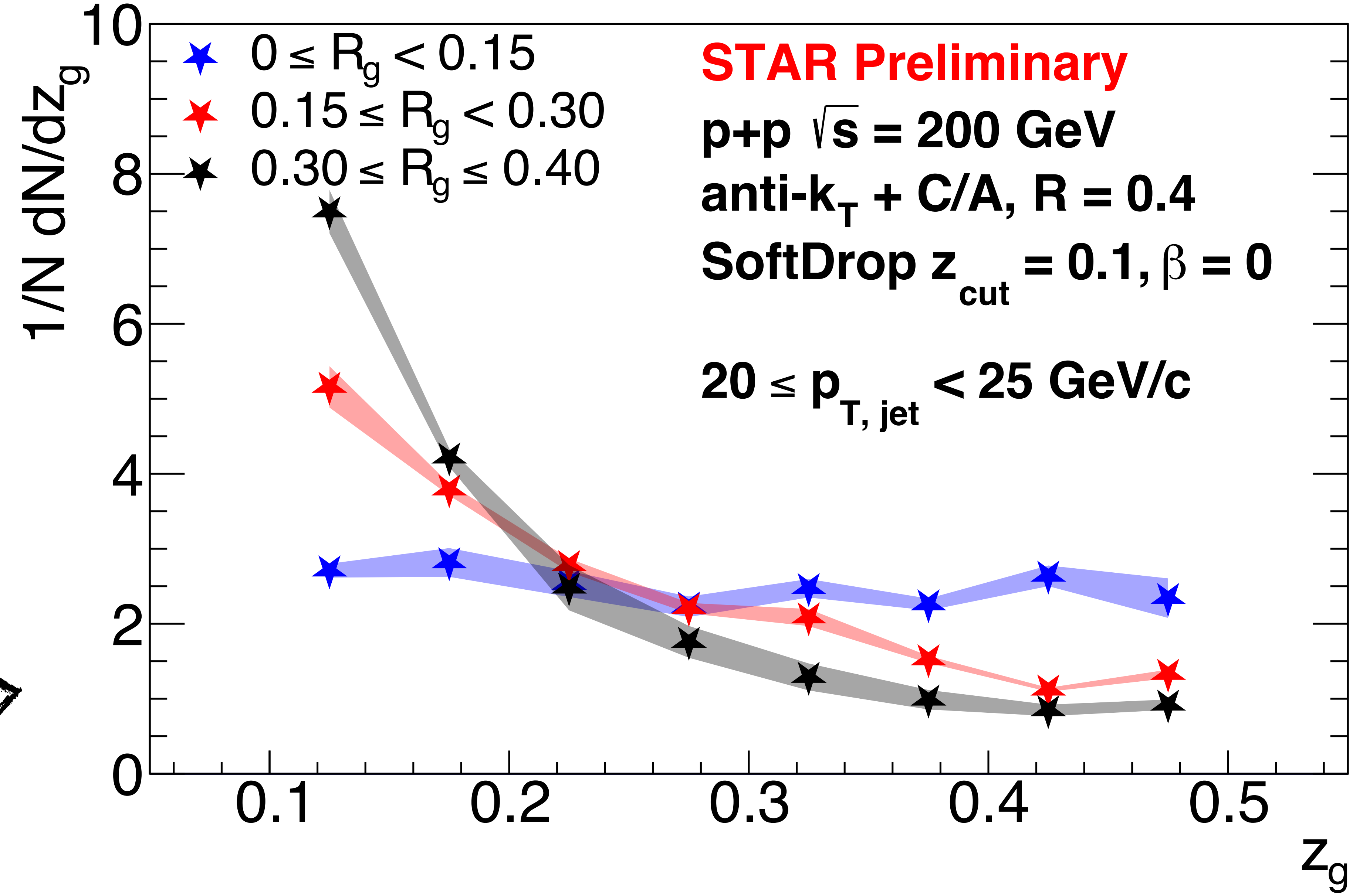


Correlations between substructure observables at the first split

Fully corrected results



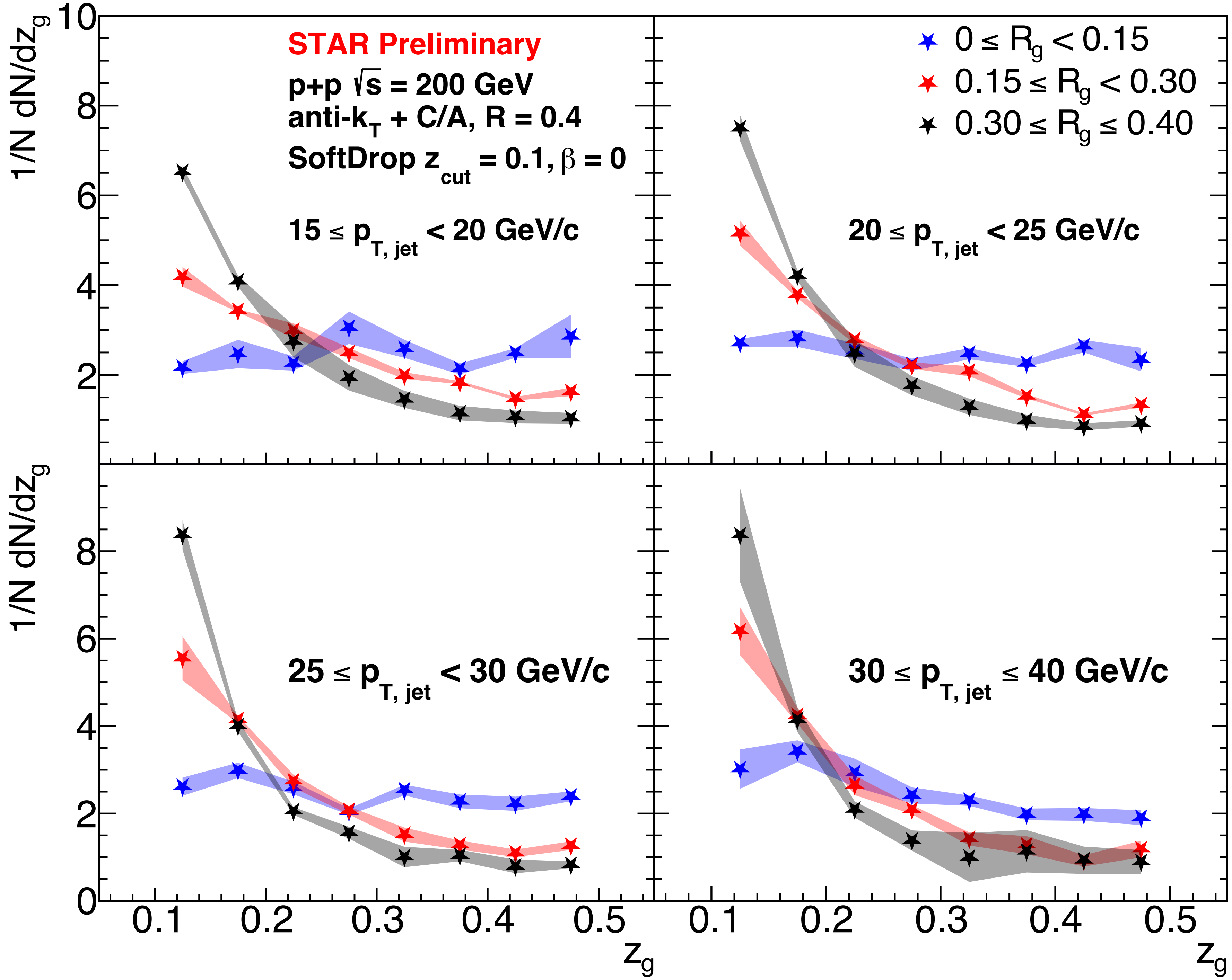
z_g **for various** R_g **at** $p_{T,jet}$ **[20, 25] GeV/*c***



- Significant dependence on R_g
- Evolution from **soft-wide angle splits** to **hard-collinear splits**

Evolution vs. $p_{\mathrm{T,jet}}$

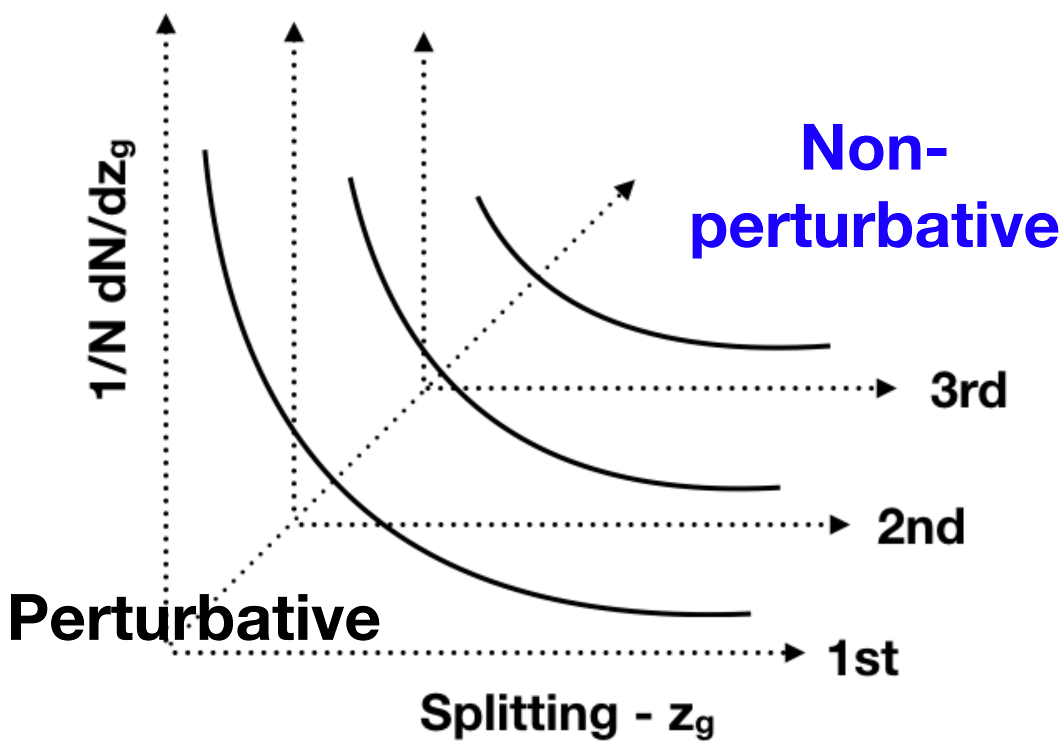
z_g **for various** R_g **at** $p_{\mathrm{T,jet}}$ **GeV/c**

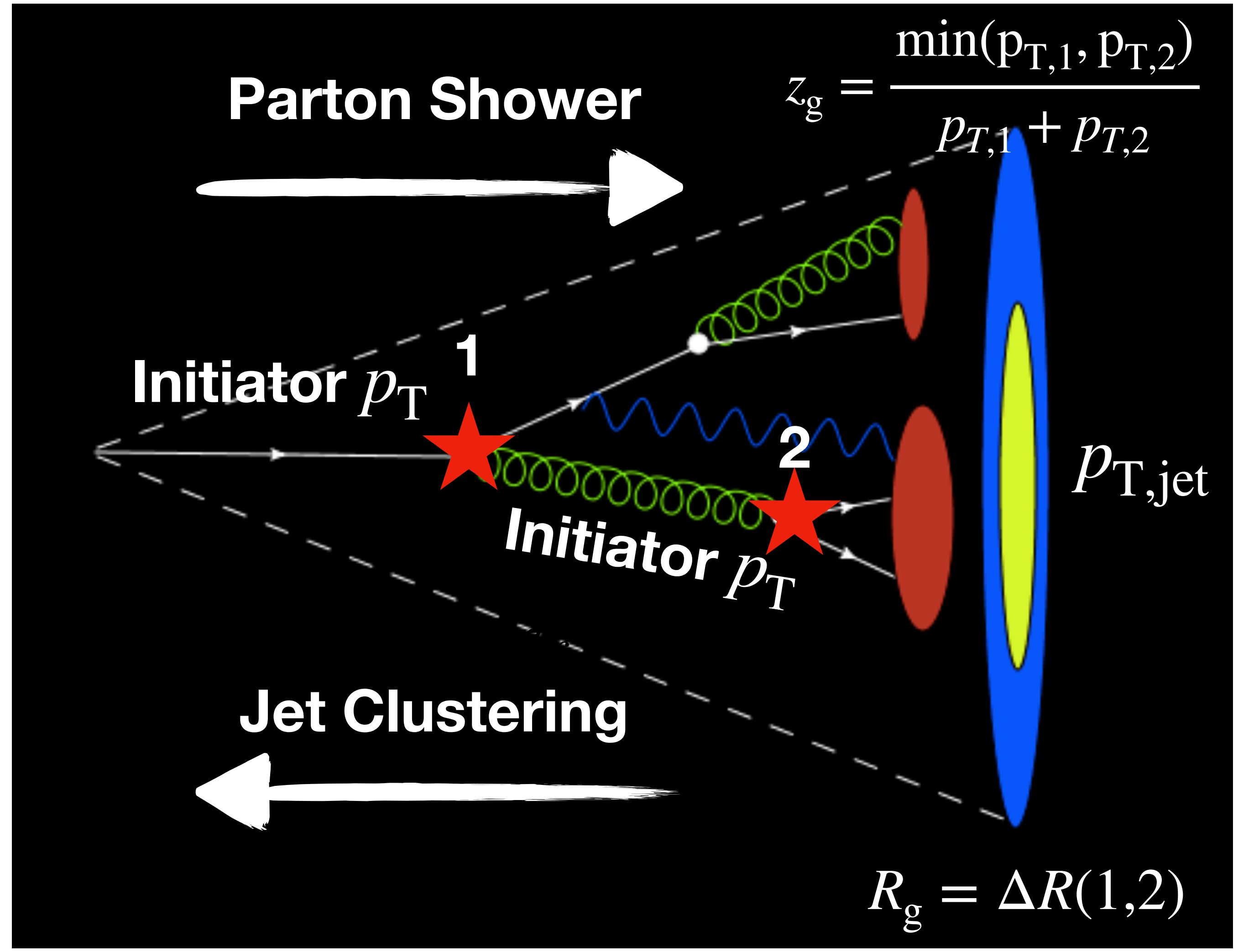


- Increasing $p_{\mathrm{T,jet}}$ has a mild effect on substructure
- Selection on R_g determines the z_g shape - high degree of correlation
- **Phase space restrictions** have a large impact!

$\#\# < p_{\mathrm{T,jet}} < \#\#$ GeV/c

$\#\# < p_{\mathrm{T,initiator}} < \#\#$ GeV/c



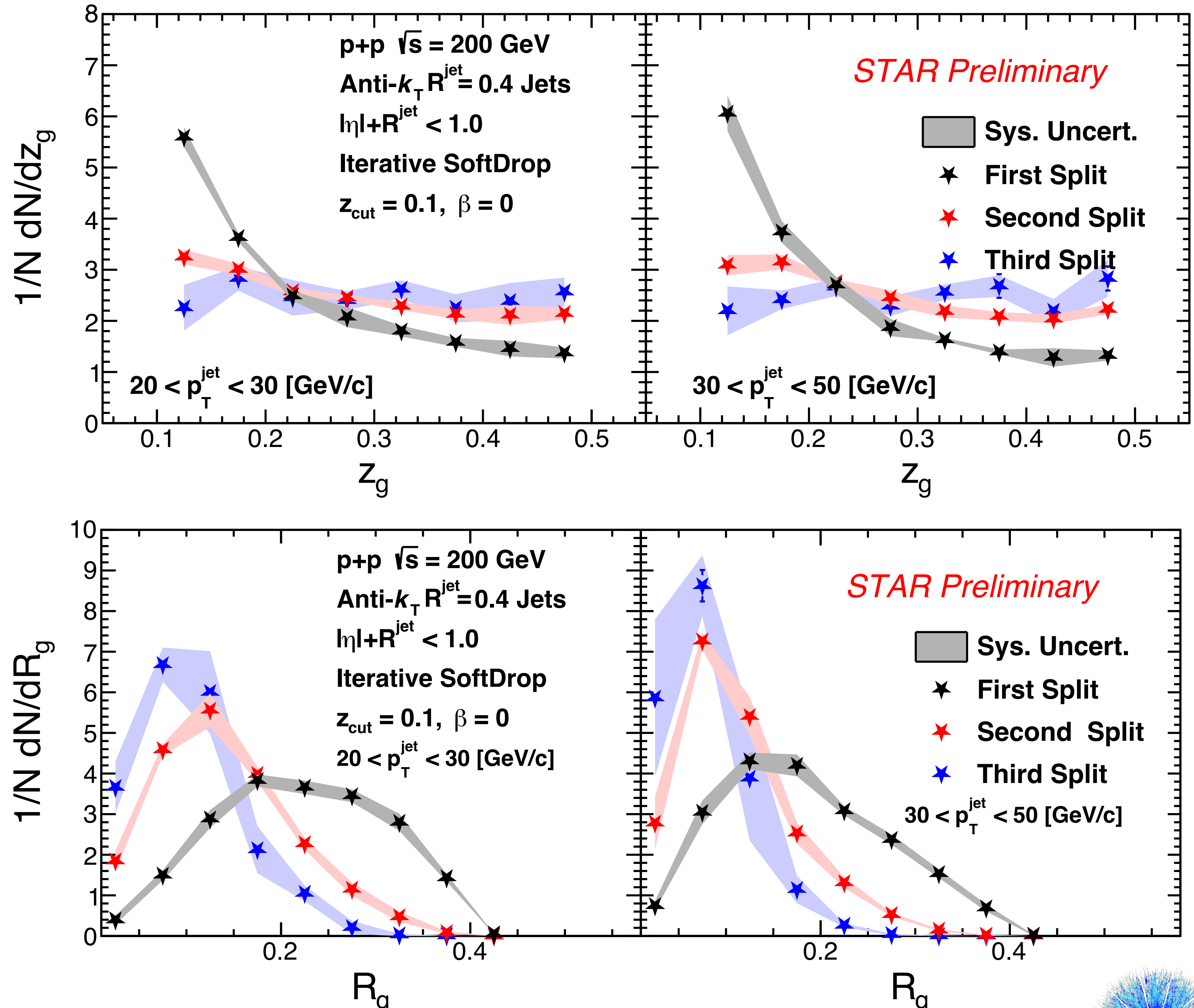


Evolution of the splitting observables as we travel along the jet shower

Fully corrected results

1st, 2nd, 3rd splits for various $p_{\mathrm{T,jet}}$

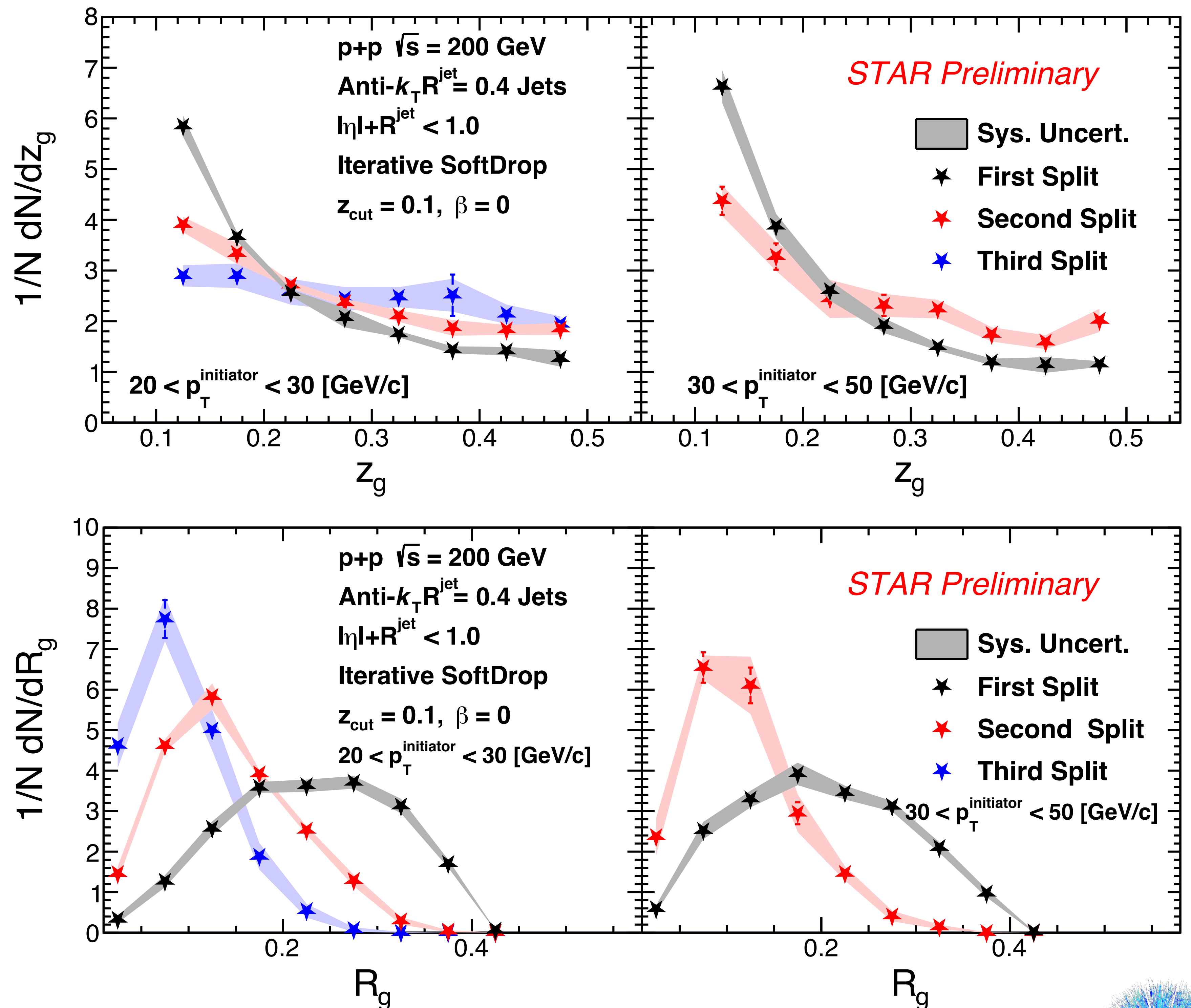
- **For a given $p_{\mathrm{T,jet}}$,** what are the z_g, R_g at 1st, 2nd and 3rd splits? Follow a jet…
- Significant differences between **first**, **second** and **third** splits
- **Flat z_g distribution and smaller $\langle R_g \rangle$** for the third split, where we observe collinear emissions



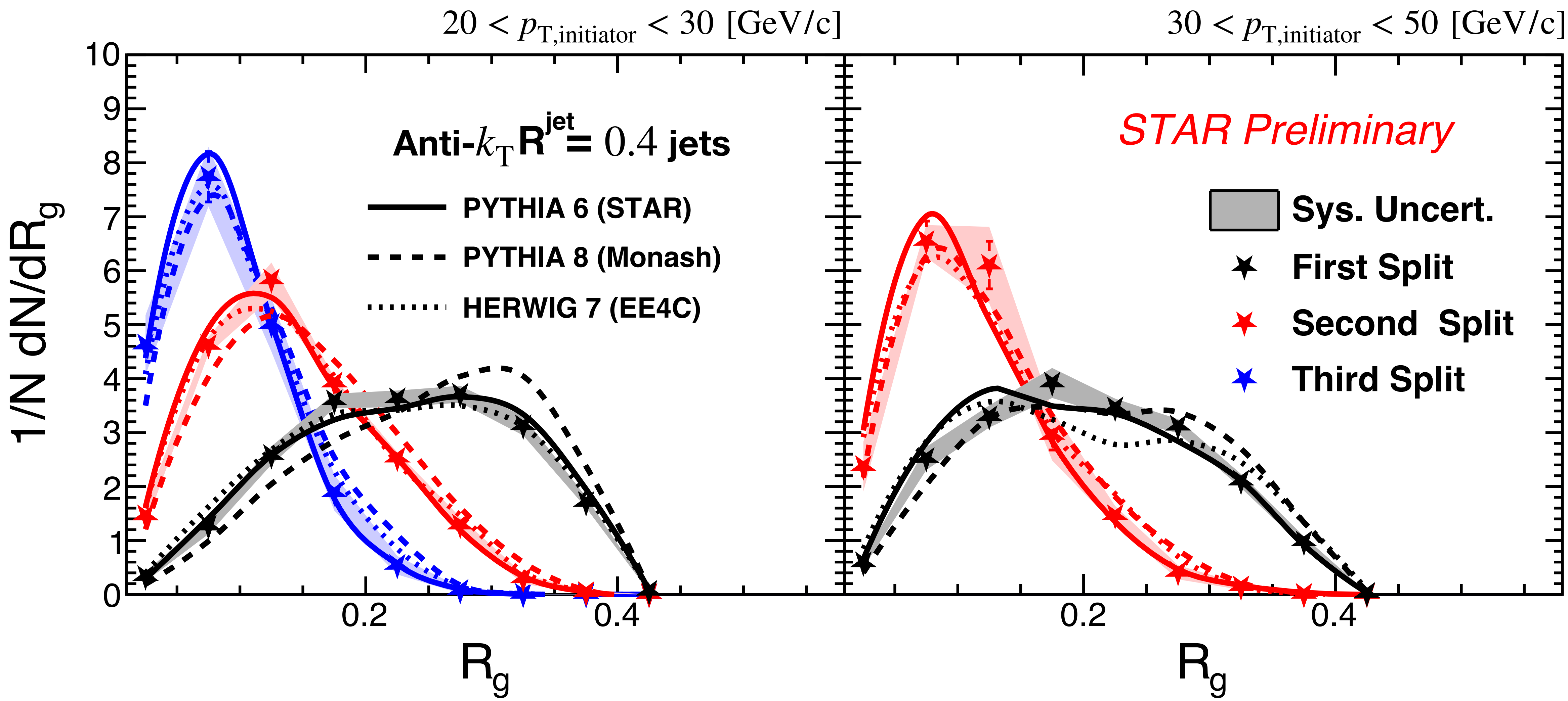
Fully corrected results

1st, 2nd, 3rd splits for various $p_{\mathrm{T,initiator}}$

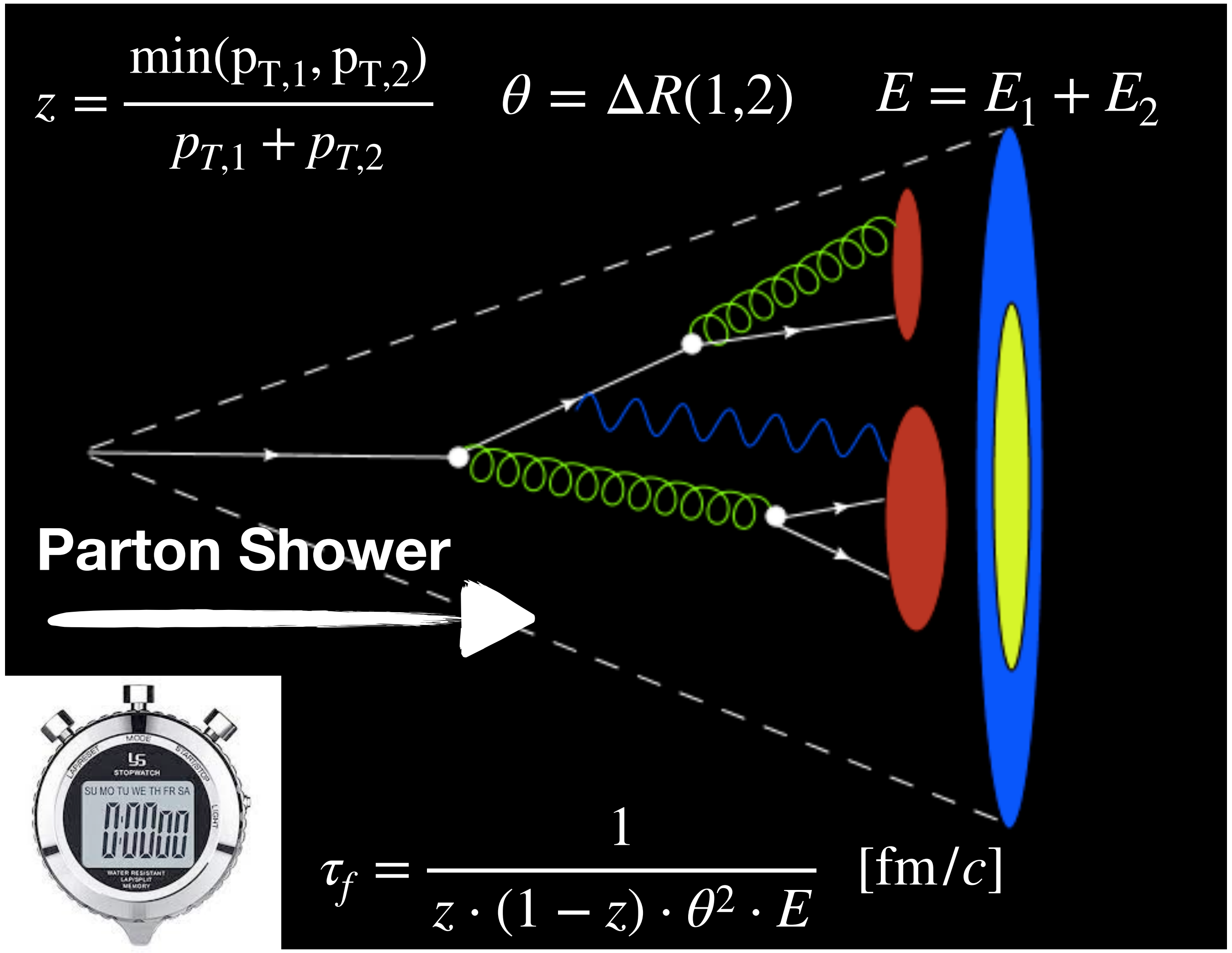
- **For a given split with** $p_{\mathrm{T,initiator}}$, what are the z_g, R_g for 1st, 2nd and 3rd splits? Follow a split…
- **Splits are directly comparable** to each other - only difference is where they occur in the shower
- Hint of differences at the **second split** z_g (similar R_g) for initiator vs. jet momenta selection

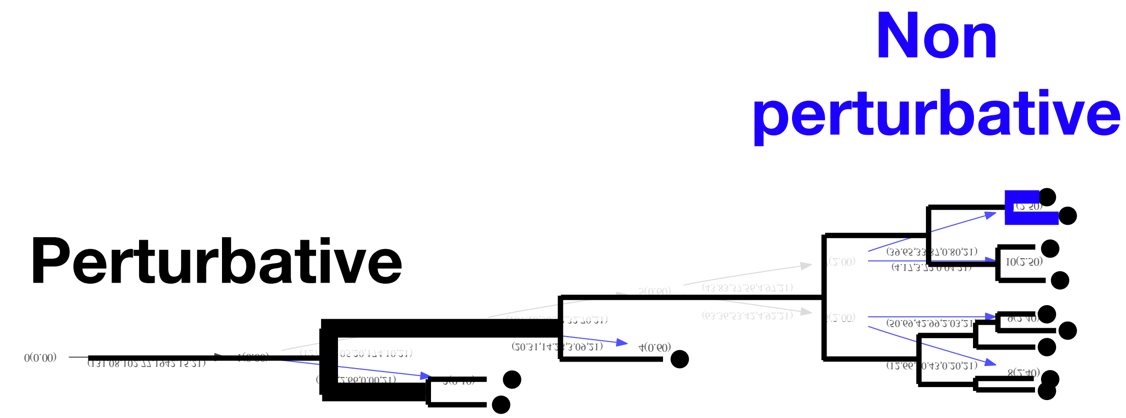


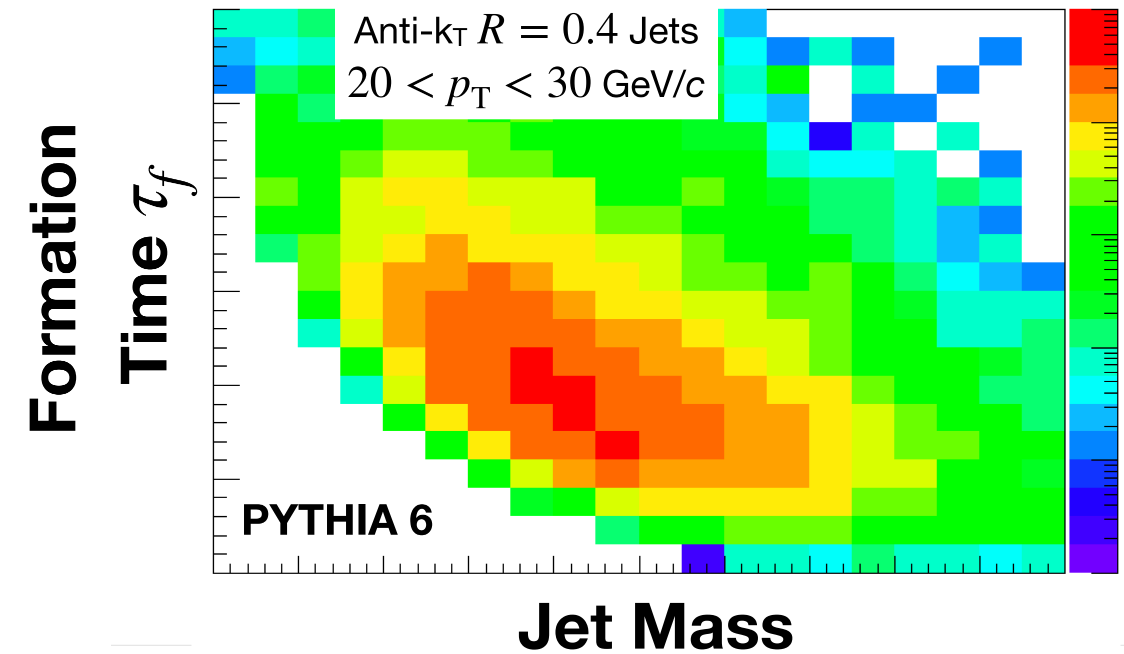
Comparisons with leading order MC - R_g for various $p_{T,\mathrm{initiator}}$



- Three MC (PYTHIA 6, PYTHIA 8, HERWIG 7) **models describe the overall trend of narrowing** of jet substructure for higher splits
- Availability of emission phase space depends on both jet momenta and split number - similar peaks of R_g for **third splits** on the left to **second splits** on the right



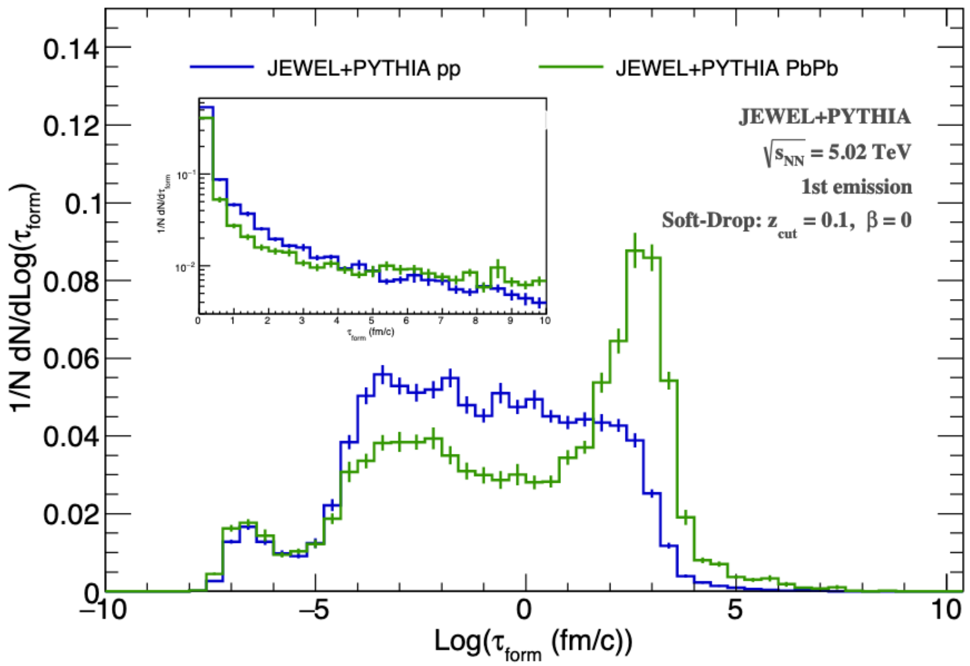




Formation time connecting jet splitting and charged particles in the jet

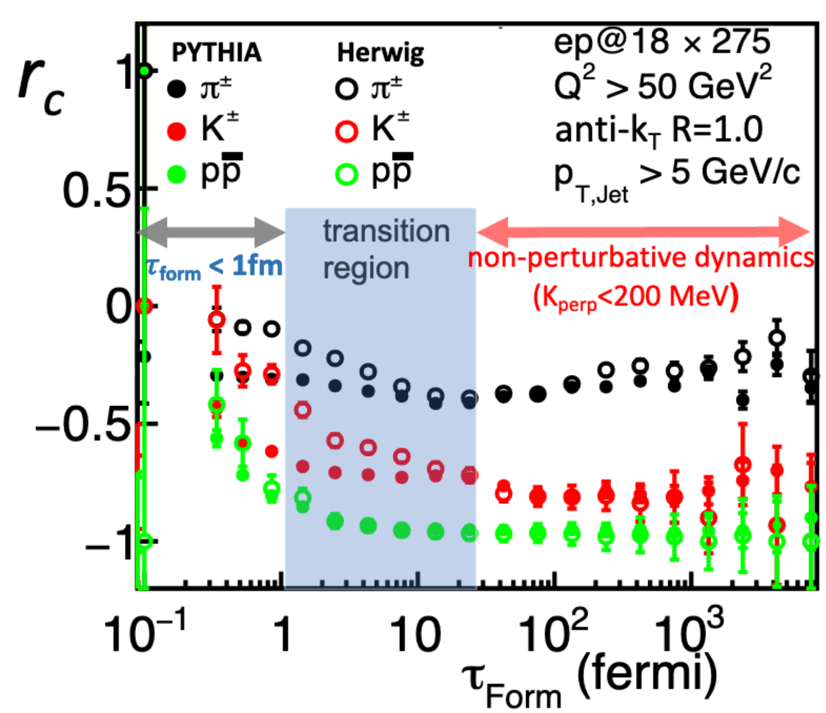
Recent work on formation times

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



- τ_f is a combination of substructure observables that results in a 'time' $$\tau_f = \frac{1}{z \cdot (1-z) \cdot \theta^2 \cdot E} \quad [\mathrm{fm}/c]$$
- Ensemble distributions of τ contain information related to the parton shower
- Useful handle in jet quenching studies

- 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 τ



$r_c \equiv \frac{N_{CC} - N_{C\bar{C}}}{N_{CC} + N_{C\bar{C}}}$

Formation time : $[2z(1-z)\,P]/k_{perp}^2$

z : momentum fraction of NL particle

k_{perp}: relative transverse momentum between L & NL

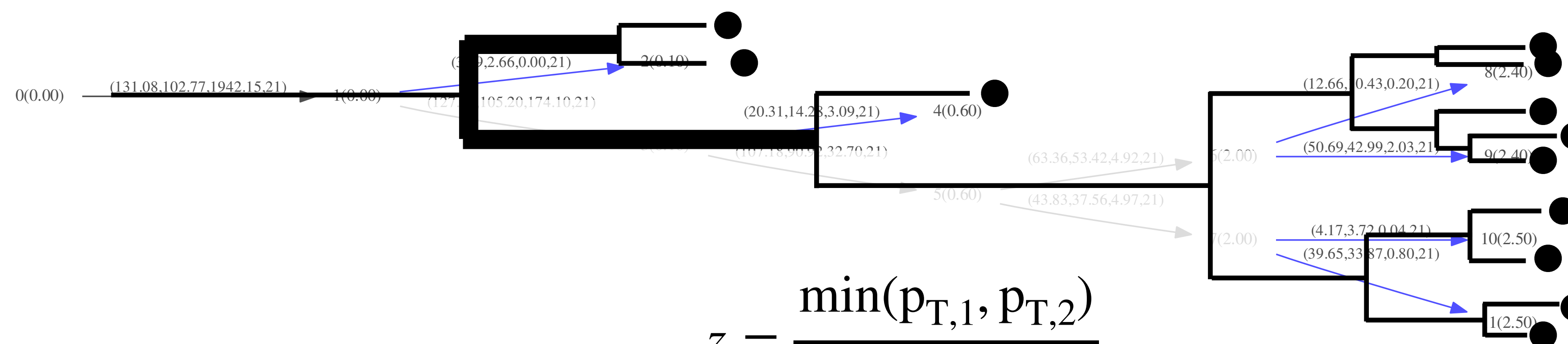
- There is strong flavor dependence in r_c
- In specific kinematic region PYTHIA and Herwig differ significantly

Mondal et. al. @ BOOST 2021

Formation time in jets

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

- SoftDrop first split τ_f (varying z_{cut})



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

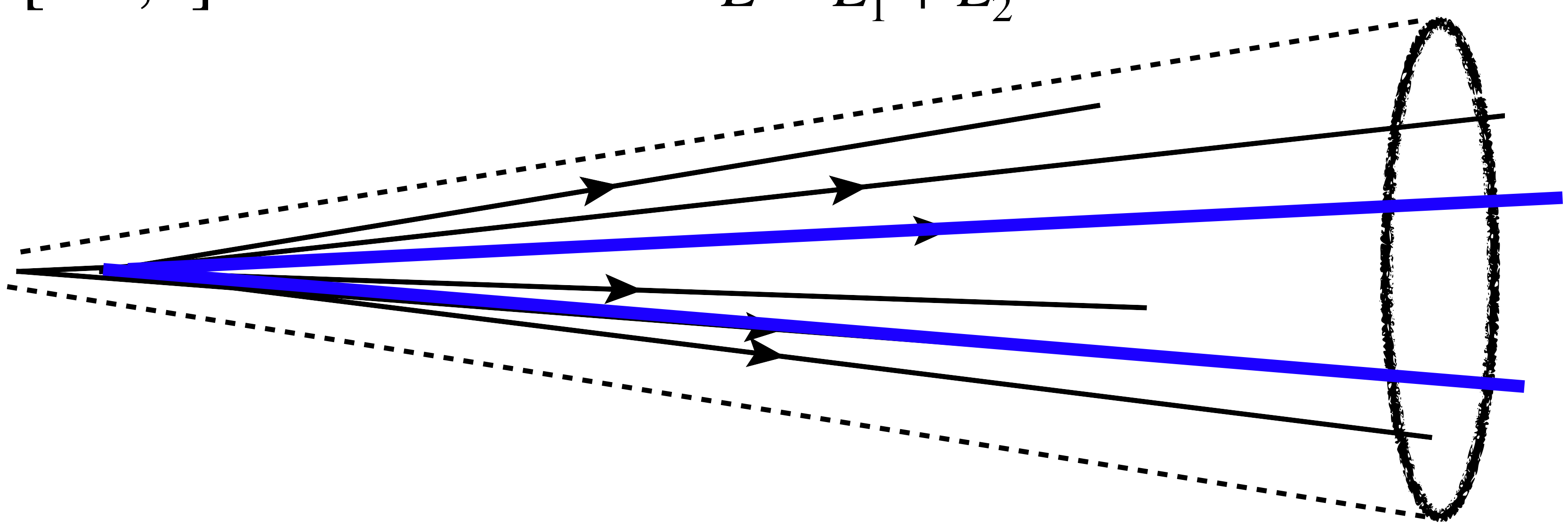
$$z = \frac{\min(\mathrm{p_{T,1}}, \mathrm{p_{T,2}})}{p_{T,1} + p_{T,2}}$$

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

$$E = E_1 + E_2$$

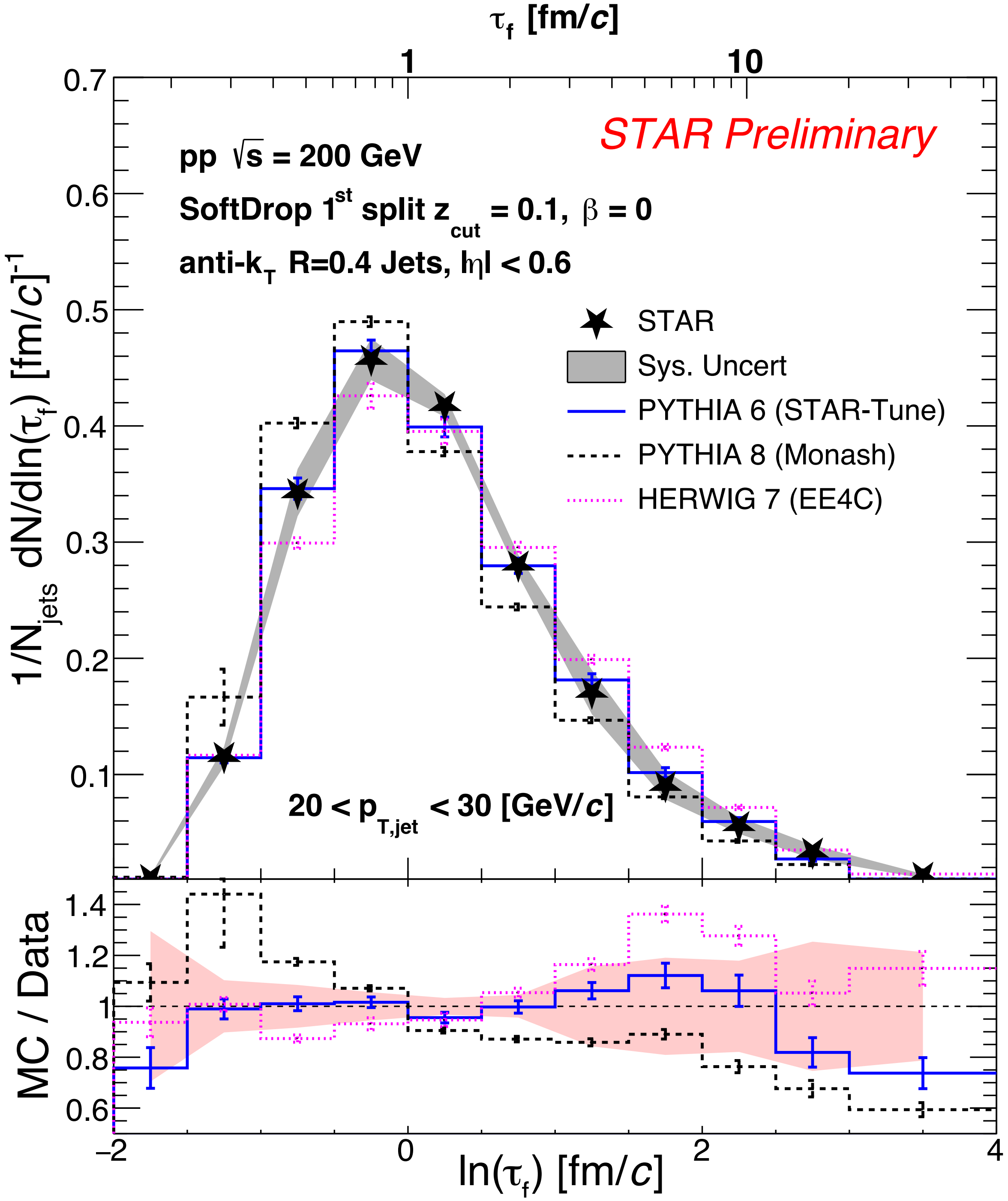
Measure $\ln \tau_f \in [-2,4]$

- Leading and subleading ch-particle τ_f



Mondal et. al. *@ BOOST 2021*

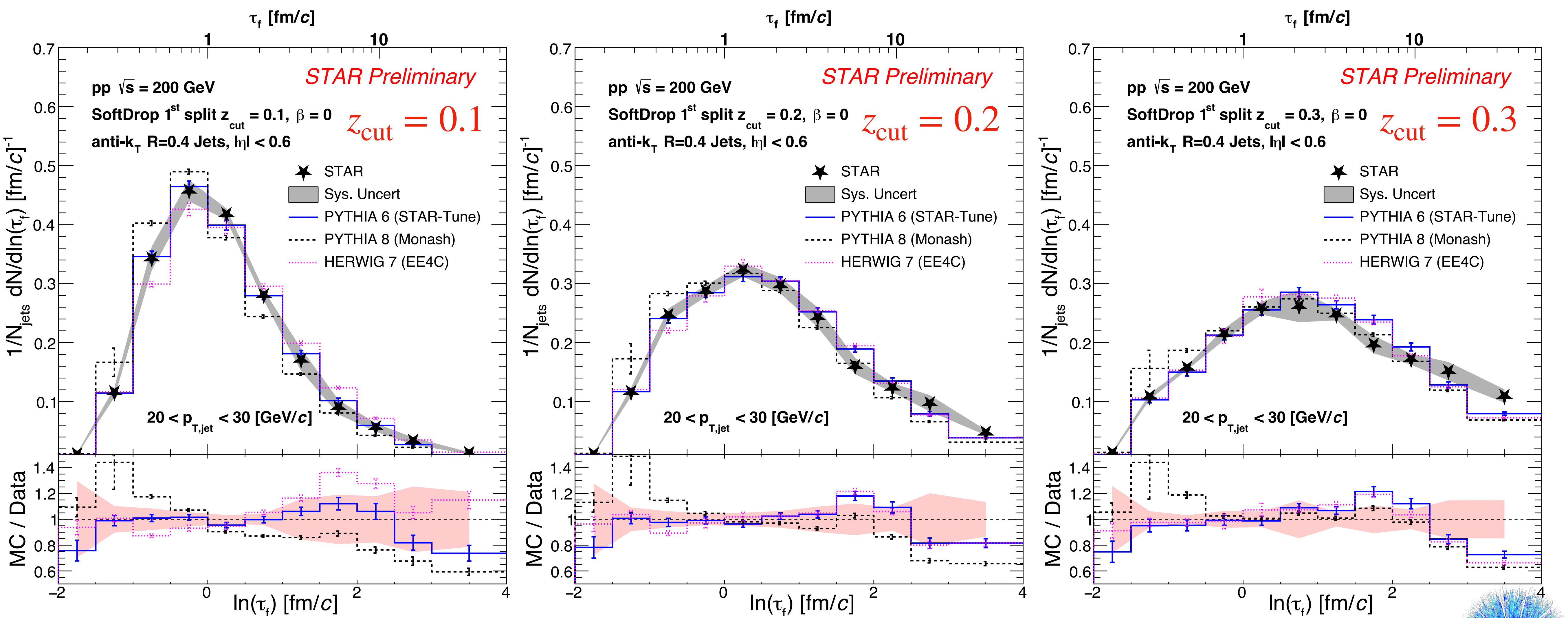
Fully unfolded SoftDrop first split τ_f



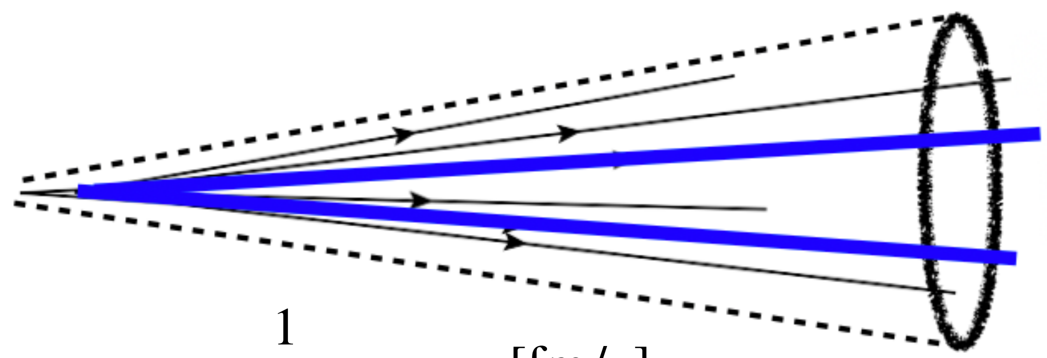
- Peak of the distribution sits roughly around 1 fm/c for jets in our kinematics with $20 < p_T < 30$ [GeV/c]
- PYTHIA 6 generally describes the trend while HERWIG 7 and PYTHIA 8 sandwich the data
- How does this look like if we vary the SD criterion?

Impact of increasing z_{cut}

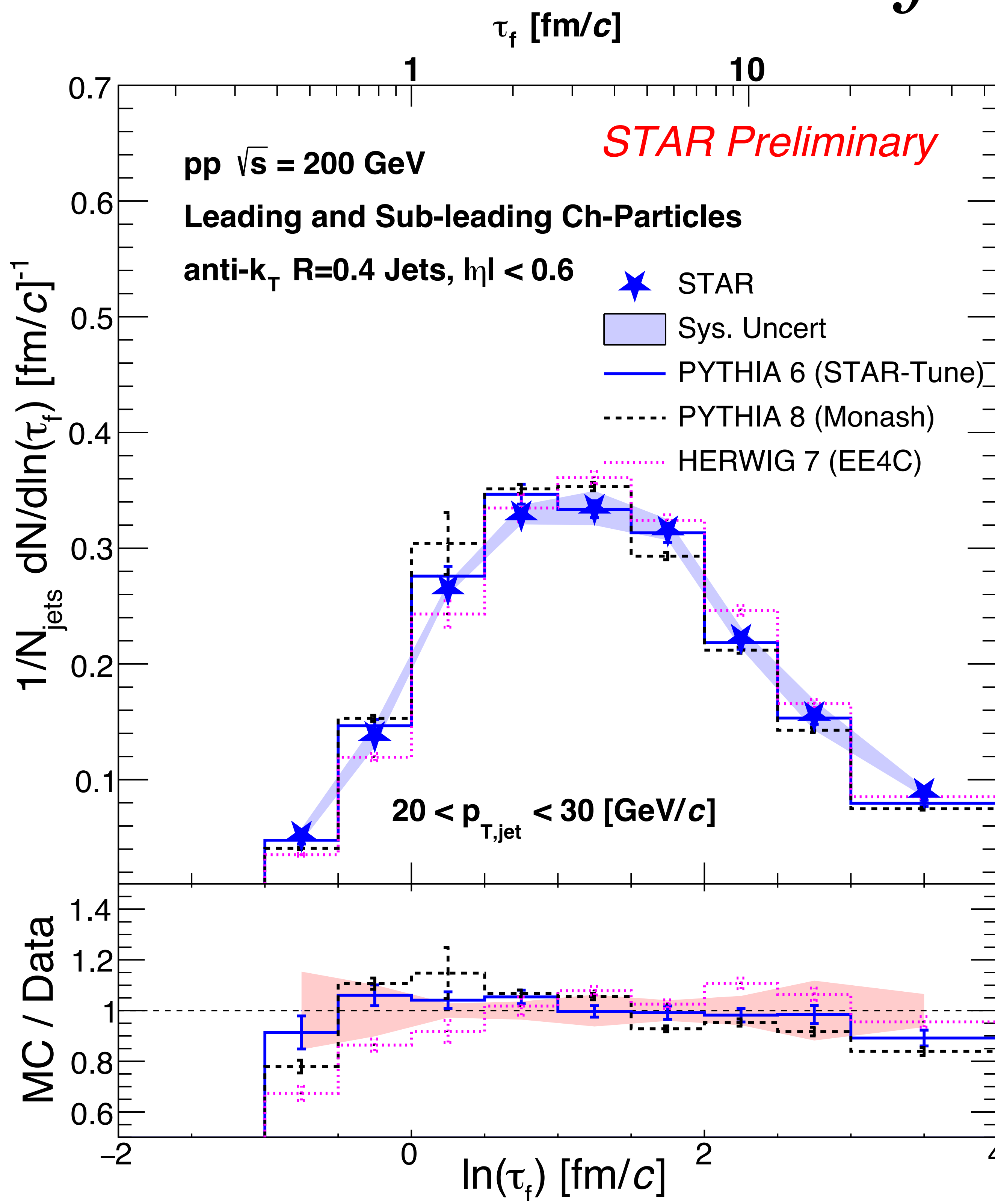
- Increasing z_{cut} effectively grooms away more branches before the criterion is passed
- Similar to traveling further along the shower - evident by the shift in the $\langle \tau_f \rangle$ towards the right



Charged particle τ_f



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



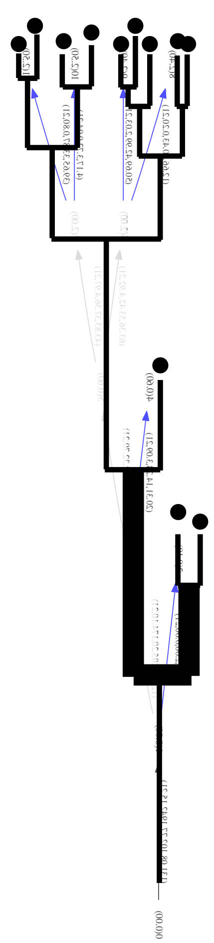
- τ_f calculated using the leading and sub-leading charged particles within jets
- These have much larger $\langle \tau_f \rangle$ than the SD first splits
- These exist in the jet clustering tree somewhere - where/when exactly does the tree resolve these particles?

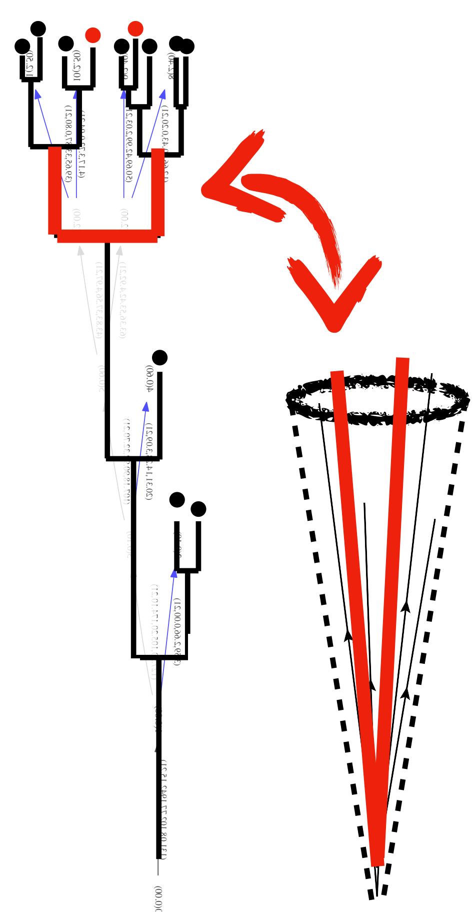
Connecting the two regimes

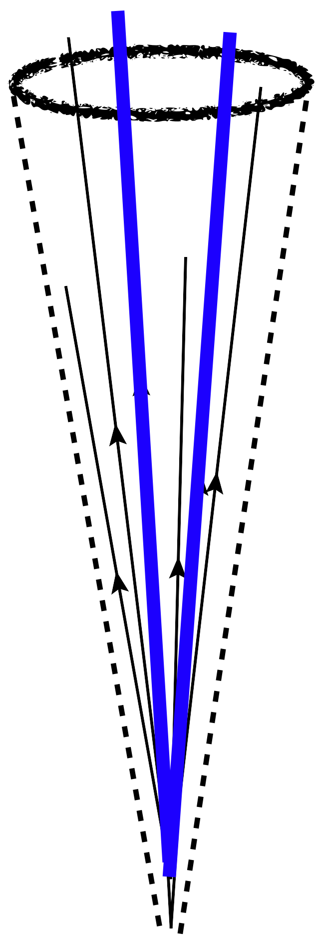
- SoftDrop first split τ_f (varying $z_{\rm cut}$)

- SoftDrop split (varying $z_{\rm cut}$) resolving the two leading charged particles

- Leading and subleading ch-particle τ_f





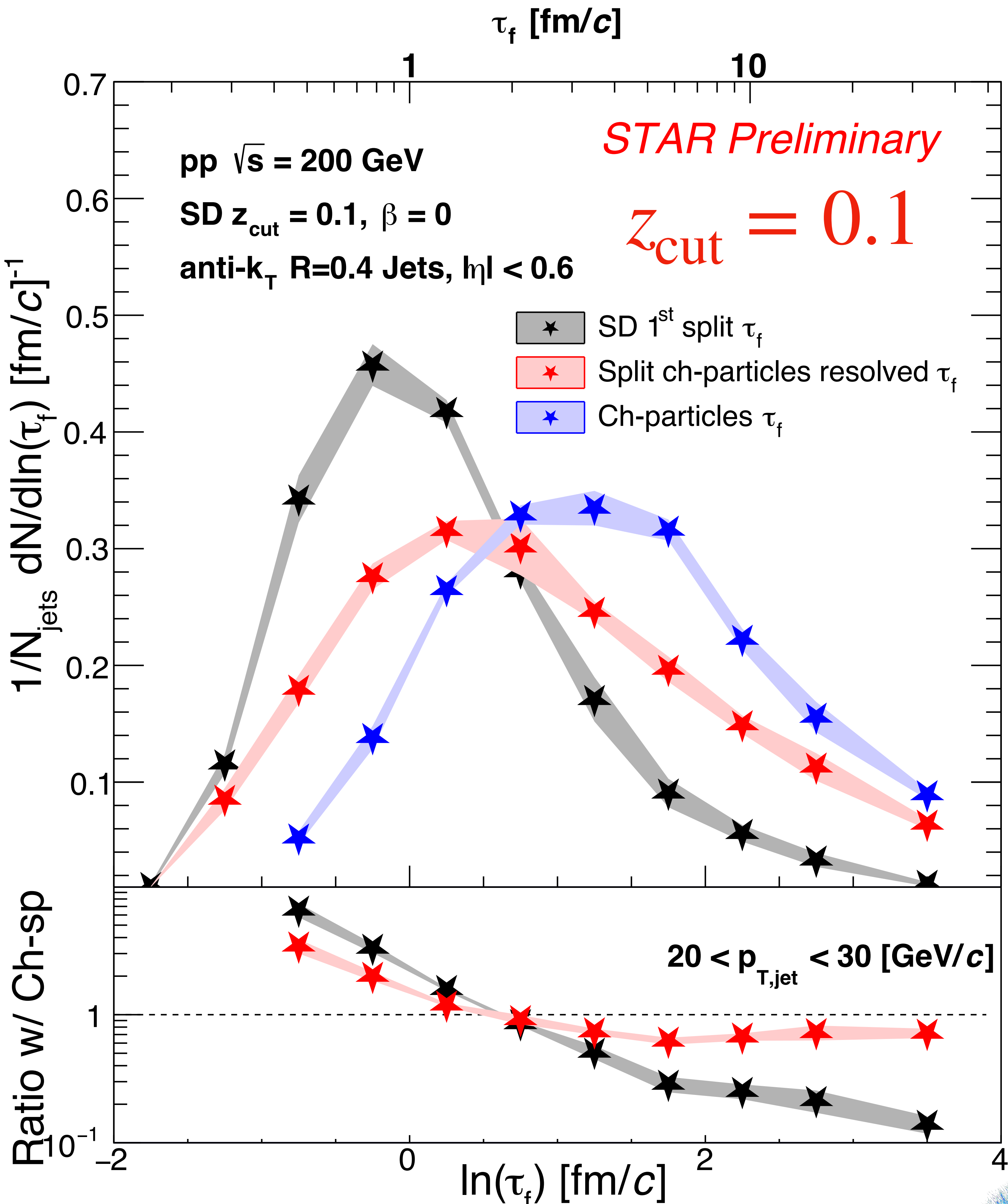


- **SD first splits are significantly earlier in time** compared to the **charged particles**

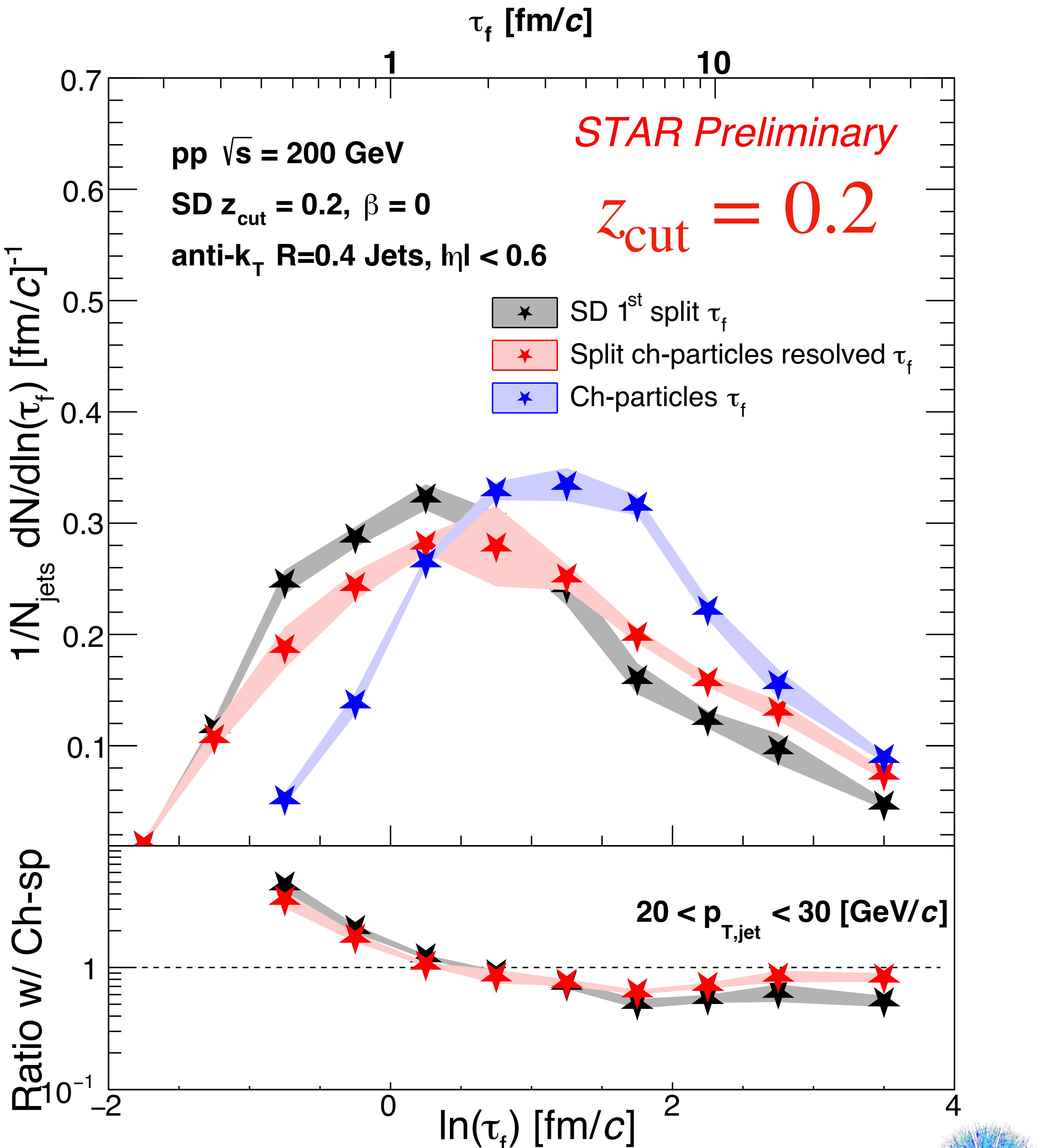
- At $\approx 2-3$ fm/*c*, we see the ratio for SD splits go less than 1

- **Resolved splits have similar shape** to the ch-particle splits after $\approx 3-5$ fm/*c*

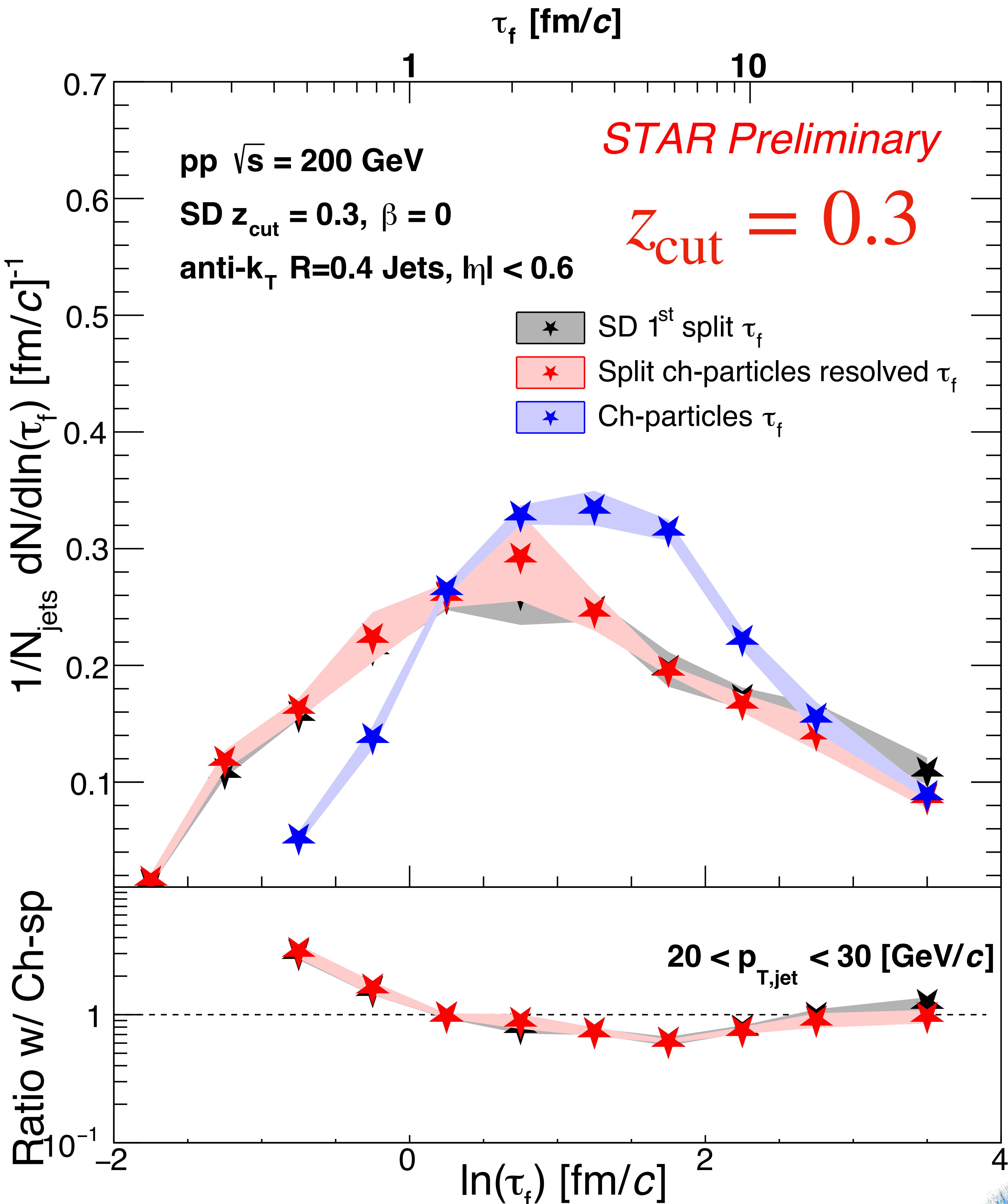
- What happens if we increase z_{cut}?



- Increasing to z_{cut} = 0.2 requires harder splitting scale
- The **first split** and **resolved split** distributions start to become similar
- Meaning that we are moving **further along the shower in time** towards the **charged particle τ_f**

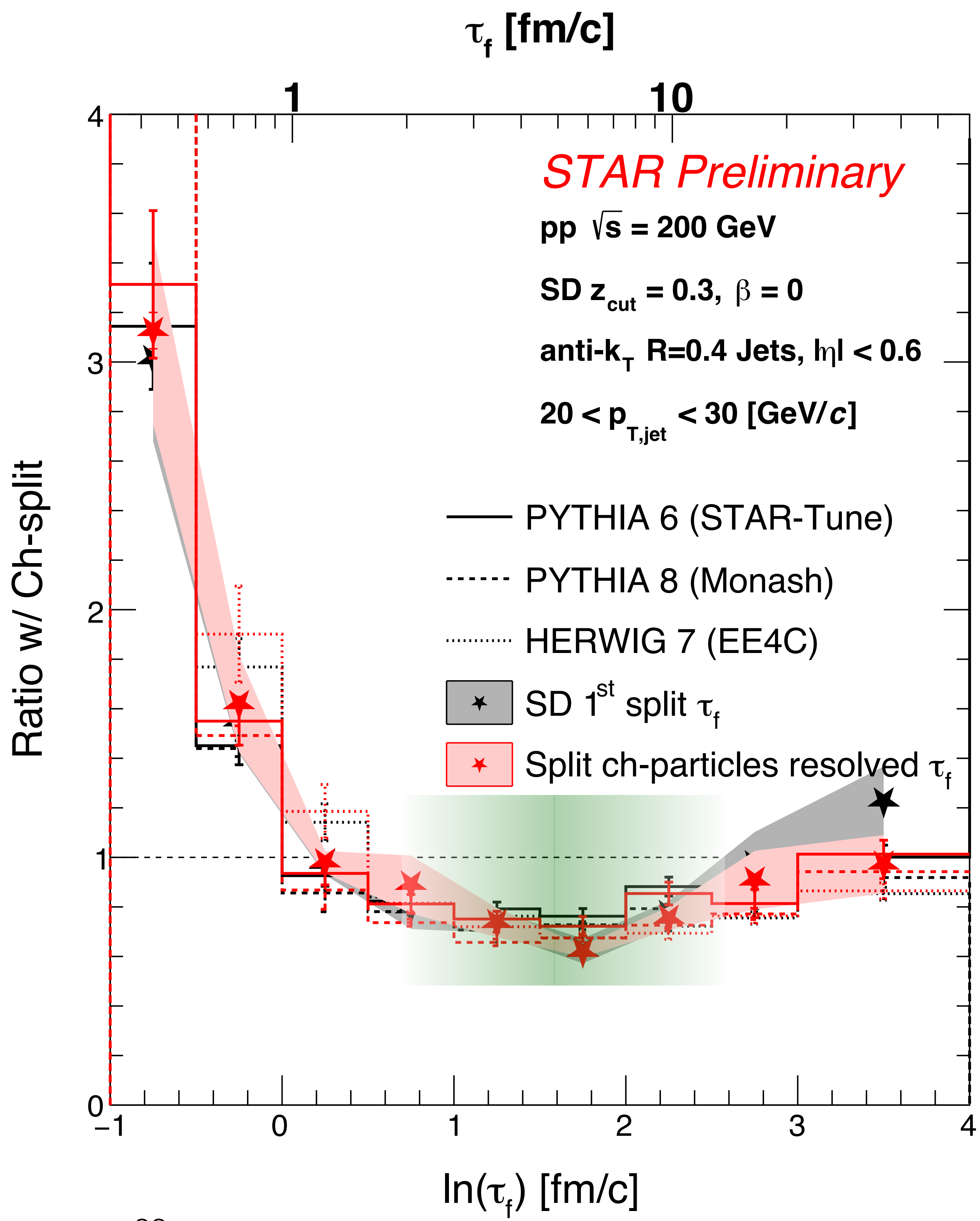


- No difference between the first spilt with extreme z_{cut} and the resolved split!
- Surviving jets have a **formation time bias** to have later splits that are in the **(mostly) non-perturbative region**



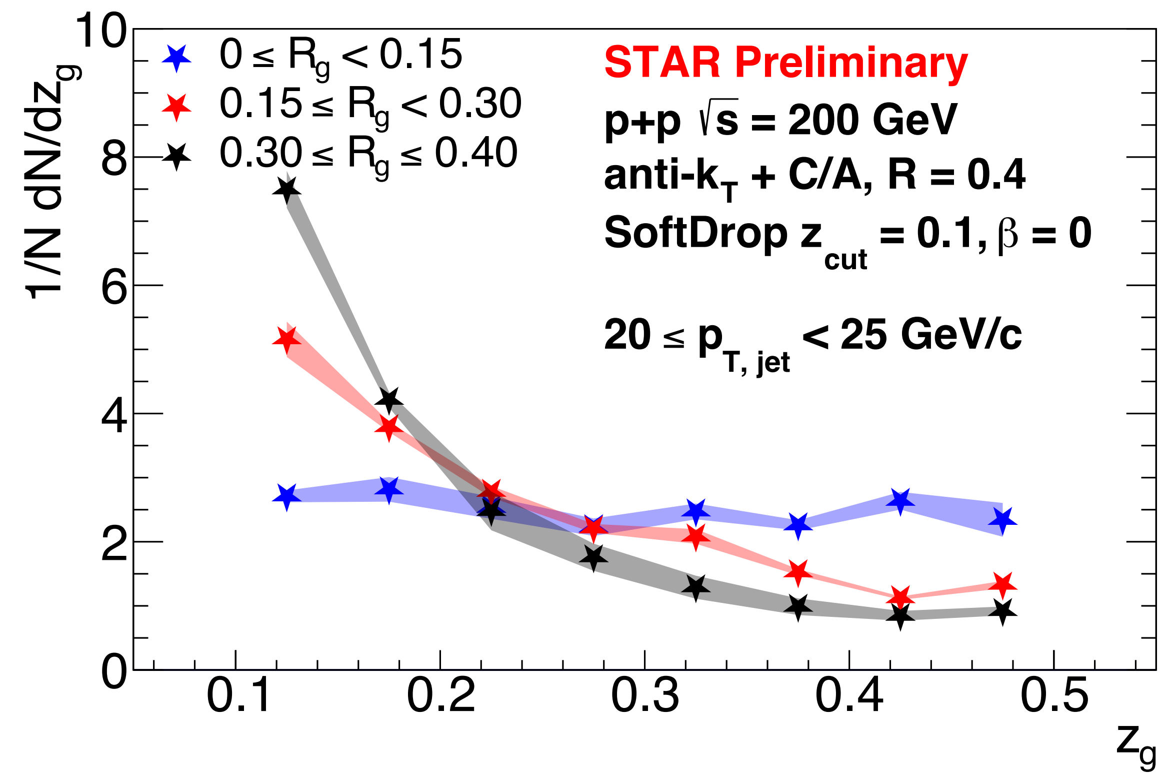
Comparison to MC

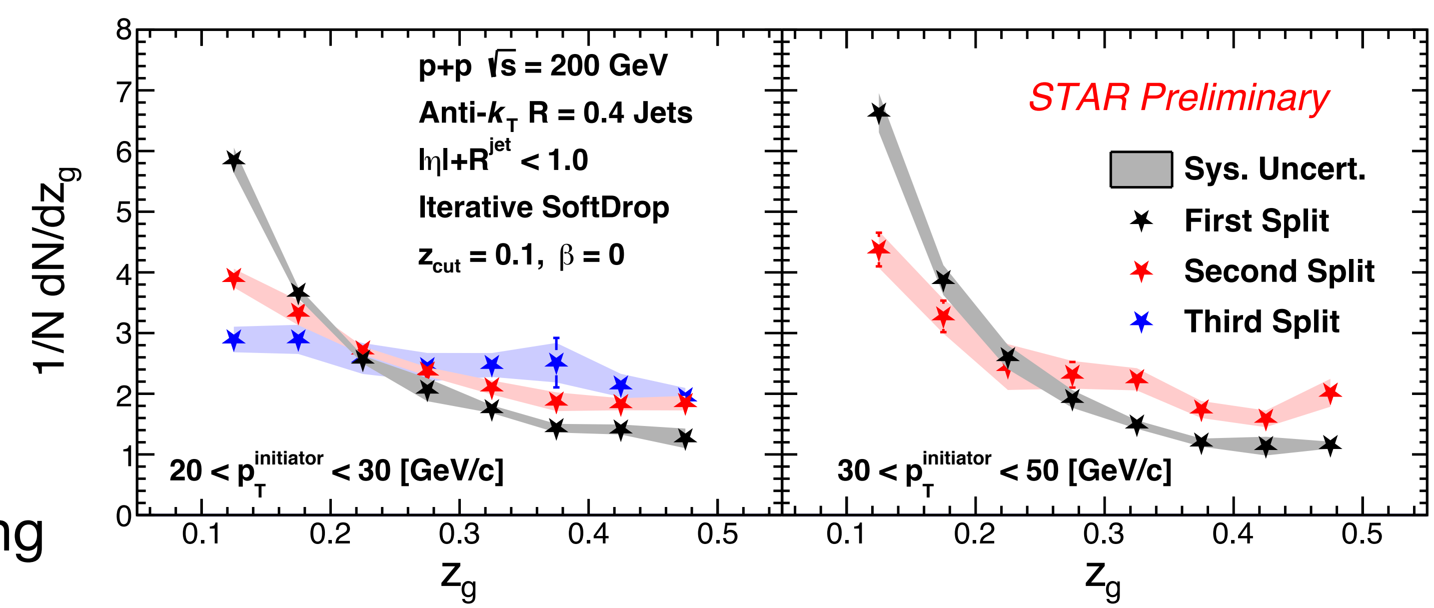
- PYTHIA 8, PYTHIA 6 and HERWIG 7 show similar behavior of crossover and flattening
- Hints of differences between PYTHIA 6/8 and HERWIG 7 in the crossover region (ratio goes from > 1 to < 1)
- Comparison of hadronization models to data across the measured τ_f range will be crucial in studying the pQCD -> npQCD transition region (shown in the green box on the figure)



Conclusions - I

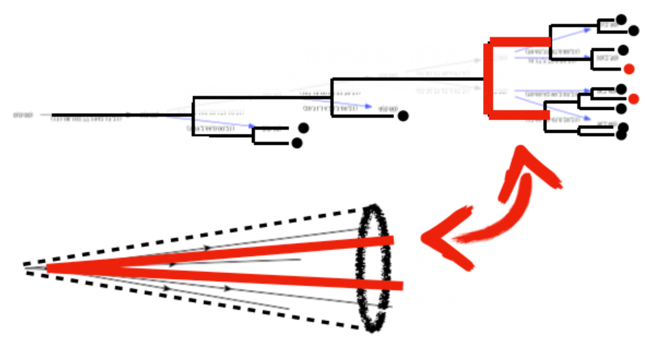
- Jet substructure program at STAR aims at **mapping jet evolution** at RHIC energies
- Data show a **gradual variation in the available phase space**
  - leading to modifications (e.g. virtuality evolution) in the observed splitting kinematics
- Observe increased probability of **significantly harder/symmetric splittings** at the **third/narrow split** compared to the first and second splits
- Subjets at RHIC allow to **disentangle perturbative and non-perturbative dynamics of jet evolution** - these **third and narrow splits** for our low p_T jets end up being quite close to the Λ_{QCD} scale

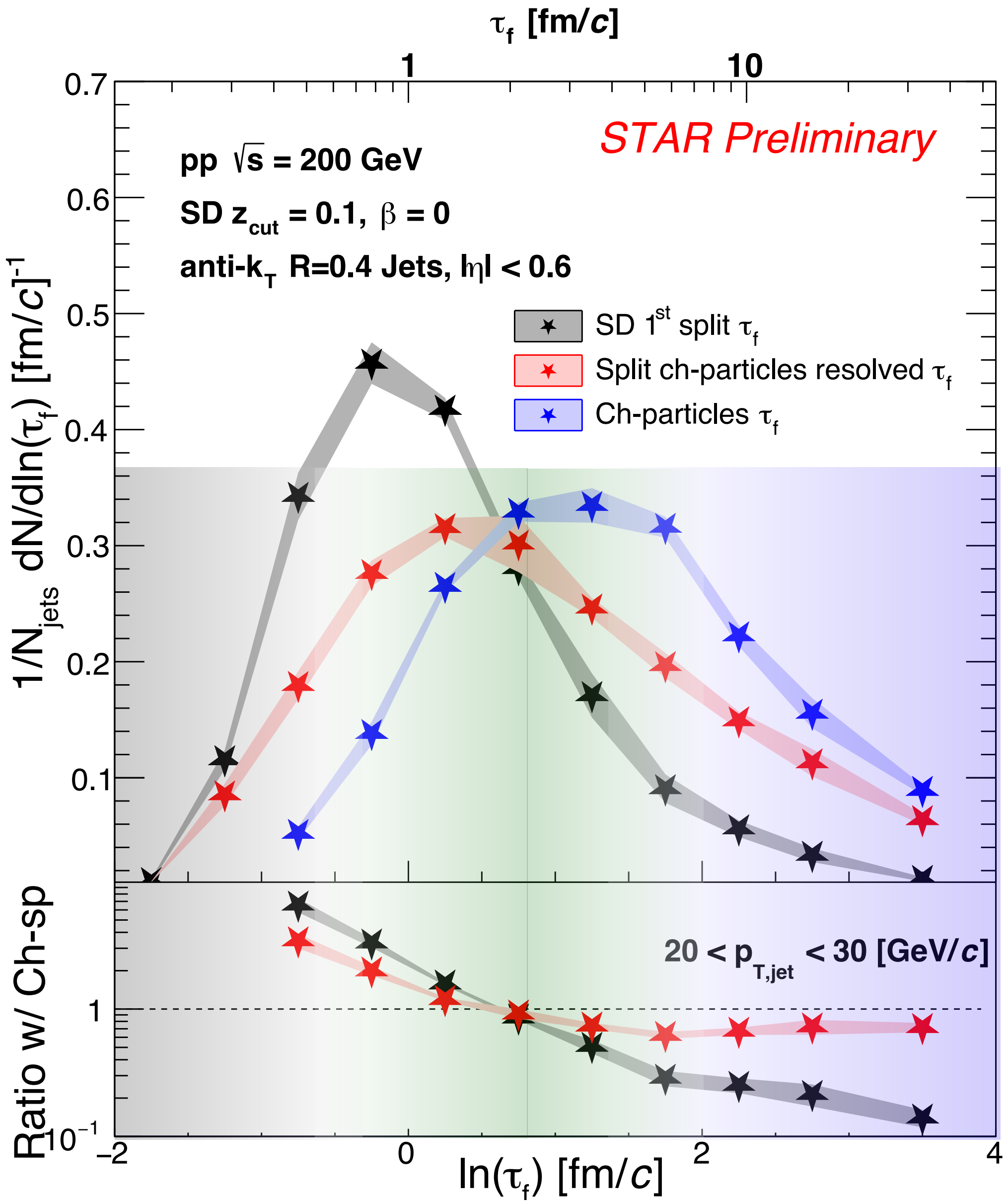




Conclusions - II

- **First measurements of formation time** from the jet splitting trees and from charged particles in the jet
- As the z_{cut} increases, the **crossover in τ_f moves to the earlier time**
- **Resolved SD splits** show **similar shape** as the **charged particle split** at large τ_f values occurring in the predominantly **non-perturbative region**
- Comparison of the different splits highlights the transition from **pQCD to npQCD**





Backup

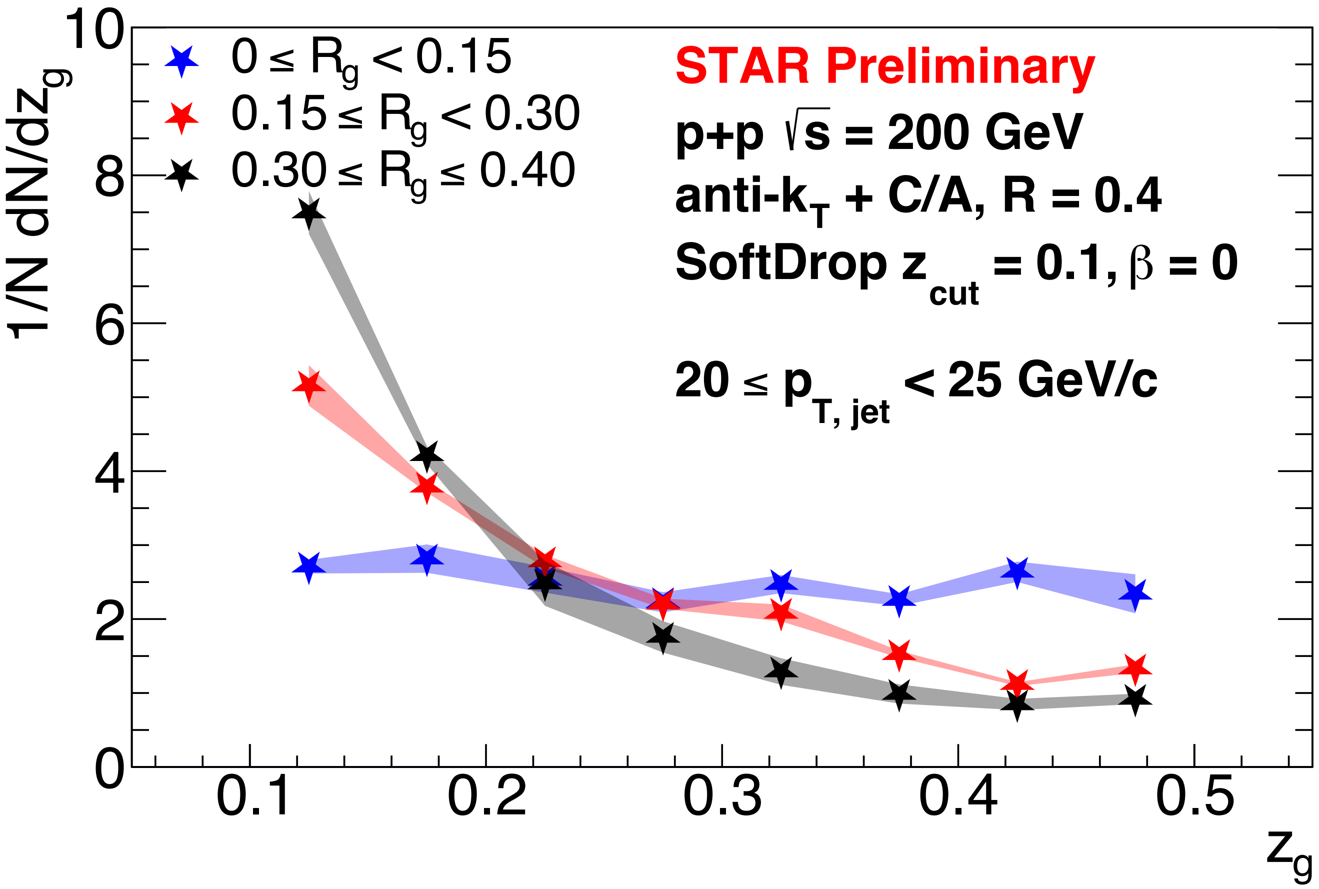
Next steps

- In our upcoming final results we will delve further into comparisons
  1. Various handles in the MC -

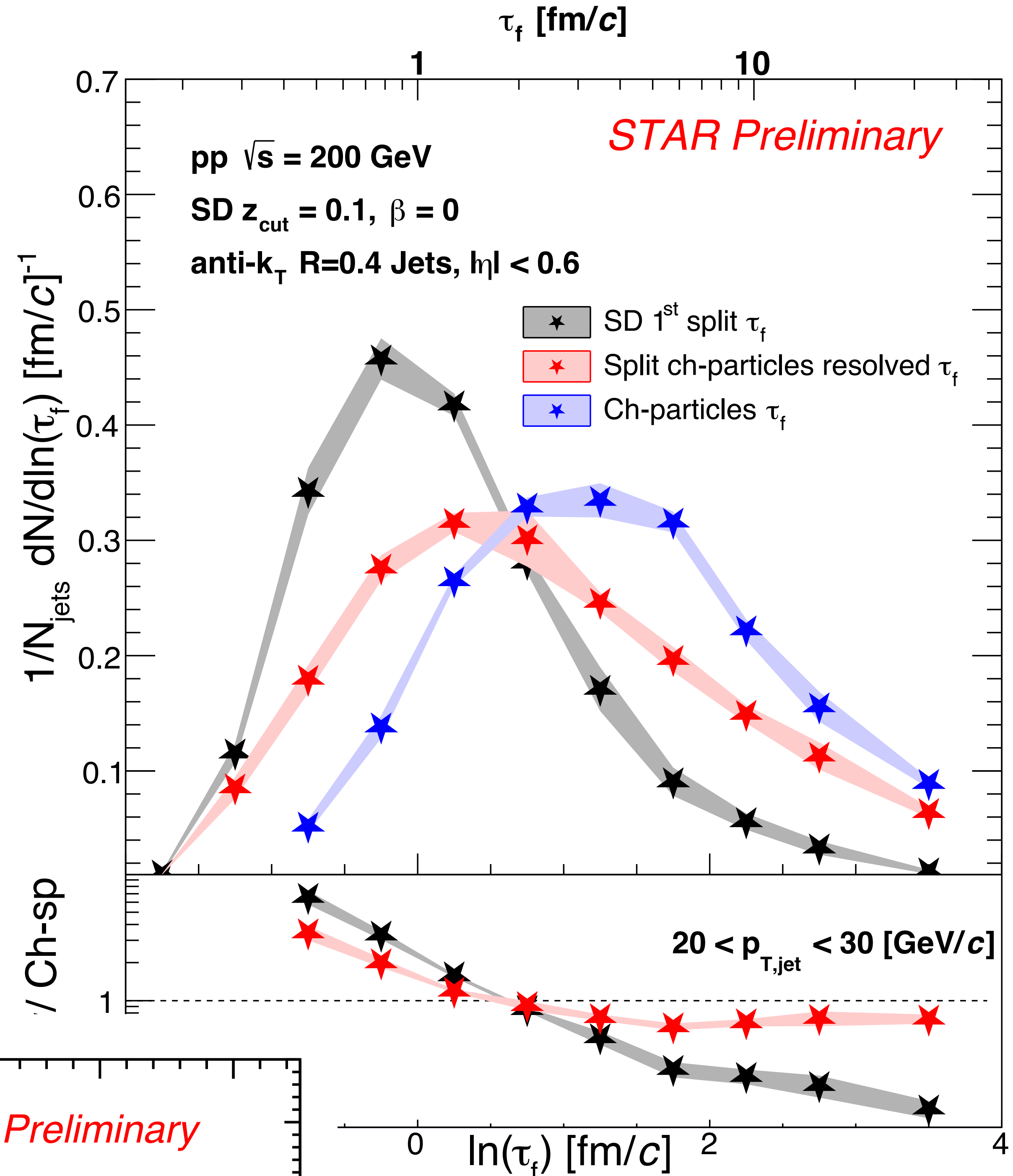
	Parton Shower	Hadronization	UE Tune
PYTHIA-6	k_T	Lund	RHIC
PYTHIA-8	Dipole/Vincia/p_T	Lund	RHIC/LHC
HERWIG-7	Angular/Dipole	Cluster	LHC
SHERPA	Dipole	Lund/Cluster	LHC

  2. In discussion with our theory colleagues on feasibility of calculations

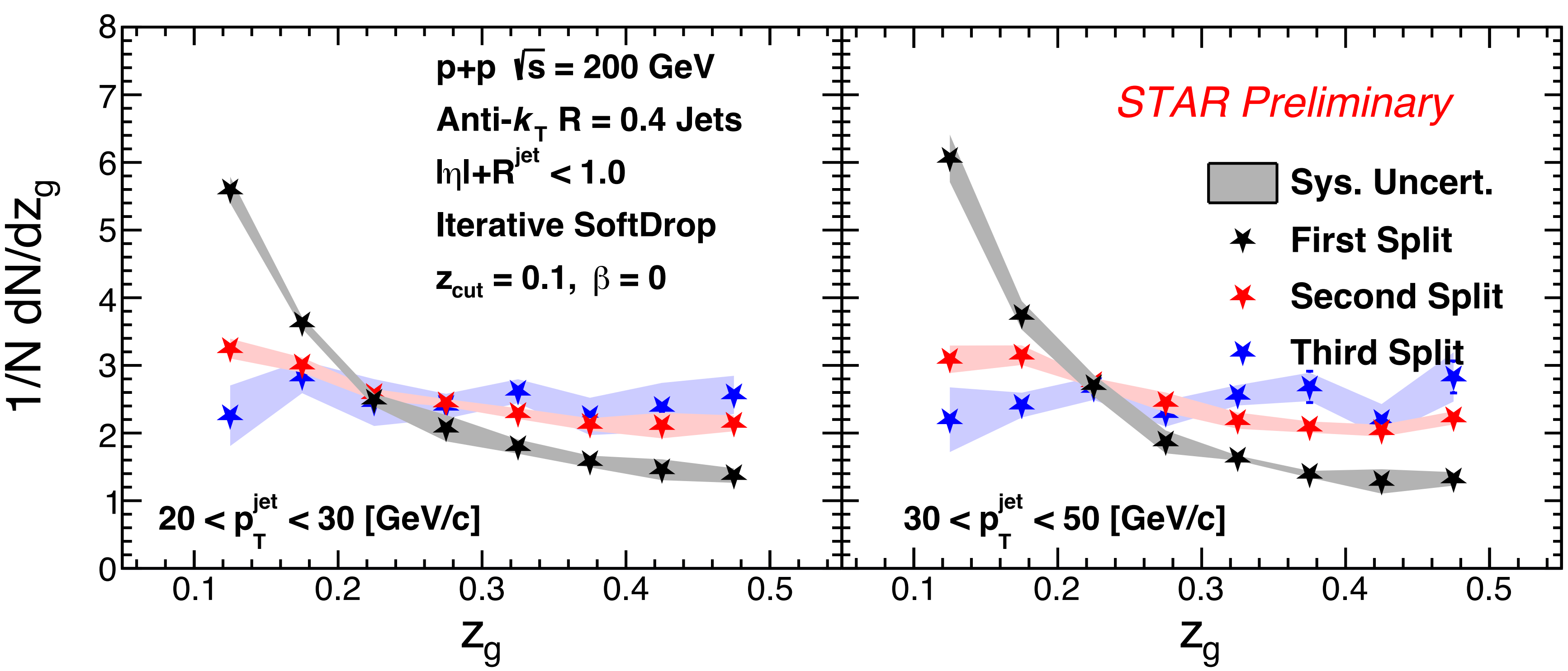
- First measurement that can potentially **distinguish experimental quantities according to a 'time scale'** via formation time of splits - Extremely useful in a heavy ion environment



0 ≤ Rg < 0.15
0.15 ≤ Rg < 0.30
0.30 ≤ Rg ≤ 0.40
STAR Preliminary
p+p √s = 200 GeV
anti-kT + C/A, R = 0.4
SoftDrop zcut = 0.1, β = 0
20 ≤ pT, jet < 25 GeV/c
1/N dN/dzg
zg



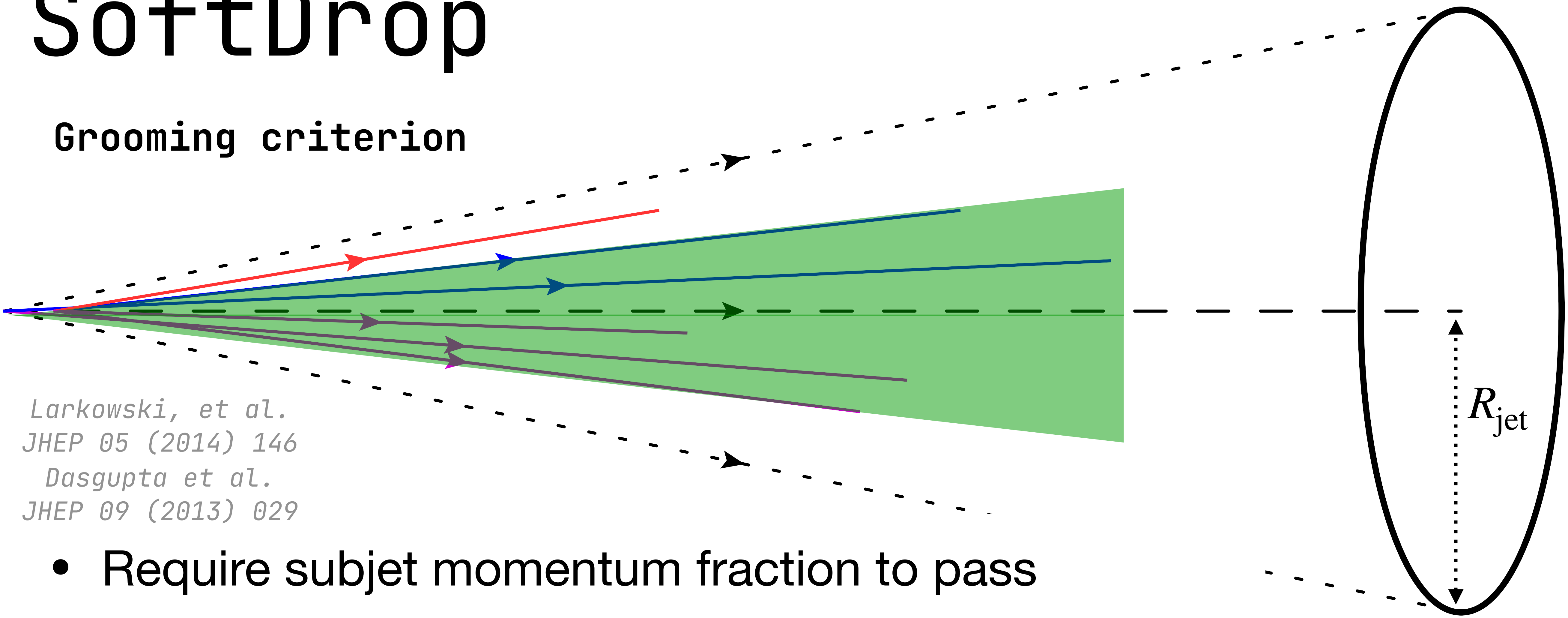
τf [fm/c]
STAR Preliminary
pp √s = 200 GeV
SD zcut = 0.1, β = 0
anti-kT R=0.4 Jets, |η| < 0.6
SD 1st split τf
Split ch-particles resolved τf
Ch-particles τf
1/Njets dN/dln(τf) [fm/c]-1
/ Ch-sp
20 < pT,jet < 30 [GeV/c]
ln(τf) [fm/c]



p+p √s = 200 GeV
Anti-kT R = 0.4 Jets
|η|+Rjet < 1.0
Iterative SoftDrop
zcut = 0.1, β = 0
STAR Preliminary
Sys. Uncert.
First Split
Second Split
Third Split
20 < pTjet < 30 [GeV/c]
30 < pTjet < 50 [GeV/c]
1/N dN/dzg
zg

SoftDrop

Grooming criterion

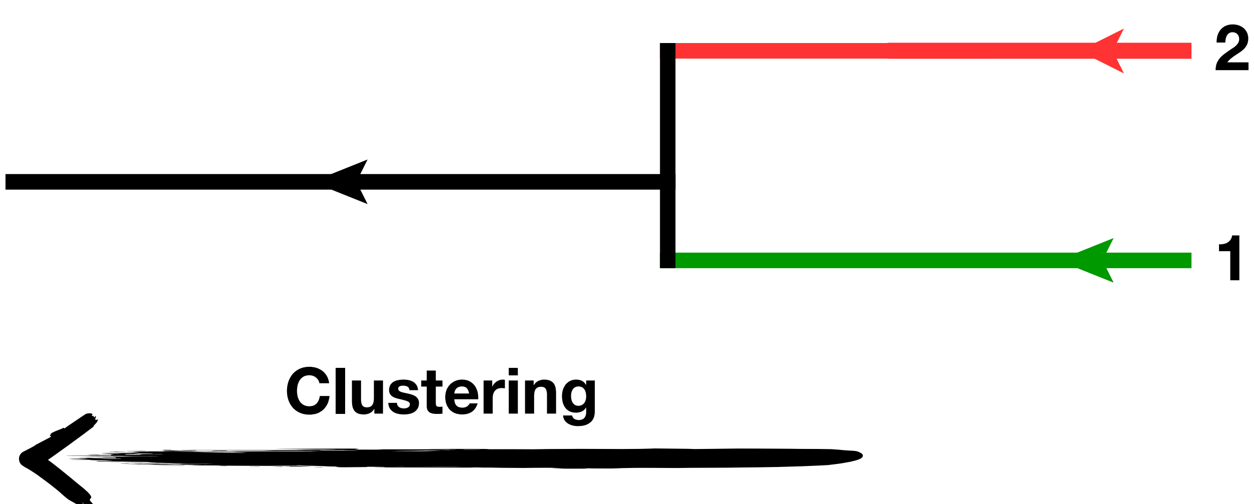


Larkowski, et al. JHEP 05 (2014) 146
Dasgupta et al. JHEP 09 (2013) 029

- Require subjet momentum fraction to pass

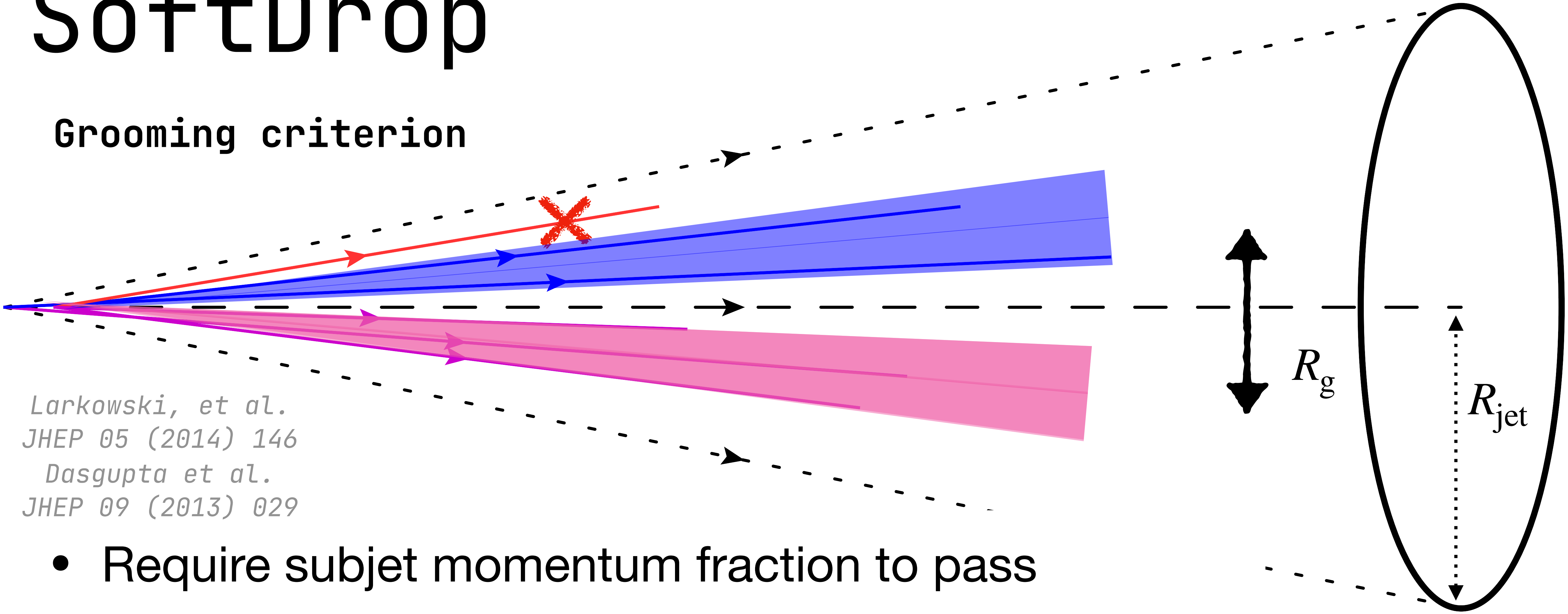
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{\mathrm{cut}}(R_g/R_{\mathrm{jet}})^{\beta}$$

$$z_{\mathrm{cut}} = 0.1$$
$$\beta = 0$$



SoftDrop

Grooming criterion

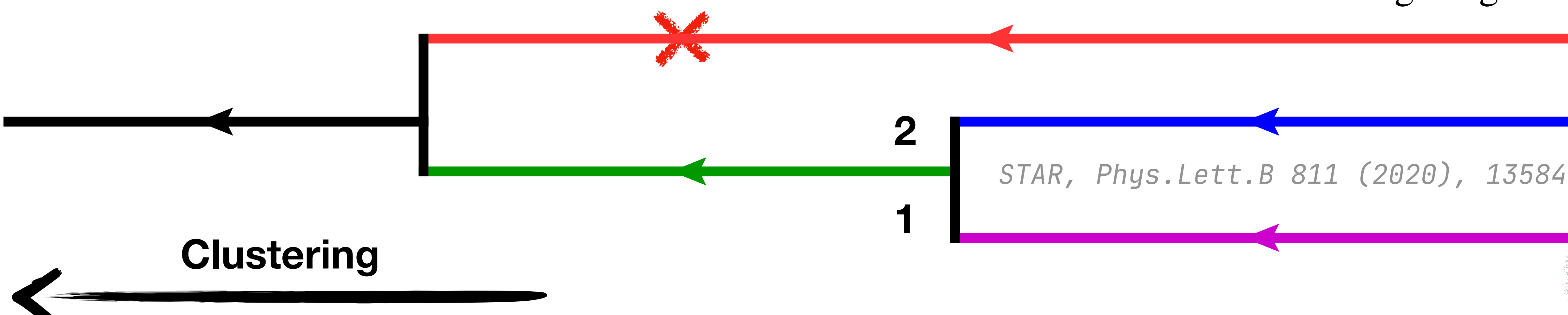


Larkowski, et al. JHEP 05 (2014) 146
Dasgupta et al. JHEP 09 (2013) 029

- Require subjet momentum fraction to pass

$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta} \qquad z_{cut} = 0.1 \quad \beta = 0$$

- With the two surviving branches (first hard split) - we define observables that characterize jet substructure z_g, R_g

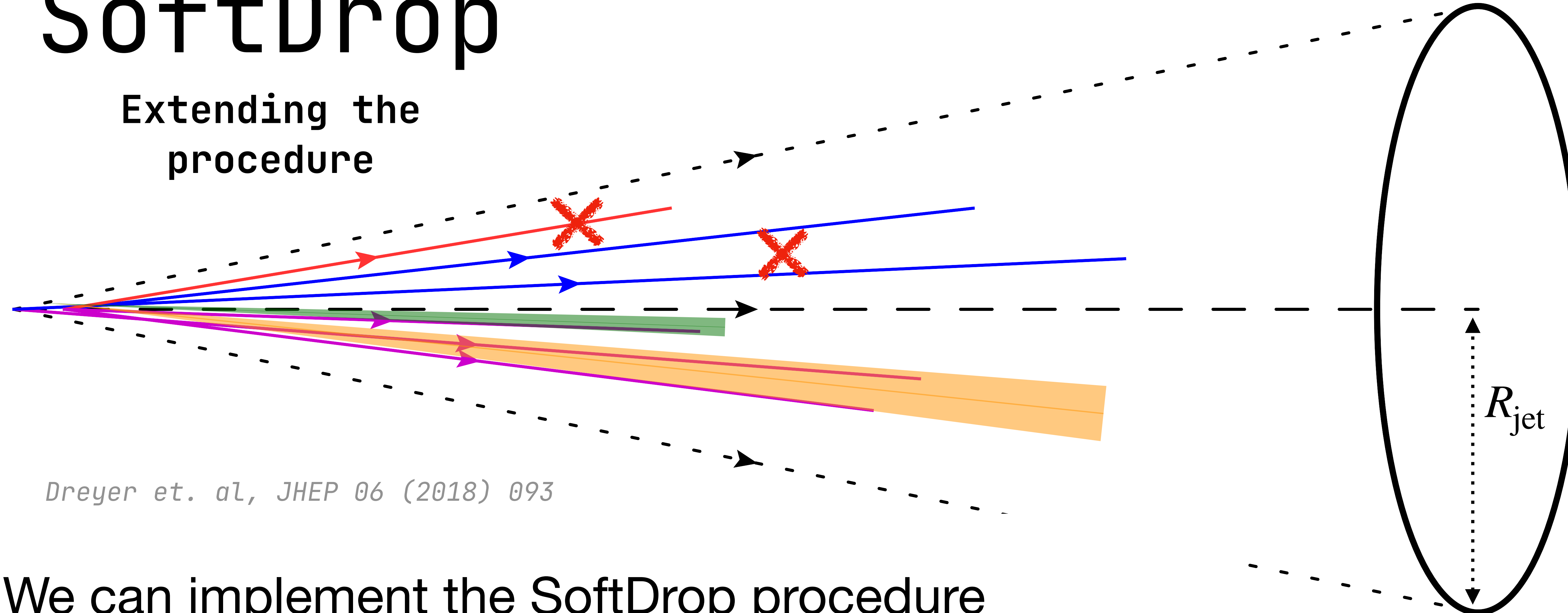


STAR, Phys.Lett.B 811 (2020), 135846

STAR

SoftDrop

Extending the procedure

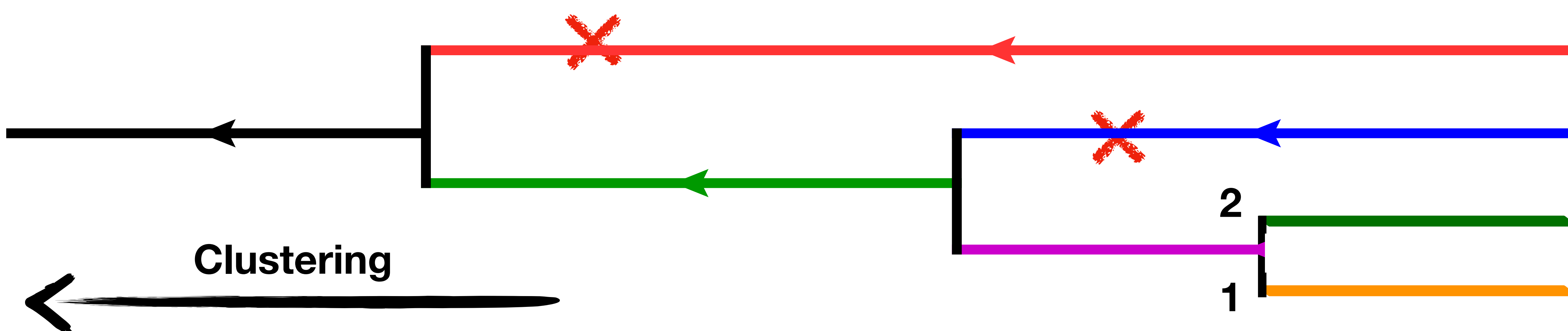


Dreyer et. al, JHEP 06 (2018) 093

We can implement the SoftDrop procedure throughout the C/A tree -

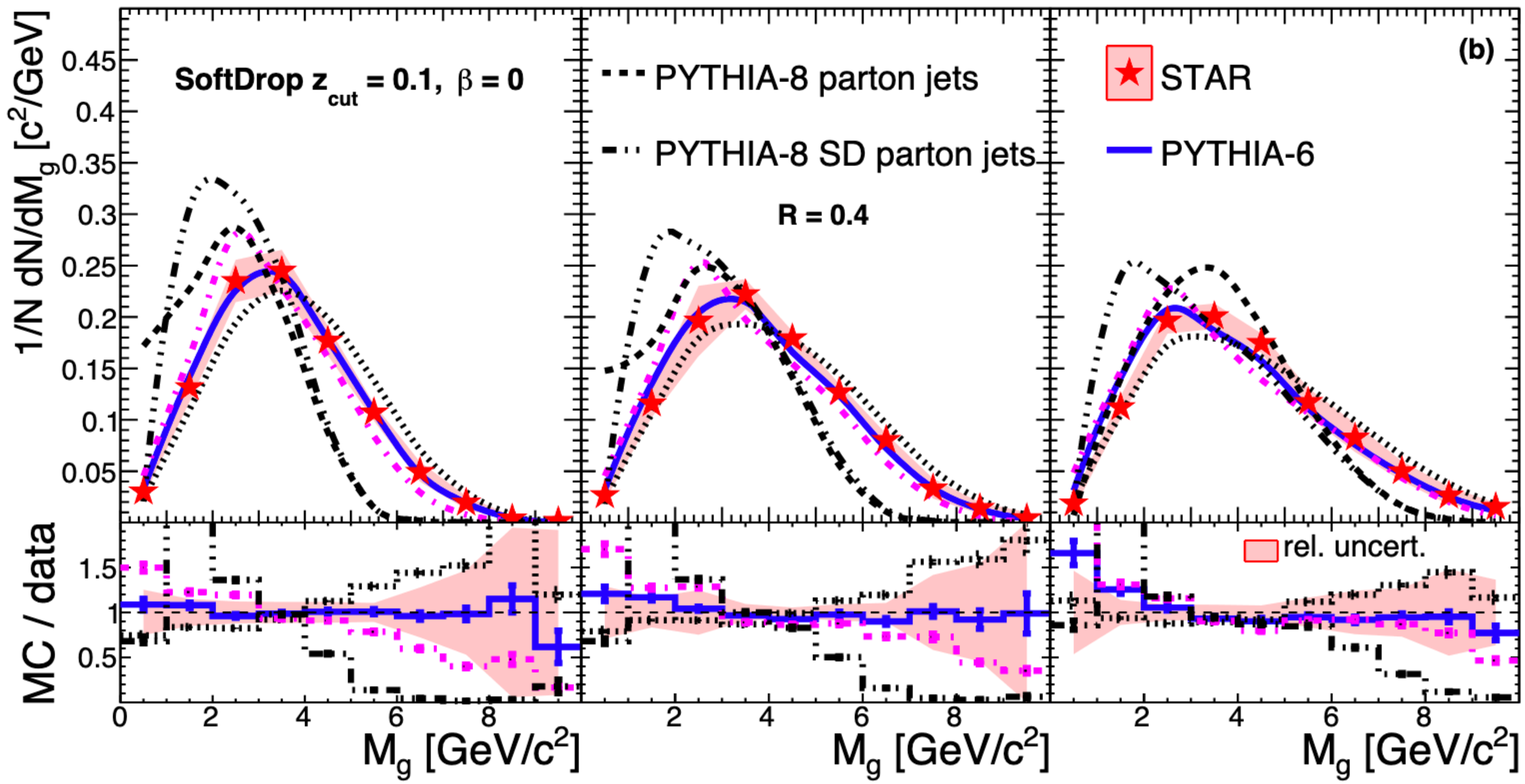
- Follow the hardest branch - Iterative SoftDrop
- Following all branches - Recursive SoftDrop

$$n_{\mathrm{SD}},\ z_{\mathrm{g}}^{n},\ R_{\mathrm{g}}^{n}$$



Groomed Jet Mass

STAR arXiv:2103.13286, Accepted in PRD



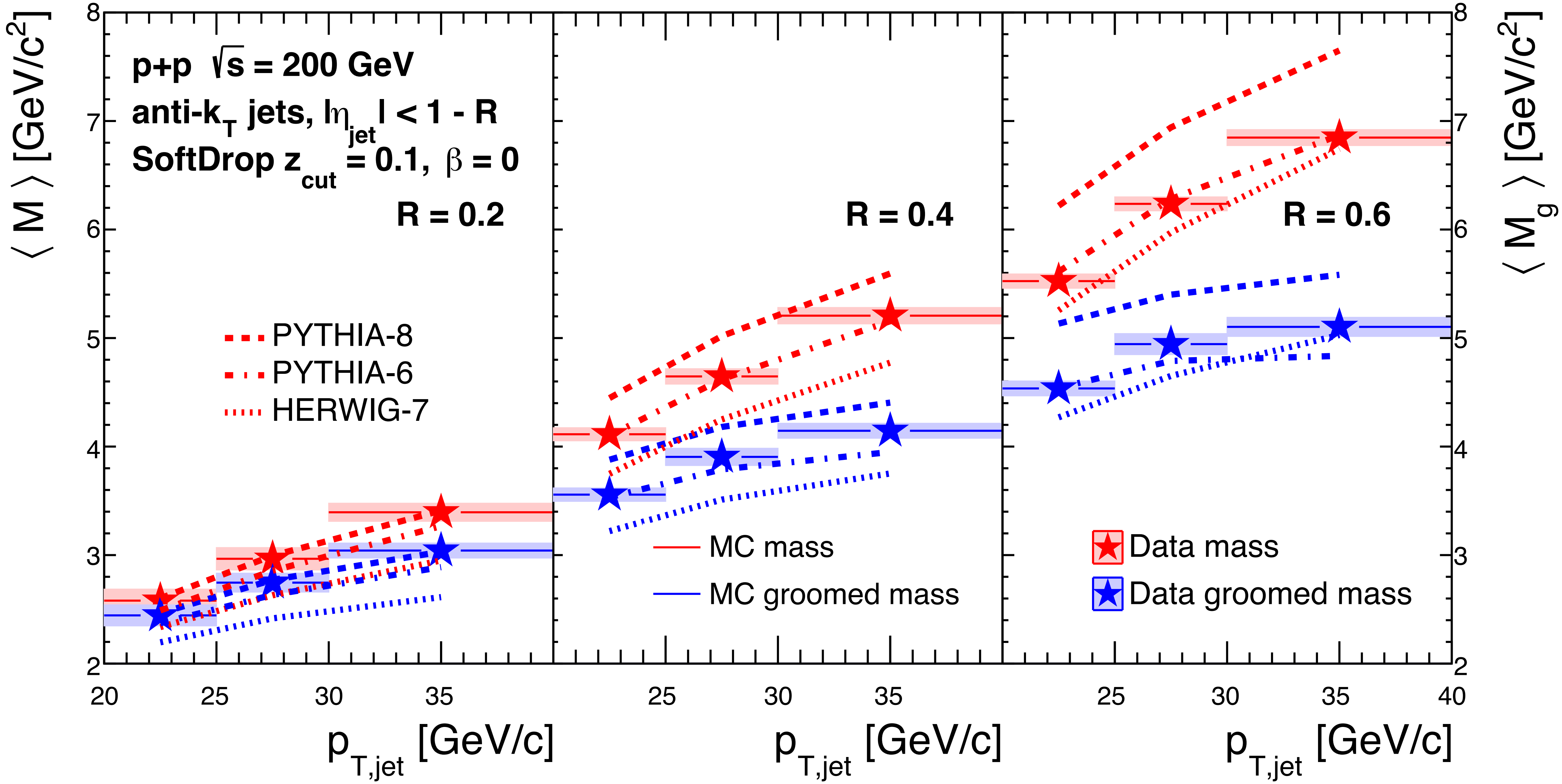
RHIC-tuned **PYTHIA-6** describes data

HERWIG-7 under-predicts and **PYTHIA-8** over-predicts

Mass (angularity) ~ $z\theta^2$ Can we isolate these two scales in jets?

Evolution of jet mass as a function of jet momenta and radii

STAR arXiv:2103.13286, Accepted in PRD



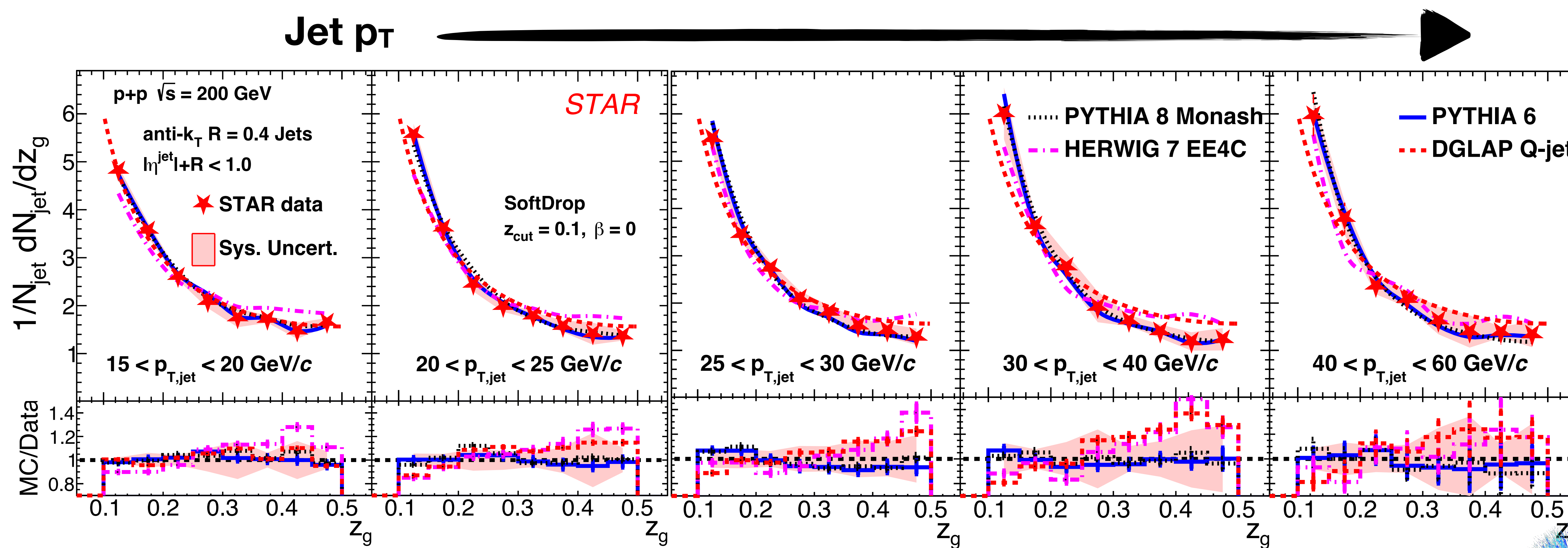
Increase in jet mass with increasing p_T and R is reduced with grooming - reduces overall impact of non-perturbative contributions to jets

SoftDrop z_g

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

- ★ Recover the universal $1/z$ behavior starting from $p_T \sim 25$ GeV/c
- ★ **PYTHIA-6** and **PYTHIA-8** describe data
- ★ **HERWIG-7** predicts harder splitting

STAR, Phys.Lett.B 811 (2020)

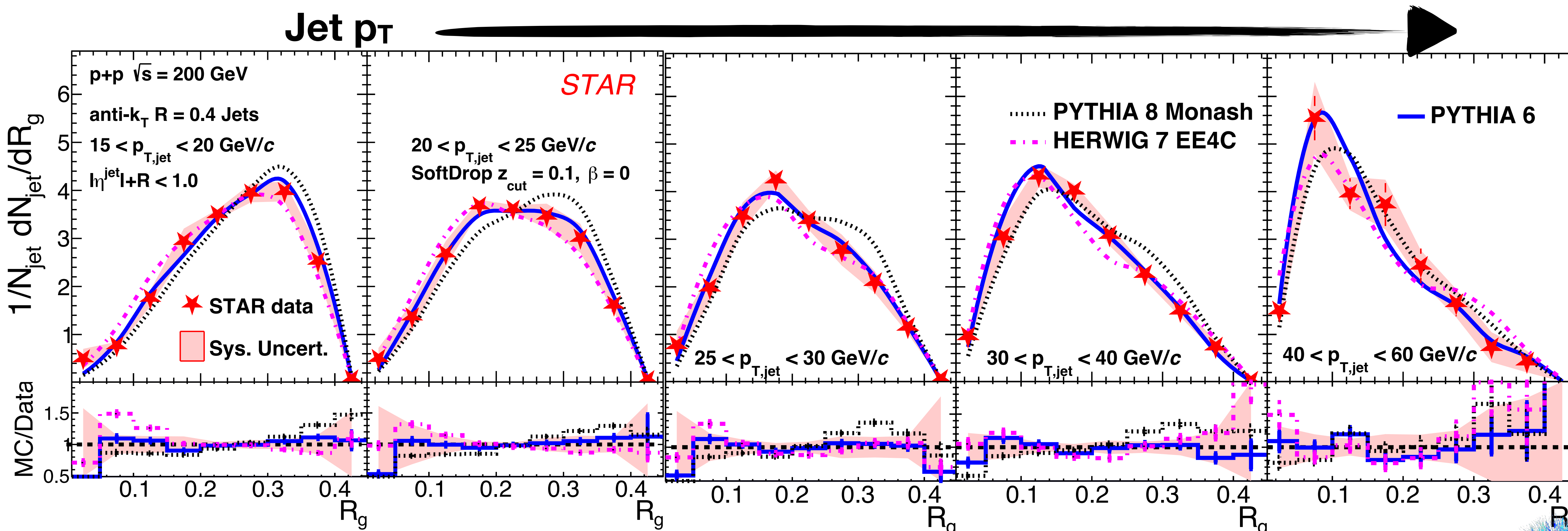


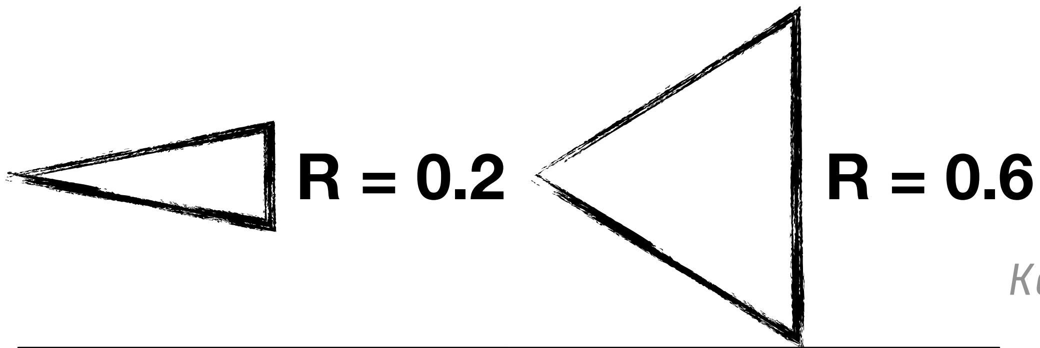
SoftDrop R_g

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

- ★ R_g reflects momentum-dependent narrowing of jet structure
- ★ **PYTHIA-6** describes data
- ★ **PYTHIA-8** predicts larger groomed jet angular scale

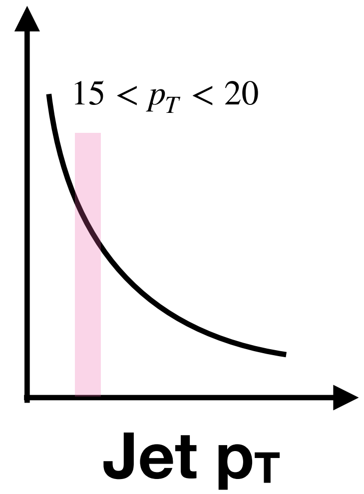
STAR, Phys.Lett.B 811 (2020)

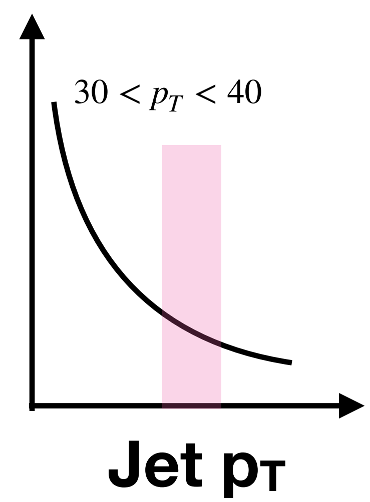


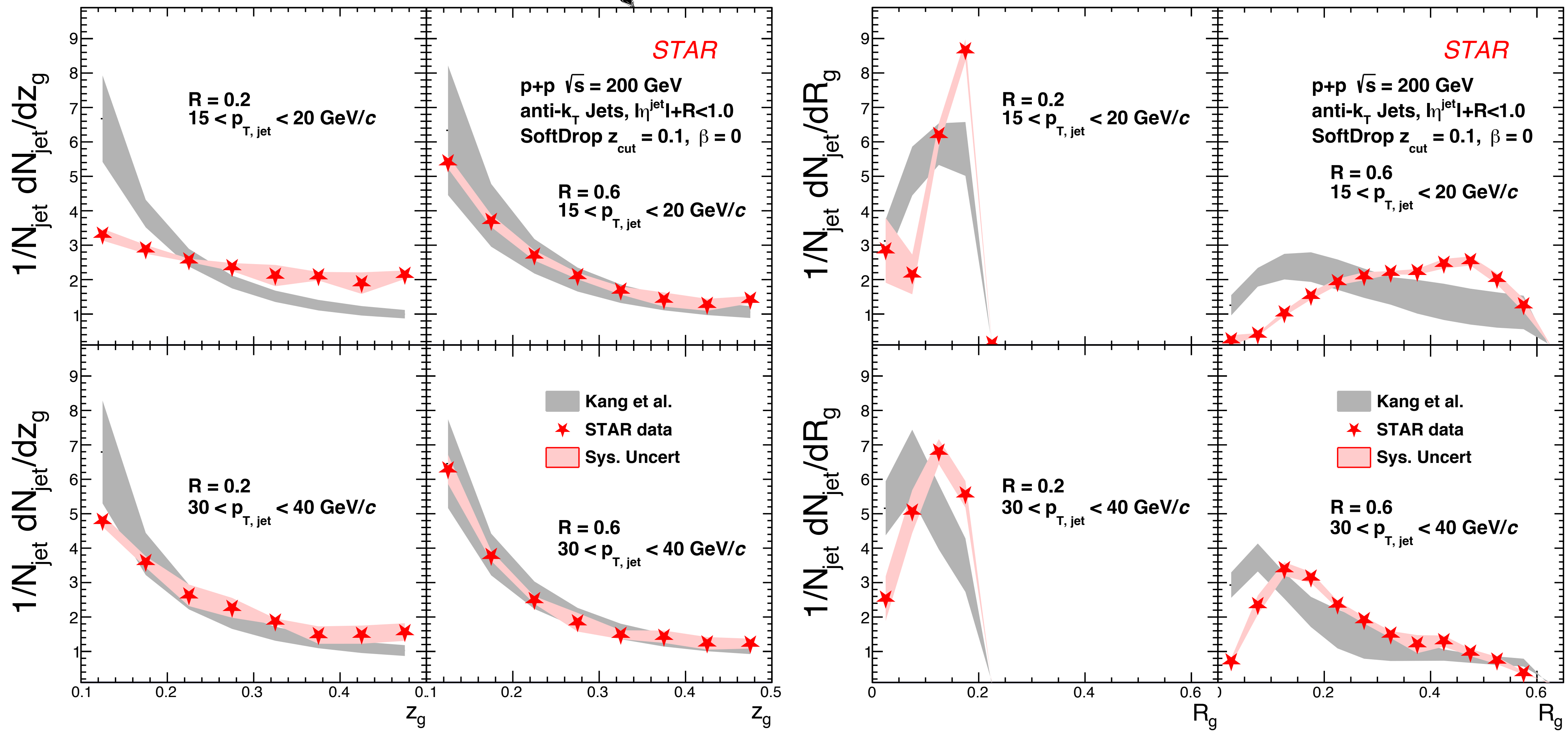


STAR, Phys.Lett.B 811 (2020)

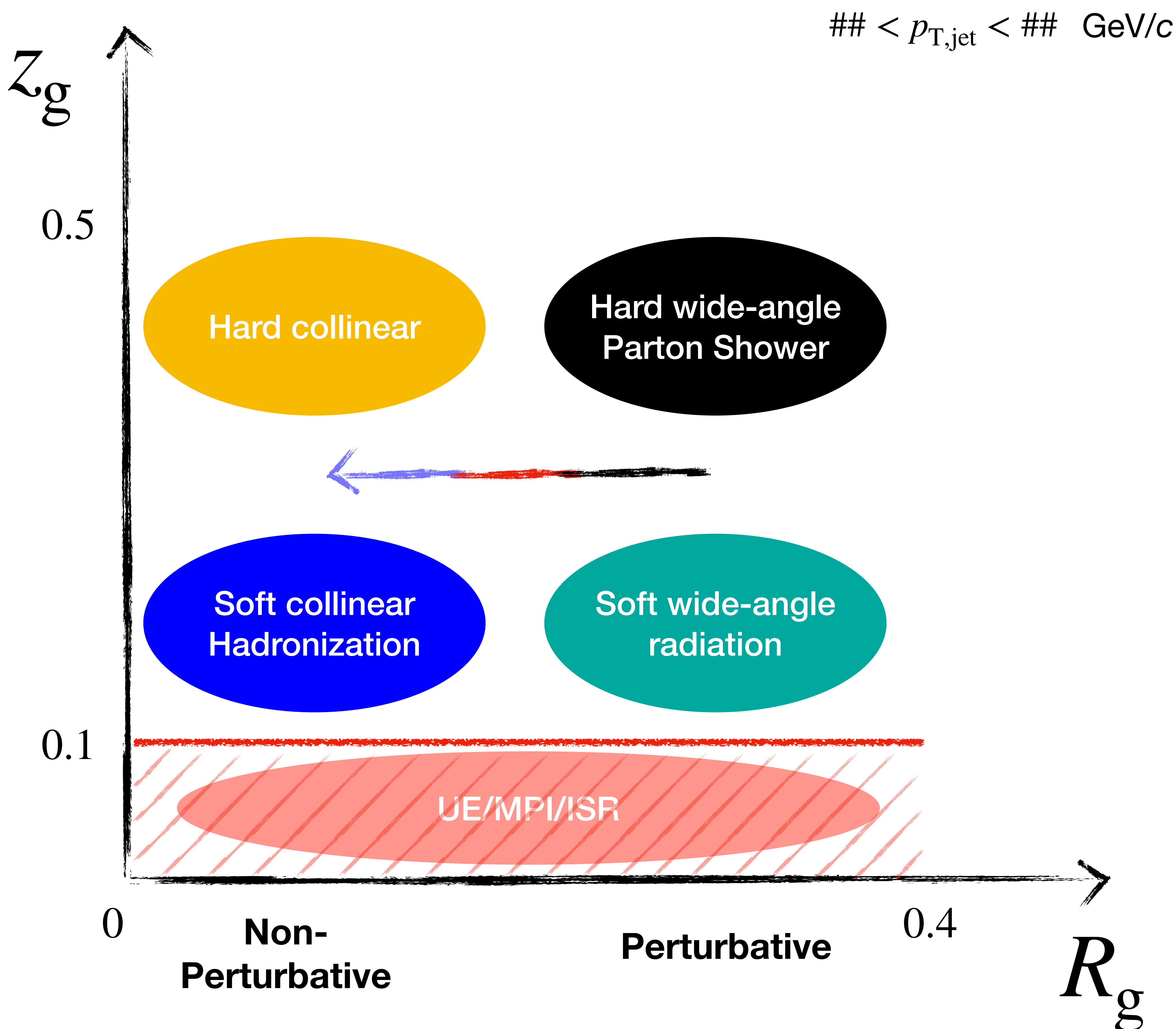
Kang, Lee, Liu, Neill and Ringer, JHEP (2020)







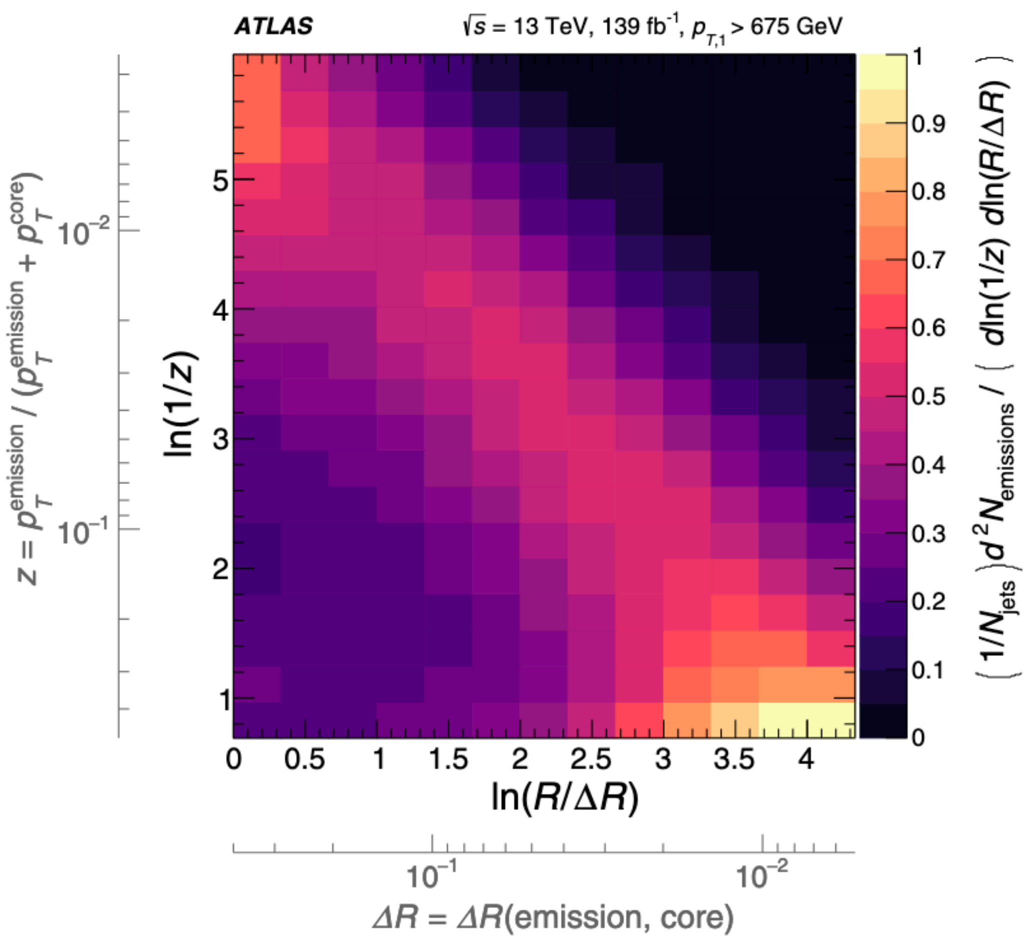
- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and p_T
- Significantly worse for jets of narrow R and low p_T - tighter constraints on jet splittings

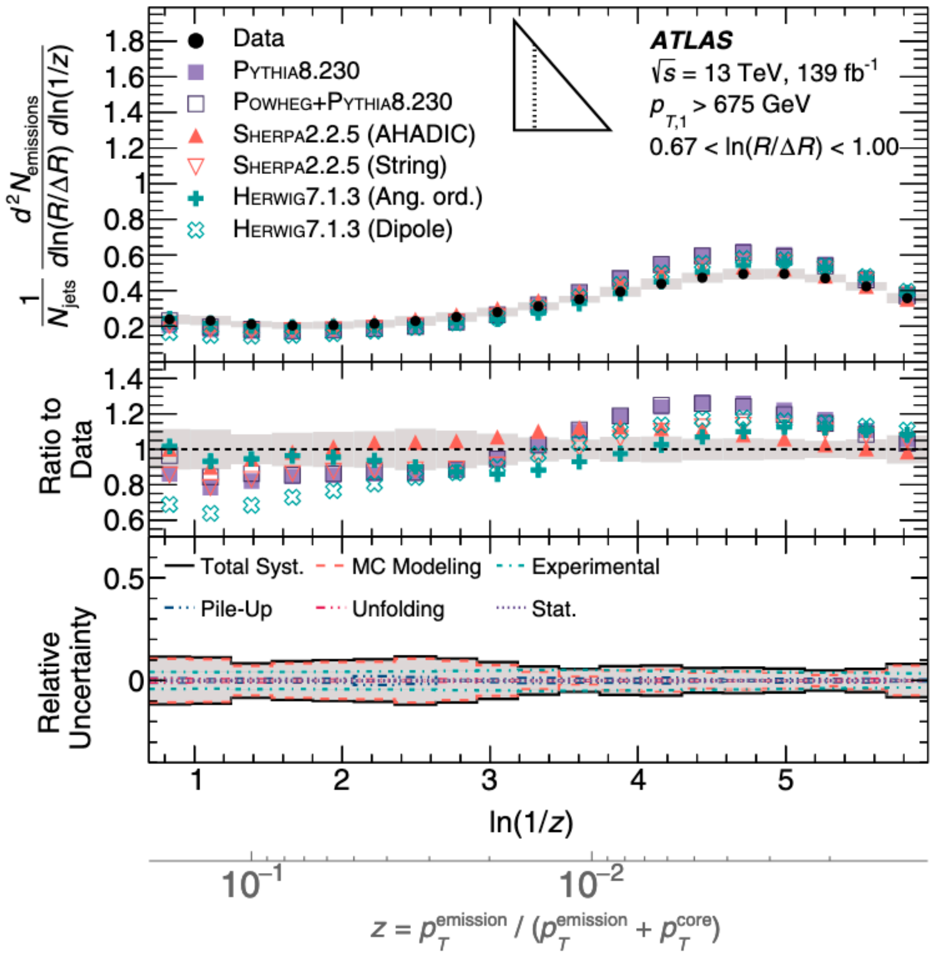


< $p_{\mathrm{T,jet}}$ < ## GeV/c
z_g
0.5
0.1
0
0.4
R_g
Hard collinear
Hard wide-angle Parton Shower
Soft collinear Hadronization
Soft wide-angle radiation
UE/MPI/ISR
Non-Perturbative
Perturbative

Recent measurements of Lund Plane and their projections at the LHC

ATLAS, Phys. Rev. Lett. 124, 222002 (2020)

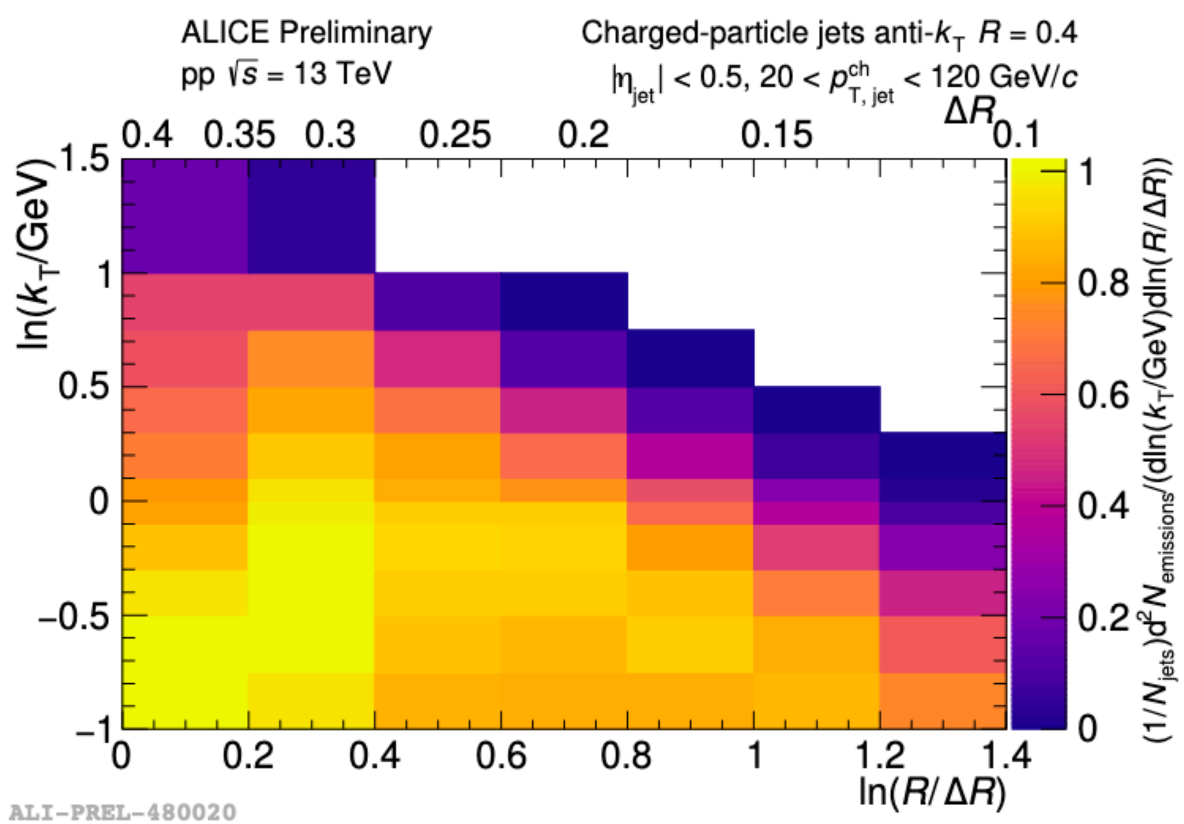


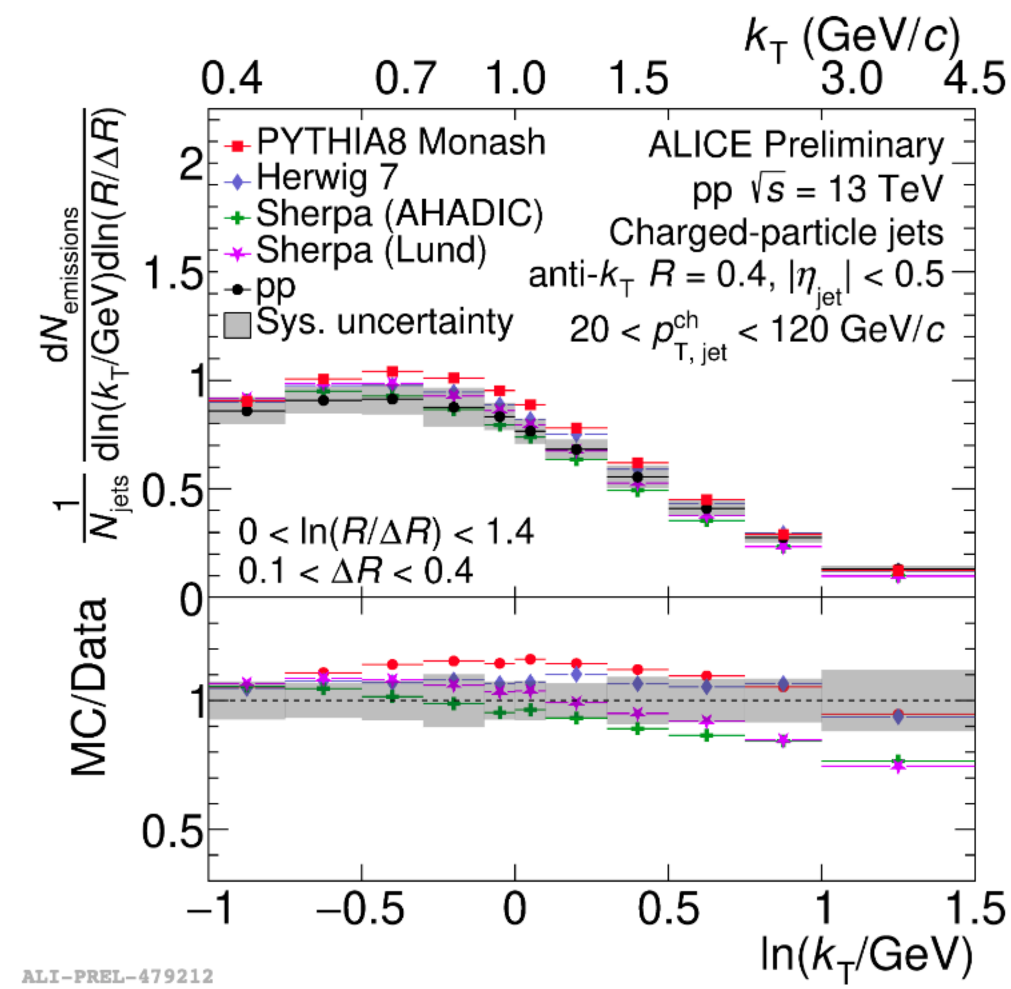


- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcase differences

Recent measurements of Lund Plane and their projections at the LHC

ALICE-PUBLIC-2021-002





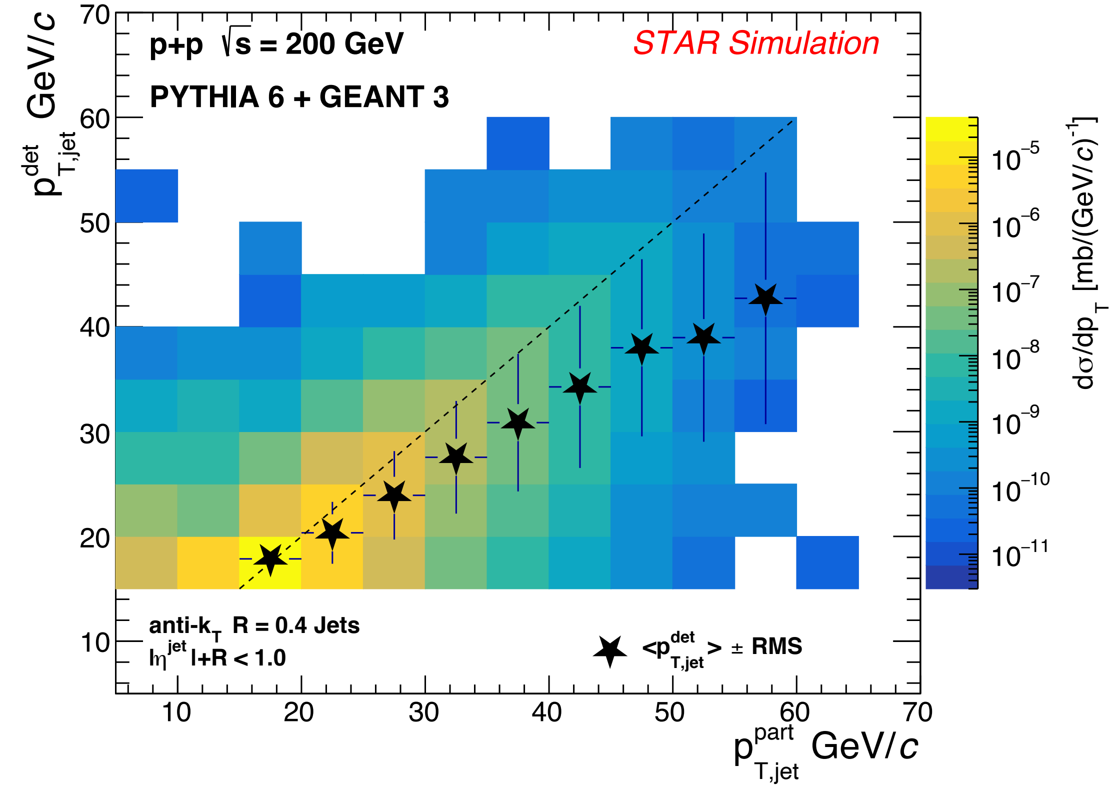
- Lower p_T jets at ALICE (20 - 120 GeV) also show interesting differences for large k_T splits
- Lund plane integrates over splits - can we measure the evolution of these observables along the jet shower?

Corrections in 3-D
Jet $p_{\mathrm{T}}, z_{\mathrm{g}}, R_{\mathrm{g}}$

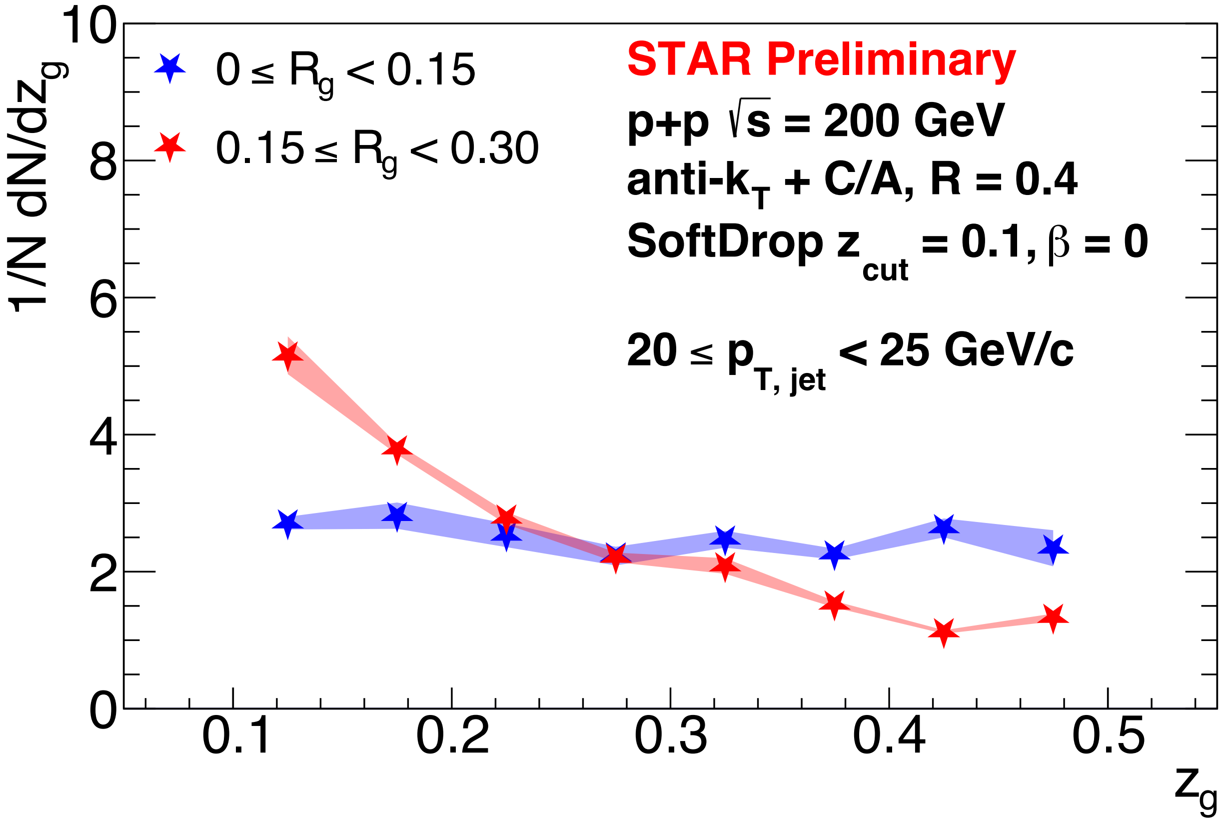
- Correlations between z_{g} vs. R_{g} at fixed detector-level jet p_{T} unfolded by iterative Bayesian procedure = $U(z_{\mathrm{g}}, R_{\mathrm{g}})\,|_{\mathrm{det-p_T}}$

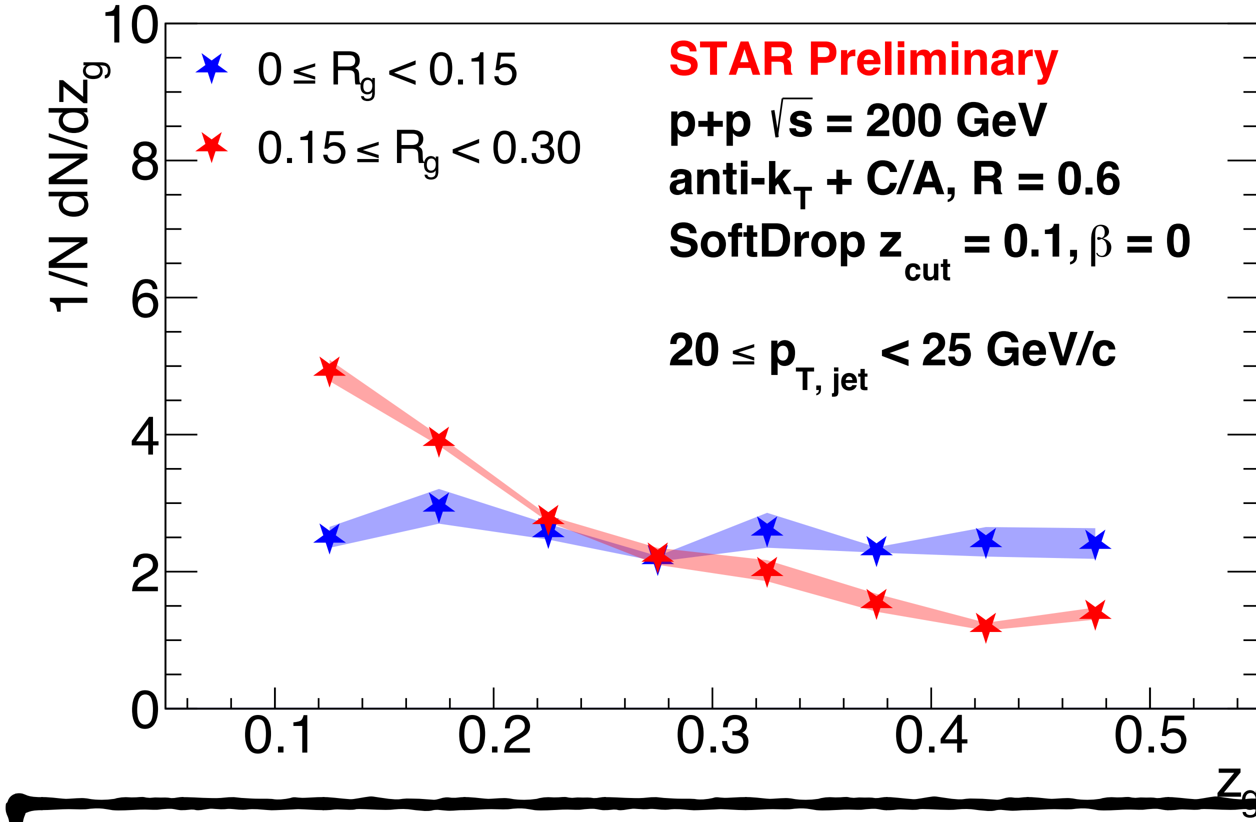
- Since results are presented for true/particle-level jet momentum selections, corrections are done by weighted sum according to the p_{T} response matrix

$$\sum_{i \in \mathrm{det-p_T}} \omega_i \cdot U(z_{\mathrm{g}}, R_{\mathrm{g}})\,|_{\mathrm{det-p_T}}$$



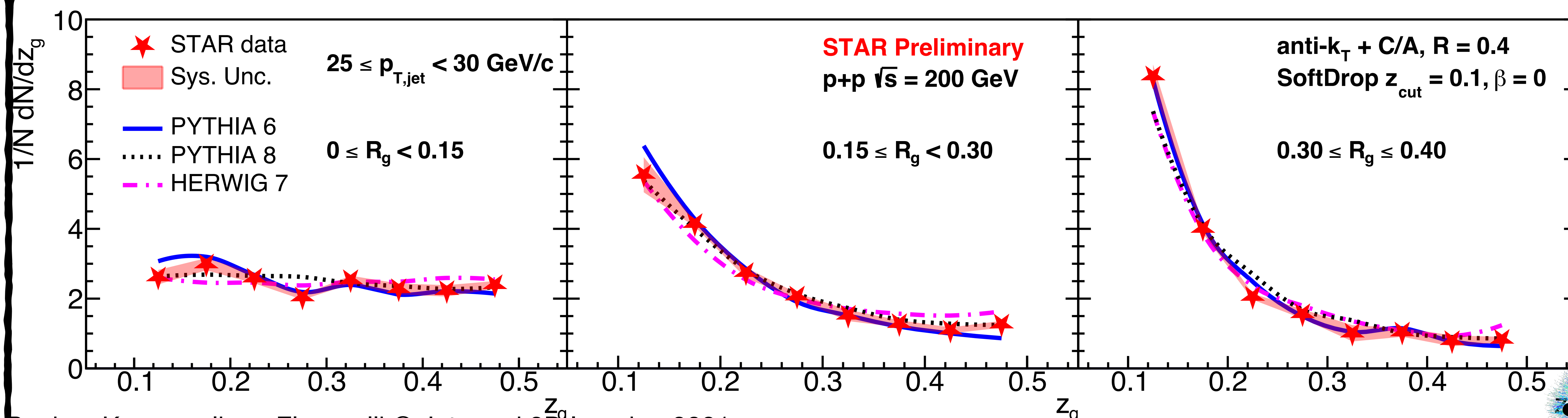
Details on systematic uncertainties available in backup



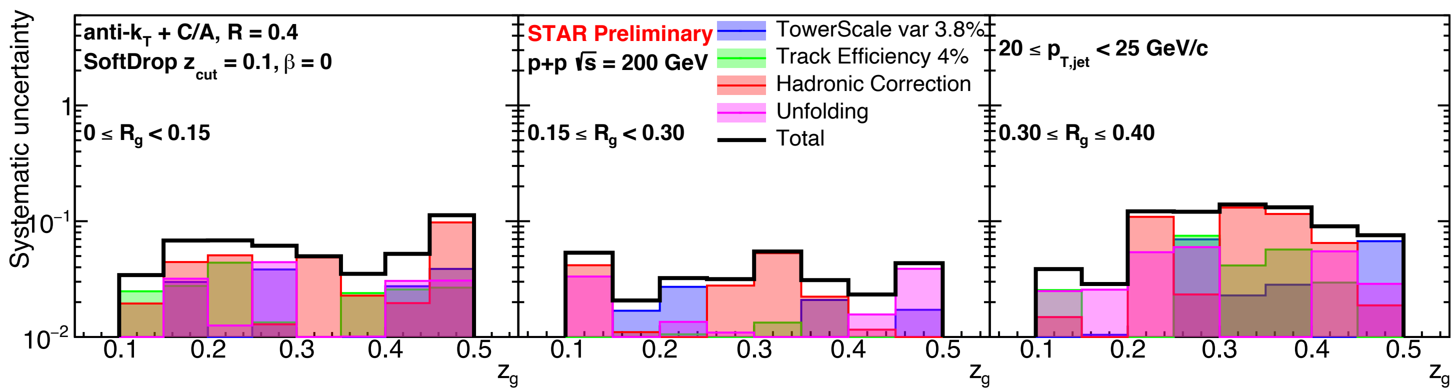


- No significant differences in substructure due to jet radius selections

- Leading order monte carlo models reproduce the evolution with different hadronization models

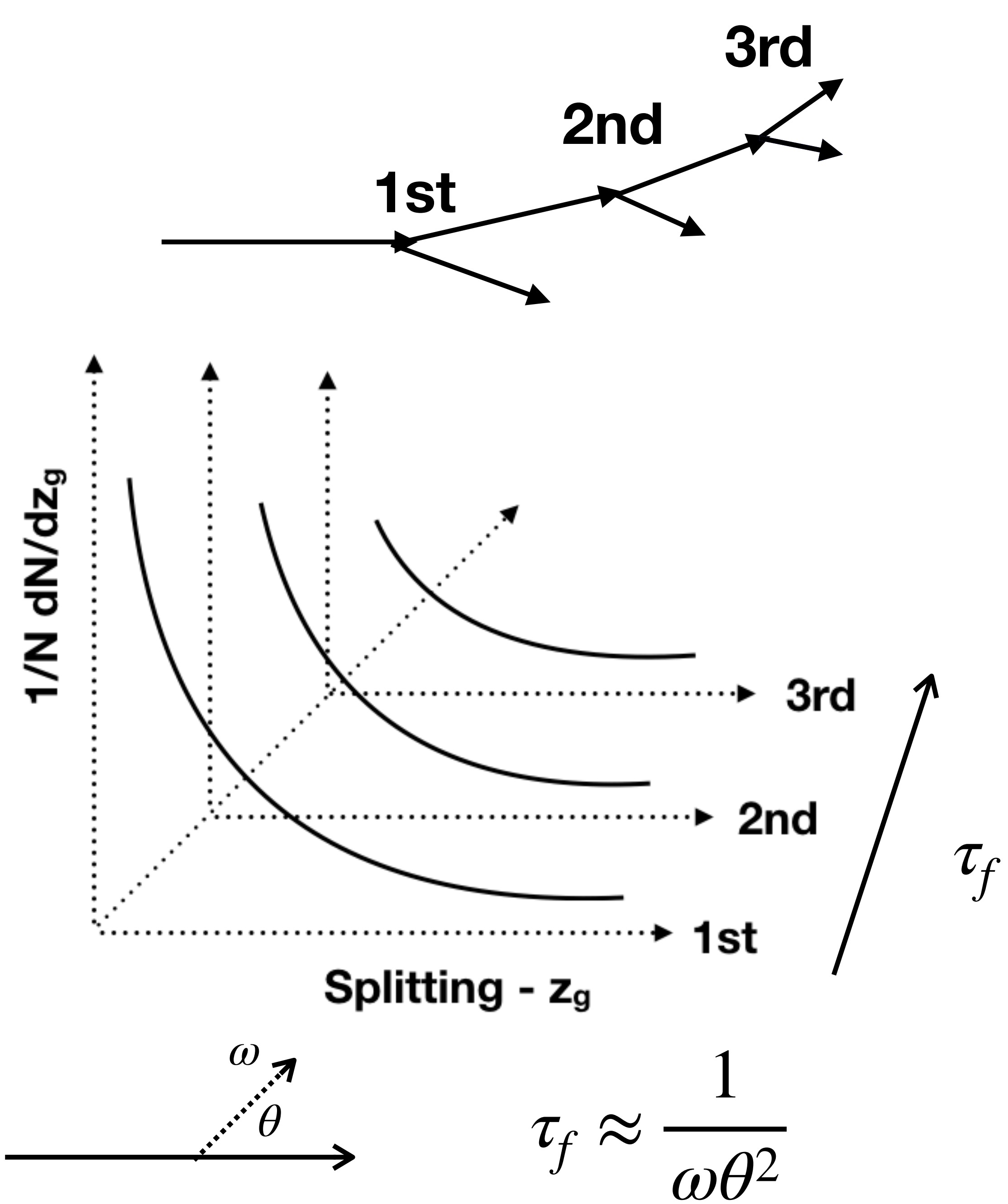


Systematic Uncertainties



- Tracking efficiency : 4%
- Tower energy scale : 3.8%
- Hadronic correction (Matched track-tower energy subtraction) : 50% - 100%
- Bayesian unfolding iteration parameter : 2 - 6
- Prior shape variation : Priors reweighed at 1st, 2nd and 3rd split as seen in PYTHIA 6 vs PYTHIA 8 and HERWIG 7
- Split Matching criteria : $\Delta R \ < \ 0.075, 0.1, 0.125$
- Variation in truth level shape correction for trigger and jet finding efficiencies via differences observed in PYTHIA 6 vs PYTHIA 8 and HERWIG 7

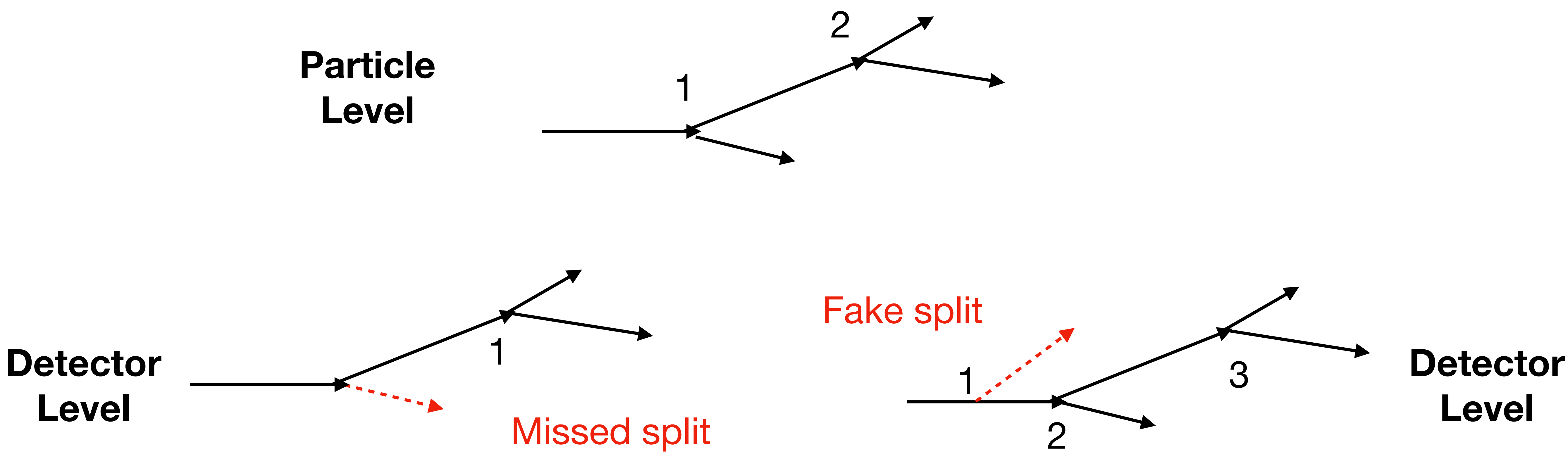
Measure the splittings along the jet clustering tree



- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution
- **Given a jet (p_T^{jet})** what are the z_g, R_g at 1st, 2nd and 3rd splits? **Follow a jet**
  - Compare these distributions at varying jet kinematics
  - Indirect constraint on splitting kinematics
- **Given a split ($p_T^{initiator}$)**, what are the z_g, R_g for 1st, 2nd and 3rd splits? **Follow a split**
  - Compare these at varying initiator kinematics (direct handle on splits)
  - Indirect constraint on jet kinematics

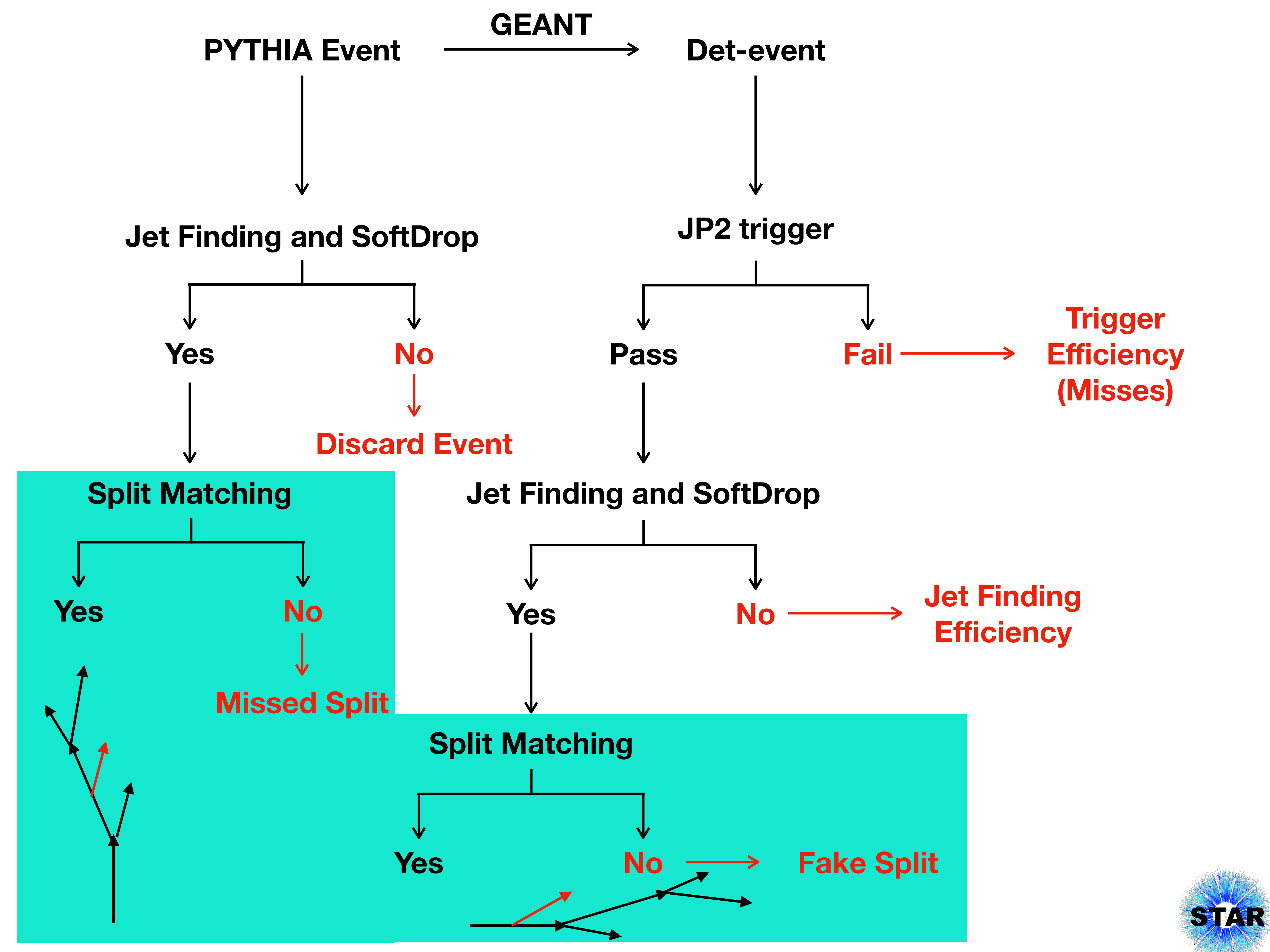
Corrections in 3-D Jet/Initiator $p_{\mathrm{T}}, z_{\mathrm{g}}/R_{\mathrm{g}}$, n

Finite detector efficiency and resolution can alter the splits that are reconstructed in the detector

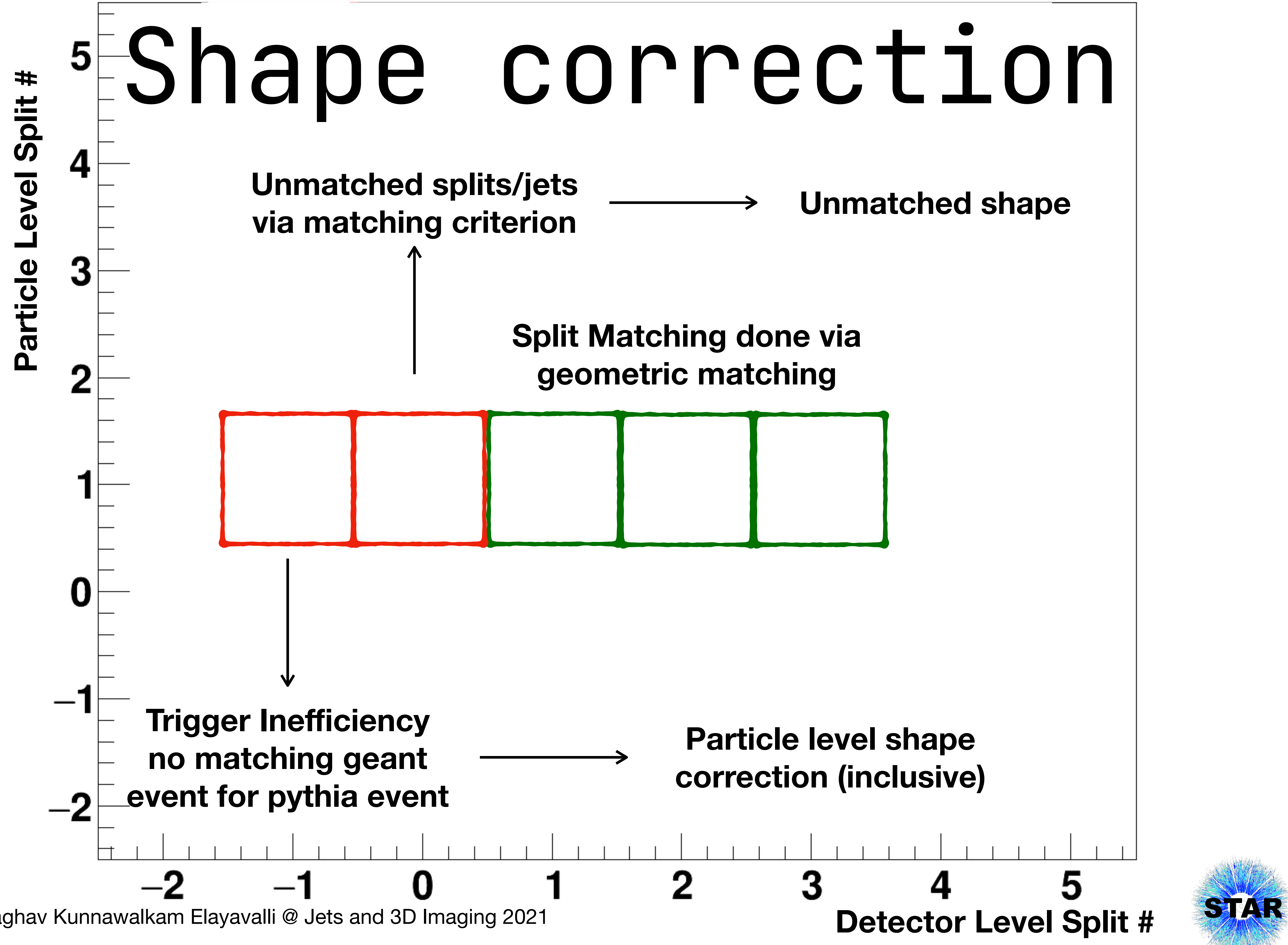


- Observables ($p_{\mathrm{T,jet/initiator}}$, z_{g}, R_{g}) at a given split are smeared
- Splitting hierarchy also modified going from particle to detector level jets

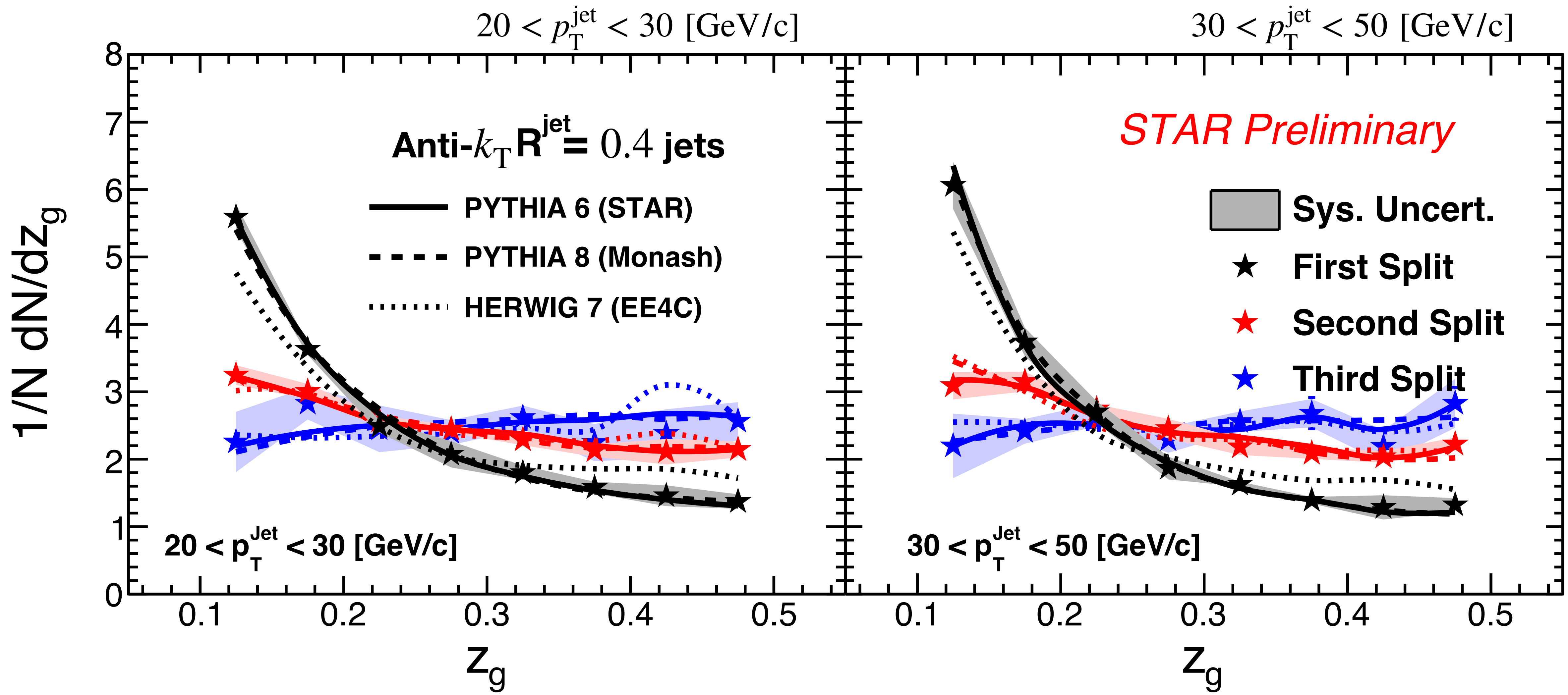
Details of unfolding and systematic uncertainties available in backup


PYTHIA Event
GEANT
Det-event
Jet Finding and SoftDrop
JP2 trigger
Yes
No
Pass
Fail
Trigger Efficiency (Misses)
Discard Event
Split Matching
Jet Finding and SoftDrop
Yes
No
Yes
No
Jet Finding Efficiency
Missed Split
Split Matching
Yes
No
Fake Split
STAR

Shape correction



Comparisons with leading order MC - z_g for various jet p_T



- **Flattening of the splitting z_g as we increase split number** captured by the MC
- Small differences between PYTHIA and HERWIG seen in the **first** split appear to be reduced at the **second**/**third** splits