Measurement of jet substructure $\sqrt{s} = 200$ GeV pp collisions at STAR

Raghav Kunnawalkam Elayavalli (Yale/BNL)
For the STAR Collaboration

BOOST Online 2021

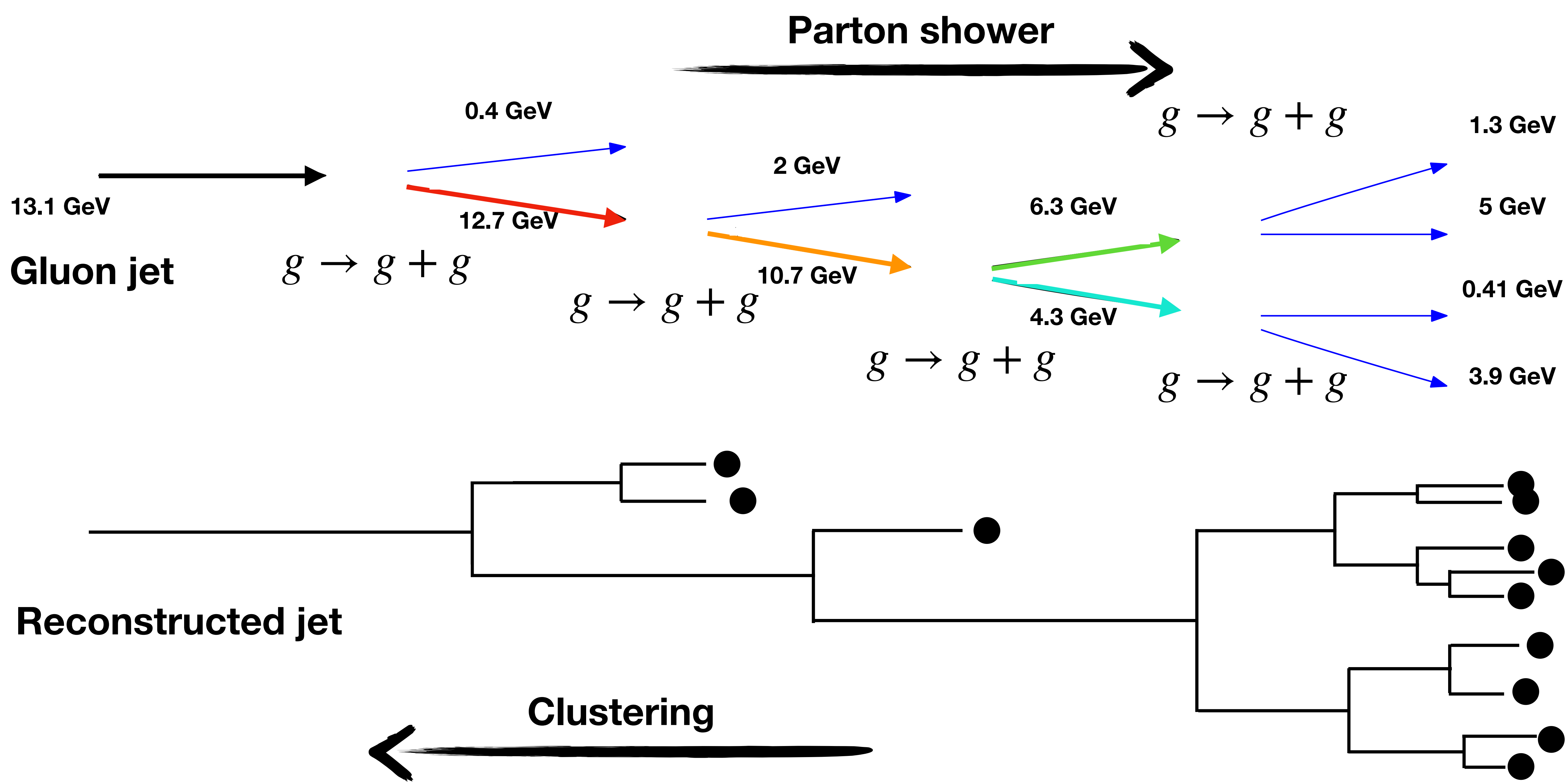
August 3rd, 2021

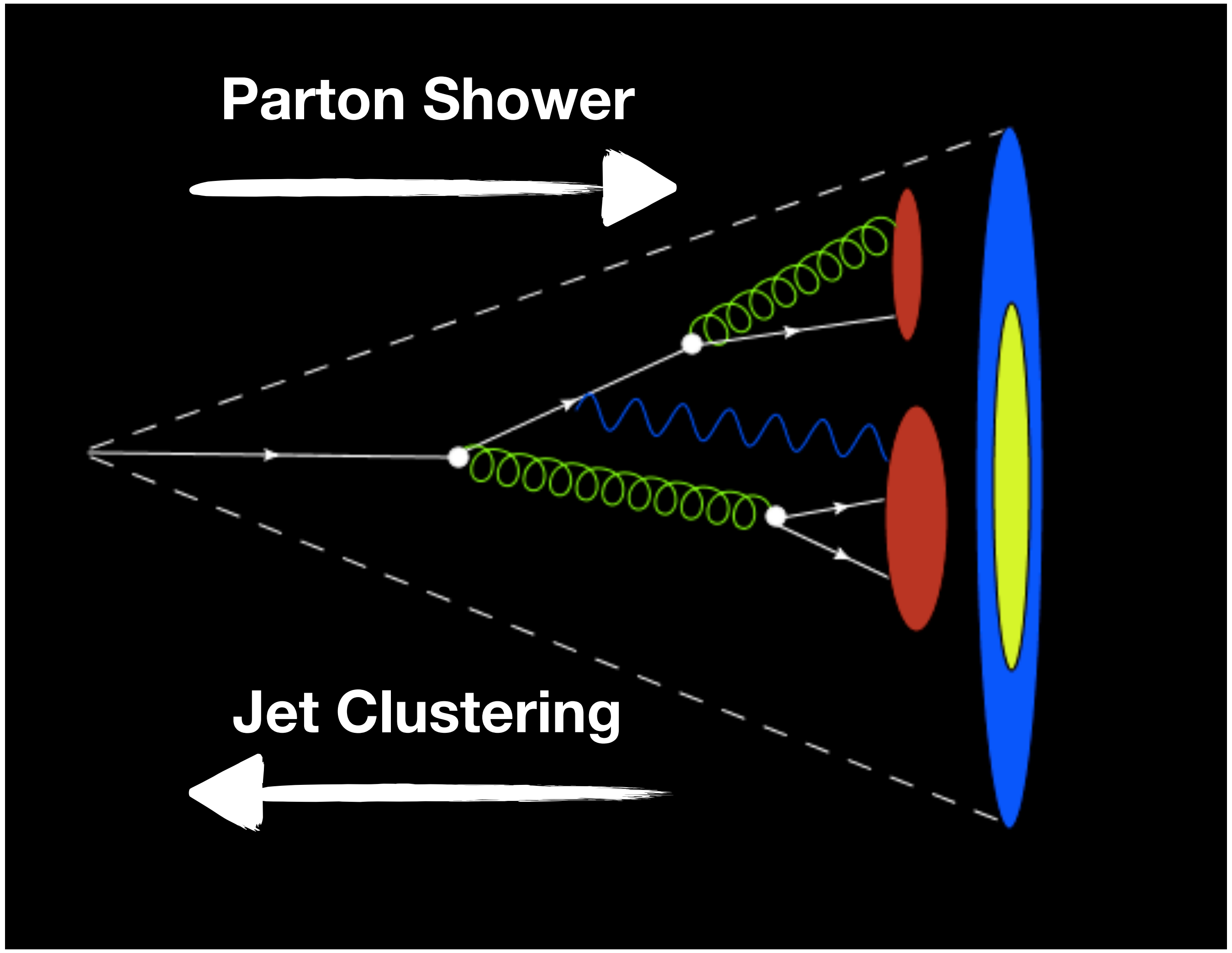
Discussion Session

Supported in part by U.S. DEPARTMENT OF ENERGY | Office of Science

What do we want to measure?

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

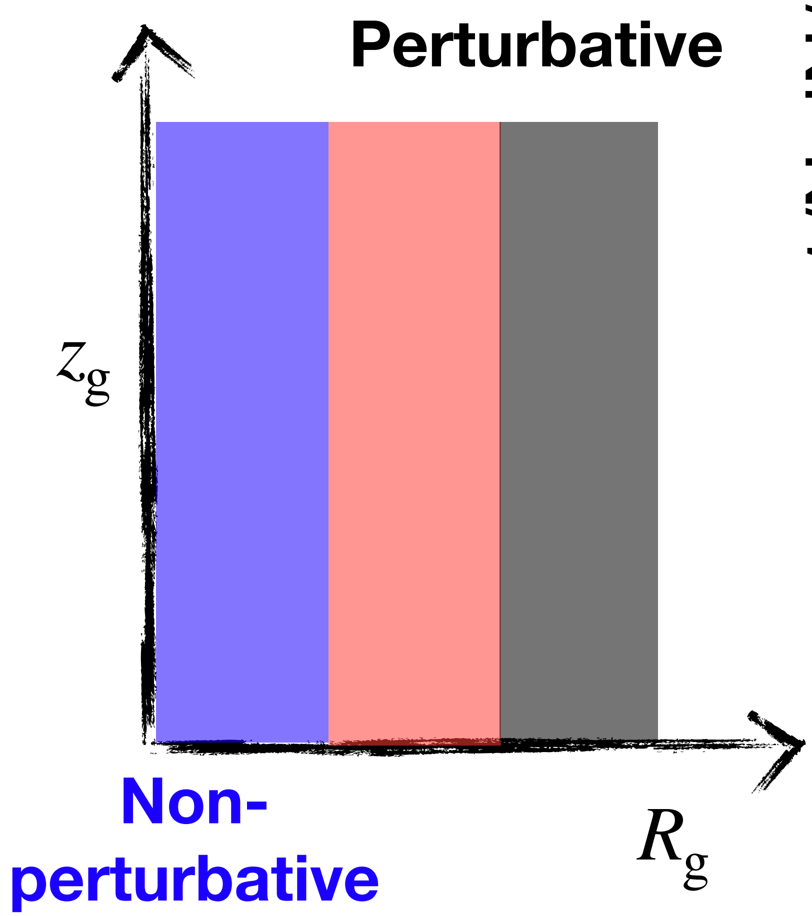




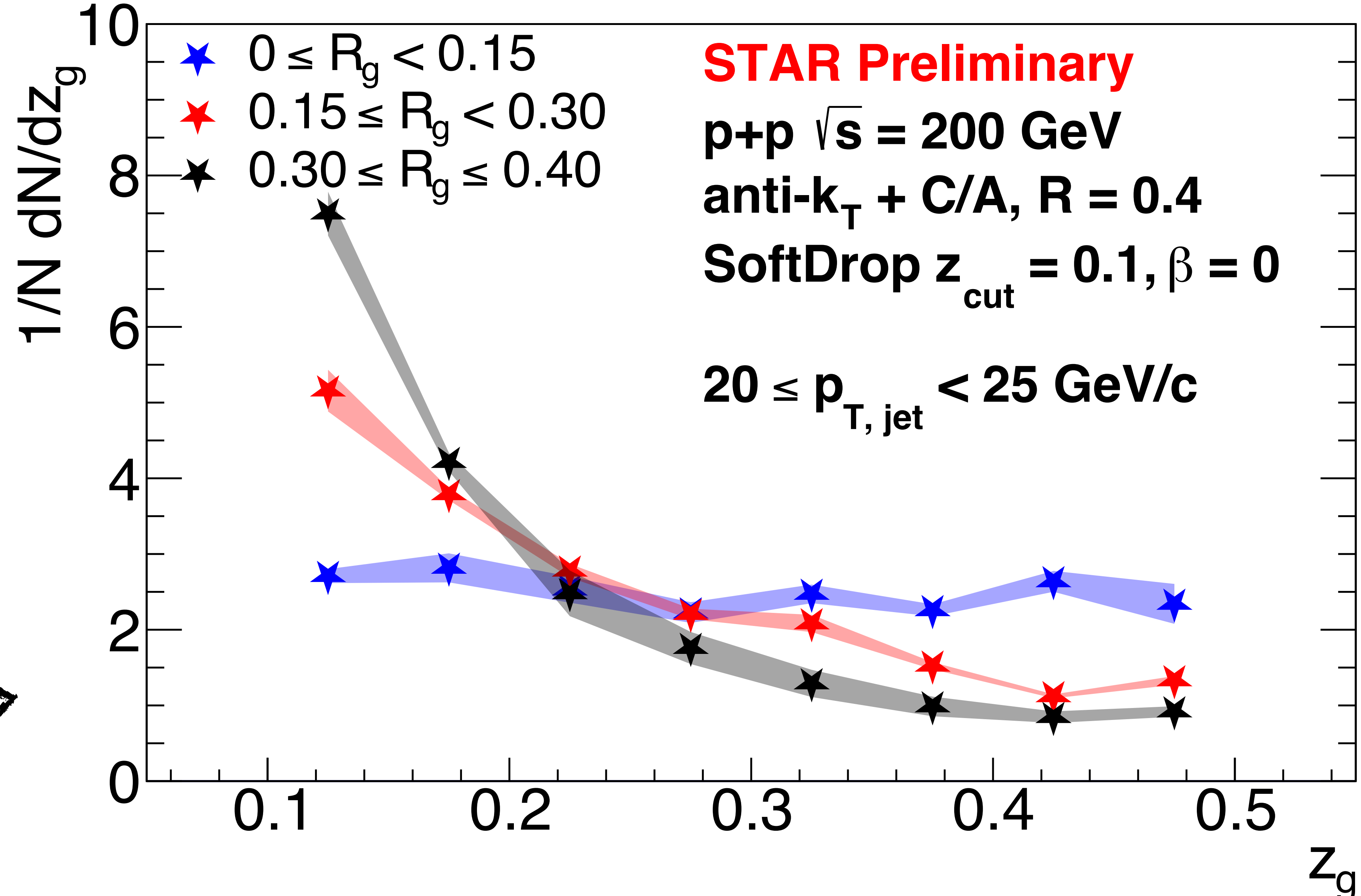
Correlations between substructure observables at the first split

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

Fully corrected results



z_g **for various** R_g **at** $p_{T,jet}$ **range**

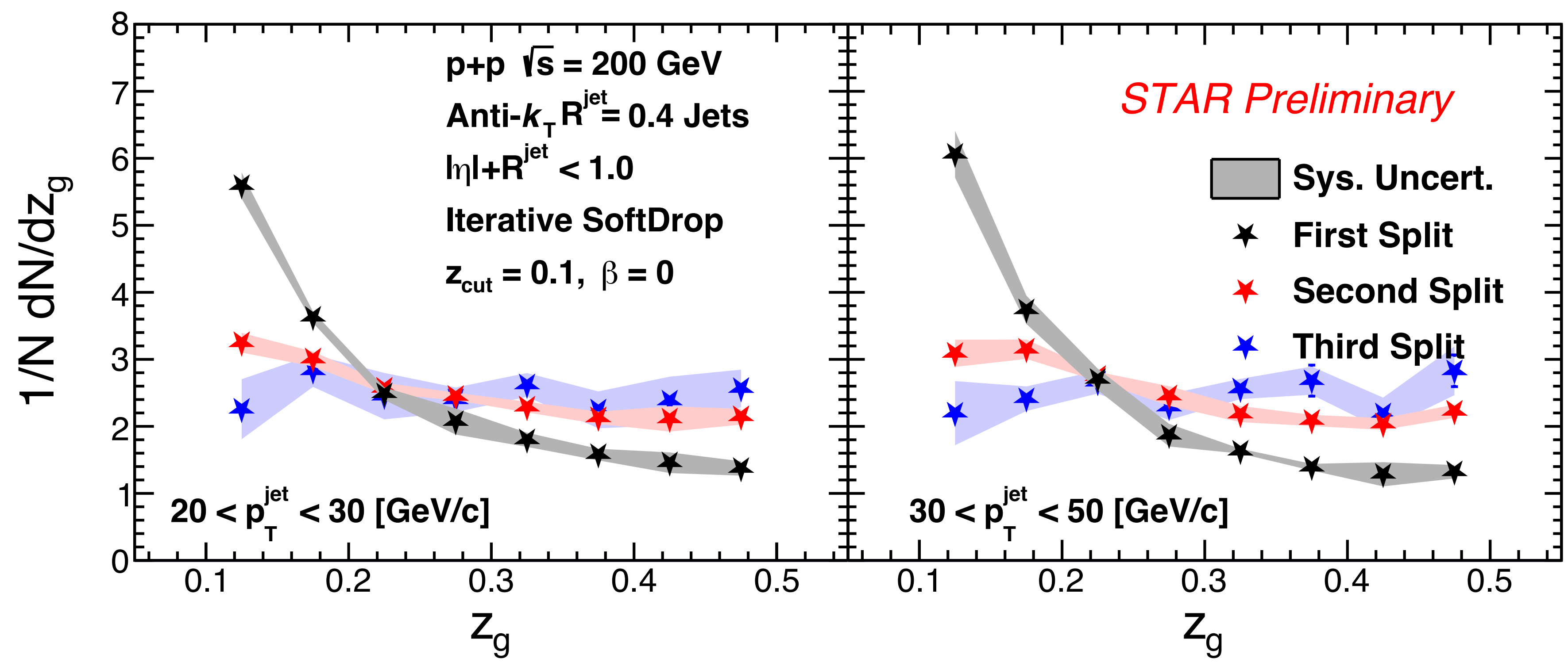


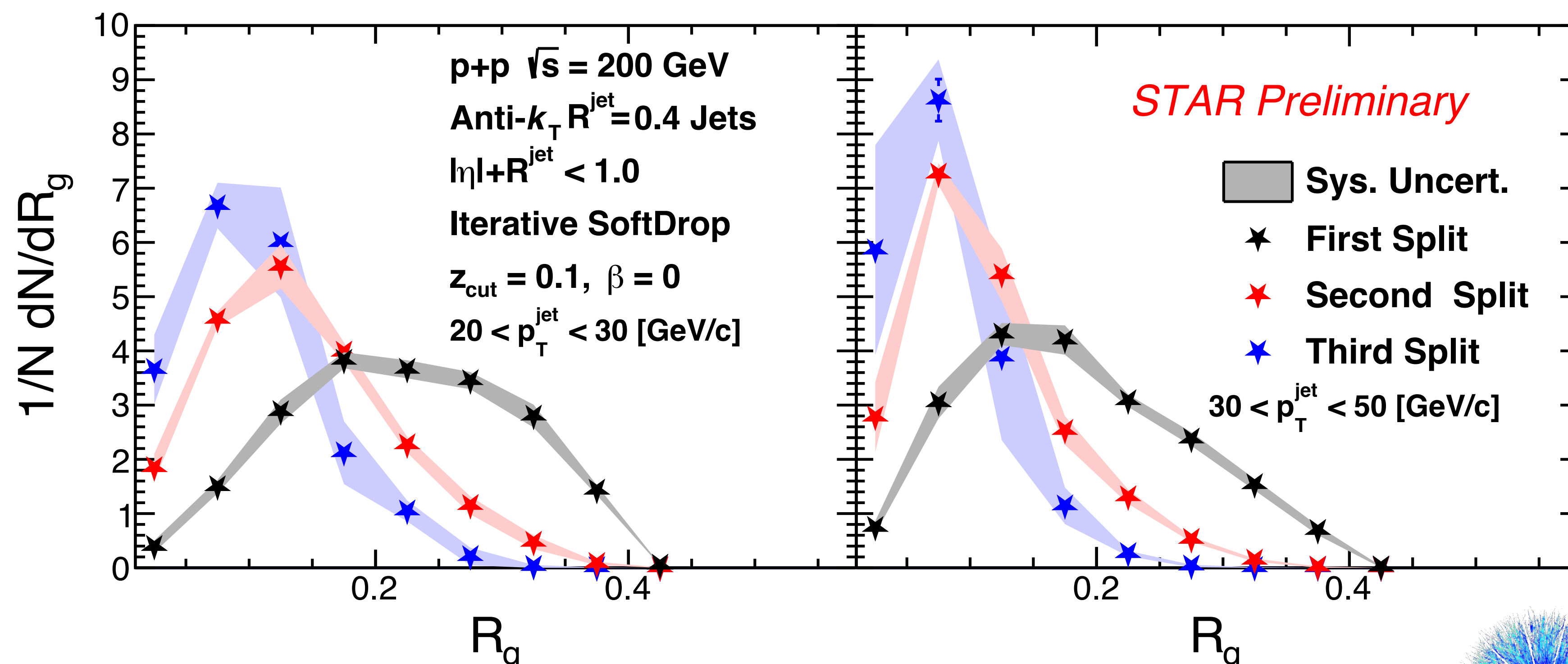
- Significant variation from selecting on R_g
- Evolution from **soft-wide angle splits** to **hard-collinear splits**

Fully corrected results

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

- **For a given jet $p_{\mathrm{T,jet}}$,** what are the z_g, R_g at 1st, 2nd and 3rd splits? Follow a jet…
- **Significant differences between first, second and third** splits
- Splitting **'z' becomes flat and the R_g quite narrow** for the third split where we observe collinear emissions





Similar trends vs initiator p_T

Conclusions

- 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 quite close to Λ_{QCD}

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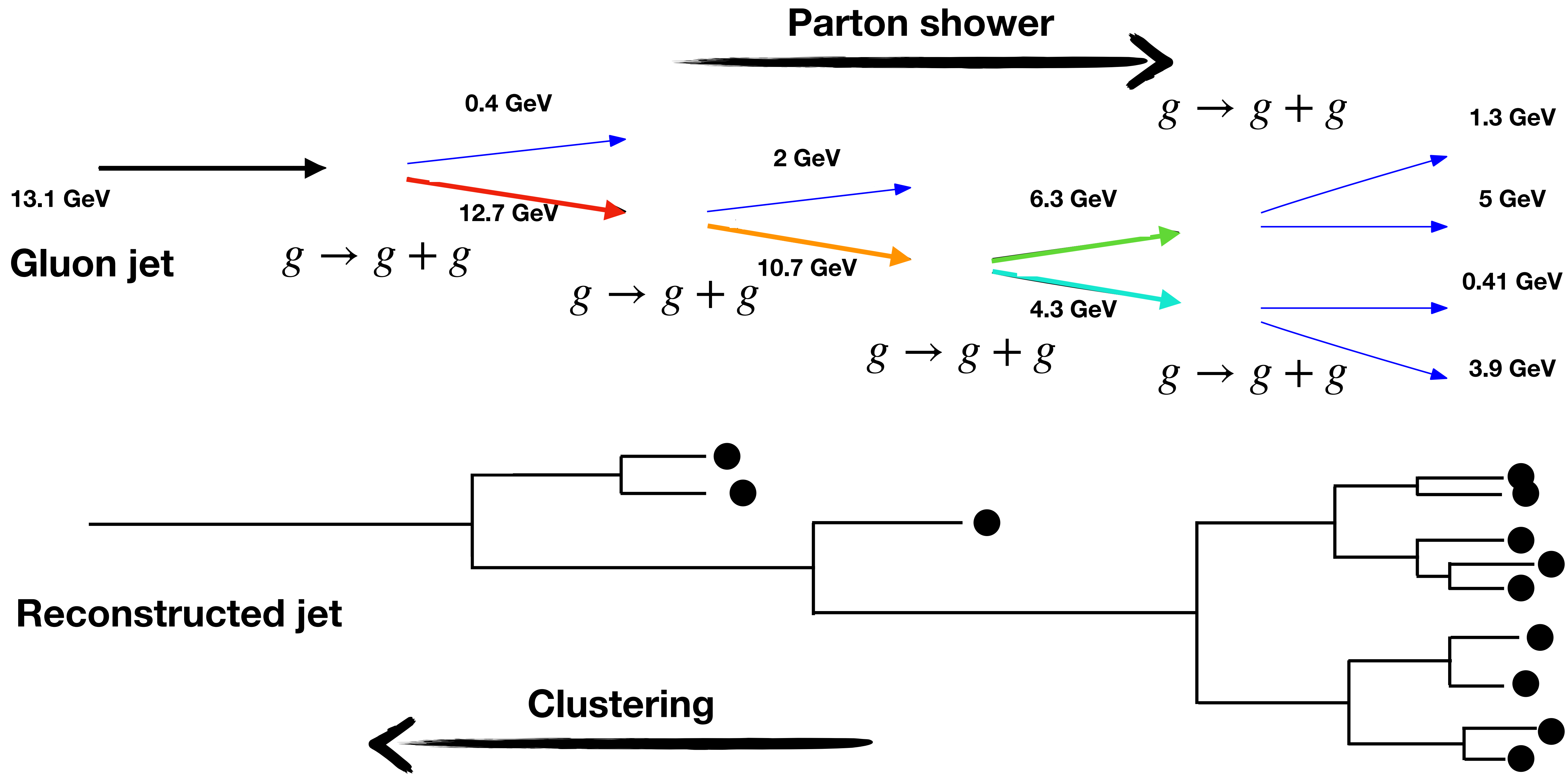
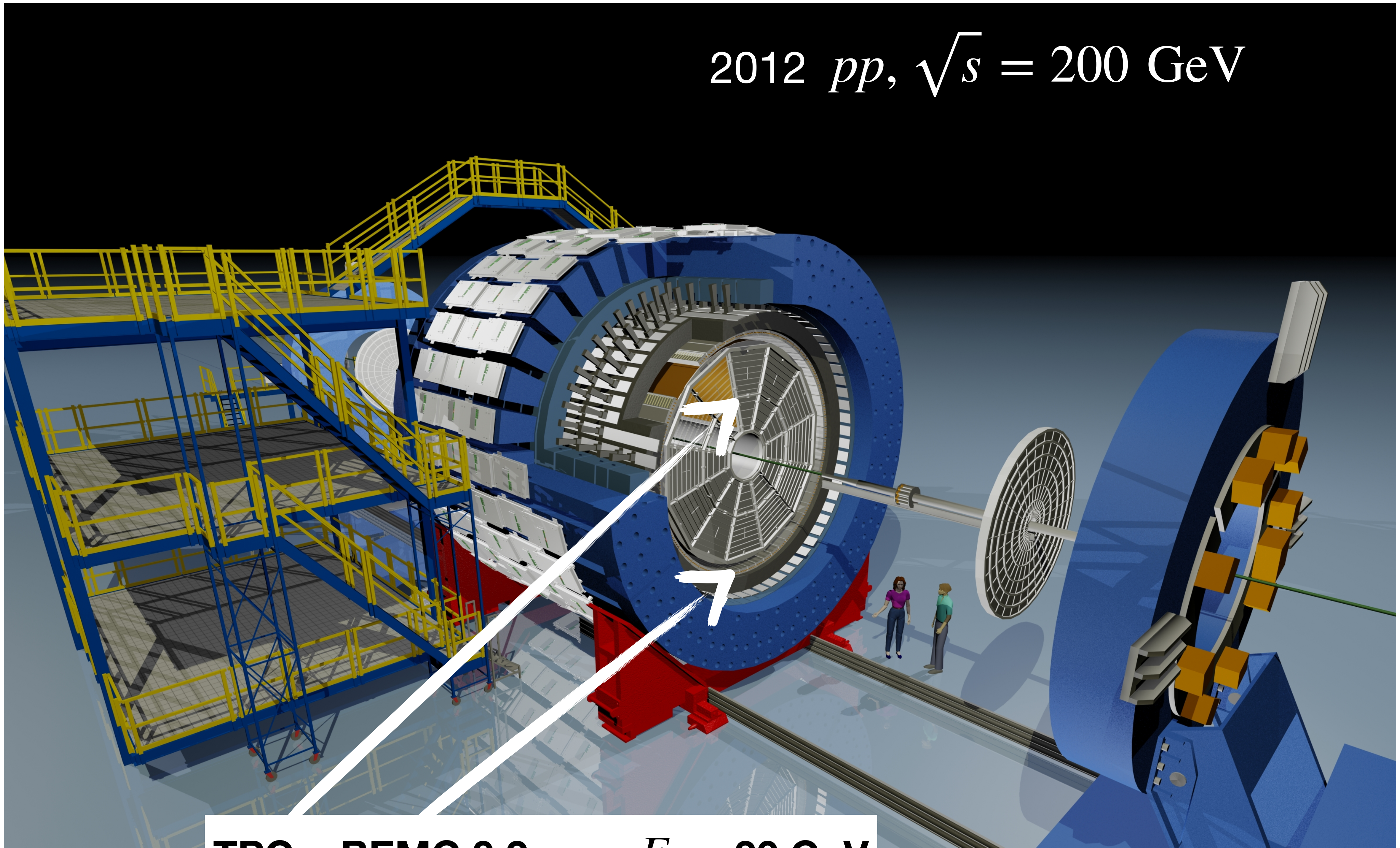
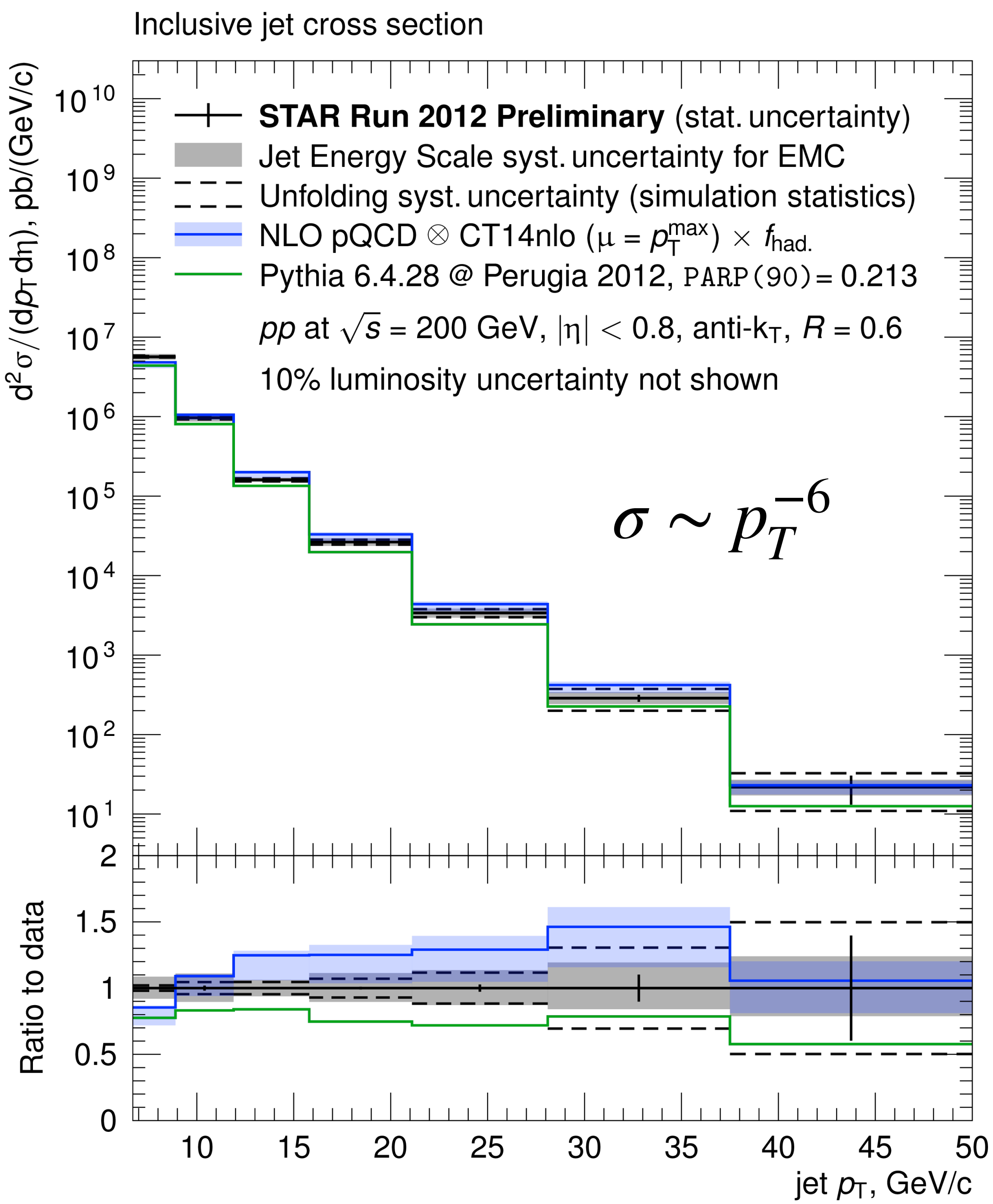


Jet reconstruction at STAR



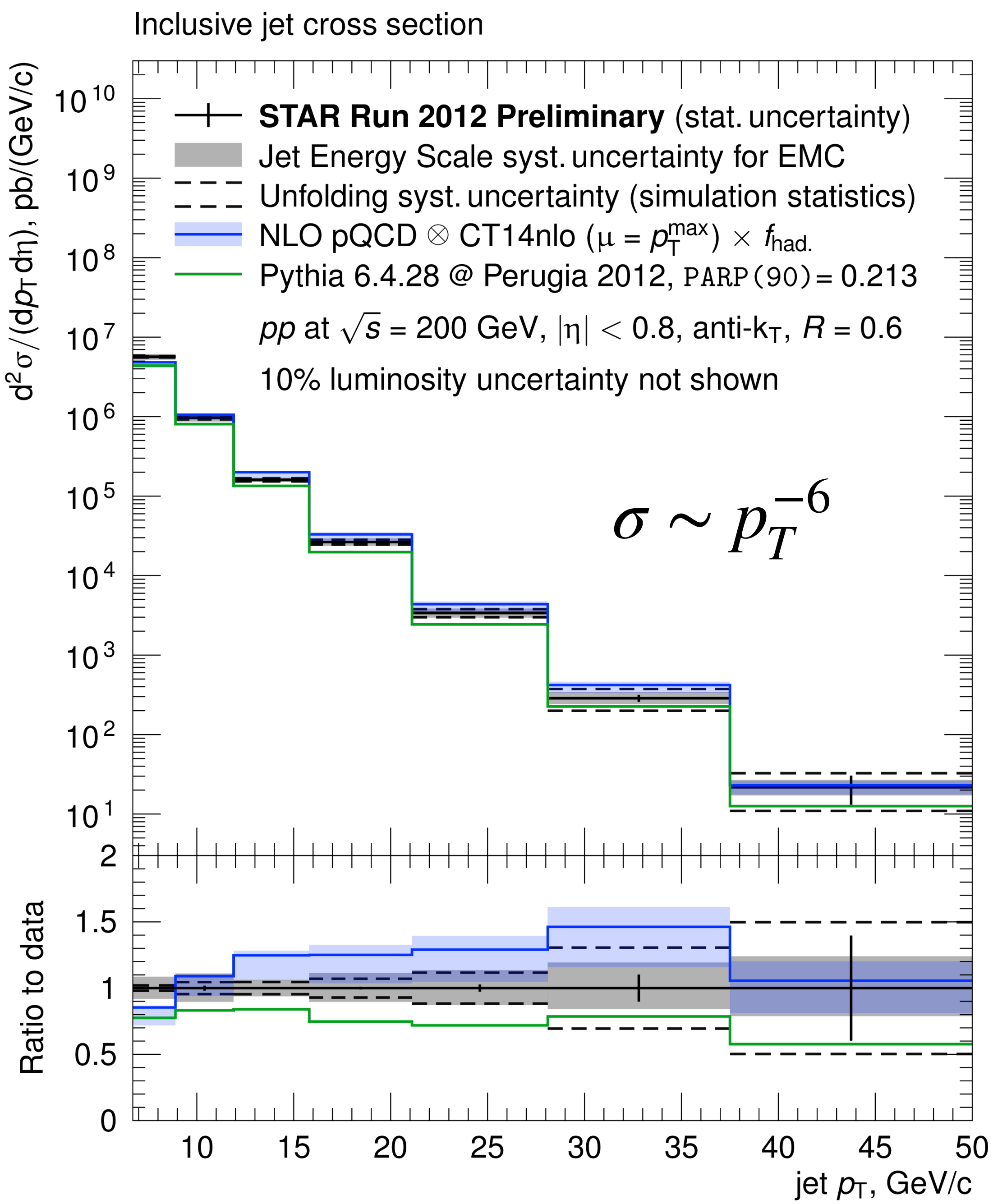
- Anti-k_{T} Ch+Ne jets
- Nominal R_{jet}= 0.4, 0.6; $|\eta_{\mathrm{jet}}| + R_{\mathrm{jet}} < 1$

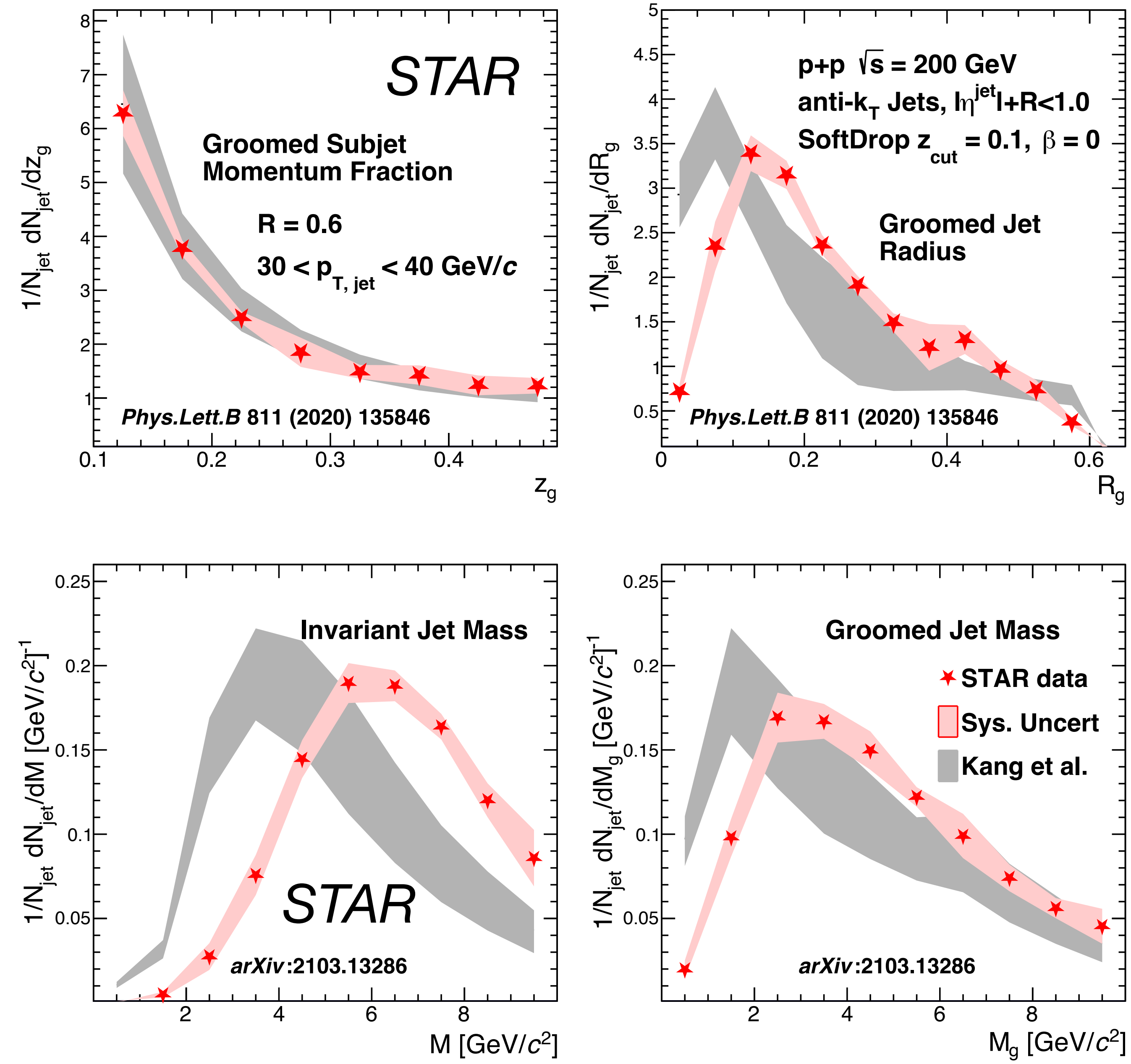
Jets in pp $\sqrt{s} = 200$ GeV



Steeply falling jet spectra - Comparable to NLO within uncertainties

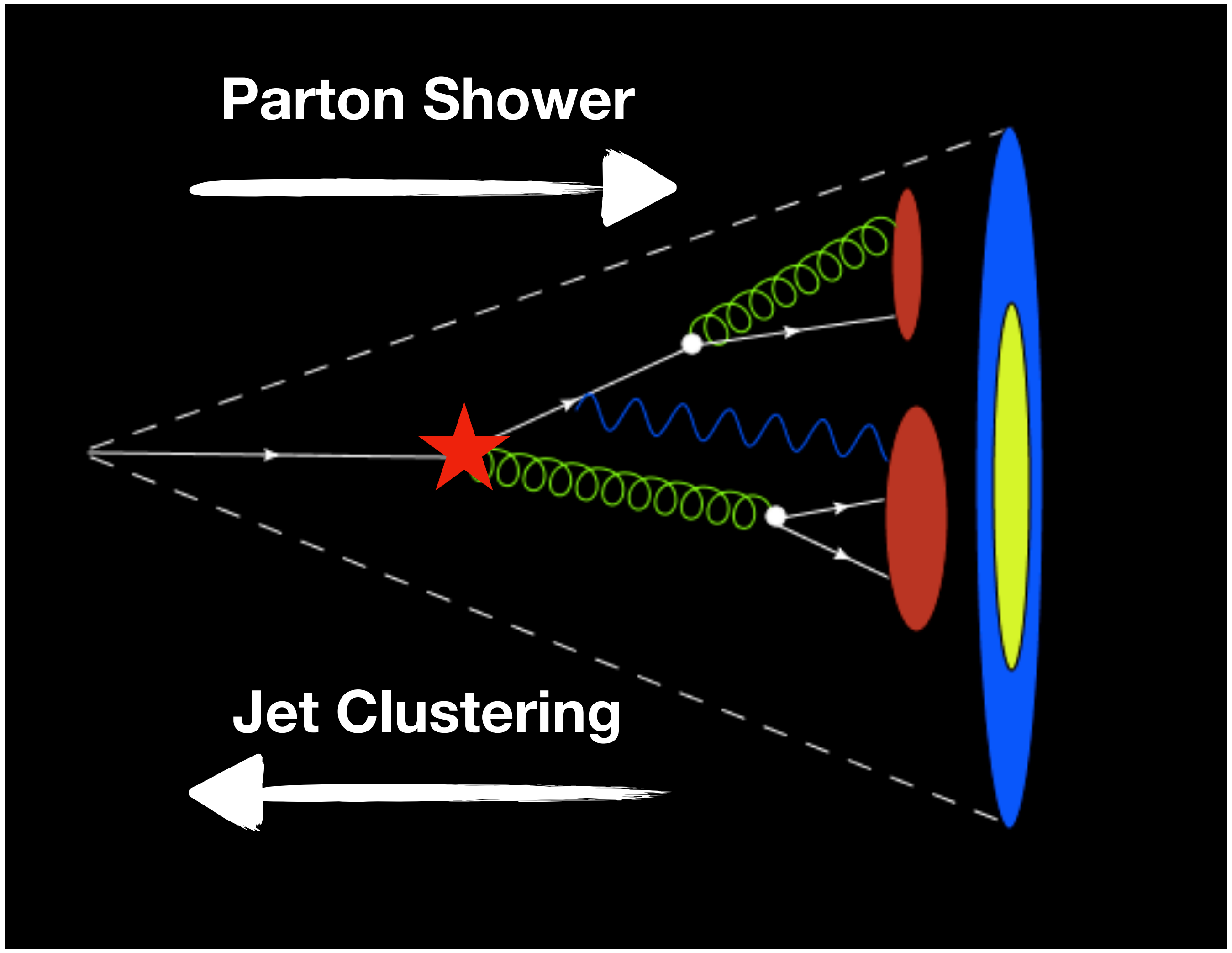
Jets in pp $\sqrt{s} = 200$ GeV

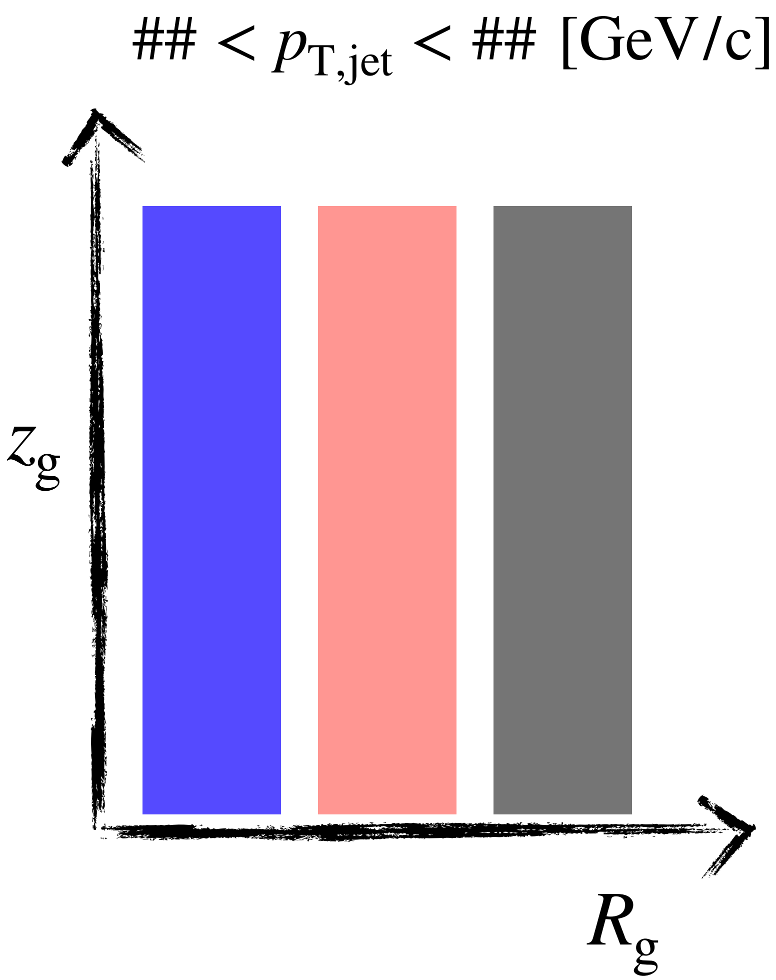




Unique population of jets with varied substructure!

Scales extend from jet $p_T \rightarrow \Lambda_{QCD}$

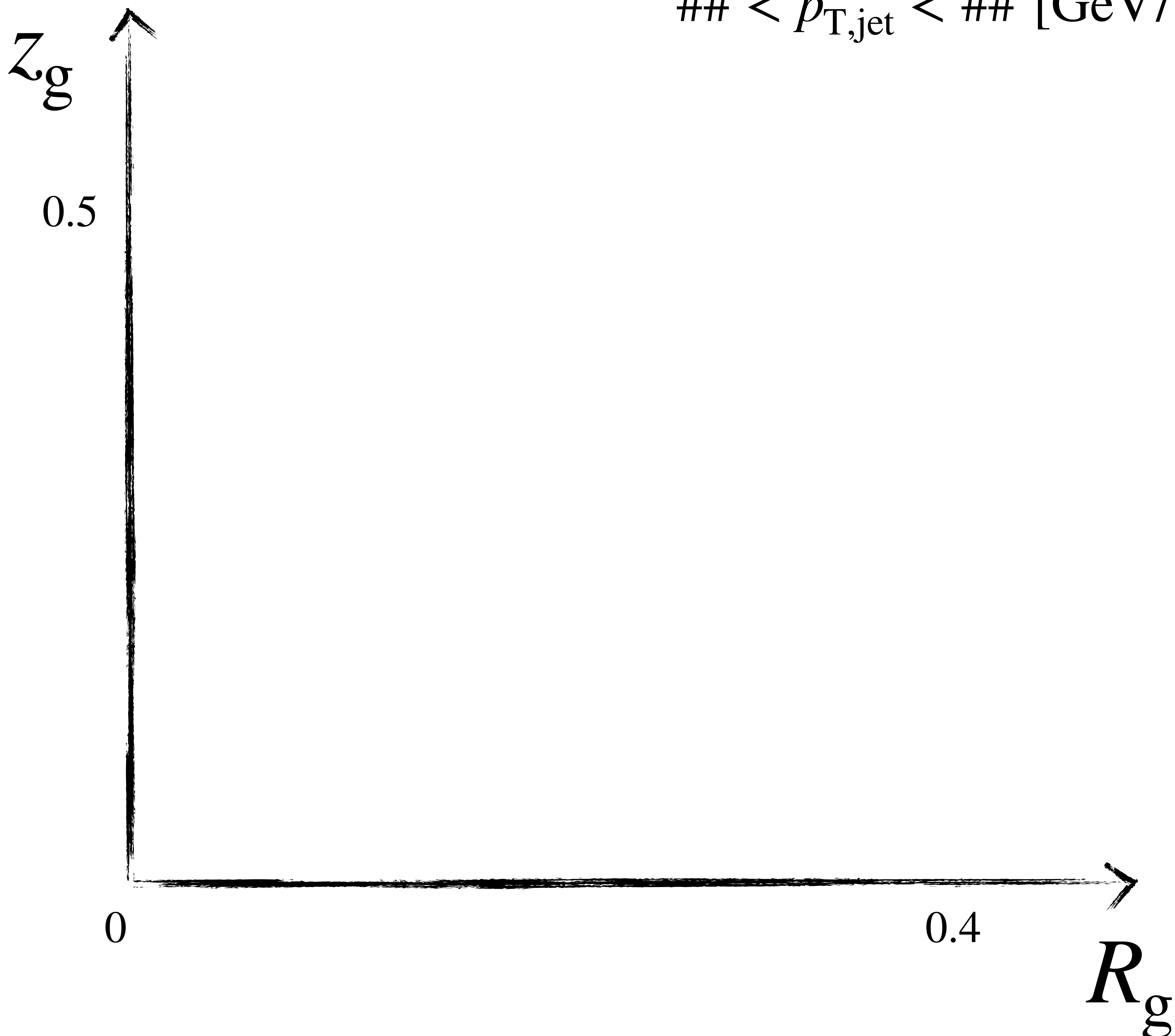


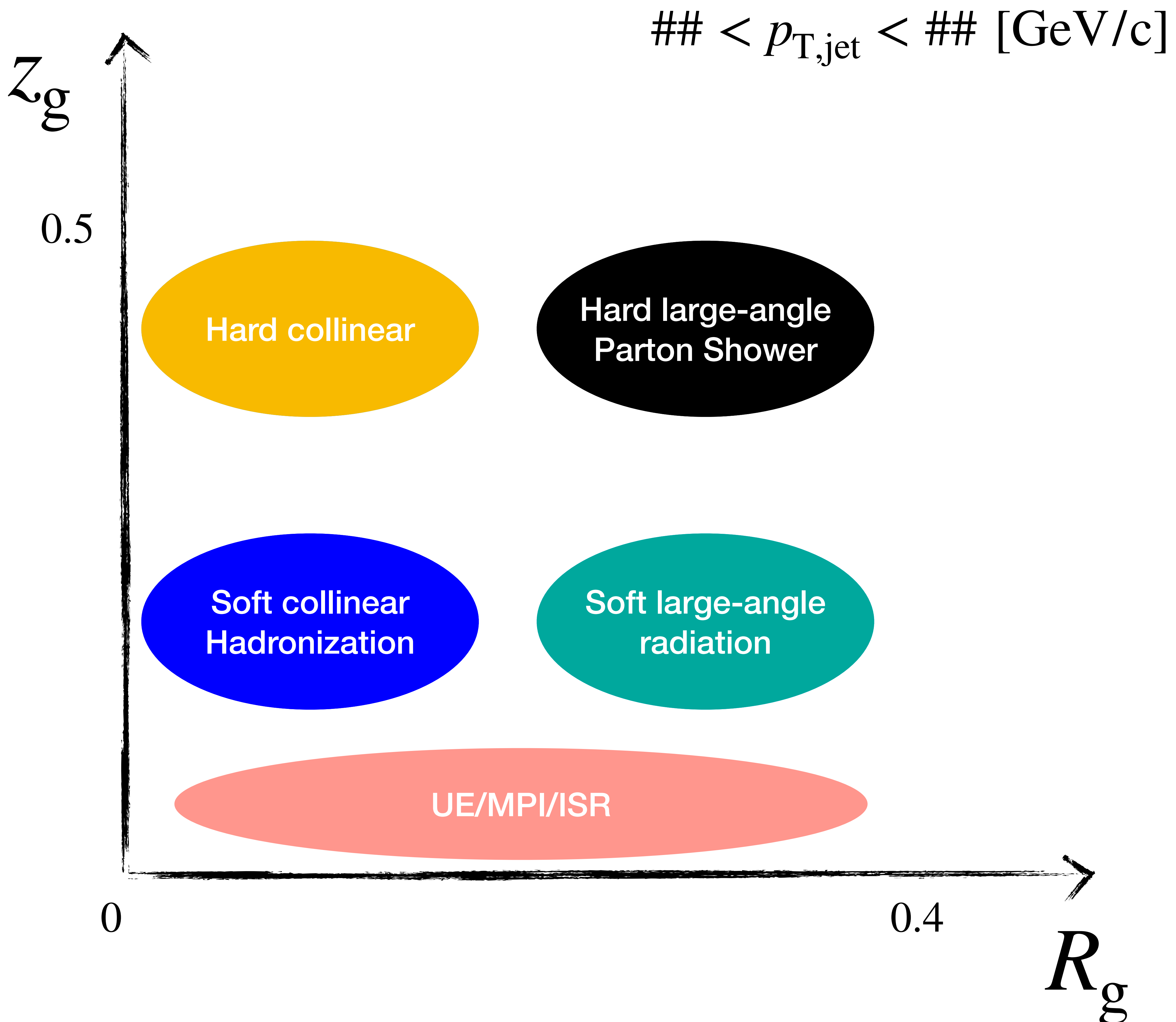


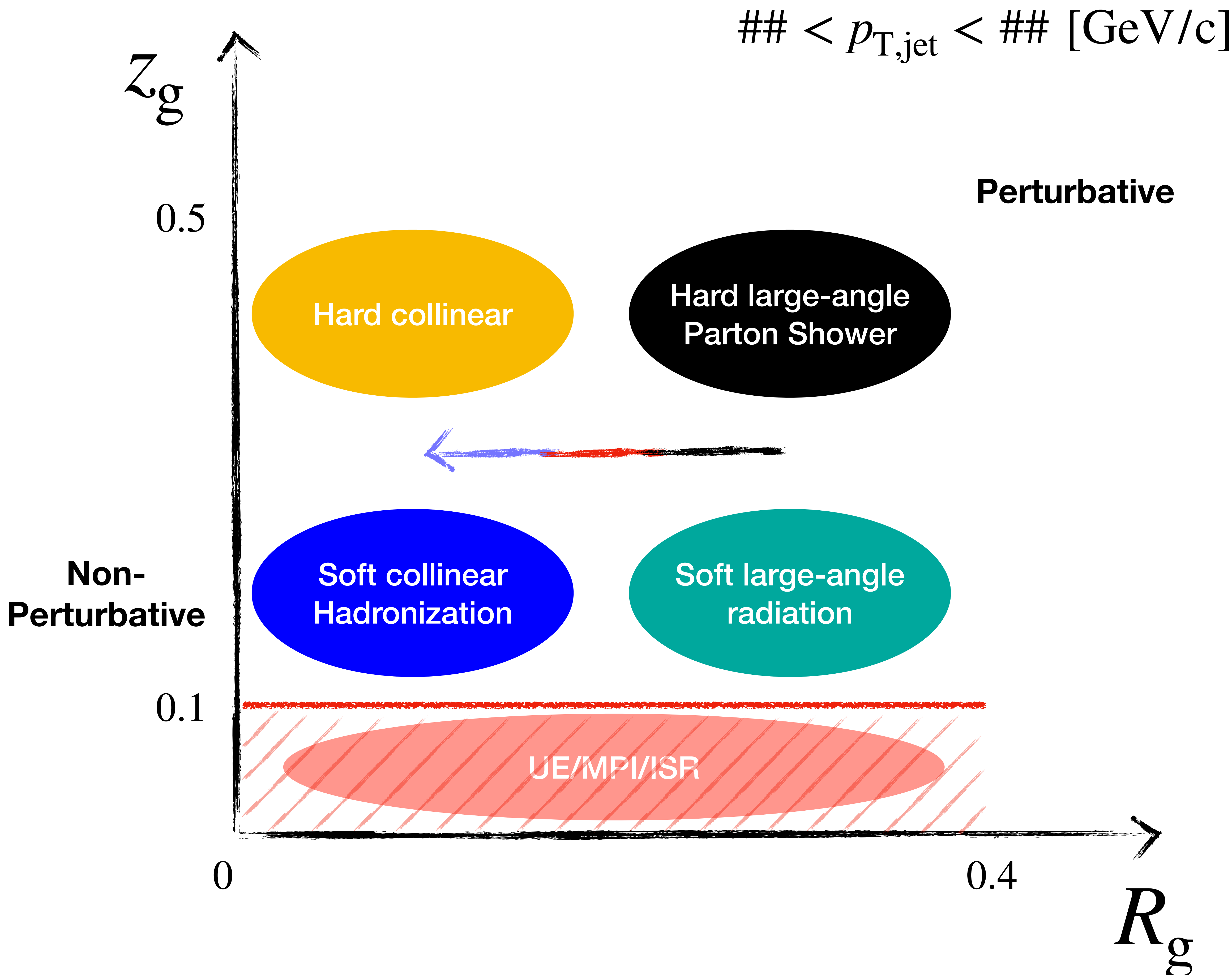
Correlations between substructure observables at the first split

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

$## < p_{T,jet} < ##$ [GeV/c]




< $p_{T,jet}$ < ## [GeV/c]
z_g
0.5
Hard collinear
Hard large-angle
Parton Shower
Soft collinear
Hadronization
Soft large-angle
radiation
UE/MPI/ISR
0
0.4
R_g



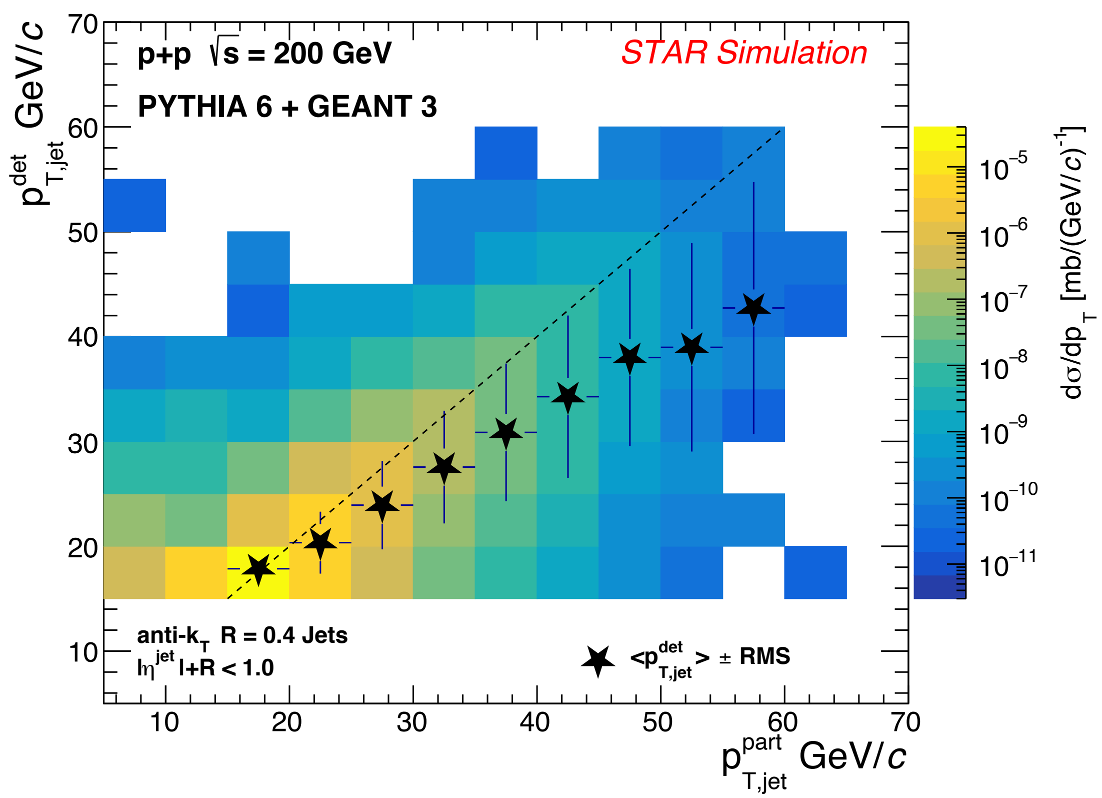
< $p_{T,jet}$ < ## [GeV/c]
z_g
0.5
0.1
0
0.4
R_g
Perturbative
Non-
Perturbative
Hard collinear
Hard large-angle
Parton Shower
Soft collinear
Hadronization
Soft large-angle
radiation
UE/MPI/ISR

Corrections in 3-D
Jet p_T, z_g, R_g

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

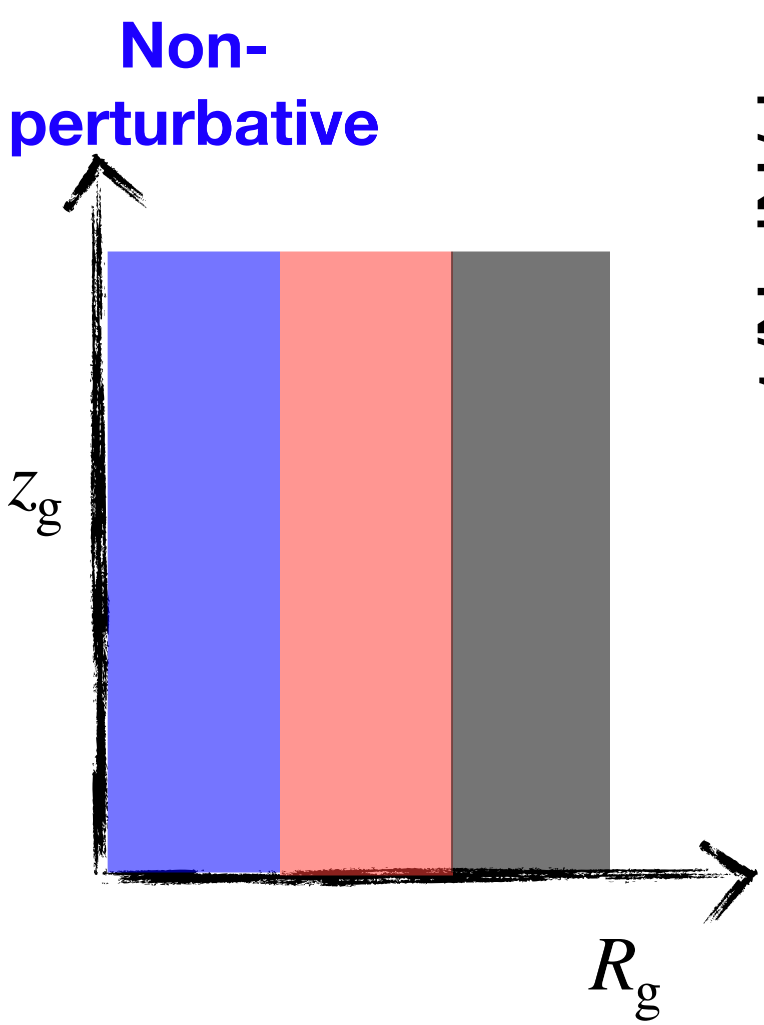
- Since results are presented for true/particle-level jet momentum selections, corrections are done by weighted sum according to the p_T response matrix

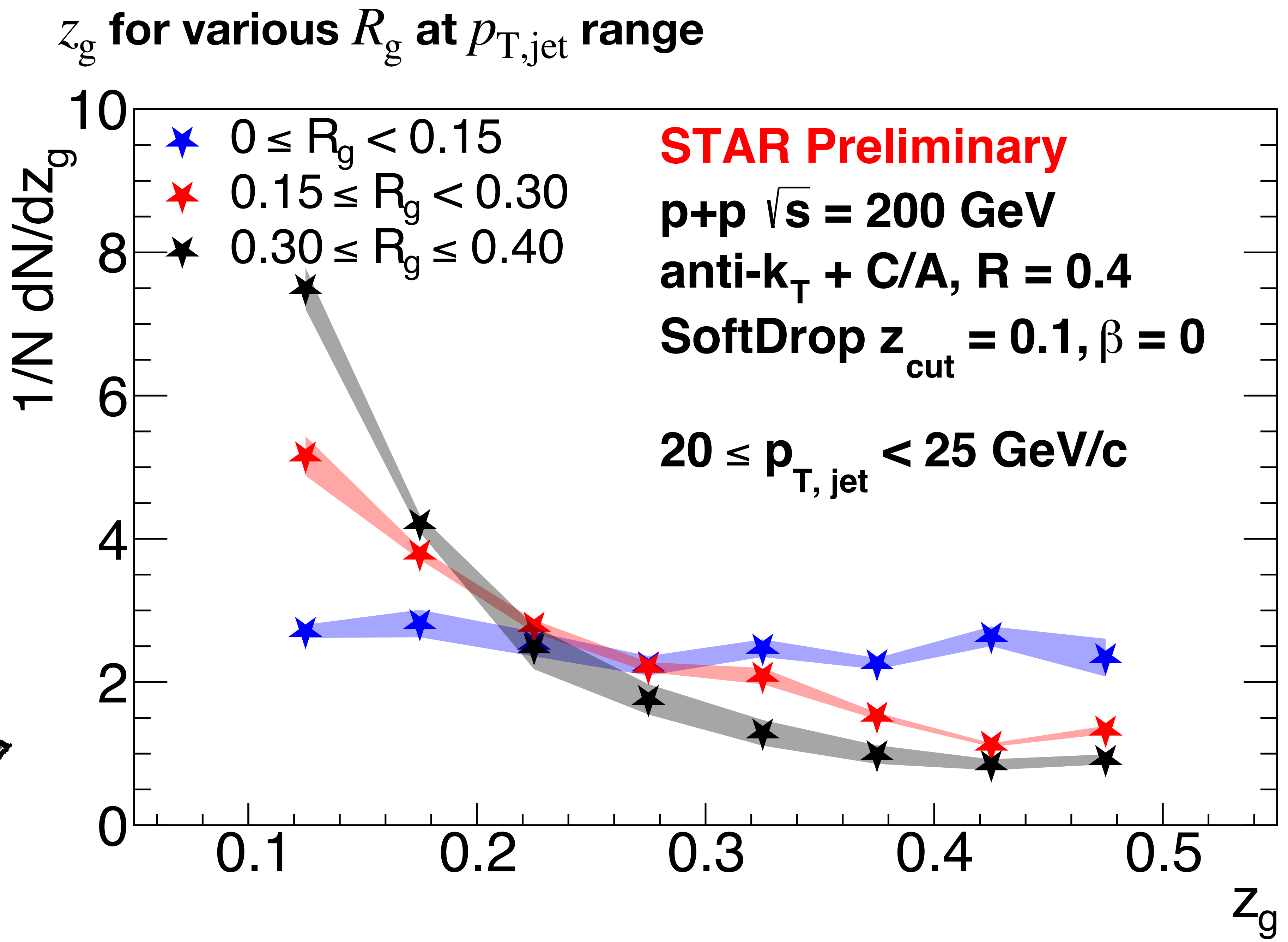
$$\sum_{i \in \mathrm{det-p_T}} \omega_i \cdot U(z_g, R_g)|_{\mathrm{det-p_T}}$$



Details on systematic uncertainties available in backup

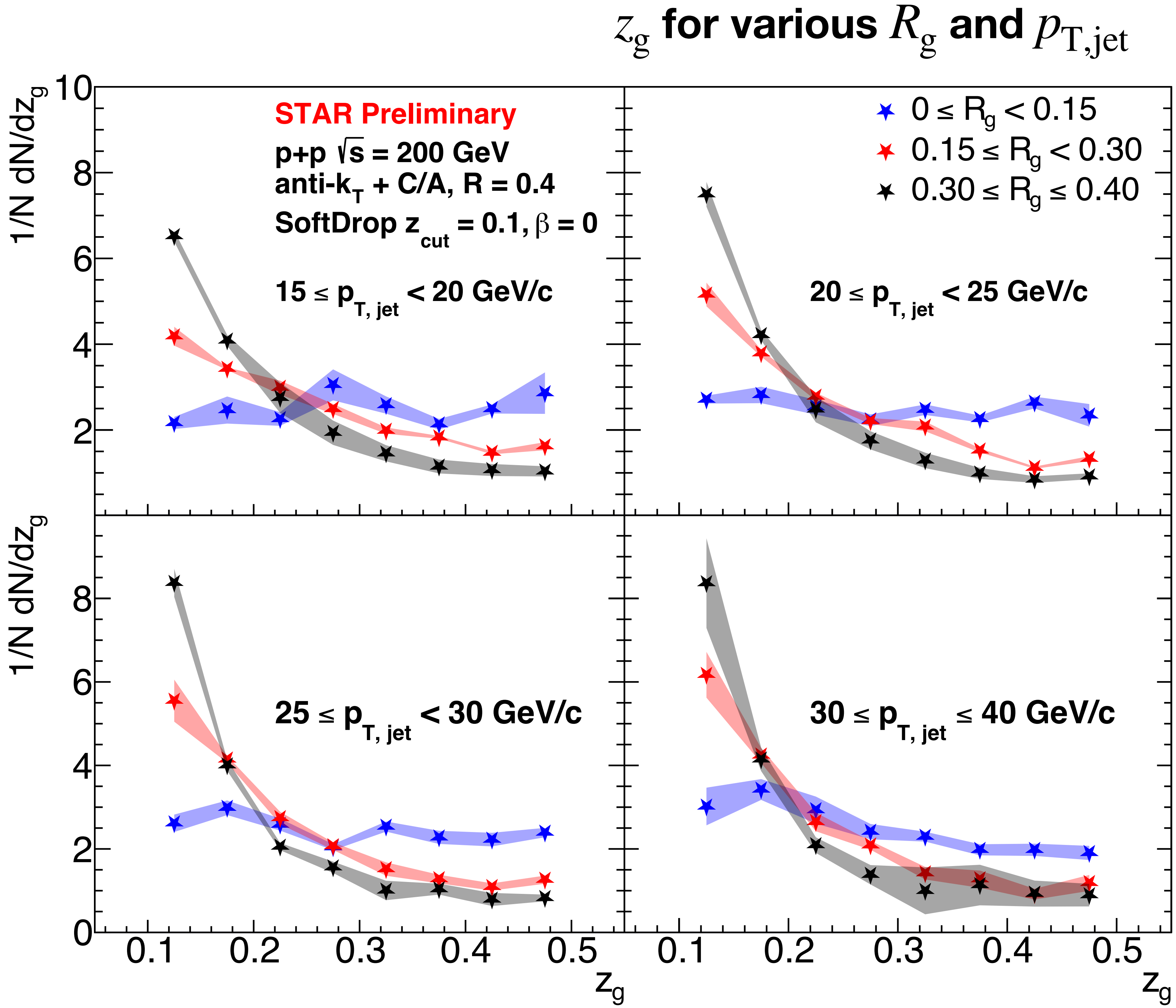
Fully corrected results



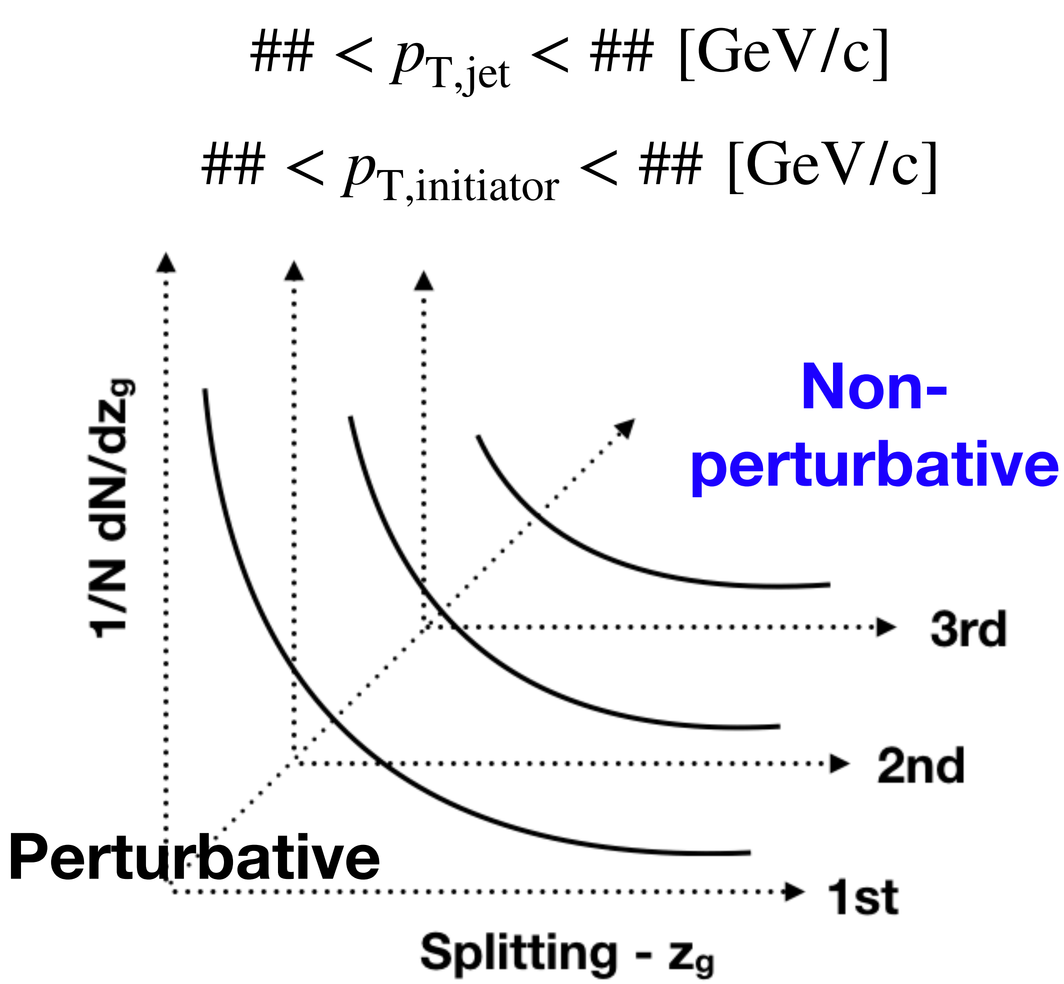


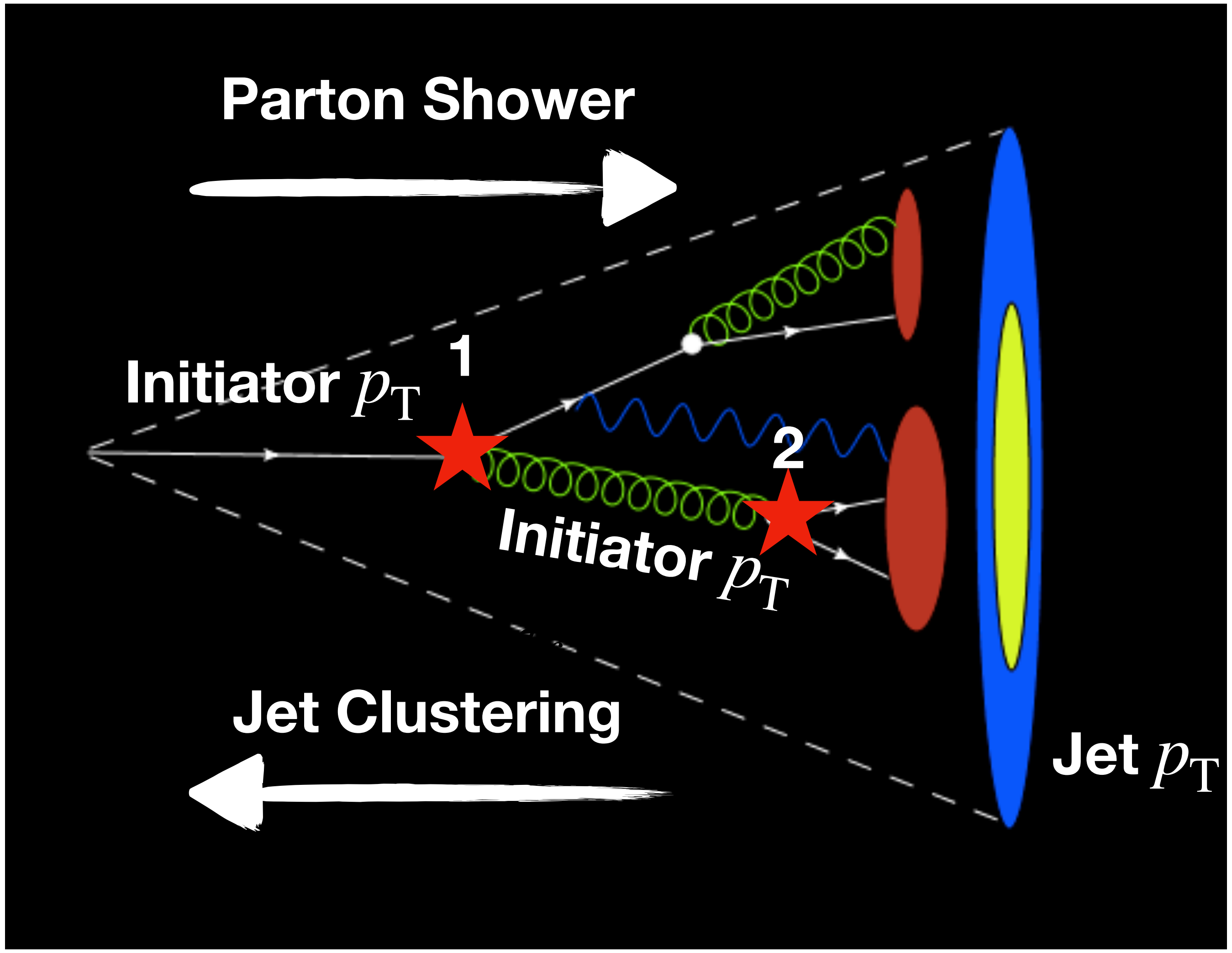
- Significant variation from selecting on R_g
- Evolution from **soft-wide angle splits** to **hard-collinear splits**

Evolution vs. $p_{T,jet}$



- Increasing jet p_T has a small to mild effect on substructure
- Selection on R_g determines **the z_g shape** - high degree of correlation
- **Phase space restrictions** matter!



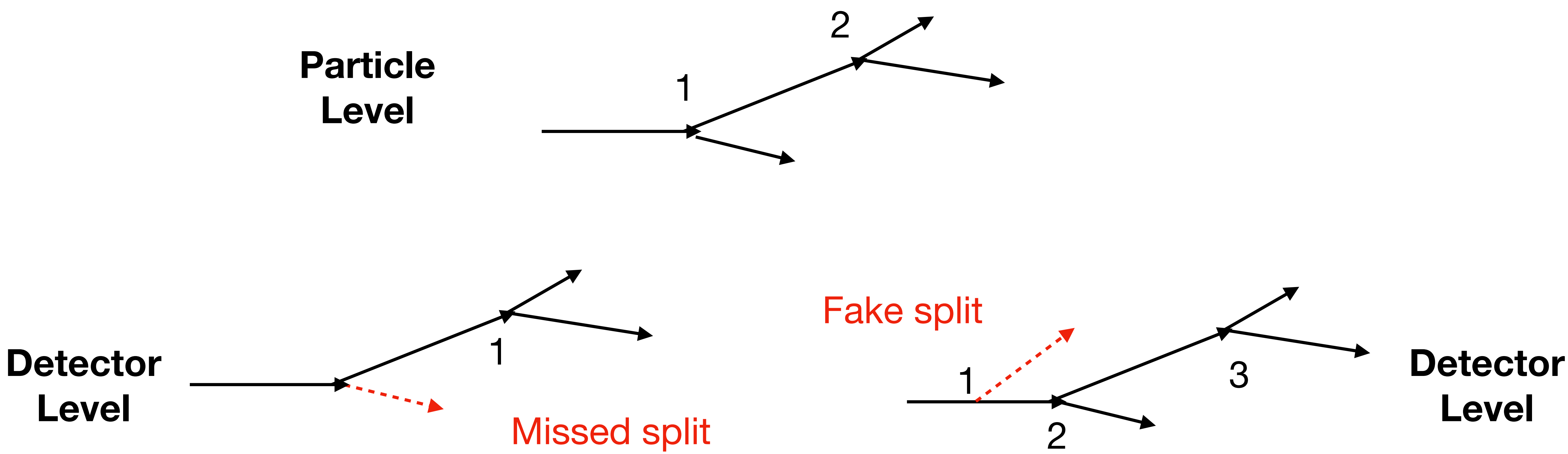


Correlations between substructure observables at the first split

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

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



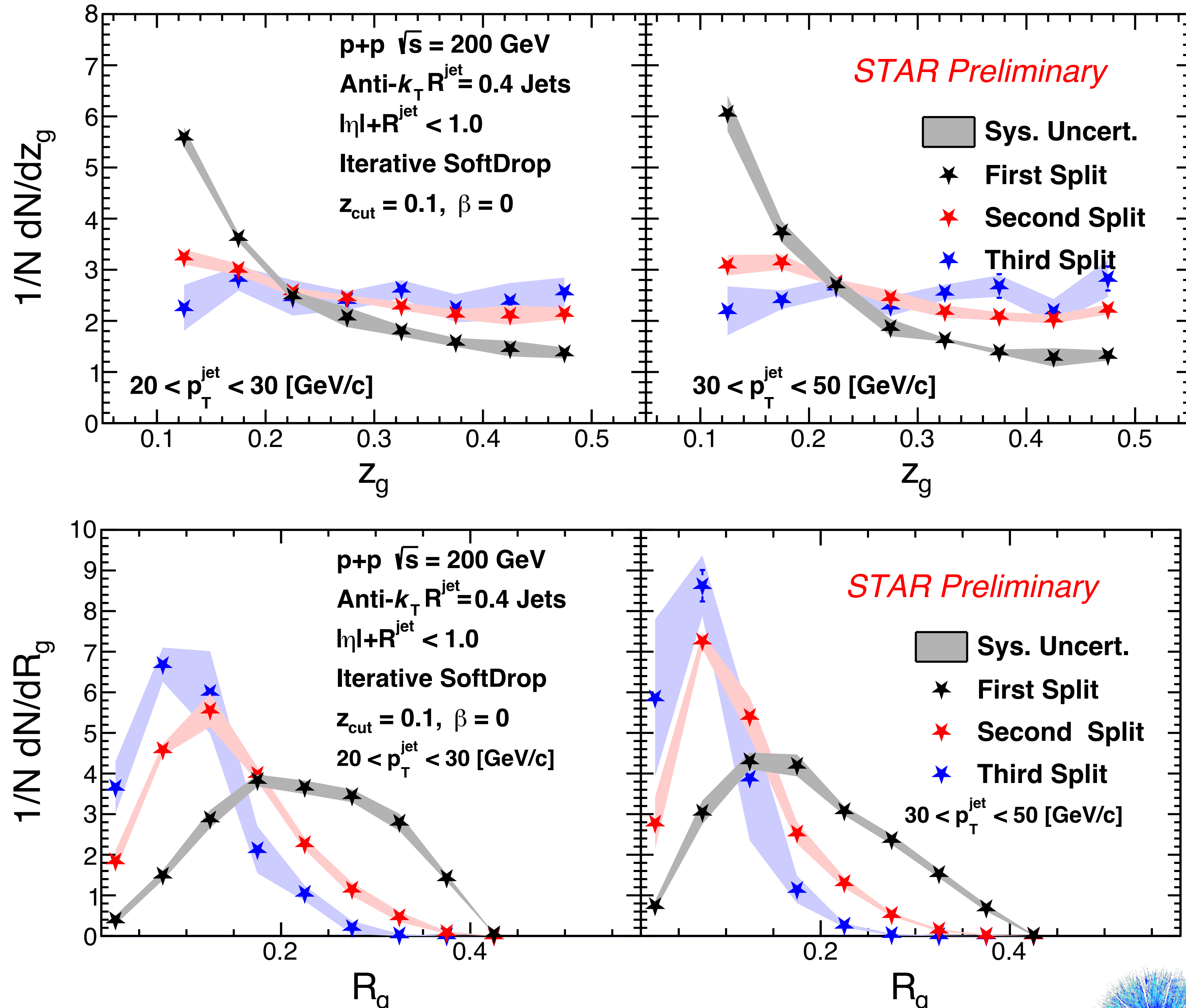
- Observables ($p_{\mathrm{T,jet/initiator}}$, z_{g}, R_{g}) at a given split are smeared
- Splitting hierarchy also modified going from particle to detector level jets

Details of unfolding and systematic uncertainties available in backup

Fully corrected results

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

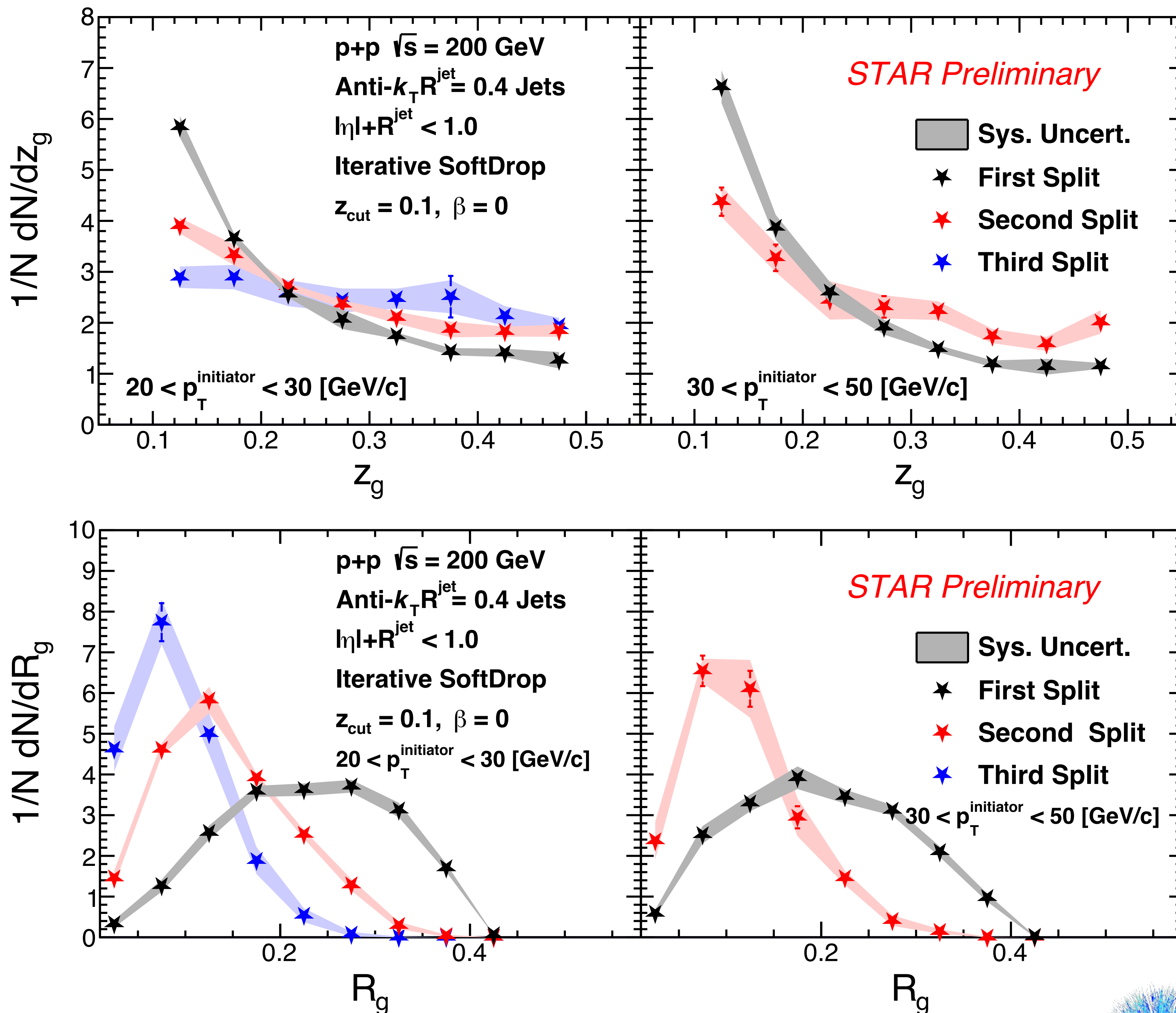
- **For a given jet $p_{\mathrm{T,jet}}$,** what are the z_g, R_g at 1st, 2nd and 3rd splits? Follow a jet…
- **Significant differences between first, second and third splits**
- Splitting **'z' becomes flat and the R_g quite narrow** for the third split where we observe collinear emissions



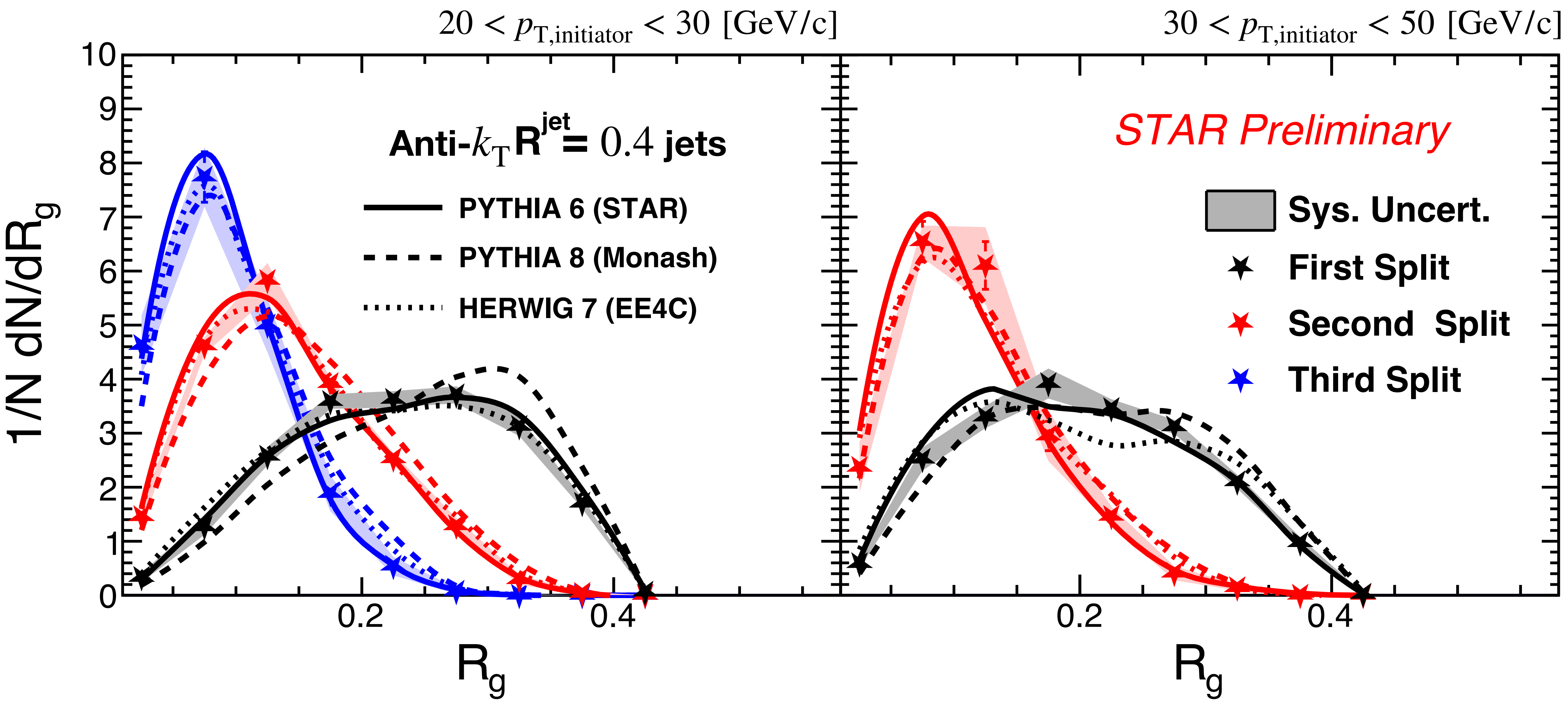
Fully corrected results

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** with each other - only difference is where they occur in the shower
- **Hint of differences between second split** z_g (similar R_g) for initiator vs. jet momenta selection



Comparisons with leading order MC - R_g for various initiator p_T



- 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 # - similar peaks of R_g for **third splits** on the left to **second splits** on the right

Conclusions

- 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 quite close to Λ_{QCD}

Next steps

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

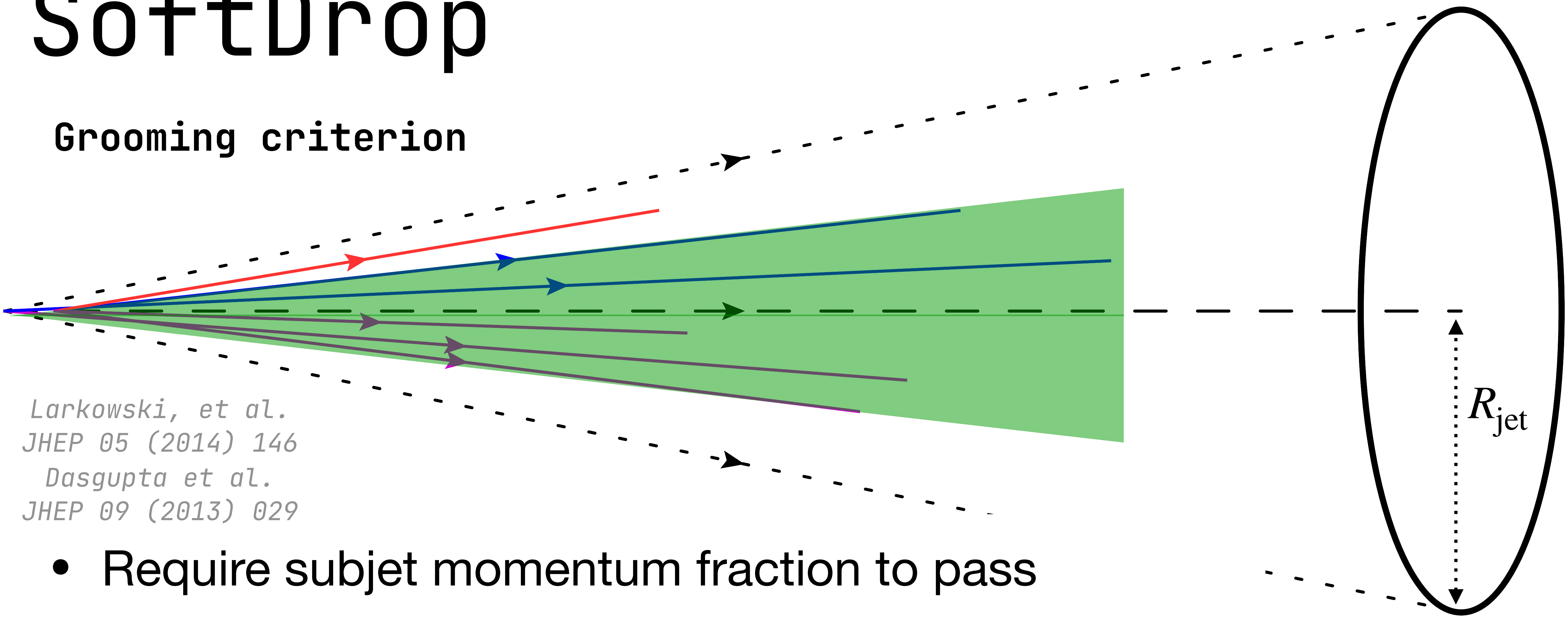
	Parton Shower	Hadronization	UE Tune
PYTHIA-6	k_T	Lund	RHIC
PYTHIA-8	Dipole/Vincia/p_T	Lund	RHIC/LHC
HERWIG-7	Angular/Dipole	Cluster	LHC
SHERPA	Dipole	Lund/Cluster	LHC

  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

SoftDrop

Grooming criterion



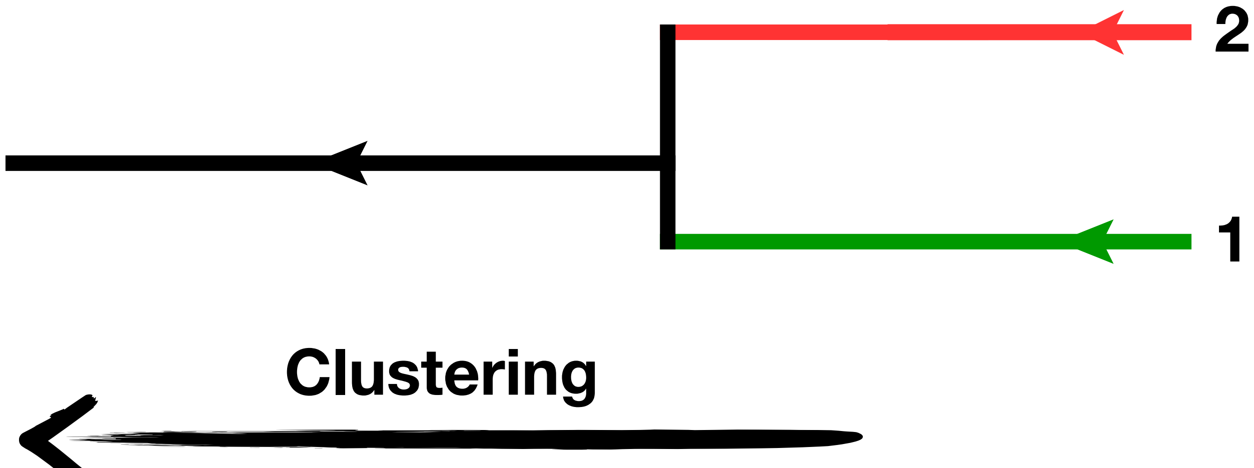
Larkowski, et al. JHEP 05 (2014) 146
Dasgupta et al. JHEP 09 (2013) 029

- Require subjet momentum fraction to pass

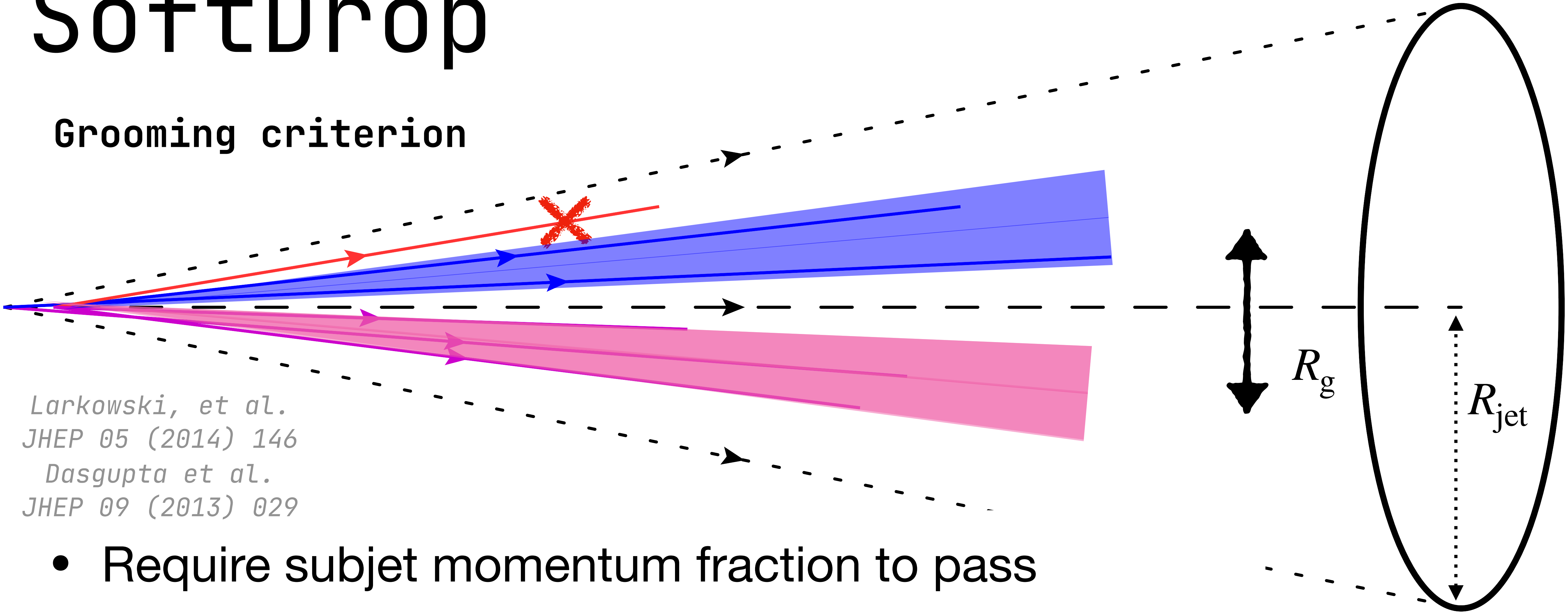
$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$

$z_{cut} = 0.1$

$\beta = 0$



SoftDrop



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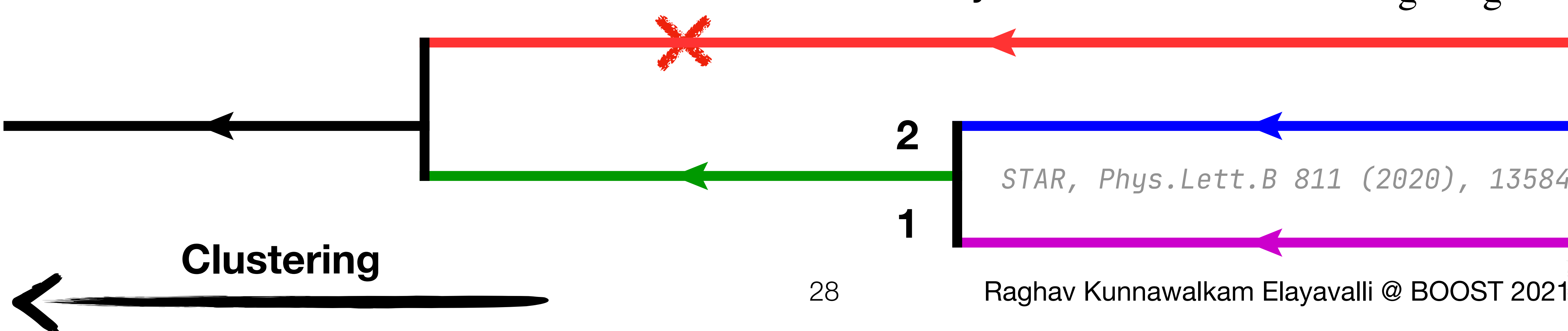
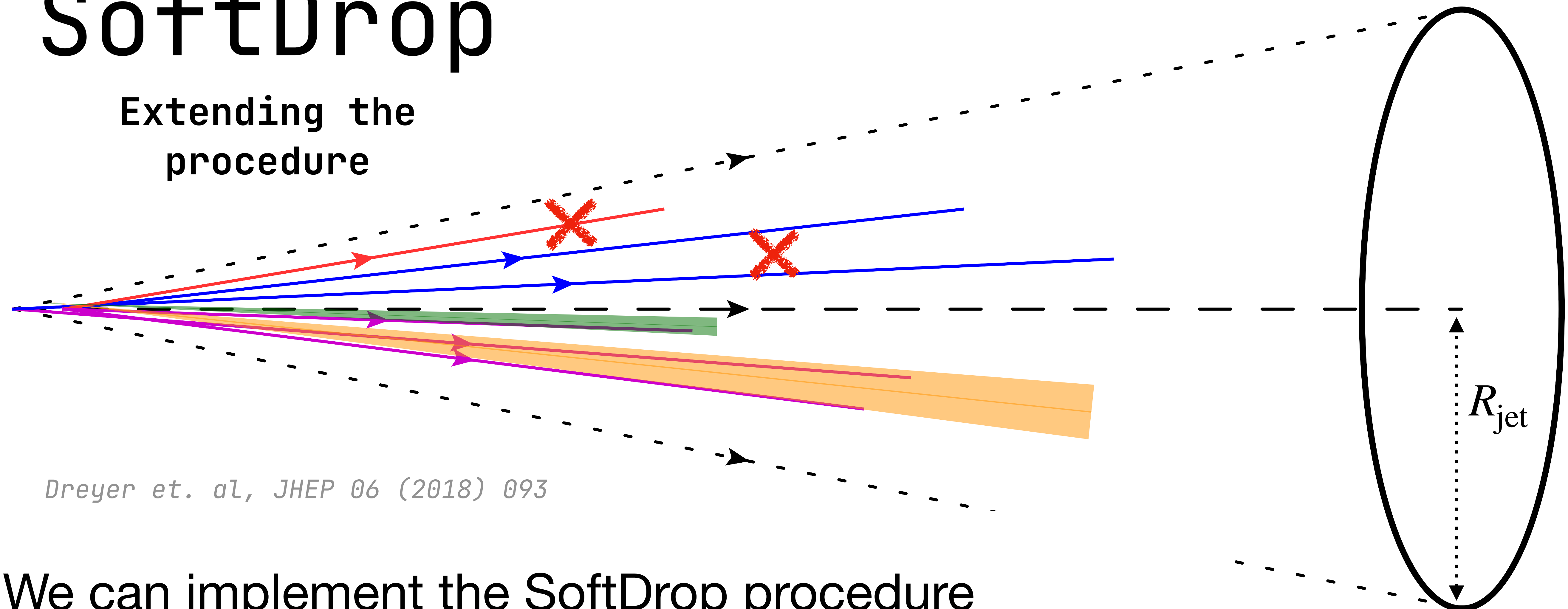
- With the two surviving branches (first hard split) - we define observables that characterize jet substructure z_g, R_g



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

SoftDrop

Extending the procedure

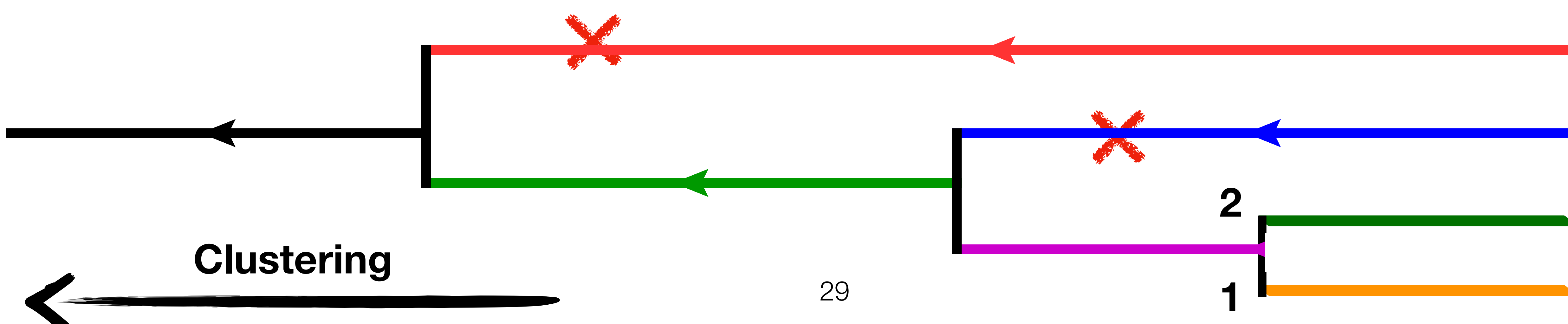


Dreyer et. al, JHEP 06 (2018) 093

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

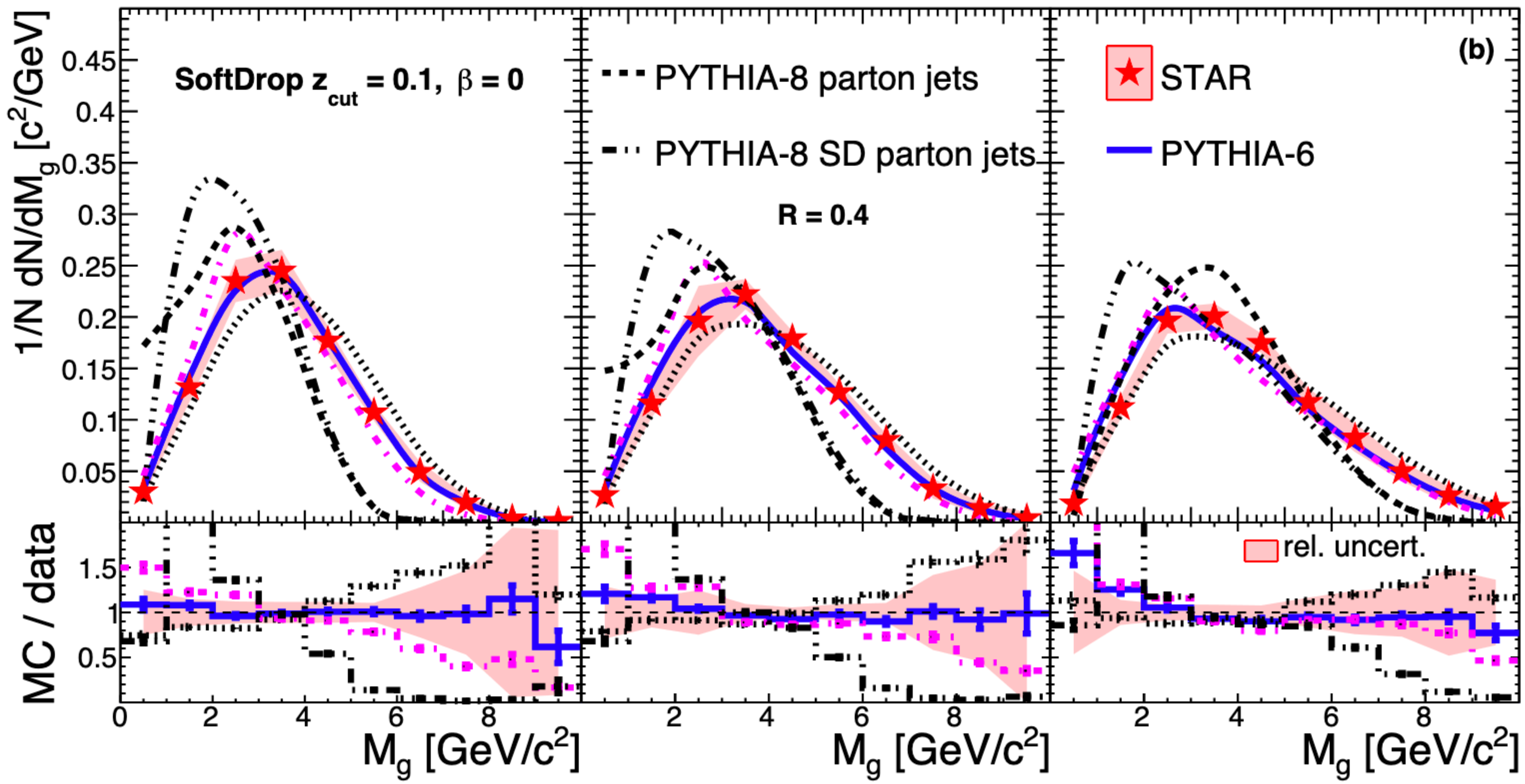
- Follow the hardest branch - Iterative SoftDrop
- Following all branches - Recursive SoftDrop

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



Groomed Jet Mass

STAR arXiv:2103.13286, Accepted in PRD



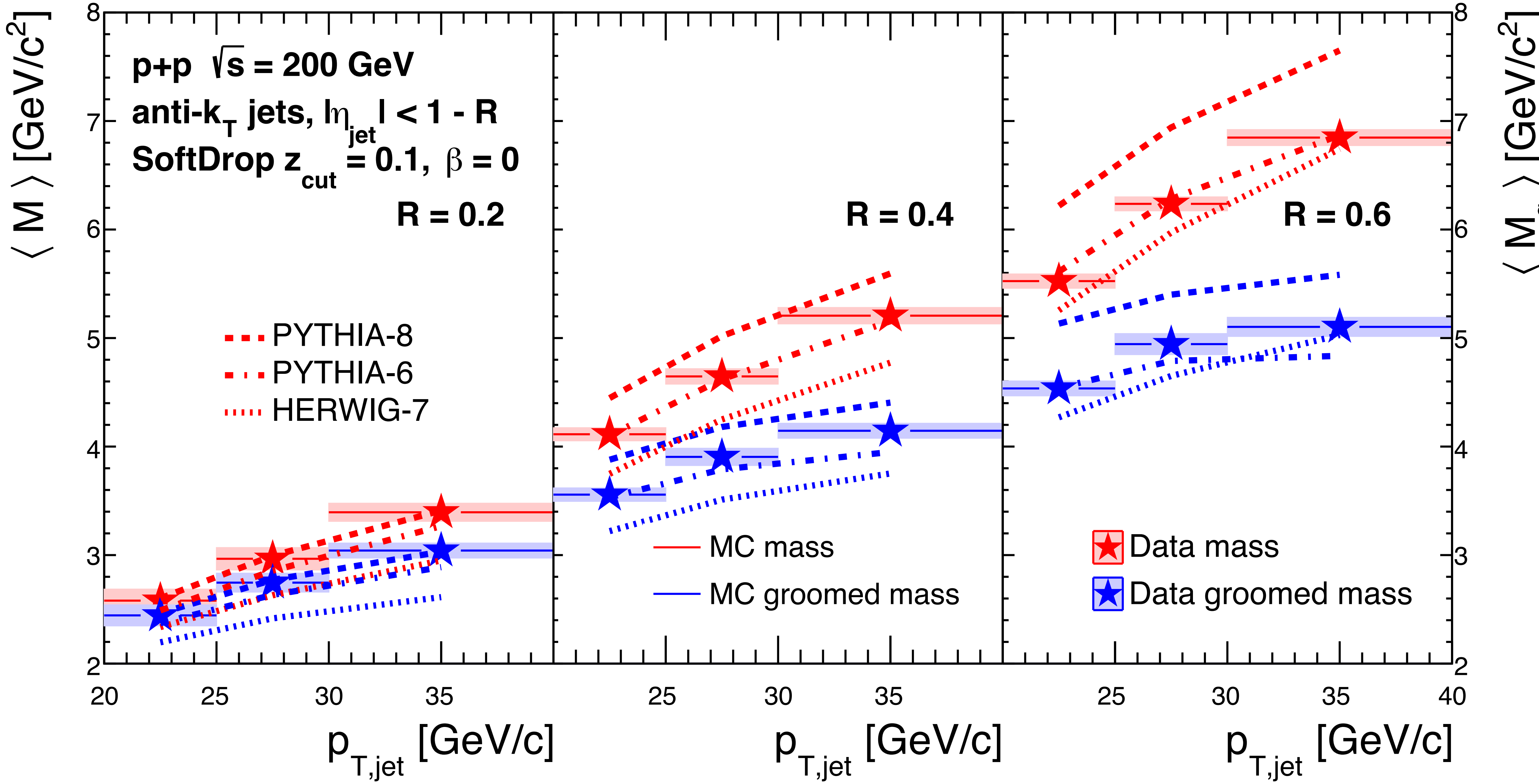
RHIC-tuned **PYTHIA-6** describes data

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



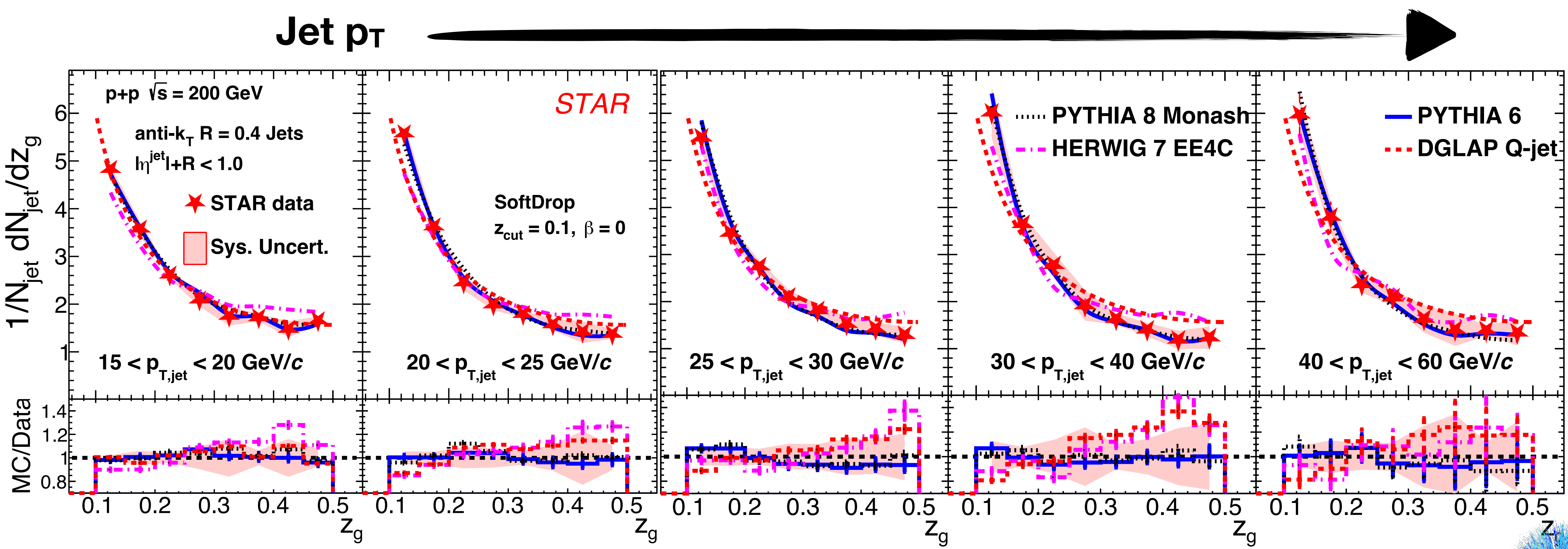
Increase in jet mass with increasing p_{T} and R is reduced with grooming - reduces overall impact of non-perturbative contributions to jets

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 ~ 25 GeV/*c*
- ★ **PYTHIA-6** and **PYTHIA-8** describe data
- ★ **HERWIG-7** predicts harder splitting

STAR, Phys.Lett.B 811 (2020)

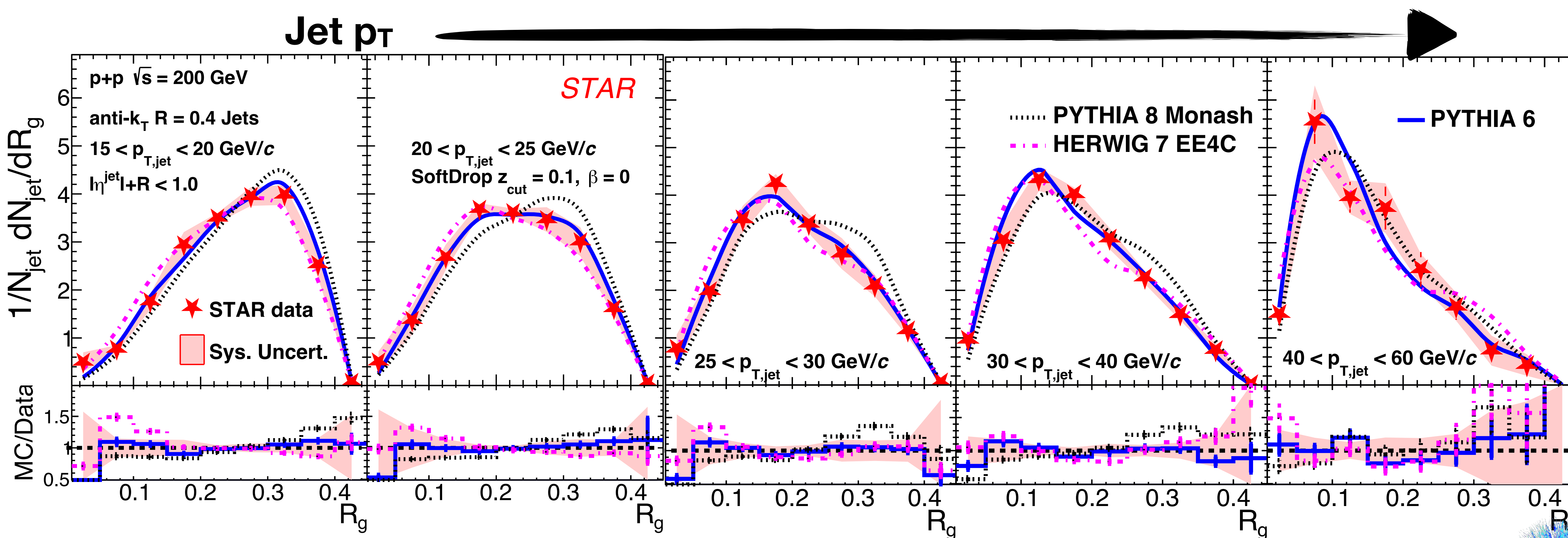


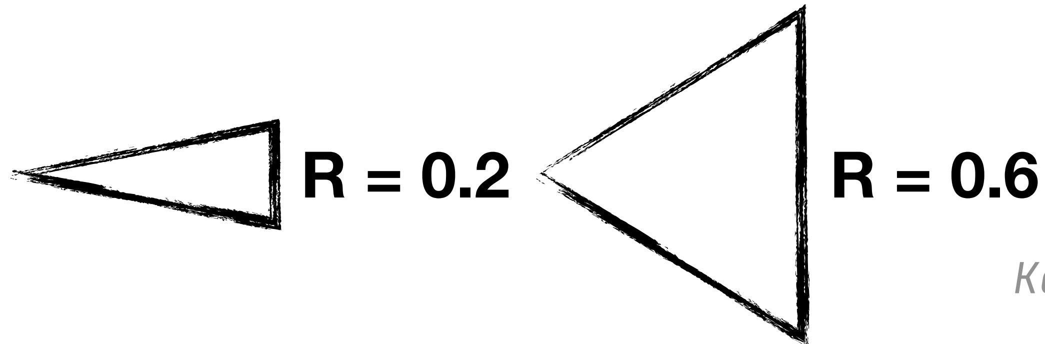
SoftDrop R_g

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

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

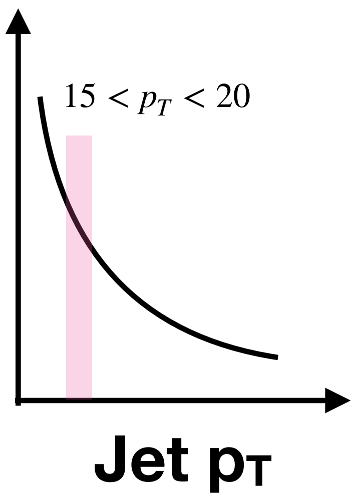
STAR, Phys.Lett.B 811 (2020)

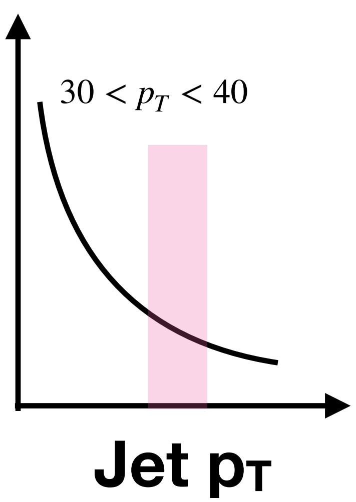


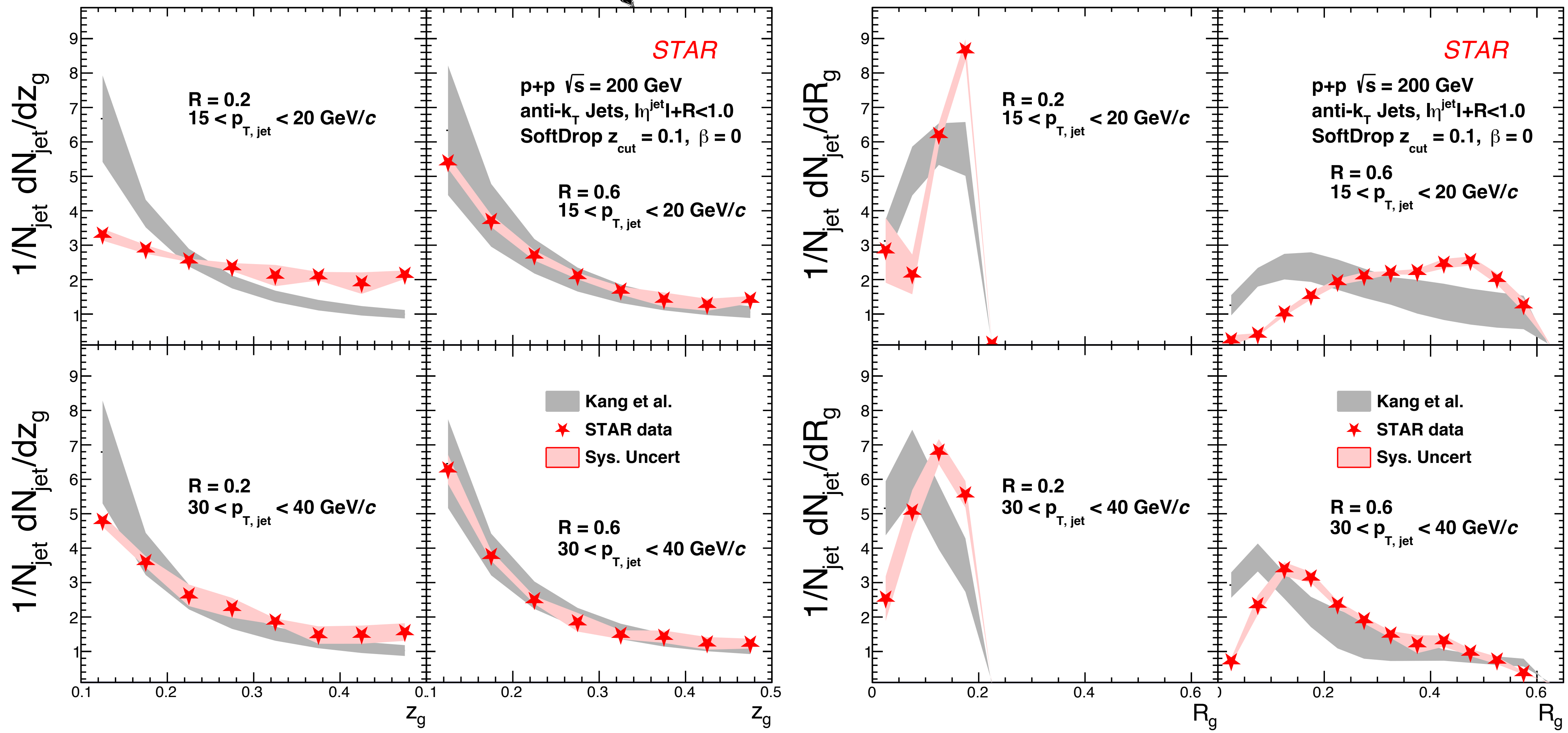


STAR, Phys.Lett.B 811 (2020)

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



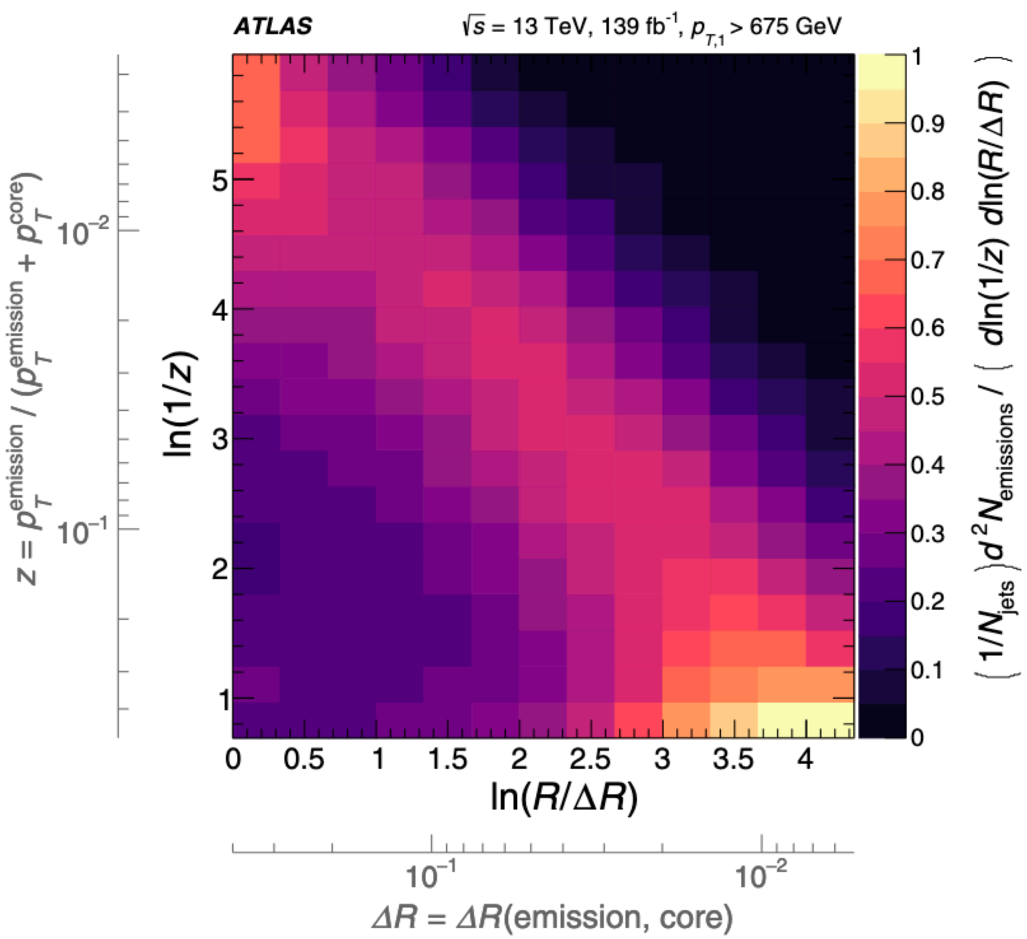


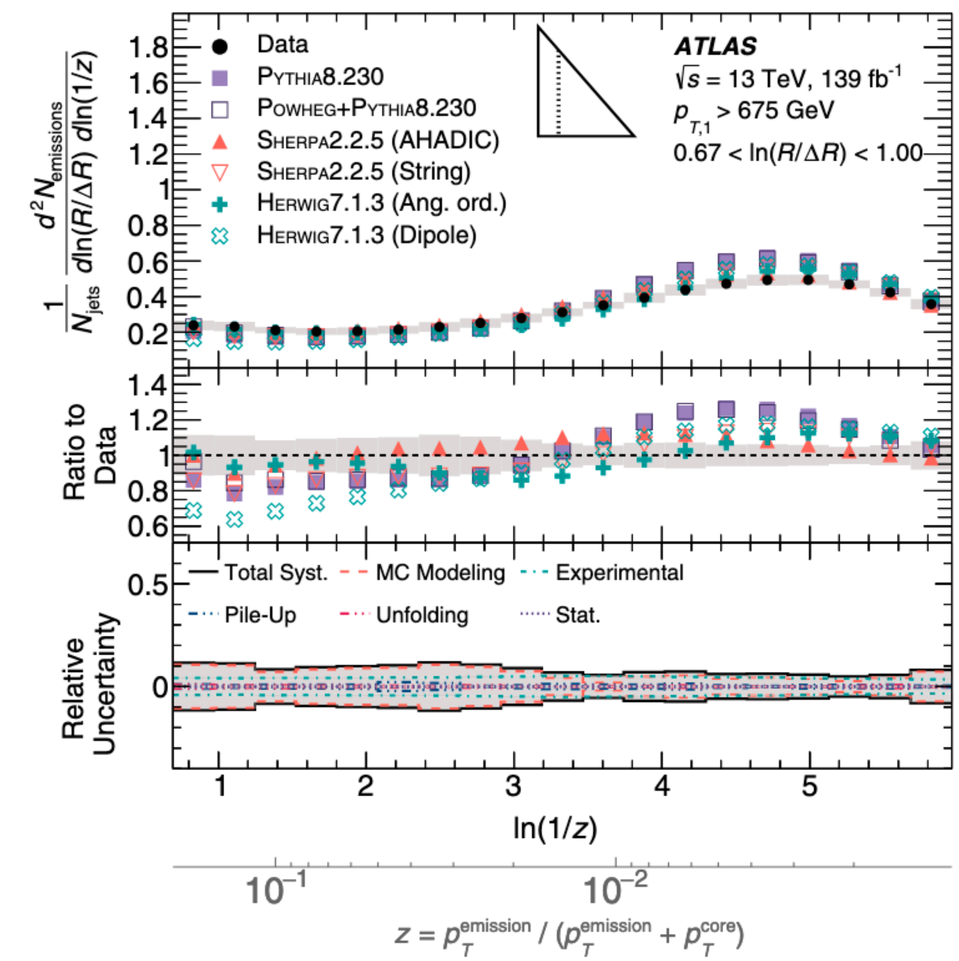


- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and p_T
- Significantly worse for jets of narrow R and low p_T - tighter constraints on jet splittings

Recent measurements of Lund Plane and their projections at the LHC

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

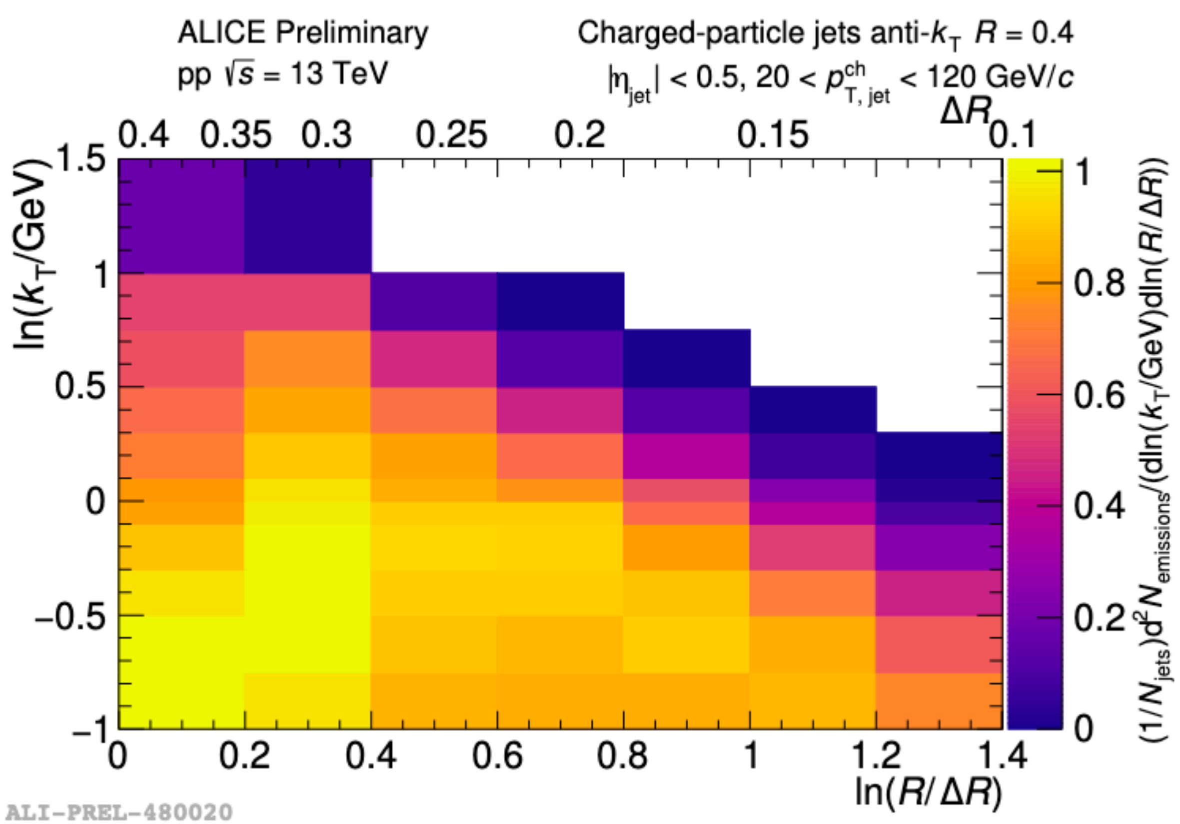


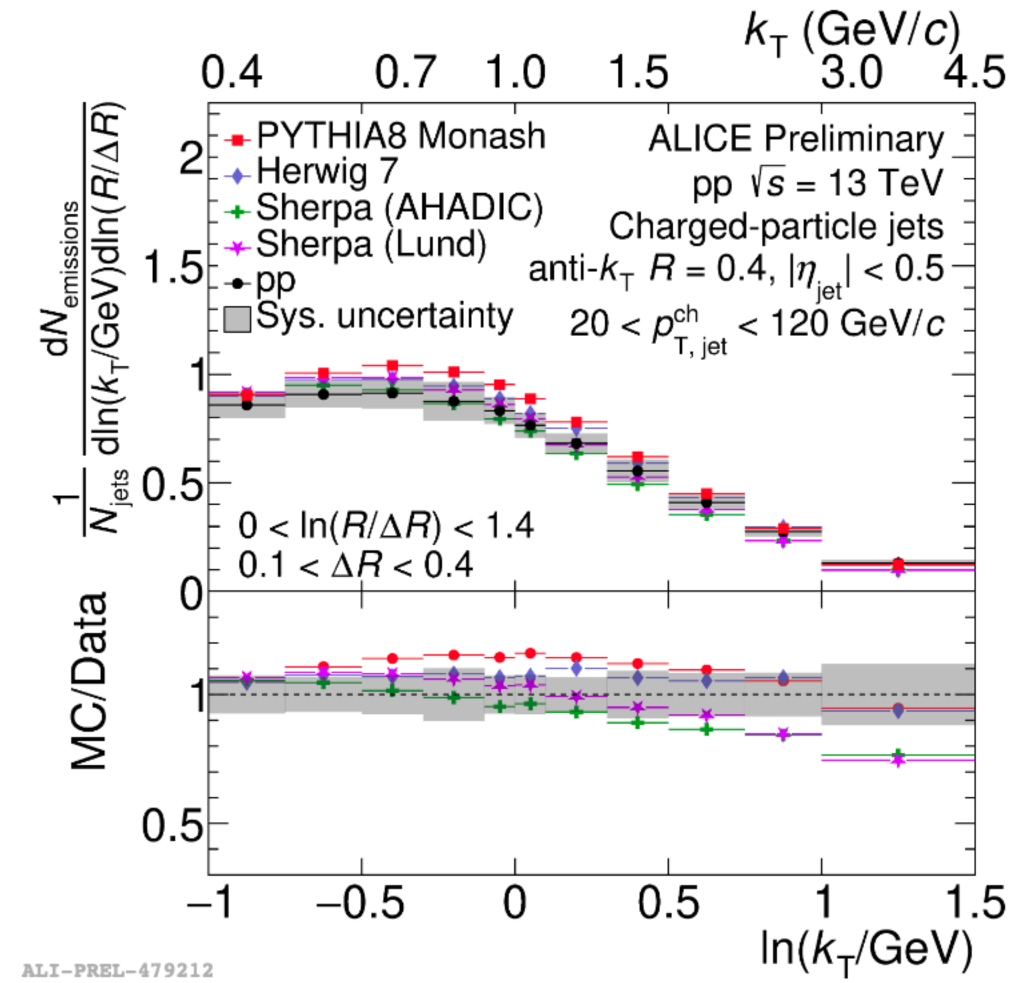


- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcase differences

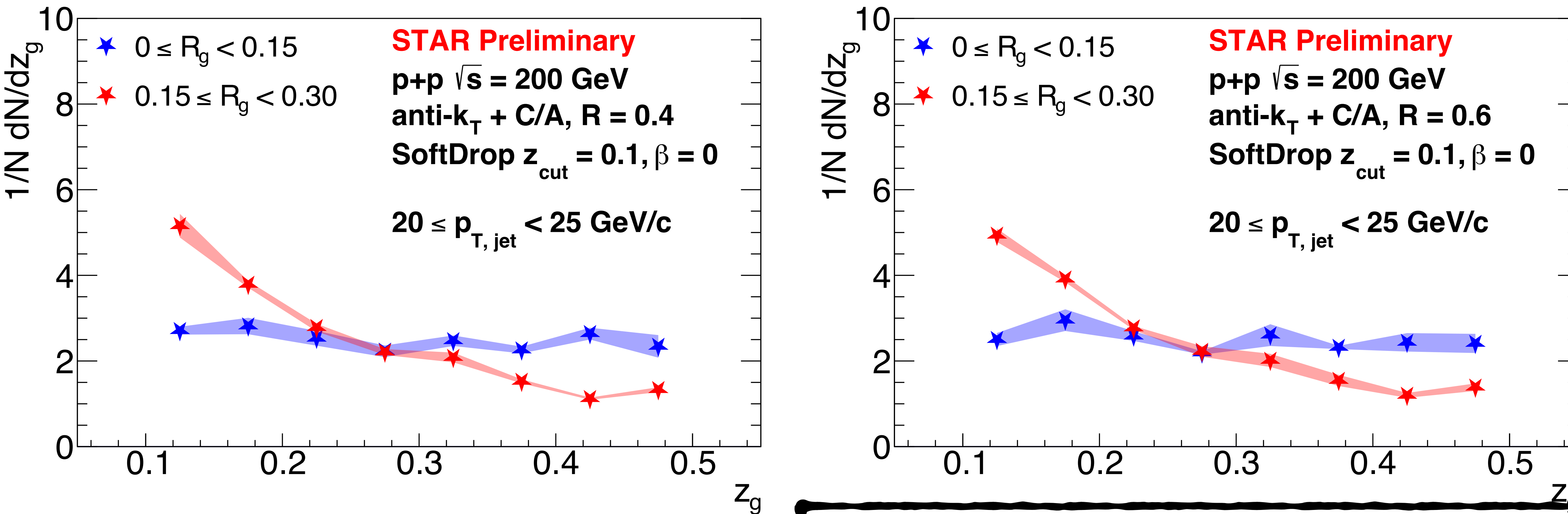
Recent measurements of Lund Plane and their projections at the LHC

ALICE-PUBLIC-2021-002



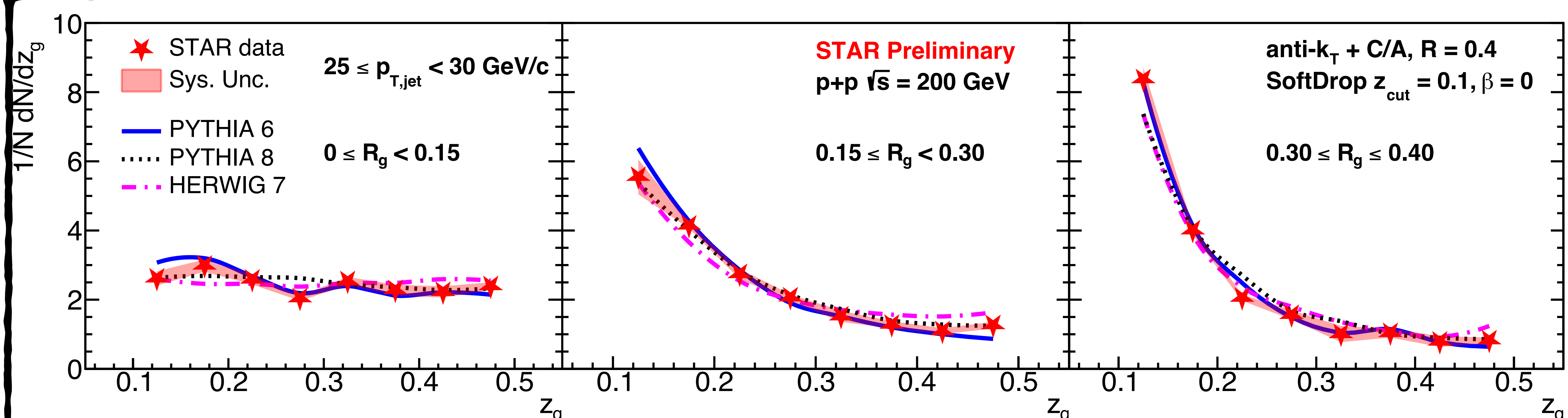


- Lower p_T jets at ALICE (20 - 120 GeV) also show interesting differences for large k_T splits
- Lund plane integrates over splits - can we measure the evolution of these observables along the jet shower?

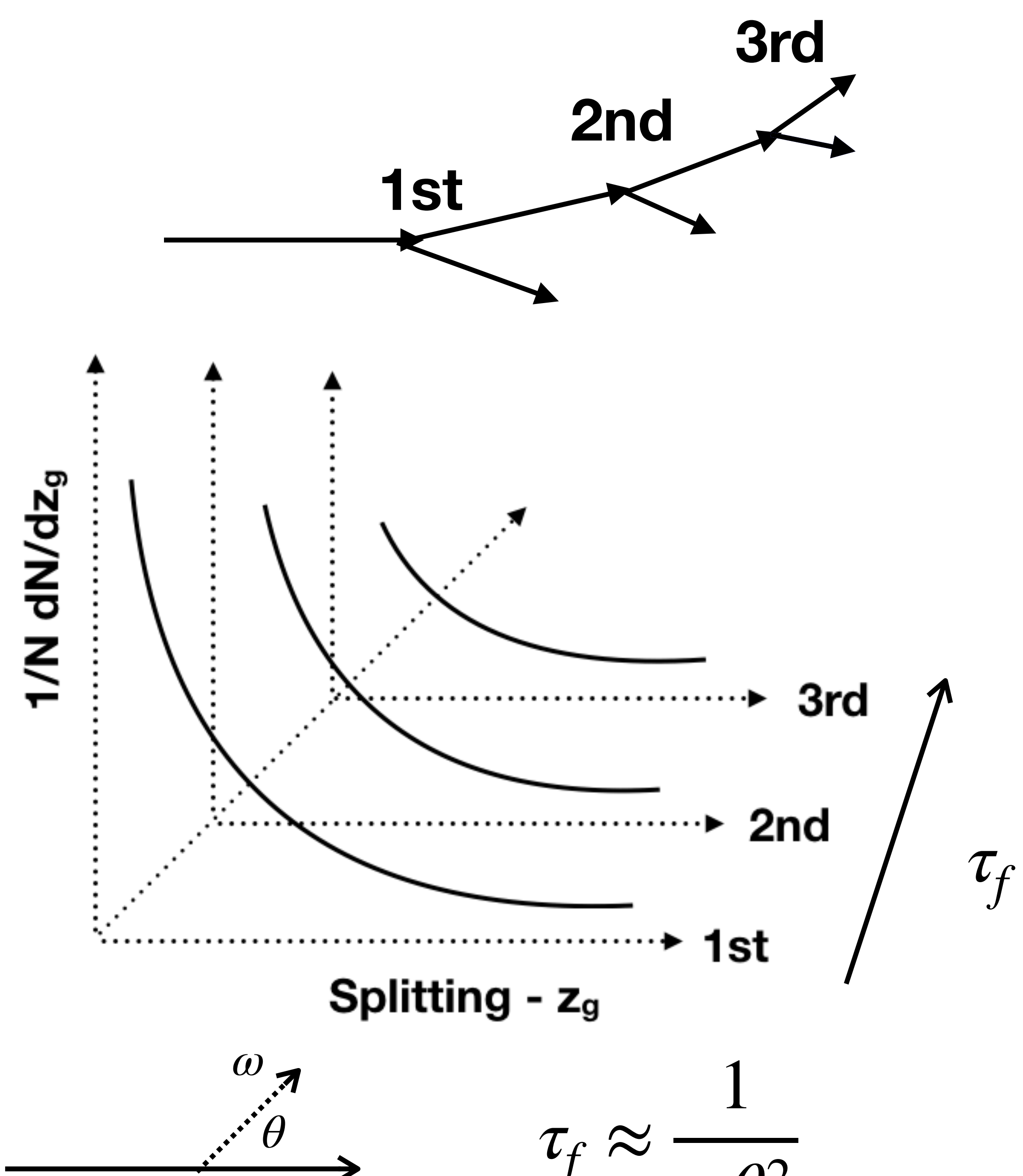


- No significant differences in substructure due to jet radius selections

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

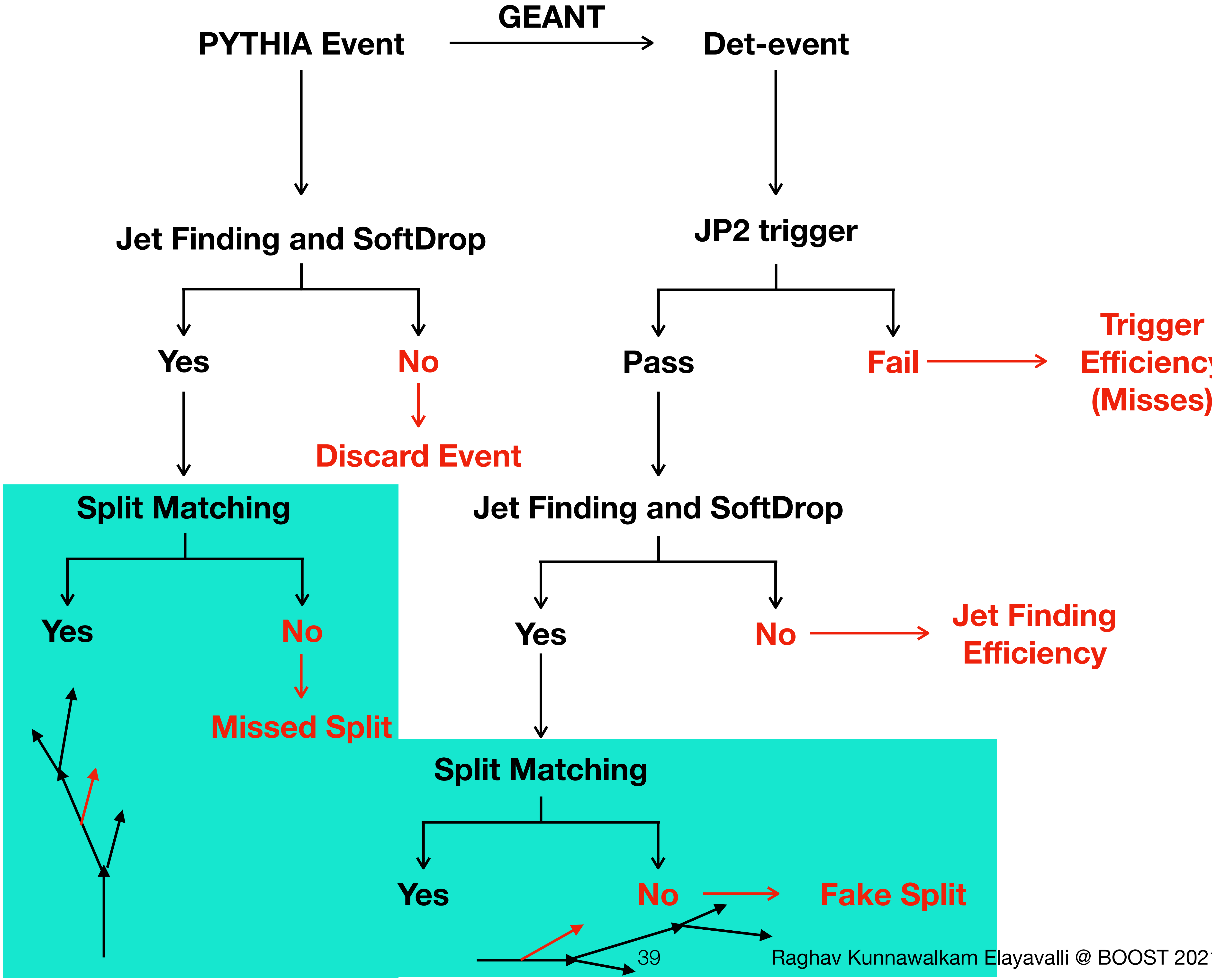


Measure the splittings along the jet clustering tree

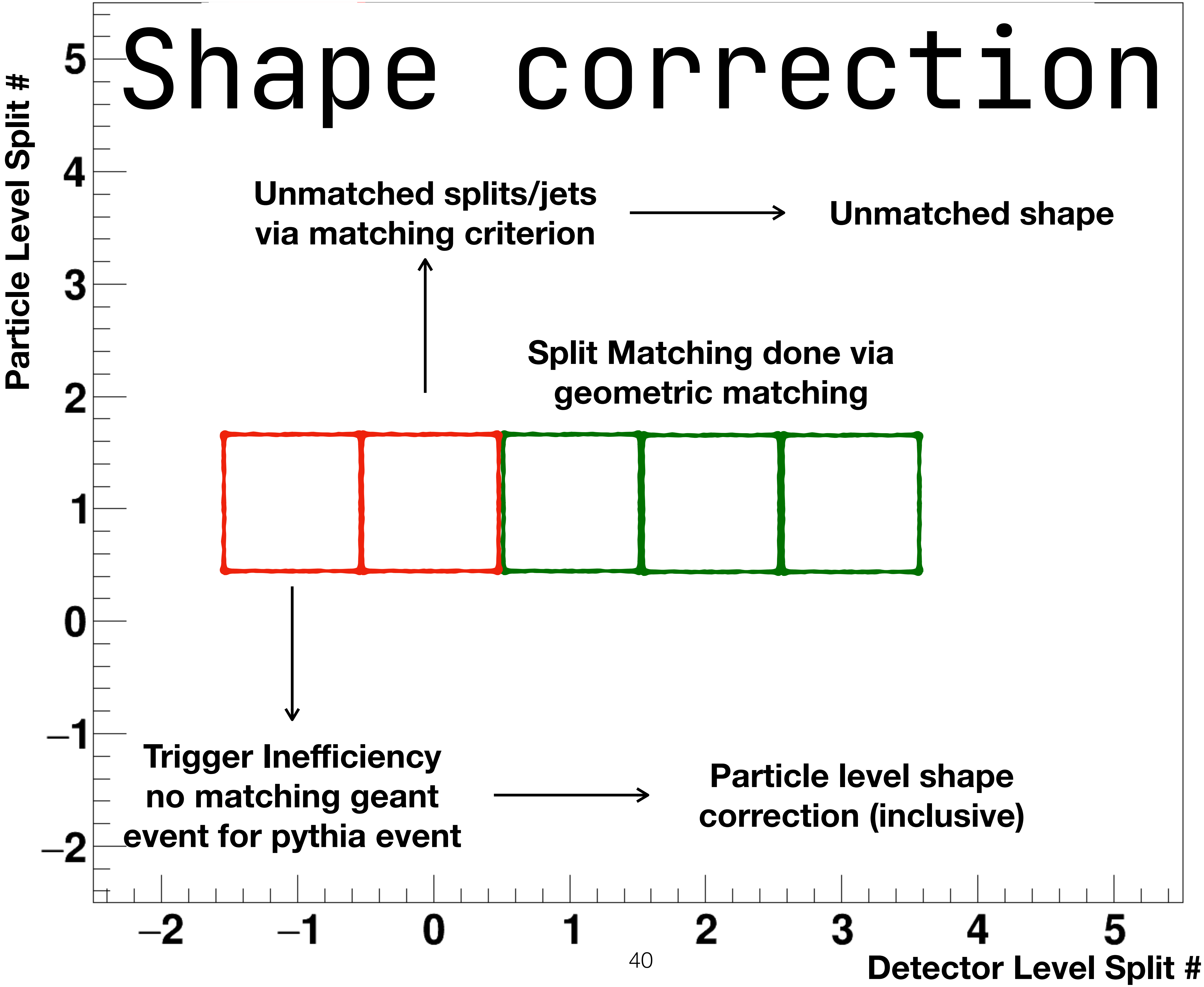


$$\tau_f \approx \frac{1}{\omega\theta^2}$$

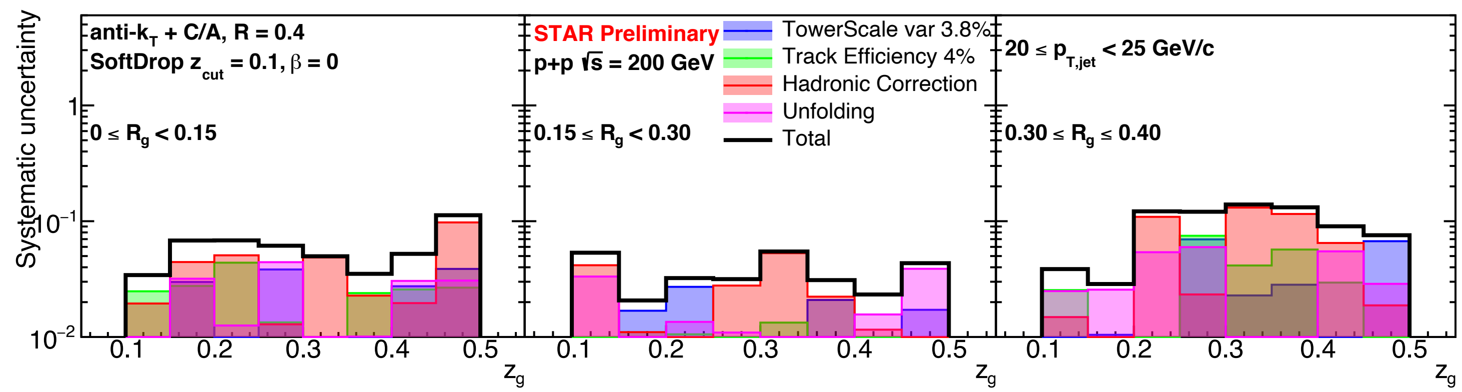
- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution
- **Given a jet (p_T^{jet})** what are the z_g, R_g at 1st, 2nd and 3rd splits? **Follow a jet**
  - Compare these distributions at varying jet kinematics
  - Indirect constraint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


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

Shape correction

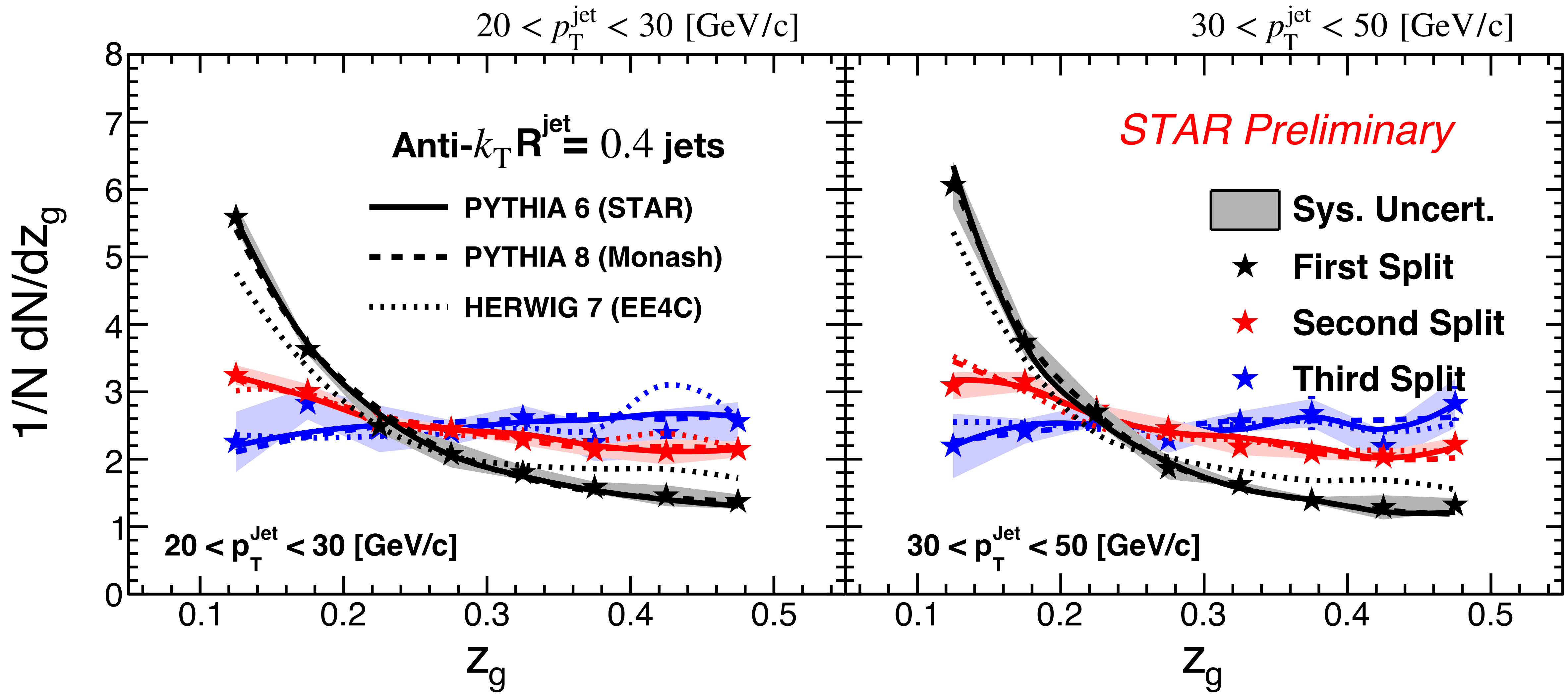


Systematic Uncertainties



- 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

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