Measurement of splittings along a jet shower in $\sqrt{s} = 200$ GeV pp collisions at STAR

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

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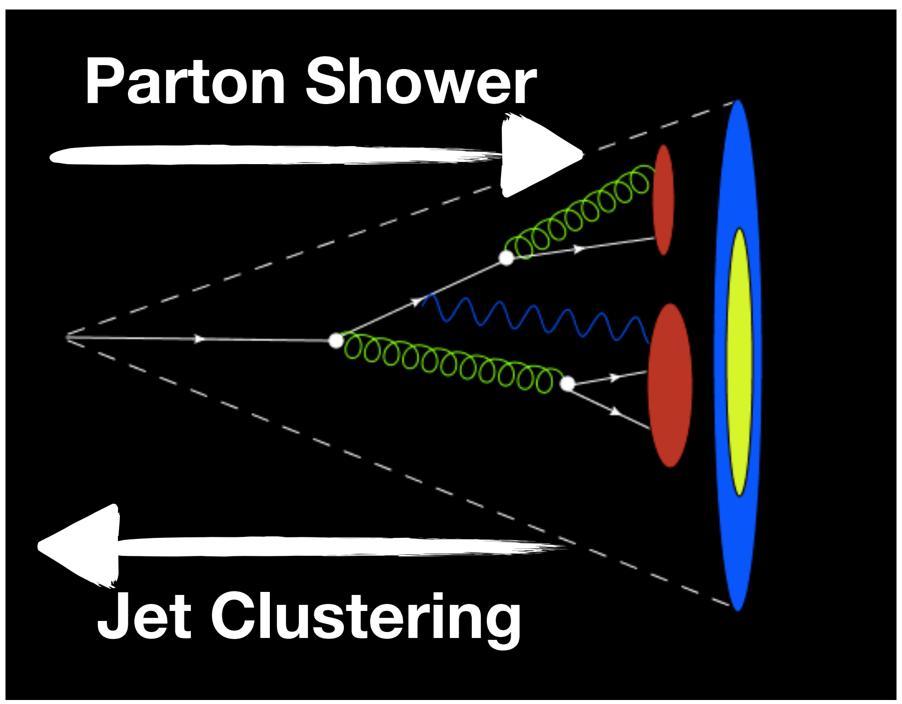
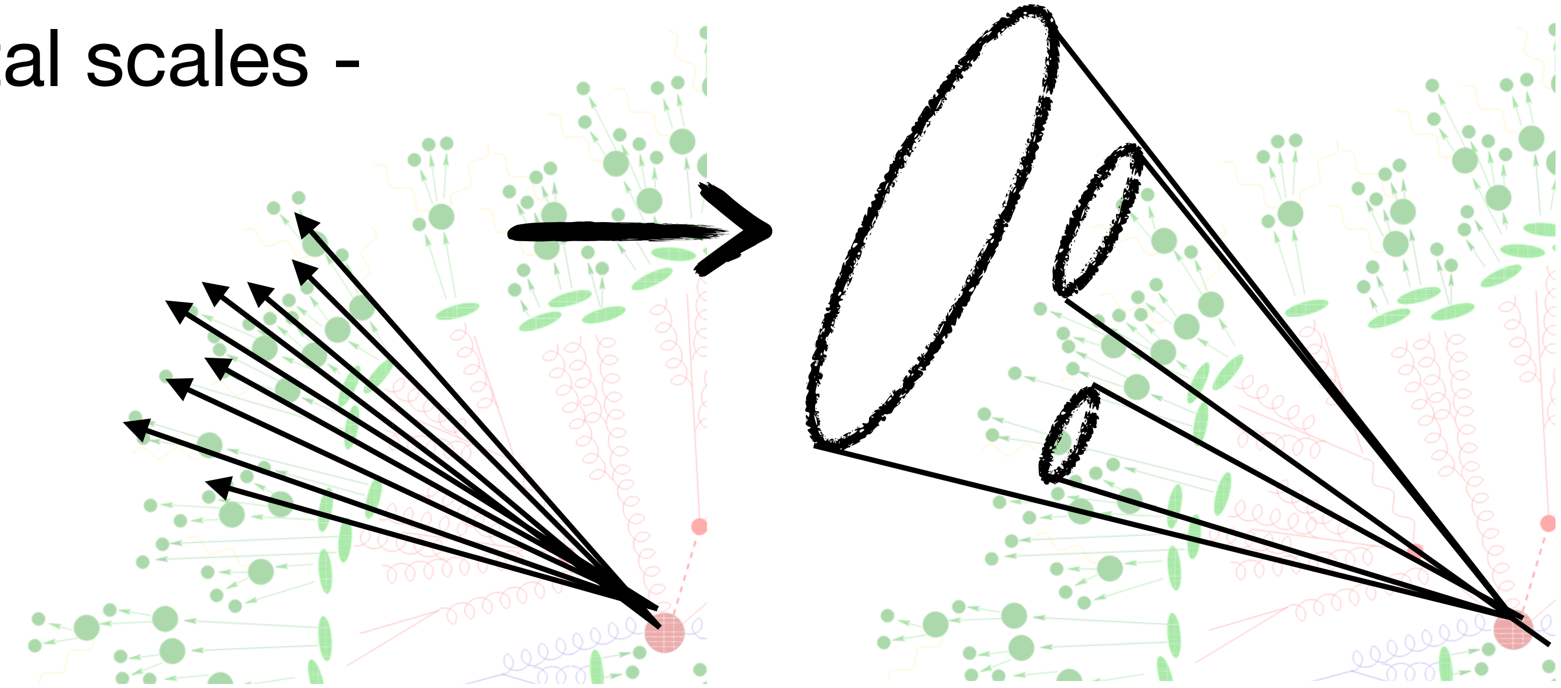
Office of Science

Physics of jet substructure

Jet evolution/parton shower in vacuum is described by two fundamental scales - angle/virtuality (θ) and momentum fraction (z)





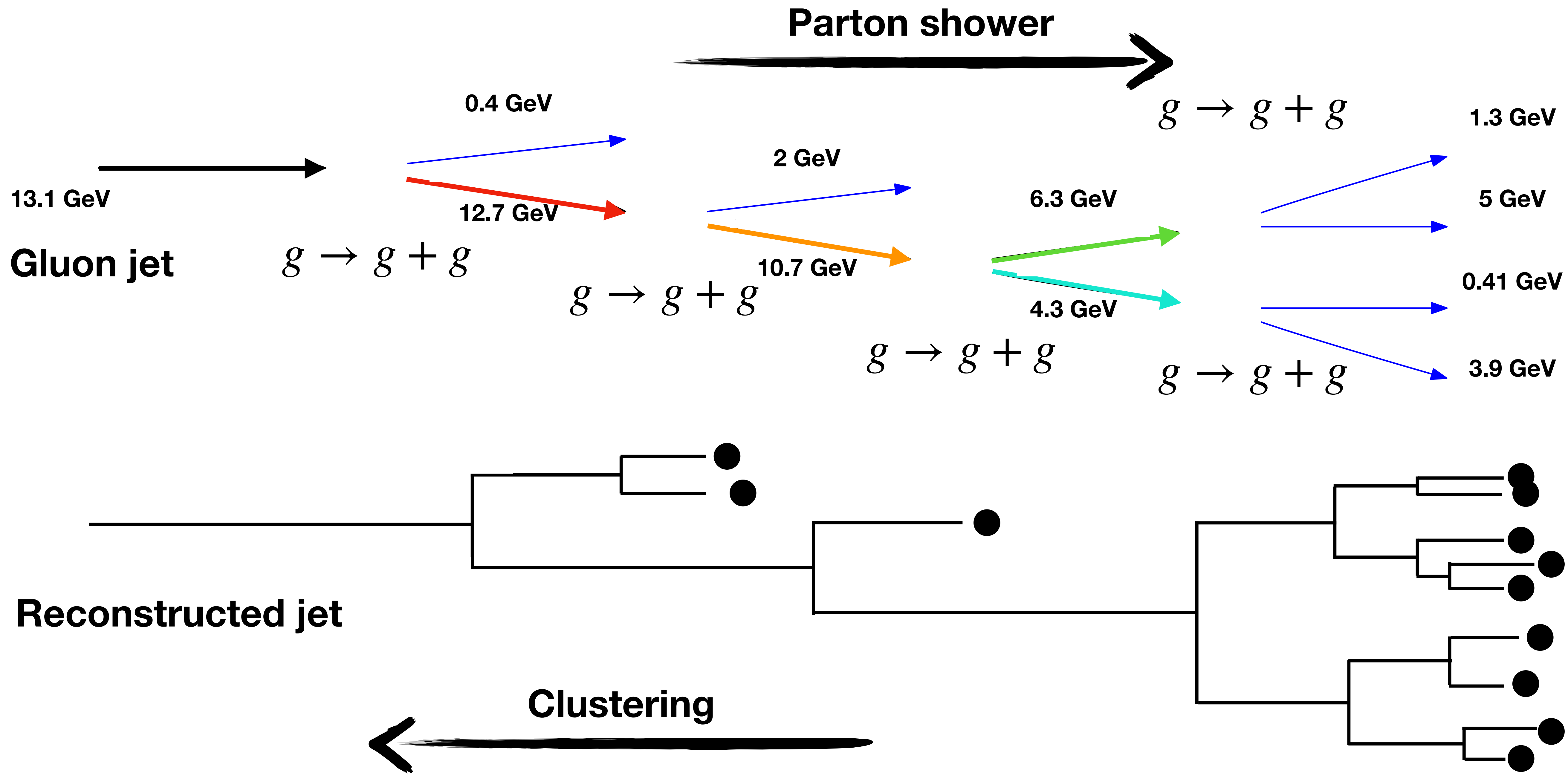
Utilize algorithmic structure of jet finding via re/de-clustering techniques

Probe fundamental QCD properties via parton shower e.g. virtuality evolution

Tuning Monte-Carlo generators and (improving on) hadronization models as a function of $\sqrt{s}$

What do we want to measure?

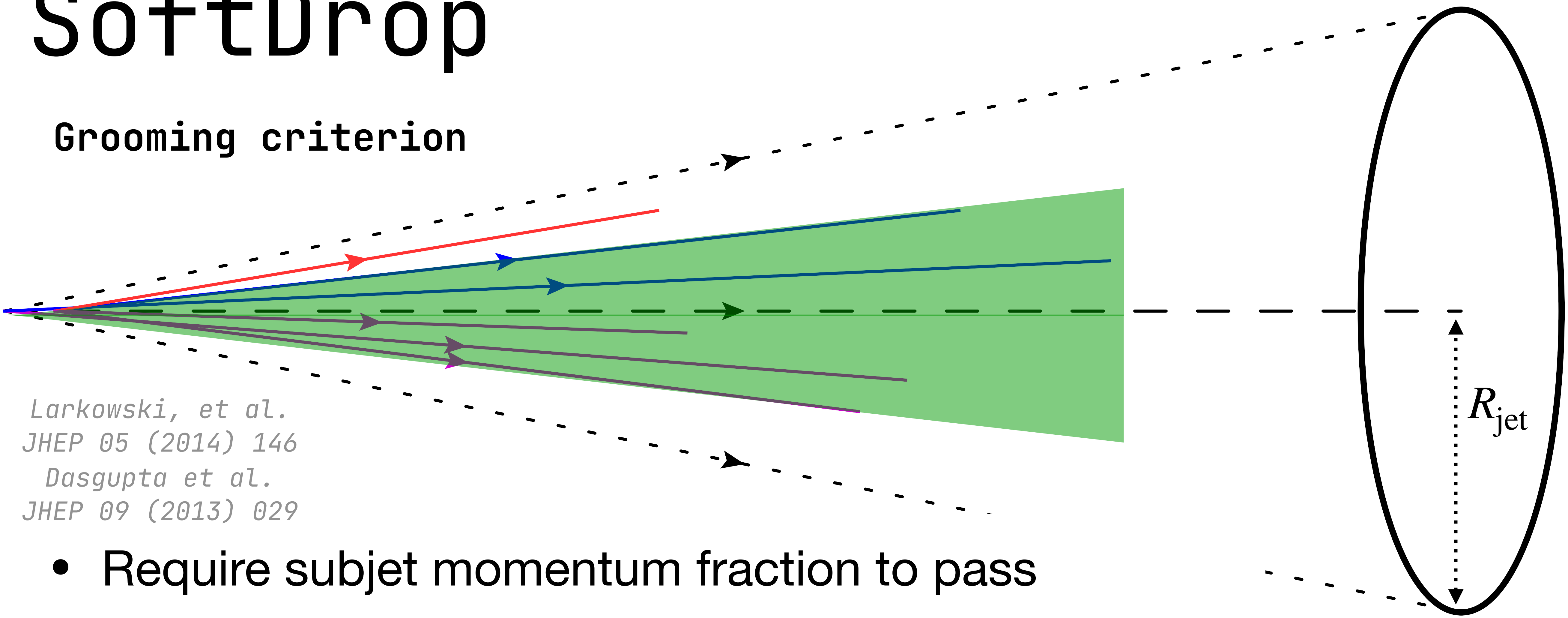
We want to translate an intrinsic (and unmeasurable) parton shower to experimentally accessible observable(s)



STAR

SoftDrop

Grooming criterion



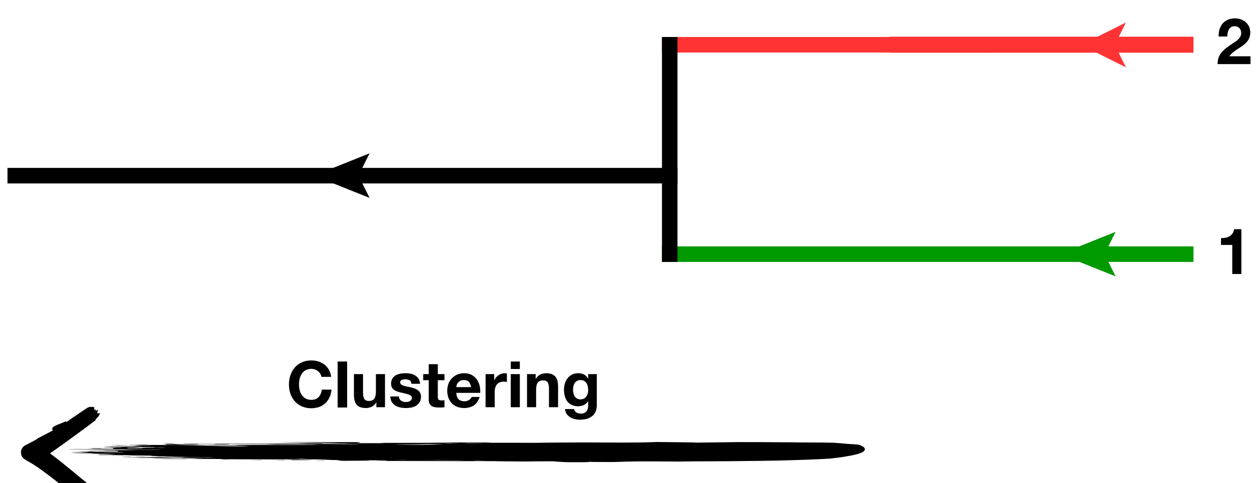
Larkowski, et al.
JHEP 05 (2014) 146
Dasgupta et al.
JHEP 09 (2013) 029

- Require subjet momentum fraction to pass

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

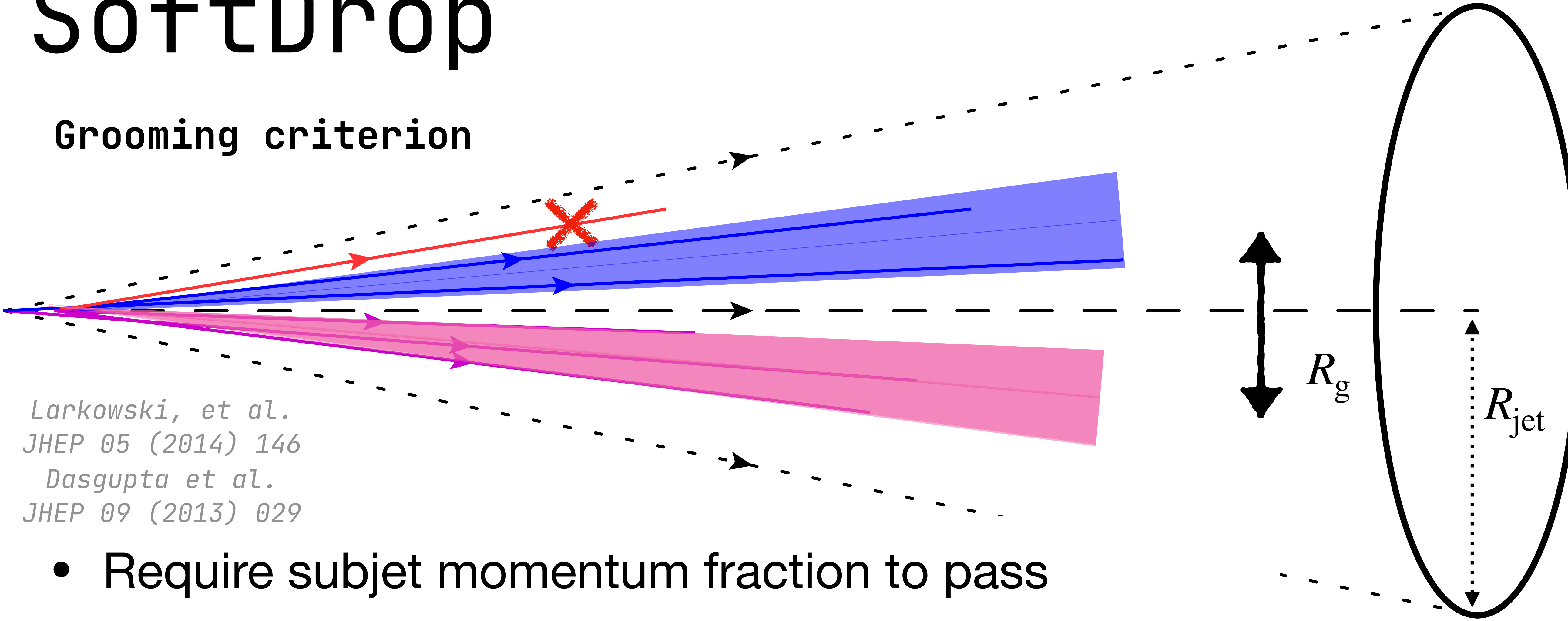
$z_{\mathrm{cut}} = 0.1$

$\beta = 0$



SoftDrop

Grooming criterion



Larkowski, et al.
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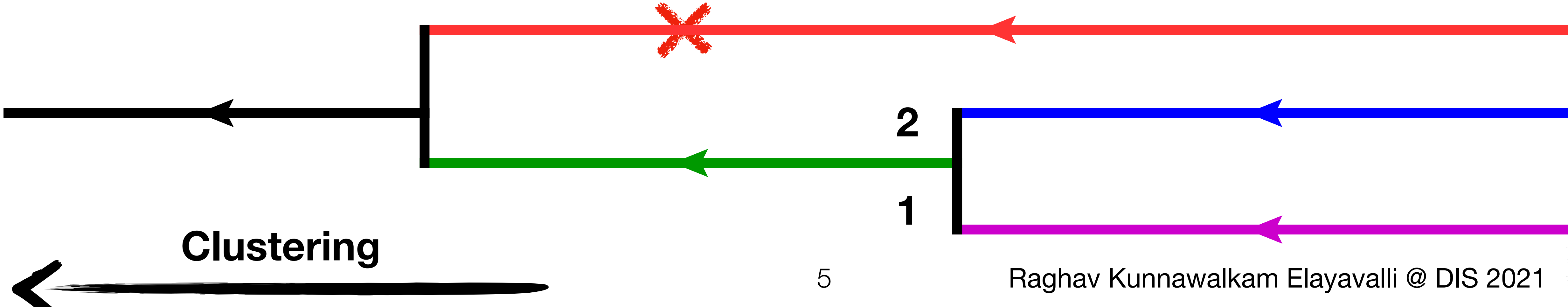
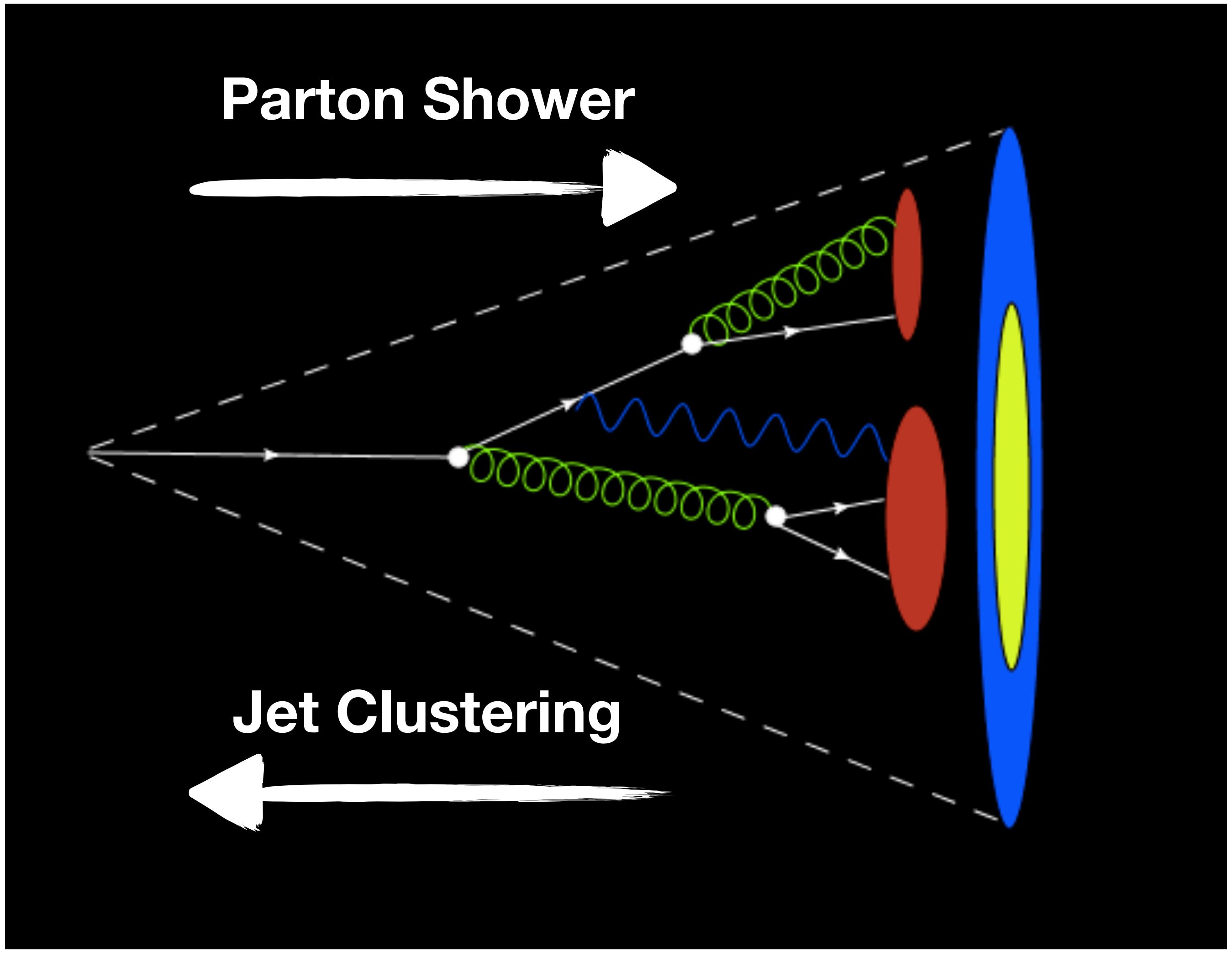
- Require subjet momentum fraction to pass

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

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





Correlations between substructure observables at the first split

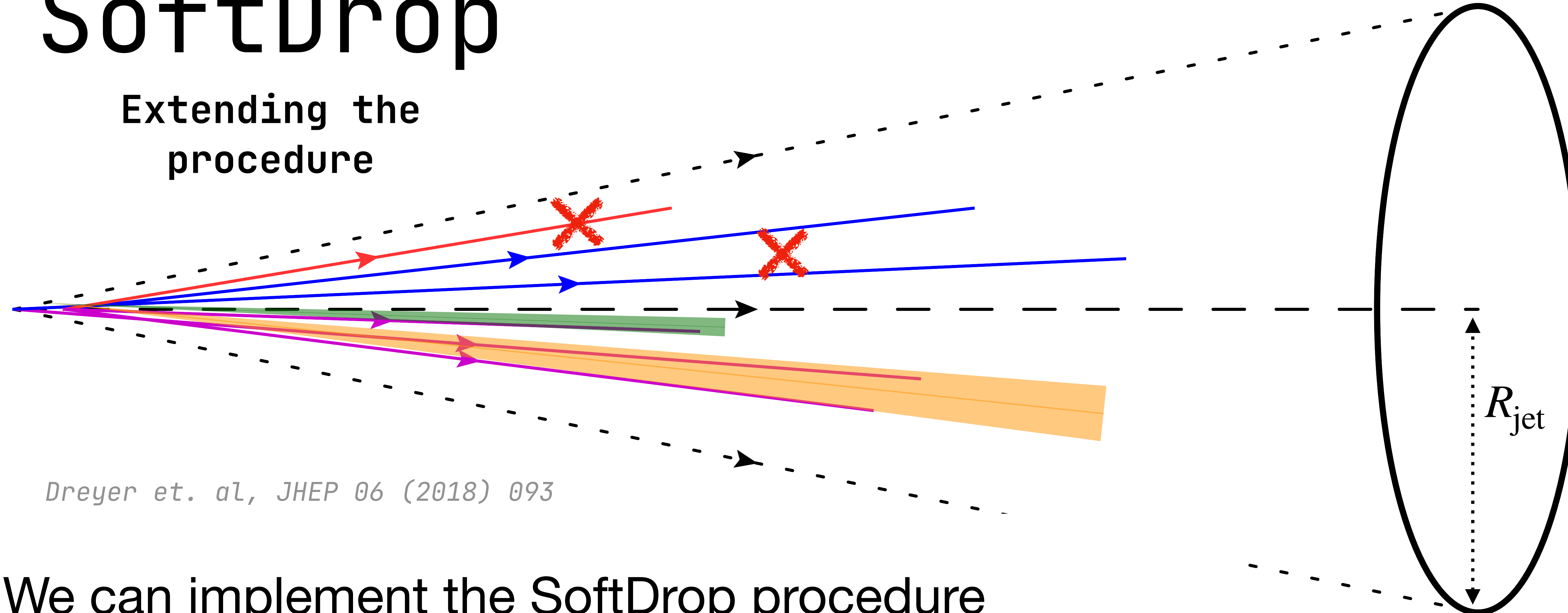
See Monika Robotková's talk later today!

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

Main physics question of today's talk!

SoftDrop

Extending the procedure

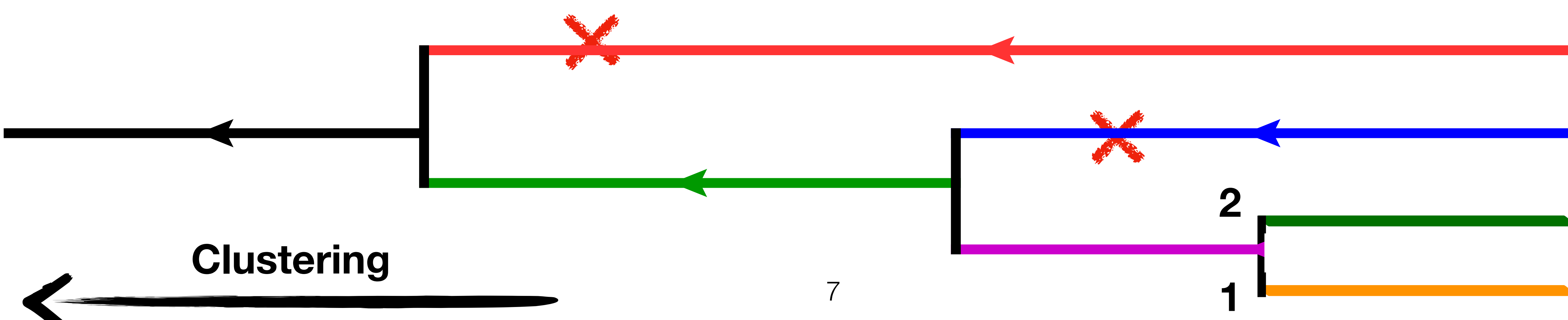


Dreyer et. al, JHEP 06 (2018) 093

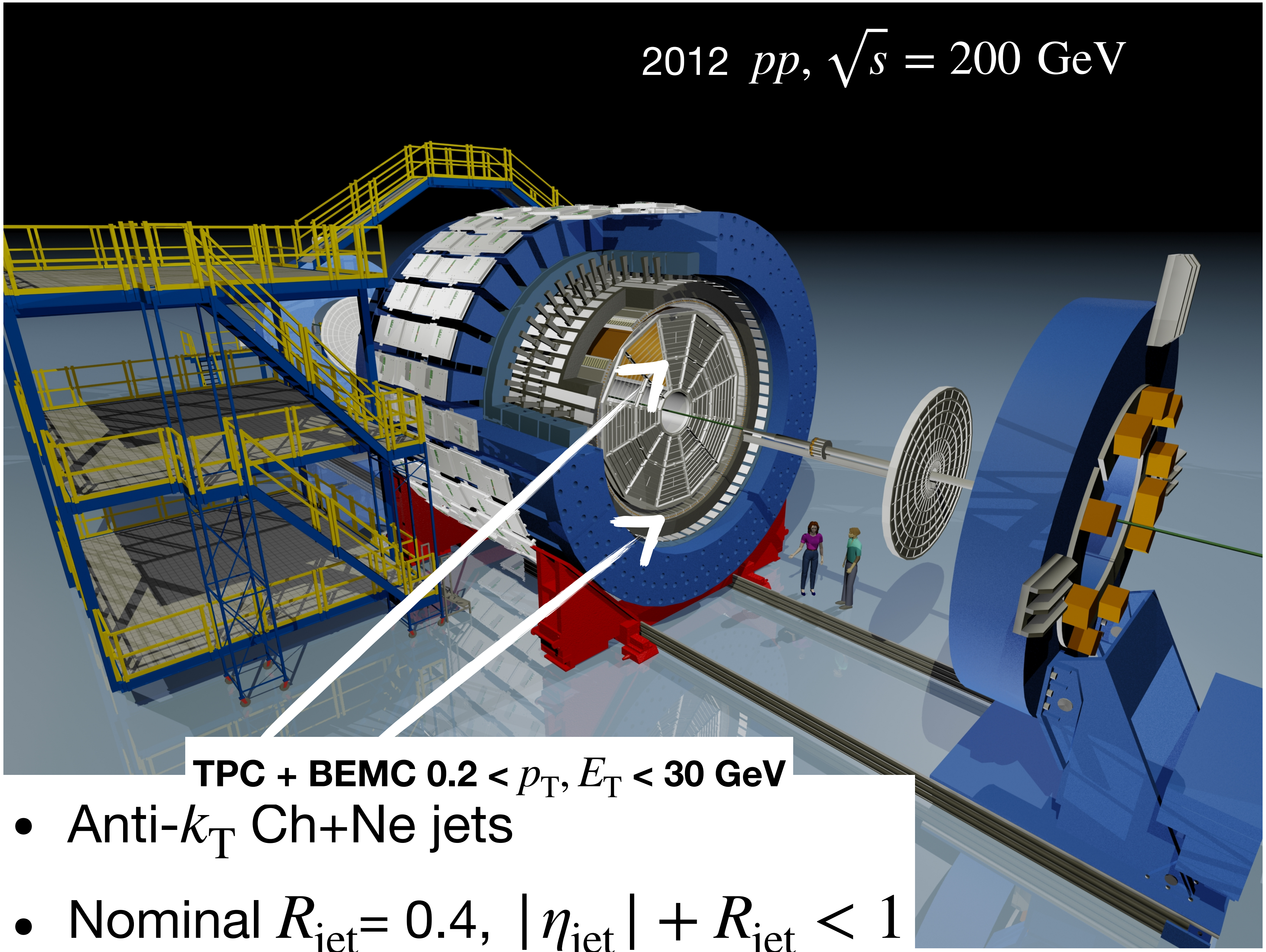
We can implement the SoftDrop procedure throughout the C/A tree -

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

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



Jet reconstruction at STAR

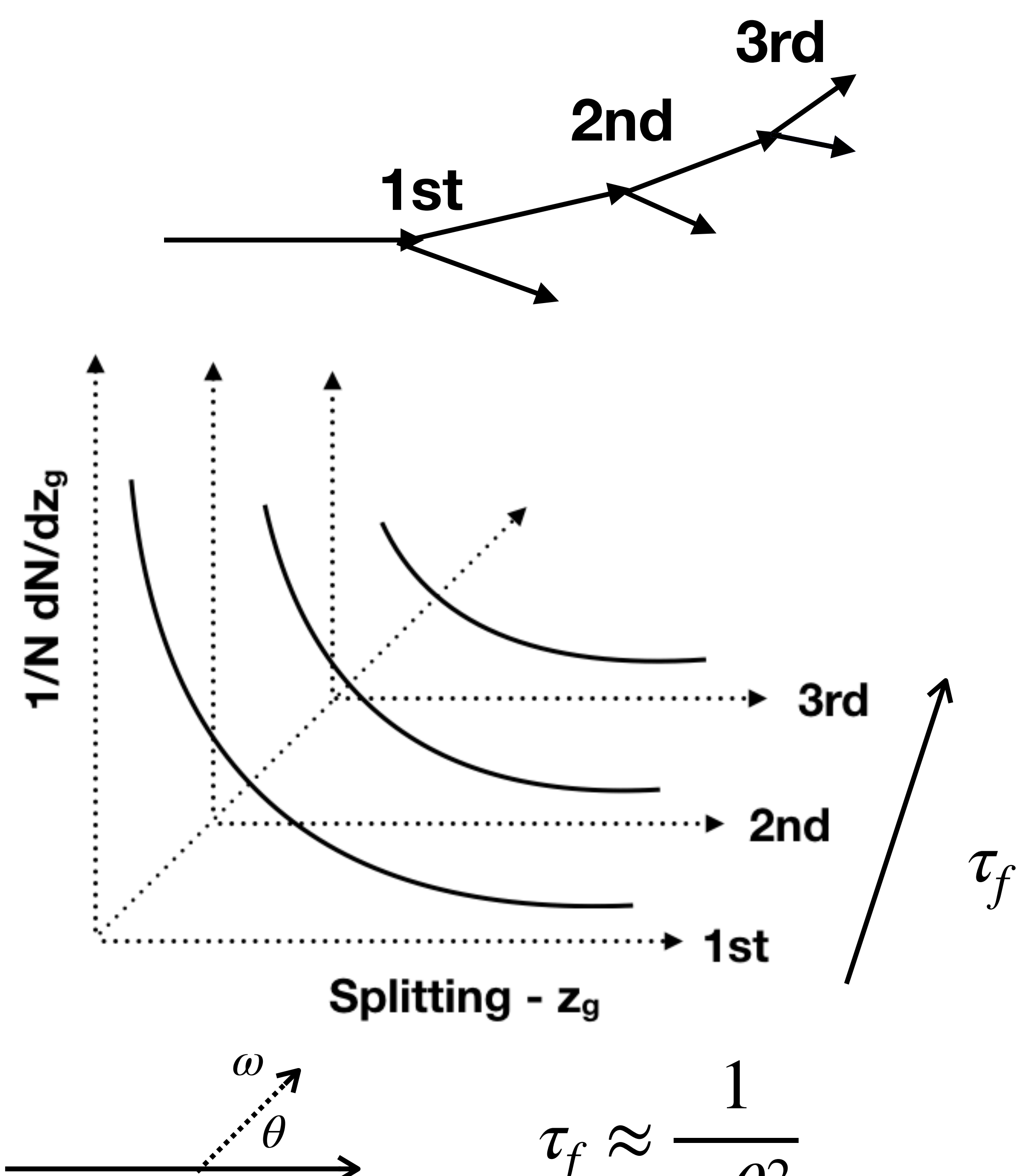


TPC + BEMC 0.2 < $p_{\mathrm{T}}, E_{\mathrm{T}}$ < 30 GeV

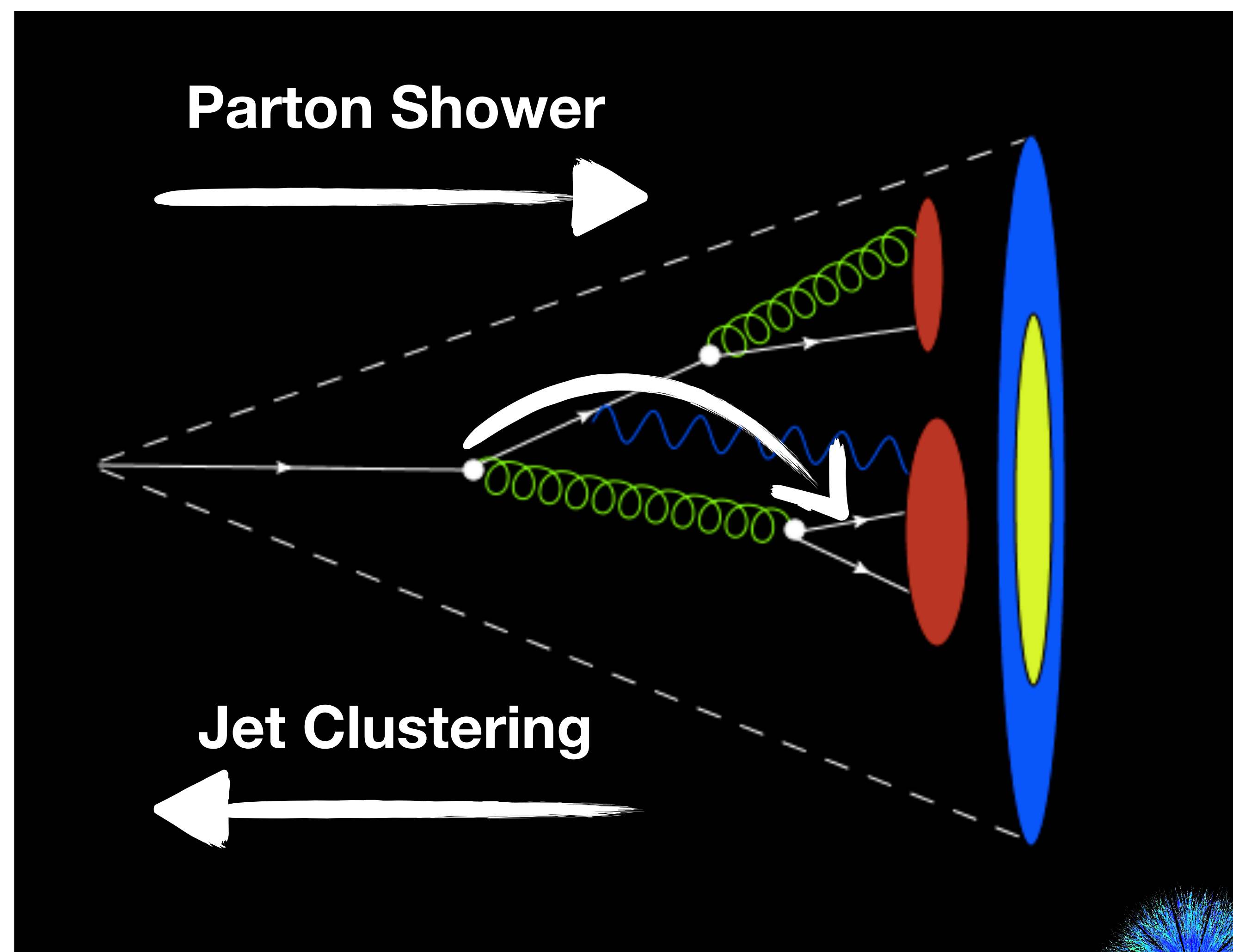
- Anti-k_{T} Ch+Ne jets
- Nominal R_{jet}= 0.4, $|\eta_{\mathrm{jet}}| + R_{\mathrm{jet}} < 1$

Measure the splittings along the jet clustering tree

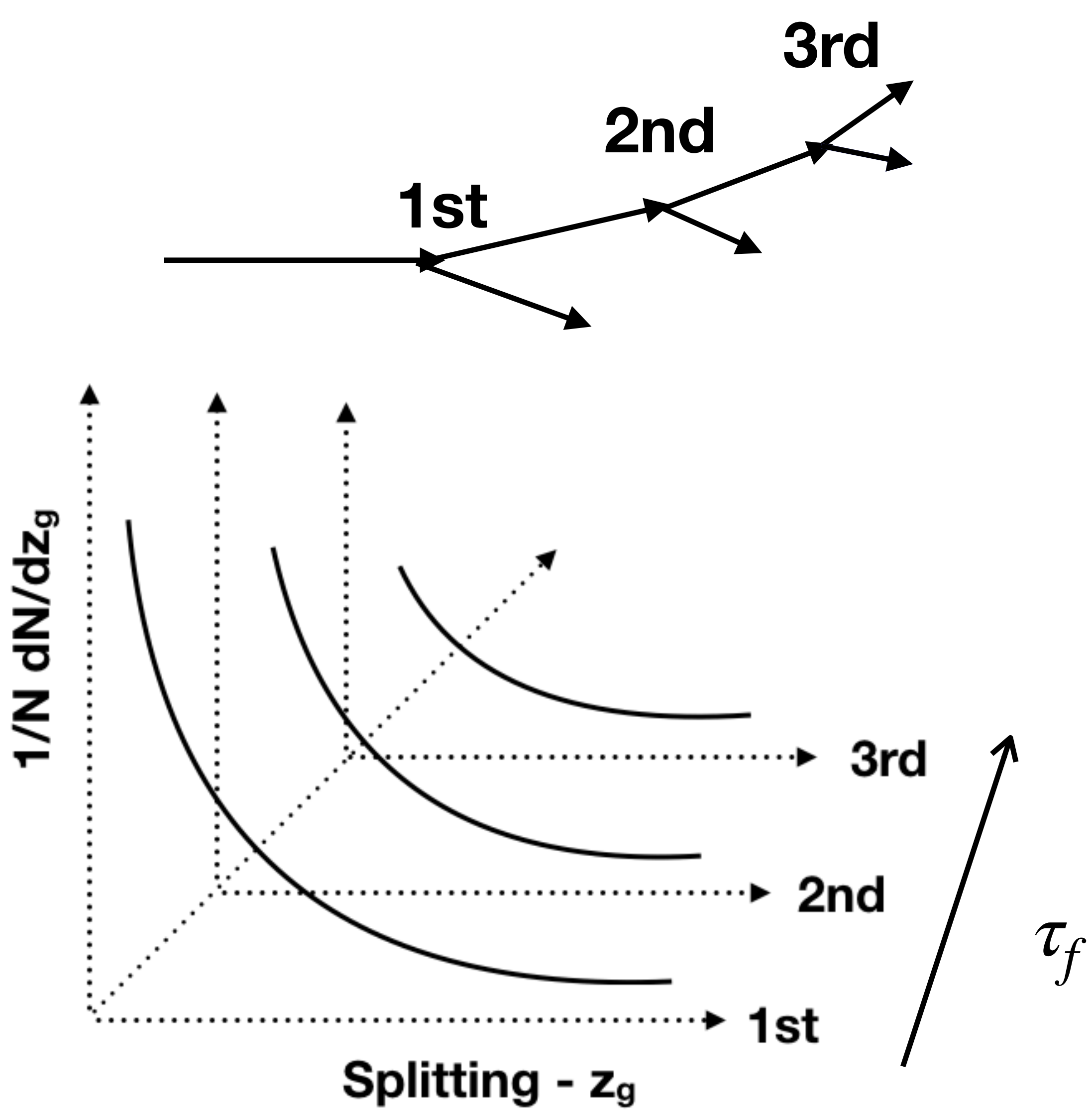
- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution

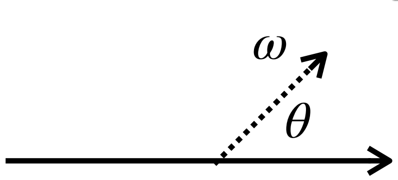


$$\tau_f \approx \frac{1}{\omega\theta^2}$$



Measure the splittings along the jet clustering tree





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

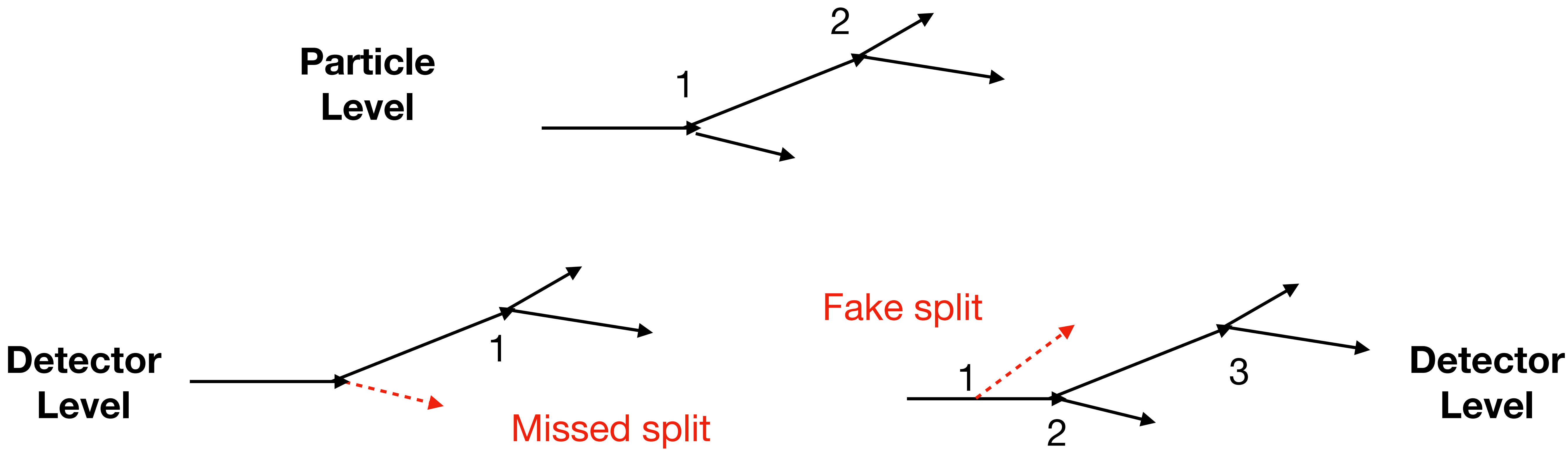
- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution

- **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

Need for unfolding

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



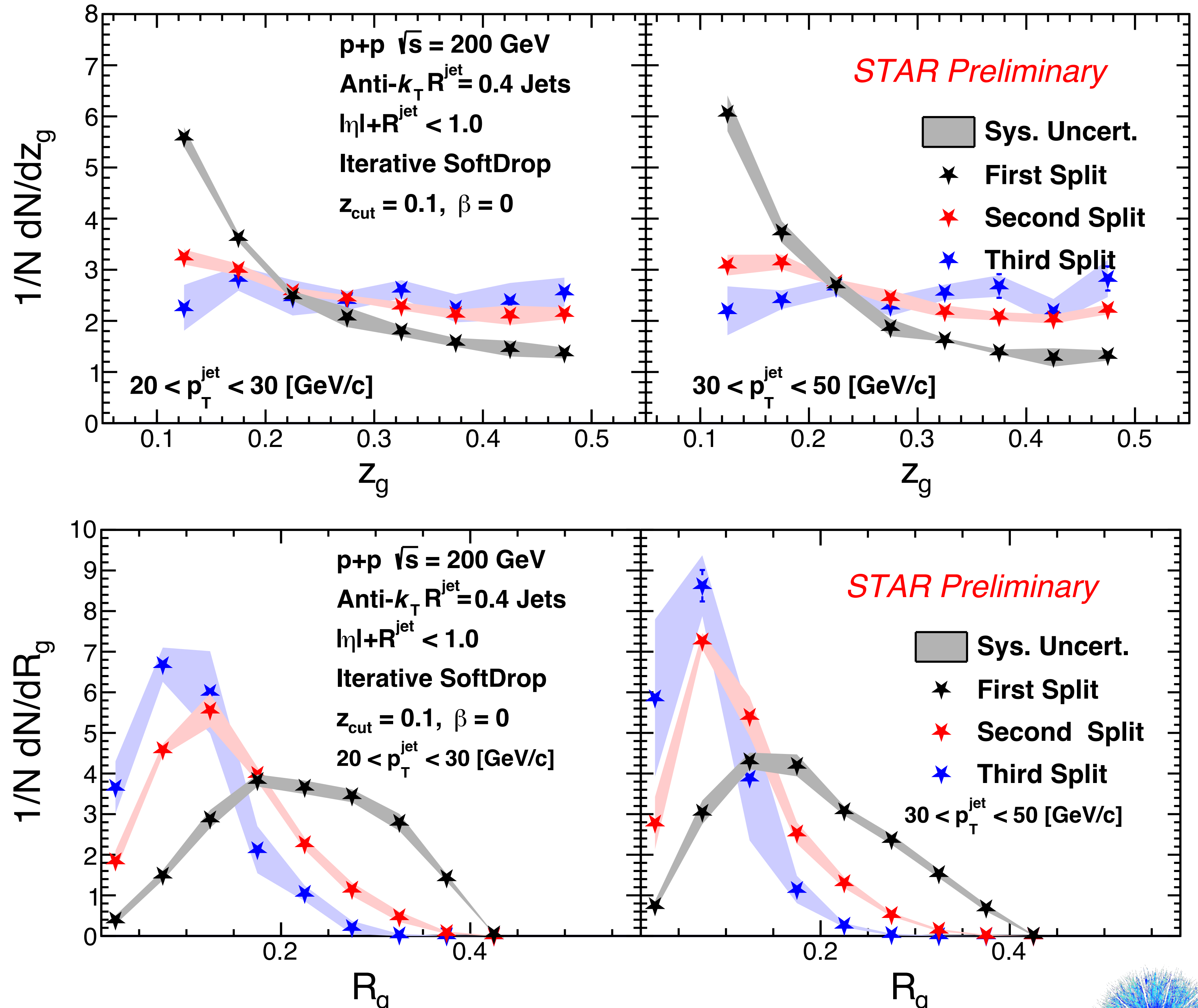
- Observables ($p_T^{\text{jet, initiator}}$, z_g, R_g) at a given split are smeared
- Splitting hierarchy also modified going from particle to detector level jets

Details of unfolding and systematic uncertainties available in backup

Fully corrected results

1st, 2nd, 3rd splits for various p_T^{jet}

- **Given a jet (p_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



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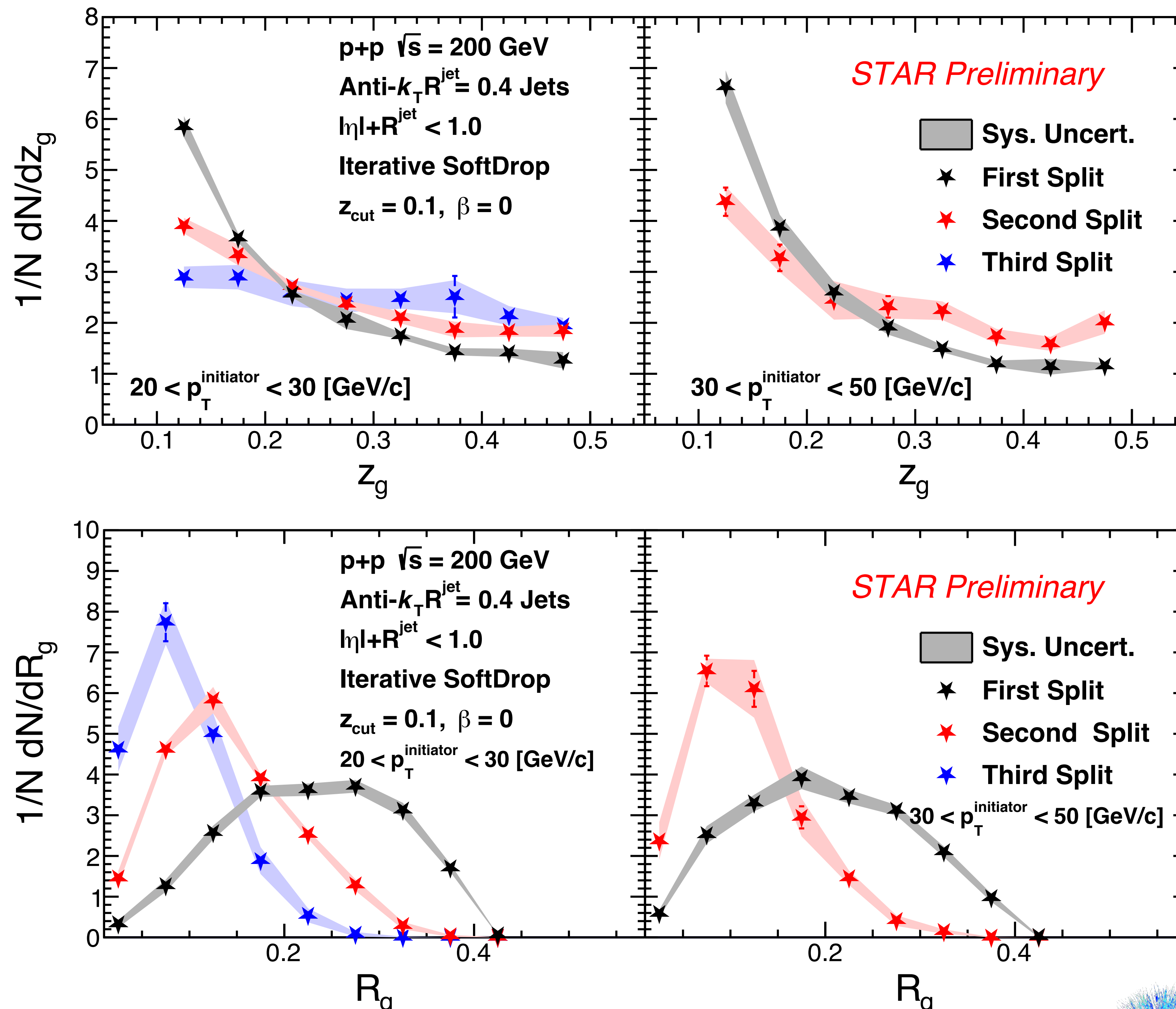
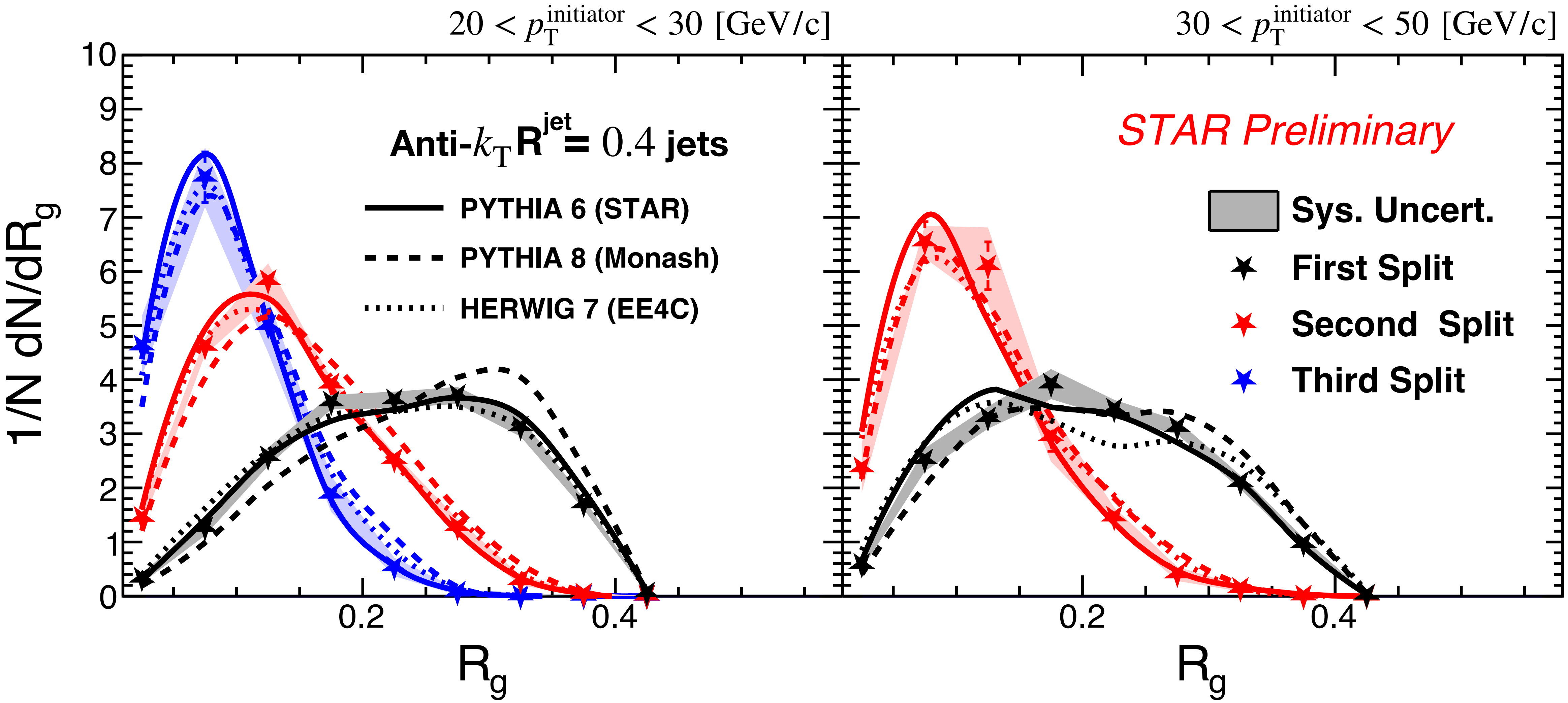
Fully corrected results

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

- **Given a split ($p_{\mathrm{T}}^{\mathrm{initiator}}$),** 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
- **Significant differences in second split z_{g}** (similar R_{g}) for initiator vs. jet momenta selection

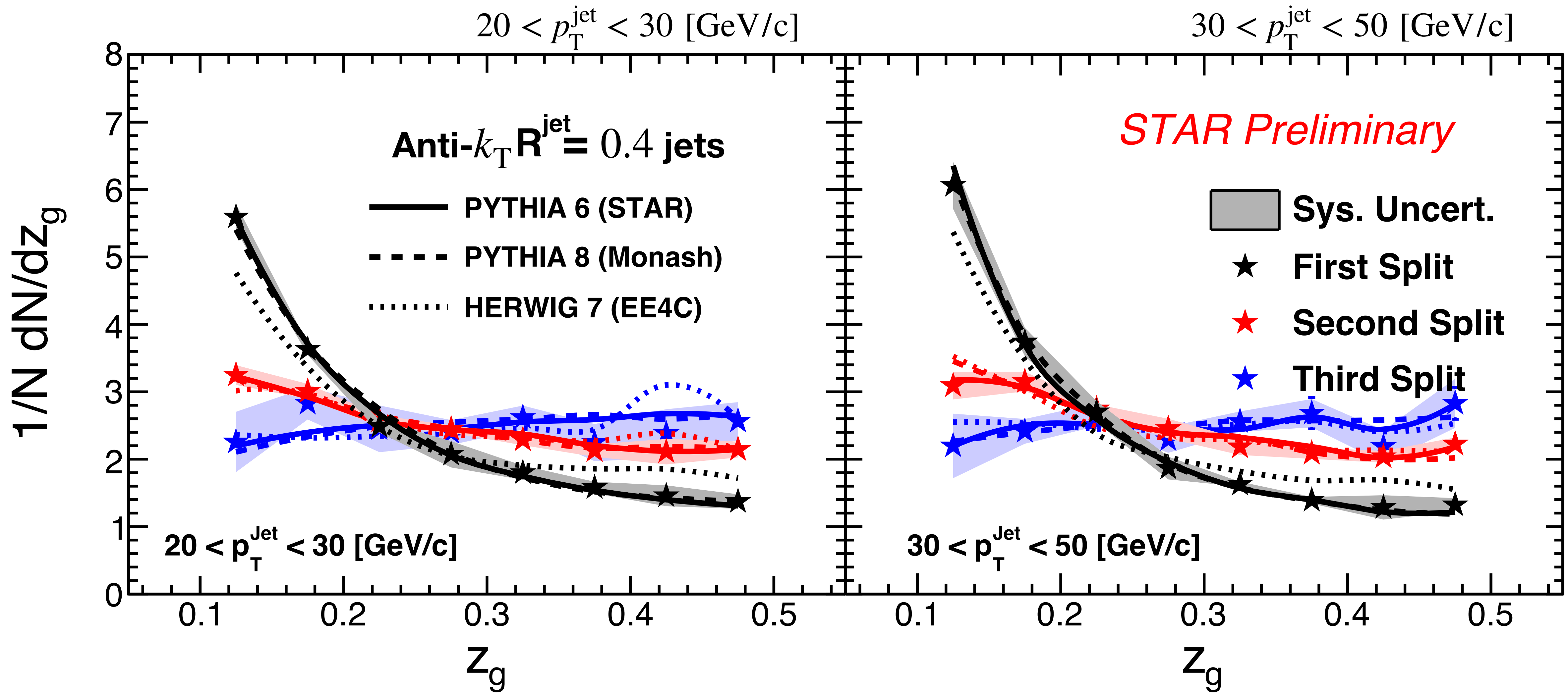


Comparisons with leading order MC - R_g for various initiator p_T



- 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

Comparisons with leading order MC - z_g for various jet p_T



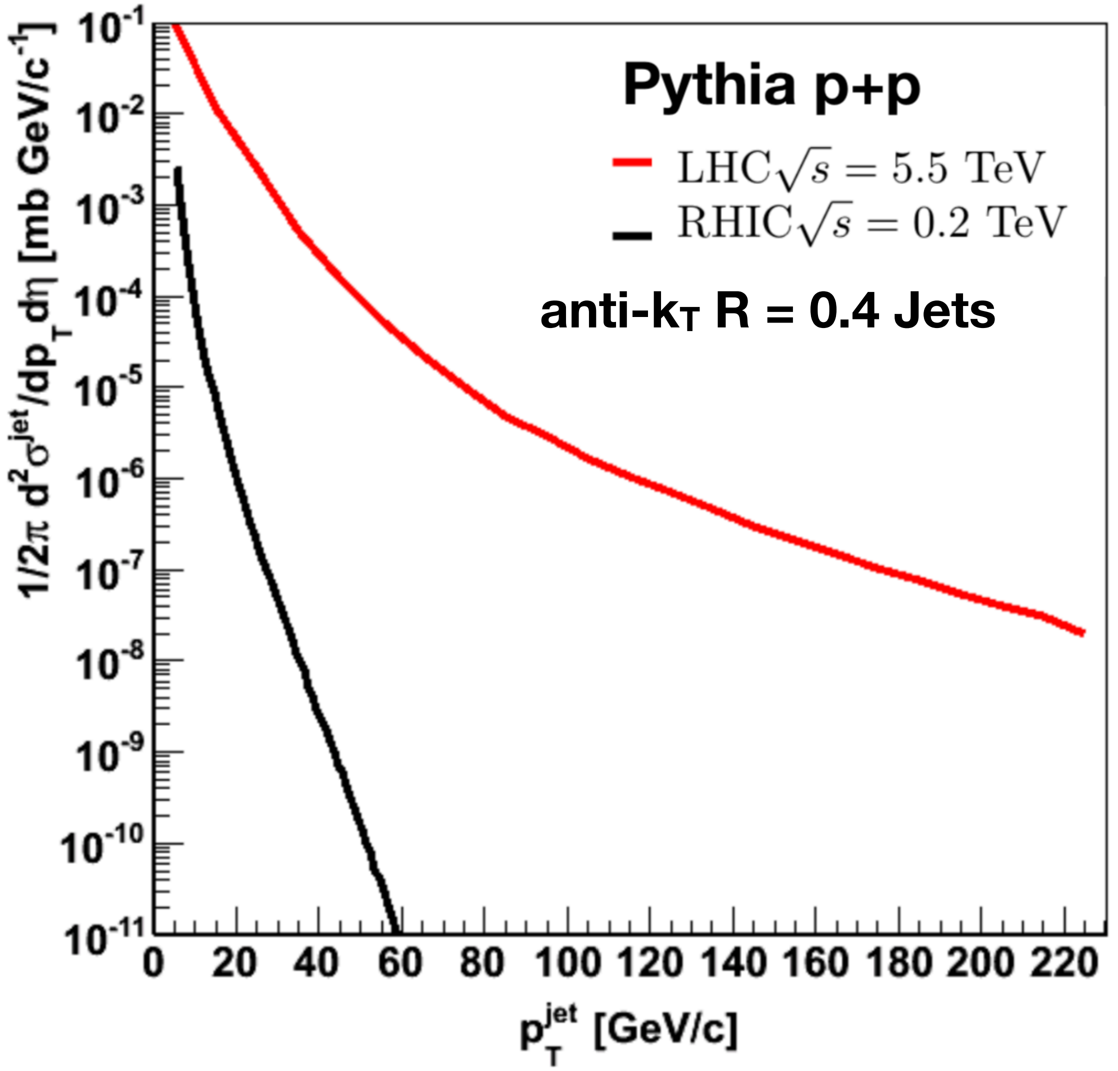
- **Flattening of the splitting z_g as we increase split number** captured by the MC
- Small differences between PYTHIA and HERWIG seen in the **first** split appear to be reduced at the **second**/**third** splits

Conclusions

- Jet substructure program at STAR aims at **mapping jet evolution** at RHIC energies
- Data show a **gradual variation in the available phase space** along the jet shower
  - leading to modifications (e.g. virtuality evolution) in the observed splitting kinematics
- Observe **significantly harder/symmetric splittings** at the **third split** which are the **most collinear** in a shower
- First measurement that can potentially **distinguish experimental quantities in a 'time scale'** via formation time of splits - Extremely useful in a heavy ion environment
- In our upcoming final results we will delve further into comparisons
  1. Various handles in the MC -
     A. hadronization (Sherpa - Lund vs Ahadic),
     B. parton shower (Herwig - angular vs dipole, Pythia - dire vs vinca vs p_{T} ordered)
     C. tune variation in both PY6 and PY8 (STAR is currently working on a new PY8 tune via Professor and existing analysis in RIVET)
  2. In discussion with our theory colleagues on feasibility of calculations
- Subjets at RHIC allow to **disentangle perturbative and non-perturbative dynamics of jet evolution**
  - These **third splits** for our low p_{T} jets end up quite close to Λ_{QCD}

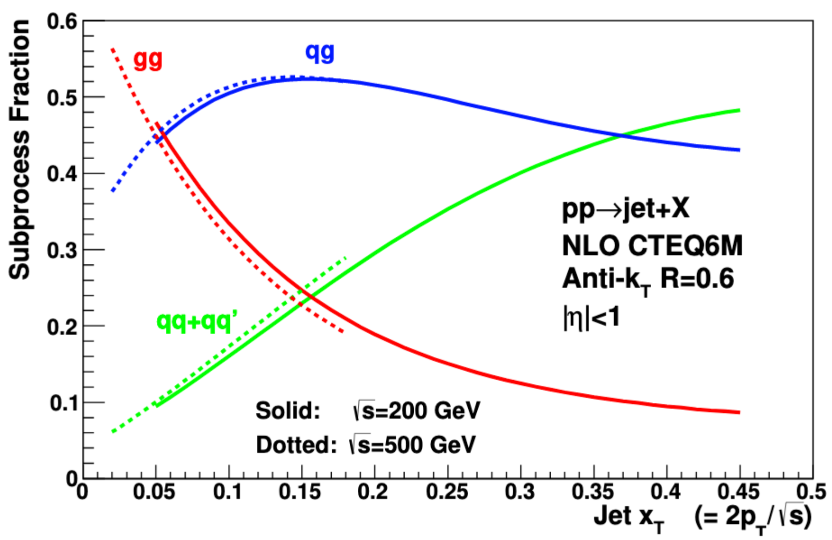
Backup

Jets at RHIC



- Significantly steeper spectra compared to LHC
- Access to 10 ~ 60 GeV/c Jets at $\sqrt{s} = 200$ GeV

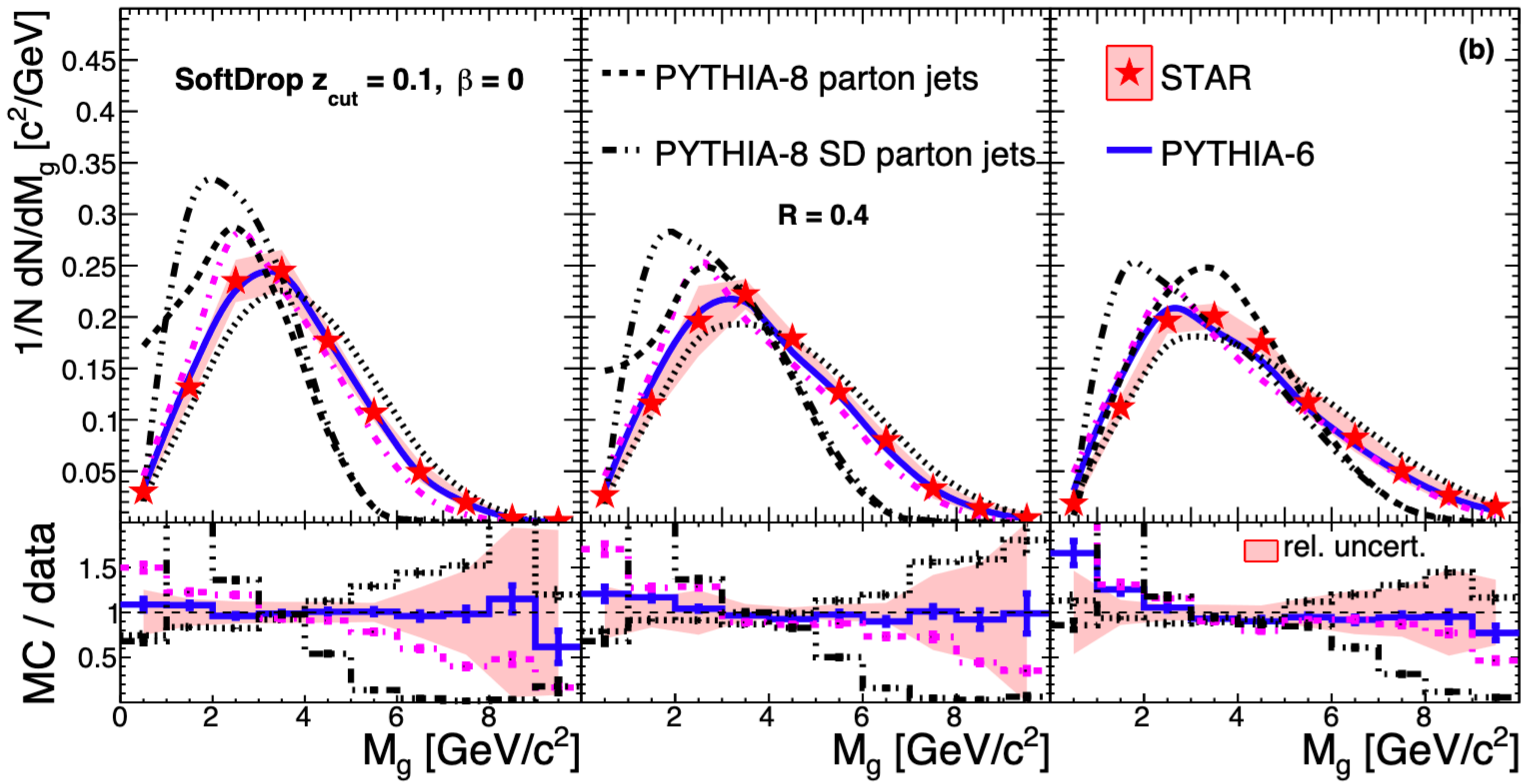
STAR, PRD 100,052005 (2019)



Extending to lower jet momenta leads to varying q/g fractions in pp collisions - interesting comparisons with similar kinematics at LHC (EIC)

Groomed Jet Mass

STAR arXiv:2103.13286



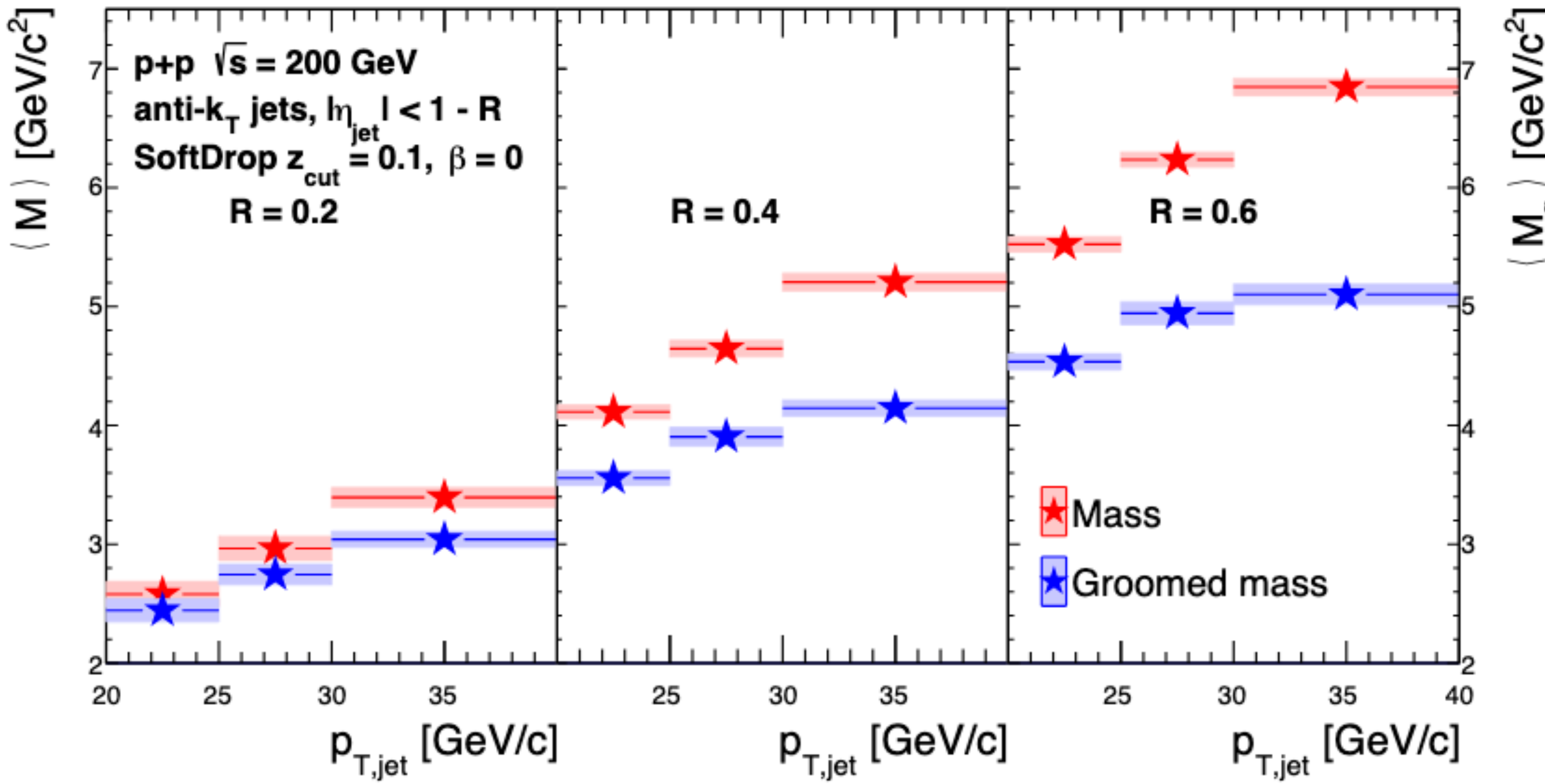
RHIC-tuned **PYTHIA-6** describes data

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 radius

STAR arXiv:2103.13286



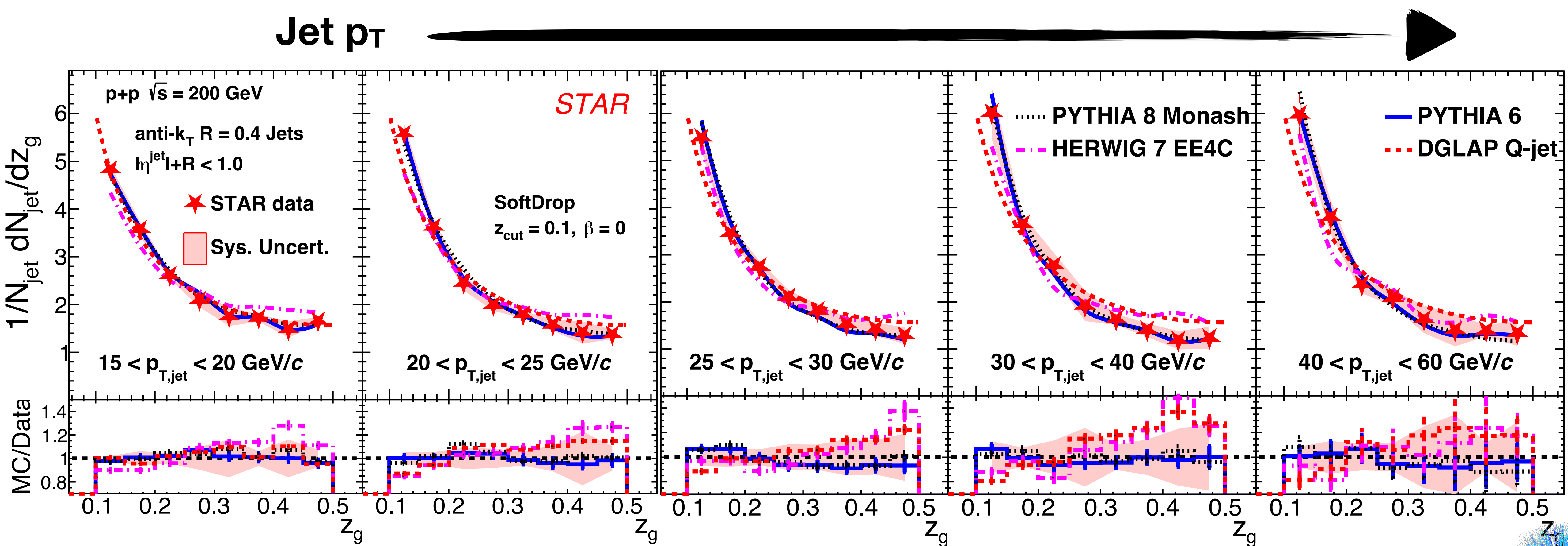
Increase in jet mass with increasing pT and R is reduced with grooming
- reduces overall impact of non-perturbative contributions to jets

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)

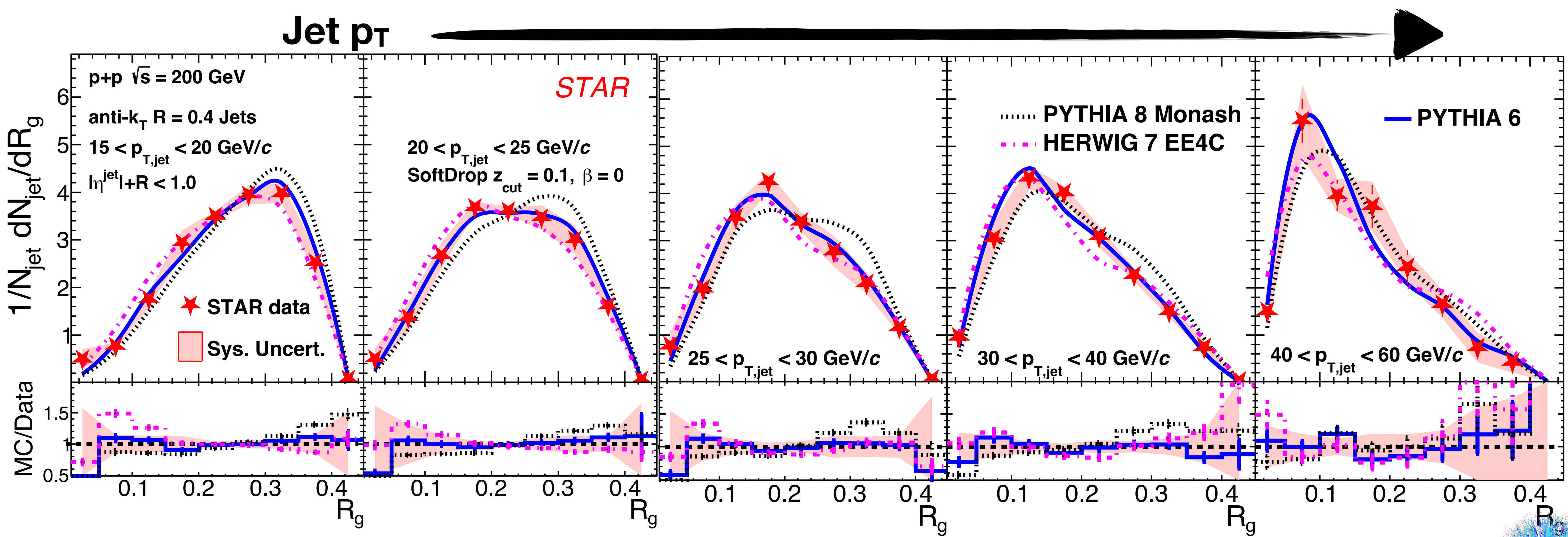


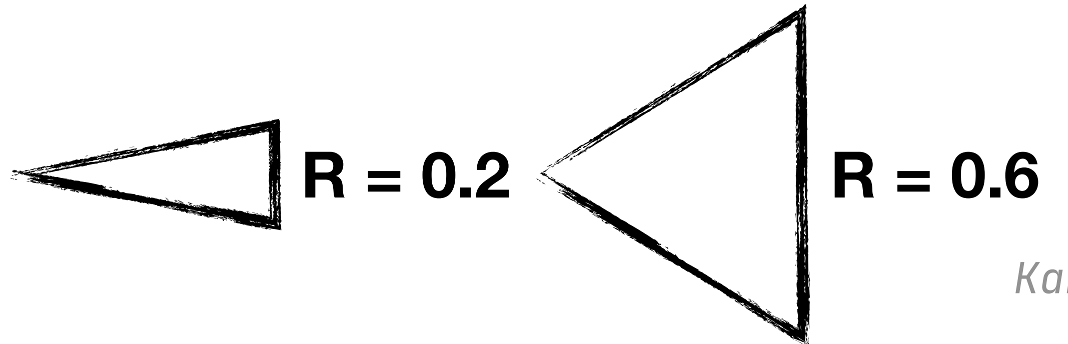
SoftDrop R_g

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

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

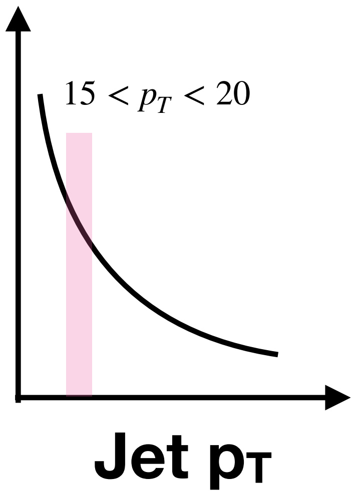
STAR, Phys.Lett.B 811 (2020)

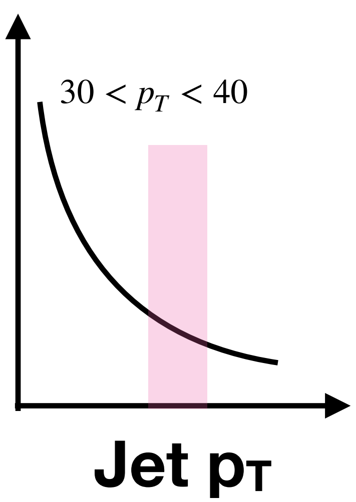


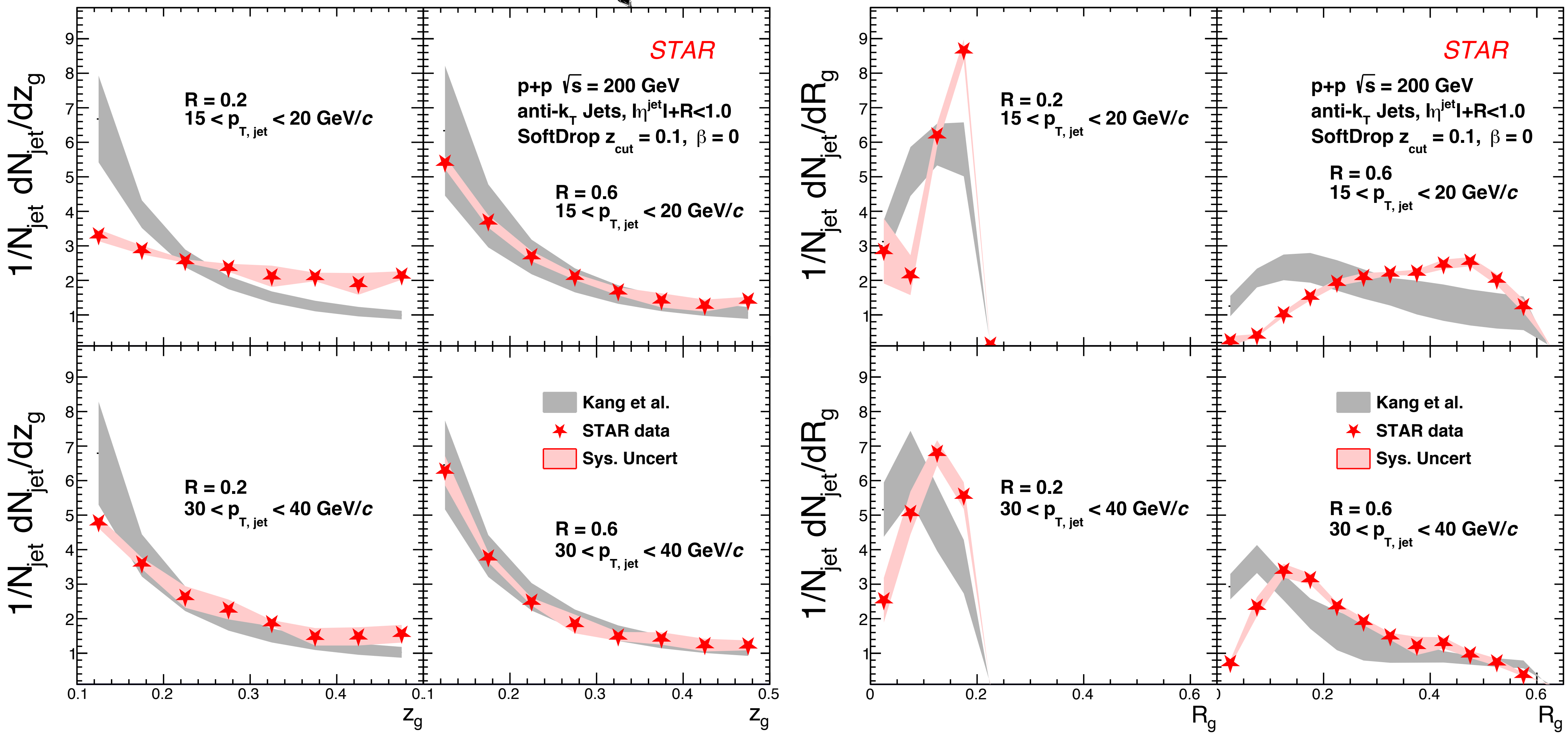


STAR, Phys.Lett.B 811 (2020)

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



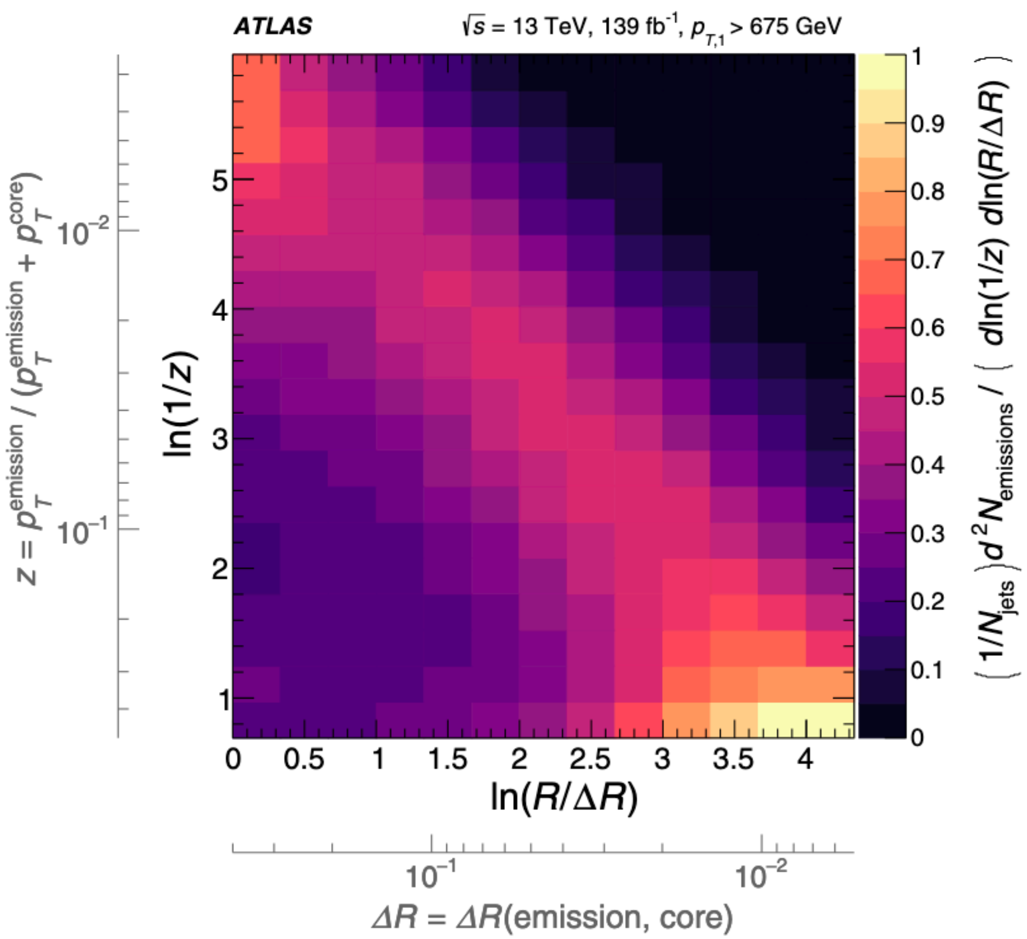


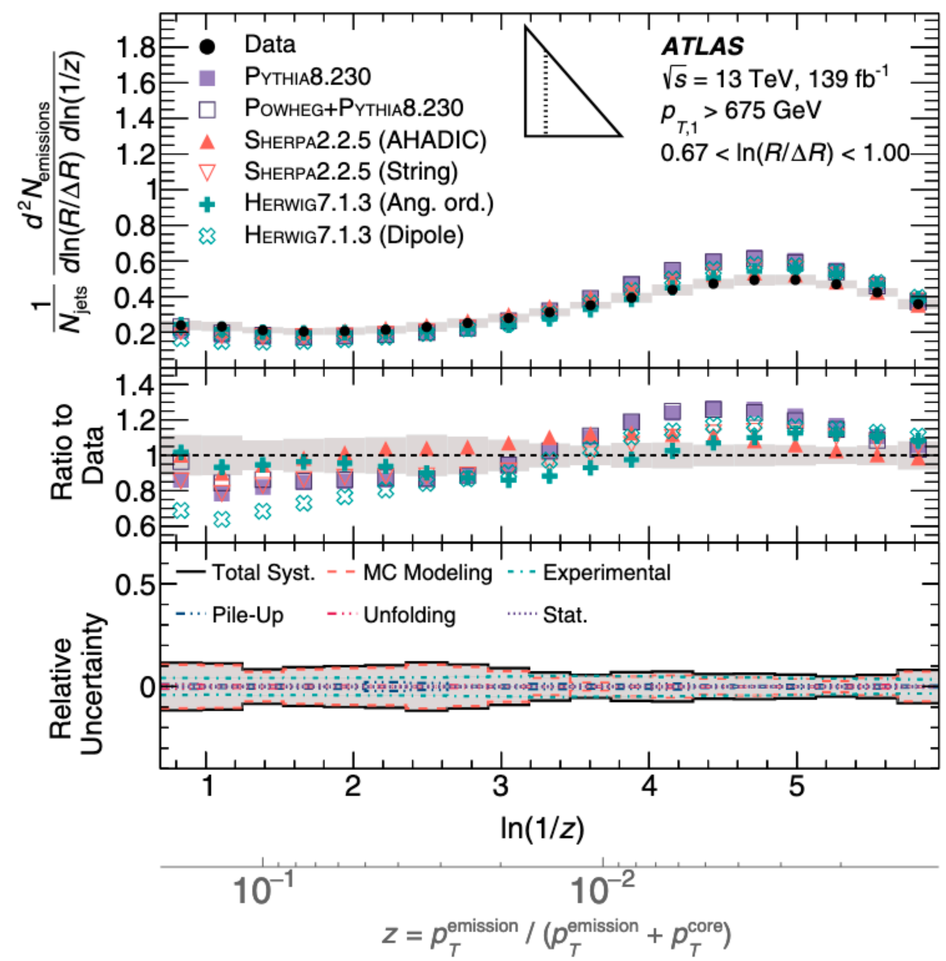


- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and p_T
- Significantly worse for jets of narrow R and low p_T - tighter constraints on jet splittings

Recent measurements of Lund Plane and their projections at the LHC

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

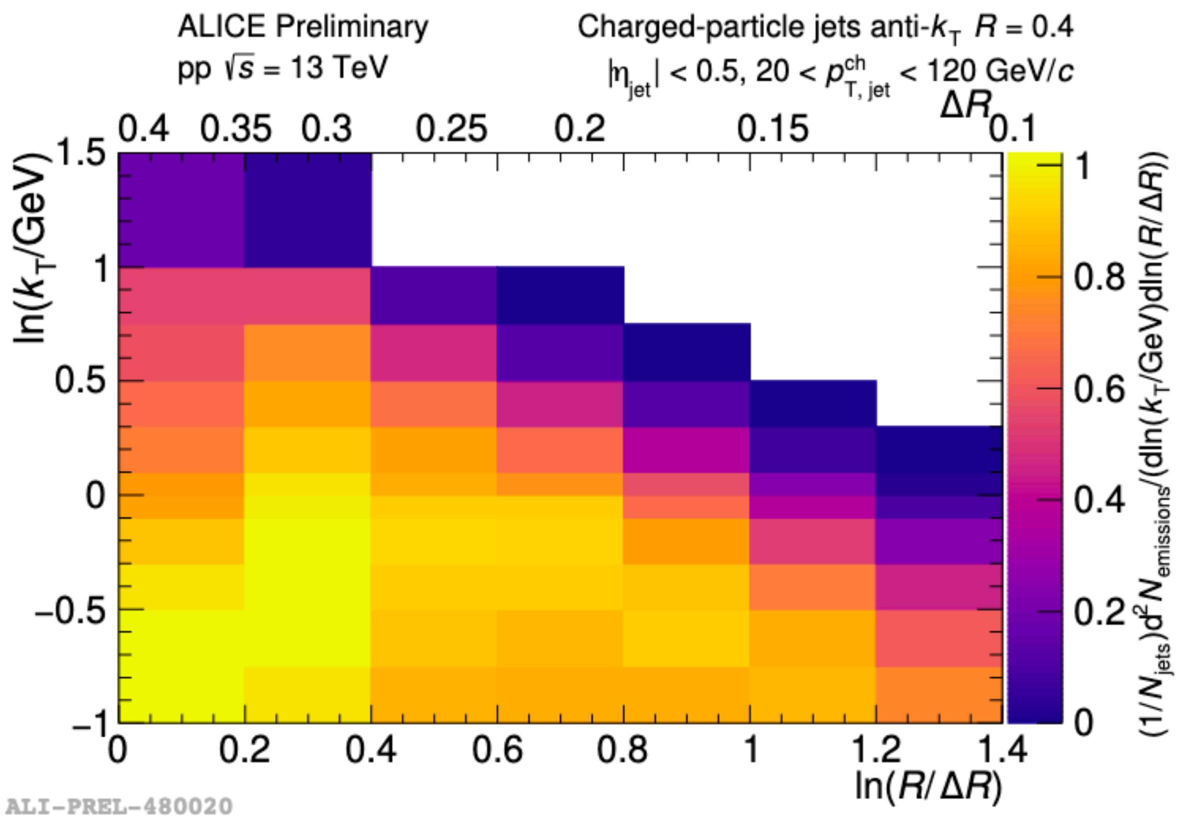


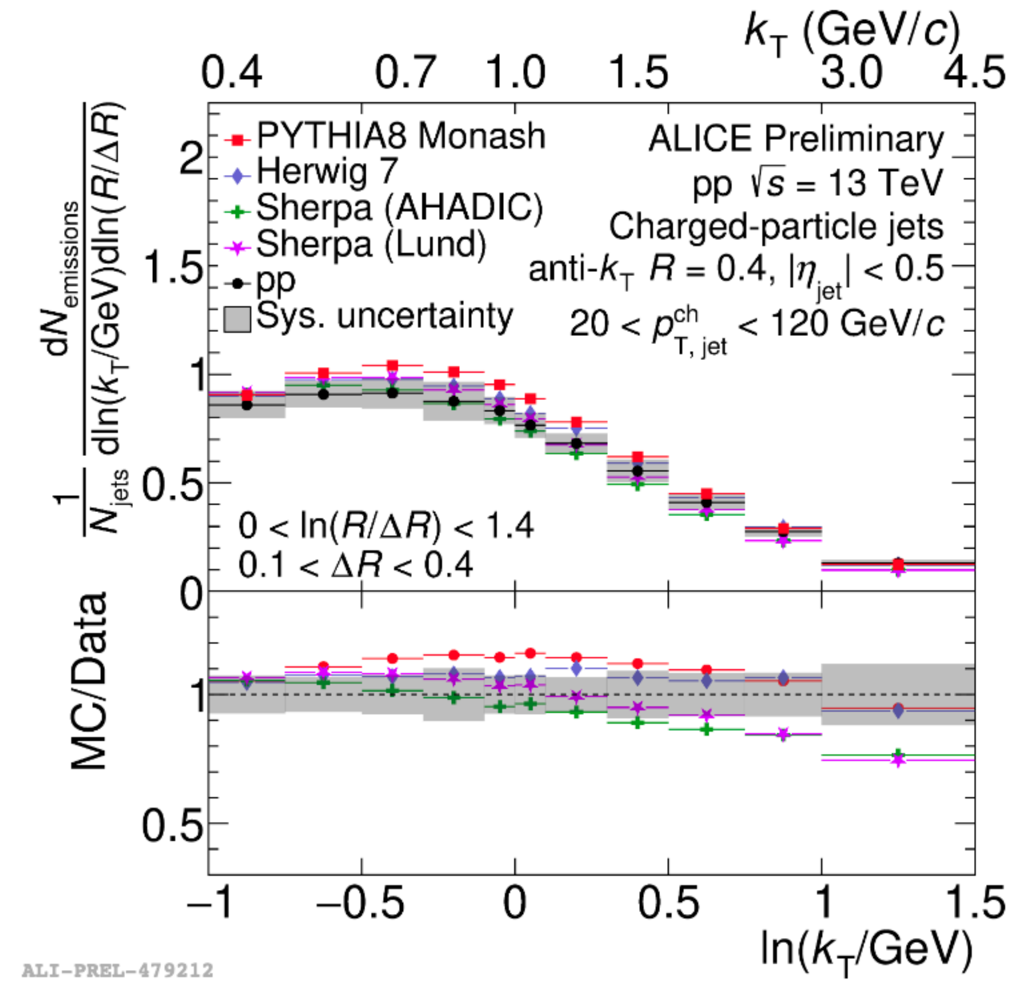


- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcase differences

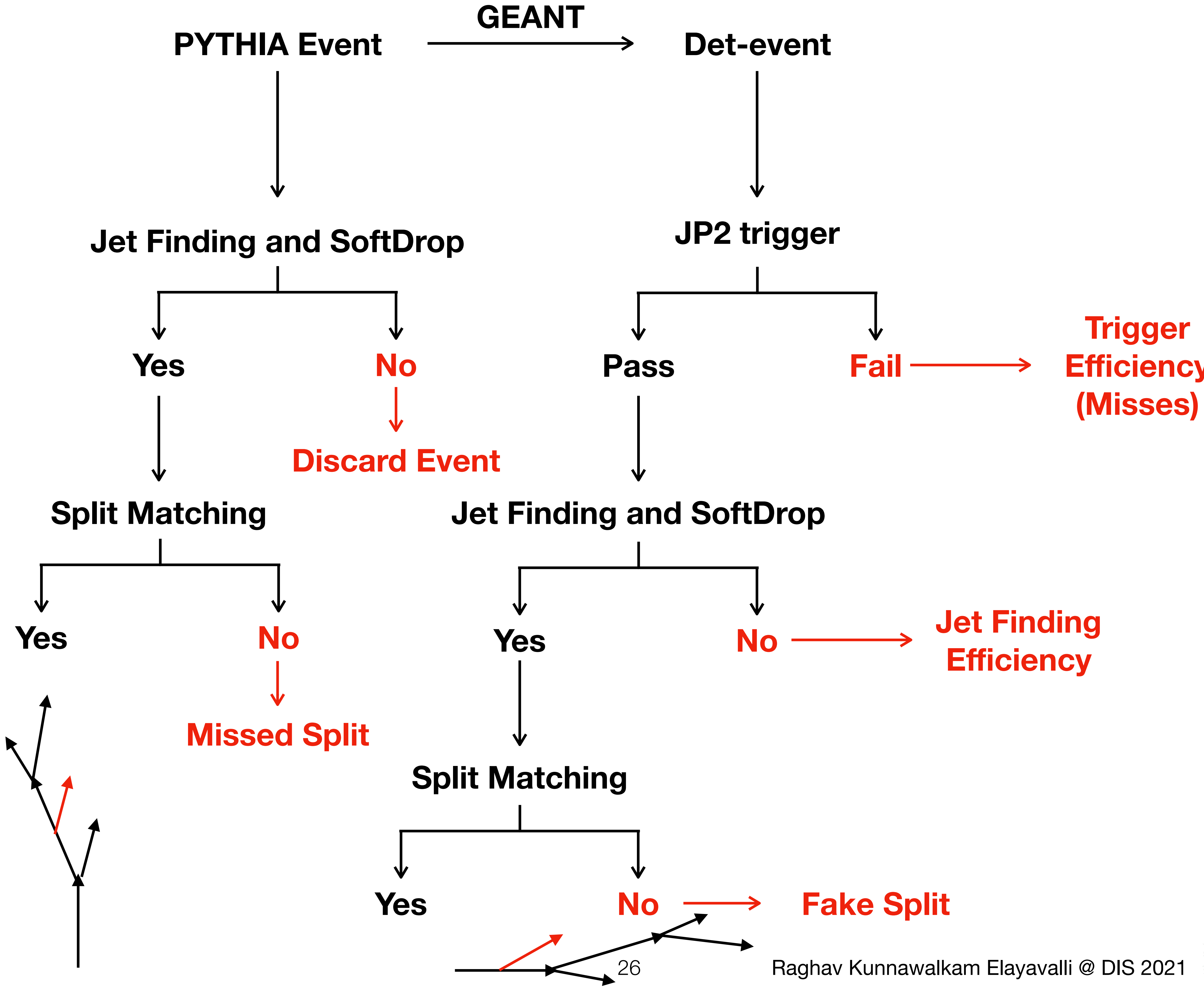
Recent measurements of Lund Plane and their projections at the LHC

ALICE-PUBLIC-2021-002

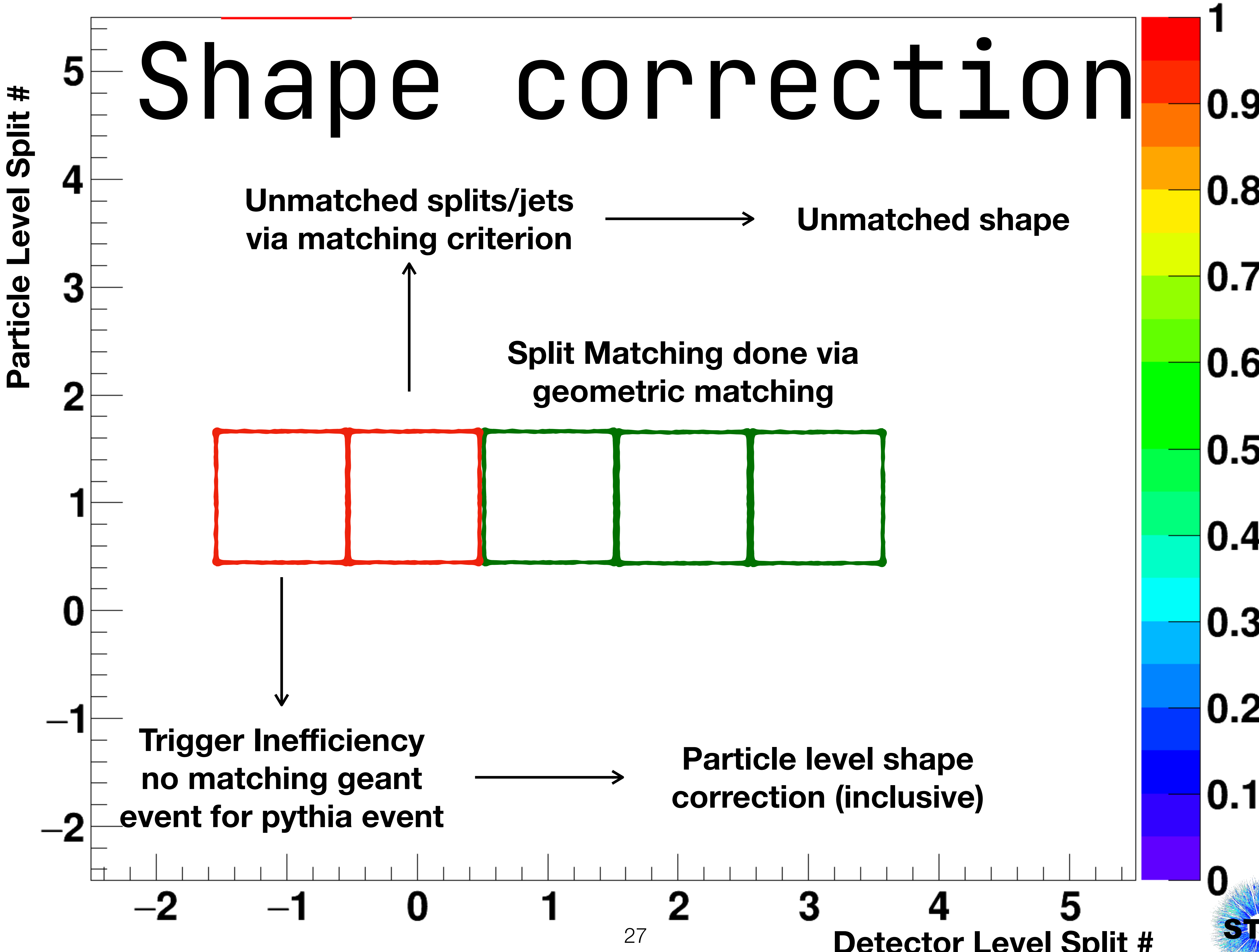




- Lower p_T jets at ALICE (20 - 120 GeV) also show interesting differences for large k_T splits
- Lund plane integrates over splits - can we measure the evolution of these observables along the jet shower?


GEANT
PYTHIA Event
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

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