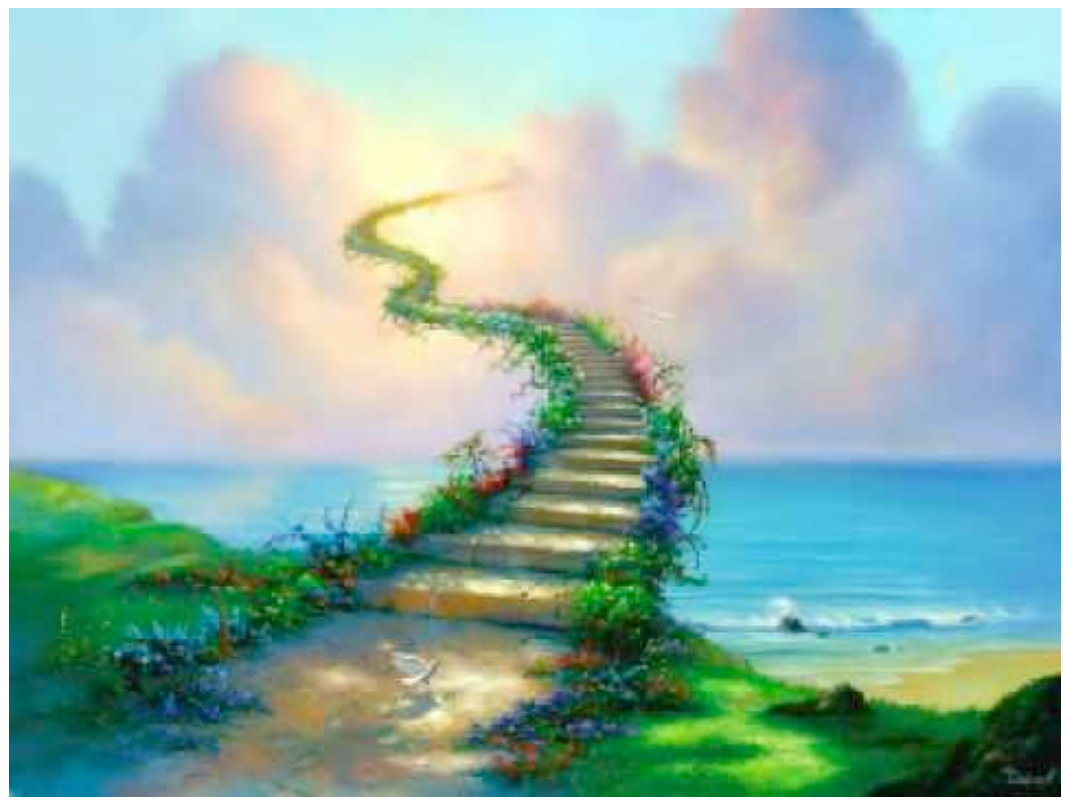
Jets and their substructure

A journey from

LHC → RHIC → EIC



Raghav Kunnawalkam Elayavalli (Yale/BNL)

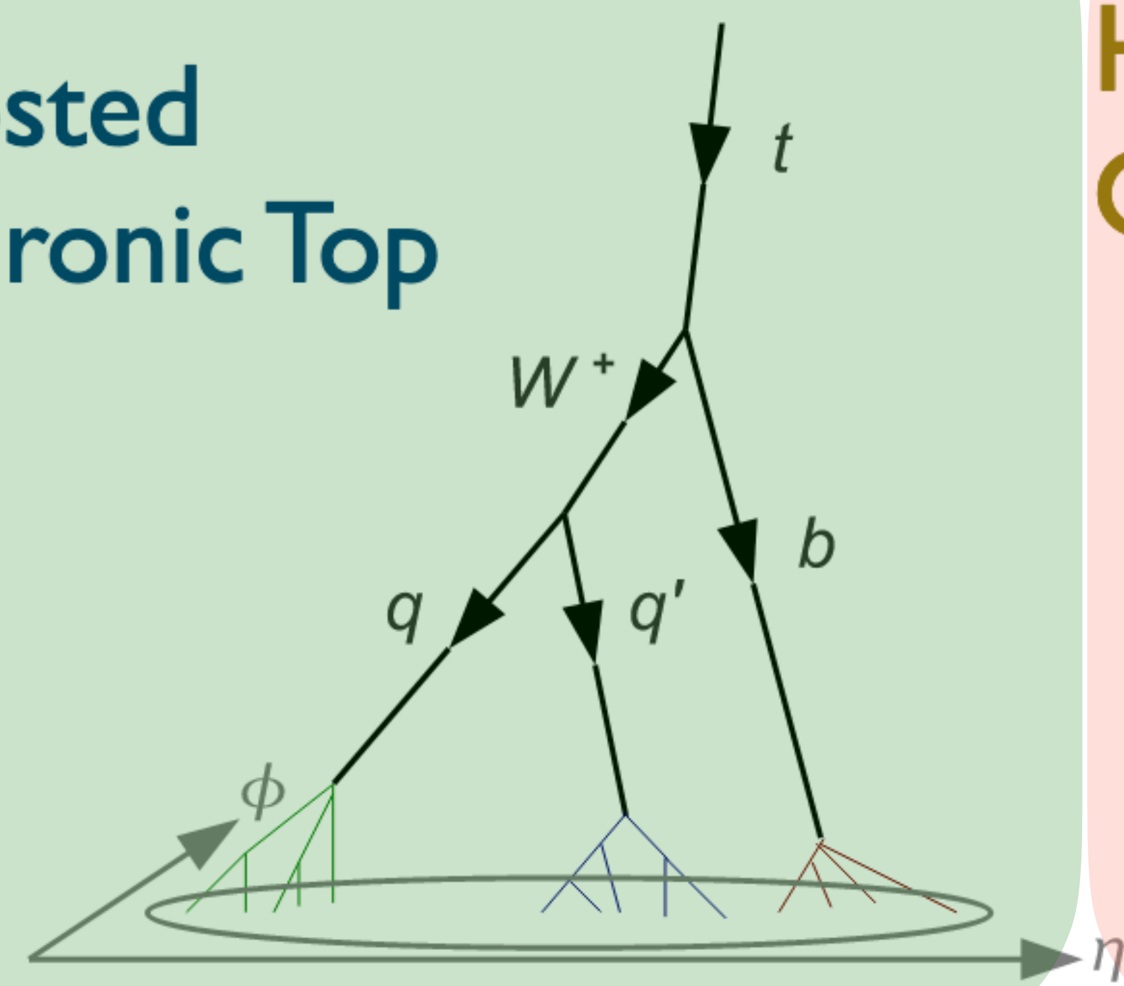
July 1st, 2022 CFNS @ Stony Brook, New York

Workshop: Jet Physics: From RHIC/LHC to EIC

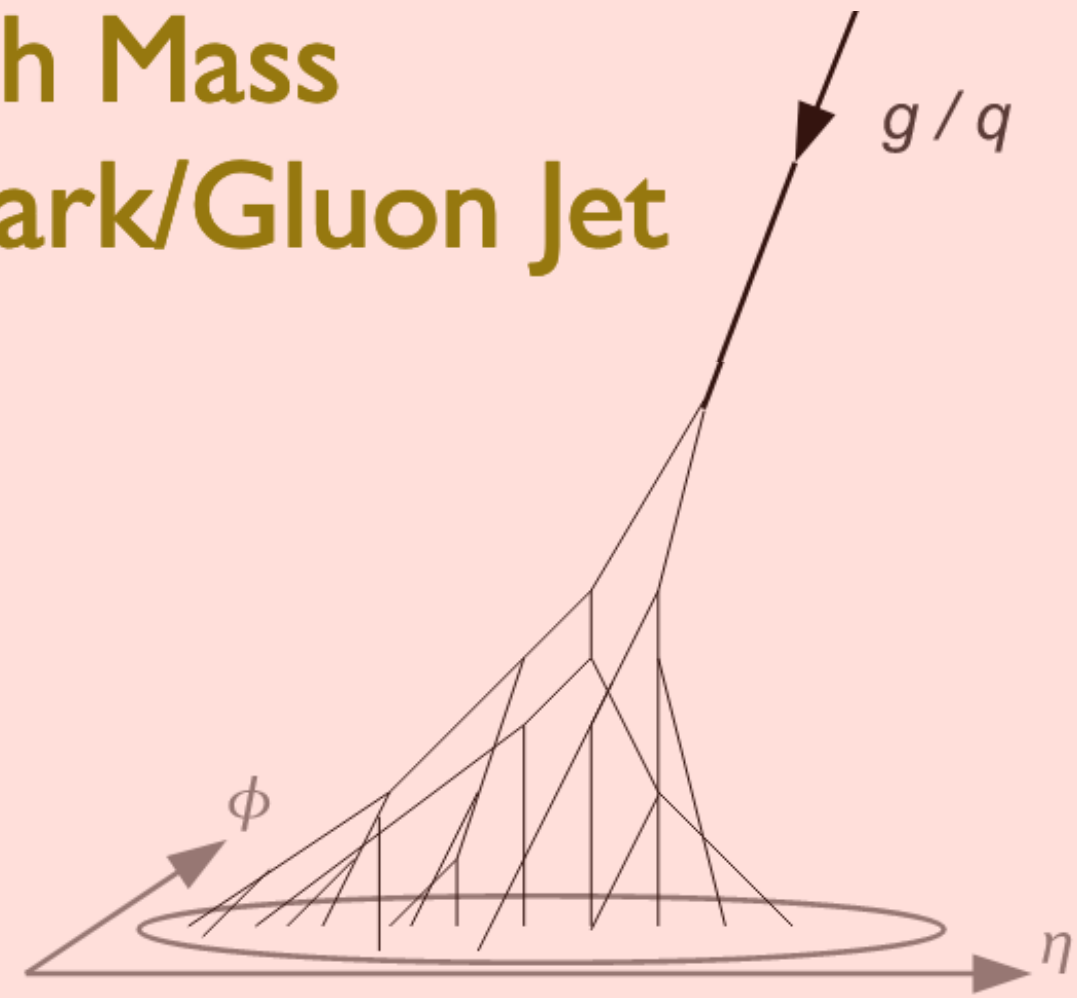
Origin story of jet substructure

Jesse Thaler in 2011

Boosted Hadronic Top



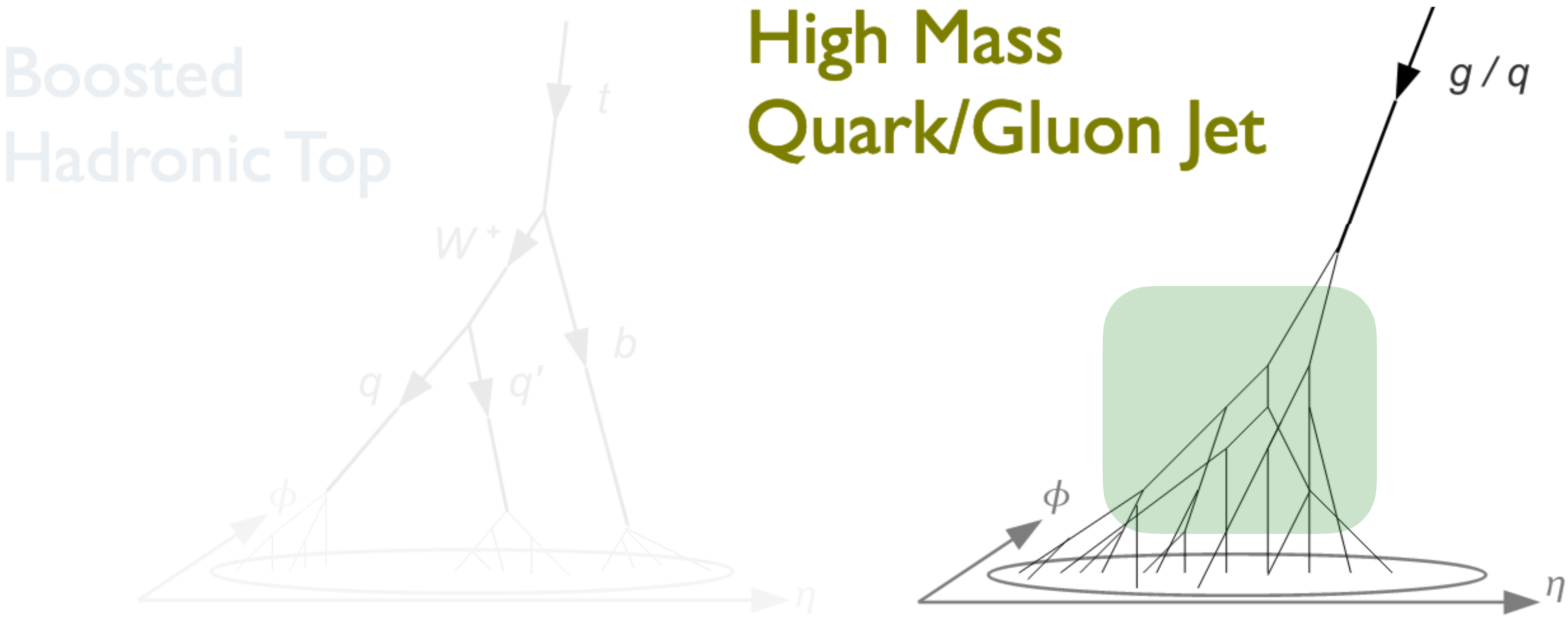
High Mass Quark/Gluon Jet



Started with the goal of identifying boosted decay versus standard QCD

Origin story of jet substructure

Jesse Thaler in 2011

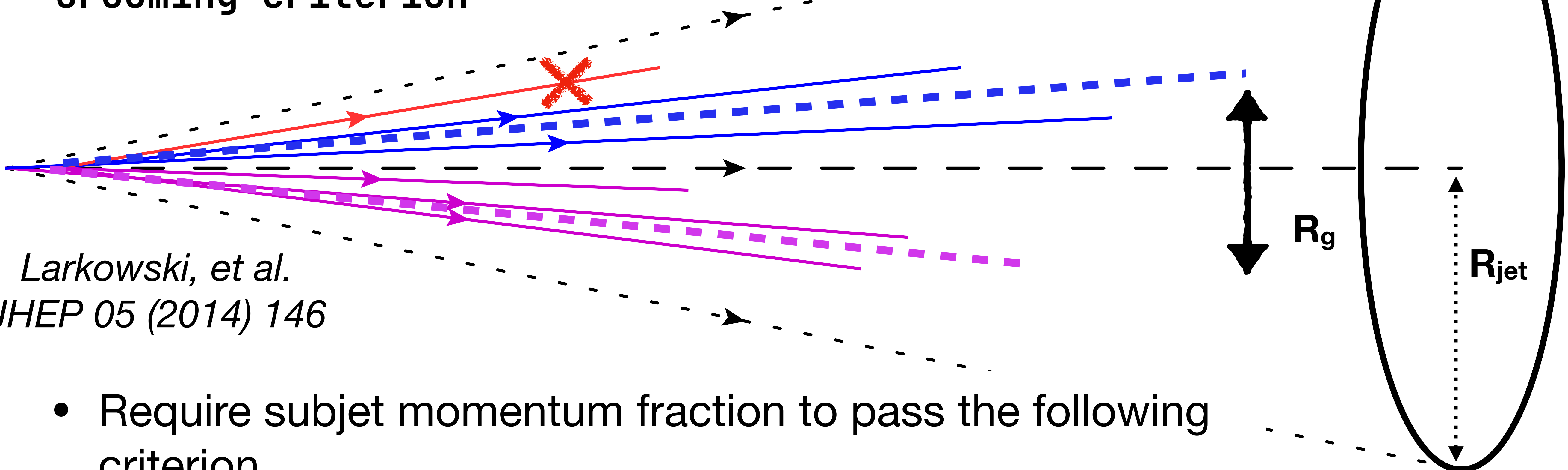


Transitioned to studies of fundamental QCD (parton showers) and non-perturbative processes (hadronization)

SoftDrop

Dasgupta et al.
JHEP 09 (2013) 029

Grooming criterion



Larkowski, et al.
JHEP 05 (2014) 146

- Require subjet momentum fraction to pass the following criterion

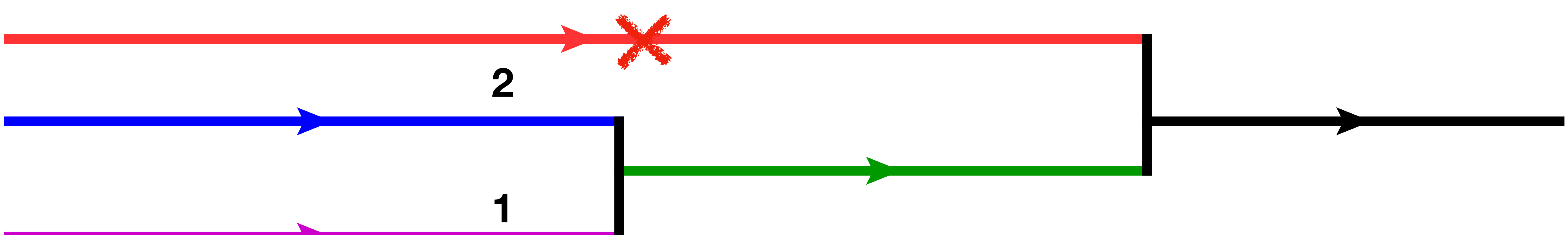
$$z_g = \frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^{\beta}$$

$$z_{cut} = 0.1$$

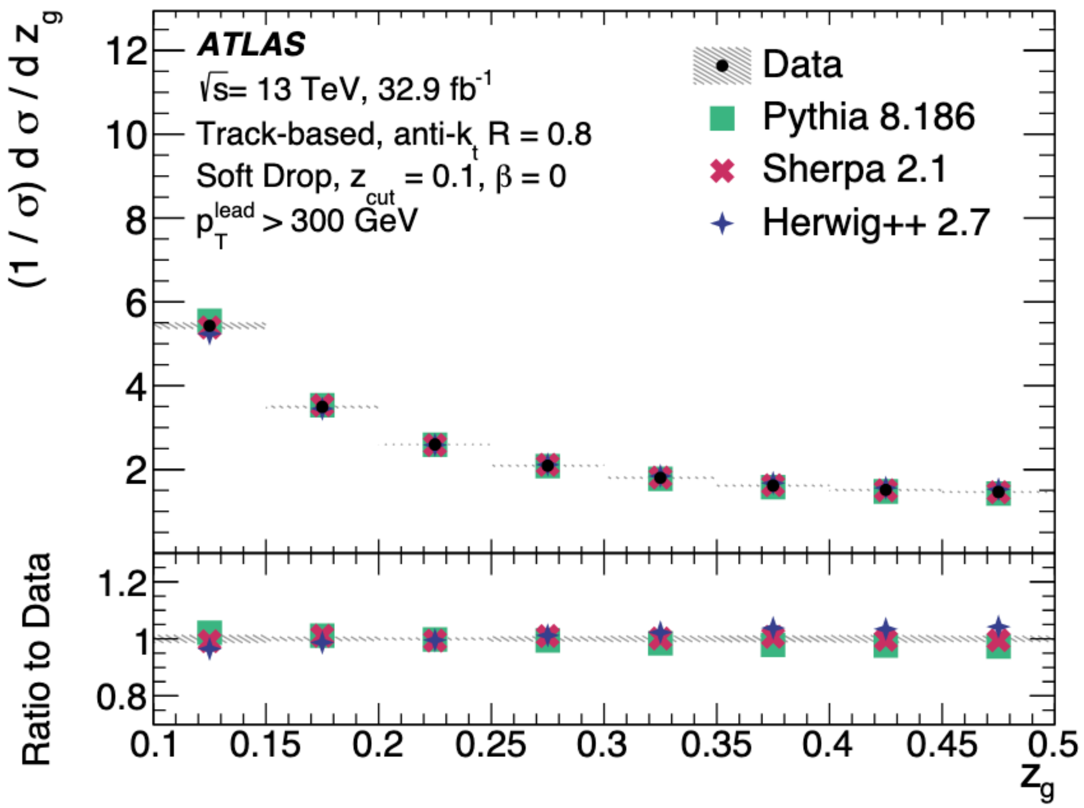
$$\beta = 0$$

- With the two surviving branches (first hard split) - we have two observables that characterize a jet's substructure

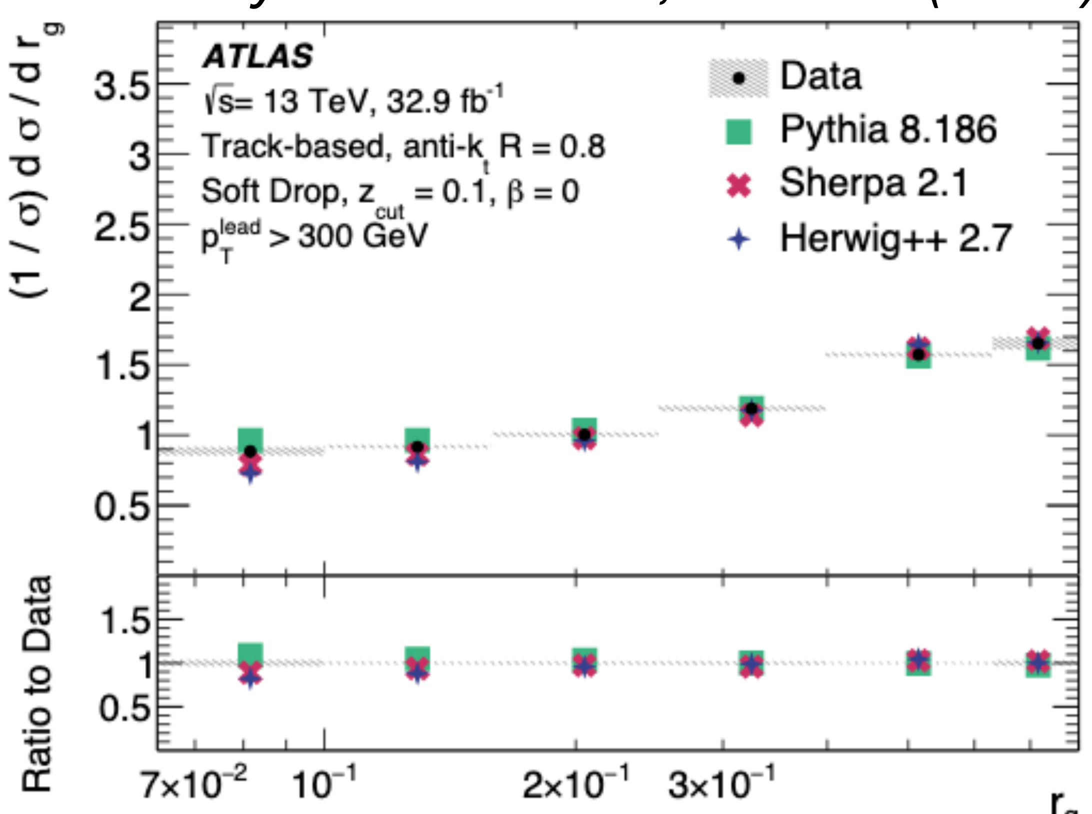
$$z_g,\ R_g$$

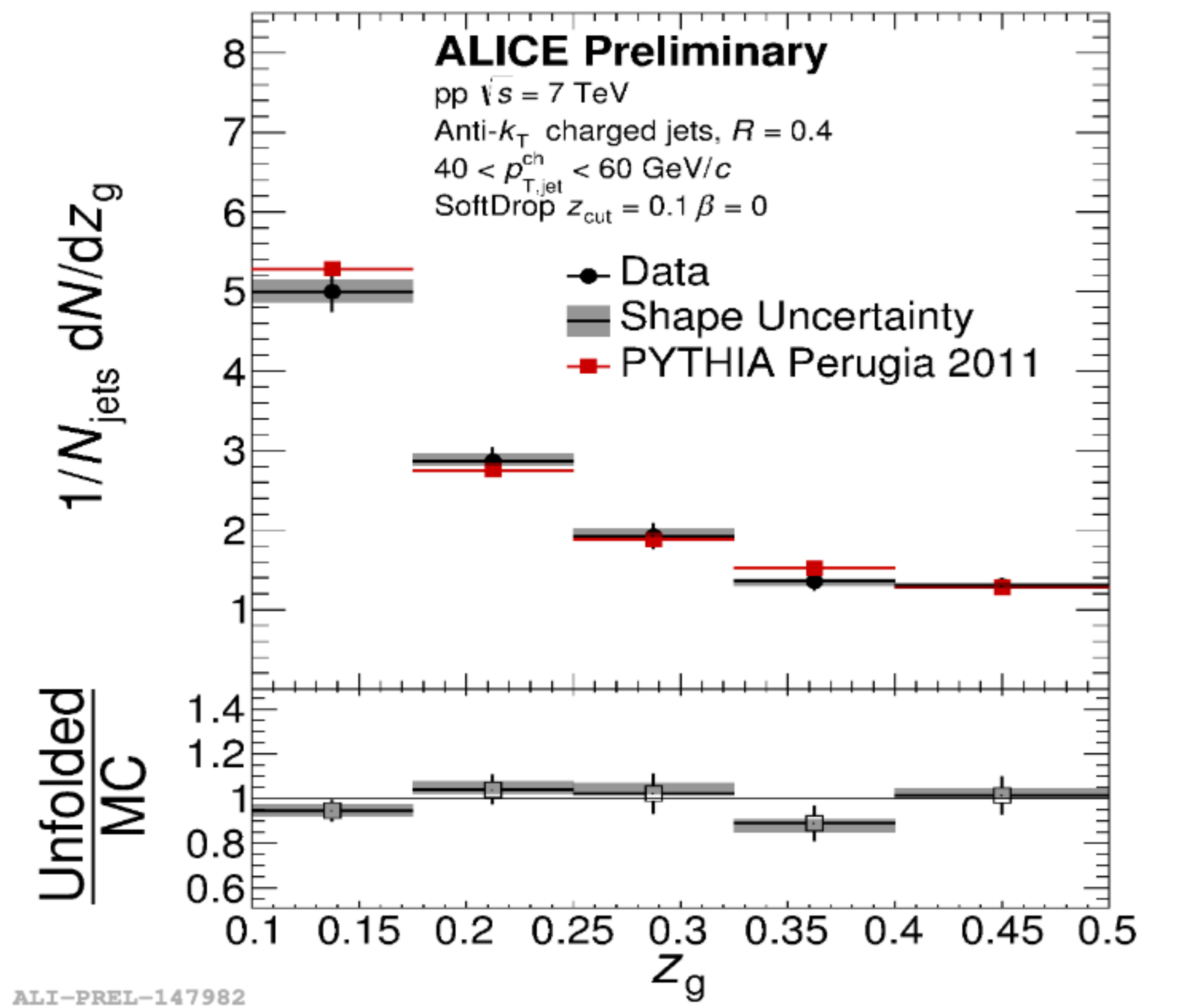


SoftDrop distributions in pp



ATLAS Phys. Rev. D 101, 052007 (2020)

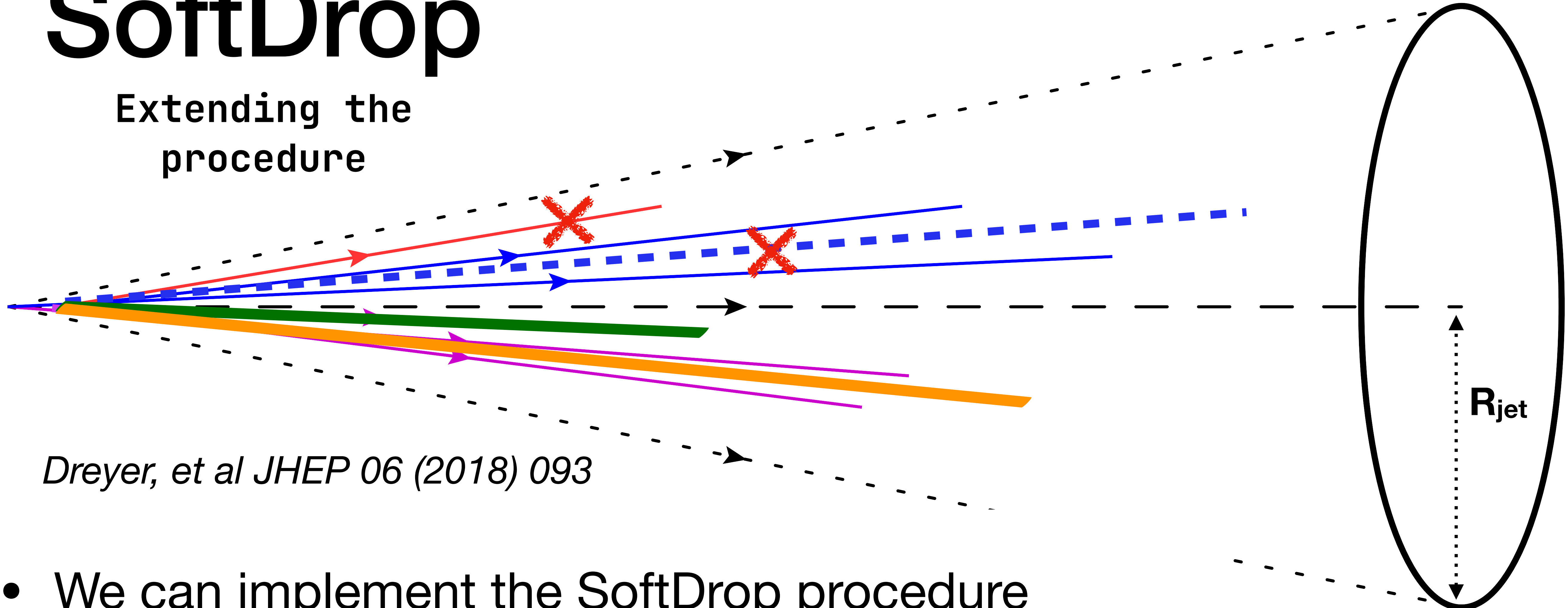




- Overall good agreement with MC
- Track based observables come with better precision

SoftDrop

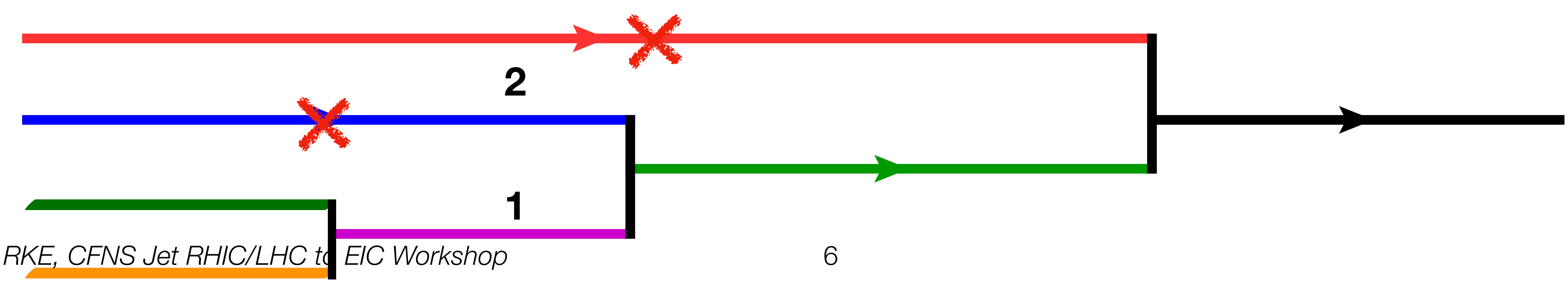
Extending the procedure



Dreyer, et al JHEP 06 (2018) 093

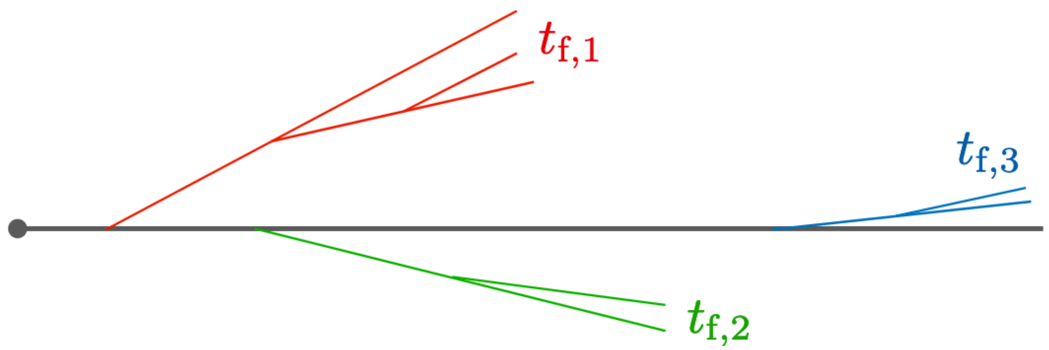
- We can implement the SoftDrop procedure throughout the CA tree -
  - Follow the hardest branch - Iterative SoftDrop
  - Following all branches - Recursive SoftDrop

$$n_{\mathrm{SD}},\ z_g^n,\ R_g^n$$

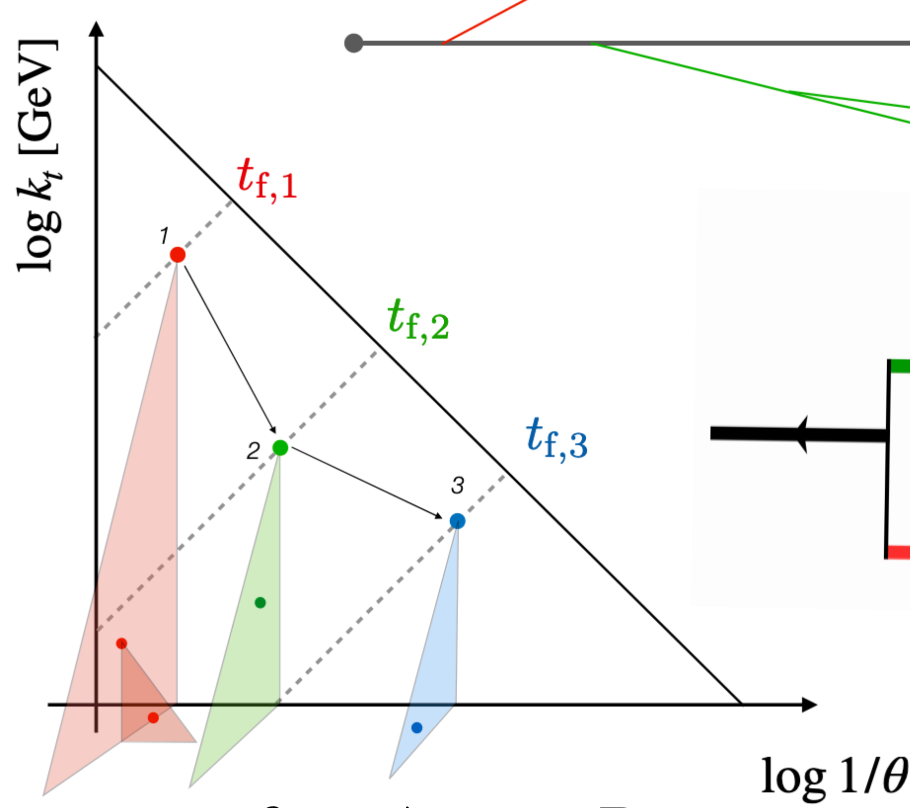


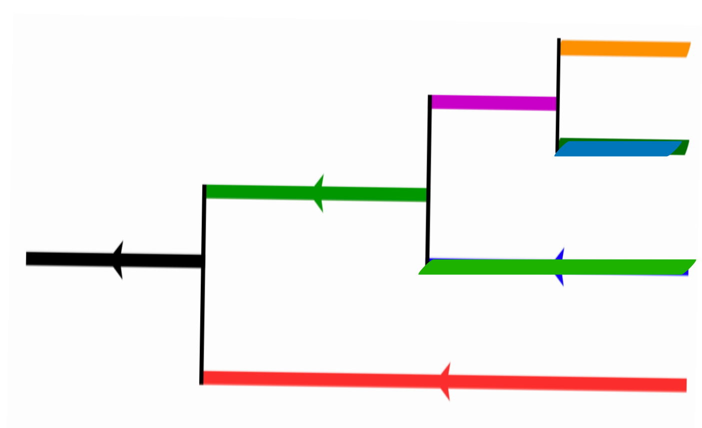
Phase space of jet evolutions
Lund Diagrams

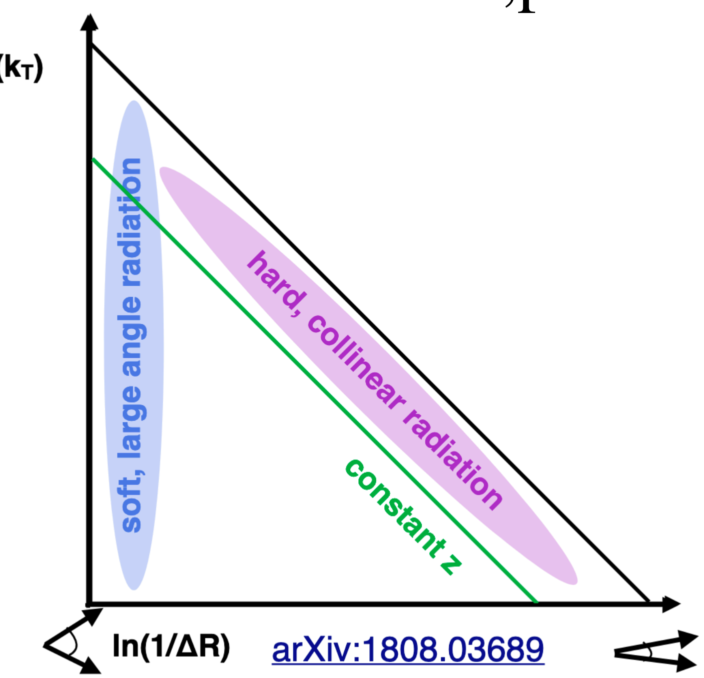
Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)



$$k_t = z \cdot p_{T,\mathrm{parent}} \cdot \Delta R$$







K. Tywoniuk (UiB)

$\theta = \Delta R$ or R_g

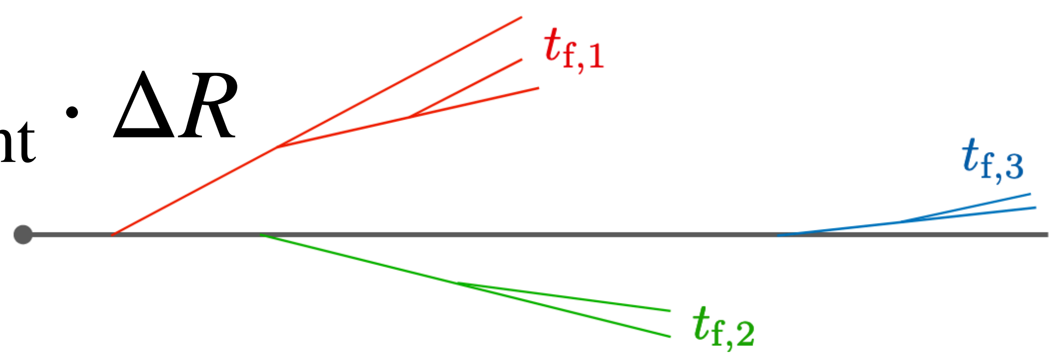
5

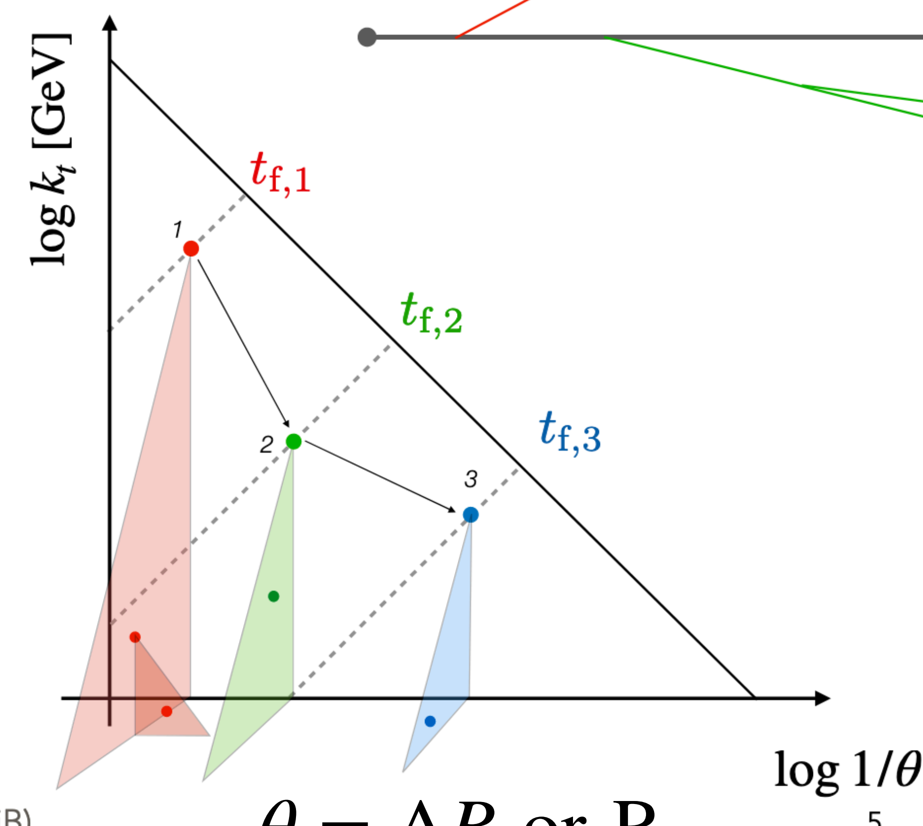
- Builds a 2D picture of jet showers
- Primary Lund plane refers to following the hardest branch sequentially
- Different axis representations: ln(kT), ln($z\theta$), ln(1/z)

Phase space of jet evolutions
Lund Diagrams

Andersson, Gustafson, Lönnblad, Pettersson Z.Phys.C (1989)
Andersson, Gustafson, Samuelsson NPB (1996)

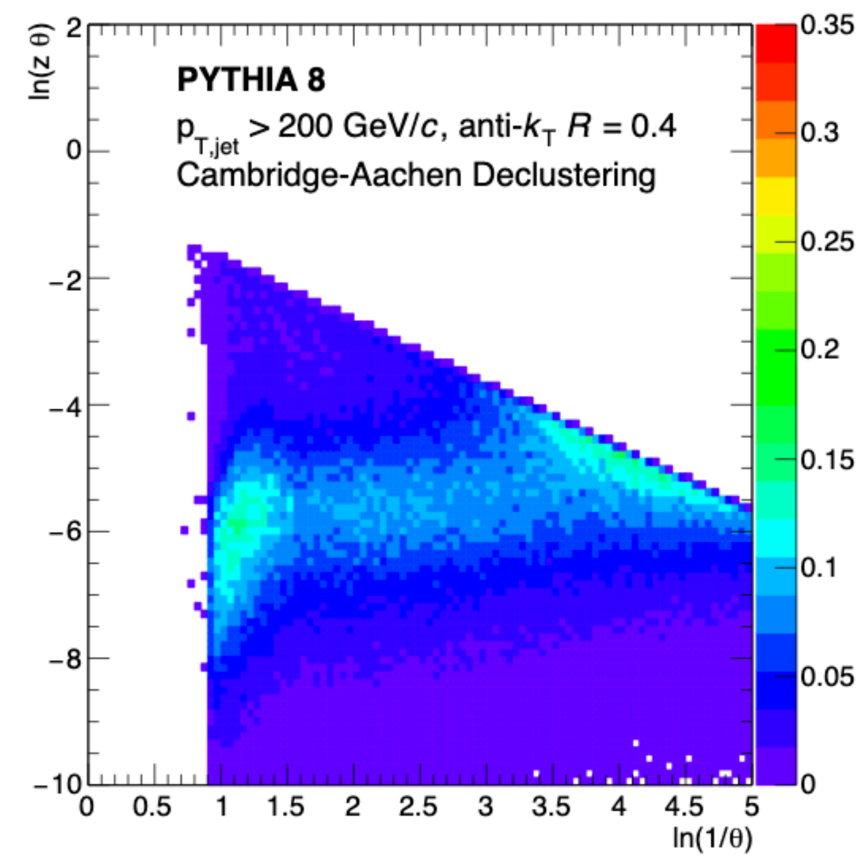
$$k_t = z \cdot p_{\mathrm{T,parent}} \cdot \Delta R$$





K. Tywoniuk (UiB)

$\theta = \Delta R$ or $\mathrm{R_g}$

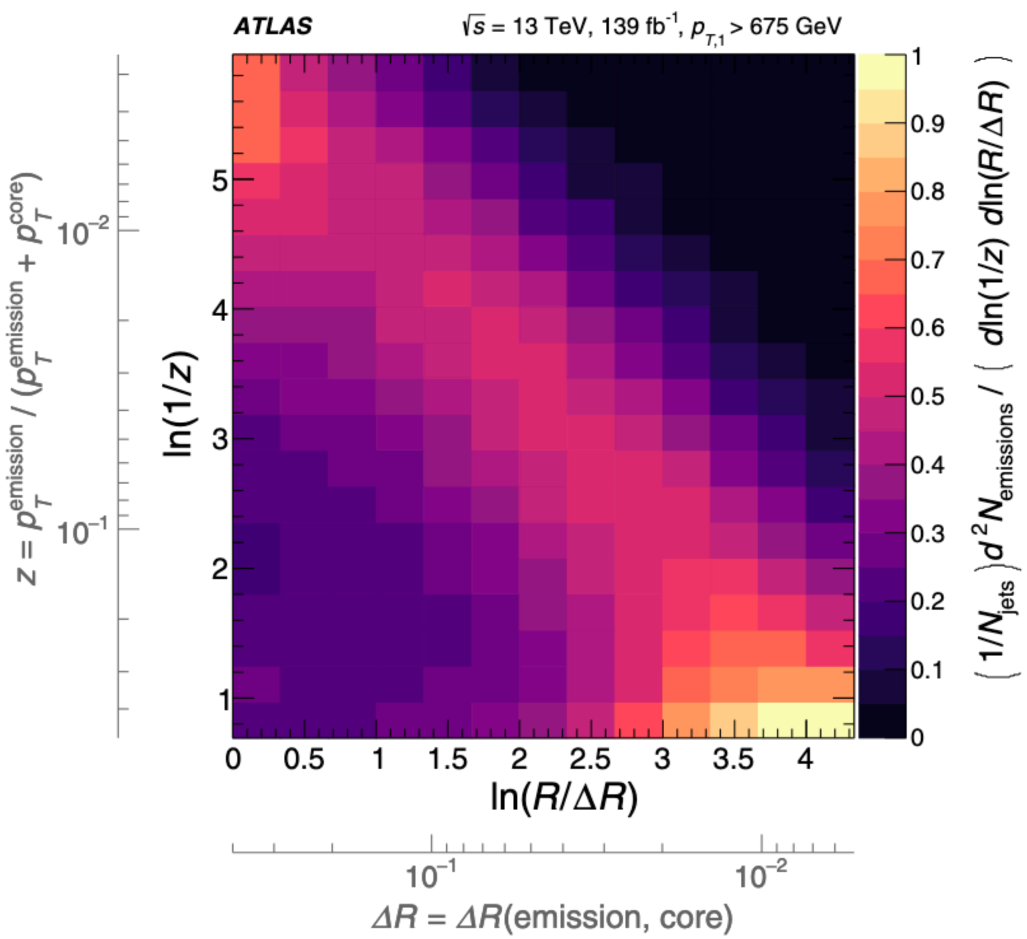


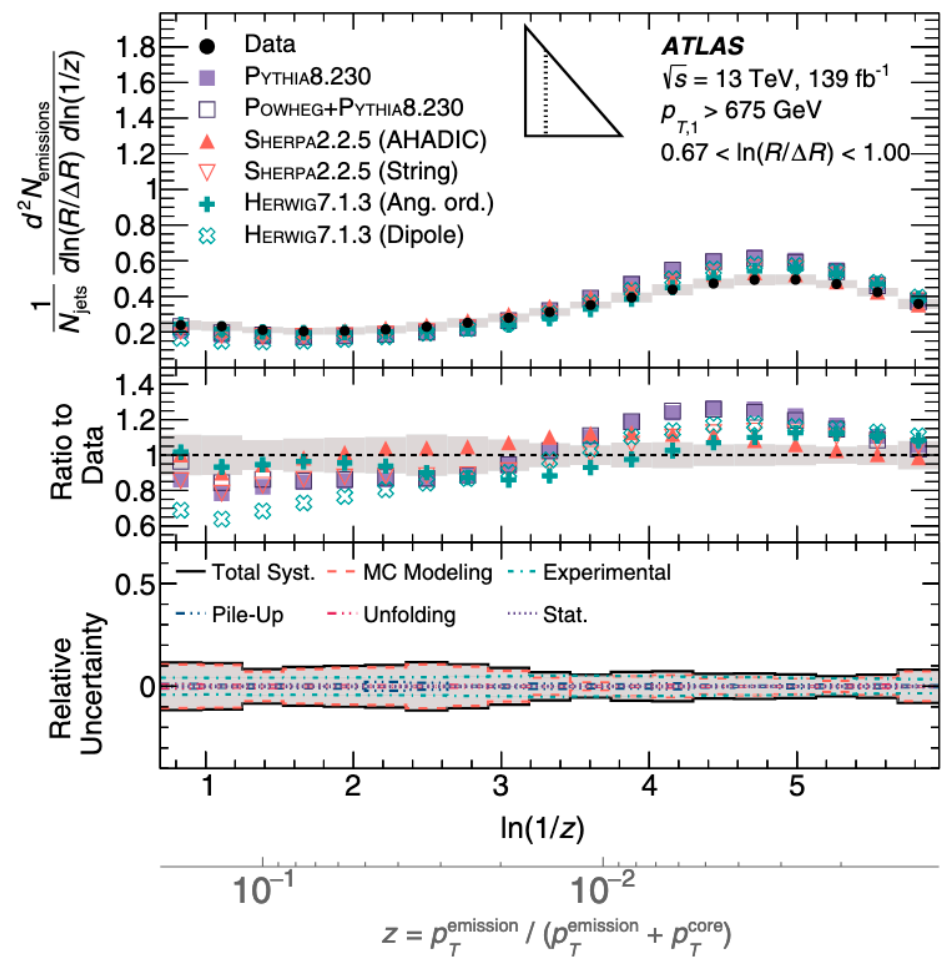
Jets fill up the emission space!

- Vacuum jet shower for R=0.4 jets (note lower end of x-axis cutoff)
- Effect of hadronization shown as low momentum and across all θ

Recent measurements of Lund Plane and their projections at the LHC

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

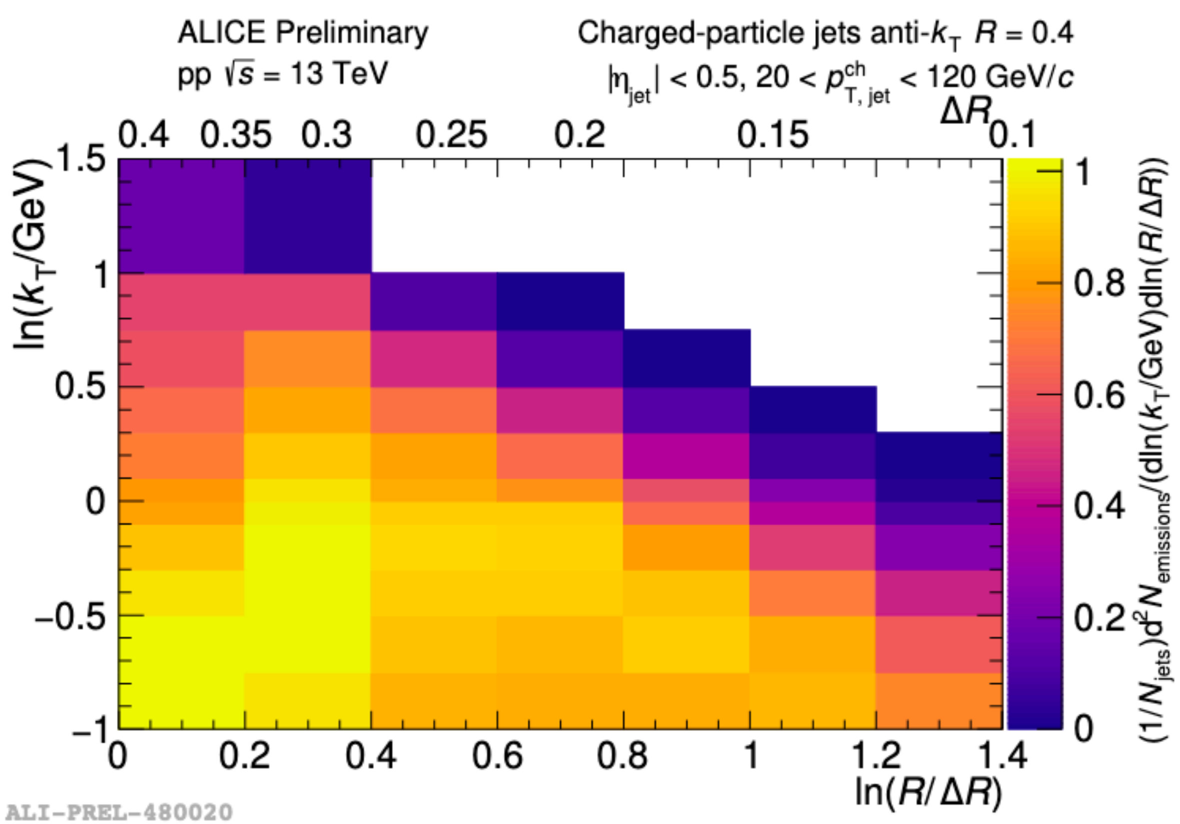


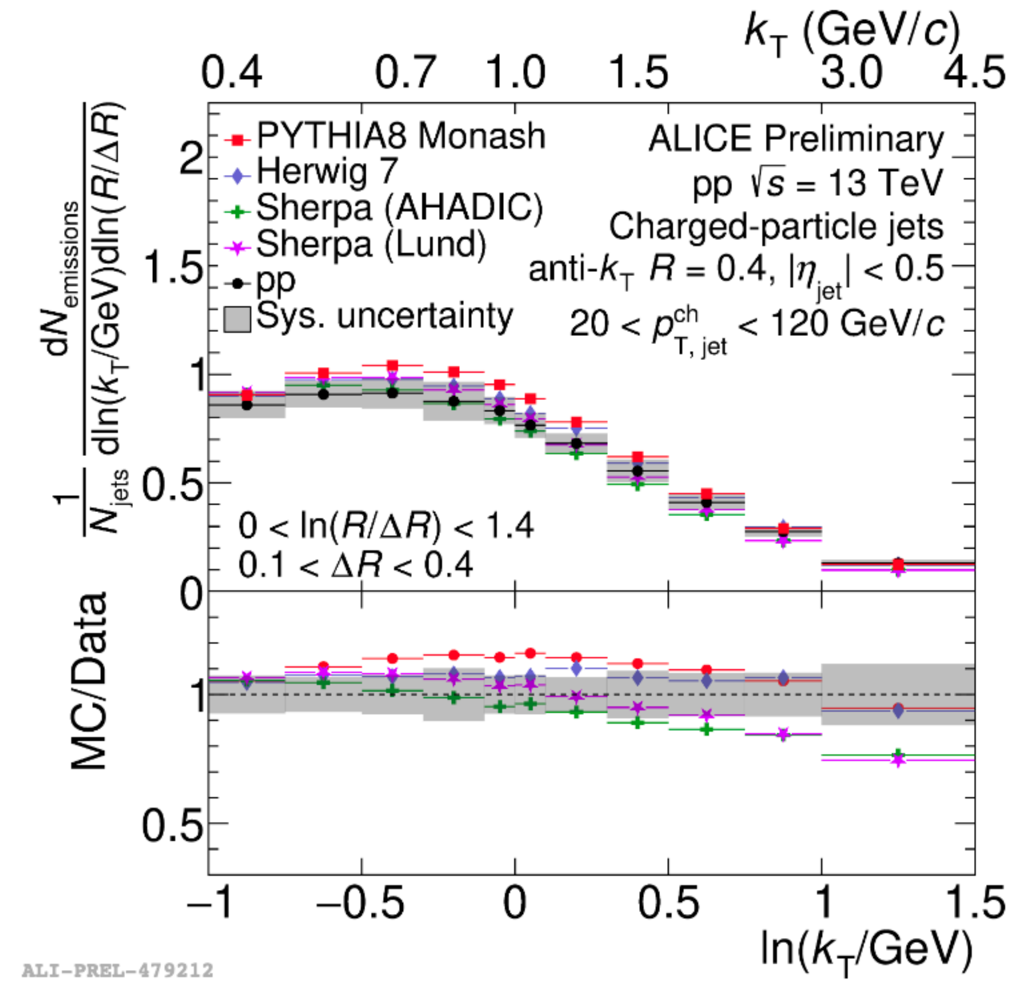


- Each split along the harder branch makes an entry here in the 2D Lund plane
- Comparison with particle level MC w/ varied shower/ hadronization models showcase differences

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?

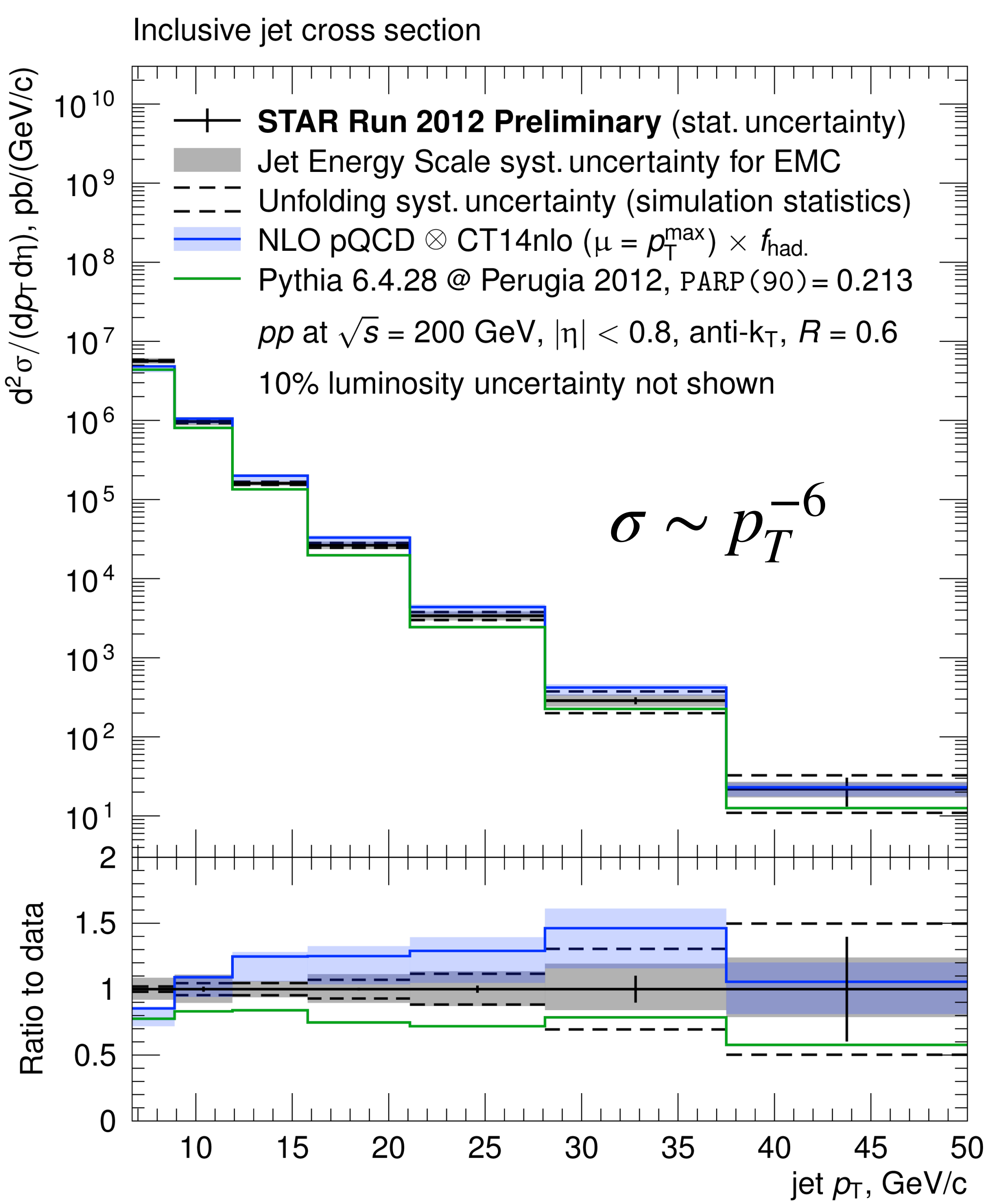
Jets and their substructure

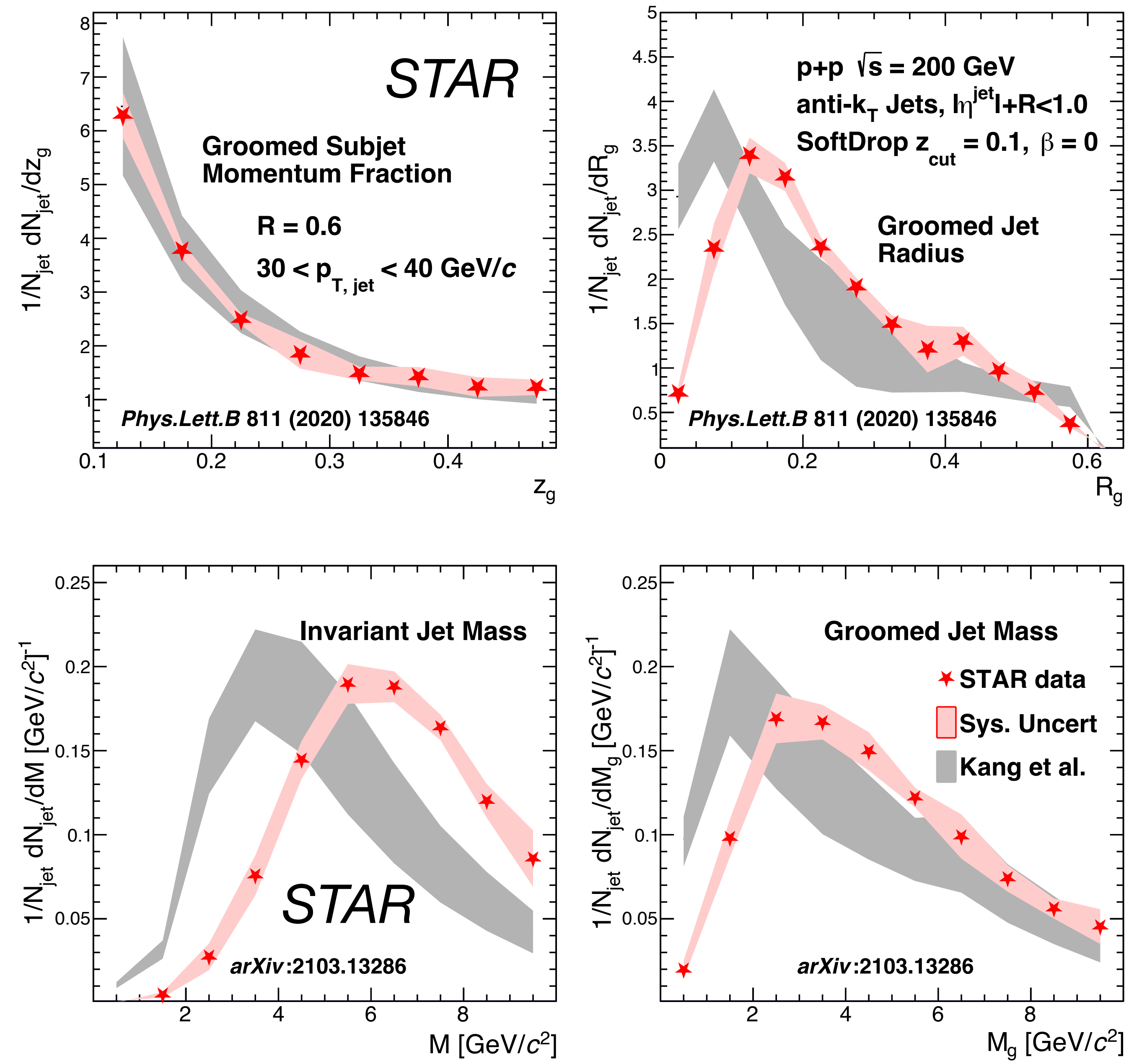
A journey from

LHC → RHIC → EIC

- Almost all measurements have overall good agreement with MC
- Track based observables come with better precision
- Precision helps in the differential comparisons across the Lund plane w/ varied shower/hadronization models showcase differences
- Lower p_T jets at ALICE (20 - 120 GeV) also show interesting differences for large k_T splits

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



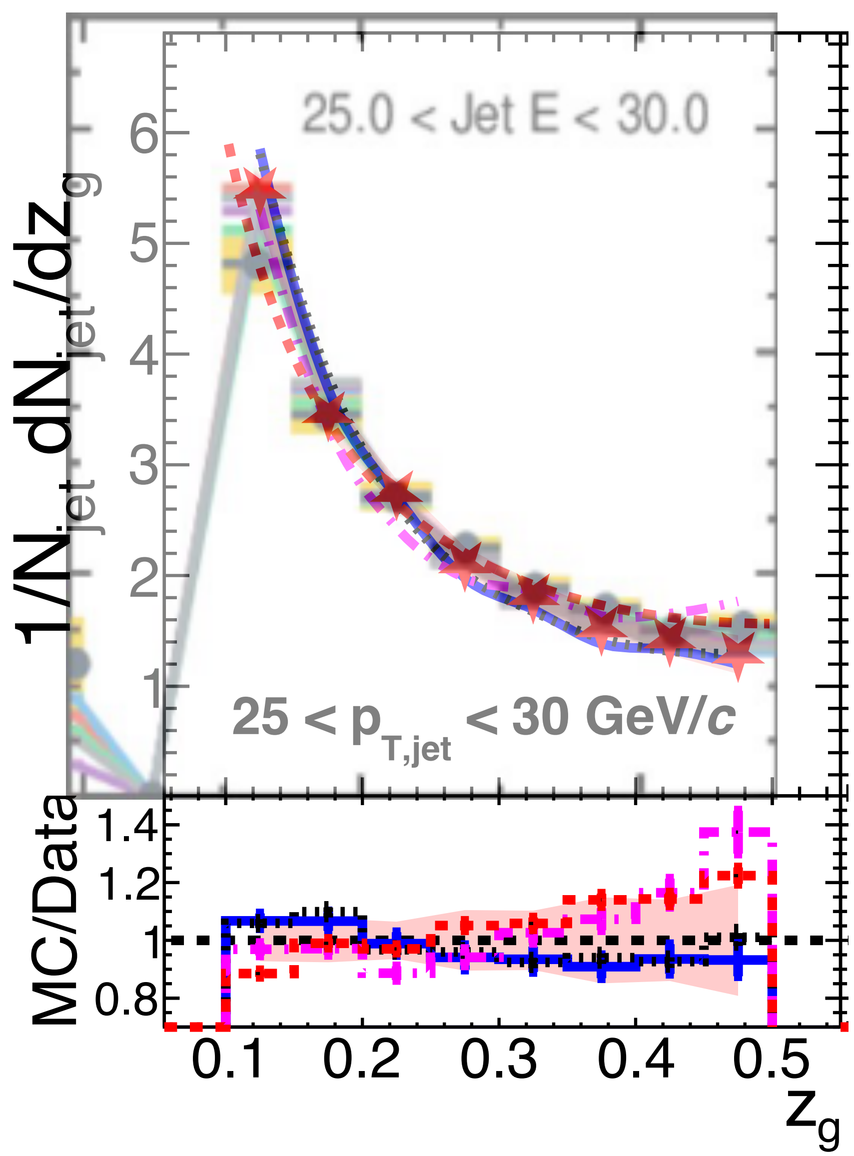


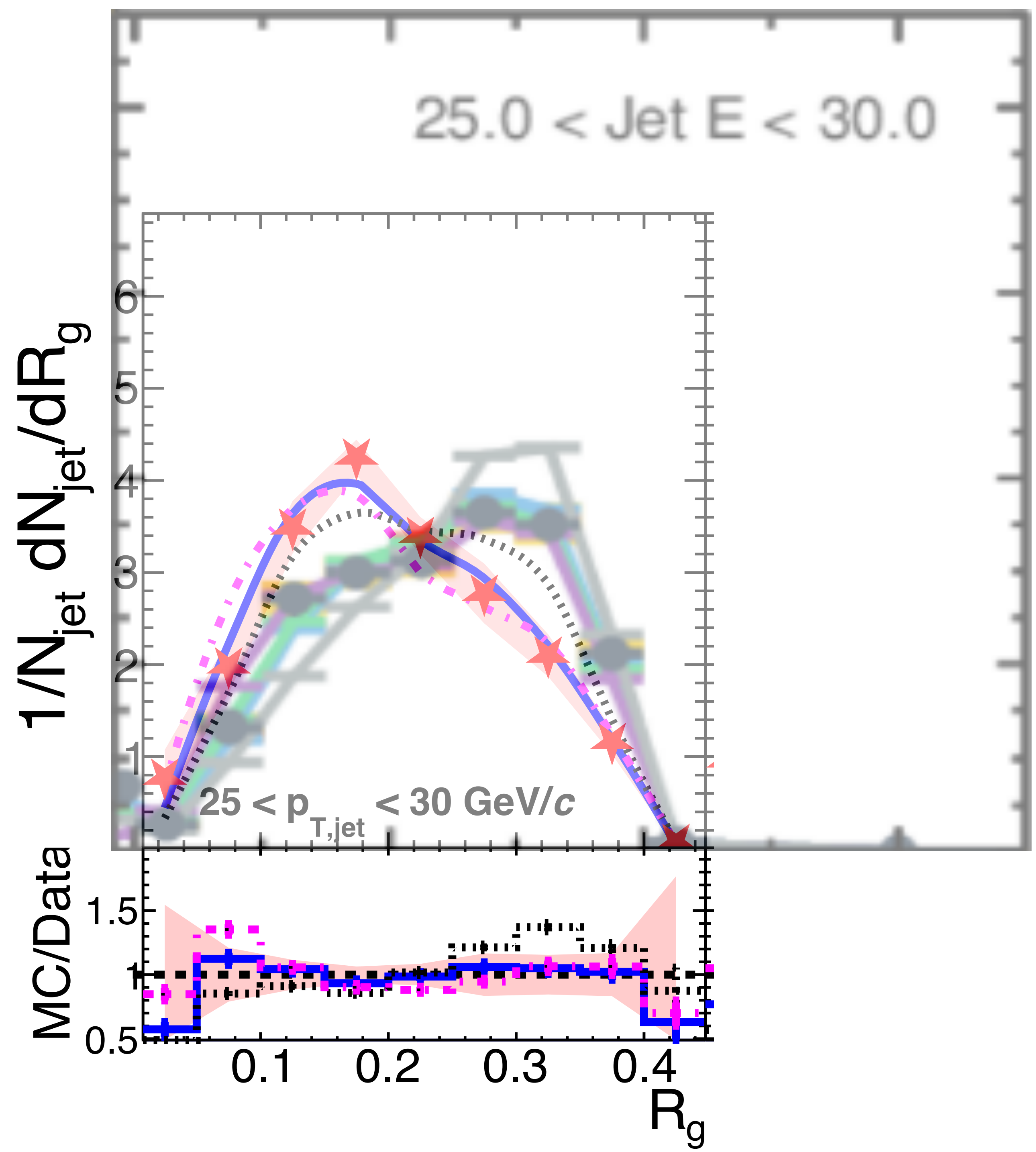
Unique population of jets with varied substructure!

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

Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g

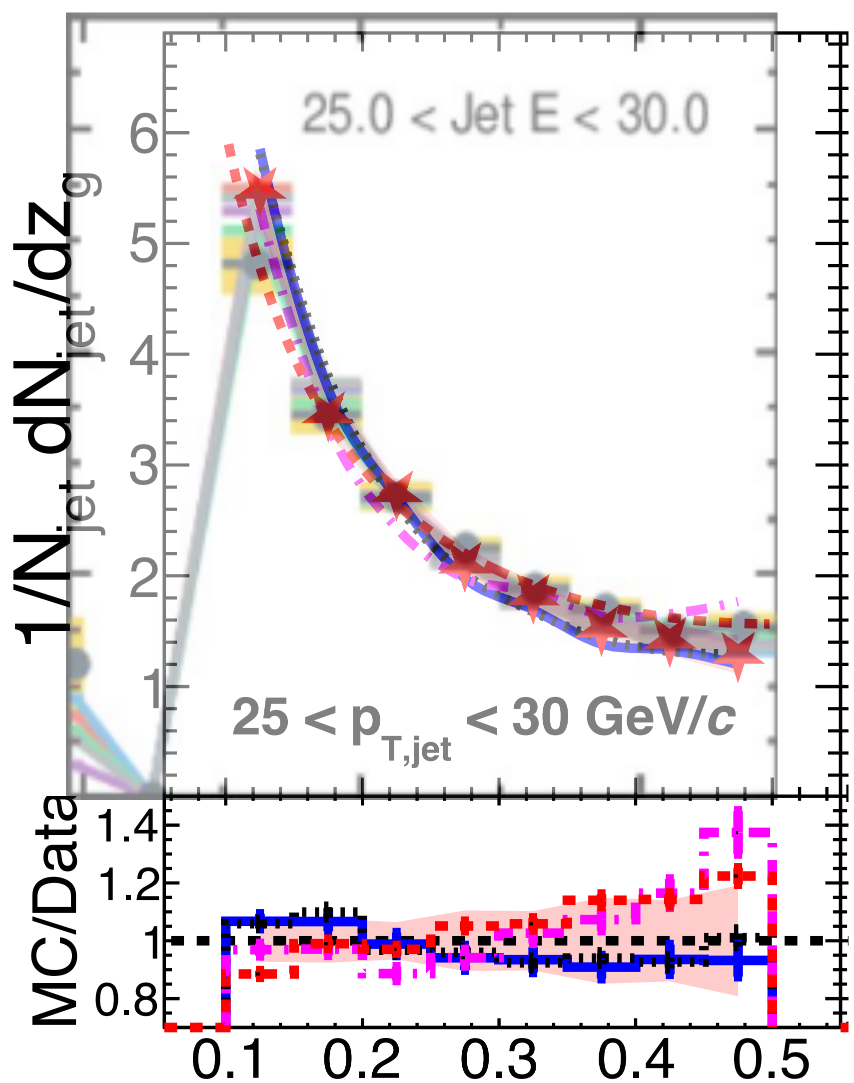


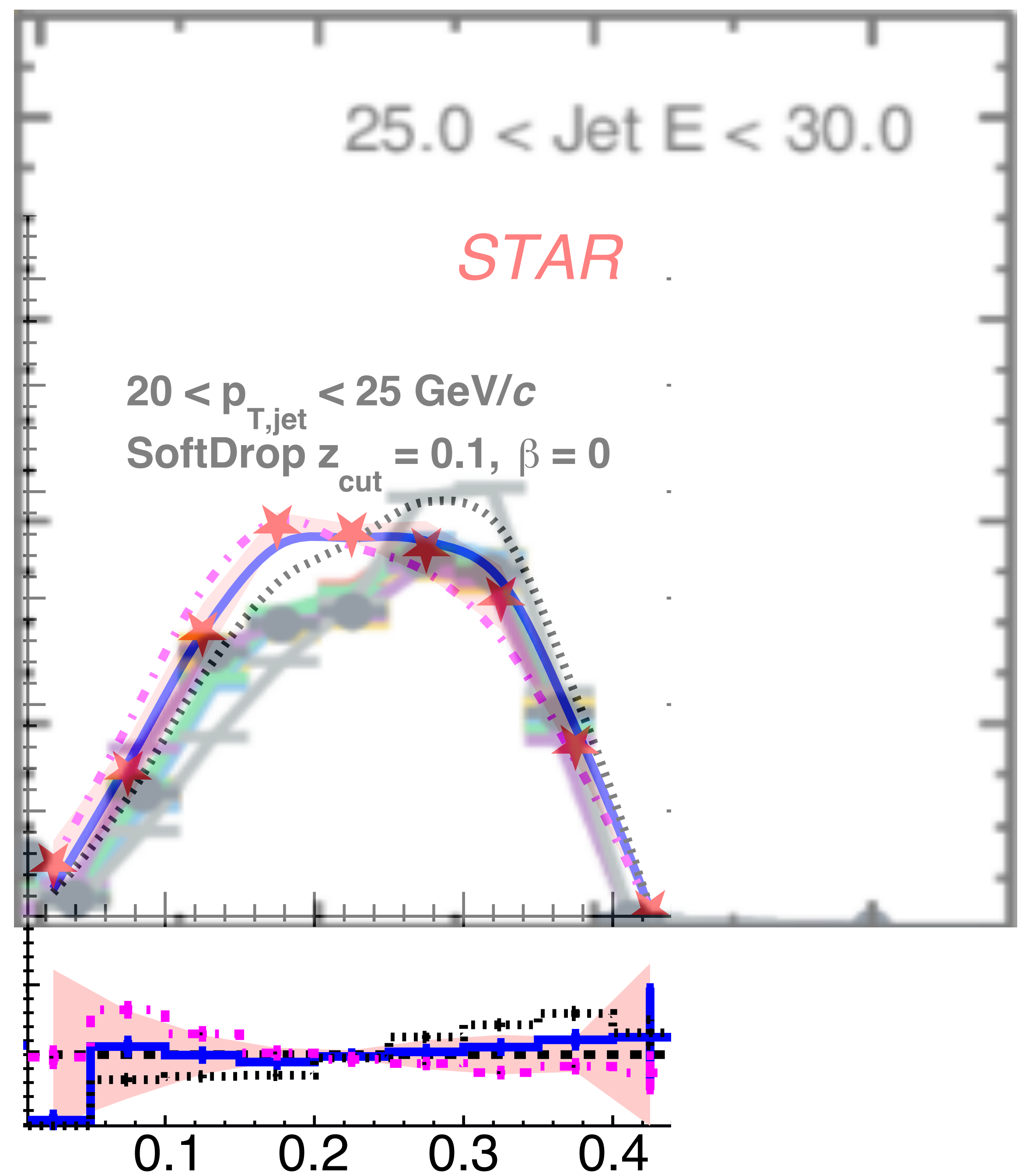


Is the comparison apples to apples?

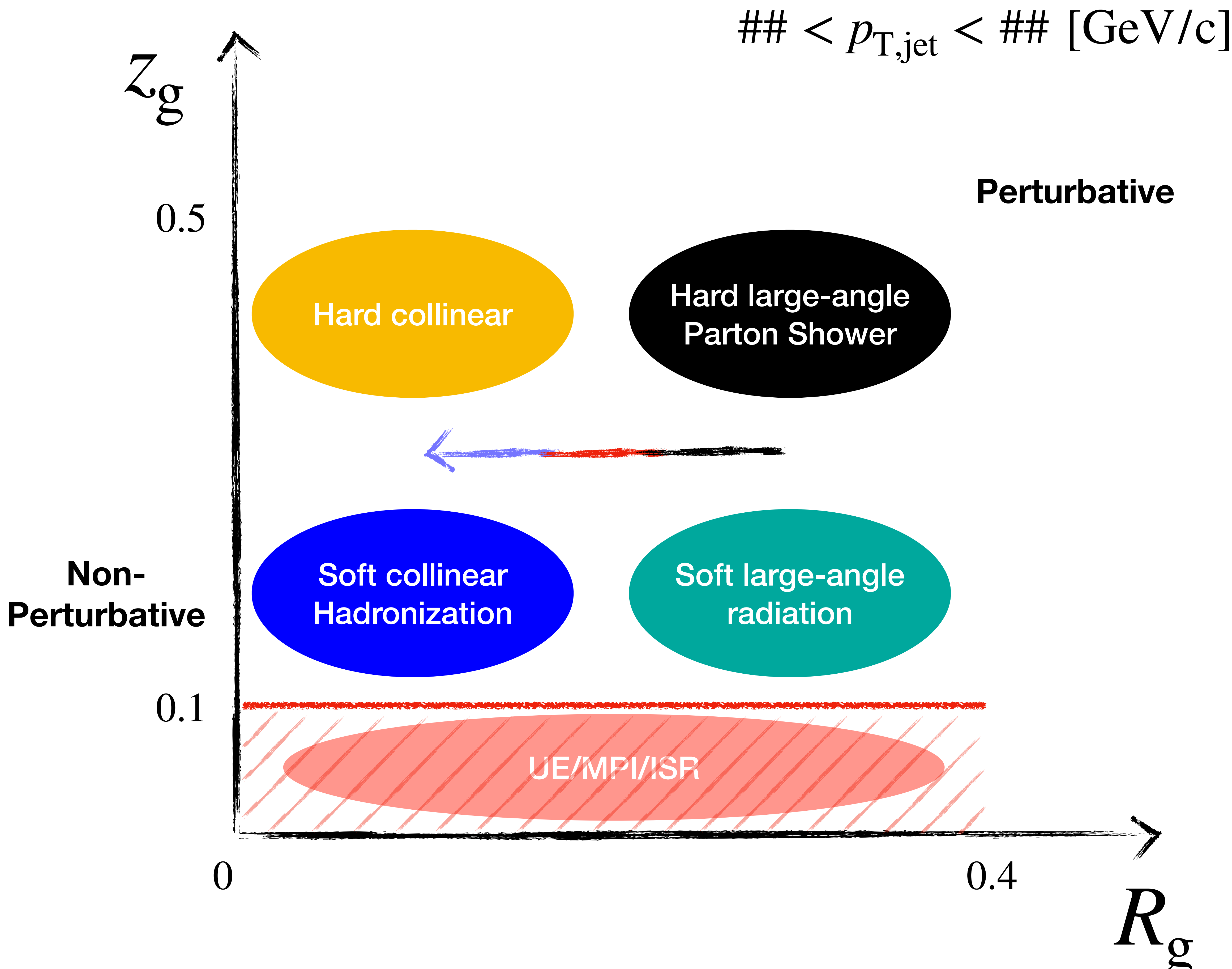
Comparing STAR vs ALEPH

- z_g is reasonable but very interesting differences in the R_g

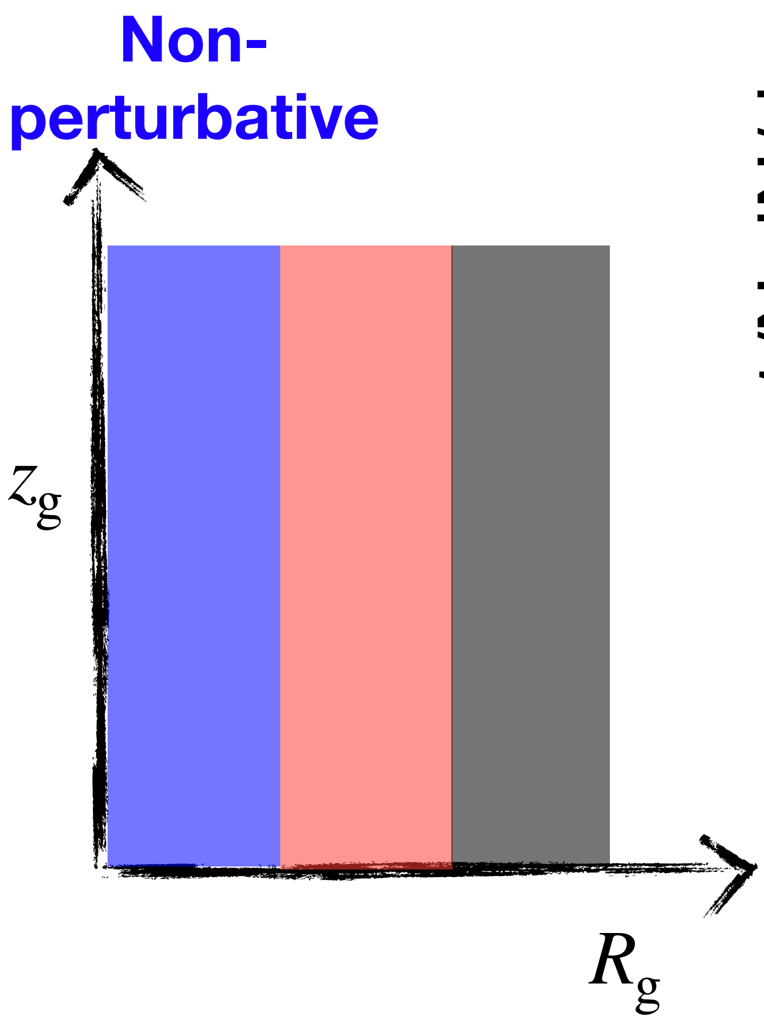




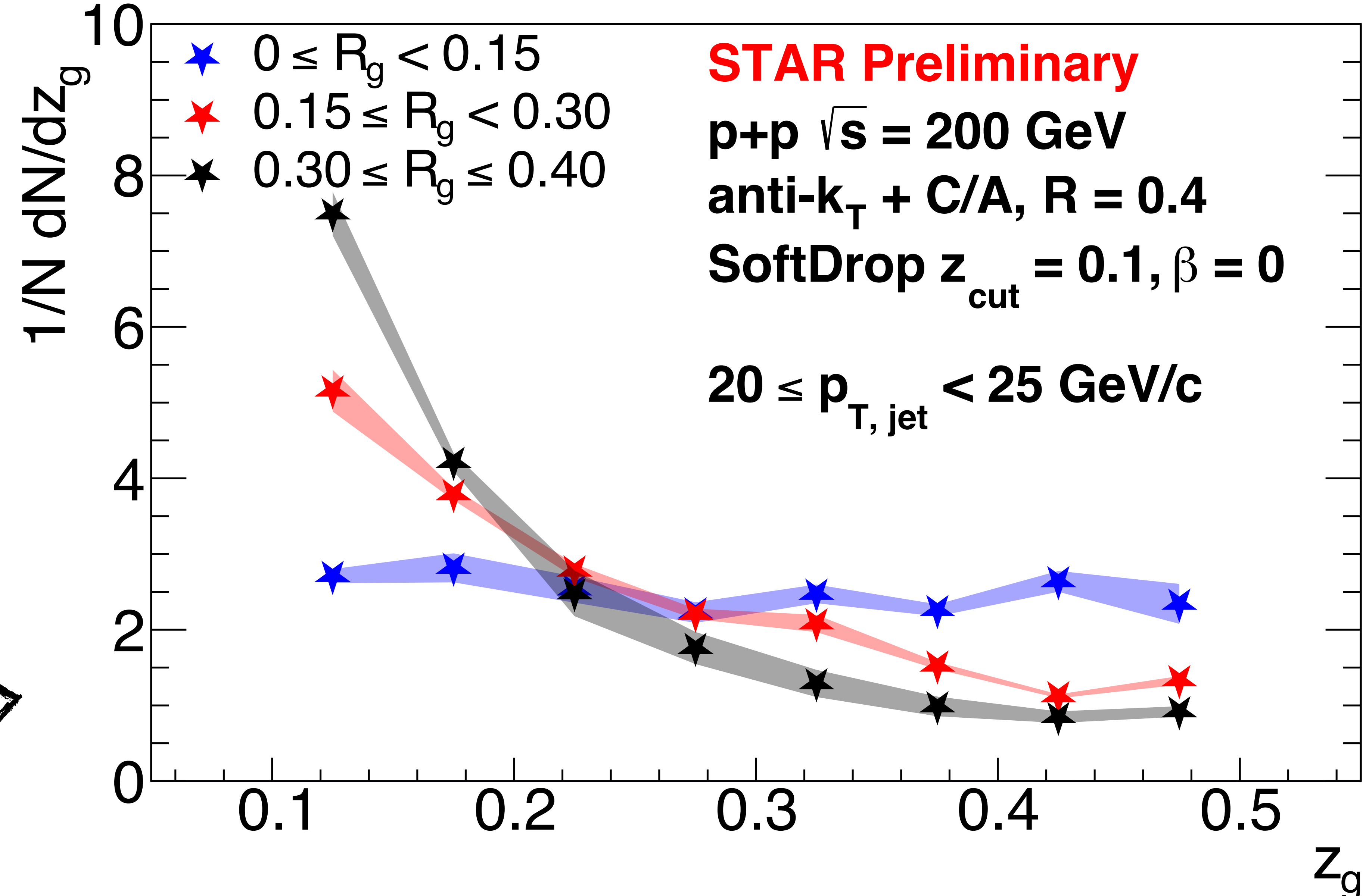
These jets in pp collisions have a $\langle M \rangle \approx 3$ GeV/c^2 plus there's hadronic component!


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

Correlation between the splitting scales



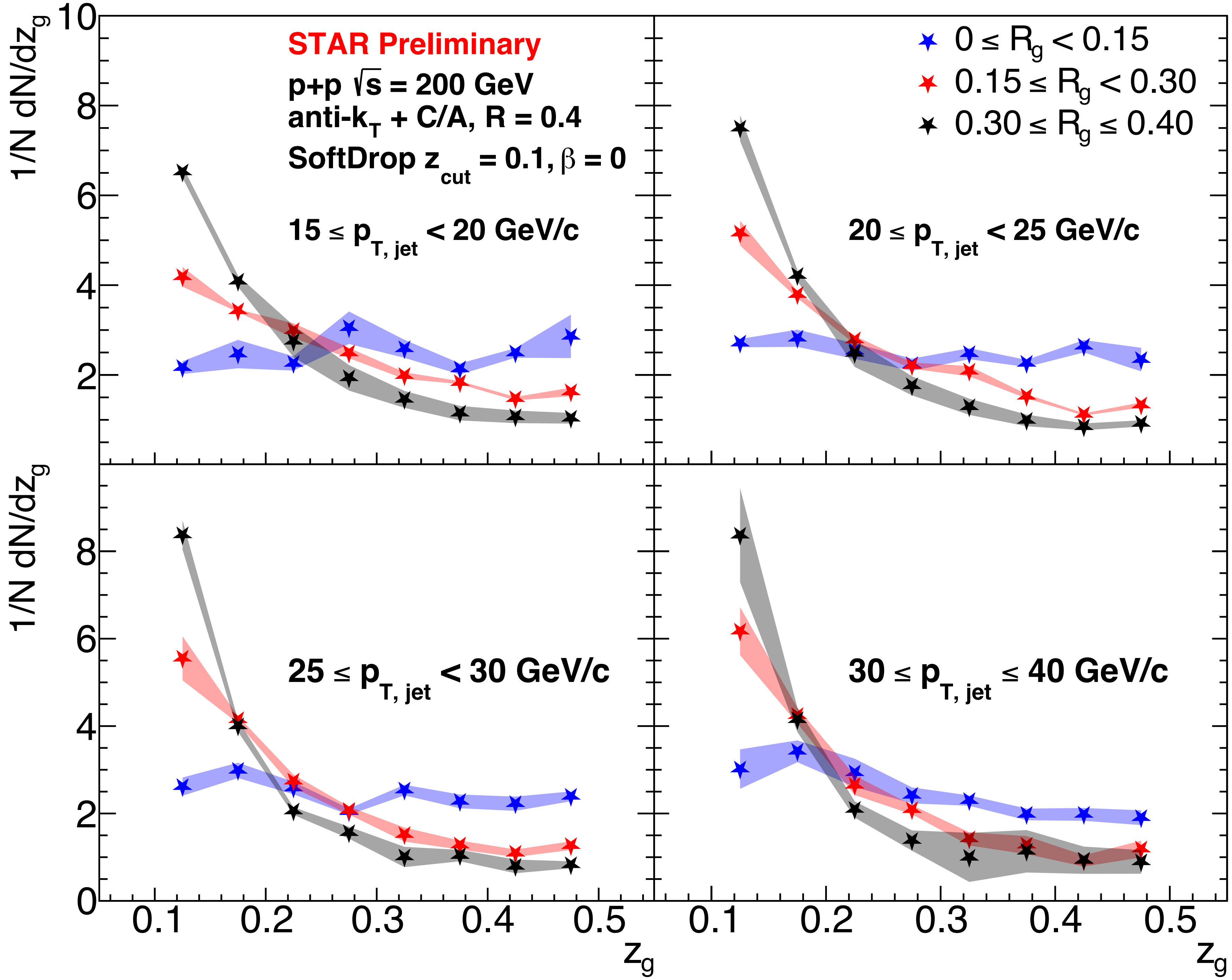
z_g **for various** R_g **at** $p_{T,jet}$ **range**



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

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

z_g **for various** R_g **and** $p_{\mathrm{T,jet}}$

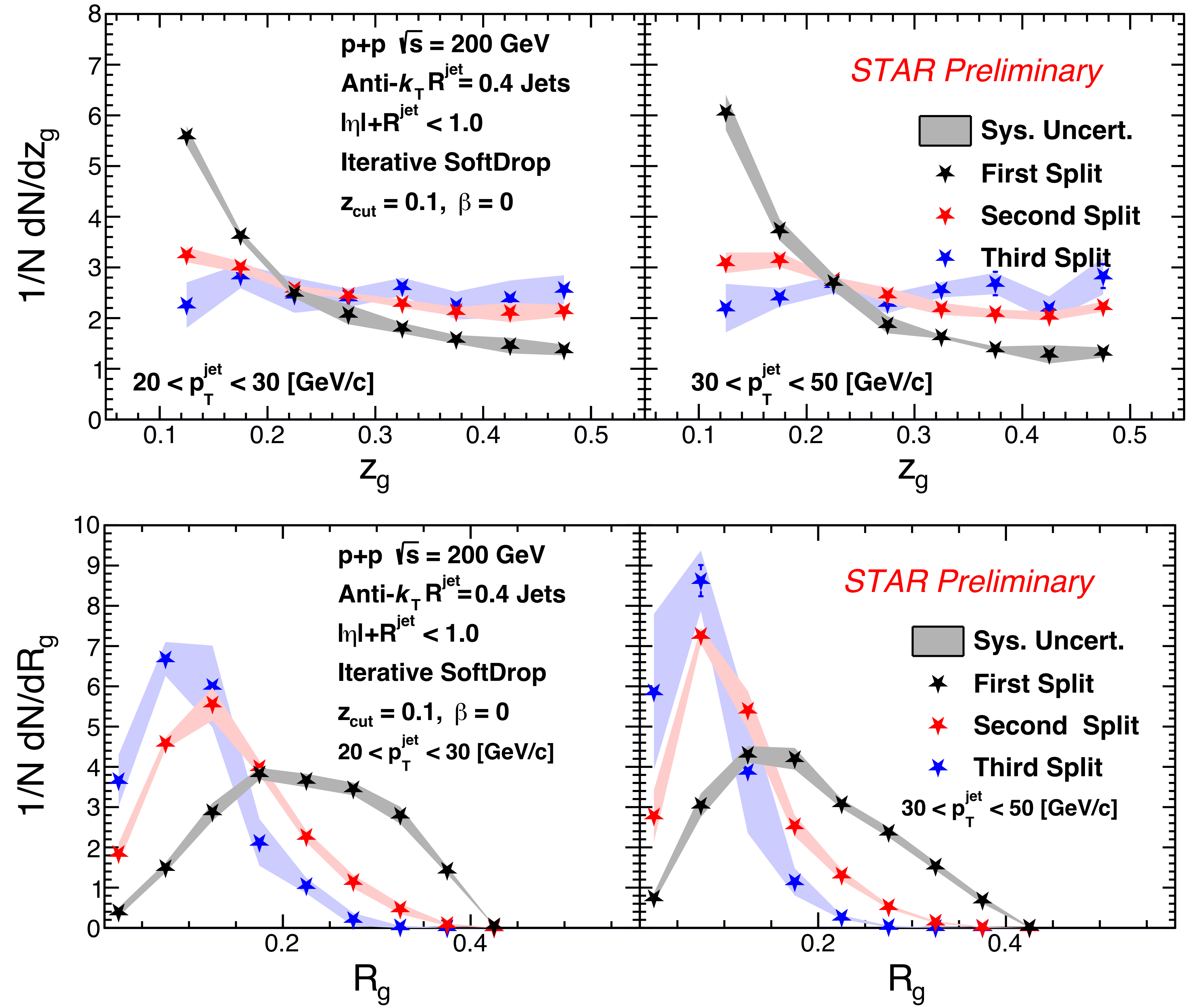


- Increasing jet p_T has a small to mild effect on substructure
- Selection on R_g determines **the z_g shape** - high degree of correlation
- **Phase space restrictions** matter!

Evolution of the splittings

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

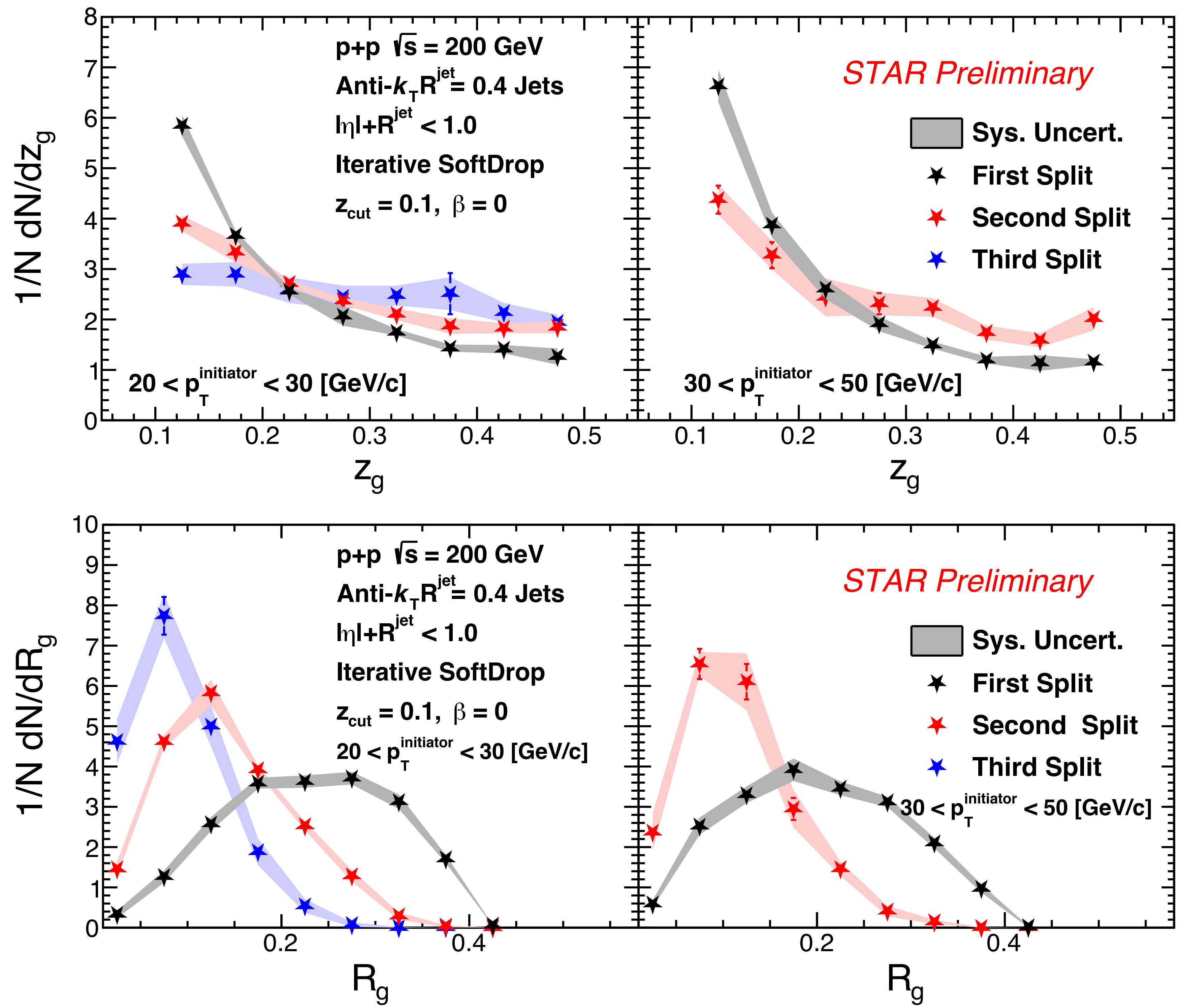
- **For a given jet $p_{\mathrm{T,jet}}$,** what are the z_g, R_g at 1st, 2nd and 3rd splits? Follow a jet…
- **Significant differences between first, second** and **third** splits
- Splitting **'z' becomes flat and the R_g quite narrow** for the third split where we observe collinear emissions



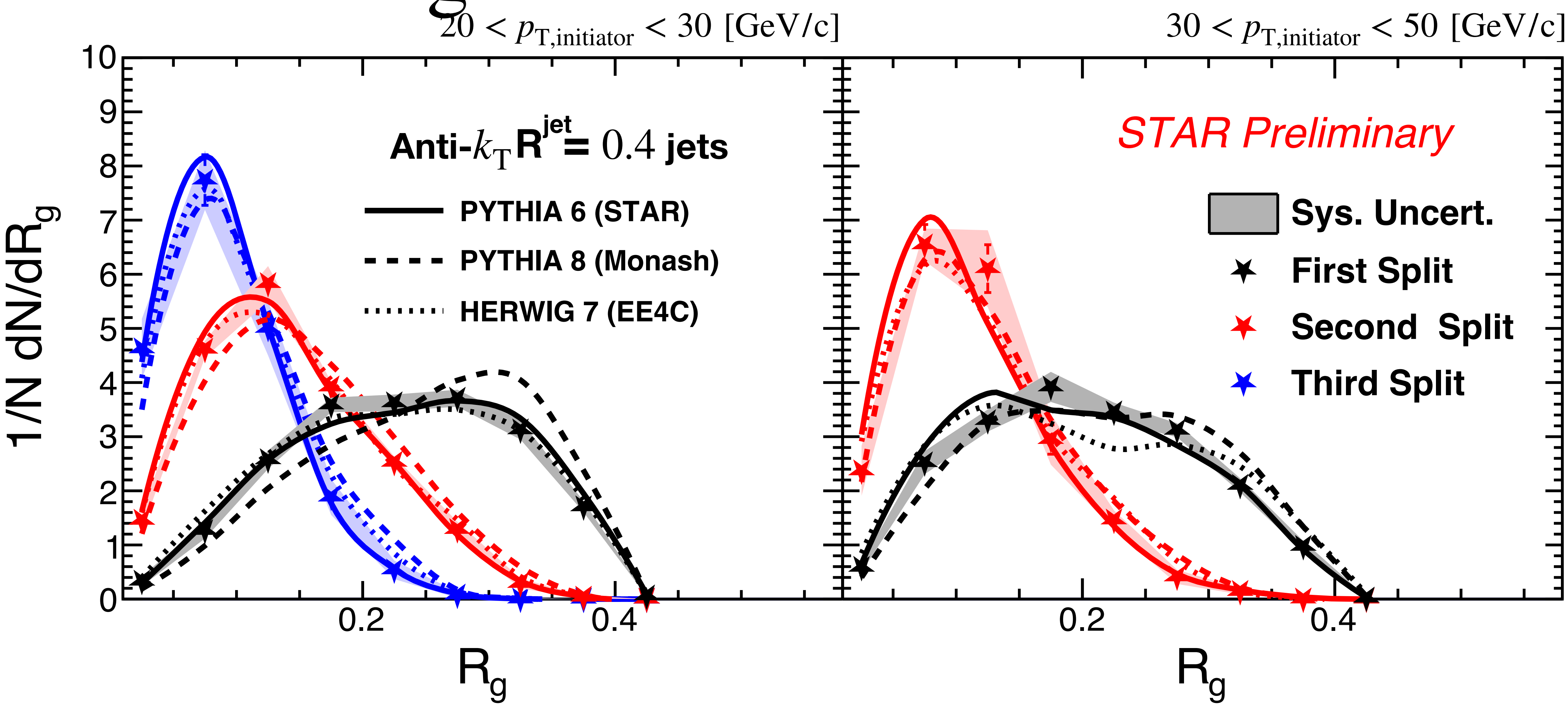
Evolution of the splittings

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

How to experimentally measure the formation time τ_f

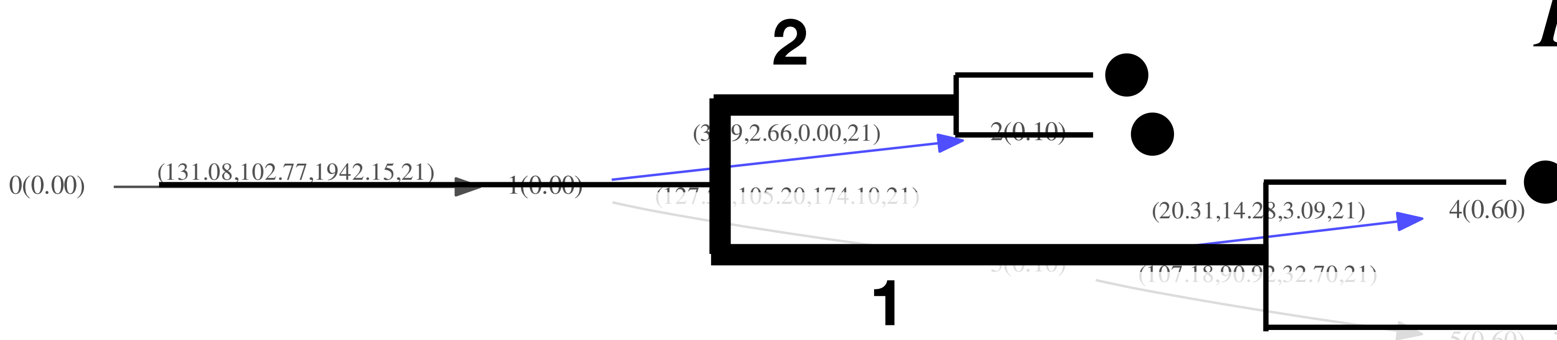
Take any two objects - in this case the first two surviving prongs after SoftDrop grooming

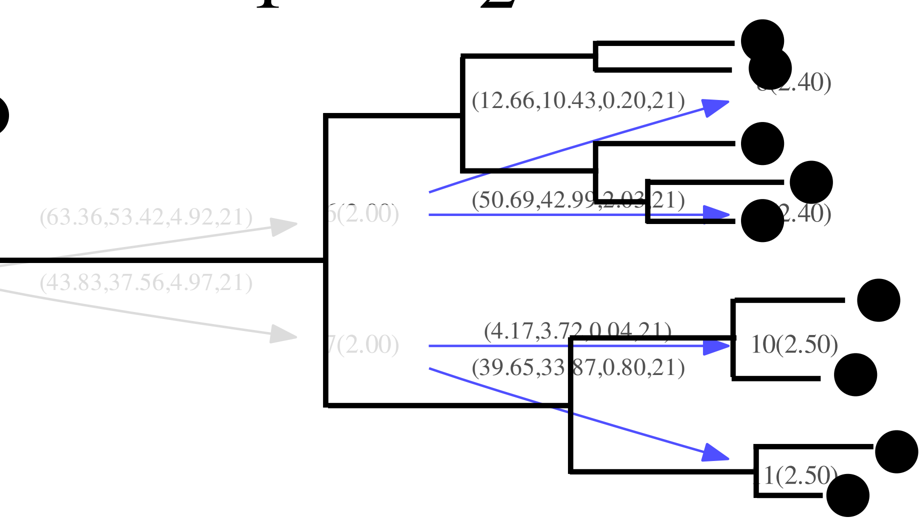
Dasgupta et al. JHEP 09 (2013) 029

Larkowski, et al. JHEP 05 (2014) 146

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

$$E = E_1 + E_2$$





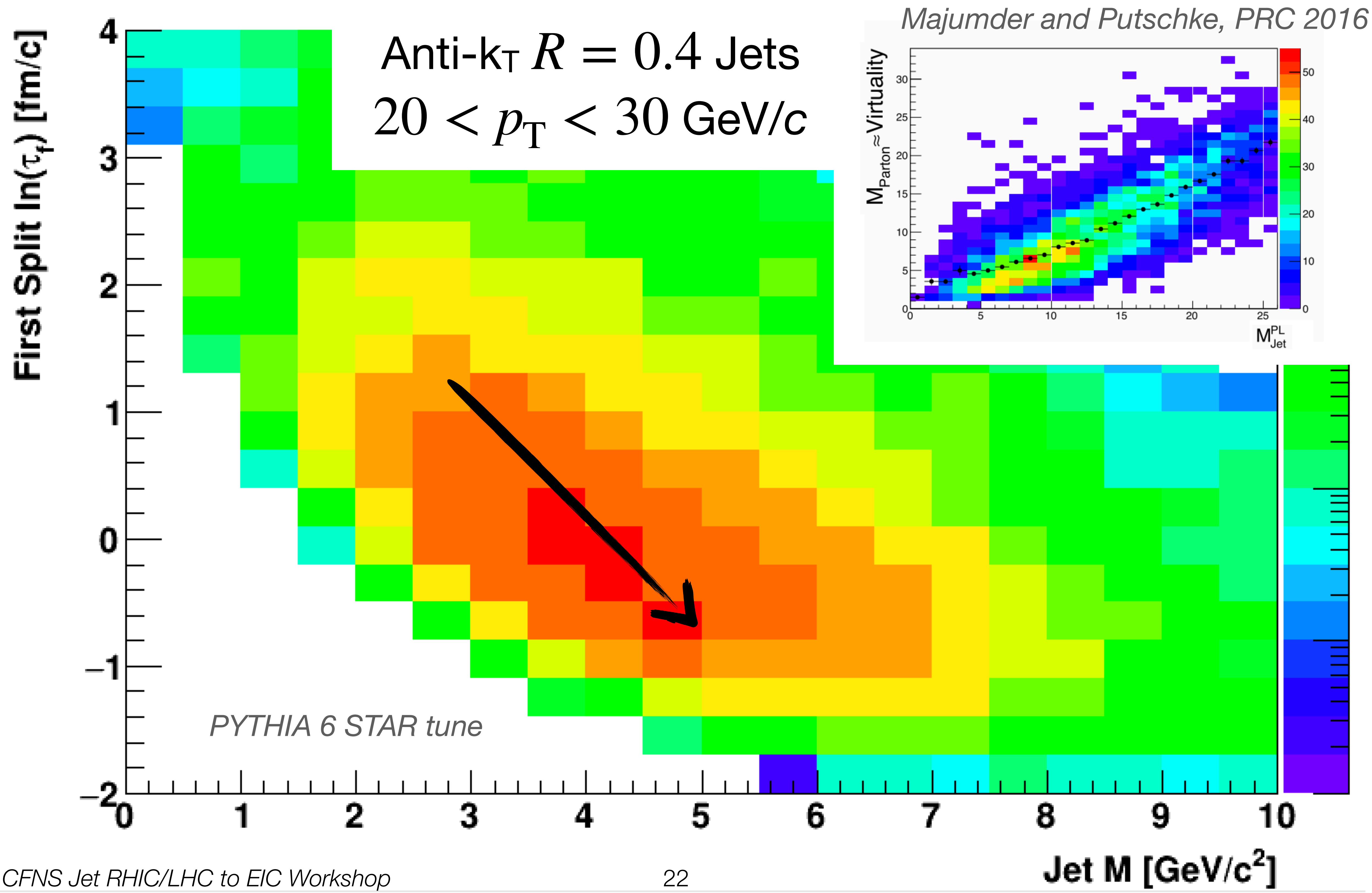
$$\tau_f = \frac{1}{z \cdot (1 - z) \cdot \theta^2 \cdot E} \quad [\mathrm{fm}/c]$$

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

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

Chien et. al. 2109.15318

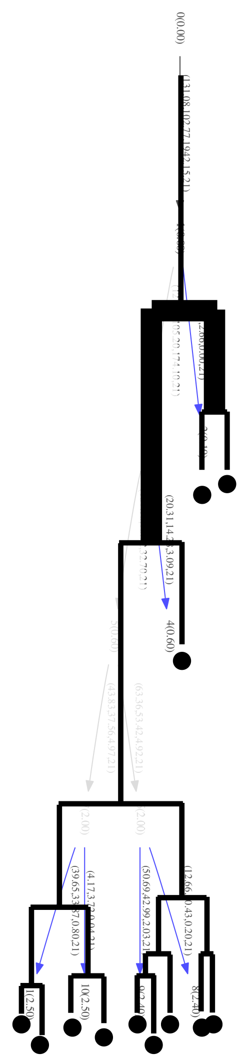
Formation time vs jet mass



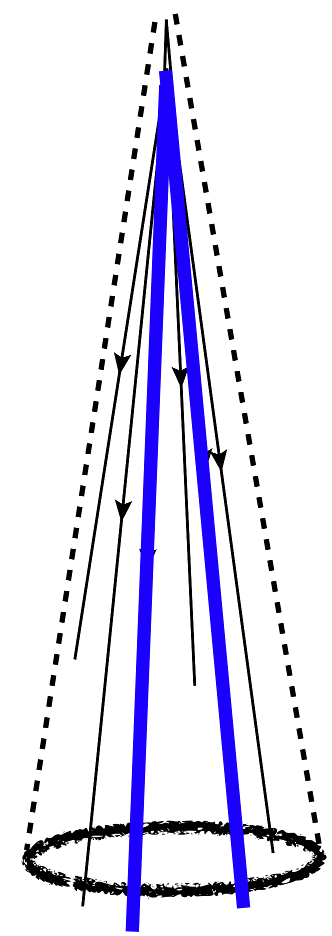
Identifying two regimes

- SoftDrop first split τ_f

Expectations:
- **happen early in time with the expectation that first splits correspond to partonic splits**
- **Mostly perturbative in nature**



- Leading and subleading ch-particle τ_f



Expectations:
- **Occur later in time since its calculated using charged particles which occur at the end**
- **Mostly non-perturbative**

STAR Phys. Lett. B 811, 135846 (2020)
STAR Phys. Rev. D 104, 052007 (2021)
Kang, Lee, Liu, Neill and Ringer, JHEP (2020)

- SoftDrop first split τ_f

Expectations:
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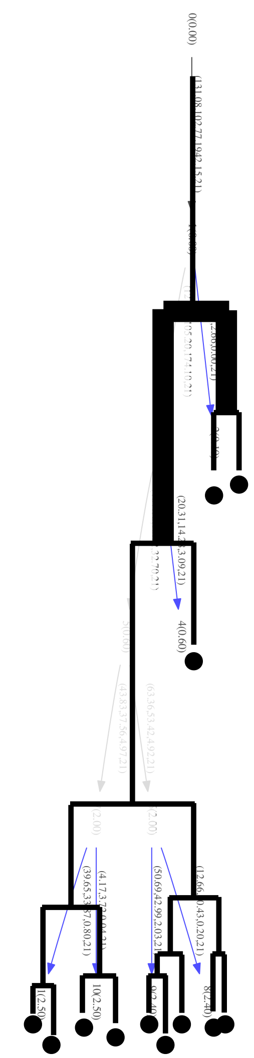
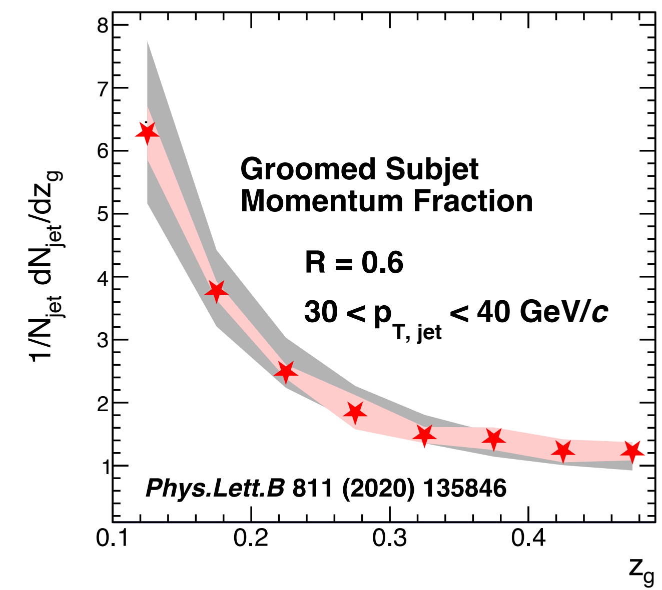
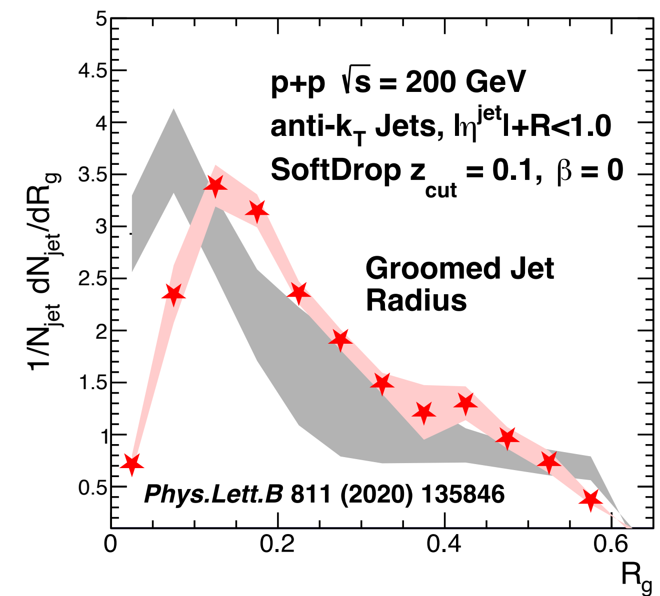
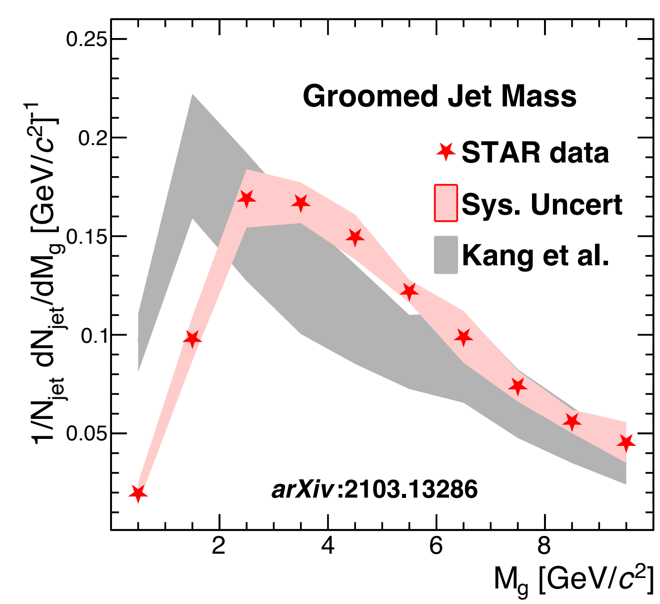


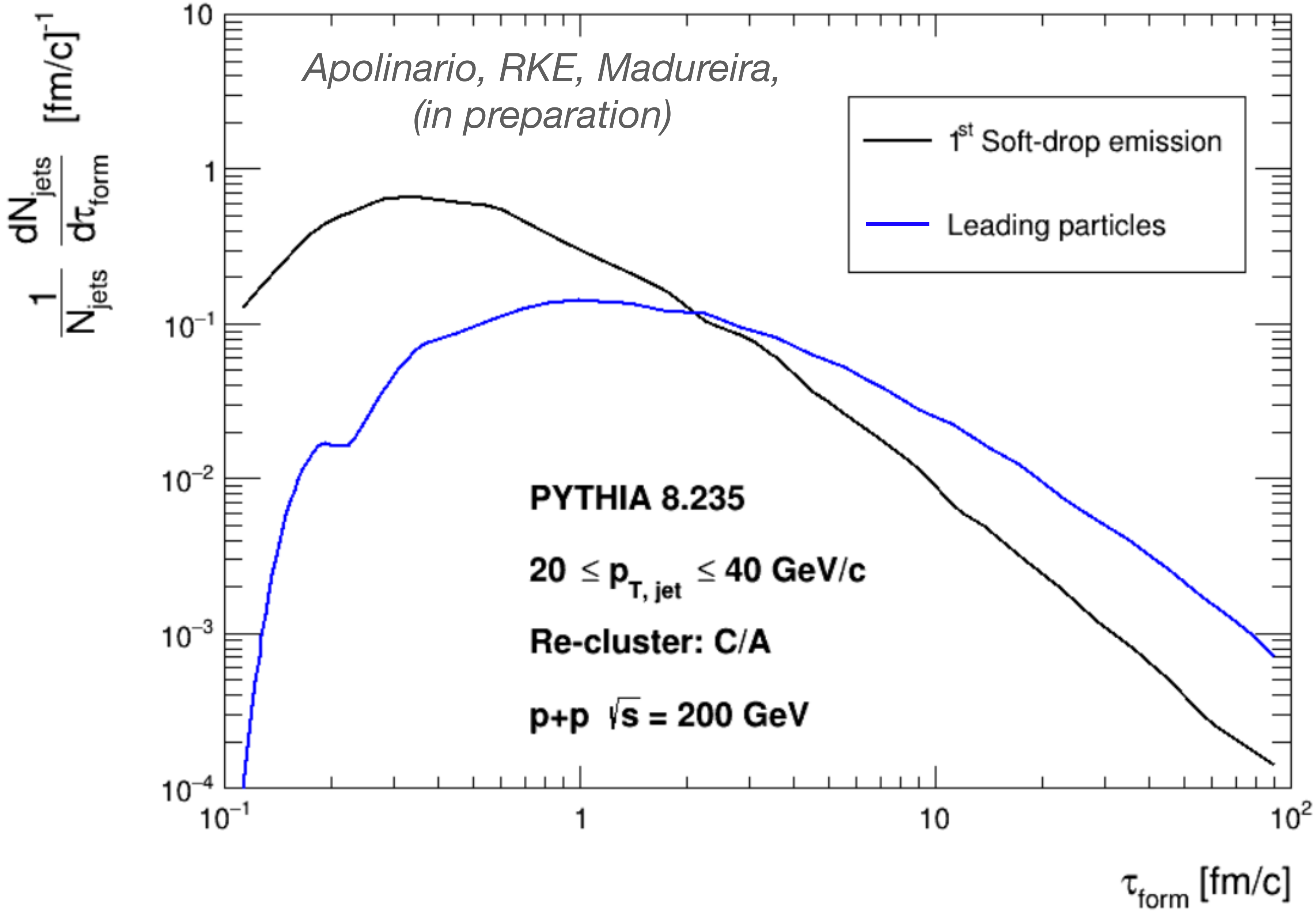




- NLL calculations (w/o non-perturbative corrections) matches data at large jet R and high p_T



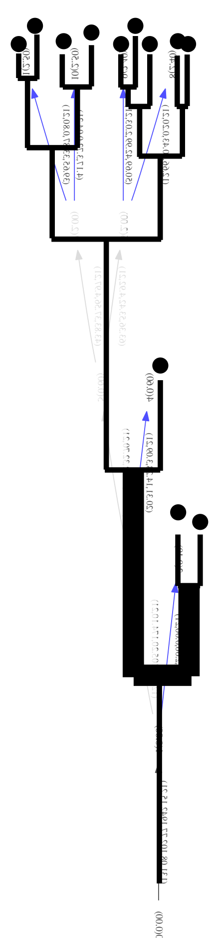
What do these distributions look like in PYTHIA?

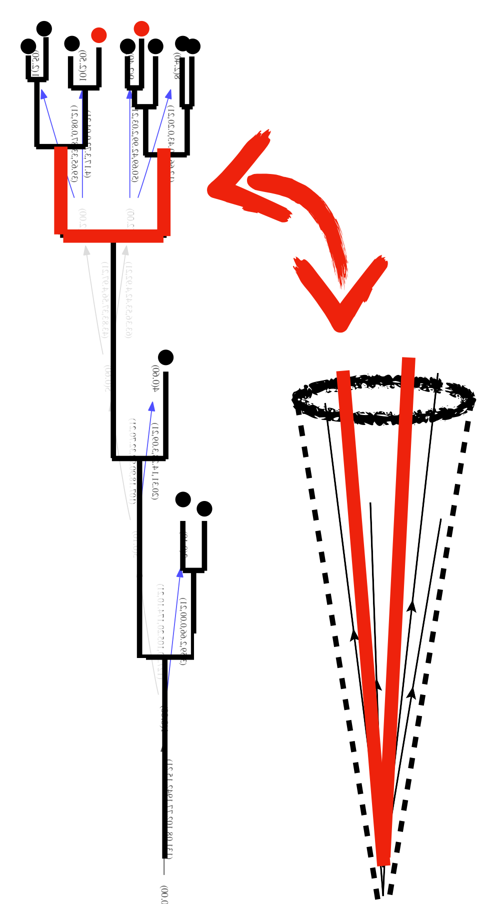


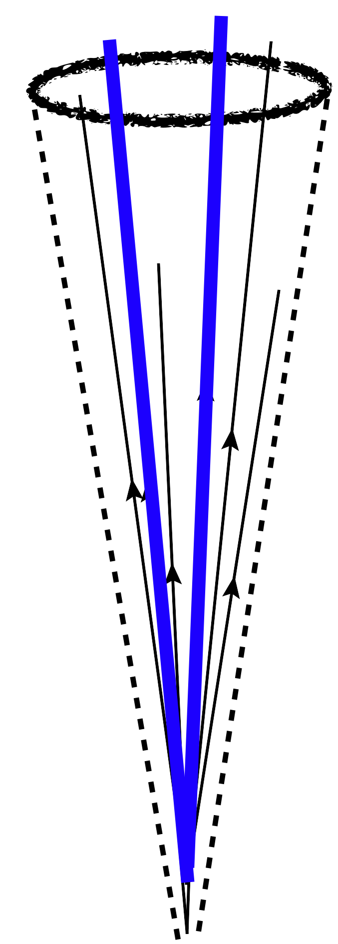
- As expected we see a significant shift between the two distributions
- Charged particles generally have a formation time much larger than the first splits

Connecting the two regimes

- SoftDrop first split τ_f
- SoftDrop split (varying $z_{\rm cut}$) resolving the two leading charged particles
- Leading and subleading ch-particle τ_f





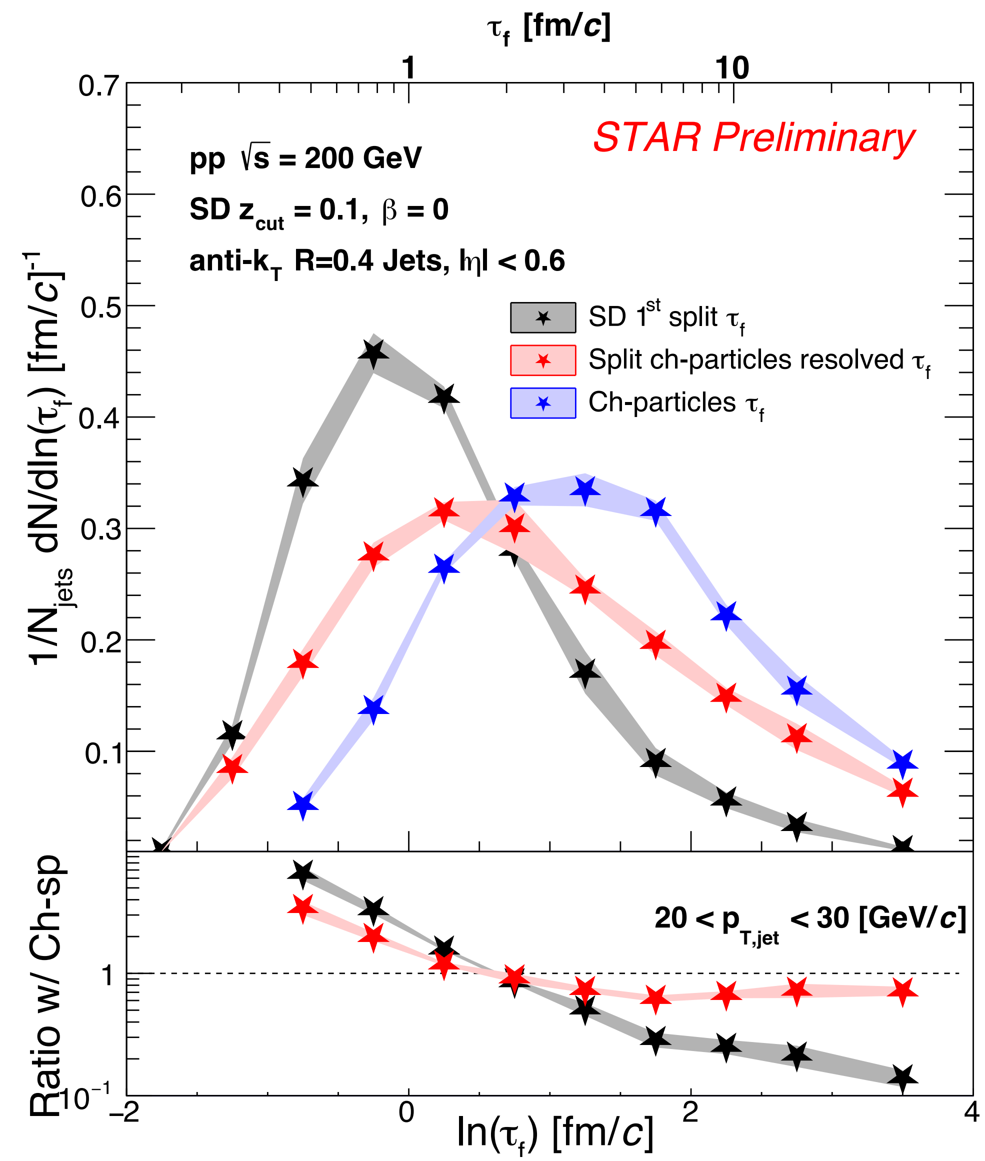


Formation times across various regimes within the jet shower

- **First measurements of formation time** from the jet splitting trees and from charged particles in the jet

- **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**



RKE (for STAR) pdf
Jets and 3D Imaging at the EIC Workshop

Jets and their substructure

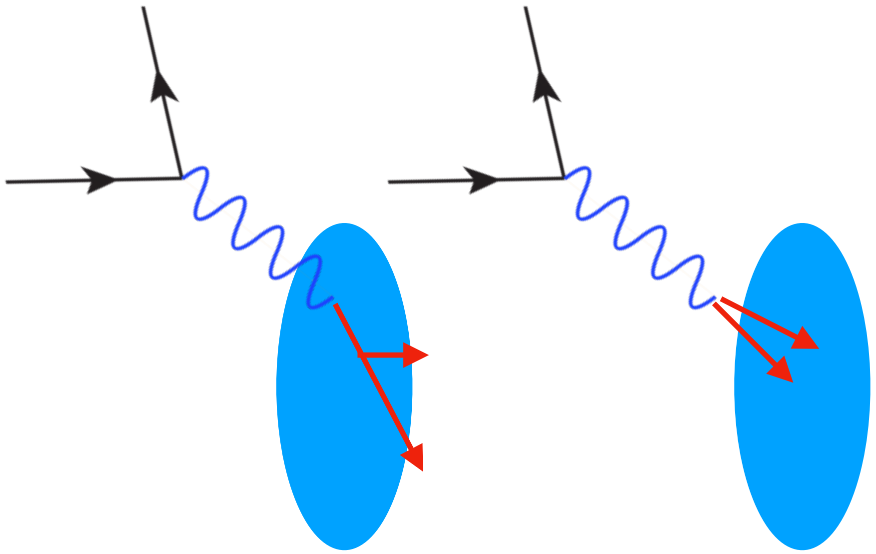
A journey from

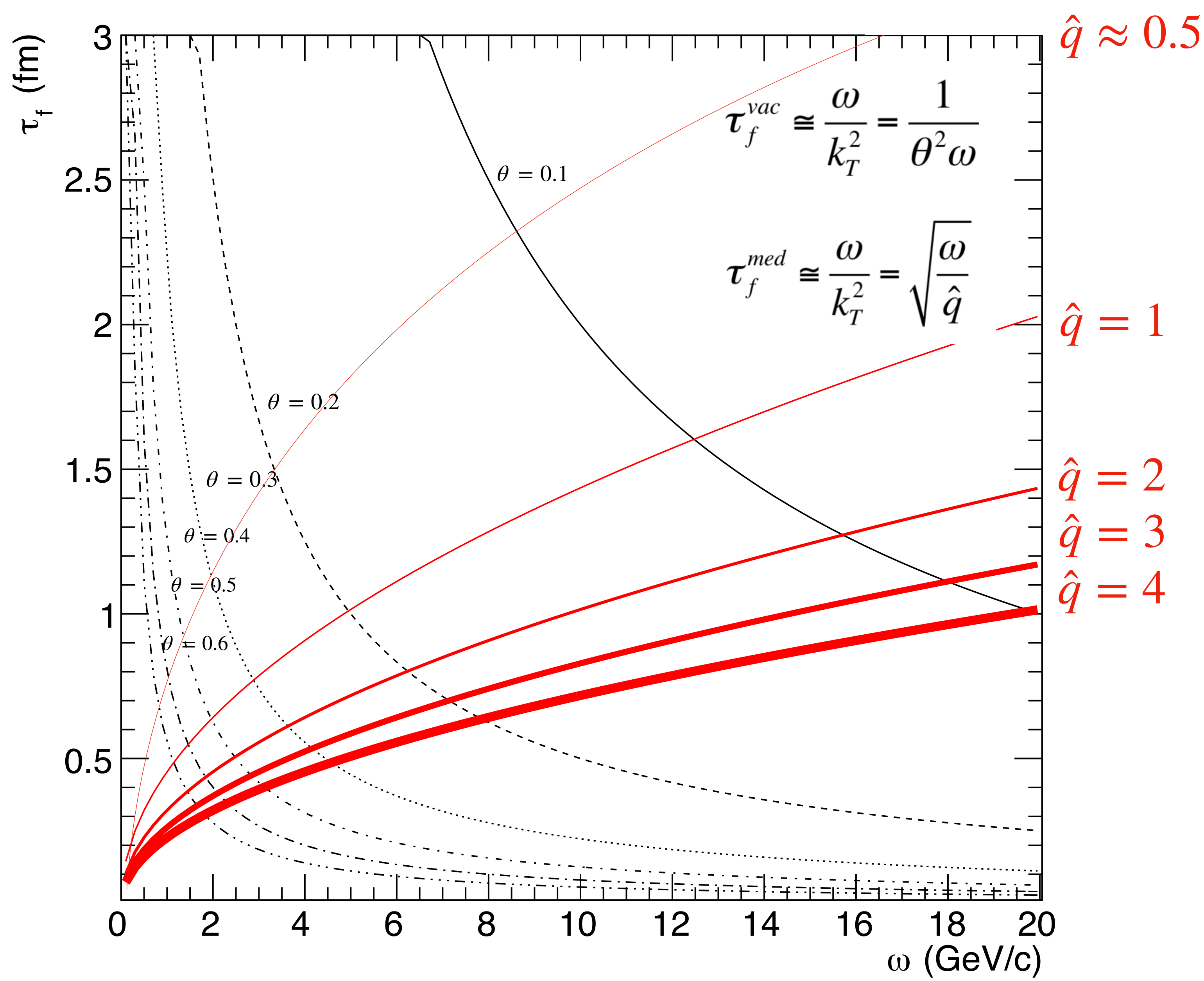
LHC → RHIC → EIC

- Unique population of jets with varied substructure!
  Scales extend from jet $p_{\mathrm{T}} \rightarrow \Lambda_{\mathrm{QCD}}$
- Splitting **‘z’ becomes flat and the R_{g} quite narrow** for the third split where we observe collinear emissions
- **Resolved SD splits** show **similar shape** as the **charged particle split** at large τ_f values occurring in the predominantly **non-perturbative region**

Measuring the parton shower

Studies of CNM and initial state vs resolution scale and τ_f



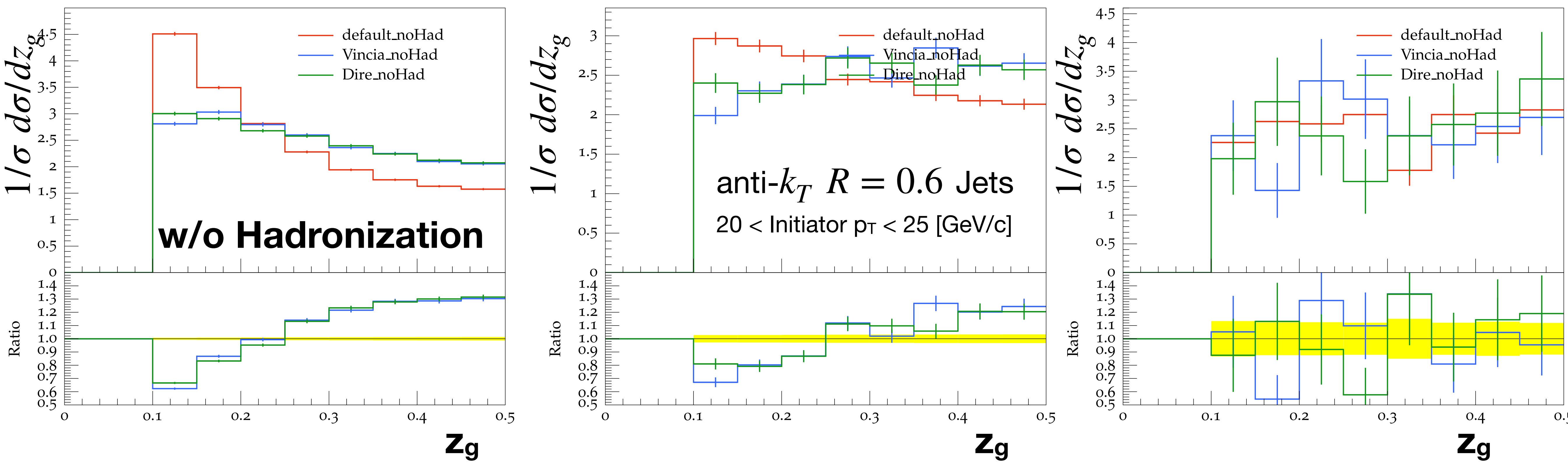


- With splitting/dijet energies roughly 5-30 GeV, we can study resolutions O(1-5) fm!
- Enabling differential measurements of similar kinematics but varying shower topology!

Effect of Parton Showers

PYTHIA 8.301

First Split **Second Split** **Third Split**



- At parton level, variations between shower models
- z_g shape becomes flatter as we move along the shower

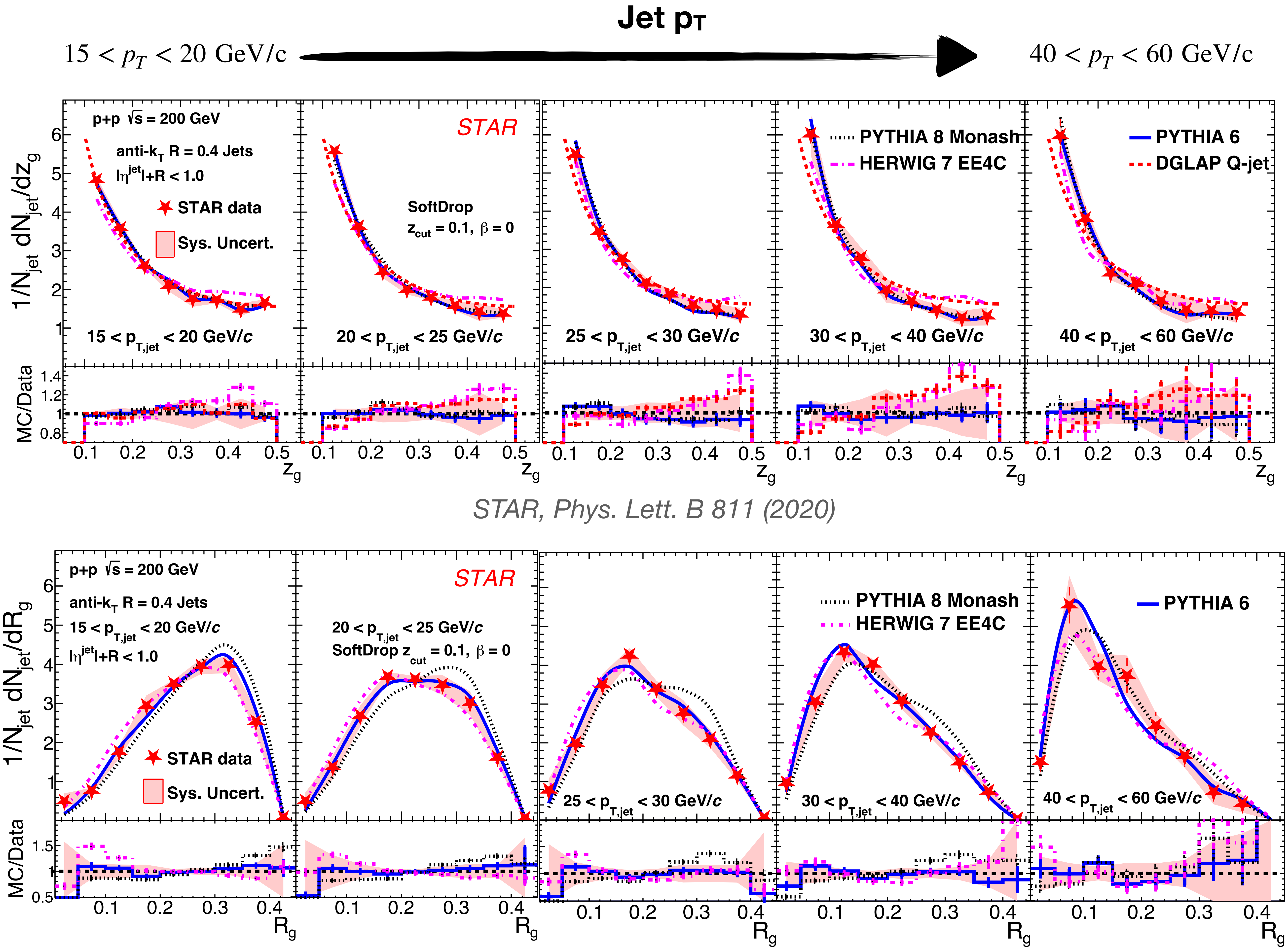
Jets and their substructure

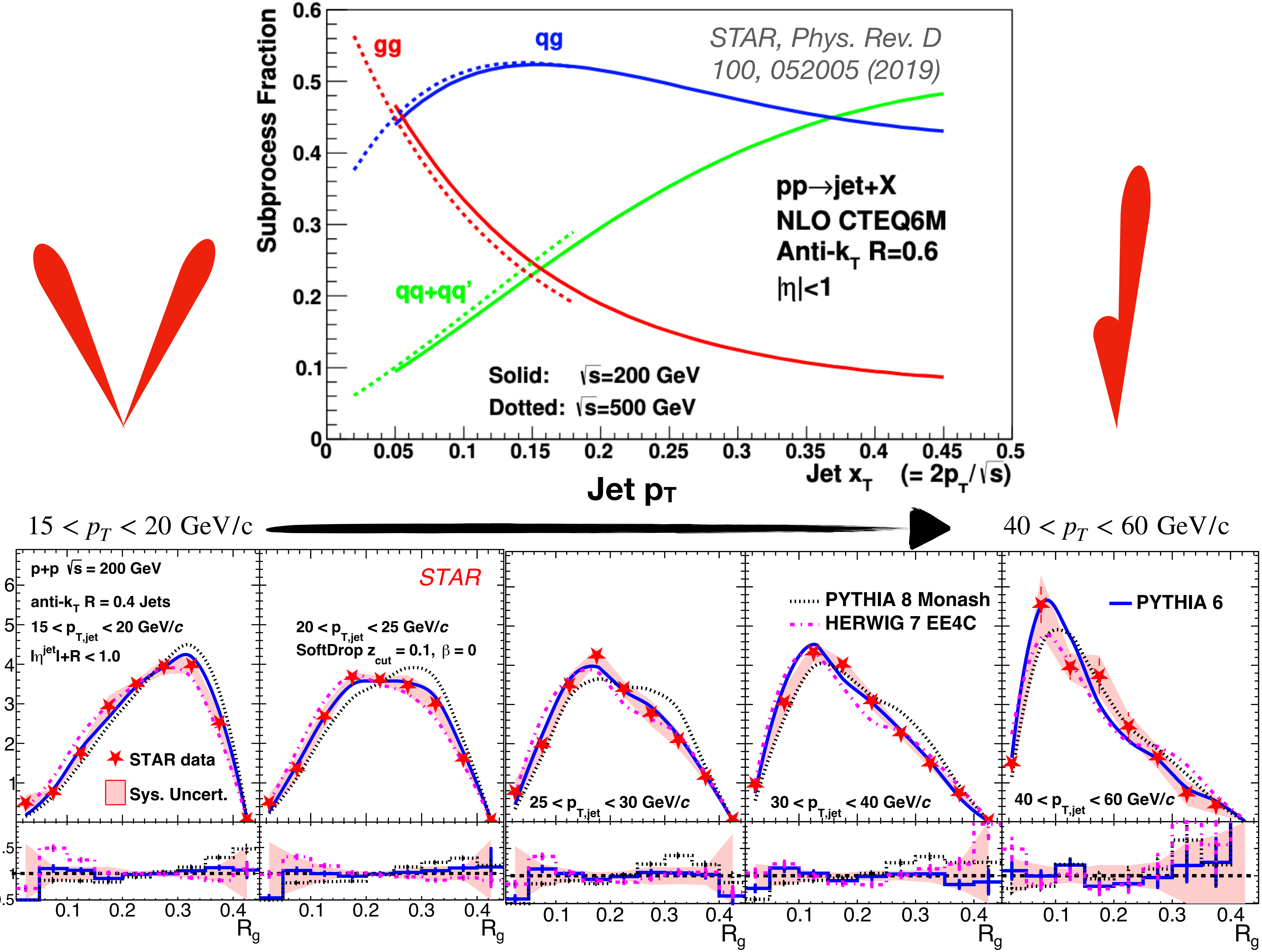
A journey from

LHC → RHIC → EIC

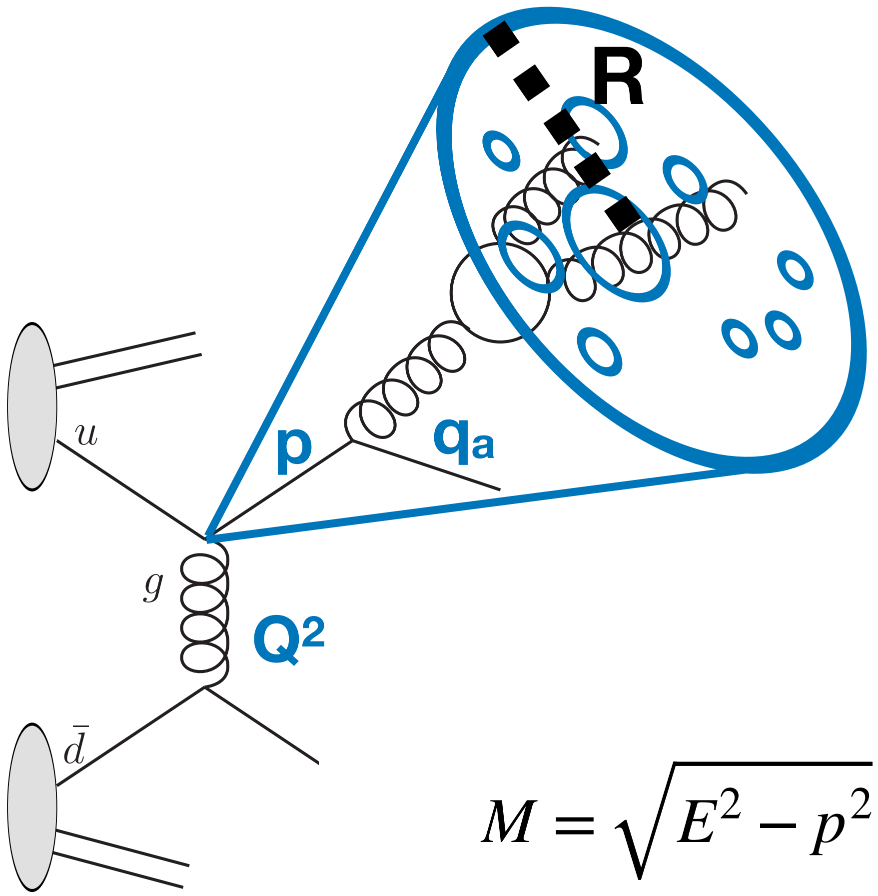
- Ongoing quantifications of novel substructure techniques to map the jet evolution
- EIC will provide a cleaner environment and energy scale selection (re: STAR vs ALEPH) leading to precision mapping of the emission phase-space
- Lead to discovery physics about non-perturbative effects and hadronization within jets

Backup

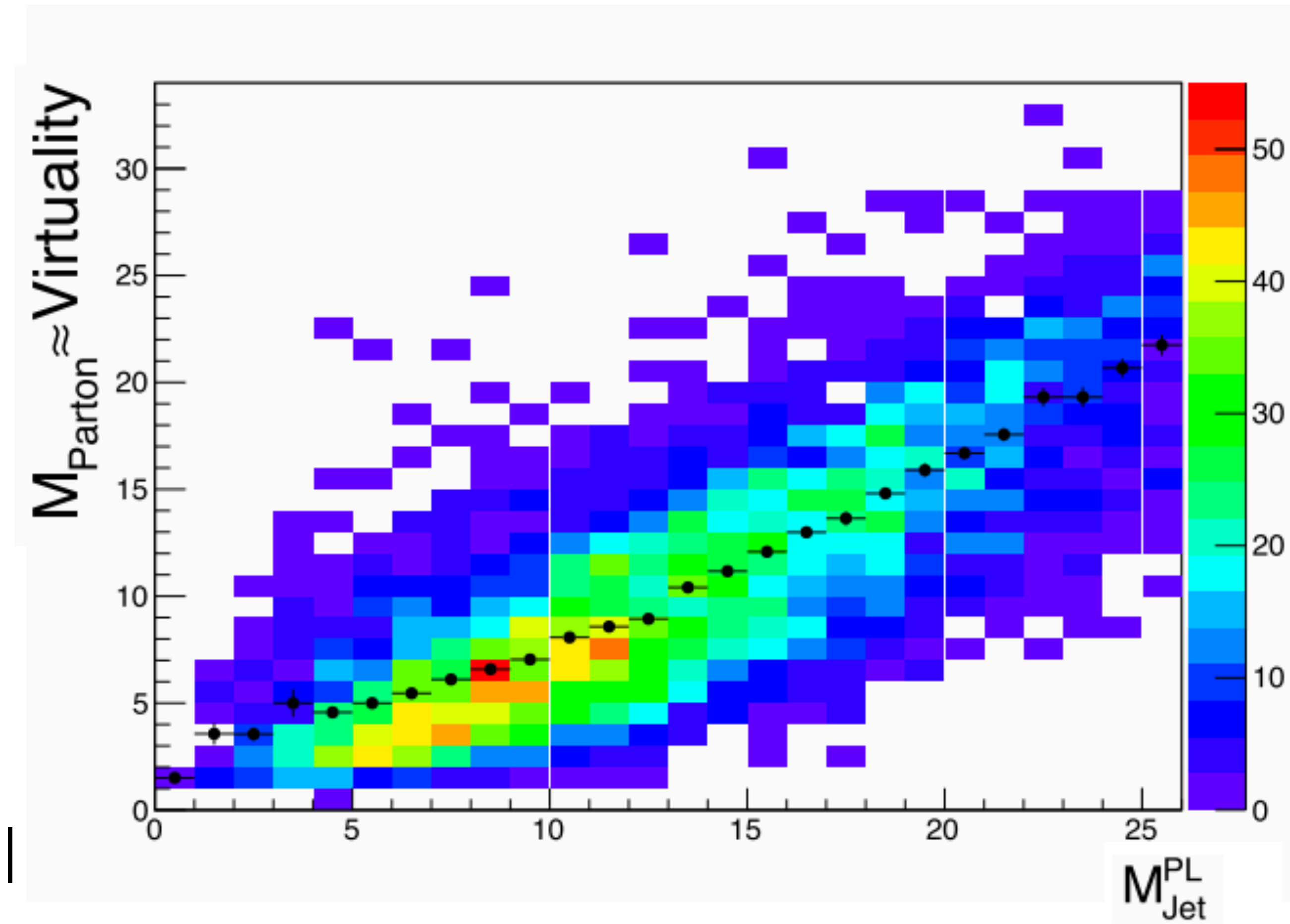

Jet p_T
$15 < p_T < 20$ GeV/c
$40 < p_T < 60$ GeV/c
p+p $\sqrt{s}$ = 200 GeV
anti-k_T R = 0.4 Jets
$|\eta^{jet}|$+R < 1.0
STAR data
Sys. Uncert.
STAR
SoftDrop
z_{cut} = 0.1, β = 0
PYTHIA 8 Monash
HERWIG 7 EE4C
PYTHIA 6
DGLAP Q-jet
$1/N_{jet}\ dN_{jet}/dz_g$
$15 < p_{T,jet} < 20$ GeV/c
$20 < p_{T,jet} < 25$ GeV/c
$25 < p_{T,jet} < 30$ GeV/c
$30 < p_{T,jet} < 40$ GeV/c
$40 < p_{T,jet} < 60$ GeV/c
MC/Data
z_g
STAR, Phys. Lett. B 811 (2020)
$1/N_{jet}\ dN_{jet}/dR_g$
SoftDrop z_{cut} = 0.1, β = 0
R_g


Subprocess Fraction
gg
qg
qq+qq'
STAR, Phys. Rev. D 100, 052005 (2019)
pp→jet+X
NLO CTEQ6M
Anti-k$_T$ R=0.6
|η|<1
Solid: √s=200 GeV
Dotted: √s=500 GeV
Jet x$_T$ (= 2p$_T$/√s)
Jet p$_T$
15 < p_T < 20 GeV/c
40 < p_T < 60 GeV/c
p+p √s = 200 GeV
anti-k$_T$ R = 0.4 Jets
15 < p$_{T,jet}$ < 20 GeV/c
|η^{jet}|+R < 1.0
STAR data
Sys. Uncert.
STAR
20 < p$_{T,jet}$ < 25 GeV/c
SoftDrop z$_{cut}$ = 0.1, β = 0
25 < p$_{T,jet}$ < 30 GeV/c
PYTHIA 8 Monash
HERWIG 7 EE4C
30 < p$_{T,jet}$ < 40 GeV/c
PYTHIA 6
40 < p$_{T,jet}$ < 60 GeV/c
1/N$_{jet}$ dN$_{jet}$/dR$_g$
MC/Data
R$_g$

Jet Mass



$$M = \sqrt{E^2 - p^2} = |\mathbf{p}|$$

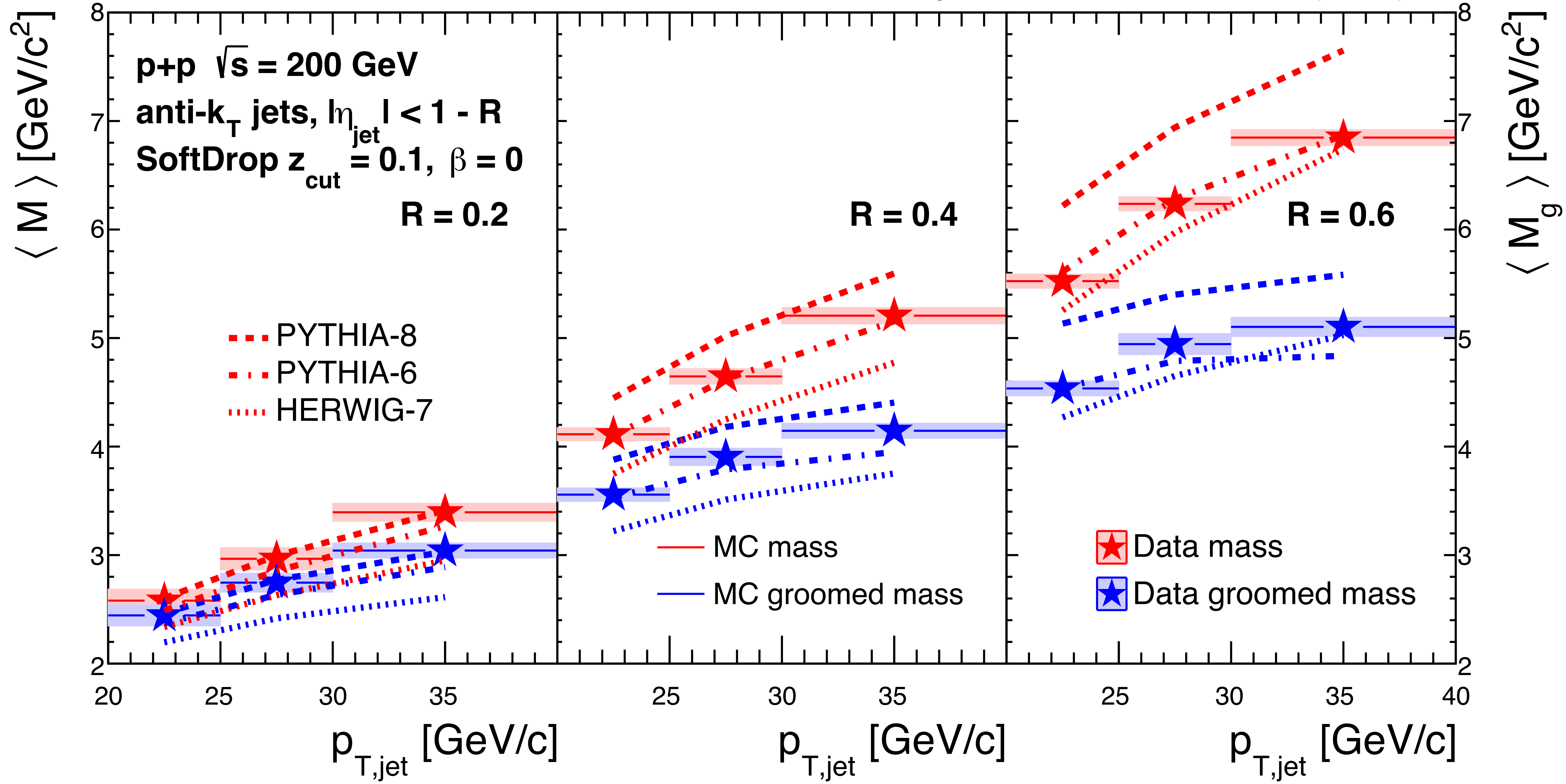


[no hadronization here - would smear correlation]

- Part of a broader class of angularity observables *Kang, Lee and Ringer, JHEP 2018*
- Sensitive to partonic dynamics i.e. virtuality *Majumder and Putschke, PRC 2016*
- Governs essentially the energy spread within a jet - ability to study differential properties of jets *ATLAS-CONF-2018-014 ALICE, PLB 2018 CMS, JHEP 2018*

Evolution of jet mass

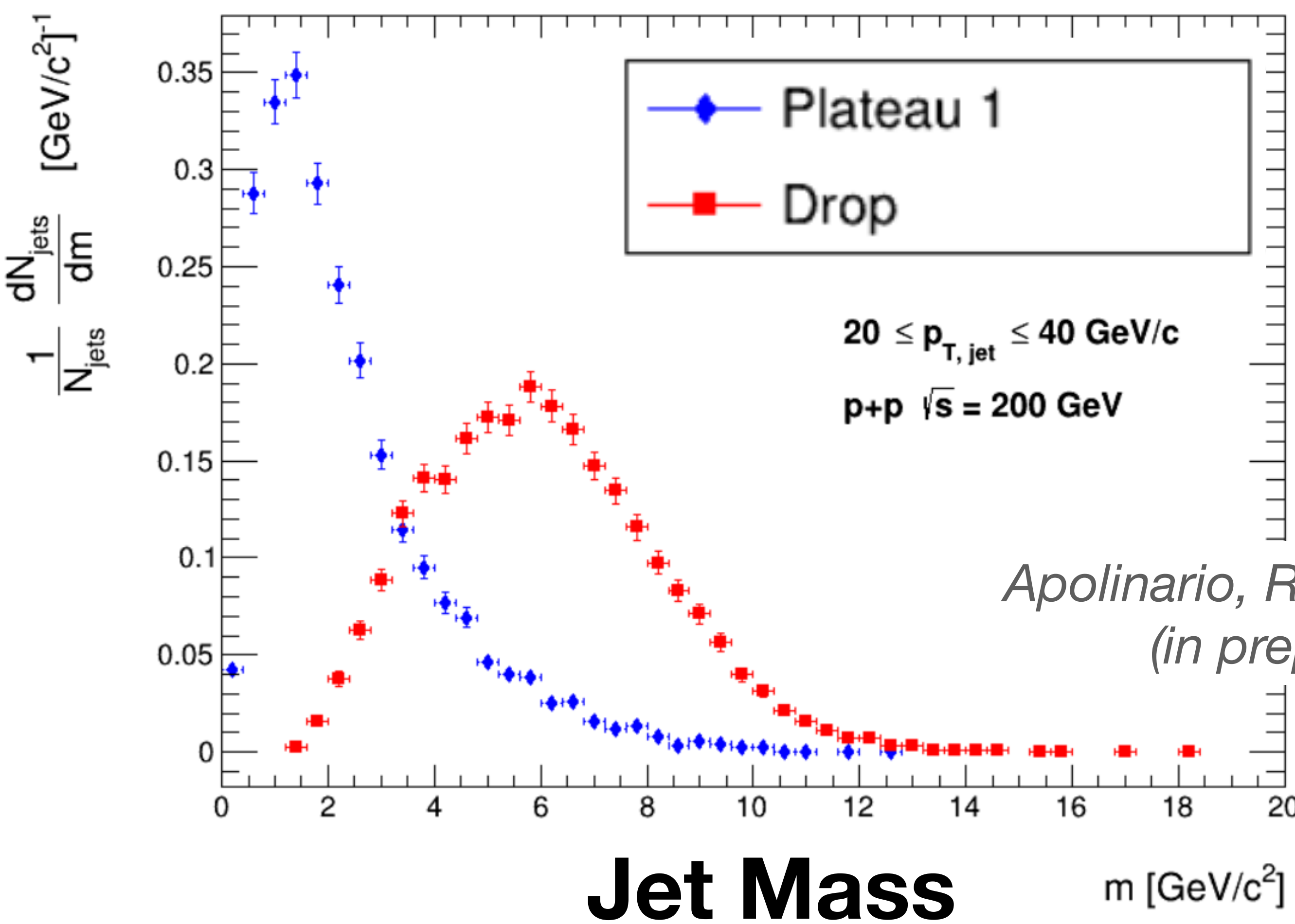
STAR Phys. Rev. D 104, 052007 (2021)

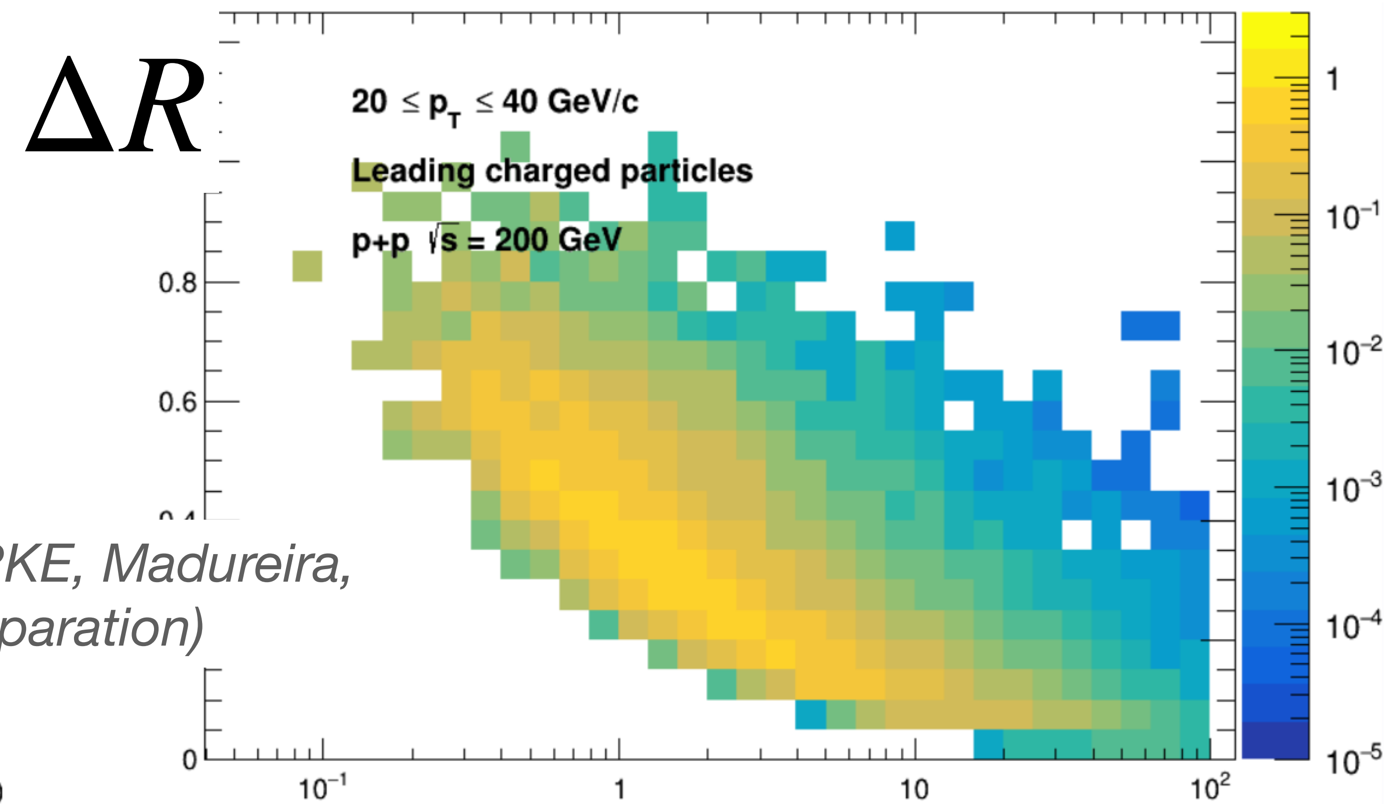


Significant reduction in the groomed jet mass due to removal of non-perturbative contributions around the jet periphery

Where do we go from here?

Studying the plateau





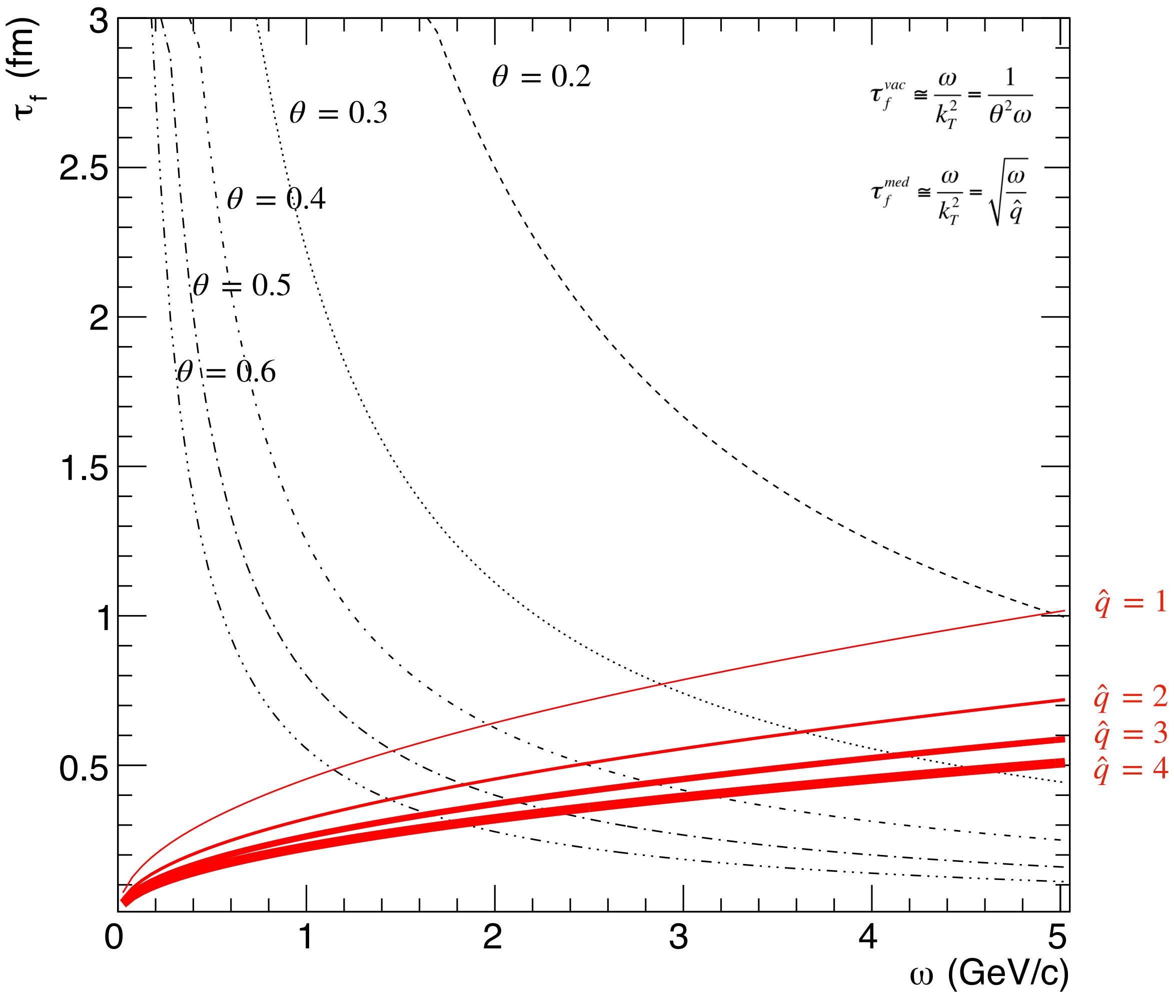
Apolinario, RKE, Madureira,
(in preparation)

Jet Mass **Charged Particle τ_f fm/c**

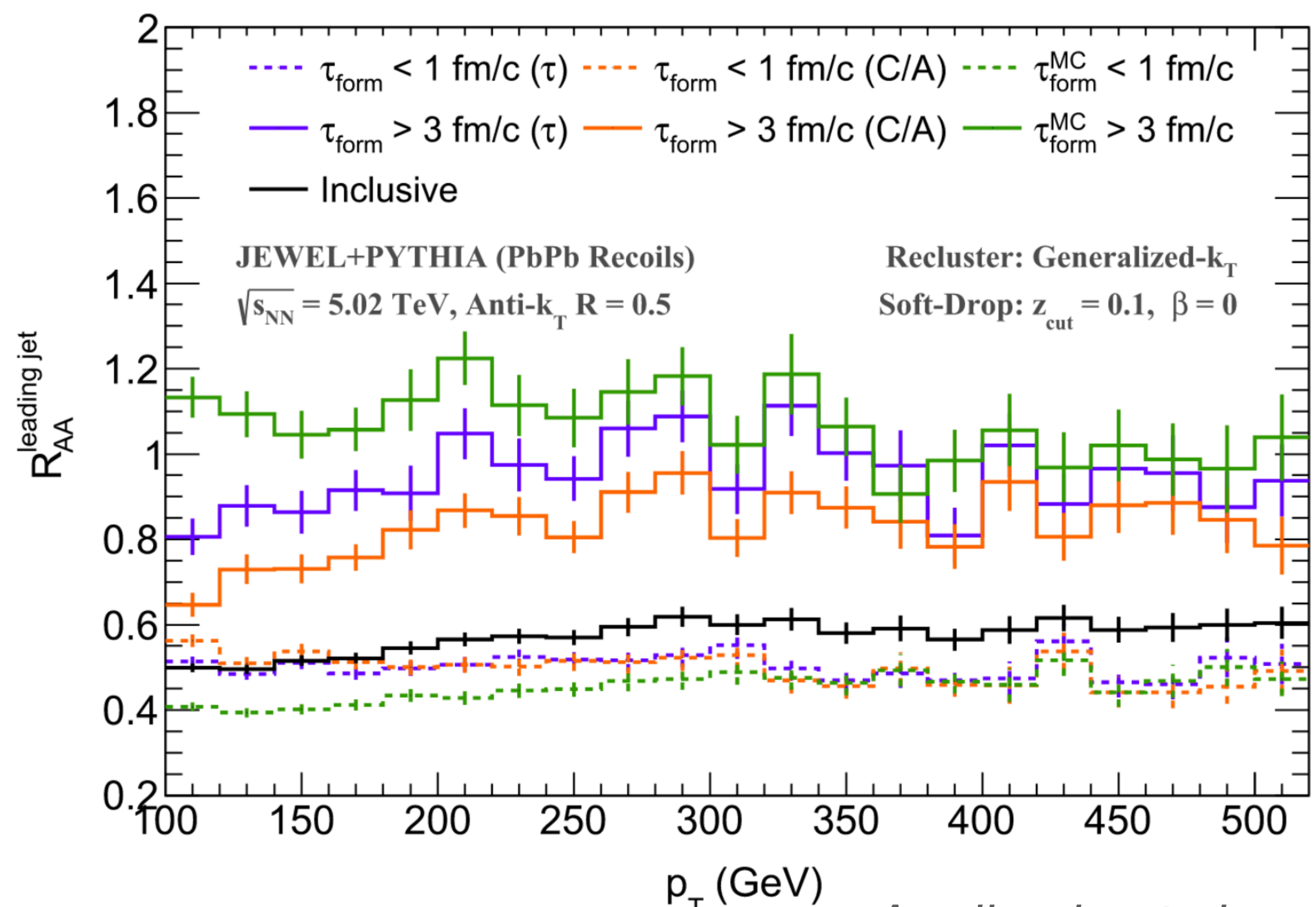
- Selection on the resolved formation time essentially sculpts the jet mass and opening angles
- Reproduce correlation between later times and smaller masses (virtuality) and narrower opening angles - Important handle on particle production and hadronization

Where do we go from here?

Time resolved QGP tomography



- Scan across emission phase-space leads to first ever space-time tomography of the QGP

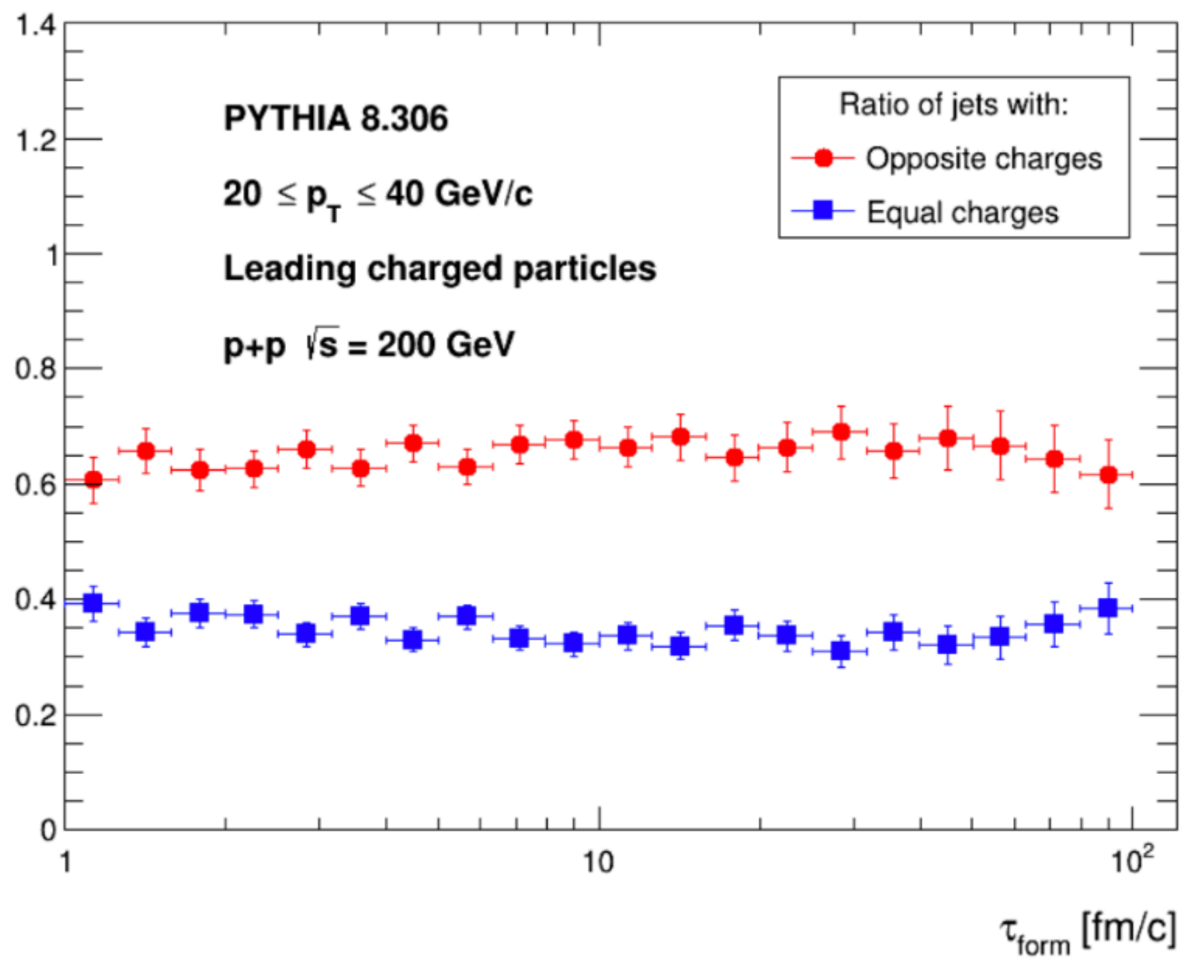


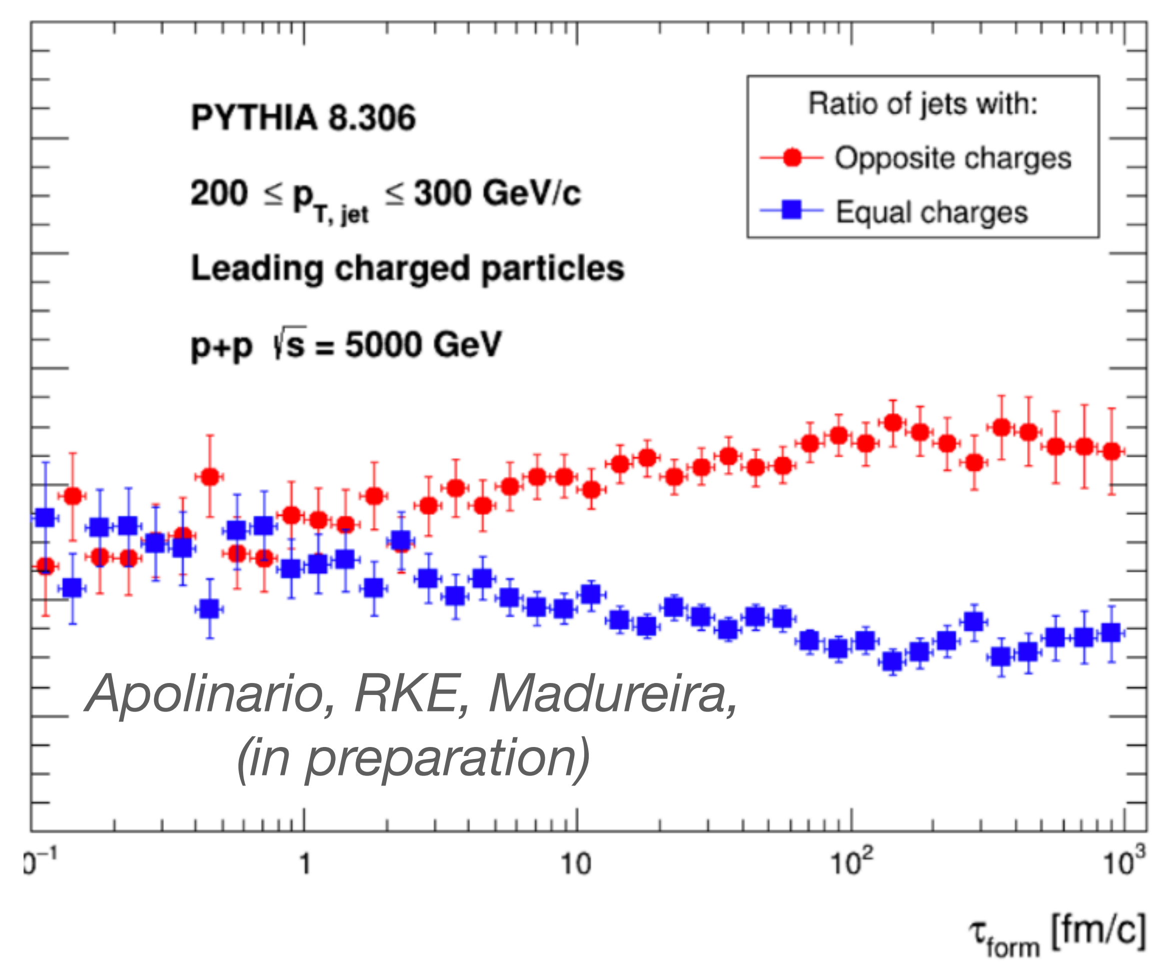
- Searching for hard medium induced gluon emissions, medium coherence length etc…

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

Where do we go from here?

Extending the charge-correlations in formation time

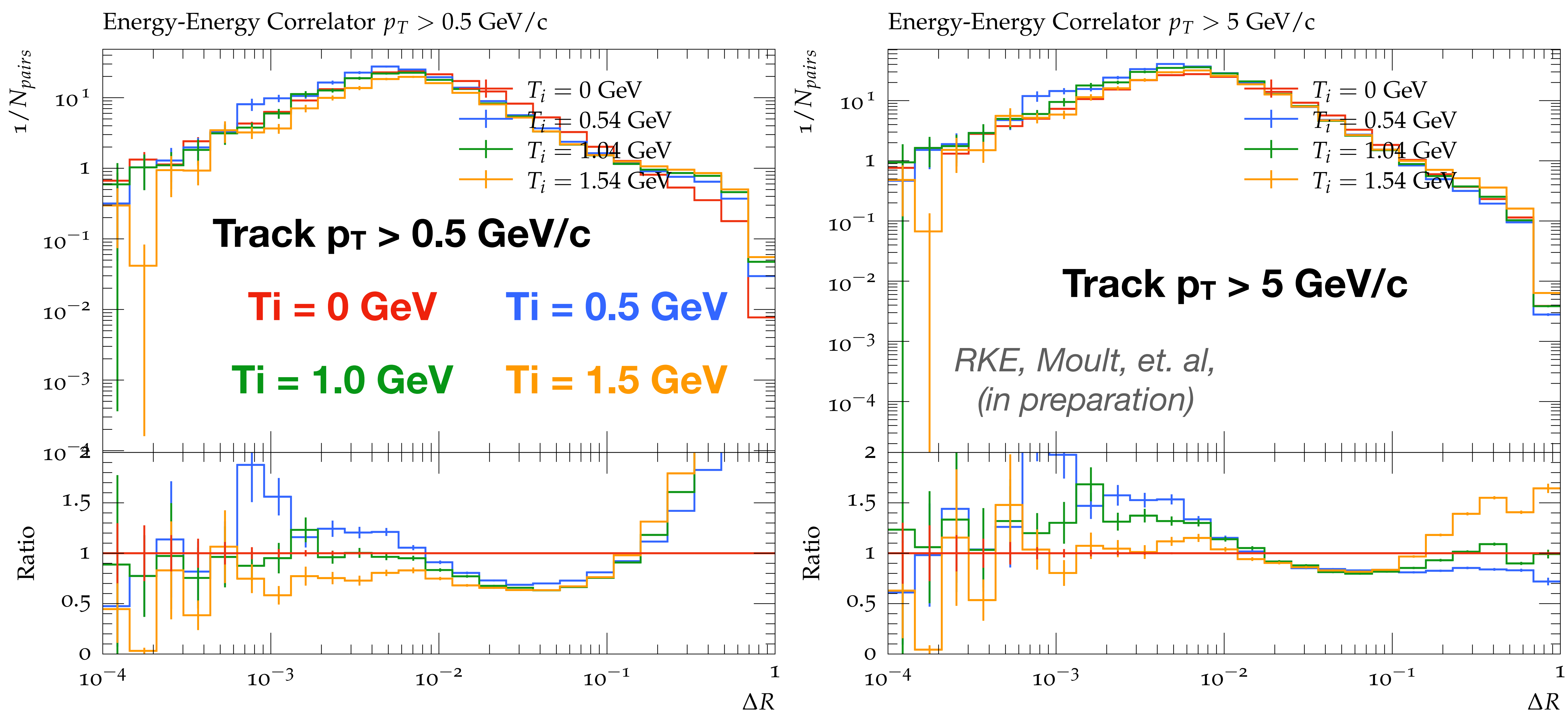




- Significant split in the formation times for 3rd particle to be opposite sign - quantitative categorizing of charge conservation in jets vs time
- Emerging as a new avenue thats complementary to jet substructure focused on understanding hadronization mechanisms

Where do we go from here?

Energy-Energy Correlators in Heavy Ions



- Energy correlators highlight impact of varying 'Temperature' on the jet shower

Measurements ongoing at STAR in pp and AuAu Collisions