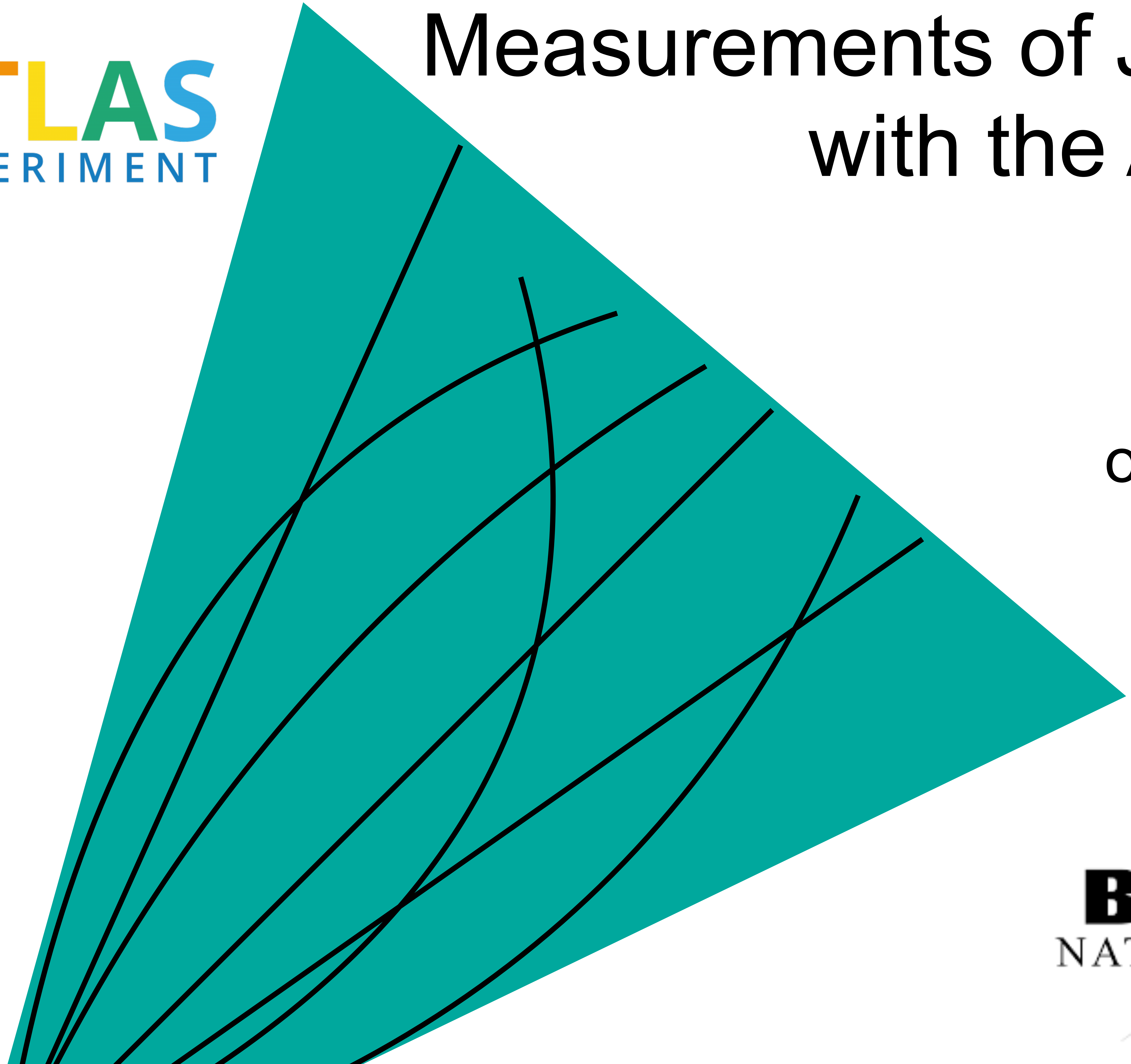
Measurements of Jet Substructure with the ATLAS Detector



Jennifer Roloff,
on behalf of the ATLAS collaboration

October 19, 2020

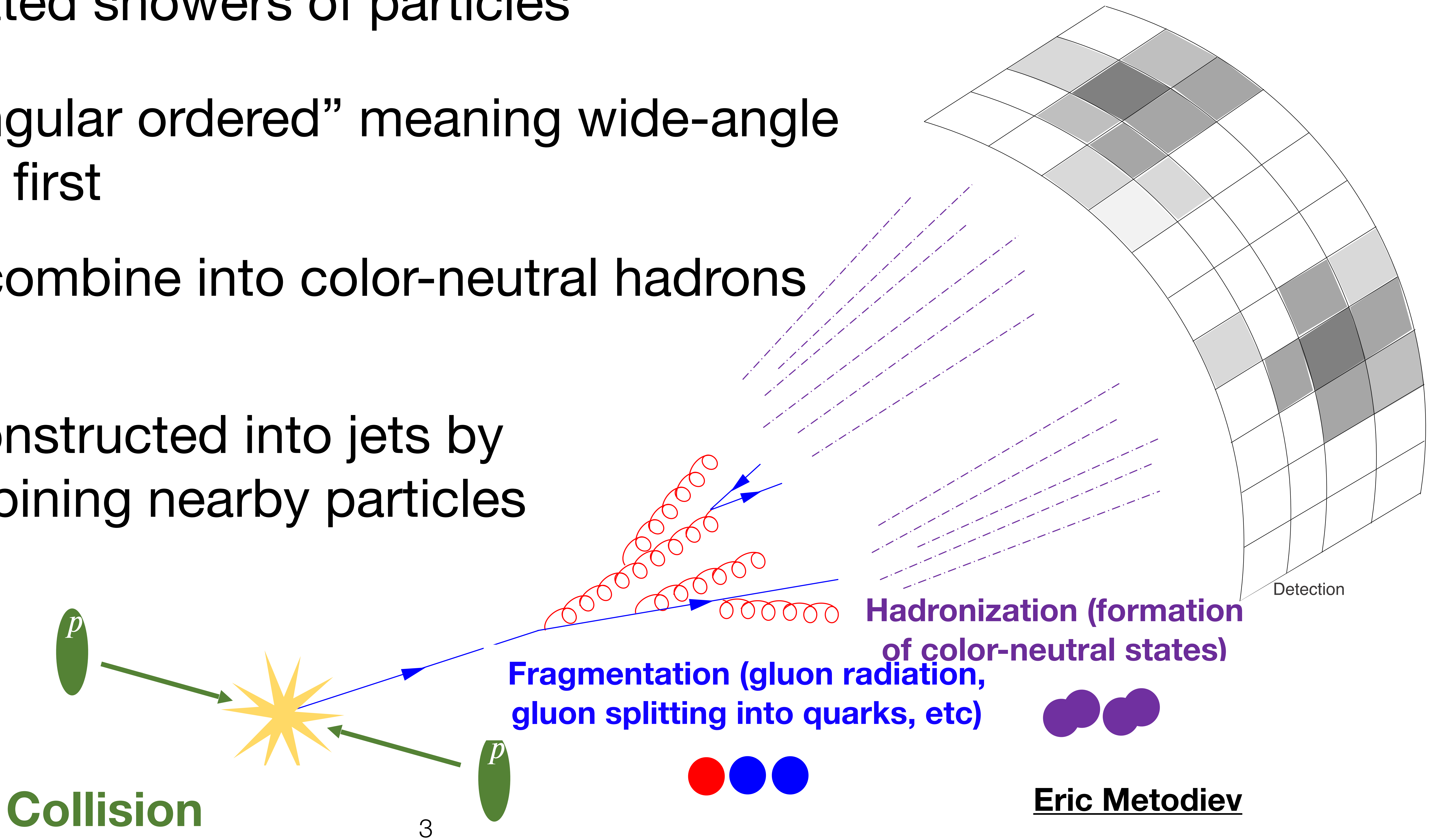
BROOKHAVEN NATIONAL LABORATORY

qcd at the lhc

- LHC collides protons → understanding of QCD is critical to entire physics program
  - **Parton Distribution Functions**: necessary for any calculation at a hadron collider
  - **The strong coupling constant (α_s)**: fundamental parameter of QCD, becoming increasingly relevant for things like Higgs measurements
  - **Jet modeling**: important for creating any Monte Carlo samples, one of the dominant uncertainties for the jet energy scale corrections

qcd at the lhc

- Quarks and gluons produced in hard-scatter collisions *fragment* into collimated showers of particles
  - Approximately “angular ordered” meaning wide-angle emissions happen first
- Particles eventually combine into color-neutral hadrons during *hadronization*
- Showers can be reconstructed into jets by some algorithm combining nearby particles
- Rely on Monte Carlo models to describe fragmentation and hadronization

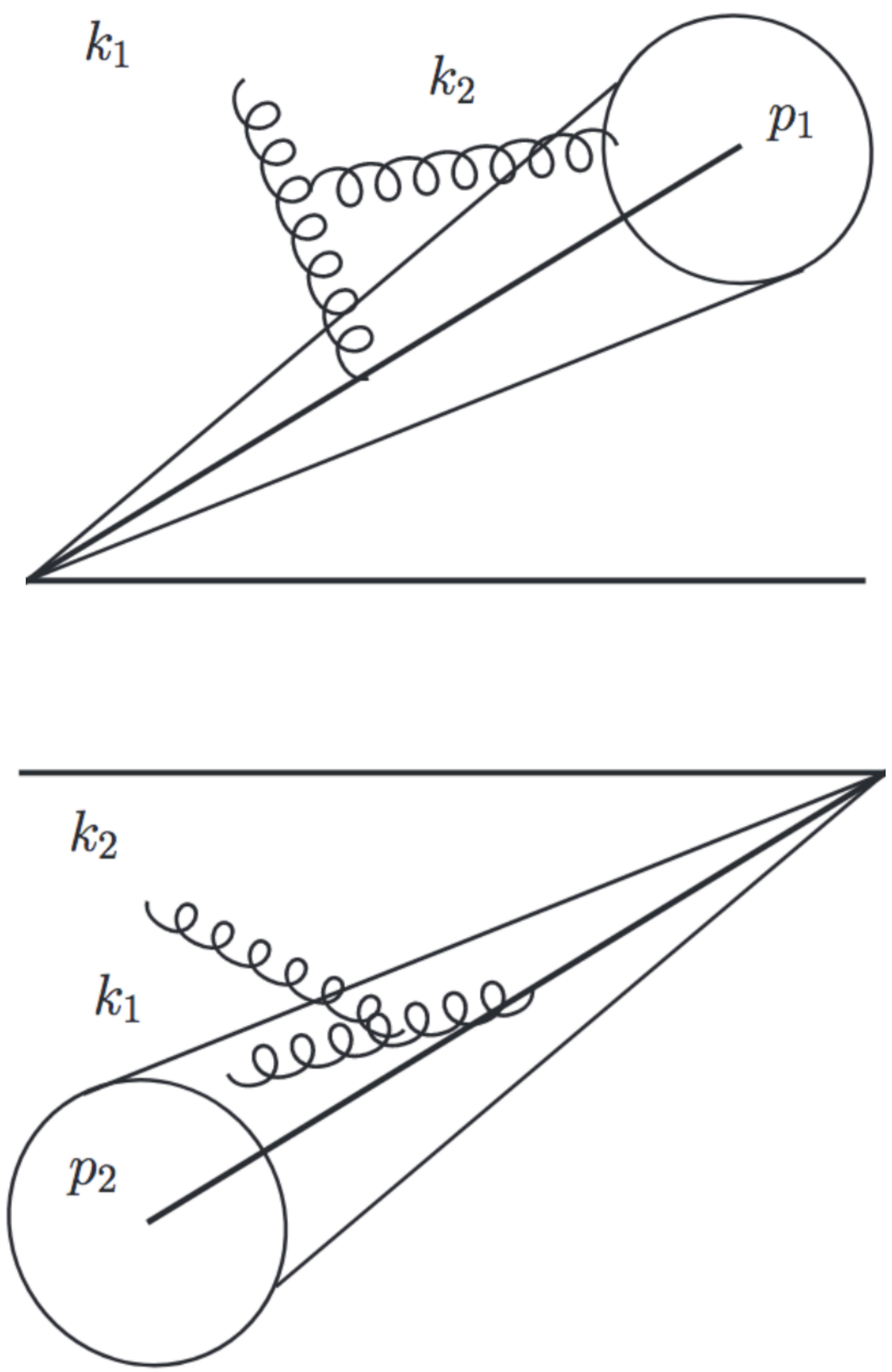


why jet substructure measurements?

- Jet substructure provides insight into several *different scales of QCD*
  - Can be used to understand everything from fixed order effects to parton showers to hadronization
- *Jet modeling* is one of the dominant sources of uncertainties for many analyses
  - Deeper understanding of jet formation can be used to develop better Monte Carlo models of jets
  - Gluons in particular tend to be poorly modeled
- Better understanding of jets leads to better, *more robust observables* for tagging jets

jet substructure: dijets

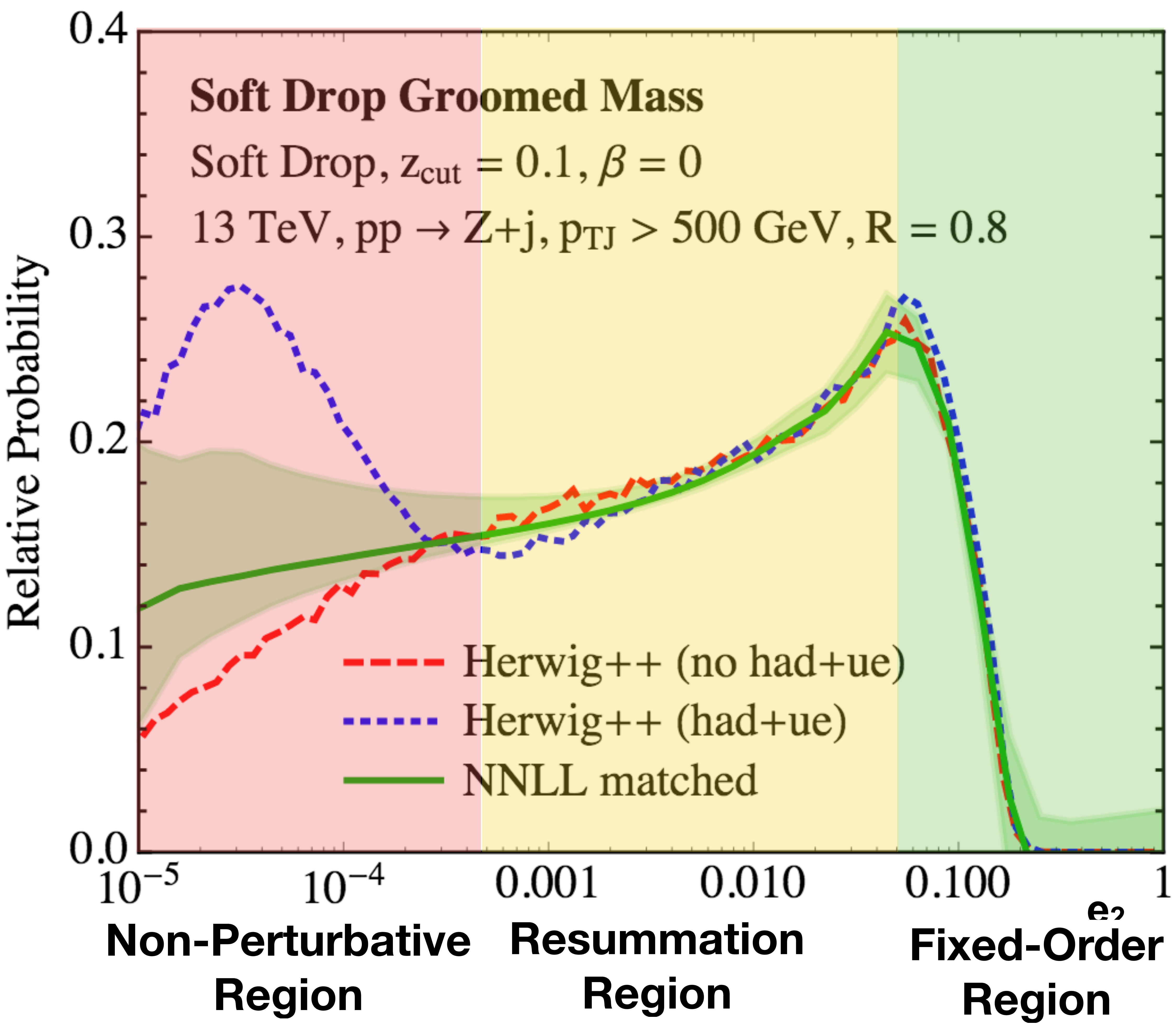
soft drop



- Fixed order calculations (e.g. NLO) do not capture the fragmentation
- Calculations of substructure observables are further complicated by the presence of non-global logarithms
  - These tend to be soft (low-p_T) and wide-angle radiation
- Grooming algorithms remove soft and wide-angle radiation from jets
  - ***Soft drop*** is a grooming algorithm which removes these non-global logarithms → able to perform precision calculations to beyond leading logarithmic accuracy

the jet mass

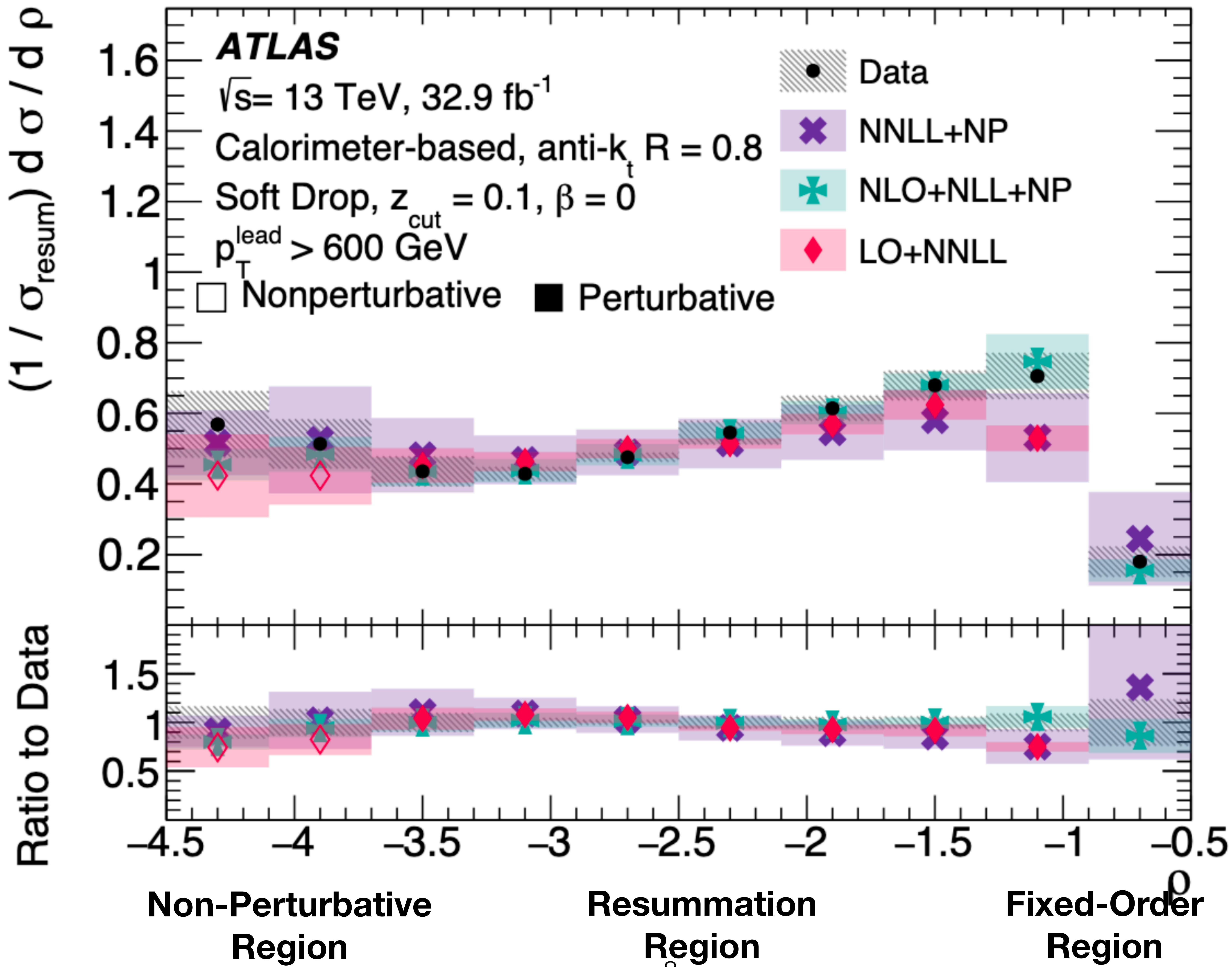
- The jet mass is one of the most commonly used jet substructure observables
- Quarks and gluons are very light, but jets can be very massive because of fragmentation
- Measuring $\rho = \log[(m^{\text{Soft Drop}} / p_T^{\text{Ungroomed}})^2]$
  - *Logarithmic dependence on p_T* means less dependence on underlying p_T spectrum



C. Frye, A. Larkoski, M. Schwartz, K. Yan, JHEP 07 (2016) 064

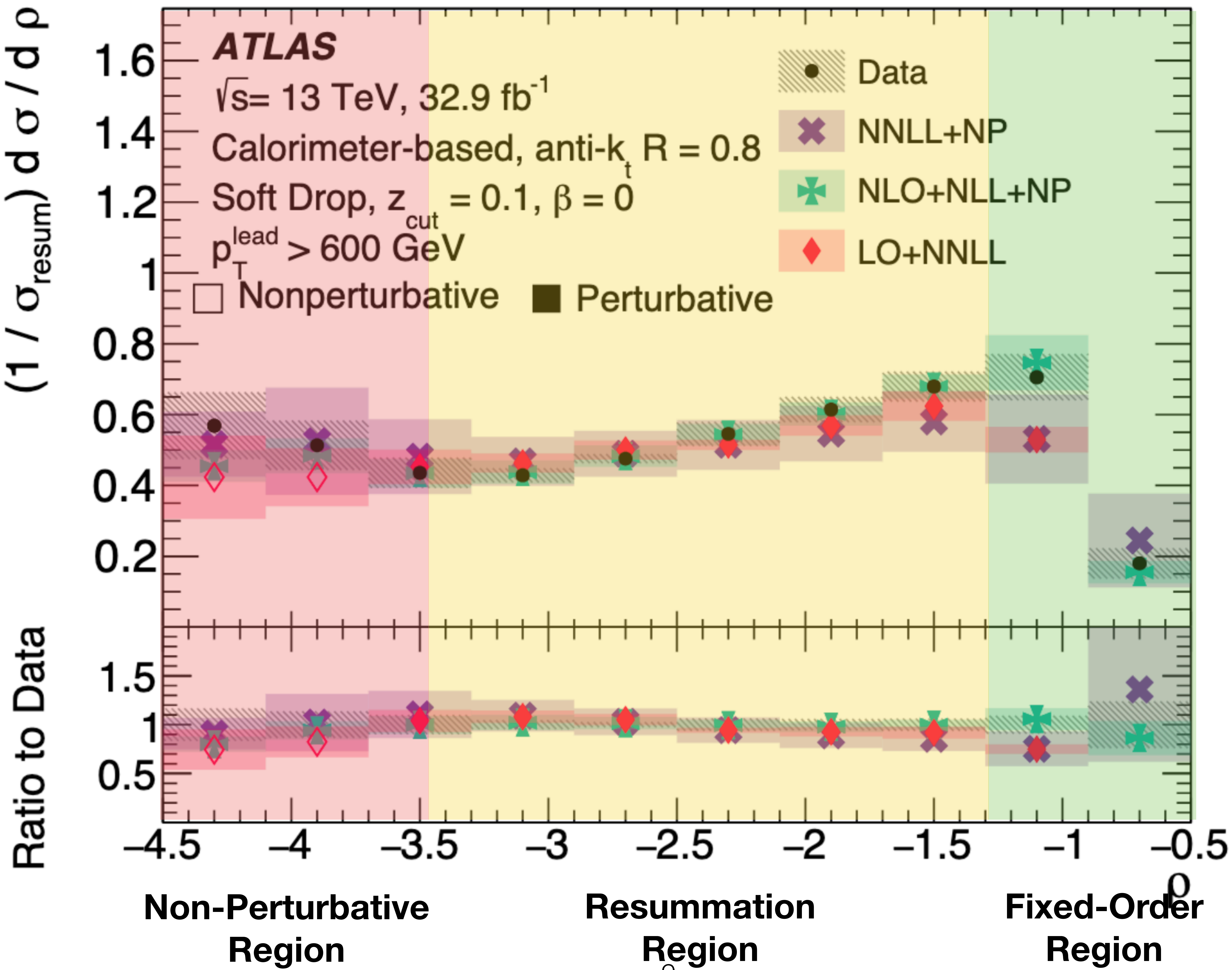
- High-mass region dominated by single hard splitting
  - Use *log-scale binning* to understand the resummation region
- The jet mass calculation is *factorizable* → different effects dominant in specific places

the unfolded jet mass



1912.09837

the unfolded jet mass



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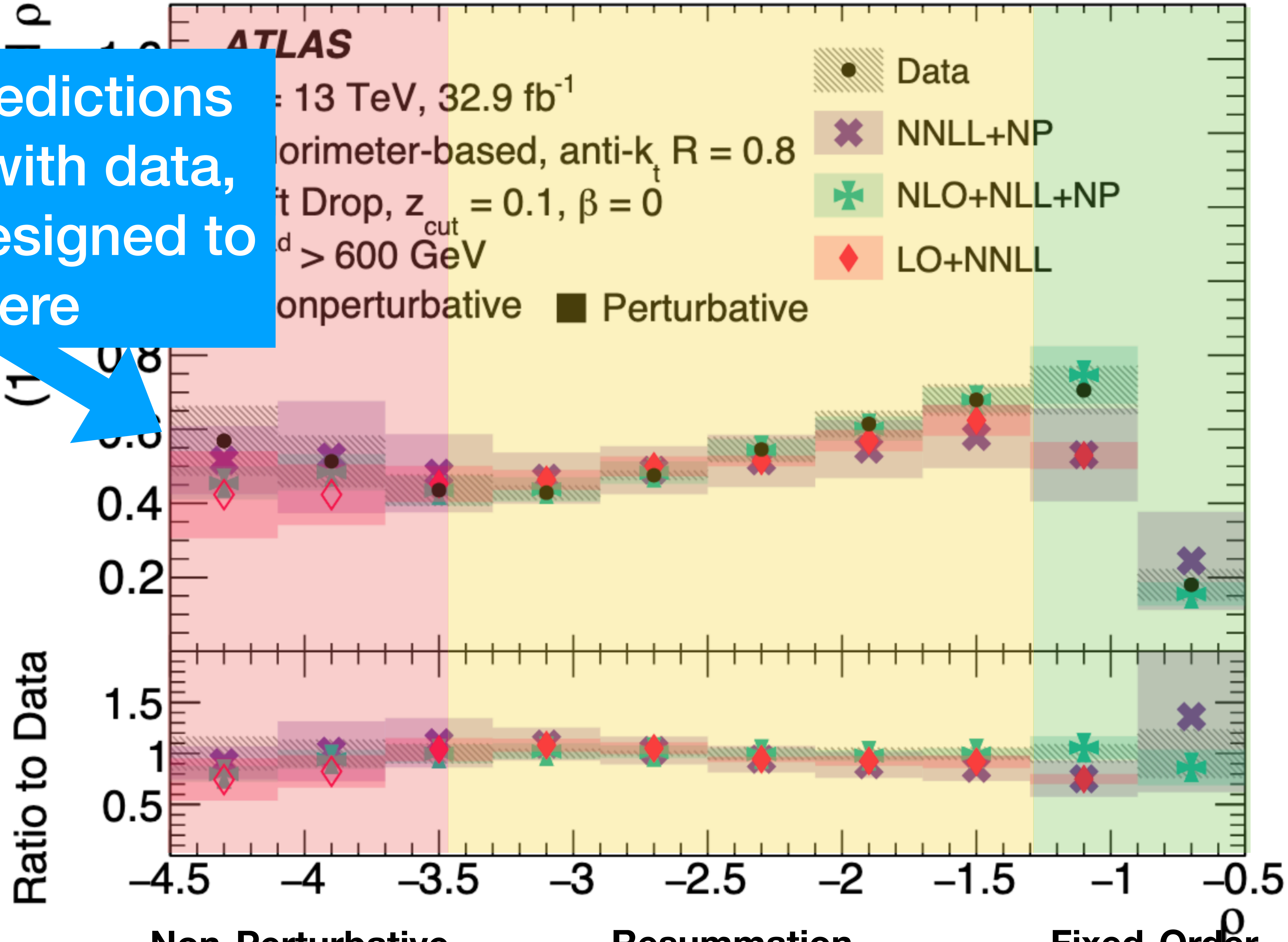


Analytical predictions don’t agree with data, but are not designed to work here

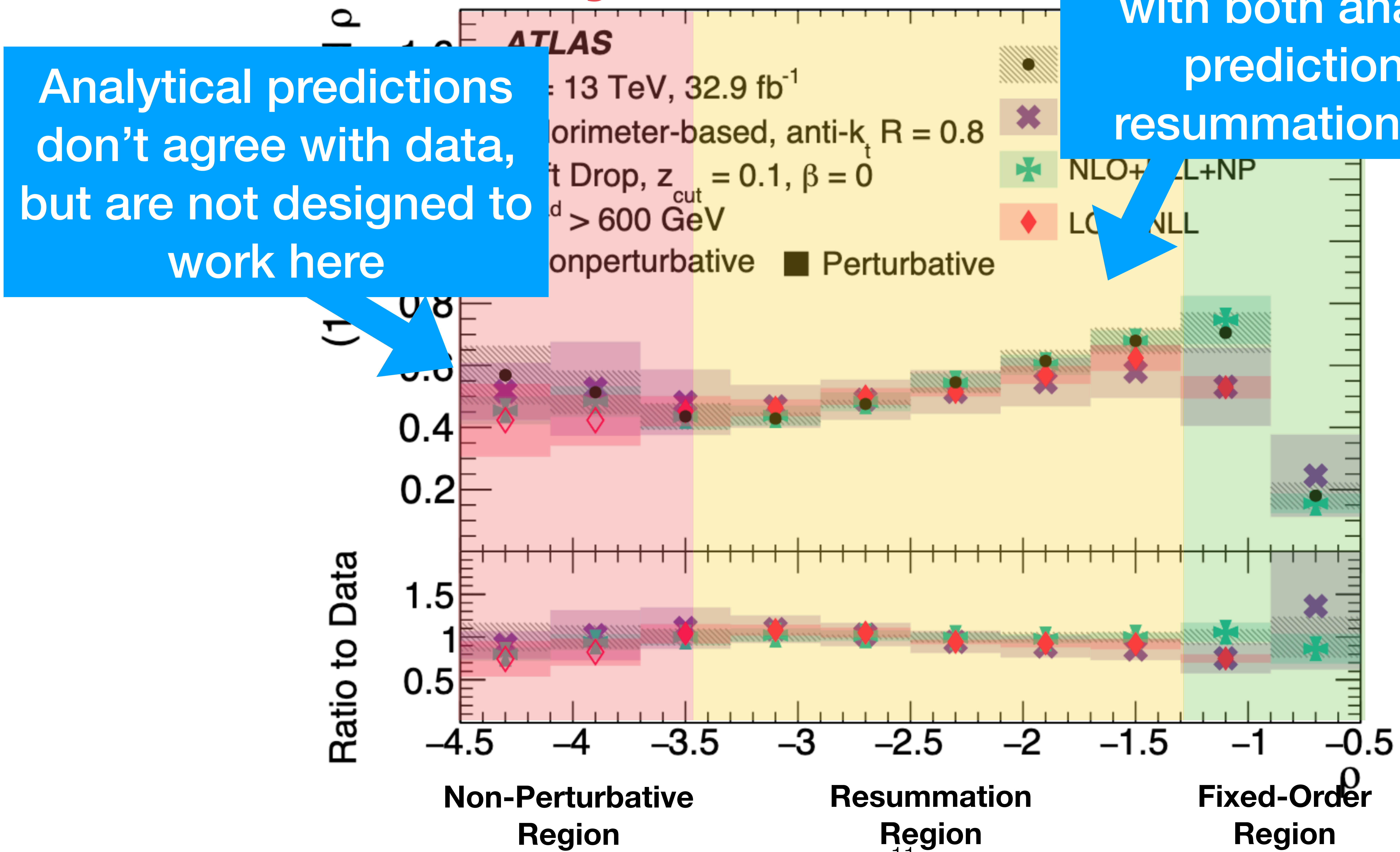
Non-Perturbative Region

Resummation Region

Fixed-Order Region

the unfolded jet mass

1912.09837



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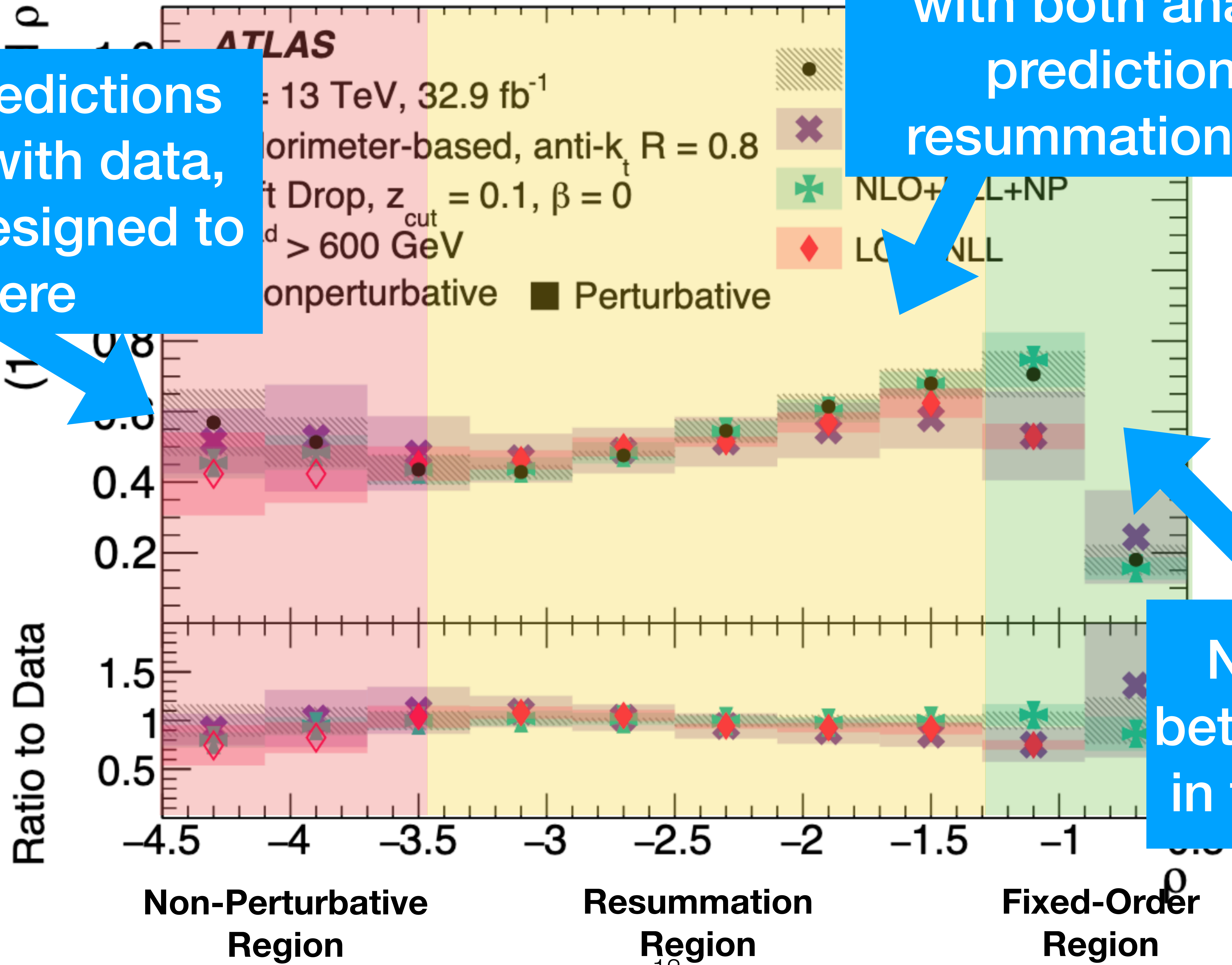


Analytical predictions don't agree with data, but are not designed to work here

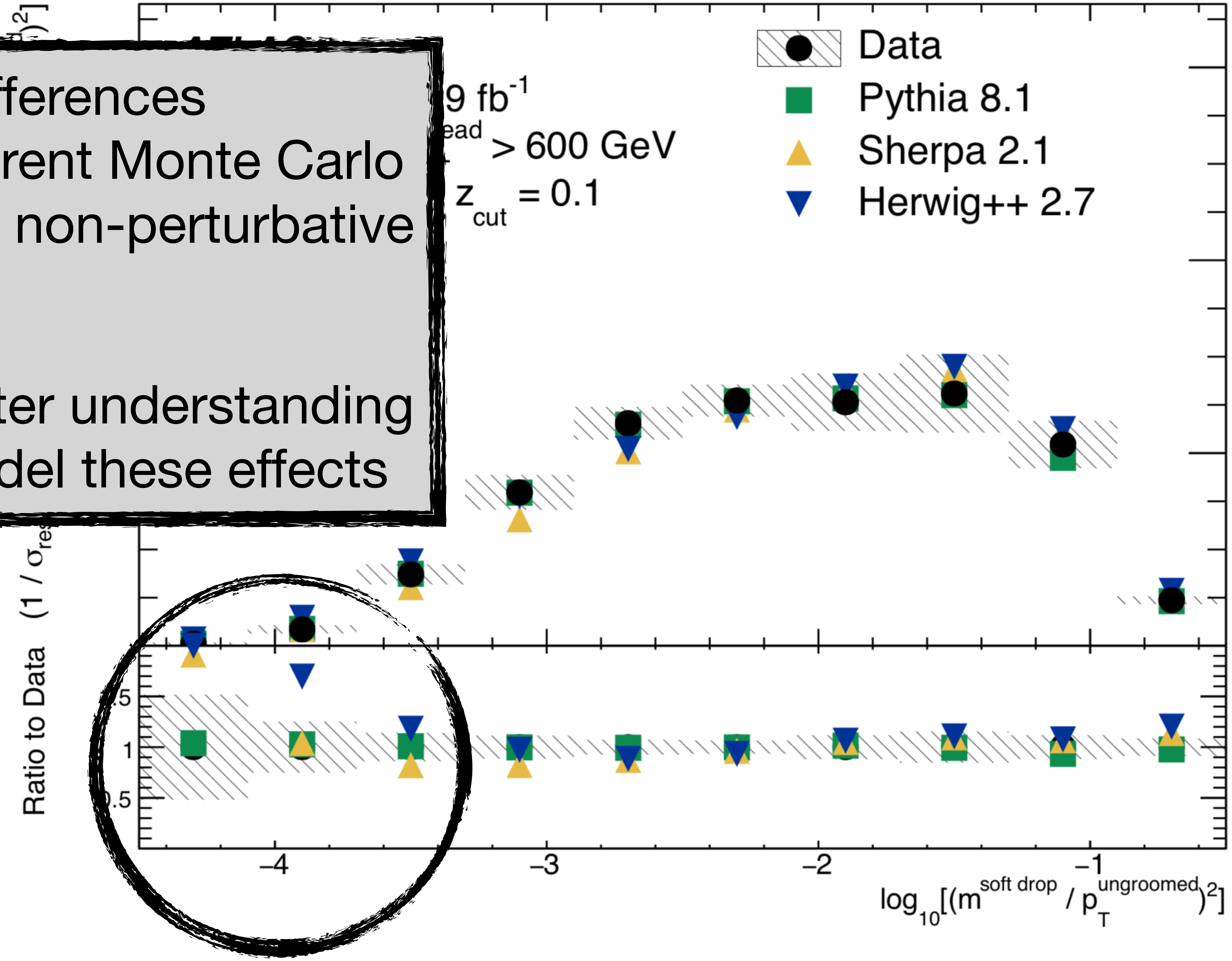
Very good agreement with both analytical predictions in resummation region

NLO+NLL agrees better than LO+NNLL in fixed order region

1711.08341

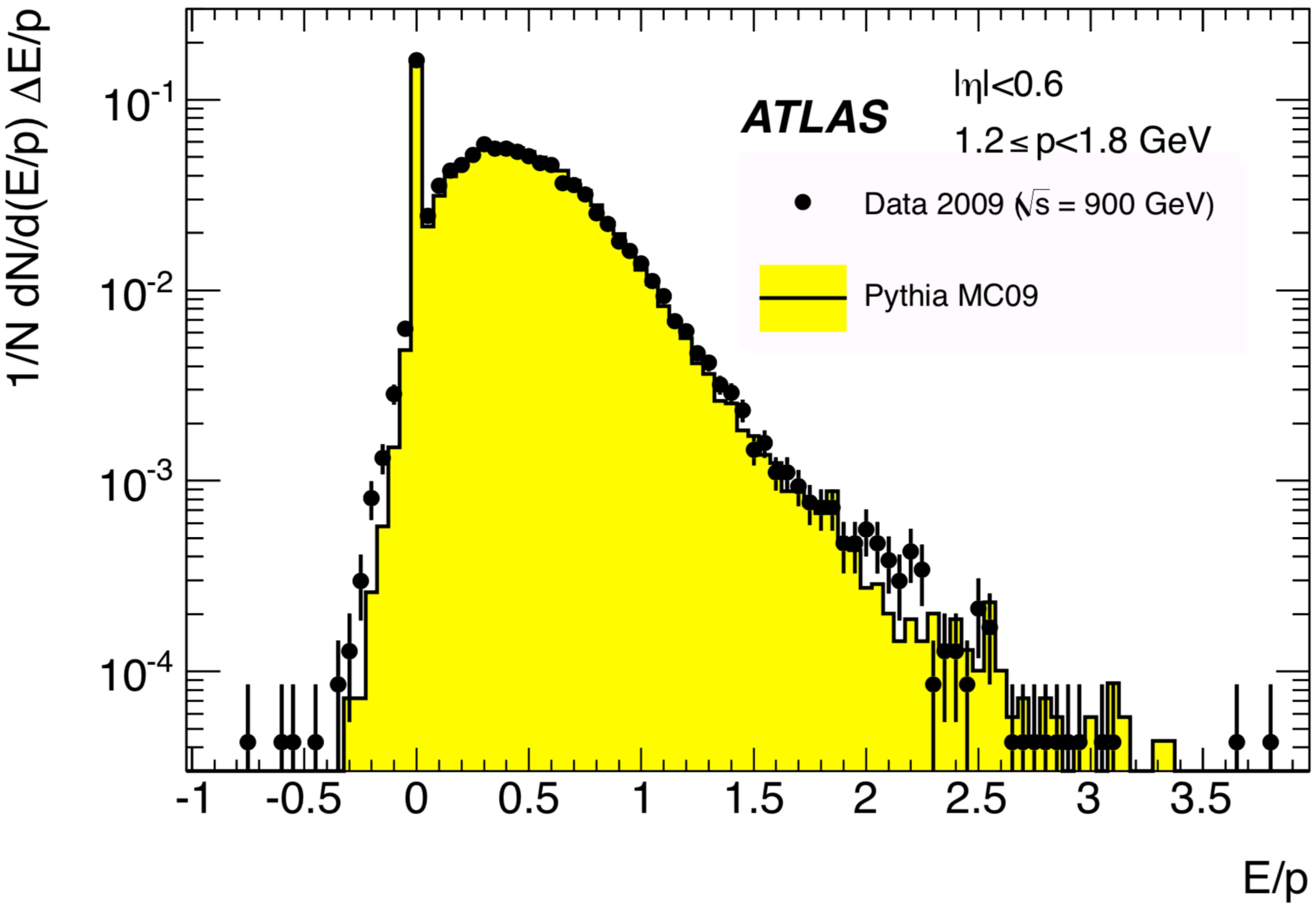
the unfolded jet mass

- Significant differences between different Monte Carlo predictions in non-perturbative region
- Still need better understanding of how to model these effects

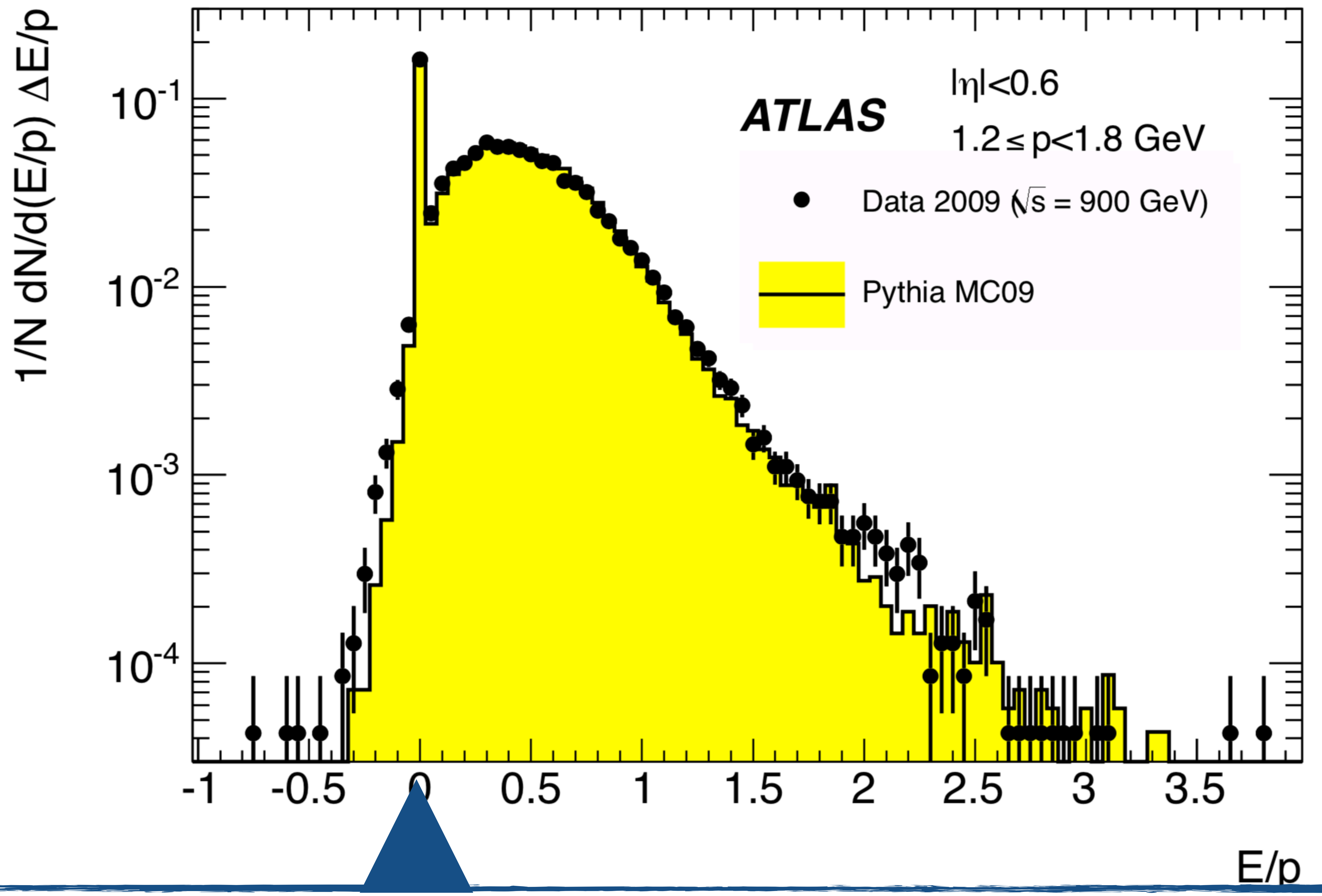


Uncertainties

cluster-based uncertainties



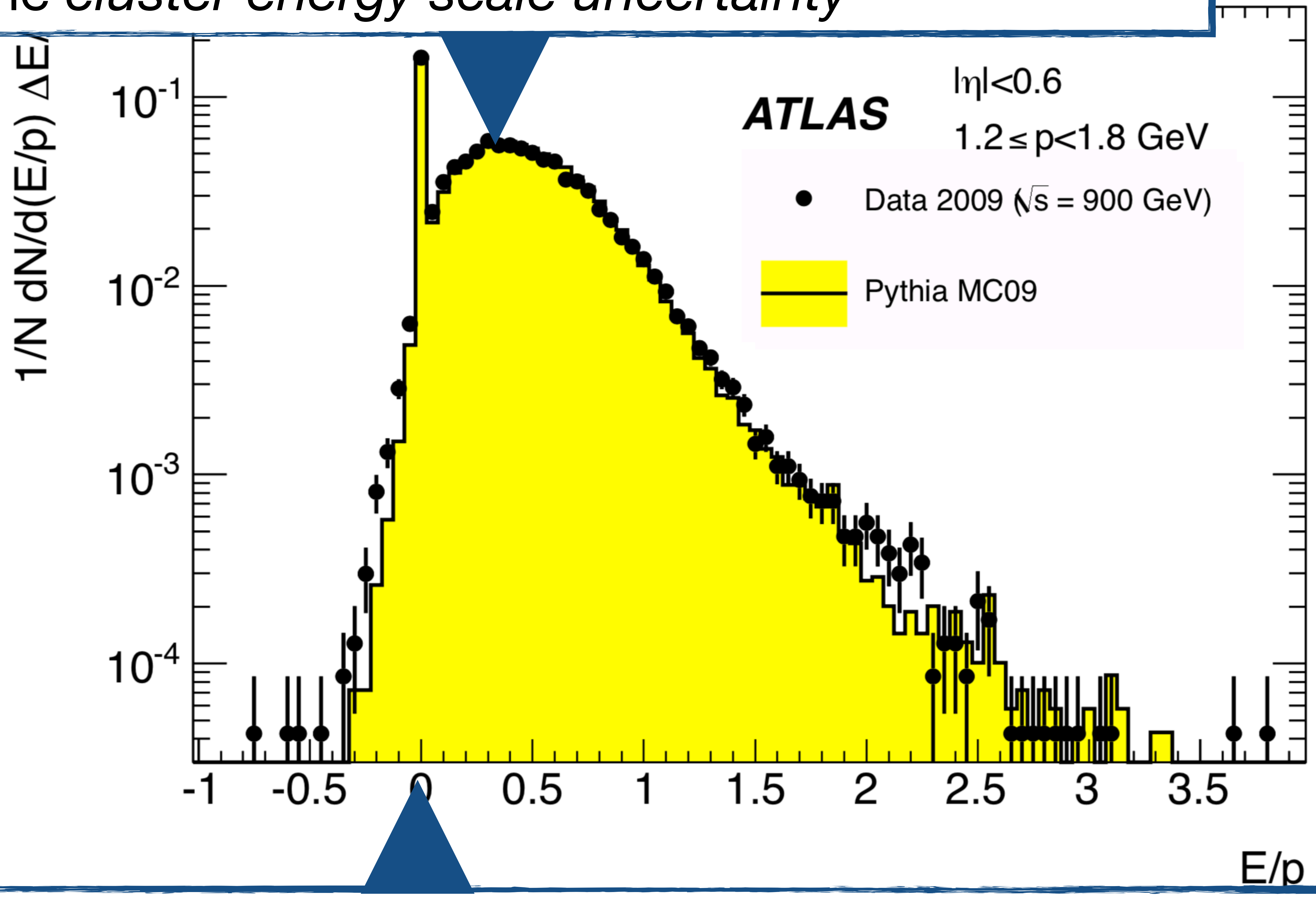
cluster-based uncertainties



- Percentage of events in the 0 bin describes the probability of not having a cluster → Data-MC difference gives *cluster efficiency uncertainty*

cluster-based uncertainties

- Data/MC difference of the mean of the fitted distribution describes the *cluster energy scale uncertainty*



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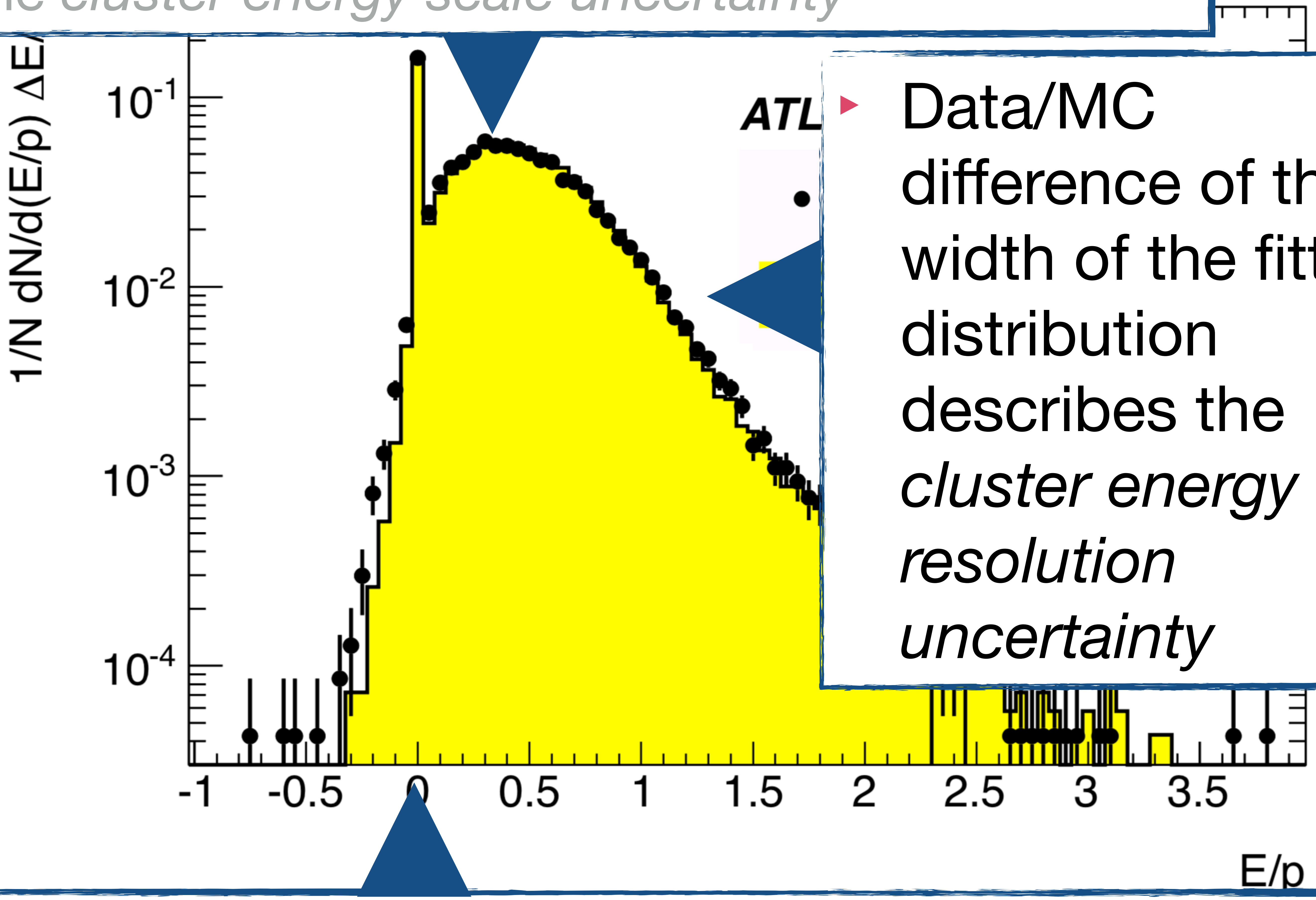
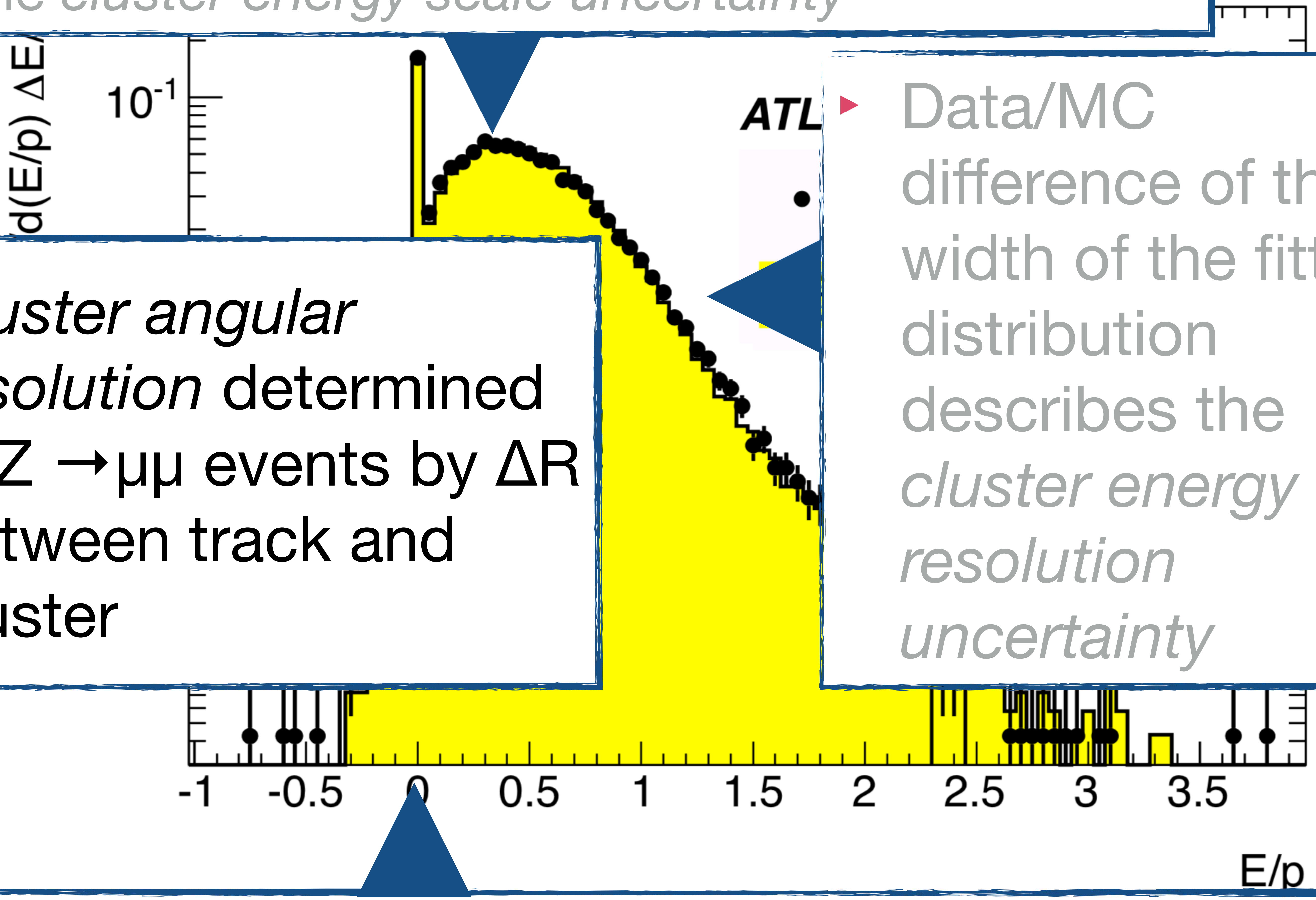


- Data/MC difference of the width of the fitted distribution describes the *cluster energy resolution uncertainty*

- Percentage of events in the 0 bin describes the probability of not having a cluster → Data-MC difference gives *cluster efficiency uncertainty*

cluster-based uncertainties

- Data/MC difference of the mean of the fitted distribution describes the *cluster energy scale uncertainty*



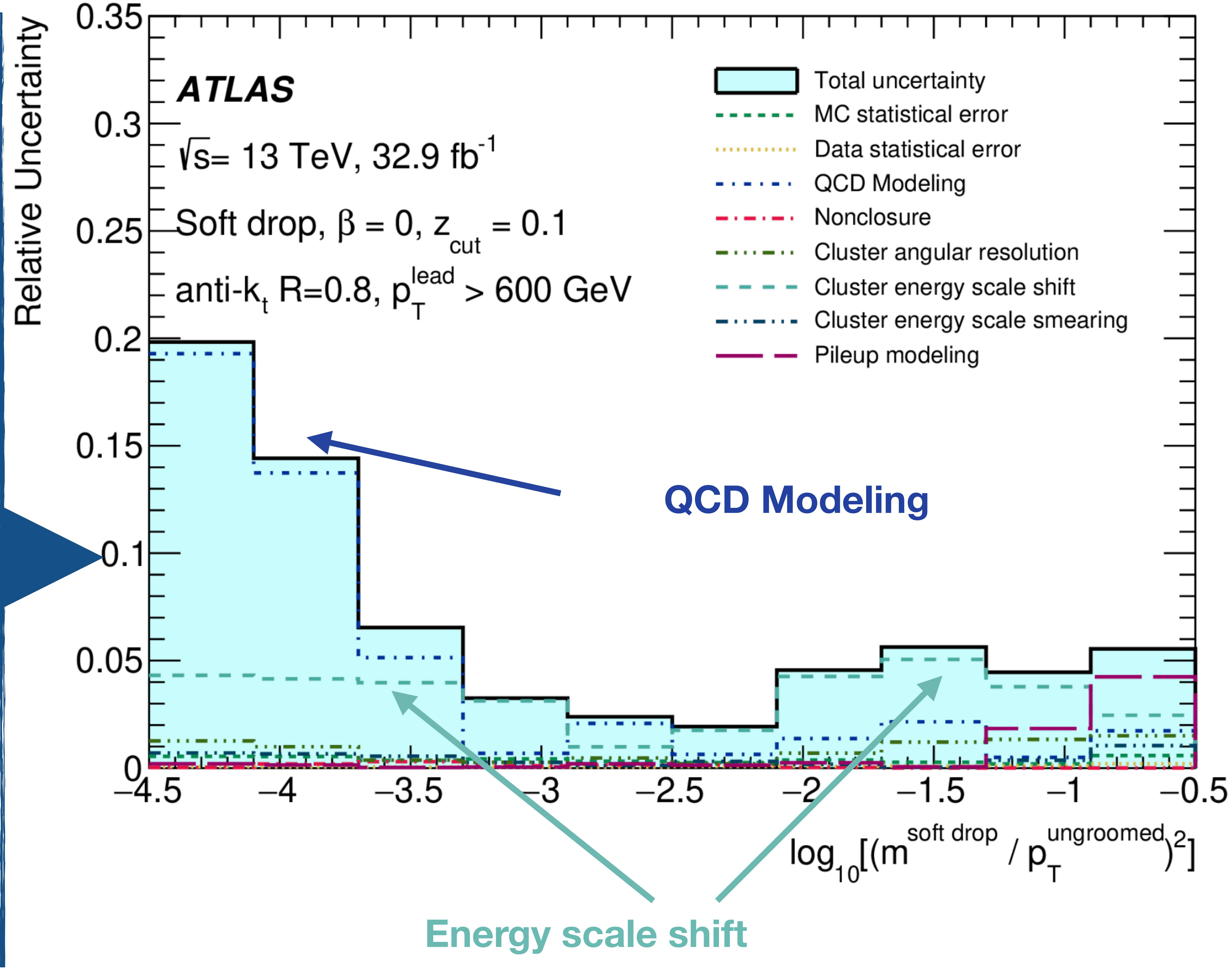
- *Cluster angular resolution* determined in Z →μμ events by ΔR between track and cluster

- Data/MC difference of the width of the fitted distribution describes the *cluster energy resolution uncertainty*

- Percentage of events in the 0 bin describes the probability of not having a cluster → Data-MC difference gives *cluster efficiency uncertainty*

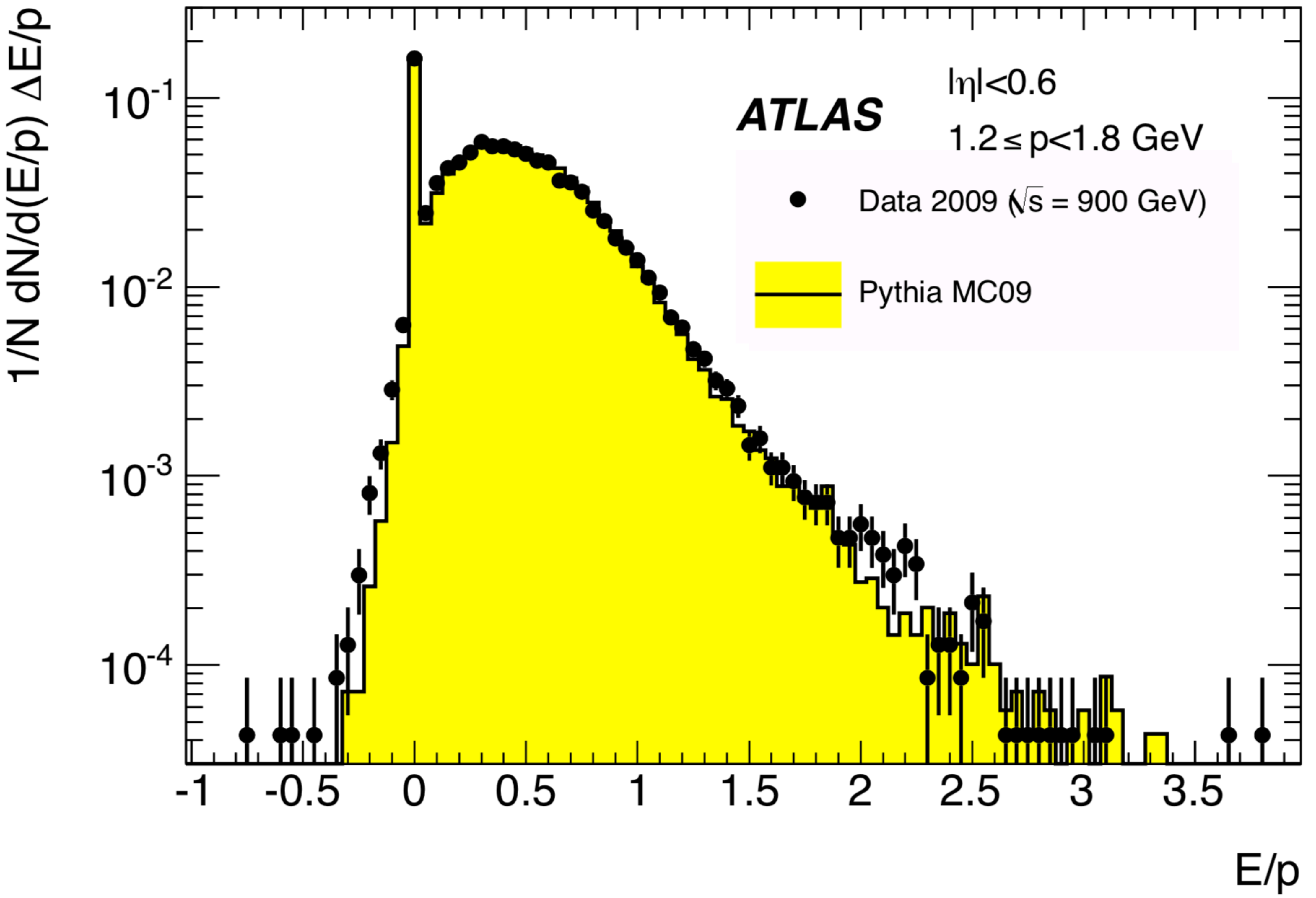
uncertainties

- **QCD modeling** uncertainties dominate, especially in the non-perturbative region
- **Cluster energy scale shift** uncertainty large at lower masses where there are few clusters per jet
- **Cluster energy scale smearing** and **cluster energy scale shift** become more important at higher masses where the energy of hard prongs dominates



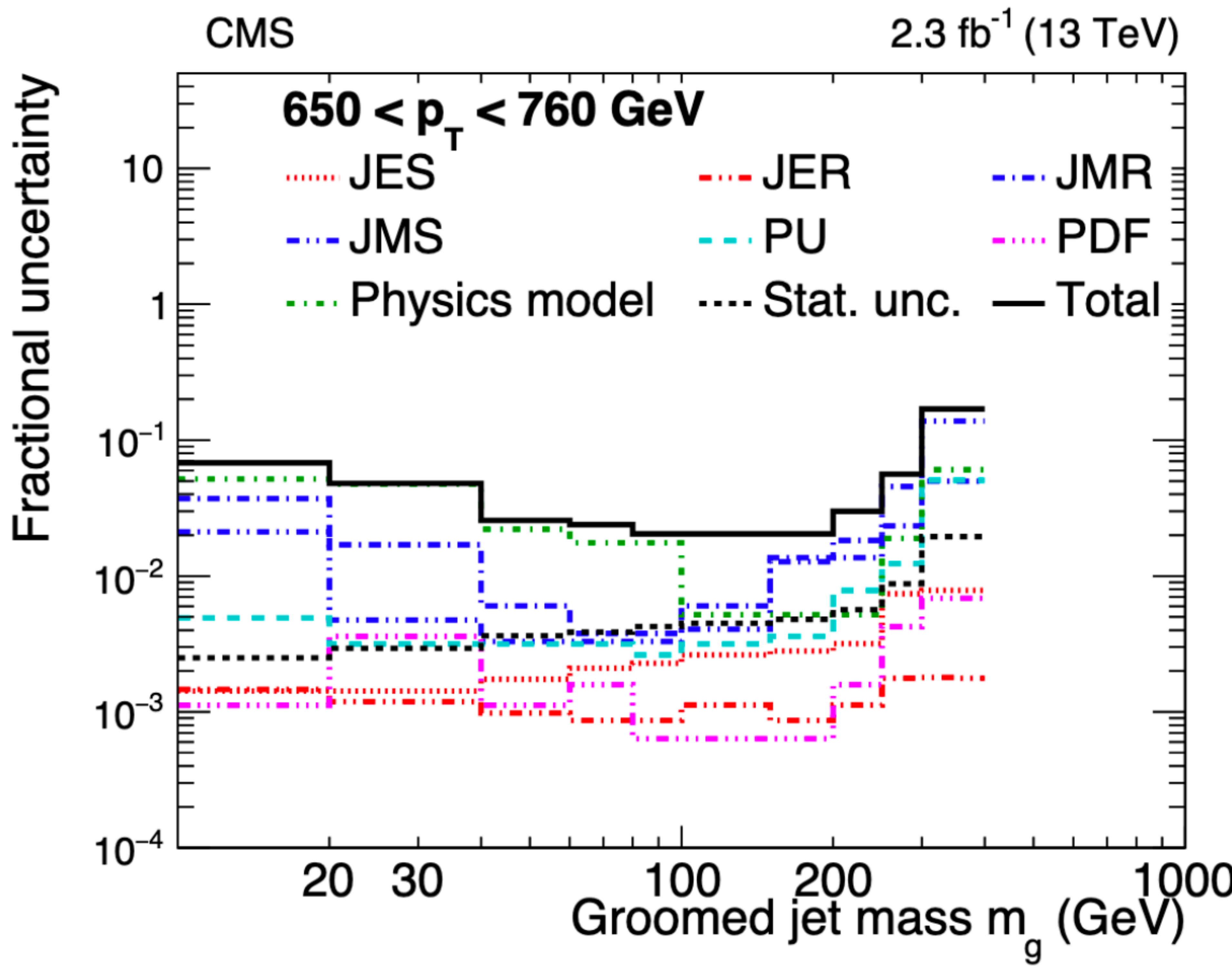
cluster-based uncertainties

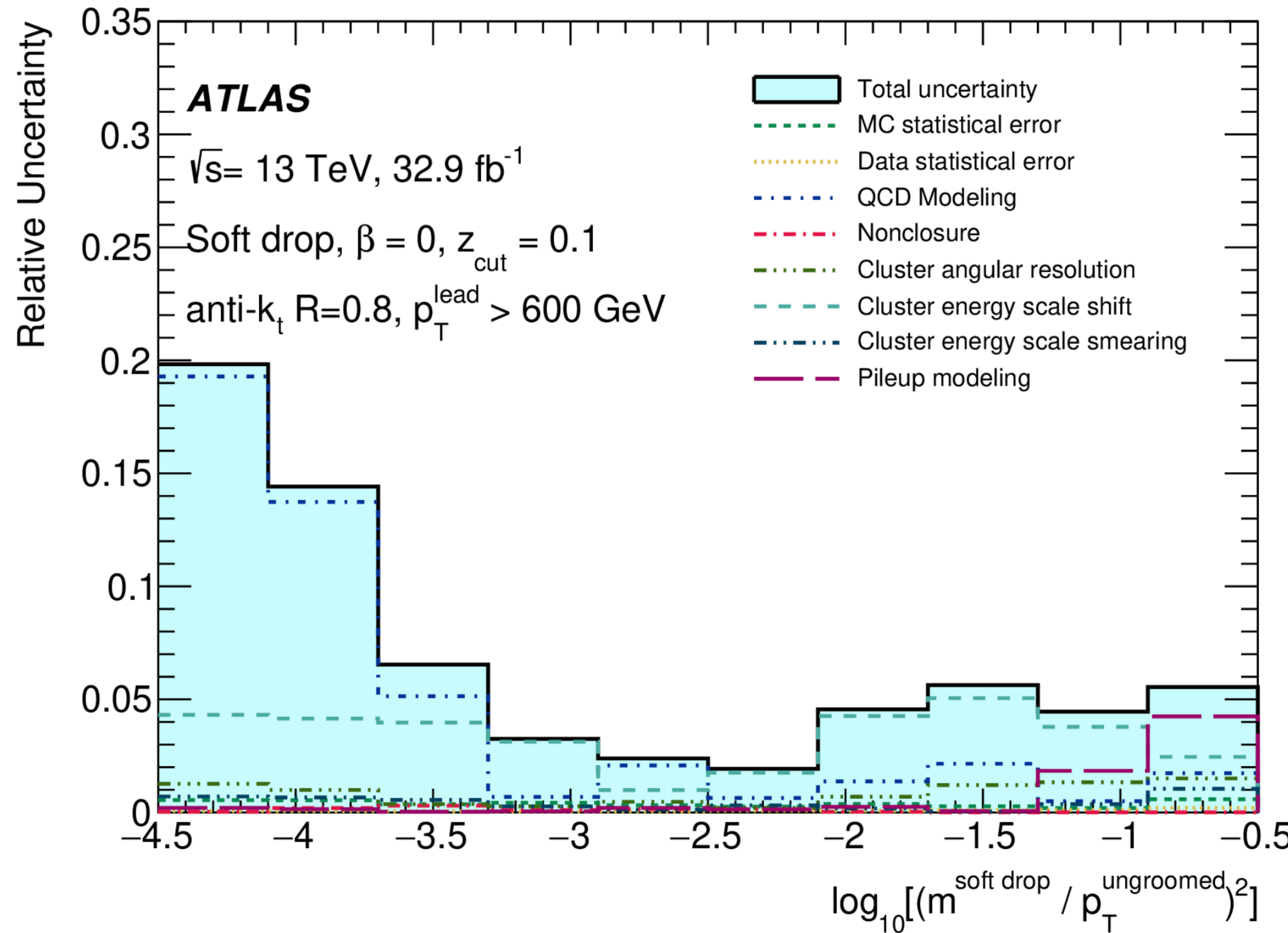
- Cluster uncertainties rely on using the tracks to create an unbiased estimate of the uncertainties
  - Cluster uncertainties are propagated to the observable of interest
- For particle flow, the subtraction algorithm can subtract individual cells from the clusters to form charged PFlow objects
  - PFlow objects are correlated with the tracks → need a different way to estimate this
  - This is very complicated, and so we are unable to account for this



comparison to cms

- CMS uses the data/MC agreement of *W* jets to determine the JMS and JMR
  - Assumes that detector uncertainties will be the same for *W* jets and q/g jets
- Hard to compare uncertainties directly since CMS plot is for the mass, and ATLAS plot is for ρ





comparison to cms

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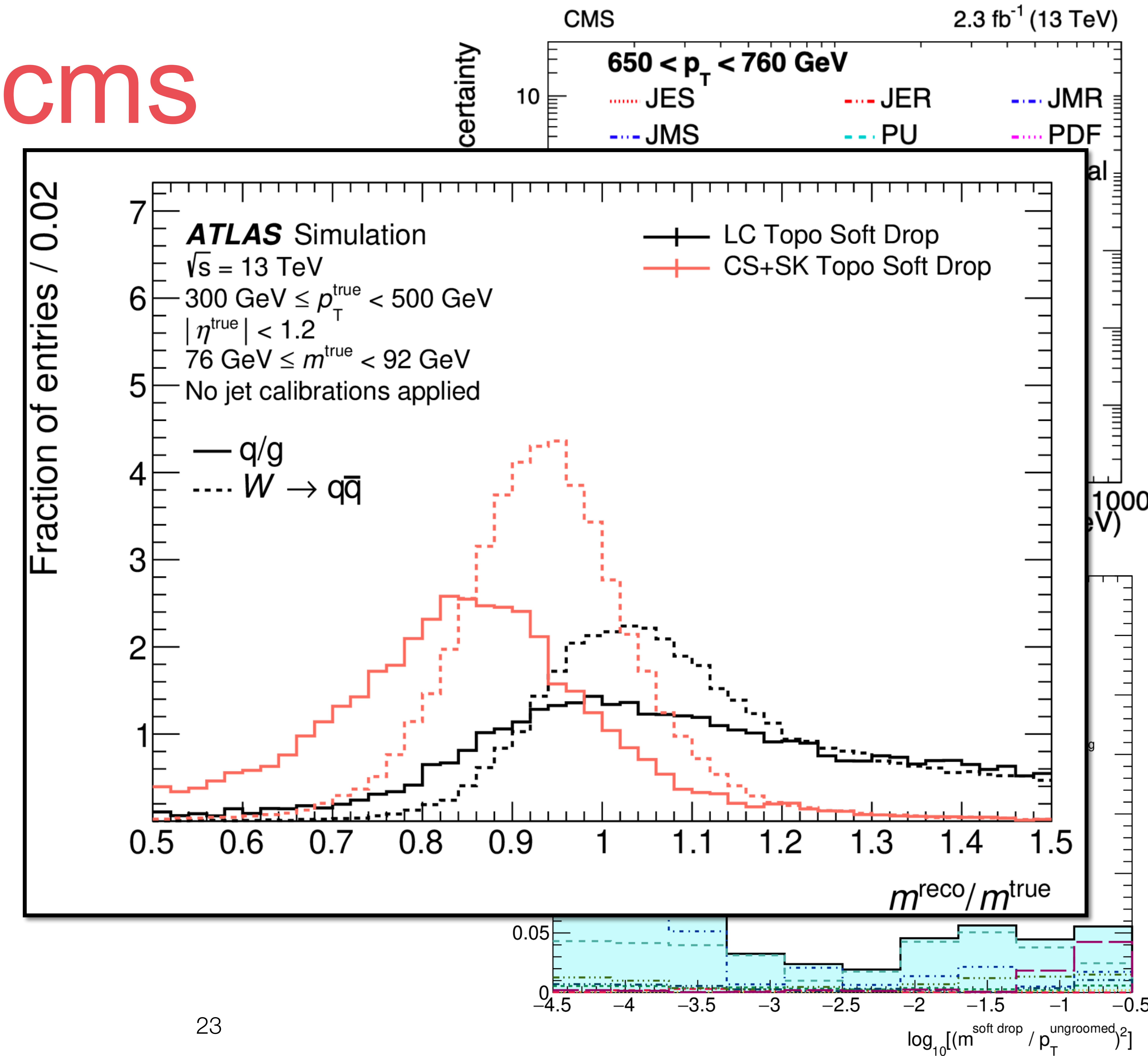
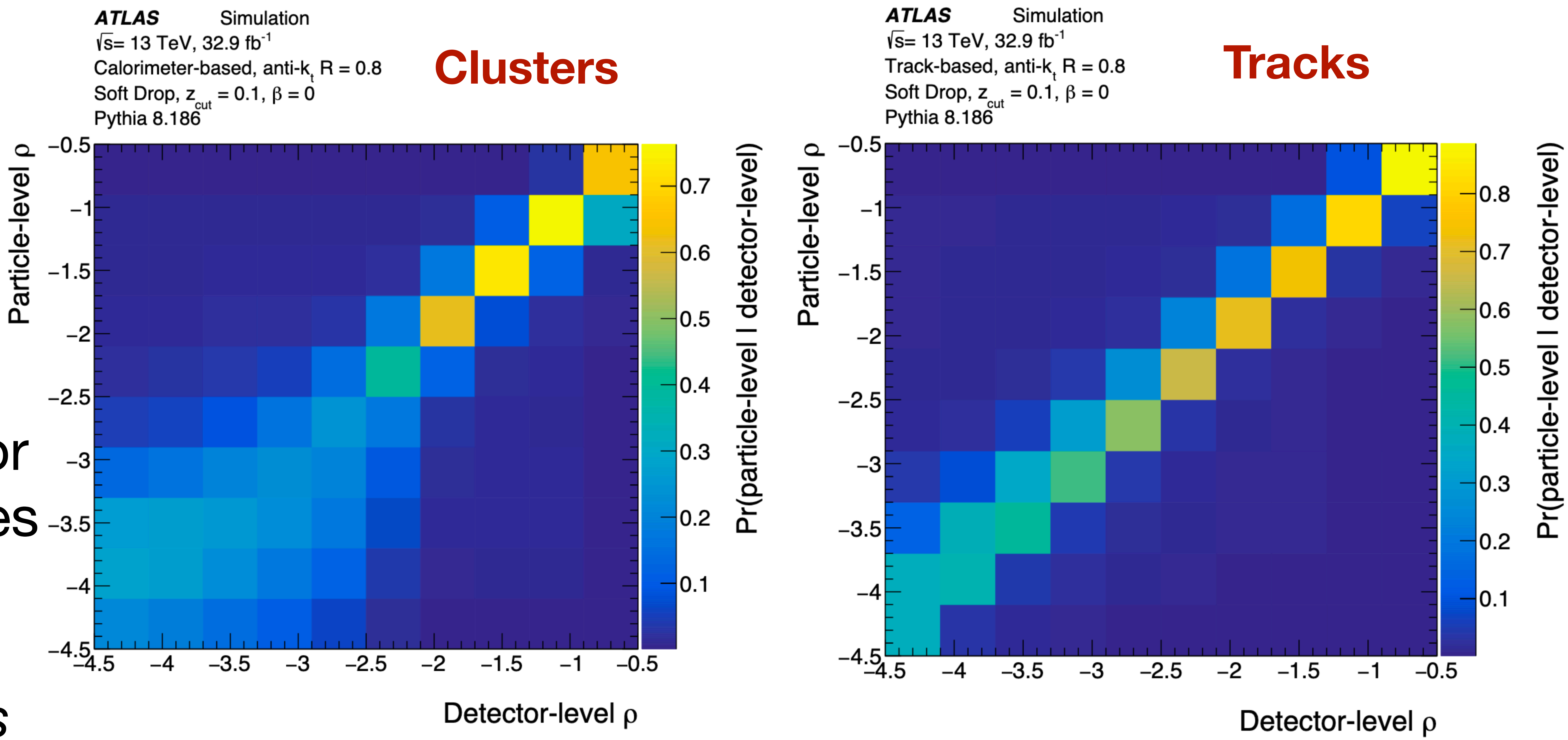
  - Assumes that detector uncertainties will be the same for *W* jets and q/g jets
- At least on ATLAS, the JMS and JMR look very different for *W* jets vs. q/g jets
  - The mass is dominated by different effects (e.g. hard splitting for *W*, fragmentation for q/g)



the jet mass

[1912.09837](1912.09837)

- Tracks have better angular resolution and are less sensitive to detector effects
- Non-trivial to produce analytical predictions for track-based observables
- *Optimal input to jet reconstruction depends on purpose of measurement*



the jet mass

1912.09837

- Tracks h
angular
are less
detector

- Non-triv
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- *Optimal
reconstr
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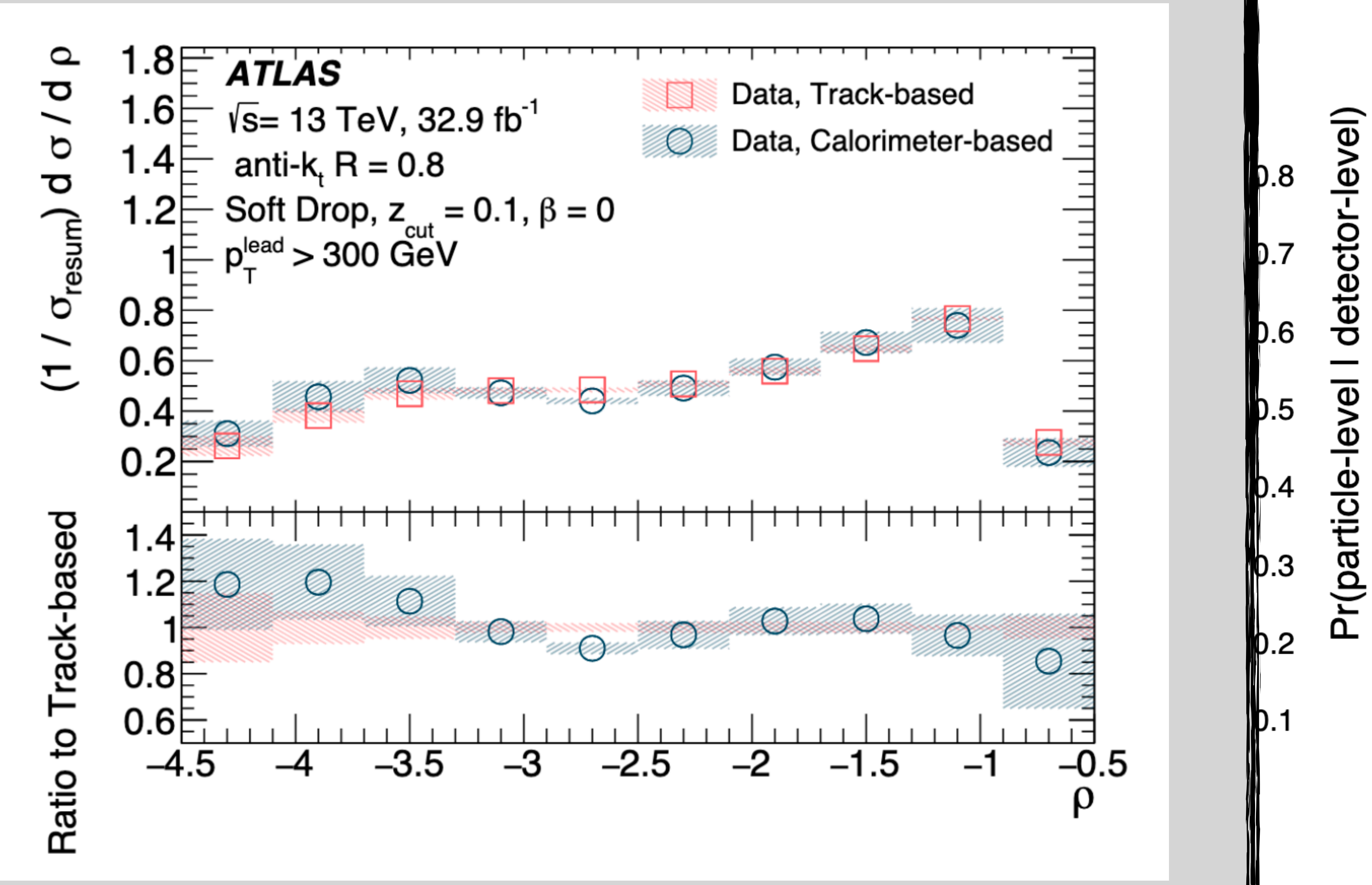
measurement*

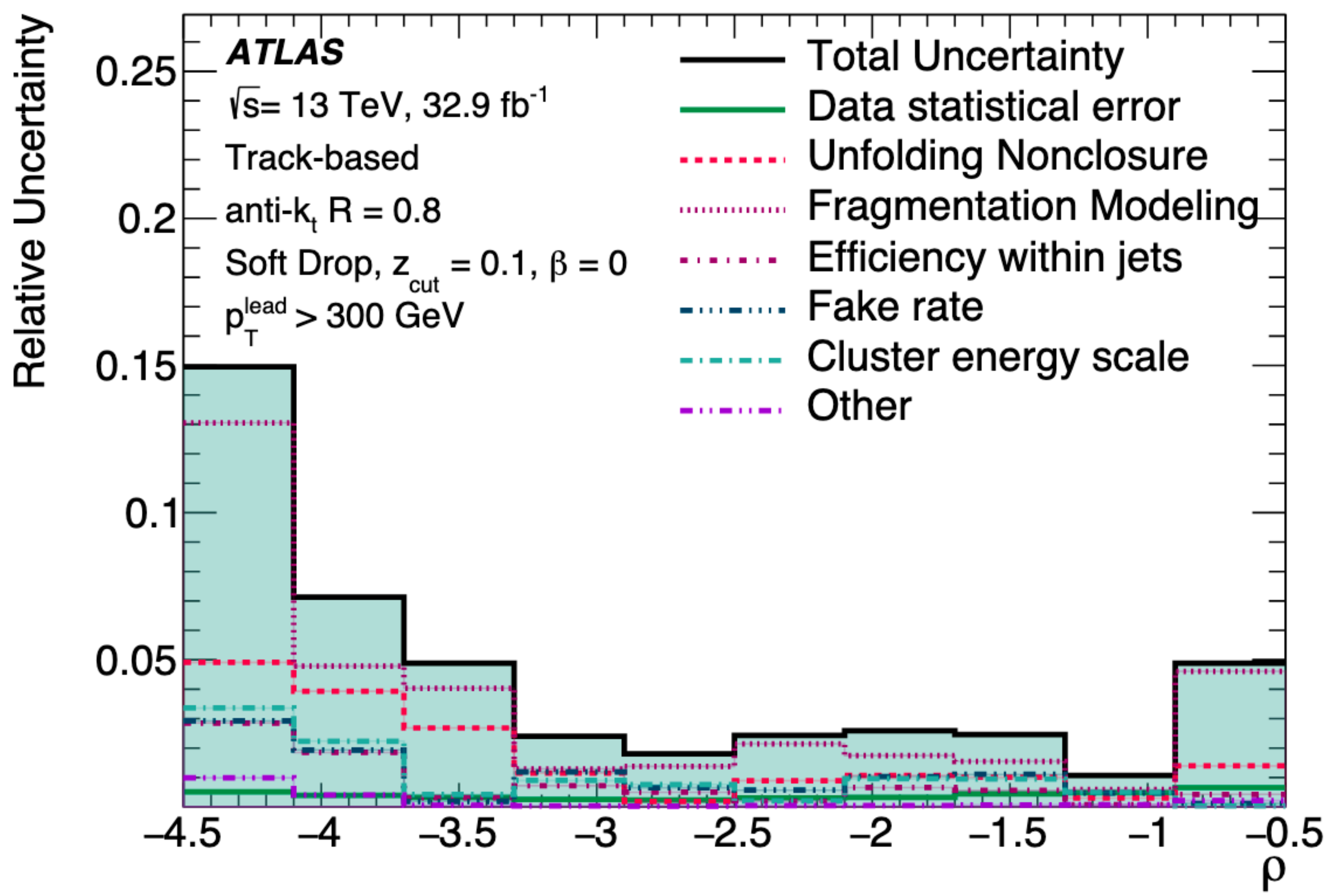
- Some track and cluster observables look similar on average
  - Particularly true where non-perturbative effects are small
- Tracking uncertainties are much smaller
  - No calculations exist for track-based observables (yet), but would be powerful experimentally

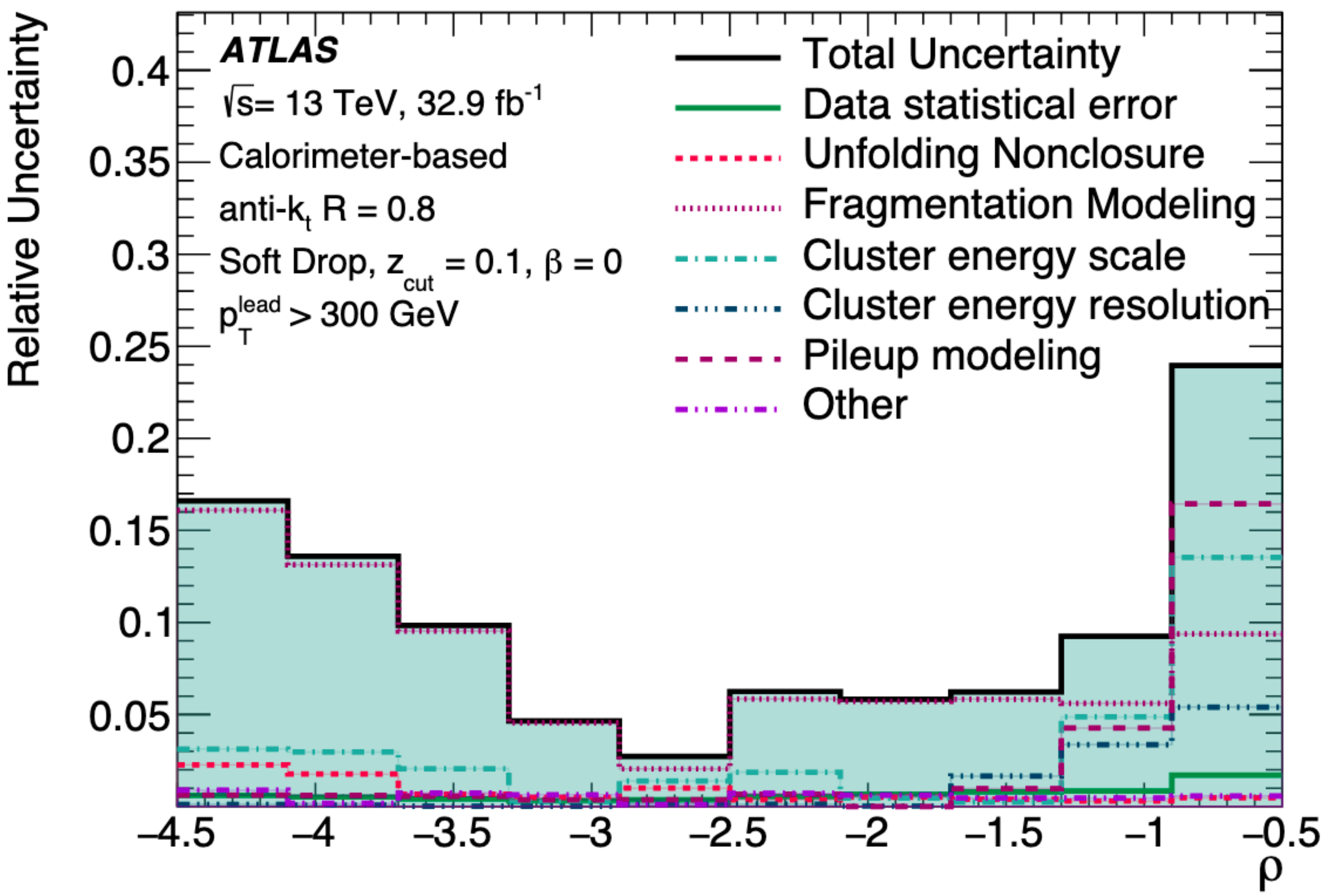


the jet mass

[1912.09837](1912.09837)

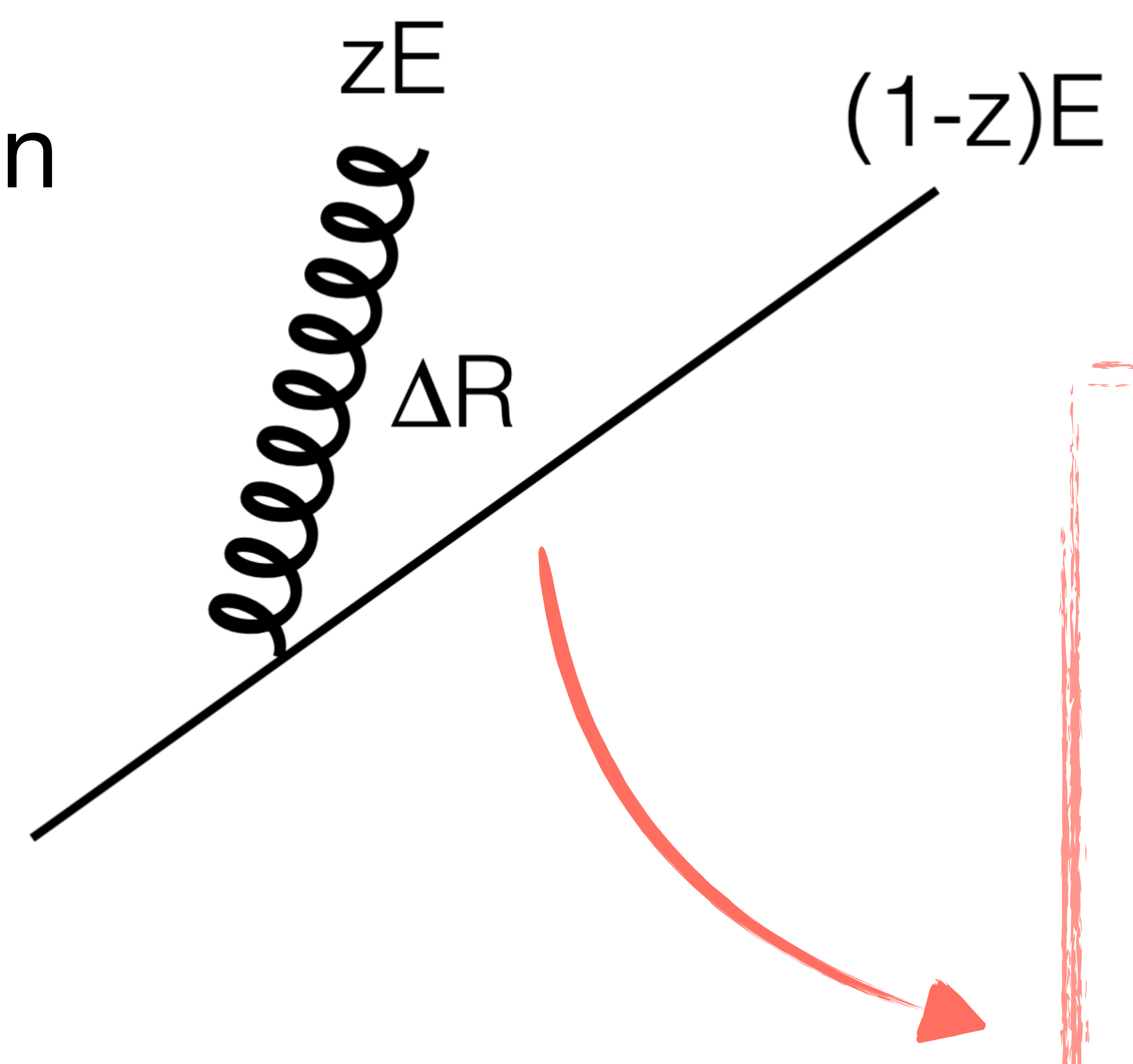
- Tracking uncertainties generally much smaller than cluster uncertainties
  - Track-based measurements are useful for increasing precision when not comparing to analytical predictions
- Modeling uncertainty also smaller, due to smaller migrations in the response matrix





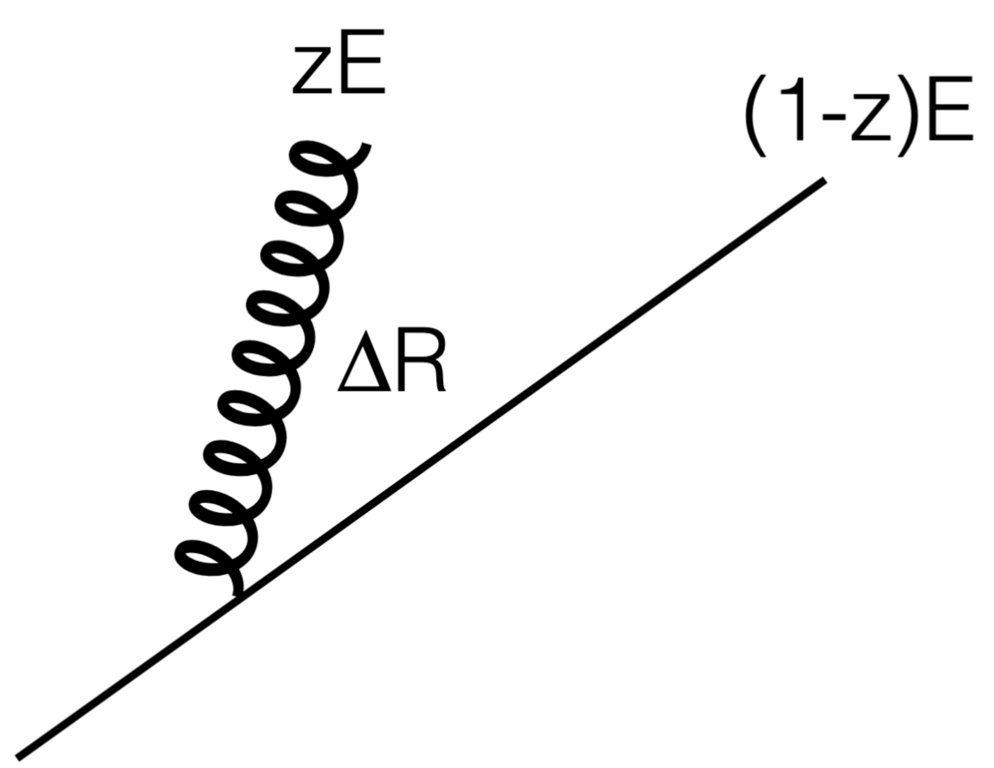
another direction: the lund plane

- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon
- Emissions may be characterized by
  - z = relative momentum of emission relative to the jet core
  - ΔR = angle of emission relative to the jet core



The Lund Plane is the phase space of these emissions: it naturally factorises perturbative and non-perturbative effects, UE/MPI, etc.

another direction: the lund plane



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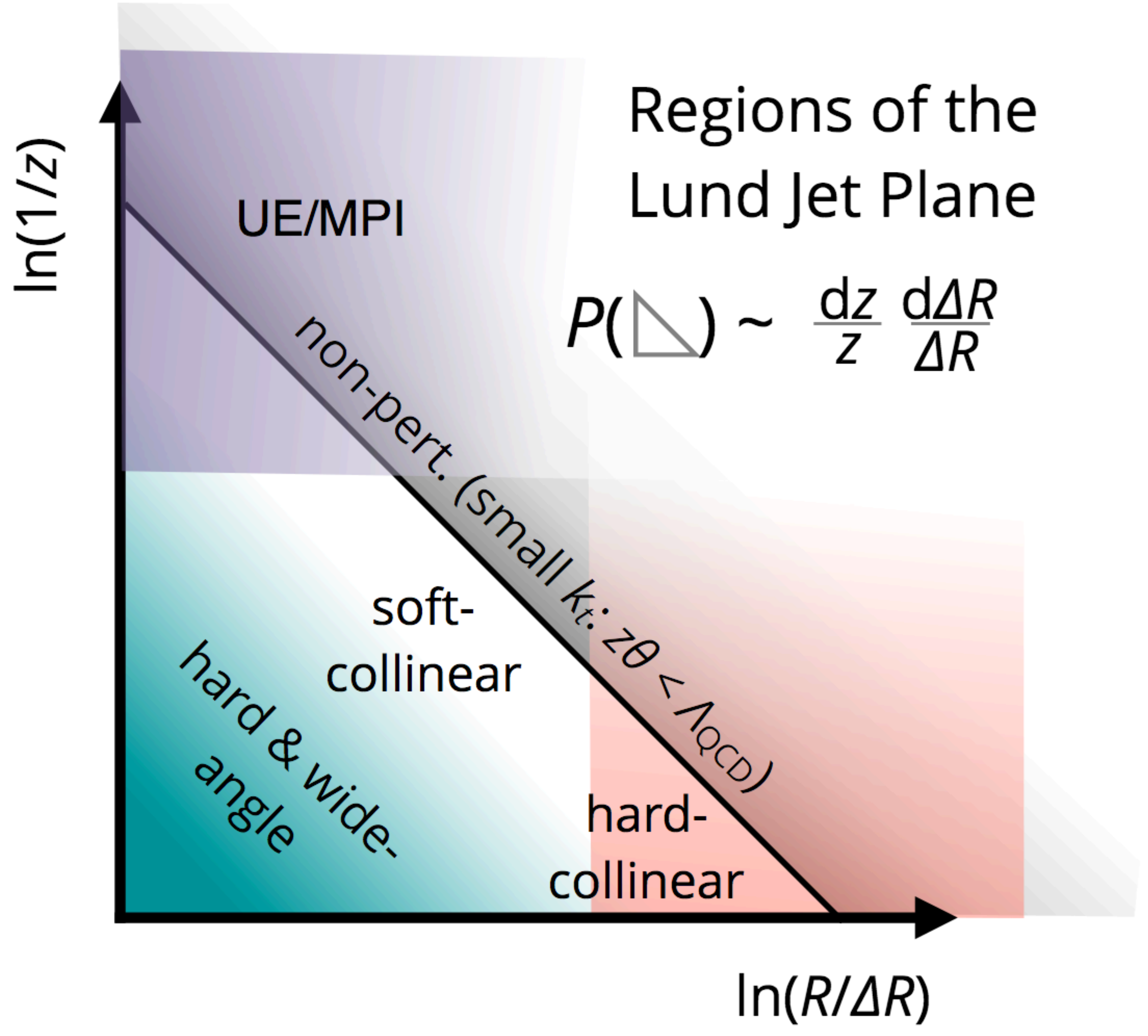

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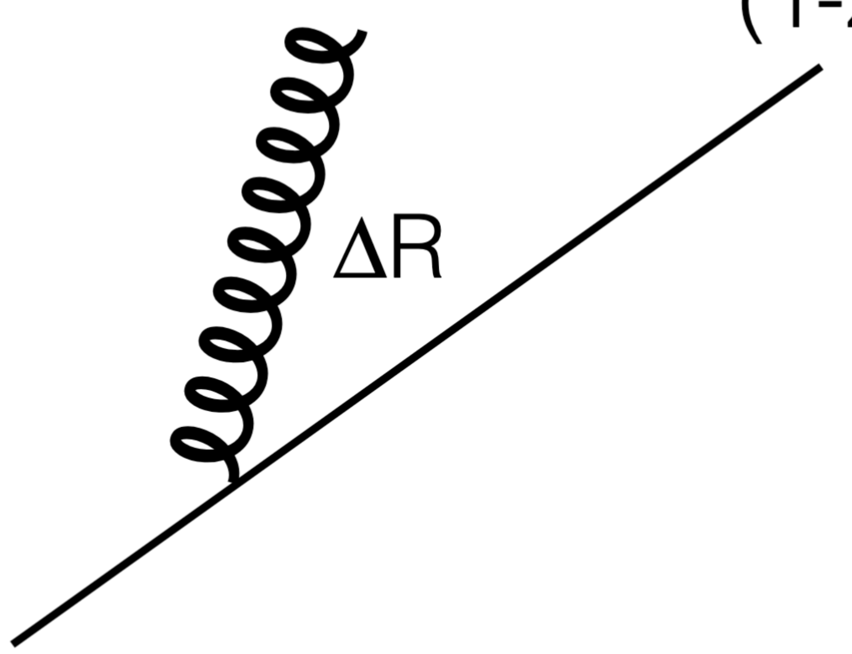

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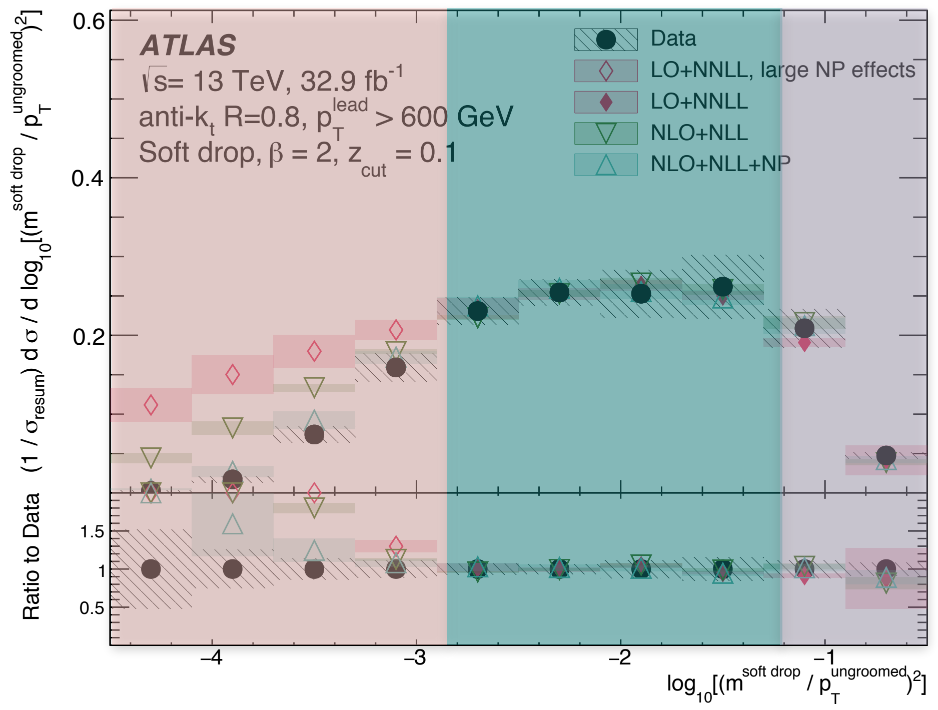
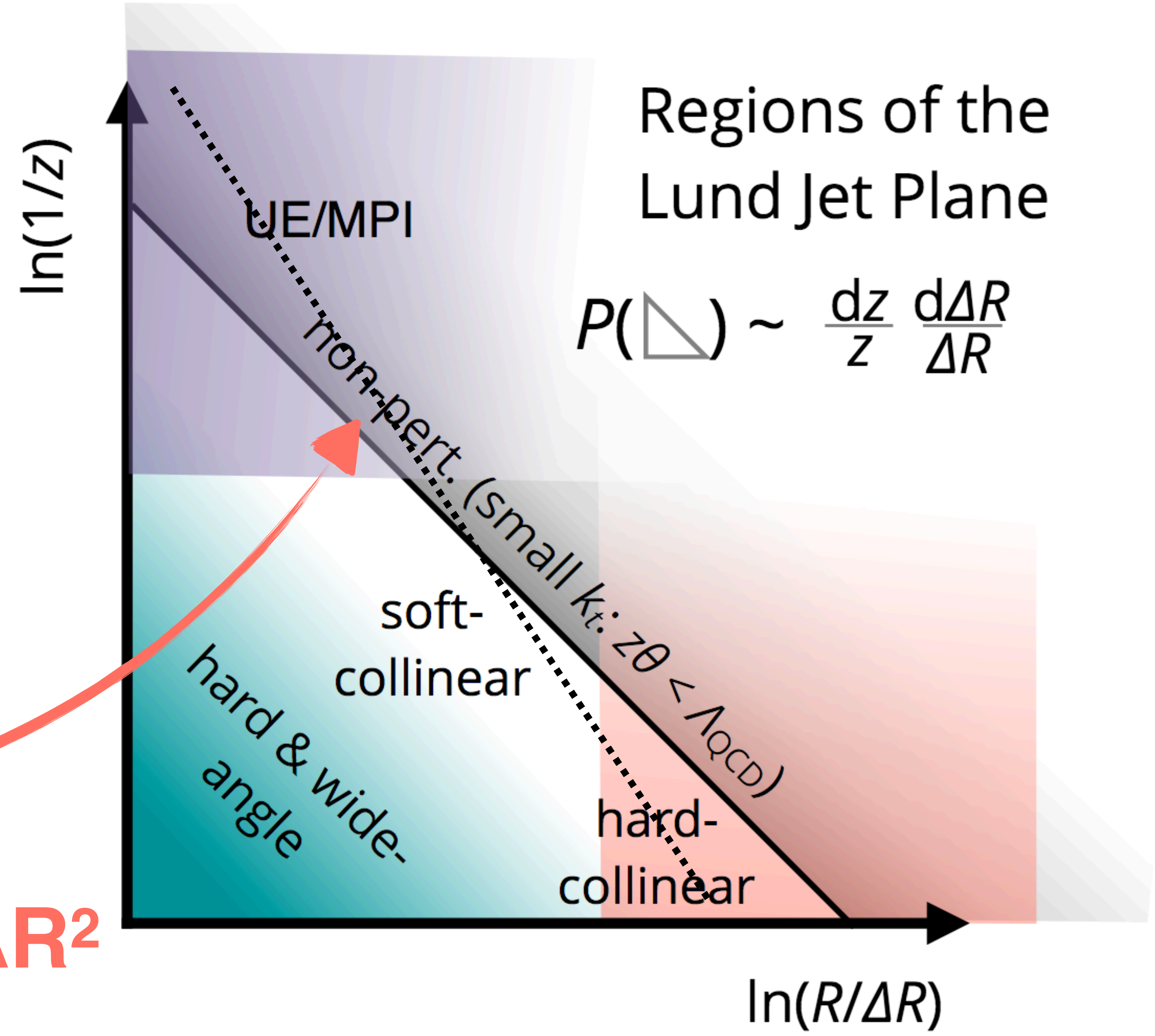


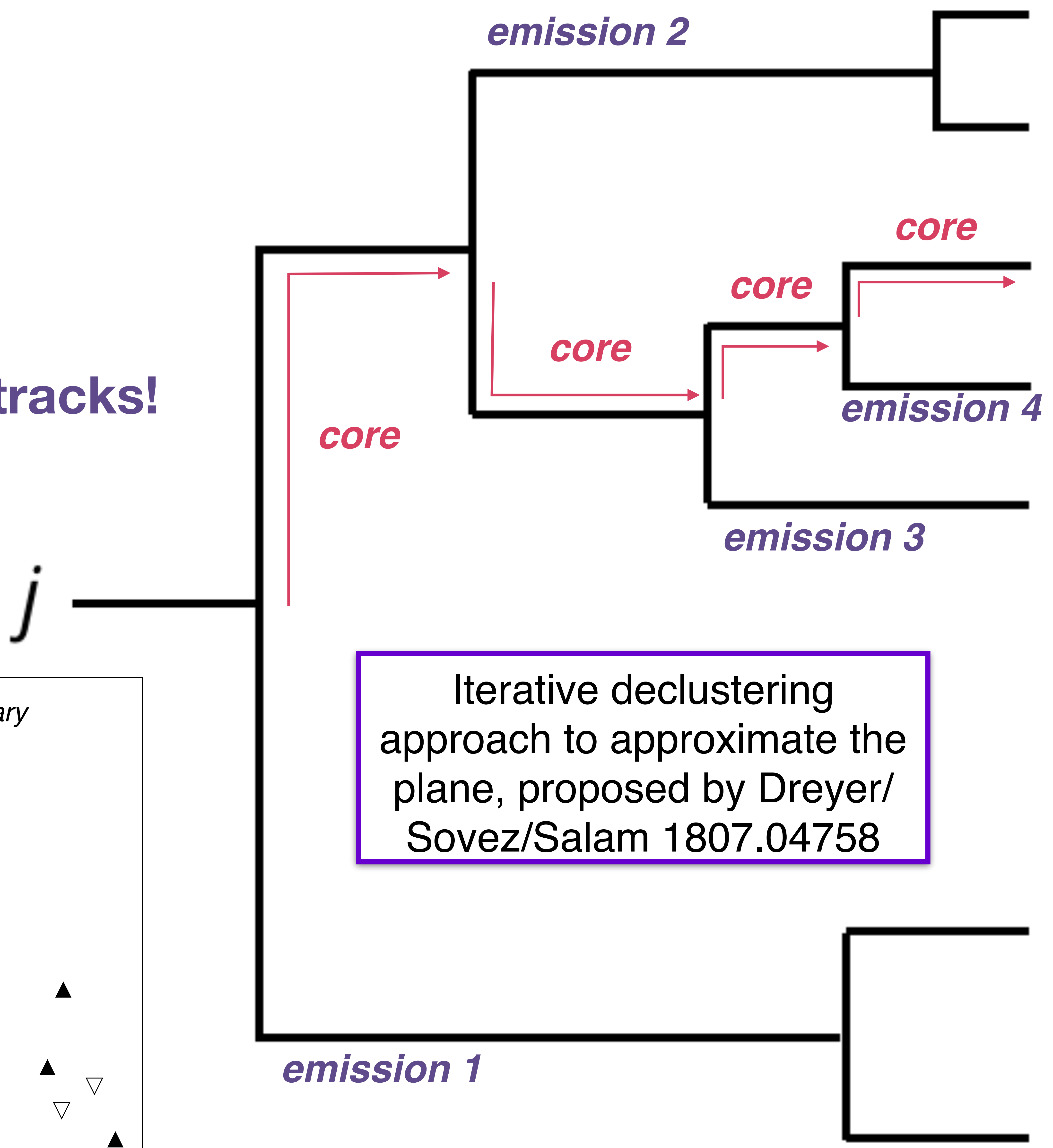
The jet mass is just one diagonal line in this space

m ~ z*ΔR²



the lund jet plane

ATLAS-CONF-2019-035

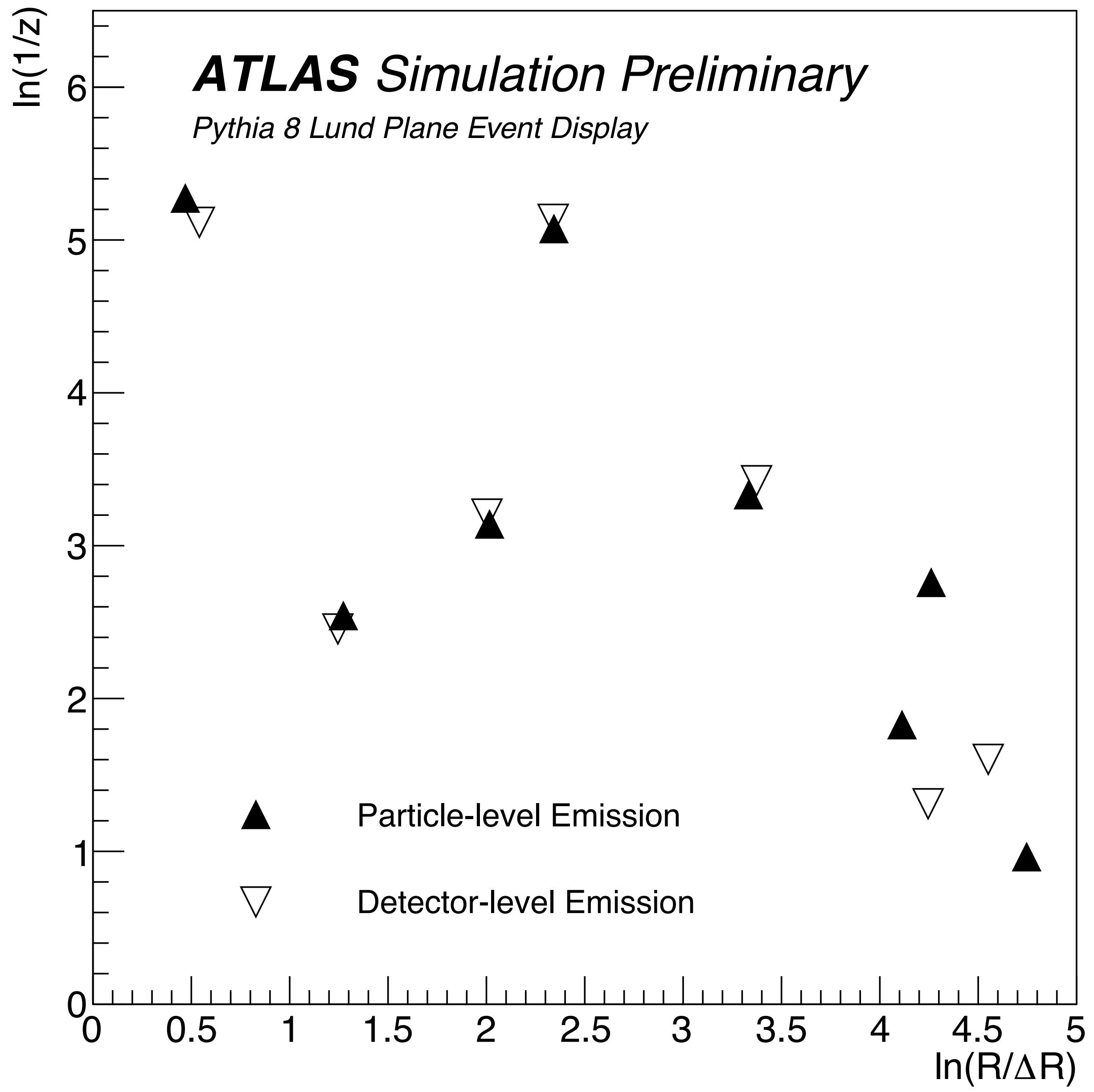


1. Jet Finding:
Cluster jets using your favorite jet algorithm

2. C/A Reclustering:
Combine closest pairs of **charged particles or tracks!**

3. C/A Declustering:
Unwind, widest angles first. Each step is an **emission**, or, a point in the Lund Jet Plane!

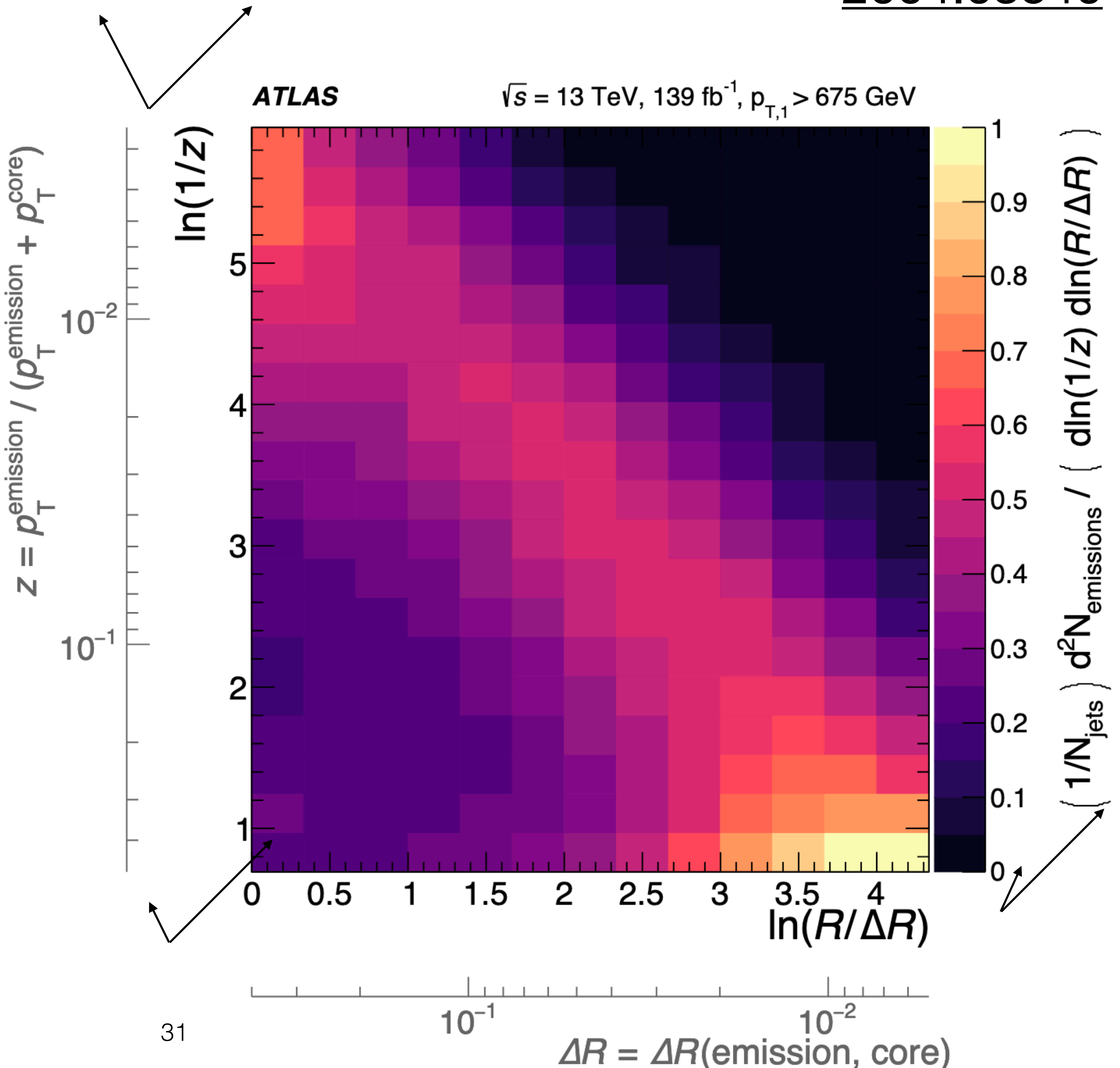
4. Plot Emissions:
Characerize emissions based on their angle (ΔR), and the hardness of the splitting and $z = p_T^{emission} / p_T$



2004.03540

the lund jet plane

- Unfolded the primary Lund plane in dijet events
- Use tracks associated to the jets in order to have precise measurements for small splittings
  - Unfolded to charged particle level



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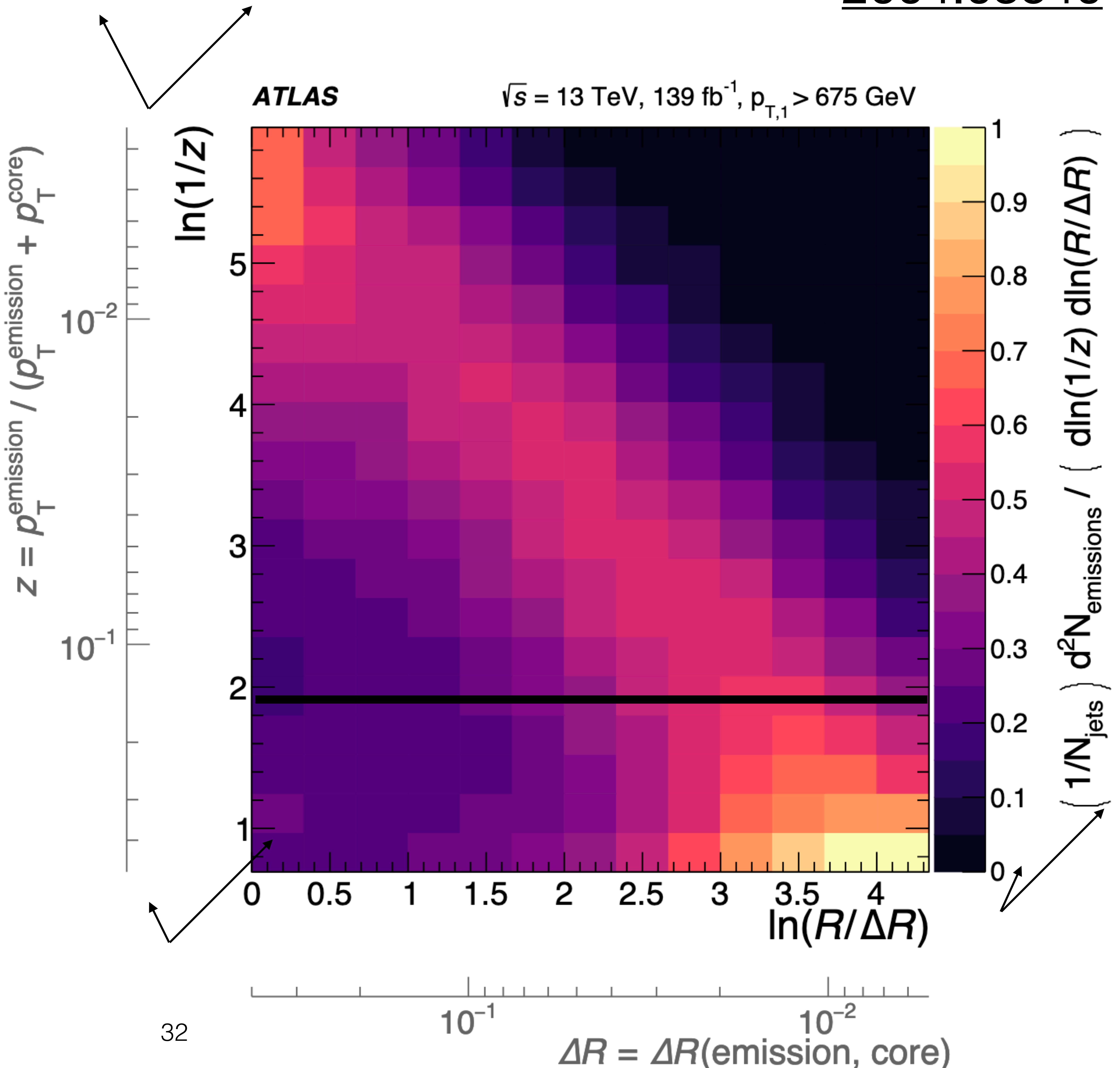

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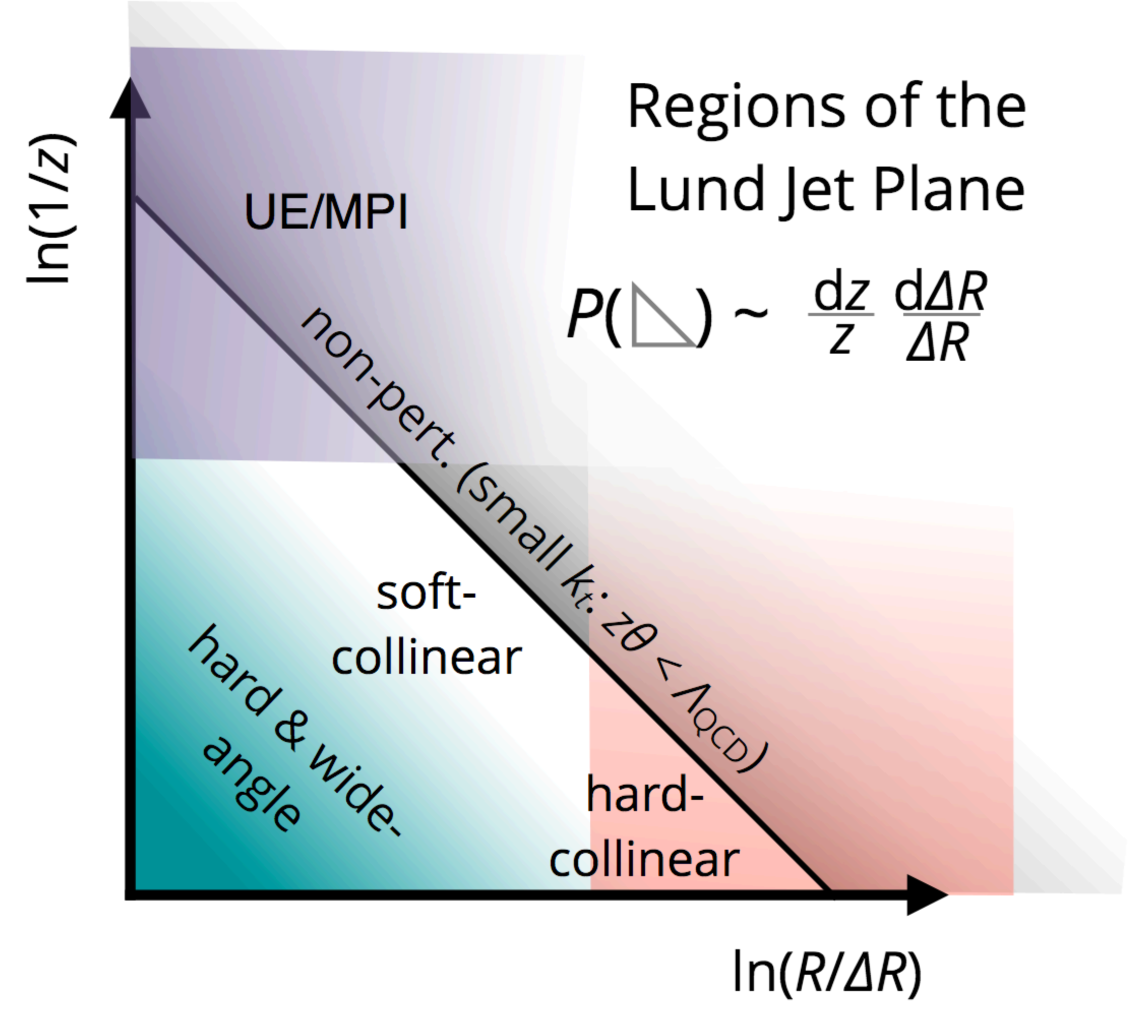
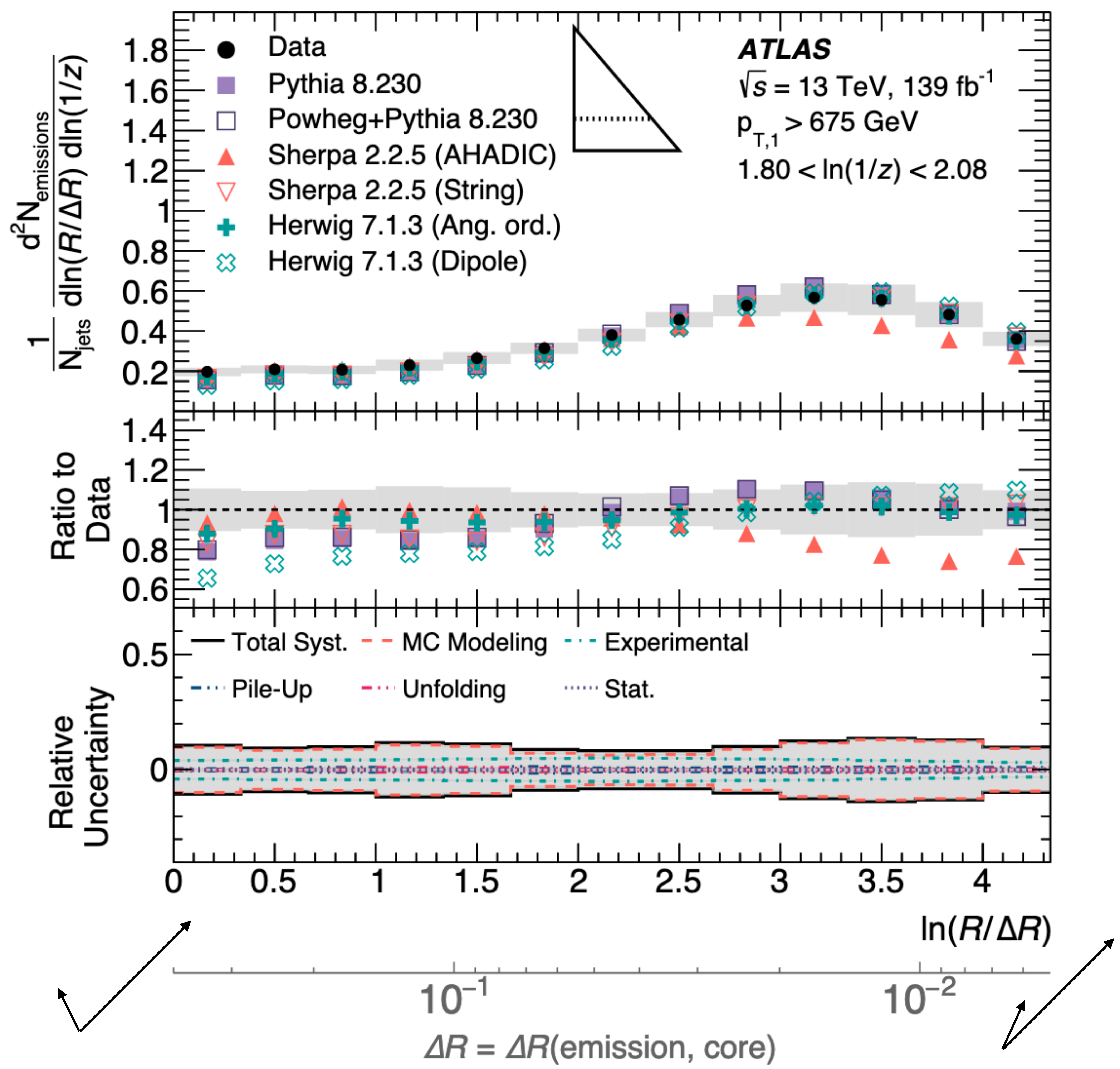
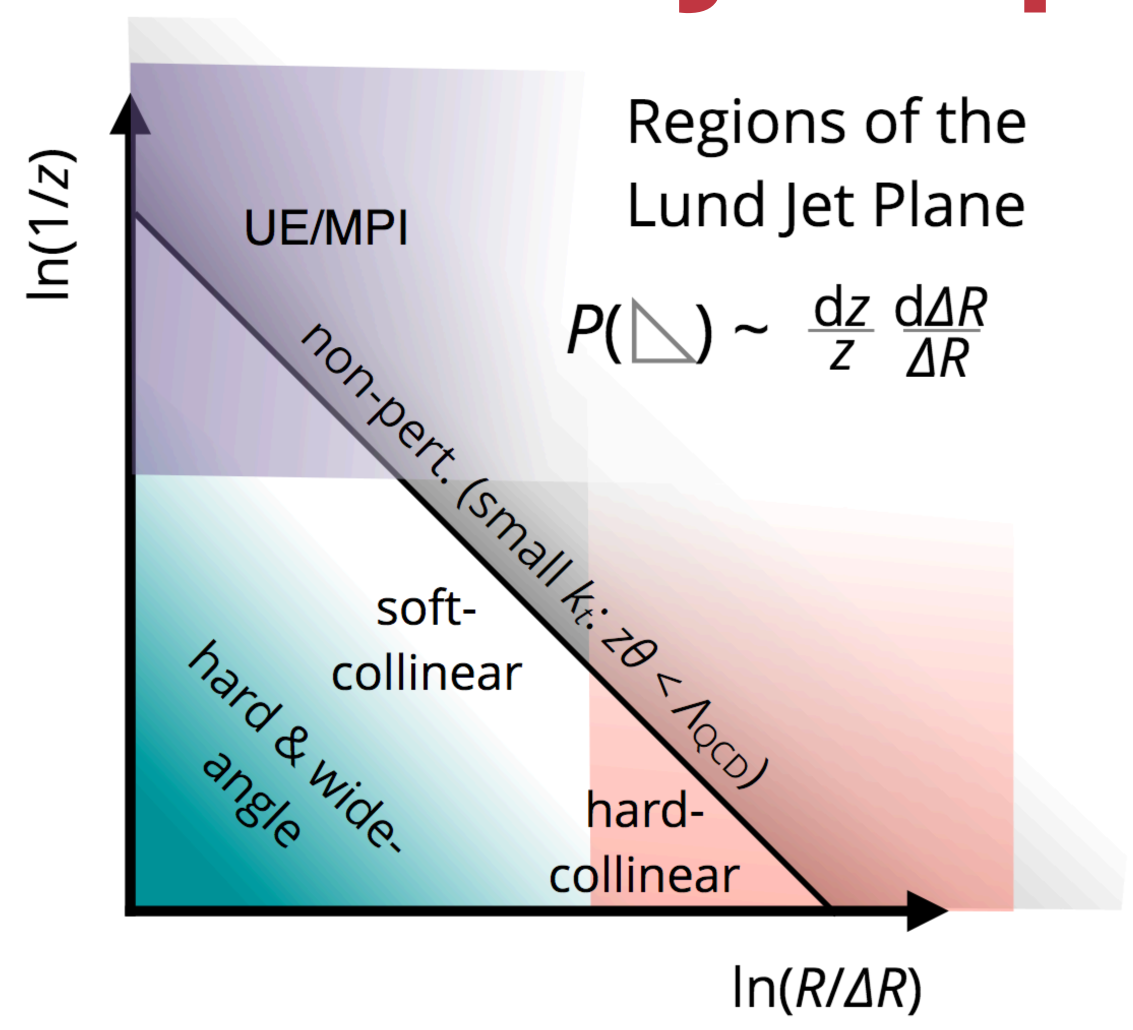


$P(\triangle) \sim \frac{dz}{z}\frac{d\Delta R}{\Delta R}$



- Non-trivial differences between different generators and unfolded data
- Region dominated by hard and wide-angle splitting is affected by parton shower
- Hadronization effects in region with non-perturbative effects

the lund jet plane



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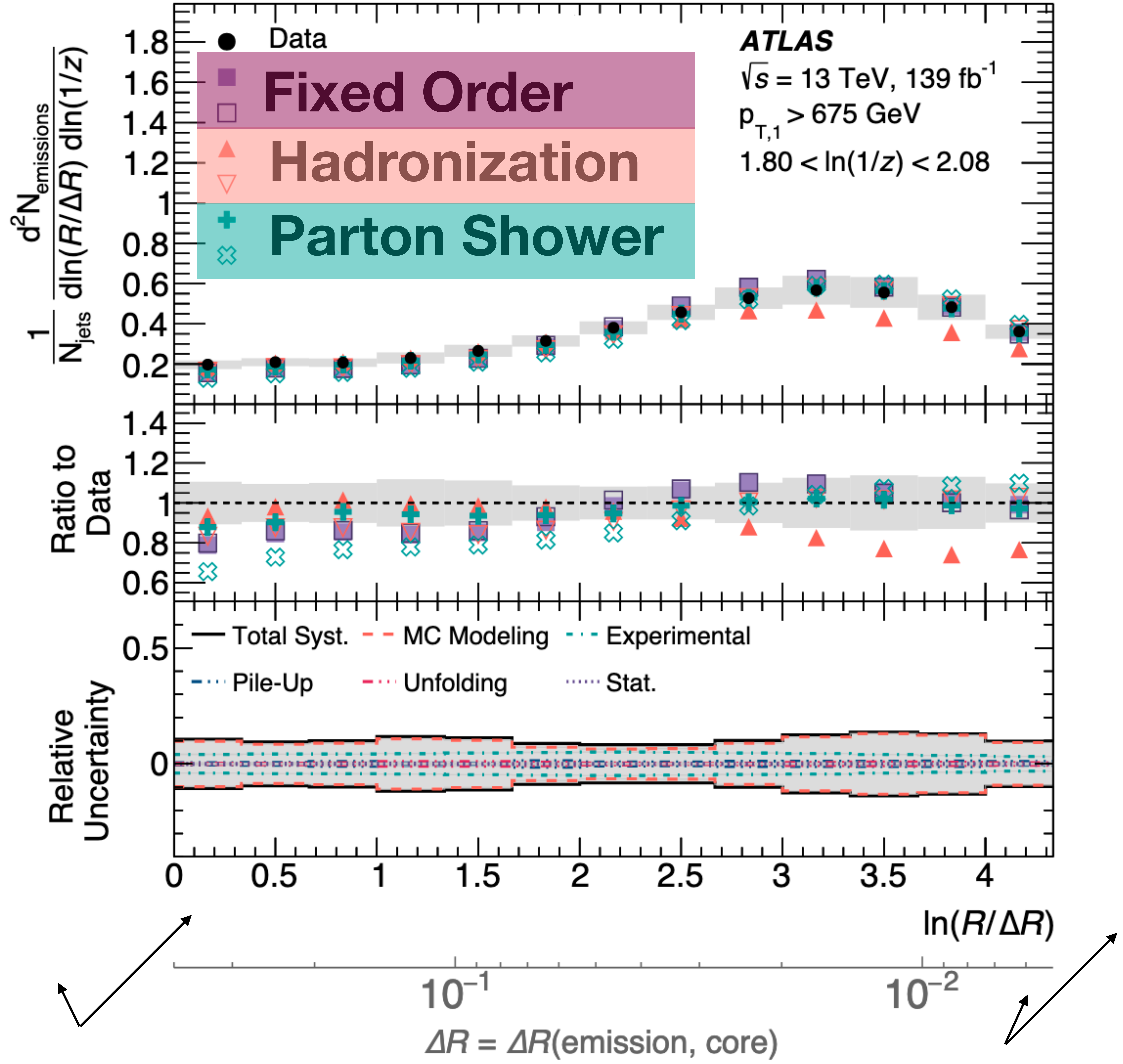

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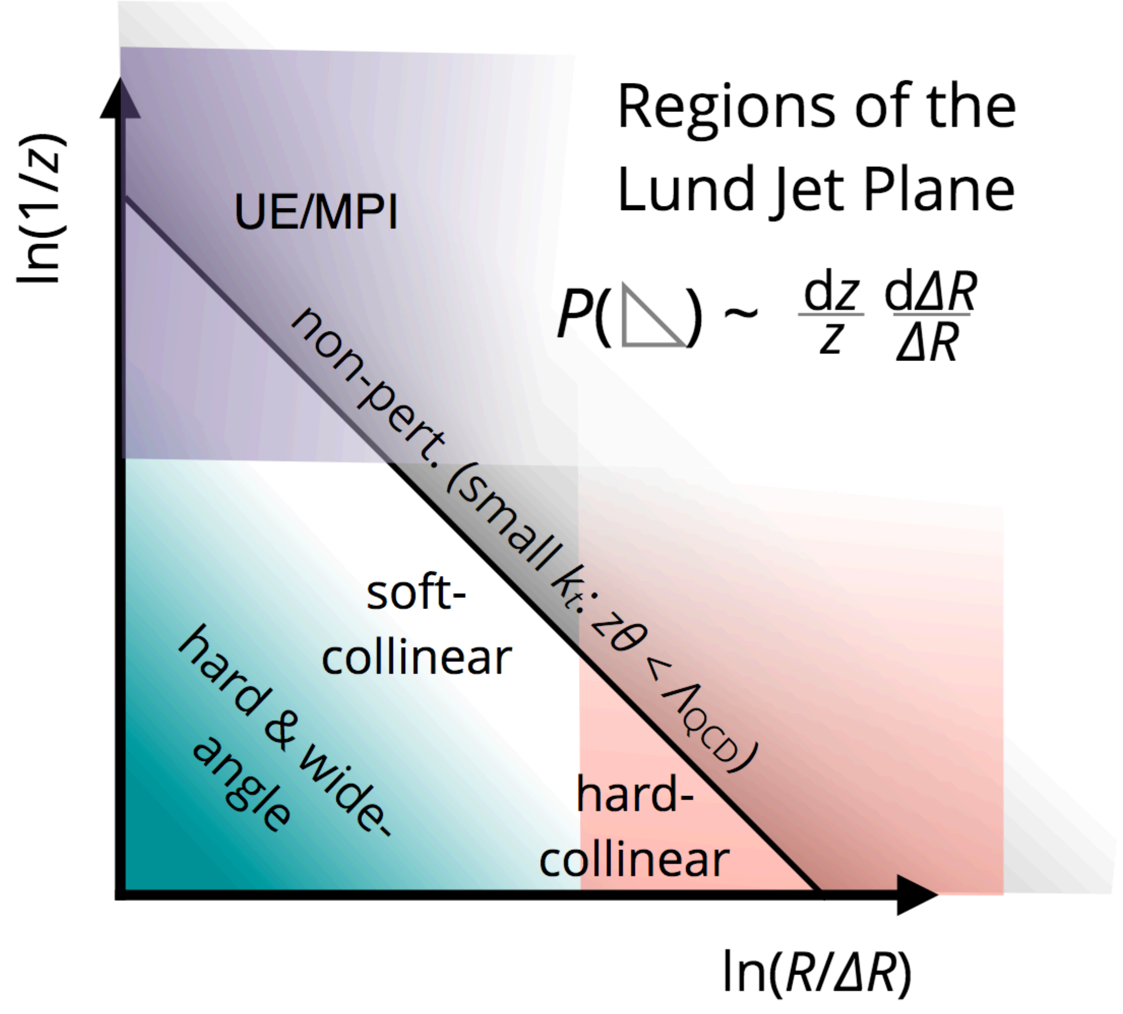

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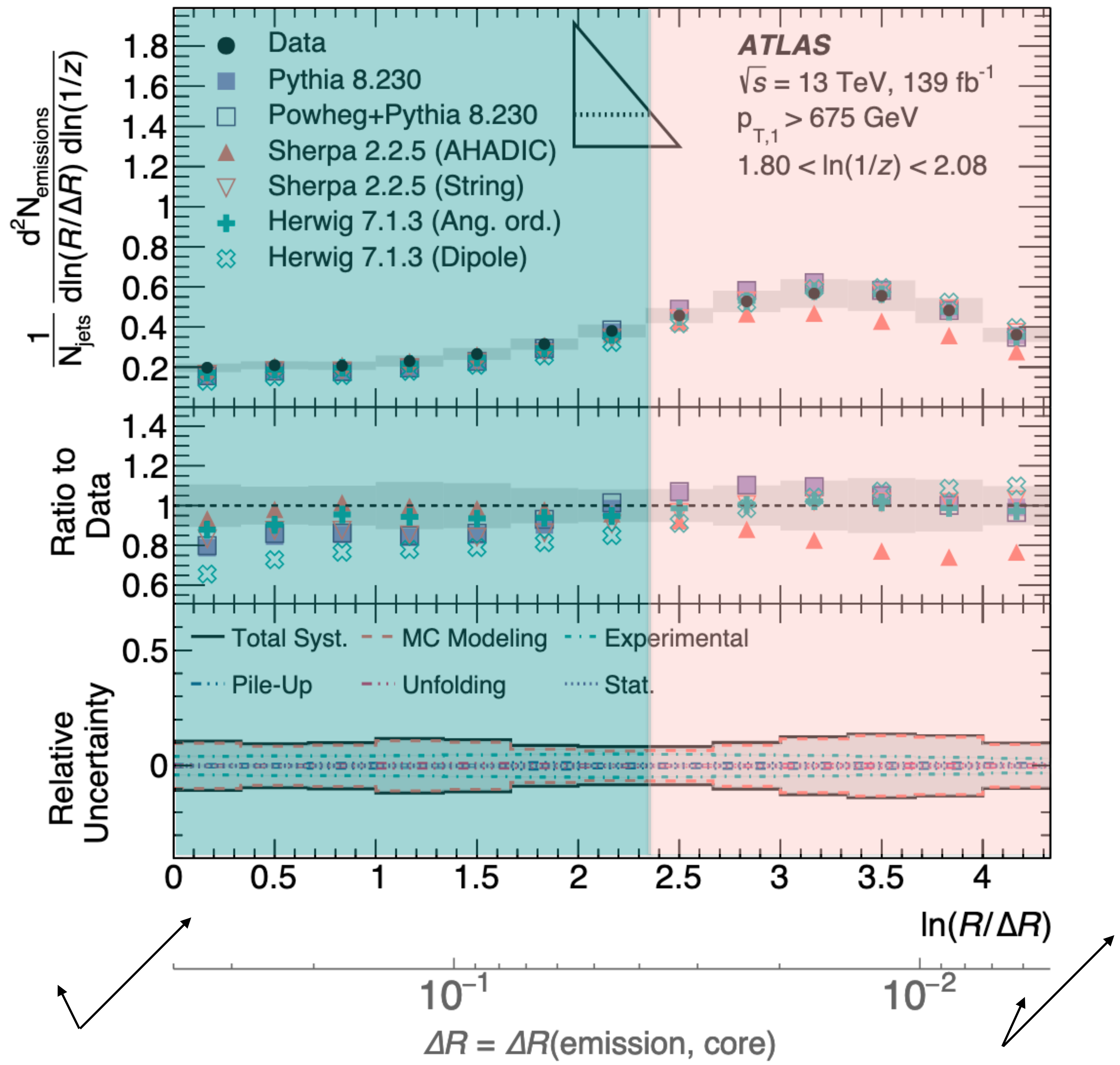
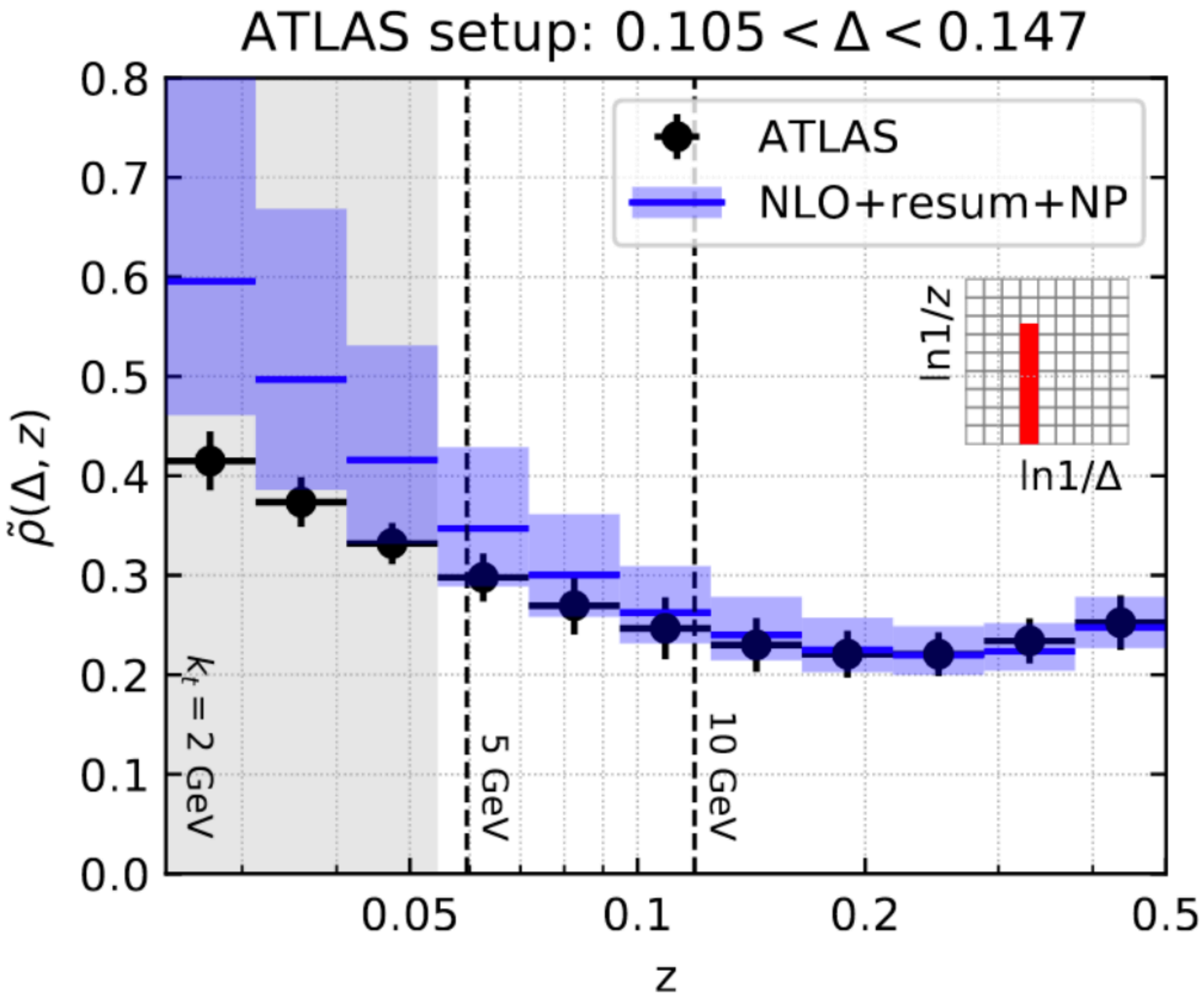


the lund jet plane

A. Lifson, G. Salam, G. Soyez

2007.06578

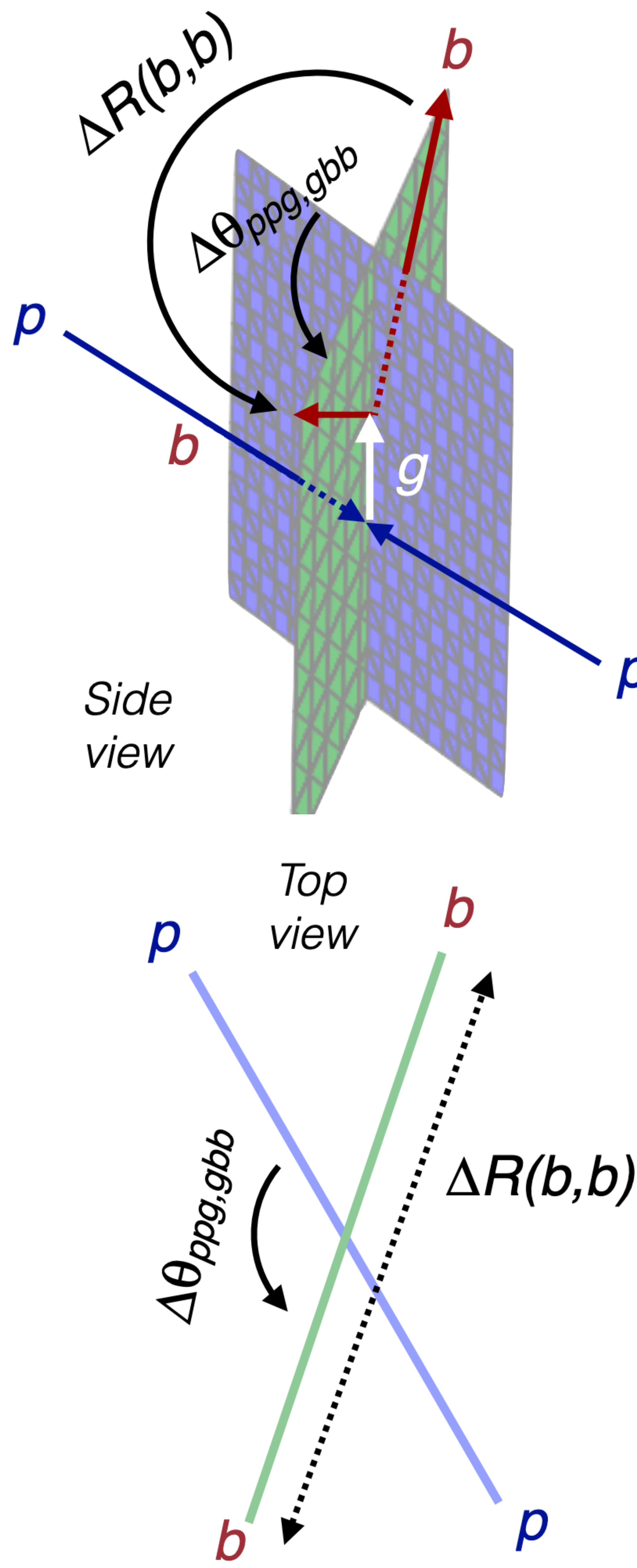
- Possible to produce predictions for parts of the Lund jet plane
  - Accurate down to k_t of ~5 GeV
- Example of substructure prediction without grooming algorithm!
  - Work ongoing to extend this to higher logarithmic accuracy



1812.09283

measurement of g→bb properties

- Gluon fragmentation is challenging to measure, and also important for background modeling
  - In particular, focusing on small angular scales, by using b-tagged subjets within large-R jets
- Using templates to estimate the background for g→bb events



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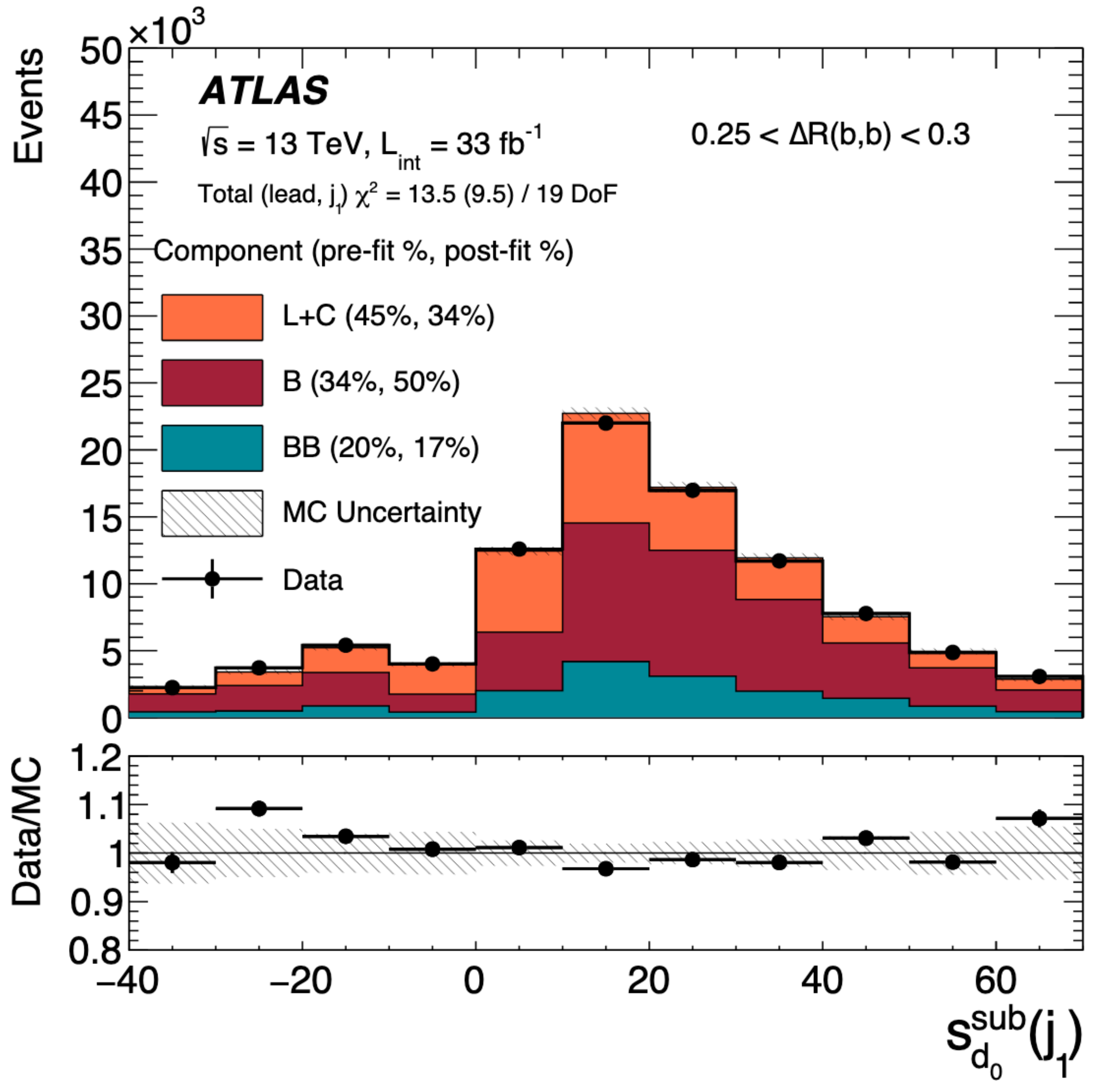
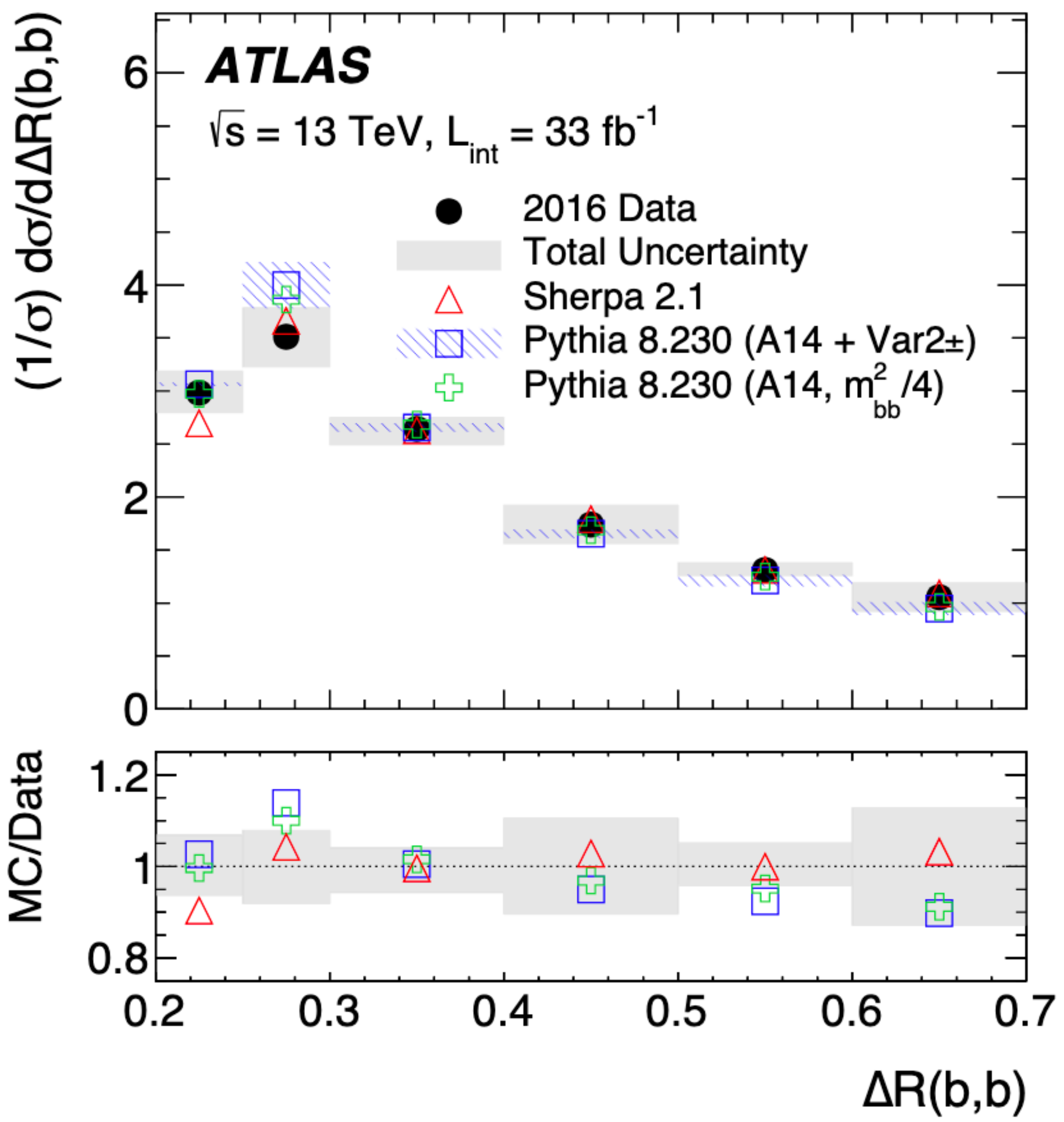
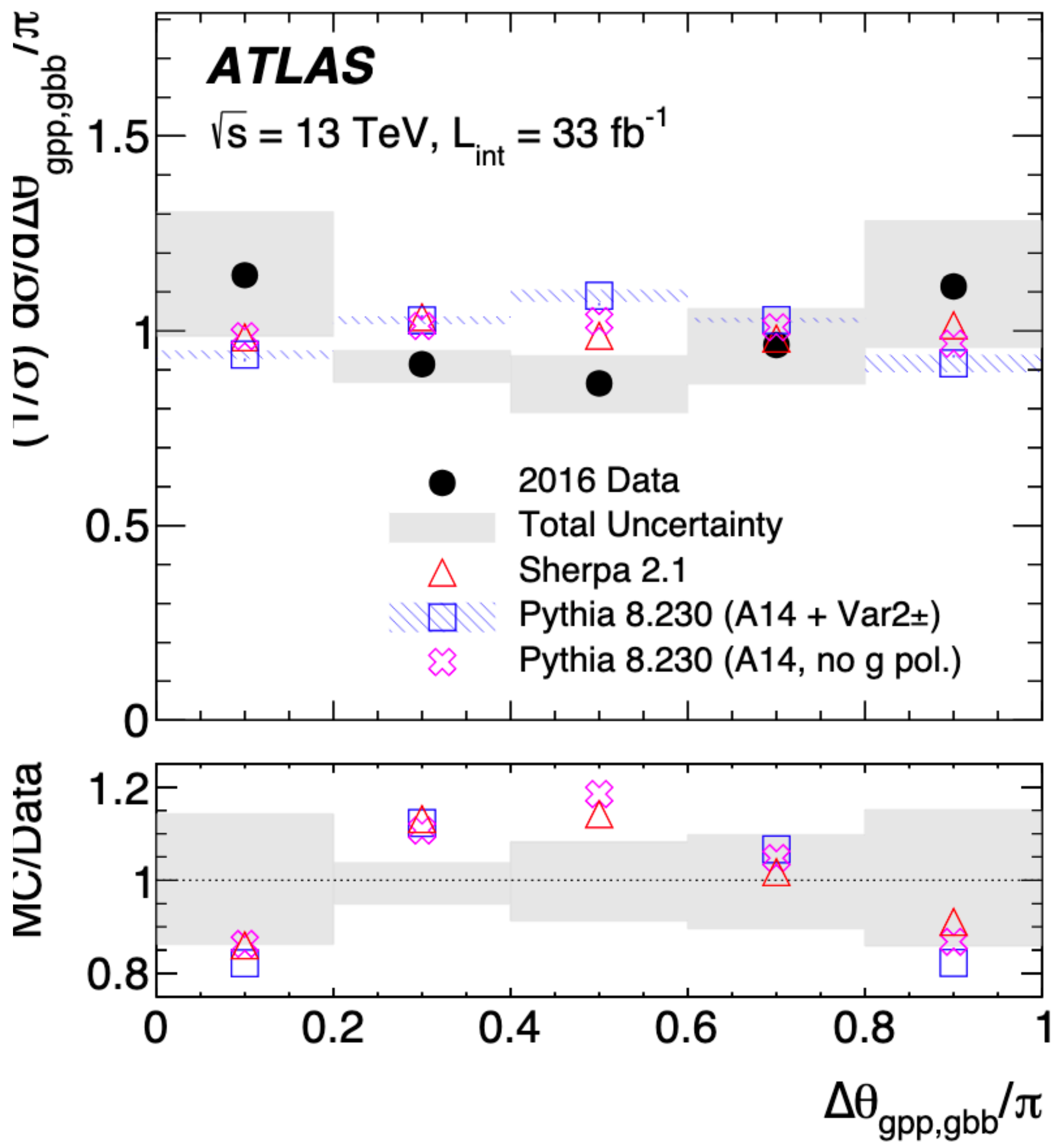
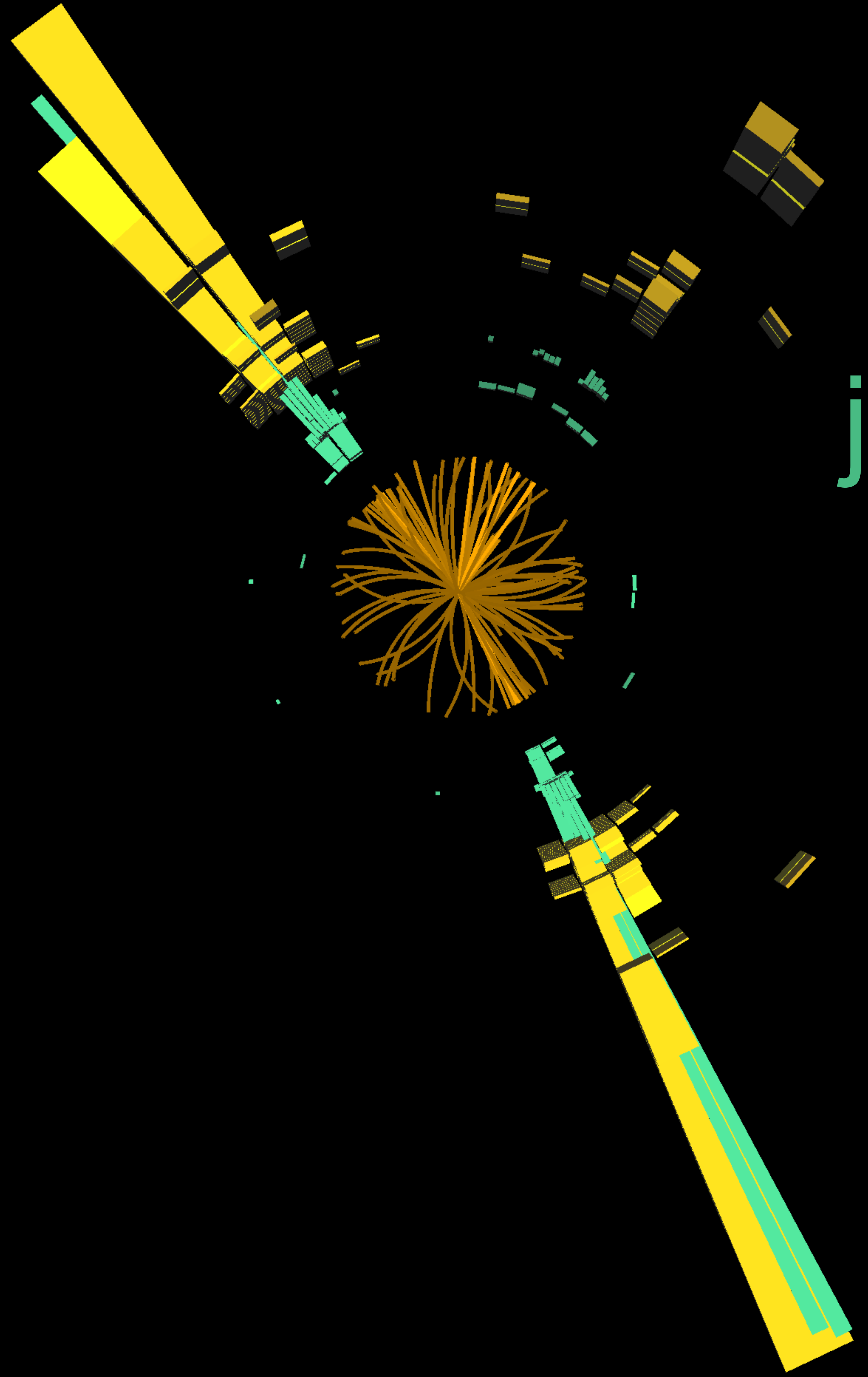




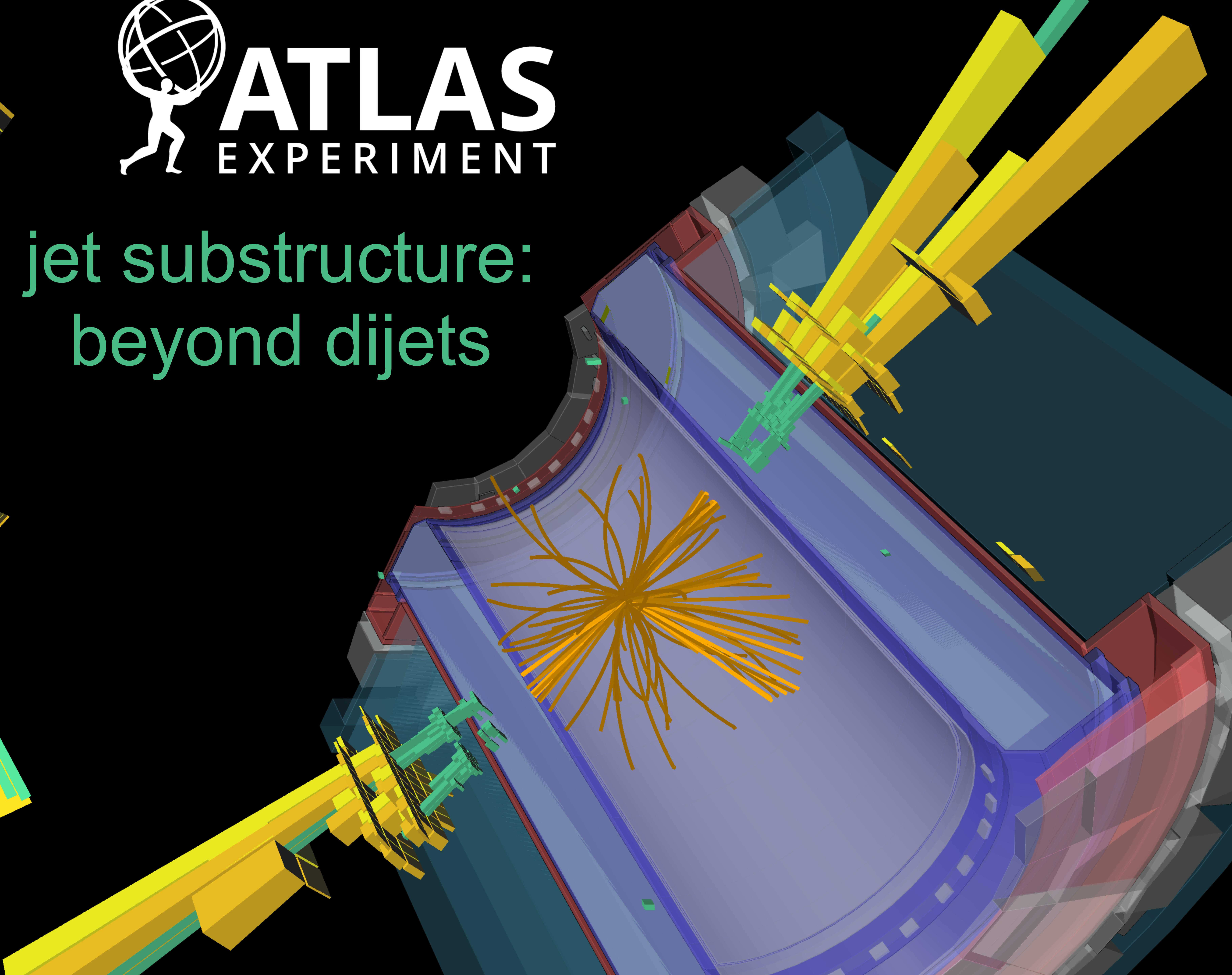


- Certain aspects of the gluon fragmentation are not well-modeled by any of the studied MC predictions

ATLAS
EXPERIMENT



jet substructure: beyond dijets



jet substructure observables in top quark, *W* boson, and light jet production

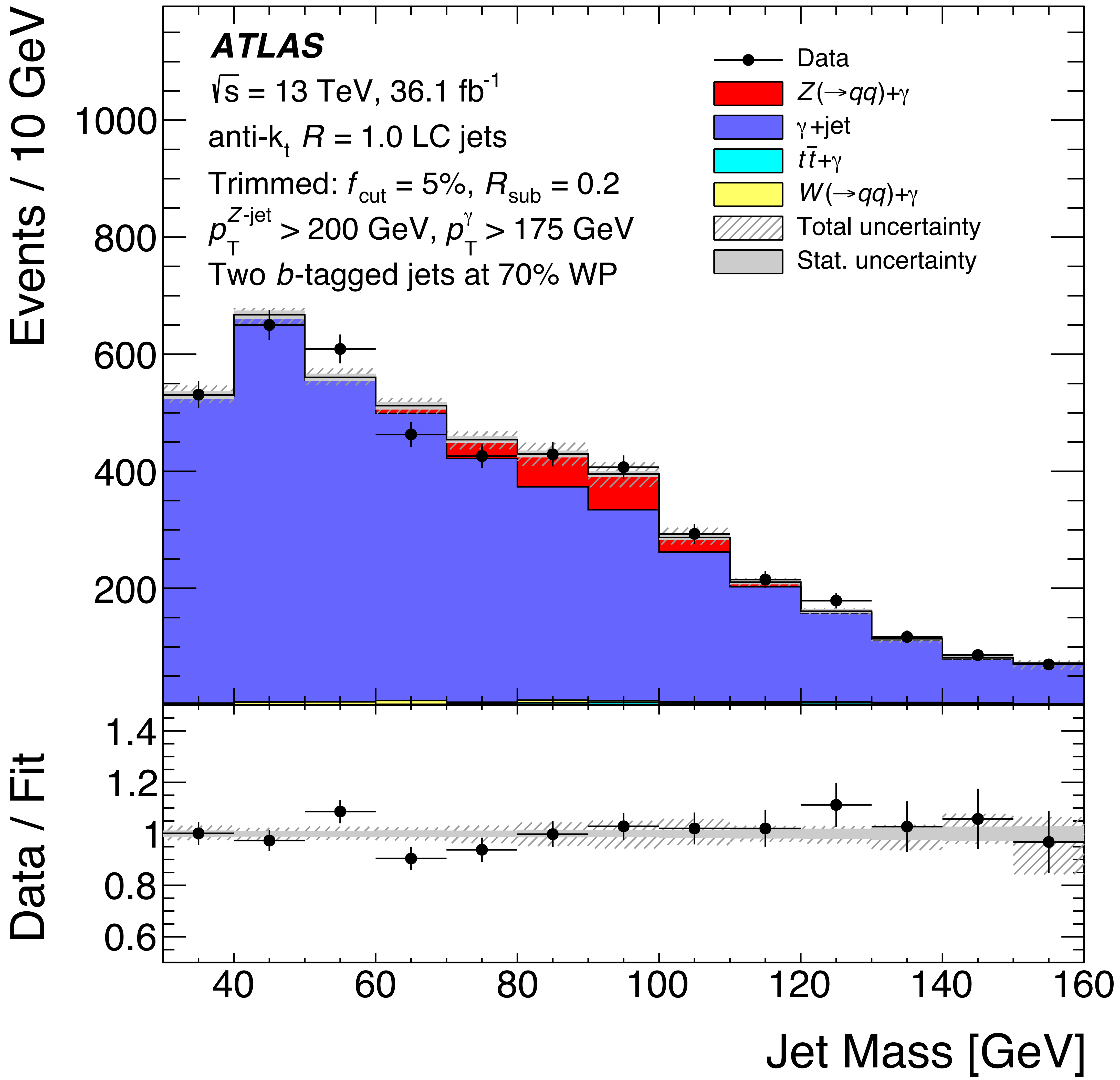
- Measured a wide range of substructure observables in 3 different topologies
  - Studied observables commonly used for tagging → important input for tuning MC generators
- Measured using cluster-based uncertainties (like the soft drop jet mass)

1903.0294

$Z(\rightarrow bb) + \gamma$

1907.07093

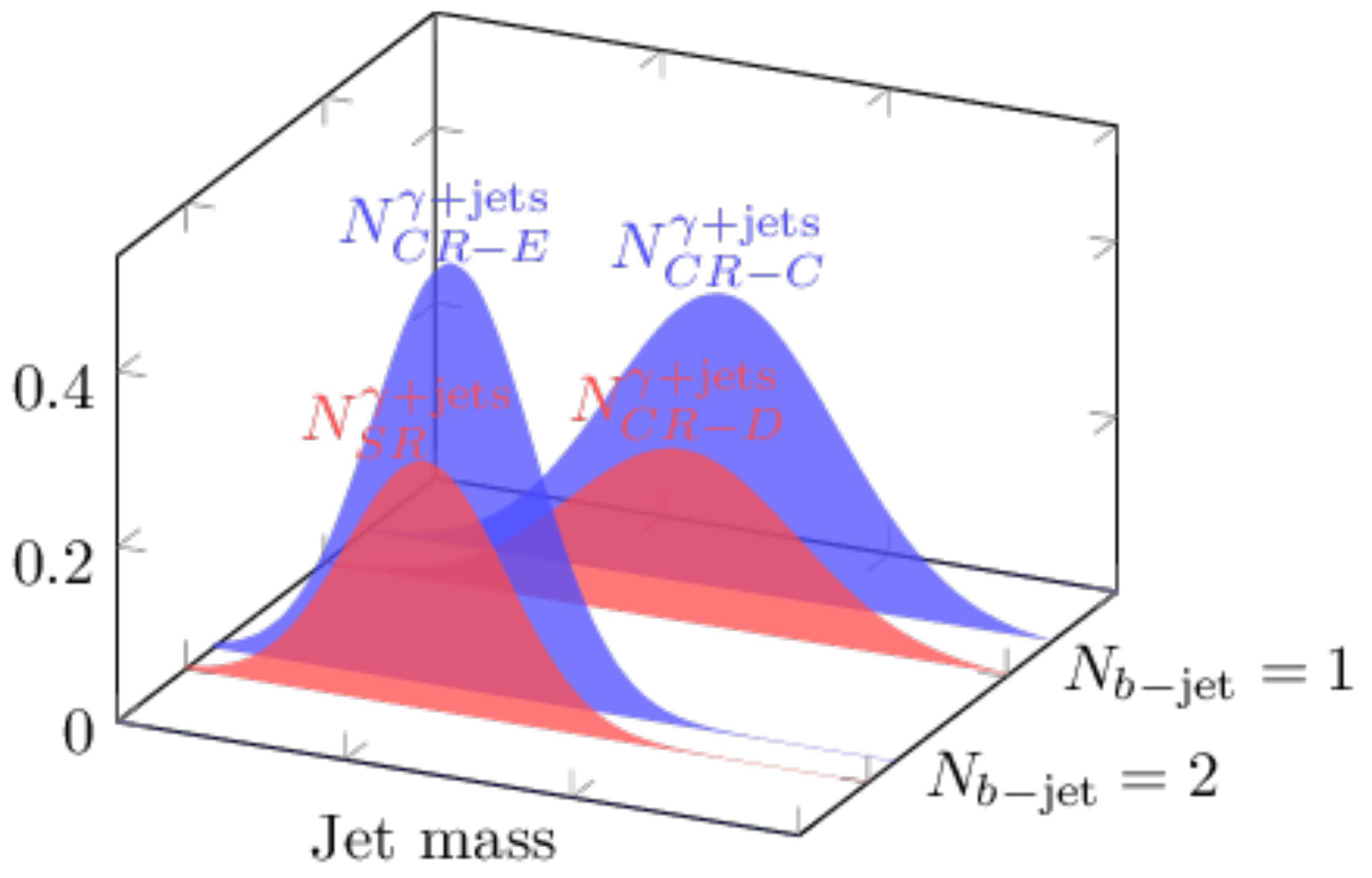
- First measurement of unfolded jet mass spectrum of hadronically decaying Z bosons at the LHC
- Important for understanding boosted boson hadronic decays (color singlets)
  - Have measurements of color octet states such as $g \rightarrow bb$



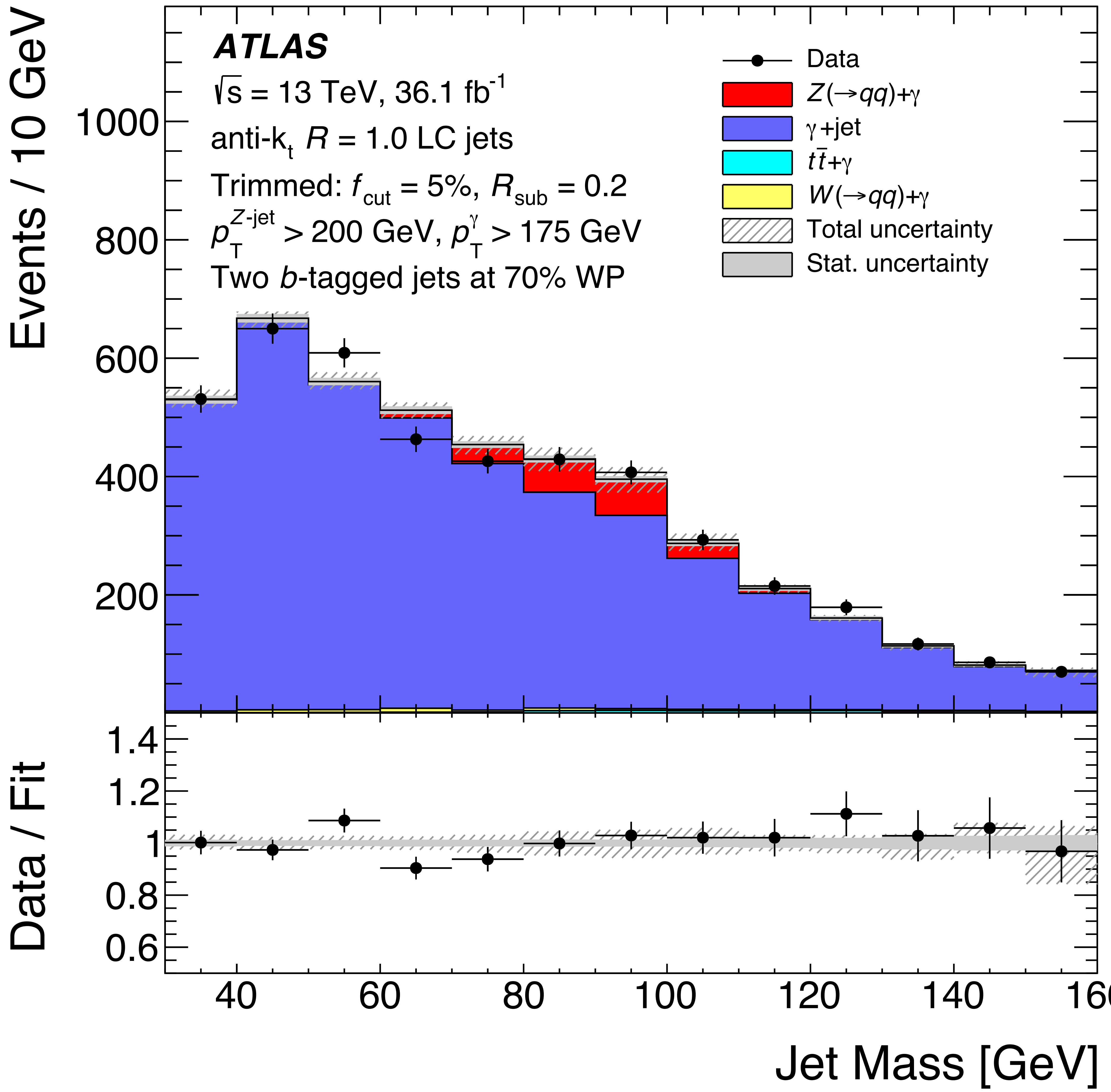
Z(→bb) + γ

1907.07093

- Use γ to trigger on events and for background estimation
- Reconstructing both Z boson decay products within a single large-R jet
  - Require two R=0.2 b-tagged subjets to be associated to the large-R jet
- Simultaneously fit signal and background templates to Z(→bb) mass distribution

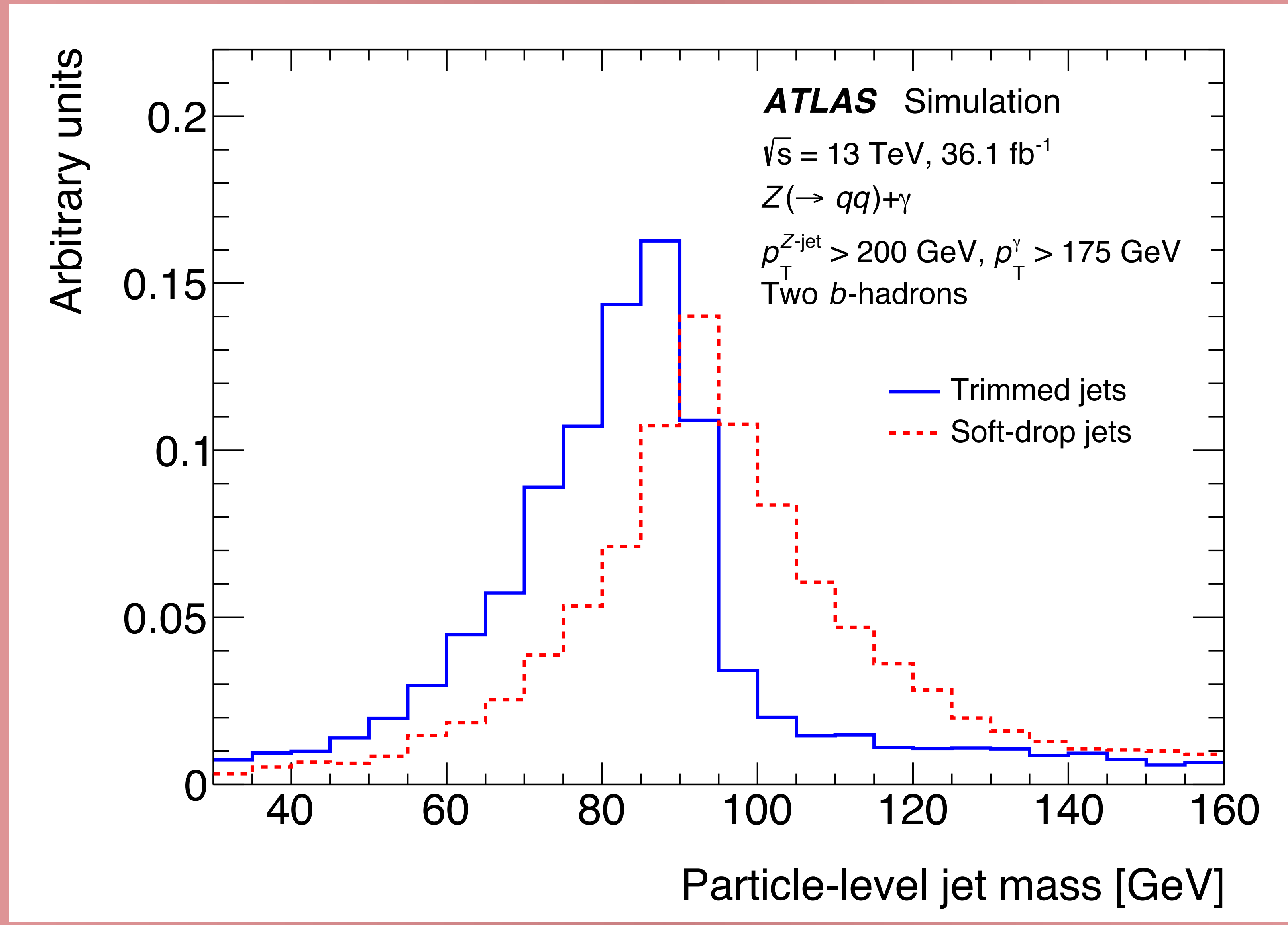


non-tight γ, tight γ

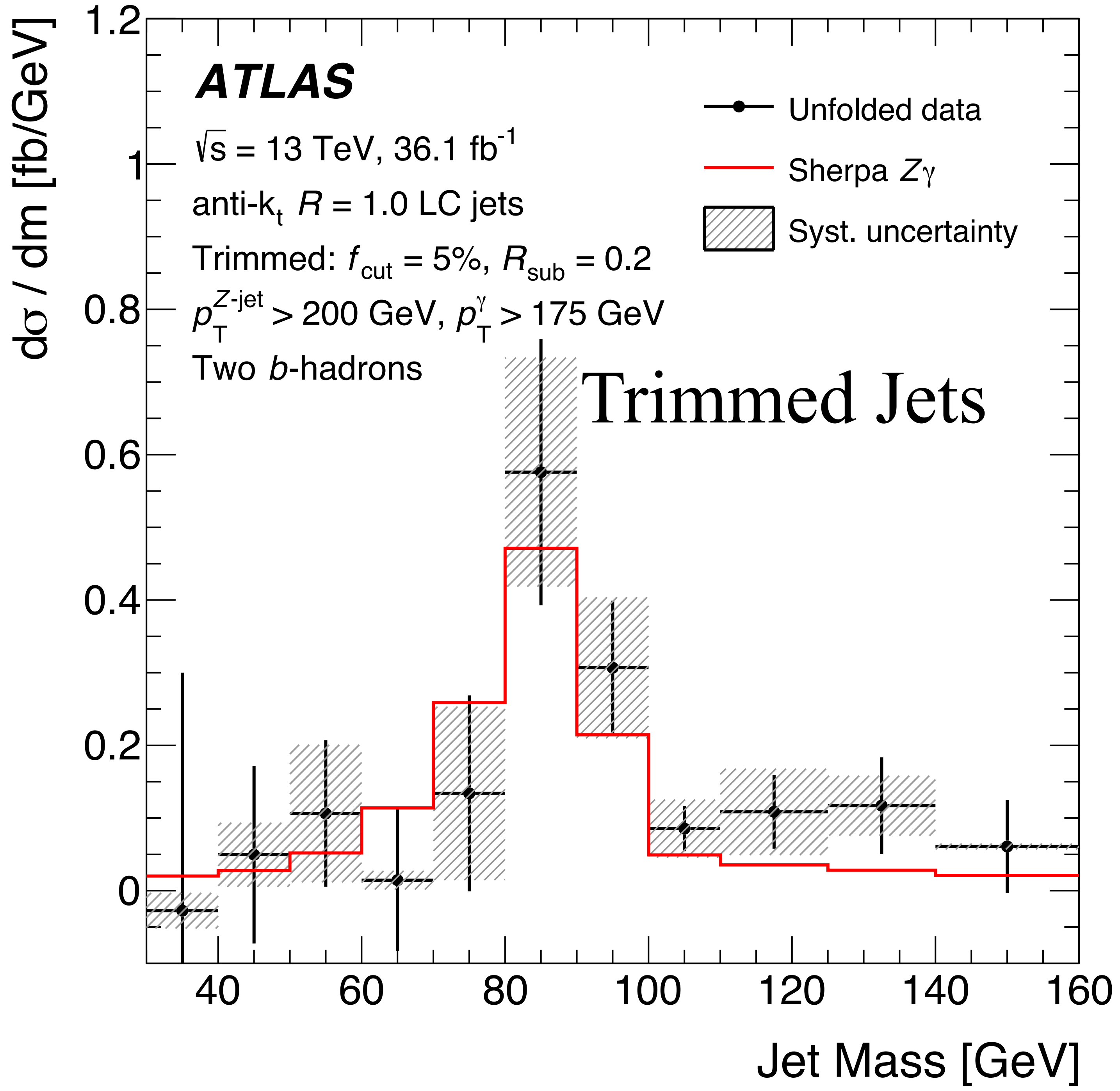


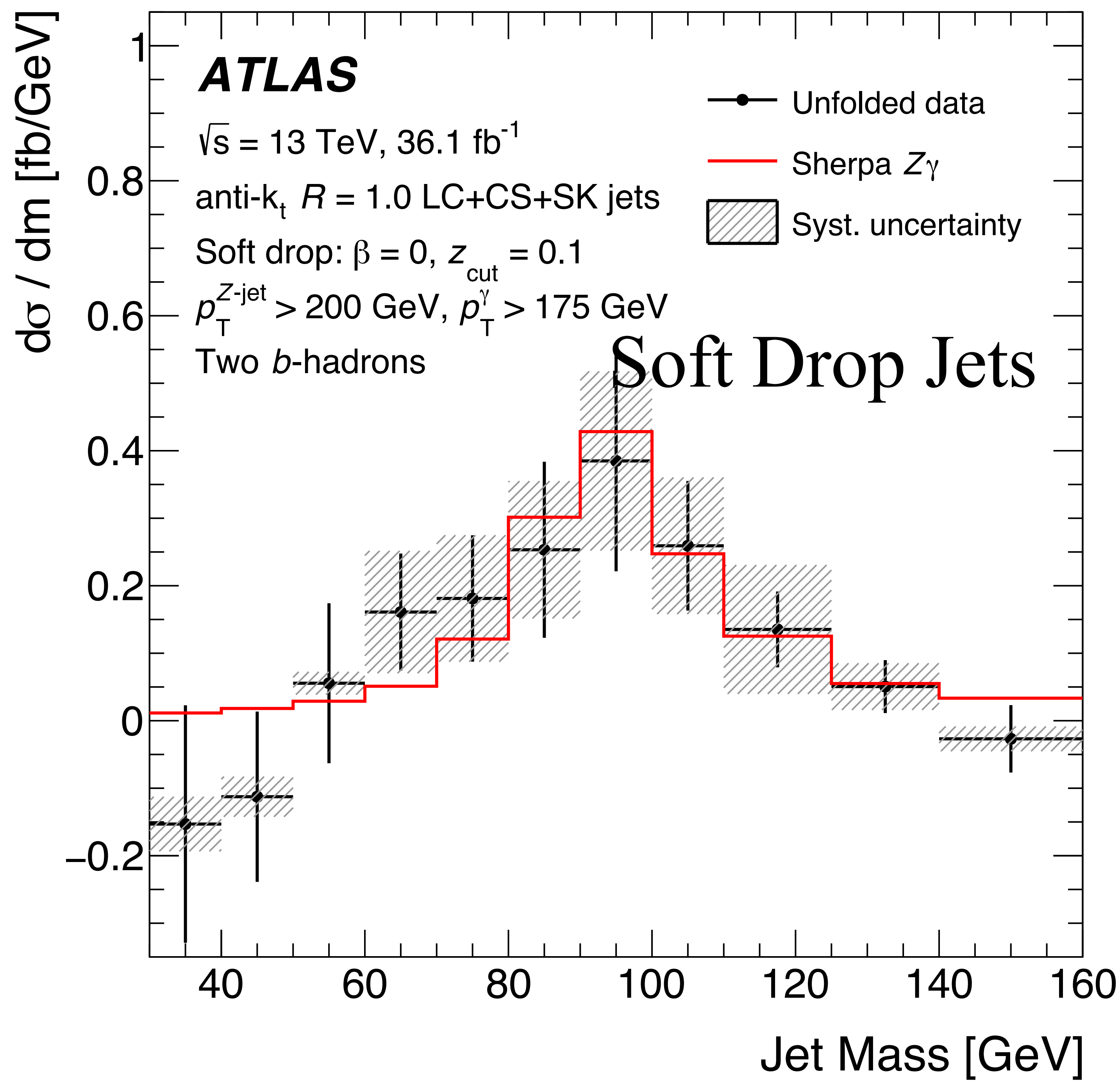
Z(→bb) + γ

- Measuring with both Soft Drop and trimmed jets
  - Mass distributions have different shapes, even at particle level
  - Applied pileup mitigation (Constituent Subtraction + SoftKiller) to Soft Drop jets due to pileup instabilities



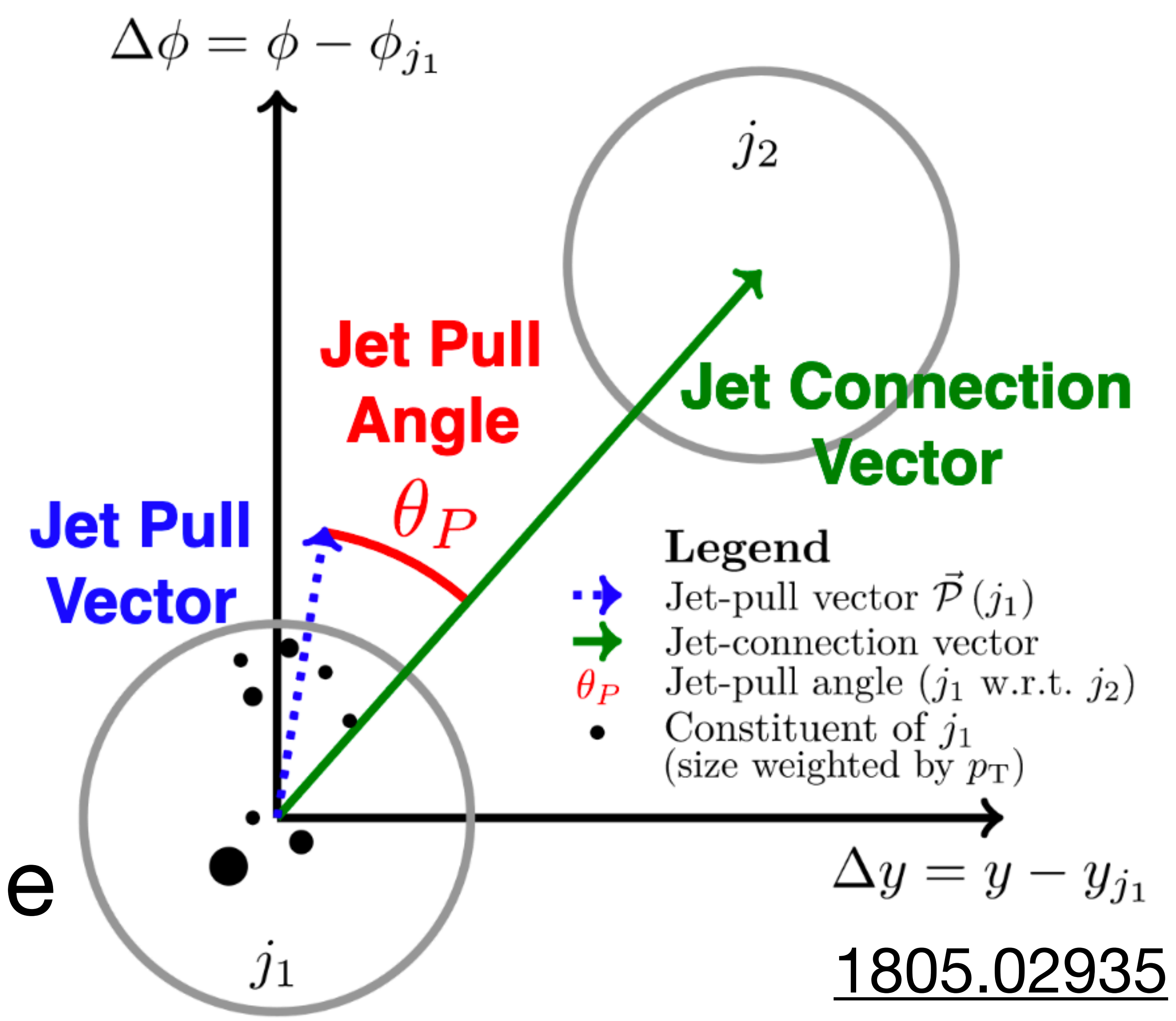
- Z decay products are captured within a single large-R jet
- Jet mass distribution unfolded to particle level after background subtraction
- Able to reconstruct the shape of both distributions



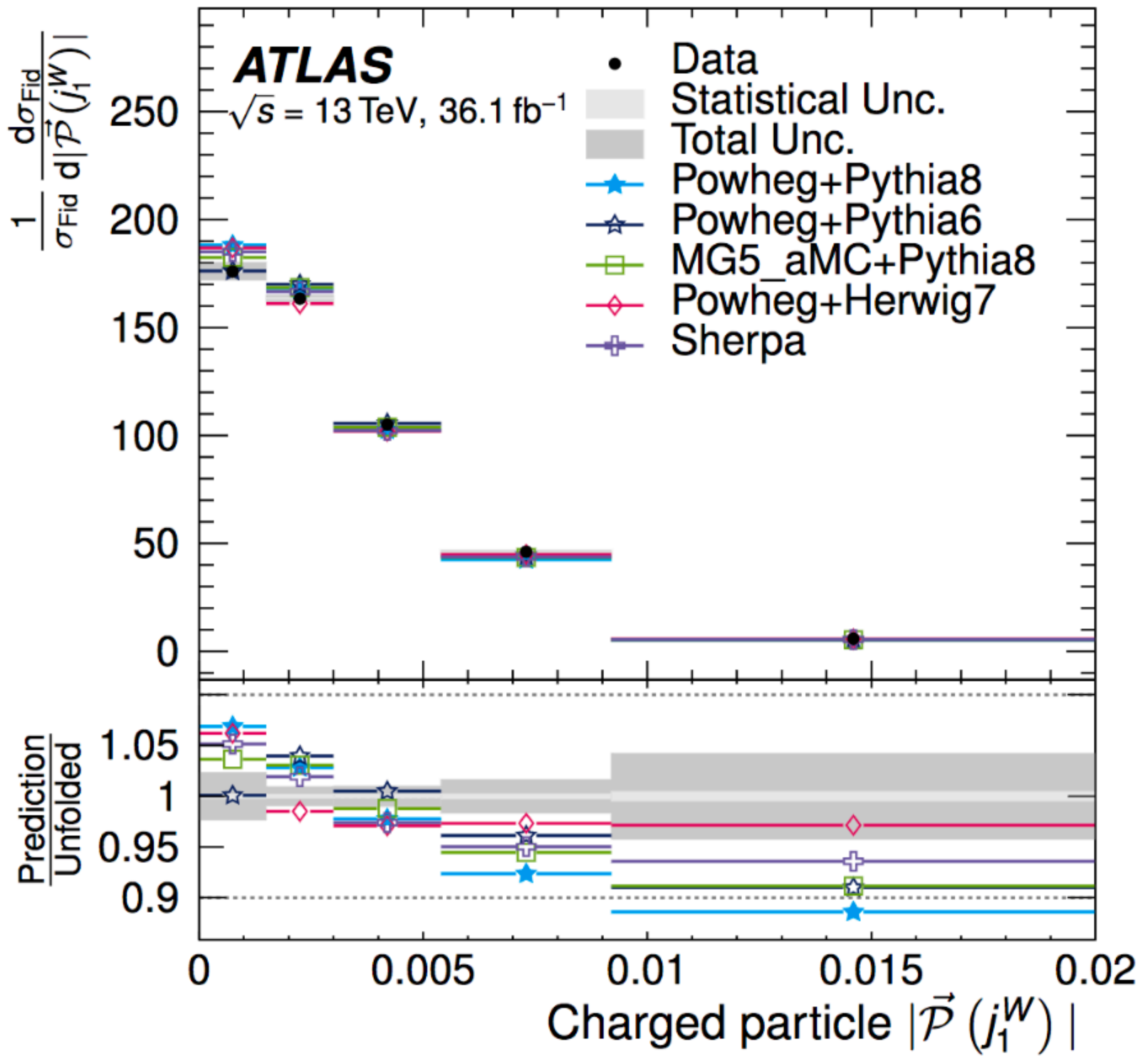


measurement of the jet pull

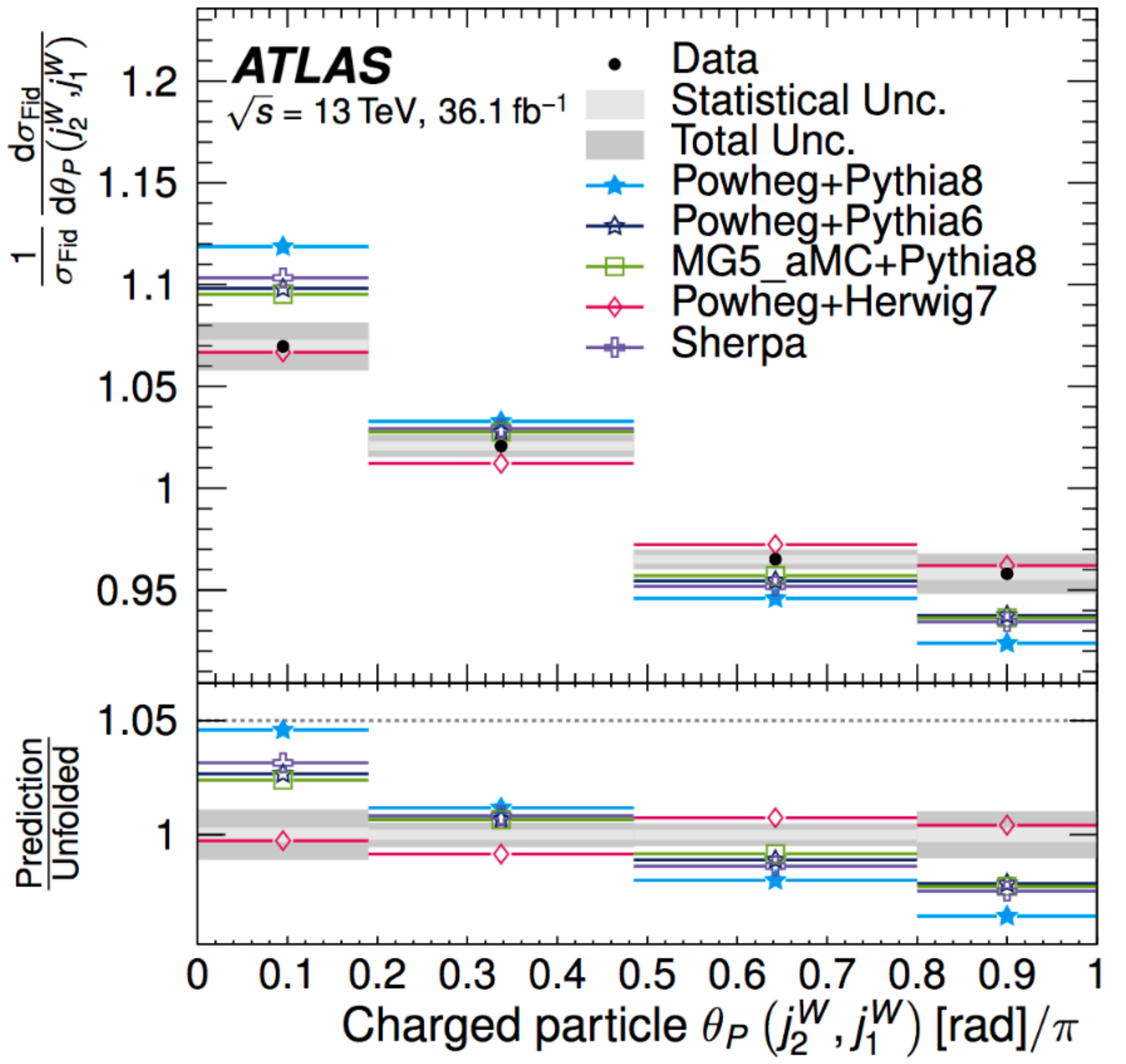
- The jet pull is sensitive to color connection in QCD
- ttbar events can contain both color connected and non-connected jets
- No prediction is able to model both the pull angle and magnitude



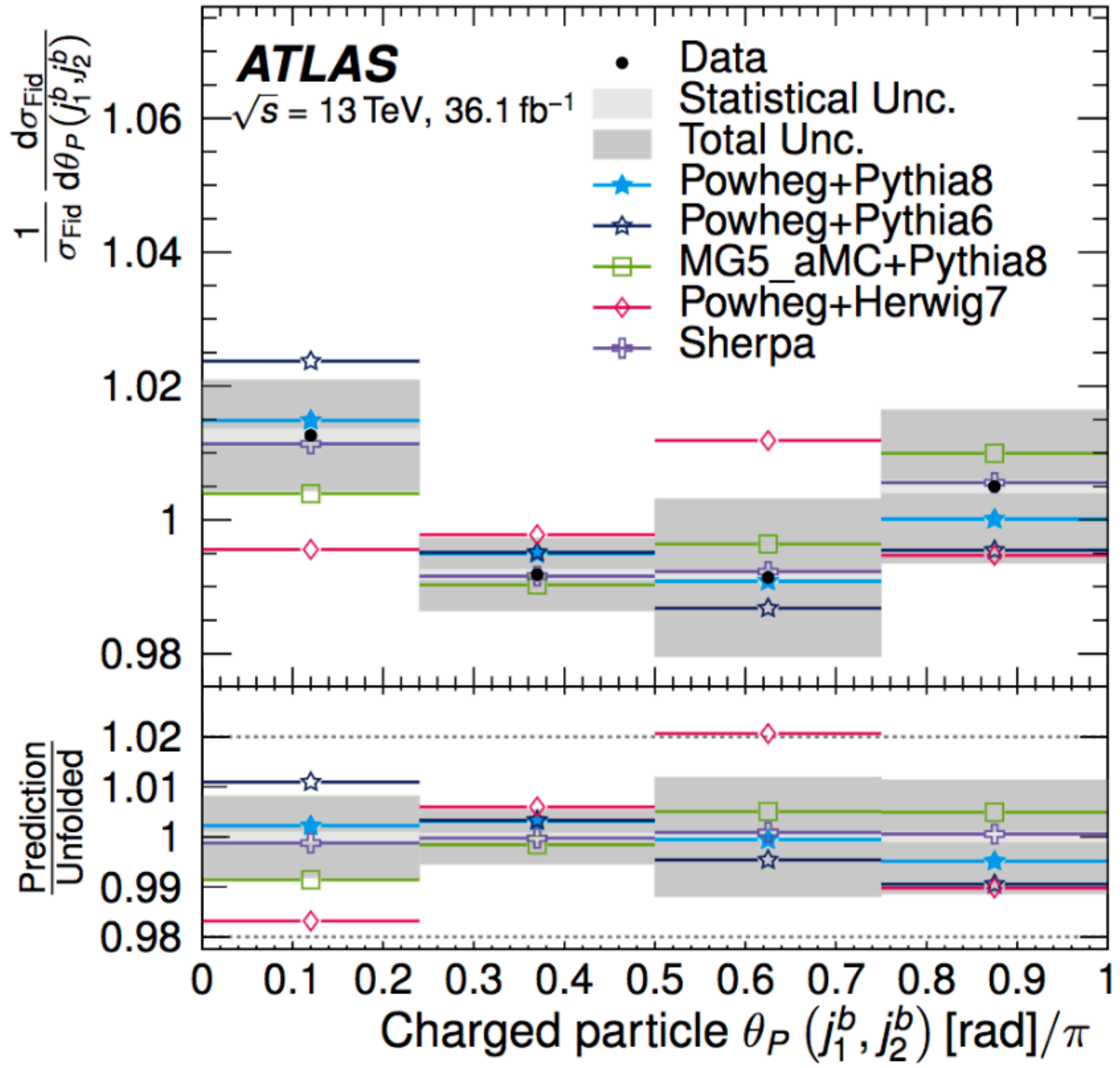
1805.02935



Magnitude of the pull vector



Backward pull angle



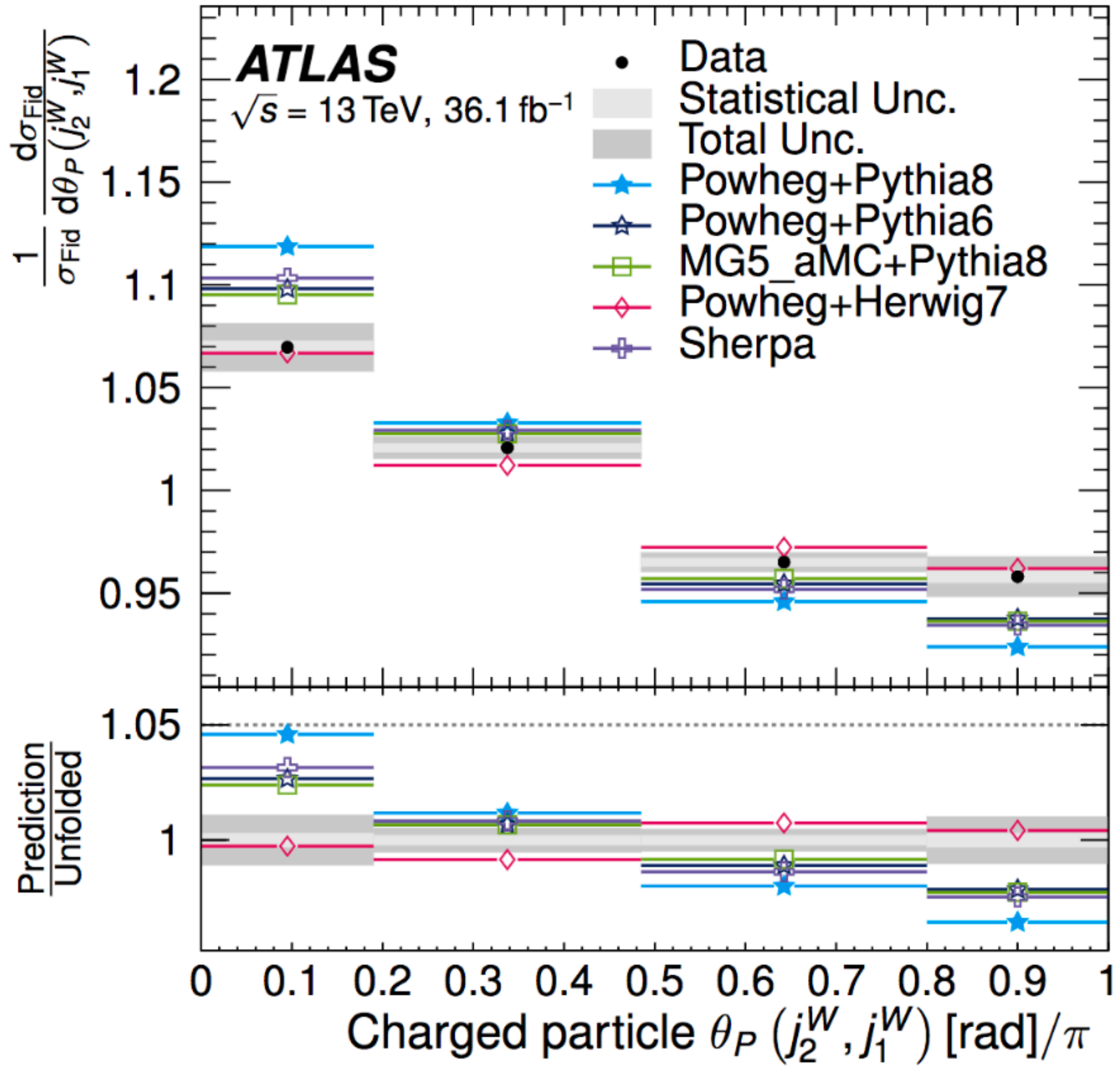
b-quarks (not color connected) Forward Pull Angle

measurement of the jet pull

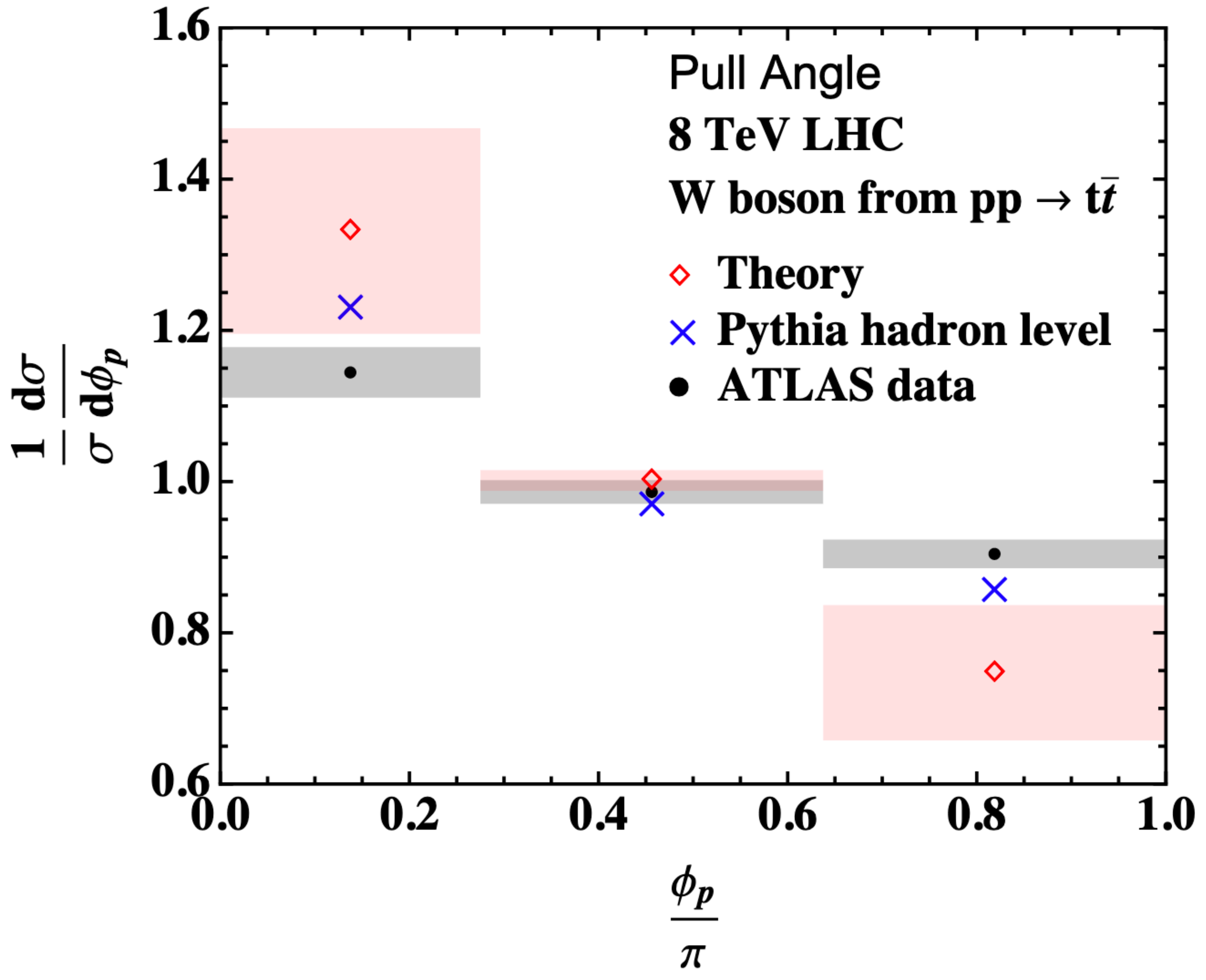
1805.02935

1903.02275

- The jet pull is not infra-red and collinear safe, but is Sudakov safe
  - *Note that the theory is compared to a different measurement of the jet pull*
- Demonstrates the potential of theoretical predictions for a broader class of observables



Backward pull angle

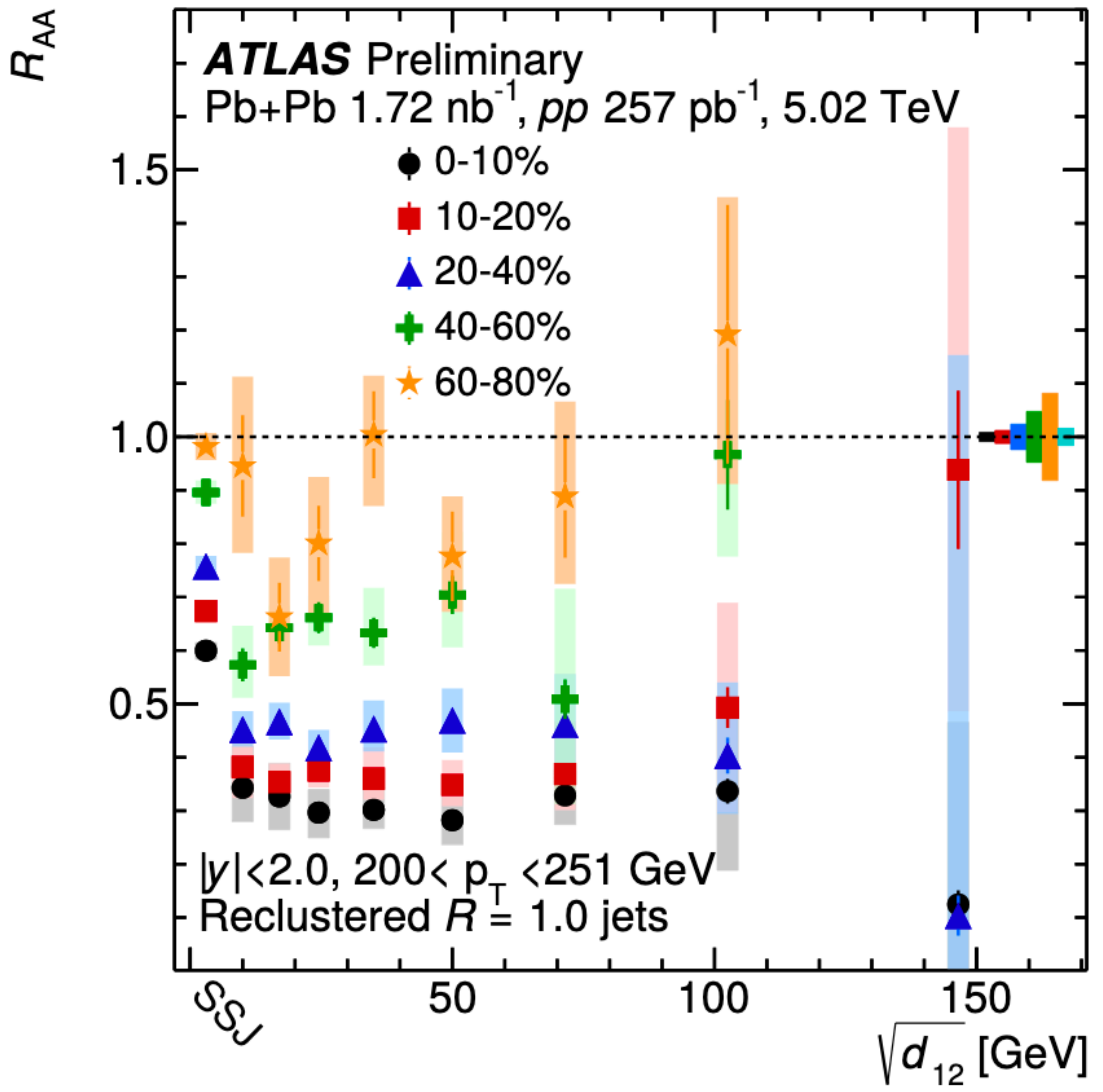


Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS EXPERIMENT
Calorimeter Towers
E_T [GeV]
Heavy Ion Collision Event with 2 Jets

https://cds.cern.ch/record/2701506

substructure in heavy ions

- Studies of jet substructure help provide insight into jet quenching
- Recent measurement uses *reclustered* large-R jets in order to probe larger angular scales
- Measuring $\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$
  - More suppression seen for jets with complex substructure (more than one subjet)
- Reclustered jets are sensitive to different effects than other recent measurements of substructure in heavy ions
  - Different behavior seen from different measurements → need better understanding of substructure in heavy ions



concluding thoughts

- ***We are entering a new era of precision jet substructure***
  - Measurement of the jet mass demonstrates experimental and theoretical understanding of jet substructure
  - Opens the door for many precision measurements of substructure observables like the strong coupling constant or the top quark mass
- ***Understanding of jets is critical to the physics program at the LHC***
  - Factorizable observables like the Lund jet plane provide powerful ways of understanding jet modeling
  - Improving modeling of gluons can have significant impact on the overall physics program at the LHC
  - Object reconstruction is critical to producing high-quality measurements of jet substructure

concluding thoughts

- ***Substructure measurements are useful for understanding a broad range of phenomena***
  - Covers everything from understanding hadronization, parton showers, color connection, behavior of color singlets, and more
- ***Collaboration between theorists and experimentalists is essential***
  - Using tracks can be helpful experimentally, but need better understanding of how to address this theoretically
  - Lots of progress towards predictions of different types of substructure observables, and in different topologies

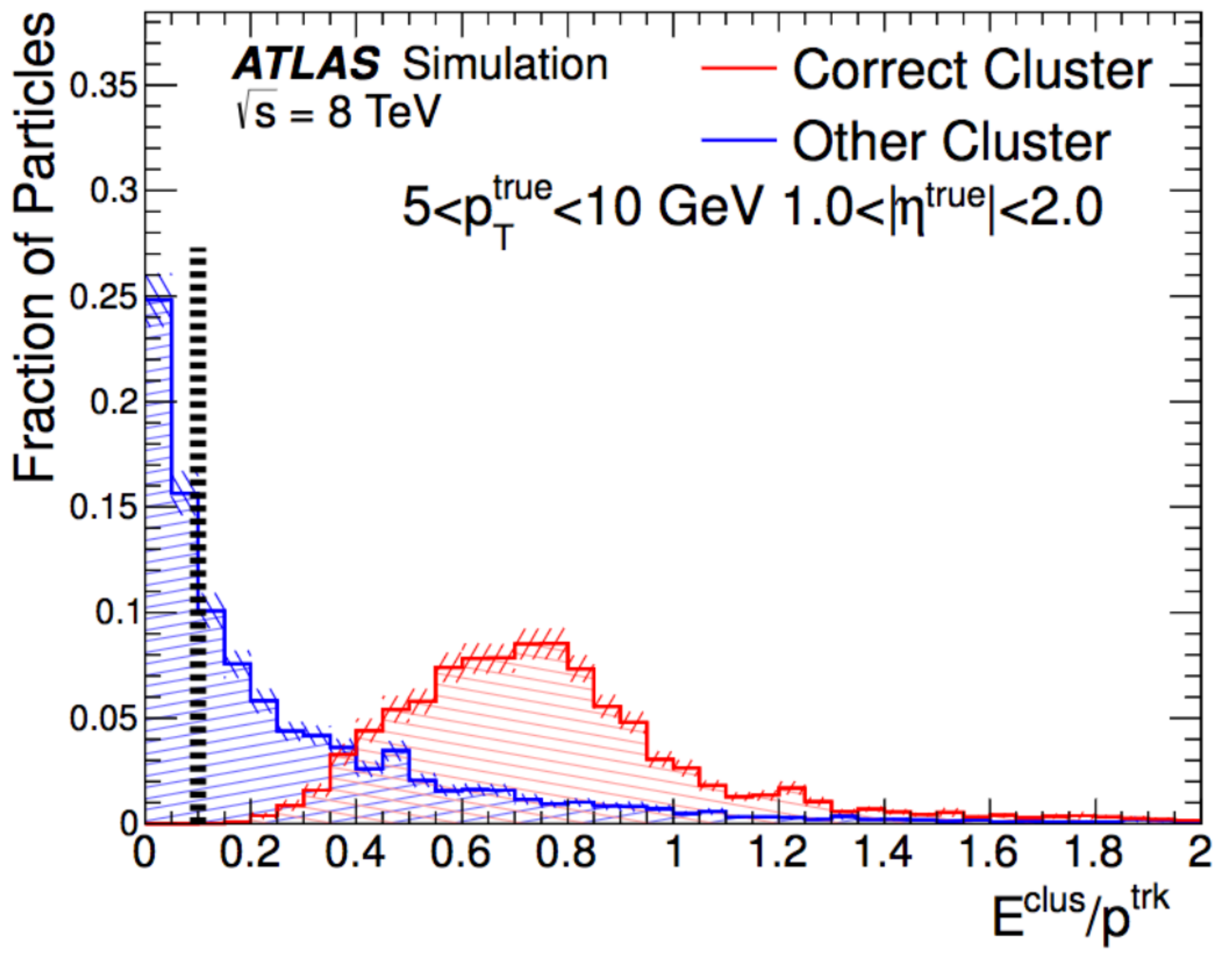
thanks!

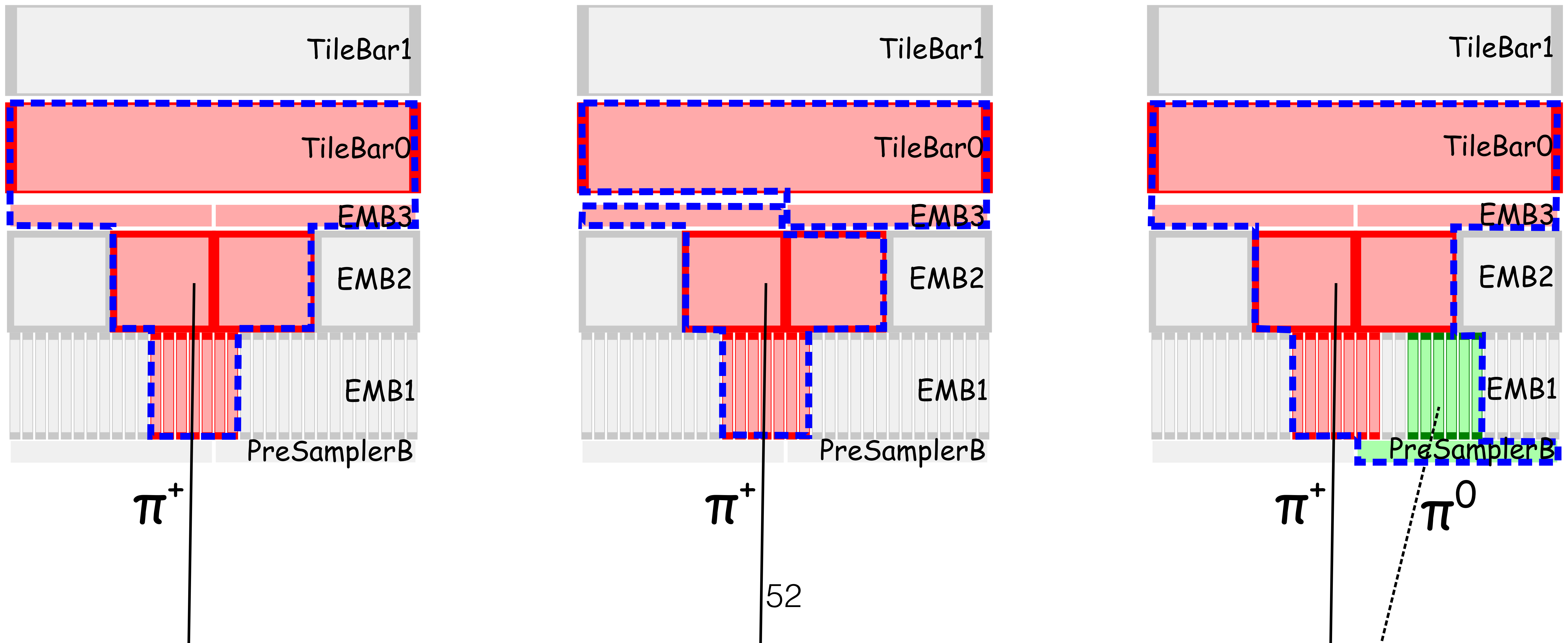

Run: 271516
Event: 7786087
2015-07-13 09:38:38 CEST
ATLAS
EXPERIMENT

Inputs: PFlow

PFlow Paper

- Tracks are matched to one (or more) clusters where $E_{cluster} / p_{Track} > 0.1$
  - Uses the EM-scale energy of the cluster
- Cell-by-cell subtraction based on the expected amount of energy deposited by a track with that momentum
- Clusters with no associated tracks are kept as neutrals
- Not applied to high p_T clusters, since tracker resolution worsens at high p_T





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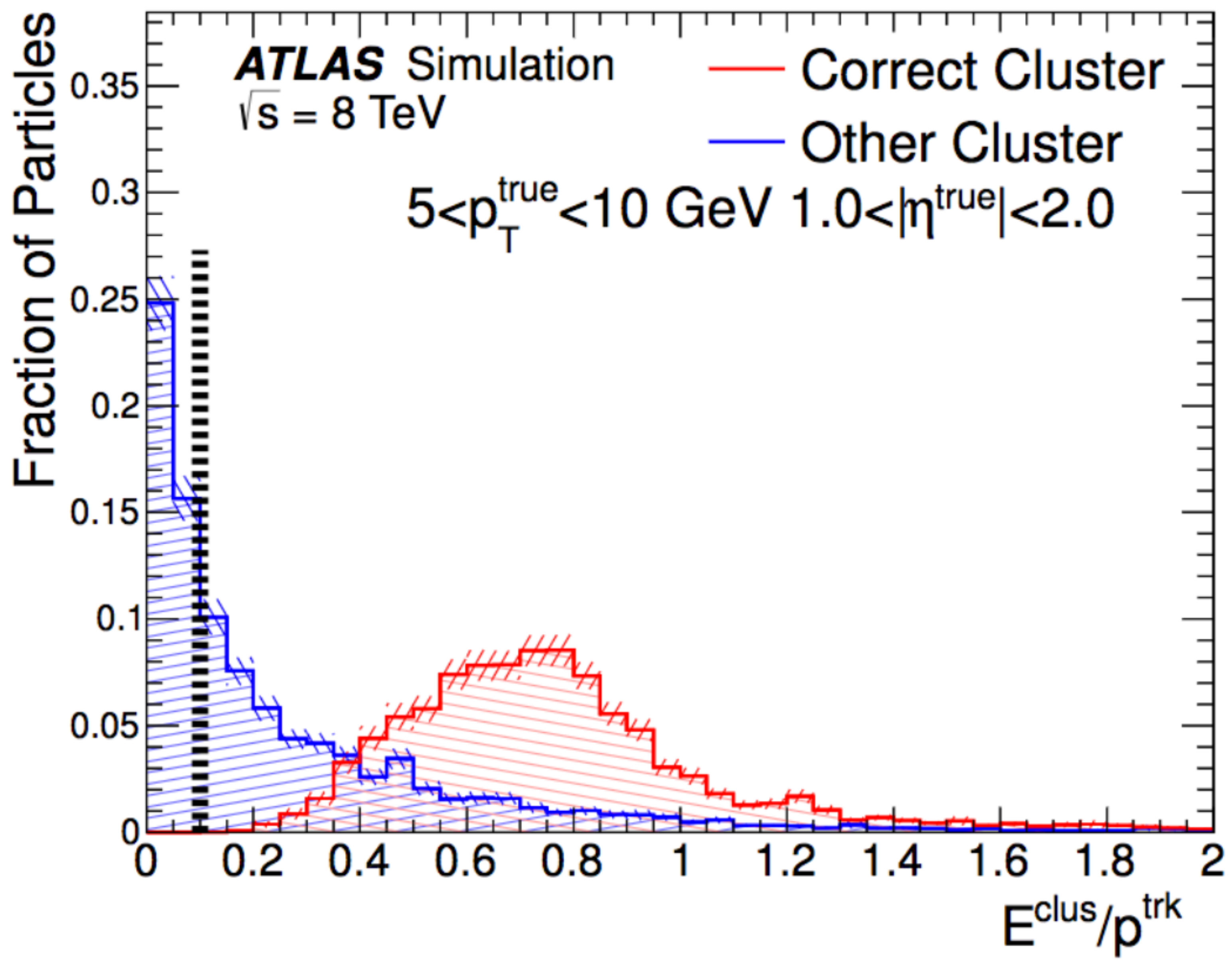
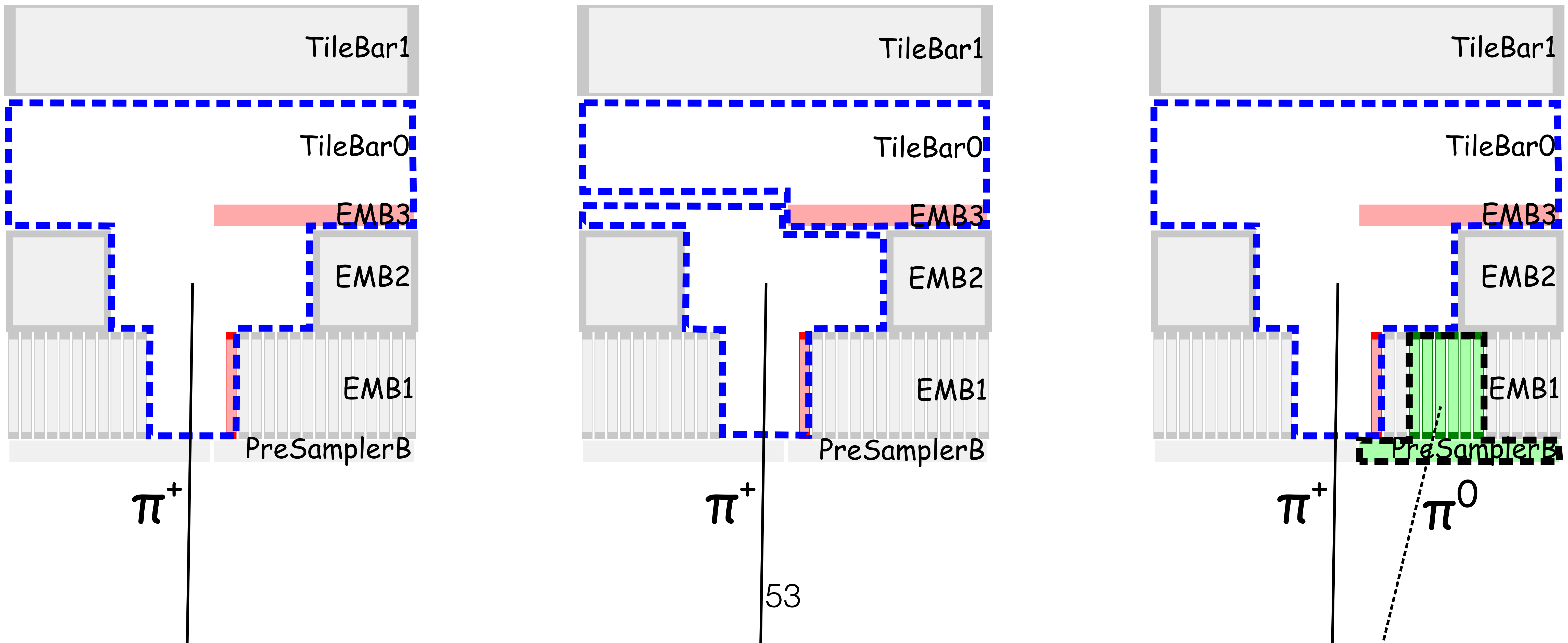
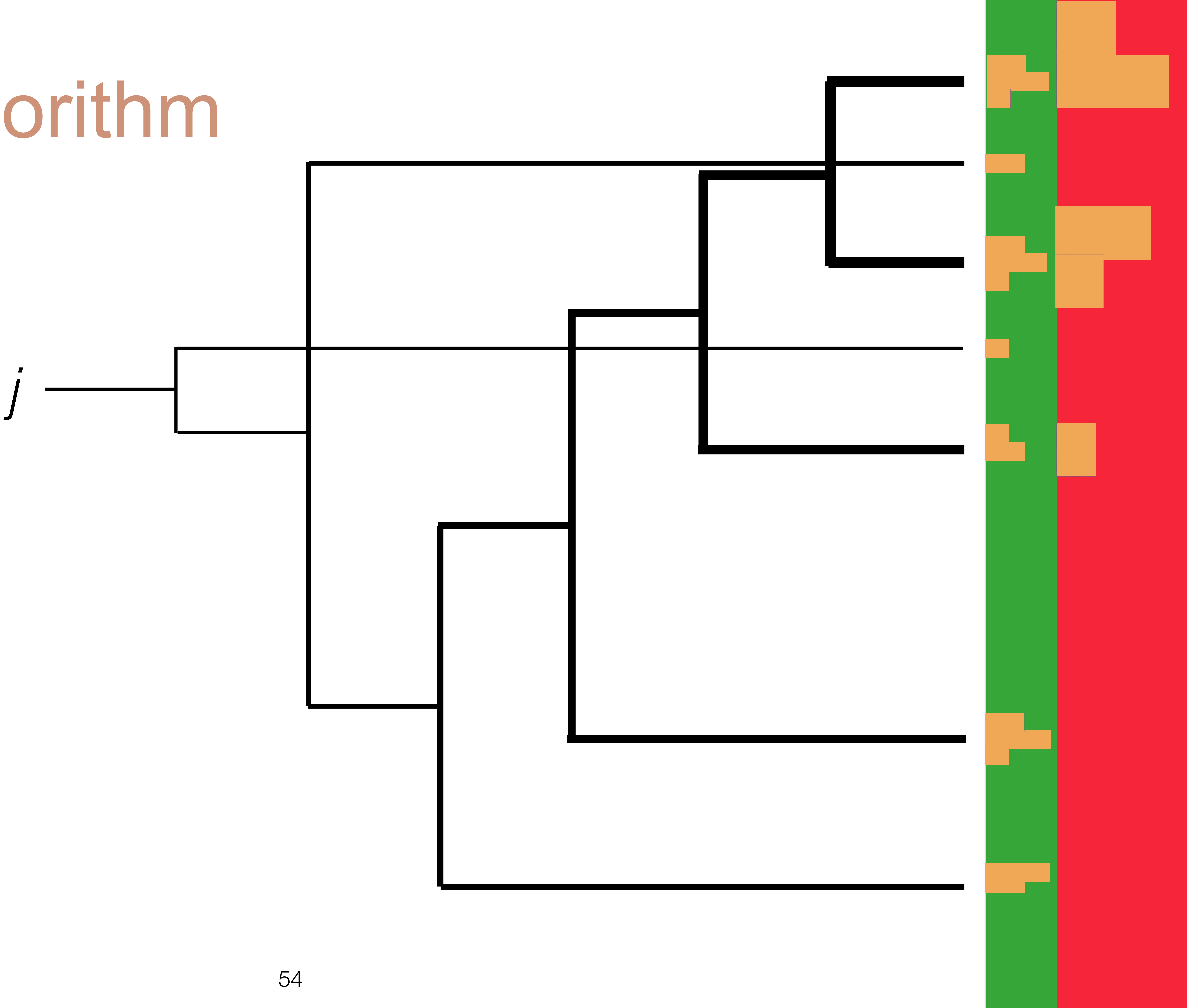




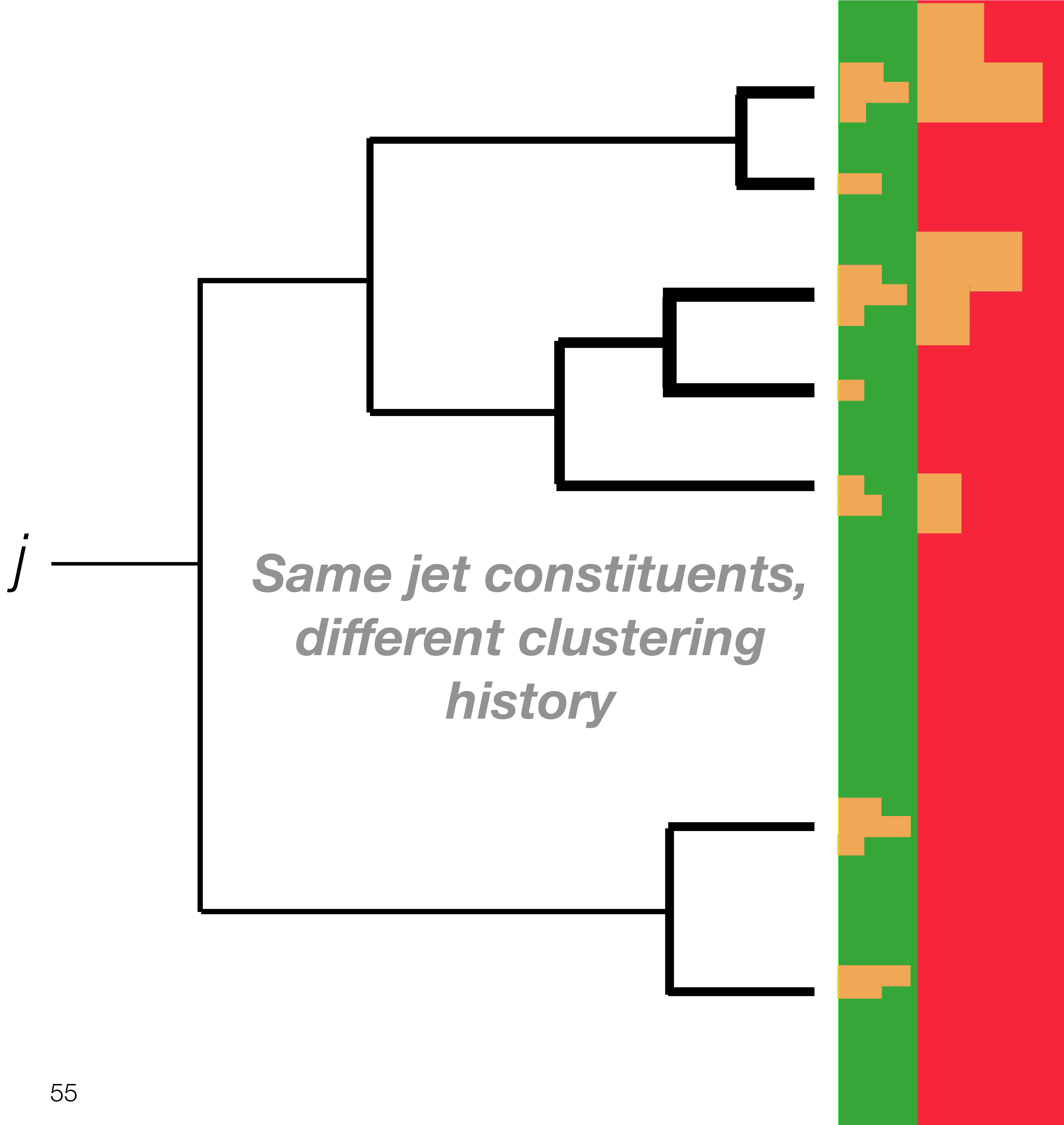
the soft drop algorithm

- Run jet finding using the **anti-k_t algorithm**

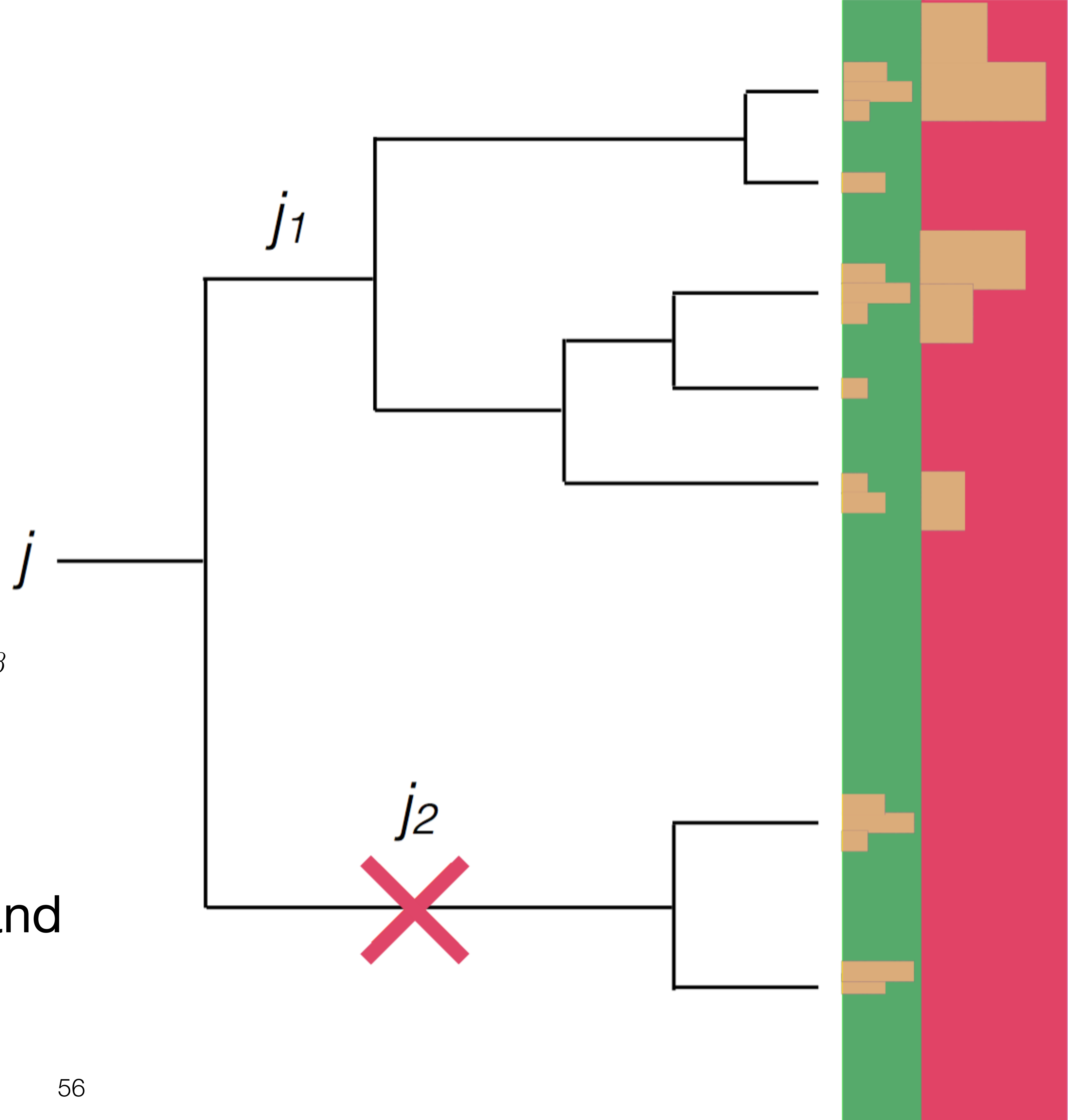


the soft drop algorithm

- Recluster its constituents with the Cambridge/Aachen algorithm to get an **angular-ordered shower history**

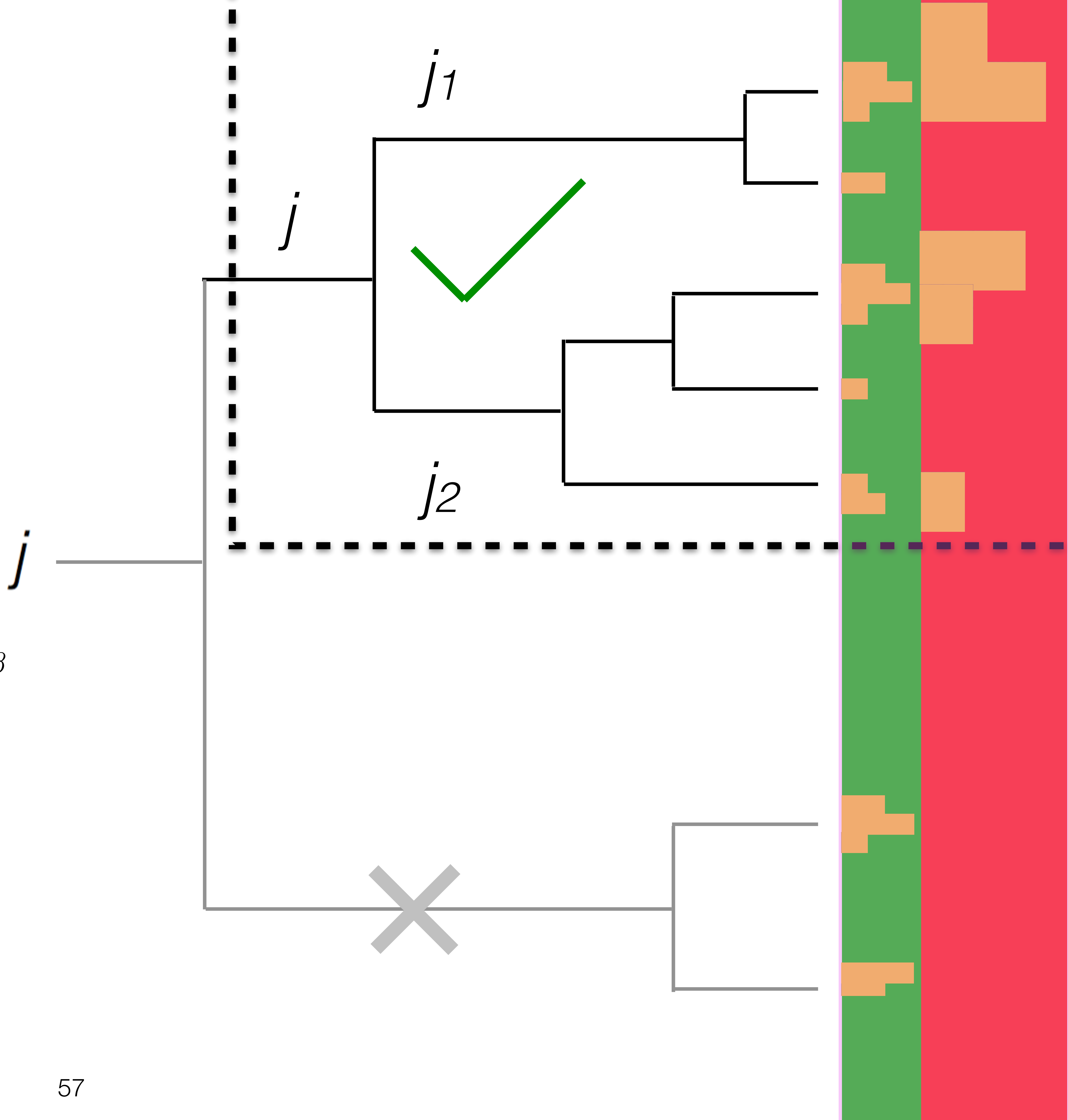


the soft drop algorithm



- Check if $\frac{min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}(\frac{\Delta R_{j1,j2}}{R})^{\beta}$
  - If not, drop the softer branch (*j2*), and repeat with the harder branch (*j1*)

the soft drop algorithm

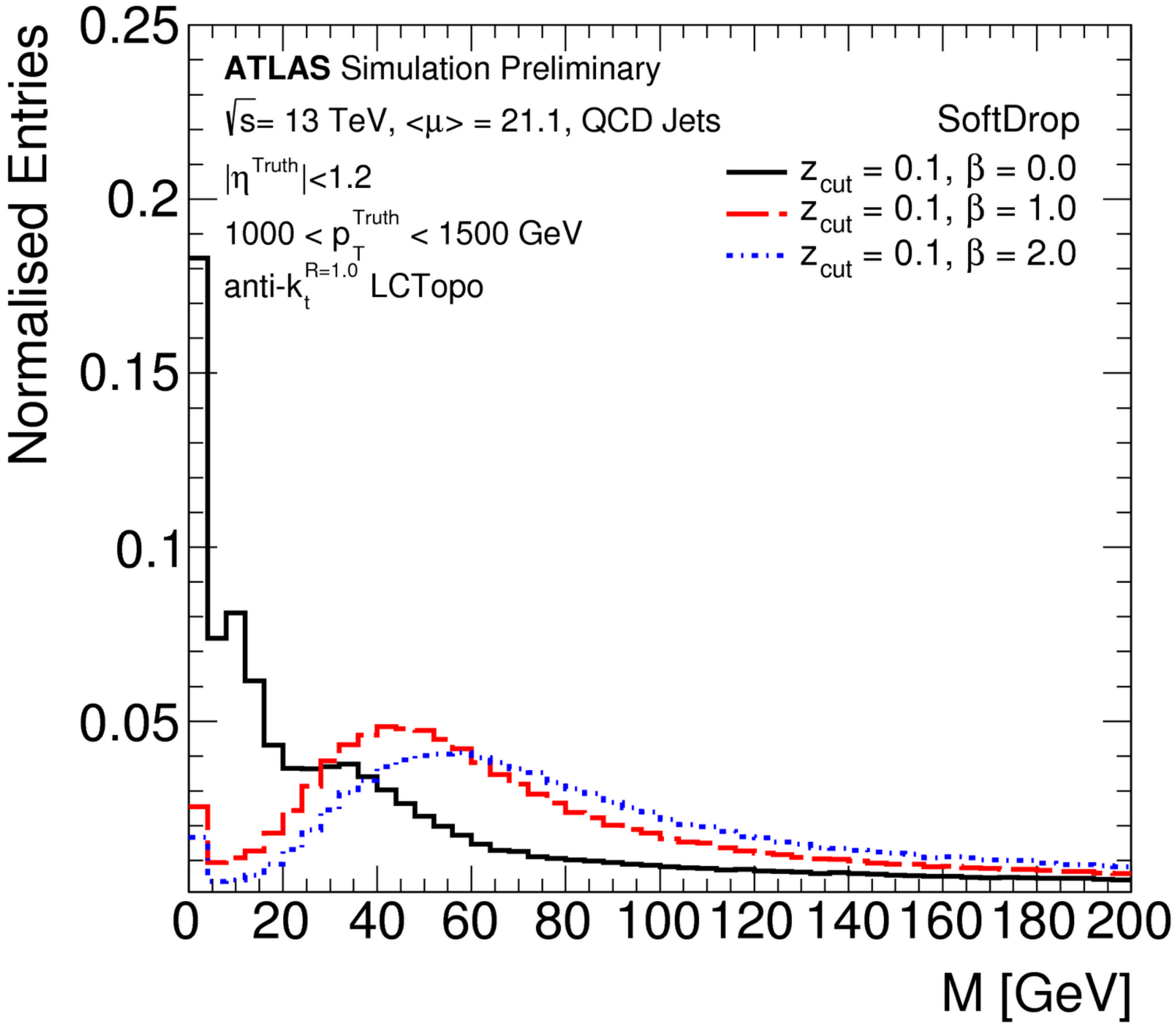


- Check if $\frac{min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}(\frac{\Delta R_{j1,j2}}{R})^{\beta}$
  - If so, stop grooming, and the jet is defined

the soft drop algorithm

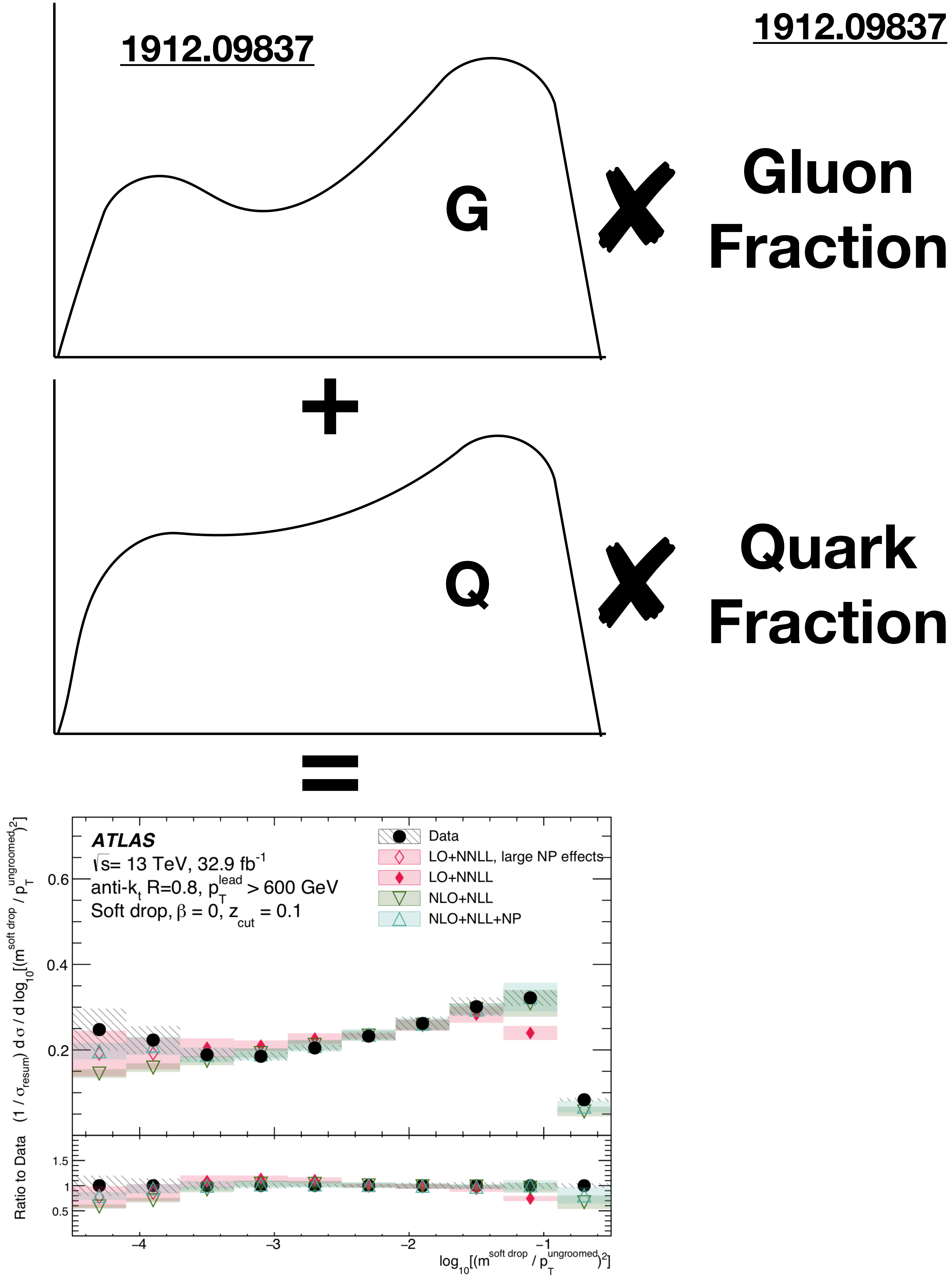
$$\frac{min(p_{T,j1}, p_{T,j2})}{(p_{T,j1} + p_{T,j2})} > z_{cut}\left(\frac{\Delta R_{j1,j2}}{R}\right)^{\beta}$$

- Two free parameters: z_{cut} and β
- z_{cut} sets the **scale of energy removal**
  - Larger values of z_{cut} mean the more of the jet is groomed away
- β determines the **sensitivity to wide-angle radiation**
  - Smaller values of β mean that more aggressive grooming is applied



the jet mass

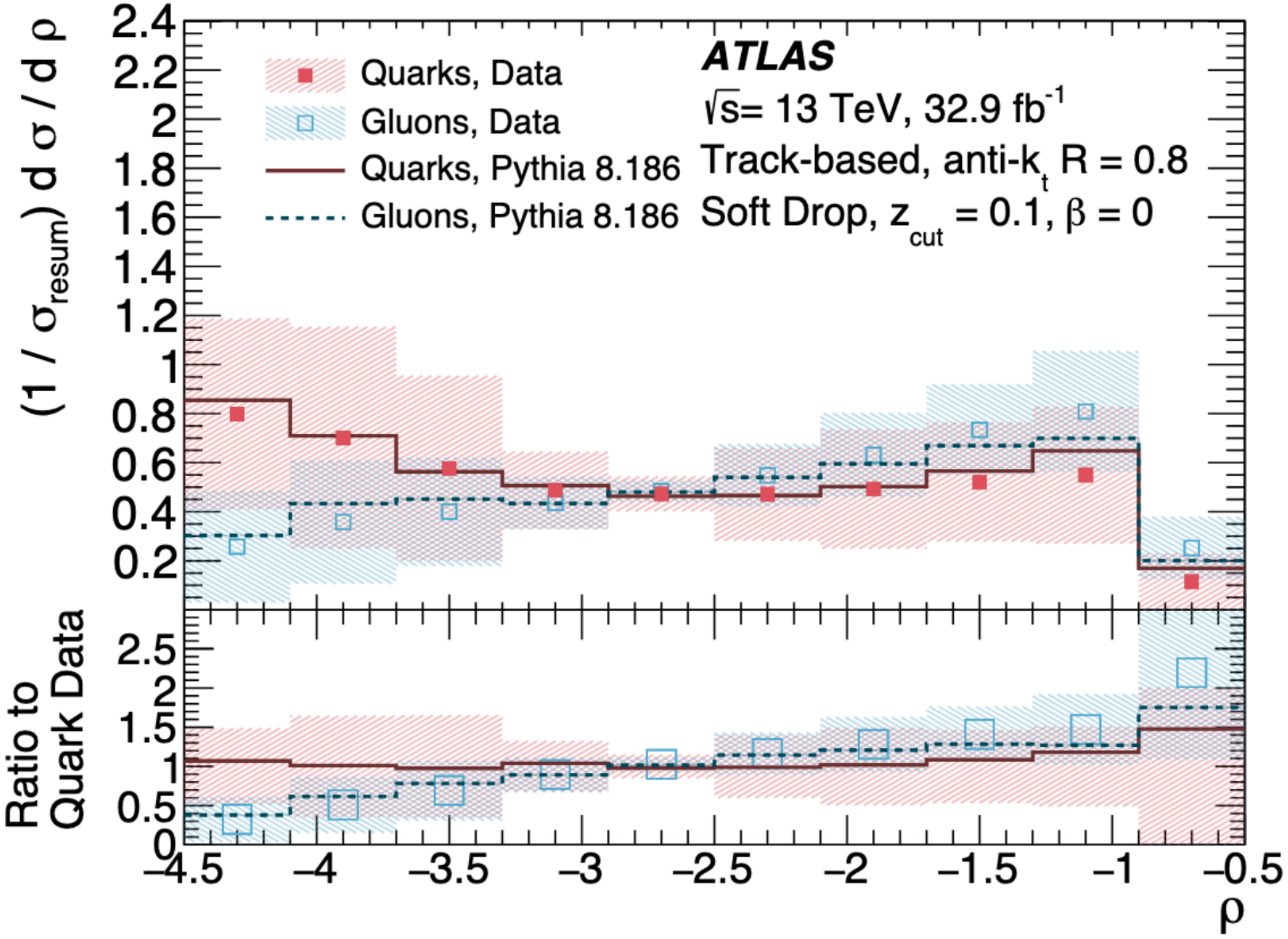
- Gluons tend to radiate more → higher mass on average
- Measurements are a mixture of quark- and gluon-initiated jets
  - Mass distribution can be thought of as a sum of the quark mass distribution and gluon mass distribution
  - *Just a 2-variable linear equation for each bin!*
- The fraction of quark-initiated jets varies as a function of η → Mass distribution changes with η
  - This fraction comes from parton distribution functions



the jet mass

1912.09837

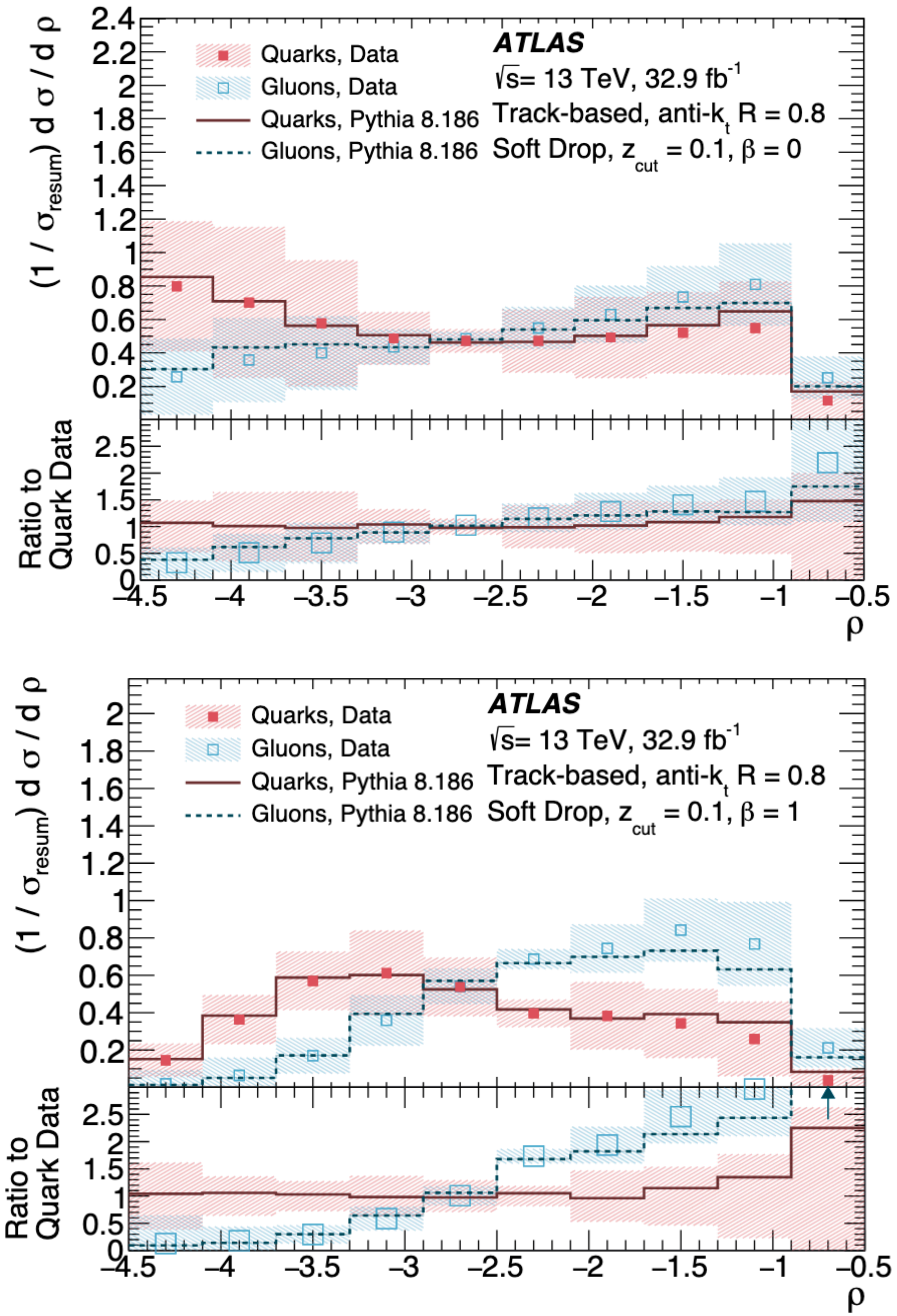
- $m(\eta) = Q \times f_Q(\eta) + G \times f_G(\eta)$
- Recent mass measurement performed in two η bins
  - If we have quark and gluon fractions, can solve for the quark and gluon distributions
- Quark and gluon fractions currently taken from Pythia, so some model dependence
- Done with *tracks*, since uncertainties are much smaller



the jet mass

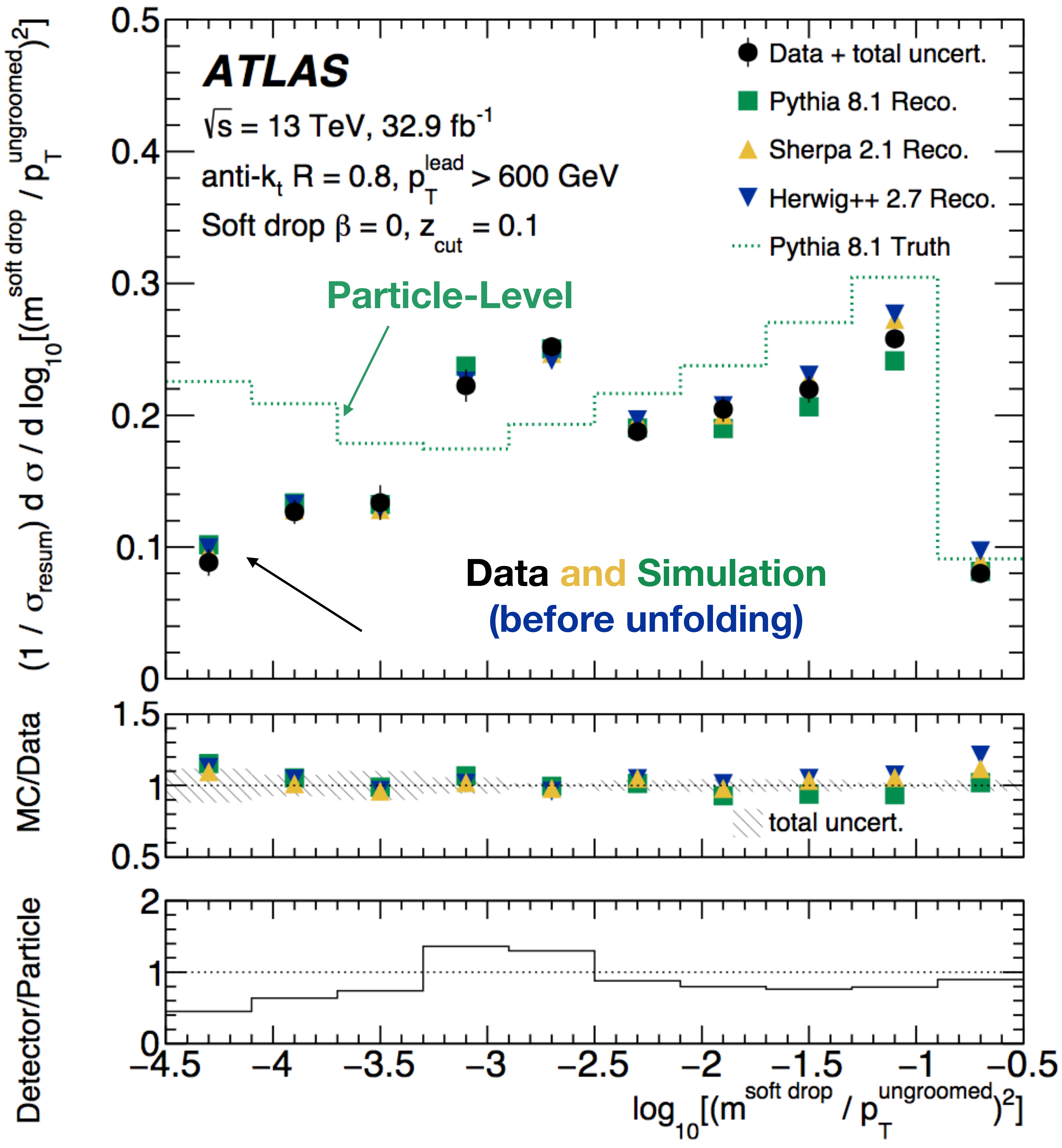
1912.09837

- Much better separation for quarks vs. gluons for β>0
-



the jet mass

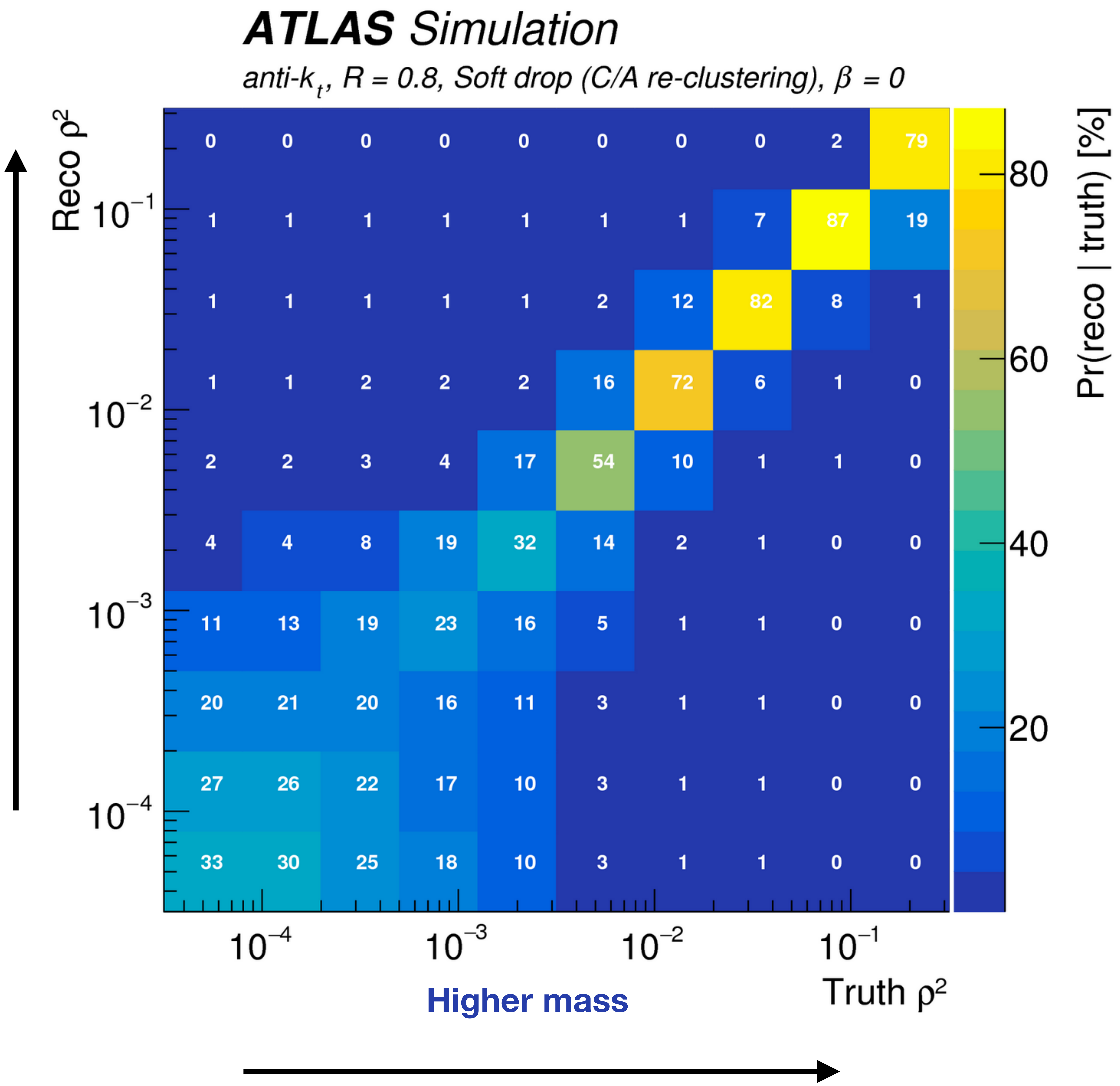
- Performing the measurement in dijet events (two balanced jets in the event)
- Apply Soft Drop grooming to R=0.8 jets made from clusters
  - Measuring z_{cut} = 0.1, and β = 0, 1, and 2
- Use calorimeter objects (*topoclusters*) as the inputs to the jet reconstruction algorithms
  - Uses all particles → can be compared to theoretical predictions
- The calorimeter-based jet mass is affected by **non-trivial detector corrections**
  - Unfold the data to particle level to correct for these effects



1711.08341

the jet mass

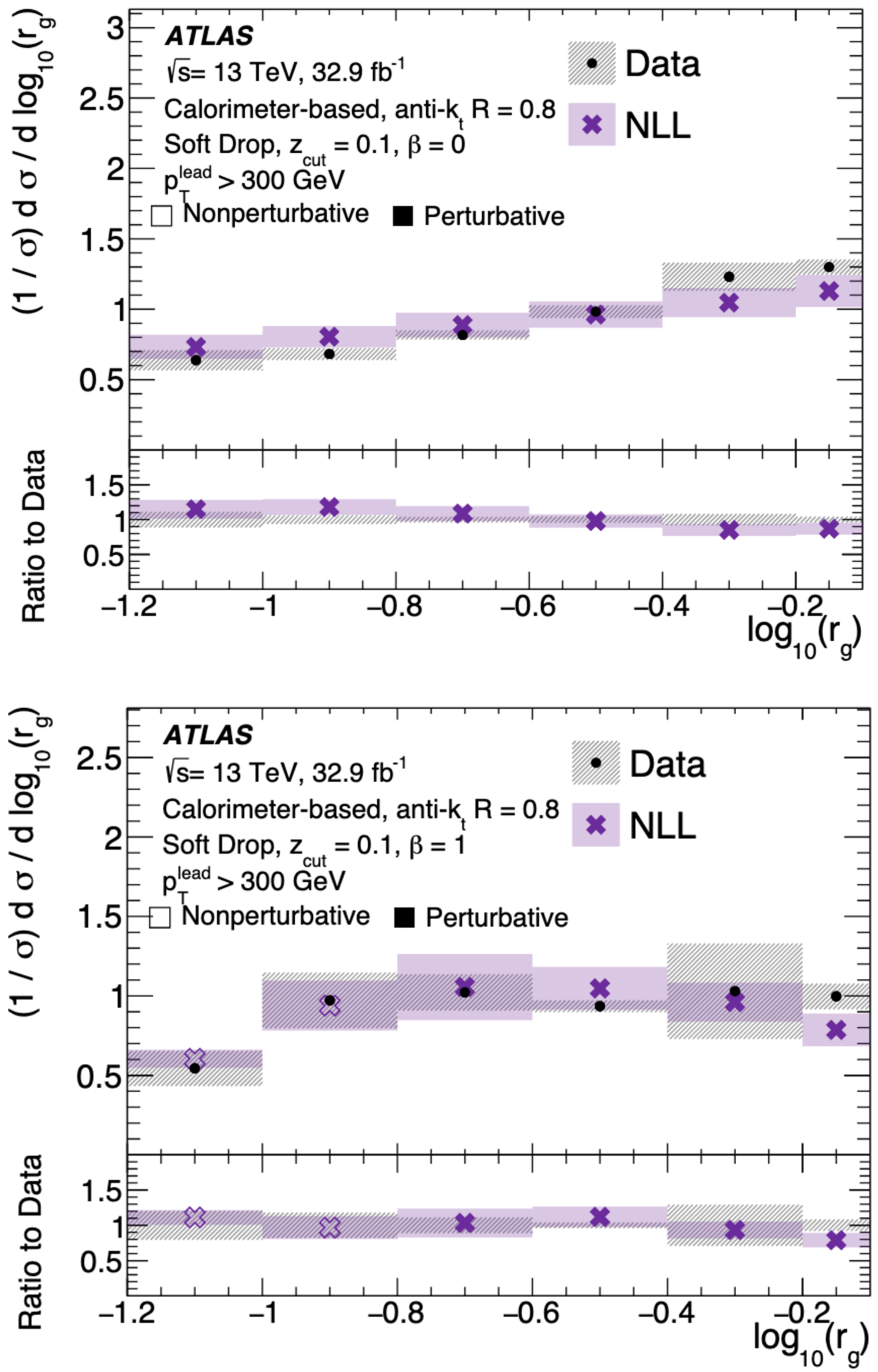
- The calorimeter-based jet mass is affected by **non-trivial detector corrections**
- Unfolding creates a mapping between a detector-level measurement and a truth-level distribution
  - Corrects for several detector effects, reconstruction efficiencies, and fake rates
- **Simultaneously unfold ρ and p_T** using Bayesian unfolding
  - Showing results inclusive in p_T



the jet mass

[1912.09837](1912.09837)

- r_g measures the opening angle between the subjets that pass the Soft Drop condition
- Able to compare to the first calculations of this observable!



the jet mass

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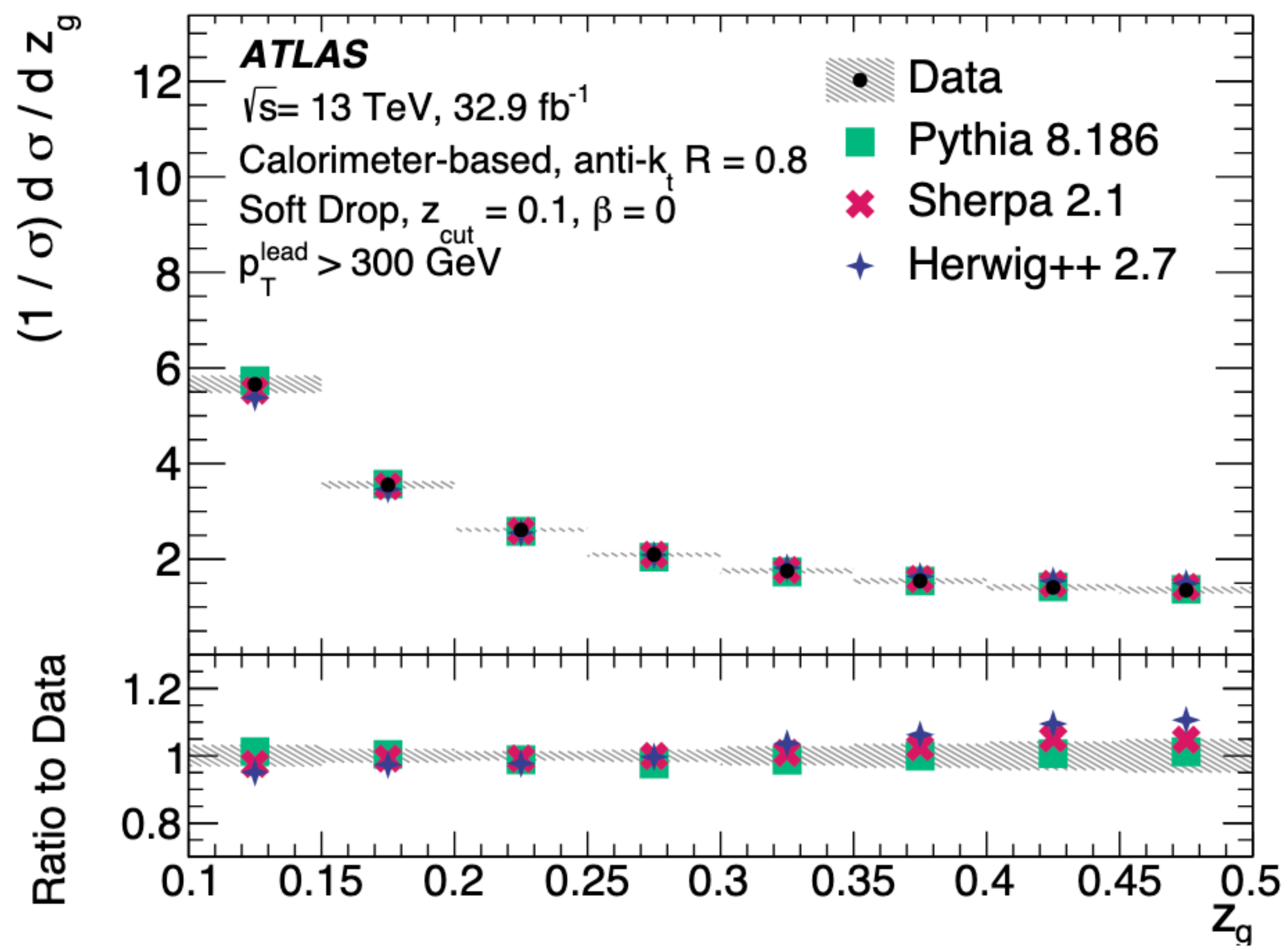
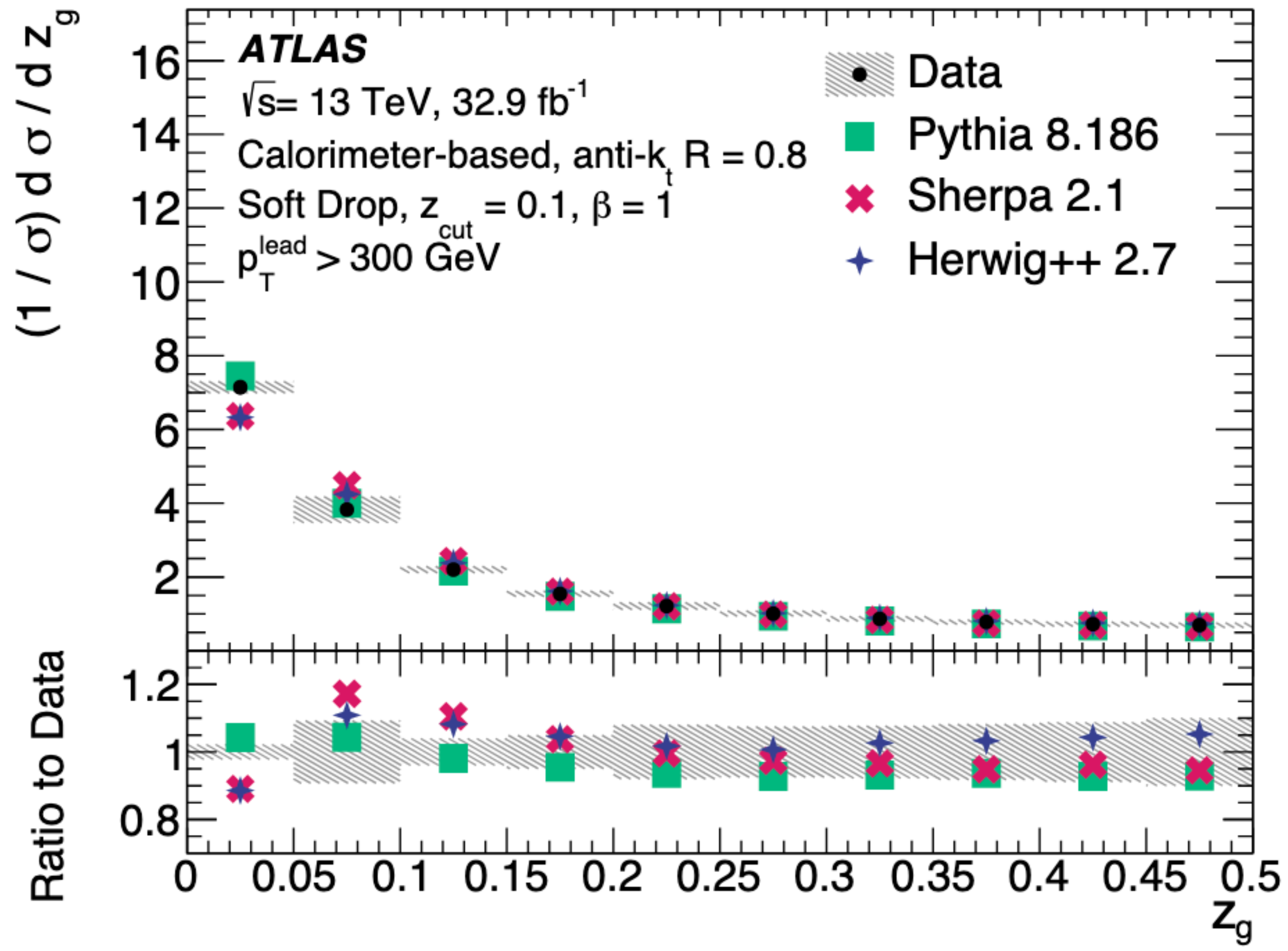
- z_g measures the p_T balance of the two subjets passing the Soft Drop condition
- Independent of α_s to leading order
- Small values of z_g are poorly modeled

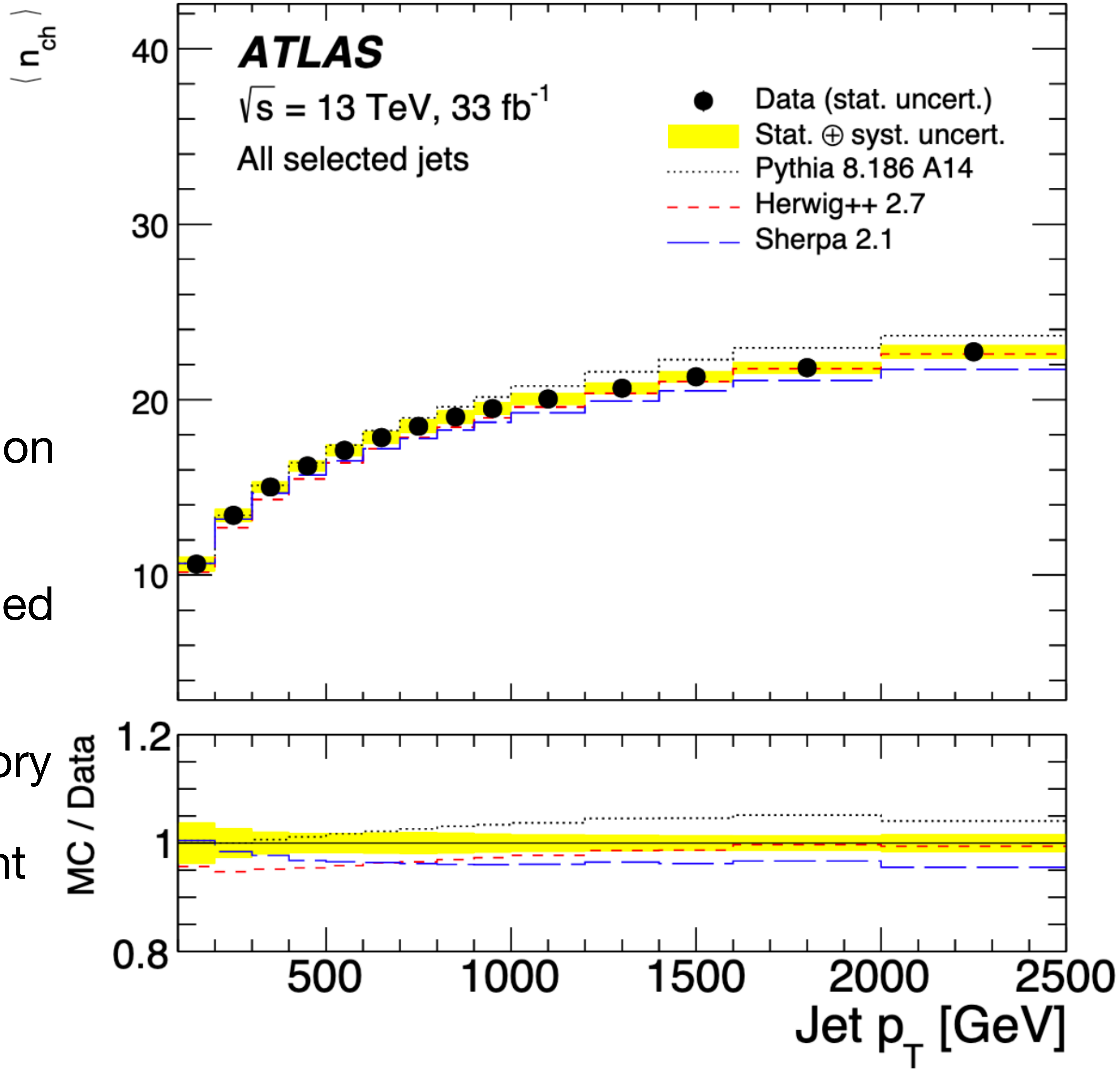




1906.09254

jet fragmentation

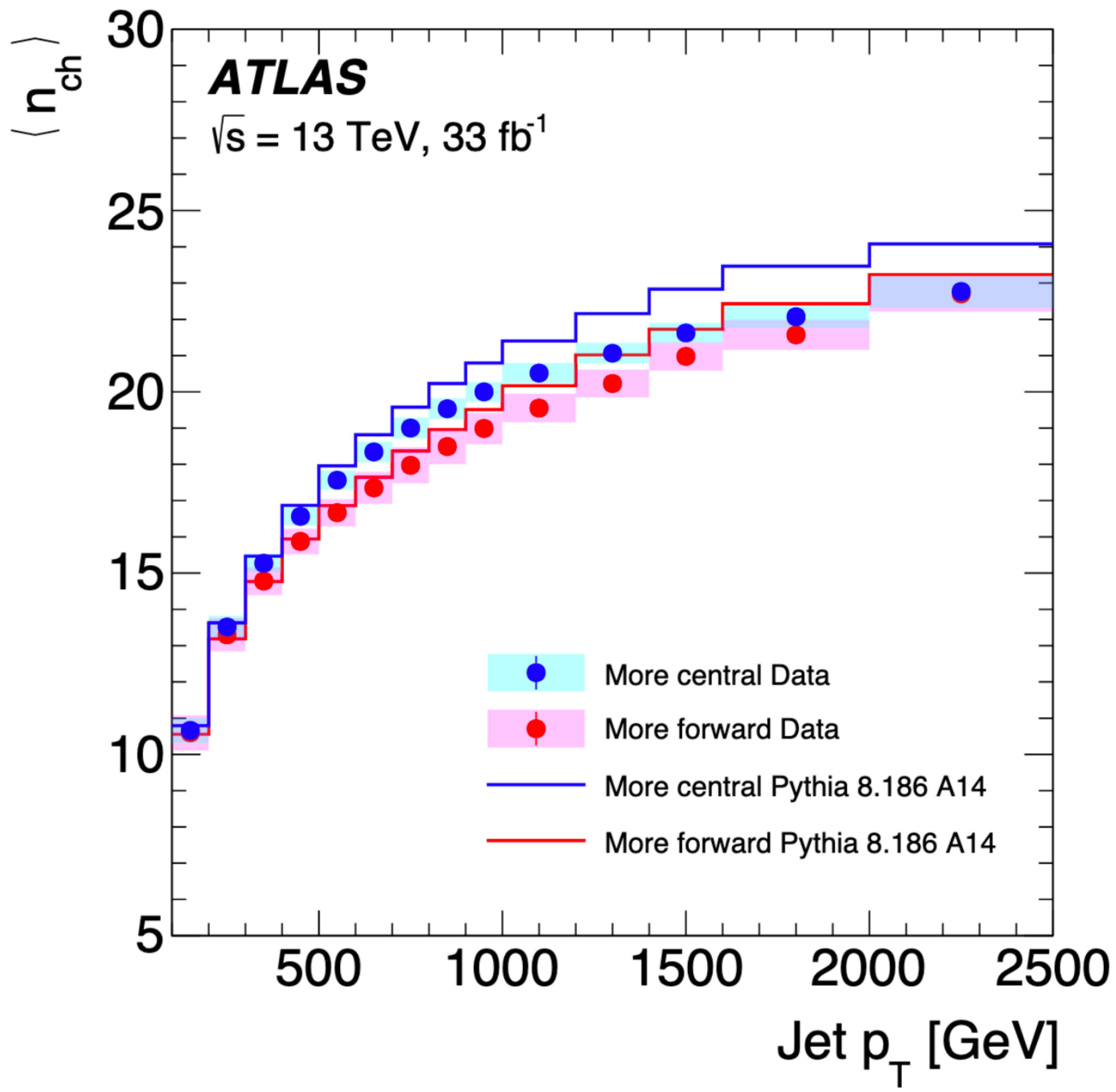
- Jet formation is complicated, and is not fully describable by perturbation theory
  - Rely on Monte Carlo models in order to produce predictions involving jets
- Jet fragmentation measurements study the distribution of particles within a jet
  - Includes observables such as the number of charged particles, the radial profile, and more
  - Energy dependence calculable in perturbation theory
  - Important input for tuning MC, and some significant disagreements between data and MC
- Using tracks to calculate fragmentation to improve precision

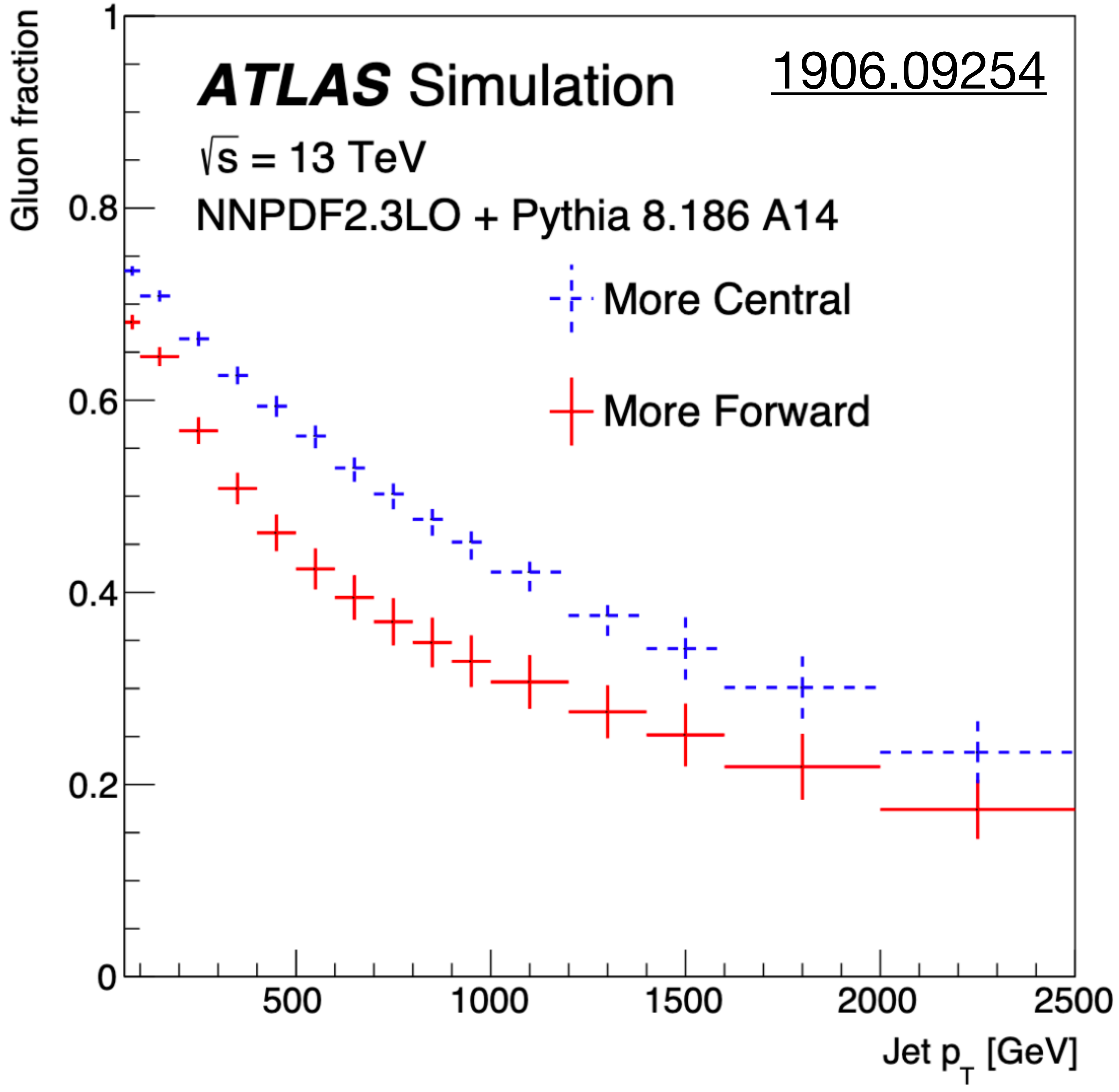


jet fragmentation

- Jet fragmentation does not depend strongly on η, just on the initiating parton

- Central jets tend to be gluon initiated more often than forward jets



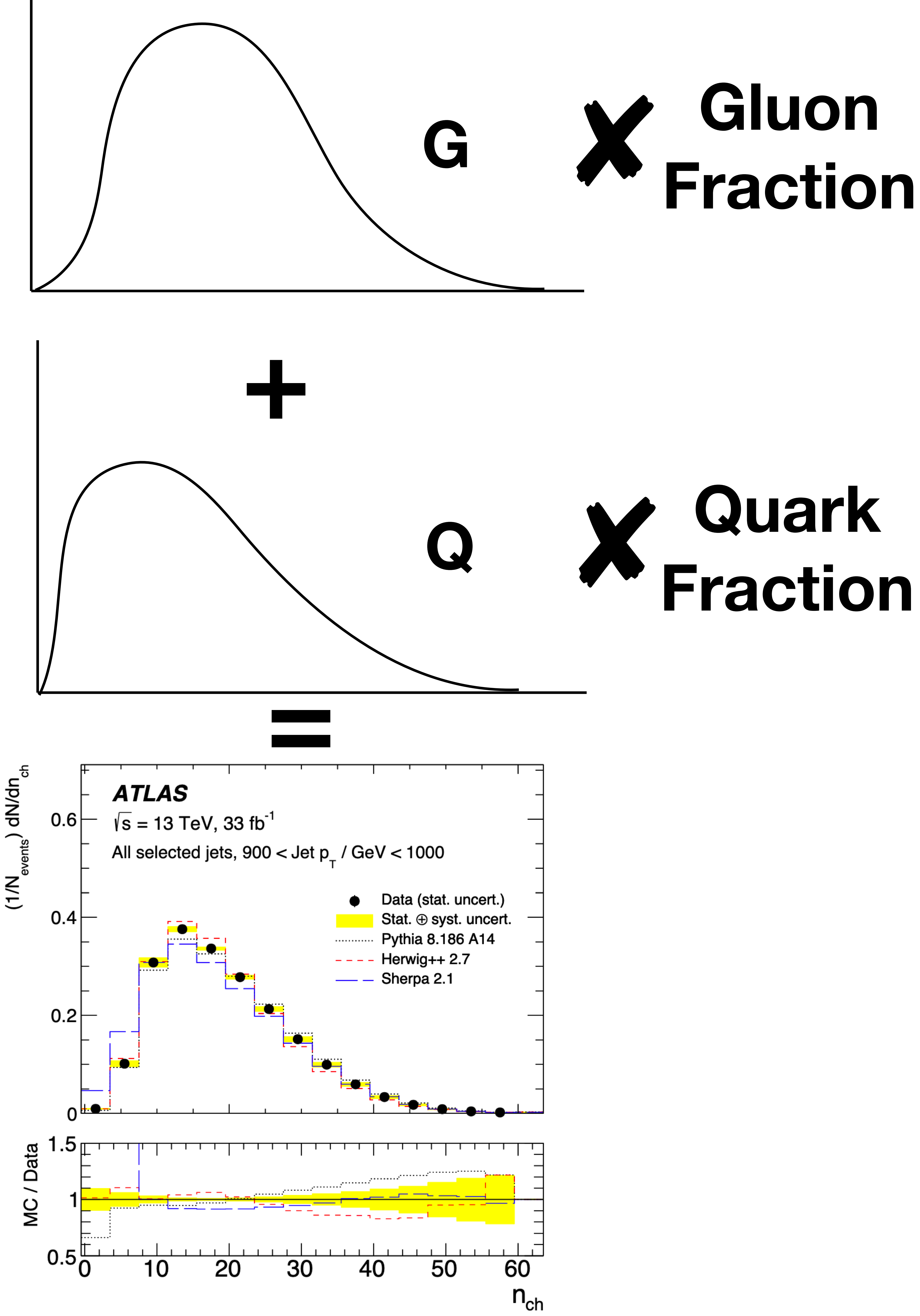


- Measuring forward and central jets separately gives us access to differences between quarks and gluons

jet fragmentation

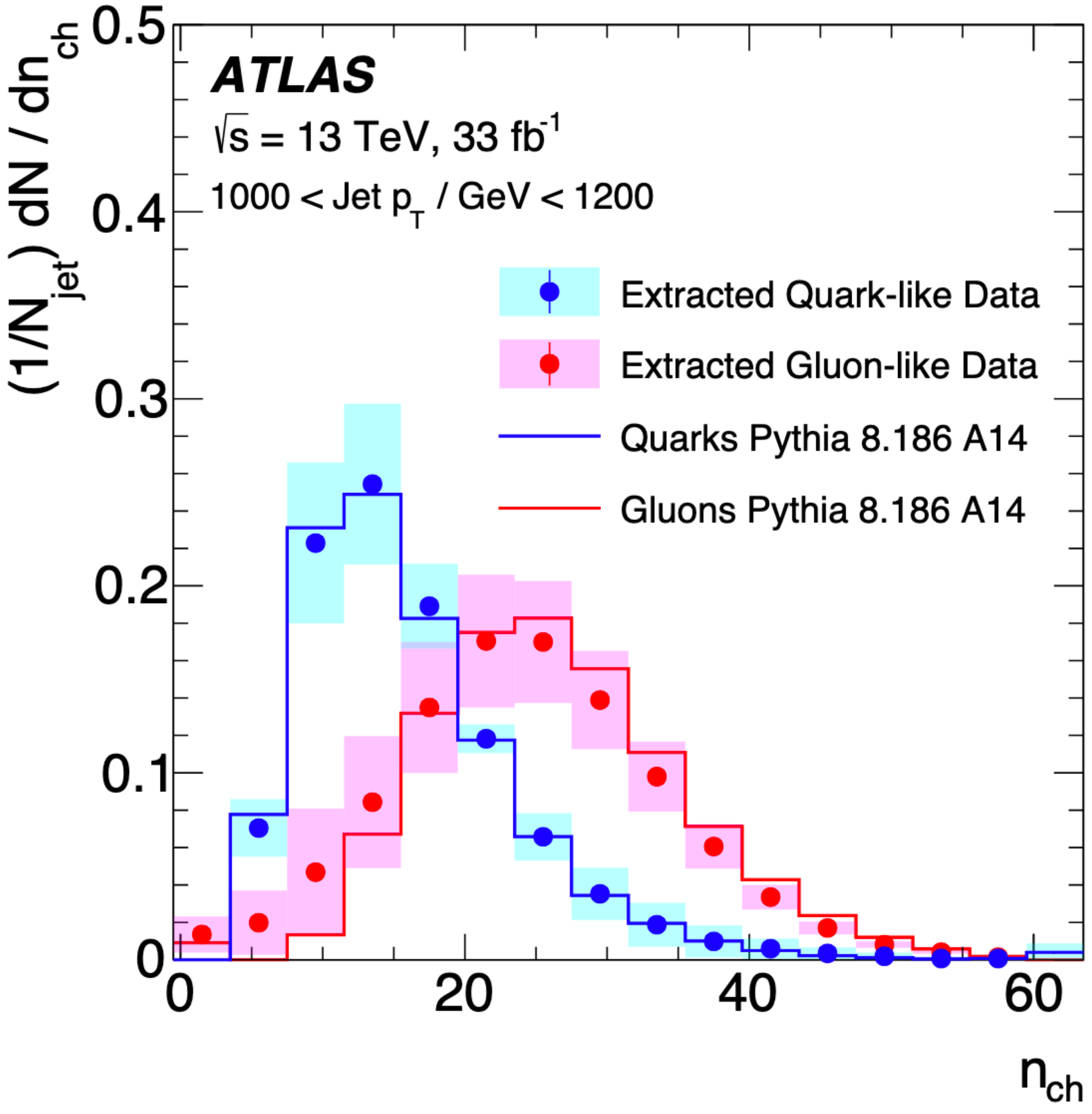
1906.09254

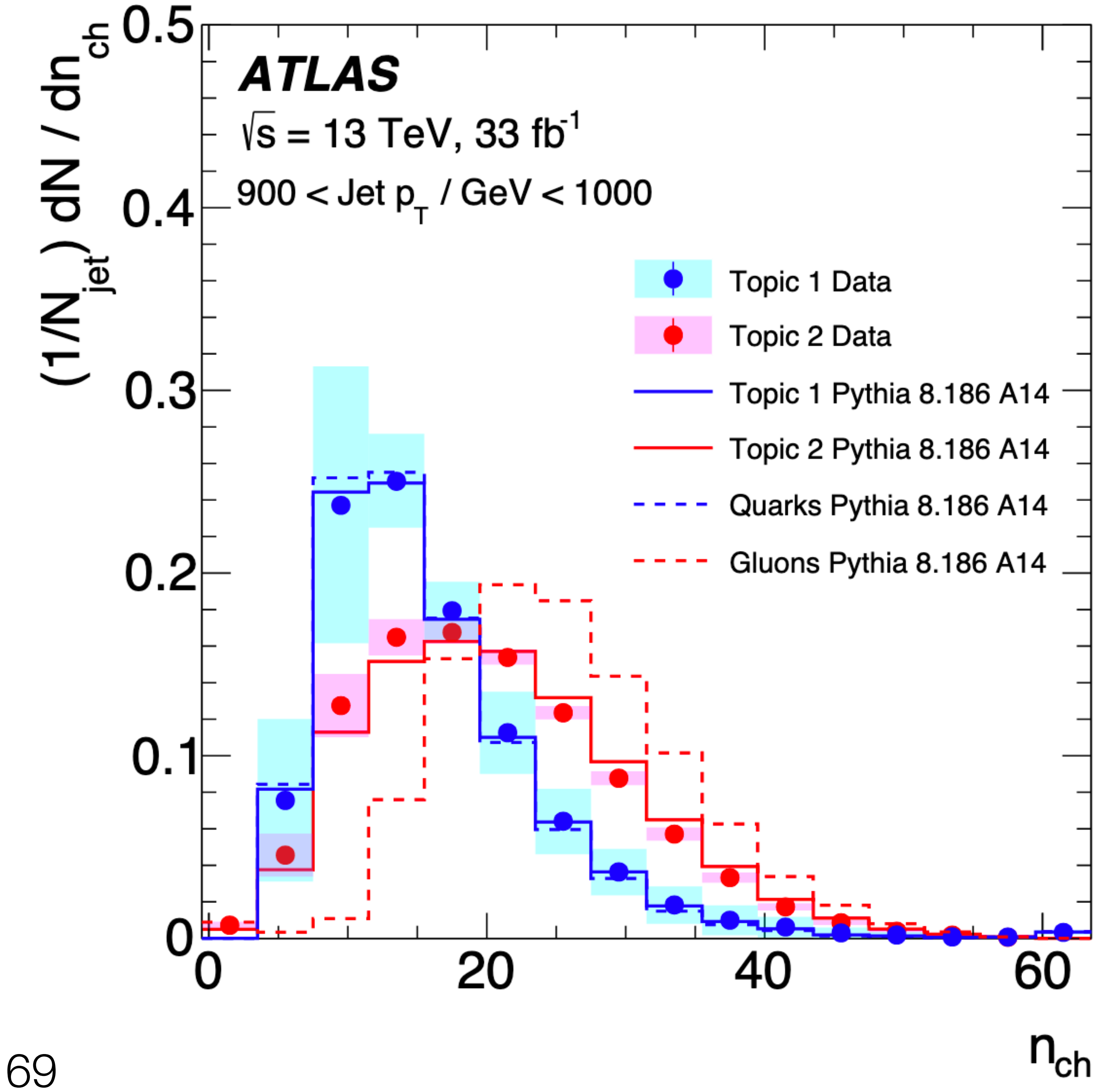
- The measured distributions are a linear combination of the quark and gluon distributions, multiplied by the fraction of quarks and gluons
    - Can invert this to extract the quark and gluon distributions in data
- Two methods:
    - Use the quark and gluon fractions determined in an MC generator (e.g. Pythia)
    - Use topic modeling to extract the distributions, which uses a minimization to separate mutually irreducible distributions



jet fragmentation

- Both methods provide similar results for the extracted quark and gluon distributions
- First time topic modeling has been used in a measurement!
  - Provides more model-independent way of extracting this information





Jet substructure observables in top quark, W boson, and light jet production

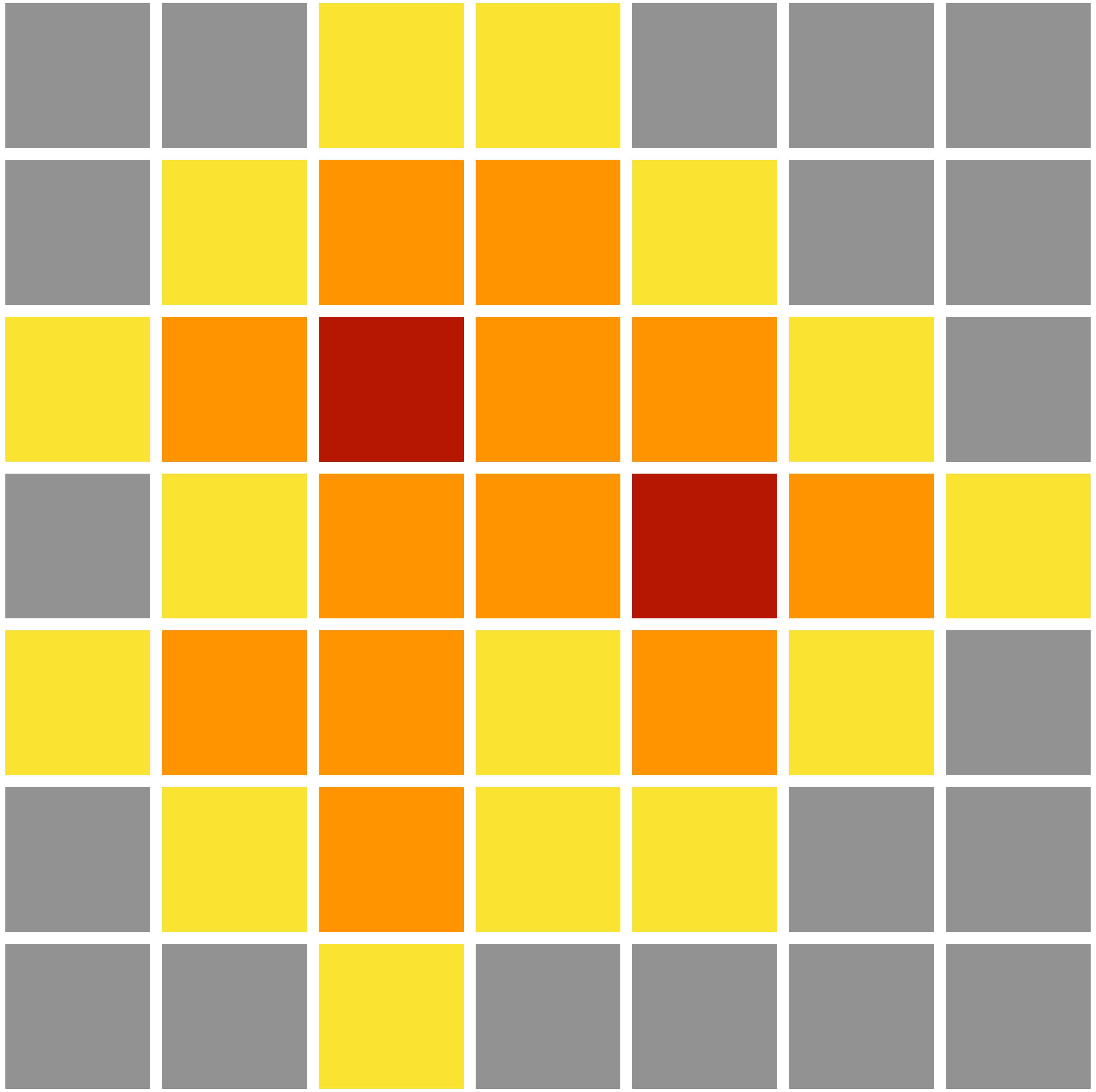
1903.0294

- Slightly different event selections for each different final state
-

	Detector level	Particle level
Dijet selection:		
Two trimmed anti-k_t $R = 1.0$ jets	$p_T > 200$ GeV $\|\eta\| < 2.5$	$p_T > 200$ GeV $\|\eta\| < 2.5$
Leading-p_T trimmed anti-k_t $R = 1.0$ jet	$p_T > 450$ GeV	
Top and W selections:		
Exactly one muon	$p_T > 30$ GeV $\|\eta\| < 2.5$ $\|z_0 \sin(\theta)\| < 0.5$ mm and $\|d_0/\sigma(d_0)\| < 3$	$p_T > 30$ GeV $\|\eta\| < 2.5$
Anti-k_t $R = 0.4$ jets	$p_T > 25$ GeV $\|\eta\| < 4.4$ JVT output > 0.5 (if $p_T < 60$ GeV)	$p_T > 25$ GeV $\|\eta\| < 4.4$
Muon isolation criteria	If $\Delta R(\mu, \text{jet}) < 0.04 + 10\text{ GeV}/p_{T,\mu}$: muon is removed, so the event is discarded	None
E_T^{miss}, m_T^W	$E_T^{miss} > 20$ GeV, $E_T^{miss} + m_T^W > 60$ GeV	
Leptonic top	At least one small-radius jet with $0.4 < \Delta R(\mu, \text{jet}) < 1.5$	
Top selection:		
Leading-p_T trimmed anti-k_t $R = 1.0$ jet	$\|\eta\| < 1.5$, $p_T > 350$ GeV, mass > 140 GeV ΔR(large-radius jet, b-tagged jet) < 1 $\Delta\phi(\mu$, large-radius jet) > 2.3	
W selection:		
Leading-p_T trimmed anti-k_t $R = 1.0$ jet	$\|\eta\| < 1.5$, $p_T > 200$ GeV, mass > 60 GeV and mass < 100 GeV $1 < \Delta R$(large-radius jet, b-tagged jet) < 1.8 $\Delta\phi(\mu$, large-radius jet) > 2.3	

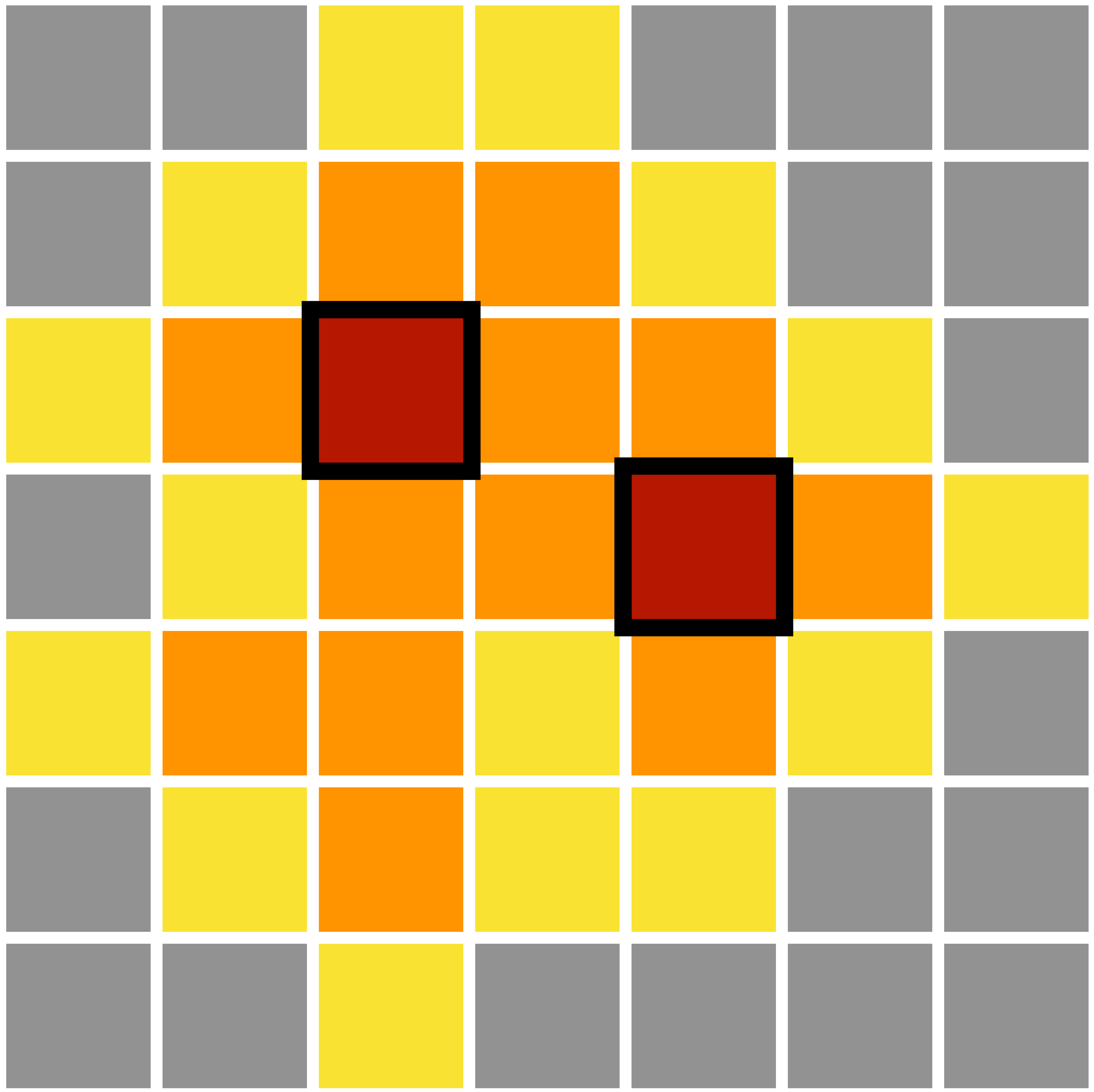
jet inputs: topoclusters

- Jets are composed of both charged and neutral hadrons
  - Some observables have similar behavior when reconstructed only out of charged particles
- Analytical predictions only for all-particles
  - Need to use the information from the *calorimeter*
- Combine nearby groups of calorimeter cells into *clusters* in order to produce object which approximately corresponds to a single particle



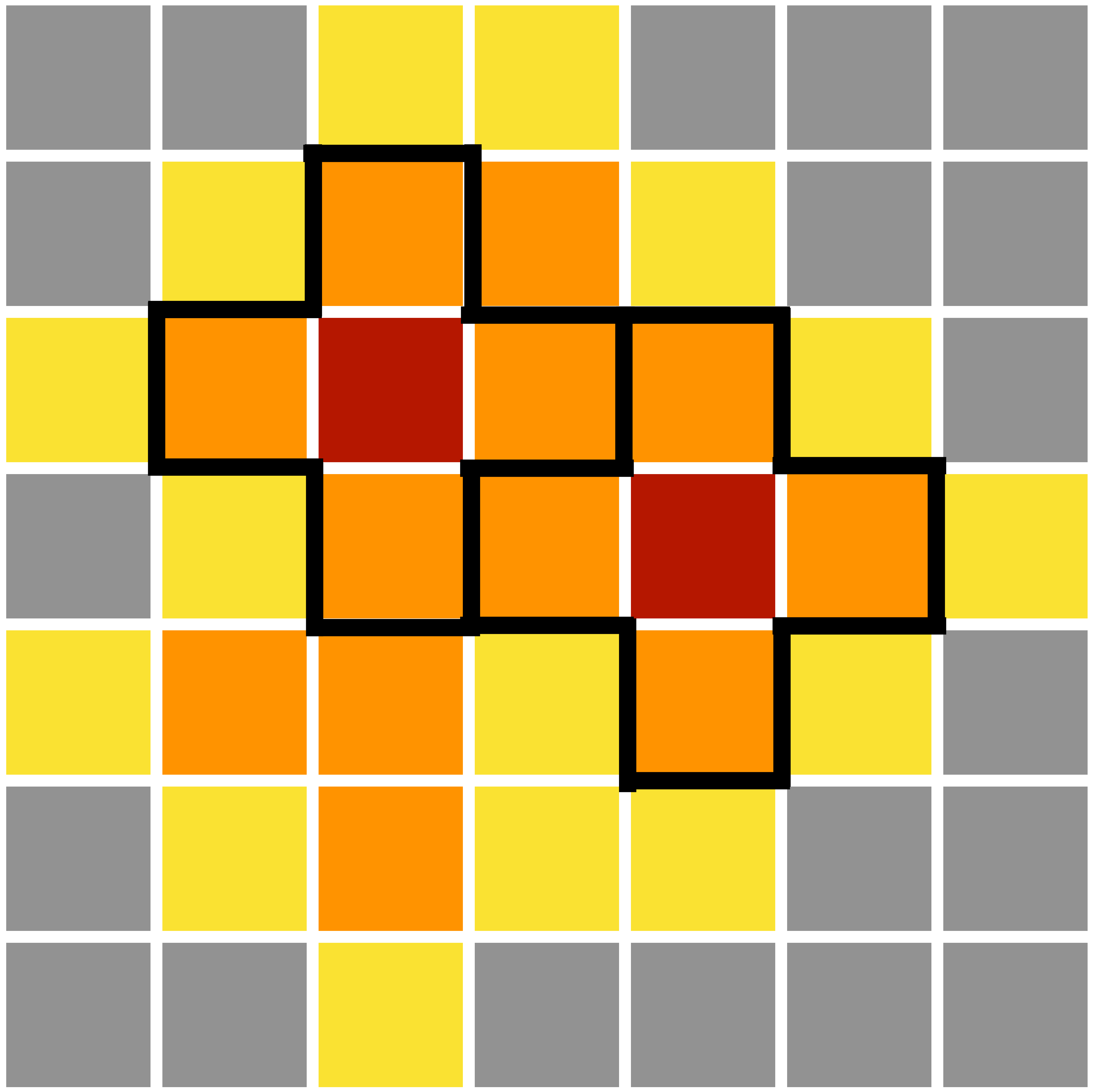
jet inputs: topoclusters

- Use the '4-2-0' algorithm for reconstruction
  - Clusters are seeded by cells with energy of 4σ above the expected noise



jet inputs: topoclusters

- Use the ‘4-2-0’ algorithm for reconstruction
  - Clusters are seeded by cells with energy of 4σ above the expected noise
  - Any neighboring cells with E>2σ are added recursively until no high-energy neighboring cells remain



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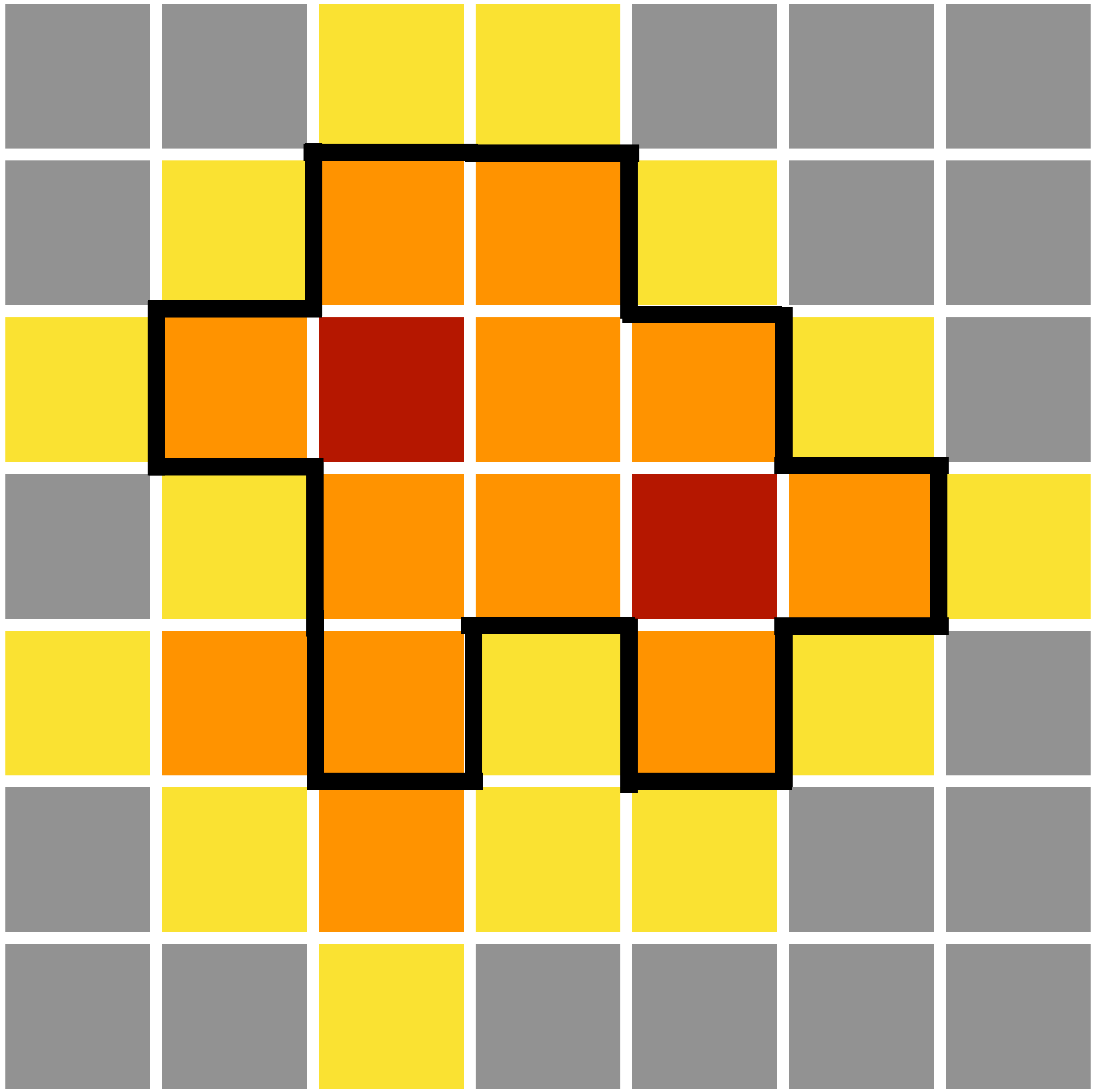

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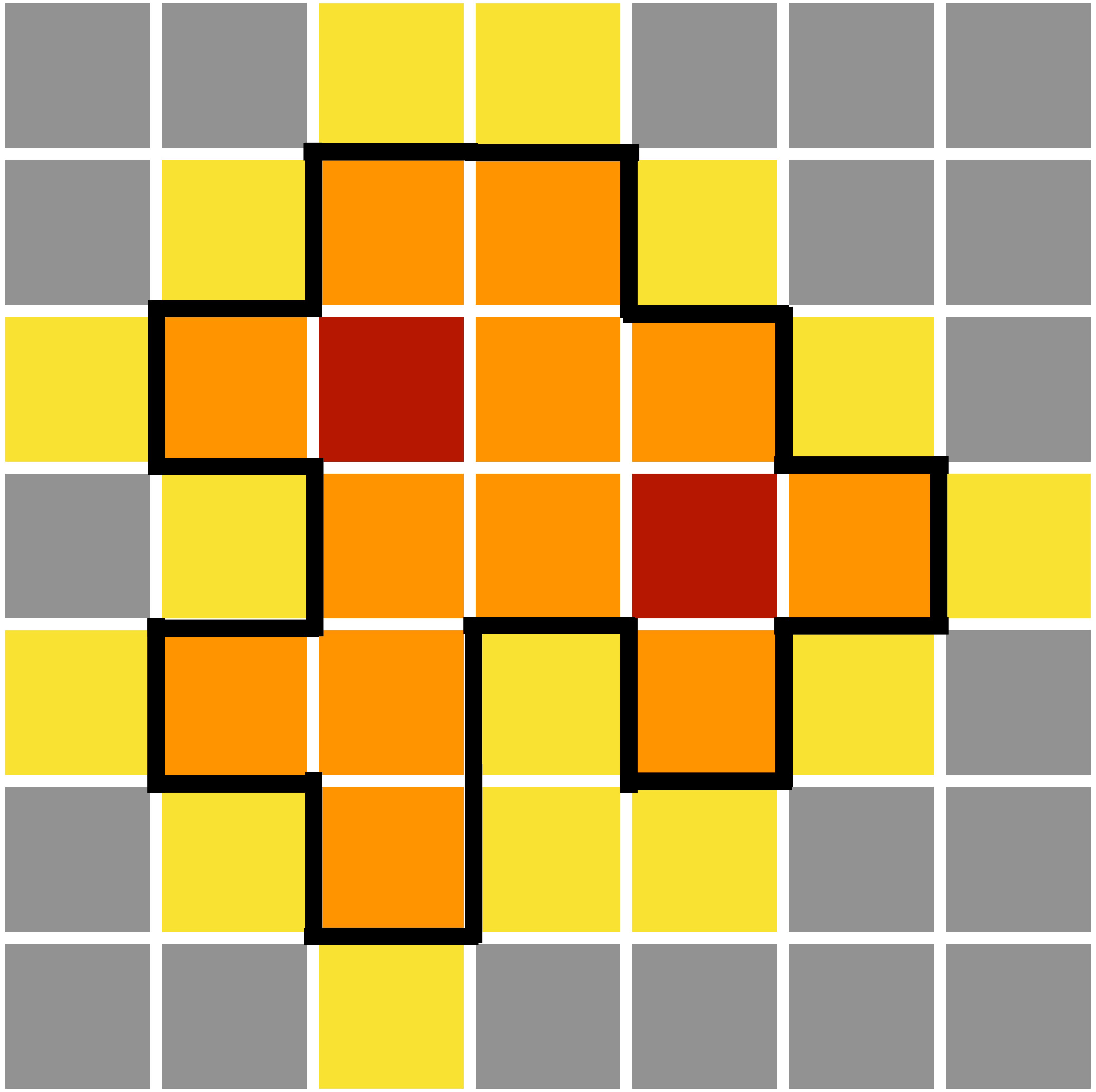
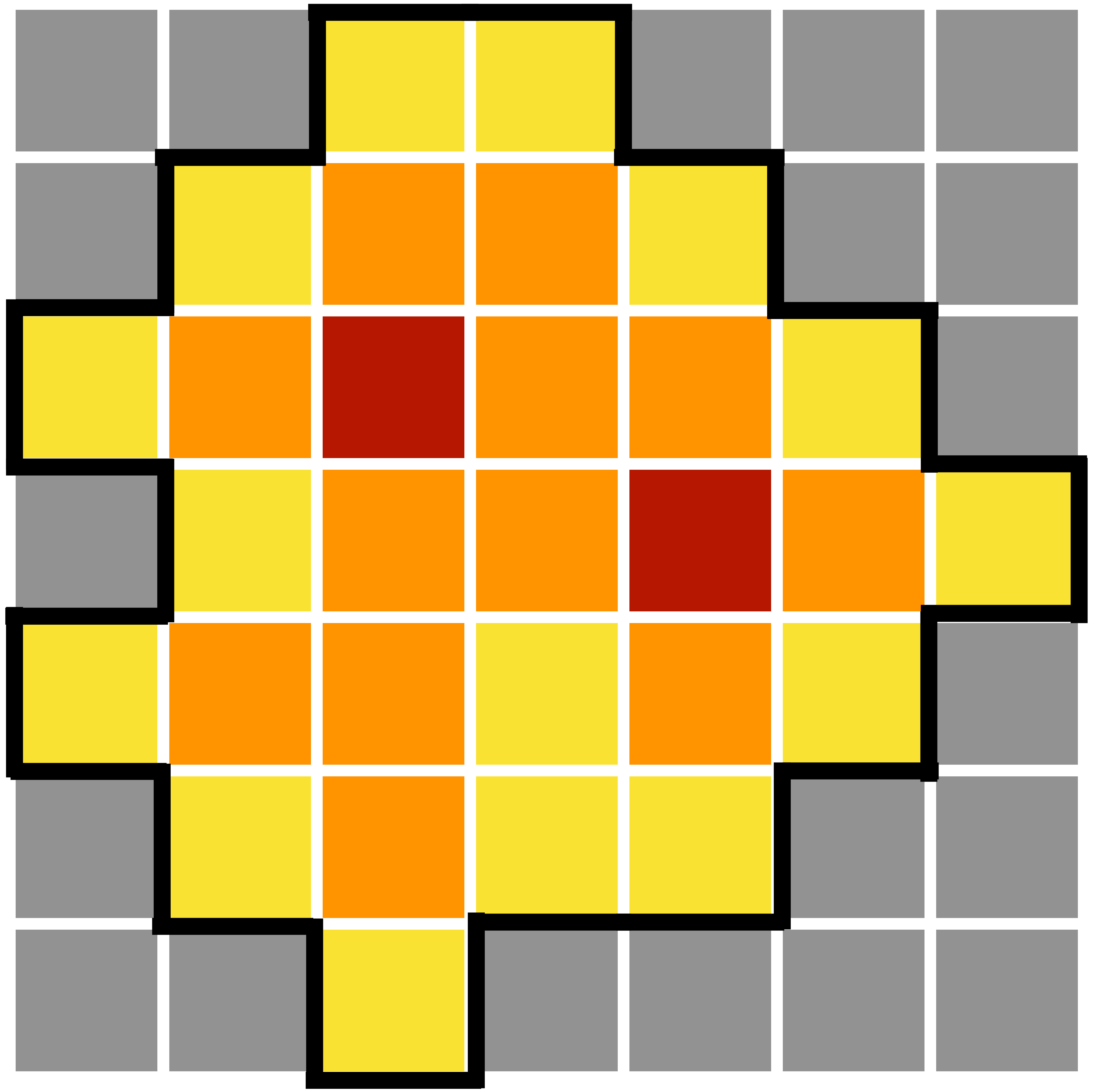


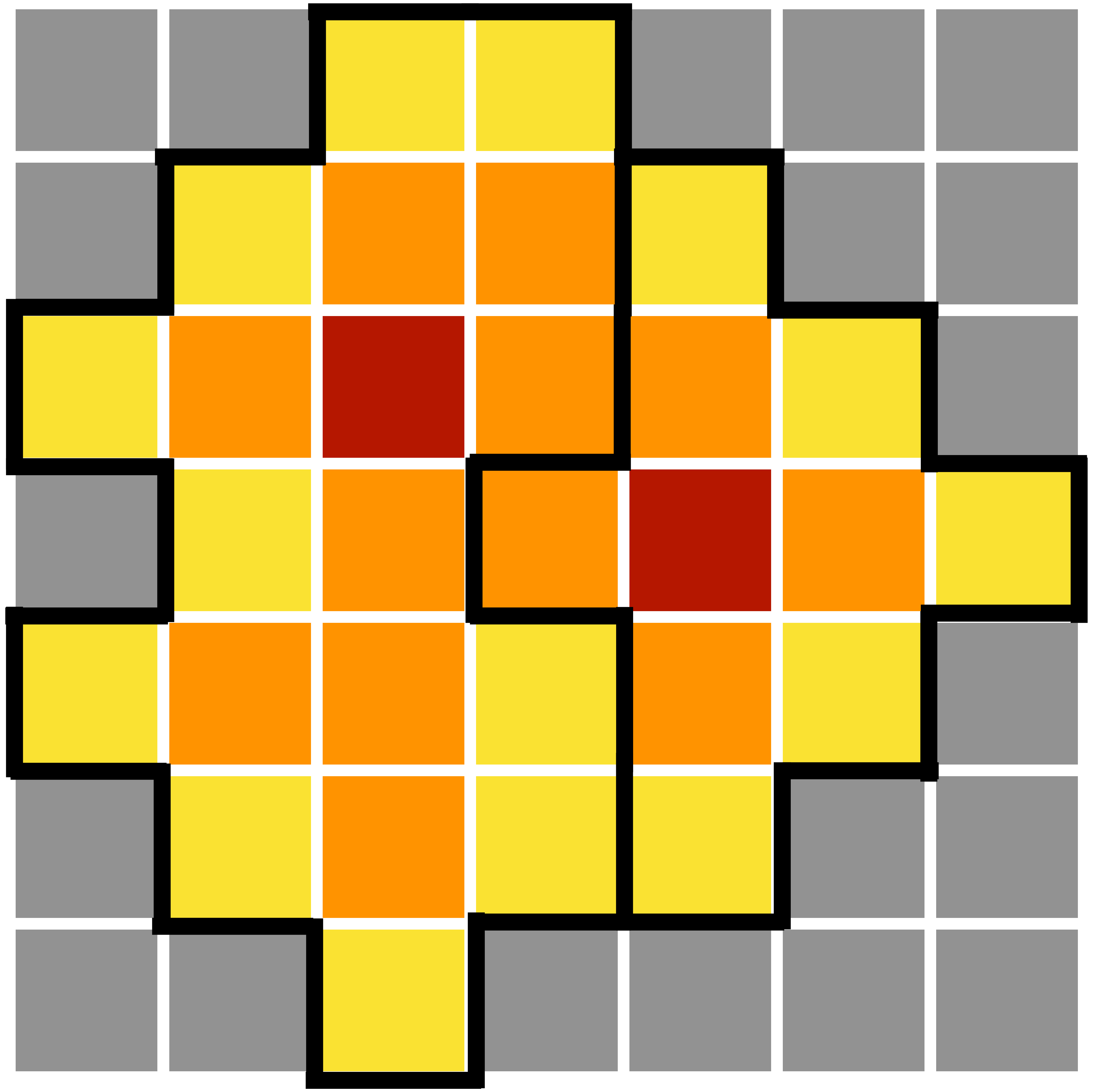
jet inputs: topoclusters

- Use the '4-2-0' algorithm for reconstruction
  - Clusters are seeded by cells with energy of 4σ above the expected noise
  - Any neighboring cells with E>2σ are added recursively until no high-energy neighboring cells remain
  - All neighboring cells are added, regardless of their energy



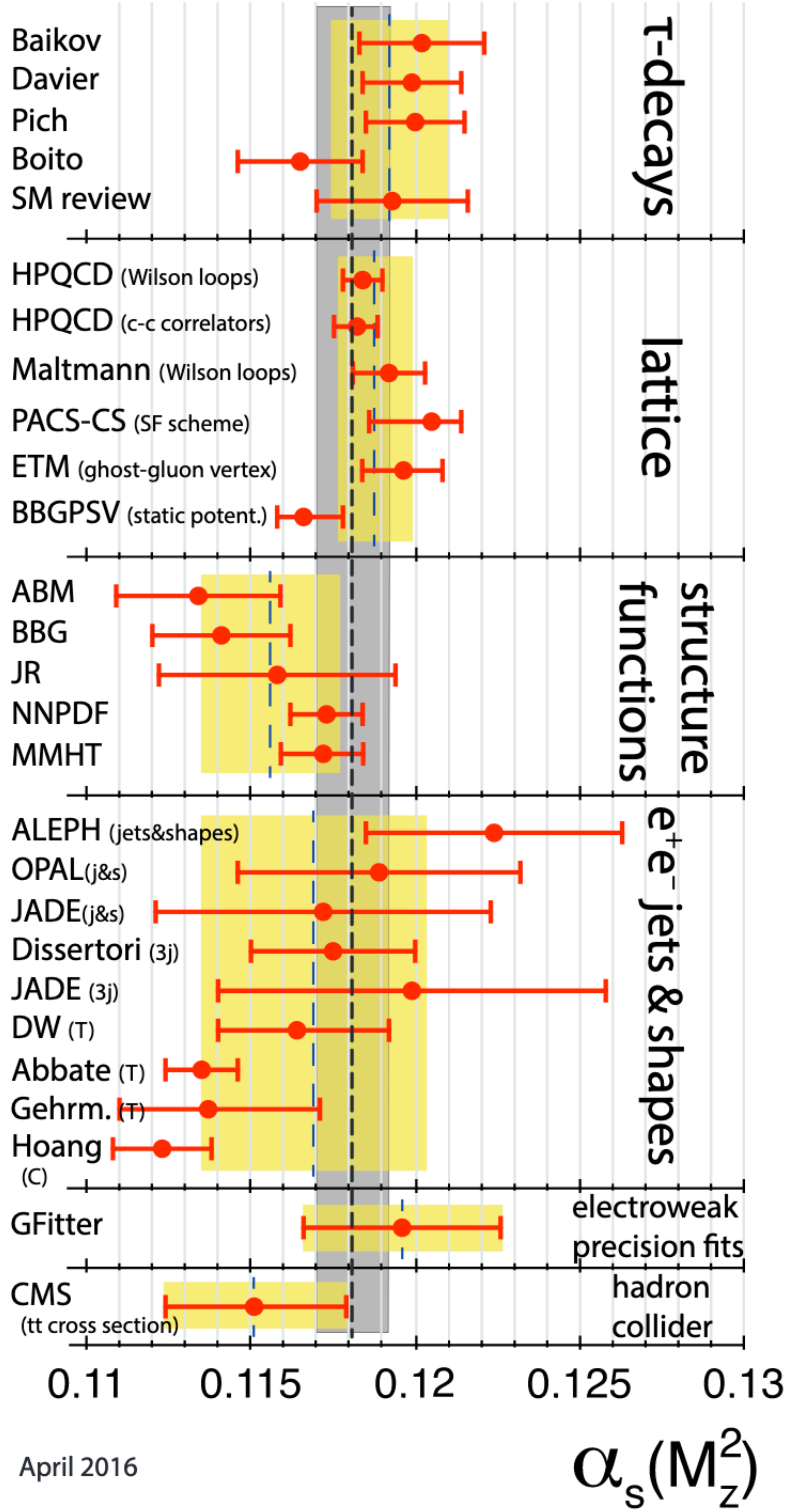
jet inputs: topoclusters

- Use the '4-2-0' algorithm for reconstruction
  - Clusters are seeded by cells with energy of 4σ above the expected noise
  - Any neighboring cells with E>2σ are added recursively until no high-energy neighboring cells remain
  - All neighboring cells are added, regardless of their energy
  - Clusters with multiple local maxima are split



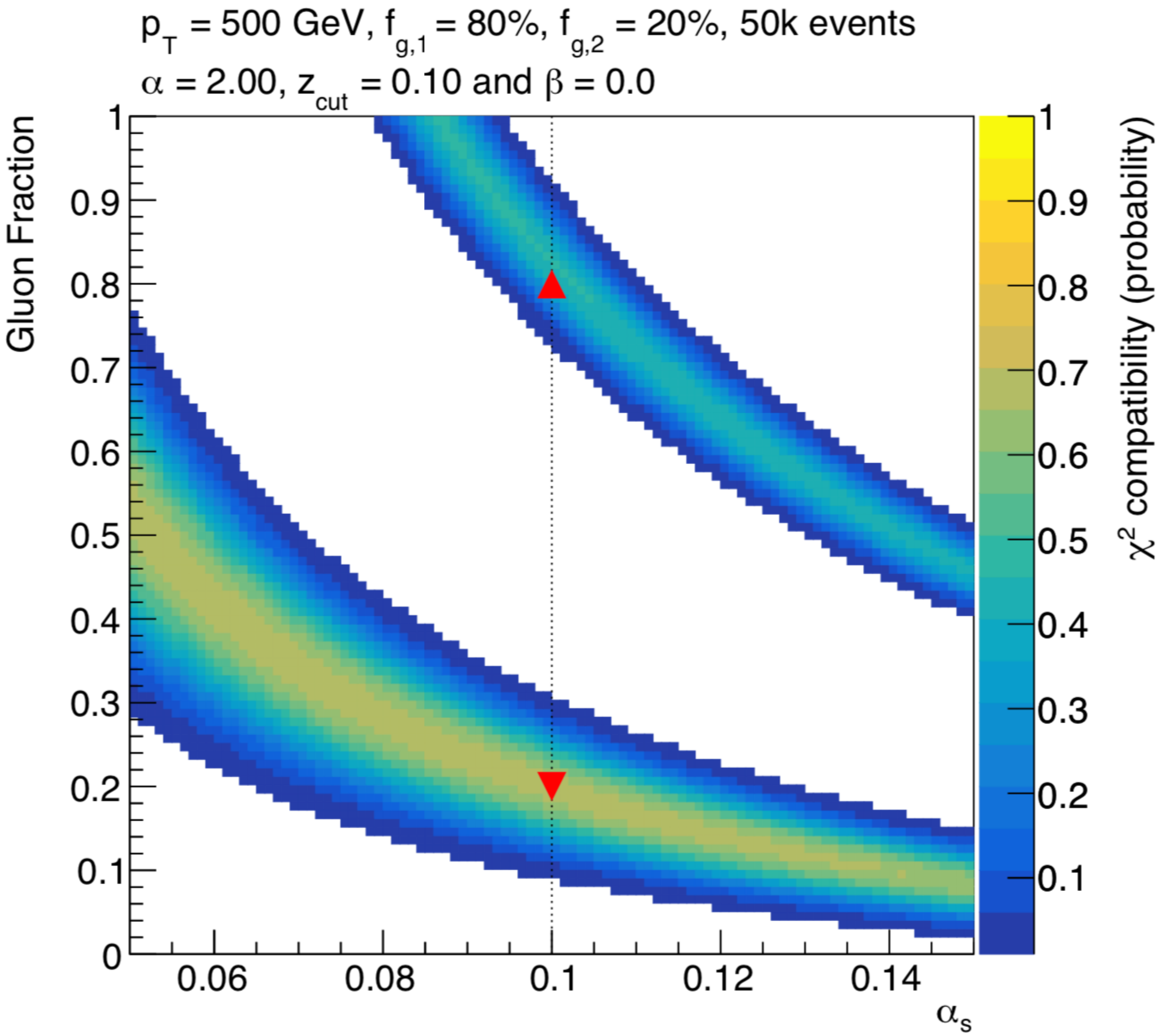
measuring α_s

- α_s is a challenging parameter to measure
  - Precise determination important for many precision measurements like for the Higgs
  - Need observables sensitive to α_s, but not too sensitive to non-perturbative effects or to PDFs
  - Need observables which are calculable to NNLO → currently only one measurement from a hadron collider!
- Significant tensions between some of the most precise measurements of α_s
  - Need independent measurements in order to understand this discrepancy



looking forward: α_s

- Differential cross section for jet mass is proportional to α_s x C_i in the resummation region
- Measurements of mass with multiple samples with different quark/gluon fractions could be used to extract α_s
- May be able to get somewhere around 5-10% precision



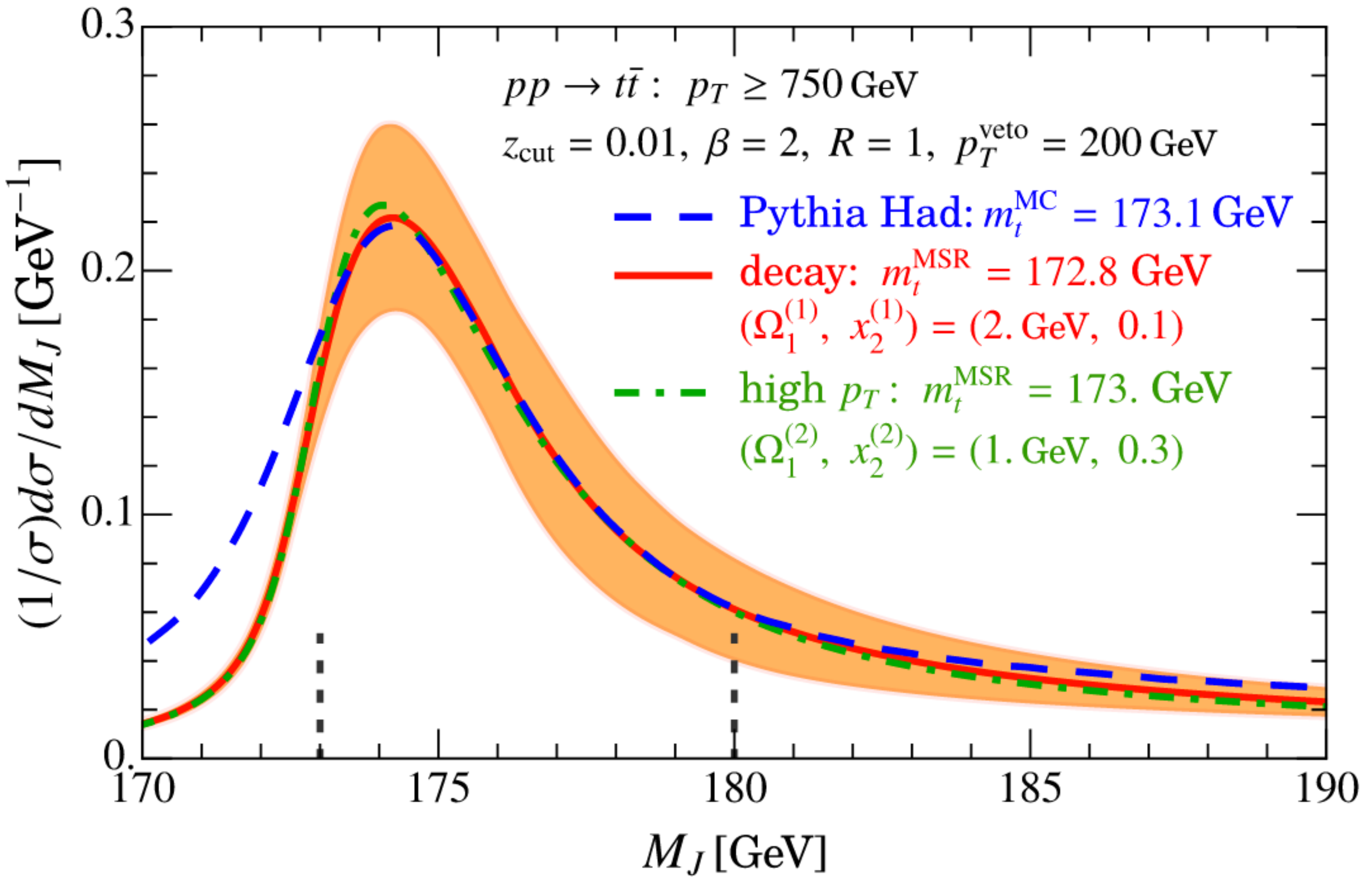
Les Houches 2017

- Not competitive with precise measurements, could be used to better understand discrepancies between existing measurements
- Also could provide measurement of running of α_s

1708.02586

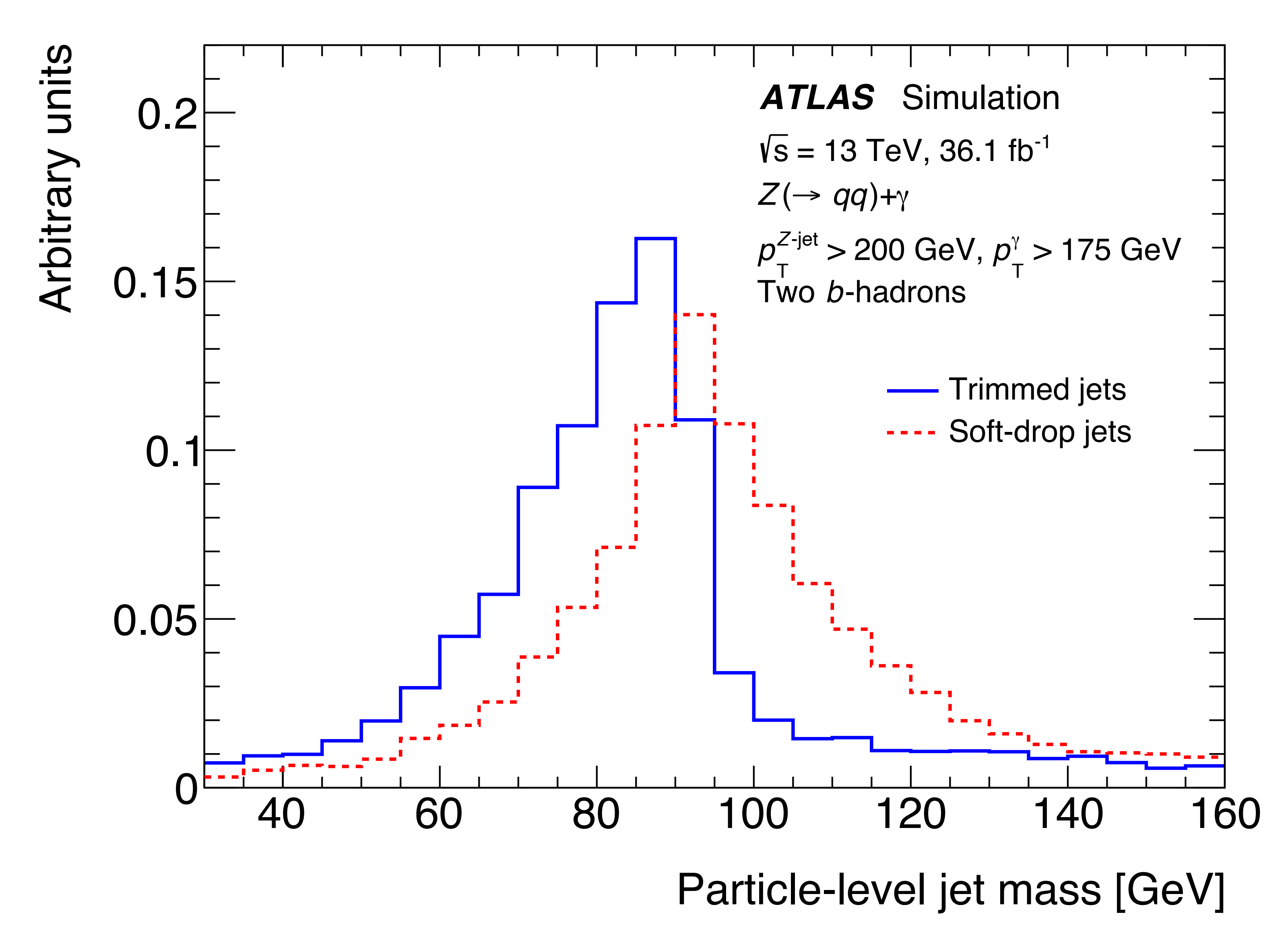
looking forward: the top mass

- Currently, most precise measurements of the top mass are done using direct reconstruction
  - Provides measurement of the MC top mass
- Soft drop can be used to isolate a boosted top quark from the rest of the event
  - May be possible to factorize the calculation in a meaningful way
  - Would not rely on MC templates for measurement



Z(→bb) + γ

- Measuring with both Soft Drop and trimmed jets
  - Mass distributions have different shapes, even at particle level
  - Applied pileup mitigation (Constituent Subtraction + SoftKiller) to Soft Drop jets due to pileup instabilities

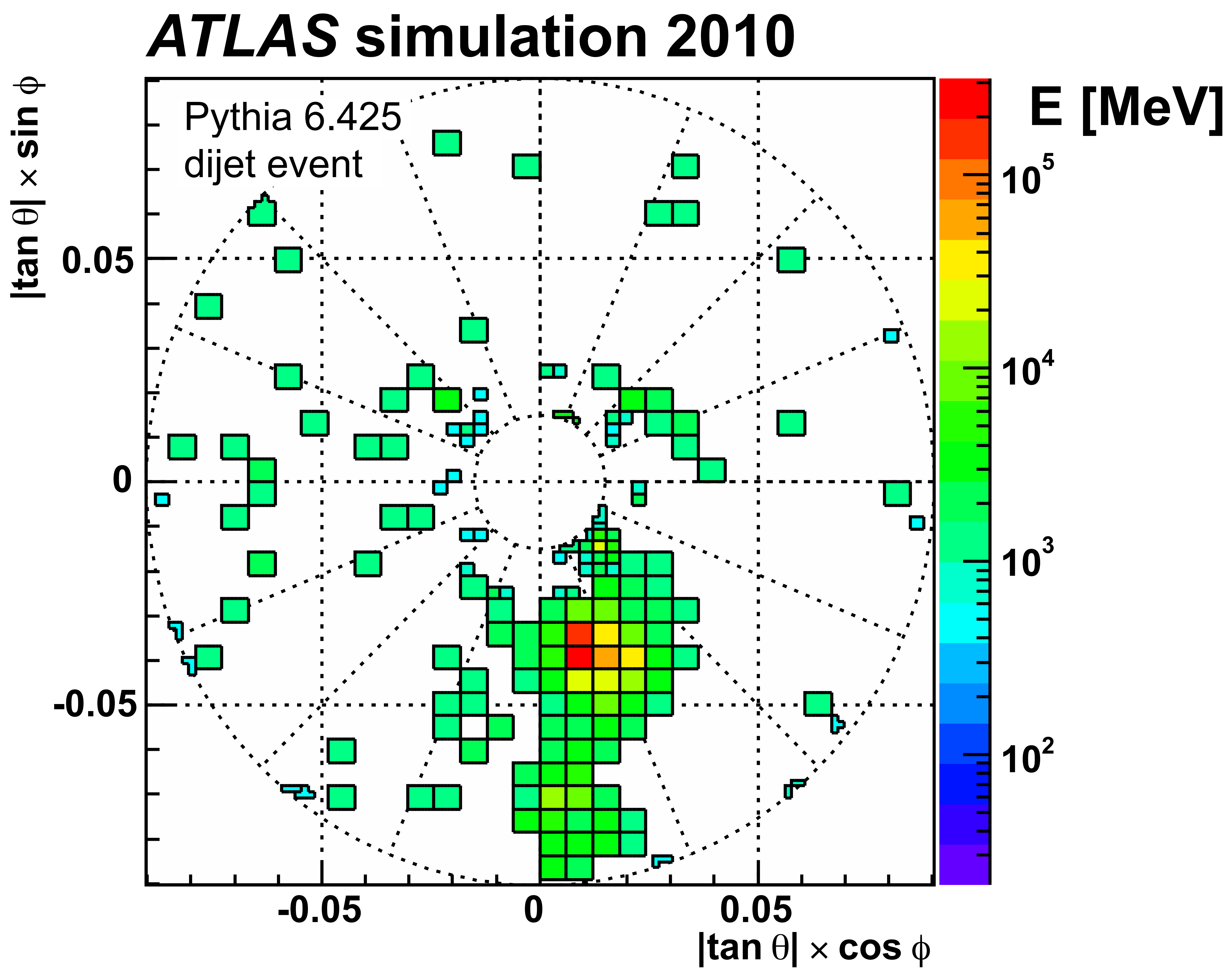


	Trimmed jets	Soft-drop jets
Expected significance	3.8	2.7
Observed significance	3.9	2.7

Jet definition	$\sigma\ (Z(\to b\bar{b})\gamma,\ p_T^{Z\text{-jet}} > 200$ GeV, $p_T^{\gamma} > 175$ GeV, $30 < m^{Z\text{-jet}} < 160$ GeV) [fb]	
Trimmed jets	Data	17.0 ± 5.0 (stat.) ± 3.6 (syst.)
	SHERPA $Z\gamma$ prediction	13.4 ± 0.2 (stat.)
	MADGRAPH+PYTHIA 8 $Z\gamma$ prediction	9.1 ± 0.1 (stat.)
Soft-drop jets	Data	12.5 ± 4.9 (stat.) ± 3.1 (syst.)
	SHERPA $Z\gamma$ prediction	15.4 ± 0.1 (stat.)
	MADGRAPH+PYTHIA 8 $Z\gamma$ prediction	10.2 ± 0.1 (stat.)

jet inputs: topoclusters

- Topoclusters are the standard inputs to jet reconstruction, which only use calorimeter information
- Use the '4-2-0' algorithm for reconstruction
  - Clusters are seeded by cells with energy of 4σ above the expected noise
  - Any neighboring cells with E>2σ are added recursively until no high-energy neighboring cells remain



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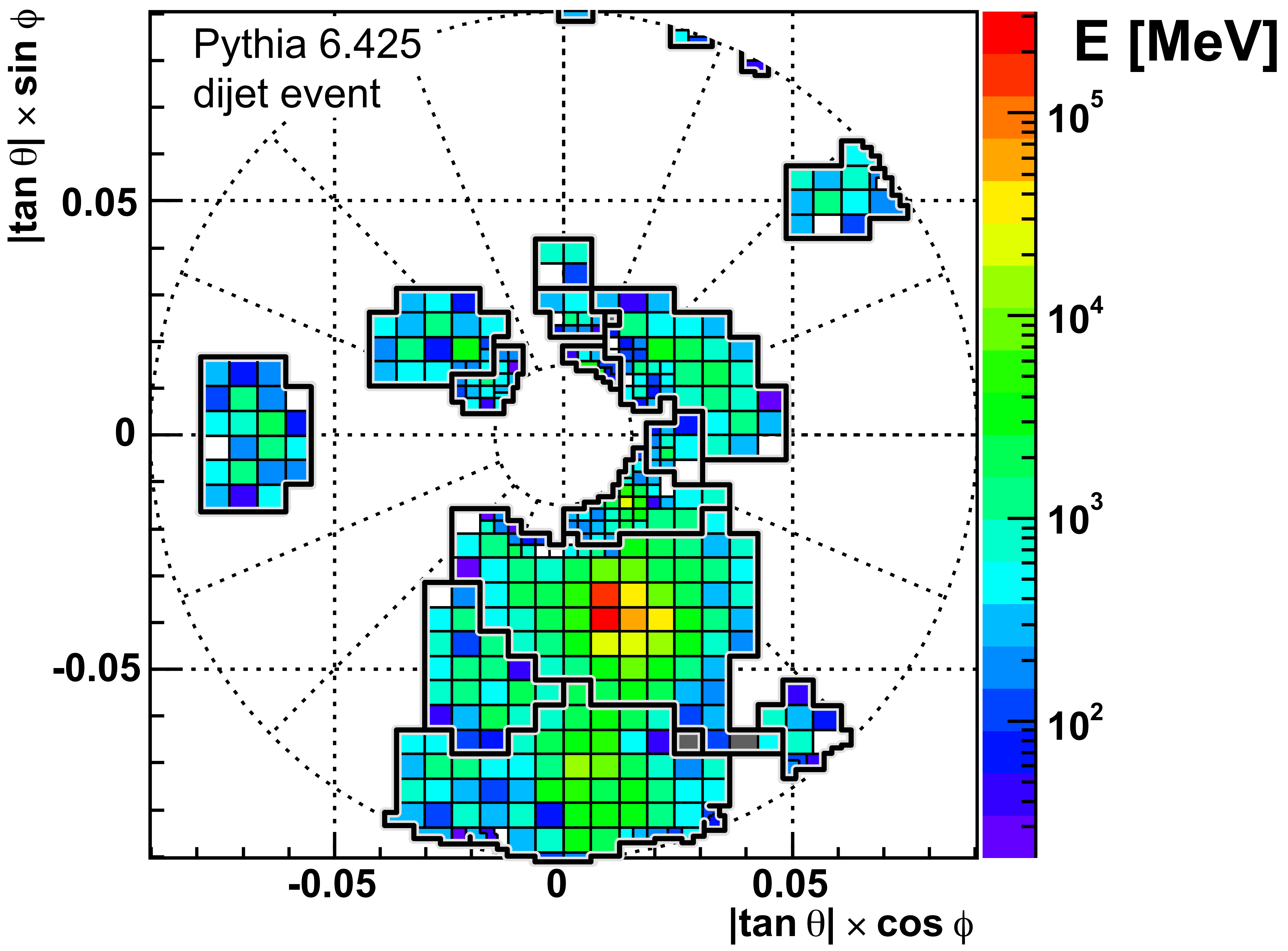
  - All neighboring cells are added, regardless of their energy



other substructure measurements

- Studies of jet substructure help provide insight into jet quenching
- Recent measurement uses *reclustered* large-R jets in order to probe larger angular scales
  - Similar behavior as R=0.4 jets for the jet p_T, but more suppression