Measurement of jet substructure and jet fragmentation using the ATLAS detector

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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
- Many aspects of jets require Monte Carlo (MC) generators
  - *Jet modeling* is one of the dominant sources of uncertainties for many analyses
  - Deeper understanding of jet formation can be used to develop better models of jets
- Better understanding of jets leads to better, *more robust observables* for tagging jets

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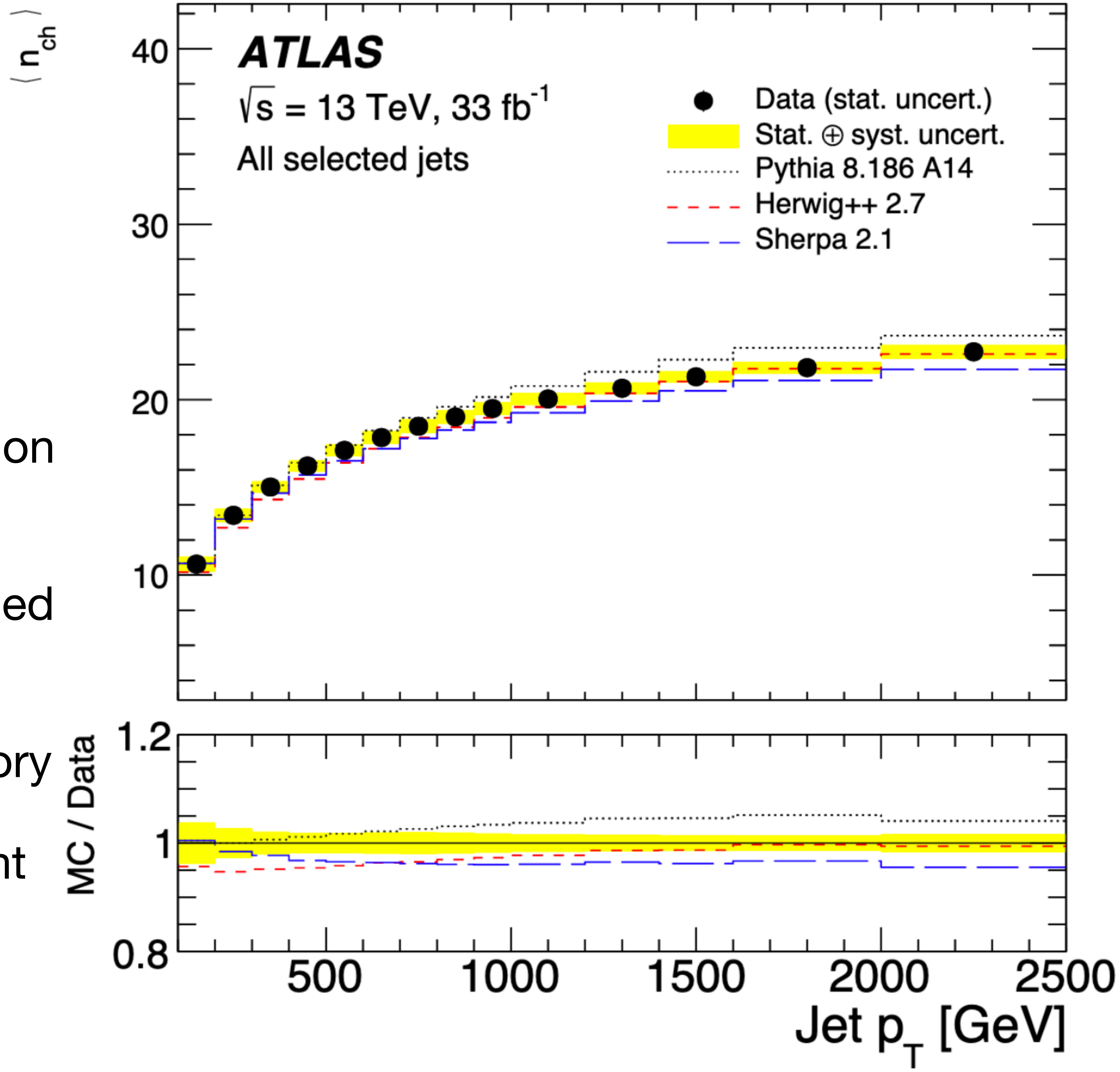
jet fragmentation

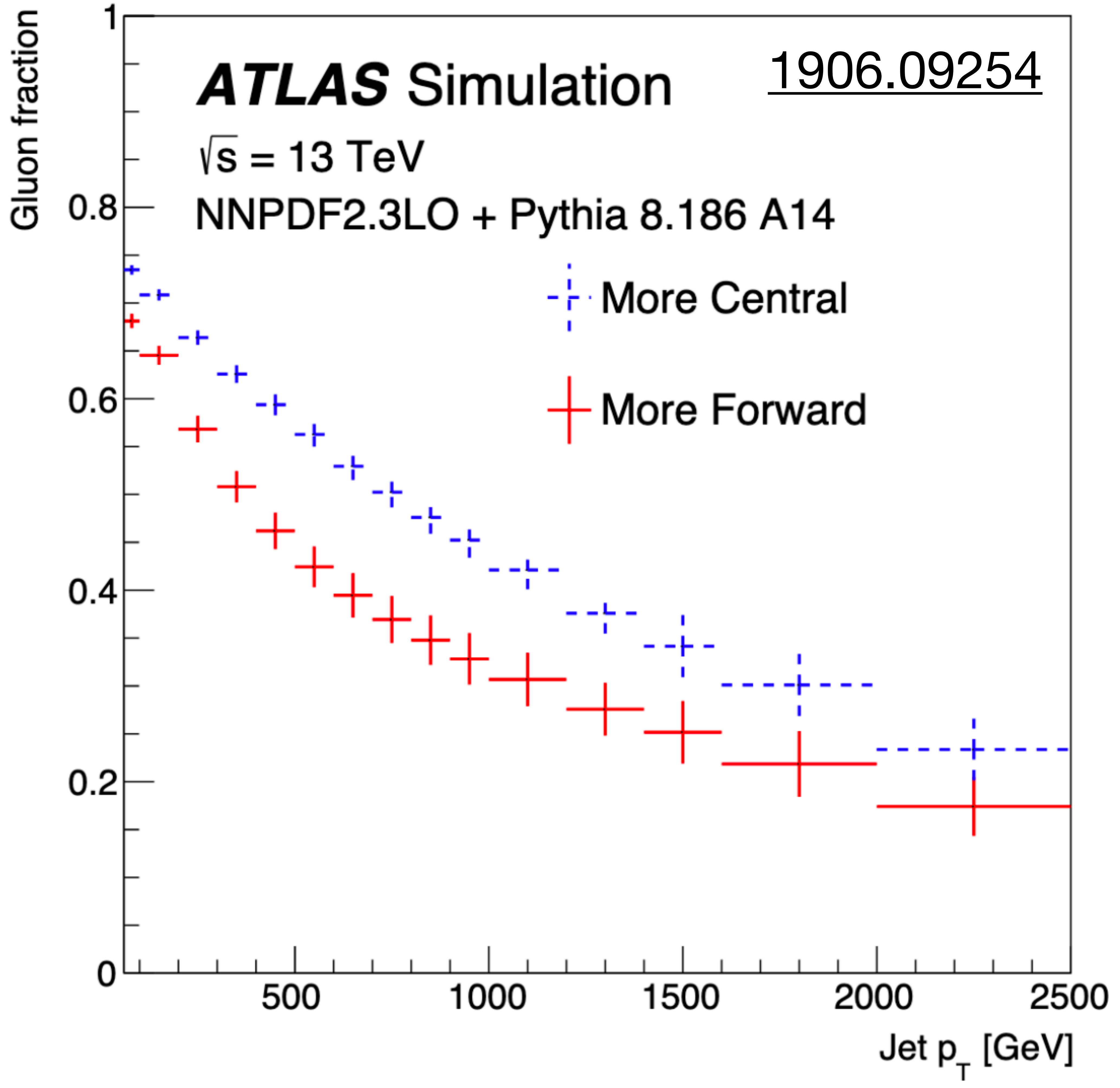
- Jet formation is complicated, and is not fully describable by perturbation theory
  - Rely on Monte Carlo models in order to produce predictions involving jets
- Jet fragmentation measurements study the distribution of particles within a jet
  - Includes observables such as the number of charged particles, 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

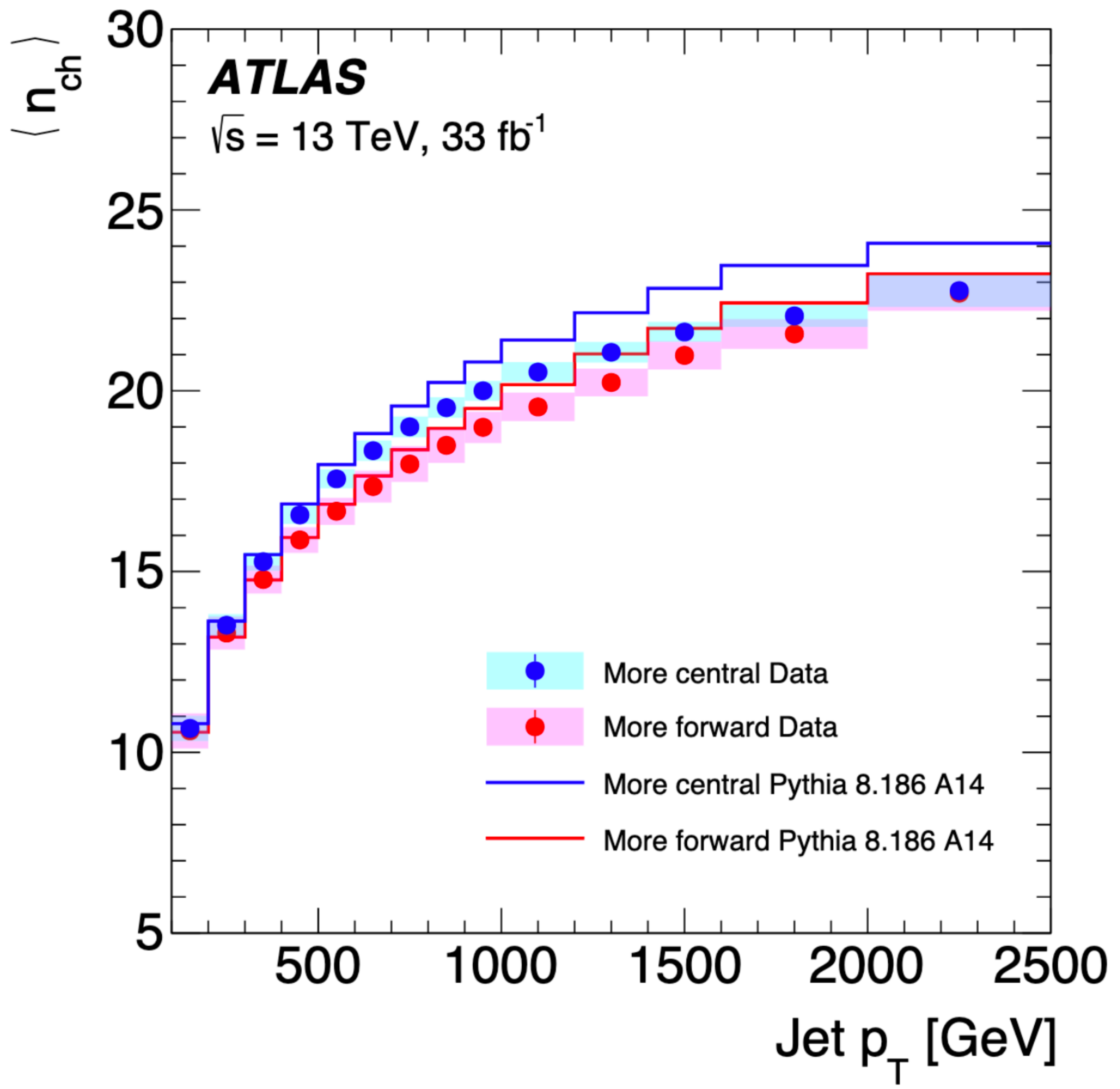


jet fragmentation

- 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

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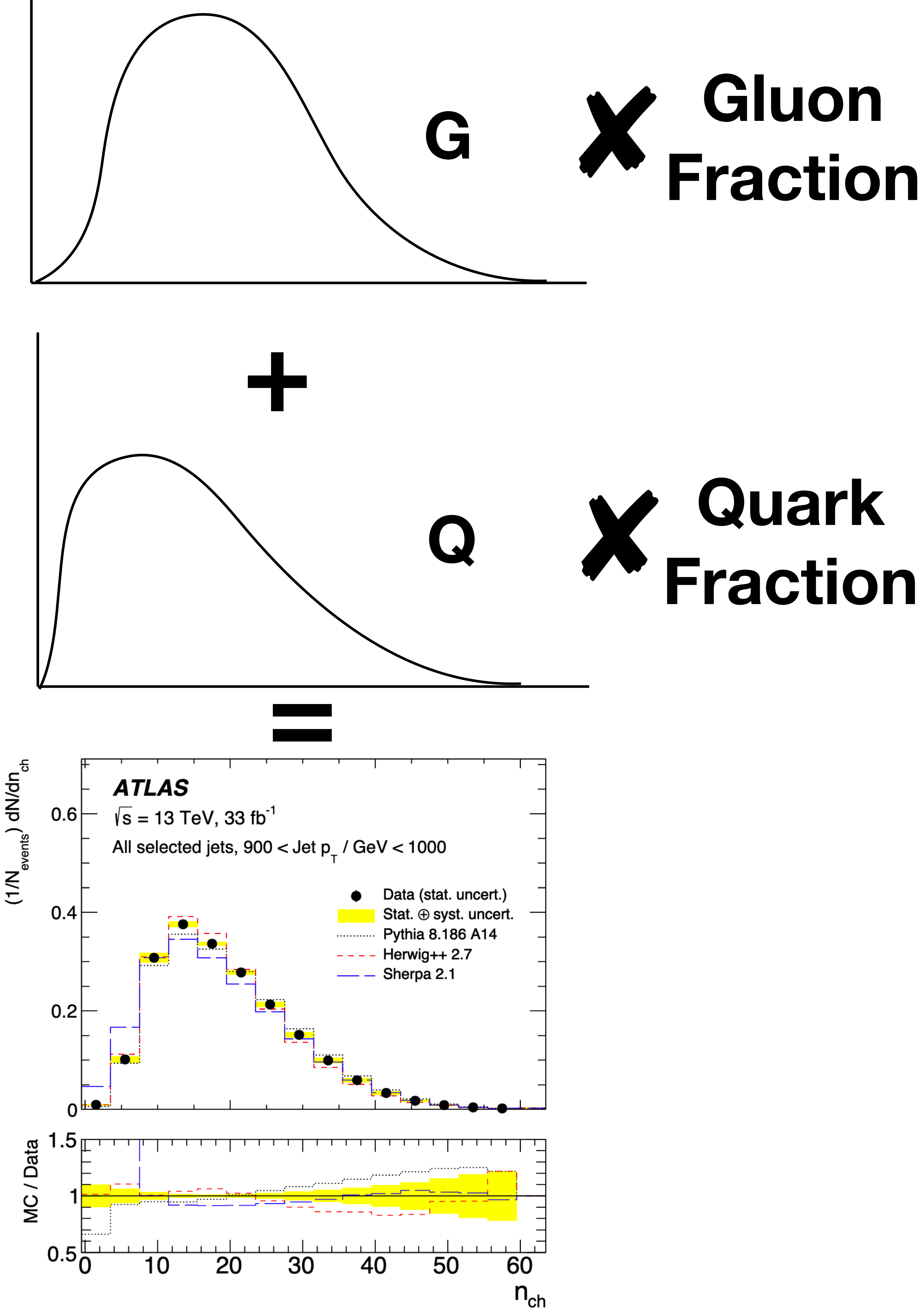
- The measured distributions are a linear combination of the quark and gluon distributions, multiplied by the fraction of quarks and gluons
  - Can invert this to extract the quark and gluon distributions in data
- Two methods:
  - Use the quark and gluon fractions determined in an MC generator (e.g.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



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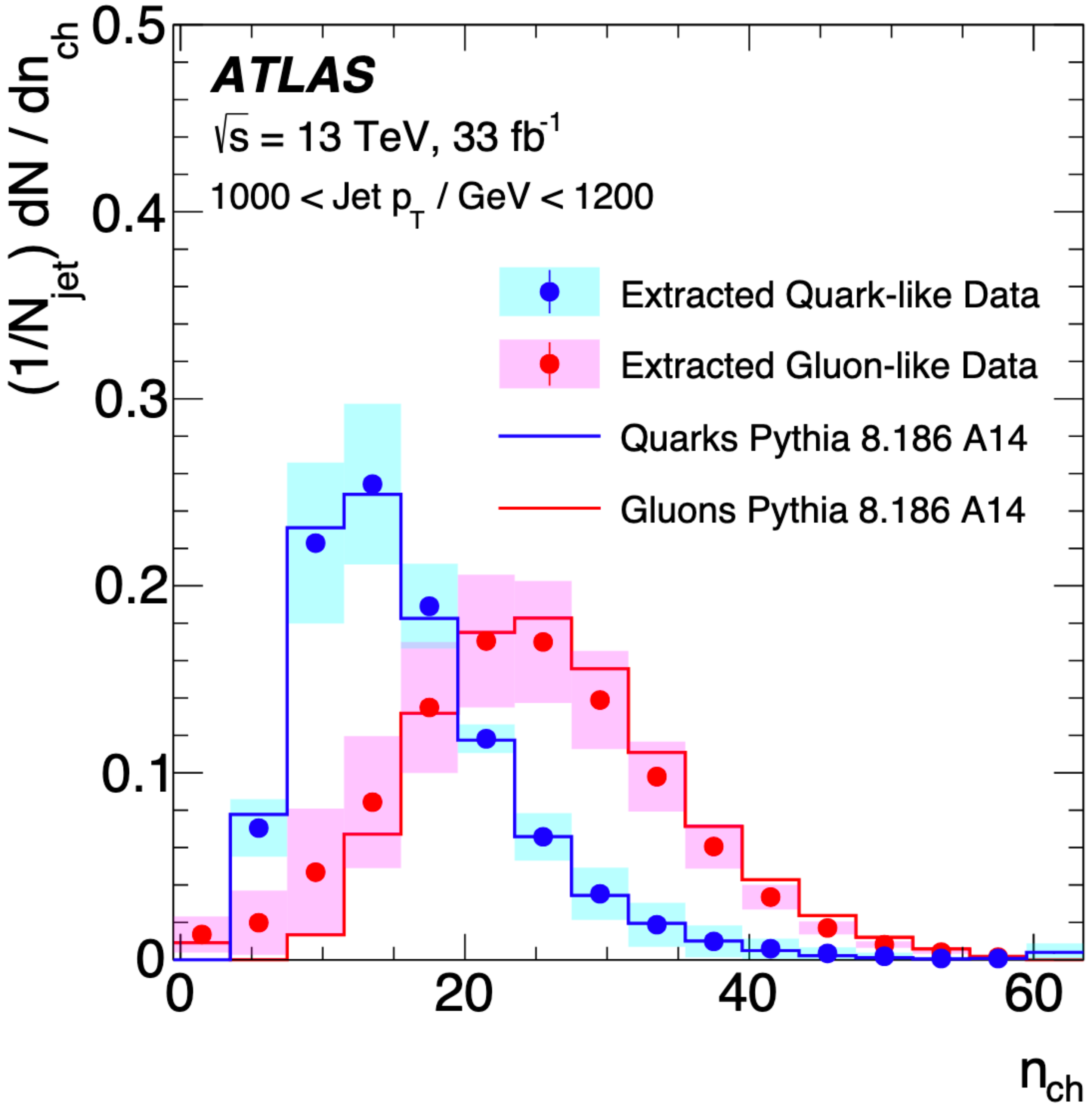
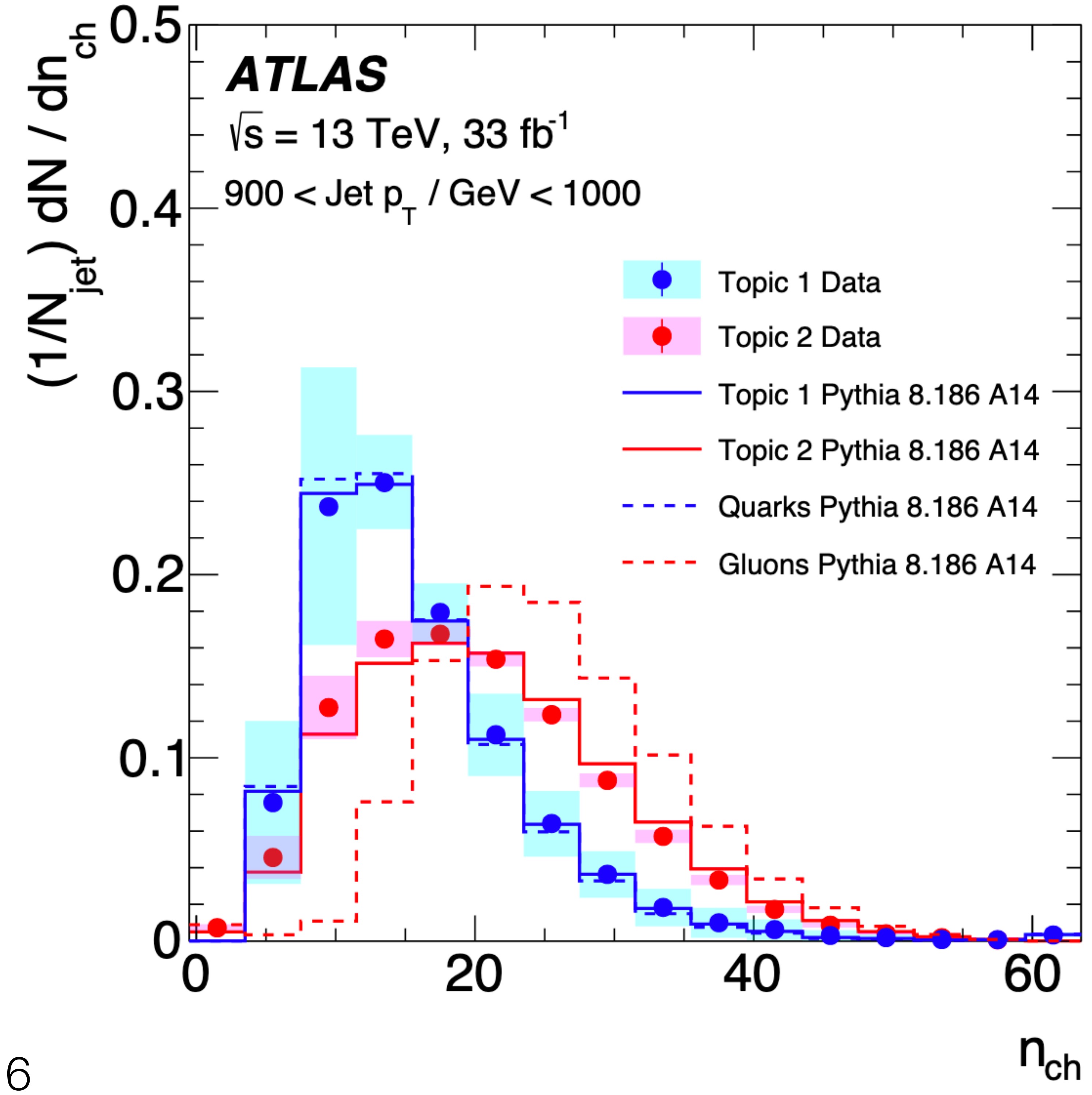
jet fragmentation

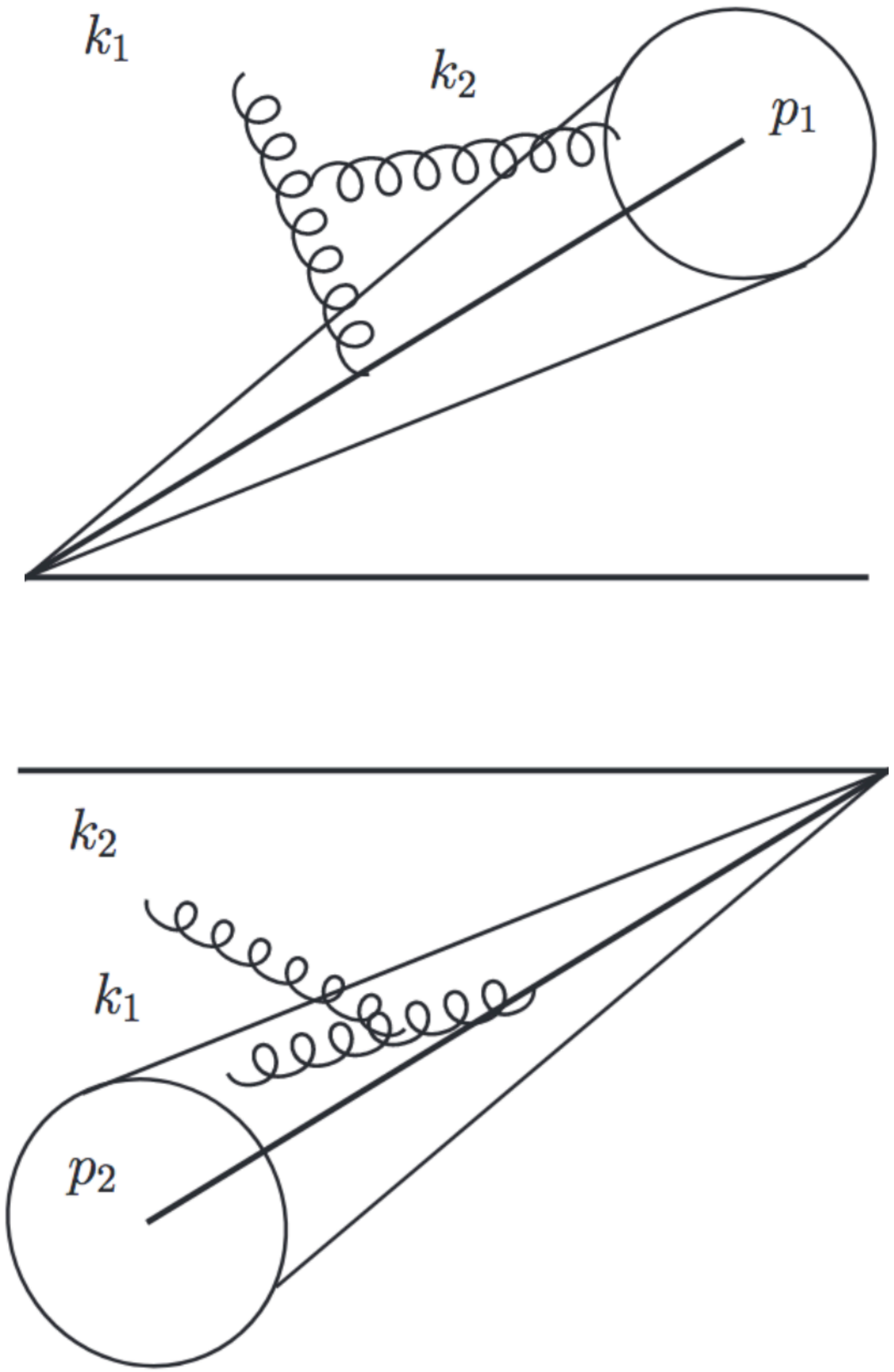
- Both methods provide similar results for the extracted quark and gluon distributions
- First time topic modeling has been used in a measurement!
  - Provides more model-independent way of extracting this information



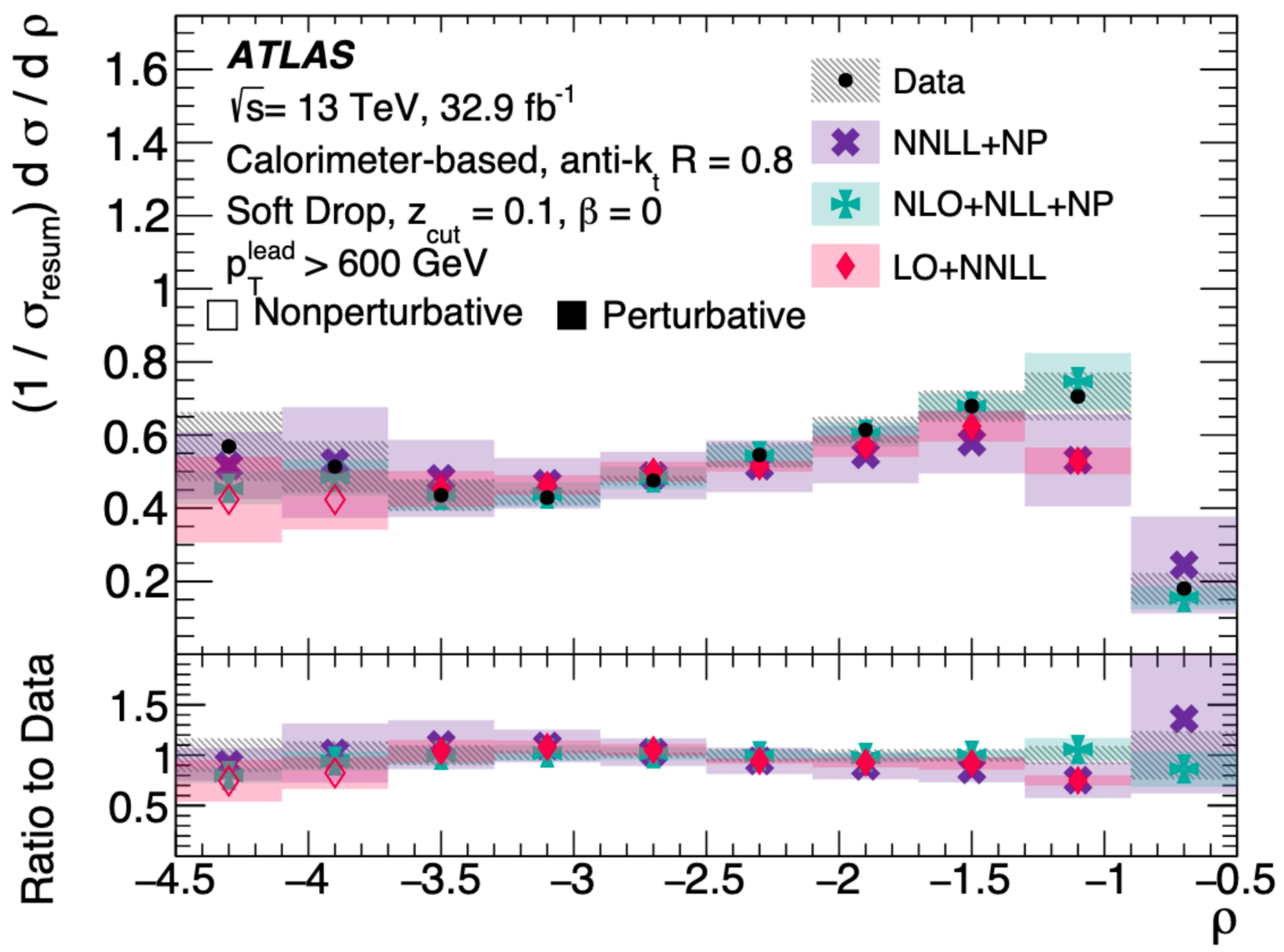


soft drop grooming

- Jet substructure observables (like the jet mass, D2, etc) are not typically calculable
  - Contributions from non-global logarithms make it difficult to produce accurate calculations
- Soft drop is a type of grooming algorithm → removes soft and wide angle radiation from a jet
  - Does this in a theoretically nice way such that the non-global logarithms are removed
  - Able to produce accurate calculations beyond leading logarithmic accuracy



the unfolded jet mass



- Measured the soft drop jet mass in dijet events
  - Measured the relative mass (m/p_T) to reduce mass dependence on p_T of the jet
  - Used logarithmic scale for sensitivity to the resummation region
  - $\rho = \log(m_2 / p_T^2)$
- Compared to three different calculations of the jet mass

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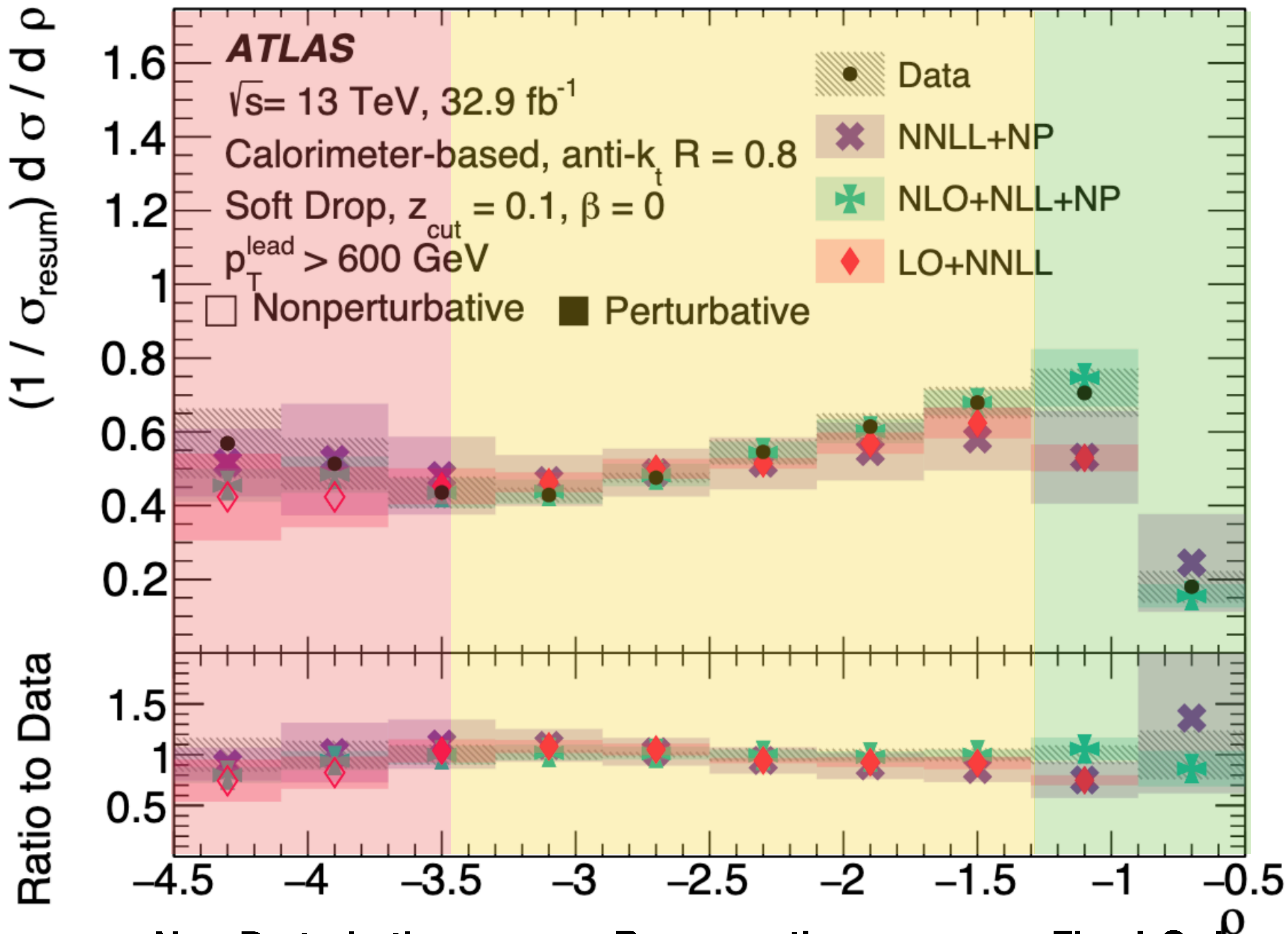
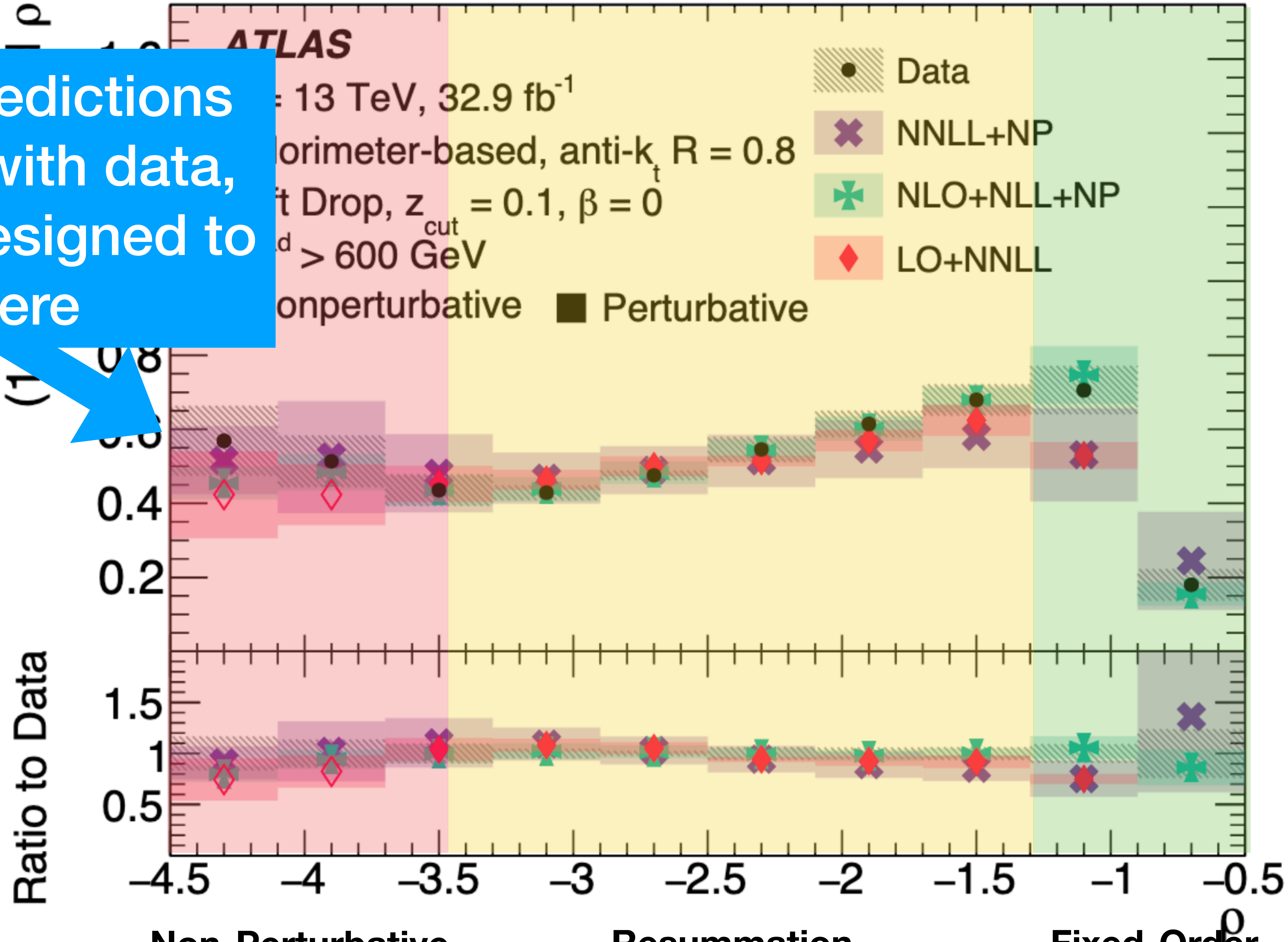
the unfolded jet mass



Non-Perturbative Region **Resummation Region** **Fixed-Order Region**

the unfolded jet mass



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

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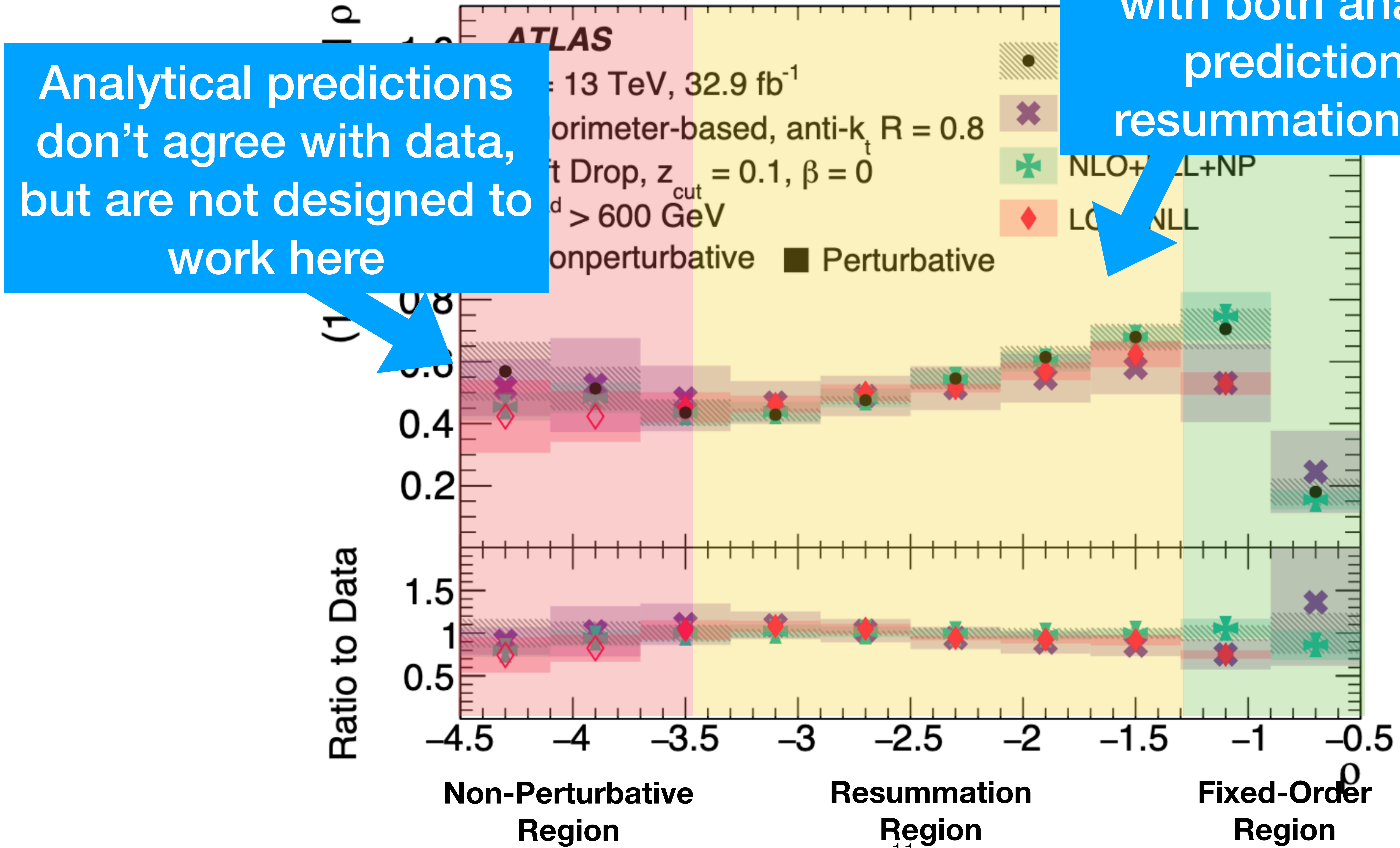

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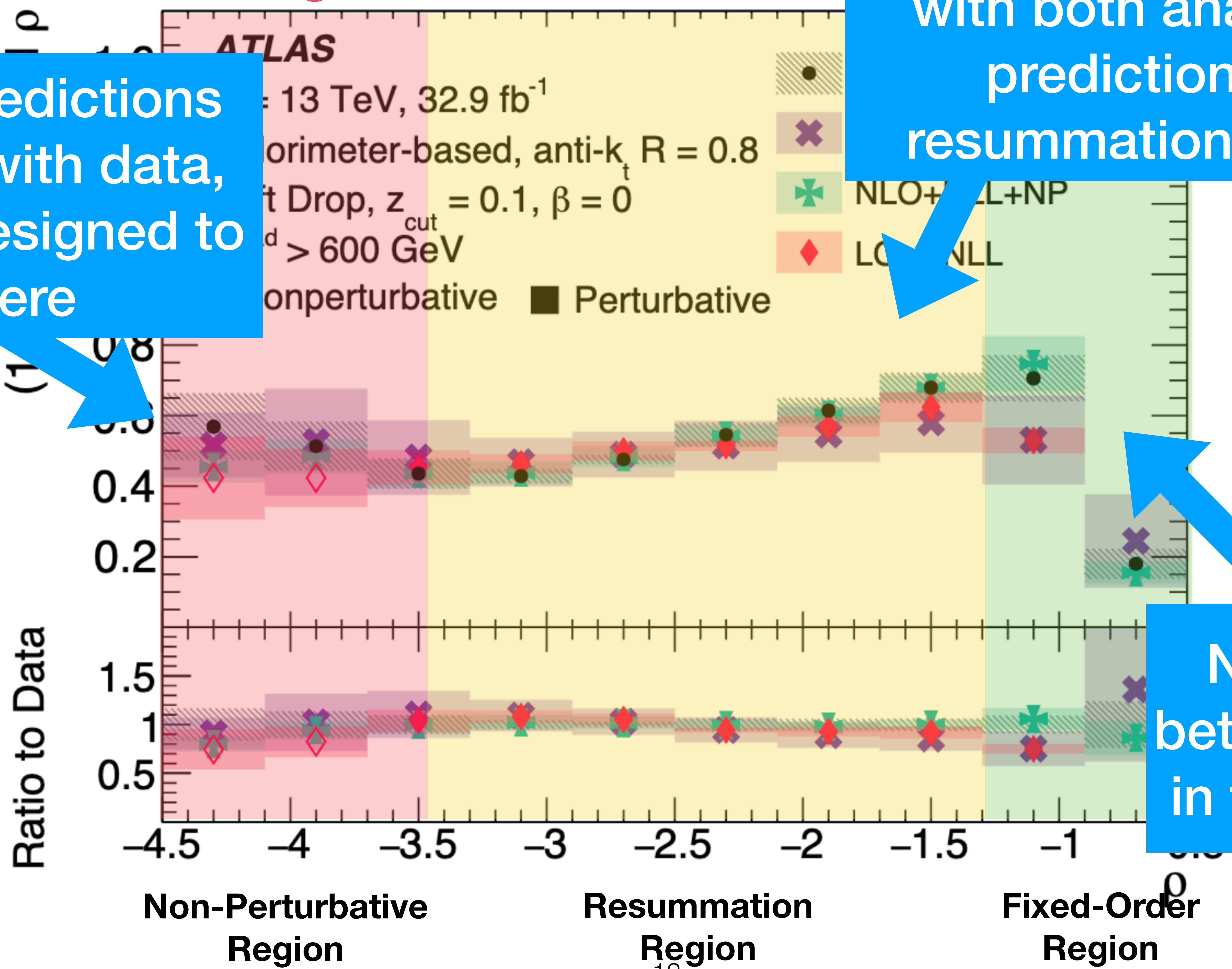
the unfolded jet mass

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

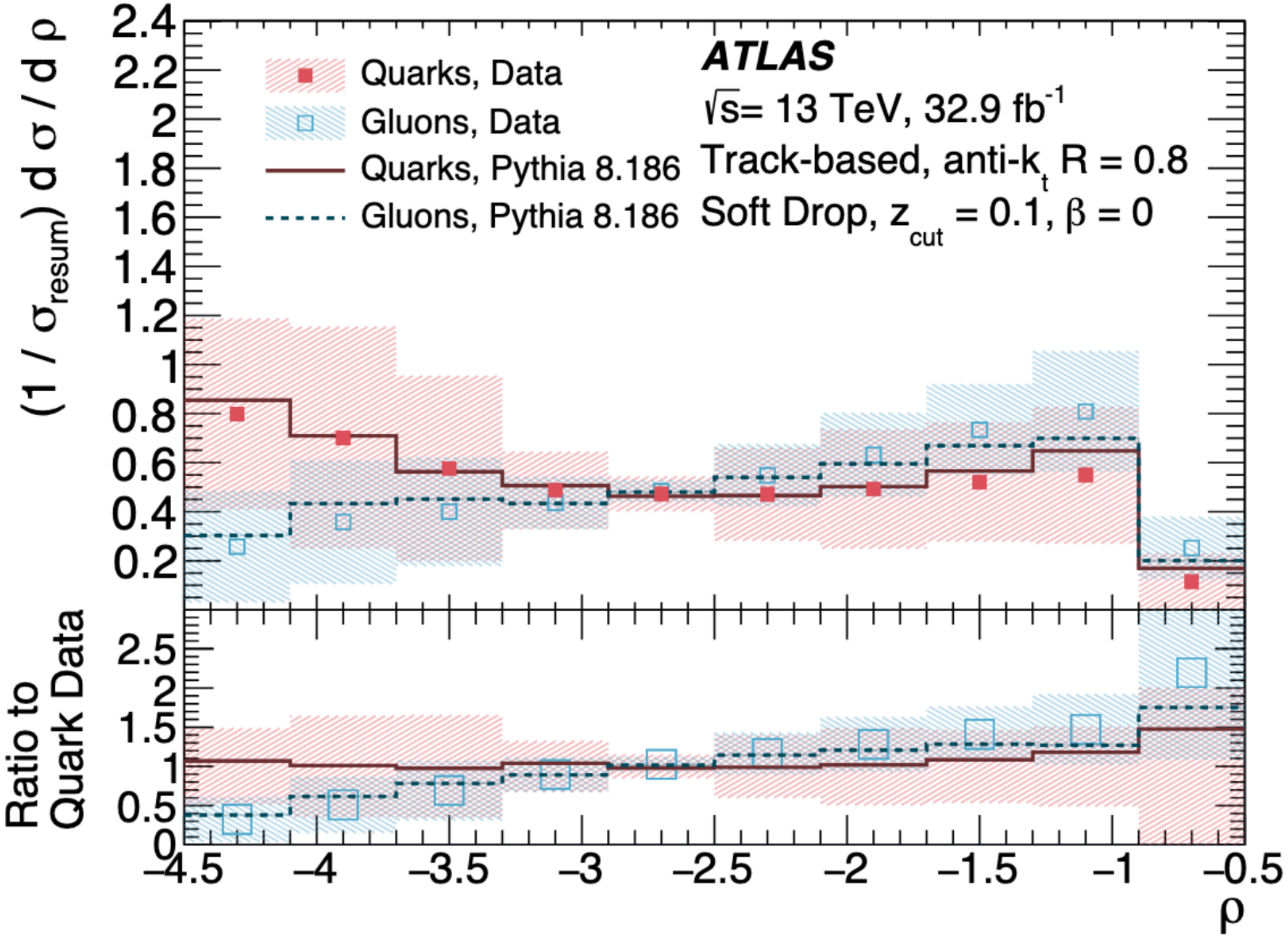
Very good agreement with both analytical predictions in resummation region



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

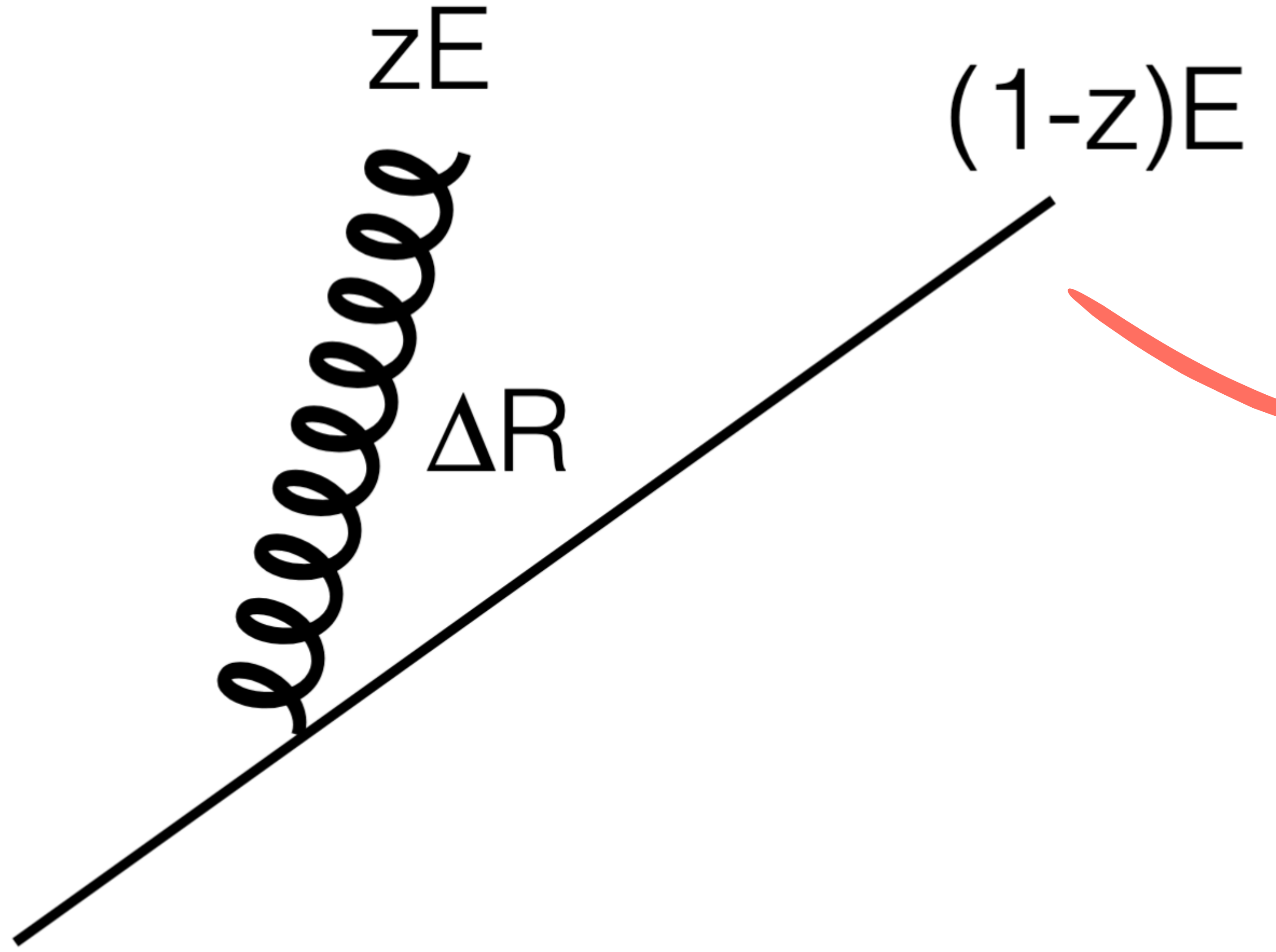
the unfolded jet mass

- Can extract the quark and gluon distributions for these as well
  - Using *track-based* measurement to improve precision of results
  - In the resummation region, the slope should be proportional to $\alpha_s \times C_F$
  - Gluon slope is larger than quark slope in this region
- Quark and gluon fractions currently taken from Pythia, so some model dependence
- Dominant uncertainty is the jet modeling

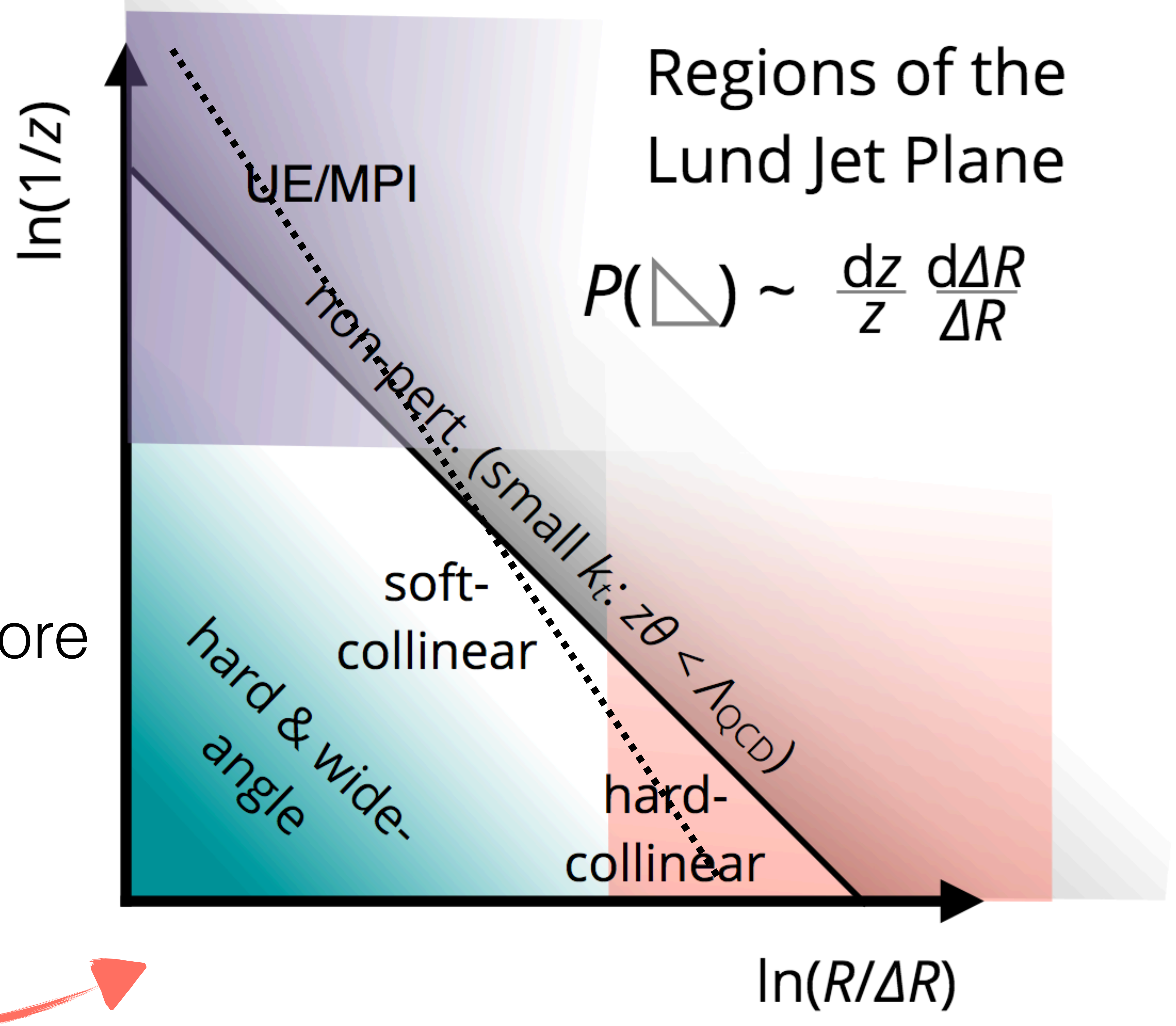


The Lund Plane

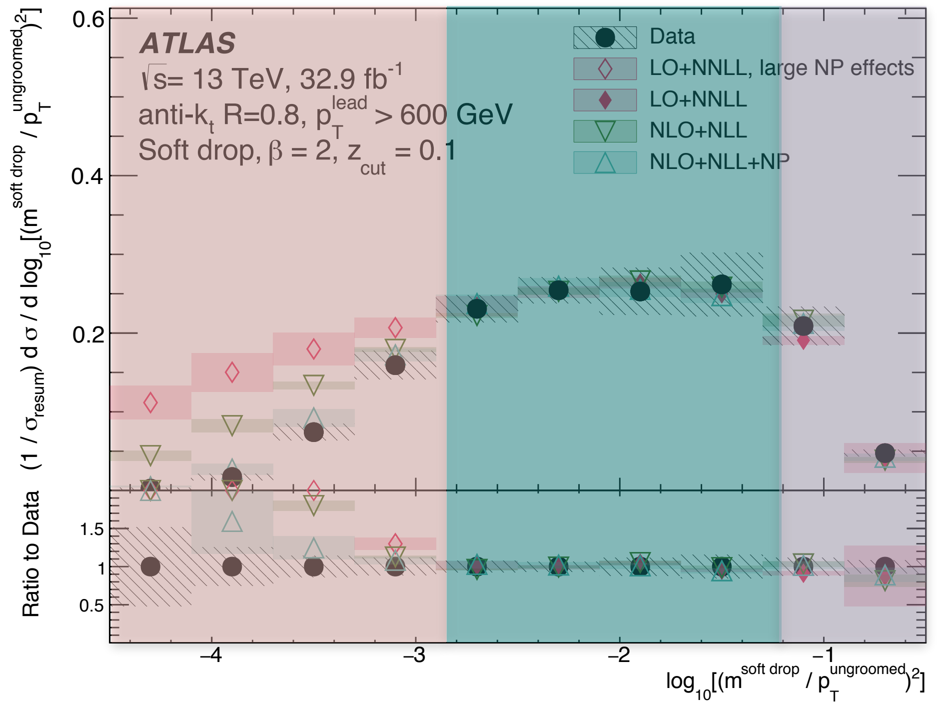
- A jet may be approximated as soft emissions around a hard core which represents the originating quark or gluon
- Emissions may be characterized by
  - z = relative momentum of emission wrt jet core
  - ΔR = angle of emission relative to the jet core



$m \sim z^*\Delta R^2$



The jet mass is just one diagonal line in this space

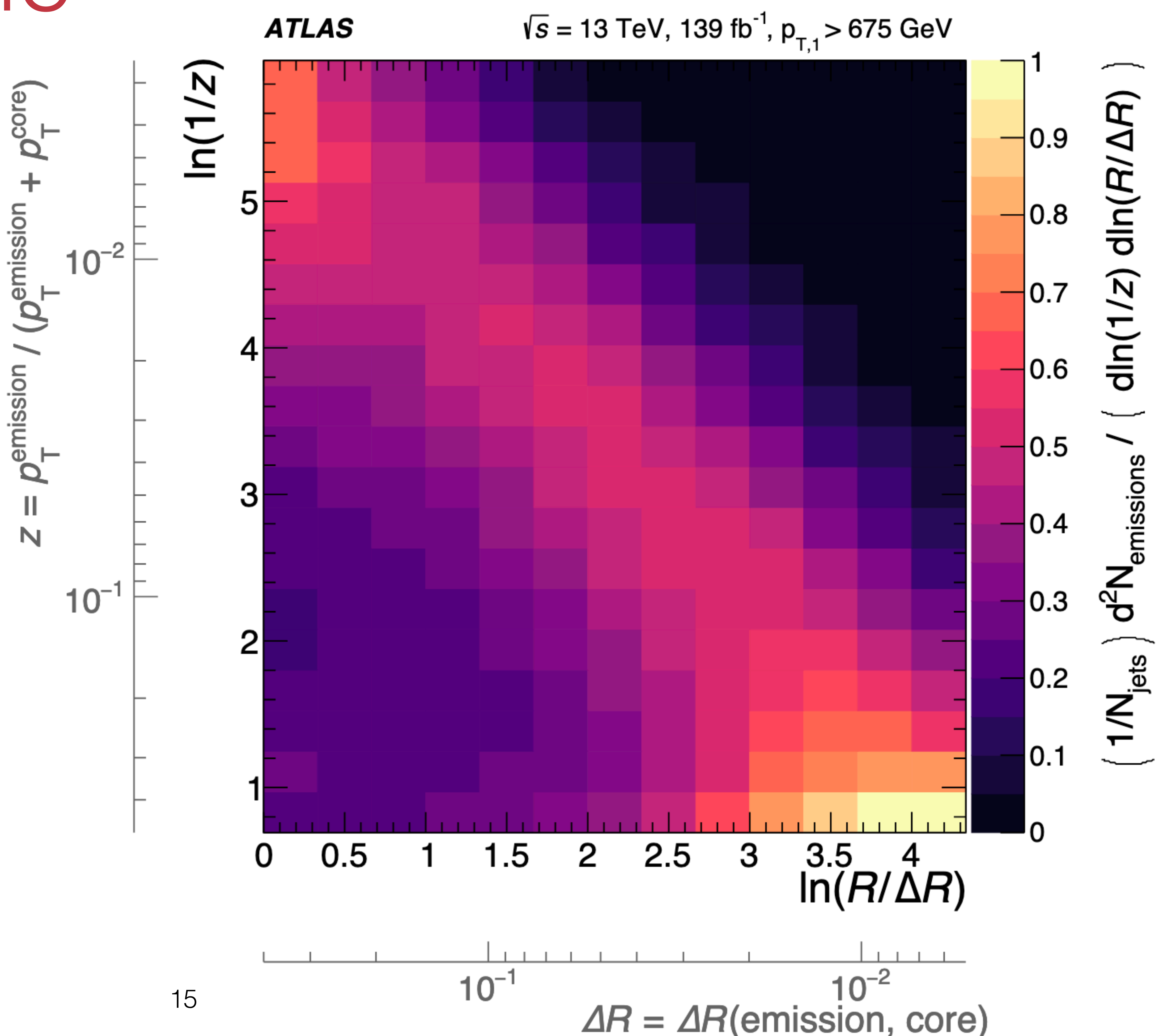


So what if we could measure the whole thing?

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

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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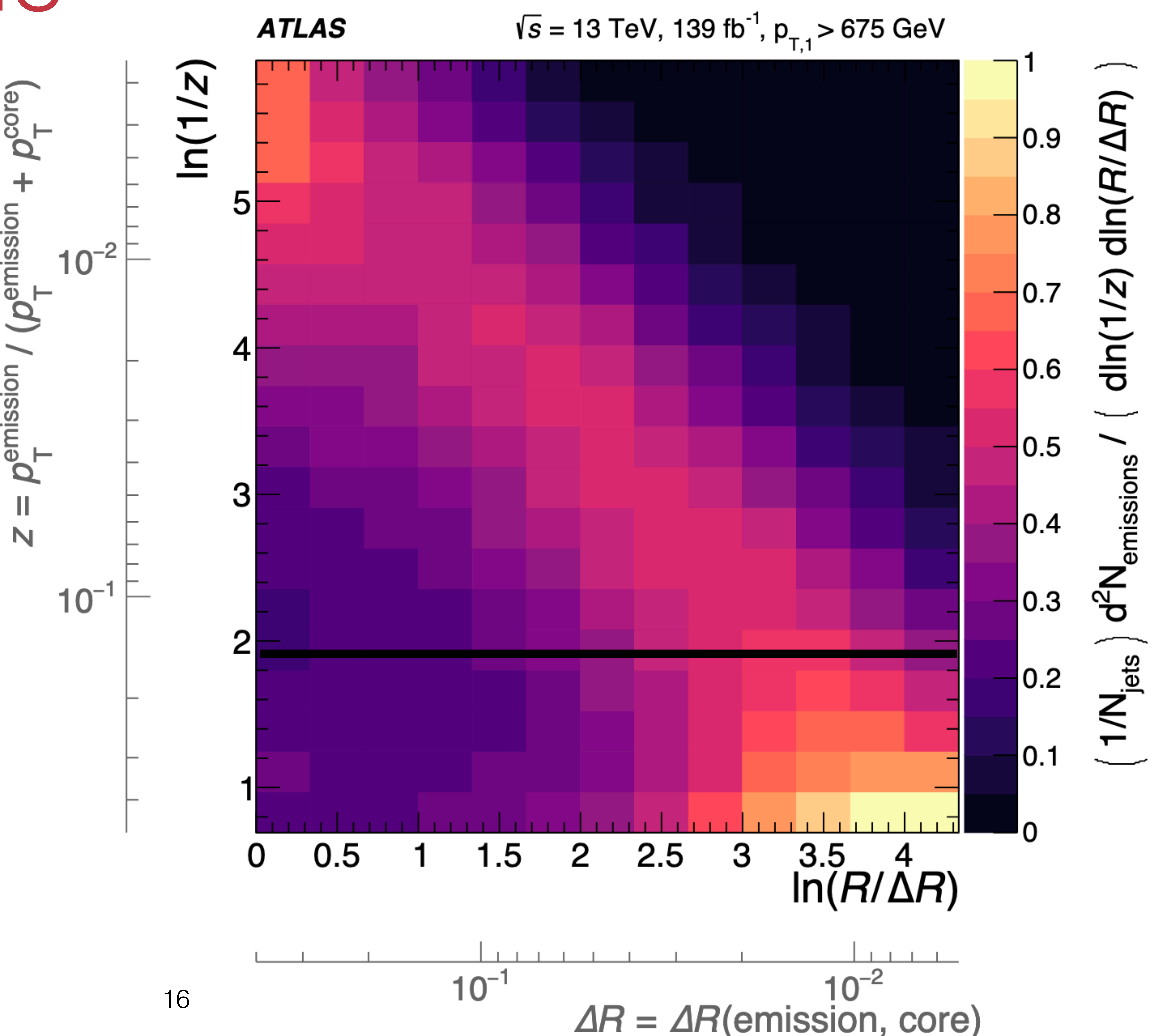

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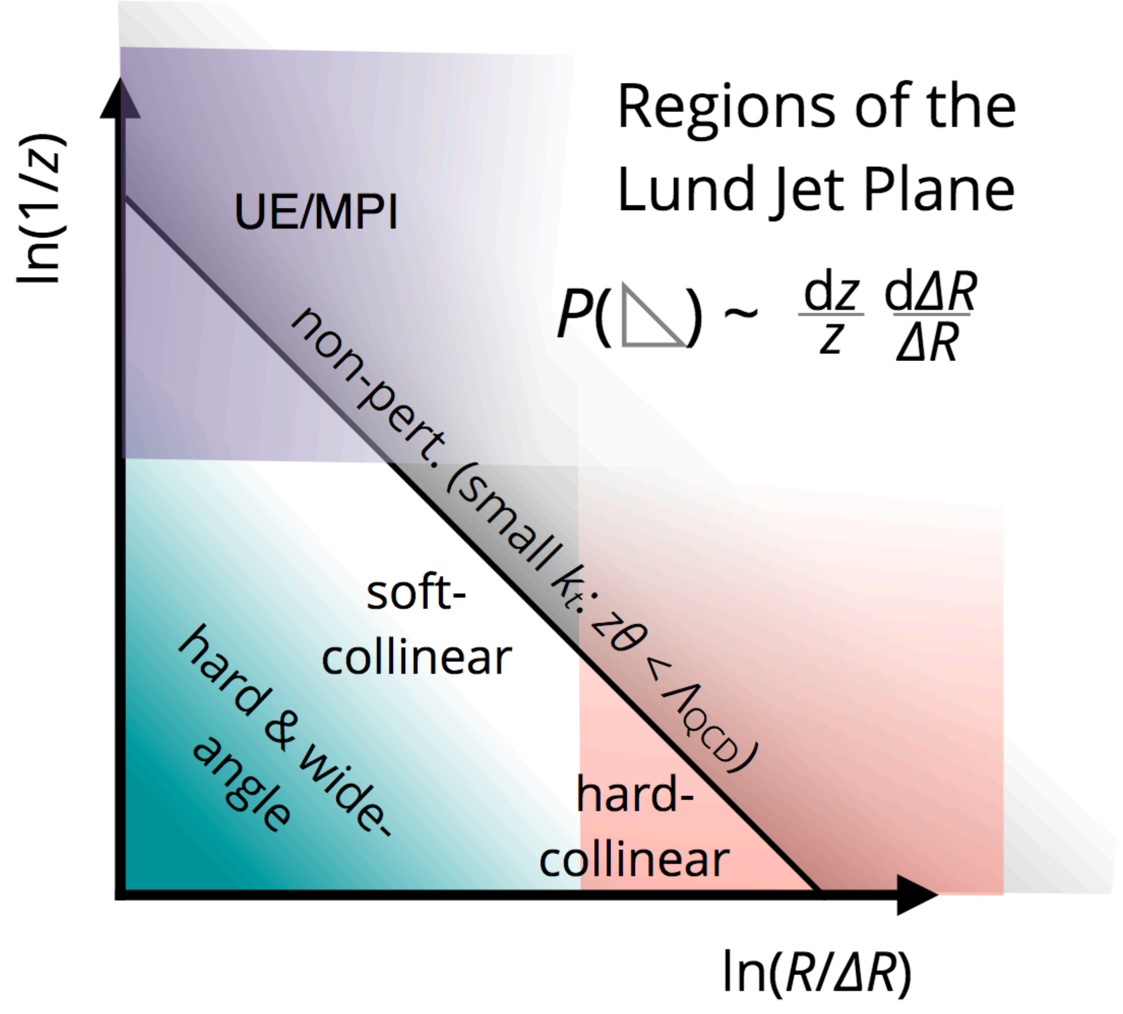
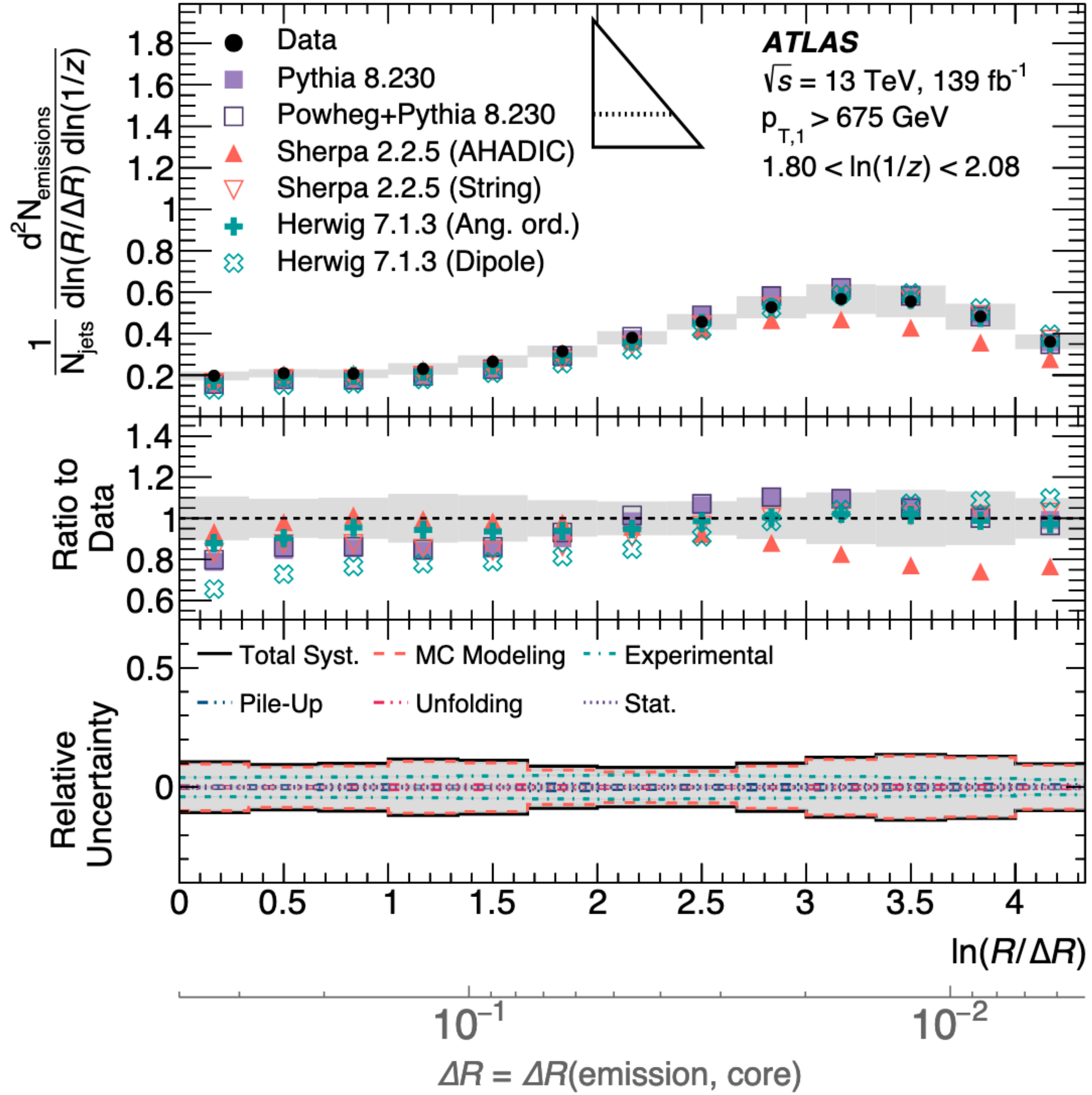


- Non-trivial differences between different generators and unfolded data
- Region dominated by hard and wide-angle splitting is affected by parton shower
- Hadronization effects in region with non-perturbative effects



summary

- Jet substructure measurements are a powerful tool for studying QCD across multiple scales
  - New grooming algorithms enable comparisons of measurements and theoretical predictions for substructure observables
- New observables make it possible to separate out different effects into different regions of a measurement
  - First measurement of the Lund jet plane demonstrates importance of factorization
- Gluon measurements are critical for improving jet modeling
  - New methods such as topic modeling allow for model-independent extractions of this behavior

The Lund Jet Plane

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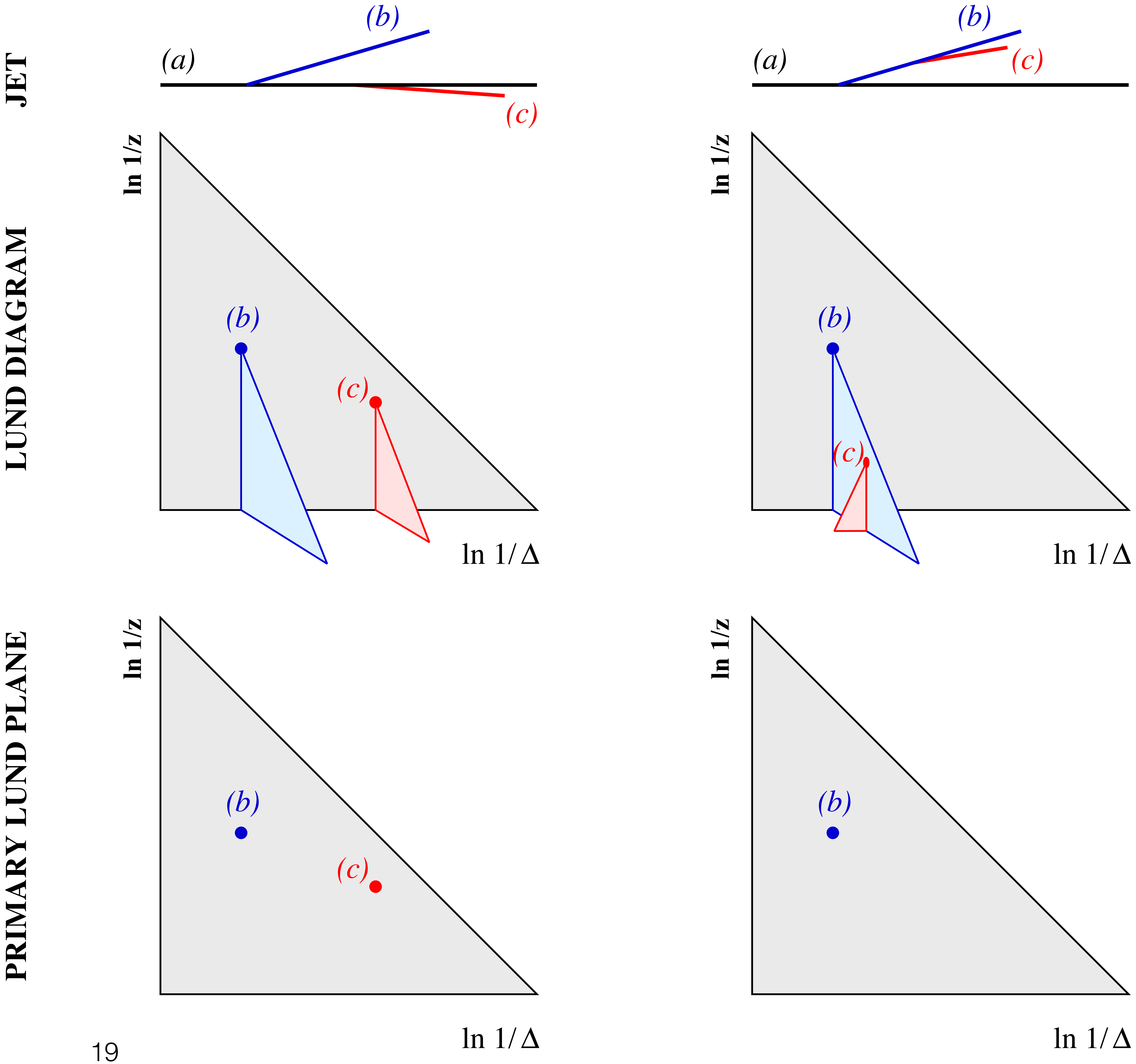
- Similar method may be used for understanding the issues *within a jet*

- Recluster constituents with C/A algorithm

- Decluster the jet, and plot emission on the plane

  - Emissions characterized based on their angle (ΔR), and the hardness of the splitting and $z = p_T^{emission} / p_T$

- Continue declustering the harder branch until no more emissions remain



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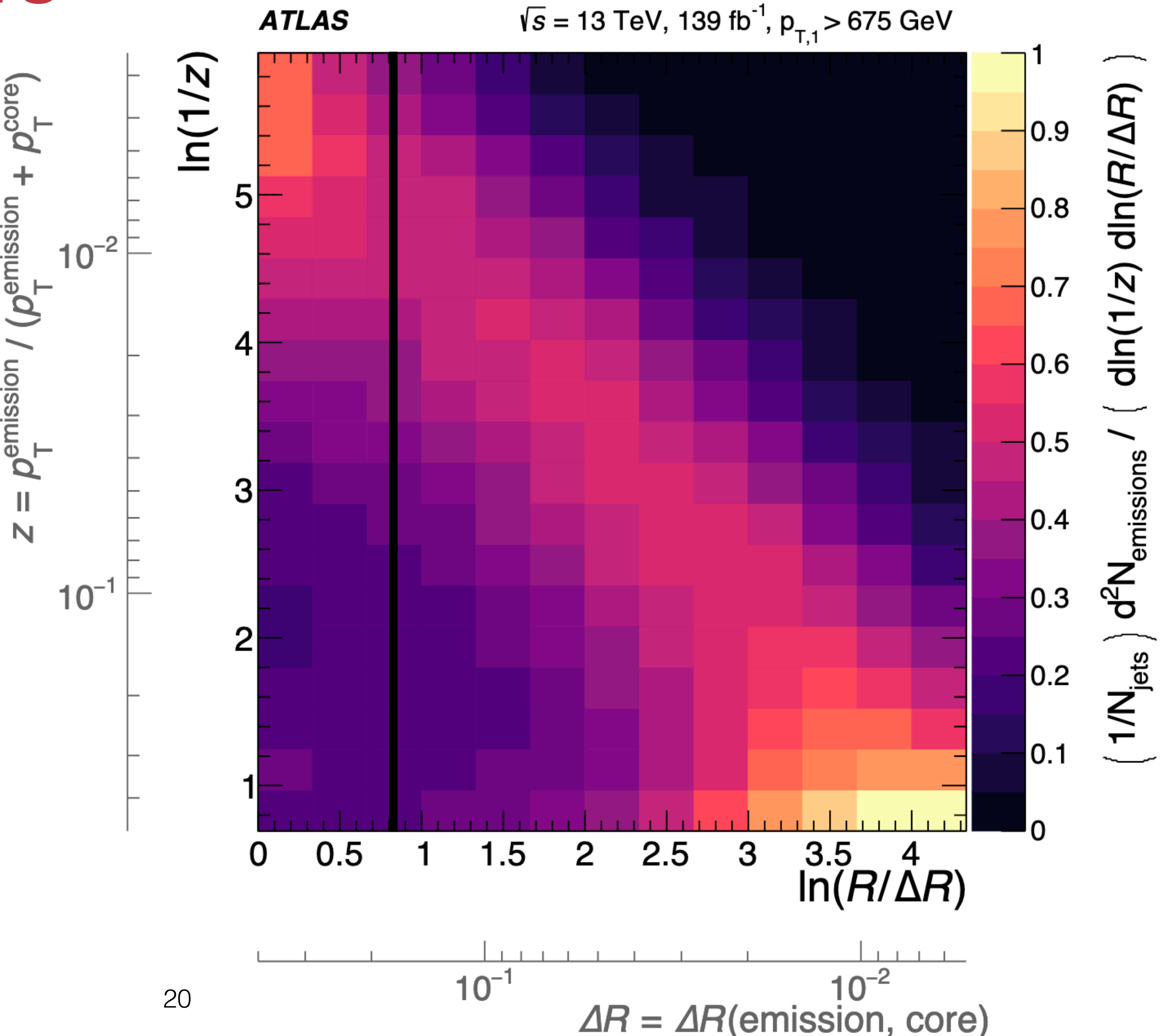

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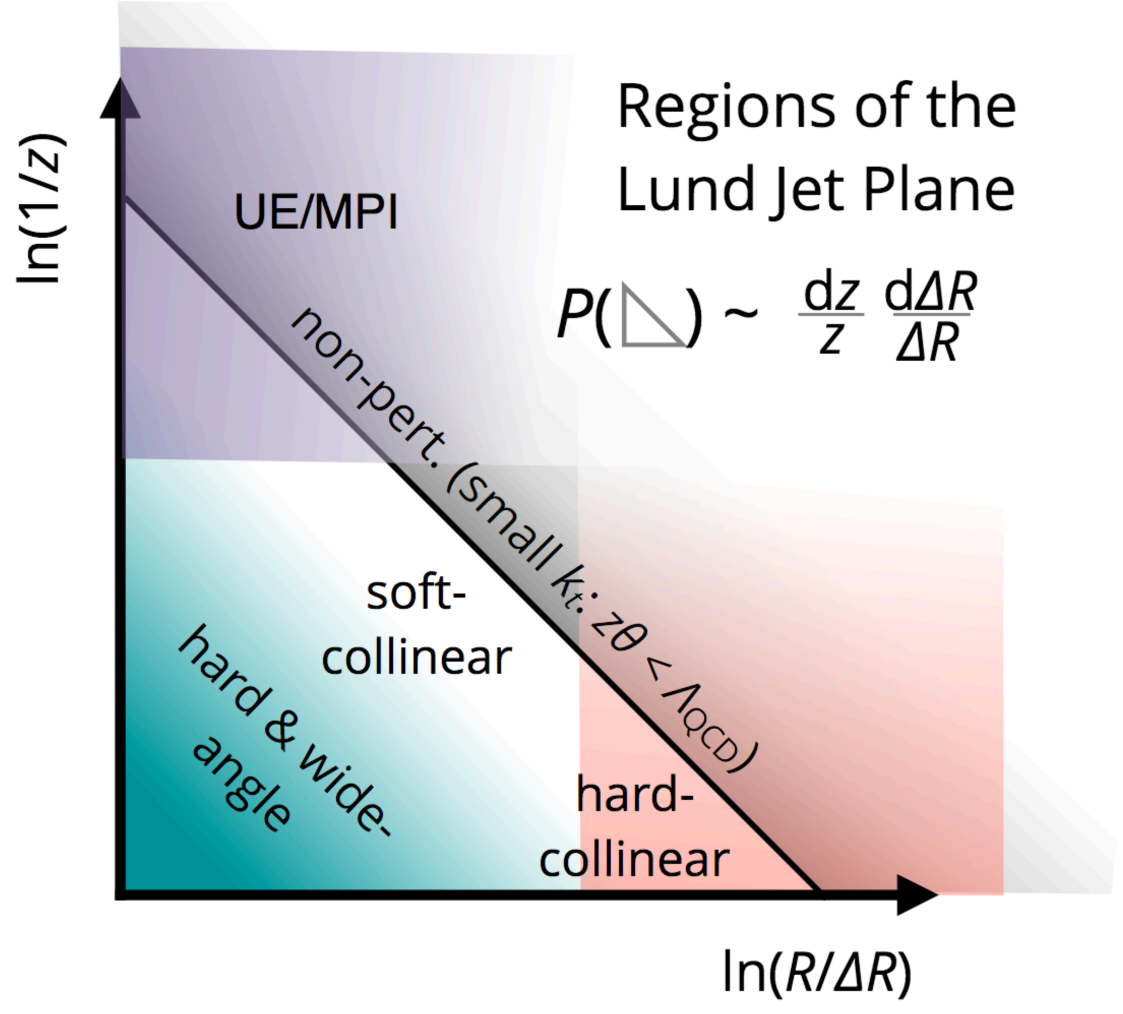

- Non-trivial differences between different generators and unfolded data
- Region dominated by hard and wide-angle splitting is affected by parton shower
- Only small effects seen from UE/ MPI (as expected)