Jet Substructure Measurements with the ATLAS Detector

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on behalf of the ATLAS Collaboration

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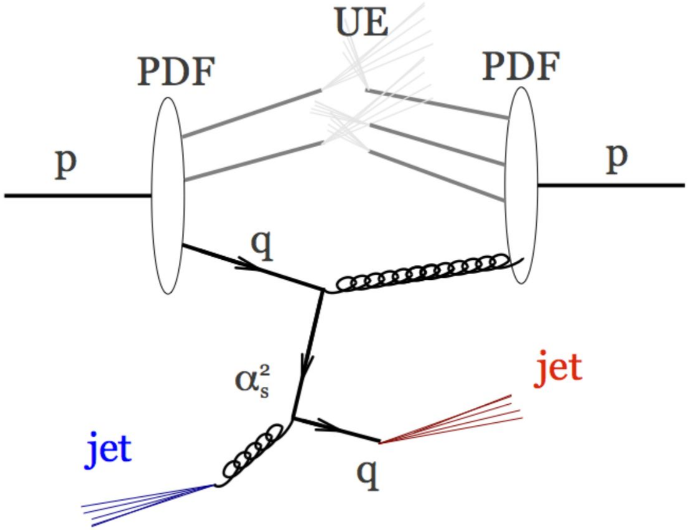
Outlook

- **Short introduction to jet reconstruction and substructure**
- **The Soft Drop algorithm**
- **Measurement of the soft-drop jet mass in ATLAS at 13 TeV**

What is a jet?

- At short distances quarks and gluons move as quasi-free particles (asymptotic freedom)
- When they are energetic, they produce bremsstrahlung cascades of gluons and qqbar pairs, which then hadronise
- We see jets of tightly collimated hadrons



- There are a lot at the LHC! (dominant high p_T process)
- Jet properties reflect those of the quarks and gluons which originated them
- A good handle to test the QCD sector of the SM over several orders of magnitude
  - Proton structure (PDF)
  - Strong coupling constant, α_s
  - Perturbative QCD effects
  - Fragmentation/Hadronization effects

Jet reconstruction

- Sequential recombination algorithms most popular in the LHC era (G. Salam, arXiv:0906.1833)
- Collinear and infrared safe!

- The clustering inverts the parton shower by combining the constituents of the jet according to subsequent ‘distance’ criteria

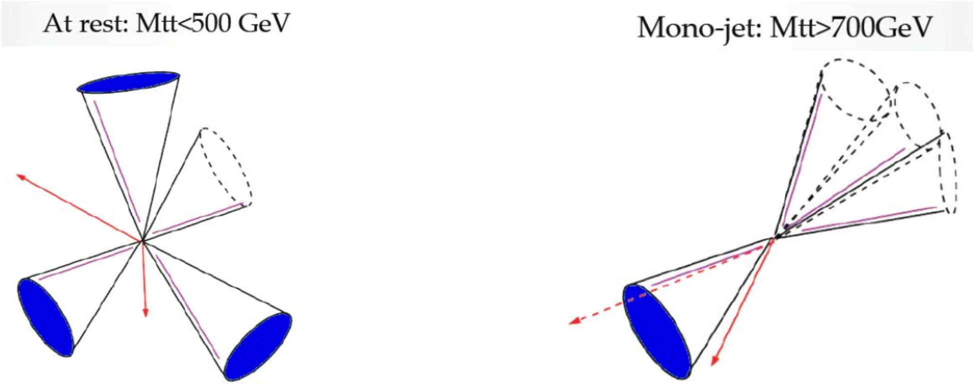
$$
\begin{aligned}
d_{ij} &= \min(p_{Ti}^{2n}, p_{Tj}^{2n}) \times \frac{\Delta R_{i,j}^2}{R^2} \\
d_{iB} &= p_T^{2n}
\end{aligned}
$$

- Inclusive jet reconstruction: clustering continues until the minimum distance is found to be d_{iB}

- **(n=1) k_t :** Softest pair of constituents clustered first. Follows IR and collinear splittings.
- **(n=0) Cambridge-Aachen (C/A):** Closest pair of constituents clustered first. Mimics angular-ordered parton shower.
- **(n=-1) anti-k_t :** Hardest constituent clustered with closest neighbour. Regularly shaped jets.

Jet substructure

- Classical “resolved” algorithms run into problems for highly boosted final states
- A large radius jet of $R > 2m/p_T$ can contain all decay products of a given particle
  - Top quark, Higgs/W/Z bosons, new heavy particles ...



- Internal structure of the large R jet shows interesting features that can be used to identify the origin of the jet
  - distinguish multi-jet background from signals

Jet substructure: measurements

- Jet substructure techniques are paramount to deal with boosted objects in the LHC

- New measurements of jet substructure are also solidifying our understanding of the internal structure of jets and the theory of QCD

    - k_T splitting scales in $Z \rightarrow ll$ events at 8 TeV with the ATLAS detector. JHEP08 (2017) 26
    - Colour flow using jet-pull observables in $t\bar{t}$ events at 13 TeV. ATLAS-CONF-2017-069
    - **Soft-drop jet mass at 13 TeV. Phys. Rev. Lett. 121, 092001**

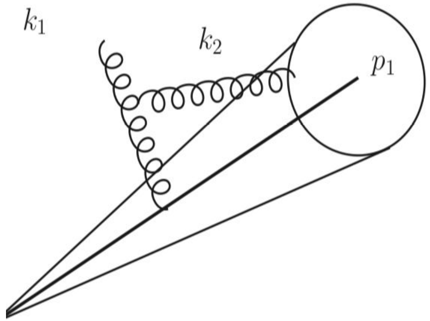
- Non-negligible differences from data are observed in MC predictions

- Can constrain both analytic calculations in perturbative regime and soft hadronic activity in non-perturbative region

Soft Drop

- Jet substructure tests QCD in a regime where a fixed-order is insufficient
  - Sensitive to soft and collinear radiation

- A precise analytic calculation of substructure variables (beyond leading log) not possible due to the presence of non-global logarithmic ressumation terms (NGLs).
  - Related to particles radiating out of and then into jet



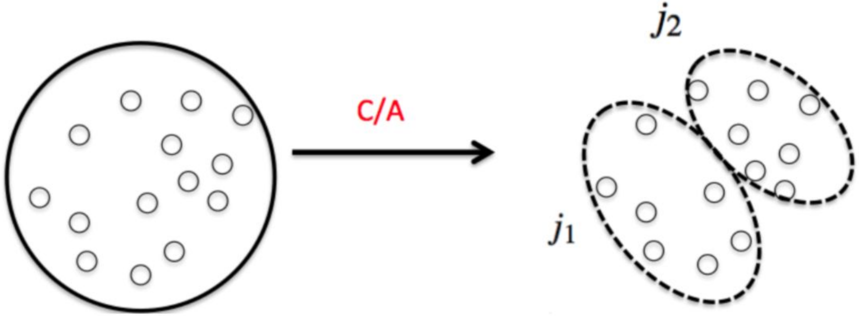
- A perfect example is jet mass
  - Dominated by resummation and not fixed-order

- Soft drop. [JHEP 1405 (2014) 146]
  - Jet grooming procedure that removes energy related to soft parton emission and pile-up
  - Formally insensitive to NGLs

- The distribution of the soft-drop mass has now been calculated at
  - NLO with NLL. [JHEP07(2016)064]
  - LO with NNLL. [JHEP07(2017)132]

The Soft Drop algorithm

- Take a jet, re-cluster its constituents with C/A, and go backwards in the C/A clustering sequence



- If $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1}+p_{T,2}} > z_{cut}\left(\frac{\Delta R_{12}}{R}\right)^{\beta}$ then the jet is a soft drop jet.
- Otherwise, the highest p_T sub-jet is taken as a new candidate and the procedure is iterated.
- z_{cut} sets the scale of energy removal. Higher z_{cut} means more energy removed by grooming.
- β determines the sensitivity to wide-angle radiation.
  - Larger β means smaller fraction of soft small-angle radiation removed -> less grooming.

ATLAS measurement of the soft-drop jet mass

Phys. Rev. Lett. 121, 092001 (2018)

Soft-drop jet mass measurement

- Using anti-k_T R=0.8 jets built from locally calibrated calorimeter-cell clusters
- Lowest un-prescaled trigger (400 GeV) and $p_{T,1}$> 600 GeV
- Dijet topologies: $p_{T,1}/p_{T,2} < 1.5$ for two leading jets
- Measuring dimensionless mass parameter, $\rho = m_{softdrop} / p_T^{ungroomed}$
  - Weak dependence on p_T
  - Distribution of $\log_{10}(\rho^2)$ studied for β =0,1,2 and $z_{cut} = 0.1$
- Simultaneously unfolding in $\log_{10}(\rho^2)$ and jet p_T distributions using Pythia LO predictions
- Three distinct regions
  - Non-perturbative region: $\log_{10}(\rho^2) < -3.7$ (soft and collinear emissions)
  - Resummation region: $-3.7 < \log_{10}(\rho^2) < -1.7$ (resummation dominates)
  - Fixed-order region: $\log_{10}(\rho^2) > -1.7$ (wide-angle hard gluon emissions)

Unfolding

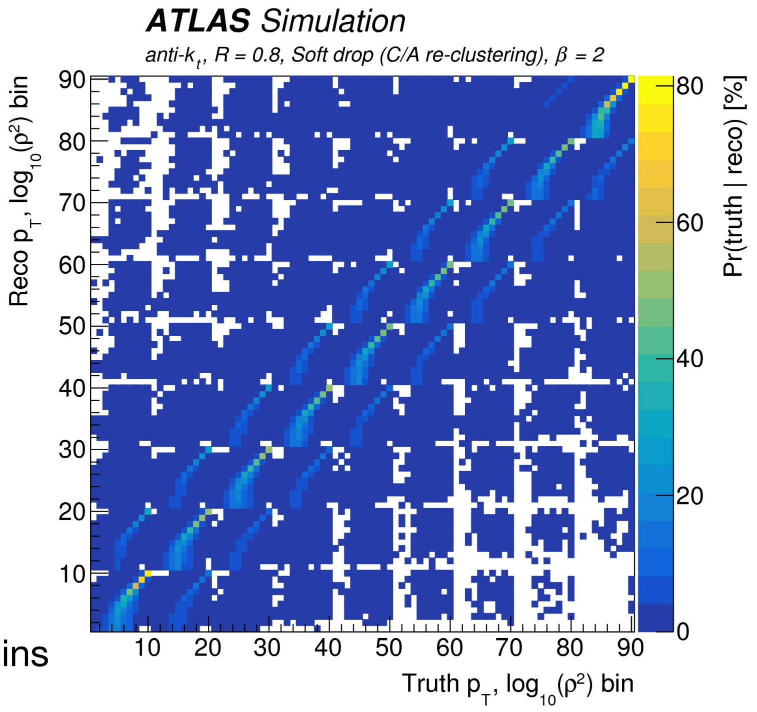
- Pythia used as nominal
  - Sherpa and Herwig++ to evaluate uncertainty

- Particle-level selection as close as possible to detector-level
  - Jets built using the same algorithm
  - Events must pass the same dijet requirement
  - Additional correction for the acceptance included

- $\log_{10}(\rho^2)$ and p_T unfolded simultaneously

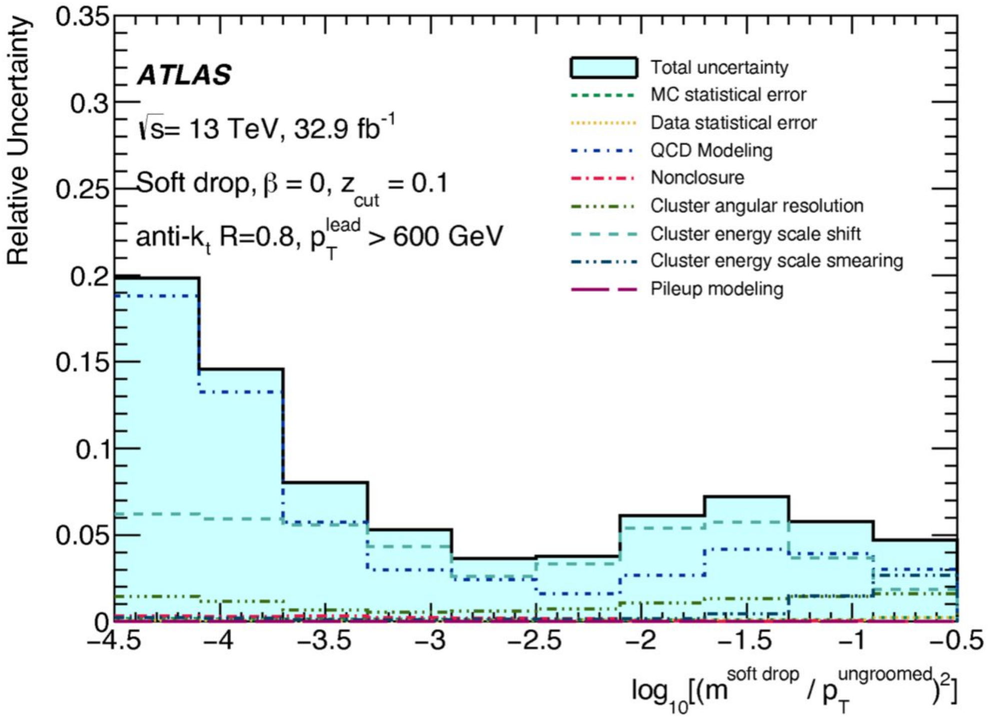
- Example of response matrix for the combined p_T and $\log_{10}(\rho^2)$ bins
  - Each group of 10 bins corresponds to a different p_T bin
  - Each bin within the p_T bin corresponds to 10 evenly spaced bins in $\log_{10}(\rho^2)$
  - The bins are normalized so that the z-axis corresponds to the probability of a jet lying in a particular truth bin, given its reconstructed bin

- There are substantial migrations between the detector- and particle-level distributions, which cause large off-diagonal terms in the unfolding matrix especially at low values of $\log_{10}(\rho^2)$



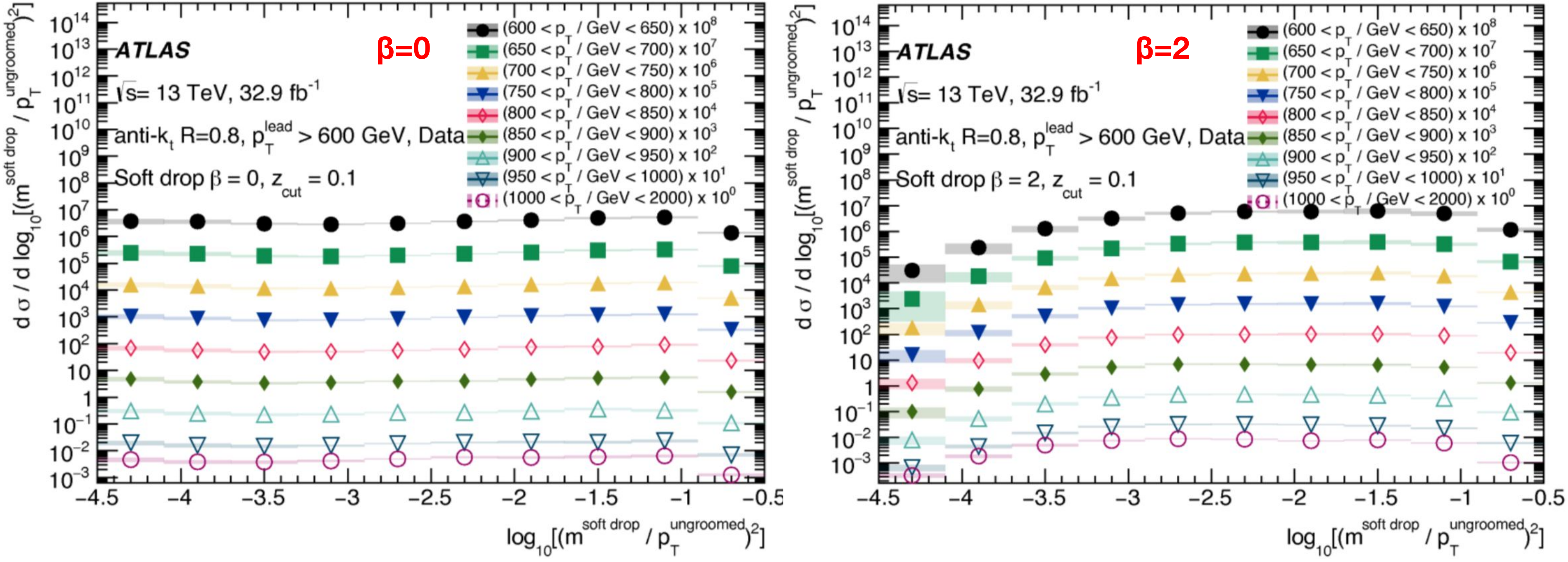
Uncertainties

- Many uncertainties cancel since ρ is a ratio
- QCD modeling uncertainties dominate
  - Particularly large at low mass where non-perturbative effects are largest
- Cluster energy uncertainties
  - Large at lower masses
    - Low cluster multiplicity



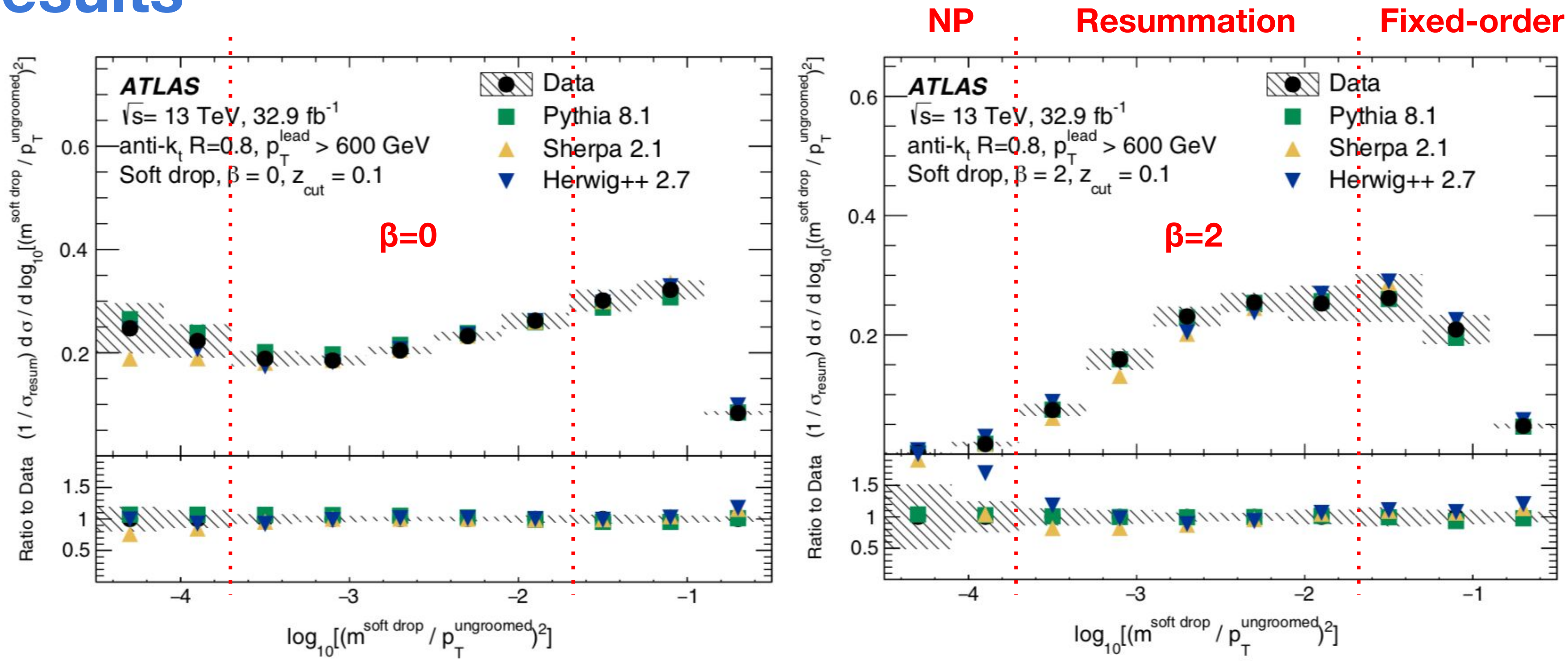
  - Also important at higher masses
    - Energy of hard prongs dominates the mass resolution instead of the opening angle
- Other uncertainties are subdominant
  - Pile-up negligible as expected

Results: $\log_{10}(\rho^2)$ vs p_T



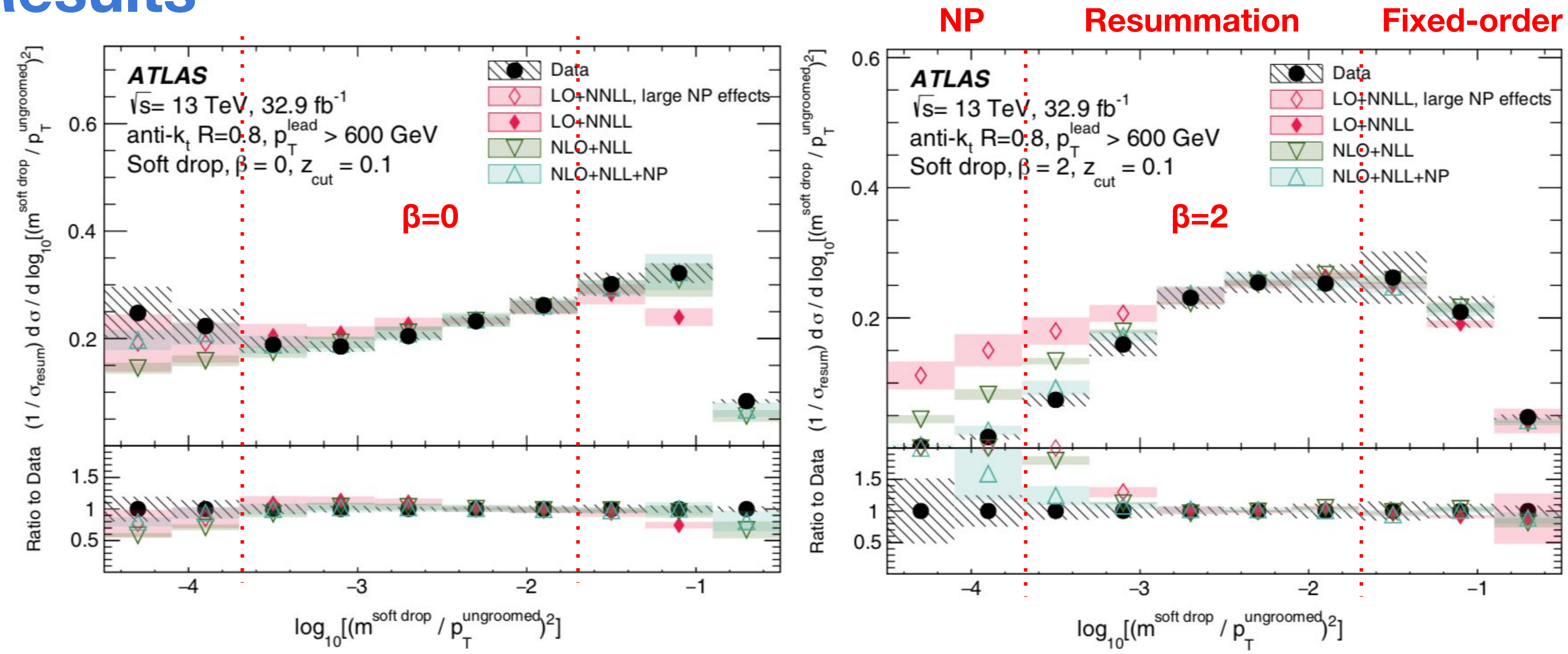
- $\log_{10}(\rho^2)$ for the p_T bins used in the analysis (from 600 GeV up to 2000 GeV)
- As expected, there is no strong dependence on p_T

Results



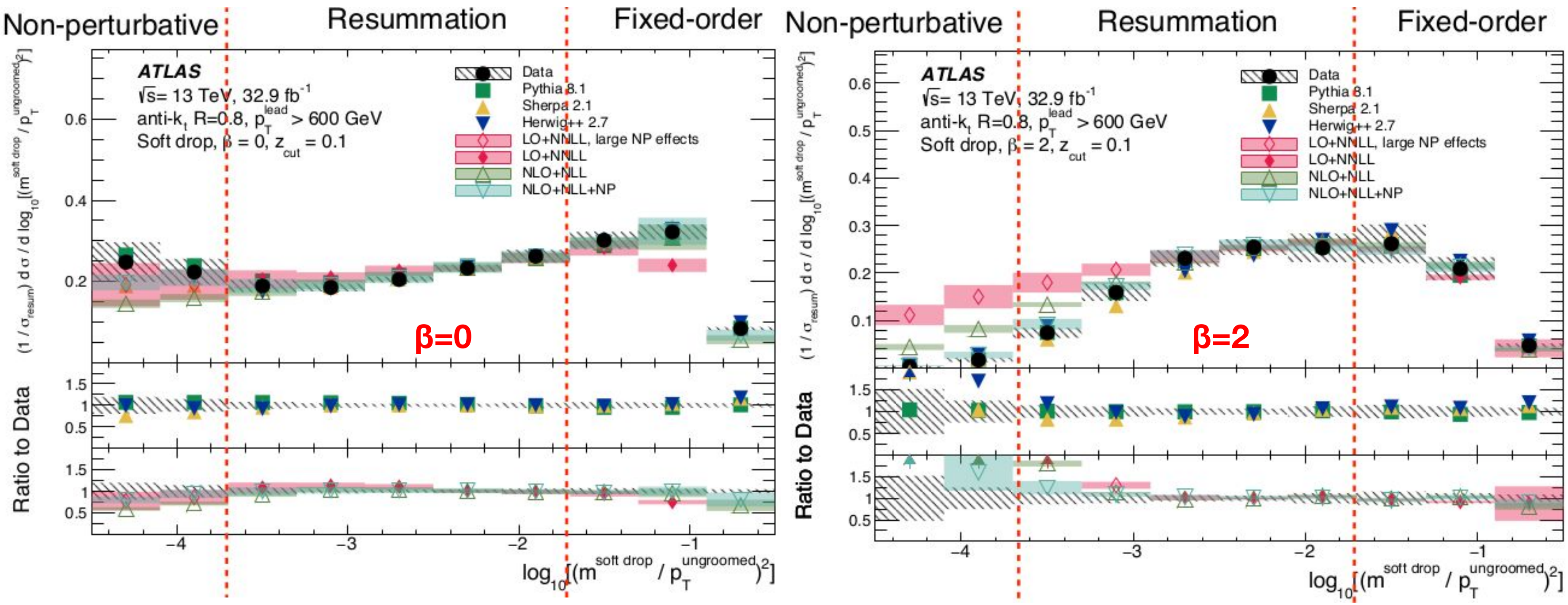
- Distributions normalised to data in resummation region
- MC generators do an excellent job of describing data over entire mass range

Results



- Good agreement between data and analytic calculations in resummation region
  - and fixed-order region for NLO calculations
- Including non-perturbative effects improves the accuracy of the NLO+NLL prediction

Results



- Largest difference between data and MC/analytic predictions in non-perturbative regime
  - Effect larger for higher β (smaller fraction of soft energy removed)

Conclusions

- Jet substructure studies are essential to find new physics in post-Higgs era
- Proper estimation of uncertainties, and robustness against pile-up is critical
- Need measurements, and best possible MC modeling
- Presented ATLAS measurement of the soft-drop jet mass at 13 TeV. Phys. Rev. Lett. 121, 092001
    - Good agreement between data and calculations in resummation and fixed-order regions
    - MC generators do better in non-perturbative region
    - Results to be used to constrain future calculations and MC generator predictions
- Future directions include measurements of related soft-dropped observables, and track based measurements which can potentially reduce the systematic uncertainties

Thanks

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MC generators

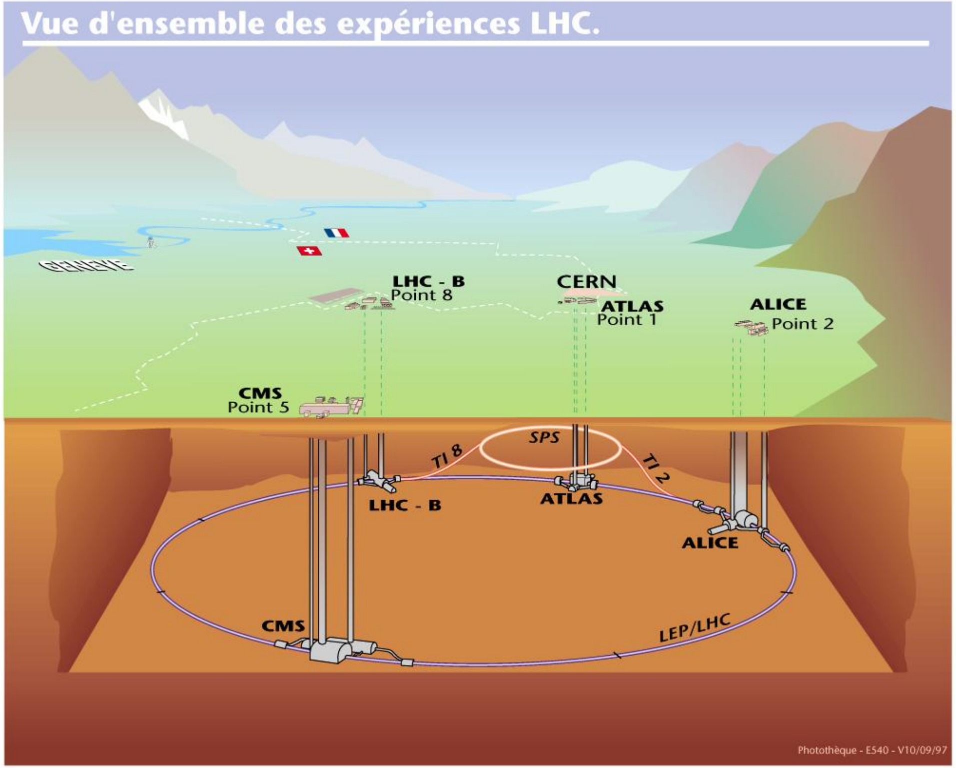
- **Pythia 8.186**
  - NNPDF2.3LO PDF
  - A14 for PS and UE
  - p_T-ordered PS

- **Sherpa 2.1.1**
  - CT10 LO PDF
  - Default Sherpa event tune for PS and UE
  - Angular-ordered PS

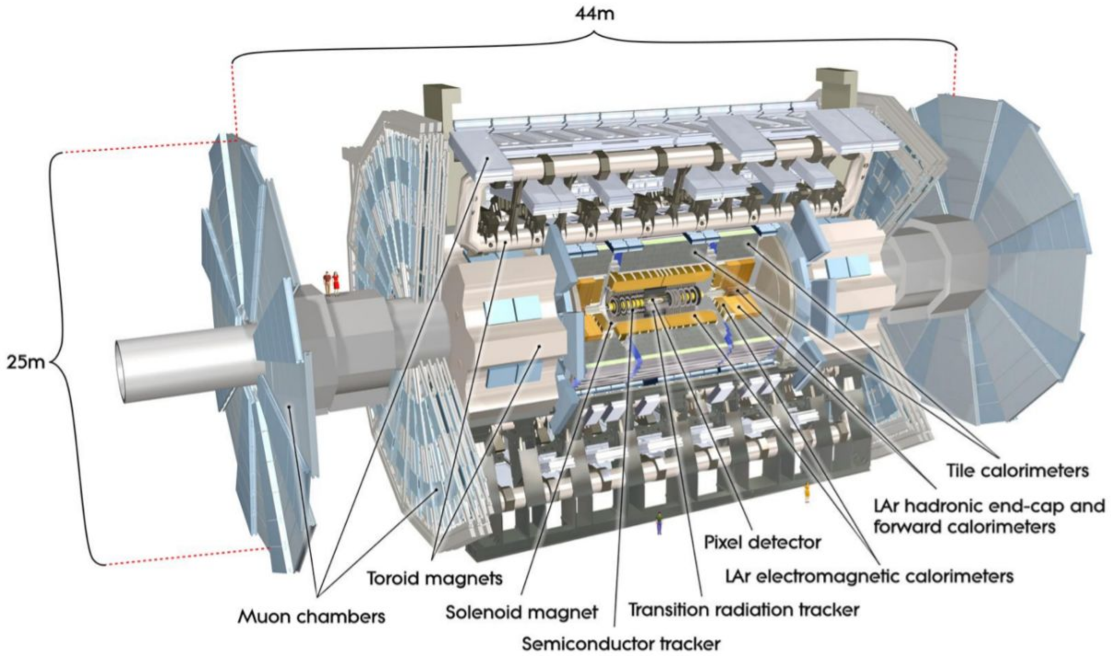
- **Herwig++ 2.7.1**
  - CTEQ6L1 PDF
  - UE- EE-5 tune
  - Angular -ordered PS

- All MC samples use Pythia 8 minimum bias events to simulate pile-up
  - MSTW2008LO PDF and A2 tune

The Large Hadron Collider (LHC)

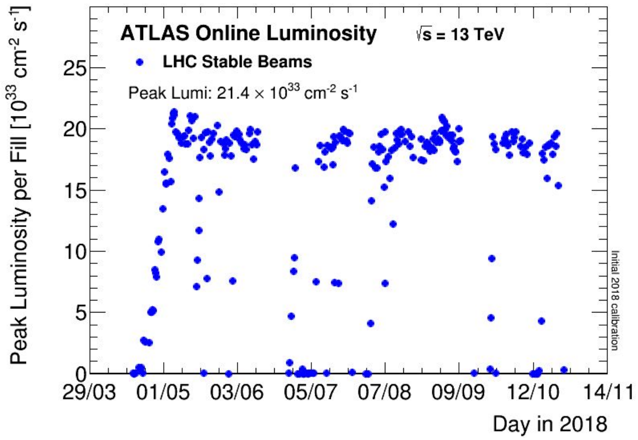


The ATLAS detector

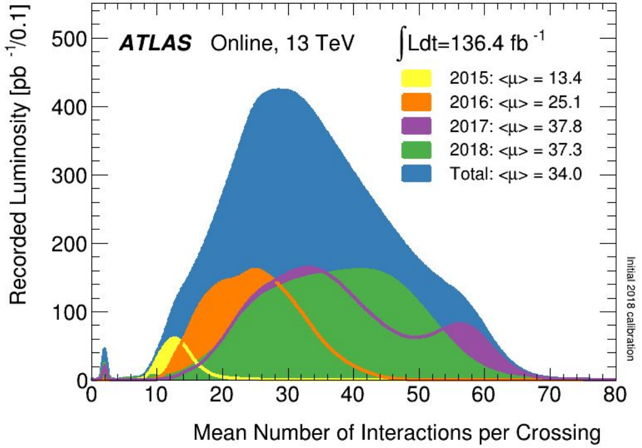


- **A** **T**oroidal **L**HC **A**pparatu**S**
  - 44 m long, 25 m of diameter
  - 4 layers of detectors
- Inner detector
  - pixel, strip, TRT
- Electromagnetic calorimeter
- Hadronic calorimeter
- Muon detector

LHC and ATLAS performance

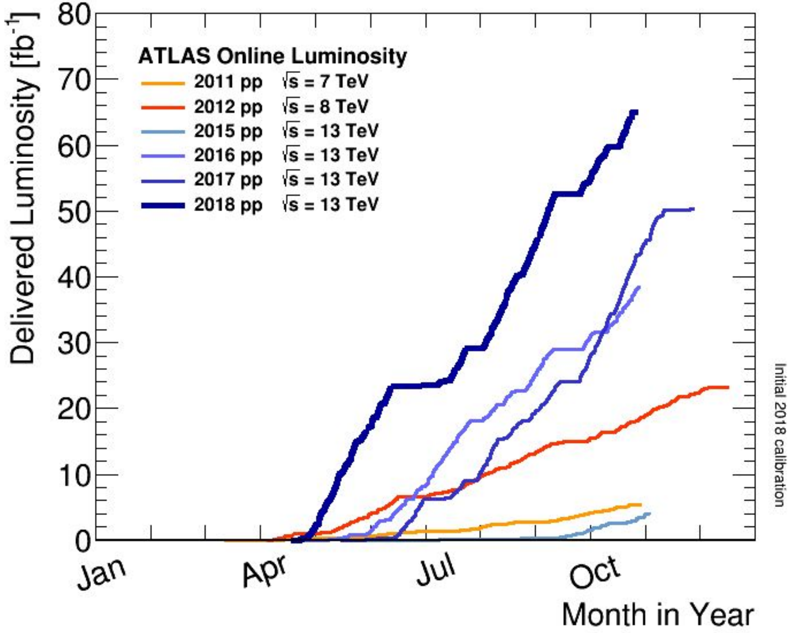


- At LHC two bunches of protons collide every 25 ns (40 MHz)
- LHC design instantaneous luminosity: 10^{34} cm^{-2} s^{-1}



- Hard collisions -> between two elementary components of the protons (q or g)
- Other components of the same hadrons produce “underlying event”
- Several collision events per proton bunch crossing “pile-up events”

LHC and ATLAS performance



- Current center of mass energy $\sqrt{s}$=13 TeV
- Originally expected to get up to 120 fb^{-1} by the end of 2018
- ~ 160 fb^{-1} (!!) of proton-proton collision data registered by ATLAS in Run-II

Jets in ATLAS

- Jet production is the dominant high-p_T process in the LHC
- Jet observables play an important role in the study of:
  - The structure of the proton
  - The color interaction and its coupling strength α_s
- Anti-k_T jets
- Built considering topological clusters of calorimeter cells
- Clusters corrected for pileup prior to jet building
- Multi-stage calibration scheme