Jet substructure measurements in ATLAS

Mario Campanelli
University College London
On behalf of the ATLAS collaboration

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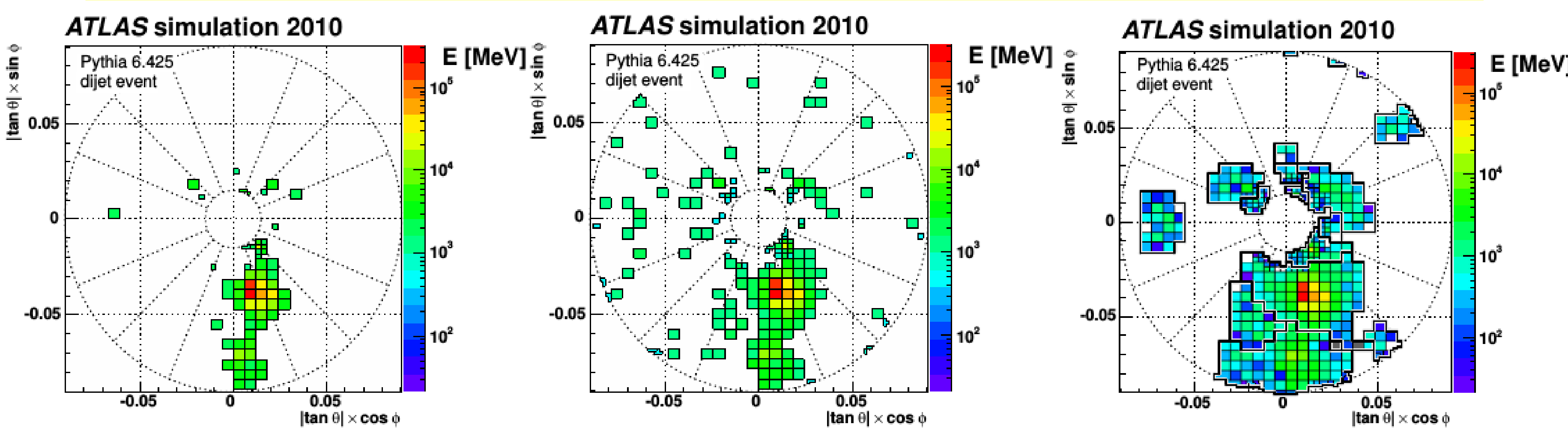
- Performance
  - Large-R jet calibration
  - Bottom-up uncertainties
- Phenomenology
  - Soft-drop
  - Jet shapes
- Measurements
  - SoftDrop jet mass
  - SoftDrop and Trimmed Jet shapes

Jets in ATLAS

- Internal structure of jets interesting to study QCD and to distinguish jets coming from light quarks, gluons or hadronic decays of heavy particles (W, Z,top, H…)
- Many different types of jets are used in ATLAS:
  - R = 0.2, 0.4, 0.6, 0.8, 1.0, variable-R
  - Calorimeter-based, p-flow (PF0 and TCC), track-assisted, ReClustered
- For substructure studies, so far most of results for calorimeter-based large-R jets

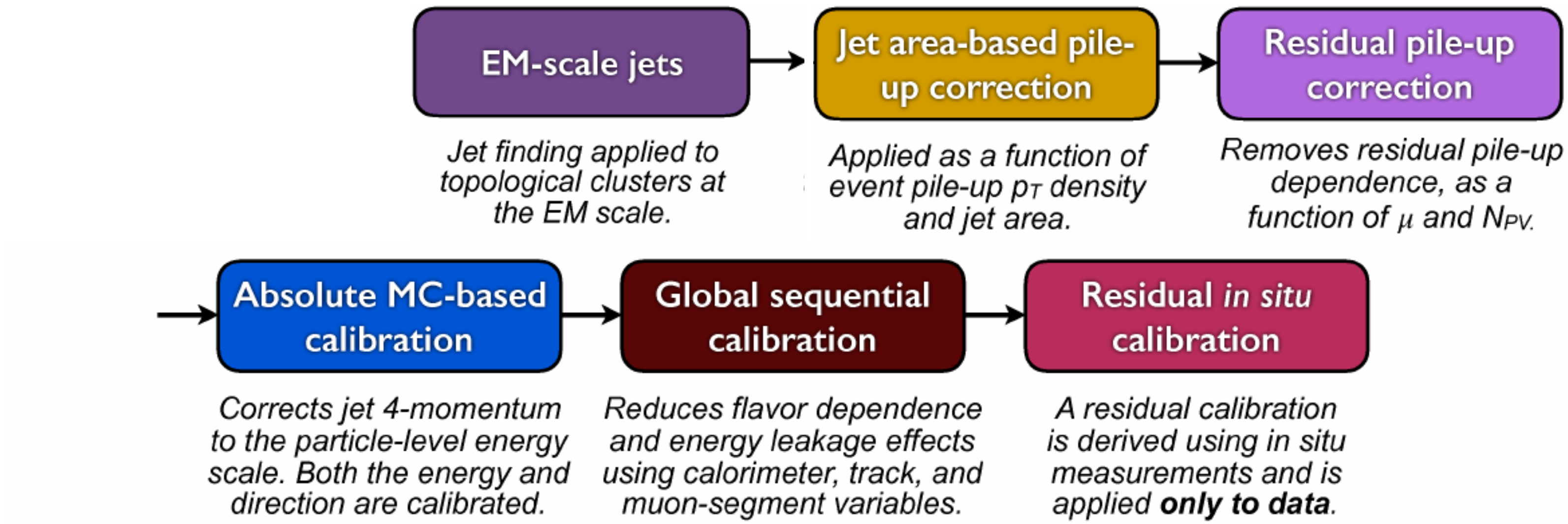
Initial constituents for calorimeter jets are topological clusters, supposed to represent a particle deposition
Starting from a cell 4σ above noise, neighbouring cells with 2σ and a surrounding layer are added.
Splitting algorithm separates nearby cluster, and a calibration is applied to account for non-compensation, dead material and out-of-cluster effects



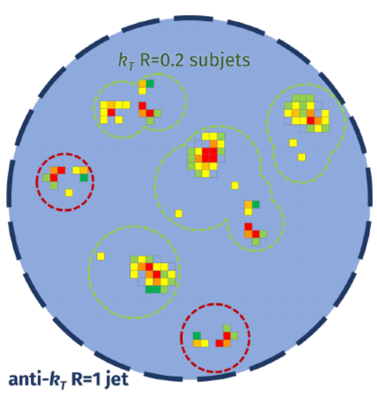
TopoClusters are then merged into jets using the anti-kt algorithm
→ cluster and jet calibrations and uncertainties are very important

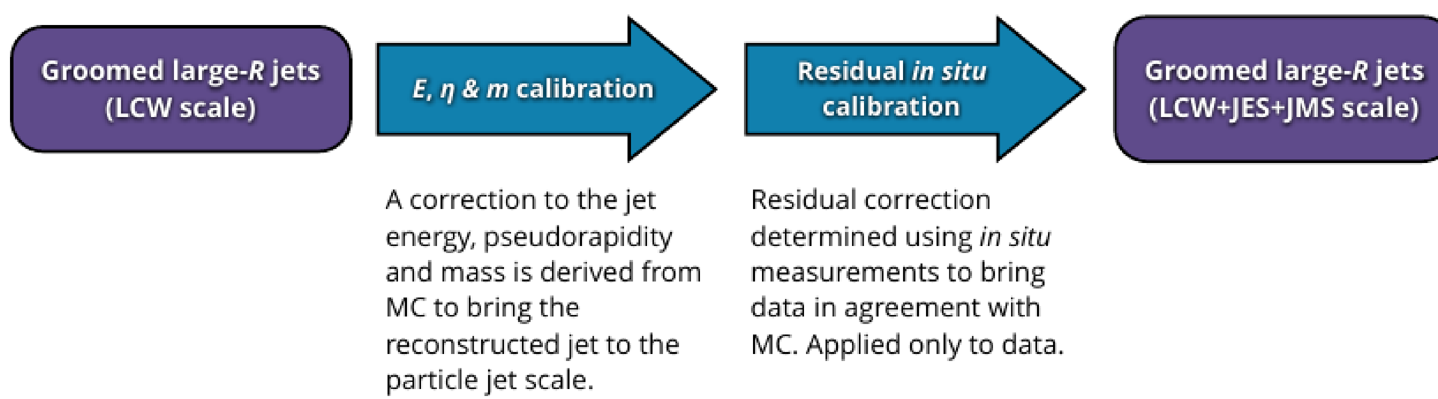
Jet calibration

Jets are calibrated using a combination of MC- and data-based methods. Steps for small-R:

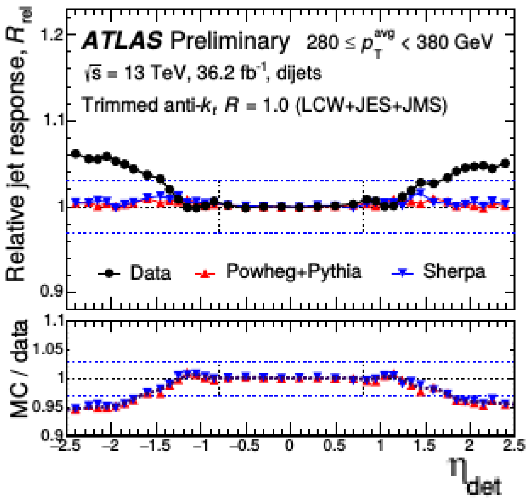


For large-R jets an additional grooming procedure (by default trimming, that removes R = 0.2 subjets with <5% of jet p_T) can be applied before a dedicated MC and in-situ calibration

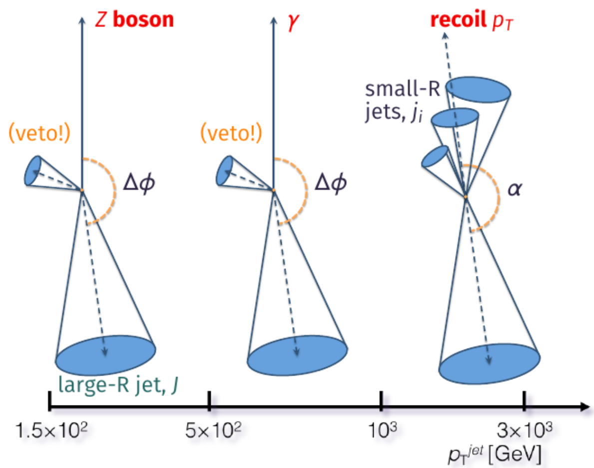




In-situ energy calibration

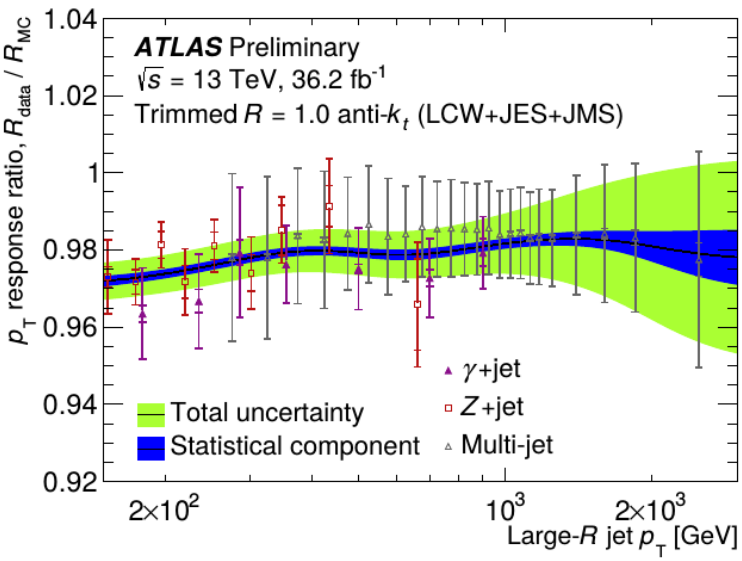


Even after jets are corrected to particle level, residual central-forward asymmetries in data are corrected to achieve a uniform response



Jet energy further calibrated in-situ by balancing the response with well-measured objects (photons, Z→ll, small-R jets).

This “top-down” approach calibrates and provides uncertainties for average values, not differential quantities.



The results for the balancing methods are combined into a pt-dependent scale factor, used to rescale the whole jet 4-momentum.

Bottom-up uncertainties from clusters

Calibrations and uncertainties on jets as 4-vectors are only the first step for a substructure measurement. Jet constituents are combined to produce more variables, like the jet mass, jet shapes etc.

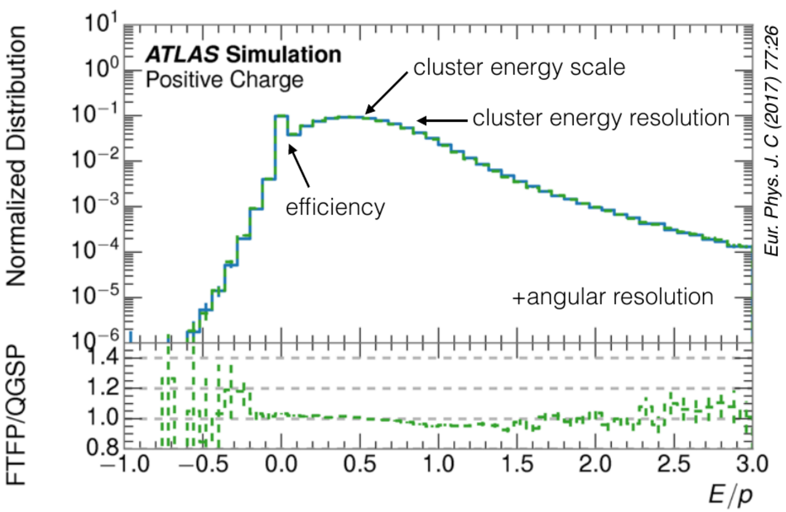
Uncertainties on these quantities computed directly from the topoclusters, using a bottom-up approach

Cluster reconstruction efficiency, energy scale and resolution obtained from E/p on simulated isolated pion interactions

Uncertainties are applied to jet mass and shapes by smearing TopoCluster efficiency, energy and positions around these mean values

Additional uncertainties come from different assumptions on:
- energy correlations between clusters
- fractions of non-pion hadrons
- cluster splitting and merging

Bottom-up uncertainties have comparable size to top-down uncertainties computed from track/calo ratios, (only possible for average quantities not distributions)

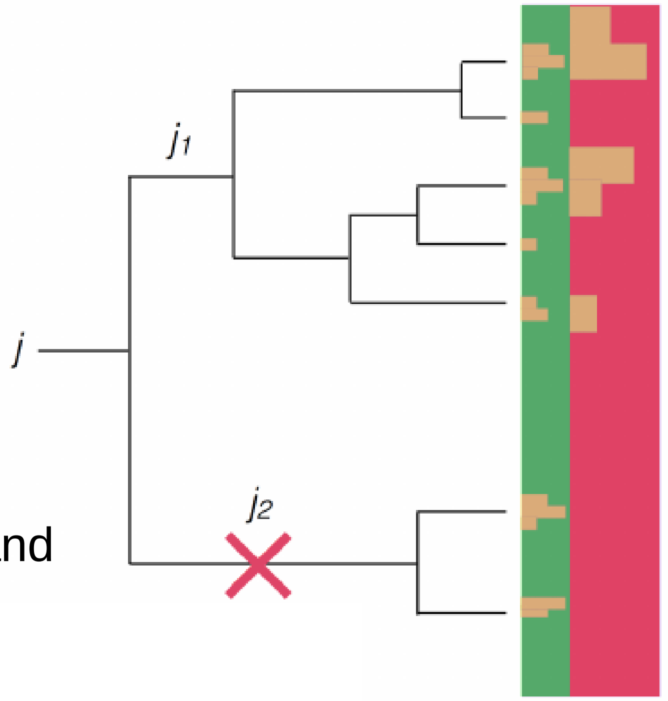


An improved groomer: SoftDrop

Trimmed jets are very stable wrt pileup, but the procedure is not analytically calculable- only possible to compare trimmed jets to MC (NNL precision)

The Soft-Drop algorithm clusters jet constituents with Cambridge-Aachen, and retraces the clustering history from the last branching. For each branch, it checks that

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



If it is satisfied, the algorithm stops.
If not, the soft branch j2 is removed, and the algorithm is applied recursively on j1.

This procedure removes soft radiation, according to the scale z_{cut}, and large-angle emission, according to the parameter β (chosen)

In most ATLAS analyses, event selection is based on the calibrated trimmed jets; soft-drop can be applied instead of trimming to the jet ungroomed constituents to produce observables calculable at NLO + NLL

Jet shapes

Apart from mass, other jet variables are used for QCD studies (e.g. tuning) and to identify jet type. ATLAS measured:

- Number of R=0.2 anti-kt subjets with pT > 10 GeV
- Les Houches angularity:

$$\lambda^{\kappa}_{\beta^{\mathrm{LHA}}} = \sum_{i\in J} z_i^{\kappa}\theta_i^{\beta^{\mathrm{LHA}}}$$

  where z is the momentum fraction and θ the angle wrt jet axis of the i[th] component, with (k = 1, β = 0.5)

- Energy Correlation ratios, C2 and D2

$$\mathrm{ECF1} = \sum_{i\in J} p_{\mathrm{T}_i},$$

$$\mathrm{ECF2}(\beta^{\mathrm{ECF}}) = \sum_{i<j\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} \left(\Delta R_{ij}\right)^{\beta^{\mathrm{ECF}}},$$

$$\mathrm{ECF3}(\beta^{\mathrm{ECF}}) = \sum_{i<j<k\in J} p_{\mathrm{T}_i} p_{\mathrm{T}_j} p_{\mathrm{T}_k} \left(\Delta R_{ij}\Delta R_{ik}\Delta R_{jk}\right)^{\beta^{\mathrm{ECF}}},$$

$$e_2 = \frac{\mathrm{ECF2}}{(\mathrm{ECF1})^2}, \qquad C_2 = \frac{e_3}{(e_2)^2},$$

$$e_3 = \frac{\mathrm{ECF3}}{(\mathrm{ECF1})^3}. \qquad D_2 = \frac{e_3}{(e_2)^3}.$$

- N-subjettiness ratios $\tau_{21} = \frac{\tau_2}{\tau_1}$ and $\tau_{32} = \frac{\tau_3}{\tau_2}$ (used to distinguish W and top jets)

$$\tau_0(\beta^{\mathrm{NS}}) = \sum_{i\in J} p_{\mathrm{T}_i} R_0^{\beta^{\mathrm{NS}}},$$

$$\tau_1(\beta^{\mathrm{NS}}) = \frac{1}{\tau_0(\beta^{\mathrm{NS}})} \sum_{i\in J} p_{\mathrm{T}_i} \Delta R_{a_1,i}^{\beta^{\mathrm{NS}}},$$

$$\tau_2(\beta^{\mathrm{NS}}) = \frac{1}{\tau_0(\beta^{\mathrm{NS}})} \sum_{i\in J} p_{\mathrm{T}_i} \min(\Delta R_{a_1,i}^{\beta^{\mathrm{NS}}}, \Delta R_{a_2,i}^{\beta^{\mathrm{NS}}}),$$

$$\tau_3(\beta^{\mathrm{NS}}) = \frac{1}{\tau_0(\beta^{\mathrm{NS}})} \sum_{i\in J} p_{\mathrm{T}_i} \min(\Delta R_{a_1,i}^{\beta^{\mathrm{NS}}}, \Delta R_{a_2,i}^{\beta^{\mathrm{NS}}} \Delta R_{a_3,i}^{\beta^{\mathrm{NS}}}),$$

Jet mass in dijet events PhysRevLett.121.092001

- Event selection on ungroomed $R = 0.8$ jets:
  - $P_{T1} > 600$ GeV (to be on trigger plateau), $p_{T1} < 1.5 * p_{T2}$ (to select dijet events)
- Groom with SoftDrop ($z = 0.1$, $\beta = 0, 1, 2$)
- Groomed mass normalised to ungroomed p_T (collinear safe for $\beta = 0$) for more stability:

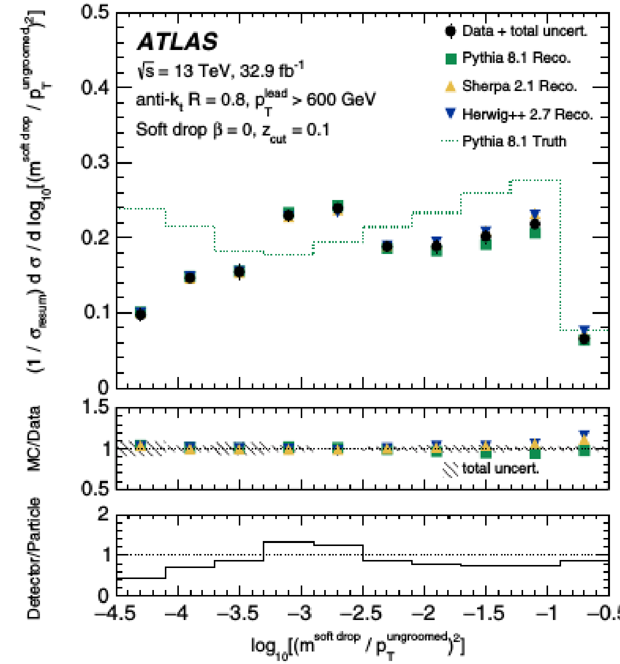
$$\rho = \log[(m^{\text{Soft Drop}} / p_T^{\text{Ungroomed}})^2]$$

- Normalised to data in the resummation region

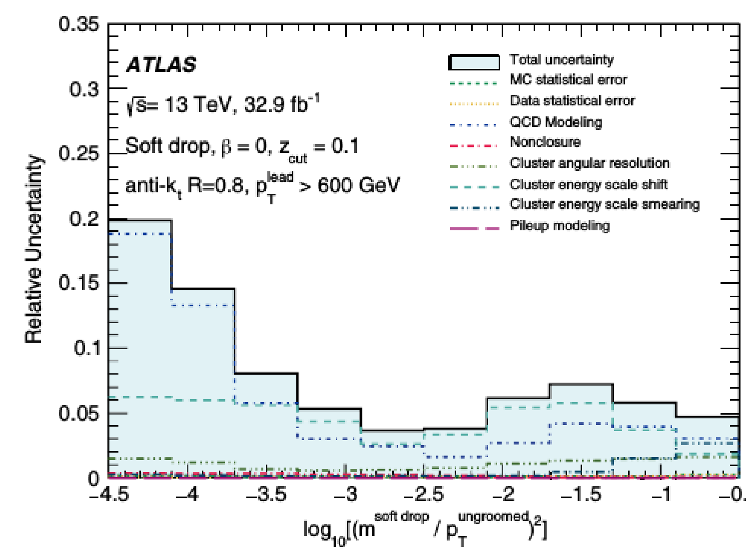
  $-3.7 < \rho < -1.7$

Uncertainties

- Detector-level and particle-level quite different
  - Large off-diagonal terms in unfolding
- Differences between MC models
  - MC modeling dominant uncertainty



- Cluster uncertainties:
  - Energy scale large at small masses (low mult.)
  - Angular and energy smearing large at large masses



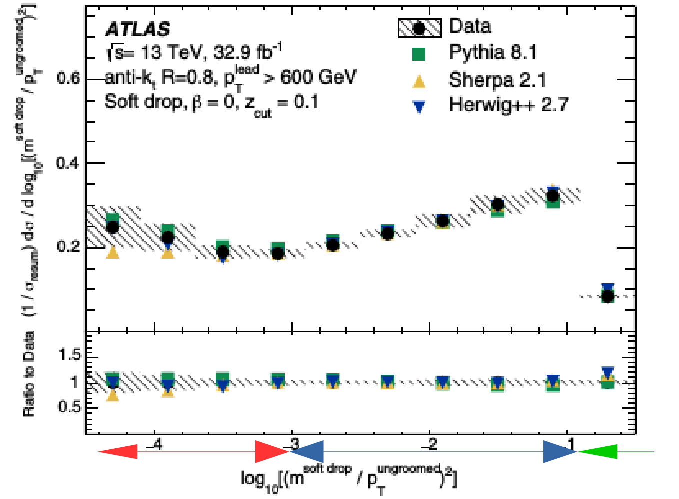
Results

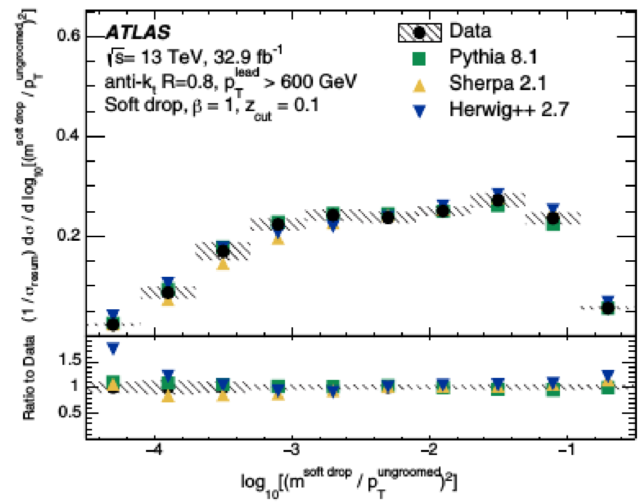
Regions probed:

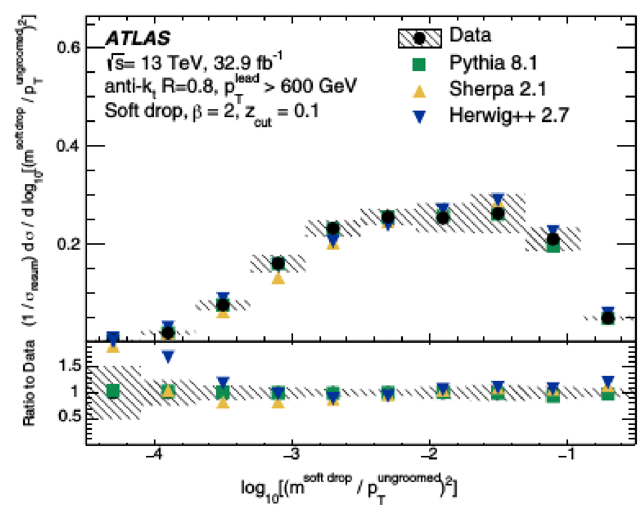
- Non-perturbative
- Resummation
- Fixed-order

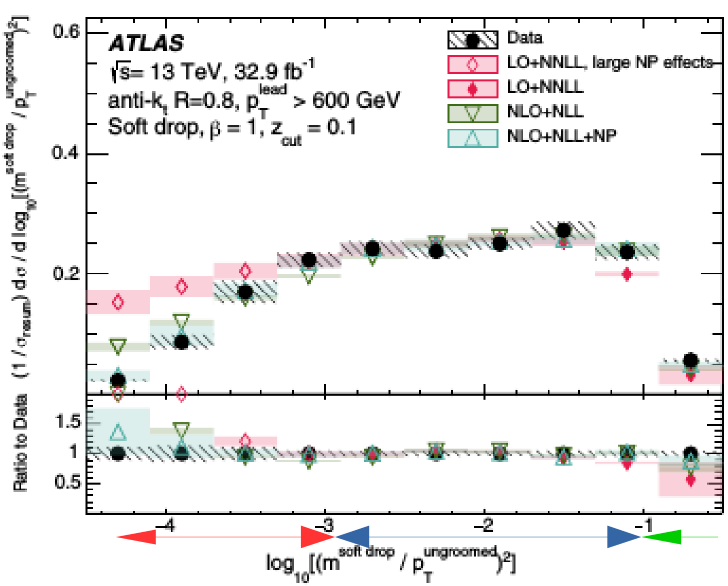
Good agreement with MC models within uncertainties (some discrepancies at low-mass)

Comparison with calculations requires NLO + NLL + NP corrections to agree beyond resummation region









Jet-shape measurements for top, W and dijets: event selections

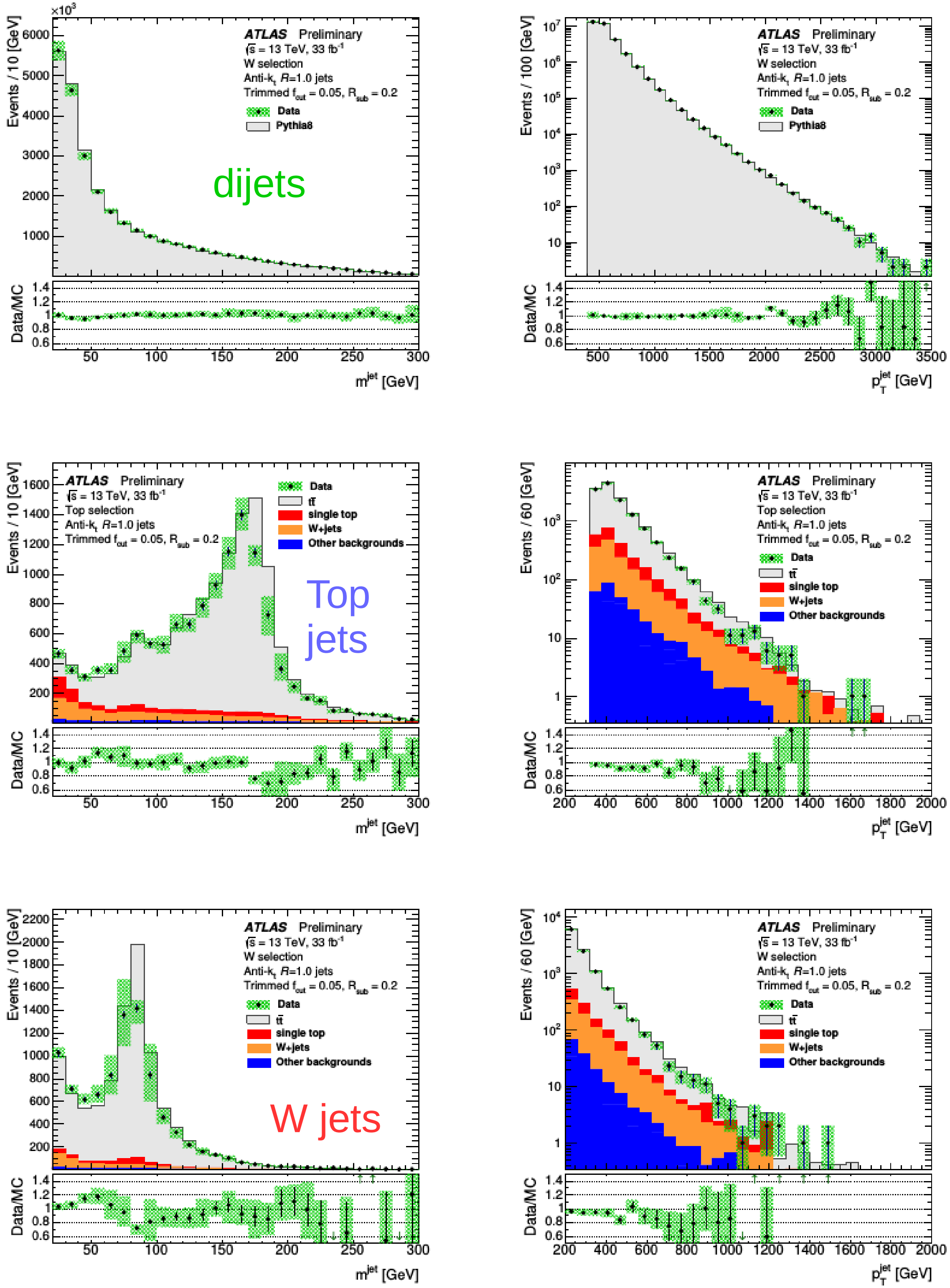
NEW!

	Detector level	Particle level
Dijet selection:		
Two trimmed anti-k_t $R = 1.0$ jets	$p_T > 200$ GeV $\lvert\eta\rvert < 2.0$	$p_T > 200$ GeV $\lvert\eta\rvert < 2.0$
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 $\lvert\eta\rvert < 2.5$ $\lvert z_0 \sin(\theta)\rvert < 0.5$ mm and $\lvert d_0/\sigma(d_0)\rvert < 3$	$p_T > 30$ GeV $\lvert\eta\rvert < 2.5$
Anti-k_t $R = 0.4$ jets	$p_T > 25$ GeV $\lvert\eta\rvert < 4.4$ JVToutput > 0.5 (if $p_T < 60$ GeV)	$p_T > 25$ GeV $\lvert\eta\rvert < 4.4$
Overlap removal using small-radius jets	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	$p_T > 300$ 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	$p_T > 300$ 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	

Two separate event selections:

- Dijets
- Semi-leptonic tt
  - Top jets
  - W jets

Selection based on trimmed jets, jet shape measurement for both trimmed and soft-drop

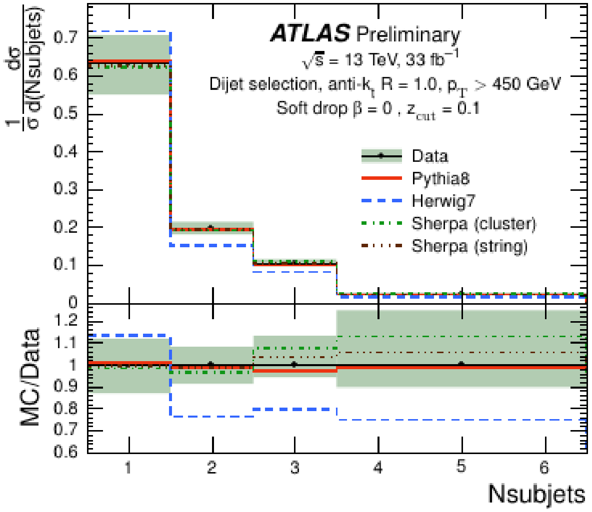


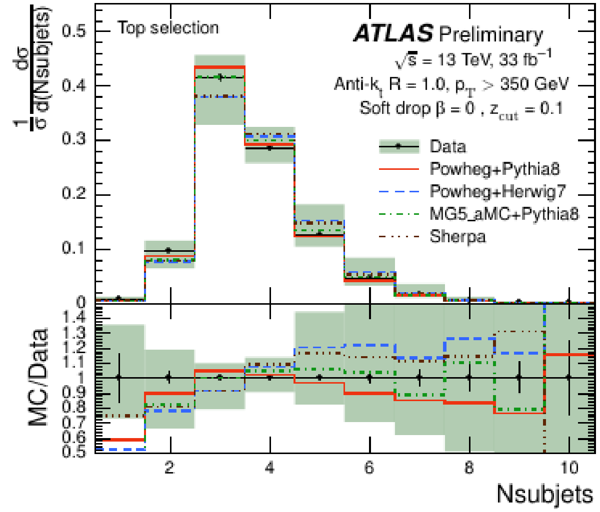
Detector-level distributions

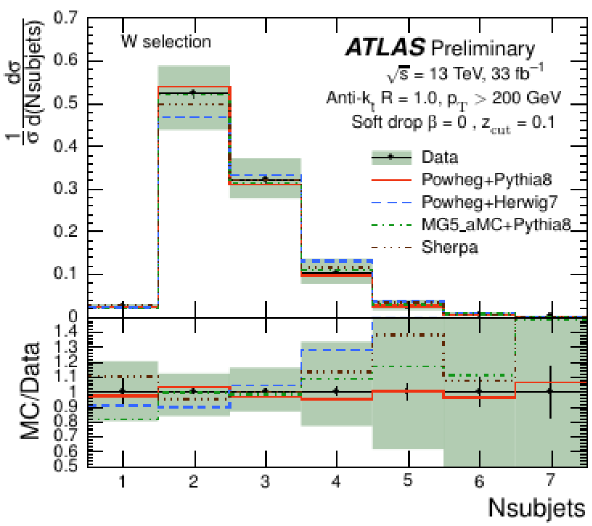
A Data-MC shift is observed in the detector-level mass, because no in-situ calibration is applied in this analysis.

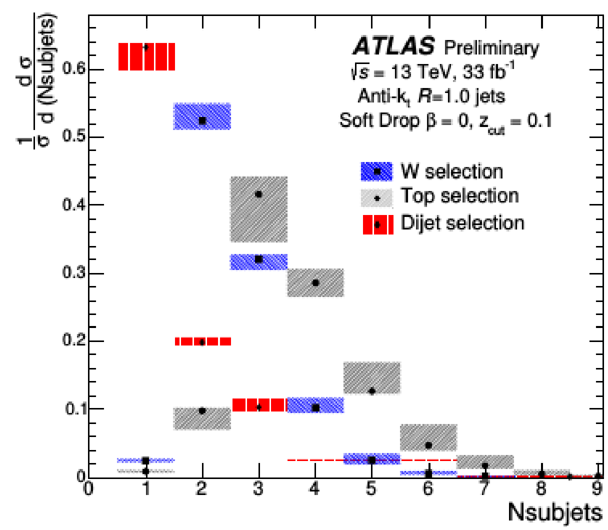
The mass window for jet selection has been chosen to account for this effect.

Multiplicity



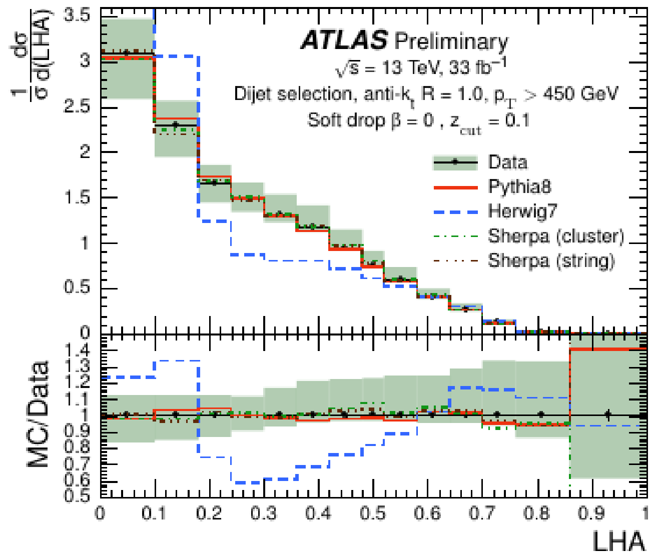


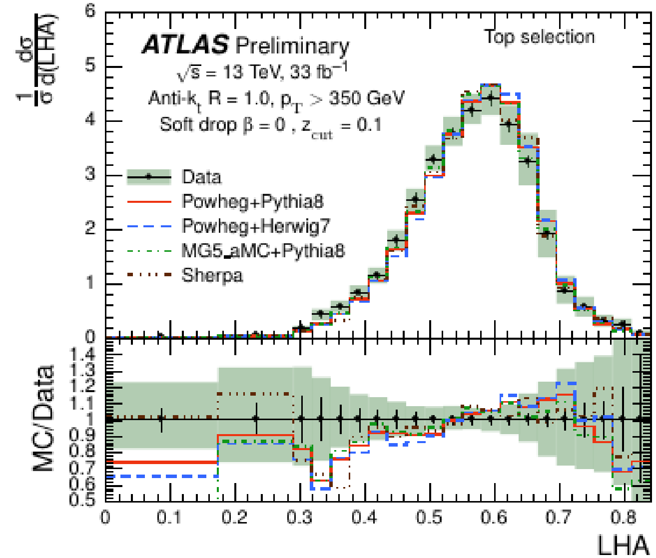


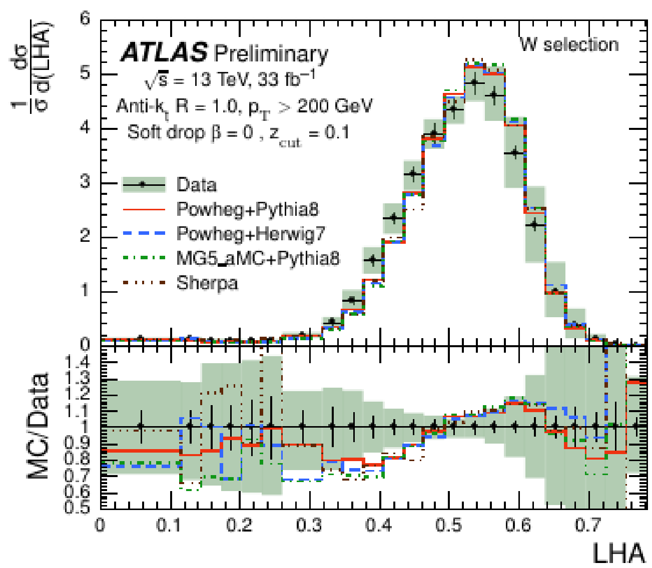


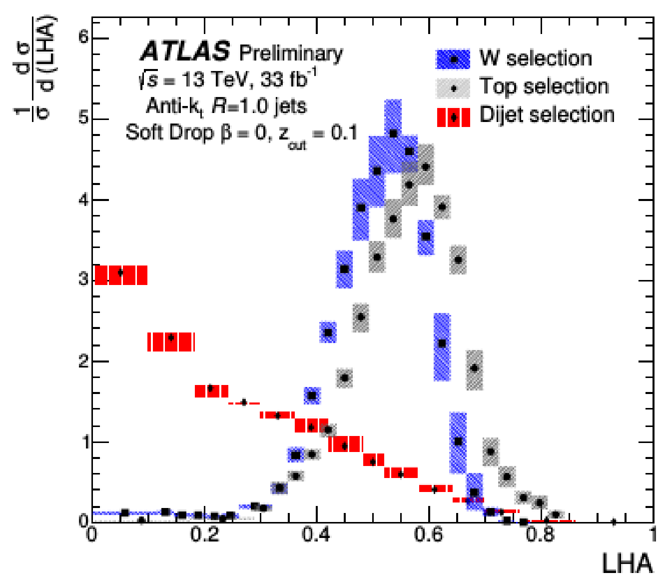
Largest uncertainties from calibrations: jet pT and mass calibration for selection, and clusters. Herwig 7 shows large disagreement for dijets

Angularity



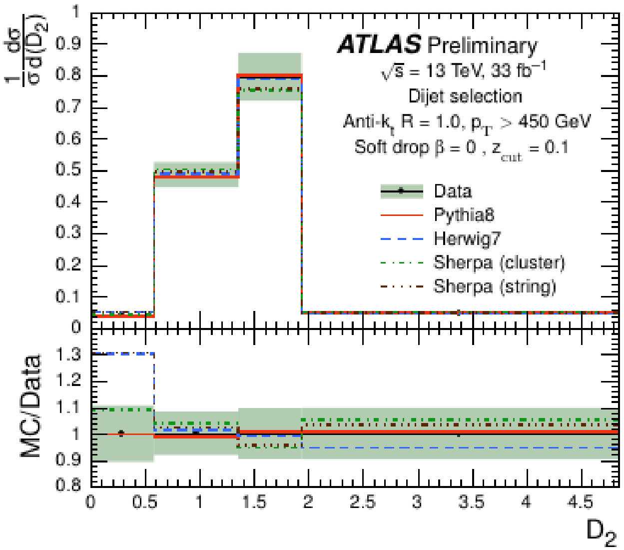


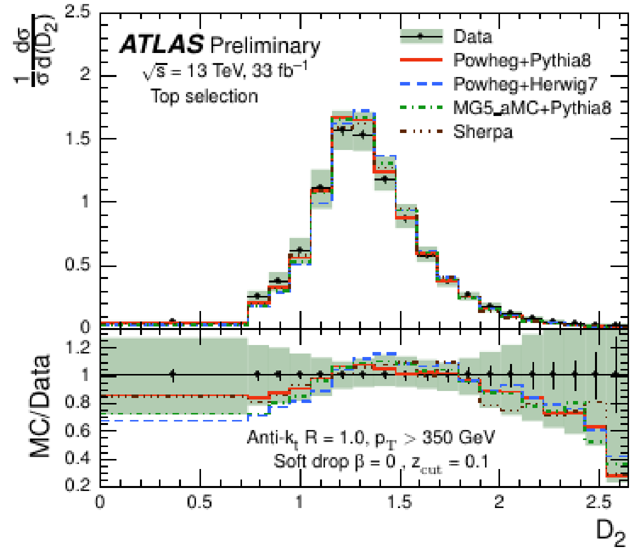




All models show tensions in W/top

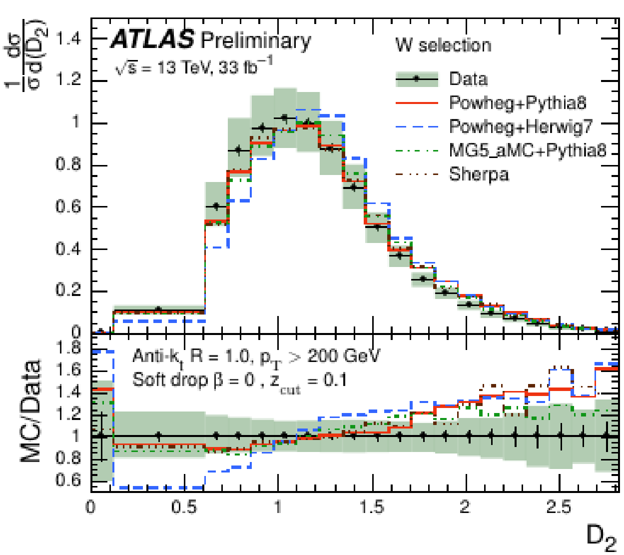
D2

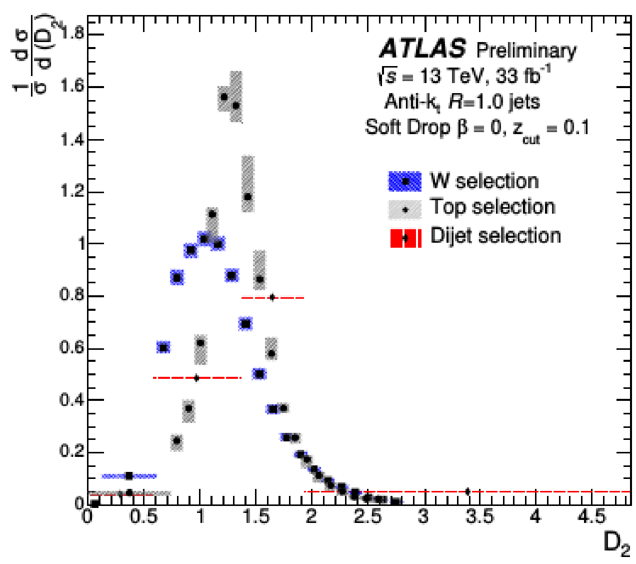




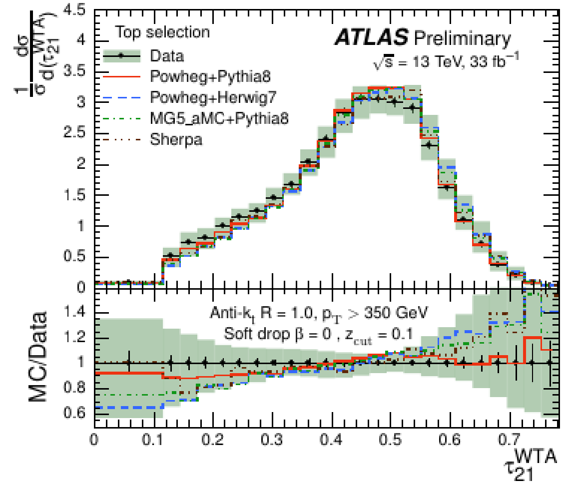
Widely used variable for W tagging

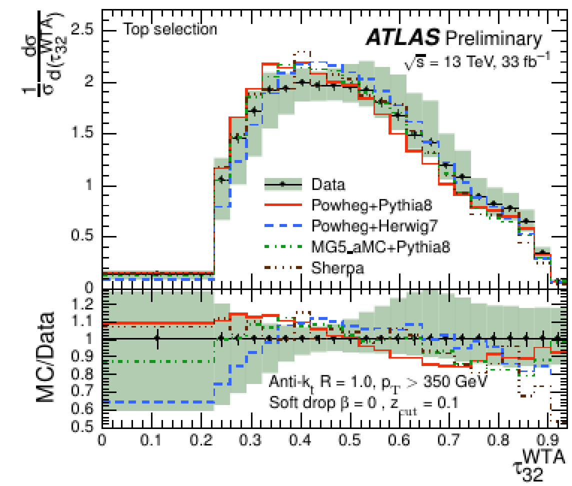
Significant shifts observed for all MC models in W events.





N-subjettiness τ_{21},τ_{32}

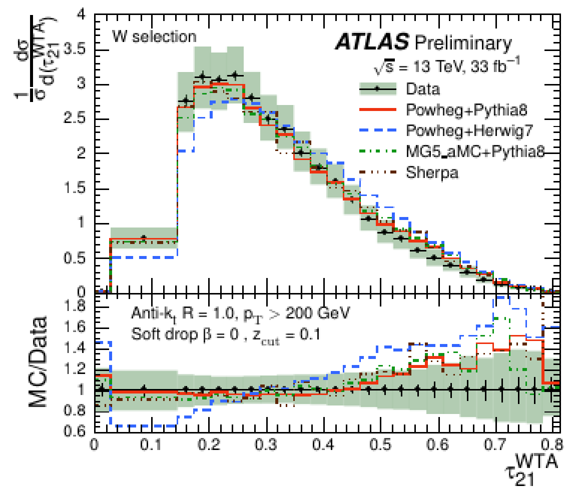


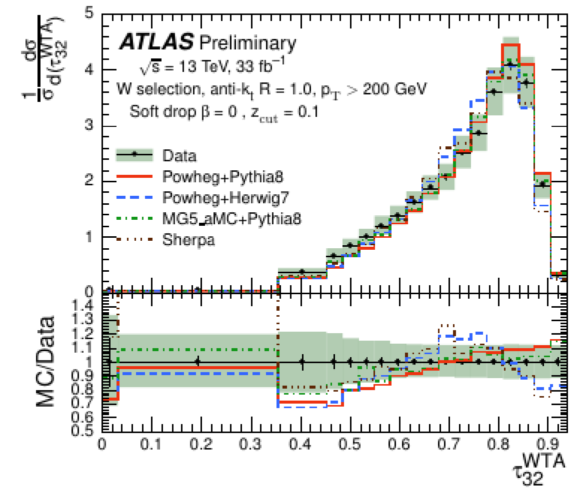


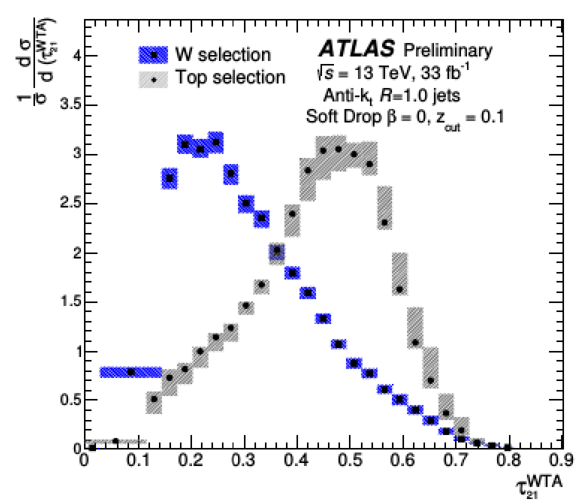
Used for W/top separation

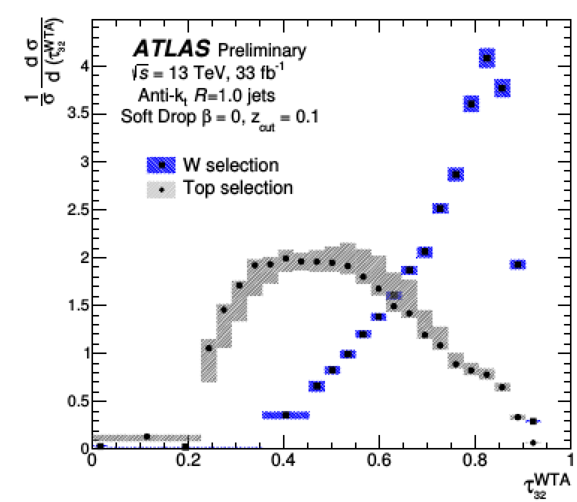
Dijet events have less hard splitting, so are more sensitive to cluster split-merge uncertainties, that lead to very large errors

→ no dijet measurements for n-subjettiness









Conclusions

- Jet substructure is widely used in searches for heavy states decaying into boosted objects like top and W
- Its MC modelling is difficult, and measurements are needed to help improve it
- With careful control of uncertainties at jet and cluster level, precisions of O(10%) in the bulk of distributions and O(20%) in the tails are now possible, helping to discriminate models
- Additional performance work, and the possibility of higher-order calculations provided by SoftDrop will provide more stringent tests in the near future.