Measurement of multi-jet cross sections at ATLAS

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on behalf of the ATLAS Collaboration

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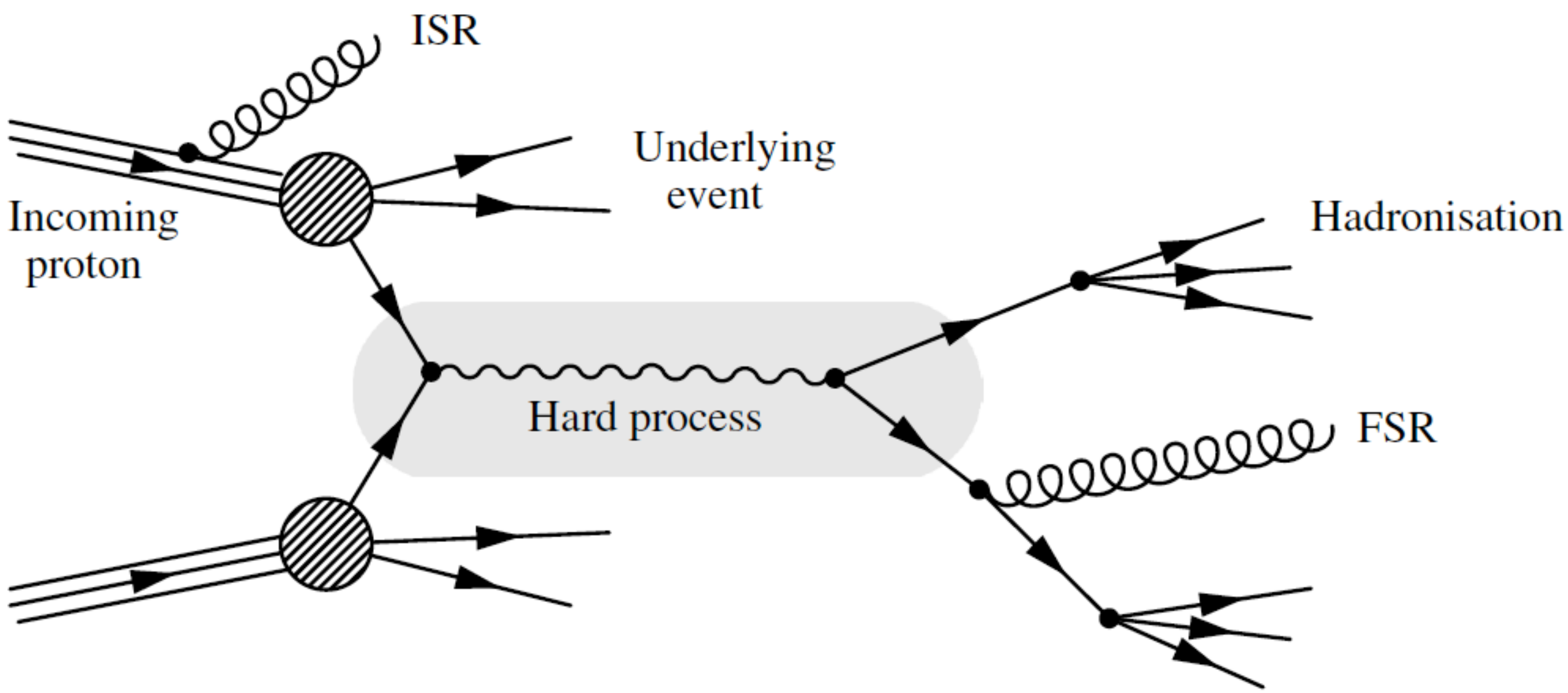
Multi-jet physics

At hadron colliders, events containing multiple jets in the final state are plentiful.

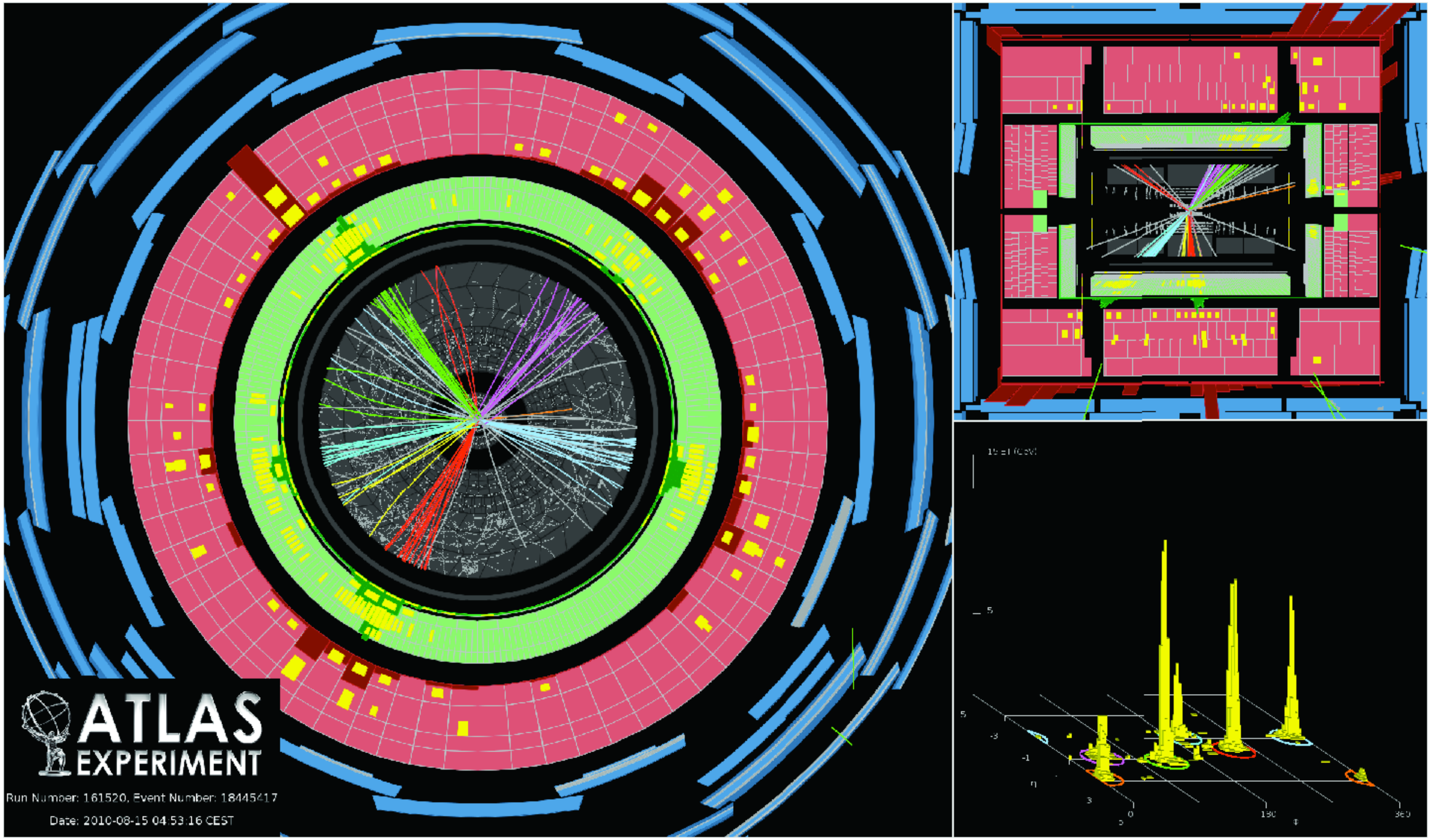


Multi-jet σ generally decreases by an additional power of α_s (~0.1) per additional jet.

Energy and angular distribution of multi-jet events provides one of the most fundamental and direct tests of **QCD**.

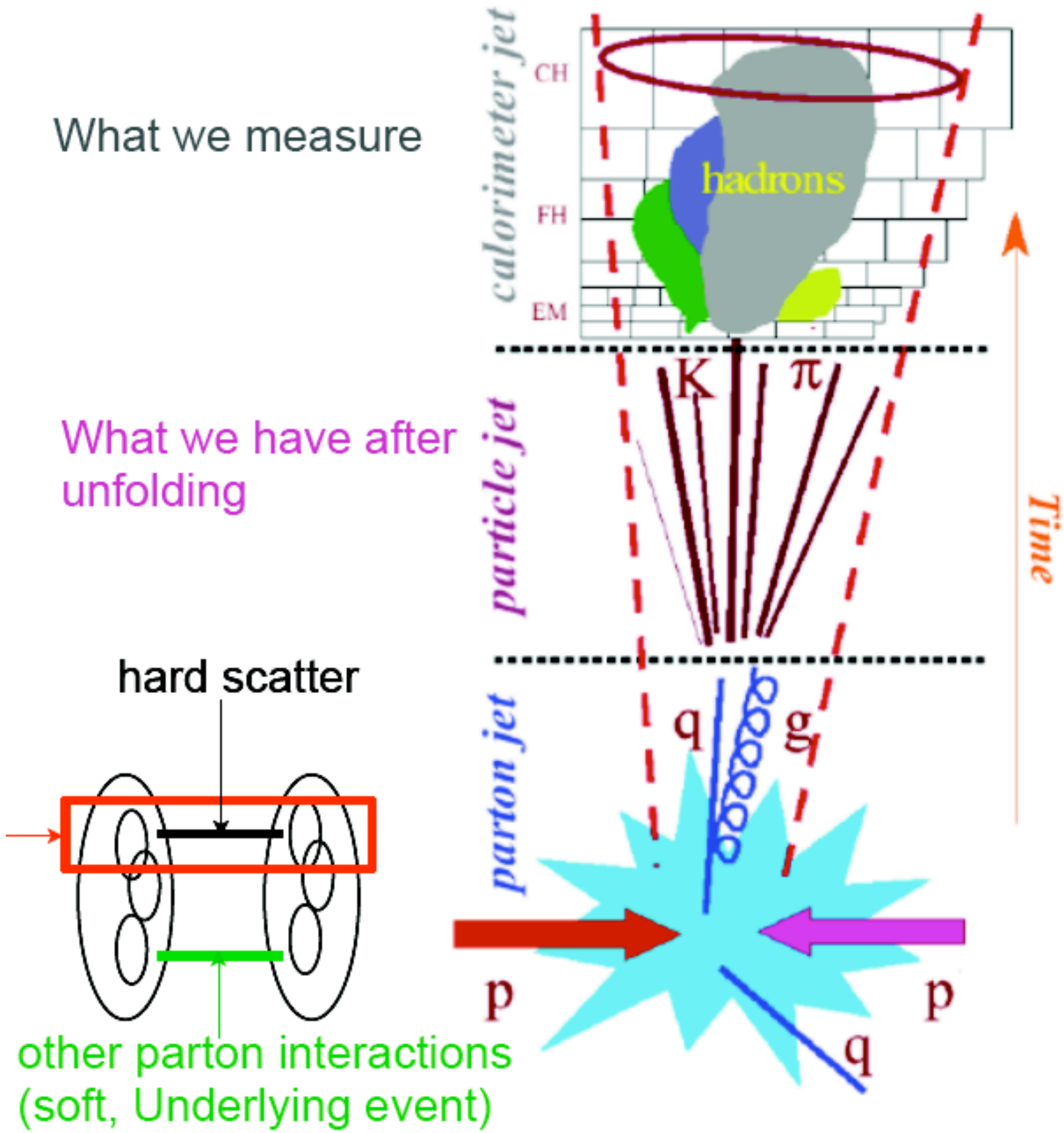
- Have to contend with non-perturbative factors.
- Great relevance to searches for new particles and new interactions at high energies.

Multi-jet event display



- 6-jet event, all jets with p_T > 60 GeV, |y| < 2.8.

A jet analysis in stages



Initial results measured at "detector level".

- Compared to LO MC with full-simulation of the ATLAS detector.

These are then "unfolded" to particle level.

- Corrects the observed data for detector effects.
- Allows detector independent comparisons of results.
- And much easier comparison to MC.

NLO calculations do not included non-perturbative effects or detector simulation.

- Therefore must also be corrected for non-perturbative effects.

Final results compare:

- Unfolded data.
- Particle (truth) level LO MC.
- NLO results with non-perturbative corrections.

Event and Jet selection

This analysis studies $\int \mathcal{L}\, dt = 2.43 \pm 0.08\ pb^{-1}$.

Event selection:

- A list of good collisions where LHC and ATLAS conditions are nominal.
- Selected by a multi-jet trigger above the 99% efficiency threshold.
- ≥ 1 primary vertex, with ≥ 5 tracks.

Jet selection:

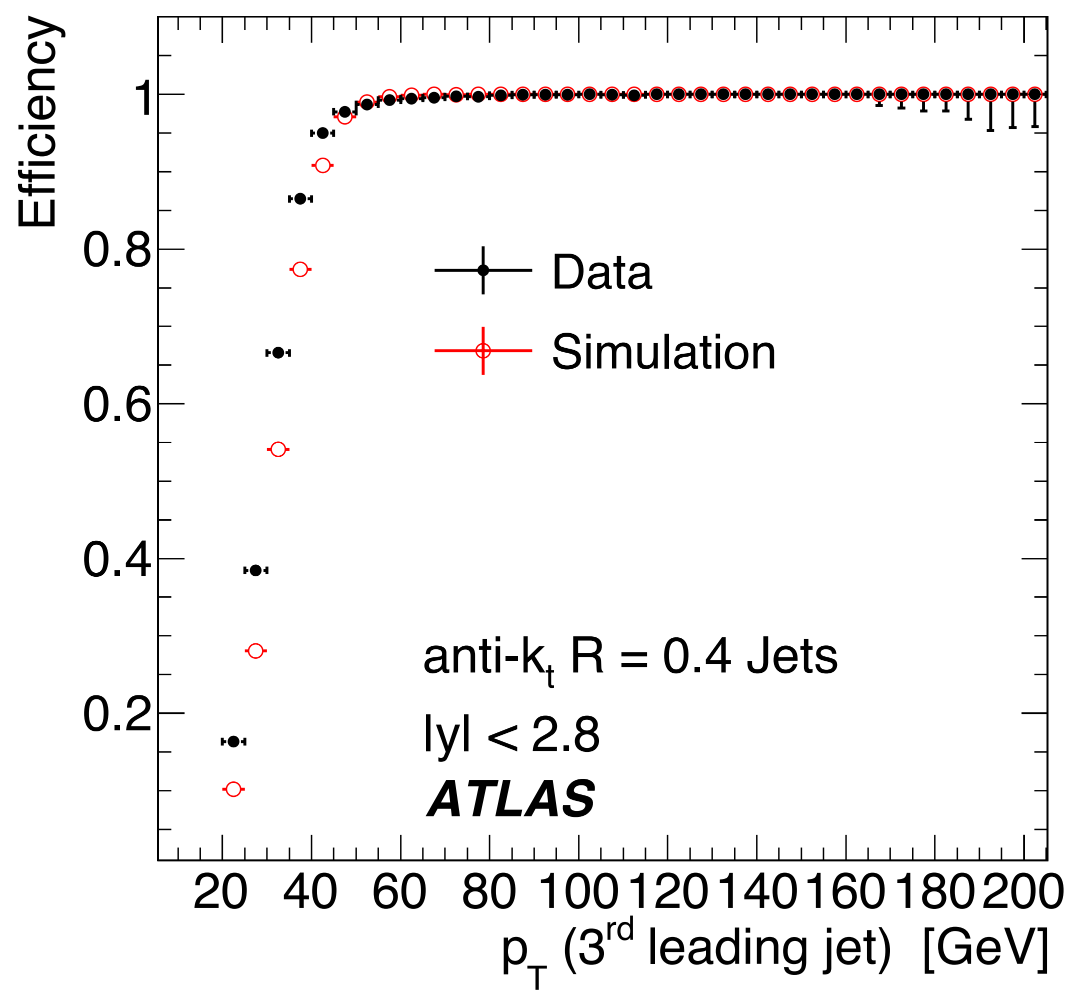
- Anti-k_T jets built from topological clusters of calorimeter energy with $R = 0.4$ & 0.6, $|y| < 2.8$.
- Selected using standard ATLAS *jet cleaning*.
  - cleaning is designed to eliminate various detector effects and suppress beam and other non-collision backgrounds.
- At least 2-jets $p_T \geq 60$ GeV, and leading jet $p_T \geq 80$ GeV.
- | *Jet vertex fraction* | ≥ 0.7.
  - a variable used to control the effects of additional soft proton-proton interactions.

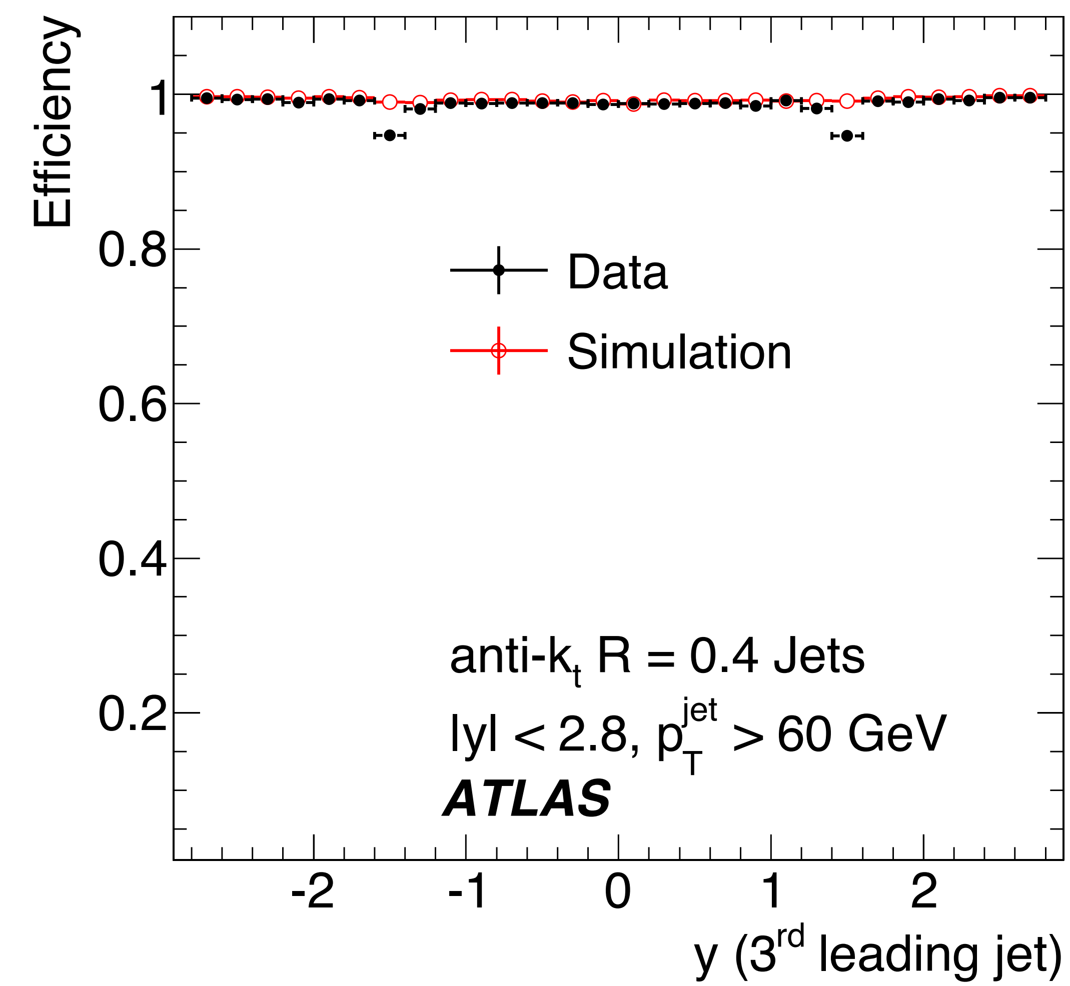
Inclusive jet multiplicity	Number of events	
≥2	500,148	selected by the di-jet trigger: which was *prescaled*
≥3	112,740	selected by the tri-jet trigger: never prescaled
≥4	10,999	prescaled: only a fraction of events passing this trigger are selected
≥5	1,100	
≥6	115	

Triggering

The first level (level-1) multi-jet triggers are used to select events.

- A hardware based sliding window algorithm which measures energy deposited in 0.8 η x 0.8 ϕ regions of the detector.
- Single jet trigger with a 10 GeV level-1 threshold is fully efficient to select events with ≥ 1 anti-k_T jet (R=0.4) with calibrated $p_T > 60$ GeV.





- Di-jet events with 2 jets above the 99% threshold are selected using di-jet triggers.
- Events with ≥ 3 jets above the 99% threshold are selected by tri-jet triggers.
  - Small differences between data and MC are included as systematic uncertainties.

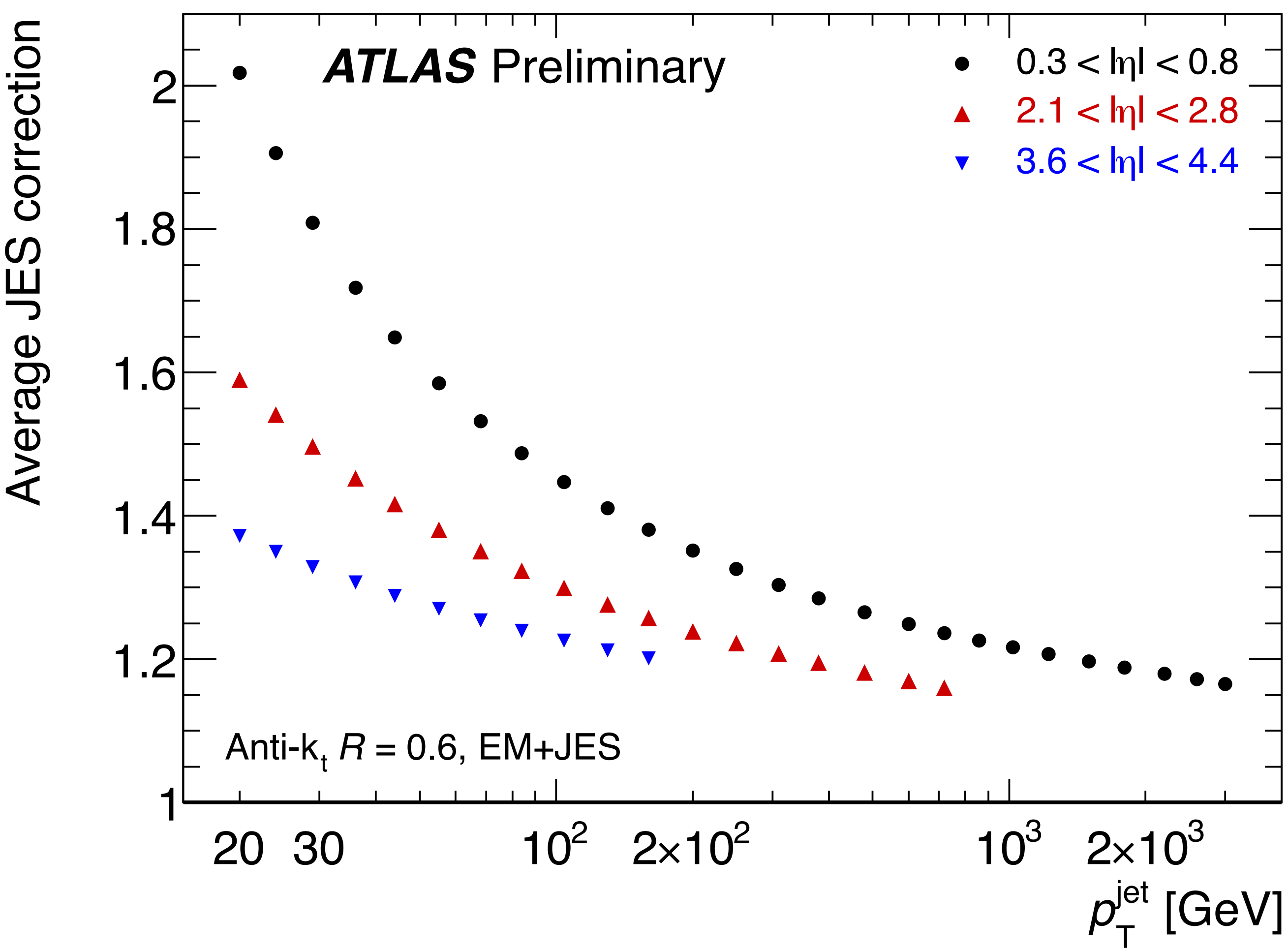
Jet energy scale (JES) calibration and uncertainty

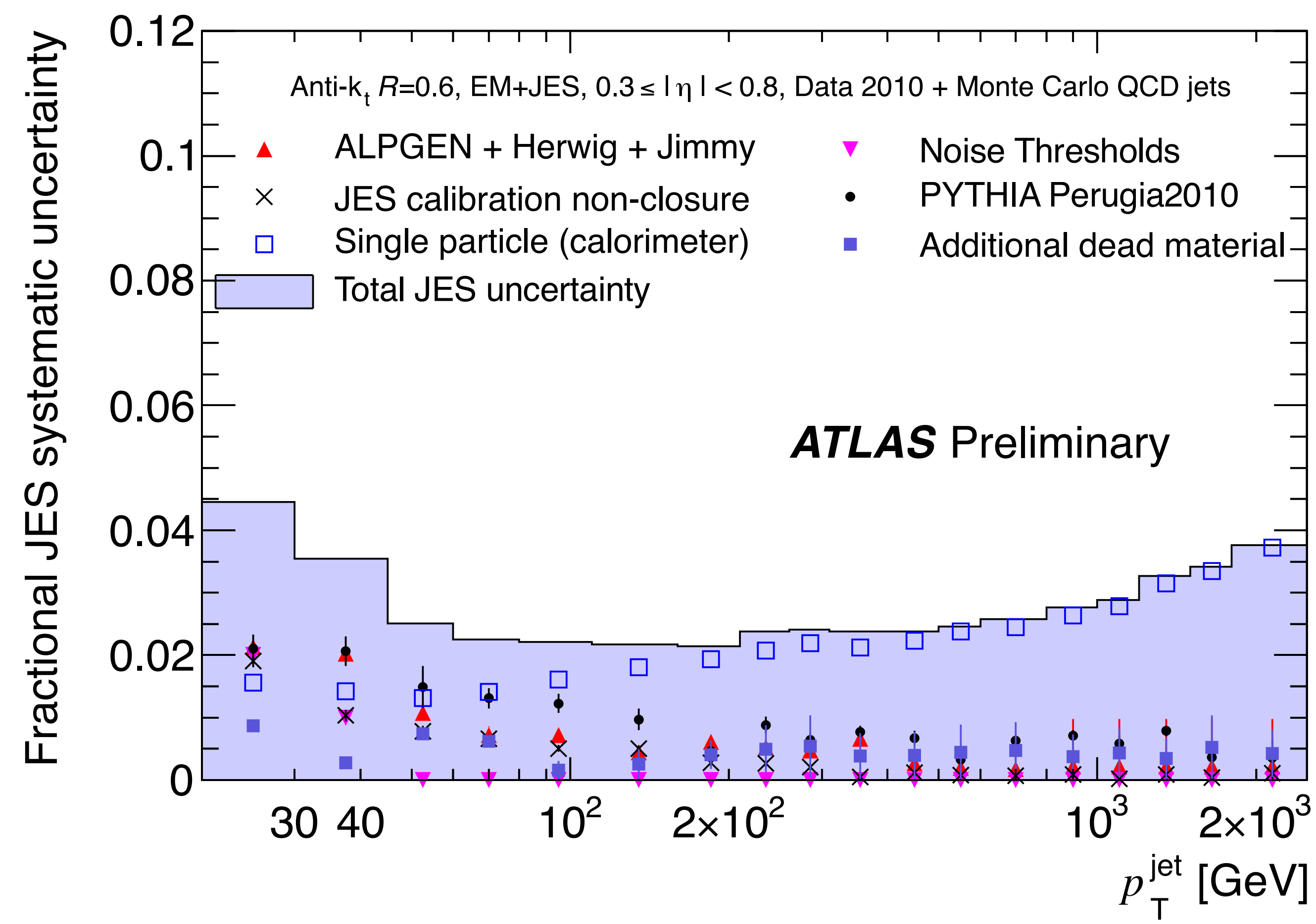
Jets are reconstructed at the *electromagnetic energy scale* which is derived from test beams and Z→ee data.

- lower than true energy of a jet due to different calorimeter responses to strongly interacting objects.

A calibration is applied derived for jets in a di-jet sample which corrects for these effects based on jet p_T and y.

The uncertainty on this calibration is one of the dominant sources of systematic uncertainty for the results presented here.





For isolated jets the dominant sources of uncertainty are: JES calibration method, calorimeter response, detector simulation, different MCs and MC tunes.

For multi-jets also important are: differences in the calorimeter response to jets of different flavours, the impact of nearby calorimeter activity.

Data correction for efficiencies and resolutions

A correction is needed to compare measurements to theoretical predictions.

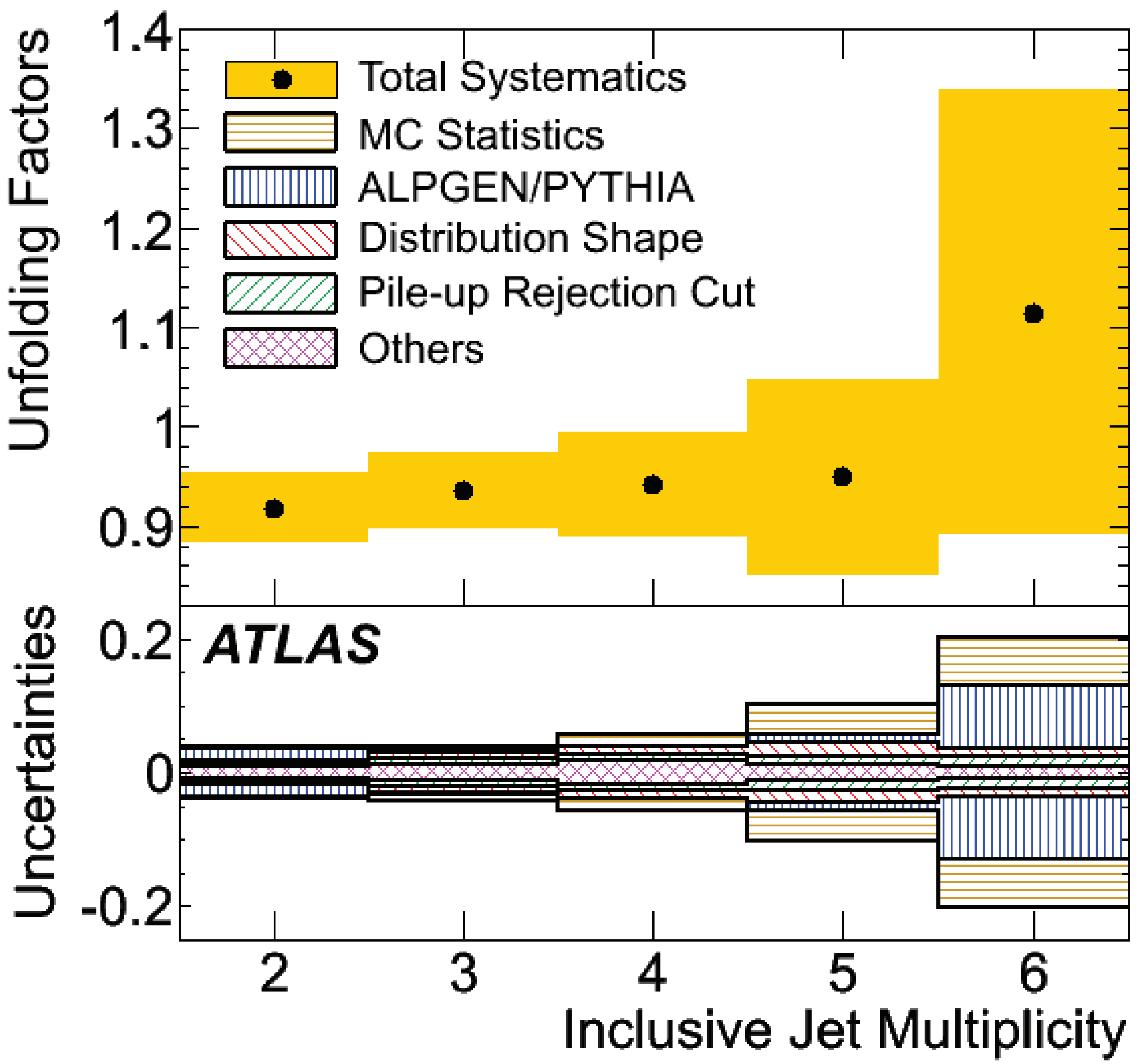
This accounts for:

- Trigger inefficiencies
- Detector resolutions
- Other detector effects.

Often called unfolding.

This analysis calculates a multiplicative correction factor for the data.

- Based on the ratio of reconstructed MC to particle level (truth) MC.
- Bin by bin in a single step.

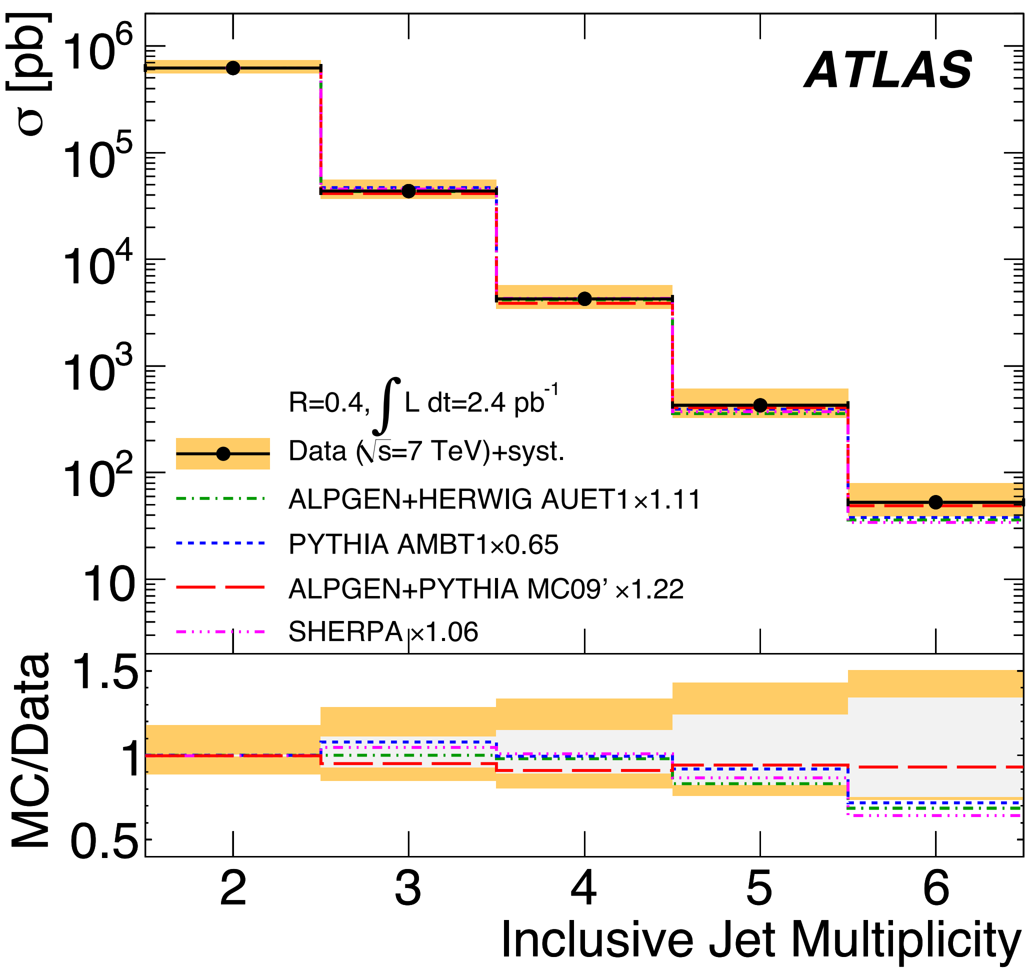


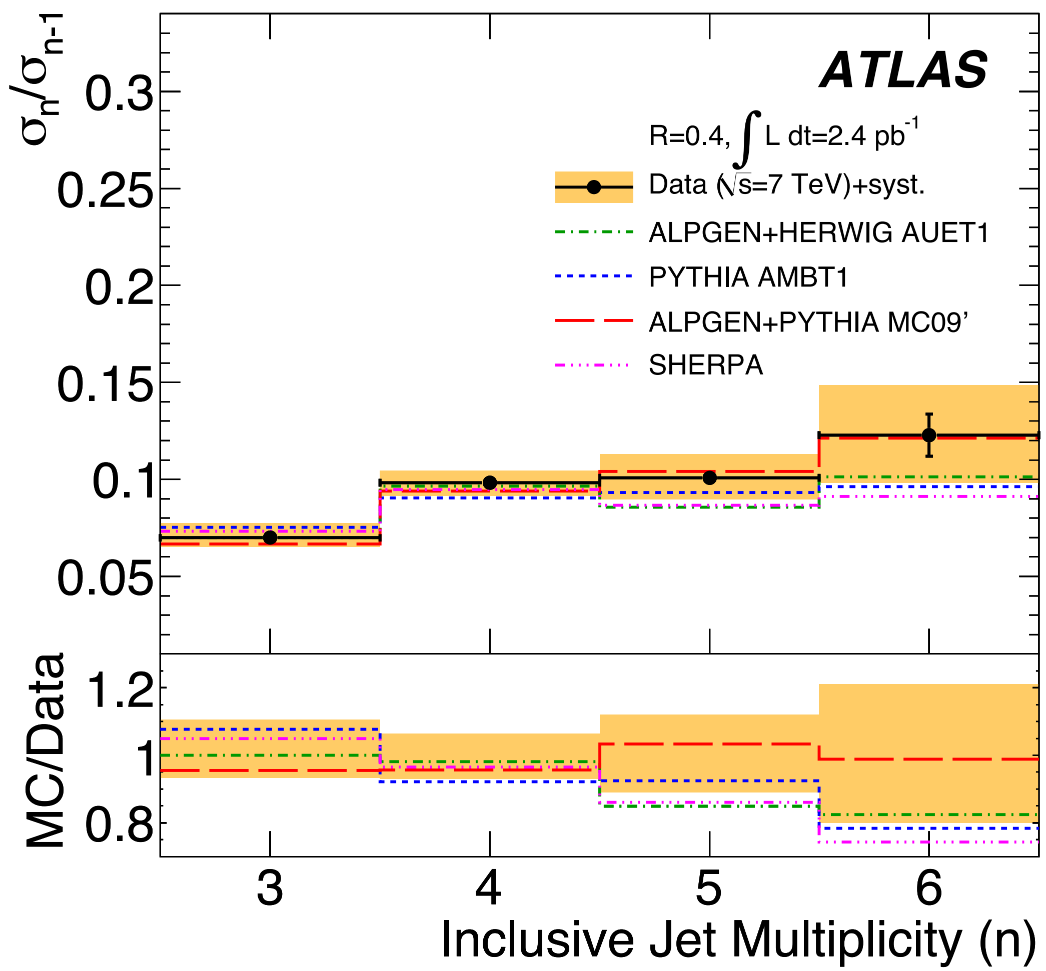
Sources of systematic uncertainty

- Different predictions by different MC generators.
- Limited MC statistics.
- Uncertainty on the detector p_T, y and ϕ resolutions.
- Distribution shape in MC
  - Varied to account for possible method biases.
- Trigger efficiency differences.
- Pileup rejection.
- Vertex multiplicity.
- Multiple proton-proton interactions.

Results: Inclusive jet multiplicity

The unfolded measurements are compared to LO MC simulations (normalised to measured inclusive di-jet σ).





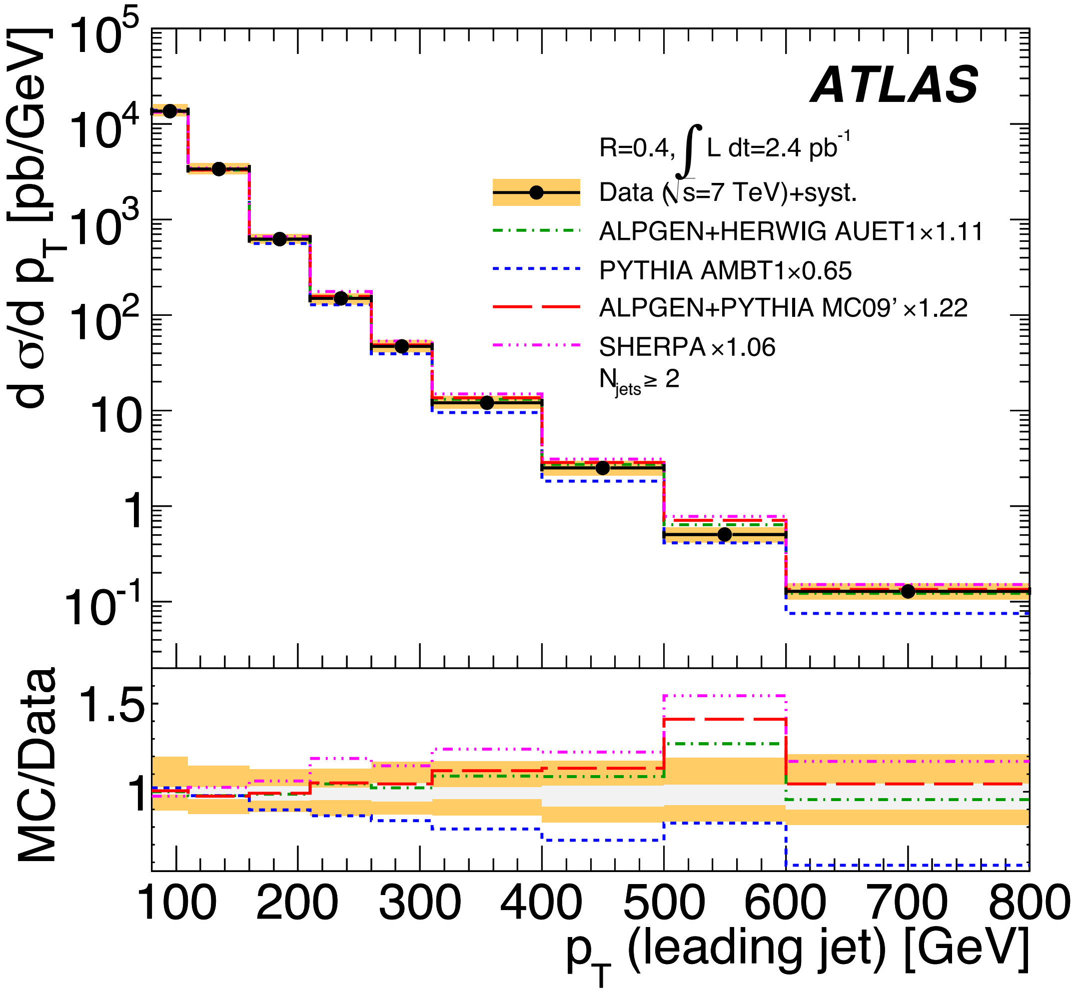
Uncertainty bands: grey = measurement (only shown in left figure), yellow = grey ⊕ unfolding.

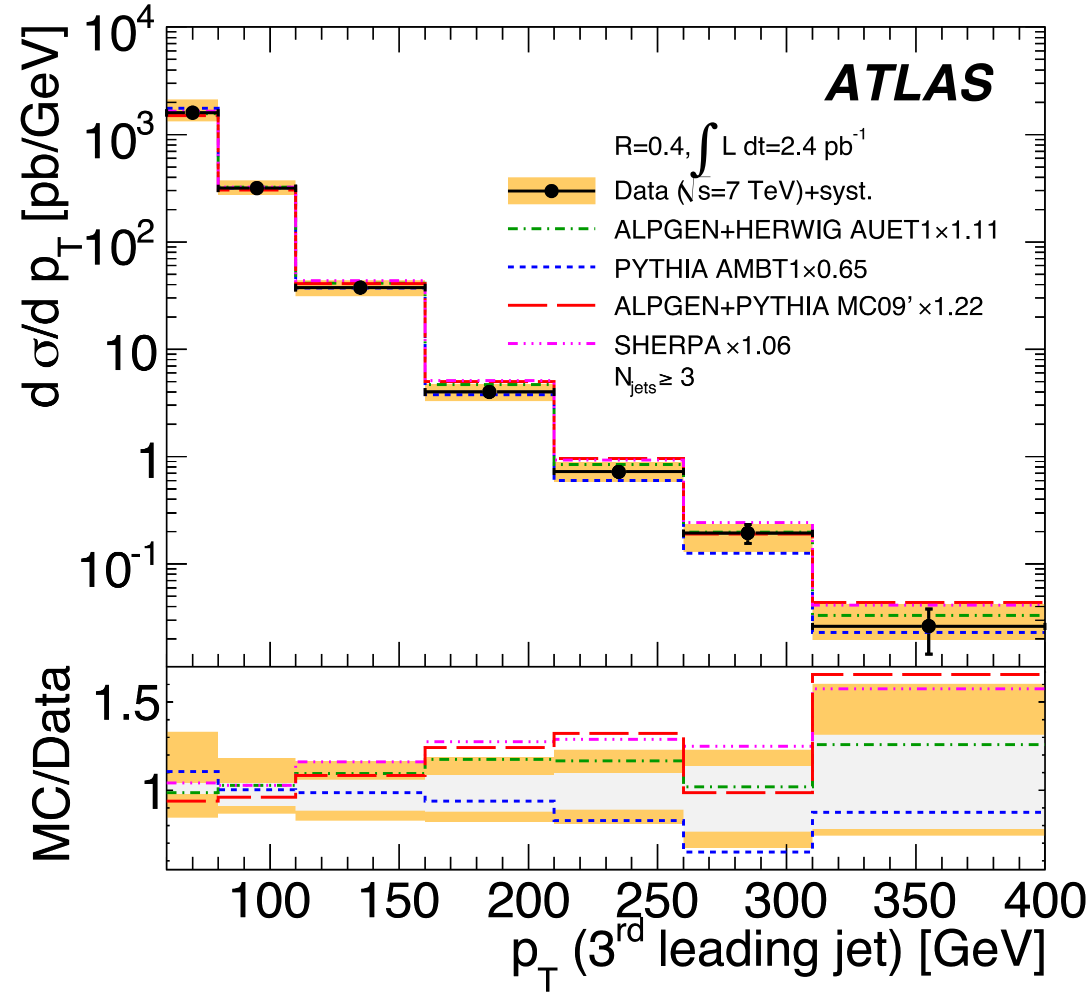
Generally very good shape agreement is observed between LO MCs and data.

- 2 → N MC Alpgen tends to describe the data better Sherpa and than 2 → 2 MCs (Pythia).

Alpgen and Sherpa normalisation factors are typically ~1, whilst Pythia factors are ~0.6.

Results: Differential cross section vs jet p_T





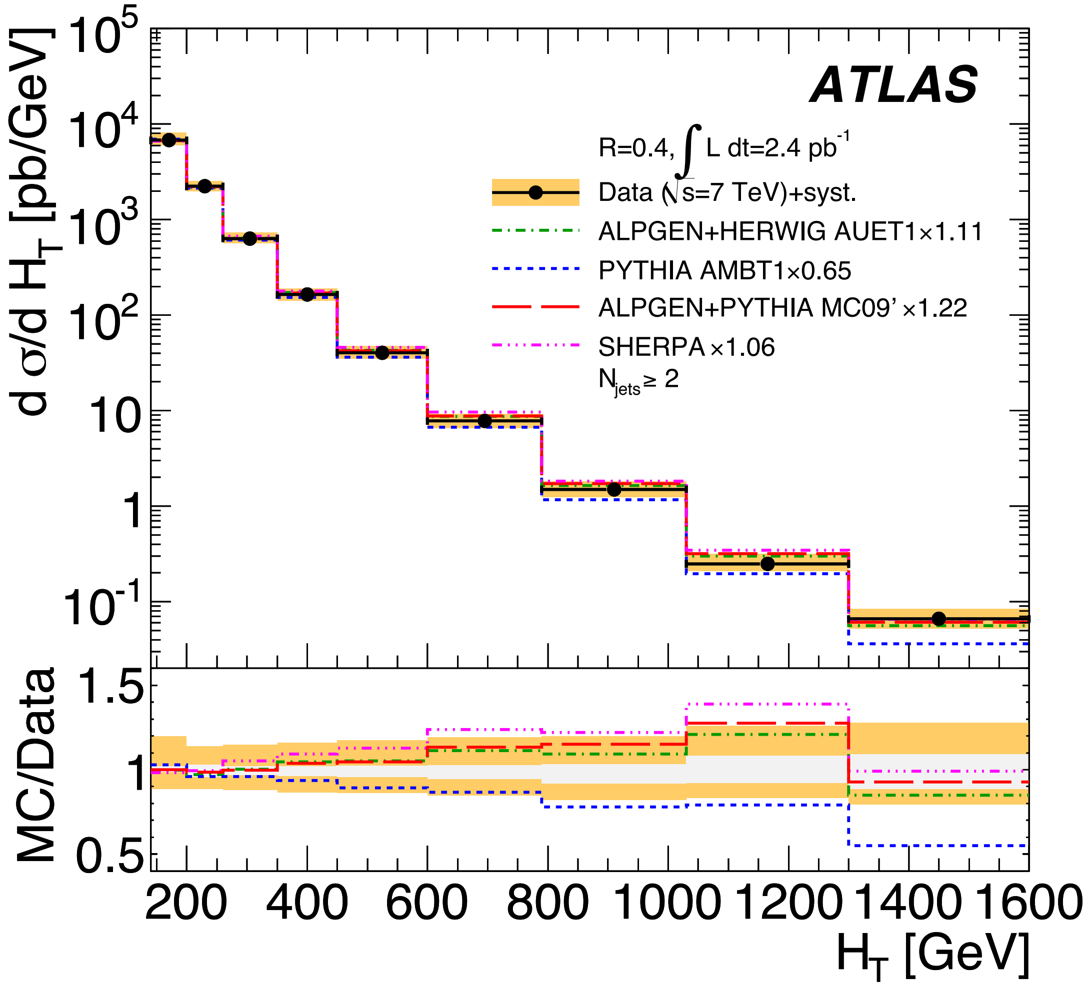
Differential cross section as functions of the leading (left) jet and third leading (right) jet p_T.

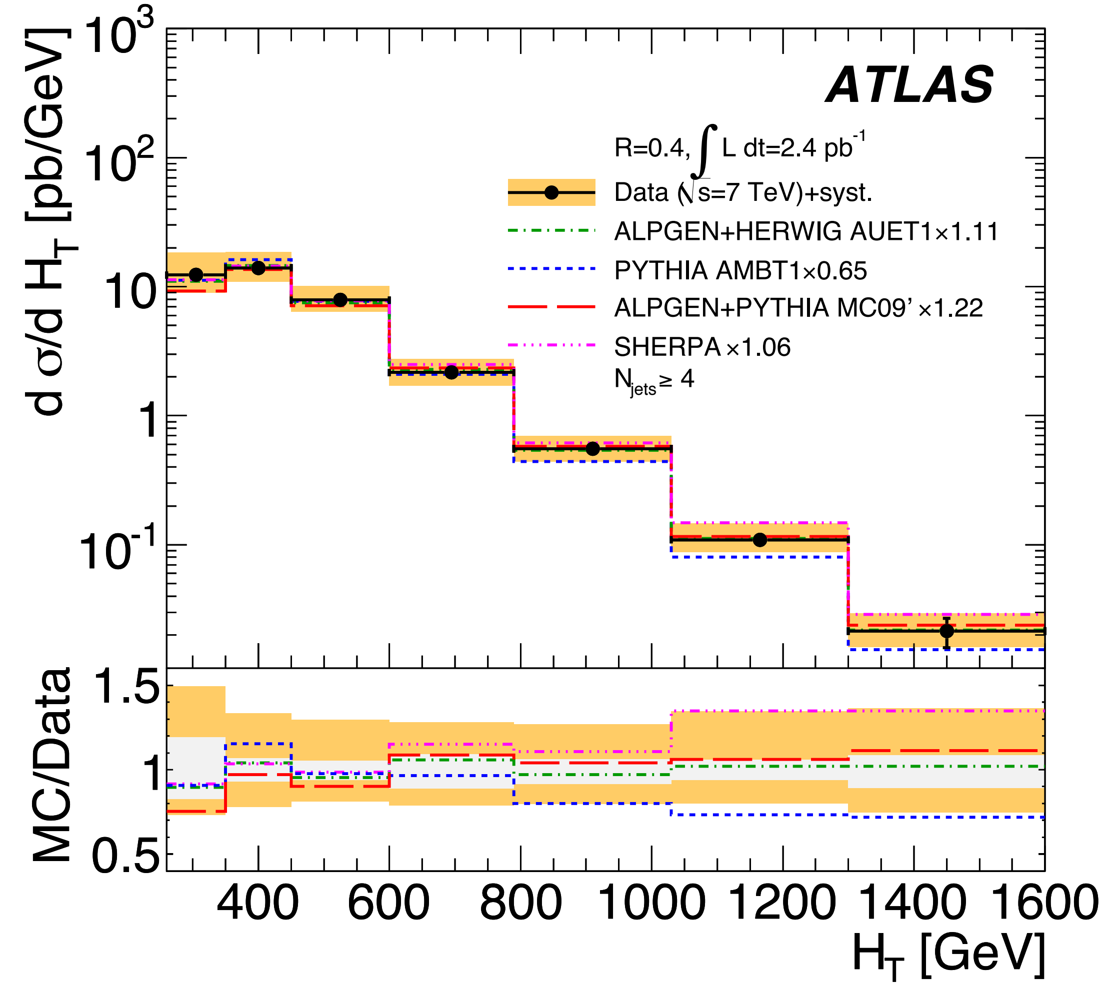
Uncertainty is ~10% for most of the p_T range (larger for higher multiplicity jet), with JES uncertainty remaining the dominant source.

All MC simulations agree reasonably well.

- Pythia AMBT1 predicts a steeper slope than measured.
- Alpgen and Sherpa predict a shallower slope than measured.

Results: Differential cross section vs H_T





H_T is defined as the scalar sum of the p_T of all selected jets in the event.

A measure of the total activity within an event.

Typically used for top-quark studies.

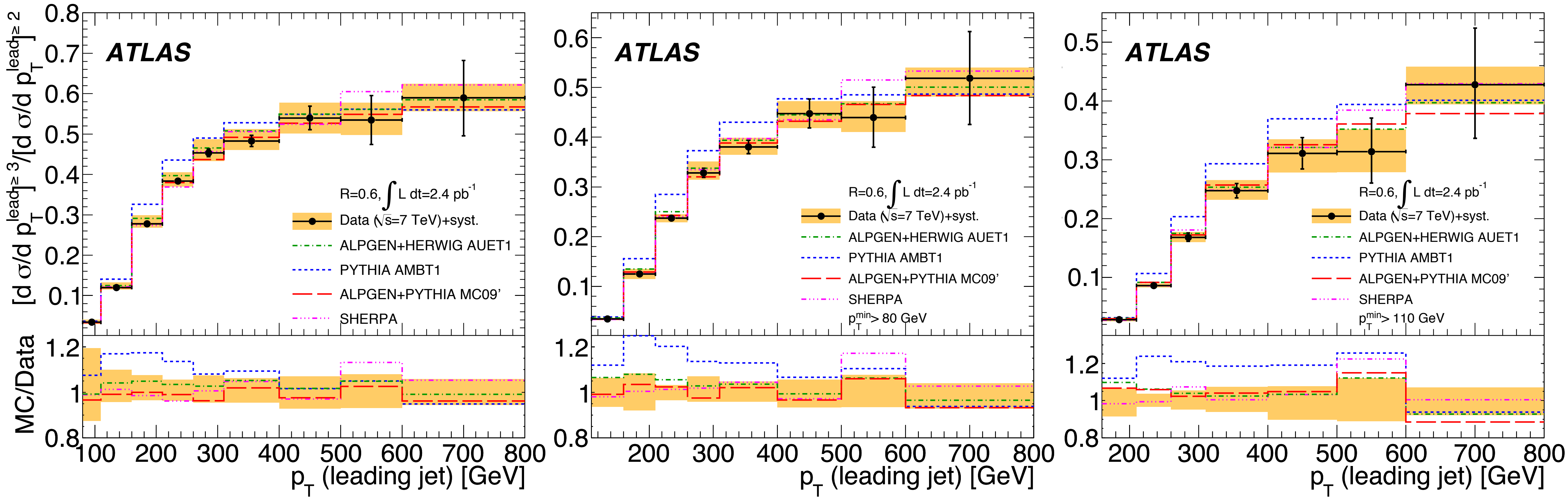
Similar properties observed as for differential cross section as a function of p_T.

Results: Differential cross section ratio vs p_T

Ratio measurements significantly reduce systematic errors as these cancel in the ratio.

Here the ratio of the inclusive tri-jet to di-jet cross sections ($R_{3/2}$) is shown as a function of the p_T of the leading jet ($p_T$max) for various minimum-jet p_T ($p_T$min) requirements.

- $R_{3/2}$($p_T$max) represents the conditional probability for an inclusive di-jet event at $p_T$max to contain a third jet with p_T > $p_T$min.



$p_T$min cuts of **60 GeV (left)**, **80 GeV (middle)** and **110 GeV (right)** are applied.

Systematic uncertainties are small ~5%, except in the lowest p_T bin.

Alpgen and Sherpa both describe the data well, seemingly independent of the tune used.

Pythia predicts a larger ratio than is measured and it's deviation from data increases with increasing $p_T$min.

Results: Differential cross section ratio vs p_T

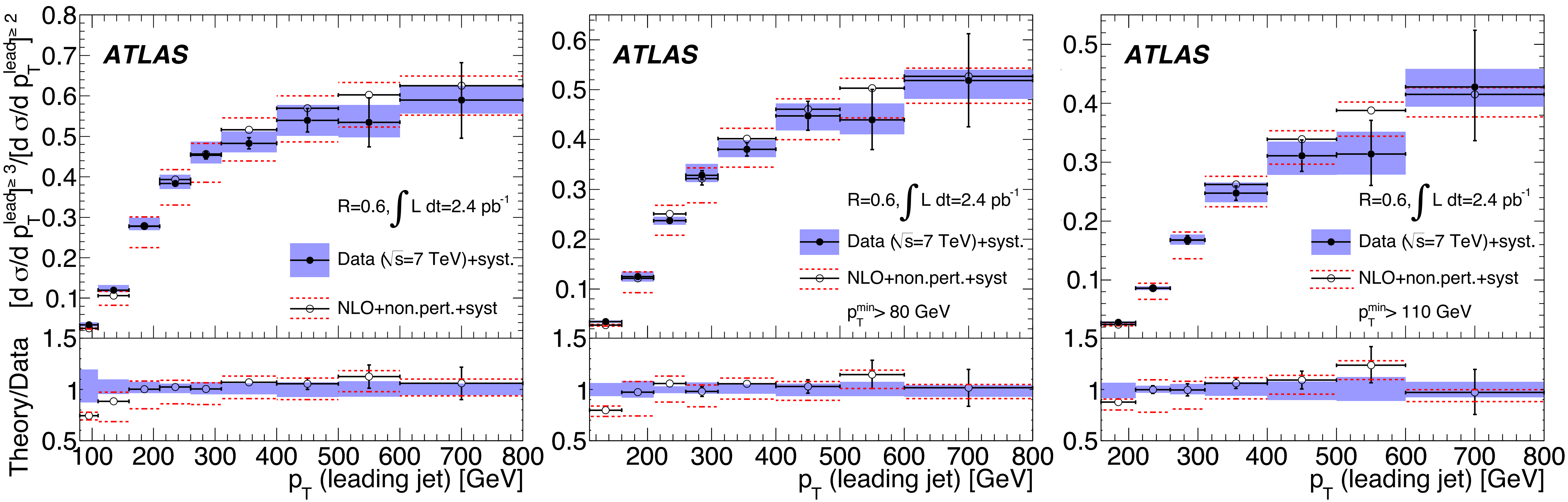
Same result as previous slide now compared to NLO pQCD calculation from NLOJet++.

Uncertainty sources on the NLO calculation:

- Variation of renormalisation (μ_R) and factorisation (μ_F) scales by a factor of 2.
- PDF variation MSTW, CTEQ.
- α_S variation.

Non-perturbative effects accounted for using a multiplicative correction factor.

Calculated using MCs without underlying event or parton showers.



NLO calculations describe data well except in first bin.

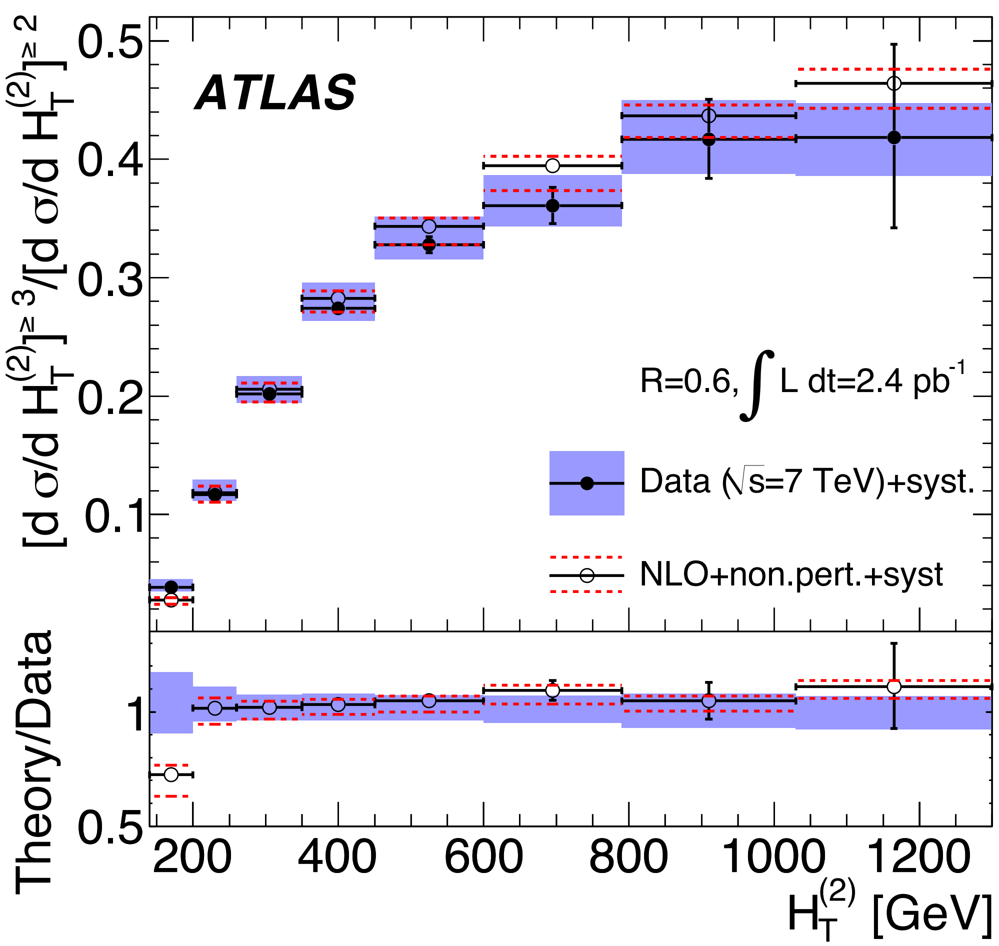
However, for this observable the uncertainty associated with the variation of μ_R and μ_F are large.

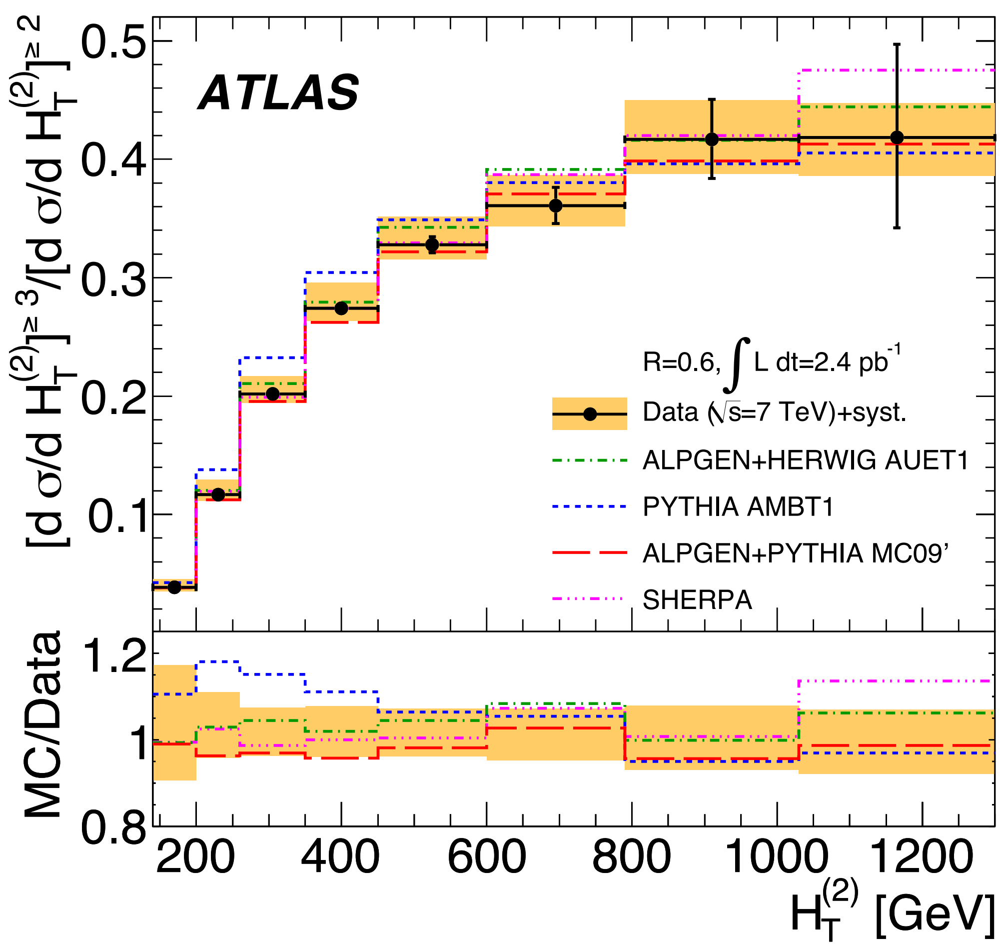
Results: Differential cross section ratio vs $H_T^{(2)}$

$R_{3/2}$ as a function of $H_T^{(2)}$: defined as the scalar sum of the p_Ts of the two leading jets.

This gives a much small uncertainty due to variation in μ_R and μ_F.

Therefore is much more sensitive to input parameters such as α_s.





The left figure shows the measured $R_{3/2}(H_T^{(2)})$ compared to LO MC simulations, the right figure shows this compared to the NLO pQCD calculation.

Good agreement observed, except in first bin.

This is postulated to be due to the NLO pQCD calculation only being an effective NLO calculation in the first bin and therefore being subject to large theoretical uncertainties

Conclusions and Outlook

A first study of multi-jet events has been performed in proton-proton collisions at a centre of mass energy of 7 TeV.

Using the ATLAS detector and $\int L\,dt = 2.43 \pm 0.08\ pb^{-1}$.

Leading order MC simulations and NLO pQCD calculations are compared to the data up to jet p_Ts of 800 GeV and event H_Ts of 1.6 TeV.

In addition, MC simulations are compared to events with up to 6 jets in the final state.

Submitted to EPJC.

After normalisation to the measured inclusive di-jet cross section, reasonable agreement is found between MC simulations and the measurement.

The $2\rightarrow2$ MC calculations show some departure from the data.

- Predicts a larger $R_{3/2}$ than observed, and a steeper differential cross section as a function of both p_T and H_T

$2\rightarrow N$ calculations describe all observables well including ratios, with only a small dependence on tune observed.

- Although they do predict a less steep differential cross section as functions of both p_T and H_T than is observed.

NLO pQCD calculations describe the data well albeit with a discrepancy in the lowest p_T bin.

Future comparisons with NLO pQCD calculations could constrain parton distribution functions, or the value of α_s.

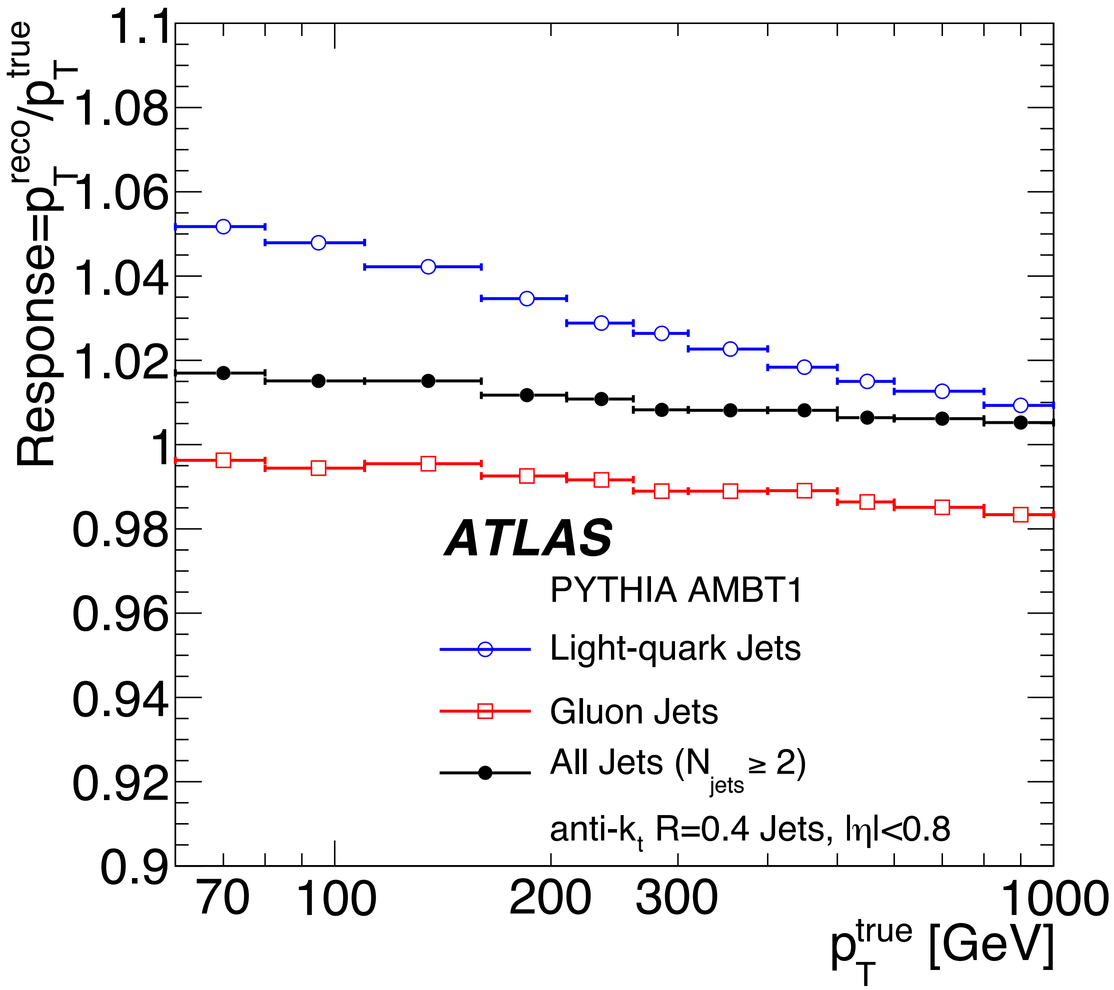
Systematic uncertainties from the measurement are currently comparable to the theoretical uncertainties, but should be reduced with larger data samples and higher collision energies.

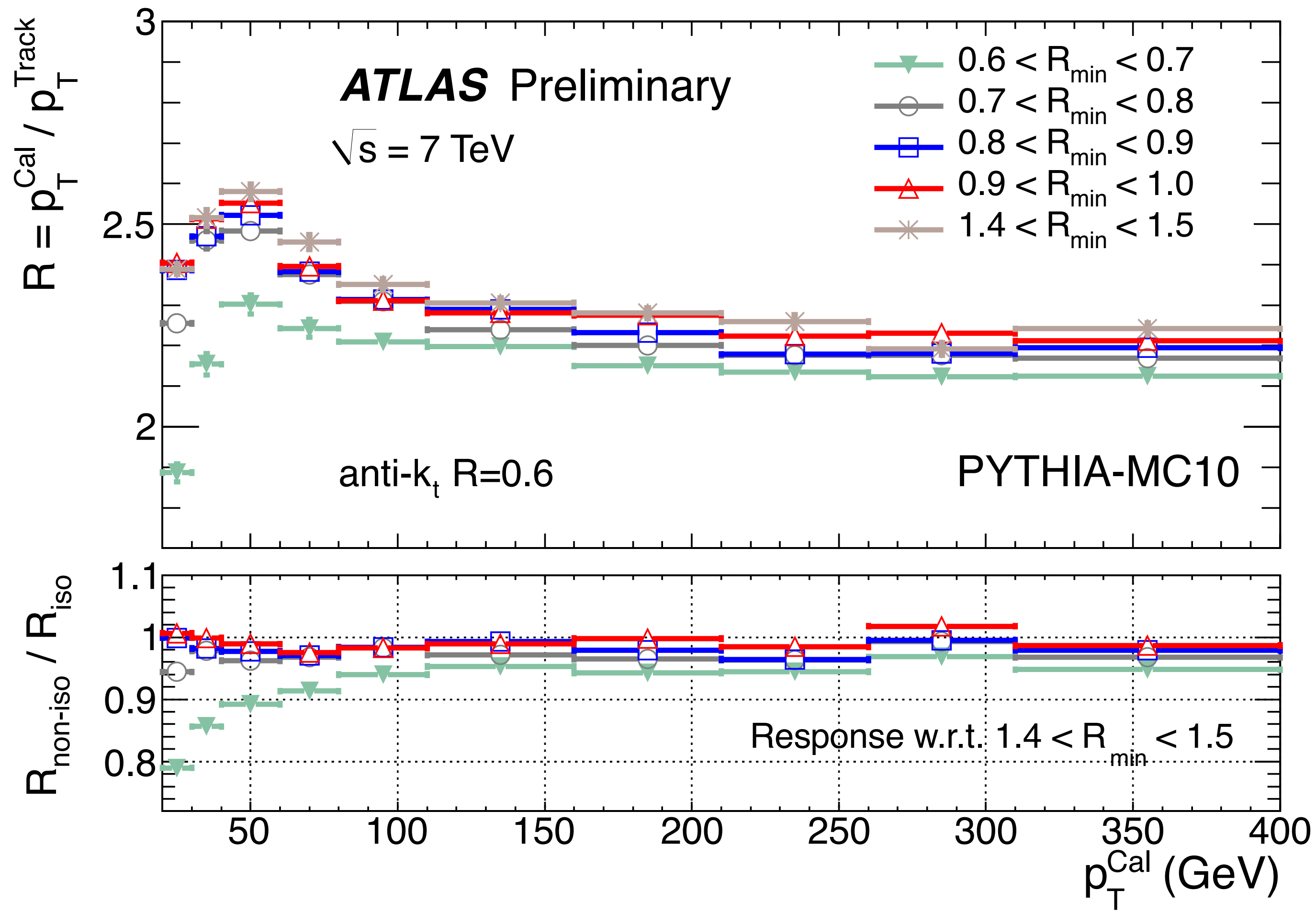
Backup Slides

Jet energy scale (JES) calibration and uncertainty

For this analysis additional sources of uncertainty are considered arising from:

- Differences in the calorimeter response to jets of different flavours (left).
- The impact of nearby calorimeter activity (right).





The uncertainty due to isolated jets is the largest contributor in most regions, except in five and six jet events where the flavour composition uncertainty becomes comparable.

Overall JES uncertainty varies from ~5% at low p_T to ~3% at high p_T.