SM and jet measurements at the LHC

Andy Pilkington – IPPP and Manchester

Presented at the Young Experiment and Theory Institute, Durham, January 2011

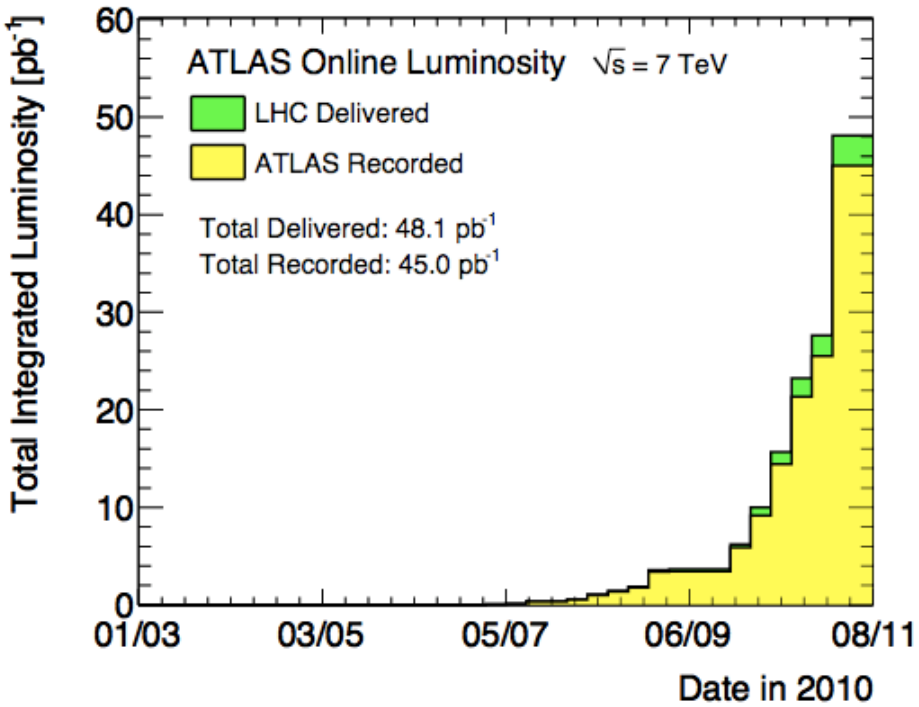
Part I – jet characteristics

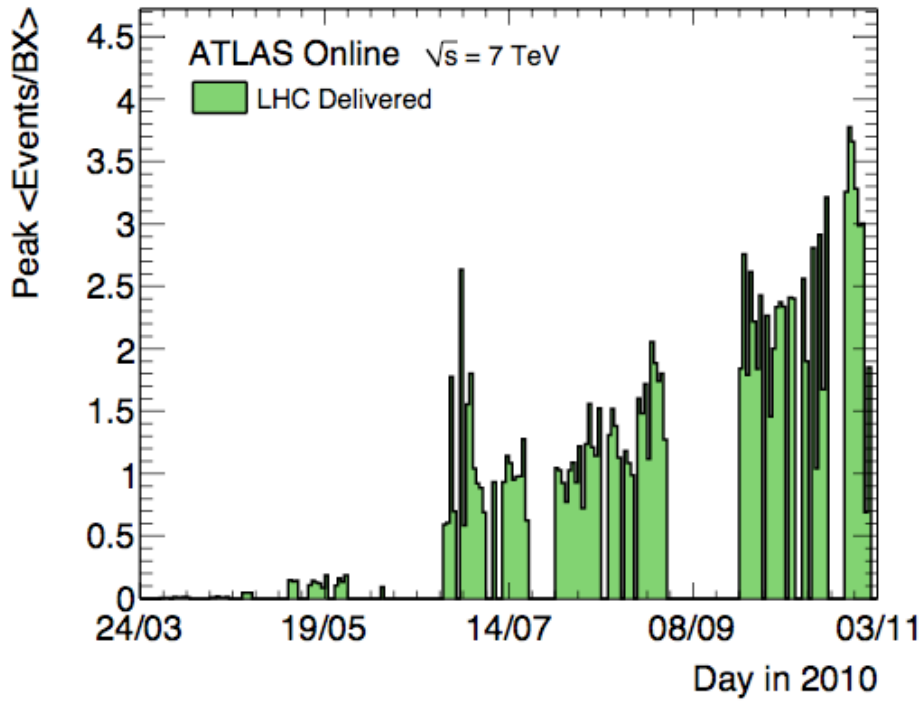
1) Introduction to ATLAS and the LHC
2) Jet reconstruction and performance
3) Inclusive jet measurements

Part II – event structure

4) Multi-jet final states
5) Vector boson production (with/without jets)
6) What to expect from 2011

The LHC in 2010





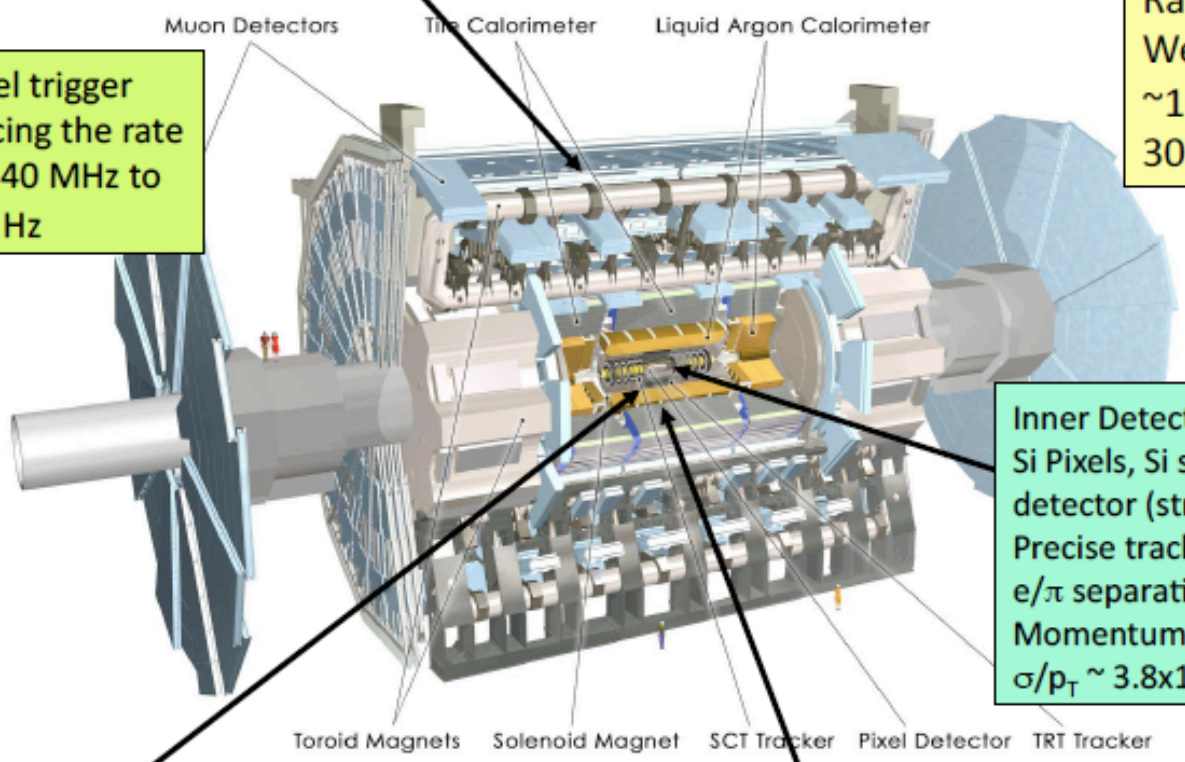
- 45pb^{-1} of data taken in total.
- Average number of interactions per bunch crossing was about 3.5 for the final runs.
- The plan is to take at least 1fb^{-1} of data in 2011 at √s=7TeV.
  - Likely that the luminosity will be higher than this, possibly even increase in energy to 8-9TeV (under discussion)

The ATLAS detector – a general multipurpose detector

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger reducing the rate from 40 MHz to ~200 Hz



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

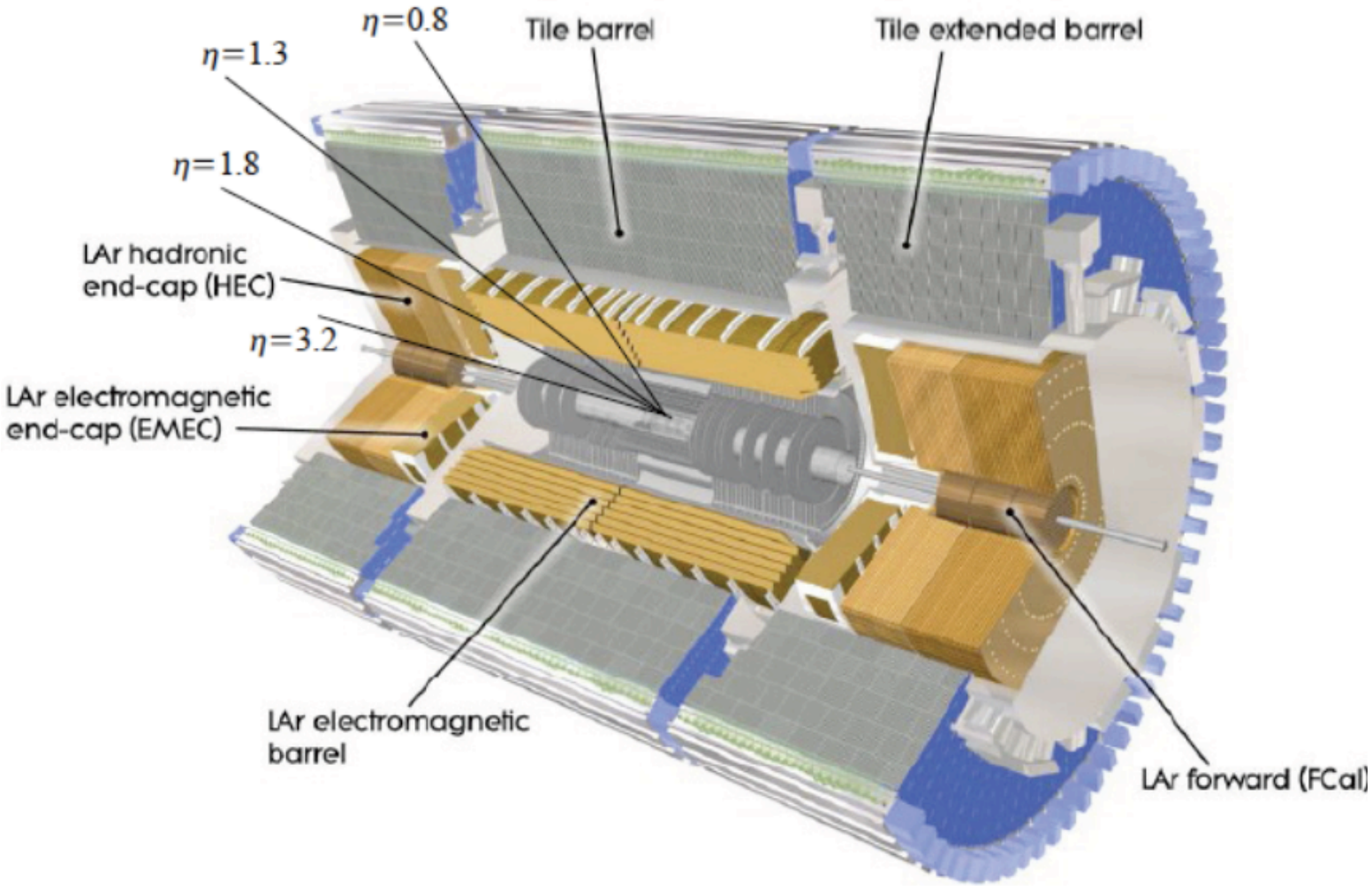
HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS Detector Status

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.3%
SCT Silicon Strips	6.3 M	99.2%
TRT Transition Radiation Tracker	350 k	97.1%
LAr EM Calorimeter	170 k	97.9%
Tile calorimeter	9800	96.8%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.5%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.4%

Jets at ATLAS: reconstruction and performance in 2010

The ATLAS calorimeter



The anti-k_T algorithm

JHEP04(2008)063

- Default algorithm for studying jets at both ATLAS and CMS.
- For each object, 'i', and each pair of objects, 'ij', define the merging parameters:

$$d_{ij} = \min(k_{Ti}^{-2}, k_{Tj}^{-2}) \frac{(\Delta R)_{ij}^2}{R^2}$$

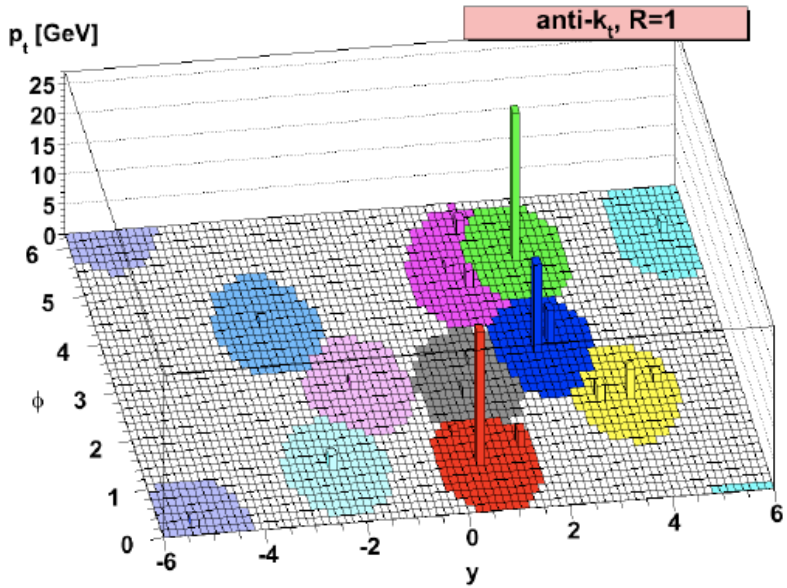
$$d_{iB} = k_{Ti}^{-2},$$

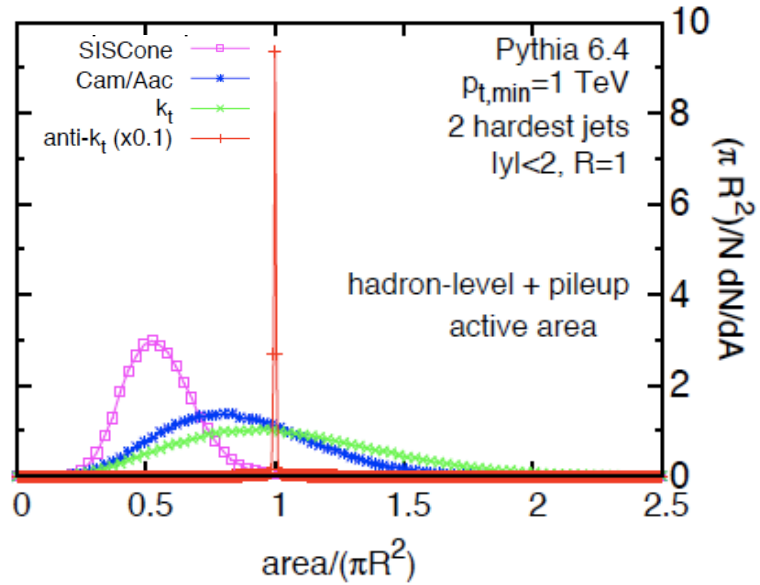
where

$$(\Delta R)_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

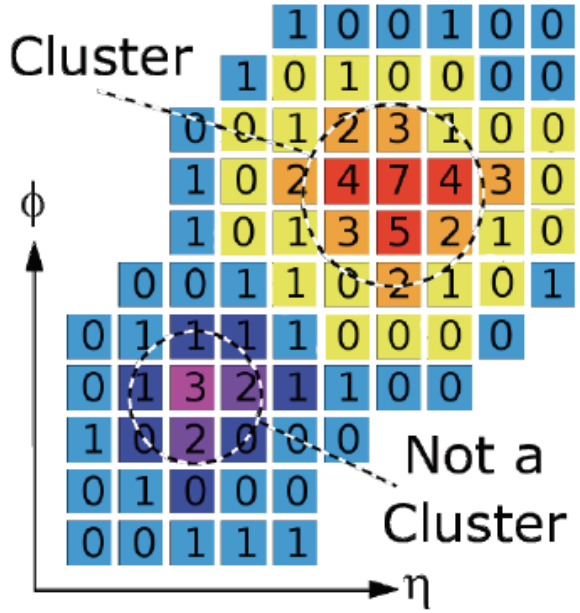
- If d_{ij} is smallest, merge objects 'i' and 'j'
- If d_{iB} is smallest, define object 'i' as a jet and remove from the list.
- Repeat procedure until no objects remaining.

- Algorithm is both infra-red and collinear safe.
- Generally produces jets of definite size

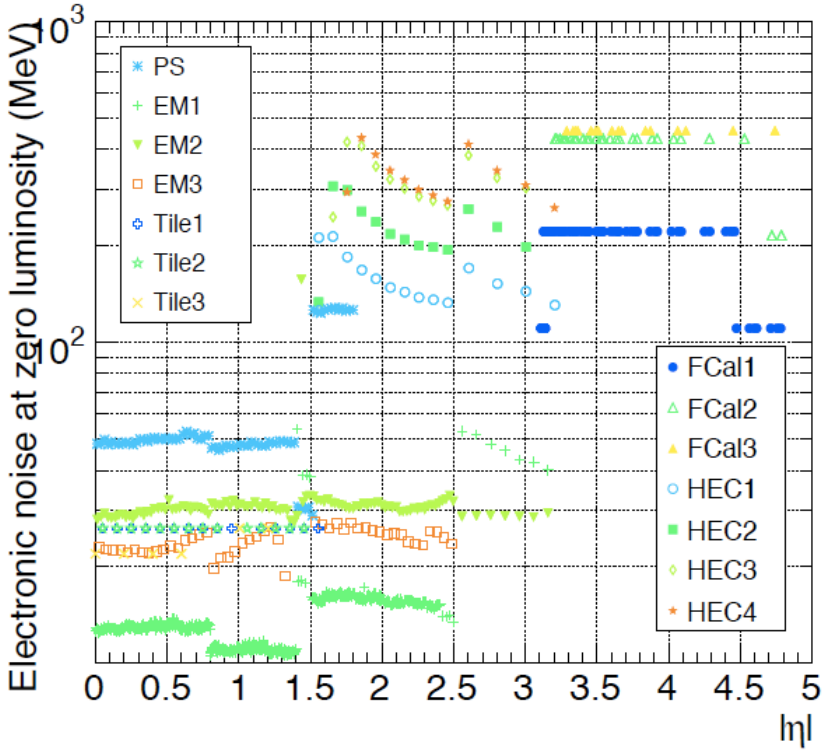




Jet inputs

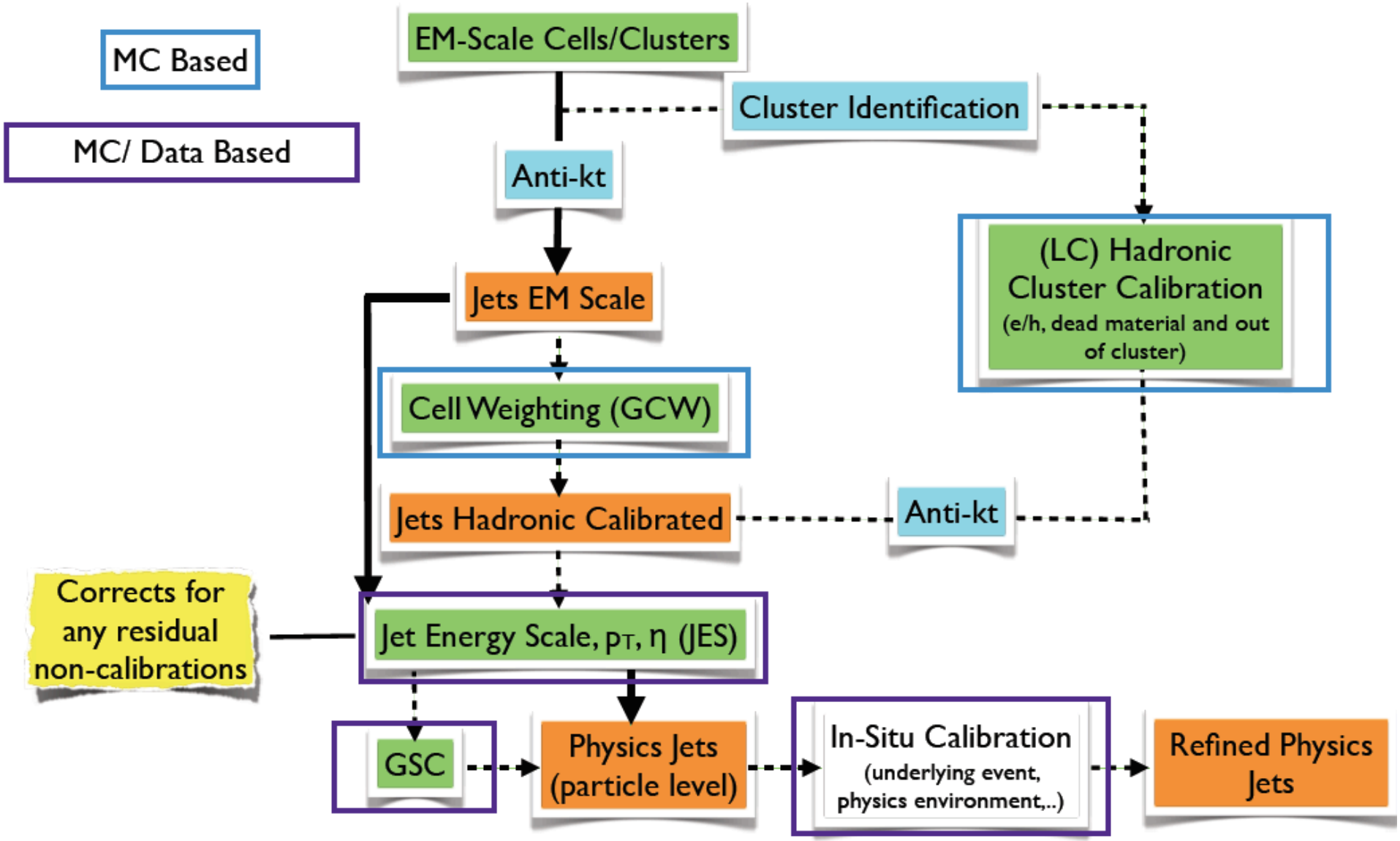


- Topo-clusters are 3D objects:
  - Clustering across many layers of calorimeter
  - Seed cell identified by |E| > 4σ initiates the cluster
  - Neighbour cells iteratively added to cluster if |E| > 2σ
  - Ring of Guard cells added (|E| > 0σ)



- Towers are constructed by using cells that are aligned along a given η-ϕ direction
  - 6400 towers in ATLAS,
  - Noise suppressed towers are those constructed from cells that belong to topo-clusters

Jet calibration schemes



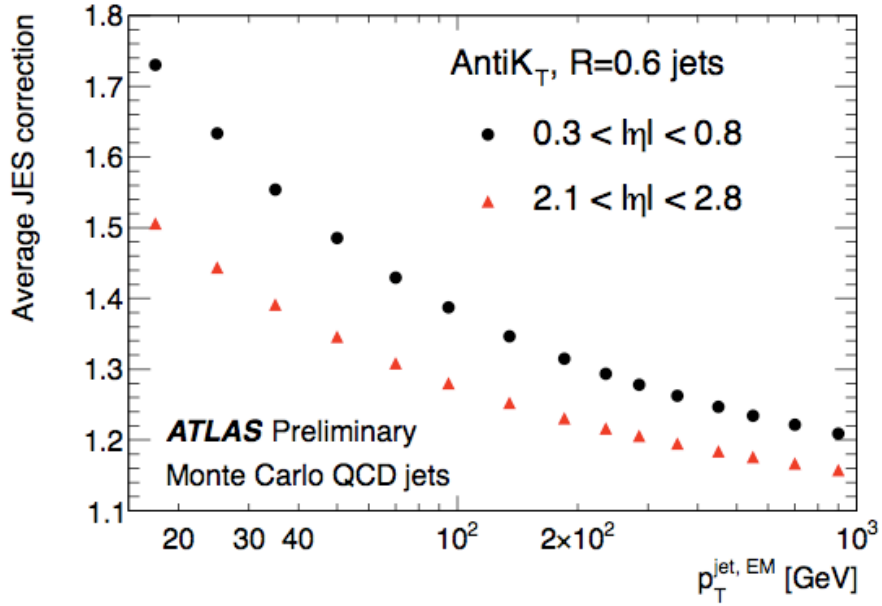
Default jet energy scale calibration and uncertainty

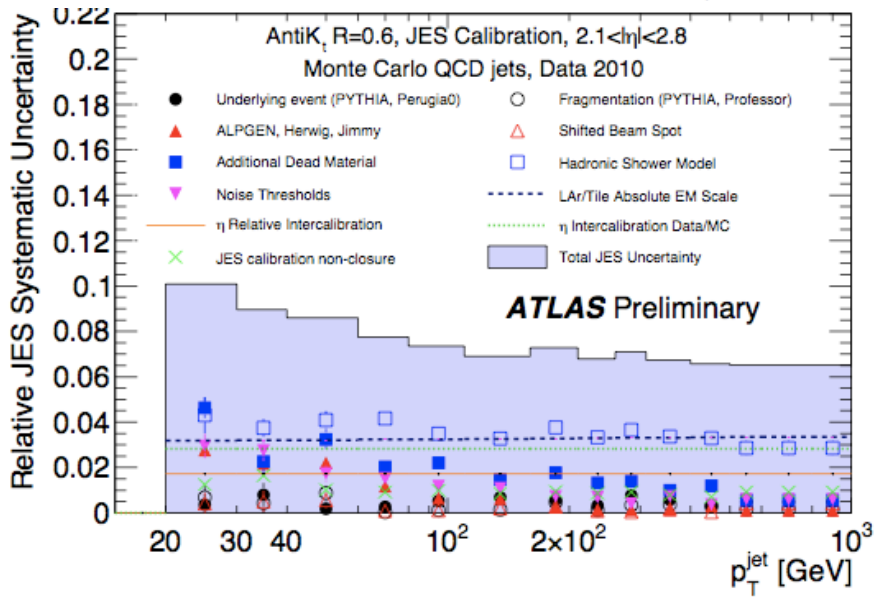
- The default calibration scheme currently corrects EM-scale jets.
- Response, R, of a jet in the calorimeter is studied for jets in PYTHIA:

$$p_{\mathrm{T}}^{EM} = R(p_{\mathrm{T}}^{truth}, \eta)\ p_{\mathrm{T}}^{truth}$$

- Response parameterized and inverted to give the jet energy scale (JES) correction

- Using the MC derived response introduces uncertainty due to:
  - Detector simulation (e.g. geometry, dead material, noise, hadronic shower models…)
  - Event generator modeling (hadronization, parton shower and underlying event)

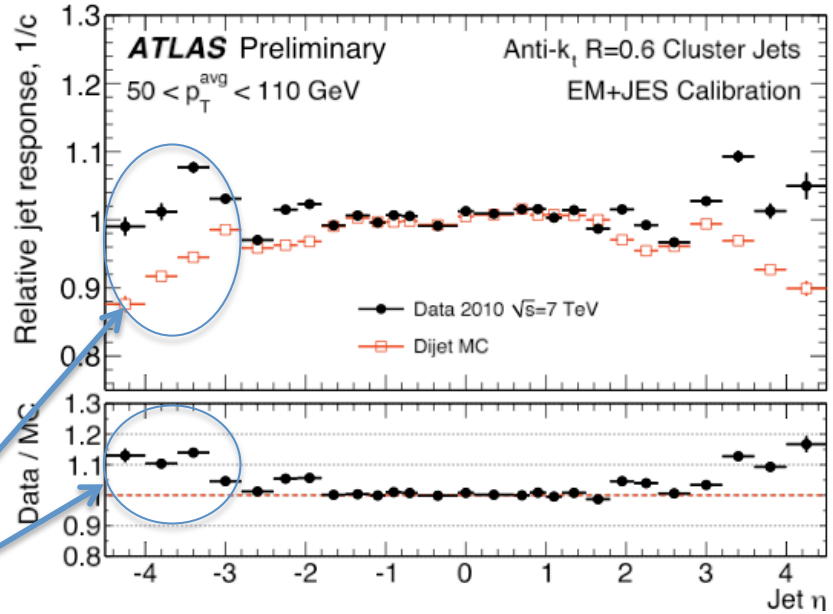


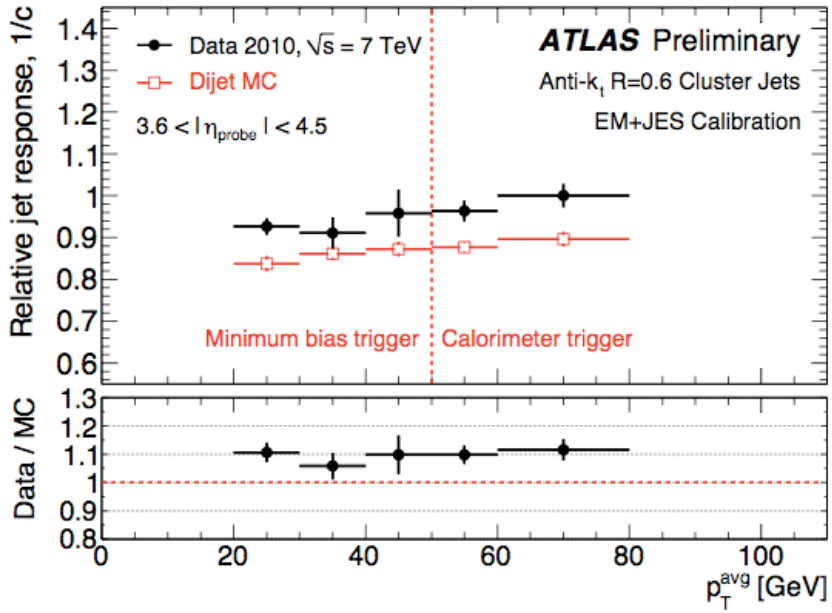


The problem with forward jets

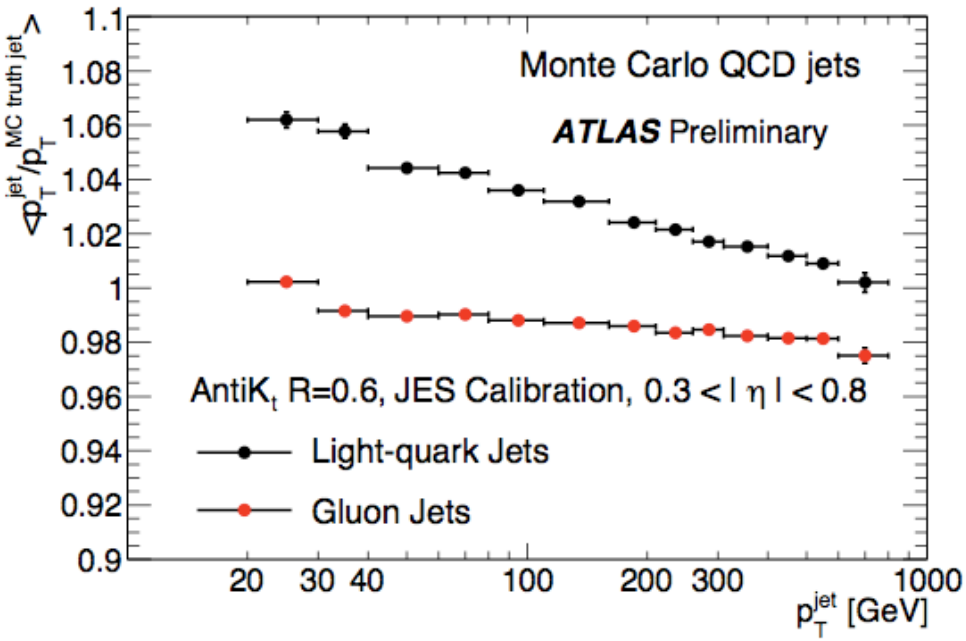
- The relative response as a function of pseudo-rapidity is measured in-situ:
  - Dijet events selected
  - ISR/FSR suppressed by selecting back-to back jets ($|\Delta\phi|>2.6$) and cutting on third jet p_T
  - Asymmetry of dijets measured to give the relative response

- Data and MC do not agree well in the forward region! Could be:
  - Detector simulation problem (should calibrate).
  - A physics modeling problem (should not calibrate





The difference between ‘quark’ and ‘gluon’ jets

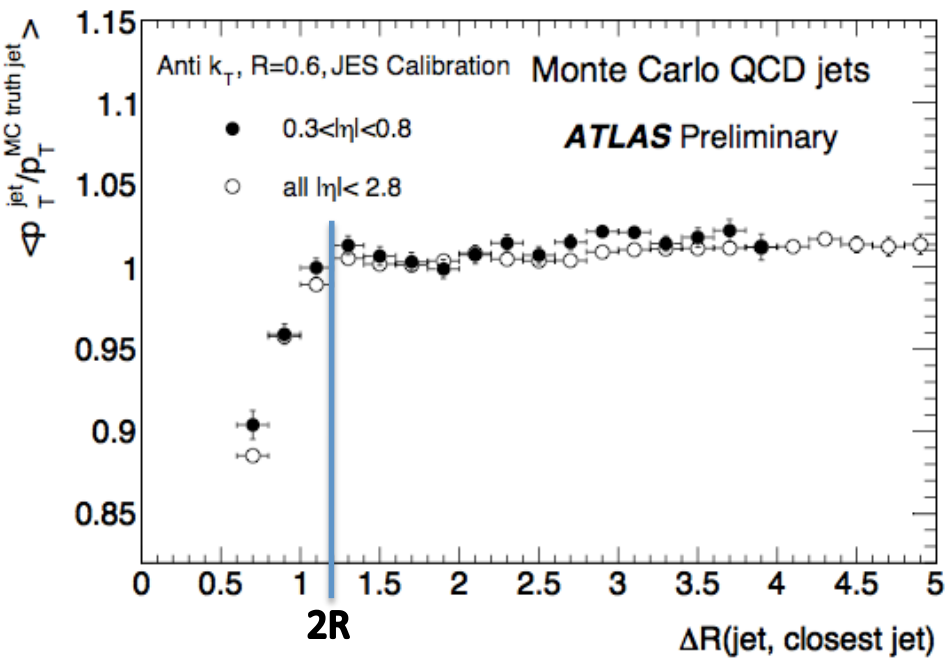


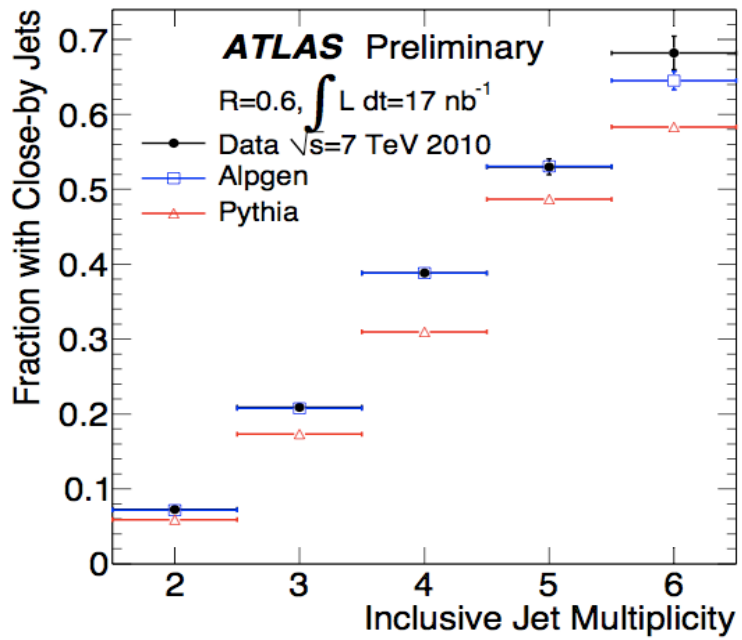
- Jets studied so far include jets originating from both hard gluons and hard quarks in the MC:
  - jets from gluons typically softer and soft particles typically deposit less energy

- This causes a problem if the sample of jets we are looking at do not have the same mixture of quarks/gluons as the inclusive MC sample
  - Additional uncertainty needed that is analysis specific (no ‘one calibration fits all’ approach)

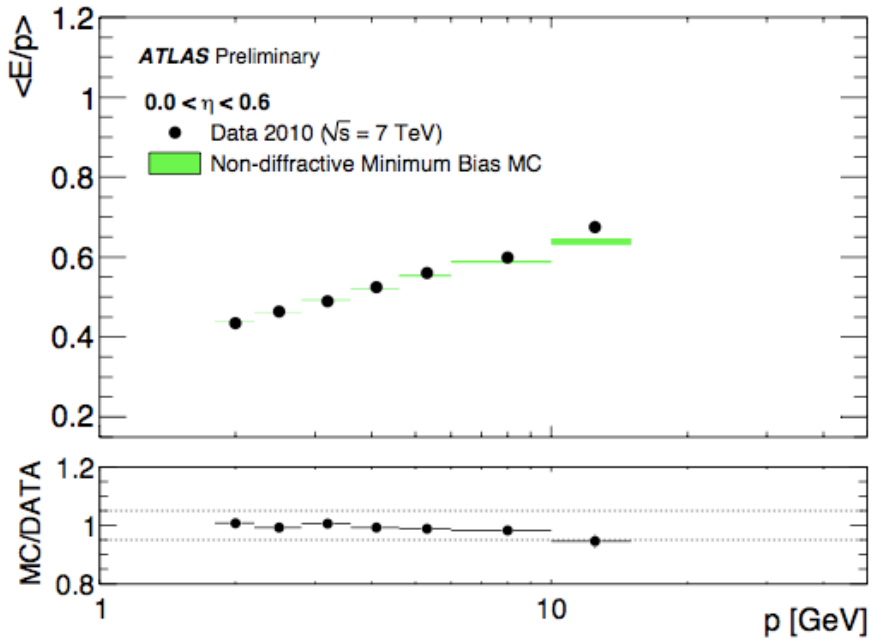
The problem of near-by jets

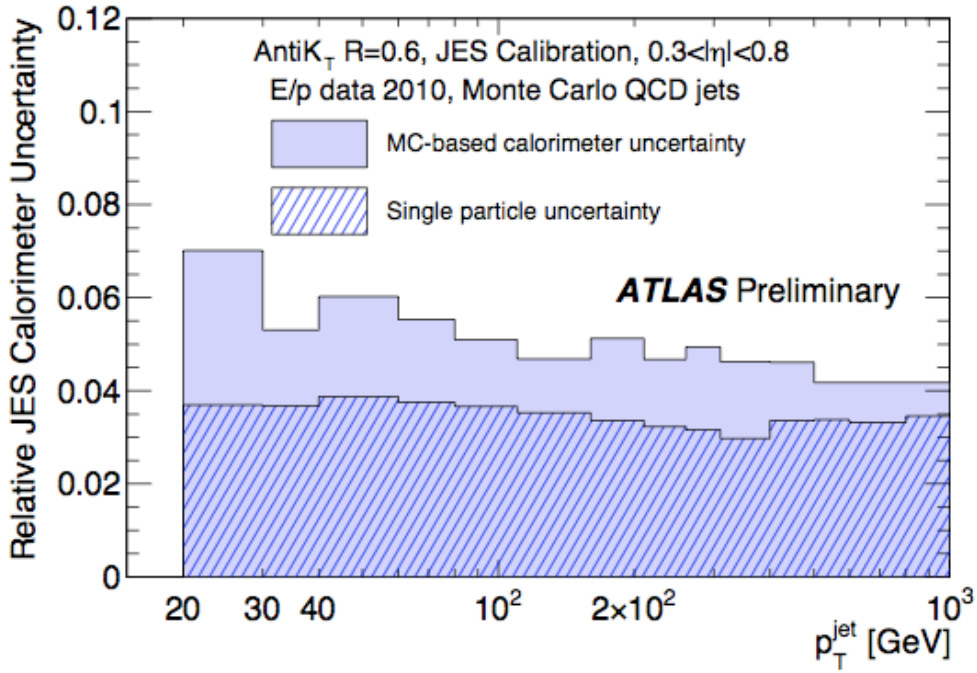
- The jet calibration was calculated for jets that are well separated from any other jet activity
- Response is much lower in jets if there are 'nearby' jets
- Additional uncertainty in multi-jet analyses
  - depends on the topology of the event in question.





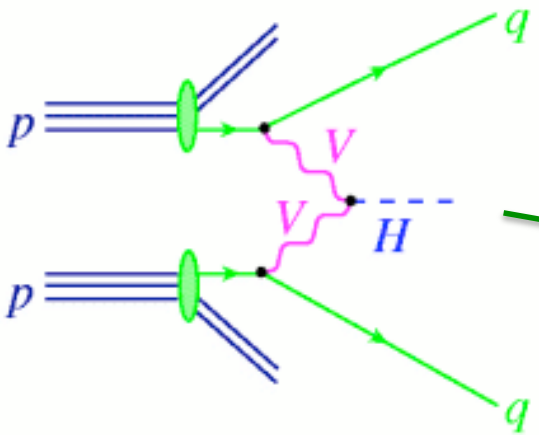
How good is this calibration? – current ATLAS view

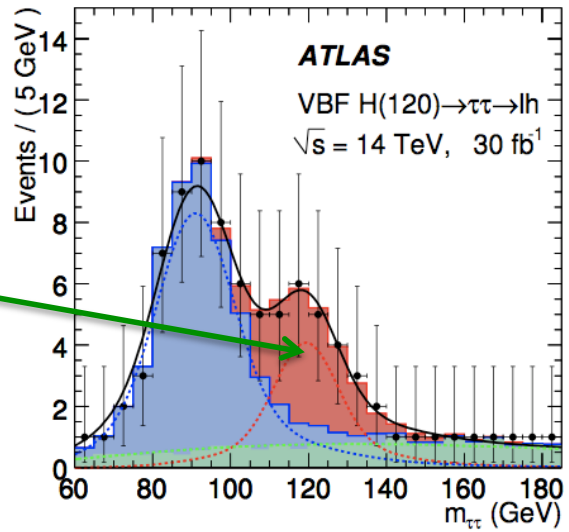




- Validation of the energy scale was performed with the single hadron response, measuring the E/p for charged particles. Little deviation between data and MC.
- Propagating this uncertainty to the jet-level [using pseudo-experiments], yields a much smaller intrinsic uncertainty than the default MC-based approach.

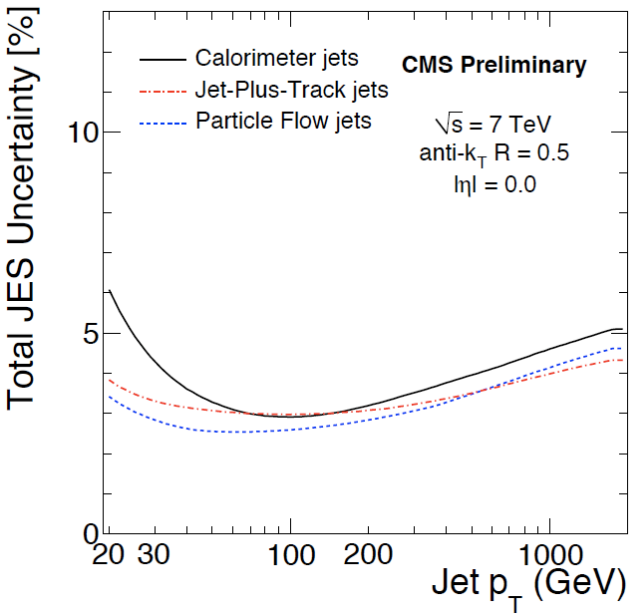
How good is this calibration? – some pre-data expectations

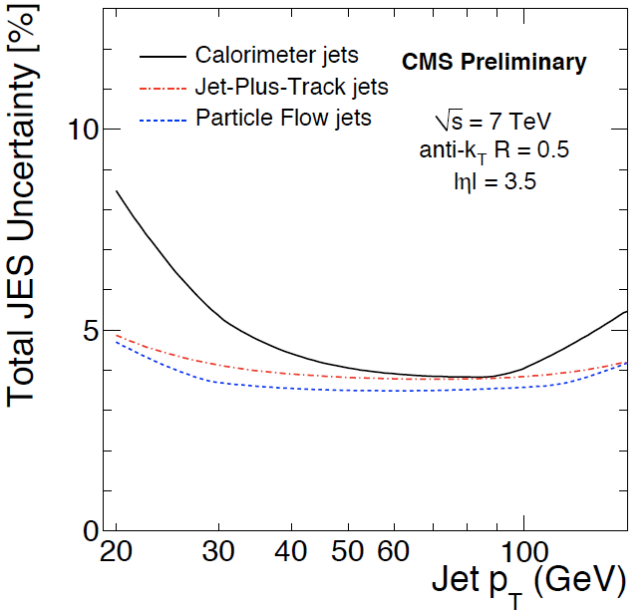


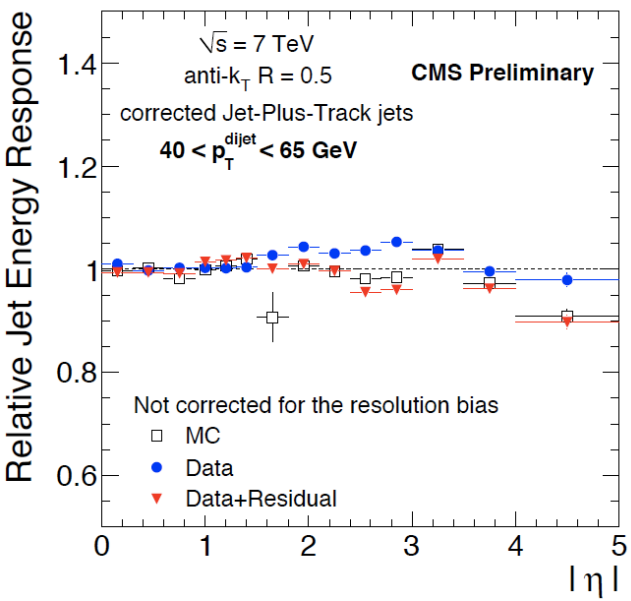


- The measurement of the production cross-section of VBF Higgs is crucial to the extraction of the Higgs couplings. Dominant uncertainty from JES.
  - The CSC study assumed 7% (15%) JES uncertainty for central (forward) jets.
  - We already have that precision!
- The measurement of the top-quark mass in semi-leptonic and hadronic channels is dominated by JES
  - 0.7GeV uncertainty per percent JES uncertainty.
  - A long way to go for top-studies.

How good is this calibration? – comparison with CMS



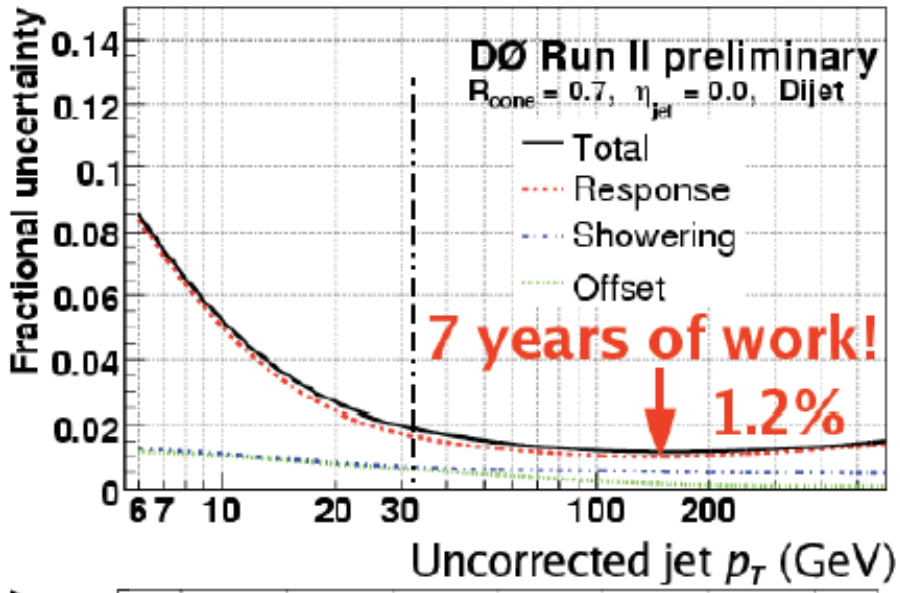


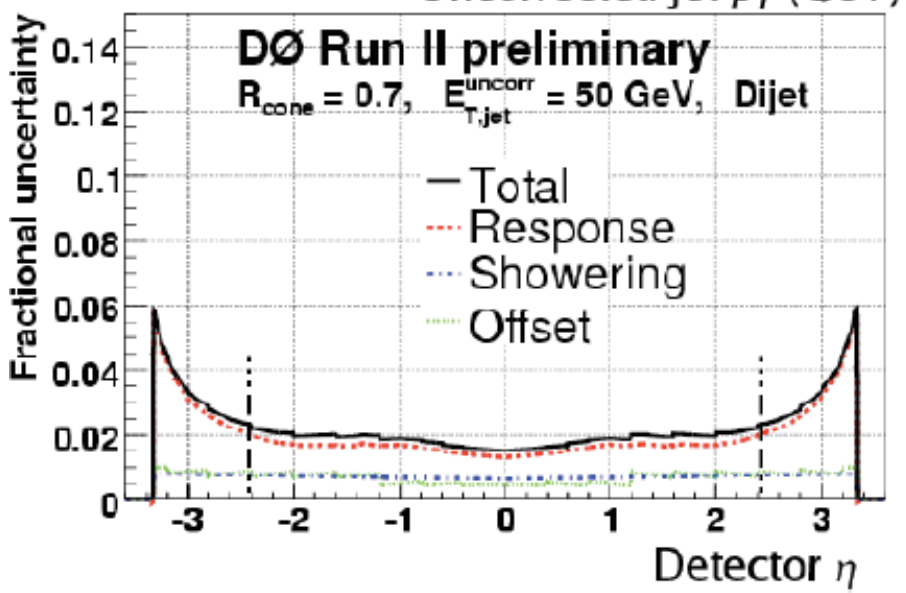


- The CMS basic jet energy scale is smaller than the current ATLAS one in the central region
  - This makes sense, as they have used 2.9pb^{-1} of data and photon-jet balancing to get an in-situ handle on the JES. The ATLAS JES will be similar.
- In the forward region, the CMS uncertainty is MUCH smaller than the ATLAS one.
  - MC/data discrepancy is calibrated away after extrapolating the discrepancy to $p_{T,3}$=0
  - This assumes that the discrepancy is NOT due to physics effects. ATLAS does not attempt to claim this yet.

How good is this calibration? – comparison with D0

- It shouldn't come as a surprise that the JES at D0 is better than that at ATLAS and CMS
- Central uncertainty determined by photon-jet balance to be <2% for jets in the central region.
- Uncertainty grows to about 4% by |η|~3
- The ATLAS/CMS goal of a 1% uncertainty in the JES is realistic (at least for central jets)





Inclusive jet measurements at ATLAS

Inclusive jet measurements – the benefits

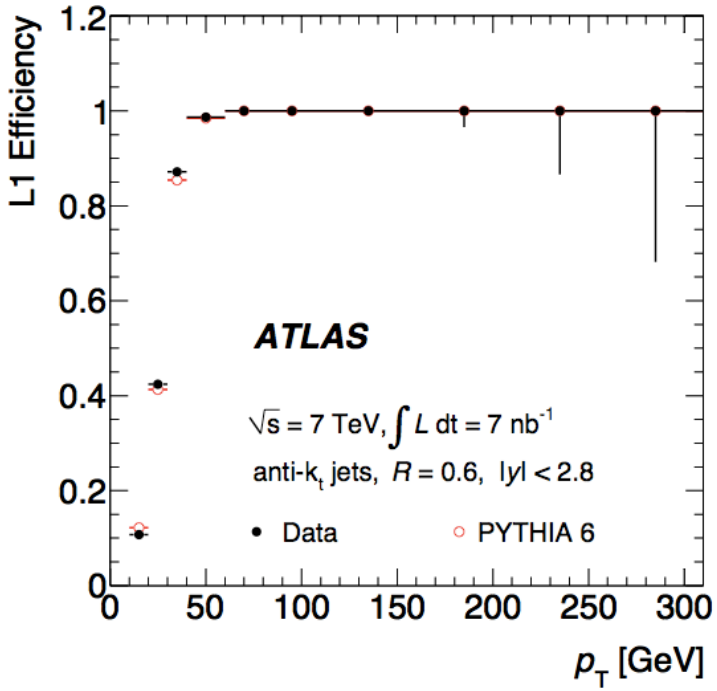
- Key observable in particle physics
  - previously measured in e^+e^-, ep, pp and $p\bar{p}$ colliders

- The inclusive measurement is an ideal stepping stone to more complicated jet topologies.
  - Simplest possible jet measurement
  - NLO prediction known for over 20 years, with small uncertainty

- Once the inclusive jet measurement has been made to high accuracy, can use to
  - provide precise measurement of α_s
  - determine the structure of the proton (PDF fits)
  - study BSM physics (see talk by C.Issever)

Event selection

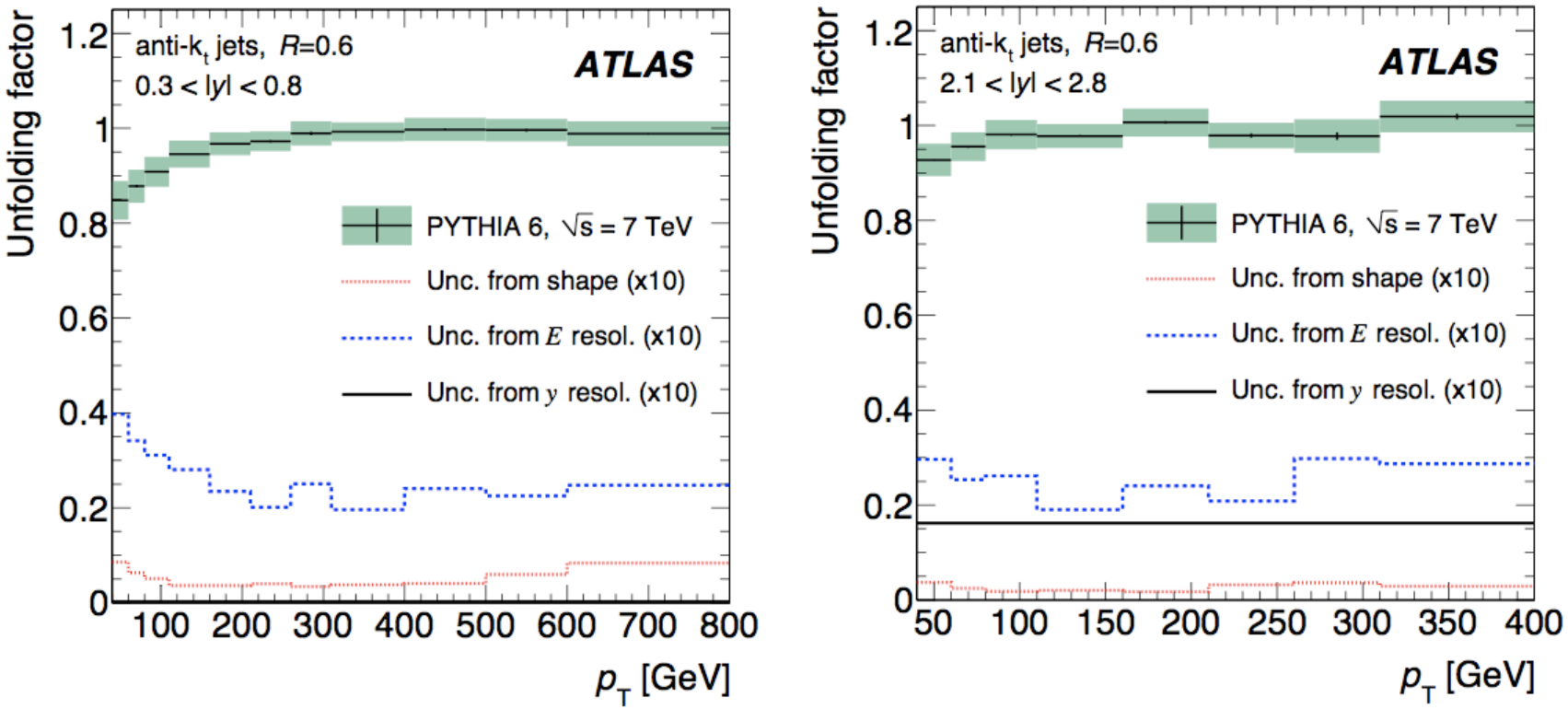
- Anti-k_T algorithm used with R=0.4 and R=0.6 and compared to QCD calculations
  - Different soft physics effects for different jet radii
- Inclusive cross-section measured as a function of jet p_T and y for *all* jets with p_T>60GeV and |y|<2.8
  - All jets in region of central jet-trigger plateau
  - No forward jets (MC/data JES discrepancy)
- Dijet cross-section measured as a function of m_{jj} and $\chi=\exp(|y_1 - y_2|)$
  - Leading jet satisfies p_T>60GeV and |y|<2.8
  - Second jet satisfies p_T>30GeV and |y|<2.8
  - High purity and efficiency of jet reconstruction for both jets
  - Stability of NLO improved by asymmetric cuts



Also:

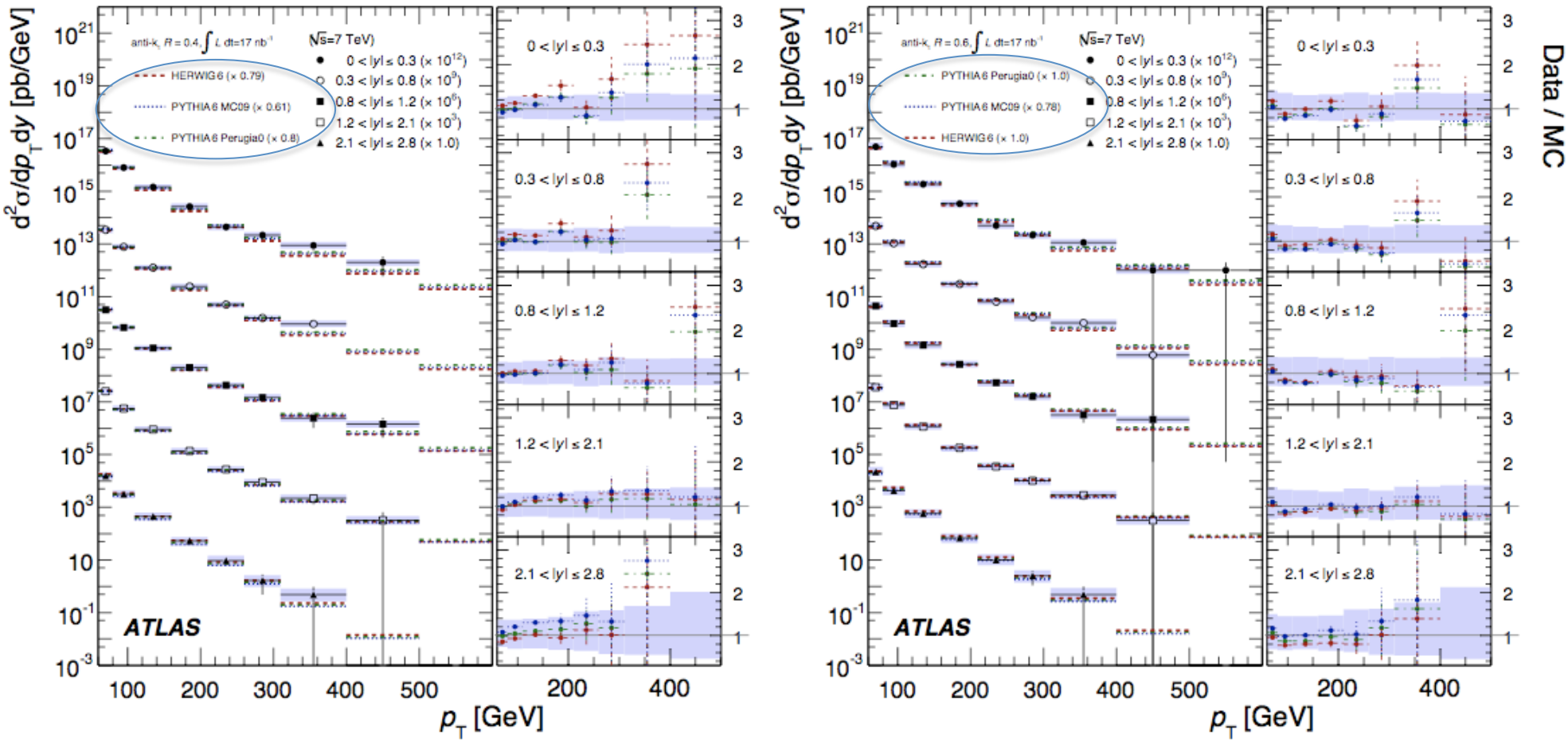
1) Vertex required with 5+ tracks
2) Jets cleaned to remove jets from 'noise' and poorly reconstructed regions of detector

Unfolding detector effects



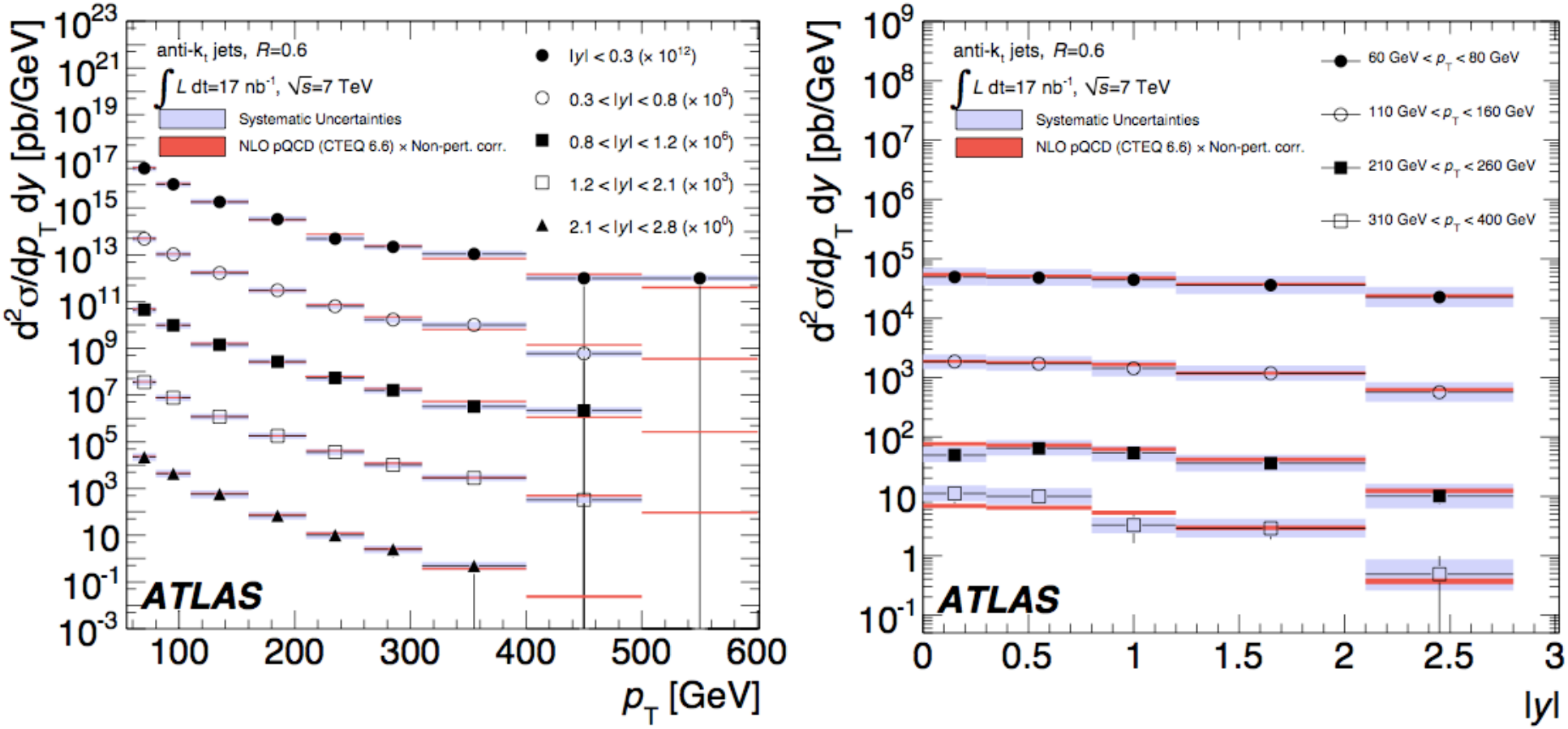
- Bin-by-bin unfolding to remove effect of detector inefficiencies and resolutions.
- Unfolding factor ($\sigma_{truth}/\sigma_{reco}$) determined using PYTHIA 6, uncertainty on this evaluated by (i) using different generators (ii) changing the resolution (iii) changing the shape of the input distributions.
- Typically 5% (or less) uncertainty in unfolding factors.

Inclusive jets: comparison to LO event generators



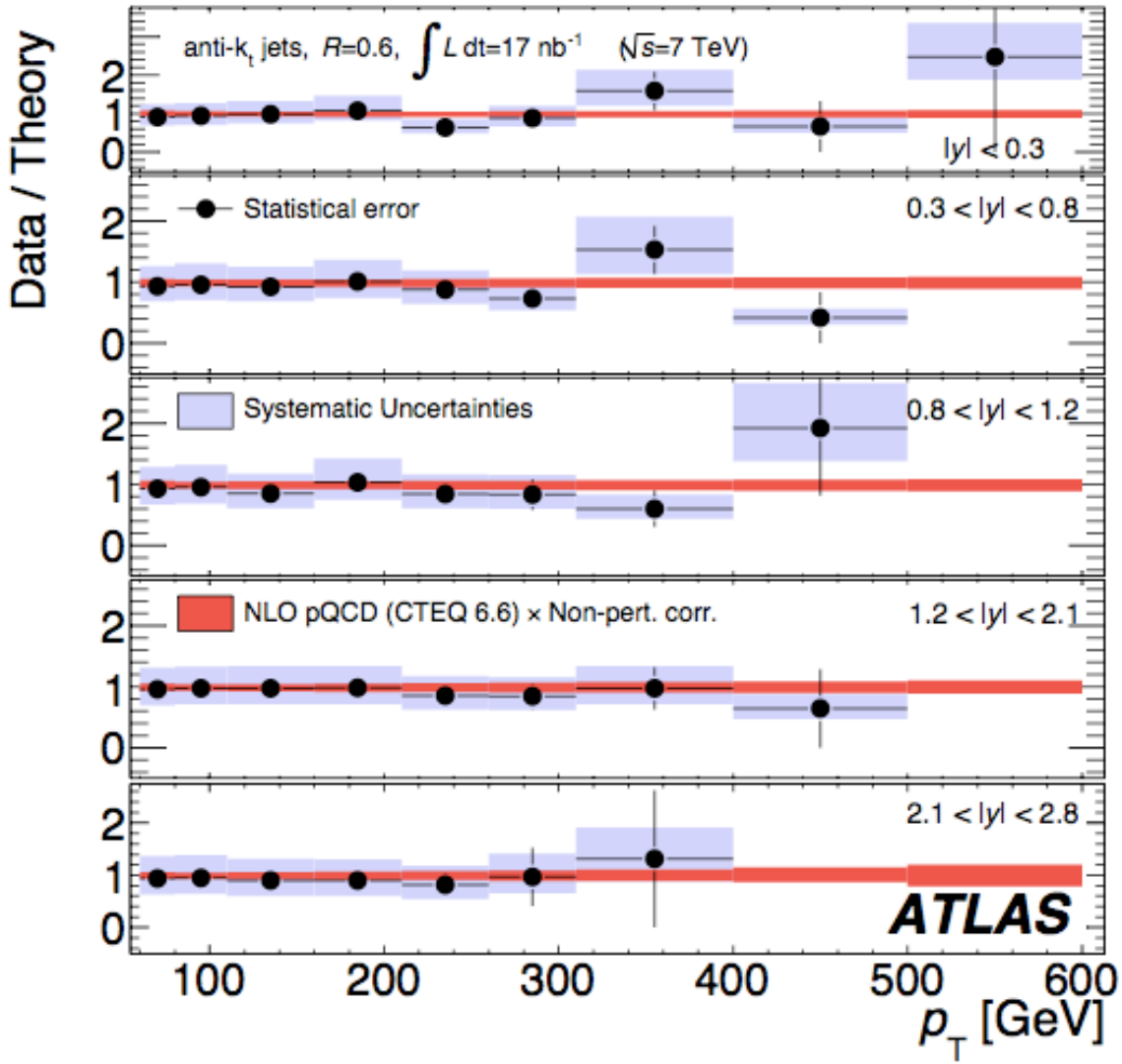
- Shape is well described by the LO 2-> 2 matrix element + parton shower approach
- Cross-sections determined at leading order – normalization required to get the MC to match the data

Inclusive jets: comparison with NLO predictions



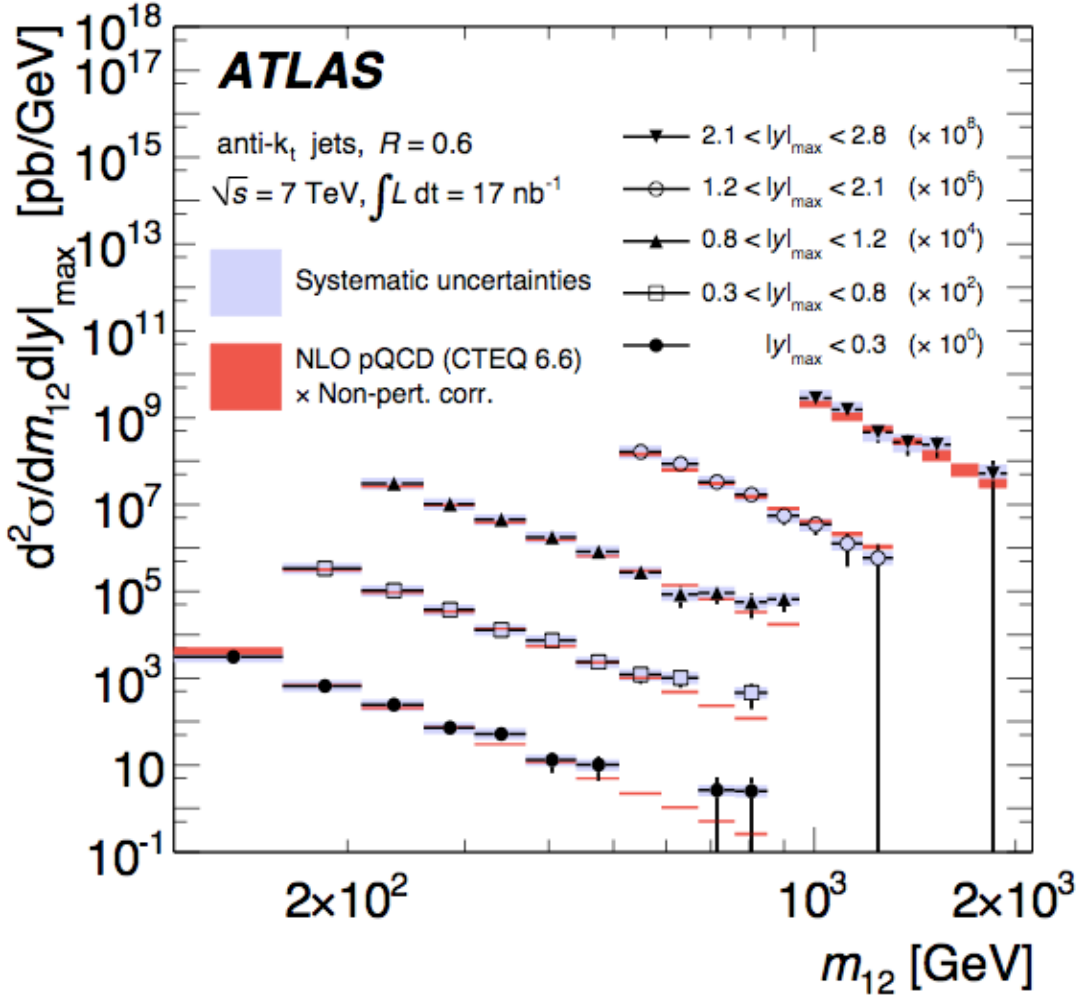
- NLO prediction at parton-level from NLOJet++ using CTEQ6.6 PDF (checked with JETRAD)
- Soft (non-perturbative) corrections applied to parton level predictions to allow comparison to data

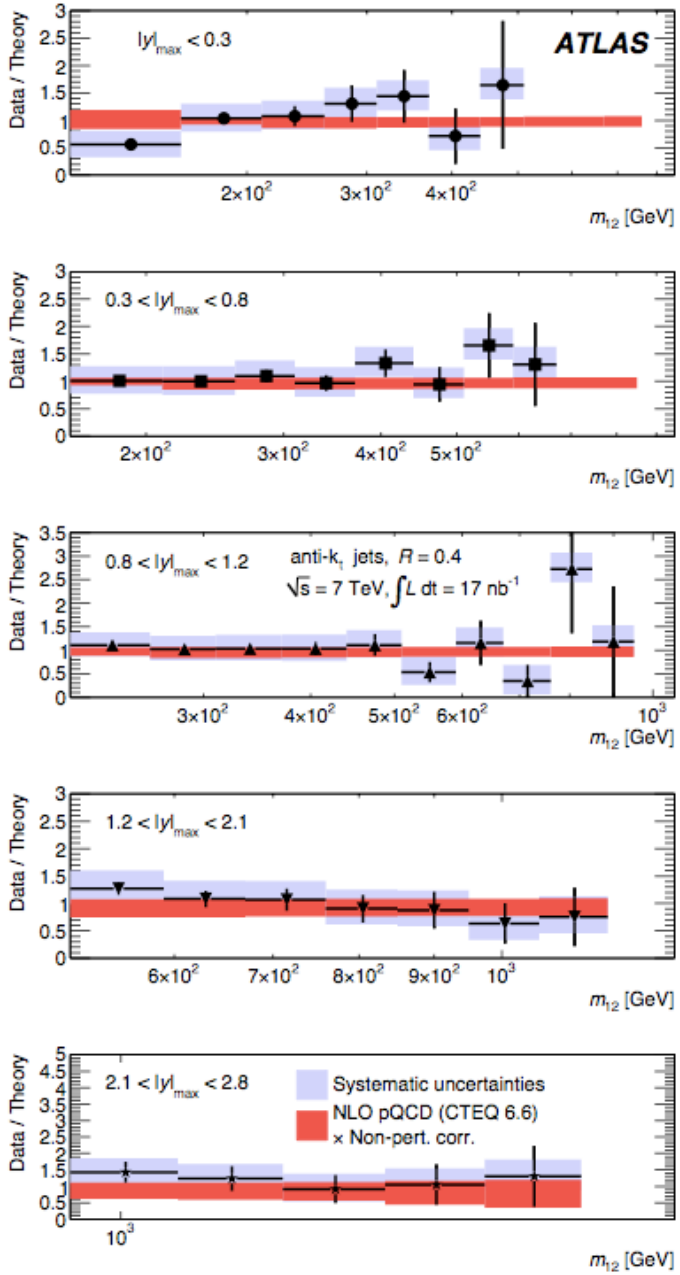
Comparison with NLO predictions, in a bit more detail



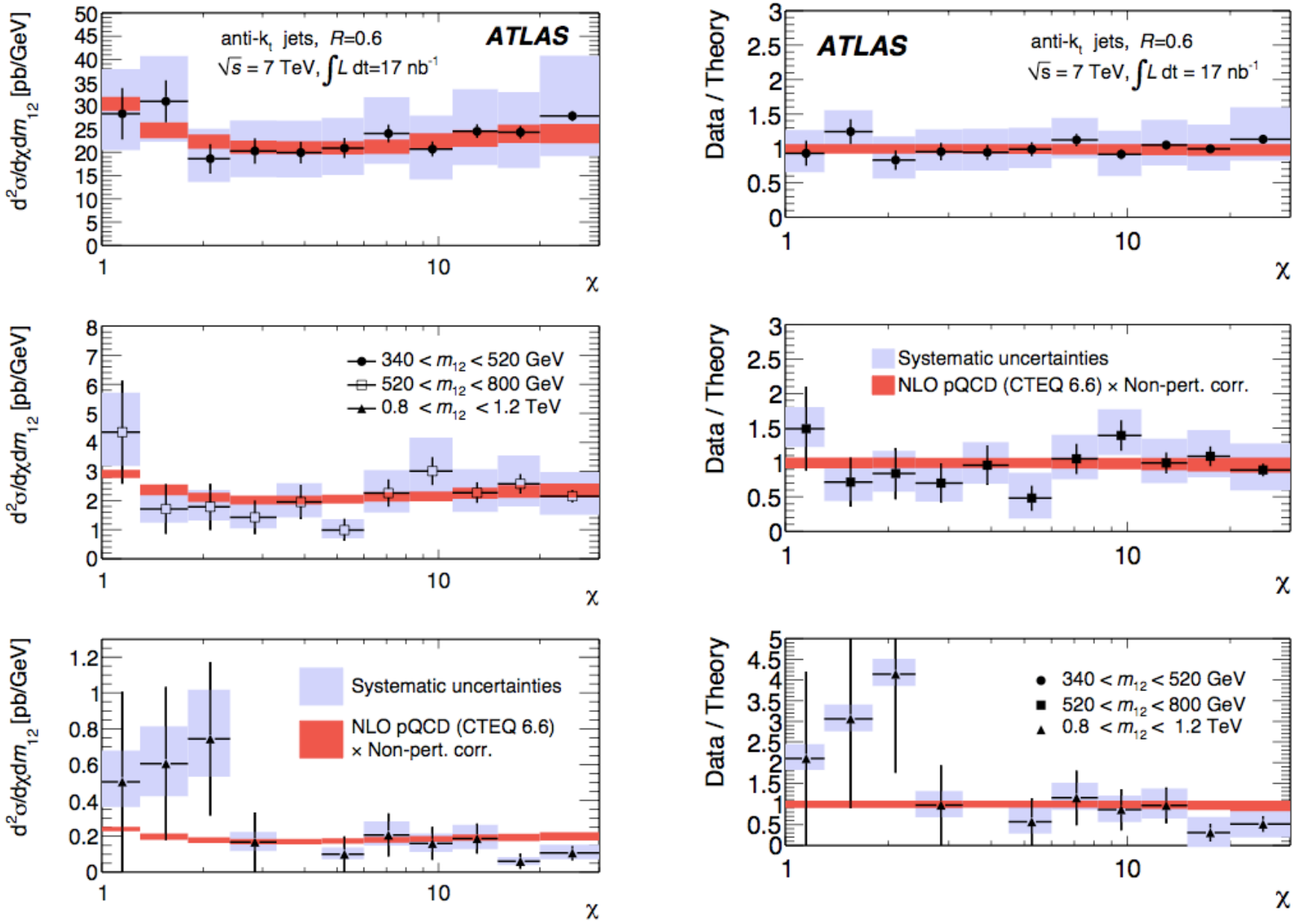
Approximately 5% uncertainty in NLO theory, compared to 30% experimental uncertainty - this is JES dominated, should be able to drastically improve on this in the near future

Dijet mass distributions

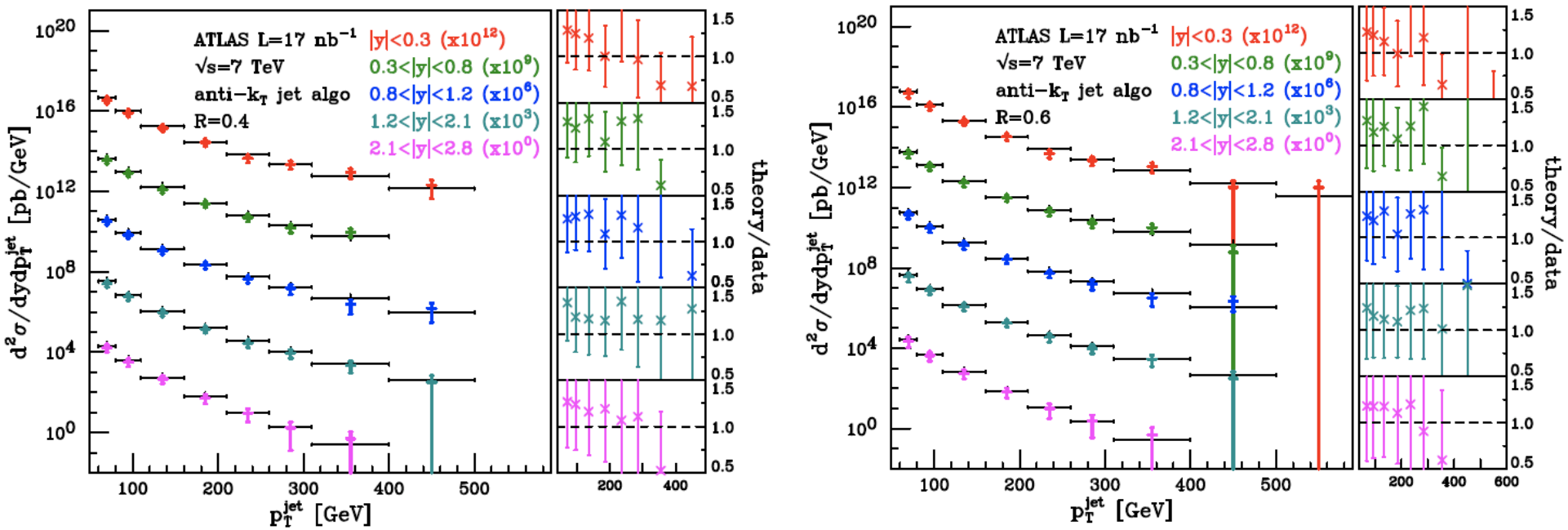




Dijet angular distributions



Inclusive jet cross-section comparison with POWHEG



- POWHEG-Box recently implemented dijet production (published in arXiv:1012.3380)
- NLO matrix element interfaced to PYTHIA/HERWIG to benefit from parton shower, hadronization and underlying event.
  - Allows out-of-box particle level comparison (shown above)
- But, for the experiments, POWHEG could be used to
  - improve the uncertainty in the unfolding corrections
  - Reduce physics modeling dependence of JES determination using dijet balancing

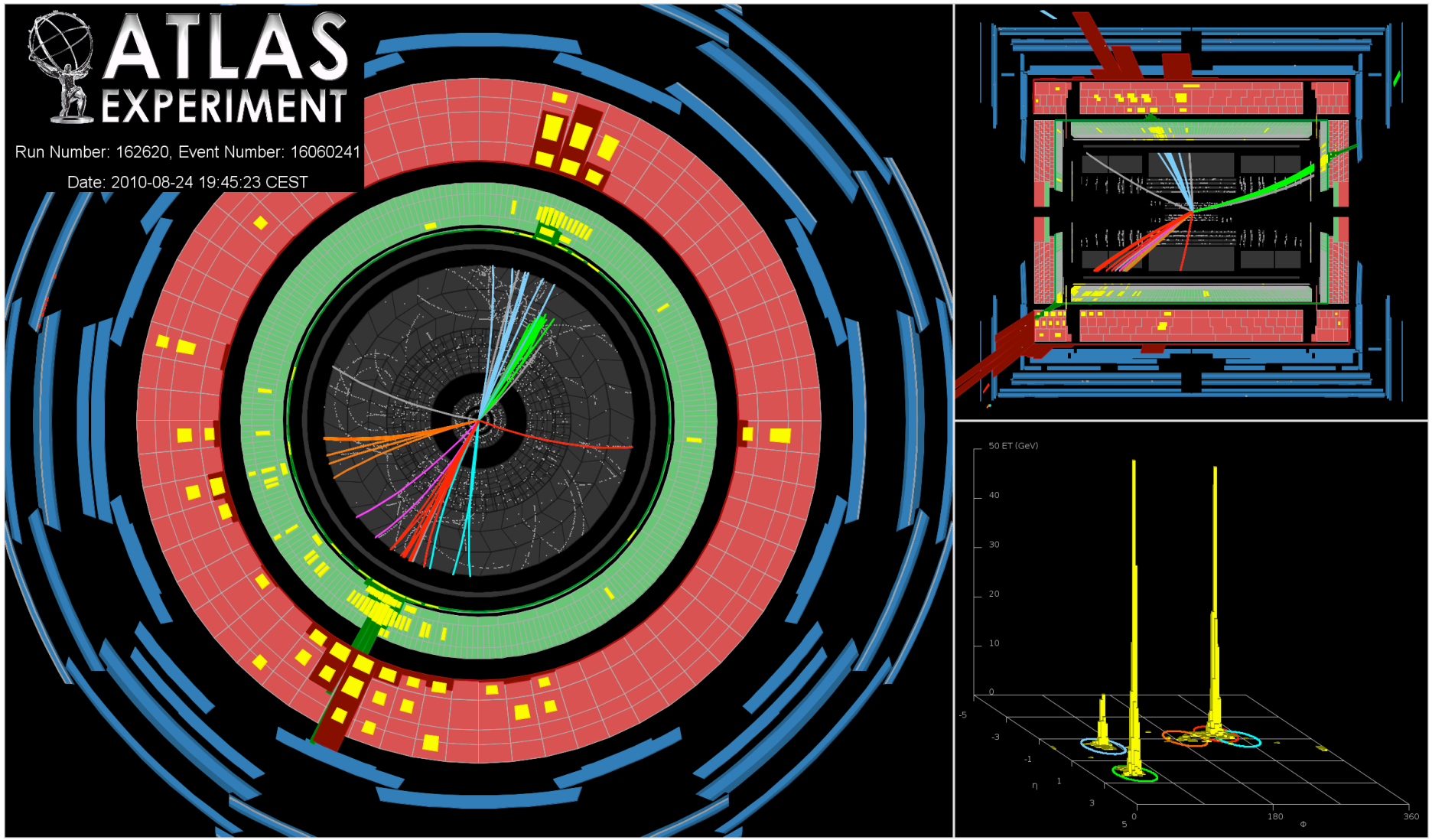
Summary – part I

<u>The measurement of jets in a collider experiment</u>

1) A lot of work is needed to calibrate the energy of jets in a collider experiment to the accuracy required for precision measurements
2) The current public ATLAS (CMS) uncertainty is about 7% (4%) for central jets and is improving steadily through in-situ measurements.

<u>The inclusive jet cross-section measurement</u>

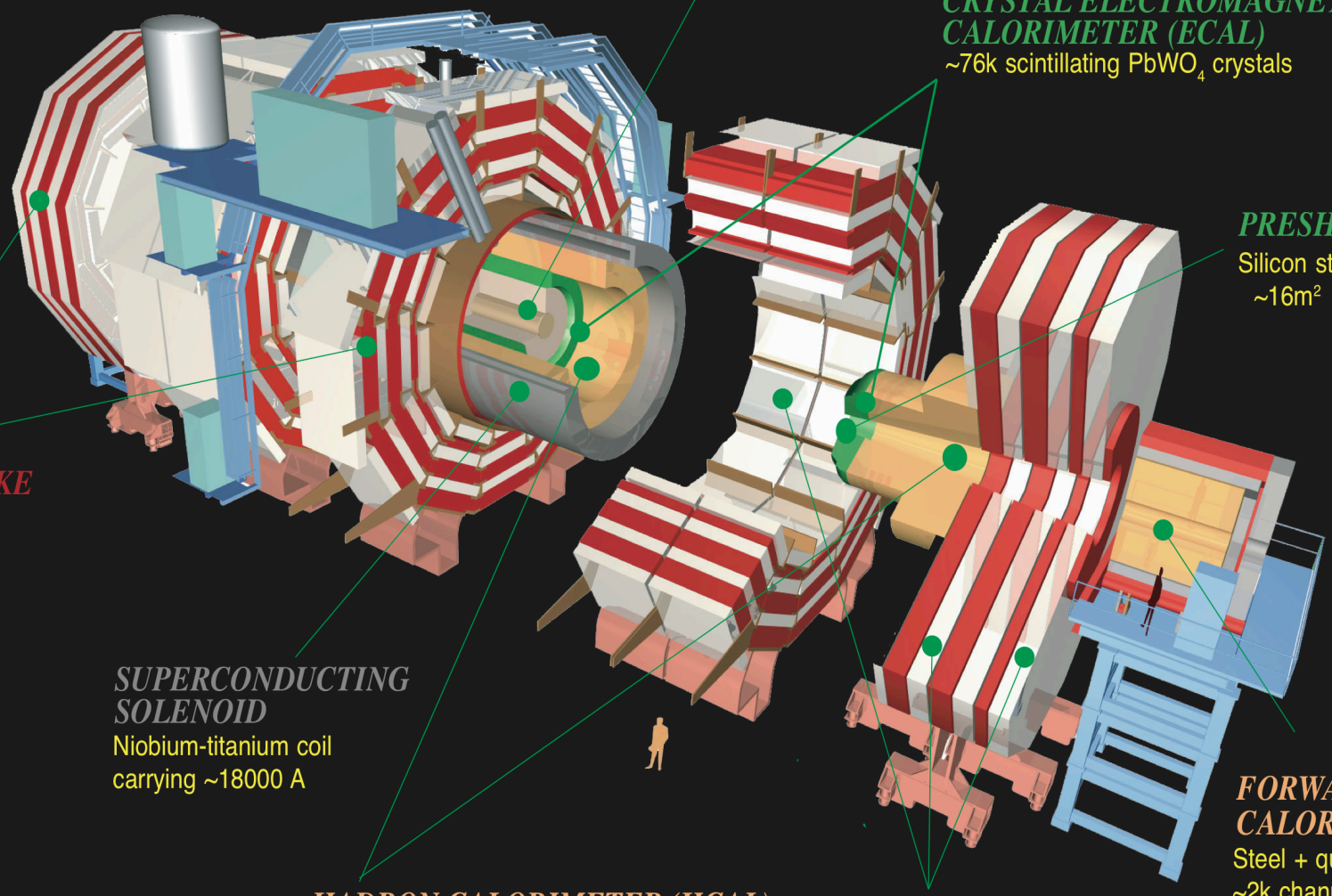
1) The simplest measurement of jet production at the LHC - a stepping stone to the more complicated, exclusive final states discussed in the next lecture
2) Dominated by JES uncertainty (>30%)
3) NLO predictions accurate to about 5% in the inclusive single jet measurement



Event with dijet mass, m_{jj}=3.1TeV – the SM at unprecedented energies

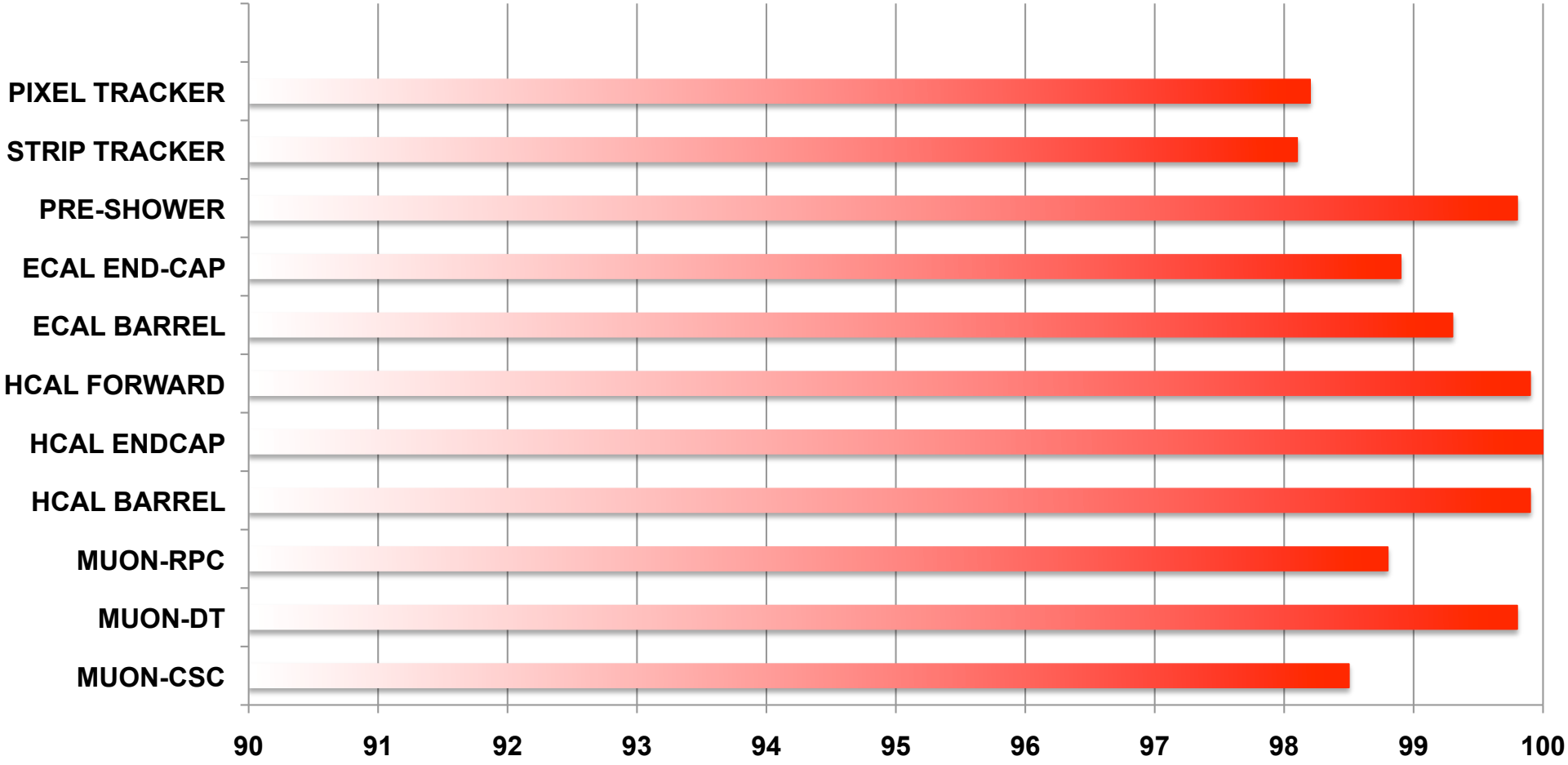
Extras

CMS Detector



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Status of the CMS detectors



	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

The limitations of the inclusive jet measurements

- Low statistics: measurement performed with less than 1/1000th of the current available data.
- Conservative JES estimate – results in experimental uncertainty 6x larger than NLO uncertainty
- Covers a limited p_T range ($60<p_T<500$GeV) and low rapidity range ($|y|<2.5$).

- Future extensions (probably for the winter conferences):
  - Improved JES on its way!
  - Full dataset of 2010, allowing larger p_T and m_{jj} to be probed
  - As well as probing smaller p_T (as low as 20GeV) and larger $|y|$ (up to 4.5)