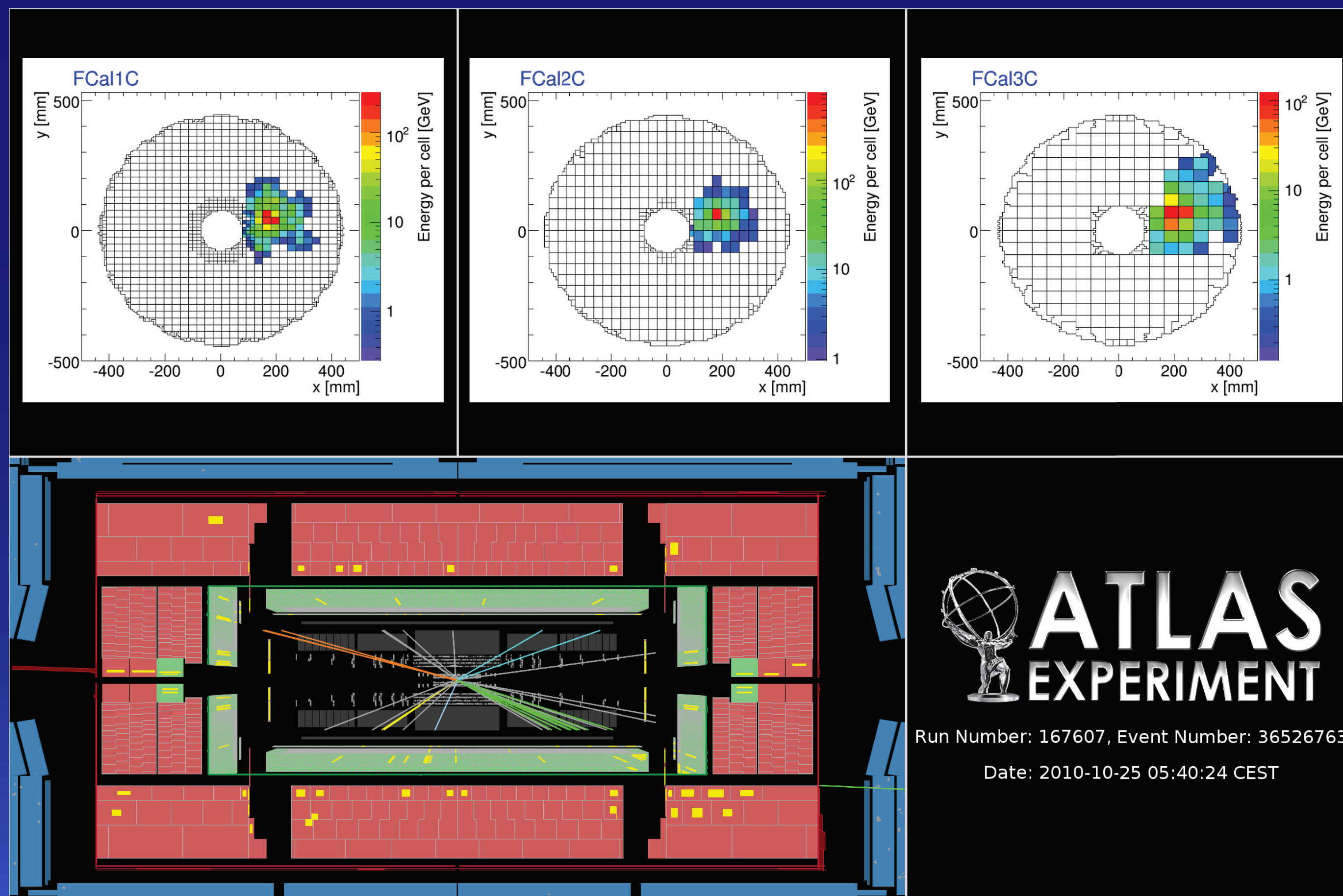
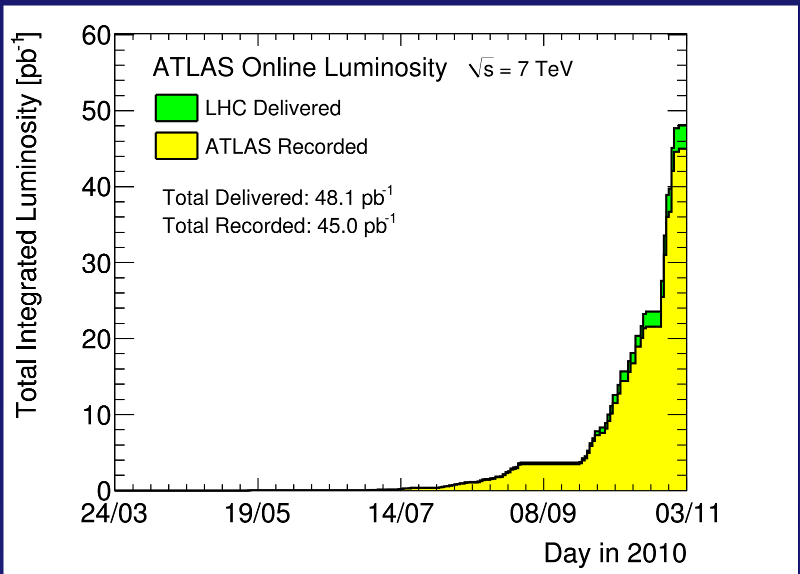
Hard QCD Results with Jets @ LHC (ATLAS + CMS)

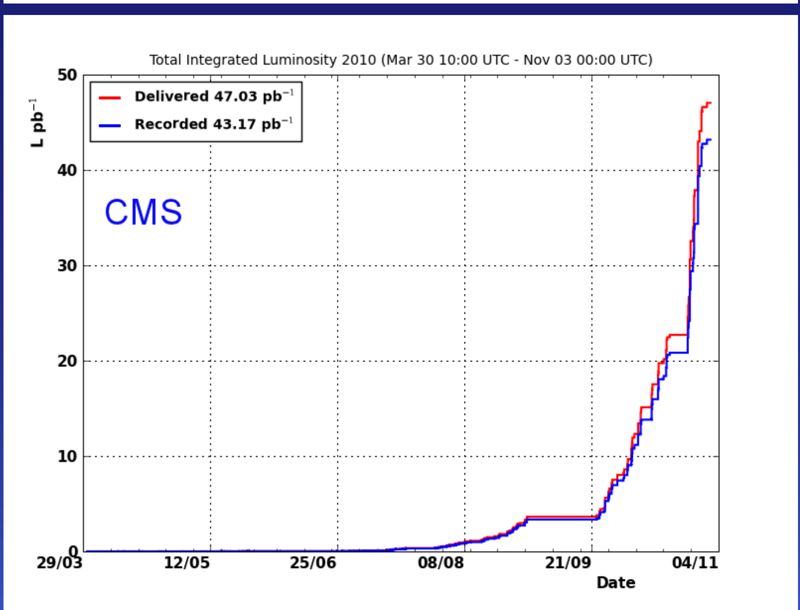
Hadron Collider Physics Symposium 2011 Sven Menke, MPP München, 16. Nov. 2011, Paris, France
on behalf of the ATLAS and CMS collaborations

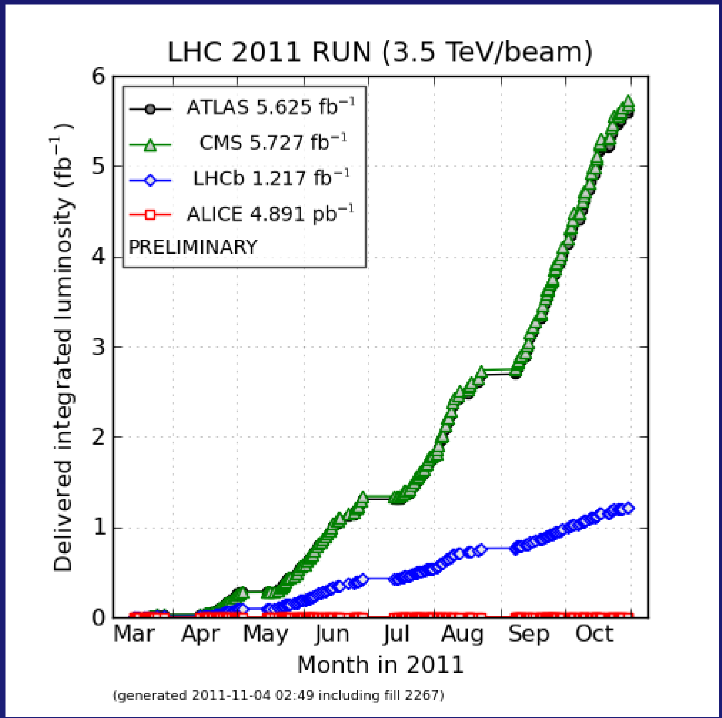
- **Introduction**
  - ATLAS+CMS
  - jet reconstruction and calibration
- **Cross sections**
  - inclusive jet cross sections
  - di-jet event studies
- **Jet properties**
  - sub structure
  - jet mass
- **Conclusions**



Highest Energetic Jet in ATLAS from 2010 @ $\sqrt{s} = 7$ TeV with $E_j = 3.37$ TeV

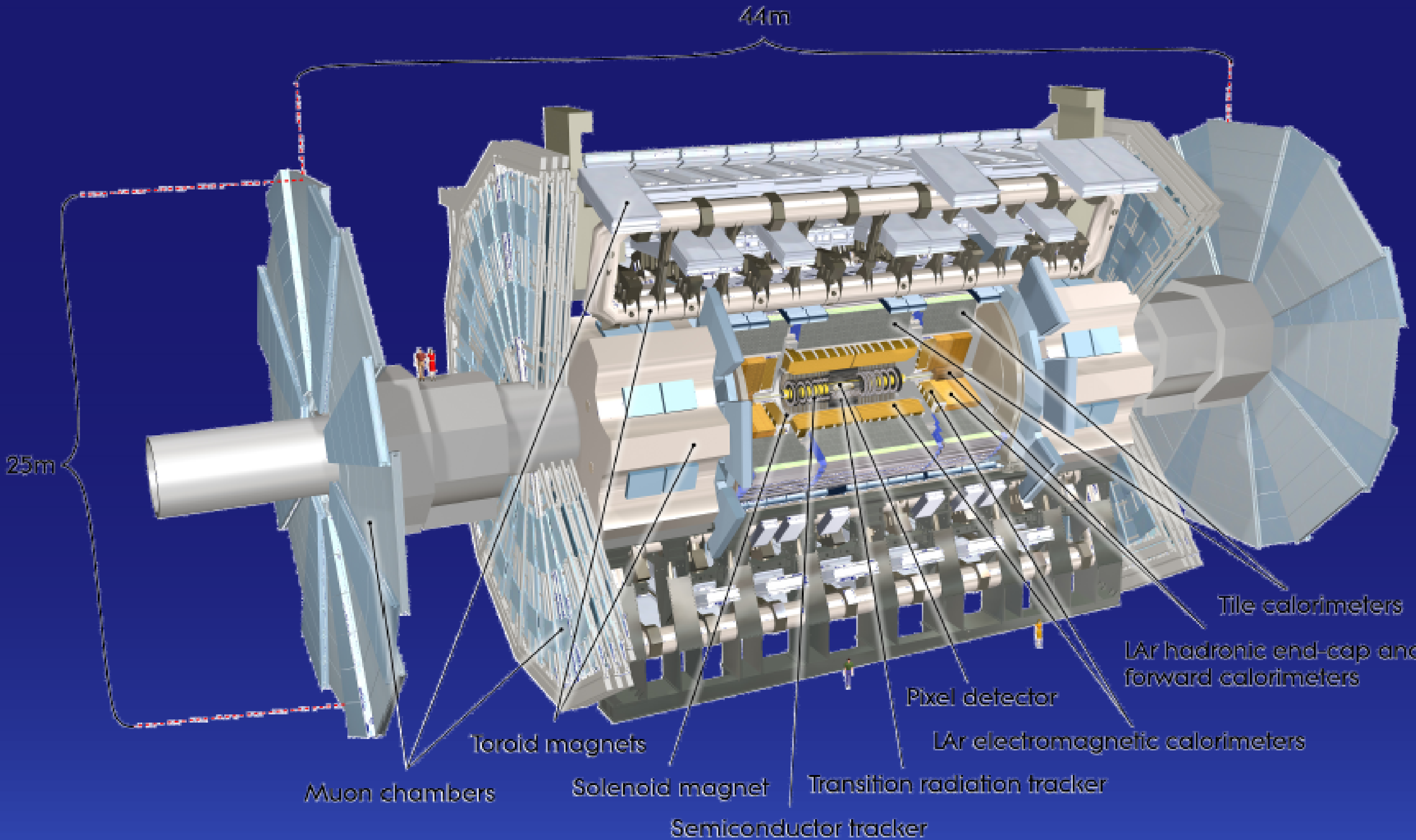






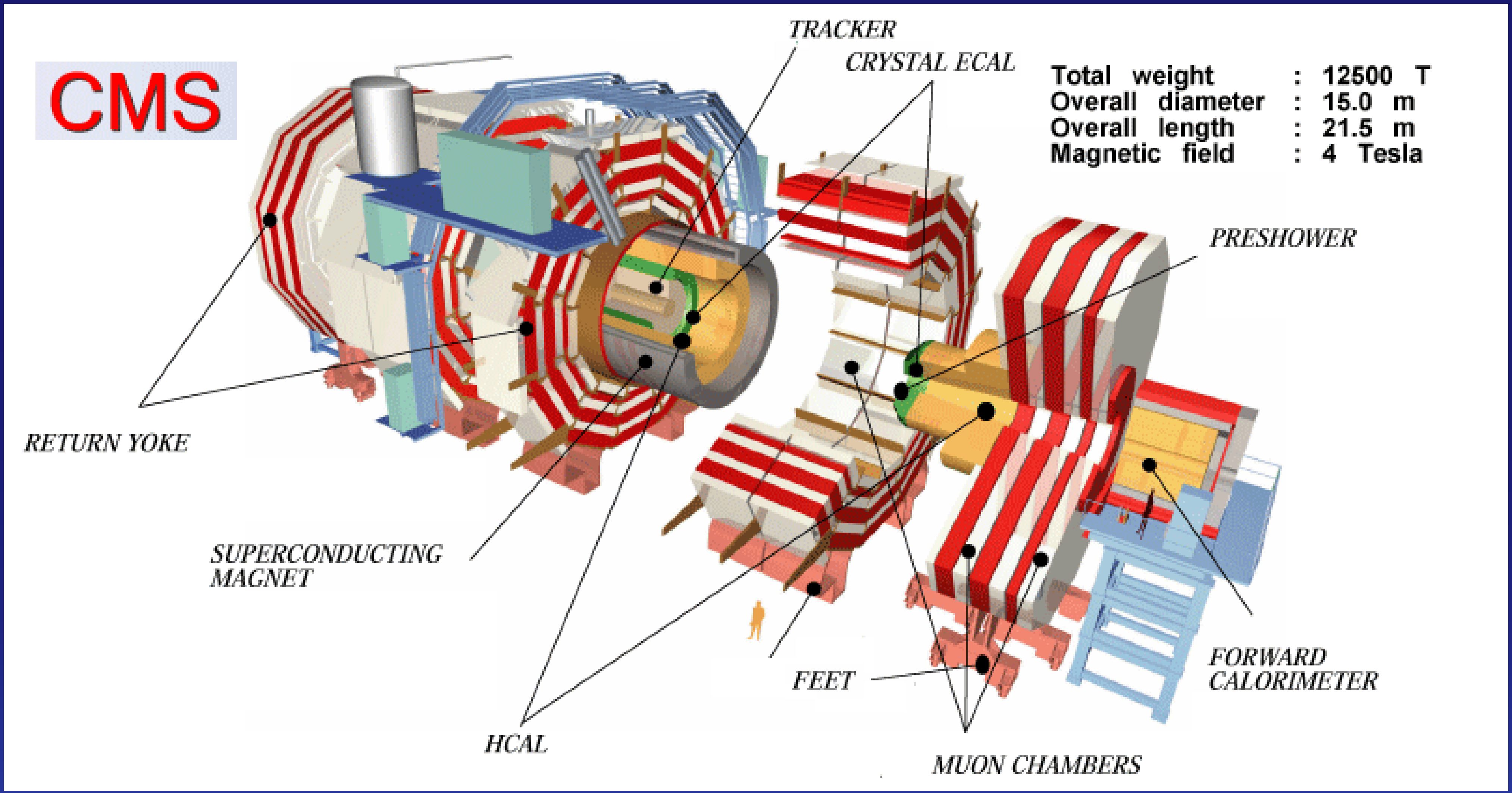
- LHC: pp Collisions @$\sqrt{s} = 7\,\text{TeV}$ since March 2010
- 2011 ATLAS/CMS recorded integrated luminosity @$\sqrt{s} = 7\,\text{TeV}$: $L = 5.25\,\text{fb}^{-1}$, and $L = 5.22\,\text{fb}^{-1}$, respectively as of 30-Oct-2011 (stop of pp-run)
- Results based on $\sim 40\,\text{pb}^{-1}$ collected by each experiment in 2010 are presented here

The ATLAS Detector



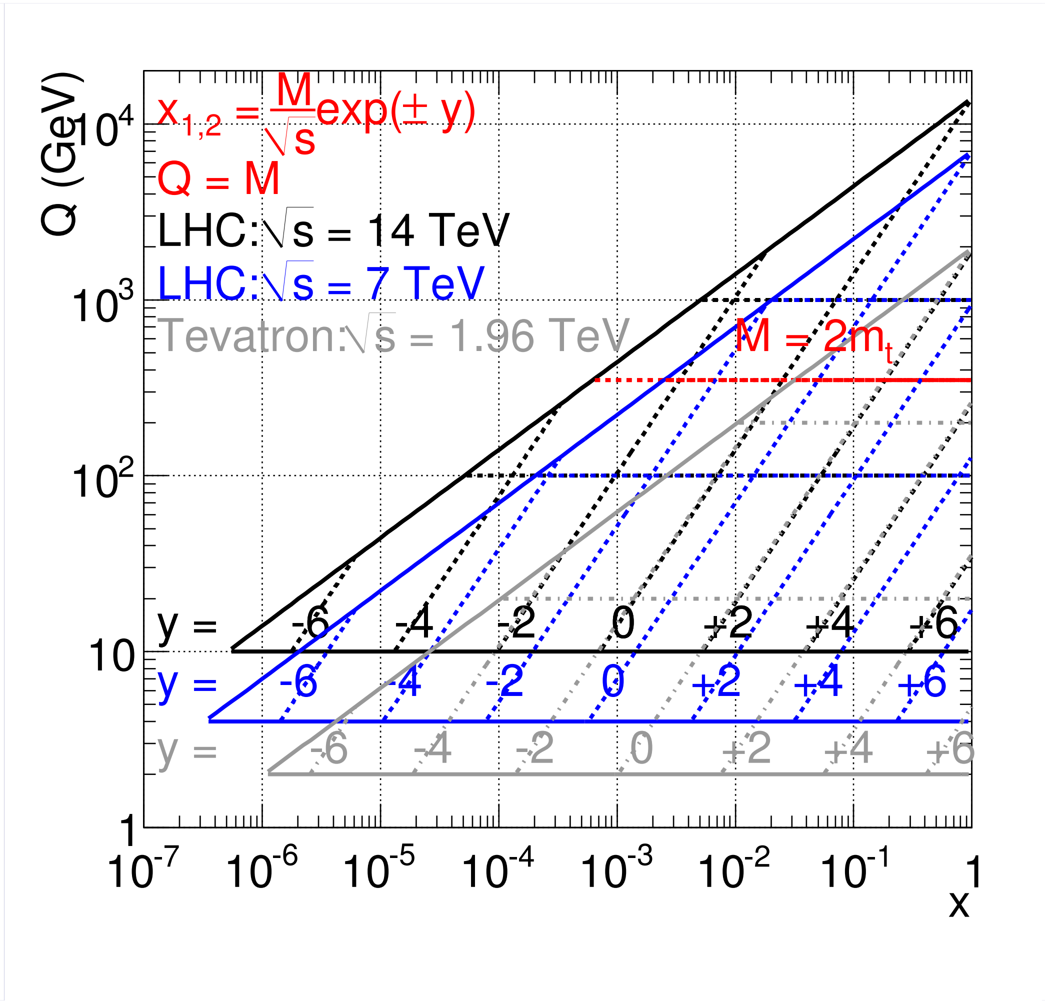
A Torodial **L**HC **A**paratu**S**: 25 m high; 44 m long; 7000 t heavy

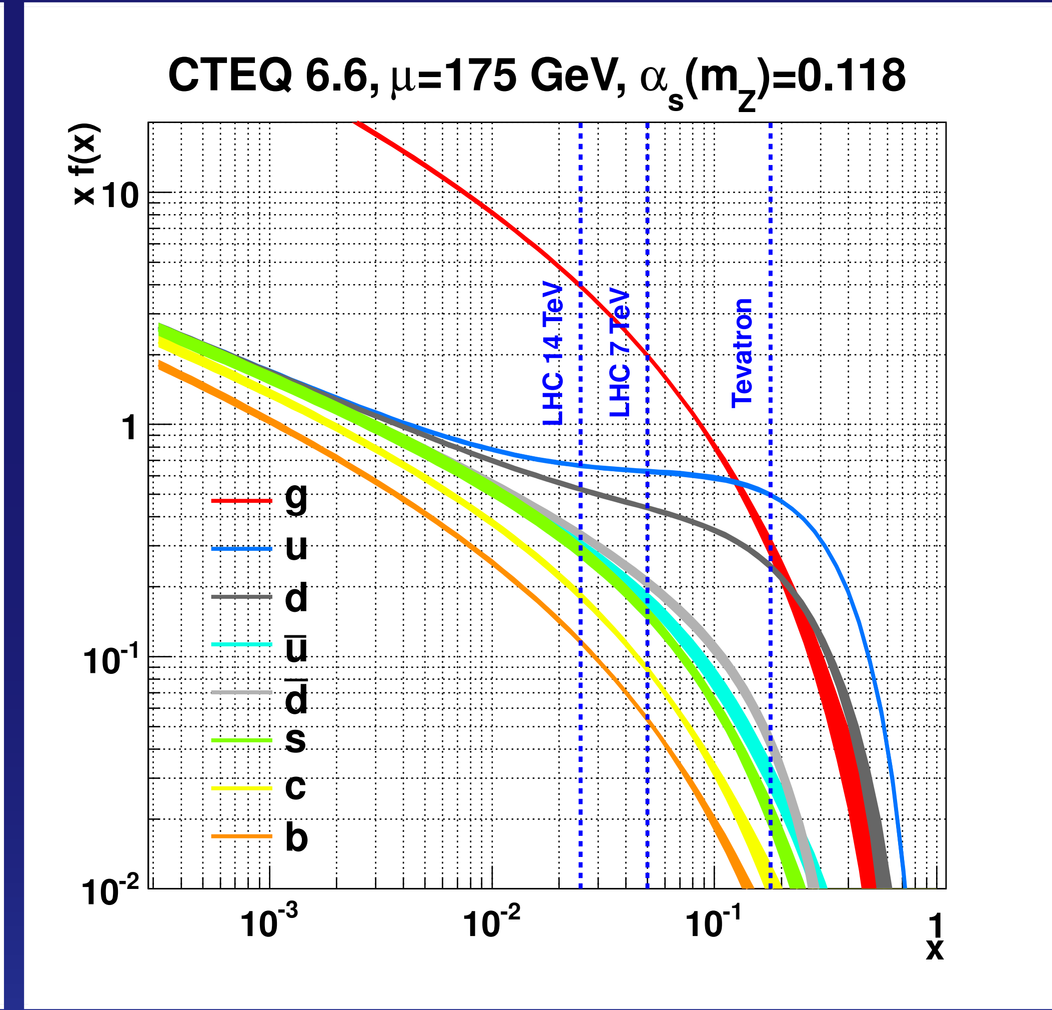
The CMS Detector



Compact **M**uon **S**olenoid: 15 m high; 22 m long; 12500 t heavy

Kinematics ► Tevatron vs. LHC





- Q vs. $x_{1,2}$ for Tevatron and LHC (left)
- red curve shows top-pair production as example
- QCD measurements constrain α_s and PDF's (here CTEQ 6.6, right)

Jet Reconstruction in ATLAS and CMS

- Traditionally all calorimeter cells are grouped in fixed size towers with $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ including all em and hadronic layers per grid point
- ATLAS and CMS use refined reconstruction methods to feed jet algorithms
- CMS uses Particle Flow (PF)
  - PF reconstructs leptons, photons, charged and neutral hadrons by linking tracks to ECAL and HCAL clusters
  - energy of each particle measured by all subsystems
  - ECAL and HCAL energy is calibrated to respective particle level (electromagnetic or hadronic)
- ATLAS uses TopoClusters
  - topological 3D clustering over all $190\,\mathrm{k}$ calorimeter cells
  - individual energy blobs separated by local maxima correspond to particle level
  - in 2010 em-scale clusters were used as input to jets
  - jet-level corrections correct for non-compensation, PileUp, dead material

Jet Reconstruction in ATLAS and CMS

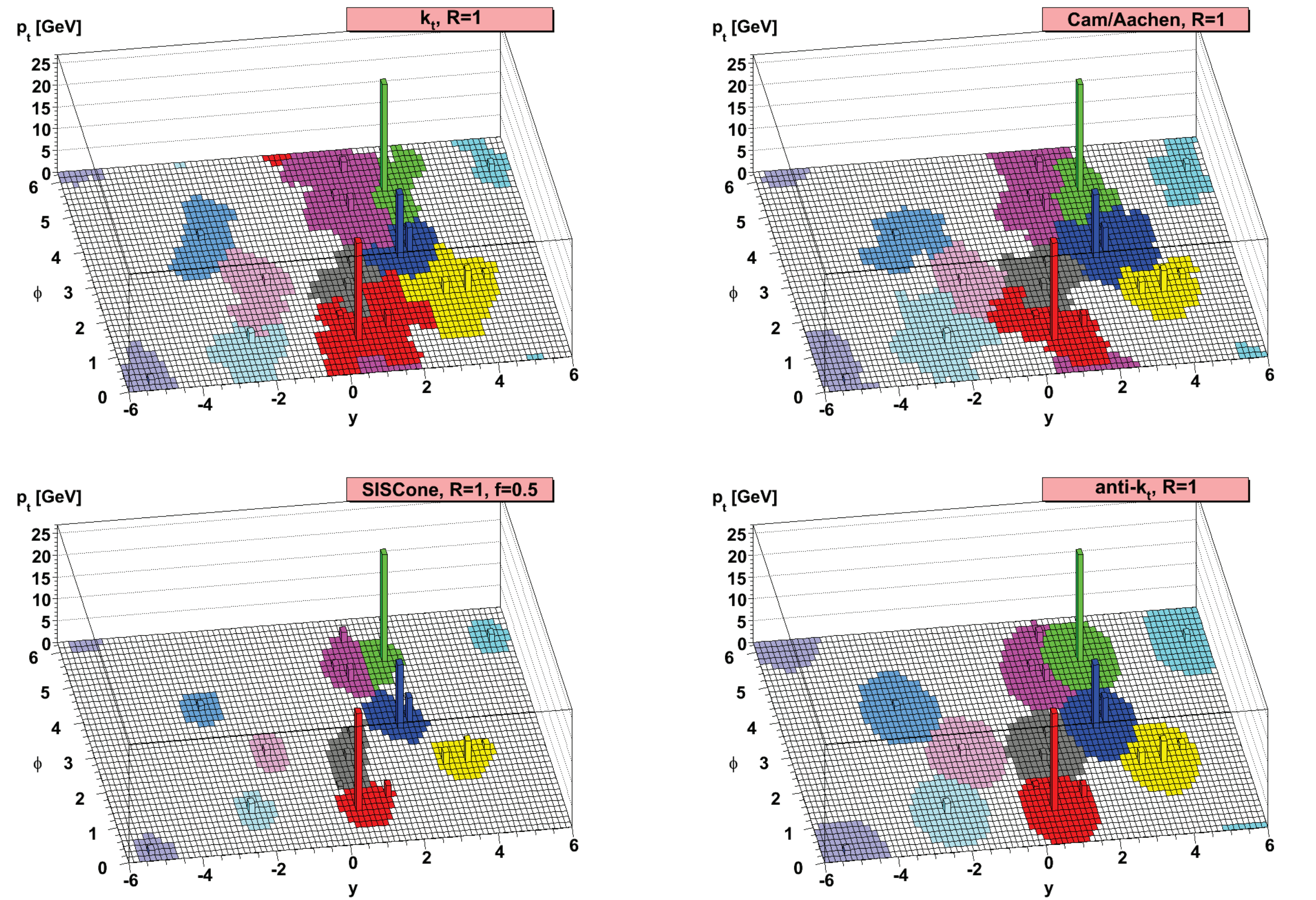
- Modern standardized jet algorithms like `SISCone` (JHEP 0705 (2007) 086), `Kt` (Nucl. Phys. B 406 (1993) 187, Phys. Rev. D 48 (1993) 3160), and `AntiKt` (JHEP 0804 (2008) 063) have been evaluated by ATLAS and CMS
  - these jets are collinear and infrared safe
  - are available in a standard `C++` library (`FastJet` by Matteo Cacciari, Gavin Salam and Gregory Soyez)
  - are seedless and iterative

- `AntiKt` in inclusive mode was found to be the most useful algorithm for ATLAS and CMS
  - `AntiKt` combines like `Kt` pairs of objects based on a $\min\left({p_T^i}^{2x}, {p_T^j}^{2x}\right)$ scaled distance metric $\Delta R_{ij}^2/R^2$ in $y-\phi$-space
  - `Kt` uses $x = 1$ and treats objects with the smallest p_T first
  - `AntiKt` uses $x = -1$ and treats objects with the largest p_T first
  - the net result is that `AntiKt`-jets are much more regular shaped in $y - \phi$ space and don't suffer from the "vacuum cleaner" effect like `Kt` making them easier to calibrate
  - CMS uses $R = 0.5$ (incl.) and $R = 0.7$ (di-jet), while ATLAS uses $R = 0.4$ and $R = 0.6$ (both)

Jet Reconstruction in ATLAS and CMS

Jets, G. Salam (p. 27)
└2. Getting the basics right
  └FastJet

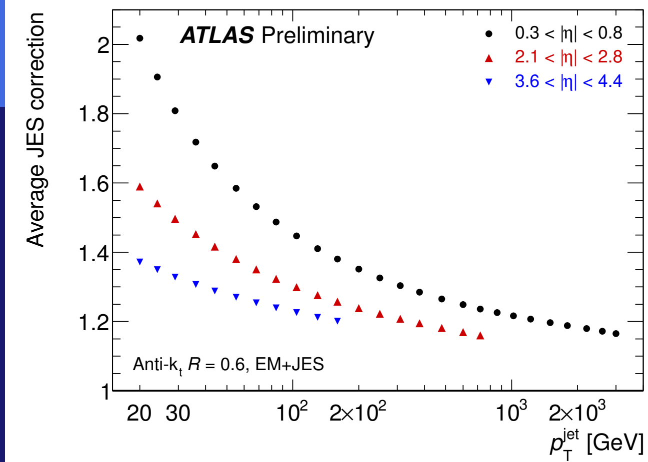
Jet contours – visualised

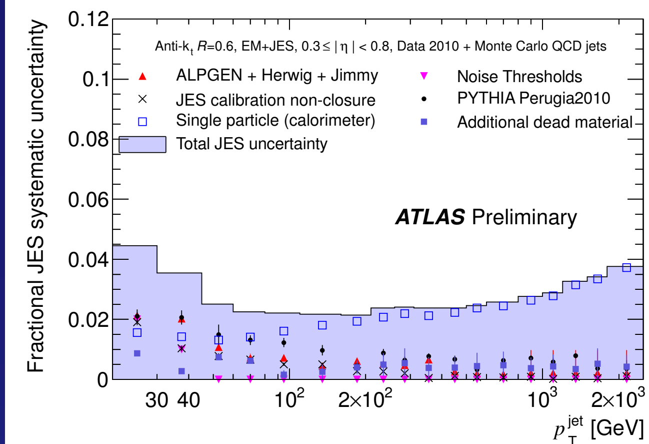


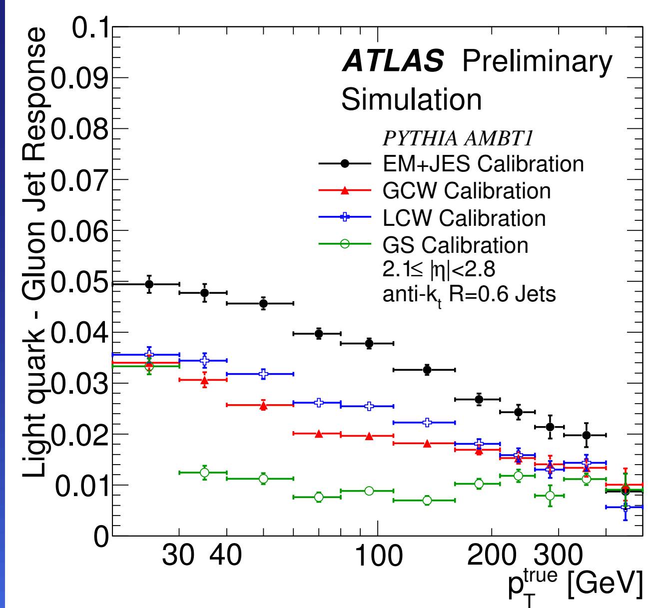
G. Salam, 2008

Jet Calibration in ATLAS

- most analyses on 2010 data used simple EM+JES scheme
  - topo clusters on EM-scale as input to jet algorithms
  - MC based correction function $f(p_\perp, |\eta|)$ to restore jet $p_\perp$ to stable hadron level
  - top plot shows correction as function of $p_\perp$ for 3 y ranges
  - middle plot shows systematic uncertainties on jet energy scale (JES) for $0.3 < |y| < 0.8$
- more sophisticated approaches exist
  - global cell weighting (GCW) applies energy-density dependent weights to all calorimeter cells
  - local hadron calibration (LCW) classifies and calibrates topo clusters as em or hadronic
  - global sequential calibration (GSW) modifies EM+JES by jets-shape based correction factors
  - bottom plot compares light-quark – gluon-jet-response for different calibration schemes
- LCW is used in ATLAS for missing transverse energy and in jets for 2011
- Jet mass and substructure studies reported here also used this already for 2010 data

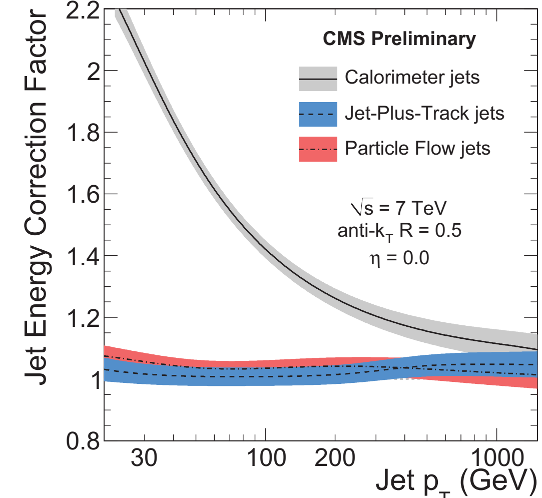


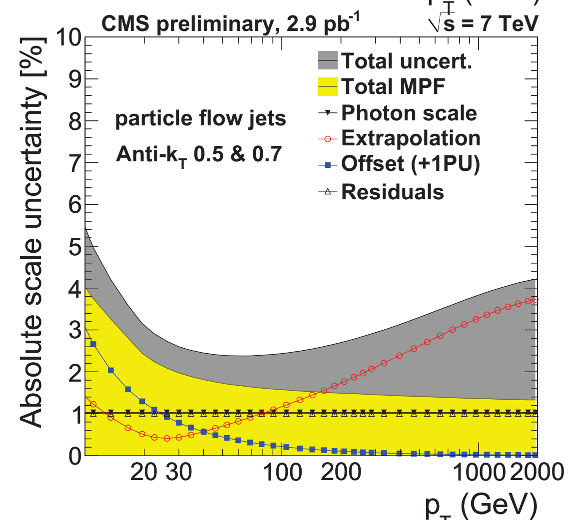


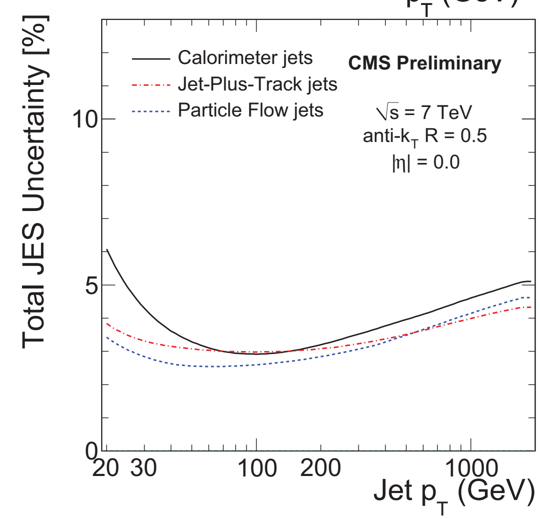


Jet Calibration in CMS

- most analyses use jets with particle flow (PF) objects as input
- jet energy scale uncertainties are evaluated for three types of jets in CMS
  - calorimeter only jets
  - jet-plus-track jets (calorimeter jets with corrections based on associated tracks)
  - particle flow jets (all subsystems are used to reconstruct individual stable particles)
- in all three cases the jet energy is corrected by a MC based correction function in jet $p_\perp$ and η
  - top plot shows jet energy correction factors for central jets vs. $p_\perp$
- scale and uncertainty are validated with di-jet events ($p_\perp$ balance for relative JES) and γ-jet events (MPF and $p_\perp$ balance for absolute JES)
  - middle plot shows absolute JES uncertainty for particle-flow jets vs. $p_\perp$
  - bottom plot shows total JES uncertainty for all three jet types vs. $p_\perp$ for central jets



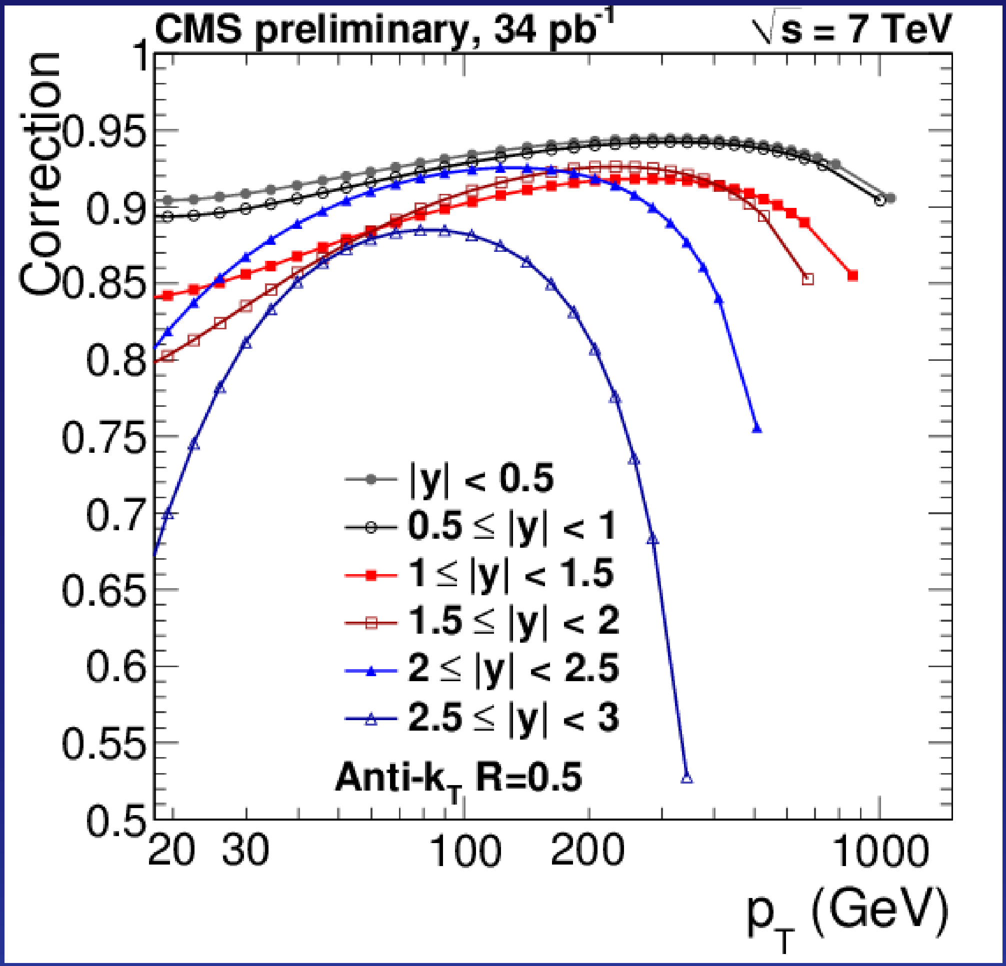




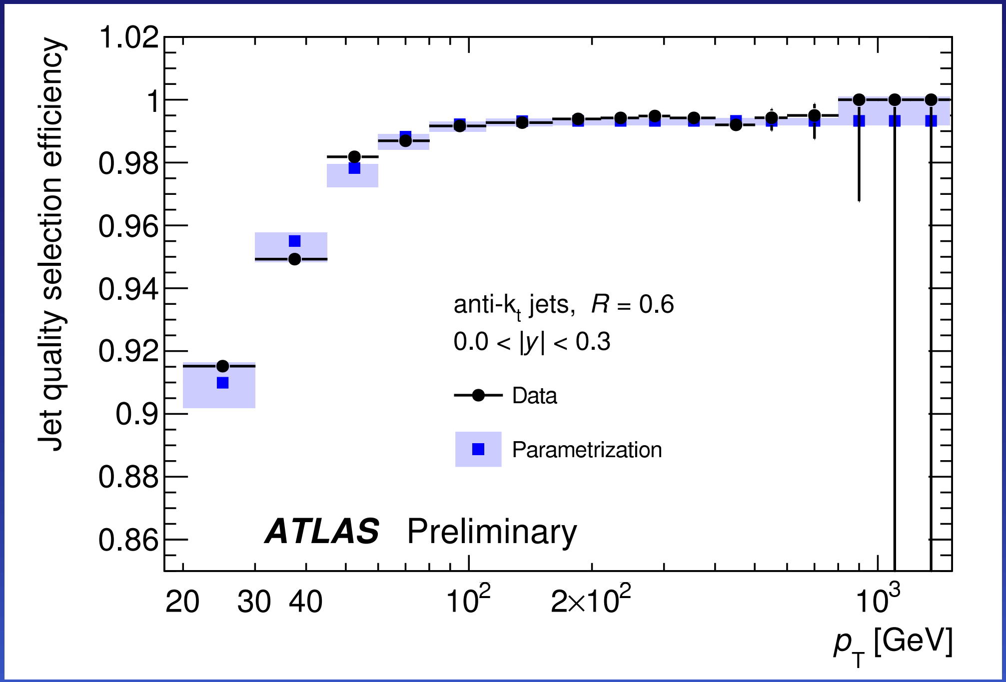
$$\frac{d^2\sigma_{\text{jet}}}{dp_\perp dy} = \frac{N_{\text{jet}}}{\Delta p_\perp \Delta y}\frac{1}{\epsilon\,\mathcal{L}}$$

- measured spectrum is corrected bin-by-bin for migration effects in $p_\perp$
  - by Gaussian smearing with $p_\perp$ resolution of modified power-law spectrum obtained by fit to data (CMS)
  - by correction factors obtained from full detector simulations including also detector inefficiencies (ATLAS)
- NLO pQCD predictions
  - `NLOJet++ 4.1.2` with `CTEQ 6.6` NLO PDFs as baseline (ATLAS)
  - `NLOJet++ 2.0.1` with average of `CT10`, `MSTW2008NLO`, `NNPDF2.0` NLO PDFs as baseline (CMS)
- NLO predictions on parton-level are corrected bin-by-bin for non-pert effects due to hadronisation and underlying event
  - from ratio of leading log generator spectrum with and without hadronisation and underlying event (ATLAS+CMS)

- corrections applied to data and respective uncertainties

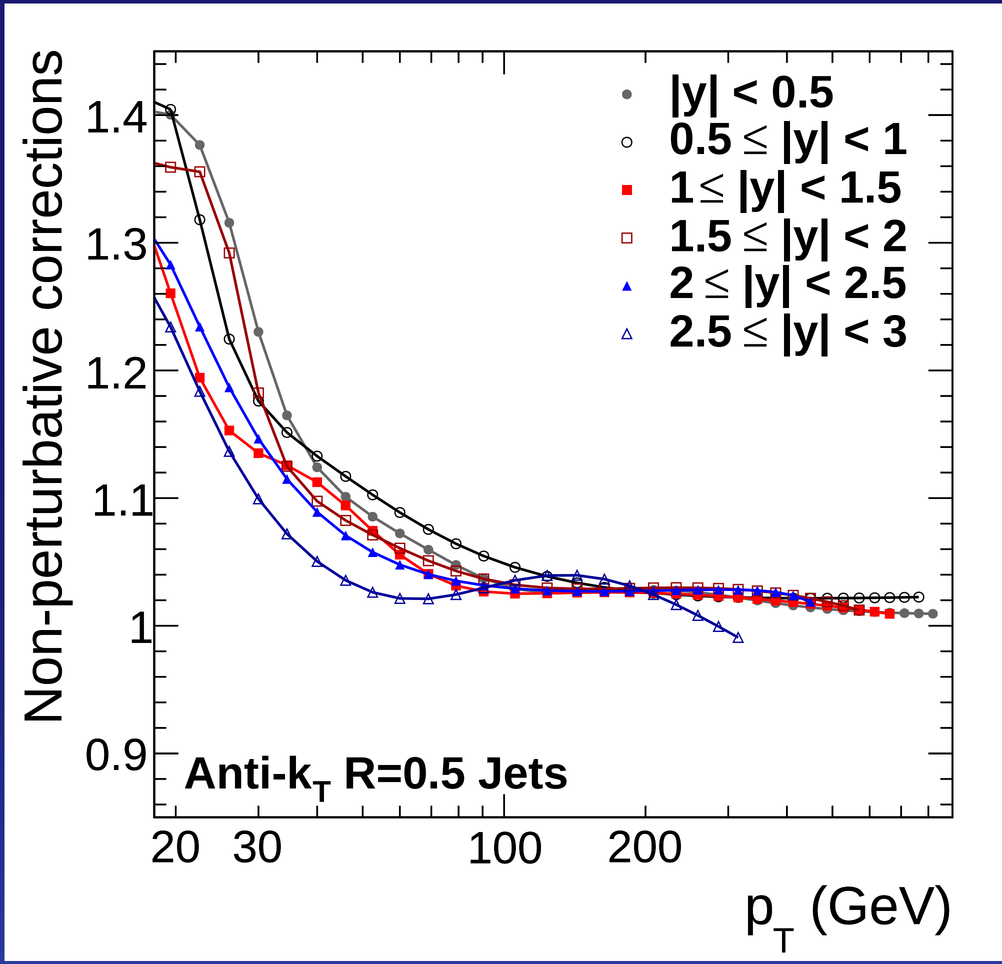


- un-smearing factors as function of $p_\perp$ for various y
- mainly due to $p_\perp$ resolution and steeply falling $p_\perp$ spectrum



- efficiency for reconstructing jets as function of $p_\perp$ for $|y| < 0.3$ (ATLAS)

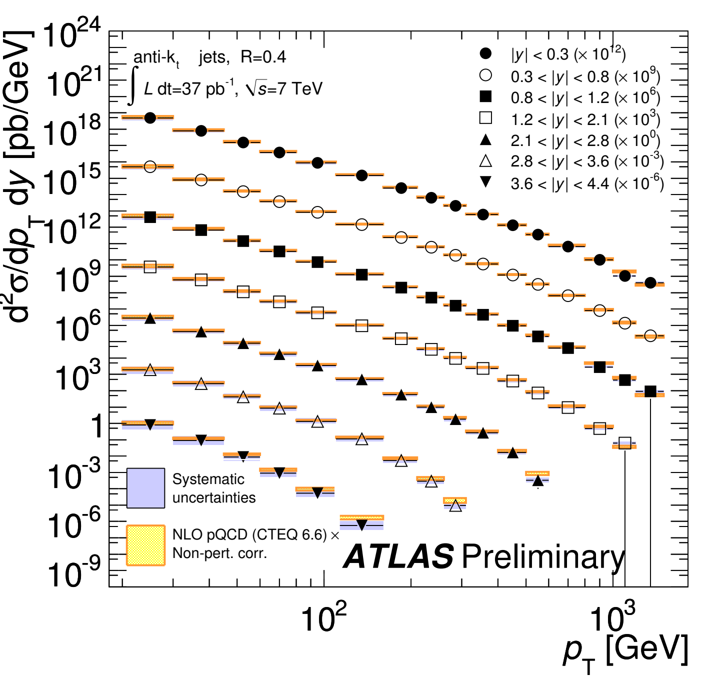
- corrections applied to NLO pQCD predictions
- non-perturbative corrections for `AntiKt`-jets with $R = 0.5$ vs $p_\perp$ for various $|y|$ (CMS)
- similar correction factors for `AntiKt`-jets with $R = 0.6$ are observed by ATLAS and found to be dominated by the underlying event
- systematic uncertainties are derived by comparing multi-parton-interactions and hadronisation for different generators



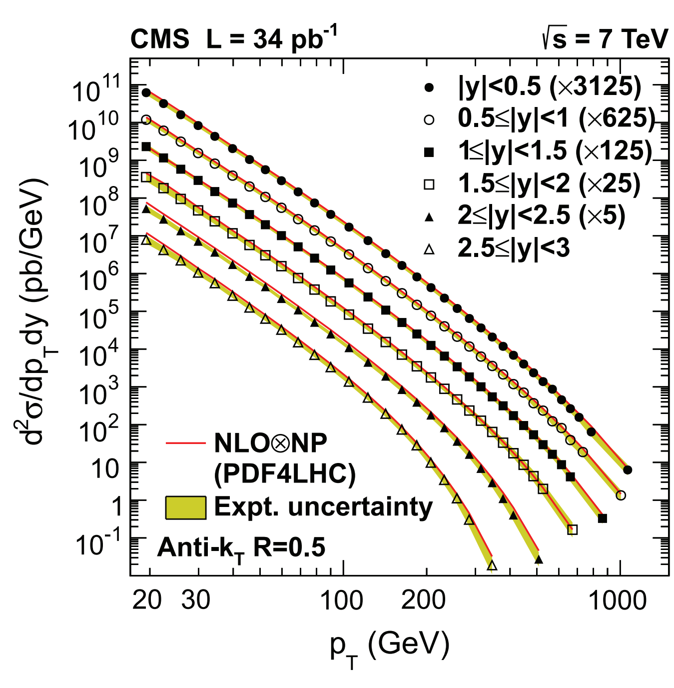
- for the smaller $R = 0.4$ the correction is dominated by hadronisation; its value is 0.8 at low $p_\perp$ and approaches unity at large $p_\perp$ (ATLAS)

Cross sections ► Inclusive jet cross section

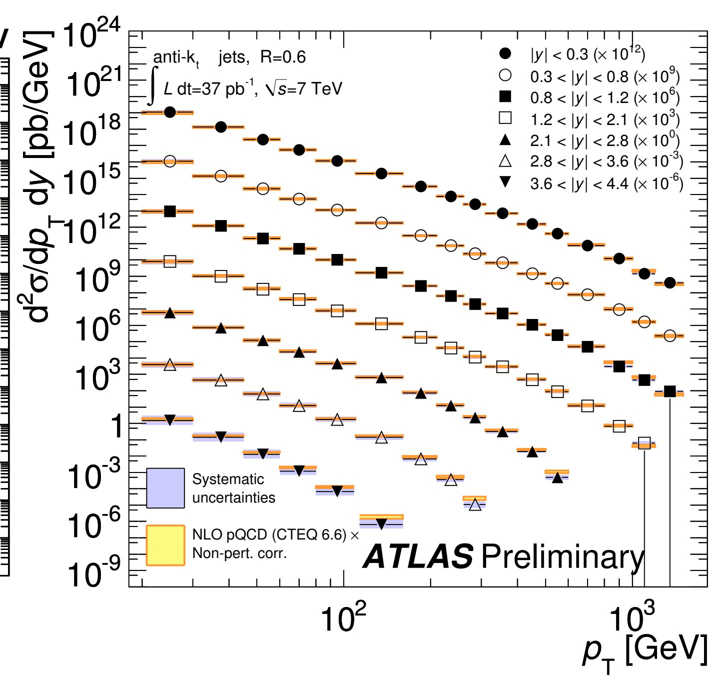
- results for $\frac{d^2\sigma_{\text{jet}}}{dp_\perp dy} = \frac{N_{\text{jet}}}{\Delta p_\perp \Delta y} \frac{1}{\epsilon \mathcal{L}}$ at $\sqrt{s} = 7\,\text{TeV}$ with `AntiKt`-jets



$R = 0.4$ (ATLAS)



$R = 0.5$ (CMS)

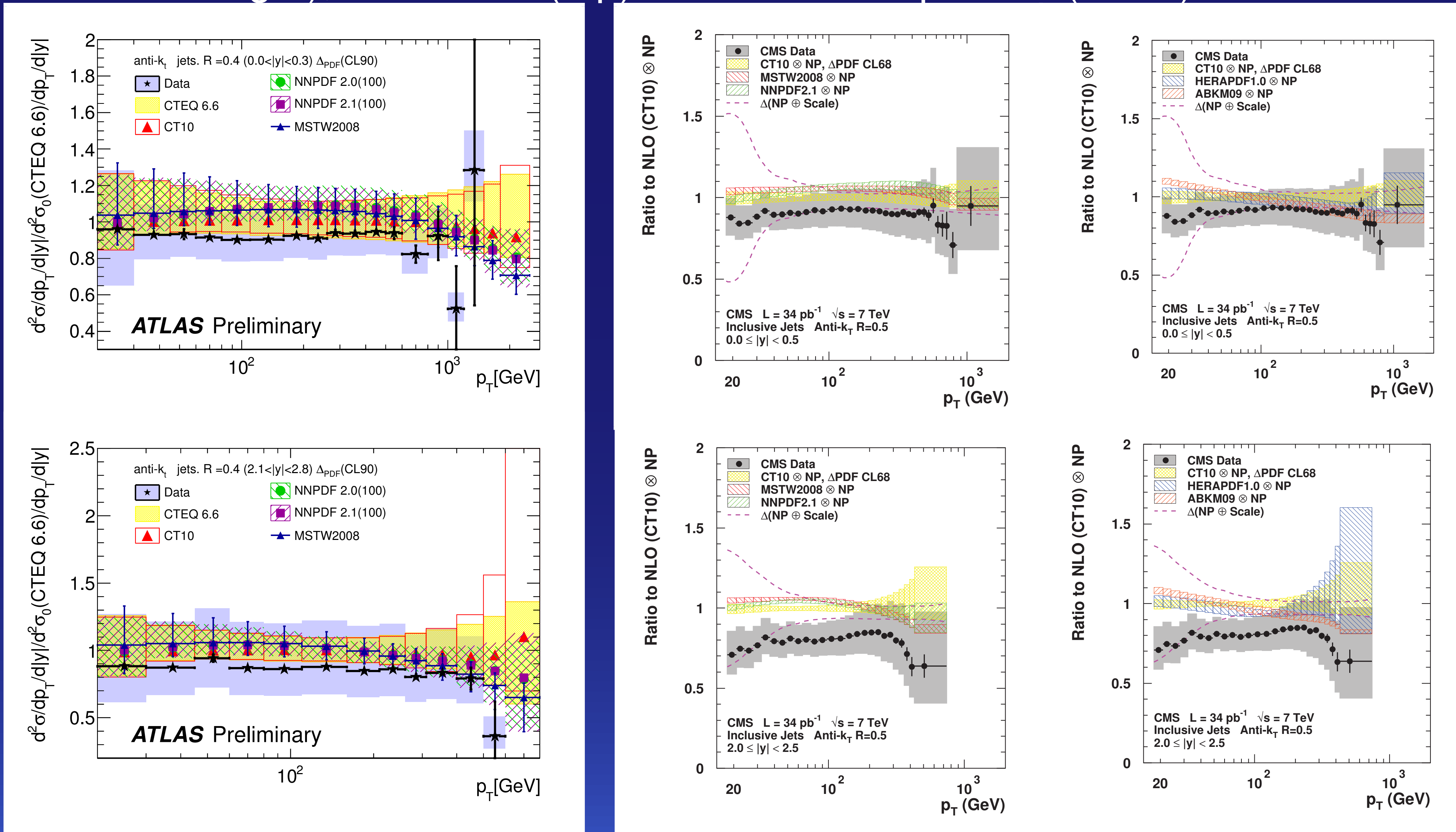


$R = 0.6$ (ATLAS)

- dominant exp. systematic uncertainties stem from the Jet Energy Scale uncertainty (ATLAS+CMS) and resolution (CMS)
  - $\sim 10 - 20\%$ (CMS)
  - $\sim 10 - 30\%$ (ATLAS)
- overall normalisation error of 3.4% (ATLAS, not included above) and 4% (CMS) from luminosity measurements

Inclusive jet cross section ► comparison to different PDF sets

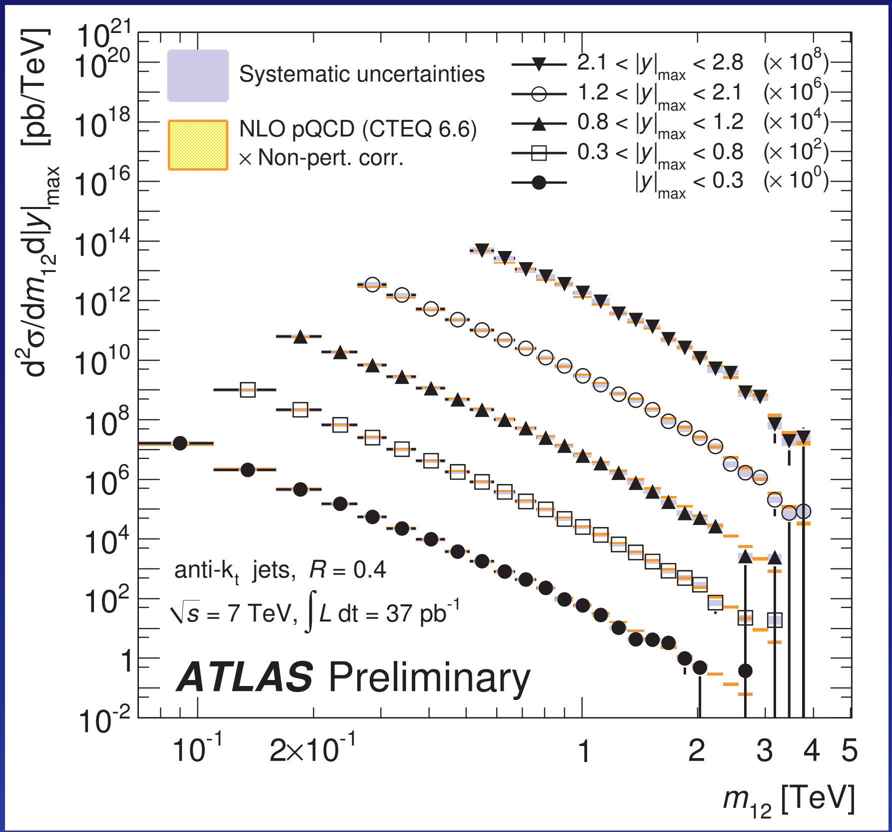
- data and PDF over prediction (ATLAS, `CTEQ 6.6`: left); (CMS, `CT10`: middle+right); for central (top) and forward rapidities (down)

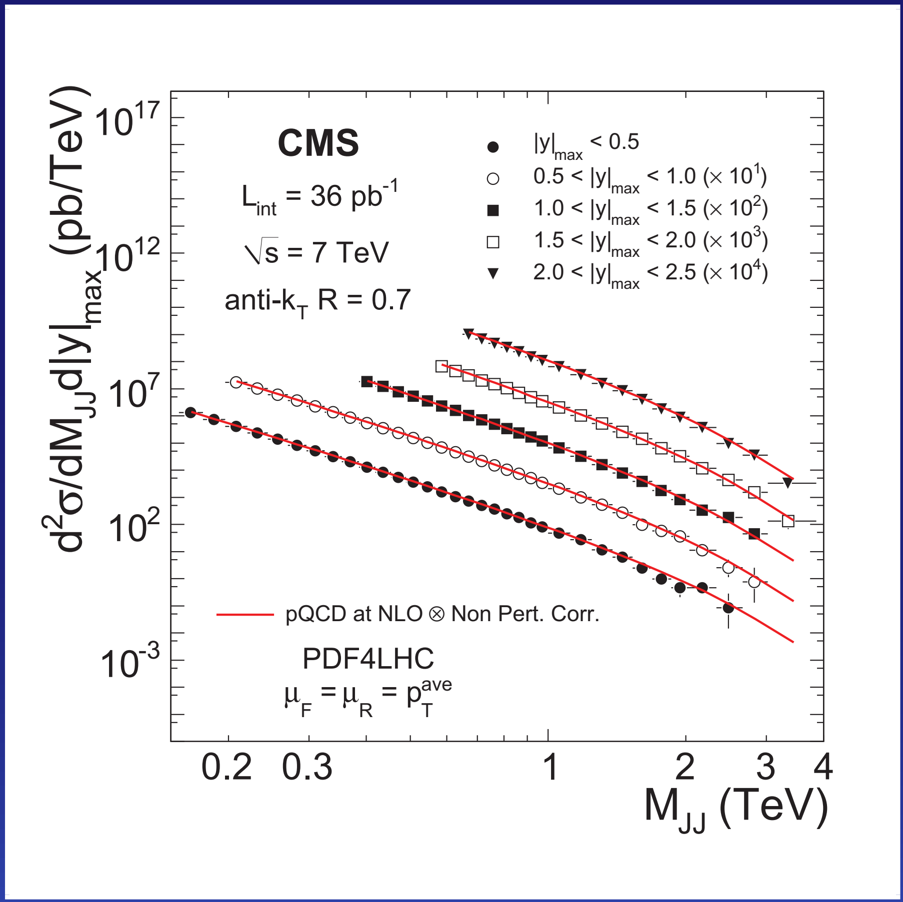


- NLO predictions are systematically above the data but within uncertainties; larger deviations at large $|y|$ and $p_\perp$

Cross sections ► di-jet events

- double differential cross-section in $|y|_{\max}$ and m_{12}
- both ATLAS and CMS use bin-by-bin corrections in the observed spectra derived from simulations
- deviations from the QCD would indicate new physics
  - compositeness, excited quarks
- good agreement with NLO QCD predictions is observed



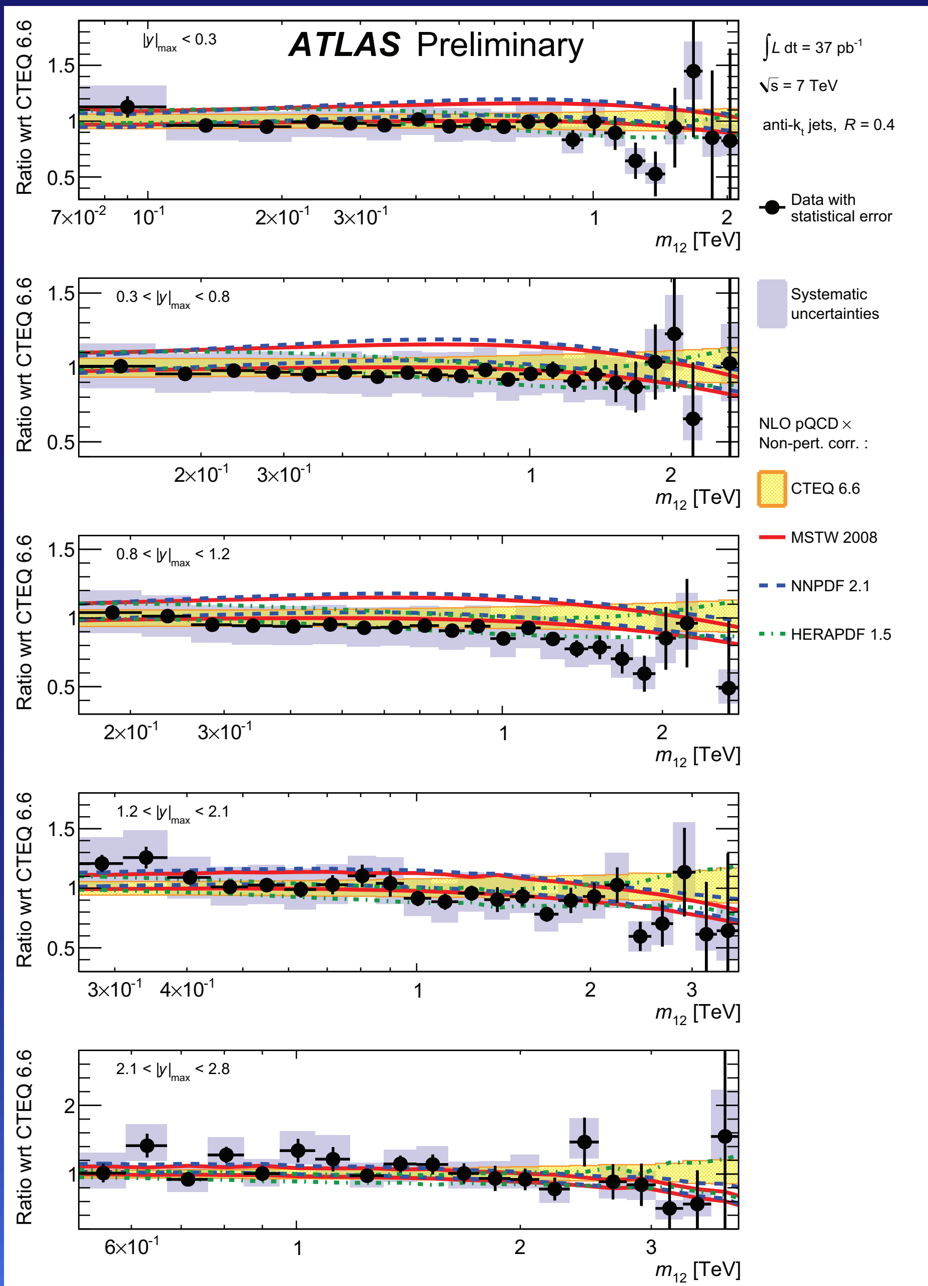


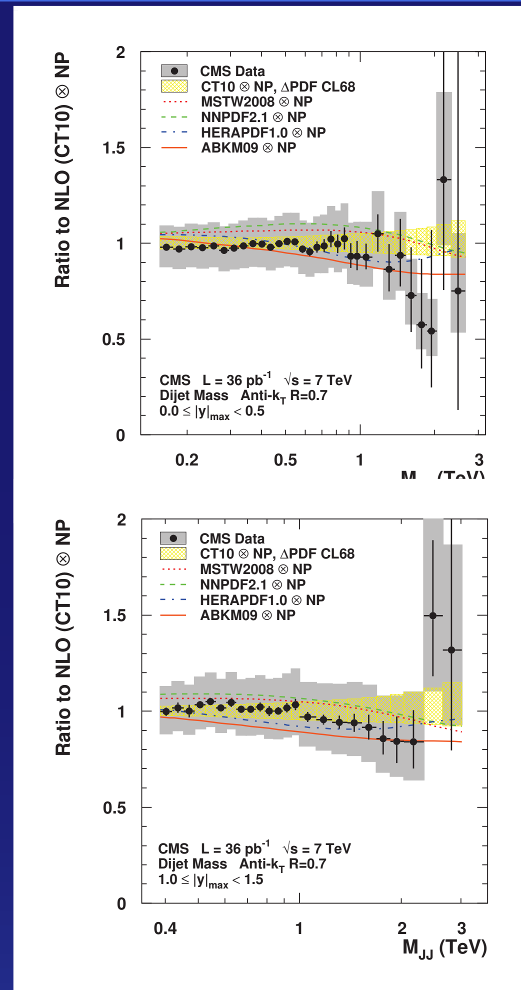
$R = 0.4$ (ATLAS) $R = 0.7$ (CMS)

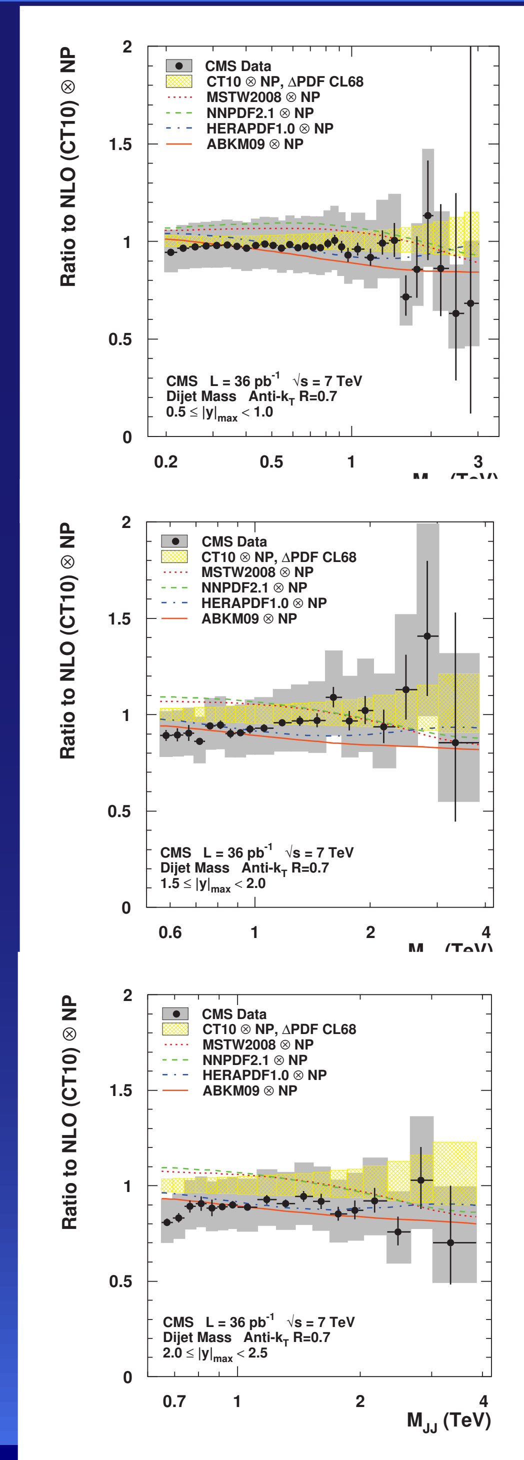
- dominant exp. systematic uncertainties stem from the Jet Energy Scale uncertainty (ATLAS+CMS)
  - $\sim 15 - 30\%$ (ATLAS)
  - $\sim 15\%$ at low mass; $\sim 60\%$ at high mass (CMS)

Di-jet Cross section ► comparison to different PDF sets

- data and PDF over prediction (ATLAS, `CTEQ 6.6`: left); (CMS, `CT10`: middle+right); for various $|y|_{\max}$ bins

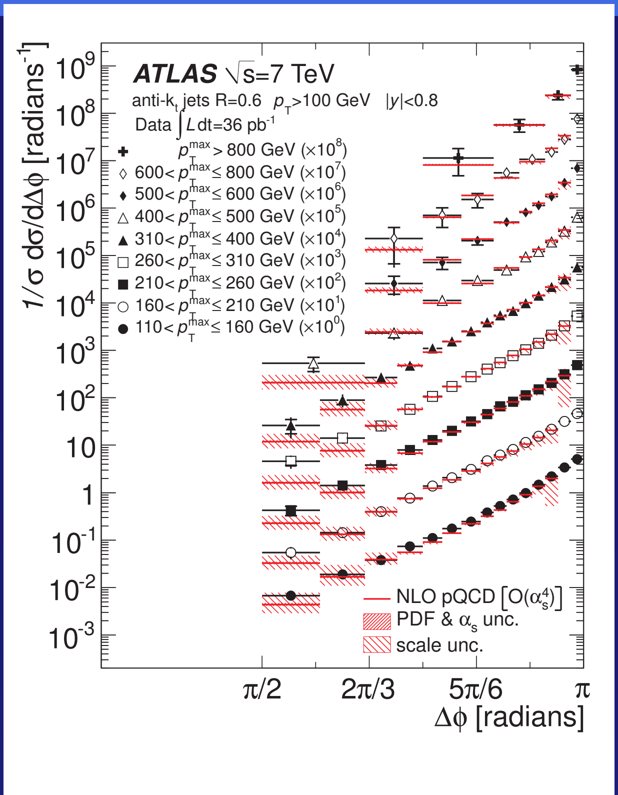




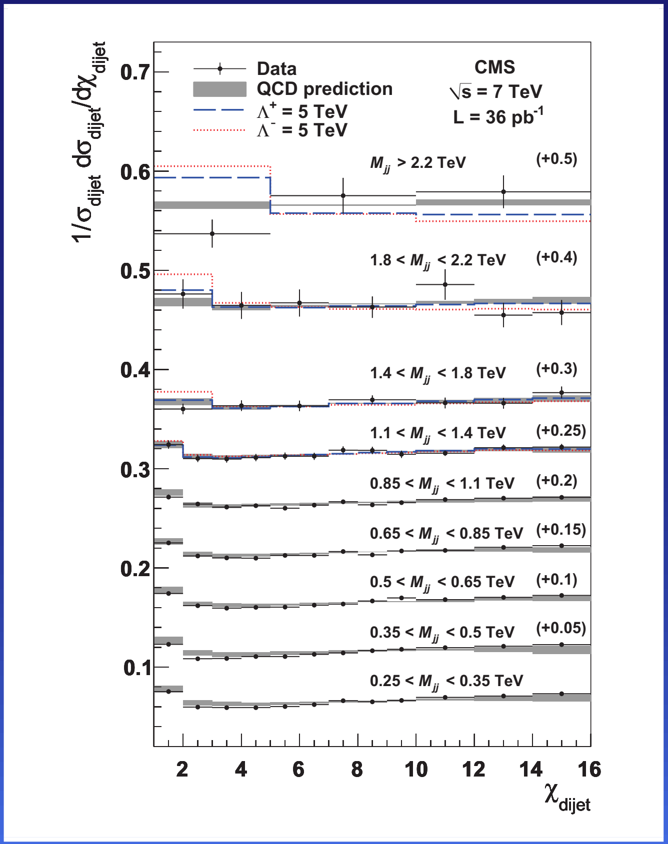


- `HERAPDF` closest to data for both ATLAS and CMS, but others agree as well within uncertainties

Di-jet Cross section ► angular properties

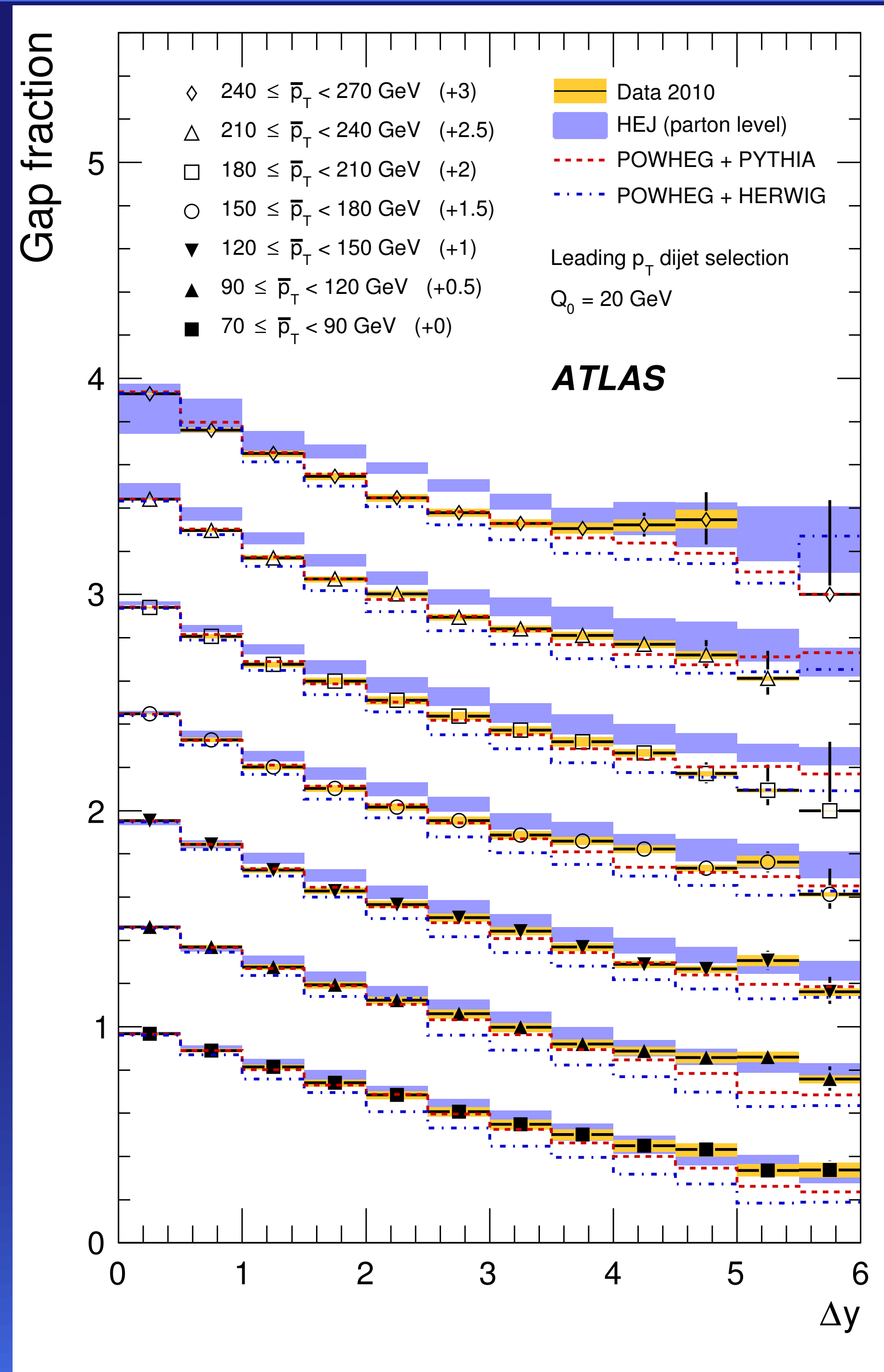


- ► Decorrelation in $\Delta\phi$ between two most energetic jets is indirect way to study radiation in di-jet events and to look for new physics
  - events with only two high-$p_\perp$ jets should have small decorrelations ($\Delta\phi \sim \pi$)
  - events with $\Delta\phi \ll \pi$ indicate more high-$p_\perp$ jets
  - plot to the right shows ATLAS data compared to NLO pQCD (`NLOJet++` with `MSTW2008`)
- ► NLO pQCD calculations agree with data for $\Delta\phi < \pi$
- ► leading log simulations (Pythia, Herwig, Sherpa) describe the data too including $\Delta\phi = \pi$

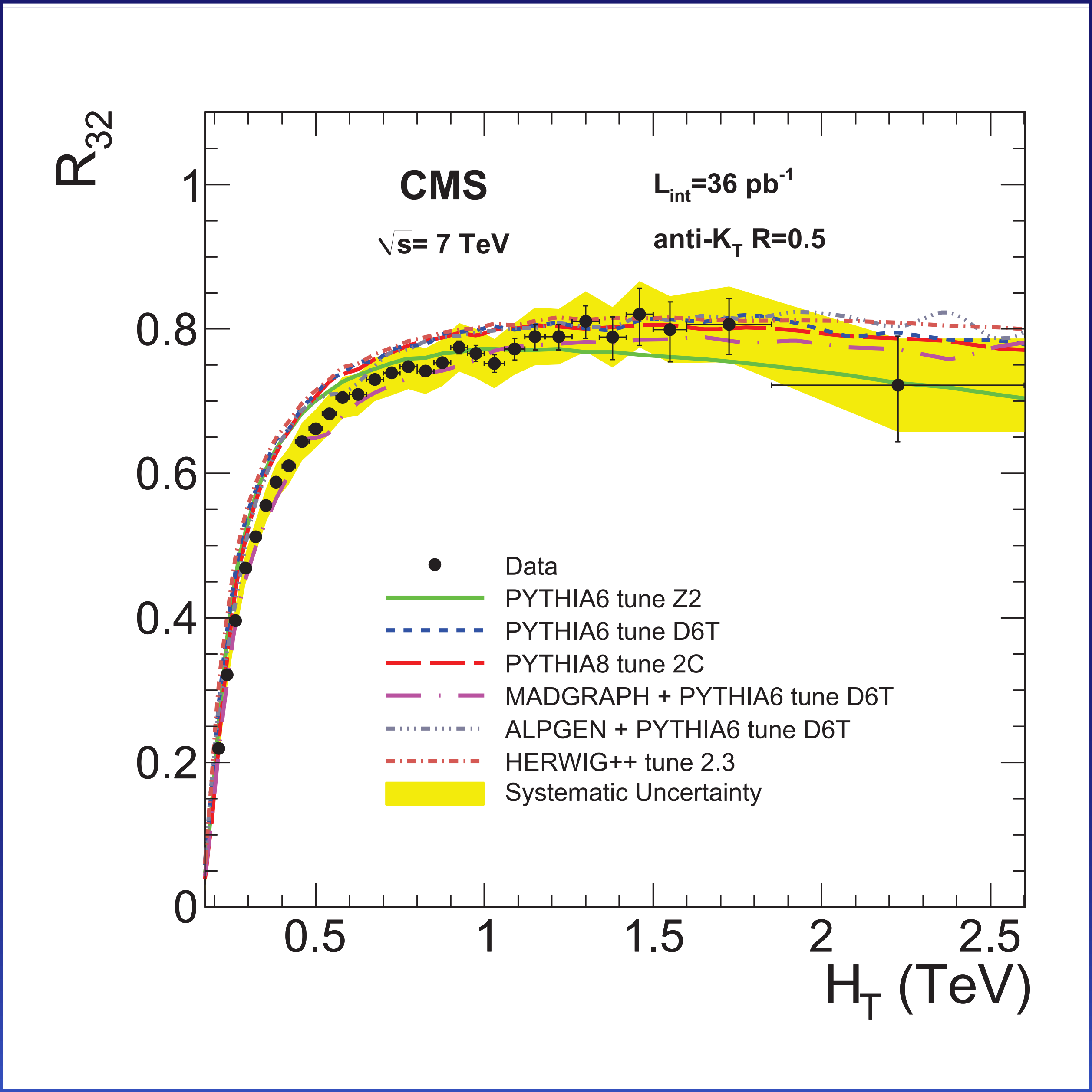


- ► Angular distributions in different di-jet mass bins are sensitive to new physics
  - $\chi = e^{|y_1 - y_2|} \simeq \frac{1 + |\cos\theta^*|}{1 - |\cos\theta^*|}$; correlated to inv. mass but independent of calibration
  - QCD is almost flat in χ, while new physics (compositeness) might peak at lower χ values
  - plot to the left shows CMS data compared to NLO pQCD (`NLOJet++` with `CTEQ 6.6`)
  - also plotted contact interactions with compositeness scale of $\Lambda^{\pm} = 5$ TeV ($\sim$ observed limits)
- ► NLO pQCD calculations agree with data

- Look at the activity inside the rapidity gap between a di-jet system defined by
  - either the two leading jets in $p_\perp$
  - or the two jets with the largest rapidity gap Δy
  - gap fraction is the fraction of events without additional jet activity in the rapidity interval between the jets
  - the veto scale is $Q_0 = 20$ GeV or larger to stay away from $\Lambda_{\rm QCD}$
- plot to the right shows gap fraction for leading jets in $p_\perp$ as function of Δy for various $p_\perp$ ranges (ATLAS)
- Powheg+Pythia describes data best; HEJ deviates at high $p_\perp$



Di-jet and Tri-jet events ► ratio R_{32}



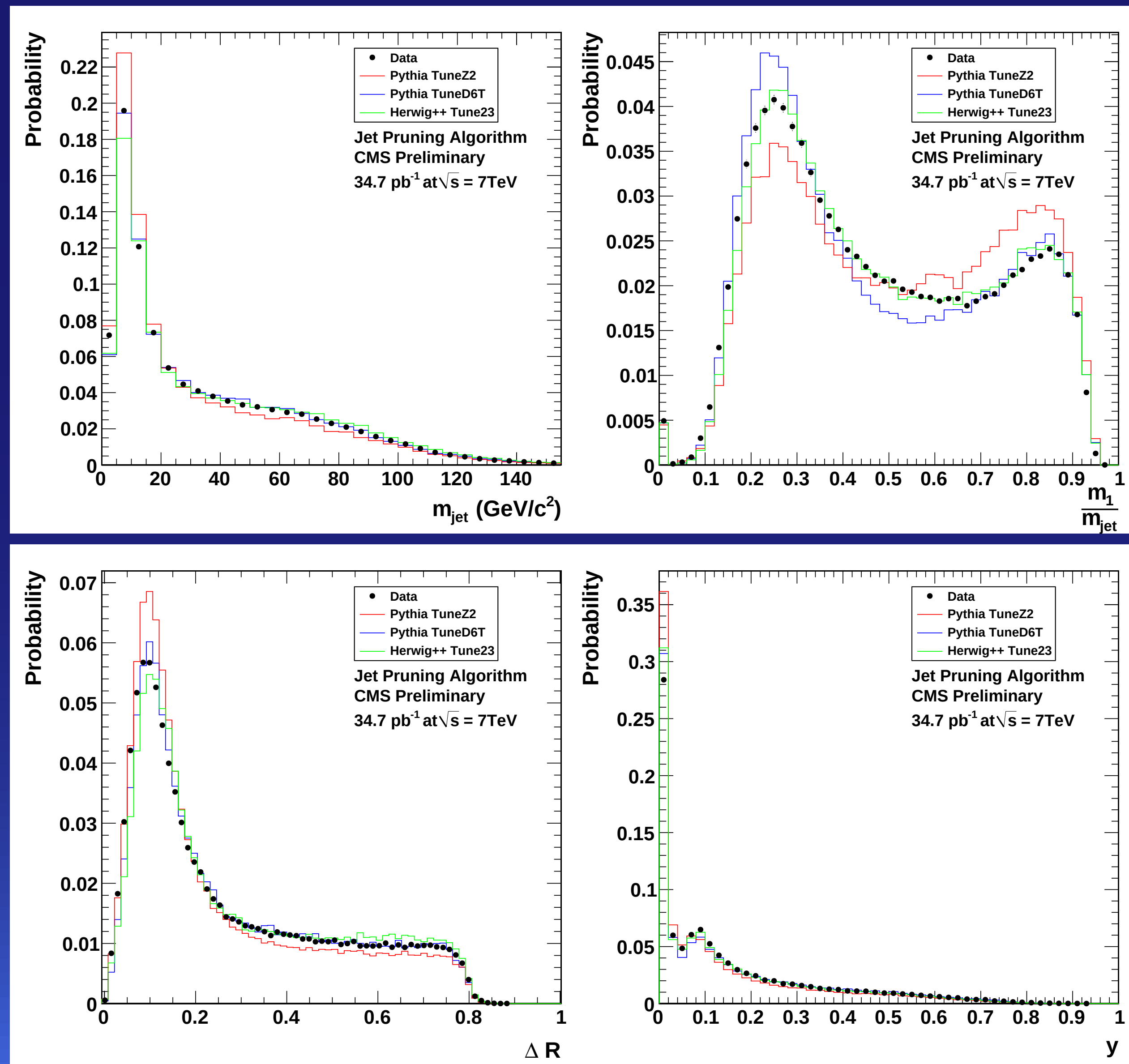
- Another measure of additional activity is the ratio of the inclusive 3-jet over the 2-jet cross sections
  - measured as function of the total transverse momentum $H_\perp = \sum |p_\perp^{\text{jet}}|$
  - jets are required to have $p_\perp > 50$ GeV and $|y| < 2.5$
  - uncertainties like jet energy scale and luminosity drop in the ratio
- plot to the left shows R_{32} as function of $H_\perp$ (CMS)
- different simulations agree for $H_\perp > 0.5$ TeV

Jet properties

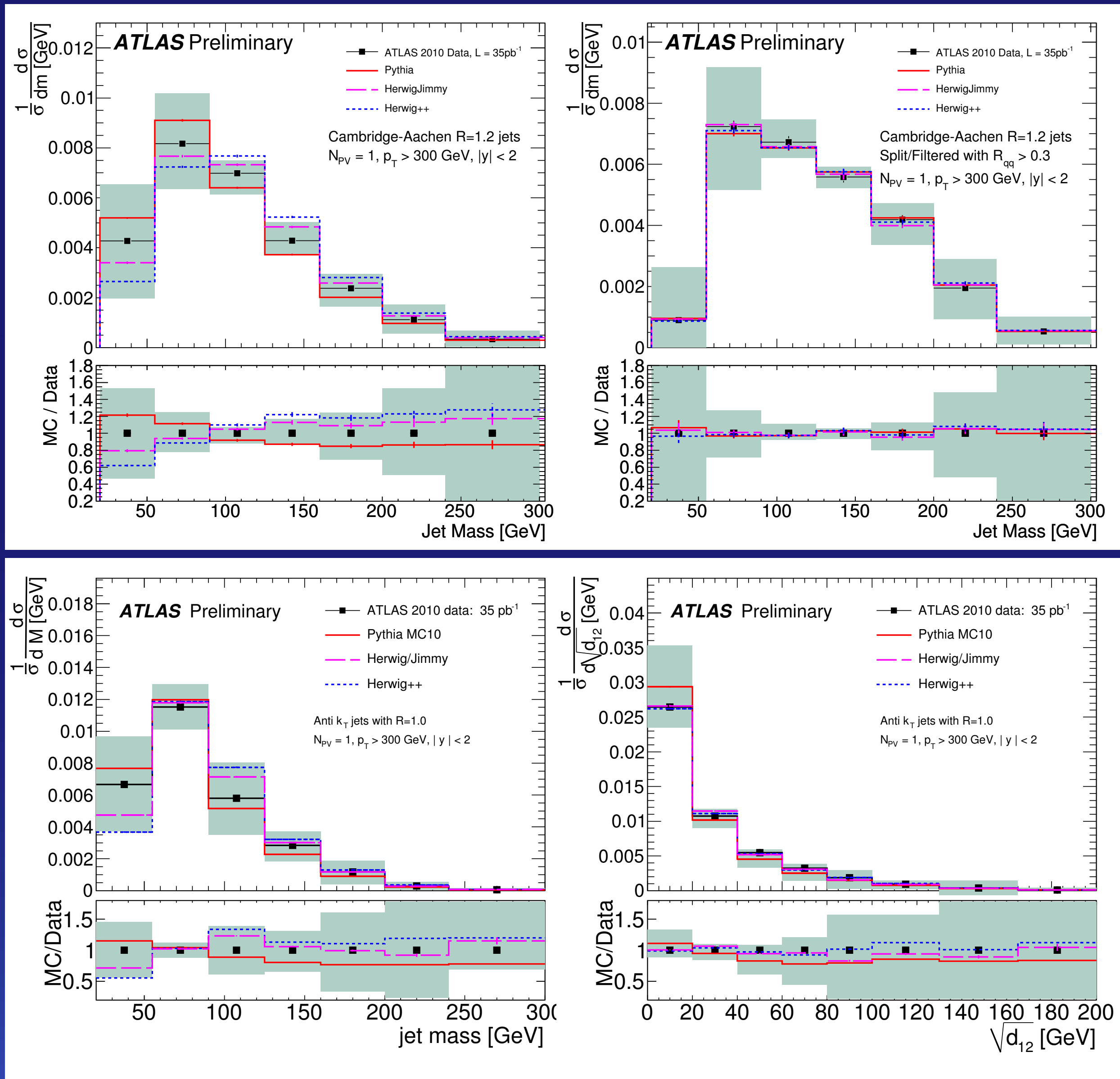
- Lots of different techniques to identify sub-structure inside jets mainly for boosted heavy objects
- C/A Filtering
  - reverse clustering of large Cambridge-Aachen ($R \simeq 1.2$) jets looking for a large drop in mass
  - recluster remaining constituents with smaller R
  - good for $\mathrm{H} \to \mathrm{bb}$ for example
- Trimming
  - find small $k_\perp$ subjets and remove those with small fraction of jet $p_\perp$
  - improves di-jet mass resolution for heavy di-jets
- Pruning
  - run C/A or kT on jet and check $\mathrm{min}(p_\perp^1, p_\perp^2)/p_\perp^{\mathrm{jet}} < z_{\mathrm{cut}}$ and $\Delta R_{1,2} > D_{\mathrm{cut}}$ in each step
  - if so discard the daughter with smaller $p_\perp$
  - removes radiation from heavy particles
- N-Subjettiness
  - test how well a jet can be described by N 4-vectors
  - add distances of all constituents to nearest sub-jet as measure
- lots of others ...

Jet properties ► sub structure

- For the jet sub structure algorithms to be useful they have to be tested on QCD jets as this will be the main background
- Jet pruning is studied in CMS for W tagging
  - C/A is used with $R = 0.8$
  - require at least 2 high $p_\perp > 200$ GeV jets with $\Delta\phi > 2.1$ and $|\eta| < 2.5$
- the plots show CMS data compared to two `Pythia` tunes and `Herwig++`
  - leading jet pruned mass (top left)
  - mass drop (ratio of masses of highest $p_\perp$ subjet to full jet) (top right)
  - subjet ΔR (bottom left)
  - subjet $p_\perp$ asymmetry $y = \left(\frac{\min(p_\perp^1, p_\perp^2) \times \Delta R_{1,2}}{m_{\rm jet}} \right)$ (bottom right)



Jet properties ► jet mass



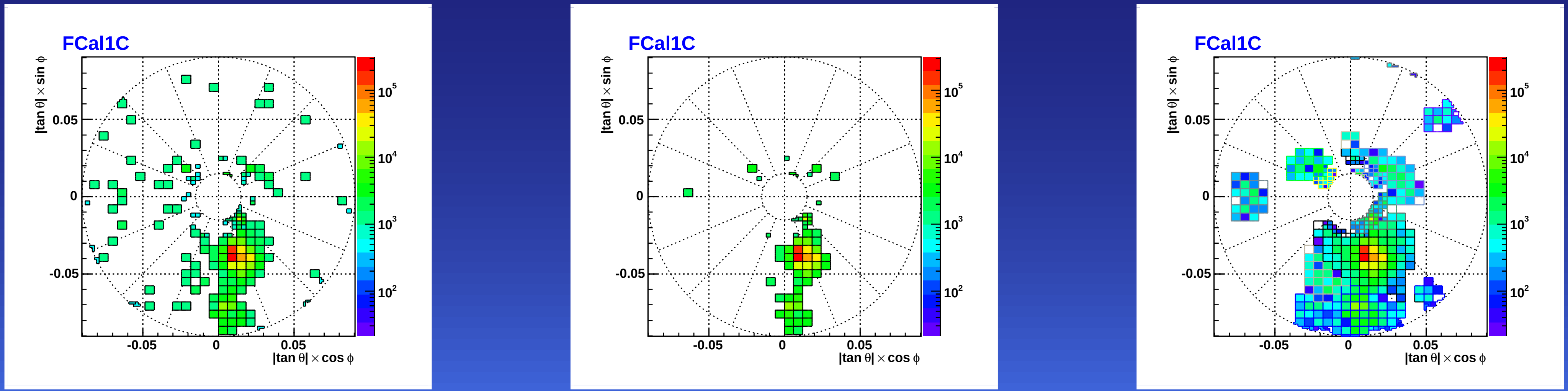
- Jet mass is studied in ATLAS to identify tops and in Higgs searches
  - either C/A with $R = 1.2$, $|y| < 2$ and $p_\perp > 300$ GeV and C/A splitting/filtering
  - or AntiKt with $R = 1.0$, $|y| < 2$ and $p_\perp > 300$ GeV and Kt reclustering
  - jets are made from calibrated topological clusters plus final jet energy scale
- the plots show ATLAS data compared to `Pythia`, `Herwig/Jimmy` and `Herwig++`
  - invariant mass of C/A jets before splitting and filtering (top left)
  - and after splitting and filtering (top right)
  - invariant mass of AntiKt jets (bottom left)
  - $\sqrt{d_{12}} = \min(p^1_\perp, p^2_\perp) \times \Delta R_{1,2}$ for the same jets (bottom right)
- For CMS `Herwig++` fits best, while it predicts slightly too high masses in ATLAS

Conclusions

- rich QCD program at ATLAS and CMS
- jet reconstruction and calibration
  - reconstruction algorithms like Particle Flow for CMS and Topological Clustering for ATLAS show very good performance
  - challenge on 2011 data is the increased amount of PileUp
- cross section measurements
  - both experiments have impressive results on inclusive and di-jet differential cross sections
  - most comprehensive studies of NLO pQCD predictions
  - excellent agreement with NLO calculations was found
  - regions of phase space not explored before already constrain PDF's
- jet properties
  - very exciting field to identify heavy boosted objects
  - QCD comparisons are vital to establish validity of the used methods
  - first results look very promising
- we are looking forward to the increased 2011 data set and the QCD results it will contain

- Calorimeter showers are grouped by a topological clustering algorithm into 3D energy blobs
- Noise related threshold control seeding and growth of the clusters
- Proto-clusters are split around local energy maxima
- Example below shows a typical simulated QCD event in forward region (just the first layer) with different noise thresholds and final clustering and splitting applied
- The algorithm suppresses calorimeter noise and leads to dynamically sized clusters corresponding on average to 1.6 final state particles

$|E| > 2\,\sigma_{\text{noise}}$ $|E| > 4\,\sigma_{\text{noise}}$ $4/2/0$ topological clusters



- Use all sub-systems to reconstruct stable particles
  - electrons from tracks linked to ECAL clusters
  - charged hadrons from tracks linked to ECAL+HCAL clusters
  - muons from links between tracker and muon system tracks
  - photons from ECAL clusters without links
  - neutral hadrons from remaining ECAL+HCAL clusters
- only neutral hadrons need hadronic calibration of calorimeter energy
- residual jet energy corrections on the order of $5 - 10\%$
- top plots show track links to ECAL (left) and HCAL (right) clusters
- bottom plots show PF reconstructed energy fractions from data (left) and simulation (right)