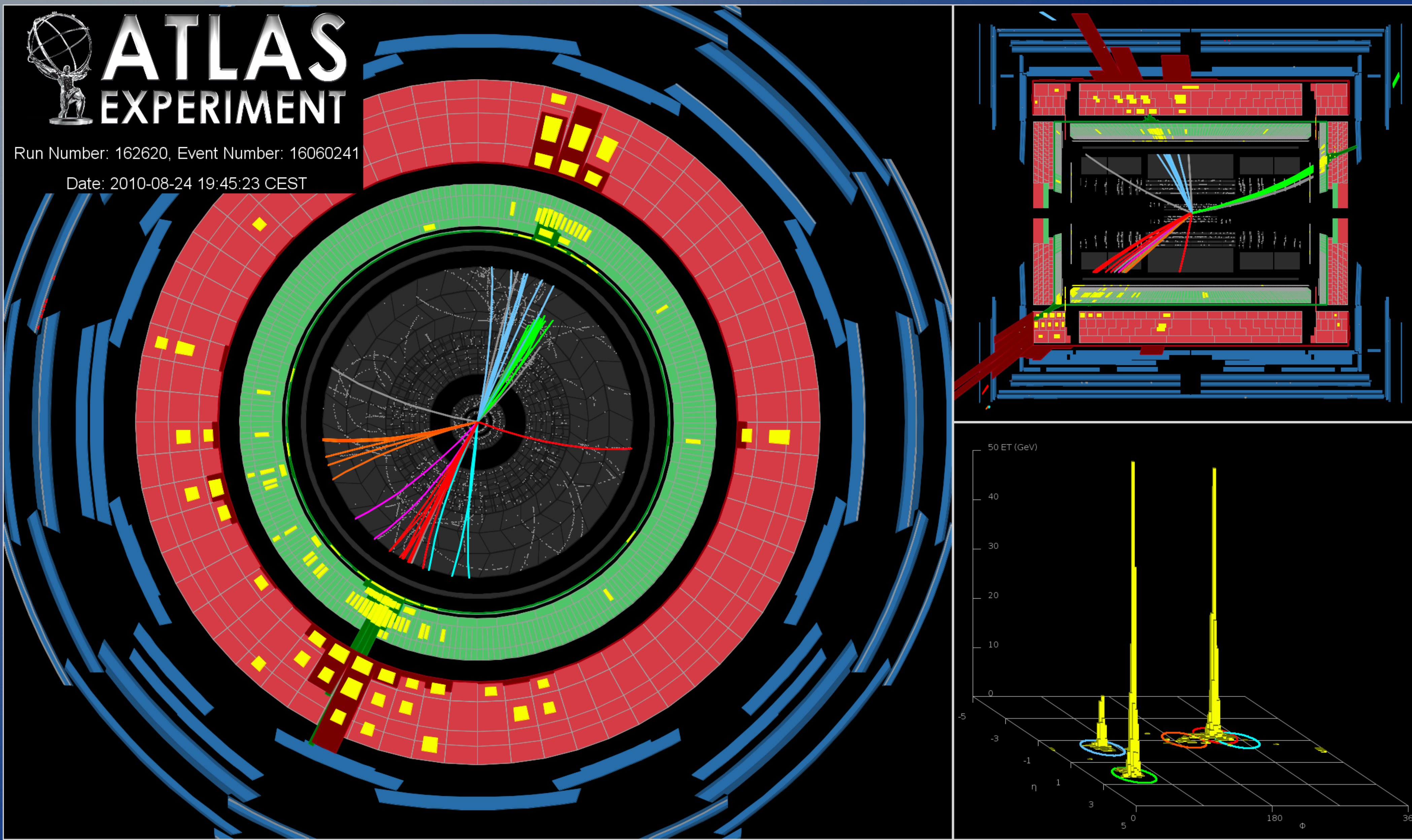
Hard QCD with ATLAS

why we do it, how we do it, what we learnt so far

Mario Campanelli/ UCL



Guidelines

Probe QCD in a new energy regime and with unprecedented detector coverage

Learn the lessons from the past, and provide state-of-the art publications that could serve as an example for the future

Collaborate with the theory community, some times as early as in the analysis preparation phase, and make results available using common tools (HEPData, Rivet)

More specifically, I will talk about

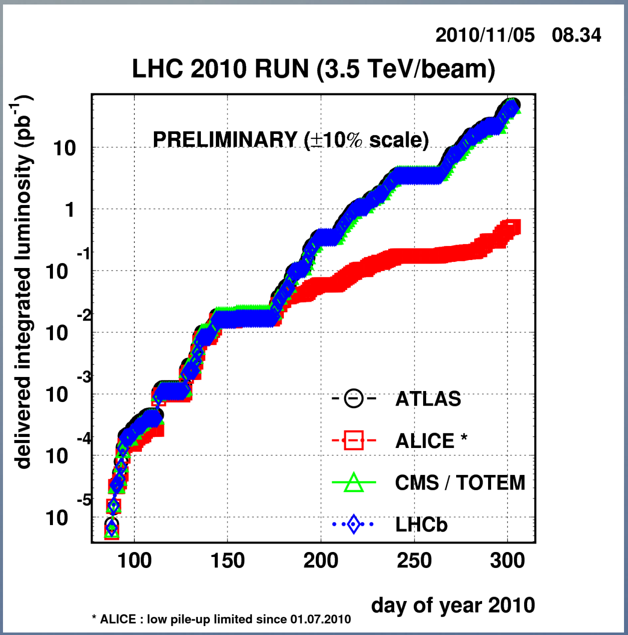
- Jets
  - triggers, calibration, JES
  - Jet proprties: shapes, fragmentation, mass
  - Inclusive and dijet cross section
  - b-jets
  - azimuthal de-correlations and jet veto
- Photons
  - Inclusive and di-photon cross-section
- Vector bosons
  - Inclusive production
  - Dibosons
  - W, Z + jets

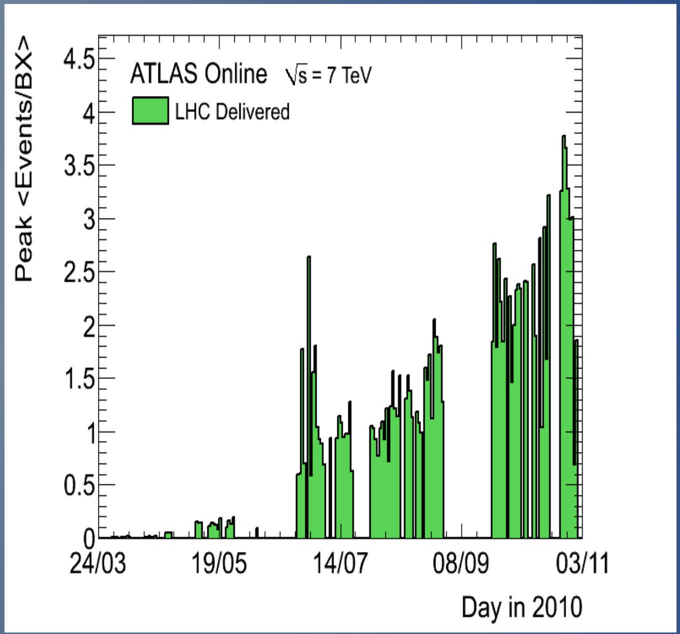
Caveat

This talk may look like “pictures from an exhibition”:
I will present many results, to give a bird's view of what Atlas has measured in the last year or so

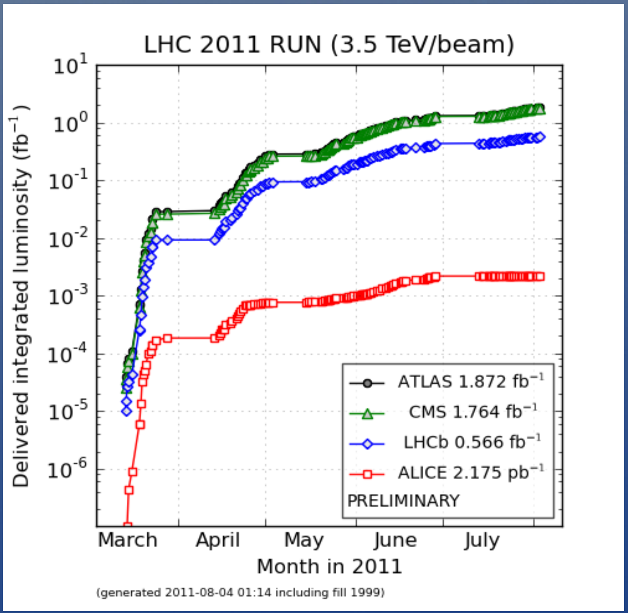
Do not hesitate to ask for more details
(or give suggestions)

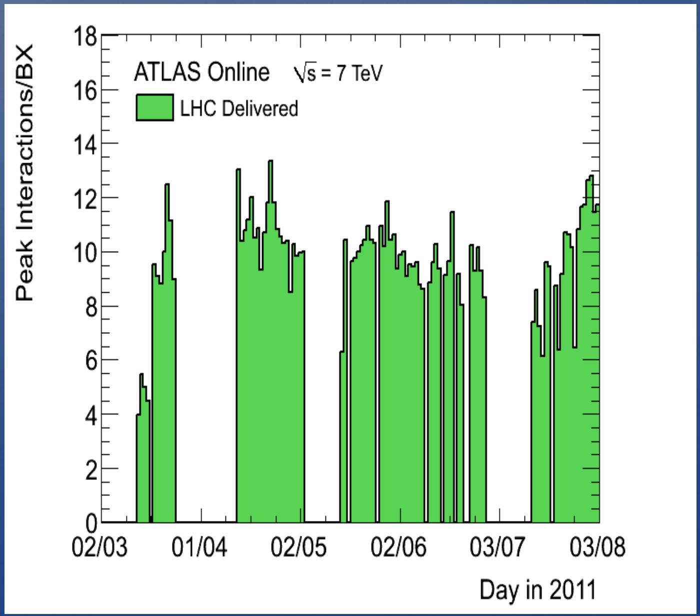
LHC performances: 2010 vs 2011

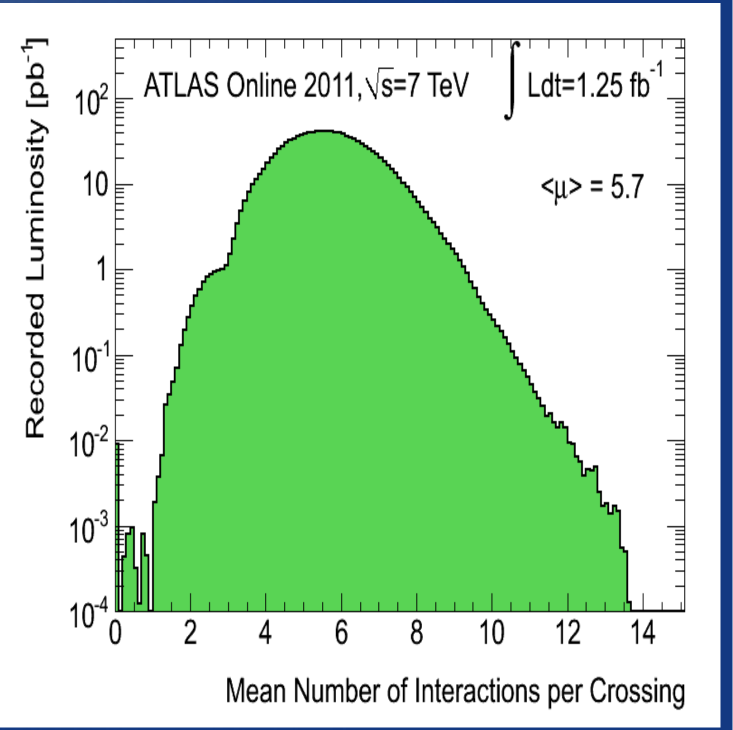




Interest of 2010 data lies in the low pileup, and in the low prescales of soft triggers (most of low-Pt jets and photons taken in the first months of 2010!)



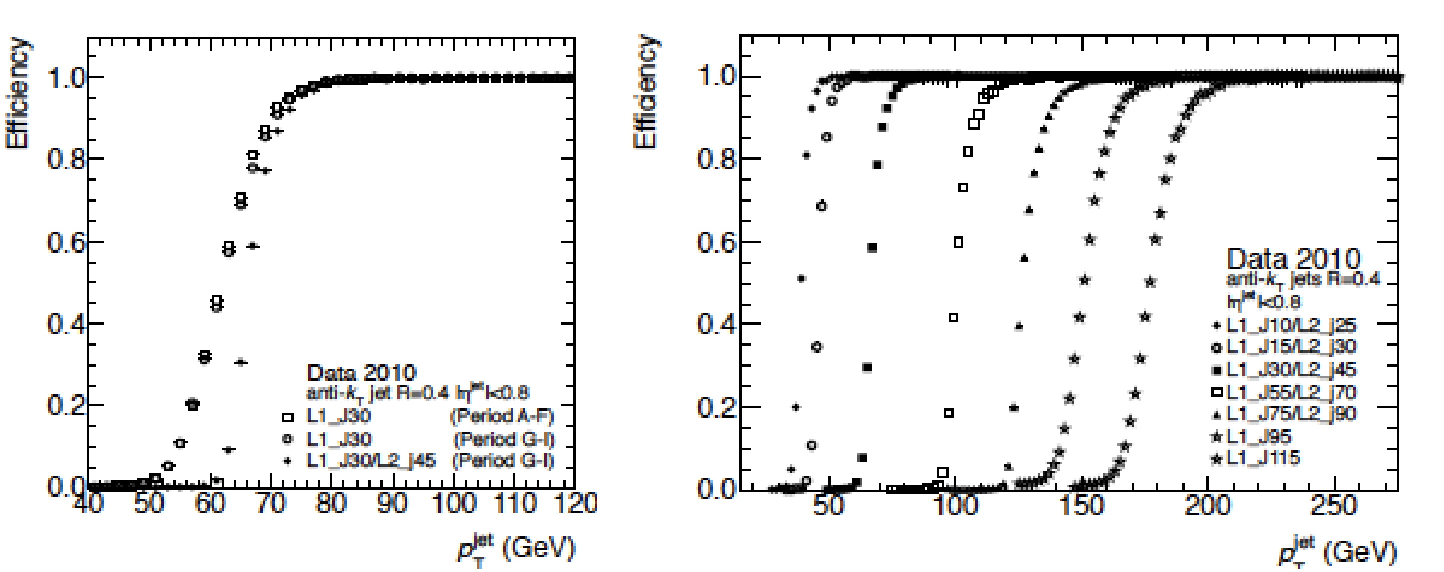




Triggering on jets

Last year in Atlas we had a rich jet trigger menu, with inclusive jets, dijets, multijets, sum et; also topological triggers cutting on Δη or ΔΦ were used.

The menu is even more complicated this year, with asymmetric multijets, low-pt thresholds seeded by the random trigger and virtual thresholds

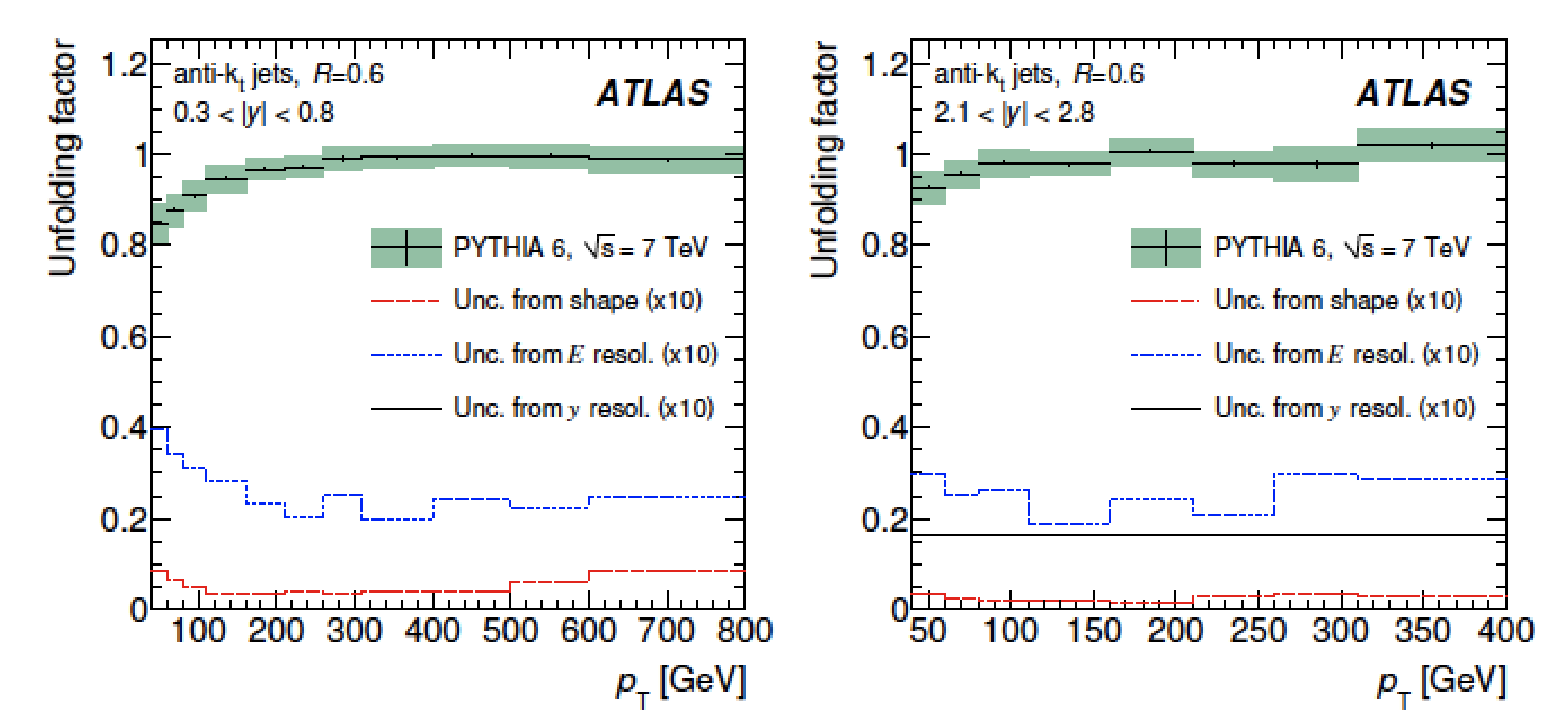


(a) efficiency for different data periods

(b) efficiency over all data periods

Since typically each trigger takes a constant rate (0.5 Hz), apart from the highest momenta the collected luminosity is proportional to the running time rather than to integrated one.

Correction for detector effects

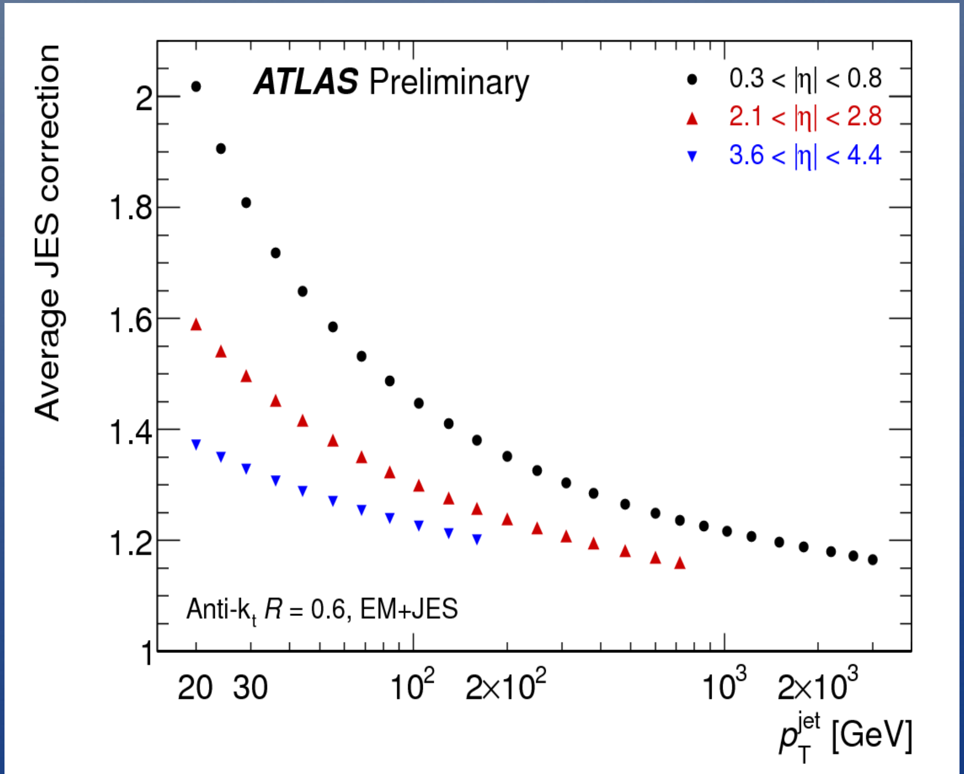


Results we want to publish should be corrected for efficiency and resolution inside a well-defined phase-space region, and are directly compared to hadron level. So far still using bin-by-bin unfolding: in each distribution data is corrected by hadron/reconstruction level ratio in MC; inclusive jet paper will use iterative

Energy scale calibration

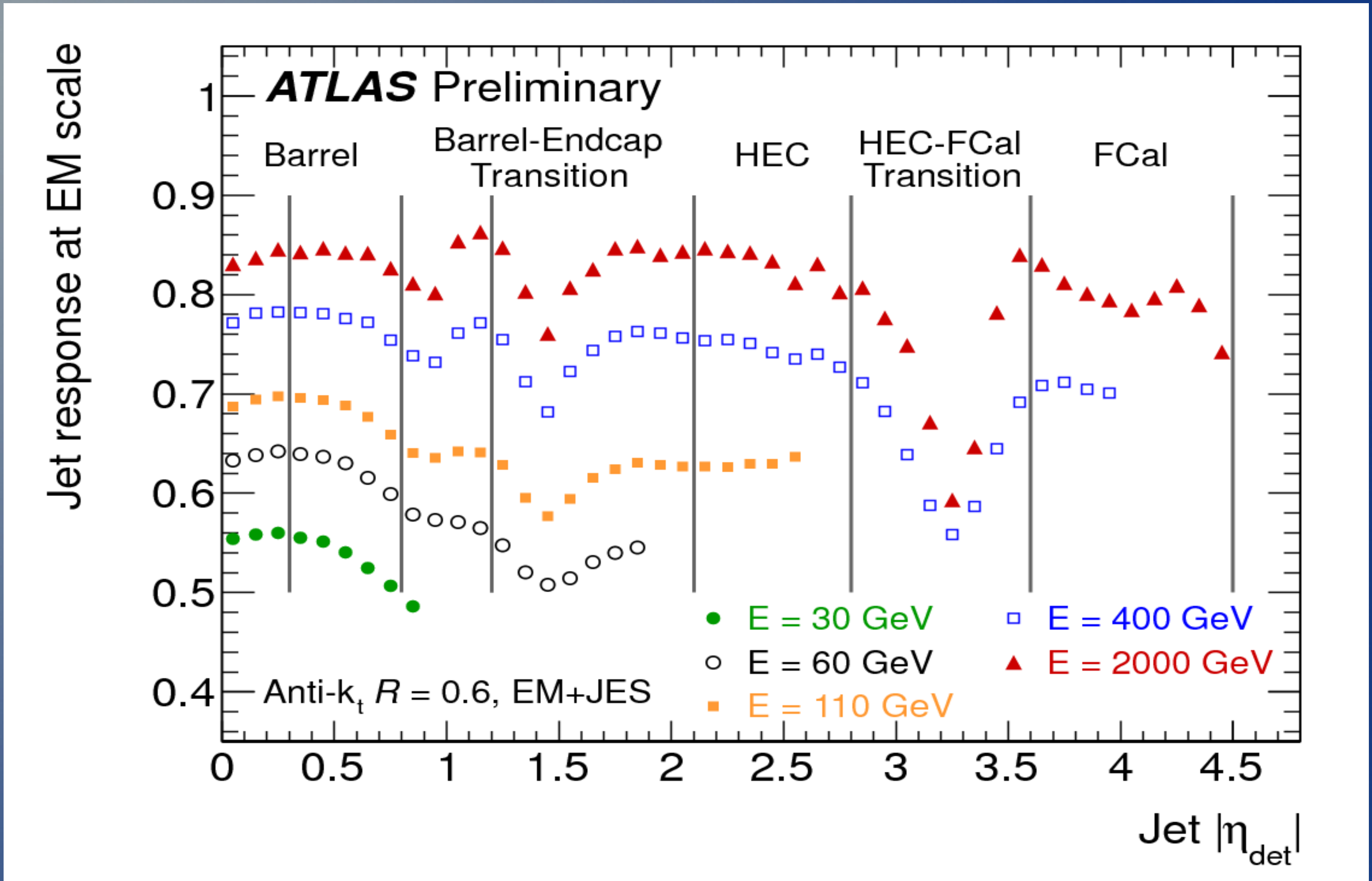
ATLAS-CONF-2011-032

In 2010, lacking enough statistics to perform a proper in-situ calibration with γ-jet balancing, calibration constants have been derived from MonteCarlo. For added stability, calibration constants were applied to the sum (em+had), not separately to the two components.



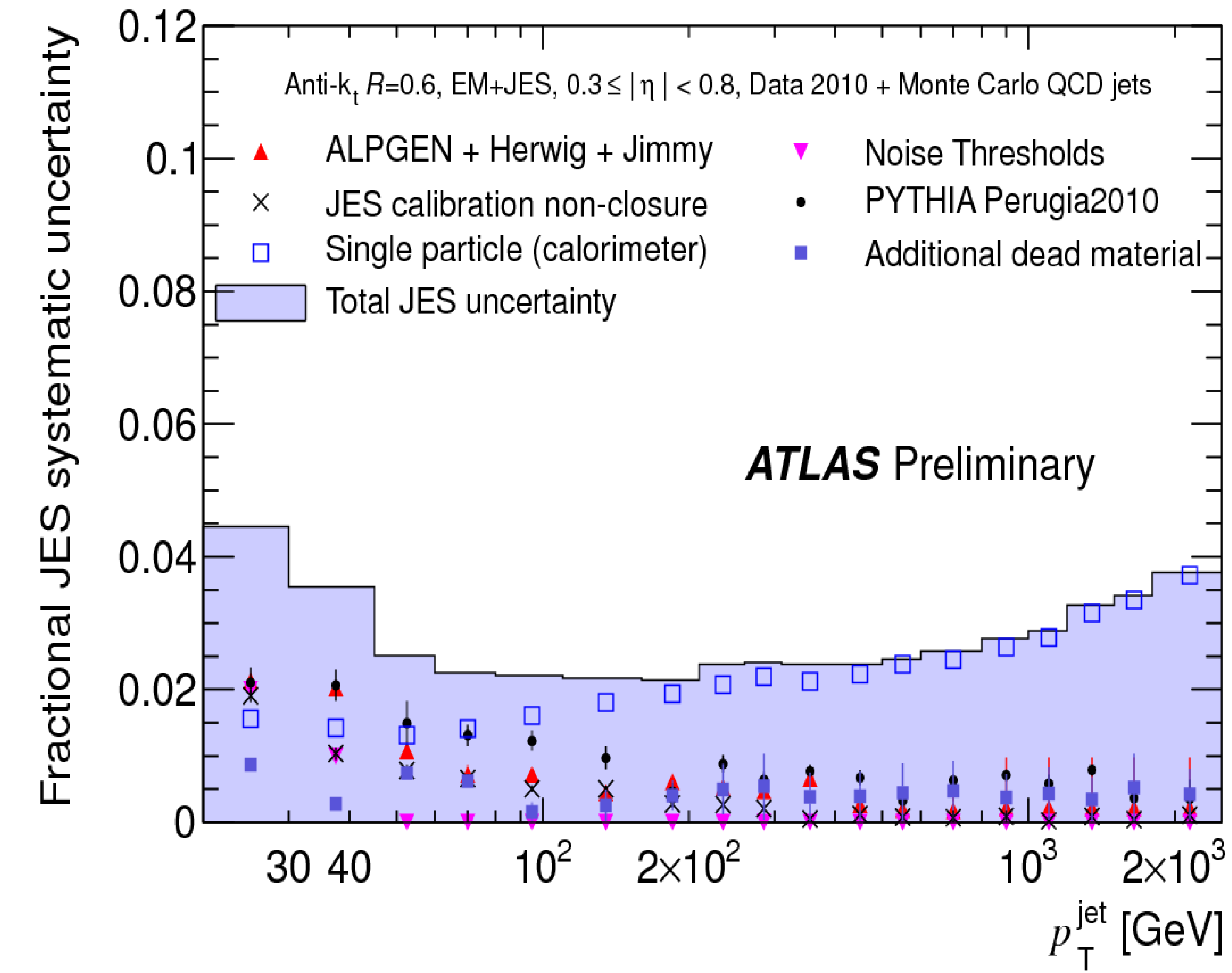
Correction factors depend on jet Pt and eta, and have been cross-checked with test-beam data, single-particle response and track jets. Also cross-checked with limited statistics using γ-jet and dijet balancing. A proper calibration accounting for the energy deposited in each calorimeter layer is used in the analysis of 2011 data

Simulated Calorimeter response



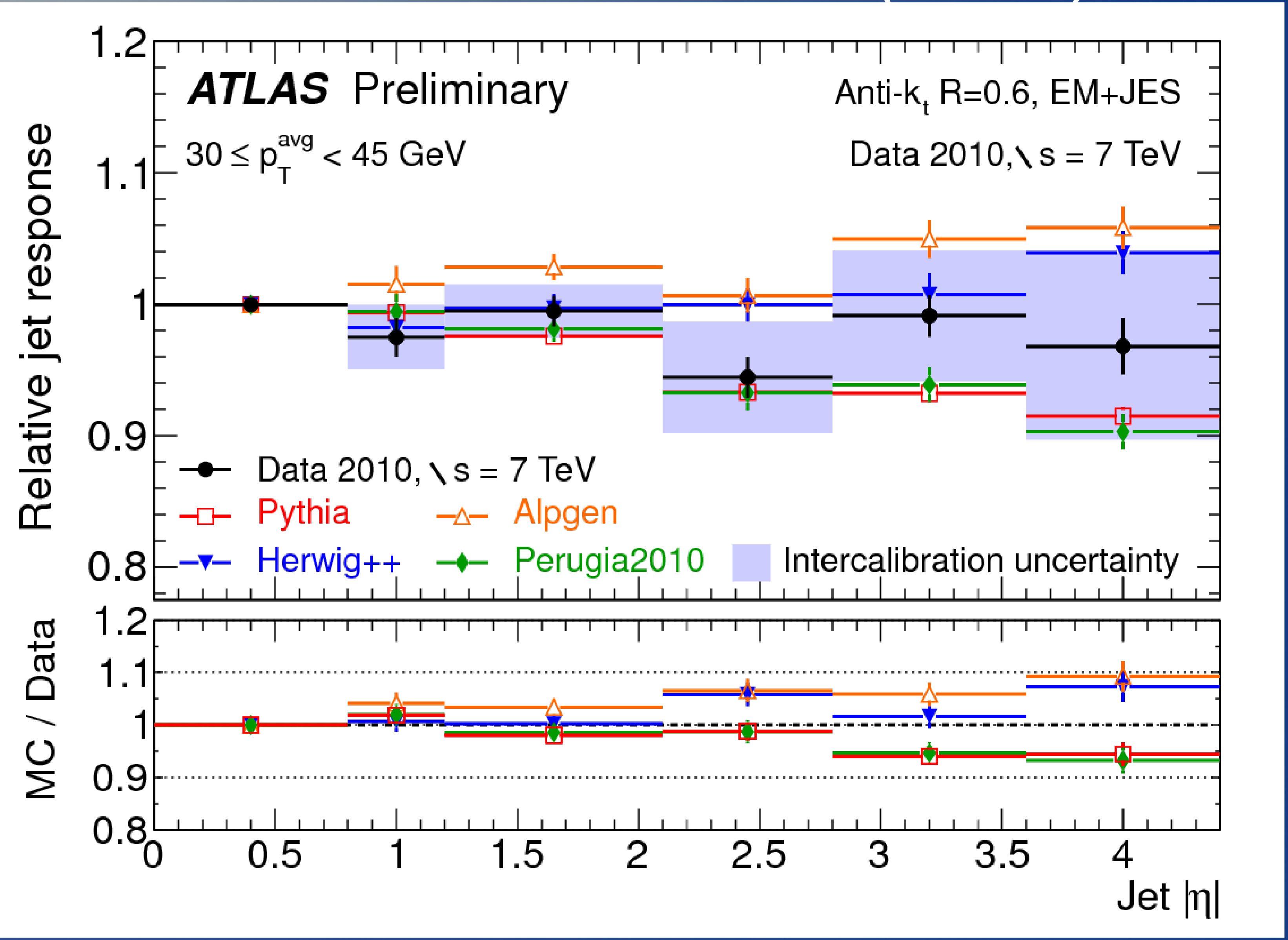
Inverse of correction factors used in JES calibration, for various jet momenta and rapidity.
We clearly see the transition regions between the various calorimeters

Jes uncertainty in 2010



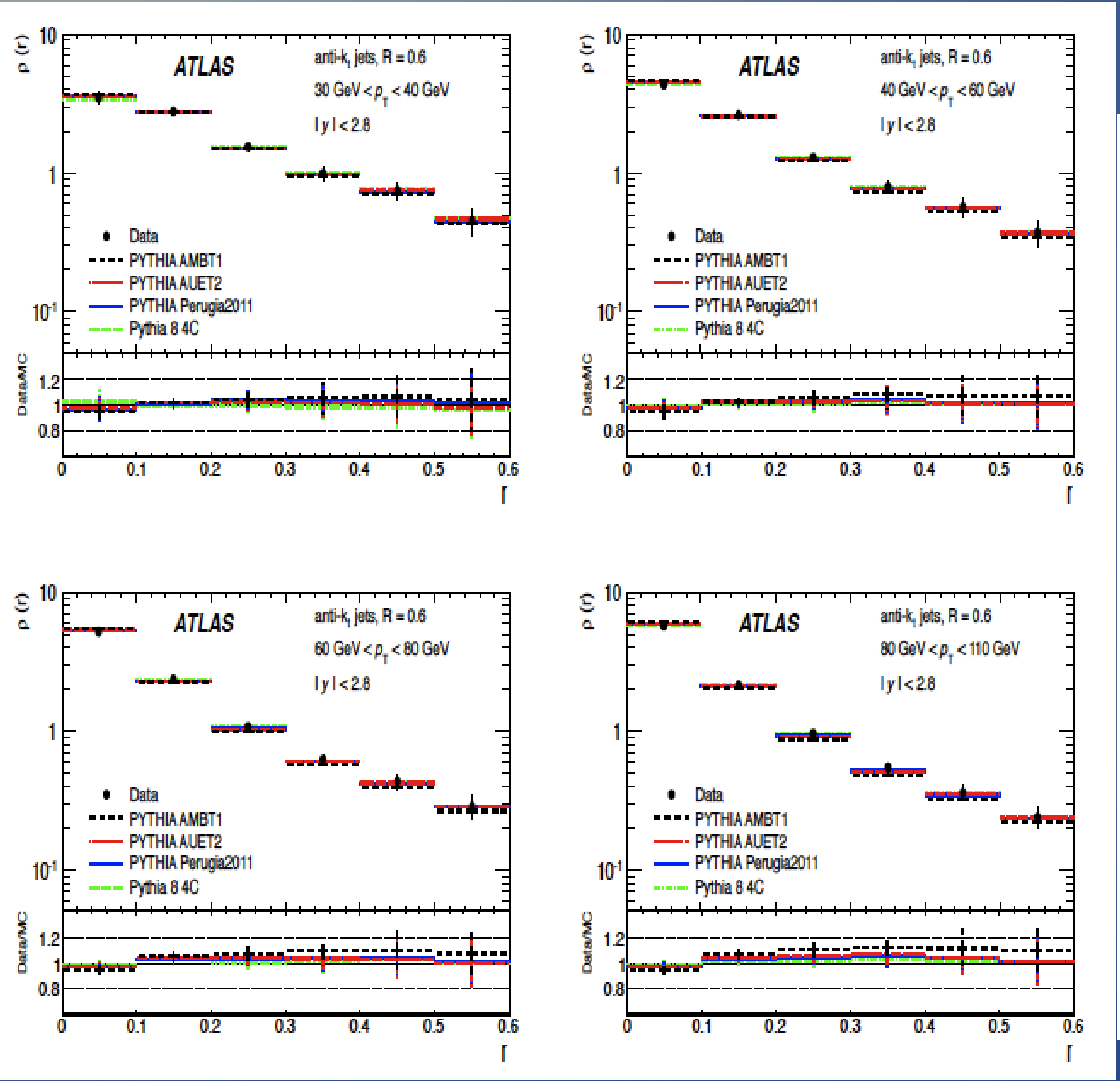
Largest source of systematics for any steeply-falling distribution, and a lot of effort to reduce it.
Already a factor 2 better than last summer's result
Dominated by statistics of single particle response

Forward JES calibration and (more) uncertainty

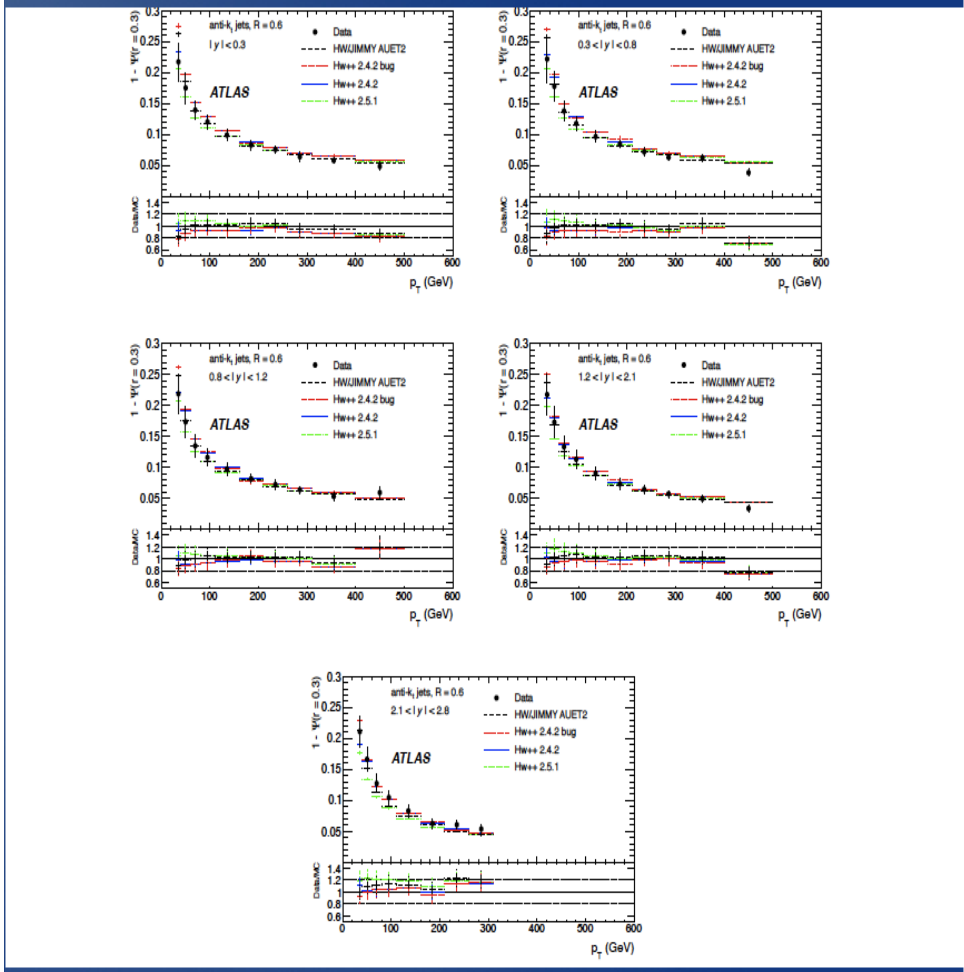


Without tracking, the only way to cross-check the JES in the forward region is central-forward jet balance, in the limit of vanishing third jet. Dicrepancies O(10%) have been found, going in opposite directions between Pythia and Herwig (Alpgen + Herwig) showering. Additional systemetic uncertainties applied.

Are they really jets as we expect from QCD?



→ Jet shapes (ATL-PHYS-PUB-2011-010)

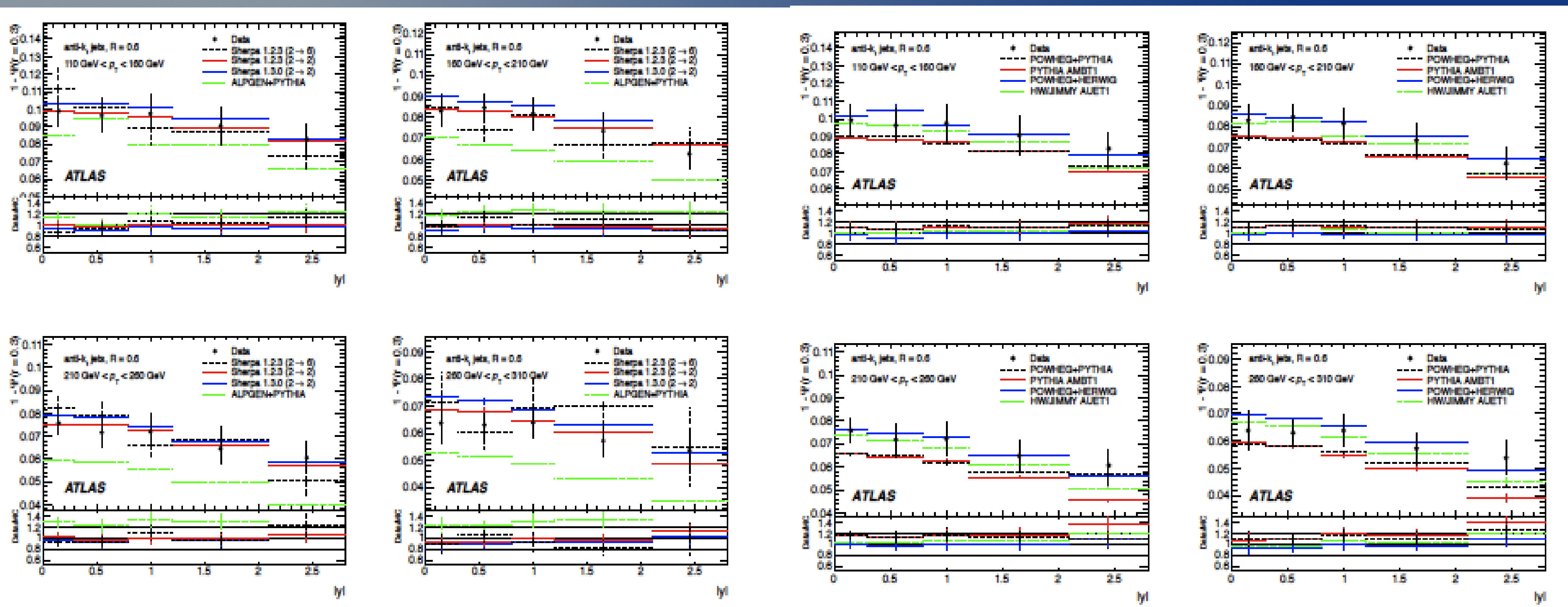


Measure differential and integral jet shape for various hadronisation models

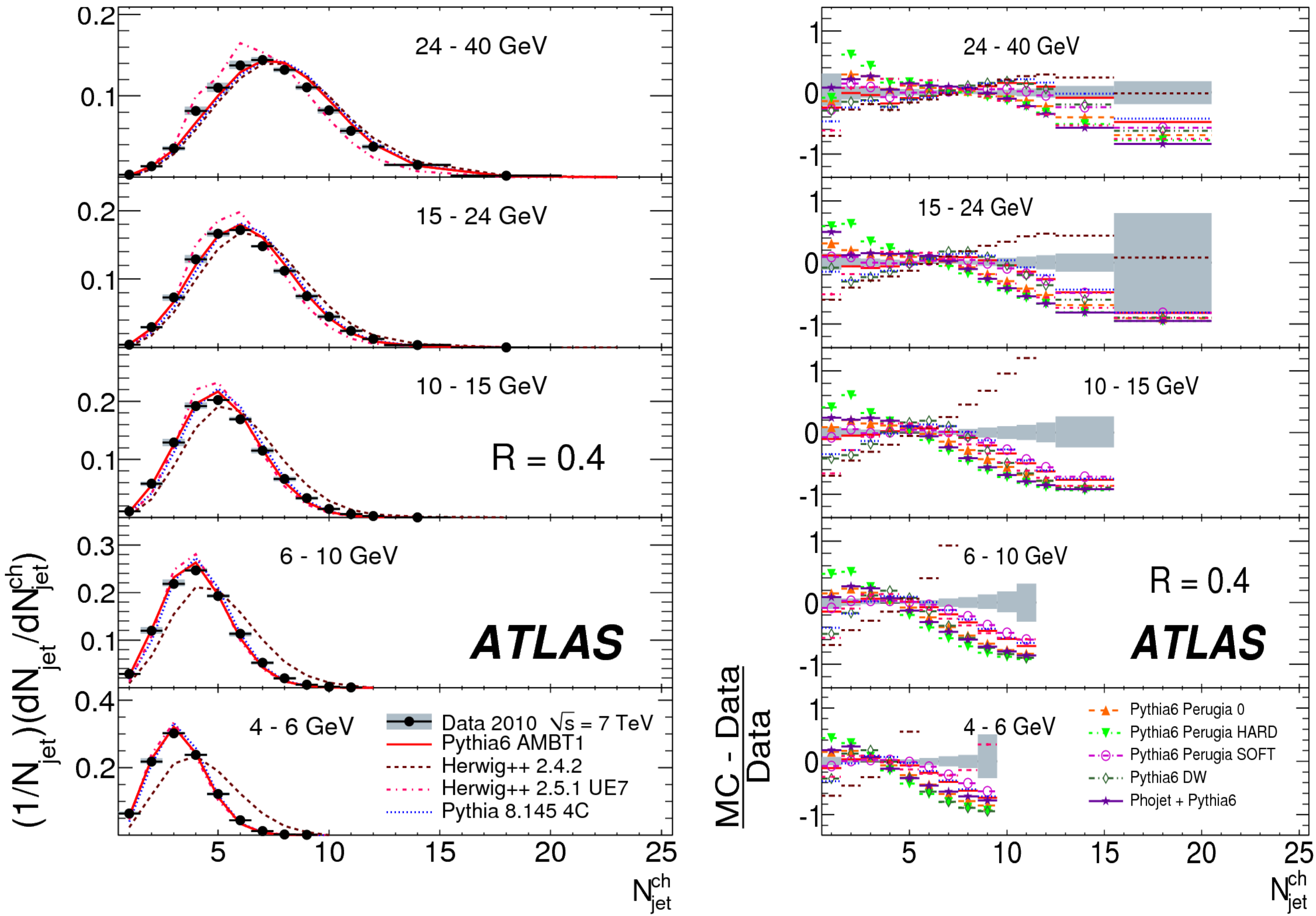
$$\rho(r) = \frac{1}{\Delta r}\frac{1}{N^{\rm jet}}\sum_{\rm jets}\frac{p_T(r-\Delta r/2, r+\Delta r/2)}{p_T(0,R)},\ \Delta r/2 \le r \le R - \Delta r/2,$$

$$\Psi(r) = \frac{1}{N^{\rm jet}}\sum_{\rm jets}\frac{p_T(0,r)}{p_T(0,R)},\ 0 \le r \le R,$$

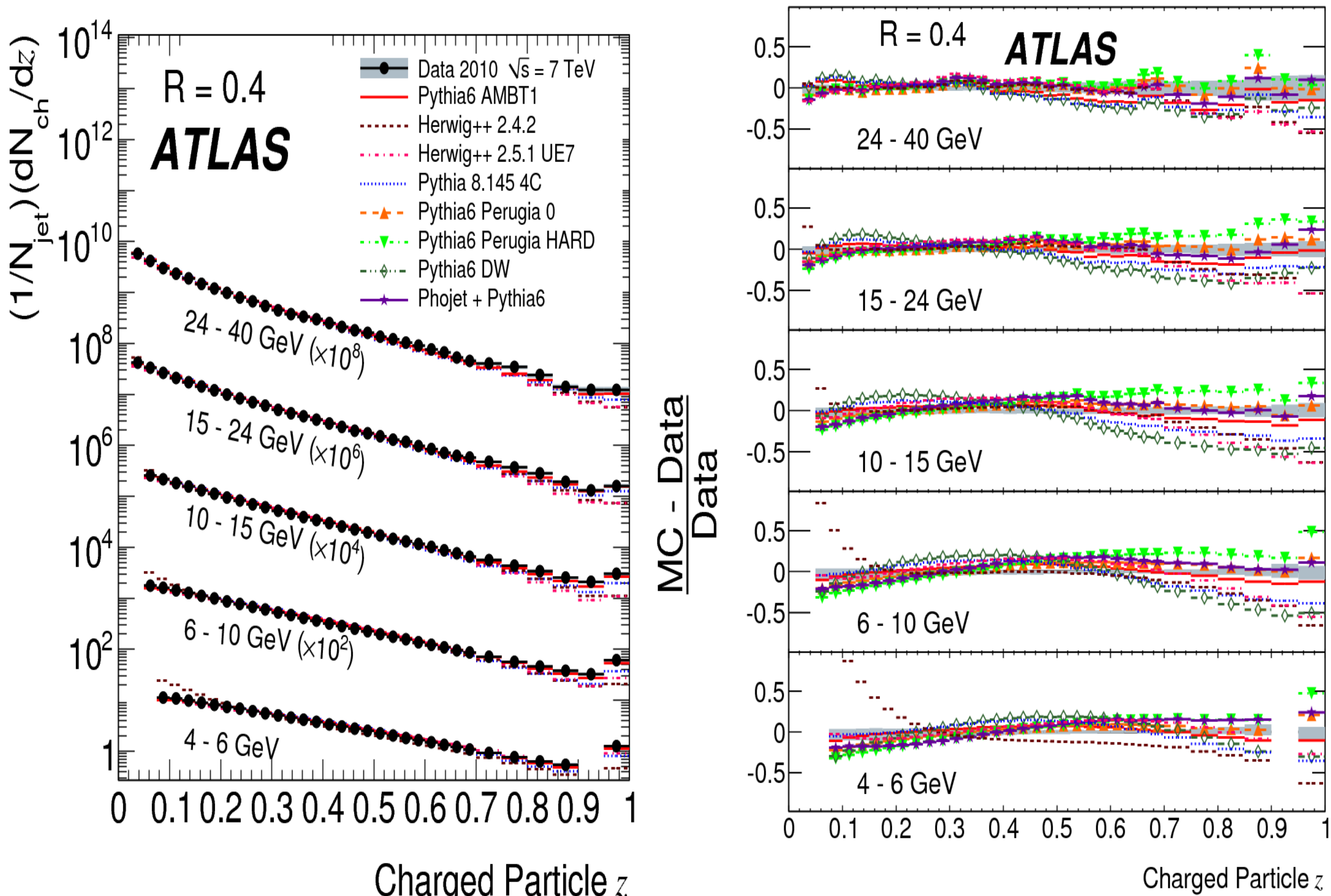
Rapidity dependence



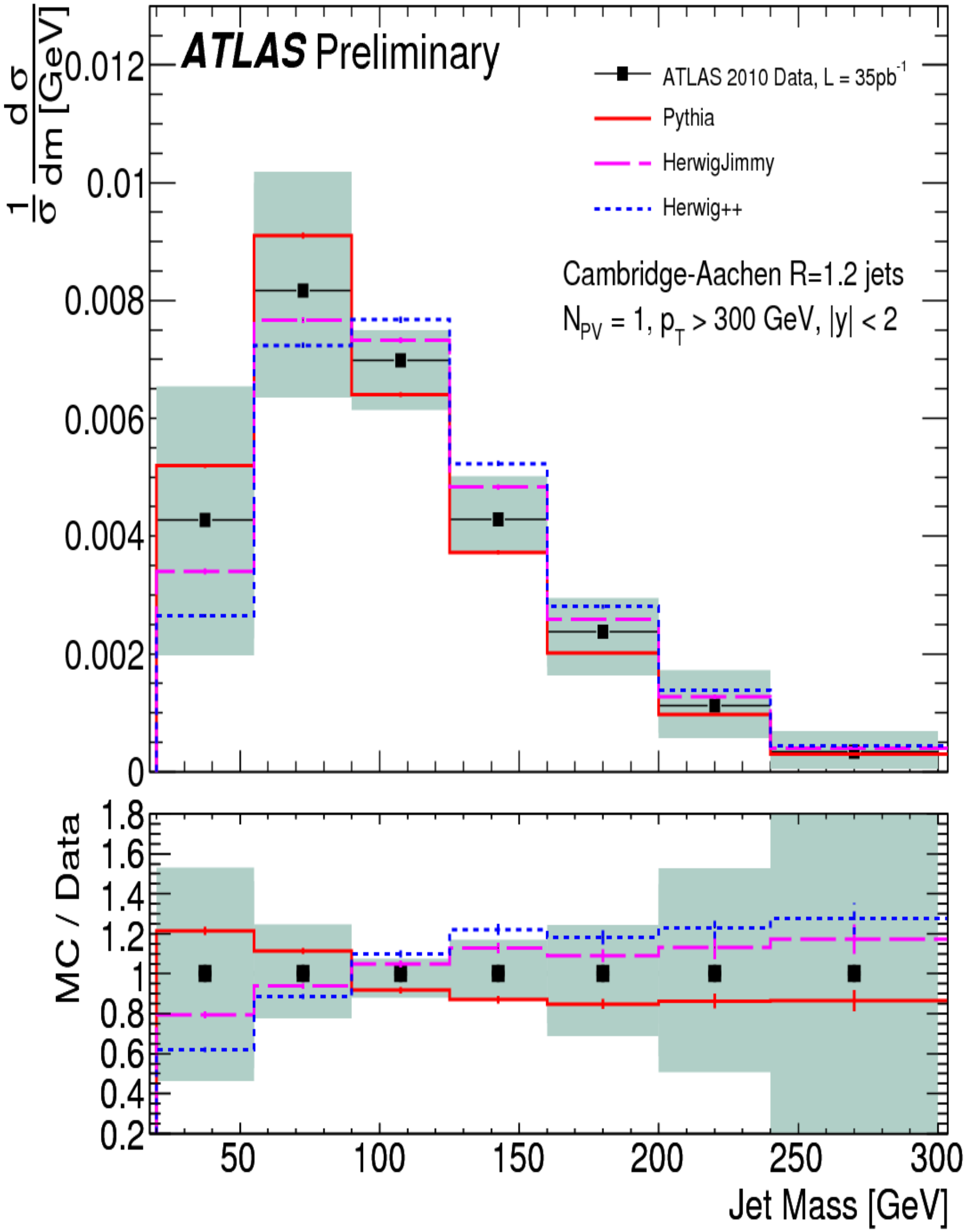
Charged particle multiplicity in jets

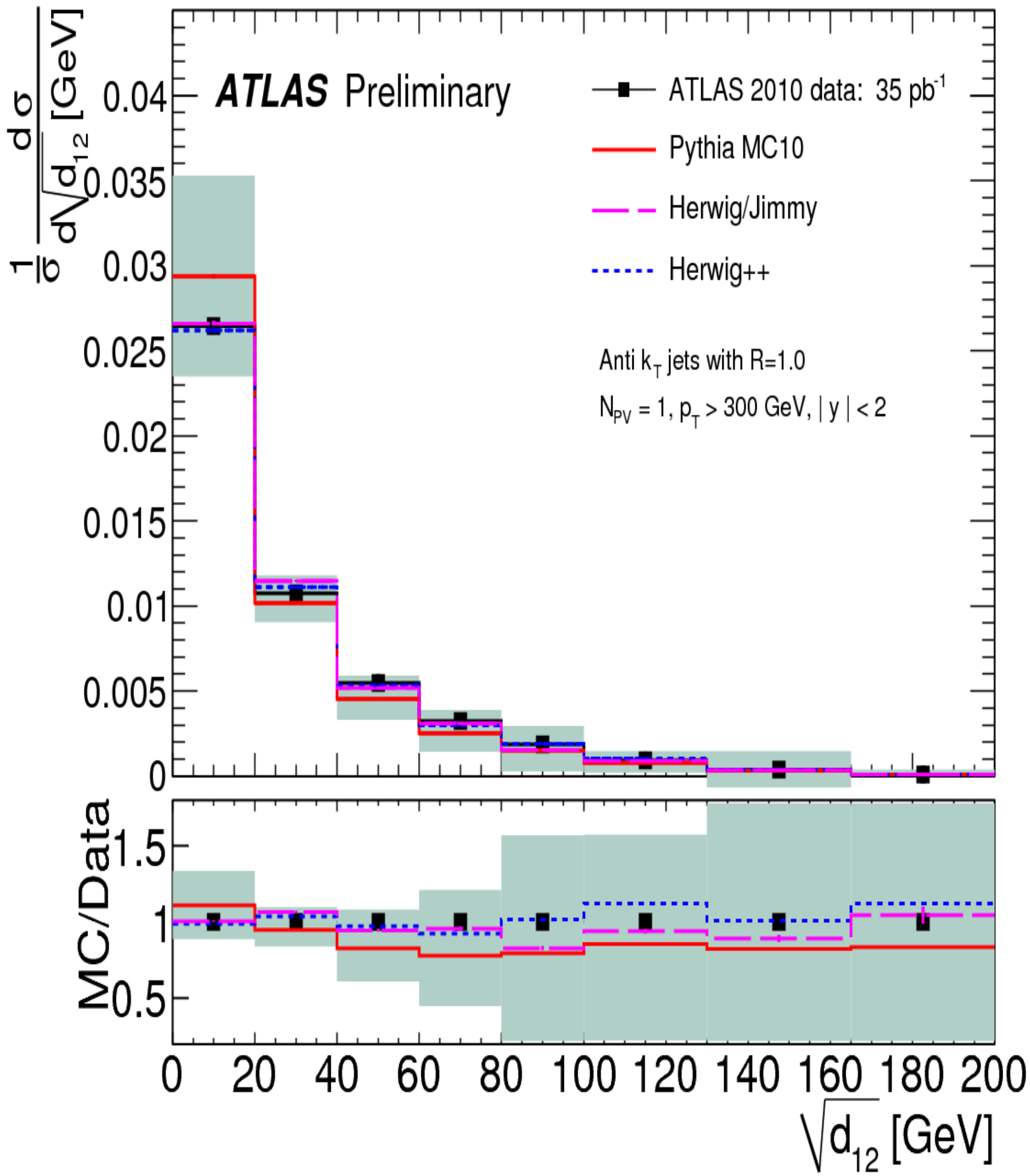


Charged fragmentation function



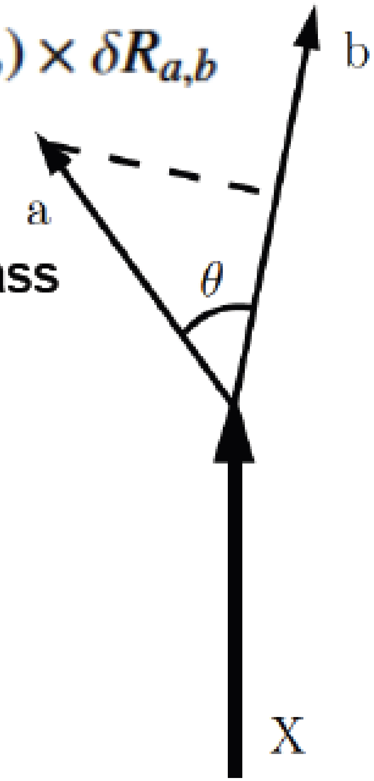
Properties of calorimeter jets: mass, y12





Variables

$$\sqrt{d_{12}} = \min(p_{Ta}, p_{Tb}) \times \delta R_{a,b}$$



d_{12} (a.k.a. k_T splitting scales, y-scale, y_2)

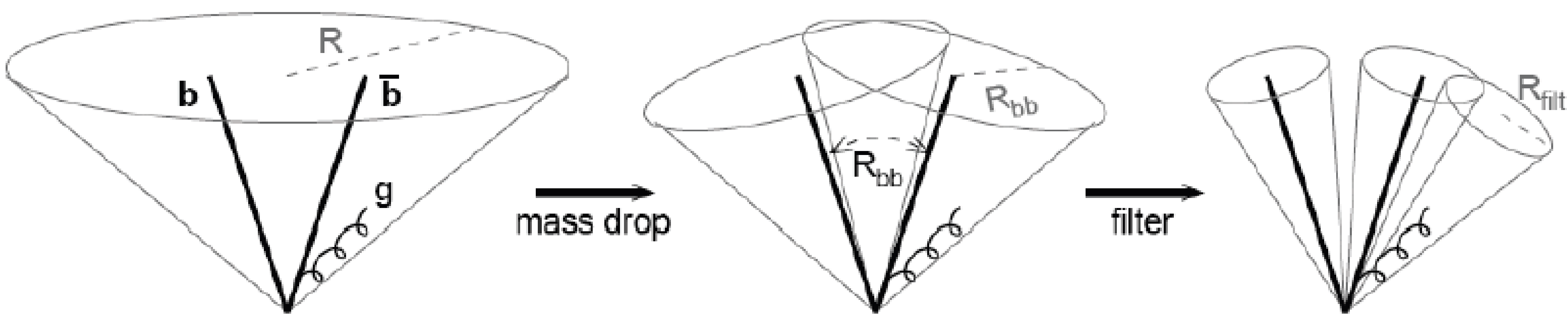
Add-on variable usable to enhance analyses using jet mass
Measure of hardness of final k_T splitting in a jet

J.M. Butterworth, B.E. Cox, J.R. Forshaw **Phys. Rev. D 65 (2002)**
M. H. Seymour **Z Phys C62 (1994) 172**

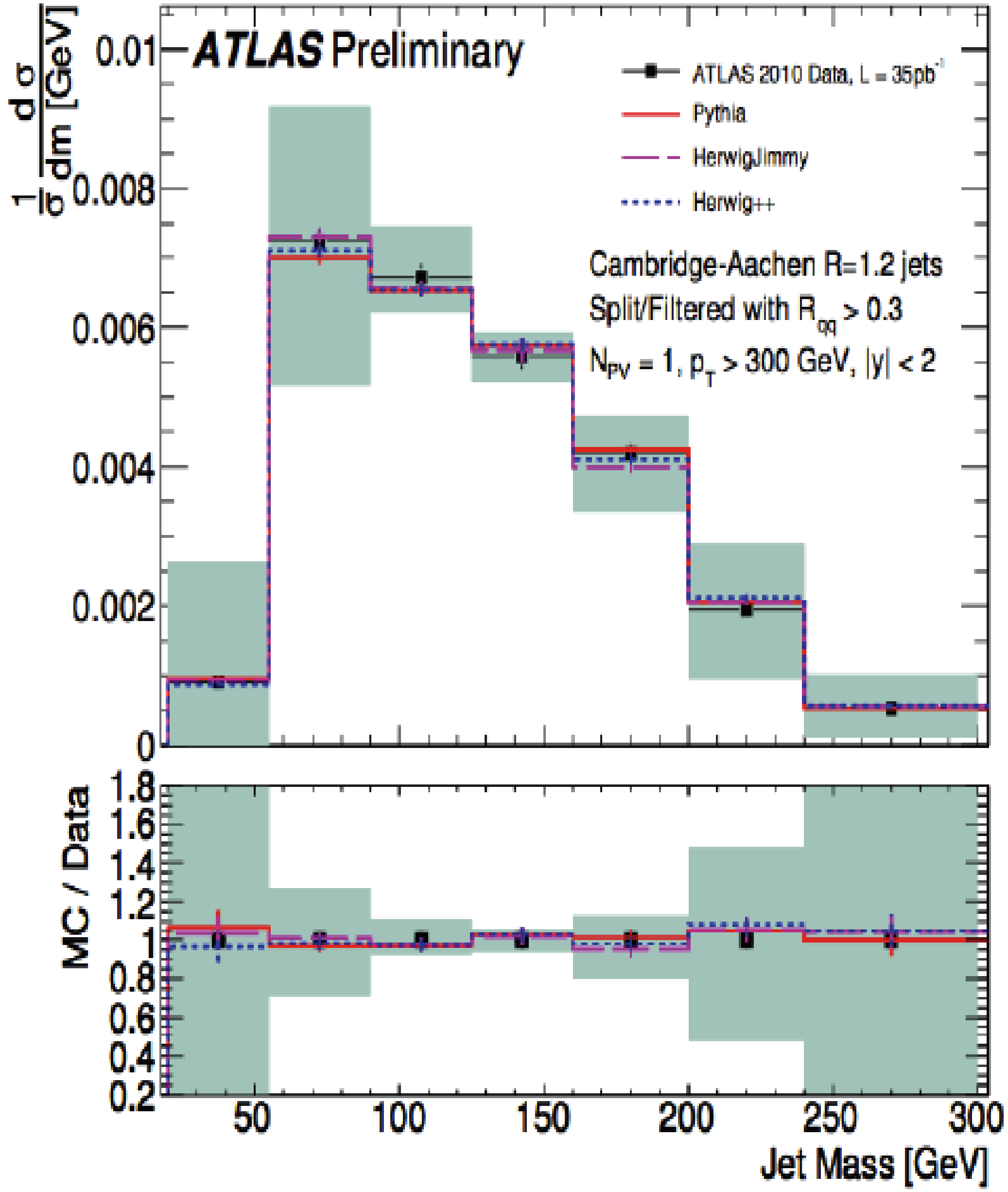
Splitting and Filtering (a.k.a. BDRS filtering, C-A filtering)

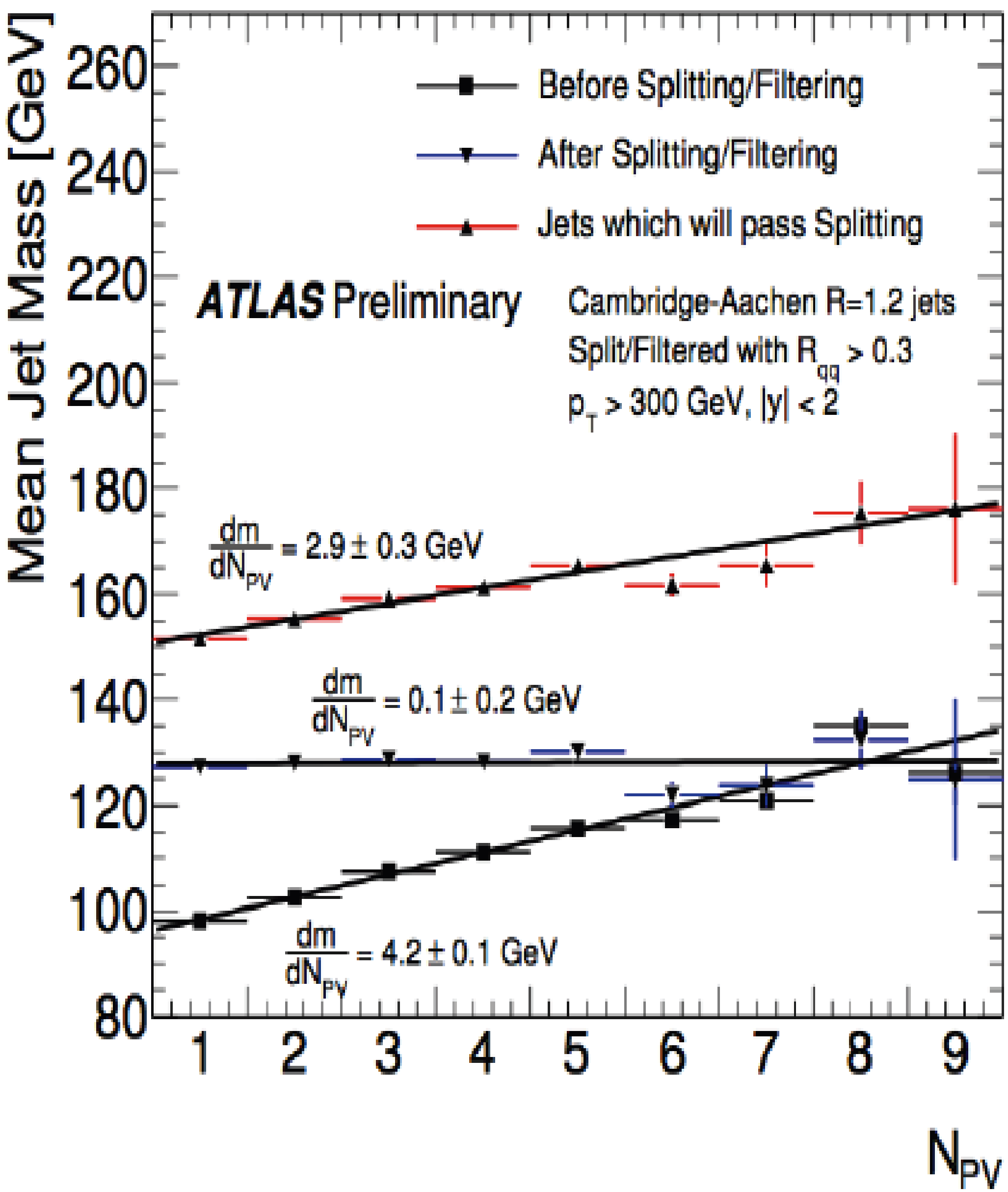
Take jets and search for symmetric splittings with large mass drop, recluster filtering out large angle radiation. Yields new jets which can be treated as heavy particle candidates.
Include additional cut R_{qq} > 0.3 here.

J. M. Butterworth, AD, M. Rubin and G. P. Salam **Phys. Rev. Lett. 100, 242001 (2008)**

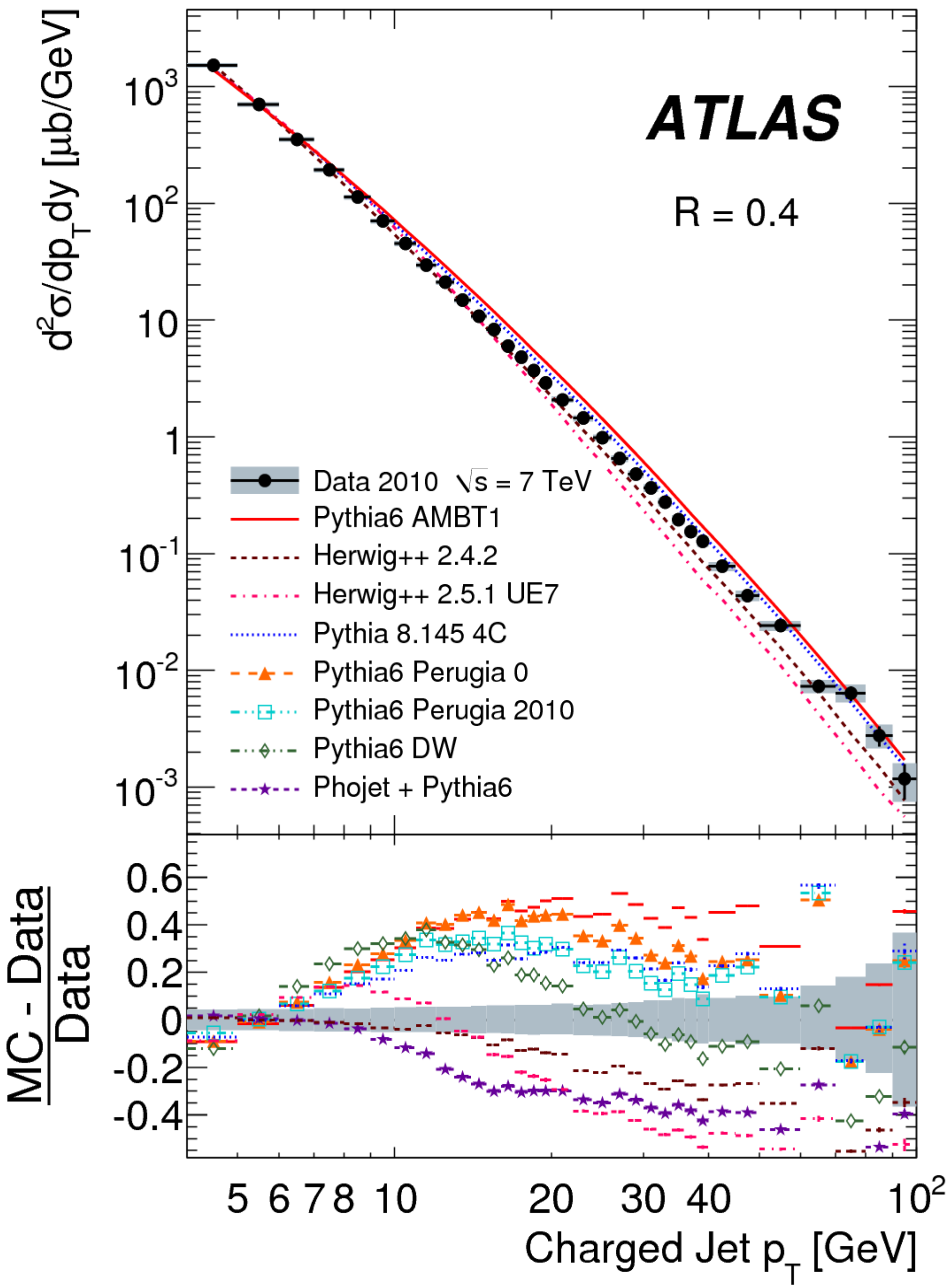


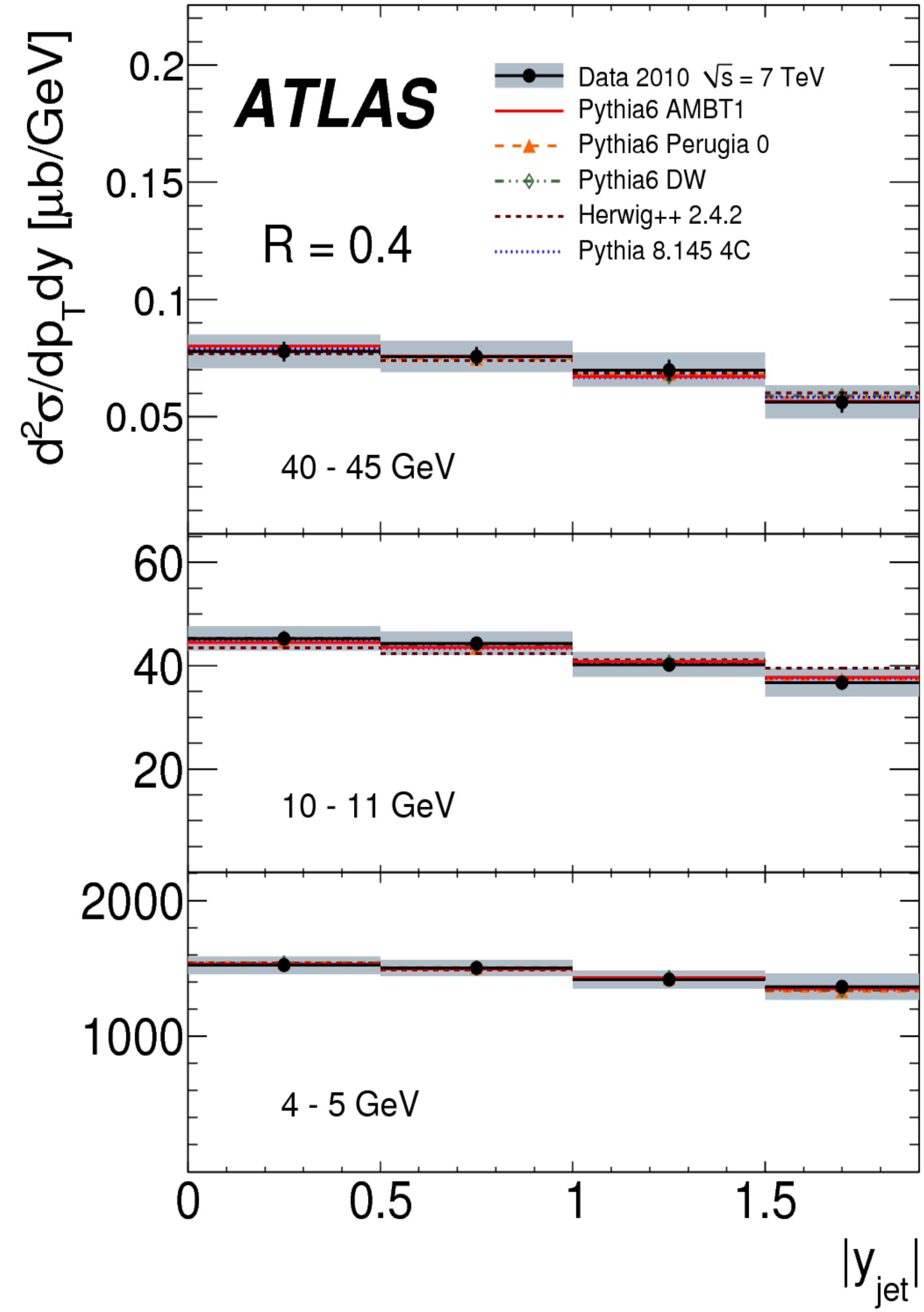
Filtered mass: stable vs pileup!





Cross-section from track jets



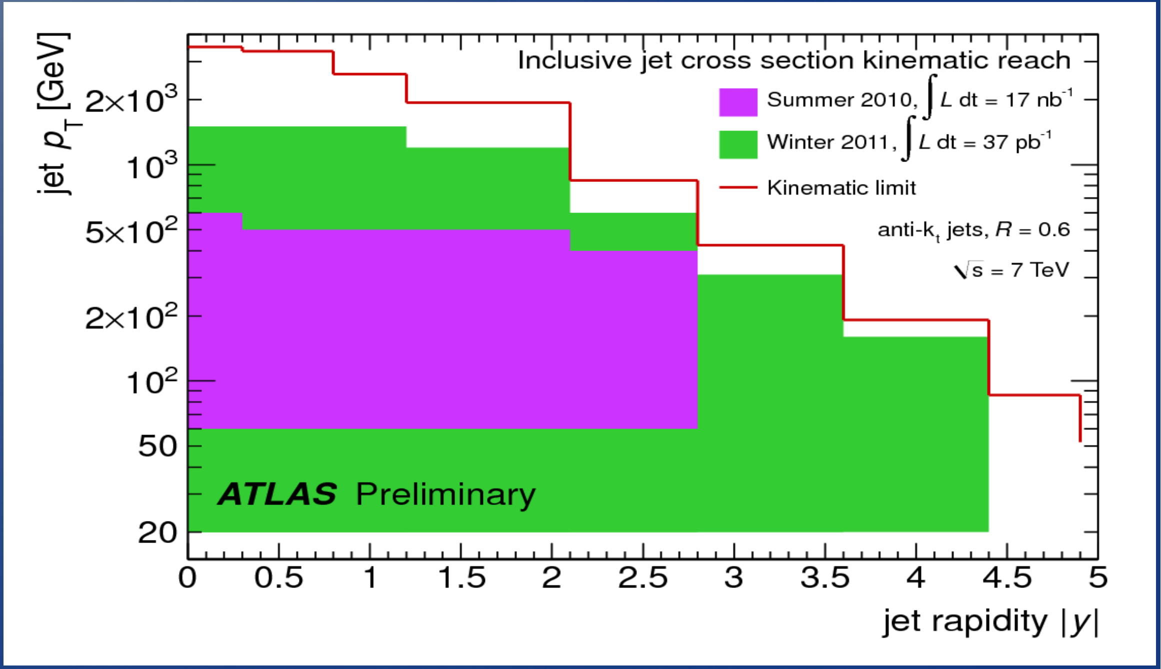


Inclusive jet and dijet cross-section using calorimeter information

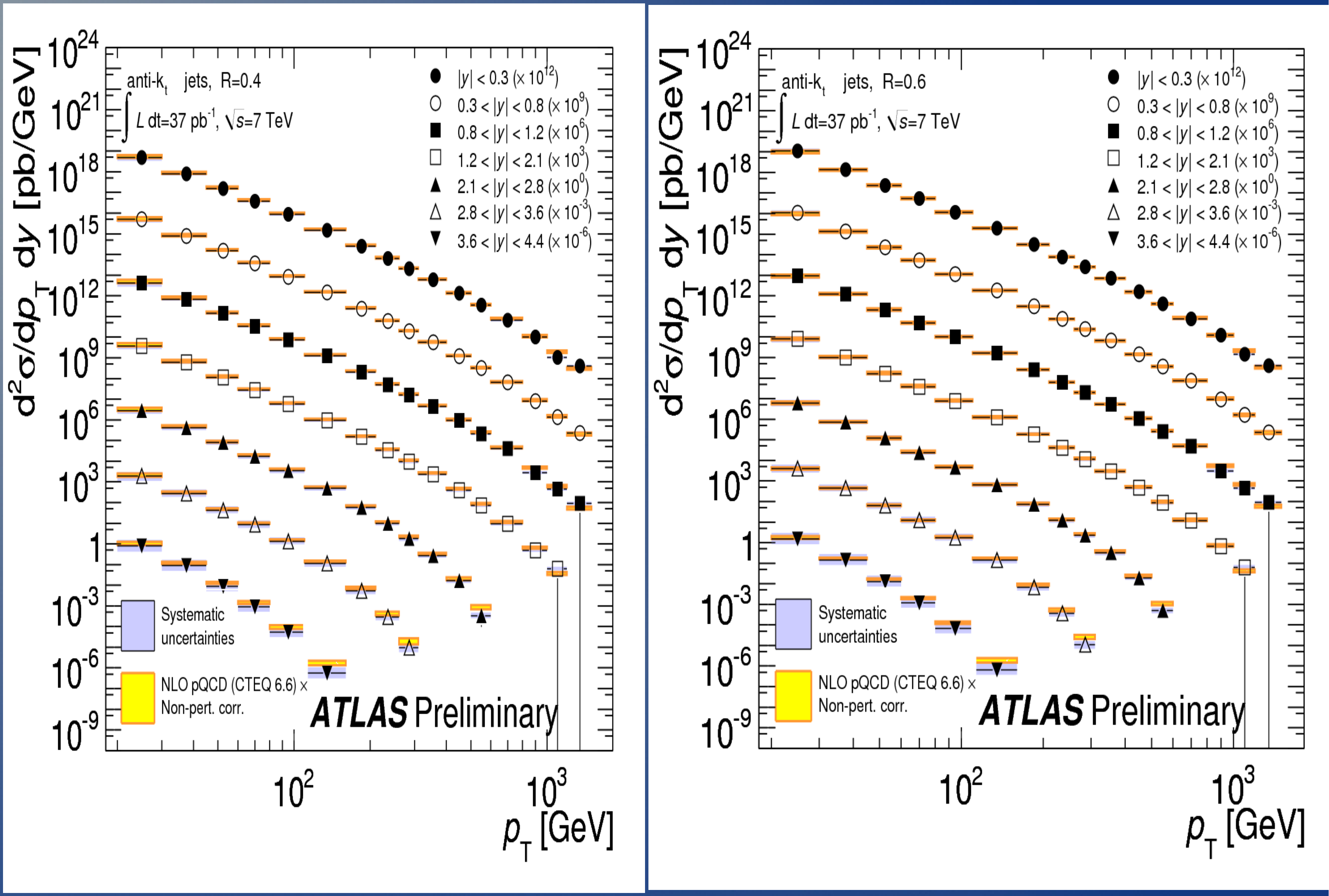
Our “flagship” hard QCD measurement
Work on 2010 data very close to be finalised, but only winter conference results presented here

Measure jets clustered with akt04 and akt06 almost to kinematic limit

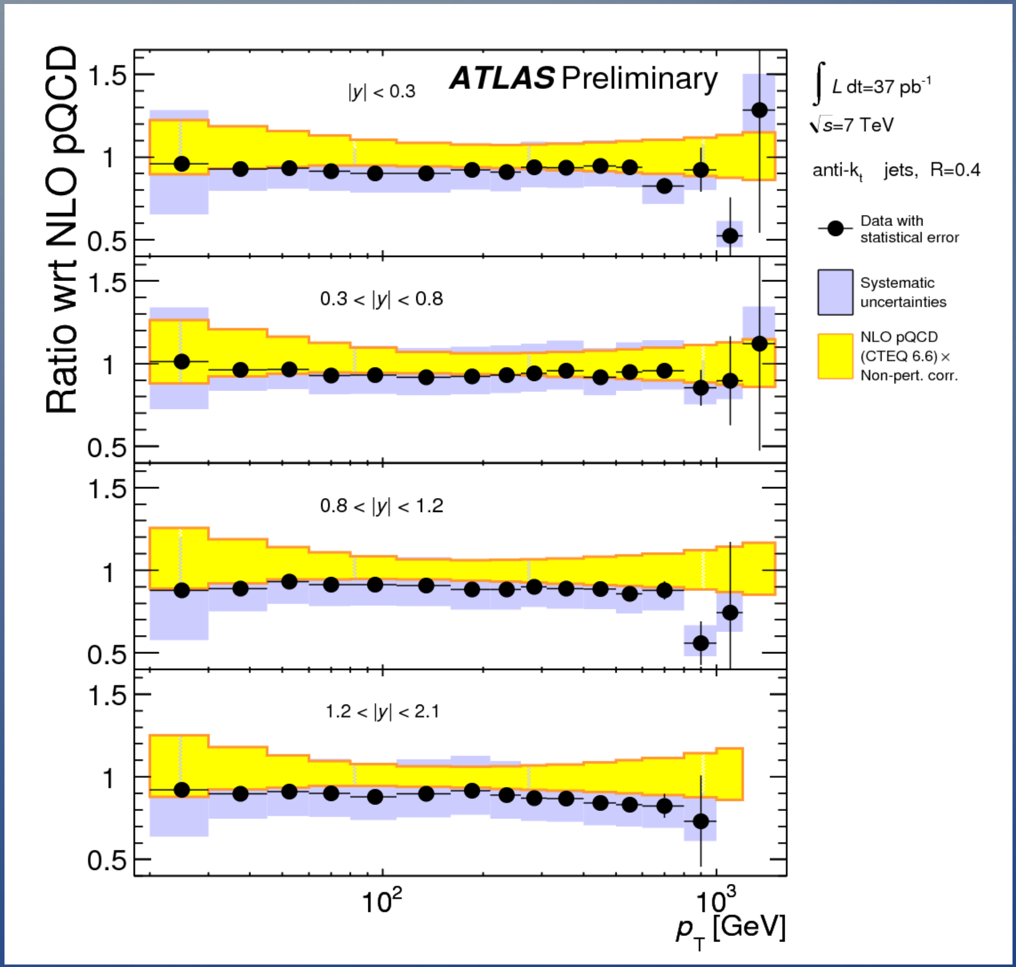
Results compared to several Pdf sets and NLO MC (powheg)

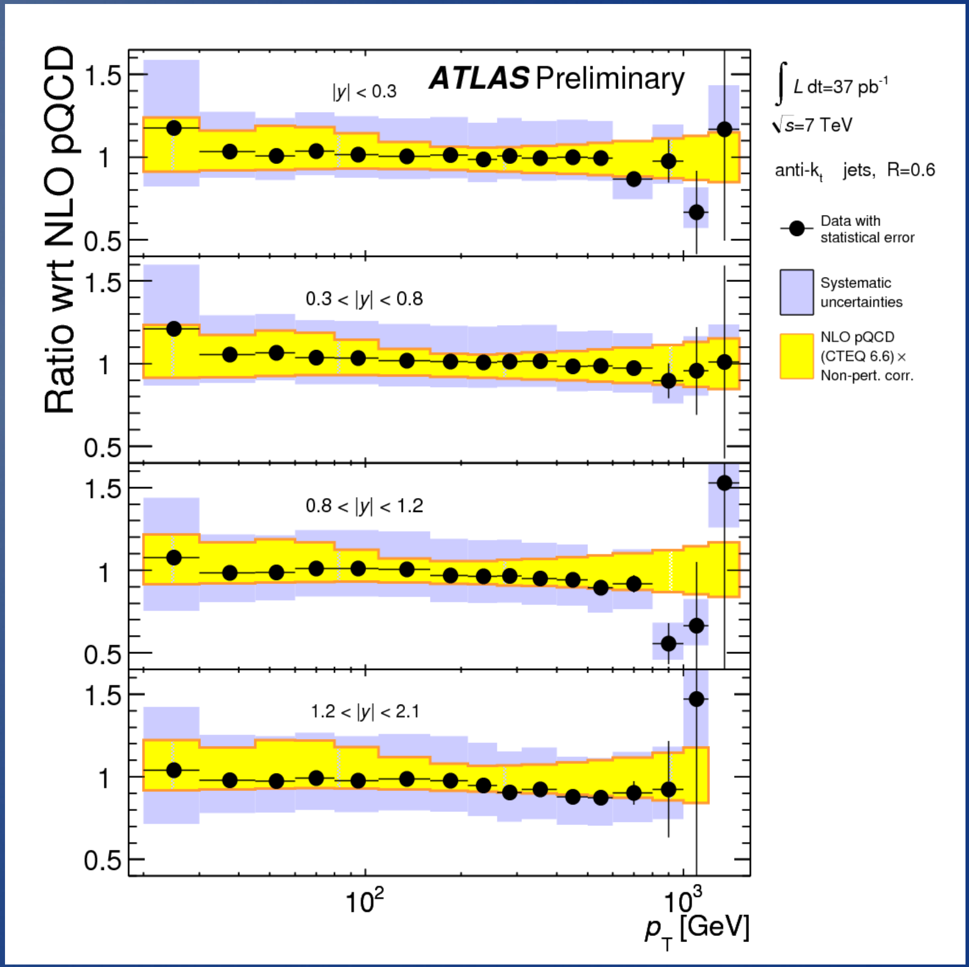


Inclusive jet cross section for antikt 06 jets after detector unfolding. Pt range from 60 to 600 GeV, rapidity < 2.8

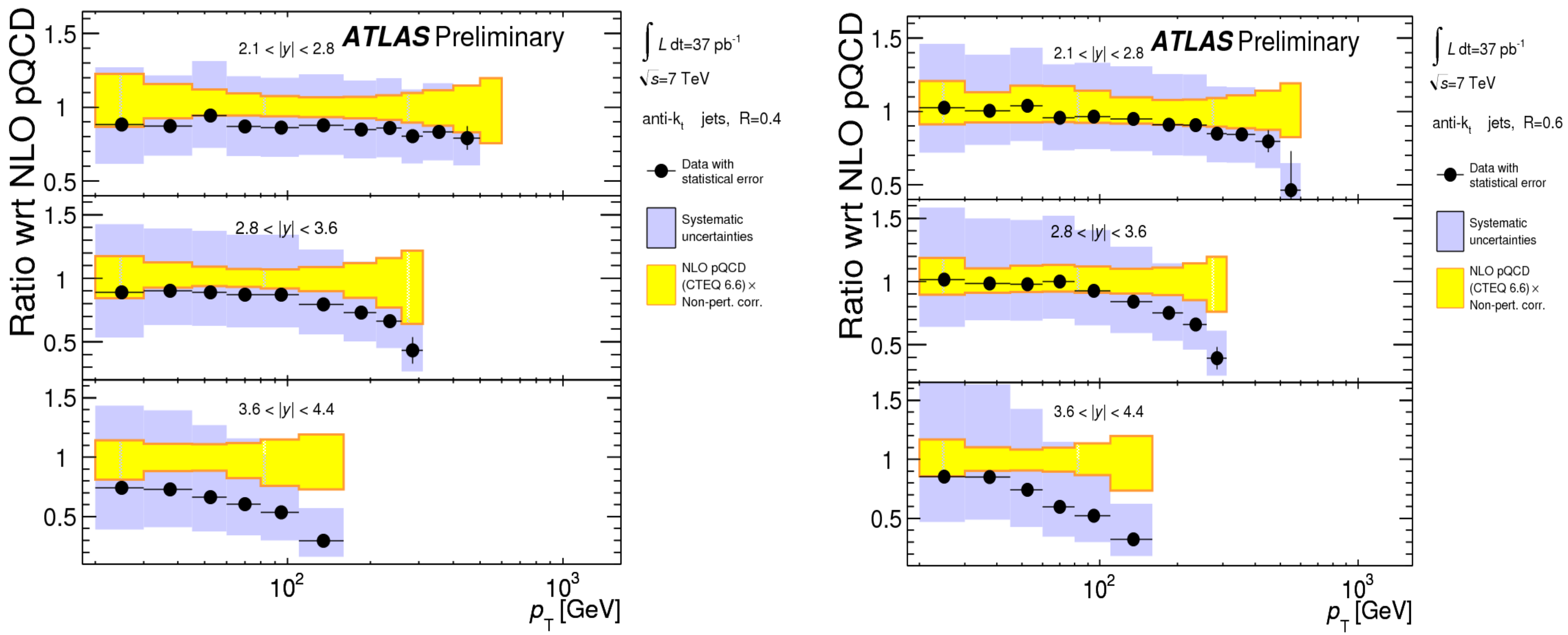


Ratio with NLO + soft corrections comparison between jet sizes (central)



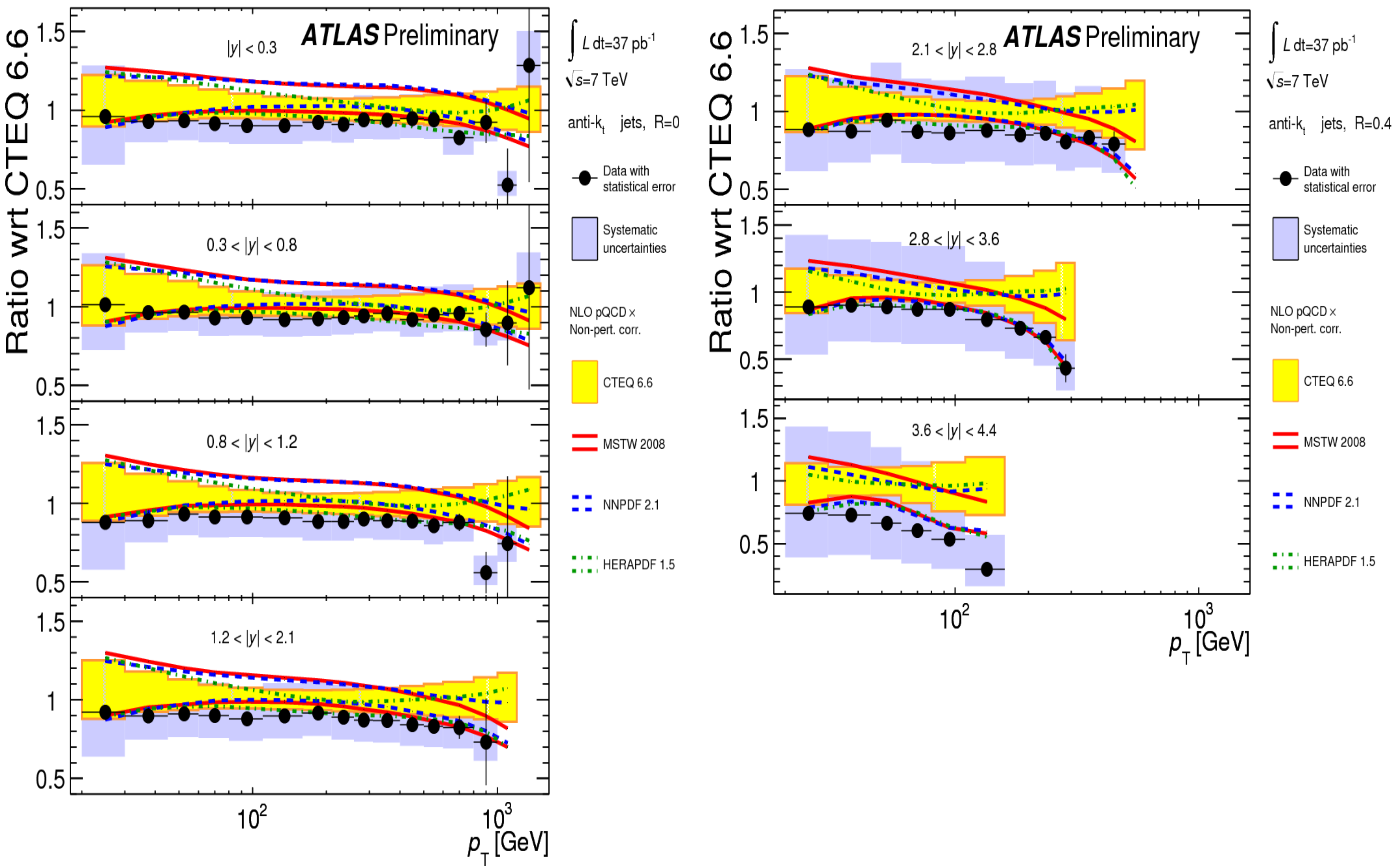


Ratio with NLO + soft corrections comparison between jet sizes (forward)

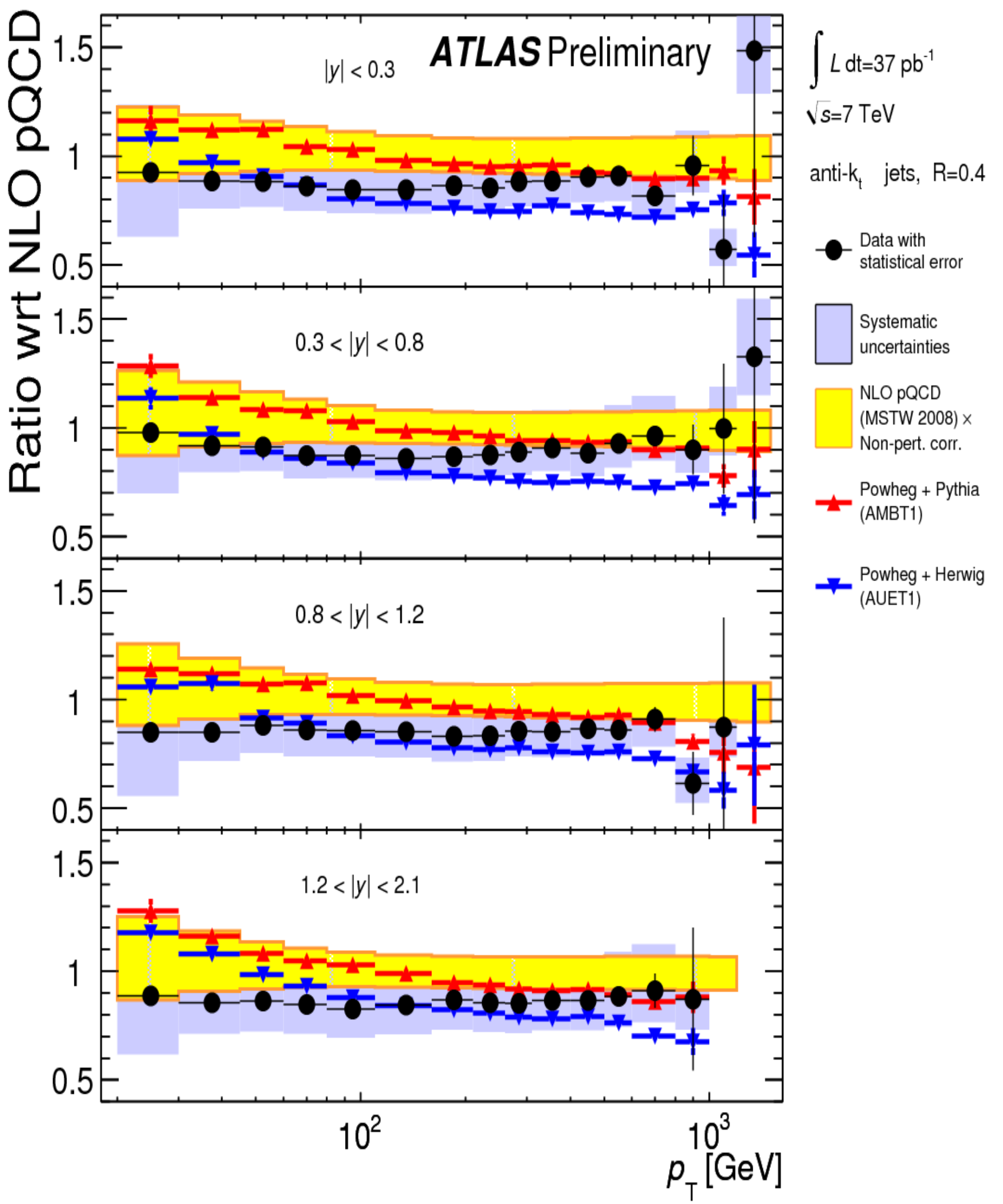


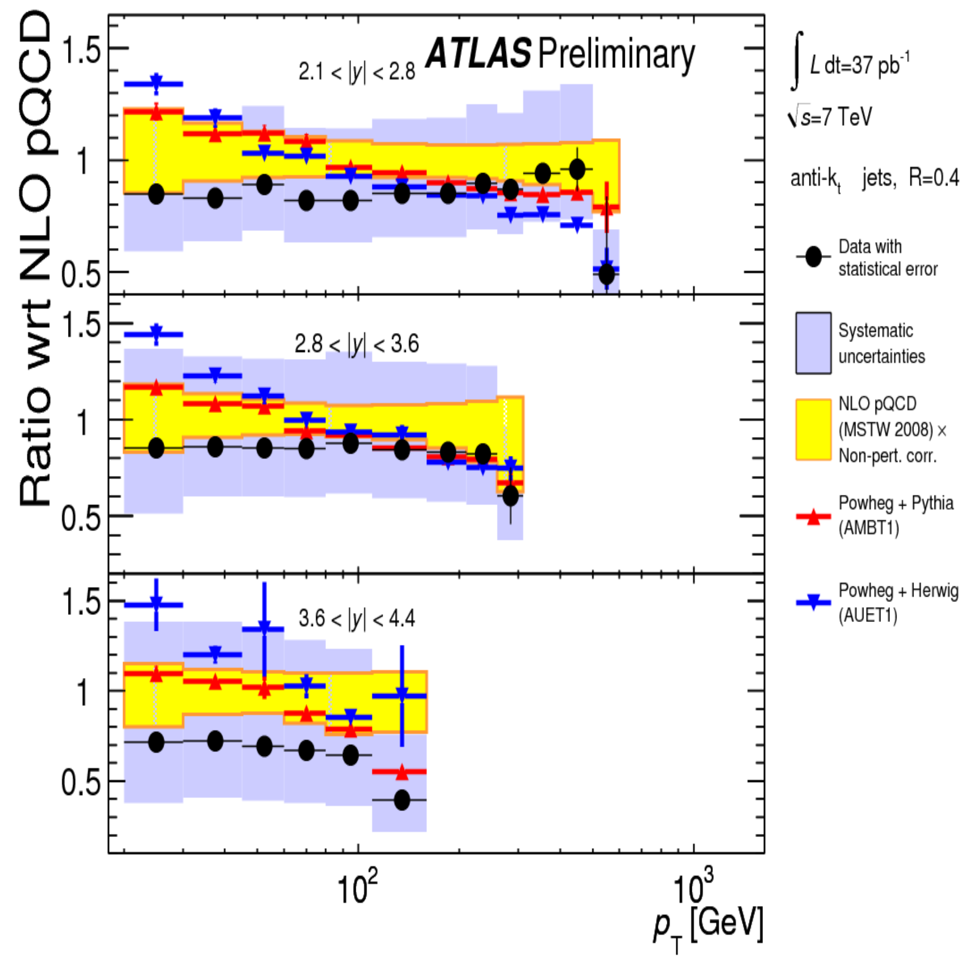
No big differences between cone sizes once soft corrections are applied

Comparison with various Pdf sets (0.4)

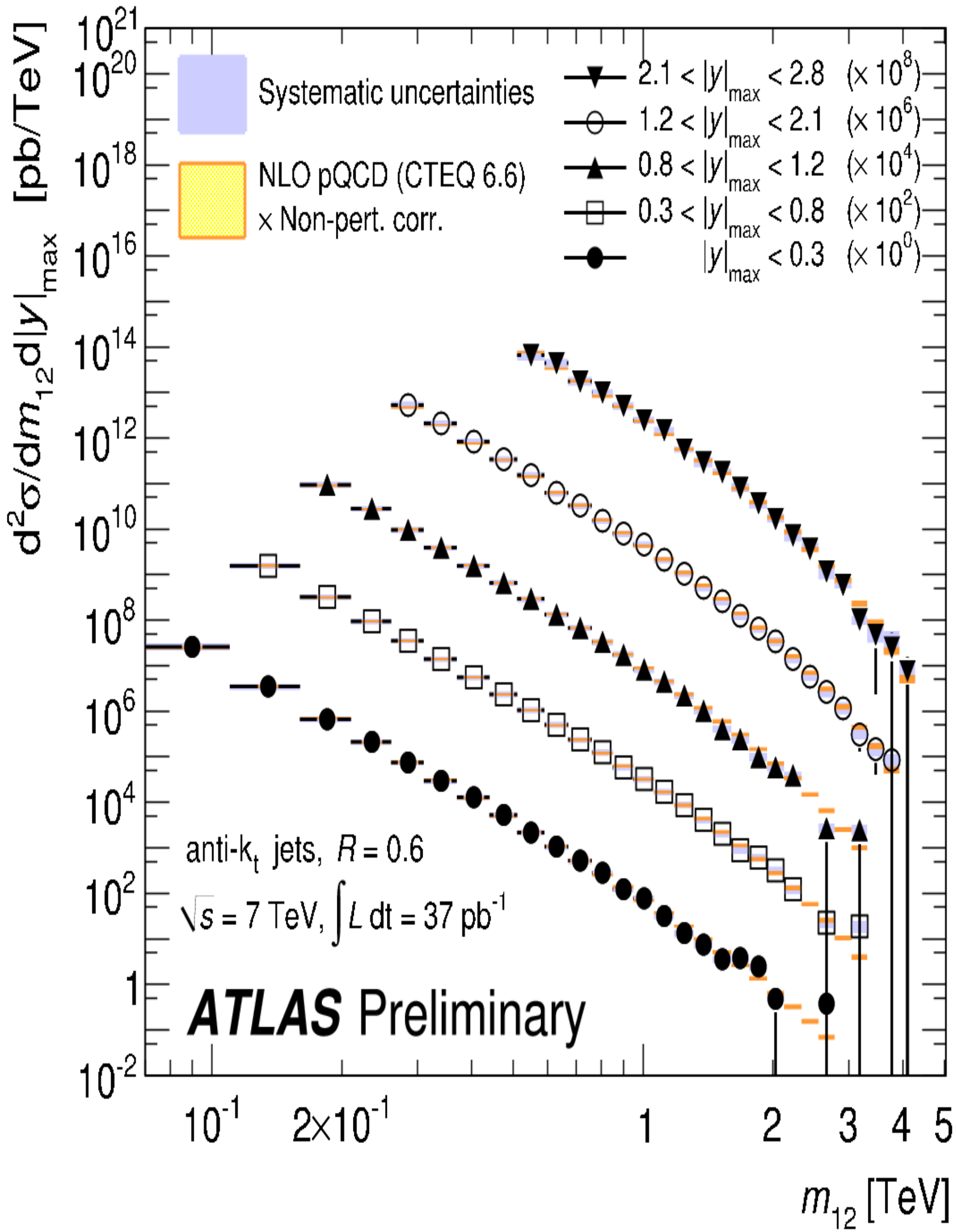


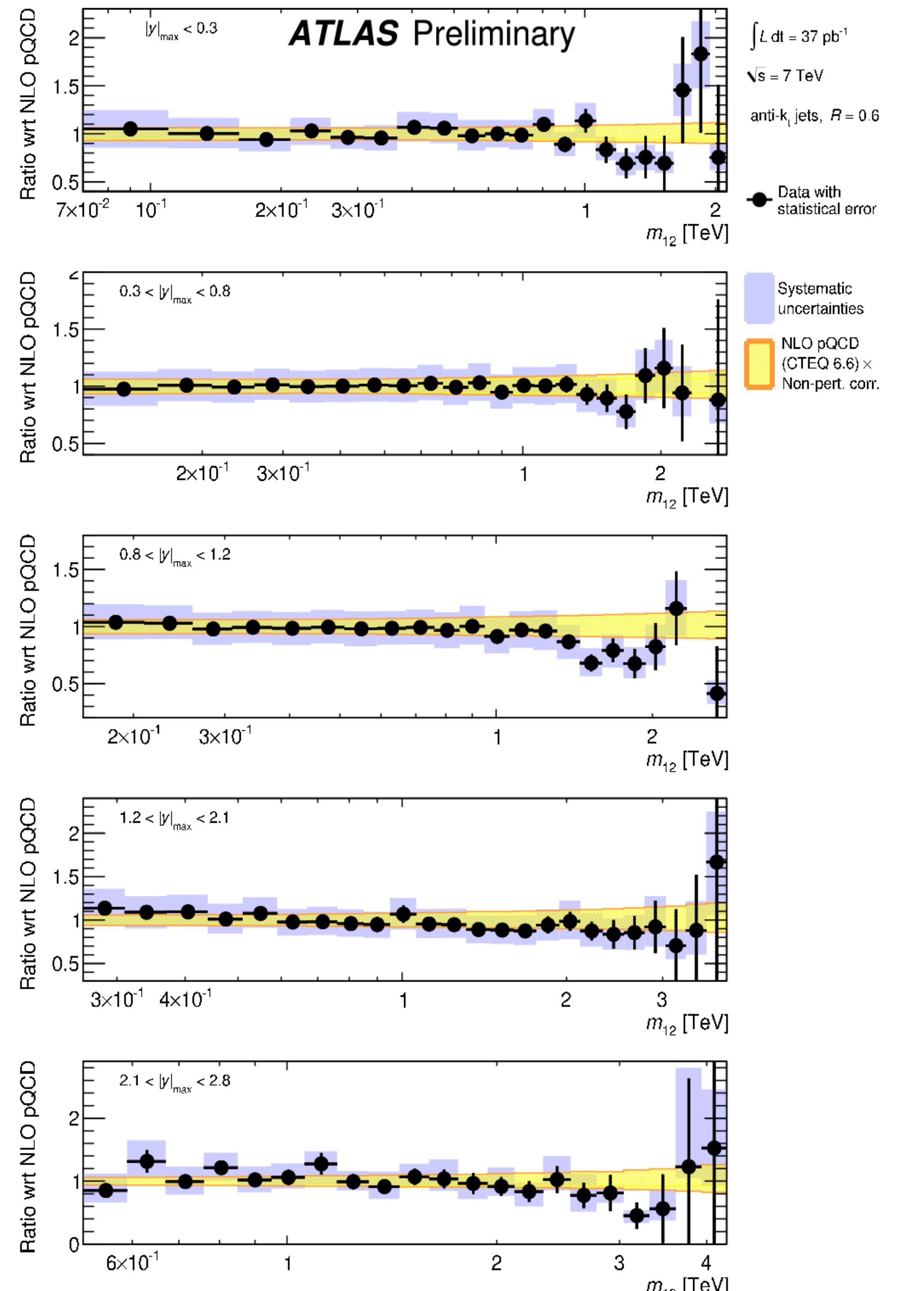
Comparison with Powheg (0.4)



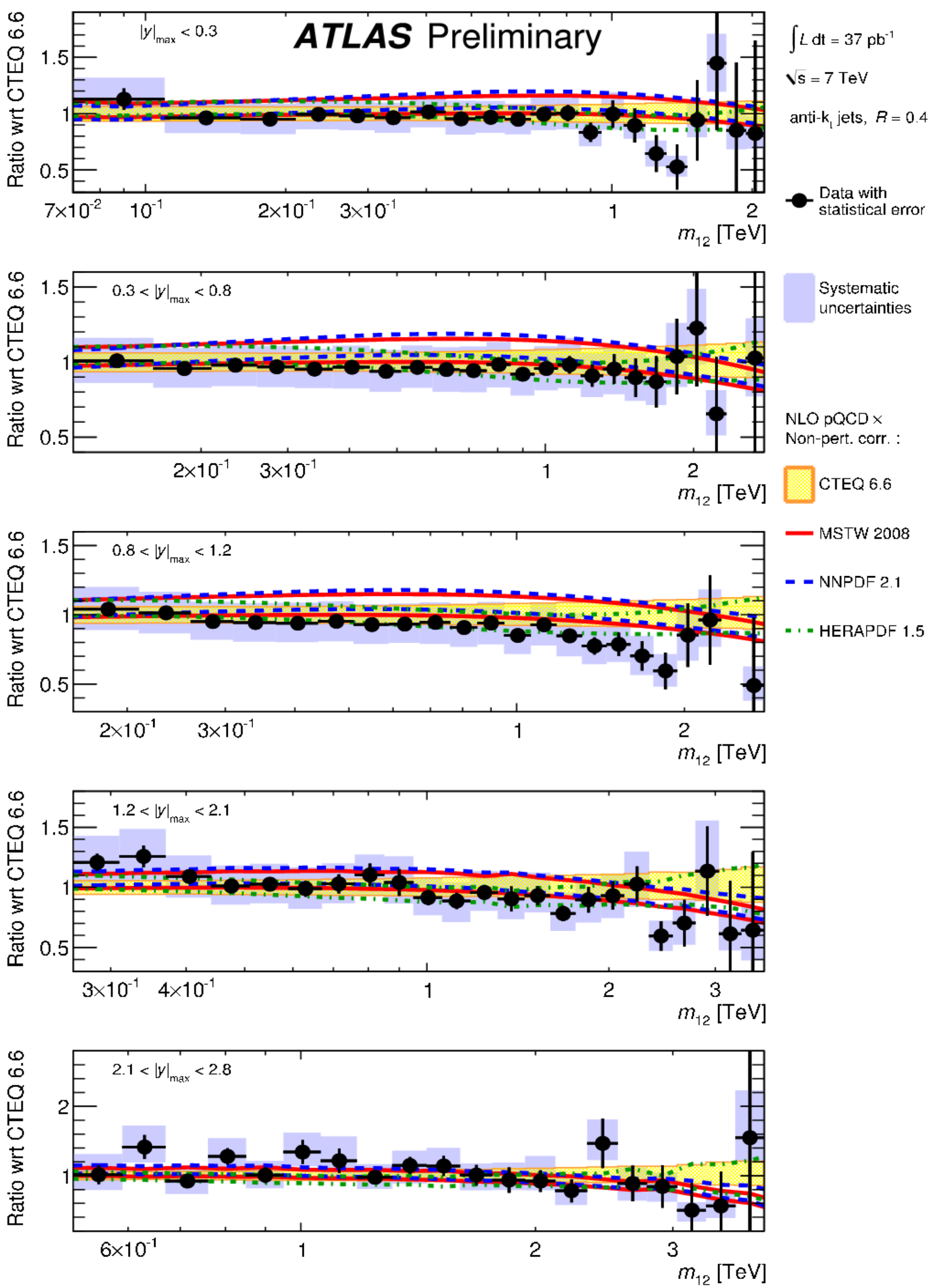


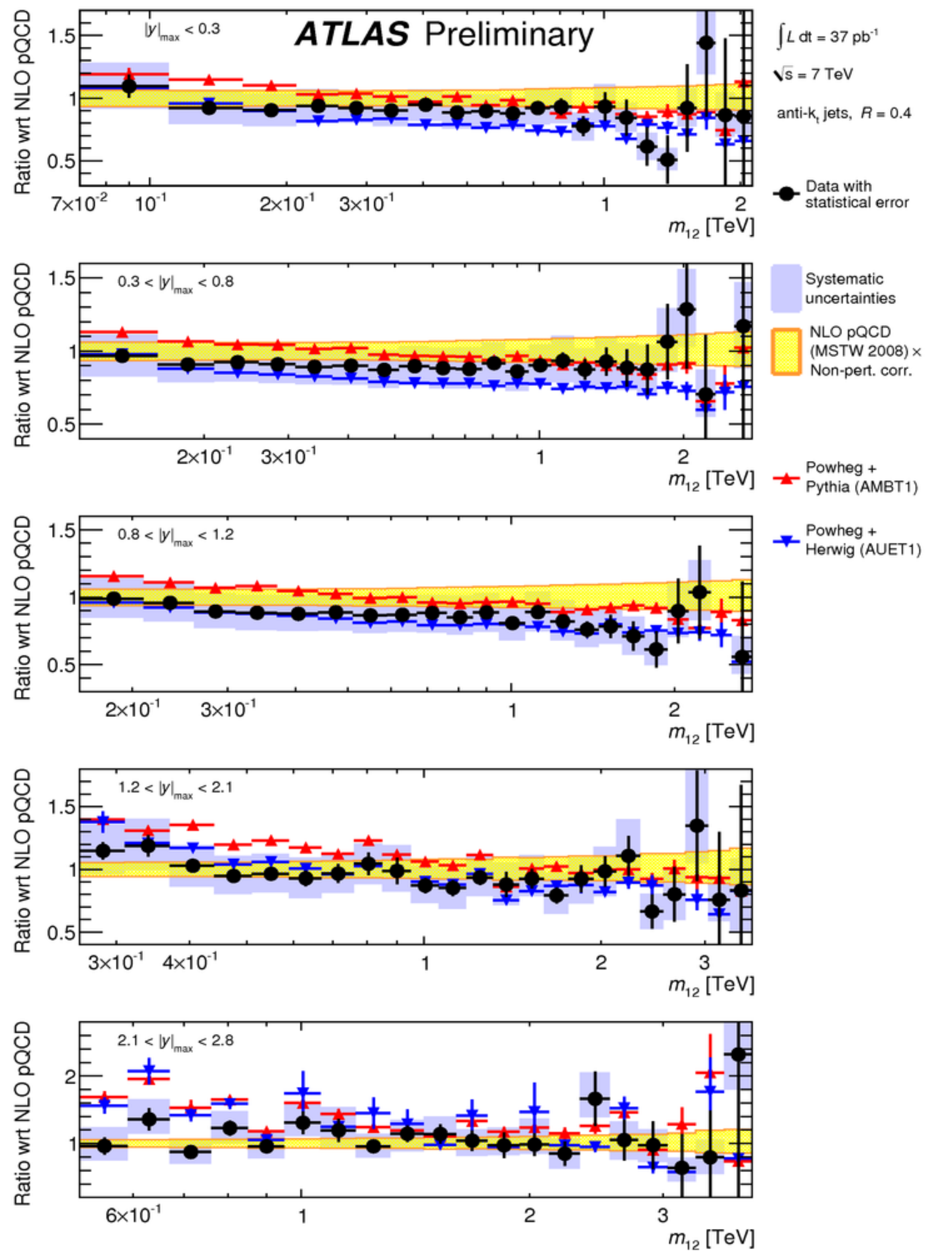
Dijet cross-section and ratio (0.6)





Pdf and Powheg comparisons (0.4)

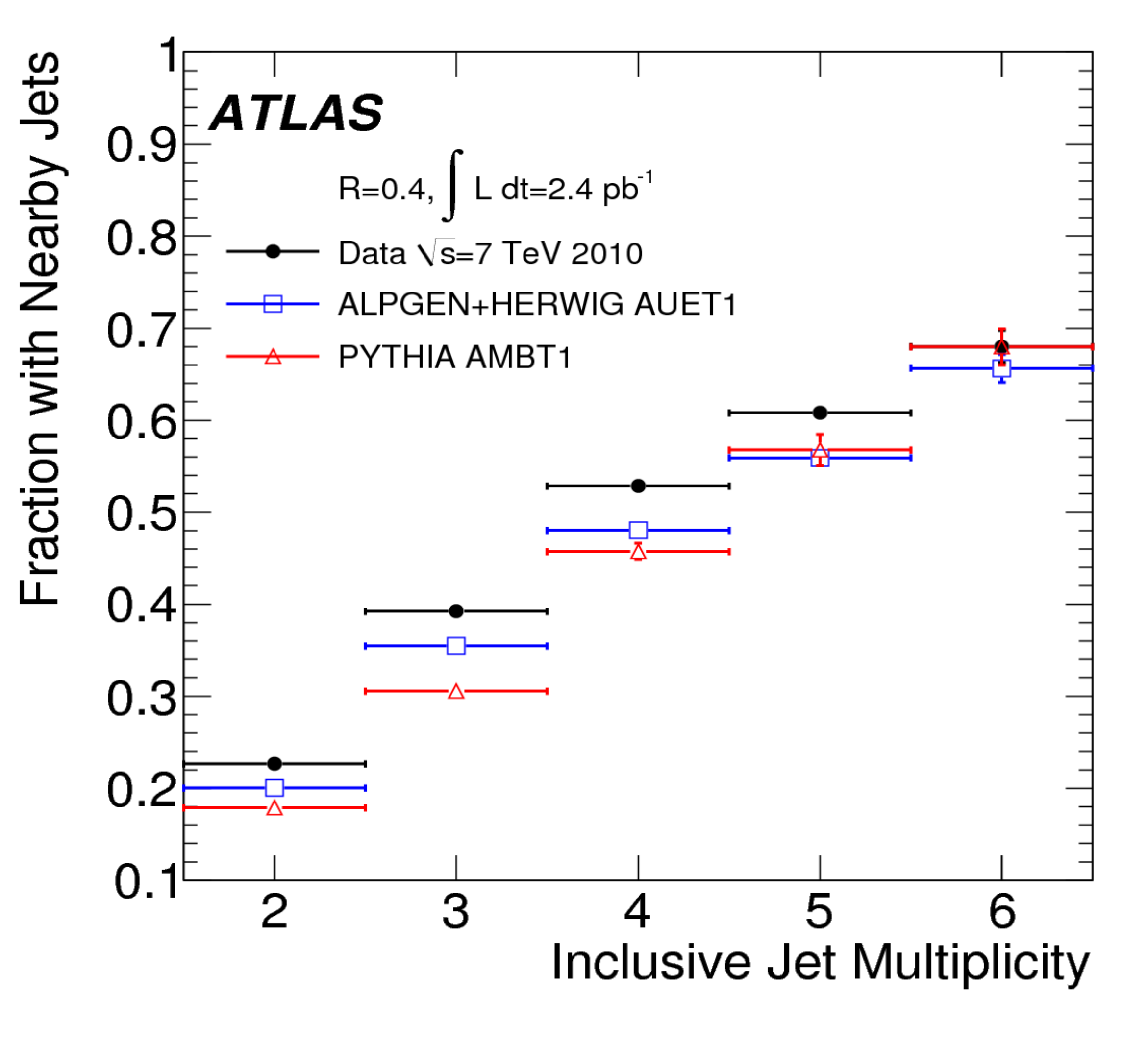




Multi-jet production

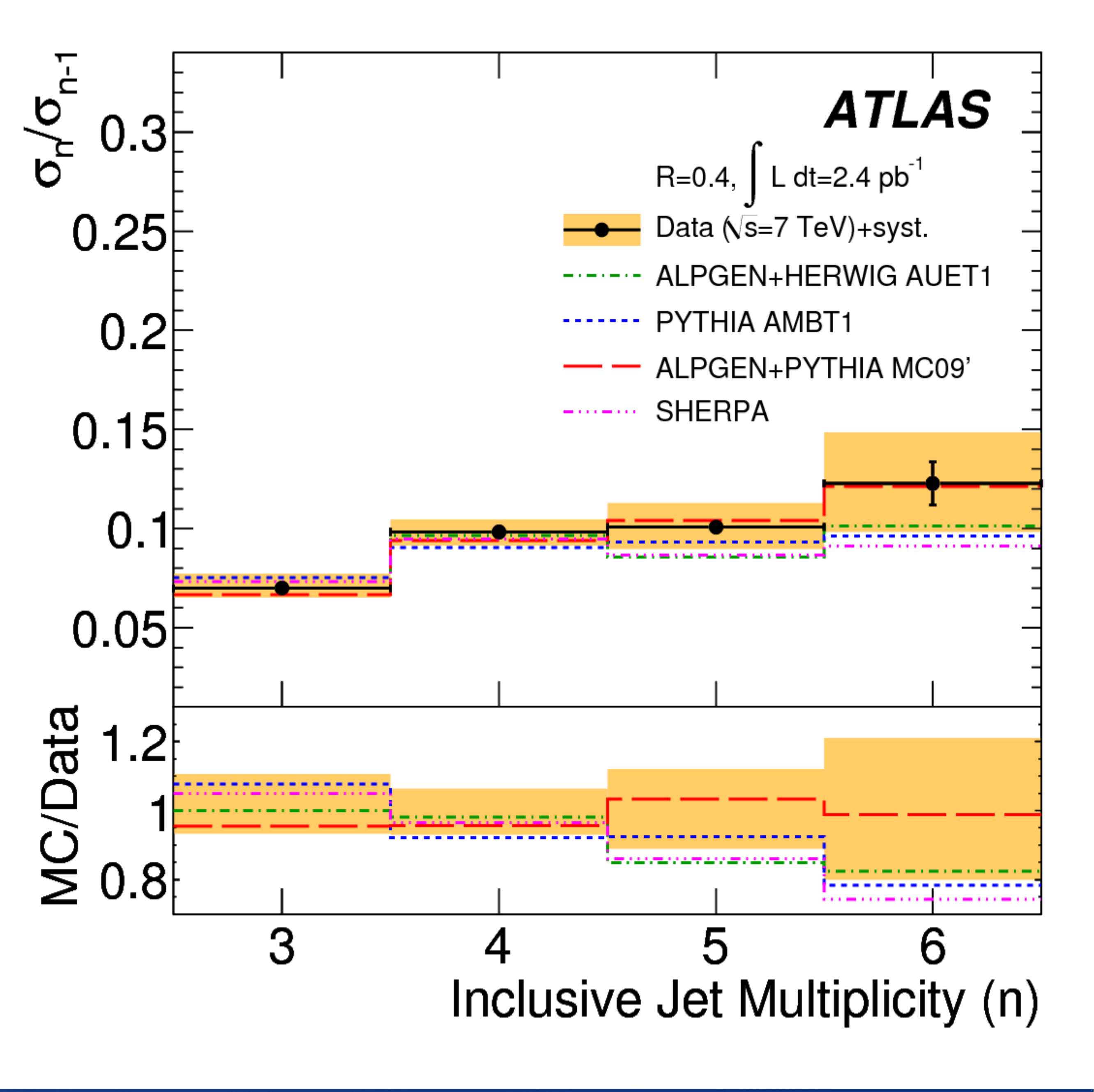
Not a trivial extension of the inclusive/dijet analysis: main systematics is migration between jet multiplicities, that depends on jet resolution and split-merging between nearby jets.

The fraction of events with another selected jet within 1.5 is better described by Alpgen; however, the full difference in bin migration is taken as systematic error

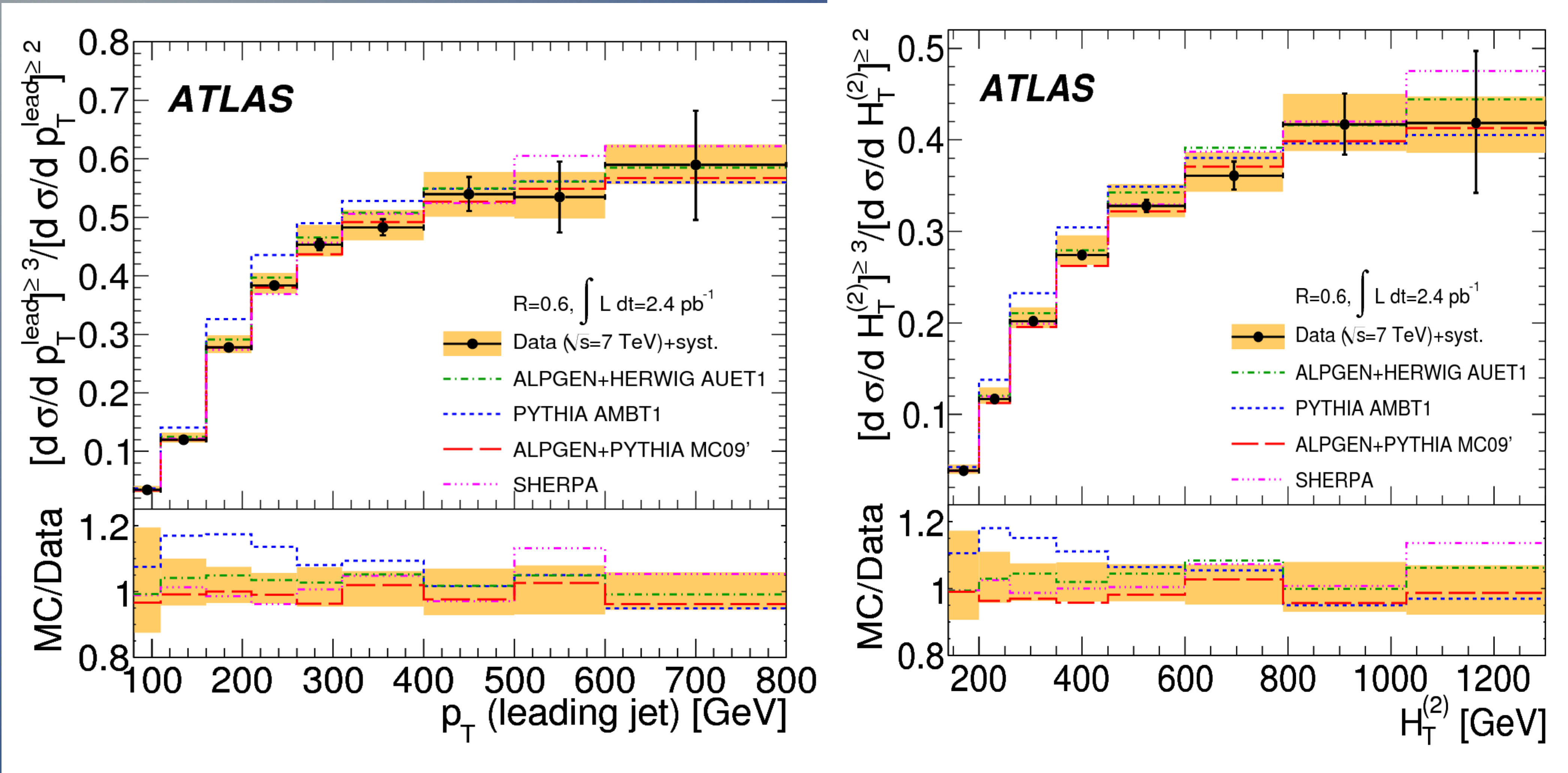


Scaling behaviour

Data tend to agree better with Alpgen/Pythia, even if the large systematics due to the merging prevent final conclusions

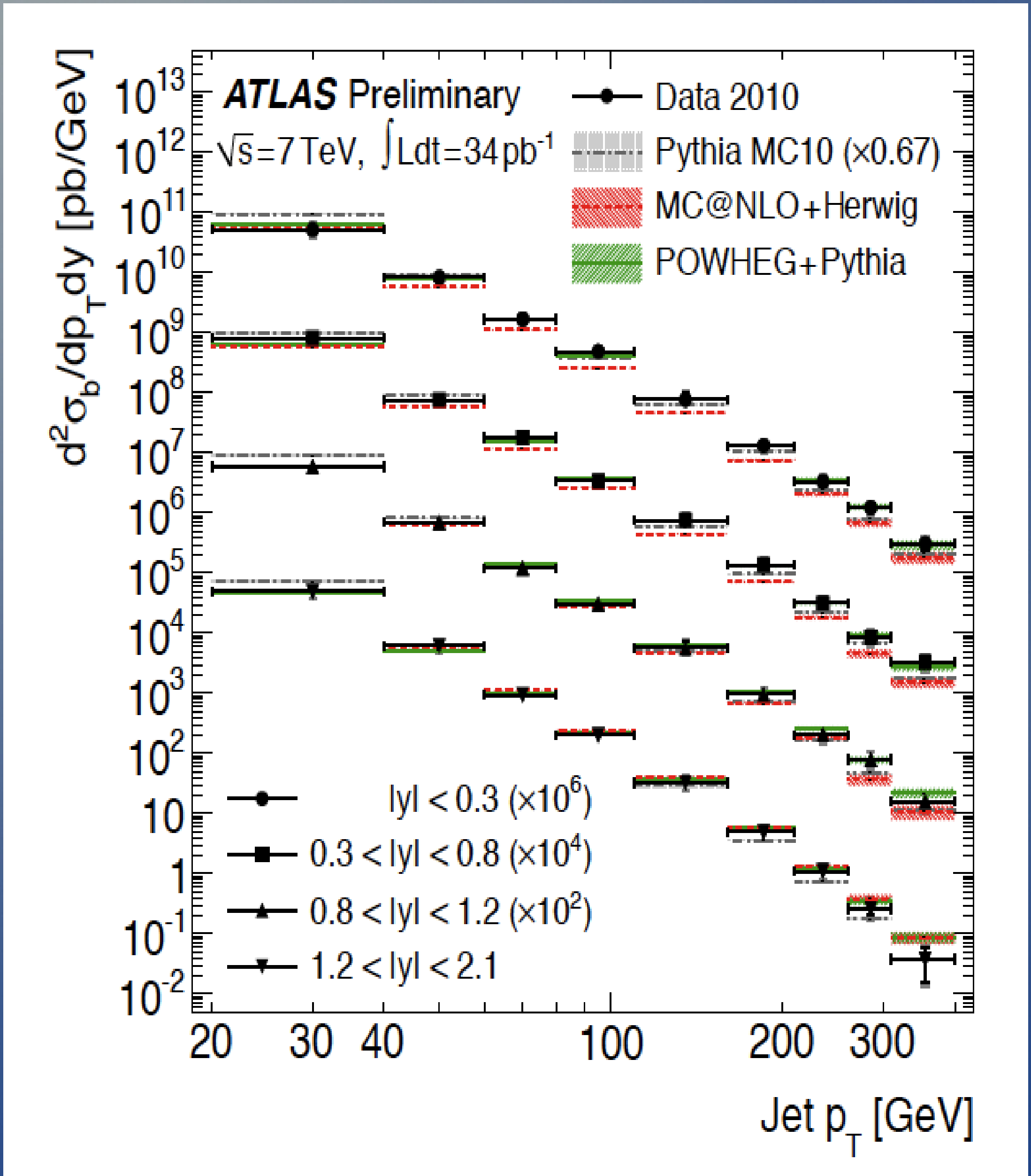


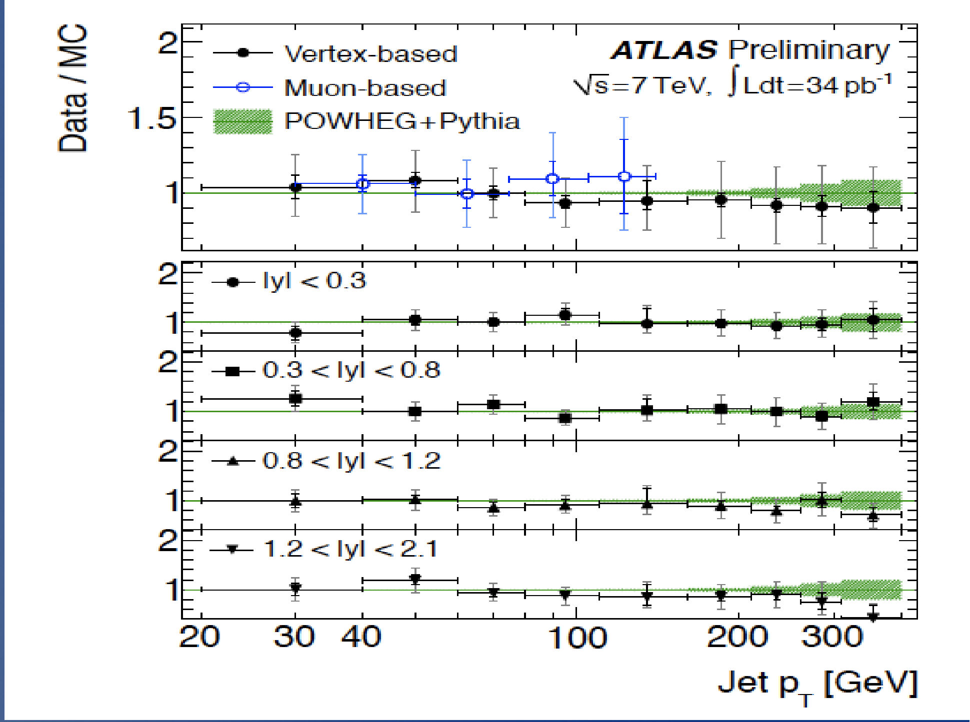
2- to 3- jet fraction vs pT and HT(2)

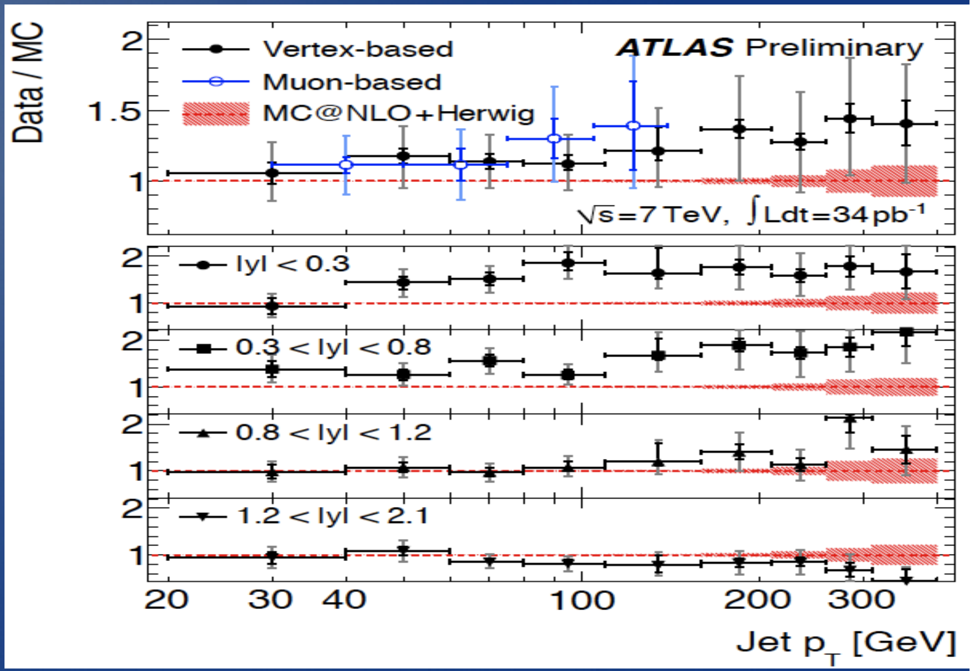


As expected, Pythia alone does not seem to give a good agreement with data; errors yet too big to discriminate Alpgen and Sherpa

B-jet cross-section

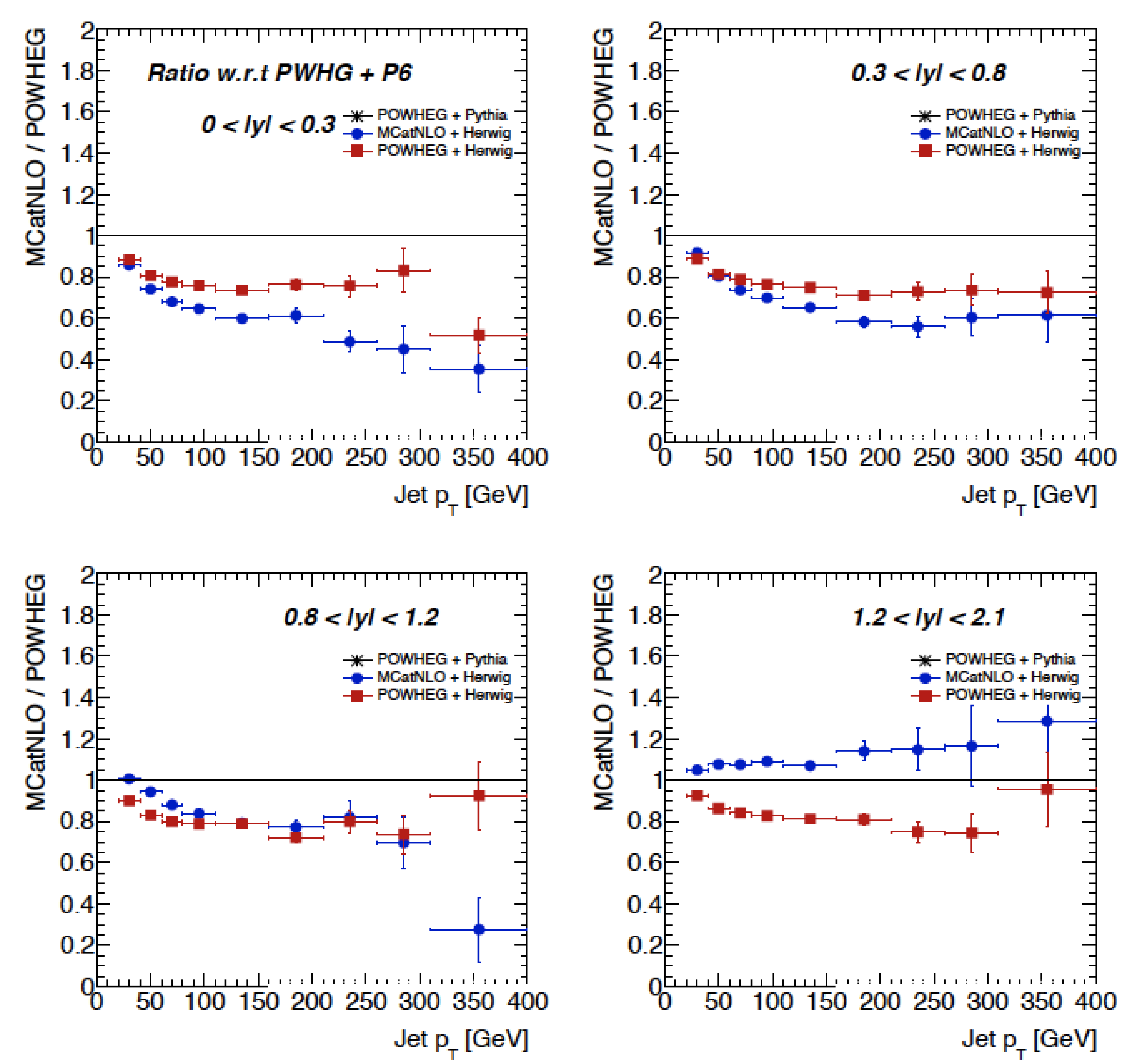




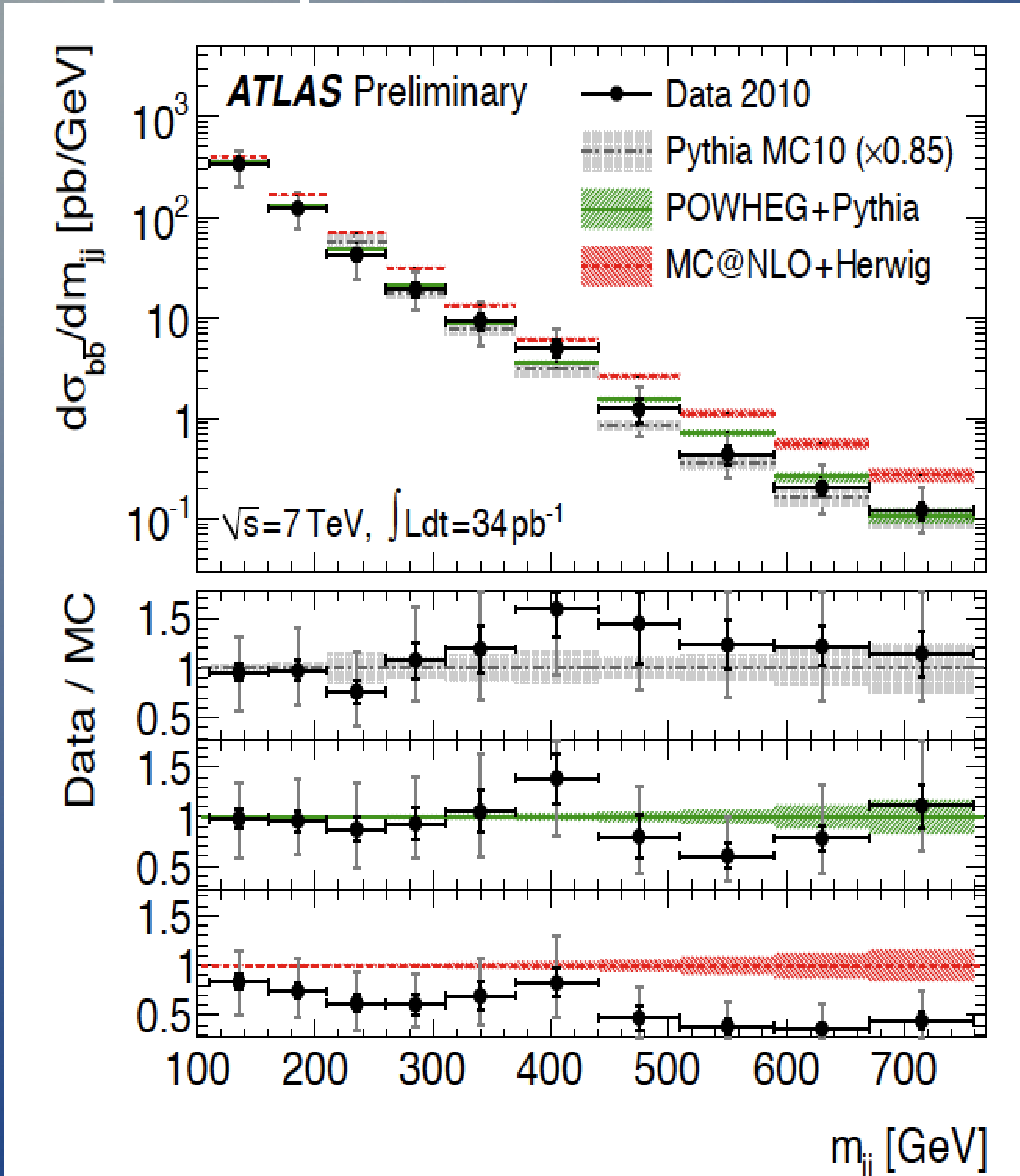


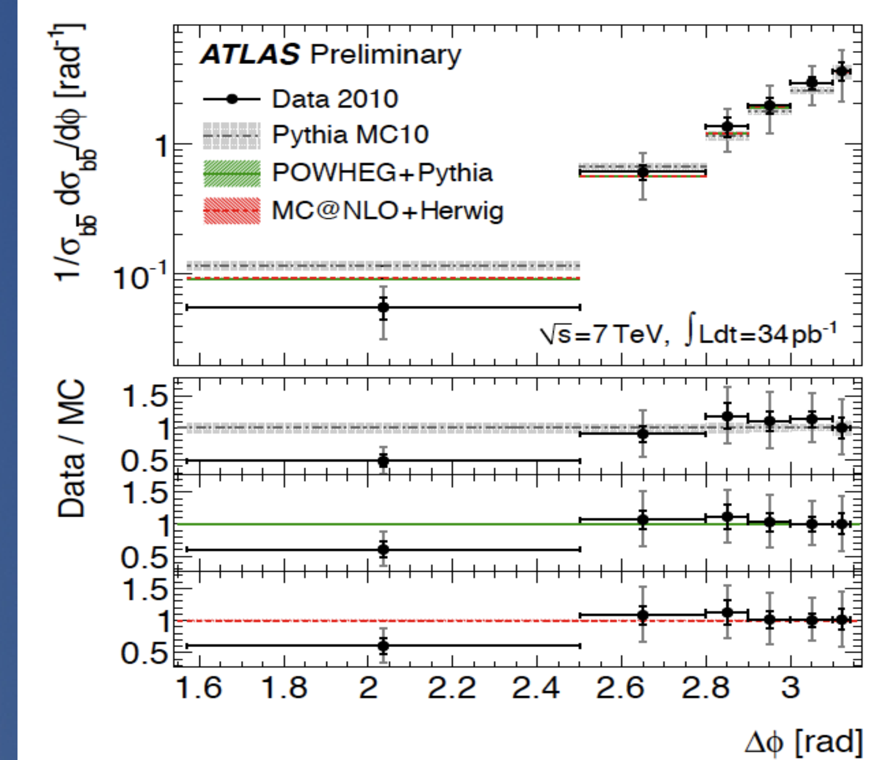
Measurement with secondary vertex tagging, and cross-checked with muon pT_rel, limited to tracking acceptance region

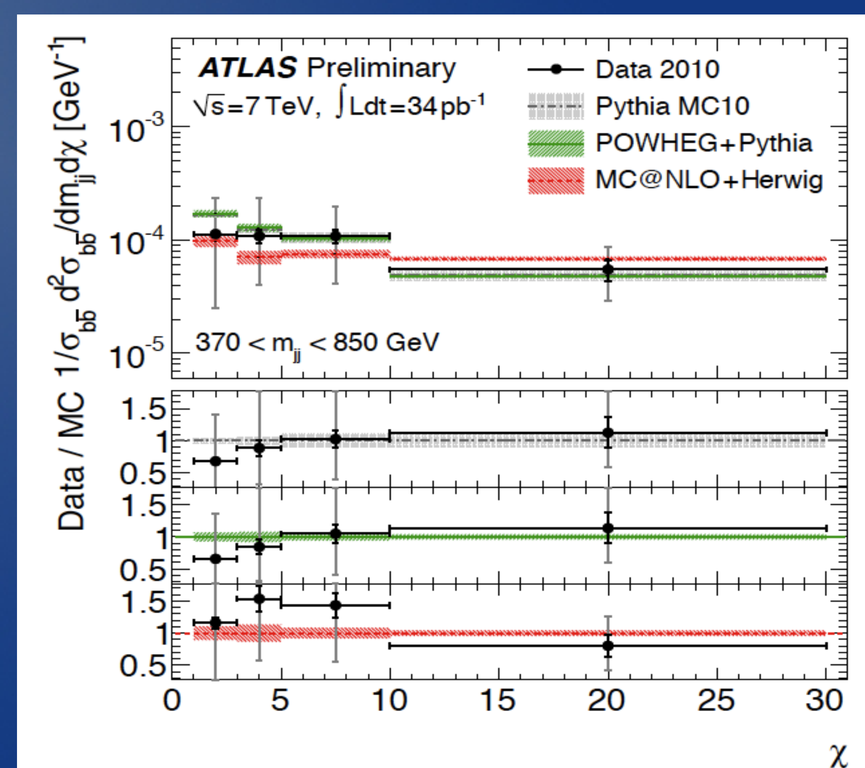
Is it the hard scattering or the shower?



b-pair production

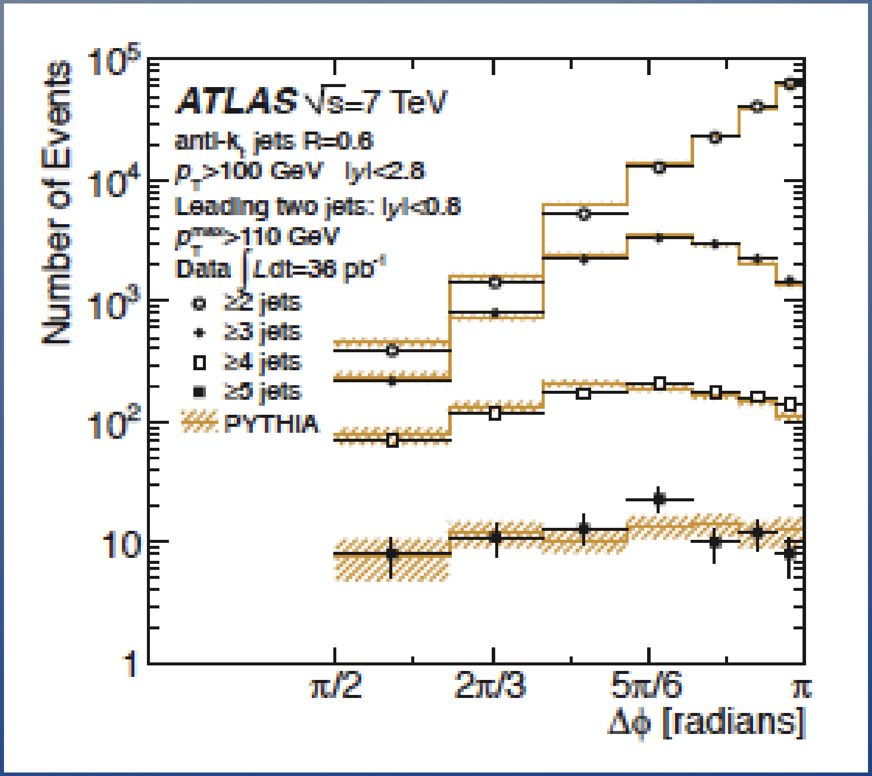


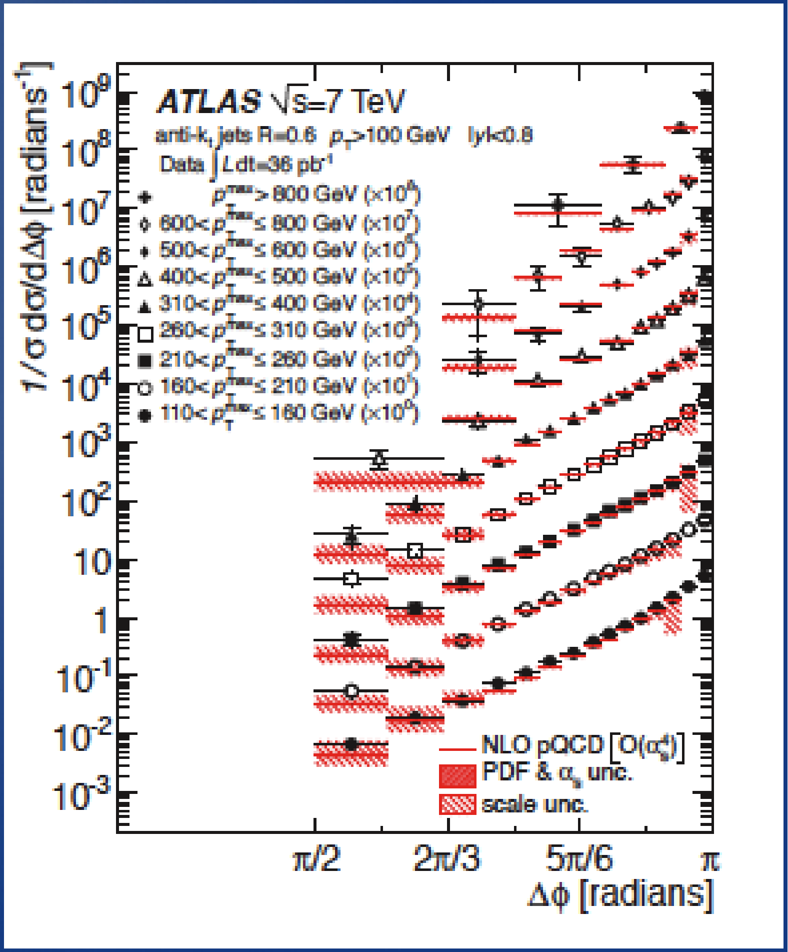




An indirect way to look at higher orders: azimuthal de-correlation

Pure dijet final states have to be back-to-back because of momentum conservation. Any deviation from that is an indication of higher-order terms





Comparison made with Pythia and NLO++
Only in central region

Measuring the jet veto

Which is the fraction, given two (possibly forward) jets, in which there is not a third jet between them?
This question is very much connected to the azimuthal de-correlation, to the 2/3 ratio, and in general to radiation from/between jets.

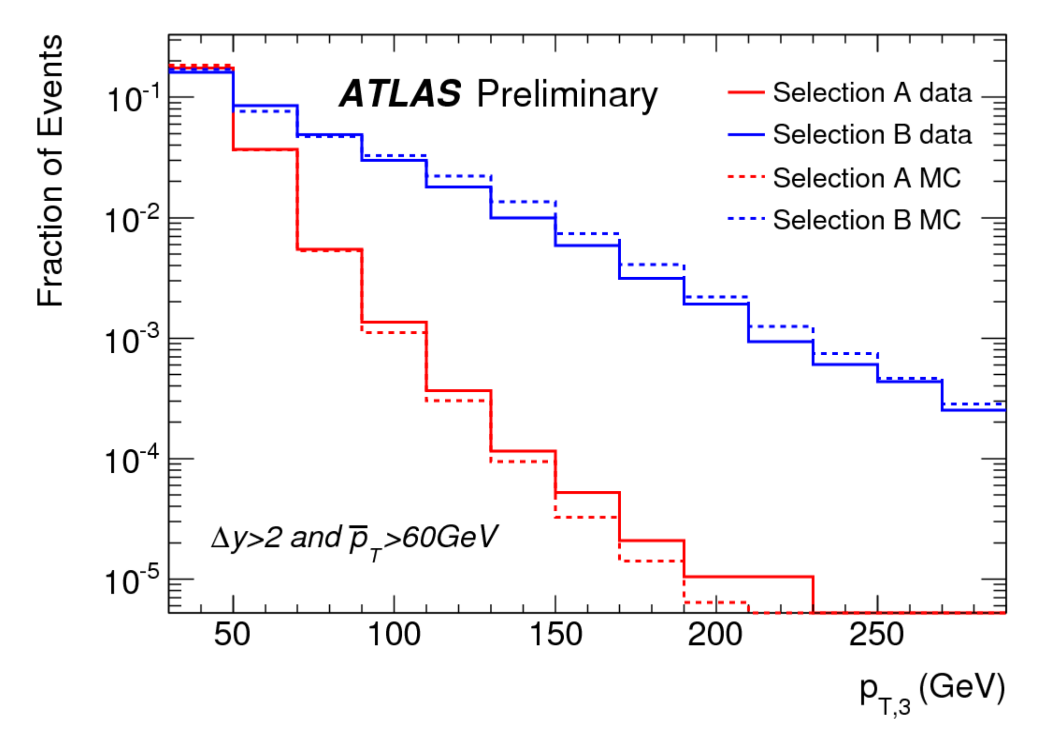
Two approaches to define “boundary jets”:

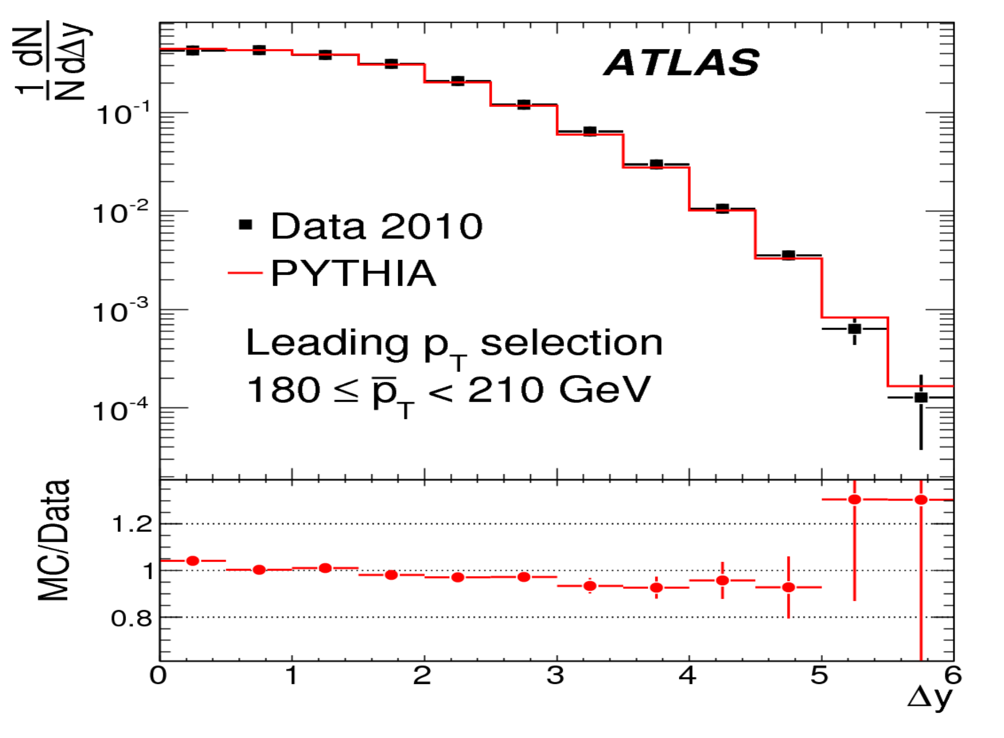
- The two leading jets in the event (probes high-Q^2 – DGLAP-like approach)
- The most forward and backward jets above a given threshold (gives larger gaps, should probe more BFKL-like dymanics)

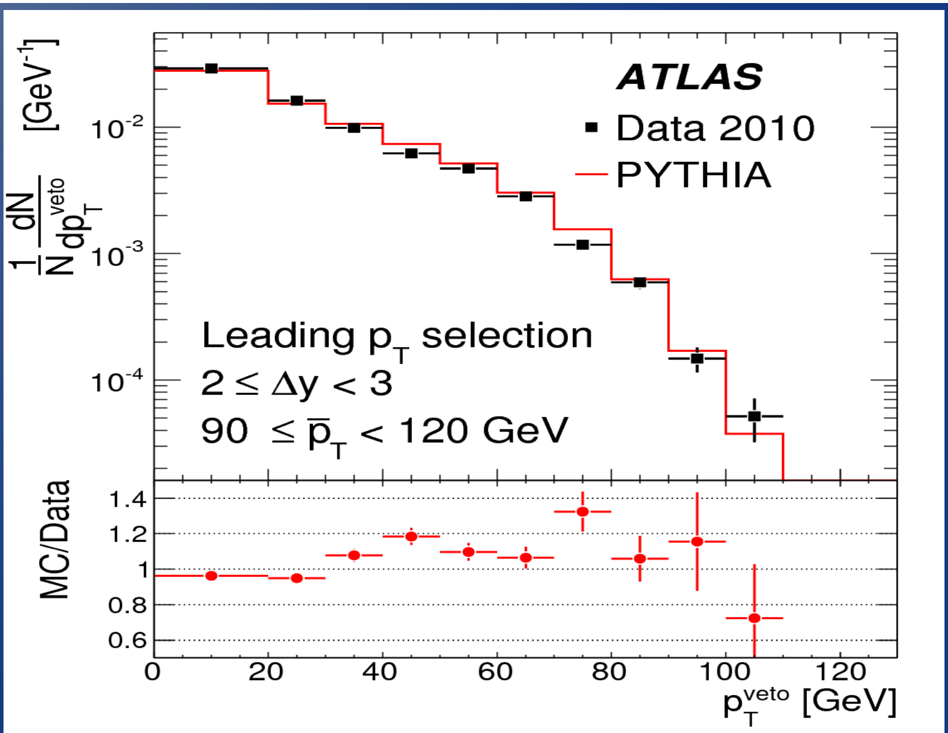
Testing ground for theory and experimental techniques to search for VBF Higgs

Kinematics for the two approaches

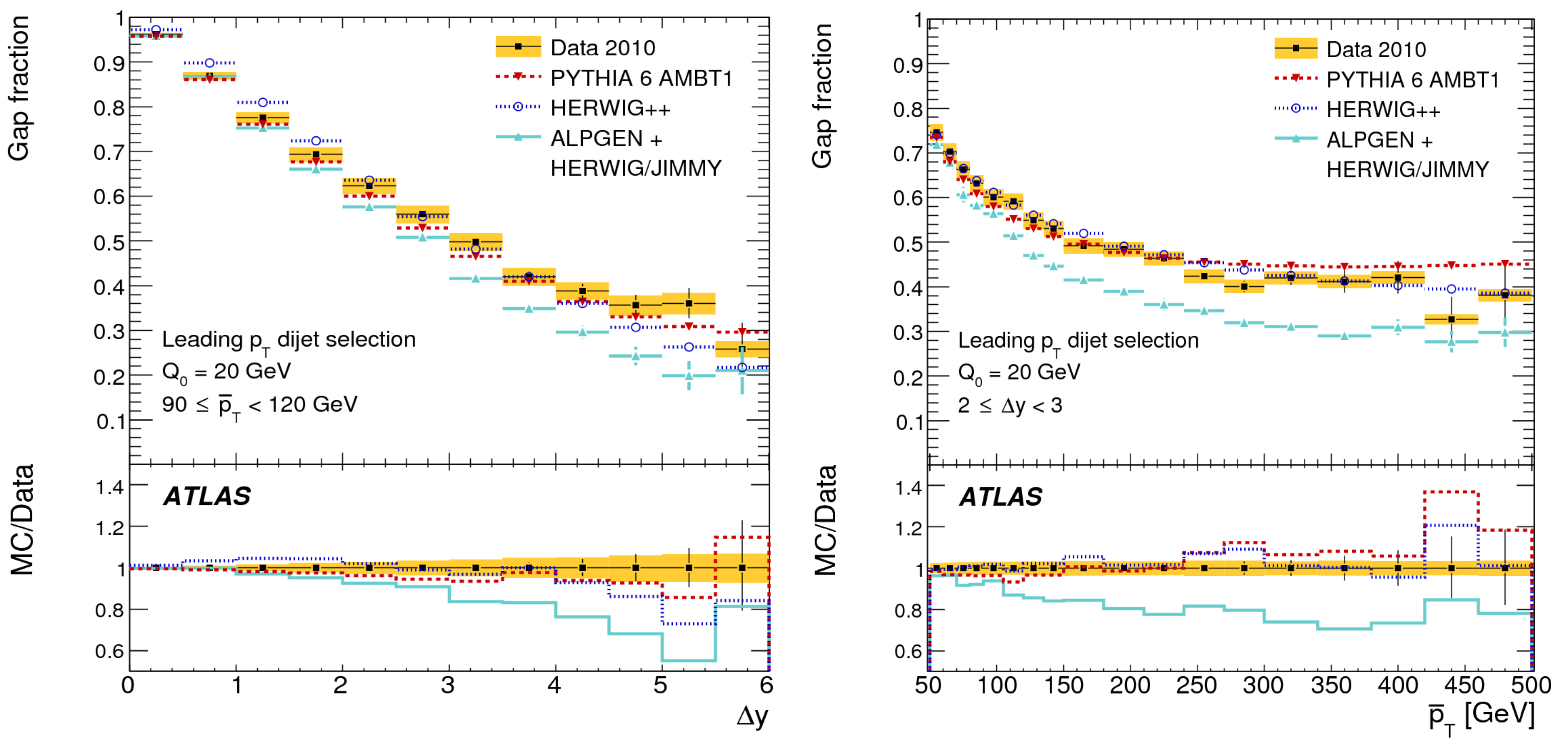
In f/b selection, the veto jet can also be the leading in the event, and is on average much harder than leading pT selection, and delta eta Is larger.
We require average Pt of two jets above 60 GeV, to be selected by inclusive trigger







Integrated gap fractions vs LO generators

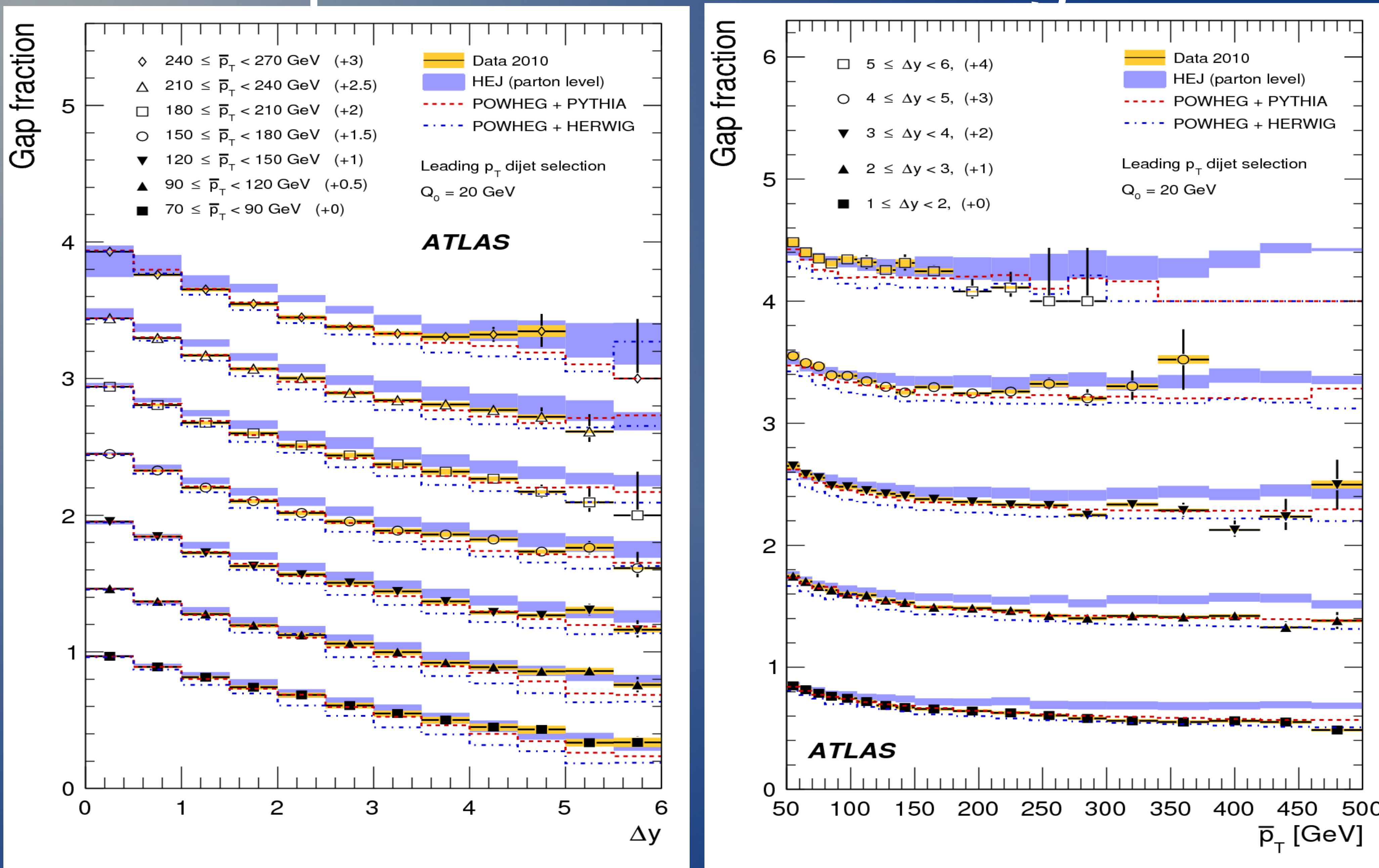


Being a ratio measurement, systematics far smaller than, e.g. a cross section

Single vertex requirement to avoid pileup

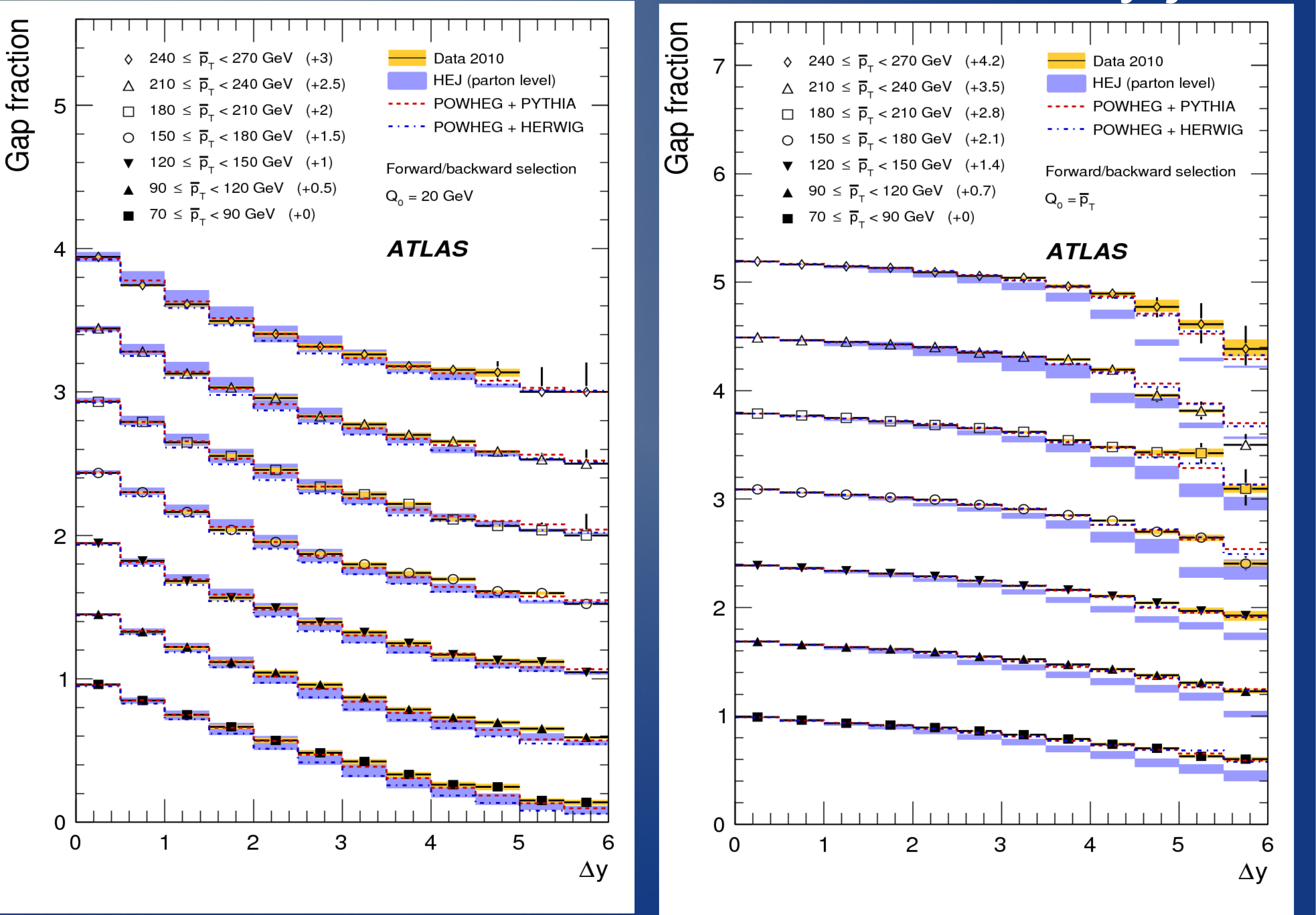
Limited agreement with Alpgen + Herwig

Comparisons with Powheg/HEJ

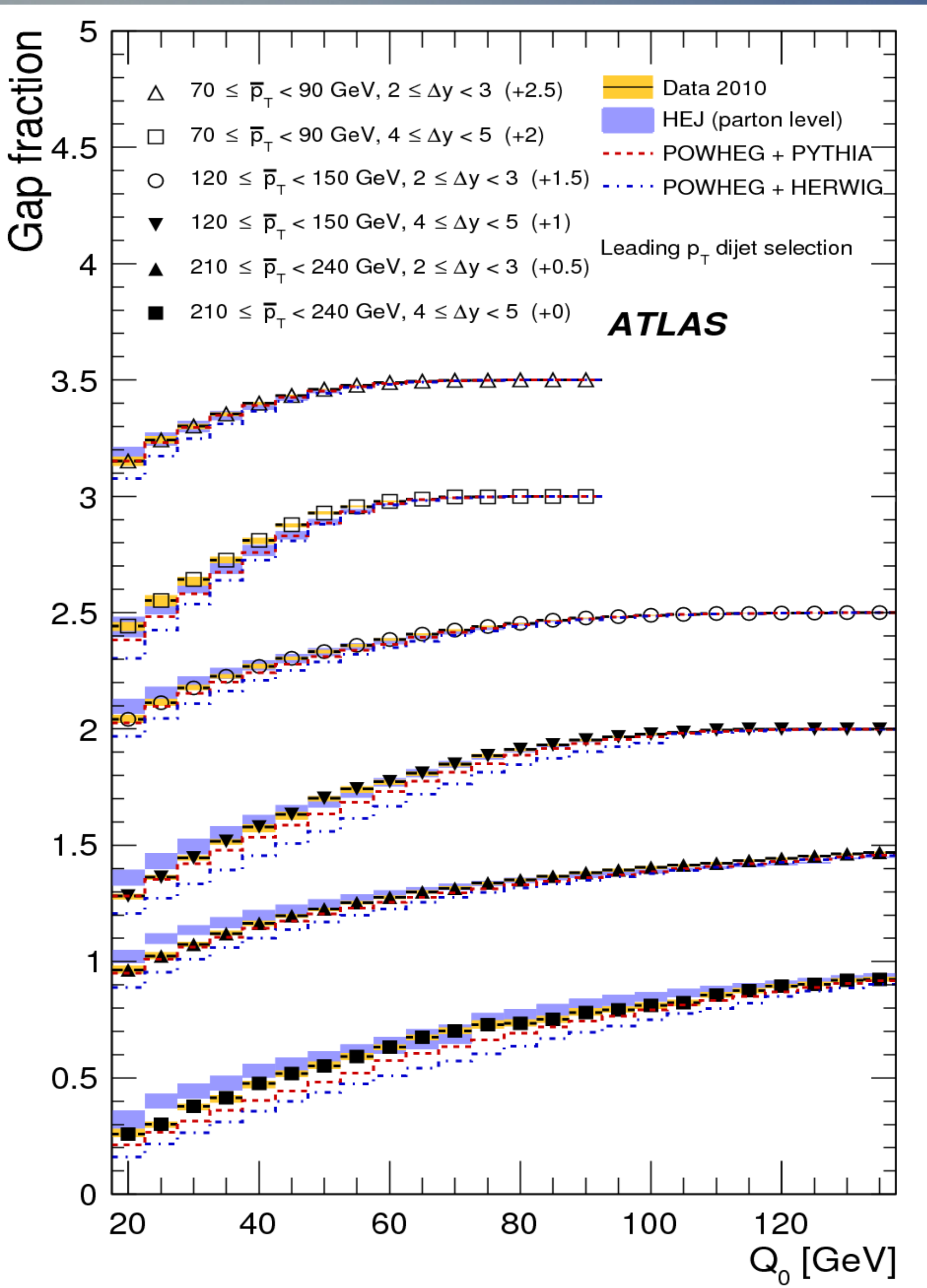


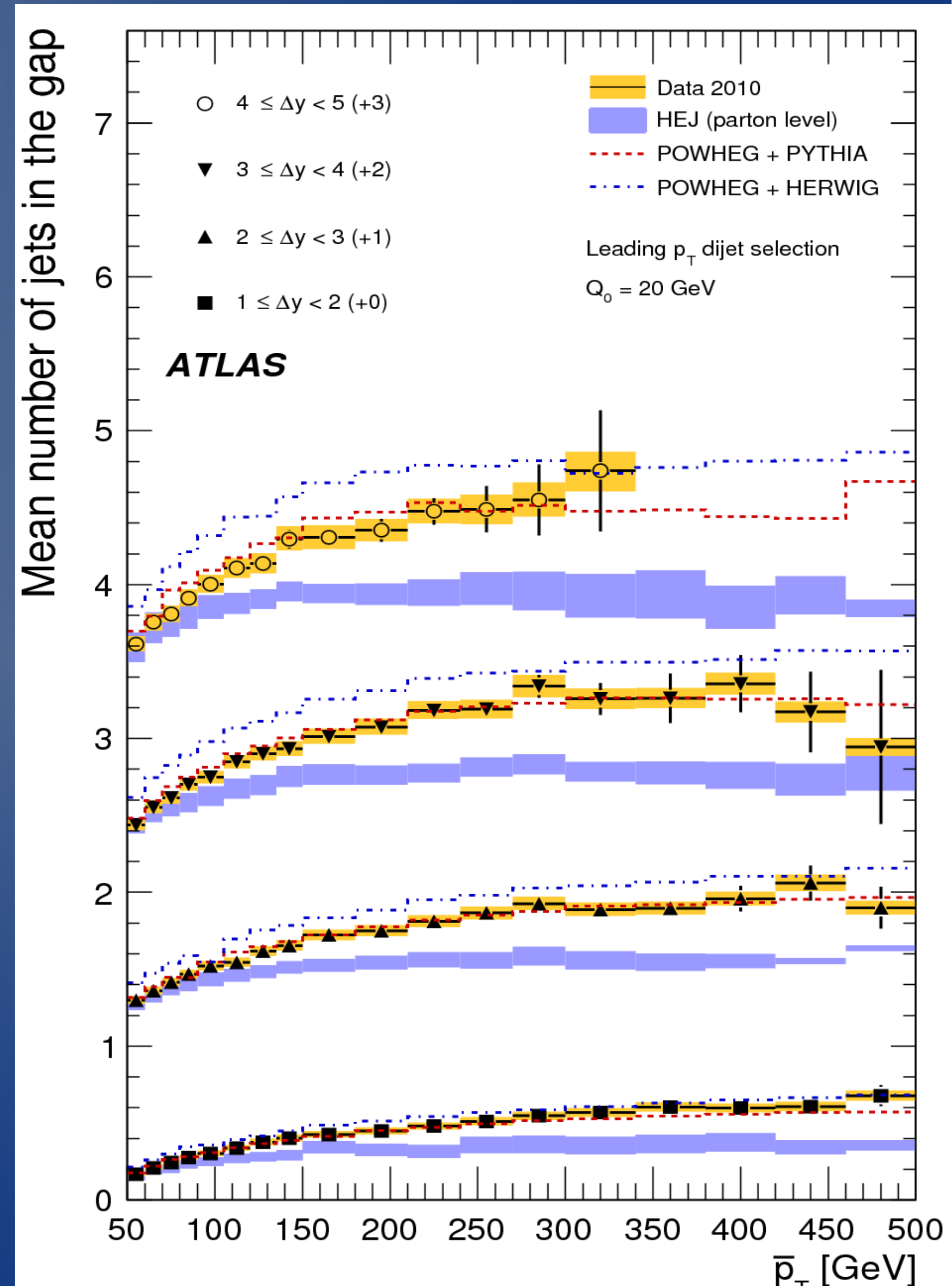
Best agreement with Powheg + Pythia, apart from the low-Pt high rapidity difference region

Same for forward/backward boundary jets



Gap vs pT_veto and jets in the gap





Photon identification

Isolation variable ETIso computed using cells from both EM/Hadronic calorimeter in a cone $\Delta R<0.4$ around the γ, subtracting the central 5x7 cells.

• Corrected for transverse energy leakage of photon candidate in above region

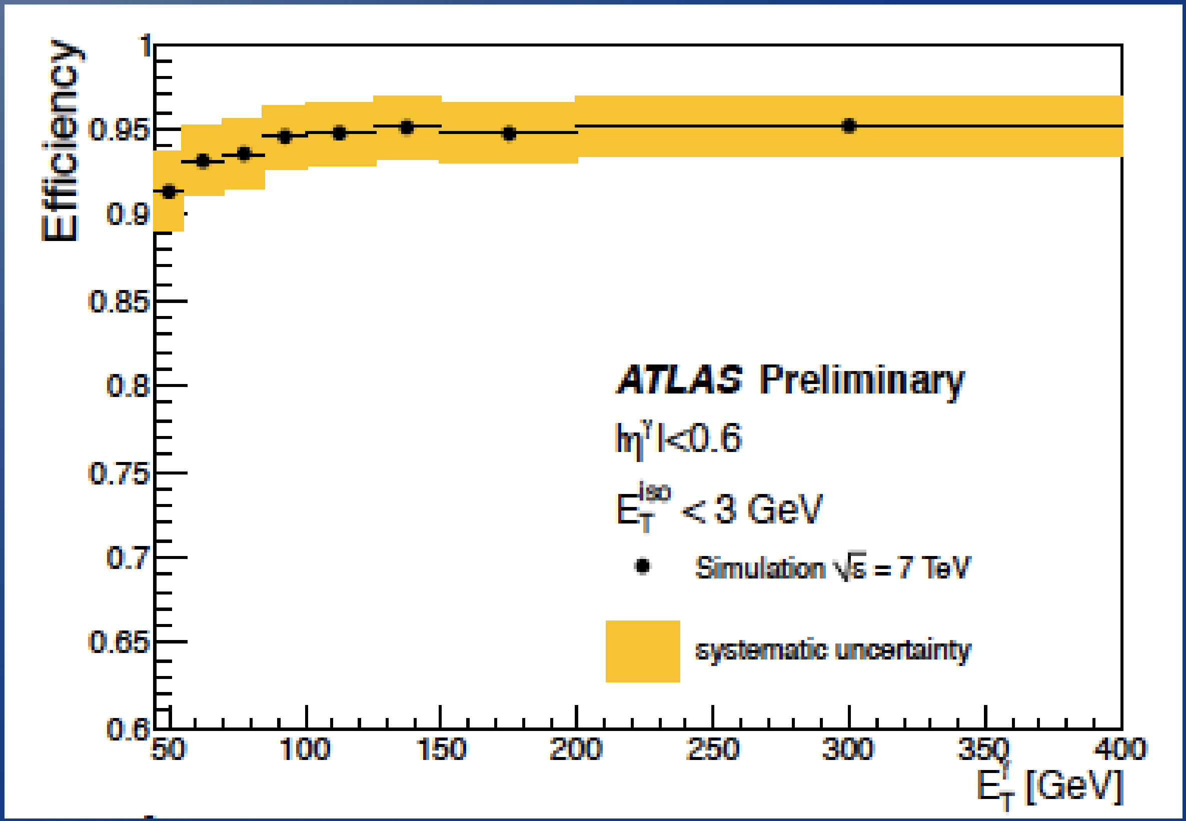
• Jet-area corrections (a la Cacciari-Salam) help sto mitigate the effects of in-time pileup (O(500 MeV))

Other In-time pileup effects small compared to uncertainty in the above method

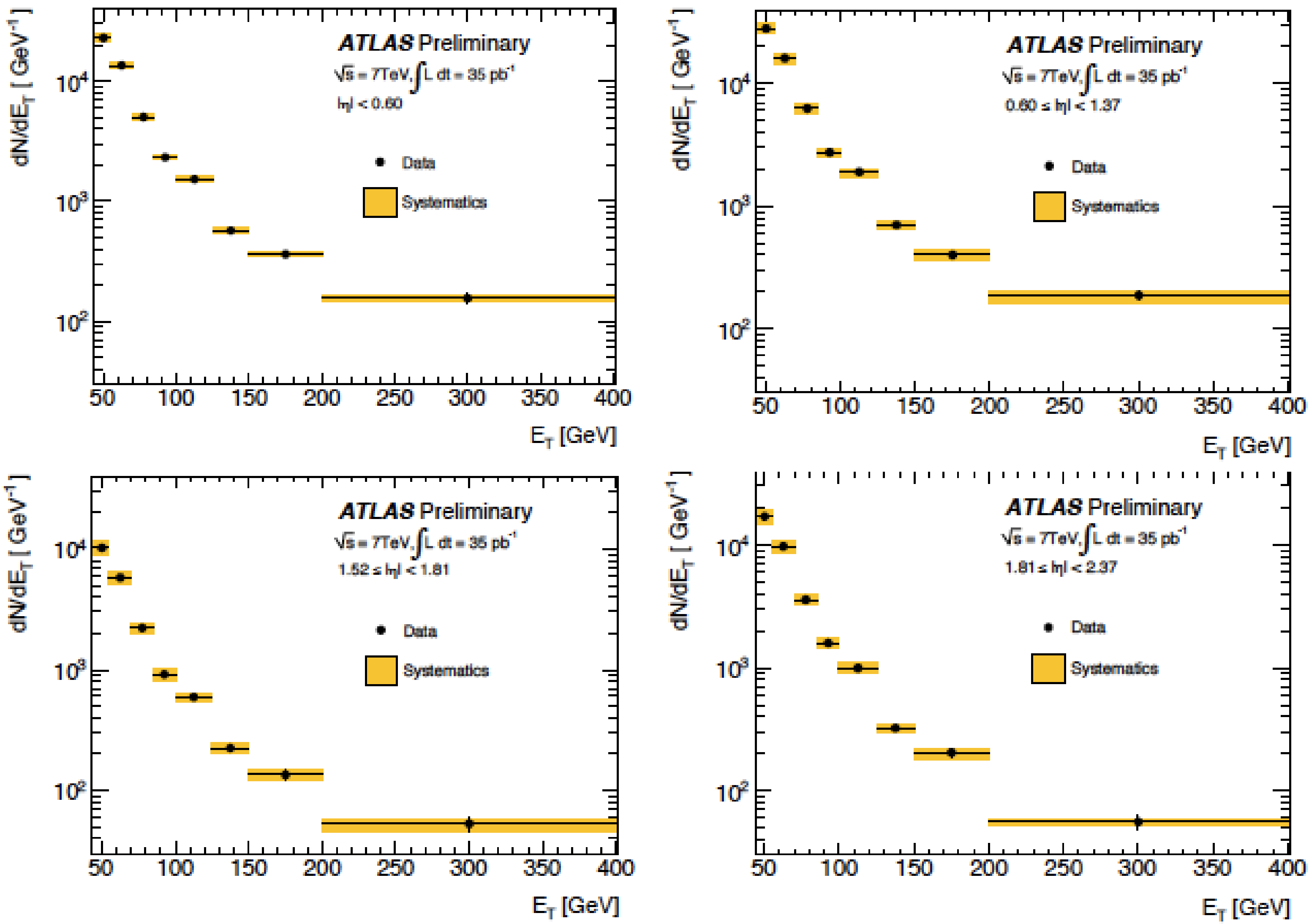
• Out-of-time pileup:

  • Effects found to be minimal

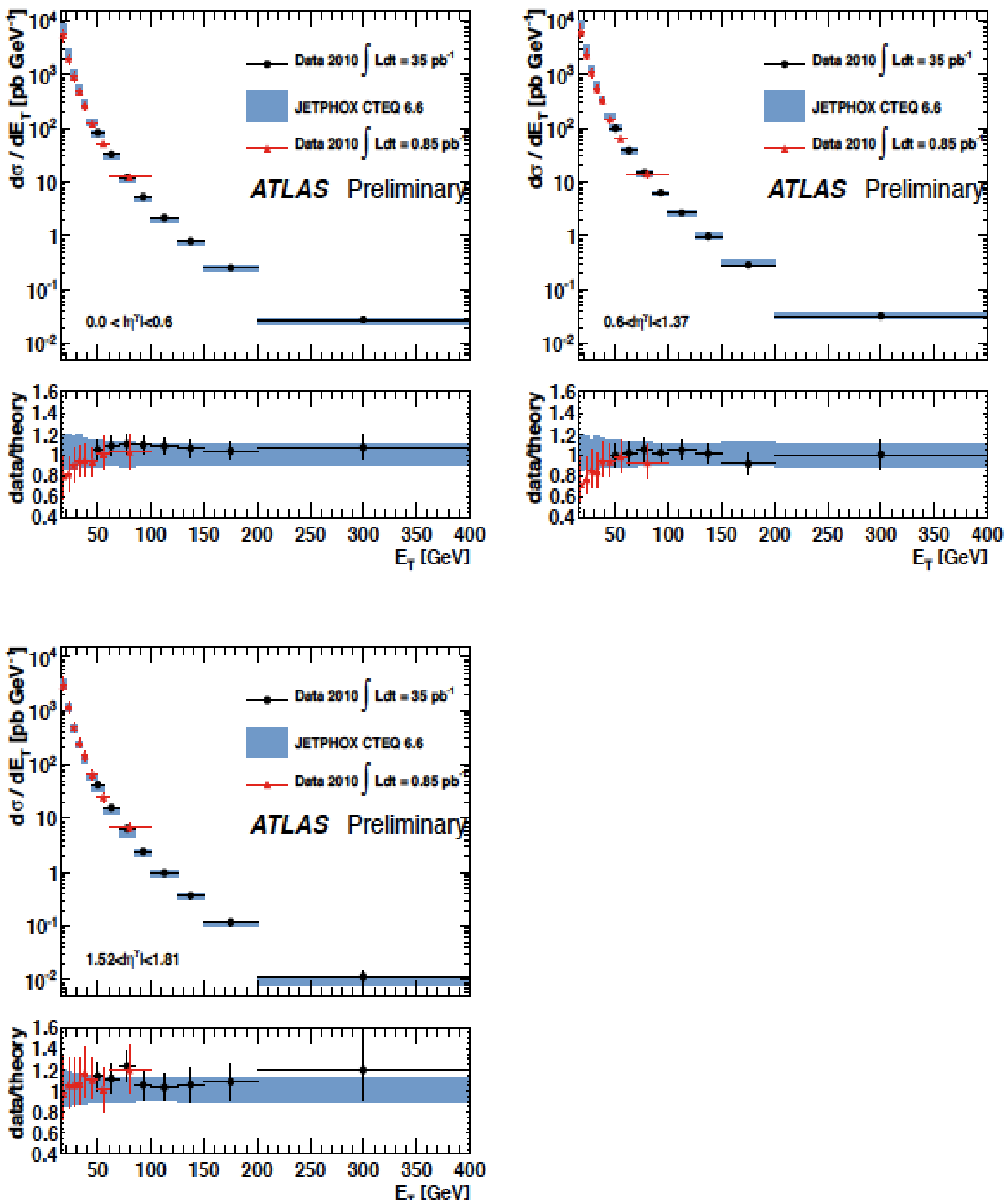
Photon efficiency (from MC)



- Systematics assigned for background control region definitions, signal leakage, material, photon energy scale, pile-up and MC simulation.
- NEW Background correlation (R^{MC}):
  - Systematic (per η bin): $\Delta Y = (Y_R - Y)$ → $\Delta Y/Y$ decreases with E_T as expected.



Inclusive photon cross-section

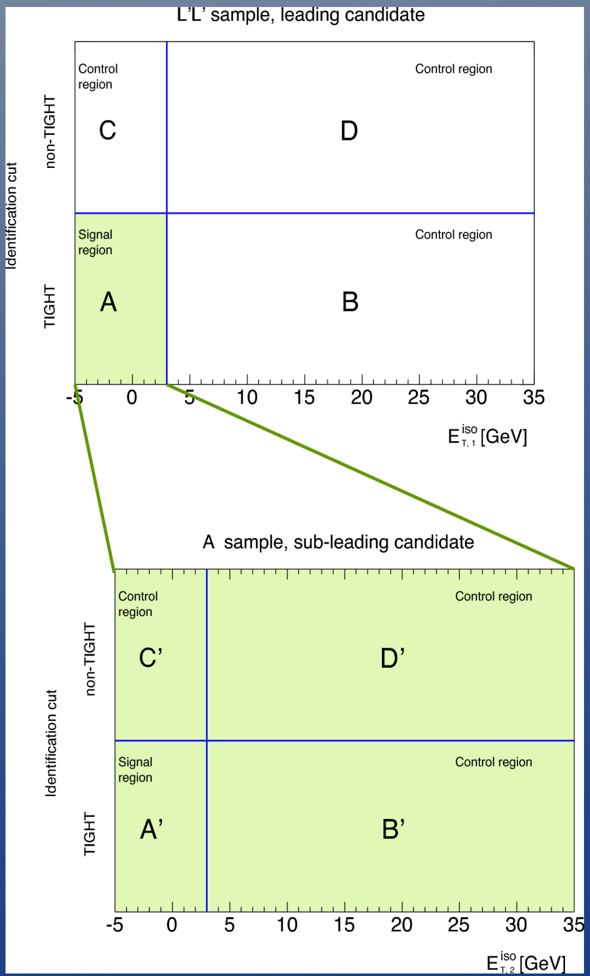


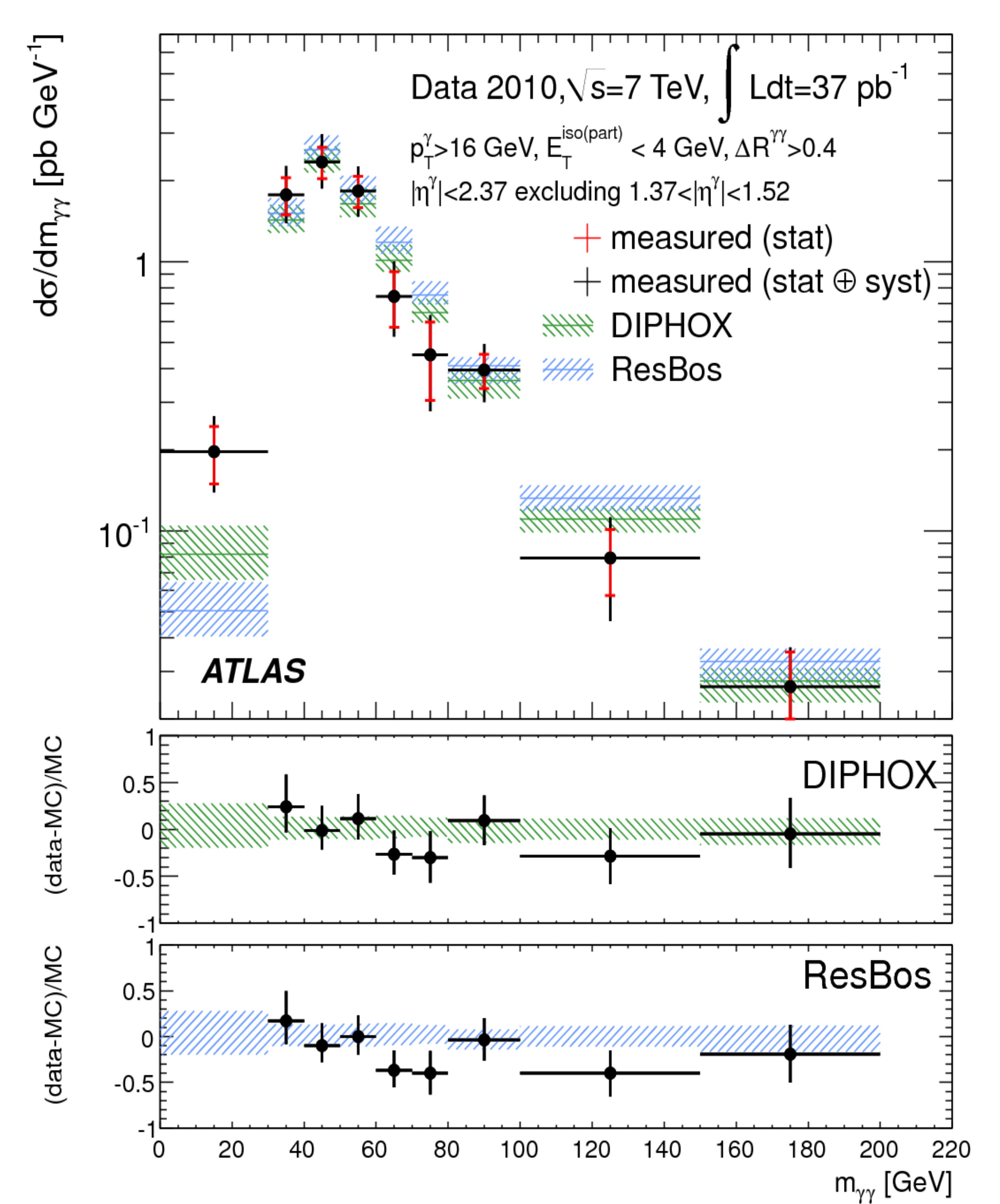
Red points are previous low-pt measurement

MSTW Pdf's show similar level of agreement

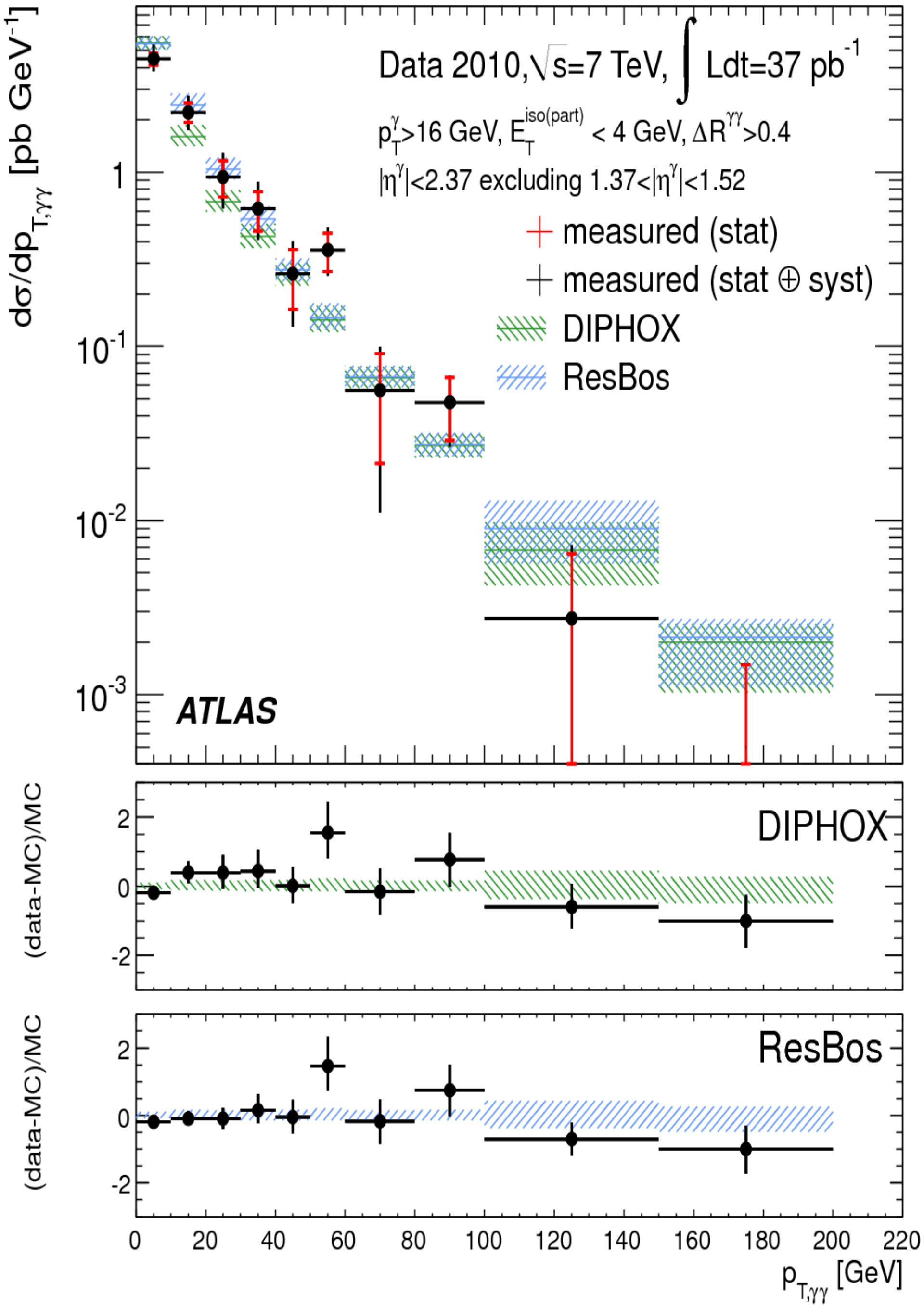
Di-photon measurement

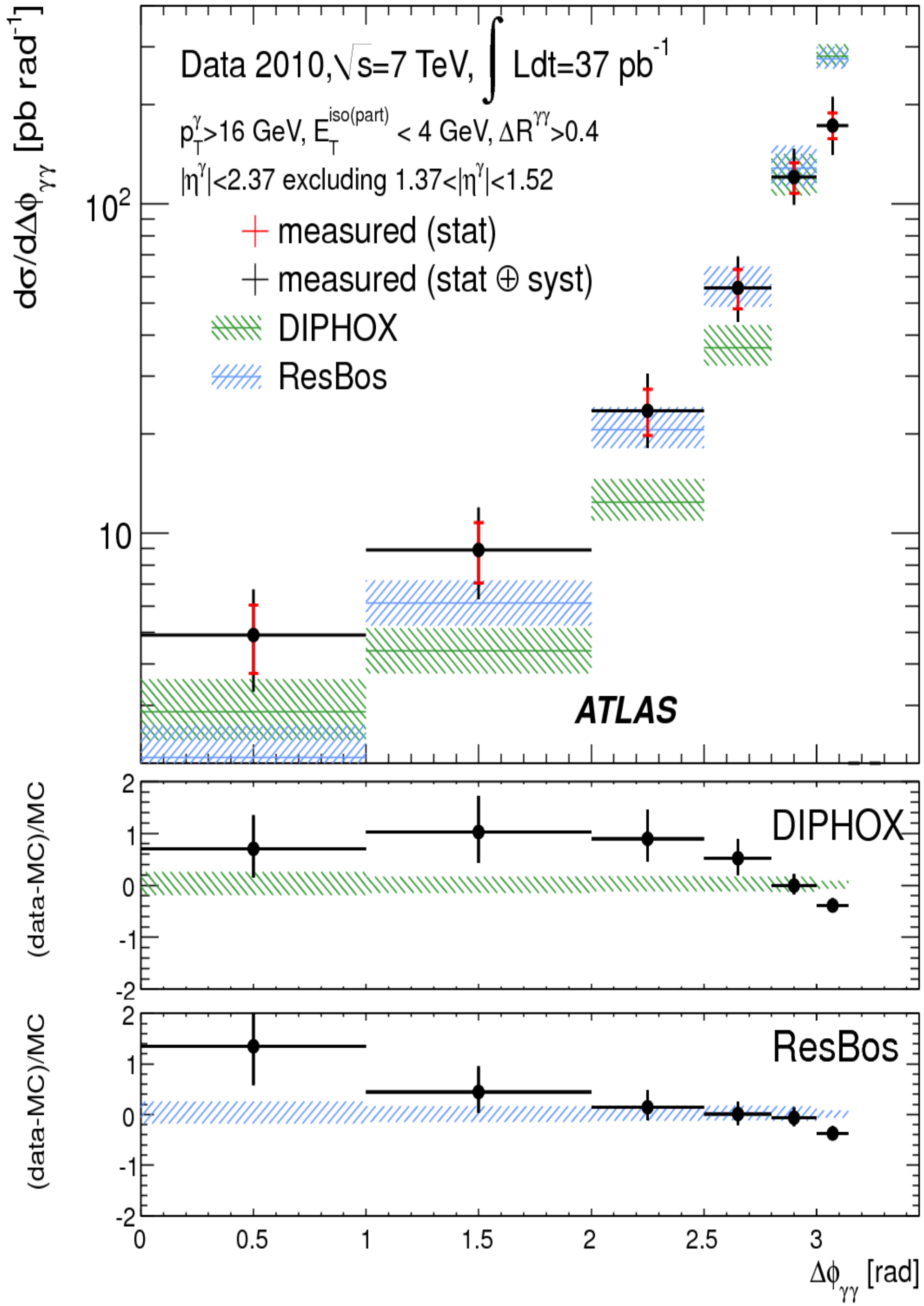
4-dimensional background subtraction, for leading and sub-leading jet





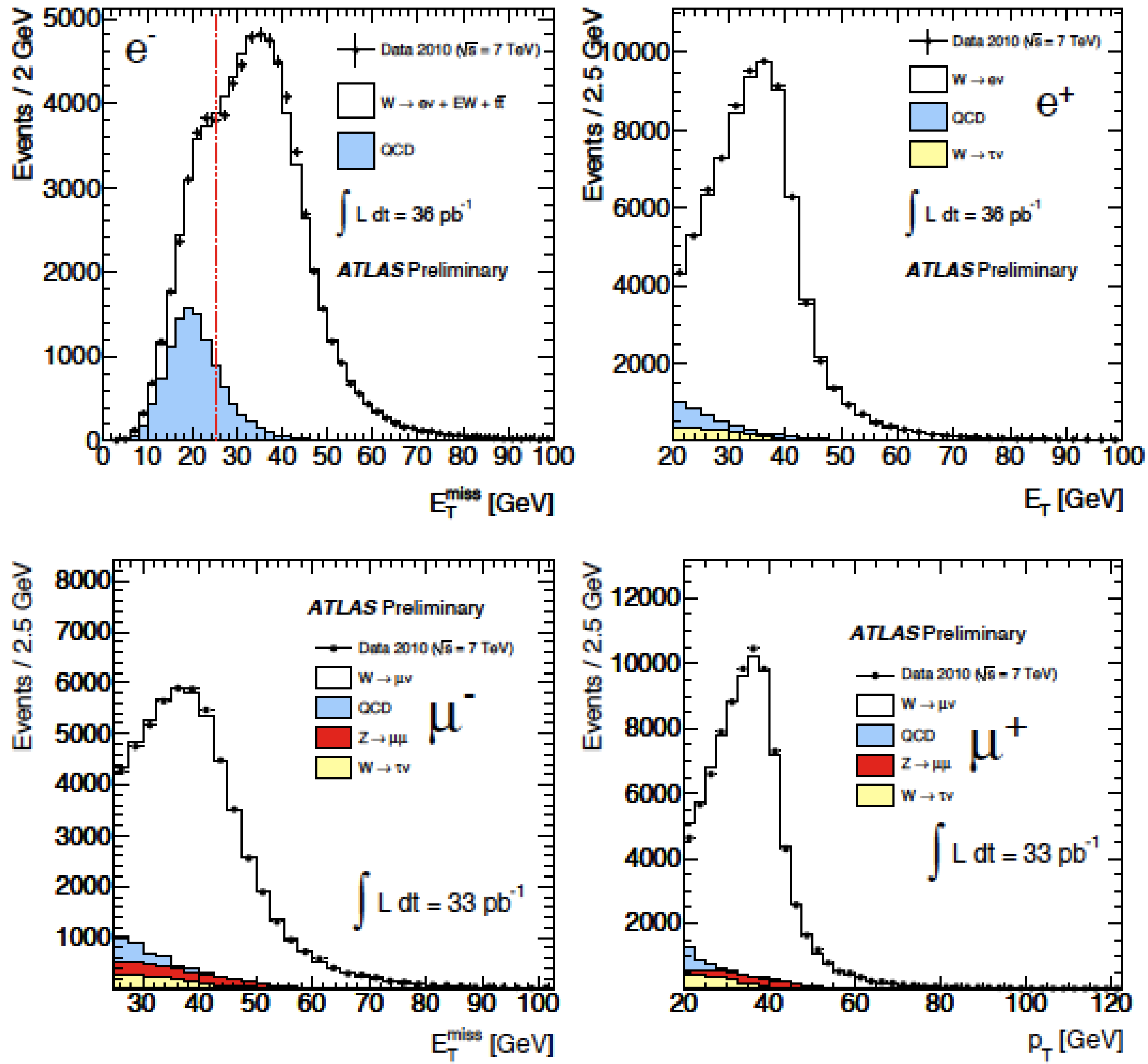
Di-photon results





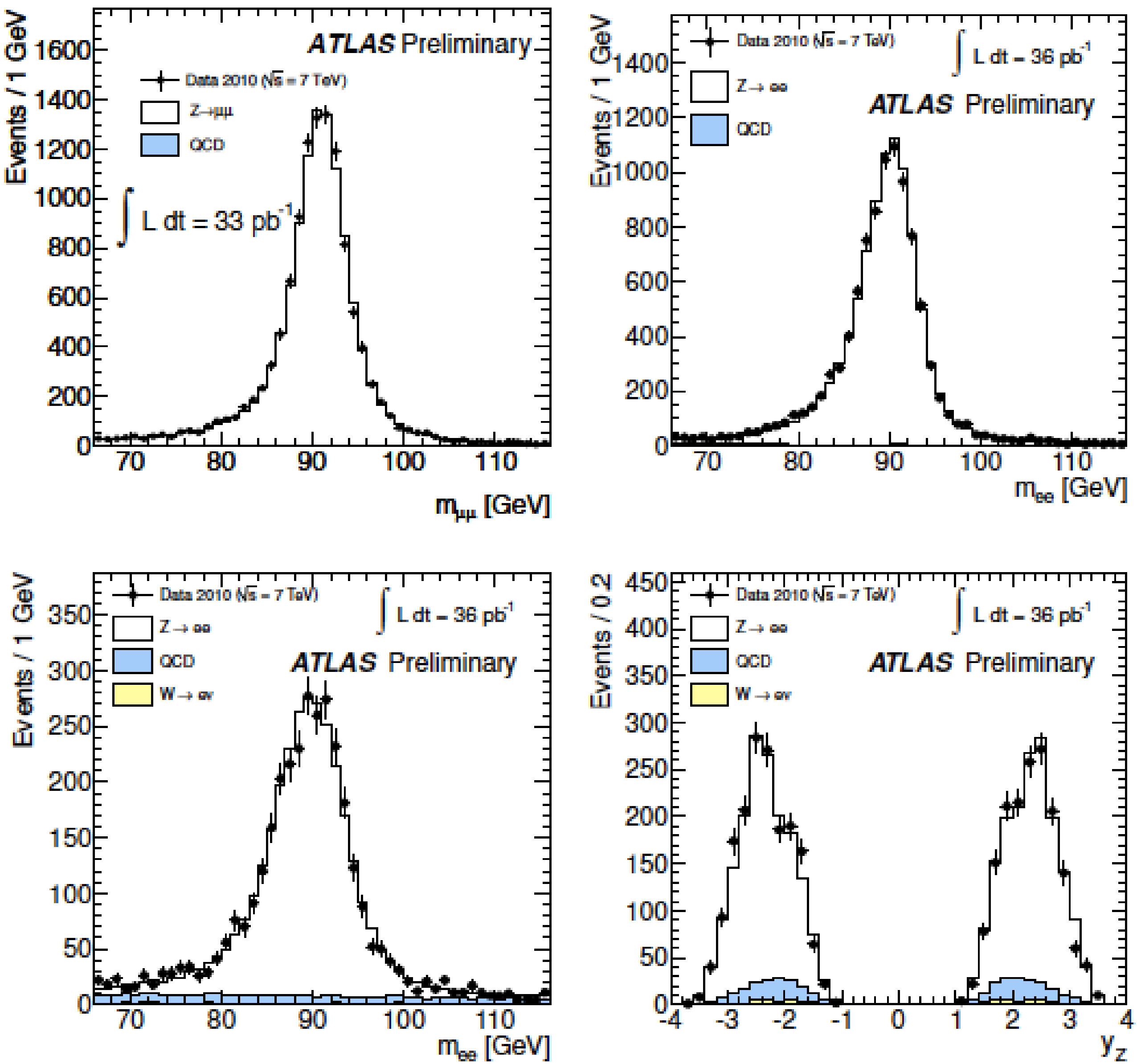
W identification

- Single lepton triggers with high efficiency
- $p_{T,l} > 20\,GeV$
  $|\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
  (elec. excl. calo crack)
  isolated leptons
  $E_T^{miss} > 25\,GeV$
  $m_T > 40\,GeV$
- QCD from data fitting E_T^{miss} (e) and studying control regions in $iso - E_T^{miss}$ plane (μ)
- $131 - 140\,K$ candidates with $7 - 9\,\%$ background



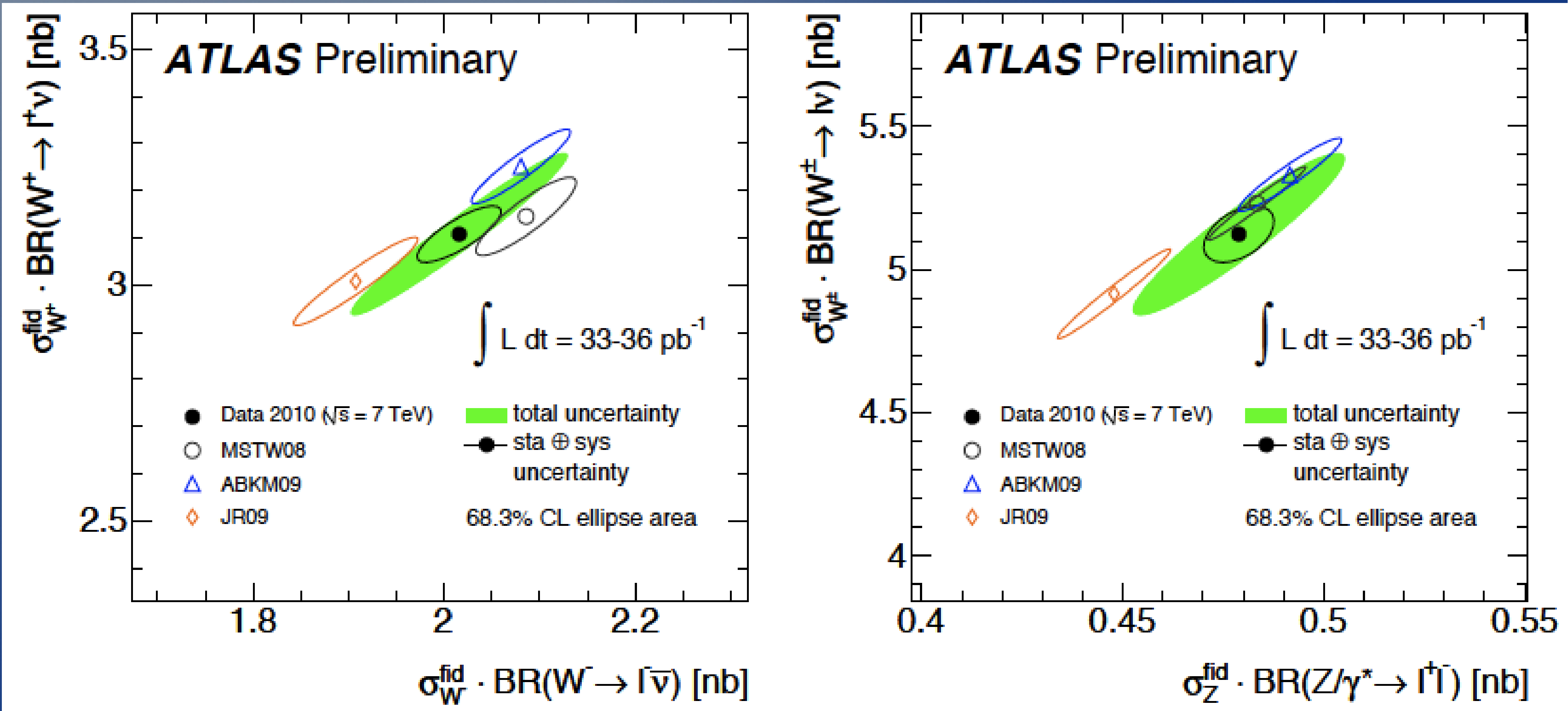
Z-> ll selection

- Single lepton triggers with high efficiency
- $p_{T,l} > 20\,GeV$
  $|\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
  (elec. excl. calo crack)
  isolated leptons
  opposite charge
  $66 < m_{\ell\ell} < 116\,GeV$
- QCD from data fitting $m_{\ell\ell}$ lineshape and studying control regions in $(iso, m_{\ell\ell})$
- $\sim 10-12\,K$ candidates with $1-2\,\%$ background

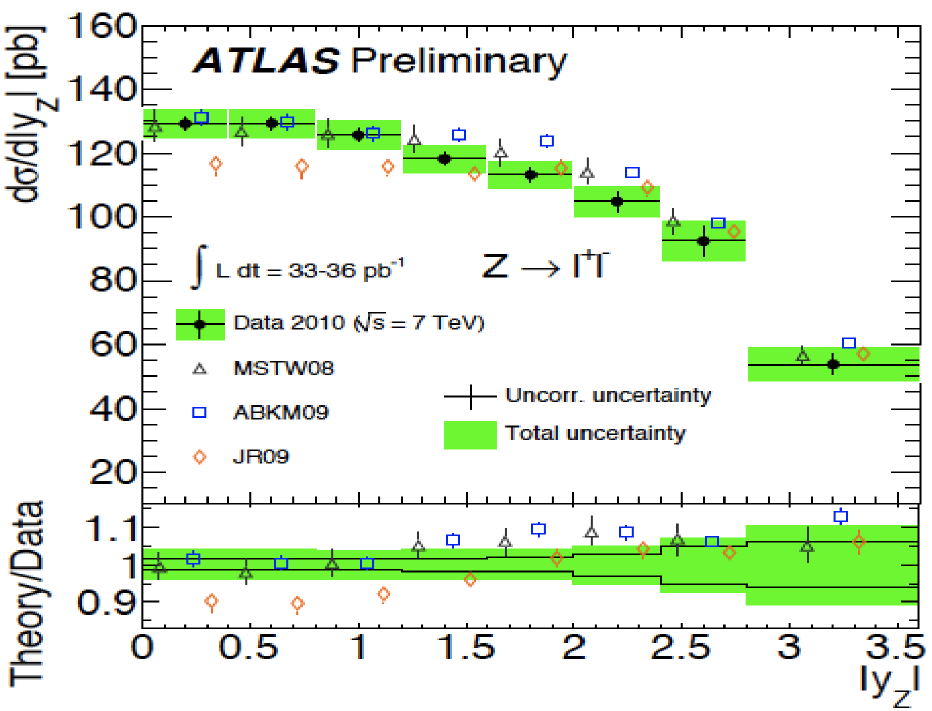


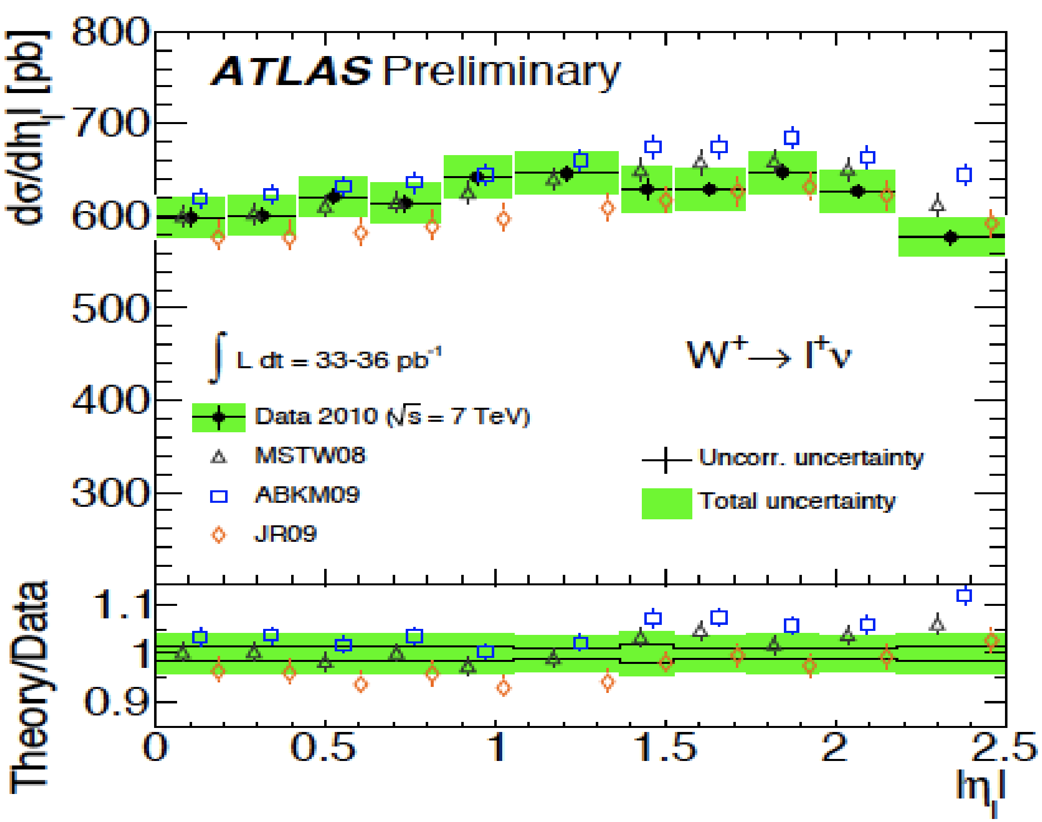
Total cross section

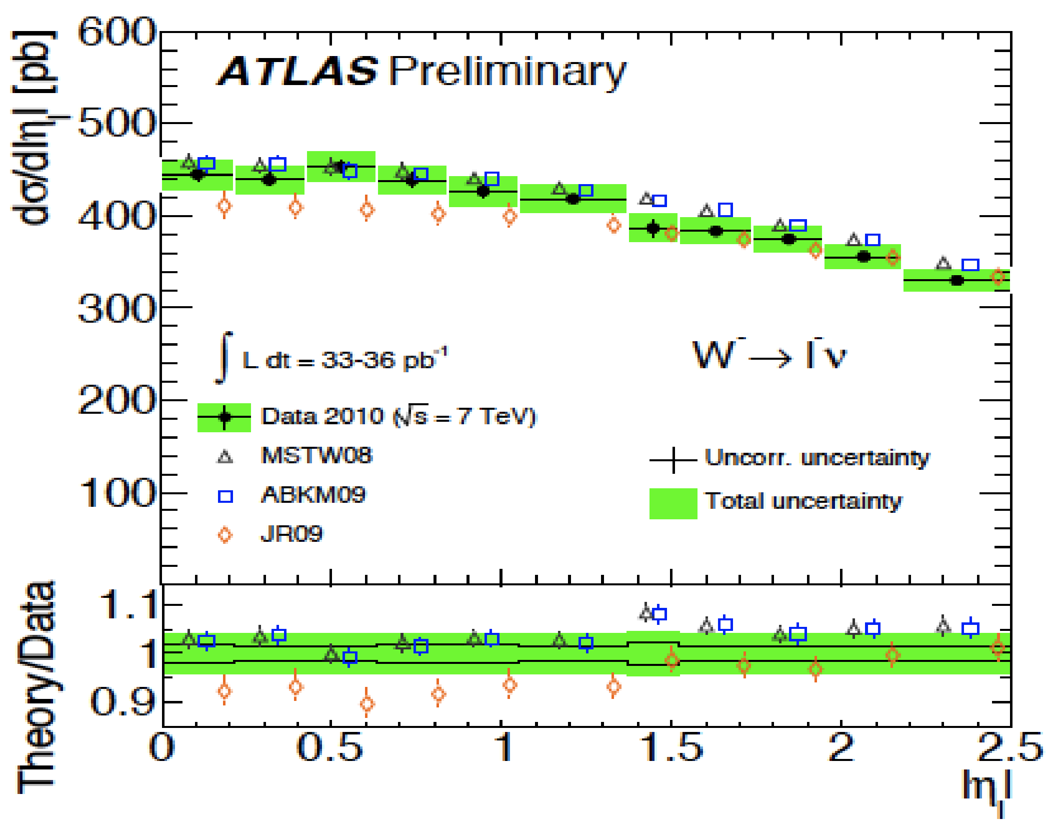
Comparison made in the fiducial region to minimise extrapolation uncertainties and be more sensitive to Pdf
NNLO predictions based on FEWZ and DYNNLO



Differential distributions also compared to NNLO (FEWZ and DYNNLO) with NNLO Pdf's

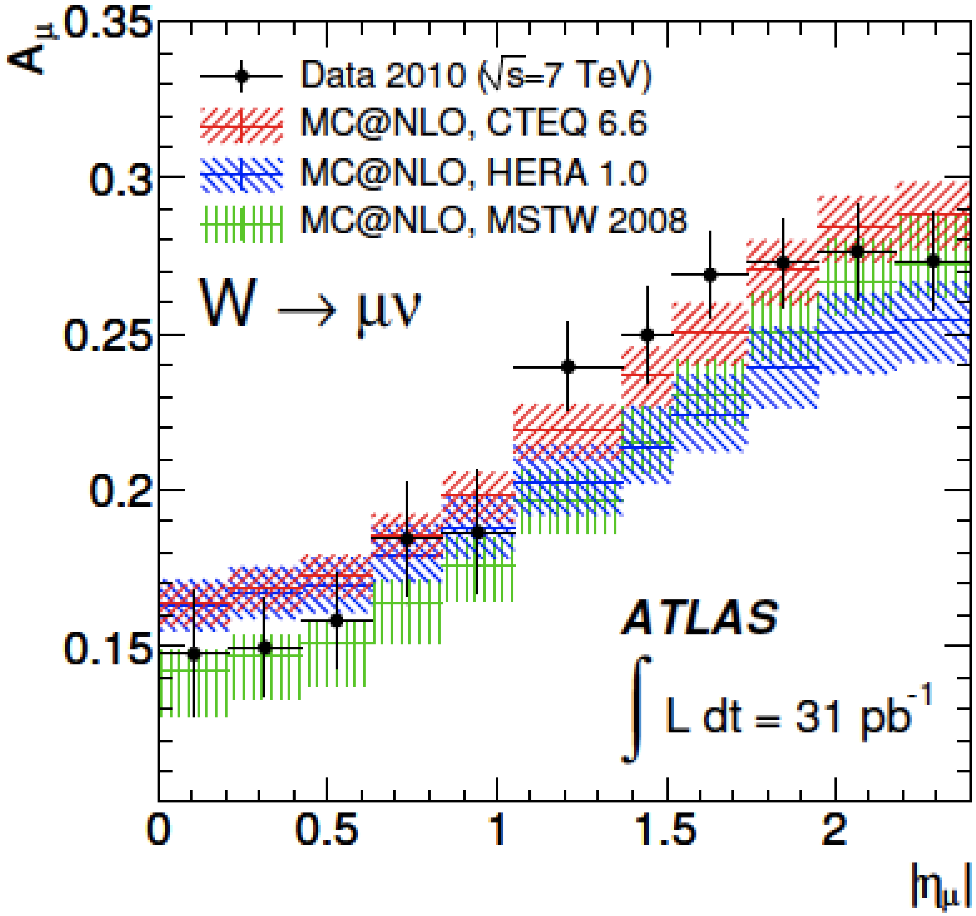


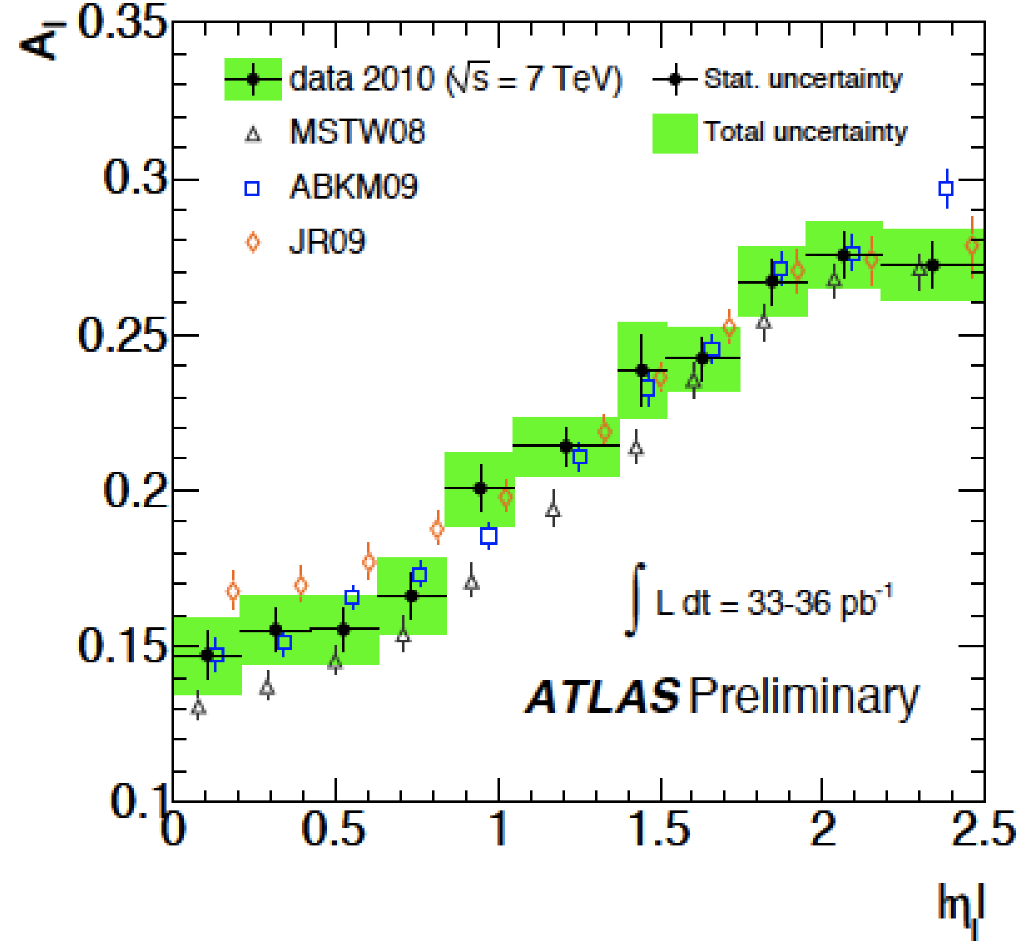




W asymmetry

- W differential charge asymmetry : $A(\eta_l) = \frac{\sigma^{W^+}(\eta_l) - \sigma^{W^-}(\eta_l)}{\sigma^{W^+}(\eta_l) + \sigma^{W^-}(\eta_l)}$
- Update of recent ATLAS muon measurement combining electron and muon channels together





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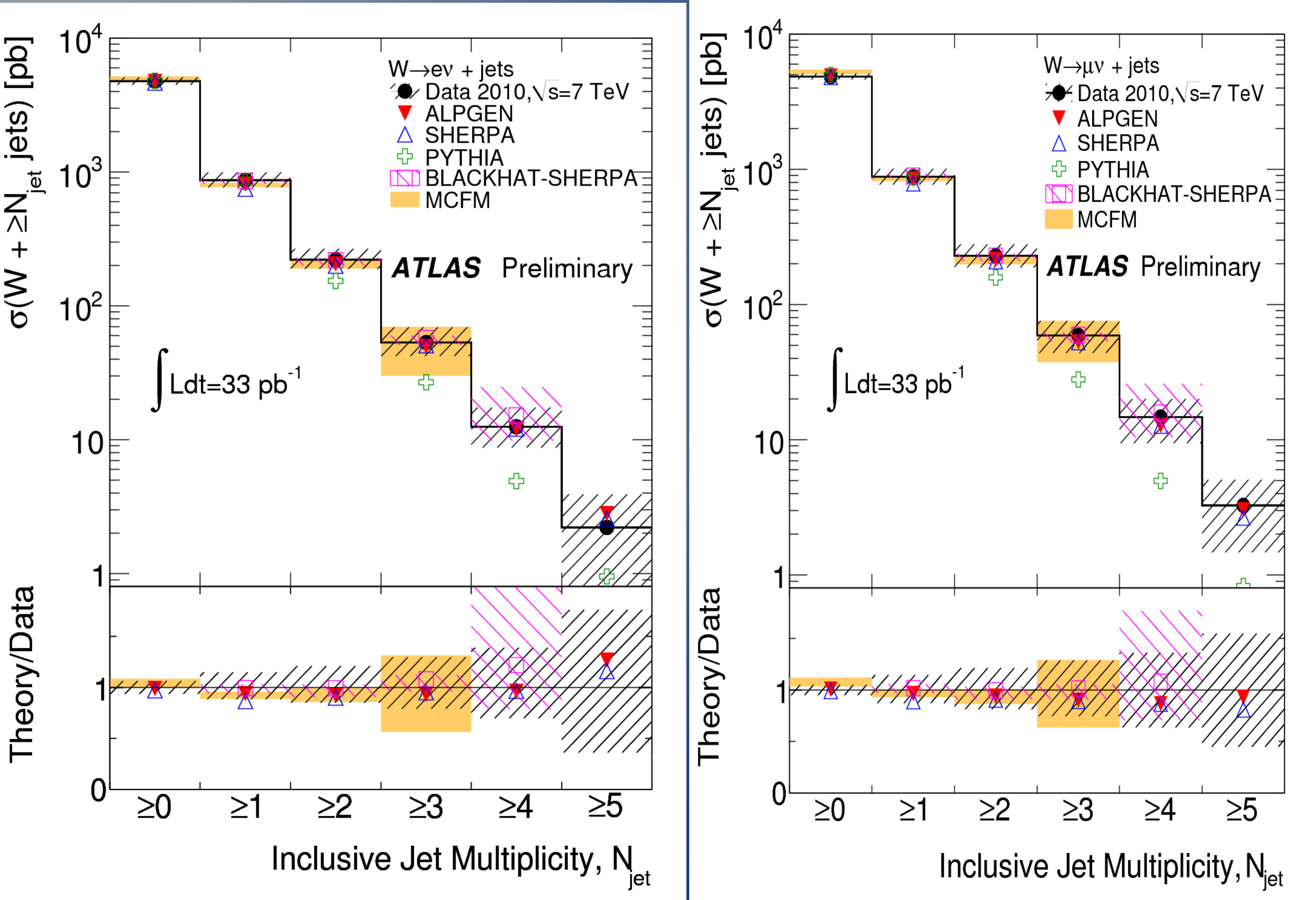
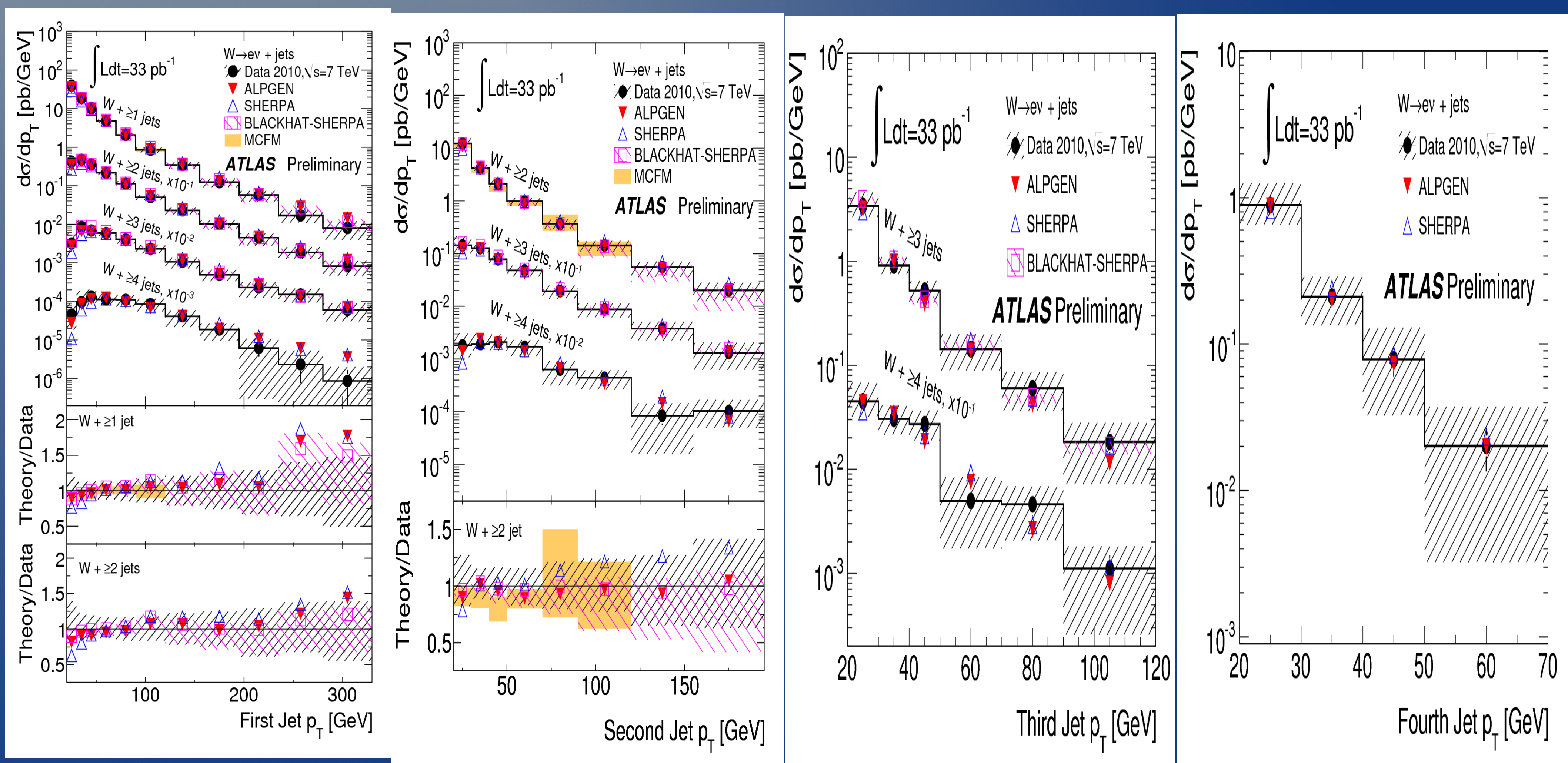
W + jets: e and mu channels

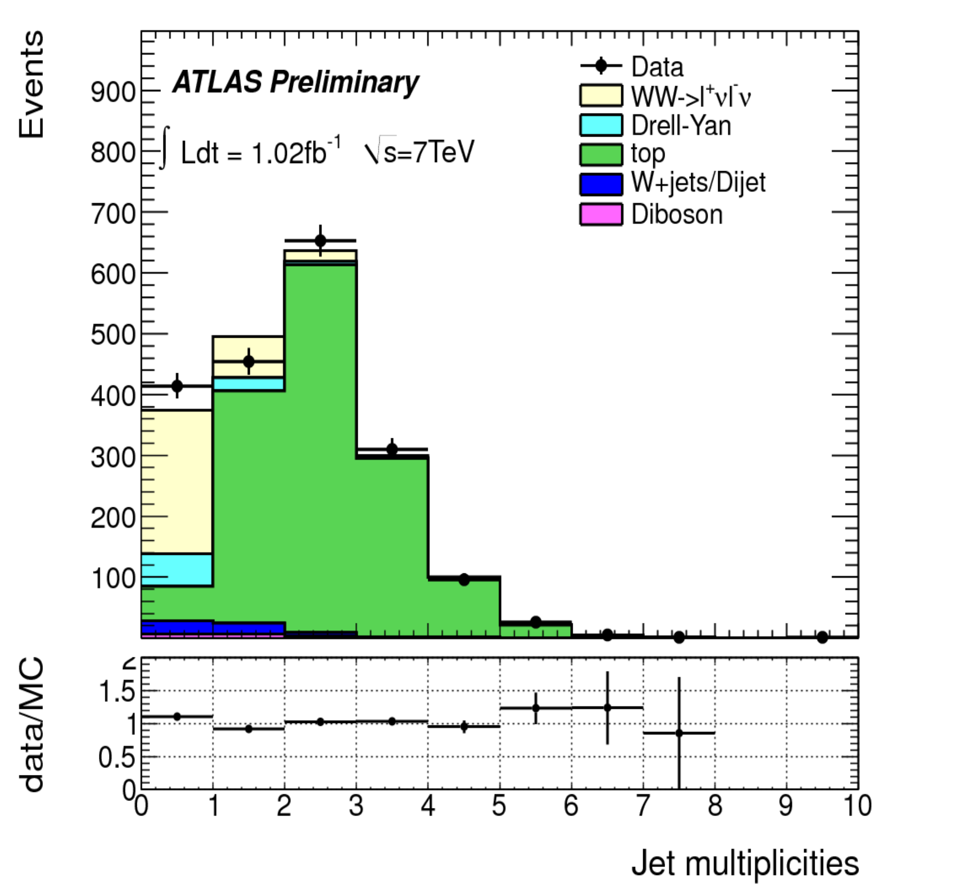


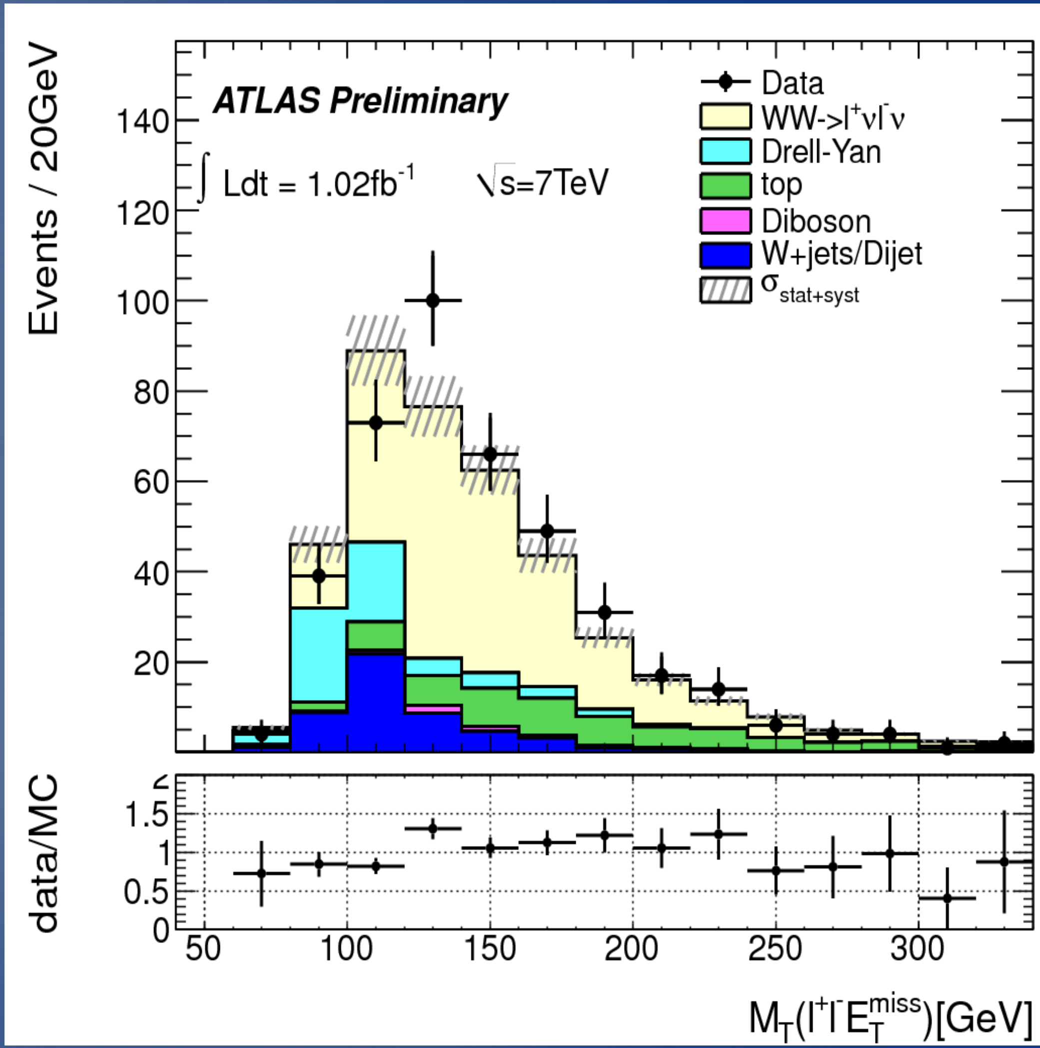
Jet pT distributions

Theory uncertainties only shown for MCFM (NLO for Njet <= 2, LO for Njets=3) and Blackhat-Sherpa (NLO for Njet<=3, LO for Njets = 4)



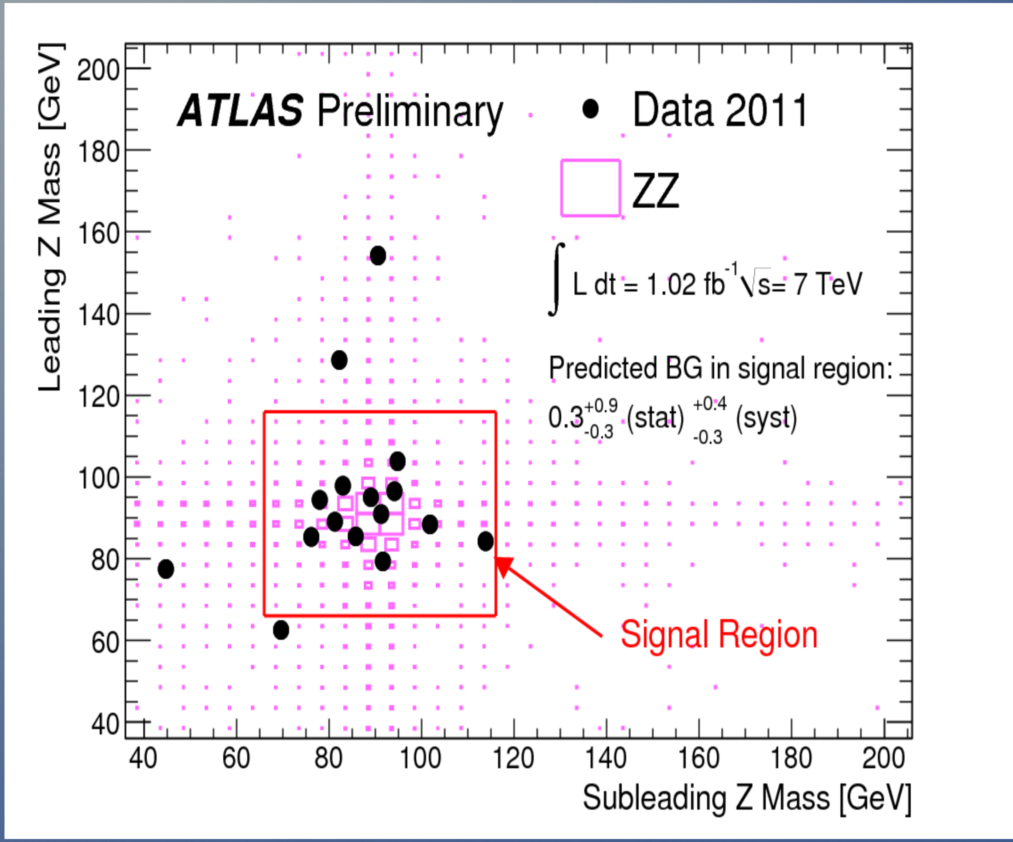
Dibosons:WW

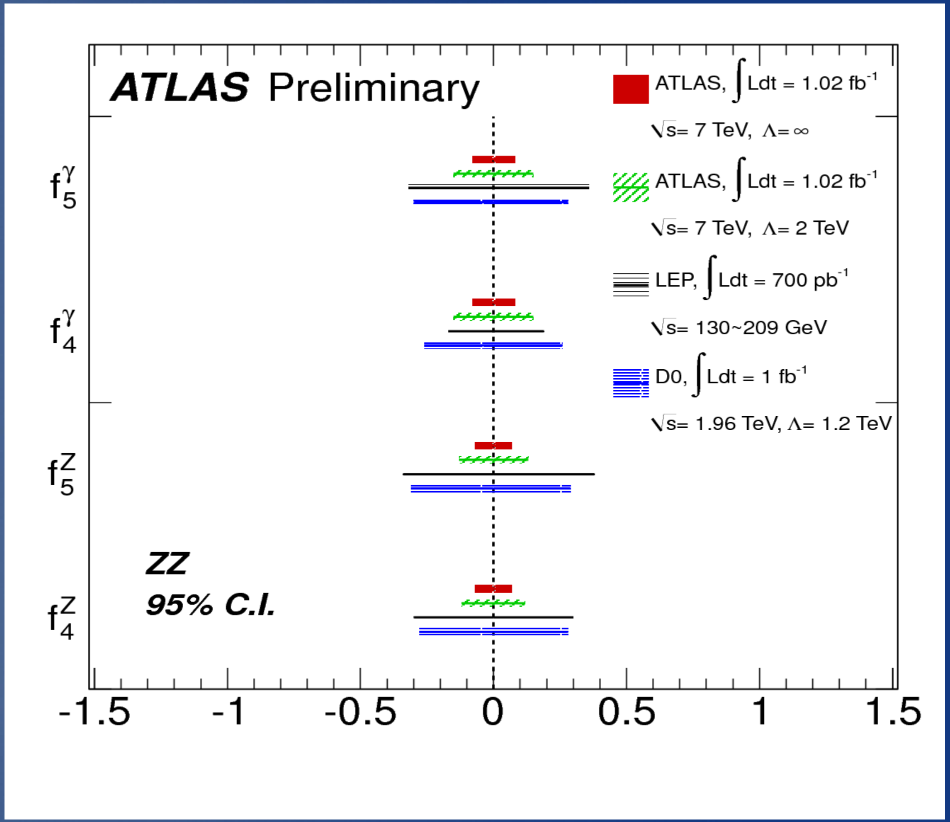




Fully leptonic channel; jet veto removes most of top background, additional cuts on MET and invariant mases

Dibosons: ZZ





Very clean channel, both in electron and muon mode
Angular distribution allows limits on anomalous couplings

Conclusions

- Could only rapidly flash some results, full list growing every day in https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- Analysis of 2010 data almost complete (stay tuned for imminent inclusive jets/dijets), but it will take some time to exploit full potential of 2011 data due to pileup
- Most bread'n butter measurements have been performed, and in general good agreement with theory has been found
- It is time now to challenge more complex observables, like jet substructures and corners of phase-space