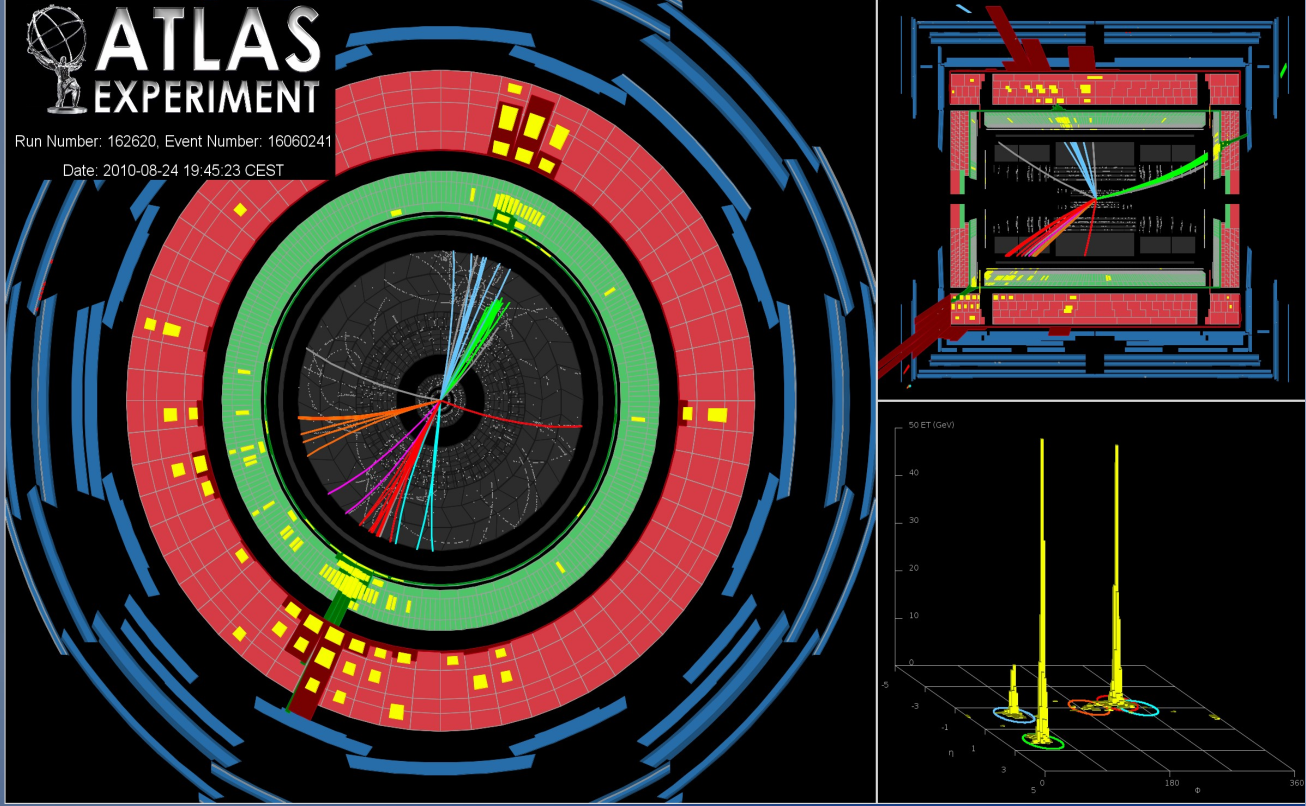
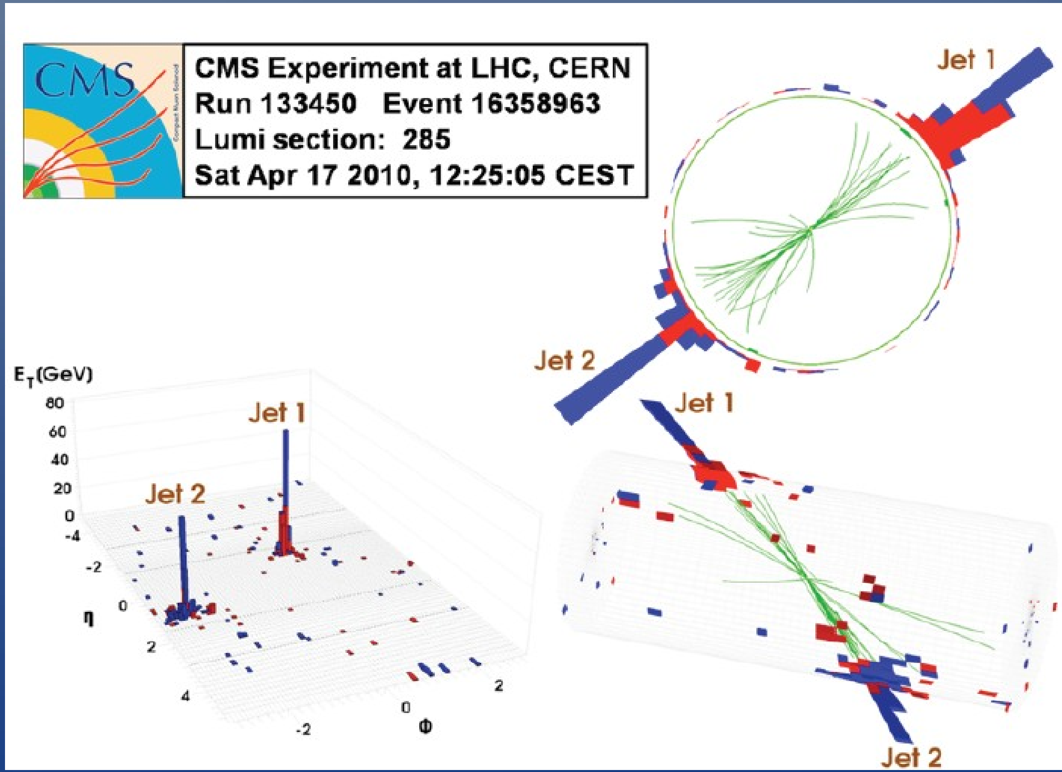
Hard QCD at the LHC
why we do it, how we do it, what we learnt so far





Mario Campanelli/ UCL

Guidelines

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

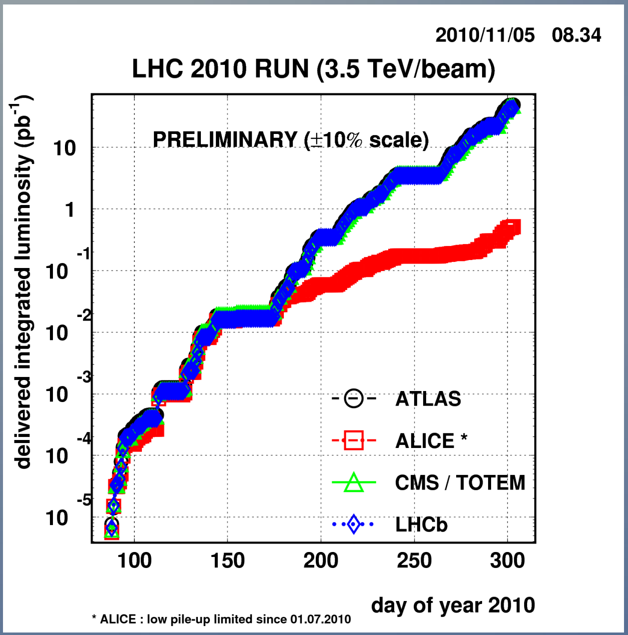
Learn the lessons from the past, and provide state-of-the art publications that could serve as an example for the future

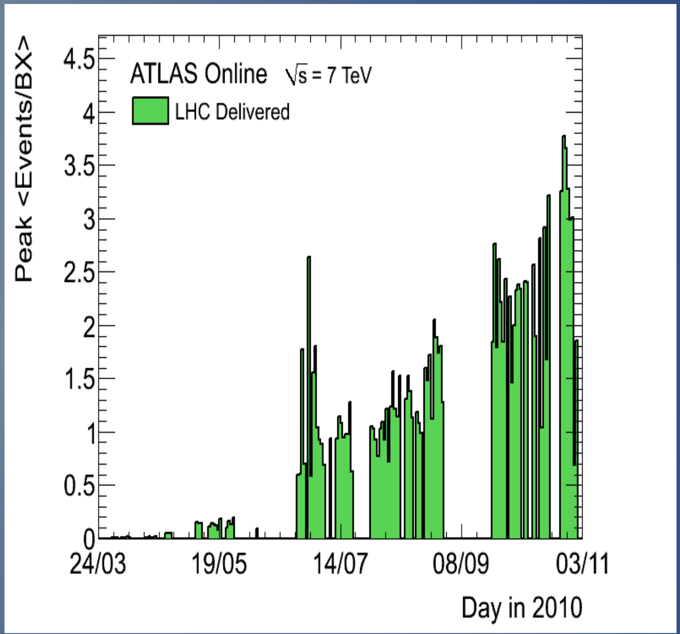
Collaborate with the theory community, some times as early as in the analysis preparation phase, and make results available using common tools (HEPData, Rivet)

More specifically, I will talk about

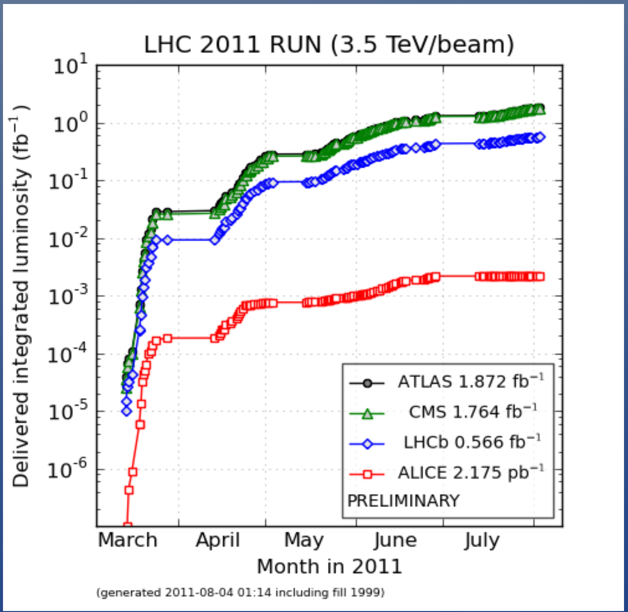
- Jets
  - triggers, calibration, JES
  - Jet proprties: shapes, fragmentation, mass
  - Inclusive and dijet cross section
  - b-jets
  - azimuthal de-correlations and jet veto
- Photons
  - Inclusive and di-photon cross-section
- Vector bosons
  - Inclusive production

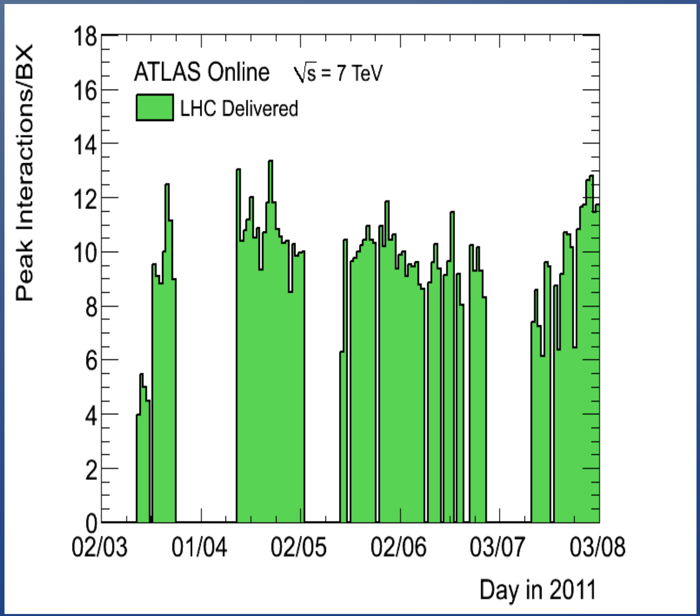
LHC performances: 2010 vs 2011

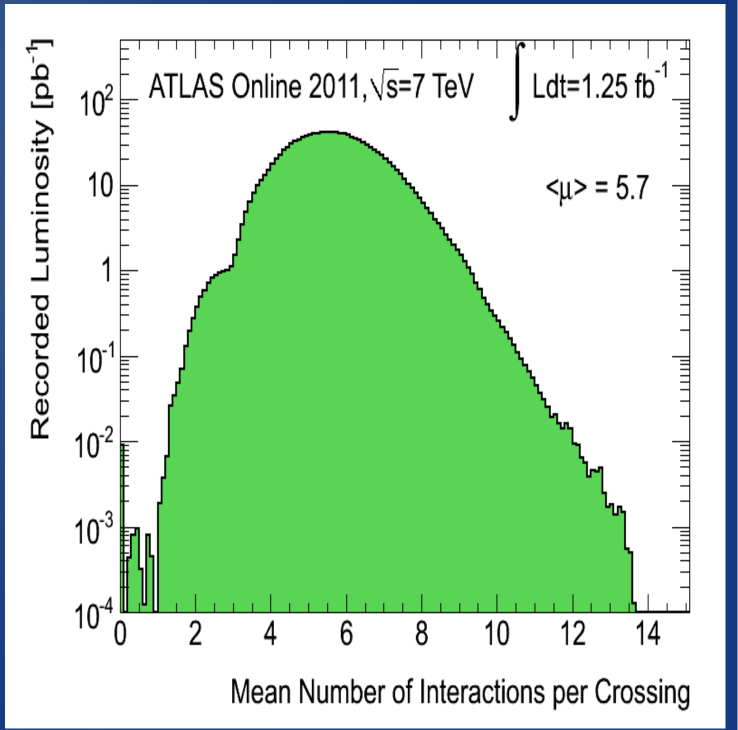




Interest of 2010 data lies in the low pileup, and in the low prescales of soft triggers (most of low-Pt jets and photons taken in the first months of 2010!)



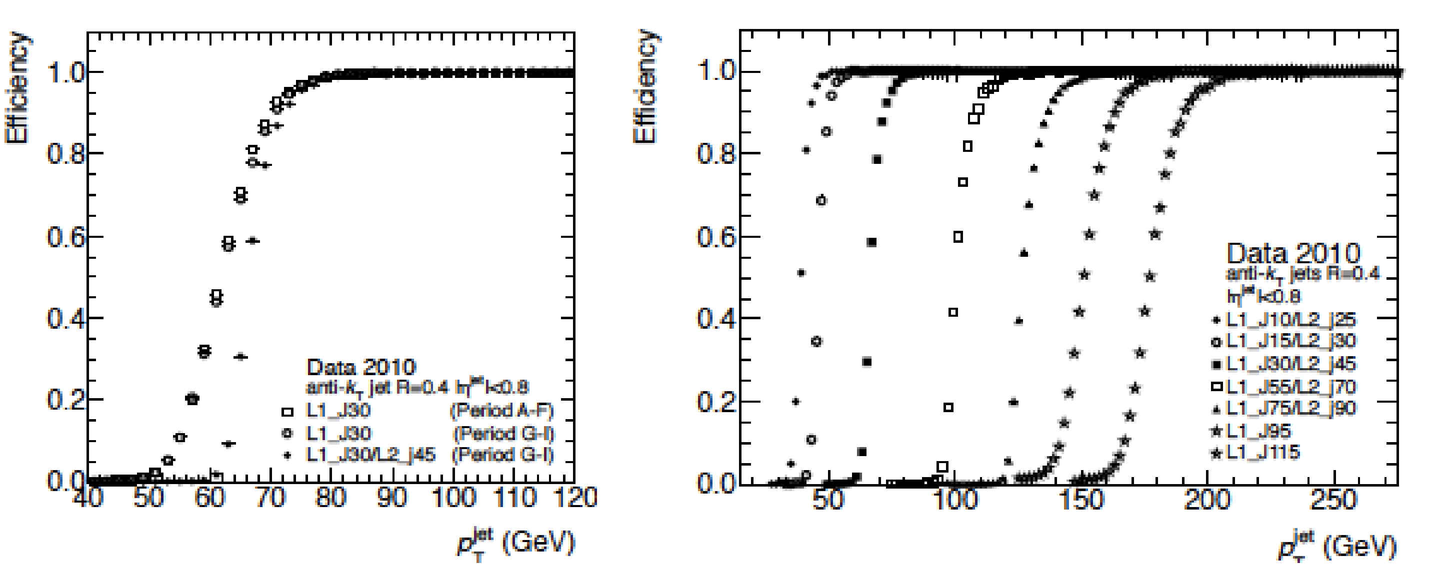




Triggering on jets

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

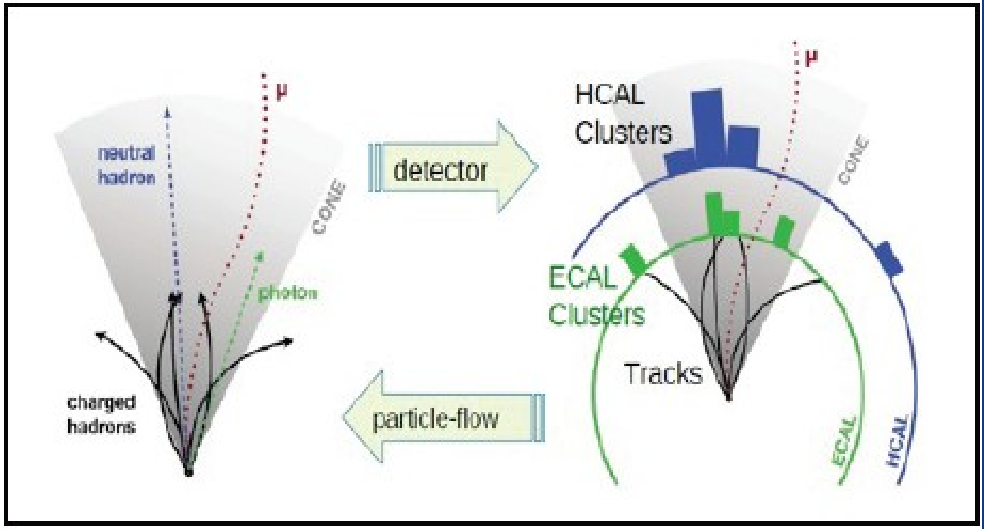
(b) efficiency over all data periods

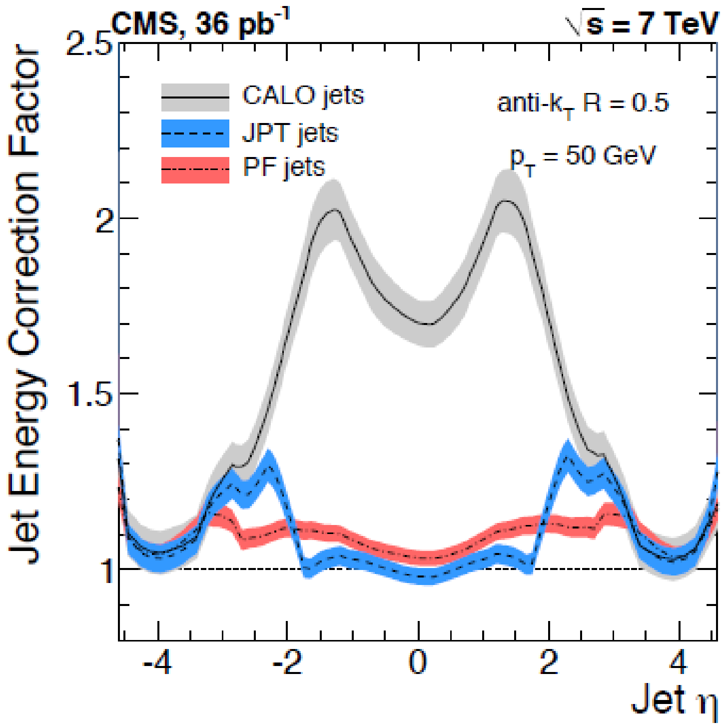
Since typically each trigger takes a constant rate (0.5 Hz), apart from the highest momenta the collected luminosity is proportional to the running time rather than to integrated one.

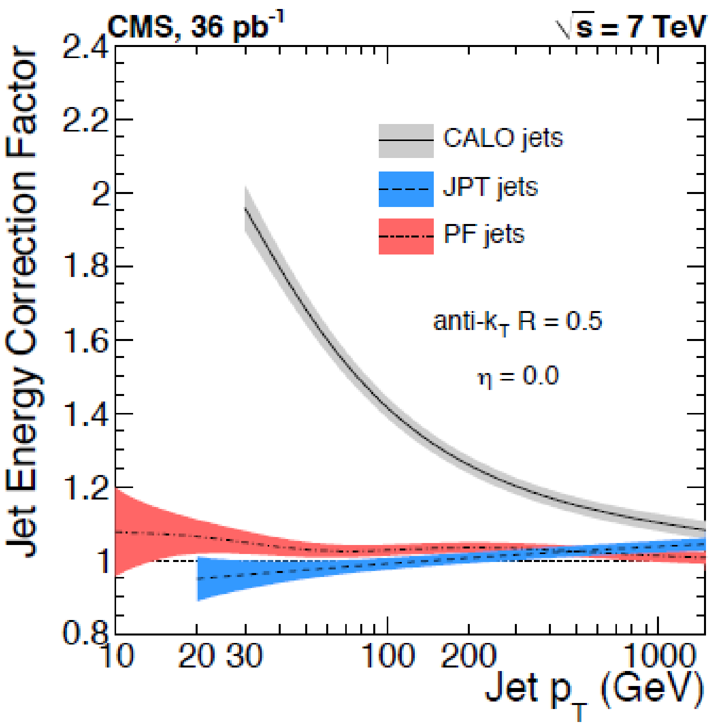
Particle-flow in CMS

✦ **Sophisticated "particle flow" reconstruction algorithm**
- exploits the excellent tracker performance and the fine ECAL granularity

✦ **Reconstructed individual particles according to their detection signature**

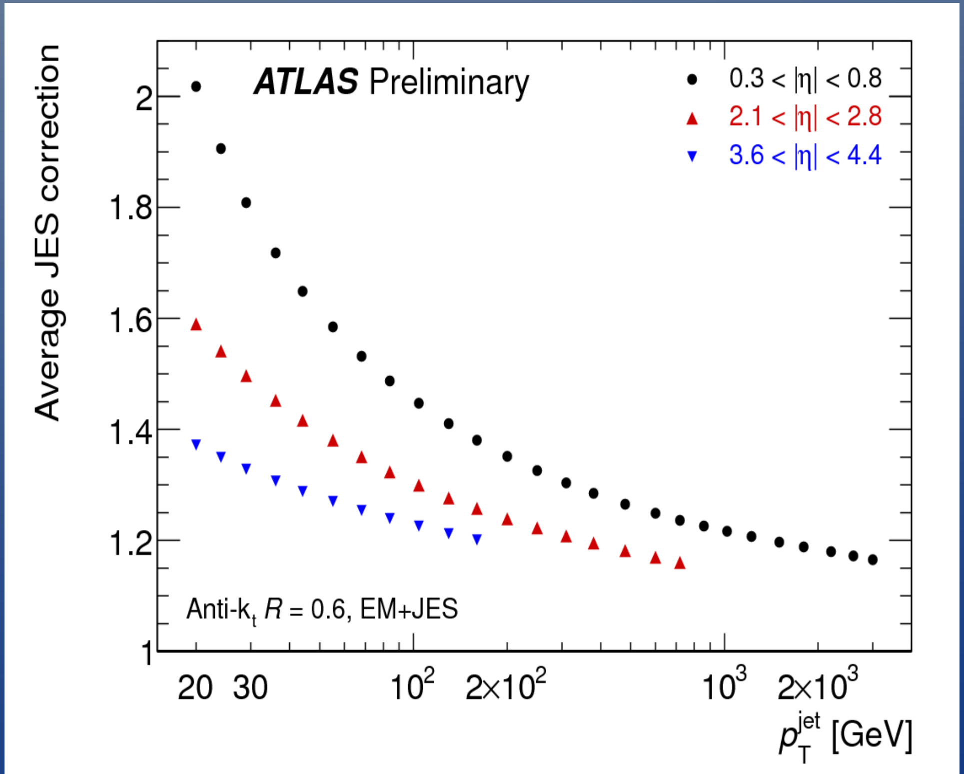






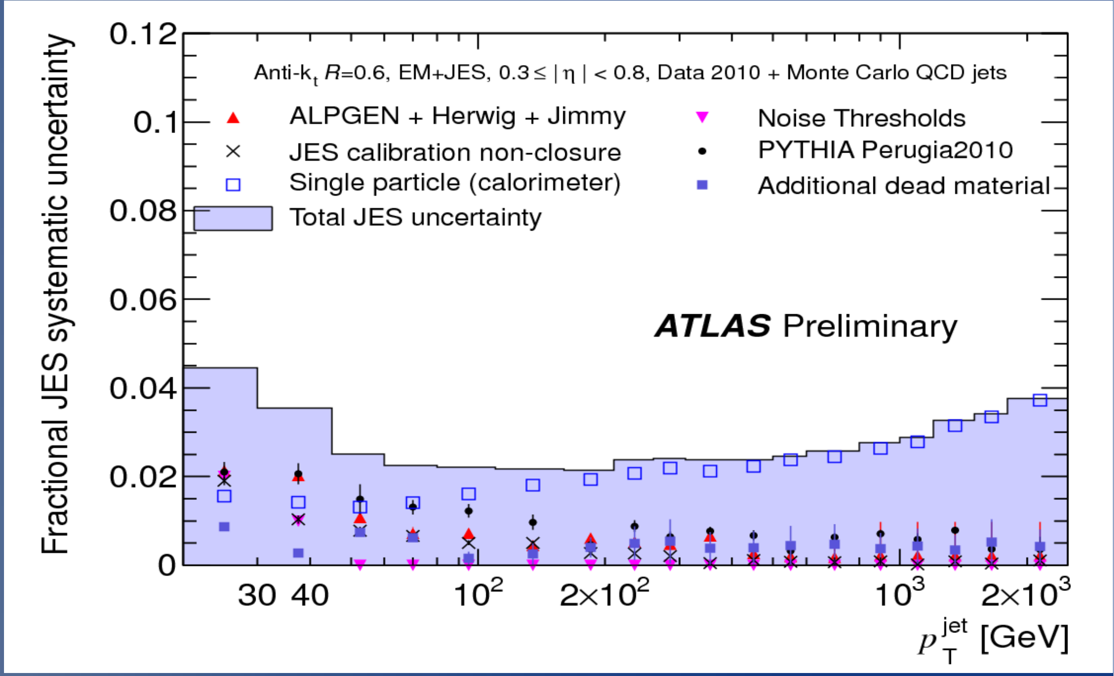
Energy scale calibration in Atlas

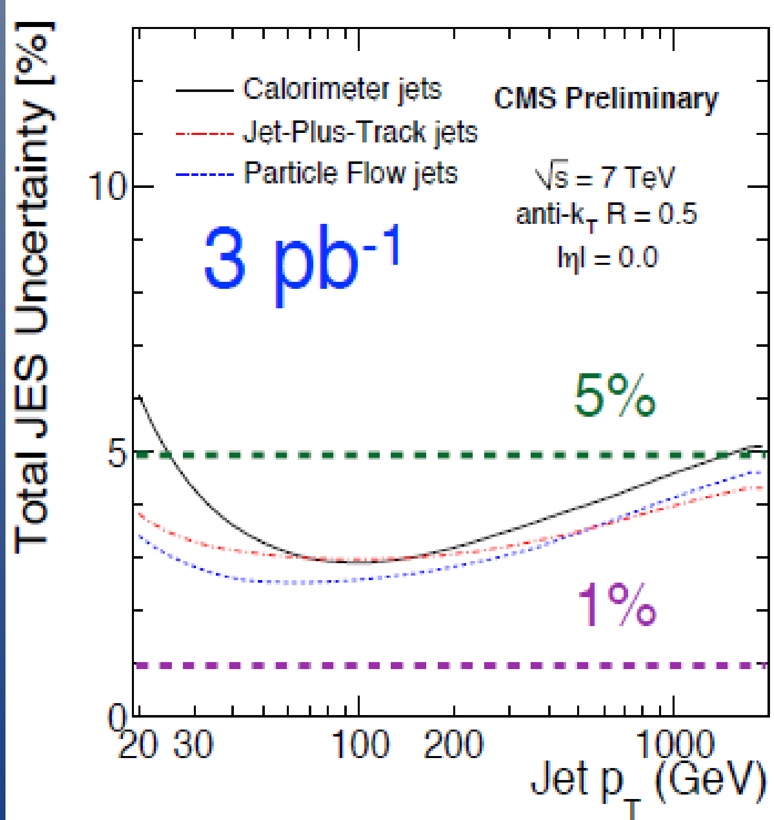
In 2010, lacking enough statistics to perform a proper in-situ calibration with γ-jet balancing, calibration constants have been derived from MonteCarlo. For added stability, calibration constants were applied to the sum (em+had), not separately to the two components.



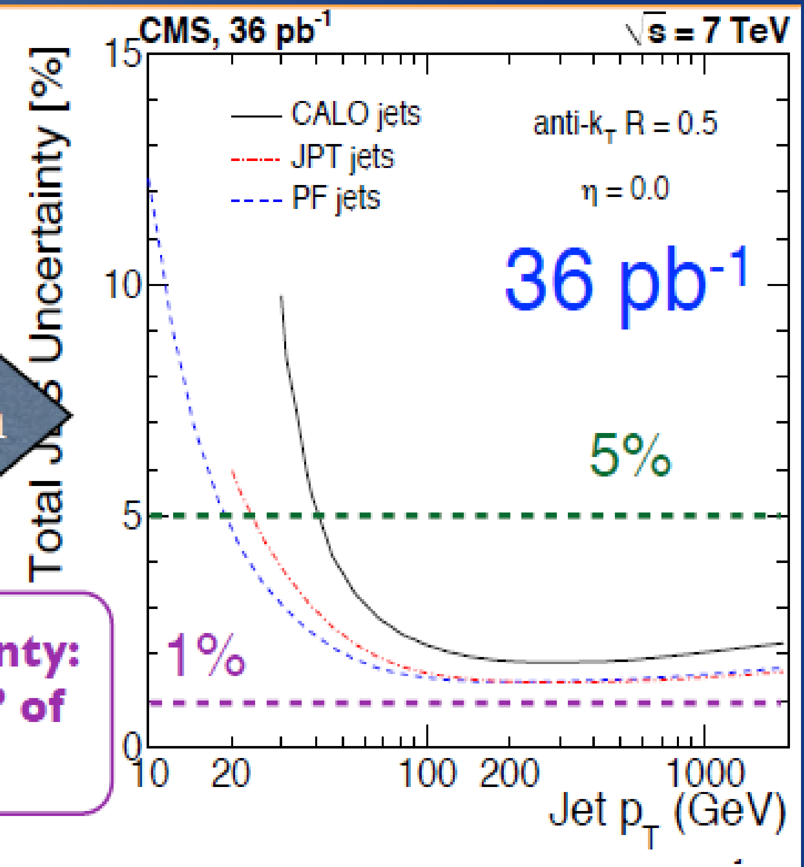
Correction factors depend on jet Pt and eta, and have been cross-checked with test-beam data, single-particle response and track jets. Also cross-checked with limited statistics using γ-jet and dijet balancing. A proper calibration accounting for the energy deposited in each calorimeter layer is used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

Jes uncertainty in 2010



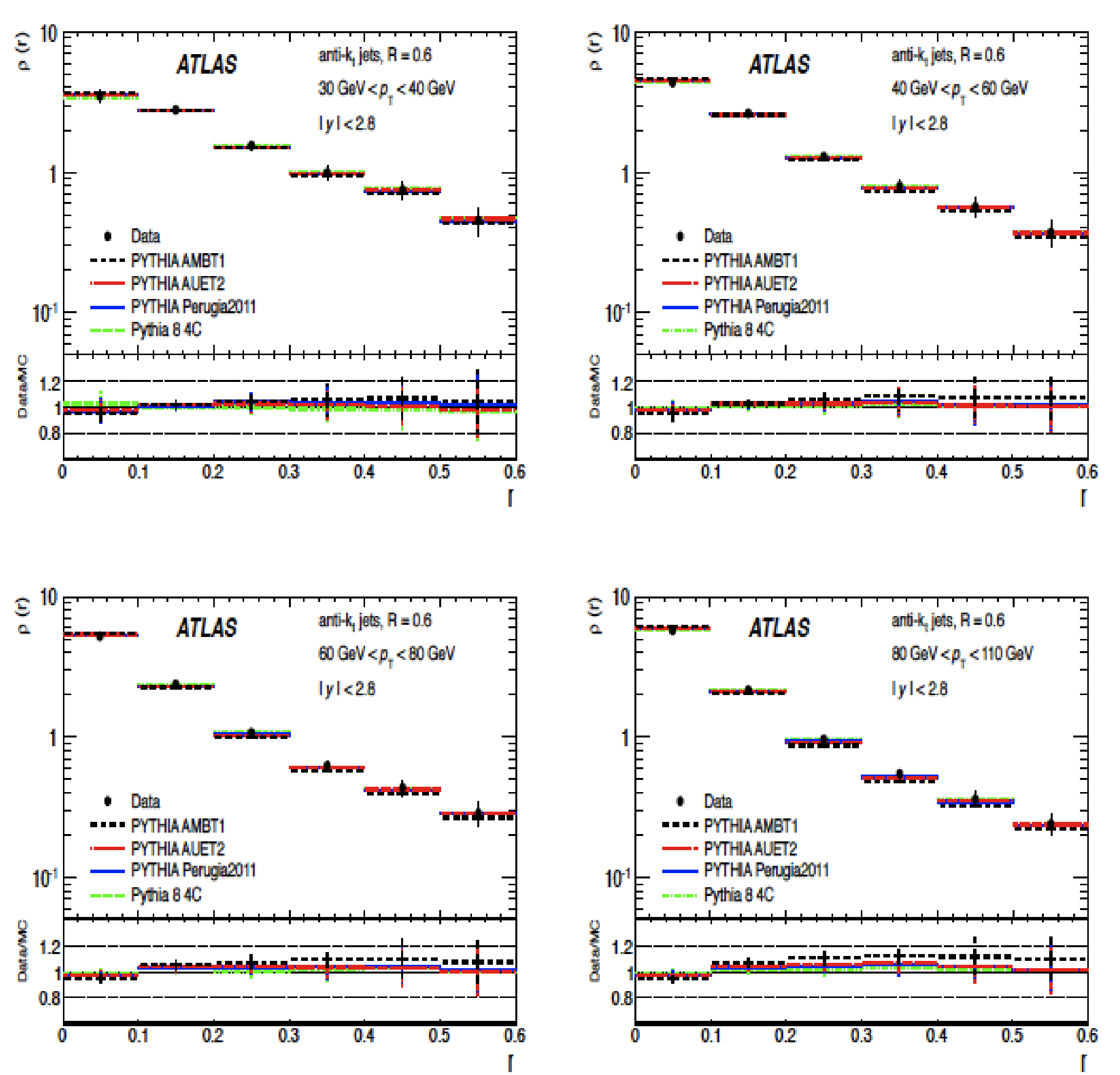


10x more data

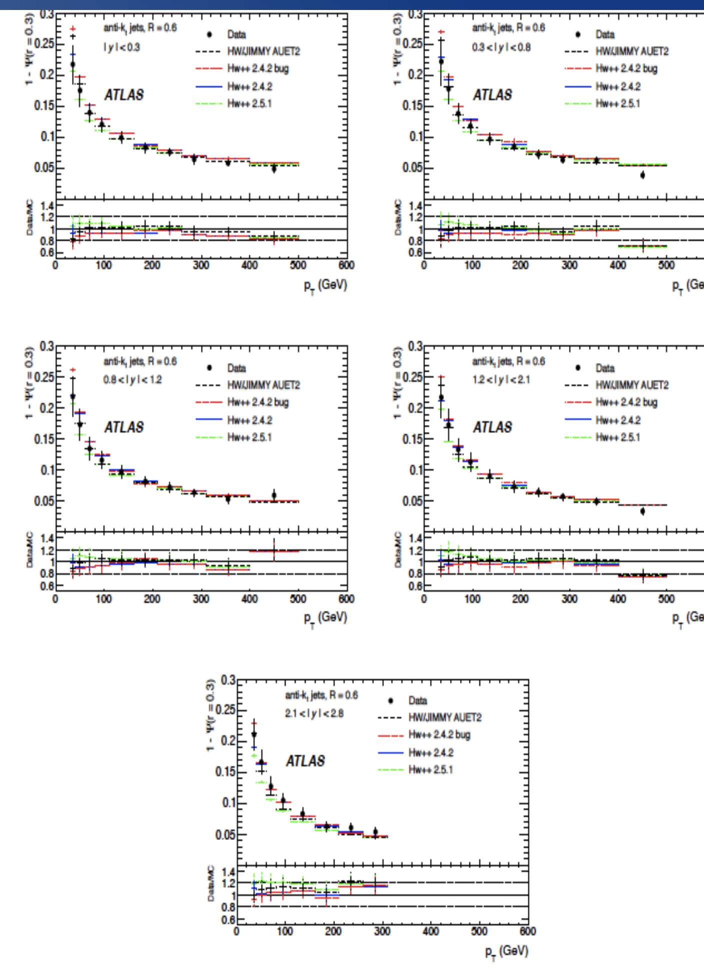


1% JES uncertainty: the "holy grail" of jet physics

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

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

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

Hadronic Event Shapes (I)

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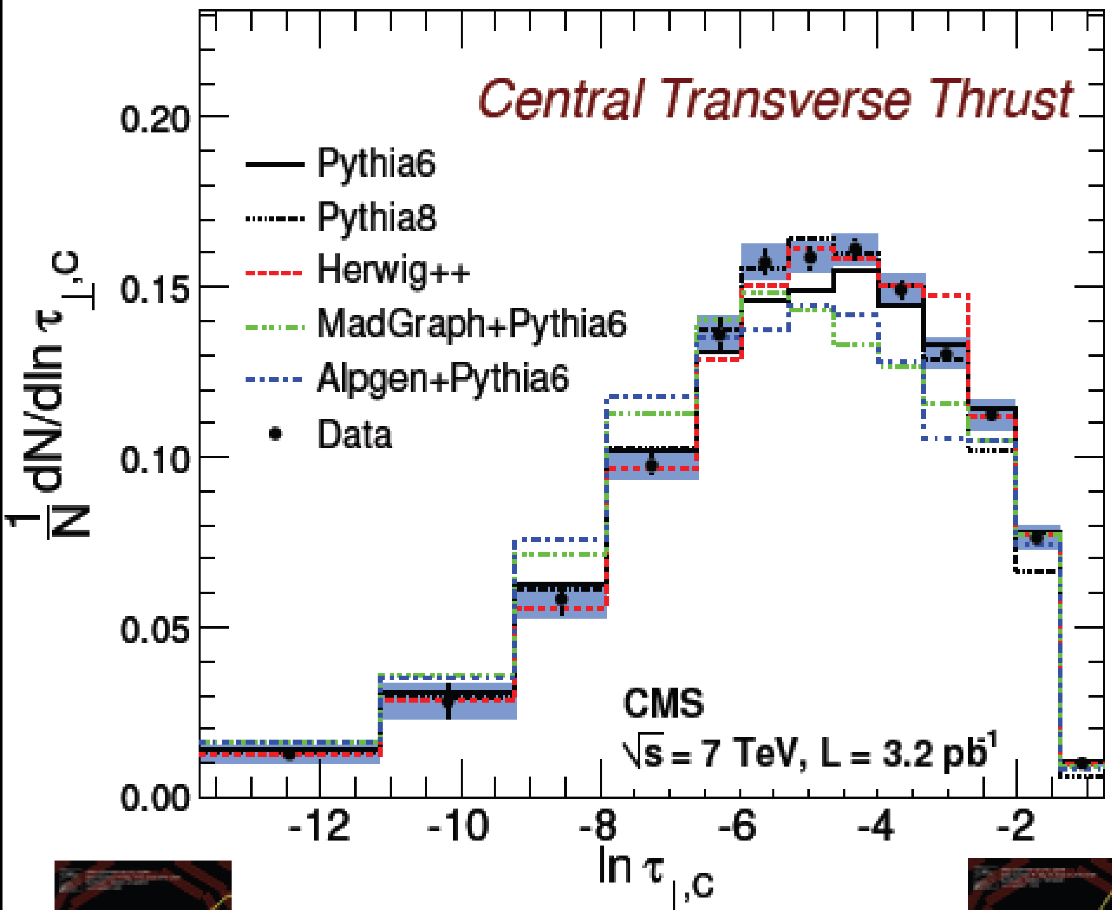
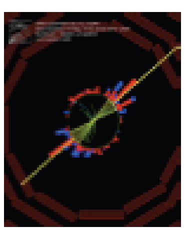
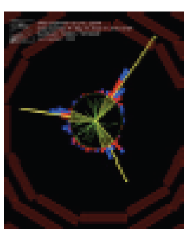




$$\tau_{\perp,\mathcal{C}} \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$

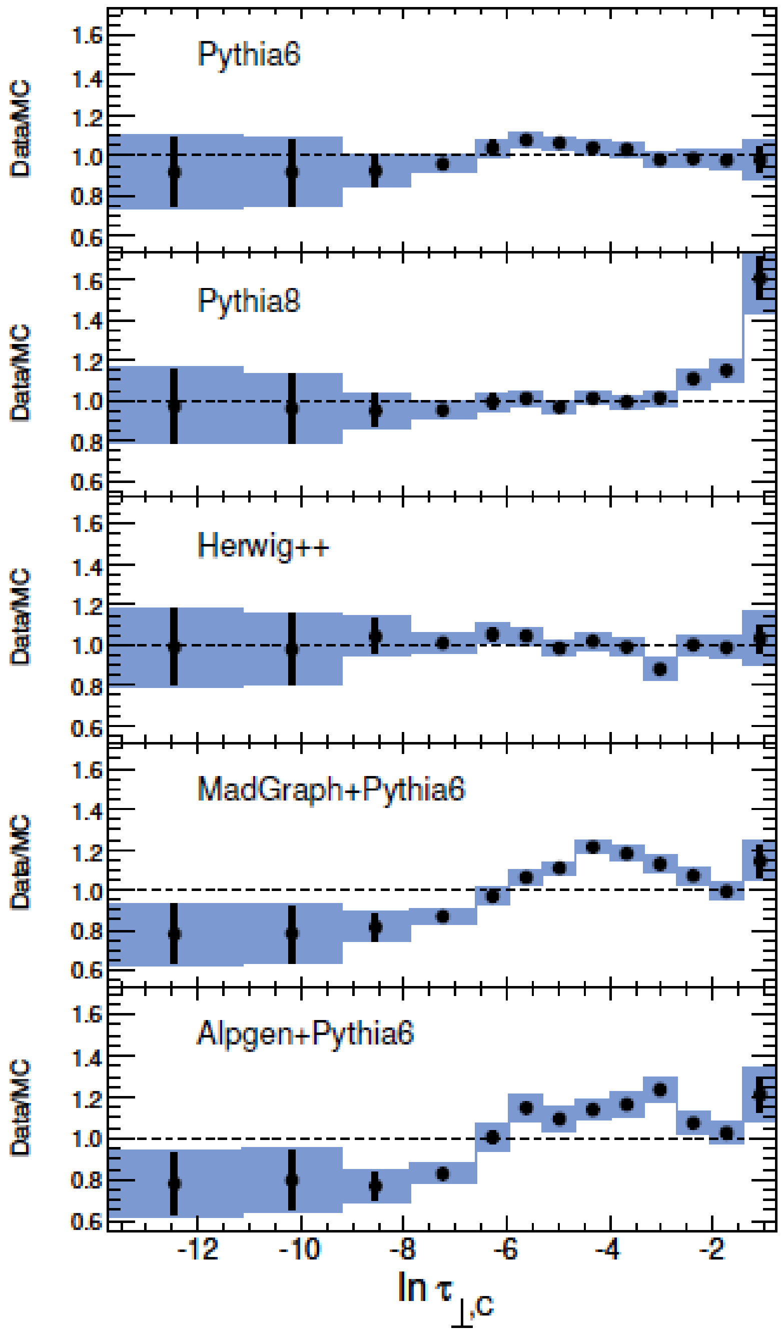


$$T_{m,\mathcal{C}} \equiv \frac{\sum_i |\vec{p}_{\perp,i} \times \hat{n}_{T,\mathcal{C}}|}{\sum_i p_{\perp,i}}$$

✦ **Event-shape variables**
- central transverse thrust
- central thrust minor
- probe QCD radiative processes
- sensitive to 2j and 3j topologies
- dijets events have small values

✦ **Experimental measurement**
- anti-k_T, R=0.5, PF Jets
- event-shape variables from the central jets in 3 bins of $p_{T,max}$
- 3.2 pb^{-1}
- cancellation of many jet unc.
- unfolding using the SVD method

Hadronic Event Shapes (II)

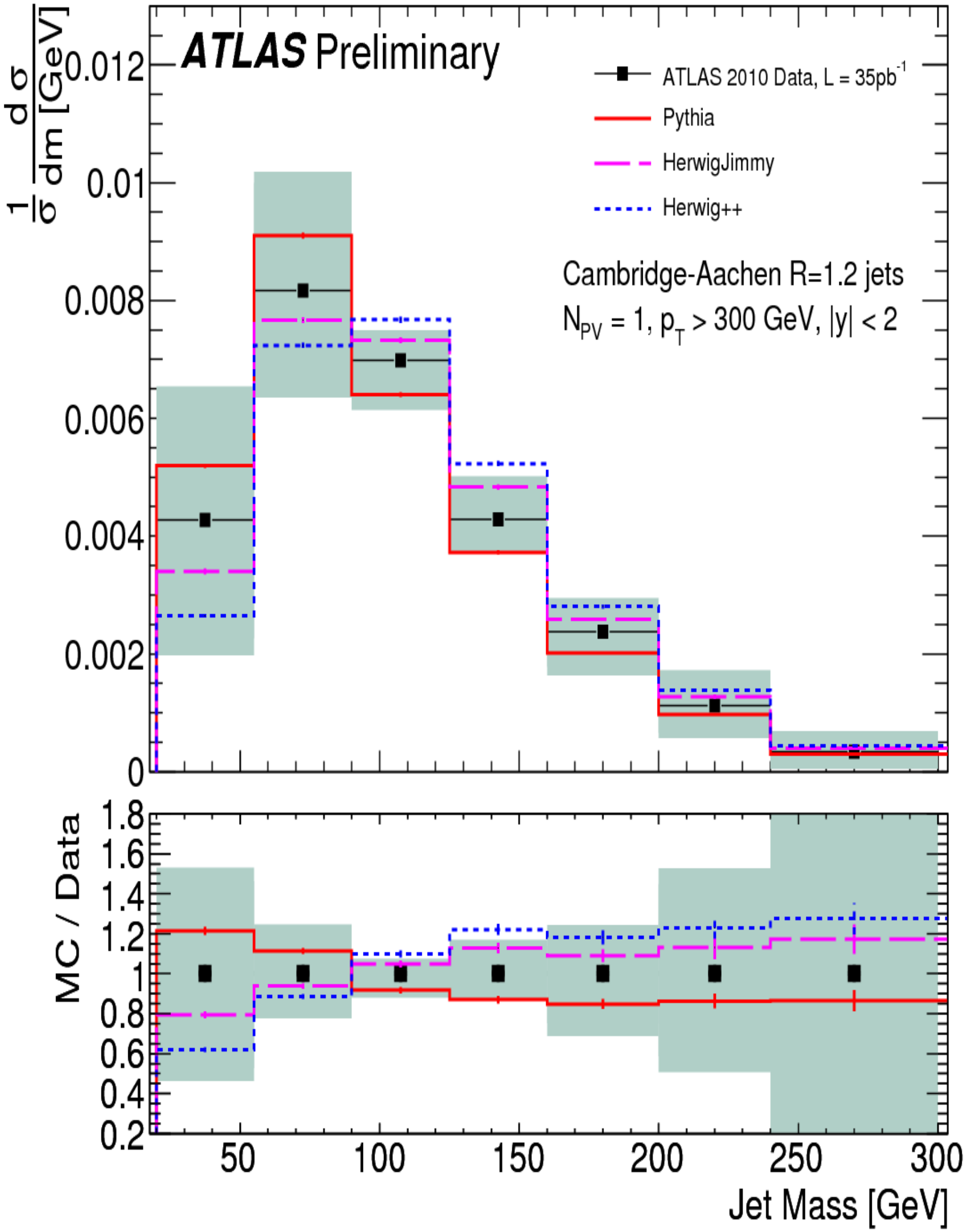


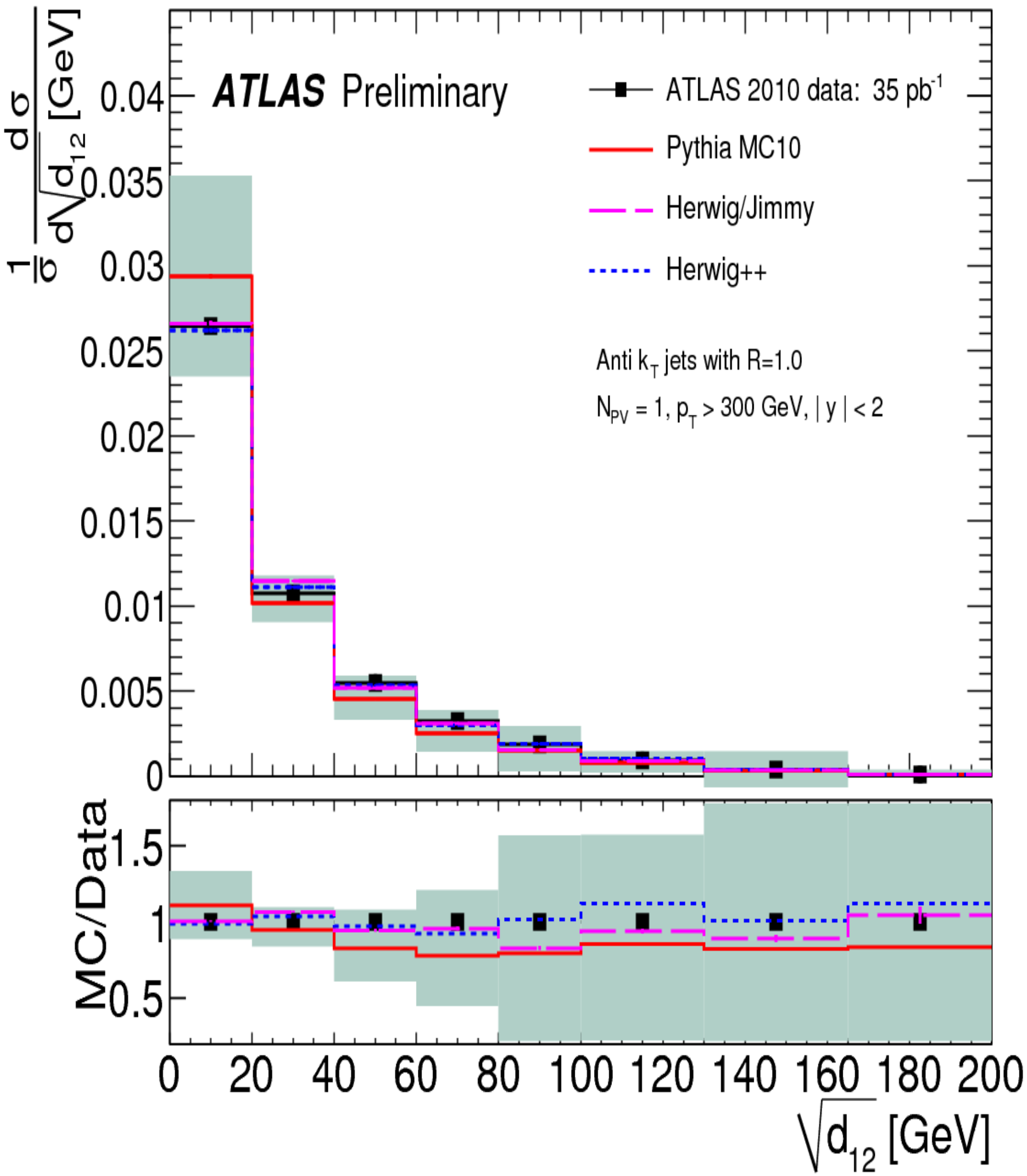
✦ **Data vs MC comparison**

- Pythia6 and Herwig++ predictions are in good agreement with the data
- Pythia8 agrees with the data in the 2 lowest bins, but shows a dijet deficit in the highest bin
- Madgraph and Alpgen show a similar discrepancy with the data (overestimate of dijet events)

  ▸ *further investigation revealed that the ME generators reproduce the leading-jet p_T spectrum, but produce harder second jets*

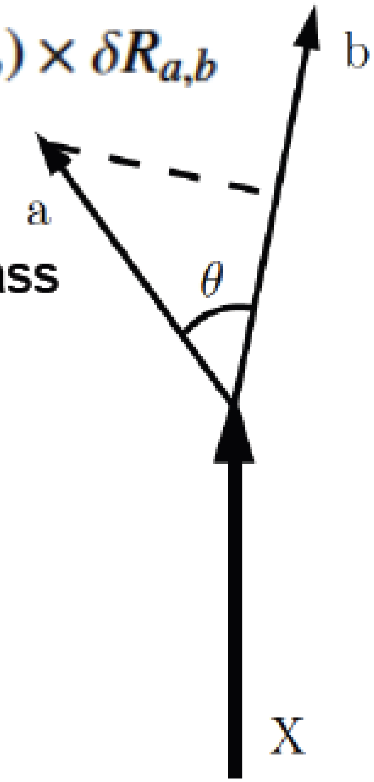
Properties of calorimeter jets: mass, y12





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)

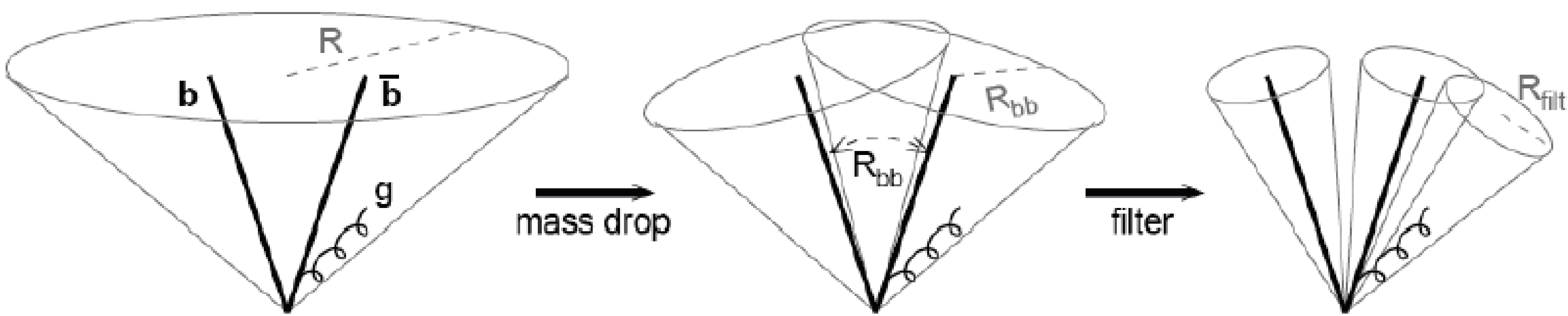
Add-on variable usable to enhance analyses using jet mass
Measure of hardness of final k_T splitting in a jet

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

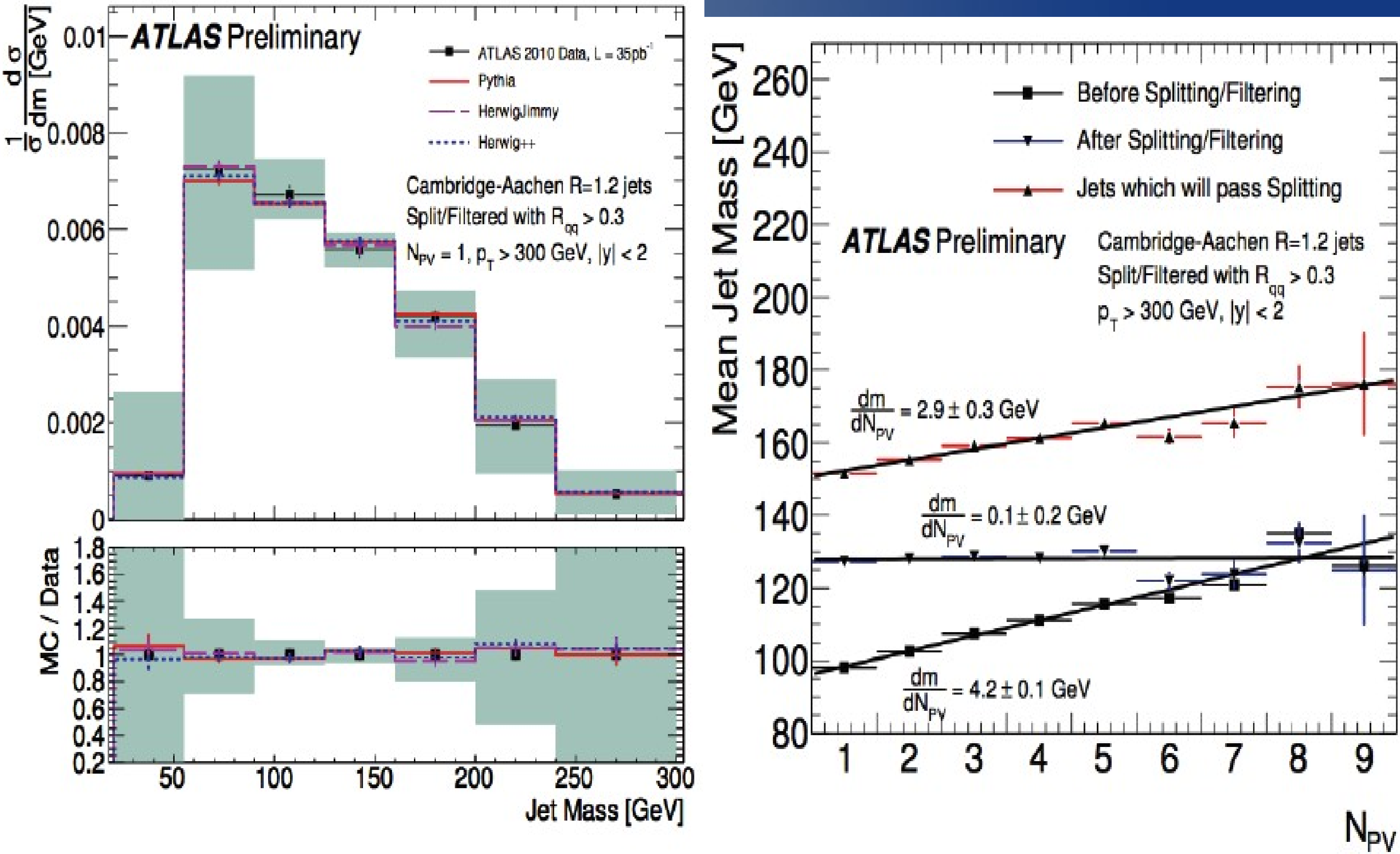
Splitting and Filtering (a.k.a. BDRS filtering, C-A filtering)

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.

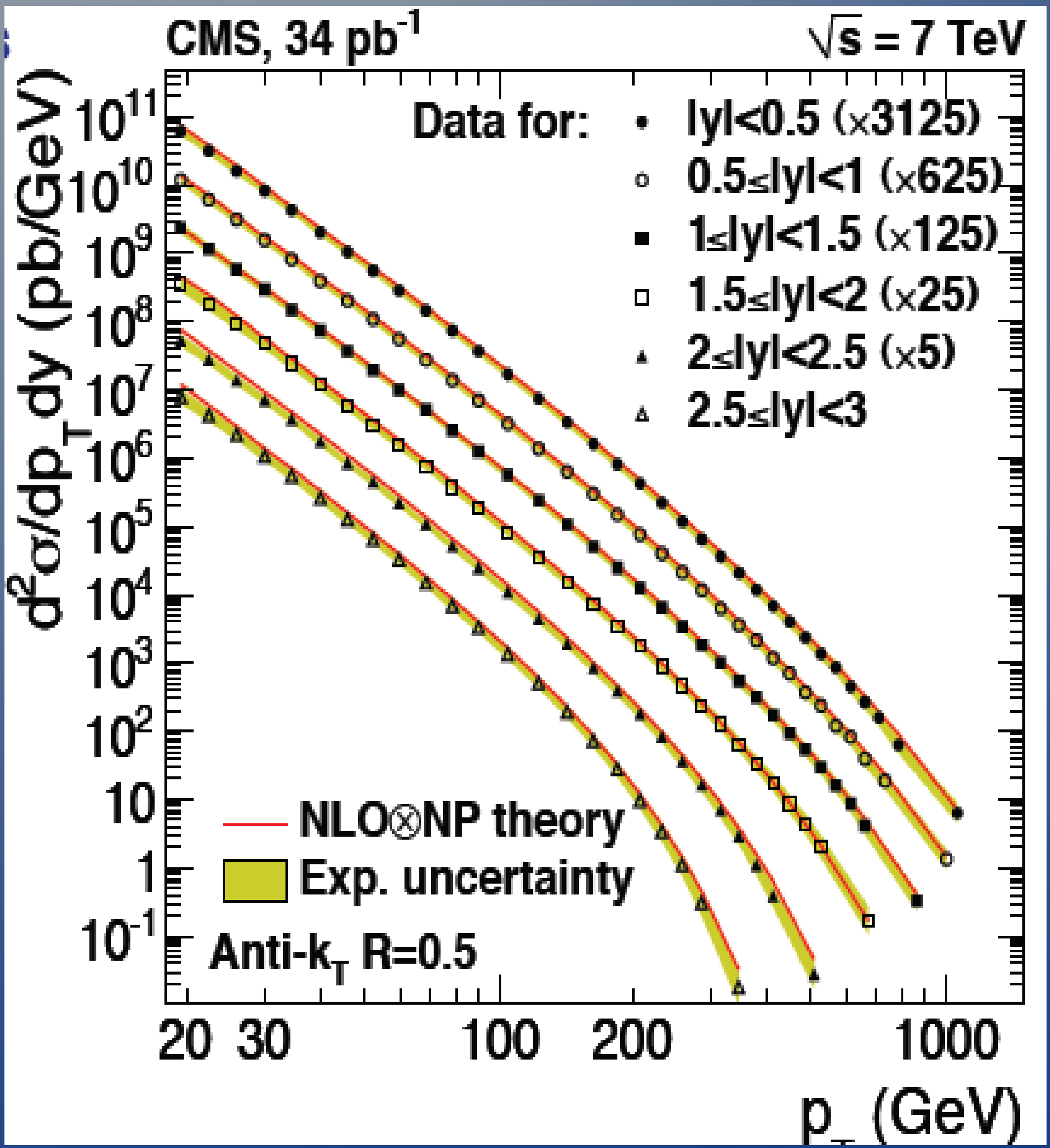
J. M. Butterworth, AD, M. Rubin and G. P. Salam **Phys. Rev. Lett. 100, 242001 (2008)**

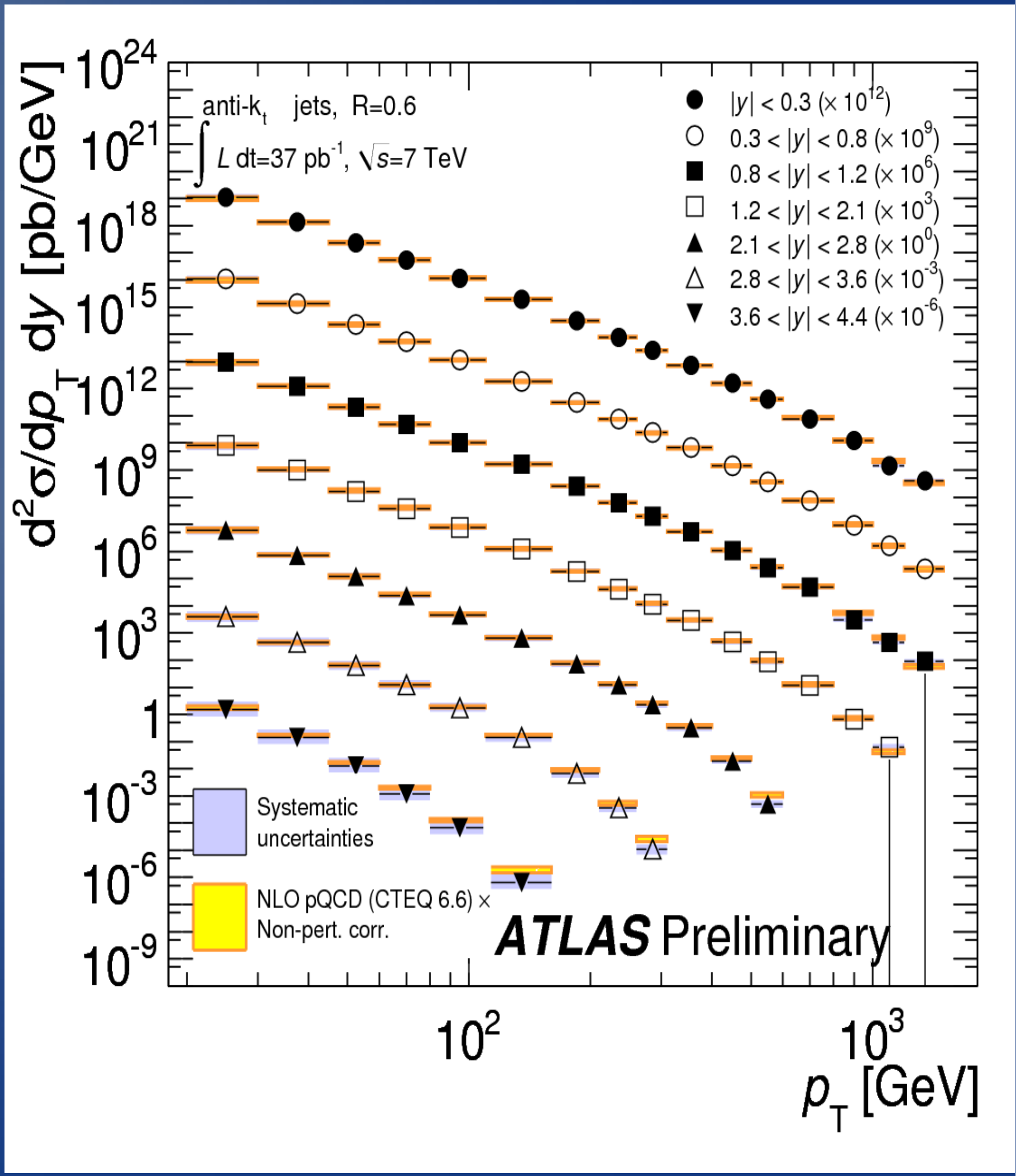


Filtered mass: stable vs pileup!

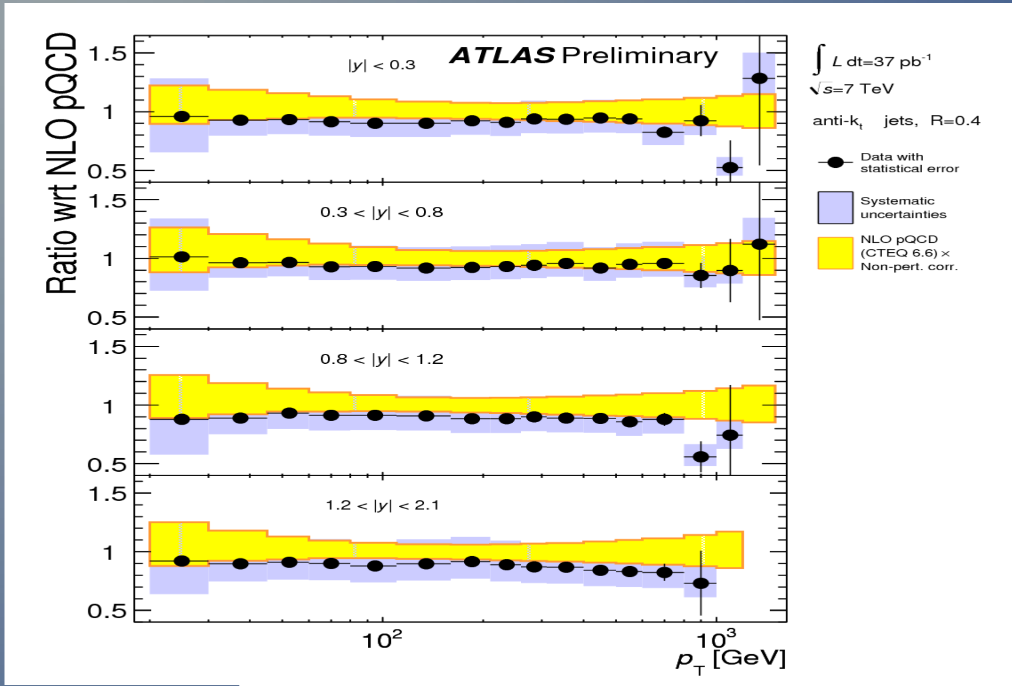


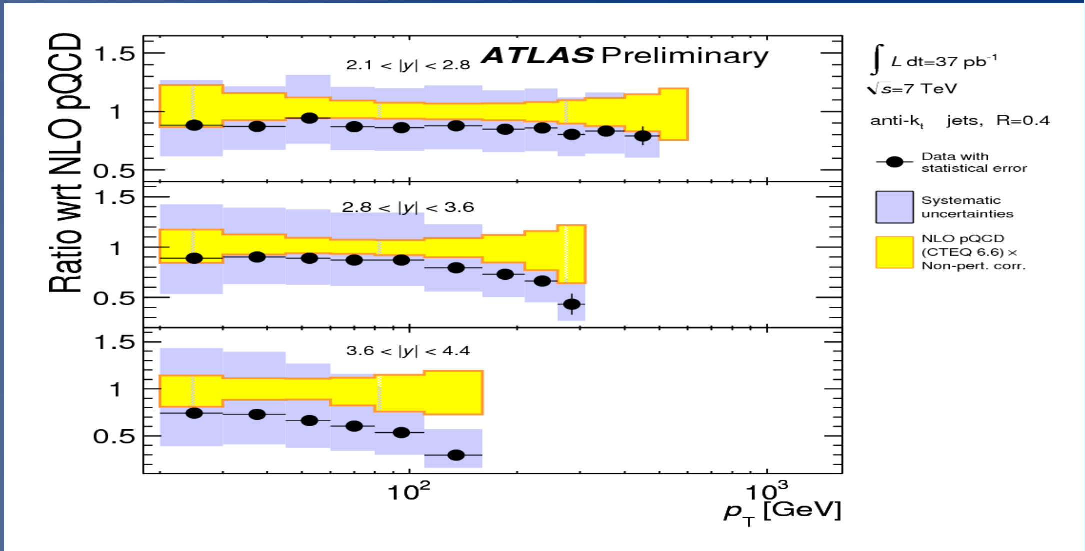
Inclusive jet cross section for antikt jets: (0.4, 0.6 width in Atlas, 0.5, 0.7 in CMS) jets after detector unfolding.

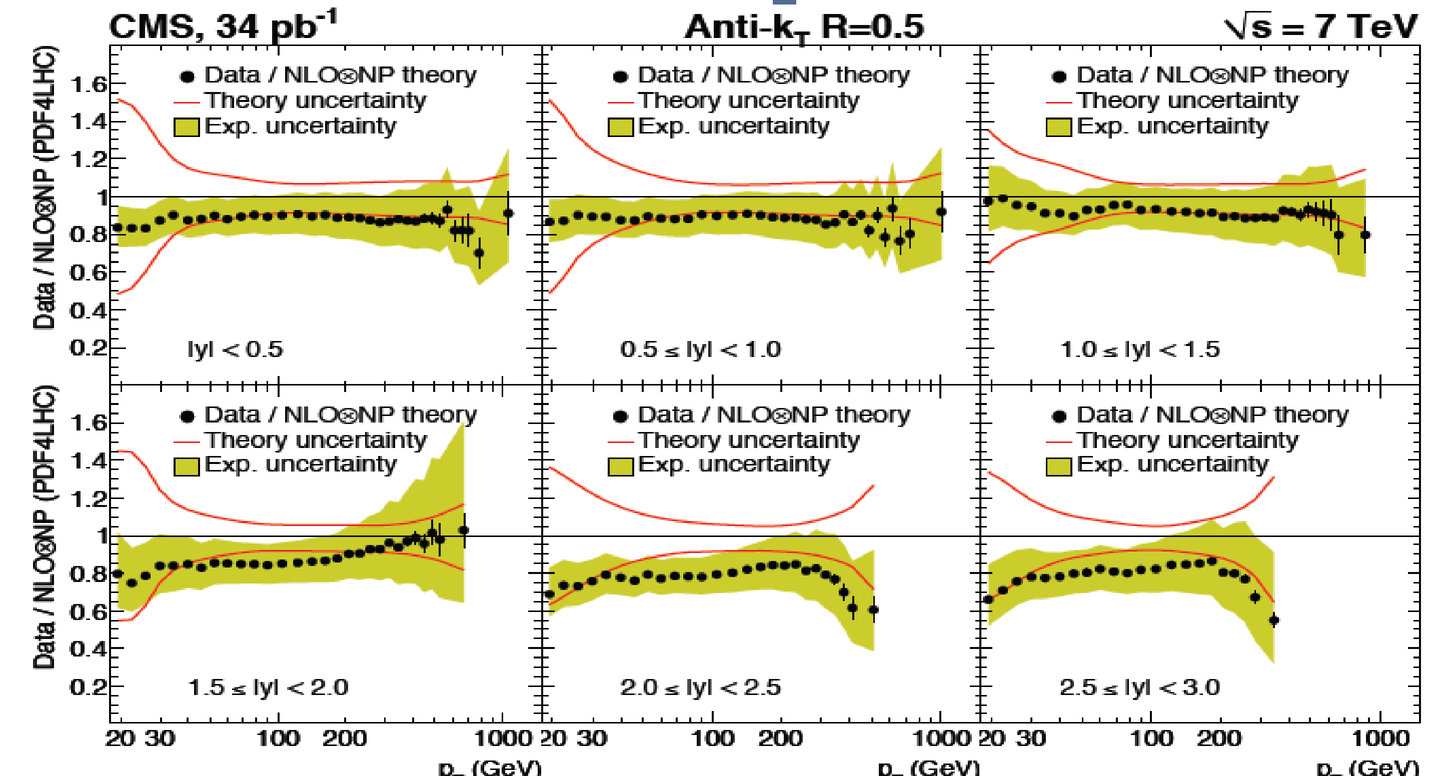




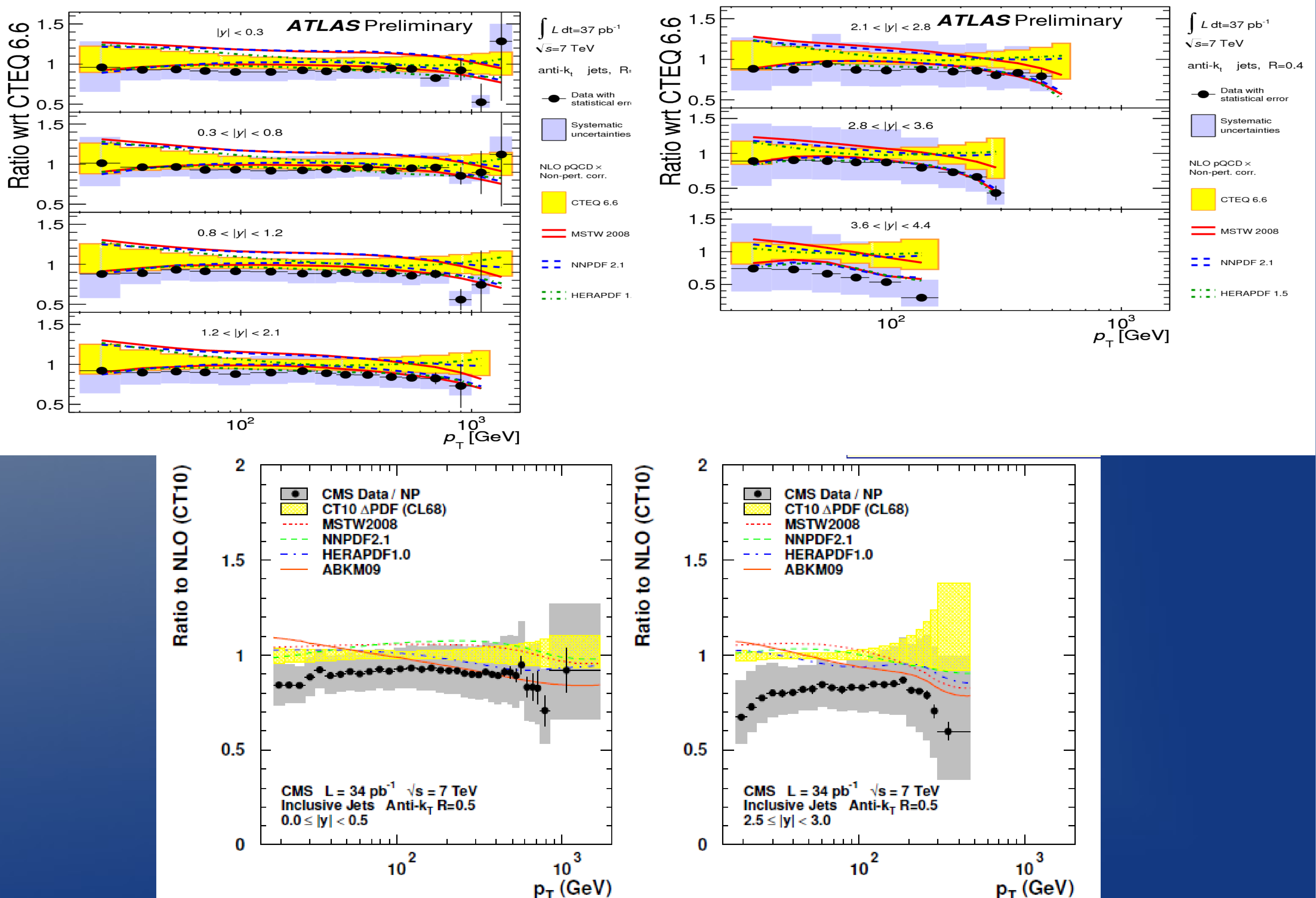
Ratio with NLO + soft corrections



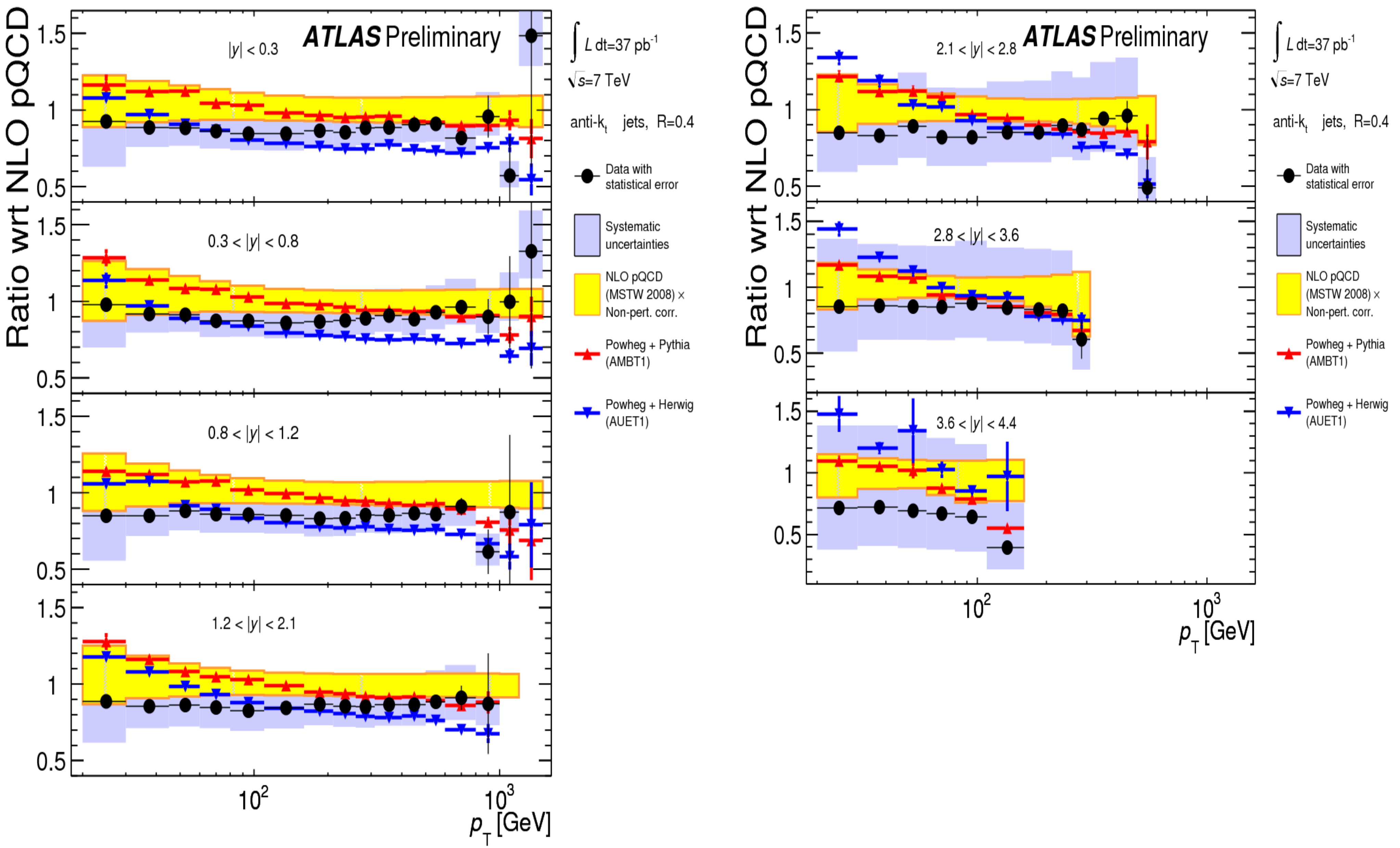




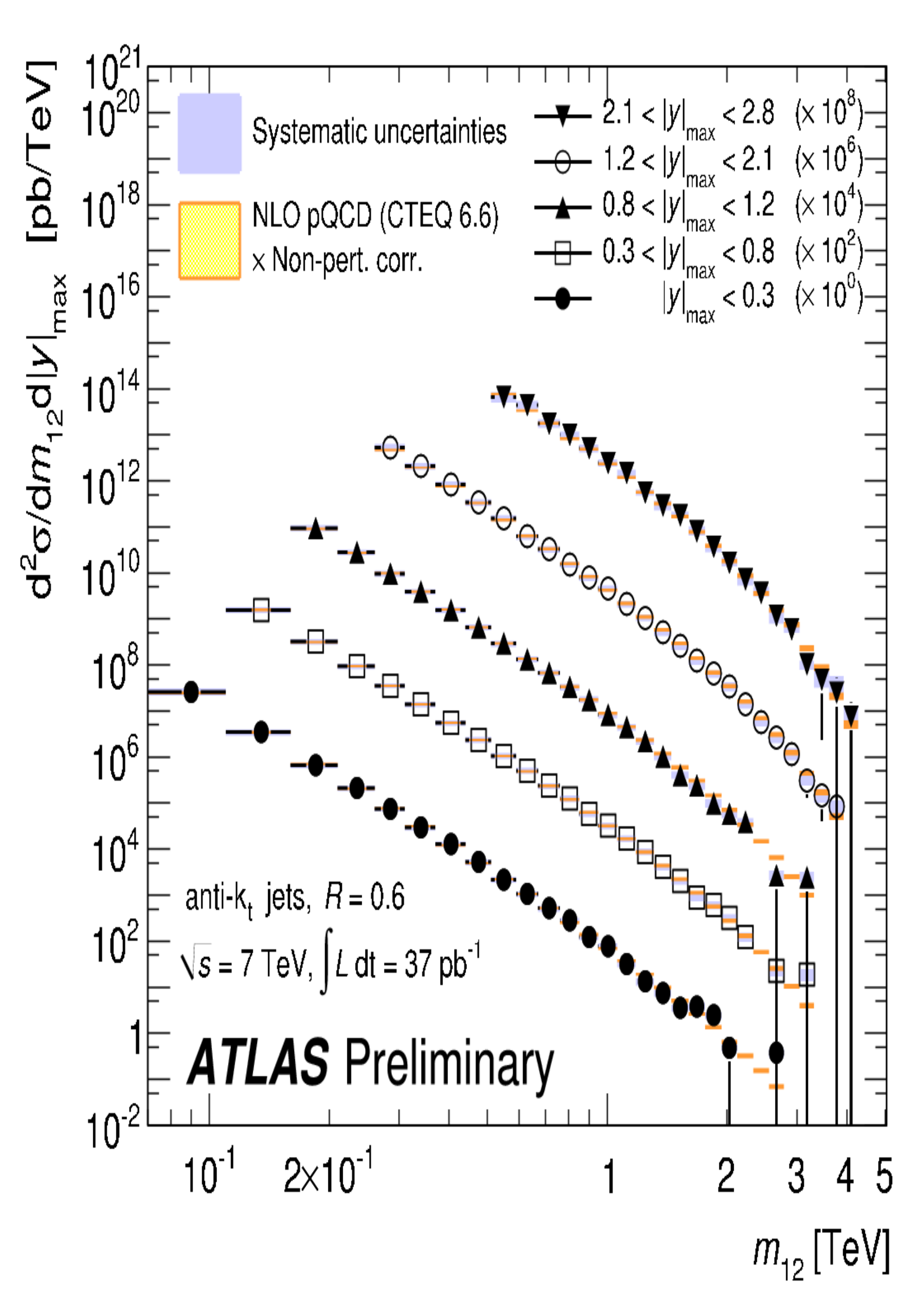
Comparison with various Pdf sets (0.4)

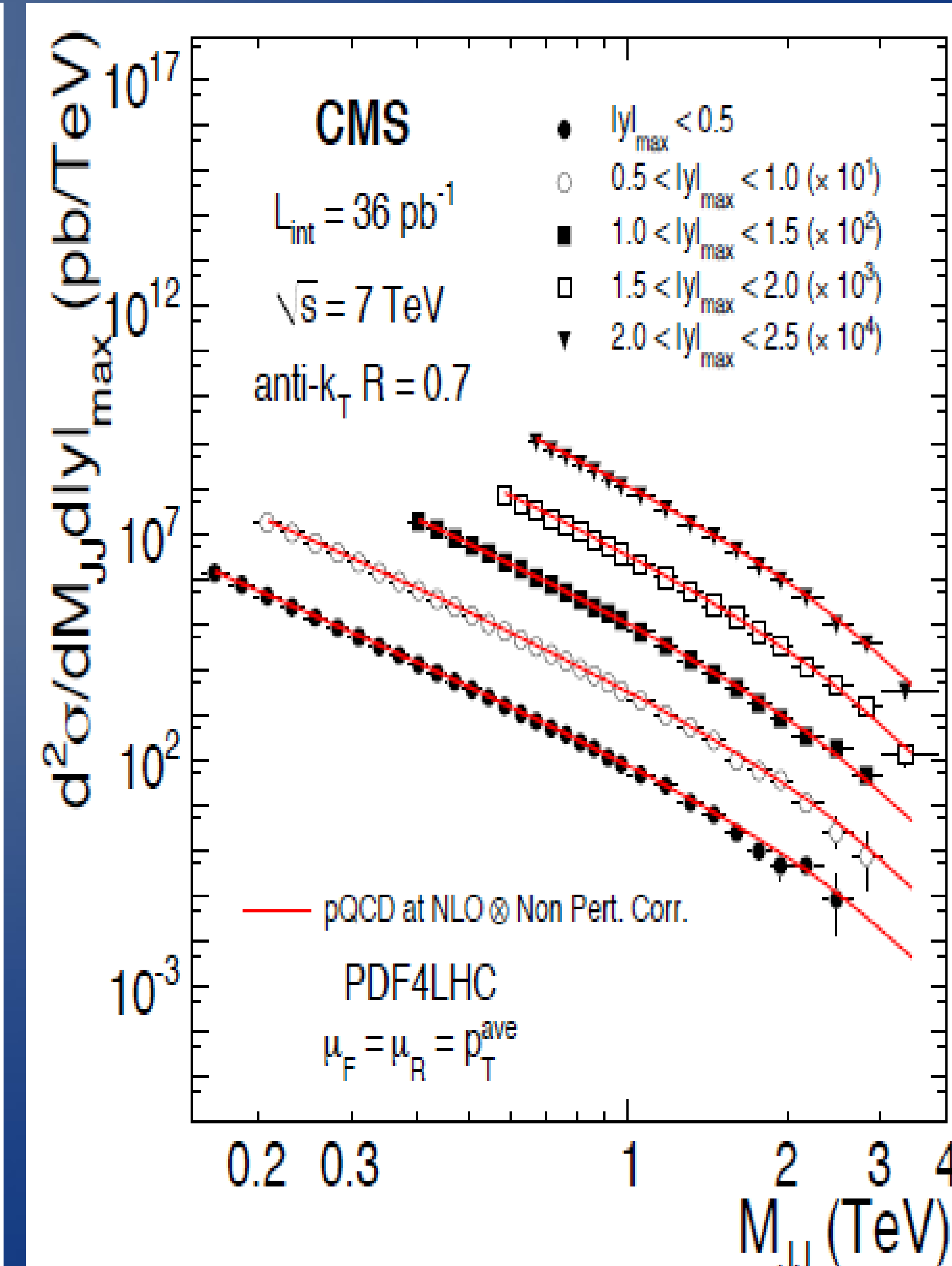


Comparison with Powheg (0.4)

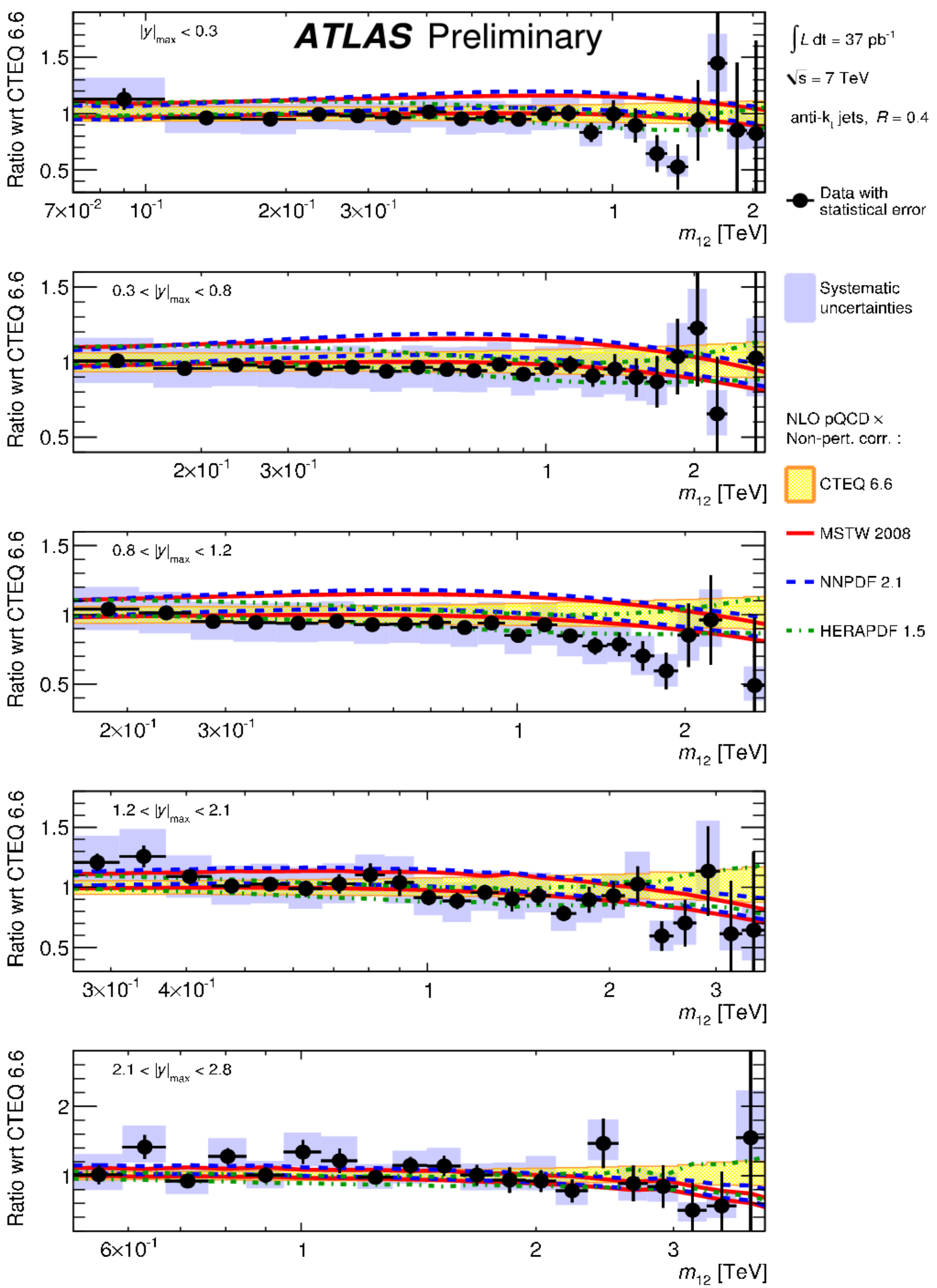


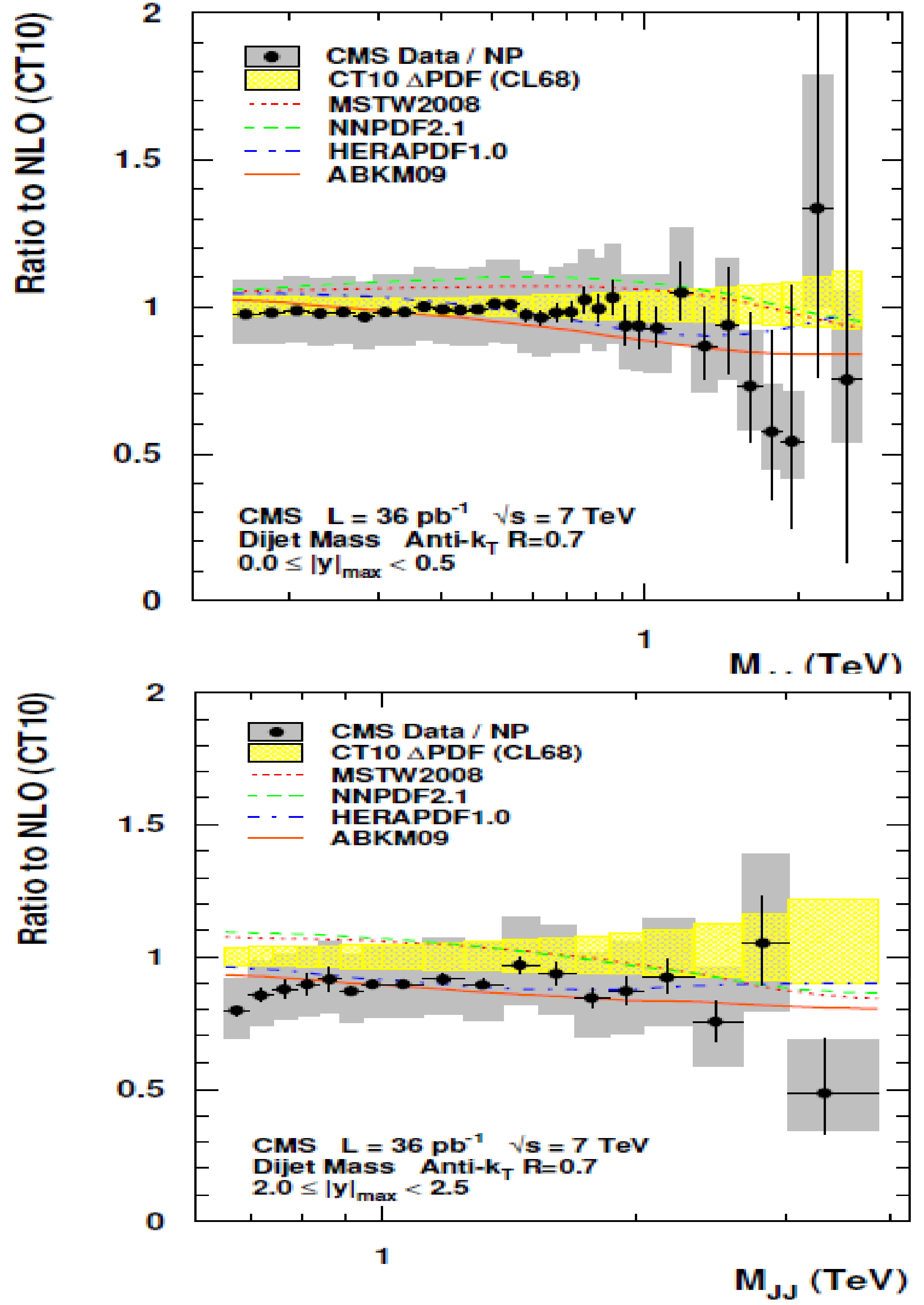
Dijet cross-section and ratio (0.6)



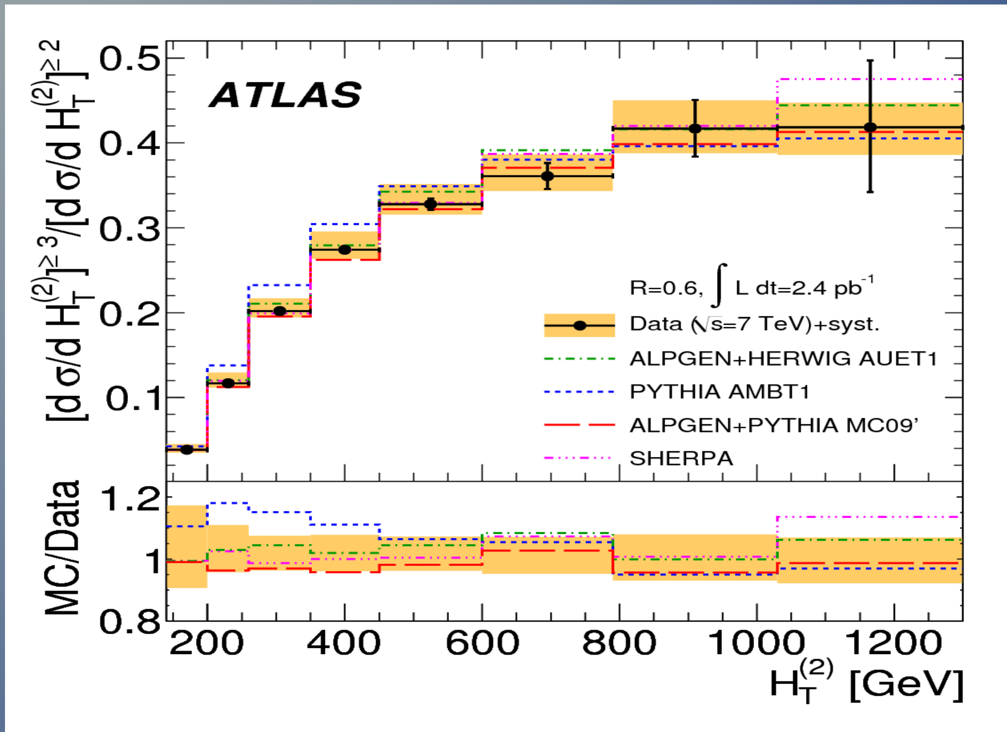


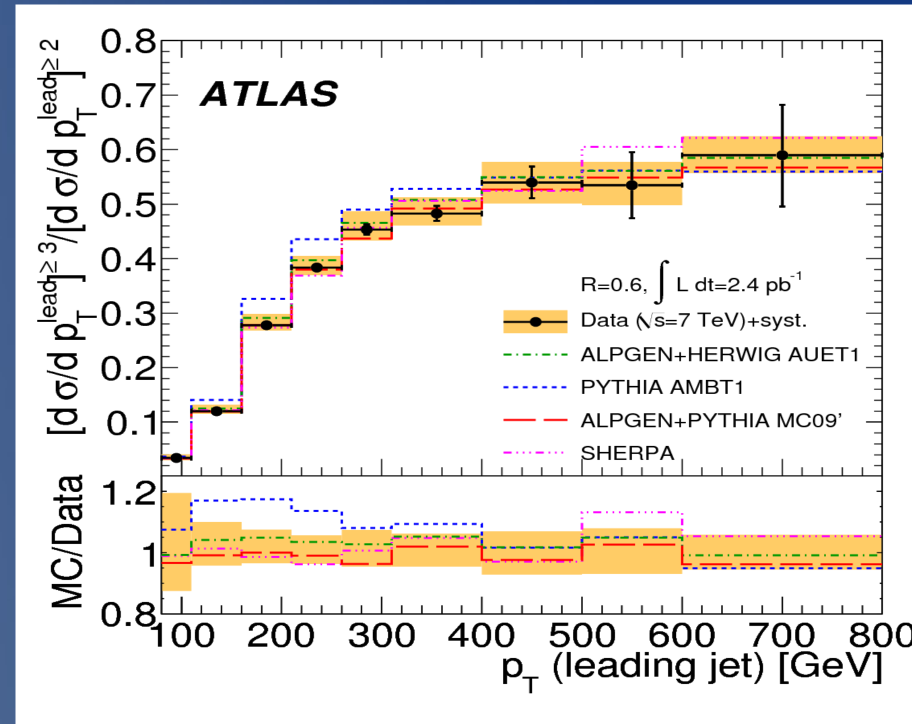
Pdf comparisons

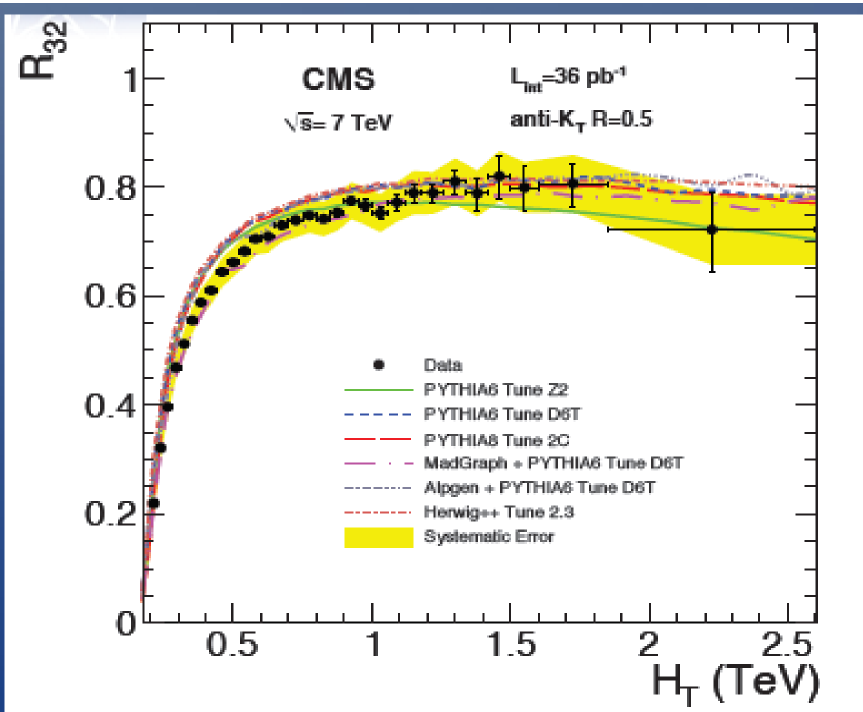


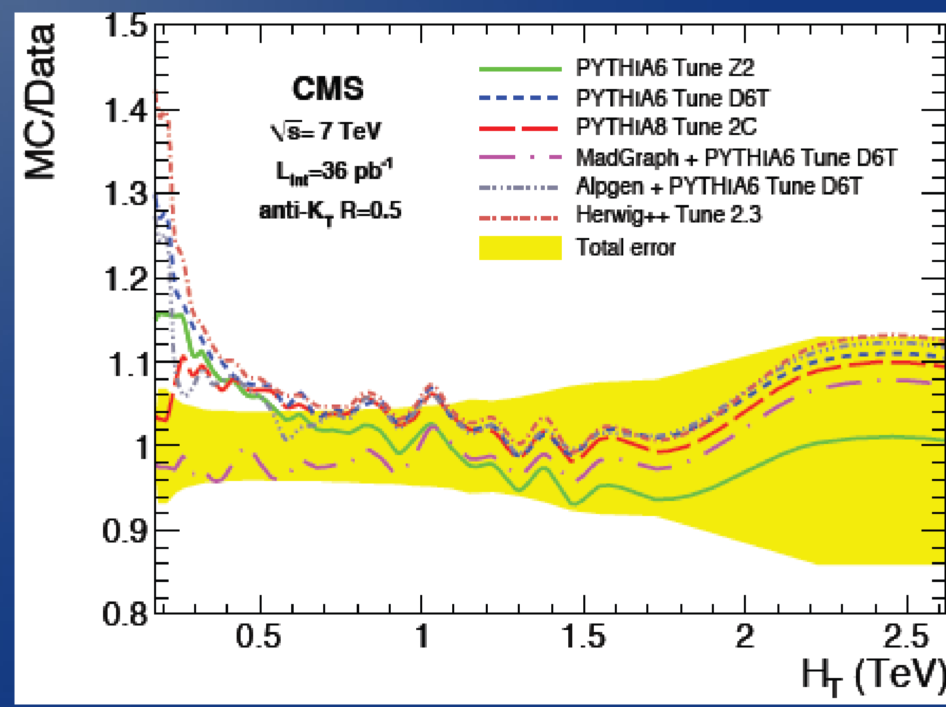


2- to 3- jet fraction vs pT and HT(2)

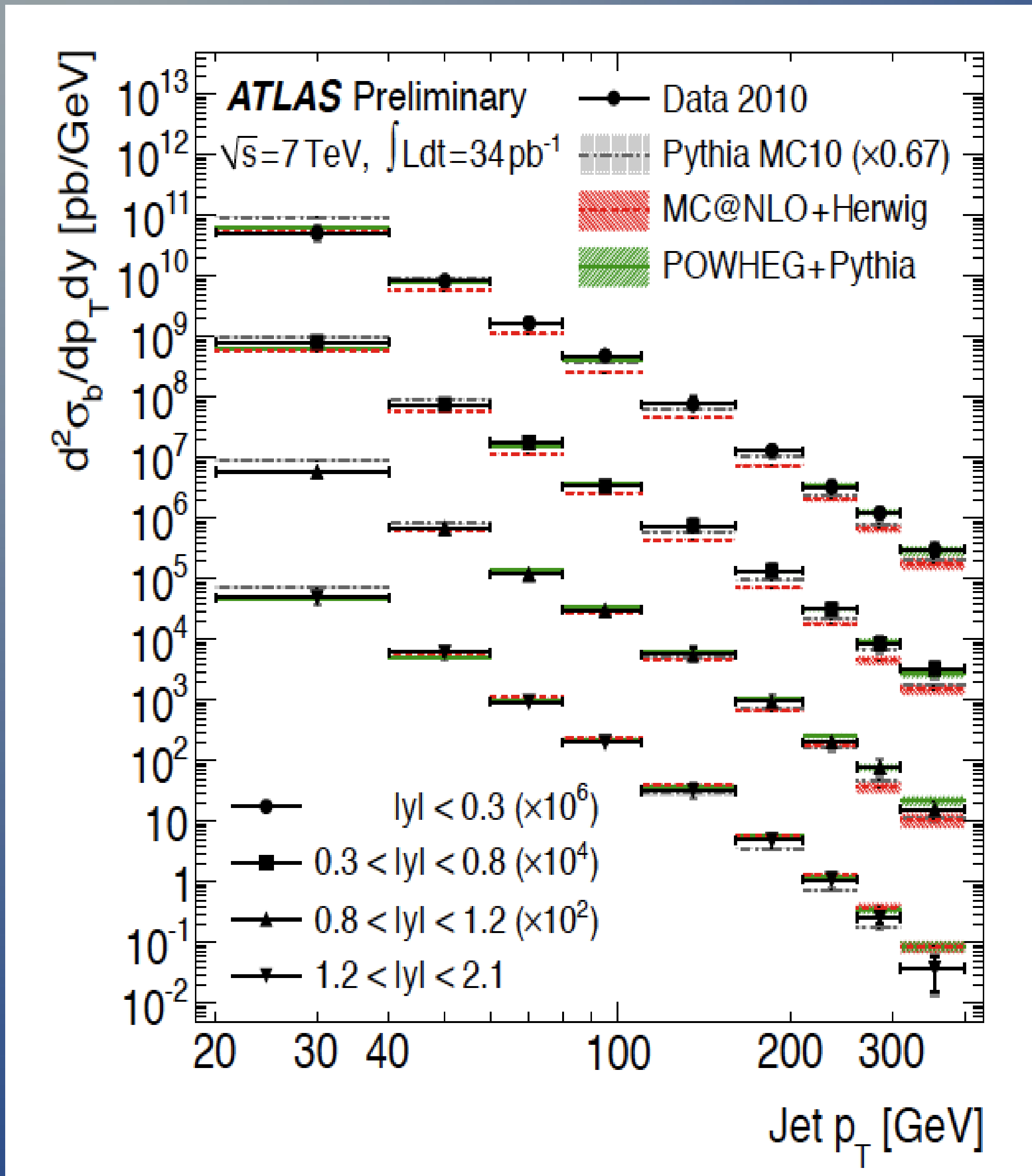


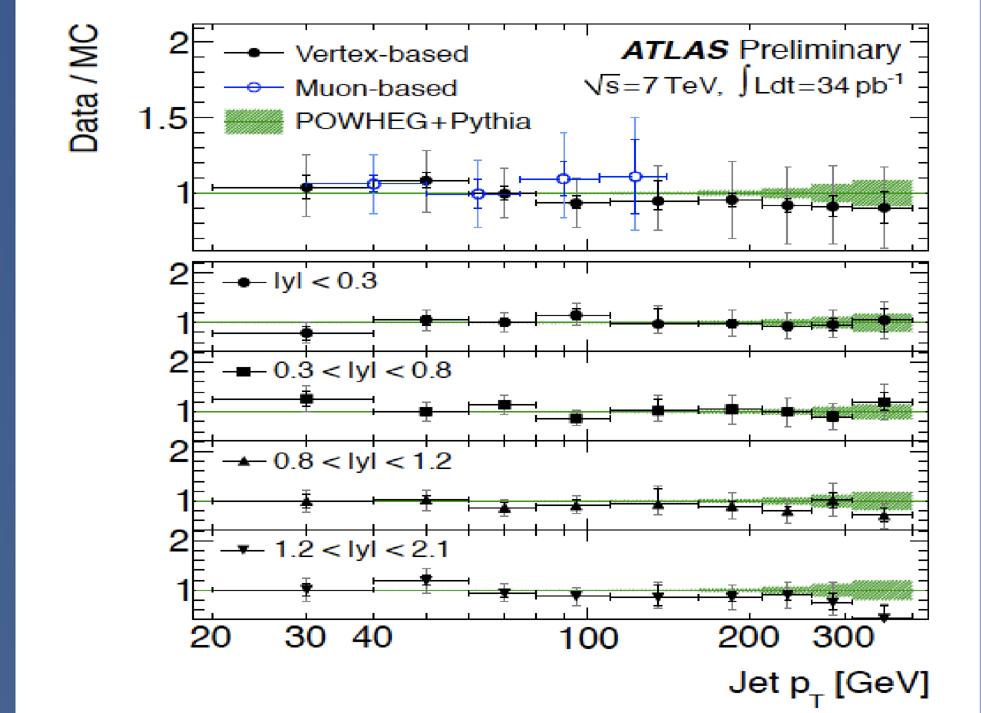


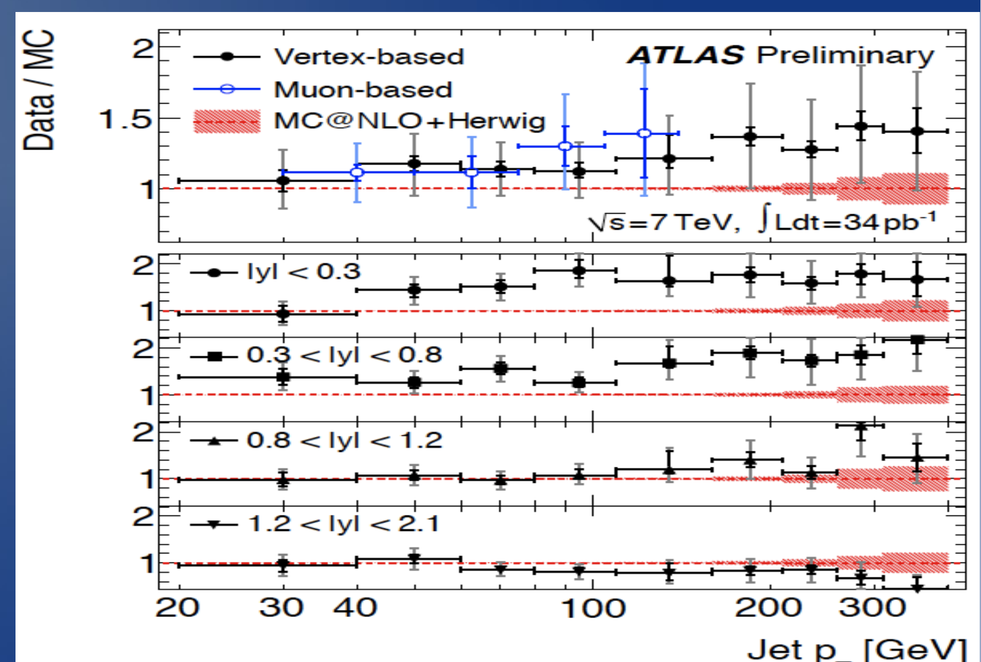




B-jet cross-section

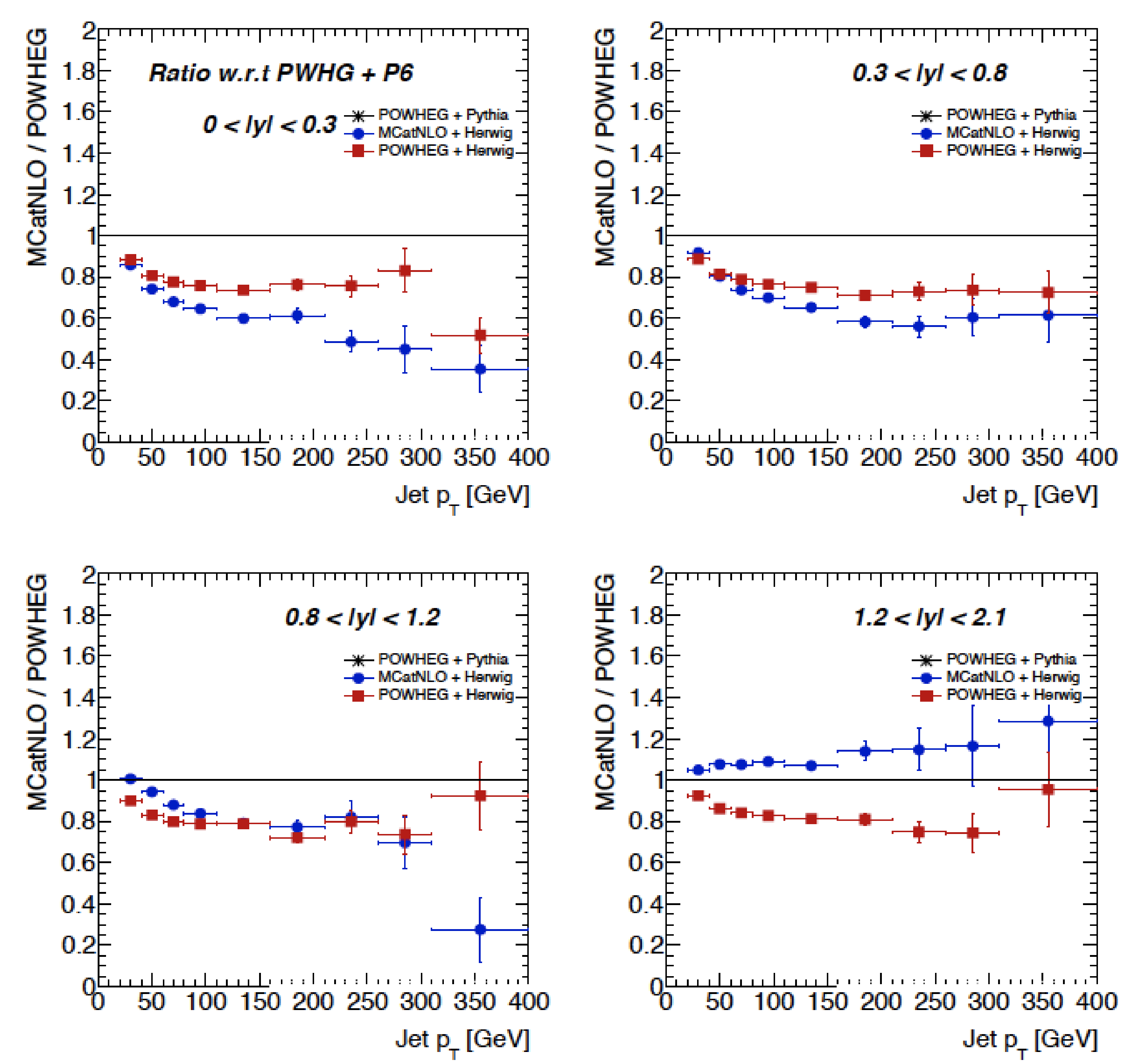






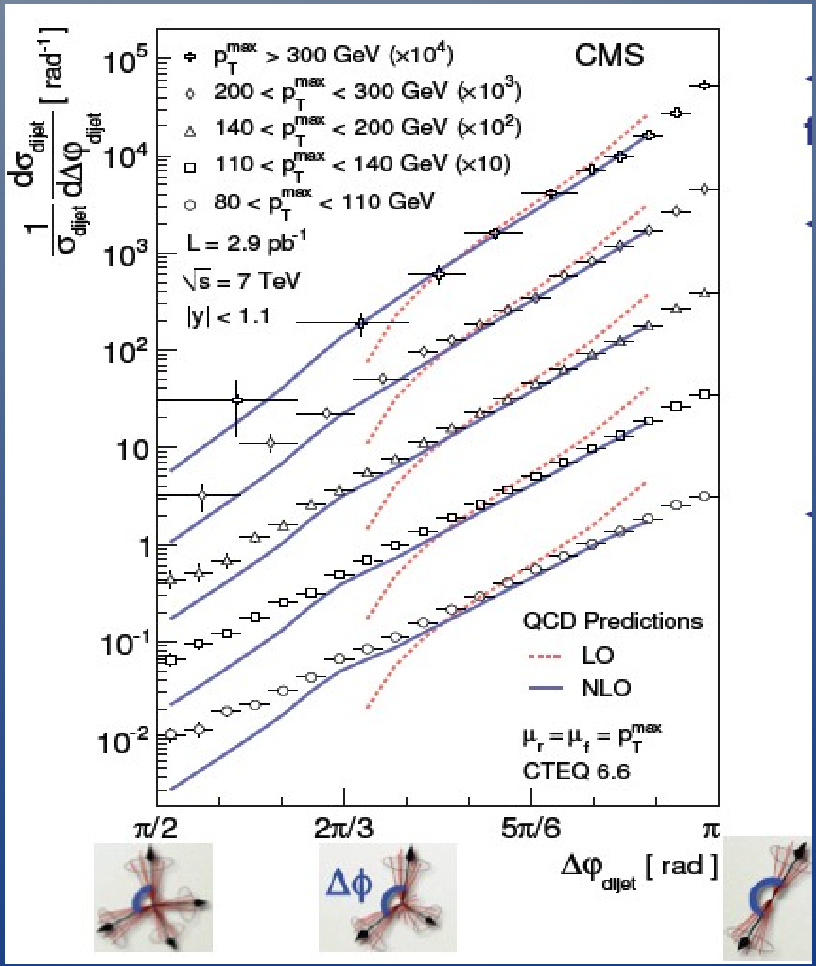
Measurement with secondary vertex tagging, and cross-checked with muon pT_rel, limited to tracking acceptance region

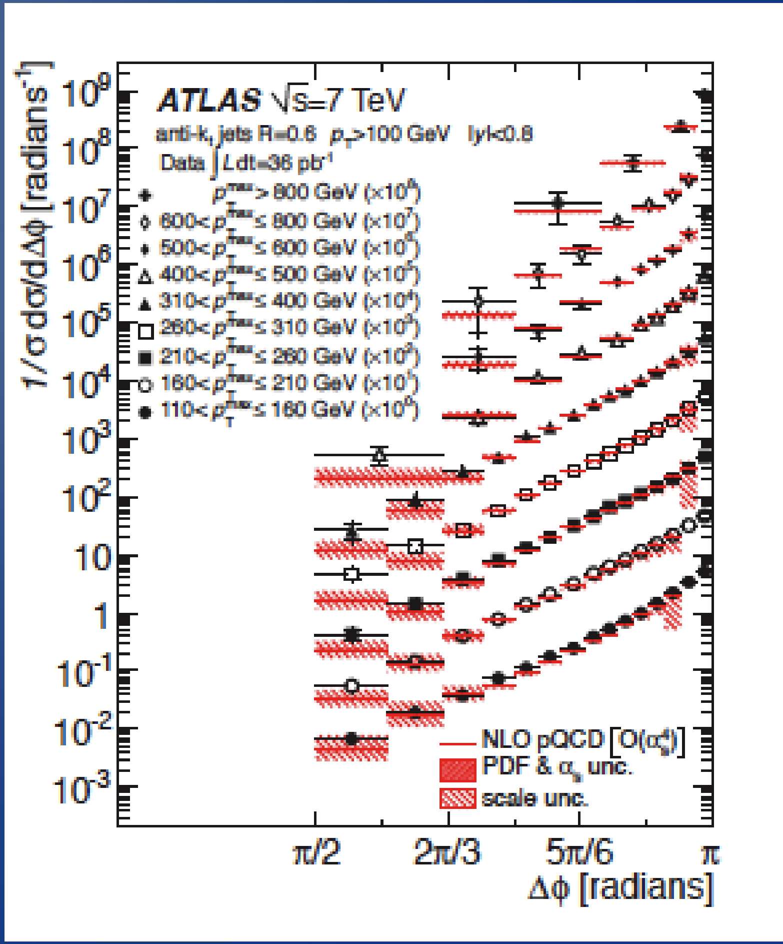
Is it the hard scattering or the shower?



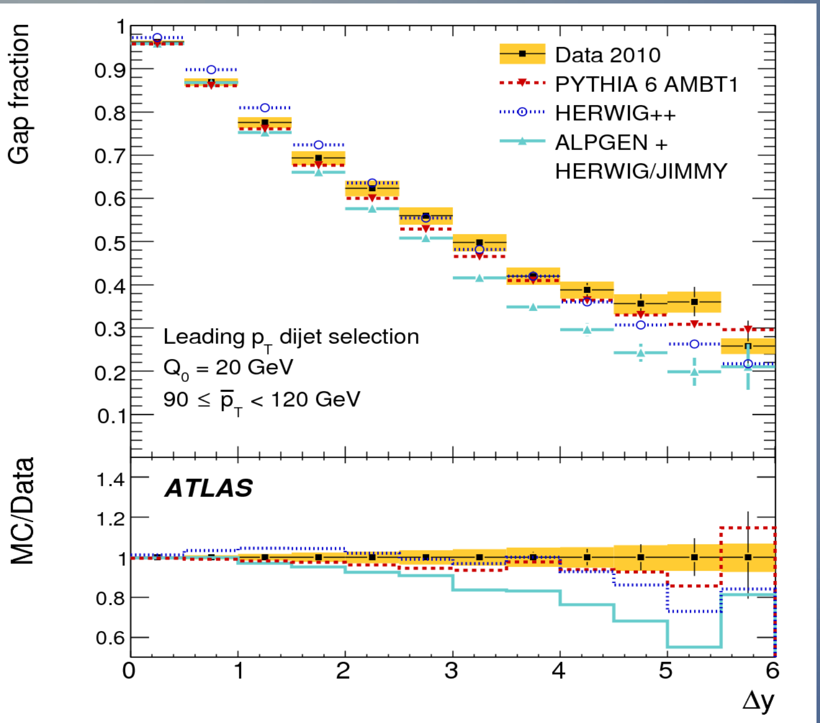
An indirect way to look at higher orders: azimuthal de-correlation

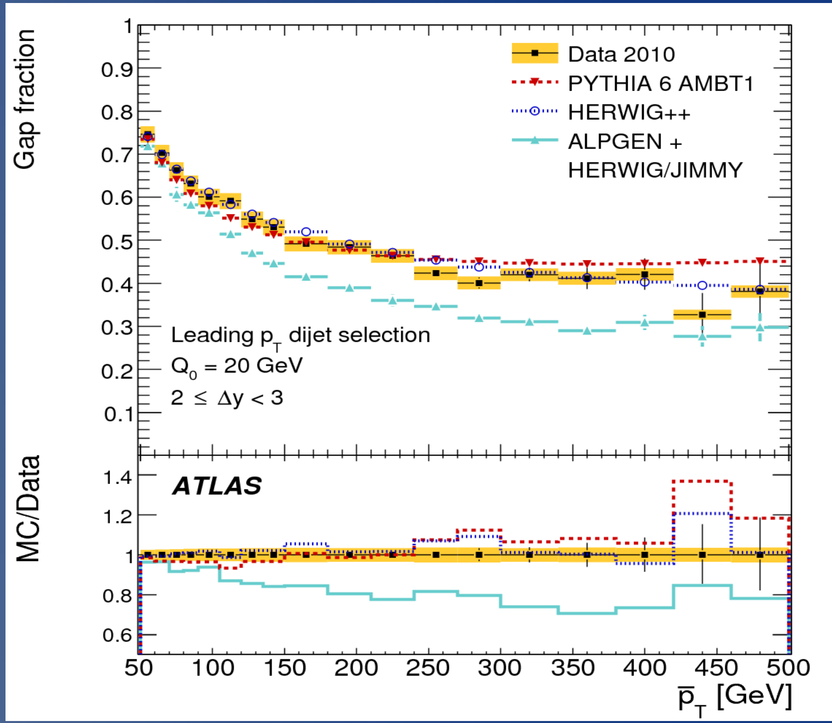
Pure dijet final states have to be back-to-back because of momentum conservation. Any deviation from that is an indication of higher-order terms

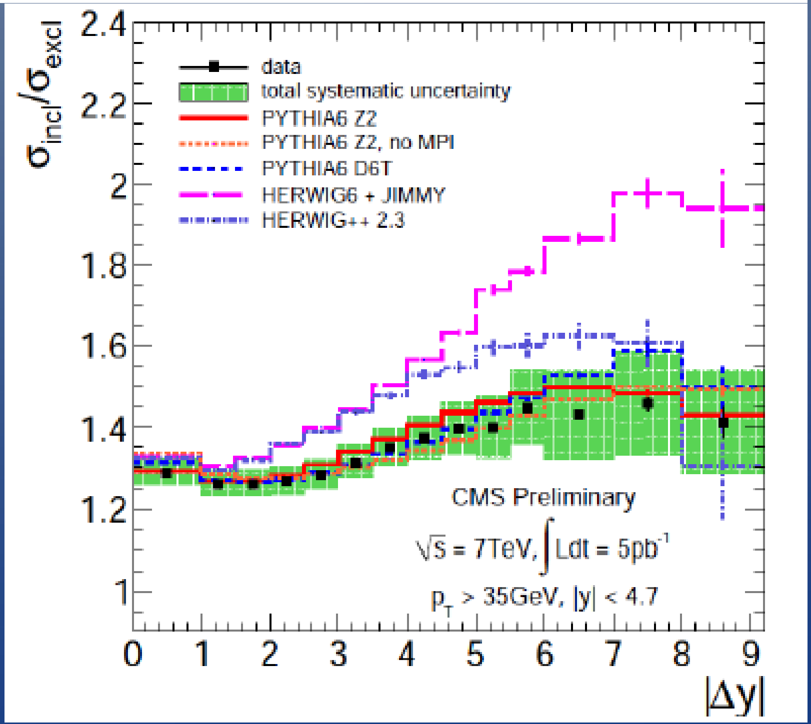


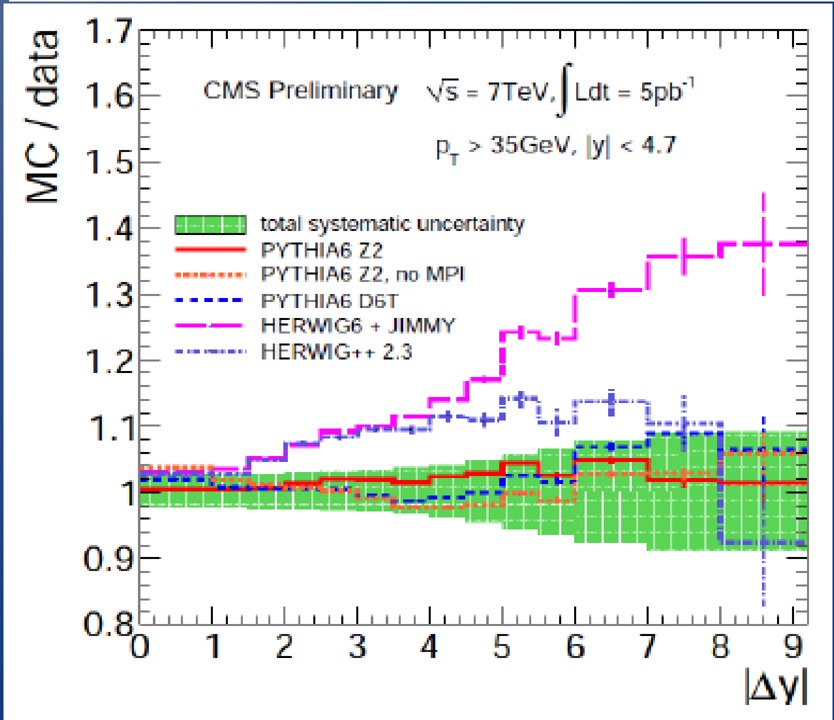


Integrated gap fractions vs LO generators

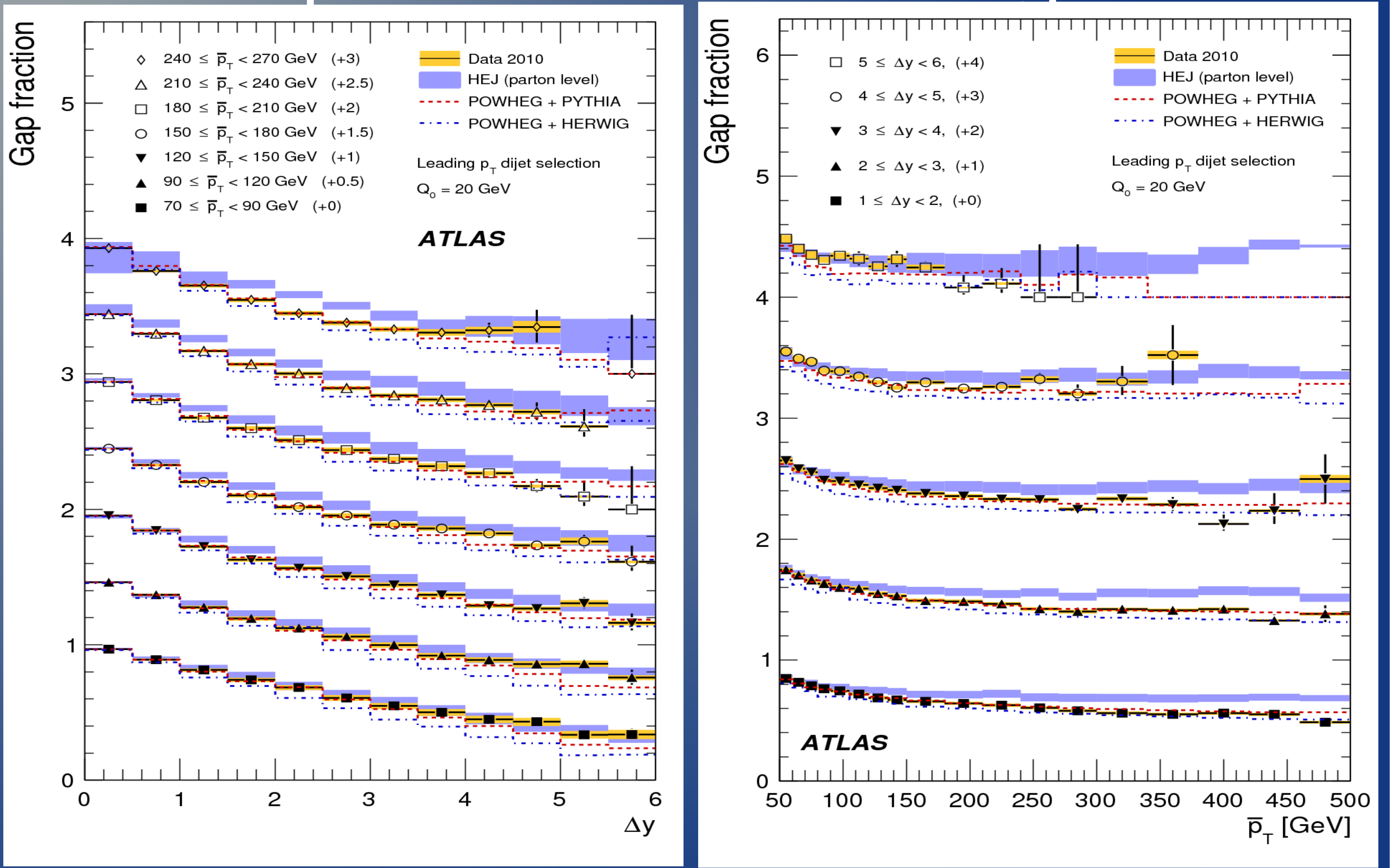






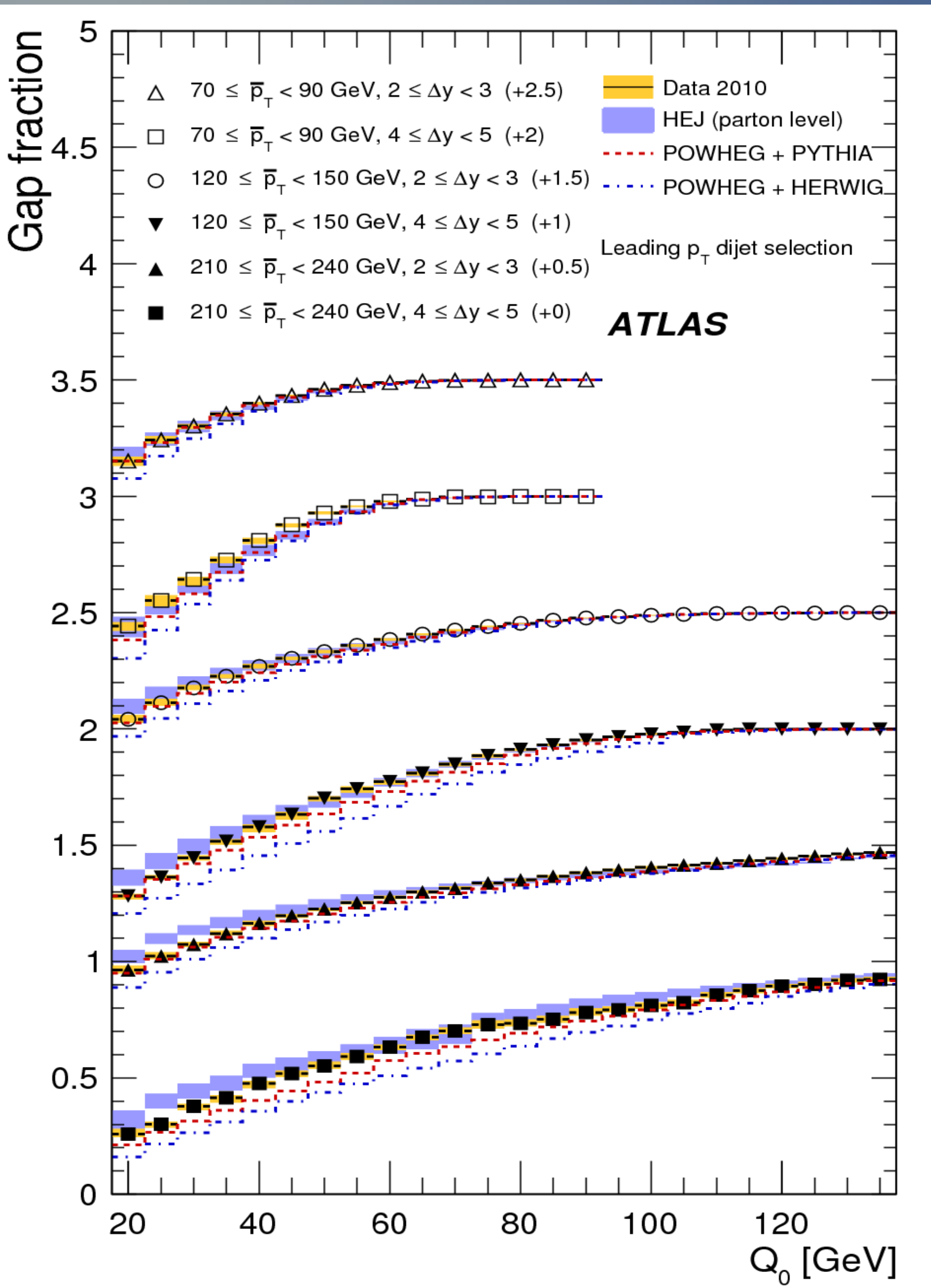


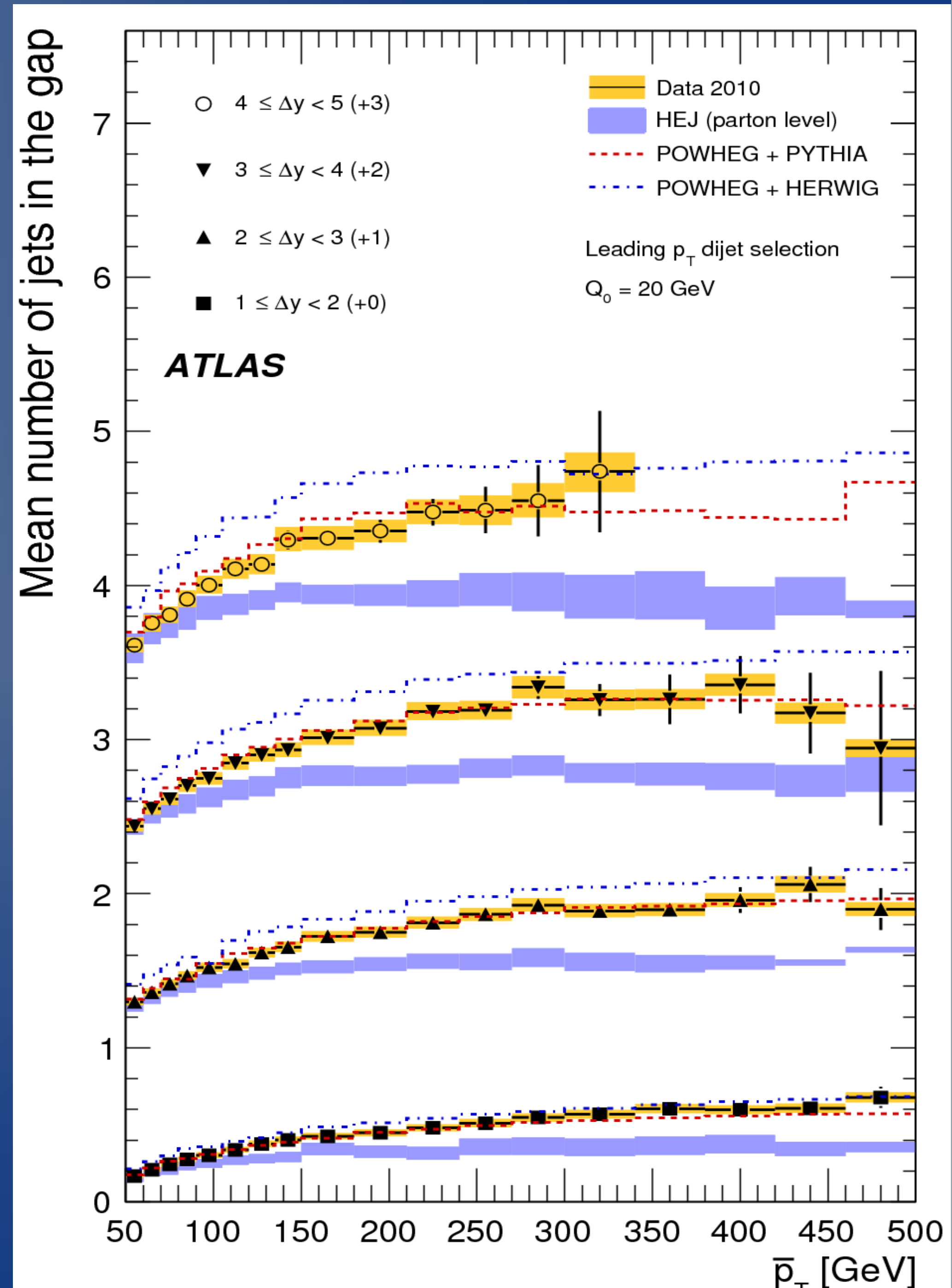
Comparisons with Powheg/HEJ



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

Gap vs pT_veto and jets in the gap



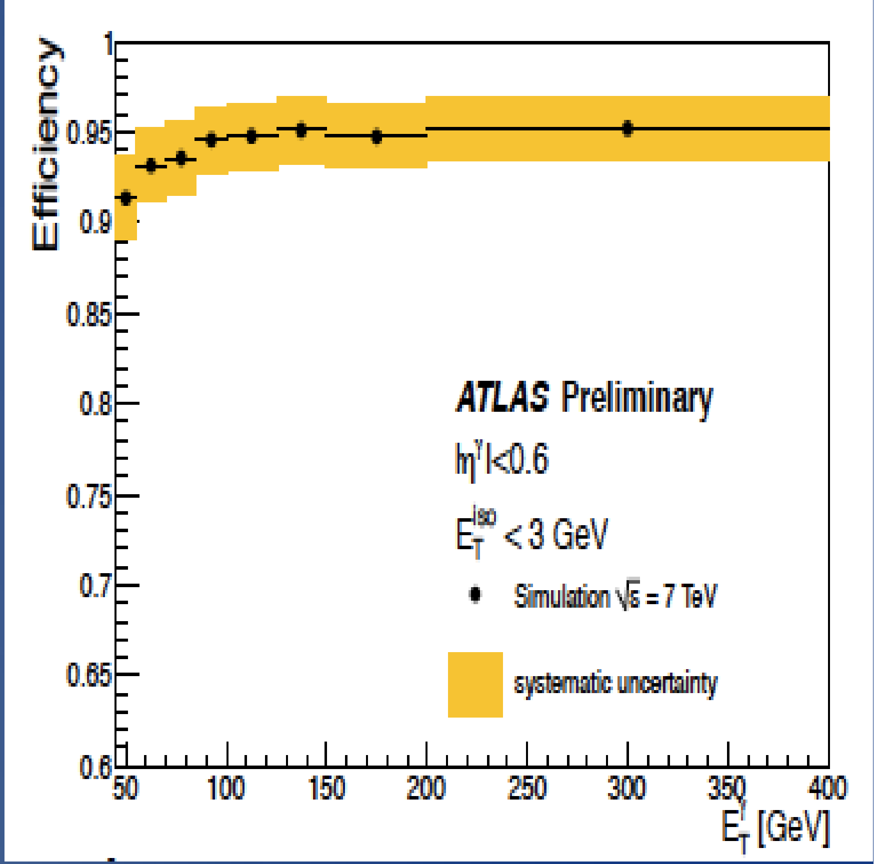


Photon identification

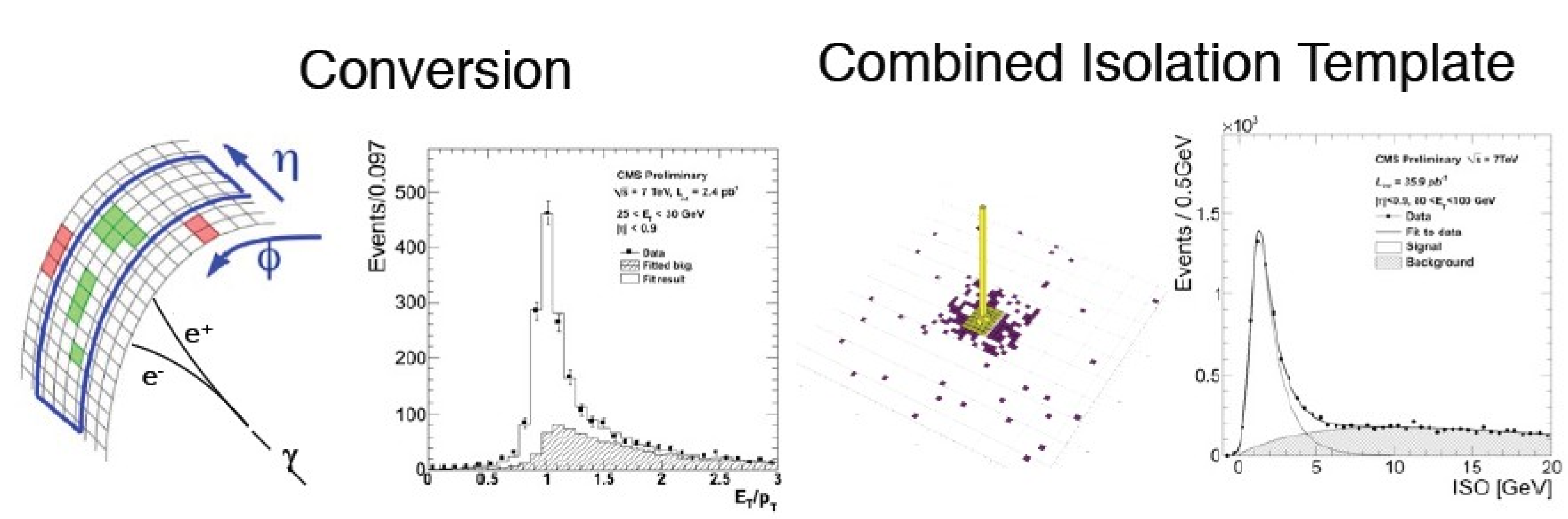
ATLAS: Isolation variable ETIso computed using cells from both EM/Hadronic calorimeter in a cone $\Delta R<0.4$ around the γ, subtracting the central 5x7 cells.

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

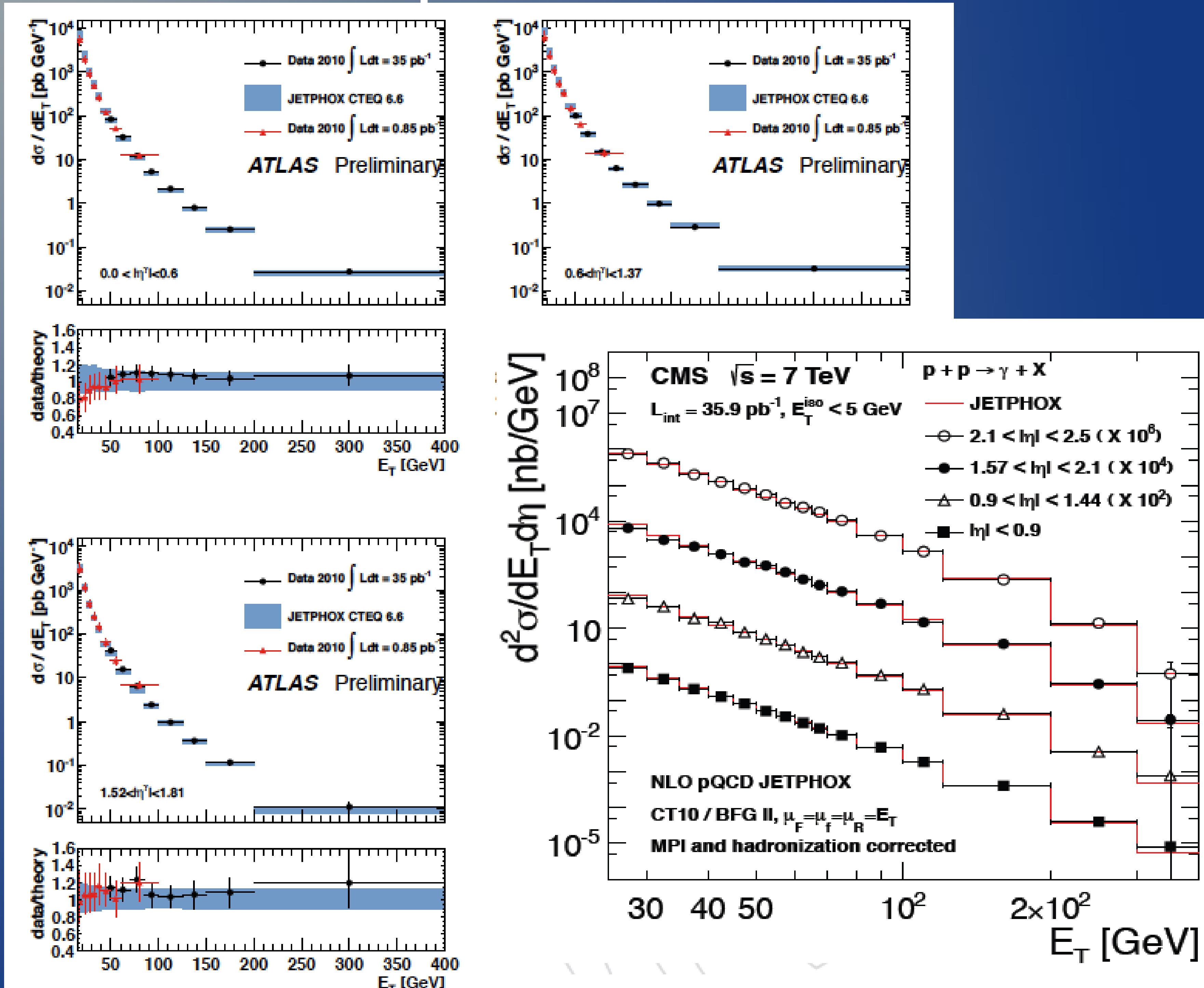
- Jet-area corrections (a la Cacciari-Salam) help sto mitigate the effects of in-time pileup (O(500 MeV)) Other pileup effects small compared to uncertainty in the above method



CMS: use of converted photons at low-Pt, isolation criteria at high-pt

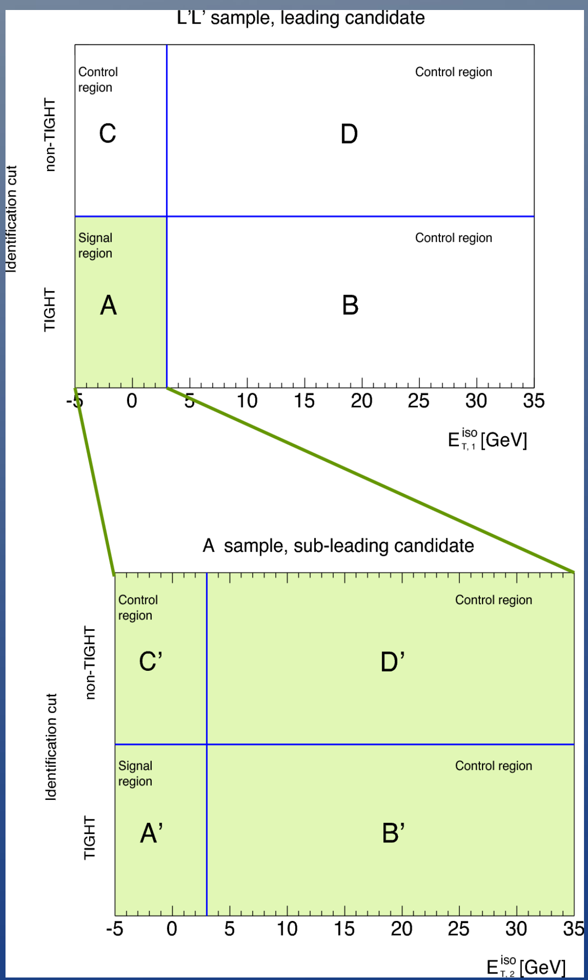


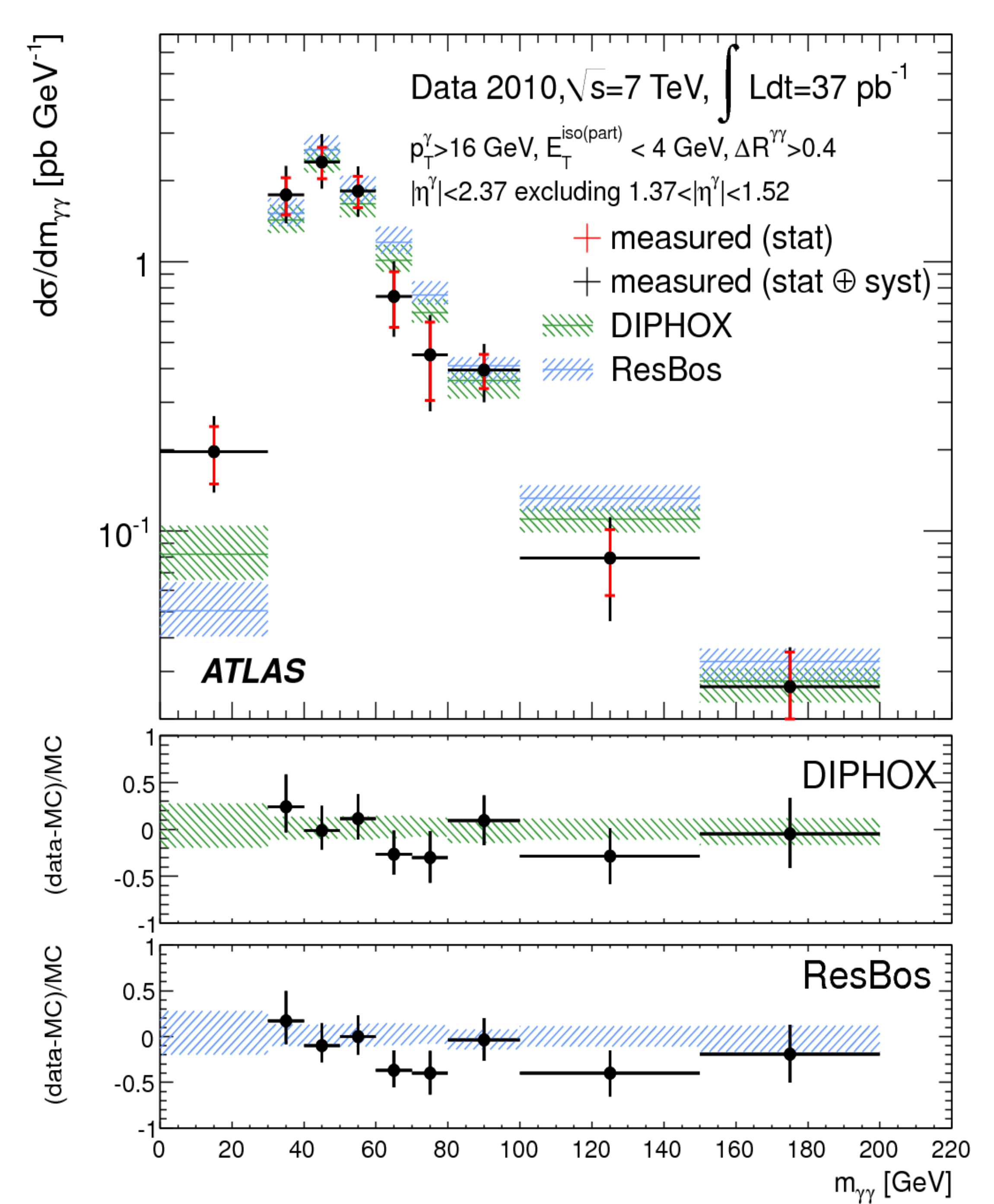
Inclusive photon cross-section



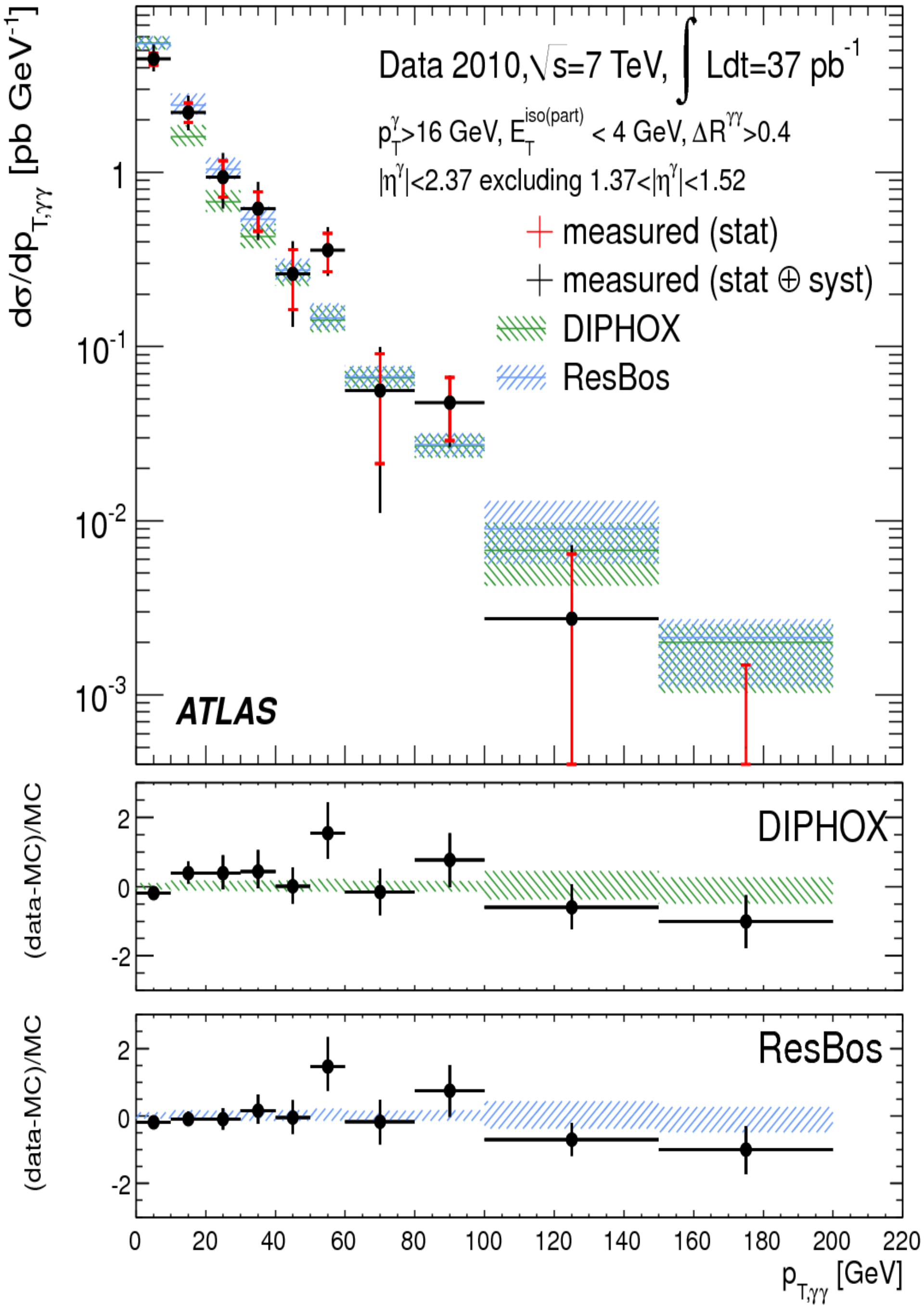
Di-photon measurement (ATLAS)

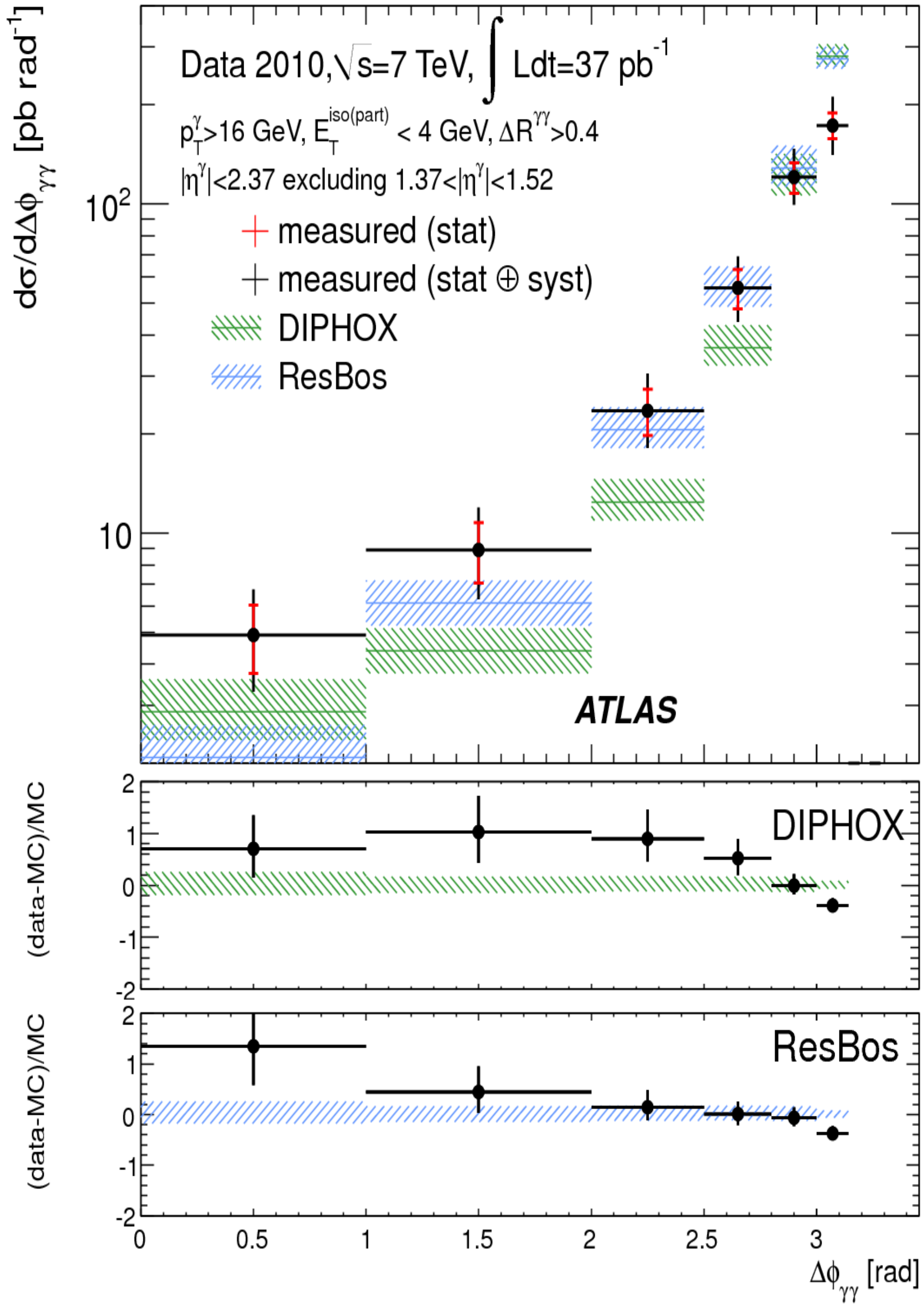
4-dimensional background subtraction, for leading and sub-leading jet





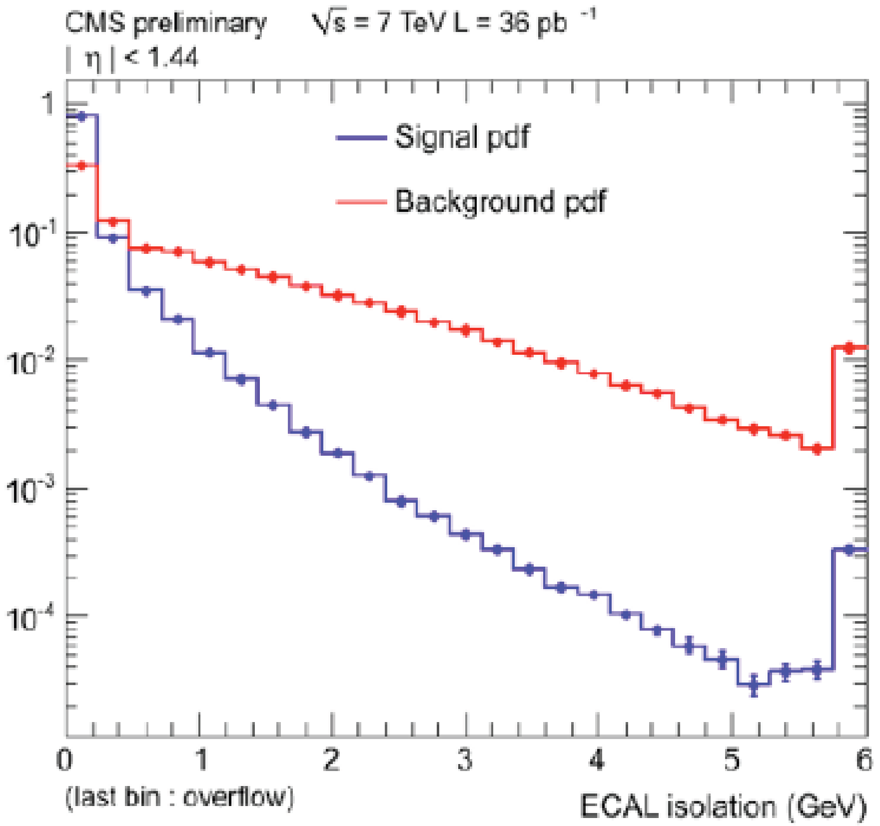
Di-photon results

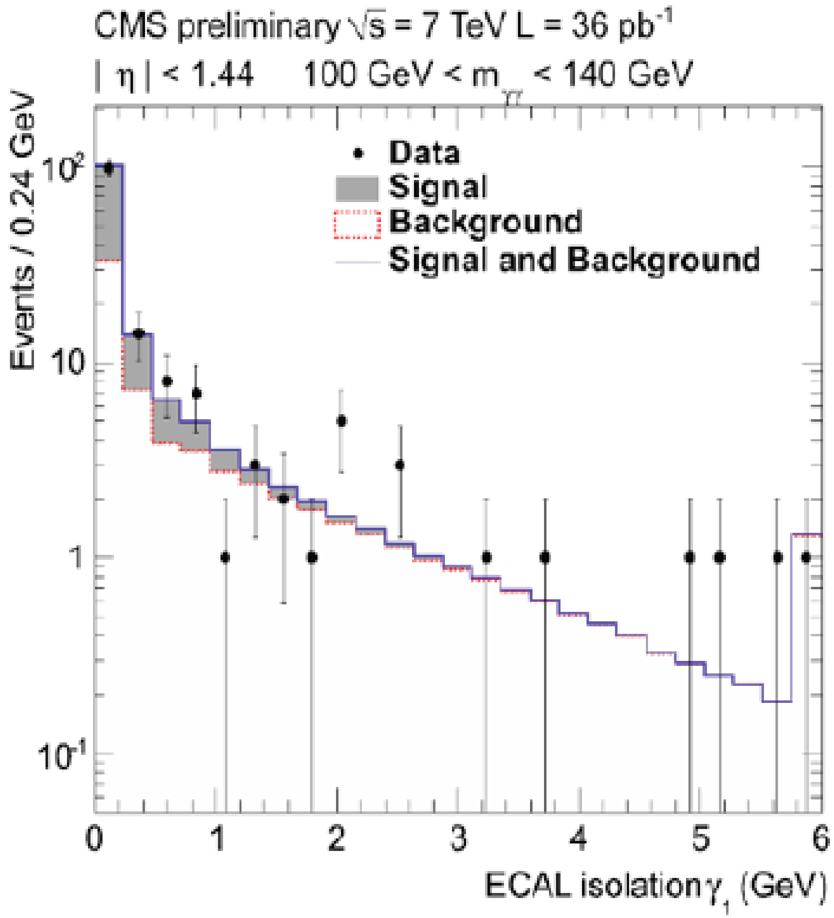




Di-photon Signal Extraction

CMS-QCD-10-035





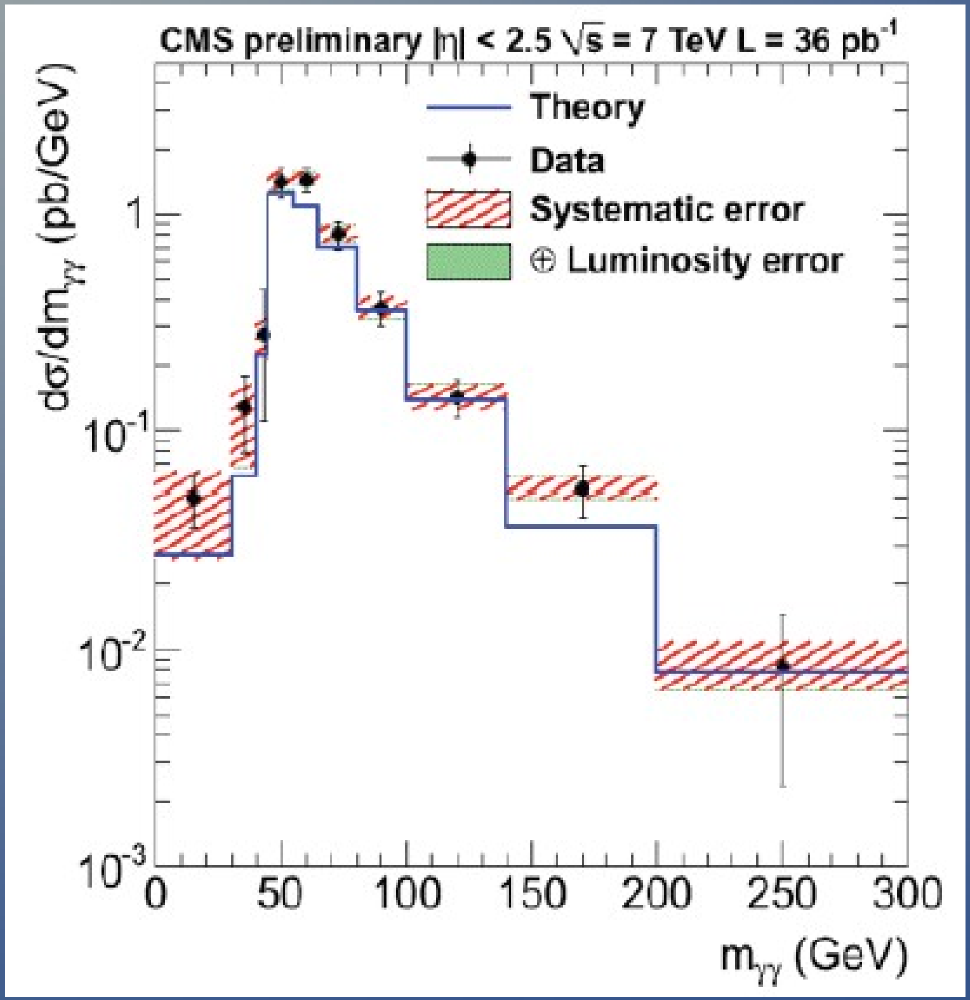
✦ Reconstruction

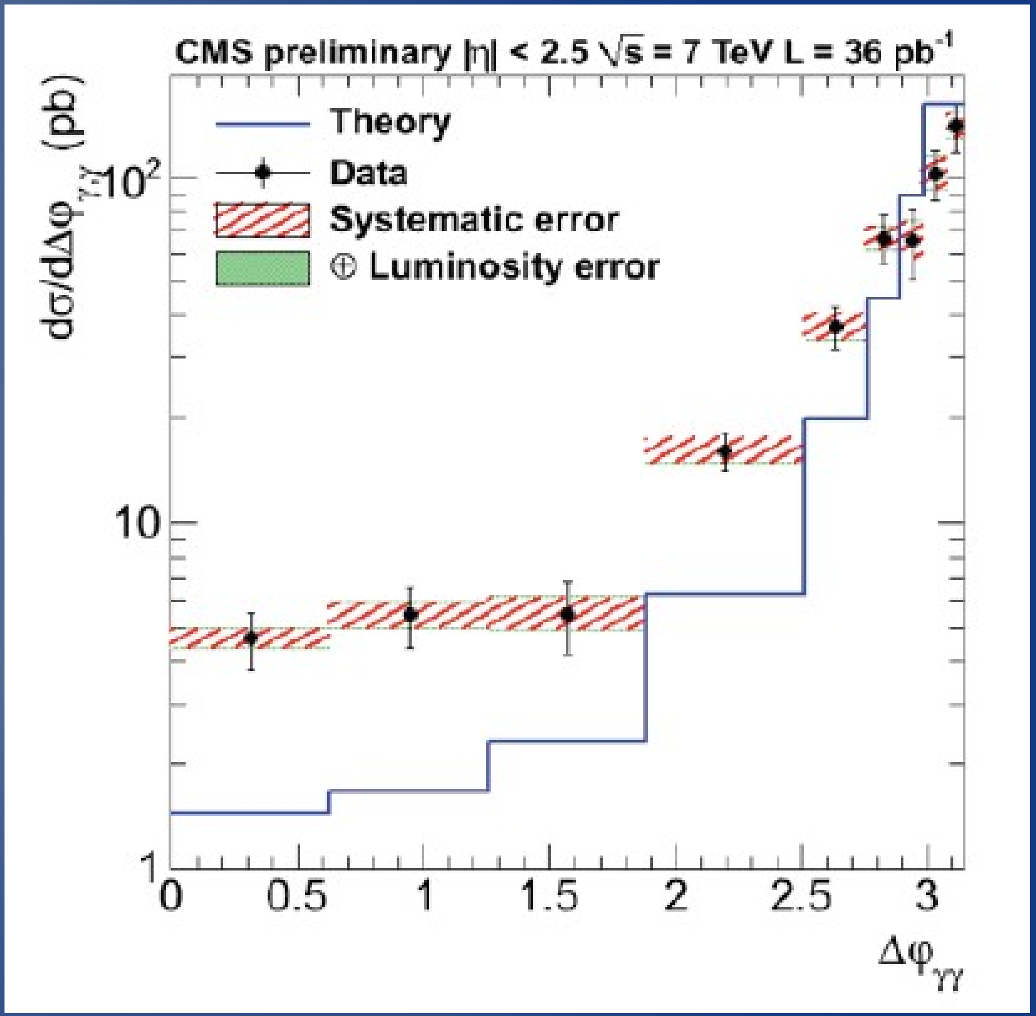
- photon candidates based on identification & isolation preselection criteria
- $E_{T,1} > 23$ GeV, $E_{T,2} > 20$ GeV, $R_{\gamma\gamma} > 0.45$ in η-φ,

✦ Signal yield

- signal extracted statistically
- ECAL isolation template

Diphoton cross-section (CMS)

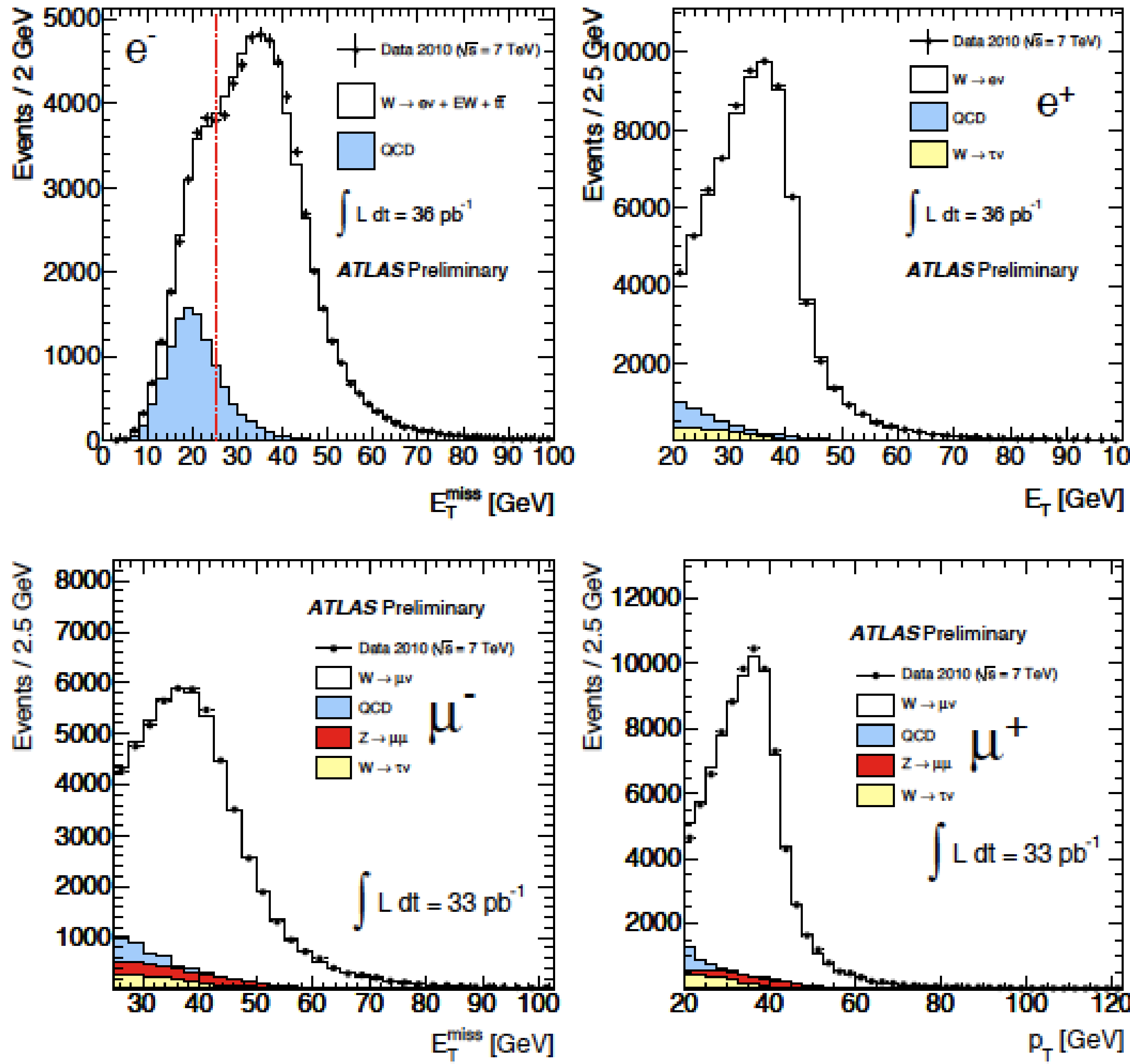




- Theory from Diphox and Gamma2MC (for box diagrams) undershoots at low angles, but the Higgs search region seems ok

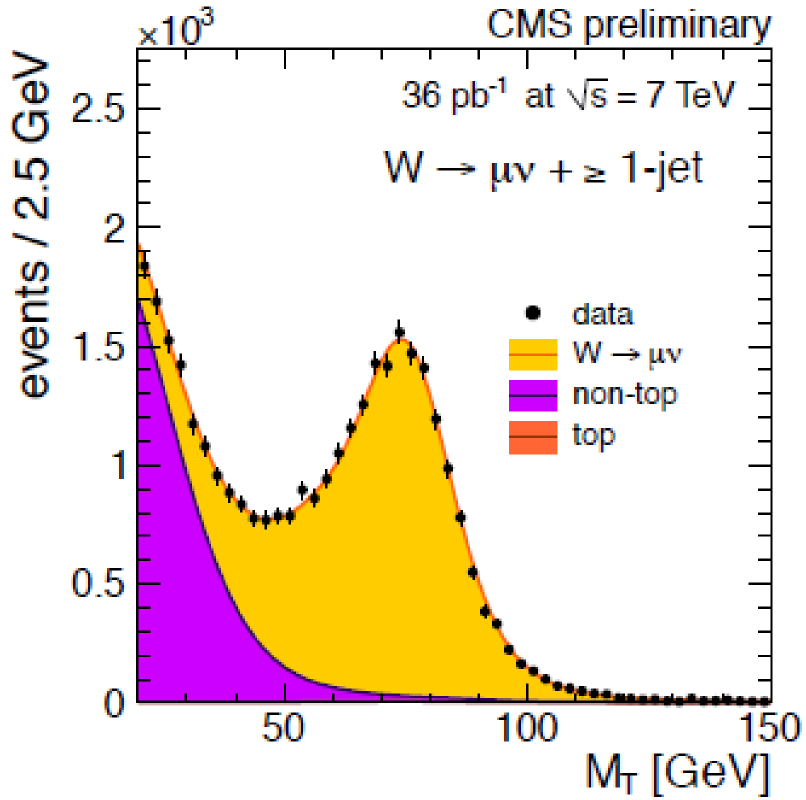
W identification (ATLAS)

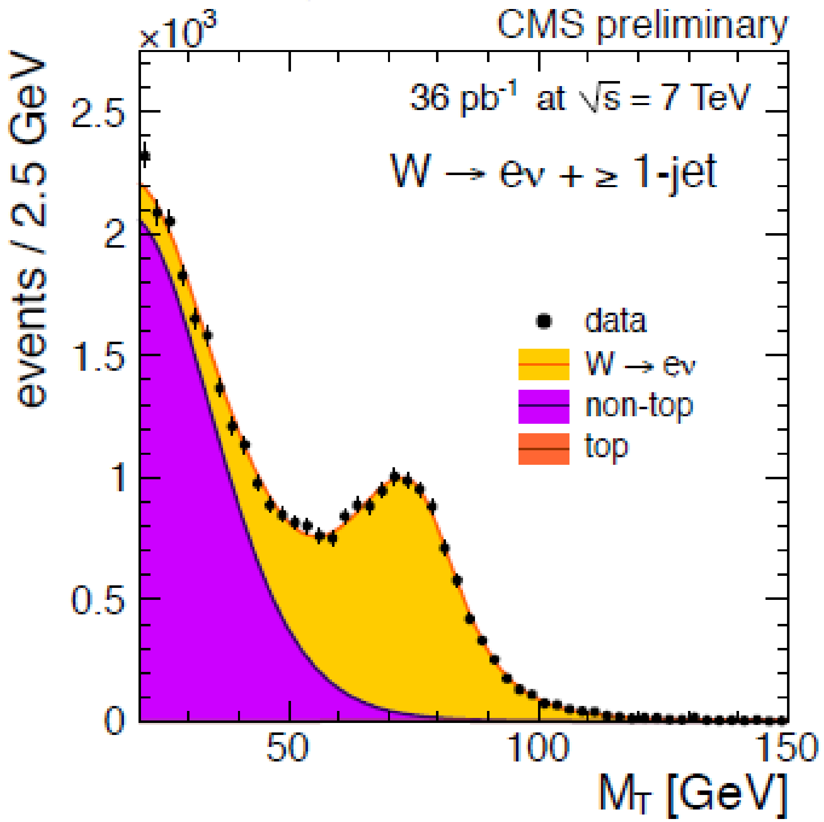
- Single lepton triggers with high efficiency
- $p_{T,l} > 20\,GeV$
  $|\eta_e| < 2.47,\ |\eta_\mu| < 2.4$
  (elec. excl. calo crack)
  isolated leptons
  $E_T^{miss} > 25\,GeV$
  $m_T > 40\,GeV$
- QCD from data fitting E_T^{miss} (e) and studying control regions in $iso - E_T^{miss}$ plane (μ)
- $131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



W identification (CMS)

$$M_T = \sqrt{2 p_T \not{E}_T (1 - \cos\Delta\phi)},$$





✦ **W(μν) reconstruction**

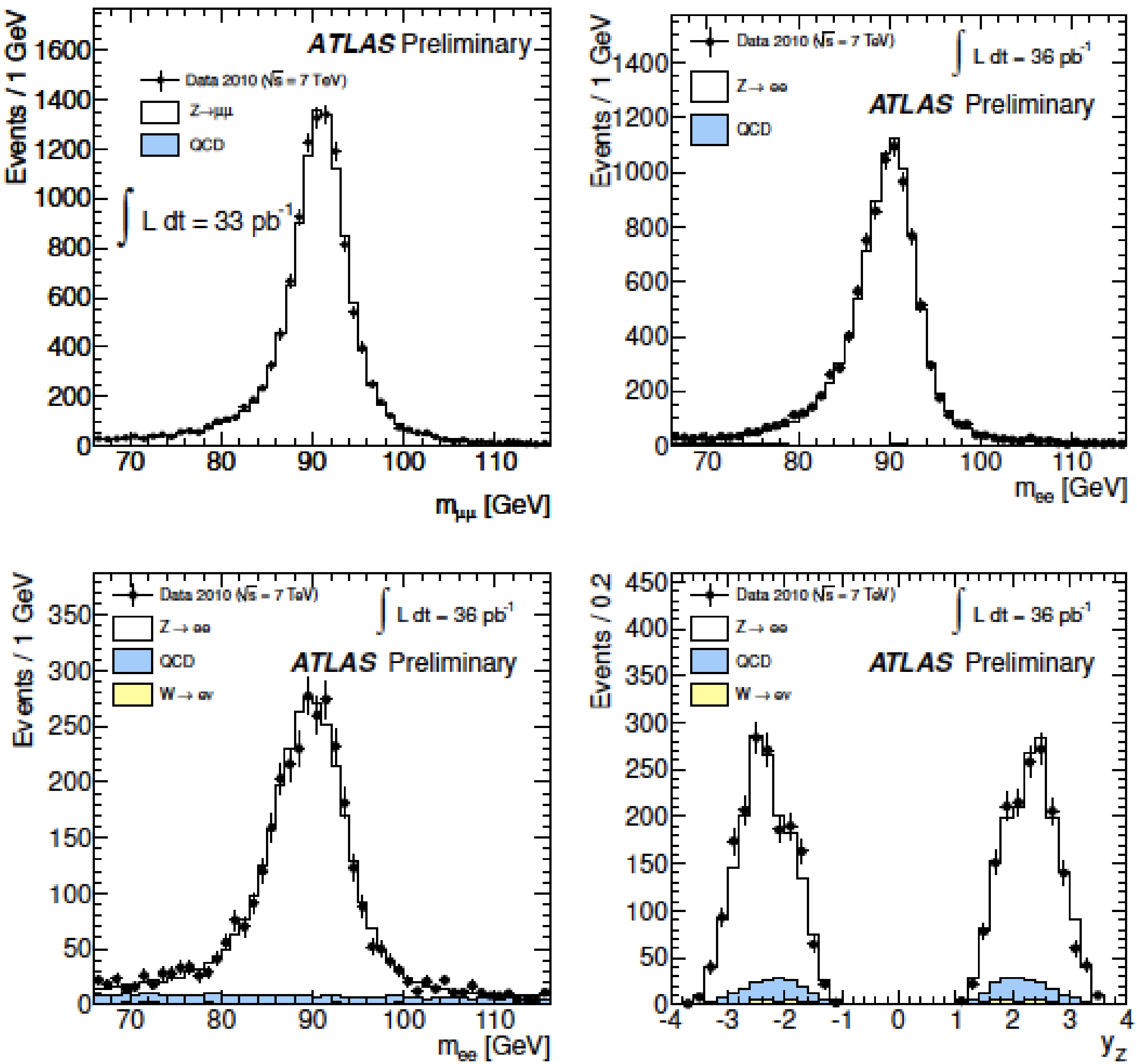
- muons with $p_T > 20$ GeV and $|\eta| < 2.1$
- isolation & ID requirements
- $M_T > 20$ GeV
- Z veto

✦ **W(eν) reconstruction**

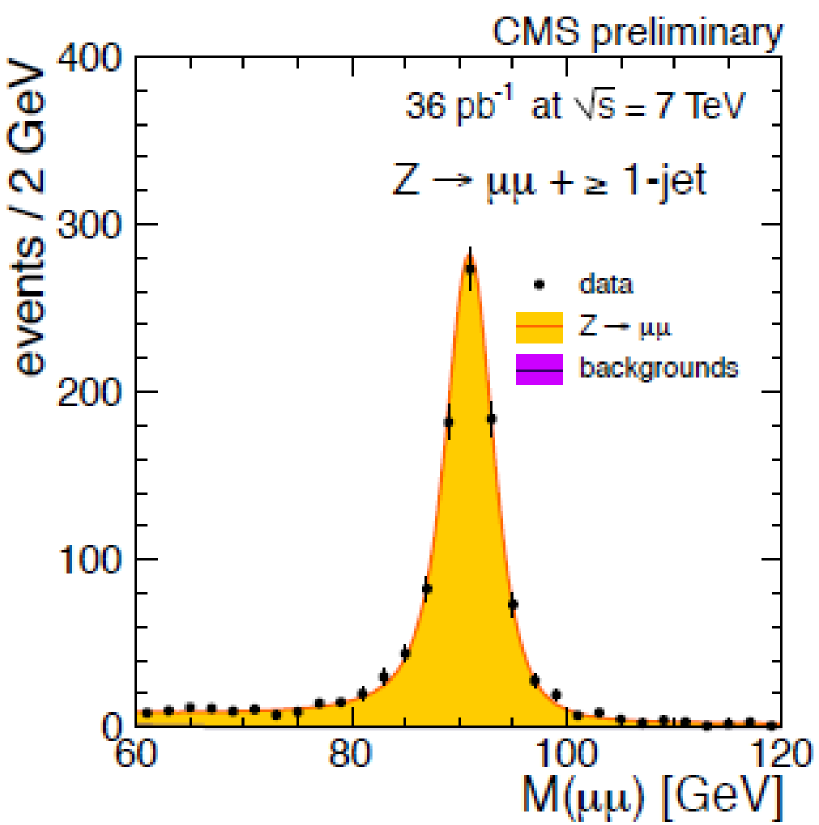
- electrons with $p_T > 20$ GeV and $|\eta| < 2.5$
- $1.44 < |\eta| < 1.57$ excluded
- isolation & ID requirements
- $M_T > 20$ GeV
- Z veto

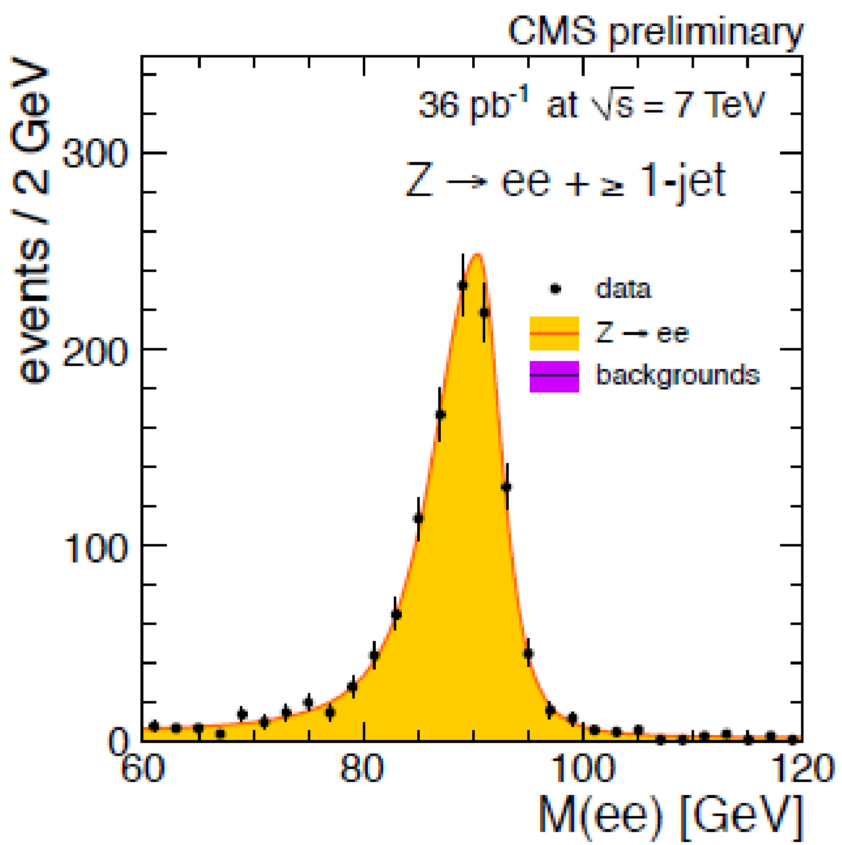
Z-> ll selection (ATLAS)

- 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



Z->ll selection (CMS)





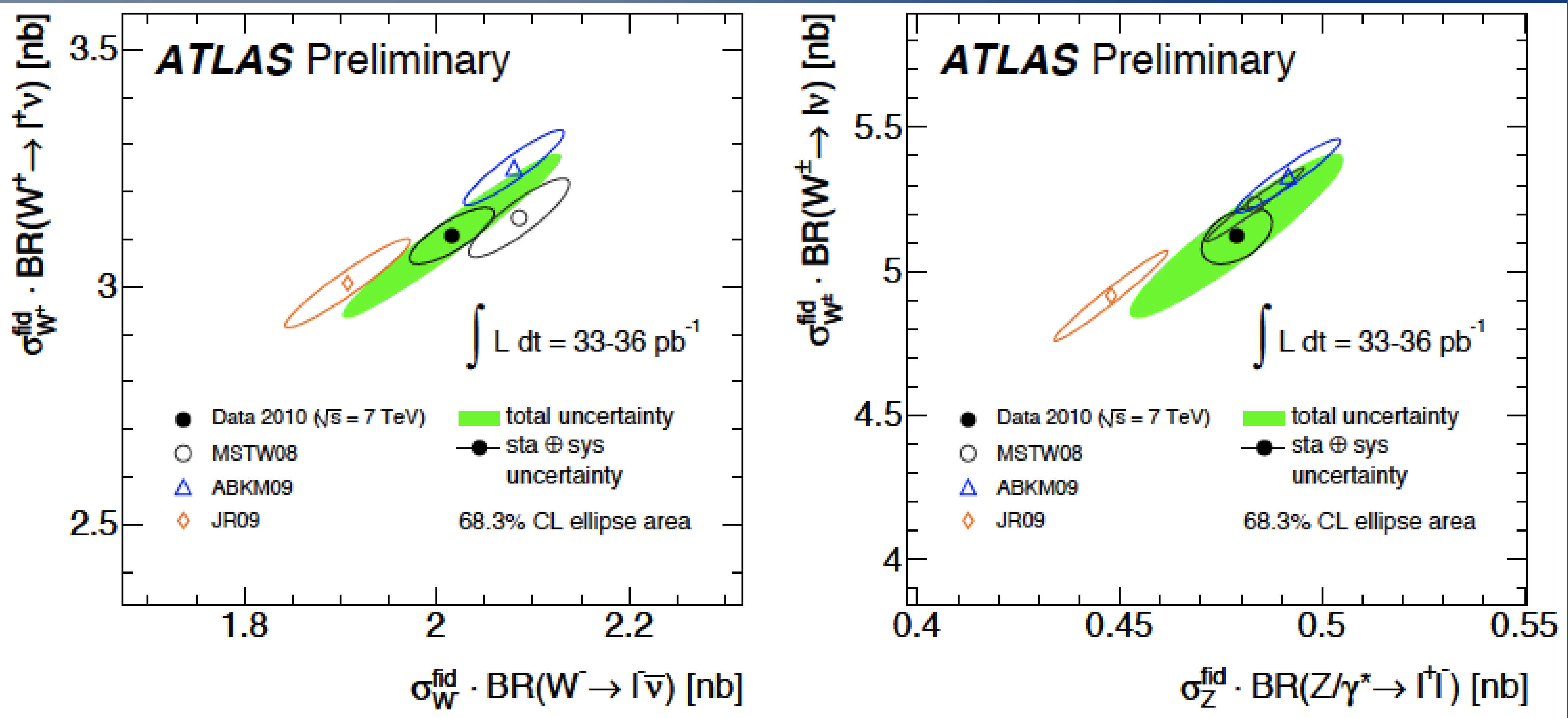
- **Z(μμ) reconstruction**
  - muons with $p_T > 10$ GeV and $|\eta| < 2.4$
  - identification requirements
  - $60 < M_{ll} < 120$ GeV

- **Z(ee) reconstruction**
  - electrons with $p_T > 10$ GeV and $|\eta| < 2.4$
  - $1.44 < |\eta| < 1.57$ excluded
  - isolation requirements
  - $60 < M_{ll} < 120$ GeV

Total cross section (ATLAS)

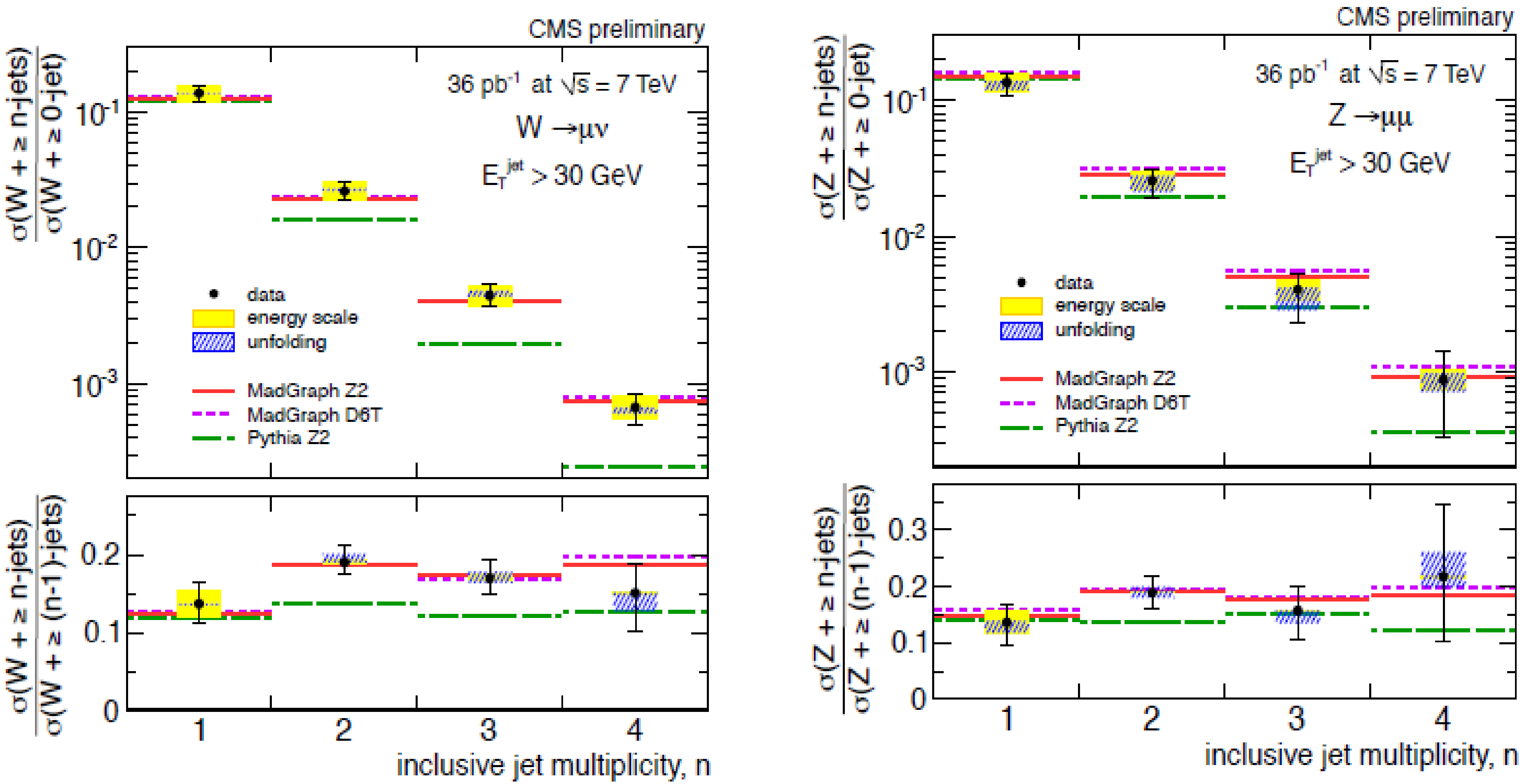
Comparison made in the fiducial region to minimise extrapolation uncertainties and be more sensitive to Pdf

NNLO predictions based on FEWZ and DYNNLO



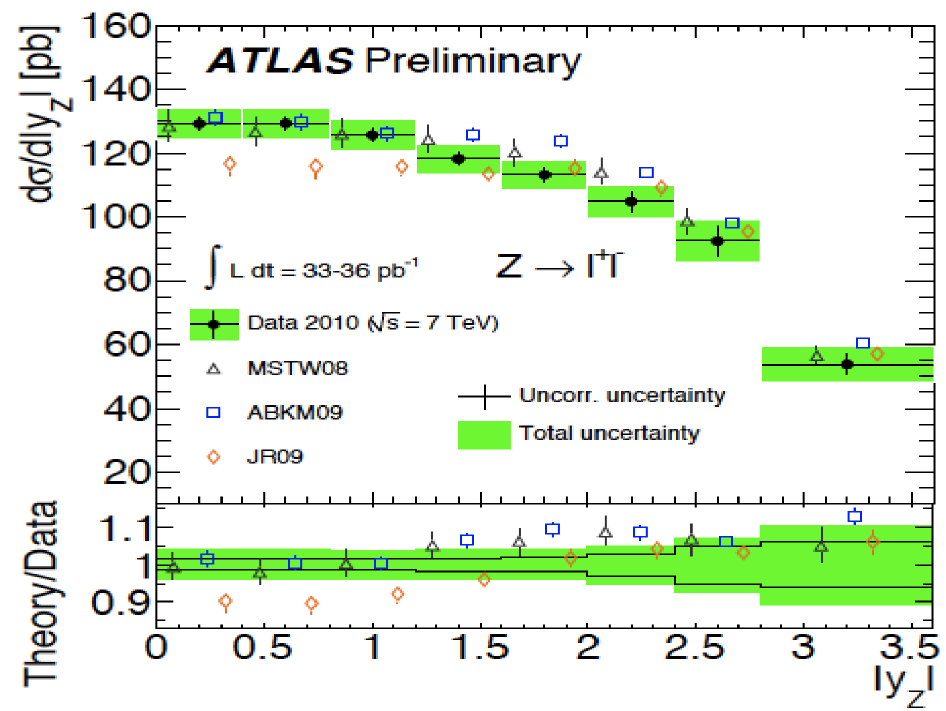
Ratio of Cross Sections

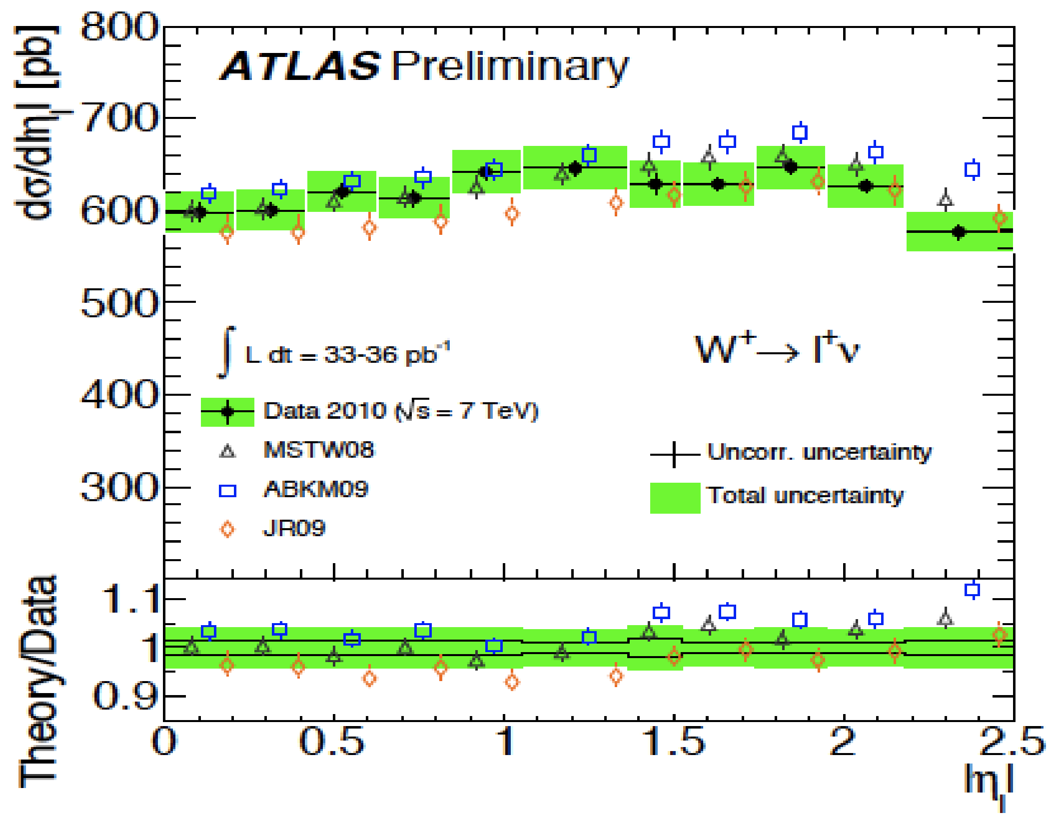
CMS-EWK-10-012

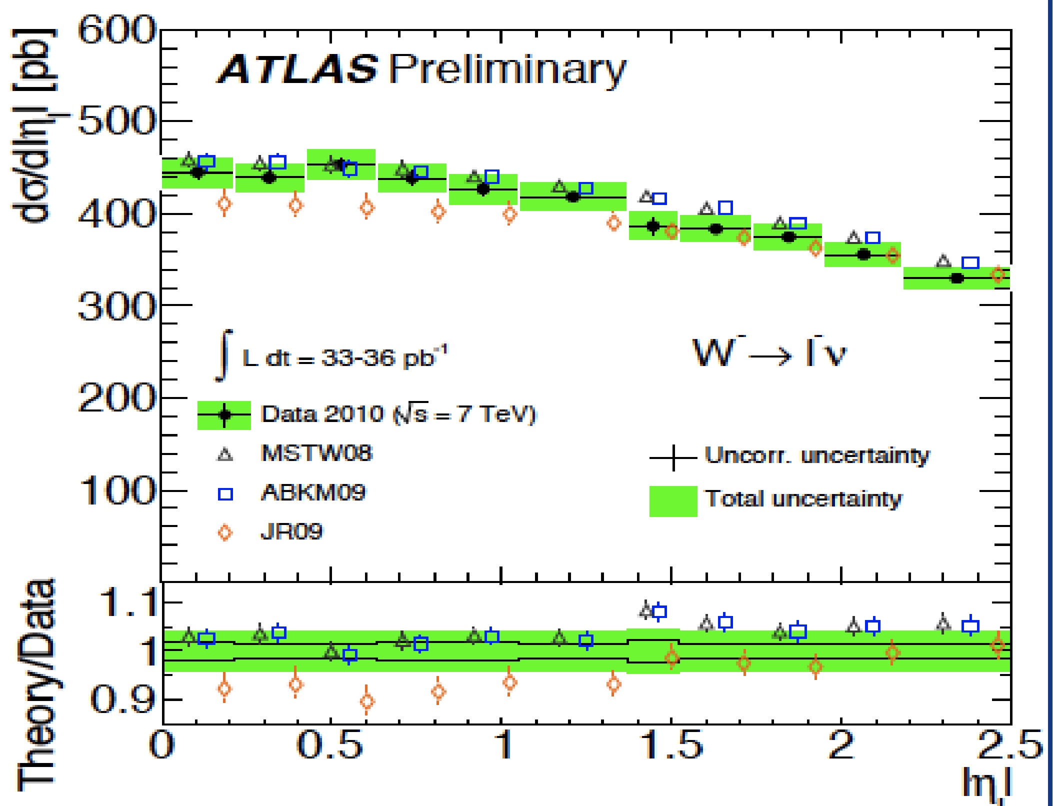


- ✦ **Measurement in inclusive N-jet bins**
  - unfolding using the SVD method
  - JES and unfolding (at high jet multiplicities) the dominant systematic uncertainties
- ✦ **Comparisons to the MC**
  - Madgraph describes the data well, while Pythia6 succeeds only in the 1-jet bin (as expected)

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

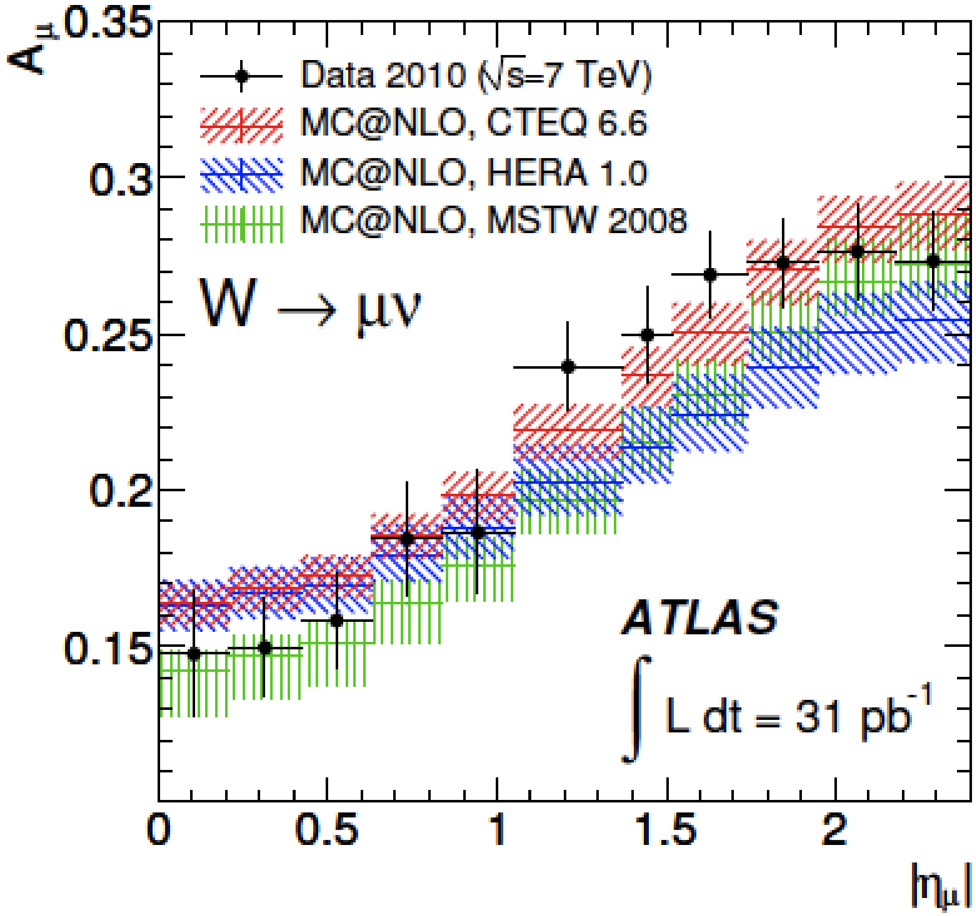


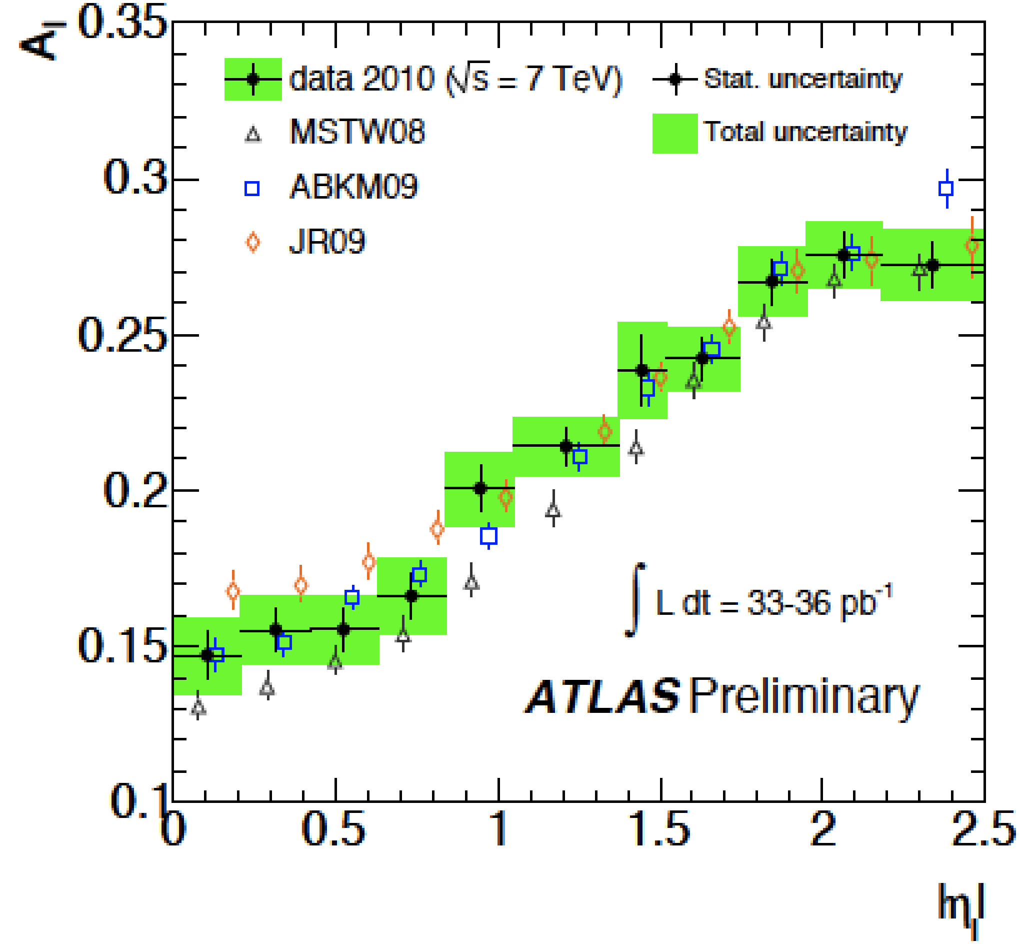




W asymmetry

- 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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Conclusions

- Could only rapidly flash some results, full list growing every day
- 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