Probing QCD with Jets, Photons and Weak Bosons at the LHC with ATLAS

QCD@Work – International Workshop on QCD

Lecce, 18th – 21st June 2012

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UCL

On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

QCD at ATLAS

Strong interactions dominate the physics at the LHC p-p collider. We have to understand it to search for new physics!

Motivations

Opportunity to probe QCD in a new unchartered high energy kinematic regime – will the theory hold-up here? Evidence of new physics?

This talk will summarise ATLAS measurements of "hard" QCD processes

Studies of soft QCD, diffraction, underlying event covered separately

Use anti-K_T R = 0.4 and/or 0.6 jets.

Measurements cover the largest energy ranges and go out to higher rapidities than ever before.

Kinematic ranges defined by detector-acceptance to minimise signal modelling systematics

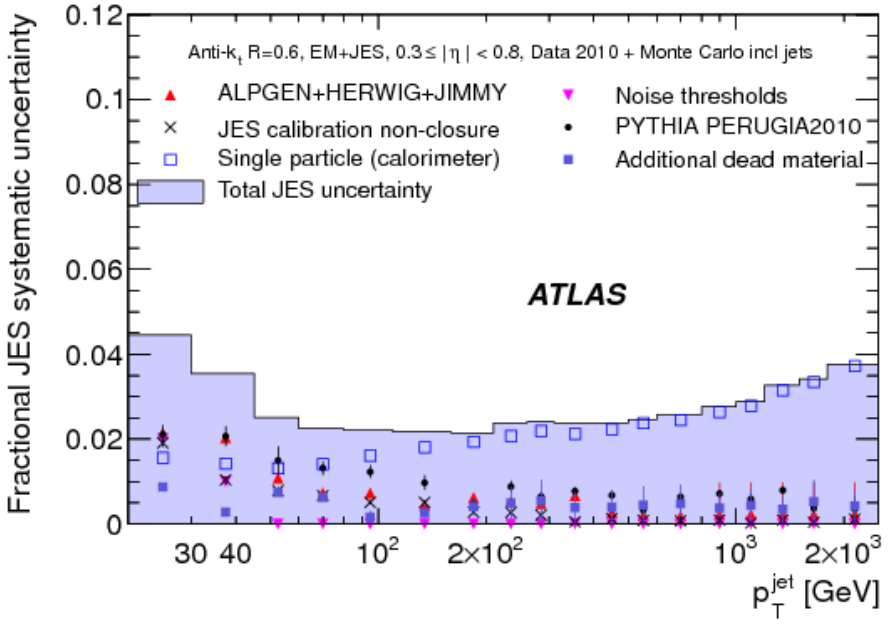
Unfolded to particle-level for direct comparison to theory.

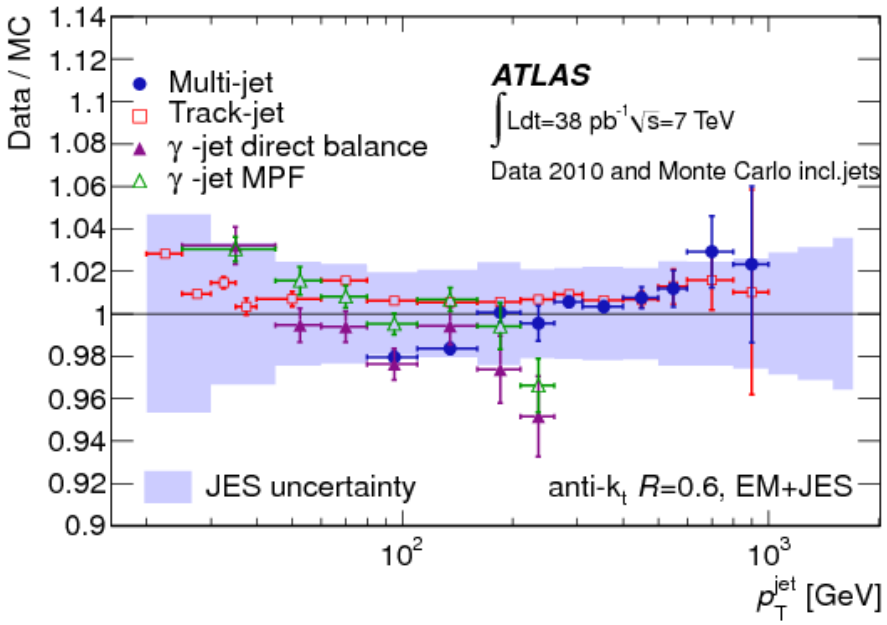
NLO pQCD requires corrections to theory for non-perturbative effects (n.p.c)

Compare to latest NLO pQCD, NLO+MC and LO +MC predictions

Experimental Systematics

- Dominant systematic for most jet-based observables is the Jet Energy Scale (JES) uncertainty.
- JES calibrations correct jet p_T back to particle-level energy on average. Derived w/ simulation.
- Comes with p_T and η-dependent uncertainty 2% - 7%.

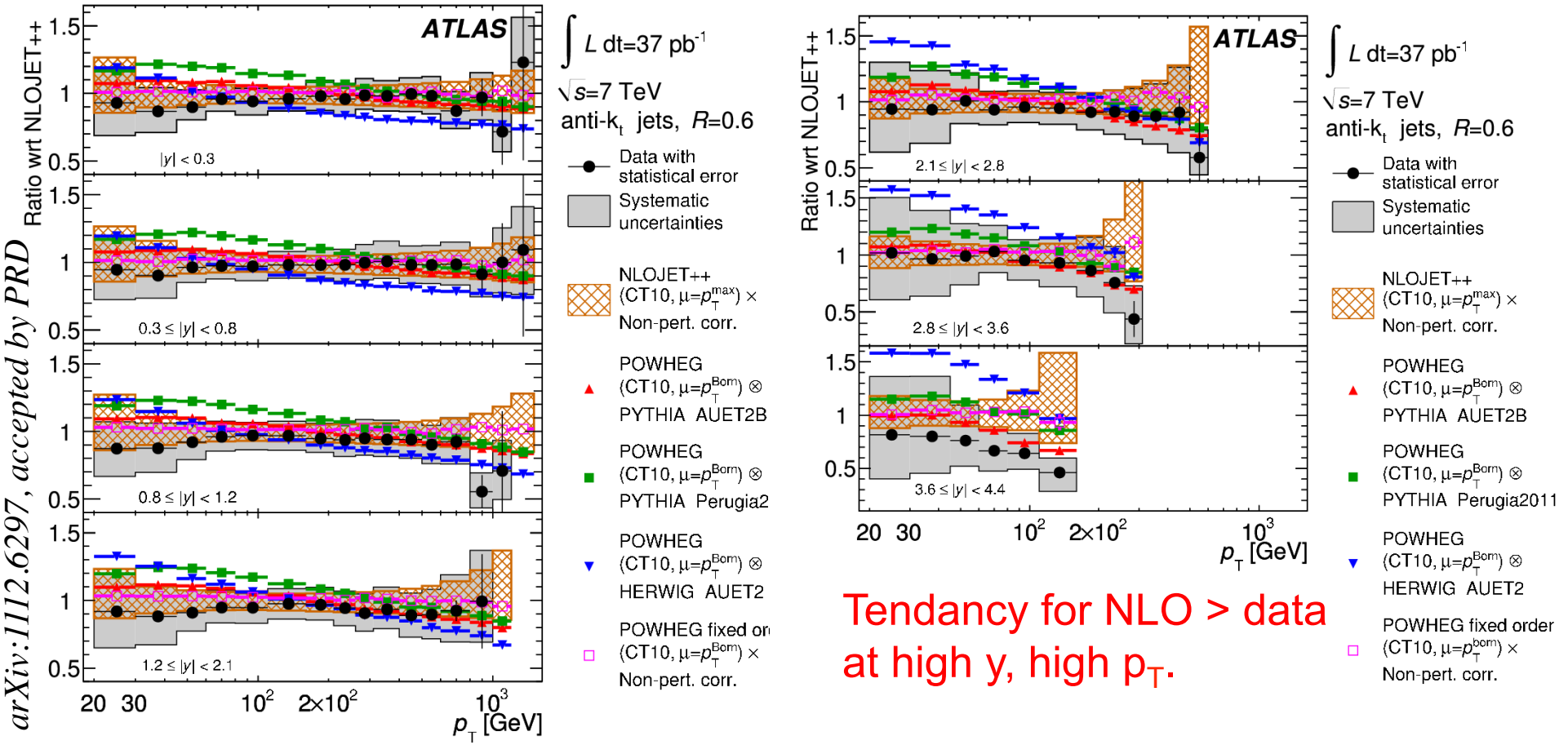




- Make an in-situ validation of JES and its uncertainties:
  - γ + jet balancing.
  - Multi-jet balance at high p_T.
  - Comparisons to track-jets.

arXiv:1112:6426, submitted to EPJC

Inclusive Jets (37pb^{-1})

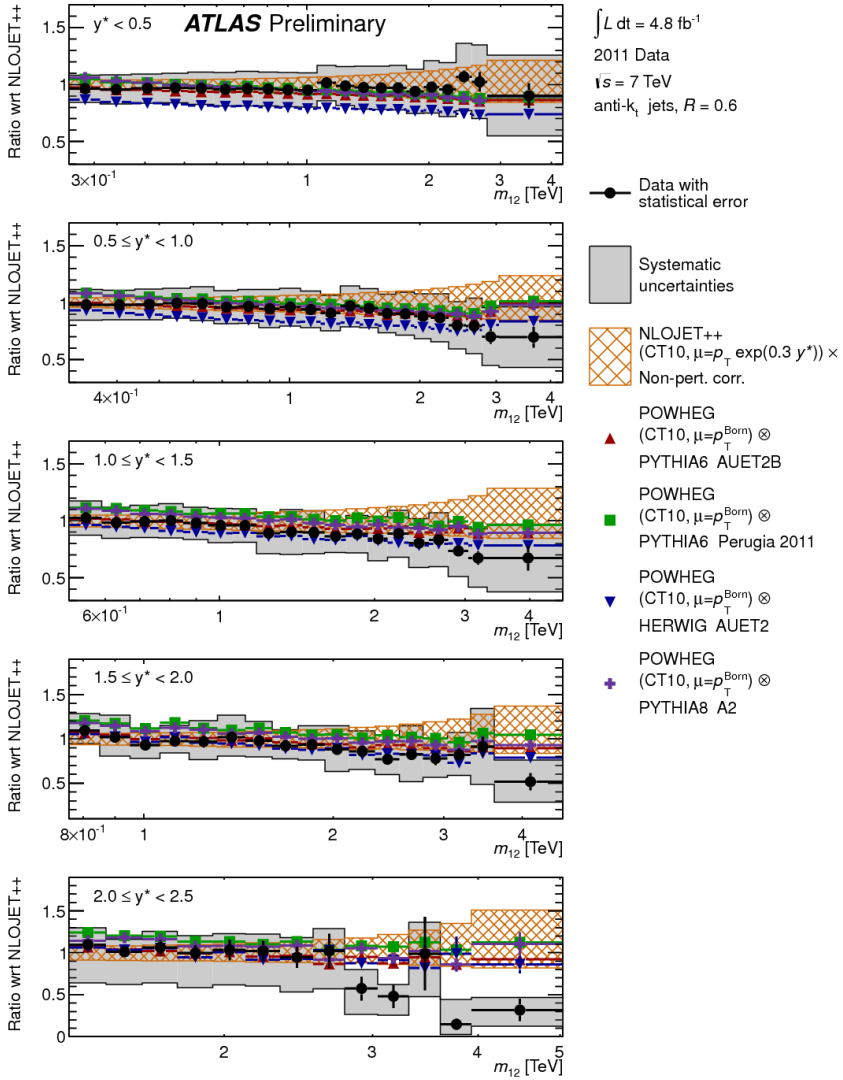


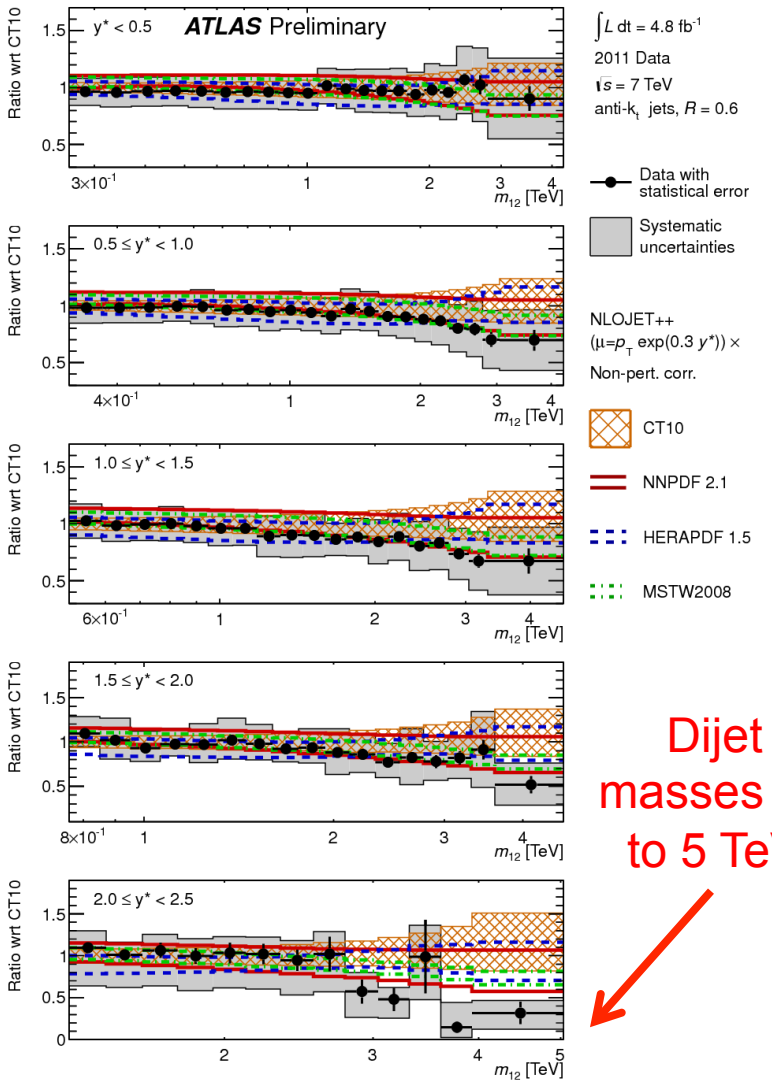
Tendancy for NLO > data at high y, high p_T.

- Double-differential jet production cross-section in p_T and rapidity.
- Good agreement between data, NLOJET++ and POWHEG fixed order NLO.
- Significant deviations from data at low/high p_T in POWHEG + PS MC.
- Full correlation information for the systematic uncertainties available!

Dijet Production (4.8fb^{-1})

ATLAS-CONF-2012-021

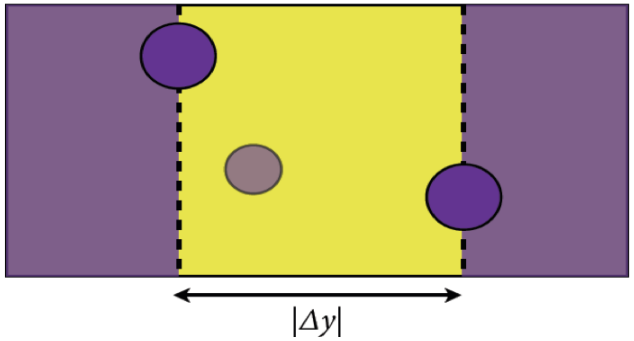


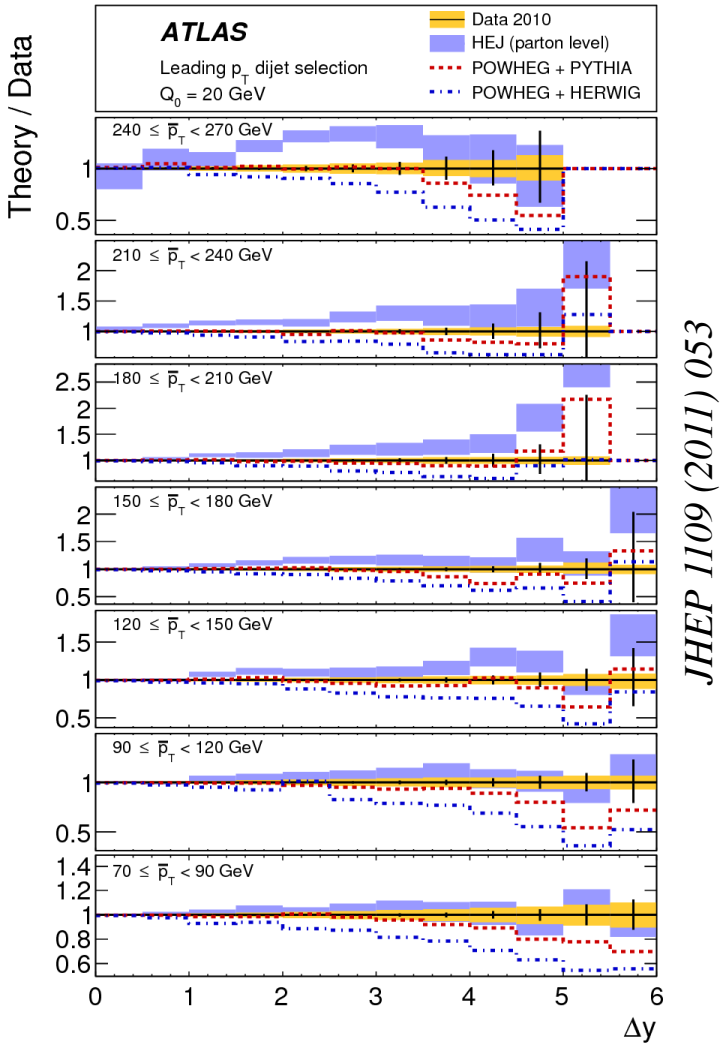


Dijet masses up to 5 TeV!

- Double-differential dijet production as a function of mass and $y^* = |y_1 - y_2|/2$.
- Up to 40% discrepancies with NLOJET++ at high mass/high y^*.

Dijets with Central Veto



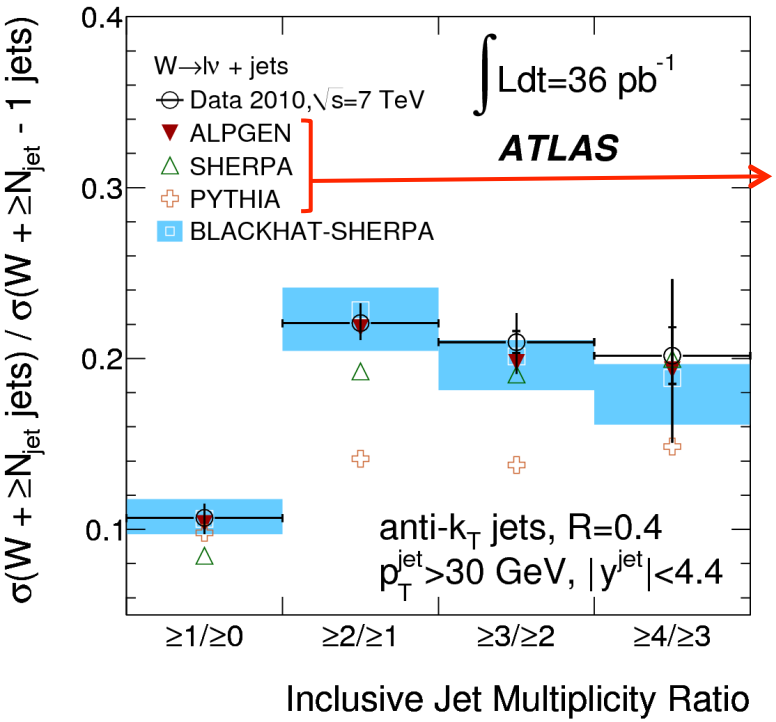


JHEP 1109 (2011) 053

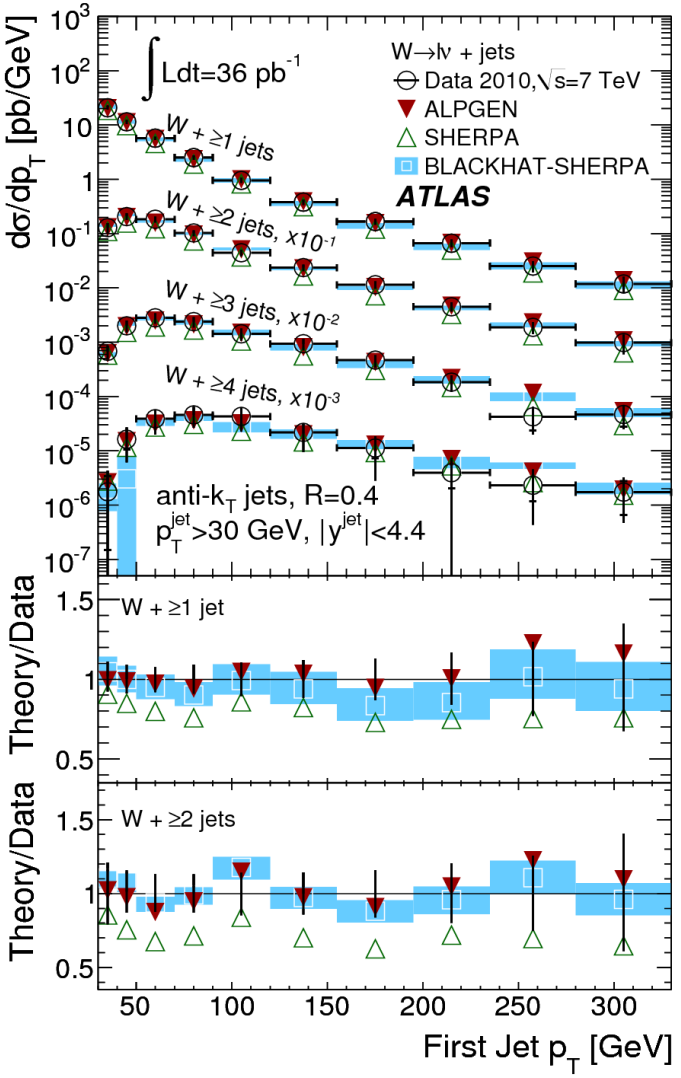
- Define a dijet system as highest two p_T or largest Δy jets.
- Measure "Gap Fraction" - fraction of events with no jets > 20 GeV within Δy of dijets.
- Sensitive to:
  - BFKL-like dynamics
  - wide-angle soft-gluon radiation
- Very similar topology to central jet veto used in VBF Higgs.
- Comparisons to HEJ (all-order description of wide-angle emissions), Powheg+Pythia and Powheg+Herwig (also Alpgen, Herwig++ and Pythia).
- Powheg+Pythia gives best description as Δy increases.

W plus Jets (36pb^{-1})

Phys. Rev. D85 (2012) 092002



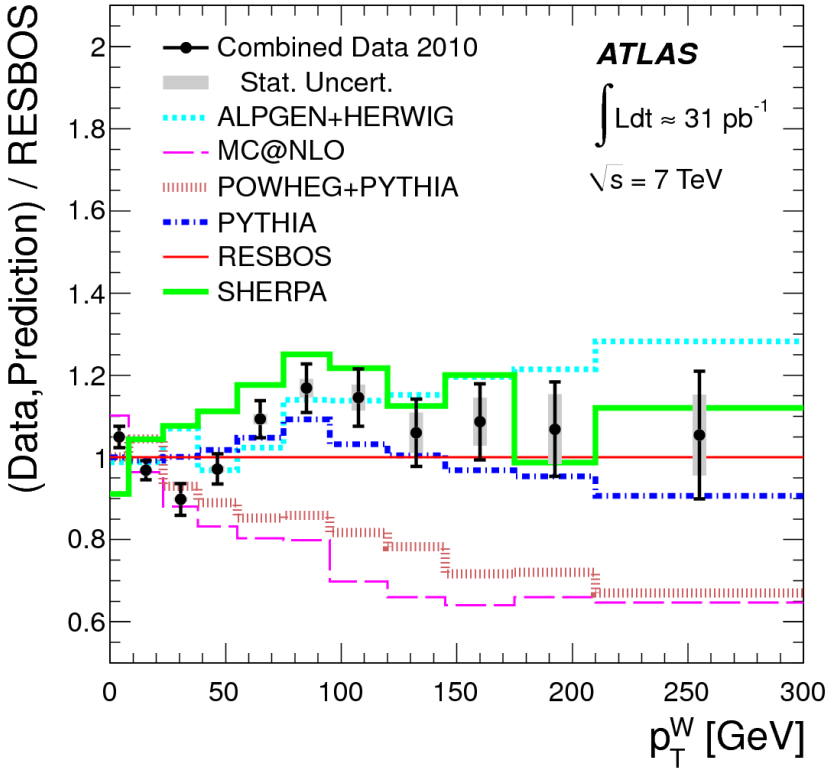
Normalised to total NNLO



- Differential cross-sections as a function of many different kinematic variables:
  - N_{jets}, 1st-4th jet p_T, H_T, mass, y, Δy, Δϕ, ΔR
- Generally good agreement with Blackhat-Sherpa NLO.
- Sherpa in sightly worse agreement than Alpgen.
- Complementary Z + jets measurement also made.

Vector Boson Transverse Momenta

W Transverse Momentum (31pb^{-1})



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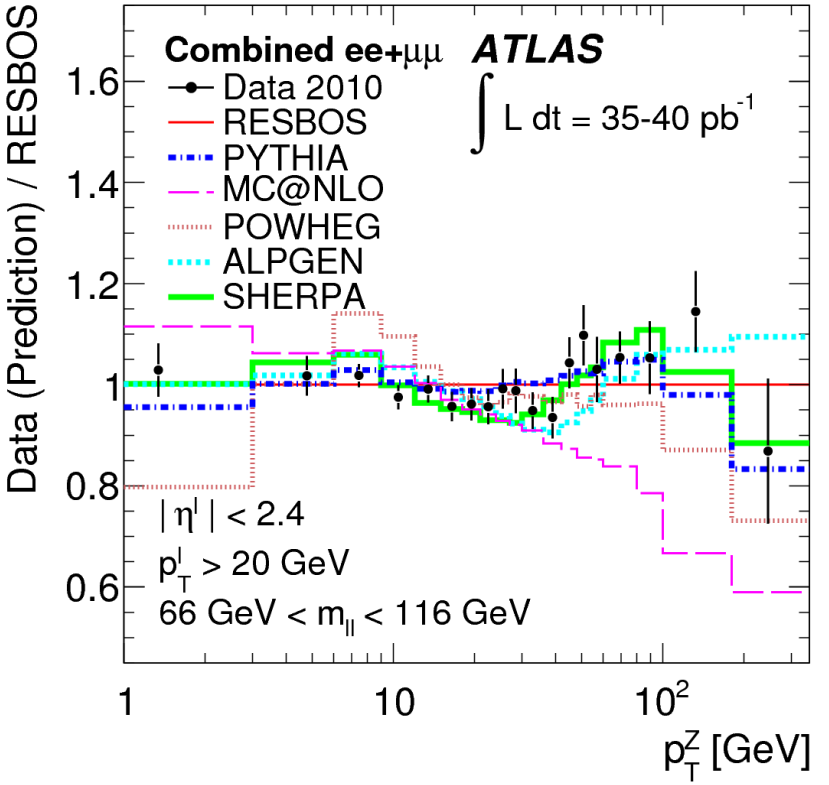
Z Transverse Momentum (35-40pb^{-1})

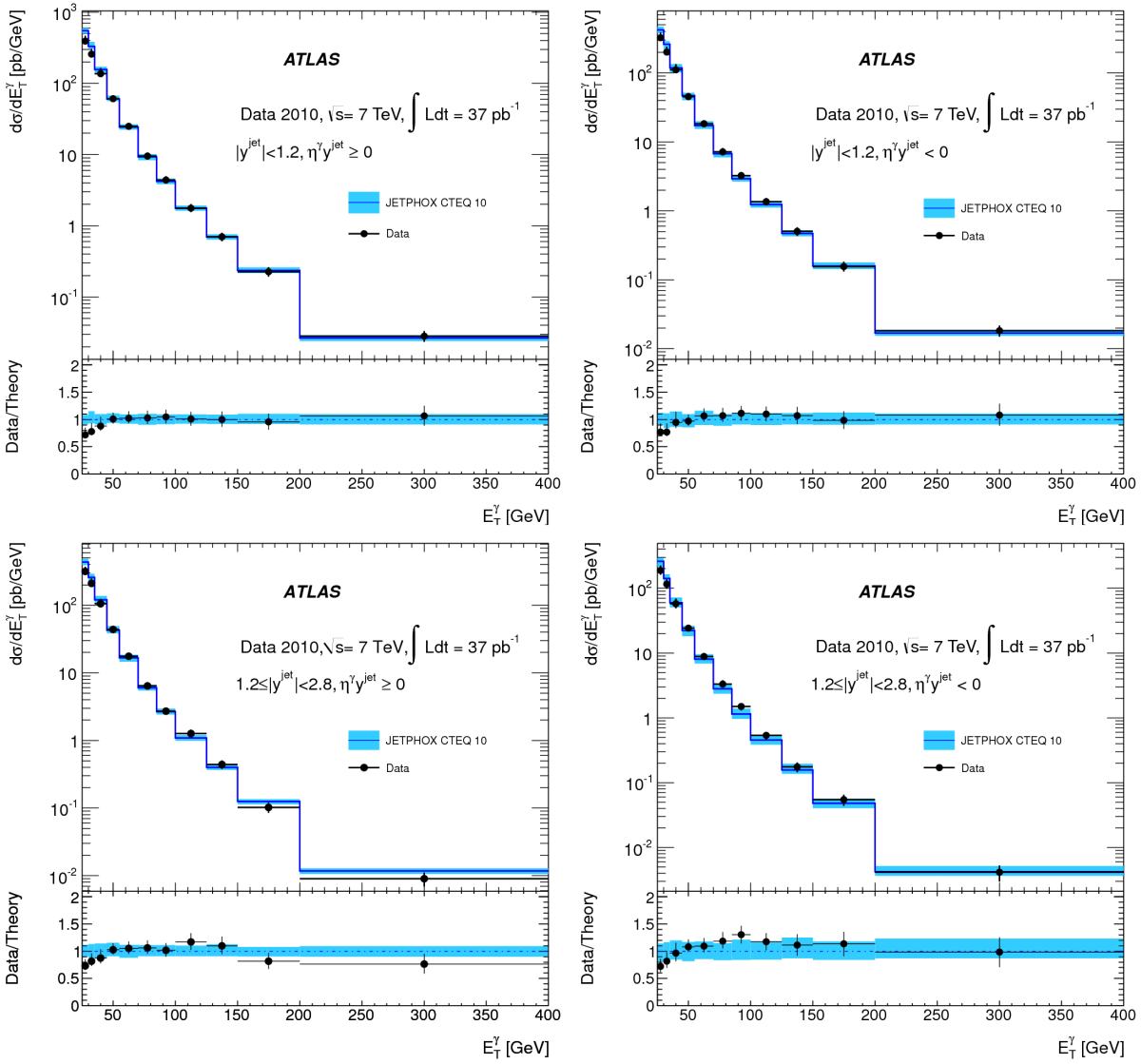


Phys.Lett. B705 (2011) 415-434

- Differential cross-section for the production of vector bosons as a function of their transverse momenta.
- RESBOS matches soft gluon resummation prediction (NNLL) at low p_T^V with pQCD (order α_s^2) at high p_T^V. Reproduces data well over full range.
- Good agreement with Sherpa, Alpgen and Pythia (normalised to inclusive) also found.

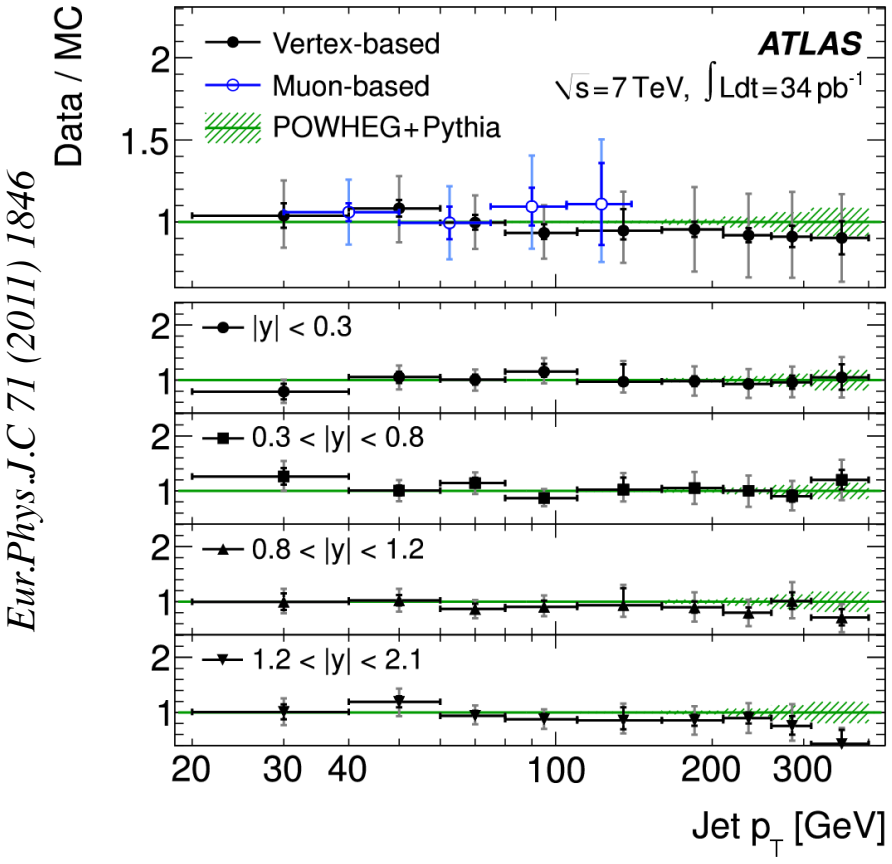
Photon plus Jets (37pb^{-1})

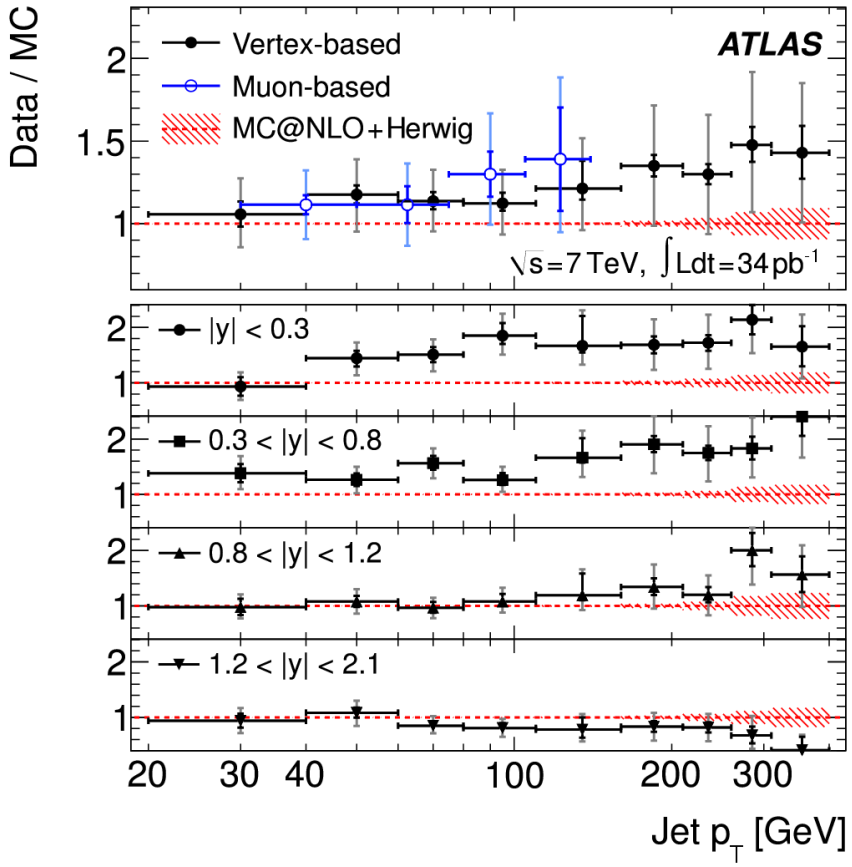
- Differential cross-section for isolated γ + jet production as function E_T^{γ}, y^{jet} and for $\eta_{\gamma} y^{jet} > 0$ and $\eta_{\gamma} y^{jet} < 0$ configurations.
- Varying *direct* and *fragmentation* photon contributions and regions of *x*.
- Comparison to JETPHOX NLO (+ n.p.c) - good agreement except at low E_T^{γ} (as observed in inclusive photon measurement).
- Also a measurement of diphoton production.



Phys. Rev. D 85, 092014 (2012)

Inclusive b-jet Production (34pb^{-1})

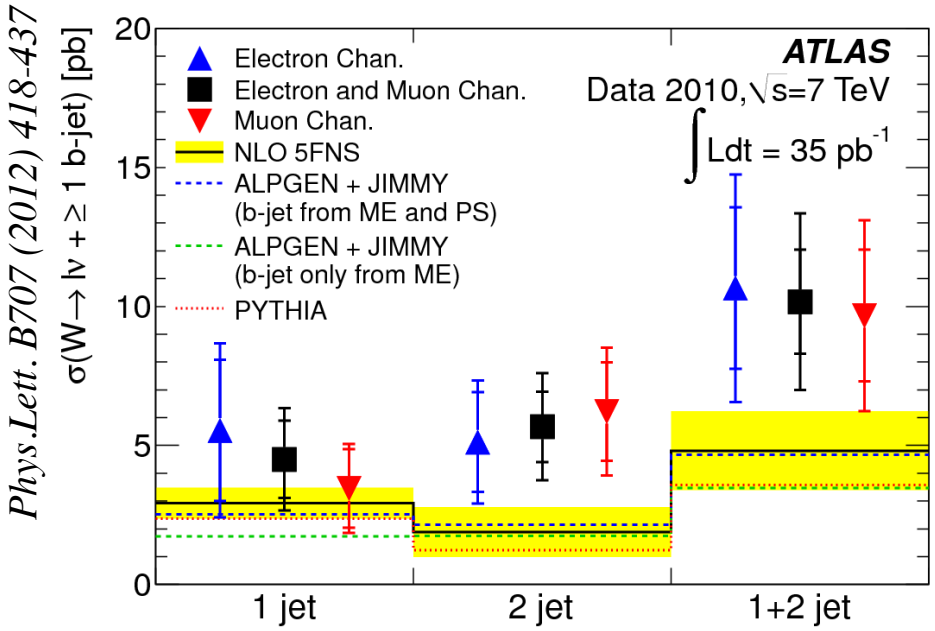




- Differential b-jet production cross-section as a function of p_T.
- POWHEG + Pythia performs well, MC@NLO + Herwig less so….
- Also a bb dijet mass measurement made (low statistics - less discrimination between generators).

Vector Boson plus b-jets (35pb^{-1})

W+≥1 b-jet



Phys.Lett. B707 (2012) 418-437

- Differential cross-section as a function of the number of b-jets in the event.
- Tension between measurement and NLO 5FNS (+ n.p.c) calculation.

Inclusive Z+b-jet production

Experiment	$3.55^{+0.82}_{-0.74}(\text{stat})^{+0.73}_{-0.55}(\text{syst}) \pm 0.12(\text{lumi})$ pb
MCFM	3.88 ± 0.58 pb
ALPGEN	2.23 ± 0.01 (stat only) pb
SHERPA	3.29 ± 0.04 (stat only) pb

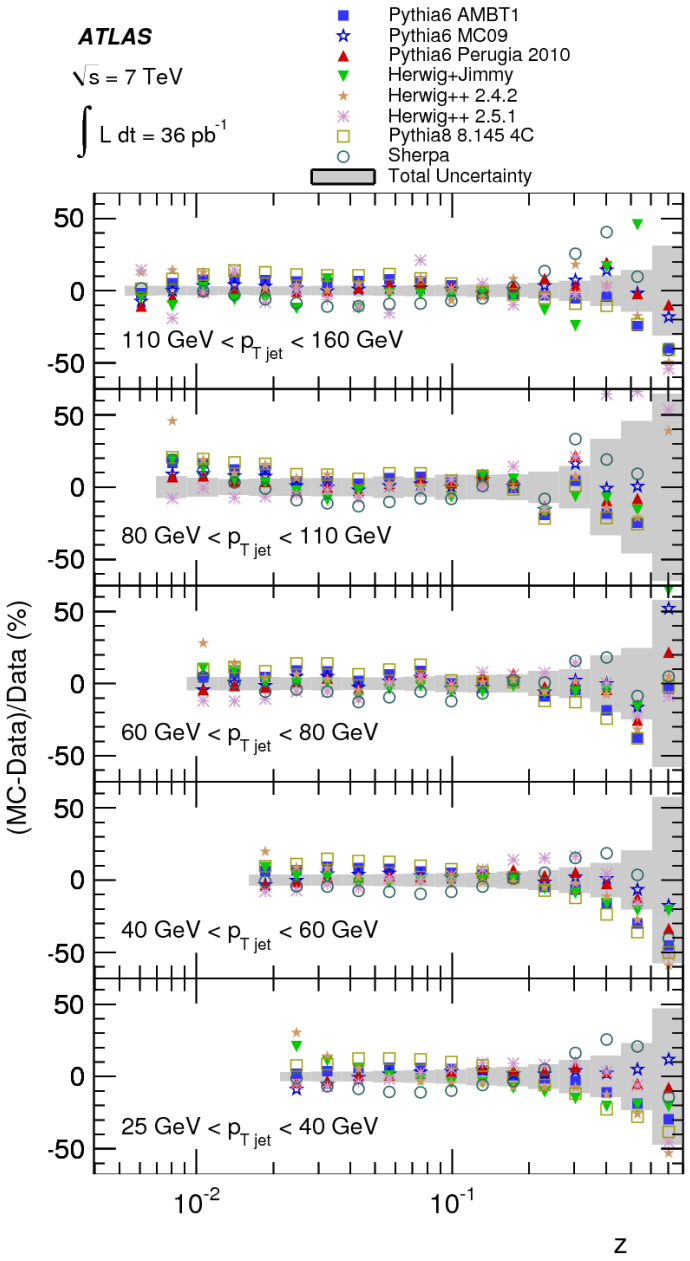
Average # b-jets in Z+b-jet events

Experiment	$(7.6^{+1.8}_{-1.6}(\text{stat})^{+1.5}_{-1.2}(\text{syst})) \times 10^{-3}$
MCFM	$(8.8 \pm 1.1) \times 10^{-3}$
ALPGEN	$(6.2 \pm 0.1$ (stat only)$) \times 10^{-3}$
SHERPA	$(9.3 \pm 0.1$ (stat only)$) \times 10^{-3}$

Phys.Lett. B706 (2012) 295-313

- Good agreement with MCFM NLO (+ n.p.c) calculations in Z+b-jet production.
- Significant differences between Alpgen & Sherpa, but both consistent with measurement.

Fragmentation and Shape (36pb^{-1})



Eur.Phys.J.C 71 (2011) 1795

- Structure of jets studied using associated charged particle tracks.
- Measurement of the jet fragmentation function and transverse profile in different jet p_T bins:

$$F(z, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

$$\rho_{ch}(r, p_{\mathrm{T\,jet}}) \equiv \frac{1}{N_{jet}} \frac{dN_{ch}}{2\pi r dr}$$

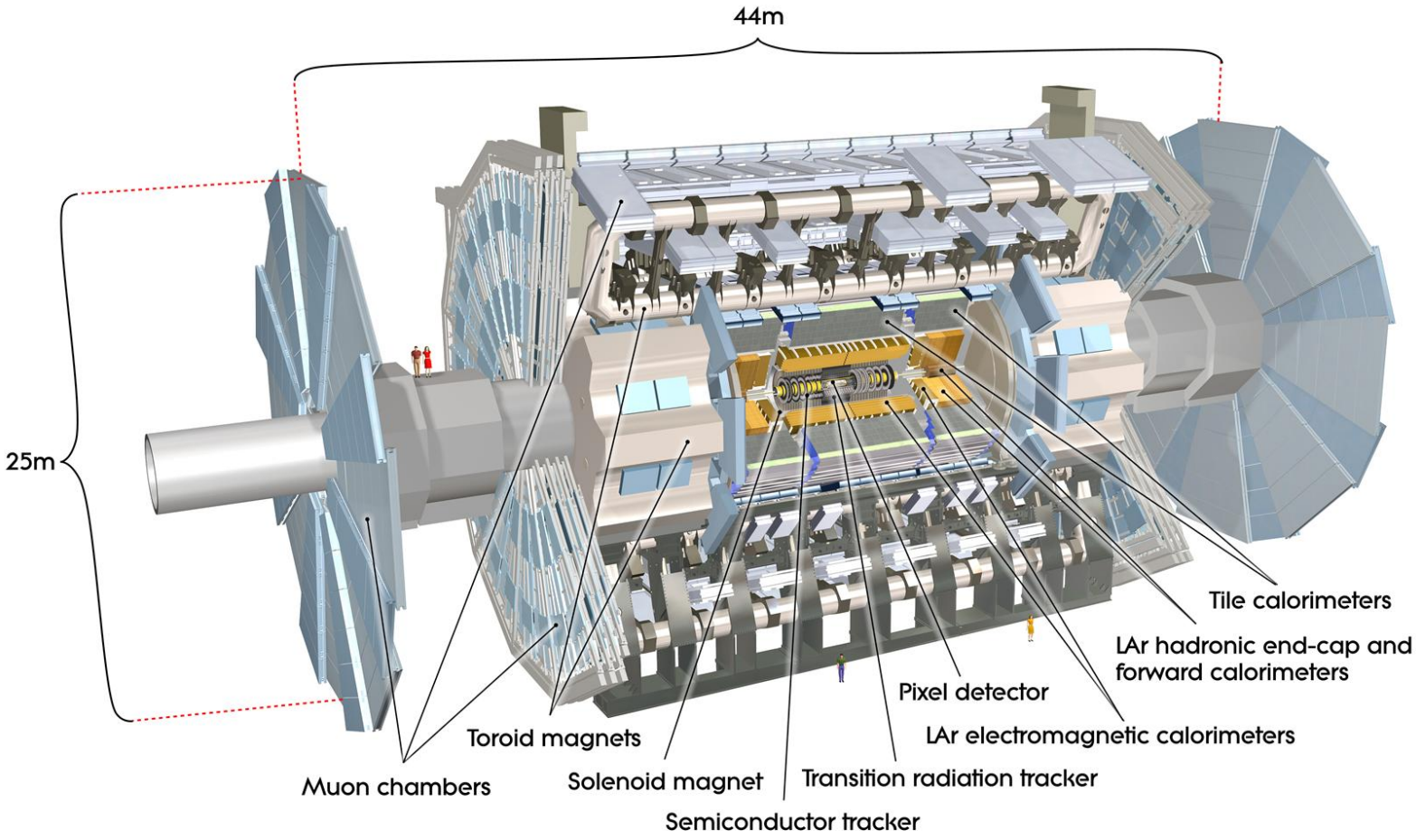
- Test of fragmentation models/tunes of many MC event generators. Pythia6 tunes come out on top – Sherpa, Herwig++ and Pythia8 struggle…
- Also measurements of boosted jet shape and substructure variables.

Conclusions

- In its first years of operation ATLAS has conducted a thorough and comprehensive test of QCD at a new high energy frontier.
- A wide-range of different processes have been measured at an accuracy and depth not seen before.
- These measurements have enabled extensive testing of the new generation of NLO pQCD, NLO+MC and LO+MC predictions:
  - NLO pQCD calculations are generally performing very well, with some exceptions.
  - Important differences between matched NLO+MC predictions are evident.
  - Also see some significant differences between LO+MC predictions in terms of their ability to describe the kinematics of hard QCD.
- This extensive mapping of the dominant physics processes at the LHC place the searches for new physics on solid ground.
- ~5fb^{-1} 2011 dataset measurements imminent! (dijets, V+jets, V+HF)
- Analysis of the 8 TeV data already under way…

Backup Slides

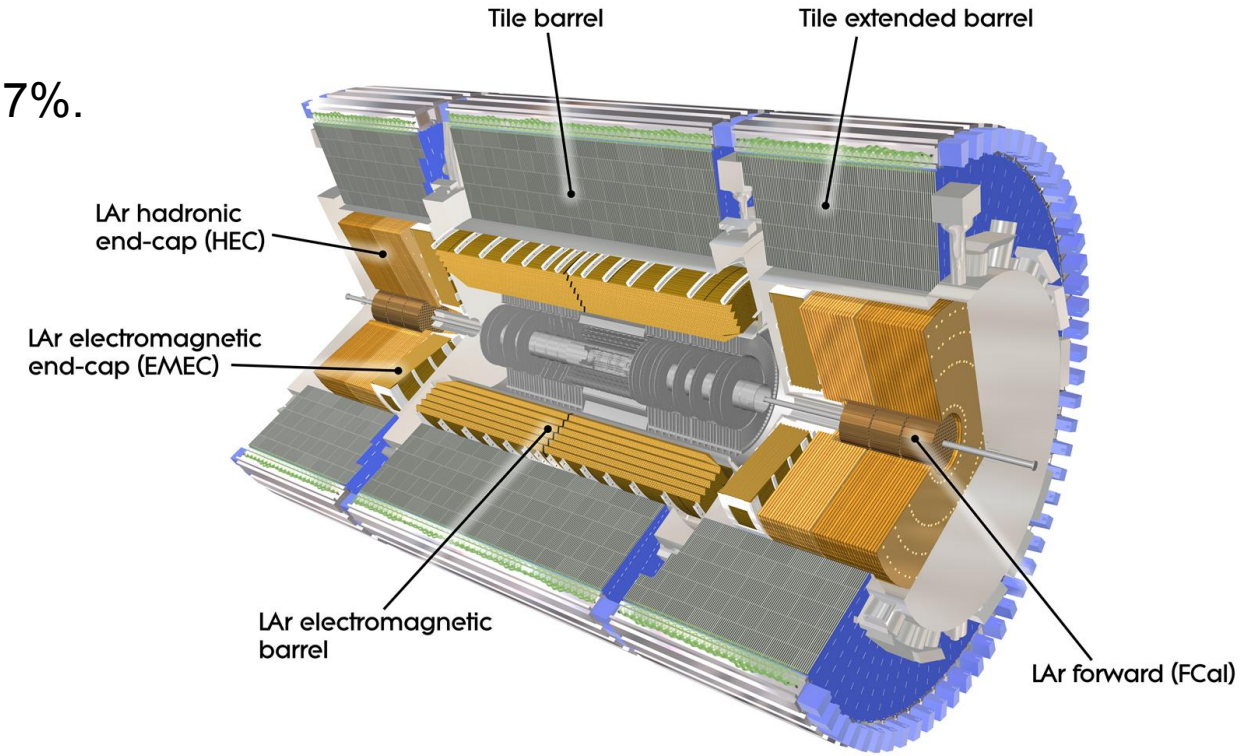
The ATLAS Detector



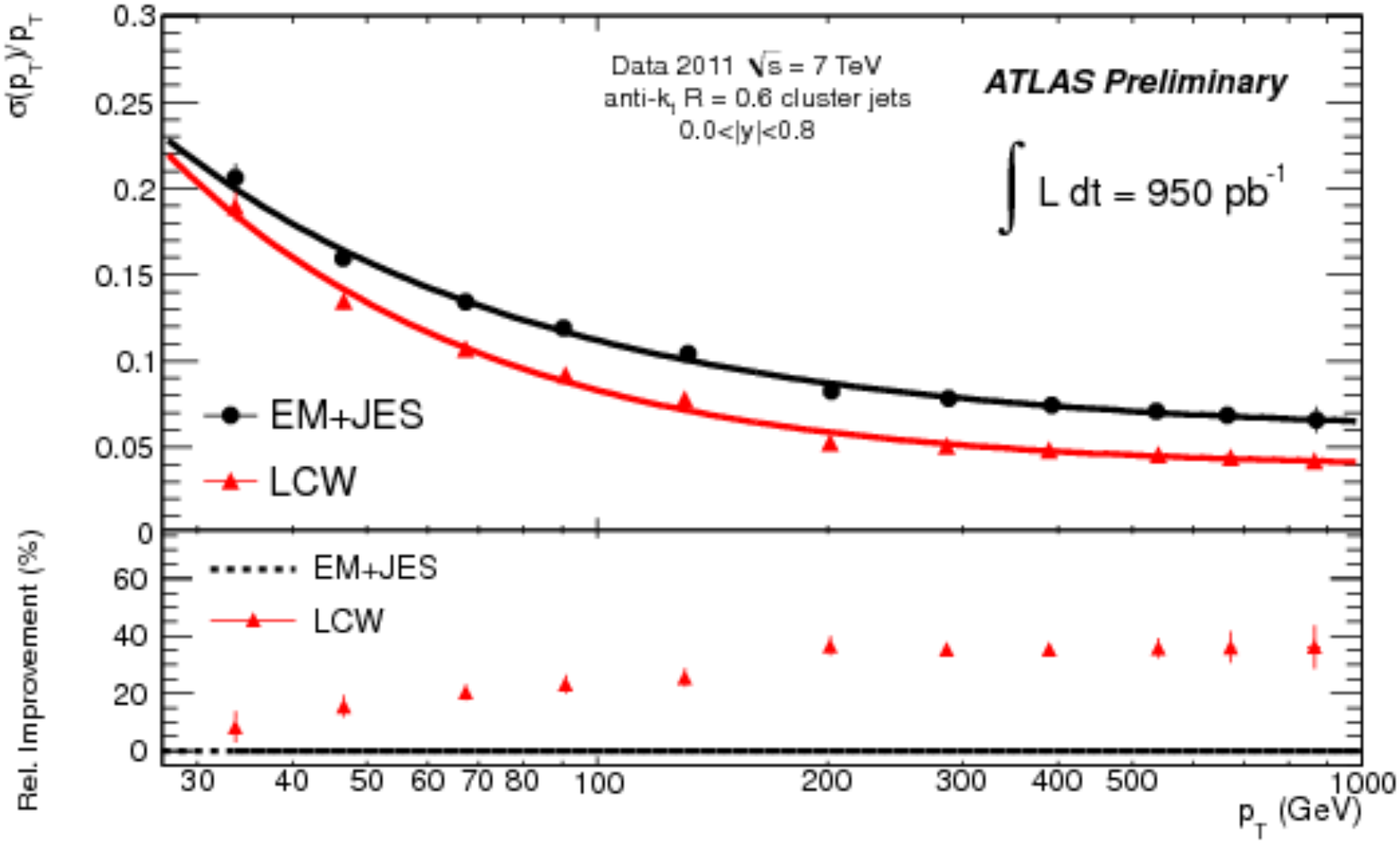
- The measurements presented here utilise the inner tracker, calorimeter and muon chamber components.

ATLAS Calorimetry

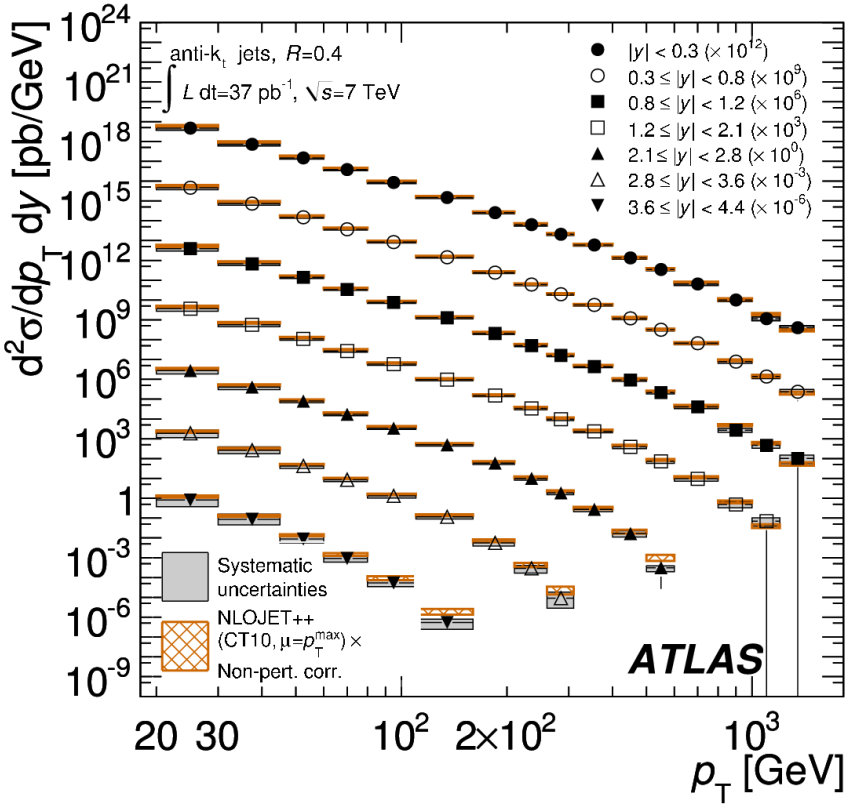
- EM barrel/endcap:
  - Pb/LAr accordion
  - $|\eta| < 3.2$
  - $\sigma/E \approx 10\text{-}17\%/\sqrt{E} + 0.7\%$.
- HAD barrel:
  - Fe/scintillator tiles.
  - $|\eta| < 1.7$
  - $\sigma/E \approx 50\%/\sqrt{E} + 3\%$.
- HAD endcap:
  - Cu/LAr
  - $1.5 < |\eta| < 3.2$
  - $\sigma/E \approx 50\%/\sqrt{E} + 3\%$.
- EM/HAD forward (FCal):
  - Cu/W-LAr
  - $3.1 < |\eta| < 4.9$
  - $\sigma/E \approx 100\%/\sqrt{E} + 10\%$.

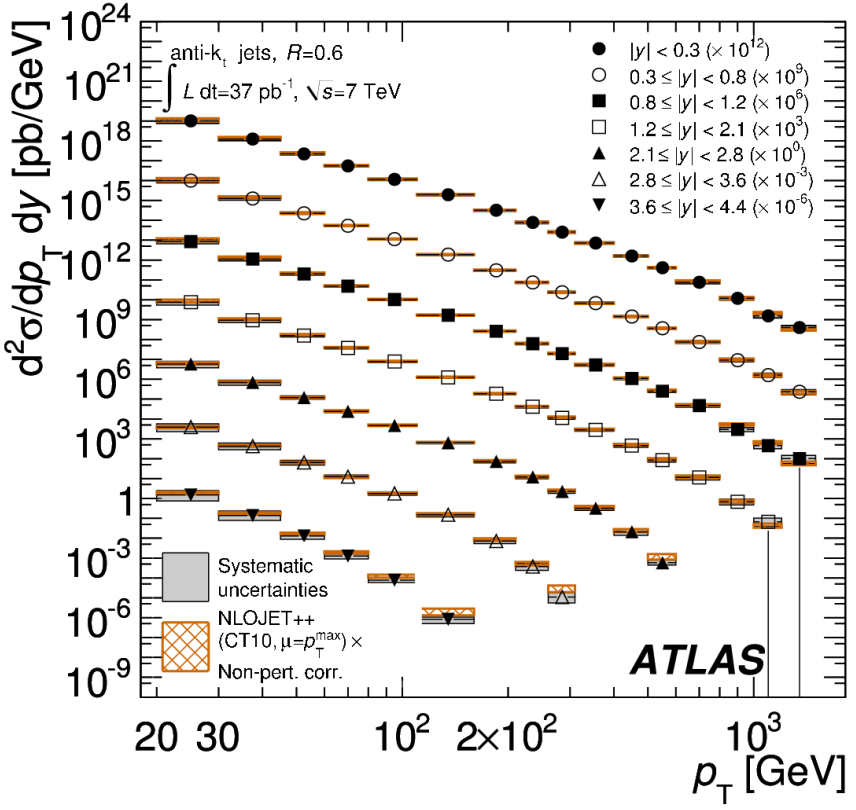


Jet Resolution

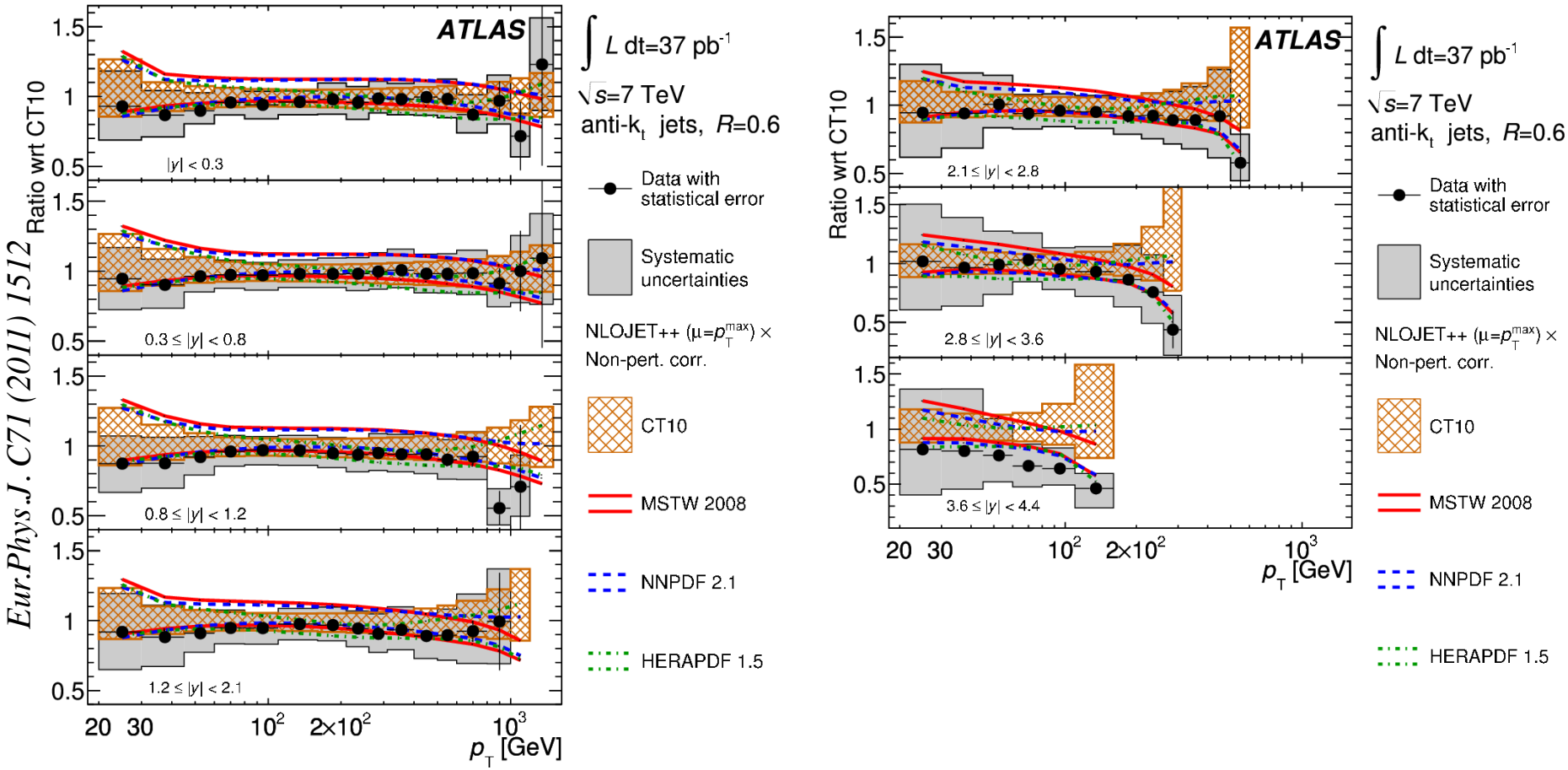


Inclusive Jets (37pb^{-1})



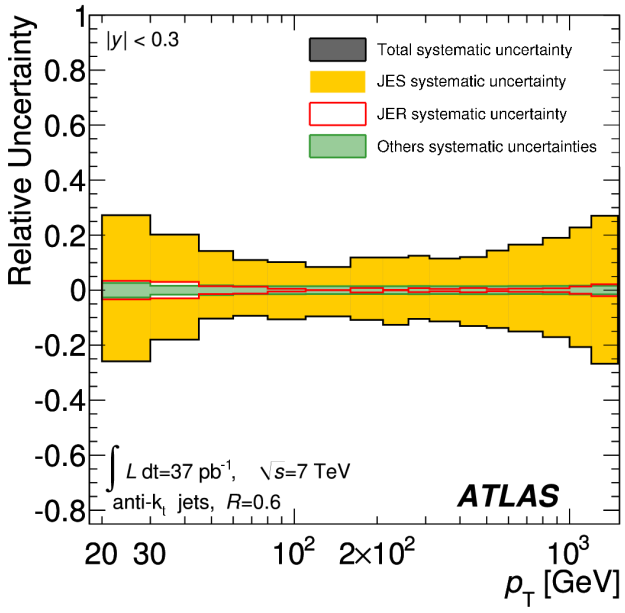


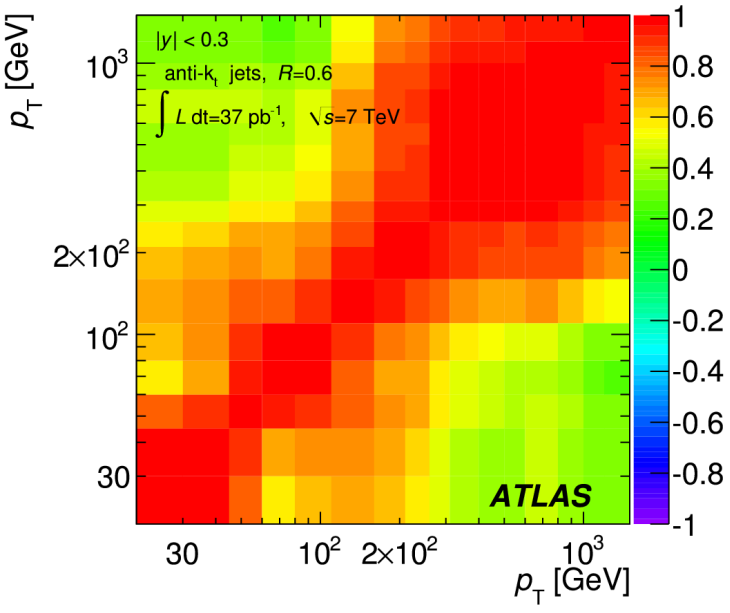
Inclusive Jets (37pb^{-1})

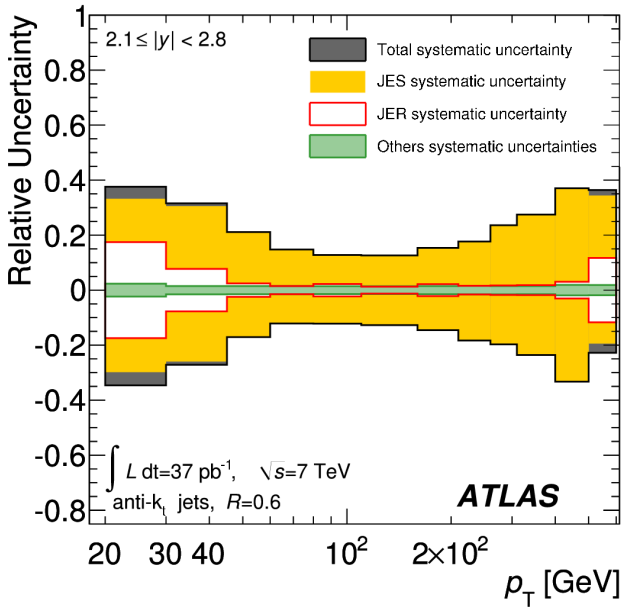


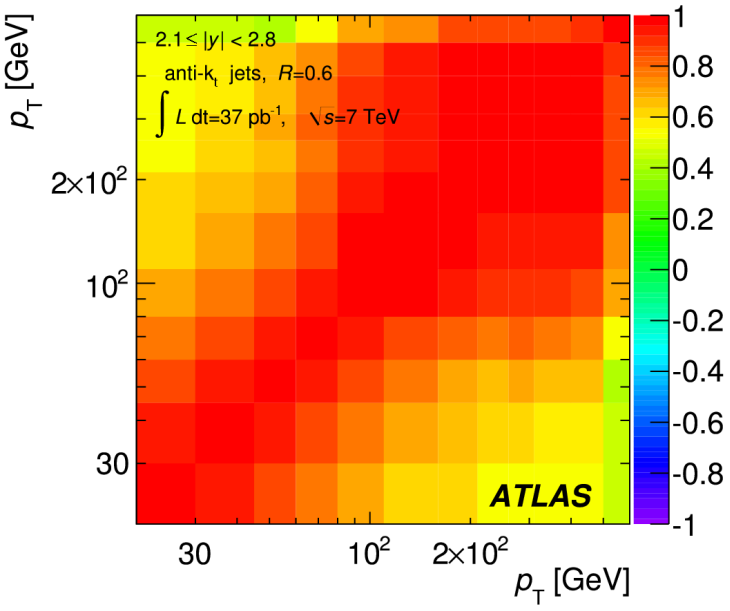
- Comparisons to NLOJET++ using different PDF sets.

Inclusive Jets Systematics

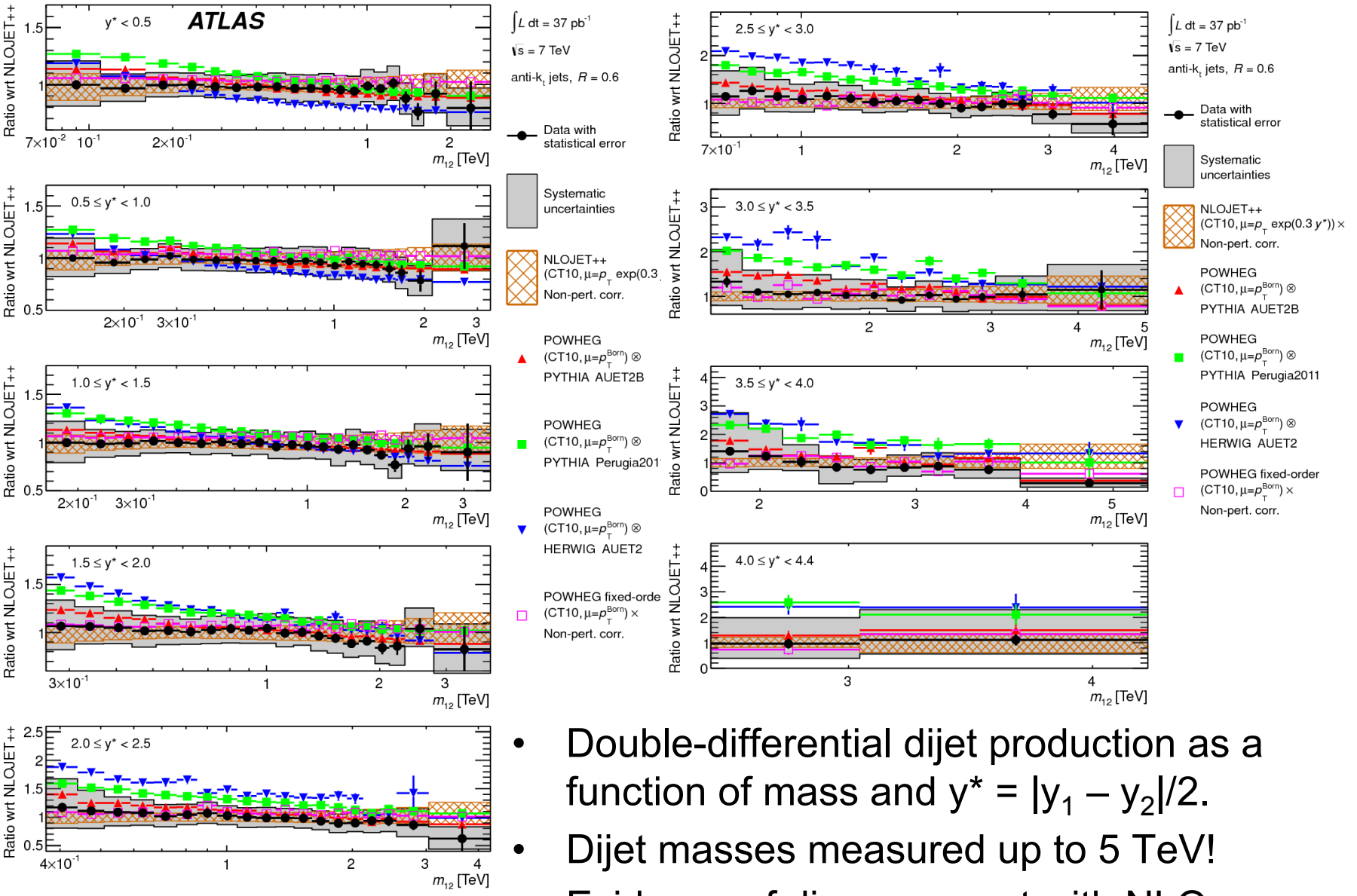








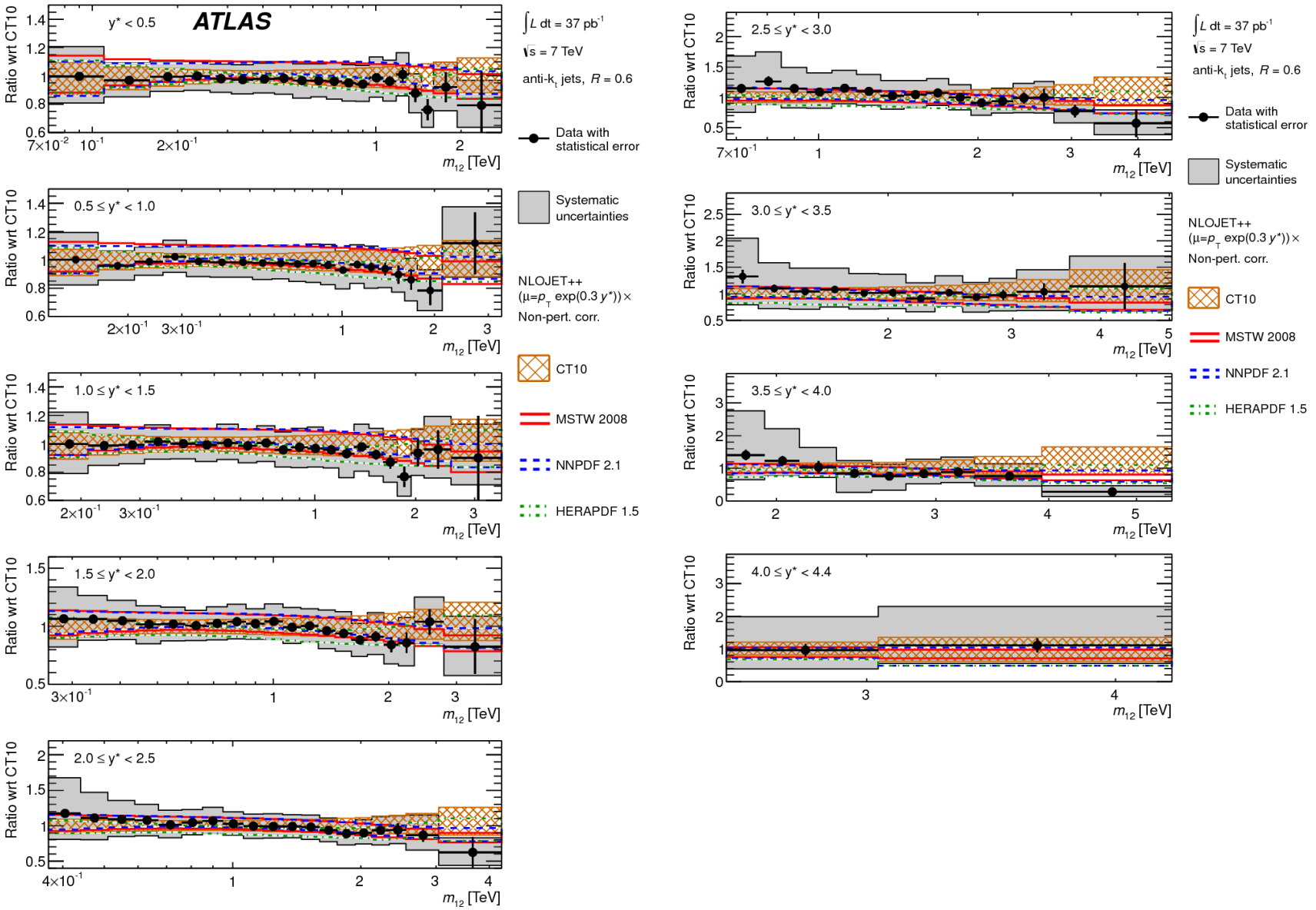
Dijet Production (37pb^{-1})



arXiv:1112.6297, accepted by PRD

- Double-differential dijet production as a function of mass and $y^* = |y_1 - y_2|/2$.
- Dijet masses measured up to 5 TeV!
- Evidence of disagreement with NLO…

Dijet Production (37pb^{-1})



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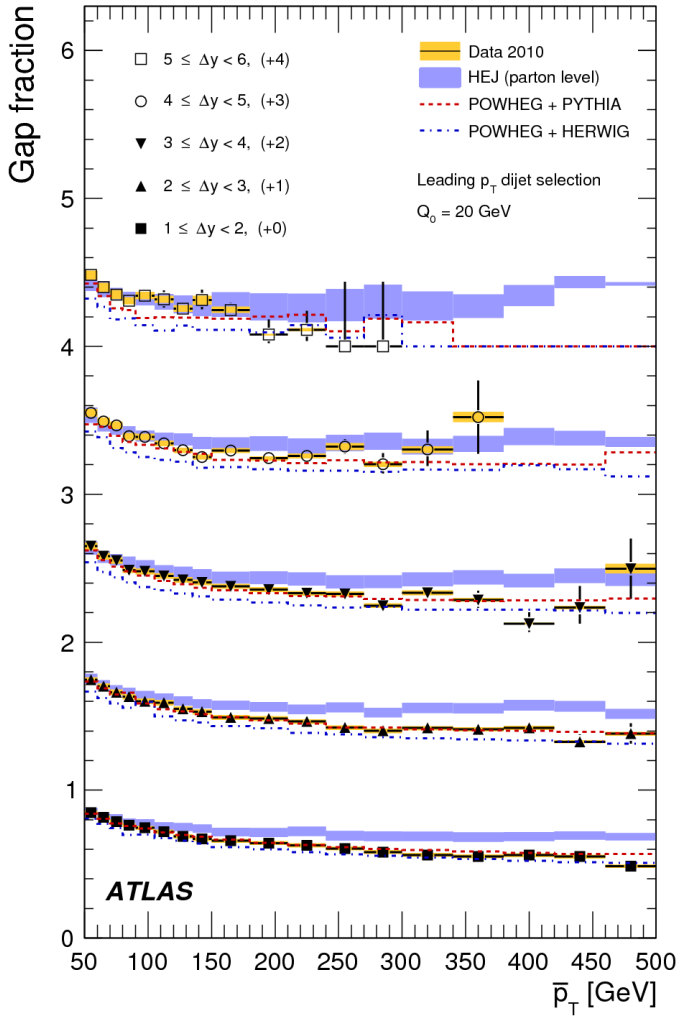
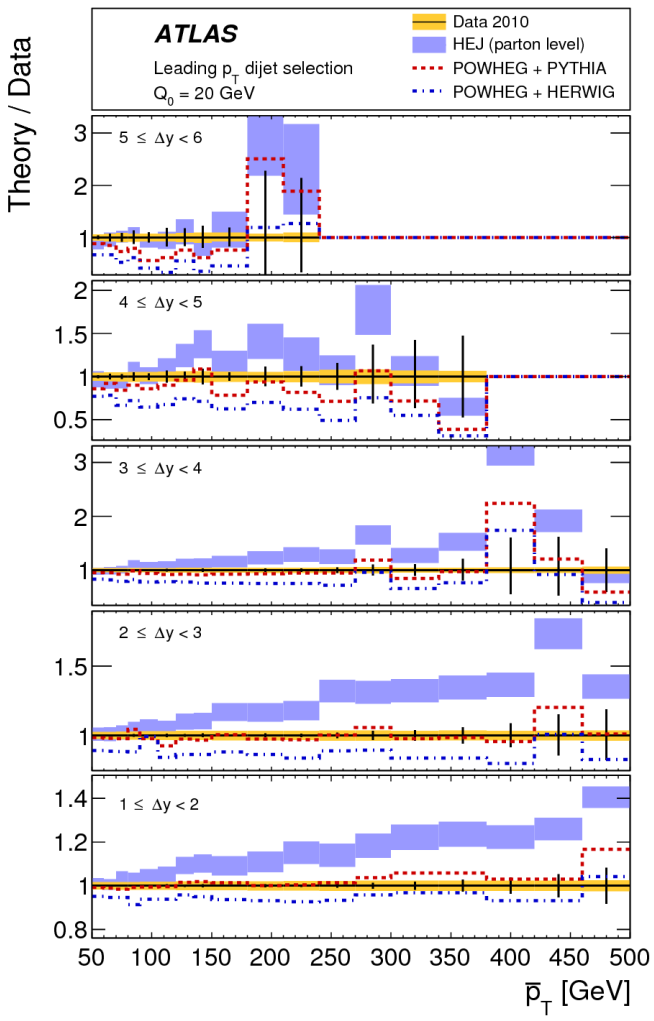
Dijets with Central Veto

JHEP 1109 (2011) 053





Dijets with Central Veto

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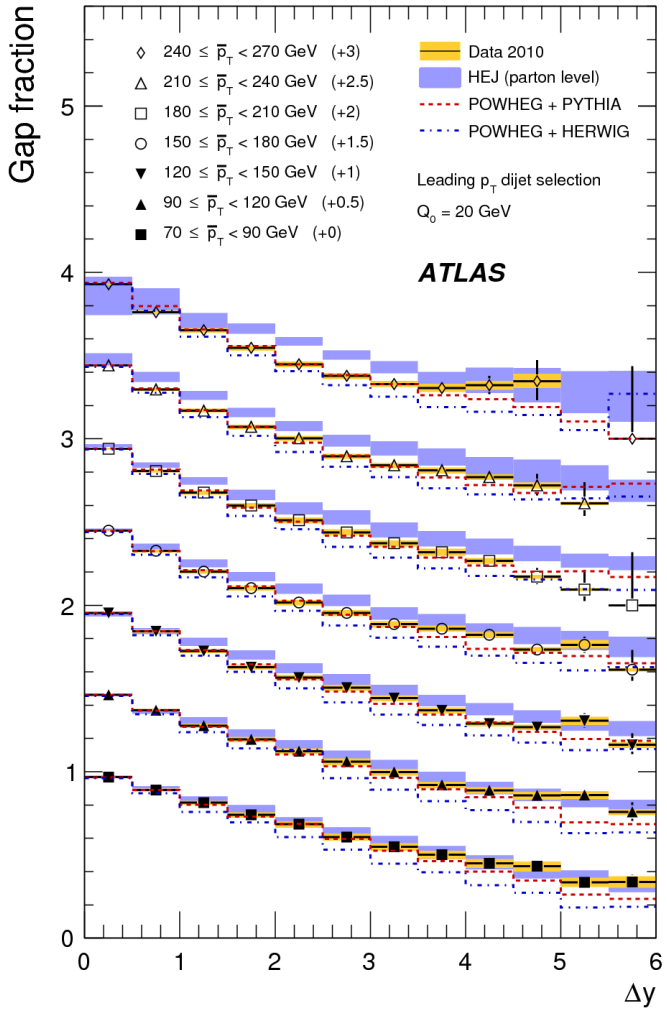
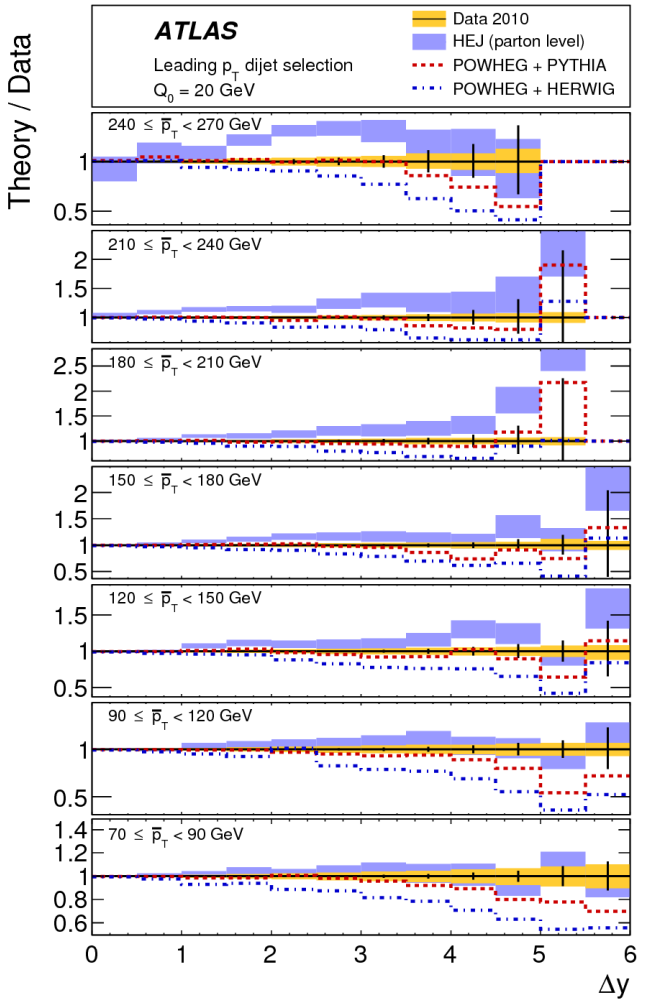
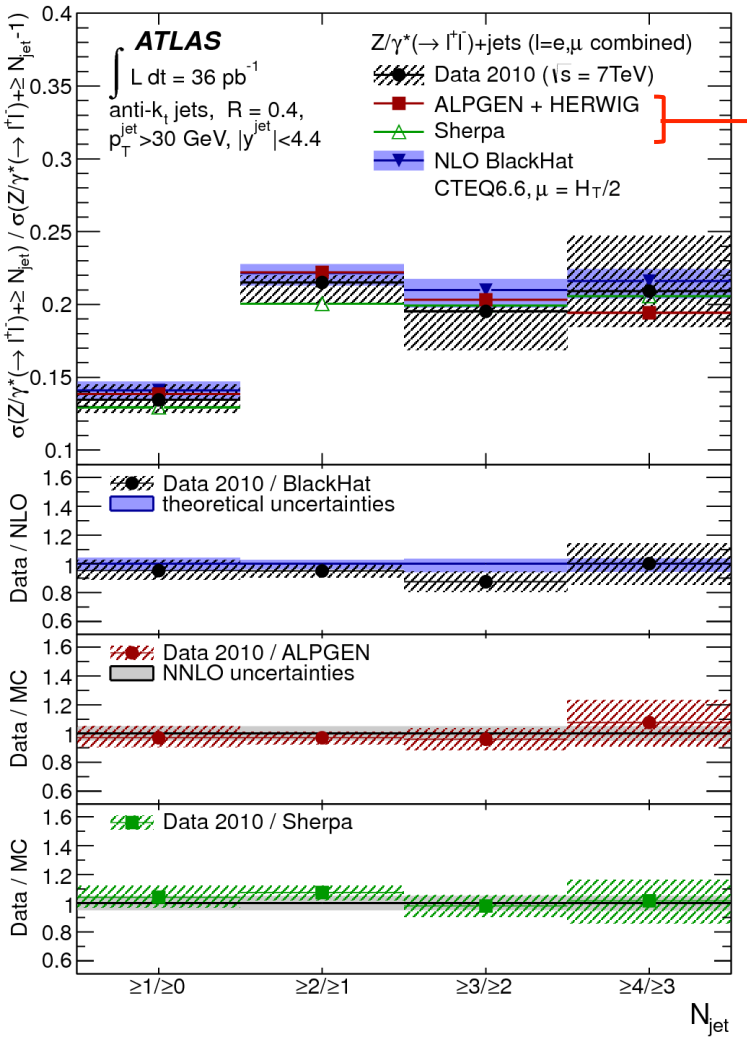


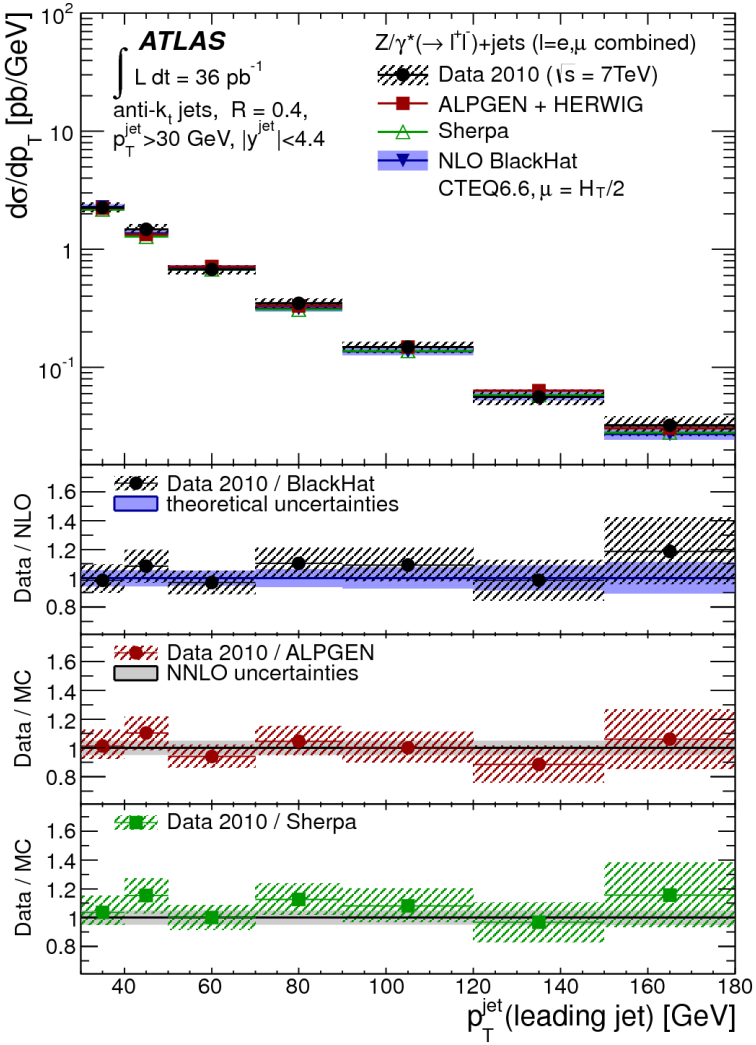


Z/γ* plus Jets (35pb^{-1})

Phys. Rev. D85 (2012) 032009

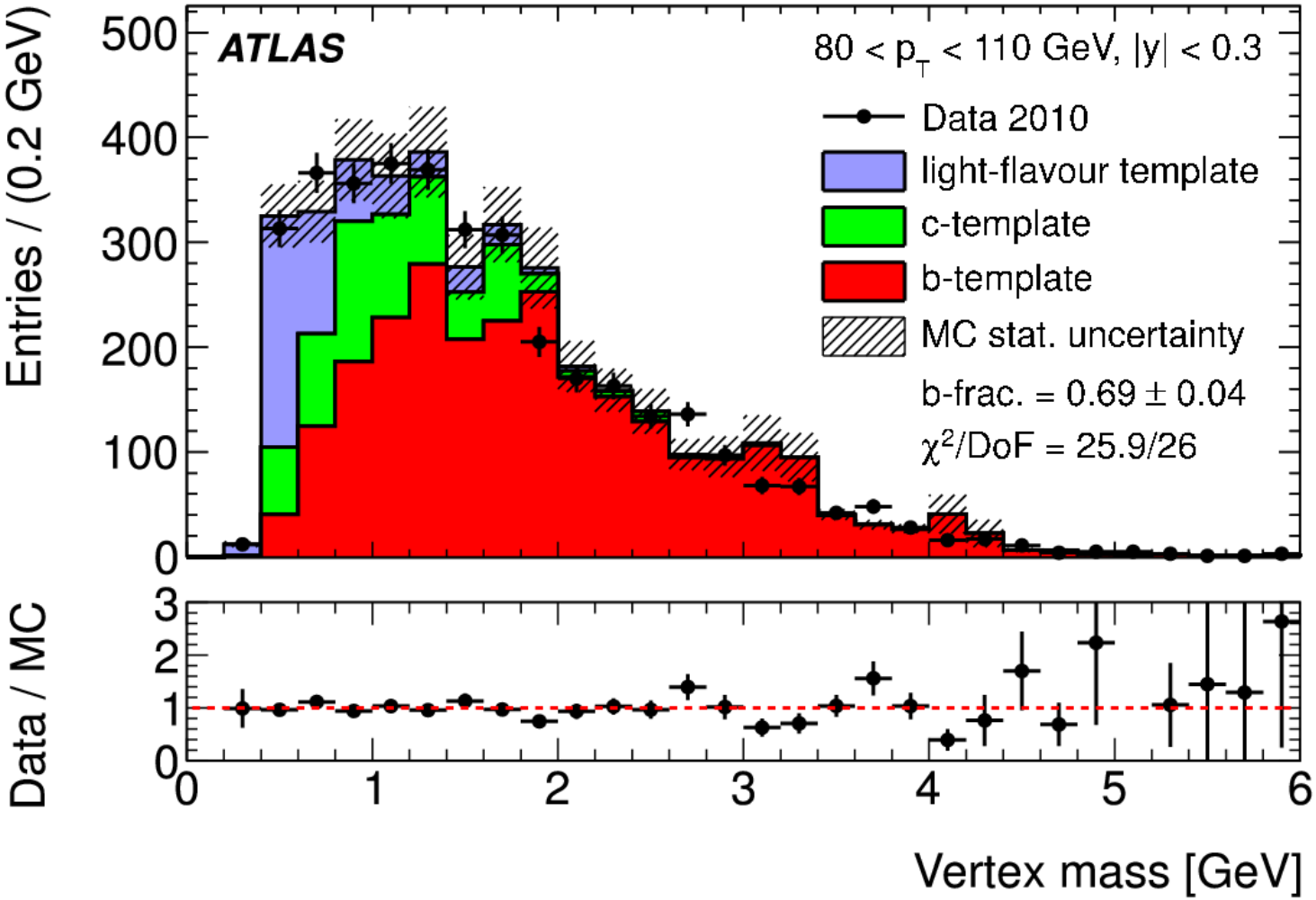


Normalised to total NNLO

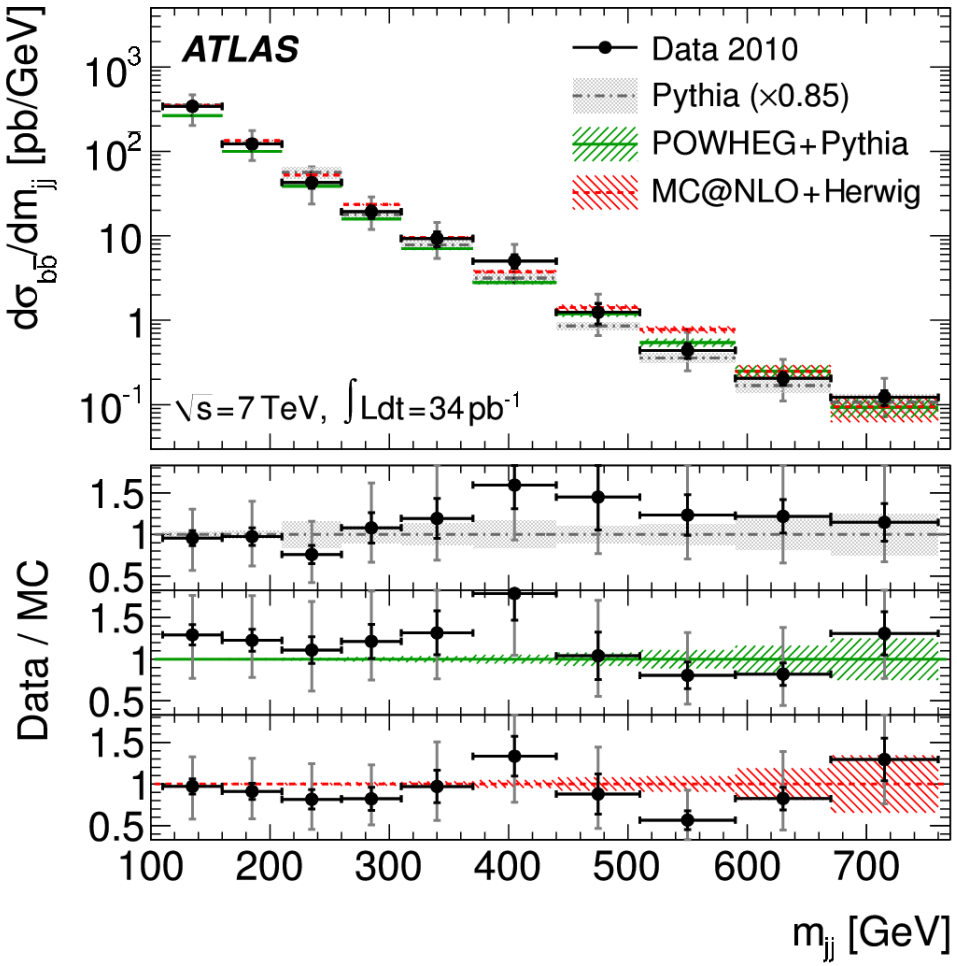


- Differential cross-sections as a function of N_{jets}, 1st and 2nd jet p_T, y,
- Comparisons to Blackhat NLO (+ n.p.c), Sherpa and Alpgen + Herwig-Jimmy. Good agreement within uncertainties.

Inclusive b-jet Purity Determination

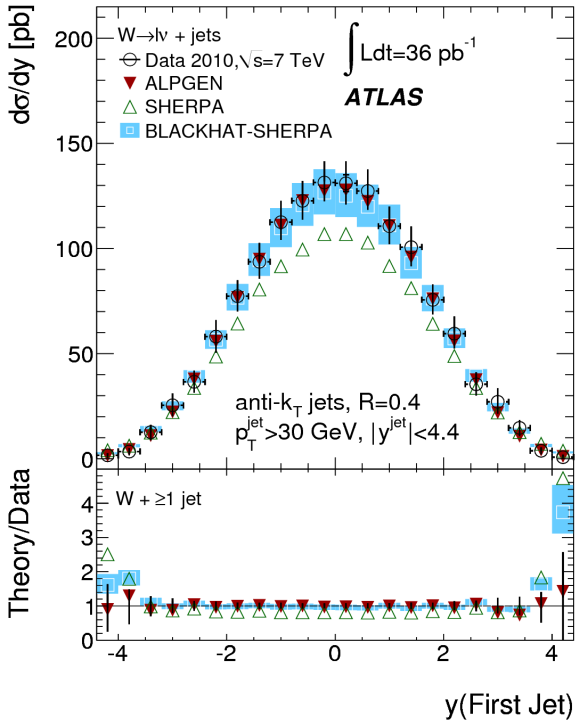


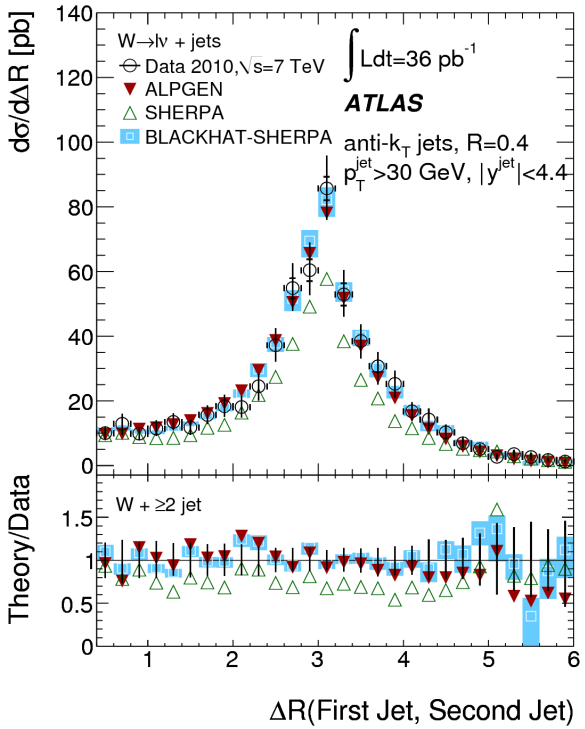
Dijet b-jet Production

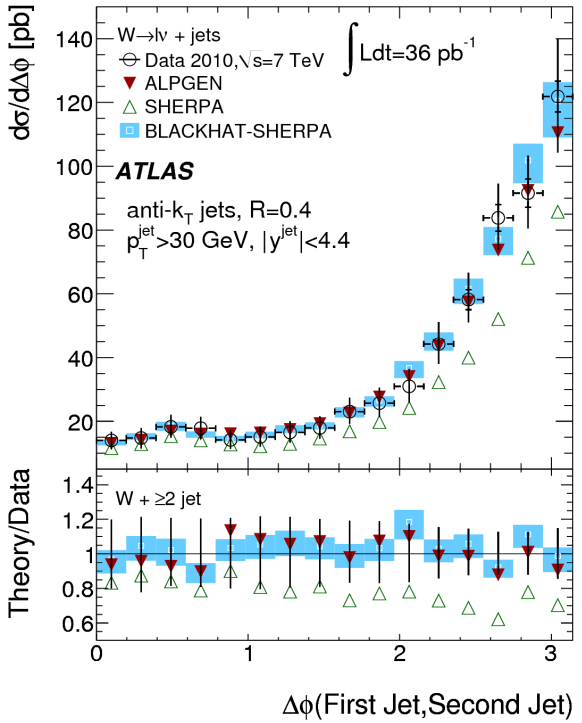


- bb production cross-section as a function of the dijet mass.
- Statistically limited in the 2010 dataset.

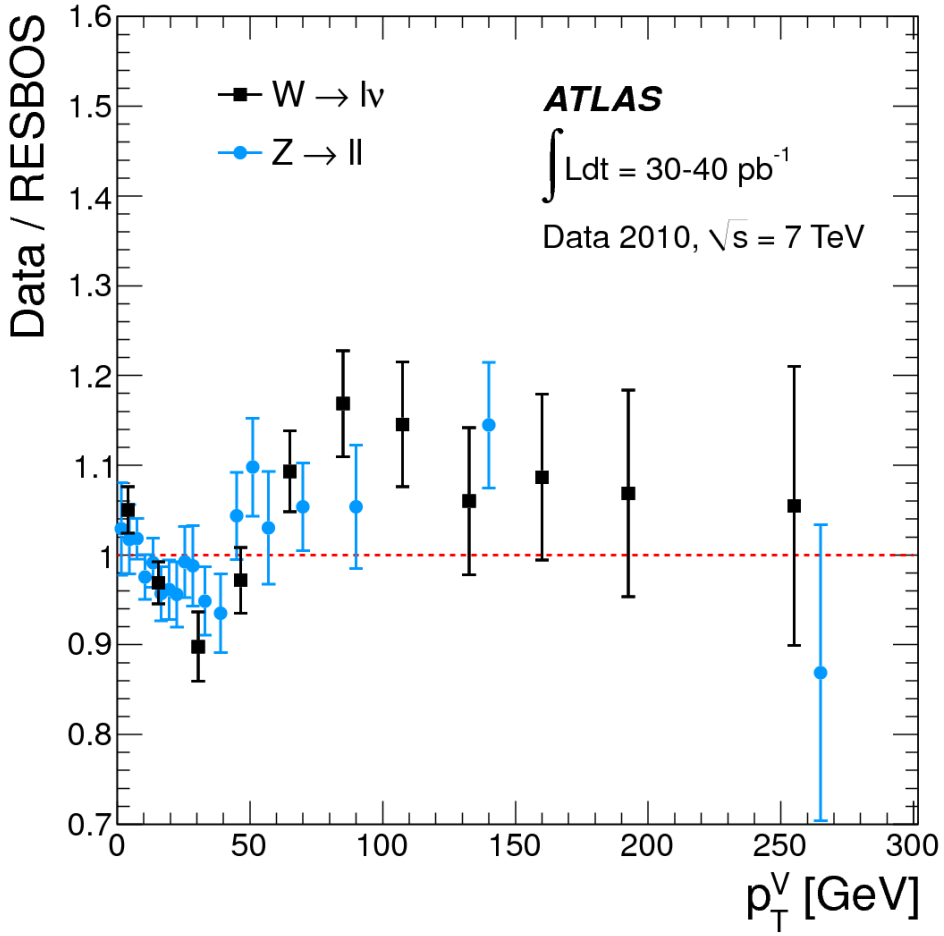
W plus Jets (36pb^{-1})







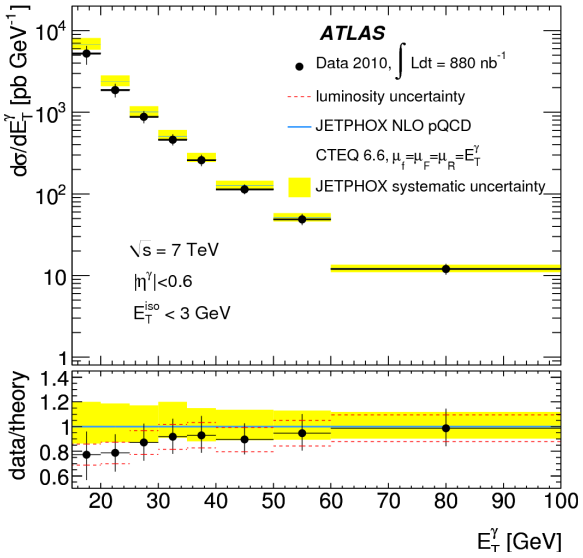
Vector Boson Transverse Momenta

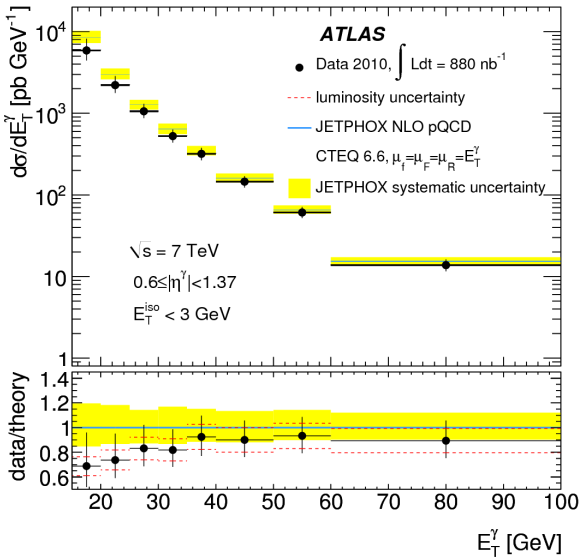


- Good consistency between W and Z transverse momenta measurements and their comparison to RESBOS.

Inclusive Photon and Diphotons

- Inclusive photon cross-section as a function E_T^γ (880nb^{-1}).
- See similar discrepancy to γ+jets measurement at low E_T^γ





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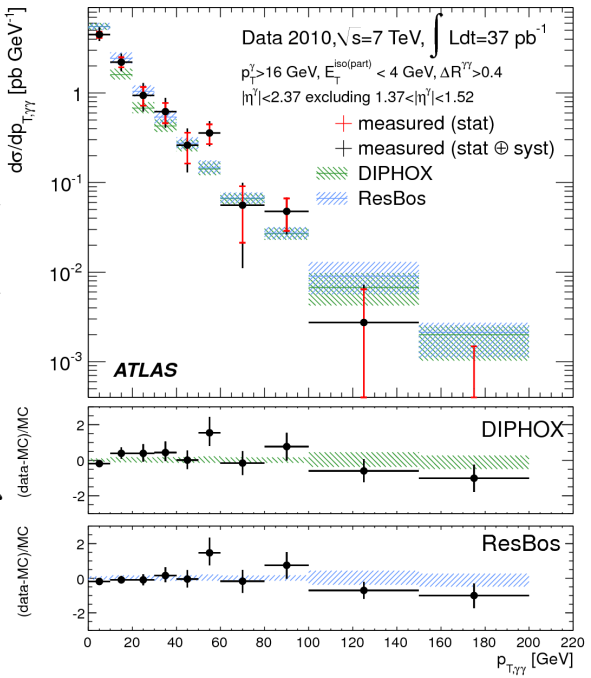

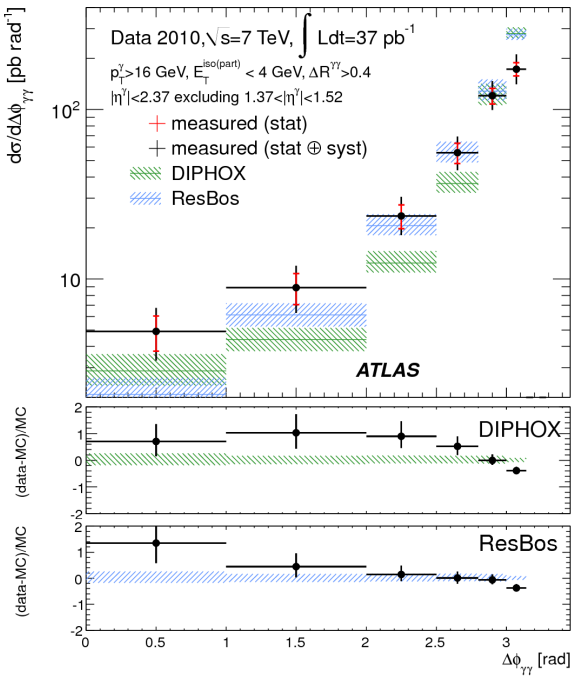

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- Diphotons (37pb^{-1}): $d\sigma/dm_{\gamma\gamma}$, $d\sigma/dp_{T,\gamma\gamma}$, $d\sigma/d\Delta\phi_{\gamma\gamma}$.
- Diphoton p_T well reproduced by perturbative QCD but Δϕ separation broader in data (sensitive to photon fragmentation).

Fragmentation and Shape (36pb^{-1})

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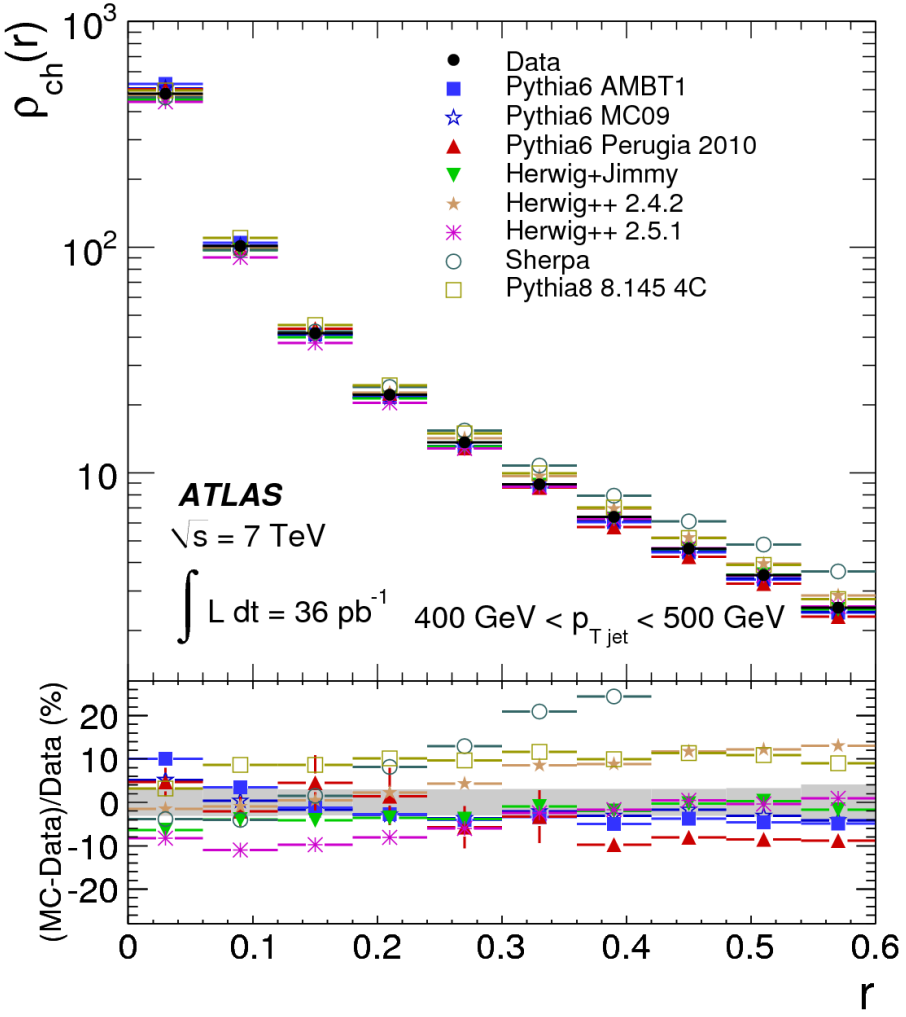

- Jet transverse profile at high jet p_T.

Boosted Jet Substructure (35pb^{-1})

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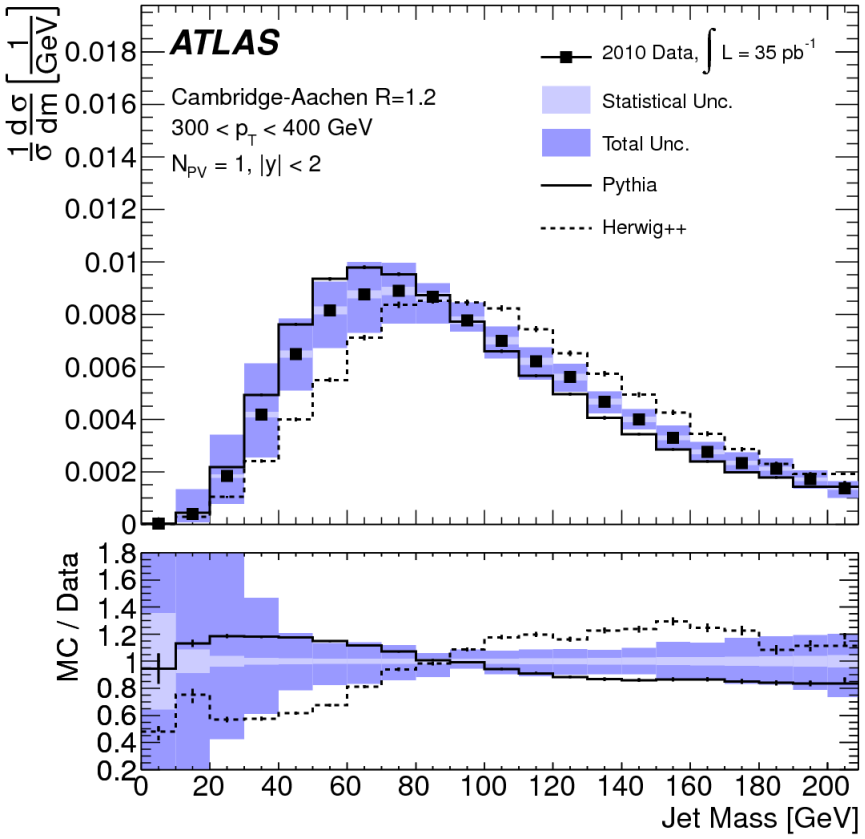

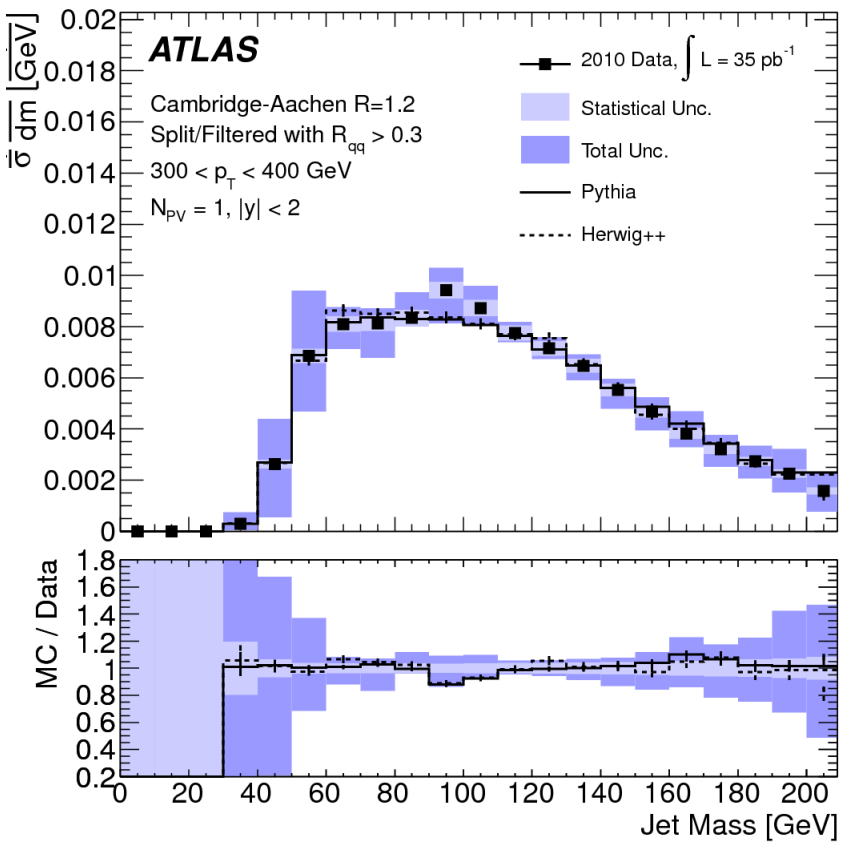

- Inclusive measurements of jet variables capable of discriminating between hadronic boosted heavy particle decays and QCD jets e.g. C-A R=1.2 mass.
- C-A “splitting-filtering” procedure reduces sensitivity to soft physics.
- After filtering the mass is well reproduced by Pythia and Herwig++ within systematics.