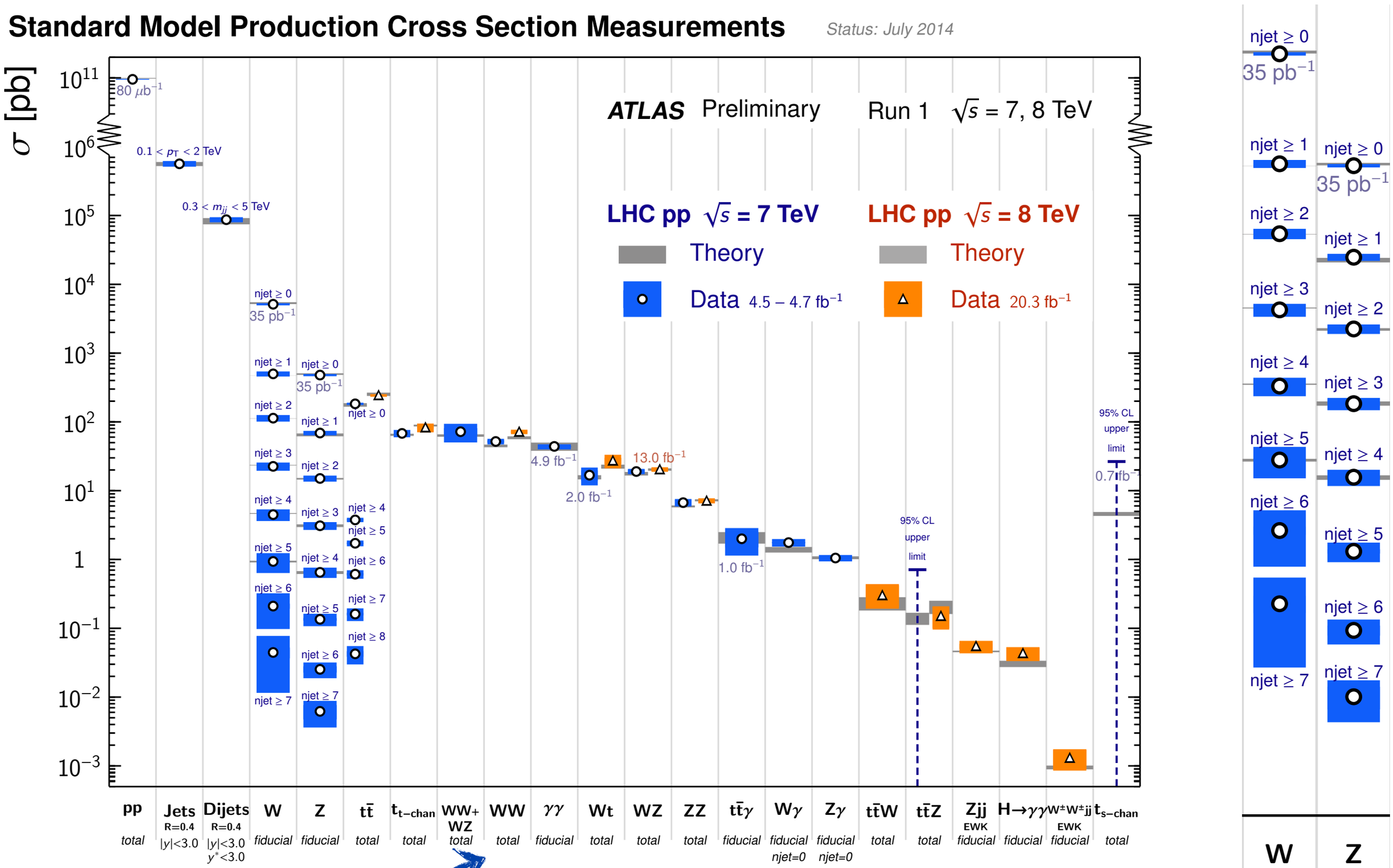
QCD and Vector Boson + jets measurements with ATLAS

Les Rencontres de Physique de la Vallee d'Aoste, La Thuile, March 2015

Kristof Schmieden, on behalf of the ATLAS collaboration

The Summary at the Beginning



di-Boson results: see K. Bachas and J. Gao talks on Thursday

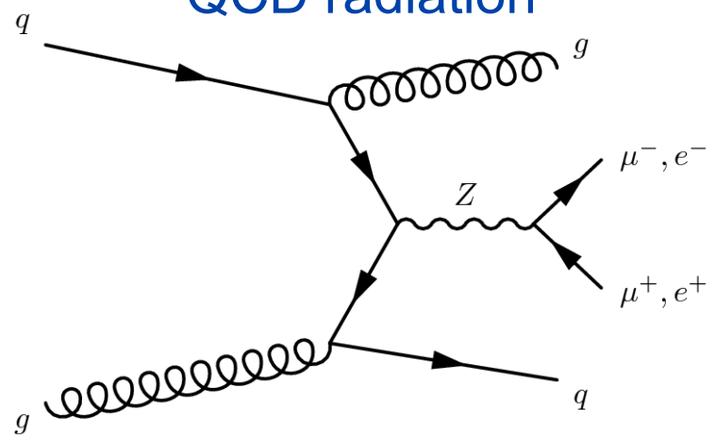
Motivation: jets and V+jets

- Jet inclusive measurement:
  - QCD dominated
  - sensitive pQCD effects PDFs, ...

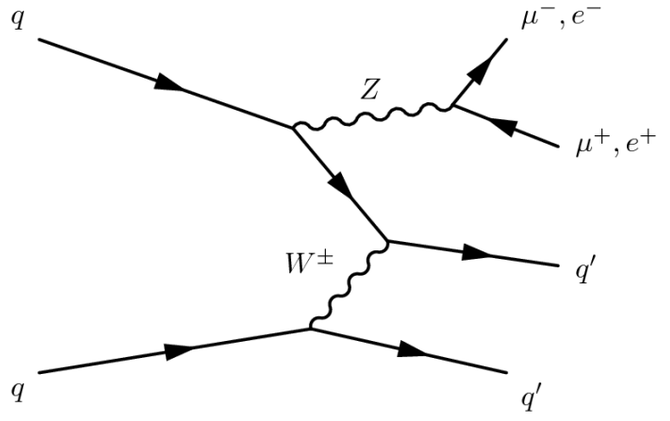
- Jet production in association with W/Z bosons is dominated by strong interactions:
  - Number of jets:
    - Sensitive to pQCD effects → parton shower
  - Jet transverse momentum
    - Sensitive to higher order ME, QCD & EWK!
  - Angular separation and invariant mass of leading jets
    - Sensitive to higher order ME & pQCD effects

- Clean leptonic signature of V decay

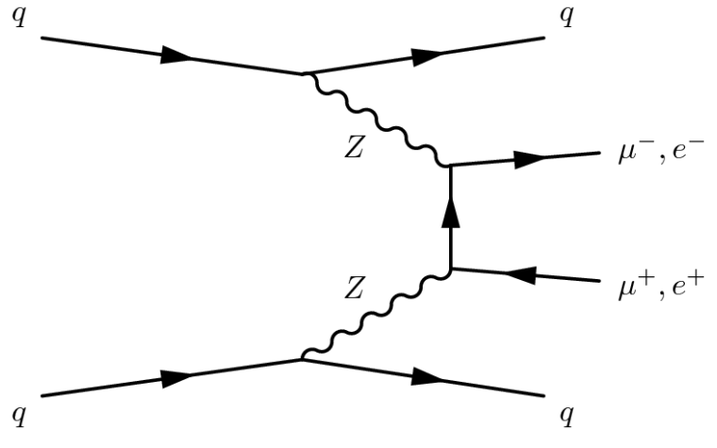
QCD radiation



Z-boson Bremsstrahlung



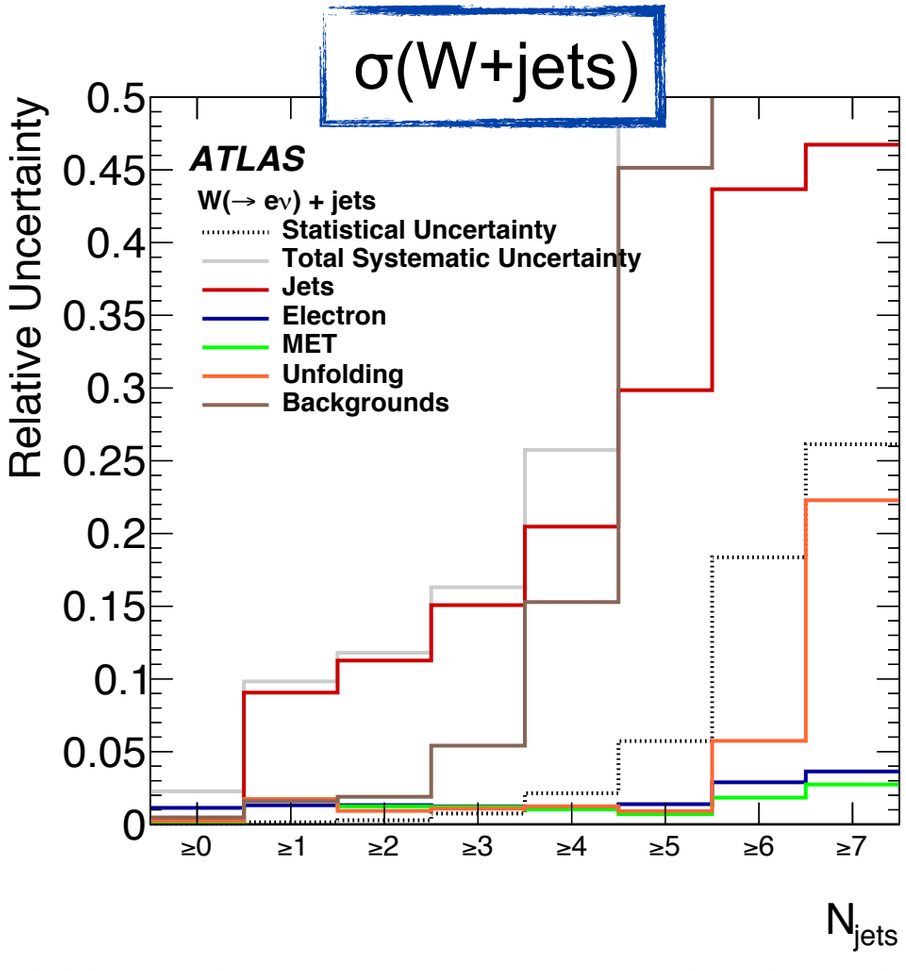
Non resonant

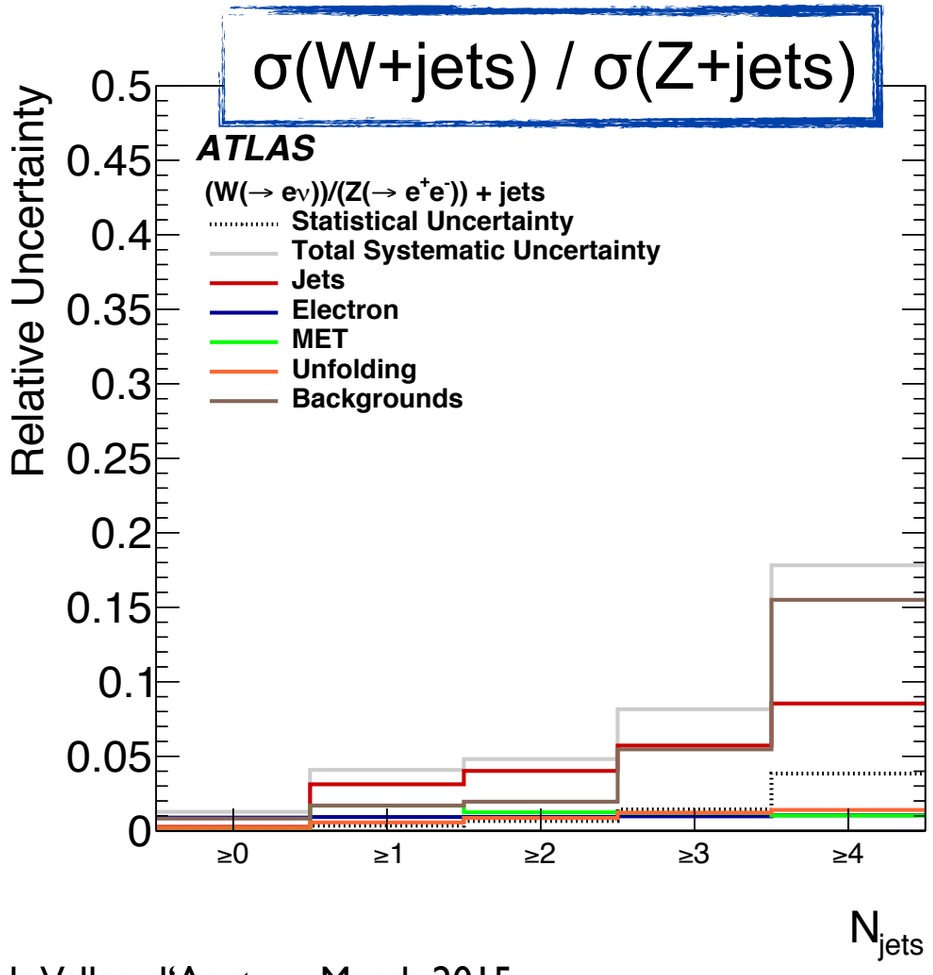


Motivation: Ratio Measurements σ(W+jets) / σ(Z+jets)

- Probes kinematic differences of jet-system recoiling against W or Z

- Many uncertainties cancel!
  - Experimental:
    - Positively correlated uncertainties (Energy scales / backgrounds / Jet uncertainties)
  - Prediction:
    - Scale & PDF uncertainties
    - Parton shower / hadronization





Recent ATLAS measurements

- W + jets cross section (Accepted by EPJC; arXiv:1409.8639) (Sep. 2014)

- W + jets/Z + jets cross section ratio (Eur. Phys. J. C (2014) **74**:3168)
- Z + b-jets cross section (JHEP10(2014)141) (Nov. 2014)
- Inclusive Jet cross section (arXiv:1410.8857) (Oct. 2014)
- Differential 3 Jet measurement (arXiv:1411.1855) (Nov. 2014)
- Z + jets cross section (JHEP 07 (2013) 032) (not discussed)
- W +b-jets cross section (JHEP 06 (2013) 084)
- W +c-jets cross section (JHEP 05 (2014) 068)

- All shown results are obtained using the data measured in 2011 (4.6fb^{-1} @ 7 TeV)

Theory Predictions - overview of tools

- Several Monte Carlo generators used to calculate predictions
  - Alpgen:
    - Multiparton LO ME generator for SM processes
    - Special emphasis on multijet final states: explicitly takes **helicity correlations** of intermediate gauge bosons and final state particles into account
    - PS by external program
  - Sherpa
    - Multiparton LO ME, provides complete hadronic final states, sophisticated **ME/PS merging**
  - BlackHat + Sherpa for PS
    - Evaluates QCD one-loop matrix elements for up to 4 final state jets
  - HEJ
    - All-order summation of perturbative terms
    - Any number of hard jets > 2, jet rates (up to 4 jets) fully matched to tree-level accuracy.
  - MEPS@NLO
    - Merge resumed logs from PS with fixed order ME calculation
    - Jets evolve with PS, cross section accurate to Born level
  - NLOJET
    - NLO pQCD (fixed order) calculations, including hadronisation and electroweak corrections

arXiv:1409.8639 &
Eur. Phys. J. C (2014) 74

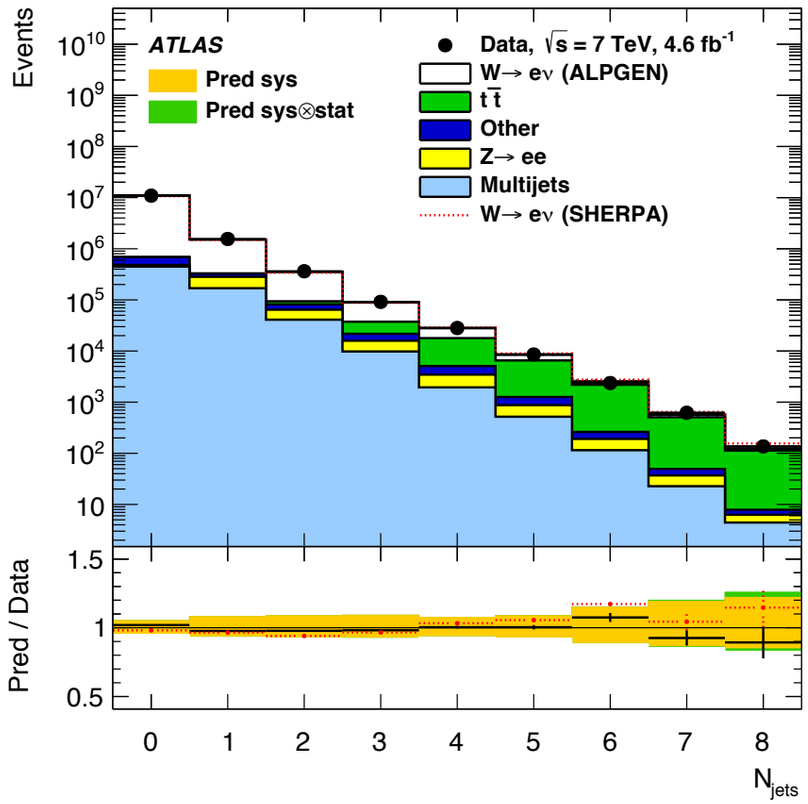
Results for W+jets and Ratio W/Z + jets measurements

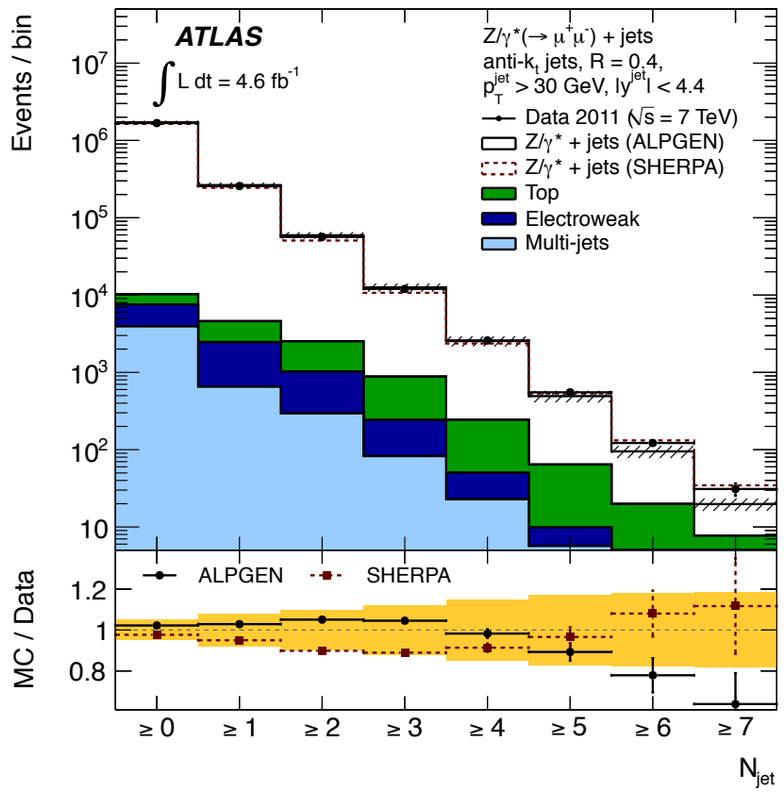
Event Selection

arXiv:1409.8639 &
Eur. Phys. J. C (2014) **74**

- $W \to \ell\nu$
  - Exactly 1 lepton
    - p_T > 25GeV,|η| < 2.4 / 2.47 (μ/e)
  - E_T^{miss} > 25 GeV
  - m_T > 40 GeV
  - Jets:
    - p_T > 30 GeV
    - |y| < 4.4
    - Removed if overlapping with lepton ΔR > 0.4

- $Z \to \ell\ell$
  - Exactly 2 leptons with opposite charge
    - p_T > 20GeV, |η| < 2.4 / 2.47 (μ/e)
  - ΔR(l,l) > 0.2
  - $66 \leq m_{ll} \leq 116$ GeV
  - Jets:
    - p_T > 30 GeV
    - |y| < 4.4
    - Removed if overlapping with lepton ΔR > 0.4





Inclusive number of jets

arXiv:1409.8639 &
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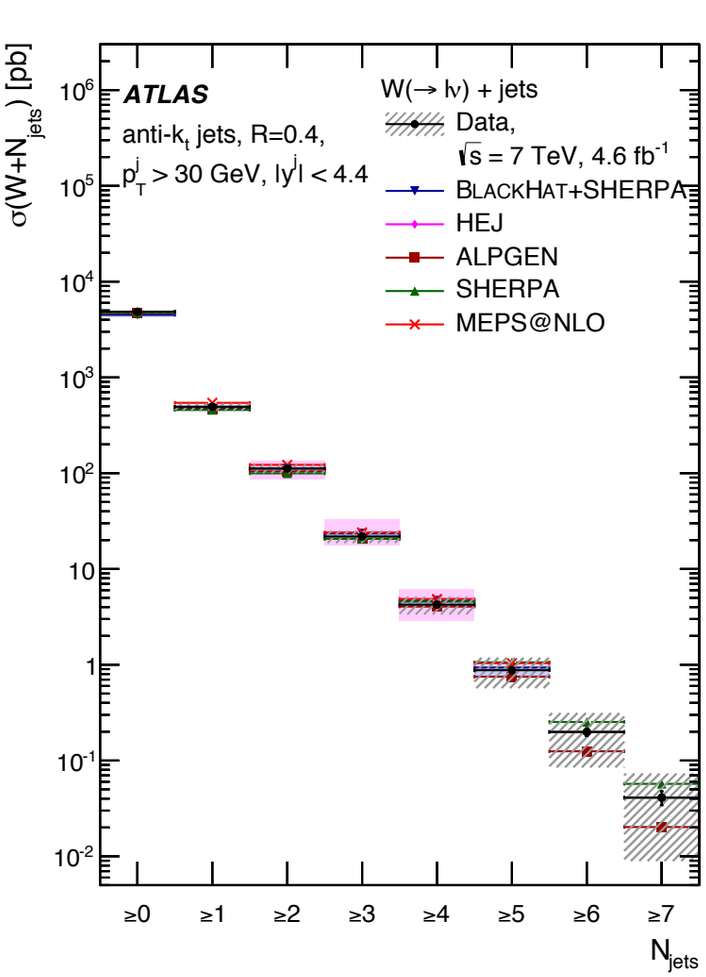
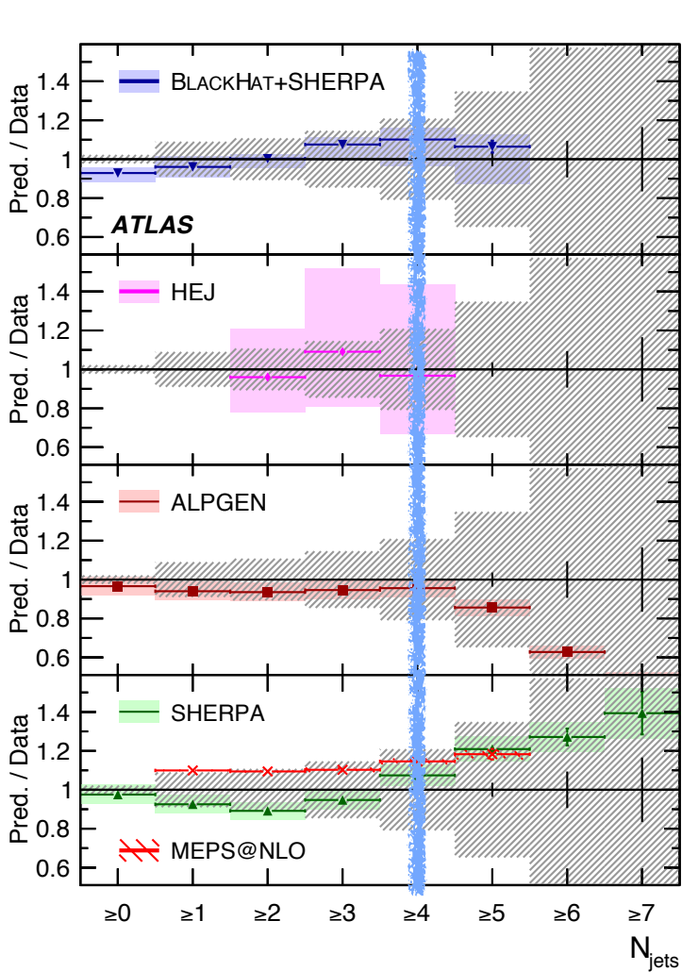
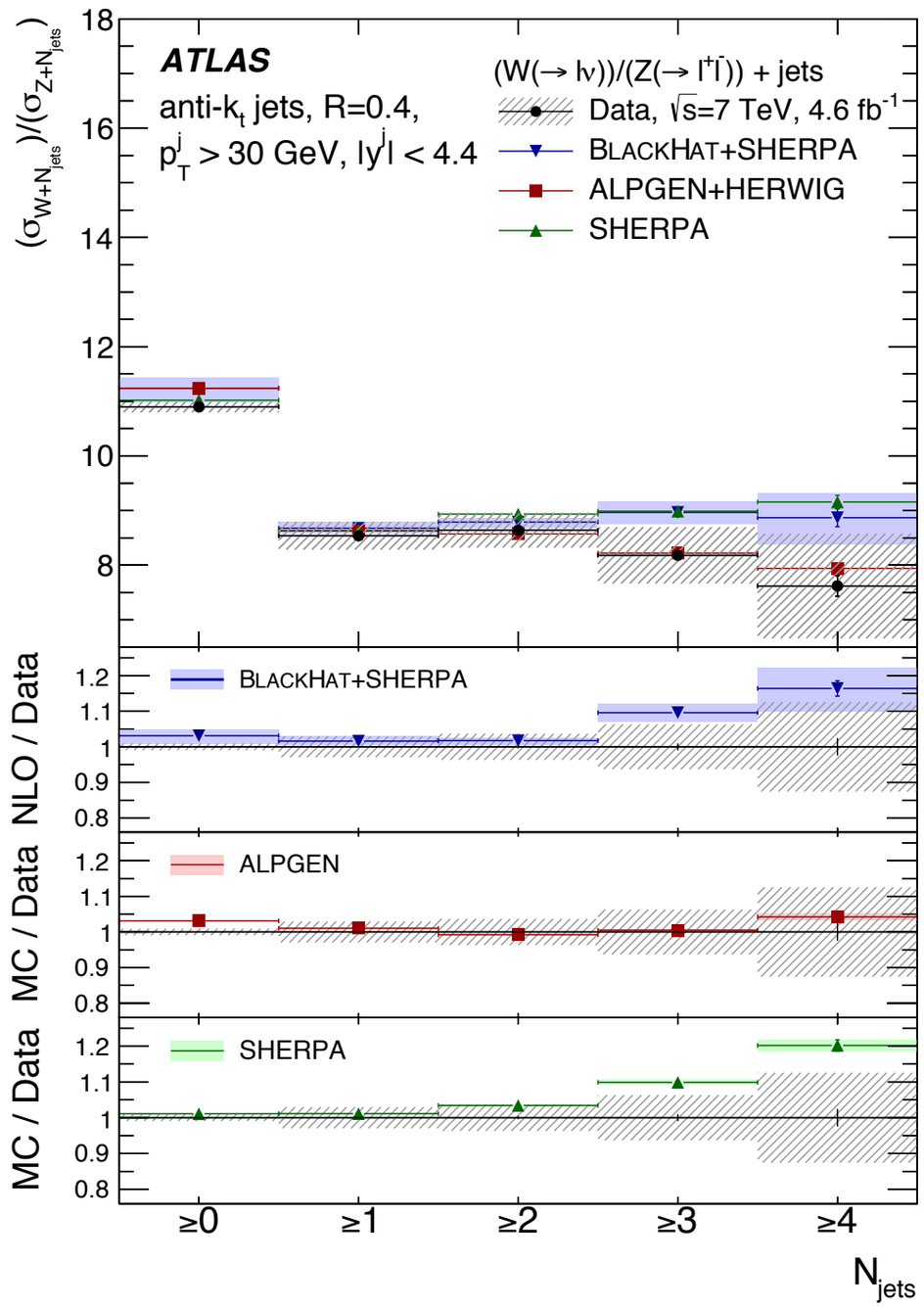
- BlackHat and ALPGEN give good description of data for $N_{jets} < 5$
- Trend toward large N_{jets} (Alpgen & Sherpa)
  - still compatible with data within the large errors
- In ratio measurement: deviation of Sherpa prediciton becomes significant

$$W \rightarrow \ell\nu$$





Ratio measurement



Transverse Momentum of Leading Jet (≥ 1 jet)

- Alpgen and Sherpa describe data well
- BH and LoopSim underestimate high p_T cross section

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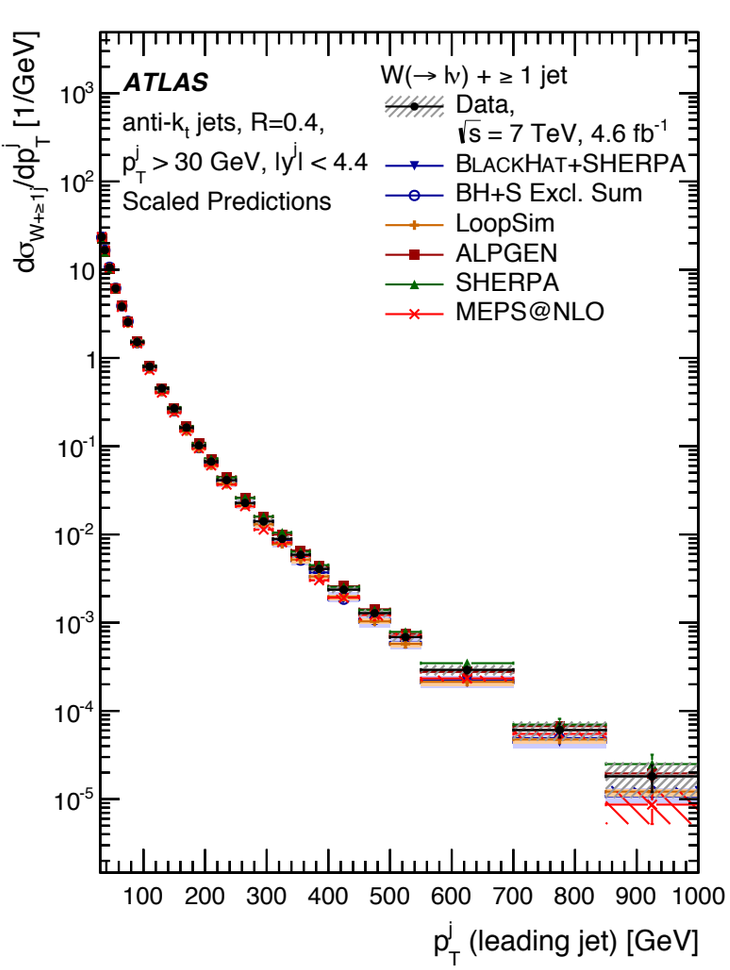
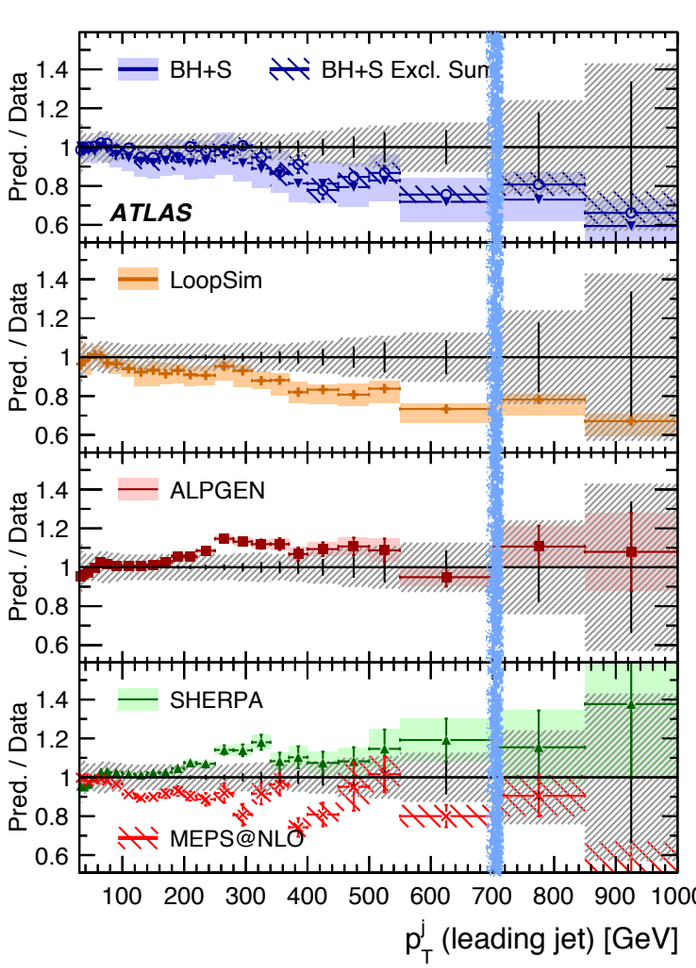
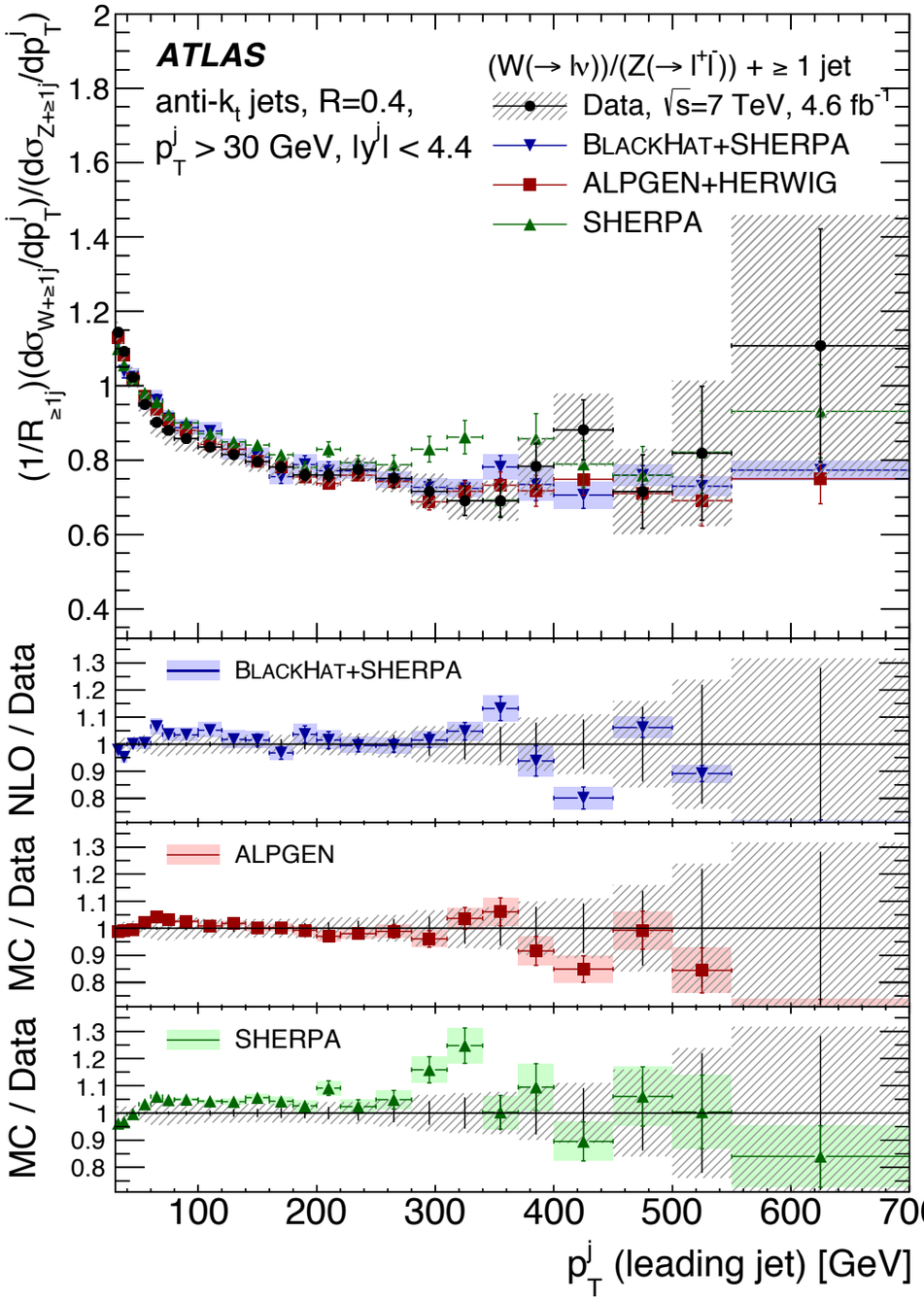
$W \rightarrow \ell\nu$





Ratio measurement

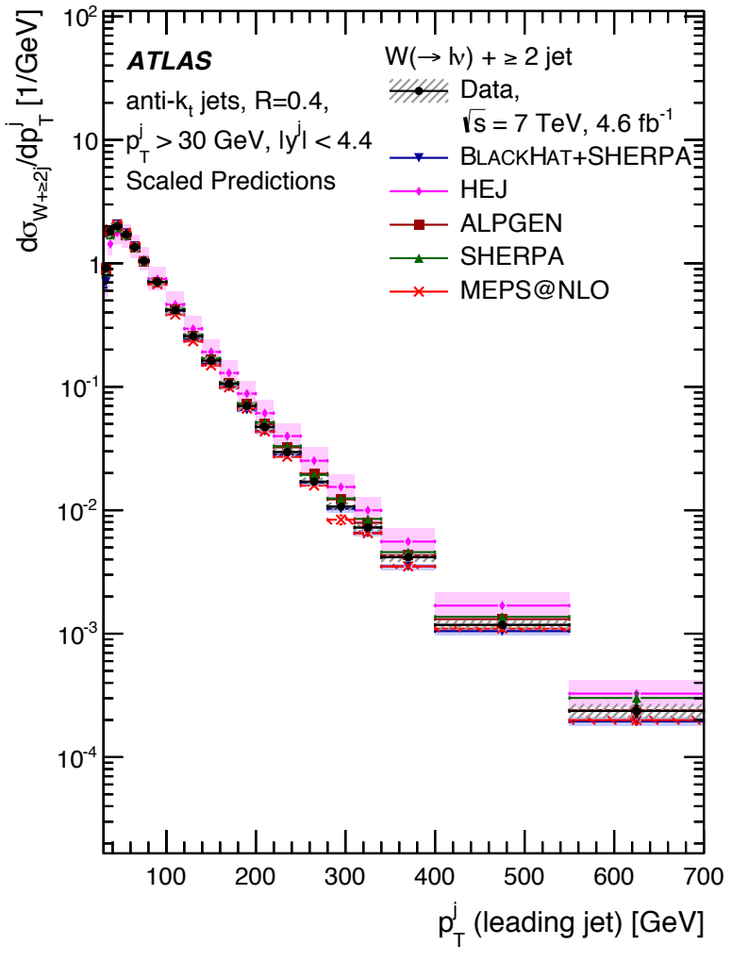


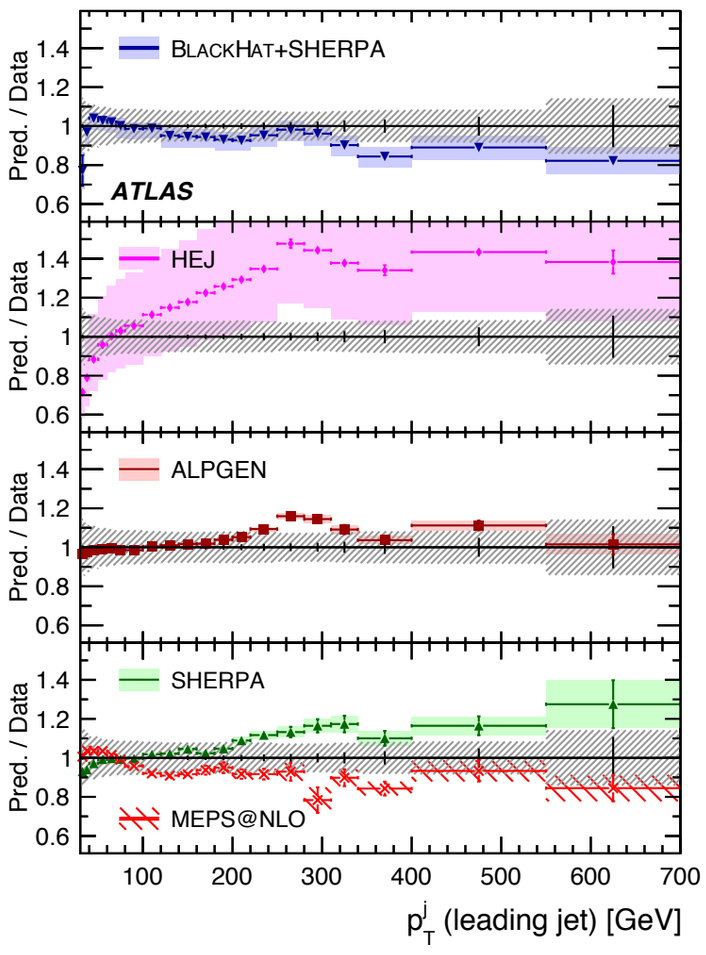
Transverse Momentum of Leading Jet (≥2 jets)

- Pronounced offset in HEJ prediction
- Ratio is modeled well, except for very low p_T

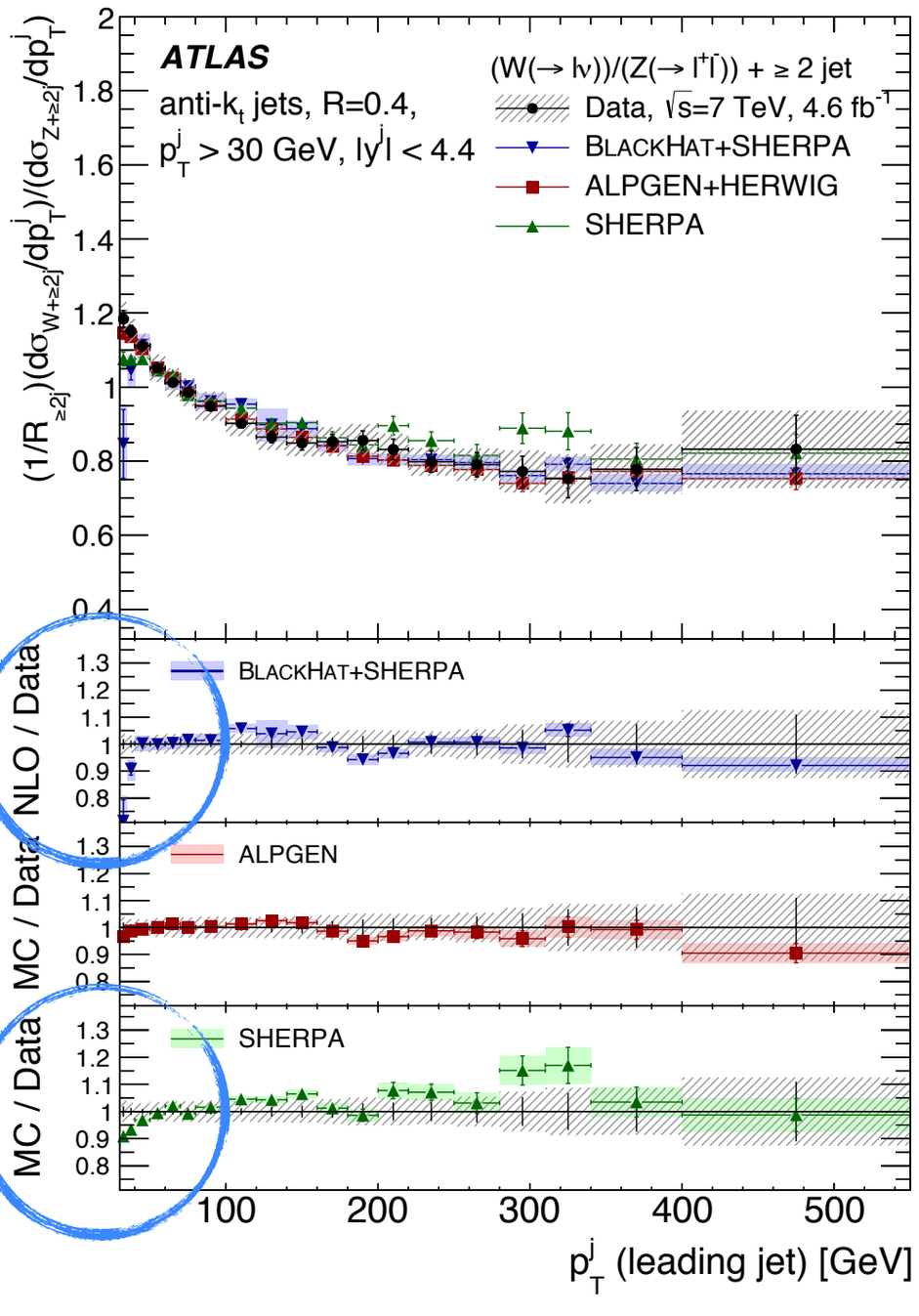
arXiv:1409.8639 &
Eur. Phys. J. C (2014) **74**

$W \rightarrow \ell\nu$





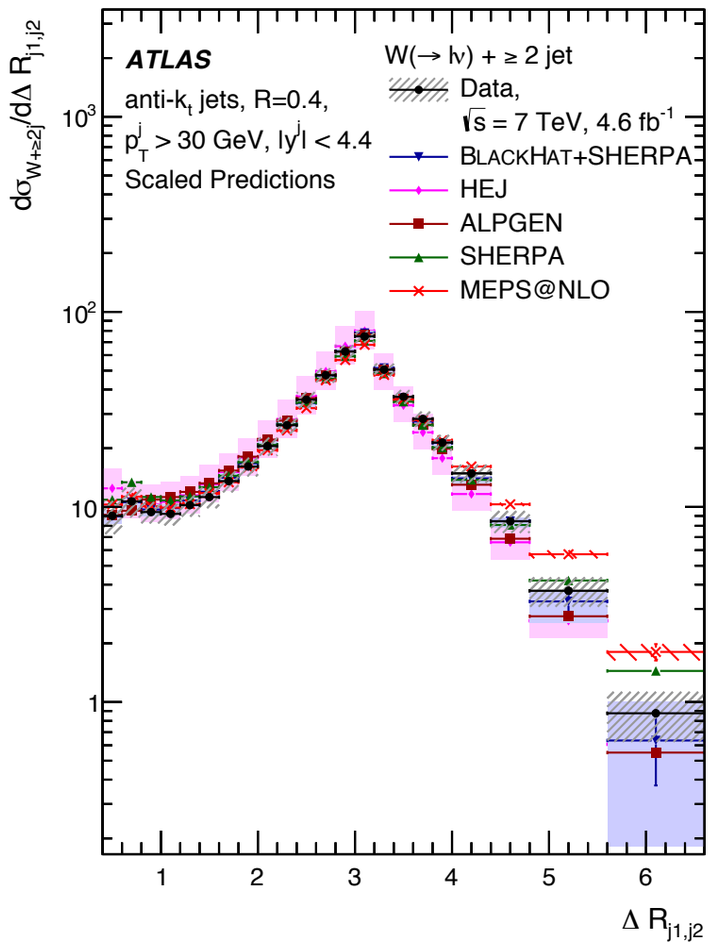
Ratio measurement

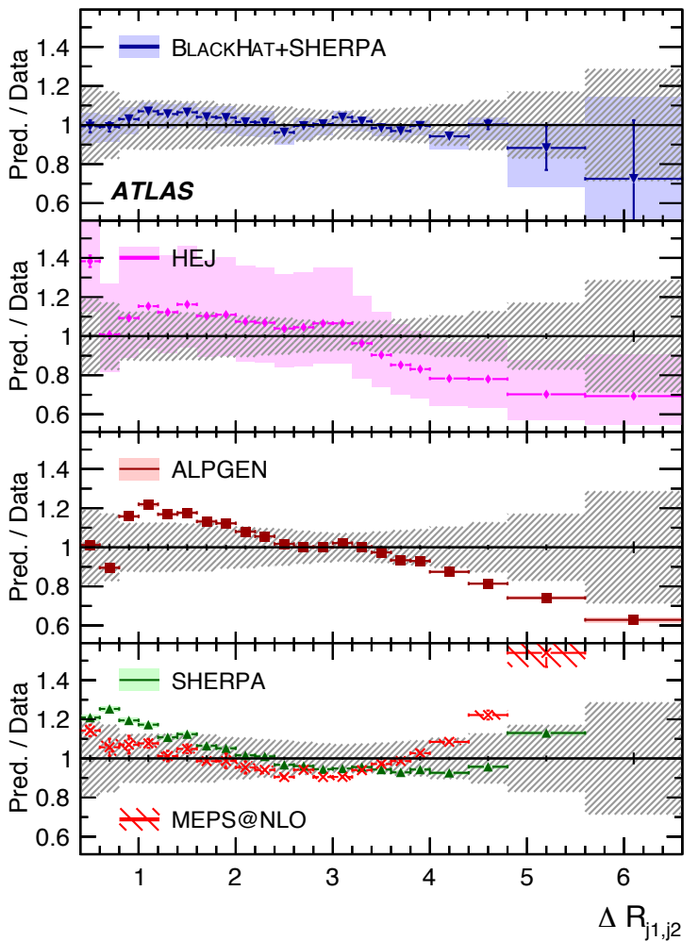


Angular separation of jets

- sensitive to hard parton radiation at large angles
  - ME / PS matching
- MEPS@NLO: trend at large separation
- ALPGEN: trend over full range

$W \rightarrow \ell\nu$





arXiv:1409.8639 &
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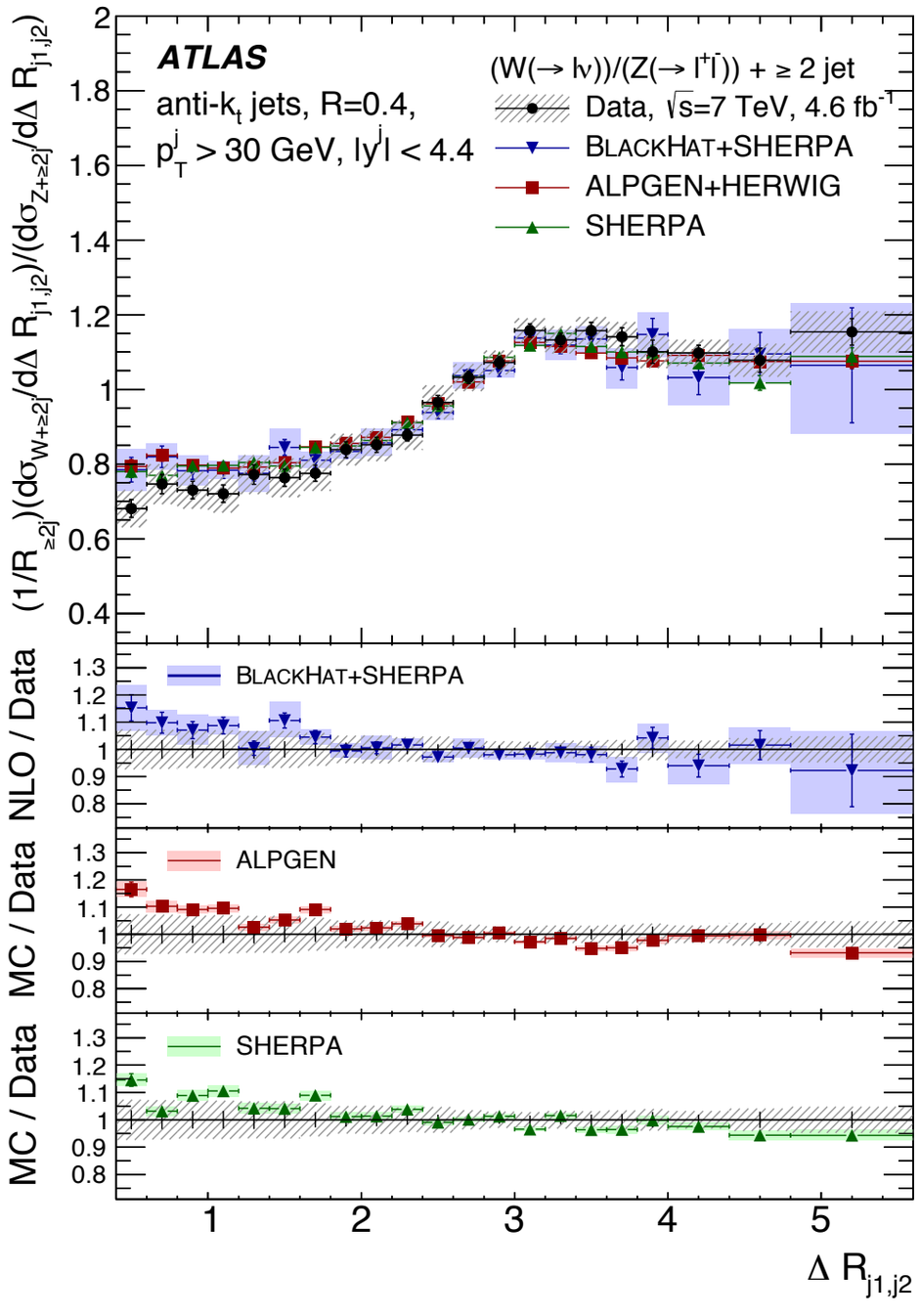
Ratio measurement

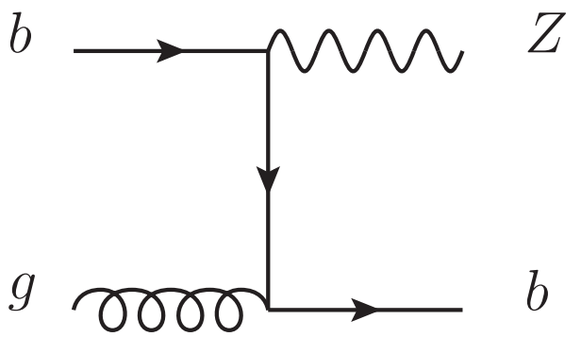


JHEP10(2014)141

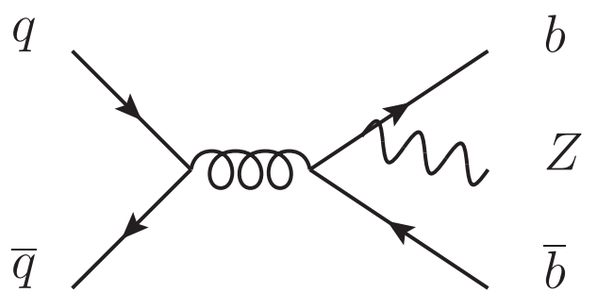
Z + b-jets

Motivation

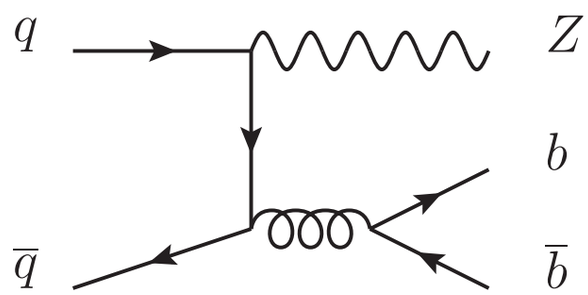
JHEP10(2014)141



(a)



(b)



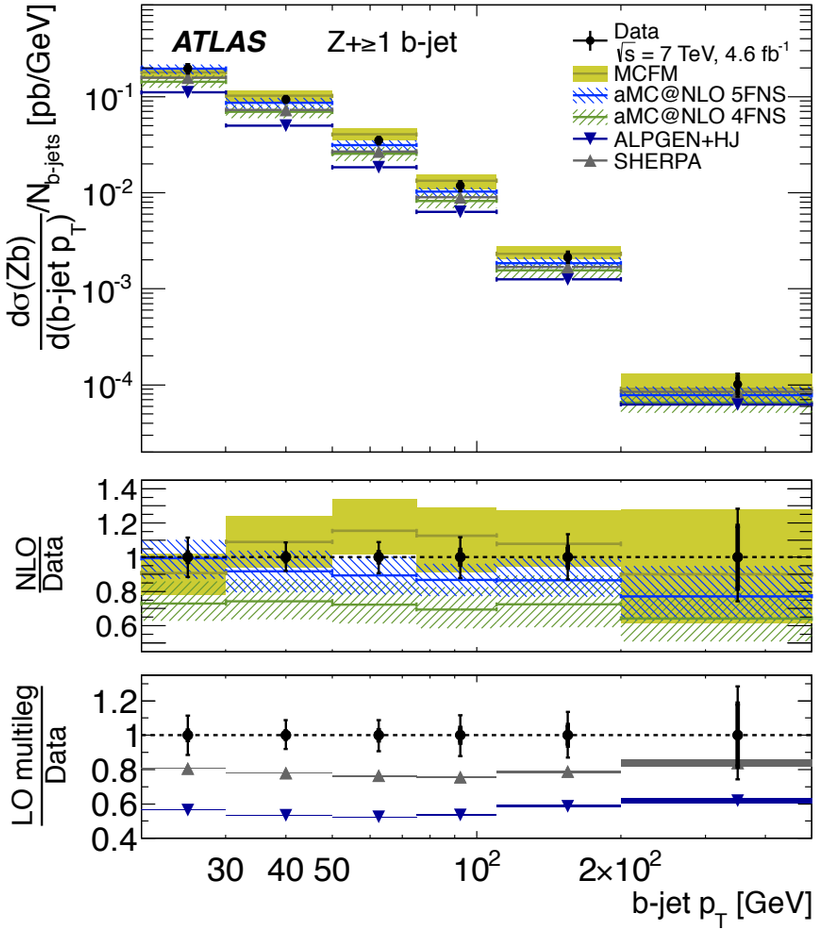
(c)

- Important BG for associated Higgs production with H → bb and BSM models
- 2 schemes used in pQCD calculations: 4 and 5 flavors in initial state
  - (a) only existent in 5 flavor scheme
    - sensitive to b-quark PDF

Z+b-jets: Results

JHEP10(2014)141

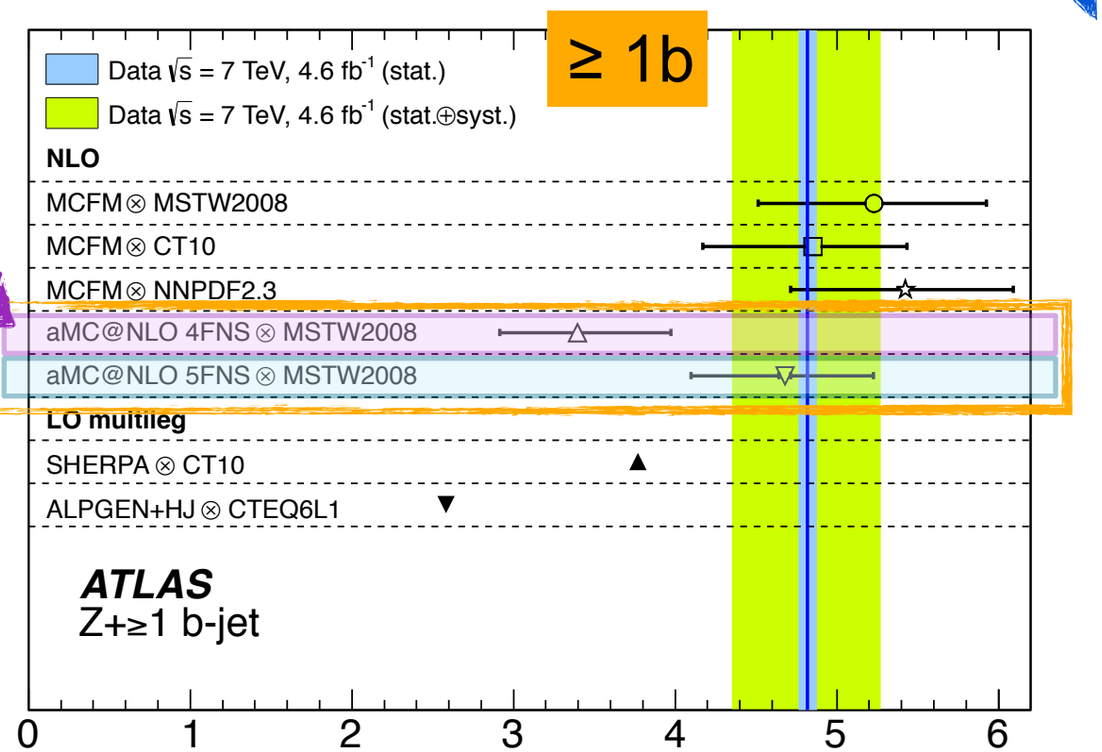
- Sensitivity to PDF
  - In particular N flavors
- Shape of b-jet p_T fairly well described



4FNS

5FNS

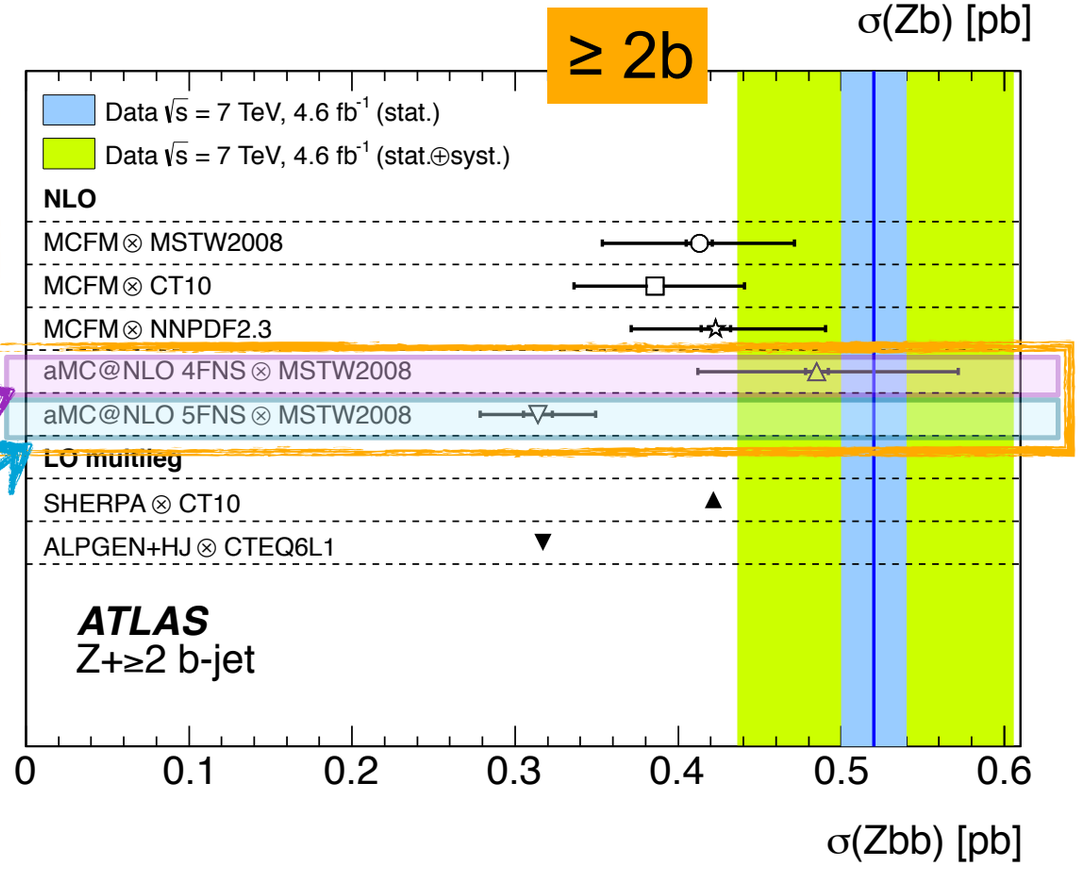
Good agreement in 5 FNS (≥ 1b)



Bad agreement in 5 FNS! (≥ 2b)

4FNS

5FNS



Inclusive Jet Double Differential Measurement

Inclusive Jet Double Differential Measurement

- Anti-k_t reconstruction algorithm, radius R=0.4 (0.6)
- Jets calibrated using insitu methods
- $p_T > 100$ GeV & $|y| < 3$

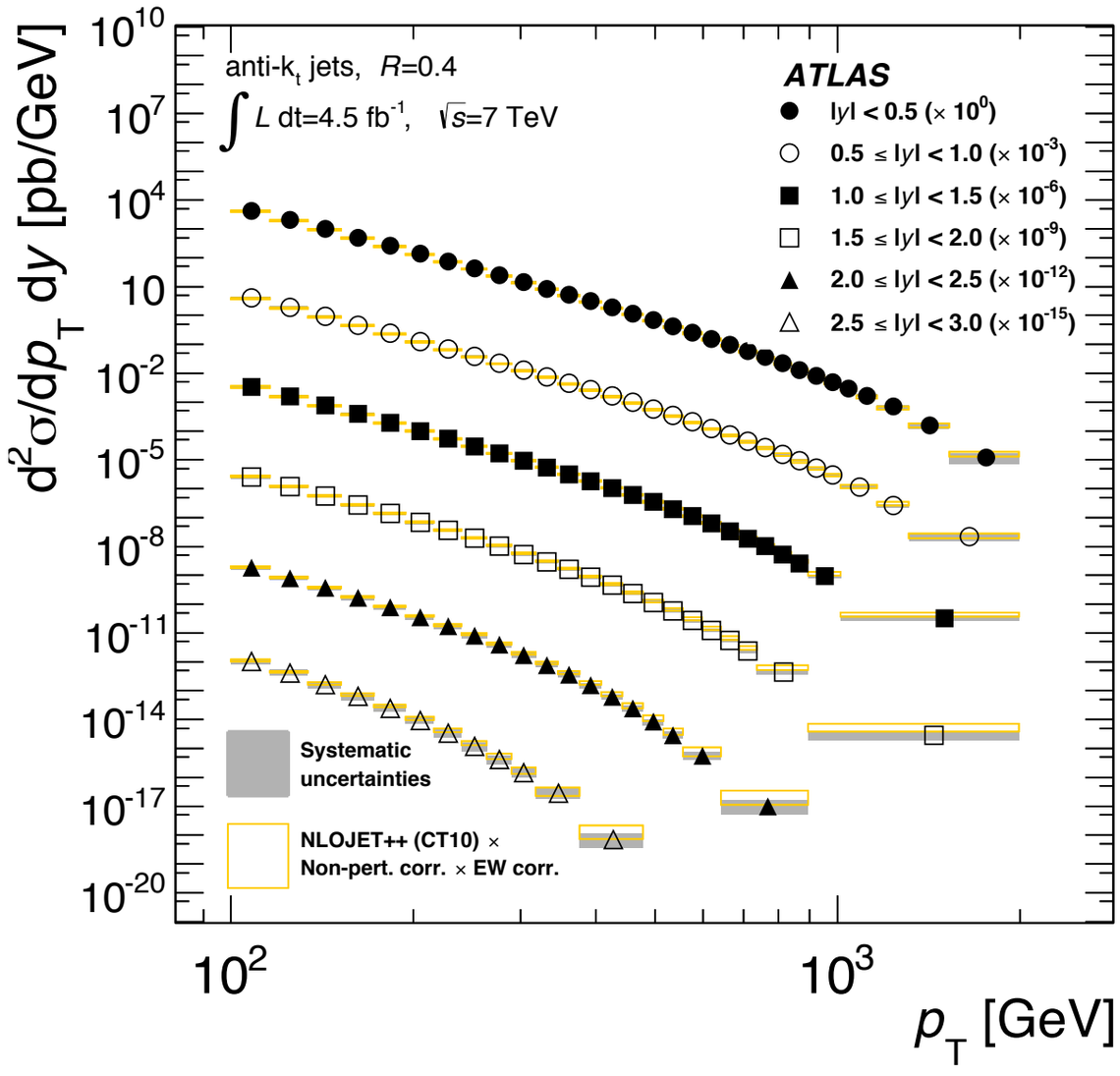
- Data from 2011 and 2010 are consistent

- Larger dataset: extension to higher p_T values (2 TeV), reduces systematics

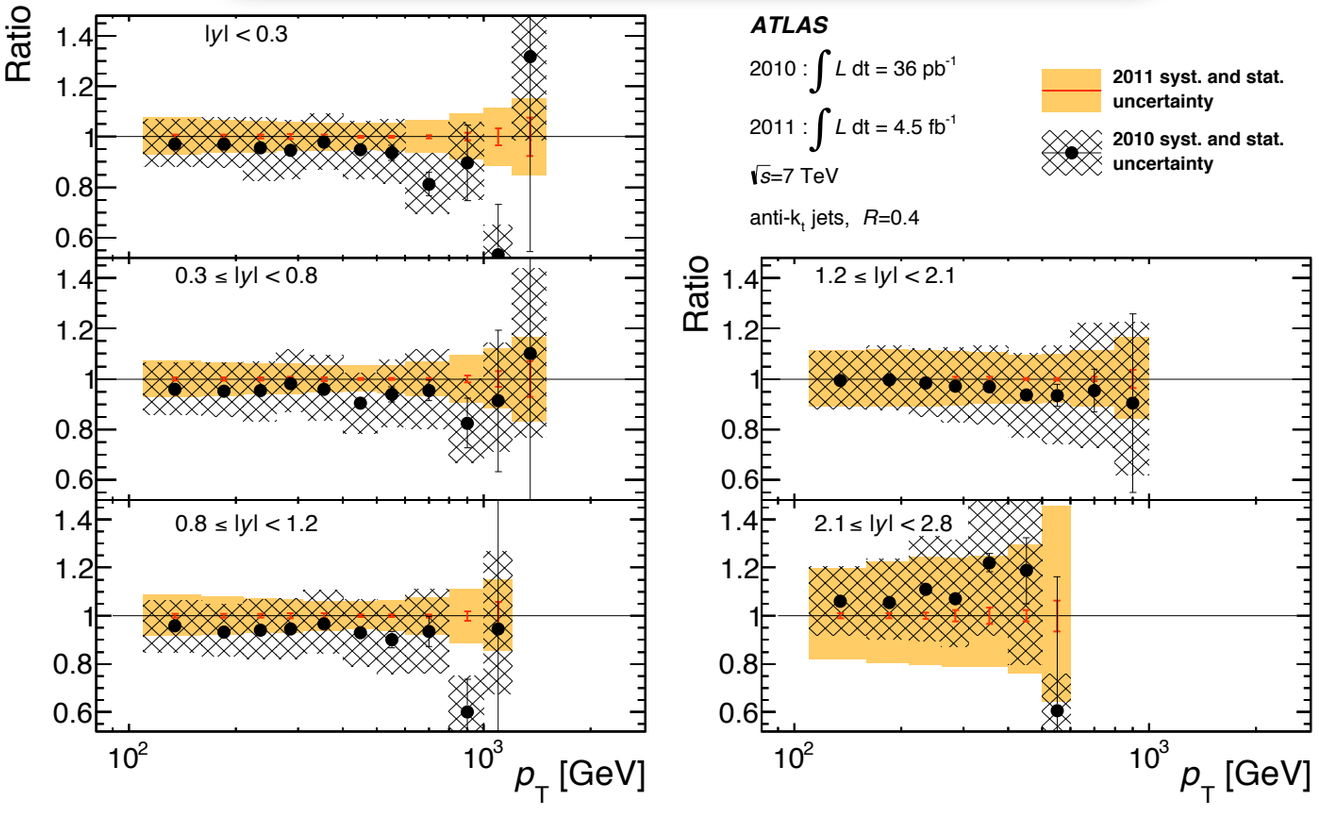
arXiv:1410.8857

NLOJET prediction matched well with double differential measured cross section

Double differential cross sections:



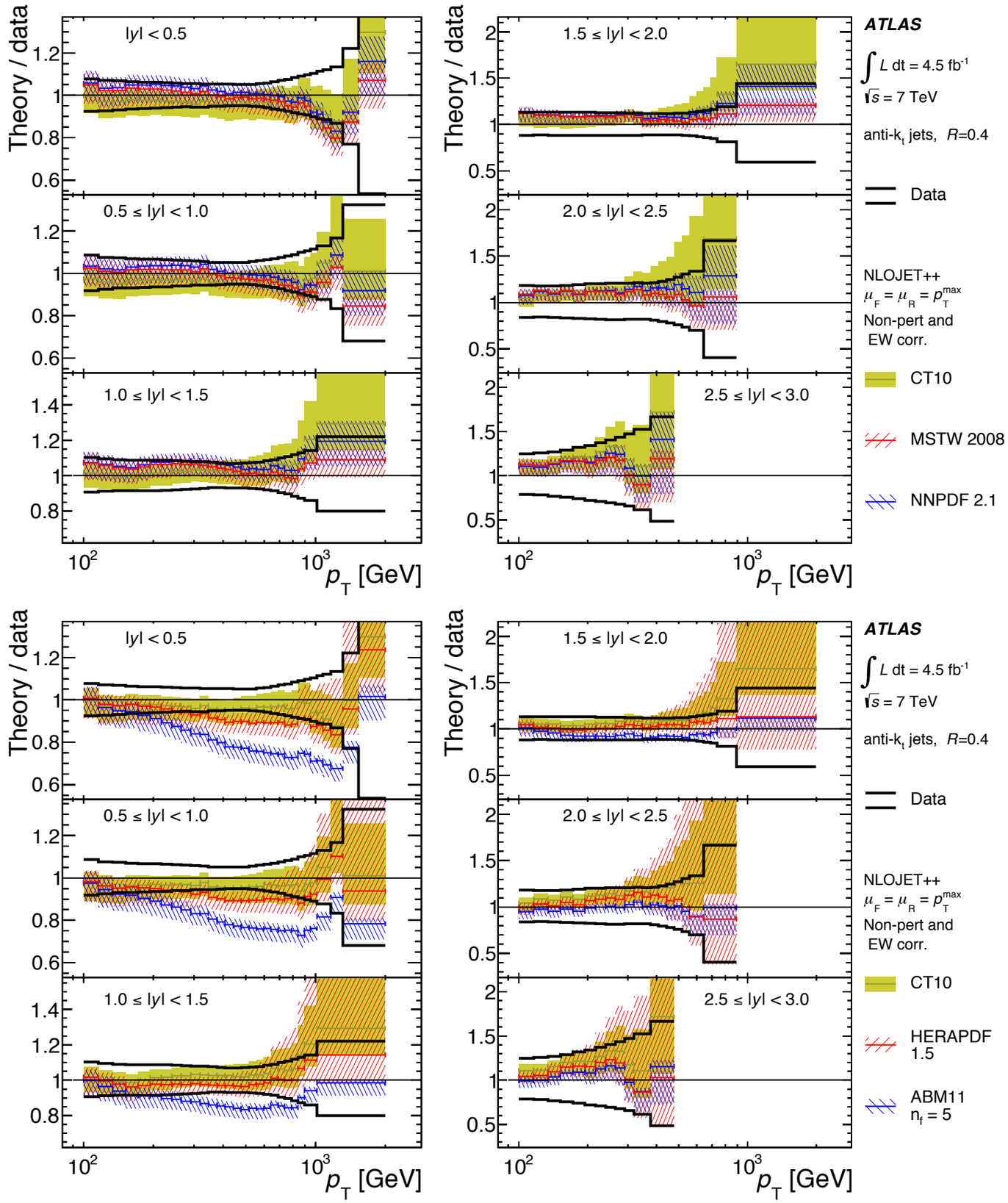
Comparison of 2011 and 2010 data:



Impact on PDFs

arXiv:1410.8857

- Dominant systematic uncertainty:
  - Jet Energy Scale
- Data compared to NLOJET prediction with several different PDF sets (including corrections for non perturbative and electroweak effects):
  - Only ABM11 PDF shows significant deviations from measured values
  - Fairly good agreement for all other tested PDF sets
- Similar results for R=0.6
- Quantitative comparison including correlations of uncertainties
  - All information published

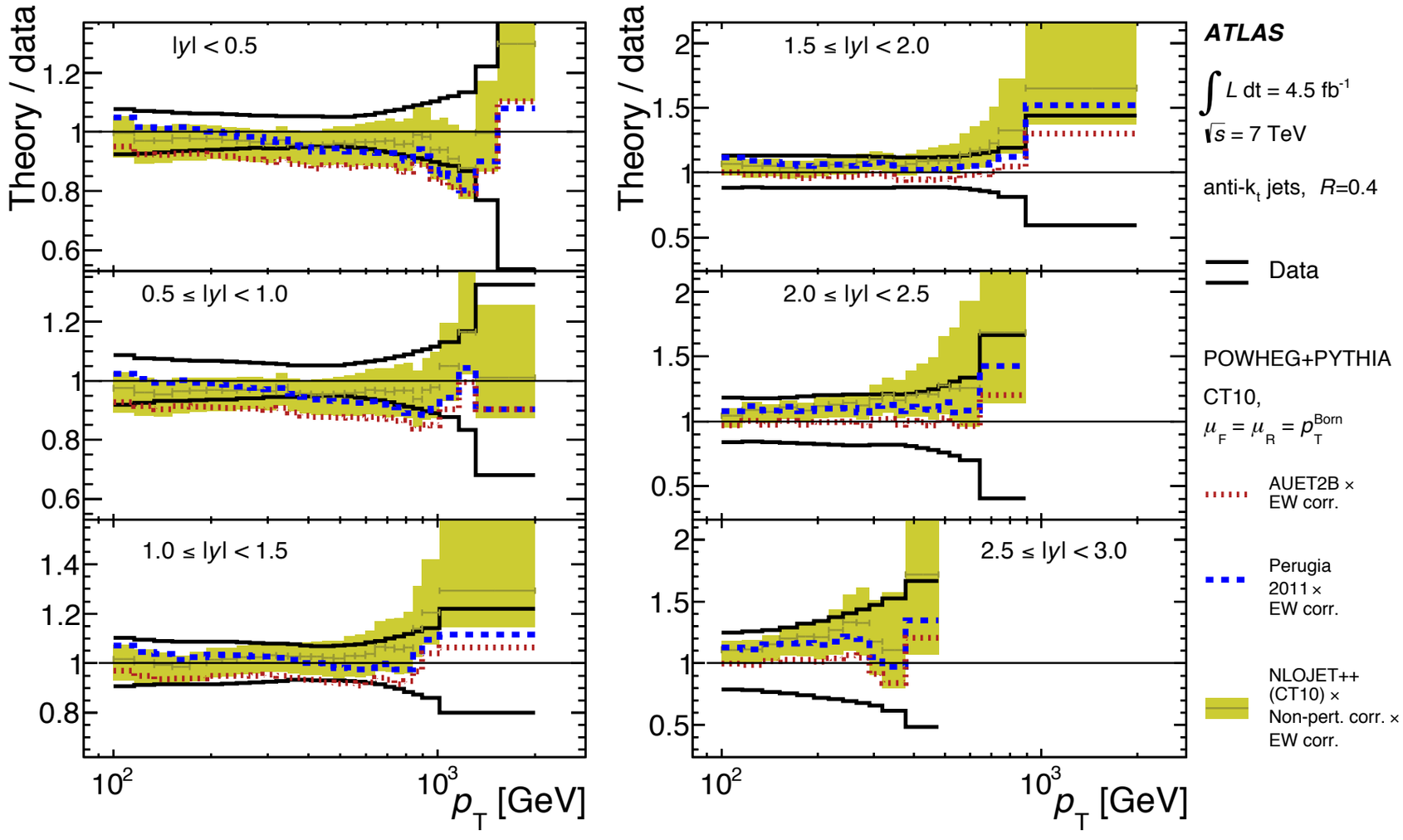


ME+PS element generator vs. pQCD calculation

- Comparison of Perugia 2011 and AUET2B tunes

  arXiv:1410.8857

  - Perugia tune yields consistently larger cross section prediction than AUET2B
- Shape well reproduced by POWHEG
- Similar Results for R=0.6



3 Jet Production

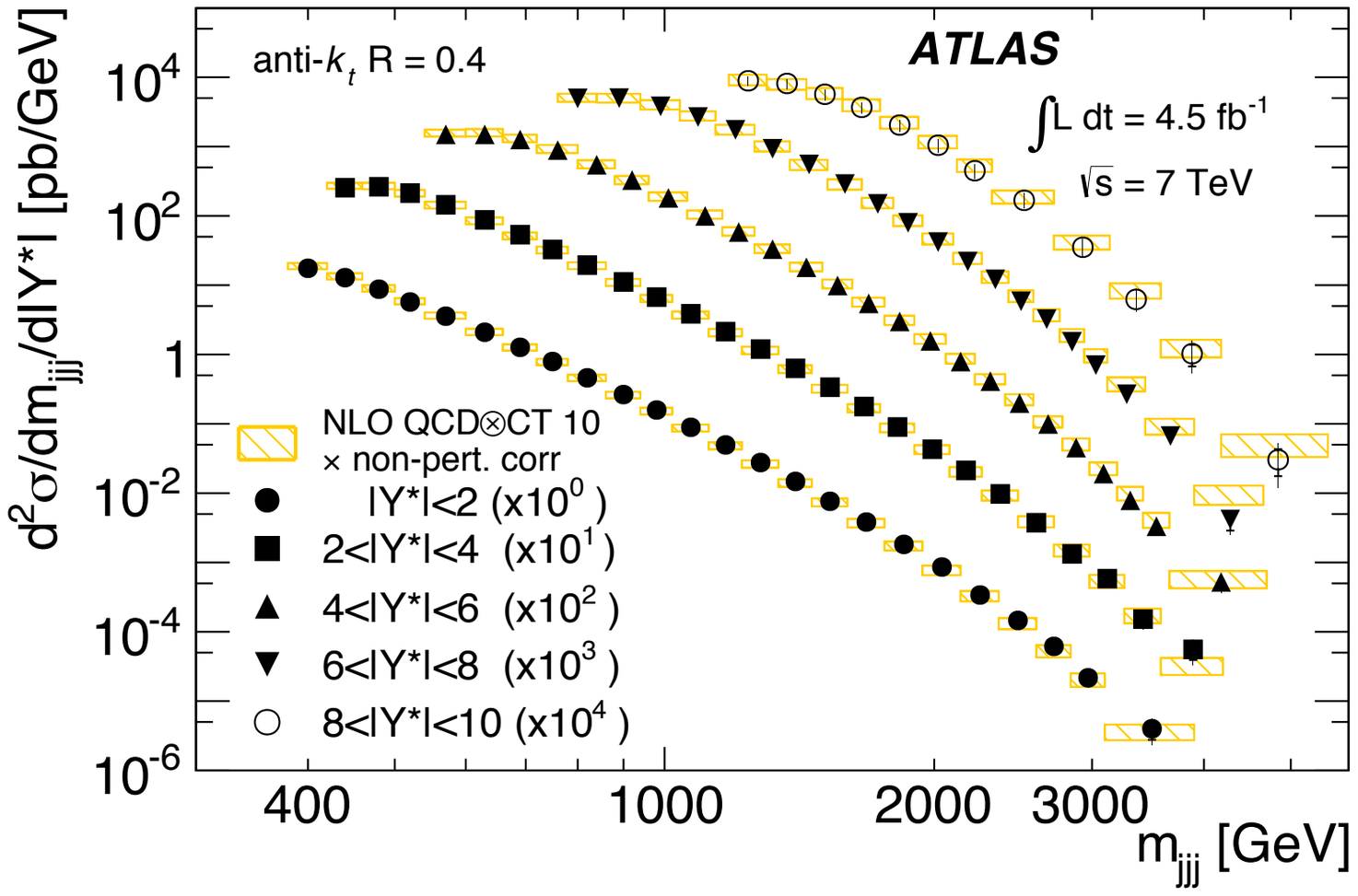
3 Jet Production

arXiv:1411.1855

- Double differential measurement in Rapidity and tri-jet mass
- Dominating systematic uncertainty: JES
- Good agreement with prediction over 7 orders of magnitude!

Event Selection:

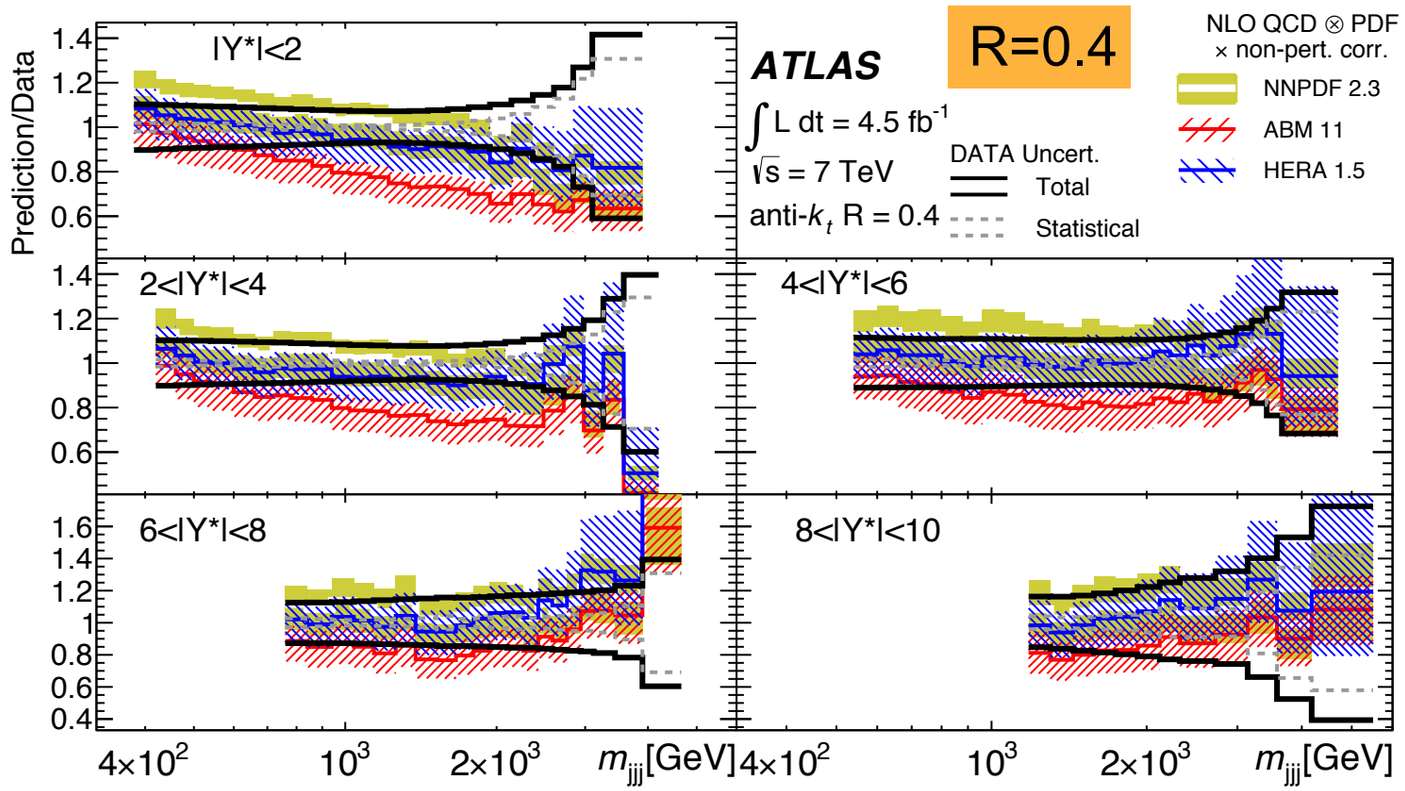
- Anti-k_t reconstruction algorithm, radius R=0.4 (0.6)
- Jets calibrated using insitu methods
- At least 3 jets with
  - $p_T > 50$ GeV & $|y| < 3$
  - leading jet: $p_T > 150$ GeV
  - sub-leasing jet: $p_T > 100$ GeV
- $|Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3|$

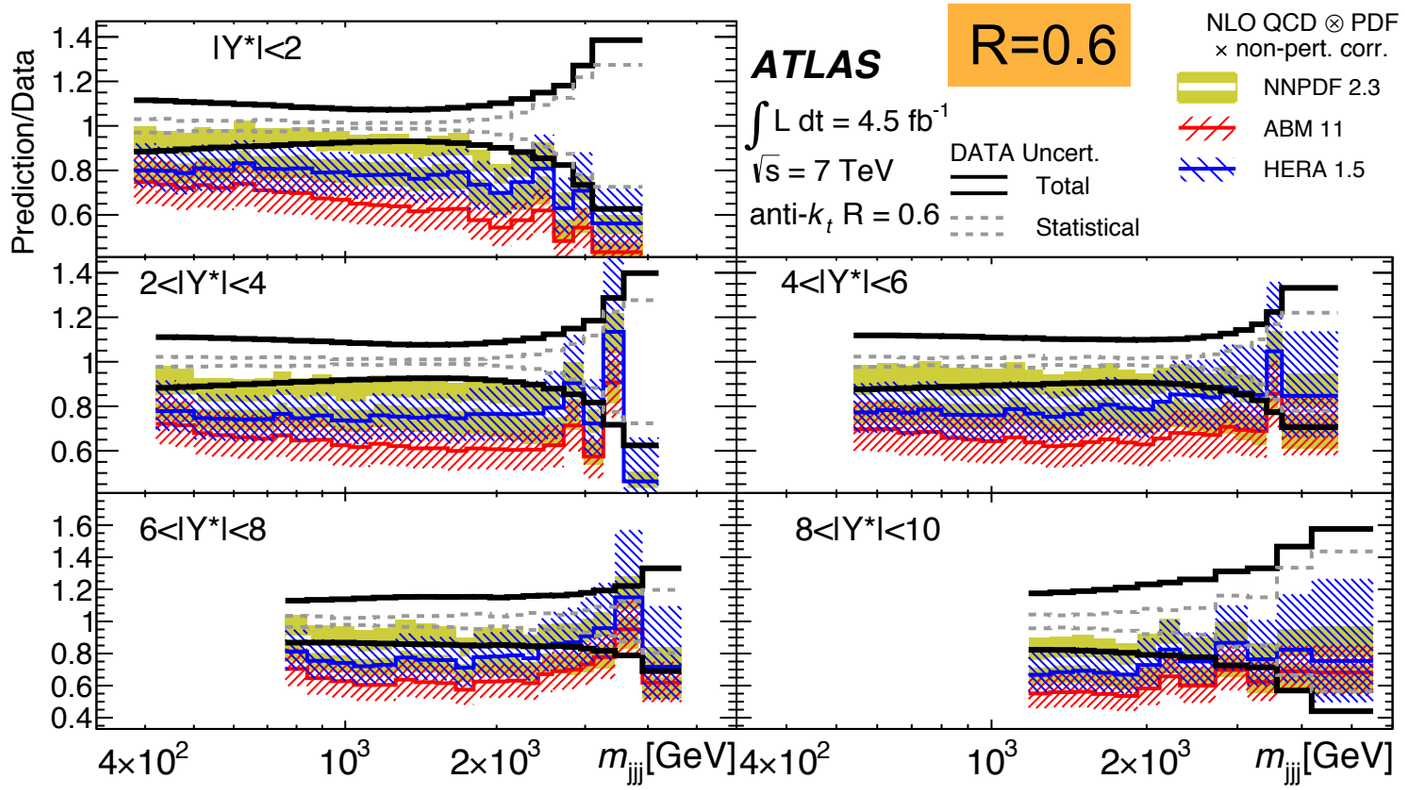


3 Jet Production - PDF impact

arXiv:1411.1855

- Similar picture to previous analysis
  - ABM11 PDF yield systematically lower predictions, in particular in low rapidity region
- Good agreement for R=0.4
- Shifted prediction/data ratio for R=0.6 towards lower values





Conclusions

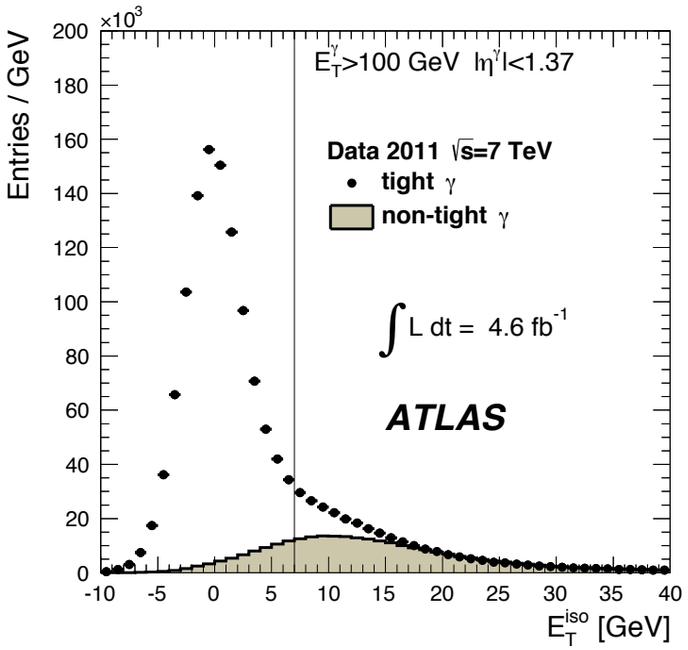
- Inclusive Jet production and the association with Vector Bosons contain interesting physics!

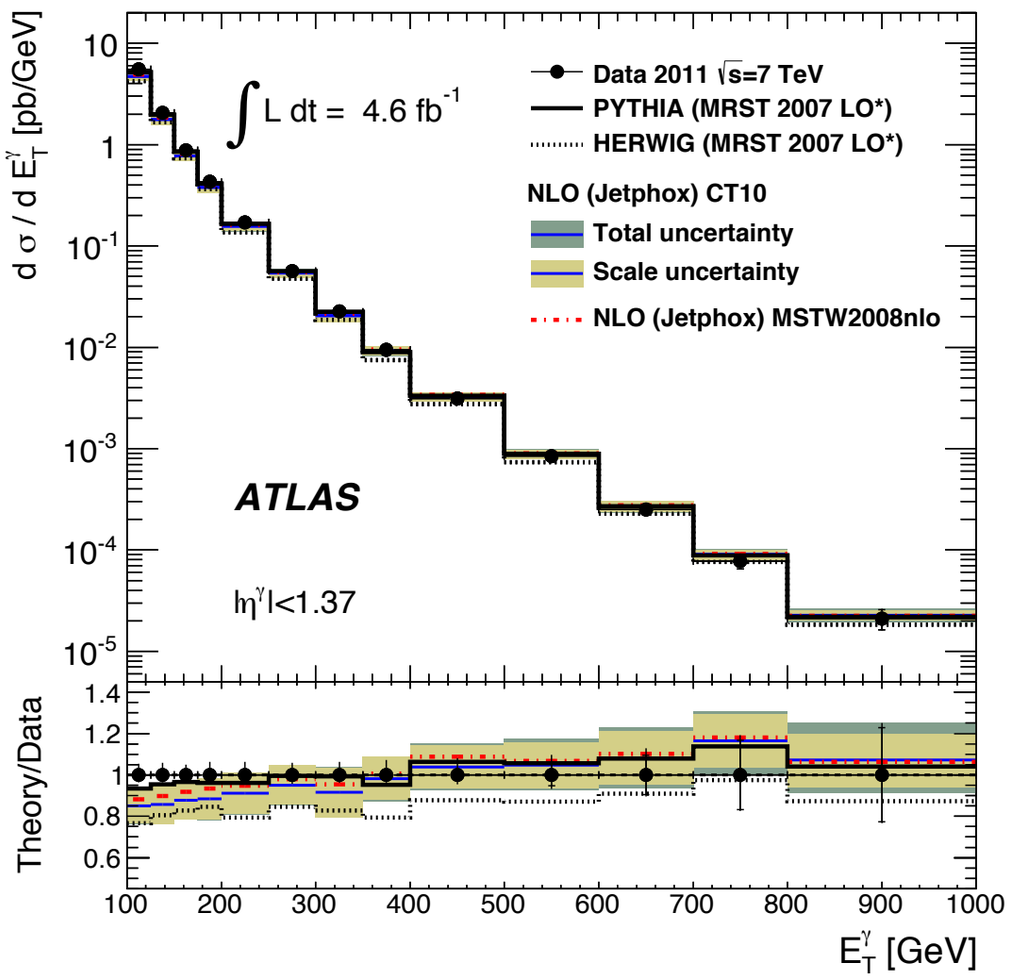
- Many results from ATLAS
  - Few are shown:
    - W+jets: large sensitivity to higher order ME corrections, PS and merging technique. **Still room for improvements!**
    - W/Z + jets ratios: smaller uncertainties, well modeled by generators
    - Z+b-jets: sensitivity to PDFs and initial state description
    - Inclusive Jets: good agreement with fixed-order NLOpQCD calculations + corrections (non perturbative & EWK) and ME + matched PS
    - 3 Jet production: similar to inclusive Jets: **ABM11** PDF shows deviations from measurement in low Y* region;
      for R=0.6: ratio theory / data systematically lower compared to R=0.4

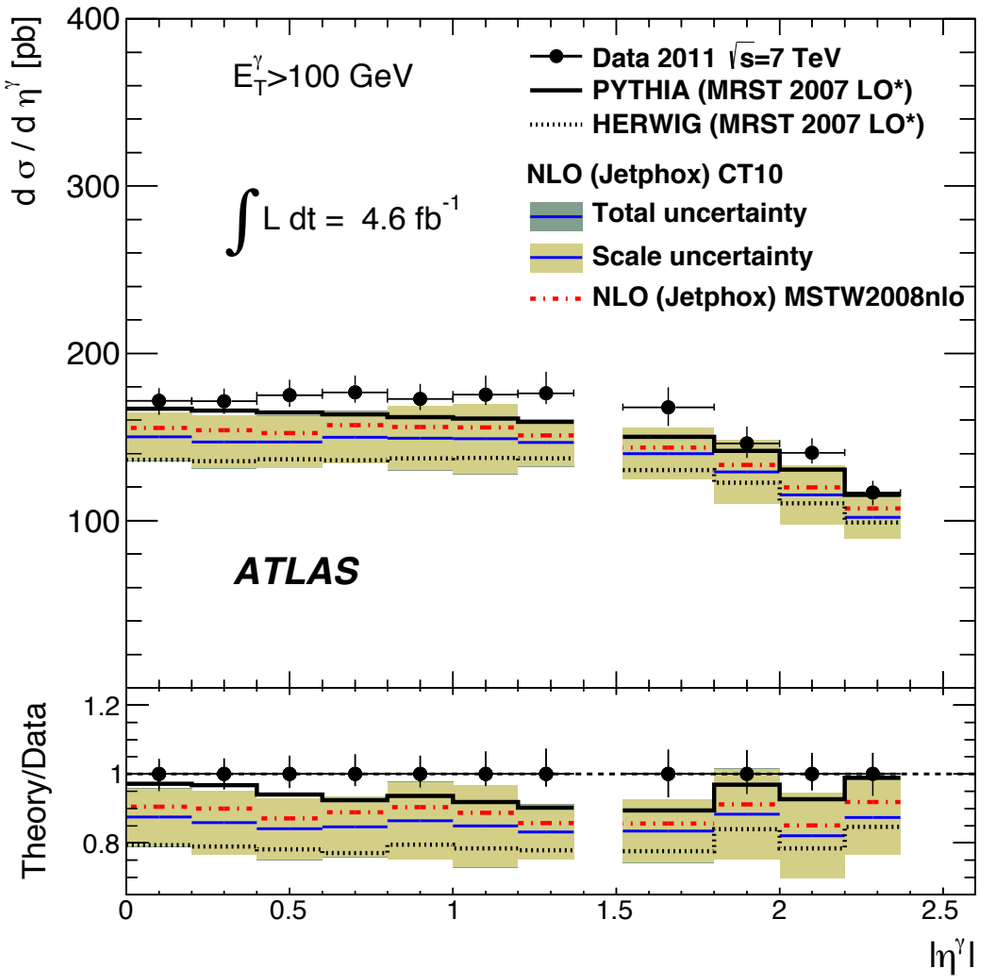
BACKUP

Promt Photon Production

- Promt, isolated photon production cross section
- Shape well described by Pythia and Herwig
- Absolute cross section predicted lower than measuremed
- PDF uncertainties become important for high E_T
- Good agreement with NLO pQCD predictions



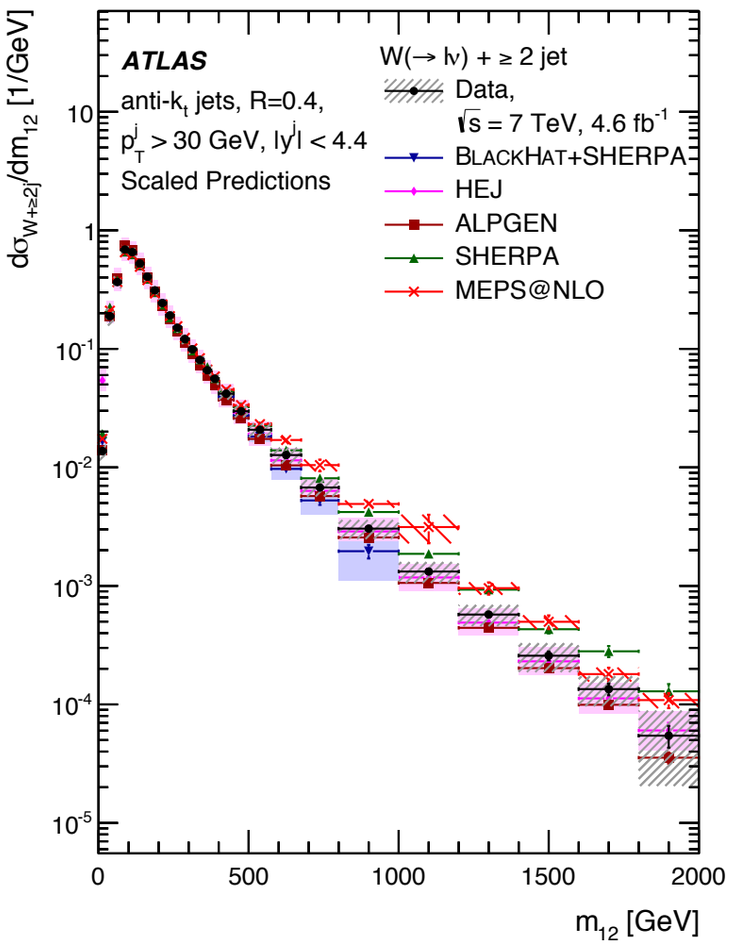


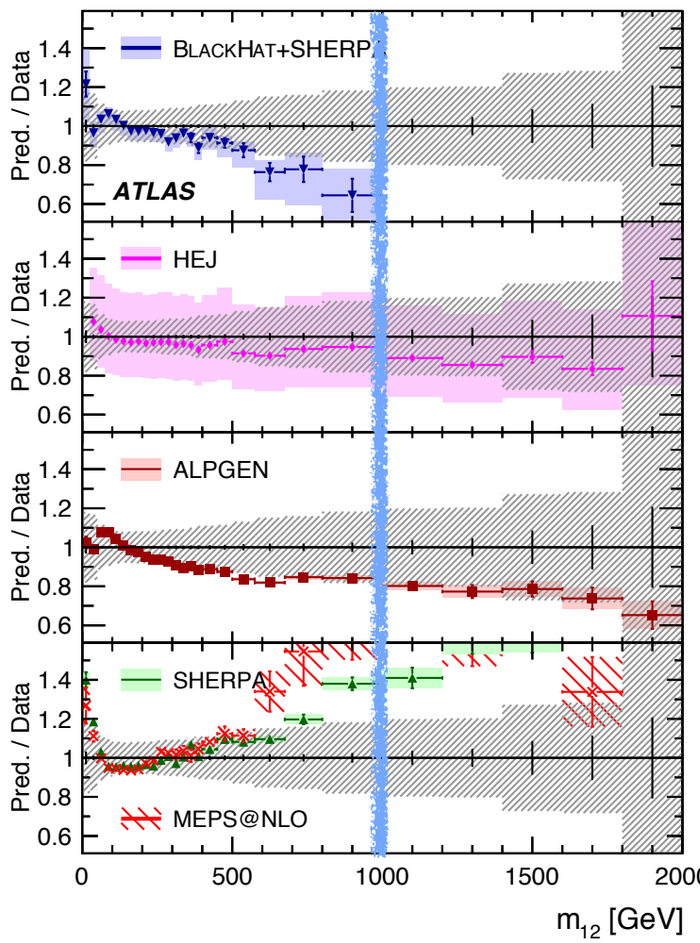


Invariant di-jet mass

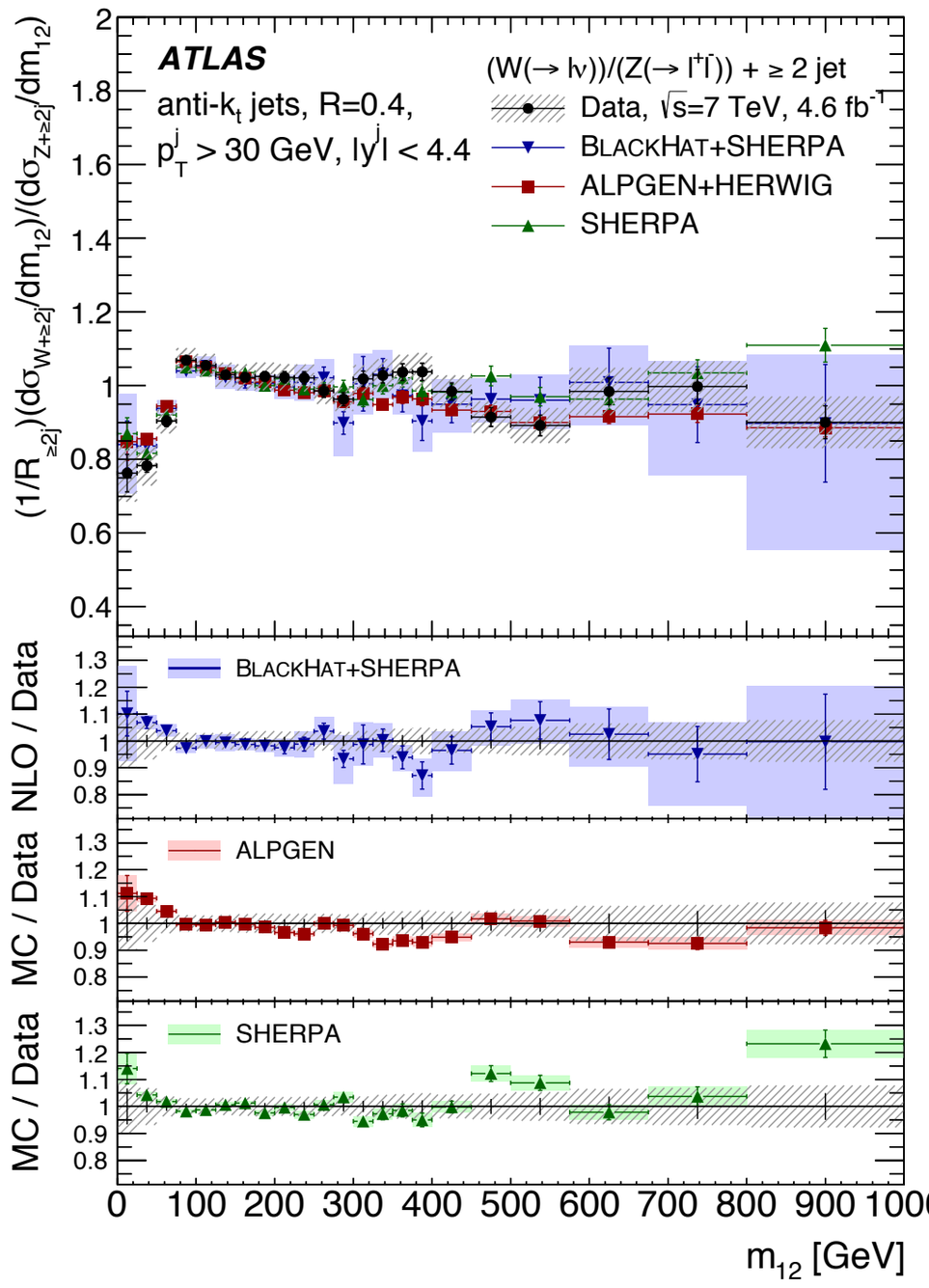
- Ratio well described by all generators
- Good description by HEJ for single channel

$W \longrightarrow \ell\nu$

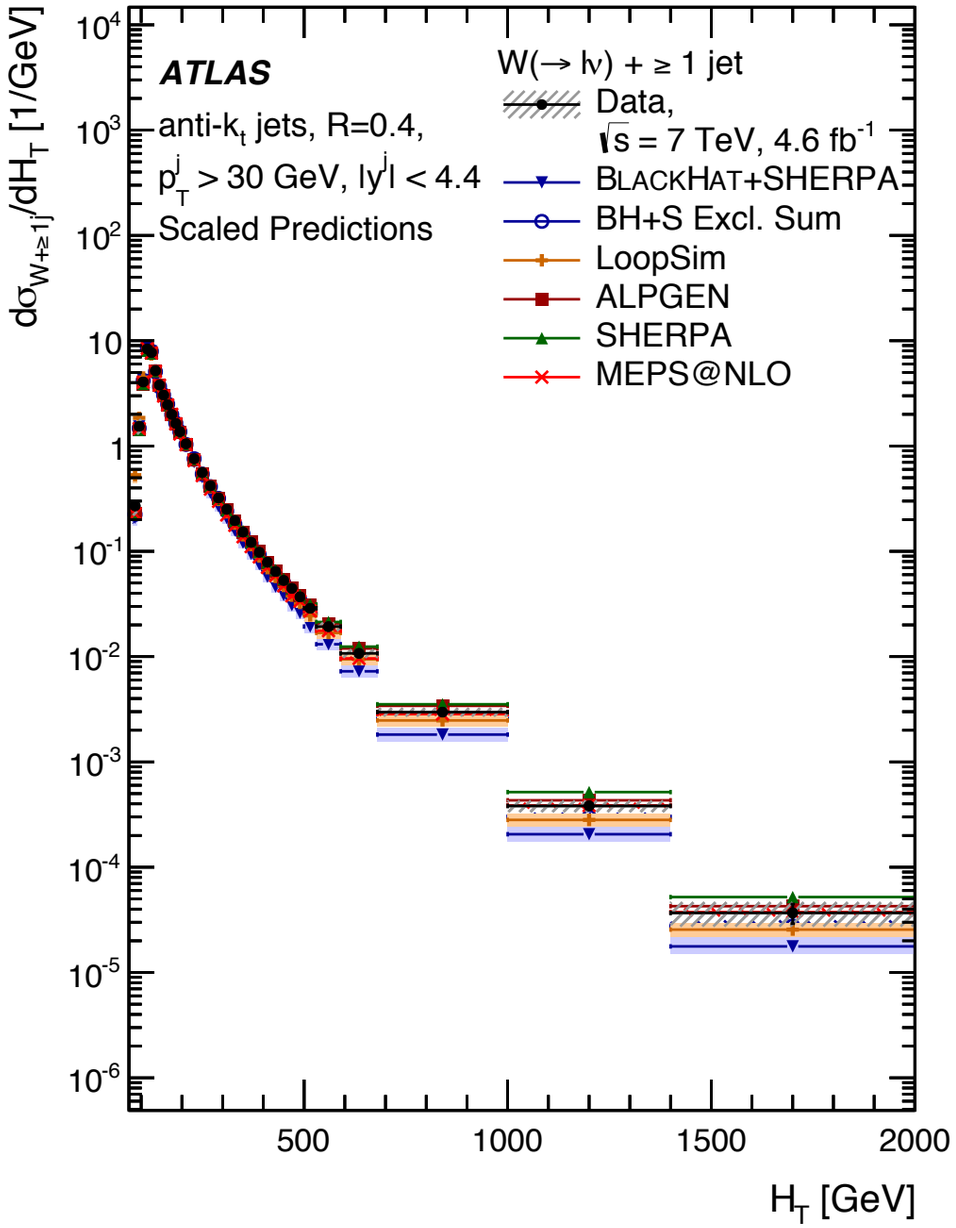


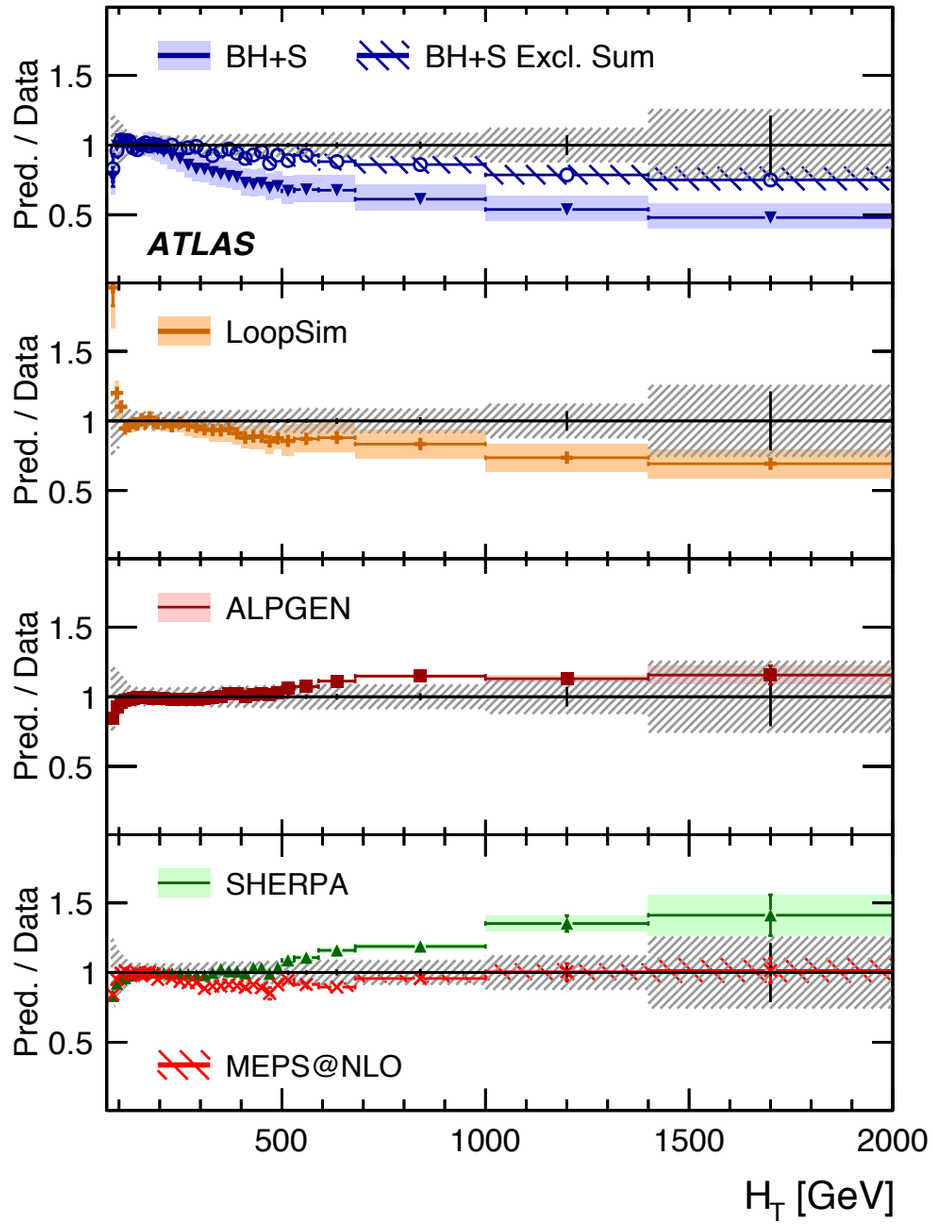


Ratio measurement

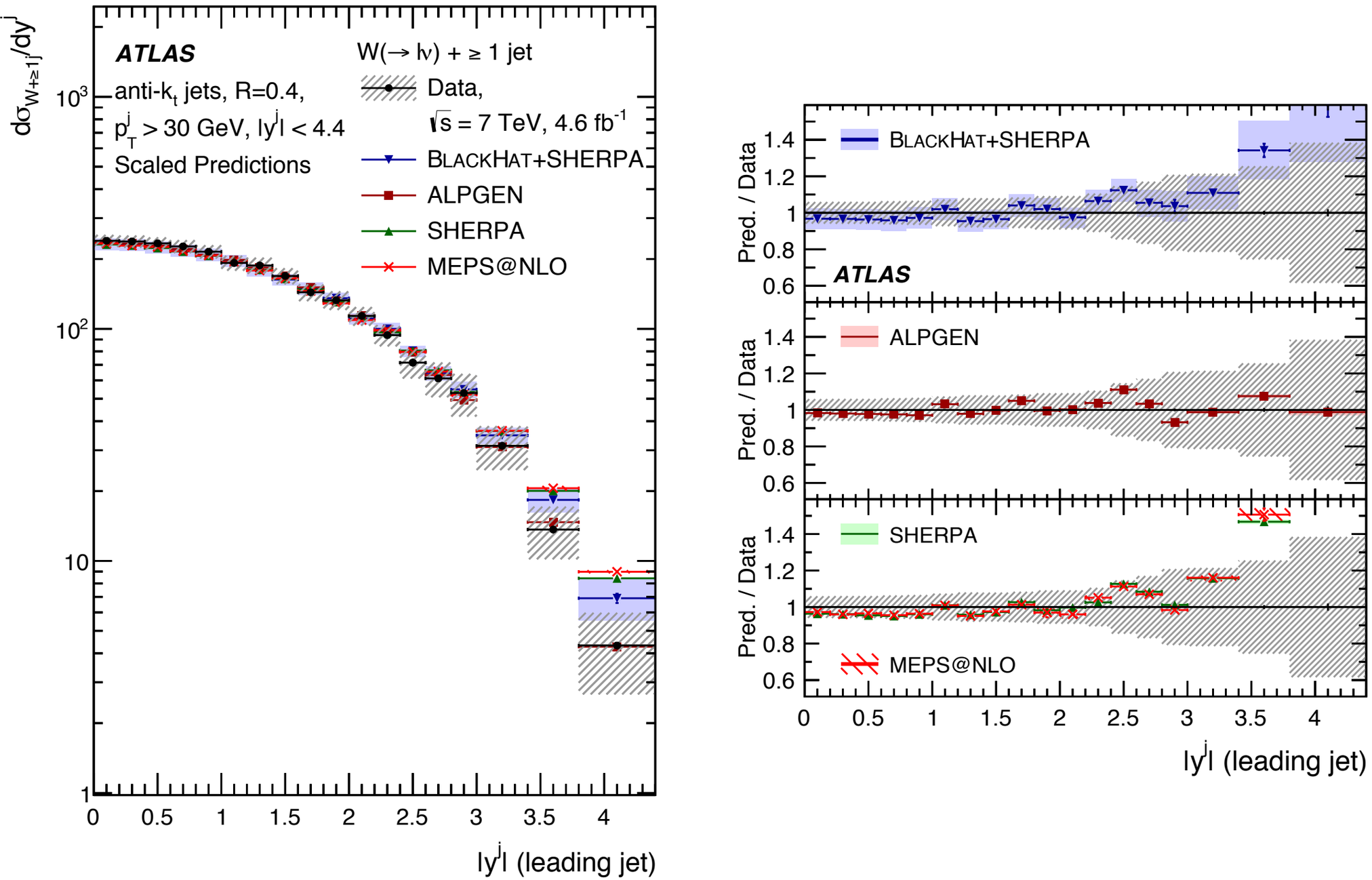


Inclusive Jets - H_T





Inclusive Jets - Rapidity Leading Jet

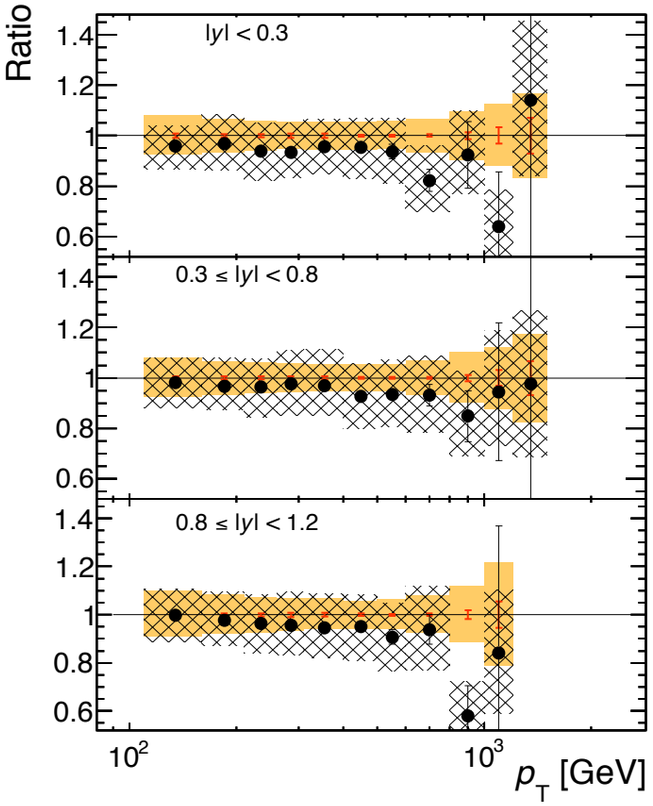


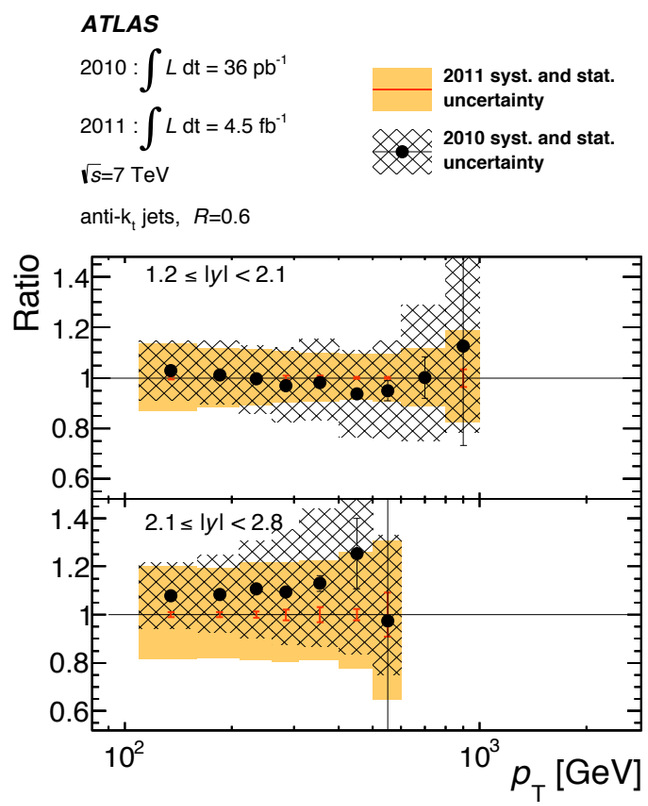
Inclusive Jets Double Differential Measurement

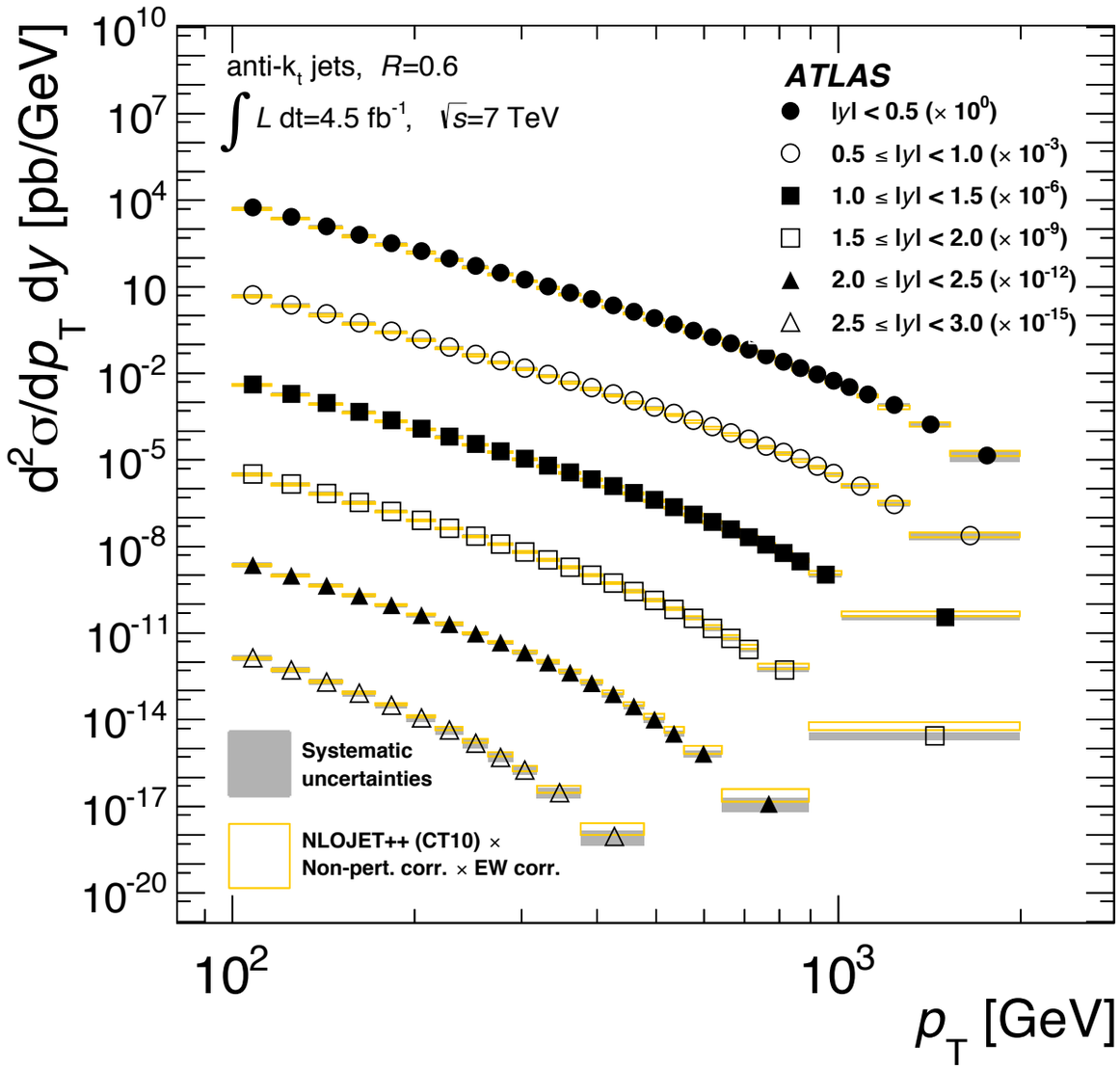
- Anti-k_t reconstruction algorithm, radius R=0.6
- Jets calibrated using local hadronic calibration weights (LCW)
- $p_T > 100$ GeV & $|y| < 3$

- Data from 2011 and 2010 are consistent

- NLOJET prediction matched well with double differential measurement







Impact of PDFs

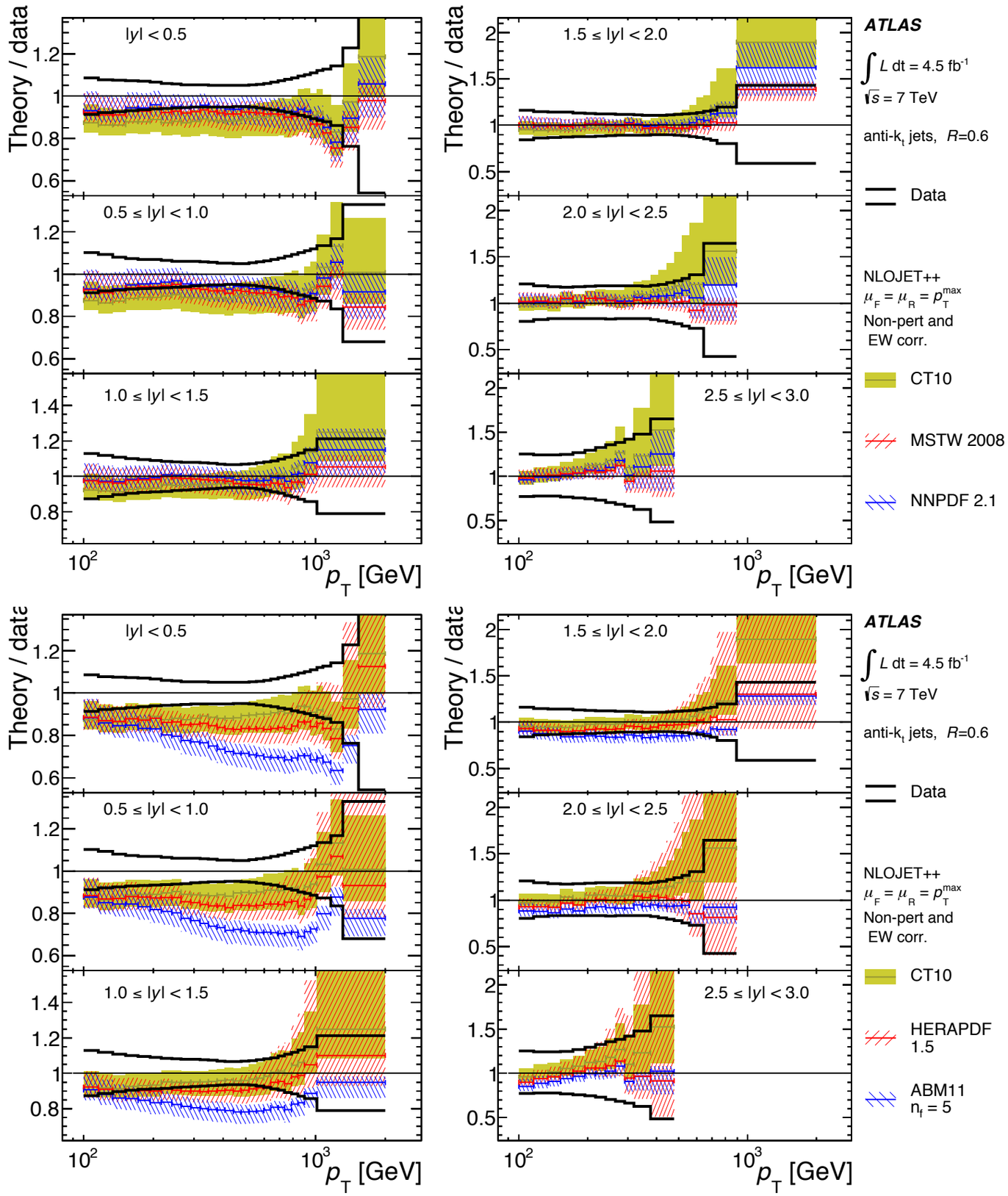
- Dominant systematic uncertainty:
  - Jet Energy Scale

- Data compared to NLOJET prediction with several different PDF sets (including corrections for non perturbative and electroweak effects):

  - Only ABM11 PDF shows significant deviations from measured values

  - Fairly good agreement for all other tested PDF sets

- Similar results for R=0.4



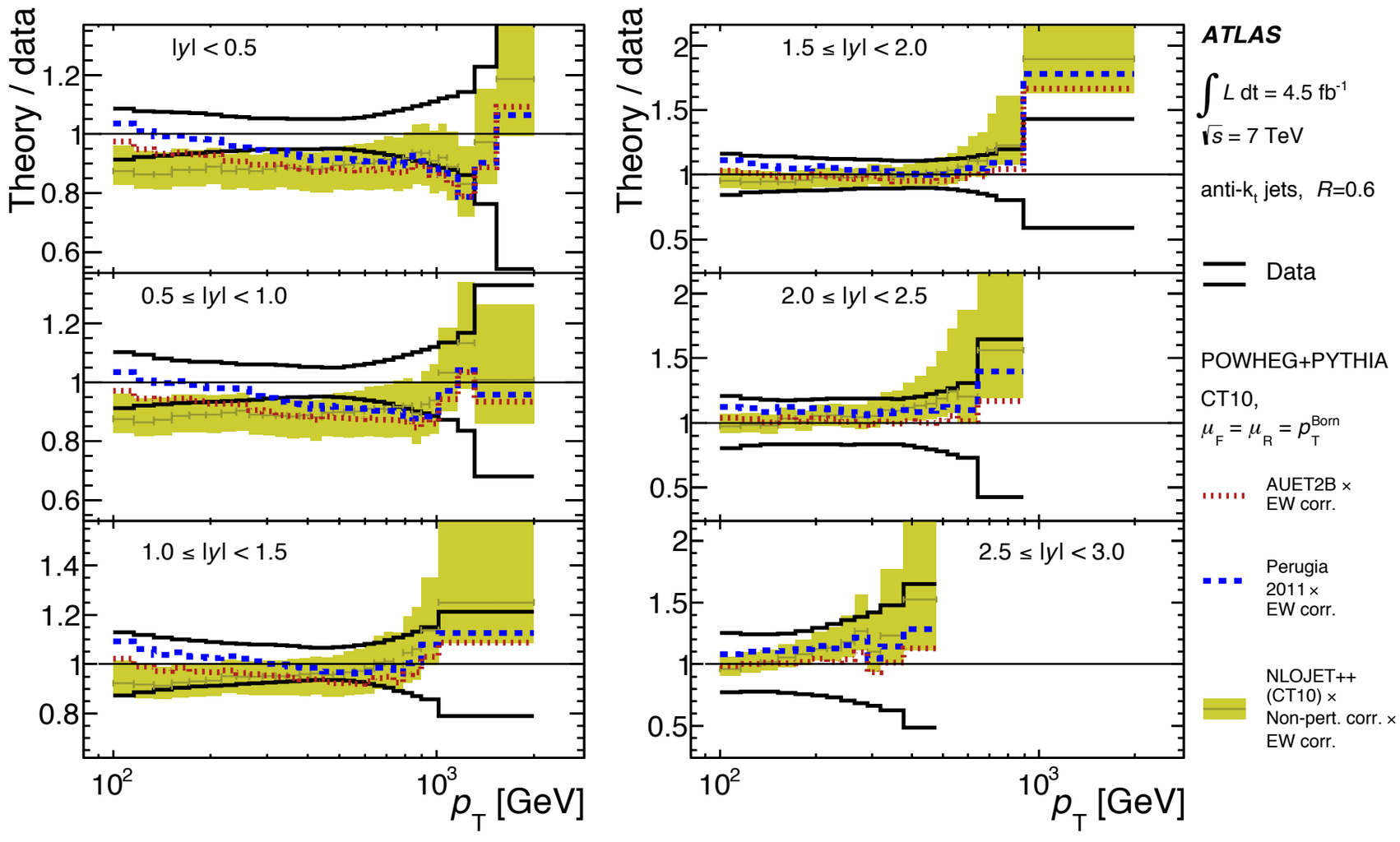
ME element generator vs. pQCD calculation

- Comparison of Perugia 2011 and AUET2B tunes

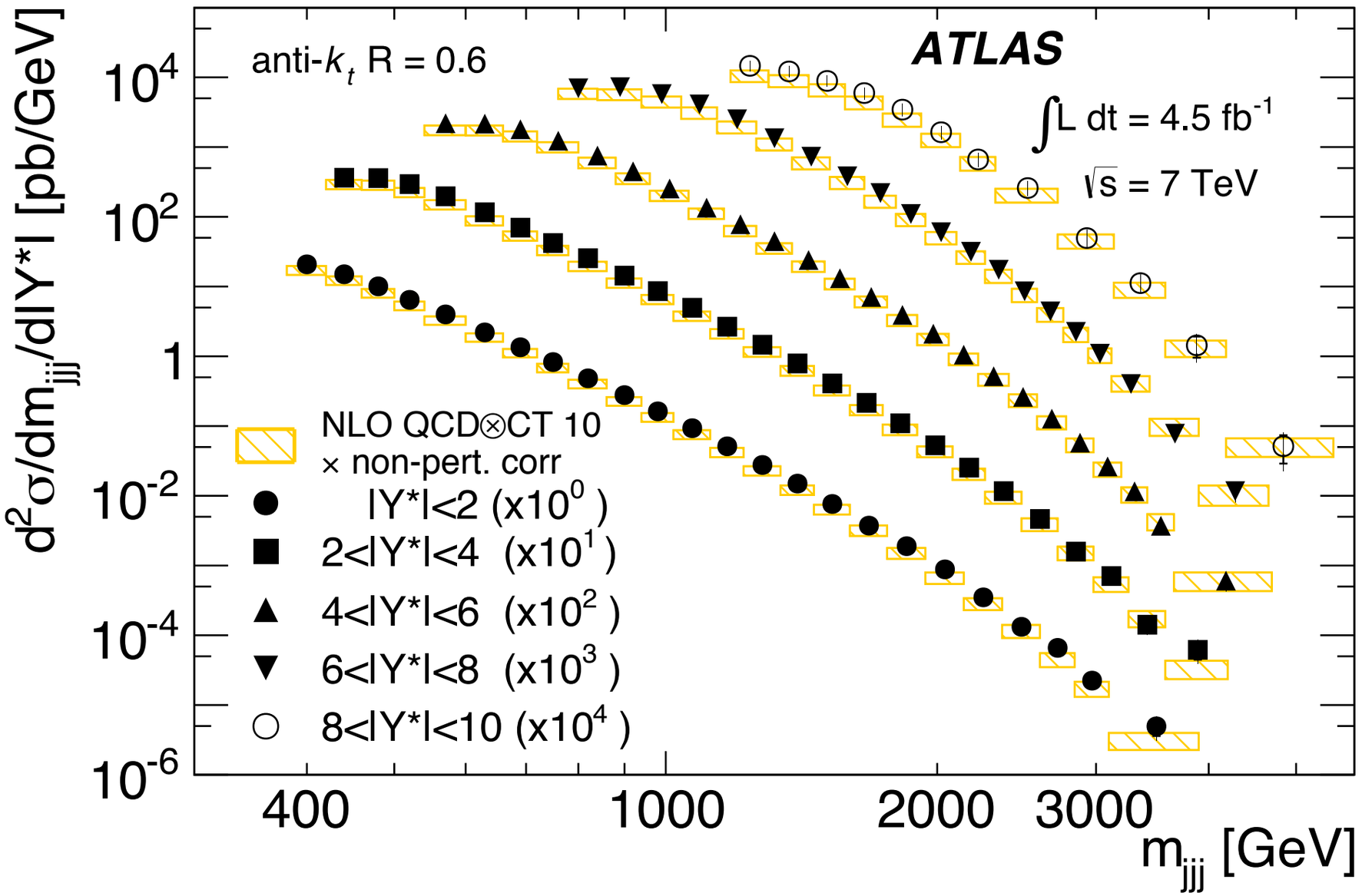
  Perugia tune yields consistently larger cross section prediction than AUET2B

- Shape well reproduced by POWHEG

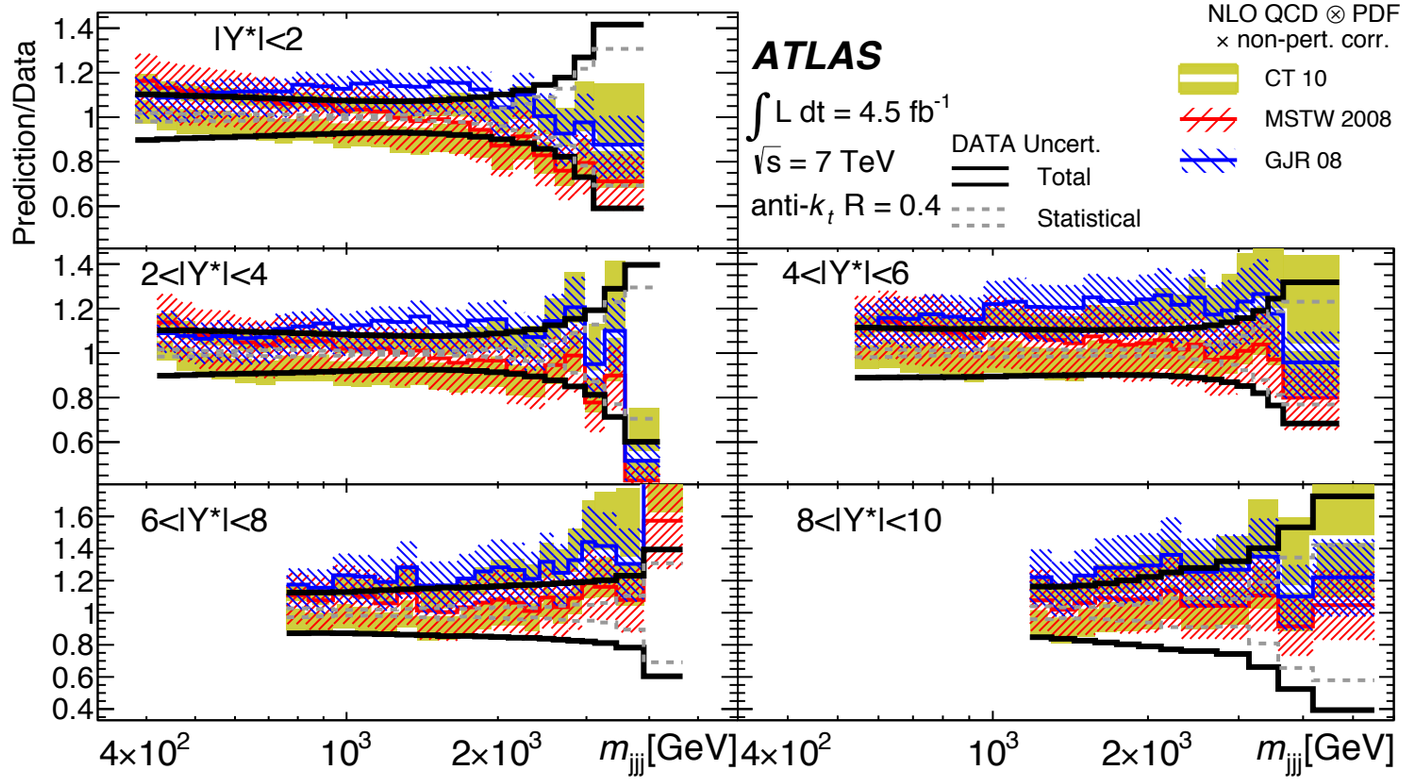
- Similar Results for R=0.4

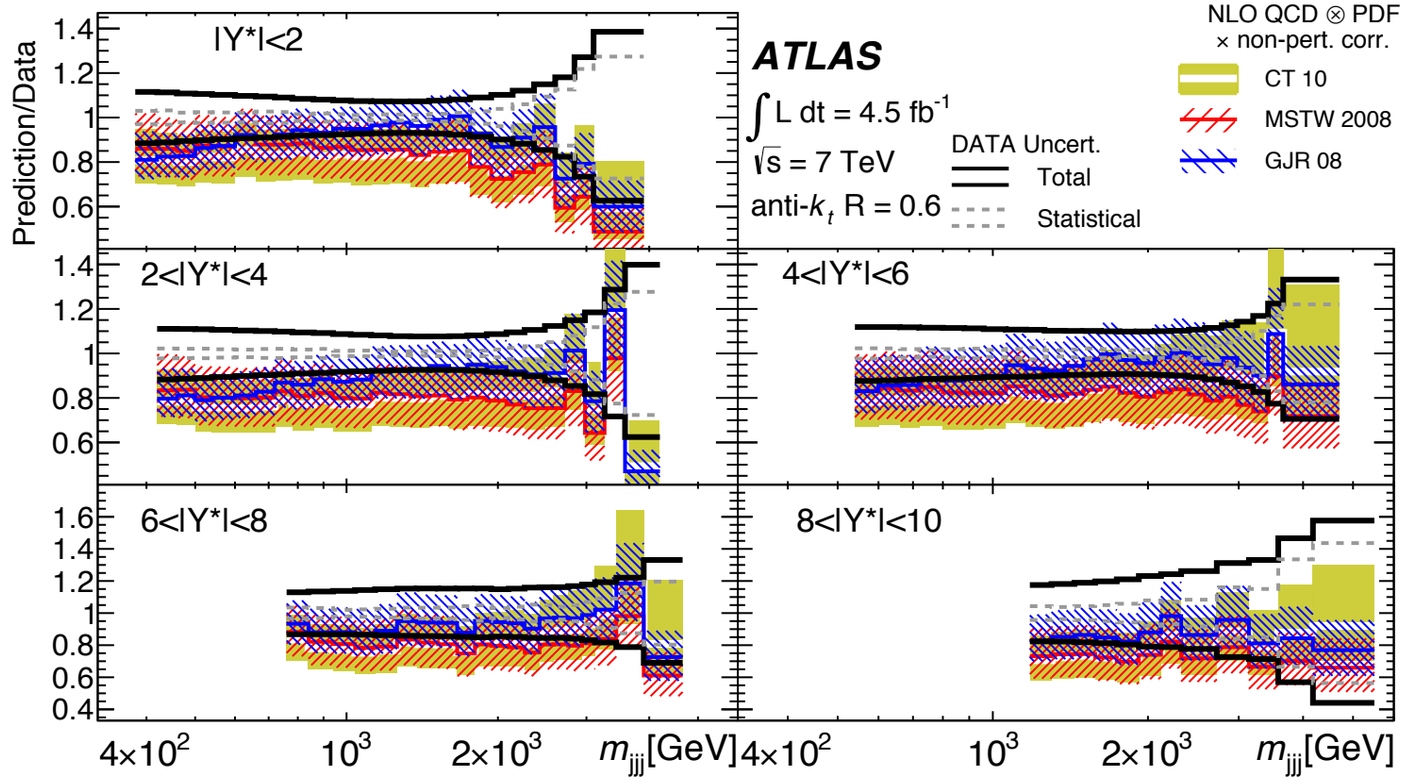


3 Jet Production - R=0.6



3 Jet Production - more PDFs



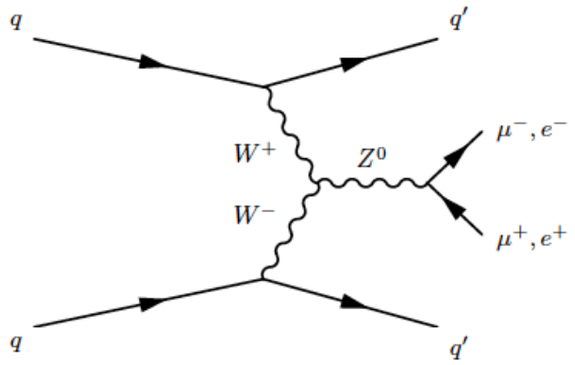


Electroweak production of V+jets

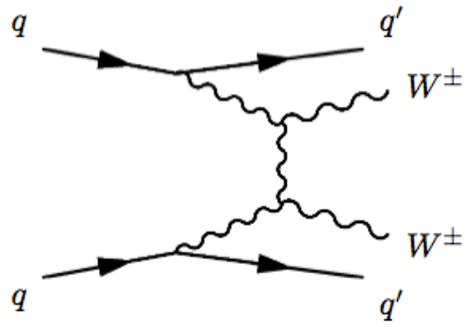
Motivation - EWK production

- Production via purely electroweak processes is rare
  - Mainly interested in:

Vector Boson fusion



Vector Boson scattering

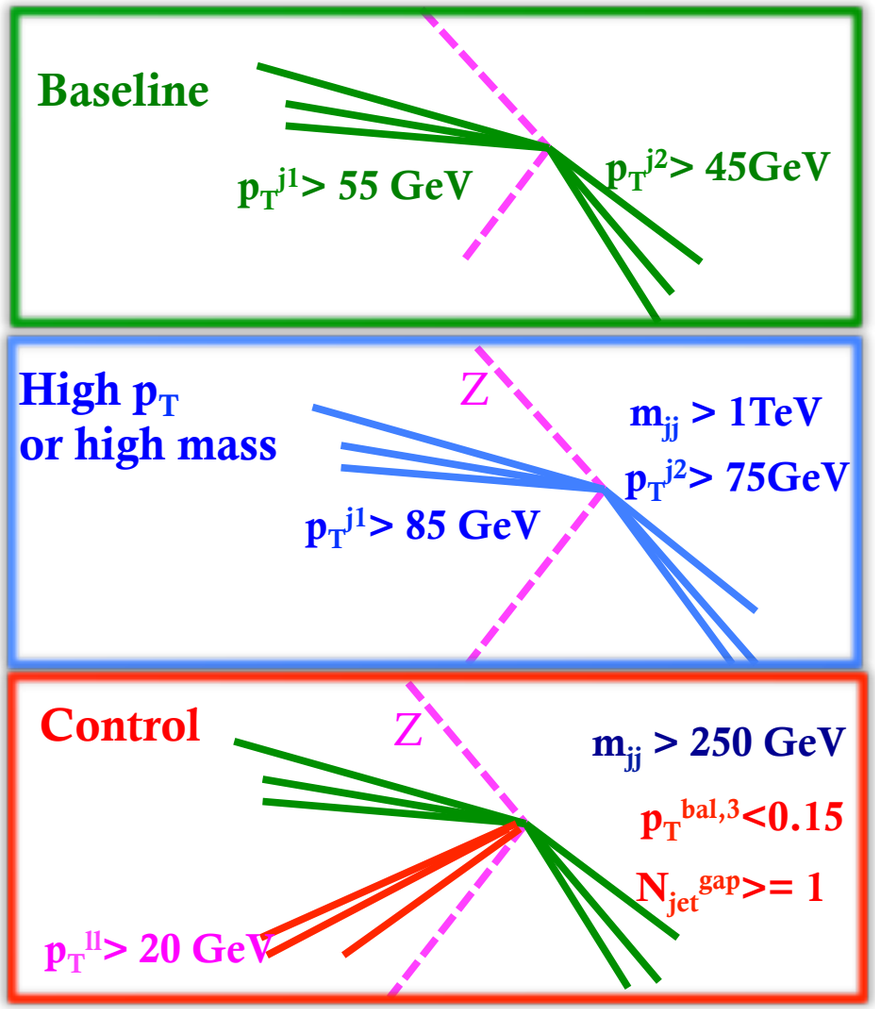


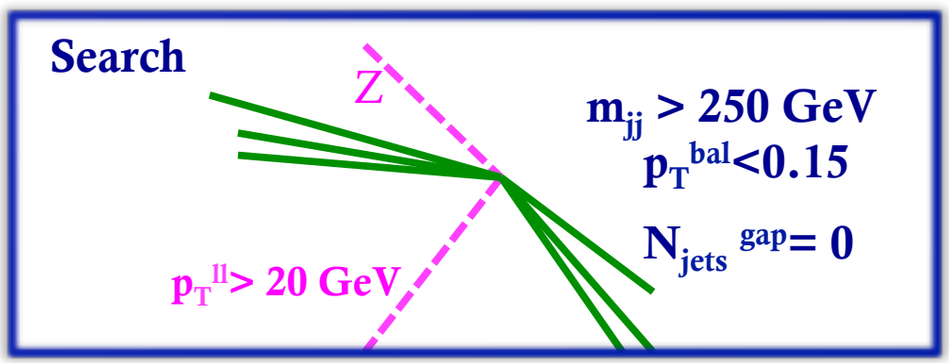
- What we can learn from them?
  - Probe triple and quadratic gauge boson self-interactions
    - Can be used in a model independent approach to explore new physics, that modifies gauge boson self-interactions (anomalous couplings)
  - Probe the nature of the EW symmetry breaking, testing the unitarization in VV scattering by HVV contribution (VBS)
  - Understand irreducible background to Higgs and beyond-SM searches
    - Constrain MC modeling of QCD-initiated processes in VBF-like regions

Zjj:VBF - strategy of measurement

- Measure inclusive (QCD+EW) Zjj cross section and differential distributions in 5 fiducial regions with varying sensitivity to the EW component:

  - 3 regions with simple topologies:
    - "baseline"
    - "high pT" and "high mass"
      - probe impact of EW component
  - 2 ad hoc selections:
    - "search region" and "control region"





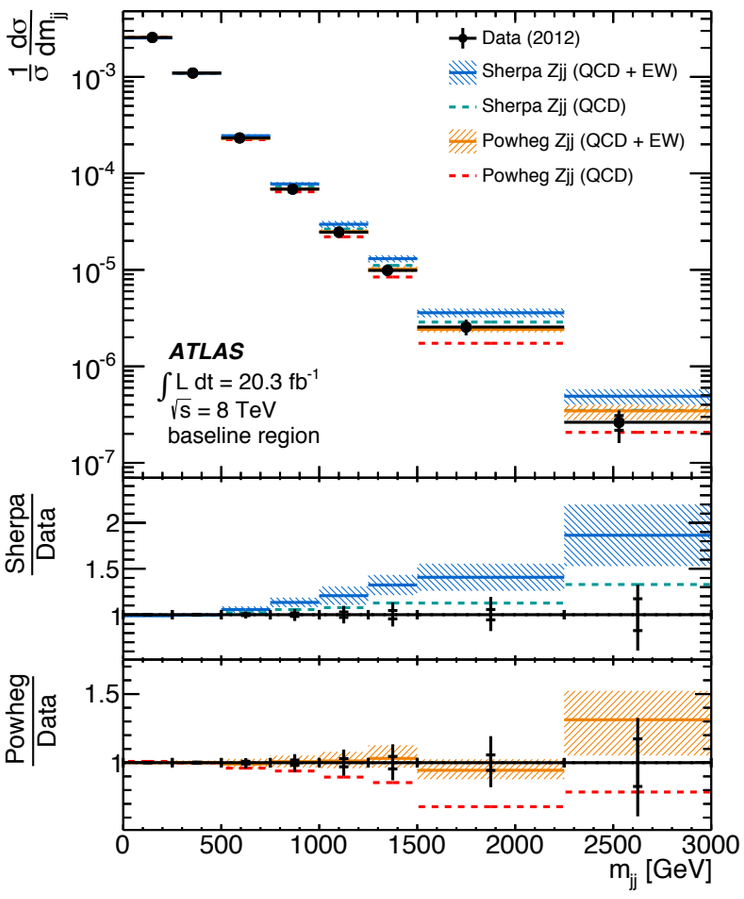
- Extract electroweak component cross section from "search region", constraining background modeling (QCD Zjj) from "control region"

- Set limits on anomalous triple gauge couplings

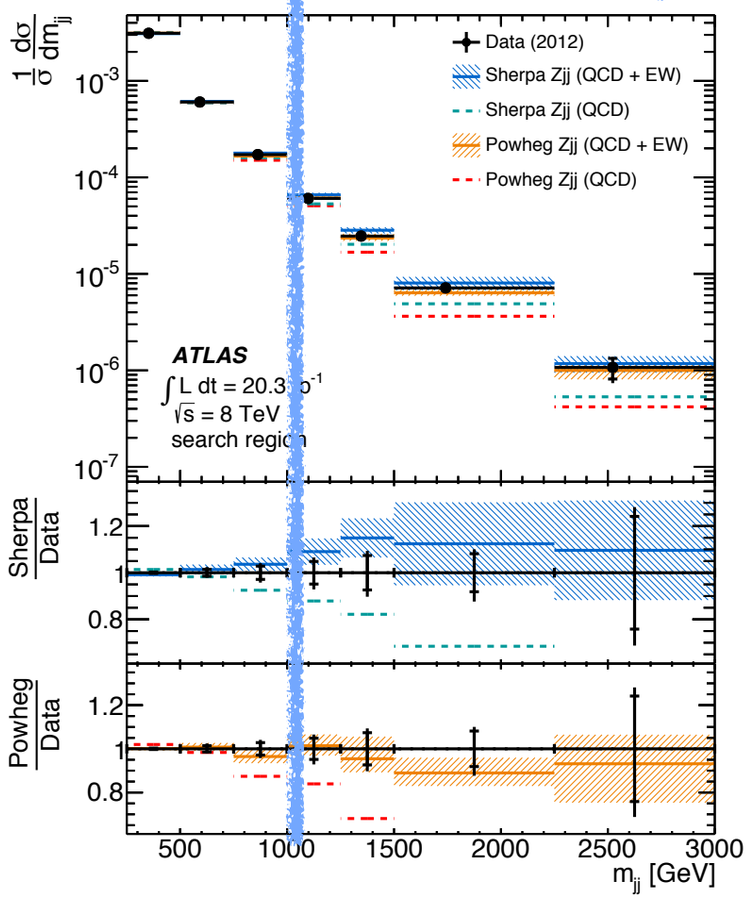
Zjj:VBF - Results

- Electroweak production becomes important!
  - Overestimated in Sherpa
- Sherpa predicts harder mass spectrum
- Powheg is in good agreement with data

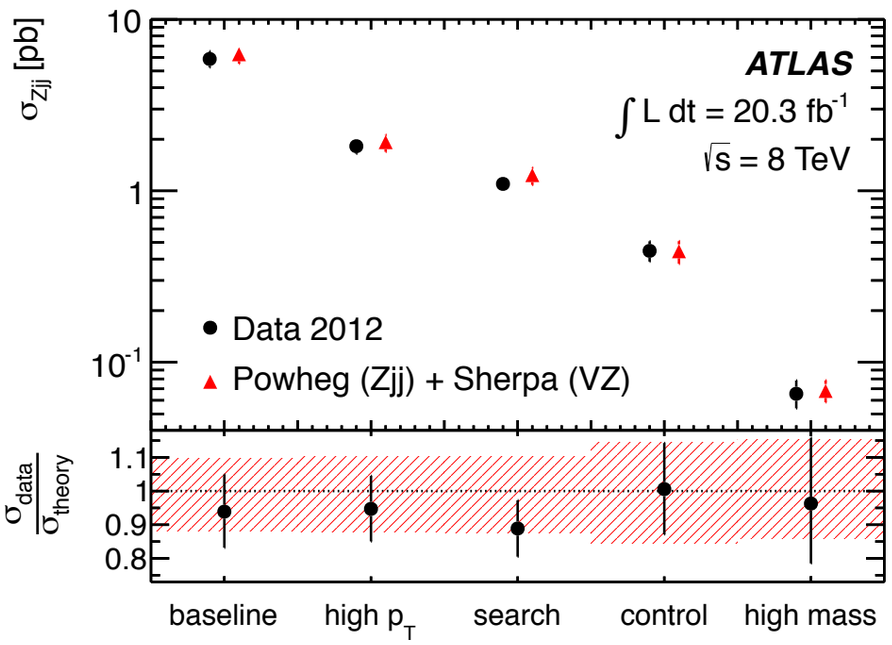
baseline region



search region



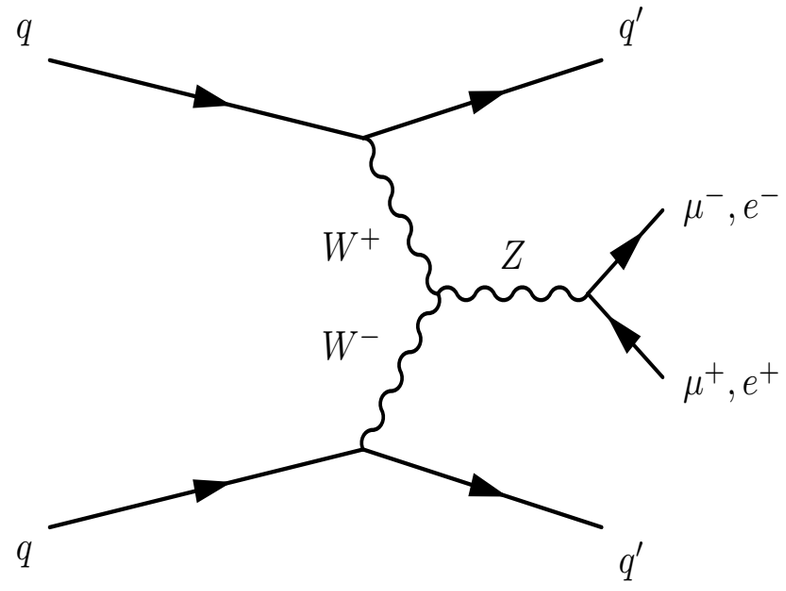
used to get aTGC limits



Limit on anomalous triple gauge coupling

- Zjj sensitive to TGC
  - Sensitivity to new physics modifying gauge boson self-interaction

- Generic aTGC couplings parametrized by effective Lagrangian
  - 3 contributing couplings
    - $g_{1,Z}$, λ_Z, κ_Z



95% confidence intervals

aTGC	$\Lambda = 6$ TeV (obs)	$\Lambda = 6$ TeV (exp)	$\Lambda = \infty$ (obs)	$\Lambda = \infty$ (exp)
$\Delta g_{1,Z}$	$[-0.65, 0.33]$	$[-0.58, 0.27]$	$[-0.50, 0.26]$	$[-0.45, 0.22]$
λ_Z	$[-0.22, 0.19]$	$[-0.19, 0.16]$	$[-0.15, 0.13]$	$[-0.14, 0.11]$

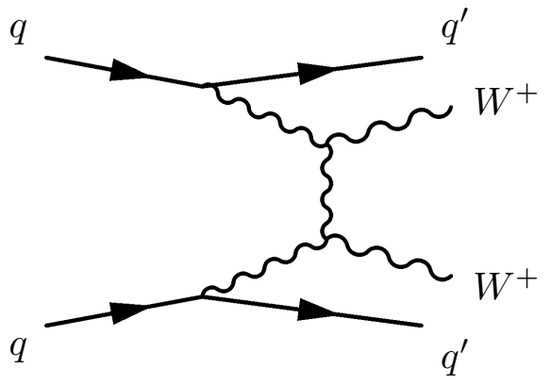
- Limits weaker but complementary than those from di-boson production
  - Di-boson: all 3 bosons have time-like momentum
  - Here 2 W have space-like momentum

Vector Boson scattering

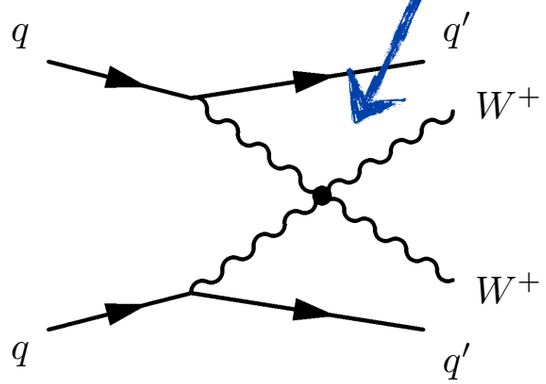
- Strategy of the measurement is about the same as for EW Zjj:
  - Measure inclusive (QCD+EW) $W^{\pm}W^{\pm}jj$ cross section in 2 fiducial regions
    - ("inclusive region" and "VBS region"): varying sensitivity to the EW component
- Extraction on the EW $W^{\pm}W^{\pm}jj$ production from the "VBS region"
- Set limits on anomalous quadratic gauge couplings

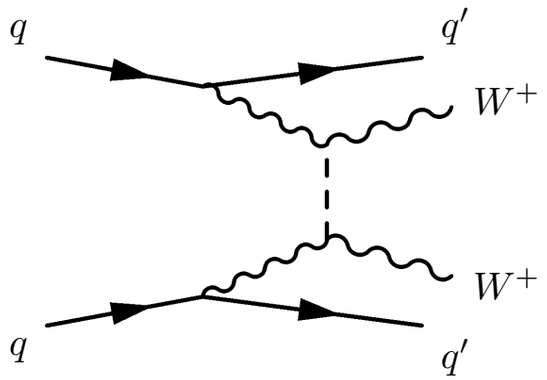
Electroweak process:

Sensitive to anomalous quartic gauge couplings

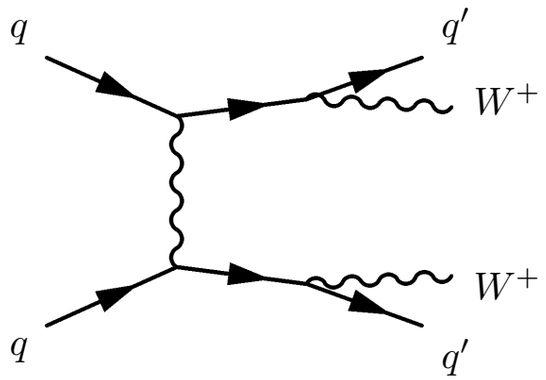


Self-interaction





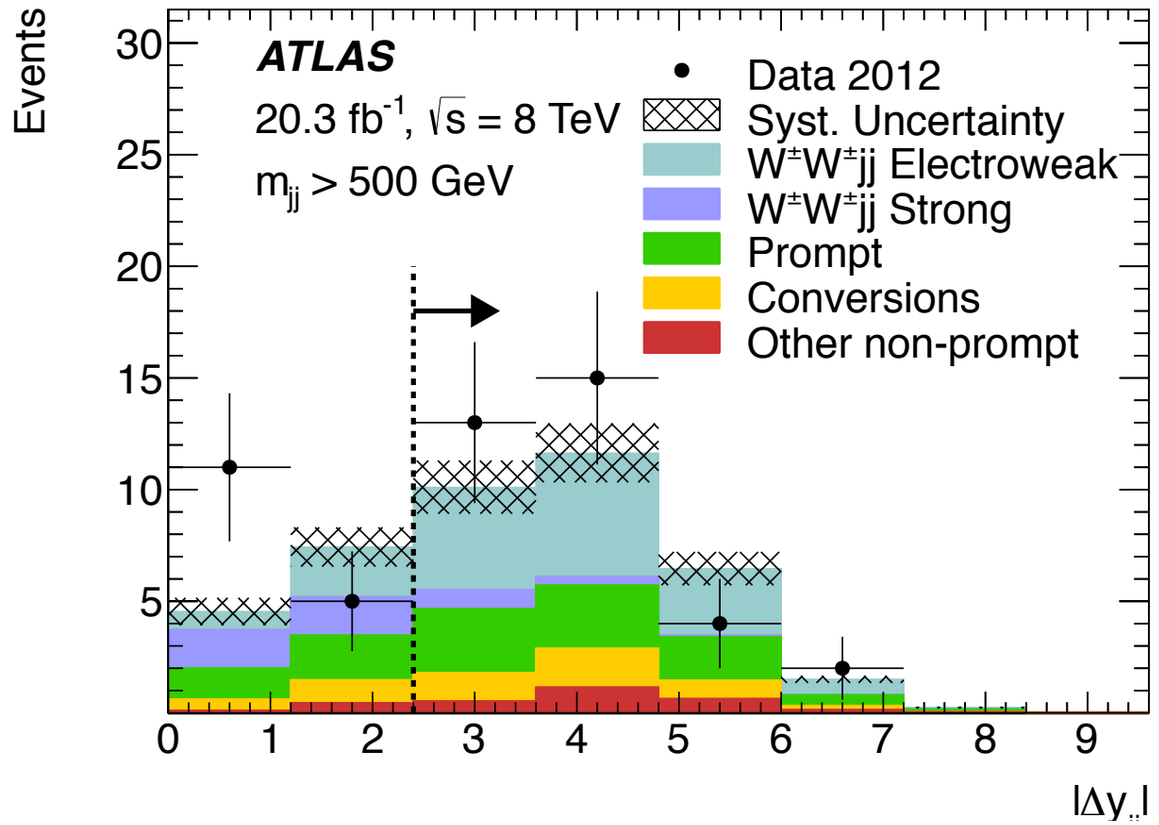
Higgs contribution



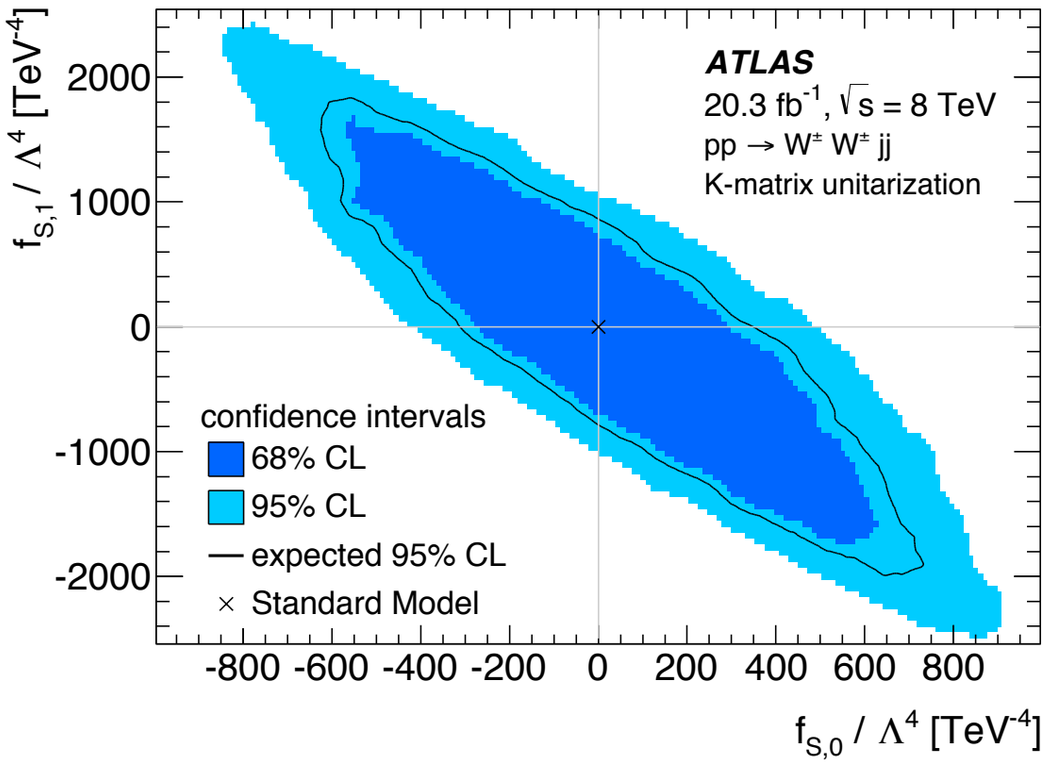
Non resonant

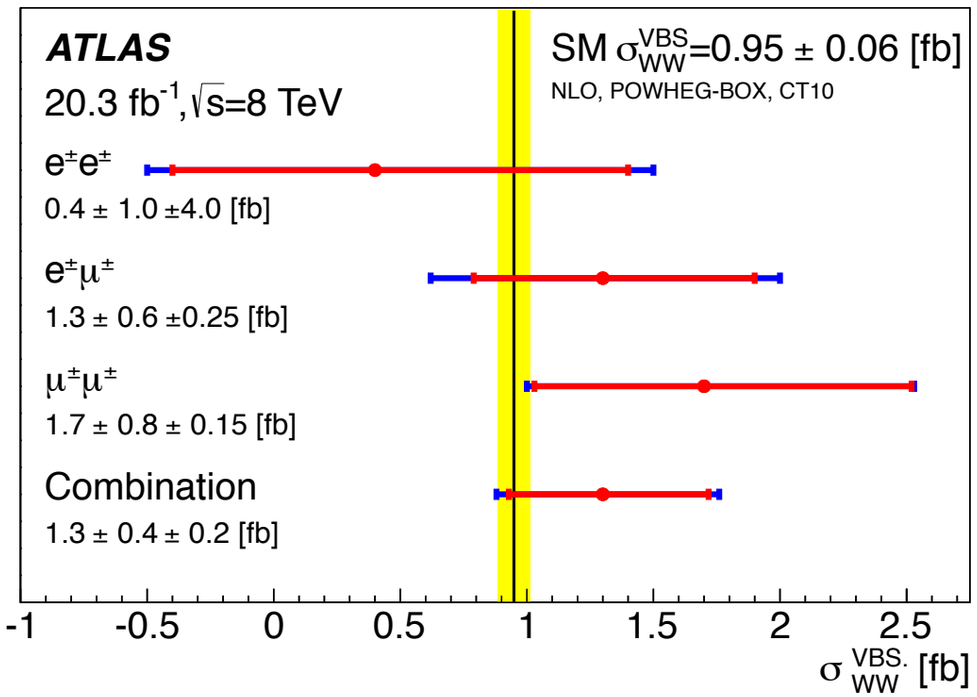
Vector Boson Scattering

- First evidence for VBS
  - BG only hypothesis excluded at 4.5σ
  - Counted 34 events, ~16 BG events
- Measurement in agreement with SM prediction



aQGC interpretation:





Conclusion EWK production

Electroweak prod.: evidence of VBS, sensitive to anomalous coupling

no deviation from SM predictions observed