ATLAS results on jet-related physics with V+jets

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on behalf of the ATLAS Collaboration

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Motivation

- Studying jets with V(W/Z bosons)+jets events:
  -- W/Z bosons decaying to leptons provide a clear experimental signature at a hadron collider, which can be used as a probe of the underlying collision processes at a large scale (O(Mw, Mz))
  → Test of perturbative QCD (pQCD)

- High statistics of LHC data will allow a comprehensive exploration
  -- on various QCD aspects, for instance
    * Choice by scale, matrix element (ME) / parton shower (PS) matching, flavor schemes, etc.
  -- at a large phase space, for instance
    * Jet multiplicities > 5
    * Jet p_T in TeV range
  -- by comparing the precise data with a large variety of theory predictions which have been recently rapidly advanced, for instance
    * NLO calculations up to W+5 partons
    * NNLO for W/Z + 1 parton
    * NLO MC matched to PS
    * Resummation

See backup slides for a list of predictions/models shown in this talk

Contents of this talk

- **Test of pQCD**
  - -- Z + jets cross sections (JHEP 07 (2013) 032)
  - -- W + jets cross sections (Eur. Phys. J. C (2015) 75:82)
  - -- σ(W+jets)/σ(Z+jets) cross sections (Eur. Phys. J. C (2014) 74:3168)

- **Inputs for Parton Distribution Functions (PDFs) fits, test of pQCD**
  - -- W + c-jet, W + D/D* (JHEP05 (2014) 068)
    - → s-quark PDF
  - -- Z + b-jets cross sections (JHEP10 (2014) 141)
    - → b-quark PDF, g→bb splitting

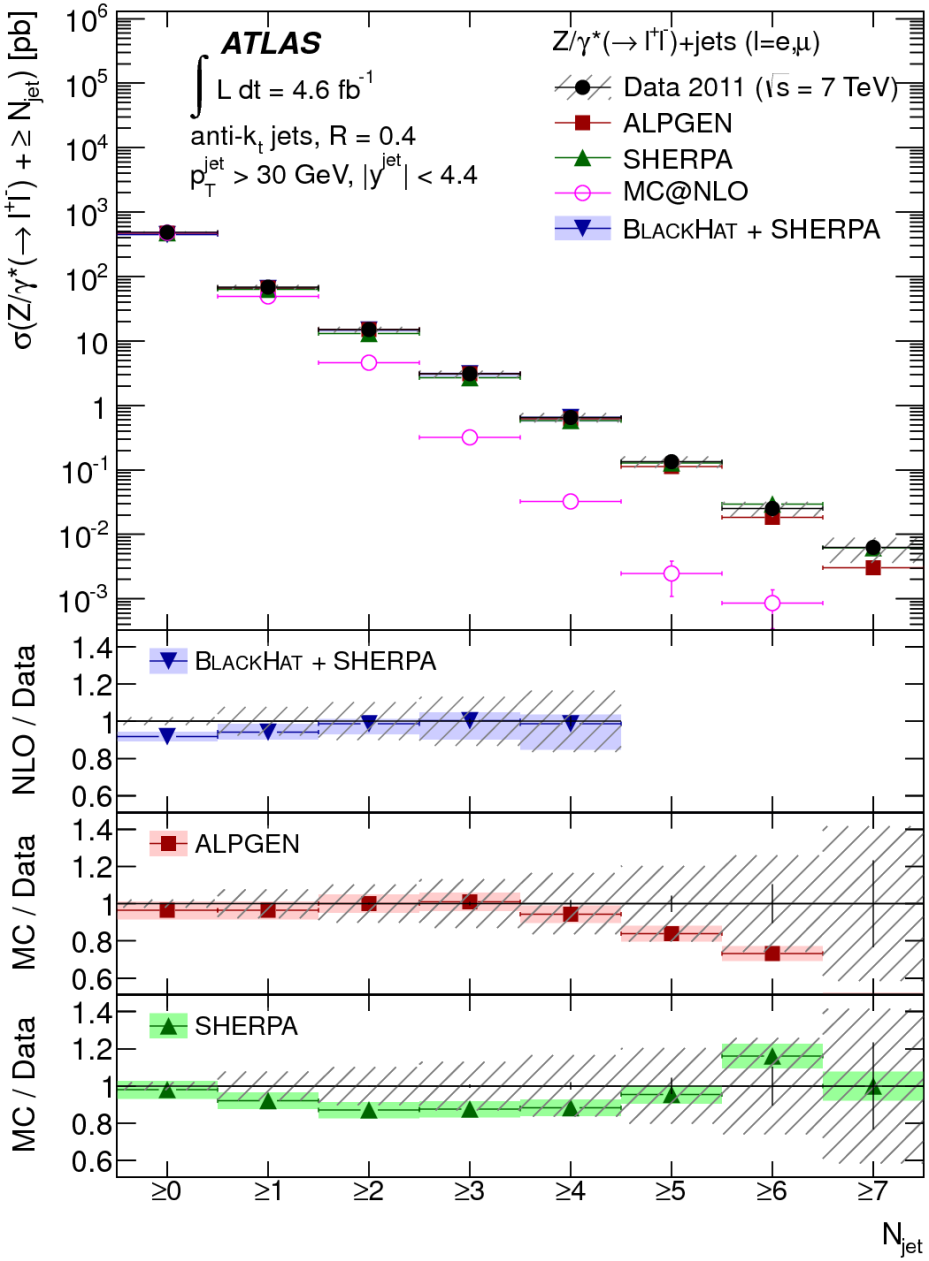
  See backup slides

- **Fresh results from 13 TeV pp collisions ("Run2")**
  - -- Z + jets (ATLAS-CONF-2015-054) ← *NEW AT THIS CONFERENCE!*

JHEP07 (2013) 032

Reminder: Z+jets

σ(N jets)



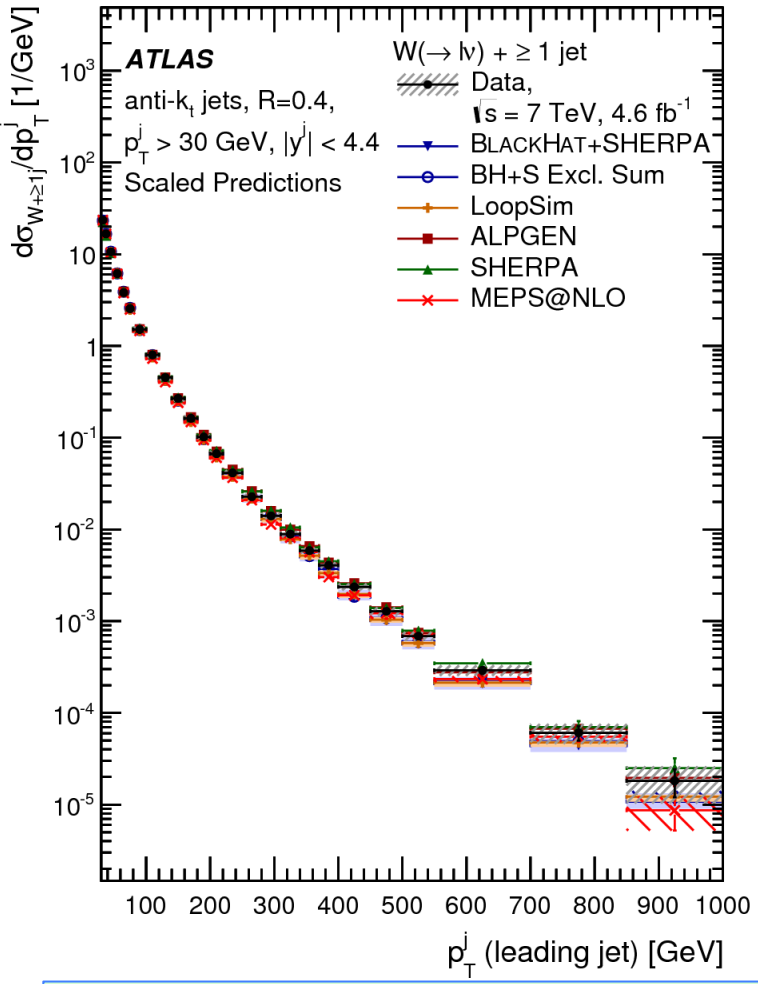
- Multi-parton LO + PS
  -- ALPGEN
  -- SHERPA
- NLO ME + PS
  -- MC@NLO
- Fixed-order calculation
  -- Blackhat +SHERPA
    * NLO (QCD one-loop ME) for V+up to 5 jets

Data have discriminating power among models/theories (MC@NLO fails to describe)

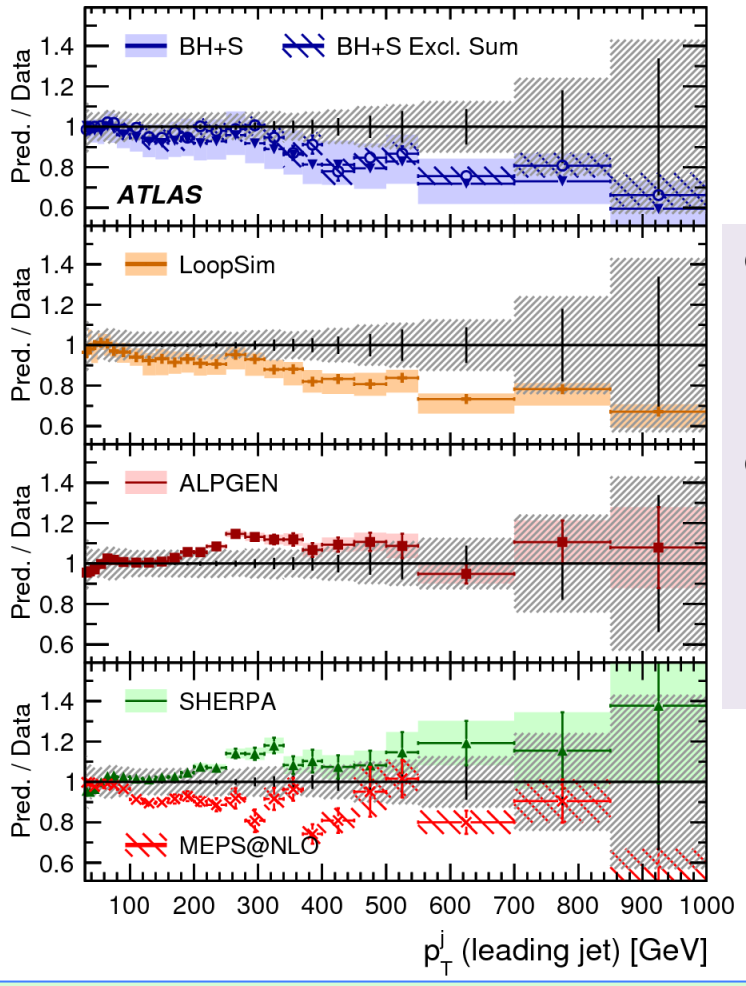
EPJC (2015) 75:82

W+jets: p_T of leading jet

Cross section



Prediction / Data



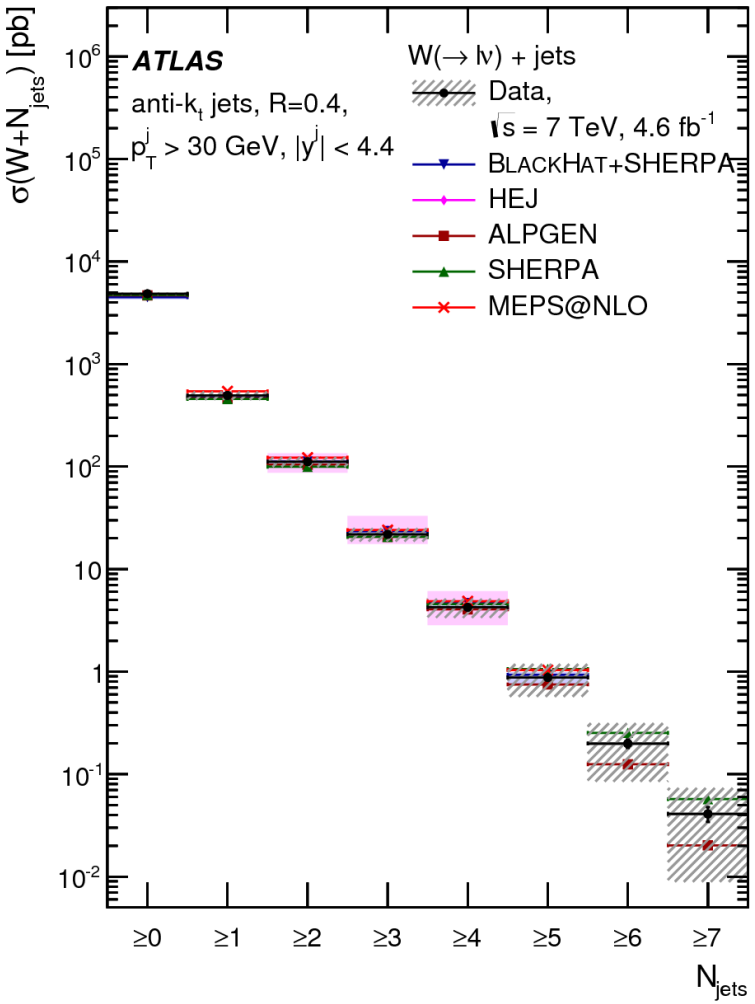
- LoopSim -- Approx. NNLO
- MEPS@NLO -- NLO for V+up to 2 partons merged to PS

- Measured until leading jet p_T ~ 1 TeV
- Blackhat+SHERPA ("BH+S" in the figure) and LoopSim underestimate at high p_T where higher-order is expected to be significant.

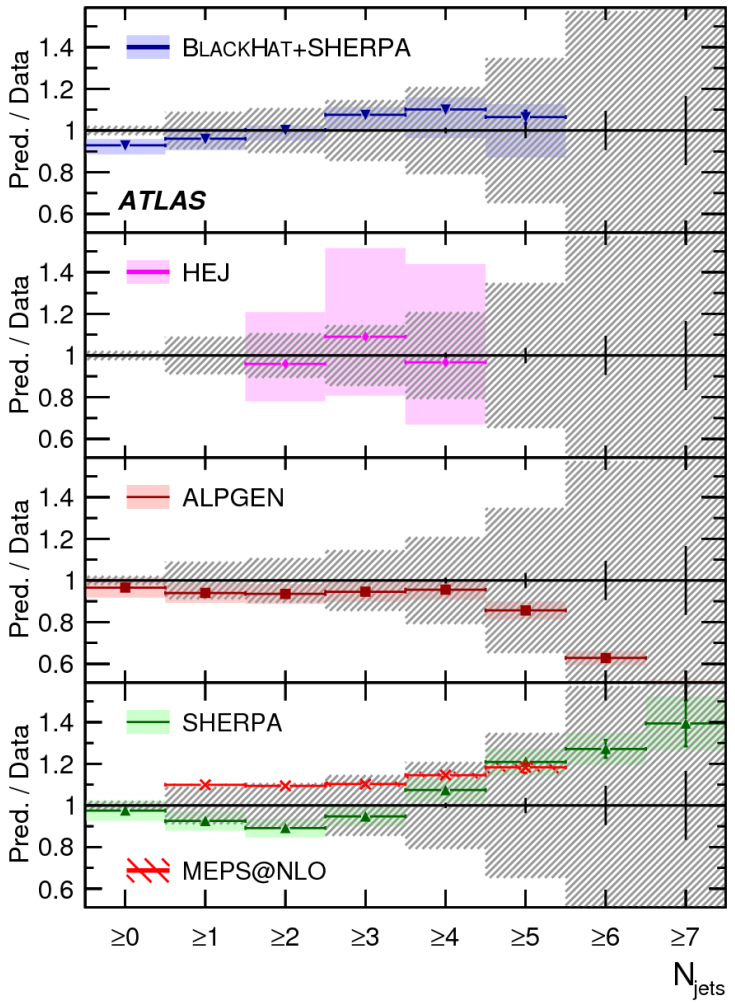
EPJC (2015) 75:82

W+jets: number of jets

Cross section



Prediction / Data

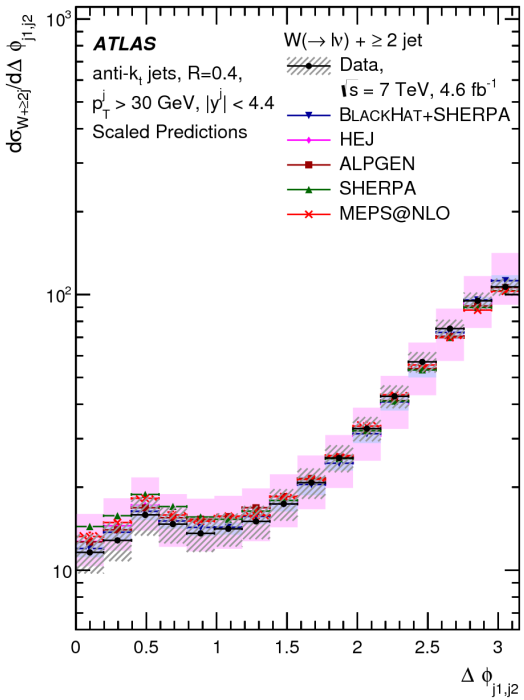


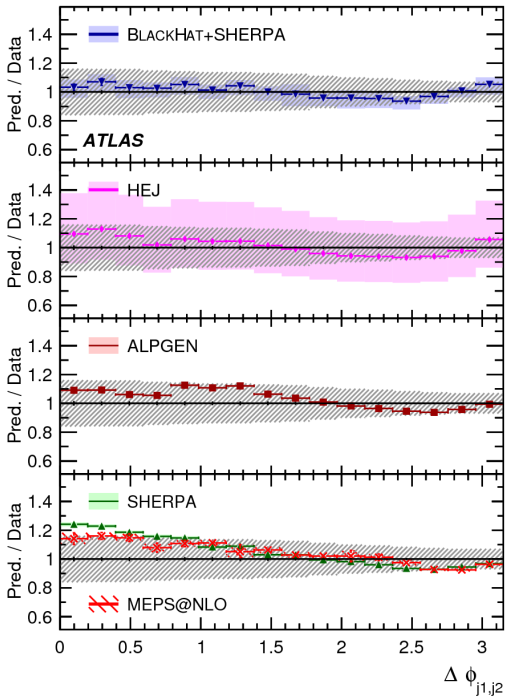
- HEJ Resummation

- Measured up to Njet >= 7
- ALPGEN and SHERPA show different trend at Njet >=5, however within experimental uncertainty

EPJC (2015) 75:82

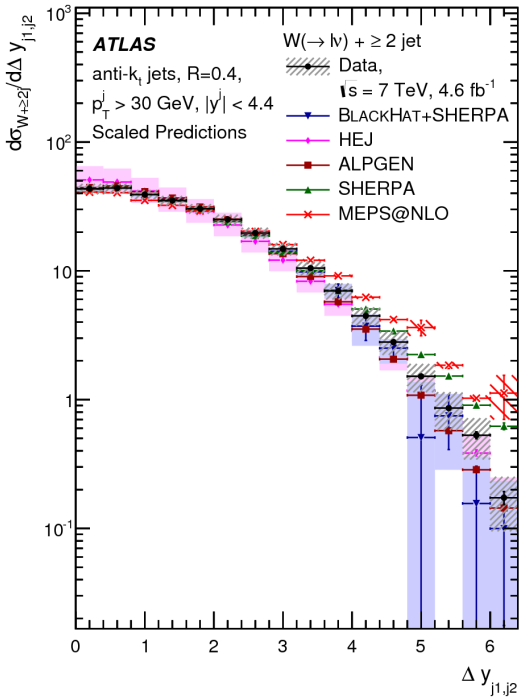
W+jets: angular variables

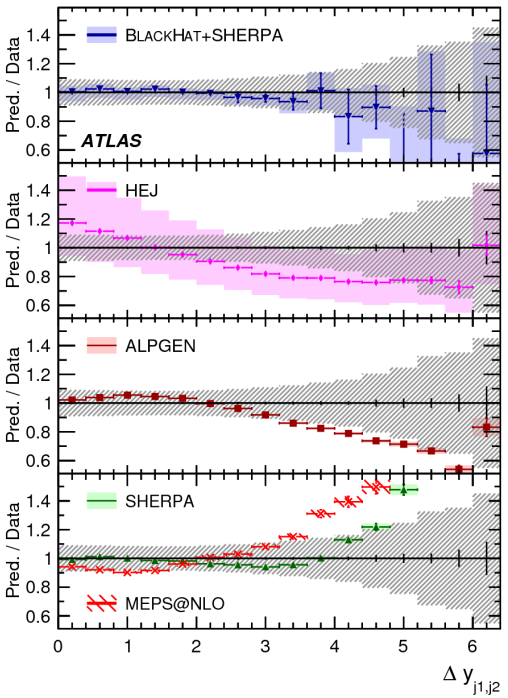




Δφ (j1, j2)

- Tests of hard radiation at large angles and ME/PS matching schemes





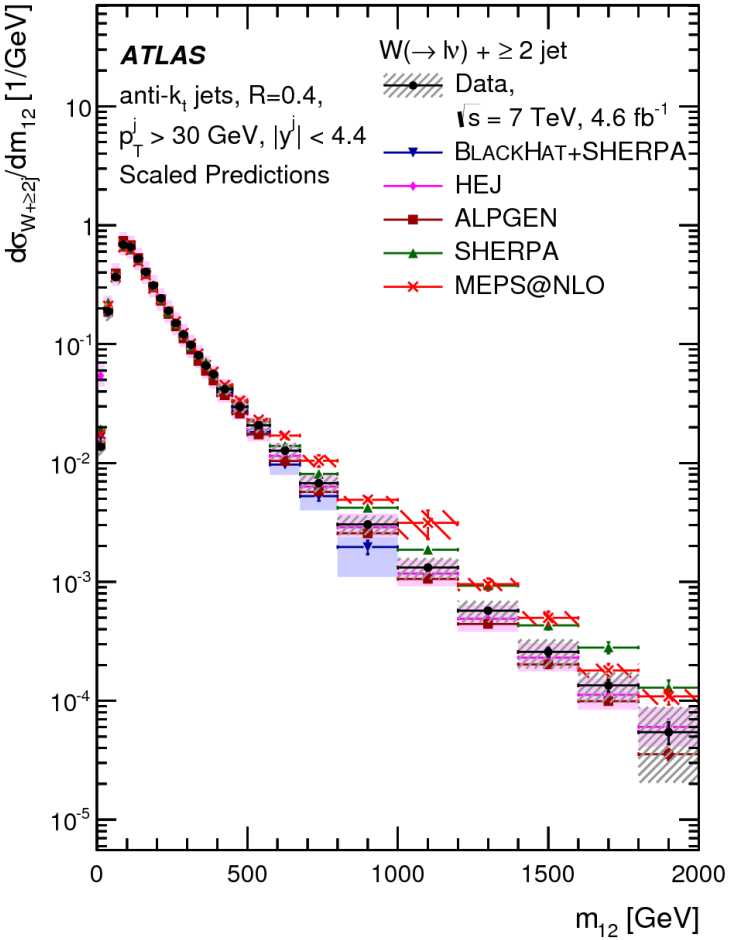
Δy (j1, j2)

- BlackHat+SHERPA describe data well
- ALPGEN underestimate for large Δy (j1,j2)
- SHERPA and MEPS@NLO overestimated for large Δy (j1,j2)

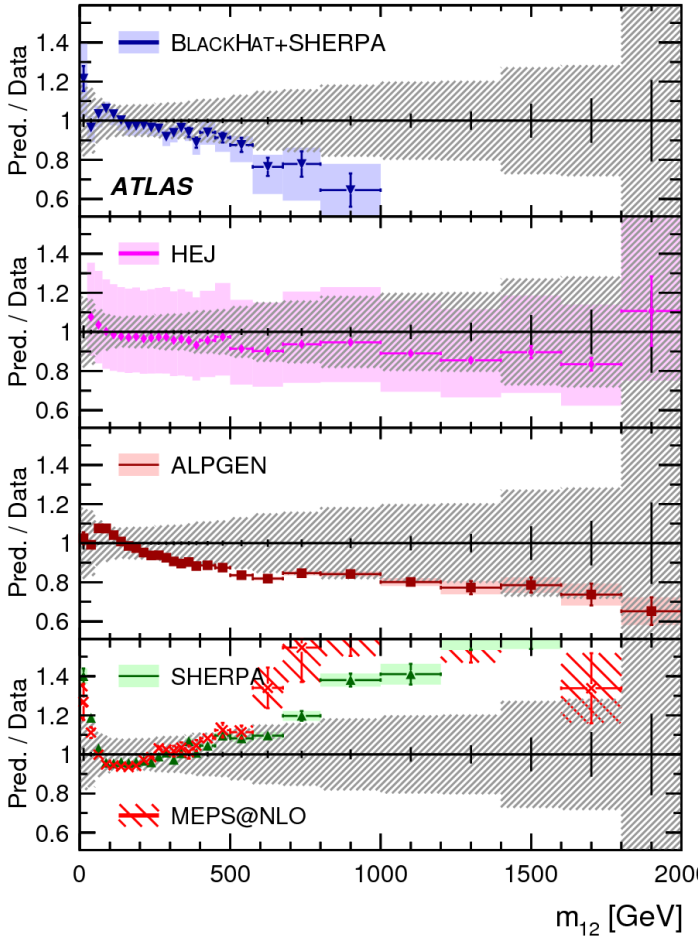
EPJC (2015) 75:82

W+jets: di-jet mass

Cross section



Prediction / Data



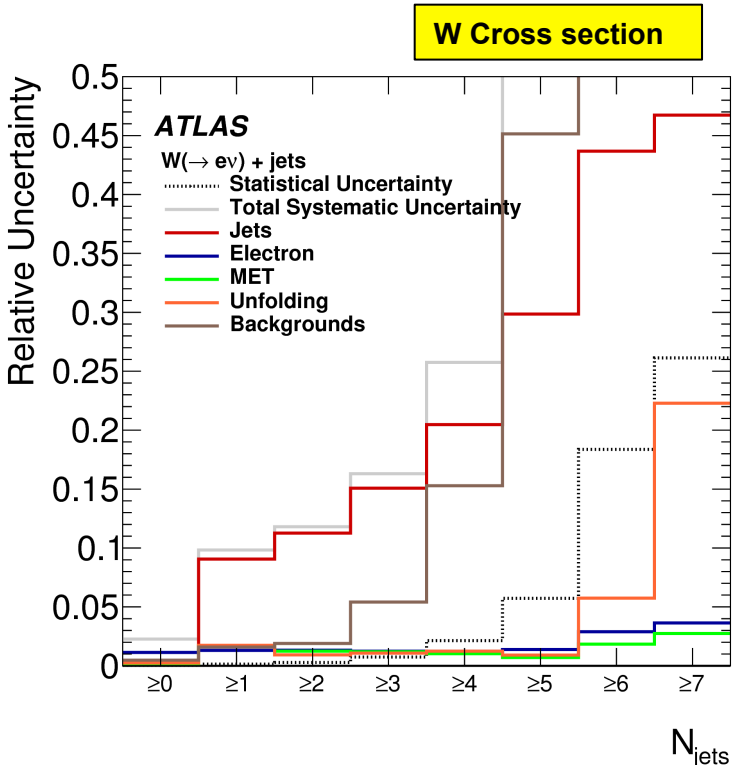
These data are being used in improving MC modeling (e.g. SHERPA v2.2, MEPS@NLO, etc)

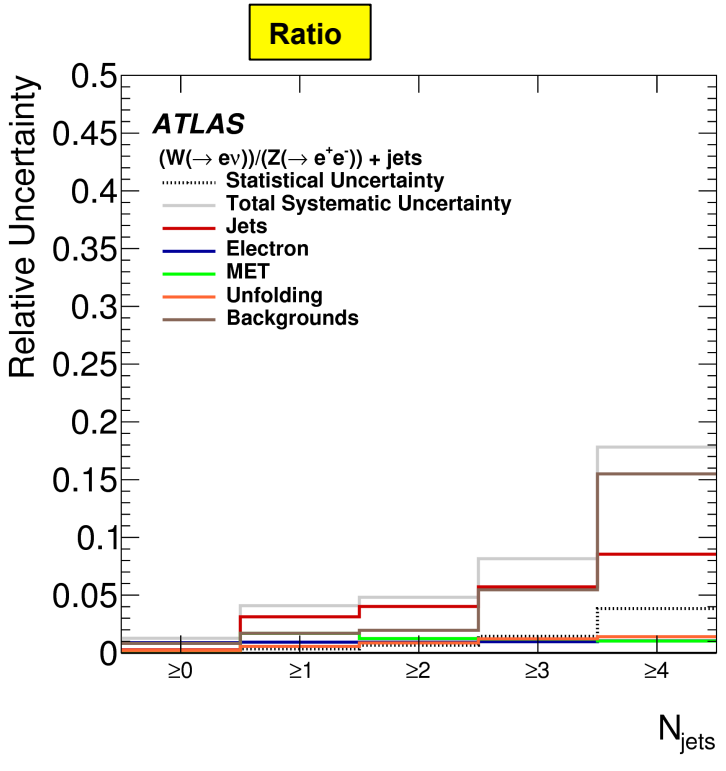
- Measured until m(j1,j2) ~ 2 TeV
- BlackHat+SHERPA: shows indication of underestimation at large mass
- HEJ provides a good description
- SHERPA and MEPS@NLO fail to describe at large mass

EPJC (2014) 74:3168

Rjets = σ(W+jets)/σ(Z+jets)

- Probes kinematic differences of jet-system recoiling against W or Z
  -- At low energies: different hadronic radiation pattern and PDF, given different momentum transfer
  -- At high energies: difference expected to decrease
- More precise test of pQCD is possible, as some of experimental uncertainties and non-perturbative effects (e.g. hadronization, multi-parton interaction) are largely cancelled





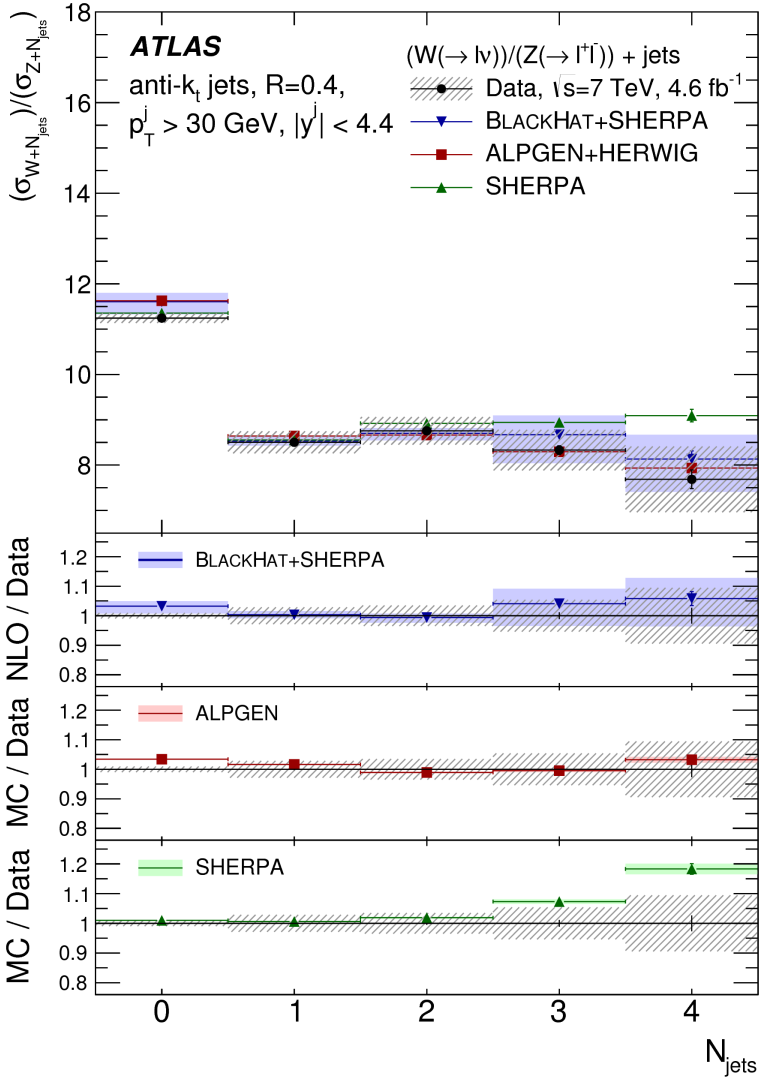
Note two figures have different x-axis range

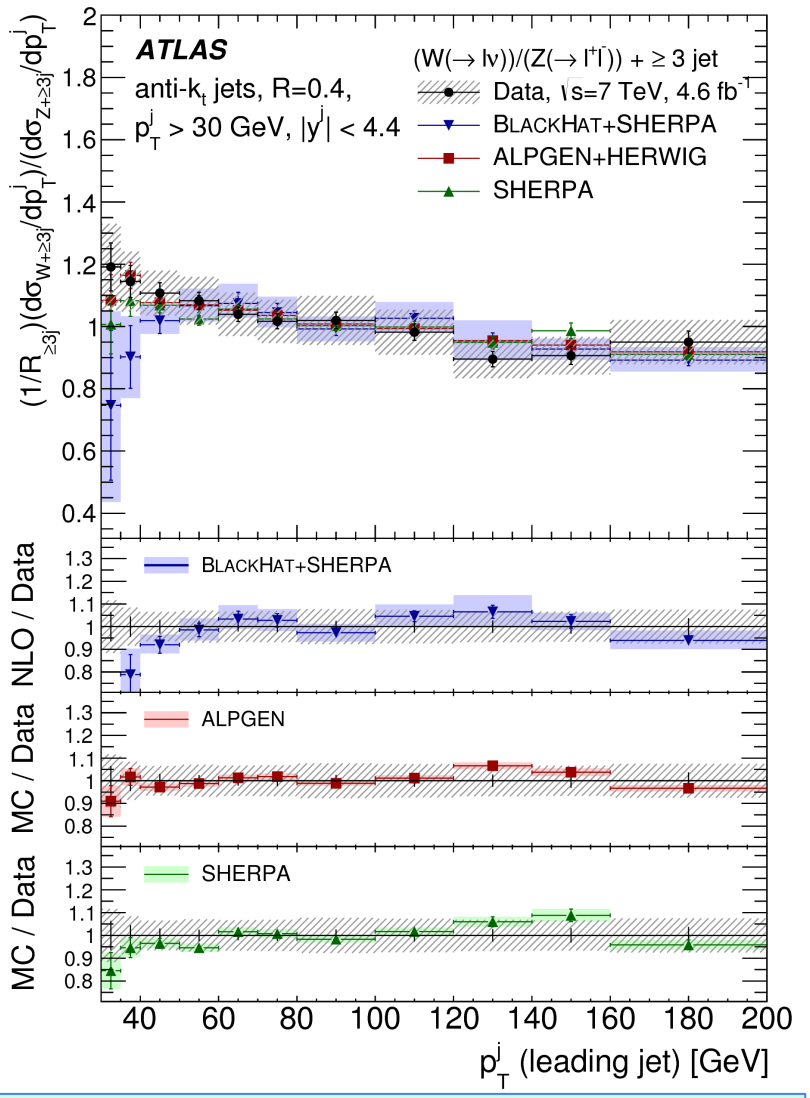
EPJC (2014) 74:3168

N jets

Rjets: number of jets, leading jet p_T

Leading jet p_T (>= 3 jets)



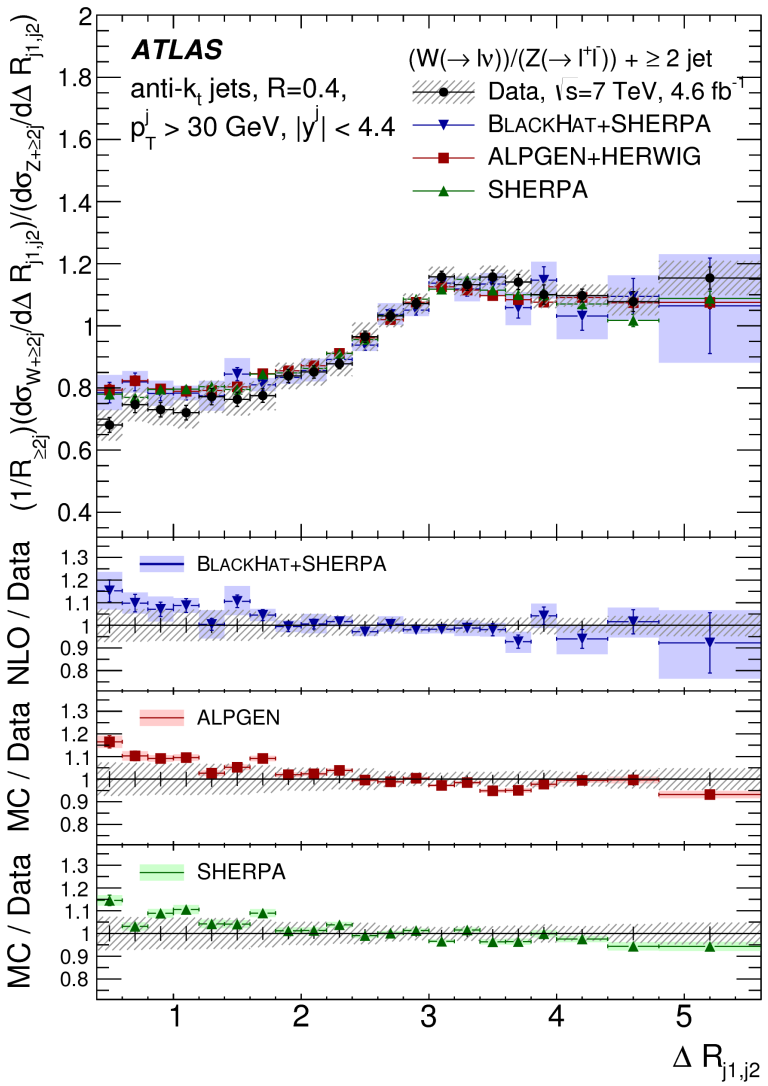


- SHERPA 1.5σ high for Njets>=4 (where hard QCD rad. effect is tested)
- Different trend at low p_T (where rad. PS effect is major)

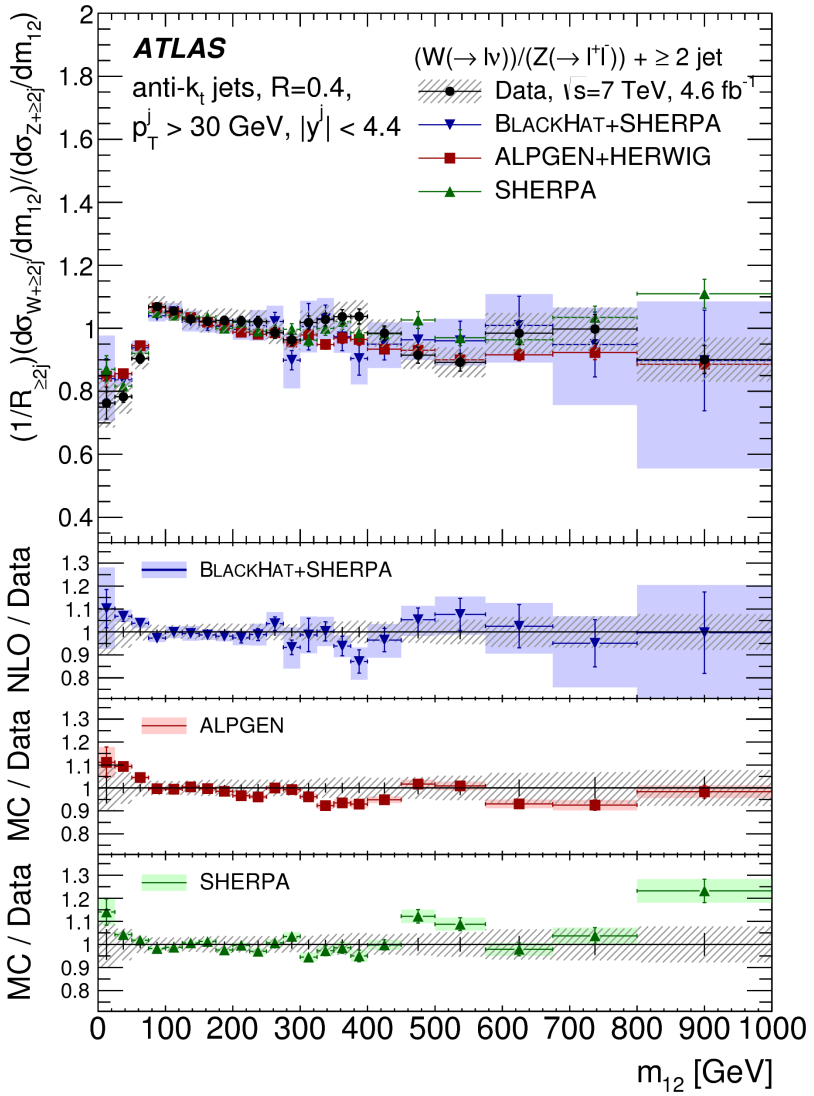
EPJC (2014) 74:3168

Rjets: angular separation, di-jet mass

ΔR (j1, j2)



m (j1, j2)

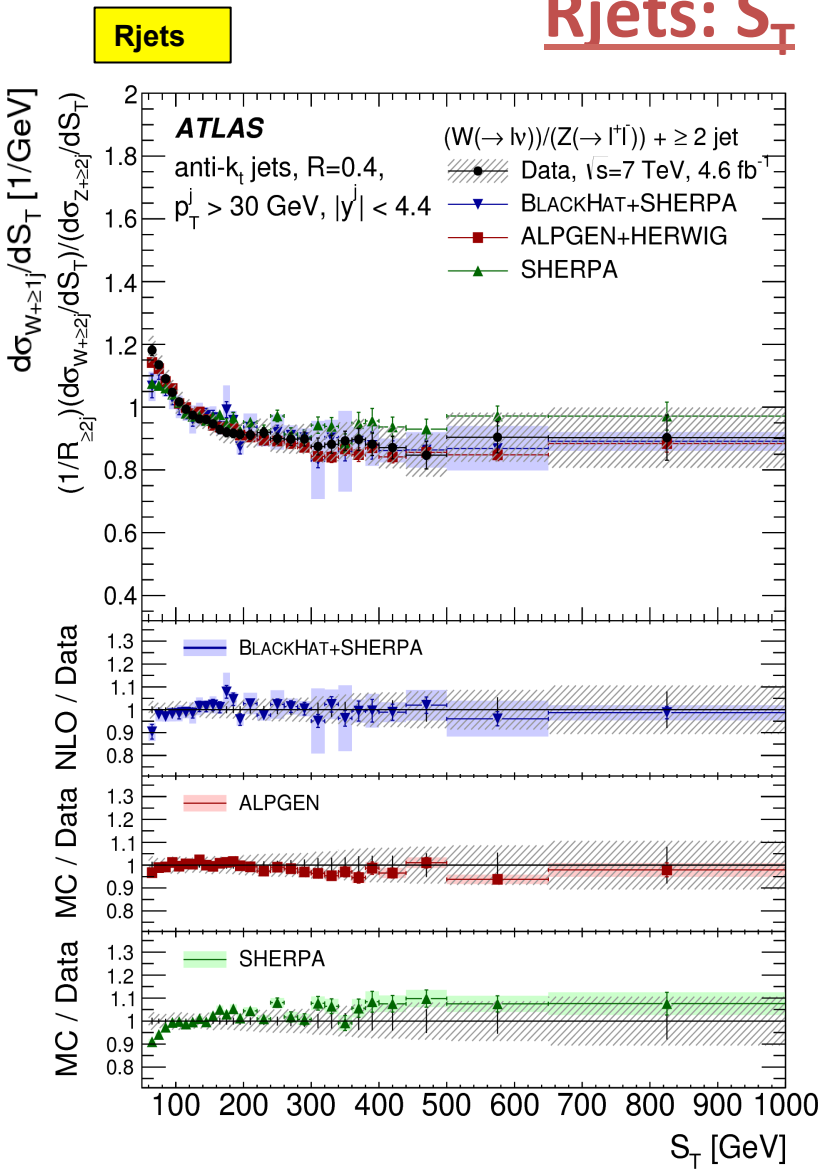


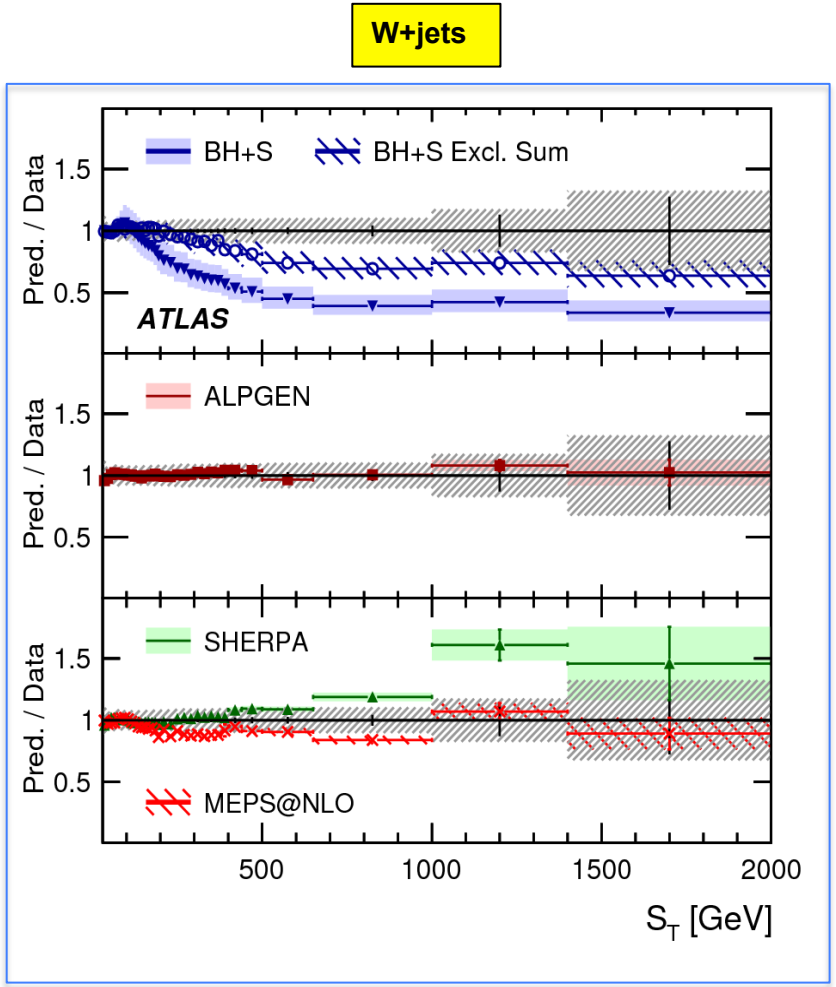
- Predicated shapes differ at low ΔR, mass, because non-pQCD effects that enhance soft QCD radiation do not fully cancel

EPJC (2014) 74:3168

Rjets: S_T

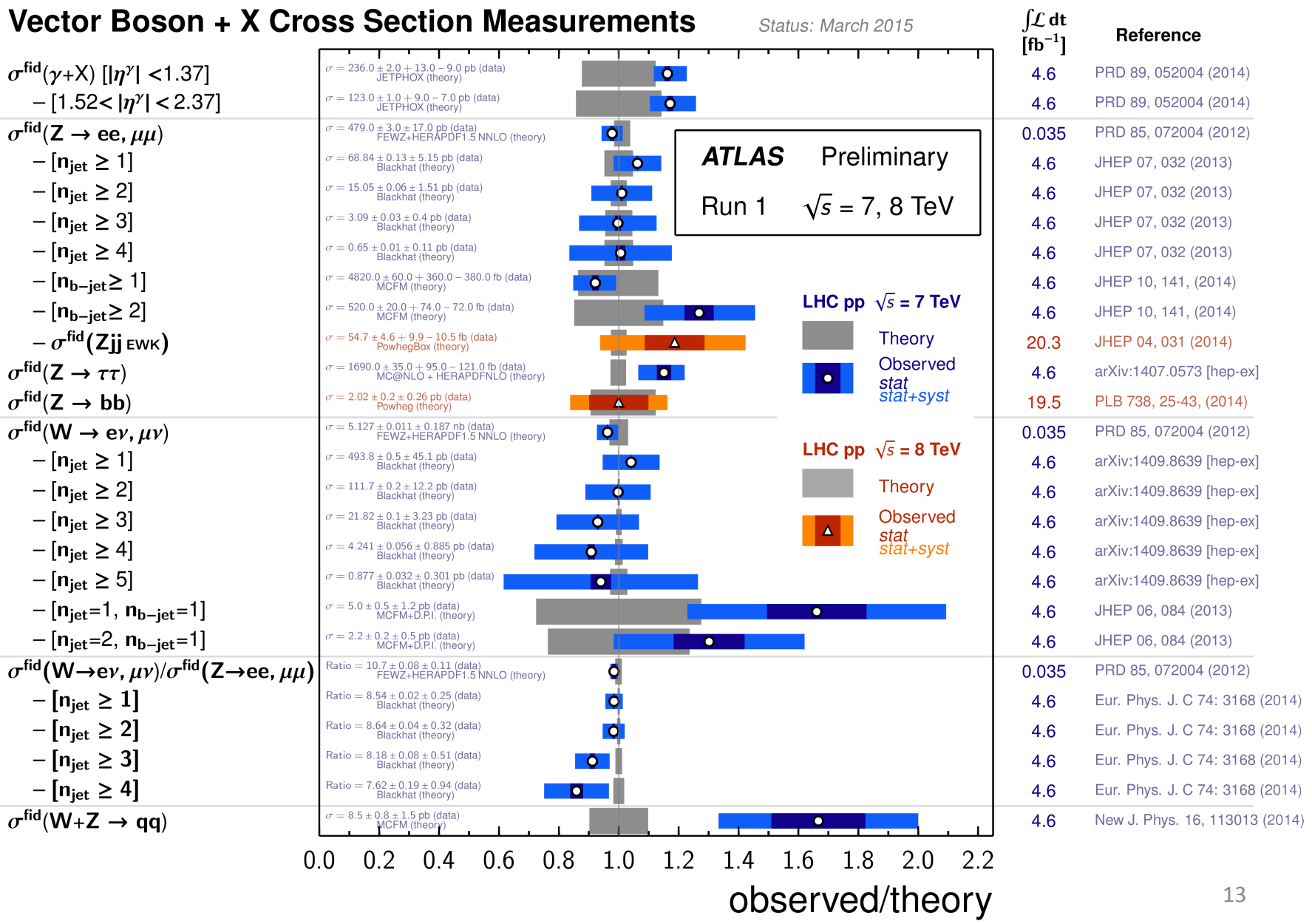
- S_T: scalar sum p_T of jets, often used in searches





- BH+S does not reproduce W/Z+jet due to missing higher-orders, but does reproduce Rjets due to cancellation of higher-order effects

A summary plot of V+jets cross sections



$\int \mathcal{L}\,dt$ [fb^{-1}]	Reference
4.6	PRD 89, 052004 (2014)
4.6	PRD 89, 052004 (2014)
0.035	PRD 85, 072004 (2012)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 07, 032 (2013)
4.6	JHEP 10, 141, (2014)
4.6	JHEP 10, 141, (2014)
20.3	JHEP 04, 031 (2014)
4.6	arXiv:1407.0573 [hep-ex]
19.5	PLB 738, 25-43, (2014)
0.035	PRD 85, 072004 (2012)
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	arXiv:1409.8639 [hep-ex]
4.6	JHEP 06, 084 (2013)
4.6	JHEP 06, 084 (2013)
0.035	PRD 85, 072004 (2012)
4.6	Eur. Phys. J. C 74: 3168 (2014)
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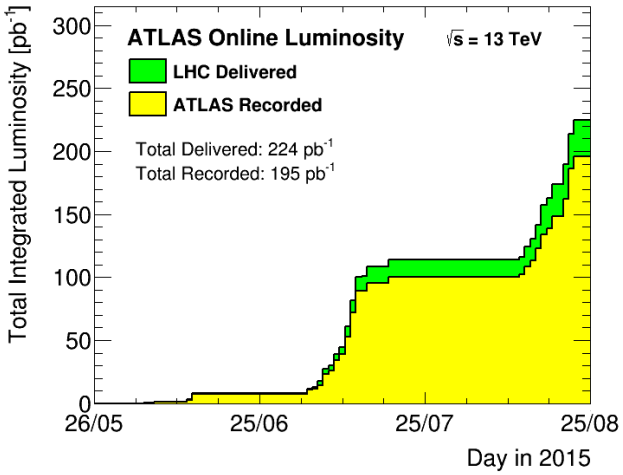
4.6	Eur. Phys. J. C 74: 3168 (2014)
4.6	New J. Phys. 16, 113013 (2014)

ATLAS-PHYS-PUB-2015-037 (*NEW IN THE LAST WEEK*)
ATLAS-PHYS-PUB-2015-041 (*NEW AT THIS CONFERENCE*)

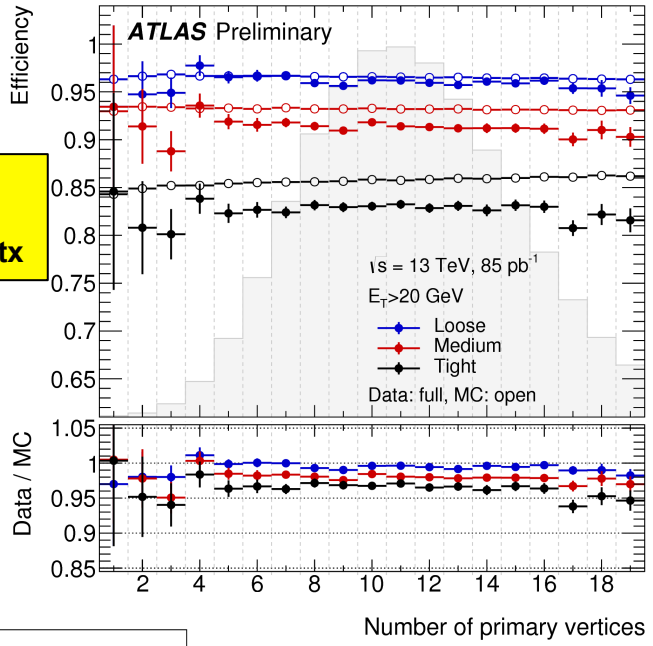
Run2 ongoing!

- LHC ramping up at 13 TeV, after a long shutdown!

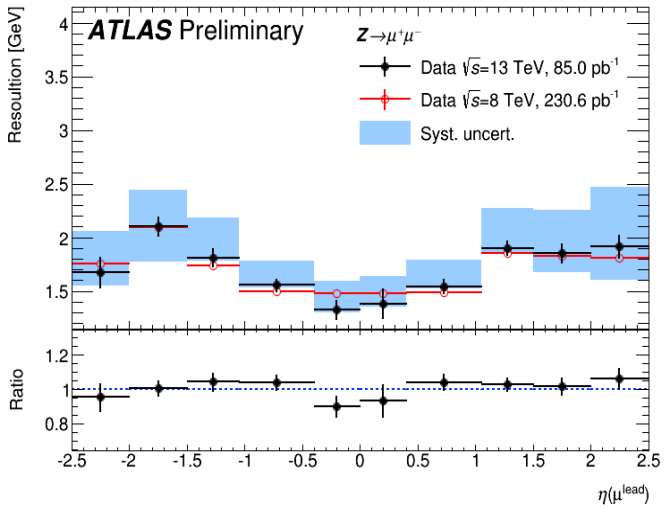


- Good performance of the ATLAS detector

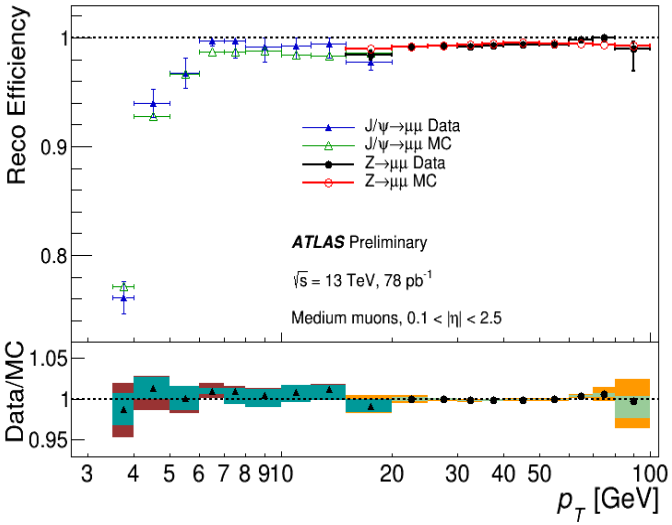
Electron reconstruction efficiency wrt Nvtx



μ resolution



μ reconstruction efficiency



ATLAS has already started to produce physics results at 13 TeV!

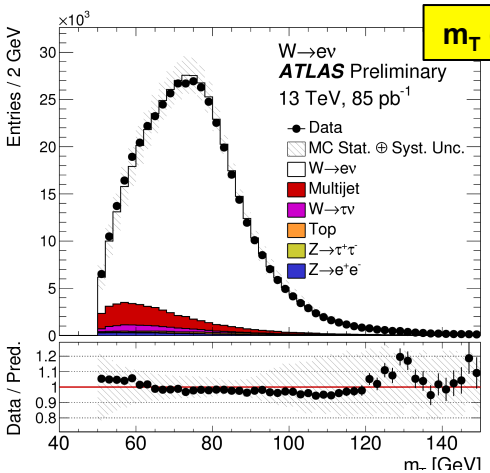
ATLAS-CONF-2015-039 (*NEW AT THIS CONF*)

13 TeV, 85 pb^{-1}

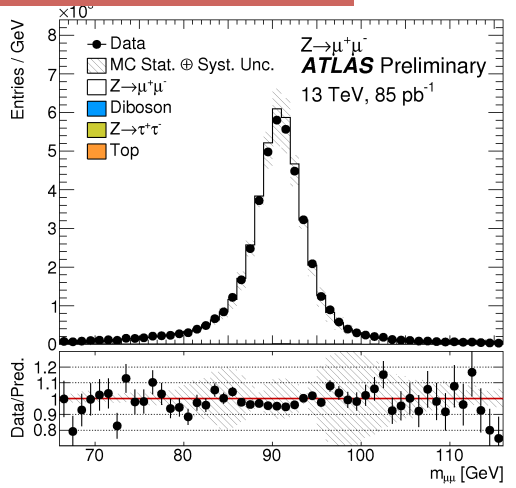
(inclusive) W/Z in pp @ 13 TeV

See J.Nielsen's talk (SM EM-1) for more detail

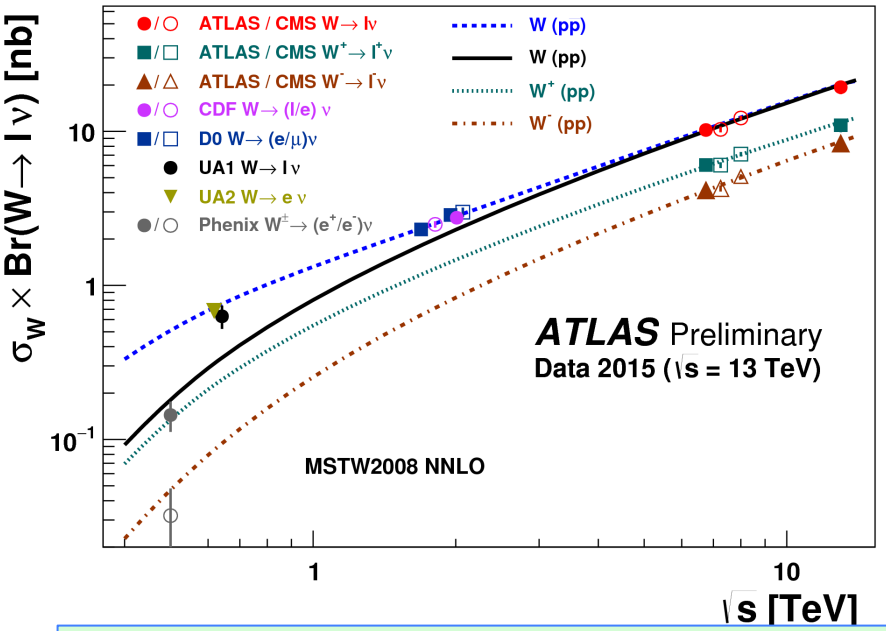
m_T (W→eν)



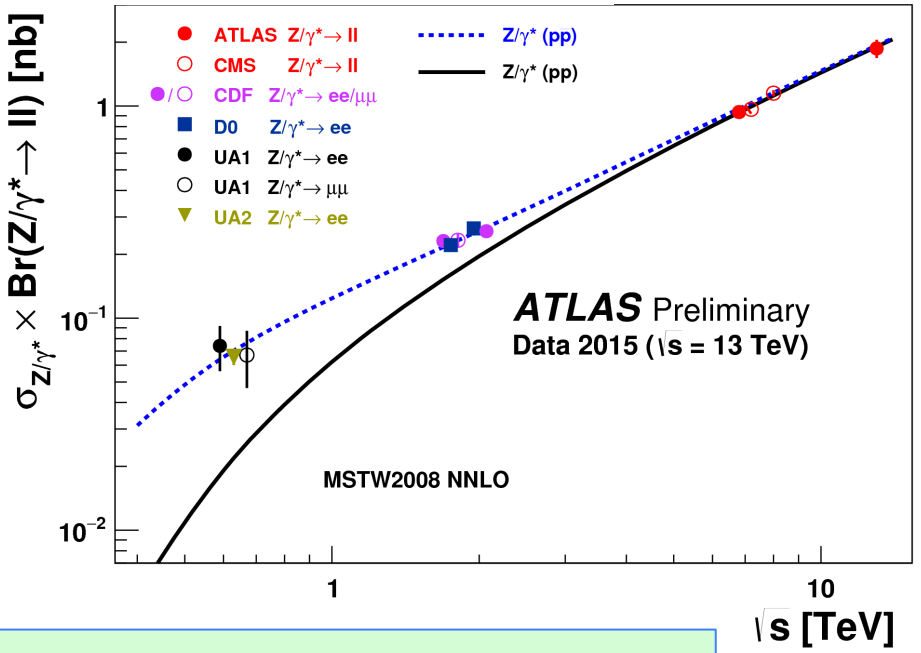
m(Z→μμ)



W cross setion



Z cross setion



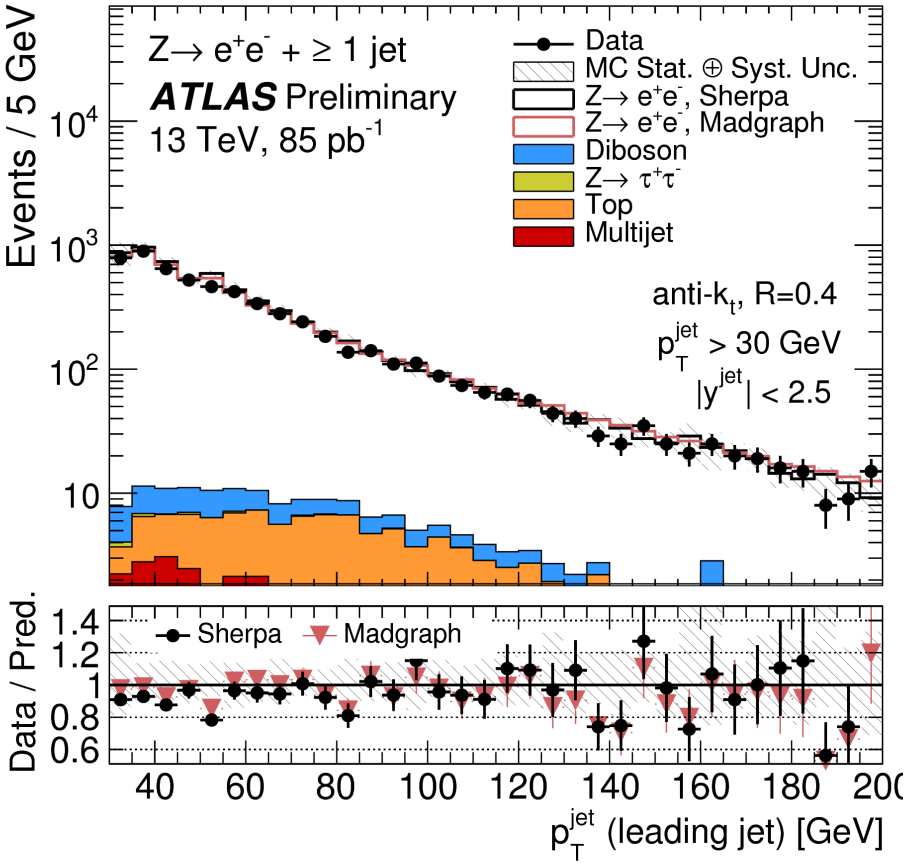
- Inclusive W/Z production cross sections at 13 TeV agree with theoretical calculations based on NNLO QCD → Z+jets (next pages)

13 TeV, 85 pb^{-1}

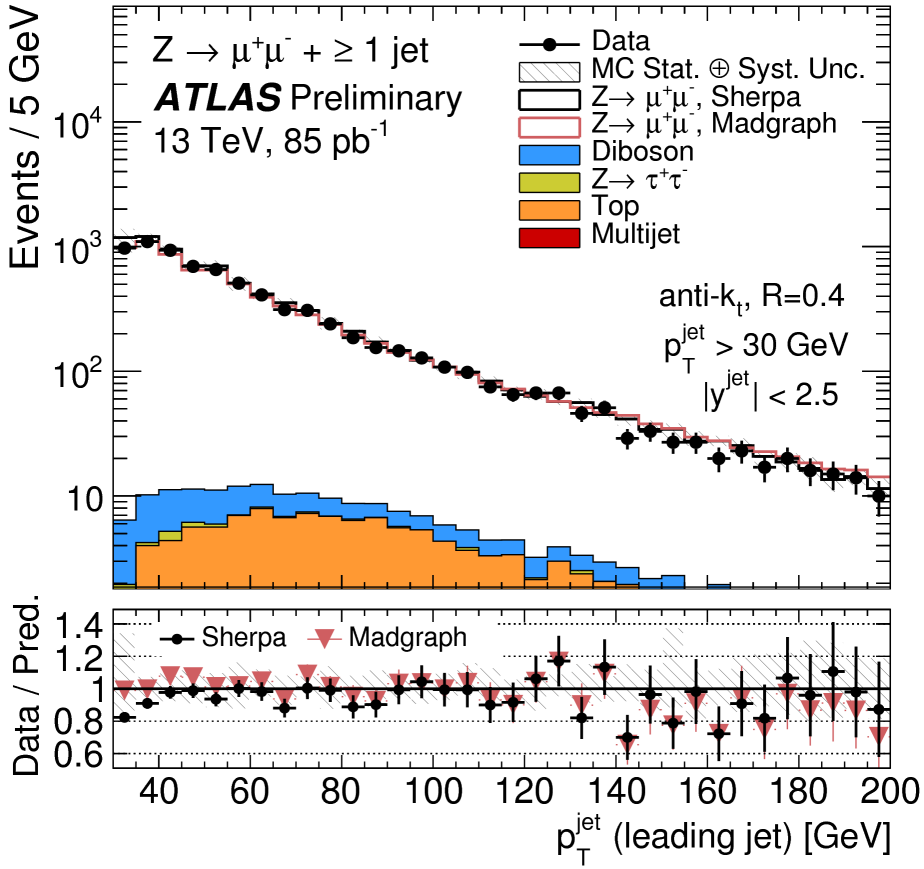
Z+jets in pp @ 13 TeV: leading jet p_T

Anti-k_T, R=0.4
p_T > 30 GeV, |y|<2.5

Z→ee



Z→μμ

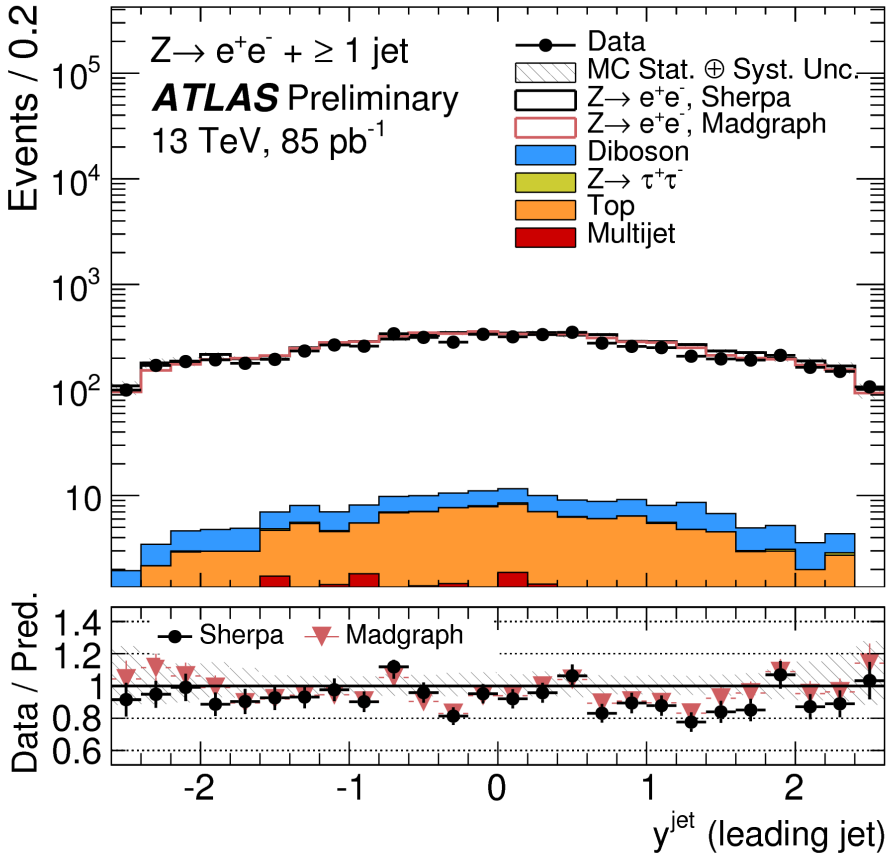


- SHEPA v2.1.1 (ME up to 2 ptn at NLO+up to 4 ptn at LO + PS)
- MadGraph5_aMC@NLO v2.2.2 (ME up to 4 ptn at LO + Pythia PS)

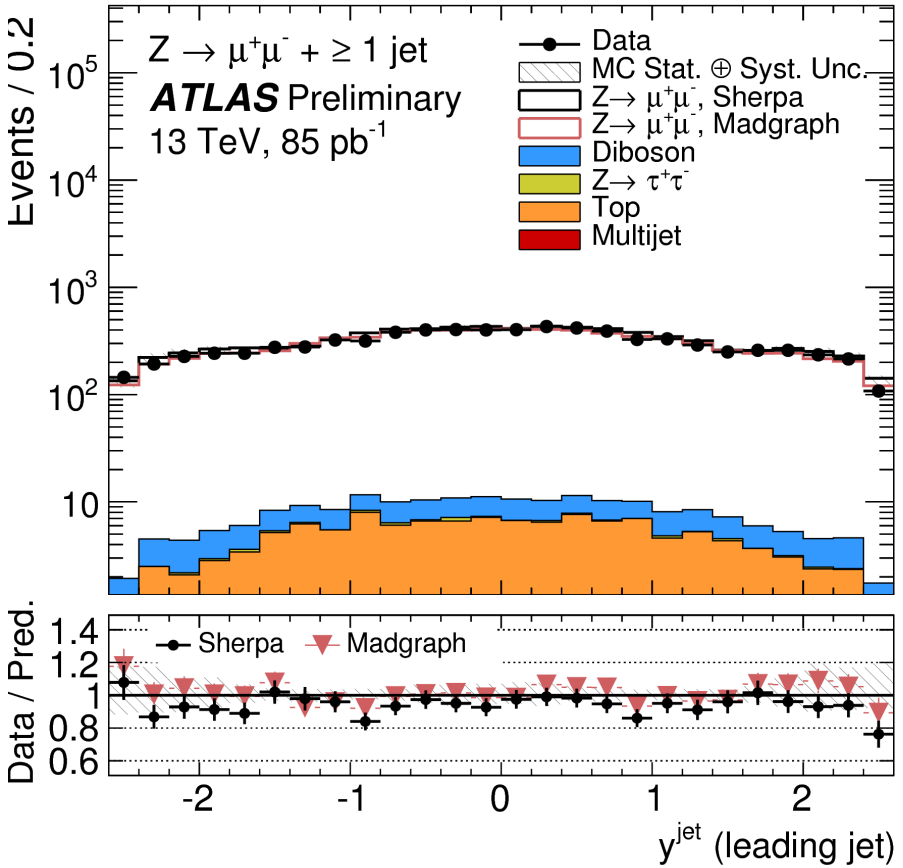
Z+jets in pp @ 13 TeV: leading jet rapidity

Anti-k_T, R=0.4
p_T > 30 GeV, |y|<2.5

Z→ee



Z→μμ

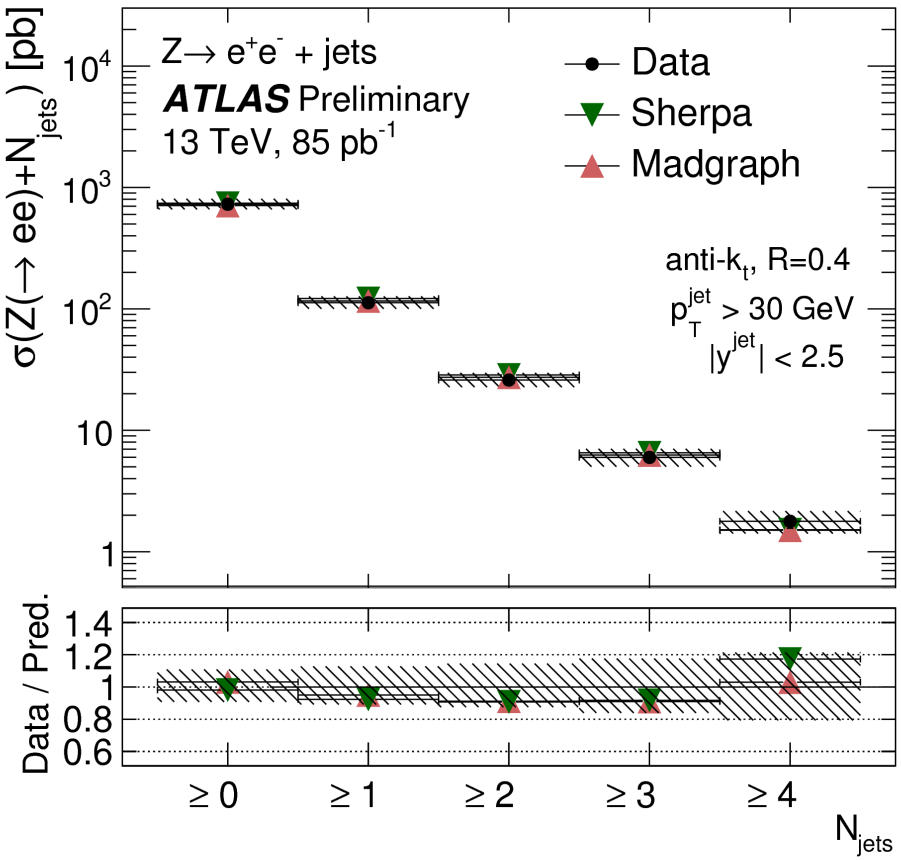


- Data and predictions (Sherpa, Madgraph) agree well within uncertainties

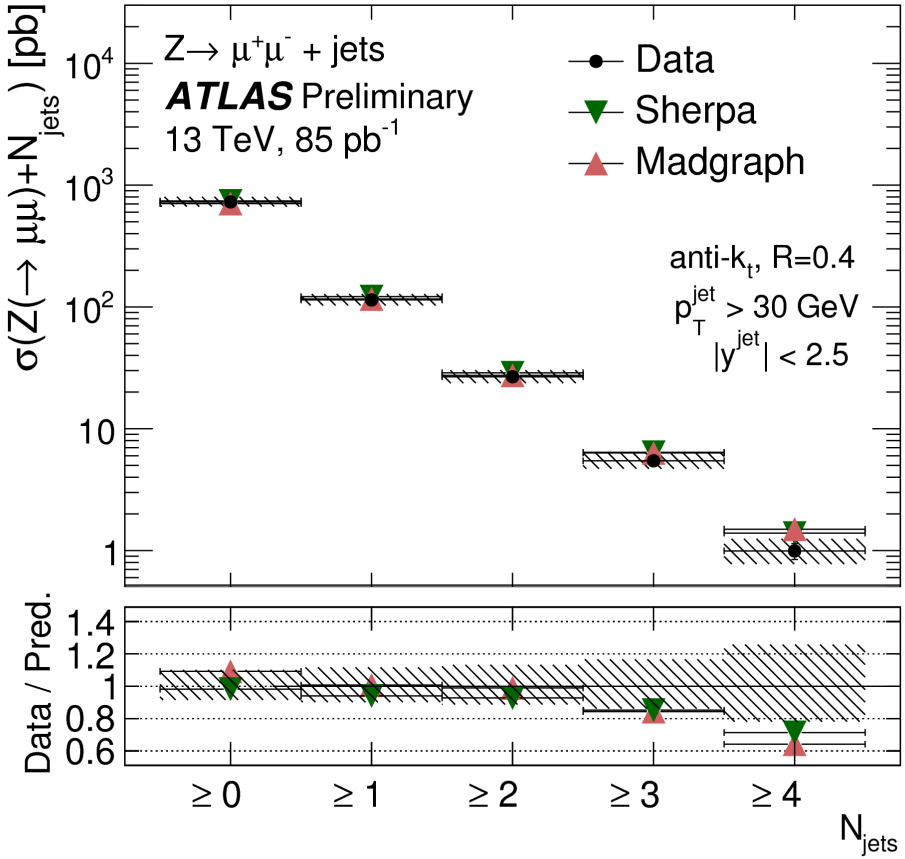
Z+jets in pp @ 13 TeV: number of jets

Anti-k_T, R=0.4
p_T > 30 GeV, |y|<2.5

Z→ee

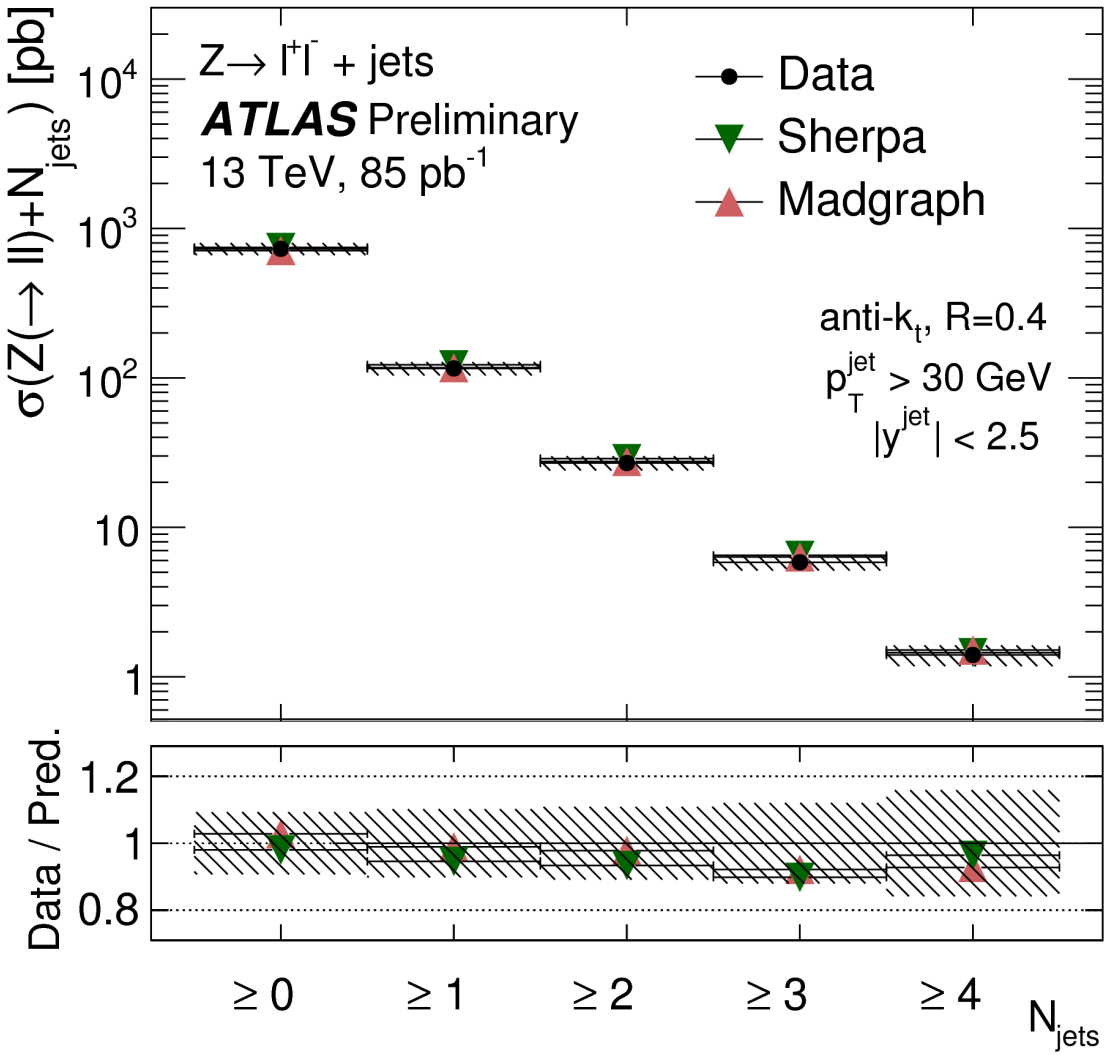


Z→μμ



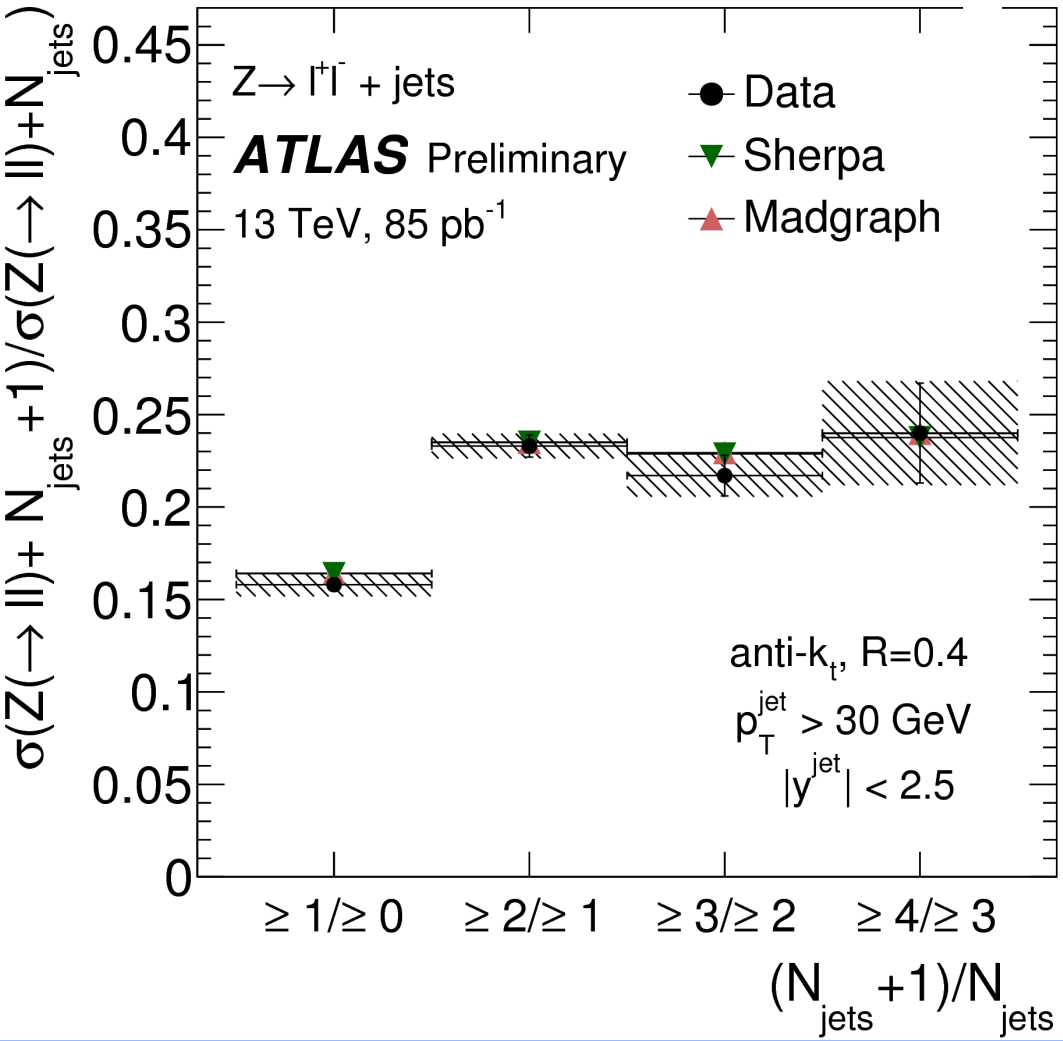
- Sherpa and Madgraph show reasonable agreement with the measured cross sections.

Z+jets in pp @ 13 TeV: number of jets -cont'd-



- Sherpa and Madgraph show reasonable agreement with the measured cross sections.

Z+jets in pp @ 13 TeV: (Njet+1)/Njet



See backup slides for electron and muon channels separately

- Sherpa and Madgraph show reasonable agreement with the measured cross sections.

Summary

- QCD is one of fundamentals of the Standard Model, and understanding QCD is essential in particular at hadron colliders
- Like a pair of wheels, experiment and theory have rapidly advanced further understanding of QCD
  - -- More and more precise results from LHC
  - -- Theoretical developments
- V+jets provides unique probes on QCD, e.g. pQCD, PDFs
- Run1 measurements being finalized
- Run2 data is accumulating, and ATLAS has already starting to produce results; precision measurements in new kinematic regions.

Backup Slides

QCD calculations and MC generators used in this talk

- Multi-parton LO + PS
  -- ALPGEN
  -- SHERPA

- NLO ME + PS
  -- MC@NLO (NLO matching)
  -- MEPS@NLO (multi-jet matching): NLO for V+up to 2 partons

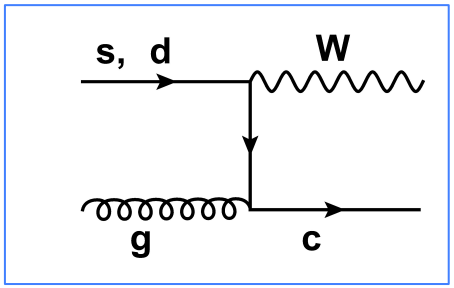
- Fixed-order calculation
  -- BlackHat + SHERPA: NLO for V+up to 5 jets

- Resummation
  -- HEJ

- Approx. NNLO
  -- LoopSim

JHEP05 (2014) 068

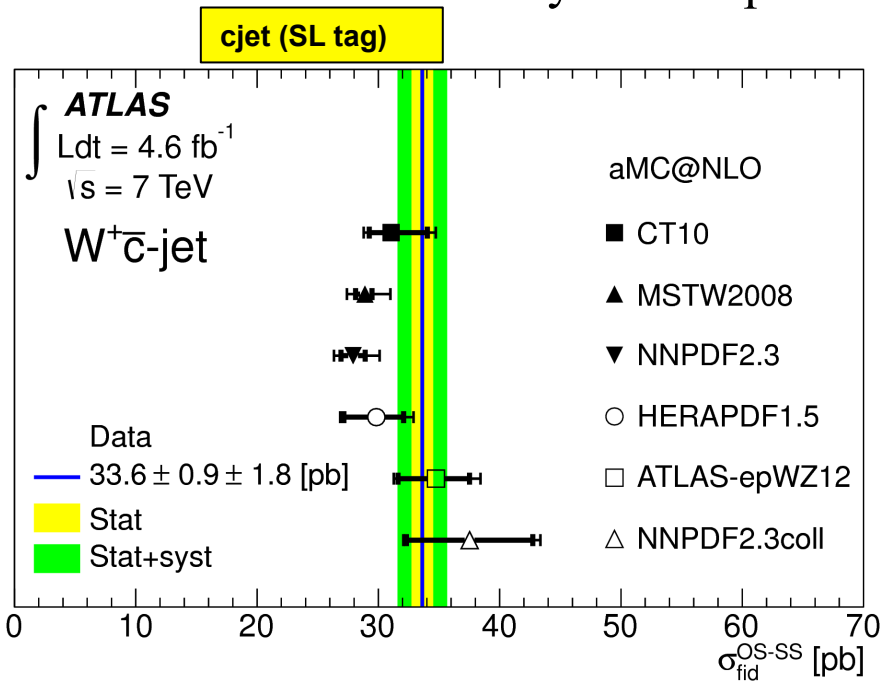
W+charm

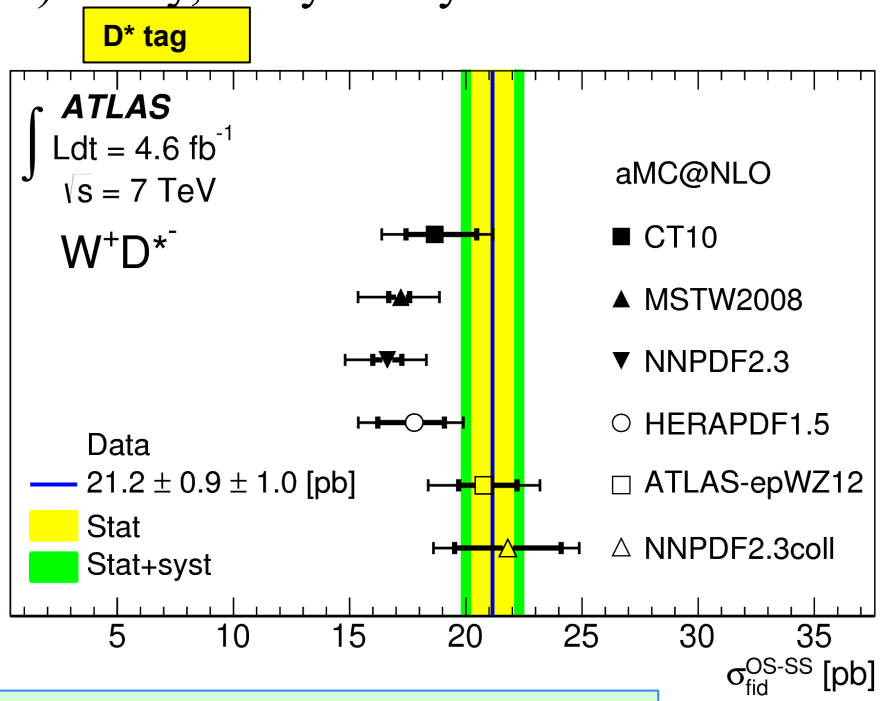


- Large sensitivity on s and $\bar{s}$ content of the proton
- Charge correlation between W and c
  - -- Clean signal extraction by OS-SS
- Charge correlation between W and initial quark charge
  - -- Separate sensitivity to s and $\bar{s}$
- Charm is identified by semi-leptonic (SL) decay, or by decay to D-mesons

$$g\bar{s} \rightarrow W^{-}c$$

$$gs \rightarrow W^{+}\bar{c}$$

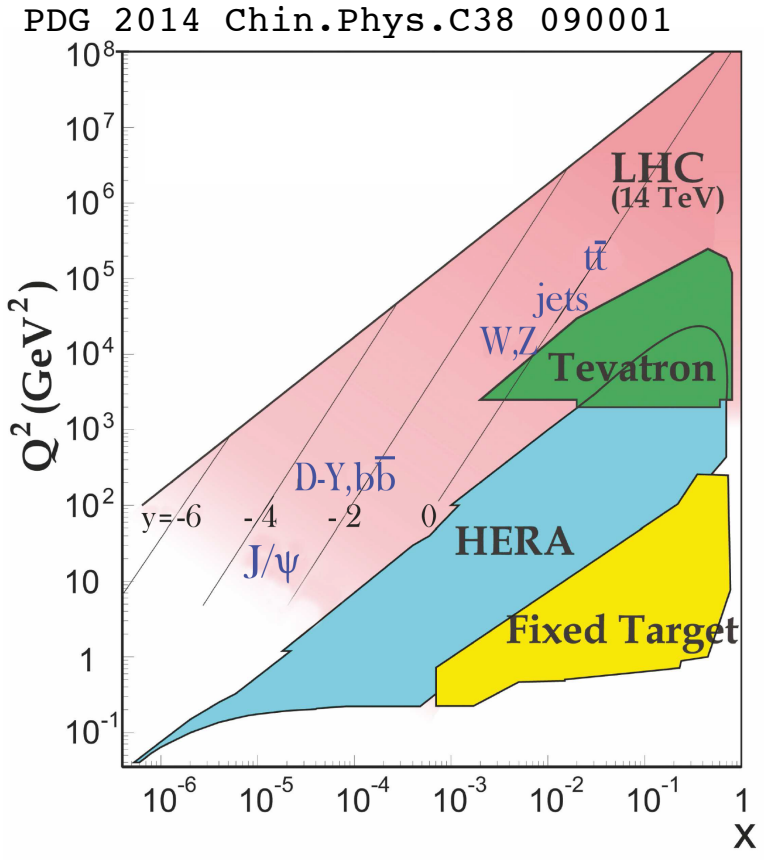




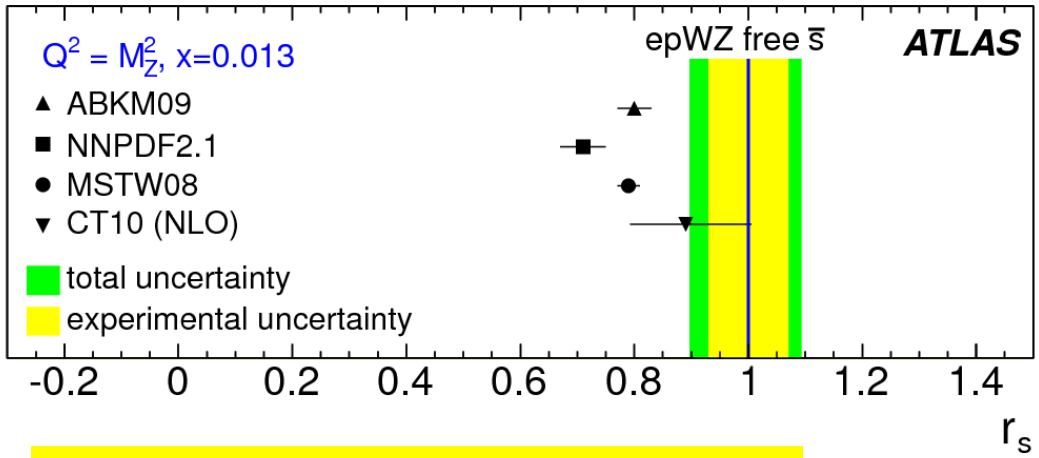
- Data precision is comparable to PDF variations
  → substantial impact to PDF determination

strange PDF

- Strange PDF has been determined by νN DIS data at low Q^2 (~10 GeV^2) and large x (~0.1). However, interpretation of these data is sensitive to modeling of c-quark fragmentation and nuclear effects
  - -- Some analyses suggest suppression of s/d in the sea at all x values
  - -- while, some analyses suggest SU(3) symmetry restored as x decreases



- A joint analysis of ATLAS inclusive W/Z and HERA DIS data indicates SU(3)-symmetric sea at x ~ 0.01
  (PRL 109 (2012) 012001)

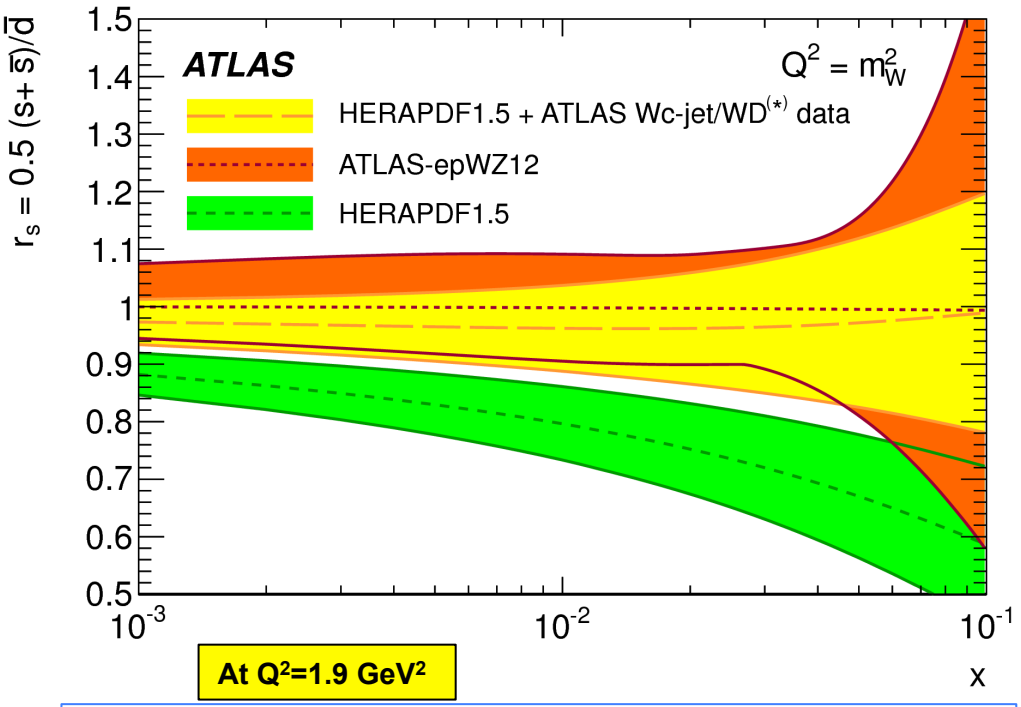


How W+charm (exclusive, direct sensitive) impacts? → Next slide

JHEP05 (2014) 068

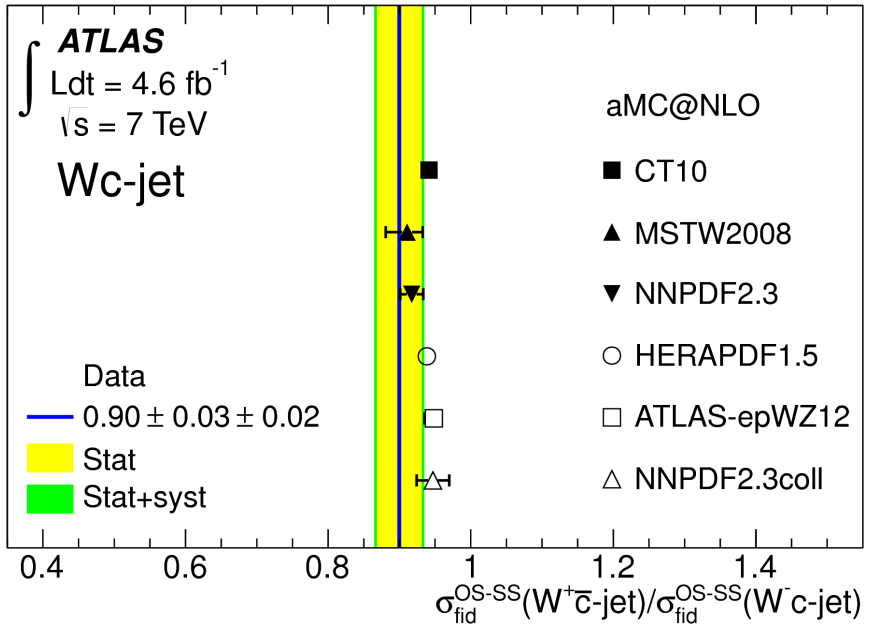
W+charm impacts to PDF

- Rs=0.5(s+sbar)/dbar from a PDF fit by including W+charm data



$$r^s \equiv 0.5(s+\bar{s})/\bar{d} = f_s/(1-f_s) = 0.96\ ^{+0.16\ +0.21}_{-0.18\ -0.24}$$

- $R_c^{\pm} \equiv \sigma(W^+ + \bar{c})/\sigma(W^- + c)$



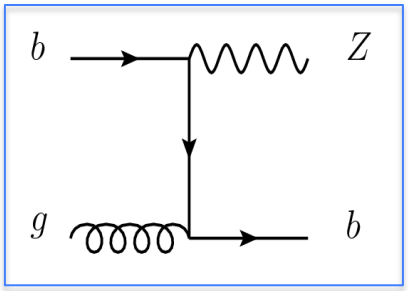
$$A_{s\bar{s}} = \frac{\langle s(x,Q^2)\rangle - \langle \bar{s}(x,Q^2)\rangle}{\langle s(x,Q^2)\rangle}$$

$2 \pm 3\%$

- Rs value determined in this analysis is in agreement with the inclusive W/Z + HERA analysis, and supports SU(3) symmetric sea

JHEP10 (2014) 141

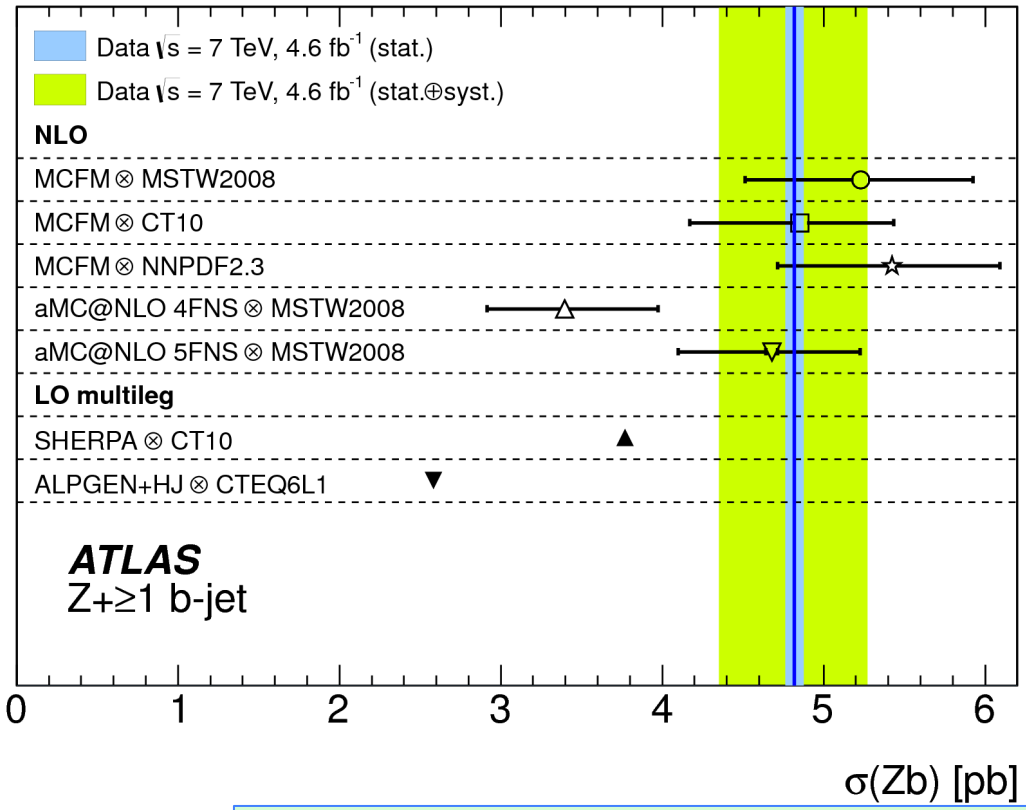
Z+b



b as initial state parton from DGLAP evolution **5FNS**

b from initial state gluon splitting to bb **4FNS**

- Interplay between b-PDF and gluon splitting, depending on flavor number schema (FNS) as well as b-mass treatment



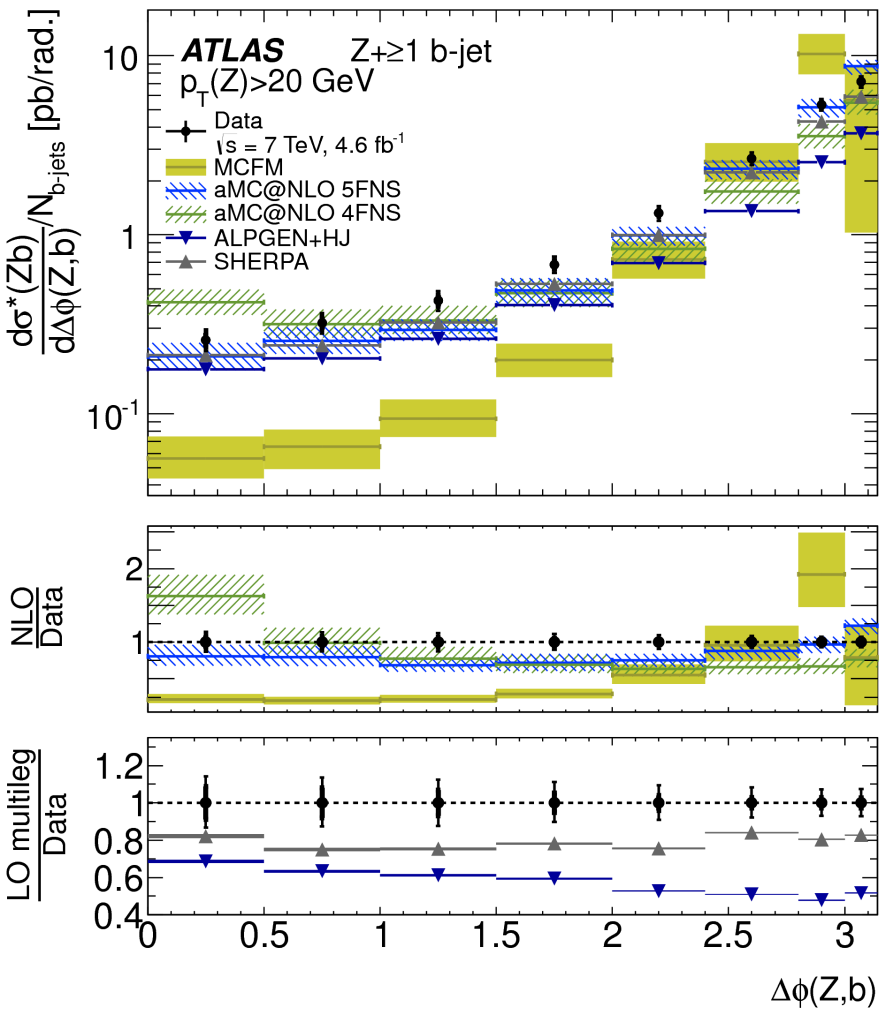
- MCFM
  -- Fixed order NLO
  -- 5FNS, massless-b
- aMC@NLO
  -- NLO ME

- MCFM and aMC@NLO in agreement with data: differences from PDF sets ~ 1 σ (exp) < 1 σ (theory)
- Large theory errors dominated by scale uncertainties

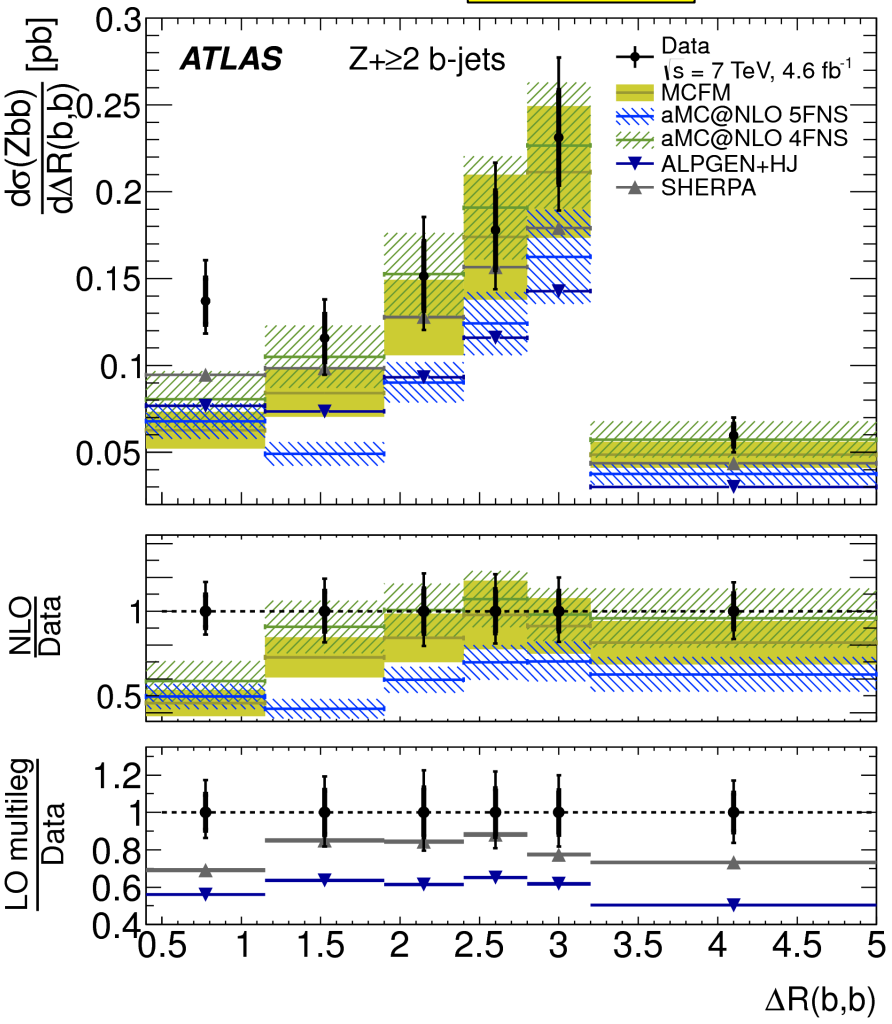
JHEP10 (2014) 141

Z+bb: angular distributions

Δφ(Z, b)



ΔR (b, b)



- MCFM significant discrepancy
- aMC@NLO 4FNS some evidence of slope difference

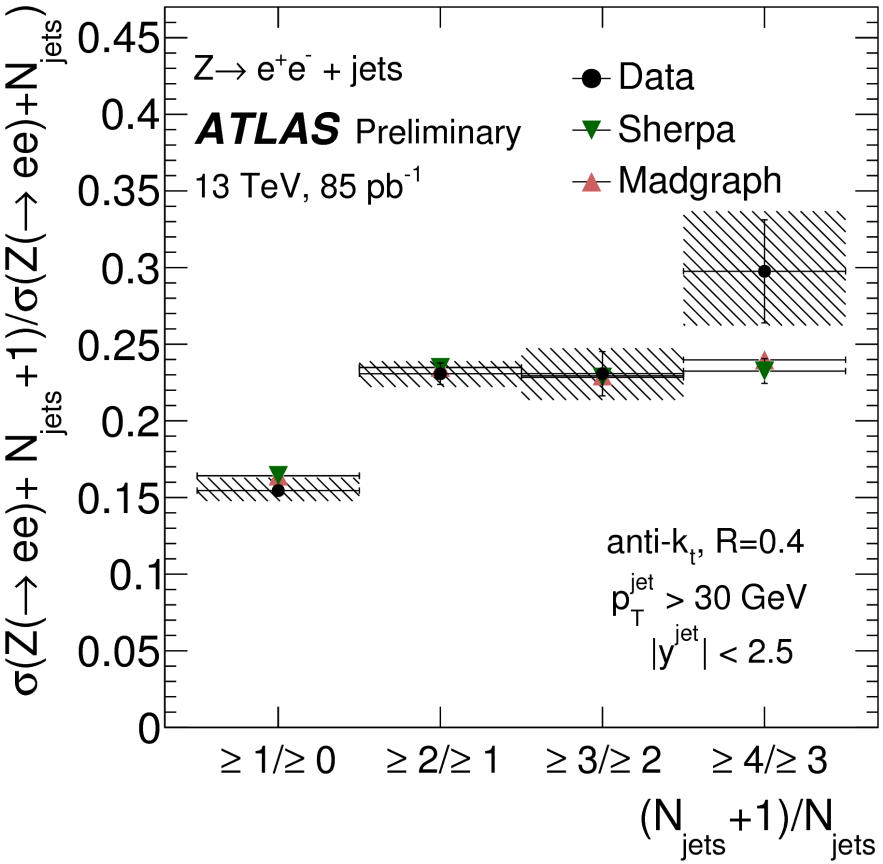
- Disagreements between predictions and data at low ΔR(b,b)

13 TeV, 85 pb^{-1}

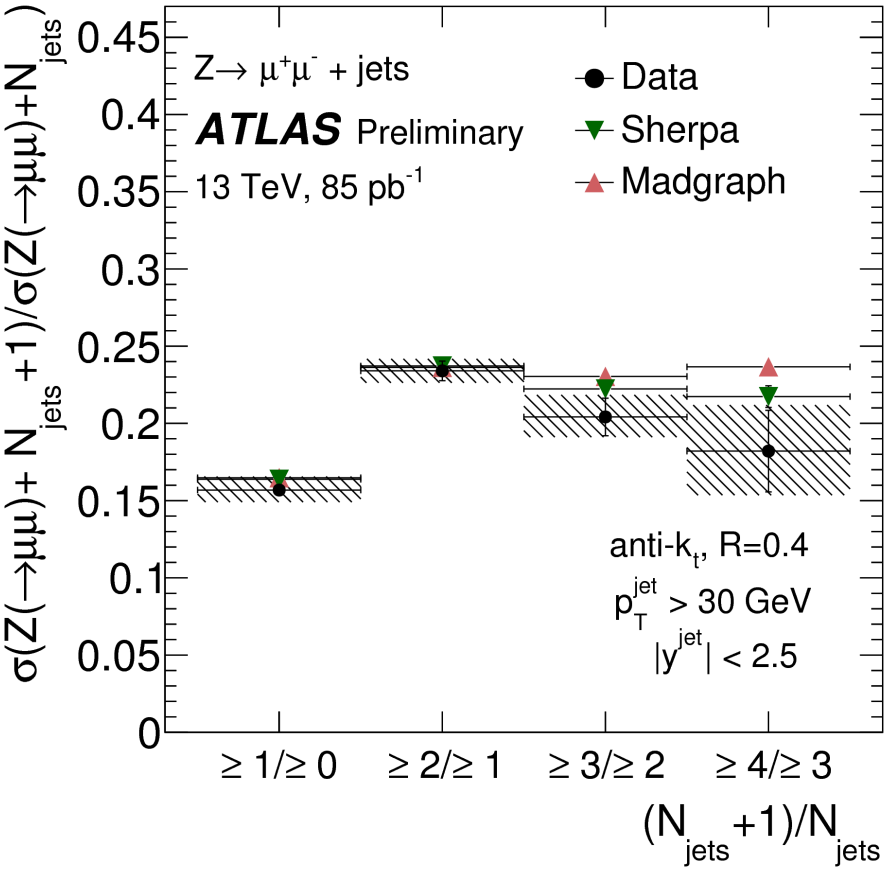
Z+jets in pp @ 13 TeV: (Njet+1)/Njet

Anti-k_T, R=0.4
p_T > 30 GeV, |y|<2.5

Z→ee



Z→μμ



- Sherpa and Madgraph show reasonable agreement with the measured cross sections.