Measurements of vector boson production in association with jets in ATLAS

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on behalf of the ATLAS collaboration

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Why measure *V*+jets?

Vector Bosons (*V* = *W*,*Z*) are standard candles at hadron colliders

- Large production cross sections
- Clean experimental signature in leptonic decay
  - No color flow between Vector Boson and QCD final state (ISR partons → jets)
- Can select kinematic regime of lepton and jets to study signatures

Ideal test bench for QCD

- Precision tests of fixed-order NLO pQCD predictions at high p_T scales
- Precision tests of resummation techniques at low p_T scales
- Measurements can be sensitive to or independent of PDFs (flavor selectable)

Important for background modeling

- Measurements test modeling in current generators
- Improve model uncertainties from *V*+jets
- Relevant in measurements of Higgs boson production and BSM searches
  - In particular for boosted *V* in associated Higgs production

Recent ATLAS Publications on *V*+jets

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults#W_Z_Physics

- To date all ATLAS *V*+jets measurements using *pp* collisions at $\sqrt{s}$ = 7 TeV
- Will only show a selection of highlights from these results

V Recoil

p_T^W	36 pb^{-1}	Phys.Rev. D85 (2012) 012005	←
$Z\ \phi_\eta^*$	4.6 fb^{-1}	Phys. Lett. B 720 (2013) 32-51	←
p_T^Z	36 pb^{-1}	Phys.Lett. B705 (2011) 415-434	

V + Inclusive Flavor

Z + jets	4.6 fb^{-1}	JHEP 07 (2013) 032	←
W + jets	36 pb^{-1}	Phys. Rev. D85 (2012) 092002	←
R_{jets}	36 pb^{-1}	Phys. Lett. B708 (2012) 221-224	←

V + Heavy Flavor

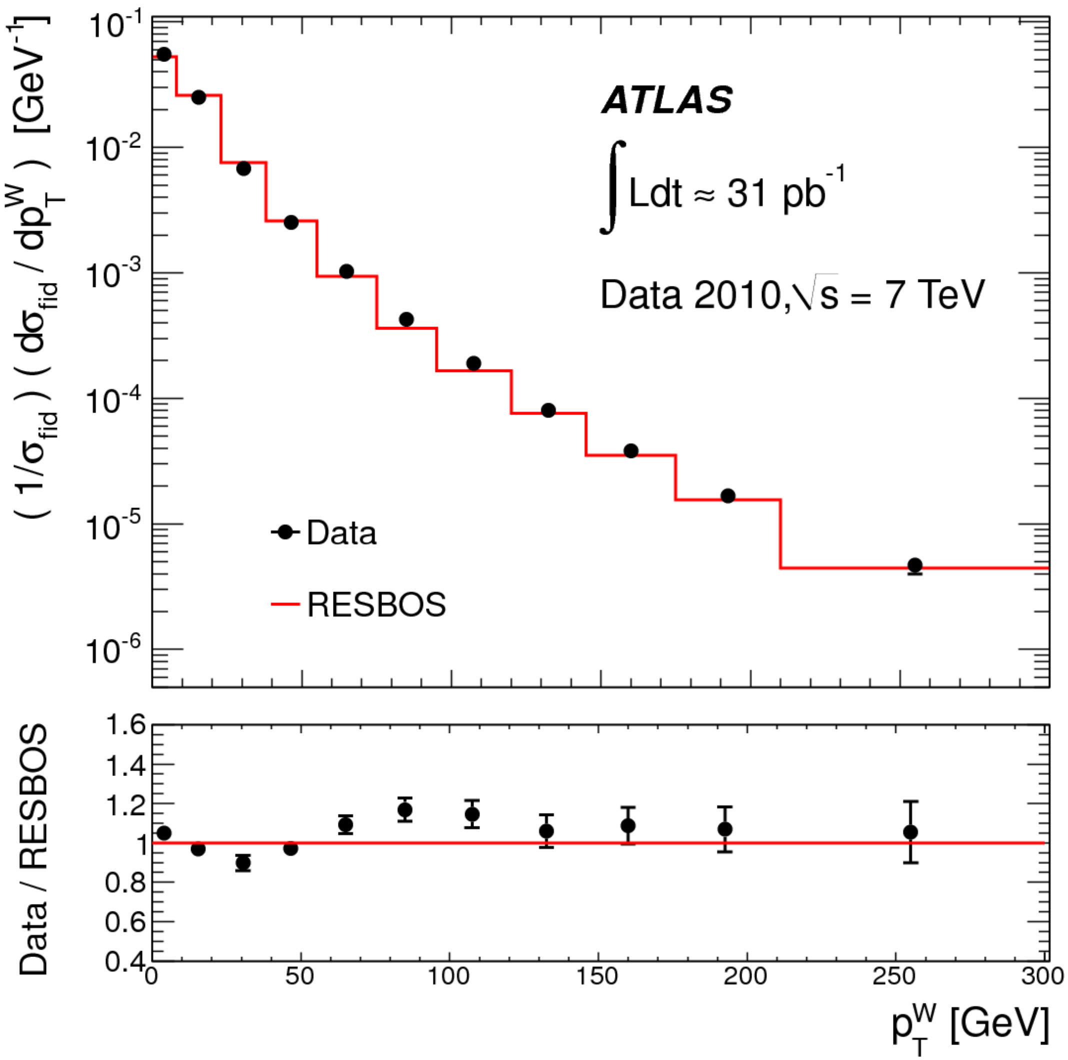
W + *b* jets	4.6 fb^{-1}	JHEP 06 (2013) 084	←
W + *c* jets	4.6 fb^{-1}	ATLAS-CONF-2013-0045	←
Z + b jets	36 pb^{-1}	Phys. Lett. B706 (2012) 295-313	

MPI

W + 2 jets DPI	36 pb^{-1}	New J. Phys. 15 (2013) 033038

p_T^W

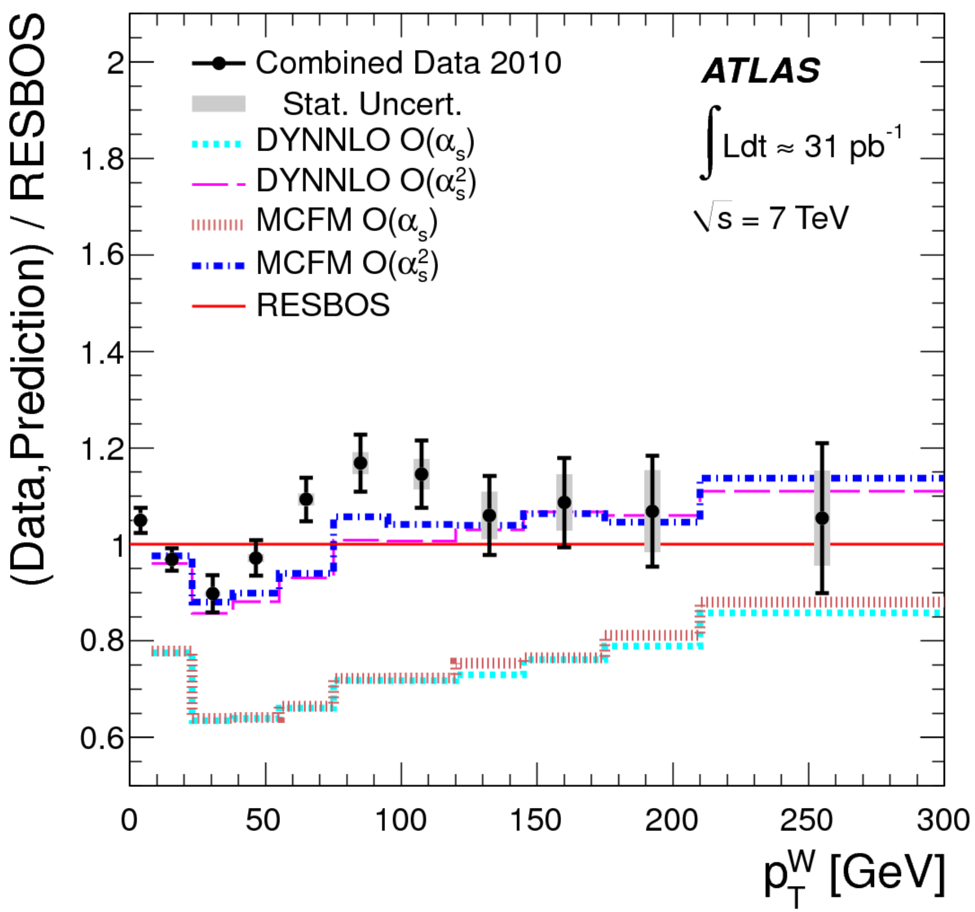
- Most inclusive test of QCD dynamics: Look at hadronic recoil of vector boson
- Expect to describe high p_T^W via pQCD, low p_T^W via resummation
- W+jets: Measure p_T^W via the hadronic recoil in $W\rightarrow e\nu$ and $W\rightarrow \mu\nu$ channels
- Not optimal resolution but ~10x statistics and complementary to p_T^Z measurement

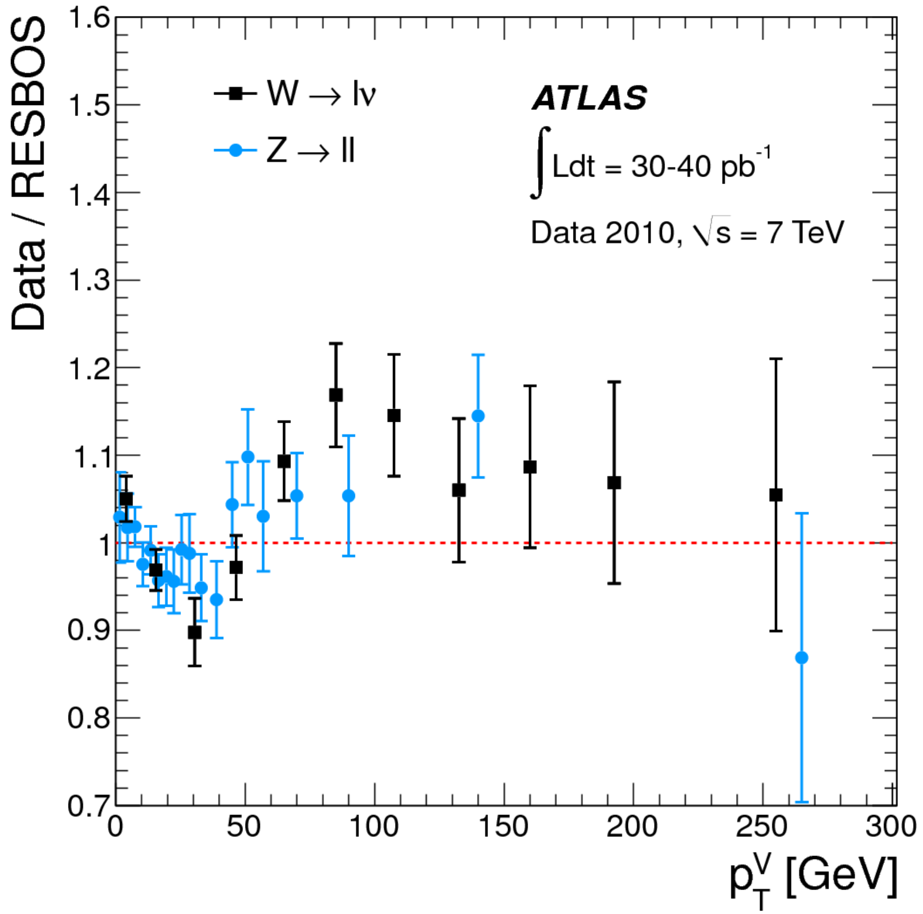


- Data described within 20% over covered p_T^W range by the RESBOS calculation NNLL Resummation matched to $O(\alpha_s) + O(\alpha_s^2)$

p_T^W and p_T^Z

Phys. Lett. B705 (2011) 415-434
Phys.Rev. D85 (2012) 012005





- Leading order predictions at O(α_s) are Insufficient
- Also good to 20%: LO+PS

- Can compare p_T^Z and p_T^W measurements to RESBOS in resp. phase spaces
- Ratios show similar trends
- Strong support for expected universality of QCD effects in *W*, *Z* production

Boosted Z bosons: ϕ_η^*

Phys. Lett. B 720 (2013) 32-51

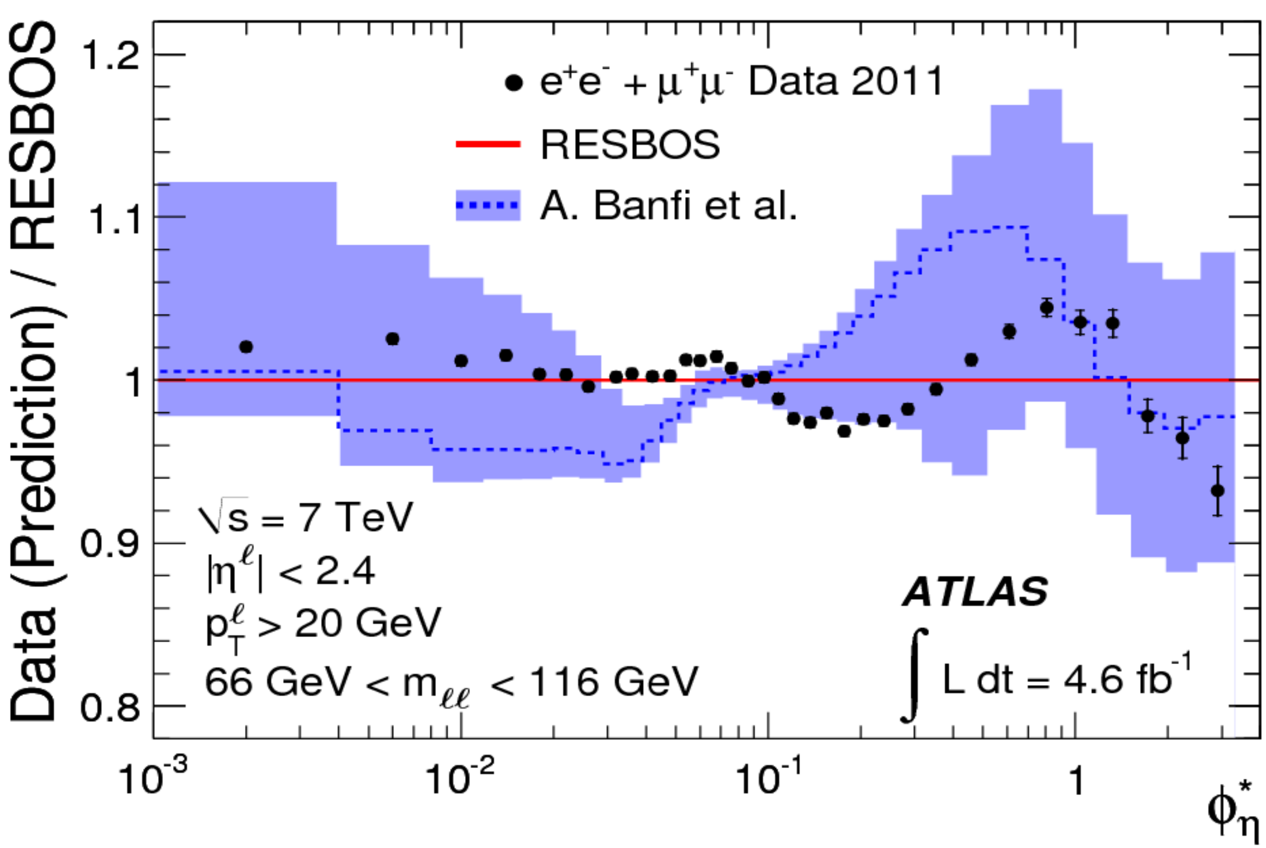
- Further improve precision of measurement of $Z/\gamma^* \rightarrow ll$ + X final state by introducing a new variable

A. Banfi et al.,
PLB 715 (2012) 152

$$\phi^*_\eta \equiv \tan(\phi_{\rm acop}/2) \cdot \sin(\theta^*_\eta)$$

$$\phi_{\rm acop} \equiv \pi - \Delta\phi, \quad \cos(\theta^*_\eta) \equiv \tanh[(\eta^- - \eta^+)/2]$$

- Correlated to $\phi_\eta^* \sim p_T^Z/m_{ll}$
- Probe same physics, but use only precisely measured track directions

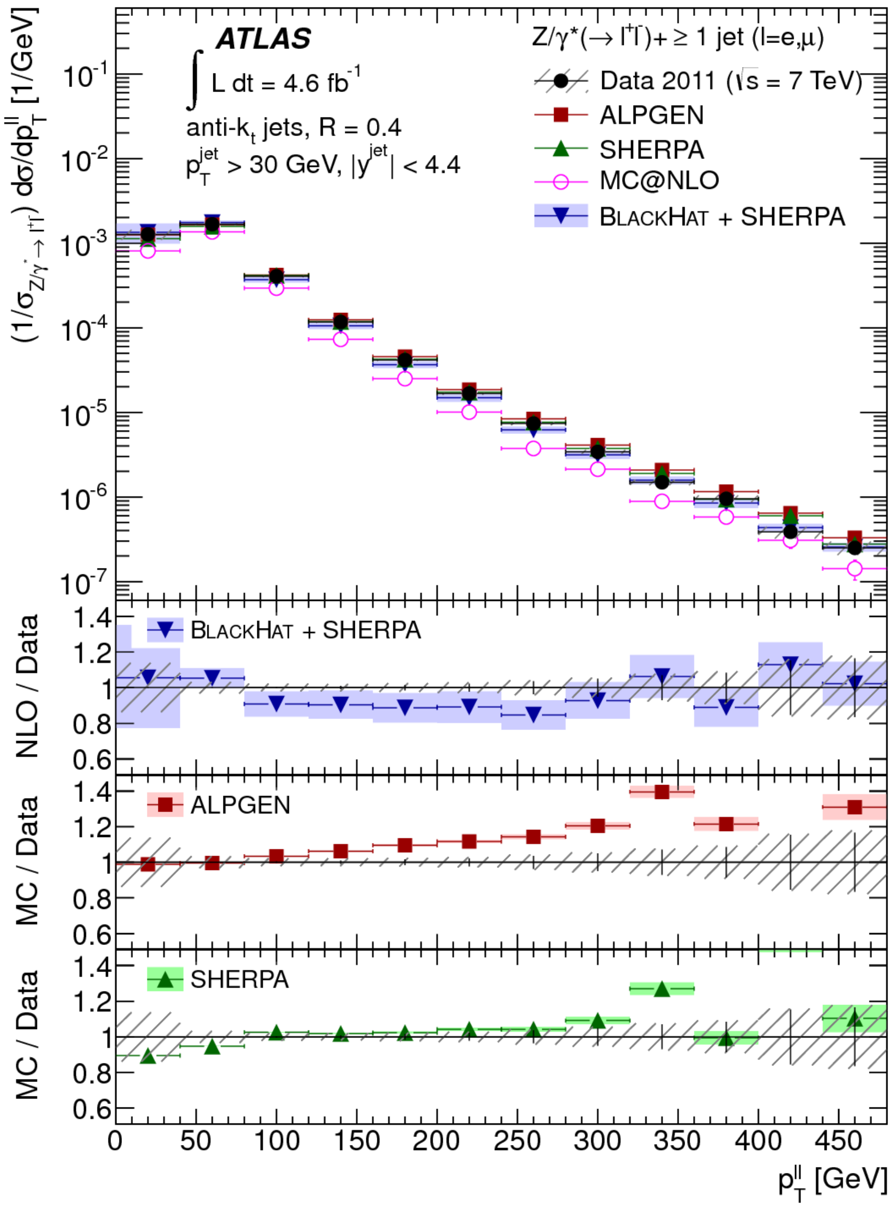


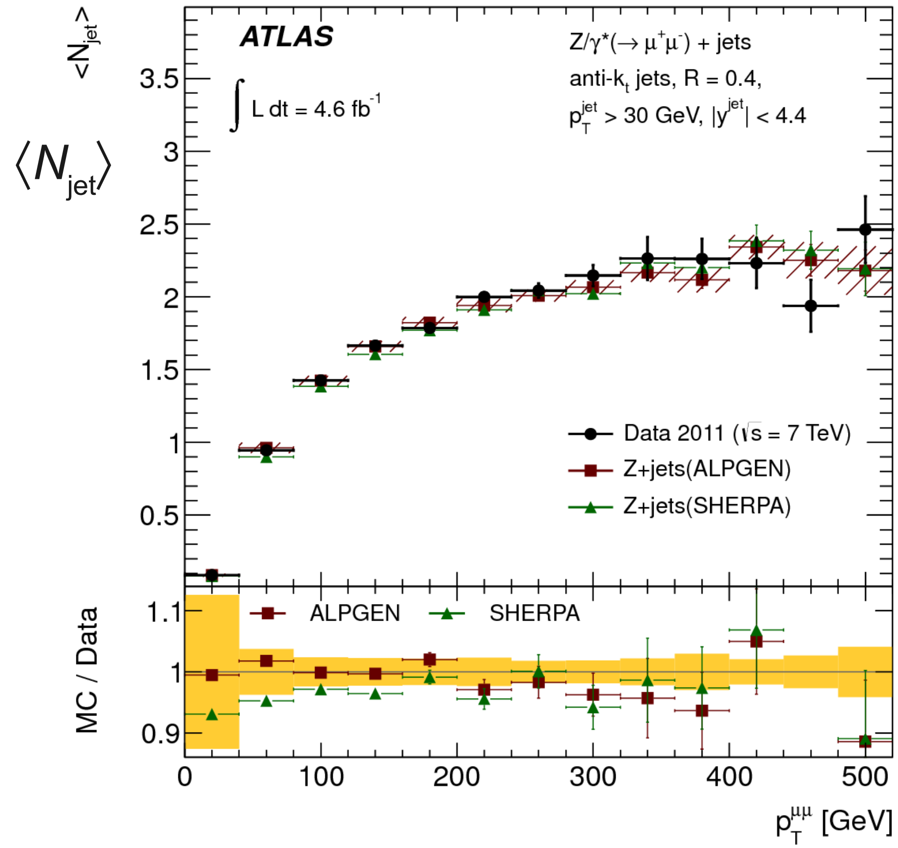
- RESBOS
  ~2% - 5% agreement with data (uncertainty dominated by PDF uncertainty)
- NNLL matched to NLO from MCFM agrees within ~10%
- Experimental uncertainty one order of magnitude more precise than predictions
- Valuable information for MC tuning

Z+jets: p_T^Z

JHEP07(2013)032

- Measurement of production of *Z* bosons in association with at least one jet

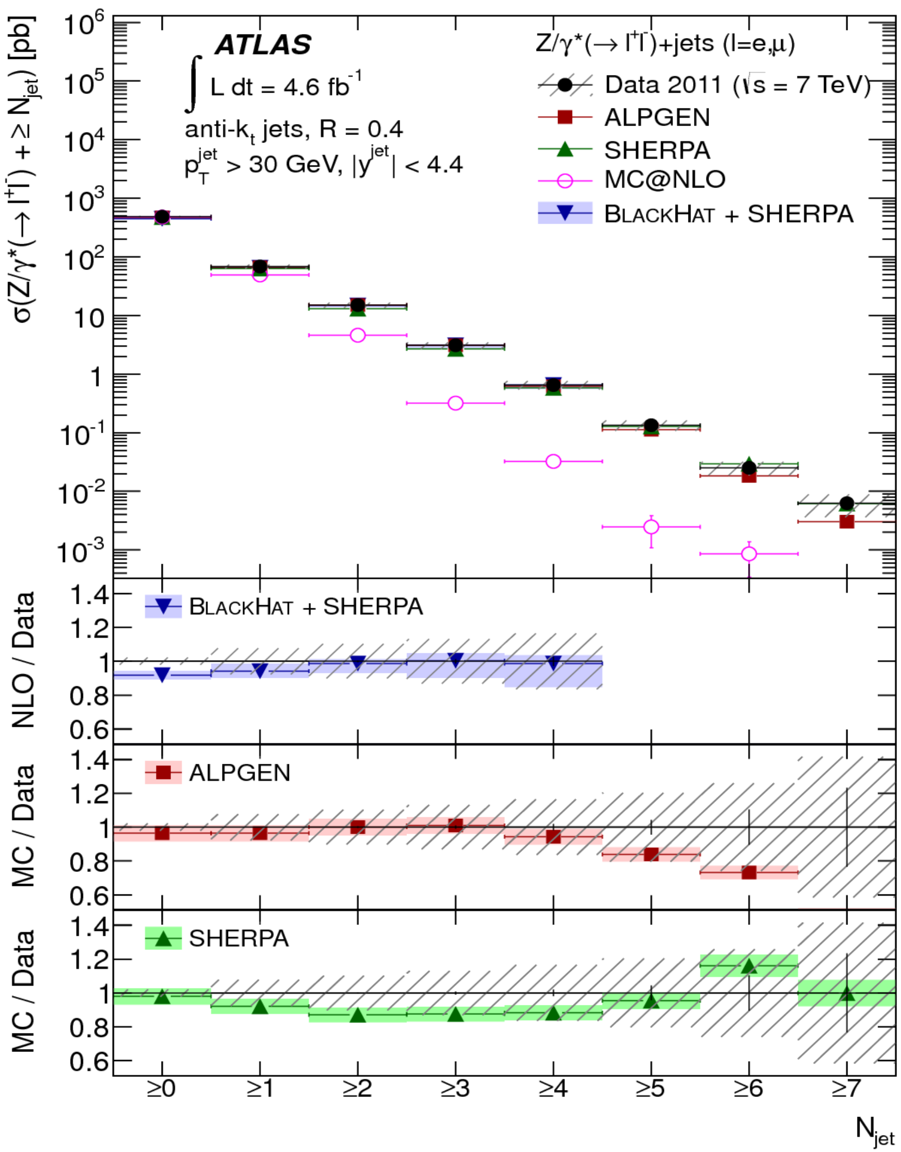


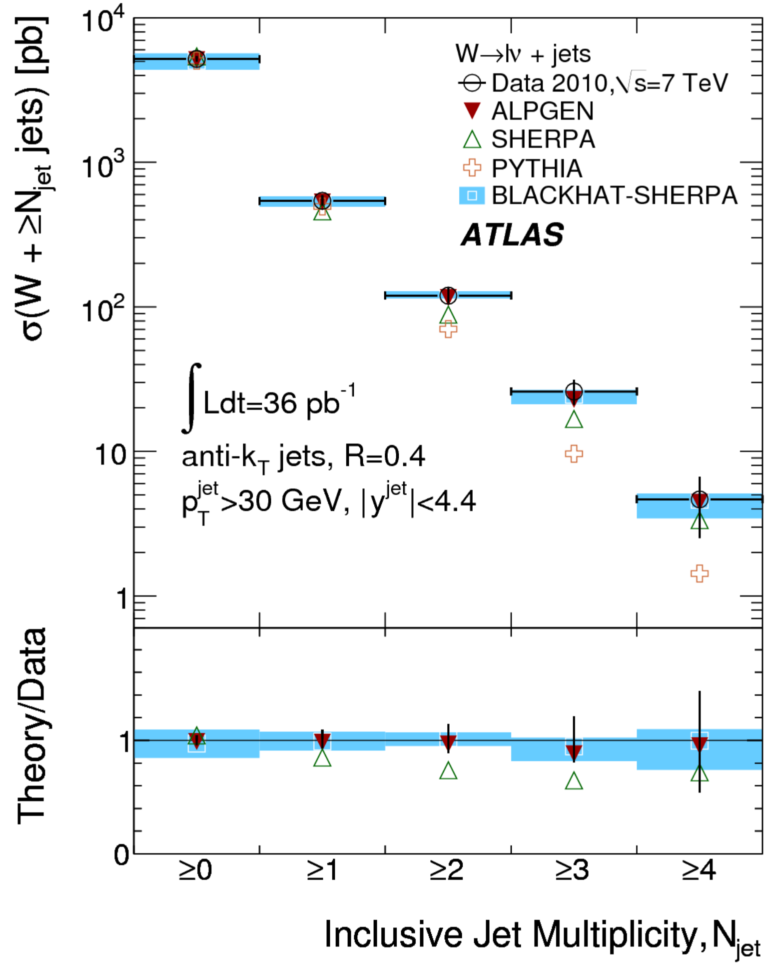


- Compare normalised (NNLO) cross section to LO and NLO predictions
- Above $p_T^Z > 100$ GeV where $\langle N_{jet} \rangle > 2$
  - Missing EW corrections
  - Missing pQCD in fixed order NLO Z + ≥1 jets
- ALPGEN tends to overestimate cross section at high $p_T^Z > 200$ GeV

Incl. jet multiplicity in *V*+jets

- Z+jets: 4.6 fb^{-1} measured up to 7 jets and p_T^{jet} = 700 GeV
- W+jets: 36 pb^{-1} up to 4 jets (cross section 10x larger than Z+jets)





- Good overall description of higher N_{jet}
- by NLO (BlackHat+SHERPA)
- LO multi-leg described within errors,
- some tensions with central value at high N_{jet}

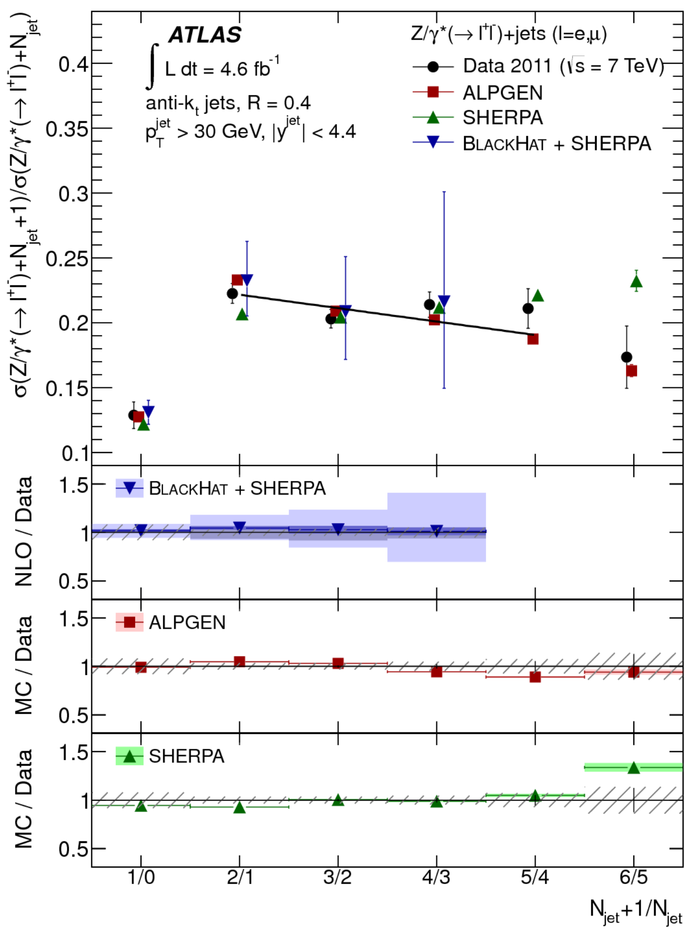
QCD scaling in Z+jets

JHEP07(2013)032

- Exploitation of QCD scaling properties can be useful for analyses using jet vetoes
- Can be applied in background prediction of V+jets between different jet bins

Staircase scaling

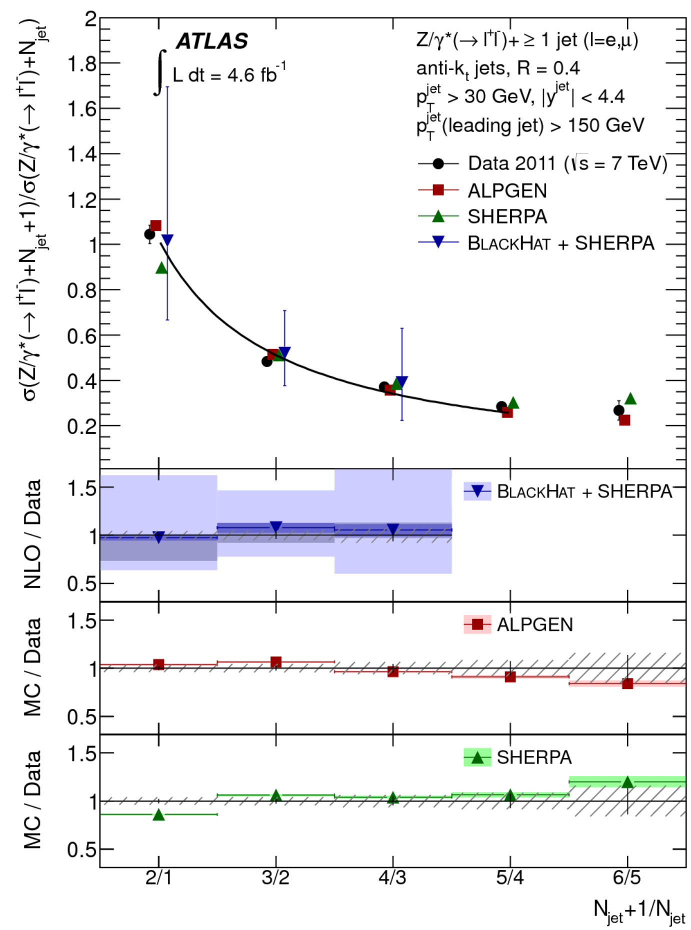
- Symmetric jet p_T requirements
- PDF suppression
- Z+(N+1) / Z+N ~ constant



Poisson scaling

- Asymmetric jet pT requirements
- No PDF suppression
- Z+(N+1) / Z+N ~ <N>/N

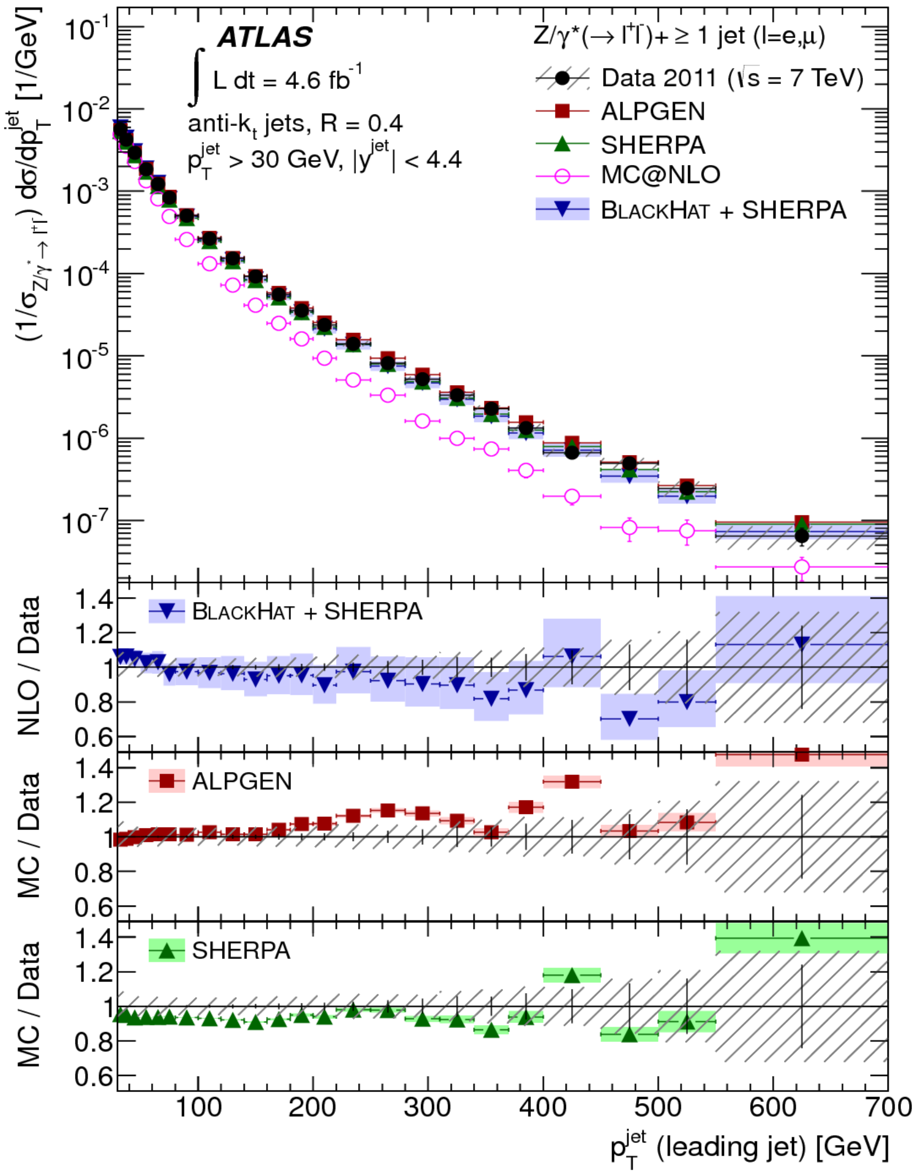
Gerwick et al. arXiv:1208.3676

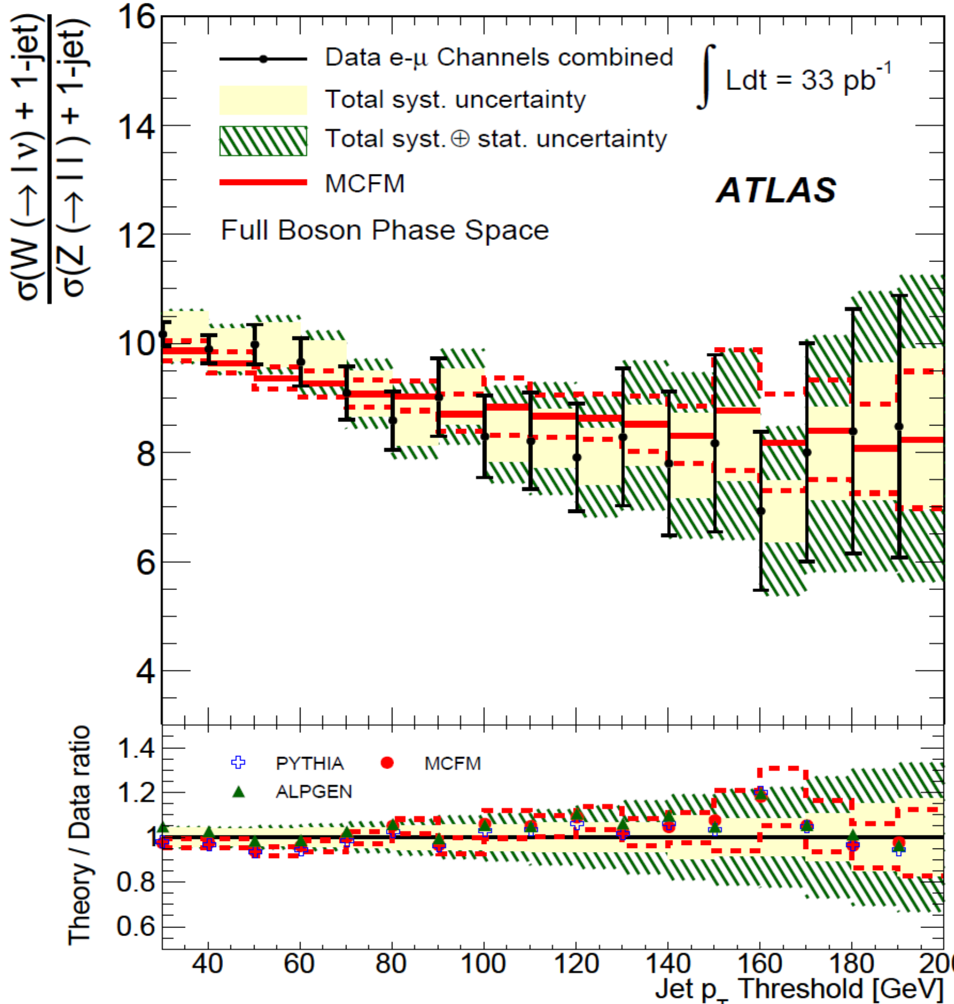


Both kinematic extremes well modeled by predictions

Leading jet p_T and R_{jets}

JHEP07(2013)032
Phys. Rev. D85 (2012) 092002
Phys. Lett. B708 (2012) 221-224



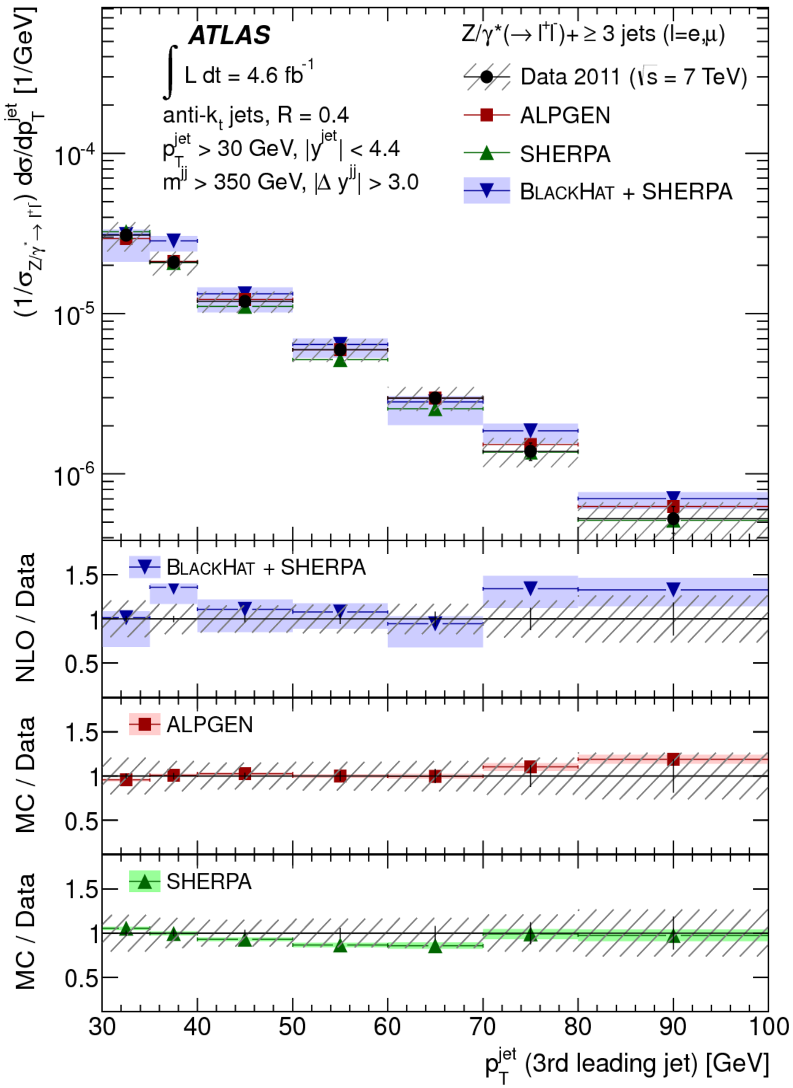


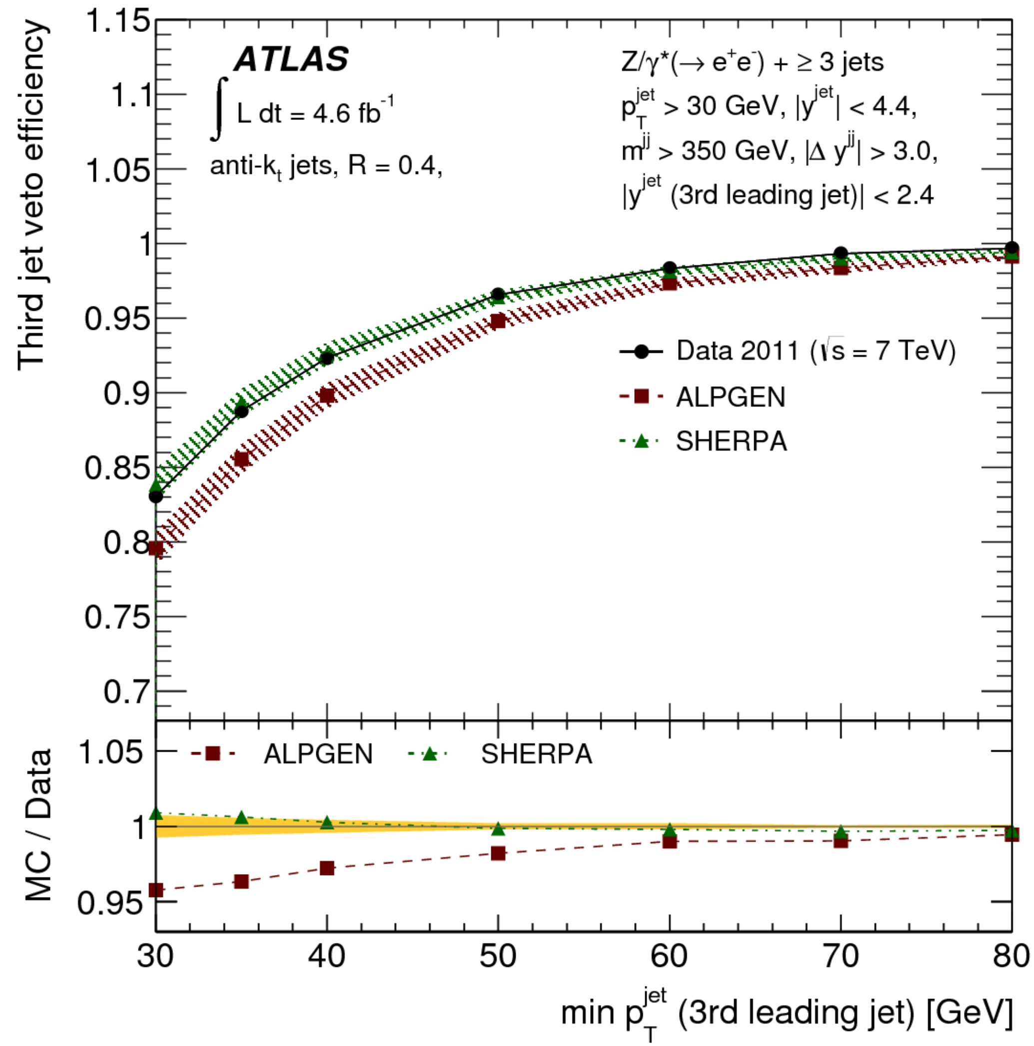
- Leading jet p_T well described by NLO
- Described within errors by LO
  - tensions at high values

- Also measured ratio
  $R_{1\text{-jet}} = N(W + 1\text{-jet}) / N(Z + 1\text{-jet})$
- Statistically limited for $p_T > 100$ GeV, potential cancellation of many experimental uncertainties while still retaining all sensitivity to dynamics of QCD effects

Z+jets VBF-like topologies

- Within *Z*+jets also look at VBF-like selection: two well-separated high mass, high p_T jets





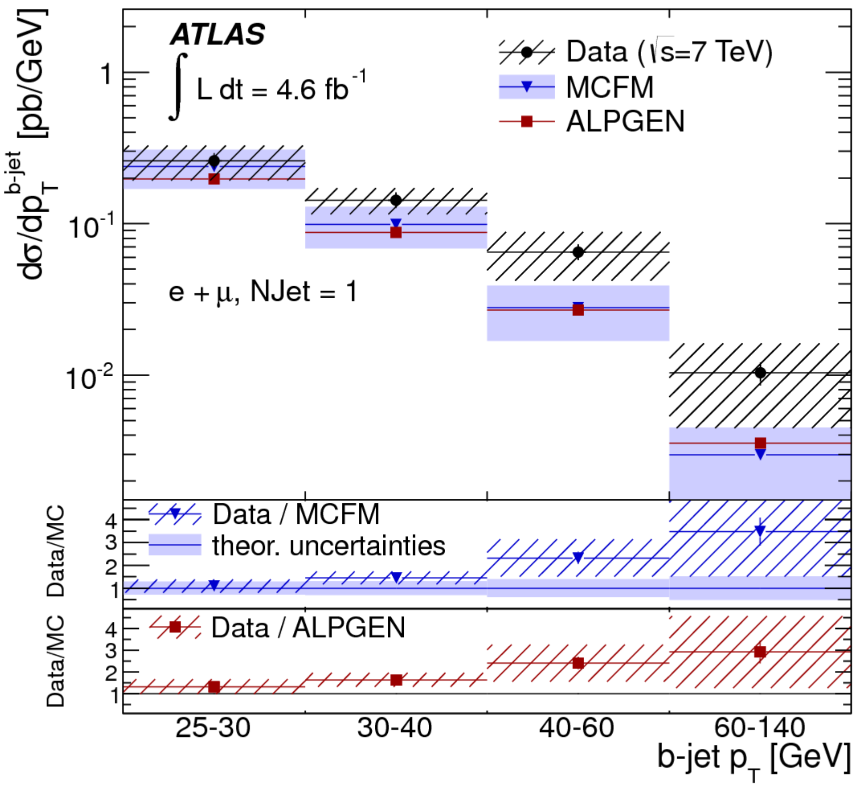
- Look at modelling of 3[rd] jet in central gap
- Well modelled up to $p_T \sim 70$ GeV, lack of data beyond
- Test of ME+PS matching, important for jet veto efficiency

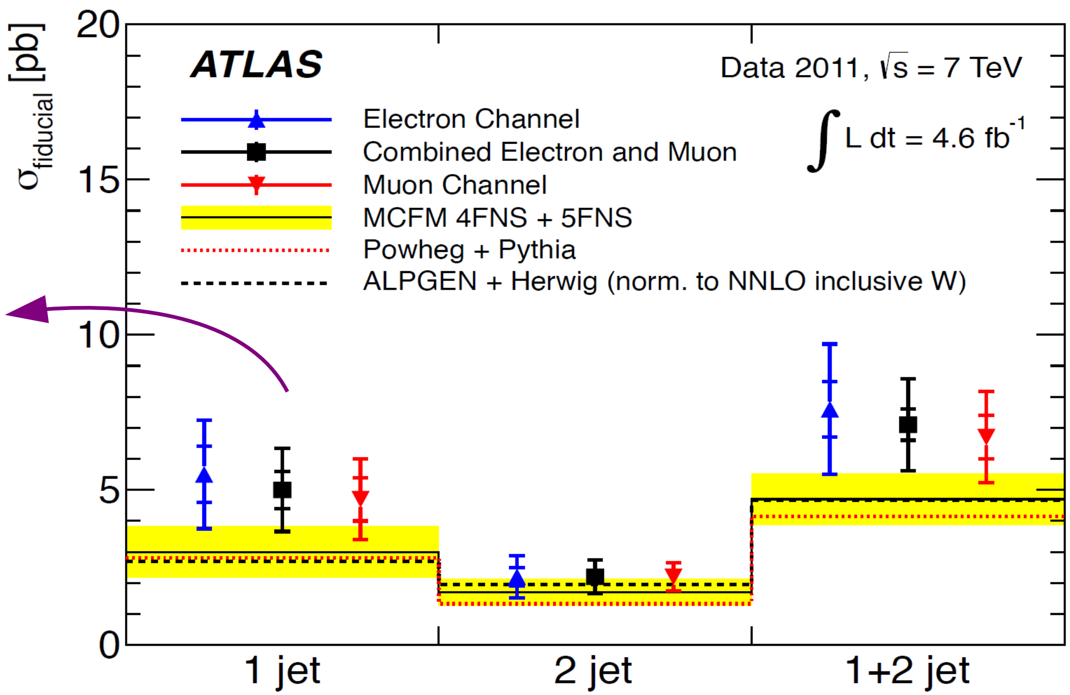
Fraction of events passing jet veto requirement
- Described by SHERPA
- ALPGEN underestimates gap fraction

W + ≥1 *b*

JHEP 06 (2013) 084

- Differential measurement of σ(W + ≥ 1 *b*-jet) in excl. 1 jet, 2 jet and 1+2 jet bins





5FNS:
bq → Wbq
bg → Wbqq

4FNS:
qq → Wbb
gq → Wbbq

+ DPI
(~25% of 1+2 jet)

- Comparison of data to predicitions using various schemes to include heavy flavor
  - 4FNS: no *b*-PDF in initial state at LO (ALPGEN), NLO (POWHEG)
  - 5FNS: considering *b*-PDF in initial state at NLO (MCFM)

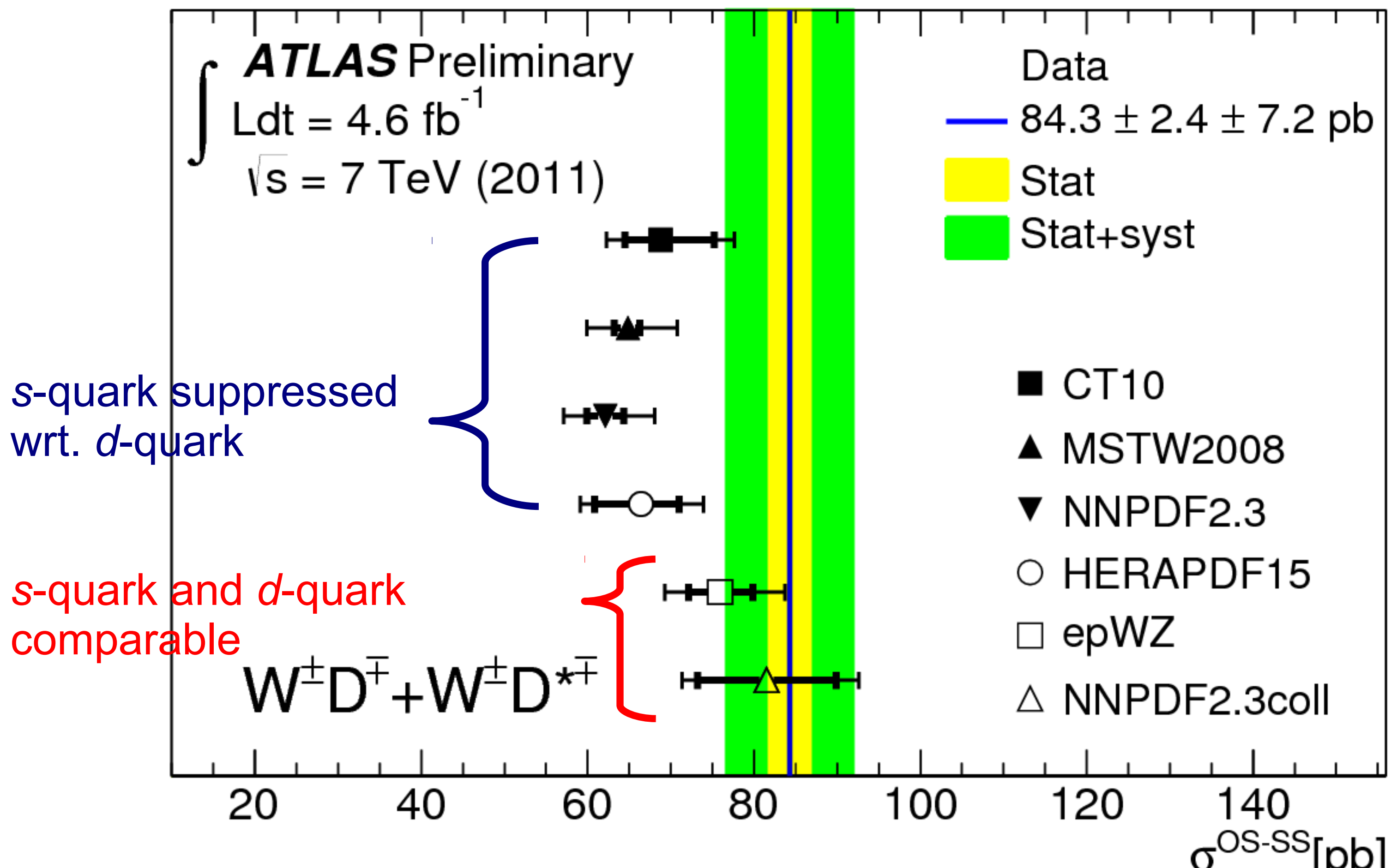
- Data and predictions agree within uncertainties (dominated by JES, JER)
  - Central values about 1.5σ above predictions (trend rising with *b*-jet p_T)

$W + c$

ATLAS-CONF-2013-045

- Preliminary measurement of $\sigma(W^{-/+} + D^{(*)+/-})/\sigma(W^{-/+})$
- In *pp* → *WcX* at 7 TeV *gs* → *Wc* dominant (~90%) : sensitive to strange PDF at x ~ 0.01

- Compare measured cross section to aMC@NLO + HERWIG++
  - Cross section prediction depends strongly on chosen PDF
  - PDFs where d ≅ s at x ~ 0.01: SU(3) symmetric sea favoured



Summary

ATLAS 7 TeV data largely exploited for *V*+jets measurements

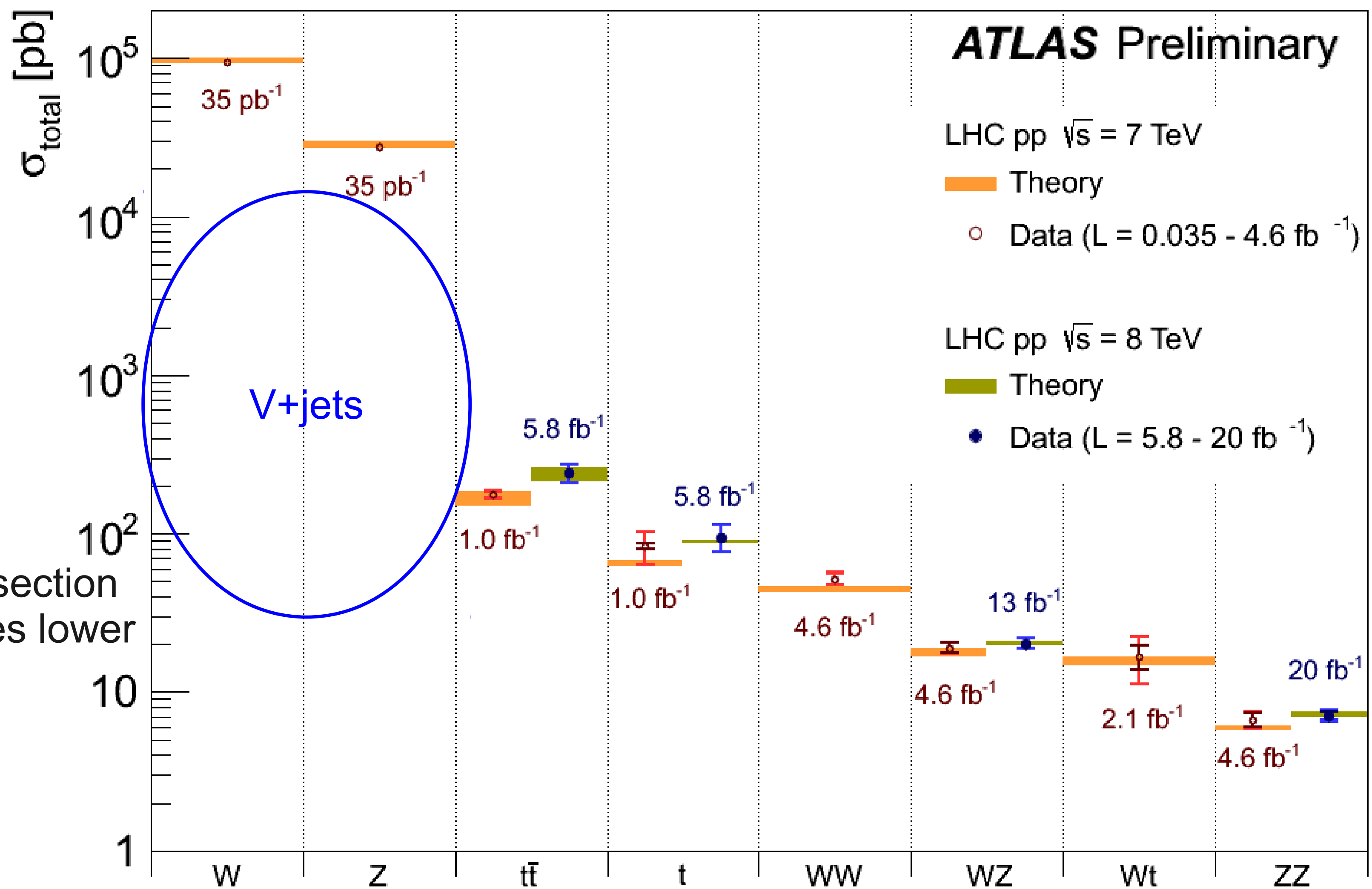
- Many accurate experimental results compared to recent predictions at LO, NLO, NNLL
- Experimental uncertainties smaller than theoretical uncertainties in large regions of phase space

Main observations

- Mostly good agreement of data and predictions
  - Nevertheless tensions of data and theory **central values** in some regions for example high p_T and high N_{jet}
  - Needs confirmation using higher statistics / from other experiments
  - Opportunity to compare to even higher-order pQCD predictions
- In *W*+*c* preference for flavor-symmetric light-quark sea

BACKUP

SM Measurements Summary



Cross section
~5 times lower
per jet

SM processes well understood over many orders of magnitude production rate