ATLAS Measurements of Vector Boson Production with Associated Jets

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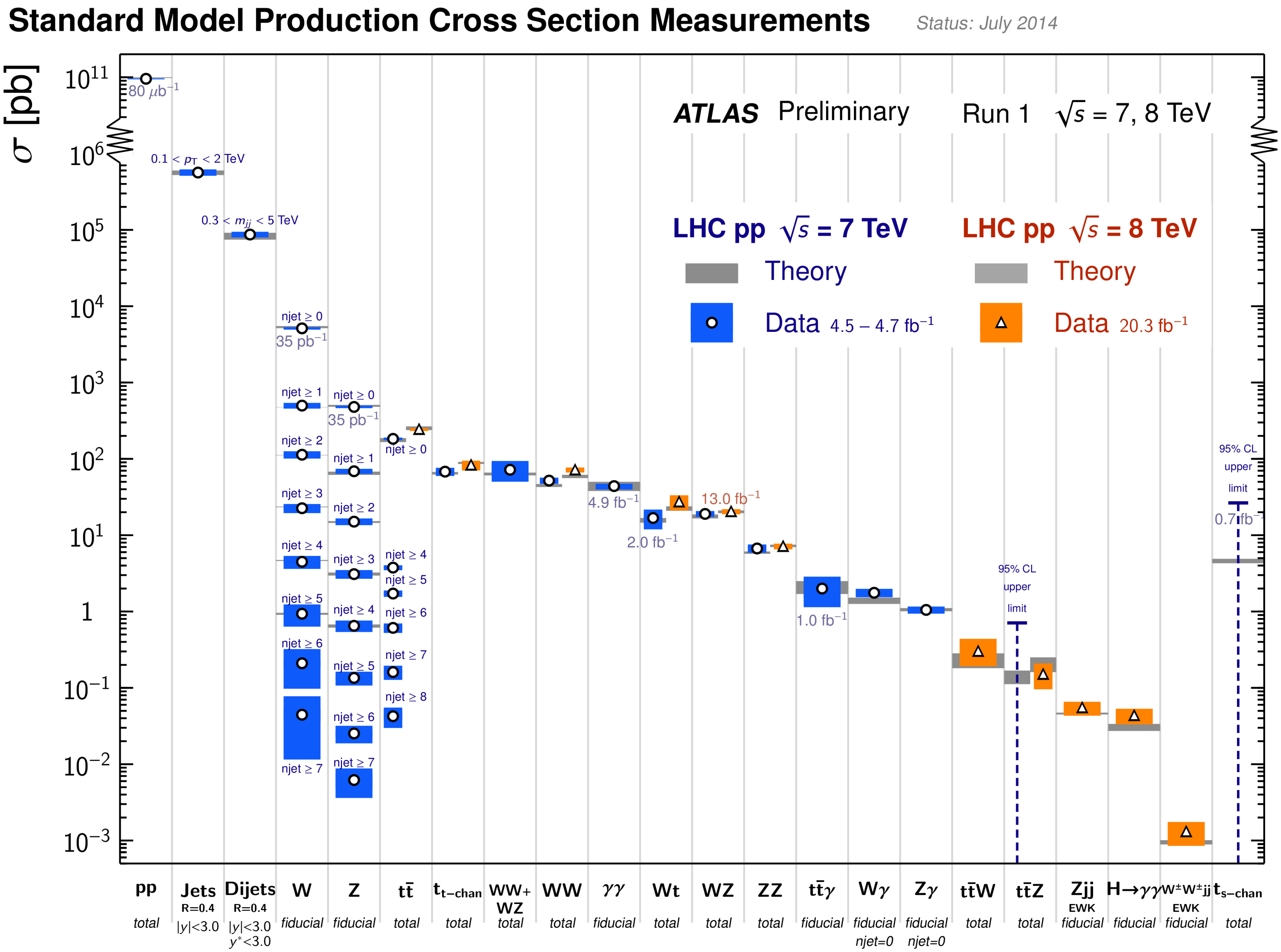
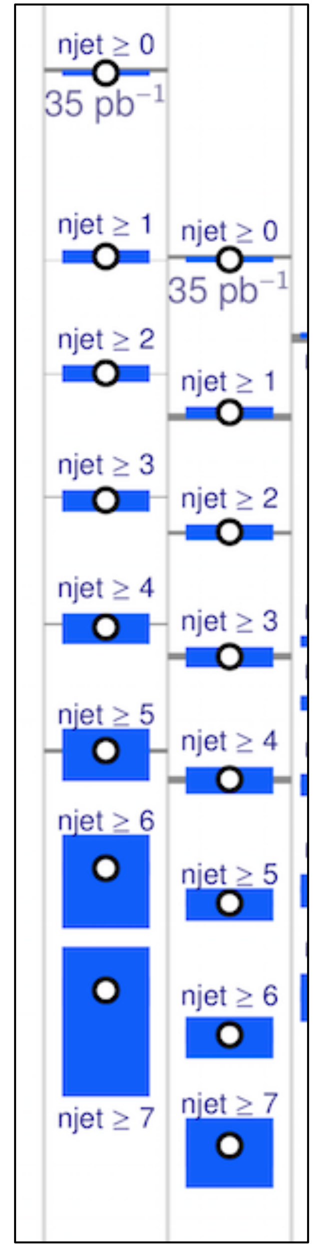
PANIC 2014

V+jets Inclusive Status





- **Experiment:**
  W & Z + up to 7 jets;
  Unfolded to particle level

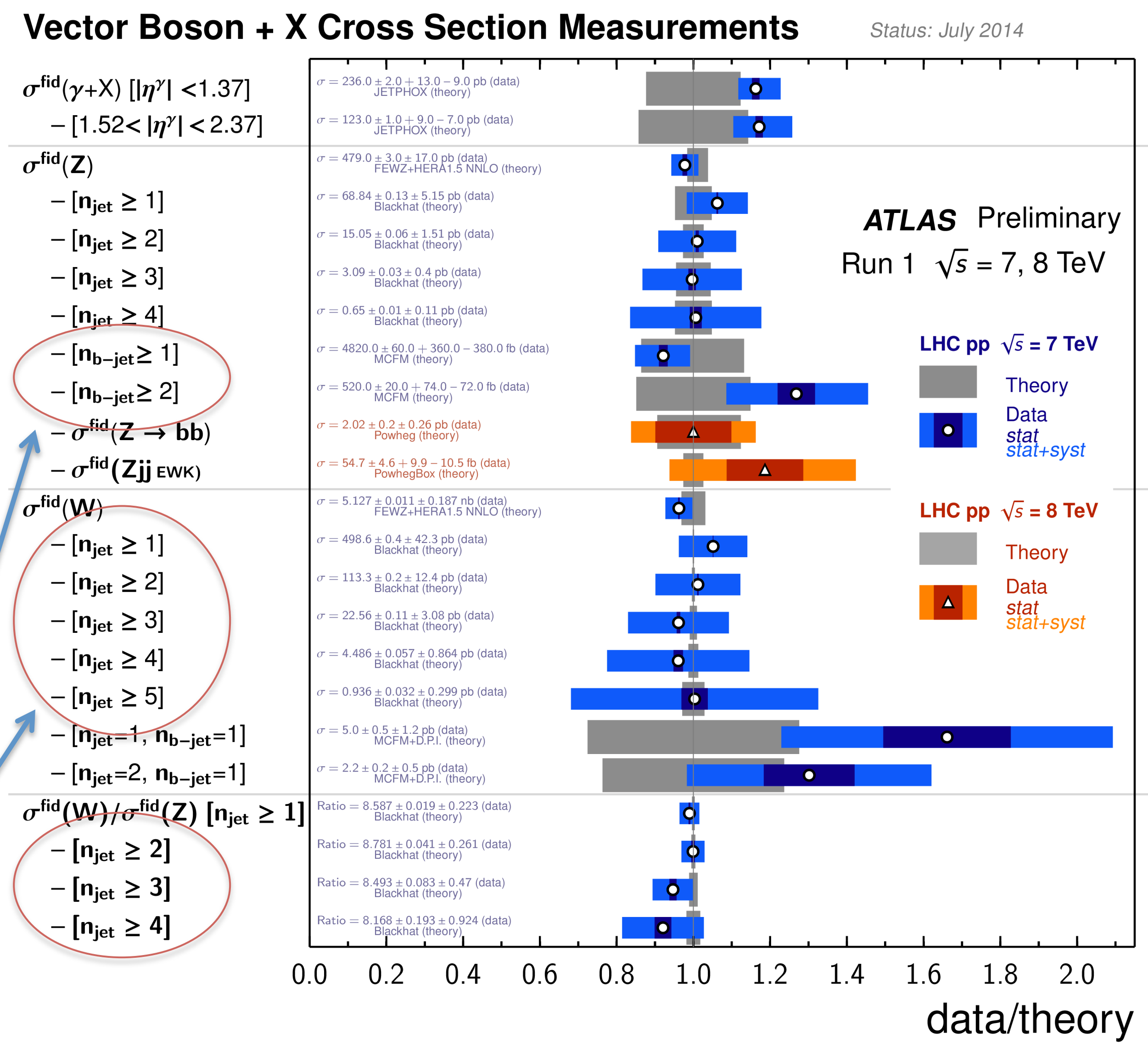
Theory:
W+jets NLO up to 5 jets
Z+jets NLO up to 4 jets

- **Excellent agreement over 5 orders of magnitude**
  QCD works at the LHC!

V+jets ATLAS Results

- **Abundance of results from 7 TeV pp data**

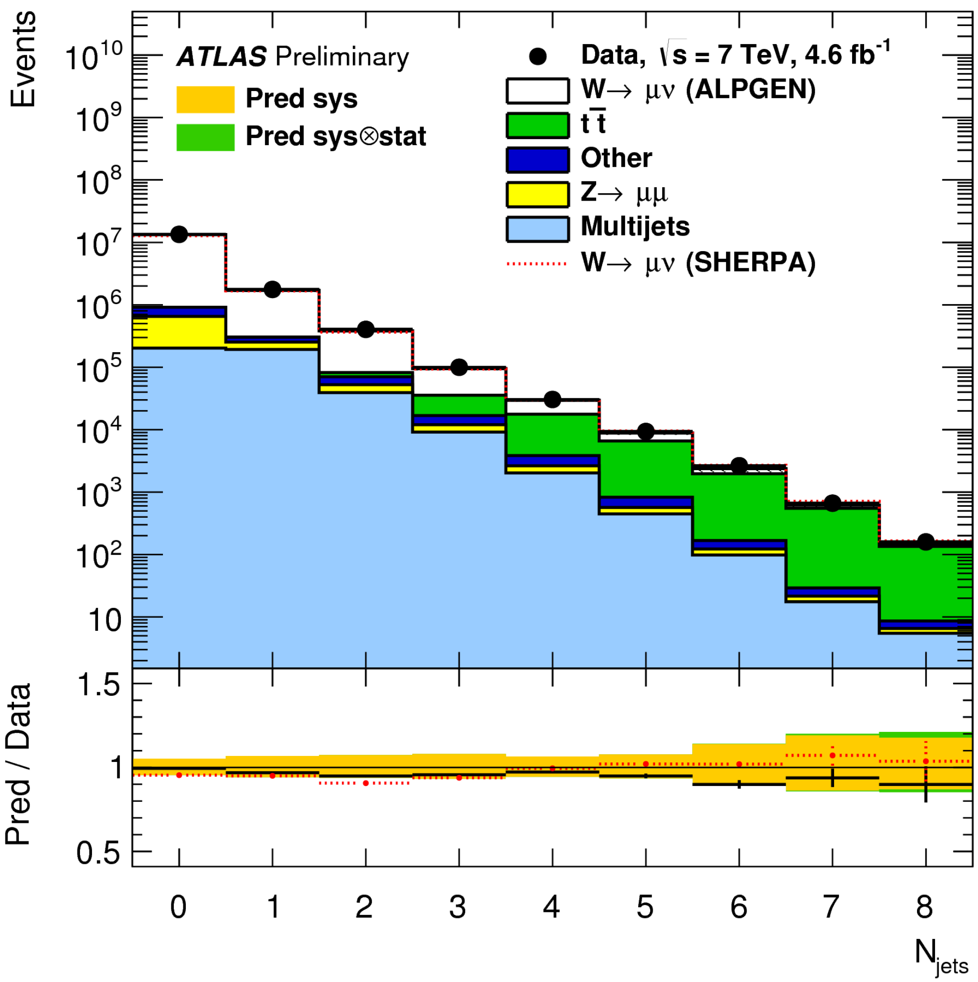
- **W+jets & Z+jets:**
  Numerous differential kinematic distributions
- **R_{jets}:**
  Differential ratios W+jets/Z+jets to reduce uncertainties
- **Heavy flavour:**
  First differential distributions;
  4F vs 5F & b-PDF
- **Also:**
  W+c sensitive to s-PDF;
  Zjj & Z->bb at 8 TeV



Updates July & August 2014: This talk

W+jets: Overview

Muon channel, detector level:



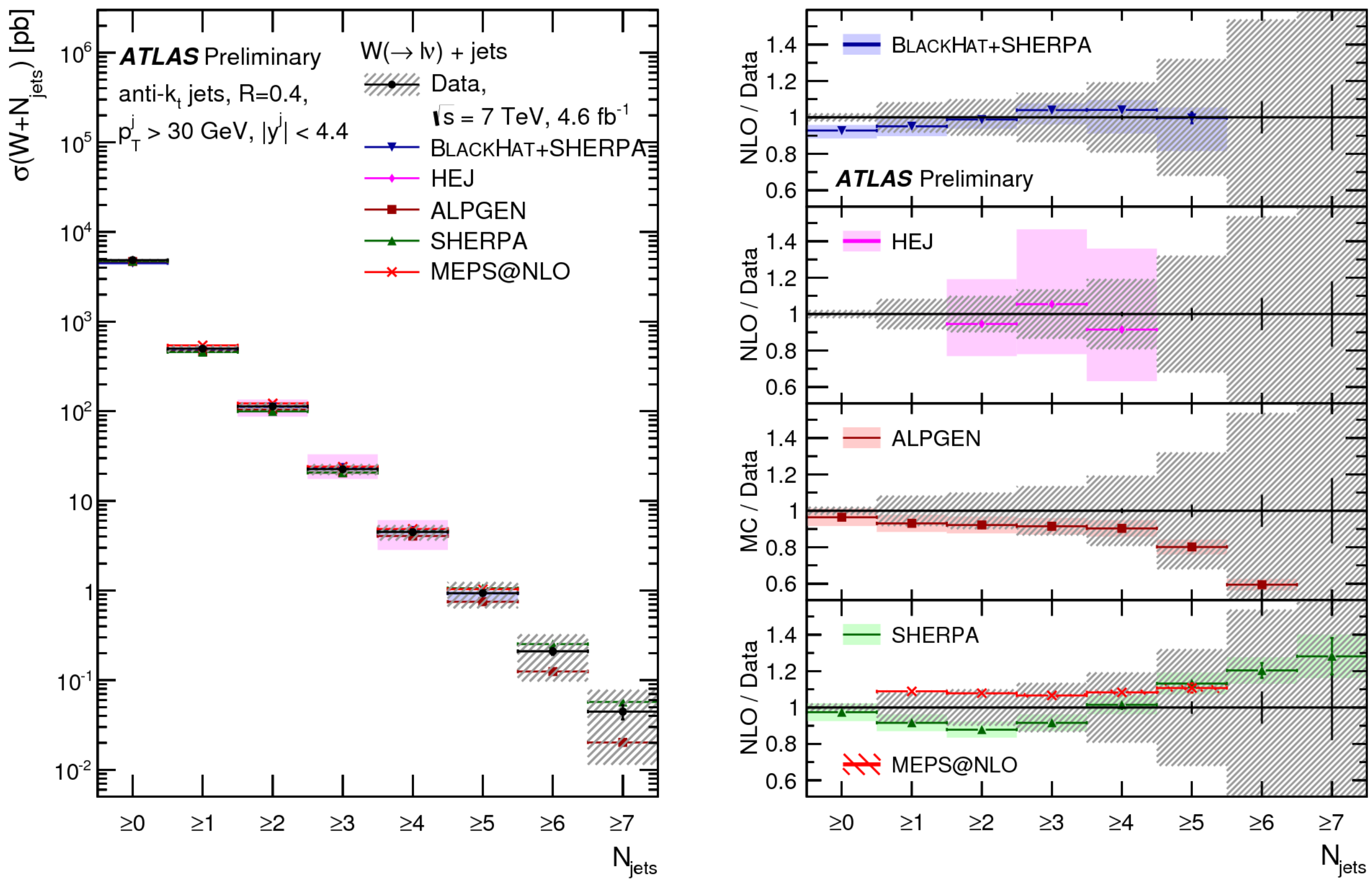
W+jets:	Particle level selection
Lepton	p_T>25 GeV; |η|<2.5
W->lv	E_T^{miss}>25 GeV; m_T>40 GeV
Jets	p_T>30 GeV; |y|<4.4 ΔR(l,jet)>0.5

- **Probe of QCD with jets up to 1TeV**
- **Differential cross-sections**
  - Incl. & excl. jet multiplicities
  - Jet pT & |y|, up to 5 jets incl.
  - Scalar sums HT & ST, up to 5 jets incl.
  - W+≥2jets
    - Leading jets Δφ, Δy, ΔR, mjj
- **Dominant systematics:**
  - Jet energy and resolution dominates
  - Top background uncertainty for Njets=4 and higher

ATLAS-CONF-2014-035

W+jets: Comparison to Theory

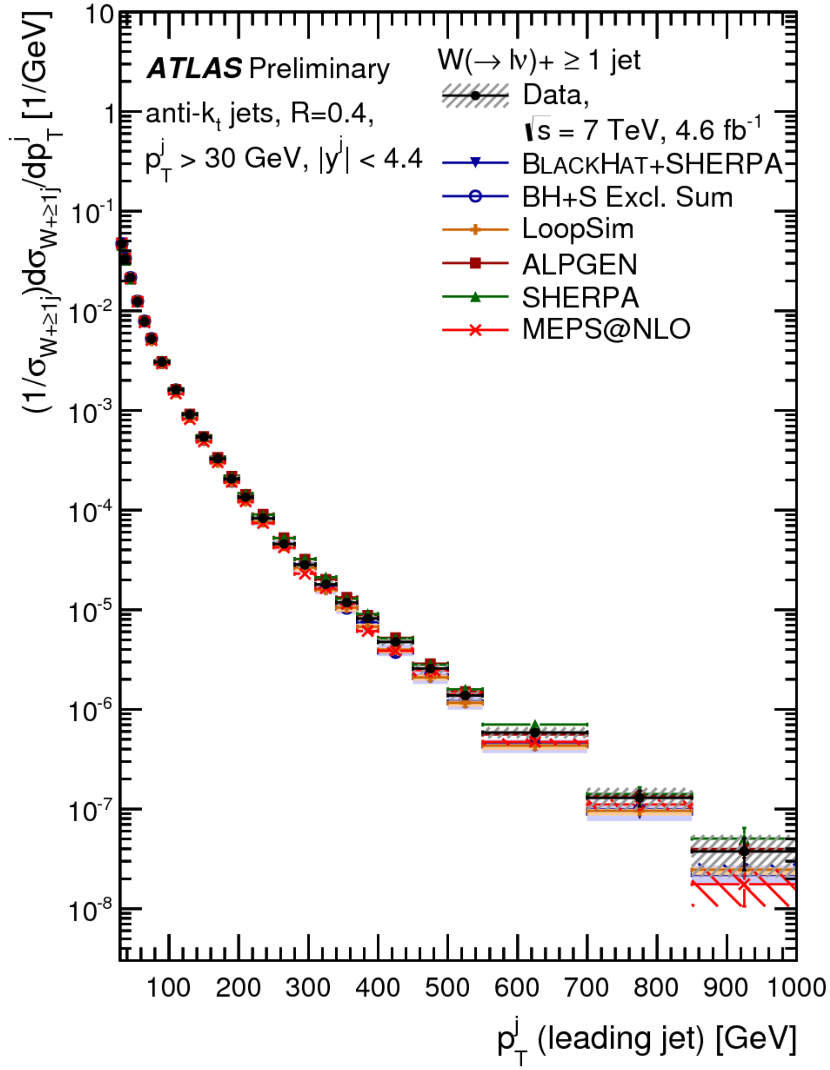
- **Blackhat+Sherpa**
  - NLO up to 5 jets
  - Exclusive sums: approx NNLO for Njets≥1jet
- **Loopsim**
  - Approx NNLO Njets≥1jet only
- **HEJ**
  - All order appox. for wide angle emissions, LL resummation
  - Uncorrected parton level Njets≥2
- **LO multileg**
  - **Alpgen** ME up to 5 partons
  - **Sherpa** ME up to 4 partons
- **MEPS@NLO**
  - Blackhat NLO W+1jet & W+2jet merged with LO W+ up to 4jets

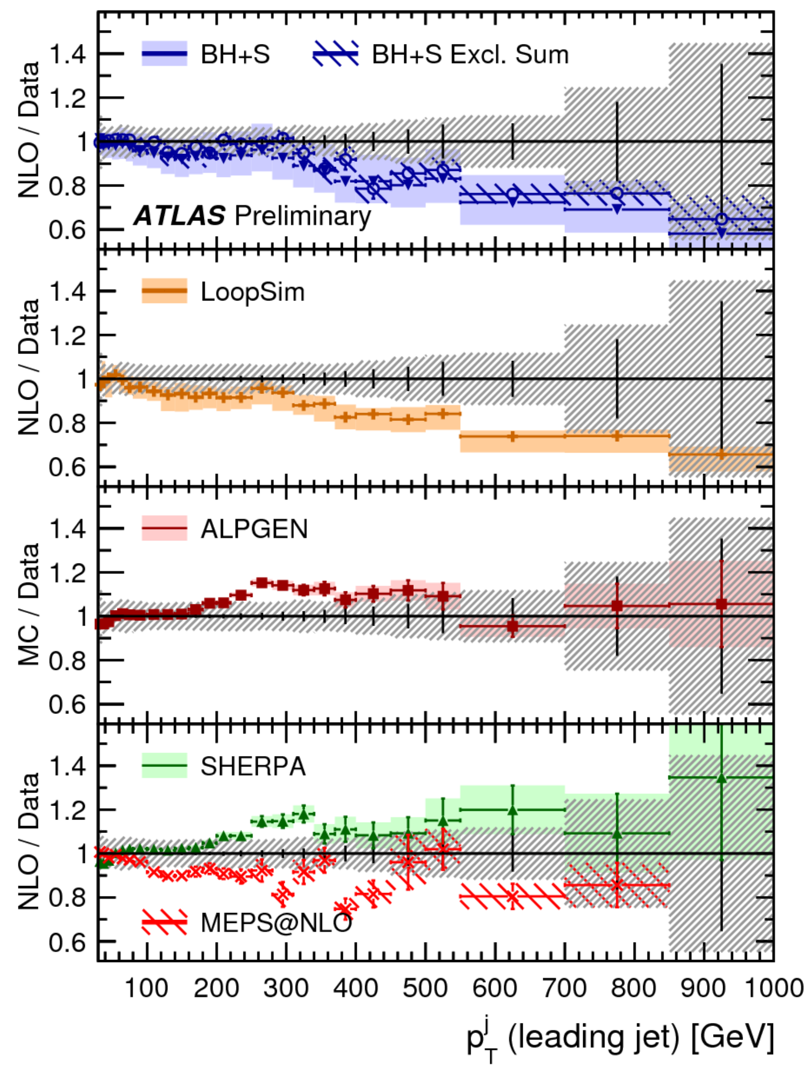


- **Excellent agreement for NLO**
- **LO deviates at high Njets, within uncertainties**
  - MCs bracket the data, current data can't discriminate these deviations

W+≥1jet: Jet pT

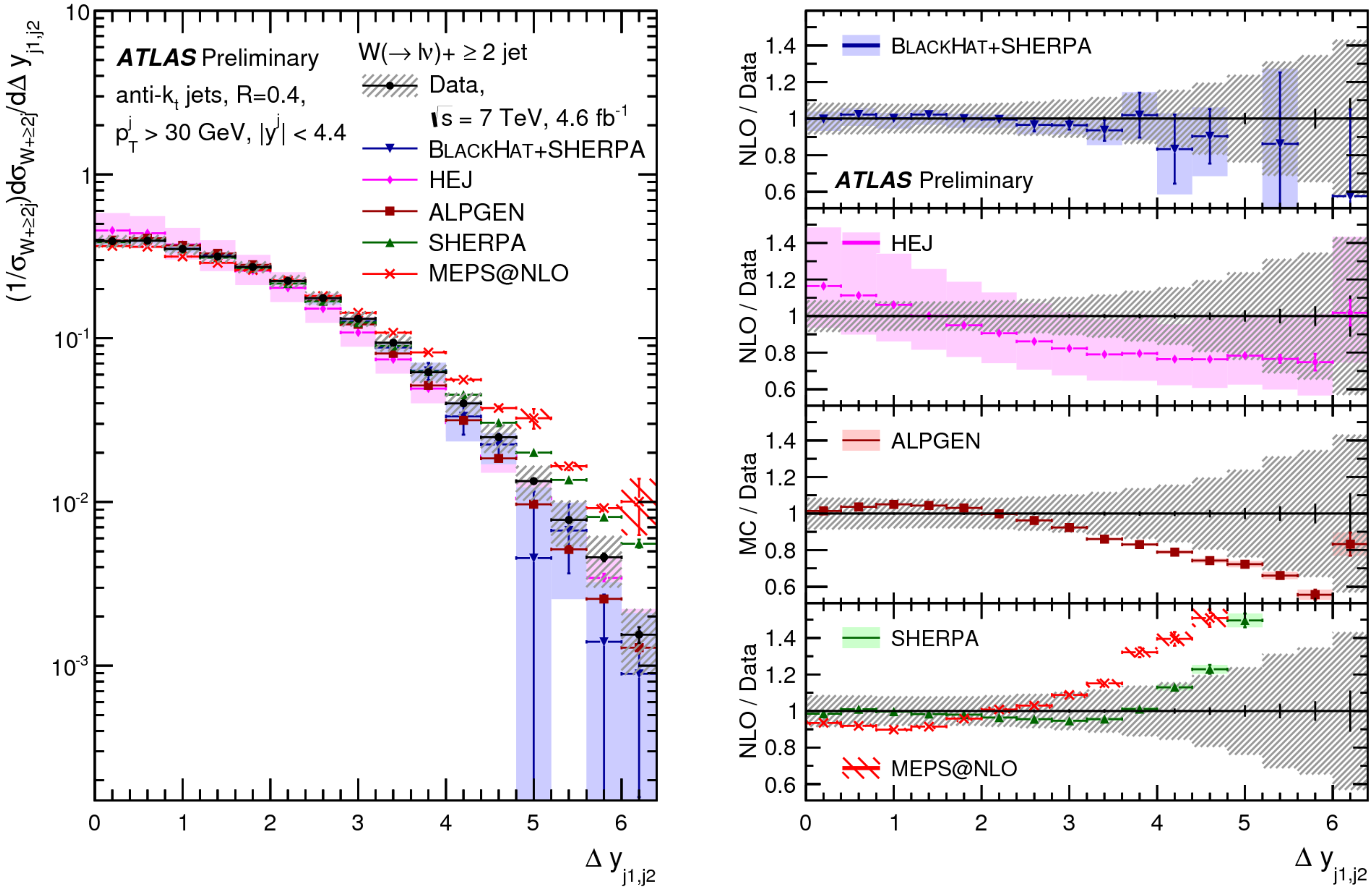
Differential over 6 orders of magnitude!





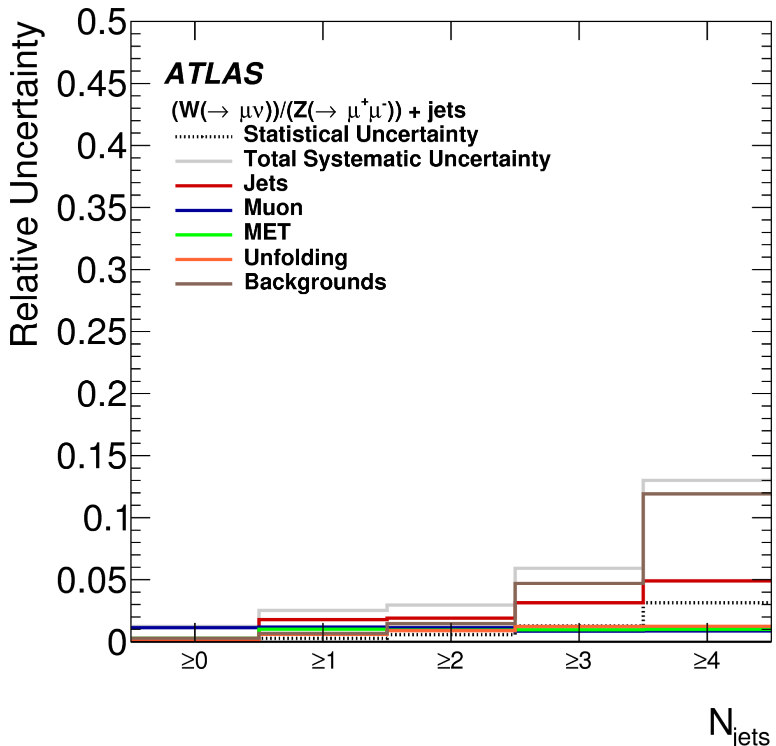
- **Approx NNLO no real improvement over NLO**
- **No EWK corrections, calculations suggest would increase discrepancy at high pT**

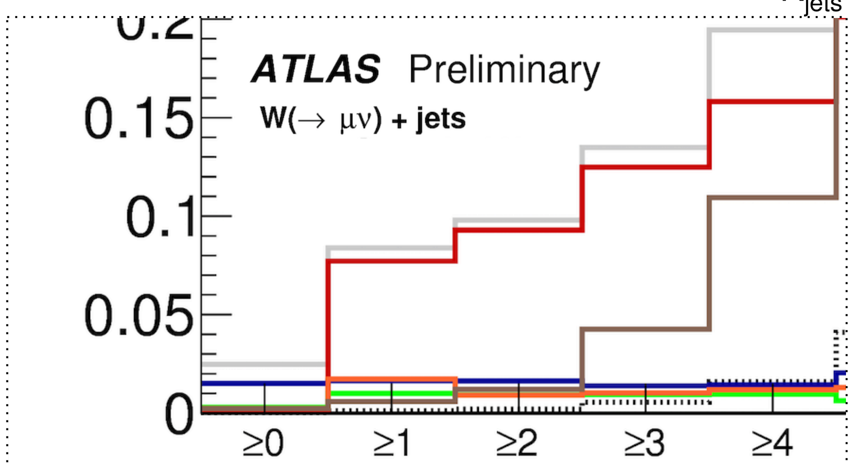
W+≥2jets: Jet Separation



- **Blackhat within uncertainties**
- **Alpgen & HEJ underestimate large separation**
- **Sherpa & MEPS@NLO overestimate large separation**

R_{jets}: Overview





Jet uncertainty reduced >x2 wrt W+jets

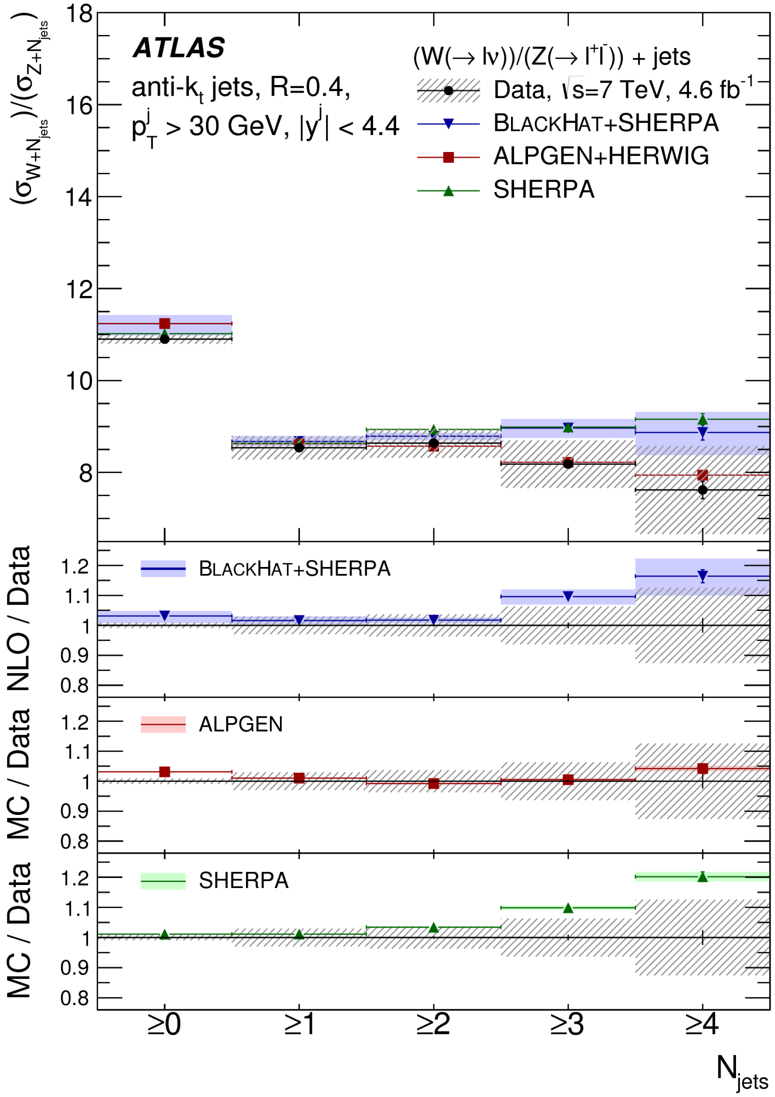
NB: Selection slightly revised wrt published ATLAS Z+jets

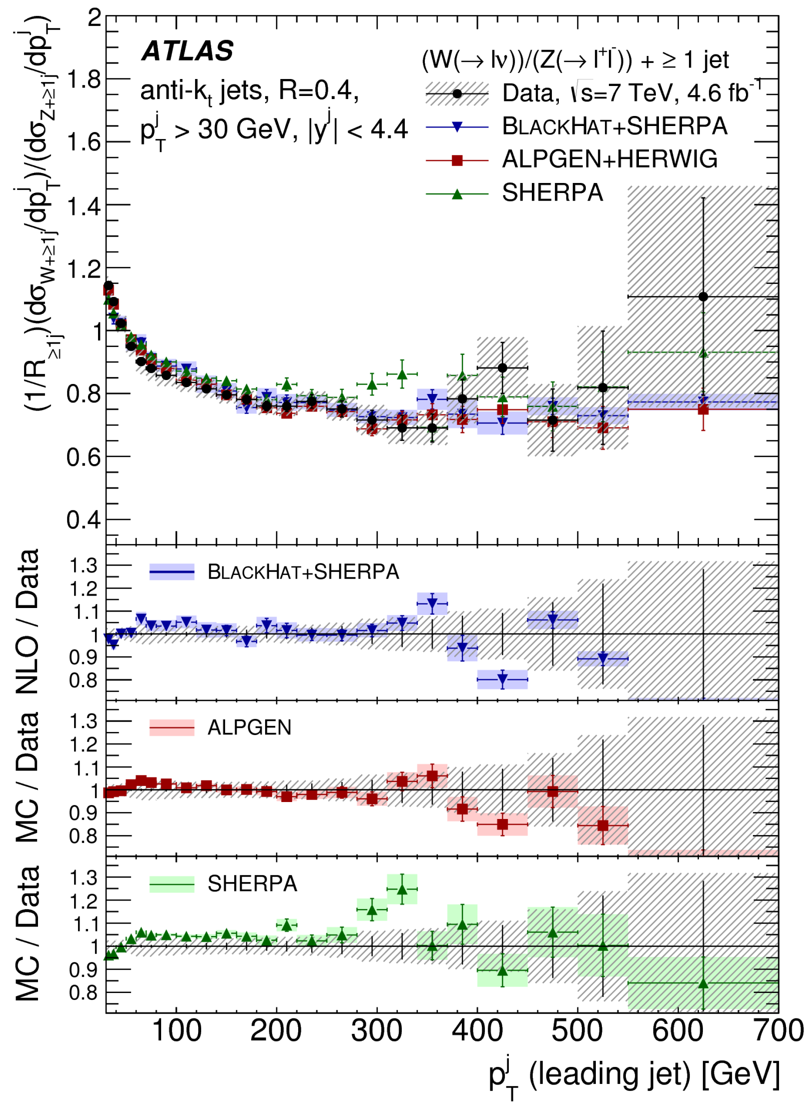
Z+jets:	**Particle level selection**
Lepton	p_T>25 GeV; $\|\eta\|$<2.5
Z->ll	66<m_{ll}<116 GeV; ΔR(l,l)>0.2
Jets	p_T>30 GeV; $\|y\|$<4.4 ΔR(l,jet)>0.5

- **Ratio of unfolded cross-sections**
  - **R_{jets}=W+jets/Z+jets**
- **Reduce expt & theory uncertainties wrt individual measurements**
- **Differential cross-sections**
  - Incl. & excl. jet multiplicities
  - Jet pT & |y| up to 3 jets
  - Scalar sum ST up to 3 jets
  - ≥2jets
    - Leading jets Δφ, ΔR, mjj

Submitted to EPJC today! arXiv:1408.6510

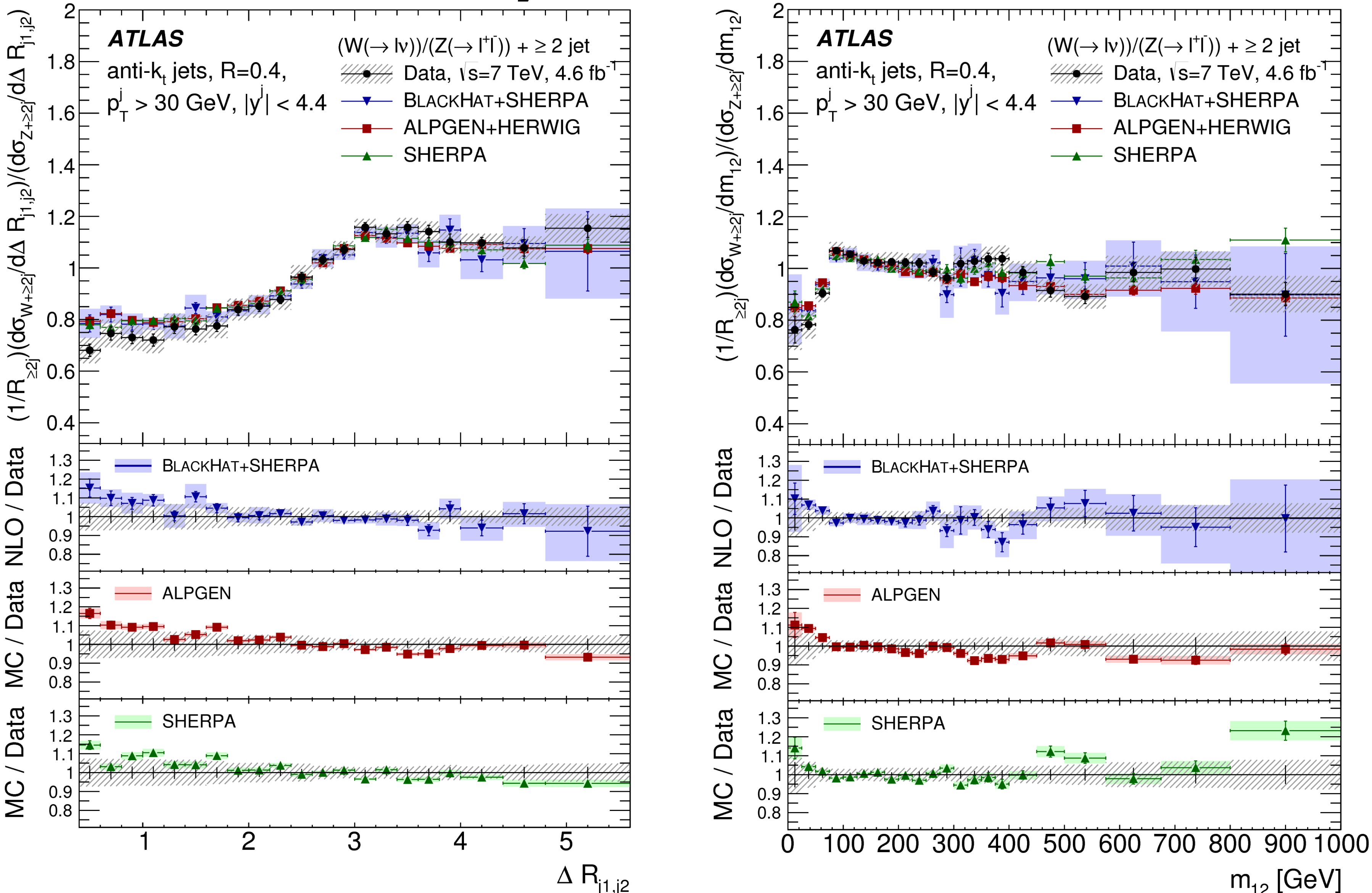
R_{jets}: Jet Multiplicity & ≥1jet pT





- **Generally good agreement with predictions**
- **pT dependence reflects W & Z mass difference, modelled well**

R_{jets}: ΔR & m_{12}

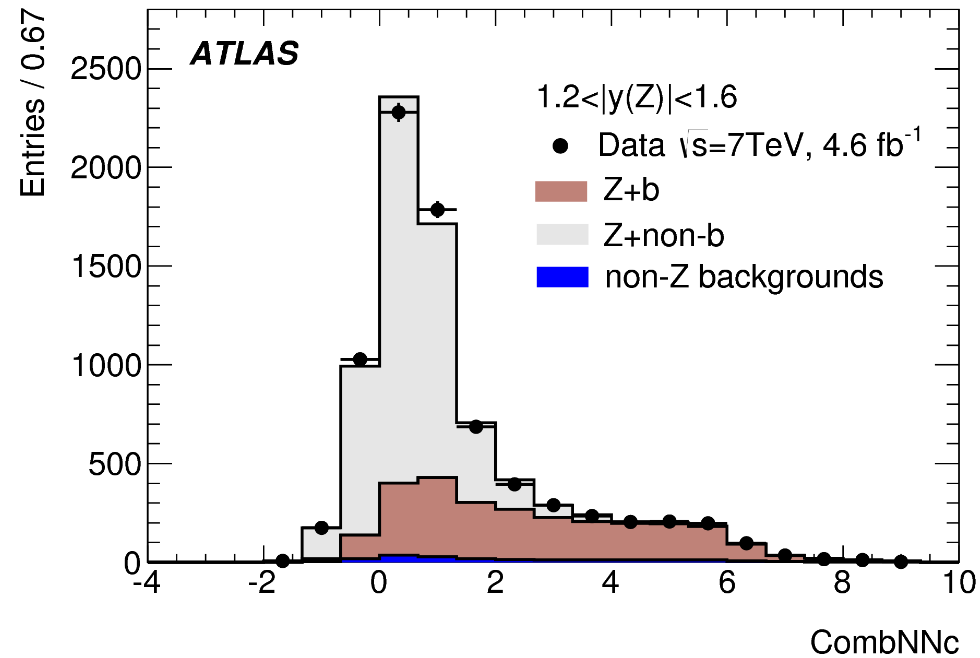


- **Deviations at low end where NPCs important**
  - less significant deviations than W+jets

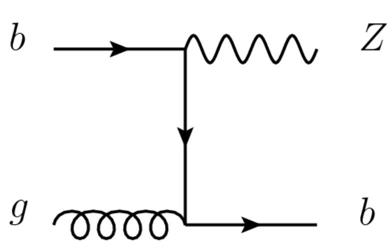
Z+b-jets: Overview

Submitted to JHEP arXiv:1407.3643

Z+b-jets:	Particle level selection
Lepton	p_T>20 GeV; $\|\eta\|$<2.5
Z->ll	76<m_{ll}<106 GeV
b-jets	p_T>20 GeV; $\|y\|$<2.4 ΔR(l,jet)>0.5 ΔR(b-hadron,jet)<0.3



- **Probe pQCD heavy flavour calculations**
- Z+>=1b-jet differential cross-sections
    - b-jet pT & |y|
    - Z boson pT & |y|
    - Z, b-jet separations Δφ, Δy, ΔR, y_{boost}
- Z+>=2b-jets differential cross-sections
    - Z boson pT & |y|
    - Leading jets ΔR, mbb

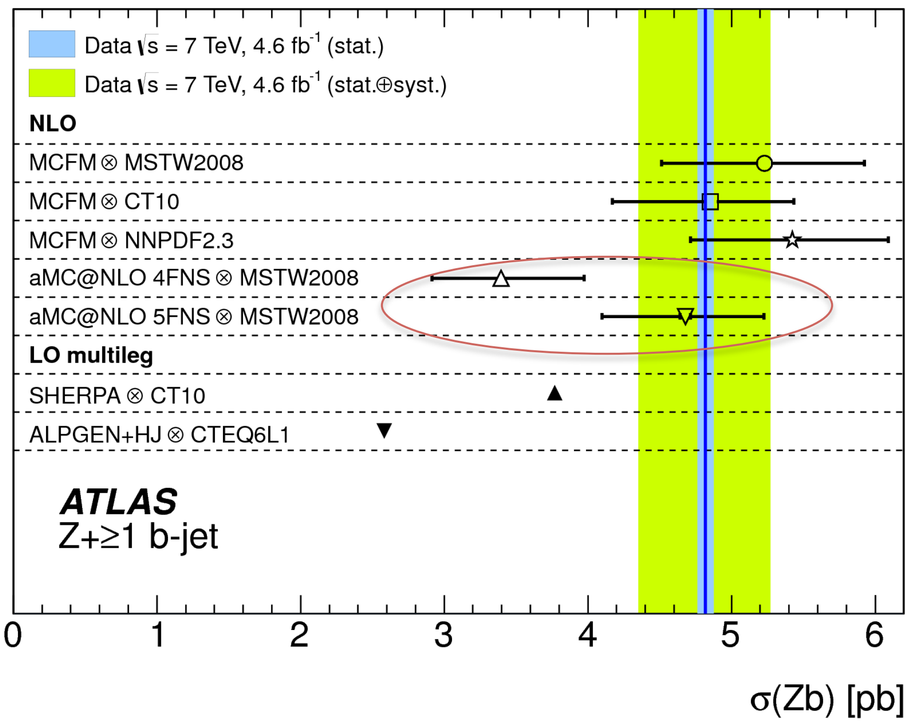


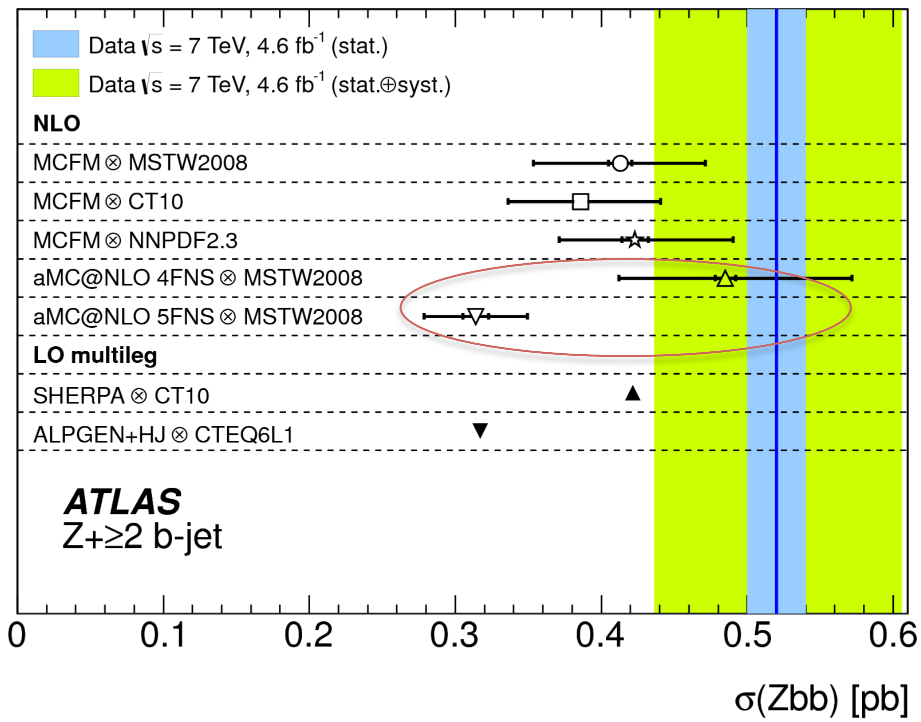
5 flavour: initial state b

- **Extracting b-jet yields in data:**
    - Tag jets to enrich b-jet content
        - 75% b-jet efficiency
    - Fit to b-tagging discriminant
        - NN trained to separate b-jets from c- and light-jets
- **Dominant systematics:**
    - b-tagging efficiency
    - b-jet template shape

Z+b-jets: Comparison to Theory

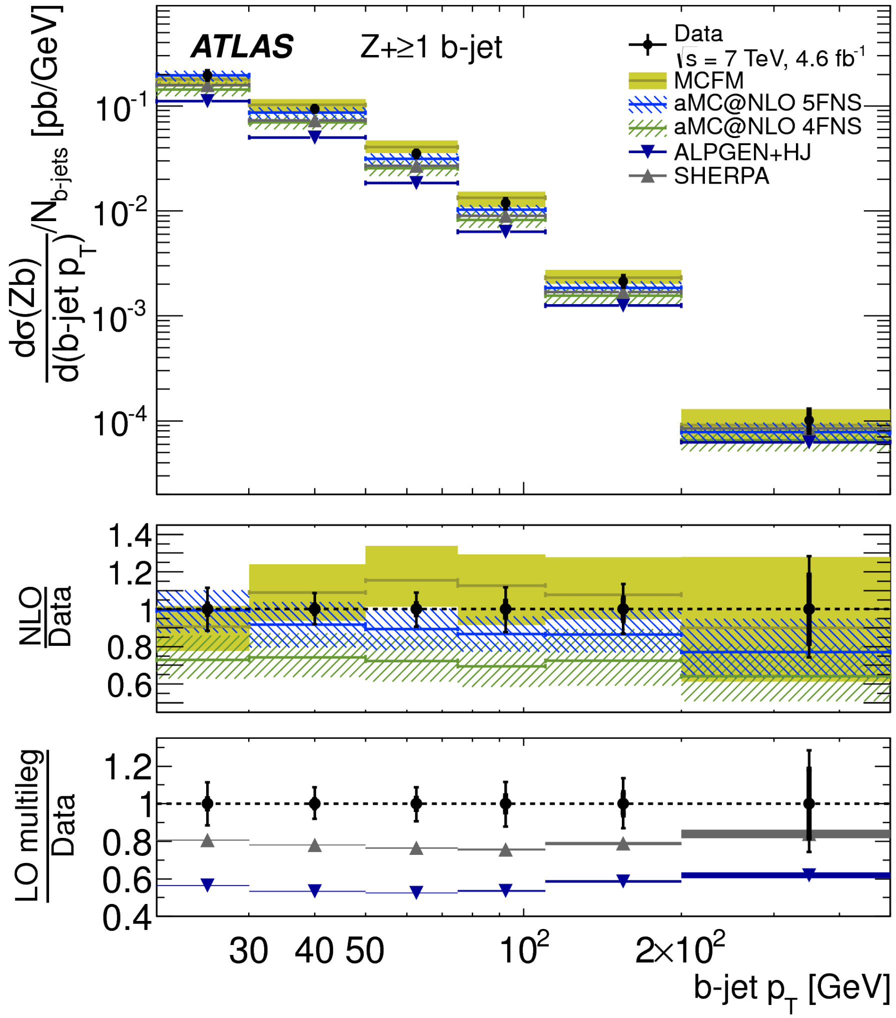
- **NLO calculations in 4 & 5 flavour schemes**
  - MCFM corrected to particle level, different PDF sets
  - aMC@NLO
  - Scale uncertainties dominate
- **LO multileg calculations**
  - Alpgen (4F)
  - Sherpa (5F)

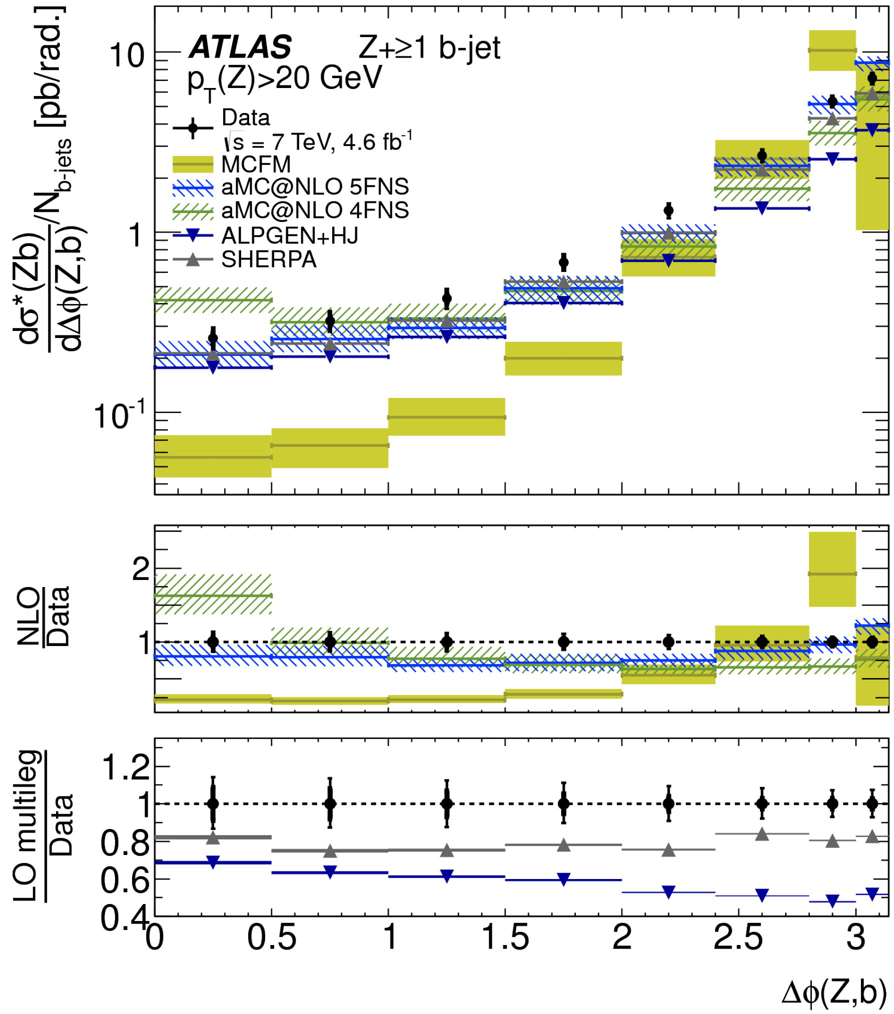




- 5F NLO for Zb describes data well
  NLO matrix element for Zbb in 4F underestimates
- NLO matrix element for Zb in 5F low since it is LO Zbb

Z+≥1b-jet: b-jet pT & Δφ(Z,b)

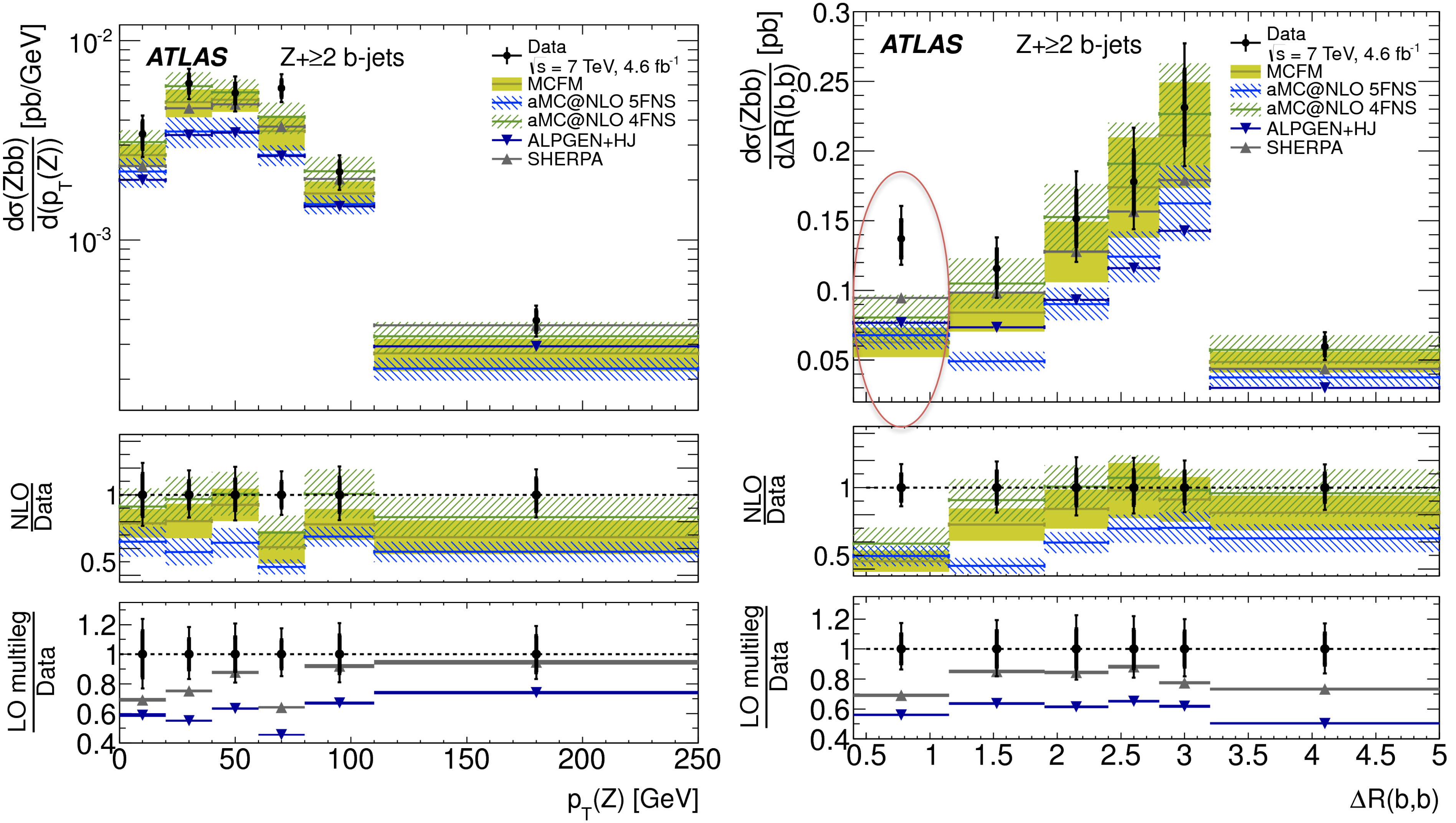




- **b-jet pT well modelled over 3 orders of magnitude**

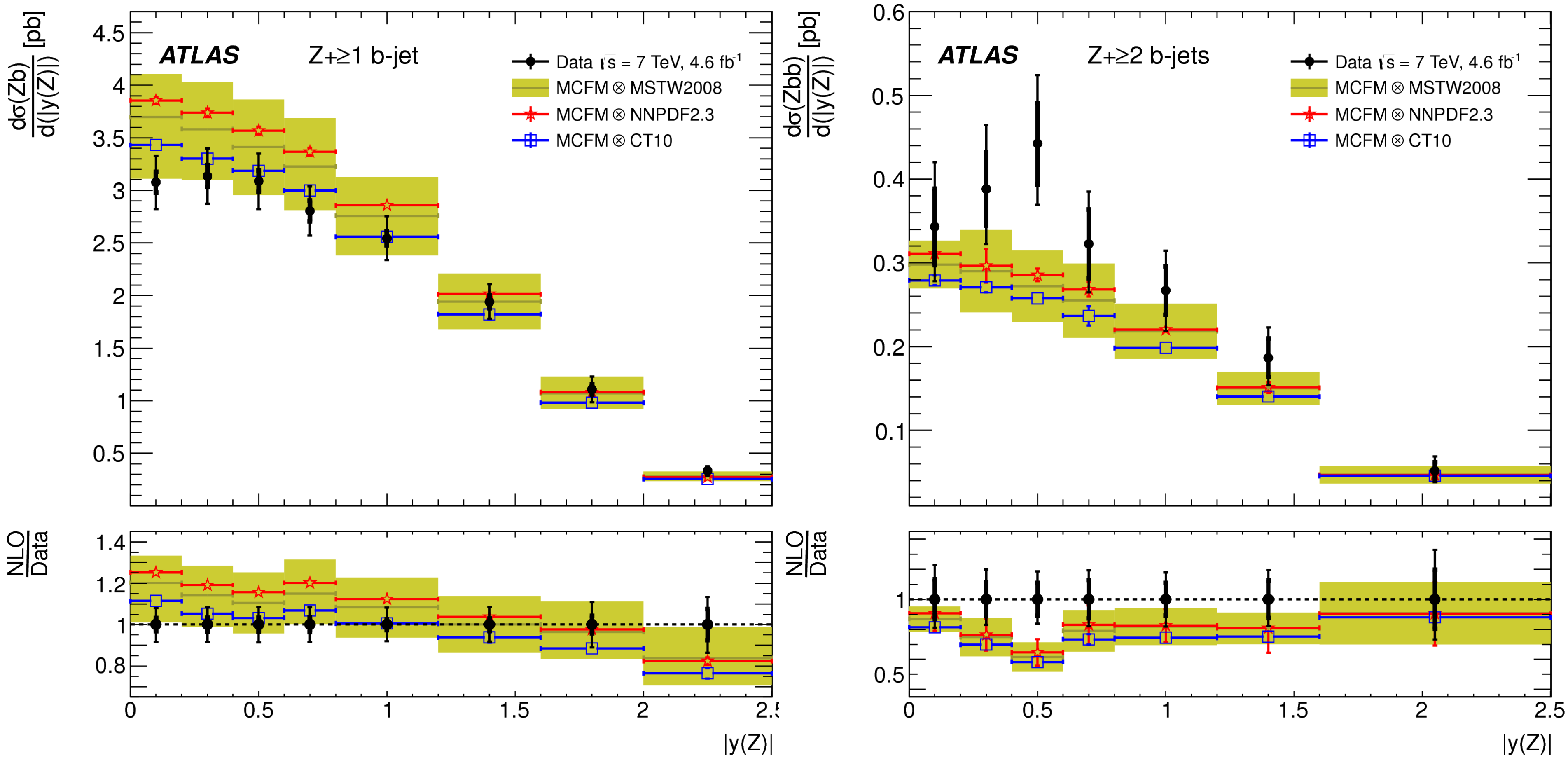
- **Δφ(Z,b) phi breaks down for parton level NLO with NPCs derived indirectly from LO**
- **Better for NLO + full parton shower**
- **Good shape description from LO multileg**

Z+≥2b-jets: Z pT & ΔR(b,b)



- **Z pT well modelled within data precision**
- **Suggestion of deviation at low ΔR(b,b)**
- **Analogous to CMS Z+b-hadron result**

Z+b-jets: Sensitivity to b-PDF



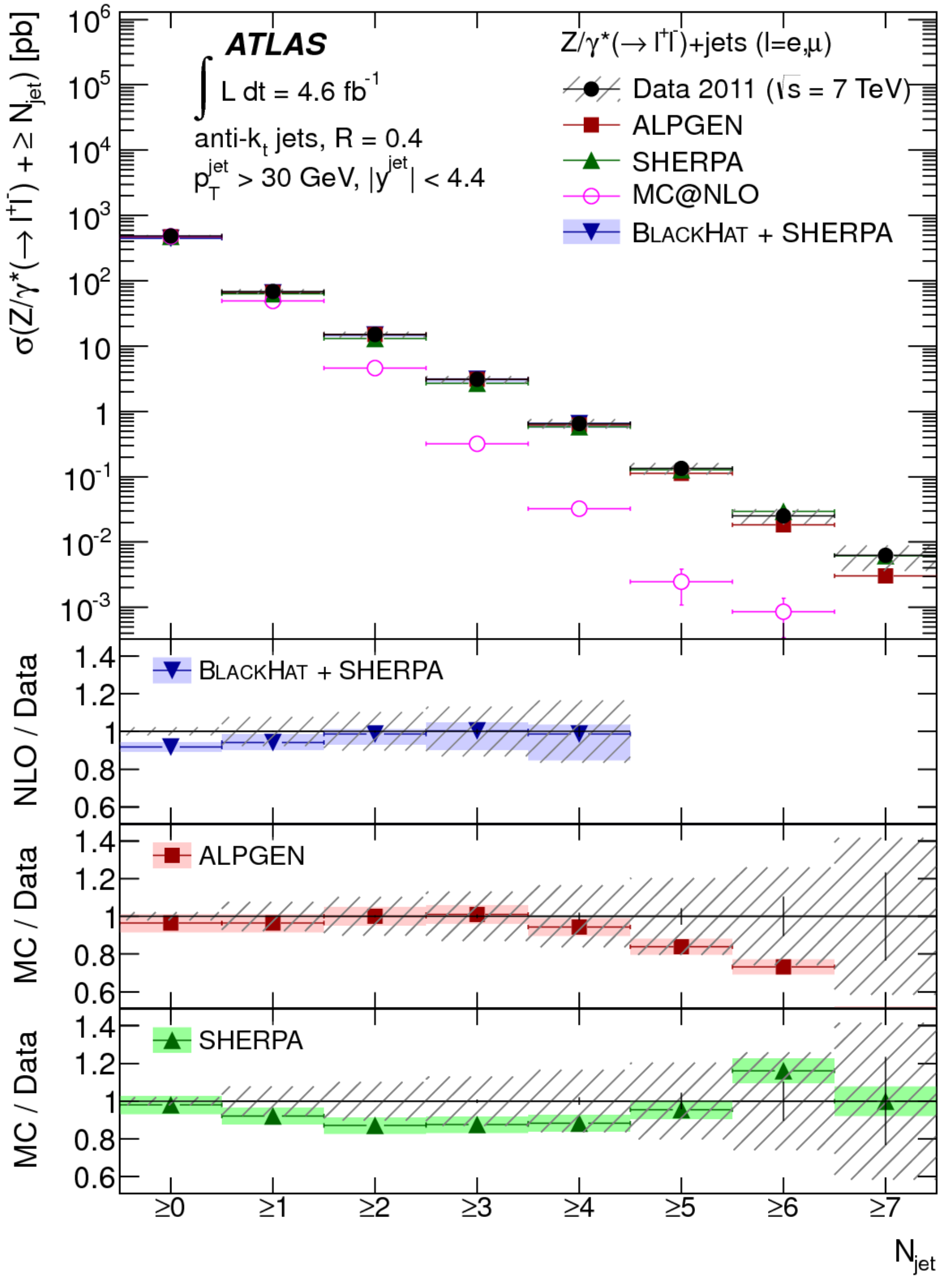
- **Theory scale uncertainty limits sensitivity to b-PDF**

Summary

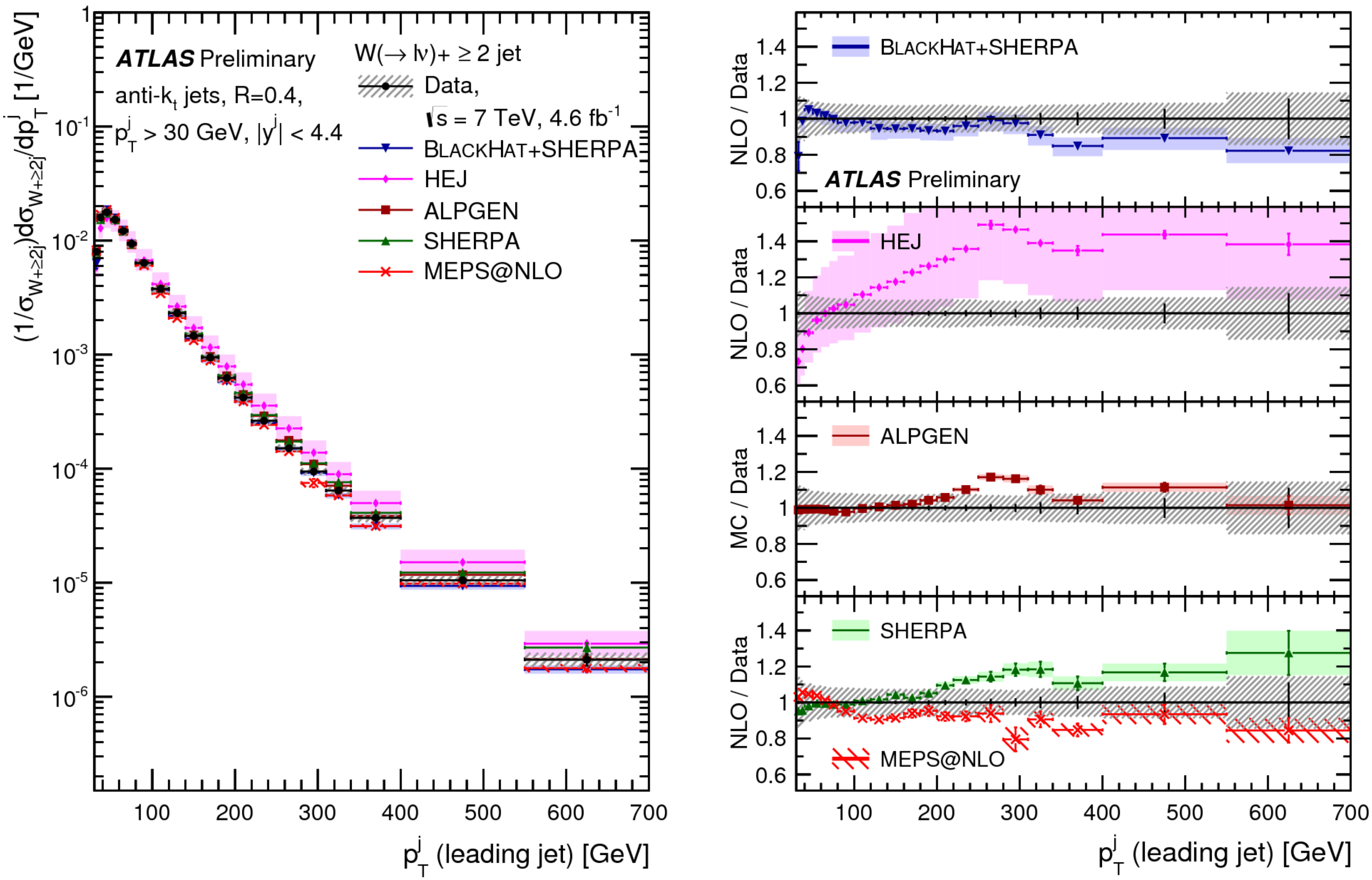
- Extensive V+jets analysis program at ATLAS probing cross-sections over several orders of magnitude
  - Numerous differential cross-sections measured
- Can investigate high multiplicity states and jets up to 1TeV
- NLO calculations model inclusive rates well even with reduced uncertainties from ratios
- Modelling of kinematics generally ok but room for improvement
  - No one MC models all distributions well
- New heavy flavour results provide valuable input to flavour scheme dependence of predictions
- Sensitivity to b-PDF requires higher order Z+b-jets calculations to reduce scale uncertainties
- Run 1 analysis program not yet finished: 8TeV data!

Backup

Z+jets: Jet Multiplicity

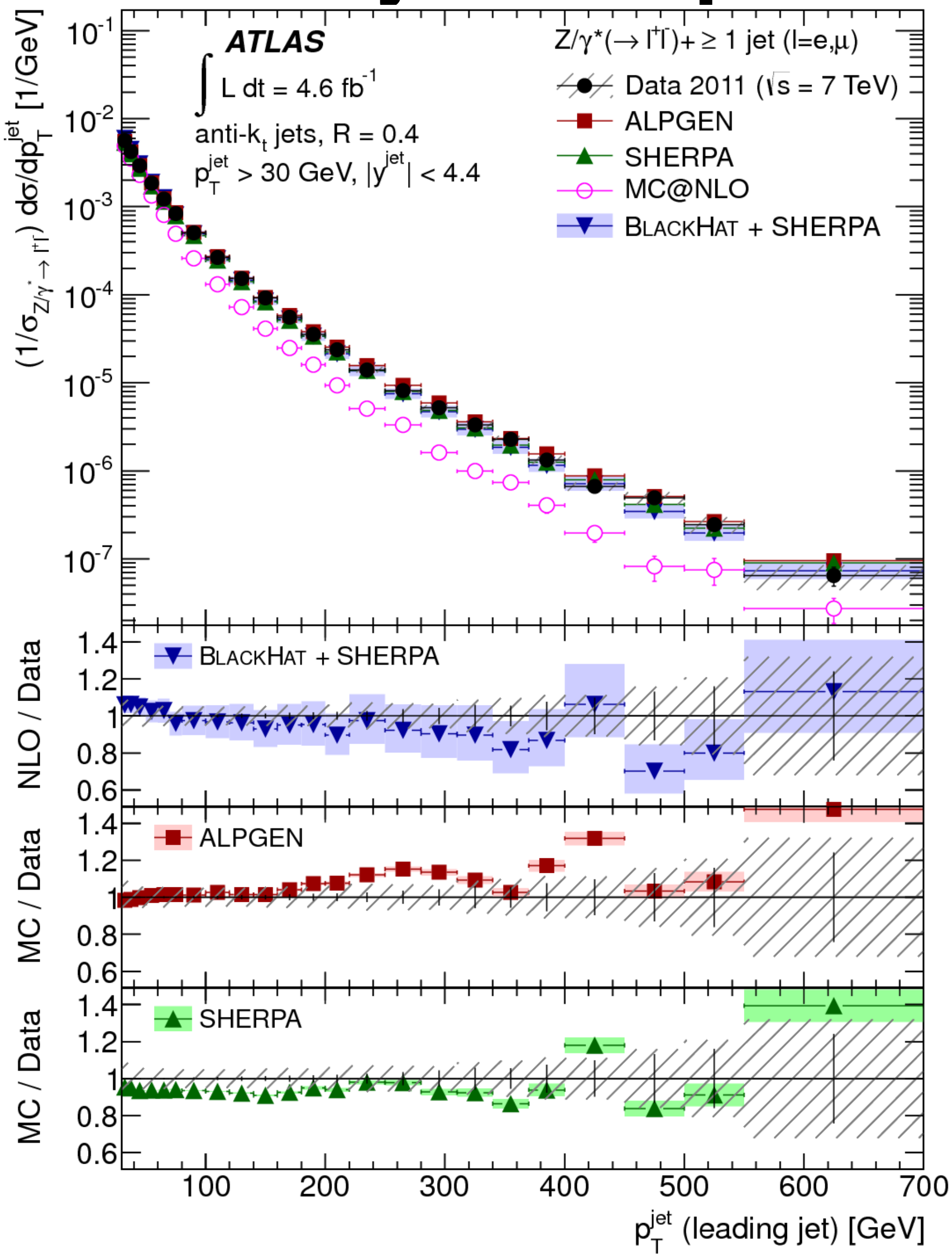


W+≥2jets: Jet pT

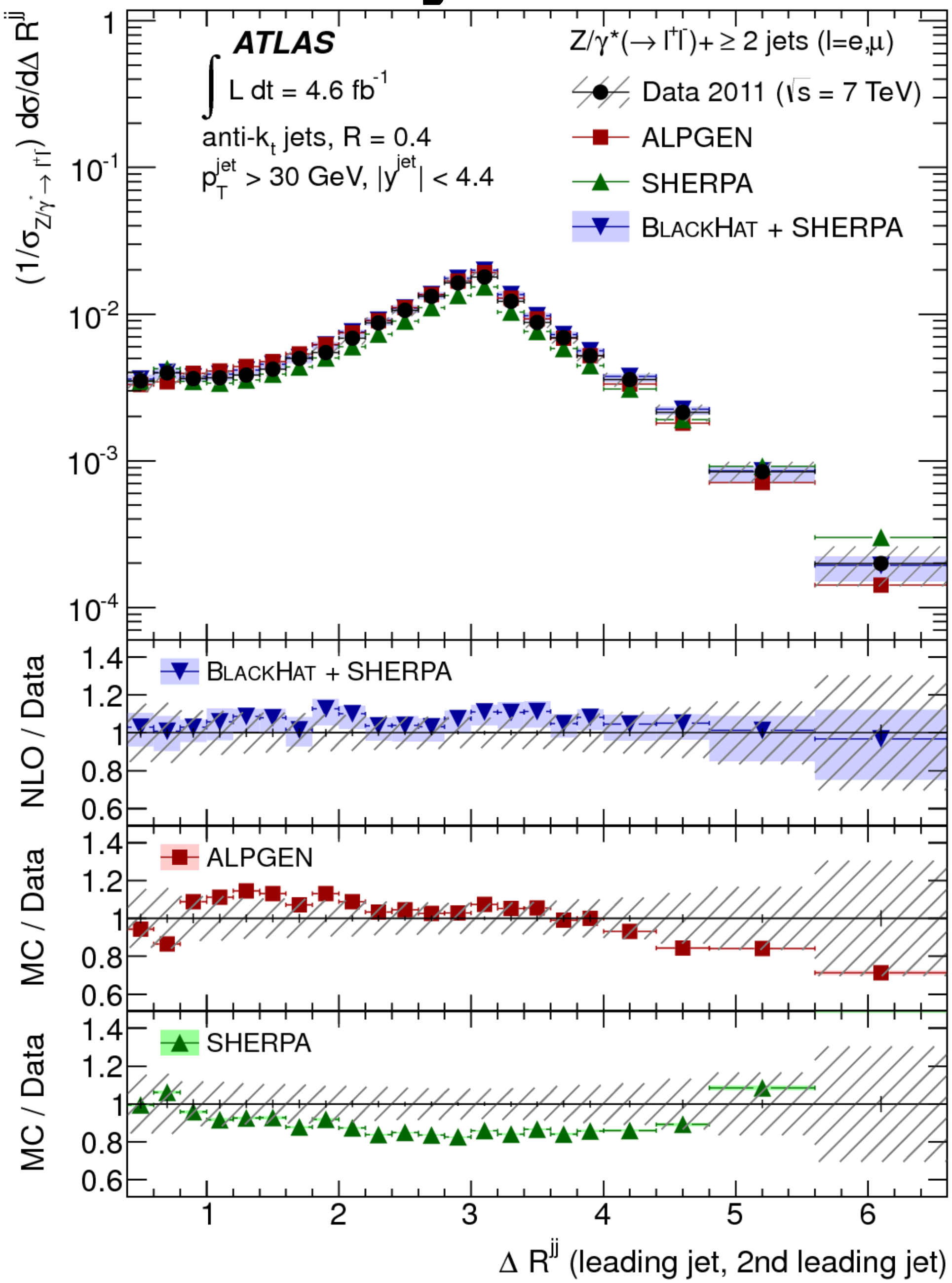


• **NLO agrees well, HEJ predicts harder pT but with large uncertainties**

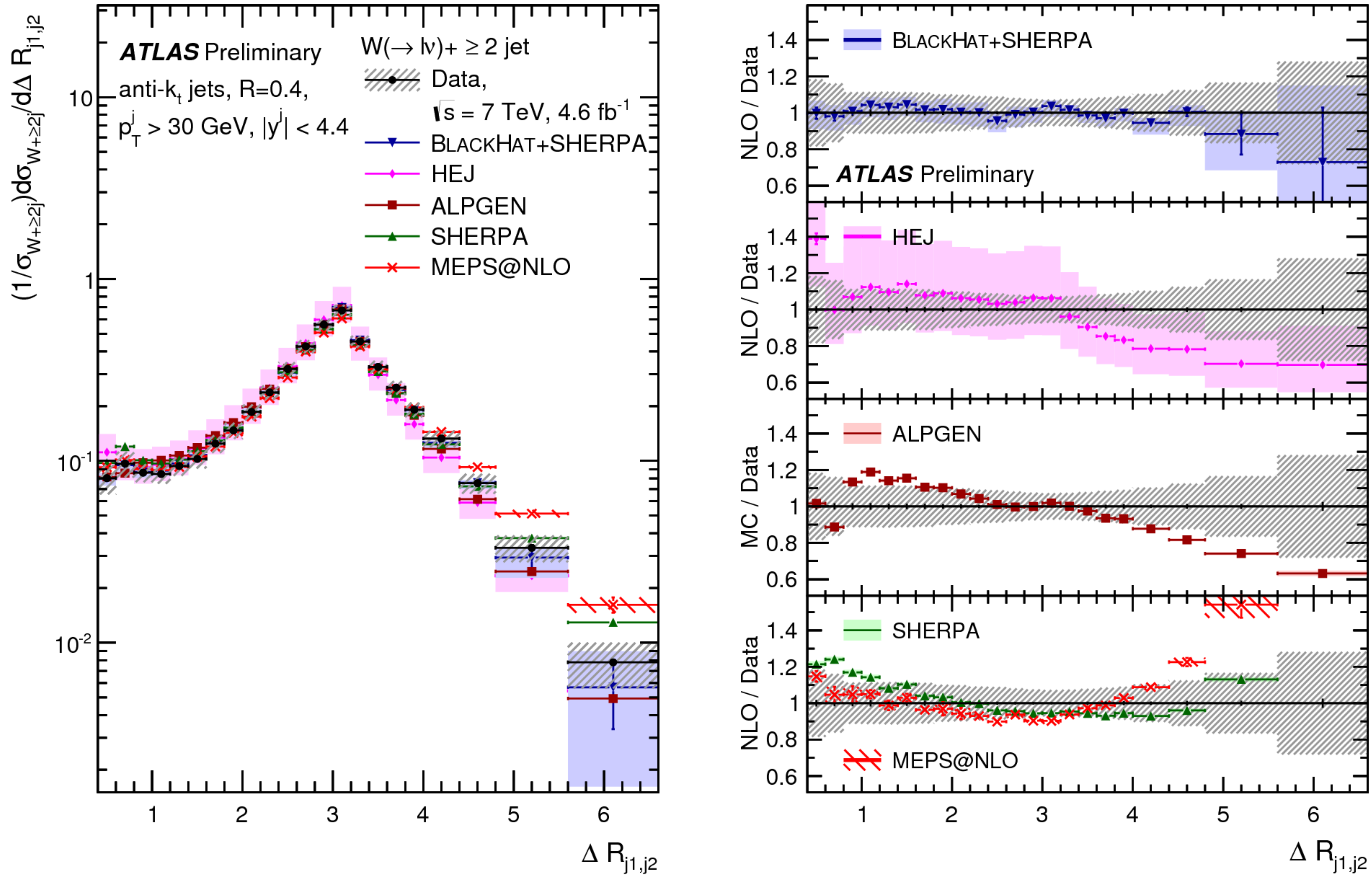
Z+≥1jet: Jet pT


ATLAS
∫ L dt = 4.6 fb⁻¹
anti-k_t jets, R = 0.4
p_T^jet > 30 GeV, |y^jet| < 4.4
Z/γ*(→ l⁺l⁻)+ ≥ 1 jet (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
MC@NLO
BLACKHAT + SHERPA
(1/σ_{Z/γ*→l⁺l⁻}) dσ/dp_T^jet [1/GeV]
NLO / Data
MC / Data
MC / Data
p_T^jet (leading jet) [GeV]

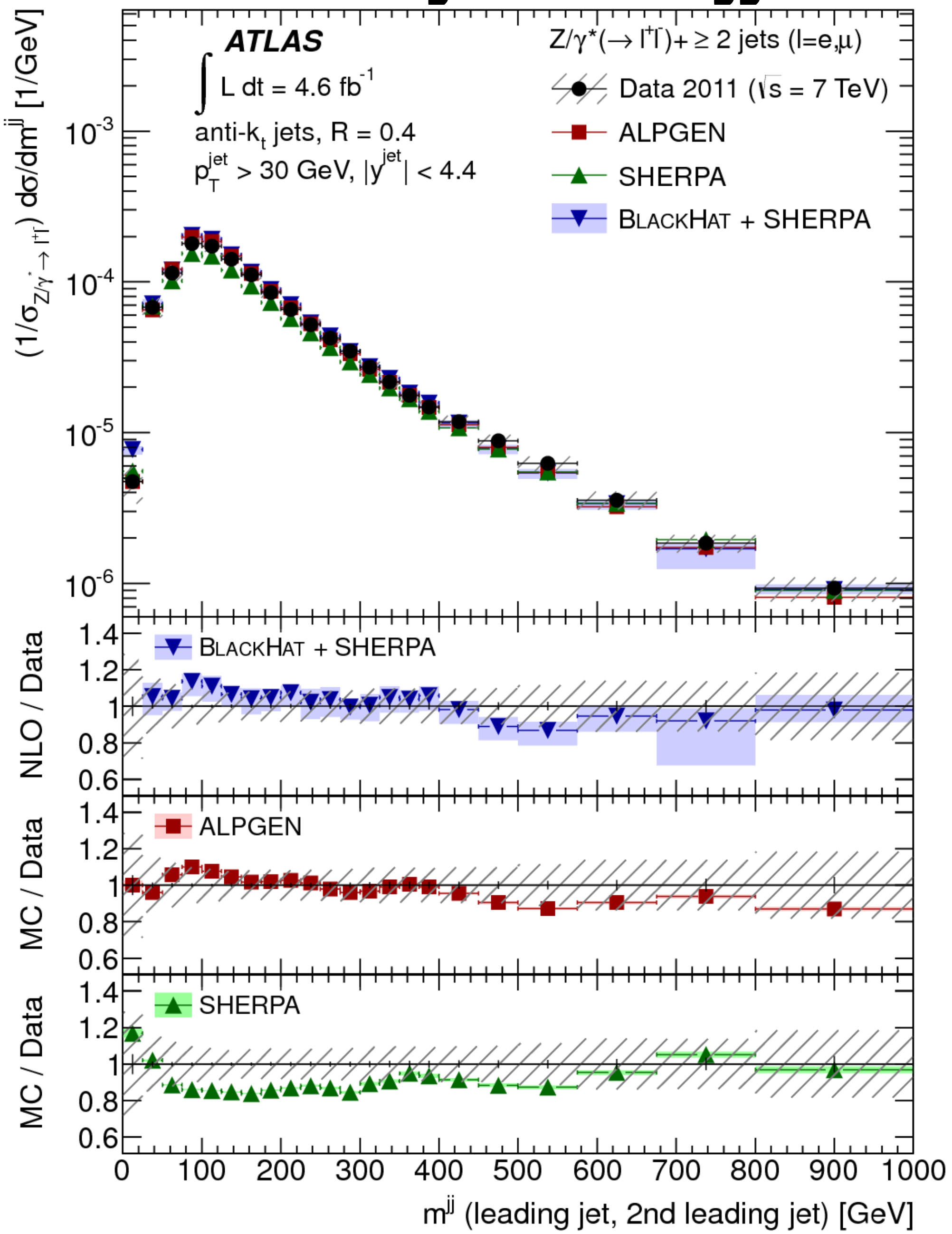
Z+≥2jets: ΔR


ATLAS
∫ L dt = 4.6 fb⁻¹
anti-kt jets, R = 0.4
pT jet > 30 GeV, |y jet| < 4.4
Z/γ*(→ l⁺l⁻)+ ≥ 2 jets (l=e,μ)
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
BLACKHAT + SHERPA
(1/σZ/γ*→l⁺l⁻) dσ/dΔ R^jj
NLO / Data
MC / Data
MC / Data
Δ R^jj (leading jet, 2nd leading jet)

W+≥2jets: ΔR


ATLAS Preliminary
anti-kt jets, R=0.4,
pTj > 30 GeV, |yj| < 4.4
W(→ lν)+ ≥ 2 jet
Data,
√s = 7 TeV, 4.6 fb-1
BLACKHAT+SHERPA
HEJ
ALPGEN
SHERPA
MEPS@NLO
(1/σW+≥2j)dσW+≥2j/dΔ Rj1,j2
Δ Rj1,j2
NLO / Data
MC / Data
ATLAS Preliminary

Z+≥2jets: mjj



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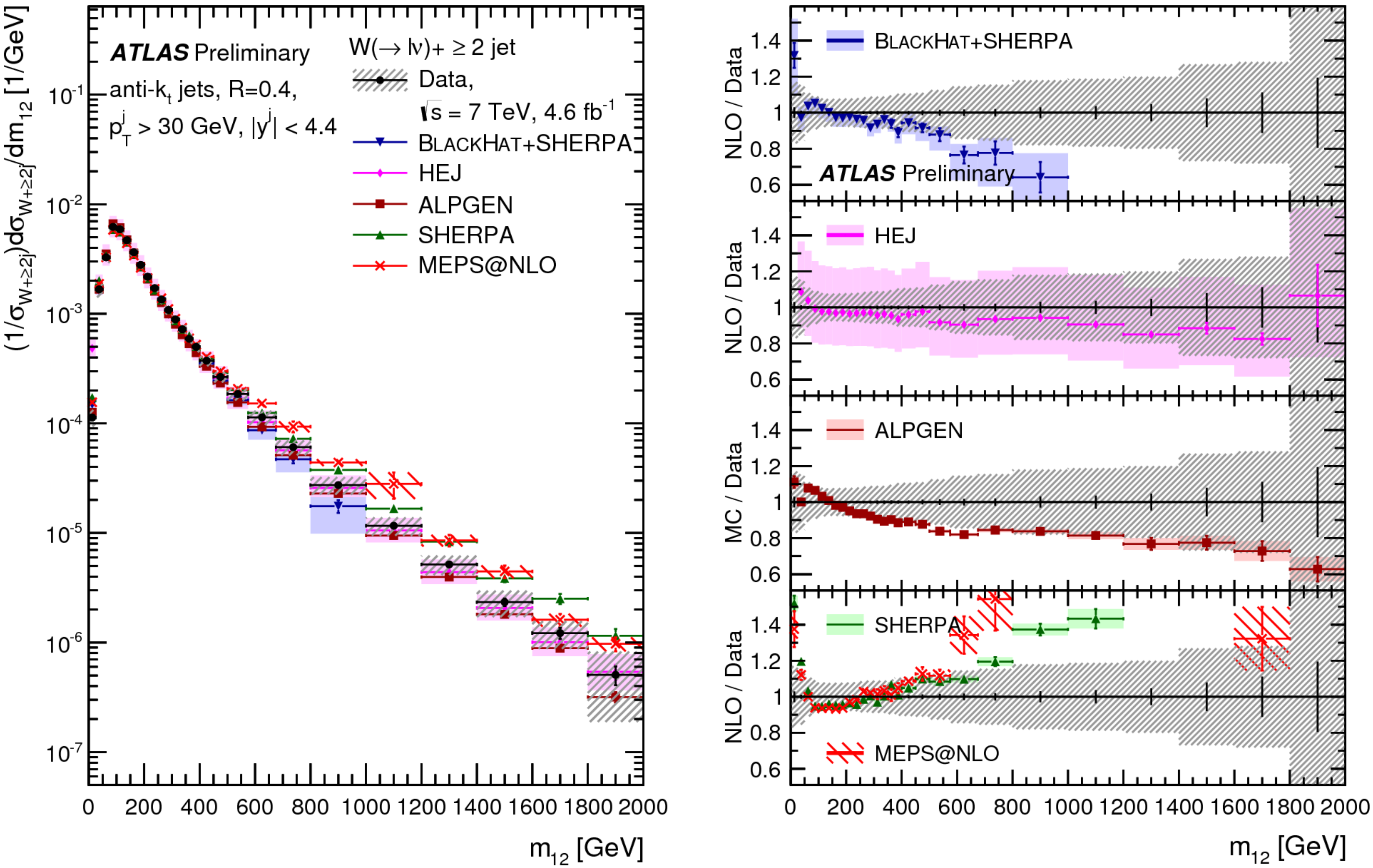
Data 2011 (√s = 7 TeV)
ALPGEN
SHERPA
BLACKHAT + SHERPA
(1/σ_Z/γ*→l⁺l⁻) dσ/dm^jj [1/GeV]
NLO / Data
MC / Data
MC / Data
m^jj (leading jet, 2nd leading jet) [GeV]

W+≥2jets: mjj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pT^j > 30 GeV, |y^j| < 4.4
W(→ lν)+ ≥ 2 jet
Data,
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BLACKHAT+SHERPA
HEJ
ALPGEN
SHERPA
MEPS@NLO
(1/σW+≥2j)dσW+≥2j/dm12 [1/GeV]
m12 [GeV]
NLO / Data
MC / Data