Experimental results for V+jets

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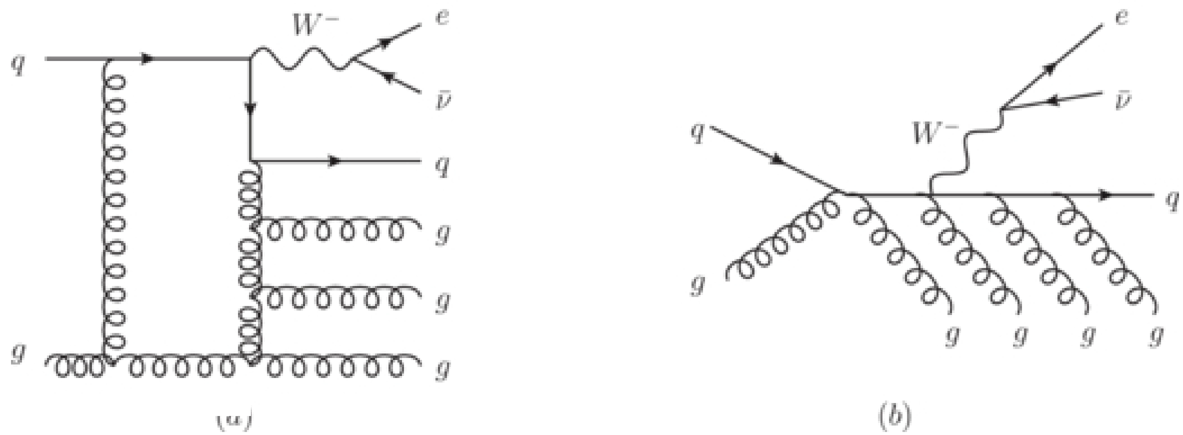
Outline

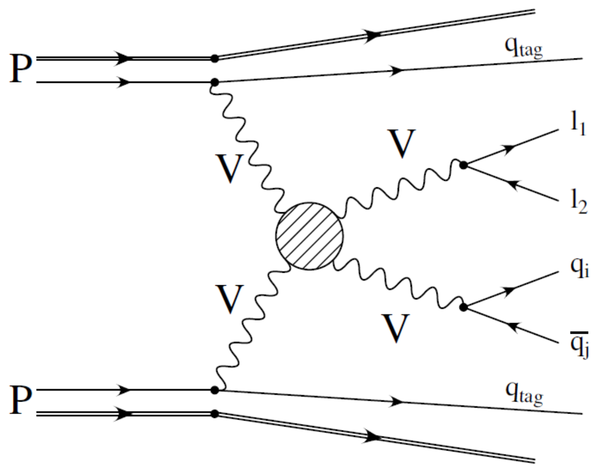
- Motivation for V+jets measurements
- Experimental issues: backgrounds and instrumental uncertainties
- High cross-section: V+jets (V=W,Z)
- Low cross-section: V+b-jets
- Conclusions

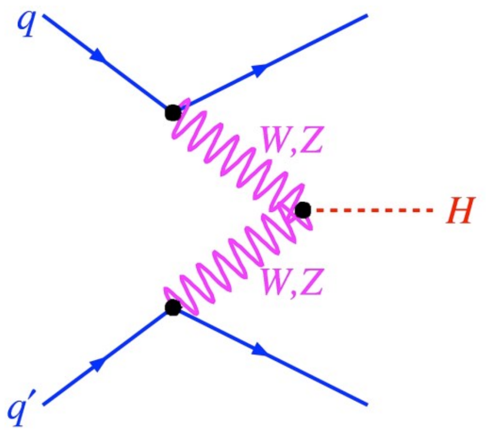
Motivation for studies of jets produced with a *W* or *Z* boson



- Well-understood process to test pQCD calculations and to validate detector performance
  - m(V) gives a scale to the QCD calculations
- Foundation for development of novel pQCD calculations; choices of scales, jet-parton matching schemes, and parton showering
  - Alpgen, Sherpa, MCFM, BlackHat-Sherpa, Madgraph, etc.
- Z+jets is complementary to W+jets
  - Z+jets and W+jets subject to different instrumental effects and backgrounds; it is useful to look at both processes

Motivation for studies of jets produced with a *W* or *Z* boson





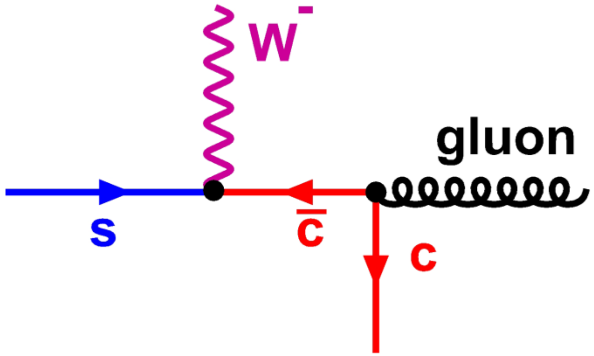
- An irreducible background to SM measurements:
  - $t\bar{t}$, single top
  - VBF, WW-scattering
  - Higgs (H→WW, WH→Wbb)
- and new physics
  - SUSY etc.

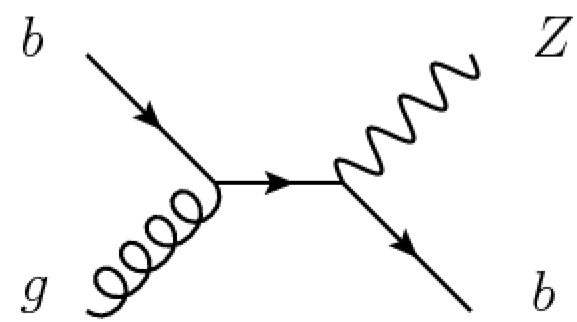
- Forward jets at large rapidities
- Rapidity gaps
- Jet vetoes
- Di-jet masses (H→bb)
- Multi-jet processes
- Processes with large H_T

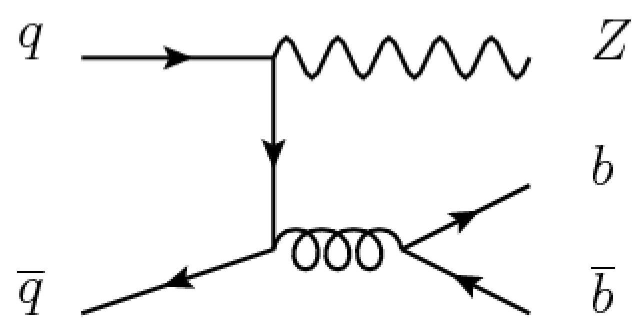
Motivation for studies of associated production of heavy flavor (*b*- and *c*-) jets and a gauge boson

- Background to new physics
- **Background to WH→Wb$\bar{b}$**
- Constraints on PDFs
- The final states are tricky to calculate → the experimental input is key for future theory developments (QCD calc)

- The LHC gives sensitivity to a different phase-space than the Tevatron:
  - pp instead of p$\bar{p}$ (better probe of sea quark and gluons)
  - 7 TeV instead of 1.96 TeV (wider reach in transferred momenta)

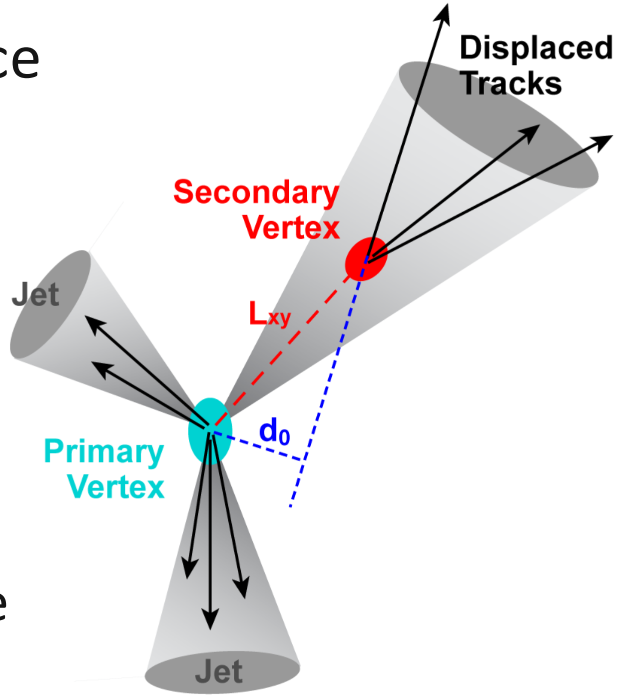




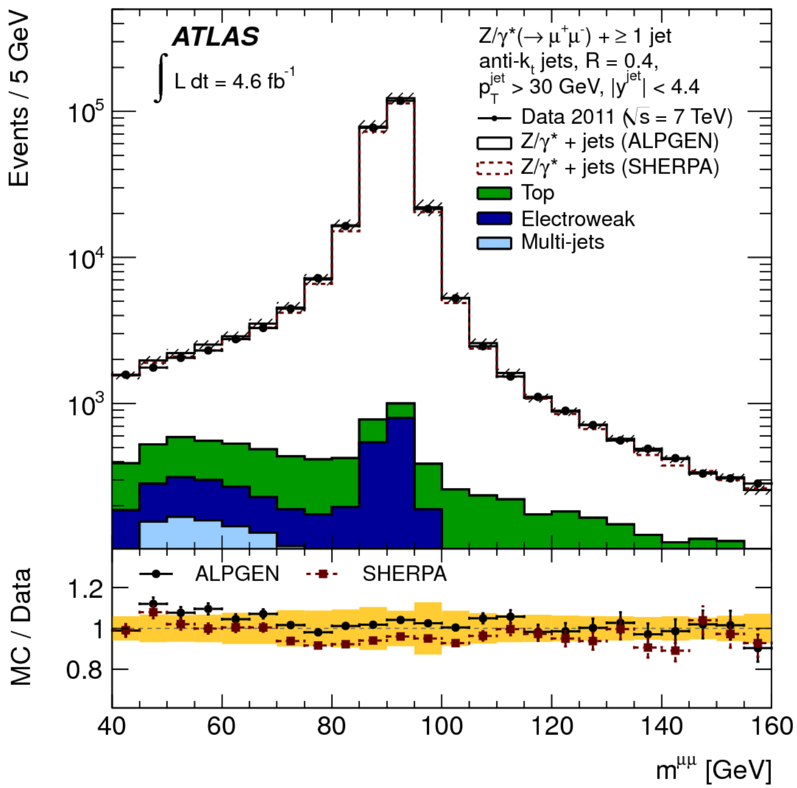


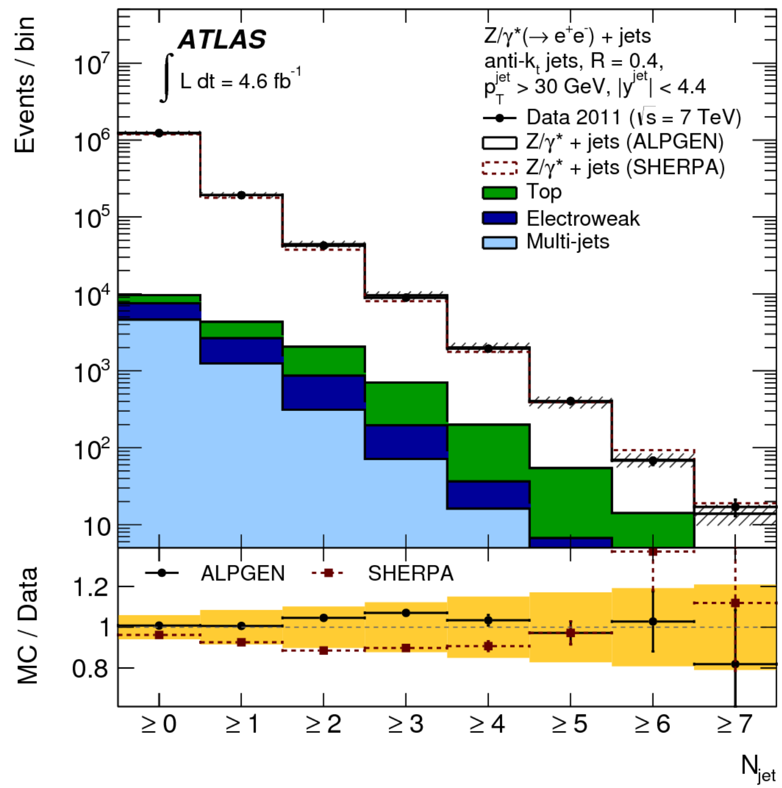
Observables

- Cross sections and their ratios
  - **Inclusive $\sigma(V + \geq N \text{ jets})$**
  - **Differential: e.g. $d\sigma/dp_T(N^{th} \text{ jet})$**
  - **Ratios of cross sections: $\sigma(V + \geq N \text{ jets})/\sigma(V + \geq N\text{-}1 \text{ jets})$**
    →Cancelation of uncertainties
- Those are often calculated for phase-space resembling the detector acceptance
  - W's and Z's are identified using **central electrons and muons**
  - Identification of heavy quarks (b- and c-) utilizes **secondary vertices** (lifetime and mass)
- Understanding of backgrounds is the key issue



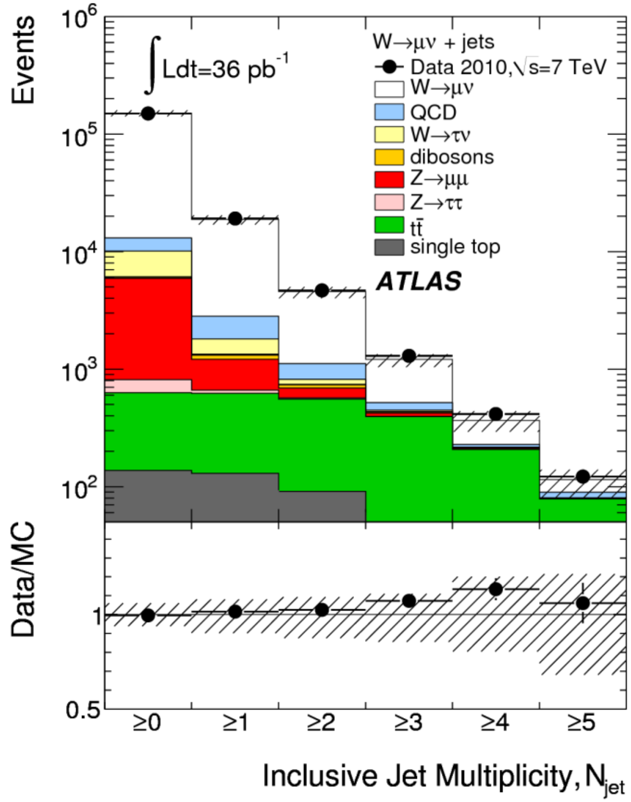
Backgrounds to Z+jets ($Z \rightarrow ee$ or $Z \rightarrow \mu\mu$)

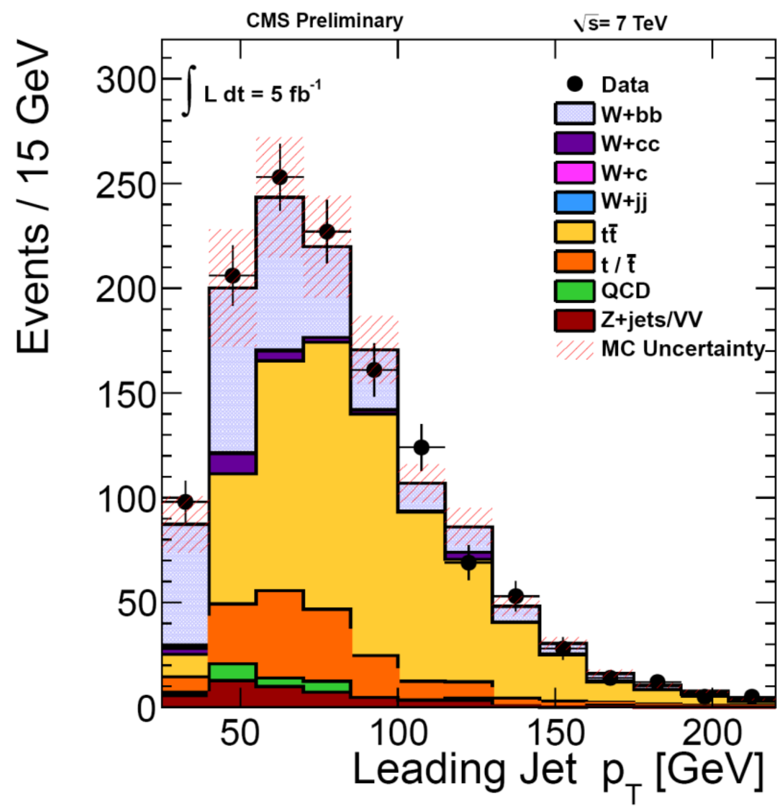




- Irreducible backgrounds ($t\bar{t}$, Wt, WZ, ZZ, WW, and Z+γ) are small and estimated using simulations
  - $t\bar{t}$ is constrained using data (di-lepton e-μ events)
- “fake” (non-prompt) leptons are from multi-jet production and are obtained using data

Backgrounds to W+jets

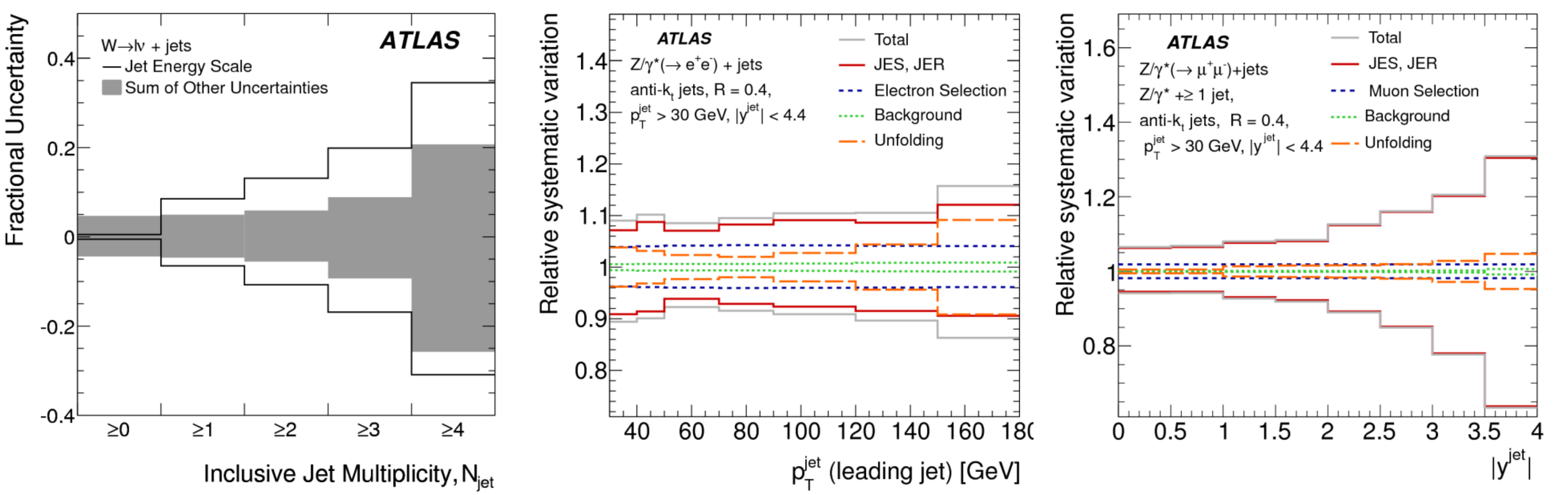




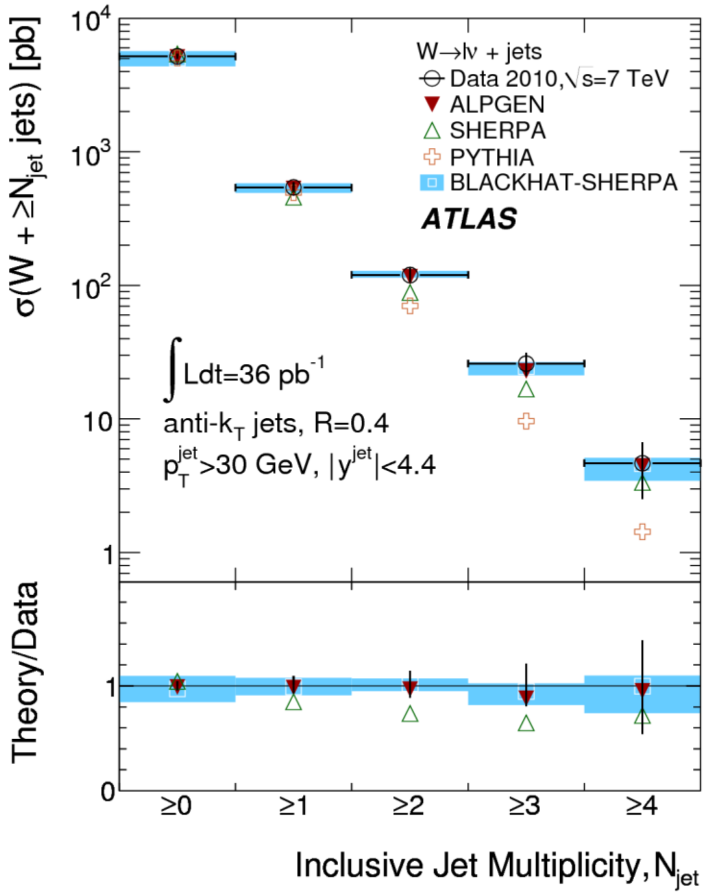
- Nicely complements the Z+jets processes with higher statistics, different background composition, and sensitivity to different PDFs
- Multi-jet events is a significant background at low jet multiplicities → **Important to do electron and muon channels simultaneously**
- The top quark pair production becomes the dominant background at high jet multiplicity (at 3-4) → One of the limiting factors

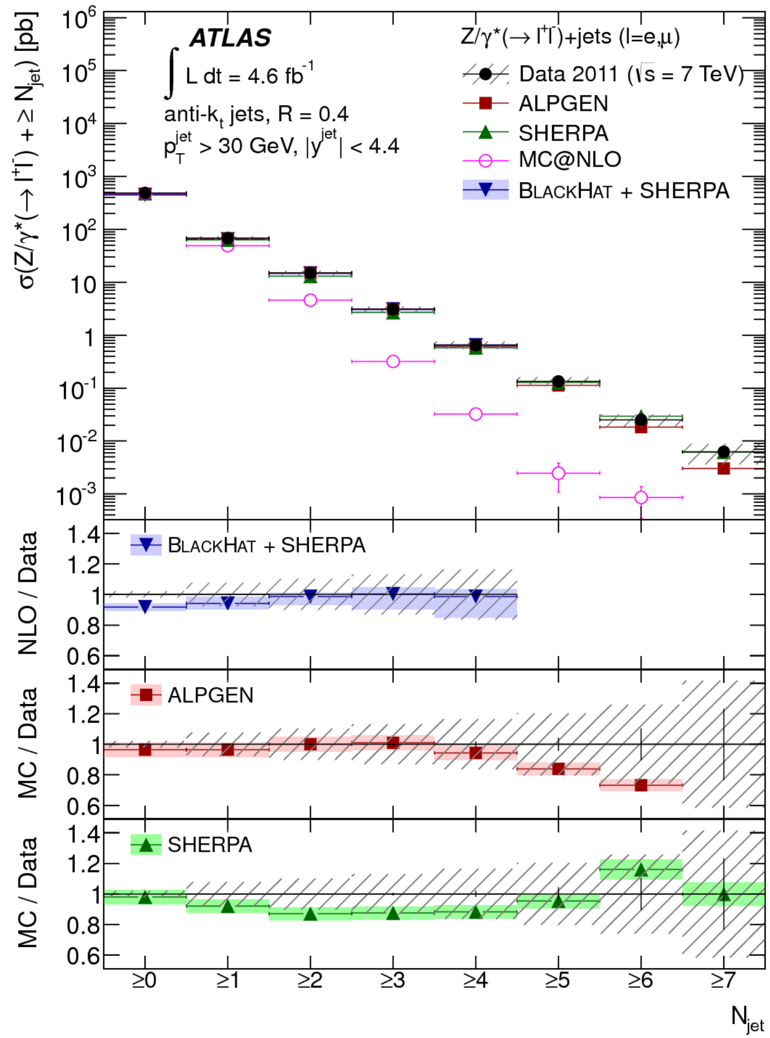
Systematic Uncertainties

- Dominated by the uncertainty on the jet response (JES)
  - Increases for forward jets and decreased with jet p_T
  - b-tagging efficiency is important for the corresponding channels (W+b, Z+b, Z+bb)



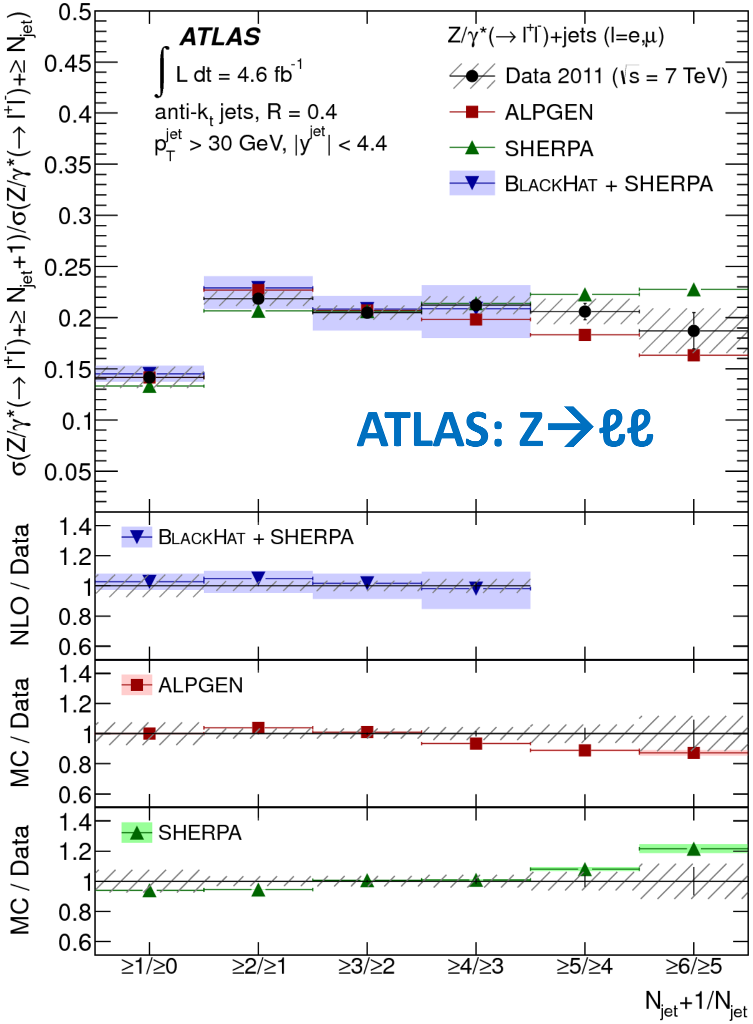
Jet multiplicity

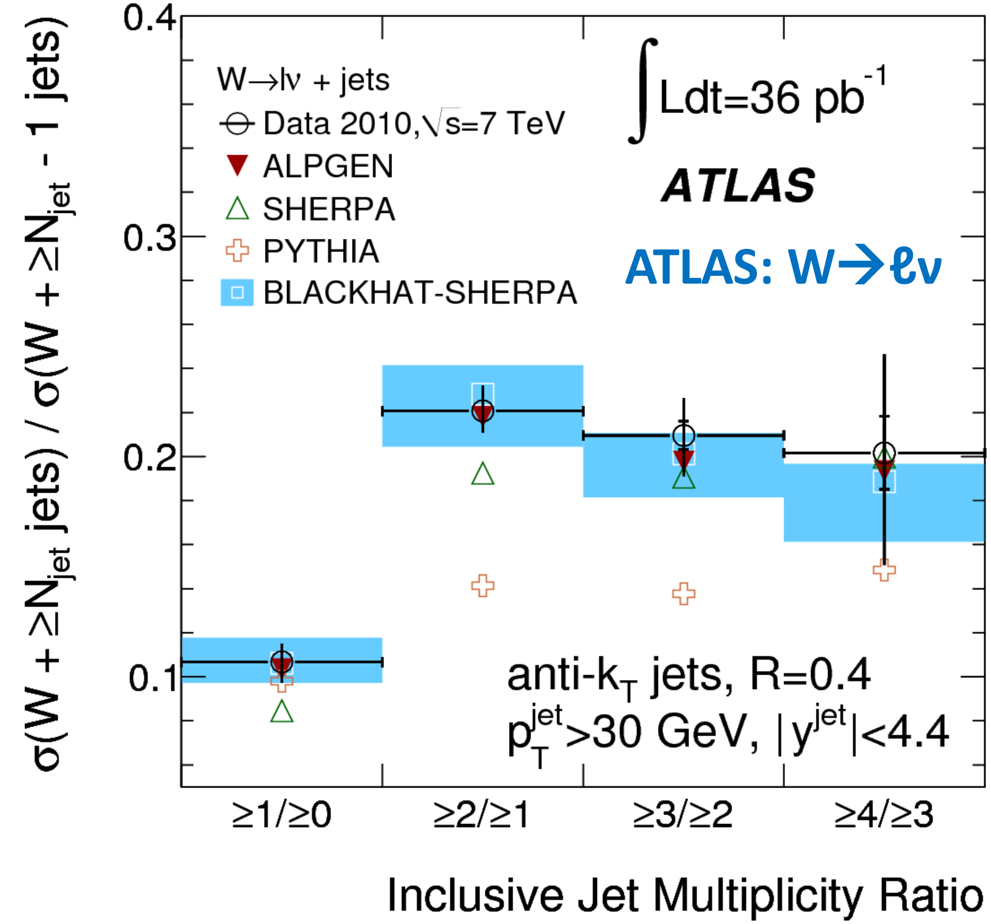




- Accurate predictions require ME+PS approach (Alpgen, MadGraph, & Sherpa); PS-only simulations (Pythia) fail at high jet multiplicity, >1 jet
- Crucial for multiple measurements and searches (e.g. separation between WW and tt; BSM searches using high jet multiplicities)
- NLO calculation (BlackHat-Sherpa) are superbly accurate.

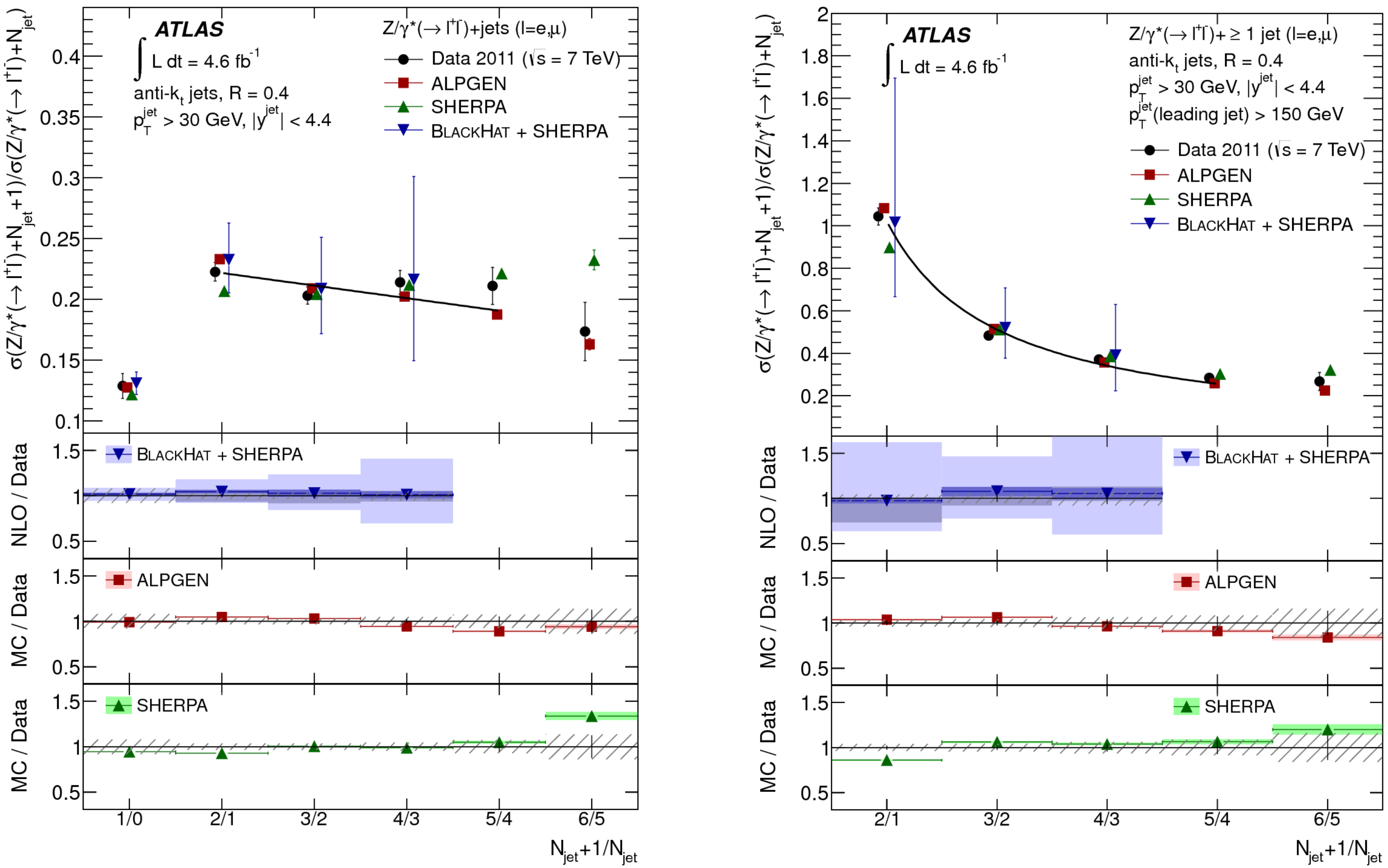
Ratios of cross sections: $\sigma(V+N_{jet})/\sigma(V+N_{jet}-1)$





- Cancelation of systematic and theory uncertainties → Robust way to compare data and theory
- Again, superior agreement with NLO calculations in W+jets and Z+jets

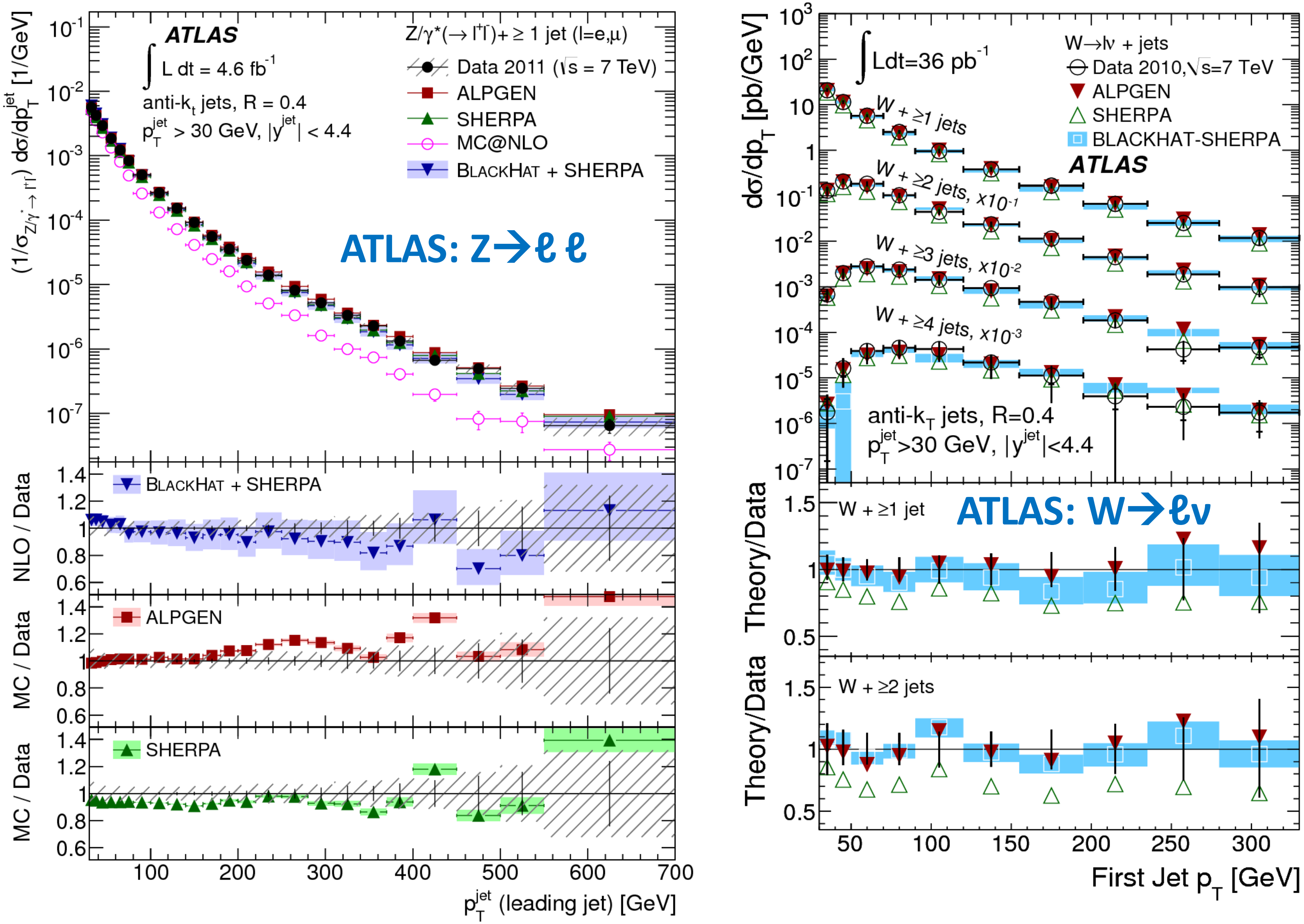
Ratios of cross sections: $\sigma(Z+N_{jet})/\sigma(Z+N_{jet}-1)$



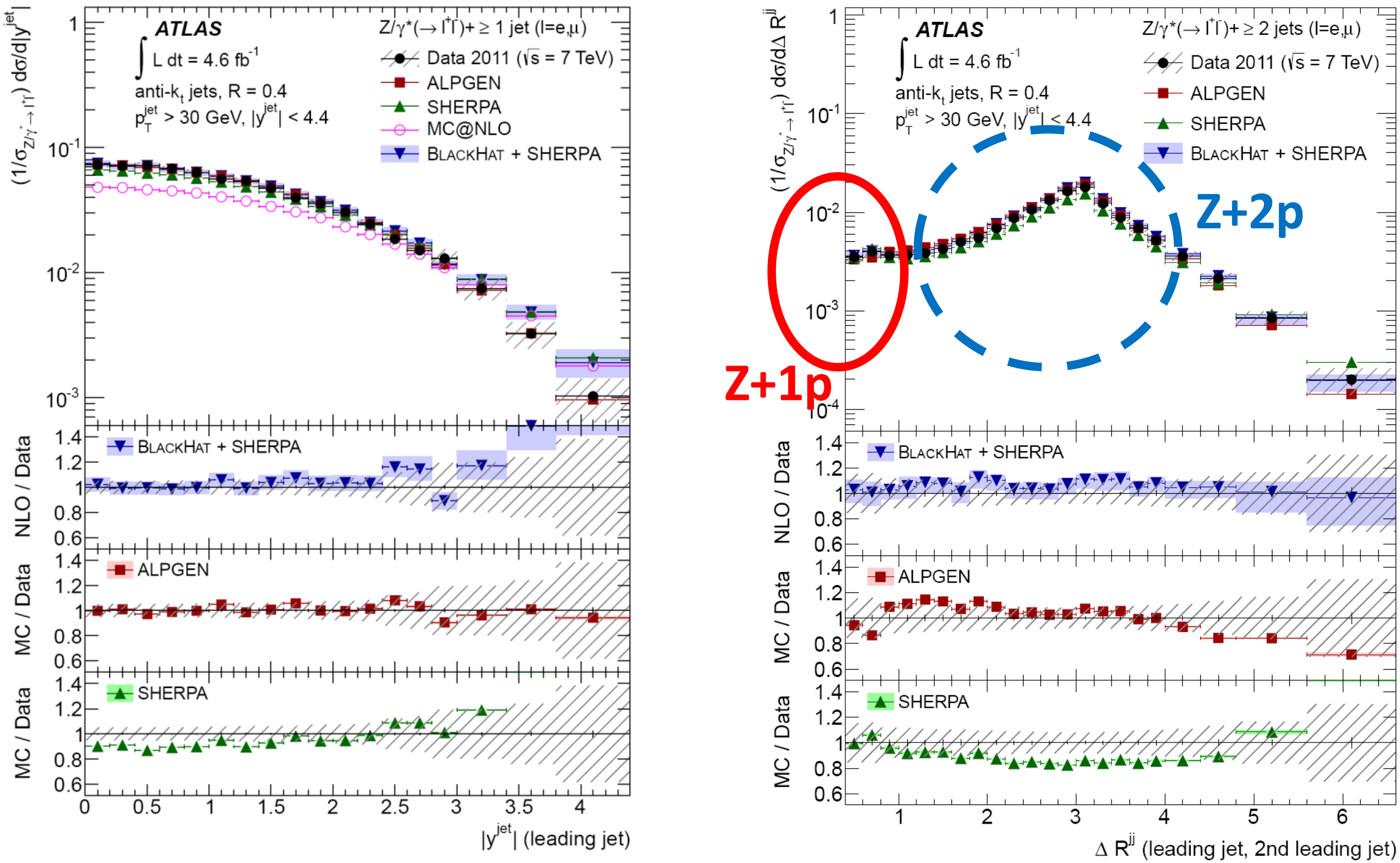
- Predictions work quite well for
  - exclusive jet multiplicities (left)
  - Events with an energetic jet: pt(jet 1)>150 GeV (right)

Kinematic properties of jet production: p_T

- Well reproduced by NLO and LO (ME+PS) predictions

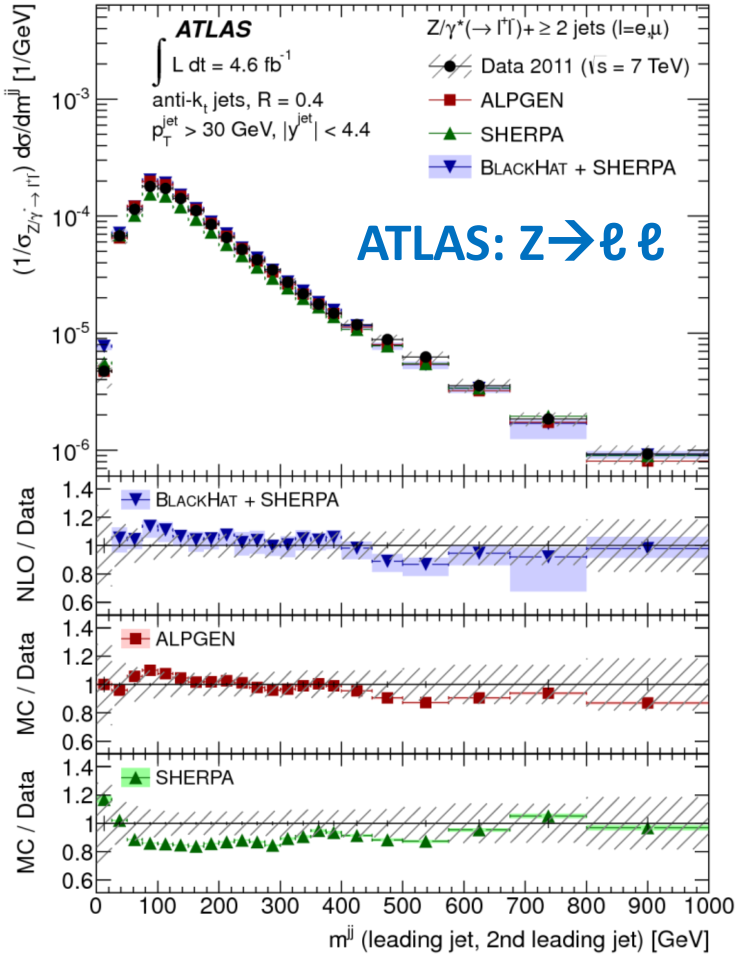


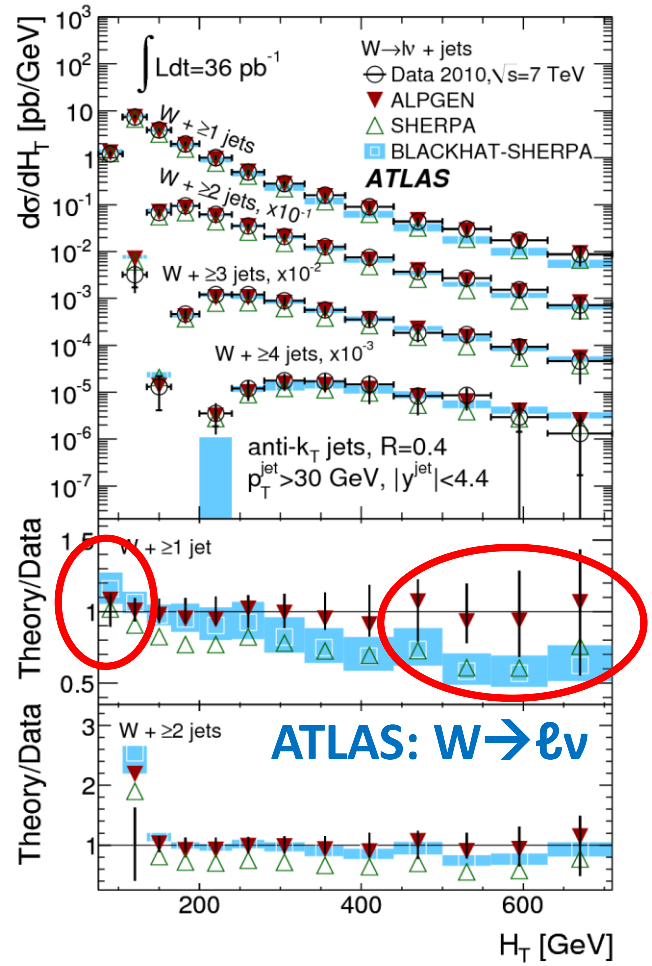
Rapidity of jets; di-jet separation



- ATLAS provides wide coverage for rapidity of jets.
- Required for development of ME-PS simulations
- Jet kinematic distributions are key for WW-scattering and VBF

Event observables - sensitivity to new physics

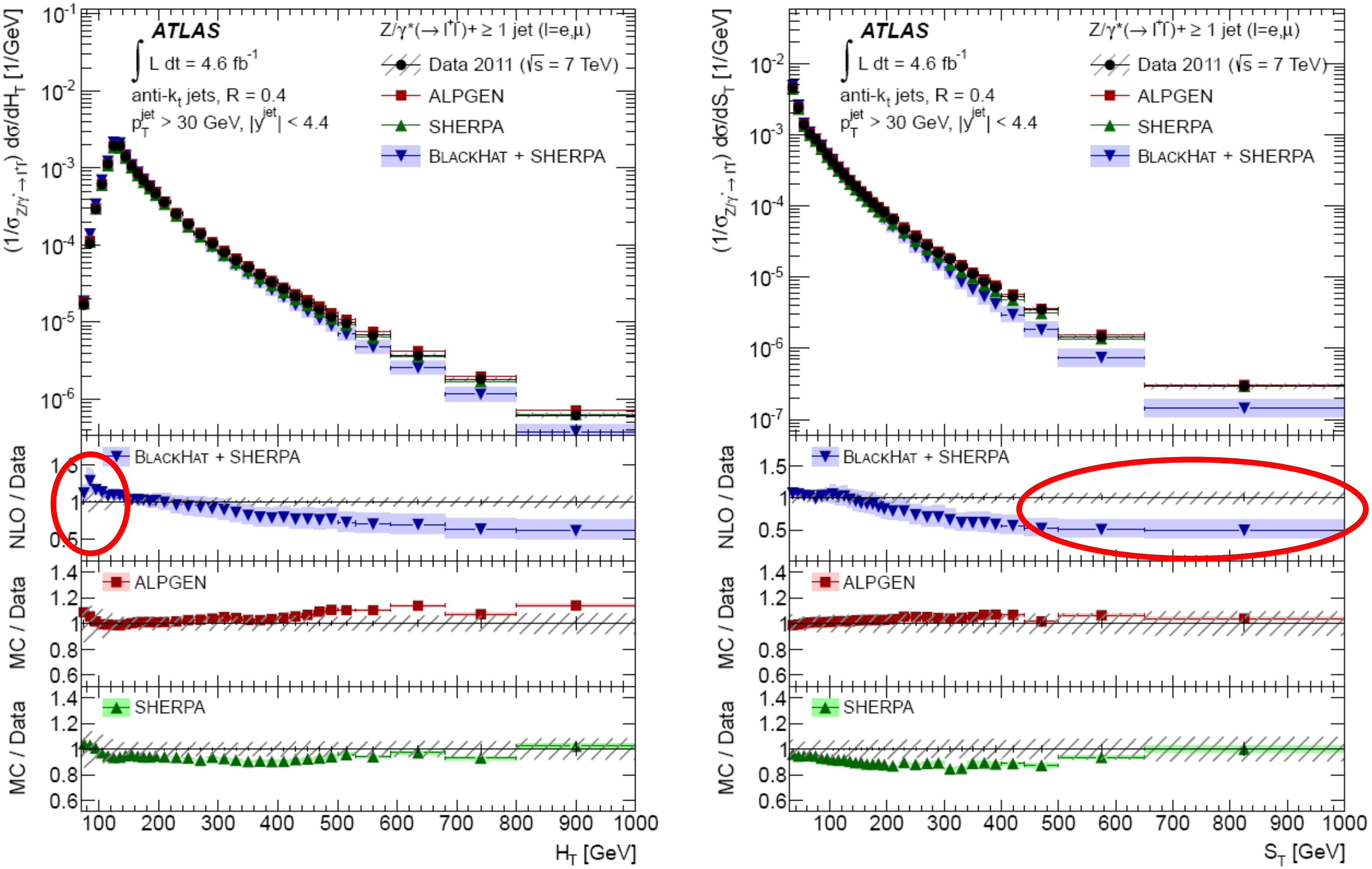




- Searches for heavy particles use H_T (scalar sum of p_T of all reconstructed objects) or M(jets); the discrepancy is by definition
- They are often used as a scale in NLO calculations:
  - The choice of scales evolved M(W) → M(W)+p_T(W) → H_T (or M(jets))

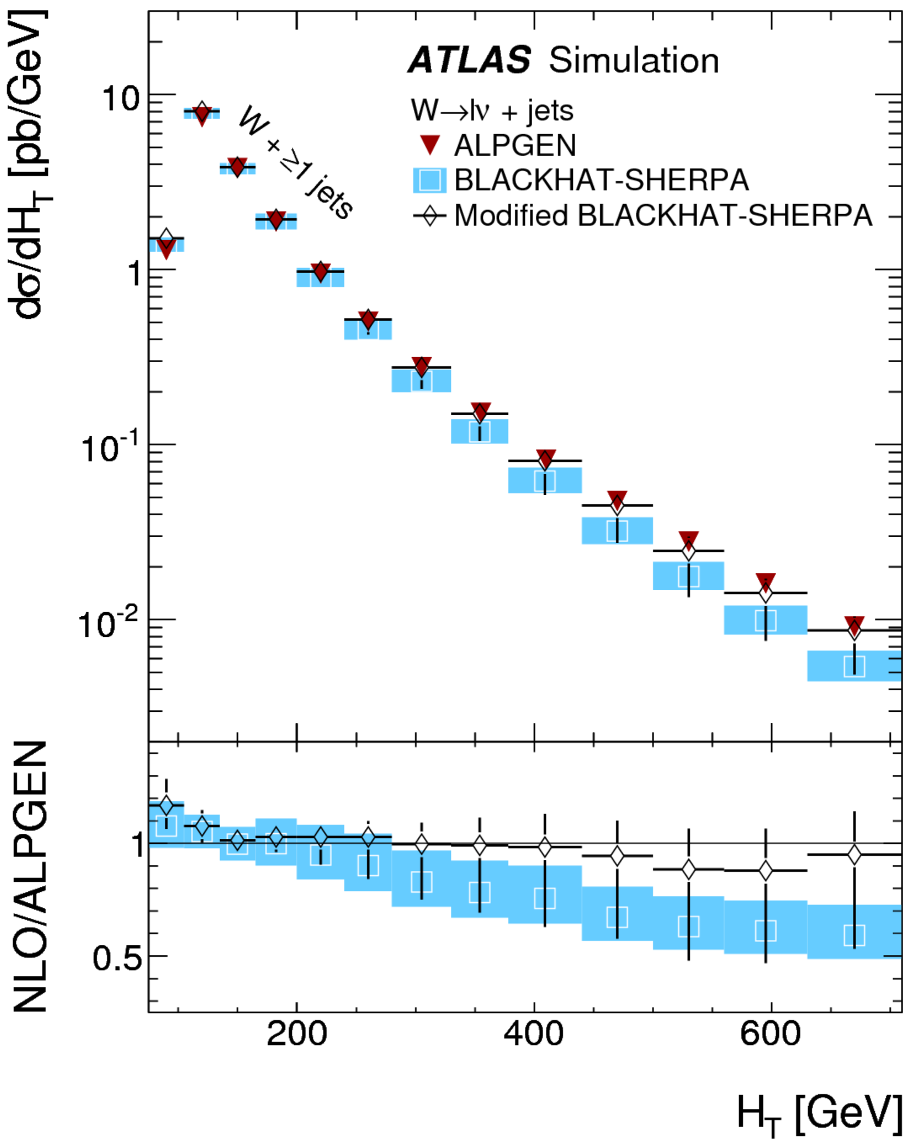
Discrepancies in the H_T distribution

- Observed in the Z+jets as well.

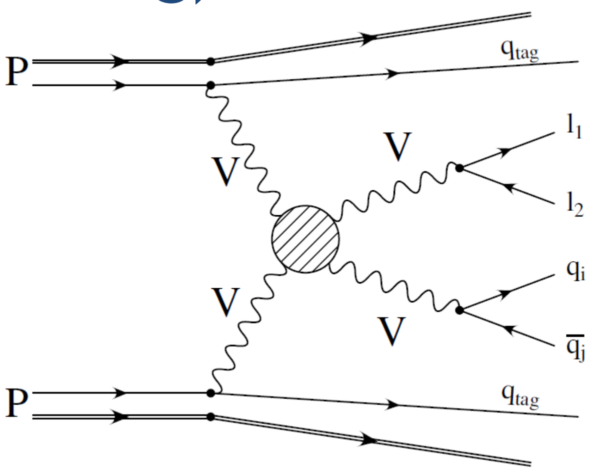


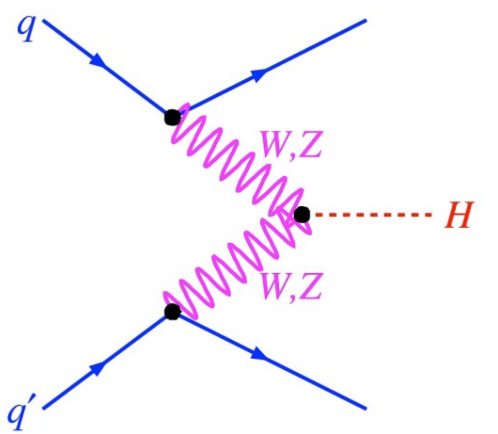
NLO calculation for H_T

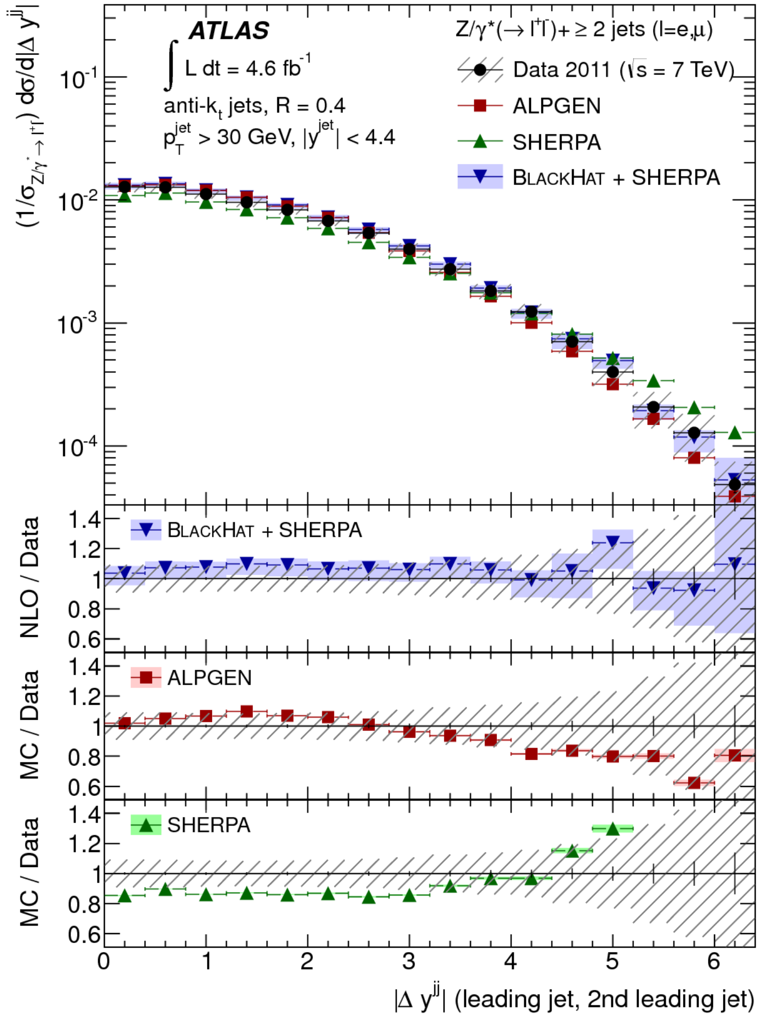
- Each NLO sample contains one additional emission beyond the base number of parton emission
- Events with high HT contain multiple jets → The conventional NLO calculations does not access the phase space
- Exclusive (matched) some of NLO calculations describes the high-H_T tail well



Jets in the future measurements (VBF and WW-scattering)



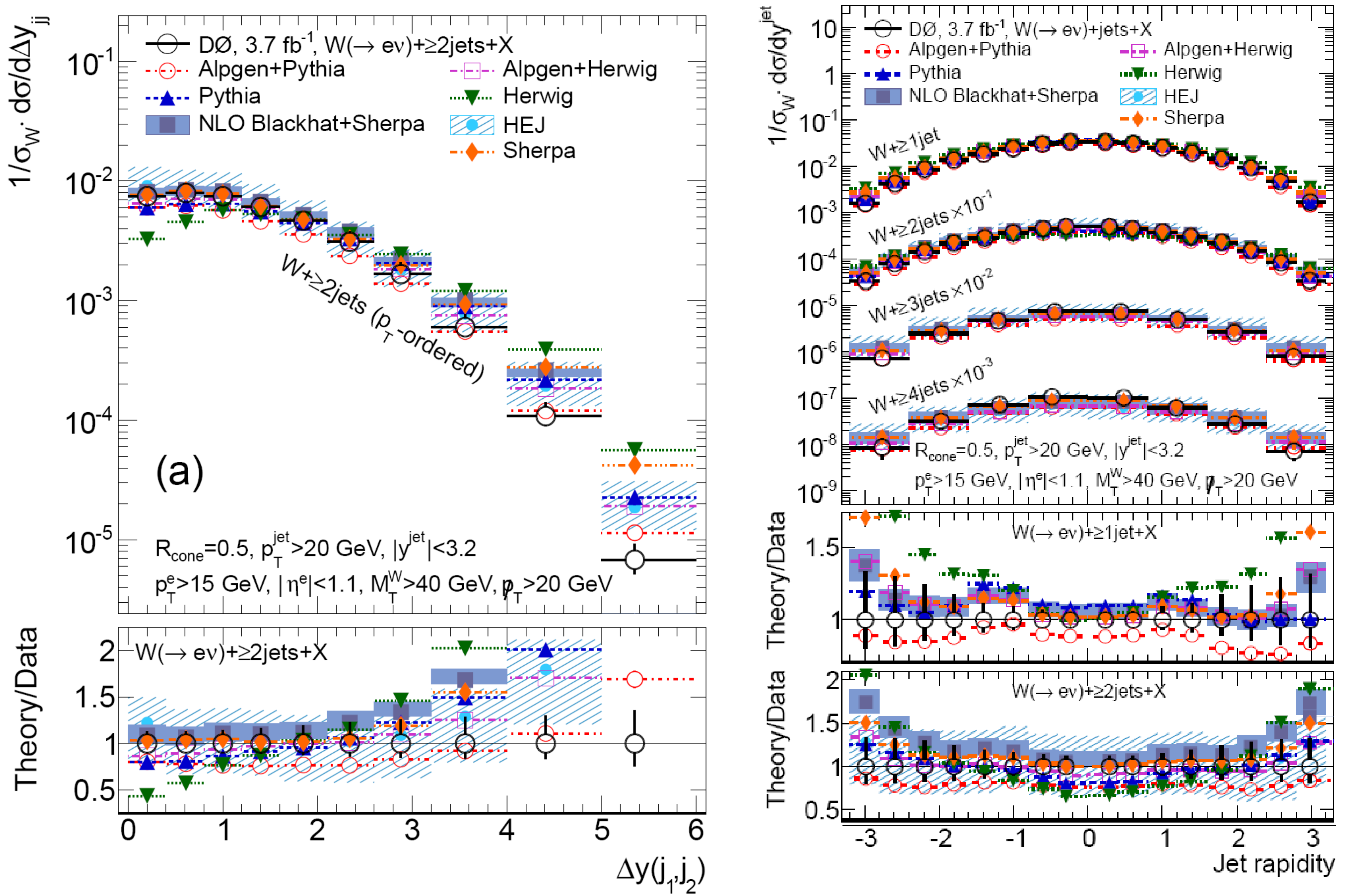




- Future observations of VBF and WW-scattering will rely on our understanding of forward jets and rapidity gaps between jets.
  - W, Z, and H bosons via VBF

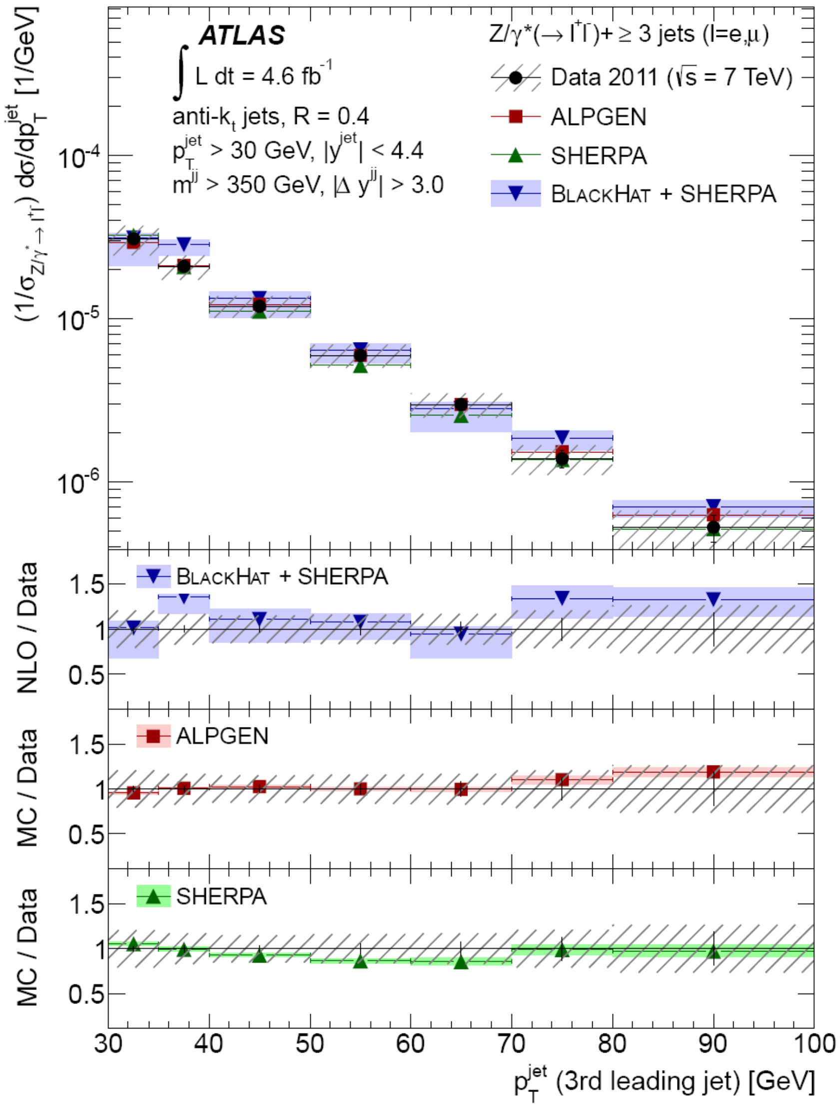
Two-jet rapidity separation in $p\bar{p}$ collisions

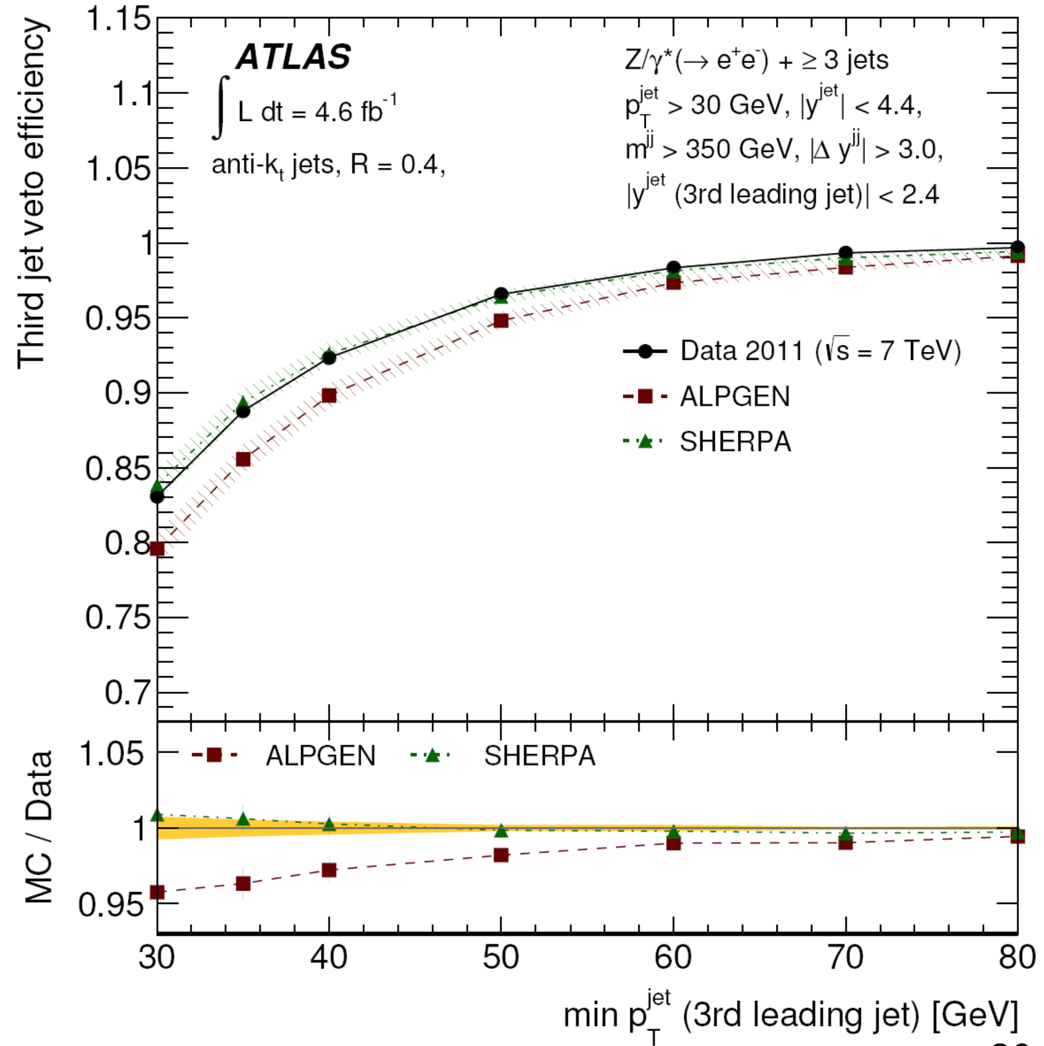
- Simulations tend to predict more jets separated by large rapidities



VBF Selection and Jet Veto

- Pre-selection: m(j1,j2)>350 GeV && |y(j1)-y(j2)|>3.0





Measurement of Z+b and Z+bb production

- Test of perturbative QCD and heavy-flavor quark PDF's

CMS 5 fb^{-1}: Z+b+jets

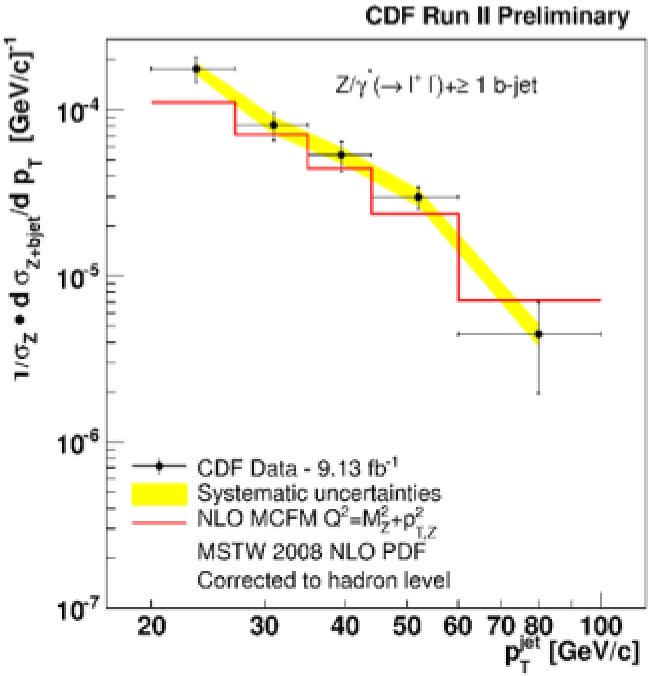
Multiplicity bin	Measured	MadGraph 5F	MadGraph 4F
$\sigma(Z(\ell\ell)$+1b) (pb)	$3.52 \pm 0.02 \pm 0.20$	3.66 ± 0.02	3.11 ± 0.03
$\sigma(Z(\ell\ell)$+2b) (pb)	$0.36 \pm 0.01 \pm 0.07$	0.37 ± 0.01	0.38 ± 0.01
$\sigma(Z(\ell\ell)$+b) (pb)	$3.88 \pm 0.02 \pm 0.22$	4.03 ± 0.02	3.49 ± 0.03
$\sigma(Z(\ell\ell)+b)/\sigma(Z(\ell\ell)+j)$ (%)	$5.15 \pm 0.03 \pm 0.25$	5.35 ± 0.02	4.60 ± 0.03

- At CDF the measured cross section are in agreement with MCFM

$$\frac{\sigma_{Z+bjet}}{\sigma_Z} = 0.261 \pm 0.023^{stat} \pm 0.029^{syst}\%$$

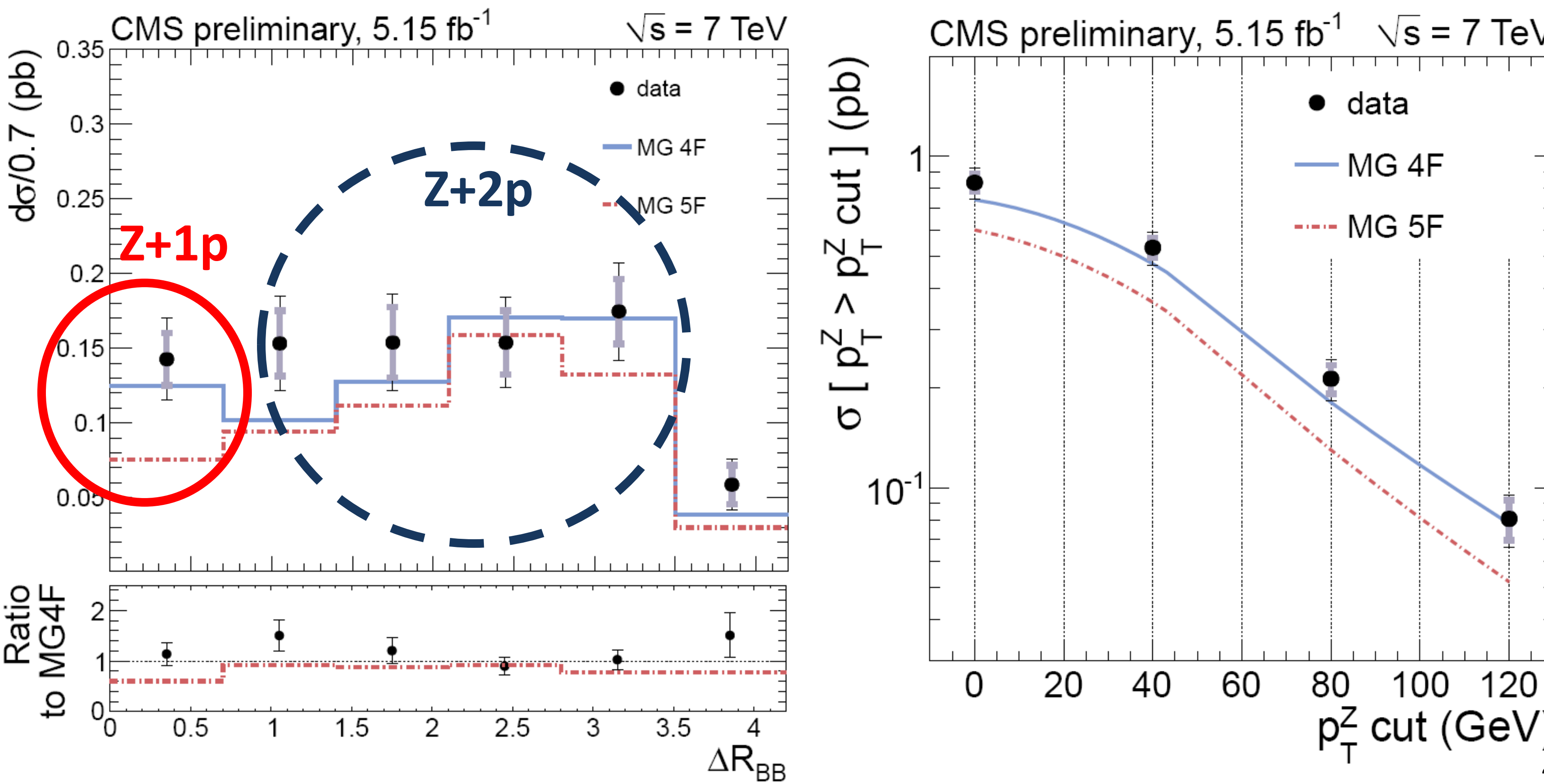
$$\frac{\sigma_{Z+bjet}}{\sigma_{Zjet}} = 2.08 \pm 0.18^{stat} \pm 0.27^{syst}\%$$

	NLO $Q^2 = m_Z^2 + p_{T,Z}^2$	NLO $Q^2 = < p_{T,jet}^2 >$
$\frac{\sigma(Z+b)}{\sigma(Z)}$	2.3×10^{-3}	2.9×10^{-3}
$\frac{\sigma(Z+b)}{\sigma(Z+jet)}$	1.8×10^{-2}	2.2×10^{-2}



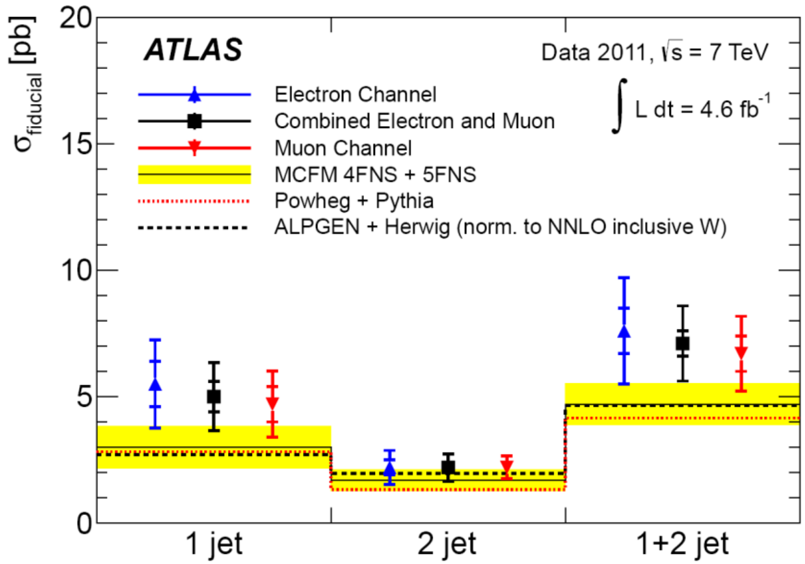
Z+bb → Angular separation

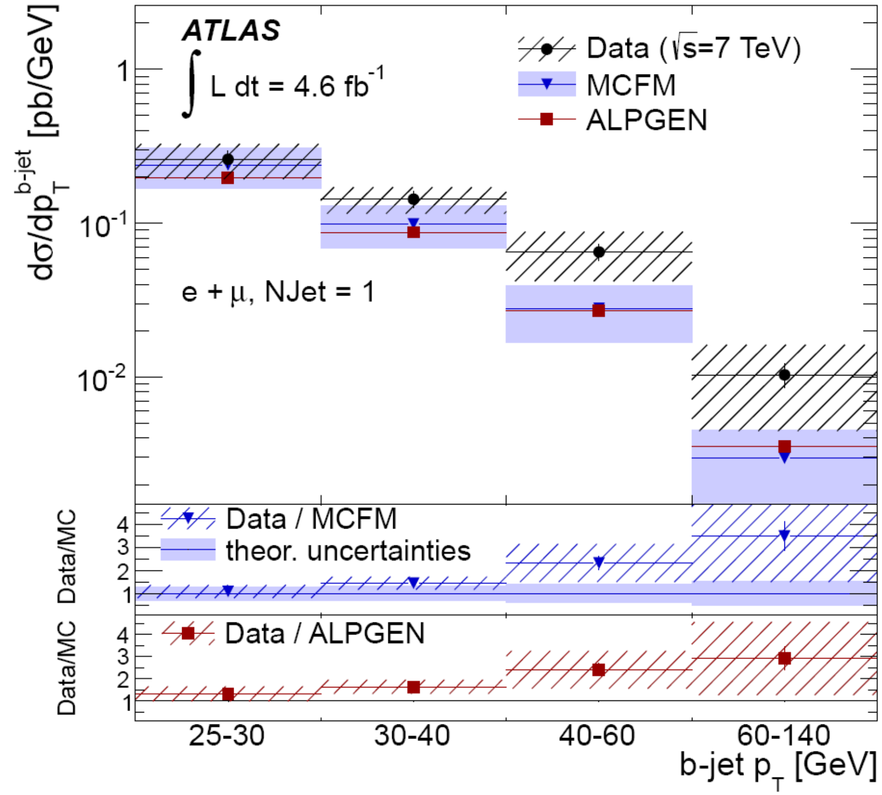
- Z→ee and Z→μμ
- Jets are not used; reconstructed B-hadrons, B→D+X, using secondary vertices: pT(B)> 15 GeV && |η(B)|<2.0



Measurement of W+b and W+bb

- Background to VH, H→$b\bar{b}$
- $t\bar{t}$ background is the limiting factor to measure W+$b\bar{b}$ (2 b-jets)
- Veto additional jets and leptons in events with (n_{jet}≤2)





D0 results for W+b show agreement between data and MCFM: NLO<DATA

$$\sigma(pp \to \mathrm{W} + \mathrm{b}\overline{\mathrm{b}}, p_T^{\mathrm{b}} > 25\ \mathrm{GeV}, |\eta^{\mathrm{b}}| < 2.4) \times \mathcal{B}(\mathrm{W} \to \mu\nu, p_T^{\mu} > 25\ \mathrm{GeV}, |\eta^{\mu}| < 2.1) =$$

CMS:

$$= 0.53 \pm 0.05\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.06\,(\mathrm{theo.}) \pm 0.01\,(\mathrm{lum.})\ \mathrm{pb.}$$

MCFM: 0.52±0.03 pb

Conclusions and Outlook

- Mostly good agreement between NLO and ME+PS predictions and data
- Accuracy of the measurement is already systematically **limited by uncertainties on the JES and b-/c- tagging efficiencies**
- Novel NLO calculations (BlackHat-Sherpa) work well up to V+4 jets!
- The comprehensive set of measurements enables development of future ME+PS simulations (Alpgen, Sherpa, etc)
  - Currently we have up to W+5p and Z+5p in ME+S → need up to **V+8p or V+10p**

- Precise understanding of the kinematic variables is crucial for the future measurements: WW-scattering, VH→Vb$\bar{b}$, searches for BSM, etc

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