W/Z + Jets Production

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On behalf of the ATLAS, CMS and LHCb Collaborations

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Outline

- W + jets
  - CMS: @ 7 TeV: arXiv.1406.7533 Phys. Lett. B 741 (2015) 12
  - ATLAS: @ 7 TeV: arXiv.1409.8639 Eur. Phys. J. C (2015) 75:82
- Z + jets
  - CMS: @ 7 TeV: arXiv.1408.3104 Phys. Rev. D 91 (2015) 052008
  - CMS: @ 8 TeV: http://cds.cern.ch/record/1728322 CMS-PAS-SMP-13-007
    http://cds.cern.ch/record/1728345 CMS-PAS-SMP-14-009
  - ATLAS: @ 7 TeV: arXiv:1304.7098 JHEP 07 (2013) 032
  - LHCB: @ 7 TeV: arXiv:1310.8197 JHEP 01 (2014) 033
- Vector Bosons reconstructed as single jets: ATLAS: @ 7 TeV: arXiv:1407.0800 J. Phys. 16 (2014) 113013
- Ratios
  - CMS: R(Z+jets/γ+jets) @ 8 TeV: http://cds.cern.ch/record/1740969 CMS-PAS-SMP-14-005
  - ATLAS: R(W+jets/Z+jets) @ 7 TeV: arXiv.1408.6510 Eur. Phys. J. C (2014) 74:3168
- W/Z + heavy flavor
  - CMS: Z + b, bb @ 7 TeV: arXiv:1402.1521 JHEP 06 (2014) 120, arXiv:1310.1349 JHEP 12 (2013) 39
  - ATLAS: Z + b @ 7 TeV: arXiv:1407.3643 JHEP 10 (2014) 141
  - LHCB: Z + b @ 7 TeV: arXiv:1411.1264 JHEP 01 (2015) 064
  - ATLAS: W + bb @ 7 TeV: arXiv:1302.2929 JHEP 06 (2013) 084
  - CMS: W + bb @ 7 TeV: arXiv:1312.6608 PLB 735 (2014) 204
  - ATLAS: W + c @ 7 TeV: arXiv:1402.6263 JHEP 05 (2014) 068
  - CMS: W + c @ 7 TeV: arXiv:1310.1138 JHEP 02 (2014) 013

Introduction (I)

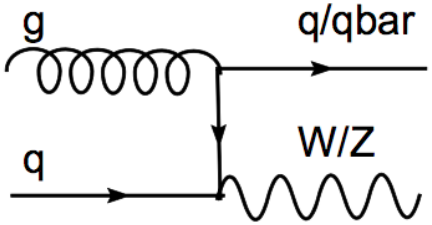
- Accurate modeling of V+jets is importance for many measurements at the LHC
  - W/Z+jets is dominant background for precision top quark measurements
  - Important for precision Higgs physics (background modeling)
  - Important for modeling of SM background in searches of new physics (SUSY, …)
- With W/Z+jets we can probe different aspects of QCD calculations
  - Tests of perturbative QCD in a new energy regime, in a totally unexplored kinematic region
  - Tune Monte Carlo generators in order to better describe the data
- Constraints for Parton Distribution Functions
  - Key ingredient to make theoretical predictions at hadron colliders
  - Probe region of high Q^2
  - Test flavor fractions with associated HF production
  - LHC probes gluons and sea quarks

Introduction (II)

- W/Z + jet production is sensitive to gluon content of the proton:

$$u + g \rightarrow W^{+} + q - jet$$

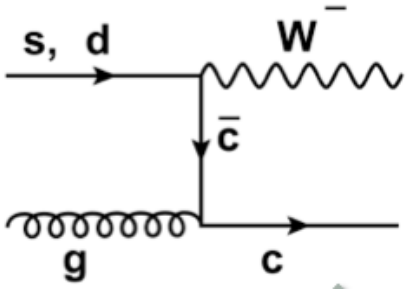
$$d + g \rightarrow W^{-} + q - jet$$



- When associated to specific jet flavors, there is sensitivity to other PDFs too:

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

$$b + g \rightarrow Z^{0} + b$$



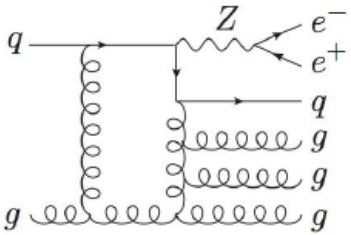
- Presented Results:
  - Corrected for all detector effects (efficiencies & resolution)
  - Correct to jets of stable particles
  - Correct fixed order NLO generators for non−pQCD effects (fragmentation & underlying event)
  - Response matrix obtained from LO+PS

Introduction (III)

- Three types of theory predictions for the V+jets signal
  - LO+PS: always normalized to NNLO inclusive (FEWZ)
    - Exception γ+jets analysis, where LO x-section is used
  - NLO: always normalized to its native cross section
    - Difficult to provide NLO predictions at higher multiplicities
  - NLO+PS: always normalized to its native cross section
- Despite great theoretical progress there are still theory uncertainties related to various sources which can be constrained by data
  - Higher-order QCD corrections (NNLO)
  - Electroweak corrections
  - Parton Shower and its matching to Matrix Element
  - Parton Density Functions
  - Underlying Event modeling

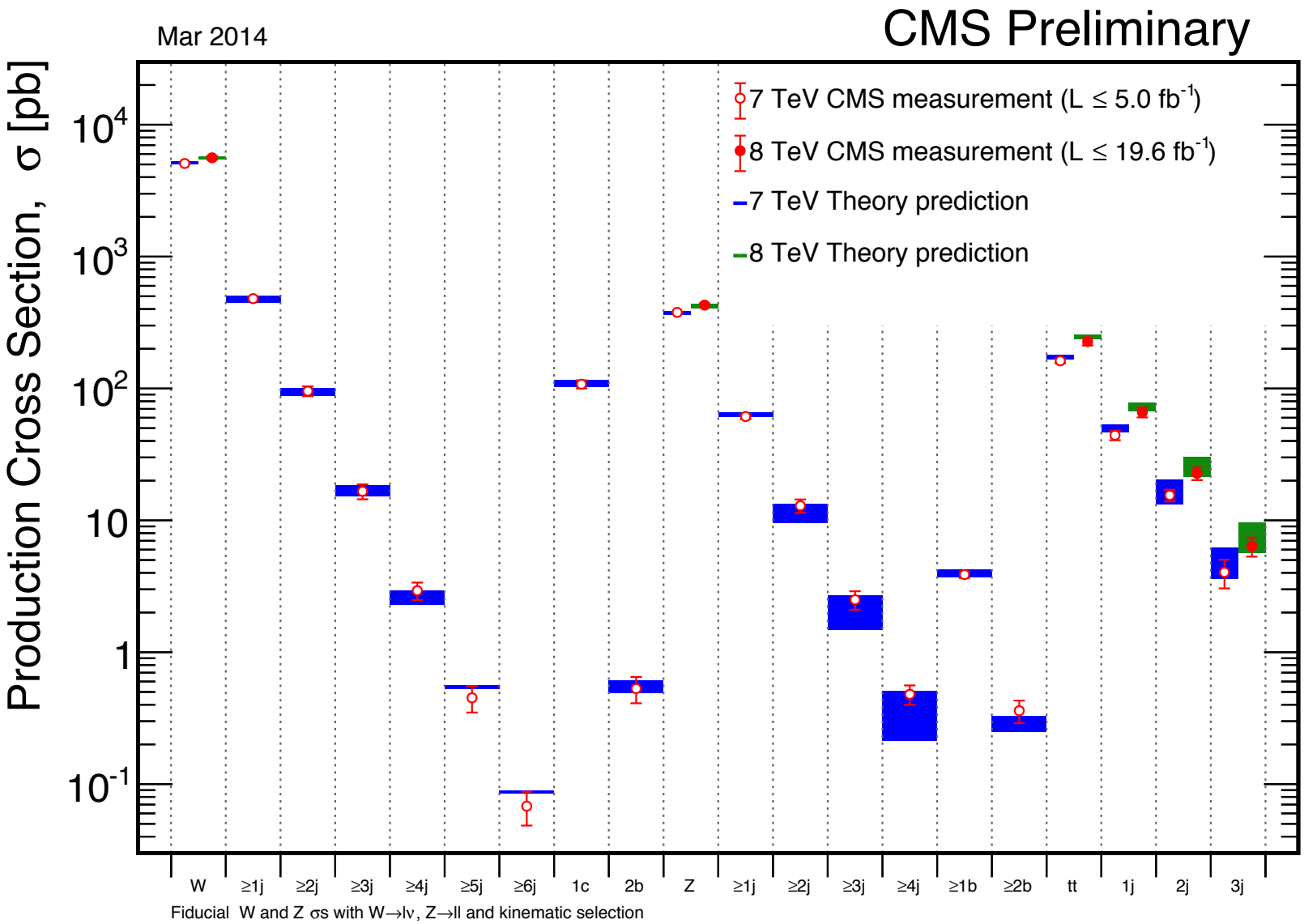
Monte-Carlo Models

- Two approaches
  - Fixed order generators e.g. NLO(Np=0), LO(Np=1), LL(Np≥2)
    - PS (LL) jet p_T spectrum can be too soft or hard depending on the scheme applied
    - Examples: MC@NLO, POWHEG, SHERPA, MCFM (Np≤2), BlackHat +SHERPA (Np≤4)
  - Multi-leg generators e.g. LO(Np≤5), LL(>5)
    - Require tuning, since sensitive to scale choice
    - Examples: ALPGEN LO (Np≤5), LL(>5), MadGraph LO (Np≤5), LL(>5), PYTHIA LO (Np≤1), LL(>1)



- Fixed order matrix element and parton shower merging more difficult with NLO predictions

Overview

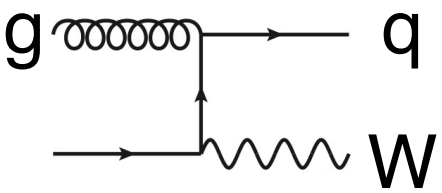


Excellent agreement with theory

W + jets

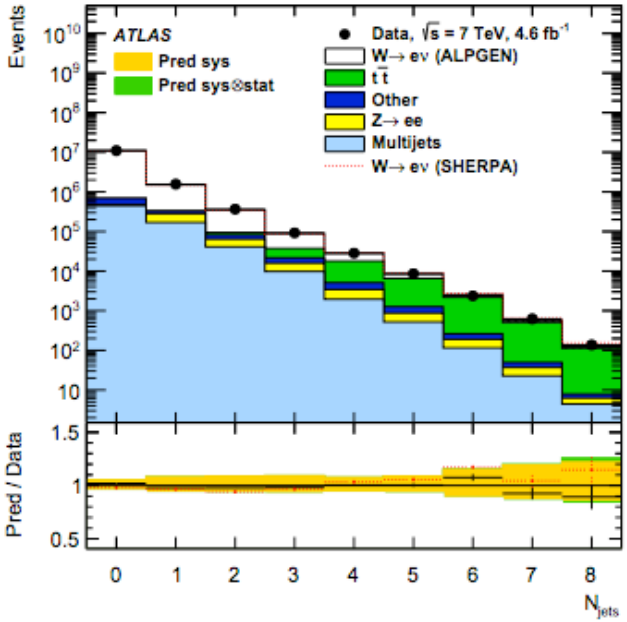
Eur. Phys. J. C (2015) 75:82

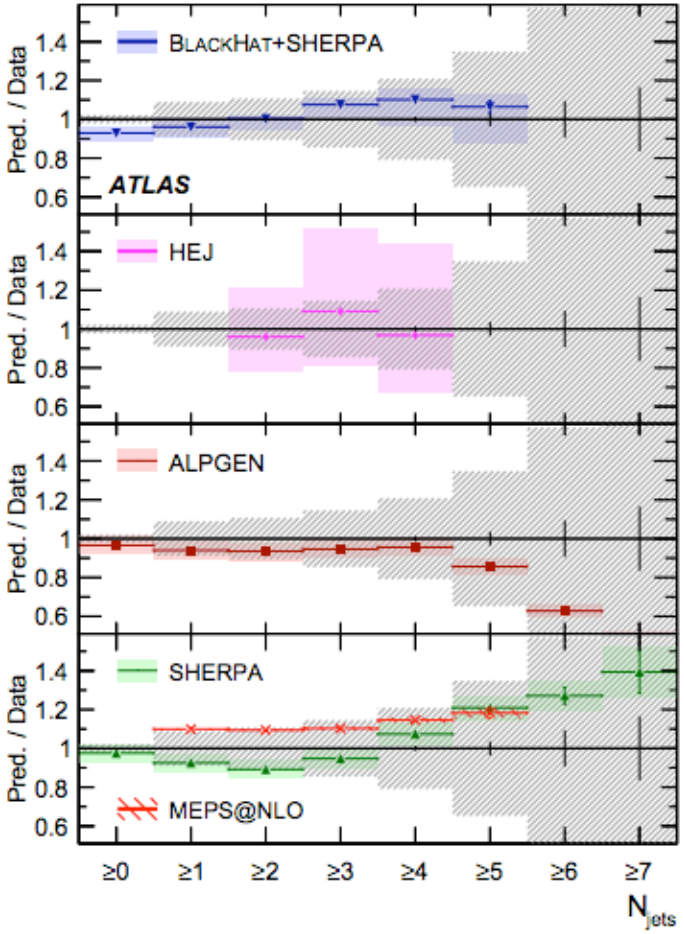
- Measurements of W+(n≥0,...,7) jets unfolded to particle level
- Signal and background processes simulated with MC, apart from data-driven tt, multijets estimate
- Data confronted with NLO fixed-order, resummed calculations and MEPS programs
- Agreement between measurements and theory over 5 orders of magnitude in cross-sections



W selection:
- Lepton p_T > 25 GeV
- Lepton |η| < 2.5
- E_T^{miss} > 25 GeV
- M_T > 40 GeV

Jet selection:
- Jet p_T > 30 GeV
- Jet |y| < 4.4
- ΔR(lep,jet) > 0.5





W + jets

- W+jets measurements which reach 1 TeV of jet transverse energy
- In general measurements are in agreement with theory, but there are several regions with 2-3σ excursions
- Discrepancies with predictions:
  - LO QCD multi-leg + Parton Shower overestimate data at high jet scales (jet p_T)

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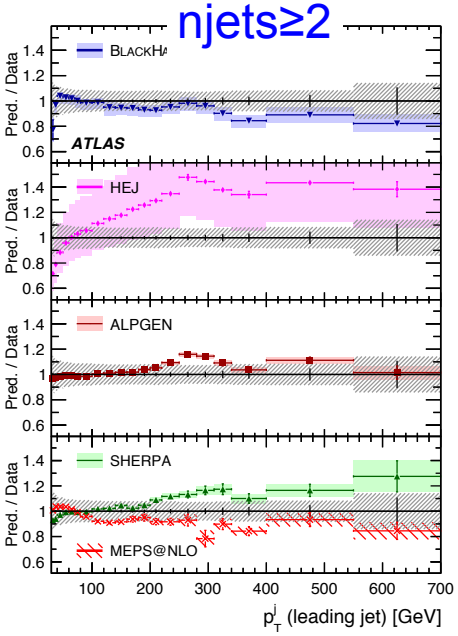
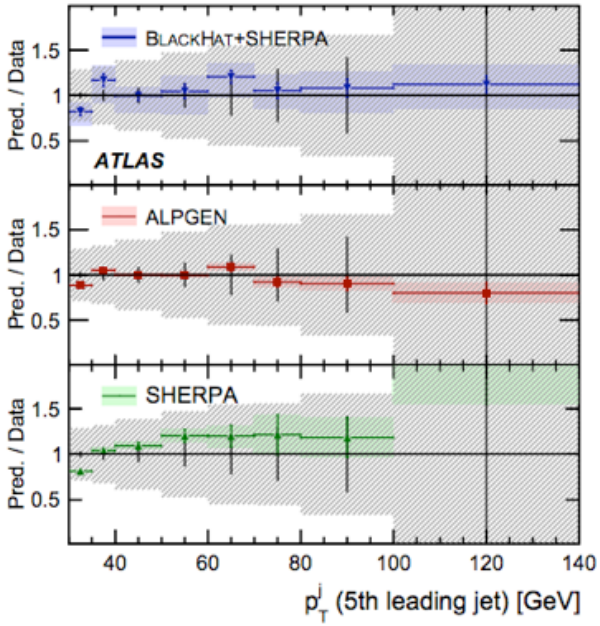
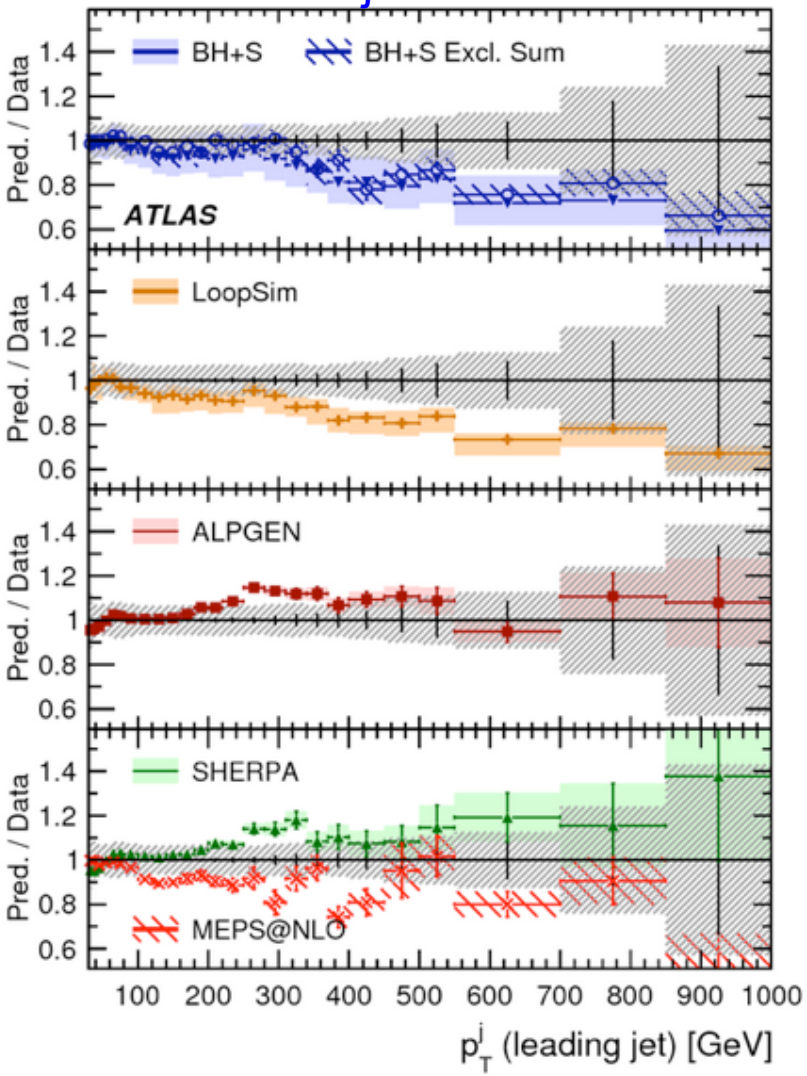
njets≥2





njets≥1



W + jets

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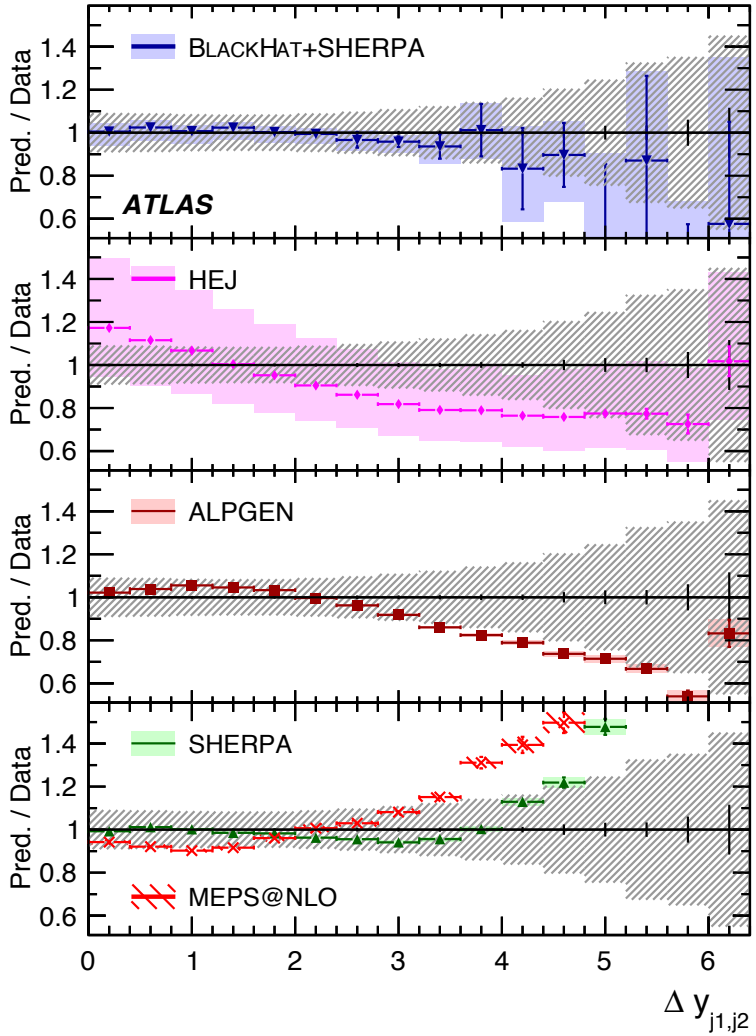
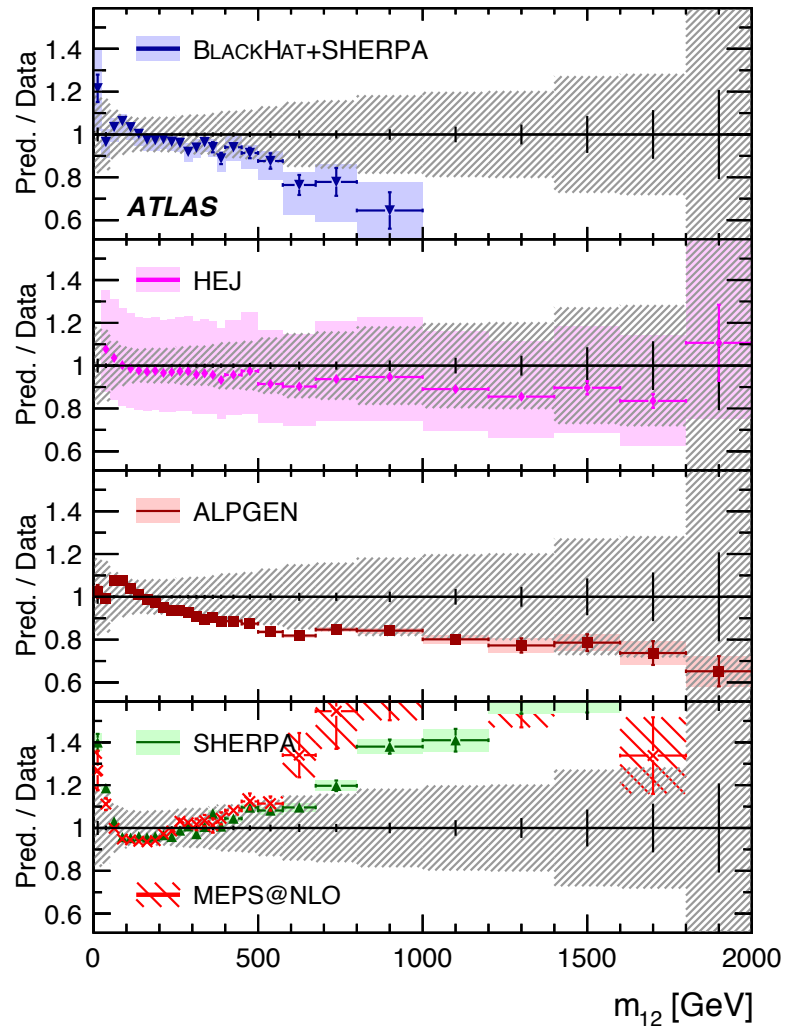


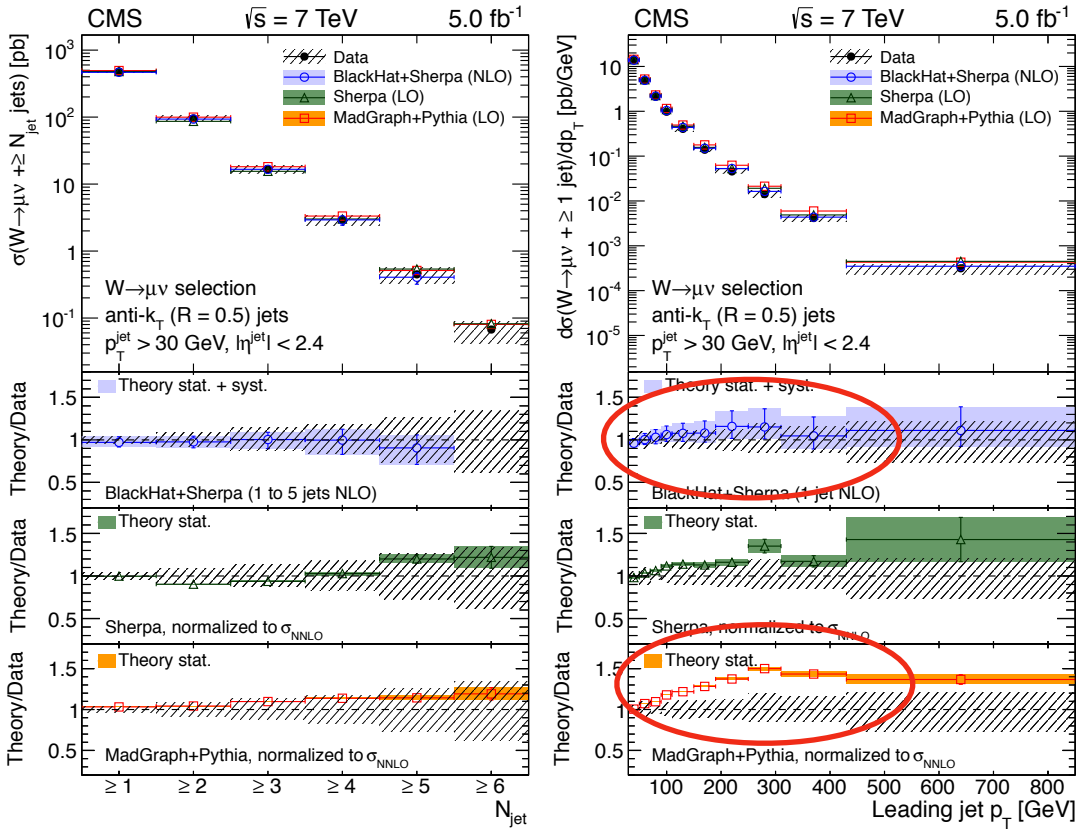


Discrepancy between data and theory, including SHERPA, MEPS@NLO

W + jets

Phys. Lett. B 741 (2015) 12

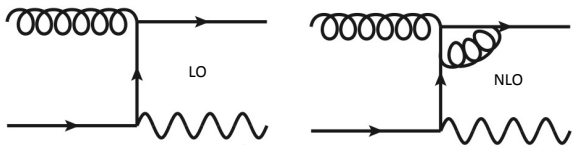
- Inclusive jet multiplicity spectrum has reasonable data/theory agreement
- MadGraph predicts too many high-p_T jets and higher H_T
- LO ME + PS calculations overestimate the p_T jet spectrum at high values:
  - LO+PS are accompanied with stat uncertainty, no theory systematic uncertainty, making the disagreement looking spectacular
  - Effect not related to PDFs



Phase space:

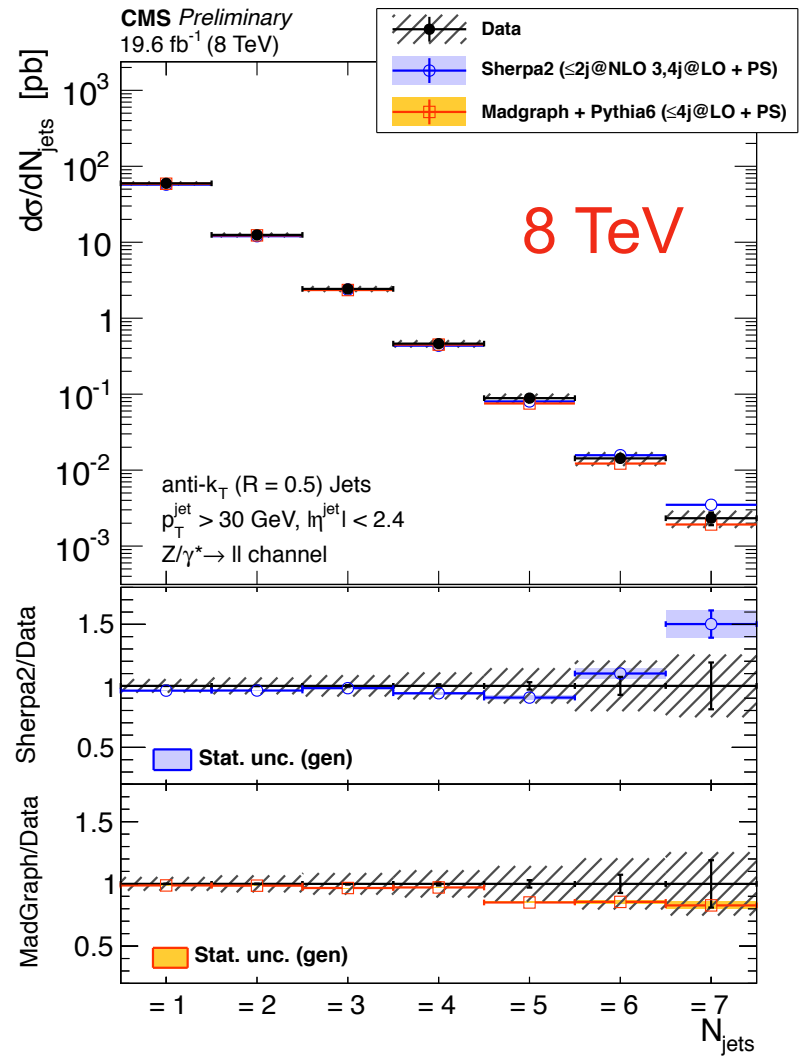
- muon $p_T > 25$ GeV, $|\eta| < 2.1$
- jets: anti-kT $\Delta R = 0.5$
- $p_T > 30$ GeV, $|\eta| < 2.4$
- $\Delta R(\text{jet},\mu) > 0.5$

Z + jets



CMS-PAS-SMP-13-007

- Unfolded total and differential cross sections as function of jet variables using ~20 fb^{-1} of pp collision data at $\sqrt{s}$ = 8 TeV
  - allows detailed analysis of QCD dynamics
- Data compared to predictions from:
  - Sherpa2+Blackhat: NLO accuracy for $n_{jets} \leq 2$
  - MadGraph normalized to NNLO
- Data rates very well described up to accuracy of matrix element calculation (4), and agreement within errors for all multiplicities



Phase space:

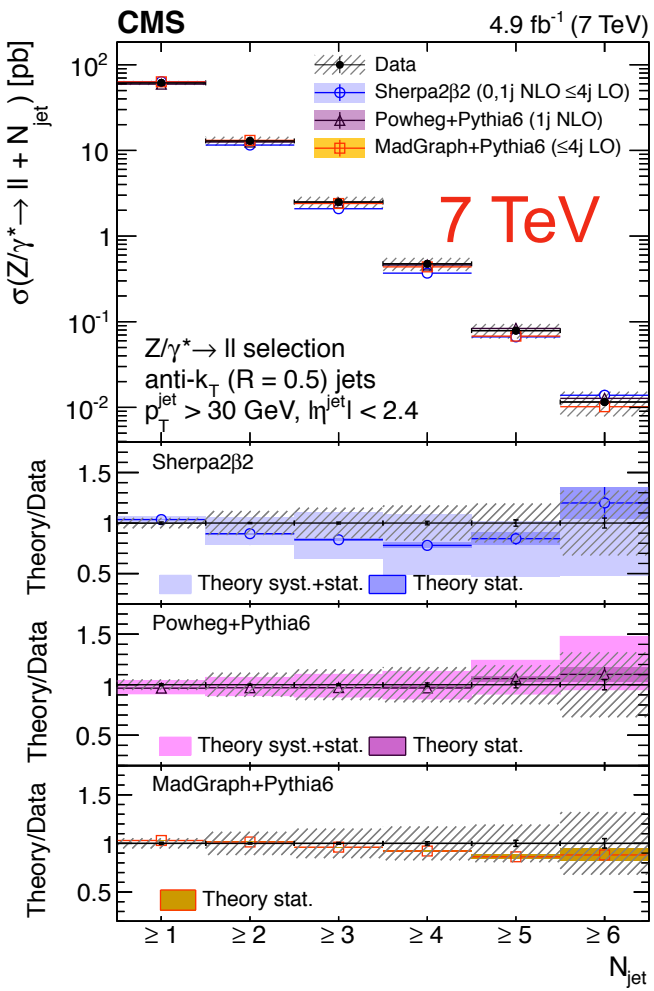
- *dressed* leptons: p_T > 20 GeV, $|\eta|$ < 2.4
- 71 < M_{ll} < 111 GeV
- jets: anti-kT ΔR = 0.5, p_T > 30 GeV, $|\eta|$ < 2.4, ΔR(jet,μ) > 0.5

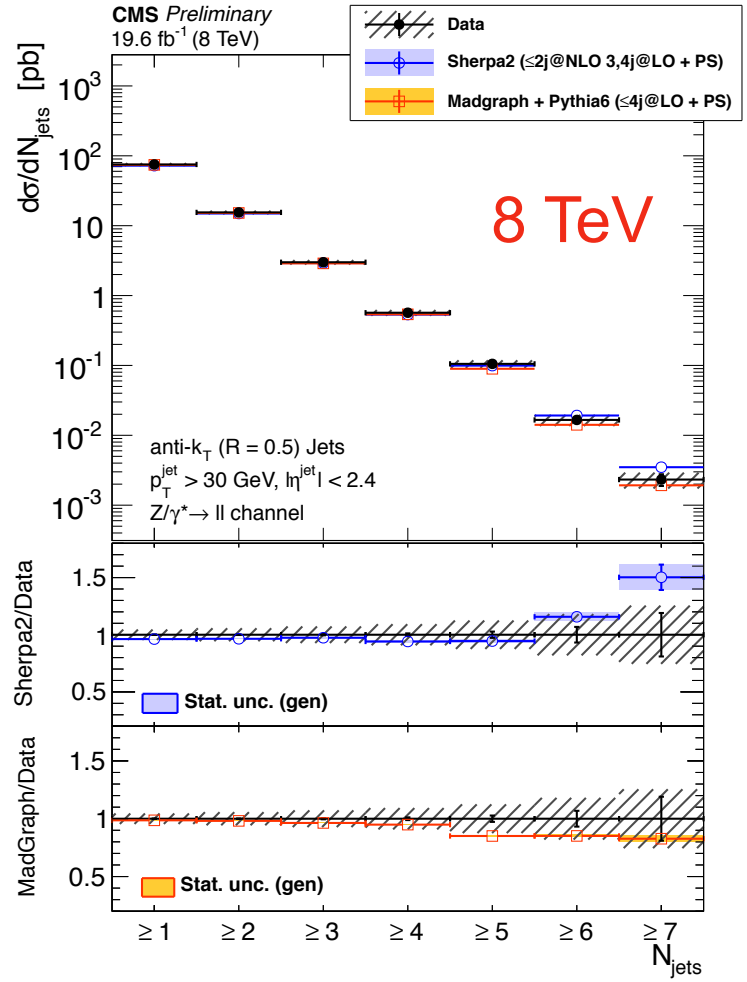
Z + jets

Jet multiplicity

Phys. Rev. D 91 (2015) 052008

CMS-PAS-SMP-13-007



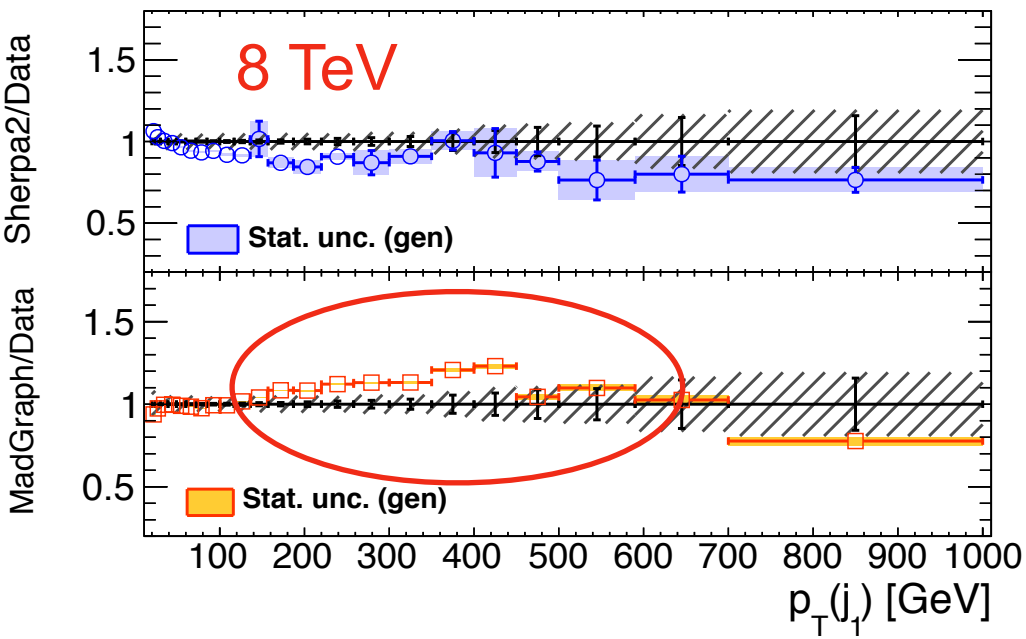


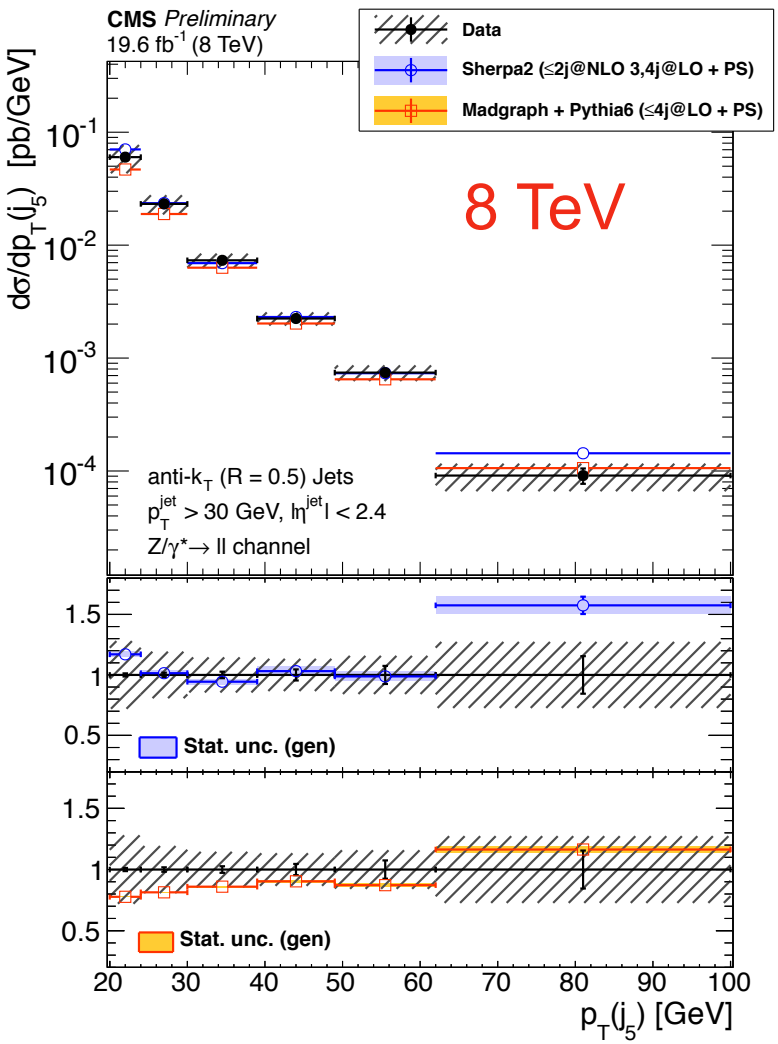
good agreement with the predictions

Z + jets

- Some discrepancy between measurement and predictions for $100 < p_T^{jet} < 450$ GeV in 1 jet bin
  - MadGraph normalized to NNLO total cross section overestimates the 1st jet p_T spectrum for $p_T \gtrsim 100$ GeV
- First Z+5 jet differential cross section measurements

CMS-PAS-SMP-13-007



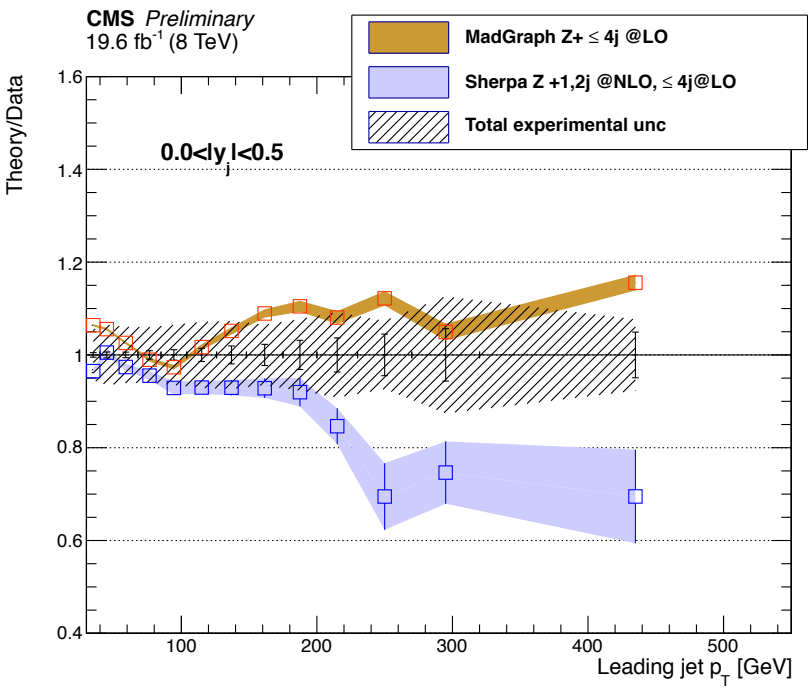


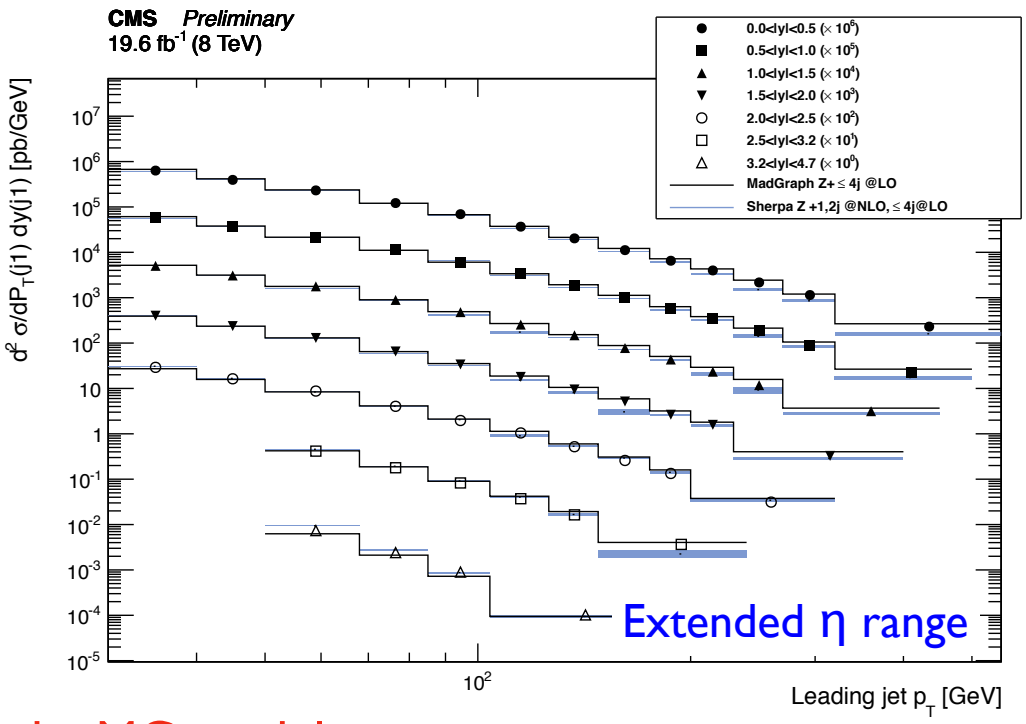
Z + jets

- Double differential measurement in muon channel and over full rapidity acceptance of detector:

CMS-PAS-SMP-14-009

$$\frac{d^2\sigma}{dp_T^j dy^j} = \frac{1}{\mathcal{L}\times\epsilon}\times\frac{N}{2\times\Delta|y^j|\times\Delta p_T^j}$$





- Overall good description of data by MC models
- ~10% disagreement between measurement and MadGraph for leading jet p_T^{jet} > 100 GeV and all y
- Sherpa undershoots data in high-p_T region

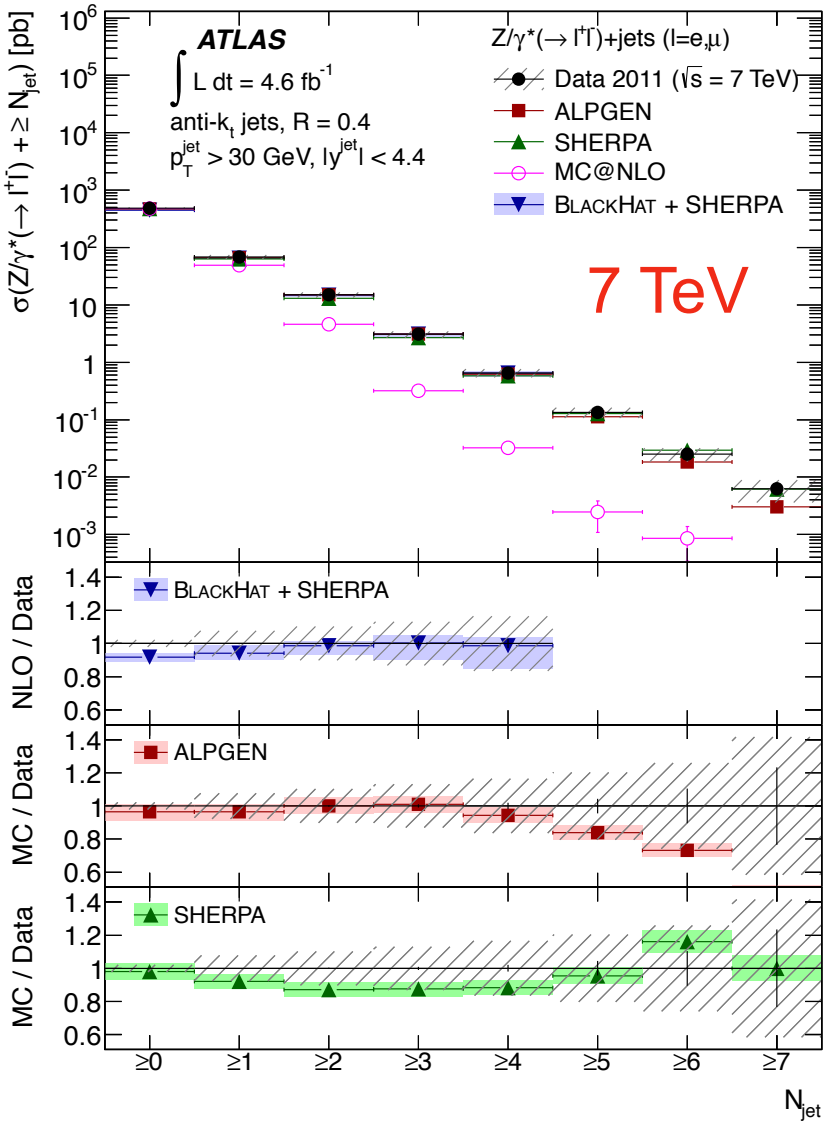
Z + jets

JHEP 07 (2013) 032

- Data with Z + ≥ 7 jets
- Good agreement with NLO BlackHat + Sherpa up to 4 jets
- LO Matrix Elements (ME) with up to 5 partons
- Parton Shower (PS) copes with the additional radiation

- MC@NLO fails to model the p_T of the leading jet and higher jet multiplicities

Phase space:
- *dressed* leptons: p_T > 20 GeV, |η| < 2.4 (2.47)
- 66 < M_{ll}< 116 GeV
- jets: anti-kT ΔR = 0.4, p_T > 30 GeV, |η| < 4.4, ΔR(jet,μ) > 0.5



Z + jets

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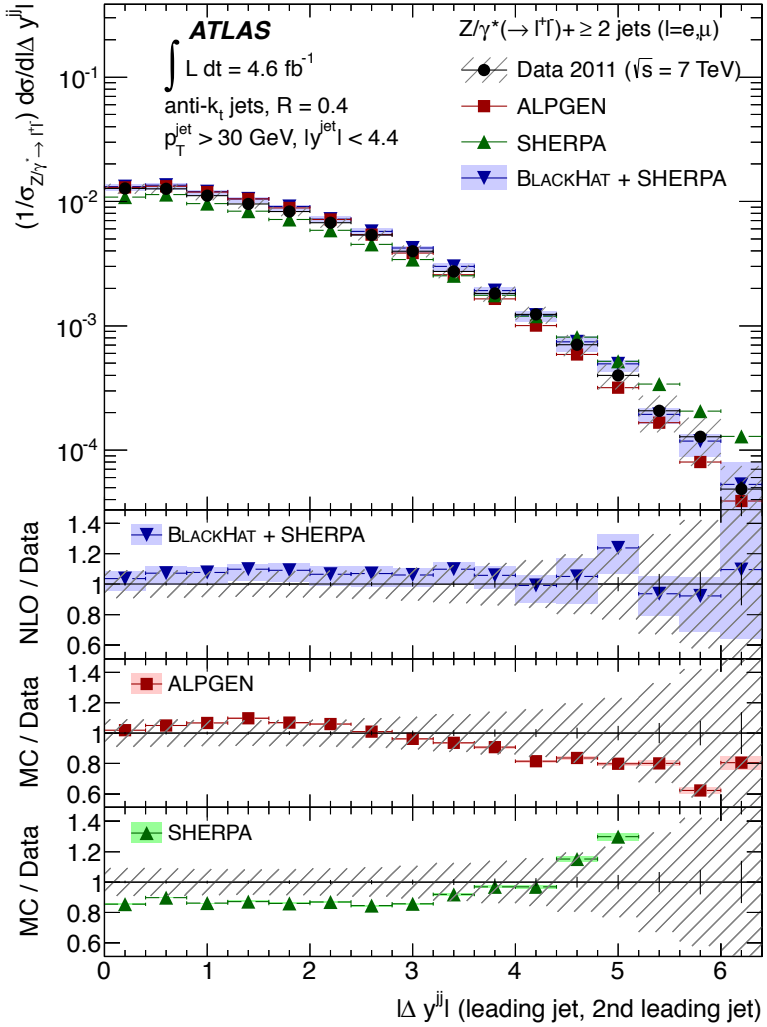
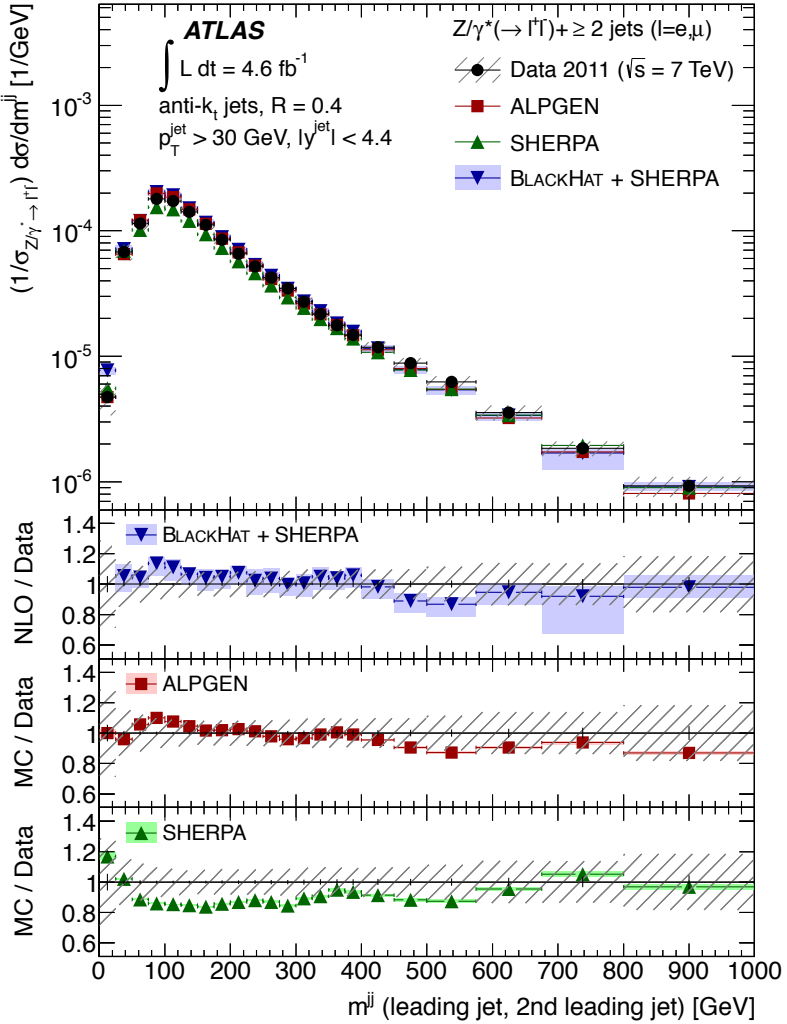
Rapidity gap



Dijet mass



Important for VBF Higgs searches

Forward Z + jet Production

JHEP 01 (2014) 033

Z → μμ selection

- muons: p_T>20 GeV, 2<η<4.5
- mass: 60<M(μμ)<110 GeV
- background <0.3%

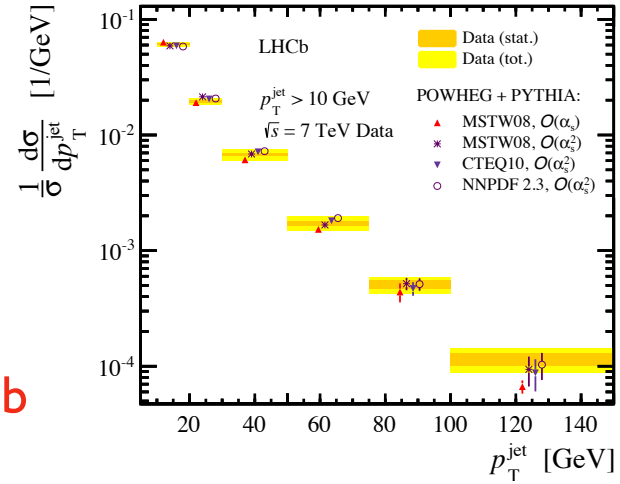
Jets:

– Anti-kT (R=0.5), 2<η<4.5, p_T>10 (20 GeV), Δr(jet,μ)>0.4

– Dominant uncertainties: jet energy scale and resolution, jet reconstruction efficiency

p_T^{jet}>10 GeV: σ = 16.0 ± 0.2(stat) ± 1.2(syst) ± 0.6(lumi) pb

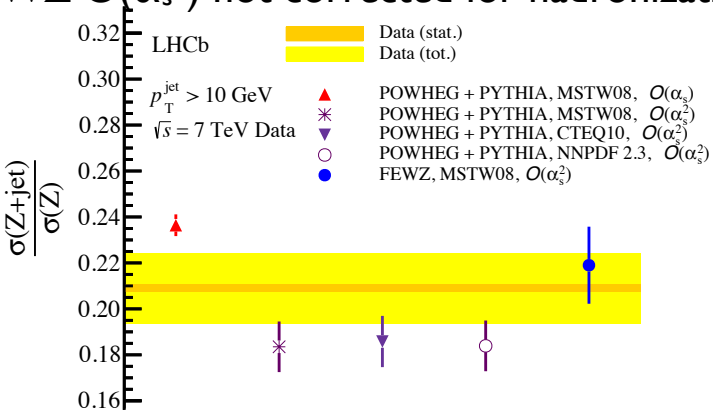
p_T^{jet}>20 GeV: σ = 6.3 ± 0.1(stat) ± 0.5(syst) ± 0.2(lumi) pb

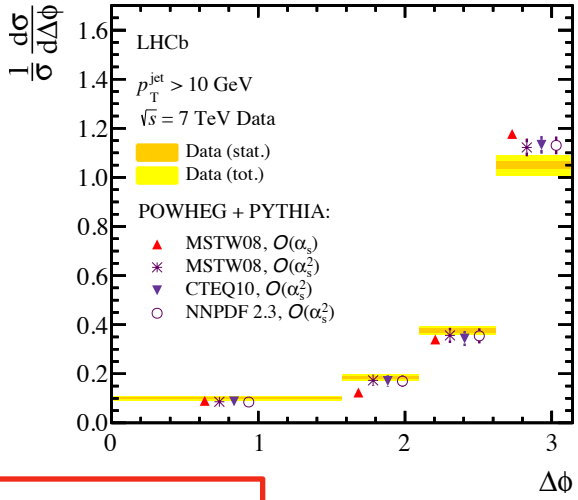


Predictions:

– POWHEG+PYTHIA at O(α_s) and O(α_s^2) and different PDF sets

– FEWZ O(α_s^2) not corrected for hadronization and underlying event

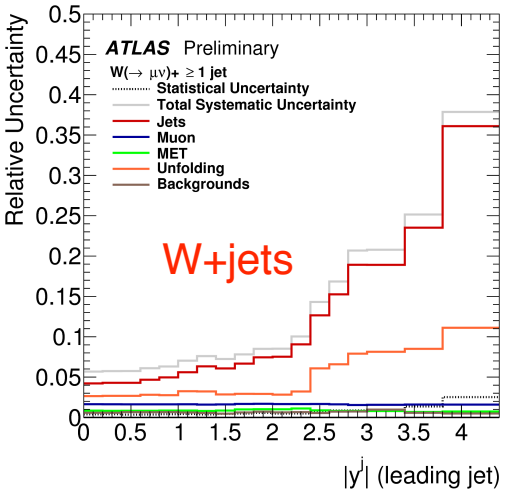


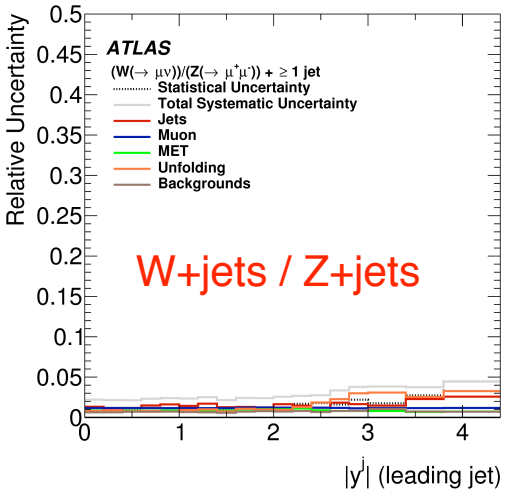


Shapes well described by NLO predictions
LO fails to describe Δφ(Z, jet)

Ratios

- Ratio measurements allow for cancellations of uncertainties (exp. and theory)
  - Experimental: jet calibration uncertainties, lumi etc.
  - Theory: scale+PDF uncertainties: 20% (W+1j) → 2-4% on W+1j/Z+1j at jet p_T=800 GeV
- Accurate test of SM predictions
- Important for Z(νν)+jets background estimation in searches
- Model-independent searches of new physics





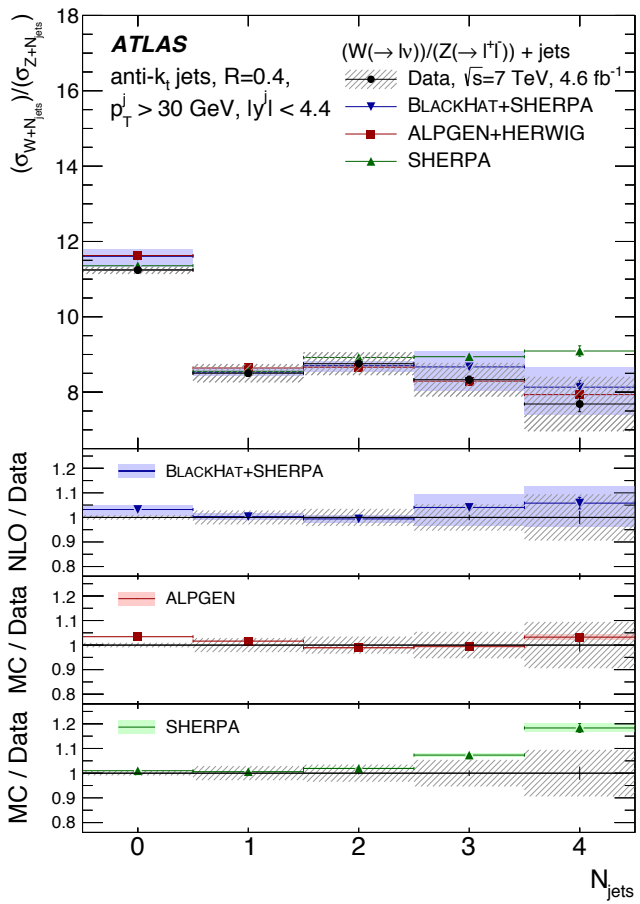
R(W+jets/Z+jets)

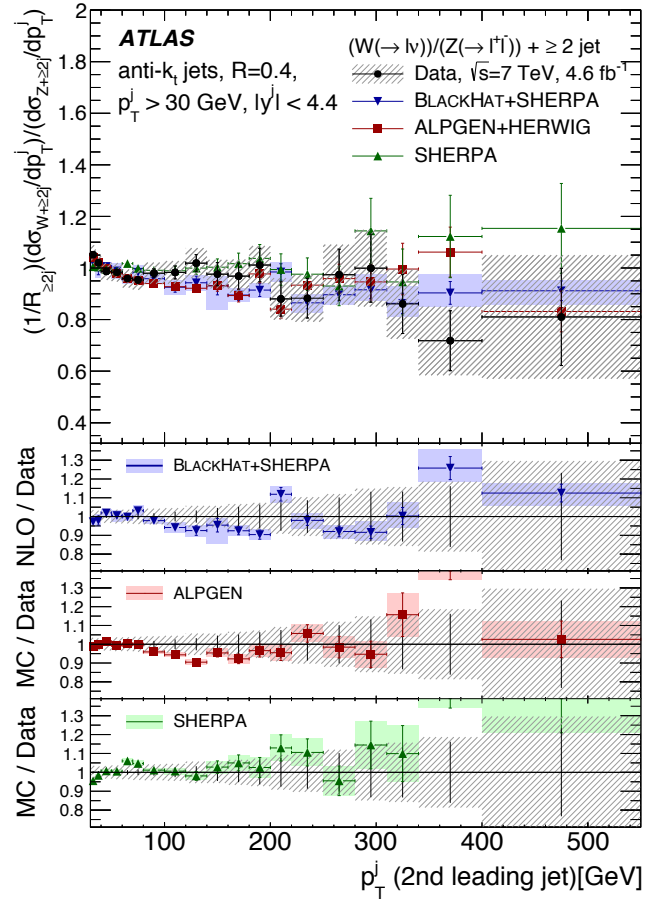
- Probes difference between kinematics of the jet system recoiling against W or Z
- Very good description by NLO pQCD

Eur. Phys. J. C (2014) 74:3168

Phase Space:

- Lepton p_T>25 GeV, |η|<2.5
- Anti-k_T jets R=0.4, p_T>30 GeV, |y|<4.4
- ΔR(l,j) > 0.5
- W: Missing E_T>25 GeV, M>40 GeV
- Z: 66<m_{ll}<116 GeV



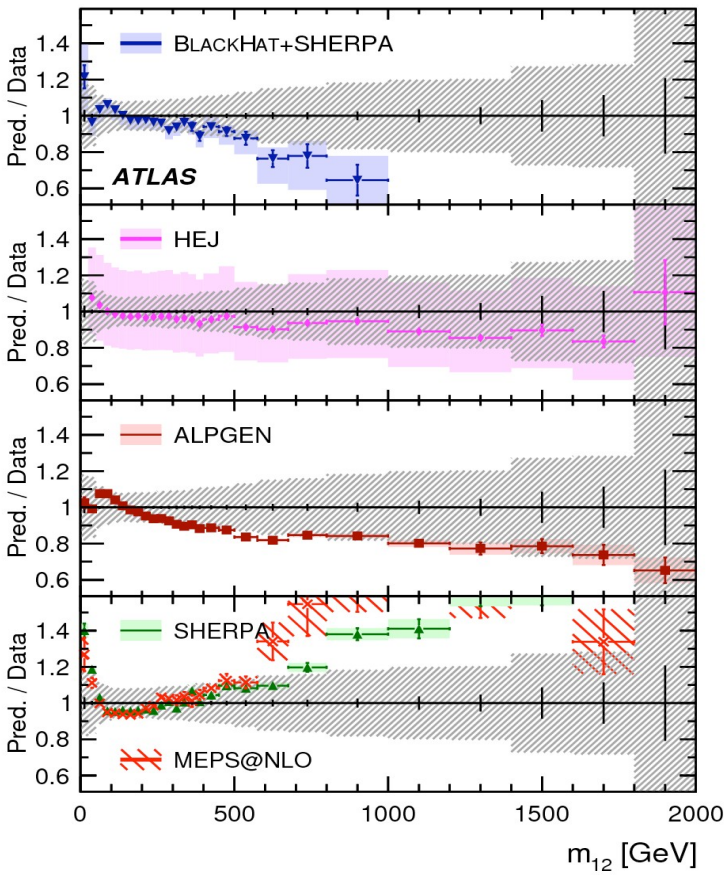


R(W+jets/Z+jets)

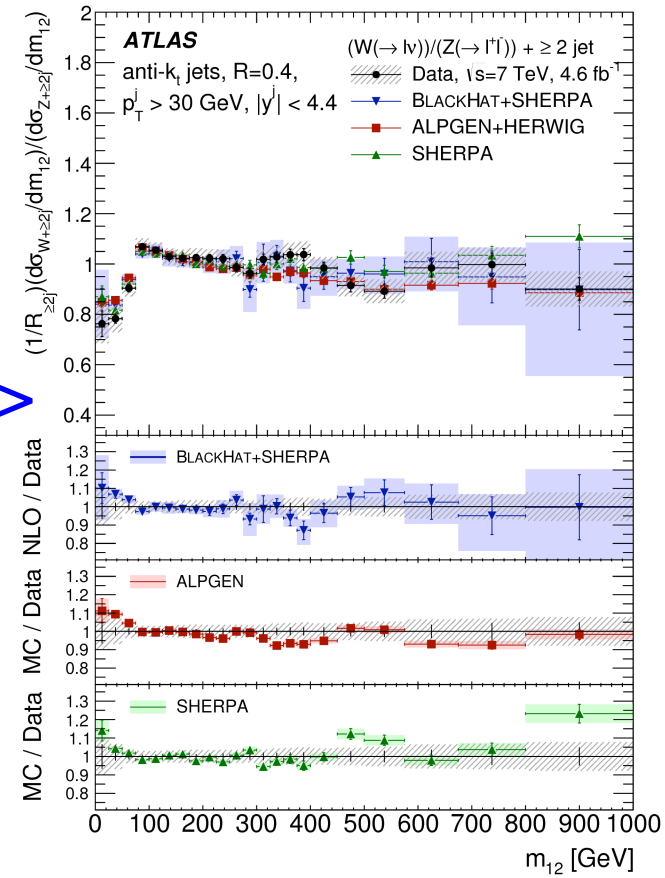
- Mismodeling seen in W+jets and Z+jets separately mostly cancel in R_{jets}
- Significant discrepancies with theory in some regions of phase space

Eur. Phys. J. C (2014) 74:3168

W+jets

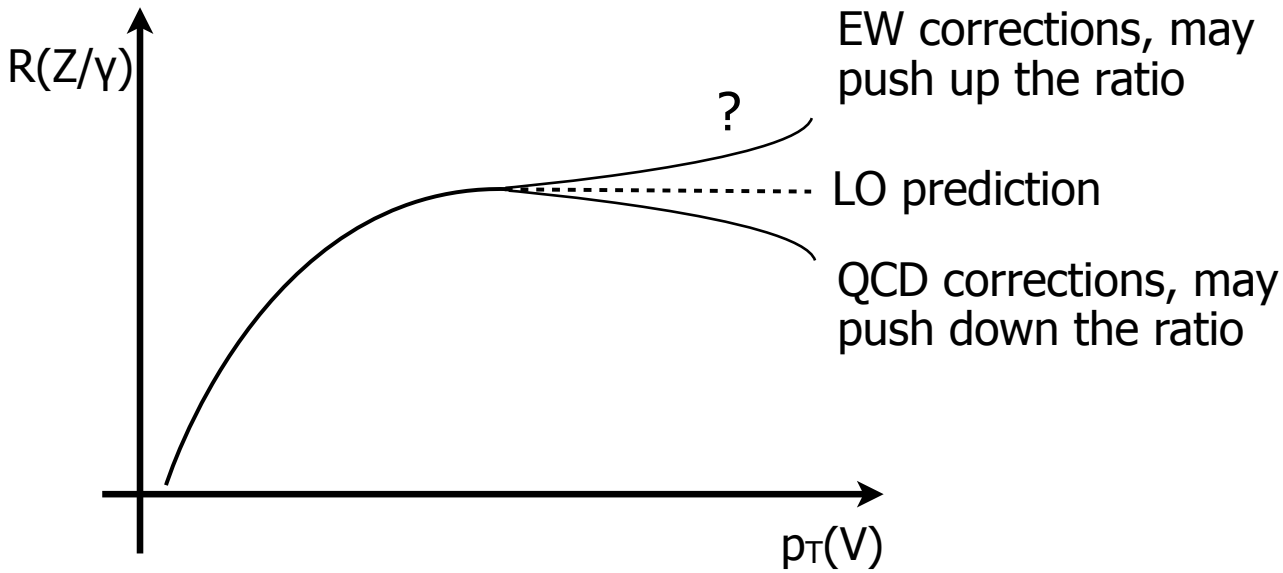


W+jets / Z+jets



Ratio σ(Z+jets)/σ(γ+jets)

- Important observable for new physics searches
  - Ratio expected to be constant above p_T region where Z mass effects are important
    - LO predicts a plateau at high $p_T(V)$
  - The $p_T(\gamma)$ is used as proxy to estimate $p_T(Z \rightarrow \nu\nu)$ i.e. MET
- Test for potential large log effects at high energy, not always included in perturbative calculations

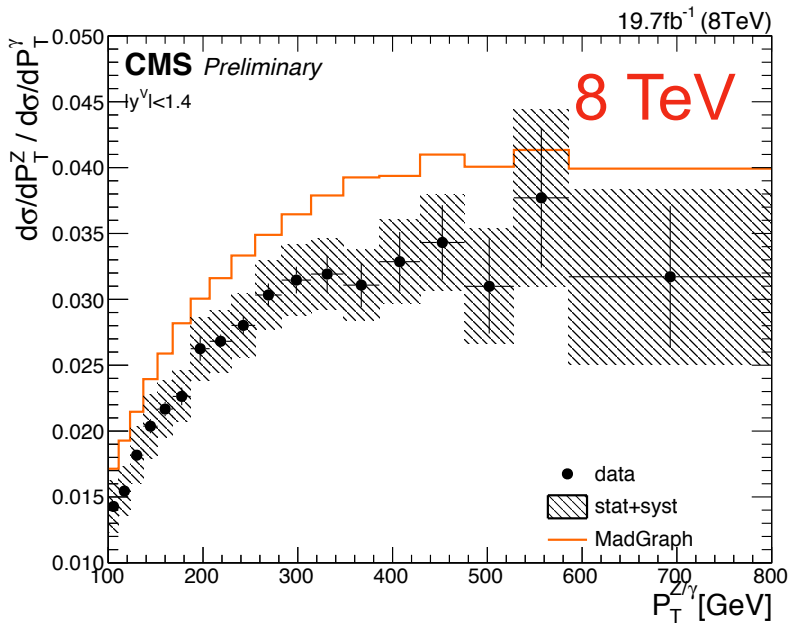


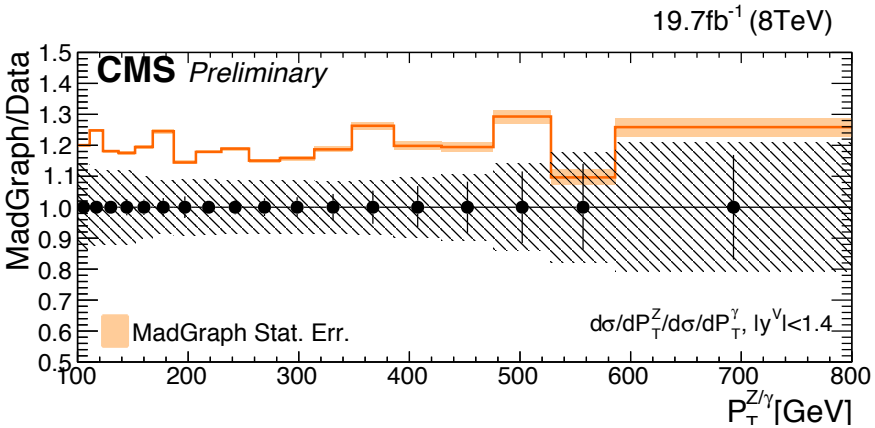
R(Z+jets/γ+jets)

- R(Z+jets/γ+jets)[data] / R(Z+jets/γ+jets)[MC]

CMS-PAS-SMP-14-005

  - Double ratio ~1.2, is flat across all probed p_T [100,800] GeV
  - No evidence for a deviation from flatness within uncertainties
  - Fiducial measurement in agreement with theory
  - MadGraph can describe shape of ratio in p_T but predicts ~20% normalization difference (at LO). Higher order effects are expected to be smaller than experimental uncertainties.



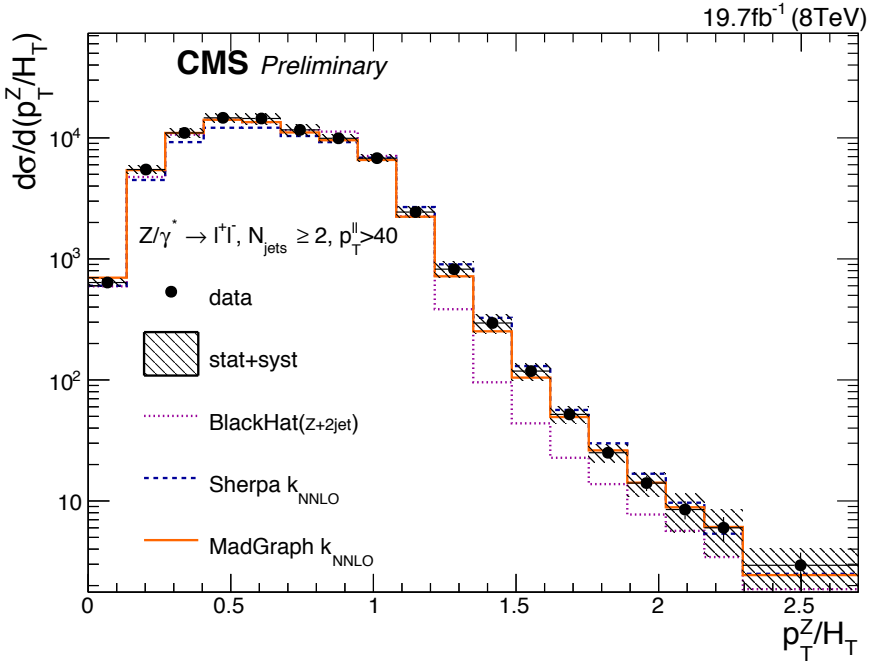


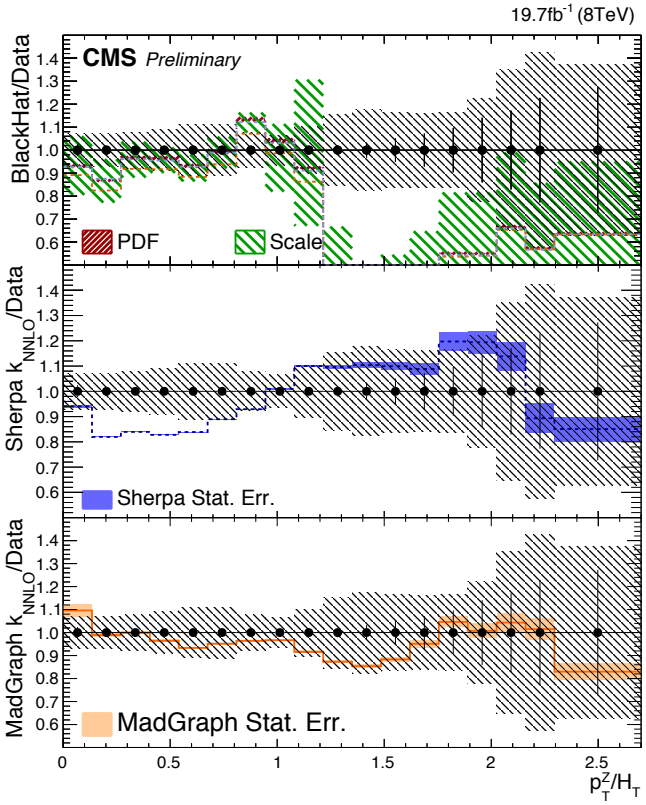
$$R_{\text{dilep}} = \frac{\sigma_{Z\to ll}(p_T^Z > 314\,\text{GeV})}{\sigma_\gamma(p_T^\gamma > 314\,\text{GeV})} = 0.0322 \pm 0.0008(\text{stat}) \pm 0.0020(\text{syst})$$

Z + jets

CMS-PAS-SMP-14-005

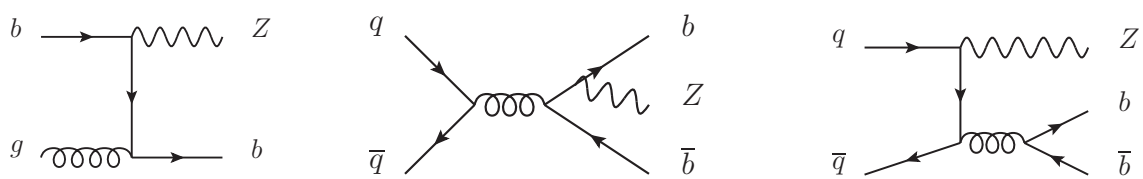
- Bulk of p_T^Z/H_T distribution contain events with Z balanced by hard jets inside acceptance
  - tail includes events with additional radiation outside acceptance
- BlackHat fails to describe data above 1 in ratio due to lack of soft or forward jets, but describes data below 1, indicating no evidence for missing large-log contributions.





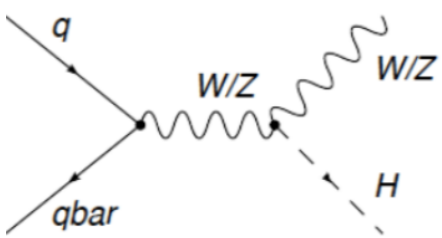
W/Z + b-jets

- Theoretical uncertainties on W/Z+heavy flavour jets are larger than for light jets
  - heavy-quark content in the proton
  - modeling of gluon splitting (initial state, final state)
  - massive vs massless b-quark in calculations

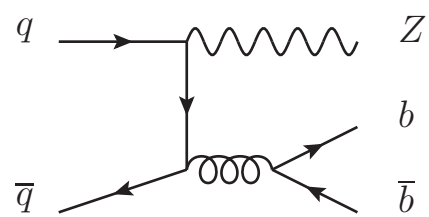


- Very important processes as background to Higgs and searches

Signal



Background



Z + b-jet Production

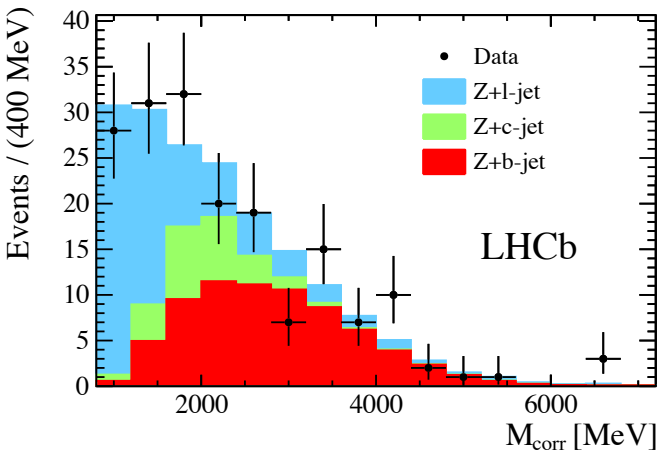
JHEP 01 (2015) 064

Measure Z production cross-section in association with a bottom quark

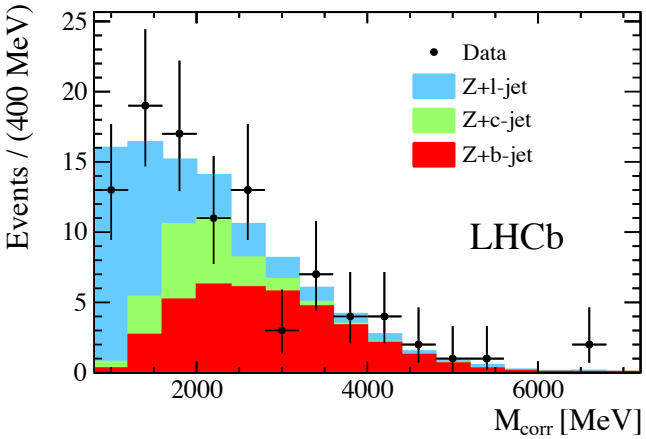
- Normalize to Z+jet measurement
- Complements measurements from ATLAS and CMS with jet p_T>25 GeV and |η|<2.1

- Z: same fiducial acceptance
- Jet:
  - Particle flow: charged tracks; clusters for neutrals,
  - Subtracting charged particle energy deposits
  - Anti-kT clustering algorithm, R=0.5 in standard η range; isolated from muons: $\Delta R(\text{jet},\mu)>0.4$
  - p_T > 10; 20 GeV/c
- b-tag: search for secondary vertices (SV) using 2,3,4 particles in the jet
- Correct mass of SV for missing particles and fit:

$$M_{corr} = \sqrt{M^2 + p^2 \sin^2\theta} + p \sin\theta$$



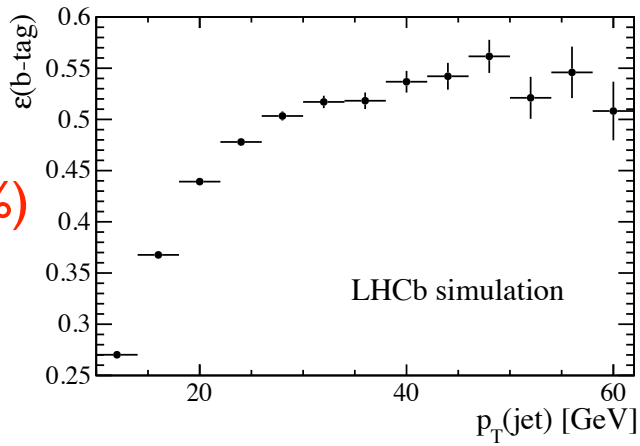
179 candidates with b-tag and p_T>10 GeV/c
72 ± 15 Z+b-jet events
Templates for M_{corr} taken from MC

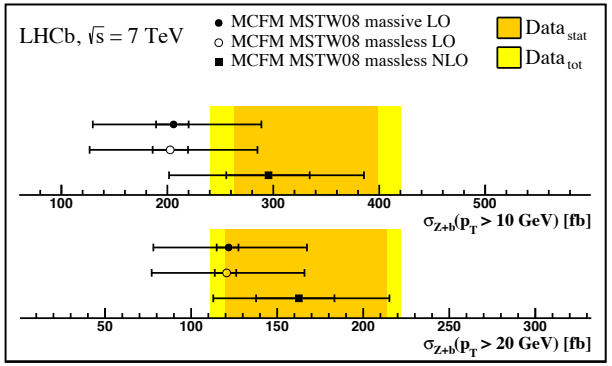


Z + b-jet Production

JHEP 01 (2015) 064

- Efficiencies
  - Assume Z+jet reconstruction inefficiencies
  - Determine b-tagging efficiency(p_T,η) from MC
- Systematic uncertainties
  - Dominated by b-tag and purity determination (15%)
  - Common uncertainties from Z+jet applied (10%)
  - Reconstruction efficiencies differ by 2%
- Results
  - Compare to MCFM calculations using massless (LO, NLO) and massive (LO) b-quarks
  - Correct MCFM predictions for fragmentation and hadronization using Pythia 8

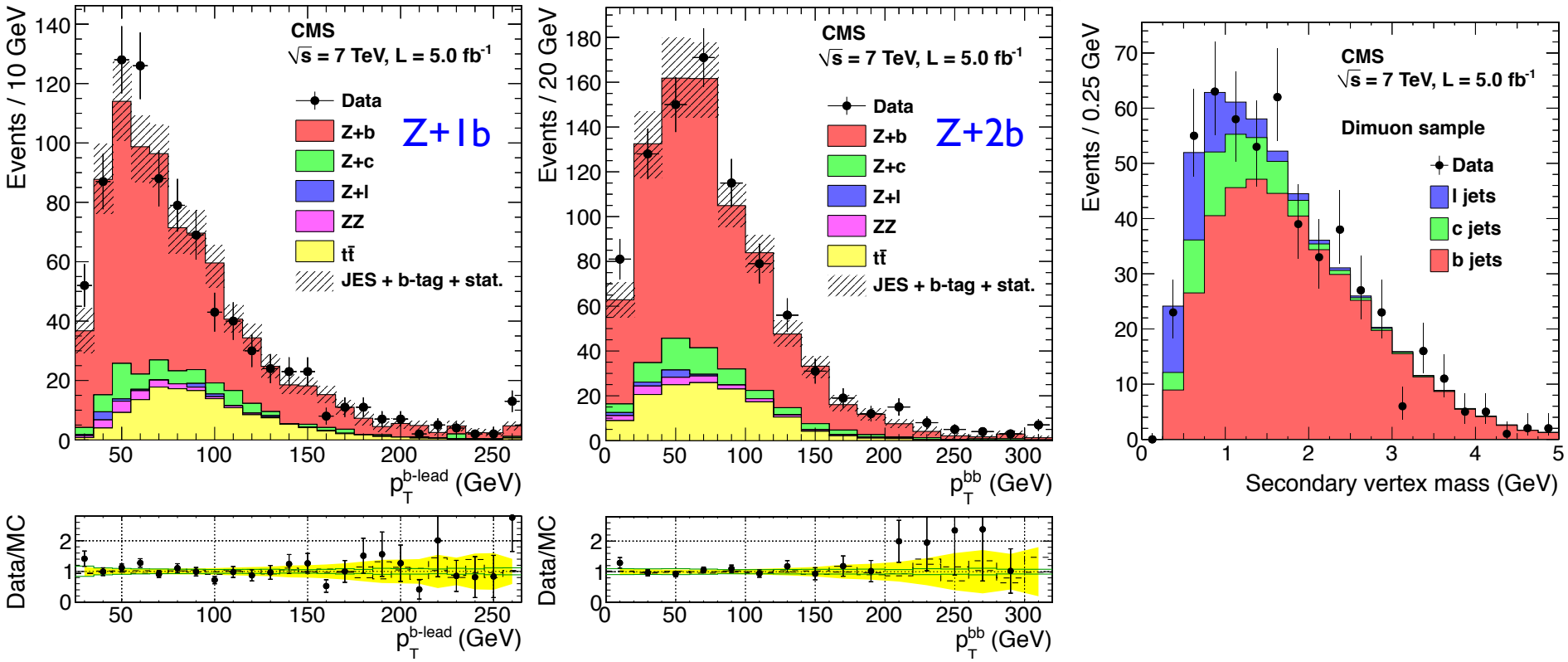




$$\sigma = 295 \pm 60\ (\text{stat.}) \pm 51\ (\text{syst.}) \pm 10\ (\text{lumi.})\ \text{fb}$$

Z + b-jets

JHEP 06 (2014) 120

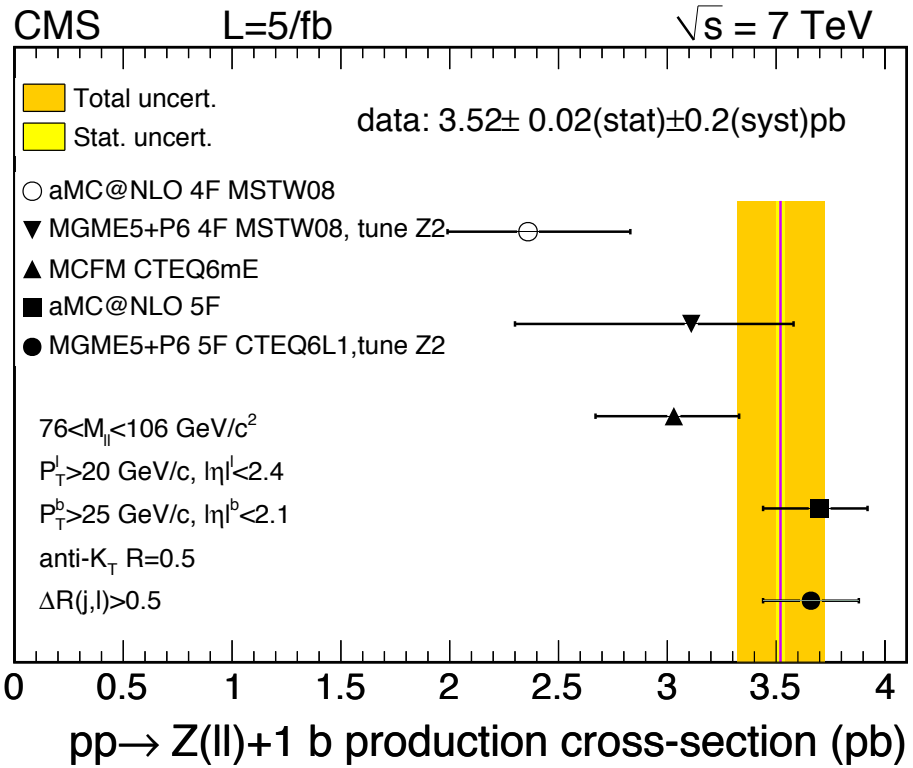


- Z + Jet selection (Jet p_T > 25 GeV)
  - Cut on *MET* < 40 GeV to eliminate top background
- b-tagging: simple secondary vertex algorithm; mistags estimated from template fit to secondary vertex mass
  - Purity/Efficiency from fit to data (2nd vertex mass)

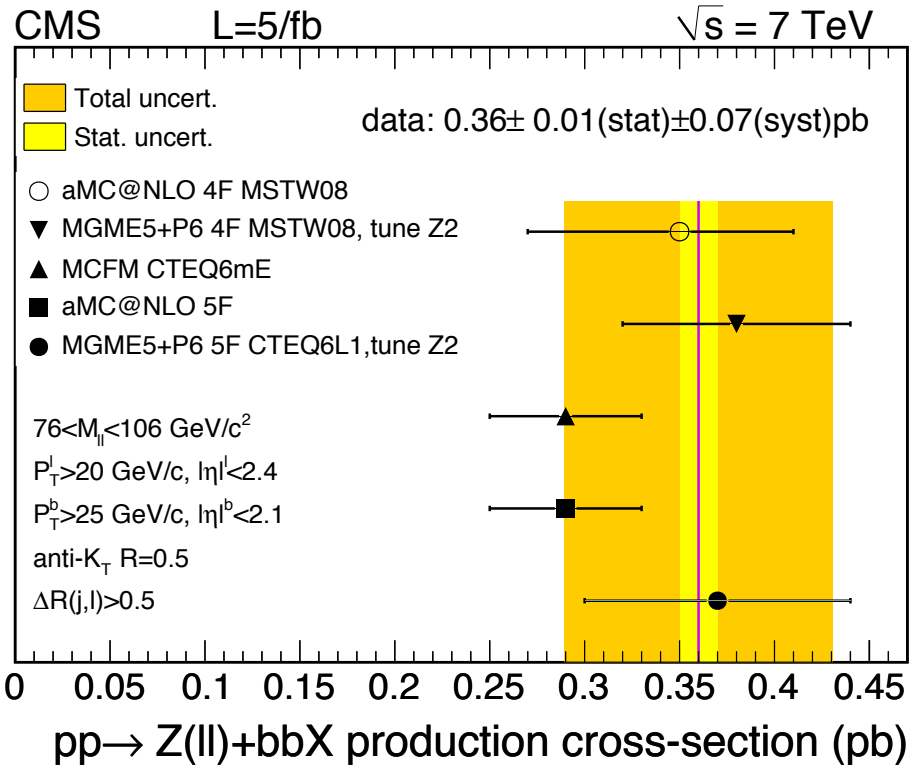
Z + b-jets

JHEP 06 (2014) 120

Z+1b



Z+2b

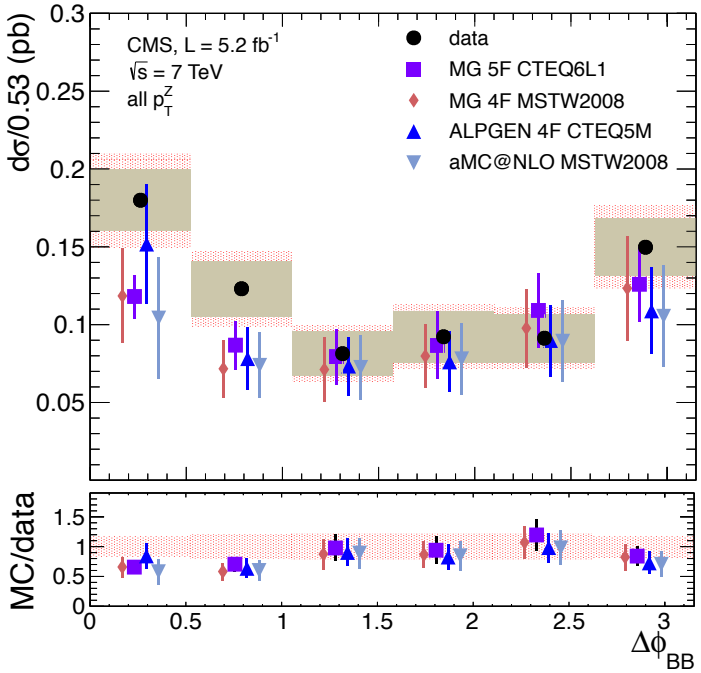


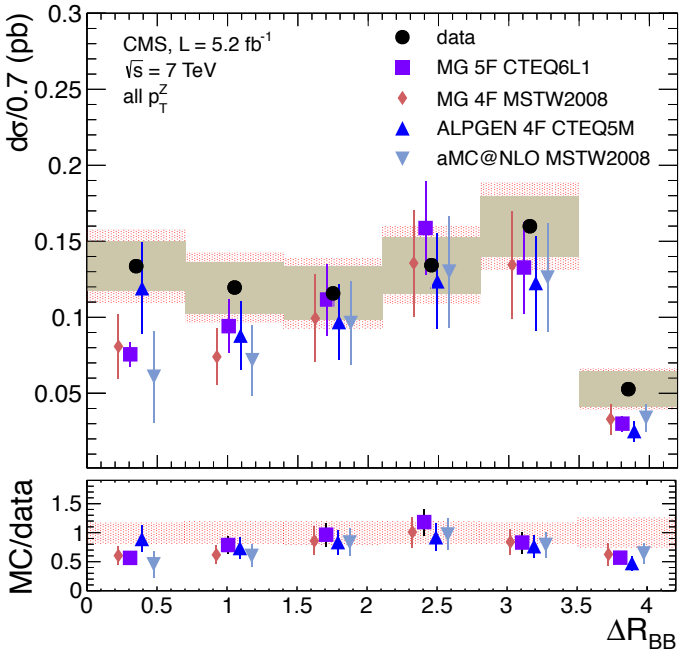
Data in best agreement with 5-flavor NLO predictions

Z + ≥2 b-jets

JHEP 12 (2013) 39

- Inclusive and differential cross sections as function of the angular separation between B hadrons produced in association with a Z
  - B hadrons are identified as displaced secondary vertices without use of jets, which allows to study B-hadron pair production at small angular separation.
  - The production differential cross section as function of the angular separation and boost of the Z boson are compared to several predictions from simulations at tree-level and NLO accuracies.

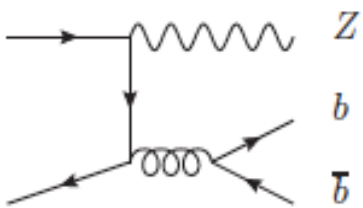




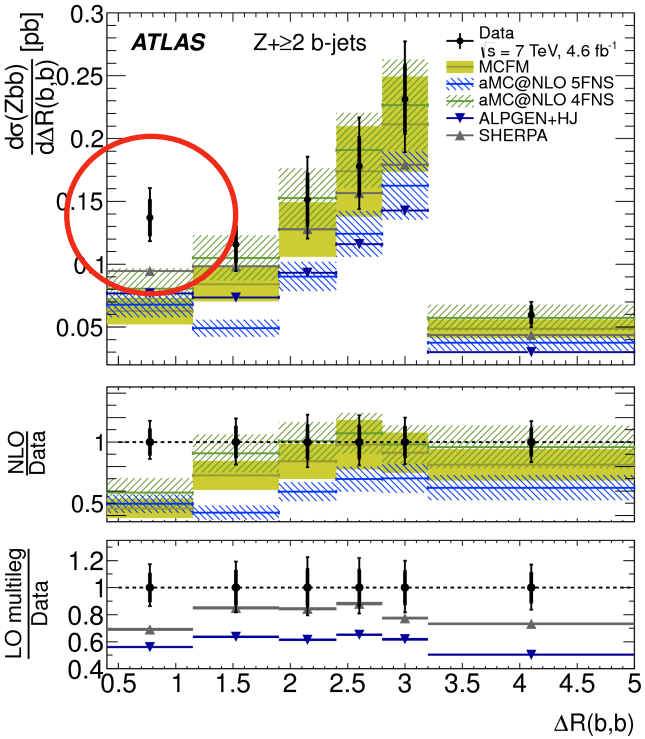
Z + bb

JHEP 10 (2014) 141

- Z+bb data sensitive to different underlying processes
  - Contribution from two hard initial state or final state gluon splitting with resolved b-jets



- Distribution shapes generally well described by predictions
- Except for configurations with nearby b-jets, dominated by gluon splitting
  - Exclusive reconstruction of B-hadrons in Z+ BB avoids limitation of b-jet size radius
  - B-hadrons identified from displaced secondary vertices, reconstructed from charged decay products

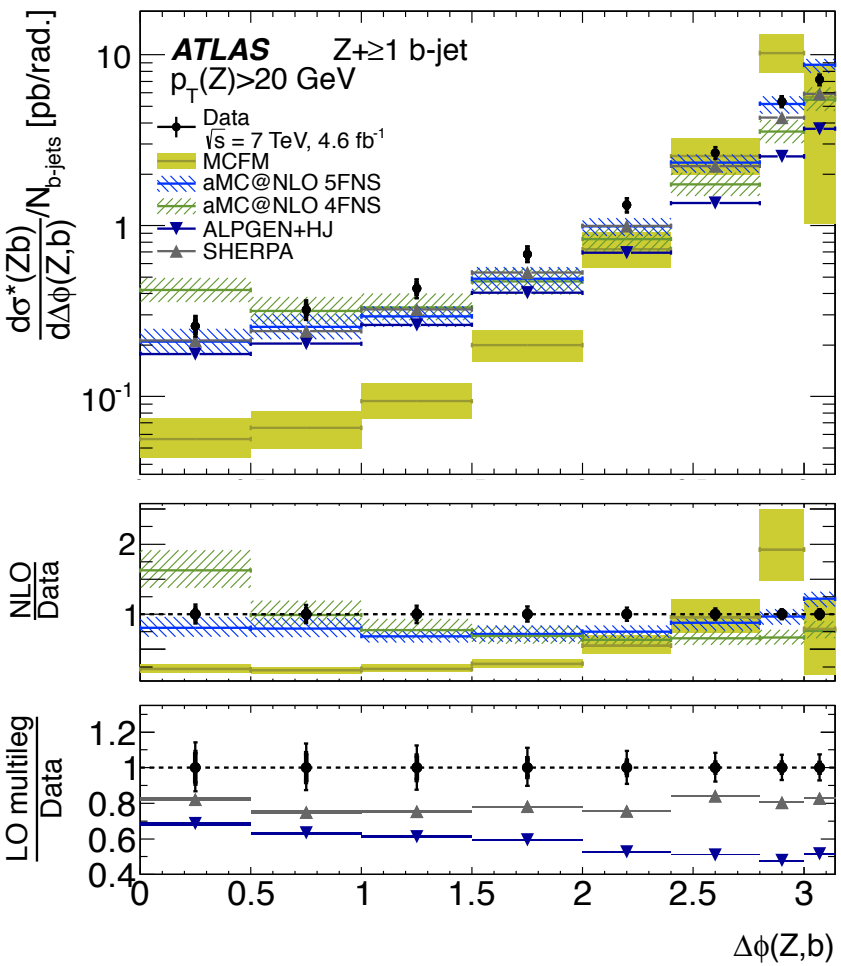


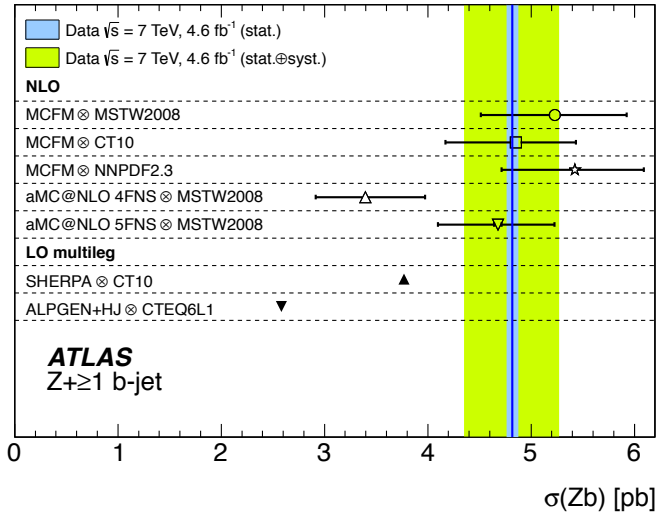
Phase space:
- Lepton p_T>20 GeV, |η|<2.4
- Anti−kT jets: R=0.4, p_T>20 GeV, |y|<2.4
- At least 1 or 2 b-jets
- b-hadron: p_T>15 GeV, |η|<2
- 81< M_{ll} < 101 GeV

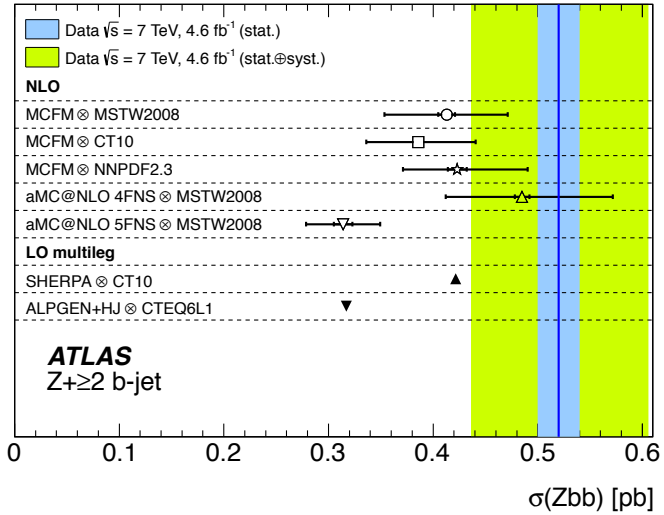
Z + bb

JHEP 10 (2014) 141

- Additional, unfolded differential cross sections in a variety of kinematic variables
- Comparable measurement & theory uncertainties+bb data sensitive to different underlying processes

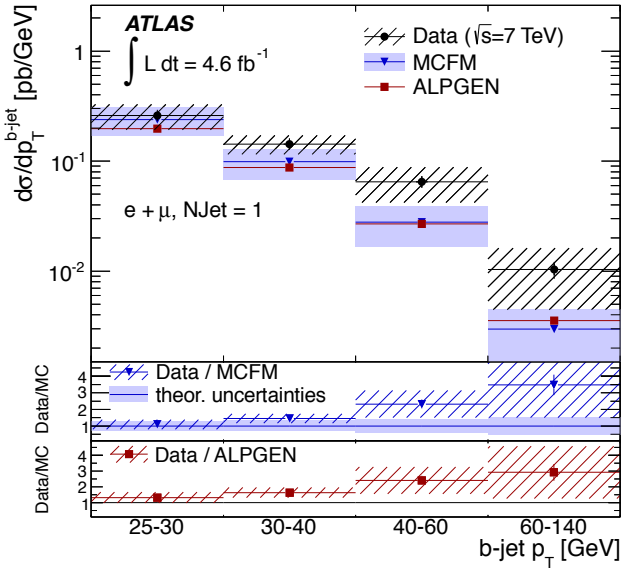


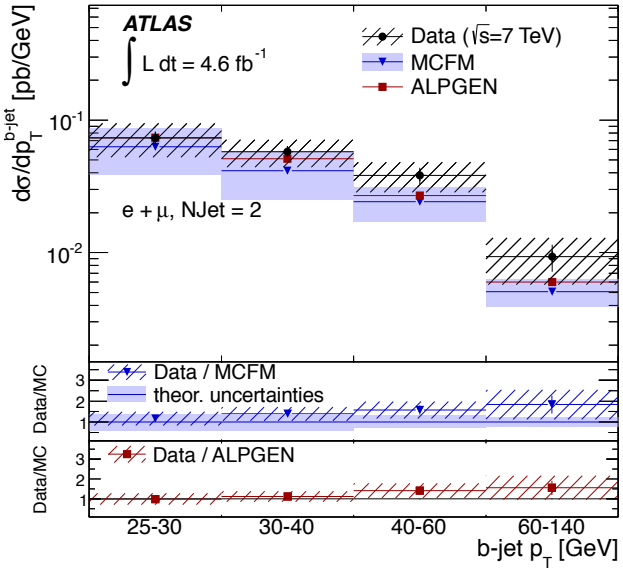


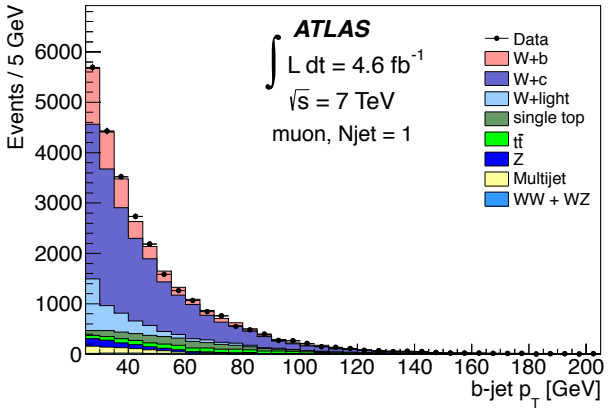


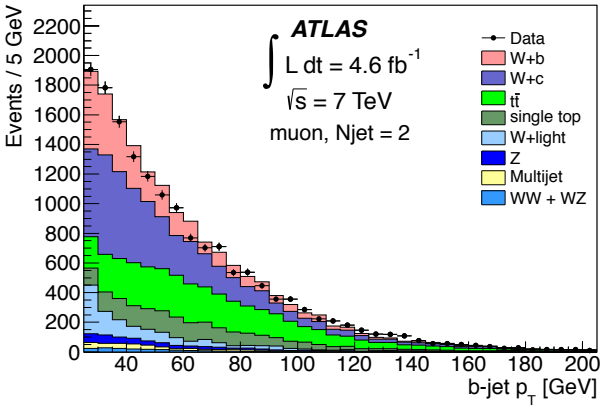
W + b-jets

JHEP 06 (2013) 084



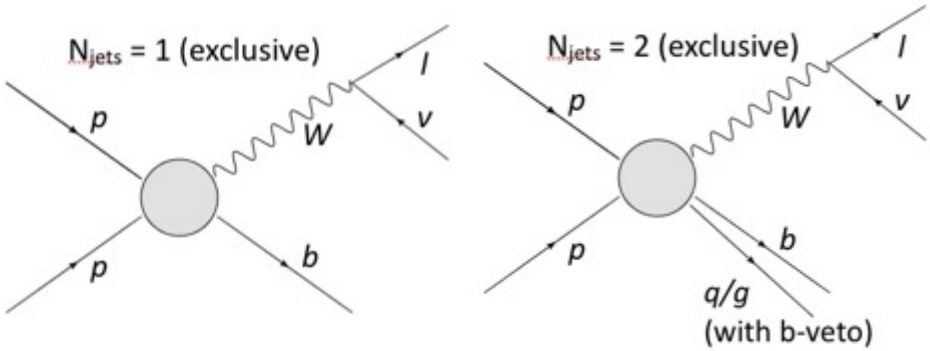




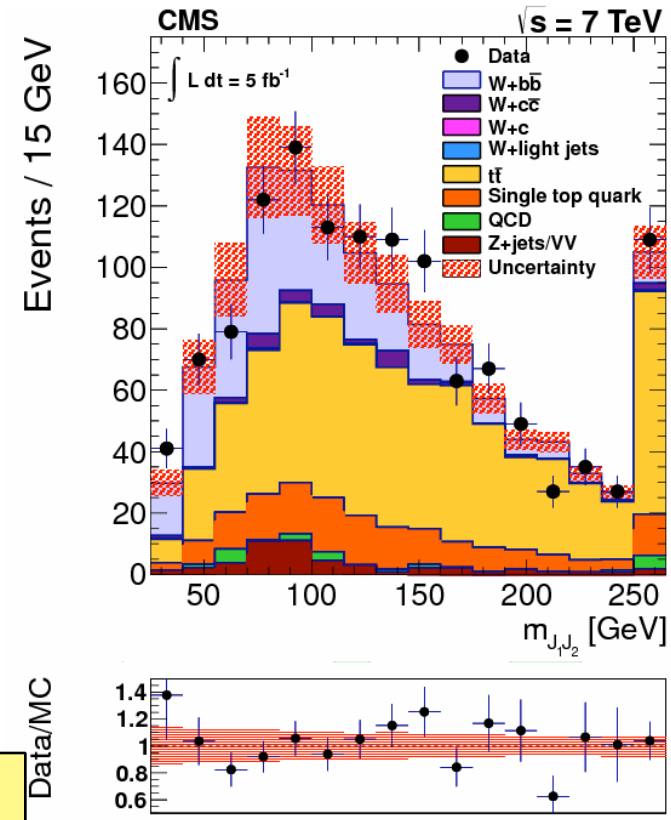


- First measurement of W + 1 b-jet differentially: $d\sigma/dp_T$
- Data/MC increases as function of b-jet p_T
- In the one jet bin, the measurement is systematically higher than the MCFM prediction, but compatible within uncertainties
- In the two jet bin, the measurement is in agreement with the MCFM prediction within uncertainties

W + b-jets



PLB 735 (2014) 204



Measured fiducial cross section

σ (pp → W + bb) × B(W → μν)

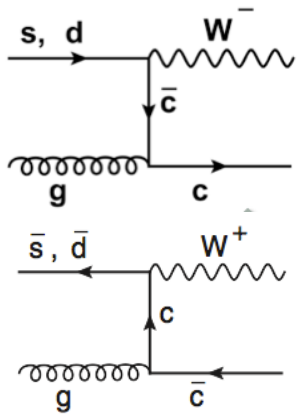
	σ(W→bb)
Data (CMS)	0.53 ± 0.05 stat ± 0.1 sys [pb]
MCFM (MSTW08NNLO)	0.52 ± 0.03 [pb]

Phase Space:

- muon: p_T > 25 GeV, |η| < 2.1
- exactly two anti-kT jets with R=0.5, p_T > 25 GeV and |η| < 2.4 and with each containing at least one b hadron with p_T > 5 GeV.
- Events with extra jets with p_T > 25 GeV and |η| < 4.5 are vetoed.

W + c

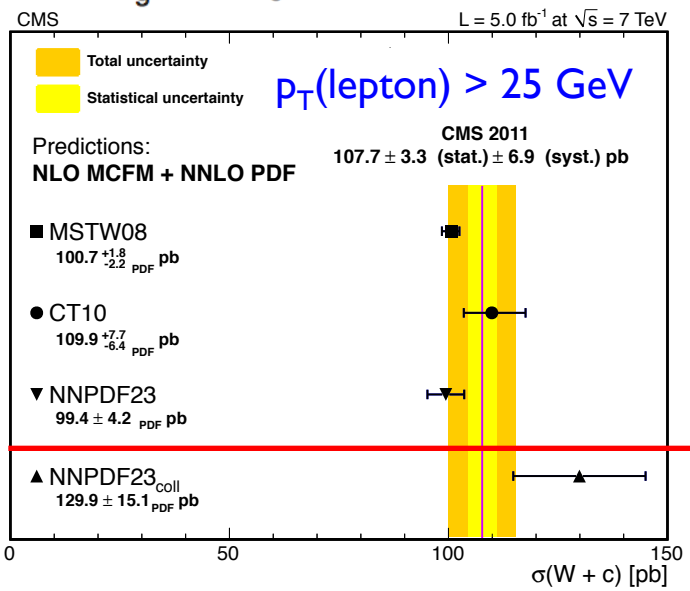
JHEP 02 (2014) 013

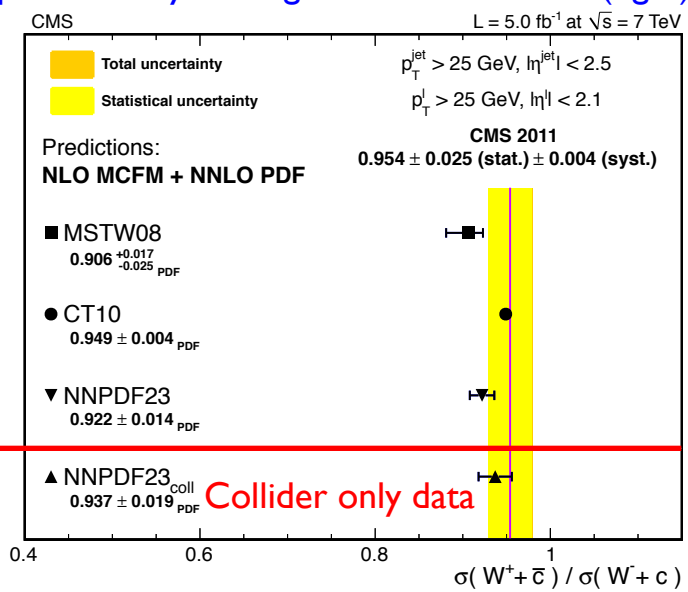


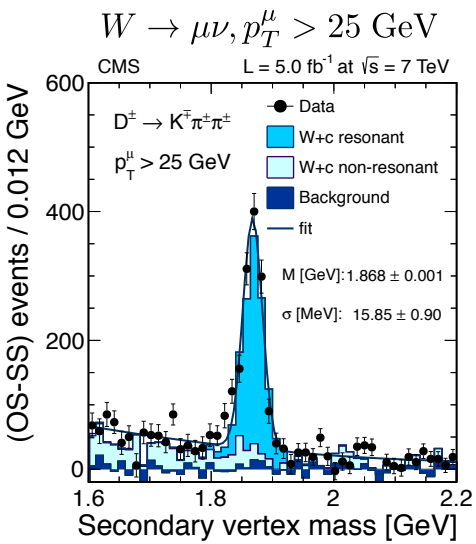
In W+c events the charge of the **W** (and the lepton) and the charge of the **c quark** are of **opposite sign**

W→lν + a leading jet with charm content, identified as:

- Displaced secondary vertex with 3 tracks, consistent with a $D^{\pm}$ decay
- Displaced secondary vertex with 2 tracks, consistent with a D^0 decay associated to a previous D* decay
- Semi-leptonic decay leading to a well identified (tight) muon





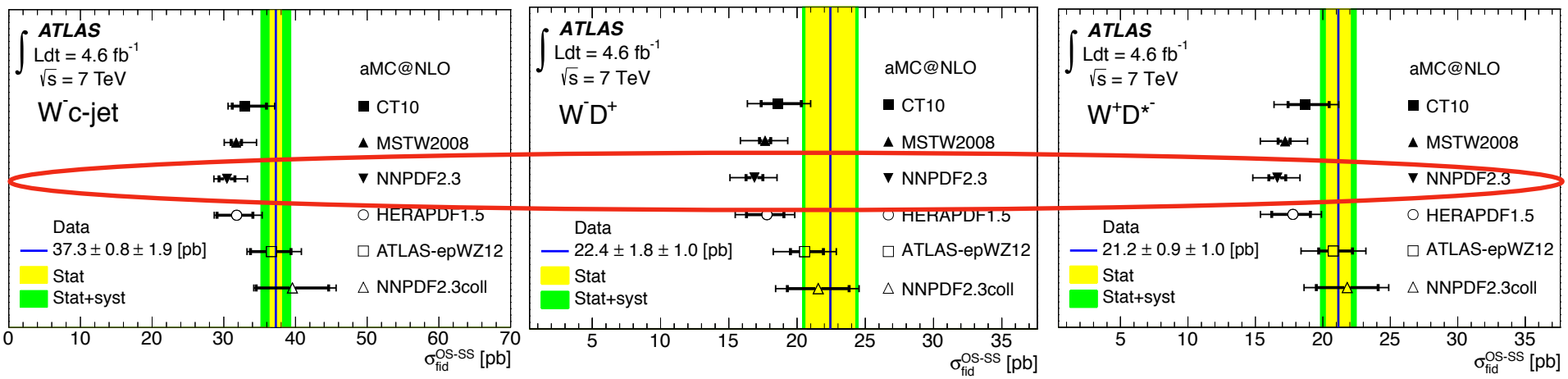


- σ(W+c−jet) sensitive to strange content of the proton
- PDF with collider data only predict a symmetric light sea, but with large uncertainty
  - In agreement with data within 1σ
- Results used (together with W charge asymmetry) for PDFs extraction

W + c

JHEP 05 (2014) 068

- The integrated and differential cross sections as a function of the pseudorapidity of the lepton from the W-boson decay are measured.
- Two methods are used to tag the charm quark: either the presence of a muon from semileptonic charm decay within a hadronic jet or the presence of a charged D or D* meson.



The ratio of the strange-to-down sea-quark distributions is found to be enhanced and compatible with 1, which supports the hypothesis of an SU(3)-symmetric composition of the light-quark sea.

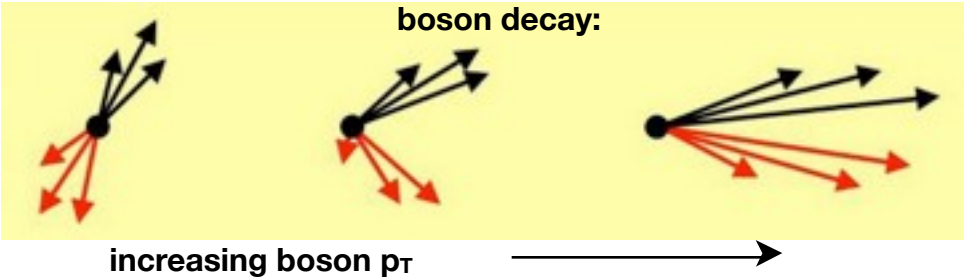
Slight tension between ATLAS and CMS on strange quark PDF.

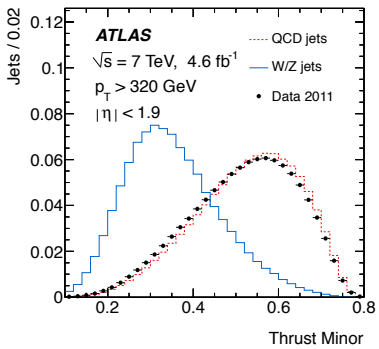
W/Z reconstructed as single jets

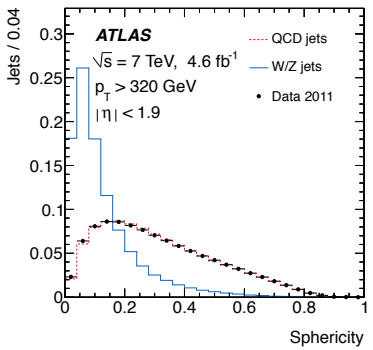
J. Phys. 16 (2014) 113013

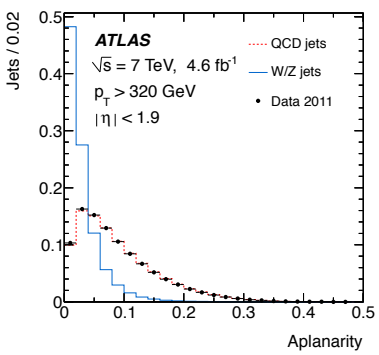
- New heavy resonances can decay to highly boosted W and Z bosons.
- Proof of principle that W and Z hadronic decay products can be distinguished from partonic jets
- Hadronically decaying W and Z bosons reconstructed as broad single jets with p_T>320 GeV and |η|<1.9, in pp collisions at $\sqrt{s}$=7 TeV.
  - anti-k_T clustering algorithm with R=0.6
- Likelihood discriminant derived from three jet shape variables
  - thrust minor
  - sphericity
  - aplanarity
- **Result:** $\sigma_{W+Z} = 8.5 \pm 0.8\,(\text{stat.}) \pm 1.5\,(\text{syst.})\ \text{pb}$

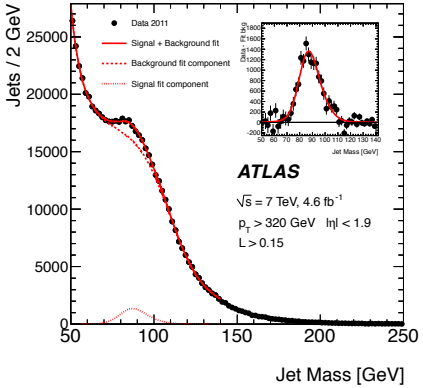
NLO QCD prediction: $\sigma_{W+Z} = 5.1 \pm 0.5\,\text{pb}$











Summary

- Several Run I results have been produced on V+jets exploiting the p-p datasets at 7 TeV (2011) and 8 TeV (2012).
- Good understanding of perturbative QCD calculations and proton PDFs is the key to success in physics analyses at $\sqrt{s}$ = 13 TeV.
- No major excursions of data from predictions; but many measurements that MC theorists can dig into.
- In general the NLO calculations merged with PS yield the best description of data and are becoming a standard
  - Leading edge calculations, performs better as expected, but with known limitations due to the lack of PS
  - In some cases LO+PS gives a better prediction
- Run II will continue to provide precision measurements in kinematic regions where new physics will be searched for.
  - Stay tuned for Run II