Inclusive W, Z and W/Z+jets Production at the LHC

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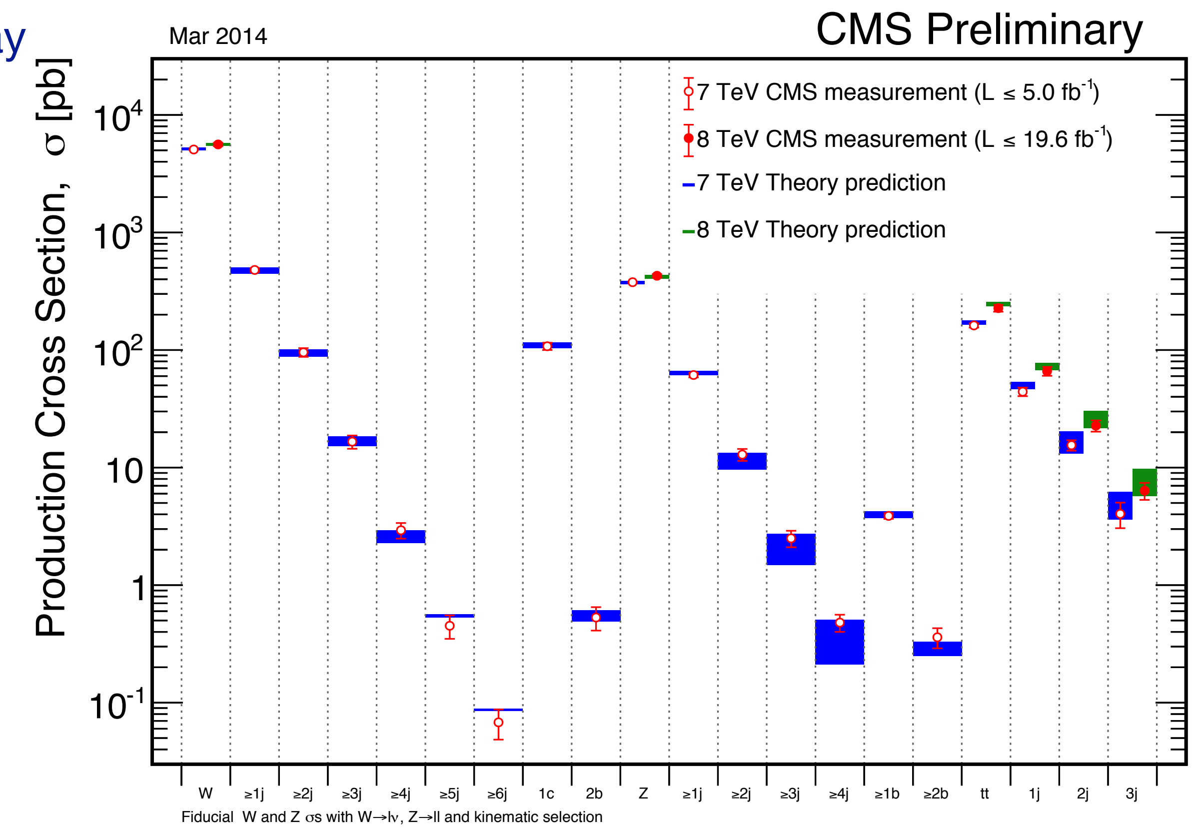
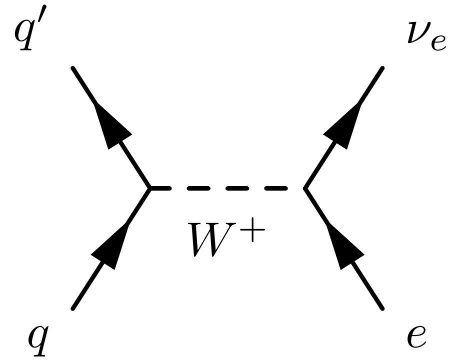
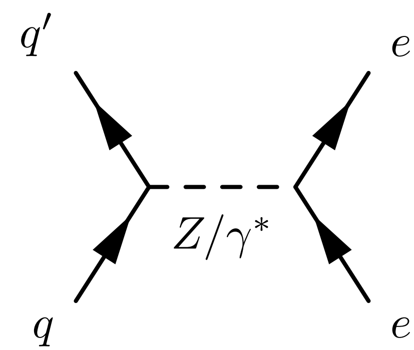
Introduction

- Studies of Vector boson production play several important roles in the physics program of the LHC:
  - Provide important tests of QCD calculations.
  - Constrain parton distribution functions.
  - Non-negligible backgrounds for many searches.
  - Valuable control samples.
- First time probing:
  - Jet multiplicities up to 7.
  - Jet p_T in TeV range.
- V+jets cross sections span 5 orders of magnitude.
- Will summarize a selection of recent results.

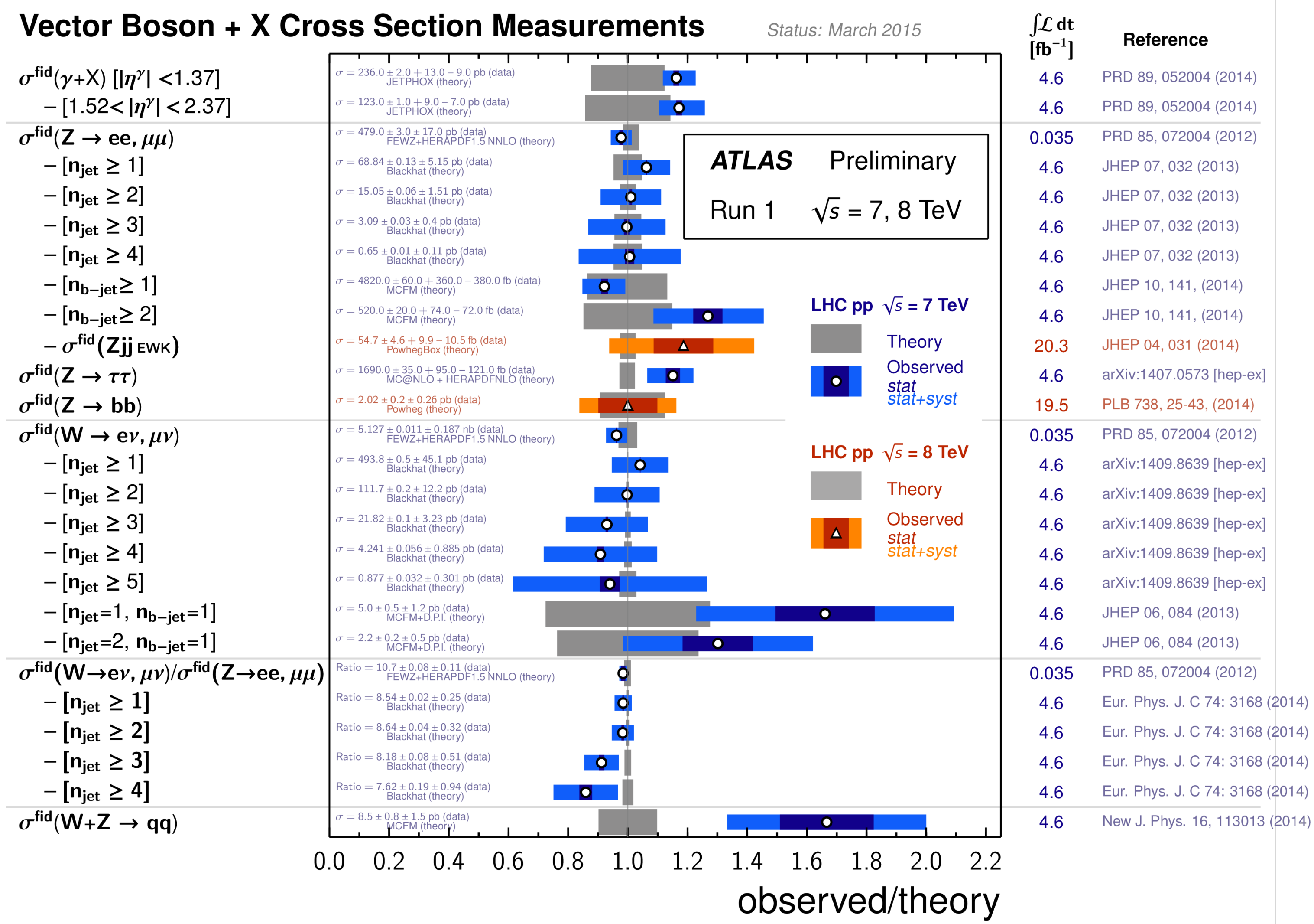






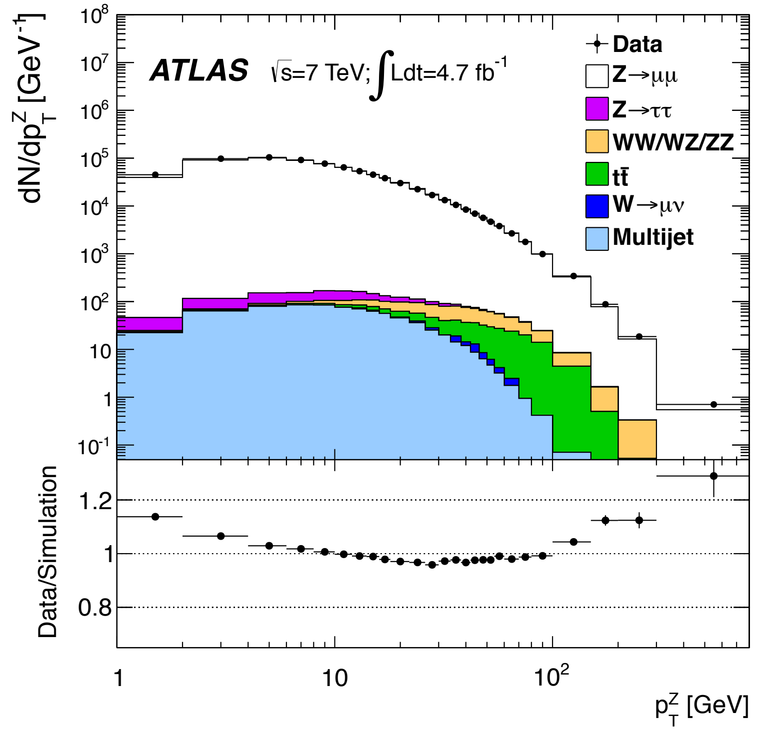
Introduction

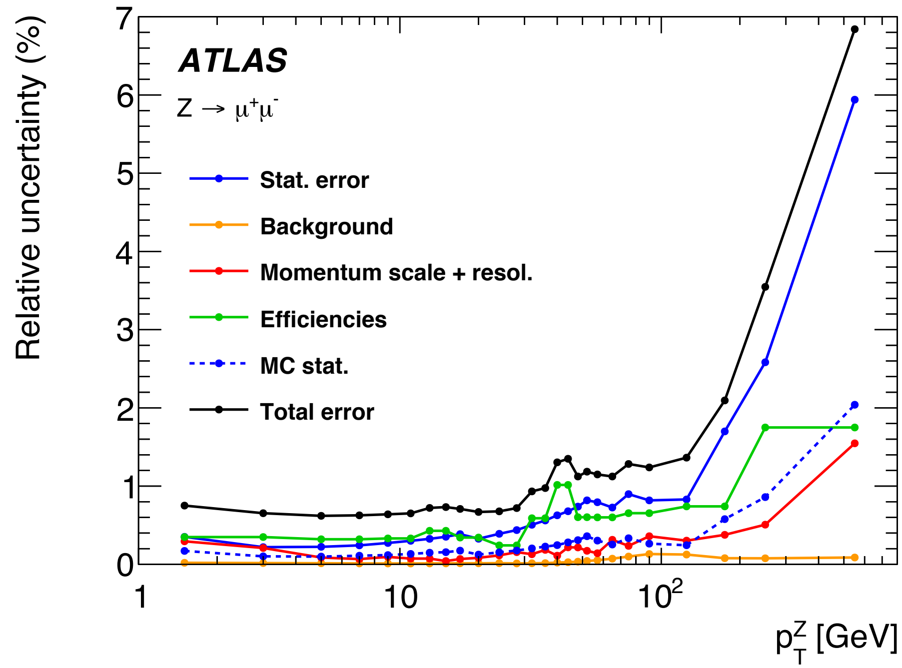
- Recent advances in predictions:
  - New higher-multiplicity calculations at NLO available in recent years
  - Many aspects need data to validate and tune, e.g. choice of scale, matrix element/parton shower matching, flavor schemes
- Overall good agreement over many measurements and jet multiplicities



Z p_T

- Sensitive to ISR, intrinsic p_T of partons at low p_T, and pQCD at high p_T
- Useful to constrain parton shower parameters
- Needed for W mass measurement
- After background subtraction, data unfolded in |y|<1, 1<|y|<2, & 2<|y|<2.4 regions
- Uncertainties ~1% for p_T < 100 GeV
- Used to tune parton shower model in generators





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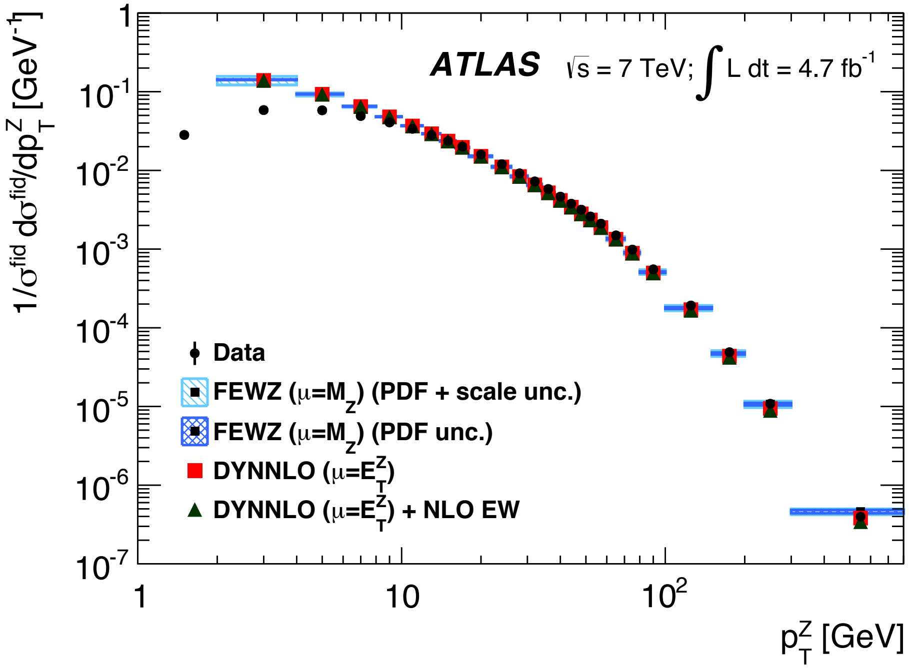
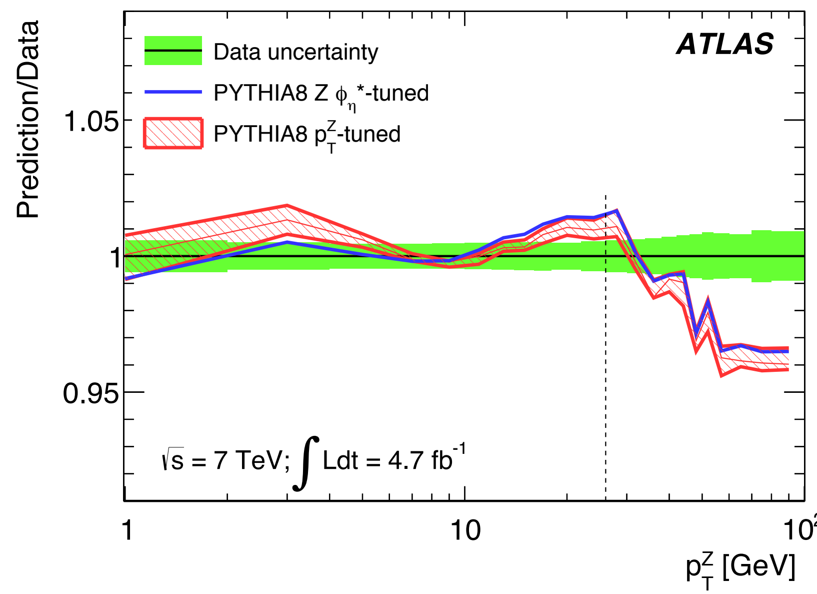
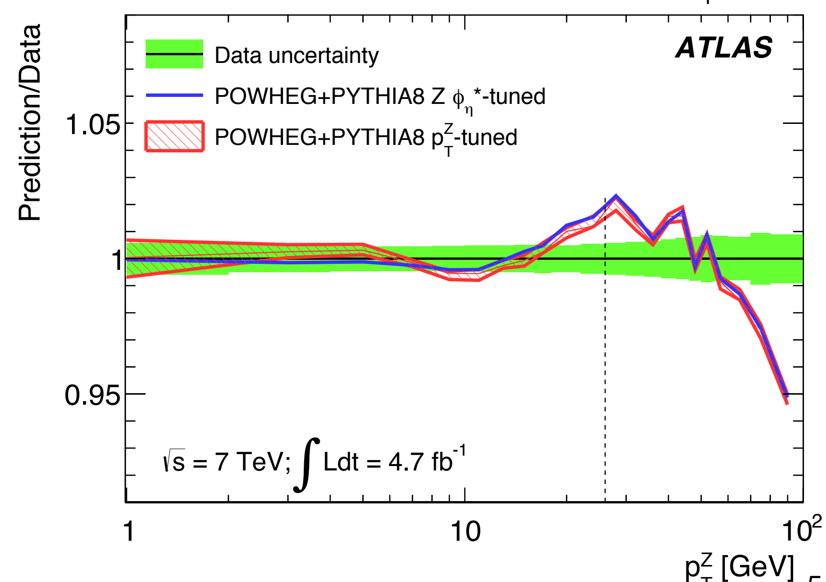
Z p_T





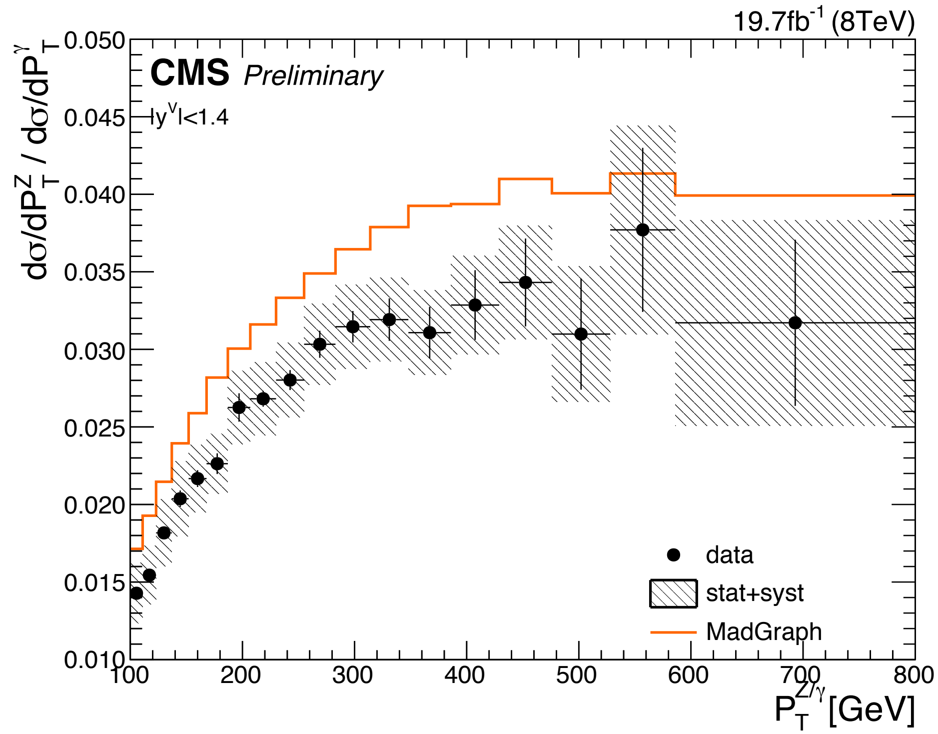


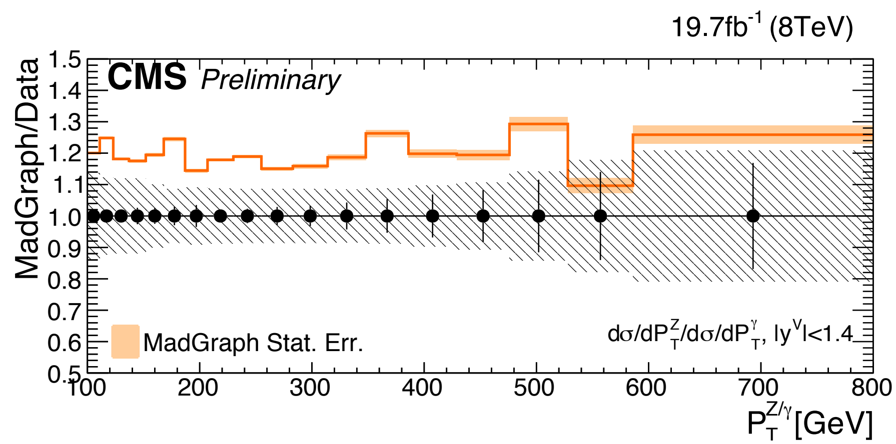
- Overall good agreement with predictions; see a few known features of predictions
- Unfolded results used to tune Pythia8 and Powheg+Pythia8 parton shower
- Tuned predictions agree to within 2% in range used for tuning

	Pythia8	Powheg+Pythia8	Base tune
Tune Name	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_S^{ISR}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-

(Z+γ*)/γ Ratio

- Ratio expected to be constant in limit of high p_T where Z mass term can be neglected - plateau at high p_T
- Provides information useful to inform about possible log contributions in calculations at higher p_T
- Analysis performed for $p_T(Z/\gamma) > 100$ GeV and then four kinematic regimes considered: nJets ≥ 1, 2, 3, and $H_T > 100$ GeV
- Result compared to LO MadGraph+Pythia6 prediction
- Observe ~20% normalization difference in ratio. Higher-order corrections expected to be smaller than experimental uncertainties





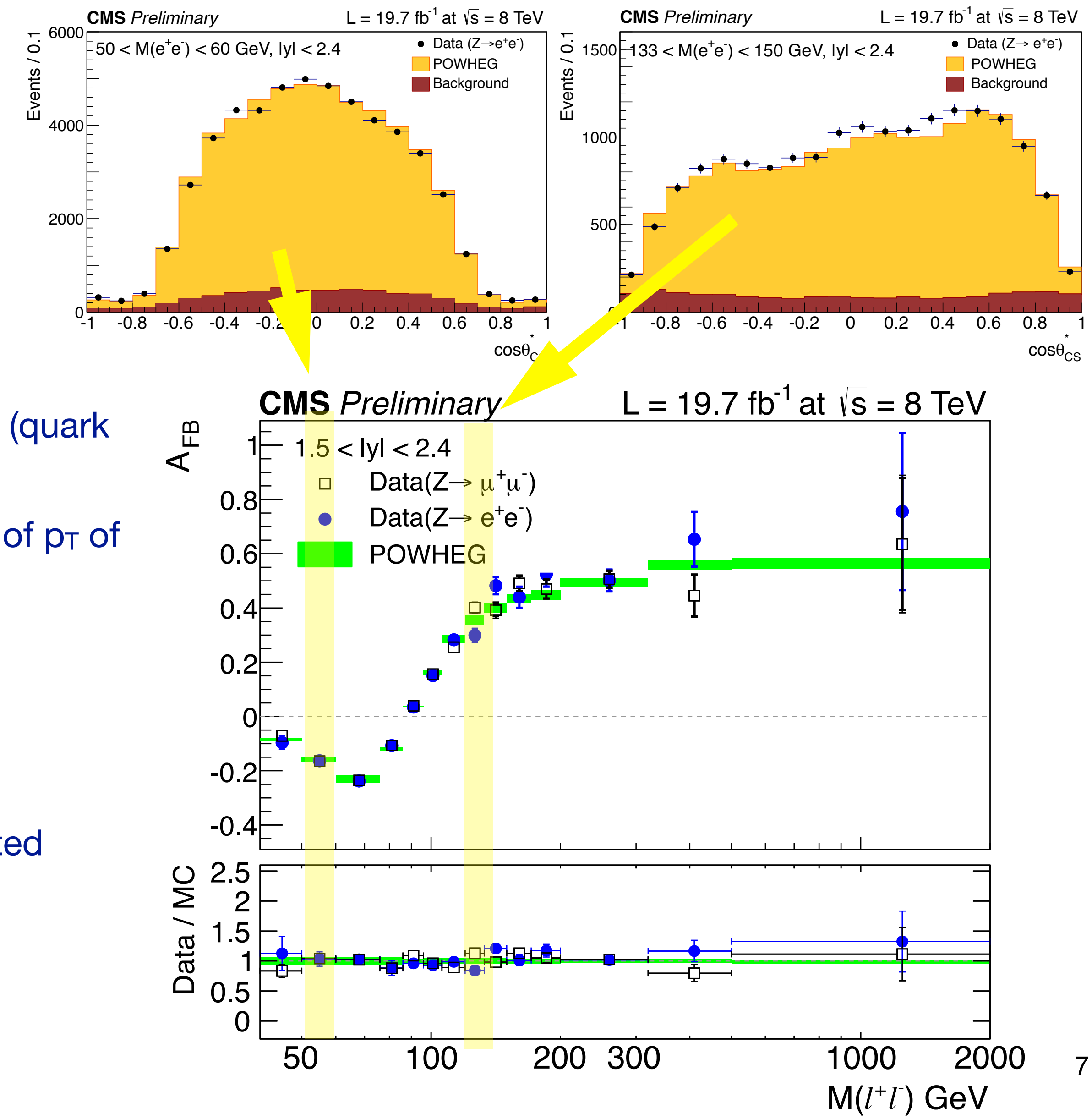
CMS-PAS-SMP-14-005

Drell-Yan A_{FB}

$$\frac{d\sigma}{d(\cos\theta)} = A(1+\cos^2\theta) + B\cos\theta$$

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Sensitive to $\sin^2\theta_W$
- “Forward” direction most likely to be along direction of Z boson z-momentum direction (quark vs. gluon PDF)
- Collins-Soper frame used to reduce effects of p_T of incoming quarks
- Weak-EM interference — Expect:
  - AFB < 0 below Z pole
  - AFB > 0 above Z pole
- Interference from NP would alter the expected asymmetry



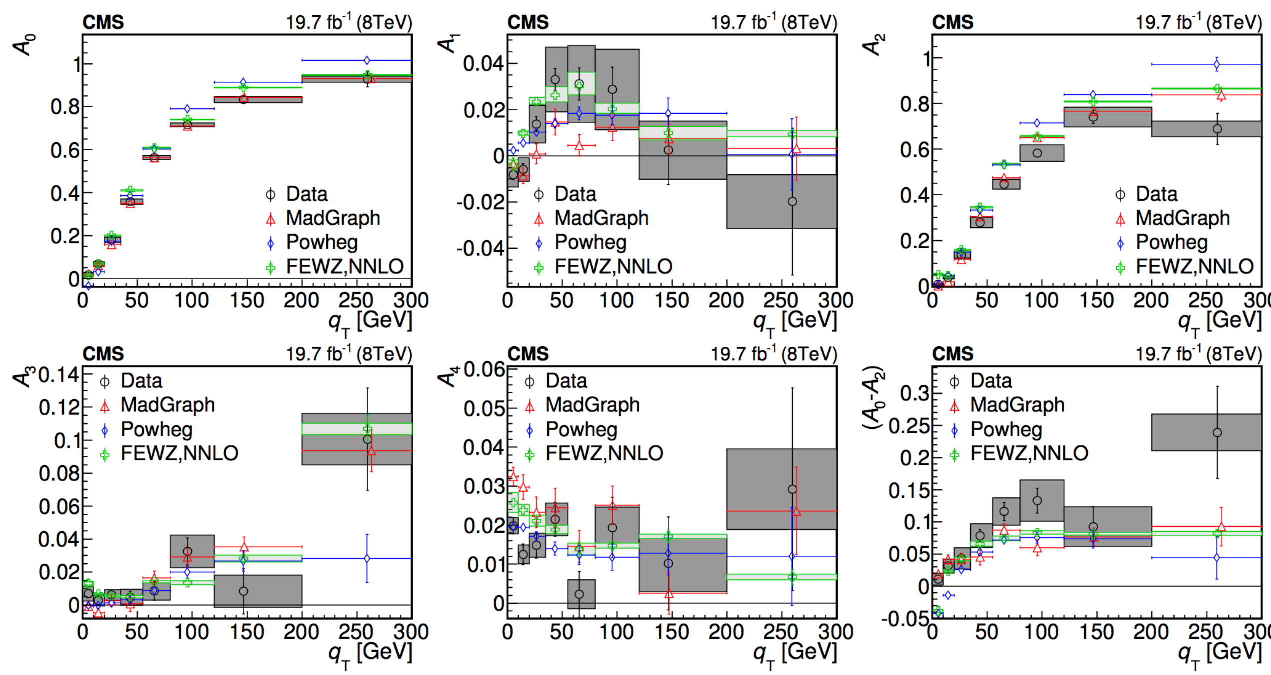
CMS-PAS-SMP-14-004

Atlas 7TeV Sin2thetaW: CERN-PH-EP-2014-259

Z Angular Coefficients

$$\frac{d^2\sigma}{d\cos\theta^* d\phi^*} \propto \left[(1+\cos^2\theta^*) + A_0\frac{1}{2}(1-3\cos^2\theta^*) + A_1\sin(2\theta^*)\cos\phi^* + A_2\frac{1}{2}\sin^2\theta^*\cos(2\phi^*)\right.$$
$$\left. + A_3\sin\theta^*\cos\phi^* + A_4\cos\theta^* + A_5\sin^2\theta^*\sin(2\phi^*) + A_6\sin(2\theta^*)\sin\phi^* + A_7\sin\theta^*\sin\phi^*\right].$$

- First measurement at LHC
- Play important role in future measurements of W mass and weak mixing angle
- $A_i(q_T)$ are related to Z polarization, V-A structure of fermion-boson couplings, and electroweak parity violation
- Template fits for A_0-A_4 performed in Collins-Soper frame
- Performed as a function of boson transverse momentum q_T and rapidity y
- $A_0(q_T)$ and $A_2(q_T)$ larger than in ppbar collisions due to qg process at LHC
- Results compared to a variety of calculations and used to improve predictions

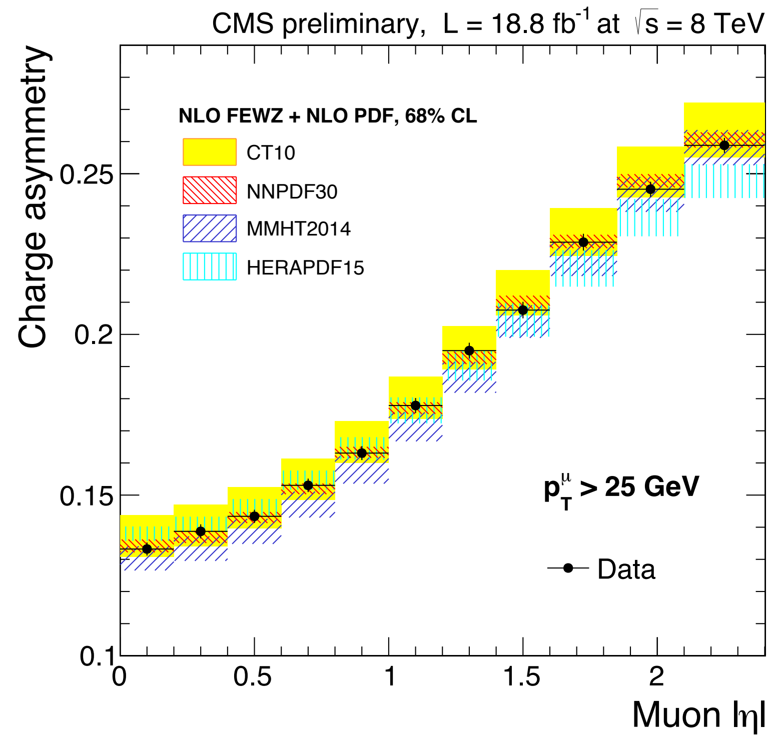


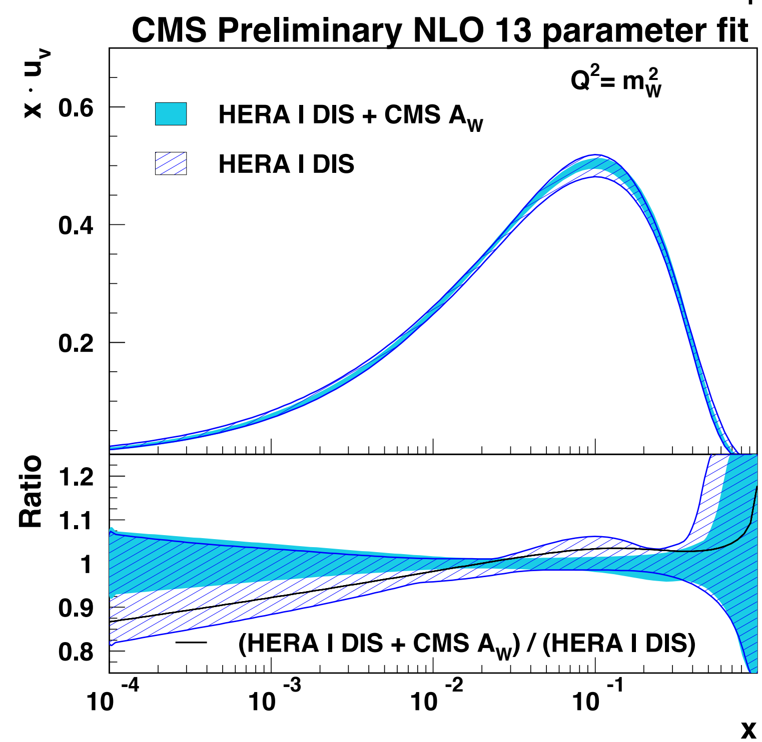
CERN-PH-EP-2015-046

W Asymmetry

$$\mathcal{A}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu})}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\nu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\bar{\nu})}$$

- W^+ produced more than W^- in pp collisions
- Sensitive to both valence and sea quark Parton Distribution Functions
- Measured as a function of η_μ
- Asymmetry corrected for different efficiencies for μ^+ and μ^-
- Result used along with HERA data to improve valence quark PDFs

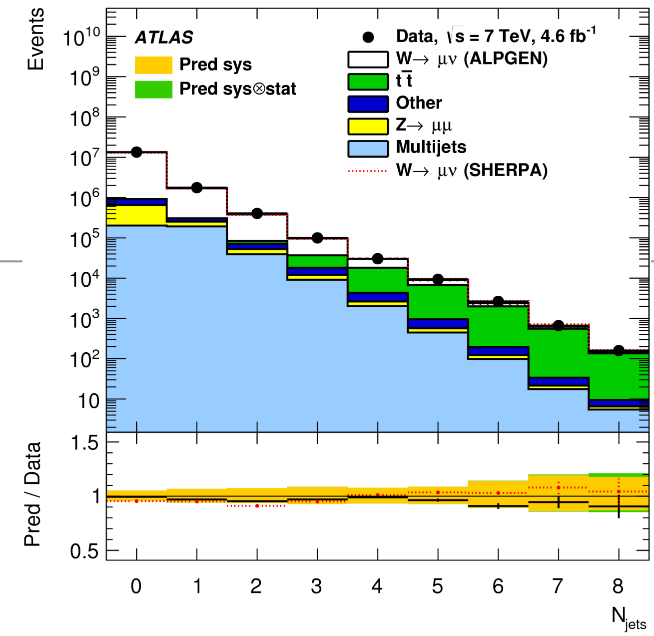


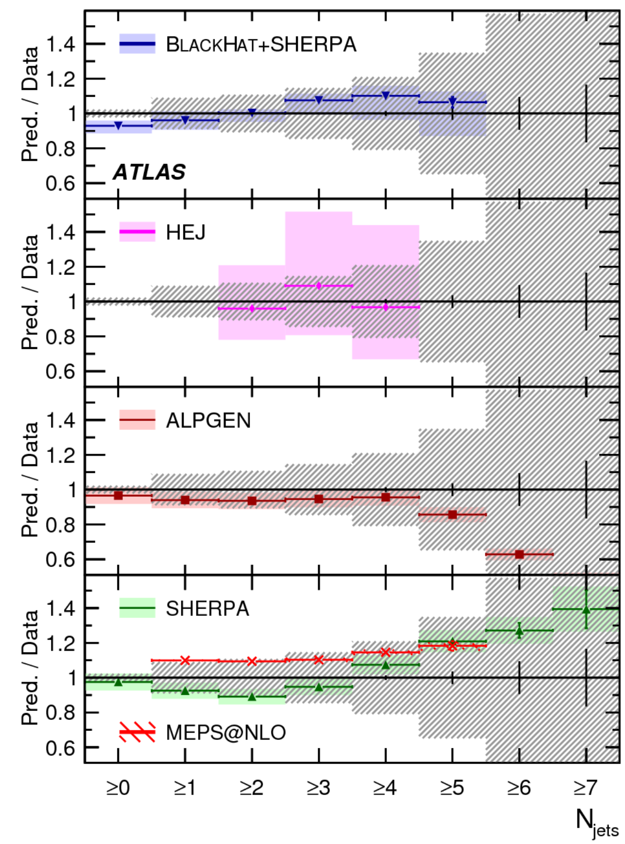


CMS-PAS-SMP-14-022

W+Jets

- Useful to validate pQCD calculations over large kinematic range
- Dominant background for many SM measurements and Exotica searches
- Unfolded to particle level up to 7 jets
- Differential distributions studied for approximately 40 observables
- Data are compared with variety of NLO predictions
- Signal and Background modeled with MC, except for data-driven ttbar and multijet estimates
- Electron and Muon channels show agreement and are combined



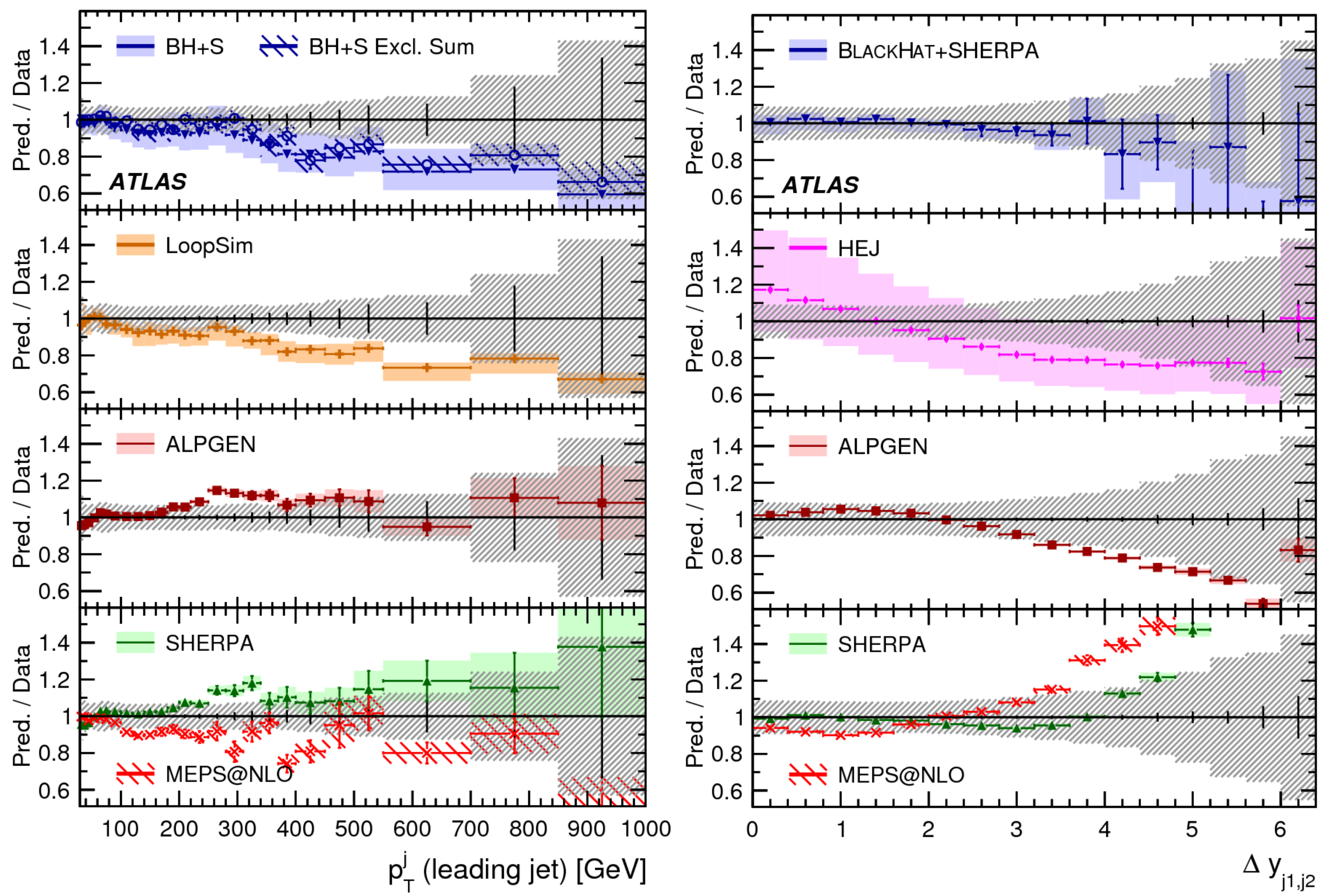


Eur. Phys. J. C (2015) 75:82

CMS 7 TeV: Phys. Lett. B 741 (2015) 12

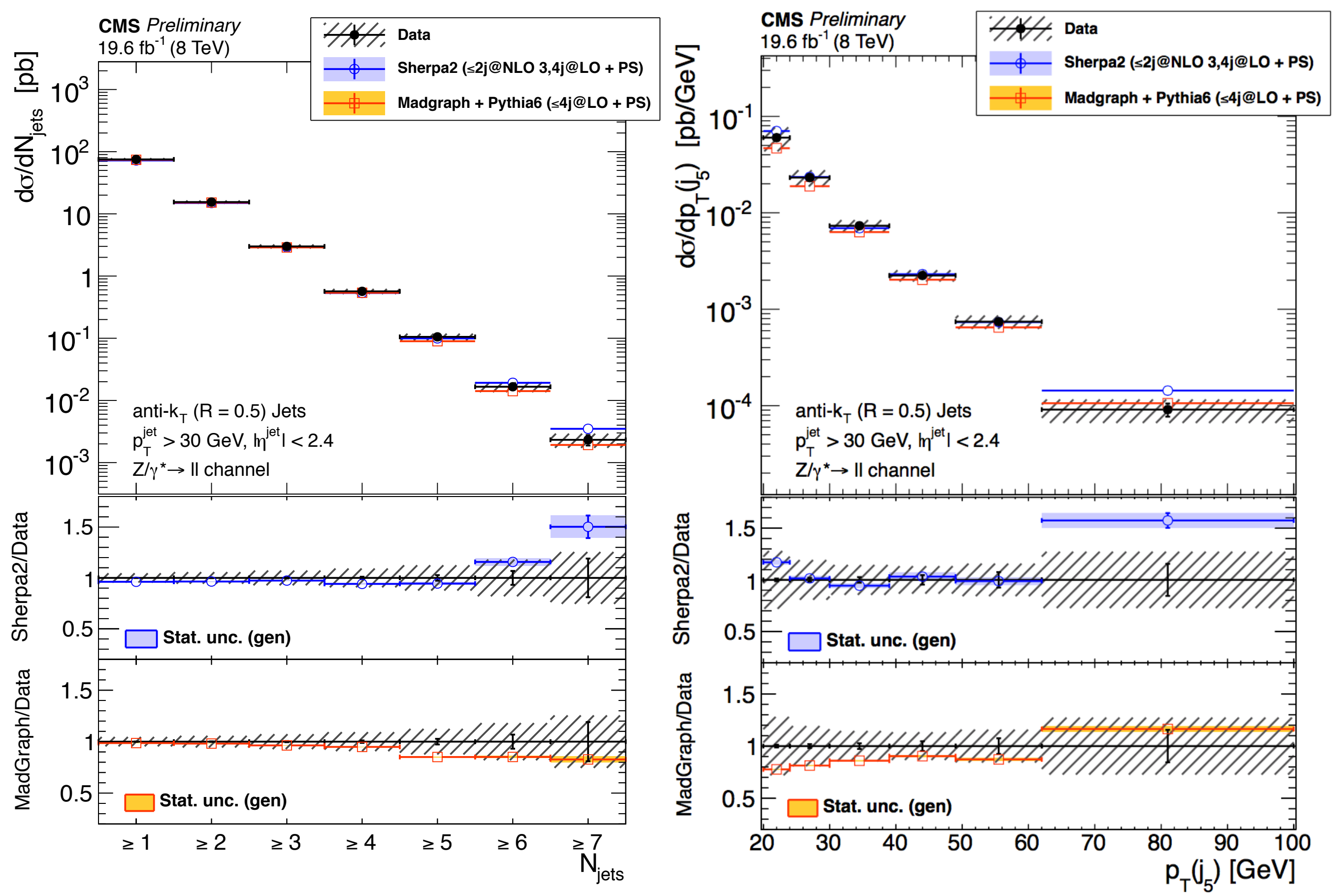
W+Jets

- Large statistics sample allows thorough exploration of many distributions
- Jet p_T explored to 1 TeV
- Various predictions show better agreement in different kinematic observables
- Valuable comparison between data and predictions for Monte Carlo developers
- Level of agreement varies somewhat across observables and predictions



Z+jets

- Useful to validate pQCD calculations over large kinematic range
- Background for many SM measurements and Exotica searches
- Full 8 TeV 20/fb dataset allows comparison over 20+ observables
- Predictions from MadGraph +Pythia normalized to NNLO from FEWZ and Sherpa2+Blackhat for 1-loop corrections
- Unfolded differential distributions in inclusive and exclusive jet multiplicities, p_T, H_T, eta, for nJets up to 5



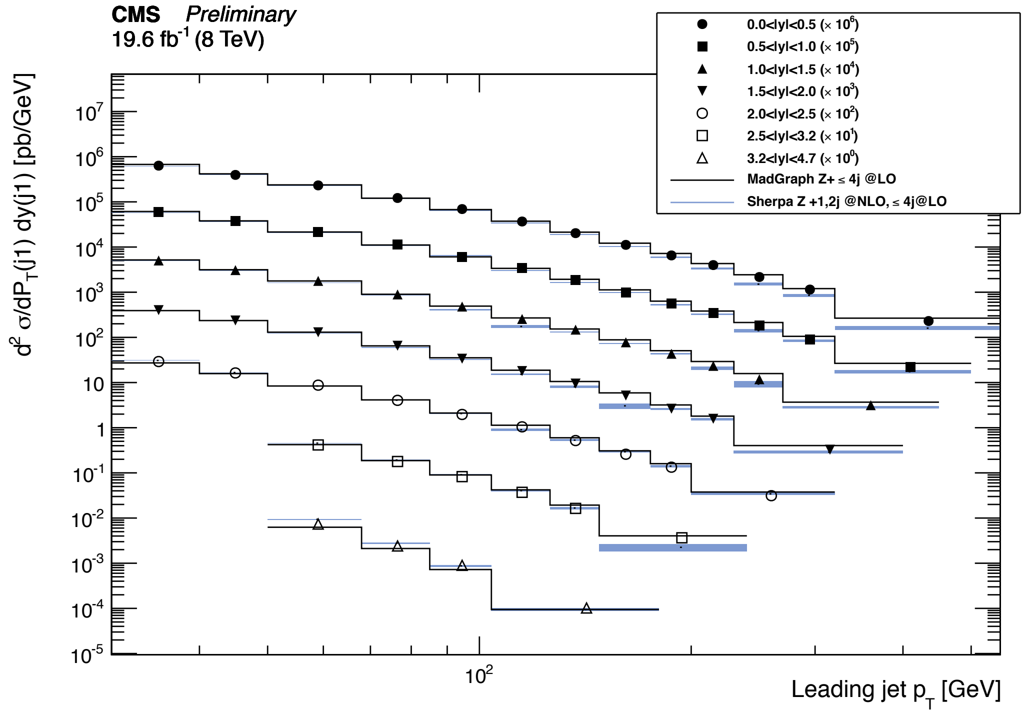
CMS-PAS-SMP-13-007

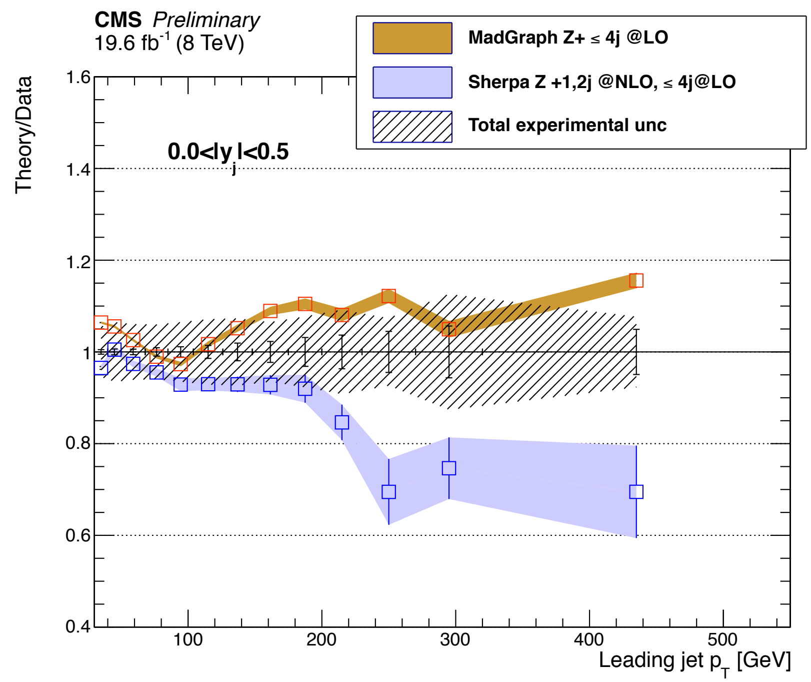
ATLAS 7 TeV: JHEP07(2013)032

Z+jets Double-differential σ

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

- Muon channel unfolded double-differential distribution in p_T and y to 4.7
- Overall good agreement of MC predictions with data
- Discrepancies (10%) of MadGraph with measurement at higher p_T (> 100 GeV)
- Overall agreement with Sherpa except in a few p_T and y ranges
- Discrepancy seen in 7 TeV data (both CMS and ATLAS) in 1-jet bin from 100-450 GeV remains





CMS-PAS-SMP-14-009

W+jets/Z+jets (R-jets)

- Systematics significantly reduced in ratio, esp. in dominant jet uncertainties, compared to individual V+jets measurements
- Precision test of pQCD
- Generic sensitivity to New Physics coupling to W or Z
- Updated result using 5/fb allows measurement of many kinematic distributions including p_T, S_T, H_T, y, ΔR, ΔΦ, m_{12}, for nJets = 0-3.
- Signal and Background modeled with MC, except for data-driven ttbar and multijet estimates
- Electron and Muon channels show agreement and are combined

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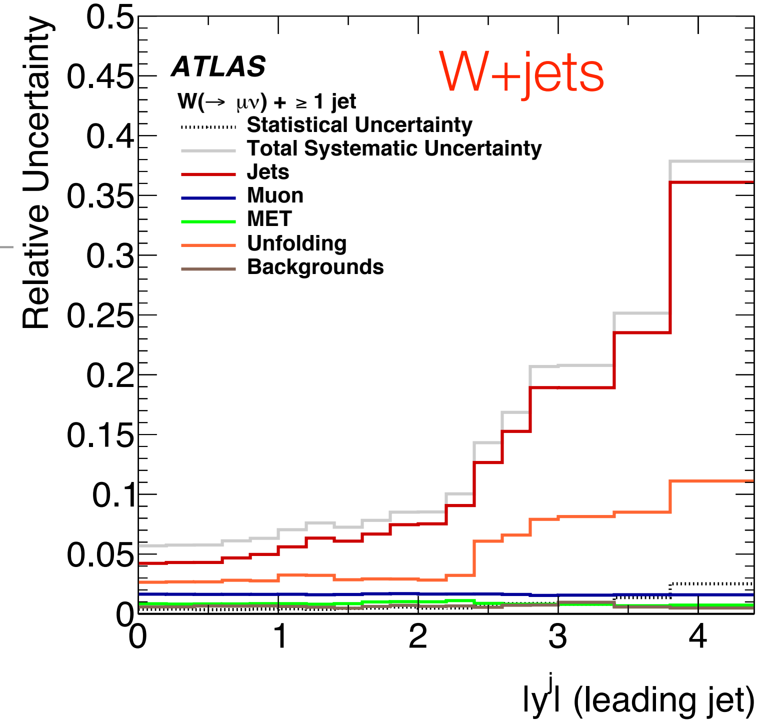
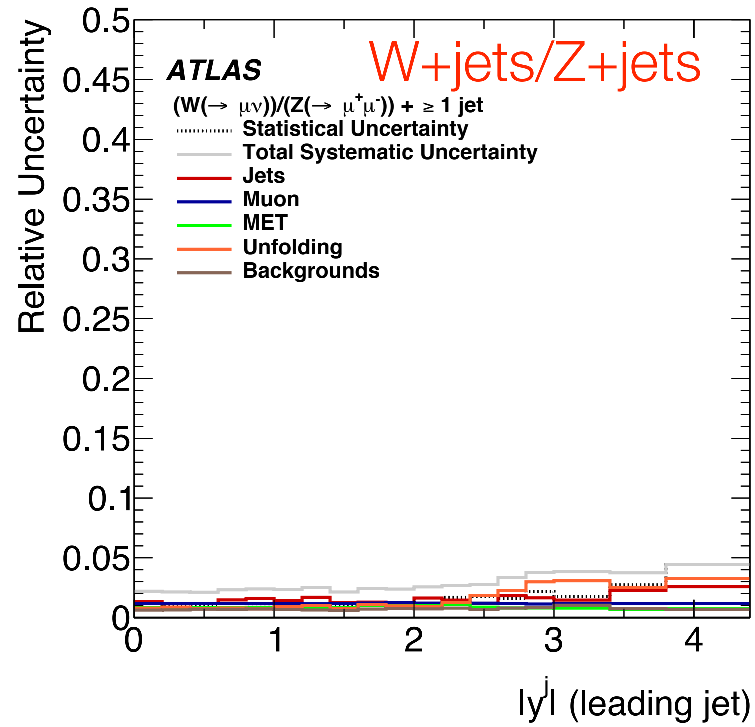
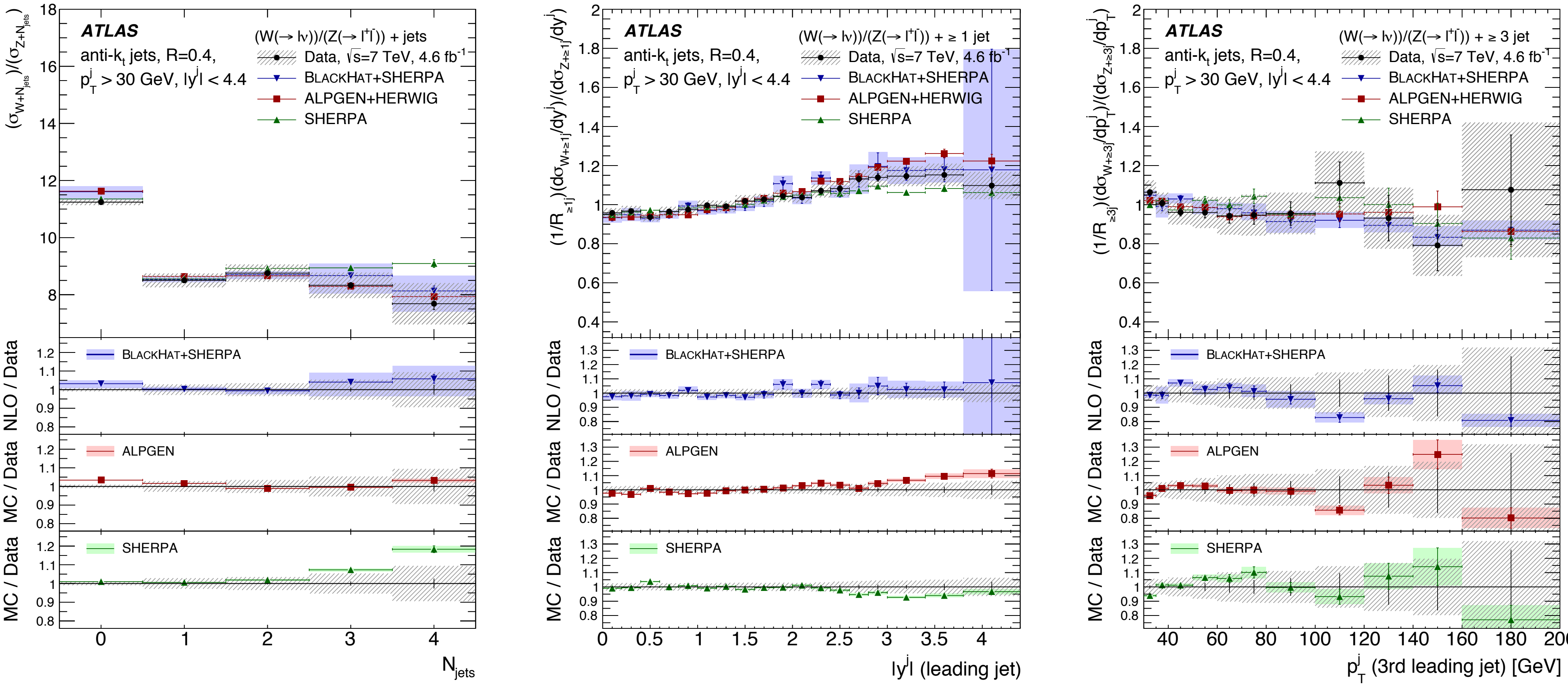




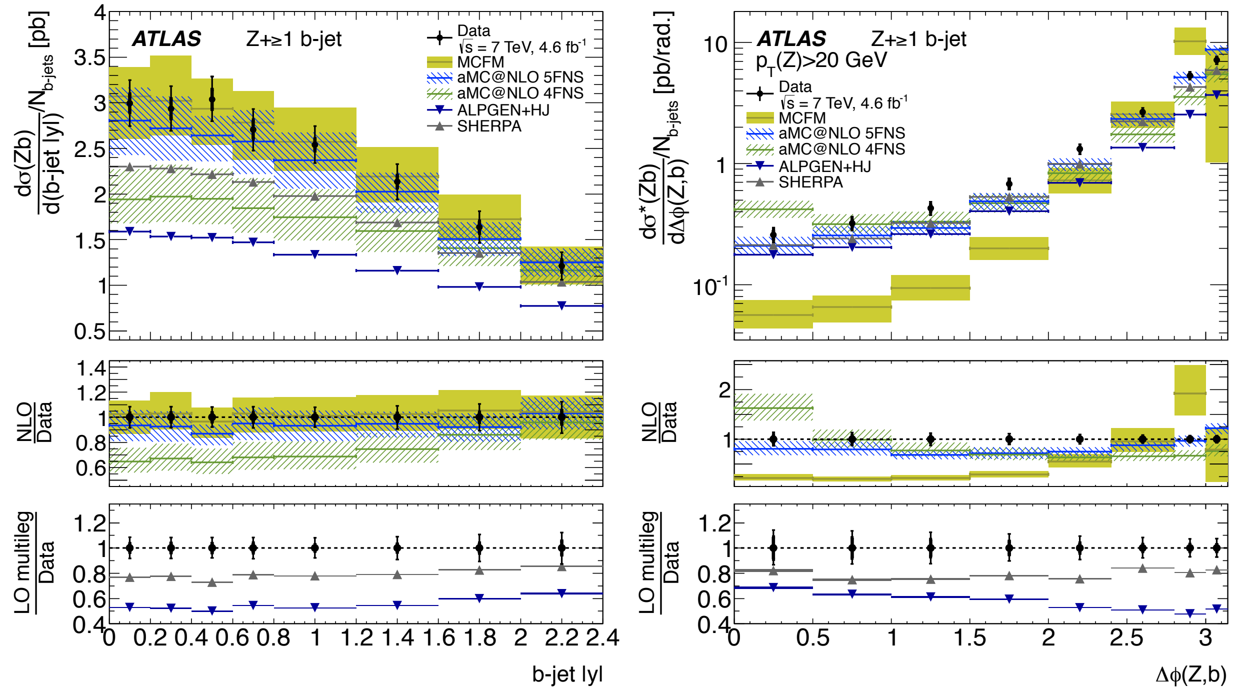
W+jets/Z+jets (R-jets)



- All observables studied both exclusively and inclusively to nJets=3
- Many distributions studied; overall predictions show good agreement with data

Z+b(b)

- Z+b probes b-quark content of proton
- Z+bb background for Higgs associated production and BSM searches
- Jets are tagged with Neural Net b-tagging using jet kinematics and impact parameter information
- Differential cross sections in 12 observables compared to NLO JHEP10(2014)141
- Iterative Bayesian (1-tag) and fiducial/efficiency (2-tag) unfolding to particle-level
- Fixed-order MCFM discrepant at $\Delta\Phi = \pi$. Likely because it includes at most 2 outgoing partons in association with Z



		$\sigma(Zb)$[fb]	$\sigma(Zb)\times N_{b\text{-jet}}$ [fb]	$\sigma^*(Zb)\times N_{b\text{-jet}}$[fb]	$\sigma(Zbb)$[fb]
	Data	$4820\pm60^{+360}_{-380}$	$5390\pm60\pm480$	$4540\pm55\pm330$	$520\pm20^{+74}_{-72}$
	MCFM⊗MSTW2008	$5230\pm30^{+690}_{-710}$	$5460\pm40^{+740}_{-740}$	$4331\pm30^{+400}_{-480}$	$410\pm10^{+60}_{-60}$
5FNS	MCFM⊗CT10	$4850\pm30^{+580}_{-680}$	$5070\pm30^{+640}_{-710}$	$4030\pm30^{+350}_{-450}$	$386\pm5^{+55}_{-50}$
	MCFM⊗NNPDF23	$5420\pm20^{+670}_{-710}$	$5660\pm30^{+720}_{-740}$	$4490\pm30^{+380}_{-460}$	$420\pm10^{+70}_{-50}$
	aMC@NLO 4FNS⊗MSTW2008	$3390\pm20^{+580}_{-480}$	$3910\pm20^{+660}_{-560}$	$3290\pm20^{+580}_{-460}$	$485\pm7^{+80}_{-70}$
	aMC@NLO 5FNS⊗MSTW2008	$4680\pm40^{+550}_{-580}$	$5010\pm40^{+590}_{-620}$	$4220\pm40^{+460}_{-510}$	$314\pm9^{+30}_{-30}$
5FNS	SHERPA⊗CT10	3770 ± 10	4210 ± 10	3640 ± 10	422 ± 2
4FNS	ALPGEN+HJ⊗CTEQ6L1	2580 ± 10	2920 ± 10	2380 ± 10	317 ± 2

JHEP10(2014)141

Conclusions

- Vector Boson production is one of the most important benchmark channels at the LHC.
- Background for Higgs and many other measurements and searches — important to model well.
- Most measurements show good agreement over many observables; a few show some tension in some corners of phase space.
- Many precise measurements enable checks of predictions against many observables - should help improve predictions.
- Looking forward to studying V+jets in new energy regime at 13 TeV.

Backup

Particle-Level Final State Kinematics: Born, Bare, Dressed, Unfolded

- Born: Lepton Kinematics before FSR
- Bare: After FSR
- Dressed: Bare + Photons within cone of $\Delta R < 0.1$
- Unfolding: Correcting data for detector resolution, QED FSR, fiducial acceptance back to Born-level in order to facilitate comparison with predictions

W/Z as merged jets

- Proof of principle that boosted hadronic decays of W/Z can be reconstructed with jet substructure algorithms
- High-pT broad (anti-kt R=0.6) jets analyzed with Likelihood discriminant from jet-shape variables
- Jet mass used as discriminant
- Cross section in agreement within 2σ with NLO MCFM prediction:

This measurement:

$$\sigma_{W+Z} = 8.5 \pm 0.8\ (\text{stat.}) \pm 1.5\ (\text{syst.})\ \text{pb}$$

MCFM:

$$\sigma_{W+Z} = 5.1 \pm 0.5\,\text{pb}$$

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