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Measurement of the Transverse Momentum Spectrum of the Z Boson at 13 TeV with the ATLAS Detector

Prof. Dr. Matthias Schott

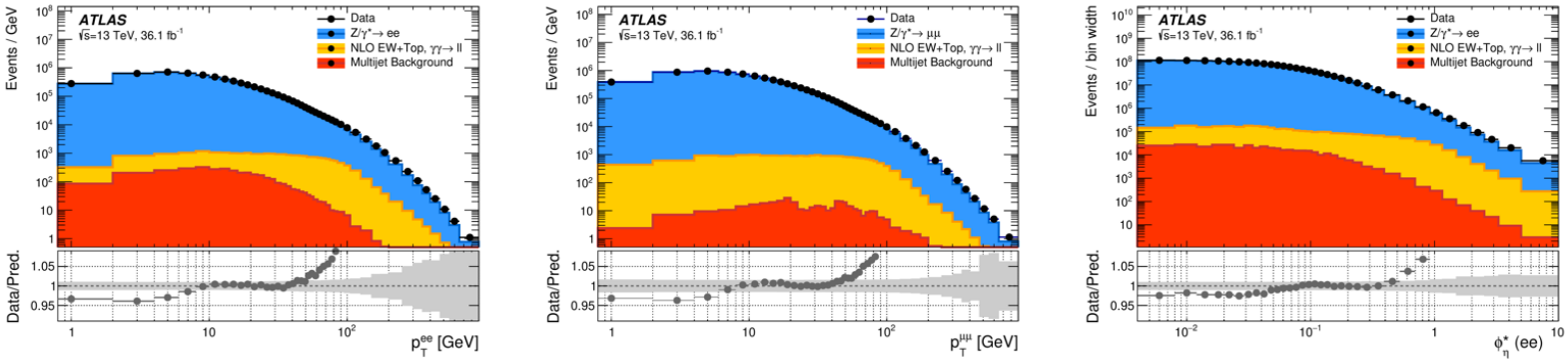
Goal of the Measurement

- Precision measurement of the transverse momentum as well as the ϕ^* distribution of the Z boson
  - Based on 36.1 fb^{-1} (2015/2016 data-set)
- Fiducial Volume
  - p_T(lepton) > 27 GeV,
  - $|\eta_{ll}| < 2.5$
  - m_{ll} = 66-116 GeV
- Results based on the electron and muon decay channel
  - Dressed, bare and born-level results
  - Reaching a precision of <0.2% up to 30 GeV

Bin [GeV]	$1/\sigma_{fid} \times d\sigma/dp_T^{\ell\ell}$ [1/GeV]	Corr. uncert.	Uncorr. uncert.	k_{dr}	Bin	$1/\sigma_{fid} \times d\sigma/d\phi_{\eta}^{*}$	Corr. uncert.	Uncorr. uncert.	k_{dr}
0-2	0.024189	± 0.15%	± 0.18%	0.978	0-0.004	8.8053	± 0.03%	± 0.13%	0.992
2-4	0.051144	± 0.06%	± 0.08%	0.985	0.004-0.008	8.6969	± 0.03%	± 0.13%	0.993
4-6	0.053232	± 0.05%	± 0.08%	0.994	0.008-0.012	8.5624	± 0.02%	± 0.13%	0.993
6-8	0.047383	± 0.05%	± 0.08%	1.000	0.012-0.016	8.3378	± 0.02%	± 0.13%	0.994
8-10	0.040568	± 0.04%	± 0.09%	1.010	0.016-0.02	8.0881	± 0.03%	± 0.14%	0.994
10-12	0.034317	± 0.06%	± 0.11%	1.010	0.02-0.024	7.7920	± 0.03%	± 0.14%	0.995
12-14	0.029157	± 0.07%	± 0.12%	1.010	0.024-0.029	7.4174	± 0.02%	± 0.12%	0.995
14-16	0.024804	± 0.06%	± 0.14%	1.010	0.029-0.034	7.0360	± 0.02%	± 0.13%	0.996
16-18	0.021268	± 0.05%	± 0.15%	1.010	0.034-0.039	6.5989	± 0.02%	± 0.13%	0.998
18-20	0.018325	± 0.04%	± 0.16%	1.010	0.039-0.045	6.1608	± 0.02%	± 0.12%	0.998
20-22.5	0.015605	± 0.03%	± 0.14%	1.010	0.045-0.051	5.7085	± 0.01%	± 0.13%	0.999
22.5-25	0.01318 0	± 0.03%	± 0.15%	1.000	0.051-0.057	5.2791	± 0.02%	± 0.14%	1.000
25-27.5	0.011207	± 0.04%	± 0.17%	1.000	0.057-0.064	4.8488	± 0.02%	± 0.13%	1.000
27.5-30	0.0095568	± 0.05%	± 0.19%	0.999	0.064-0.072	4.4139	± 0.01%	± 0.12%	1.000
30-33	0.0081029	± 0.06%	± 0.17%	0.998	0.072-0.081	3.9705	± 0.01%	± 0.12%	1.000
33-36	0.0067881	± 0.08%	± 0.19%	0.996	0.081-0.091	3.5515	± 0.01%	± 0.12%	1.000
36-39	0.0057563	± 0.09%	± 0.21%	0.994	0.091-0.102	3.1421	± 0.02%	± 0.13%	1.000
39-42	0.0048769	± 0.12%	± 0.23%	0.993	0.102-0.114	2.7659	± 0.01%	± 0.13%	1.000
42-45	0.0041688	± 0.12%	± 0.25%	0.992	0.114-0.128	2.4125	± 0.01%	± 0.13%	1.000
45-48	0.0035213	± 0.14%	± 0.28%	0.993	0.128-0.145	2.0648	± 0.01%	± 0.12%	1.000
48-51	0.0029751	± 0.17%	± 0.31%	0.991	0.145-0.165	1.7299	± 0.02%	± 0.13%	1.000
51-54	0.0025433	± 0.18%	± 0.35%	0.992	0.165-0.189	1.4282	± 0.02%	± 0.13%	1.000
54-57	0.0021832	± 0.20%	± 0.38%	0.994	0.189-0.219	1.1469	± 0.02%	± 0.12%	1.000
57-61	0.0018779	± 0.15%	± 0.31%	0.994	0.219-0.258	0.8848	± 0.02%	± 0.12%	1.000
61-65	0.0015932	± 0.17%	± 0.35%	0.994	0.258-0.312	0.6470	± 0.03%	± 0.11%	1.000
65-70	0.0013519	± 0.16%	± 0.32%	0.995	0.312-0.391	0.4387	± 0.03%	± 0.11%	1.000
70-75	0.0011323	± 0.17%	± 0.37%	0.995	0.391-0.524	0.2610	± 0.03%	± 0.10%	1.000
75-80	0.0009574	± 0.20%	± 0.43%	0.995	0.524-0.695	0.1414	± 0.04%	± 0.13%	1.000
80-85	0.0008150	± 0.22%	± 0.49%	0.995	0.695-0.918	0.07462	± 0.07%	± 0.17%	1.000
85-95	0.0006537	± 0.14%	± 0.29%	0.996	0.918-1.153	0.04047	± 0.12%	± 0.27%	1.000
95-105	0.0004849	± 0.18%	± 0.37%	0.995	1.153-1.496	0.02167	± 0.14%	± 0.30%	1.000
105-125	0.0003291	± 0.12%	± 0.25%	0.996	1.496-1.947	0.01084	± 0.18%	± 0.42%	1.000
125-150	0.0001861	± 0.16%	± 0.32%	0.994	1.947-2.522	0.005386	± 0.23%	± 0.59%	1.000
150-175	0.0001050	± 0.24%	± 0.51%	0.993	2.522-3.277	0.002738	± 0.31%	± 0.79%	1.000
175-200	$6.1279 \cdot 10^{-5}$	± 0.30%	± 0.78%	0.992	3.277-5.000	0.0011730	± 0.29%	± 0.72%	1.000
200-250	$3.0584 \cdot 10^{-5}$	± 0.22%	± 0.66%	0.995	5.000-10.00	0.0003372	± 0.30%	± 0.78%	0.997
250-300	$1.2211 \cdot 10^{-5}$	± 0.34%	± 1.4%	0.997					
300-350	$5.9026 \cdot 10^{-6}$	± 0.56%	± 2.3%	0.994					
350-400	$2.7742 \cdot 10^{-6}$	± 0.90%	± 3.8%	0.991					
400-470	$1.2513 \cdot 10^{-6}$	± 0.82%	± 4.9%	0.991					
470-550	$5.5219 \cdot 10^{-7}$	± 1.2%	± 7.9%	0.994					
550-650	$2.0165 \cdot 10^{-7}$	± 1.5%	± 13%	0.995					
650-900	$5.1153 \cdot 10^{-8}$	± 1.8%	± 16%	0.990					
900-2500	$1.5735 \cdot 10^{-9}$	± 6.3%	± 60%	0.964					

Backgrounds

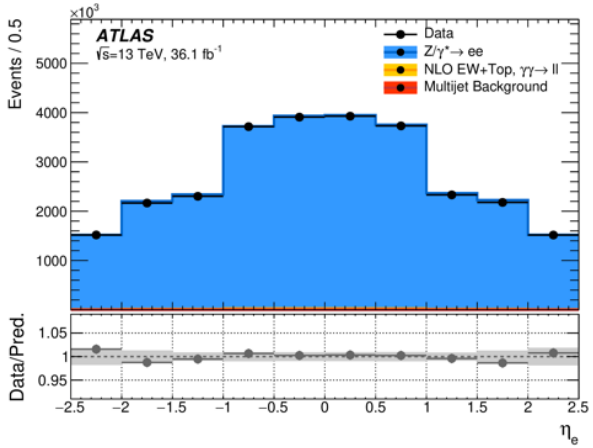
- Top- and electroweak background is estimated using MC predictions
  - Shape of top quark background verified using a e/μ selection
- Multijet background and W+jets is estimated using a data-driven approach using isolation and E_T^{Miss} to define control-regions
  - Overall background is very small

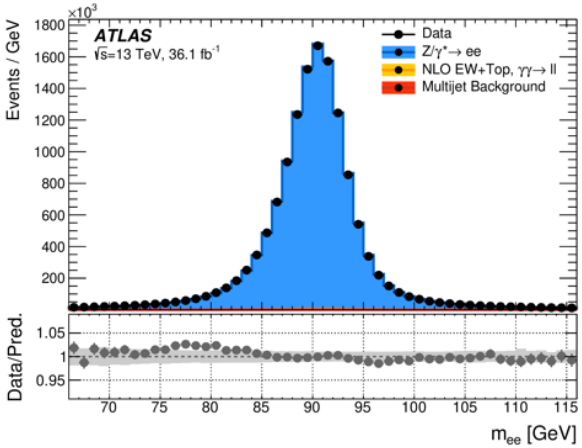


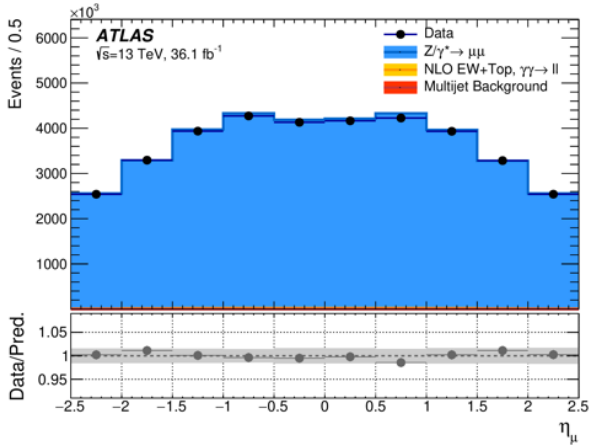
	$Z/\gamma^* \to ee$	$Z/\gamma^* \to \mu\mu$
Two reconstructed leptons within fiducial volume	13 649 239	18 162 641
Electroweak background ($Z \to \tau\tau$, WW, WZ, ZZ)	40 000 ± 2000	39 000 ± 2000
Photon-induced background	2900 ± 140	4100 ± 200
Top-quark background	38 000 ± 1900	45 400 ± 2200
Multijet background	8500 ± 4900	1000 ± 200

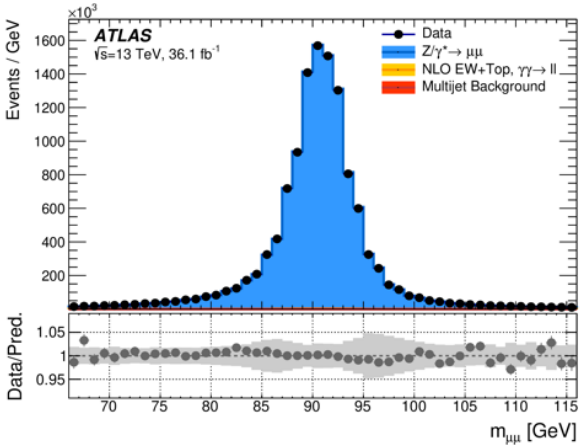
Basic Control Plots

- Test lepton performance by comparing invariant mass and lepton-rapidity distributions
- Normalized control distributions indicate a good Data/MC agreement









Inclusive Cross Section

- Measurement of the fiducial inclusive cross-section limited by
  - Uncertainties on the lepton identification
  - Muon uncertainties larger than in previous 13 TeV measurement
  - However, many uncertainties highly correlated vs. lepton p_T, i.e. will be reduced for the normalized $p_T(Z)$ spectrum
- Very good agreement with previously measured inclusive cross-section
  - Different fiducial volume

	Electron channel		Muon channel	
	Born	Dressed	Born	Dressed
C_Z	0.509 ± 0.005	0.522 ± 0.005	0.685 ± 0.011	0.702 ± 0.011
Trigger efficiencies	± 0.0004		± 0.0004	
Identification & reconstruction efficiencies	± 0.0049		± 0.0102	
Isolation efficiencies	± 0.0009		± 0.0029	
Energy/momentum scale and resolution	± 0.0014		± 0.0010	
Pile-up	± 0.0011		± 0.0019	
Model uncertainties	± 0.0001		± 0.0001	

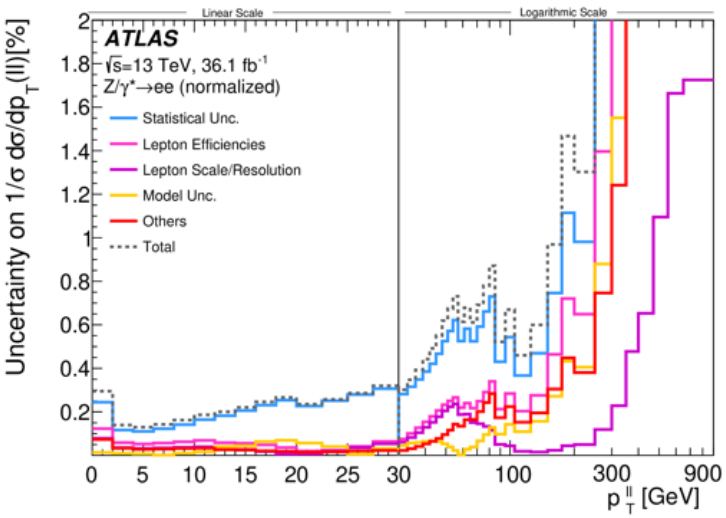
Channel	Measured cross-section $\times\, \mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value $\pm$ stat. $\pm$ syst. $\pm$ lumi.)	Predicted cross-section $\times\, \mathcal{B}(Z/\gamma^* \to \ell\ell)$ (value $\pm$ PDF $\pm\, \alpha_S$ $\pm$ scale $\pm$ intrinsic)
$Z/\gamma^* \to ee$	$738.3 \pm 0.2 \pm 7.7 \pm 15.5$ pb	
$Z/\gamma^* \to \mu\mu$	$731.7 \pm 0.2 \pm 11.3 \pm 15.3$ pb	
$Z/\gamma^* \to \ell\ell$	$736.2 \pm 0.2 \pm 6.4 \pm 15.5$ pb	$703^{+19}_{-24}\,{}^{+6}_{-8}\,{}^{+4}_{-6}\,{}^{+5}_{-5}$ pb **[STDM-2016-02]**

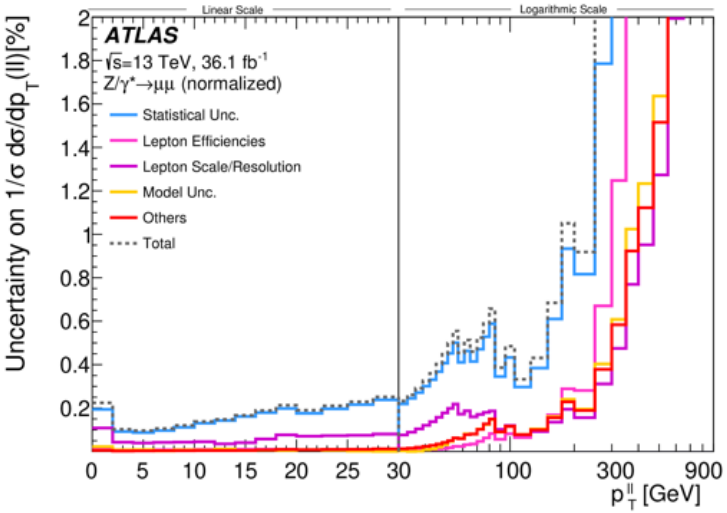
Unfolding and Uncertainties

- Iterative Bayesian Unfolding with 4 Iterations
- Model uncertainty tested by reweighting the MC Truth Prior to the observed difference between data and MC on detector level
  - Take difference as systematic uncertainty
- It was also shown that this uncertainty covers when taking an alternative MC Generator (Sherpa) as Pseudo Data
- Statistical uncertainties are estimated with MC Toys
- Systematic uncertainties are estimated by up- and down- variations of all uncorrelated nuisance parameters

Uncertainties: $P_T(Z)$

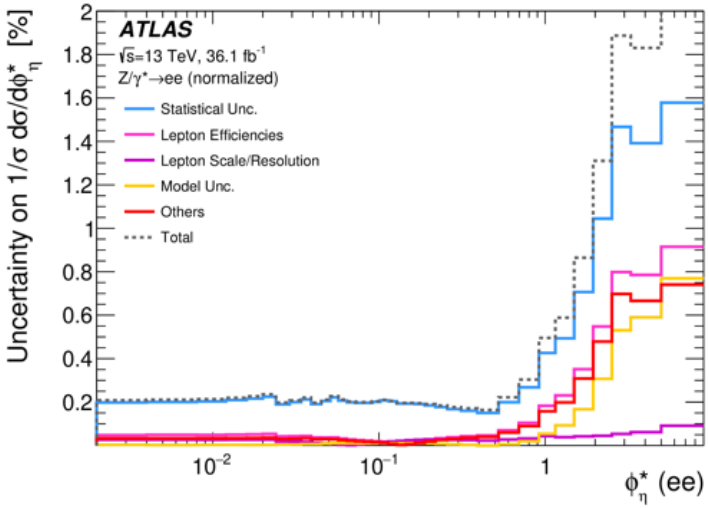
- Dominant uncertainties are statistical ones
  - While data statistics are dominant everywhere, also limited MC statistics is not negligible
- Lepton efficiency uncertainties become important for the very high p_T regime
- Lepton momentum/energy scale uncertainties are highly correlated vs. bins, i.e. can lead to an overall change of the spectrum
  - Important for combination

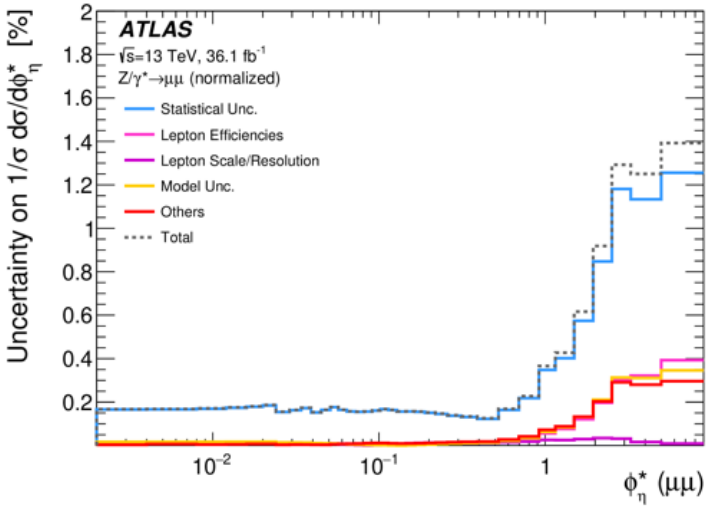




Uncertainties: ϕ^*

- Dominant uncertainties are statistical ones
  - While data statistics are dominant everywhere, also limited MC statistics is not negligible
- Lepton related uncertainties significantly reduced (by construction of ϕ^*)
- The unfolding matrix for ϕ^* is very diagonal (high purity), hence very small model uncertainties are expected

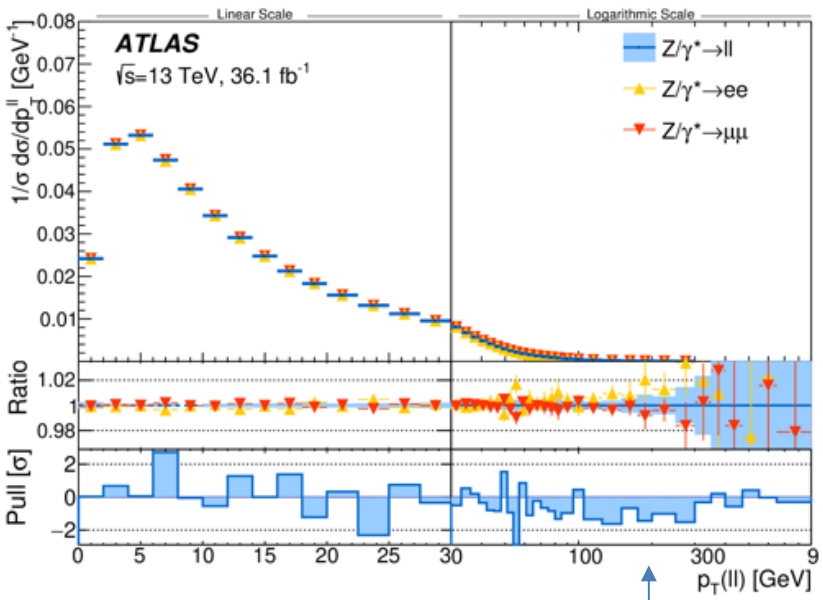


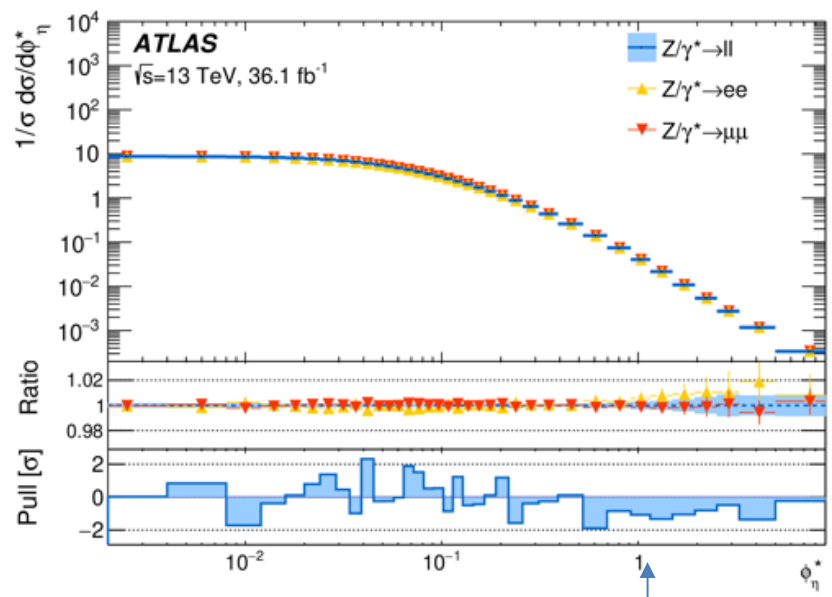


Combination

- Treat statistical uncertainties uncorrelated between channels (and nearly uncorrelated vs. bins)
  - Split efficiency systematics in bin-to-bin uncorrelated and correlated components
  - Several uncertainties are also correlated vs channels, e.g. z-positioning, pile-up, model-uncertainties

- We observe a chi2/ndf=47/44 and 32/36 for $P_T(Z)$ and ϕ^*, respectively

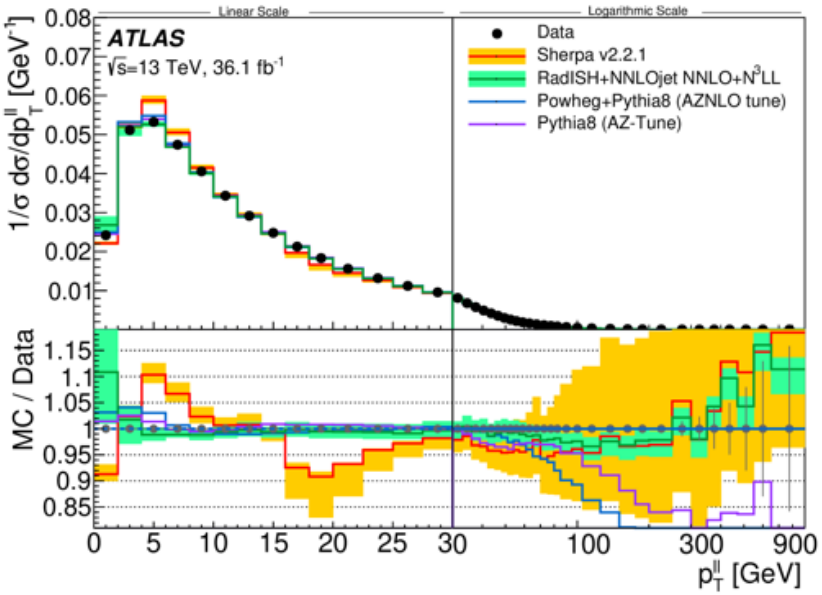


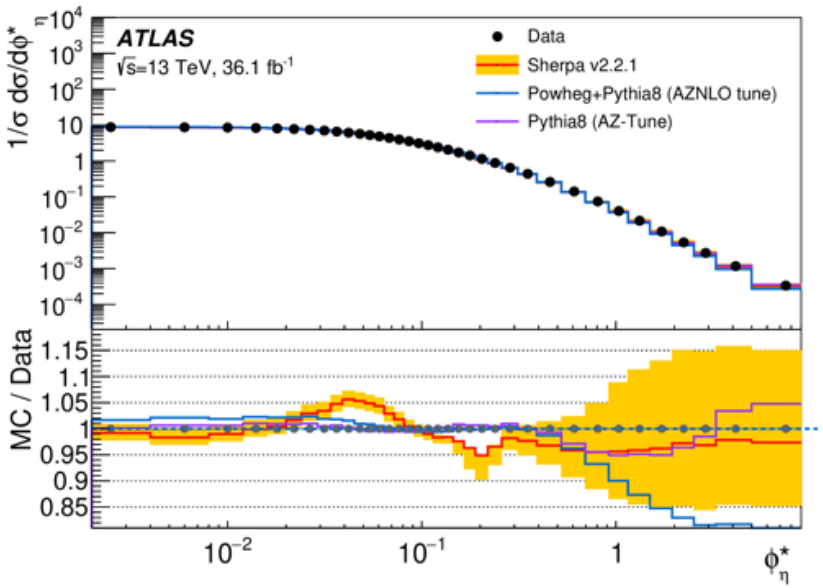


This discrepancy is not significant when taking correlations into account

Comparison to Theory (1/2)

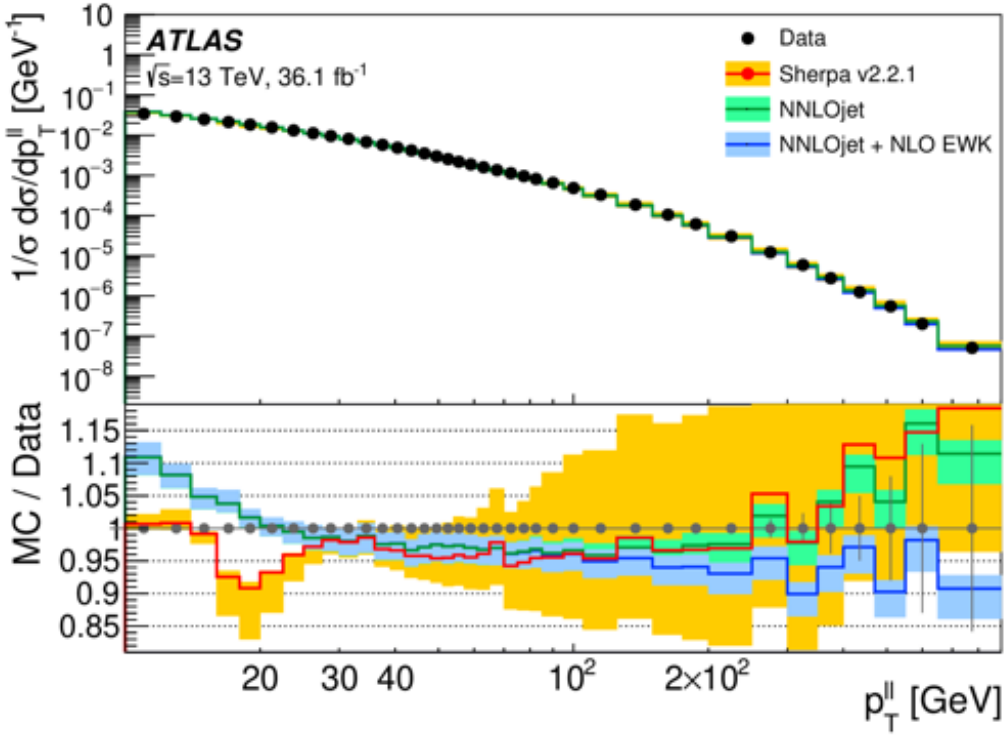
- Comparison to Powheg+Pythia (Baseline MC), Sherpa2.2.1, Pythia8, RadISH+NNLOjet+N2LL
  - As expected, similar trends for $p_T(Z)$ and ϕ^*
  - Theory uncertainties significantly larger than experimental uncertainties
  - Good description with RadISH over the full spectrum (prediction for ϕ^* in preparation)
  - Pythia8 with AZ tune (as used for the W mass measurement) describes the data well at low pT





Comparison to Theory (2/2)

- Comparison to NNLOjet and NNLOjet+NLO EWK
- Expect larger sensitivity for electroweak contributions at high p_T
- Need a detailed study on correlations, if there is a tension



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Summary

- First ATLAS measurement of $p_T(Z)$ and ϕ^* at 13 TeV based on the 2015/2016 data-set
- Measurement performed in the electron and the muon decay channel
- Combination yields a precision of 0.2% and better for $P_T(Z)<30$ GeV