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

- Precision measurement of the transverse momentum as well as the $\phi^*$ distribution of the Z boson
  - Based on 36.1 fb$^{-1}$ (2015/2016 data-set)

- Fiducial Volume
  - $p_T(\text{lepton}) > 27$ GeV,
  - $|\eta| < 2.5$
  - $m_{ll} = 66$-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

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Prof. Dr. M. Schott (Johannes Gutenberg University, Mainz)
- 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

<table>
<thead>
<tr>
<th>Two reconstructed leptons within fiducial volume</th>
<th>Z/γ^{*} → ee</th>
<th>Z/γ^{*} → µµ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroweak background (Z → ττ, WW, WZ, ZZ)</td>
<td>40 000 ± 2000</td>
<td>39 000 ± 2000</td>
</tr>
<tr>
<td>Photon-induced background</td>
<td>2900 ± 140</td>
<td>4100 ± 200</td>
</tr>
<tr>
<td>Top-quark background</td>
<td>38 000 ± 1900</td>
<td>45 400 ± 2200</td>
</tr>
<tr>
<td>Multijet background</td>
<td>8500 ± 4900</td>
<td>1000 ± 200</td>
</tr>
</tbody>
</table>
Basic Control Plots

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

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

- The unfolding matrix for $\phi^*$ is very diagonal (high purity), hence very small model uncertainties are expected
- 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 $\chi^2/\text{ndf}=47/44$ and $32/36$ for $P_T(Z)$ and $\phi^*$, 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 $\phi^*$
  - Theory uncertainties significantly larger than experimental uncertainties
  - Good description with RadISH over the full spectrum (prediction for $\phi^*$ in preparation)
  - Pythia8 with AZ tune (as used for the W mass measurement) describes the data well at low $p_T$
- 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
Summary

- First ATLAS measurement of $p_T(Z)$ and $\phi^*$ 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