Low pile-up $p_T(W)$ measurement from ATLAS

Zhibo Wu
On behalf of ATLAS
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The motivation the $p_T^W$ measurement

Reduce the $p_T^W$ modelling uncertainty in the $m_W$ measurement.

- ATLAS 7 TeV $m_W$ analysis:
  6 MeV $p_T^W$ modelling uncertainty dominated by the $p_T^Z \rightarrow p_T^W$ extrapolation uncertainties.
- Solution:
  -> Direct $p_T^W$ measurement.

Targeted $p_T^W$ precision:
- A granularity of 6~7 GeV.
- 1~2% uncertainty in the low values of $p_T^W$ where the fixed-order perturbative prediction fails.
Event topology: leptonic decay of W/Z

- Only **two objects** to measure:
  1. The charged lepton
  2. Hadronic recoil $\mathbf{u}_T = \sum \mathbf{p}_T^{\text{ISR}} q, g = -\mathbf{p}_T^V$

  \[
  \begin{align*}
  W \text{ events}: & \quad \mathbf{u}_T \rightarrow \mathbf{p}_T^W \\
  Z \text{ events}: & \quad \mathbf{p}_T^L \rightarrow \mathbf{p}_T^Z \text{ or } \mathbf{u}_T \rightarrow \mathbf{p}_T^Z
  \end{align*}
  \]

- Detector calibrations are needed for lepton and recoil.
- Detector resolution of $\mathbf{u}_T$ is affected by underlying event and pile-up.

\[m_T = \sqrt{2\mathbf{p}_T^l \mathbf{p}_T^{\text{miss}} (1 - \cos(\phi_l - \phi_{\mathbf{p}_T^{\text{miss}}}))}
\]

\[\mathbf{p}_T^{\text{miss}} = - (\mathbf{p}_T^l + \mathbf{u}_T) \text{ for the neutrino}
\]

Figure taken from M. Schott

Lower pile-up in the dataset

\[\rightarrow \text{ More precise measurement of } \mathbf{p}_T^W\]
ATLAS Run 2 low pile-up data

Probes of perturbative and non-perturbative QCD in $W$ events, as well as in $Z$ events at 5.02 TeV.

<table>
<thead>
<tr>
<th>Probes</th>
<th>2017, $\sqrt{s}=5.02$ TeV</th>
<th>2017+2018, $\sqrt{s}=13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (pb$^{-1}$)</td>
<td>255</td>
<td>338</td>
</tr>
<tr>
<td>$W^+$ events after selection</td>
<td>888K</td>
<td>2.45M</td>
</tr>
<tr>
<td>$W^-$ events after selection</td>
<td>562K</td>
<td>1.91M</td>
</tr>
<tr>
<td>Total $W$ events after selection</td>
<td>1.45M</td>
<td>4.36M</td>
</tr>
<tr>
<td>Total $Z$ events after selection</td>
<td>122K</td>
<td>379K</td>
</tr>
</tbody>
</table>
Event display of the low pile-up data

The event display of a $W^-$ boson candidate at 13 TeV.
- Orange line: muon
- Red arrow: missing transverse momentum

Event kinematics:
- $p_T^\mu = 35$ GeV
- Reconstructed $p_T^W = 16$ GeV
- $m_T = 77$ GeV
- $p_T^{\text{miss}} = 49$ GeV.
MC samples and event selection

MC simulations were produced to match the low pile-up condition in data.

- **W & Z production**: Powheg+Pythia8 AZNLO, CT10 PDF
- **Top-related background**: Powheg+Pythia8
- **Di-boson background**: Sherpa
- **Minimum-bias events**: Pythia8 A3 tune with NNPDF2.3LO

### Analysis cuts for W signal selection

<table>
<thead>
<tr>
<th>Cut</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>One charged lepton</td>
<td>Exactly one electron or muon</td>
</tr>
<tr>
<td>Lepton trigger matched</td>
<td>• 1 electron, $E_T &gt; 15$ GeV, loose ID.</td>
</tr>
<tr>
<td></td>
<td>• Or 1 muon, $E_T &gt; 14$ GeV.</td>
</tr>
<tr>
<td>Isolation</td>
<td>$P_{t\text{cone20}} / \min(p_T, 50\text{GeV}) &lt; 0.1$</td>
</tr>
<tr>
<td>Kinematics</td>
<td>$p_T &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>$p_T^{\text{miss}} &gt; 25$ GeV</td>
</tr>
<tr>
<td></td>
<td>$m_T &gt; 50$ GeV</td>
</tr>
</tbody>
</table>
Physics corrections

- Vertex z-position correction.
- Vertex efficiency correction: Correct the efficiency of primary vertex association for $W \rightarrow l \nu$ events in the simulations.
- QED FSR: Powheg+Pythia8 interfaced to PHOTOS++.
- $W$, $Z$ polarization: Ai’s are calculated by DYTURBO at fixed-order NNLO using CT10NNLO PDF.
- $p_T^V$ modelling correction: The underling $p_T^V$ spectra predicted by Powheg+Pythia8 are reweighted by functions of $p_T^V$ to optimize the reco-level data/MC agreement.

➢ 8 different $p_T^V$ reweighting functions are determined individually for $W^\pm$, $Z$ ($u_T$) and $Z$ ($p_T^U$) at two center-of-mass energies.
Detector calibration: lepton

The lepton momentum in the simulation is corrected to reproduce the resonance of Z-boson in data.

Efficiency measured in Z-\(\rightarrow \ell\ell\) events with tag & probe:
- Tighten the selection on one of the leptons (tag) to ensure the signal purity.
- Measure the selection efficiency on the second, unbiased lepton (probe).
Detector calibration: hadronic recoil

- In $Z\rightarrow\ell\ell$ events, the transverse momentum of the di-lepton pair ($p_T^{\ell\ell}$) is well-measured.
- $p_T^{\ell\ell}$ corresponds to the transverse momentum of $Z$-boson ($p_T^Z = p_T^{\ell\ell}$).

Use the $p_T^{\ell\ell}$ constraint to calibrate the response and resolution of $u_T$ in $Z\rightarrow\ell\ell$ events. Then extrapolate the results to $W$ events.
Hadronic recoil calibration and correction

The calibration is obtained as a function of $\Sigma \overline{E}_T$ and $p_T^V$: $(\Sigma \overline{E}_T = \Sigma E_T - u_T)$
- $\Sigma \overline{E}_T$ modelling
- Azimuthal angle corrections
- Response and resolution corrections

Uncertainty sources:
- $\Sigma \overline{E}_T$ reweighting uncertainty.
- Response and resolution uncertainties.
- Since the $Z$-based calibration is applied to $W$, the uncertainties due to this extrapolation are taken into account.

13 TeV $Z \rightarrow \mu \mu$ events

Mean value for bias $b = u_\parallel + p_T^{\parallel}$. STDEV of $u_\perp$. 
Multijet estimation

- MJ sources: heavy quark decay, in-flight pion decay, photon conversion.

- Data-driven methods are applied to both W and Z:
  (a) Determination of yield.
  (b) Derivation of MJ shape.

- The MJ fraction is below 0.1% for all Z channels.
- MJ fraction 0.6%~2.9% for W at 13 TeV, 0.1%~0.8% for W at 5.02 TeV
Reconstructed level control plots

$u_T$ in 5.02 TeV
$W^−\rightarrow e\nu$ channel

$W\rightarrow e\nu$ channel

$Z\rightarrow e\nu$ channel

$Z\rightarrow e\nu$ channel
Unfolding

IBU using the migration matrix

• Iterative Bayesian unfolding for \( p_T^W \): \( \tilde{u}_T = \sum p_{T}^{ISR} q.g = -p_T^V \)

• \( p_T^Z \) spectrum can be obtained by unfolding \( u_T \) and \( p_T^U \).

--> Compatibility test of the unfolding
Unfolding

Iterative Bayesian Unfolding:
• $u_T \rightarrow p^W_T$: 9 (25) iterations with 7 GeV bin width in the low $p^W_T$ region for W channels at 5.02 (13) TeV.
• $p^l_T \rightarrow p^Z_T$: 2 iterations with 7 GeV bin width at low $p^Z_T$ for Z.

Fiducial volume:
• $p^l_T > 25$ GeV, $|\eta_l| < 2.5$
• W events: $p^V_T > 25$ GeV and $m^W_T > 50$ GeV
• Z events: $66 < m_{ll} < 116$ GeV

The variations & non-closures of the data-driven $p^V_T$ modelling correction are accounted for as unfolding bias uncertainties.
**Combination and $\chi^2$**

- At each center-of-mass energy, the electron and muon channels are combined for each charge of the boson.
- Statistical procedure: BLUE prescription with 4 iterations.

Good compatibility is found between electron and muon channels.
Uncertainty break-down for $p_T^W$

Break-down of $p_T^W$ uncertainty for the combined $W^-\rightarrow l\nu$ measurements at 5.02 TeV (left) and at 13 TeV (right).

Leading systematic sources in the low $p_T$ region:
- Unfolding uncertainties
- Recoil calibration systematics.
- “Sherpa vs Powheg” generator systematics

Total uncertainty achieves the goal: **1-2%** in the low $p_T$ with a granularity of **7 GeV**.
Uncertainty break-down for $p_T^Z(p_T^{ll})$

Break-down of $p_T^Z$ uncertainty for the combined $Z\to ll$ measurements at 5.02 TeV (left) and at 13 TeV (right).
- Dominated by statistical uncertainty.
Measurement compared with various MC generators at 5.02 TeV.
- The differential cross-sections are valuable input to $m_W$ measurement.
- Good data MC agreement for the $W^+/W^-$ ratio.
$p_T^W$ differential cross-section: 5.02 TeV

DYTURBO @NNLO+NNLL for $pp \to W \to lv$.
- The differential cross-sections are valuable input to $m_W$ measurement.
- Good data MC agreement for the $W^+/W^-$ ratio.
Measurement compared with various MC generators at 13 TeV.
• The differential cross-sections are valuable input to $m_W$ measurement.
• Tension in the low $p_T$ region of the $W^+/W^-$ ratio.
DYTURBO @NNLO+NNLL for pp -> W -> lv.

- The differential cross-sections are valuable input to $m_W$ measurement.
- Tension in the low $p_T$ region of the $W^+/W^-$ ratio.
The parton showers tuned using ATLAS 7 TeV data agrees with the measurement at 5.02 TeV.

Some discrepancy in the low $p_T$ region at 13 TeV.
$p_T^W$ measurement: integrated cross-sections

Integrated fiducial cross-section

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section at $\sqrt{s} = 5.02$ TeV [pb]</th>
<th>Cross section at $\sqrt{s} = 13$ TeV [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^- \rightarrow \ell \nu$</td>
<td>$1385 \pm 2$ (stat.) $\pm 5$ (sys.) $\pm 15$ (lumi.)</td>
<td>$3486 \pm 3$ (stat.) $\pm 18$ (sys.) $\pm 34$ (lumi.)</td>
</tr>
<tr>
<td>$W^+ \rightarrow \ell \nu$</td>
<td>$2228 \pm 3$ (stat.) $\pm 8$ (sys.) $\pm 23$ (lumi.)</td>
<td>$4571 \pm 3$ (stat.) $\pm 21$ (sys.) $\pm 44$ (lumi.)</td>
</tr>
<tr>
<td>$Z \rightarrow \ell \ell$</td>
<td>$333.0 \pm 1.2$ (stat.) $\pm 2.2$ (sys.) $\pm 3.3$ (lumi.)</td>
<td>$780.3 \pm 2.6$ (stat.) $\pm 7.1$ (sys.) $\pm 7.1$ (lumi.)</td>
</tr>
</tbody>
</table>

- Sufficient statistics and small systematics.
- High precision luminosity calibration: 1% at 5.02 TeV & 0.92% at 13 TeV.
- One of the most accurate cross-section measurements at hadron colliders.

Integrated cross-section ratios

<table>
<thead>
<tr>
<th>Processes</th>
<th>Cross-section ratio at $5.02$ TeV</th>
<th>Cross-section ratio at $\sqrt{s} = 13$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+/W^-$</td>
<td>$1.611 \pm 0.003$ (stat.) $\pm 0.004$ (sys.)</td>
<td>$1.312 \pm 0.001$ (stat.) $\pm 0.003$ (sys.)</td>
</tr>
<tr>
<td>$W^-/Z$</td>
<td>$4.16 \pm 0.01$ (stat.) $\pm 0.05$ (sys.)</td>
<td>$4.46 \pm 0.01$ (stat.) $\pm 0.07$ (sys.)</td>
</tr>
<tr>
<td>$W^+/Z$</td>
<td>$6.69 \pm 0.02$ (stat.) $\pm 0.08$ (sys.)</td>
<td>$5.84 \pm 0.01$ (stat.) $\pm 0.09$ (sys.)</td>
</tr>
<tr>
<td>$W^{\pm}/Z$</td>
<td>$10.85 \pm 0.04$ (stat.) $\pm 0.11$ (sys.)</td>
<td>$10.31 \pm 0.02$ (stat.) $\pm 0.15$ (sys.)</td>
</tr>
</tbody>
</table>

$Z\rightarrow ll$: $p_T^l > 25$ GeV, $|\eta_l| < 2.5$, and $66 < m_{ll} < 116$ GeV

$W\rightarrow l\nu$: $p_T^l > 25$ GeV, $|\eta_l| < 2.5$, $p_T^\nu > 25$ GeV, and $m_T > 50$ GeV
**$p_T^W$ measurement: integrated cross-sections**

<table>
<thead>
<tr>
<th>PDF set</th>
<th>$W^- \rightarrow \ell\nu$</th>
<th>$W^+ \rightarrow \ell\nu$</th>
<th>$Z \rightarrow \ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross-section at 5.02 TeV [pb]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT18</td>
<td>1364</td>
<td>2199</td>
<td>320.9</td>
</tr>
<tr>
<td>MSHT20</td>
<td>1351</td>
<td>2185</td>
<td>324.3</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>1381</td>
<td>2232</td>
<td>329.8</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>$1384 \pm 16$</td>
<td>$2228 \pm 25$</td>
<td>$333.0 \pm 4.1$</td>
</tr>
<tr>
<td><strong>Cross-section at 13 TeV [pb]</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT18</td>
<td>3410</td>
<td>4462</td>
<td>749.8</td>
</tr>
<tr>
<td>MSHT20</td>
<td>3397</td>
<td>4457</td>
<td>766.1</td>
</tr>
<tr>
<td>NNPDF3.1</td>
<td>3452</td>
<td>4513</td>
<td>771.4</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>$3486 \pm 38$</td>
<td>$4571 \pm 49$</td>
<td>$780.3 \pm 10.4$</td>
</tr>
</tbody>
</table>

Measured integrated fiducial cross-sections are compared with predictions of DYTURBO @NNLO+NNLL, using different PDF sets.

The best compatibility is found between data and NNPDF3.1.

$Z\rightarrow\ell\ell$: $p_T^\ell > 25$ GeV, $|\eta_\ell| < 2.5$, and $66 < m_\ell < 116$ GeV

$W\rightarrow\ell\nu$: $p_T^\ell > 25$ GeV, $|\eta_\ell| < 2.5$, $p_T^\nu > 25$ GeV, and $m_T > 50$ GeV
Conclusions

• The transverse momentum spectra of the W and Z bosons at 5.02 TeV and 13 TeV have been measured using ATLAS Run 2 low pile-up data.

• The dedicated datasets, reconstruction, calibration and data-driven multijet estimation render a granularity of 7 GeV in the low p_T^W region, with typically a 1~2% level precision.

• The measured p_T^W and p_T^Z differential cross-sections are compared with a variety of MC predictions, including the higher-order DYTURBO analytical resummation. All predictions show a small discrepancy with data for W^+/W^- at 13 TeV.

• The integrated cross-sections are reported with high precision. An improvement by a factor of ≥2 is found after the updated luminosity measurement.

Important input to the low pile-up m_W measurement!
Backup
A MC 16 campaign was produced to match the low pile-up condition in data:
• W & Z production: Powheg+Pythia8 AZNLO, CT10 PDF
• Top-related background: Powheg+Pythia8
• Di-boson background: Sherpa
• Minimum-bias events: Pythia8 A3 tune with NNPDF2.3LO

<table>
<thead>
<tr>
<th>Cut</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSSF dilepton</td>
<td>Electron pair or muon pair</td>
</tr>
</tbody>
</table>
| At least one lepton triggers the event | • Electron, $E_T > 15$ GeV, loose ID.  
  • Or muon, $E_T > 14$ GeV. |
| Isolation                   | $P_{Tcone20} / \text{Min}(p_{Tl}, 50\text{GeV}) < 0.1$ |
| Additional lepton veto      | Veto $\geq3$ muons (electrons) with $p_{Tl} > $ 20 GeV + medium (loose) ID |
| Kinematics                  | $66 < m_{ll} < 116$ GeV                                |

Analysis cuts for Z signal selection
Electron SF and calibration

- The electron reconstruction SF: extrapolation of the standard high-mu SFs to the low-mu regime applied to both the 5.02 and 13 TeV datasets.
- The identification SF: measured in-situ separately for the 5.02 and 13 TeV data.
- Isolation and trigger efficiencies SF: measured in-situ using the 5.02 and 13 TeV combined datasets.
- Electron energy scale and resolution corrections are measured in-situ using Z->ee events from the low-mu dataset.
Muon SF and calibration

- Muon reconstruction efficiencies: extrapolated from high-mu measurements.
- The muon trigger, isolation and TTVA efficiencies: measured in-situ.
- Momentum scale and resolution: derived from the high-mu data.
- Sagitta bias corrections: derived from 2017 low-mu datasets.
Iterative Bayesian unfolding

• Assuming the true distribution after the fiducial cut is $T_j$:

$$D_i = \sum_j M_{ij} \varepsilon_j T_j + B_i$$

• Then the unfolded spectrum $\hat{U}_j$ estimates the underlying $T_j$:

$$\hat{U}_j = \sum_i U_{ij} (D_i - B_i) \times p_i$$

$i = \text{reco-level bin, } j = \text{unfolded-level bin}$

$M_{ij}$: Migration matrix

$\varepsilon_j$: Reconstruction efficiency

$p_i$: Reconstruction purity

$U_{ij}$: The unfolding transformation

References:

[1] doi.org/10.1016/0168-9002(95)00274-X

Uncertainty propagation

• **Data statistics** $\tilde{U}_j^\alpha = \sum_i U_{ij} (D_i^\alpha - B_i)$
Fluctuate the data -> calculate the spread at unfolded level.

• **MC statistics** $\tilde{U}_j^\alpha = \sum_i U_{ij}^\alpha (D_i - B_i)$
Fluctuate the migration matrix, efficiency and purity corrections -> calculate
the spread at unfolded level.

• **Experimental** systematics $\tilde{U}_j^\alpha = \sum_i U_{ij}^\alpha (D_i - B_i)$
Vary the migration matrix, efficiency and purity corrections.

• **Background** systematics $\tilde{U}_j^\alpha = \sum_i U_{ij} (D_i - B_i^\alpha)$
Vary the estimation of background.
\( p_T^V \) reweighting

- For a first fit, the data/MC agreement is optimized at reco-level by reweighting the truth-level \( p_T^V \) distribution. Once the reweighting function is determined, it will be used to correct the \( p_T^V \) distribution in the MC.

- A second fit is performed after \( p_T^V \) reweighting as a closure test. The uncertainties in the fit parameters are propagated to the unfolding.

**Optimization of reco-level distribution.**

\[
\chi^2 = \sum_{ij} \Delta_i^T C_{ij}^{-1} \Delta_j, \quad \text{i: reco-level bin} \\
\Delta_i = (D_i - B_i) - \sum_j R_{ij} \times (w_T(p_T^W))_j, \quad \text{j: truth level bin}
\]

\[
(w_T(p_T^W))_j = N_j \left[ \left( 1 + a p_{T,j}^W + b p_{T,j}^W \right)^2 \left( 1 - c + c \times r_{NPDF/CT10}(p_T^W) \right) \right]
\]

Fitted truth reweighting functions of \( p_T^W \). The final choice is the \( e\mu \) average.

Data/MC ratio for reco-level \( u_T \) in 13 TeV \( W^-\rightarrow\mu\nu \) channel, before and after the \( p_T^V \) modelling correction.
Unfolding bias uncertainty for $p_T^W$

• Fit uncertainty: uncertainties in the parameters of the $p_T^W$ reweighting function.

• Parametrization uncertainty: the difference caused by determining the $p_T^W$ reweighting using an alternative function.

• Initial $(p_T^W, y)$ uncertainty: reweight $(p_T^W, y)$ to alternative MC predictions to get different initial spectra.

• The non-closure of the reweighting.
The measurement of the $p_T^Z$ spectrum

- $p_T^Z(p_T^{ll}) - p_T^Z(u_T)$ compatibility and uncertainty break-down

<table>
<thead>
<tr>
<th></th>
<th>5.02 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (Stat. + Syst.)</td>
<td>14.9 / 14</td>
<td>8.7 / 16</td>
</tr>
<tr>
<td>$p$-value</td>
<td>38.5%</td>
<td>85%</td>
</tr>
</tbody>
</table>

The $p_T^Z(p_T^{ll}) - p_T^Z(u_T)$ compatibility test at 5.02 TeV (left) and at 13 TeV (right). Good compatibility is found at both center-of-mass energies.

Break-down of unfolded-level shape uncertainties for $p_T^{ee}$ at 5.02 TeV (left) and at 13 TeV (right).

The data statistics dominates the uncertainty.

The unfolding bias and the optimization of unfolding for $p_T^Z$ follow the methods described for $p_T^W$. 

The data statistics dominates the uncertainty.
$p_T^Z$ differential cross-section

Measured $p_T^Z$ spectra vs NNLO+NNLL DYTURBO predictions using different PDF sets.
W/Z ratios

ATLAS Preliminary
\( \sqrt{s} = 5.02 \text{ TeV}, 255 \text{ pb}^{-1} \)
W → ℓν/ Z → ll

ATLAS Preliminary
\( \sqrt{s} = 13 \text{ TeV}, 338 \text{ pb}^{-1} \)
W → ℓν/ Z → ll

\( 1/\sigma \frac{d\sigma}{dp_T} \text{ [GeV}^{-1}] \) W/Z

\( p_T \text{ [GeV]} \)
## MJ yield

<table>
<thead>
<tr>
<th>Channel</th>
<th>$W^- \rightarrow e^-\nu$</th>
<th>$W^+ \rightarrow e^+\nu$</th>
<th>$W^- \rightarrow \mu^-\nu$</th>
<th>$W^+ \rightarrow \mu^+\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MJ background yield</td>
<td>2200</td>
<td>2300</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Statistics</td>
<td>300 (14%)</td>
<td>340 (14%)</td>
<td>120 (40%)</td>
<td>140 (25%)</td>
</tr>
<tr>
<td>Extrapolation</td>
<td>290 (13%)</td>
<td>340 (15%)</td>
<td>210 (70%)</td>
<td>230 (40%)</td>
</tr>
<tr>
<td>$\mu_T$-dependence</td>
<td>600 (29%)</td>
<td>800 (40%)</td>
<td>270 (90%)</td>
<td>300 (50%)</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>700 (32%)</td>
<td>900 (40%)</td>
<td>340 (110%)</td>
<td>400 (70%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>$Z \rightarrow ee$</th>
<th>$Z \rightarrow \mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.02 TeV</td>
<td>$Z \rightarrow \ell\ell$</td>
<td></td>
</tr>
<tr>
<td>MJ background yield</td>
<td>$0^{+100}_{-0}$</td>
<td>16 ± 8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>$Z \rightarrow ee$</th>
<th>$Z \rightarrow \ell\ell$</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 TeV</td>
<td>$Z \rightarrow \ell\ell$</td>
<td></td>
</tr>
<tr>
<td>MJ background yield</td>
<td>110 ± 70</td>
<td>180 ± 40</td>
</tr>
</tbody>
</table>