Measurement of the W-boson mass at the ATLAS experiment

Oleh Kivernyk

LAPP-CNRS

September 4, 2017

Workshop on the Standard Model and Beyond

Corfu2017
Motivation

- Relation in EW sector of the SM:
  \[ M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_F} \cdot \frac{1}{1 - \Delta r} \]

- Loop corrections

\[ \Delta r(M_t^2, \ln(M_H), M_W, M_Z, \ldots) \]

Current world average exp.
\[ M_W = 80.385\pm0.015 \text{ GeV} \]

- Probe consistency of the SM via \( M_W \)

<table>
<thead>
<tr>
<th>measurement [GeV]</th>
<th>prediction [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_H )</td>
<td>125.09\pm0.24</td>
</tr>
<tr>
<td>( m_t )</td>
<td>172.84\pm0.70</td>
</tr>
<tr>
<td>( M_W )</td>
<td>80.385\pm0.015</td>
</tr>
</tbody>
</table>

- Objective: experimental precision of about 8 MeV
- Sensitive to several BSM scenarios

Global EW fit

- Measure SM observables
- Fit SM relations to precision data

\[ (O_{\text{indirect}} - O) / \sigma_{\text{tot}} \]

arXiv:1407.3792
Strategy of $W$-mass measurement

- **Basic objects:** single isolated lepton $p_T^\ell$, recoil $u_T = \sum \vec{E}_T$ (a measure of $p_T^W$)
- **Observables sensitive to $M_W$:**
  - Lepton transverse momentum $p_T^\ell$
  - (Neutrino transverse energy) $E_T^\nu = |p_T^\nu|$, $p_T^\nu = -(p_T^\ell + \vec{u})$
  - Transverse mass $m_T^W = \sqrt{2p_T^\ell p_T^\nu(1 - \cos \Delta\phi_{\ell\nu})}$

**Template fit method:**

- The $p_T^\ell, m_T^W$ and $E_T^{\text{miss}}$ distributions are computed with MC for different values of $M_W$
- Each template is compared to data by means of $\chi^2$
- The preferred value of $M_W$ corresponds to minimum of the $\chi^2$ function

$p_T^\ell > 30 \text{ GeV}, E_T^\nu > 30 \text{ GeV}$
$u < 30 \text{ GeV}, m_T^W > 60 \text{ GeV}$

$\delta M_W^{\text{stat}} = 10/13 \text{ MeV}$ for $p_T^\ell / m_T^W$
### Experimental corrections

#### Lepton calibration
- **Momentum scale and resolution** corrected to match well-known $M_Z$ distribution in $Z \rightarrow \ell\ell$ resonance
- Lepton reconstruction and selection requirements corrected using $Z \rightarrow \ell\ell$ via Tag-and-Probe method

#### Recoil calibration
- Event activity correction (Nb of pile-up interactions, $\Sigma E_T$)
- Recoil response calibrated using $p_T$ balance between lepton-pair and $u_T$ in $Z \rightarrow \ell\ell$

![Z boson diagram](image)

**Total lepton uncertainty:** 10/14 MeV for muons/electrons
**Recoil uncertainty:** 2.6/13.0 MeV for $p_T^\ell / m_W$
Physics modeling

No available generator can describe all these effects

As starting point, we use **PowhegPythia** generator

Corrections to **PowhegPythia** are based on factorization of fully differential leptonic DY cross section into 4 pieces:

- Variation of $d\sigma/dm$ is modeled with Breit-Wigner+EW corrections
  \[ \frac{d\sigma}{dm} \sim \frac{m^2}{(m^2 - m_V^2)^2 + m^4 \Gamma_V^2 / m_V^2} \]
- The $d\sigma/dp_T$ is modeled with parton shower MC
- The $d\sigma/dy$ and $A_i$ (describe spin correlations) are modeled with NNLO QCD predictions

A model in each part is constrained using experimental measurements of Z and W production
Rapidity and pseudorapidity distributions

- Modeled with NNLO QCD predictions using DYNNO
- PDF set CT10nnlo: best agreement with 7 TeV data (sub-% precise measurement)
- Predictions validated with $W^+$, $W^-$ and $Z$ data: $\chi^2 = 45/34$ satisfactory
- **Uncertainty:** from CT10nnlo, envelope of CT14 and MMHT

\[
R_s = \frac{s+\bar{s}}{u+d}
\]

\[Q^2 = 1.9 \text{ GeV}^2, \ x=0.023\]

![Graphs showing distributions of rapidity and pseudorapidity for ATLAS data compared to predictions](image)

\[\sqrt{s} = 7 \text{ TeV}, 4.6 \text{ fb}^{-1}\]

\[\text{Data} \quad \text{Prediction (CT10nnlo)}\]

\[\text{Data} (W^-) \quad \text{Data} (W^+) \quad \text{Prediction (CT10nnlo)}\]

\[\text{Data (W^-)} \quad \text{Data (W^+)} \quad \text{Prediction (CT10nnlo)}\]
Angular coefficients $A_i$

- Fully differential cross section for spin-1 boson production, to all orders:

- $A_i$’s are modeled with NNLO QCD predictions using DYNNLO

- Predictions are validated by comparisons to the Z measurement at 8 TeV (arXiv:1606.00689)

- **Uncertainty**: experimental uncertainty + observed discrepancy for $A_2$

\[
\frac{d\sigma}{dp_T^Z dy Z m_Z^2 d\cos \phi d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z dy Z m_Z^2} \left\{ (1 + \cos^2 \theta) + \frac{1}{2} A_0(1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi + \frac{1}{2} A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi \right\}.
\]

\[
\begin{array}{l}
\textbf{ATLAS} \\
\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \\
pp \rightarrow Z + X
\end{array}
\]

$A_0$ and $A_2$ comparison with data and DYNNLO predictions.
$p_T^W$ modeling

- $p_T^V$ easy to measure in $Z \rightarrow ll$ events, but hard for $W \rightarrow l\nu$
- Calibration $W$ with $Z$: 
  \[
  \frac{d\sigma(W)}{dp_T} = \left[ \frac{d\sigma(W)/dp_T}{d\sigma(Z)/dp_T} \right]_{\text{pred}} \times \left[ \frac{d\sigma(Z)}{dp_T} \right]_{\text{meas}}
  \]
- Use **Pythia8** parton shower, tuned to $p_T^Z$ data at 7 TeV (AZ tune) → tuned parameters: $\alpha_s$, intrinsic $k_T$, $Q_0$
- Apply model to $W$ relying on good prediction of $W/Z$ ratio → **validated on data**
- More advanced DYRES, Resbos, Powheg MiNLO+Pythia8 are disfavoured by data
- **Uncertainty:** $p_T^Z$ data, PS parameters, $\mu_F$, heavy quark masses
Missing part: backgrounds

- EW and top backgrounds are from MC
- Multijets background is estimated from data
  → from control region with large activity around leptons
  → normalized in jet-enriched region with relaxed kinematic cut(s)

\( W \)–mass sensitive distributions:

![ATLAS W-boson mass in ATLAS](image)
Mass measurements

- A crucial aspect is the categorisation ($p_T^\ell$, $m_W^T$; electrons, muons; $W^+/W^-$; $|\eta|$-bins)
- Consistent results → validates the detector calibration and physics modeling
- Compatibility test: $\chi^2/\text{n.dof} = 29/27$
- Precision compatible to the single most precise measurement (CDF)

Results

$m_W = 80369.5 \pm 6.8 \text{ MeV (stat.)} \pm 10.6 \text{ MeV (exp. syst.)} \pm 13.6 \text{ MeV (mod. syst.)}$

$m_W = 80369.5 \pm 18.5 \text{ MeV},$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T-p_T^\ell$, $W^\pm$, e-(\mu)</td>
<td>80369.5</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
<td>29/27</td>
</tr>
</tbody>
</table>

$m_{W^+} - m_{W^-} = -29 \pm 28 \text{ MeV}$
Standard Model consistency

- **Consistent** with the SM prediction and with the current world average value
- No signs of new physics

**SM prediction for** $m_W$ **assuming**

$m_H = 125.09 \pm 0.24$ GeV

$m_t = 172.84 \pm 0.70$ GeV

**SM prediction for** $m_W$ **vs** $m_t$ **assuming** $m_H = 125.09 \pm 0.24$ GeV
Combined results

- Good compatibility between partial combinations
- Dominant contribution from $p_T^\ell$
- Significant contribution from electron channel

### Results

\[
m_W = 80369.5 \pm 6.8 \text{ MeV (stat.)} \pm 10.6 \text{ MeV (exp. syst.)} \pm 13.6 \text{ MeV (mod. syst.)} \\
= 80369.5 \pm 18.5 \text{ MeV,}
\]

### Table

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T-p_T^\ell, W^\pm, e-\mu$</td>
<td>80369.5</td>
<td>6.8</td>
<td>6.6</td>
<td>6.4</td>
<td>2.9</td>
<td>4.5</td>
<td>8.3</td>
<td>5.5</td>
<td>9.2</td>
<td>18.5</td>
<td>29/27</td>
</tr>
</tbody>
</table>
Multijet background

EW and top backgrounds are from MC; MJ background is estimated from data

- **General method:**
  - Define a background dominated fit region with relaxed kinematic cut(s)
  - Signal distribution from MC; background from control region with inverted lepton isolation cut (large activity around leptons)
  - The multijet background is normalized with fraction fit

- **Variations:**
  - 3 observables ($p_T^{miss}$, $m_W$, $p_\ell^T/m_W$); 2 fitting regions
  - Different isolation criteria → extrapolate to the signal region

- **Uncertainty:** $\sim 4$ MeV ($\mu$); $\sim 8$ MeV ($e$)
W-like transverse mass $m_T(l)$:
- Reconstructed from recoil and lepton

Calibration is verified with $M_Z \rightarrow$ compatibility within $< 1\sigma (p_T^l)$ and $1.4\sigma (m_T^Z)$ with the PDG value
Theoretically more advanced resummed predictions were also tried (DYRES, ResBos, Cute)

They predict harder $p_T$ spectrum wrt Pythia

Such behaviour is strongly disfavoured by the $u_{\parallel}(l)$ distribution in data → not used
**$p_T^{W/Z}$ Modeling Uncertainty**

- Difference between $W$ and $Z$: PDF and heavy-quark effects
- $Z \to W$ extrapolation uncertainty:
  - variation of remaining parton shower parameters
  - choice of LO parton shower PDF: CTEQ6L1, CT14, MMGT2014 and NNPDF2.3
  - factorization scale (decorrelated between light and heavy quark induced production)
  - heavy quark masses ($\delta m_c = \pm 0.5$ GeV)

![Graph showing $\sigma_W/\sigma_Z$ vs. $p_T^{W/Z}$]

**ATLAS Simulation**

$\sqrt{s}=7$ TeV, $pp \to W^{\pm}+X, pp \to Z+X$
Summary of modeling uncertainties

- CT10nnlo PDFs (synchronized in DYNNLO and Pythia) + envelop CT10 to CT14 and MMHT: dominant uncertainty, followed by $p_T^W$ uncertainty due to heavy-flavour-initiated production
- PDF uncertainty are **anti-correlated** between $W^+$ and $W^-$ → significant reduction from the combination
- AZ tune uncertainty; parton shower PDF and factorization scale; heavy-quark mass effects
- $A_i$ uncertainties from Z data + envelope for $A_2$ discrepancy

<table>
<thead>
<tr>
<th>$W$-boson charge Kinematic distribution</th>
<th>$W^+$</th>
<th>$W^-$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^W, m_T$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed-order PDF uncertainty</td>
<td>13.1</td>
<td>14.9</td>
<td>12.0</td>
</tr>
<tr>
<td>AZ tune</td>
<td>3.0</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>Charm-quark mass</td>
<td>1.2</td>
<td>1.5</td>
<td>1.2</td>
</tr>
<tr>
<td>Parton shower $\mu_F$ with heavy-flavour decorrelation</td>
<td>5.0</td>
<td>6.9</td>
<td>5.0</td>
</tr>
<tr>
<td>Parton shower PDF uncertainty</td>
<td>3.6</td>
<td>4.0</td>
<td>2.6</td>
</tr>
<tr>
<td>Angular coefficients</td>
<td>5.8</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Total</td>
<td>15.9</td>
<td>18.1</td>
<td>14.8</td>
</tr>
</tbody>
</table>

$\delta m_W$ [MeV]
Electroweak corrections

- **Effects present in MC simulation:**
  - $\rightarrow$ FSR modeled with Photos (dominant effect)
  - $\rightarrow$ ISR modeled in Pythia PS

- **Missing effects:**
  - $\rightarrow$ fermion pair emission
  - $\rightarrow$ NLO EW corrections

- Related uncertainties estimated using dedicated MC (Winhac)

<table>
<thead>
<tr>
<th>Kinematic distribution</th>
<th>$p_T^c$</th>
<th>$m_T^{c\ell}$</th>
<th>$p_T^{\ell}$</th>
<th>$p_T^{\gamma}$</th>
<th>$m_T^{\gamma\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m_W$ [MeV]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FSR (real)</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>FSR (pair production)</td>
<td>3.6</td>
<td>0.8</td>
<td>&lt; 0.1</td>
<td>4.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Pure weak and IFI corrections</td>
<td>3.3</td>
<td>2.5</td>
<td>0.6</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Total [MeV]</strong></td>
<td>4.9</td>
<td>2.6</td>
<td>0.6</td>
<td>5.6</td>
<td>2.6</td>
</tr>
</tbody>
</table>
Challenges @LHC

Additional complications at LHC wrt TeVatron

- Higher **pile-up** environment complicates the **hadronic recoil** calibration
- Larger role of sea-quarks in $W$-boson production $\rightarrow$ implies larger uncertainty on the $p_T^W$ distribution
- Asymmetric production of $W^+$ and $W^-$ $\rightarrow$ charge-dependent analysis
- Large role of heavy $2^{nd}$ generation quarks $\rightarrow$ implies larger uncertainty from modeling of $p_T^W$ and $W$-polarisation

PDF uncertainty $\rightarrow$ $W$ polarization $\rightarrow$ uncertainty on $p_T^W$
Summary of uncertainties

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \to \mu^+, \eta &lt; 0.8$</td>
<td>80371.3</td>
<td>29.2</td>
<td>12.4</td>
<td>0.0</td>
<td>15.2</td>
<td>8.1</td>
<td>9.9</td>
<td>3.4</td>
<td>28.4</td>
<td>47.1</td>
</tr>
<tr>
<td>$W^+ \to \mu^+, 0.8 &lt; \eta &lt; 1.4$</td>
<td>80354.1</td>
<td>32.1</td>
<td>19.3</td>
<td>0.0</td>
<td>13.0</td>
<td>6.8</td>
<td>9.6</td>
<td>3.4</td>
<td>23.3</td>
<td>47.6</td>
</tr>
<tr>
<td>$W^+ \to \mu^+, 1.4 &lt; \eta &lt; 2.0$</td>
<td>80426.3</td>
<td>30.2</td>
<td>35.1</td>
<td>0.0</td>
<td>14.3</td>
<td>7.2</td>
<td>9.3</td>
<td>3.4</td>
<td>27.2</td>
<td>56.9</td>
</tr>
<tr>
<td>$W^+ \to \mu^+, 2.0 &lt; \eta &lt; 2.4$</td>
<td>80334.6</td>
<td>40.9</td>
<td>112.4</td>
<td>0.0</td>
<td>14.4</td>
<td>9.0</td>
<td>8.4</td>
<td>3.4</td>
<td>32.8</td>
<td>125.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^- \to \mu^-$, $\eta &lt; 0.8$</td>
<td>80375.5</td>
<td>30.6</td>
<td>11.6</td>
<td>0.0</td>
<td>13.1</td>
<td>8.5</td>
<td>9.5</td>
<td>3.4</td>
<td>30.6</td>
<td>48.5</td>
</tr>
<tr>
<td>$W^- \to \mu^-$, $0.8 &lt; \eta &lt; 1.4$</td>
<td>80417.5</td>
<td>36.4</td>
<td>18.5</td>
<td>0.0</td>
<td>12.2</td>
<td>7.7</td>
<td>9.7</td>
<td>3.4</td>
<td>22.4</td>
<td>49.7</td>
</tr>
<tr>
<td>$W^- \to \mu^-$, $1.4 &lt; \eta &lt; 2.0$</td>
<td>80379.4</td>
<td>35.6</td>
<td>33.9</td>
<td>0.0</td>
<td>10.5</td>
<td>8.1</td>
<td>9.7</td>
<td>3.4</td>
<td>23.1</td>
<td>56.9</td>
</tr>
<tr>
<td>$W^- \to \mu^-$, $2.0 &lt; \eta &lt; 2.4$</td>
<td>80334.2</td>
<td>52.4</td>
<td>123.7</td>
<td>0.0</td>
<td>11.6</td>
<td>10.2</td>
<td>9.9</td>
<td>3.4</td>
<td>34.1</td>
<td>139.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+ \to e^+, \eta &lt; 0.6$</td>
<td>80352.9</td>
<td>29.4</td>
<td>0.0</td>
<td>19.5</td>
<td>13.1</td>
<td>15.3</td>
<td>9.9</td>
<td>3.4</td>
<td>28.5</td>
<td>50.8</td>
</tr>
<tr>
<td>$W^+ \to e^+, 0.6 &lt; \eta &lt; 1.2$</td>
<td>80381.5</td>
<td>30.4</td>
<td>0.0</td>
<td>21.4</td>
<td>15.1</td>
<td>13.2</td>
<td>9.6</td>
<td>3.4</td>
<td>23.5</td>
<td>49.4</td>
</tr>
<tr>
<td>$W^+ \to e^+, 1.2 &lt; \eta &lt; 2.0$</td>
<td>80352.4</td>
<td>32.4</td>
<td>0.0</td>
<td>26.6</td>
<td>16.4</td>
<td>32.8</td>
<td>8.4</td>
<td>3.4</td>
<td>27.3</td>
<td>62.6</td>
</tr>
<tr>
<td>$W^+ \to e^+, 2.0 &lt; \eta &lt; 2.4$</td>
<td>80297.5</td>
<td>33.0</td>
<td>0.0</td>
<td>18.7</td>
<td>11.2</td>
<td>12.8</td>
<td>9.7</td>
<td>3.4</td>
<td>23.9</td>
<td>49.0</td>
</tr>
<tr>
<td>$W^+ \to e^+, 2.4 &lt; \eta &lt; 2.8$</td>
<td>80423.8</td>
<td>42.8</td>
<td>0.0</td>
<td>33.2</td>
<td>12.8</td>
<td>35.1</td>
<td>9.9</td>
<td>3.4</td>
<td>28.1</td>
<td>72.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^- \to e^-$, $\eta &lt; 0.6$</td>
<td>80415.8</td>
<td>31.3</td>
<td>0.0</td>
<td>16.4</td>
<td>11.8</td>
<td>15.5</td>
<td>9.5</td>
<td>3.4</td>
<td>31.3</td>
<td>52.1</td>
</tr>
<tr>
<td>$W^- \to e^-$, $0.6 &lt; \eta &lt; 1.2$</td>
<td>80381.5</td>
<td>30.4</td>
<td>0.0</td>
<td>21.4</td>
<td>15.1</td>
<td>13.2</td>
<td>9.6</td>
<td>3.4</td>
<td>23.5</td>
<td>49.4</td>
</tr>
<tr>
<td>$W^- \to e^-$, $1.2 &lt; \eta &lt; 2.0$</td>
<td>80352.4</td>
<td>32.4</td>
<td>0.0</td>
<td>26.6</td>
<td>16.4</td>
<td>32.8</td>
<td>8.4</td>
<td>3.4</td>
<td>27.3</td>
<td>62.6</td>
</tr>
<tr>
<td>$W^- \to e^-$, $2.0 &lt; \eta &lt; 2.4$</td>
<td>80423.8</td>
<td>42.8</td>
<td>0.0</td>
<td>33.2</td>
<td>12.8</td>
<td>35.1</td>
<td>9.9</td>
<td>3.4</td>
<td>28.1</td>
<td>72.3</td>
</tr>
</tbody>
</table>

$|\eta|$ comb. $e \to \sim 15$ MeV
$\mu \to \sim 11$ MeV

Strongly correlated
Strongly correlated

$|\eta|$ comb. $W^+/W^-$ comb. $\to \sim 8$ MeV

Fit ranges: $32<p_T<45$ GeV; $66<m_T<99$ GeV, minimizing total expected measurement uncertainty.
Lepton calibration

Correct for imperfect knowledge of magnetic field, material, detector alignment, response:

Momentum corrections
- Momentum scale and resolution corrected to match well-known $M_Z$ distribution in $Z \rightarrow \ell\ell$ resonance

Efficiency corrections
- Lepton reconstruction and selection requirements are corrected in MC using $Z \rightarrow \ell\ell$ with Tag-and-Probe method

Total lepton uncertainty:
- 10 MeV (muon) and 14 MeV (electron)
Hadronic recoil corrections

Calibration relies on momentum balance in the transverse plane
- Match event activity in data and MC (Number of pile-up interactions, $\Sigma E_T$)
- Residual recoil scale and resolution corrections based on parallel and perpendicular projections to Z direction

**Uncertainty:** 2.6/13.0 MeV with $p_T^\ell/m_W$

---

**ATLAS**
\[ \sqrt{s} = 7 \text{ TeV}, \ 4.1 \text{ fb}^{-1} \]

- Data
- $Z\rightarrow \mu^+\mu^-$ (before transf.)
- $Z\rightarrow \mu^+\mu^-$ (after transf.)

---

**ATLAS**
\[ \sqrt{s} = 7 \text{ TeV}, \ 4.1 \text{ fb}^{-1} \]

- Data
- $Z\rightarrow \mu^+\mu^-$ (before corr.)
- $Z\rightarrow \mu^+\mu^-$ (after corr.)