Recent diboson and polarization measurements at ATLAS

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on behalf of the ATLAS Collaboration

University of Freiburg

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Overview

- Probe self-couplings between massive vector bosons in the Standard Model
- Important test of perturbative QCD and electroweak corrections and resummation schemes
- Higgs mechanism provides mass and longitudinal polarization to gauge vector bosons
- Sensitivity to new physics via anomalous couplings or preferential couplings to polarization modes

**Zγ+JETS CROSS-SECTIONS**

[arXiv:2212.07184] (Accepted by JHEP)

- Anomalous triple gauge couplings
- Sensitive to PDFs

**W⁺W⁻ CROSS-SECTIONS**

[ATLAS-CONF-2023-012]

- Triple gauge couplings
- Important background for \( H \to WW \) and BSM searches

**WZ JOINT POLARIZATION**

[arXiv:2211.09435] (Accepted by PLB)

- First observation joint \( W^\pm Z \) polarization
**Study jet activity and 2D differential distributions**

**Zγ+jets: including jet activity**

Sensitive to γ content of p

- Tight photon $p_T > 30$ GeV.
- $Z \rightarrow \ell\ell$, with $\ell = e, \mu$ and $m_{\ell\ell} > 40$ GeV
- $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV (enrich ISR)
- No requirements on $N_{\text{jets}}$
- Pile-up and Z+jets contributions estimated using data-driven techniques

(From [arXiv:1911.04813])
Z\gamma+JETS CROSS-SECTIONS

- Fiducial differential cross-sections across
  - 13 observables related to lepton, jet and $E_{T}^{\text{miss}}$ kinematics
  - 3 2D distributions sensitive to pQCD
  - 2 2D distributions sensitive to polarization effects in [Collins-Soper frame]

- Integrated fiducial cross section

\[ \sigma_{\text{fid}}^{\text{exp}} = 533.7 \pm 2.1 \text{(stat)} \pm 12.4 \text{(syst)} \pm 9.1 \text{(lumi)}, \]

versus predictions \[ \sigma_{\text{fid}}^{\text{Sherpa 2.2.11}} = 479.5 \pm 0.3 \text{ and } \sigma_{\text{fid}}^{\text{MiNNLO}} = 493.0 \pm 3.0. \]

- Total uncertainty of 2.9% on $\sigma_{\text{fid}}^{\text{exp}}$.
  - 4% (0 jet) up to 10% ($\geq 2$ jets), dominated by pile-up and jet-related uncertainties.

- Good agreement between Data and theory predictions
**W⁺W⁻ JET-INCLUSIVE MEASUREMENT**

- Largest diboson production cross-section + clean signature \( \Rightarrow \) **Precision**
- Large contributions from irreducible backgrounds, especially \( t\bar{t} \)

**FIRST W⁺W⁻ DIFFERENTIAL CROSS-SECTION MEASUREMENTS IN FULLY JET-INCLUSIVE PHASE SPACE**

- Accurate top-quark and lepton misID background estimates using **data-driven techniques**
- High precision in **fully jet-inclusive phase space**

- Fully leptonic final states, different flavor and opposite charge, \( WW \to e^±\mu^±ν_εν_μ \)
- Suppress \( Z \to ττ \) and \( H \to WW \) by \( m_{eμ} > 85 \text{ GeV} \)
- Reduce top-quark contributions using **b-jet veto**

**b-JET COUNTING METHOD** [arXiv:1910.08819]

- Measure \( N_{1b,2b}^{t\bar{t}} \) in 1 b-jet and 2 b-jet regions
- Determine both \( t\bar{t} \) effective cross-section and b-jet reconstruction efficiency \( ε_b \) **bin-by-bin**
- Estimate differential \( N_{0b}^{t\bar{t}} \) (SR)
**W^+W^- Jet-inclusive: Results**

- Precision measurement of $WW$ production in fully leptonic final state across 12 observables on lepton, jet and $E_T^{miss}$ kinematics
- **Fiducial** (integrated and differential) and **total cross-sections**
- **Precision of 3.1%**, dominated by top modelling and fake background estimate

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**ATLAS Preliminary**

\[ \sqrt{s} = 13 \text{ TeV}, \ 140 \text{ fb}^{-1} \]

$pp \rightarrow W^+W^-$

**Matrix 2.0 nNNLO $\otimes$ NLO EW**

$123 \pm 1 \text{ (pdf)} \pm 2 \text{ (scale)} \text{ pb}$

This measurement

$127 \pm 1 \text{ (stat.)} \pm 4 \text{ (syst.) \ pb}$

CMS 36 fb$^{-1}$[1]

$118 \pm 1 \text{ (stat.)} \pm 7 \text{ (syst.) \ pb}$

ATLAS 36 fb$^{-1}$[2]

$137 \pm 2 \text{ (stat.)} \pm 10 \text{ (syst.) \ pb}$


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**Excellent agreement of state-of-the-art theory predictions with Data**

Compatible precision between Data and SM prediction
**WZ JOINT POLARIZATION**

Polarization states measured in

**MODIFIED HELICITY COORDINATE SYSTEM**

Helicity fractions $f_{00}$, $f_{0T}$, $f_{T0}$, $f_{TT}$ are not Lorentz invariant

- Maximize decorrelation of 00 and TT polarization modes

**PREDICTIONS OF WZ JOINT POLARIZATION STATES AVAILABLE**

- LO + real corrections at reco level (MadGraph+Pythia) $\implies$ Insufficient [arXiv:2010.07149]
- NLO-QCD at particle level (MoCaNLO)

**METHODOLOGY**

- Virtual corrections via DNN reweighting

**VALIDATION**

- Closure to folded fixed-order predictions

- DNN classifies each joint polarization state
- 4 categories to disentangle mixed states (0T,T0)

**JOINT POLARIZATIONS AT NLO-QCD USING DNN**

**VIRTUAL CORRECTIONS VIA DNN**

**CLASSIFICATION**

- 4 categories DNN score

<table>
<thead>
<tr>
<th>Events / 0.2</th>
<th>Data / Pred.</th>
</tr>
</thead>
</table>

**4-CATEGORY DNN SCORE**

- Data / Pred. | WZ, ZZ Post-Fit (fs = 13 TeV, 139 fb⁻¹) |

**DNN REGRESSION**

- WZ SR Post-Fit

**DIBOSON AND POLARIZATION AT ATLAS**

José Pretel (University of Freiburg)
**WZ Joint Polarization: Results**

- **First observation** of $f_{00}$ state: $7.1\sigma$ obs ($6.2\sigma$ exp)
  \[ f_{0T}, f_{T0} \text{ and } f_{TT} \text{ with } 3.4\sigma (5.4\sigma), 7.1\sigma (6.6\sigma) \text{ and } 11\sigma (9.7\sigma), \text{ respectively} \]

- Joint and individual WZ polarization measurements compared to predictions

- Differential cross-sections across observables sensitive to polarization states

- $\sigma_{\text{exp}}^{\text{fid}} = 64.6 \pm 0.5 (\text{stat}) \pm 1.8 (\text{syst}) \pm 1.1 (\text{lumi}) \text{ fb} (\sigma_{\text{MATRIX}}^{\text{fid}} = 64.0 \pm 1.4 (\text{scale}))$

**Individual polarization**

**Joint WZ polarization**

- $f_{00} = 0.067 \pm 0.010$
- $f_{TT} = 0.644 \pm 0.032$
- $f_{0T} = 0.110 \pm 0.029$
- $f_{T0} = 0.179 \pm 0.023$

Dominated by theory uncertainties
Conclusions

- Recent experimental results on diboson production cross-sections and polarization measurements with the ATLAS detector were presented
- Overall, excellent agreement with state-of-the-art SM predictions is observed

**Zγ+jets cross-sections**

- Differential cross-section measurements across 13 observables, including jet activity and kinematics
- 5 2D distributions sensitive to pQCD and polarization effects
- Fiducial cross-section up to 4% (0 jet) and 10% (≥2 jets) precision

**W⁺W⁻ cross-sections**

- Fully jet-inclusive measurement of \( W⁺W⁻ \), benefited from data-driven top-quark background estimation
- Differential cross-sections across 12 observables related to lepton, jet and \( E_{miss} \) kinematics
- Integrated cross-section with precision of 3.1%

**WZ joint polarization**

- First observation of \( f_{00} \) state: 7.1σ obs (6.2σ exp)
- Joint and individual \( WZ \) polarization measurements in agreement with predictions
- Differential cross-sections of angular observables sensitive to polarization states
- Integrated cross-section with 3.4% precision

Thank you for your attention
Backup slides
# $Z\gamma + \text{jets uncertainties}$

<table>
<thead>
<tr>
<th>$N_{\text{jets}}$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>$&gt;2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source</strong></td>
<td>Uncertainty [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrons</td>
<td>1.0</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Muons</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
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<tr>
<td>Jets</td>
<td>1.7</td>
<td>1.7</td>
<td>4.5</td>
<td>8.8</td>
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<tr>
<td>Photons</td>
<td>1.4</td>
<td>1.3</td>
<td>1.3</td>
<td>1.2</td>
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<tr>
<td>Pile-up</td>
<td>2.1</td>
<td>0.8</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>Background</td>
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<td>1.8</td>
<td>3.0</td>
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<tr>
<td>MC statistical</td>
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<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Data statistical</td>
<td>0.8</td>
<td>1.5</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Theory</td>
<td>0.6</td>
<td>0.2</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4.2</td>
<td>3.8</td>
<td>6.3</td>
<td>10.3</td>
</tr>
</tbody>
</table>
**ATLAS Preliminary**

\( \sqrt{s} = 13 \text{ TeV}, 140 \text{ fb}^{-1} \)

\( pp \rightarrow e^\pm\nu\mu^\pm\bar{\nu} \)

This measurement

\( 707 \pm 7 \text{ (stat)} \pm 20 \text{ (syst)} \text{ fb} \)

**Predictions**

- **Powheg MiNNLO + Pythia8, NNPDF3.0 (*)**
  
  \( 654 \pm 10 \text{ (PDF)} \pm 15 \text{ (scale)} \text{ fb} \)

- **Sherpa 2.2.12 (0-1j@NLO, 2-3j@LO), NNPDF3.0 (*)**
  
  \( 660 \pm 10 \text{ (PDF)} \pm 48 \text{ (scale)} \text{ fb} \)

- **MATRIX 2.0 nNNLO, NNPDF3.1**
  
  \( 711 \pm 7 \text{ (PDF)} \pm 16 \text{ (scale)} \text{ fb} \)

- **MATRIX 2.0 nNNLO \( \otimes \) NLO EW, NNPDF3.1**
  
  \( 688 \pm 7 \text{ (PDF)} \pm 15 \text{ (scale)} \text{ fb} \)

\( (*) + \text{Sherpa 2.2.2 } gg \rightarrow WW \times 1.7 \)

\( + \text{Sherpa 2.2.12 EW } qq \rightarrow WWjj \)
## WW Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total uncertainty</td>
<td>3.1%</td>
</tr>
<tr>
<td>Stat. uncertainty</td>
<td>1.1%</td>
</tr>
<tr>
<td>Top modelling</td>
<td>1.6%</td>
</tr>
<tr>
<td>Fake lepton background</td>
<td>1.5%</td>
</tr>
<tr>
<td>Flavour tagging</td>
<td>0.7%</td>
</tr>
<tr>
<td>Other background</td>
<td>0.9%</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>1.0%</td>
</tr>
<tr>
<td>Jet calibration</td>
<td>0.6%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.8%</td>
</tr>
<tr>
<td>Other systematic uncertainties</td>
<td>0.9%</td>
</tr>
</tbody>
</table>
## WW Theory Predictions

<table>
<thead>
<tr>
<th>Process</th>
<th>Code</th>
<th>PDF</th>
<th>Perturbative order</th>
<th>Fid. cross-section</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \to WW$</td>
<td>MATRIX2.0.1</td>
<td>NNPDF3.1</td>
<td>NNLO QCD</td>
<td>674 fb</td>
<td>±1.8 %</td>
</tr>
<tr>
<td>$q\bar{q} \to WW$</td>
<td>MiNNLO + PYTHIA8</td>
<td>NNPDF3.0</td>
<td>NNLO QCD + PS</td>
<td>624 fb</td>
<td>±1.1 %</td>
</tr>
<tr>
<td>$q\bar{q} \to WW$</td>
<td>SHERPA2.2.12</td>
<td>NNPDF3.0</td>
<td>NLO QCD + PS †</td>
<td>630 fb</td>
<td>±7.2 %</td>
</tr>
<tr>
<td>$gg \to WW$</td>
<td>MATRIX2.0.1</td>
<td>NNPDF3.1</td>
<td>NLO QCD</td>
<td>32 fb</td>
<td>±13 %</td>
</tr>
<tr>
<td>$gg \to WW$</td>
<td>SHERPA2.2.2</td>
<td>NNPDF3.0</td>
<td>LO QCD + PS †</td>
<td>15 fb</td>
<td>±30 %</td>
</tr>
<tr>
<td>$\gamma\gamma \to WW$</td>
<td>MATRIX 2.0.1</td>
<td>NNPDF3.1</td>
<td>LO</td>
<td>5 fb</td>
<td>±2.3 %</td>
</tr>
<tr>
<td>$\gamma\gamma \to WW$</td>
<td>MATRIX 2.0.1</td>
<td>NNPDF3.1</td>
<td>NLO EW</td>
<td>11 fb</td>
<td>±2.3 %</td>
</tr>
<tr>
<td>$q\bar{q} \to WWjj$ (EW)</td>
<td>SHERPA2.2.12</td>
<td>NNPDF3.0</td>
<td>LO + PS</td>
<td>4 fb</td>
<td>±7.0 %</td>
</tr>
</tbody>
</table>

For calculation of NLO EW correction:
<table>
<thead>
<tr>
<th>Process</th>
<th>Code</th>
<th>PDF</th>
<th>Perturbative order</th>
<th>Fid. cross-section</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \to WW$</td>
<td>MATRIX2.0.1</td>
<td>NNPDF3.1</td>
<td>LO</td>
<td>436 fb</td>
<td>±5.1 %</td>
</tr>
<tr>
<td>$q\bar{q} \to WW$</td>
<td>MATRIX2.0.1</td>
<td>NNPDF3.1</td>
<td>NLO EW</td>
<td>418 fb</td>
<td>±5.1 %</td>
</tr>
</tbody>
</table>

†: Includes matrix elements with additional parton emissions, matched and merged with the parton shower, which increases the accuracy of the simulation of high jet multiplicity events but also increases the nominal scale uncertainty.
**WW Pre-fit and Post-fit Distributions**

The plots show the distribution of events in the transverse scalar sum ($S_T$) for pre-fit and post-fit conditions. The data is compared to predictions for various processes, including WW, Top, Drell-Yan, Fakes, and WZ, ZZ, Vγ. The plots highlight the differences in the distributions before and after the fit, with a focus on the agreement between data and predictions.

- **ATLAS Preliminary Data**
- **Pre-fit and Post-fit**
- **$\sqrt{s} = 13$ TeV, 140 fb$^{-1}$**
- **$e^+\mu^-$**

The plots display the number of events in bins of $S_T$ and the ratio of data to prediction, with uncertainties shown as shaded areas. The data points are marked with solid circles, and the lines represent the predictions.

- **Pre-fit**
- **Post-fit**

The graphs provide insights into the performance of the ATLAS experiment in measuring diboson and polarization at the LHC.
### Absolute uncertainties joint polarizations

<table>
<thead>
<tr>
<th></th>
<th>$f_{00}$</th>
<th>$f_{0T}$</th>
<th>$f_{T0}$</th>
<th>$f_{TT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$ energy scale and id. efficiency</td>
<td>0.00018</td>
<td>0.0009</td>
<td>0.0012</td>
<td>0.0019</td>
</tr>
<tr>
<td>$\mu$ energy scale and id. efficiency</td>
<td>0.0004</td>
<td>0.0004</td>
<td>0.0004</td>
<td>0.0008</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ and jets</td>
<td>0.0017</td>
<td>0.0021</td>
<td>0.0020</td>
<td>0.0023</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.00031</td>
<td>0.00027</td>
<td>0.0007</td>
<td>0.0010</td>
</tr>
<tr>
<td>Misidentified lepton background</td>
<td>0.0012</td>
<td>0.0026</td>
<td>0.0013</td>
<td>0.0016</td>
</tr>
<tr>
<td>ZZ background</td>
<td>0.0005</td>
<td>0.00028</td>
<td>0.0005</td>
<td>0.0004</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>0.0016</td>
<td>0.0025</td>
<td>0.0021</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

| Parton Distribution Function | 0.0025 | 0.0029 | 0.0014 | 0.0028 |
| QCD scale               | 0.0010 | 0.014  | 0.0014 | 0.012  |
| Modelling               | 0.005  | 0.007  | 0.005  | 0.008  |

Total systematic uncertainty: $0.006$, $0.017$, $0.006$, $0.016$

Luminosity: $0.00019$, $0.0004$, $0.0004$, $0.00034$

Statistical uncertainty: $0.007$, $0.016$, $0.019$, $0.019$

Total: $0.010$, $0.029$, $0.023$, $0.032$

### Absolute uncertainties individual polarizations

<table>
<thead>
<tr>
<th></th>
<th>$W^\pm$ in $W^\pm Z$</th>
<th>$Z$ in $W^\pm Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_0$ $f_L-f_R$</td>
<td>$f_0$ $f_L-f_R$</td>
</tr>
</tbody>
</table>

| $e$ energy scale and id. efficiency | 0.0029 | 0.00030 | 0.0027 | 0.0007 |
| $\mu$ energy scale and id. efficiency | 0.004  | 0.0018  | 0.0015 | 0.0005 |
| $E_T^{\text{miss}}$ and jets | 0.004  | 0.0011  | 0.0006 | 0.0028 |
| Pile-up              | 0.0028  | 0.0015  | 0.0024 | 0.0029 |
| Misidentified lepton background | 0.007  | 0.00032 | 0.0033 | 0.0011 |
| ZZ background        | 0.0015  | 0.00025 | 0.0012 | 0.0023 |
| Other backgrounds    | 0.0020  | 0.0005  | 0.0013 | 0.0012 |

| Parton Distribution Function | 0.0011 | 0.0011 | 0.00011 | 0.0005 |
| QCD scale               | 0.012  | 0.0025 | 0.0004  | 0.005  |
| Modelling               | 0.025  | 0.0012 | 0.004   | 0.018  |

Total systematic uncertainty: $0.030$, $0.004$, $0.007$, $0.019$

Luminosity: $0.0005$, $0.00004$, $0.00012$, $0.00018$

Statistical uncertainty: $0.028$, $0.015$, $0.018$, $0.08$

Total: $0.04$, $0.016$, $0.019$, $0.08$
ATLAS
\( \sqrt{s} = 13 \) TeV, 139 fb\(^{-1} \)

Pulls \( f_{00} \) fit

Pol. templates, DNN reweighting method
Pol. templates, NLO QCD modelling

Nuis. Param. Pull

Pre-fit Impact on \( f_{00} \)
Post-fit Impact on \( f_{00} \)

Jet energy scale, NP I
Misid. leptons, NP I
Jet energy scale, NP II
Misid. leptons, NP II
ZZ background, PDFs
WZjj-EW background
tZ background
Muon isolation efficiency
Jet energy scale, NP III
Jet energy scale, NP IV
Jet energy resolution, NP I
ZZ background, PDFs
Misid. leptons, NP III
Jet energy scale, NP V
Jet energy scale, NP VI
Jet energy resolution, NP II

Nuis. Param. Pull

Pre-fit Impact on \( f_{00} \)
Post-fit Impact on \( f_{00} \)
**WZ Fid. Cross Section Uncertainties**

<table>
<thead>
<tr>
<th>Relative uncertainty [%]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$ energy scale and id. efficiency</td>
<td>0.8</td>
</tr>
<tr>
<td>$\mu$ energy scale and id. efficiency</td>
<td>1.1</td>
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<tr>
<td>$E_T^{\text{miss}}$ and jets</td>
<td>0.4</td>
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<tr>
<td>Pile-up</td>
<td>1.6</td>
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<tr>
<td>Misidentified lepton background</td>
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<tr>
<td>ZZ background</td>
<td>0.09</td>
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<tr>
<td>Other backgrounds</td>
<td>0.9</td>
</tr>
<tr>
<td>Parton Distribution Function</td>
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<td>QCD scale</td>
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<td>Modelling</td>
<td>0.04</td>
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<tr>
<td>Total systematic uncertainty</td>
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<tr>
<td>Luminosity</td>
<td>1.7</td>
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<tr>
<td>Statistical uncertainty</td>
<td>0.9</td>
</tr>
<tr>
<td>Total</td>
<td>3.4</td>
</tr>
</tbody>
</table>
$p_T^\nu$ \textbf{REGRESSION}

\begin{itemize}
\item \textbf{ATLAS Simulation}
\item Powheg+Pythia
\item DNN reco.
\item $\mu = -1.2, \text{RMS} = 190$
\item Analytical reco.
\item $\mu = -0.1, \text{RMS} = 209$
\item Perfect reco.
\item $\text{ATLAS Simulation}
\item Powheg+Pythia
\item DNN reco.
\item $\mu = 0.01, \text{RMS} = 1.33$
\item Analytical reco.
\item $\mu = 0.01, \text{RMS} = 1.26$
\item Perfect reco.
\end{itemize}

\begin{itemize}
\item \textbf{ATLAS Simulation}
\item Powheg+Pythia
\item DNN reco.
\item $\mu = 0.04, \text{RMS} = 0.31$
\item Analytical reco.
\item $\mu = 0.13, \text{RMS} = 0.41$
\item Perfect reco.
\end{itemize}

\begin{itemize}
\item \textbf{ATLAS Simulation}
\item Powheg+Pythia
\item DNN reco.
\item $\mu = -0.4, \text{RMS} = 0.1$
\item Analytical reco.
\item $\mu = -0.4, \text{RMS} = 0.1$
\item Perfect reco.
\end{itemize}