Measurement of the $Z/\gamma^*$ transverse momentum distribution in $pp$ collisions at $\sqrt{s} = 7$TeV with the ATLAS detector

On behalf of the ATLAS collaboration

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Outline

• Introduction
• Collision data and Simulation
• Analysis
  – Event selection
  – Background estimation
  – Unfolding
  – Systematics
• Results
• Summary and Conclusions
Introduction (1/2)

- The transverse momenta of $Z/\gamma^*$ bosons ($P_T^Z$) produced in pp collisions are a result of the QCD initial state radiation.

- $P_T^Z$ is sensitive to the nature of the QCD radiation.
  - An excellent testing ground for QCD predictions
    - Soft gluon resummation in low $P_T^Z$
    - Fixed order pQCD in high $P_T^Z$
  - An ideal laboratory for evaluating the phenomenology of vector boson production (e.g. event generators).
Introduction (2/2)

- We measure the normalized $P_T^Z$ distribution within the fiducial phase space using the $Z\rightarrow\mu\mu$ and $Z\rightarrow ee$ decays.
  
  - "normalized" measurement
    
    $\frac{1}{\sigma} \frac{d\sigma(Z)}{dp_T(Z)}$
    
    - A lot of systematic uncertainties cancel out leading to a better precision.
  
  - Fiducial phase space
    
    - $P_T^{e/\mu}>20$ GeV, $|\eta|<2.4$, 66 GeV<$M_{ll}$<116 GeV
    - Very close to the phase space defined by the event selection -> minimal model-dependent extrapolation
  
  - Leptonic decays
    
    - well reconstructed final states with little background making a precision measurement possible.

- We also produce correction factors to extrapolate the fiducial $P_T^Z$ to the full phase space.
Event Samples and Selection

- **Event samples**
  - Collision data
    - 7 TeV pp collisions recorded with ALTAS in 2010
    - ee channel: 35 pb\(^{-1}\), \(\mu\mu\) channel: 40 pb\(^{-1}\)
  - Simulation
    - Pythia Z->\(\mu\mu\) and Z->ee with pileup simulated

- **Event selection**
  - A good primary vertex
  - Lepton Selection
    - Muon: \(P_T > 20\text{GeV}, |\eta| < 2.4\), isolated
    - Electron: \(E_T > 20\text{GeV}, |\eta| < 1.37\) or \(1.52 < |\eta| < 2.4\)
  - Z->\(ll\) (\(l=e/\mu\)) selection
    - two good electrons or two good muons
    - Oppositely charged
    - 66 GeV < \(M_{ll}\) < 116 GeV
\( M_{\parallel} \) after final selection

\[ M(e^+e^-) \quad M(\mu^+\mu^-) \]

- Good data and MC agreement in the di-lepton invariant mass distributions
$P_T^{(ll)}$ after final selection

- Observed $P_T^{(ll)}$ is well described by the simulation.
- Very low level of background with slight $P_T^Z$ dependence
  - Background estimation
    - $Z \rightarrow \tau\tau$, $W \rightarrow \ell\nu$ and $t\bar{t}$: simply using MC
    - QCD: data driven approach
  - Total background
    - $ee$ channel: $1.5\%\pm0.6\%$, $\mu\mu$ channel: $0.4\%\pm0.2\%$
**P_TZ Unfolding**

- Bin-by-bin unfolding is used to correct the observed P_TZ for detector effects and QED FSR.
  - 0-350 GeV with 19 bins
  - Bin purity >60% at low P_TZ and >90% at P_TZ

- Bayesian/Matrix unfolding methods are tried as well for cross-check and systematics.

- Observed P_TZ is unfolded to different levels of lepton QED FSR corrections within the fiducial phase space.

  - *bare:* after QED FSR radiation.
  - *dressed:* “bare” + photons in cone with ΔR < 0.1.
  - *propagator:* before QED FSR.

- The “propagator” unfolded P_TZ from the ee and μμ channels are combined to increase the measurement sensitivity.
Systematics

- Lepton efficiencies
  - 1%-3% in most of the $P_T^Z$ bins

- Lepton energy/momentum scale and resolution
  - Scale: 0.2%-4% (ee), ~0.4% (μμ)
  - Resolution: ~0.5% (ee), 0.1%-0.7% (μμ)

- Unfolding bias
  - $P_T^Z<$6 GeV: 3.6% (ee), 4.7% (μμ)
  - 6 GeV<$P_T^Z<$100 GeV: 2.0% (ee), 1.3% (μμ)
  - $P_T^Z>$100 GeV: 4.2% (ee), 2.9% (μμ)

- Others
  - Background estimation: 0.5% (ee), 0.6% (μμ)
  - Pileup modeling: 0.3%
  - QED FSR corrections: 0.6%
### normalized $P_T^Z$ distribution

<table>
<thead>
<tr>
<th>$p_T^Z$ bin (GeV)</th>
<th>$1/\sigma_{\text{ref}}^\text{fid} \frac{d\sigma_{\text{ref}}^\text{fid} (pp \to Z/\gamma^* \to \ell^+\ell^-)}{dp_T^Z}$ (GeV$^{-1}$)</th>
<th>$Z/\gamma^* \to e^+e^-$</th>
<th>uncert. (%)</th>
<th>$Z/\gamma^* \to \mu^+\mu^-$</th>
<th>uncert. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>prop. dressed bare $k$ stat. syst.</td>
<td>prop. dressed bare $k$ stat. syst.</td>
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<tr>
<td>0 - 3</td>
<td>3.48 3.40 3.21 $10^{-2}$ 3.3 4.7</td>
<td>3.75 3.66 3.58 $10^{-2}$ 2.6 5.0</td>
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<tr>
<td>3 - 6</td>
<td>5.85 5.78 5.60 $10^{-2}$ 2.4 3.3</td>
<td>5.81 5.74 5.68 $10^{-2}$ 2.0 4.0</td>
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<tr>
<td>6 - 9</td>
<td>4.61 4.62 4.64 $10^{-2}$ 2.7 2.3</td>
<td>4.67 4.68 4.69 $10^{-2}$ 2.1 1.6</td>
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<tr>
<td>9 - 12</td>
<td>3.43 3.46 3.56 $10^{-2}$ 3.1 2.4</td>
<td>3.50 3.54 3.58 $10^{-2}$ 2.4 1.6</td>
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<tr>
<td>12 - 15</td>
<td>2.93 2.97 3.09 $10^{-2}$ 3.3 2.7</td>
<td>2.67 2.72 2.76 $10^{-2}$ 2.8 1.7</td>
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<tr>
<td>15 - 18</td>
<td>2.04 2.08 2.16 $10^{-2}$ 3.9 3.0</td>
<td>2.13 2.17 2.20 $10^{-2}$ 3.1 1.7</td>
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<tr>
<td>18 - 21</td>
<td>1.64 1.67 1.73 $10^{-2}$ 4.4 3.3</td>
<td>1.69 1.72 1.74 $10^{-2}$ 3.5 1.8</td>
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<tr>
<td>21 - 24</td>
<td>1.32 1.33 1.37 $10^{-2}$ 4.8 3.6</td>
<td>1.35 1.36 1.37 $10^{-2}$ 4.0 1.8</td>
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<tr>
<td>24 - 27</td>
<td>1.08 1.08 1.11 $10^{-2}$ 5.5 3.8</td>
<td>1.15 1.16 1.17 $10^{-2}$ 4.3 1.9</td>
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<tr>
<td>27 - 30</td>
<td>1.02 1.03 1.03 $10^{-2}$ 6.5 4.0</td>
<td>0.87 0.88 0.88 $10^{-2}$ 5.0 2.0</td>
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<tr>
<td>30 - 36</td>
<td>7.22 7.24 7.26 $10^{-3}$ 4.8 4.2</td>
<td>6.45 6.46 6.45 $10^{-3}$ 4.1 2.1</td>
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<tr>
<td>36 - 42</td>
<td>4.89 4.88 4.85 $10^{-3}$ 5.8 4.5</td>
<td>4.63 4.63 4.62 $10^{-3}$ 4.9 2.2</td>
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<tr>
<td>42 - 48</td>
<td>3.66 3.64 3.59 $10^{-3}$ 7.0 4.8</td>
<td>3.97 3.95 3.94 $10^{-3}$ 5.3 2.4</td>
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<tr>
<td>48 - 54</td>
<td>3.26 3.25 3.20 $10^{-3}$ 7.8 5.0</td>
<td>2.90 2.88 2.86 $10^{-3}$ 6.2 2.6</td>
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<tr>
<td>54 - 60</td>
<td>2.14 2.13 2.08 $10^{-3}$ 9.2 5.4</td>
<td>2.14 2.13 2.11 $10^{-3}$ 7.2 2.7</td>
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<tr>
<td>60 - 80</td>
<td>1.21 1.20 1.17 $10^{-3}$ 6.5 5.7</td>
<td>1.31 1.30 1.28 $10^{-3}$ 5.1 3.0</td>
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<tr>
<td>80 - 100</td>
<td>5.69 5.63 5.44 $10^{-4}$ 9.8 5.9</td>
<td>5.52 5.47 5.40 $10^{-4}$ 7.8 3.5</td>
<td></td>
<td></td>
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<tr>
<td>100-180</td>
<td>1.74 1.73 1.67 $10^{-4}$ 9.6 6.1</td>
<td>1.52 1.51 1.49 $10^{-4}$ 7.5 4.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180-350</td>
<td>0.78 0.77 0.73 $10^{-5}$ 27.0 7.8</td>
<td>1.14 1.14 1.11 $10^{-5}$ 18.9 6.6</td>
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</table>

- Acceptance and lepton efficiency: $\mu\mu > ee$, so more statistics in $\mu\mu$, thus for statistical uncertainties: $\mu\mu < ee$
- Electron energy scale contributes a lot to the systematic uncertainties in ee in most of the bins.
Comparison between channels

\[
\frac{1}{\sigma d p_T(Z)} \frac{d\sigma(Z)}{d p_T(Z)} \text{(ee, propagator)} / \frac{1}{\sigma d p_T(Z)} \frac{d\sigma(Z)}{d p_T(Z)} \text{(\(\mu\mu\), propagator)}
\]

• Good agreement between the two channels within uncertainties

ATLAS
\[
\int L \, dt = 35-40 \, \text{pb}^{-1}
\]
The two channels are combined using a $\chi^2$ minimization method that takes into account the correlated systematic uncertainties.

- $\chi^2 / \text{d.o.f} = 17.0/19$ -> good compatibility of the measurements in the two channels

$A_C^{-1} =$ correction factor needed to extrapolate the fiducial measurement to the full phase space.
Comparison with theoretical predictions

- In good agreement with data over the entire $P_T^Z$ range indicating the importance of resummation even at relatively large $P_T^Z$.
- Slightly higher than data in $P_T^Z$ of [10,40] GeV and slightly lower than data when $P_T^Z$ above 40 GeV.

- FEWZ (fixed order pQCD prediction)
  - Diverging in low $P_T^Z$ region.
  - Its $O(\alpha_s^2)$ prediction is lower than data by ~10%. But still comparable with uncertainty.
  - 26-36% $O(\alpha_s^2)$ correction for $P_T^Z > 18$ GeV with significant uncertainties indicate non-negligible missing higher order corrections.

- RESBOS (combination of resummed and fixed order pQCD calculation)
  - In good agreement with data over the entire $P_T^Z$ range indicating the importance of resummation even at relatively large $P_T^Z$. 
Comparison with Generators

- ALPGEN and SHERPA implement tree-level diagrams up to 5 additional hard partons. So they both give good description of data up to large $P_T^Z$.
- MC@NLO and POWHEG deviate from data at low and high $P_T^Z$.
- PYTHIA describes data very well over the entire $P_T^Z$ range.
Summary and Conclusions

• Normalized $P_T^Z$ distribution has been measured up to $P_T^Z=350$ GeV in both $Z\to ee$ and $Z\to \mu\mu$ channels.
• The measurements in the two channels at the “propagator” level are quite compatible, and are combined to increase the measurement sensitivity.
• RESBOS agrees with the measurement. FEWZ is below the measurement by about 10%.
• The measurement is found to be in good agreement with SHERPA, ALPGEN and PYTHIA.
• A better measurement is expected with more data available and novel techniques (e.g. $\phi^*_\eta$) to be used.
Backup
ATLAS Detector

Muon Spectrometer ($|\eta|<2.7$): air-core toroids with gas-based muon chambers. Muon trigger and measurement with momentum resolution $<10\%$ up to $E_\mu \sim 1\ TeV$

Length: $\sim 46\ m$  
Radius: $\sim 12\ m$  
Weight: $\sim 7000\ tons$  
$\sim 10^8$ electronic channels  
3000 km of cables

3-level trigger reducing the LVL1 rate to $\sim 300\ Hz$

Inner Detector ($|\eta|<2.5, B=2T$): Si Pixels, Si strips, TRT  
Precise tracking and vertexing,  
$\sigma/p_T \sim 3.8 \times 10^{-4} p_T\ (GeV) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion  
e/$\gamma$ trigger, identification and measurement  
E-resolution: $\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$  
High granularity

Hadron calorimetry ($|\eta|<4.9$)  
Fe/scintillator Tiles (central), Cu-LAr (endcap)  
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$  
FWD calorimetry: Cu/W-LAr $\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$
Collision data and MC

- **Collision data**
  - Triggered on single leptons ($E_T^e > 15 \text{GeV}$ or $P_T^\mu > 13 \text{GeV}$)
  - 7 TeV pp data recorded in 2010 with all relevant sub-detectors fully operational
  - 35pb$^{-1}$ for ee channel and 40pb$^{-1}$ for $\mu\mu$ channel

- **MC samples**
  - Signal (Z$\rightarrow$mm and Z$\rightarrow$ee) generation
    - Pythia (MRST2007LO*) as default, MC@NLO(CTEQ6.6)/HERWIG/Jimmy
  - Background generation
    - W$\rightarrow$lv: Pythia;
    - Z$\rightarrow$ttautau: Pythia, MC@NLO
    - Dijet: Pythia
    - ttbar: MC@NLO, PowHeg;
  - Detector simulation based on GEANT4
  - Pileup simulated by overlaying minimum bias MC events
Event Selection

- **A good primary vertex (PV)**
- **Lepton selection**
  - **Muon**
    - Reconstructed by associating a track in the Muon spectrometer track with an track in the inner detector.
    - $P_T > 20 \text{GeV}$, $|\eta| < 2.4$
    - Isolated: $\Sigma P_T(\text{cone0.2})/P_T^\mu < 0.2$
    - Originated from PV: $|z_{\text{w.r.t. PV}}| < 5 \text{mm} \land |d_{\text{w.r.t. PV}}| < 1 \text{mm}$
  - **Electron**
    - Electron identification based on the information from the sub-detectors of ID/ECal/HCal
    - $E_T > 20 \text{GeV}$, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
- **$Z \rightarrow ll$ selection**
  - Exactly two good electrons or at least two good muons
  - Oppositely charged
  - $66 \text{GeV} < M_{ll} < 116 \text{GeV}$
Background Estimation

- Contributions from $Z\rightarrow\tau\tau$, $W\rightarrow l\nu$ and $t\bar{t}$ are estimated using MC and normalized to the data integrated luminosities using NNLO or NLL-NLO cross sections.

- Data driven methods are used for QCD multiple-jet contributions.
  - Total contribution
    - fit signal and QCD templates to the $M_{ll}$ with loosened electron identification requirements.
    - scale the result from the fit.
  - Background shape in $p_T^Z$ is determined using a QCD-enriched di-electron sample with inverted electron identification criteria and $M_{ll}$ cut

<table>
<thead>
<tr>
<th>isolated inverted-isolation</th>
<th>40...60 GeV</th>
<th>66...116 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>A (Signal)</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

- $ee$ channel

- $\mu\mu$ channel
  - ABCD method for total contribution.
  - Background shape from region C.
Details of Generators

• ALPGEN
  – v2.13,
  – interfaced to HERWIG-v6.510 for parton shower and to JIMMY-v4.31 for underlying events
  – CTEQ6L1
  – tree-level diagrams up to 5 additional hard partons implemented

• SHERPA
  – v1.2.3,
  – CTEQ66
  – tree-level diagrams up to 5 additional hard partons implemented

• MC@NLO
  – interfaced to HERWIG and JIMMY
  – CTEQ66

• POWHEG
  – interfaced to PYTHIA
  – CTEQ66

• PYTHIA
  – v6.4 with pt-ordered parton shower
  – MRST2007LO*
  – underlying event parameters tuned to Tevatron data