Measurements of differential $Z$ boson production cross sections in pp collisions with CMS at $\sqrt{s} = 13$ TeV (SMP-17-010)

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Introduction

- Purpose of the talk is to show a short summary on the differential $Z$ boson cross section measurements using dilepton events
- Making use of full 2016 dataset at $\sqrt{s} = 13$ TeV
- Selecting two dimuons or dielectrons compatible with a $Z$ boson decay
  - simple selection
  - very low background level
- Fiducial region emulates selection at the reconstruction level
- Measurements: differential and normalized cross sections
  - $p_T^Z$
  - $|y^Z|$
  - $\phi^*$
  - $p_T^Z$ in $|y^Z|$ regions
- Analysis went from a simple 2017 Summer student project to a huge R&D enterprise
  - simple experimental analysis, but requiring an unprecedented precision in CMS
Selection Strategy

- **Reconstruction level (RECO):**
  - two opposite-sign same-flavor leptons (electrons or muons)
  - “medium” identification & isolation lepton requirements
  - $p_T^{\ell_1,\ell_2} > 25$ GeV, $|\eta^{\ell_1,\ell_2}| < 2.4$
  - $|m_{\ell\ell} - m_Z| < 15$ GeV

- **Fiducial definition at generation level (GEN):**
  - making use of so-called dressed leptons
    - accounting for photons in $\Delta R_{\ell,\gamma} < 0.1$
  - two opposite-sign same-flavor leptons (electrons or muons)
  - $p_T^{\ell_1,\ell_2} > 25$ GeV, $|\eta^{\ell_1,\ell_2}| < 2.4$
  - $|m_{\ell\ell} - m_Z| < 15$ GeV
  - tested that muon and electron cross sections agree better than the sample statistical precision with this definition

<table>
<thead>
<tr>
<th>Final state</th>
<th>Data</th>
<th>$Z \rightarrow \ell\ell$</th>
<th>Resonant bkg.</th>
<th>Nonresonant bkg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$</td>
<td>$\sim 20.4 \times 10^6$</td>
<td>$\sim 20.7 \times 10^6$</td>
<td>$\sim 30 \times 10^3$</td>
<td>$\sim 41 \times 10^3$</td>
</tr>
<tr>
<td>ee</td>
<td>$\sim 12.1 \times 10^6$</td>
<td>$\sim 12.0 \times 10^6$</td>
<td>$\sim 19 \times 10^3$</td>
<td>$\sim 26 \times 10^3$</td>
</tr>
</tbody>
</table>
Systematic Uncertainties

- **Luminosity:**
  - using current recommended 2.5%
- **Lepton trigger, reconstruction & identification:**
  - computed “in-house” due to the required precision
  - effects due to the signal and background components taken into account
- **Momentum scale:**
  - relevant on differential measurements
- **Background:**
  - $VV$ resonant bkg. from simulation
  - nonresonant bkg. from data
- **Data and simulated sample size**
Summary of Systematic Uncertainties (Differential)
Summary of Systematic Uncertainties (Normalized)

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>35.9 fb⁻¹ (13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>µµ</strong></td>
<td></td>
</tr>
<tr>
<td><strong>ee</strong></td>
<td></td>
</tr>
</tbody>
</table>

Uncertainty Breakdown:
- Total uncertainty
- Unfolding
- Momentum resolution
- Background
- Identification & trigger
- Reconstruction
- Statistical

Total uncertainty contributions include:
- Unfolding
- Momentum resolution
- Background
- Identification & trigger
- Reconstruction
- Statistical

Graphical representation for each channel (µµ, ee) showing the breakdown of uncertainties in δpₜ (GeV) and y for different |φ| ranges.
### Inclusive Fiducial Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$Z \rightarrow \mu\mu$ (%)</th>
<th>$Z \rightarrow ee$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Muon reconstruction efficiency</td>
<td>0.4</td>
<td>-</td>
</tr>
<tr>
<td>Muon selection efficiency</td>
<td>0.7</td>
<td>-</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Electron reconstruction efficiency</td>
<td>-</td>
<td>0.9</td>
</tr>
<tr>
<td>Electron selection efficiency</td>
<td>-</td>
<td>1.0</td>
</tr>
<tr>
<td>Electron momentum scale</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Background estimation</td>
<td>$&lt; 0.1$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td><strong>Total (excluding luminosity)</strong></td>
<td>0.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

### Cross section

<table>
<thead>
<tr>
<th>Cross section</th>
<th>$\sigma B$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Z \rightarrow \mu\mu}$</td>
<td>$694 \pm 6$ (syst.) $\pm 17$ (lum.)</td>
</tr>
<tr>
<td>$\sigma_{Z \rightarrow ee}$</td>
<td>$712 \pm 10$ (syst.) $\pm 18$ (lum.)</td>
</tr>
<tr>
<td>$\sigma_{Z \rightarrow \ell\ell}$</td>
<td>$699 \pm 5$ (syst.) $\pm 17$ (lum.)</td>
</tr>
</tbody>
</table>

$\sigma_{Z \rightarrow \ell\ell} = 682 \pm 55$ pb ($\text{MadGraph5\_aMC@NLO, NNPDF 3.0}$)
In principle, we could just report our results, but we tried to be pretty generic.

Experimental distributions compared with several theoretical predictions (and more to come):

- MadGraph5_aMC@NLO
- POWWEG
- FEWZ ($p_T^Z > 30$), NNLO inclusive
- $Z + 1$ jet at NNLO
- MINLO
- RESBOS
- GENEVA

Data unfolded uncertainties include all experimental effects.

Theory uncertainties include QCD scales and PDF uncertainties.

MINLO:

- before you ask, aware of large theory uncertainties
- not a mistake, long discussions about it, will use another prescription for the paper
Normalized Measurements

\[ \text{Normalized Measurements} \]

\[ \text{Data} \]

\[ \text{MINLO} \]

\[ \text{aMC@NLO} \]

\[ \text{POWHEG} \]

\[ \text{Preliminary} \]

\[ \text{CMS} \]

\[ >25 \text{ GeV} \]

\[ |<2.4, p_\eta| \]

\[ (13 \text{ TeV}) \]

\[ 35.9 \text{ fb}^{-1} \]

\[ \sigma \]
Reported results on the differential Z boson production cross section measurements using dilepton events

- large effort to improve lepton efficiency uncertainties
- Paper publication in progress

Read details on https://cds.cern.ch/record/2675022
Back-Up Slides
Unfolding & Binning

Using TUnfold method to perform the unfolding, as officially suggested

- $p_T^{Z}$ (in GeV): \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 25, 28, 32, 37, 43, 52, 65, 85, 120, 160, 190, 220, 250, 300, 400, 500, 800, 1500\}

- $|y^{Z}|$: \{0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4\}

- $\phi^{*}$: \{1 \cdot 10^{-3}, 2 \cdot 10^{-3}, 3 \cdot 10^{-3}, 4 \cdot 10^{-3}, 5 \cdot 10^{-3}, 6 \cdot 10^{-3}, 7 \cdot 10^{-3}, 8 \cdot 10^{-3}, 9 \cdot 10^{-3}, 1 \cdot 10^{-2}, 2 \cdot 10^{-2}, 3 \cdot 10^{-2}, 4 \cdot 10^{-2}, 5 \cdot 10^{-2}, 6 \cdot 10^{-2}, 7 \cdot 10^{-2}, 8 \cdot 10^{-2}, 9 \cdot 10^{-2}, 1 \cdot 10^{-1}, 2 \cdot 10^{-1}, 3 \cdot 10^{-1}, 4 \cdot 10^{-1}, 5 \cdot 10^{-1}, 6 \cdot 10^{-1}, 7 \cdot 10^{-1}, 8 \cdot 10^{-1}, 9 \cdot 10^{-1}, 1, 3, 5, 7, 10, 20, 30, 50\}

- $p_T^{Z}$ in $|y^{Z}|$ regions (in GeV): \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 18, 20, 22, 25, 28, 32, 37, 43, 52, 65, 85, 120, 160, 190, 220, 250, 300, 400, 1500\}
QED Uncertainty

- Making use of dressed leptons instead of born level leptons
- Easier way to compare with theory predictions
- Cross sections for electrons and muons agree better than statistical precision of the samples
- Experimental uncertainty due to FSR effects taken into account
- Neglected theoretical uncertainty in the prediction