Electroweak precision measurements with the CMS detector

Rafael Coelho Lopes de Sá
Fermilab

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DPF meeting of the APS
Several cross section measurements (total, fiducial and differential) performed at CMS — see talk by Jay Lawhorn. Focus here on very precise measurements of Z and W boson production and decay.

Several aspects only partially understood:
- Resummation at low $p_T$
- Higher-order QED correction
- Effect of heavy quarks in the initial state
- Power corrections

Can very precise measurements help understand these issues?

**CMS Preliminary**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed (pb)</th>
<th>Theory (NNPDF3.0)</th>
<th>Uncertainty (lumi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+\to l^+\nu$</td>
<td>$11390 \pm 300 \pm 230_{\text{stat}} \pm 550_{\text{lumi}}$</td>
<td>$11390 \pm 300$</td>
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<tr>
<td>$W^-\to l^-\nu$</td>
<td>$8580 \pm 50_{\text{stat}} \pm 160_{\text{lumi}} \pm 410_{\text{th}}$</td>
<td>$8580 \pm 50$</td>
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<td>$W\to l\nu$</td>
<td>$8370 \pm 230$</td>
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<tr>
<td>$Z\to l^+l^-$</td>
<td>$19900 \pm 360_{\text{stat}} \pm 960_{\text{lumi}} \pm 520_{\text{th}}$</td>
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<tr>
<td>$Z\to l^+l^-$</td>
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<tr>
<td>$W^\pm\to l^\mp\nu / W^\pm\to l^\mp\nu$</td>
<td>$1.253 \pm 0.010_{\text{stat}} \pm 0.021_{\text{th}}$</td>
<td>$1.354 \pm 0.011$</td>
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<tr>
<td>$W^\pm\to l^\mp\nu / Z\to l^+l^-$</td>
<td>$3.36 \pm 0.04_{\text{th}} \pm 0.1_{\text{th}}$</td>
<td>$6.06 \pm 0.06$</td>
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<tr>
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<td>$4.48 \pm 0.02$</td>
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<td>$W\to l\nu / Z\to l^+l^-$</td>
<td>$10.46 \pm 0.06_{\text{th}} \pm 0.16_{\text{th}}$</td>
<td>$10.55 \pm 0.07$</td>
<td></td>
</tr>
</tbody>
</table>

Ratio (exp./th.) of total cross sections and ratios:

**CMS Preliminary**

43 pb$^{-1}$ (13 TeV)

Data

aMC@NLO

Stat. + Syst.
Precision measurements

- Measurement of ratios of production cross sections

\[
\left( \frac{1}{\sigma_W} \frac{d\sigma}{dp_W^{T}} \right) / \left( \frac{1}{\sigma_Z} \frac{d\sigma}{dp_Z^{T}} \right), \left( \frac{1}{\sigma_{W^+}} \frac{d\sigma}{dp_{W^+}^{T}} \right) / \left( \frac{1}{\sigma_{W^-}} \frac{d\sigma}{dp_{W^-}^{T}} \right)
\]

- Differential cross sections of high-resolution observables

\[
\phi^* = \tan \left( \frac{\phi_{acop}}{2} \right) \sin(\theta^*_\eta) \quad \phi_{acop} = \phi - \Delta\phi \quad \theta^*_\eta = \tanh[(\eta_- - \eta_+)/2]
\]

- Effective weak mixing angle \( \sin(\theta^{\ell}_{\text{eff}}) \)

- W-like Z boson mass

First presented at EPS-HEP this year!
Some tension in the \((d\sigma/dp_T^W)/(d\sigma/dp_T^Z)\) cross section measurement

First bin is too large to resolve Sudakov peaks

The limitation is the poor resolution at low \(W p_T\)
φ* differential cross section at 8 TeV

CMS Preliminary 19.7 fb⁻¹ (8 TeV)

- For Z \( p_T < 100 \text{ GeV} \), φ* ~ \( p_T \)
- Much better resolution at low φ* (low Z \( p_T \)) since only the tracker is used
- Similar disagreement observed in Z \( p_T \) differential cross section measurements.
φ* differential cross section at 13 TeV

Similar behavior observed in events with $\sqrt{s} = 13$ TeV

The result here uses only 2.3 fb$^{-1}$ of integrated luminosity collected in 2015.

Much more data already in CMS tapes!
Weak mixing angle measurement

- The mixing angle is measured using the forward-backward asymmetry in Z events.

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \]

- Whether an event is forward or backward is defined by the angle of the negatively charged lepton in the Collins-Soper frame.

\[ \cos \theta^* = \frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{\sqrt{M^2(M^2 + p_T^2)}} \times \frac{p_z}{|p_z|} \]

- The weak mixing angle is extracted using \( m_\ell \ell \) templates where the vector couplings of leptons to the Z boson are varied:

\[ v_f = T_3^f - 2Q_f \sin^2 \theta_W, \]

\[ a_f = T_3^f, \]

This is the tree level relation. After renormalization, the angle is called the effective mixing angle \( \theta^\ell_{eff} \).
The forward-backward asymmetry depends strongly on the initial state quarks and on the dilepton rapidity.

Therefore, the CMS measurement uses $m_{\ell\ell}$ templates in six different dilepton rapidity $|y_{\ell\ell}|$ bins.

Similarly, NNPDF3.0 MC replicas are used to reweight the templates and reduce the PDF uncertainty in the measurement.
The measurement uses events with two electrons or two muons selected by single leptons triggers.

In the muon channel, the leading and sub-leading muons are required to satisfy $p_T > 20$ and 15 GeV respectively. In the electron channel, the leading and sub-leading electrons are required to satisfy $p_T > 30$ and 20 GeV respectively.

$Z$ boson decays are selected with $|\eta_{\ell\ell}| < 2.4$ and $60 < m_{\ell\ell} < 120$ GeV. The $m_{\ell\ell}$ distribution is used to calibrate the electron and muon energy scale and resolution.
Not all events are born equal

- Events with different $\cos(\theta^*)$ have different sensitivity to the weak mixing angle.
- CMS weighs each selected event with a weight proportional to their sensitivity to the forward-backward asymmetry.

$$w_D = \frac{1}{2} \frac{c^2}{(1 + c^2 + h)^3},$$

Denominator (normalization) weight

$$w_N = \frac{1}{2} \frac{|c|}{(1 + c^2 + h)^2},$$

Numerator (asymmetry) weight

$$h = 0.5A_0(1 - 3c^2)$$

$A_0 = A_0(m_{\ell\ell}, p_T^{\ell\ell}, y_{\ell\ell})$ from the angular decomposition of the Z decay cross section

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta^*} = \frac{3}{8} \left( 1 + \cos^2\theta^* + \frac{A_0}{2}(1 - 3\cos^2\theta^*) + A_4\cos\theta^* \right).$$

$$D_F = \sum_{c>0} w_D, D_B = \sum_{c<0} w_D,$$

$$N_F = \sum_{c>0} w_N, N_B = \sum_{c<0} w_N,$$

$$A_{FB} = \frac{3}{8} \frac{N_F - N_B}{D_F + D_B}.$$
Observed distributions

- Data-MC comparison of $m_{e\ell\ell}$ templates with best fit $\sin(\theta_{\text{eff}}^\ell)$ in $|y_{\ell\ell}|$ bins after PDF reweighting.

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Electroweak Precision Measurements with CMS
PDF reweighting using MC replicas was first proposed in Nucl. Phys. B849 (2011) 112-143 [arXiv:1012.0836].

Each MC replica of the NNPDF3.0 ensemble is weighted with a probability density determined by comparing the $A_{FB}$ values between data and MC.
Weak mixing angle results

Combined results

\[ \sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf}) \]
\[ \sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00052. \]

Uncertainty sources

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<td>Total</td>
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<td>0.00039</td>
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Comparison to other results
Weakening mixing angle results

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<tr>
<td>FSR model (PHOTOS vs PYTHIA)</td>
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<td>UE tune</td>
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<tr>
<td>Electroweak (( \sin^2 \theta_{\text{eff}}^\text{lept} - \sin^2 \theta_{\text{eff}}^d ))</td>
<td>0.00001</td>
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<td>0.00015</td>
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Comparison to other results

- CMS ee+\( \mu \mu \) Preliminary
  \[ 0.23101 \pm 0.00052 \]

- CMS ee 19.6 fb\(^{-1}\) Preliminary
  \[ 0.23056 \pm 0.00086 \]

- CMS \( \mu \mu \) 18.8 fb\(^{-1}\) Preliminary
  \[ 0.23125 \pm 0.00060 \]

- LHCb \( \mu \mu \) 3 fb\(^{-1}\)
  \[ 0.23142 \pm 0.00106 \]

- ATLAS ee+\( \mu \mu \) 4.8 fb\(^{-1}\)
  \[ 0.23080 \pm 0.00120 \]

- D0 ee 9.7 fb\(^{-1}\)
  \[ 0.23147 \pm 0.00047 \]

- CDF ee+\( \mu \mu \) 9.4 fb\(^{-1}\)
  \[ 0.23221 \pm 0.00046 \]

- SLD: \( A_l \)
  \[ 0.23098 \pm 0.00026 \]

- LEP + SLD: \( A_{FB}^{0,b} \)
  \[ 0.23221 \pm 0.00029 \]

- LEP + SLD
  \[ 0.23153 \pm 0.00016 \]
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Comparison to other results

- CMS ee+\(\mu\mu\)
  - Preliminary
  - 8TeV, 19.6 fb\(^{-1}\)
  - 0.23101 \pm 0.00052

- CMS e+e\(-\mu+\mu\)
  - Preliminary
  - 19.6 fb\(^{-1}\)
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- CMS \(\mu\mu\)
  - Preliminary
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- SLD: \text{A}_l
- LEP + SLD: \text{A}^{0,b}_\text{FB}
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Weak mixing angle results

Combined results

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Comparison to other results

TeV combined: CDF+D0
July 2017: preliminary

CMS ee+\(\mu\mu\) Preliminary
0.23056 ± 0.00086

CMS \(\text{\(e\)e} \ 19.6 \text{ fb}^{-1}\)
0.23125 ± 0.00060

CMS \(\mu\mu \ 18.8 \text{ fb}^{-1}\)
0.23142 ± 0.00106

LHCb \(\mu\mu \ 3 \text{ fb}^{-1}\)
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0.23221 ± 0.00029

LEP + SLD
0.23153 ± 0.00016
CMS has performed a measurement of the Z boson mass using methods similar to those used for a W boson mass measurement.

The measurement uses \(Z \rightarrow \mu\mu\) decays where one of the muons is removed from the \(Z\) boson reconstruction. Muons are required to have \(|\eta| < 0.9\) and \(p_T > 30\) GeV.

Half of the reconstructed \(Z\) bosons are used for recoil calibration. Muon momentum calibration is done with \(J/\psi\) and \(Y\) decays.
The Z boson mass is measured using $m_T$, $p_T$, and $E_T^{\text{miss}}$ templates with different Z boson mass.

Templates are generated by reweighting the MC simulation using Breit-Wigner factors with different input masses.
W-like Z boson mass result

- Uncertainty dominated by statistical component.
- QED radiation uncertainty is very preliminary and will be re-evaluated for a final W mass measurement.
- No $Z \rightarrow W$ extrapolation uncertainties (experimental and theoretical)!

- Important first step towards a W mass measurement.
- Experimental methods for muon momentum and recoil scale calibrations are under control.
- The next step is to understand how to extrapolate this results to W boson events
- Need to understand well theoretical differences between W and Z production at the LHC

<table>
<thead>
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<th>Sources of uncertainty</th>
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<th>$M_{Z_{W-like}}^-$</th>
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A quick look at other W mass efforts

Uncertainties in the recent ATLAS W mass measurement
[from S. Camarda @ W mass workshop at CERN, and arXiv:1701.07240]

Includes also Ai uncertainties

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<td>27.2</td>
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Main theoretical uncertainties:
- QCD modeling of W and Z production in hadron collisions
- PDF modeling

ATLAS uses a dedicated Pythia tune to model W and Z production.
Conclusions

- CMS has a strong program of electroweak measurements. Several W and Z boson cross sections have been published at 7, 8, and 13 TeV.

- Some of these measurements can be performed with very high precision. Examples are cross section ratios, asymmetries, and differential cross sections of high-resolution observables.

- The \( \frac{d\sigma/dp_T^W}{d\sigma/dp_T^Z} \) measurement performed at low instantaneous luminosity shows some tension with theoretical predictions, but the current precision is not sufficient to resolve the Sudakov peaks.

- The \( \phi^* \) differential cross section measurement probes the same type of physics as the Z \( p_T \) differential measurement but with much higher precision. The measurements at 8 and 13 TeV show clear tension with theoretical predictions.

- The CMS measurement of the effective weak mixing angle \( \sin\theta^\ell_{\text{eff}} \) with the complete 8 TeV dataset is presented. The uncertainty is twice as large as the world best single measurement, but most of the uncertainty is from the statistical component and will improve in the future.

- Finally, a future W mass measurement at CMS is discussed, highlighting the steps taken towards this measurement, what remains unknown about DY production at hadron colliders, and how high precision measurements can help improve our understanding.