Electroweak precision measurements in CMS

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on behalf of the CMS collaboration

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Moriond EW
La Thuile, Italy
Overview of the Electroweak Sector

- Electroweak (EW) precision observables
  - \(\alpha_{em}, G_F, m_W, m_Z, \sin^2 \theta_W, m_h\)
  - Not independent but related through Standard Model (SM)

\[
m_W^2 \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F} \quad \sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \text{(Tree level)}
\]

- Precision EW measurements
  - SM is over constrained with \(m_h\)
  - Testing the consistency of the SM
- Non-abelian Gauge structure
  - Are there anomalous couplings?

- Focus of this talk:
  - \(\sin^2 \theta_W\)
  - EW production of same sign WW

03/12/17
Dilepton production at the LHC

- Neutral current process: $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$
- Z boson couplings are different for left and right-handed fermions
- Forward-backward asymmetry ($A_{FB}$) in the polar angle distribution of negatively charged lepton in the rest frame of di-lepton system
  - Defined with respect to the incoming quark

\[
\frac{d\sigma}{dp_T^Z dy^Z dm^Z d\cos\theta} = \frac{3}{8} \frac{d\sigma^{U+L}_{Z\gamma^*\rightarrow Y\mu\mu}}{dp_T^Z dy^Z dm^Z} \left\{ (1 + \cos^2\theta) + \frac{1}{2} A_0 (1 - 3 \cos^2\theta) + A_4 \cos\theta \right\}
\]

- $A_{FB}$ defined in Collin-Soper (CS) frame $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \quad F: \cos\theta > 0 \quad B: \cos\theta < 0$

Minimize the impact of incoming quark transverse momentum
Effective weak mixing angle

- $A_{FB}$ is sensitive to $\sin^2 \theta_W$ near Z peak
  - Product of vector and axial couplings
- Electroweak corrections:
  - Tree level couplings are replaced by effective couplings
    \[ \sin^2 \theta_{\text{eff}}^f = \kappa_Z^f \sin^2 \theta_W \]
    \[ g_A^f = \sqrt{\rho_f} t_{3L}^f \]
    \[ g_V^f = \sqrt{\rho_f} (t_{3L}^f - 2Q_f \kappa_f \sin^2 \theta_W) \]
- Template fit to extract the $\sin^2 \theta_{\text{eff}}^\ell$
- Large discrepancy (~3 standard deviations) between the two most precise LEP/SLD measurements
Forward-backward Asymmetry

- $A_{FB}$ measured as function of di-lepton mass in muon and electron final states (mass dependence from the $Z$/gamma* interference)
- Proton-proton collisions: where is the quark?
  - Direction of longitudinal boost of the di-lepton system in the laboratory frame chosen as the positive axis
  - Quark direction is not always along the positive axis
    - Dependence on PDF from large-x antiquarks

![Graphs showing $A_{FB}$ as a function of di-lepton mass in muon and electron final states for True and Diluted cases.](image-url)
**$A_{FB}$ and $\sin^2 \theta^\ell_{\text{eff}}$**

- Dilution strongly depends on rapidity->maximal at Y=0->$A_{FB}=0$
- $A_{FB}$ is measured in 6 bins of rapidity and 12 bins of dilepton mass
- Extract $\sin^2 \theta^\ell_{\text{eff}}$ by fitting the measured $A_{FB}$ with different templates
  - Angular event weighting->less sensitive to $\cos \theta$ acceptance modeling
- Precise lepton momentum calibration

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![Graphical representation of $A_{FB}$ vs. $M_\| (GeV)$ and $M_{\mu\mu} (GeV)$ with data and fit, along with angular event weighting and lepton momentum calibration details.](image)
Statistical and systematic uncertainties

- **Statistical uncertainties dominate**

<table>
<thead>
<tr>
<th>channel</th>
<th>statistical uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon</td>
<td>0.00044</td>
</tr>
<tr>
<td>electron</td>
<td>0.00060</td>
</tr>
<tr>
<td>combined</td>
<td>0.00036</td>
</tr>
</tbody>
</table>

- **Experimental uncertainties are small** *(dominated by limited number of simulated events)*

<table>
<thead>
<tr>
<th>Source</th>
<th>muons</th>
<th>electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistics</td>
<td>0.00015</td>
<td>0.00033</td>
</tr>
<tr>
<td>Lepton momentum calibration</td>
<td>0.00008</td>
<td>0.00019</td>
</tr>
<tr>
<td>Lepton selection efficiency</td>
<td>0.00005</td>
<td>0.00004</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.00003</td>
<td>0.00005</td>
</tr>
<tr>
<td>Pileup modeling</td>
<td>0.00003</td>
<td>0.00002</td>
</tr>
<tr>
<td>Total</td>
<td>0.00018</td>
<td>0.00039</td>
</tr>
</tbody>
</table>

- **Modeling uncertainties small compared to the statistical uncertainties**
  - **Dominated by QCD scale**

<table>
<thead>
<tr>
<th>model variation</th>
<th>Muons</th>
<th>Electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton $p_T$ reweighting</td>
<td>0.00003</td>
<td>0.00003</td>
</tr>
<tr>
<td>QCD $\mu_{R/F}$ scale</td>
<td>0.00011</td>
<td>0.00013</td>
</tr>
<tr>
<td>POWHEG MiNLO Z+j vs NLO Z model</td>
<td>0.00009</td>
<td>0.00009</td>
</tr>
<tr>
<td>FSR model (PHOTOS vs PYTHIA)</td>
<td>0.00003</td>
<td>0.00005</td>
</tr>
<tr>
<td>UE tune</td>
<td>0.00003</td>
<td>0.00004</td>
</tr>
<tr>
<td>Electroweak ($\sin^2 \theta_{\text{eff}}^\text{lep} - \sin^2 \theta_{\text{eff}}^u,d$)</td>
<td>0.00001</td>
<td>0.00001</td>
</tr>
<tr>
<td>Total</td>
<td>0.00015</td>
<td>0.00017</td>
</tr>
</tbody>
</table>
PDF uncertainties

- Measured $A_{FB}$ is sensitive to the PDFs
  - Different couplings of $u$ and $d$-type quarks to Z boson
  - Size of the dilution effect (large-$x$ antiquarks)
- PDF dependence is large at small and large masses, small near the peak
PDF uncertainties

- Bayesian $\chi^2$ reweighing method used to constrain the PDFs
- Perform the $\sin^2 \theta_{\text{eff}}^\ell$ fit for each NNPDF3.0 replica
- Weight each replica by:

$$w_i = e^{-\frac{\chi^2_{\text{min}}}{2}},$$

$$\frac{1}{N} \sum_{i=1}^{N} e^{-\frac{\chi^2_{\text{min}}}{2}},$$

- Consistent between electron/muon
- PDF uncertainties reduced by $x^2$

<table>
<thead>
<tr>
<th>Channel</th>
<th>without constraining PDFs</th>
<th>with constraining PDFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon</td>
<td>$0.23125 \pm 0.00054$</td>
<td>$0.23125 \pm 0.00032$</td>
</tr>
<tr>
<td>Electron</td>
<td>$0.23054 \pm 0.00064$</td>
<td>$0.23056 \pm 0.00045$</td>
</tr>
<tr>
<td>Combined</td>
<td>$0.23102 \pm 0.00057$</td>
<td>$0.23101 \pm 0.00030$</td>
</tr>
</tbody>
</table>

- Similar picture with Hessian PDF sets
Results

• Results are consistent with the mean value of LEP and SLD and other available measurements

• Comparable to precision at the Tevatron!

• Statistical uncertainties dominate

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

\[ \sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00052. \]
Future

- What can we expect at the high-luminosity LHC
  - Negligible statistical uncertainties
  - PDF uncertainties further constrained with profiling
  - Extended lepton acceptance with the upgraded CMS detector

- Smaller $A_{FB}$ at 14 TeV (less valence quark contribution)

- Larger lepton $|\eta|$ acceptance

LEP+SLD

CMS-PAS-FTR-17-001

03/12/17
Gauge boson couplings

- Shift from precision observables to first measurements
- Probe the non-Abelian gauge structure of the EW interactions
- Vector boson scattering processes
  - What mechanism ensures the unitarity is respected
  - Is the 125 GeV Higgs boson the only solution
  - Characterized by VV and 2 jet final state

03/12/17
Vector boson scattering

- Events are selected by requiring 2 same-sign leptons and 2 jets with large pseudorapidity separation and large mass
- First observation of EW production of same-sign W boson pairs
  - Observed (expected) significance is 5.5 (5.7) standard deviations
  - Observed signal is consistent with SM predictions
  - Evidence by ATLAS and CMS in Run 1

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Electroweak Z+2jet production

- Pure EW production of dileptons in association with two jets
- Measured cross section is in agreement with the leading order SM predictions
  \[ \sigma_{EW}(\ell\ell jj) = 552 \pm 19 \text{ (stat)} \pm 55 \text{ (syst)} \text{ fb} \]
  \[ m_{\ell\ell} > 50 \text{ GeV}, \quad m_{jj} > 120 \text{ GeV}, \quad \text{and transverse momenta } p_T > 25 \text{ GeV}. \]
- Best limits of anomalous triple gauge couplings
Summary

• Electroweak precision measurements with the CMS detector
• Precise measurement of the effective weak mixing angle
  • Comparable to precision at the Tevatron!
  • PDF and statistical uncertainties dominate
  • Experimental uncertainties are under control
• First observation of electroweak production of same sign W boson pairs
  • Observed (expected) significance is 5.5 (5.7) standard deviations
• Many more results to come
ADDITIONAL MATERIAL
Angular coefficients

- Accurate modeling of QCD effects is crucial to perform the EW precision measurements.
- Factorizing the Drell-Yan production cross section from the decay kinematics is non-zero for QCD calculations beyond NLO: Lam-Tung relation violated.

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

A0-A2 is non-zero for QCD calculations beyond NLO: Lam-Tung relation violated.

\[
A_0 - A_2
\]

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Angular event weighting


- For each event with $\cos\theta=c$, define two weights:
  
  \[ w_D = \frac{1}{2} \frac{c^2}{(1 + c^2 + h)^3}, \quad h = 0.5A_0(1 - 3c^2) \]

\[
D_F = \sum_{c>0} w_D, \quad D_B = \sum_{c<0} w_D, \\
N_F = \sum_{c>0} w_N, \quad N_B = \sum_{c<0} w_N.
\]

\[ A_{FB} = \frac{3}{8} \frac{N_F - N_B}{D_F + D_B} \]

- In $4\pi$, Raw $A_{FB} =$ Weighted $A_{FB} =$ Weighted $A_{FB}$ within lepton acceptance
  => less sensitive to $\cos\theta$ acceptance modeling

- Also, weighted $A_{FB}$ yield smaller stat. uncertainty of extracted $\sin^2\theta_{\text{eff}}$

The slide is from:
https://indico.cern.ch/event/661916/contributions/2702568/attachments/1536039/2406301/171005_WmW.pdf