Determination of the Weak Mixing Angle

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What is the weak mixing angle

- Key parameter in the electroweak sector of the SM
  \[ \sin^2(\theta_w) = 1 - \frac{m_w^2}{m_Z^2}, \]
- We can also define an effective leptonic mixing angle which at leading order
  \[ k_\ell \sin^2(\theta_w) = \sin^2(\theta_{\text{lep}}^{\text{eff}}) = \frac{1}{4|Q|} \left( 1 - \frac{g_\nu}{g_a} \right) \]
- Electroweak radiative corrections in \( k_\ell \) are accurately calculated in standard model
- Precise \( \sin^2(\theta_{\text{lep}}^{\text{eff}}) \) measurement can probe new physics contributions to \( m_W \) (an indirect \( m_W \) measurement) and \( k_\ell \)
Current Status

- Current precision driven by LEP/SLD
- Hadron collider measurements are becoming competitive

![Graph showing the current status of the weak mixing angle with data points for various experiments.](image-url)

ATLAS-CONF-2018-037
The 2 most precise measurements LEP and SLD measurements disagree by $\sim 3\sigma$. Could be hint of non standard model processes

The recent $W$ mass measurement from CDF II has tensions with other measurements and disagrees with the SM at an order of $7\sigma$
Measuring $\sin^2(\theta_{\text{eff}}^{\text{lep}})$ at the LHC

- The full differential cross section in leading order

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

- At first order, only the annihilation $q\bar{q} \rightarrow Z$ is present

$$\frac{d\sigma}{d(\cos \theta^*)} \propto 1 + \cos^2 \theta^* + A_4 \cos \theta^*,$$

ATLAS-CONF-2018-037
CMS, arxiv: 1806.00863
Measuring $\sin^2(\theta_{\text{lep}}^{\text{eff}})$ at the LHC

- The mixing of vector and axial vector couplings creates a forwards backwards asymmetry in the decay of $Z$ bosons to dilepton pairs $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell\bar{\ell}$

- Measure this asymmetry Collins-Soper rest frame (CS frame)

$$A_{FB} = \frac{3}{8} A_4 = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- The $Z$-axis of the CS frame is along the direction of the $q\bar{q}$ collision

- $Z$ boson rapidity defines the quark direction

$$\cos \theta^* = \frac{2(P_1^+ P_2^1 - P_1^- P_2^2)}{\sqrt{m_{ll}^2(m_{ll}^2 + p_{T,\ell}^2)}} \frac{p_{Z,\ell}}{|p_{Z,\ell}|}$$

CMS, arxiv: 1806.00863
Measuring $\sin^2(\theta_{\text{lep}}^{\text{eff}})$ at the LHC

- $A_{FB}$ increases with the rapidity of the $Z$ boson, $Y_Z$
- Only valence quarks contribute to $A_{FB}$
- At higher $Y_Z$ the high $X$ parton is likely to be a valence quark and the low $X$ parton the antiquark

CMS, arxiv: 1806.00863
Weighted $A_{FB}$

- Weight $A_{FB}$ by $\cos \theta^*$
- Weighted $A_{FB}$ cancels uncertainties that come from efficiencies and acceptance

CMS, arxiv: 1806.00863
Extracting $\sin^2(\theta_{\text{lep}}^{\text{eff}})$

- $A_{FB}$ has a high dependence on mass, this comes from interference of $Z$ with virtual photon

- By creating templates by varying the value of $\sin^2(\theta_w)$ we can test which value that the data agrees with

CMS, arxiv: 1806.00863
PDFs

- Measurement of $\sin^2(\theta^\text{lep}_{\text{eff}})$ has strong dependence on PDFs
- Less effect in high rapidity regions
- ATLAS and CMS constrain PDFs in situ

CMS Weighted PDF

18.8 fb$^{-1}$ (8 TeV)

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<th>$\sin^2\theta^\text{eff}$</th>
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CMS, arxiv: 1806.00863
Combination of 7TeV (1 fb$^{-1}$) and 8TeV (2 fb$^{-1}$) data

Measurement uses the dimuon channel

High rapidity measurement $2.0 < \eta < 4.5$ with raw $A_{FB}$

\[
\sin^2(\theta_{lep}^{eff}) = 0.23142 \pm 0.0011
\]

The error breaks down as ±0.00073 (statistical), ±0.00052 (systematic) and ±0.00056 (theoretical)
Measurement made on 8TeV data

18.8 fb\(^{-1}\) in the dimuon channel and 19.6 fb\(^{-1}\) in the dielectron channel

Uses weighted \(A_{fb}\) and constrains PDFs using the high mass region

\[
\sin^2(\theta^\text{lep}_{\text{eff}}) = 0.23101 \pm 0.00053
\]

The error breaks down as \(\pm 0.00036\) (stat) \(\pm 0.00018\) (syst) \(\pm 0.00016\) (theo) \(\pm 0.00031\) (parton distributions in proton)
- Measurement made on 8TeV data with 20.2 fb$^{-1}$
- 6 million electron pairs, 7.5 million muon pairs
- Using events with a forward electron extends the rapidity coverage to 3.6
- 1.5 million electron pairs with a forward electron (reconstructed from calorimeter, no tracker)
Extracts weak mixing angle from $A_4(m, y)$ instead of $A_{FB}$

$\sin^2(\theta_{lep}^{\text{eff}}) = 0.23101 \pm 0.00036$

The error breaks down as $\pm 0.00021$ (stat) $\pm 0.00024$ (PDF) $\pm 0.00016$ (syst.)
LHC EW working group activities

- Tuned comparison/benchmarking of NLO and higher order weak and QED corrections, including FSR, ISR and IFI
- Main focus on $\frac{d\sigma}{dM(\ell\ell)}$ and $A_{FB}$
- Studying various electroweak input schemes, in particular new $\sin(\theta_W)$ EW input scheme, which is needed for this measurement
- Preparatory studies in view of Run2 and future combinations

$A_4(m_{\ell\ell})$ for $y_{\ell\ell} < 3.6$

$A_4(y_{\ell\ell})$ for $86 < m_{\ell\ell} < 96$
Future measurements

- CMS Hi-lumi extended acceptance projections (CMS-PAS-FTR-17-001)
- ATLAS projections (ATL-PHYS-PUB-2018-037)
- LHCb projections (LHCb-PUB-2018-013)
- The statistical sensitivity can be expected to improve by up to a factor of $\sqrt{2}$
- Increased statistics will also allow for the analysis to be done as a function of rapidity
- Expect uncertainties to be competitive with LEP+SLD at $L > 100 fb^{-1}$
- Extension of tracker will increase acceptance to Z rapididities up to 2.8
- Studies in the muon channel predict to have uncertainties on PDFs competitive with LEP+SLD at $L > 300 fb^{-1}$
- Extension of inner tracker from $|\eta| \leq 2.4$ to $|\eta| \leq 4.0$
- Projections for $L > 300 fb^{-1}$ for different PDF scenarios
Conclusions

- Important probe to test the SM in the electroweak sector and to search indirectly for new physics
- Run2 uncertainties expected to be competitive with LEP/SLD
- The LHC (ATLAS, CMS, LHCb) has promising plans for future measurements, and for combinations of these measurements

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