Measurement of the effective weak mixing angle at D0

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Motivation

The weak mixing angle ($\sin^2 \theta_W$) measurement

- fundamental parameter of Standard Model
- most precise results from LEP/SLD
- the least precise one among all electroweak fundamental parameters
- the 2000 prediction for the Tevatron experiments single channel: \(~0.00050\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Relative Uncertainty from Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine structure constant $\alpha$</td>
<td>$\sim 10^{-8}$</td>
</tr>
<tr>
<td>fermi-constant $G_F$</td>
<td>$\sim 10^{-5}$</td>
</tr>
<tr>
<td>Z boson mass $M_Z$</td>
<td>$\sim 10^{-5}$</td>
</tr>
<tr>
<td>weak mixing angle $\sin^2 \theta_W$</td>
<td>best single measurement: $10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>LEP/SLD combine: $6 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Weak mixing angle from $A_{FB}$

Forward-backward charge asymmetry ($A_{FB}$)

- Observed as a function of dilepton mass
- Sensitive to the weak mixing angle

$$g_V^i \equiv t_{3L}(i) - 2q_i \sin^2 \theta_W$$
$$g_A^i \equiv t_{3L}(i)$$

$\cos \theta > 0$: forward
$\cos \theta < 0$: backward

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$
Tevatron and the D0 detector

- tracking:
  - scintillating fiber + silicon microstrip trackers
  - 2T solenoid
- calorimeter (for electrons)
  - Central Calorimeter (CC) $\eta<1.1$
  - Endcap Calorimeters (EC) $1.5<\eta<3.2$
- muon system: $\eta<2.0$

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D0 measurements review

2008, D0 1 fb⁻¹
electron channel
precision: 0.0019
first measurement at hadron collider

2011, D0 5.1 fb⁻¹
electron channel
precision: 0.0010

2015, D0 9.7 fb⁻¹
electron channel
precision: 0.00047
D0 electron final result
First time close to LEP/SLD

2018, D0 8.6 fb⁻¹
muon channel
precision: 0.00064
D0 muon final result
Best muon channel to date

D0 Combined precision: 0.00040
Best single hadron collider experiment to date
Best light-quark measurement

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2008 D0 electron channel

A first measurement at hadron collider experiment

- Tevatron RunII, 1 fb$^{-1}$
- PDF: CTEQ6, with a simple higher order correction: ZGRAD2 vs. pythia
- use result to predict precision with 10 fb$^{-1}$

$$\sin^2 \theta_{\text{eff}}^{\ell} = 0.2326 \pm 0.0019$$
$$= 0.2326 \pm 0.0018(\text{stat.}) \pm 0.0003(\text{syst.}) \pm 0.0005(\text{PDF})$$

---

**Predicted for 10 fb$^{-1}$ using 1 fb$^{-1}$ results**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat.</td>
<td>0.0005</td>
</tr>
<tr>
<td>syst.</td>
<td>negligible</td>
</tr>
<tr>
<td>PDF</td>
<td>negligible</td>
</tr>
<tr>
<td>total</td>
<td>~0.0005</td>
</tr>
</tbody>
</table>
2011 D0 electron channel

An important next step estimation

- Tevatron RunII, 5 fb⁻¹
- PDF: CTEQ6L
- expectation for future not optimistic as before, syst. uncertainty becomes very important!
  - syst. not reducing as data accumulates
  - syst. limits data sample (bad quality events removed)

\[
\sin^2 \theta_{\text{eff}}^\ell = 0.2326 \pm 0.0010
\]
\[
= 0.2309 \pm 0.0008\text{(stat.)} \pm 0.00029\text{(syst.)} \pm 0.00048\text{(PDF)}
\]

<table>
<thead>
<tr>
<th></th>
<th>predicted for 10 fb⁻¹ using 1 fb⁻¹ result</th>
<th>predicted for 10 fb⁻¹ using 5 fb⁻¹ result</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat.</td>
<td>0.0005</td>
<td>0.0006</td>
</tr>
<tr>
<td>syst.</td>
<td>negligible</td>
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<tr>
<td>PDF.</td>
<td>negligible</td>
<td>0.00048</td>
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<tr>
<td>total</td>
<td>~0.0005</td>
<td>~0.00085</td>
</tr>
</tbody>
</table>


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Lepton calibrations

Large uncertainty

• due to noise and detector aging
• affects mass reconstruction, thus affects $A_{FB}$ vs. mass
• the electron energy calibration was ±0.1%, but to avoid being dominated by systematics, need ±0.01%

Difficult to calibrate

• hard to simulate detector aging effects
• simple one parameter calibration $E_{corr} = k \times E_{obs}$ is insufficient

At hadron colliders, lepton energy can be calibrated using $Z$ mass. However, the only one constraint limits the number of parameters

\[
E_{corr} = k \times E_{obs} \quad \checkmark \\
E_{corr} = k \times E_{obs} + b \quad \times
\]
Lepton calibrations (2)

General idea

- multip-parameters

\[ E(\eta)_{\text{corr}} = k(\eta) \times E(\eta)_{\text{obs}} + b(\eta) \]

- more constraints: separating Z samples
  - large opening angle between leptons: lower energy
  - small opening angle between leptons: higher energy

- reduce correlation between \( k \) and \( b \) parameters

Data/MC separately calibrated

- calibrate to generator level information
- not directly calibrate data to MC, because MC itself has eta-dependence
Electron calibration

Multiple-parameter calibration

- improve the electron energy calibration precision to ~0.01%
- reduce energy-eta dependence

\[ E(\eta)_{\text{corr}} = k(\eta) \times E(\eta)_{\text{obs}} + b(\eta) \]

**di-electron mass before (a) and after (b) our additional calibrations as a function of electron \( \eta \).** For events where both electrons in CC (CC-CC), both in EC (EC-EC) and one in CC and one in EC (CC-EC), the major difference is in the absolute energy of electrons. EC-EC electrons have highest energy due to Z boost, and CC-EC electrons have lowest energy.
First time high precision!
- 10 fb$^{-1}$, full RunII data
- improved by novel electron calibration method
  - 75% more statistics than simple sample size scaling (increased acceptance and improved track reconstruction)
- negligible syst. uncertainty

$$\sin^2 \theta_{\text{eff}} = 0.23147 \pm 0.00047$$

$$\sin^2 \theta_{\text{eff}} = 0.23137 \pm 0.00047$$

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<th>predicted for 10 fb$^{-1}$ using 5 fb$^{-1}$ result</th>
<th>10 fb$^{-1}$ results</th>
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<td>0.00043</td>
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<td>PDF.</td>
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<td>0.00048</td>
<td>0.00017</td>
</tr>
<tr>
<td>total</td>
<td>~0.0005</td>
<td>~0.00085</td>
<td>0.00047</td>
</tr>
</tbody>
</table>
2018 D0 muon channel channel

Last channel at Tevatron

- 8.6 fb\(^{-1}\) RunII data
- PDF: NNPDF3.0
- Not previously included in D0 high precision plan
  - charge-eta dependence in muon momentum reconstruction
  - solved by special calibration similar to the electron channel

\[
\sin^2 \theta_{\text{eff}}^\ell = 0.23016
\]

\[
= \pm 0.00059\,(\text{stat}) \pm 0.00006\,(\text{syst}) \pm 0.00024\,(\text{PDF})
\]

\[
= 0.23016 \pm 0.00064
\]
2018 D0 combination

Best result from single hadron experiment

- full RunII data
- PDF: NNPDF3.0
- higher order correction based on zfitter calculation and ResBos event generator
- good agreement compared with world average

\[ \sin^2 \theta^\ell_{\text{eff}} = 0.23095 \pm 0.00040 \]
\[ = 0.23095 \pm 0.00035(\text{stat}) \]
\[ \pm 0.00007(\text{syst}) \pm 0.00019(\text{PDF}) \]