Electroweak Precision Measurement at Hadron Colliders

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Hadron Colliders

D0 experiments at Fermilab Tevatron
• proton-antiproton collider, 1.96 TeV

ATLAS experiments at LHC
• proton-proton collider, 13 TeV
Electroweak precision measurement and global fitting

Basic idea
• Observation on fundamental parameters
  • $\alpha$, $G_\mu$, $M_Z$, $M_W$, $\sin^2\theta_W$, $M_H$, $M_{\text{top}}$
• Input to the global fitting
• Starting from 1960s

Key parameters
• $M_W$ and $\sin^2\theta_W$ are the most important parameters since LEP/SLC
• LEP/SLC: “for the first time the experimental precision is sufficient to probe the predictions at loop level”
• $M_W$ and $\sin^2\theta_W$: ~6% and 4% shift due to loop effects on their experimental observations
• Currently the parameters with worst precision
Pre-Top-Higgs Era

Aiming for top quark and Higgs boson

- Top quark and Higgs boson, missing freedoms
- Major task: predicting $M_{\text{top}}$ and $M_{H}$ under standard model assumptions
- Before their discoveries: $M_{\text{top}}$ prediction within 50 GeV, $M_{H}$ within 30 GeV
Weak mixing angle @ $M_Z$

Asymmetry at $Z$ pole
- Forward-Backward Asymmetry ($A_{FB}$)
- A function of invariant mass

\[ A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = A_{FB}(\sin^2 \theta_{eff}) \]

\[ \cos \theta > 0, \text{ forward} \]
\[ \cos \theta < 0, \text{ backward} \]
Measurement from LEP/SLC (1)

Electron Positron Collider LEP and SLC

- **LEP**: Spatial asymmetry AFB, **SLC**: Polarization asymmetry
- **Final state**: $ee$, mumu, tautau, qqbar (including light quark and heavy quark)

Dominant uncertainties

- **Statistical uncertainty**
- **Loop correction**
  - Contribution from loops 3.7%
  - Not being systematically studied before LEP
Measurement from LEP/SLC (2)

Results (by 2006, from 1980s)

- Most precise ones: \( \Delta \sin^2 \theta_W \) (LEP) = 0.00029, \( \Delta \sin^2 \theta_W \) (SLD) = 0.00026
- Statistical dominated
- Completely two loops + leading 3 loops: \( \Delta \sin^2 \theta_W \) (loop) = 0.00005

\[
\begin{array}{c|c|c}
\hline
 & \text{LEP} & \text{average} \\
\hline
\Delta \sin^2 \theta_{\text{eff, lepton}} & 0.00029 & 0.00016 \\
\hline
\end{array}
\]
Post-Top-Higgs Era

Aiming for SM global test, and new physics

- All freedoms have been experimentally fixed, allow for SM global test
- Predictions for potential beyond standard model new physics
- Measurement dominated by hadron colliders

\[ M_{\text{eff}}^2 = \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{\sqrt{8\alpha(1 + \Delta r)}}{G_F M_Z^2}} \right) \]

\[ \sin^2 \theta_{\text{eff}} = \left( 1 - \frac{M_W^2}{M_Z^2} \right) (1 + \Delta \kappa_f) \]

New challenges at hadron colliders

- Precision need to be at O(0.01%)
- New uncertainty sources (systematics, PDF, nPQCD)
- Separate measurements for different fermions (final states)
Measurements at Hadron Colliders

2008, D0 1 fb\(^{-1}\)  
electron channel  
precision: 0.0019  
first hadron collider measurement

2011, D0 5.1 fb\(^{-1}\)  
electron channel  
precision: 0.0010

2013, CDF 2.1 fb\(^{-1}\)  
electron channel  
precision: 0.0011

2014, CDF 9.2 fb\(^{-1}\)  
muon channel  
precision: 0.0010  
CDF muon final result

2016, CDF 9.4 fb\(^{-1}\)  
electron channel  
precision: 0.00053  
CDF electron final result

2015, D0 9.7 fb\(^{-1}\)  
electron channel  
precision: 0.00047  
D0 electron final result

2016 LHCb 7+8 TeV  
precision: 0.00105

2017 CMS 8 TeV  
precision: 0.00052

2018, Tevatron combined  
precision: 0.00033

2015 ATLAS 7 TeV  
precision: 0.00012

2015, D0 9.7 fb\(^{-1}\)  
electron channel  
precision: 0.00047  
D0 electron final result

Best single channel to date  
First time close to LEP/SLD

Best single experiment to date  
Best light-quark measurement
Measurement at hadron colliders

Dominant uncertainties and related topics

<table>
<thead>
<tr>
<th>by 2011</th>
<th>( \Delta \sin^2 \theta_{\text{eff,lept}} )</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW loops</td>
<td>0.00005</td>
<td>Achieved by LEP age ☑</td>
</tr>
<tr>
<td>Statistics</td>
<td>&gt;0.00030 (Tevatron) &lt;0.00010 (LHC future)</td>
<td>Will be reduced</td>
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<td>PDF</td>
<td>0.00048</td>
<td>New</td>
</tr>
<tr>
<td>Initial State Radiation</td>
<td>&gt;0.00010 (LHC)</td>
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<tr>
<td>Systmatics</td>
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PDFs in the weak mixing angle measurement

**Tevatron**
- Assume q from proton, qbar from antiproton
- \( \sim 5\% \) opposite direction (sea quarks)
- PDF describes valence/sea quark fraction

**LHC**
- Assume \( q = Z \) boost direction (valence quark \( E > \) sea quark \( E \))
- Large possibility opposite directions (dilution)
- PDF describes valence/sea quark energy spectrum

More significant PDF uncertainty at LHC
PDF and related measurements (1)

**W asymmetry**
- W asymmetry at Tevatron: u/d quark energy spectrum
- W asymmetry at LHC: u/d quark fraction
- Large cross section and statistics

\[
A(y_W) = \frac{\frac{d\sigma_{W^+}}{dy_W} - \frac{d\sigma_{W^-}}{dy_W}}{\frac{d\sigma_{W^+}}{dy_W} + \frac{d\sigma_{W^-}}{dy_W}}
\]
PDF and related measurements (2)

Other measurements which could contribute

- Z rapidity, Z pT, AFB @ high mass and low mass

PDF update using Z rapidity

PDF update using Z pT

PDF update using W asymmetry

PDF update using AFB
Initial state radiation and QCD

Significant at LHC

- Significantly affects boson pT
- QCD resummation: low transverse momentum of Z (Z pT), non-perturbative QCD
- Rely on the Z pT and W pT measurement

Z pT distribution at LHC pp collision. Majority of the events have low Z pT (<20 GeV)
Initial state radiation and QCD

Z pT spectrum with QCD scale changes

Compared to nominal Z pT, changing scales gives unreasonable large shifts. It means a better experimental constraint is needed.
Overall planning for EW measurement

A collection of physics topics

• Drell-Yan and AFB@Z pole: weak mixing angle
• W asymmetry, Z rapidity, AFB@high mass/low mass : PDF
• W pT, Z pT: QCD resummation
• PDF/QCD/Weak mixing angle extraction

However

• Difficult, long time schedule, less paper publication
• physics, experimental technique, theory
• Systematic control
Systematics: lepton performance (1)

Above topics limited by lepton performance
- lepton energy/momentum: AFB, weak mixing angle, Z pT, W pT
- direction/selection efficiency: W asymmetry, Z rapidity

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<th>needed precision</th>
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<td>electron energy</td>
<td>0.1% - 1%</td>
<td>0.01%</td>
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<td>muon momentum</td>
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<td>efficiency</td>
<td>1% ~ 10%</td>
<td>&lt;1%</td>
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lepton performance limits the related W/Z measurements
Systematics: lepton performance (2)

Hadron collider and e+e- collider

- e+e- colliders:
  - mass (c.m.s. energy) determined from beam
  - efficiency almost 100%

- hadron colliders:
  - mass reconstructed from final state particles
  - efficiency ~50%, depends on particle directions

- Especially forward regions!
# Measurement at hadron colliders

## Dominant uncertainties and related topics

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<td>0.00030</td>
<td>Key Point</td>
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Systematic at hadron colliders

Traditional method
- based on detector simulation and hardware calibration
  - material, electronics …
- systematic controlled to 0.1% - 1%

Difficulties
- aiming for 0.01%, effects which are not simulable become significant

<table>
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<th>Detector response</th>
<th>Problem</th>
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<td>electron energy</td>
<td>pileup noise, calorimeter, energy loss</td>
</tr>
<tr>
<td>muon momentum</td>
<td>magnetic, misalignment, photon radiation, multiple interaction</td>
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How to control systematics

Parameterization

• Factorize all potential effects into parameters, e.g.:

\[ E_{\text{obs}} = b + k \times E_{\text{truth}} + \gamma \times E_{\text{truth}}^2 + \cdots \]

• Use physics constraints to determine their values
• Precision determined by how many parameters considered
• Difficulties: number of parameters limited by the only physics constraint we have: $M_Z$
Lepton calibrations

More physics constraints

- At hadron colliders, Z boson boost varies from initial quark energy difference
- Final state leptons are dominated by the Z boost rather than Z decay
- Difference Z boost provide difference lepton kinematics

\[ E_{\text{obs}} = b + k \times E_{\text{truth}} + \gamma \times E_{\text{truth}}^2 + \cdots \]
Calibration on particles

Improvement both on D0 and ATLAS performance

• 2018: accepted as standard calibration procedure (electron energy calibration + efficiency corrections) by ATLAS collaboration

<table>
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<th>improvement</th>
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Calibration on physics

AFB vs mass in D0 muon channel before/after calibration

AFB vs mass in ATLAS muon channel before/after calibration
**D0 electron final state measurement**

**A collection of records**  

- The first time that
  - weak mixing angle measurement at hadron collider has a precision close to the best LEP/SLD
- The most precise measurement of:
  - electron-final state determination @ hadron colliders
  - light quark involved determination (including LEP/SLD)
  - single channel determination @ hadron colliders

\[
\sin^2 \theta_{ee} = 0.23137 \pm 0.00047
\]

The original expected unc. is >0.00085!
D0 muon final state measurement

A collection of records

- The first time that
  - muon final state used at D0 in precision measurement
- One of the most precise measurements of:
  - muon final state determination (including LEP/SLD)
- Combined with D0 electron:
  - the most precise single experimental determination

\[
\sin^2 \theta^{\mu\mu}_{\text{eff}} = 0.23016 \pm 0.00064
\]

Muon channel was not planned in D0 precision measurement!
Tevatron combination


$$\sin^2 \theta_{\text{eff}}^{\text{lept}} = 0.23148 \pm 0.00033$$
Academic Influences

Invited talks at international conferences

- 14 talks at top conferences
- 2014 Moriond, 2014 ICHEP
- 2015 LHCP
- 2016 Blois, 2016 ICHEP
- 2017 Mriond, 2017 MITP, 2017 EPS (2 talks), 2017 PANIC
- 2018 ICHEP (2 talks)
- 2019 Moriond, 2019 EPS
On-going work

ATLAS
$\Delta \sin^2 \theta_W < 0.00010$

- Electron calibration
- Muon calibration
- Efficiency

W asymmetry
13 TeV/5 TeV ATLAS

- Z boson rapidity at D0
- W/Z boson pT at D0
- W/Z decay angular coefficients
- High mass DY

QCD and PDF
(ePump ResBos Project (ERP) collaboration)
Coming soon …

Next few years

• Weak mixing angle determination using ATLAS 2015+2016 data, $\Delta \sin^2 \theta_W \sim 0.00045$
  • followed by measurement using full Run 2 data, $\Delta \sin^2 \theta_W < 0.00025$
• W pT measurement using D0 data
• Z rapidity measurement using D0 data
• W asymmetry measurement using ATLAS Run 2 data (ongoing)
• PDF study in CT18 vs precision EW measurement
• QCD resummation vs precision EW measurement at LHC
Thanks
Backup
electron calibration

Electron calibration at ATLAS

Electron calibration at D0
Muon calibration @ ATLAS

Red: before calibration  
Green: calibrate using traditional method  
Blue: calibrate using new method

Muon calibration at ATLAS
Systematics: lepton performance (3)

Lepton calibration

- Limited precision using hardware-level corrections and simulation
- Physics calibration: $M_Z$

\[ M_Z^{\text{LEP}} = 91.1876 \pm 0.0021 \text{ GeV} \]

\[ M^2 = 2E_1 E_2 (1 - \cos \theta_{12}) \]
ATLAS performance