Precision Electroweak Measurements at $e^+e^-$ colliders - Determining the Next Energy Scale

Ashutosh Kotwal
Duke University

(Summary of Snowmass 2013 Studies)

Beijing-Chicago Workshop
14-15 September 2015
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To be precise
we must measure precisely

Beijing-Chicago Workshop
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Spontaneous Symmetry Breaking

- Is the mechanism of Electroweak Symmetry Breaking, the Standard Model Higgs mechanism? Or is there more to it??
Spontaneous Symmetry Breaking of Gauge Symmetry

- The Higgs potential in the SM is a parameterization that respects certain rules of QFT

- Phase transition → vacuum state possesses non-trivial quantum numbers
  - Dynamical origin of this phase transition is not known
  - Implies vacuum is a condensed, superconductor-like state

- Discovery of the “radial excitation” a.k.a the Higgs boson means that we have taken the first, big step in establishing the properties of this potential
Next Big Question: Why is the Higgs Boson so Light?

\[ m_H^2 - m_{\text{bare}}^2 = \left( \begin{array}{c} H \\ H \\ \end{array} \right) + \left( \begin{array}{c} t \\ H \\ \end{array} \right) + \left( \begin{array}{c} W,Z \\ H \\ \end{array} \right) \]

\[ \Lambda \int \lambda \, d^4k \, (k^2 - m_H^2)^{-1} \sim \Lambda^2 \lambda \]

The Higgs boson ought to be a very heavy particle, naturally.

However, observed \( m_H \ll \Lambda \).
Radiative Corrections to Higgs Self-Coupling

- $\lambda |\phi|^4$ receives radiative corrections from Higgs and top loops

Paul Steinhardt's talk on 7/15/2013 at Argonne USATLAS Workshop
Radiative Corrections to Higgs Self-Coupling

- $\lambda |\phi|^4$ receives radiative corrections from Higgs and top loops
Next Steps for Electroweak Measurements

- For the first time: All SM fields in the Electroweak sector are detected and parameters are measured
  - Since Higgs boson mass is measured to $\sim 1$ GeV

- We must over-constrain SM by measuring electroweak observables as precisely as possible
  - Complementary to direct searches for new particles
  - New physics may be revealed through precision measurements of W and Z bosons
Next Steps for Electroweak Measurements

- Electroweak observables access all the mechanisms that can stabilize / explain the light Higgs mass
  - Is it stabilized by a symmetry such as SuperSymmetry?
  - Is the Higgs boson a pseudo Nambu-Goldstone Boson?
  - Is there new strong dynamics?
  - Do extra-dimensional models bring the Planck scale close to Electroweak scale?

- Our Snowmass report discusses two areas of electroweak physics
  - Electroweak precision observables (EWPOs) : $M_W$ and $\sin^2\theta_W$
  - $\hat{\j}$ $\text{J} \text{U} \text{N} \text{E} \text{C} \text{P} \text{O} \text{A} \text{K}$ $\text{O} \text{U} \text{B} \text{I} \text{J}$ $\text{E} \text{K} \text{B} \text{E} \text{K}$ $\text{I}$ $\text{E}$ $\text{N}$ $\text{E}$ $\text{C} \text{P} \text{O} \text{A} \text{K}$ $\text{M} \text{E} \text{A}$ $\text{J}$ $\text{P} \text{U} \text{T} \text{U} \text{F} \text{A} \text{K}$
\( \sin^2 \theta_{\text{eff}} \) and \( M_W \)

- Both EWPOs are now precisely predicted in the SM
  - And correlated range predicted in beyond-SM models such as MSSM
Projecting the $M_W$ Precision

- Tevatron experience:
  - Larger calibration and control samples of data + increasing experience
### Projecting the $M_W$ Precision at Tevatron

- **Tevatron experience:**
  - Larger calibration and control samples of data + increasing experience

<table>
<thead>
<tr>
<th>$\Delta M_W$ [MeV]</th>
<th>CDF</th>
<th>D0</th>
<th>combined</th>
<th>final CDF</th>
<th>final D0</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}[fb^{-1}]$</td>
<td>2.2</td>
<td>4.3 (+1.1)</td>
<td>7.6</td>
<td>10</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>PDF</td>
<td>10</td>
<td>11</td>
<td>10</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>QED rad.</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$p_T(W)$ model</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>other systematics</td>
<td>10</td>
<td>18</td>
<td>9</td>
<td>4</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td>$W$ statistics</td>
<td>12</td>
<td>13</td>
<td>9</td>
<td>6</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>26 (23)</td>
<td>16</td>
<td>10</td>
<td>15</td>
<td>9</td>
</tr>
</tbody>
</table>

**Table 1-4.** Current and projected uncertainties in the measurement of $M_W$ at the Tevatron.

- **Tevatron final uncertainty of 9-10 MeV**
  - Assuming factor of two improvement in PDF uncertainty (possible with LHC measurements of boson distributions)
LHC Target for $M_W$ Precision

- Larger PDF sensitivity than Tevatron by factor of $\sim 2$

<table>
<thead>
<tr>
<th>$\Delta M_W$ [MeV]</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ [TeV]</td>
<td>8</td>
</tr>
<tr>
<td>$\mathcal{L}$ [fb$^{-1}$]</td>
<td>20</td>
</tr>
</tbody>
</table>

- Target LHC uncertainty of 5 MeV requires further factor of $\sim 3$ improvement in PDFs
- improved generators and radiative corrections
$M_w$ Precision at Lepton Colliders

- WW threshold scan being revisited at ILC: new estimates in progress
  - 3-4 MeV complementary measurements possible with kinematic fitting and final-state reconstruction

<table>
<thead>
<tr>
<th>$\Delta M_W$ [MeV]</th>
<th>LEP2</th>
<th>ILC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ [GeV]</td>
<td>161</td>
<td>161</td>
<td>161</td>
</tr>
<tr>
<td>$\mathcal{L}$ [fb$^{-1}$]</td>
<td>0.040</td>
<td>100</td>
<td>480</td>
</tr>
<tr>
<td>$P(e^-)$ [%]</td>
<td>0</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>$P(e^+)$ [%]</td>
<td>0</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

- CEPC/TLEP promises higher statistics: 25 million $WW$ pairs at threshold
  - Warrants detailed investigation of systematics, beam energy calibration and polarization: could deliver $\sim$1 MeV measurement of $M_w$

- Lepton colliders heading towards $\sim$2 MeV measurement of $M_w$ or better?

Work in progress (from Graham Wilson)
\( \sin^2 \theta_j \) Precision at Hadron Colliders

- Tevatron projection: \( \sim 40 \times 10^{-5} \)

<table>
<thead>
<tr>
<th>( \Delta \sin^2 \theta_{\text{eff}} ) ([10^{-5}])</th>
<th>CDF</th>
<th>D0</th>
<th>final CDF</th>
<th>final CDF</th>
<th>final CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>final state</td>
<td>e^+e^-</td>
<td>e^+e^-</td>
<td>( \mu^+\mu^- )</td>
<td>e^+e^-</td>
<td>( 90 \mu\mu + 9 \ e^+e^- )</td>
</tr>
<tr>
<td>( \mathcal{L} ) [fb(^{-1})]</td>
<td>2.1</td>
<td>5.0</td>
<td>9.0</td>
<td>9.0</td>
<td>9.0</td>
</tr>
<tr>
<td>PDF</td>
<td>12</td>
<td>48</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>higher order corr.</td>
<td>13</td>
<td>8</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>other systematics</td>
<td>5</td>
<td>38</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>statistical</td>
<td>90</td>
<td>80</td>
<td>80</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>total ( \Delta \sin^2 \theta_{\text{eff}} )</td>
<td>92</td>
<td>101</td>
<td>82</td>
<td>44</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 1-6. Current and target uncertainties in the measurement of \( \sin^2 \theta_{\text{eff}} \) at the Tevatron.

<table>
<thead>
<tr>
<th>( \Delta \sin^2 \theta_{\text{eff}} ) ([10^{-5}])</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHC/\text{per experiment}</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sqrt{s} ) [TeV]</td>
<td>7</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>( \mathcal{L} ) [fb(^{-1})]</td>
<td>4.8</td>
<td>1.1</td>
<td>20</td>
</tr>
<tr>
<td>PDF</td>
<td>70</td>
<td>130</td>
<td>35</td>
</tr>
<tr>
<td>higher order corr.</td>
<td>20</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>other systematics</td>
<td>70</td>
<td>181</td>
<td>60(35)</td>
</tr>
<tr>
<td>statistical</td>
<td>40</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>108</td>
<td>319</td>
<td>75(57)</td>
</tr>
</tbody>
</table>

Table 1-7. Current and target uncertainties in the measurement of \( \sin^2 \theta_{\text{eff}} \) at the LHC.

- LHC may reach \( \sim 20 \times 10^{-5} \) if current PDF uncertainties reduced by factor \( \sim 7 \)
- Moller Experiment (polarized \( ee \) scattering) at JLAB also targets \( \sim 20 \times 10^{-5} \)
- Interesting to compare LEP, SLC precision \( \sim 27 \times 10^{-5} \) with 3\( \sigma \) difference
\[ \sin^2 \theta \] Precision at Lepton Colliders

- ILC/GigaZ projection: \(~1.3 \times 10^{-5}\)

\[
\begin{array}{|c|c|c|}
\hline
\Delta \sin^2 \theta^l_{\text{eff}} [10^{-5}] & \text{ILC/GigaZ} & \text{TLEP(Z)} \\
\hline
\text{systematics} & 1.2 & \\
\text{statistical} & 0.5 & 0.2 \\
\text{total} & 1.3 & \\
\hline
\end{array}
\]

Table 1-11. *Projected uncertainties in the measurement of \( \sin^2 \theta^l_{\text{eff}} \) at lepton colliders.*

- CEPC/TLEP has further statistical potential: 100B to trillion \( Z \) bosons
  polarization to be investigated: could achieve precision \(~1 \text{ to } 3 \times 10^{-6}\)

- More than factor of 10 improvement over LEP, SLC precision with ILC/GigaZ
- Factor of 50 with CEPC/TLEP
# Parametric and Theoretical Uncertainties

- Anticipate missing higher-order corrections will be calculated

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m_t = 0.9$ GeV</th>
<th>$\Delta (\Delta \alpha_{\text{had}}) = 1.38(1.0) \cdot 10^{-4}$</th>
<th>$\Delta M_Z = 2.1$ MeV</th>
<th>missing h.o.</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M_W$ [MeV]</td>
<td>5.4</td>
<td>2.5(1.8)</td>
<td>2.6</td>
<td>4.0</td>
<td>7.6(7.4)</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}[10^{-5}]$</td>
<td>2.8</td>
<td>4.8(3.5)</td>
<td>1.5</td>
<td>4.5</td>
<td>7.3(6.5)</td>
</tr>
</tbody>
</table>

Table 1-2. Current parametric and theory uncertainties of SM predictions of $M_W$ and $\sin^2 \theta_{\text{eff}}$.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta m_t = 0.6(0.1)$ GeV</th>
<th>$\Delta (\Delta \alpha_{\text{had}}) = 5 \times 10^{-5}$</th>
<th>$\Delta M_Z = 2.1$ MeV</th>
<th>missing h.o.</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M_W$ [MeV]</td>
<td>3.6(0.6)</td>
<td>1.0</td>
<td>2.6</td>
<td>1.0</td>
<td>4.7(3.0)</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}[10^{-5}]$</td>
<td>1.9(0.3)</td>
<td>1.8</td>
<td>1.5</td>
<td>1.0</td>
<td>3.2(2.6)</td>
</tr>
</tbody>
</table>

Table 1-3. Anticipated parametric and theory uncertainties of SM predictions.
### Parametric and Theoretical Uncertainties

- Anticipate missing higher-order corrections will be calculated

<table>
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<tr>
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<td>2.6</td>
<td>4.0</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}[10^{-5}]$</td>
<td>2.8</td>
<td>4.8(3.5)</td>
<td>1.5</td>
<td>4.5</td>
</tr>
</tbody>
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**Table 1-2.** Current parametric and theory uncertainties of SM predictions of $M_W$ and $\sin^2 \theta_{\text{eff}}$.

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<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta M_W$ [MeV]</td>
<td>3.6(0.6)</td>
<td>1.0</td>
<td>2.6</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}[10^{-5}]$</td>
<td>1.9(0.3)</td>
<td>1.8</td>
<td>1.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Table 1-3.** Anticipated parametric and theory uncertainties of SM predictions.

- Desirable to improve $m_{\text{top}}$ precision below 0.5 GeV

  Non-perturbative QCD effects in connecting reconstructed and pole mass

- Hadronic loops in running $\alpha_{\text{EM}}$ → need factor 2-3 improvement (lattice?)
What could we learn?

- SUSY-breaking parameter space is large
- Consider scenario after light stop discovery with mass = \((400 \pm 40)\) GeV
- MW predicts correlation with sbottom mass and heavy stop mass in MSSM
  - Parameter space shrinks rapidly depending on value and precision of \(M_W\)

\[ \Delta M_W = \pm 5 \text{ MeV} \]
Summary - EWPOs

68% and 95% CL fit contours w/o $M_W$ and $m_t$ measurements

- Present SM fit
- Prospects for LHC
- Prospects for ILC/GigaZ

$m_t \pm 1\sigma$

$M_W \pm 1\sigma$
Summary - EWPOs

68% and 95% CL fit contours w/o $M_W$ and $\sin^2(\theta^l_{\text{eff}})$ measurements

- Present SM fit
- Prospects for LHC
- Prospects for ILC/GigaZ

Present measurement
ILC precision
LHC precision

$M_W \pm 1\sigma$

$\sin^2(\theta^l_{\text{eff}}) \pm 1\sigma$
**STU Parameterization**

- Generic parameterization of new physics contributing to W and Z boson self-energies through radiative corrections in propagators
  

![Diagram of STU Parameterization](image-url)
Summary - EWPOs

68% and 95% CL fit contours for U=0
(SM_{ref}: M_H=126 GeV, m_t=173 GeV)

- Present fit
- Present uncertainties
- Prospects for LHC
- Prospects for ILC/GigaZ

SM Prediction
M_H = 125.7 ± 0.4 GeV
m_t = 173.20 ± 0.87 GeV
What Can We Learn About New-Physics Scale?

\[
\frac{G_\mu}{\sqrt{2}} = \frac{\pi \alpha M_Z^2}{2 M_W^2 (M_Z^2 - M_W^2)} (1 + \Delta r)
\]

\[
\Delta r \approx \Delta r^{\text{SM}} + \frac{\alpha}{2 s_W^2} \Delta S - \frac{\alpha c_W^2}{s_W^2} \Delta T + \frac{s_W^2 - c_W^2}{4 s_W^4} \Delta U,
\]

\[
\sin^2 \theta_{\text{eff}} \approx (\sin^2 \theta_{\text{eff}})^{\text{SM}} + \frac{\alpha}{4 (c_W^2 - s_W^2)} \Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2} \Delta T,
\]

\[
\Delta S = 0.04, \Delta T = 0 \quad \Rightarrow \quad \Delta M_W = 27 \text{ MeV}, \Delta \sin^2 \Theta = 14 \times 10^{-5}
\]

(1-2 sigma of current uncertainties)

\[
\Delta S = 0, \Delta T = 0.03 \quad \Rightarrow \quad \Delta M_W = 32 \text{ MeV}, \Delta \sin^2 \Theta = 8 \times 10^{-5}
\]

Note: world average measurement: \(\Delta M_W = 15 \text{ MeV}\)
What Can We Learn About New-Physics Scale?


\[
\mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D^\mu} H \right) \left( H^\dagger \overleftrightarrow{D_\mu} H \right)
\]

\[
- \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H f_L H f_R + \text{h.c.} \right)
\]

\[
+ \frac{ic_W g}{2m_\rho^2} \left( H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2} \left( H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu})
\]

\[
+ \frac{ic_{HW} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{ic_{HB} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}
\]

\[
+ \frac{c_\gamma g'^2}{16\pi^2 f^2} \frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_5^2}{16\pi^2 f^2} \frac{y_t^2}{g_\rho^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}.
\]

(15)

\[
\Delta \rho \equiv \hat{T} = c_T \xi,
\]

\[
\xi \equiv \frac{v^2}{f^2}, \quad v = \left( \sqrt{2} G_F \right)^{-1/2} = 246 \text{ GeV}
\]

\[
\hat{S} = (c_W + c_B) \frac{m_W^2}{m_\rho^2}
\]

Higgs couplings change by factor

\[
1 - \xi c_H/2
\]
What Can We Learn About New-Physics Scale?

$\Delta S = 0.04, \Delta T = 0 \Rightarrow if C_w + C_B = 1, m_\rho = 4.5 \text{ TeV}$

$\Delta S = 0, \Delta T = 0.03 \Rightarrow if c_T = 1, f = 15 \text{ TeV}$

Higgs coupling change by 6% (1.5%)

$\Leftrightarrow if c_H = 1, f = 1 \ (2) \text{ TeV}$

Conclusion: interpreted in a dimension–6 operator framework, EWPOs are already probing multi–TeV scale

Equivalent to Higgs coupling change of order 0.5 %

(caveat: different operators, different coefficients)

10,000 times the LEP statistics → EWPO improved by ~100 (statistical error) → new physics energy scale probed factor of 10 higher → 50–100 TeV
What Can We Learn About New-Physics Scale?

Gfitter Group
What Can We Learn About New-Physics Scale?

Warped Extra Dimension with Custodial Symmetry

- $M_{KK} = 10$ TeV
- $M_{KK} = 2$ TeV
- $M_{KK} = 1$ TeV

($M_H = 250$ GeV)

68%, 95%, 99% CL fit contours
($M_H = 120$ GeV, $m_t = 173$ GeV, $U = 0$)

$M_{KK} \in [0.5, 10]$ TeV
$L \in [5, 37]$

$M_H \in [114, 158]$ GeV
$m_t = 173.3 \pm 1.1$ GeV

Gfitter Group
Combined Fit to Higgs and Anomalous Trilinear Gauge Couplings

- Illustrates the complementary of approaches to new physics via coupling deviations (equivalent to dimension-6 operators)

Corbett et al.,
arXiv:1304.1151
LHC and ILC Comparison for Anomalous Trilinear Gauge Couplings

- equivalent to dimension-6 operator coefficients

![Graph showing comparison between LEP, Tevatron, LHC, ILC 500, ILC 800, ILC 500 TeV, ILC 800 TeV, and ILC 5000 TeV for \( \Delta \kappa_\gamma \) and \( \Delta \lambda_\gamma \).]

**Figure 1-22.** Comparison of \( \Delta \kappa_\gamma \) and \( \Delta \lambda_\gamma \) at different machines. For LHC and ILC three years of running are assumed (LHC: 300 fb\(^{-1}\), ILC \( \sqrt{s} = 500 \) GeV: 500 fb\(^{-1}\), ILC \( \sqrt{s} = 800 \) GeV: 1000 fb\(^{-1}\)). If available the results from multi-parameter fits have been used. Taken from Ref. [193, 194].

Generally, electron-positron collider probes dimension-6 operators, through diboson production, much better than LHC
Conclusions

- Electroweak physics is directly connected with the next big question after Higgs discovery: the mechanism for stabilizing the Higgs potential

- Electroweak Precision Measurements can test SM and probe BSM parameter space
  
  - High precision measurements of $M_w$ (factor of 5 improvement $\rightarrow \sim 3$ MeV) and $\sin^2 \theta_{\text{eff}}$ (factor of 10 improvement $\rightarrow \sim 1.3 \times 10^{-5}$) are good goals for ILC/GigaZ

  - CEPC/TLEP gives high statistics potential: factor 3-10 higher precision than ILC/GigaZ possible including systematics
    
    - $< 1$ MeV precision on $M_w$
    - $1-3 \times 10^{-6}$ precision on $\sin^2 \theta_{\text{eff}}$
Conclusions

- Complementary approaches to precision measurements for estimating the energy scale of new physics
  - Higgs branching ratios
  - Z-pole measurements
  - W mass measurement at WW threshold
  - Diboson measurements and anomalous couplings

- Precision measurements can probe energy scales of many TeV to many 10's of TeV
Conclusions – parametric uncertainties

Measurements of $M_W$ at the few MeV level, and $\sin^2 \theta_{\text{eff}}$ at the level of $10^{-5}$, require that the parametric uncertainties from $m_{\text{top}}, M_Z$, and $\Delta \alpha_{\text{had}}$ (the contribution to the running of $\alpha_{EM}$ from hadronic loops) as well as the missing higher order calculations be addressed. Parametric uncertainties from $m_{\text{top}}$ and $\Delta \alpha_{\text{had}}$, if reduced by a factor of 2 compared to current uncertainties, will prevent them from exceeding the anticipated total precision on $M_W$ at the LHC. At the ILC and TLEP a factor of 5 and 10 improvement, respectively, in the parametric uncertainties is needed, which is only achievable if the precision on $M_Z$ is considerably improved as well. TLEP can improve the $M_Z$ precision by a factor of at least 10. It is anticipated that calculations in the coming years will reduce the effect of missing higher-order calculations by a factor of 4 which is sufficient for the LHC and ILC target uncertainties, but further effort will be needed for TLEP.
THANK YOU

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