Precision Electroweak Measurements at the Energy Frontier - Determining the next Energy Scale

Ashutosh Kotwal
Duke University

(Summary of Snowmass 2013 Studies)

Center for Future High Energy Physics
IHEP Beijing, 16 July 2013
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To be precise
we must
measure
precisely

Center for Future High Energy Physics
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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 $\rightarrow$ 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?

\[ m_H^2 - m_{bare}^2 = (\text{Diagram 1}) + (\text{Diagram 2}) + (\text{Diagram 3}) \]

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

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
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 ~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 $\sin^2\theta_{\text{eff}}$
  - Vector boson scattering and tri-boson production
$\sin^2 \theta_{\text{eff}}$ 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>$\Delta M_\text{W}$ [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>$\mathcal{L}[\text{fb}^{-1}]$</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 $M_\text{W}$ 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)
\[ \sin^2 \theta_{\text{eff}} \] 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>( \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>

(From Arie Bodek)

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/( \sqrt{s} ) 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>

(ATLAS preliminary from Regino Caputo)

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
\[ \sin^2 \theta^l_{\text{eff}} \] Precision at Lepton Colliders

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

<table>
<thead>
<tr>
<th>( \Delta \sin^2 \theta^l_{\text{eff}} [10^{-5}] )</th>
<th>ILC/GigaZ</th>
<th>TLEP(Z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>systematics</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>statistical</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>total</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

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

- TLEP/CEPC has further statistical potential: trillion Z bosons
  polarization to be investigated: could achieve precision \( \sim 1 \) 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>$\Delta(\Delta\alpha_{\text{had}}) = 1.38(1.0) \times 10^{-4}$</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>
<thead>
<tr>
<th>$\Delta m_t$ = 0.9 GeV</th>
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<th>$\Delta M_Z$ = 2.1 MeV</th>
<th>missing h.o.</th>
<th>total</th>
</tr>
</thead>
<tbody>
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<td>2.6</td>
<td>4.0</td>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}^{\ell}[10^{-5}]$</td>
<td>2.8</td>
<td>4.8(3.5)</td>
<td>1.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

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

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<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>
</tr>
<tr>
<td>$\Delta \sin^2 \theta_{\text{eff}}^{\ell}[10^{-5}]$</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
Summary - EWPOs

- 68% and 95% CL fit contours w/o $M_W$ and $\sin^2(\theta_{\text{eff}})$ measurements
- Present SM fit
- Prospects for LHC
- Prospects for ILC/GigaZ
- Present measurement
- ILC precision
- LHC precision
- $M_W \pm 1\sigma$
- $\sin^2(\theta_{\text{eff}}) \pm 1\sigma$
**STU Parameterization**

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

Summary - EWPOs

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

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

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

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

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

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

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

(1-2 sigma of current uncertainties)

\[\Delta S = 0, \Delta T = 0.03 \implies \Delta M_W = 32 \text{ MeV}, \Delta \sin^2 \Theta = 8 \times 10^{-5}\]
What Can We Learn About New-Physics Scale?


\[ \mathcal{L}_{\text{SILH}} = \frac{c_H}{2f^2} \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) + \frac{c_T}{2f^2} \left( H^\dagger \overleftrightarrow{D_\mu} H \right) \left( H^\dagger \overleftrightarrow{D^\mu} \mu H \right) \\
- \frac{c_6 \lambda}{f^2} (H^\dagger H)^3 + \left( \frac{c_y y_f}{f^2} H^\dagger H f_L H f_R + \text{h.c.} \right) \\
+ \frac{ic_{\rho W} g}{2m_\rho^2} \left( H^\dagger \sigma^i \overleftrightarrow{D_\mu} H \right) \left( D^\nu W_{\mu\nu} \right)^i + \frac{ic_{B\rho} g'}{2m_\rho^2} \left( H^\dagger \overleftrightarrow{D_\mu} H \right) \left( \partial^\nu B_{\mu\nu} \right) \\
+ \frac{ic_{H\rho W} g}{16\pi^2 f^2} (D^\mu H)^\dagger \sigma^i (D^\nu H) W_{\mu\nu}^i + \frac{ic_{H\rho B} g'}{16\pi^2 f^2} (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
+ \frac{c_\gamma g'^2}{16\pi^2 f^2} g_\rho^2 H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_\gamma g_\rho^2 y_t^2}{16\pi^2 f^2} H^\dagger H G_{\mu\nu}^a G^{a\mu\nu}. \tag{15} \]

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

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

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

Higgs couplings change by factor

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

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

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

Higgs coupling change by 6% (1.5%) $\iff \text{if } c_H = 1, f = 1 \text{ (2) TeV}$

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

Equivalent to Higgs coupling change of order few %

(caveat: different operators, different coefficients)
Vector Boson Scattering

- This is a key process accessible for the first time at LHC
- A prime motivator for LHC/SSC: without Higgs (or some other) mechanism, longitudinally-polarized vector boson scattering amplitudes would violate tree-level unitarity above $\sim 1$ TeV

Vector Boson Scattering is intimately connected with EWSB
Vector Boson Scattering

- This is a key process accessible for the first time at LHC

- A prime motivator for LHC/SSC: without Higgs (or some other) mechanism, longitudinally-polarized vector boson scattering amplitudes would violate tree-level unitarity above \( \sim 1 \text{ TeV} \)

We still have to demonstrate experimentally that unitarizing mechanism is working, and how it is working
A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scalar $S$: $f \phi^{\dagger} \phi S$
- Via $S$ exchange, can mediate scattering process: $\phi \phi \rightarrow \phi \phi$

$$\left[\Box - m_s^2\right]^{-1} \sim m_s^{-2}[1 + \Box/m_s^2]$$

- For energies $<< m_s$, induces effective field theory operators:
  
  - Dimension-4: $(f/m_s)^2 (\phi^{\dagger} \phi)^2$
  - Dimension-6: $O_{\phi_d} = \left(f^2/m_s^4\right) \left[\partial_\mu (\phi^{\dagger} \phi) \partial^\mu (\phi^{\dagger} \phi)\right]$
  
  - This is one of the operators predicted in strongly-interacting light Higgs models
    
    - Alternate mechanism to SUSY for ensuring light Higgs boson
    
    - alters VBS compared to SM
A Toy Model for BSM extension

- Consider a term coupling the Higgs to a singlet scaler $S$: $f \phi^\dagger \phi S$
- Via $S$ exchange, can mediate scattering process: $\phi\phi \rightarrow \phi\phi$

- For energies $\ll m_S$, induces effective field theory operators:
  - Dimension-4: $(f / m_S)^2 (\phi^\dagger \phi)^2$
  - Dimension-6: $O_{\phi d} = (f^2 / m_S^4) \nabla_\mu (\phi^\dagger \phi) \nabla^\mu (\phi^\dagger \phi)$
  - This is one of the operators predicted in strongly-interacting light Higgs models
  - Observing a deviation in VBS consistent with this model would immediately point to model parameter values
Another Toy Model

- Consider the analogy with light-by-light scattering via electron loop

- Euler-Heisenberg effective lagrangian at low energies

\[
\mathcal{L} = \frac{1}{2} (E^2 - B^2) + \frac{2\alpha^2}{45m^4} \left[ (E^2 - B^2)^2 + 7(E \cdot B)^2 \right]
\]

- Second term can be re-written in terms of

\[
F_{\mu \rho} F^{\mu \sigma} F^{\nu \rho} F_{\nu \sigma} \quad \left( F_{\mu \nu} F^{\mu \nu} \right)^2
\]
Another Toy Model

- Consider the analogy with light-by-light scattering via electron loop

- Euler-Heisenberg effective lagrangian at low energies

\[ \mathcal{L} = \frac{1}{2} (E^2 - B^2) + \frac{2\alpha^2}{45m^4} \left[ (E^2 - B^2)^2 + 7(E \cdot B)^2 \right] \]

- Second term can be re-written in terms of

\[ F_{\mu\rho}F^{\mu\sigma}F^{\nu\rho}F_{\nu\sigma} \quad (F_{\mu\nu}F^{\mu\nu})^2 \]

Operator coefficients contain information on mass and coupling of new dynamical degrees of freedom
Another Analogy – Primakoff Production of $\pi^0$

- Primakoff production by photon interacting with strong nuclear EM field

- Therefore following operators can describe scalar resonance production in VBS

$$F_{\mu\rho} F^{\mu\sigma} F^{\nu\rho} F^{\nu\sigma} \quad (F_{\mu\nu} F^{\mu\nu})^2$$

Operator coefficients contain information on mass and coupling of new scalar resonance
Effective Field Theory Operators

- All dimension-6 and dimension-8 operators have been catalogued

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{|c_i|}{\Lambda^2} \mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4} \mathcal{O}_j \]

- LHC has shown the potential for

  - measuring new physics parameterized by higher-dimension operators
  - Differentiating between different operators using
    - Direct measurement of energy-dependence
    - different channels

- Dimension-8 operators tested:

  \[ \mathcal{O}_{S,0} = \left[ (D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[ (D^\mu \Phi)^\dagger D^\nu \Phi \right] \]

  \[ \mathcal{O}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta} \]

  \[ \mathcal{O}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha} \]

  \[ \mathcal{O}_{T,1} = \text{Tr} \left[ W_{\alpha\nu} W^{\mu\beta} \right] \times \text{Tr} \left[ W_{\mu\beta} W^{\alpha\nu} \right] \]
VBS Studies using Forward Tagged Jets

**ZZ → leptons**

Threshold of interest for dim-6 operator coefficient $< v^{-2} \sim 16 \text{ TeV}^{-2}$

**WZ → leptons**

dim-8 operator coefficient implies sensitivity to strong dynamics at TeV-scale

Complementarity of VBS and Triboson production

Anomalous $Z_{\gamma\gamma}$ production at high mass also very sensitive to “T” operators

$\Rightarrow$ Comparison of VBS and triboson production is another powerful capability for characterizing the new physics
Program of VBS and Triboson Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>$\Lambda_{UV}$ [TeV]</th>
<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_\phi W/\Lambda^2)</td>
<td>6</td>
<td>ZZ</td>
<td>1.9</td>
<td>34 TeV(^{-2})</td>
<td>16 TeV(^{-2})</td>
</tr>
<tr>
<td>(f_{S0}/\Lambda^4)</td>
<td>8</td>
<td>$W^\pm W^\pm$</td>
<td>2.0</td>
<td>10 TeV(^{-4})</td>
<td>4.5 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T1}/\Lambda^4)</td>
<td>8</td>
<td>WZ</td>
<td>3.7</td>
<td>1.3 TeV(^{-4})</td>
<td>0.6 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T8}/\Lambda^4)</td>
<td>8</td>
<td>$Z\gamma\gamma$</td>
<td>12</td>
<td>0.9 TeV(^{-4})</td>
<td>0.4 TeV(^{-4})</td>
</tr>
<tr>
<td>(f_{T9}/\Lambda^4)</td>
<td>8</td>
<td>$Z\gamma\gamma$</td>
<td>13</td>
<td>2.0 TeV(^{-4})</td>
<td>0.7 TeV(^{-4})</td>
</tr>
</tbody>
</table>

Table 5: 5\(\sigma\)-significance discovery values and 95% CL limits for coefficients of higher-dimensional electroweak operators. $\Lambda_{UV}$ is the unitarity violation bound corresponding to the sensitivity with 3000 fb\(^{-1}\) of integrated luminosity.

Conclusions:

1) factor of 2-3 improvement in sensitivity with HL-LHC upgrade

2) single-channel sensitivities pushed into the TeV-scale if new dynamics is strongly-coupled to Higgs and vector bosons

3) a powerful method of probing models of strongly-interacting light Higgs

4) model-independent tests of BSM dynamics
### Example Test of Unitarization by Higgs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>$\Lambda_{UV}$ [TeV]</th>
<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\phi d}/\Lambda^2$ at 14 TeV</td>
<td>6</td>
<td>$WZ$</td>
<td>1.9</td>
<td>29 TeV$^{-2}$</td>
<td>15 TeV$^{-2}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>17 TeV$^{-2}$</td>
<td>8.7 TeV$^{-2}$</td>
</tr>
</tbody>
</table>

**Conclusion:**

We are not really testing unitarization by SM Higgs until operator $< 16$ TeV$^{-2}$

$$O_{\phi d} = \frac{c_{\phi d}}{M_S^2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi)$$
# Example Test of Unitarization by Higgs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>dimension</th>
<th>channel</th>
<th>$\Lambda_{UV}$ [TeV]</th>
<th>$300 \text{ fb}^{-1}$</th>
<th>$3000 \text{ fb}^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\phi d}/\Lambda^2$ at 14 TeV</td>
<td>6</td>
<td>WZ</td>
<td>1.9</td>
<td>29 TeV$^{-2}$</td>
<td>17 TeV$^{-2}$</td>
</tr>
</tbody>
</table>

**Conclusion:**

We are not really testing unitarization by SM Higgs until operator $< 16$ TeV$^{-2}$

Single-channel tests of unitarization achievable with HL-LHC
Conclusion:
triboson production is dramatically more sensitive to new physics at higher beam energy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>channel</th>
<th>300 fb$^{-1}$ at 14 TeV</th>
<th>3000 fb$^{-1}$ at 14 TeV</th>
<th>3000 fb$^{-1}$ at 33 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{\phi W}/\Lambda^2$</td>
<td>$ZZjj$</td>
<td>34 TeV$^{-2}$</td>
<td>16 TeV$^{-2}$</td>
<td>12 TeV$^{-2}$</td>
</tr>
<tr>
<td>$f_{T1}/\Lambda^4$</td>
<td>$WZjj$</td>
<td>1.3 TeV$^{-4}$</td>
<td>0.6 TeV$^{-4}$</td>
<td>0.3 TeV$^{-4}$</td>
</tr>
<tr>
<td>$f_{T0}/\Lambda^4$</td>
<td>$WWW$</td>
<td>1.2 TeV$^{-4}$</td>
<td>0.5 TeV$^{-4}$</td>
<td>0.05 TeV$^{-4}$</td>
</tr>
</tbody>
</table>

Table 1-23. 5$\sigma$-significance discovery values for coefficients of higher-dimension operators.
Table 1-25. In $pp \rightarrow W^\pm W^\pm + 2j \rightarrow \ell\nu\nu + 2j$ processes, 5$\sigma$-significance discovery values and 95% CL limits are shown for coefficients the higher-dimension operator, $f_{T,1}/\Lambda^4$, for different machine scenarios without the UV cut and with the UV cut in parenthesis. Pileup refers to the number of $pp$ interactions per crossing.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\sqrt{s}$ [TeV]</th>
<th>Luminosity [fb$^{-1}$]</th>
<th>pileup</th>
<th>$5\sigma$ [TeV$^{-4}$]</th>
<th>95% CL [TeV$^{-4}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>14</td>
<td>300</td>
<td>50</td>
<td>0.2 (0.4)</td>
<td>0.1 (0.2)</td>
</tr>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>14</td>
<td>3000</td>
<td>140</td>
<td>0.1 (0.2)</td>
<td>0.06 (0.1)</td>
</tr>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>14</td>
<td>3000</td>
<td>0</td>
<td>0.1 (0.2)</td>
<td>0.06 (0.1)</td>
</tr>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>100</td>
<td>1000</td>
<td>40</td>
<td>0.001 (0.001)</td>
<td>0.0004 (0.0004)</td>
</tr>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>100</td>
<td>3000</td>
<td>263</td>
<td>0.001 (0.001)</td>
<td>0.0008 (0.0008)</td>
</tr>
<tr>
<td>$f_{T,1}/\Lambda^4$</td>
<td>100</td>
<td>3000</td>
<td>0</td>
<td>0.001 (0.001)</td>
<td>0.0008 (0.0008)</td>
</tr>
</tbody>
</table>

Table 1-26. In the $pp \rightarrow WW\gamma \rightarrow 3\ell + 3\nu$ process, the 5$\sigma$-significance discovery values are shown for the coefficients of higher order operators. The values in parentheses are obtained with the UV bound applied. $pp$ colliders at $\sqrt{s} = 14$, 33 and 100 TeV are studied.
Conclusion:
VBS and triboson production is dramatically more sensitive to new physics at higher beam energy

Dimension-8 operators are probed much more strongly than dimension-6 operators (due to stronger growth of amplitude with energy)

For dimension-8 operator coefficients of order $\sim 1$:
LHC probes energy scale $\Lambda \sim 1.6$ TeV
VLHC probes $\Lambda \sim 6$ TeV (with 3/ab)

LHC probes dimension-8 operators much more sensitively than ILC
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

Generally, ILC 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 → $\sim 3$ MeV) and $\sin^2\theta_{\text{eff}}$ (factor of 10 improvement → $\sim 1.3 \times 10^{-5}$) are good goals for ILC/GigaZ.
  - CEPC/TLEP gives high statistics potential: factor 3-4 higher precision than ILC/GigaZ possible including systematics.
  - Near-term: Tevatron and LHC pushing towards $\Delta M_W \sim 10$ MeV and 5 MeV respectively.
Conclusions – parametric uncertainties

Measurements of $M_W$ at the few MeV level, and $\sin^2 \theta^\ell_{\text{eff}}$, 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 $\alpha_{\text{EM}}$ 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.
Conclusions

- **LHC opens up new and important area of vector boson scattering (VBS) and triboson production**
  - single-channel tests of unitarization of VBS achievable with HL-LHC
  - Significantly extended sensitivity to new dynamics in the Higgs sector using VBS and multi-boson production
- **ILC1000 vs LHC sensitivity to higher-dimension operators in VBS and multi-boson production**
  - ILC more sensitive to dimension-6 operators through diboson production (clean environment, sensitivity through interference with SM)
  - LHC more sensitive (by 1-2 orders of magnitude) to dimension-8 operators compared to ILC1000, as probed by VBS and triboson production
Conclusions

- For the next decade, the LHC will continue to be the facility to explore these processes at higher levels of precision.

- The LHC will improve the sensitivity to anomalous trilinear gauge couplings by 1-2 orders of magnitude beyond LEP and the Tevatron.

- The HL-LHC is needed to demonstrate that the Higgs couplings to the electroweak vector bosons is an essential component of the unitarization mechanism for vector boson scattering. An integrated luminosity of 300 fb$^{-1}$ is not enough.

- The sensitivity to higher-dimensional operators improves by a factor of 2-3 with the HL-LHC, in comparison with the 300 fb$^{-1}$ at the LHC.

- Tribozon production and vector boson scattering are sensitive and complementary probes of dimension-8 operators. These processes becomes rapidly more sensitive with increasing beam energy, providing strong motivation for a 100 TeV $pp$ collider.

- Anomalous trilinear gauge couplings, which are induced by dimension-6 operators, are significantly better probed by the high-energy ILC options compared to the LHC. On the other hand, anomalous quartic gauge couplings, which are induced by dimension-8 operators, are significantly better probed (by 1-2 orders of magnitude) by the LHC, due to the stronger growth of the anomalous cross section with energy. Interpreting the latter as being induced by electroweak resonances, the LHC is sensitive to resonance masses that are higher by more than a factor of two, as compared to ILC1000.
THANK YOU

- Thanks to the Snowmass Energy Frontier Electroweak working group members!

Conveners: A. Kotwal and D. Wackeroth


Electroweak Report posted at:


and arXiv:1310.6708
VBS Study using same-sign WW → leptons

**ATLAS** Simulation Preliminary

\[\int L = 3000 \text{ fb}^{-1}\]

- VBS ssWW (SM)
- SM VBS ssWW + \( f_{S0} = 10 \text{ TeV}^4 \)
- SM ssWW QCD
- SM WZ + mis-ID

Stronger SM interference for “S0” operator → different kinematic dependence