Electroweak Parameter Fits

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Based on:

J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina, L. Silvestrini,
JHEP 1612 (2016) 135 + In Preparation

J.B., M. Cepeda, J. D’Hondt, R. K. Ellis, C. Grojean, B. Heinemann, F. Maltoni, A. Nisati, E. Petit, R. Rattazzi,

**Introduction**

- **Electroweak precision observables (EWPO):** Legacy measurements of Z & W properties from the LEP/SLC ($e^+ e^-$) Tevatron ($p \bar{p}$) era:

  \[
  M_Z, \Gamma_Z, \sigma_{\text{had}}^0, \sin^2 \theta_{\text{Eff}}^\text{lept}, P^{\text{pol}}_\tau, A_f, A_{FB}^0, R_f^0
  \]

  - Z-pole (LEP/SLC) 0.002-O(1)%
  - W obs. (LEP2/Tevatron) 0.02-O(1)%
  - $m_t$ Tevatron O(0.5%)

**Precision in many cases of the order of 1 ‰**

- What can you do with 1 ‰ EWPO?
  - **Test** the validity of the SM description of EW interactions (**2-loop level**)
  - **Indirect sensitivity** to the mass of heavy particles entering in the loops

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**Introduction**

- **Electroweak precision observables (EWPO):** Legacy measurements of $Z$ & $W$ properties from the LEP/SLC ($e^+ e^-$) Tevatron ($p\bar{p}$) era:

$$M_Z, \Gamma_Z, \sigma^0_{\text{had}}, \sin^2 \theta^\text{lept}_{\text{Eff}}, P^\text{pol}_\tau, A_f, A^0,f_{FB}, R_f^0$$

- **W obs. (LEP/Tevatron)**
  - $M_W, \Gamma_W$
  - $W$-pole (LEP/SCL) $0.002-0(1)%$
  - $m_t$ Tevatron $O(0.5)%$

**Precision in many cases of the order of 1 %**

- What can you do with 1 % EWPO?
  - Test the validity of the SM description of EW interactions (2-loop level)
  - Indirect sensitivity to the mass of heavy particles entering in the loops

**EW fit before the Higgs discovery (2010)**
**Introduction**

- **Electroweak precision observables (EWPO):** Legacy measurements of $Z$ & $W$ properties from the LEP/SLC ($e^+e^-$) Tevatron ($p\bar{p}$) era:

  \[
  M_Z, \Gamma_Z, \sigma^0_{\text{had}}, \sin^2 \theta^\text{lept}_\text{Eff}, P^\text{pol}_\tau, A_f, A^0_f, R^0_f, \quad \text{Z-pole (LEP/SLC)}
  \]

  \[
  M_W, \Gamma_W, \quad \text{W obs. (LEP2/Tevatron)} \\
  m_t, \quad \text{Tevatron O(0.5%)}
  \]

  Precision in many cases of the order of 1 \%

- **What can you do with 1 \% EWPO?**
  - **Test** the validity of the SM description of EW interactions (**2-loop level**)
  - **Indirect sensitivity** to the mass of heavy particles entering in the loops

**EW fit in the LHC era: after the Higgs discovery**

- **Large Hadron Collider (LHC)**

  \[
  M_H \quad 0.2\%
  \]

  Also, with similar precision as Tevatron

  \[
  m_t, M_W, \sin^2 \theta^\text{lept}_\text{Eff}
  \]

  **SM:** All SM inputs known. EWPO can be fully predicted

  \[ \Rightarrow \text{Test consistency of SM} \]

  **BSM:** Strong unambiguous constraints on NP modifying the EW sector

  **Graph:**

  - *SM: All SM inputs known. EWPO can be fully predicted*
  - \( \Rightarrow \text{Test consistency of SM} \)
  - **BSM:** Strong unambiguous constraints on NP modifying the EW sector
The Standard Model Electroweak fit

Electroweak limits on New Physics

Projections at Future Particle Colliders: Interplay of Electroweak/Higgs

Summary
The Standard Model Electroweak fit
EW fit input/output

\{ G_{\mu}, \alpha_{\text{em}} \} \quad \text{(Fixed)}
\{ m_h, m_t, M_Z, \alpha_s(M_Z^2), \Delta\alpha_{\text{had}}(M_Z^2) \} \quad \text{(Floating)}

SM

BSM

\{ C_i^{\text{NP}} \}_{i=1}^n

EWPO: Theory

\begin{align*}
M_W^2 &= \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2}} (1 + \Delta r) \right) \\
\Gamma_f &\propto |\rho_{fZ}|^2 \left[ \left| \frac{g_V}{g_A} \right|^2 R_V^f + \frac{g_V}{g_A} R_A^f \right] + \Delta_{\text{EW/QCD}} \\
A_{L,R}^{0,f} &= A_f = \frac{2 \text{Re} \left( \frac{g_L}{g_A} \right)}{1 + \text{Re} \left( \frac{g_L}{g_A} \right)^2}
\end{align*}

Fitting Framework

Statistical Tests: Hypothesis testing, limits, ...

EWPO: Data
The Standard Model Electroweak fit

EW fit input/output

**Experimental inputs**

- \{ G_\mu, \alpha_{em} \} (Fixed)
- \{ m_h, m_t, M_Z, \alpha_s(M_Z^2), \Delta \alpha^{(5)}_{had}(M_Z^2) \} (Floating)

**SM**

- EWPO: Theory
  \[ M_W^2 = \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2}G_\mu M_Z^2} (1 + \Delta r)} \right) \]
  \[ \Gamma_f \propto \left| \rho_Z^f \right| \left[ \left| \frac{g_V^f}{g_A^f} \right|^2 R_V^f + R_A^f \right] + \Delta_{EW/QCD} \]
  \[ A_{L,R}^{0,f} = A_f = \frac{2 \text{Re} \left[ \frac{g_V^f}{g_A^f} \right]}{1 + \text{Re} \left[ \frac{g_V^f}{g_A^f} \right]^2} \]

**BSM**

- Experimental inputs

**EWPO: Data**

- Fitting Framework

**Statistical Tests:**
Hypothesis testing, limits, ...

29th International Symposium on Lepton Photon Interactions at High Energies
Toronto, August 6, 2019

Jorge de Blas
*INFN - University of Padova*
**Electromagnetic constant**

Largest source of uncertainty on
\[ \alpha_{\text{em}}(M_Z) \]
comes from the light quark contribution to the running \[ \Delta \alpha_{\text{had}}^{(5)}(M_Z) \].

Most recent combination (2018)
\[ \Delta \alpha_{\text{had}}^{(5)}(M_Z) = 0.027611 \pm 0.000111 \]
\[ \left( \alpha^{-1}(M_Z^2) = \left( 1 - \Delta \alpha_{\text{lep}}(M_Z^2) - \Delta \alpha_{\text{had}}^{(5)}(M_Z^2) - \Delta \alpha_{\text{top}}(M_Z^2) \right) \alpha^{-1} \right) = 128.946 \pm 0.015. \]

**A. Keshavarzi et al.**
**Phys.Rev. D97 (2018) no.11, 114025**

See also:

**Experimental inputs: SM input parameters**

**Strong coupling constant**

\[ \alpha_s(M_Z) = 0.1180 \pm 0.0010 \]

2018 PDG world average
(Excluding EW fit results)
Conclusions

The Standard Model Electroweak fit

Experimental inputs: SM input parameters

Top quark mass

\[ m_t = 172.9 \pm 0.4 \text{ GeV} \]

PDG average

Higgs mass

\[ m_H \pm \text{tot} = (\pm \text{stat} \pm \text{syst}) \]

Run 1 + Run2 combination:

\[ M_H = 125.13 \pm 0.17 \text{ GeV} \]

Z mass

\[ M_Z = 91.1875 \pm 0.0021 \text{ GeV} \]
The Standard Model Electroweak fit

Experimental inputs: EWPO at Hadron Colliders

**W mass**

\[ M_W^{\text{ATLAS}} = 80.370 \pm 0.019 \text{ GeV} \]

First LHC measurement of \( M_W \) (2017)

Similar precision to Tevatron

Combination LEP/Tevatron/LHC:

\[ M_W = 80.379 \pm 0.012 \text{ GeV} \]

**Effective Weak Mixing angle**

Several determinations from Tevatron and the LHC experiments (ATLAS, CMS, LHCb)

Uncertainty ~2x LEP/SLC

\[ \sin^2 \theta_{\text{eff}} \]

Combination Tevatron/LHC:

\[ \sin^2 \theta_{\text{Eff}}^{\text{lept}} \bigg|_{\text{Tev+LHC}} = 0.23140 \pm 0.00023 \]
The Standard Model Electroweak fit

**EW fit input/output**

\[
\{ G_\mu, \alpha_{em} \} \quad \text{(Fixed)}
\]

\[
\{ m_h, m_t, M_Z, \alpha_s(M_Z^2), \Delta\alpha_{\text{had}}(M_Z^2) \} \quad \text{(Floating)}
\]

**Theory inputs**

**SM**

\[\{ C_i^{\text{NP}} \}_{i=1}^n\]

**BSM**

**EWPO: Theory**

\[
M_W^2 = \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_\mu M_Z^2}} (1 + \Delta r) \right)
\]

\[
\Gamma_f \propto \rho_Z^f \left[ \left| \frac{g_f}{g_A} \right|^2 R_V^f + R_A^f \right] + \Delta_{\text{EW/QCD}}
\]

\[
A_{L,R}^{0,f} = A_f = \frac{2\Re \left\{ \frac{g_f}{g_A} \right\}}{1 + \Re \left\{ \frac{g_f}{g_A} \right\}^2}
\]

**Fitting Framework**

**EWPO: Data**

**Statistical Tests:**
Hypothesis testing, limits, 

Jorge de Blas
*University of Padova*
The Standard Model Electroweak fit

**Theory inputs: SM calculations**

- Status of SM theory calculations for EWPO:
  - $\Gamma_W$ : EW one loop
  - $M_W$ : Full EW 2-loop + leading 3-loop & some 4-loop
  - $\sin^2 \theta_{\text{Eff}}^f$ (light fermions): Full EW 2-loop + leading higher order
  - $\Gamma_Z^f$ : Full EW 2-loop + higher-loop QCD corrections in the large $y_t$ limit
  - $\sin^2 \theta_{\text{Eff}}^b$ : Full EW 2-loop + higher-loop QCD corrections in the large $y_t$ limit

- Experimental vs Theory uncertainties:

<table>
<thead>
<tr>
<th></th>
<th>$M_W$</th>
<th>$\Gamma_Z$</th>
<th>$\sigma^0_{\text{had}}$</th>
<th>$R_b$</th>
<th>$\sin^2 \theta^\ell_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. error</td>
<td>15 MeV</td>
<td>2.3 MeV</td>
<td>37 pb</td>
<td>$6.6 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Theory error</td>
<td>4 MeV</td>
<td>0.5 MeV</td>
<td>6 pb</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$0.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

**The Standard Model Electroweak fit**

**EW fit input/output**

\[ \{G_\mu, \alpha_{\text{em}}\} \quad \text{(Fixed)} \]
\[ \{m_h, m_t, M_Z, \alpha_s(M_Z^2), \Delta\alpha_{\text{had}}^{(5)}(M_Z^2)\} \quad \text{(Floating)} \]

**SM**

**BSM**

**EWPO: Theory**

\[ M_W^2 = \frac{M_Z^2}{2} \left( 1 + \sqrt{1 - \frac{4\alpha}{\sqrt{2}G_\mu M_Z^2} (1 + \Delta r)} \right) \]

\[ \Gamma_f \propto \rho_Z^f \left[ \left| g_V^f \right|^2 R_V^f + R_A^f \right] + \Delta_{\text{EW/QCD}} \]

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\[ \ldots \]

**EWPO: Data**

**Fitting Framework**

**Statistical Tests:**

Hypothesis testing, limits, ...
The Standard Model Electroweak fit

Several groups/codes for the EW fit

- **Zfitter (LEP EWWG)**
  - On-shell ren. scheme
  - Frequentist stat. analysis

- **GAPP (PDG)**
  - MS ren. scheme
  - Frequentist stat. analysis

- **Gfitter**
  - On-shell ren. scheme
  - Frequentist stat. analysis

In this talk I will focus on the results obtained with the **HEPfit** code

- On-shell renormalization scheme
- Bayesian statistical analysis

**Mainly from:**
J.B., M. Ciuchini, E. Franco, S. Mishima, M. Pierini, L. Reina & L. Silvestrini
The Standard Model Electroweak fit

**The HEPfit code**

- General **High Energy Physics** fitting tool to combine indirect and direct searches of new physics (available under GPL on GitHub)
  
  https://github.com/silvest/HEPfit

- Webpage: http://hepfit.roma1.infn.it
SM fit results: Indirect determination of input parameters

**Indirect determination**: Fit prediction excluding direct measurement from the fit

Agreement at the **1 σ level** with experimental value
The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

Also good agreement between indirect determination of EWPO and experimental measurements,
The Standard Model Electroweak fit

SM fit results: Predictions for EWPO

Also good agreement between indirect determination of EWPO and experimental measurements, with one notable exception

~2.5 σ discrepancy in forward-backward asymmetry of the b quark

Requires modifications of (right-handed) $Zbb$ couplings

$$g_{L,R}^b = g_{L,R}^{b,SM} + \delta g_{L,R}^b$$

<table>
<thead>
<tr>
<th>Fit result</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta g_R^b$</td>
<td>0.017±0.007</td>
</tr>
<tr>
<td>$\delta g_L^b$</td>
<td>0.003±0.001</td>
</tr>
</tbody>
</table>
Electroweak constraints on New Physics
Electroweak constraints on New Physics

**EW fit input/output**

\[ \{ G_\mu, \alpha_{em} \} \quad \text{(Fixed)} \]
\[ \{ m_h, m_t, M_Z, \alpha_s(M_Z^2), \Delta \alpha_{\text{had}}(M_Z^2) \} \quad \text{(Floating)} \]

**SM**

**BSM**

\[ \{ C_i^{NP} \}_{i=1}^n \quad \text{(Floating)} \]

**EWPO: Theory**

\[ O = O_{SM} + \delta O_{NP} \]

**EWPO: Data**

**Fitting Framework**

**Statistical Tests:**
- Hypothesis testing
- Limits, ...
**Oblique parameters:** New physics contributing to gauge boson self-energies

**EWPO depend only on 3 parameters**

\[
\alpha S = 4e^2 \left[ \Pi_{33}^{NP}'(0) - \Pi_{3Q}^{NP}'(0) \right] \\
\alpha T = \frac{e^2}{s_W^2 c_W^2 M_Z^2} \left[ \Pi_{11}^{NP}(0) - \Pi_{33}^{NP}(0) \right] \\
\alpha U = 4e^2 \left[ \Pi_{11}^{NP}'(0) - \Pi_{33}^{NP}'(0) \right]
\]

**EWPO dependence on STU:**

\[
A = S - 2s_W^2 T - \frac{(c_W^2 - s_W^2)}{2s_W^2} U \\
B = S - 4s_W^2 T \\
C = -10(3 - 8s_W^2) S + (63 - 126s_W^2 - 40s_W^4) T
\]

**Fit result and Correlations**

<table>
<thead>
<tr>
<th></th>
<th>Fit result</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>0.04±0.10</td>
<td>1.00</td>
</tr>
<tr>
<td>T</td>
<td>0.08±0.12</td>
<td>0.90 1.00</td>
</tr>
<tr>
<td>U</td>
<td>0.00±0.09</td>
<td>-0.63 -0.85 1.00</td>
</tr>
</tbody>
</table>

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<tr>
<td>S</td>
<td>0.03±0.07</td>
<td>1.00</td>
</tr>
<tr>
<td>T</td>
<td>0.107±0.06</td>
<td>0.91 1.00</td>
</tr>
</tbody>
</table>
Constraints on the dimension-6 SMEFT

- **The dimension 6 SMEFT:**
  
  **Particles and symmetries of the low-energy theory:** SM
  
  Assumes new physics is heavy + decoupling
  
  ⇒ EFT expansion in canonical dim. of operators

  \[ \mathcal{L}_{\text{Eff}} = \sum_{d=4}^{\infty} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \]

  \[ \mathcal{L}_d = \sum_i C_i \mathcal{O}_i \quad [\mathcal{O}_i] = d \quad \rightarrow \quad \left( \frac{q}{\Lambda} \right)^{d-4} \]

  \[ \Lambda: \text{Cut-off of the EFT} \]

  Effects suppressed by \[ q = v, E < \Lambda \]

- **LO new physics effects “start” at dimension 6:** 59 B & L preserving operators


  (2499 counting flavor)

  1st complete basis: aka Warsaw basis

- **SMEFT describes correlations of new physics effects in different types of observables, e.g.**

  \[ \mathcal{O}_{\phi WB} = \phi^\dagger \sigma_\alpha \phi B^{\mu\nu} W^a_{\mu\nu} \]

  \[ v^2 B^{\mu\nu} W^3_{\mu\nu} \quad \text{(dim 4)} \]

  \[ \text{Modifies neutral gauge boson self-energies} \]

  \[ v h B^{\mu\nu} W^3_{\mu\nu} \quad \text{(dim 5)} \]

  \[ h \rightarrow ZZ, \gamma\gamma \]

  ⇒ Use global EW/Higgs fits to estimate sensitivity to NP effects

  EWSB

  EWPT

  Higgs phys.
### Operators contributing to Higgs/EW interactions

<table>
<thead>
<tr>
<th>Class</th>
<th>Operator</th>
<th>Notation</th>
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</tr>
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<tbody>
<tr>
<td><strong>Class 1</strong></td>
<td>( \phi^6 )</td>
<td>((\phi^\dagger \phi)^3)</td>
<td>(O_\phi)</td>
<td>((\phi^\dagger D_\mu \phi) \left((D_\mu \phi)^\dagger\right))</td>
</tr>
<tr>
<td></td>
<td>(\phi^4 D^2)</td>
<td>((\phi^\dagger \phi) \Box (\phi^\dagger \phi))</td>
<td>(O_{\phi \Box})</td>
<td>(\phi^\dagger \phi W^a_\mu W^a_\mu)</td>
</tr>
<tr>
<td></td>
<td>(X^2 \phi^2)</td>
<td>(\phi^\dagger \phi B_\mu \nu B^{\mu \nu})</td>
<td>(O_{\phi B})</td>
<td>(\phi^\dagger \phi G^A_\mu G^A_\mu)</td>
</tr>
<tr>
<td></td>
<td>(X^3)</td>
<td>(\varepsilon_{abc} W^a_\mu W^b_\nu W^c_\rho)</td>
<td>(O_W)</td>
<td></td>
</tr>
<tr>
<td><strong>Class 2</strong></td>
<td>(\psi^2 \phi^2)</td>
<td>((\phi^\dagger \phi) (\bar{L}_L^i \gamma^\mu e_R^j))</td>
<td>(O_{\phi e})_{ij})</td>
<td>((\phi^\dagger \phi) (\bar{q}_L^i \phi u_R^j))</td>
</tr>
<tr>
<td></td>
<td>(\psi^2 \phi^2 D)</td>
<td>((\phi^\dagger i D_\mu \phi)(\bar{L}_L^i \gamma^\mu l_L^i))</td>
<td>(O^{(1)}<em>{\phi l})</em>{ij})</td>
<td>((\phi^\dagger i D_\mu ^a \phi)(\bar{L}_L^i \gamma^\mu \sigma^a l_L^i))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\phi^\dagger i D_\mu \phi)(\bar{e}_R^i \gamma^\mu e_R^j))</td>
<td>(O_{\phi e})_{ij})</td>
<td>((\phi^\dagger i D_\mu ^a \phi)(\bar{q}_L^i \gamma^\mu \sigma^a q_L^j))</td>
</tr>
<tr>
<td></td>
<td></td>
<td>((\phi^\dagger i D_\mu \phi)(\bar{q}_L^i \gamma^\mu q_L^j))</td>
<td>(O^{(1)}<em>{\phi q})</em>{ij})</td>
<td>((\phi^\dagger i D_\mu \phi)(\bar{d}_R^i \gamma^\mu d_R^j))</td>
</tr>
<tr>
<td><strong>Class 3</strong></td>
<td>(G_F)</td>
<td>((\bar{l}_1 \gamma^\mu l_2) (\bar{l}_2 \gamma^\mu l_1))</td>
<td>(O_{l l})_{1221})</td>
<td></td>
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Excluding dipole ops.
### Operators contributing to Higgs/EW interactions

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<tr>
<td>1</td>
<td>$\phi^4 D^2$</td>
<td>$O_{\phi\Box}$</td>
<td>2</td>
<td>$\psi^2 \phi^2$</td>
<td>$O_{e\phi, d\phi}$</td>
</tr>
<tr>
<td></td>
<td>$(\phi^\dagger \phi)^2$</td>
<td>$O_\phi$</td>
<td></td>
<td>$(\phi^\dagger \phi) B_{\mu\nu} B^{\mu\nu}$</td>
<td>$O_{\phi B}$</td>
</tr>
<tr>
<td></td>
<td>$\phi^\dagger \phi W^a_{\mu\nu} B^{\mu\nu}$</td>
<td>$O_{\phi WB}$</td>
<td></td>
<td>$\epsilon_{abc} W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\rho\mu}$</td>
<td>$O_W$</td>
</tr>
<tr>
<td>3</td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{l}^i_L \gamma^\mu l^i_L)$</td>
<td>$O^{(1)}_{\phi l}$</td>
<td></td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{l}^i_L \gamma^\mu \nabla^\nu l^i_L)$</td>
<td>$O^{(3)}_{\phi l}$</td>
</tr>
<tr>
<td></td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{q}^i_L \gamma^\mu q^i_L)$</td>
<td>$O^{(1)}_{\phi q}$</td>
<td></td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{q}^i_L \gamma^\mu \nabla^\nu q^i_L)$</td>
<td>$O^{(3)}_{\phi q}$</td>
</tr>
<tr>
<td></td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{u}^i_R \gamma^\mu u^i_R)$</td>
<td>$O_{\phi u}$</td>
<td></td>
<td>$(\phi^\dagger i D_\mu \phi)(\bar{d}^i_R \gamma^\mu d^i_R)$</td>
<td>$O_{\phi d}$</td>
</tr>
<tr>
<td></td>
<td>$(\bar{l}<em>1 \gamma</em>\mu l_2)(\bar{l}<em>2 \gamma</em>\mu l_1)$</td>
<td>$O_{ll, 1221}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Constraints on the dimension-6 SMEFT

**~ΔT**
- $\phi^\dagger D_\mu \phi((D_\mu \phi)^\dagger \phi)$: $O_{\phi D}$

**~ΔS**
- $\phi^\dagger \phi W^a_{\mu\nu} W^{a\mu\nu}$: $O_{\phi W}$
- $\phi^\dagger \phi G^A_{\mu\nu} G^{A\mu\nu}$: $O_{\phi G}$

**~Zff Wff**
- $\phi^\dagger \phi W_{\mu\nu} W^{\mu\nu}$: $O_W$

### 10 operators in the Warsaw basis contributing to EWPO

Excluding dipole ops.
Constraints on the dimension-6 SMEFT

Global fit to EW data (2019)
Sensitive to eight combinations of dimension-6 operators

Flat directions in Warsaw basis

\[ \hat{C}_{\phi l}^{(1)} = C_{\phi l}^{(1)} + \frac{1}{4} C_{\phi D} \]
\[ \hat{C}_{\phi l}^{(3)} = C_{\phi l}^{(3)} + \frac{c_w}{4 s_w^2} C_{\phi D} + \frac{c_w}{s_w} C_{\phi WB} \]
\[ \hat{C}_{\phi q}^{(1)} = C_{\phi q}^{(1)} - \frac{1}{12} C_{\phi D} \]
\[ \hat{C}_{\phi q}^{(3)} = C_{\phi q}^{(3)} + \frac{c_w}{4 s_w^2} C_{\phi D} + \frac{c_w}{s_w} C_{\phi WB} \]
\[ \hat{C}_{\phi e} = C_{\phi e} + \frac{1}{2} C_{\phi D} \]
\[ \hat{C}_{\phi u} = C_{\phi u} - \frac{1}{3} C_{\phi D} \]
\[ \hat{C}_{\phi d} = C_{\phi d} + \frac{1}{6} C_{\phi D} \]
\[ \hat{C}_{ll} = C_{ll} \]

Combination with WW/Higgs lifts degeneracies in this basis

New Physics assumptions: CP-even, U(3)\(^5\)
For O(1) couplings, bound on New Physics scale \(\sim 1-10\) TeV

See also:
J. Ellis et al., JHEP 1806 (2018) 146,
A. Biekötter et al. arXiv:1812.07587 [hep-ph],

Preliminary
Global fit to EW and Higgs data: inputs

**Constraints on the dimension-6 SMEFT**

**EWPO (LEP/SLC+Tevatron+LHC)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_s (M_Z^2)$</td>
<td>3.2</td>
</tr>
<tr>
<td>$\Delta \alpha_s (M_Z^2)$</td>
<td>4.3</td>
</tr>
<tr>
<td>$m_t$</td>
<td>0.4</td>
</tr>
<tr>
<td>$M_H$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\Gamma_W$</td>
<td>0.2</td>
</tr>
<tr>
<td>$M_Z$</td>
<td>0.1</td>
</tr>
<tr>
<td>$\Gamma_Z$</td>
<td>0.0</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^0$</td>
<td>0.9</td>
</tr>
<tr>
<td>$R_t$</td>
<td>0.8</td>
</tr>
<tr>
<td>$A_{FB}^0$</td>
<td>0.7</td>
</tr>
<tr>
<td>$p_T^\text{pol}$</td>
<td>0.6</td>
</tr>
<tr>
<td>$A_t (SLD)$</td>
<td>0.5</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.4</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.3</td>
</tr>
<tr>
<td>$A_{FB}^0$</td>
<td>0.2</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1</td>
</tr>
<tr>
<td>$R_b^0$</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Diboson (LEP 2)**

**Higgs (Tevatron+ LHC Run 1+2)**

**Parameter normalized to SM value**

**ATLAS Preliminary**

<table>
<thead>
<tr>
<th>Process</th>
<th>Total</th>
<th>Stat.</th>
<th>Syst.</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF $\gamma\gamma$</td>
<td>0.96</td>
<td>0.14</td>
<td>0.11</td>
<td>0.09</td>
</tr>
<tr>
<td>ggF $ZZ$</td>
<td>1.04</td>
<td>0.16</td>
<td>0.14</td>
<td>0.06</td>
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<tr>
<td>ggF $WW$</td>
<td>1.08</td>
<td>0.19</td>
<td>0.11</td>
<td>0.15</td>
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<td>0.46</td>
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<td>ggF comb.</td>
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<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>VBF $\gamma\gamma$</td>
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<td>0.35</td>
<td>0.30</td>
<td>0.19</td>
</tr>
<tr>
<td>VBF $ZZ$</td>
<td>2.68</td>
<td>0.36</td>
<td>0.21</td>
<td>0.20</td>
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<td>VBF $WW$</td>
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<td>0.20</td>
<td>0.21</td>
<td>0.01</td>
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<td>VBF $tt$</td>
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<td>0.59</td>
<td>0.40</td>
<td>0.35</td>
</tr>
<tr>
<td>VBF $bb$</td>
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<td>1.07</td>
<td>1.23</td>
<td>0.29</td>
</tr>
<tr>
<td>VBF comb.</td>
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<td>0.55</td>
<td>0.13</td>
</tr>
<tr>
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<td>0.49</td>
<td>0.22</td>
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<td>0.20</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>VH $bb$</td>
<td>1.19</td>
<td>0.27</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>VH comb.</td>
<td>1.15</td>
<td>0.33</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>ttH $\gamma\gamma$</td>
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<td>0.35</td>
<td>0.29</td>
<td>0.19</td>
</tr>
<tr>
<td>ttH $VV$</td>
<td>1.50</td>
<td>0.59</td>
<td>0.43</td>
<td>0.41</td>
</tr>
<tr>
<td>ttH $tt$</td>
<td>1.38</td>
<td>0.56</td>
<td>0.42</td>
<td>0.39</td>
</tr>
<tr>
<td>ttH $bb$</td>
<td>0.79</td>
<td>0.23</td>
<td>0.28</td>
<td>0.52</td>
</tr>
<tr>
<td>ttH comb.</td>
<td>1.21</td>
<td>0.34</td>
<td>0.24</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**J. B. et al., In preparation**

+ CMS results (pre EPS-HEP 2019)
Constraints on the dimension-6 SMEFT

Global fit to EW and Higgs data (2019)

New Physics assumptions: CP-even, U(3)\(^5\)

For O(1) couplings, bound on New Physics scale ~1-10 TeV

See also:
J. Ellis et al., JHEP 1806 (2018) 146,
A. Biekötter et al. arXiv:1812.07587 [hep-ph],
# Constraints on the dimension-6 SMEFT

**Global fit to EW and Higgs data (2019)**

J. B. et al., In preparation

---

## SMEFT EW/Higgs fit

| \(O_W\) | 100 | 17 | 23 | 23 | 28 | -22 | 2 | 22 | -30 | 22 | -17 | -29 | -19 | 9 | -3 | 3 | -21 | 3 | 0 |
| \(O_{\psi G}\) | 17 | 100 | 22 | 12 | 20 | -10 | -6 | 10 | -44 | 10 | -7 | -45 | -9 | 4 | -65 | 17 | -70 | 33 | 0 |
| \(O_{\psi W}\) | 23 | 22 | 100 | 29 | 71 | -67 | -45 | 67 | -20 | 67 | -45 | -22 | -49 | 20 | 1 | -30 | -2 | 6 | -1 |
| \(O_{\psi B}\) | 23 | 12 | 29 | 100 | 88 | -87 | -14 | 87 | -4 | 87 | -59 | -5 | -66 | 27 | 8 | -4 | 3 | 5 | 0 |
| \(O_{\psi WB}\) | 28 | 20 | 71 | 88 | 100 | -96 | -33 | 97 | -13 | 98 | -66 | -15 | -73 | 30 | 6 | -18 | 1 | 7 | 0 |
| \(O_{\phi D}\) | -22 | -10 | -67 | -87 | -98 | 100 | 41 | -99.5 | -8 | -99.9 | 66 | -5 | 73 | -28 | -9 | 24 | -17 | -5 | 1 |
| \(O_{\phi D}^{(1)}\) | 2 | -6 | -45 | -14 | -33 | 41 | 100 | -41 | -36 | -41 | 29 | -38 | 32 | -14 | 9 | 76 | -38 | -6 | 1 |
| \(O_{\phi D}^{(3)}\) | -30 | -44 | -20 | -4 | -13 | -8 | -36 | 7 | 100 | 8 | 1 | 92 | 3 | -9 | 14 | -25 | 76 | -6 | 14 |
| \(O_{\phi W}\) | 22 | 10 | 67 | 87 | 97 | -99.5 | -41 | 100 | 7 | 99.6 | -65 | 4 | -72 | 27 | 9 | -24 | 17 | 5 | -9 |
| \(O_{\phi W}^{(1)}\) | -17 | -7 | -45 | -59 | -66 | 66 | 29 | -65 | 1 | -66 | 100 | -6 | 79 | 16 | -5 | 17 | -11 | -4 | -5 |
| \(O_{\phi W}^{(3)}\) | -29 | -45 | -22 | -5 | -15 | -5 | -38 | 4 | 92 | 5 | -6 | 100 | -13 | 10 | 13 | -27 | 77 | -6 | 1 |
| \(O_{\phi U}\) | -19 | -9 | -49 | -66 | -73 | 73 | 32 | -72 | 3 | -73 | 79 | -13 | 100 | -14 | -5 | 19 | -12 | -5 | -5 |
| \(O_{\phi G}\) | 9 | 4 | 20 | 27 | 30 | -28 | -14 | 27 | -9 | 27 | 16 | 10 | -14 | 100 | 1 | -9 | 4 | 2 | 0 |
| \(O_{\psi}\) | -3 | -65 | 1 | 8 | 6 | -9 | 9 | 9 | 14 | 9 | -5 | 13 | -5 | 1 | 100 | -29 | 26 | -25 | -1 |
| \(O_{\psi}^{(1)}\) | 3 | 17 | -30 | -4 | -18 | 24 | 76 | -24 | -25 | -24 | 17 | -27 | 19 | -9 | -29 | 100 | -25 | 26 | 1 |
| \(O_{\psi}^{(3)}\) | -21 | -70 | -2 | 3 | 1 | -17 | -38 | 17 | 76 | 17 | -11 | 77 | -12 | 4 | 26 | -25 | 100 | -11 | -1 |
| \(O_{\psi G}\) | 3 | 33 | 6 | 5 | 7 | -5 | -6 | 5 | -6 | 5 | -4 | -6 | -5 | 2 | -25 | 26 | -11 | 100 | 0 |
| \(O_{\phi}\) | 0 | 0 | -1 | 0 | 0 | 1 | 1 | -9 | 14 | -1 | -5 | 1 | -5 | 0 | -1 | 1 | -1 | 0 | 100 |

Preliminary
Constraints on the dimension-6 SMEFT

Global fit to EW and Higgs data (2019)
Both errors and correlations needed to project EFT results to BSM

J. B. et al., In preparation
Projections at Future Particle Colliders: Interplay EW/Higgs
This paper focuses on physics providing also an overview on the machine. It is complemented by an Addendum describing further aspects of the LHeC project such as the operation and timelines for the no pile-up, high precision collider detector in the decade(s) hence.

The development of multi-turn, high current, 802 MHz ERL technology, required for the LHeC, is described in an accompanying, separate strategy contribution of the PERLE accelerator and the detector. The development of high quality superconducting RF developments, a major contribution to the huge increased brightness. The main LHeC innovation is the first ever high energy application of energy recovery technology, based on modern technology. The ERL has major future applications, with ep at HE-LHC and FCC-eh, as an injector for FCC-ee, as a maximal exploitation of the LHC infrastructure.

Realising an “Electrons for LHC” programme would represent a unique opportunity for CERN and its associated laboratories to build a full, new accelerator and dynamics inside nuclei for the first time. The very high luminosity and the substantial extension of the kinematic range in deep inelastic scattering elucidating the chromodynamic origin of the Quark-Gluon-Plasma and clarifying the partonic substructure to be further developed and exploited in a new generation, 4 green detector prospects for the LHeC with the intention to publish an update of the CDR in early 2019. Following the current luminosity upgrade, the LHC can be further upgraded with a high energy, linear (ERL) electron accelerator which enables TeV energy electron-proton collisions at high luminosity, exceeding that of HERA by nearly three orders of magnitude. The discovery of the Higgs boson and the surprising absence of BSM physics at LHC demand to extend the experimental base of particle physics through the extension of the kinematic range by about three orders of magnitude in lepton-nucleus (eA) scattering, the LHeC is the most powerful electron-ion research facility one can build in the next decades. Following a mandate of the CERN Directorates and guided by an International Advisory Committee, this motivated representatives of more than 100 institutes to proceed, as sketched here, with the development of the accelerator, physics and clean environment ⇒ precision measurements Sensitivity to NP with EW interactions

Limited E reach for direct searches

Sensitivity to NP with EW interactions

A mix of the two (both pros and cons)

Large E reach ⇒ Direct searches
“Dirty” environment
Mass reach limited by PDF
Sensitivity to NP with strong interactions

Future Particle Colliders

Hadron Colliders

LHC → HE-LHC

Electron-Proton Colliders

HERA → LHeC

Lepton Colliders

LEP/SLC → iLC

Executive Summary

The Large Hadron Collider determines the energy frontier of experimental collider physics for the next two decades.

The Large Hadron Electron Collider (LHeC) published in 2012. The LHeC uses a novel, energy recovery injector for FCC-ee, as a twin-collider facility, in which ep operates concurrently with pp. A joint ECFA, CERN and NuPECC initiative led to a detailed conceptual design report (CDR) for the physics at HL-LHC by providing new discovery potential in its final phase of operation. The LHeC and PERLE Collaboration

Contacts: Oliver Br¨uning (CERN) and Max Klein (U Liverpool)

oliver.bruning@cern.ch, max.klein@liverpool.ac.uk
**Circular $e^+e^-$ colliders**

Higgs factory preceded by a Z factory (TeraZ)

<table>
<thead>
<tr>
<th>Experimental Inputs</th>
<th>Higgs</th>
<th>aTGC</th>
<th>EWPO</th>
<th>Top EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee</td>
<td>Yes ($\mu$, $\sigma_Z$) (Complete with HL-LHC)</td>
<td>Yes (aTGC dom.)</td>
<td>Yes (Tera Z)</td>
<td>Yes (365 GeV, Ztt)</td>
</tr>
<tr>
<td>ILC</td>
<td>Yes ($\mu$, $\sigma_Z$) (Complete with HL-LHC)</td>
<td>Yes (HE limit)</td>
<td>Yes (via Rad. Return) GigaZ?</td>
<td>Yes (500 GeV, Ztt)</td>
</tr>
<tr>
<td>CEPC</td>
<td>Yes ($\mu$, $\sigma_Z$) (Complete with HL-LHC)</td>
<td>Yes (aTGC dom)</td>
<td>Yes (Tera Z)</td>
<td>No</td>
</tr>
<tr>
<td>CLIC</td>
<td>Yes ($\mu$, $\sigma_Z$)</td>
<td>Yes (Full EFT parameterization)</td>
<td>Yes (via Rad. Return) GigaZ?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

**Linear $e^+e^-$ colliders**

Higgs factory
EW measurements available via radiative return to the Z

Could also operate at the Z-pole (Giga Z) (Not in current plans)

<table>
<thead>
<tr>
<th>Experimental Inputs</th>
<th>Higgs</th>
<th>aTGC</th>
<th>EWPO</th>
<th>Top EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE-LHC</td>
<td>Extrapolated from HL-LHC</td>
<td>N/A $\rightarrow$ LEP2</td>
<td>LEP/SLD + HL-LHC ($M_W$, $\sin^2\theta_W$)</td>
<td>-</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>Yes ($\mu$, BR/BR) Used in combination with FCCee/eh</td>
<td>From FCC-ee</td>
<td>From FCC-ee</td>
<td>-</td>
</tr>
<tr>
<td>LHeC</td>
<td>Yes ($\mu$)</td>
<td>N/A $\rightarrow$ LEP2</td>
<td>LEP/SLD + HL-LHC ($M_W$, $\sin^2\theta_W$)</td>
<td>-</td>
</tr>
<tr>
<td>FCC-eh</td>
<td>Yes ($\mu$) Used in combination with FCCee/hh</td>
<td>From FCC-ee</td>
<td>From FCC-ee + Zuu, Zdd</td>
<td>-</td>
</tr>
</tbody>
</table>
Interplay EW/Higgs at future colliders

EW $Zff$ couplings at future particle colliders (from EFT fit)

$\delta g_i/g_i [%]$ Improvement wrt. HL-LHC

Preliminary

Higgs couplings at future particle colliders (from EFT fit)

\[ g_{hXX}^{\text{eff}} = \frac{\Gamma_{H \rightarrow XX}}{\Gamma_{H \rightarrow XX}^{\text{SM}}} \]

Assuming precision from rad. ret. to Z

Perfect EW measurements

Small “contamination” on Higgs couplings from EW parameters

Jorge de Blas
INFN - University of Padova
Interplay EW/Higgs at future colliders

Figure 5: A scheme-ball illustration of the correlations between Higgs and EW sector couplings. The $Z$-pole runs are included for both FCC-ee and CEPC. Projections from HL-LHC and measurements from LEP and SLD are included in all scenarios. The outer bars give the one-sigma precision on the individual coupling (see tables 1 and 2).

The potential impact of Higgs measurements on EW parameters is assessed by correlating the fits:

- **CEPC/FCC-ee**: $Z$-pole run largely decouples EWPO and Higgs fits.
- **ILC**: precision of $HZZ$ limited by absence of $Z$-pole run (Less pronounced at 500 GeV)
- **CLIC**: High-E run compensate the absence of $Z$-pole run (for $HZZ$)

ILC: precision of $HZZ$ limited by absence of $Z$-pole run (Less pronounced at 500 GeV)

CLIC: High-E run compensate the absence of $Z$-pole run (for $HZZ$)

Correlation Map at Future Lepton Colliders

Interplay EW/Higgs at future colliders

CEPC/FCC-ee: Z-pole run largely decouples EWPO and Higgs fits

ILC: precision of $HZZ$ limited by absence of Z-pole run (Less pronounced at 500 GeV)

CLIC: High-E run compensates the absence of Z-pole run (for $HZZ$)

Interplay EW/Higgs at future colliders

Higgs couplings at future particle colliders (from EFT fit)

\[ g_{\text{eff}}^2 = \frac{\Gamma_{H \rightarrow XX}}{\Gamma_{\text{SM}}^H \rightarrow XX} \]

Assuming precision from rad. ret. to Z

Perfect EW measurements

Small “contamination” on Higgs couplings from EW parameters

Interplay EW/Higgs at future colliders

Higgs couplings at future particle colliders (from EFT fit)

Assuming precision from Giga Z

Perfect EW measurements

Small “contamination” on Higgs couplings from EW parameters almost removed by GigaZ run

Summary
Summary

• Precision tests of the properties of the SM particles serve as an indirect window to new physics ⇒ look for deviations with respect to the SM predictions (virtual effects of new particles).

• The LHC provides not only direct access to the Higgs properties, but also remarkable experimental information on other inputs of the global fit to electroweak precision observables (Top, W mass, effective weak mixing angle).

• In absence of any hint of new physics, global fits in a “model-independent” theoretical framework are required to assess the sensitivity to new physics in the EW/Higgs sector in a robust manner.

⇒ Current EFT bounds can be interpreted as limits on NP scale ~1-10 TeV (for O(1) couplings).

• Future particle colliders could bring at least 1 order of magnitude improvement in the experimental knowledge of the properties of the different SM particles:
  • A lot of attention dedicated to the study of future Higgs factories. But a precise determination of Higgs properties requires to keep under control uncertainties associated to other EW parameters!