Loop-induced Bounds on Higgs Effective Operators

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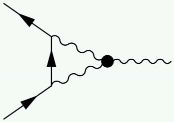
H. Mebane, N. Greiner, C. Zhang, S. Willenbrock, arXiv:1306.3380
C-Y. Chen, S. Dawson, C. Zhang, arXiv:1311.3107

Outline

Outline

Constraining Higgs couplings from precision test

- Limits on Higgs couplings can be inferred from precision electroweak measurements.



—modify gauge-boson self energies and *Vff* vertex,
which in turn contribute to the oblique parameters, S T and U.

- Can yield complementary information to direct Higgs production measurements.

Oblique parameters

- Precision electroweak measurements are mostly summarized by three parameters, S T and U.

Peskin and Takeuchi
PRD 46,381

$$\alpha S = \left(\frac{4s^2c^2}{m_Z^2}\right)\left\{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0) - \Pi_{\gamma\gamma}(m_Z^2) - \frac{c^2 - s^2}{cs}\Pi_{\gamma Z}(m_Z^2)\right\}$$

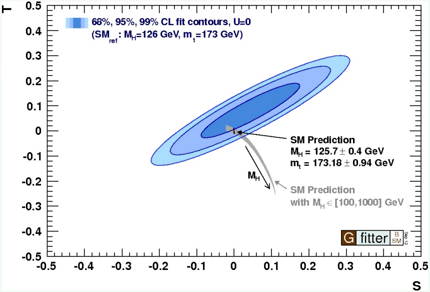
- Current limits:

Gfitter
1209.2716

$$\begin{aligned} S &= 0.03 \pm 0.10 \\ T &= 0.05 \pm 0.12 \\ U &= 0.03 \pm 0.10 \end{aligned}$$

with the correlation matrix,

$$\rho = \begin{pmatrix} 1.0 & 0.891 & -0.540 \\ 0.891 & 1.0 & -0.803 \\ -0.540 & -0.803 & 1.0 \end{pmatrix}$$



Previous studies

- Hagiwara, Ishihara, Szalapski and Zeppenfeld (HISZ), Phys.Rev.D48:2182
  Alam, Dawson and Szalapski (ADS), Phys.Rev.D57:1577
  - Consider gauge-invariant effective operators, e.g.

$$O_{WW} = \phi^\dagger \hat{W}^{\mu\nu} \hat{W}_{\mu\nu} \phi, \qquad O_{BB} = \phi^\dagger \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} \phi$$

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i c_i O_i / \Lambda^2$$

  - Compute leading log contributions

$$S = \frac{m_Z^2}{\pi^2 \Lambda^2} \left(c^2 c_{WW} + s^2 c_{BB} \right) \log \left(\frac{\Lambda^2}{m_h^2} \right)$$

$$c_{BB} = -15 \pm 26, \qquad c_{WW} = -4.6 \pm 7.8 \qquad (\Lambda = 1\mathrm{TeV})$$

- No renormalization, momentum cut off at Λ.

However. . .

More modern point of view for renormalization

- Effective theories are renormalizable.

  "Unrenormalizable theories are just as renormalizable as renormalizable theories"

  S. Weinberg
  0908.1964

- At each order in $1/\Lambda^n$, divergences can be absorbed by introducing counterterms at the same order. Results are obtained in terms of $c(\mu)$.

- The $c(\mu)$'s will evolve and mix as μ changes. The μ dependences are controlled by RG equations.

  Alonso et al.
  1312.2014
  Elias-Miro et al.
  1312.2928

Previous results

Previous results on STU should be taken with care...

1. Have chosen $\mu = \Lambda$, enhancing the log contributions.
2. "Counterterm" operators are ignored.

$$S = \frac{1}{\Lambda^2}\left[-4\pi v^2 c_{BW}(\Lambda) + \frac{m_Z^2}{\pi}(s^2 c_{BB}(\Lambda) + c^2 c_{WW}(\Lambda))\log\left(\frac{\Lambda^2}{m_h^2}\right)\right]$$

   Need to assume $c_{BW}(\Lambda) = 0$ in order to bound c_{BB} and c_{WW}.

3. Limits on $c_i(\Lambda)$ do not tell you much about Higgs couplings. We need $c_i(m_h)$.

What we want to do

What exactly is the information about Higgs operators that can be extracted from Precision Electroweak Measurements?

- Do renormalization correctly.
- No assumptions on $c(\Lambda)$.
- Study limits on $c(m_h)$.

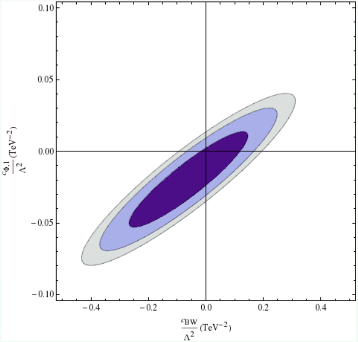
Outline

Operator basis

- HISZ basis, operators involve EW gauge field and Higgs doublet, assume SU(2)XU(1) and CP-conservation.

  - At tree level

$$
\begin{aligned}
O_{BW} &= \phi^\dagger \hat{B}^{\mu\nu} \hat{W}_{\mu\nu} \phi && (S) \\
O_{\phi,1} &= (D_\mu \phi)^\dagger \phi\, \phi^\dagger (D^\mu \phi) && (T) \\
O_{DW} &= \mathrm{Tr}\, [D^\mu, \hat{W}^{\nu\rho}][D_\mu, \hat{W}_{\nu\rho}] \\
O_{DB} &= 2\, \partial^\mu \hat{B}^{\nu\rho} \partial_\mu \hat{B}_{\nu\rho}
\end{aligned}
$$



Operator basis

- At loop level
  - Include

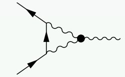
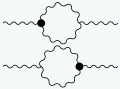
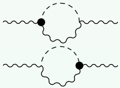
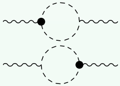
	Operators
Higgs	$O_{WW} = \phi^\dagger \hat{W}^{\mu\nu} \hat{W}_{\mu\nu} \phi$
	$O_{BB} = \phi^\dagger \hat{B}^{\mu\nu} \hat{B}_{\mu\nu} \phi$
	$O_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right)$
Higgs & TGC*	$O_W = \left(D_\mu \phi\right)^\dagger \hat{W}^{\mu\nu} \left(D_\nu \phi\right)$
	$O_B = \left(D_\mu \phi\right)^\dagger \hat{B}^{\mu\nu} \left(D_\nu \phi\right)$
TGC	$O_{WWW} = \mathrm{Tr}\, \hat{W}^\mu{}_\nu \hat{W}^\nu{}_\rho \hat{W}^\rho{}_\mu$

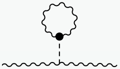
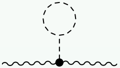
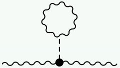
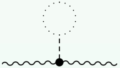
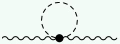
*TGC=Triple Gauge-boson Coupling

  - Neglect

$$O_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3 \quad \text{and} \quad O_{\phi,4} = (\phi^\dagger \phi)(D_\mu \phi)^\dagger (D^\mu \phi)$$

Calculations

	$\delta\Gamma_W$ $\delta\Gamma_Z$ $\delta\Gamma_\gamma$	$\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_{WWW}$, $\mathcal{O}_B$, $\mathcal{O}_W$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_B$, $\mathcal{O}_W$, $\mathcal{O}_{WW}$ $\mathcal{O}_B$, $\mathcal{O}_W$, $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_B$, $\mathcal{O}_W$, $\mathcal{O}^*_{BB}$, $\mathcal{O}^*_{WW}$ * top diagram only
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_W$ $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_B$, $\mathcal{O}_W$ $\mathcal{O}_B$, $\mathcal{O}_W$

	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$
	Π_{WW} Π_{ZZ} $\Pi_{\gamma\gamma}$ $\Pi_{\gamma Z}$	$\mathcal{O}_W$ $\mathcal{O}_W$ $\mathcal{O}_W$

Calculations

- Vertex and self-energy functions are combined in a gauge-invariant way.

Hagiwara et al.
Phys.Rev.D48:2182

$$\overline{\Pi}_{WW} = \Pi_{WW} + 2(q^2 - m_W^2)\delta\Gamma^W$$
$$\overline{\Pi}_{ZZ} = \Pi_{ZZ} + 2c\,(q^2 - m_Z^2)\delta\Gamma^Z$$
$$\overline{\Pi}_{\gamma\gamma} = \Pi_{\gamma\gamma} + 2s\,q^2\delta\Gamma^\gamma$$
$$\overline{\Pi}_{\gamma Z} = \Pi_{\gamma Z} + s\,q^2\delta\Gamma^Z + c\,(q^2 - m_Z^2)\delta\Gamma^\gamma$$

- Oblique parameters are defined with $\overline{\Pi}$.

$$\alpha\Delta S = \left(\frac{4s^2c^2}{m_Z^2}\right)\left\{\overline{\Pi}_{ZZ}(m_Z^2) - \overline{\Pi}_{ZZ}(0) - \overline{\Pi}_{\gamma\gamma}(m_Z^2) - \frac{c^2 - s^2}{cs}\left(\overline{\Pi}_{\gamma Z}(m_Z^2)\right)\right\}$$
$$\alpha\Delta T = \left(\frac{\overline{\Pi}_{WW}(0)}{m_W^2} - \frac{\overline{\Pi}_{ZZ}(0)}{m_Z^2}\right)$$
$$\alpha\Delta U = 4s^2\left\{\frac{\overline{\Pi}_{WW}(m_W^2) - \overline{\Pi}_{WW}(0)}{m_W^2} - c^2\left(\frac{\overline{\Pi}_{ZZ}(m_Z^2) - \overline{\Pi}_{ZZ}(0)}{m_Z^2}\right) - 2sc\left(\frac{\overline{\Pi}_{\gamma Z}(m_Z^2)}{m_Z^2}\right) - s^2\frac{\overline{\Pi}_{\gamma\gamma}(m_Z^2)}{m_Z^2}\right\}$$

- Always choose $\mu = m_h$.

Outline

Results on STU

Numerically:

$$S = \left\{-0.76c_{BW} + 10^{-3}(1.48c_B - 1.4c_W - 0.2c_{BB} - 0.71c_{WW} + 0.66c_{WWW})\right\}\left(\frac{1\ TeV}{\Lambda}\right)^2$$

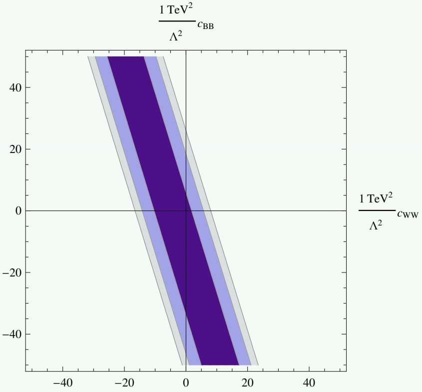
$$T = \left\{-4.0c_{\Phi,1} - 10^{-3}(0.13c_B + 0.12c_W)\right\}\left(\frac{1\ TeV}{\Lambda}\right)^2$$

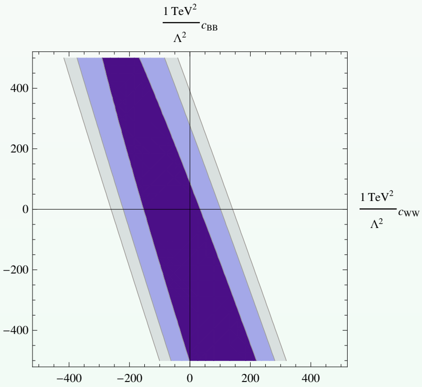
$$U = \left\{0.20c_{DW} + 10^{-3}(-0.02c_B + 2.06c_W + 0.14c_{WW} + 2.1c_{WWW})\right\}\left(\frac{1\ TeV}{\Lambda}\right)^2$$

- Loop-induced bounds are about 3 orders of magnitude weaker than the tree level ones.
- This is in contrast with previous results, where loop-induced bounds are typically 1 or 2 orders of magnitude weaker.

Plot: $\mu = \Lambda$ vs. $\mu = m_h$.

Limits on $c_{BB}(\mu)$ and $c_{WW}(\mu)$, assuming only two operators are present.



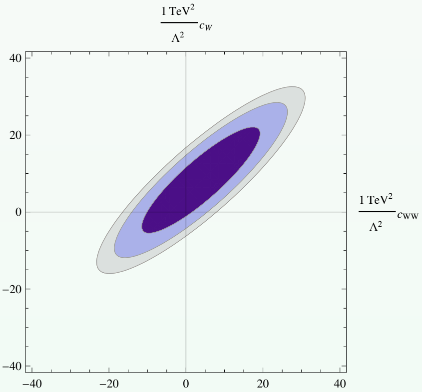


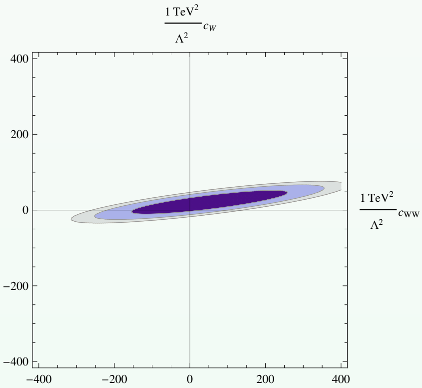
Left: $\mu = \Lambda$, assuming $c_i(\Lambda) = 0$ for $i \neq$ BB,WW.

Right: $\mu = m_h$, assuming $c_i(m_h) = 0$ for $i \neq$ BB,WW.

Plot: $\mu = \Lambda$ vs. $\mu = m_h$.

Limits on $c_W(\mu)$ and $c_{WW}(\mu)$, assuming only two operators are present.





Left: $\mu = \Lambda$, assuming $c_i(\Lambda) = 0$ for $i \neq$ W,WW.

Right: $\mu = m_h$, assuming $c_i(m_h) = 0$ for $i \neq$ W,WW.

Plot: direct vs. indirect

Combining with direct constraints from $h \to \gamma\gamma$ and $h \to \gamma Z$

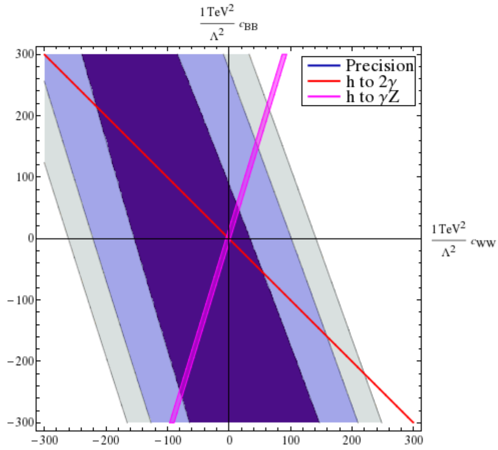
Pomarol and Riva
1308.2803

$\gamma\gamma$:

$$c_{BW} - c_{BB} - c_{WW} \in [-5.2, 7.2] \times 10^{-3}$$

γZ:

$$2\left(s^2 c_{BB} - c^2 c_{WW}\right) + \left(c^2 - s^2\right) c_{BW} + \frac{1}{2}(c_B - c_W) \in [-2.4, 4.8] \times 10^{-2}$$



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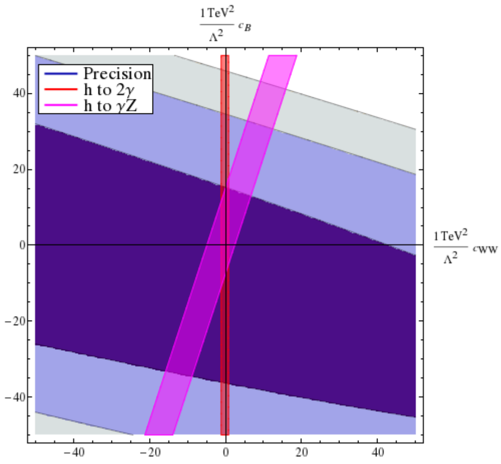

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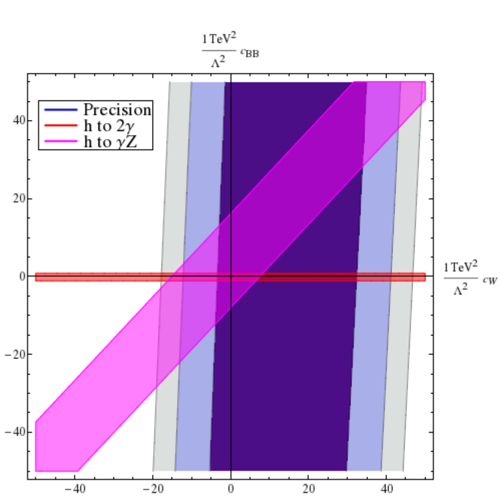
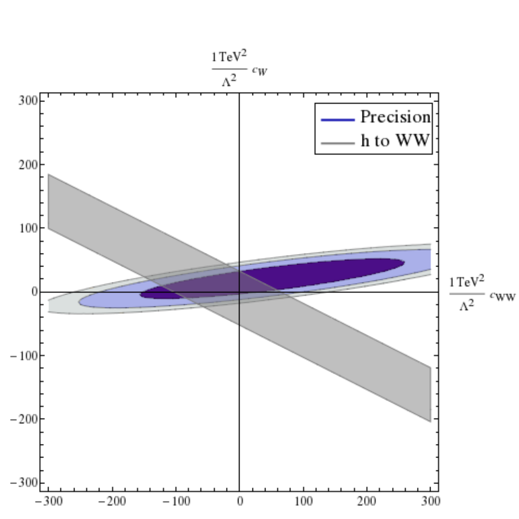


Plot: direct vs. indirect

Combining with direct constraints from $h \to WW$



Beyond STU

- We are able to perform a real fit, including all data, without using the STU formalism.

H. Mebane et al.
1306.3380

- This allows us to find bounds on $c(m_h)$ marginalizing over other (tree level) operators.

$$\begin{pmatrix} -0.913 & -0.218 & 0.145 & -0.312 & 0.011 \\ -0.156 & 0.961 & 0.184 & -0.129 & 0.031 \\ -0.099 & -0.066 & 0.727 & 0.675 & 0.030 \\ 0.361 & -0.150 & 0.645 & -0.653 & -0.062 \\ 0.040 & -0.035 & 0.011 & -0.053 & 0.997 \end{pmatrix} \times \frac{1}{\Lambda^2} \begin{pmatrix} c_{WWW} \\ c_W \\ c_B \\ c_{WW} \\ c_{BB} \end{pmatrix} = \begin{pmatrix} -149.2 & \pm & 120.9 \\ -17.7 & \pm & 187.5 \\ 589.3 & \pm & 455.1 \\ -3715 & \pm & 1904 \\ 3902 & \pm & 9964 \end{pmatrix} \mathrm{TeV}^{-2}$$

- Yet this is all we can conclude about $c(m_h)$, from Precision Electroweak Measurements.

Outline

Summary

- Previous studies of loop-induced bounds on Higgs effective operators should be understood with care.
- Renormalization plays an important role in the calculation and has large numerical impacts.
- We study loop-induced bounds on $c(m_h)$. Unfortunately, they are much weaker than direct bounds, and thus cannot provide very useful information on Higgs couplings.

Backups

$\mu = 1$ TeV vs. $\mu = m_Z$

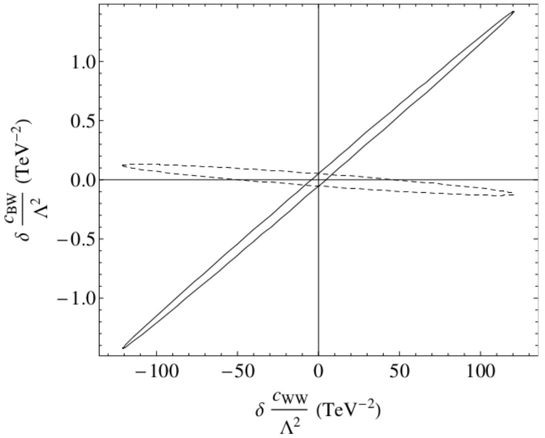


Figure 1: Two-parameter fit to precision electroweak data. The tree-level parameter c_{BW} and the one-loop parameter c_{WW} are centered at their best-fit values and allowed to float. Dashed ellipse: Renormalization scale of M_Z. Solid ellipse: Renormalization scale of 1 TeV.

PEWD

	Notation	Measurement
Z-pole	Γ_Z	Total Z width
	σ_{had}	Hadronic cross section
	$R_f(f = e, \mu, \tau, b, c)$	Ratios of decay rates
	$A_{FB}^{0,f}(f = e, \mu, \tau, b, c, s)$	Forward-backward asymmetries
	$\bar{s}_l^2$	Hadronic charge asymmetry
	$A_f(f = e, \mu, \tau, b, c, s)$	Polarized asymmetries
Fermion pair	$\sigma_f(f = q, e, \mu, \tau)$	Total cross sections for $e^+e^- \to f\bar{f}$
production at LEP2	$A_{FB}^f(f = \mu, \tau)$	Forward-backward asymmetries for $e^+e^- \to f\bar{f}$
W mass	m_W	W mass from LEP and Tevatron
and decay rate	Γ_W	W width from Tevatron
DIS	$Q_W(Cs)$	Weak charge in Cs
and	$Q_W(Tl)$	Weak charge in Tl
atomic parity violation	$Q_W(e)$	Weak charge of the electron
	g_L^2, g_R^2	ν_μ-nucleon scattering from NuTeV
	$g_V^{\nu e}, g_A^{\nu e}$	ν-e scattering from CHARM II

Summary of Precision Electroweak Measurements.