Electroweak Effective Operators and Higgs Physics

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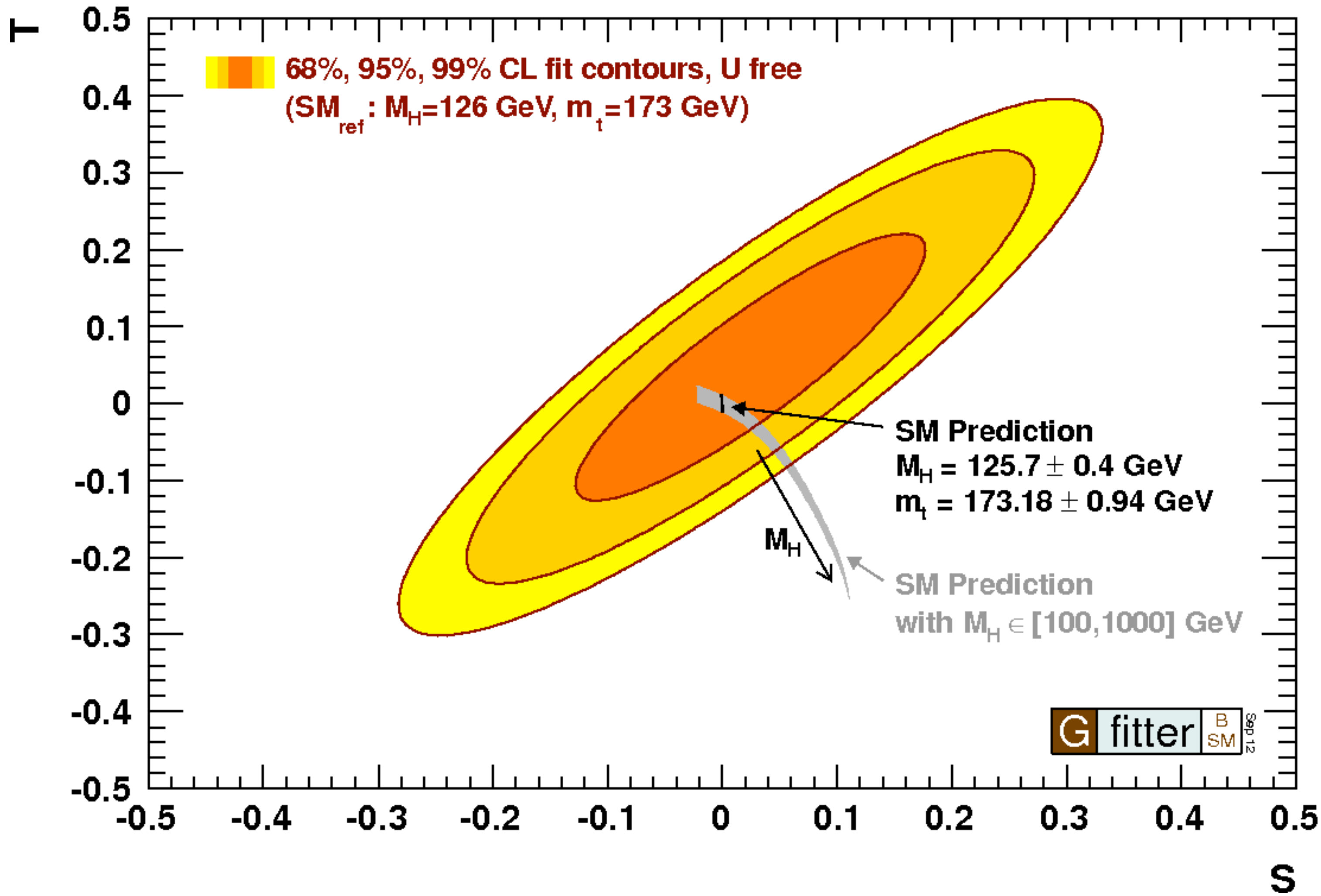
Motivations

- We've found the Higgs boson! What can we say about it's couplings to other particles?
- Can electroweak measurements tell us anything about the Higgs couplings?
- Derive bounds from the oblique parameters and the recent Higgs data on the dimension-6 operators.
- Are constraints on coefficients of the effective operators from precision test complementary to those from direct Higgs production measurements?

Oblique parameters

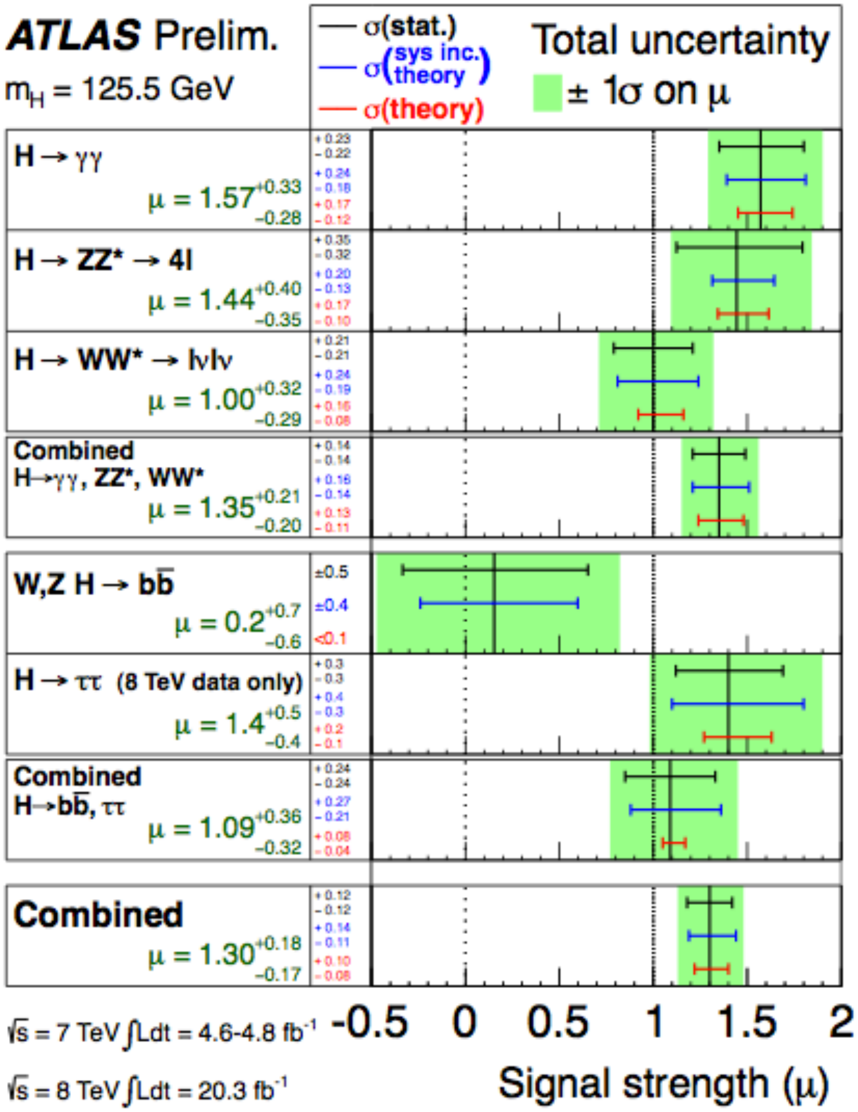
- Most of the effects on electroweak precision observables can be parametrized by S, T and U. [Phys.Rev.D46, 38, Peskin and Takeuchi]



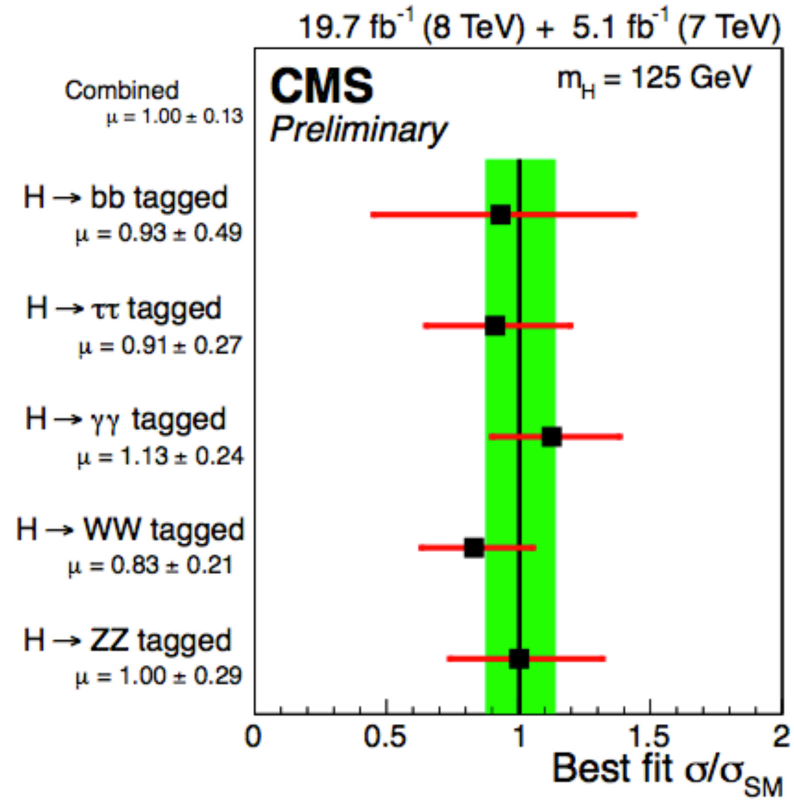
Best fit:

$S = 0.03 \pm 0.10$
$T = 0.05 \pm 0.12$
$U = 0.03 \pm 0.10$

Higgs Data: signal strength



[ATLAS-CONF-2014-009]



[HIG-14-009-PAS]

$$\mu \equiv \frac{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathtt{decay})|_{\mathrm{observed}}}{\sum_j \sigma(pp \to j \to h) \times \mathrm{B}(h \to \mathtt{decay})|_{\mathrm{SM}}}$$

- μ =1 : Standard Model Higgs
- Measuring deviations of the couplings from the SM

Approach

- Assume new physics is at a scale (Λ) much higher than that we can probe experimentally.

$$\mathcal{L}_{eff} = \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} \mathcal{O}_n + \ldots .$$

- Focus on electroweak sector of the SM

- The lowest-dimension operators, $\mathcal{O}_i$, which contribute to processes involving the SM gauge bosons and Higgs doublets are dimension six.

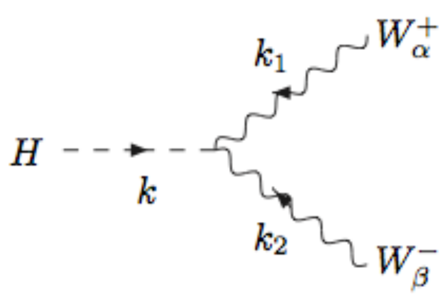
- Assume flavor and CP conservation

Approach

- Lagrangian

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\mathrm{SM}} &+ \frac{f_{DW}}{\Lambda^2}\mathcal{O}_{DW} + \frac{f_{DB}}{\Lambda^2}\mathcal{O}_{DB} + \frac{f_{BW}}{\Lambda^2}\mathcal{O}_{BW} + \frac{f_{\Phi,1}}{\Lambda^2}\mathcal{O}_{\Phi,1} \\
&+ \frac{f_{\Phi,2}}{\Lambda^2}\mathcal{O}_{\Phi,2} + \frac{f_{WWW}}{\Lambda^2}\mathcal{O}_{WWW} + \frac{f_{W}}{\Lambda^2}\mathcal{O}_{W} + \frac{f_{B}}{\Lambda^2}\mathcal{O}_{B} \\
&+ \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB}.
\end{aligned}
$$

- Derive Feynman rules: e.g. HWW

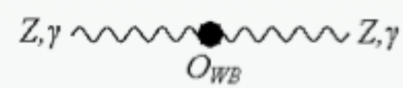


$$
\begin{aligned}
i\,\frac{g m_W}{\Lambda^2}\Big\{ &\frac{f_W}{2}\left[(k_1^\alpha k_1^\beta + k_2^\alpha k_2^\beta) - g^{\alpha\beta}(k_1^2 + k_2^2)\right] + \\
&(f_W - 2 f_{WW})\left[k_2^\alpha k_1^\beta - g^{\alpha\beta}(k_1 \cdot k_2)\right]\Big\}
\end{aligned}
$$

Approach

- Four operators that affect the gauge boson two point functions at tree level:

tree level:



$$\mathcal{O}_{DW} = -\frac{g^2}{4}\,\mathrm{Tr}([D_\mu, \sigma^a \cdot W^a_{\nu\rho}][D^\mu, \sigma^b \cdot W^{b,\nu\rho}])$$

$$\mathcal{O}_{DB} = -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$$

$$\mathcal{O}_{BW} = -\frac{gg'}{4}\Phi^\dagger B_{\mu\nu}\sigma^a \cdot W^{a,\mu\nu}\Phi$$

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger(\Phi\Phi^\dagger)(D^\mu\Phi),$$

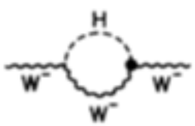
$$D_\mu = \partial_\mu - i\frac{g}{2}B_\mu - i\frac{g'\sigma^a}{2}W^a_\mu \qquad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \mp ig(W^3_\mu W^\pm_\nu - W^3_\nu W^\pm_\mu)$$

$$W^3_{\mu\nu} = \partial_\mu W^3_\nu - \partial_\nu W^3_\mu - ig(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu).$$

Approach

- There are six bosonic operators which contribute to the oblique parameters at one loop



$$\mathcal{O}_{WWW} = -i\frac{g^3}{8}\,\mathrm{Tr}(\sigma^a \cdot W_\nu^{a,\mu}\sigma^b \cdot W_\rho^{b,\nu}\sigma^c \cdot W_\mu^{c,\rho})$$

$$\mathcal{O}_W = i\frac{g}{2}(D_\mu\Phi)^\dagger\sigma^a \cdot W^{a,\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_B = i\frac{g'}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{WW} = -\frac{g^2}{4}\Phi^\dagger\sigma^a \cdot W^{a,\mu\nu}\sigma^b \cdot W^b_{\mu\nu}\Phi$$

$$\mathcal{O}_{BB} = -\frac{g'^2}{4}\Phi^\dagger B^{\mu\nu}B_{\mu\nu}\Phi$$

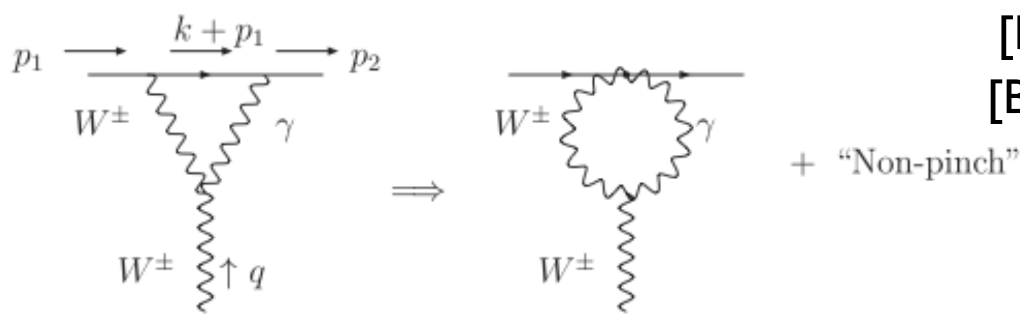
$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi).$$

- Neglect

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3 \qquad \mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger(D^\mu\Phi)(\Phi^\dagger\Phi)$$

Two point functions

- S,T and U parameters defined in terms of self-energies are gauge dependent
- Need pinch part of the vertex corrections



[Degrassi and Sirlin, 1992]
[Binosi, Papavassiliou, 2009]

- The gauge dependence of the gauge boson self-energies is exactly canceled by the pinch part of the vertex corrections.

Two point functions

$$\bar{\Pi}_{WW}(q^2) = \Pi_{WW}(q^2) + 2(q^2 - m_W^2)\Delta\Gamma_L^W(q^2)$$
$$\bar{\Pi}_{ZZ}(q^2) = \Pi_{ZZ}(q^2) + 2c(q^2 - m_Z^2)\Delta\Gamma_L^Z(q^2)$$
$$\bar{\Pi}_{\gamma Z}(q^2) = \Pi_{\gamma Z}(q^2) + sq^2\Delta\Gamma_L^Z(q^2) + c(q^2 - m_Z^2)\Delta\Gamma_L^\gamma(q^2)$$
$$\bar{\Pi}_{\gamma\gamma}(p^2) = \Pi_{\gamma\gamma}(p^2) + 2sq^2\Delta\Gamma_L^\gamma(q^2),$$

where $c \equiv \cos\,\theta_W$ and $s \equiv \sin\,\theta_W$.

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

$$\alpha\Delta T = \left(\frac{\overline{\Pi}_{WW}(0)}{m_W^2} - \frac{\overline{\Pi}_{ZZ}(0)}{m_Z^2}\right)$$

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

Results

$$\Delta S = C_S \frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^{\epsilon}\Gamma(1+\epsilon) + R_S$$

$$\Delta T = C_T \frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^{\epsilon}\Gamma(1+\epsilon) + R_T$$

$$\Delta U = C_U \frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^{\epsilon}\Gamma(1+\epsilon) + R_U\,,$$

3 order of magnitude smaller

$$C_S = \frac{m_H^2}{8\pi}\left\{\frac{f_B+f_W}{\Lambda^2}\right\} + \frac{m_Z^2}{24\pi\Lambda^2}\left\{f_B(20c^2+7) - 3f_W + 24(s^2 f_{BB} + c^2 f_{WW}) + 36c^2 g^2 f_{WWW} + \frac{8c^2}{g^2} f_{\Phi,2}\right\}$$

$$C_T = \frac{1}{16\pi c^2}\left\{9m_W^2\left(\frac{f_B+f_W}{\Lambda^2}\right) + 3m_H^2\frac{f_B}{\Lambda^2} - 12\frac{m_W^2}{g^2}\frac{f_{\Phi,2}}{\Lambda^2}\right\}$$

$$C_U = \frac{m_Z^2}{6\pi\Lambda^2}s^2 f_W\,.$$

$$R_S = \{-0.76 f_{BW} + 10^{-3}(1.48 f_B - 1.4 f_W - 0.2 f_{BB} - 0.71 f_{WW} + 0.66 f_{WWW} + 1.96 f_{\Phi,2})\}\left(\frac{1\text{ TeV}}{\Lambda}\right)^2$$

$$R_T = \{-4.0 f_{\Phi,1} - 10^{-3}(0.13 f_B + 0.12 f_W - 3.97 f_{\Phi,2})\} \times \left(\frac{1\text{ TeV}}{\Lambda}\right)^2$$

$$R_U = \{0.20 f_{DW} + 10^{-3}(-0.02 f_B + 2.06 f_W + 0.14 f_{WW} + 2.1 f_{WWW} - 0.25 f_{\Phi,2})\}\left(\frac{1\text{ TeV}}{\Lambda}\right)^2. \quad (19)$$

Renormalization

- $\overline{MS}$ scheme
- In R_ξ Gauge
- The divergences have been eliminated by the renormalization of the tree level couplings.

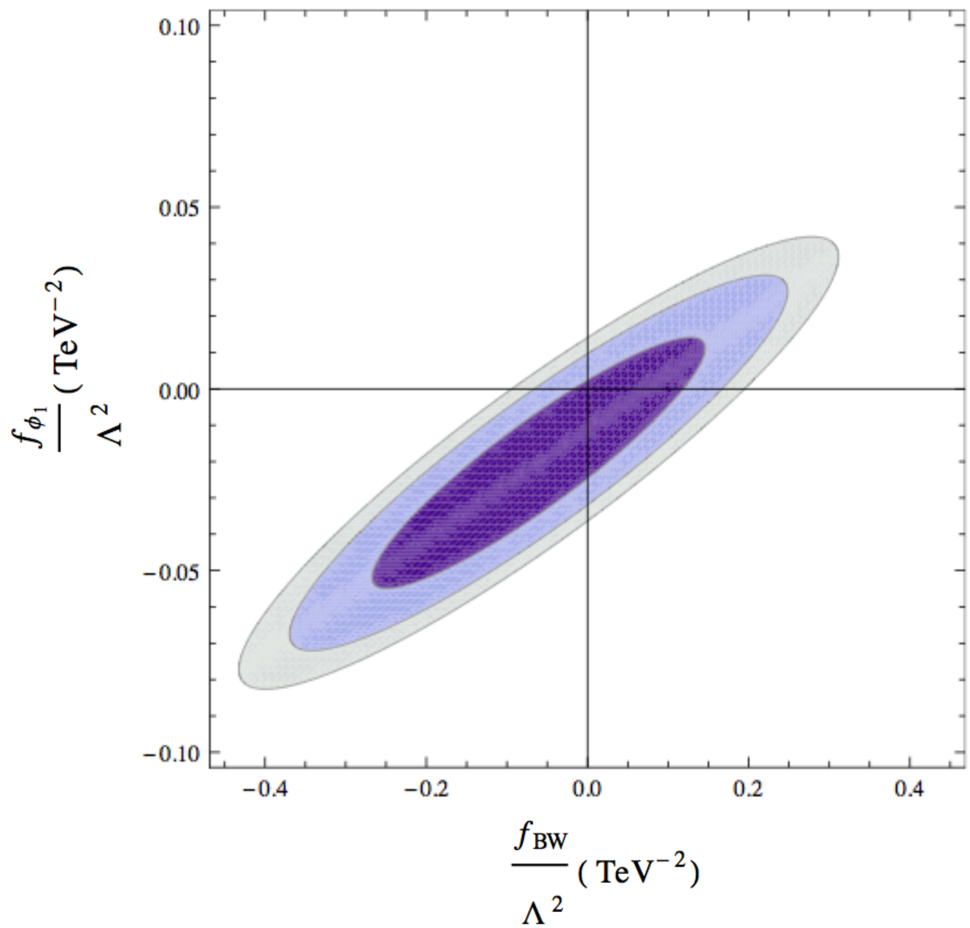
$$f_{BW}(\mu) = f_{BW} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_S$$
$$f_{DW}(\mu) = f_{DW} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_U$$
$$f_{\Phi,1}(\mu) = f_{\Phi,1} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_T.$$

- The only remaining contributions to the oblique corrections are the finite contributions at $\mu = m_Z$.

$$\Delta S = R_S \qquad \Delta T = R_T \qquad \Delta U = R_U.$$

Results

- Limits from the oblique parameters.
- Coefficients of the operators that contribute at tree level are significantly restricted (all other coefficients are set to zero.)

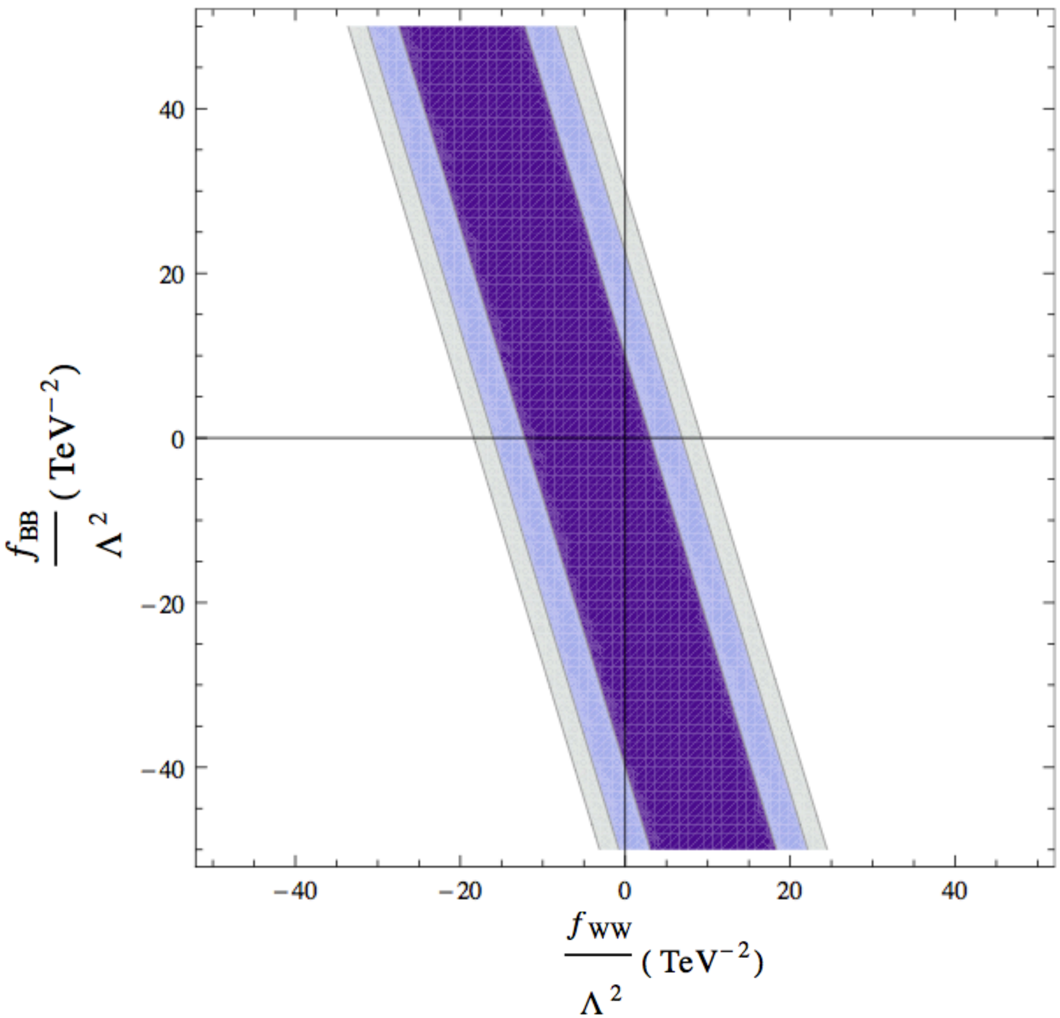


From outer to inner are 99%, 95% and 68% CL

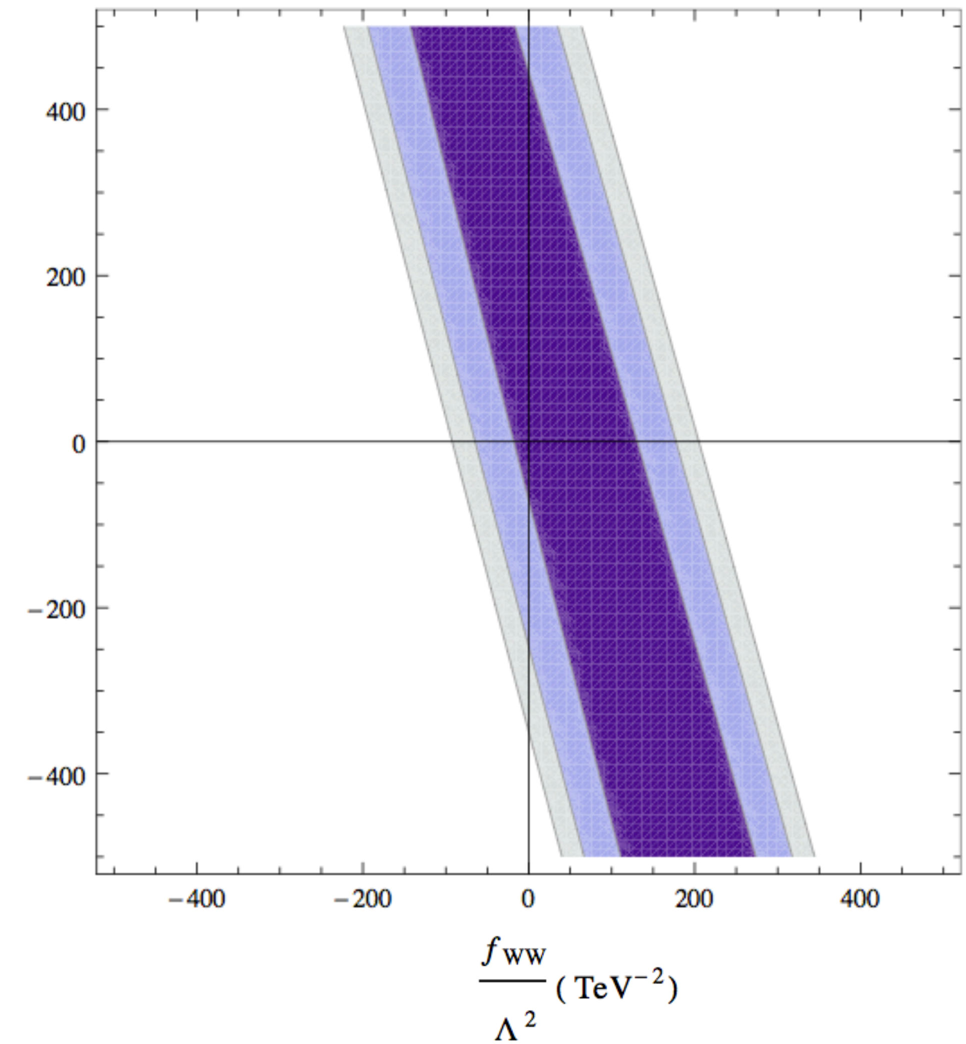
$\mu = m_Z$

Results

- Limits from the oblique parameters on f_{WW} and f_{BB} (other coefficients are set to zero.)



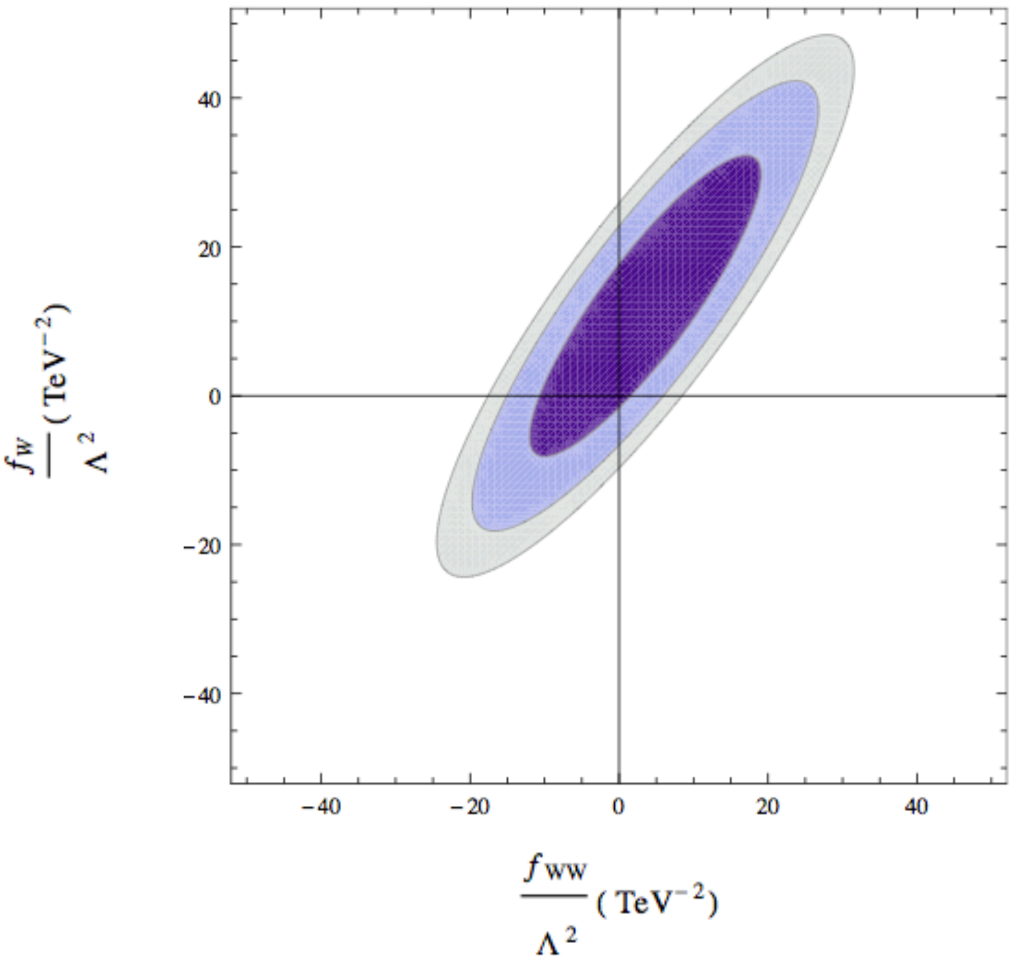
Leading logarithmic result $\mu = \Lambda$



Renormalized result at $\mu = m_Z$

Results

- Limits from the oblique parameters on f_{WW} and f_W (other coefficients are set to zero.)



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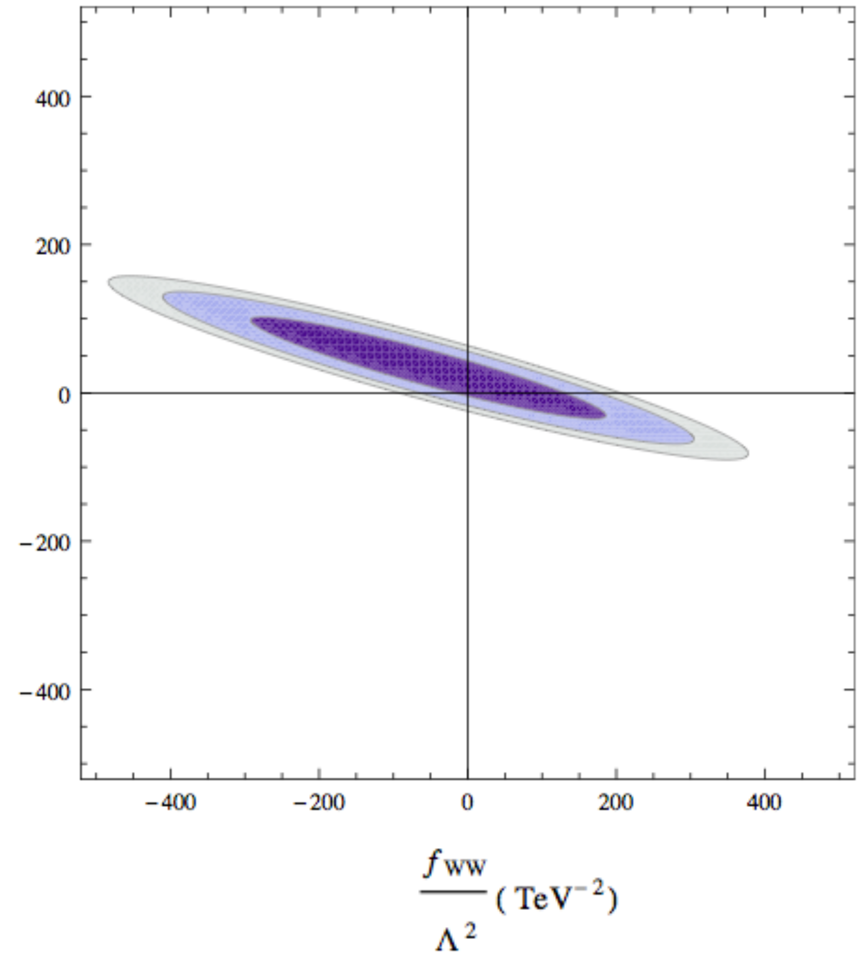
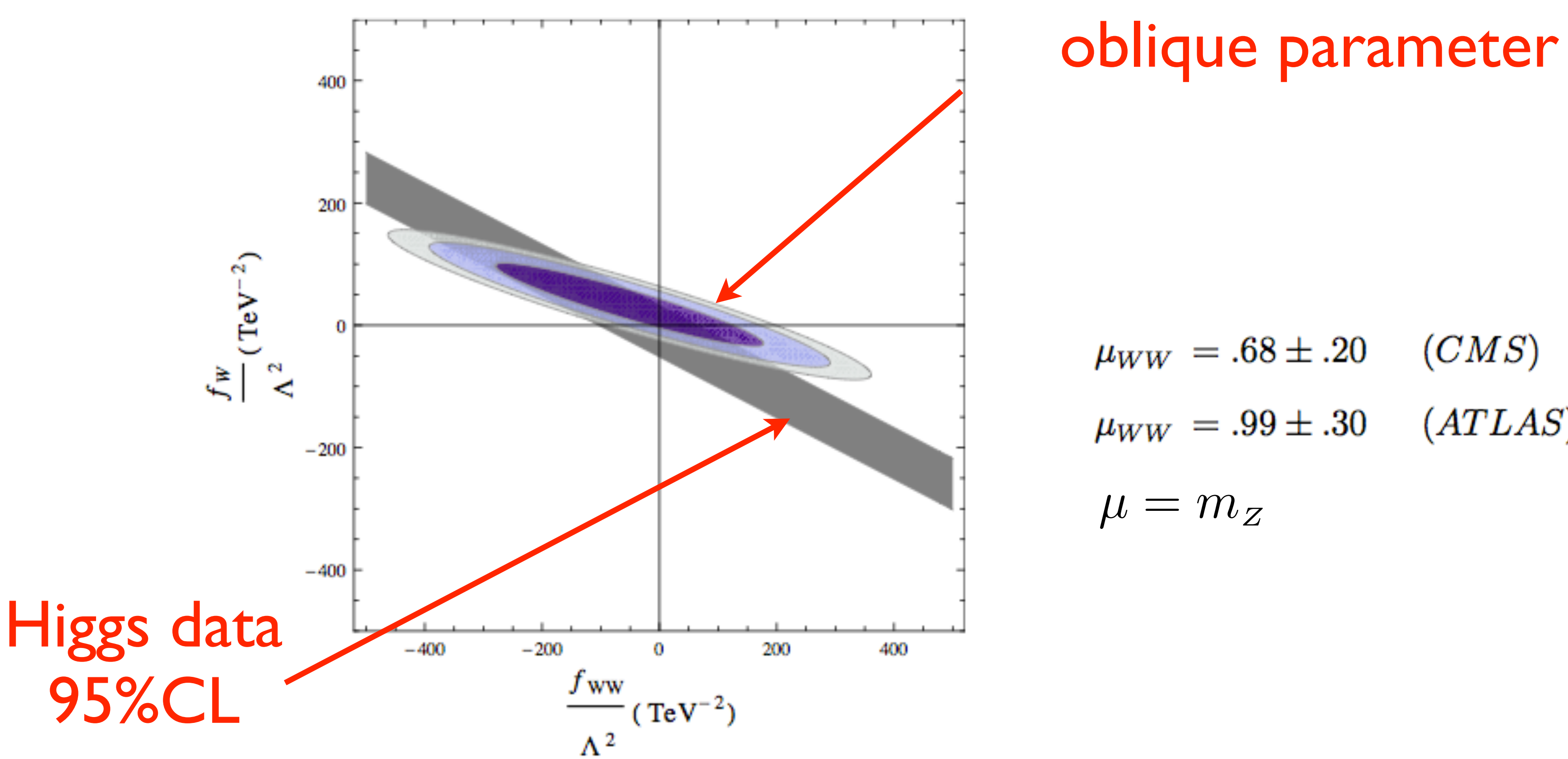


Renormalized result at $\mu = m_Z$

Oblique parameters v.s. H-> WW

- Complementary bounds from oblique parameters and Higgs data.

$$\mu_{WW} \sim 1 + [.0086 f_{WW}(m_Z) + .017 f_W(m_Z) - .03 f_{\Phi,1}(m_Z) - .06 f_{\Phi,2}(m_Z)] \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



$$\mu_{WW} = .68 \pm .20 \quad (CMS)$$

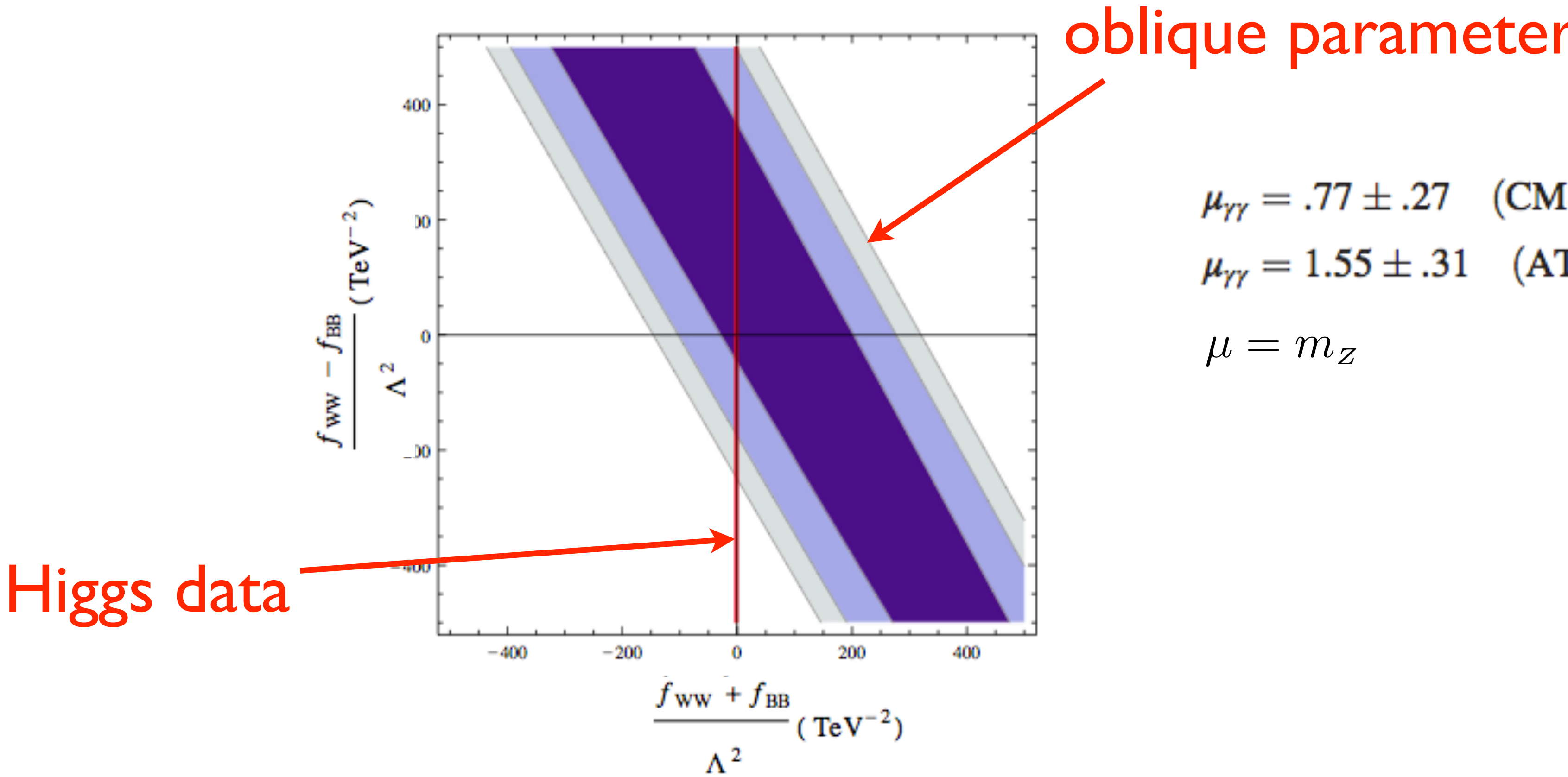
$$\mu_{WW} = .99 \pm .30 \quad (ATLAS)$$

$$\mu = m_Z$$

Oblique parameters v.s. H-> 2 photons

- Comparison of limits from the oblique parameters and H-> 2 photons on $f_{WW} + f_{BB}$ and $f_{WW} - f_{BB}$ (other coefficients are set to zero.)

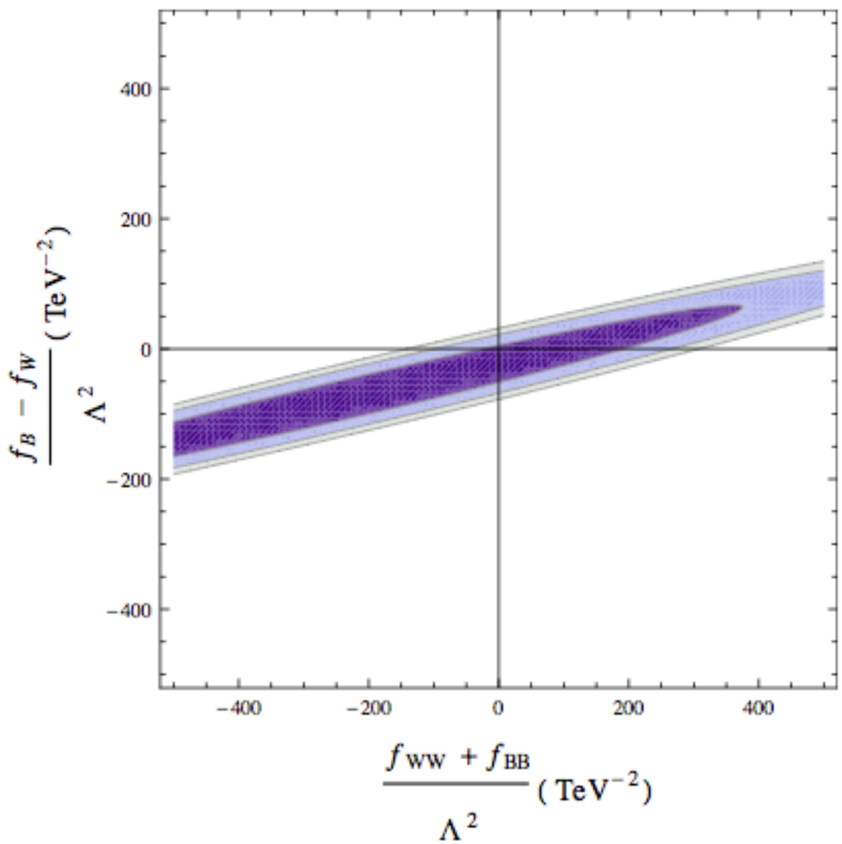
$$\mu_{\gamma\gamma} \equiv \frac{\Gamma(H \to \gamma\gamma)}{\Gamma(H \to \gamma\gamma)|_{\rm SM}} \sim 1 + 1.47 \left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 [f_{BB}(m_Z) + f_{WW}(m_Z) - f_{BW}(m_Z)] + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$



$$\mu_{\gamma\gamma} = .77 \pm .27 \quad \text{(CMS)}$$
$$\mu_{\gamma\gamma} = 1.55 \pm .31 \quad \text{(ATLAS)}.$$
$$\mu = m_Z$$

Results

- Limits from oblique parameters, which influence the decay H-> Z photon.



$\mu = m_Z$

$$\mu_{Z\gamma} \equiv \frac{\Gamma(H \to Z\gamma)}{\Gamma(H \to Z\gamma)\,|_{SM}}$$
$$= 1 + \frac{2A_{real}}{A_{real}^2 + A_{imag}^2} \frac{2\pi s c}{\alpha} \frac{m_Z^2}{\Lambda^2} g_1 + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

$$g_1 = f_B(m_Z) - f_W(m_Z) + 4s^2 f_{BB}(m_Z)$$
$$- 4c^2 f_{WW}(m_Z) + 2(c^2 - s^2) f_{BW}(m_Z)$$

- Neglect all coefficients except $f_W(m_Z)$ and $f_B(m_Z)$.

$$-80 < [f_B(m_Z) - f_W(m_Z)]\left(\frac{1\ \text{TeV}}{\Lambda}\right)^2 < 35,$$

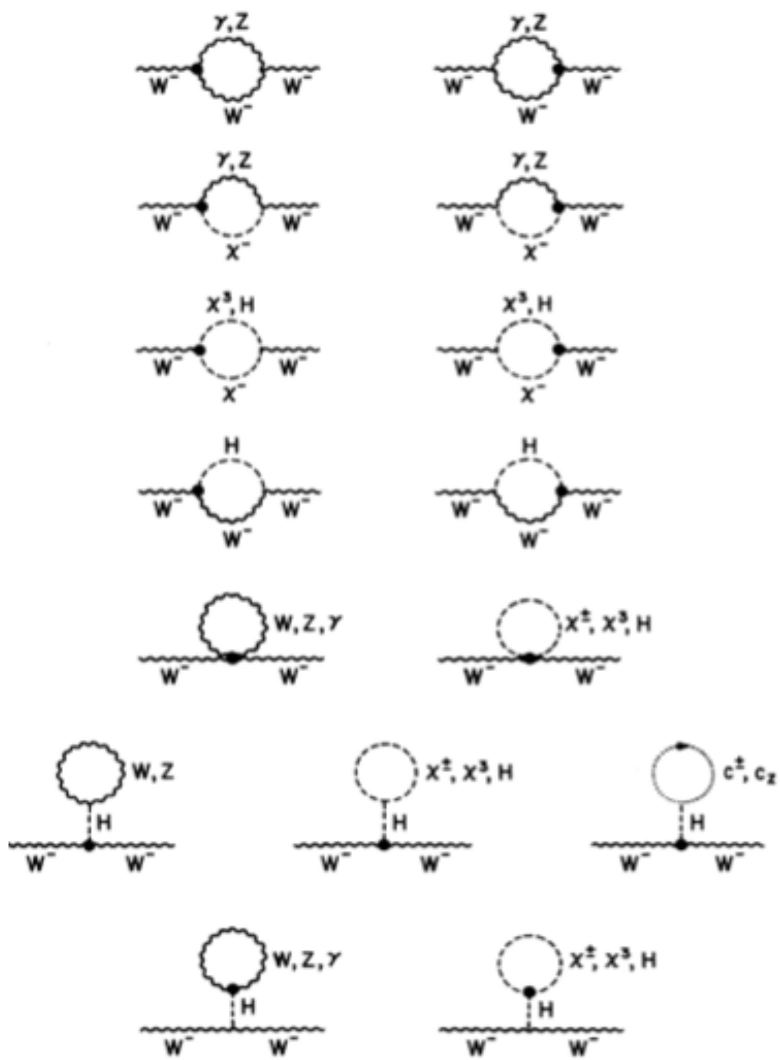
Conclusions

- Only weak limits on the couplings that contribute at one loop can be obtained from the oblique parameters.
- In contrast, the couplings that contribute at tree level, are tightly constrained.
- Loop contributions to oblique parameters yield complementary information to direct H->WW measurement.

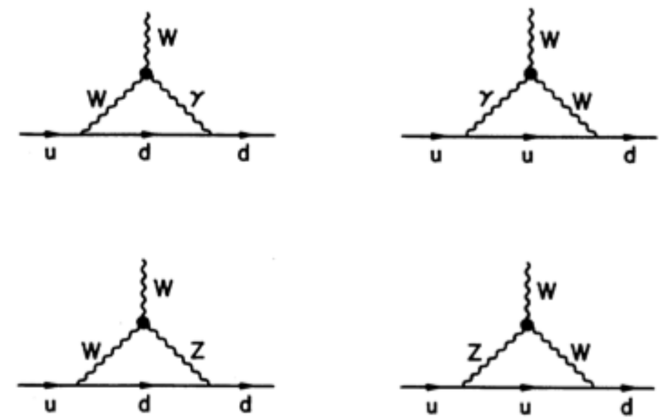
Backup slides

Example

- Anomalous contributions to Π_{WW}



- Anomalous contributions to the W u d vertex $\Delta\Gamma_L^{Wud}$



$$\Delta\Gamma_L^{Vff}(q^2) = gT_3^f\Delta\Gamma_L^V(q^2) \quad V = Z,\gamma$$
$$\Delta\Gamma_L^{Wff'}(q^2) = \frac{g}{\sqrt{2}}\Delta\Gamma_L^W(q^2).$$

$\chi^\pm$ and χ^3: Goldstone bosons
$c^\pm$ and c_Z: Faddeev-Popov ghosts.

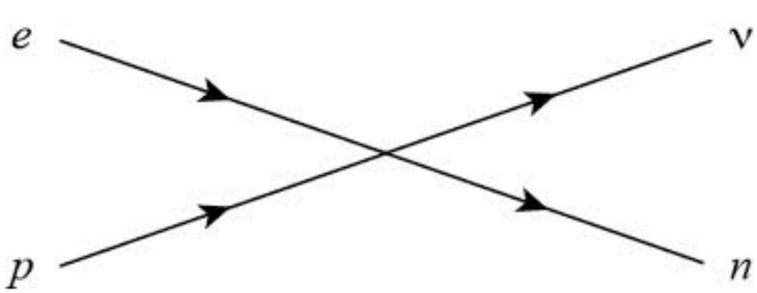
Effective field theory

- Assume new physics is at a scale (Λ) much higher than that we can probe experimentally.

$$\mathcal{L}_{eff} = \sum_{n=5}^{\infty} \frac{f_n}{\Lambda^{n-4}} \mathcal{O}_n + \dots .$$

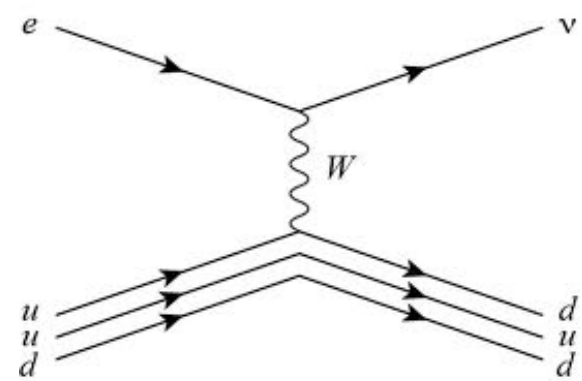
- e.g. Fermi's four fermion interaction

Below Λ



$$\mathcal{L} \sim G_F \, \bar{\nu} e \bar{p} n.$$

Above Λ



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2}$$