# Robust Determination of the Higgs Couplings: Power to the Data

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# Overview

Discovery of a $\simeq$125 GeV "Higgs-like" particle $\rightarrow$EWSB direct exploration:

- Spin
- Parity
- EWSB connected new states
- Couplings

Bottom-up model-independent effective Lagrangian approach:

$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

- Assume observed state is light electroweak doublet scalar and that $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is linearly realized in the effective theory.
- $\mathcal{L}_{\rm eff}$: describe the low energy effects of new physics in the couplings of this observed new state.
- Choice of operators and basis $\rightarrow$ **Driven by the data**

Determine coefficients of operators using all available data: Tevatron, LHC, TGV, EWPD

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# Effective Lagrangian

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Our assumptions are:

- The observed state belongs to a SU(2) doublet.
- The state is CP-even as in SM.
- Narrow resonance and no overlapping resonances.
- $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ SM local symmetry, C and P even, lepton and baryon number conservation

**59** dimension-6 operators are enough...[1]

But we can use EOM to eliminate 3 of them:

$$2\mathcal{O}_{\Phi,2} - 2\mathcal{O}_{\Phi,4} = \sum_{ij} \left( y^e_{ij} \mathcal{O}_{e\Phi,ij} + y^u_{ij} \mathcal{O}_{u\Phi,ij} + y^d_{ij} (\mathcal{O}_{d\Phi,ij})^\dagger + \text{h.c.} \right) \ ,$$

$$2\mathcal{O}_B + \mathcal{O}_{WB} + \mathcal{O}_{BB} + g'^2 \left( \mathcal{O}_{\Phi,1} - \frac{1}{2}\mathcal{O}_{\Phi,2} \right) = -\frac{g'^2}{2} \sum_i \left( -\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii} + \frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii} - \mathcal{O}^{(1)}_{\Phi e,ii} + \frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii} - \frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii} \right)$$

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In the absence of theoretical prejudice chose a basis where the operators are more directly related to the existing data

**$Z$ properties, $W$ decays, low energy $\nu$ scatt., atomic $P$, FCNC, Moller scatt. $P$ and $e^+e^- \to f\bar{f}$ at LEP2.**

EWPD at tree level, TGV

[2] $D_\mu \Phi = \left( \partial_\mu + i \frac{1}{2} g' B_\mu + i g \frac{\sigma_a}{2} W^a_\mu \right) \Phi$, $\hat{B}_{\mu\nu} = i \frac{g'}{2} B_{\mu\nu}$, $\hat{W}_{\mu\nu} = i \frac{g}{2} \sigma^a W^a_{\mu\nu}$

# The right of choice

Higgs interactions with gauge bosons[2]:

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu} \, , \quad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \, , \quad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi \, ,$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \, , \quad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \, , \quad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi) \, ,$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi \, \Phi^\dagger \, (D^\mu \Phi) \, , \quad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right) \, , \quad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \, (D^\mu \Phi) \left(\Phi^\dagger \Phi\right) \, ,$$

Higgs interactions with fermions:

$$\mathcal{O}_{e\Phi,33} = (\Phi^\dagger \Phi)(\bar{L}_3 \Phi e_{R_3}) \quad \mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_i \gamma^\mu L_j) \quad \mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j)$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j}) \quad \mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}_i \gamma^\mu Q_j) \quad \mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}_i \gamma^\mu \sigma_a Q_j)$$

$$\mathcal{O}_{d\Phi,33} = (\Phi^\dagger \Phi)(\bar{Q}_3 \Phi d_{R3}) \quad \mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_{R_i} \gamma^\mu e_{R_j})$$

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# Effective Lagrangian for Higgs Interactions

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{\rm bot}}{\Lambda^2}\mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2}\mathcal{O}_{e\Phi,33}$$

Unitary gauge:

$$\begin{aligned}\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\, HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\, HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\, HA_{\mu\nu}Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\, HZ_{\mu\nu}Z^{\mu\nu} + g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) \\ &+ g^{(2)}_{HWW}\, HW^+_{\mu\nu}W^{-\,\mu\nu}\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}'_L f'_R H + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} \quad , g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}}{2} \quad ,$$

$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} \quad , g^{(2)}_{HZ\gamma} = -\left(\frac{g^2 v}{2\Lambda^2}\right) s c f_{WW} \quad ,$$

$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} \quad , g^{(2)}_{HZZ} = -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_{WW}}{2} \quad ,$$

$$g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} \quad , g^{(2)}_{HWW} = -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW}$$

$$g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}f'_{f\Phi,ij}$$

# Effective Lagrangian for Higgs Interactions

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Unitary gauge:

$$\begin{aligned}
\mathcal{L}_{\rm eff}^{\rm HVV} &= g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\
&+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^\mu\partial^\nu H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(1)}_{HWW}\left(W^+_{\mu\nu}W^{-\,\mu}\partial^\nu H + \text{h.c.}\right) \\
&+ g^{(2)}_{HWW}\; HW^+_{\mu\nu}W^{-\,\mu\nu}
\end{aligned}$$

$$\mathcal{L}_{\rm eff}^{Hff} = g^f_{Hij}\bar{f}'_L f'_R H + \text{h.c.}$$

$$\begin{aligned}
g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} &, g_{H\gamma\gamma} &= -\left(\frac{g^2 v s^2}{2\Lambda^2}\right)\frac{f_{WW}}{2}\;, \\
g^{(1)}_{HZ\gamma} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{s(f_W - f_B)}{2c} &, g^{(2)}_{HZ\gamma} &= -\left(\frac{g^2 v}{2\Lambda^2}\right) s c f_{WW}\;, \\
g^{(1)}_{HZZ} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_W + s^2 f_B}{2c^2} &, g^{(2)}_{HZZ} &= -\left(\frac{g^2 v}{2\Lambda^2}\right)\frac{c^2 f_{WW}}{2}\;, \\
g^{(1)}_{HWW} &= \left(\frac{g^2 v}{2\Lambda^2}\right)\frac{f_W}{2} &, g^{(2)}_{HWW} &= -\left(\frac{g^2 v}{2\Lambda^2}\right) f_{WW}
\end{aligned}$$

$$g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2} f'_{f\Phi,ij}$$

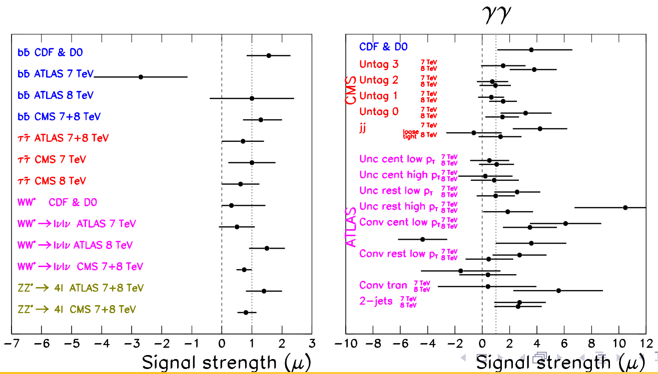
# Analysis Framework: Collider data

$$\chi^2 = \min_{\xi_{pull}} \sum_j \frac{(\mu_j - \mu_j^{\exp})^2}{\sigma_j^2} + \sum_{pull} \left( \frac{\xi_{pull}}{\sigma_{pull}} \right)^2$$

Where

$$\mu_F = \frac{\epsilon^F_{gg}\sigma^{ano}_{gg}(1+\xi_g) + \epsilon^F_{VBF}\sigma^{ano}_{VBF} + \epsilon^F_{WH}\sigma^{ano}_{WH} + \epsilon^F_{ZH}\sigma^{ano}_{ZH} + \epsilon^F_{t\bar{t}H}\sigma^{ano}_{t\bar{t}H}}{\epsilon^F_{gg}\sigma^{SM}_{gg} + \epsilon^F_{VBF}\sigma^{SM}_{VBF} + \epsilon^F_{WH}\sigma^{SM}_{WH} + \epsilon^F_{ZH}\sigma^{SM}_{ZH} + \epsilon^F_{t\bar{t}H}\sigma^{SM}_{t\bar{t}H}} \otimes \frac{\mathrm{Br}^{ano}[h \to F]}{\mathrm{Br}^{SM}[h \to F]} .$$

$$\sigma^{ano}_Y = \left.\frac{\sigma^{ano}_Y}{\sigma^{SM}_Y}\right|_{tree} \left.\sigma^{SM}_Y\right|_{soa} \qquad \Gamma^{ano}(h \to X) = \left.\frac{\Gamma^{ano}(h \to X)}{\Gamma^{SM}(h \to X)}\right|_{tree} \left.\Gamma^{SM}(h \to X)\right|_{soa}$$



# Analysis Framework: TGV and EWPD

Data on triple electroweak gauge boson vertices:

$$\mathcal{L}_{WWV} = -ig_{WWV}\left\{g_1^V\left(W^+_{\mu\nu}W^{-\,\mu}V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\,\nu\rho}V_\rho{}^\mu\right\}$$

with

$$\begin{aligned}\Delta g_1^Z &= g_1^Z - 1 = \frac{g^2v^2}{8c^2\Lambda^2}f_W \ ,\\ \Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2v^2}{8\Lambda^2}\left(f_W + f_B\right) \ ,\\ \Delta\kappa_Z &= \kappa_Z - 1 = \frac{g^2v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B\right) \ .\end{aligned}$$

LEP data:

$$\begin{aligned}g_1^Z &= 0.984^{+0.049}_{-0.049}\\ \Delta\kappa_\gamma &= 1.004^{+0.024}_{-0.025}\end{aligned}$$

with a correlation factor $\rho = 0.11$.

Data on EWPD in terms of the S,T,U parameters:

$$\Delta S = 0.00 \pm 0.10 \qquad \Delta T = 0.02 \pm 0.11 \qquad U = 0.03 \pm 0.09$$

$$\rho = \begin{pmatrix} 1 & 0.89 & -0.55 \\ 0.89 & 1 & -0.8 \\ -0.55 & -0.8 & 1 \end{pmatrix}$$

# $\Delta\chi^2$ vrs $f_X$

Columns (analysis):

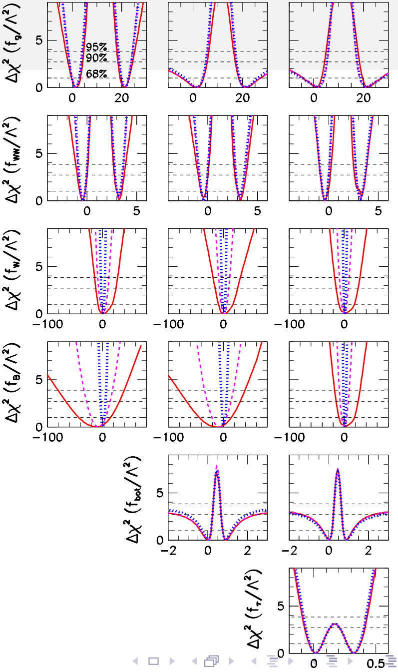
1st: $f_g$, $f_{WW}$, $f_W$, $f_B$
2nd: $f_g$, $f_{WW}$, $f_W$, $f_B$, $f_{\rm bot}$
3rd: $f_g$, $f_{WW}$, $f_W$, $f_B$, $f_{\rm bot}$, $f_\tau$

Raws (parameters):

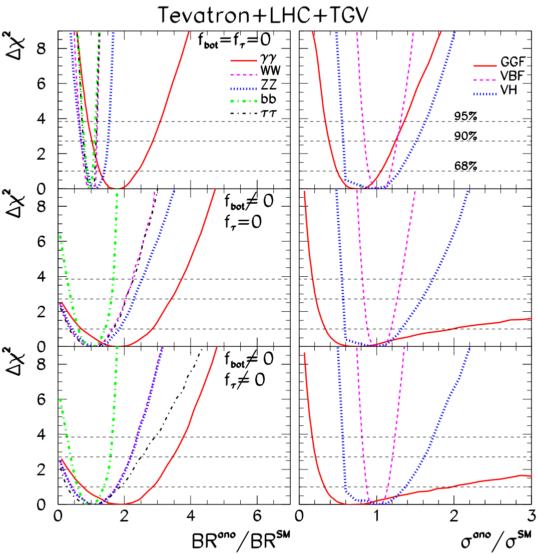
1st: $f_g$
2nd: $f_{WW}$
3rd: $f_W$
4th: $f_B$
5th: $f_{\rm bot}$

Colours/lines (data):

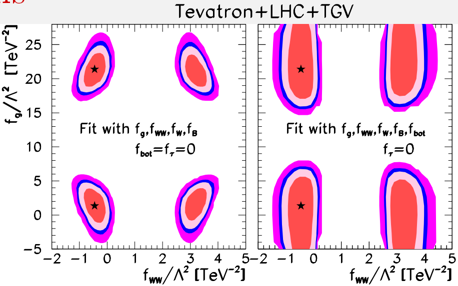
Solid red: Collider
Dash pink: Collider + TGV
Dot blue: Collider + TGV + EWPD

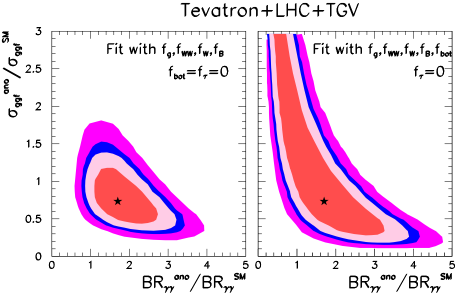


# BRs and production CS



# 2d correlations



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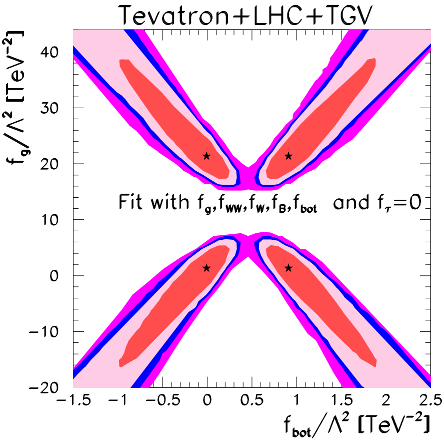

# Best fit and ranges

| | Fit with $f_{bot} = f_\tau = 0$ | | Fit with $f_{bot}$ and $f_\tau$ | |
|---|---|---|---|---|
| | Best fit | 90% CL allowed range | Best fit | 90% CL allowed range |
| $f_g/\Lambda^2$ (TeV$^{-2}$) | 1.4, 21.3 | $[-1.1, 3.8] \cup [19, 24]$ | 1.6, 21.1 | $[-27, 5] \cup [17, 50]$ |
| $f_{WW}/\Lambda^2$ (TeV$^{-2}$) | -0.43 | $[-0.85, -0.05] \cup [2.8, 3.6]$ | -0.42 | $[-0.85, 0] \cup [2.75, 3.7]$ |
| $f_W/\Lambda^2$ (TeV$^{-2}$) | 1.70 | $[-7.2, 10]$ | 0.42 | $[-7.5, 7]$ |
| $f_B/\Lambda^2$ (TeV$^{-2}$) | -7.6 | $[-29, 14]$ | 0.42 | $[-7.5, 7]$ |
| $f_{bot}/\Lambda^2$ (TeV$^{-2}$) | —– | —– | 0.01, 0.89 | $[-1.6, 0.25] \cup [0.65, 2.5]$ |
| $f_\tau/\Lambda^2$ (TeV$^{-2}$) | —– | —– | 0.02, 0.32 | $[-0.08, 0.13] \cup [0.2, 0.42]$ |
| $BR^{ano}_{\gamma\gamma}/BR^{SM}_{\gamma\gamma}$ | 1.76 | $[1.1, 2.8]$ | 1.84 | $[0.1, 3.4]$ |
| $BR^{ano}_{WW}/BR^{SM}_{WW}$ | 0.98 | $[0.75, 1.15]$ | 1.03 | $[0.05, 2.15]$ |
| $BR^{ano}_{ZZ}/BR^{SM}_{ZZ}$ | 1.13 | $[0.75, 1.5]$ | 1.03 | $[0.05, 2.15]$ |
| $BR^{ano}_{bb}/BR^{SM}_{bb}$ | 1.03 | $[0.85, 1.1]$ | 1.03 | $[0.4, 1.6]$ |
| $BR^{ano}_{\tau\tau}/BR^{SM}_{\tau\tau}$ | 1.03 | $[0.8, 1.1]$ | 0.84 | $[0.05, 2.5]$ |
| $\sigma^{ano}_{gg}/\sigma^{SM}_{gg}$ | 0.78 | $[0.4, 1.2]$ | 0.73 | $[0.25, 12]$ |
| $\sigma^{ano}_{VBF}/\sigma^{SM}_{VBF}$ | 1.03 | $[0.9, 1.25]$ | 1.03 | $[0.9, 1.15]$ |
| $\sigma^{ano}_{VH}/\sigma^{SM}_{VH}$ | 0.98 | $[0.55, 1.4]$ | 1.03 | $[0.55, 1.55]$ |

Best fit values and 90% CL allowed ranges for the combination of all available Tevatron and LHC Higgs data as well as TGV.

# Discussion and Conclusions

- **Model independent** analysis where the effects of new physics in the Higgs couplings are parametrized in $\mathcal{L}_{eff}$.
  $SU(2)_L$ doublet $\rightarrow SU(2)_L \times U(1)_Y$ gauge symmetry linearly realized:

$$\mathcal{L}_{\rm eff} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n \quad ,$$

- Choice of basis:
  **Power to the data** → operators whose coefficients are more easily related to existing data

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_{\rm bot}}{\Lambda^2} \mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2} \mathcal{O}_{e\Phi,33} \quad .$$

- Present status of the analysis using Tevatron, LHC, TGV and EWPD data:
  **SM compatible with data (60%-90% CL).**

  **Preference for larger–than–SM BR to photons and a smaller–than–SM gluon fusion production CS and decay BR into $\tau' s$**

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THANK YOU!

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# S,T,U Parameters

$$
\begin{aligned}
\alpha\Delta S &= \frac{1}{6}\frac{e^2}{16\pi^2}\Bigg\{3(f_W + f_B)\frac{m_H^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) + \\
&+ 2\Big[(5c^2-2)f_W - (5c^2-3)f_B\Big]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) \\
&- \Big[(22c^2-1)f_W - (30c^2+1)f_B\Big]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right) \\
&- 24c^2 f_{WW}\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right)\Bigg\}, \\
\alpha\Delta T &= \frac{3}{4c^2}\frac{e^2}{16\pi^2}\Bigg\{f_B\frac{m_H^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) \\
&+ (c^2 f_W + f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) \\
&+ \Big[2c^2 f_W + (3c^2-1)f_B\Big]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right)\Bigg\}, \\
\alpha\Delta U &= -\frac{1}{3}\frac{e^2 s^2}{16\pi^2}\Bigg\{(-4f_W + 5f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) \\
&+ (2f_W - 5f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right)\Bigg\}
\end{aligned}
$$

# ATLAS vrs CMS