59 ways to leave the SM
&
implications for Higgs physics

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based in work with

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- M. Montull and F. Riva

Plenty of new data from the LHC: **Implications?**

- Most of us like to look for implications in specific scenarios, motivated by naturalness, ...
  Top-down approach: MSSM, composite Higgs,...

- But not having found anything, it makes sense to be more open to alternatives

(For example, even in susy scenarios, plenty of possibilities beyond the MSSM (e.g. Higgs as a partner of a SM lepton))

↳ Approach to look for deviations from the SM more model-independent:

SM + higher-dimensional operators

Assuming new-physics scale Λ is heavier than M_W, we can perform an expansion in derivatives and SM fields

(assuming lepton & baryon number)

$$\mathcal{L}_{\rm eff} = \frac{\Lambda^4}{g_*^2}\mathcal{L}\left(\frac{D_\mu}{\Lambda}\,,\ \frac{g_H H}{\Lambda}\,,\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}}\,,\ \frac{g F_{\mu\nu}}{\Lambda^2}\right) \simeq \mathcal{L}_4 + \mathcal{L}_6 + \cdots$$

SM

deviations from the SM

$\mathcal{L}_6$: made of local dim-6 operators

- How many? What is the best basis of operators?
- What are the implications (on Higgs)?

Classification of dim-6 operators

Search for the set of independent operators forming a basis:

Long story: Buchmuller&Wyler 86 ... Grzadkowski et al. 10

from **80** operators ... to **59** operators (for one family)

Reduction of the set by using field redefinitions:

(equivalently, using EOM)

e.g.

$$H \to H\left(1+\alpha_1 g_H^2 |H|^2/\Lambda^2\right)$$

$$B_\mu \to B_\mu + i g' \alpha_B (H^\dagger \overleftrightarrow{D}^\mu H)/\Lambda^2$$

$$B_\mu \to B_\mu + \alpha_{2B}(\partial^\nu B_{\nu\mu})/\Lambda^2$$

59 dimension-six operators (for one family)

Grzadkowski et al. 10

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

Choosing the basis for dim-6 operators

Physics is basis-independent, as long as you keep all operators.
But in practice this is difficult, so people truncate the set,
giving strong dependence on the choice of the basis

we will see examples in the literature of how the use of the non-appropriate basis can mislead people

Some criteria for a convenient basis:

- Clean operator ↔ experiment connection
- Capture in few operators the impact of different BSM:
  Universal theories, weakly-coupled theories (MSSM), ...
- Keep separated operators of possible different origins and coefficients of different expected size
- Keep symmetries of the BSM manifest

Our basis will follow the SILH criteria:

Giudice,Grojean,AP,Rattazzi 07

$$
\begin{aligned}
\mathcal{L}_{\rm SILH} = \; & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right)+\frac{c_T}{2f^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)\left(H^\dagger\overleftrightarrow{D}_\mu H\right) \\
& -\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3+\left(\frac{c_y y_f}{f^2}H^\dagger H\bar{f}_L H f_R+\text{h.c.}\right) \\
& +\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i+\frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu}) \\
& +\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}+\frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& +\frac{c_\gamma {g'}^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu}+\frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.
\end{aligned}
$$

$$\boxed{\Lambda = m_\rho = g_\rho f}$$

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Giudice,Grojean,AP,Rattazzi 07

$$\mathcal{L}_{\rm SILH} = \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right)$$
$$-\frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.}\right)$$
$$+\frac{ic_W g}{2m_\rho^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i + \frac{ic_B g'}{2m_\rho^2}\left(H^\dagger\overleftrightarrow{D^\mu}H\right)(\partial^\nu B_{\mu\nu})$$
$$+\frac{ic_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{ic_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$$
$$+\frac{c_\gamma {g'}^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2}H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2}H^\dagger H G^a_{\mu\nu}G^{a\mu\nu}.$$

$$\boxed{\Lambda = m_\rho = g_\rho f}$$

"tree-level" operators

"loop" operators

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Giudice,Grojean,AP,Rattazzi 07

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$$+ \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu})$$

$$+ \frac{i c_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

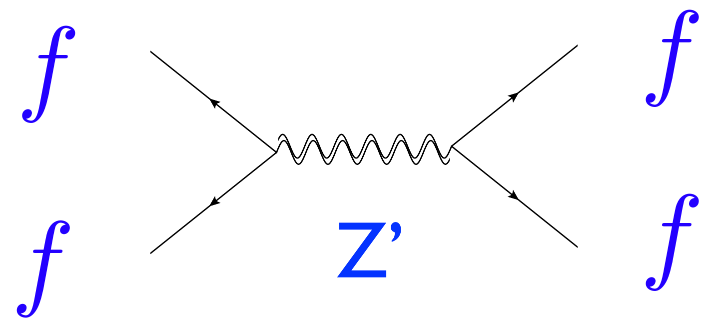
$$+ \frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}.$$

$$\boxed{\Lambda = m_\rho = g_\rho f}$$

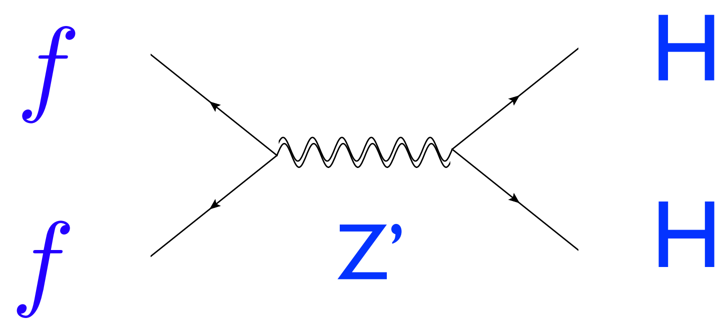
"tree-level" operators

"loop" operators

"tree-level" operators (or "current-current"):

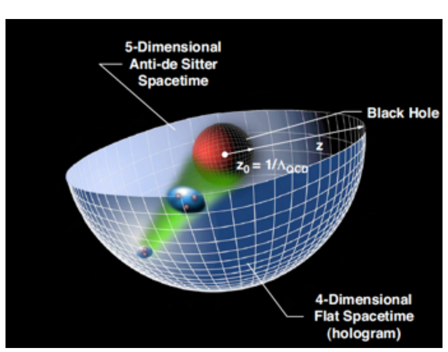


$$\frac{1}{\Lambda^2} J_f^\mu J_{f\,\mu}$$

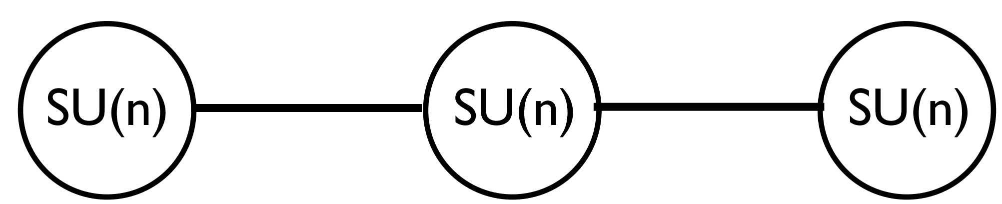


$$\frac{1}{\Lambda^2} J_f^\mu J_{H\,\mu}$$

From integrating out, at tree-level, heavy fields
as occurs, not only in renormalizable weakly-coupled theories,
but also in some holographic/deconstructed version
of strongly-coupled theories



$\mathbf{g_\rho \sim 4\pi/\sqrt{N}}$



- Also right parametrization for strongly coupled theories of a composite "meson" Higgs (with no small parameter): $\mathbf{g_\rho \sim 4\pi}$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} = {} & \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
& - \frac{c_6\lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right) \\
& + \frac{i c_W g}{2m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i c_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i c_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{c_\gamma g'^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu}.
\end{aligned}
$$

$$\boxed{\mathbf{\Lambda = m_\rho = 4\pi f}}$$

Let me open a parenthesis...

Recently this approach has been
criticized by Jenkins, Manohar, Trott 13...

They confused what we called "minimal coupling"
in the SILH paper with the usual definition
of minimal coupling: "replace derivatives with covariant
derivatives"

Our basis classification is well-defined and not ambiguous

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Giudice, Grojean, AP, Rattazzi 07

According to the general expression in eq. (2.5), four-derivative operators like those in eqs. (2.9)–(2.10) can arise at tree level. However in "normal" theories, the classical action including the heavy fields Φ involves at most two derivatives. Holographic Goldstone models and Little Higgs are of this type. To be more specific, these theories correspond to minimally-coupled field theories where the states have spin ≤ 1, and all vectors are associated to (spontaneously-broken) gauge symmetries.[6] In the case of minimally-coupled theories, higher-derivative operators like those in eqs. (2.9)–(2.10) can appear in the classical low-energy action below m_ρ only if there exists a field Φ with the appropriate quantum numbers to mediate the corresponding operator. In this respect we remark an interesting

They also claim that this separation
of “tree-level” vs “loop” operators
is not present in certain effective theories

*I fully agree, but it is present in most models
which we are interested in*

They claim neither in the QCD chiral lagrangian...

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I fully agree, but it is present in most models
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They claim neither in the QCD chiral lagrangian...

really?

Inspiration from QCD: Chiral lagrangian for pions:

Ordinary basis:

$$\mathcal{L}_\chi = \frac{f^2}{4}\langle D^\mu U D_\mu U\rangle + \cdots$$
$$- \; iL_9 \,\langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle \; + \; L_{10}\,\langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle$$

In a "SILH basis":

"*tree*": $\langle (U^\dagger \overleftrightarrow{D}_\nu U) D_\mu F_L^{\mu\nu} + (U \overleftrightarrow{D}_\nu U^\dagger) D_\mu F_R^{\mu\nu}\rangle$ "*loop*"

Experiments say: $\dfrac{c_{\rm loop}}{c_{\rm tree}} = \dfrac{L_9 + L_{10}}{L_9 - L_{10}} \simeq \dfrac{6.9 - 5.5}{6.9 + 5.5} \sim 0.1$

Smaller by a "loop" ~ 1/Nc ~ 1/3!

...parenthesis closed

Choosing the basis for dim-6 operators

As in the SILH, we will separate "tree" vs "loop" operators:

$$\mathcal{L}_6 = \sum_{i_1} g_*^2 \frac{c_{i_1}}{\Lambda^2} \mathcal{O}_{i_1} + \sum_{i_2} \frac{c_{i_2}}{\Lambda^2} \mathcal{O}_{i_2} + \sum_{i_3} \frac{\kappa_{i_3}}{\Lambda^2} \mathcal{O}_{i_3}$$

g_* = generic coupling

$$\kappa_{i_3} \equiv \frac{g_*^2}{16\pi^2} c_{i_3}$$

Our basis:

operators made of bosons

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = g\epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = g_s f_{abc} G^{a\,\nu}_{\mu} G^b_{\nu\rho} G^{c\,\rho\mu}$$

+ 6 CP-odd by $F \to \widetilde{F}$

operators made of fermions

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$ $\mathcal{O}_R^{ud} = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \, \widetilde{H} g' B_{\mu\nu}$ $\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \, \sigma^a \widetilde{H} g W_{\mu\nu}^a$ $\mathcal{O}_{DG}^u = y_u \bar{Q}_L \sigma^{\mu\nu} T^a u_R \, \widetilde{H} g_s G_{\mu\nu}^a$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \, H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \, \sigma^a H g W_{\mu\nu}^a$ $\mathcal{O}_{DG}^d = y_d \bar{Q}_L \sigma^{\mu\nu} T^a d_R \, H g_s G_{\mu\nu}^a$	$\mathcal{O}_{DB}^l = y_l \bar{L}_L \sigma^{\mu\nu} e_R \, H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^e = y_l \bar{L}_L \sigma^{\mu\nu} e_R \, \sigma^a H g W_{\mu\nu}^a$

+ 4-fermion operators

Some redundancy:

$$
\begin{aligned}
c_W \mathcal{O}_W \quad &\leftrightarrow \quad c_W \frac{g^2}{g_*^2} \left[-\frac{3}{2} \mathcal{O}_H + 2\mathcal{O}_6 + \frac{1}{2} \mathcal{O}_y + \frac{1}{4} \sum_f \mathcal{O}_L^{(3)\,f} \right] , \\
c_B \mathcal{O}_B \quad &\leftrightarrow \quad c_B \frac{g'^2}{g_*^2} \left[-\frac{1}{2} \mathcal{O}_T + \frac{1}{2} \sum_f \left(Y_L^f \mathcal{O}_L^f + Y_R^f \mathcal{O}_R^f \right) \right] ,
\end{aligned}
$$

Implication on Higgs physics

(working at the linear level: $\sim 1/\Lambda^2$)

Implication on Higgs physics:

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H \rvert^2)^2$ $\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$ $\mathcal{O}_6 = \lambda \lvert H \rvert^6$
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$ $\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$ $\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$
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$\mathcal{O}_{y_u} = y_u \lvert H \rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H \rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l \lvert H \rvert^2 \bar{L}_L H e_R$
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change of an overall scale

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l |H|^2 \bar{L}_L H e_R$
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$h \to \gamma\gamma$

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$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$ $\mathcal{O}_R^{ud} = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$

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h→γγ

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h→γγ

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h→ff

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open doors to BSM Higgs physics?

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h→γγ

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change of an overall scale

physics?

h→γγ

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Interesting for processes such as h→Zγ & h→Wff,Zff

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change of an overall scale

open doors to BSM Higgs physics?

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GG→h

h→ff

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Some groups claim yes:

B.Grinstein, C.W. Murphy and D.Pirtskhalava 13

Global fit in other bases don't show big constraints

a_{WB}	a_h	a^s_{hl}	a^t_{hl}	a^s_{hq}	a^t_{hq}	a_{hu}	a_{hd}	a_{he}	a_W
4.6 ± 7.5	$0.0 \pm 26.$	2.8 ± 6.7	$0.9 \pm 21.$	-0.9 ± 2.2	$0.9 \pm 21.$	-3.6 ± 8.9	1.7 ± 4.4	$5.6 \pm 13.$	$-3.9 \pm 32.$

TABLE I: Best fit values and 1σ errors, in units of TeV^{-2}, of the coefficients of dimension 6 operators in the HS basis when the coefficient of four-fermion operators are assumed to vanish.

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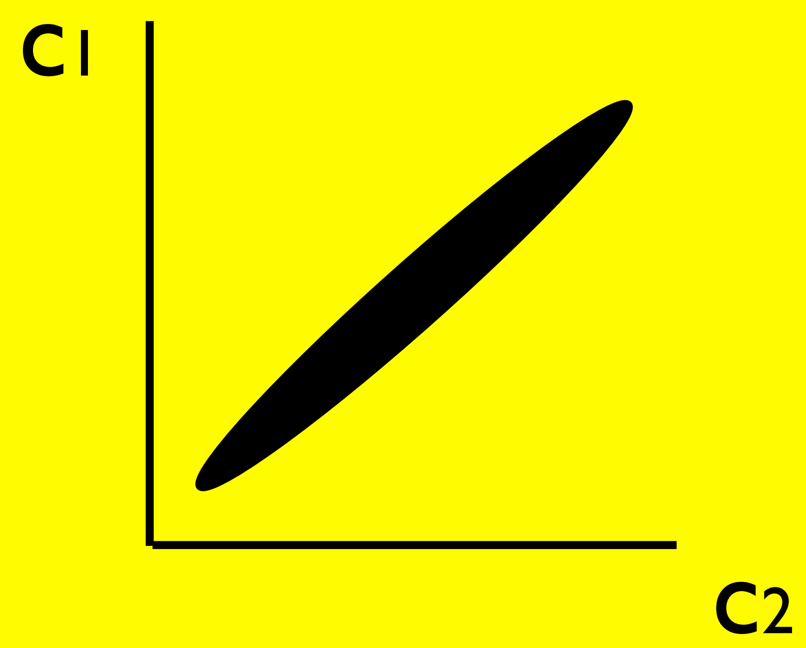
dimension 6 operato ... on operators are

Misled by the basis:



large range for $c_{1,2}$,
but strong correlation

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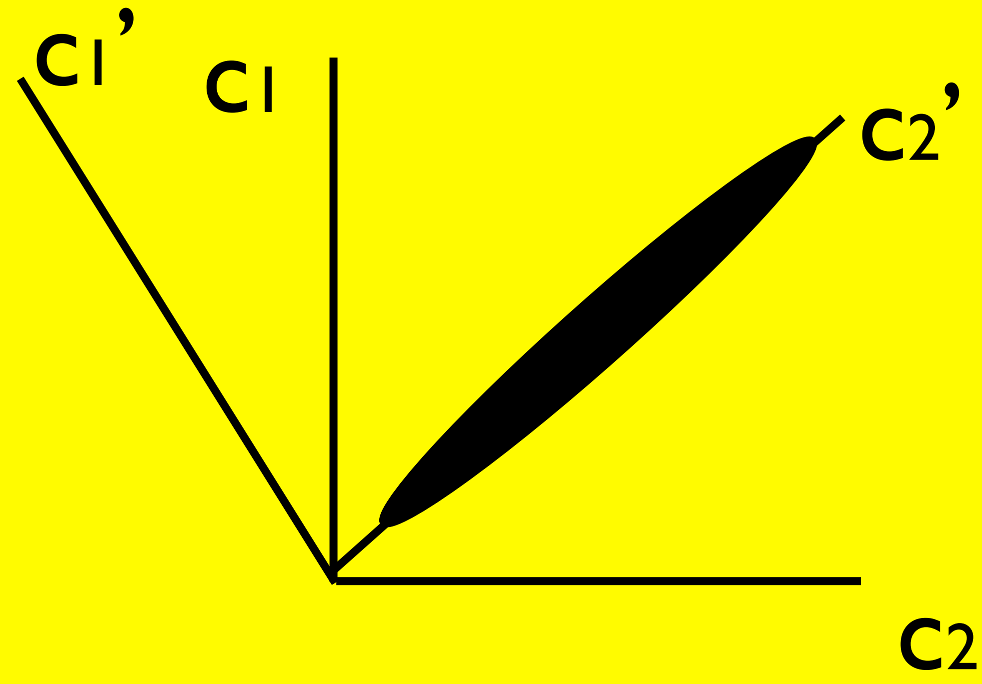

large range allowed for c_2'
but not for c_1'

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Global fit in other bases don't show big constraints

a_{WB}	a_h	a^s_{hl}	a^t_{hl}	a^s_{hq}	a^t_{hq}	a_{hu}	a_{hd}	a_{he}	a_W
4.6 ± 7.5	$0.0 \pm 26.$	2.8 ± 6.7	$0.9 \pm 21.$	-0.9 ± 2.2	$0.9 \pm 21.$	-3.6 ± 8.9	1.7 ± 4.4	$5.6 \pm 13.$	$-3.9 \pm 32.$

TABLE I: Best fit values and 1σ errors, in units of TeV^{-2}, of the coefficients of dimension 6 operators in the HS basis when the coefficient of four-fermion operators are assumed to vanish.

Some other groups claim an overconstrained set:

T.Corbett, O.J.P. Eboli, J. Gonzalez–Fraile, M.C.Gonzalez–Garcia 12

4 operators involving Higgs and gauge bosons claimed to be unconstrained from fermion physics, while we have **6**!

Some groups claim yes:

B.Grinstein, C.W. Murphy and D.Pirtskhalava 13

Global fit in other bases don't show big constraints

a_{WB}	a_h	a^s_{hl}	a^t_{hl}	a^s_{hq}	a^t_{hq}	a_{hu}	a_{hd}	a_{he}	a_W
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4 operators involving Higgs and gauge bosons

One operator moved to operators made of fermions and another thought to be constrained by the S-parameter...

but fermion physics alone cannot constrain these two!

Towards the ultimate SM fit

Put bound on coefficients model-independently
(allowing to vary the others)

↳ previous analysis always turning one by one the coefficients

Step by a step process instead of a global fit

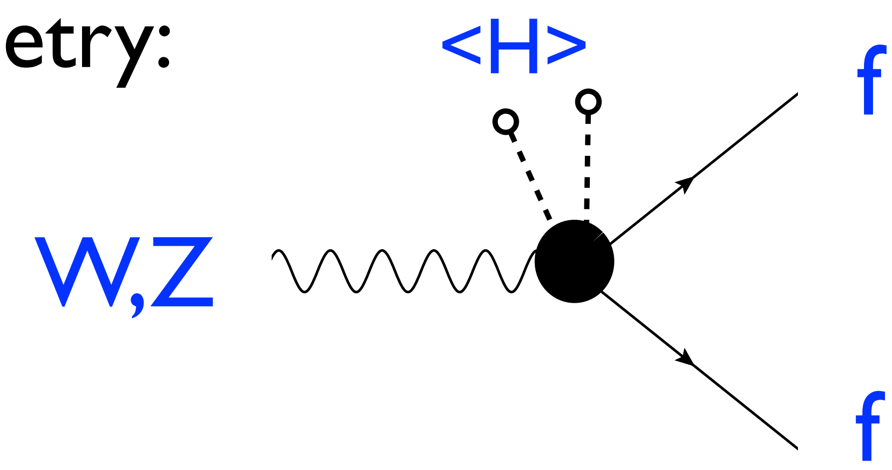
<u>Assumptions:</u>

- Lepton & baryon number
- Flavor symmetries (MFV)
- Neglect $\mathcal{O}_{3W}$ (can be relaxed without great impact)

Input: α, M_Z, G_F

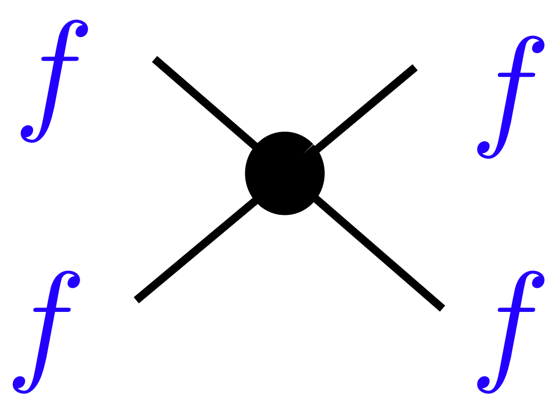
Mainly two types of SM deformations:

1) Breaking of EW symmetry:



$$\sim \frac{\mathbf{g_H^2 v^2}}{\mathbf{\Lambda^2}}$$

2) New interactions growing with the energy:



$$\sim \frac{\mathbf{E^2}}{\mathbf{\Lambda^2}}$$

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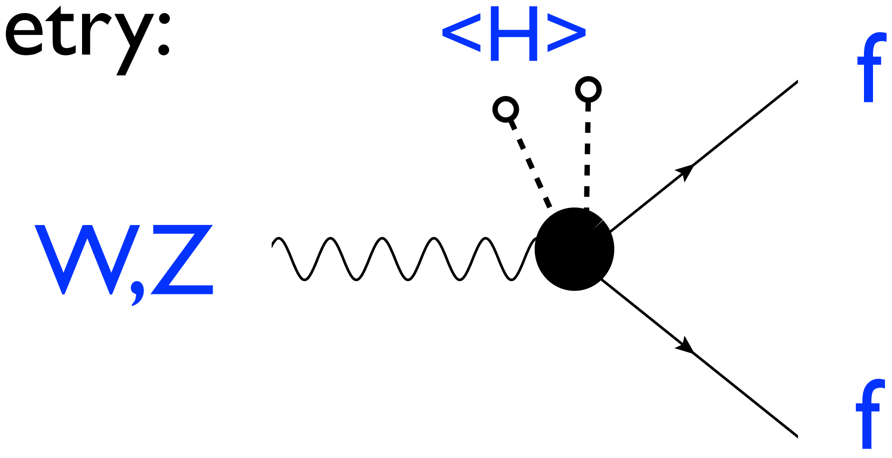
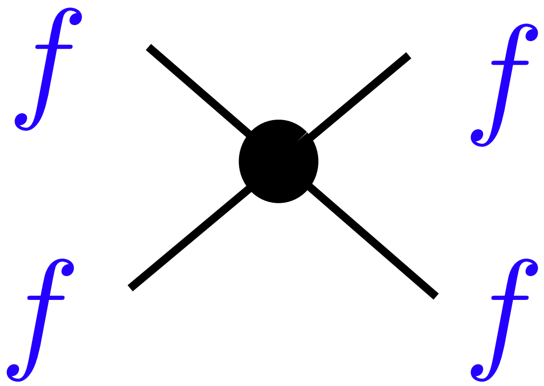


$$\sim \frac{\mathbf{g_H^2 v^2}}{\mathbf{\Lambda^2}}$$

LEP key-player

2) New interactions growing with the energy:



$$\sim \frac{\mathbf{E^2}}{\mathbf{\Lambda^2}}$$

LHC key-player

Intensity frontier vs **high-energy frontier**

1) Lepton-widths of the Z & M_W :

LEP1: $\Gamma(Z \to l_L l_L)$

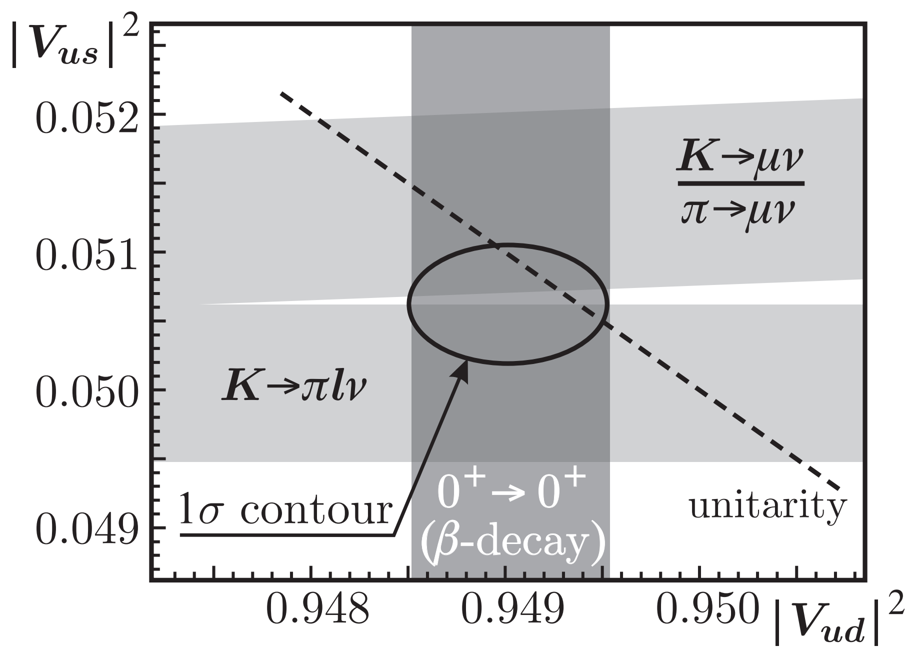
$$\Gamma(Z \to l_R l_R)$$

$$\Gamma(Z \to \nu\nu) \equiv \Gamma_Z - \Gamma_{vis}$$

Tevatron: M_W

$\hookrightarrow$ constrain deformation on Z/W propagators and Zll vertices at per-mille

2) Kaon decays (KLOE) + β-decay measurements has allowed to put a very stringent bound on quark-lepton universality of the W interactions

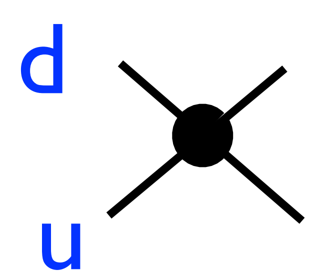


$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2 = 0.9999(6)$$

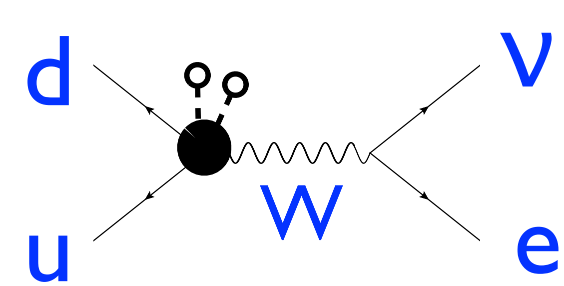
assuming unitarity

$$\frac{G_F|_{quarks}}{G_F|_{leptons}} - 1 < 10^{-3}$$

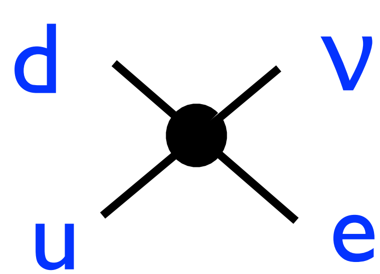
Deformation involved:



+

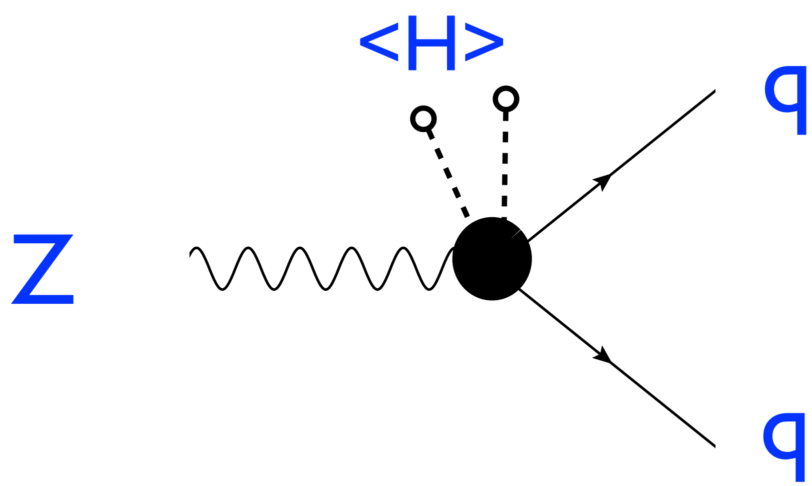


+ LHC bounds on udlν

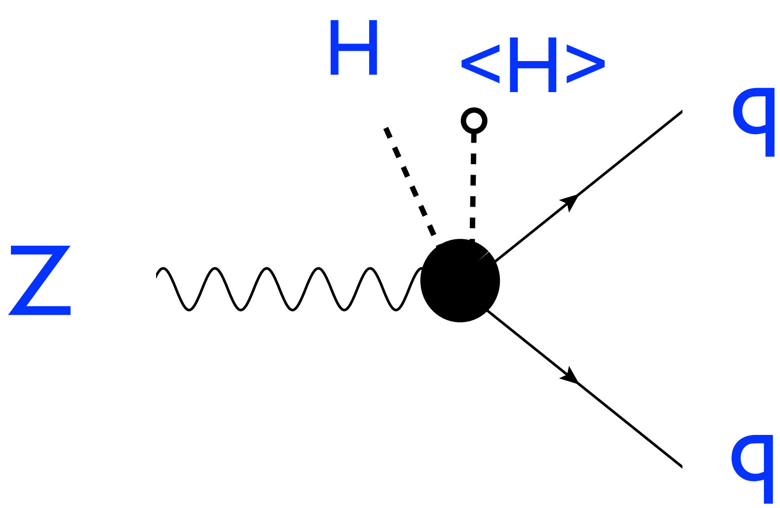


constrain deformations on the Wud vertex at per-mille

3) Z decay-widths into quarks:



difficult to disentangle the different contributions, but same combination of coefficients enter in the H decay:



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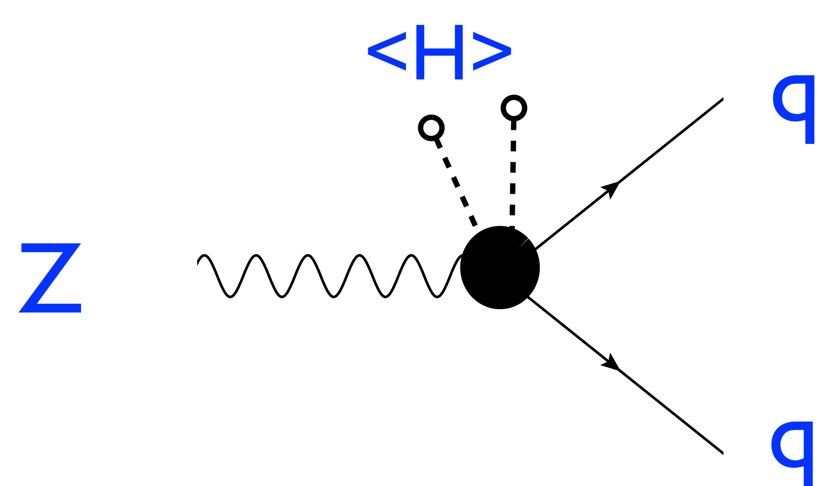


4) Gauge boson 3-vertices:

LEPII: $e^+e^- \to WW$

constrain deformation
on the ZWW vertex at per-cent

... LHC becoming also competitive

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$

$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$

$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^a_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{3W} = g\epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

$$\mathcal{O}_{3G} = g_s f_{abc} G^{a\,\nu}_{\mu} G^b_{\nu\rho} G^{c\,\rho\mu}$$

$e^+e^- \to WW$

only two combinations of the 4

lepton physics & M_W

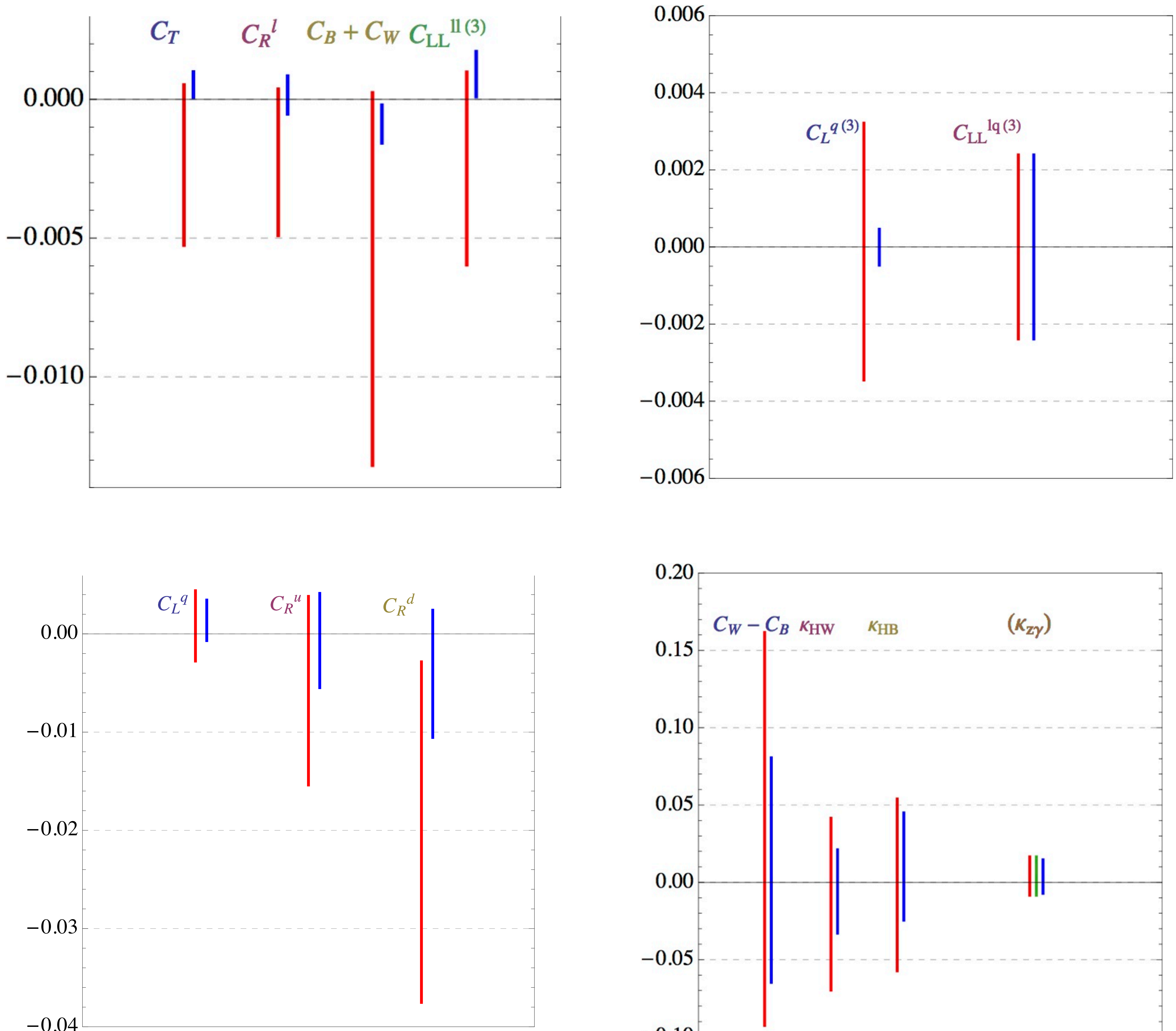
$c_W + c_B$

β-decay, K-physics & Z-physics

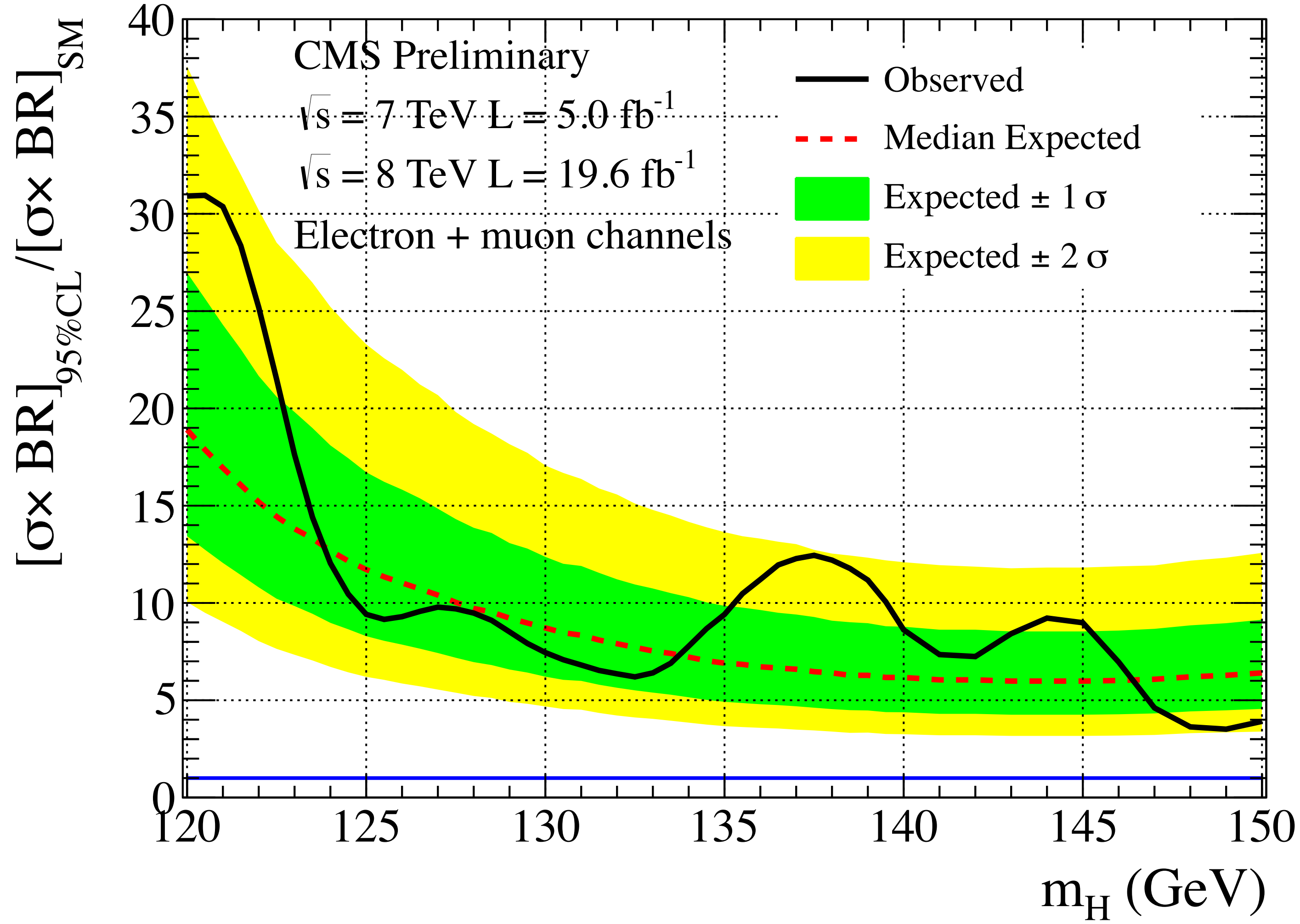
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^l_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$		redundant
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$		
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$		

per-mille bounds

per-cent bounds

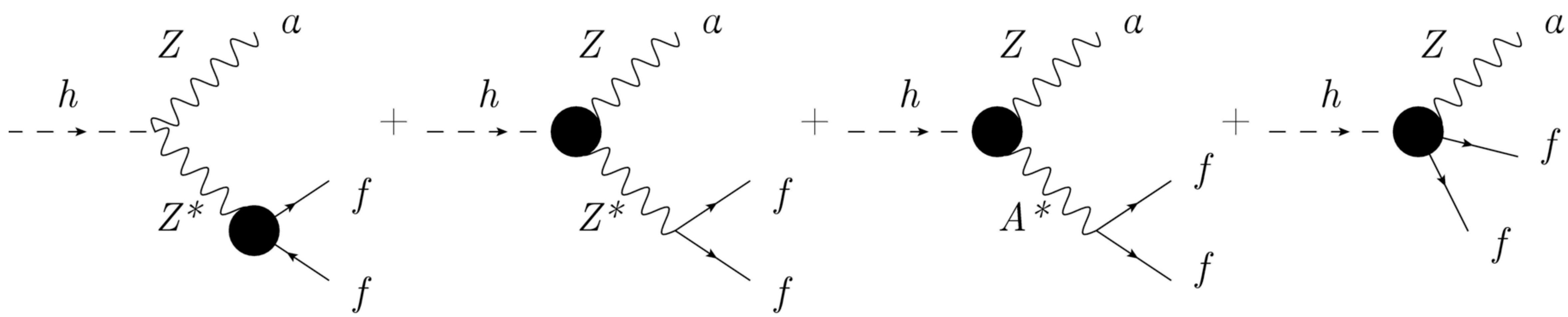


No bound from EWPT on h→Zγ (only from direct searches)



... last hope for O(1) deviations?

Predictions on h→Wff,Zff:



(assuming m_f=0 and CP-conservation)

$$\mathcal{M}(h \to VJ) = v^{-1} \epsilon_1^{*\mu} J_2^{\nu} \left[A^V m_H^2 \eta_{\mu\nu} + B^V q_{2\mu} q_{1\nu} \right]$$

$$A^V = \frac{a_1^V + a_2^V q_2^2}{q_2^2 - M_V^2} + \frac{a_3^V}{q_2^2} \quad , \quad B^V = \frac{b_1^V}{q_2^2 - M_V^2} + \frac{b_2^V}{q_2^2}$$

5 (for the Z) + 3 (for the W) (per fermion type)

parameters "ready" to be measured

Imposing bounds at per-mille:

5+3 → 2

Imposing bounds at per-cent:

2 → 0

$$
\begin{aligned}
a_1^Z &\simeq a_{1,SM}^Z\left(1 + 2c_W(1-\tan^2\theta_W) + \kappa_{HW}(1+\tan^2\theta_W)\frac{m_H^2}{M_Z^2}\right)\\
a_2^Z &\simeq 0\\
a_3^Z &\simeq 0\\
b_1^Z &\simeq -4\, g_Z^f\, \kappa_{HW}(1+\tan^2\theta_W)\\
b_2^Z &\simeq 0\\
a_1^W &\simeq a_{1,SM}^W\left(1 + 2\, c_W + \kappa_{HW}\,\frac{m_H^2}{M_W^2}\right)\\
a_2^W &\simeq 0\\
b_1^W &\simeq -4\, g_W^{ff'}\, \kappa_{HW}
\end{aligned}
$$

$$
\begin{aligned}
c_W &\in [-0.05,\ 0.08]\\
\kappa_{HW} &\in [-0.06,\ 0.04]
\end{aligned}
$$

Going beyond tree-level...

One-loop operator mixing

Interesting situations could arise:

Tree-level **One-loop induced**

$\mathcal{O}_{tree}$ $\mathcal{O}_{loop}$

RG evolution

$$c_{loop}(m_W) \sim \frac{c_{tree}}{16\pi^2} \log \frac{\Lambda}{m_W}$$

dominant effect from running!!

Jenkins,Grojean,Manohar,Trott 13 (JGMT) claimed to be the case for h→γγ:

Example given:

SILH case

When the new physics can be characterized by a single scale M_ρ and a coupling g_ρ, simple physical arguments lead to an interesting power counting for the Wilson coefficients of our operator basis [13]. For coefficients $\bar{c}_i \equiv c_i v^2/\Lambda^2$, we find the power counting

$$\bar{c}_B, \bar{c}_W, \bar{c}_{WB}, \bar{c}_{DB}, \bar{c}_{DW} \sim O\left(\frac{v^2}{M_\rho^2}\right), \tag{4.6}$$

$$\bar{c}_G, \bar{c}_{\gamma\gamma} = \bar{c}_W + \bar{c}_B - \bar{c}_{WB}, \bar{c}_{\gamma Z} = \frac{\bar{c}_W}{\tan\theta_W} - \bar{c}_B \tan\theta_W - \frac{\bar{c}_{WB}}{\tan 2\theta_W} \sim O\left(\frac{g_\rho^2}{16\pi^2}\frac{v^2}{M_\rho^2}\right), \tag{4.7}$$

where the last row follows from the fact that the Higgs boson cannot decay to $\gamma\gamma$, $Z\gamma$ and gg at tree-level in any theory that satisfies the minimal coupling assumption. Note that, when a discrete symmetry is present, there can be further suppression of the operators in the first row, as is the case in R parity conserving SUSY scenarios where there is no tree-level contribution to the S parameter. Also, if the Higgs boson emerges as a pseudo Nambu-Goldstone boson of the new physics sector, the Higgs decays to $\gamma\gamma$ and gg can only be obtained from a loop that involves couplings which break the global shift symmetry of the pseudo Nambu-Goldstone boson. In that case, we obtain a further suppression of g_{SM}^2/g_ρ^2 [13], so

$$\bar{c}_G, \bar{c}_{\gamma\gamma} \sim O\left(\frac{g_{SM}^2}{g_\rho^2}\frac{g_\rho^2}{16\pi^2}\frac{v^2}{M_\rho^2}\right). \tag{4.8}$$

Here, g_{SM} denotes a combination of the SM couplings $g_{1,2}, y_i$. The simple power counting above demonstrates the importance of the RGE mixing between the operators we are considering:

$$c_{\gamma\gamma}(\mu) \sim c_{\gamma\gamma}(\Lambda) + \frac{g_{SM}^2}{16\pi^2}\log\left(\frac{\Lambda}{\mu}\right) c_i(\Lambda), \tag{4.9}$$

and parametrically the ratio of the RGE contribution over the new physics contribution to $c_{\gamma\gamma}$ scales like $(g_{SM}^2/g_\rho^2)\log(\Lambda/\mu)$ in the general case and is further enhanced to $\log(\Lambda/\mu)$

We found that this is not the case
Another example of: proper basis, simple solution

Elias-Miro,Espinosa,Masso,AP 13

Our basis:

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right)D^\nu W^a_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$

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JGMT basis:

$$\mathcal{O}_{WB} = gg'(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}_{WW} = g^2|H|^2 W^a_{\mu\nu}W^{a\mu\nu}$$

operators are a mixture of "tree-level" and "loop" operators of our basis

Relation between both:

$$\mathcal{O}_B = \mathcal{O}_{HB} + \frac{1}{4}\mathcal{O}_{WB} + \frac{1}{4}\mathcal{O}_{BB} \ ,$$

$$\mathcal{O}_W = \mathcal{O}_{HW} + \frac{1}{4}\mathcal{O}_{WW} + \frac{1}{4}\mathcal{O}_{WB}$$

only relevant for hγγ

no mixing!

In our basis:

$$\frac{d}{d\log\mu}\begin{pmatrix} \boxed{\kappa_{BB}} \\ \kappa_{HW} \\ \kappa_{HB} \\ c_W \\ c_B \end{pmatrix} = \begin{pmatrix} \Gamma & 0_{3\times 2} \\ Y & \hat{X} \end{pmatrix} \begin{pmatrix} \kappa_{BB} \\ \kappa_{HW} \\ \kappa_{HB} \\ c_W \\ c_B \end{pmatrix}$$

calculated by JGMT

In JGMT basis:

needed to be calculated to know the full answer!

$$\frac{d}{d\log\mu}\begin{pmatrix} \boxed{\begin{matrix} c'_{BB} \\ c'_{WW} \\ c'_{WB} \end{matrix}} \\ c'_{HW} \\ c'_{HB} \end{pmatrix} = \begin{pmatrix} \hat{\Gamma} & Y' \\ 0_{2\times 3} & \hat{X} \end{pmatrix} \begin{pmatrix} c'_{BB} \\ c'_{WW} \\ c'_{WB} \\ c'_{HW} \\ c'_{HB} \end{pmatrix}$$

An even better basis:

Our basis:

$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overset{\leftrightarrow}{D^\mu} H\right)\partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overset{\leftrightarrow}{D^\mu} H\right)D^\nu W^a_{\mu\nu}$$

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$$\frac{d}{d\log\mu}\begin{pmatrix}\hat{\kappa}_{BB}\\ \hat{\kappa}_{WW}\\ \hat{\kappa}_{WB}\\ \hat{c}_{W}\\ \hat{c}_{B}\end{pmatrix} = \begin{pmatrix}\hat{\Gamma} & 0_{3\times 2}\\ 0_{2\times 3} & \hat{X}\end{pmatrix}\begin{pmatrix}\hat{\kappa}_{BB}\\ \hat{\kappa}_{WW}\\ \hat{\kappa}_{WB}\\ \hat{c}_{W}\\ \hat{c}_{B}\end{pmatrix}$$

One-loop operator mixing

Interesting situations could arise:

Tree-level | **One-loop induced**

$\mathcal{O}_{tree}$ $\qquad\qquad$ $\mathcal{O}_{loop}$

RG evolution

$$c_{loop}(m_W) \sim \frac{c_{tree}}{16\pi^2} \log \frac{\Lambda}{m_W}$$

Seems not to happen in any SM process!

dominat effect from running!!

Inspiration from QCD: Chiral lagrangian for pions:

Ordinary basis:

$$\mathcal{L}_\chi = \frac{f^2}{4}\langle D^\mu U D_\mu U\rangle + \cdots$$
$$- \; iL_9\,\langle F_R^{\mu\nu} D_\mu U D_\nu U^\dagger + F_L^{\mu\nu} D_\mu U^\dagger D_\nu U\rangle \; + \; L_{10}\,\langle U^\dagger F_R^{\mu\nu} U F_{L\mu\nu}\rangle$$

In a "SILH basis":

"tree": $\langle (U^\dagger \overleftrightarrow{D}_\nu U) D_\mu F_L^{\mu\nu} + (U \overleftrightarrow{D}_\nu U^\dagger) D_\mu F_R^{\mu\nu}\rangle$

"loop"

Experiments say: $\dfrac{c_{\rm loop}}{c_{\rm tree}} = \dfrac{L_9 + L_{10}}{L_9 - L_{10}} \simeq \dfrac{6.9 - 5.5}{6.9 + 5.5} \sim 0.1$

Smaller by a "loop" ~ 1/Nc ~ 1/3!

Not renormalized by loop of pions: $\gamma_{\rm loop} \propto \gamma_9 + \gamma_{10} = \dfrac{1}{64\pi^2} - \dfrac{1}{64\pi^2} = 0$

Final answer:

hγγ: $$\kappa_{\gamma\gamma}(m_h) = \kappa_{\gamma\gamma}(\Lambda) - \gamma_{\gamma\gamma} \log \frac{\Lambda}{m_h}$$

$$16\pi^2\gamma_{\gamma\gamma} = \left[6y_t^2 - \frac{3}{2}(3g^2 + g'^2) + 12\lambda\right] \kappa_{BB} + \left[\frac{3}{2}g^2 - 2\lambda\right] (\kappa_{HW} + \kappa_{HB}) \ .$$

dominant if $\kappa_{\gamma\gamma}$ is one-loop suppressed but not $\kappa_{HW}+\kappa_{HB}$

e.g. **H as PGB:**

H→H+c means $\kappa_{BB}=0$ but $\kappa_{HW}+\kappa_{HB}\neq 0$

Conclusions

- Dim-6 operators give a model-independent way to search for open doors to leave the SM
- Bases separating "tree" & "loop" operators can be useful for the analysis
- Implications on Higgs decays after an *educated* fit to the SM:

  Wide open door: $h\to Z\gamma$

  Open doors: $h\to\gamma\gamma$, $GG\to h$, $h\to ff$

  Almost closed doors: $h\to Zff, Wff$

- At the one-loop order, no operator mixing from "tree" to "loop" operators