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BSM Primary Effects

Rick Sandeepan Gupta (IFAE, Barcelona)

in collaboration with A. Pomarol and F. Riva (arxiv: 1405.0181)

& J. Elias-Miro, C. Grojean, D Marzocca (arxiv: 1312.2928)

Plan of Talk

- I. BSM Primary effects

with A. Pomarol and F. Riva (arxiv: 1405.0181)

- II. RG-induced constraints on BSM Primaries

with J. Elias-Miro, C. Grojean, D Marzocca (arxiv: 1312.2928)

SM as an EFT

- The absence at the LHC of new states beyond the SM (BSM) suggests that the new-physics scale must be heavier than the electroweak (EW) scale and we can write:

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

- No of measurements >No of couplings/parameters at a fixed order => Predictions relating different measurements. Predictions from $\mathcal{L}_4$ (the SM lagrangian) well known and tested:

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$$m_W = m_Z c_{\theta_W} \qquad Y_f = \sqrt{2} m_f / v \quad \text{etc}$$

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Main Goal: What are the predictions from $\mathcal{L}_6$? For eg. which (non SM) Higgs interactions are already constrained by EWPT and TGC data and which are still independent ?

BSM Primaries

- 18 quantities **best** constrain the important deformations in $\mathcal{L}_6$
- We call these **BSM Primaries.** (see also Pomarol & Riva, 2013, Elias-Miro, Espinosa, Masso & Pomarol, 2013)

Higgs (8) Physics	$h \to \gamma\gamma,\ h \to \gamma Z,\ h \to gg$ $h \to VV, h \to ff, pp \to h^* \to hh$	$hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $hW^{+\mu}W^-_\mu,\ h\bar{f}f,\ h^3$
EWPT (7) Data	$Z \to ff$ (2 can be traded for S,T)	$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$
TGC (3) Data	$ee \to WW$	$g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu}\right)$ $\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^+_\mu W^-_\nu$ $\lambda_\gamma s_{\theta_W} \hat{A}^{\mu\nu} \hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}$

(18 is not considering four fermions and MFV suppressed and CPV deformations)

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Correlated deformations

$$hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$$
$$hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$$

$$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$

$$g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^{-}_{\mu\nu} - W^{-\nu}\hat{W}^{+}_{\mu\nu}\right)$$
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Primary Deformations

Correlated deformations

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$$\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^{+}_{\mu} W^{-}_{\nu}$$
$$\lambda_\gamma s_{\theta_W} \hat{A}^{\mu\nu} \hat{W}^{-\rho}_{\mu} \hat{W}^{+}_{\rho\nu}$$

Deformations correlated at dim-6 level →

$$h^2\bar{f}f\quad hZ_{\mu\nu}Z^{\mu\nu}$$
$$hZ_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}\quad h^4$$
$$W^{+\mu}\bar{u}_L\gamma_\mu d_L$$
$$Z^\mu Z^\nu W^{-}_{\mu} W^{+}_{\nu}$$
$$h^3\bar{f}f\quad W^{-\mu}W^{+\nu}W^{-}_{\mu}W^{+}_{\nu}$$
$$hW^{+}_{\mu\nu}W^{-\mu\nu}\ \ldots\ldots$$

Primary Deformations

Correlated Deformations

+ BSM Primary directions

- Cannot generate only BSM primary deformation and no other deformation :

BSM Primary direction

$$\Delta\mathcal{L}^h_{Z\gamma} = 4\kappa_{Z\gamma}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W} A_{\mu\nu}Z^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}} Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right].$$

BSM Primary

Correlated deformations

- In other words just the BSM primary itself is not a dim-6 operator. There will be other terms from the operator.

- BSM primary directions must be mutually orthogonal. For eg. the above terms must not contribute to other 17 primaries like $h \to \gamma\gamma$.

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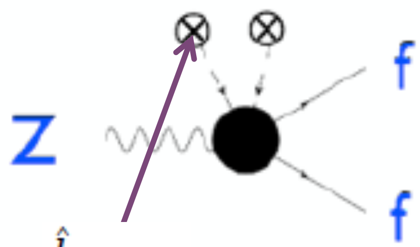
- We will take a bottom up approach to construct the dim-6 Lagrangian by building up these BSM Primary directions (operators in disguise) corresponding to each BSM Primary.

- The dim-6 Lagrangian would be the sum of all these Primary directions.

+ Z-pole Primaries

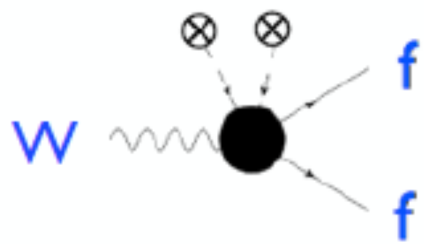
- *Zff* coupling deformations more general (beyond universal theories) and physical than S and T parameters.



$\hat{h} = v$

$H^\dagger \overleftrightarrow{D}_\mu H \bar{f}\gamma^\mu f$

$H^\dagger \sigma^a \overleftrightarrow{D}_\mu H \bar{f}\sigma^a\gamma^\mu f$

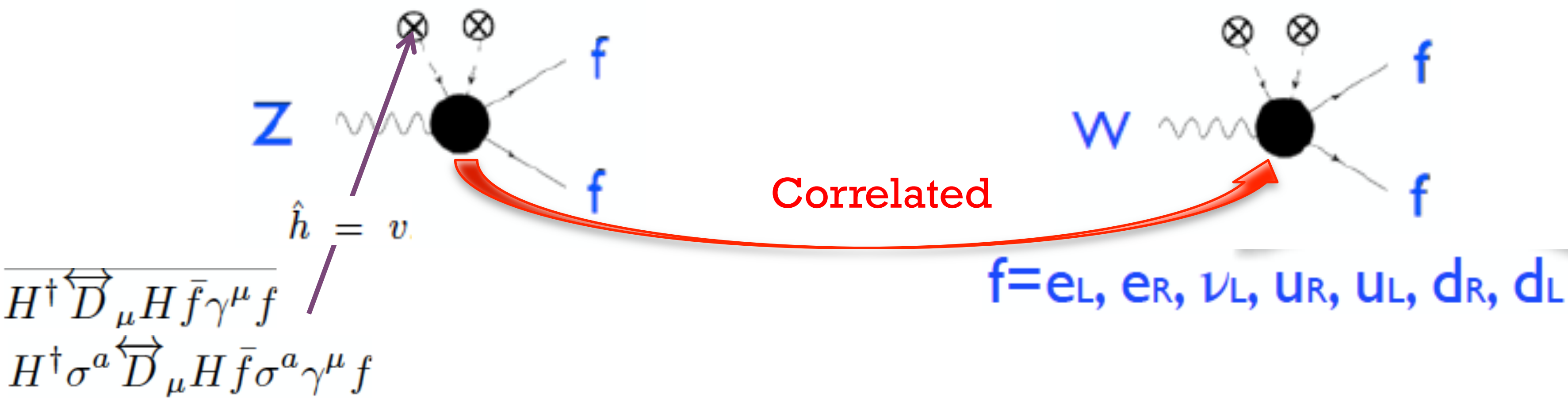


$f = e_L, e_R, \nu_L, u_R, u_L, d_R, d_L$

- 3 dim-6 structures for 4 possible W/Z-couplings to leptons *W*-couplings related to *Z*-couplings at dim-6 level

+ *Z*-pole Primaries

- *Zff* coupling deformations more general (beyond universal theories) and physical than *S* and *T* parameters.



- 3 dim-6 structures for 4 possible *W/Z*-couplings to leptons ***W*-couplings related to *Z*-couplings at dim-6 level**

Deviation from gauge coupling universality

- W/Z couplings can be *individually* altered by operators having product of currents:

Leptons

$$\Delta\mathcal{L}^V_{ee} = \delta g^Z_{eR}\frac{\hat{h}^2}{v^2}Z^\mu\bar{e}_R\gamma_\mu e_R \qquad (15)$$
$$+\,\delta g^Z_{eL}\frac{\hat{h}^2}{v^2}\left[Z^\mu\bar{e}_L\gamma_\mu e_L - \frac{c_{\theta W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right]$$
$$+\,\delta g^Z_{\nu L}\frac{\hat{h}^2}{v^2}\left[Z^\mu\bar{\nu}_L\gamma_\mu\nu_L + \frac{c_{\theta W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right]$$

Primary

Correlated interaction

Quarks

$$\Delta\mathcal{L}^V_{qq} = \delta g^Z_{uR}\frac{\hat{h}^2}{v^2}Z^\mu\bar{u}_R\gamma_\mu u_R + \delta g^Z_{dR}\frac{\hat{h}^2}{v^2}Z^\mu\bar{d}_R\gamma_\mu d_R$$
$$+\,\delta g^Z_{dL}\frac{\hat{h}^2}{v^2}\left[Z^\mu\bar{d}_L\gamma_\mu d_L - \frac{c_{\theta W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.})\right]$$
$$+\,\delta g^Z_{uL}\frac{\hat{h}^2}{v^2}\left[Z^\mu\bar{u}_L\gamma_\mu u_L + \frac{c_{\theta W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.})\right]$$

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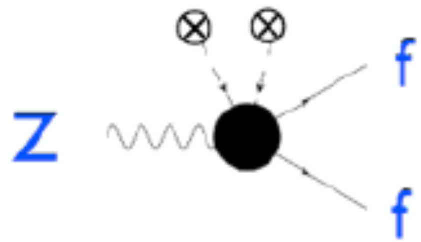
+ *S* and *T* ?

- *S* and *T* are linear combinations of above parameters:

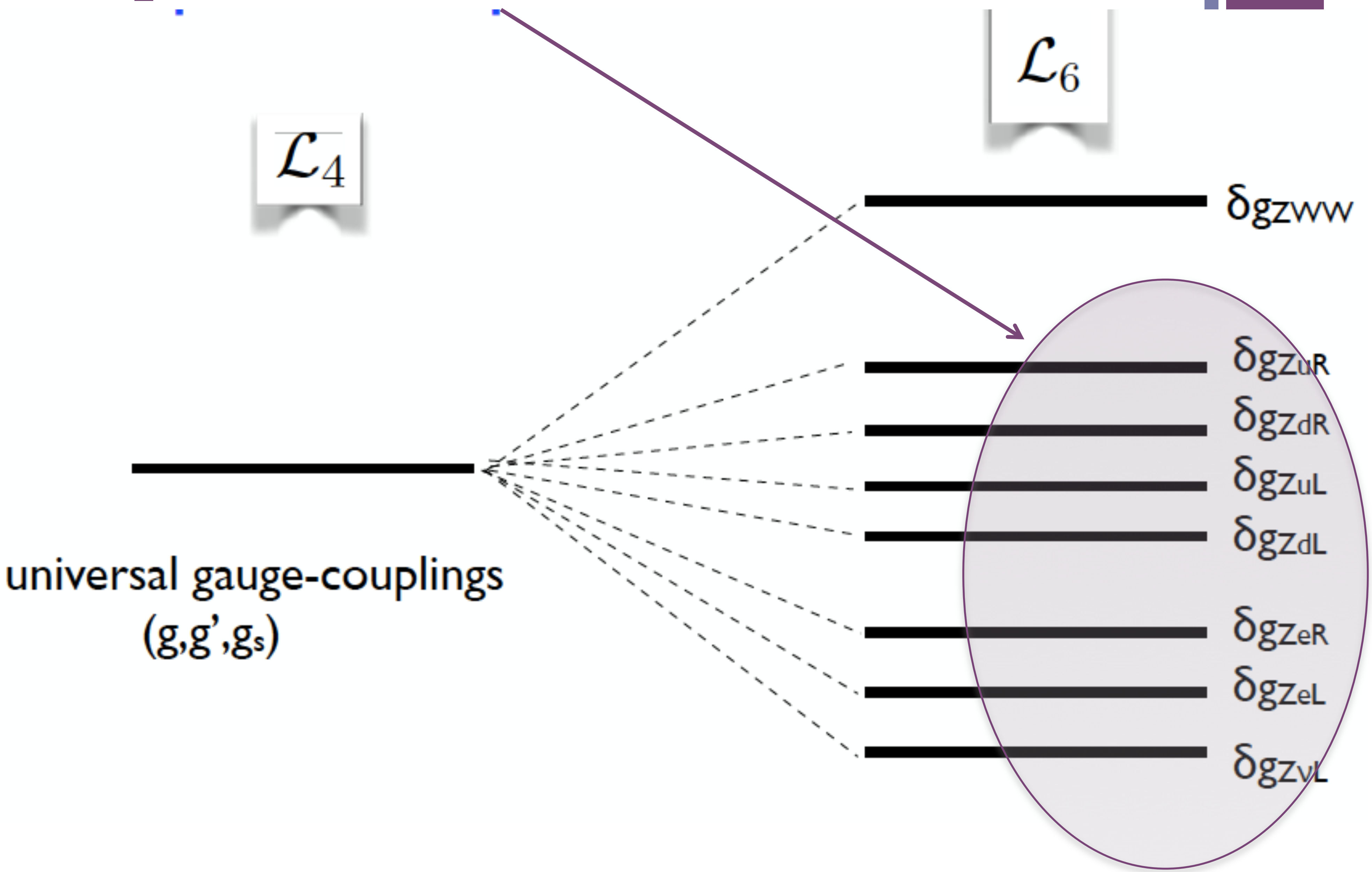
$$\Delta\mathcal{L}_{\hat{S}} = \hat{S}\,\frac{g s_{\theta_W}^2}{c_{\theta_W}^3}\frac{\hat{h}^2}{v^2}\,Z_\mu\left[J_Z^\mu - c_{\theta_W}^2 J_{em}^\mu + \frac{g}{c_{\theta_W}}\frac{\hat{h}^2}{4}Z^\mu\right]$$

$$\Delta\mathcal{L}_T = -\frac{\hat{T}}{2}\frac{\hat{h}^4}{v^4}m_Z^2 Z^\mu Z_\mu\,.$$

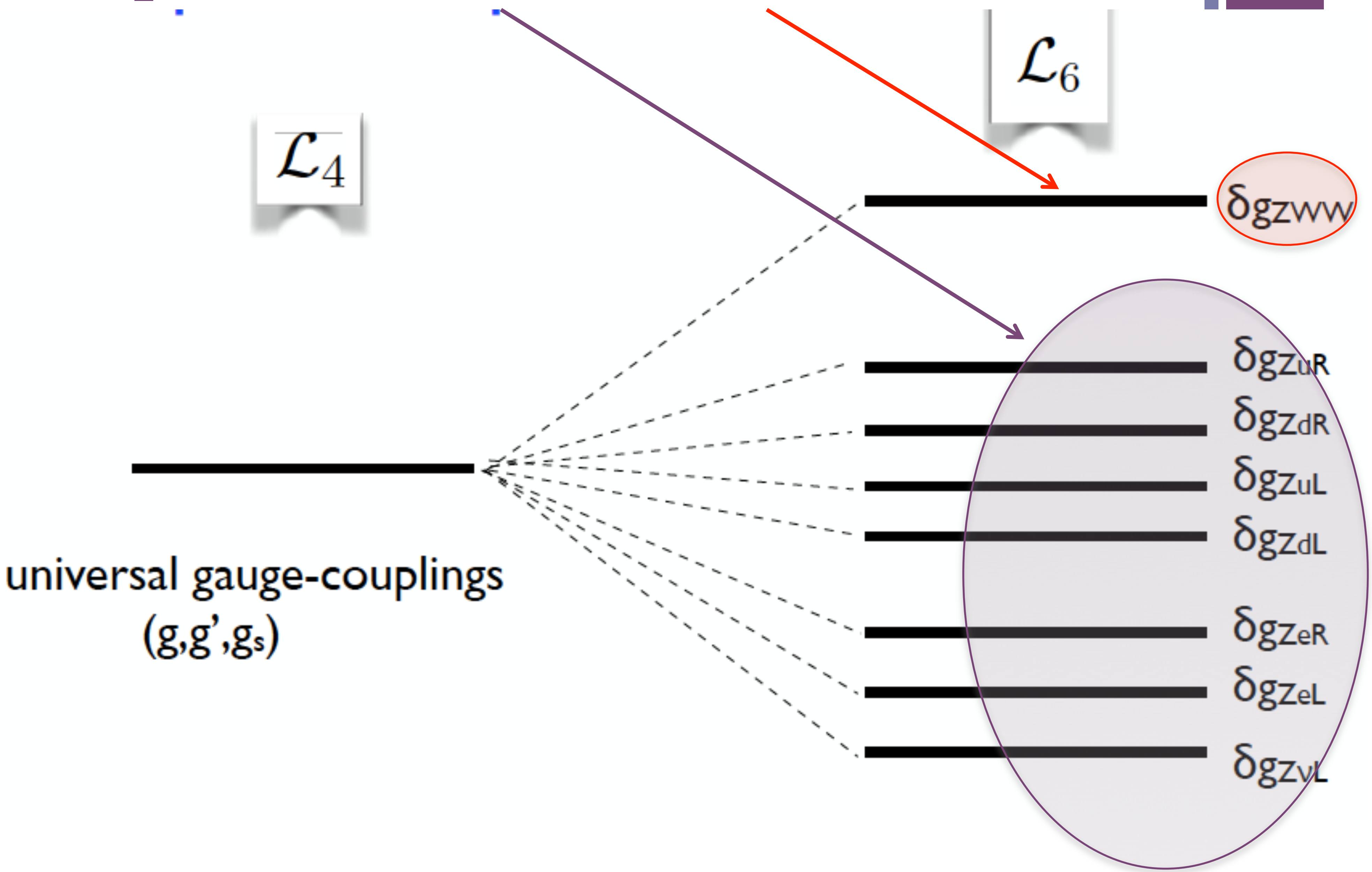
- In our parametrization we have eliminated all corrections to propagators (using EoM) so there is a **one to one correspondence between our δg_f^Z and the *Z* partial widths.**



Z-pole Primaries



Z-pole Primaries + TGC



+ Deviation from gauge coupling universality

- A shift $s^2_{\theta_W} \rightarrow s^2_{\theta_W}(1 + 2\delta g^Z_1 c^2_{\theta_W} \hat{h}^2/v^2)$ keeping e constant in the fermion –Higgs sector of SM lagrangian gives:

$$\Delta\mathcal{L}_{g_1^Z} = \delta g^Z_1 c^2_{\theta_W} \frac{\hat{h}^2}{v^2}\left[\frac{e^2\hat{h}^2}{4c^4_{\theta_W}} Z^\mu Z_\mu \right.$$
$$\left. -g(W^-_\mu J^\mu_- + \text{h.c.}) - \frac{g c_{2\theta_W}}{c^3_{\theta_W}} Z_\mu J^\mu_Z - 2e t_{\theta_W} Z_\mu J^\mu_{em}\right]$$

- For $\hat{h} = v$ this shift is just a redefinition of $s^2_{\theta_W}$.

- Opposite shift $s^2_{\theta_W} \rightarrow s^2_{\theta_W}(1 - 2\delta g^Z_1 c^2_{\theta_W})$ in only pure gauge sector gives TGC and QGCs:

$$i g \delta g^Z_1 c_{\theta_W} Z^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \quad + \text{QGCs}$$

Deviation from gauge coupling universality

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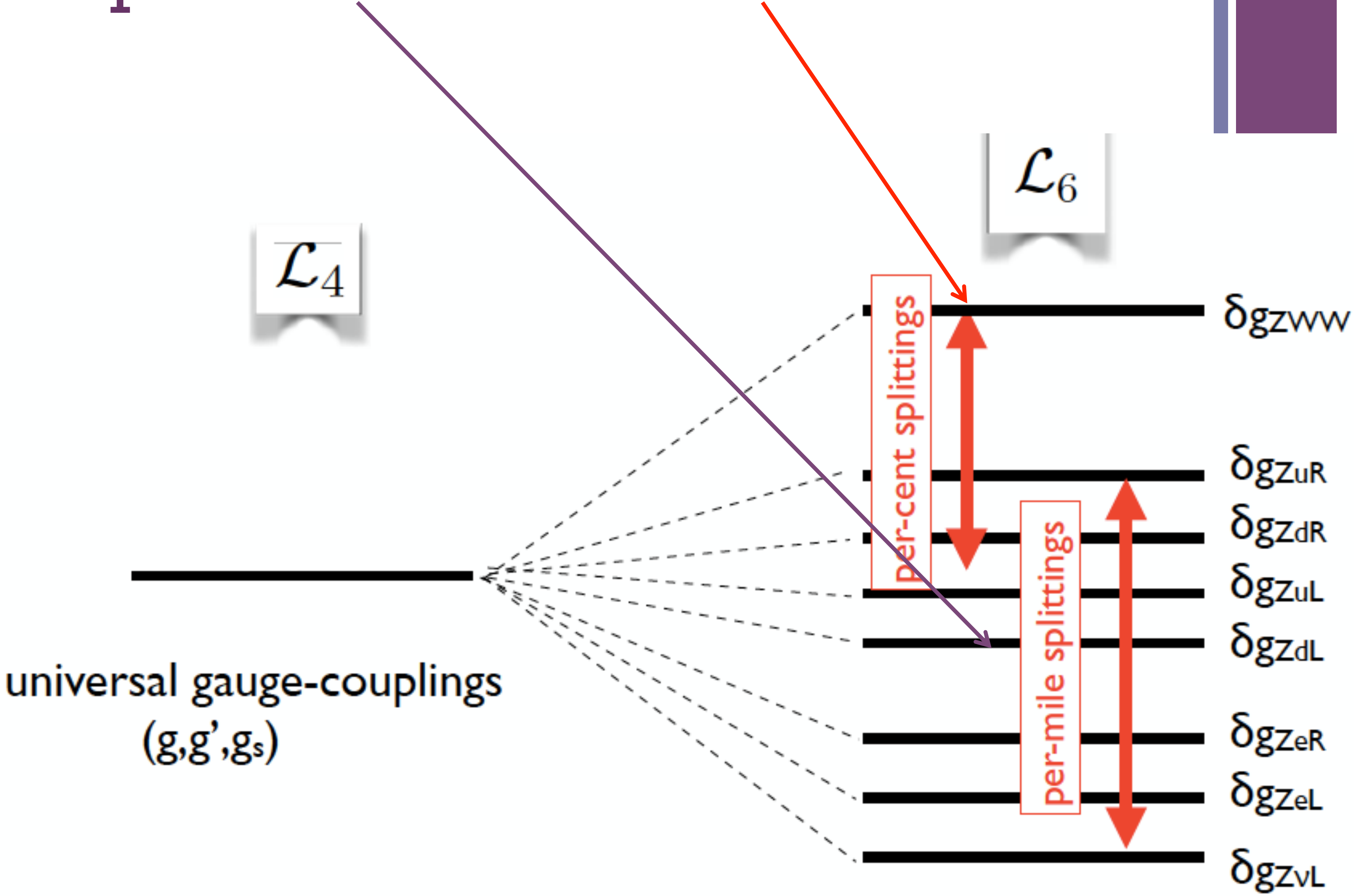
$$\delta g_1^Z = \frac{\delta g^{ZWW}}{g^{ZWW}_{SM}} = \frac{\delta g^{WWWW}}{2c^2_{\theta_W} g^{WWWW}_{SM}} = \frac{\delta g^{ZZWW}}{2g^{ZZWW}_{SM}} = \frac{\delta g^{\gamma ZWW}}{g^{\gamma ZWW}_{SM}}$$

Z-pole Primaries + TGC



Other TGC primary directions

- Notice that the deformation below contains the $\delta\kappa_\gamma$ TGC:

$$\hat{h}^2 \eta^a W^a_{\mu\nu} B^{\mu\nu} = \hat{h}^2 \left[\hat{W}^3_{\mu\nu} B^{\mu\nu} + 2igc_{\theta_W} W^-_\mu W^+_\nu (A^{\mu\nu} - t_{\theta_W} Z^{\mu\nu}) \right]$$

$$-\frac{g'\hat{h}^2}{2gv^2} W^3_{\mu\nu} B^{\mu\nu} = \frac{\Delta\mathcal{L}_{\hat{S}}}{\hat{S}} - \frac{\Delta\mathcal{L}^h_{\gamma\gamma}}{4\kappa_{\gamma\gamma}} - \frac{c_{2\theta_W} \Delta\mathcal{L}^h_{Z\gamma}}{4\kappa_{Z\gamma}} + \frac{\Delta\mathcal{L}_{\kappa_\gamma}}{\delta\kappa_\gamma}$$

- We find a combination that does not contribute to other primaries but only to $\delta\kappa_\gamma$:

$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\delta\kappa_\gamma}{v^2} \Big[ie\hat{h}^2 (A_{\mu\nu} - t_{\theta_W} Z_{\mu\nu}) W^{+\mu} W^{-\nu} + Z_\nu \partial_\mu \hat{h}^2 (t_{\theta_W} A^{\mu\nu} - t^2_{\theta_W} Z^{\mu\nu}) + \frac{(\hat{h}^2 - v^2)}{2} \times \left(t_{\theta_W} Z_{\mu\nu} A^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}} Z_{\mu\nu} Z^{\mu\nu} + W^+_{\mu\nu} W^{-\mu\nu} \right) \Big]$$

Other TGC primary directions

- Finally we also have:

$$\Delta\mathcal{L}_{\lambda_\gamma} = \frac{i\lambda_\gamma}{m_W^2}\left[(eA^{\mu\nu} + g c_{\theta_W} Z^{\mu\nu}) W_\nu^{-\rho} W_{\rho\mu}^{+}\right]$$

Relation to Higgs physics

All Primary deformations considered so far have been of the form

$$\hat{h}^2 \times \text{dim 4 deformation}$$

$$\hat{h} = v + h$$

Probed by LEP in EWPT and TGC

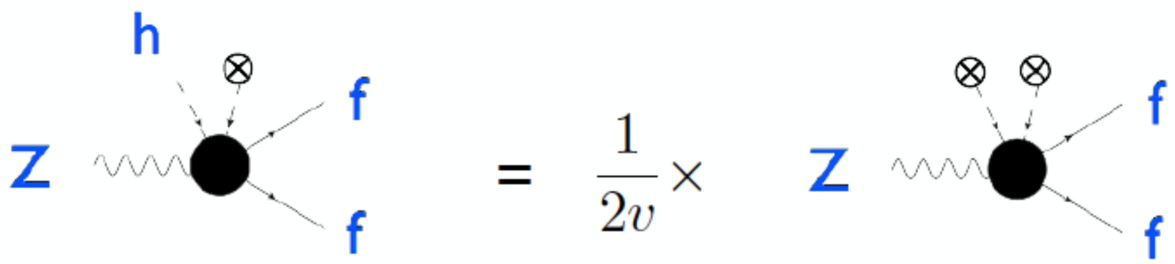
Probed by LHC in Higgs physics

Constrained already!

Relation to Higgs physics

All Primary deformations considered so far have been of the form

Eg. : $\hat{h}^2 \times Z_\mu \bar{f}_{L,R} \gamma^\mu f_{L,R}$



$\overline{H^\dagger D_\mu H \bar{f} \gamma^\mu f}$

Modifications in h→Zff related to Z→ff

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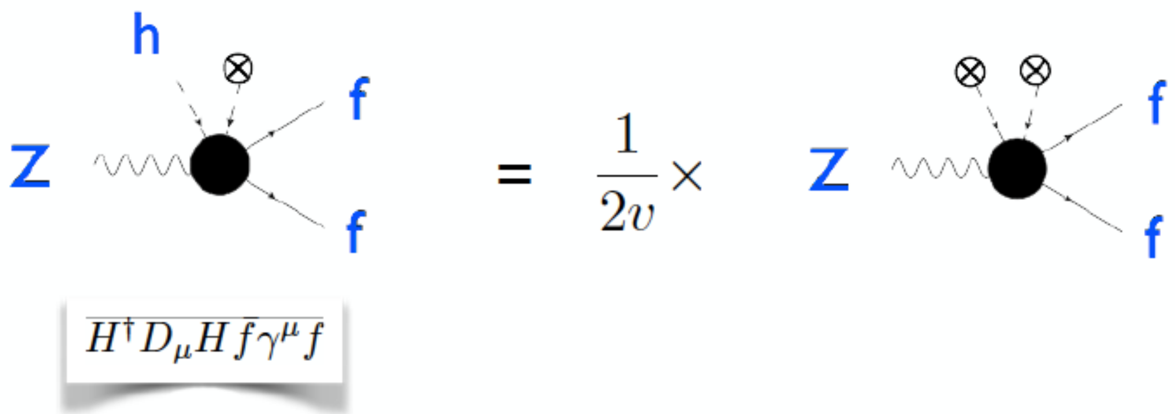

Modifications in h→Zff related to Z→ff

Contributions to Higgs physics already constrained by TGC, EWPT!

Any unconstrained BSM effect in Higgs physics?

- Yes! Deformations of the form:

$$|H|^2/\Lambda^2 \; \mathcal{O}_4 \longrightarrow \text{SM operator}$$

For $\hat{h} = v$ just a redefinition of SM parameters.

Eg.:

$$|H|^2 f_L H f_R + h.c. \longrightarrow Y_f(\hat{h}) = Y_f + \delta Y_f \hat{h}^2/v^2 + \cdots$$

$$\Delta \mathscr{L}^h_{ff} = \delta g^h_{ff} \left(h \bar{f}_L f_R + \text{h.c.} \right) \left(1 + \frac{3h}{2v} + \frac{h^2}{2v^2} \right)$$

+ Higgs Primary directions

$$e(\hat{h}),\ s_{\theta_W}(\hat{h}),\ g_s(\hat{h}),\ Y_f(\hat{h}),\ \lambda_h(\hat{h}),\ Z_h(\hat{h})$$

give

↓

$$\Delta\mathcal{L}^h_{\gamma\gamma} = \kappa_{\gamma\gamma}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[A_{\mu\nu}A^{\mu\nu}+Z_{\mu\nu}Z^{\mu\nu}+2W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{Z\gamma} = \kappa_{Z\gamma}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W}A_{\mu\nu}Z^{\mu\nu}+\frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu}+W^+_{\mu\nu}W^{-\mu\nu}\right]$$

$$\Delta\mathcal{L}^h_{GG} = \kappa_{GG}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)G^A_{\mu\nu}G^{A\,\mu\nu}\,,$$

$$\Delta\mathcal{L}^h_{ff} = \delta g^h_{ff}\left(h\bar{f}_L f_R+\text{h.c.}\right)\left(1+\frac{3h}{2v}+\frac{h^2}{2v^2}\right)$$

$$\Delta\mathcal{L}_{3h} = \delta g_{3h}h^3\left(1+\frac{3h}{2v}+\frac{3h^2}{4v^2}+\frac{h^3}{8v^3}\right)$$

$$\Delta\mathcal{L}^h_{VV} = \delta g^h_{VV}\left[h\left(W^{+\mu}W^-_\mu+\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)+\Delta_h\right]$$

Remaining deformations:

- Other deformations include four-fermion deformations CP- violating deformations and:

$$\Delta\mathcal{L}_R^W = \delta g_R^W \frac{\hat{h}^2}{v^2} W_\mu^+ \bar{u}_R \gamma^\mu d_R + \text{h.c.}\,,$$

$$\Delta\mathcal{L}_{\text{dipole}}^V = \frac{Y_q \hat{h}}{m_W^2}\Big[\delta\kappa_q^G \bar{q}_L T^A \sigma^{\mu\nu} q_R G_{\mu\nu}^A$$

$$+ \delta\kappa_q^A (T_3 \bar{q}_L \sigma^{\mu\nu} q_R A_{\mu\nu} + \frac{s_{\theta_W}}{\sqrt{2}} \bar{u}_L \sigma^{\mu\nu} d_R W_{\mu\nu}^+)$$

$$+ \delta\kappa_q^Z (T_3 \bar{q}_L \sigma^{\mu\nu} q_R Z_{\mu\nu} + \frac{c_{\theta_W}}{\sqrt{2}} \bar{u}_L \sigma^{\mu\nu} d_R W_{\mu\nu}^+) + \text{h.c.}\Big]$$

MFV suppressed

$$\Delta\mathcal{L}_{3G} = \kappa_{3G} \epsilon_{ABC} G_\mu^{A\,\nu} G_{\nu\rho}^B G^{C\,\rho\mu}$$

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(18 is not considering four fermions and MFV suppressed and CPV deformations)

Higgs Primaries (8)

$$\Delta\mathcal{L}^h_{GG} = \boldsymbol{\kappa_{GG}} \left(\frac{h}{v} + \frac{h^2}{2v^2}\right) G^A_{\mu\nu} G^{A\,\mu\nu}$$

$$\Delta\mathcal{L}^h_{ff} = \boldsymbol{\delta g^h_{ff}} \left(h \bar{f}_L f_R + \text{h.c.}\right)\left(1 + \frac{3h}{2v} + \frac{h^2}{2v^2}\right)$$

$$\Delta\mathcal{L}_{3h} = \boldsymbol{\delta g_{3h}}\, h^3 \left(1 + \frac{3h}{2v} + \frac{3h^2}{4v^2} + \frac{h^3}{8v^3}\right),$$

$$\Delta\mathcal{L}^h_{VV} = \boldsymbol{\delta g^h_{VV}} \left[h \left(W^{+\mu}W^-_\mu + \frac{Z^\mu Z_\mu}{2c^2_{\theta_W}}\right)\left(1 + \frac{2h}{v} + \frac{4h^2}{3v^2} + \frac{h^3}{3v^3}\right) + \frac{m_h^2}{12 m_W^2}\left(\frac{h^4}{v} + \frac{3h^5}{4v^2} + \frac{h^6}{8v^3}\right) + \frac{m_f}{4m_W^2}\left(\frac{h^2}{v} + \frac{h^3}{3v^2}\right)(\bar{f}_L f_R + \text{h.c.})\right],$$

$$\Delta\mathcal{L}^h_{\gamma\gamma} = 4\boldsymbol{\kappa_{\gamma\gamma}} s^2_{\theta_W}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\left[A_{\mu\nu}A^{\mu\nu} + Z_{\mu\nu}Z^{\mu\nu} + 2W^+_{\mu\nu}W^{-\mu\nu}\right],$$

$$\Delta\mathcal{L}^h_{Z\gamma} = 4\boldsymbol{\kappa_{Z\gamma}}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\left[t_{\theta_W} A_{\mu\nu}Z^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}} Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right].$$

EWPT Primaries(7)

$$\Delta\mathcal{L}^V_{ee} = \boldsymbol{\delta g^Z_{eR}}\frac{\hat{h}^2}{v^2} Z^\mu \bar{e}_R\gamma_\mu e_R + \boldsymbol{\delta g^Z_{eL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{e}_L\gamma_\mu e_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right] + \boldsymbol{\delta g^Z_{\nu L}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{\nu}_L\gamma_\mu \nu_L + \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{\nu}_L\gamma_\mu e_L + \text{h.c.})\right]$$

$$\Delta\mathcal{L}^V_{qq} = \boldsymbol{\delta g^Z_{uR}}\frac{\hat{h}^2}{v^2} Z^\mu \bar{u}_R\gamma_\mu u_R + \boldsymbol{\delta g^Z_{dR}}\frac{\hat{h}^2}{v^2} Z^\mu \bar{d}_R\gamma_\mu d_R + \boldsymbol{\delta g^Z_{dL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{d}_L\gamma_\mu d_L - \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.})\right] + \boldsymbol{\delta g^Z_{uL}}\frac{\hat{h}^2}{v^2}\left[Z^\mu \bar{u}_L\gamma_\mu u_L + \frac{c_{\theta_W}}{\sqrt{2}}(W^{+\mu}\bar{u}_L\gamma_\mu d_L + \text{h.c.})\right]$$

TGC Primaries (3)

$$\Delta\mathcal{L}_{g_1^Z} = \boldsymbol{\delta g_1^Z} c^2_{\theta_W}\frac{\hat{h}^2}{v^2}\left[\frac{e^2\hat{h}^2}{4c^4_{\theta_W}} Z^\mu Z_\mu - g(W^-_\mu J^\mu_- + \text{h.c.}) - \frac{g c_{2\theta_W}}{c^3_{\theta_W}} Z_\mu J^\mu_Z - 2e t_{\theta_W} Z_\mu J^\mu_{em}\right]$$

$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\boldsymbol{\delta\kappa_\gamma}}{v^2}\left[ie\hat{h}^2(A_{\mu\nu} - t_{\theta_W} Z_{\mu\nu})W^{+\mu}W^{-\nu} + Z_\nu \partial_\mu \hat{h}^2 (t_{\theta_W} A^{\mu\nu} - t^2_{\theta_W} Z^{\mu\nu}) + \frac{(\hat{h}^2 - v^2)}{2} \times\left(t_{\theta_W} Z_{\mu\nu}A^{\mu\nu} + \frac{c_{2\theta_W}}{c^2_{\theta_W}} Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right)\right]$$

$$\Delta\mathcal{L}_{\lambda_\gamma} = \frac{i\boldsymbol{\lambda_\gamma}}{m_W^2}\left[(eA^{\mu\nu} + g c_{\theta_W} Z^{\mu\nu})W^{-\rho}_\nu W^+_{\rho\mu}\right]$$

Dimension 6 lagrangian

- So we have finally constructed the dim-6 lagrangian in a bottom up way (not starting from operators but from measurable deformations):

$$\Delta\mathscr{L}_{\rm BSM} = \Delta\mathscr{L}^h_{\gamma\gamma} + \Delta\mathscr{L}^h_{Z\gamma} + \Delta\mathscr{L}^h_{GG} + \Delta\mathscr{L}^h_{ff} + \Delta\mathscr{L}_{3h} + \Delta\mathscr{L}^h_{VV} + \Delta\mathscr{L}^V_{ee} + \Delta\mathscr{L}^V_{qq}$$
$$+ \Delta\mathscr{L}_{g_1^Z} + \Delta\mathscr{L}_{\kappa_\gamma} + \Delta\mathscr{L}_{\lambda_\gamma} + \Delta\mathscr{L}_{3G} + \Delta\mathscr{L}_{4f} + \Delta\mathscr{L}^V_{\rm MFV} + \Delta\mathscr{L}_{\rm CPV}\,.$$

- All physical processes, eg. *h->Vff, pp->Vh, VV->h* etc can be computed as a function of the BSM primary parameters using the above Lagrangian.

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18 Primary Directions

- All physical processes, eg. *h->Vff, pp->Vh, VV->h* etc can be computed as a function of the BSM primary parameters using the above Lagrangian.

Dimension 6 lagrangian

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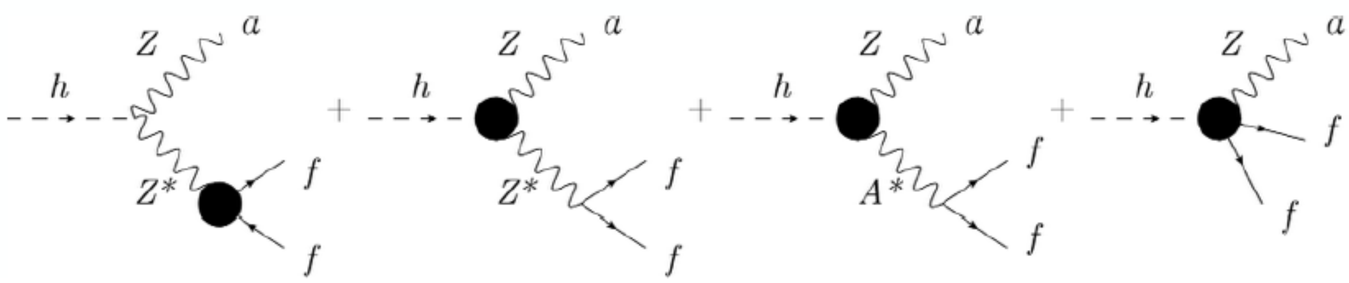
$$\Delta\mathcal{L}_{\rm BSM} = \Delta\mathcal{L}^h_{\gamma\gamma} + \Delta\mathcal{L}^h_{Z\gamma} + \Delta\mathcal{L}^h_{GG} + \Delta\mathcal{L}^h_{ff} + \Delta\mathcal{L}_{3h} + \Delta\mathcal{L}^h_{VV} + \Delta\mathcal{L}^V_{ee} + \Delta\mathcal{L}^V_{qq}$$
$$+\Delta\mathcal{L}_{g_1^Z} + \Delta\mathcal{L}_{\kappa_\gamma} + \Delta\mathcal{L}_{\lambda_\gamma} + \Delta\mathcal{L}_{3G} + \Delta\mathcal{L}_{4f} + \Delta\mathcal{L}^V_{\rm MFV} + \Delta\mathcal{L}_{\rm CPV}\,.$$

Total:59 Primary Directions

- All physical processes, eg. *h->Vff, pp->Vh, VV->h* etc can be computed as a function of the BSM primary parameters using the above Lagrangian.

+ Example: *h ->Zff*



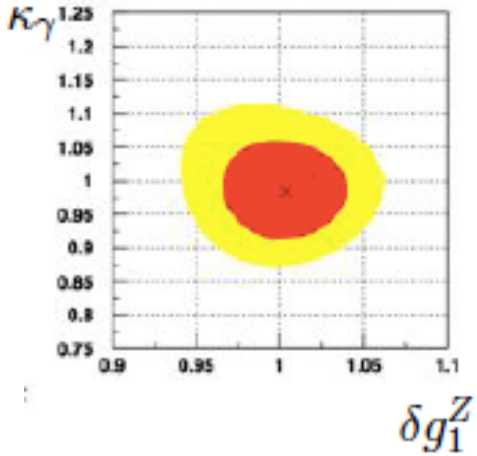
- The relevant primaries (ignoring ones constrained at per-mille level) are:

$$\Delta\mathcal{L}^h_{Z\gamma} = \delta\kappa_{Z\gamma}\left(\frac{h}{v}+\frac{h^2}{2v^2}\right)\left[t_{\theta_W}A_{\mu\nu}Z^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right].$$

$$\Delta\mathcal{L}_{g_1^Z} = \delta g_1^Z c^2_{\theta_W}\frac{\hat{h}^2}{v^2}\left[\frac{e^2\hat{h}^2}{4c^4_{\theta_W}}Z^\mu Z_\mu - g(W^-_\mu J^\mu_- + \text{h.c.}) - \frac{g c_{2\theta_W}}{c^3_{\theta_W}}Z_\mu J^\mu_Z - 2e t_{\theta_W} Z_\mu J^\mu_{em}\right]$$

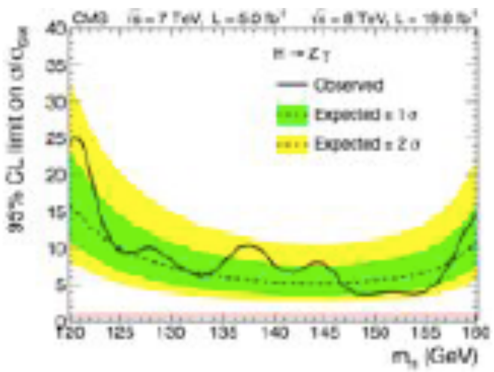
$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\delta\kappa_\gamma}{v^2}\Big[ie\hat{h}^2(A_{\mu\nu} - t_{\theta_W}Z_{\mu\nu})W^{+\mu}W^{-\nu} + Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W}A^{\mu\nu} - t^2_{\theta_W}Z^{\mu\nu}) + \frac{(\hat{h}^2 - v^2)}{2} \times\left(t_{\theta_W}Z_{\mu\nu}A^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right)\Big] \quad (24)$$

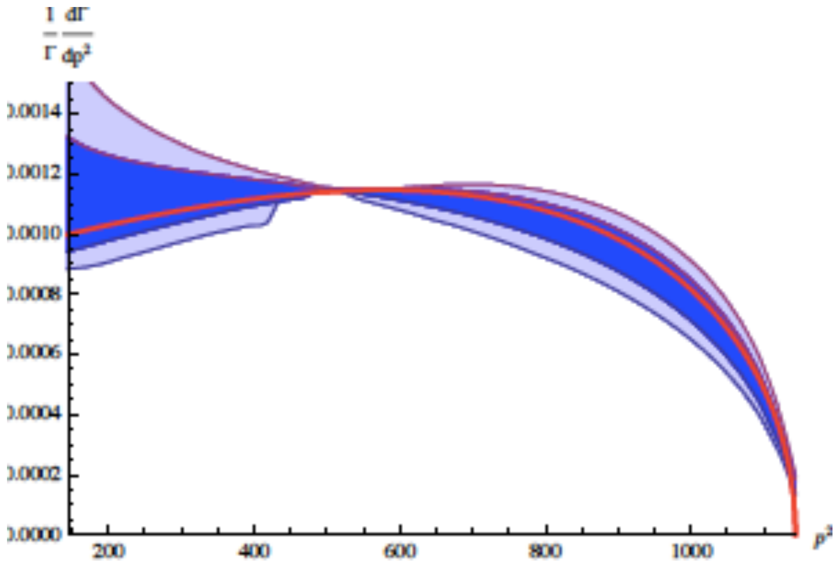
Example: *h ->Zff*



+

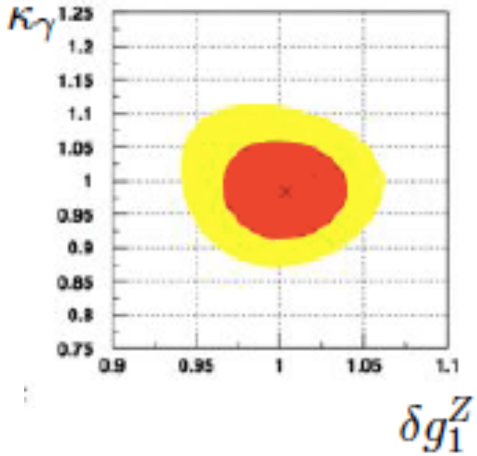
$h \to \gamma Z$





Gupta, Liu, Pomarol, Riva (in preparation)

Example: *h ->Zff*



+

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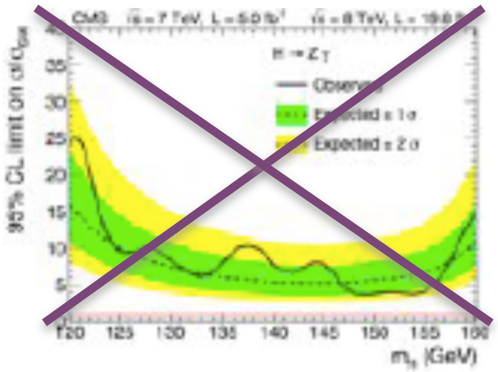
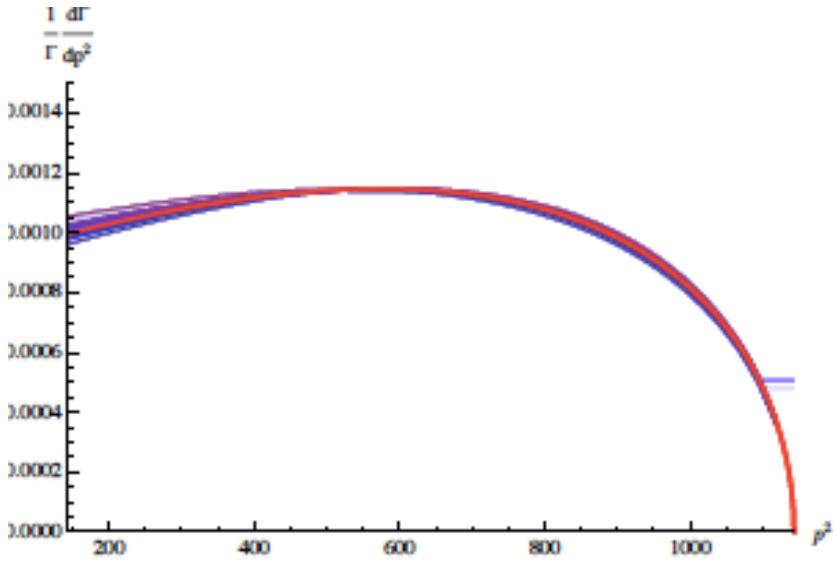
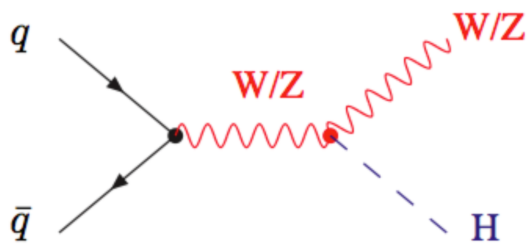
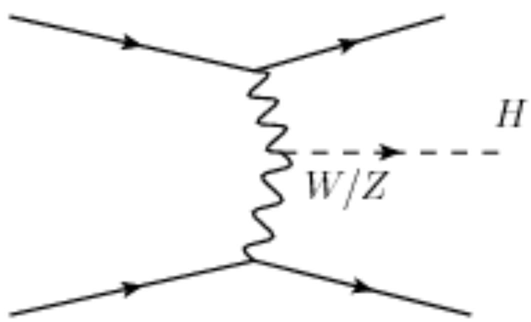


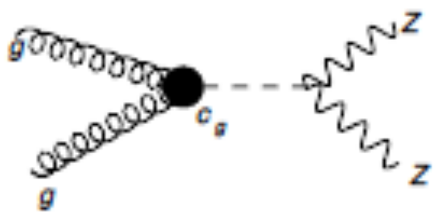


Gupta, Liu, Pomarol, Riva (in preparation)

Prediction for any BSM Process in terms of BSM primaries (at dim-6)







etc

as a function of:

$$hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$$
$$hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$$

$$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$$

$$g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu}\right)$$
$$\kappa_\gamma s_{\theta_W} \hat{A}^{\mu\nu} W^+_\mu W^-_\nu$$
$$\lambda_\gamma s_{\theta_W} \hat{A}^{\mu\nu} \hat{W}^{-\rho}_{\mu} \hat{W}^+_{\rho\nu}$$

Gupta, Liu, Pomarol, Riva (in preparation)

A Hierarchy of Constraints

$\delta g^h_{ff} \quad \delta g_{3h} \quad \delta g^h_{VV}$ } $\mathcal{O}(1)$

$\kappa_{Z\gamma}$

$\delta g^Z_1 \quad \delta\kappa_\gamma \quad \lambda_\gamma$ } percent level

$\kappa_{\gamma\gamma} \quad \kappa_{GG}$

$\delta g^Z_{eR} \quad \delta g^Z_{eL} \quad \delta g^Z_{\nu L}$

$\delta g^Z_{uR} \quad \delta g^Z_{dR} \quad \delta g^Z_{uL} \quad \delta g^Z_{dL}$ } permille level

These parameters can be identified with the Wilson coefficients of dim-6 operators c_i (m_W).

(Pomarol & Riva 2013)

A Hierarchy of Constraints

δg^h_{ff} δg_{3h} δg^h_{VV} — $\mathcal{O}(1)$

$\kappa_{Z\gamma}$
δg_1^Z $\delta\kappa_\gamma$ λ_γ — percent level

$\kappa_{\gamma\gamma}$ κ_{GG}
δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$
δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL} — permille level

These parameters can be identified with the Wilson coefficients of dim-6 operators c_i (m_W).

(Pomarol & Riva 2013)

RG-induced Constraints (diphoton example)

BSM matching scale Λ

$c_1(\Lambda), c_2(\Lambda), \ldots c_i(\Lambda)$ → Theoretically important; To constrain these need to know RG running.

$c_1(m_W), c_2(m_W), \ldots c_i(m_W)$ → Directly constrained by experiments

Experimental Observable scale $m_H \sim m_W$

Jenkins, Grojean, Manohar, Trott (2013)

Elias-Miro, Espinosa, Masso, Pomarol (2013)

+ RG-induced Constraints (diphoton example)

BSM matching scale Λ

$c_1(\Lambda), c_2(\Lambda), \ldots c_i(\Lambda)$ → Theoretically important; To constrain these need to know RG running.

→ RG running and mixing

for eg. take the diphoton operator:

$$\hat{c}_{\gamma\gamma}(m_h) = \hat{c}_{\gamma\gamma}(\Lambda) - \frac{1}{16\pi^2}\left[\left(\frac{3}{2}g^2 - 2\lambda\right)\hat{c}_{\kappa\gamma} + 3g^2\hat{c}_{\lambda\gamma}\right]\log\left(\frac{\Lambda}{m_h}\right) < \epsilon_{h\gamma\gamma}$$

$c_1(m_W), c_2(m_W), \ldots c_i(m_W)$ → Directly constrained by experiments

Experimental Observable scale $m_H \sim m_W$

Jenkins, Grojean, Manohar, Trott (2013)
Elias-Miro, Espinosa, Masso, Pomarol (2013)

+

- But aren’t these effects one loop suppressed and thus unimportant ?

+ RG-induced Constraints (diphoton example)

$$\hat{c}_{\gamma\gamma}(m_h) = \hat{c}_{\gamma\gamma}(\Lambda) - \frac{1}{16\pi^2}\left[\left(\frac{3}{2}g^2 - 2\lambda\right)\hat{c}_{\kappa\gamma} + 3g^2\hat{c}_{\lambda\gamma}\right]\log\left(\frac{\Lambda}{m_h}\right) < \epsilon_{h\gamma\gamma}$$

One loop suppression

Constrained per mille level

Constrained only at 10 % level thus allowed to be much larger than bound on $h\gamma\gamma$. This and the log enhancement can compensate for the loop factor.

Assuming no tuning/correlation between the RHS contributions we derive RG-induced bounds:

$$|\hat{c}_{\kappa\gamma}| < \Delta_{FT}\frac{16\pi^2}{\log(\Lambda/m_h)}\left|\left(\frac{3}{2}g^2 - 2\lambda\right)^{-1}\right|\epsilon_{h\gamma\gamma}\,, \quad |\hat{c}_{\lambda\gamma}| < \Delta_{FT}\frac{16\pi^2}{\log(\Lambda/m_h)}\left|\frac{1}{3g^2}\right|\epsilon_{h\gamma\gamma}$$

A Hierarchy of Constraints

$\delta g^h_{ff} \quad \delta g_{3h} \quad \delta g^h_{VV}$ — $\mathcal{O}(1)$

RG-flow ?

$\kappa_{Z\gamma}$

$\delta g^Z_1 \quad \delta\kappa_\gamma \quad \lambda_\gamma$ — percent level

RG-flow ?

$\kappa_{\gamma\gamma} \quad \kappa_{GG}$

$\delta g^Z_{eR} \quad \delta g^Z_{eL} \quad \delta g^Z_{\nu L}$ — permille level

$\delta g^Z_{uR} \quad \delta g^Z_{dR} \quad \delta g^Z_{uL} \quad \delta g^Z_{dL}$

These parameters can be identified with the Wilson coefficients of dim-6 operators c_i (mw).

(Pomarol & Riva 2013)

Anomalous Dimensional Matrix

	$\hat c_S$	$\hat c_T$	$\hat c_Y$	$\hat c_W$	$\hat c_{\gamma\gamma}$
$\gamma_{\hat c_S}$	$\frac{1}{3}g'^2+6y_t^2$	$-\frac{g^2}{2}$	$\frac{1}{8}g'^2\left(147-106\frac{g'^2}{g^2}\right)$	$\frac{1}{8}\left(77g^2+58g'^2\right)$	$16e^2$
$\gamma_{\hat c_T}$	$-9g'^2-24t_{\theta_W}^2\lambda$	$\frac{9}{2}g^2+12y_t^2+12\lambda$	$\frac{9}{2}g'^2+12t_{\theta_W}^2(g'^2+\lambda)$	$\frac{9}{2}g'^2$	0
$\gamma_{\hat c_Y}$	$-\frac{2}{3}g'^2$	0	$\frac{94}{3}g'^2$	0	0
$\gamma_{\hat c_W}$	0	0	$\frac{53}{12}g'^2\left(1-3t_{\theta_W}^2\right)$	$\frac{331}{12}g^2+\frac{29}{4}g'^2$	0
$\gamma_{\hat c_{\gamma\gamma}}$	0	0	0	0	$-\frac{9}{2}g^2-\frac{3}{2}g'^2+6y_t^2+12\lambda$
$\gamma_{\hat c_H}$	$18g'^2-t_{\theta_W}^2(9g'^2+24\lambda)$	$-9g^2+\frac{9}{2}g'^2+12\lambda$	$t_{\theta_W}^2\left(-\frac{141}{4}g'^2+12\lambda\right)$	$\frac{63}{2}g^2+\frac{51}{4}g'^2+72\lambda$	0
$\gamma_{\hat c_{\gamma Z}}$	0	0	0	0	0
$\gamma_{\hat c_{\kappa Z}}$	0	0	0	0	$-16e^2$
$\gamma_{\hat c_{gZ}}$	$-\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{g^2}{12c_{\theta_W}^2}$	$\frac{g'^2}{8c_{\theta_W}^2}(106t_{\theta_W}^2-29)$	$-\frac{1}{8c_{\theta_W}^2}(79g^2+58g'^2)$	0
$\gamma_{\hat c_{\lambda\gamma}}$	0	0	0	0	0

	$\hat c_H$	$\hat c_{\gamma Z}$	$\hat c_{\kappa\gamma}$	$\hat c_{gZ}$	$\hat c_{\lambda\gamma}$
$\gamma_{\hat c_S}$	$-\frac{1}{6}g^2$	$4(g^2-g'^2)$	$-\frac{11}{2}g^2-\frac{1}{6}g'^2-4\lambda$	$c_{\theta_W}^2\left(9g^2-\frac{1}{3}g'^2\right)$	$-2g^2$
$\gamma_{\hat c_T}$	$\frac{3}{2}g'^2$	0	$-9g'^2-24t_{\theta_W}^2\lambda$	$24s_{\theta_W}^2\lambda$	0
$\gamma_{\hat c_Y}$	0	0	$-\frac{2}{3}g'^2$	$\frac{2}{3}e^2$	0
$\gamma_{\hat c_W}$	0	0	0	$-\frac{2}{3}c_{\theta_W}^2g^2$	0
$\gamma_{\hat c_{\gamma\gamma}}$	0	0	$\frac{3}{2}g^2-2\lambda$	0	$3g^2$
$\gamma_{\hat c_H}$	$-\frac{9}{2}g^2-3g'^2+12y_t^2+24\lambda$	0	$9g'^2(2-t_{\theta_W}^2)-24t_{\theta_W}^2\lambda$	$9(g'^2s_{\theta_W}^2-g^2c_{\theta_W}^2)-24\lambda(6c_{\theta_W}^2-s_{\theta_W}^2)$	0
$\gamma_{\hat c_{\gamma Z}}$	0	$-\frac{7}{2}g^2-\frac{1}{2}g'^2+6y_t^2+12\lambda$	$c_{\theta_W}^2(2g^2-2\lambda)-s_{\theta_W}^2(g^2-2\lambda)$	0	$\frac{g^2}{2}(11c_{\theta_W}^2-s_{\theta_W}^2)$
$\gamma_{\hat c_{\kappa\gamma}}$	0	$4(g^2-g'^2)$	$\frac{11}{2}g^2+\frac{g'^2}{2}+6y_t^2+4\lambda$	0	$2g^2$
$\gamma_{\hat c_{gZ}}$	$\frac{g^2}{12c_{\theta_W}^2}$	0	$\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{17}{2}g^2-\frac{g'^2}{6}+6y_t^2$	0
$\gamma_{\hat c_{\lambda\gamma}}$	0	0	0	0	$\frac{53}{3}g^2$

Anomalous Dimensional Matrix

$$(\hat{c}_S, \hat{c}_T, \hat{c}_Y, \hat{c}_W, \hat{c}_{\gamma\gamma}, \hat{c}_{\gamma Z}, \hat{c}_{\kappa\gamma}, \hat{c}_{gz}, \hat{c}_{\lambda\gamma}, \hat{c}_H)^t (m_t) \simeq \quad (4$$

$$\simeq \begin{pmatrix} 0.9 & 0.003 & -0.03 & -0.08 & -0.02 & -0.02 & -0.04 & 0.05 & -0.01 & 0.001 \\ 0.03 & 0.8 & -0.02 & -0.009 & 0 & 0 & -0.03 & 0.01 & 0 & -0.003 \\ 0.001 & 0 & 0.9 & 0 & 0 & 0 & -0.001 & 0.001 & 0 & 0 \\ 0 & 0 & -0.001 & 0.8 & 0 & 0 & 0 & -0.003 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.9 & 0 & 0.006 & 0 & 0.02 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.9 & 0.007 & 0 & 0.03 & 0 \\ 0 & 0 & 0 & 0 & -0.02 & -0.02 & 0.9 & 0 & -0.01 & 0 \\ 0.0004 & -0.0007 & -0.0004 & 0.1 & 0 & 0 & -0.0004 & 0.9 & 0 & -0.0007 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 & 0 \\ -0.02 & 0.03 & 0.01 & -0.4 & 0 & 0 & 0.02 & -0.3 & 0 & 0.8 \end{pmatrix} \begin{pmatrix} \hat{c}_S(\Lambda) \\ \hat{c}_T(\Lambda) \\ \hat{c}_Y(\Lambda) \\ \hat{c}_W(\Lambda) \\ \hat{c}_{\gamma\gamma}(\Lambda) \\ \hat{c}_{\gamma Z}(\Lambda) \\ \hat{c}_{\kappa\gamma}(\Lambda) \\ \hat{c}_{gz}(\Lambda) \\ \hat{c}_{\lambda\gamma}(\Lambda) \\ \hat{c}_H(\Lambda) \end{pmatrix}$$

•We focus on the part of the matrix, where weakly bound couplings contribute to strongly bound couplings.

Numerical Results

Coupling	Direct Constraint	RG-induced Constraint
$\hat{c}_S(m_t)$	$[-1,2]\times10^{-3}$ [31]	-
$\hat{c}_T(m_t)$	$[-1,2]\times10^{-3}$ [31]	-
$\hat{c}_Y(m_t)$	$[-3,3]\times10^{-3}$ [22]	-
$\hat{c}_W(m_t)$	$[-2,2]\times10^{-3}$ [22]	-
$\hat{c}_{\gamma\gamma}(m_t)$	$[-1,2]\times10^{-3}$ [18]	-
$\hat{c}_{\gamma Z}(m_t)$	$[-0.6,1]\times10^{-2}$ [18]	$[-2,6]\times10^{-2}$
$\hat{c}_{\kappa\gamma}(m_t)$	$[-10,7]\times10^{-2}$ [27]	$[-5,2]\times10^{-2}$
$\hat{c}_{gZ}(m_t)$	$[-4,2]\times10^{-2}$ [27]	$[-3,1]\times10^{-2}$
$\hat{c}_{\lambda\gamma}(m_t)$	$[-6,2]\times10^{-2}$ [27]	$[-2,8]\times10^{-2}$
$\hat{c}_H(m_t)$	$[-6,5]\times10^{-1}$ [32]	$[-2,0.5]\times10^{-1}$

- We assume that there is **no tuning/correlation among different contributions** so that **each RG-induced** term in the RGE is **smaller than the bound.** This gives us new **RG-induced constraints.**

- We get bounds on some **TGC** and on C_H mainly from their RG-induced contribution to {S, T, W,Y} that are **stronger** than the direct bounds.

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- We assume that there is no tuning so that each RG-induced term in the RGE is smaller than the bound. This gives us new RG-induced constraints.

- We get bounds on some TGC and on C_H mainly from their RG-induced contribution to {S, T, W, Y} that are stronger than the direct bounds.

Summary

- We present an efficient choice of independent primary BSM deformations. All other deformations are generated in a correlated way and we derive these correlations.

- Barring 4-fermions and CPV and MFV deformations, there are 18 BSM Primary effects: 8 Higgs primaries, 7 EWPT primaries and 3 TGC Primaries.

- Predictioins: W coupling deviations not independent of Z coupling deviations. All *hVff* deformations constrained by EWPT and TGC; all QGC constrained by the g1Z TGC.

- We find that RG-induced constraints on the *hVV* and TGC primaries due to mixing with the $H\gamma\gamma$ and *S*-parameter primary directions can be stronger to (or of the same order as) tree level constraints.

Back Up slides

Part II: RG-induced constraints

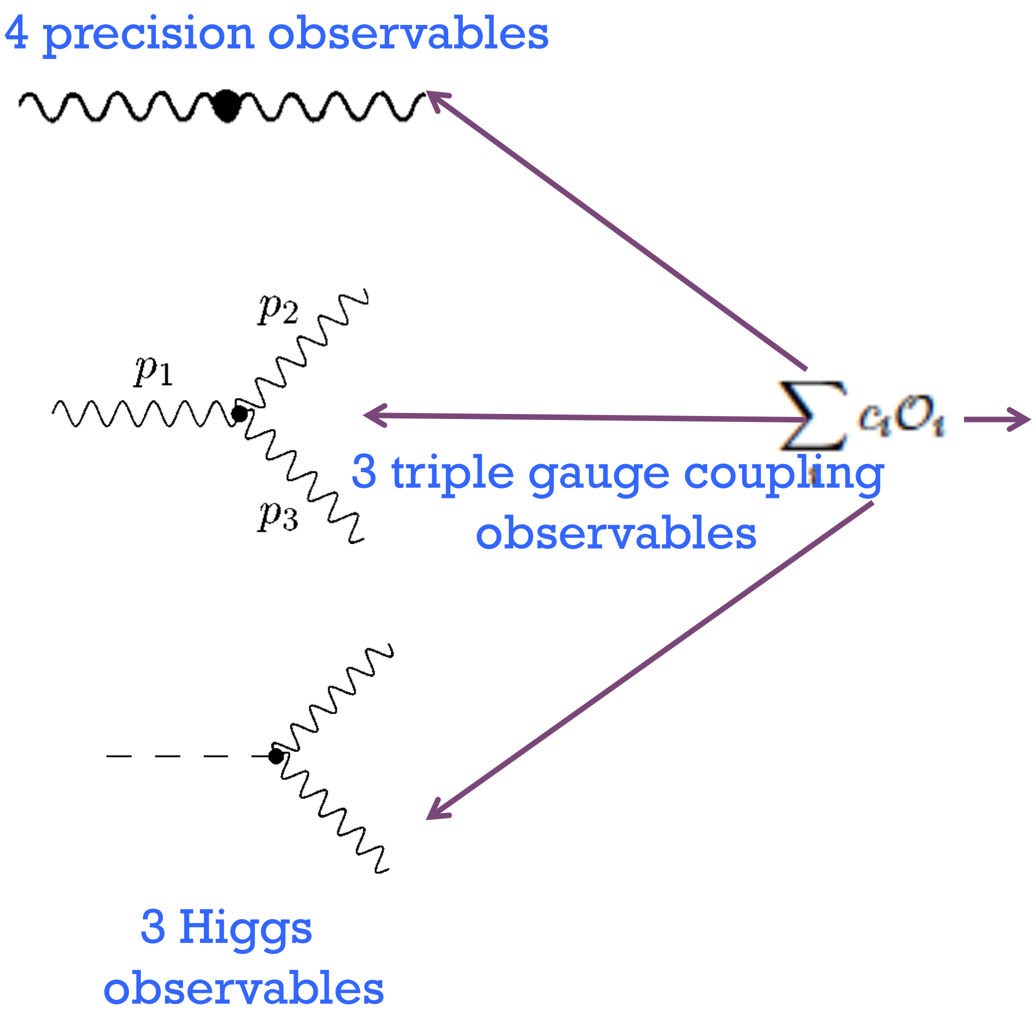
- We calculate the one-loop anomalous dimension matrix for 13 bosonic dimension-6 operators relevant for electroweak (including TGC) and Higgs physics.

- New RG-induced bounds, stronger than the direct constraints, on a universal shift of the Higgs couplings and the anomalous triple gauge couplings.

Elias-Miro, Grojean, Gupta and Marzocca (1312.2928)

Operators to Observables

- The 10 EW & Higgs operators can be related to 10 observables:



$$\hat{T} = \hat{c}_T(m_W) = \frac{v^2}{\Lambda^2} c_T(m_W)$$

$$\hat{S} = \hat{c}_S(m_W) = \frac{m_W^2}{\Lambda^2}\left[c_W(m_W) + c_B(m_W) + 4c_{WB}(m_W)\right],$$

$$Y = \hat{c}_Y(m_W) = \frac{m_W^2}{\Lambda^2} c_{2B}(m_W)$$

$$W = \hat{c}_W(m_W) = \frac{m_W^2}{\Lambda^2} c_{2W}(m_W)$$

$$\delta g_1^Z \equiv \hat{c}_{gZ}(m_W) = \frac{m_W^2}{\Lambda^2}\frac{1}{c^2_{\theta_W}} c_W(m_W)$$

$$\delta\kappa_\gamma \equiv \hat{c}_{\kappa\gamma}(m_W) = \frac{m_W^2}{\Lambda^2}(-4c_{WB}(m_W))$$

$$\lambda_Z \equiv \hat{c}_{\lambda\gamma}(m_W) = \frac{m_W^2}{\Lambda^2} c_{3W}(m_W)$$

$$\hat{c}_H(m_h) = \frac{v^2}{\Lambda^2} c_H(m_h),$$

$$\hat{c}_{\gamma\gamma}(m_h) = \frac{m_W^2}{\Lambda^2}\left(c_{BB}(m_h) + c_{WW}(m_h) - c_{WB}(m_h)\right)$$

$$\hat{c}_{\gamma Z}(m_h) = \frac{m_W^2}{\Lambda^2}\left(2c^2_{\theta_W} c_{WW}(m_h) - 2s^2_{\theta_W} c_{BB}(m_h) - (c^2_{\theta_W} - s^2_{\theta_W}) c_{WB}(m_h)\right).$$

(Pomarol & Riva 2013)

A Hierarchy of Constraints

$\delta g^h_{ff} \quad \delta g_{3h} \quad \delta g^h_{VV}$ $\Big\}$ $\mathcal{O}(1)$

$\kappa_{Z\gamma}$

$\delta g^Z_1 \quad \delta\kappa_\gamma \quad \lambda_\gamma$ $\Big\}$ percent level

$\kappa_{\gamma\gamma} \quad \kappa_{GG}$

$\delta g^Z_{eR} \quad \delta g^Z_{eL} \quad \delta g^Z_{\nu L}$

$\delta g^Z_{uR} \quad \delta g^Z_{dR} \quad \delta g^Z_{uL} \quad \delta g^Z_{dL}$ $\Big\}$ permille level

(Pomarol & Riva 2013)

Anomalous Dimensional Matrix

$$\hat{c}_i(m_h) = \hat{c}_i(\Lambda) - \frac{1}{16\pi^2}\hat{\gamma}_{ij}\hat{c}_j(\Lambda)\log\left(\frac{\Lambda}{m_h}\right)$$

Anomalous dimension matrix: connects Wilson coefficientsat BSM scale to those at experimental scale.

- The full anomalous dimension matrix is shown in the next slide:

Anomalous Dimensional Matrix

	$\hat{c}_S$	$\hat{c}_T$	$\hat{c}_Y$	$\hat{c}_W$	$\hat{c}_{\gamma\gamma}$
$\gamma_{\hat{c}_S}$	$\frac{1}{3}g'^2+6y_t^2$	$-\frac{g^2}{2}$	$\frac{1}{8}g'^2\left(147-106\frac{g'^2}{g^2}\right)$	$\frac{1}{8}\left(77g^2+58g'^2\right)$	$16e^2$
$\gamma_{\hat{c}_T}$	$-9g'^2-24t_{\theta_W}^2\lambda$	$\frac{9}{2}g^2+12y_t^2+12\lambda$	$\frac{9}{2}g'^2+12t_{\theta_W}^2(g'^2+\lambda)$	$\frac{9}{2}g'^2$	0
$\gamma_{\hat{c}_Y}$	$-\frac{2}{3}g'^2$	0	$\frac{94}{3}g'^2$	0	0
$\gamma_{\hat{c}_W}$	0	0	$\frac{53}{12}g'^2\left(1-3t_{\theta_W}^2\right)$	$\frac{331}{12}g^2+\frac{29}{4}g'^2$	0
$\gamma_{\hat{c}_{\gamma\gamma}}$	0	0	0	0	$-\frac{9}{2}g^2-\frac{3}{2}g'^2+6y_t^2+12\lambda$
$\gamma_{\hat{c}_H}$	$18g'^2-t_{\theta_W}^2(9g'^2+24\lambda)$	$-9g^2+\frac{9}{2}g'^2+12\lambda$	$t_{\theta_W}^2\left(-\frac{141}{4}g'^2+12\lambda\right)$	$\frac{63}{2}g^2+\frac{51}{4}g'^2+72\lambda$	0
$\gamma_{\hat{c}_{\gamma Z}}$	0	0	0	0	0
$\gamma_{\hat{c}_{kZ}}$	0	0	0	0	$-16e^2$
$\gamma_{\hat{c}_{gZ}}$	$-\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{g^2}{12c_{\theta_W}^2}$	$\frac{g'^2}{8c_{\theta_W}^2}(106t_{\theta_W}^2-29)$	$-\frac{1}{8c_{\theta_W}^2}(79g^2+58g'^2)$	0
$\gamma_{\hat{c}_{\lambda\gamma}}$	0	0	0	0	0

	$\hat{c}_H$	$\hat{c}_{\gamma Z}$	$\hat{c}_{\kappa\gamma}$	$\hat{c}_{gZ}$	$\hat{c}_{\lambda\gamma}$
$\gamma_{\hat{c}_S}$	$-\frac{1}{6}g^2$	$4(g^2-g'^2)$	$-\frac{11}{2}g^2-\frac{1}{6}g'^2-4\lambda$	$c_{\theta_W}^2\left(9g^2-\frac{1}{3}g'^2\right)$	$-2g^2$
$\gamma_{\hat{c}_T}$	$\frac{3}{2}g'^2$	0	$-9g'^2-24t_{\theta_W}^2\lambda$	$24s_{\theta_W}^2\lambda$	0
$\gamma_{\hat{c}_Y}$	0	0	$-\frac{2}{3}g'^2$	$\frac{2}{3}e^2$	0
$\gamma_{\hat{c}_W}$	0	0	0	$-\frac{2}{3}c_{\theta_W}^2g^2$	0
$\gamma_{\hat{c}_{\gamma\gamma}}$	0	0	$\frac{3}{2}g^2-2\lambda$	0	$3g^2$
$\gamma_{\hat{c}_H}$	$-\frac{9}{2}g^2-3g'^2+12y_t^2+24\lambda$	0	$9g'^2(2-t_{\theta_W}^2)-24t_{\theta_W}^2\lambda$	$9(g'^2s_{\theta_W}^2-g^2c_{\theta_W}^2)-24\lambda(6c_{\theta_W}^2-s_{\theta_W}^2)$	0
$\gamma_{\hat{c}_{\gamma Z}}$	0	$-\frac{7}{2}g^2-\frac{1}{2}g'^2+6y_t^2+12\lambda$	$c_{\theta_W}^2(2g^2-2\lambda)-s_{\theta_W}^2(g^2-2\lambda)$	0	$\frac{g^2}{2}(11c_{\theta_W}^2-s_{\theta_W}^2)$
$\gamma_{\hat{c}_{\kappa\gamma}}$	0	$4(g^2-g'^2)$	$\frac{11}{2}g^2+\frac{g'^2}{2}+6y_t^2+4\lambda$	0	$2g^2$
$\gamma_{\hat{c}_{gZ}}$	$\frac{g^2}{12c_{\theta_W}^2}$	0	$\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{17}{2}g^2-\frac{g'^2}{6}+6y_t^2$	0
$\gamma_{\hat{c}_{\lambda\gamma}}$	0	0	0	0	$\frac{53}{3}g^2$

+

Anomalous Dimensional Matrix

	$\hat{c}_S$	$\hat{c}_T$	$\hat{c}_Y$	$\hat{c}_W$	$\hat{c}_{\gamma\gamma}$
$\gamma_{\hat{c}_S}$	$\frac{1}{3}g'^2+6y_t^2$	$-\frac{g^2}{2}$	$\frac{1}{8}g'^2\left(147-106\frac{g'^2}{g^2}\right)$	$\frac{1}{8}\left(77g^2+58g'^2\right)$	$16e^2$
$\gamma_{\hat{c}_T}$	$-9g'^2-24t_{\theta_W}^2\lambda$	$\frac{9}{2}g^2+12y_t^2+12\lambda$	$\frac{9}{2}g'^2+12t_{\theta_W}^2(g'^2+\lambda)$	$\frac{9}{2}g'^2$	0
$\gamma_{\hat{c}_Y}$	$-\frac{2}{3}g'^2$	0	$\frac{94}{3}g'^2$	0	0
$\gamma_{\hat{c}_W}$	0	0	$\frac{53}{12}g'^2\left(1-3t_{\theta_W}^2\right)$	$\frac{331}{12}g^2+\frac{29}{4}g'^2$	0
$\gamma_{\hat{c}_{\gamma\gamma}}$	0	0	0	0	$-\frac{9}{2}g^2-\frac{3}{2}g'^2+6y_t^2+12\lambda$
$\gamma_{\hat{c}_H}$	$18g'^2-t_{\theta_W}^2(9g'^2+24\lambda)$	$-9g^2+\frac{9}{2}g'^2+12\lambda$	$t_{\theta_W}^2\left(-\frac{141}{4}g'^2+12\lambda\right)$	$\frac{63}{2}g^2+\frac{51}{4}g'^2+72\lambda$	0
$\gamma_{\hat{c}_{\gamma Z}}$	0	0	0	0	0
$\gamma_{\hat{c}_{kZ}}$	0	0	0	0	$-16e^2$
$\gamma_{\hat{c}_{gZ}}$	$-\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{g^2}{12c_{\theta_W}^2}$	$\frac{g'^2}{8c_{\theta_W}^2}(106t_{\theta_W}^2-29)$	$-\frac{1}{8c_{\theta_W}^2}(79g^2+58g'^2)$	0
$\gamma_{\hat{c}_{\lambda\gamma}}$	0	0	0	0	0

	$\hat{c}_H$	$\hat{c}_{\gamma Z}$	$\hat{c}_{\kappa\gamma}$	$\hat{c}_{gZ}$	$\hat{c}_{\lambda\gamma}$
$\gamma_{\hat{c}_S}$	$-\frac{1}{6}g^2$	$4(g^2-g'^2)$	$-\frac{11}{2}g^2-\frac{1}{6}g'^2-4\lambda$	$c_{\theta_W}^2\left(9g^2-\frac{1}{3}g'^2\right)$	$-2g^2$
$\gamma_{\hat{c}_T}$	$\frac{3}{2}g'^2$	0	$-9g'^2-24t_{\theta_W}^2\lambda$	$24s_{\theta_W}^2\lambda$	0
$\gamma_{\hat{c}_Y}$	0	0	$-\frac{2}{3}g'^2$	$\frac{2}{3}e^2$	0
$\gamma_{\hat{c}_W}$	0	0	0	$-\frac{2}{3}c_{\theta_W}^2g^2$	0
$\gamma_{\hat{c}_{\gamma\gamma}}$	0	0	$\frac{3}{2}g^2-2\lambda$	0	$3g^2$
$\gamma_{\hat{c}_H}$	$-\frac{9}{2}g^2-3g'^2+12y_t^2+24\lambda$	0	$9g'^2(2-t_{\theta_W}^2)-24t_{\theta_W}^2\lambda$	$9(g'^2s_{\theta_W}^2-g^2c_{\theta_W}^2)-24\lambda(6c_{\theta_W}^2-s_{\theta_W}^2)$	0
$\gamma_{\hat{c}_{\gamma Z}}$	0	$-\frac{7}{2}g^2-\frac{1}{2}g'^2+6y_t^2+12\lambda$	$c_{\theta_W}^2(2g^2-2\lambda)-s_{\theta_W}^2(g^2-2\lambda)$	0	$\frac{g^2}{2}(11c_{\theta_W}^2-s_{\theta_W}^2)$
$\gamma_{\hat{c}_{\kappa\gamma}}$	0	$4(g^2-g'^2)$	$\frac{11}{2}g^2+\frac{g'^2}{2}+6y_t^2+4\lambda$	0	$2g^2$
$\gamma_{\hat{c}_{gZ}}$	$\frac{g^2}{12c_{\theta_W}^2}$	0	$\frac{g'^2}{6c_{\theta_W}^2}$	$\frac{17}{2}g^2-\frac{g'^2}{6}+6y_t^2$	0
$\gamma_{\hat{c}_{\lambda\gamma}}$	0	0	0	0	$\frac{53}{3}g^2$

Anomalous Dimensional Matrix

$$
\left(\hat{c}_S, \hat{c}_T, \hat{c}_Y, \hat{c}_W, \hat{c}_{\gamma\gamma}, \hat{c}_{\gamma Z}, \hat{c}_{\kappa\gamma}, \hat{c}_{gz}, \hat{c}_{\lambda\gamma}, \hat{c}_H\right)^t (m_t) \simeq \qquad (4
$$

$$
\simeq \begin{pmatrix}
0.9 & 0.003 & -0.03 & -0.08 & -0.02 & -0.02 & -0.04 & 0.05 & -0.01 & 0.001 \\
0.03 & 0.8 & -0.02 & -0.009 & 0 & 0 & -0.03 & 0.01 & 0 & -0.003 \\
0.001 & 0 & 0.9 & 0 & 0 & 0 & -0.001 & 0.001 & 0 & 0 \\
0 & 0 & -0.001 & 0.8 & 0 & 0 & 0 & -0.003 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.9 & 0 & 0.006 & 0 & 0.02 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.9 & 0.007 & 0 & 0.03 & 0 \\
0 & 0 & 0 & 0 & -0.02 & -0.02 & 0.9 & 0 & -0.01 & 0 \\
0.0004 & -0.0007 & -0.0004 & 0.1 & 0 & 0 & -0.0004 & 0.9 & 0 & -0.0007 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.9 & 0 \\
-0.02 & 0.03 & 0.01 & -0.4 & 0 & 0 & 0.02 & -0.3 & 0 & 0.8
\end{pmatrix}
\begin{pmatrix}
\hat{c}_S(\Lambda) \\ \hat{c}_T(\Lambda) \\ \hat{c}_Y(\Lambda) \\ \hat{c}_W(\Lambda) \\ \hat{c}_{\gamma\gamma}(\Lambda) \\ \hat{c}_{\gamma Z}(\Lambda) \\ \hat{c}_{\kappa\gamma}(\Lambda) \\ \hat{c}_{gz}(\Lambda) \\ \hat{c}_{\lambda\gamma}(\Lambda) \\ \hat{c}_H(\Lambda)
\end{pmatrix}
$$

- We focus on the part of the matrix, where weakly bound couplings contribute to strongly bound couplings.

Numerical Results

Coupling	Direct Constraint	RG-induced Constraint
$\hat{c}_S(m_t)$	$[-1, 2] \times 10^{-3}$ [31]	-
$\hat{c}_T(m_t)$	$[-1, 2] \times 10^{-3}$ [31]	-
$\hat{c}_Y(m_t)$	$[-3, 3] \times 10^{-3}$ [22]	-
$\hat{c}_W(m_t)$	$[-2, 2] \times 10^{-3}$ [22]	-
$\hat{c}_{\gamma\gamma}(m_t)$	$[-1, 2] \times 10^{-3}$ [18]	-
$\hat{c}_{\gamma Z}(m_t)$	$[-0.6, 1] \times 10^{-2}$ [18]	$[-2, 6] \times 10^{-2}$
$\hat{c}_{\kappa\gamma}(m_t)$	$[-10, 7] \times 10^{-2}$ [27]	$[-5, 2] \times 10^{-2}$
$\hat{c}_{gZ}(m_t)$	$[-4, 2] \times 10^{-2}$ [27]	$[-3, 1] \times 10^{-2}$
$\hat{c}_{\lambda\gamma}(m_t)$	$[-6, 2] \times 10^{-2}$ [27]	$[-2, 8] \times 10^{-2}$
$\hat{c}_H(m_t)$	$[-6, 5] \times 10^{-1}$ [32]	$[-2, 0.5] \times 10^{-1}$

- We assume that there is **no tuning/correlation among different contributions** so that **each RG-induced** term in the RGE is **smaller than the bound.** This gives us new **RG-induced constraints.**

- We get bounds on some **TGC** and on C_H mainly from their RG-induced contribution to **{S, T, W, Y}** that are **stronger** than the direct bounds.

Numerical Results

Coupling	Direct Constraint	RG-induced Constraint
$\hat{c}_S(m_t)$	$[-1,2]\times10^{-3}$ [31]	-
$\hat{c}_T(m_t)$	$[-1,2]\times10^{-3}$ [31]	-
$\hat{c}_Y(m_t)$	$[-3,3]\times10^{-3}$ [22]	-
$\hat{c}_W(m_t)$	$[-2,2]\times10^{-3}$ [22]	-
$\hat{c}_{\gamma\gamma}(m_t)$	$[-1,2]\times10^{-3}$ [18]	-
$\hat{c}_{\gamma Z}(m_t)$	$[-0.6,1]\times10^{-2}$ [18]	$[-2,6]\times10^{-2}$
$\hat{c}_{\kappa\gamma}(m_t)$	$[-10,7]\times10^{-2}$ [27]	$[-5,2]\times10^{-2}$
$\hat{c}_{gZ}(m_t)$	$[-4,2]\times10^{-2}$ [27]	$[-3,1]\times10^{-2}$
$\hat{c}_{\lambda\gamma}(m_t)$	$[-6,2]\times10^{-2}$ [27]	$[-2,8]\times10^{-2}$
$\hat{c}_H(m_t)$	$[-6,5]\times10^{-1}$ [32]	$[-2,0.5]\times10^{-1}$

- We assume that there is no tuning so that each RG-induced term in the RGE is smaller than the bound. This gives us new RG-induced constraints.

- We get bounds on some TGC and on C_H mainly from their RG-induced contribution to {S, T, W, Y} that are stronger than the direct bounds.

A Hierarchy of Constraints

$\delta g^h_{ff} \quad \delta g_{3h} \quad \delta g^h_{VV}$ } $\mathcal{O}(1)$

$\kappa_{Z\gamma}$
$\delta g_1^Z \quad \delta\kappa_\gamma \quad \lambda_\gamma$ } percent level

$\kappa_{\gamma\gamma} \quad \kappa_{GG}$
$\delta g^Z_{eR} \quad \delta g^Z_{eL} \quad \delta g^Z_{\nu L}$
$\delta g^Z_{uR} \quad \delta g^Z_{dR} \quad \delta g^Z_{uL} \quad \delta g^Z_{dL}$ } permille level

(Pomarol & Riva 2013)

A Hierarchy of Constraints

δg^h_{ff} δg_{3h} } $\mathcal{O}(1)$

$\kappa_{Z\gamma}$ δg^h_{VV}
δg^Z_1 $\delta\kappa_\gamma$ λ_γ } percent level

Strong RG-induced constraint from S, T

$\kappa_{\gamma\gamma}$ κ_{GG}
δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$
δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL} } permille level

RG-effects measurable in future

Direct Measurement	Future Precision	$\lvert\hat{c}_{\kappa\gamma}\rvert$	$\lvert\hat{c}_{\gamma Z}\rvert$	$\lvert\hat{c}_{\lambda\gamma}\rvert$	$\lvert\hat{c}_{H}\rvert$
$\hat{c}_{\gamma\gamma}$	4×10^{-5} [36]	6×10^{-3}	-	2×10^{-3}	-
$\hat{c}_{\gamma Z}$	3×10^{-4} [36]	4×10^{-2}	-	1×10^{-2}	-
$\hat{c}_{\kappa\gamma}$	2×10^{-4} [37]	-	1×10^{-2}	1×10^{-2}	-
$\hat{c}_{gZ}$	2×10^{-4} [37]	0.4	-	-	0.25

- Minimum value of the couplings to which direct measurements of the observables in the first column would be sensitive via the one loop RG-mixing in the long term.
- A deviation in one BSM primary parameter would induce deviations in other ones in a correlated way.
- If these RG effects are not seen it would mean would mean that some tuning is needed, or it would indicate some UV correlation among Wilson coefficients pointing towards a particular structure of the new physics

Part III: Explicit Models

- We consider expectations for BSM primary effects in two models:

  (1) Composite Models

  Giudice, Grojean, Pomarol and Rattazzi (2007)

  (2)Integrating out Higgses in SUSY Models

  Gupta, Montull, Riva (2012)

Composite Models

- Strongly Interacting Light Higgs (SILH) Lagrangian:

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

(assumes Higgs is a pseudo Nambu Goldstone Boson of a strong sector)

Giudice, Grojean, Pomarol and Rattazzi (2007)

Composite Models

δg^h_{ff} δg_{3h}	$\mathcal{O}(1)$	$\frac{g_*^2}{\Lambda^2}$
$\kappa_{Z\gamma}$ δg^h_{VV} δg^Z_1 $\delta\kappa_\gamma$ λ_γ	percent level	$\frac{1}{\Lambda^2}$
	Strong RG-induced constraint from S, T (for δg^h_{VV})	
$\kappa_{\gamma\gamma}$ κ_{GG} δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$ δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL}	permille level	$\frac{g_*^2}{16\pi^2\Lambda^2}$ $\frac{g_{SM}^2}{16\pi^2\Lambda^2}$

δg^Z_{eR}, δg^Z_{eL}, $\delta g^Z_{\nu L}$, δg^Z_{uR}, δg^Z_{dR}, δg^Z_{uL}, δg^Z_{dL} → $\hat{S}$ $\hat{T}$

Composite Models

δg^h_{ff} δg_{3h} — $\mathcal{O}(1)$ — $\frac{g_*^2}{\Lambda^2}$

$\kappa_{Z\gamma}$ δg^h_{VV}

δg^Z_1 $\delta\kappa_\gamma$ λ_γ — percent level — $\frac{1}{\Lambda^2}$

Strong RG-induced constraint from S, T

$\kappa_{\gamma\gamma}$ κ_{GG}

δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$

δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL}

$\hat{S}$ $\hat{T}$

permille level

$$\frac{g_*^2}{16\pi^2\Lambda^2}$$

$$\frac{g_{SM}^2}{16\pi^2\Lambda^2}$$

Composite Models

$\delta g^h_{ff} \quad \delta g_{3h}$ — $\mathcal{O}(1)$ — $\frac{g_*^2}{\Lambda^2}$

$\kappa_{Z\gamma} \quad \delta g^h_{VV}$

$\delta g^Z_1 \quad \delta\kappa_\gamma \quad \lambda_\gamma$ — percent level — $\frac{1}{\Lambda^2}$

Strong RG-induced constraint from S, T

$\kappa_{\gamma\gamma} \quad \kappa_{GG}$

$\delta g^Z_{eR} \quad \delta g^Z_{eL} \quad \delta g^Z_{\nu L}$

$\delta g^Z_{uR} \quad \delta g^Z_{dR} \quad \delta g^Z_{uL} \quad \delta g^Z_{dL}$ — permille level — $\frac{g_*^2}{16\pi^2\Lambda^2}$, $\frac{g_{SM}^2}{16\pi^2\Lambda^2}$

$\hat{S} \quad \hat{T}$

Composite Models

δg^h_{ff} δg_{3h} — $\mathcal{O}(1)$ — $\frac{g_*^2}{\Lambda^2}$

Left-right symmetry

$\kappa_{Z\gamma}$ δg^h_{VV}

δg_1^Z $\delta\kappa_\gamma$ λ_γ — percent level — $\frac{1}{\Lambda^2}$

Strong RG-induced constraint from S, T

$\kappa_{\gamma\gamma}$ κ_{GG}

δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$

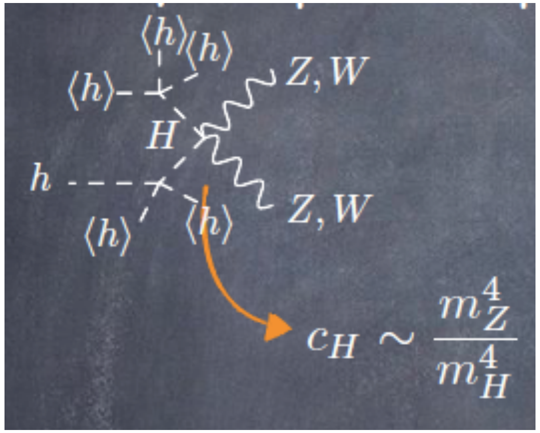
δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL} — permille level — $\frac{g_*^2}{16\pi^2\Lambda^2}$, $\frac{g_{SM}^2}{16\pi^2\Lambda^2}$

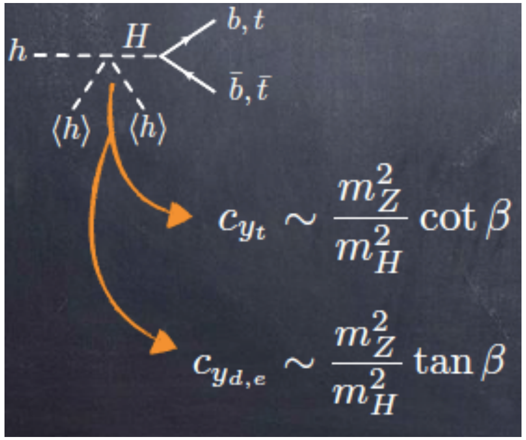
$\hat{S}$ $\hat{T}$

Custodial symmetry

Integrating out heavy Higgses in SUSY

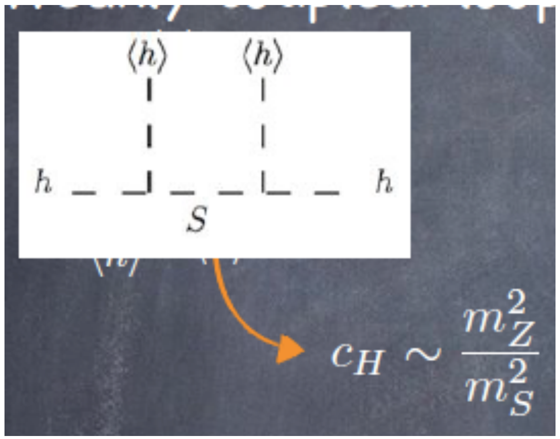
- Supersymmetric models (2HDMS)

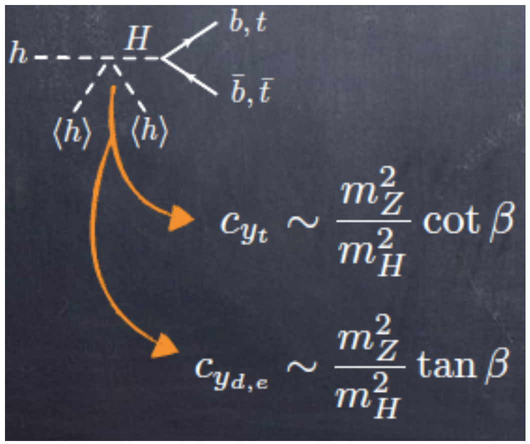




- NMSSM

($\mathcal{O}_6$ also generated)





Integrating out heavy Higgses in SUSY

2HDM: δg^h_{ff} δg_{3h} — $\mathcal{O}(1)$

$\kappa_{Z\gamma}$ δg^h_{VV}
δg^Z_1 $\delta\kappa_\gamma$ λ_γ — percent level

Strong RG-induced constraint from *S*, *T*

$\kappa_{\gamma\gamma}$ κ_{GG}
δg^Z_{eR} δg^Z_{eL} $\delta g^Z_{\nu L}$
δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL} — permille level

Integrating out heavy Higgses in SUSY

NMSSM: δg^h_{ff} δg_{3h} — $\mathcal{O}(1)$

$\kappa_{Z\gamma}$ δg^h_{VV}
δg^Z_1 $\delta\kappa_\gamma$ λ_γ — percent level

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δg^Z_{uR} δg^Z_{dR} δg^Z_{uL} δg^Z_{dL} — permille level

+ Understanding SUSY Higgs coupling deviations

- Write potential in terms of h and H, where:

$$h_1^0 = \cos\beta h + \sin\beta H$$
$$h_2^0 = \sin\beta h - \cos\beta H$$

gets full VEV

- H and h almost mass eigenstates if $\delta_i v^2/m_H^2 << 1$
- h has exactly SM couplings as it gives mass to all the particles.

quartics

Gupta, Montull, Riva (2012)

+

SUSY modifications to raise the Higgs mass would necessarily change Higgs couplings in a correlated way!

+ Understanding SUSY Higgs coupling deviations

- As quartics are turned on the lightest mass eigenstate is no longer *h* and the misalignment causes deviations from SM couplings:

$$\Delta V(H_1, H_2) = +\delta_\lambda h^4 + \delta h^3 H + \delta_2 h^2 H^2 + \delta_3 h H^3 + \delta_4 H^4$$

raises Higgs mass

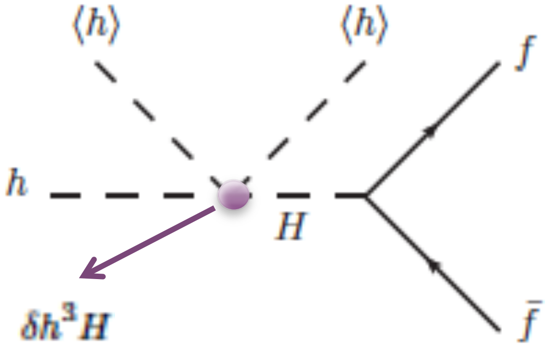
changes Higgs couplings wrt SM by inducing mixing term: *hH* and causing misalignment of {*h*,*H*} with the mass eigenstate basis

$$\Delta m_h^2 = 16\delta_\lambda v^2$$

$$\Delta m_h^2 = m_h^{obs\,2} - m_Z^2(\cos 2\beta)^2 \gtrsim (86\,\mathrm{GeV})^2$$

+ Understanding SUSY Higgs coupling deviations

- Integrate out H to obtain:



$$c_{b,\tau} \approx 1 - 4 \tan\beta\, \delta \frac{v^2}{m_H^2}$$

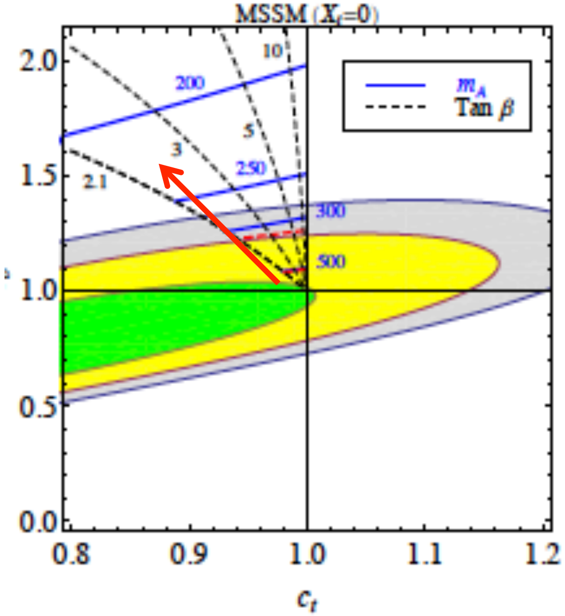
$$c_t \approx 1 + 4 \cot\beta\, \delta \frac{v^2}{m_H^2}$$

$$c_V = 1 - \mathcal{O}\left(\delta^2 \frac{v^4}{m_H^4}\right)$$

	ΔV	δ_λ	δ
MSSM	$\frac{g^2+g'^2}{8}\left(\lvert H_1^0\rvert^2 - \lvert H_2^0\rvert^2\right)^2$	$\frac{m_Z^2}{16v^2}(c_\beta^2 - s_\beta^2)^2$	$\frac{m_Z^2}{2v^2} s_\beta c_\beta (c_\beta^2 - s_\beta^2)$
Stops (no mixing)	$\frac{\lambda}{2}\lvert H_2\rvert^4 = \frac{3y_t^4}{8\pi^2}\log[m_{\tilde{t}_1} m_{\tilde{t}_2}/M_t^2]\lvert H_2\rvert^4$	$s_\beta^4 \frac{\lambda_2}{8}$	$-4 s_\beta^3 c_\beta \frac{\lambda_2}{8}$
D-term extension	$\kappa\left(\lvert H_1^0\rvert^2 - \lvert H_2^0\rvert^2\right)^2$	$\frac{m_Z^2}{16v^2}(c_\beta^2 - s_\beta^2)^2$	$\frac{m_Z^2}{2v^2} s_\beta c_\beta (c_\beta^2 - s_\beta^2)$
NMSSM	$\lambda^2 \lvert H_1^0 H_2^0\rvert^2$	$\frac{\lambda^2}{16}\sin^2 2\beta$	$-\frac{\lambda^2}{8}\sin 4\beta$

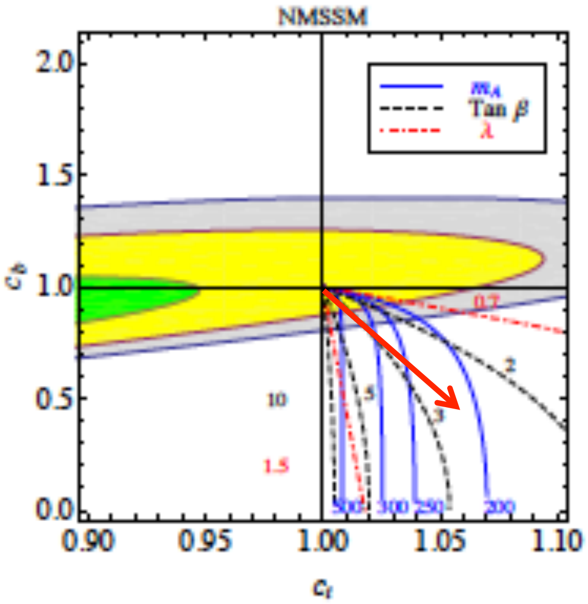
$m_Z^2/v^2 \to 4\kappa$

+



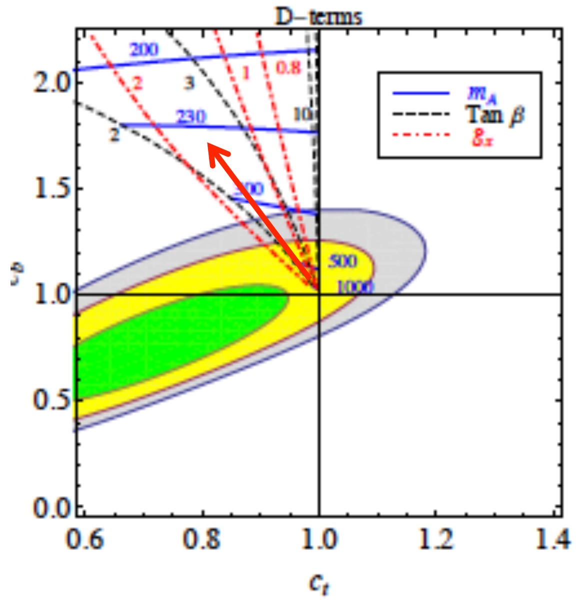
MSSM

(δ <0)



NMSSM

(δ >0)



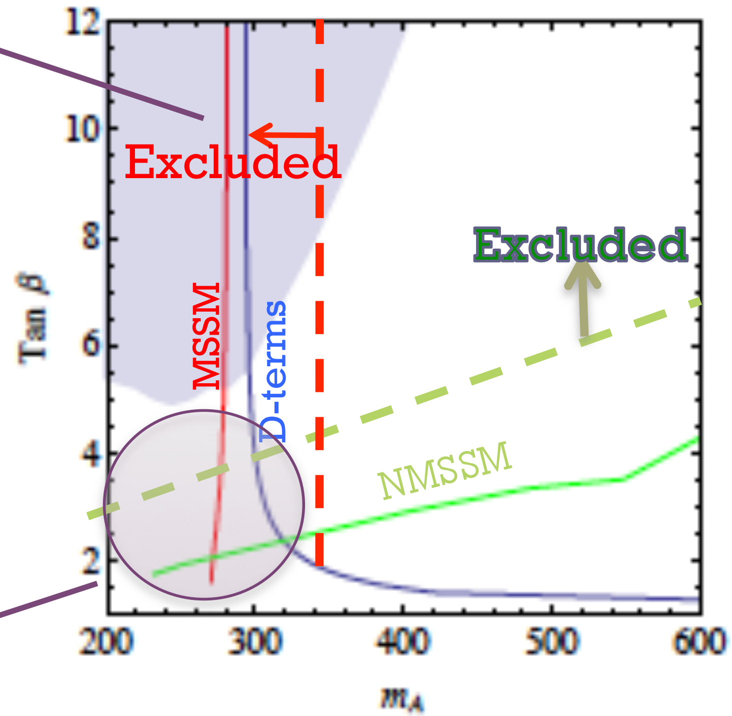
D-terms

(δ <0)

- All qualitative features of the above plots can be understood using our expansion. Quantitatively it is approximate but works well if m_A>350 GeV.

Exclusions

CMS H-> $\tau\ \tau$



Higgs coupling data more competitive than direct searches in low tan β region

Dashed: Barbieri et al (2012)
with latest data
Solid lines: our bounds

Consistency check: shift invariance

- The anomalous dimension of shift invariant combinations of couplings is a function of sift invariant combination of couplin~~:

$$\gamma_{C_i} = f(C_j)$$

	c_H	c_r	c_T	c_B	c_W
γ_{c_H}	$28\lambda + \frac{3}{2}g^2 - 4\gamma_H$	$\frac{3}{2}\left(2g^2 + g'^2\right) - 4\lambda$	$8\lambda - 6g^2 - \frac{3}{2}g'^2$	$\frac{3}{4}g'^2\left(g'^2 + 4g^2\right)$	$\frac{3}{4}g^2\left(3g^2 + 4g'^2\right) - 6\lambda g^2$
γ_{c_r}	$4\lambda - 3g^2$	$\frac{3}{2}\left(5g^2 + g'^2\right) + 20\lambda - 4\gamma_H$	$-4\lambda + 3g^2 - 6g'^2$	$\frac{3}{2}g'^2\left(2g'^2 - g^2\right) + 6\lambda g'^2$	$\frac{3}{2}g^2\left(6g^2 - g'^2\right) + 30\lambda g^2$
γ_{c_T}	$\frac{3}{2}g'^2$	$-\frac{3}{2}g'^2$	$12\lambda + \frac{27}{2}g^2 + 3g'^2 - 4\gamma_H$	$-\frac{9}{4}g'^2g^2 - 6\lambda g'^2$	$-\frac{9}{4}g'^2g^2$
γ_{c_B}	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{5}{3}$	$\frac{g'^2}{6} + 6y_t^2$	$\frac{g^2}{2}$
γ_{c_W}	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{g'^2}{6}$	$\frac{11}{2}g^2 + 6y_t^2$
$\gamma_{c_{2B}}$	0	0	0	$-\frac{2}{3}g'^2$	0
$\gamma_{c_{2W}}$	0	0	0	0	$-\frac{2}{3}g^2$

- Thus the contribution of *cB* and *cT* to γ *cT* must be connected in such a way that they can combine to form C_T

$$\gamma_{C_T} = \gamma_{c_T} - \frac{1}{4}g'^2(2\gamma_{c_B})\ldots \equiv \#c_T + \#c_B + \#c_{2B} = \frac{1}{6}\left(72\lambda + 5g'^2 + 27g^2\right)C_T$$

This will connect for eg. the contribu $c_B \to c_{T,B,2B}$ $c_T \to c_{T,B,2B}$ which have been computed completely independently.

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+ Higgs Primary directions

- For the effect from $e(\hat{h}),\ s_{\theta_W}(\hat{h})$ we write SM Lagrangian with non cannonical kinetic terms (we can get back to SM by $A_\mu \to A_\mu - s^2_{\theta_W}(v) Z_\mu$)

$$\mathcal{L}_{\rm EW} = -\frac{1}{4e^2(\hat{h})}\left(A_{\mu\nu} + s^2_{\theta_W}(\hat{h})\, Z_{\mu\nu}\right)^2 - \frac{c^2_{\theta_W}(\hat{h})}{4g^2(\hat{h})} Z^2_{\mu\nu}$$
$$- \frac{1}{2g^2(\hat{h})} W^+_{\mu\nu} W^{-\mu\nu} + \frac{\hat{h}^2}{2}\left[W^+_\mu W^{-\mu} + \frac{1}{2} Z^\mu Z_\mu\right]$$
$$+ A_\mu J^\mu_{em} + Z_\mu J^\mu_3 + W^+_\mu J^\mu_+ + W^-_\mu J^\mu_- ,$$

$$e(\hat{h}) = e\left(1 + \kappa_{\gamma\gamma}\frac{\hat{h}^2}{v^2}\right), \qquad s_{\theta_W}(\hat{h}) = s_{\theta_W}$$

$$e(\hat{h}) = e\,, \qquad s^2_{\theta_W}(\hat{h}) = s^2_{\theta_W}\left(1 - \kappa_{Z\gamma}\frac{\hat{h}^2}{v^2}\right)$$

$$\Delta\mathcal{L}^h_{\gamma\gamma} = \kappa_{\gamma\gamma}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\Big[A_{\mu\nu}A^{\mu\nu} + Z_{\mu\nu}Z^{\mu\nu} + 2W^+_{\mu\nu}W^{-\mu\nu}\Big],$$

$$\Delta\mathcal{L}^h_{Z\gamma} = \kappa_{Z\gamma}\left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\Big[t_{\theta_W} A_{\mu\nu}Z^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}} Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\Big].$$

Difference in Parametrization

- Parametrization in this part slightly different from one used so far (although essentially same):

$\Delta\mathcal{L}^h_{\gamma\gamma}$	$c^2_{\theta_W}\mathcal{O}_{BB} + s^2_{\theta_W}\mathcal{O}_{WW}$
$\Delta\mathcal{L}^h_{Z\gamma}$	$\mathcal{O}_{WW} - \mathcal{O}_{BB}$
$\Delta\mathcal{L}^h_{GG}$	$\mathcal{O}_{GG}$
$\Delta\mathcal{L}^h_{ff}$	$\mathcal{O}_{y_f}$
$\Delta\mathcal{L}_{3h}$	$\mathcal{O}_6$
$\Delta\mathcal{L}^h_{VV}$	$\mathcal{O}_H + \alpha\mathcal{O}_6 + \beta\mathcal{O}_y$
$\Delta\mathcal{L}^Z_{e_R e_R}$	$\mathcal{O}_R$
$\Delta\mathcal{L}^Z_{e_L e_L}$	$\mathcal{O}_L - \mathcal{O}_L^{(3)l}$
$\Delta\mathcal{L}^Z_{\nu_L \nu_L}$	$\mathcal{O}_L + \mathcal{O}_L^{(3)l}$
$\Delta\mathcal{L}_{g_1^Z}$	$\mathcal{O}_W - \mathcal{O}_B + 2\mathcal{O}_H - 4\mathcal{O}_r$
$\Delta\mathcal{L}_{\kappa_\gamma}$	$-4\mathcal{O}_{HB} + \frac{1}{2}\mathcal{O}_{WW} - \frac{1}{2}\mathcal{O}_{BB}$
$\Delta\mathcal{L}_{\lambda_\gamma}$	$\mathcal{O}_{3W}$

Do not contribute via RG to more constrained Primaries.

Only part that contributes to constrained primaries (used in 1312.2928).

$\{S, T\}$

Now we also considered W and Y that have been traded for four-fermions so far.