BSM Primary Effects

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(in collaboration with A. Pomarol and F. Riva)

+ 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:

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

- Predictions from $\mathcal{L}_4$ (the SM lagrangian) well known and tested.

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

- What are the predictions from $\mathcal{L}_6$? For eg. which Higgs interactions are already constrained by EWPT and TGC data and which are still independent ?

BSM Primaries

- 18 quantities **best** constrain all 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

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

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

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

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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. Due to accidental symmetries in $\mathcal{L}_6$, other accompanying terms must be present giving us a primary direction. Eg.:

BSM Primary

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

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 primaries like $h\to\gamma\gamma$,,TGC.
- This condition ensures that for a given set of BSM primaries each primary direction is uniquely defined.

+ Higgs Primary directions

$$\hat{h} \equiv v + h(x)$$

Probed by LEP
in EWPT and TGC

Probed by LHC
in Higgs physics

Higgs Primary directions

- To obtain the first set of primary directions (8 in total) we make SM parameters functions of $\hat{h} \equiv v + h(x)$:

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

where,

$$e(\hat{h}) = e + \delta e\, \hat{h}^2/v^2 + \cdots$$

- In the vacuum $\hat{h} = v$, this just gives a redefinition of SM parameters with no measurable effect. Thus these effects are measurable in Higgs physics alone.

- In operator language these are the deformations we get when we put in front of dim-4 operators $|H|^2/\Lambda^2$:

$$|H|^2/\Lambda^2\ \mathcal{O}_4$$

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

give

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

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

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

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

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 $A_\mu \to A_\mu - s^2_{\theta_W}(v) Z_\mu$)

$$\mathcal{L}_{\rm EW} = -\frac{1}{4e^2(\hat{h})}\left(A_{\mu\nu} + s^2_{\theta_W}(\hat{h})\, Z_{\mu\nu}\right)^2 - \frac{c^2_{\theta_W}(\hat{h})}{4g^2(\hat{h})} Z^2_{\mu\nu}$$
$$- \frac{1}{2g^2(\hat{h})} W^+_{\mu\nu} W^{-\mu\nu} + \frac{\hat{h}^2}{2}\left[W^+_\mu W^{-\mu} + \frac{1}{2} Z^\mu Z_\mu\right]$$
$$+ A_\mu J^\mu_{em} + Z_\mu J^\mu_3 + W^+_\mu J^\mu_+ + W^-_\mu J^\mu_- \,, \qquad (3)$$

$$e(\hat{h}) = e(1 + 4 s^2_{\theta_W} \kappa_{\gamma\gamma} \frac{\hat{h}^2}{v^2})\,, \qquad s_{\theta_W}(\hat{h}) = s_{\theta_W}$$

$$e(\hat{h}) = e\,, \qquad s^2_{\theta_W}(\hat{h}) = s^2_{\theta_W}(1 - 4\kappa_{Z\gamma} \frac{\hat{h}^2}{v^2})$$

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

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

Deviation from gauge coupling universality

- W/Z couplings

$$\hat{h}^2 V_\mu^a J_f^{\mu\,a}\ , \quad \hat{h}^2 \eta^a V_\mu^a J_{L\,f}^\mu\ , \quad \hat{h}^2 \eta^a V_\mu^a J_{R\,f}^\mu$$

$$\hat{h}^4 \eta^a \eta^b V_\mu^a V^{\mu\,b}\ , \quad \hat{h}^4 \eta^a \eta^b V_\mu^a J_{L\,f}^{\mu\,b}\ ,$$

Dim-8!

$$V_\mu^a \equiv W_\mu^a - t_{\theta_W} \delta^{a3} B_\mu$$

$$\hat{h}^2 \eta^a \in H^\dagger \sigma^a H\ , \quad \text{with} \quad \eta^a = (0, 0, 1)$$

$$J_{R\,f}^\mu = \bar{e}_R \gamma^\mu e_R \text{ etc}$$

3 dim-6 structures for 4 possible W/Z-couplings.

W-couplings related to Z-couplings at dim-6 level.

Leptons

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

All these directions constrained at per mille level by LEP precision measurements.

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- W/Z couplings

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$$\hat{h}^4 \eta^a \eta^b V_\mu^a V^{\mu\, b}\ ,\quad \hat{h}^4 \eta^a \eta^b V_\mu^a J_{L\,f}^{\mu\, b}\ ,$$

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3 dim-6 structures for 4 possible W/Z-couplings.

W-couplings related to Z-couplings at dim-6 level.

2 of these parameters can be traded for S and T

Leptons

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

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

Quarks

All these directions constrained at per mille level by LEP precision measurements.

Deviation from gauge coupling universality

- W/Z couplings

$$\hat{h}^2 V^a_\mu J^{\mu\,a}_f \;,\quad \hat{h}^2 \eta^a V^a_\mu J^\mu_{L\,f} \;,\quad \hat{h}^2 \eta^a V^a_\mu J^\mu_{R\,f}$$

$$\hat{h}^4 \eta^a \eta^b V^a_\mu V^{\mu\,b} \;,\quad \hat{h}^4 \eta^a \eta^b V^a_\mu J^{\mu\,b}_{L\,f} \,,$$

$$V^a_\mu \equiv W^a_\mu - t_{\theta_W} \delta^{a3} B_\mu$$

$$\hat{h}^2 \eta^a \in H^\dagger \sigma^a H \;,\quad \text{with} \;\; \eta^a = (0,0,1)$$

All of these couplings cannot be constrained by LEP measurement of Z couplings to fermions and $\hat{h}$ (W/Z masses) alone.

- A linear combination of the above couplings is equivalent to 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 (to keep photon couplings unchanged):

$$\Delta\mathcal{L}_{g^Z_1} = \delta g^Z_1 c^2_{\theta_W} \frac{\hat{h}^2}{v^2} \left[\frac{e^2 \hat{h}^2}{4 c^4_{\theta_W}} Z^\mu Z_\mu \right.$$

$$\left. - g(W^-_\mu J^\mu_- + \text{h.c.}) - \frac{g c_{2\theta_W}}{c^3_{\theta_W}} Z_\mu J^\mu_Z - 2 e t_{\theta_W} Z_\mu J^\mu_{em} \right]$$

Deviation from gauge coupling universality

- A linear combination of the above couplings is equivalent to a shift $s^2_{\theta_W} \rightarrow s^2_{\theta_W}(1 + 2\delta g_1^Z c^2_{\theta_W} \hat{h}^2/v^2)$ keeping e constant (to keep photon couplings unchanged):

$$\Delta\mathcal{L}_{g_1^Z} = \delta g_1^Z c^2_{\theta_W} \frac{\hat{h}^2}{v^2}\left[\frac{e^2\hat{h}^2}{4c^4_{\theta_W}} Z^\mu Z_\mu \right.$$

$$\left. -g(W^-_\mu J^\mu_- + \text{h.c.}) - \frac{g c_{2\theta_W}}{c^3_{\theta_W}} Z_\mu J^\mu_Z - 2e t_{\theta_W} Z_\mu J^\mu_{em}\right]$$

- We can, however, measure the difference in the value of $s^2_{\theta_W}$ measured by TGC measurement and Z-decays/mass.

- For $\hat{h} = v$ the above linear combination just gives the TGC:

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

The 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 $\delta\kappa_\gamma$:

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

The TGC primary directions

- Finally we also have:

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

Remaining deformations:

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

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

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

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

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

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

MFV suppressed

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

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Higgs Primaries (8)

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

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

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

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

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

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

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)

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

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

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

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):

$$
\begin{aligned}
\Delta\mathcal{L}_{\rm BSM} &= \Delta\mathcal{L}^h_{\gamma\gamma} + \Delta\mathcal{L}^h_{Z\gamma} + \Delta\mathcal{L}^h_{GG} + \Delta\mathcal{L}^h_{ff} + \Delta\mathcal{L}_{3h} \\
&+ \Delta\mathcal{L}^h_{VV} + \Delta\mathcal{L}^V_{ee} + \Delta\mathcal{L}^V_{qq} + +\Delta\mathcal{L}^W_{R} + \Delta\mathcal{L}^V_{\rm dipole} \qquad (26) \\
&+ \Delta\mathcal{L}_{g_1^Z} + \Delta\mathcal{L}_{\kappa_\gamma} + \Delta\mathcal{L}_{\lambda_\gamma} + \Delta\mathcal{L}_{3G} + \Delta\mathcal{L}_{\rm 4f} + \Delta\mathcal{L}_{\rm CPV}
\end{aligned}
$$

- 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*

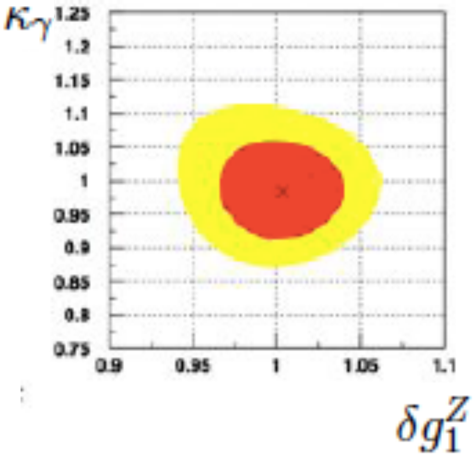
- The relevant primaries are:

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

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

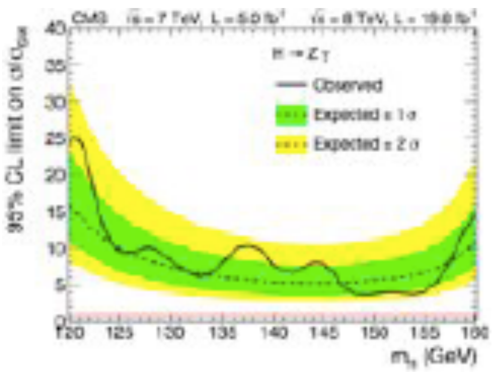
$$\Delta\mathcal{L}_{\kappa_\gamma} = \frac{\delta\kappa_\gamma}{v^2}\left[ie\hat{h}^2(A_{\mu\nu} - t_{\theta_W} Z_{\mu\nu})W^{+\mu}W^{-\nu} + Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W} A^{\mu\nu} - t^2_{\theta_W} Z^{\mu\nu}) + \frac{(\hat{h}^2 - v^2)}{2} \times\left(t_{\theta_W} Z_{\mu\nu}A^{\mu\nu} +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

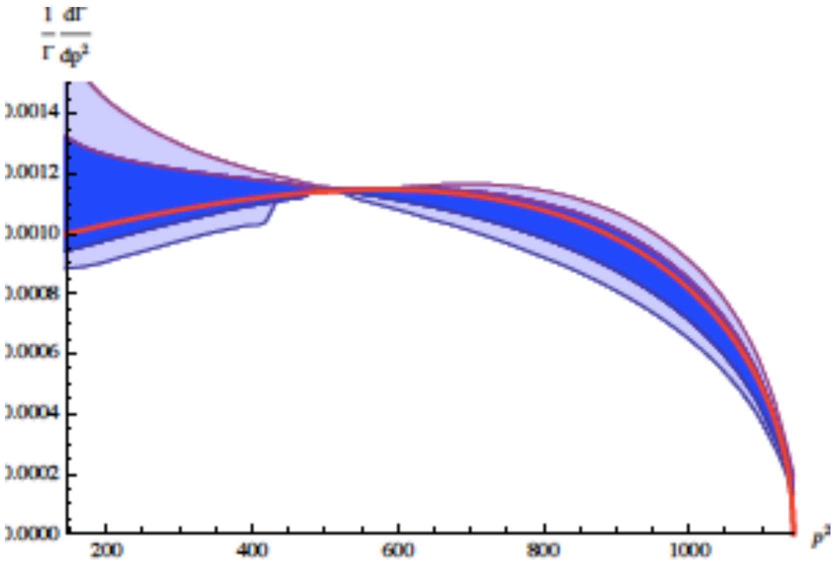
Example: *h ->Zff*



+

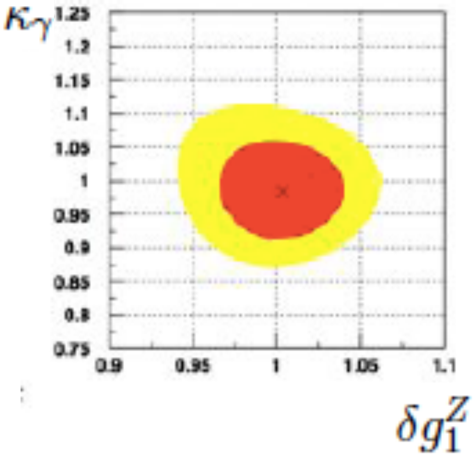
$h \to \gamma Z$





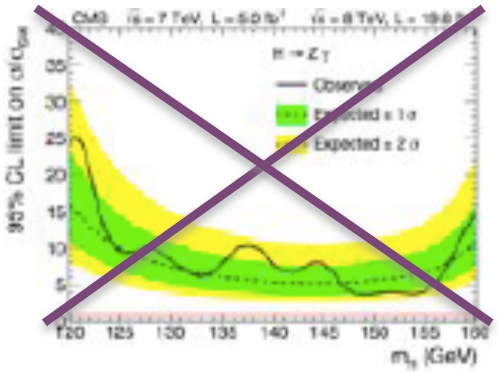
Pomarol & Riva, 2013

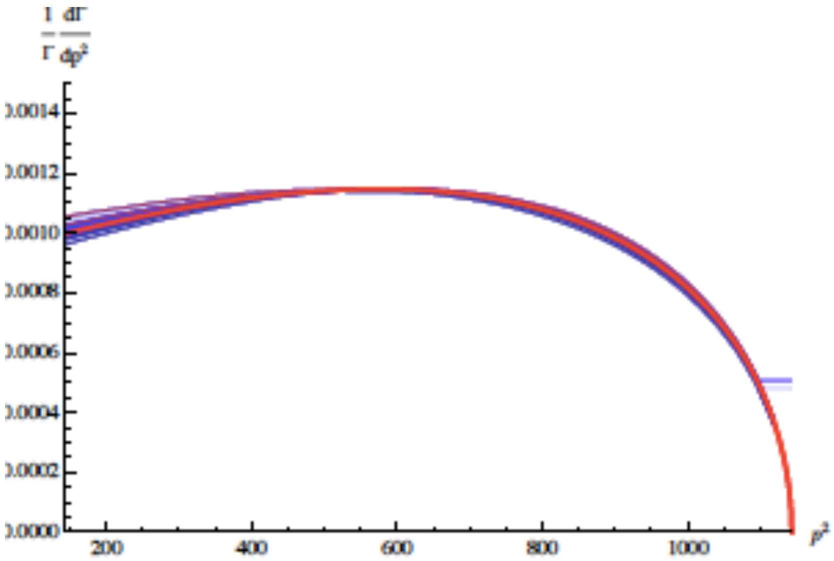
Example: *h ->Zff*



+

$h \to \gamma Z$





Pomarol & Riva, 2013

+ Conclusions

- We first identify the BSM primary effects, the set of physical quantities, that give us the best way to constrain new physics.
- To generate these deformations at the dimension 6 level, other deformations are also generated in a correlated way because of the accidental symmetries at the dimension 6 level.
- We derive these correlations and thus the predictions of the dimension 6 Lagrangian.
- There are 18 primary deformations, 8 Higgs primaries, 7 EWPT primaries and 3 TGC primaries.