BSM Primary Effects

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TIFR Free Meson Seminar

Plan of Talk

- I. BSM Primaries

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

- II. RG induced constraints

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

- III. Measuring higher dimensional deviations at LHC in diboson production.

Banerjee, Englert, RSG, McCullough and Spannowsky (work in progress)

- IV. Expectations in Explicit Models

RSG M. Montull and F. Riva (arxiv: 1312.2928)
RSG H. Rzehak and J.D. Wells (arxiv:1206.3560, 1305.6397)

What if new physics is just beyond LHC reach ?

- Naturalness does not give a strict upper bound on new physics. A factor of few larger masses can lead to an exponential drop in parton luminosities.
- New physics might just be beyond LHC reach. When integrated out this would still lead to indirect effects such as deviations in couplings involving the Higgs and gauge boson.
- Eg. : The S,T parameters at LEP constrain certain kinds of new Physics to scales higher than a few TeV. Much higher than LEP energies.
- In any case now that we have seen the Higgs we must measure its properties as precisely as possible.

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:

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

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Part I: BSM Primary effects and Predictions from the dimension 6 Lagrangian.

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

Variety of Pseudo-observables !

$hW^+_{\mu\nu}W^{-\mu\nu}$

$hA_{\mu\nu}A^{\mu\nu}$, $hA_{\mu\nu}Z^{\mu\nu}$ $hG_{\mu\nu}G^{\mu\nu}$

$h^2\bar{f}f$ $hZ_{\mu\nu}Z^{\mu\nu}$

$hW^{+\mu}W^-_\mu$, $h\bar{f}f$, h^3

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

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

$W^{+\mu}\bar{u}_L\gamma_\mu d_L$

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

$Z^\mu Z^\nu W^-_\mu W^+_\nu$

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

$W^{-\mu}W^{+\nu}W^-_\mu W^+_\nu$

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

Any vertex of SM fields in the EW broken phase in the unitary gauge can be thought of as a pseudo-observable

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Variety of Pseudo-observables !

(1) Higgs observables:

$hW^{+}_{\mu\nu}\, W^{-\mu\nu}$ $hA_{\mu\nu}A^{\mu\nu},\ hA_{\mu\nu}Z^{\mu\nu}\ hG_{\mu\nu}G^{\mu\nu}$ $h^2\bar{f}f\ \ hZ_{\mu\nu}\, Z^{\mu\nu}$

$hW^{+\mu}W^{-}_{\mu},\ h\bar{f}f,\ h^3$ $hZ_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$

These contain the physical Higgs constrained for the first time at LHC in Higgs Production/decay

(2) Electorweak precision observables:

$Z_{\mu}\bar{f}_{L,R}\gamma^{\mu}f_{L,R}$ $W^{+\mu}\bar{u}_L\gamma_{\mu}d_L$

These were measured very precisely at the W/Z-pole in W/Z decays.

(2) Triple and Quartic Gauge couplings:

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

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

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

These were measured in ee->WW process at LEP.

Organizing principle: Effective Field Theory (EFT)

- All these deformations cannot be independent at dimension 6 level. Only 18 independent operators that are involved in

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$
$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$

More observables than operators !

When expanded one operator gives rise to many deformations/vertices/observables.

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

TGCs

$\delta\kappa_\gamma$ $\delta\kappa_Z$

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

$$hA_{\mu\nu}A^{\mu\nu} \; hA_{\mu\nu}Z^{\mu\nu} \; hZ_{\mu\nu}Z^{\mu\nu} \; hW_{\mu\nu}W^{\mu\nu}$$

Higgs Physics

$$\hat{W}^3_{\mu\nu} B^{\mu\nu}$$

S-parameter

1 Operator but 7 observables

+ When Lagrangian written in unitary gauge we get many vertices (observables)

$$
\begin{aligned}
\mathcal{L}_h = \xi \Bigg\{ & \frac{c_H}{2}\left(1+\frac{h}{v}\right)^2 \partial^\mu h \partial_\mu h - c_6 \frac{m_H^2}{2v^2}\left(vh^3 + \frac{3h^4}{2} + \dots\right) + c_y \frac{m_f}{v}\bar{f}f\left(h + \frac{3h^2}{2v} + \dots\right) \\
& + \left(\frac{h}{v} + \frac{h^2}{2v^2}\right)\Bigg[\frac{g^2}{2g_\rho^2}\left(\hat{c}_W W_\mu^- \mathcal{D}^{\mu\nu} W_\nu^+ + \text{h.c.}\right) + \frac{g^2}{2g_\rho^2} Z_\mu \mathcal{D}^{\mu\nu}\left[\hat{c}_Z Z_\nu + \left(\frac{2\hat{c}_W}{\sin 2\theta_W} - \frac{\hat{c}_Z}{\tan\theta_W}\right) A_\nu\right] \\
& - \frac{g^2}{(4\pi)^2}\left(\frac{c_{HW}}{2} W^{+\mu\nu} W^-_{\mu\nu} + \frac{c_{HW} + \tan^2\theta_W c_{HB}}{4} Z^{\mu\nu} Z_{\mu\nu} - 2\sin^2\theta_W c_{\gamma Z} F^{\mu\nu} Z_{\mu\nu}\right) + \dots \\
& + \frac{\alpha g^2 c_\gamma}{4\pi g_\rho^2} F^{\mu\nu} F_{\mu\nu} + \frac{\alpha_s y_t^2 c_g}{4\pi g_\rho^2} G^{a\mu\nu} G^a_{\mu\nu}\Bigg]\Bigg\}
\end{aligned}
\tag{71}
$$

From Giudice, Grojean, Pomarol and Rattazzi (arxiv: hep-ph/0703164)

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$$\mathcal{L}_h = \xi \left\{ \frac{c_H}{2}\left(1+\frac{h}{v}\right)^2 \partial^\mu h \partial_\mu h - c_6 \frac{m_H^2}{2v^2}\left(vh^3 + \frac{3h^4}{2} + \ldots\right) + c_y \frac{m_f}{v} \bar{f} f \left(h + \frac{3h^2}{2v} + \ldots\right) \right.$$

$$+ \left(\frac{h}{v} + \ldots \right) A_\nu \Big]$$

$$- \frac{g^2}{(4\pi)^2} \ldots$$

$$\left. + \frac{\alpha g^2 c_\gamma}{4\pi g_\rho^2} F^{\mu\nu} F_{\mu\nu} + \frac{\alpha_s y_t^2 c_g}{4\pi g_\rho^2} G^{a\mu\nu} G^a_{\mu\nu} \Big] \right\} \qquad (71)$$

No of free parameters in this part of the Lagrangian

= No of Wilson coefficients=18

From Giudice, Grojean, Pomarol and Rattazzi (arxiv: hep-ph/0703164)

18 EW and Higgs Operators

18 Operators

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Many Vertices/pseudo-observables

$hW^+_{\mu\nu} W^{-\mu\nu}$ $hA_{\mu\nu}A^{\mu\nu}$, $hA_{\mu\nu}Z^{\mu\nu}$ $hG_{\mu\nu}G^{\mu\nu}$ $h^2 \bar{f} f$ $hZ_{\mu\nu}Z^{\mu\nu}$

$hW^{+\mu}W^-_\mu$, $h\bar{f}f$, h^3

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

$Z_\mu \bar{f}_{L,R}\gamma^\mu f_{L,R}$ $W^{+\mu}\bar{u}_L \gamma_\mu d_L$

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

Number of contributing operators << Number of vertices/pseudo-observables

18 EW and Higgs Operators

18 Operators

Many Vertices/pseudo-observables

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

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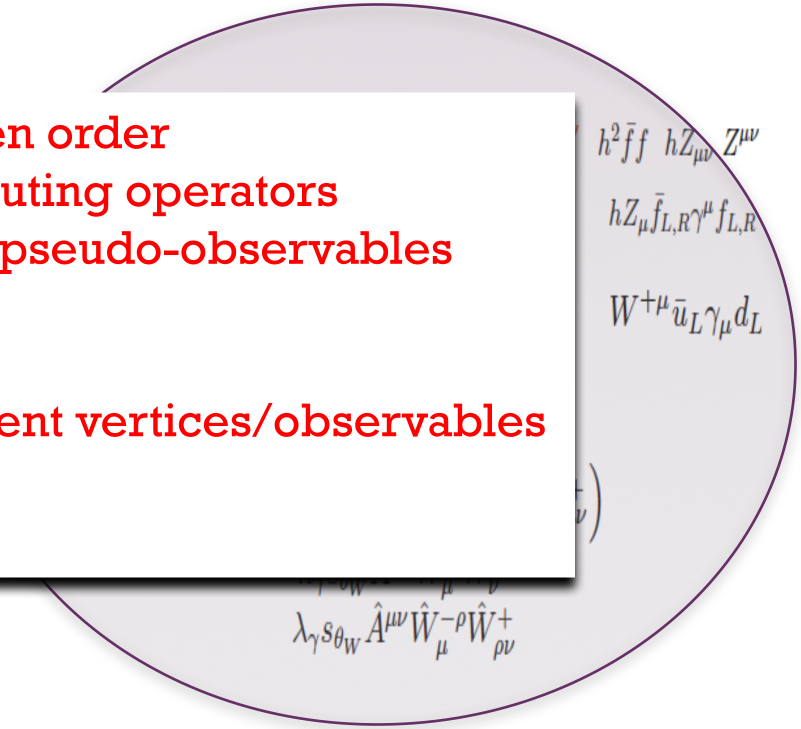
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$



At any given order
Number of contributing operators
<< Number of vertices/pseudo-observables

↓

Correlations between different vertices/observables

BSM Primaries

- 18 best constrained observables become these 18 free parameters.
- We call these BSM Primaries. (see also Pomarol & Riva, 2013, Elias-Miro, Espinosa, Masso & Pomarol, 2013)

Only at LHC

Higgs (8) Physics

$$h \to \gamma\gamma,\ h \to \gamma Z,\ h \to gg$$
$$h \to VV, h \to ff, pp \to h^* \to hh$$

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

Z-pole (7) Data

$$Z \to ff$$
(2 can be traded for S,T)

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TGC (3) Data

$$ee \to WW$$

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

Already at LEP

- A generalization of the Peskin-Takeuchi parameters.

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

Primary and Correlated observables

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

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

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

Deformations correlated at dim-6 level →

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

18 Primary Deformations/Observables

Correlated Deformations/Observables

Higgs Primaries (8)

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

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

EWPT Primaries(7)

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

$$+ Z_\nu\partial_\mu\hat{h}^2(t_{\theta_W}A^{\mu\nu} - t^2_{\theta_W}Z^{\mu\nu}) + \frac{(\hat{h}^2-v^2)}{2} \times\left(t_{\theta_W}Z_{\mu\nu}A^{\mu\nu} + \frac{c_{2\theta_W}}{2c^2_{\theta_W}}Z_{\mu\nu}Z^{\mu\nu} + W^+_{\mu\nu}W^{-\mu\nu}\right)\Bigg]$$

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

The electroweak/Higgs part of the dimension 6 Lagrangian can be written in entirely in terms of these 18 already observables (instead of unknown Wilson Coefficients)

18 Primary vertices,

Coefficient of other vertices already determined by these 18.

Higgs Primaries (8)

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

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

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

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

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

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

EWPT Primaries(7)

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

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

TGC Primaries (3)

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

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

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

BSM Primaries

- 18 observables **best** constrain all Higgs and EW deformations.
- We call these **BSM Primaries.**

(see also Pomarol & Riva, 2013, Elias-Miro, Espinosa, Masso & Pomarol, 2013)

Only at LHC

Higgs (8) Physics

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(2 can be traded for S,T)

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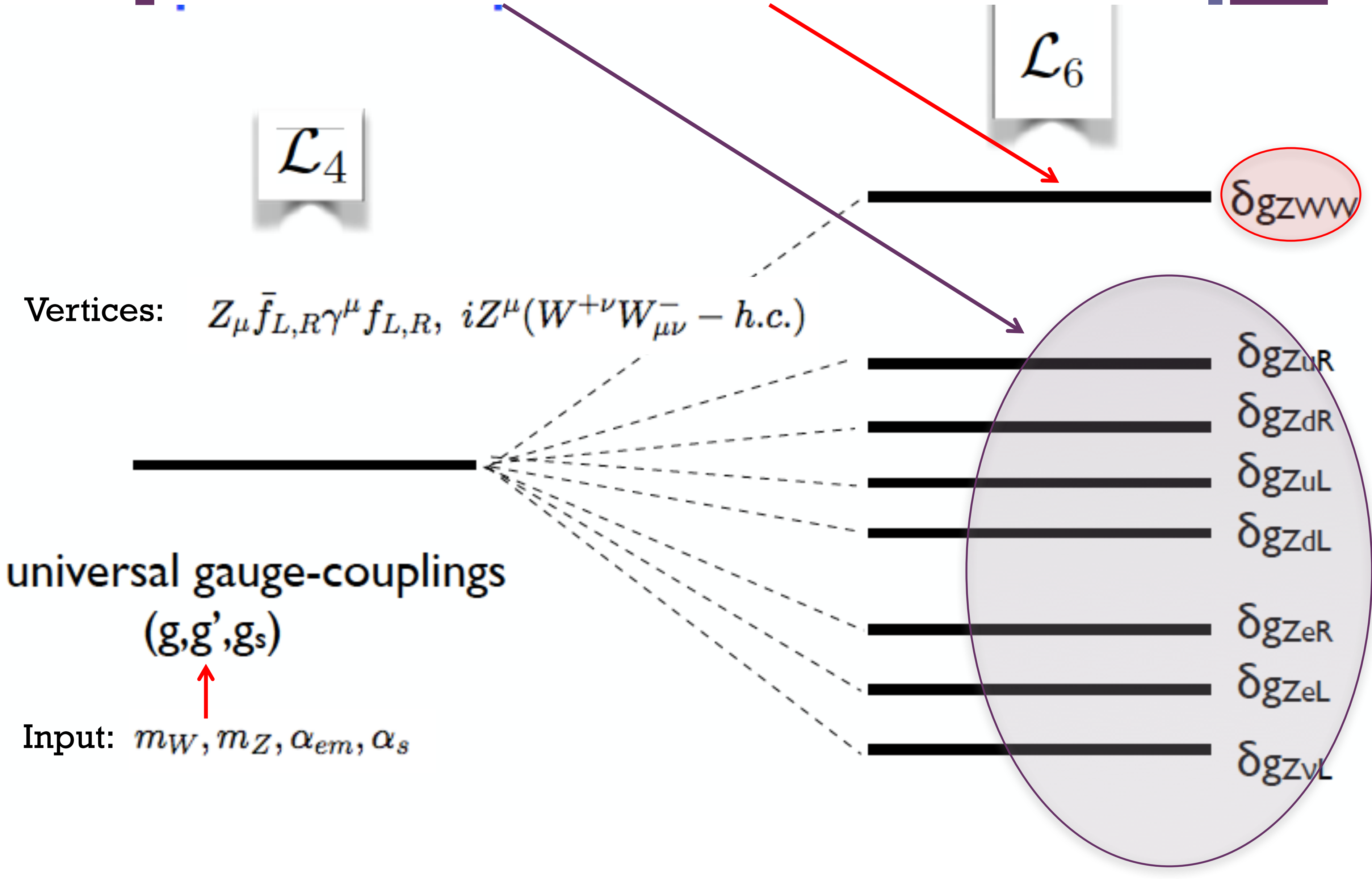
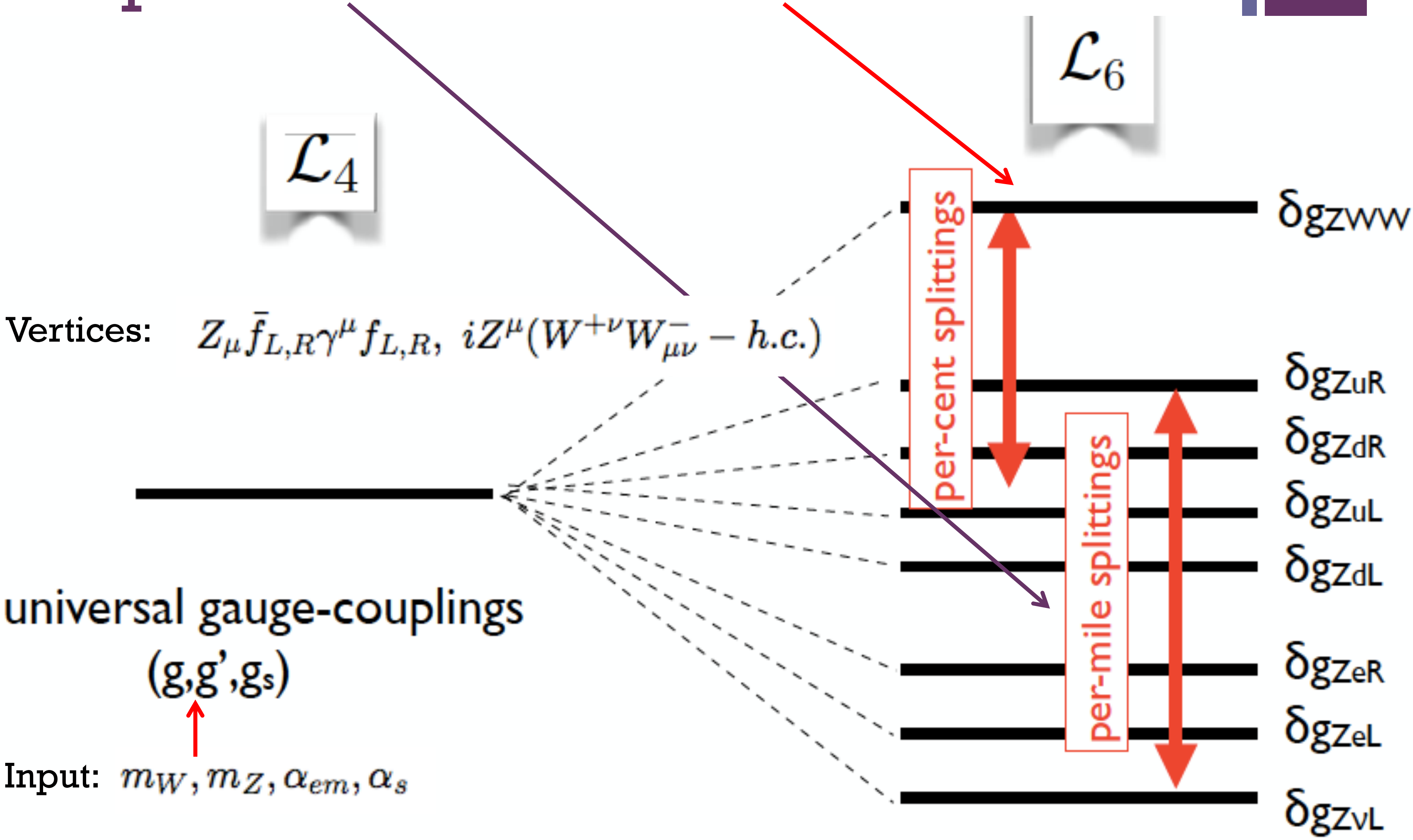
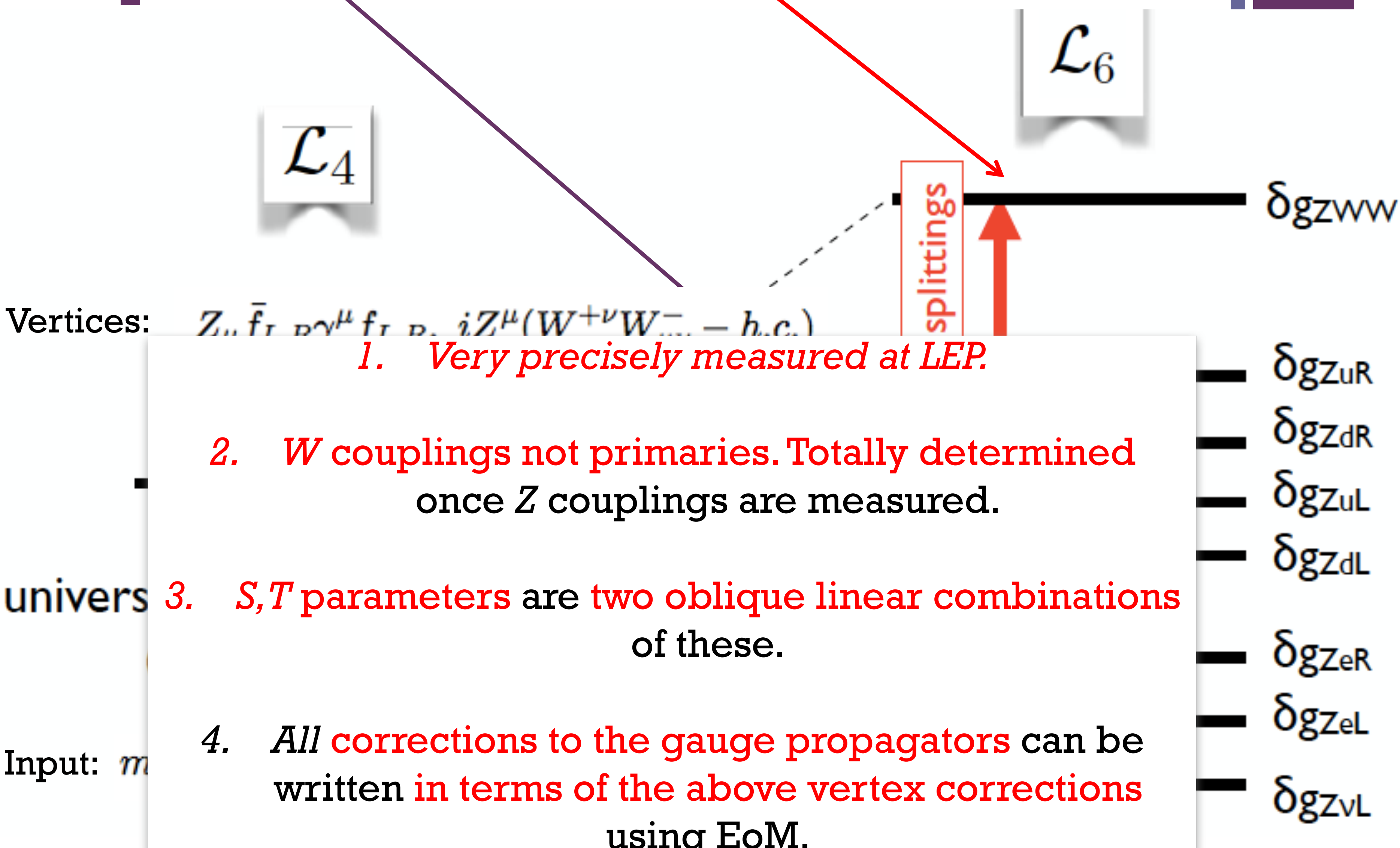
+ Z-pole Primaries + TGC



+ Z-pole Primaries + TGC



Z-pole Primaries + TGC



1. *Very precisely measured at LEP.*

2. *W* couplings not primaries. Totally determined once *Z* couplings are measured.

3. *S,T* parameters are two oblique linear combinations of these.

4. *All* corrections to the gauge propagators can be written in terms of the above vertex corrections using EoM.

Other TGC primaries

- 2 more TGC vertices are primaries:

$$\delta\kappa^{\gamma} W_{\mu}^{+} W_{\nu}^{-} A^{\mu\nu}$$

$$\lambda_{\gamma} s_{\theta_W} A^{\mu\nu} W_{\nu}^{-\rho} W_{\rho\mu}^{+}$$

- Measured at per cent level in *ee->WW* process at LEP.

The Dimension 6 Lagrangian

$$\Delta\mathcal{L}_{h^2SM} = c_V g^2 \hat{h}^4 (W^2 + Z^2/2c^2_{\theta_W}) + c_6 \hat{h}^6 + \frac{\hat{h}^2}{\Lambda^2}\left[c_{WW} g^2 W^a_{\mu\nu} W^{\mu\nu\, a} + c_{BB} g'^2 B_{\mu\nu} B^{\mu\nu}\right]$$

$$+ \; c_{y_f} y_f (\hat{h}^3 \bar{f}_L f_R + h.c)\,,$$

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

$|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$|H|^2 B_{\mu\nu} B^{\mu\nu}$

$H^\dagger H \mathcal{O}_{SM}$ → $|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$ → $e(\hat{h}),\; s_{\theta_W}(\hat{h}),\; g_s(\hat{h}),\; \lambda_h(\hat{h}),\; Z_h(\hat{h})$, $Y_f(\hat{h})$

$|H|^2 |D_\mu H|^2$

$|H|^6$

$|H|^2 \bar{f}_L H f_R + h.c.$

8 operators

Redefining 8 parameters

The Dimension 6 Lagrangian

$$\Delta\mathcal{L}_{h^2SM} = c_V g^2 \hat{h}^4 (W^2 + Z^2/2c^2_{\theta_W}) + c_6 \hat{h}^6 + \frac{\hat{h}^2}{\Lambda^2}\left[c_{WW} g^2 W^a_{\mu\nu} W^{\mu\nu\, a} + c_{BB} g'^2 B_{\mu\nu} B^{\mu\nu}\right]$$
$$+ \; c_{y_f} y_f (\hat{h}^3 \bar{f}_L f_R + h.c)\,,$$

$\hat{h} = v + h$

These operators could never have been probed at LEP as they only redefine parameters in dim-4 Lagrangian in the vacuum.

$\lambda_h(\hat{h}),\; Z_h(\hat{h})$

8 operators

$|H|^2 |D_\mu H|^2$

$|H|^6$

$|H|^2 \bar{f}_L H f_R + h.c.$

Redefining 8 parameters

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$$\Delta\mathcal{L}_{h^2SM} = c_V g^2 \hat{h}^4 (W^2 + Z^2/2c_{\theta_W}^2) + c_6 \hat{h}^6 + \frac{\hat{h}^2}{\Lambda^2}\left[c_{WW} g^2 W^a_{\mu\nu} W^{\mu\nu\, a} + c_{BB} g'^2 B_{\mu\nu} B^{\mu\nu}\right] + c_{y_f} y_f (\hat{h}^3 \bar{f}_L f_R + h.c)\,,$$

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

$H^\dagger H \mathcal{O}_{SM}$ → $|H|^2 G^A_{\mu\nu} G^{A\mu\nu}$, $|H|^2 B_{\mu\nu} B^{\mu\nu}$, $|H|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$, $|H|^2 |D_\mu H|^2$, $|H|^6$, $|H|^2 \bar{f}_L H f_R + h.c.$ → $e(\hat{h}),\ s_{\theta_W}(\hat{h}),\ g_s(\hat{h}),\ \lambda_h(\hat{h}),\ Z_h(\hat{h})$, $Y_f(\hat{h})$

8 operators

Redefining 8 parameters

+

7 Z couplings + 3 TGCs + 8 Higgs observables=18 Primaries

Measurement of these would determine all vertices involved in electroweak/Higgs processes

Amplitudes for 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.

Higgs Primaries (8)

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

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

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

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

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

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

EWPT Primaries(7)

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

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

TGC Primaries (3)

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

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

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

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):

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

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Rest of the 41 operators not considered here

Predictions for Higgs Physics

Most General interactions of a scalar *h.*

$$\mathcal{L}_h^{\text{primary}} = g_{VV}^h\, h \left[W^{+\mu}W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu\right] + g_{3h}\, h^3 + g_{ff}^h\, \left(h\bar{f}_L f_R + h.c.\right)$$
$$+ \kappa_{GG}\frac{h}{v}G^{A\,\mu\nu}G_{\mu\nu}^A + \kappa_{\gamma\gamma}\frac{h}{v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}t_{\theta_W}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}\,,$$

$$\Delta\mathcal{L}_h = \delta g_{ZZ}^h\,\frac{v}{2c_{\theta_W}^2}hZ^\mu Z_\mu + g_{Zff}^h\,\frac{h}{2v}\left(Z_\mu J_N^\mu + h.c.\right) + g_{Wff'}^h\,\frac{h}{v}\left(W_\mu^+ J_C^\mu + h.c.\right)$$
$$+ \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W_{\mu\nu}^- + \kappa_{ZZ}\frac{h}{v}Z^{\mu\nu}Z_{\mu\nu}\,,$$

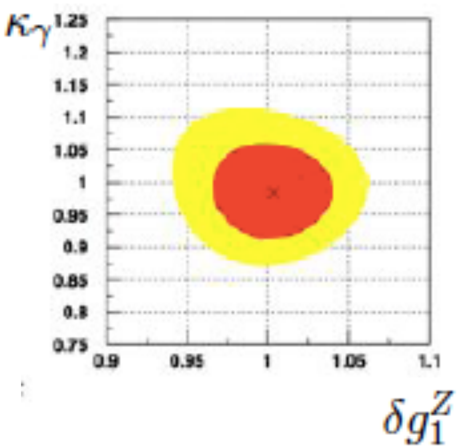
Predictions for doublet component *h* at dim-6 level:

$$\delta g_{ZZ}^h = \delta g_1^Z e^2 - \delta\kappa_\gamma \frac{e^2}{c_{\theta_W}^2}\,,$$

$$g_{Zff}^h = 2\delta g_{ff}^Z - 2\delta g_1^Z(g_f^Z c_{2\theta_W} + eQ_f s_{2\theta_W}) + 2\delta\kappa_\gamma Y_f \frac{e s_{\theta_W}}{c_{\theta_W}^3}\,, \qquad g_{Wff'}^h = 2\delta g_{ff'}^W - 2\delta g_1^Z g_f^W c_{\theta_W}^2\,,$$

$$\kappa_{ZZ} = \frac{1}{2c_{\theta_W}^2}(\delta\kappa_\gamma + \kappa_{Z\gamma}c_{2\theta_W} + 2\kappa_{\gamma\gamma}c_{\theta_W}^2)\,, \qquad \kappa_{WW} = \delta\kappa_\gamma + \kappa_{Z\gamma} + 2\kappa_{\gamma\gamma}\,,$$

+ Example: *h ->Zff*



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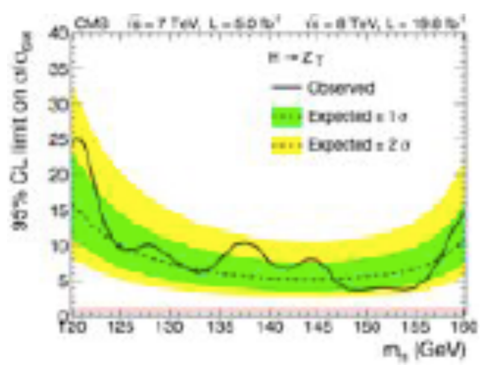
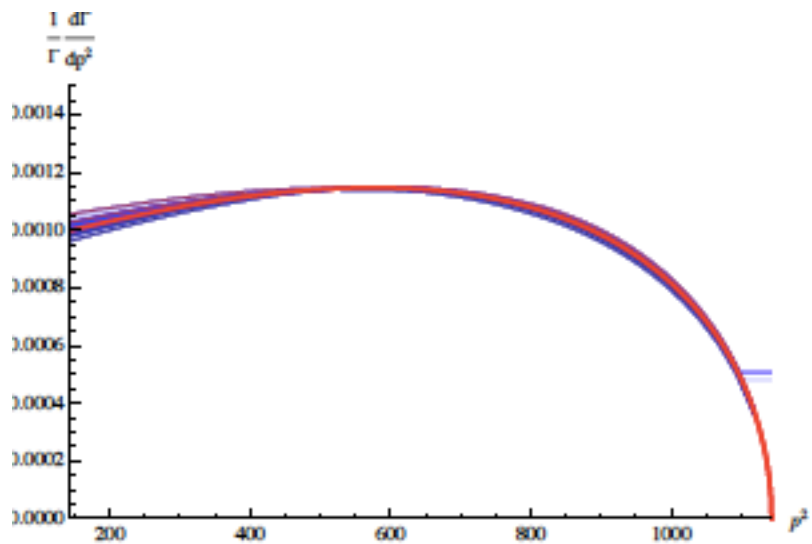
$h \to \gamma Z$



Already constrained !



+

If these predictions are not confirmed, one of our assumptions must have been wrong:

(1) h not part of a doublet.

(2) Scale of new physics not very high and dimension 8 operators cannot be ignored

+ Other Predictions (not involving Higgs)

- W couplings determined once Z couplings are measured
- Quartic Gauge Couplings (QGCs) determined once

This approach has gained some acceptance. The LHC Higgs cross-section working group has now adopted an EFT parametrisation based on this work.

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Volume 2/2017

Handbook of LHC Higgs cross sections:
4. Deciphering the nature of the Higgs sector

Report of the LHC Higgs Cross Section Working Group

Editors: D. de Florian
C. Grojean
F. Maltoni
C. Mariotti
A. Nikitenko
M. Pieri
P. Savard
M. Schumacher
R. Tanaka

Inside the report:

equivalent parameterization of the EFT with D=6 operators. The idea, put forward in Ref. [632], is to parameterize the space of D=6 operators using a subset of couplings in a mass eigenstate Lagrangian, such as the one defined in Eq. (II.2.7) of Section. II.2.1.c. The parameterization described in this section, which differs slightly from that in Ref. [632], is referred to as the *Higgs basis*.[II.8]

Independent couplings

We now describe the choice of independent couplings which defines the Higgs basis.

Dependent couplings

The number of parameters characterizing departure from the SM Lagrangian in Eq. (II.2.7) is larger than the number of Wilson coefficients in a basis of D=6 operators. Due to this fact, there must be relations among these parameters. Working in the Higgs basis, some of the parameters in the mass eigenstate

II. Diboson production at LHC

Banerjee, Englert, RSG, McCullough and Spannowsky
(work in progress)

Diboson production at LHC

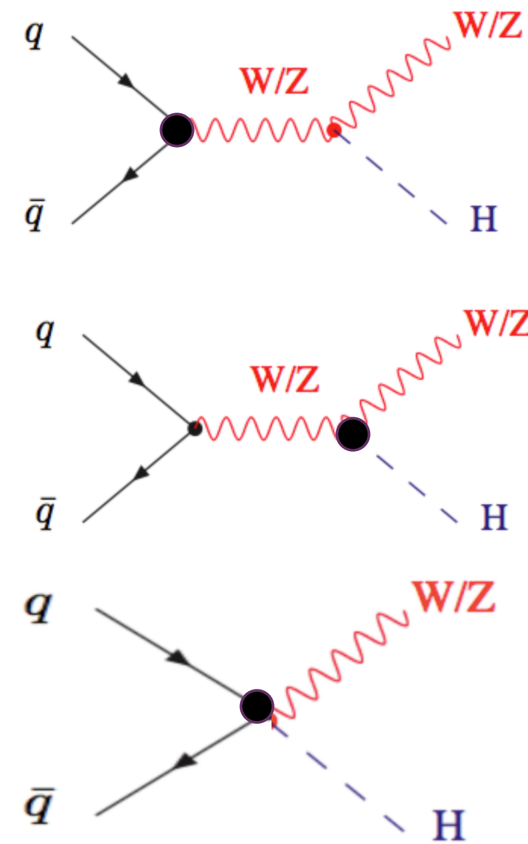
Four channels:

- ZH
- WH
- WW
- WZ

VH production at LHC

- The following vertices in the unitary gauge contribute:

$$
\begin{aligned}
\Delta\mathcal{L}_6 \supset\ & \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
+\ & g_{VV}^h\, h \left[W^{+\mu} W_\mu^- + \frac{1}{2c_{\theta_W}^2} Z^\mu Z_\mu \right] + \delta g_{ZZ}^h\, h \frac{Z^\mu Z_\mu}{2c_{\theta_W}^2} \\
+\ & \sum_f g_{Zff}^h \frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g_{Wud}^h \frac{h}{v} (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.) \\
+\ & \kappa_{Z\gamma} \frac{h}{v} A^{\mu\nu} Z_{\mu\nu} + \kappa_{WW} \frac{h}{v} W^{+\mu\nu} W_{\mu\nu}^- + \kappa_{ZZ} \frac{h}{2v} Z^{\mu\nu} Z_{\mu\nu}\,.
\end{aligned}
$$



VH production at LHC

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$$
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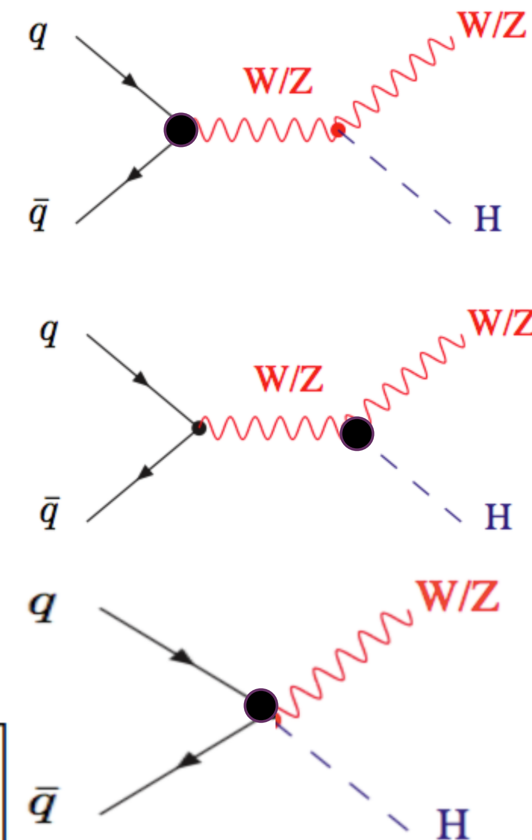
+\ & g^h_{VV}\, h\left[W^{+\mu}W^-_\mu + \frac{1}{2c^2_{\theta_W}} Z^\mu Z_\mu\right] + \delta g^h_{ZZ}\, h\frac{Z^\mu Z_\mu}{2c^2_{\theta_W}} \\
+\ & \sum_f g^h_{Zff}\frac{h}{v} Z_\mu \bar{f}\gamma^\mu f + g^h_{Wud}\frac{h}{v}(W^+_\mu \bar{u}_L\gamma^\mu d_L + h.c.) \\
+\ & \kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu} + \kappa_{WW}\frac{h}{v}W^{+\mu\nu}W^-_{\mu\nu} + \kappa_{ZZ}\frac{h}{2v}Z^{\mu\nu}Z_{\mu\nu}\,.
\end{aligned}
$$

$$
\mathcal{M}(ff \to Z_T h) = g^Z_f \frac{\epsilon^* \cdot J_f}{v}\frac{2m_Z^2}{\hat{s}}\left[1 + \left(\frac{g^h_{Zff}}{g^Z_f} - \kappa_{ZZ}\right)\frac{\hat{s}}{2m_Z^2}\right]
$$

$$
\mathcal{M}(ff \to Z_L h) = g^Z_f \frac{q \cdot J_f}{v}\frac{2m_Z}{\hat{s}}\left[1 + \frac{g^h_{Zff}}{g^Z_f}\frac{\hat{s}}{2m_Z^2}\right],
$$



Leading effect !

+ VH production at LHC

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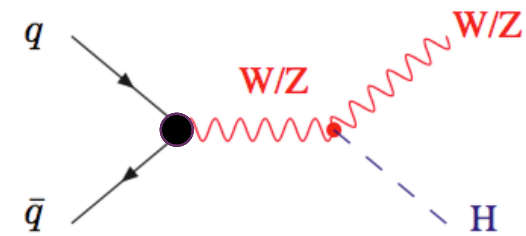
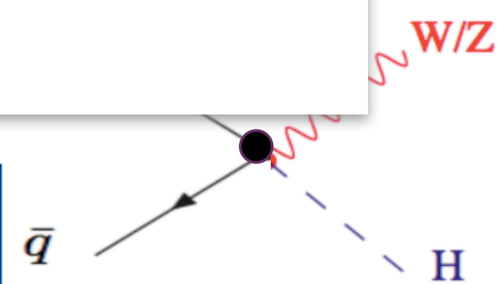
$$\Delta\mathcal{L}_6 \supset \sum_f \delta g_f^Z Z_\mu \bar{f}\gamma^\mu f + \delta g_{ud}^W (W_\mu^+ \bar{u}_L \gamma^\mu d_L + h.c.)$$

$+ \; g_{VV}^h \ldots$

$+ \; \sum_f \ldots$

$+ \; \kappa_{Z\gamma} \ldots$





But all these vertices already correlated to LEP measurements, thus already constrained ! Can LHC do better ?.. give us new information ? May be !

$$\mathcal{M}(ff \to Z_T h) = g_f^Z \frac{\epsilon^* \cdot J_f}{v} \frac{2m_Z^2}{\hat{s}} \left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \kappa_{ZZ} \right) \frac{\hat{s}}{2m_Z^2} \right]$$

$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right],$$

Leading effect !

VH production at LHC

- These vertices can be thus measured in this process. For eg. At high energies:

$$\mathcal{M}(ff \to Z_T h) = g_f^Z \frac{\epsilon^* \cdot J_f}{v} \frac{2m_Z^2}{\hat{s}} \left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \kappa_{ZZ} \right) \frac{\hat{s}}{2m_Z^2} \right]$$

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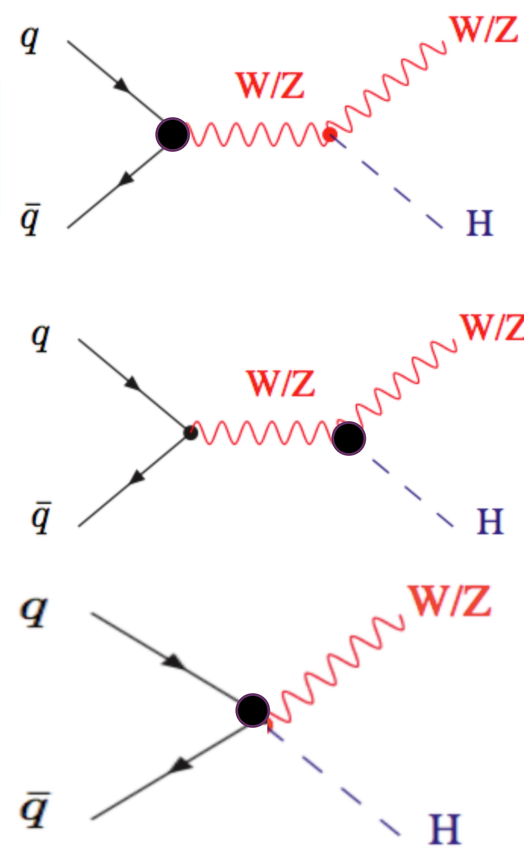

- LEP constraint at 0.001-0.01 level. LHC needs to measure it only at 10 % level because of energy enhancement

VH production at LHC

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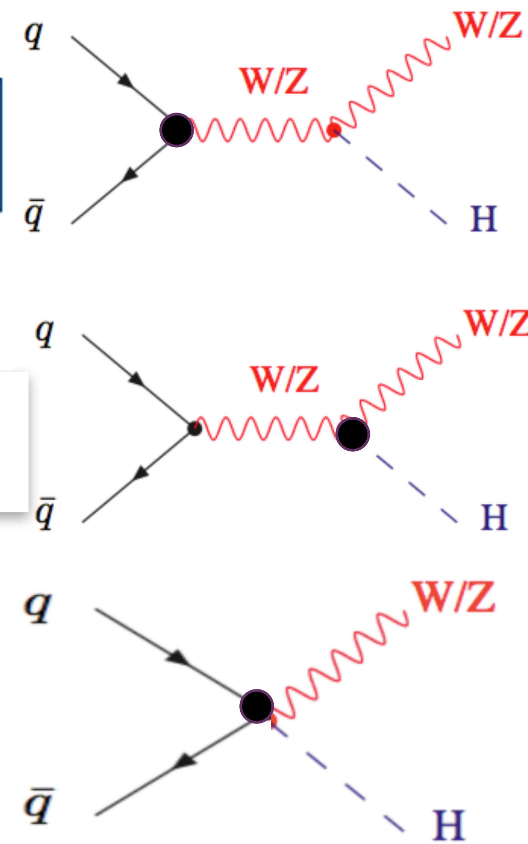
$$g^h_{Zff} = 2\delta g^Z_f - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c^2_{\theta_W}}$$



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+ VH production at LHC

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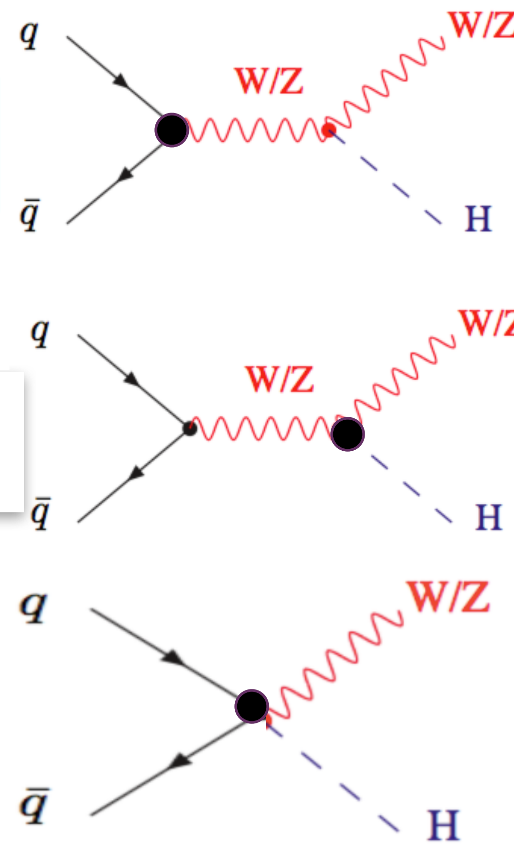
$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g^h_{Zff}}{g_f^Z} \frac{\hat{s}}{2m_Z^2}\right],$$

$$g^h_{Zff} = 2\delta g_f^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c^2_{\theta_W}}$$



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+ VH production at LHC

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$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g^h_{Zff}}{g^Z_f} \frac{\hat{s}}{2m_Z^2} \right],$$

$$g^h_{Zff} = 2\delta g^Z_f - 2\delta g^Z_1 (g^Z_f c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c^2_{\theta_W}}$$

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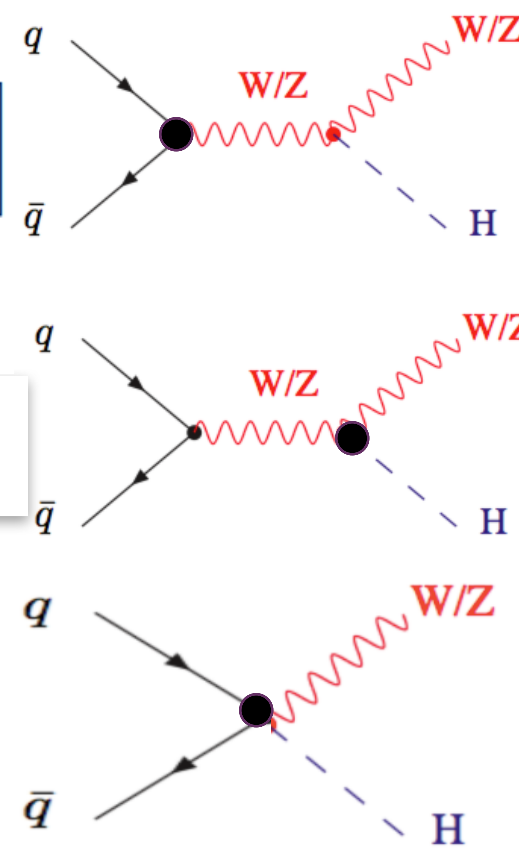


VH production at LHC

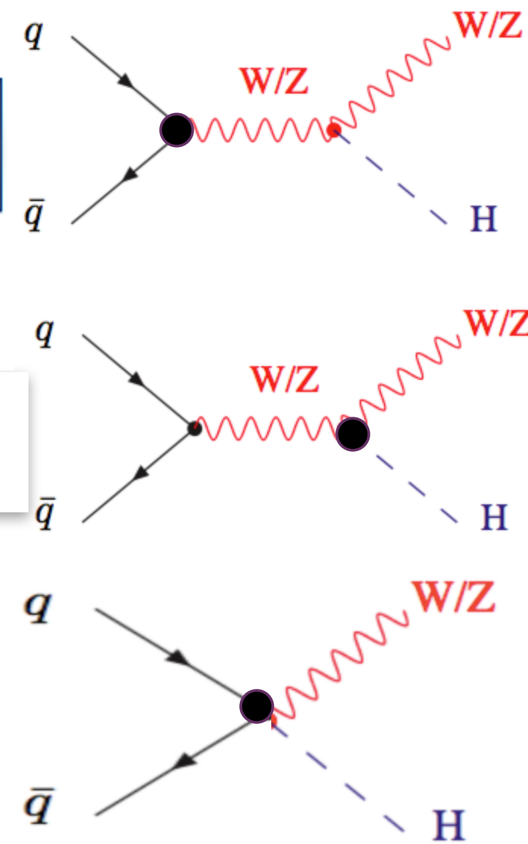
Factor of 100

- These vertices can be thus measured in this process. For eg. At high energies:

$$\mathcal{M}(ff \to Z_T h) = g_f^Z \frac{\epsilon^* \cdot J_f}{v} \frac{2m_Z^2}{\hat{s}} \left[1 + \left(\frac{g_{Zff}^h}{g_f^Z} - \kappa_{ZZ} \right) \frac{\hat{s}}{2m_Z^2} \right]$$

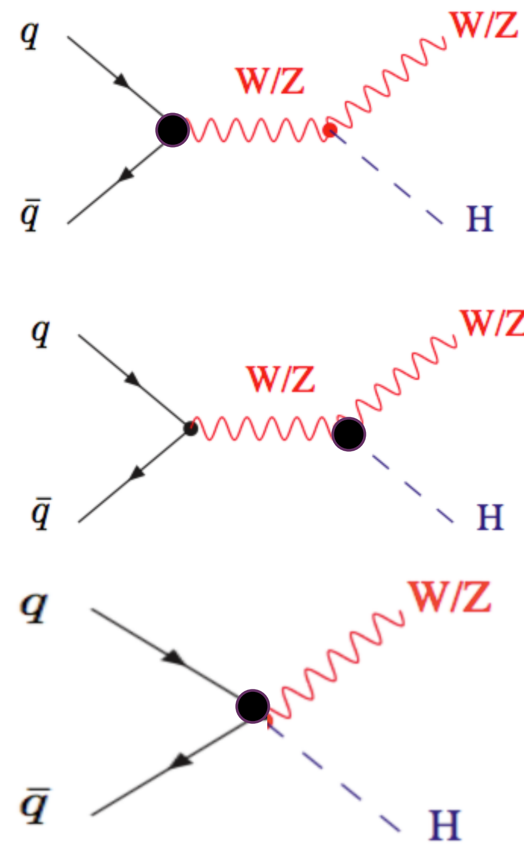
$$\mathcal{M}(ff \to Z_L h) = g_f^Z \frac{q \cdot J_f}{v} \frac{2m_Z}{\hat{s}} \left[1 + \frac{g_{Zff}^h}{g_f^Z} \frac{\hat{s}}{2m_Z^2} \right],$$

$$g_{Zff}^h = 2\delta g_f^Z - 2\delta g_1^Z (g_f^Z c_{2\theta_W} + eQ s_{2\theta_W}) + 2\delta\kappa_\gamma g' Y \frac{s_{\theta_W}}{c_{\theta_W}^2}$$



- LEP constraint at 0.001-0.01 level. To be as sensitive as LEP, LHC needs to measure this process at 10 % level because of energy enhancement

VH production at LHC



- Can a 10% accuracy be achieved in high energy bins for this process ?
- Use of subjet techniques for boosted *h->bb* likely required.

Banerjee, Englert, RSG, McCullough and Spannowsky (work in progress)

Diboson production at LHC

Four channels:

- ZH $\longrightarrow$ G^0 H
- WH $\longrightarrow$ G^+H
- WW $\longrightarrow$ G^+ G^-
- WZ $\longrightarrow$ G^+G^0

- These different final states are connected by more than nomenclature.
- At high energies longitudinal W/Z production dominates.
- Using goldstone boson equivalence theorem one can compute amplitudes for various components of Higgs doublet in the unbroken phase.
- Full SU(2) symmetry manifest

Franceschini, Panico,Pomarol, Riva & Wulzer
arxiv:712.01310

+ Diboson production at LHC

Four channels:

- ZH ⟶ G^0 H
- WH ⟶ G^+H
- WW ⟶ G^+ G^-
- WZ ⟶ G^+G^0

$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g^Z_{uL} - \delta g^Z_{dL})/g - c^2_{\theta_W}\delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{dL}/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g^Z_{uL}/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t^2_{\theta_W}\delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g^Z_{fR}/g\right]$

HV and *VV* processes amplitude connected by symmetry. They constrain the same set of observables at high energies

Franceschini, Panico, Pomarol, Riva & Wulzer
arxiv:712.01310

Diboson production at LHC

Four channels:

- ZH ⟶ G^0 H
- WH ⟶ G^+H
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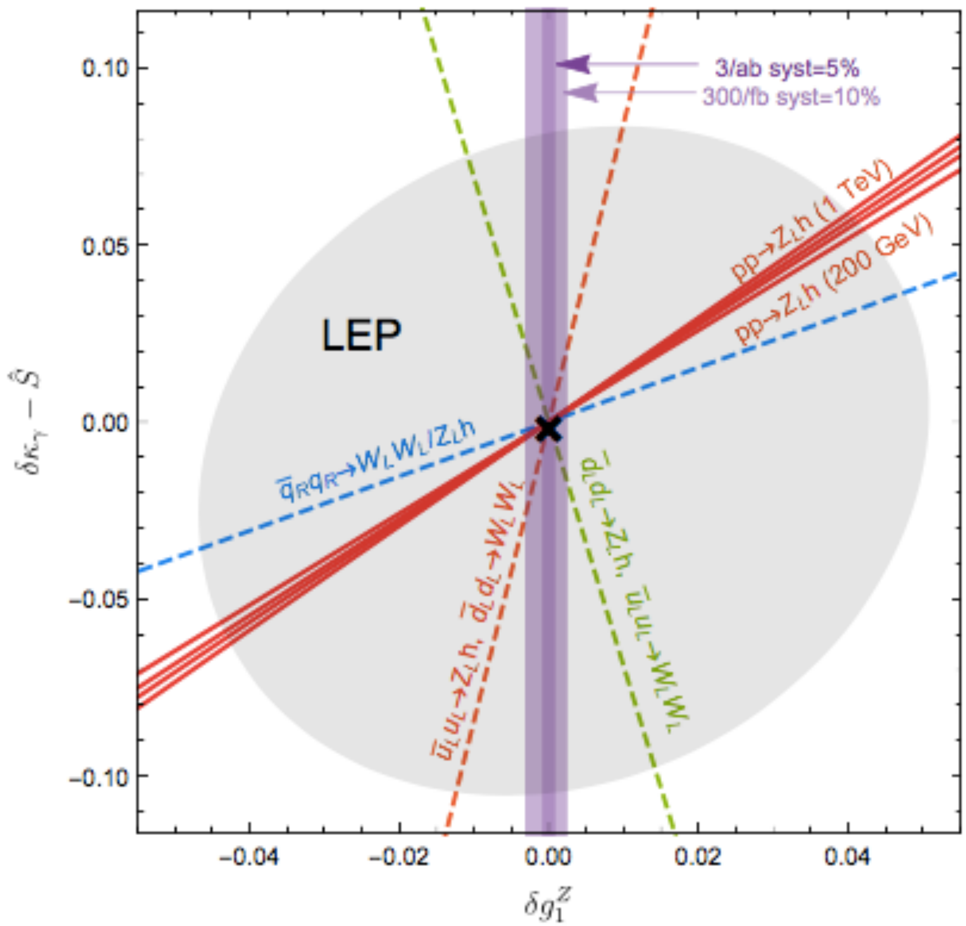


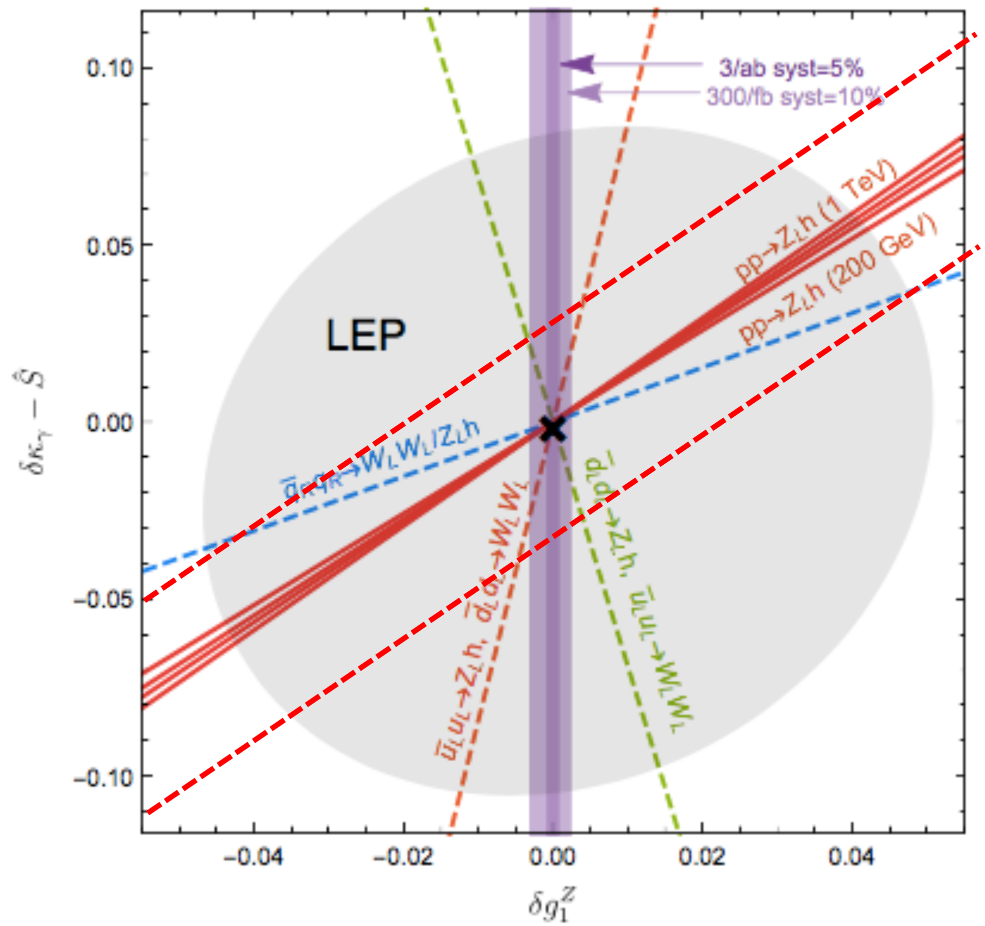
Franceschini, Panico,Pomarol, Riva & Wulzer
arxiv:712.01310

Diboson production at LHC

Four channels:

- ZH ⟶ G^0 H
- WH ⟶ G^+H
- WW ⟶ G^+ G^-
- WZ ⟶ G^+G^0

Our study pp-> ZH(bb) constrains a complementary direction in the same plane.



Franceschini, Panico,Pomarol, Riva & Wulzer
arxiv:712.01310

Part II: RG-induced constraints

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

+ 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 *hγγ*. 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

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

RG-flow ?

$\kappa_{Z\gamma}$

δg^Z_1 $\delta\kappa_\gamma$ λ_γ — percent level

RG-flow ?

$\kappa_{\gamma\gamma}$ 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 (mw).

(Pomarol & Riva 2013)

Anomalous Dimensional Matrix

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

	$\hat{c}_S$	$\hat{c}_T$	$\hat{c}_Y$	$\hat{c}_W$	$\hat{c}_{\gamma\gamma}$
$\gamma_{\hat{c}_S}$	$\frac{1}{3}g'^2+6y_t^2$	$-\frac{g^2}{2}$	$\frac{1}{8}g'^2\left(147-106\frac{g'^2}{g^2}\right)$	$\frac{1}{8}\left(77g^2+58g'^2\right)$	$16e^2$
$\gamma_{\hat{c}_T}$	$-9g'^2-24t_{\theta_W}^2\lambda$	$\frac{9}{2}g^2+12y_t^2+12\lambda$	$\frac{9}{2}g'^2+12t_{\theta_W}^2(g'^2+\lambda)$	$\frac{9}{2}g'^2$	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

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

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

- 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 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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$\hat{c}_{\gamma\gamma}(m_t)$	$[-1,2]\times 10^{-3}$ [18]	-
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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.

Part IV: 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:

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

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

Giudice, Grojean, Pomarol and Rattazzi (2007)

Composite Models

Couplings	Level	Scaling
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	$\frac{1}{\Lambda^2}$
δg^h_{VV}	Strong RG-induced constraint from *S*, *T*	$\frac{g_*^2}{16\pi^2\Lambda^2}$
$\kappa_{\gamma\gamma}$ 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	$\frac{g_{SM}^2}{16\pi^2\Lambda^2}$

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} — $\frac{g_*^2}{16\pi^2\Lambda^2}$

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

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

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

Composite Models

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

$\kappa_{Z\gamma}$ δg^h_{VV}

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

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

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

$\kappa_{\gamma\gamma}$ 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

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

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

Composite Models

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

Left-right symmetry

$\kappa_{Z\gamma}$ δg^h_{VV}

δg^Z_1 $\delta \kappa_\gamma$ λ_γ

percent level — $\dfrac{1}{\Lambda^2}$

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

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

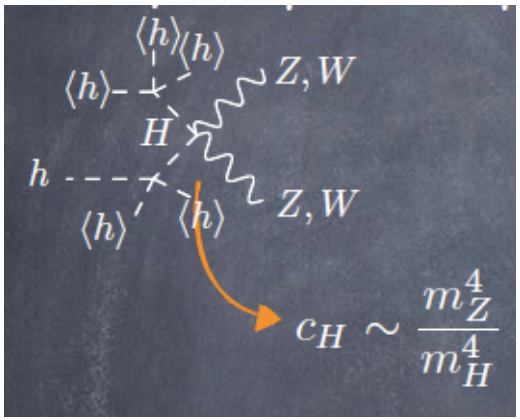
$\dfrac{g_{SM}^2}{16\pi^2\Lambda^2}$

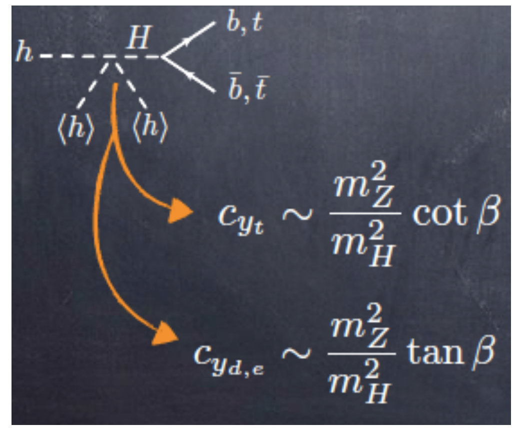
$\hat{S}$ $\hat{T}$

Custodial symmetry

Integrating out heavy Higgses in SUSY

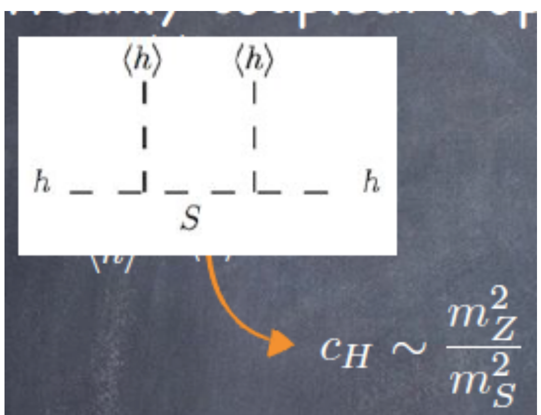
- Supersymmetric models (2HDMS)

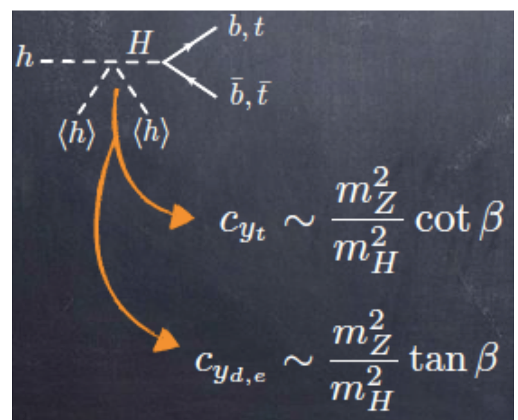




- NMSSM

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





Integrating out heavy Higgses in SUSY

2HDM: $\delta g^h_{ff} \quad \delta g_{3h}$ } $\mathcal{O}(1)$

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

$\delta g^Z_1 \quad \delta\kappa_\gamma \quad \lambda_\gamma$

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

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

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

} permille level

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

$\kappa_{\gamma\gamma}$ 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

+ 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:

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

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

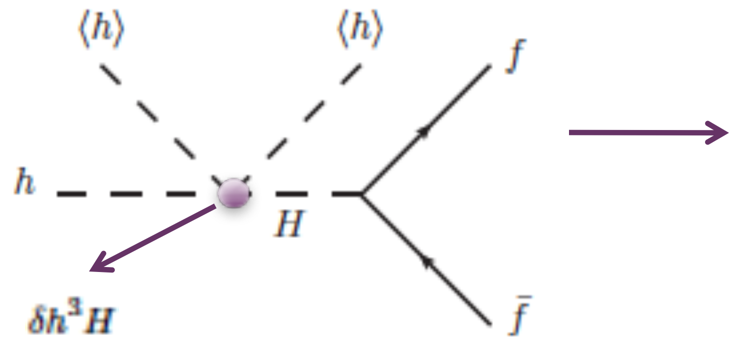
raises Higgs mass

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

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

+ Understanding SUSY Higgs coupling deviations

- Integrate out H to obtain:



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

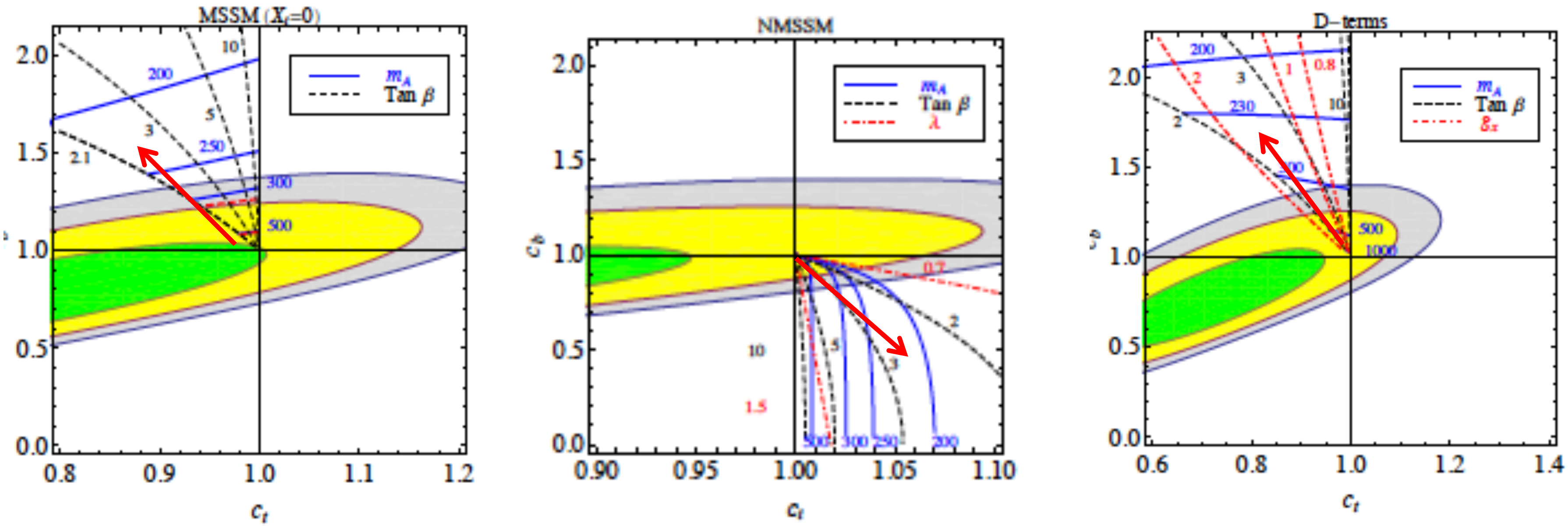
$$c_t \approx 1 + 4\cot\beta\,\delta\frac{v^2}{m_H^2}$$

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

	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)	$\frac{\lambda}{2}\lvert H_2\rvert^4 = \frac{3y_t^4}{8\pi^2}\log[m_{\tilde{t}_1}m_{\tilde{t}_2}/M_t^2]\lvert H_2\rvert^4$	$s_\beta^4\frac{\lambda_2}{8}$	$-4s_\beta^3 c_\beta\frac{\lambda_2}{8}$
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)

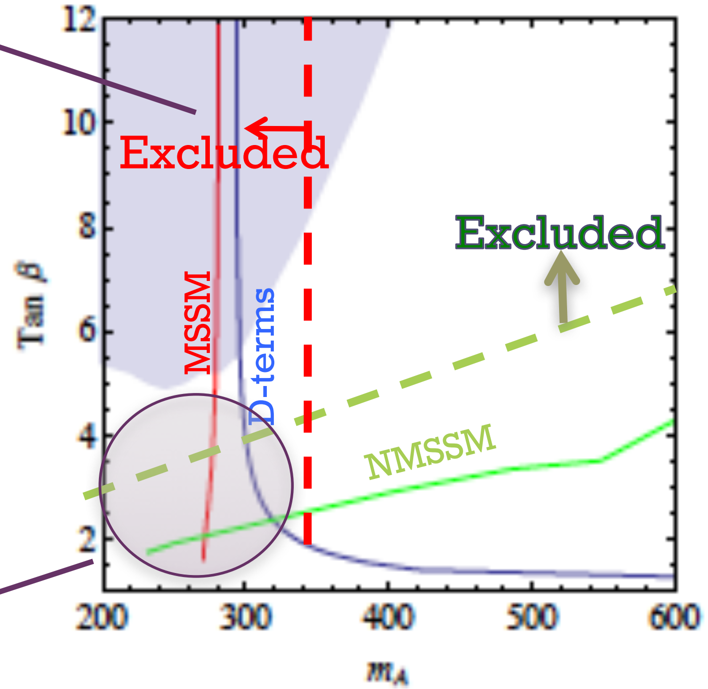
NMSSM (δ>0)

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->ττ



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

Dashed: Barbieri et al (2012)
with more recent data
Solid lines: our 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.
- Using this approach we study the diboson process at high energies at LHC and show how it can beat LEP bounds
- We find that RG-induced constraints on the *hVV* and TGC primaries due to mixing with the *Hγγ* and *S*-parameter primary directions can be stronger to (or of the same order as) tree level constraints.
- We show how Higgs coupling deviations can be used to infer the mechanism of raising Higgs mass in SUSY,