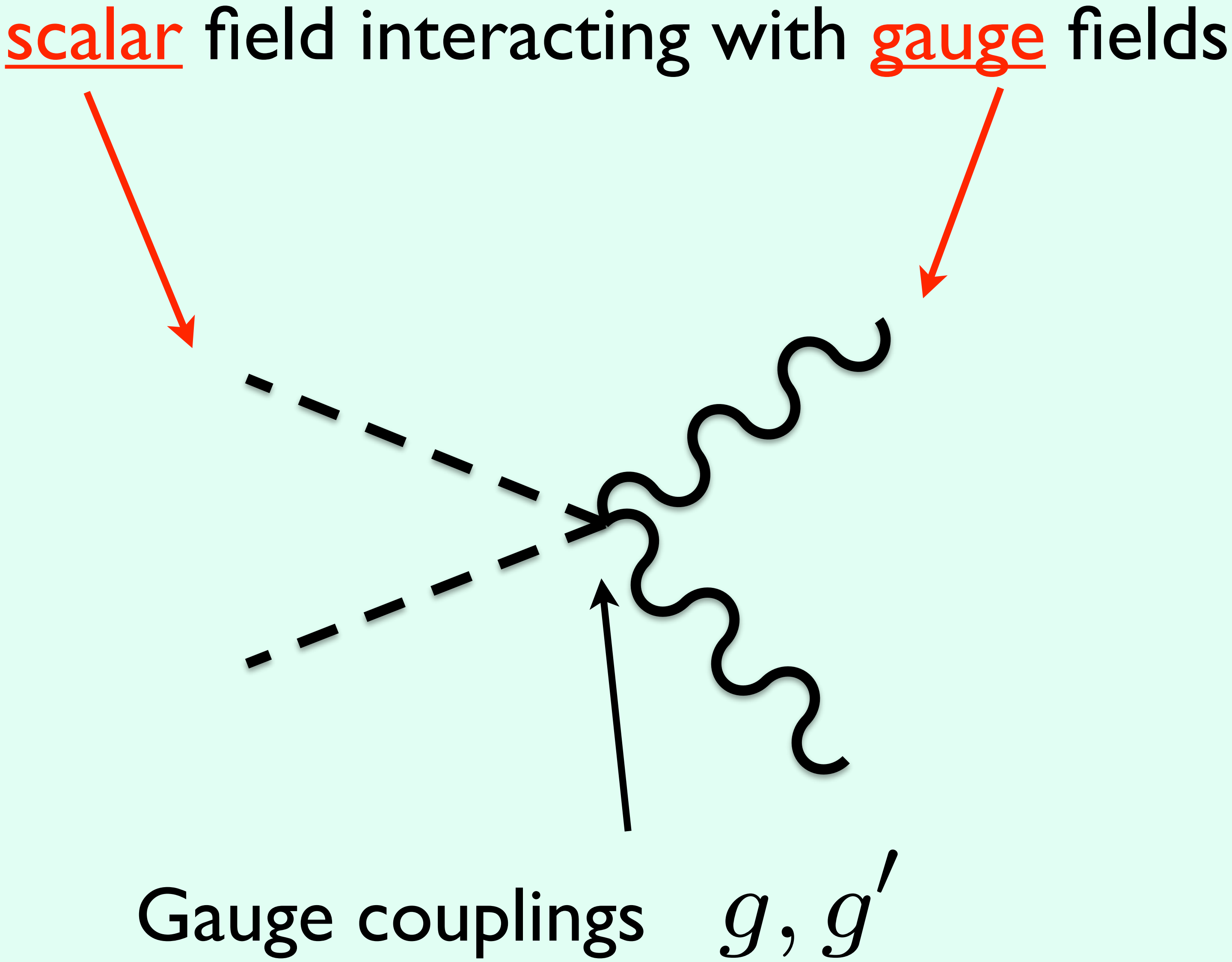
The origin of the Higgs in the Standard Model

Need to break electroweak symmetry

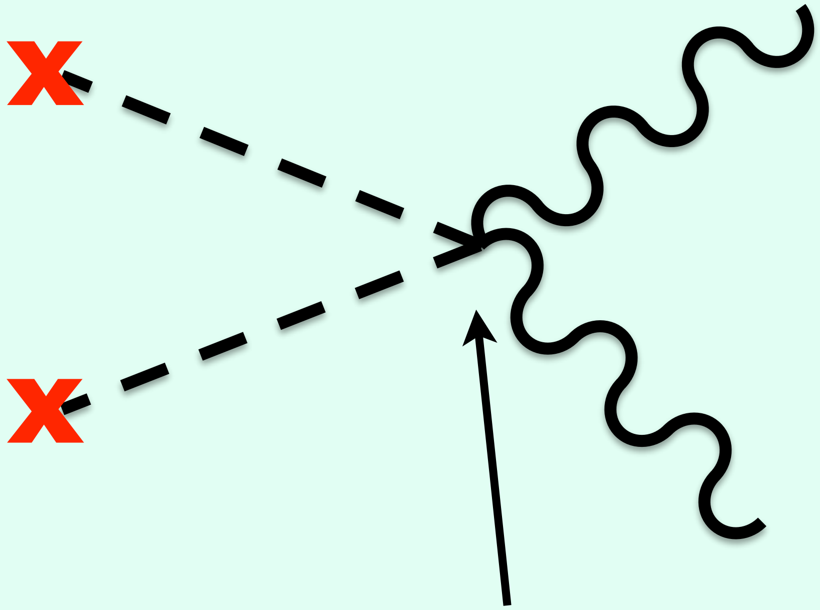


scalar field interacting with gauge fields

Gauge couplings $g\,,\,g'$

The origin of the Higgs in the Standard Model

SSB
Energy scale
v



Gauge couplings g, g'

Standard Model: most economical SSB

New degrees of freedom: 4=3+1

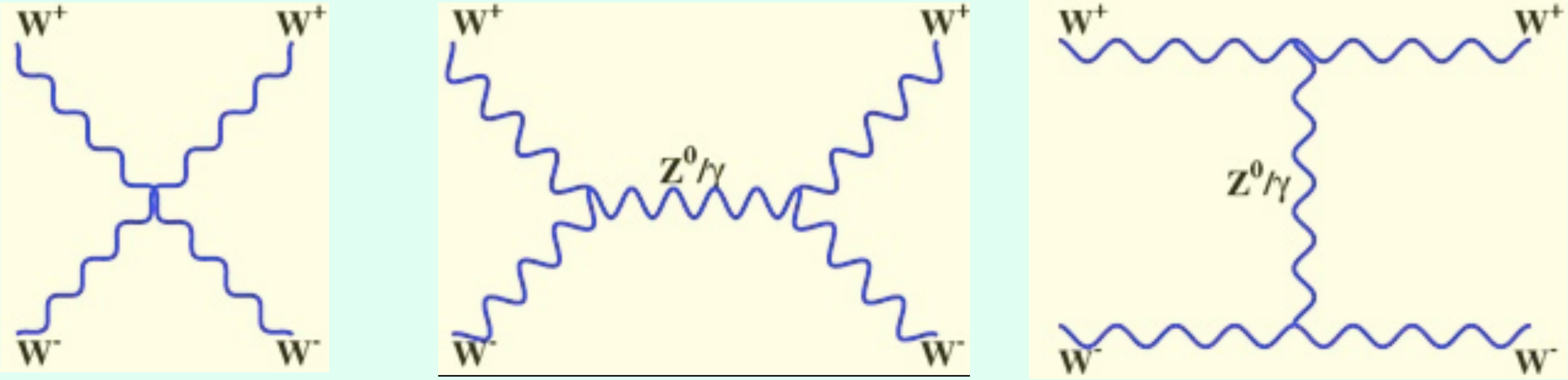
3 $W_L^\pm, Z_L$

$$M_W = \frac{g}{2} v \qquad M_Z = \frac{\sqrt{g^2 + g'^2}}{2} v \qquad M_A = 0$$

1 Higgs scalar h

Unitarity

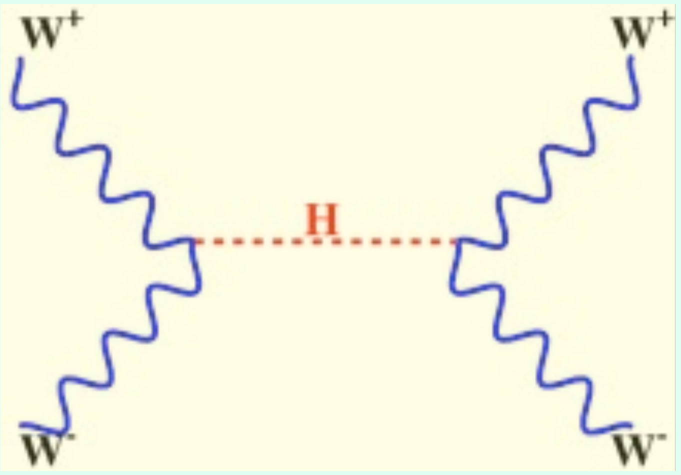
$$WW \to WW$$

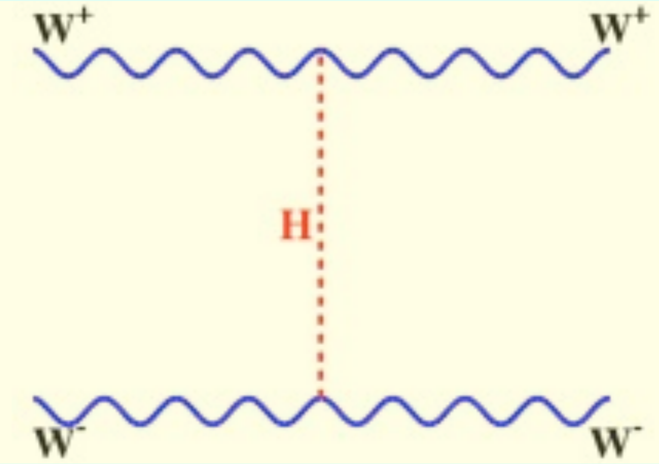


$$\mathcal{M}_{gauge} \sim \frac{s}{M_W^2} \qquad s \gg M_W^2$$

Dominant contribution from $W_L^{\pm}, Z_L$

Unitarity





Text

$$\mathcal{M}_{higgs} \sim -\frac{s}{M_W^2}\,\frac{s}{s-M_h^2}$$

Cancellation

of linear growing

$$\mathcal{M}_{gauge} + \mathcal{M}_{higgs}$$

(for a light scalar)

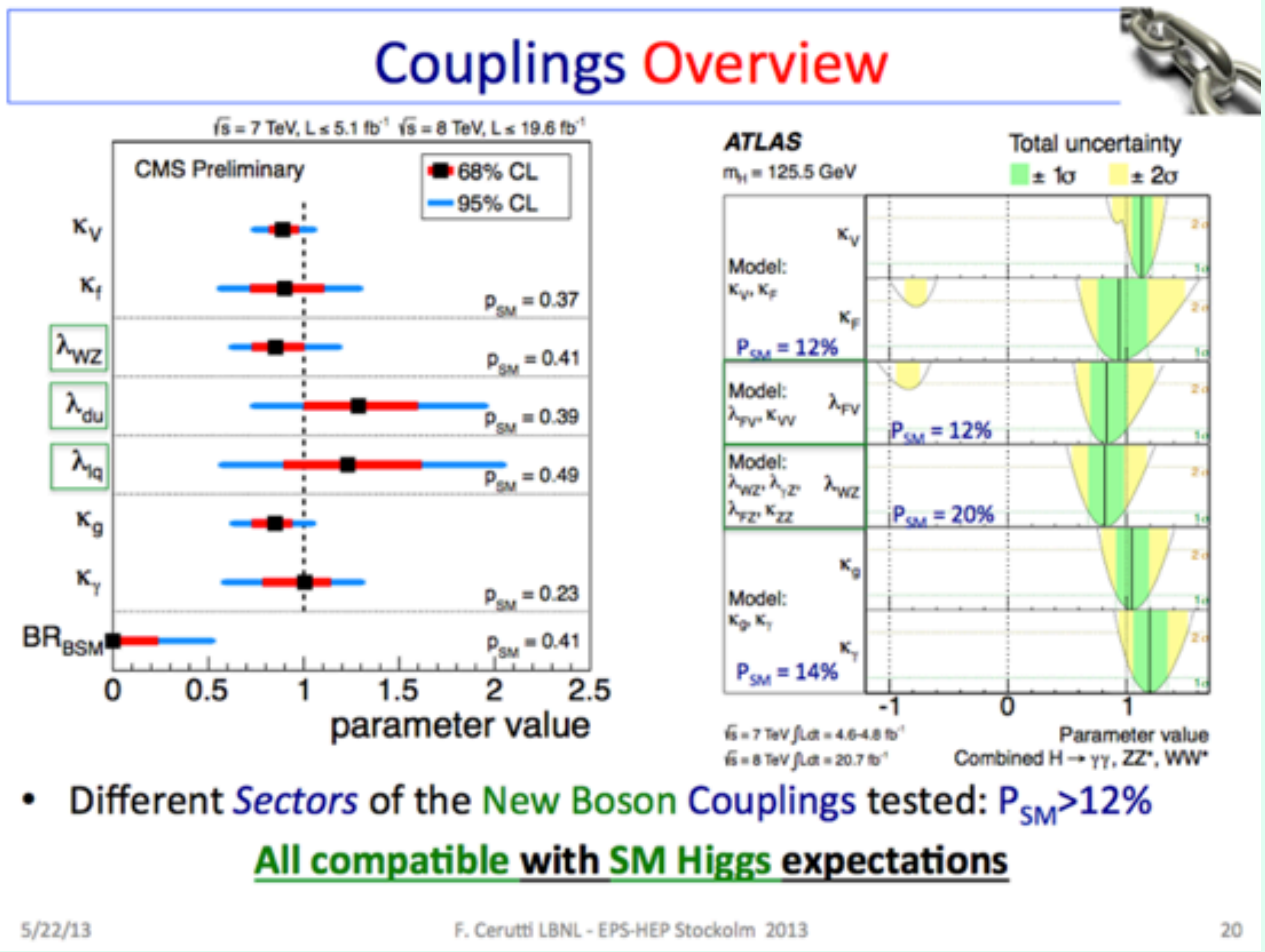
LHC searches

(and previously LEP and Tevatron)

Fundamental scalar ?

(at electroweak scale)

SM-like scalar ...



Couplings Overview

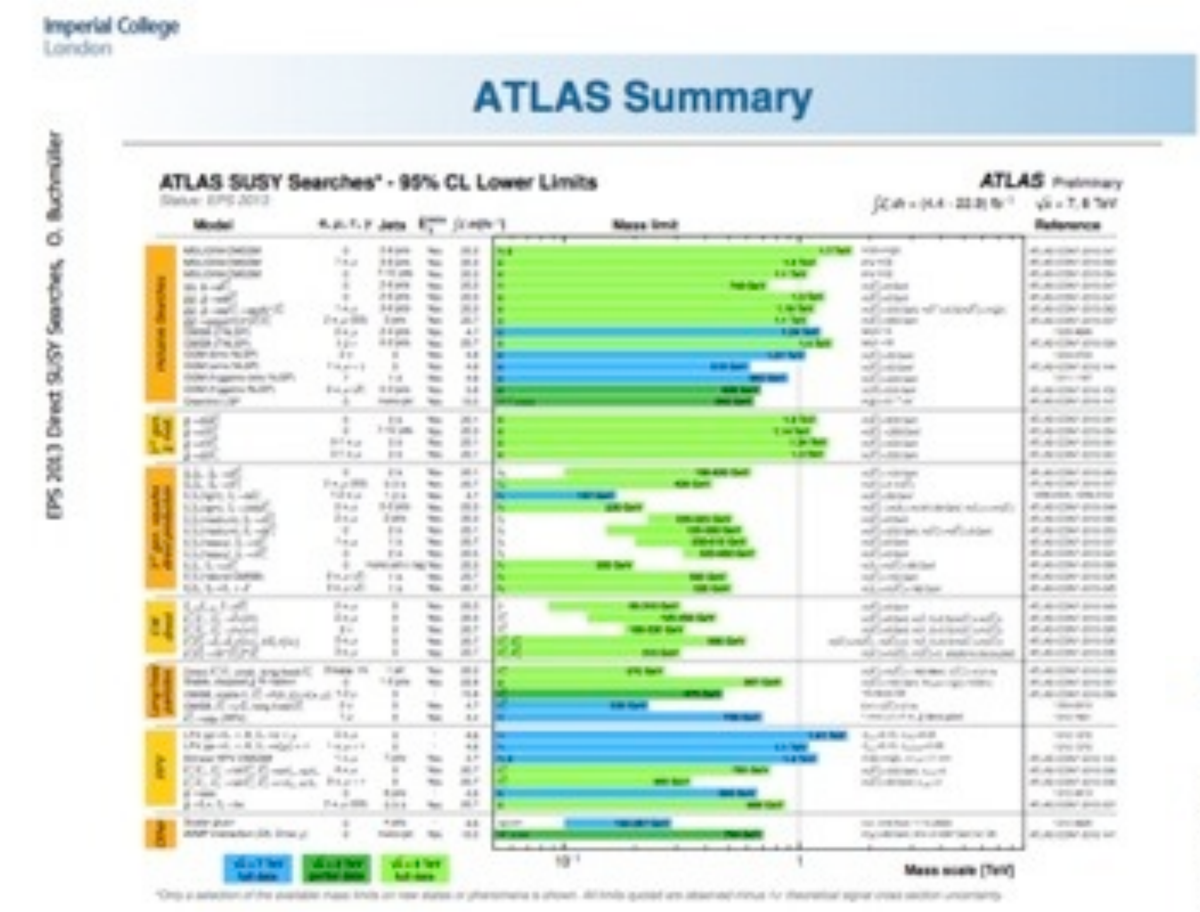
- Different *Sectors* of the New Boson Couplings tested: P_{SM}>12%

All compatible with SM Higgs expectations

5/22/13 F. Cerutti LBNL - EPS-HEP Stockolm 2013 20

F. Cerutti
EPS 2013

… and nothing else



Imperial College London

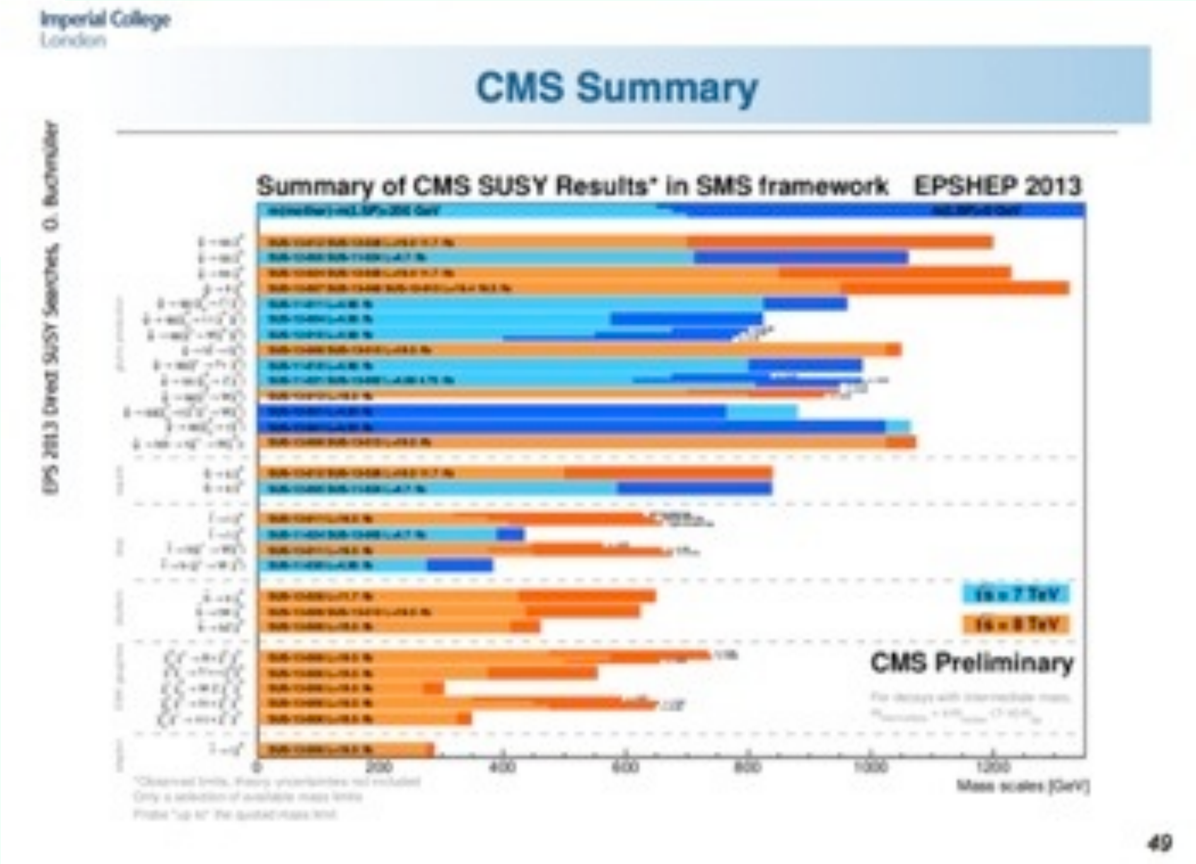
ATLAS Summary

ATLAS SUSY Searches* - 95% CL Lower Limits

ATLAS Preliminary

EPS 2013 Direct SUSY Searches, O. Buchmuller

SUSY searches
(similar for other BSM)



Imperial College London

CMS Summary

Summary of CMS SUSY Results* in SMS framework EPSHEP 2013

EPS 2013 Direct SUSY Searches, O. Buchmuller

CMS Preliminary

49

O. Buchmuller
EPS 2013

Effective Lagrangian approach

- BSM at high scale
  would modify h(126) properties

$$\Lambda \gg M_W$$

- Integrate heavy dof
  obtain d=6 operators formed with SM fields

$$c\,\frac{1}{\Lambda^2}\,\mathcal{O}_6$$

Wilson coefficient

d=6 operator

High-enery scale
(suppresses effects)

Describe quasi-SM Higgs
i.e. SM field with (slightly) modified couplings

Effective Higgs Lagrangians

Eduard Massó
Universitat Autònoma Barcelona

In collaboration with
Joan Elias-Miró, José Ramón Espinosa and Alex Pomarol
and S. Gupta and F. Riva work in progress

hep-ph 1302.5661 and 1308.1879

Outline

- Basis of d=6 operators
- Constraints on Wilson coeffs.
- Renormalization
- Conclusions

Operator basis

How many independent d=6 operators ?

(after using EOM, partial int., identities
to eliminate redundancies)

Buchmuller & Wyler 86
Grzadkowski, Iskrzynski, Misiak, Rosiek10

Operator basis

How many independent d=6 operators ?

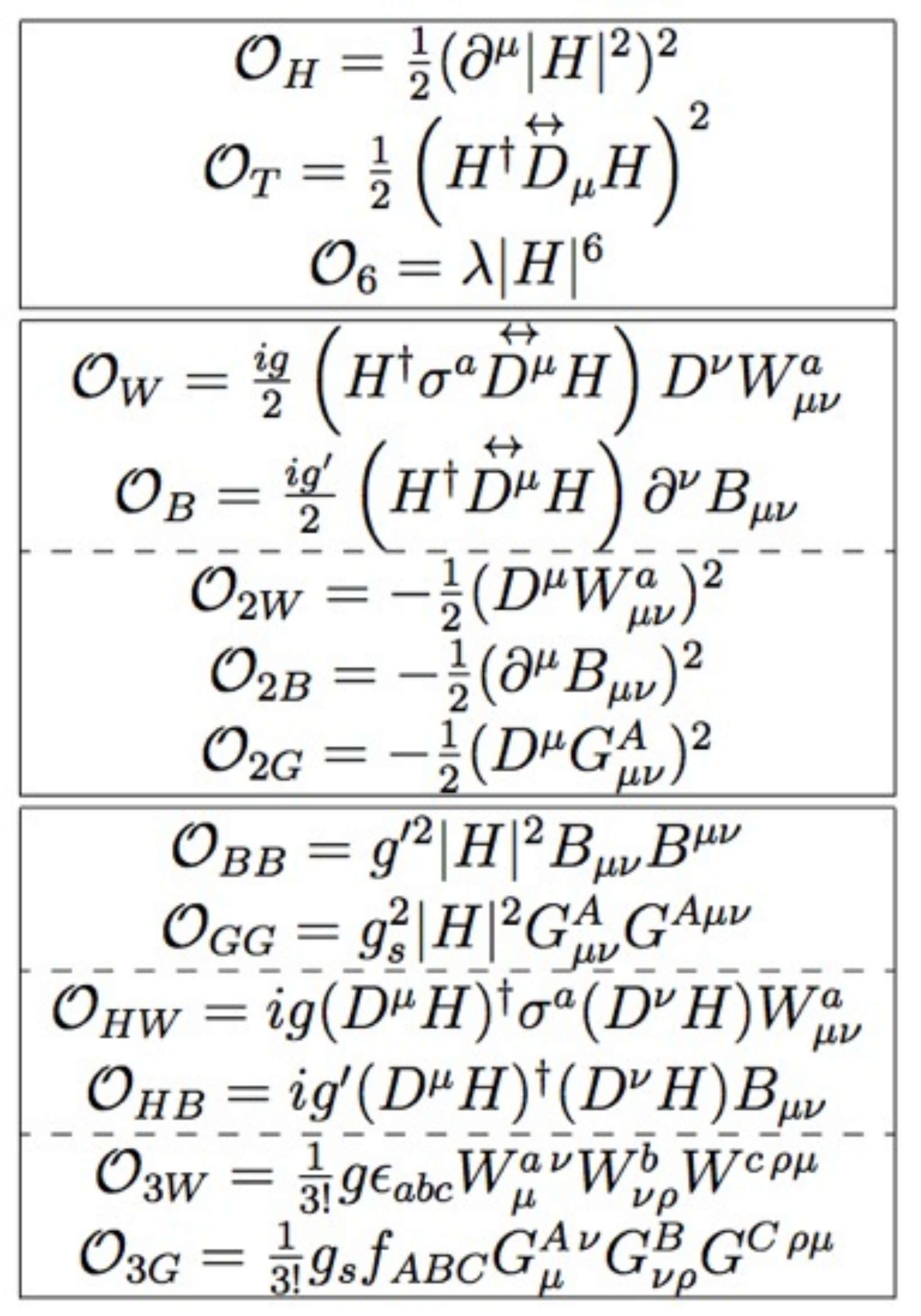
(after using EOM, partial int., identities
to eliminate redundancies)

Buchmuller & Wyler 86
Grzadkowski, Iskrzynski, Misiak, Rosiek10

59 (one family)

59 ways to modify the SM !!
(many more for 3 families)

Bosonic



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

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

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

$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
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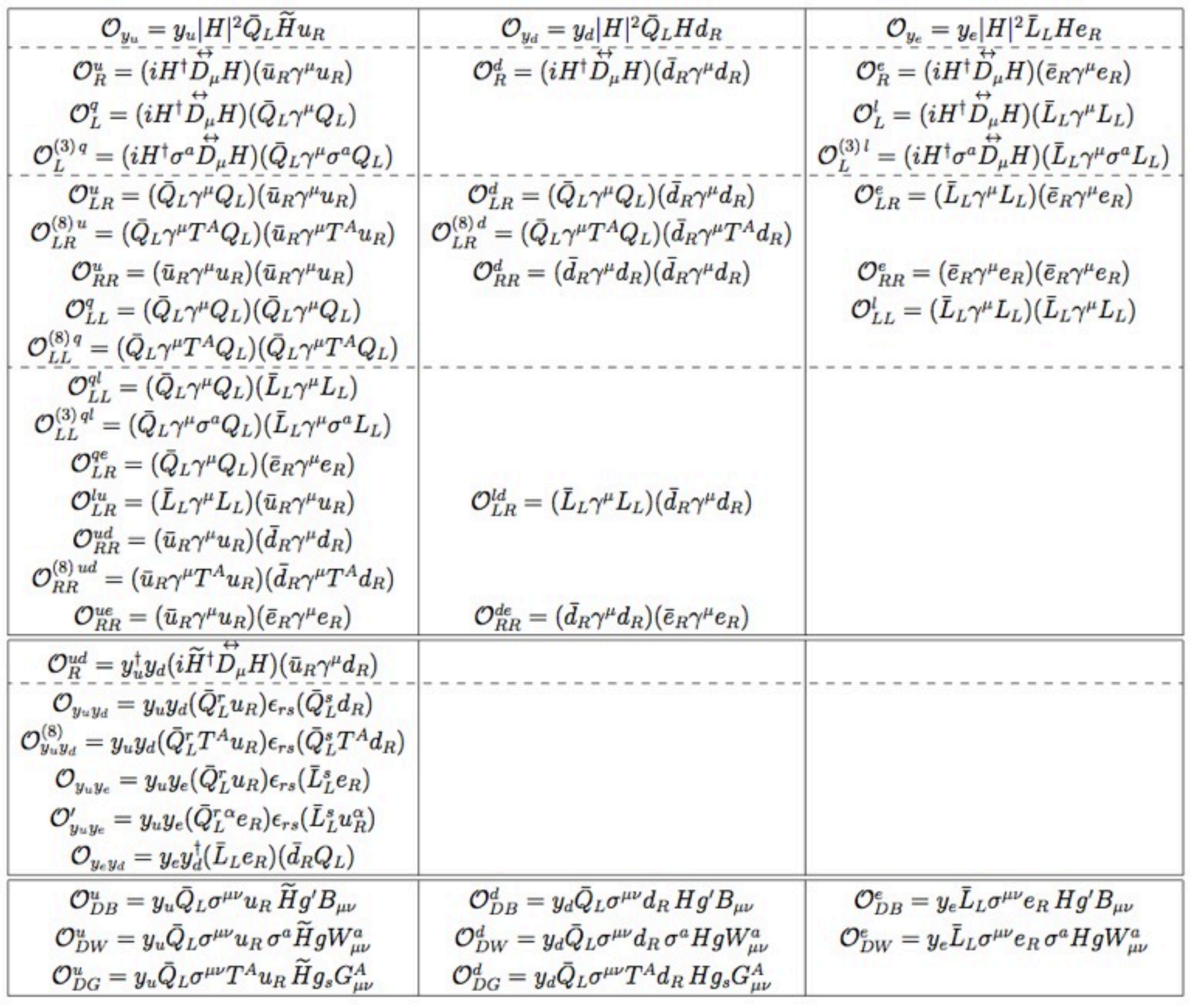
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^B_{\nu\rho} G^{C\,\rho\mu}$$

- Adopt SILH basis

Giudice Grojean
Pomarol Rattazzi 07

+ 6 pure CP-odd

Fermionic (one family)



$\mathcal{O}_{y_u} = y_u\|H\|^2\bar{Q}_L\widetilde{H}u_R$	$\mathcal{O}_{y_d} = y_d\|H\|^2\bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e\|H\|^2\bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu\sigma^a Q_L)$		$\mathcal{O}_L^{(3)\,l} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu\sigma^a L_L)$
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$\mathcal{O}_{LR}^{(8)\,u} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$	$\mathcal{O}_{LR}^{(8)\,d} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$	
$\mathcal{O}_{RR}^u = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{RR}^d = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{RR}^e = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_{LL}^q = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_{LL}^l = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$
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$\mathcal{O}_{LL}^{ql} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$		
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L\gamma^\mu\sigma^a Q_L)(\bar{L}_L\gamma^\mu\sigma^a L_L)$		
$\mathcal{O}_{LR}^{qe} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$		
$\mathcal{O}_{LR}^{lu} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{LR}^{ld} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	
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$\mathcal{O}_{RR}^{ue} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{RR}^{de} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}_R^{ud} = y_u^\dagger y_d(i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d(\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{Q}_L^s d_R)$		
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$\mathcal{O}_{y_u y_e} = y_u y_e(\bar{Q}_L^r u_R)\epsilon_{rs}(\bar{L}_L^s e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e(\bar{Q}_L^{r\alpha} e_R)\epsilon_{rs}(\bar{L}_L^s u_R^\alpha)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger(\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}_{DB}^u = y_u\bar{Q}_L\sigma^{\mu\nu}u_R\,\widetilde{H}g'B_{\mu\nu}$	$\mathcal{O}_{DB}^d = y_d\bar{Q}_L\sigma^{\mu\nu}d_R\,Hg'B_{\mu\nu}$	$\mathcal{O}_{DB}^e = y_e\bar{L}_L\sigma^{\mu\nu}e_R\,Hg'B_{\mu\nu}$
$\mathcal{O}_{DW}^u = y_u\bar{Q}_L\sigma^{\mu\nu}u_R\,\sigma^a\widetilde{H}gW_{\mu\nu}^a$	$\mathcal{O}_{DW}^d = y_d\bar{Q}_L\sigma^{\mu\nu}d_R\,\sigma^a HgW_{\mu\nu}^a$	$\mathcal{O}_{DW}^e = y_e\bar{L}_L\sigma^{\mu\nu}e_R\,\sigma^a HgW_{\mu\nu}^a$
$\mathcal{O}_{DG}^u = y_u\bar{Q}_L\sigma^{\mu\nu}T^A u_R\,\widetilde{H}g_s G_{\mu\nu}^A$	$\mathcal{O}_{DG}^d = y_d\bar{Q}_L\sigma^{\mu\nu}T^A d_R\,Hg_s G_{\mu\nu}^A$	

E. Massó

“Tree” vs “Loop”

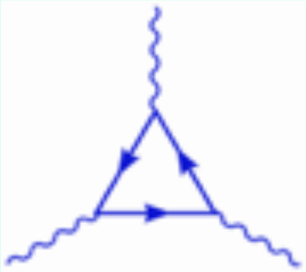
Artz Einhorn Wudka 95

In weakly renormalizable coupled theories

High-energy origin of effective opers.

$\mathcal{O}_{tree}$

$\mathcal{O}_{loop}$



$J_f^\mu\, J_{f\mu}$

Current x Current

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

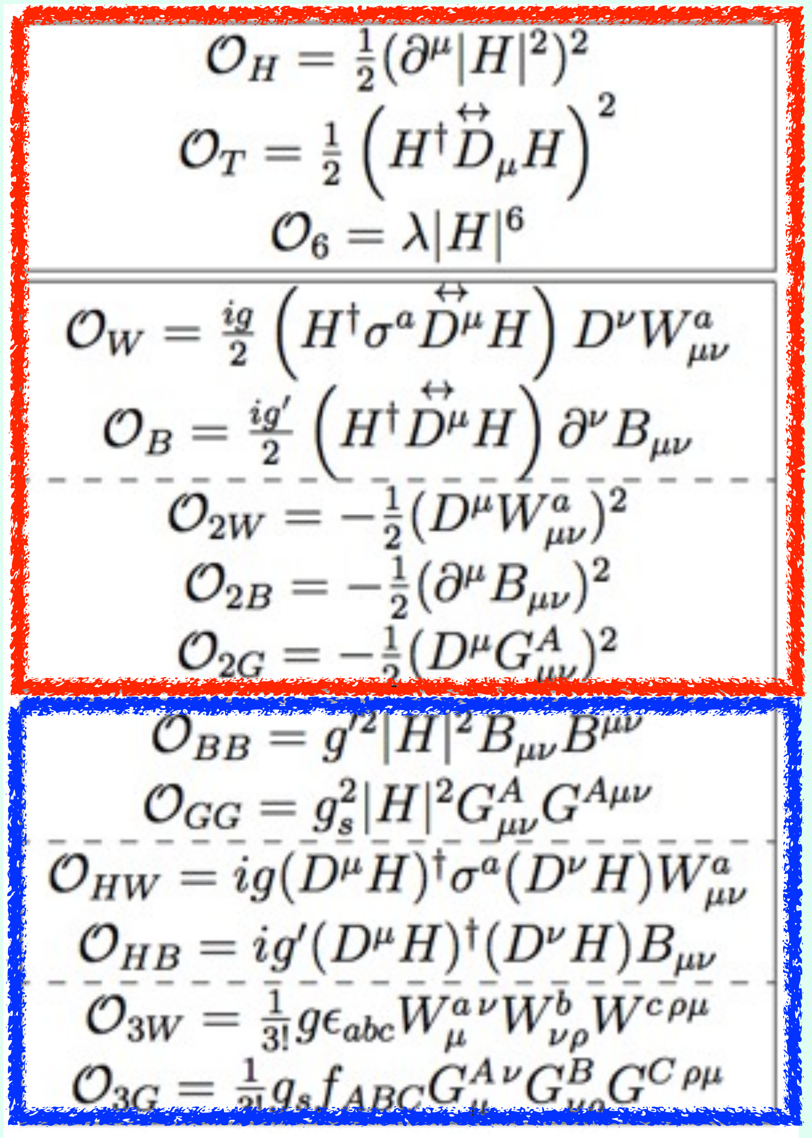
In general, we keep this separation:

- ops Current x Current (call them Tree)
- other ops (call them Loop)

- Well-defined classification
- Proves convenient for many purposes
- Expected with different sizes in many favorite theories (SUSY, 2H model, etc)

Blue or Red

TREE



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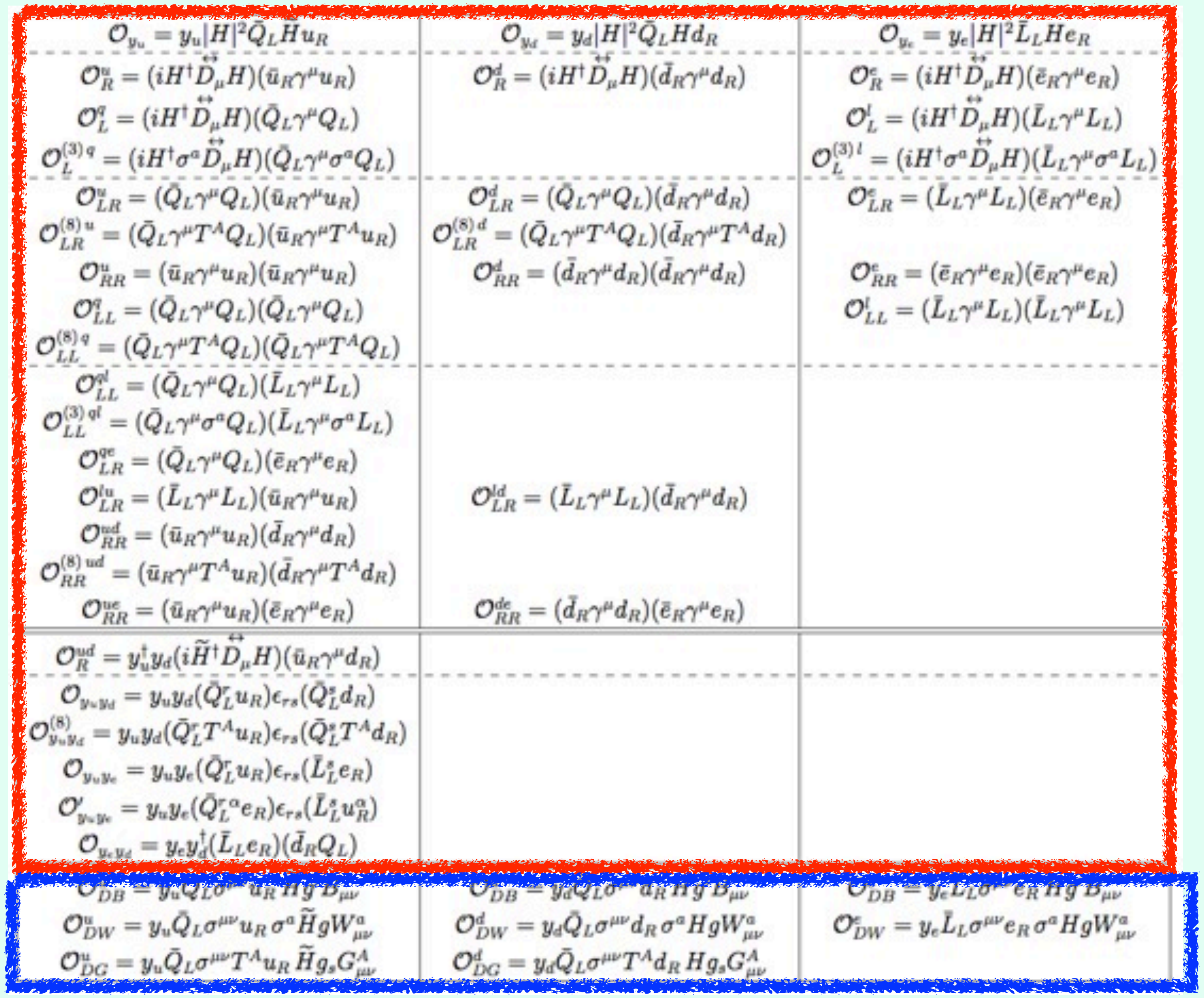
LOOP

TREE



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$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$ $\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$ $\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ $\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$ $\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ $\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$

LOOP

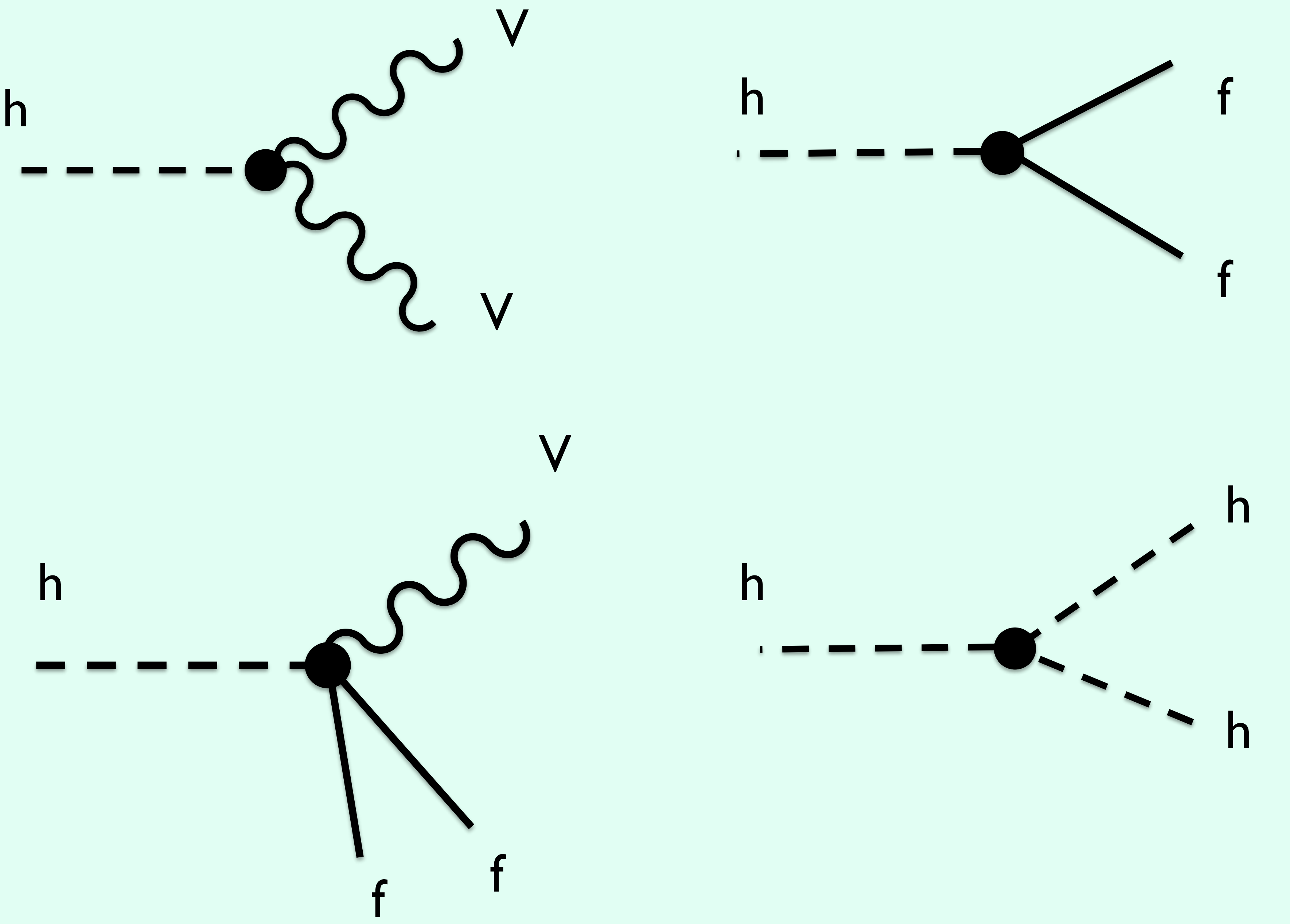
I have choosen a basis

Basis is not unique

Physics is independent of basis,
but there may be some more convenient than others
(In general it depends on the objective)

- ☆ Cleanest connection observable-operator
- ☆ Keep tree-loop separated
- ☆ Avoid (or at least control) blind directions
  i.e. directions not bounded by a set of exps.
- ☆ Capture in few opers impact of BSM models (SUSY, 2H, ...)
- ☆ Show some BSM symmetries

Modifications to Higgs couplings



- restrict to CP-even modifications

Modifications to Higgs couplings

$$\mathcal{L}_h = \quad g_{hff} h(\bar{f}_L f_R + \text{h.c.}) + g_{hVV} h V^\mu V_\mu$$

$$+g_{hZf_Lf_L} h Z_\mu \bar{f}_L \gamma^\mu f_L + \; g_{hZf_Rf_R} \; h \, Z_\mu \bar{f}_R \gamma^\mu f_R$$

$$+g_{hWf_Lf'_L} h W_\mu \bar{f}_L \gamma^\mu f'_L + g_{hhh} h^3$$

$$+g_{\partial hWW}(W^{+\mu} W^-_{\mu\nu} \partial^\nu h + \text{h.c.}) + g_{\partial hZZ} Z^\mu Z_{\mu\nu} \partial^\nu h$$

$$+g'_{hZZ} h Z^{\mu\nu} Z_{\mu\nu} + g_{hAA} h A^{\mu\nu} A_{\mu\nu} + g_{\partial hAZ} Z^\mu A_{\mu\nu} \partial^\nu h$$

$$+g_{hAZ} h A^{\mu\nu} Z_{\mu\nu} + g_{hGG} h G^{A\mu\nu} G^A_{\mu\nu}$$

Departures from SM are generated by Wilson coeff. of d=6 operators

How many ? Which ones ?
Are they already constrained ?

- One family
- Only CP-even ops.

18 Relevant Higgs operators

Bosonic

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

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

$$\begin{aligned}\mathcal{O}_{GG} &= g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu} \\ \mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\ \mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \\ \mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}\end{aligned}$$

18 Relevant Higgs operators

Fermionic

$$\begin{aligned}
\mathcal{O}_{y_u} &= y_u|H|^2\bar{Q}_L\widetilde{H}u_R \\
\mathcal{O}_{y_d} &= y_d|H|^2\bar{Q}_L H d_R \\
\mathcal{O}_{y_e} &= y_e|H|^2\bar{L}_L H e_R
\end{aligned}$$

$$\begin{aligned}
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\end{aligned}$$

$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L\gamma^\mu\sigma^a L_L)(\bar{L}_L\gamma^\mu\sigma^a L_L)$$

- Can assume 3 families,
  impose Minimal Flavour Violation MFV

Constraints from pre-Higgs era:

8 + 2

Z-peak   M_W
EW low energy meas.

$$S, T, M_W, Z \to \bar{f} f$$

LEP2 Triple-gauge-boson vertex
(LHC will do better than LEP2)

$$g_Z^1, \kappa_\gamma$$

- No dominance of tree ops assumed

Constraints from pre-Higgs era: 8 + 2

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

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

$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
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$$\mathcal{O}_{HW} = ig (D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
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$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

$$\mathcal{O}_{WW} = 4(\mathcal{O}_W - \mathcal{O}_B) - 4(\mathcal{O}_{HW} - \mathcal{O}_{HB}) + \mathcal{O}_{BB}$$

$$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$$

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✗ 8 at 10^-3

$$\left(\frac{\Lambda}{100\ \text{GeV}}\right)^2$$

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\end{aligned}}$$

╳ 8 at 10^-3

╲ 2 at 10^-2

$$\left(\frac{\Lambda}{100\ \text{GeV}}\right)^2$$

8 “only-Higgs-Physics” operators

$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$$
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- Operators have form $|H|^2\,\mathcal{O}_4 \;\rightarrow\; (v+h)^2\,\mathcal{O}_4$
- Of these 8 ops: 5 tree + 3 loop

8 “only-Higgs-Physics” operators

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

h^3 $\mathcal{O}_6 = \lambda |H|^6$

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \tilde{H} u_R$ htt

$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$ hbb

$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$ $h\tau\tau$

hGG $\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$h\gamma\gamma, h\gamma Z$

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

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- Operators have form $|H|^2 \mathcal{O}_4 \rightarrow (v+h)^2 \mathcal{O}_4$
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8 “only-Higgs-Physics” coefficients

- LHC measurements already put strict bounds on some of the coeffs of operators

$$hGG \quad h\gamma\gamma \quad h\gamma Z$$

- The Higgs LHC measurements do not lead to further constraints on non-Higgs physics.

Renormalization

Anomalous dimensions of Wilson coefficients

$$c_i(\Lambda)$$

$$\downarrow$$

$$c_i(M_H)$$

$$\Delta c_i \sim \gamma_{ij} \frac{c_j}{16\pi^2} \log \Lambda / M_H$$

- ★ Corrections will be important when more precise Higgs data will be available

We have calculated all anomalous dimensions with larger impact on Higgs physics.

Elias-Miro et al
1308.1879

Example: $\Delta c_i \equiv c_i(M_t) - c_i(2\ \mathrm{TeV})$

$$\begin{aligned}
\Delta\widehat{T} &= \Delta c_T \xi = \left[-0.003\, c_H + 0.16\, (c_L - c_R)\right] \xi\ , \\
\Delta\widehat{S} &= \Delta(c_B + c_W)\frac{M_W^2}{\Lambda^2} = \left[0.001\, c_H - 0.01\, c_R - 0.004\, c_L - 0.03\, c_L^{(3)}\right] \xi\ , \\
\Delta\frac{\delta g_Z^{b_L}}{g_Z^{b_L}} &= \frac{\Delta[c_L + c_L^{(3)}]}{1-(2/3)\sin^2\theta_W}\xi \simeq \Delta[c_L + c_L^{(3)}]\xi \\
&= \underbrace{\left[0.01\, c_R - 0.03\, c_L + 0.06\, c_L^{(3)} - 0.17\, c_{LL} - 0.0064\, c_{LL}^{(8)} + 0.08\, c_{LR}\right]}\xi\ ,
\end{aligned}$$

Very constrained

Could be large (top)

Anomalous dimensions calculated also in Jenkins et al 1308.2627 and 1310.4838

Tree -> loop mixing

$$\begin{tikzcd}
\kappa_{loop}(\Lambda) \arrow[d] \\
\kappa_{loop}(M_H)
\end{tikzcd}$$

Assume weakly coupled theories

$$\kappa_{loop} \ll c_{tree}$$

$$\Delta\kappa_{loop} \sim \gamma \, \frac{c_{tree}}{16\pi^2} \log \Lambda / M_H$$

- Mixing from tree operator can be important

$$h \to \gamma\gamma,\ \gamma Z$$

These decays described by loop ops.

Question:
Are there RGE contributions from tree ops. ?

$$h \to \gamma\gamma,\ \gamma Z$$

These decays described by loop ops.

Question:

Are there RGE contributions from tree ops. ?

Answer: NO

Easy problem to solve if one chooses a convenient basis and takes into account all elements of basis.

- ☆ Answer independent of basis

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

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

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

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

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

$$\frac{d}{d\log\mu}\begin{pmatrix}\kappa_{BB}\\ \kappa_{WW}\\ \kappa_{WB}\\ c_W\\ c_B\end{pmatrix} = \begin{pmatrix}\Gamma & 0_{3\times 2}\\ 0_{2\times 3} & X\end{pmatrix}\begin{pmatrix}\kappa_{BB}\\ \kappa_{WW}\\ \kappa_{WB}\\ c_W\\ c_B\end{pmatrix}$$

Elias-Miro et al
1302.5661

Rest of tree-loop mixing also vanishes

“Tree -> Loop” mixing
In general

- 59 = 39 (tree) + 20 (loop)

All tree->loop anomalous dimensions vanish, except for only 3 tree operators

"Tree -> Loop" mixing
In general

- 59 = 39 (tree) + 20 (loop)

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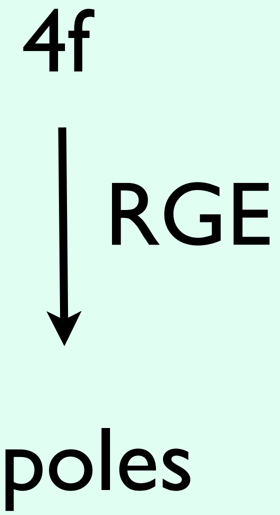
Physics:
Scalar leptoquarks and heavy double charged higgs induce 4f that:



4f

RGE

dipoles

see, for example,
Akeroyd et al 0610344
Benbrik et al 1009.3886

Conclusions

- d=6 operators used to analyze Higgs and EW data
- Convenient to separate tree and loop operators
- Found hierarchy of constraints on Wilson coeffs
- 8 Wilson coeffs describe Higgs physics at LHC
- Relevant anomalous dimensions calculated

Additional

$$c_B \mathcal{O}_B \;\leftrightarrow\; c_B \frac{g'^{\,2}}{g_*^2}\left[-\frac{1}{2}\mathcal{O}_T + \frac{1}{2}\sum_f \left(Y_L^f \mathcal{O}_L^f + Y_R^f \mathcal{O}_R^f\right)\right] ,$$

$$c_W \mathcal{O}_W \;\leftrightarrow\; c_W \frac{g^2}{g_*^2}\left[-\frac{3}{2}\mathcal{O}_H + 2\mathcal{O}_6 + \frac{1}{2}\left(\mathcal{O}_{y_u} + \mathcal{O}_{y_d} + \mathcal{O}_{y_e}\right) + \frac{1}{4}\sum_f \mathcal{O}_L^{(3)\,f}\right] ,$$

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

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

$$\begin{aligned} &\delta\mathcal{L}_{3V} \\ &= \; ig \cos\theta_W [\delta g_1^Z \, Z^\mu \left(W^{-\,\nu} W^+_{\mu\nu} - W^{+\,\nu} W^-_{\mu\nu} \right) \\ &\quad +\delta\kappa_Z \, Z^{\mu\nu} W^-_\mu W^+_\nu] \\ &\quad + ig \sin\theta_W [\delta\kappa_\gamma \, A^{\mu\nu} W^-_\mu W^+_\nu] \end{aligned}$$