The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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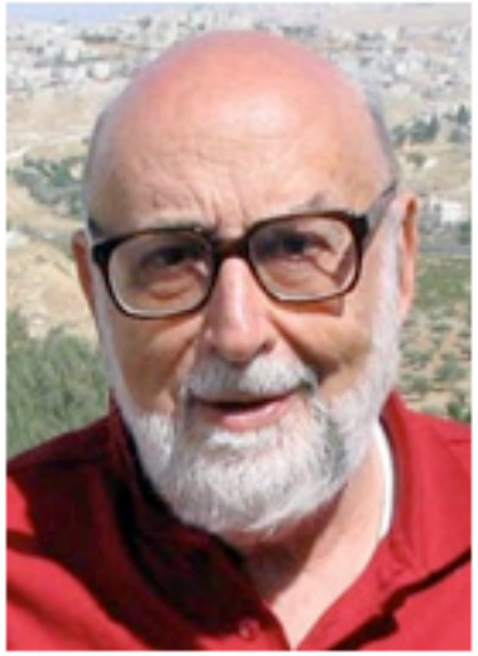


Photo: Pnicolet via Wikimedia Commons
François Englert

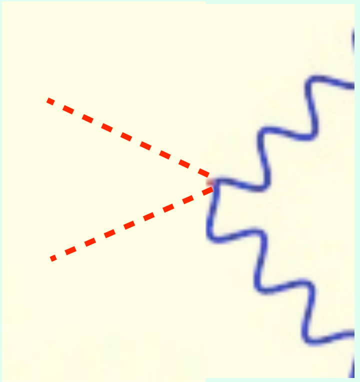
Photo: G-M Greuel via Wikimedia Commons
Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

Spontaneous electroweak symmetry breaking

New scalar field
interacting with gauge fields

Energy scale
v



Gauge couplings g, g'

Gauge boson masses

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

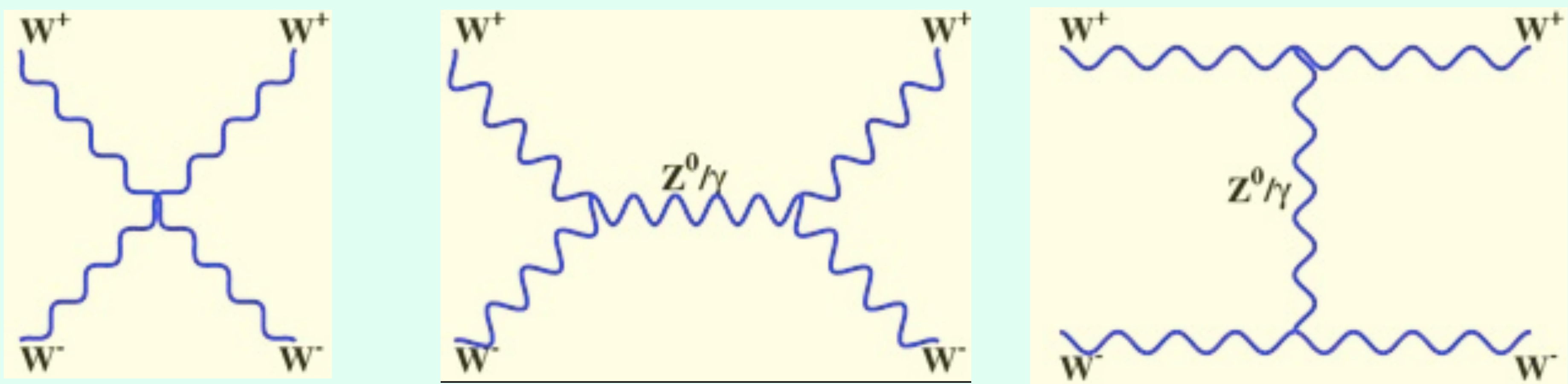
$$M_A = 0$$

New degrees of freedom: $W_L^{\pm}, Z_L$

h Higgs particle

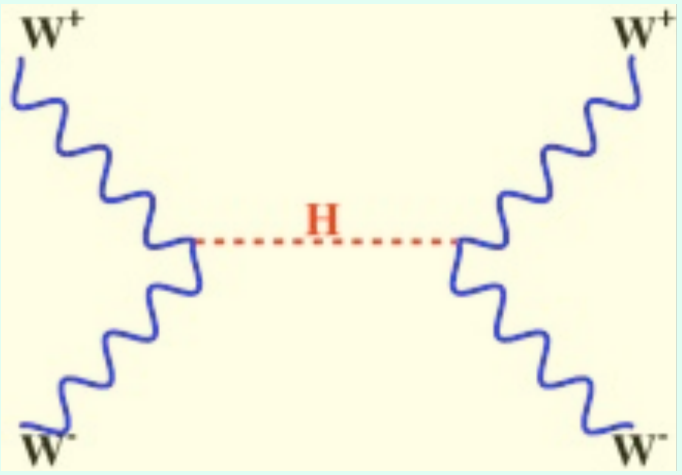
Unitarity

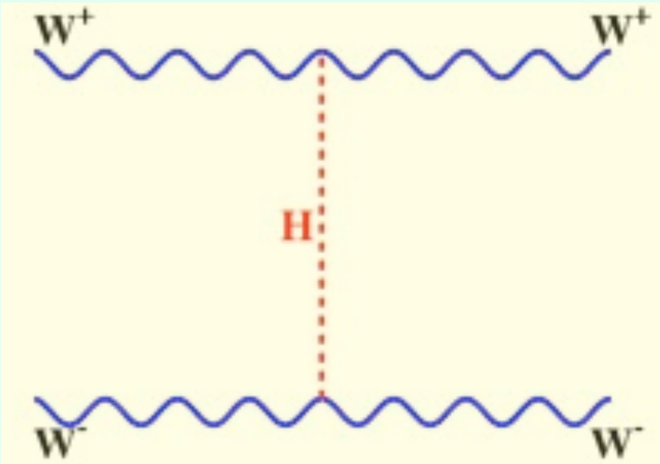
$$WW \to WW$$



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

Unitarity





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

<u>Cancellation</u> (for a light Higgs)

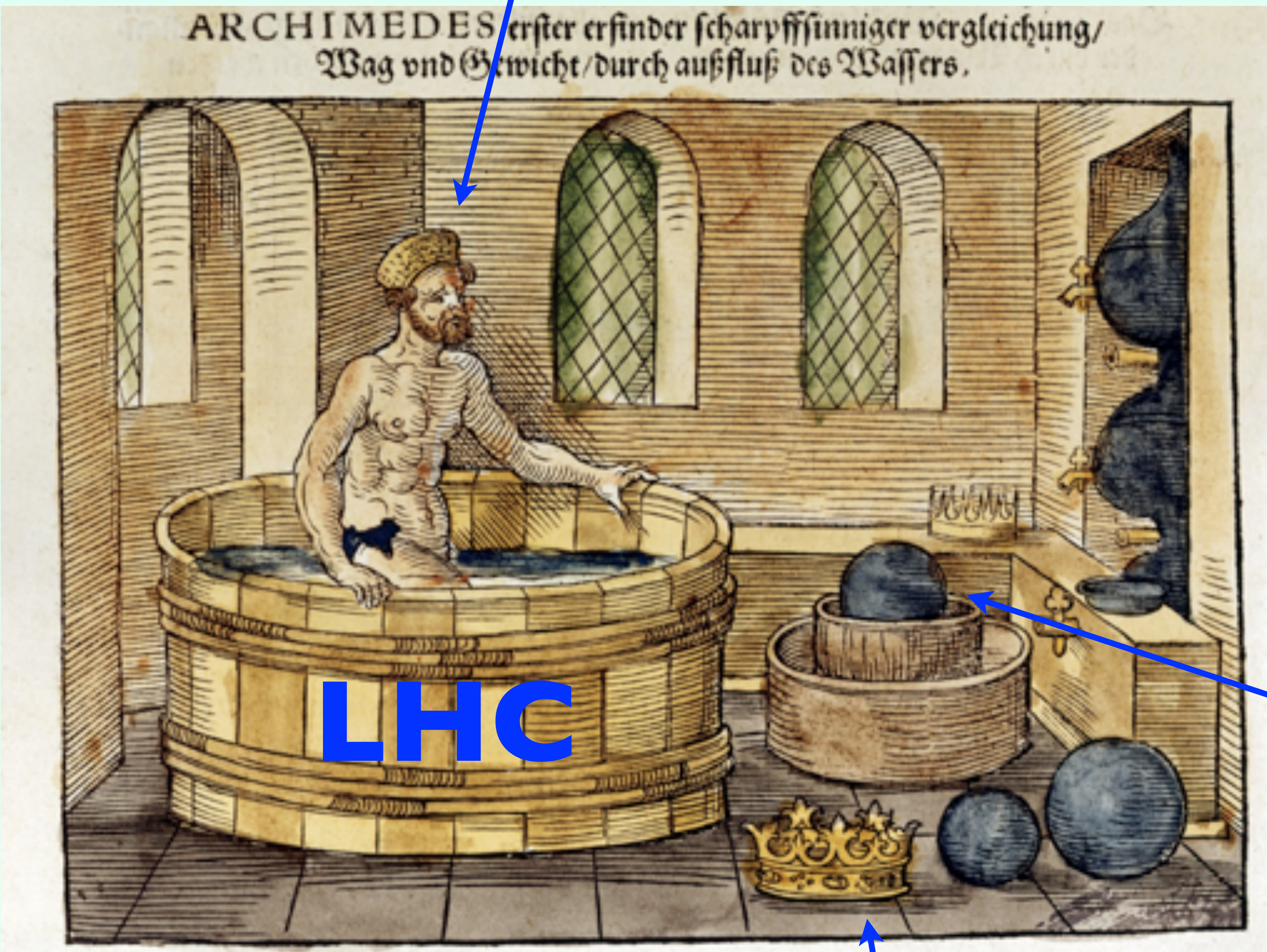
LHC

(and previously LEP and Tevatron)

Higgs ?

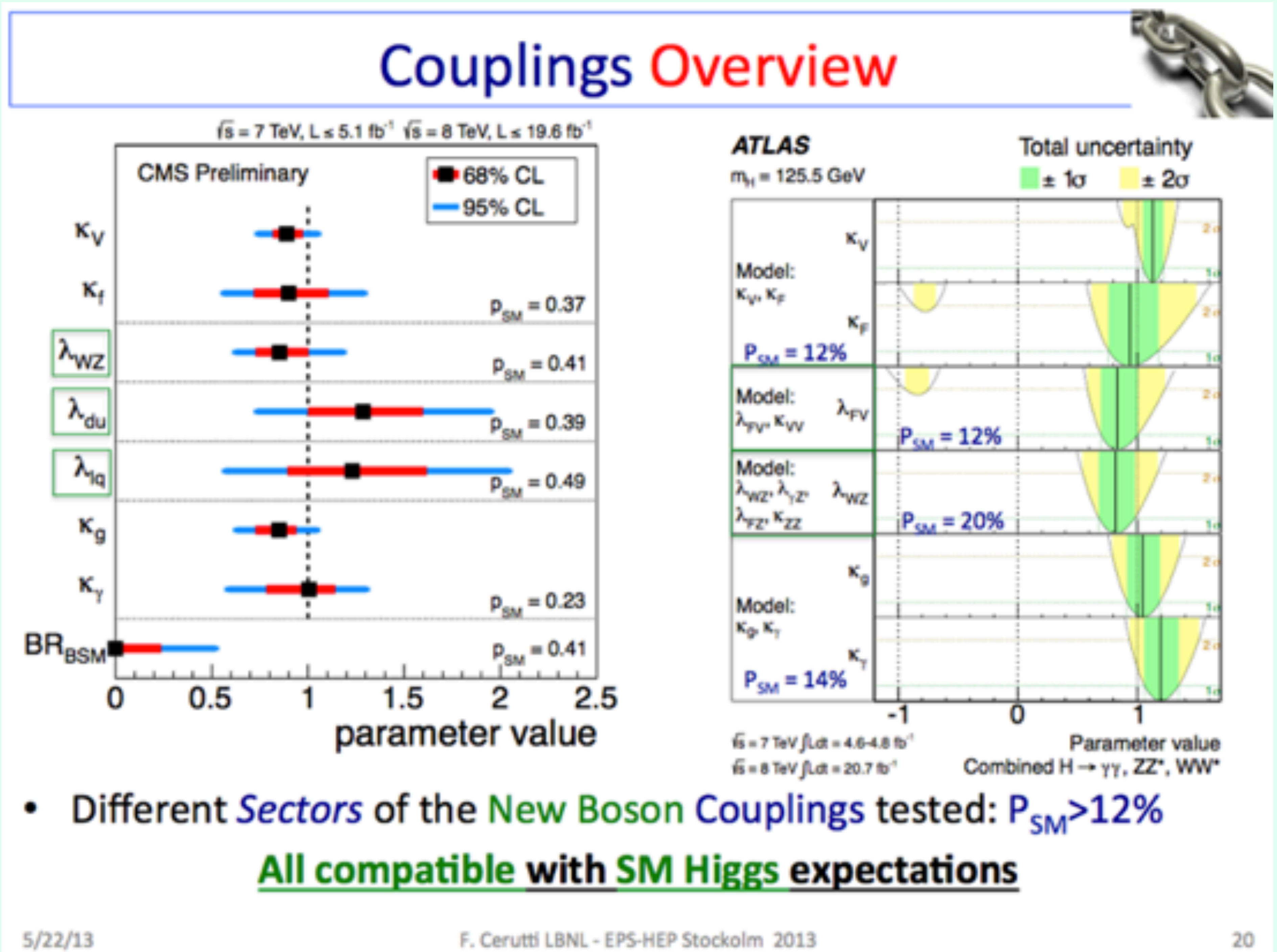
(at electroweak scale)

Eureka !



Higgs

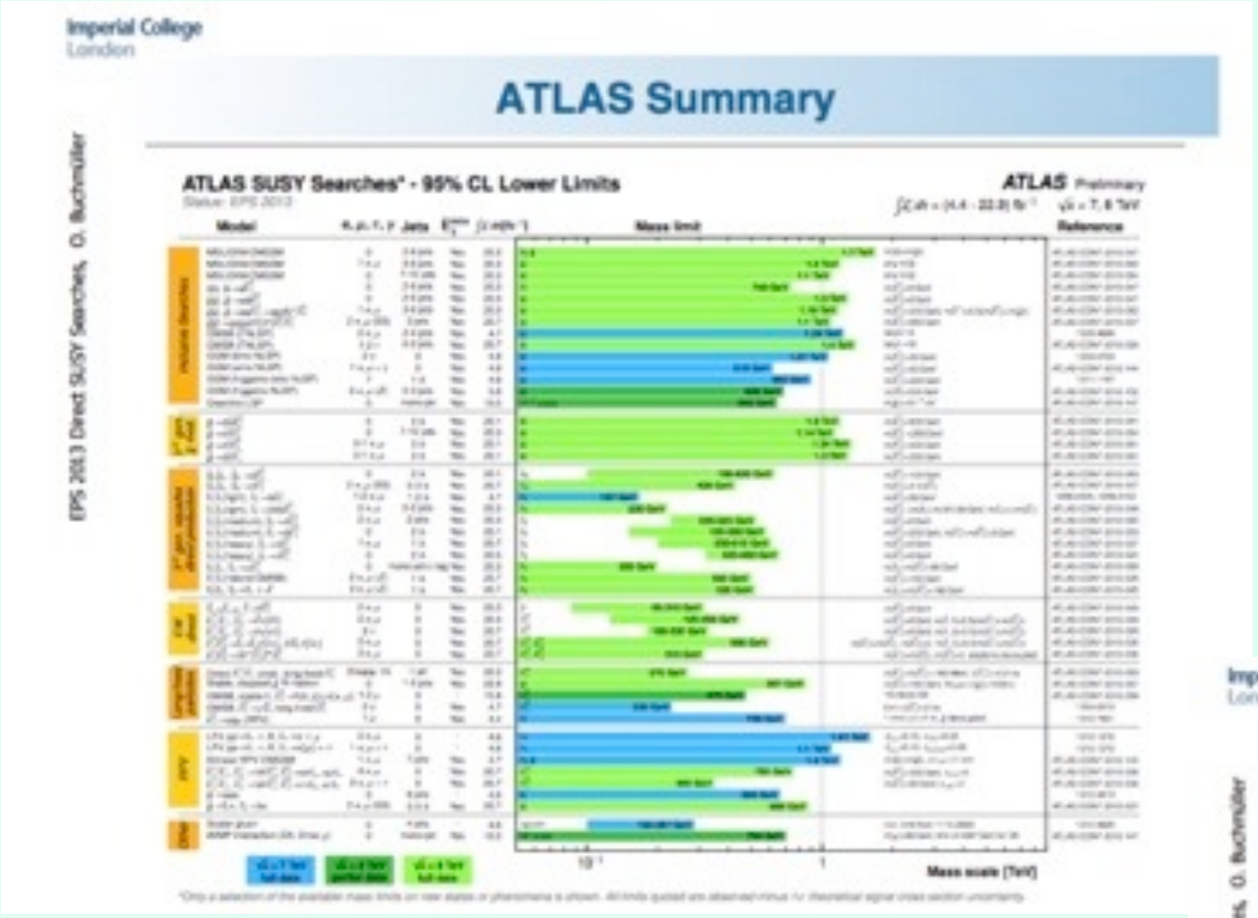
Nobel prize



F. Cerutti
EPS 2013

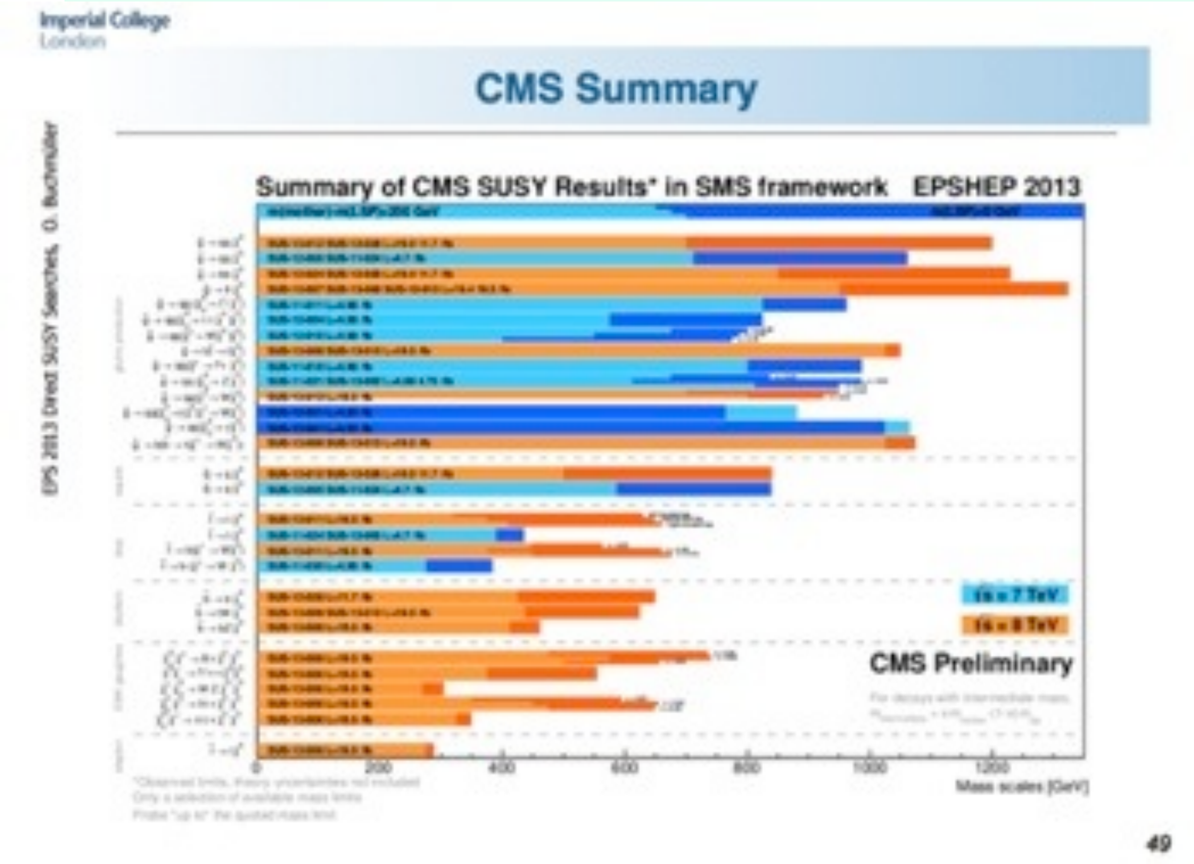
SM-like Higgs ...

... and nothing else



SUSY searches
(similar for other BSM)

O. Buchmuller
EPS 2013



E. Massó

Tuesday, November 5, 2013

Effective Lagrangian approach

BSM at high scale
would modify Higgs properties

$$\Lambda \gg M_W$$

Integrate heavy dof,
obtain d=6 ops.
formed with SM fields

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

Λ High-enery scale suppresses effects

c Wilson coefficient

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

Effective Higgs Lagrangians

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In collaboration with
Joan Elias-Miró, José Ramón Espinosa
and Alex Pomarol

hep-ph 1302.5661 and 1308.1879

Outline

- Basis of 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

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

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

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

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$

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

$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\,\nu}_\mu G^B_{\nu\rho} G^{C\,\rho\mu}$$

+ 6 CP-odd

Fermionic (one family)

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

“Tree” vs “Loop”

Artz Einhorn Wudka 95

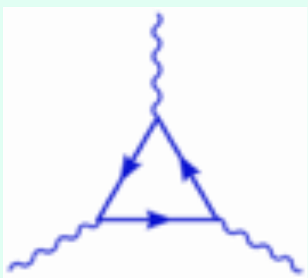
In weakly coupled theories

High-energy origin of effective opers.

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

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

Current x Current



“Tree” vs “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

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
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$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
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$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
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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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$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$
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$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
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$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$ $\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$ $\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$ $\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\alpha}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^\alpha_R)$ $\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$ $\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$ $\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ $\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$ $\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ $\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$

Blue and Red

Not an operator

Choosing a basis

Basis is not unique

Physics is independent of basis,
but there may be some more convenient than others
(In general it depends of 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 some BSM models,
  (SUSY, 2H, ...)
- Show some BSM symmetries

Modifications to Higgs couplings

$$\begin{aligned}\mathcal{L}_h = \quad & g_{hff} h(\bar{f}_L f_R + \text{h.c.}) + g_{hVV} h V^\mu V_\mu \\ & + g_{hZf_Lf_L} h Z_\mu \bar{f}_L \gamma^\mu f_L + g_{hZf_Rf_R}\, h\, Z_\mu \bar{f}_R \gamma^\mu f_R \\ & + g_{hWf_Lf'_L} h W_\mu \bar{f}_L \gamma^\mu f'_L + g_{hhh} h^3 \\ & + g_{\partial hWW} (W^{+\mu} W^-_{\mu\nu} \partial^\nu h + \text{h.c.}) + g_{\partial hZZ} Z^\mu Z_{\mu\nu} \partial^\nu h \\ & + g'_{hZZ} h Z^{\mu\nu} Z_{\mu\nu} + g_{hAA} h A^{\mu\nu} A_{\mu\nu} + g_{\partial hAZ} Z^\mu A_{\mu\nu} \partial^\nu h \\ & + g_{hAZ} h A^{\mu\nu} Z_{\mu\nu} + g_{hGG} h G^{A\mu\nu} G^A_{\mu\nu}\end{aligned}$$

- CP-even modifications
- Departures from SM are generated by Wilson coeff. of d=6 opers.

18 Relevant Higgs operators

Bosonic

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

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

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

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

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

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

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

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

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

- Adopt SILH basis

Giudice Grojean
Pomarol Rattazzi 07

- One family
- Only CP-even ops.

18 Relevant Higgs operators

Fermionic

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

$$
\begin{aligned}
\mathcal{O}_R^u &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R) \\
\mathcal{O}_R^d &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R) \\
\mathcal{O}_R^e &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R) \\
\mathcal{O}_L^q &= (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L) \\
\mathcal{O}_L^{(3)\,q} &= (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)
\end{aligned}
$$

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

- Can assume 3 families, impose MFV
- Input $G_F, \alpha, M_Z, M_h, M_f$

Constraints from pre-Higgs era:
8 + 2

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Z-peak   M_W
EW low energy meas.

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

Constraints from pre-Higgs era:
8 + 2

Z-peak   M_W
EW low energy meas.

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

- No dominance of tree ops assumed
- Limits for $\Lambda = M_W$

Constraints from pre-Higgs era: 8 + 2

$$\begin{aligned}
\mathcal{O}_T &= \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
\mathcal{O}_H &= \frac{1}{2}(\partial^\mu |H|^2)^2 \\
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$$\mathcal{O}_{WW} = 4(\mathcal{O}_W - \mathcal{O}_B) - 4(\mathcal{O}_{HW} - \mathcal{O}_{HB}) + \mathcal{O}_{BB}$$

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8 at 10^-3

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8 at 10^-3

2 at 10^-2

Tuesday, November 5, 2013

8 "only-Higgs-Physics" operators

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

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8 "only-Higgs-Physics" operators

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

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

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

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

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

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

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

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

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8 "only-Higgs-Physics" operators

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$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
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- Operators have form $|H|^2 \mathcal{O}_4 \rightarrow (v+h)^2 \mathcal{O}_4$
- Of these 8 ops: 5 tree + 3 loop
- 8 are CP-even ops. There are 3 more CP-odd

8 "only-Higgs-Physics" coefficients

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

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

Pomarol and Riva
1308.2802

- 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 the part that can have larger impact on Higgs physics.

Elias-Miro et al 1308.1879

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

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

Very constrained

Could be large (top)

Tree -> loop mixing

$$\kappa_{loop}(\Lambda)$$

$$\downarrow$$

$$\kappa_{loop}(M_H)$$

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

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

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

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

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

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

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

Elias-Miro et al
1302.5661

“Tree -> Loop” mixing
In general

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

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

“Tree -> Loop” mixing
In general

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

All tree->loop anomalous dimensions vanish,
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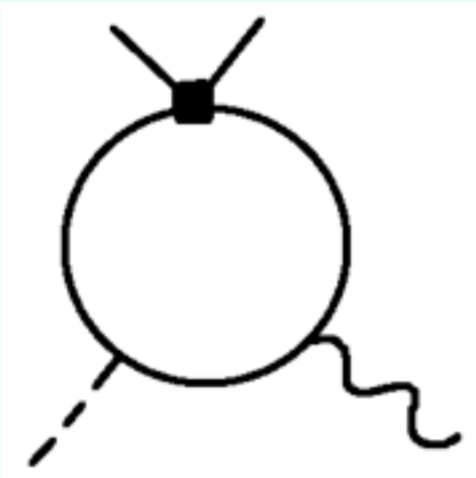
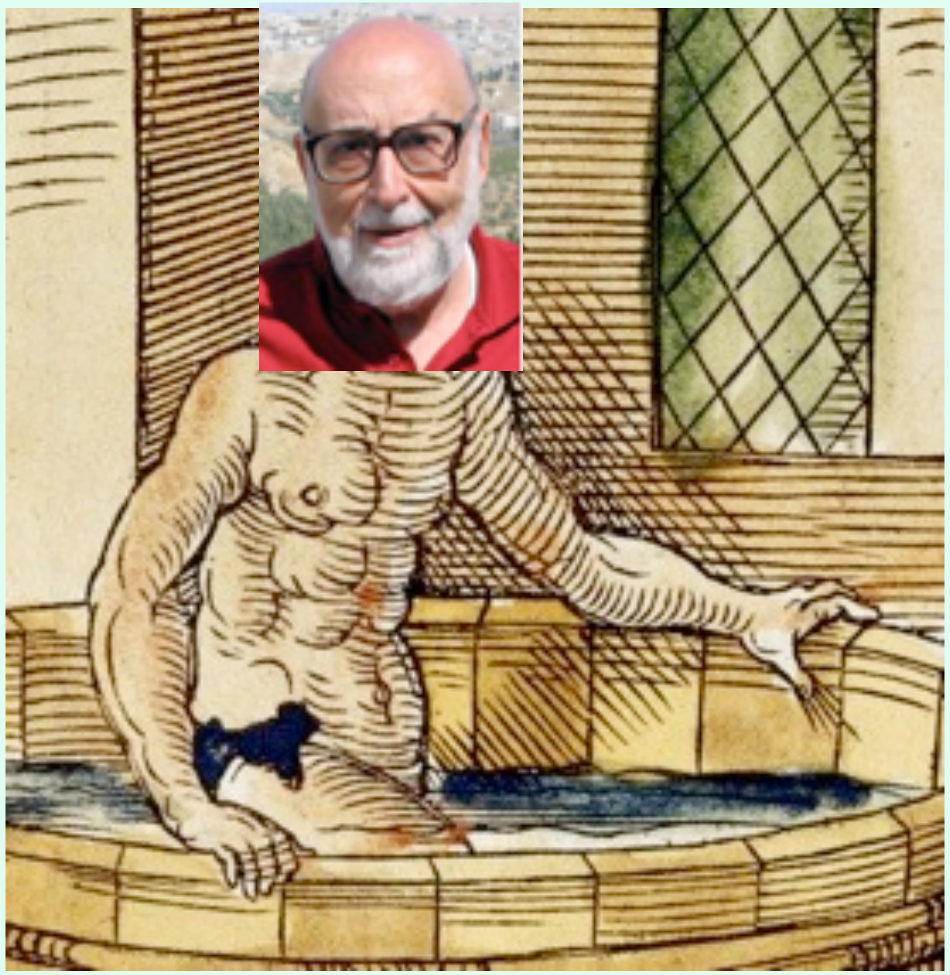
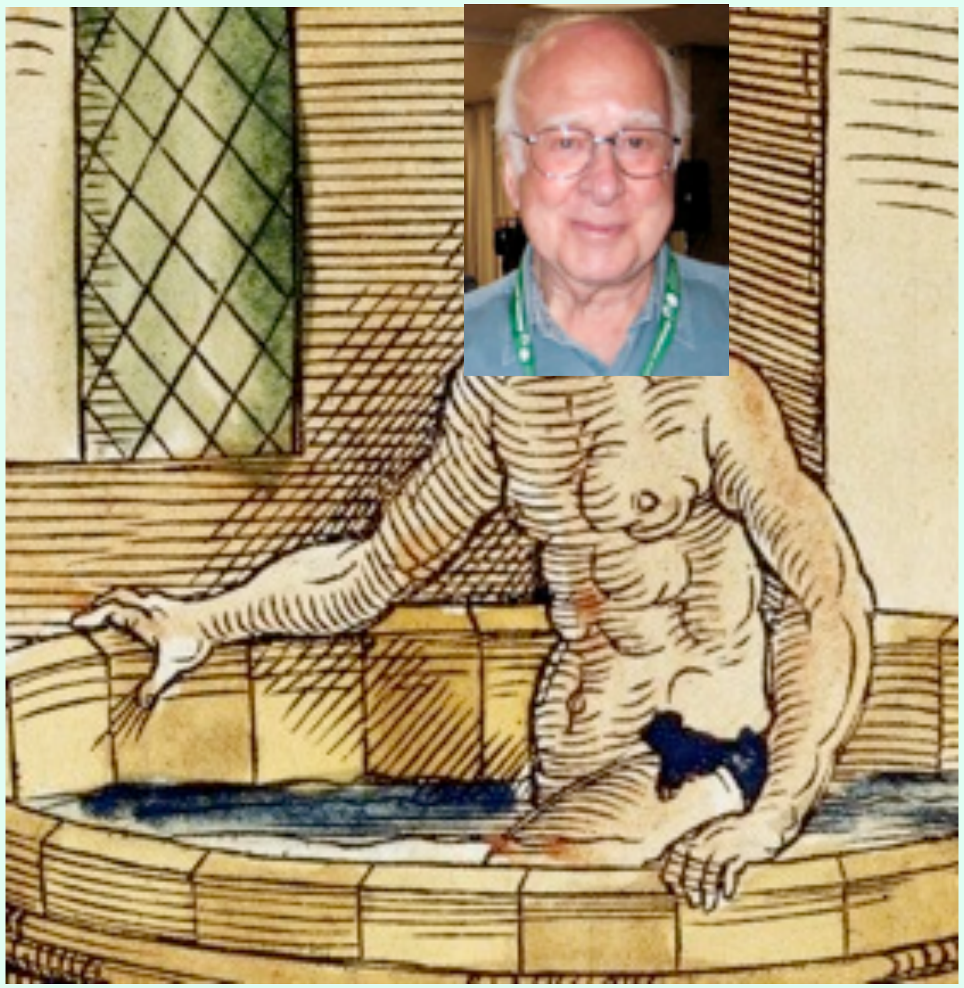
Scalar leptoquarks and heavy double charged higgs
in BSM models lead to effective 4-fermion interactions
which mix under RGEs with fermion dipoles



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

Thanks for your attention

Additional

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

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

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

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