RENORMALIZATION OF $d=6$ OPERATORS RELEVANT FOR $h \to \gamma\gamma, \gamma Z$

July 8, 2013

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KITP
LHC, the first part of the journey.

RENORMALIZATION OF $d=6$ OPERATORS RELEVANT FOR $h \to \gamma\gamma, \gamma Z$

- Model-independent approach to BSM at $\Lambda \sim$ few TeV
  - $d=6$ Operator bases
- Operator classification: current-current (tree) vs. loop
- The art of choosing a basis / potential dangers
- Example : radiative effects on $h \to \gamma\gamma, \gamma Z$
- Some conclusions

Based on :

J. Elias-Miró, JRE, E. Masso, A. Pomarol

[hep-ph/1302.5661] + [hep-ph/1307....]

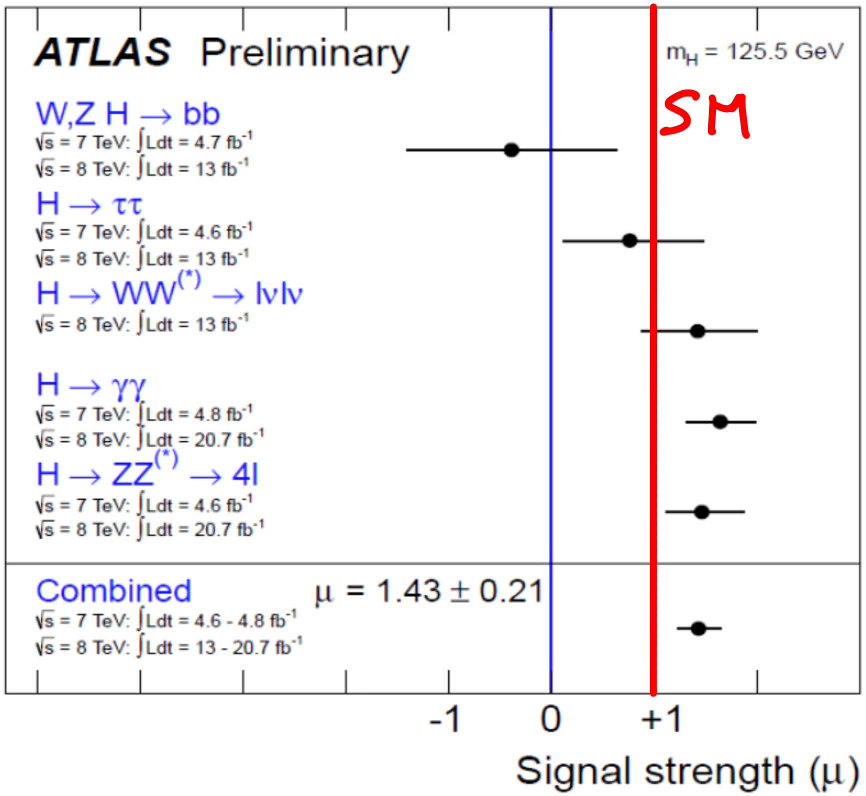
For recent related work see :

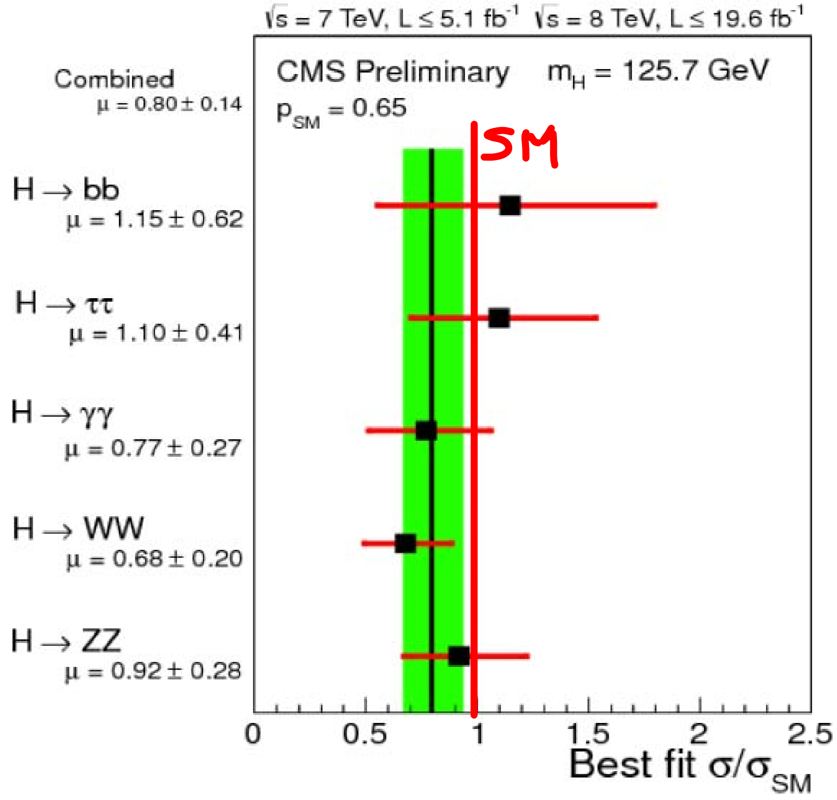
C. Grojean, E. Jenkins, M. Manohar, M. Trott

[hep-ph/1301.2588]

BSM STATUS

- Higgs discovered, close to SM-like

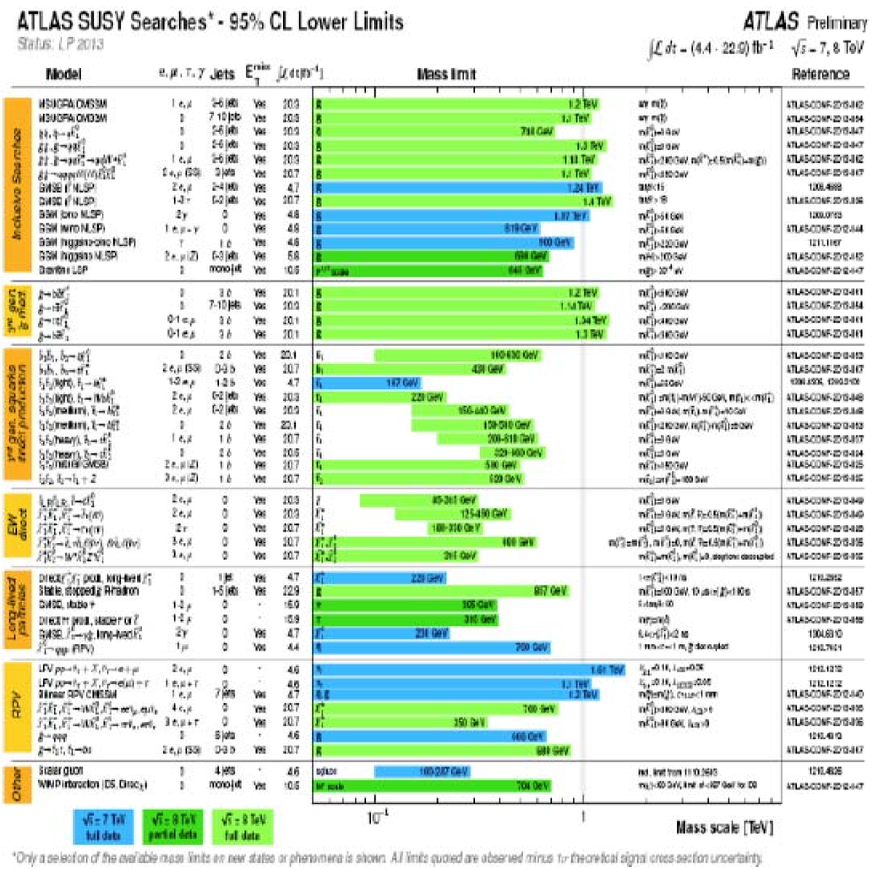




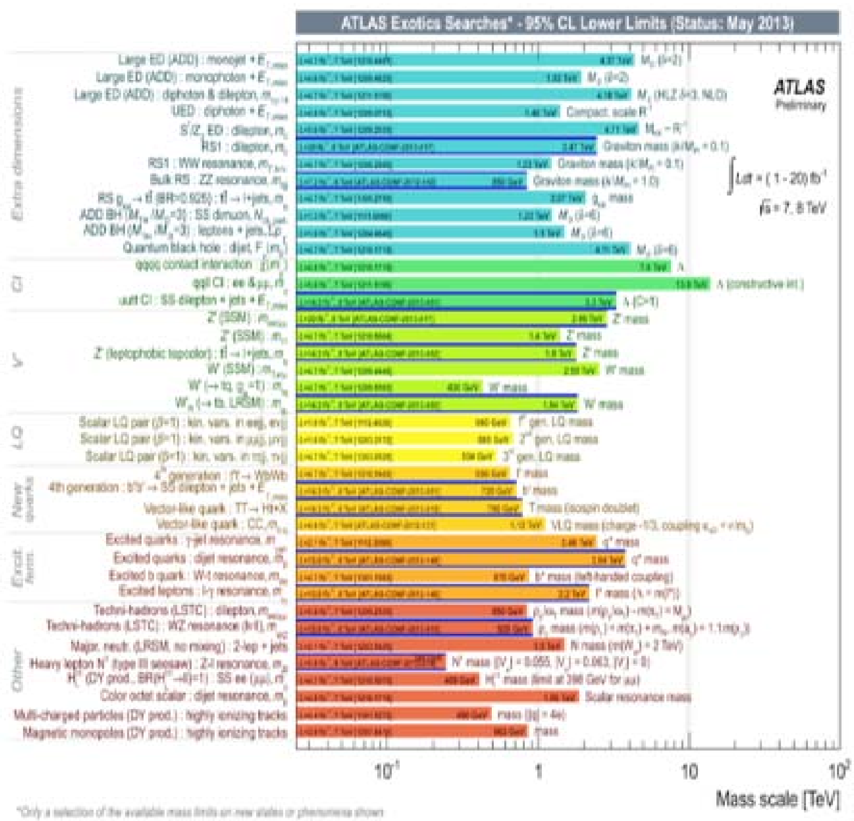
BSM STATUS

- No trace of BSM so far ⇒ $\Lambda >$ few TeV ?

"TSUNAMI" EXCLUSION PLOTS



SUSY



EXOTICS

BSM STATUS

- Higgs discovered, close to SM-like

$+$

- No trace of BSM so far $\Rightarrow$ $\Lambda >$ few TeV ?

$+$

- Holding on to naturalness

$\Downarrow$

$\Lambda \sim$ few TeV

EFFECTIVE THEORY APPROACH

Model-independent approach

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{d=6} + \ldots$$

determined by NP

$$\frac{c_i}{\Lambda^2}\, \mathcal{O}_{d=6}$$

Scale of NP

made of SM fields

$\Lambda \sim$ few TeV

- I ignore $\mathcal{L}_{d=5}$ $(\Lambda \gg M_W)$
- NP ? Generic, but in cases will assume weakly-int. renormalizable gauge theory with particles of $s \leq 1$.

Deviations from SM ($\mathcal{L}_{d=6}$) can give crucial info.

D=6 OPERATORS

Lots of them!

Buchmüller, Wyler '86, ...
Grzadkowski et al '10

Bosonic:

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

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

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

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

D=6 OPERATORS

Fermionic (1 family)

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

Many more for 3 families

D=6 OPERATORS

Directly involving the Higgs:

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$ $\mathcal{O}_R^{ud} = y_u^\dagger y_d (i\tilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$ $\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} g W_{\mu\nu}^a$ $\mathcal{O}_{DG}^u = y_u \bar{Q}_L \sigma^{\mu\nu} T^a u_R \tilde{H} g_s G_{\mu\nu}^a$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W_{\mu\nu}^a$ $\mathcal{O}_{DG}^d = y_d \bar{Q}_L \sigma^{\mu\nu} T^a d_R H g_s G_{\mu\nu}^a$	$\mathcal{O}_{DB}^l = y_l \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ $\mathcal{O}_{DW}^e = y_l \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W_{\mu\nu}^a$

Rest are 4-fermion operators.

TO KNOW IS TO LOVE : LEARNING ABOUT d=6 OPERATORS

S. Ramanujan

"Every positive integer is one of Ramanujan's personal friends."

J. Littlewood

TO KNOW IS TO LOVE : LEARNING ABOUT d=6 OPERATORS

- Some operators can be eliminated by using EoMs (eq. field redefinitions) Eg. Arzt'93

Ex: $\mathcal{O}_r \equiv |H|^2 |D_\mu H|^2$

can be removed by $H \to H\left(1 + \frac{\alpha}{\Lambda^2}|H|^2\right)$

Eliminating such "redundant" operators:

59 $\mathcal{O}_i$'s (1 family)

There is freedom in what operators to keep:

choice of BASIS OF d=6 OPS

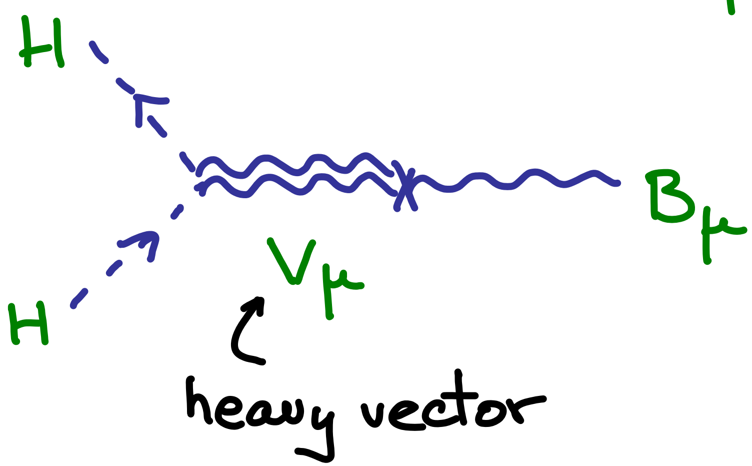
Same physics can be described by diff. op. subsets

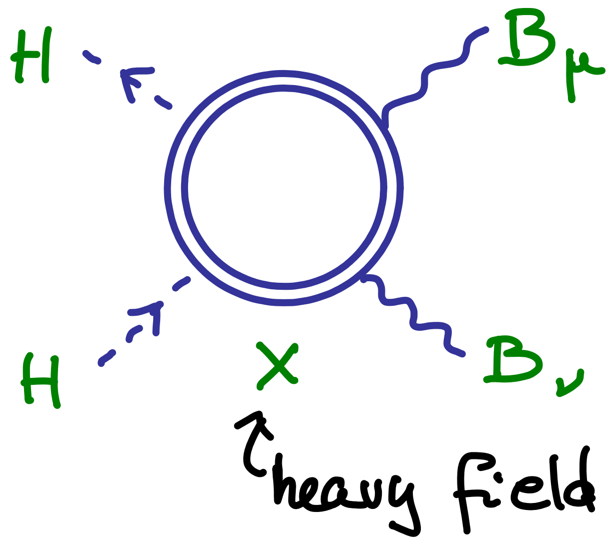
TO KNOW IS TO LOVE : LEARNING ABOUT $d=6$ OPERATORS

- Not all operators are born equal — Einhorn, Wudka '01

current-current (or tree) vs. one-loop operators

Ex: $\mathcal{O}_B \equiv \frac{ig'}{2} \underbrace{(H^\dagger \overleftrightarrow{D}^\mu H)}_{J_H^\mu} \underbrace{\partial^\nu B_{\mu\nu}}_{J_{B\mu}}$ $\qquad$ $\mathcal{O}_{BB} \equiv |H|^2 B_{\mu\nu} B^{\mu\nu}$





$$\Delta\mathcal{L} = \frac{c_B}{\Lambda^2}\mathcal{O}_B \qquad\qquad \Delta\mathcal{L} = \frac{1}{\Lambda^2}\underbrace{\frac{c_{BB}}{16\pi^2}}_{\kappa_{BB}}\mathcal{O}_{BB}$$

expect loop-size

CURRENT-CURRENT VS LOOP

Some comments:

- The classification is based on the possible origin of the operators, e.g. in weakly-coupled renormalizable theories with spin ≤ 1 particles.

- As such, the classification is perfectly well-defined

- All operators belong to one of these two classes.

CURRENT-CURRENT VS LOOP

More comments on this classification:

- Useful to estimate expected sizes of c_i's in many BSM scenarios, even some beyond weak-coupling.

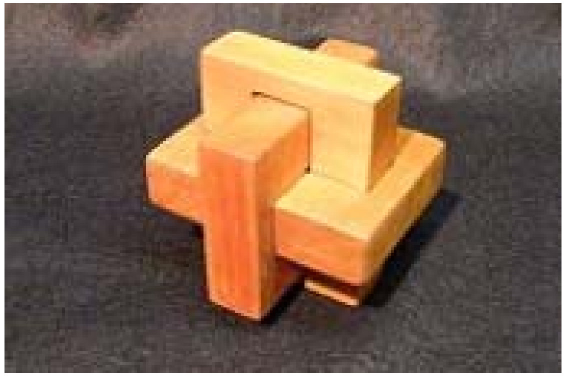
- Of course life can be more complicated.

  Eg, "tree-level" c_i might be loop suppressed (R-parity); or several Λ_i, etc, etc

- Useful in studying RG operator mixing, irrespective of UV origin. (this talk)

AN AMUSING OPERATOR PUZZLE

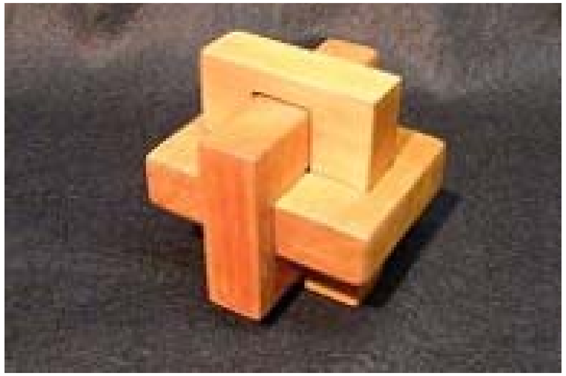
The current-current op. O_B can be broken in 3 loop-ops.



$$\underbrace{\frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}}_{O_B} = \underbrace{ig'(D_\mu H)^\dagger D_\nu H\, B^{\mu\nu}}_{O_{HB}} + \frac{1}{4}\underbrace{gg'(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}}_{O_{WB}} + \frac{1}{4}\underbrace{g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}}_{O_{BB}}$$

AN AMUSING OPERATOR PUZZLE

The current-current op. $\mathcal{O}_B$ can be broken in 3 loop ops.



$$\underbrace{\frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}}_{\mathcal{O}_B} = \underbrace{ig'(D_\mu H)^\dagger D_\nu H \, B^{\mu\nu}}_{\mathcal{O}_{HB}} + \frac{1}{4}\underbrace{gg'(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}}_{\mathcal{O}_{WB}} + \frac{1}{4}\underbrace{g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}}_{\mathcal{O}_{BB}}$$

and the same for $\mathcal{O}_W$:

$$\underbrace{\frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D_\nu W^{a\,\mu\nu}}_{\mathcal{O}_W} = \underbrace{ig(D_\mu H)^\dagger \sigma^a D_\nu H W^{a\,\mu\nu}}_{\mathcal{O}_{HW}} + \frac{1}{4}\underbrace{gg'(H^\dagger \sigma^a H) W^a_{\mu\nu} B^{\mu\nu}}_{\mathcal{O}_{WB}} + \frac{1}{4}\underbrace{g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}}_{\mathcal{O}_{WW}}$$

AN AMUSING OPERATOR PUZZLE

$$O_B = O_{HB} + \frac{1}{4} O_{WB} + \frac{1}{4} O_{BB}$$

$$O_W = O_{HW} + \frac{1}{4} O_{WB} + \frac{1}{4} O_{WW}$$

Doesn't this invalidate our classification?

NO! Still true that $O_{B,W}$ can be generated at tree-level and not $O_{HB,HW}$, $O_{WW,WB,BB}$ separately.

If we remove O_B from our basis using the above op. identity c_{HB}, c_{WB}, c_{BB} will have tree-level correlated sizes.

The correlation remembers the O_B origin.

We'll see the dangers of this below.

THE ART OF CHOOSING A BASIS

Physics is basis-independent, but some bases are more convenient than others and some can mislead you.

Possible properties of a good basis :

- Simple connection between observables and operators

  Eg, in some bases, only $|H|^2 B_{\mu\nu}B^{\mu\nu}$ contributes directly to $h \to \gamma\gamma$

- A few operators can parametrize many classes of BSM theories

  Eg. ops related to S, T in universal theories

- Keeps track simply of operators of diff. size

  Eg. bad idea to get rid of $O_B \to O_{HB}, O_{BW}, O_{BB}$

- Respects possible symmetries of the BSM theory

  Eg. shift symmetry for a PGB → SILH basis

  Giudice, Grojean, Pomarol, Rattazzi

D=6 OPERATORS & HIGGS PHYSICS

- Some d=6 ops only affect Higgs physics Eg. $|H|^2 G_{\mu\nu} G^{\mu\nu}$

  ⇨ only LHC probes them. What bounds can be set?

- Other operators also affect EW physics and are already constrained by LEP & Tevatron Eg. $O_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$

Do such constraints close the door to large effects on Higgs physics?

- Model-independent global fit desirable and doable

Won't discuss these in this talk.

RG EFFECTS

BSM theory predicts $c_i(\Lambda)$

$$c_i(\Lambda)$$

$$\Big\downarrow \text{RG} \qquad \gamma_i = \frac{dc_i}{d\log\mu} = b_{ij}c_j$$

$$c_i(M_W) = c_i(\Lambda) - \frac{b_{ij}}{16\pi^2}\, c_j \log\frac{\Lambda}{M_W}$$

RG EFFECTS

Potentially important

$$\kappa_{\gamma\gamma}(\Lambda) \xrightarrow{RG} \kappa_{\gamma\gamma}(M_W)$$

$$\kappa_{\gamma\gamma}(M_W) = \kappa_{\gamma\gamma}(\Lambda) - \frac{b_{\gamma\gamma,j}}{16\pi^2} c_j(\Lambda) \log \frac{\Lambda}{M_W}$$

loop op. — naive prediction — tree level ops. could enter here

Could be dominant term!

Does this happen?

Grojean, Jenkins, Manohar, Trott '13 claimed it does...

RG EFFECTS IN $h \to \gamma\gamma$

Operators considered and some basis choices :

$$O_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad O_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\,\mu\nu}$$

$$O_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu} \qquad O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{WB} = g g' H^\dagger \sigma^a H \, B_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{HW} = i g \, D_\mu H^\dagger \sigma^a D_\nu H \, W^{a\,\mu\nu} \qquad O_{HB} = i g' D_\mu H^\dagger D_\nu H \, B^{\mu\nu}$$

RG EFFECTS IN $h\to\gamma\gamma$

Operators considered and some basis choices :

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$O_{WB} = gg' H^\dagger\sigma^a H\, B_{\mu\nu}W^{a\,\mu\nu}$

$\to$ relevant for $h\to\gamma\gamma$

$O_{HW} = ig\, D_\mu H^\dagger\sigma^a D_\nu H\, W^{a\,\mu\nu}$ $\qquad$ $O_{HB} = ig' D_\mu H^\dagger D_\nu H\, B^{\mu\nu}$

RG EFFECTS IN $h \to \gamma\gamma$

Operators considered and some basis choices:

$$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad \mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\,\mu\nu}$$

tree tree

$$O_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu} \qquad O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{WB} = g g' H^\dagger \sigma^a H B_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{HW} = i g D_\mu H^\dagger \sigma^a D_\nu H W^{a\,\mu\nu} \qquad O_{HB} = i g' D_\mu H^\dagger D_\nu H B^{\mu\nu}$$

loop

2 ops can be discarded using the op. identities for $\mathcal{O}_{W,B}$

RG EFFECTS in $h \to \gamma\gamma$

Operators considered and some basis choices :

$$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad \mathcal{O}_W = i\frac{g}{2}(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\mu\nu}$$

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$$O_{WB} = gg' H^\dagger\sigma^a H B_{\mu\nu}W^{a\mu\nu}$$

$$O_{HW} = ig\, D_\mu H^\dagger \sigma^a D_\nu H\, W^{a\mu\nu} \qquad O_{HB} = ig' D_\mu H^\dagger D_\nu H\, B^{\mu\nu}$$

GJMT basis

RG EFFECTS IN $h \to \gamma\gamma$

Operators considered and some basis choices :

$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$

out

$\mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D_\nu W^{a\,\mu\nu}$

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

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

$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H B_{\mu\nu} W^{a\,\mu\nu}$

$\mathcal{O}_{HW} = ig\, D_\mu H^\dagger \sigma^a D_\nu H\, W^{a\,\mu\nu}$

$\mathcal{O}_{HB} = ig' D_\mu H^\dagger D_\nu H\, B^{\mu\nu}$

GJMT basis

RG EFFECTS IN $h \to \gamma\gamma$

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$$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad \mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\,\mu\nu}$$

out

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu} \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu}W^{a\,\mu\nu}$$

$$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H\, B_{\mu\nu} W^{a\,\mu\nu}$$

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GJMT basis

RG EFFECTS IN $h \to \gamma\gamma$

Operators considered and some basis choices:

$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$

$\mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\,\mu\nu}$

for RGEs only considered these 3

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

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

$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H B_{\mu\nu}W^{a\,\mu\nu}$

$\mathcal{O}_{HW} = ig\, D_\mu H^\dagger \sigma^a D_\nu H\, W^{a\,\mu\nu}$

$\mathcal{O}_{HB} = ig'\, D_\mu H^\dagger D_\nu H\, B^{\mu\nu}$

GJMT basis

large and correlated

RG EFFECTS IN $h \to \gamma\gamma$

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$$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}$$

$$\mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D_\nu W^{a\,\mu\nu}$$

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

$$O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{WB} = g g' H^\dagger \sigma^a H B_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{HW} = i g D_\mu H^\dagger \sigma^a D_\nu H W^{a\,\mu\nu}$$

$$O_{HB} = i g' D_\mu H^\dagger D_\nu H B^{\mu\nu}$$

our first basis choice

GJMT basis

RG EFFECTS in $h\to\gamma\gamma$

Operators considered and some basis choices :

$$\mathcal{O}_B = i\frac{g'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu} \qquad \mathcal{O}_W = i\frac{g}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H)D_\nu W^{a\,\mu\nu}$$

$$O_{BB} = g'^2 |H|^2 B_{\mu\nu}B^{\mu\nu} \qquad O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{WB} = gg' H^\dagger \sigma^a H B_{\mu\nu} W^{a\,\mu\nu}$$

$$O_{HW} = ig\, D_\mu H^\dagger \sigma^a D_\nu H\, W^{a\,\mu\nu} \qquad O_{HB} = ig' D_\mu H^\dagger D_\nu H\, B^{\mu\nu}$$

Even better basis

GJMT basis

RG EFFECTS IN $h \to \gamma\gamma$

In our first basis

no mixing!

$h \to \gamma\gamma$

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

potentially large

In GJMT basis

calculated

needed for full result

$h \to \gamma\gamma$

$$\frac{d}{d\log\mu}\begin{pmatrix} c'_{BB} \\ c'_{WW} \\ c'_{WB} \\ c'_{HW} \\ c'_{HB} \end{pmatrix} = \begin{pmatrix} \hat{\Gamma} & Y' \\ 0_{2\times 3} & \hat{X} \end{pmatrix} \begin{pmatrix} c'_{BB} \\ c'_{WW} \\ c'_{WB} \\ c'_{HW} \\ c'_{HB} \end{pmatrix}$$

potentially large (and correlated)

RG EFFECTS IN $h \to \gamma\gamma$

In our 2nd basis

$$\frac{d}{d\log\mu}\begin{pmatrix}\hat{\kappa}_{BB}\\ \hat{\kappa}_{WW}\\ \hat{\kappa}_{WB}\\ \hat{c}_W\\ \hat{c}_B\end{pmatrix} = \underbrace{\begin{pmatrix}\hat{\Gamma} & 0_{3\times 2}\\ 0_{2\times 3} & \hat{X}\end{pmatrix}}_{\text{block diagonal}}\begin{pmatrix}\hat{\kappa}_{BB}\\ \hat{\kappa}_{WW}\\ \hat{\kappa}_{WB}\\ \hat{c}_W\\ \hat{c}_B\end{pmatrix}$$

$h \to \gamma\gamma$

} potentially large

Also checked that no other tree-level operator enters the RGEs of $\kappa_{BB,WW,WB,HW,HB}$ (relevant for $h \to \gamma\gamma, \gamma Z$)

RG EFFECTS IN $h \to \gamma\gamma, \gamma Z$

Final results:

$$16\pi^2 \frac{d\kappa_{\gamma\gamma}}{d\log\mu} = \left[6y_t^2 + 12\lambda - \frac{3}{2}(3g^2 + g'^2)\right]\kappa_{BB} + \left(\frac{3}{2}g^2 - 2\lambda\right)(\kappa_{HW} + \kappa_{HB})$$

$$16\pi^2 \frac{d\kappa_{\gamma Z}}{d\log\mu} = \left[6y_t^2 + 12\lambda - \frac{1}{2}(7g^2 + g'^2)\right]\kappa_{\gamma Z} + \left[2g^2 - 3e^2 - 2\lambda\cos 2\theta_W\right](\kappa_{HW} + \kappa_{HB})$$

Here $\kappa_{\gamma\gamma} = \kappa_{BB}$, $\kappa_{\gamma Z} = \frac{1}{4}(\kappa_{HB} - \kappa_{HW}) - 2s_W^2 \kappa_{BB}$

In some scenarios these radiative effects could dominate:

Higgs as PGB $\Rightarrow$ $\kappa_{BB} = 0$

left-right sym $\Rightarrow$ $\kappa_{HW} = \kappa_{HB}$

$\Big\} \Rightarrow \kappa_{\gamma\gamma}(\Lambda) = 0 = \kappa_{\gamma Z}(\Lambda)$

Predicts $\dfrac{\delta\Gamma_{\gamma Z}}{\Gamma_{\gamma Z}} = 0.64 \dfrac{\delta\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}}$ $\qquad \dfrac{\delta\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}} \sim 0.4 \dfrac{v^2}{\Lambda^2}\kappa_{HB}\log\dfrac{\Lambda}{m_W}$

CONCLUSIONS

- ★ The Higgs provides a very important window to probe BSM indirectly.
- ★ Model-independent approach through $d=6$ operators very useful.
- ★ Emphasized the importance of choosing basis and the relevance of the tree vs. loop operator classification
- ★ Tree-level ops do not enter the RGEs of one-loop ops.

Implications for $h \to \gamma\gamma, \gamma Z$.