# EXPLORING THE NEW FRONTIER OF THE d=6 HIGGS LAGRANGIAN: OPERATOR MIXING FOR $h \to \gamma\gamma, \gamma Z$

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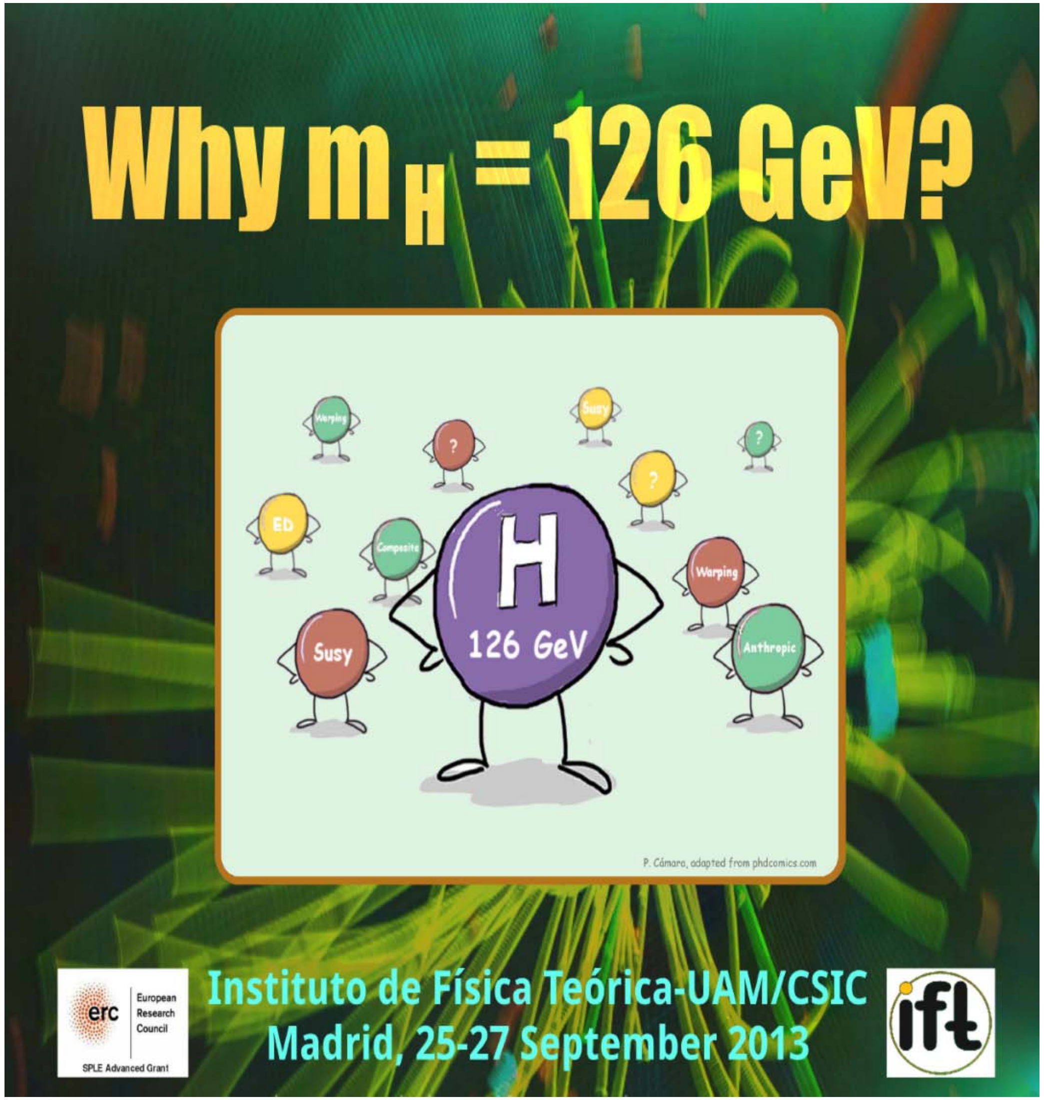



J.R.Espinosa
ICREA, IFAE
Barcelona

# EXPLORING THE NEW FRONTIER OF THE $d=6$ HIGGS LAGRANGIAN: OPERATOR MIXING 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/1308.1879]

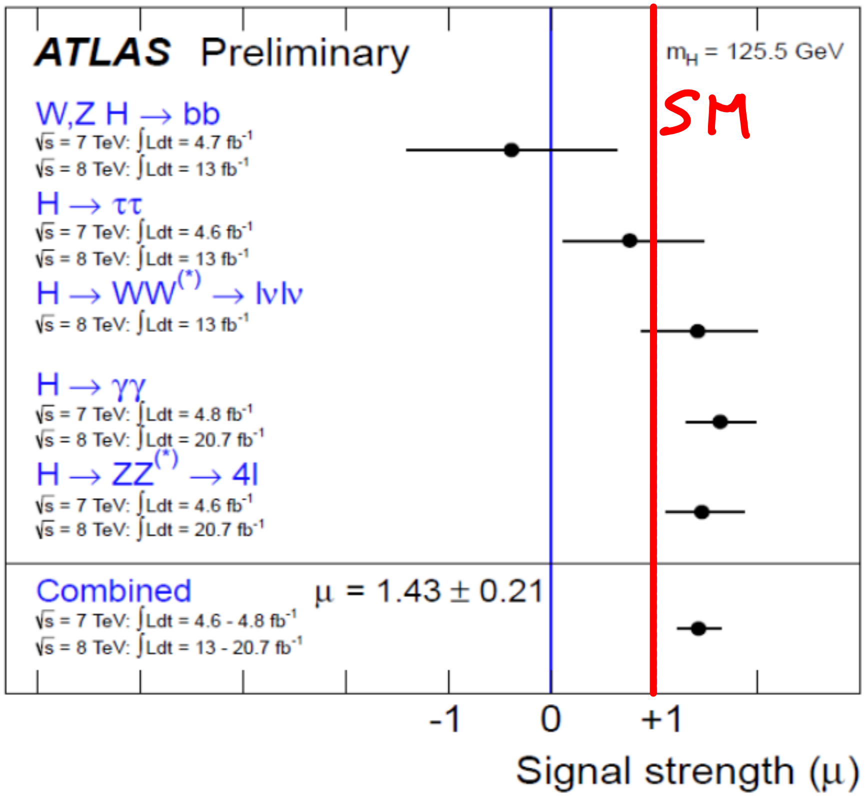
## For recent related work see:

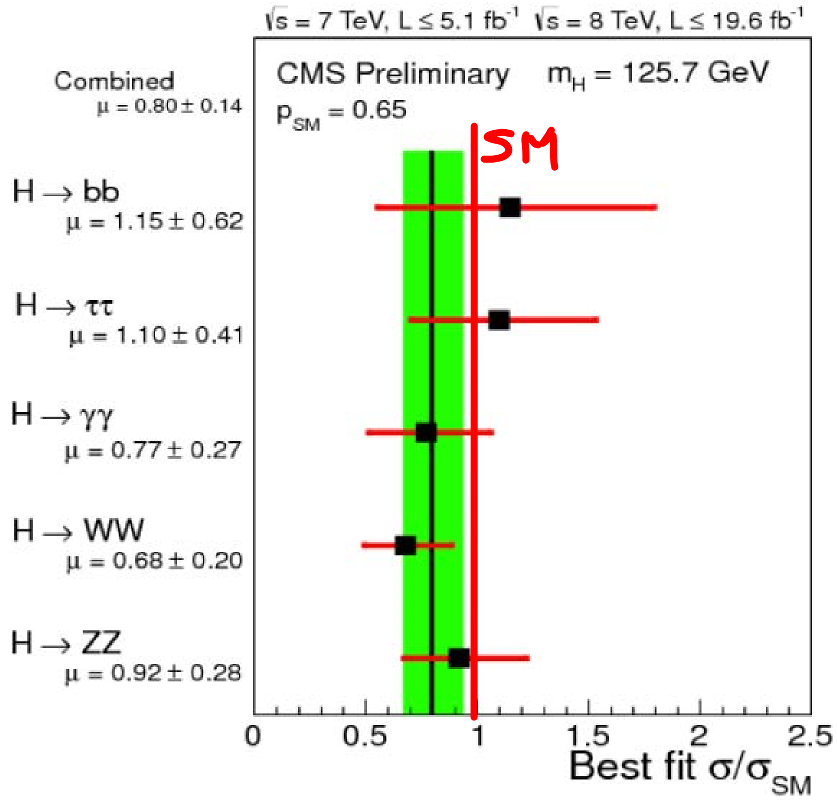
C. Grojean, E. Jenkins, M. Manohar, M. Trott

[hep-ph/1301.2588]

# BSM STATUS

- Higgs discovered, close to SM-like

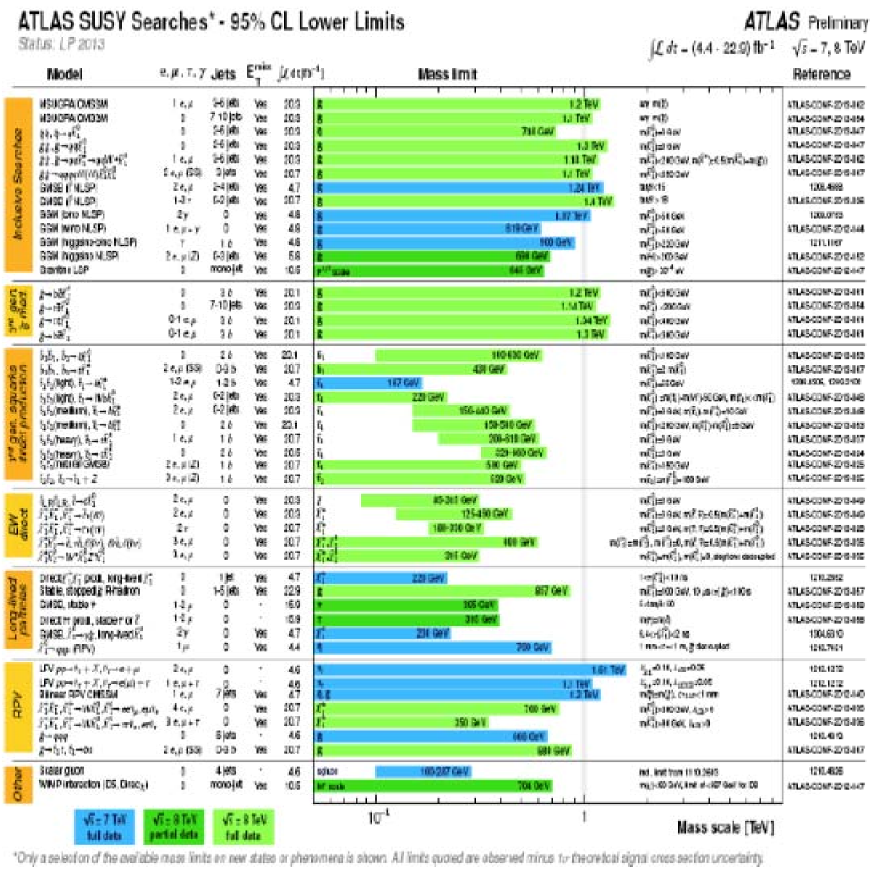


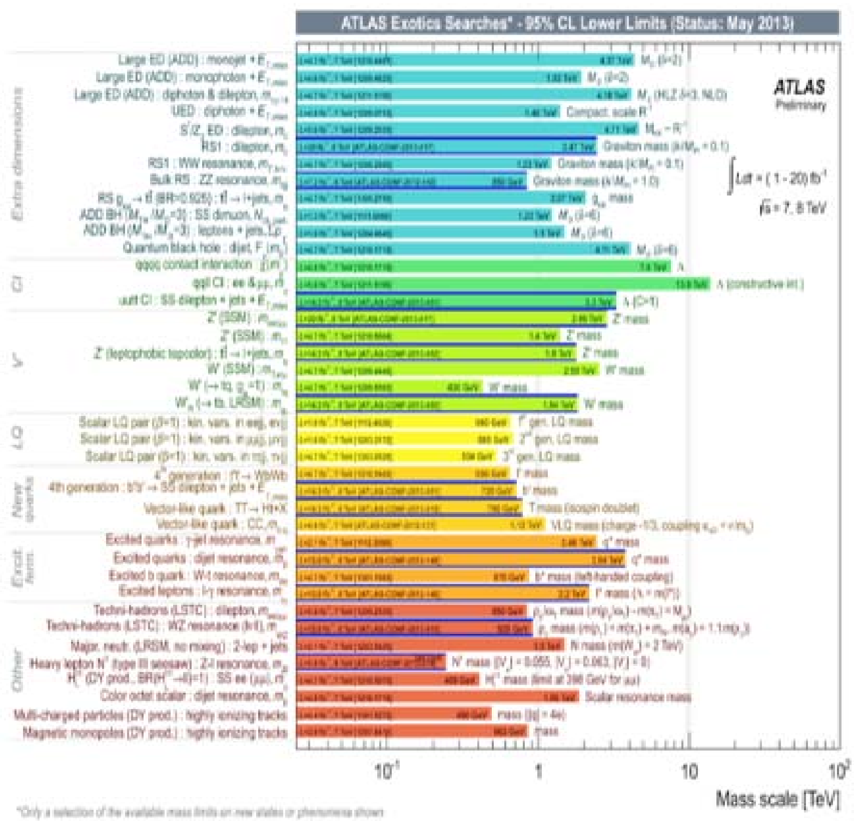
# BSM STATUS

- 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

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

determined by NP

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

Scale of NP $\qquad$ 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:

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

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

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

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

# D=6 OPERATORS

Fermionic (1 family)

| | | |
|---|---|---|
| $\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$ | $\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$ | $\mathcal{O}_{y_l} = y_l \lvert H\rvert^2 \bar{L}_L H e_R$ |
| $\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$ | $\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$ | $\mathcal{O}^l_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$ |
| $\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$ | | $\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$ |
| $\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$ | | $\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu \sigma^a L_L)$ |
| $\mathcal{O}^u_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma^\mu u_R)$ | $\mathcal{O}^d_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma^\mu d_R)$ | $\mathcal{O}^l_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{e}_R\gamma^\mu e_R)$ |
| $\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$ | $\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$ | |
| $\mathcal{O}^u_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$ | $\mathcal{O}^d_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$ | $\mathcal{O}^l_{RR} = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$ |
| $\mathcal{O}^q_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$ | | $\mathcal{O}^l_{LL} = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$ |
| $\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma^\mu T^A Q_L)$ | | |
| $\mathcal{O}^{ql}_{LL} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$ | | |
| $\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L\gamma^\mu \sigma^a Q_L)(\bar{L}_L\gamma^\mu \sigma^a L_L)$ | | |
| $\mathcal{O}^{qe}_{LR} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$ | | |
| $\mathcal{O}^{lu}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$ | $\mathcal{O}^{ld}_{LR} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$ | |
| $\mathcal{O}^{ud}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma^\mu d_R)$ | | |
| $\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma^\mu T^A d_R)$ | | |
| $\mathcal{O}^{ue}_{RR} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$ | $\mathcal{O}^{de}_{RR} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$ | |
| $\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\tilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$ | | |
| $\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^i_L u_R)\epsilon_{ij}(\bar{Q}^j_L d_R)$ | | |
| $\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^i_L T^A u_R)\epsilon_{ij}(\bar{Q}^j_L T^A d_R)$ | | |
| $\mathcal{O}_{y_u y_l} = y_u y_l (\bar{Q}^i_L u_R)\epsilon_{ij}(\bar{L}^j_L e_R)$ | | |
| $\mathcal{O}'_{y_u y_l} = y_u y_l (\bar{Q}^{i\alpha}_L e_R)\epsilon_{ij}(\bar{L}^j_L u^\alpha_R)$ | | |
| $\mathcal{O}_{y_l y_d} = y_l y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$ | | |
| $\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$ | $\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$ | $\mathcal{O}^l_{DB} = y_l \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$ |
| $\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} g W^a_{\mu\nu}$ | $\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$ | $\mathcal{O}^e_{DW} = y_l \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$ |
| $\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \tilde{H} g_s G^A_{\mu\nu}$ | $\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$ | |

Many more for 3 families

# D=6 OPERATORS

Directly involving the Higgs:

| | | |
|---|---|---|
| $\mathcal{O}_{y_u} = y_u\|H\|^2\bar{Q}_L\tilde{H}u_R$ | $\mathcal{O}_{y_d} = y_d\|H\|^2\bar{Q}_L H d_R$ | $\mathcal{O}_{y_l} = y_l\|H\|^2\bar{L}_L H e_R$ |
| $\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$<br>$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$<br>$\mathcal{O}_L^{(3)\,q} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu\sigma^a Q_L)$<br>$\mathcal{O}_R^{ud} = y_u^\dagger y_d(i\tilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$ | $\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$ | $\mathcal{O}_R^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$<br>$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$<br>$\mathcal{O}_L^{(3)\,l} = (iH^\dagger\sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu\sigma^a L_L)$ |
| $\mathcal{O}_{DB}^u = y_u\bar{Q}_L\sigma^{\mu\nu}u_R\tilde{H}g'B_{\mu\nu}$<br>$\mathcal{O}_{DW}^u = y_u\bar{Q}_L\sigma^{\mu\nu}u_R\sigma^a\tilde{H}gW_{\mu\nu}^a$<br>$\mathcal{O}_{DG}^u = y_u\bar{Q}_L\sigma^{\mu\nu}T^a u_R\tilde{H}g_sG_{\mu\nu}^a$ | $\mathcal{O}_{DB}^d = y_d\bar{Q}_L\sigma^{\mu\nu}d_R Hg'B_{\mu\nu}$<br>$\mathcal{O}_{DW}^d = y_d\bar{Q}_L\sigma^{\mu\nu}d_R\sigma^a HgW_{\mu\nu}^a$<br>$\mathcal{O}_{DG}^d = y_d\bar{Q}_L\sigma^{\mu\nu}T^a d_R Hg_sG_{\mu\nu}^a$ | $\mathcal{O}_{DB}^l = y_l\bar{L}_L\sigma^{\mu\nu}e_R Hg'B_{\mu\nu}$<br>$\mathcal{O}_{DW}^e = y_l\bar{L}_L\sigma^{\mu\nu}e_R\sigma^a HgW_{\mu\nu}^a$ |

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

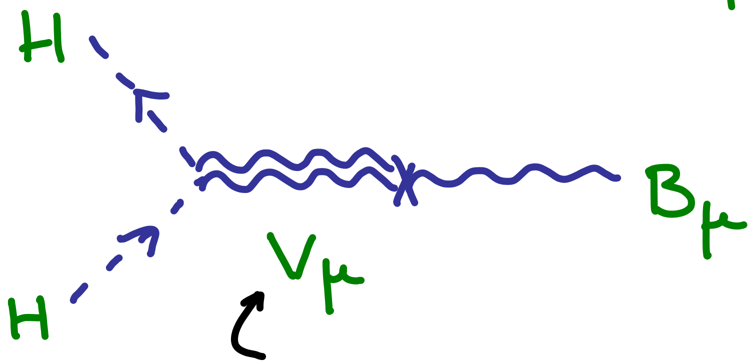
Same physics can be described by diff. op. subsets

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

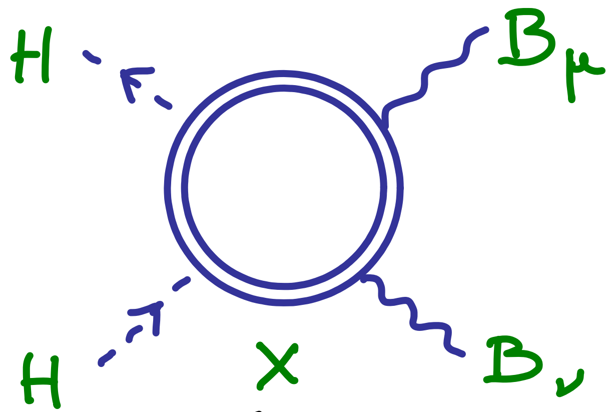
- Not all operators are born equal Arzt, Einhorn, Wudka '95

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

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




heavy vector




heavy field

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

expect loop-size

# CURRENT-CURRENT VS LOOP

## Some comments:

- The classification is based on the possible origin of the operators, eg. in weakly-coupled renormalizable theories with spin $\leq 1$ 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.

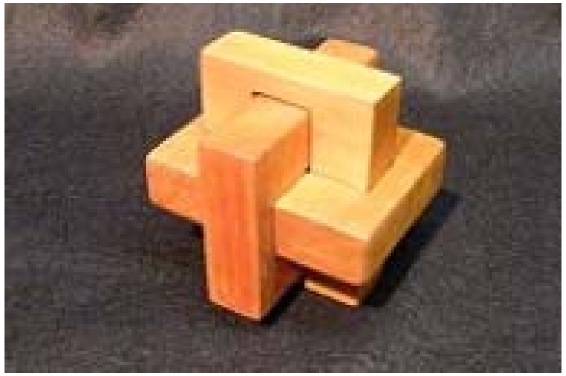
- Of course life can be more complicated.

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

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

# AN AMUSING OPERATOR PUZZLE

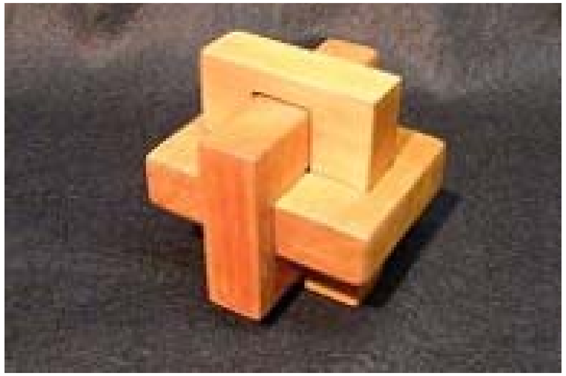
The current-current op. $O_B$ can be broken in 3 loop-ops.



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

# AN AMUSING OPERATOR PUZZLE

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



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

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

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

# 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 '07

# 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

# D=6 OPERATORS & HIGGS PHYSICS

$\mathcal{L}_{eff}$ approach $\Rightarrow$ model-independent

often $c_i$'s considered one at a time, claiming generality up to accidental cancellations.

General results should not be contradicted by particular examples.

- Concrete models give correlated $c_i$'s !
- Even a simple basis change $c\,\mathcal{O} \to \sum_i \alpha_i \mathcal{O}_i$ introduces correlations.

For a careful global analysis, see

J. Elias-Miró, JRE, E. Masso, A. Pomarol [hep-ph/1308.1879]
A. Pomarol, F. Riva [hep-ph/1308.2803]

# 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

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

$$\Big\downarrow \text{RG}$$

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

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:

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

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

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

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

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

# 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

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

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

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

loop

2 ops can be discarded using the op. identities for $O_{W,B}$

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

Operators considered and some basis choices :

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

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

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

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

GJMT basis

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

Operators considered and some basis choices :

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

out

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

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

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

GJMT basis

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for RGEs only considered these 3

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

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

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GJMT basis

large and correlated

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our first basis choice

GJMT basis

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

Even better basis

GJMT basis

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

In our first basis

no mixing!

$h\to\gamma\gamma$

$$\frac{d}{d\log\mu}\begin{pmatrix}\kappa_{BB}\\ \kappa_{HW}\\ \kappa_{HB}\\ c_W\\ c_B\end{pmatrix} = \begin{pmatrix}\Gamma & 0_{3\times2}\\ Y & \hat{X}\end{pmatrix}\begin{pmatrix}\kappa_{BB}\\ \kappa_{HW}\\ \kappa_{HB}\\ c_W\\ c_B\end{pmatrix}$$

potentially large

In GJMT basis

calculated

needed for full result

$h\to\gamma\gamma$

$$\frac{d}{d\log\mu}\begin{pmatrix}c'_{BB}\\ c'_{WW}\\ c'_{WB}\\ c'_{HW}\\ c'_{HB}\end{pmatrix} = \begin{pmatrix}\hat{\Gamma} & Y'\\ 0_{2\times3} & \hat{X}\end{pmatrix}\begin{pmatrix}c'_{BB}\\ c'_{WW}\\ c'_{WB}\\ c'_{HW}\\ c'_{HB}\end{pmatrix}$$

potentially large (and correlated)

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

In our 2nd basis

$h\to\gamma\gamma$

$$\frac{d}{d\log\mu}\begin{pmatrix}\hat\kappa_{BB}\\ \hat\kappa_{WW}\\ \hat\kappa_{WB}\\ \hat c_W\\ \hat c_B\end{pmatrix} = \underbrace{\begin{pmatrix}\hat\Gamma & 0_{3\times2}\\ 0_{2\times3} & \hat X\end{pmatrix}}_{\text{block diagonal}}\begin{pmatrix}\hat\kappa_{BB}\\ \hat\kappa_{WW}\\ \hat\kappa_{WB}\\ \hat c_W\\ \hat c_B\end{pmatrix}$$

} potentially large

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

Tree $\not\to$ Loop is generic (exception: $4f\to$ dipoles)

# 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:

$$\left.\begin{array}{l} \text{Higgs as PGB} \Rightarrow \kappa_{BB} = 0 \\ \text{left-right sym} \Rightarrow \kappa_{HW} = \kappa_{HB} \end{array}\right\} \Rightarrow \kappa_{\gamma\gamma}(\Lambda) = 0 = \kappa_{\gamma Z}(\Lambda)$$

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 (beware of correlations!) and the relevance of the tree vs. loop operator classification
- Tree-level ops do not enter the RGEs of one-loop bosonic operators: Implications for $h\to\gamma\gamma, \gamma Z$.