HIGGS EFFECTIVE FIELD THEORY

Sept. 8, 2015

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Summer School & Workshop on the SM and Beyond
Corfu

SUPPLEMENTARY MATERIAL

This lecture is based on the third one of a 3-hour lecture on EFTs for BSM I gave at TAE 2014:

http://benasque.org/2014tae/cgi-bin/talks/allprint.pl

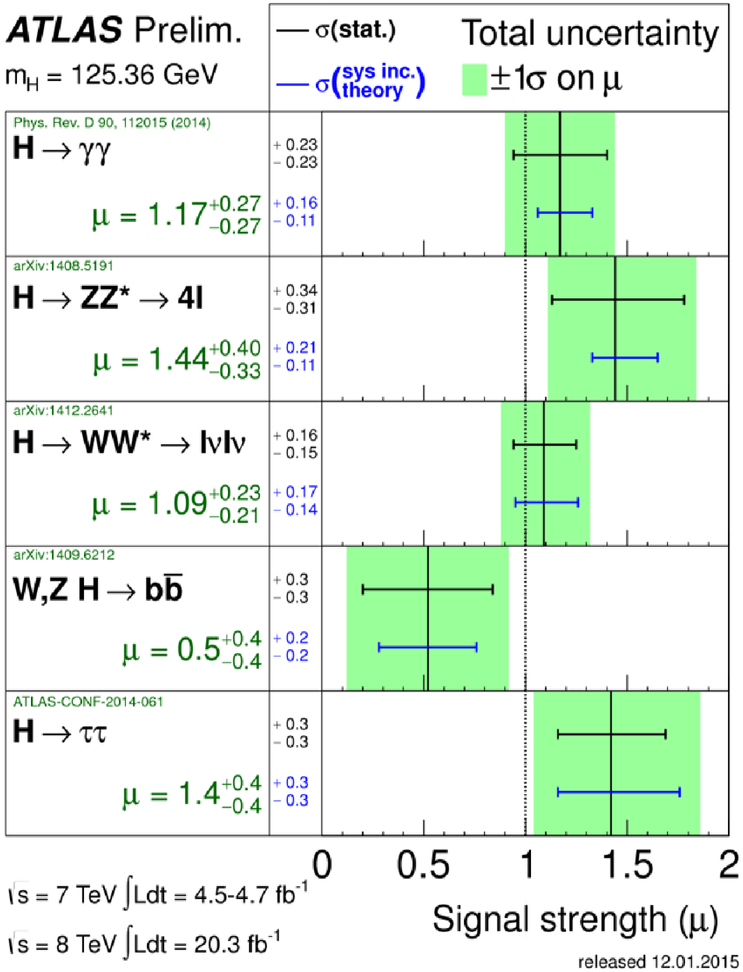
You can find there lecture notes and exercises as well as a more general introduction to the use of EFTs in the context of BSM physics in the first 2 lectures

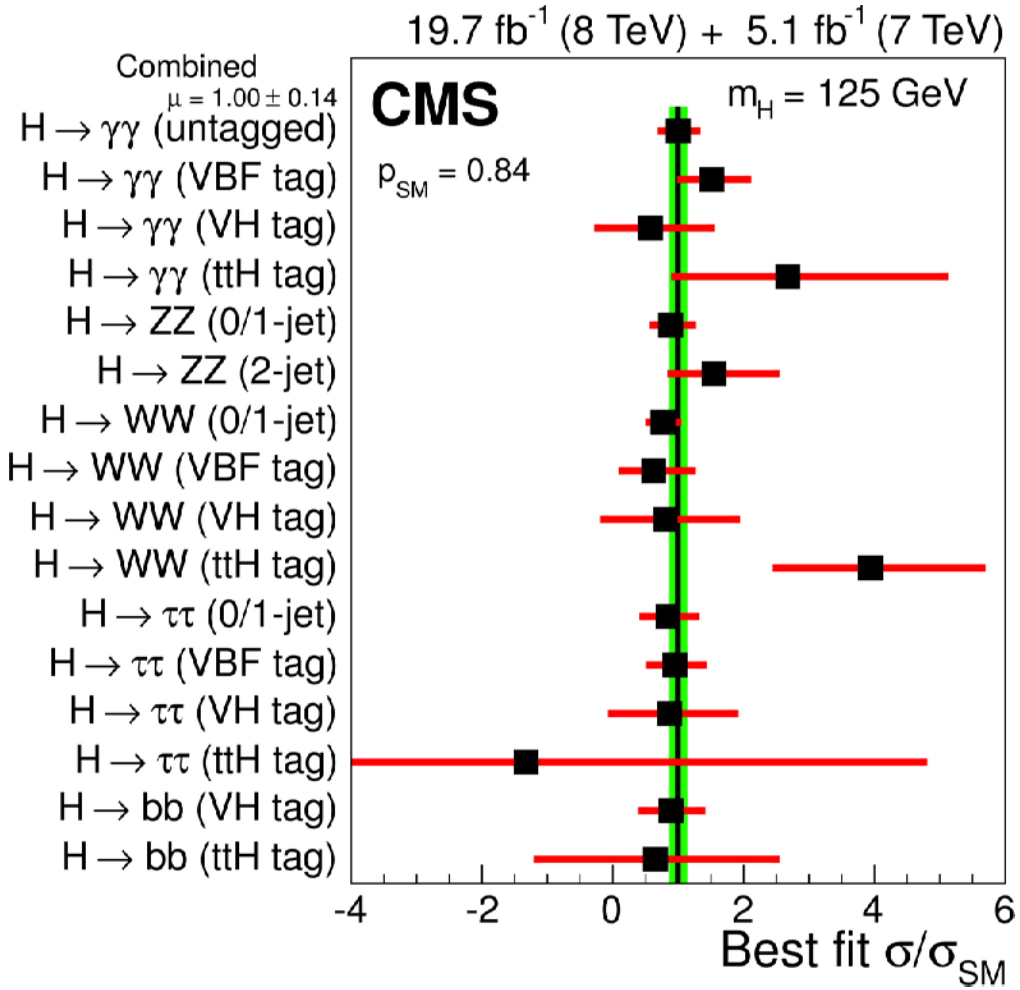
OUTLINE

1. Motivation and goals
2. Power counting
3. Operator bases
4. Experimental constraints
5. Higgs physics

1. Motivation and goals

- Higgs discovered, close to SM-like

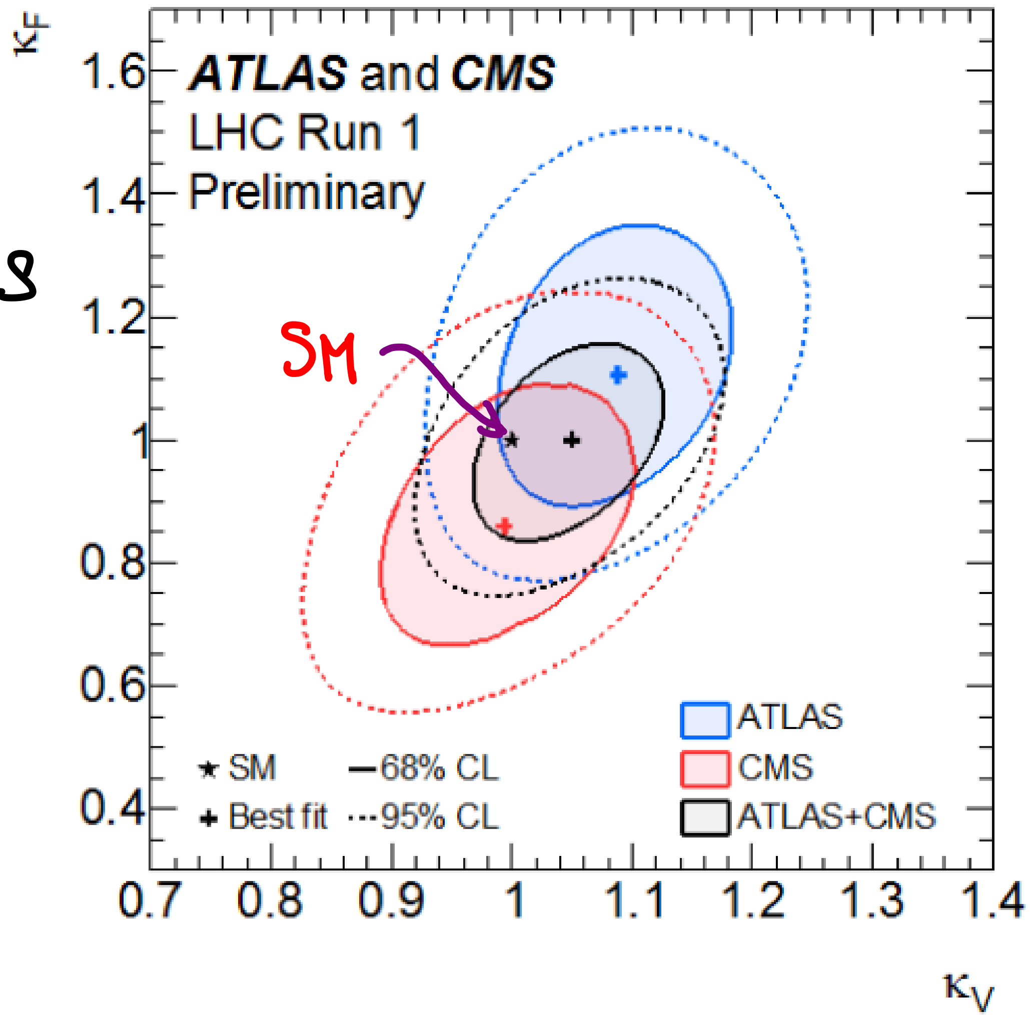




Mh/GeV = 125.09 + 0.21 (stat) + 0.11 (syst)   ATLAS+ CMS

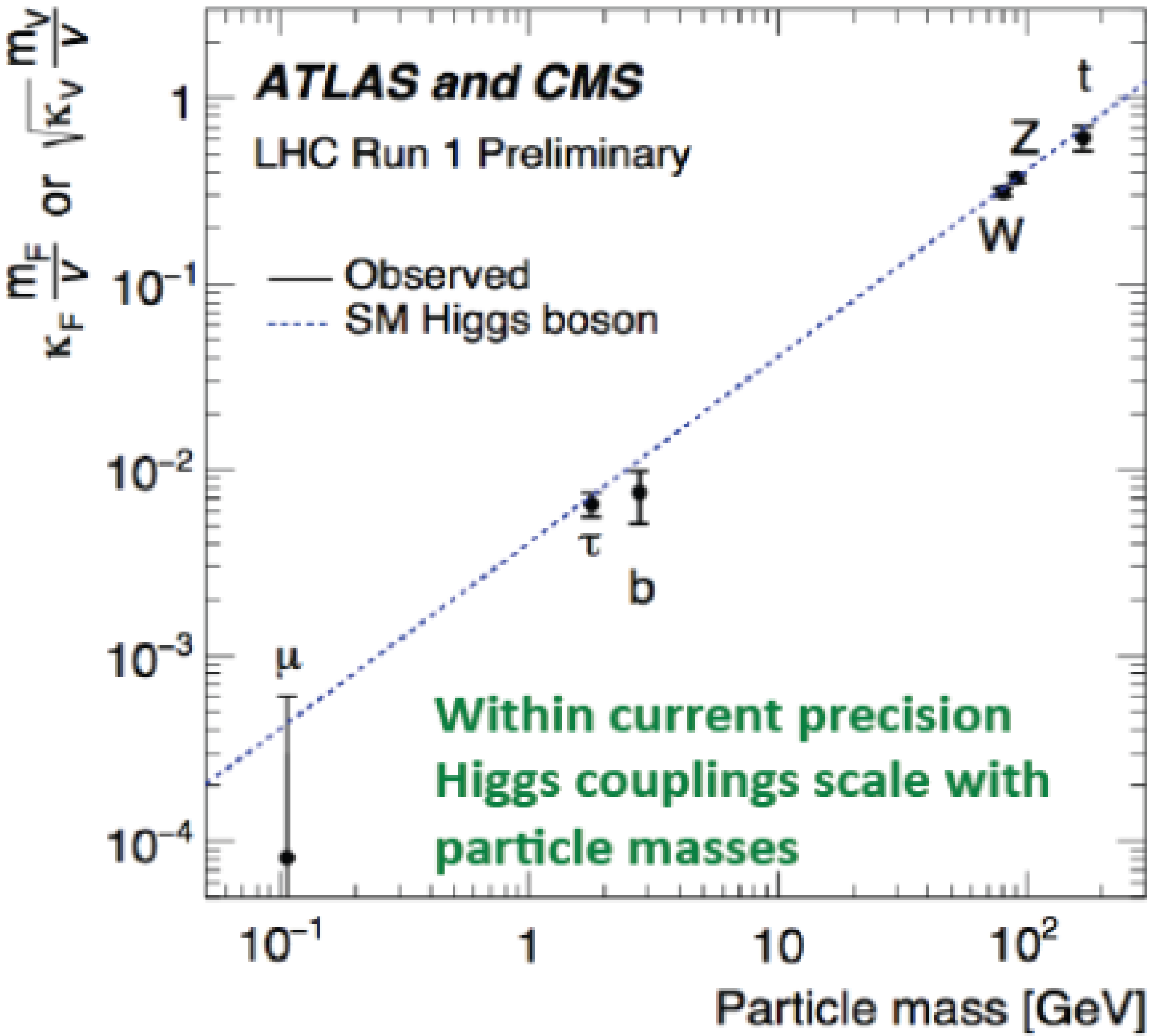
- Higgs discovered, close to SM-like

Coupling to fermions



Coupling to vector bosons

- Higgs discovered, close to SM-like



HIGGS OUROBOROS

SM Higgs sector is the most problematic

Affected by hierarchy problem

Calls for new physics at the TeV scale

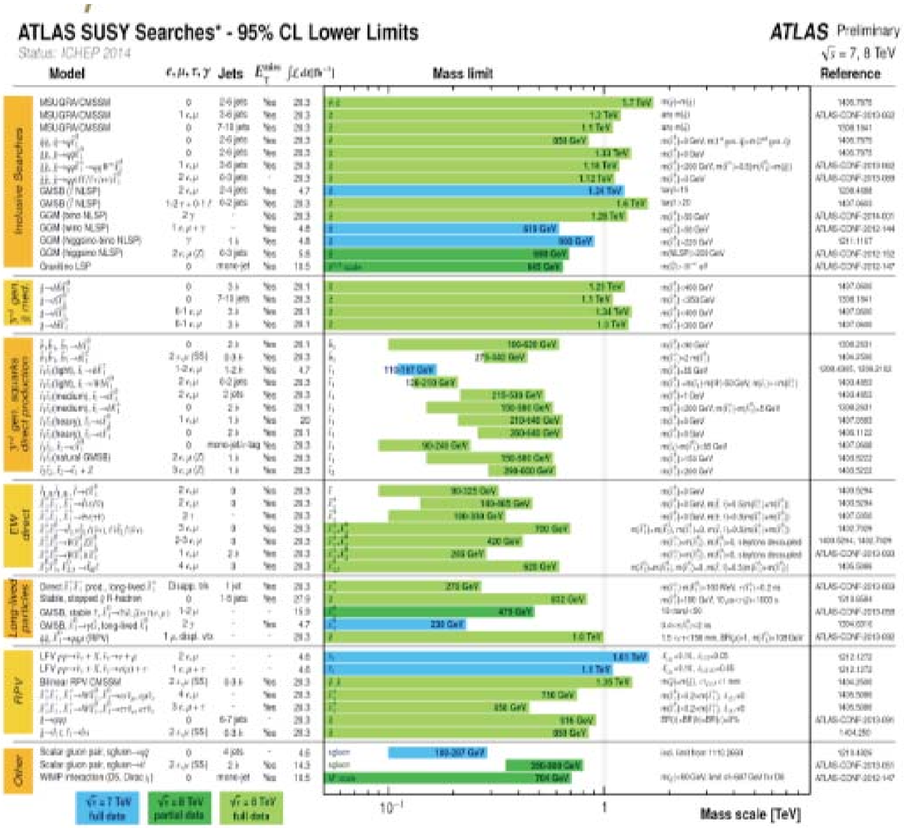
$$V = \frac{1}{2} m^2 h^2 + \frac{1}{4} \lambda h^4 \Rightarrow \langle h \rangle^2 \sim \frac{m^2}{\lambda} \sim \text{EW}$$

$$m^2 \sim \frac{1}{(4\pi)^2} \Lambda^2$$

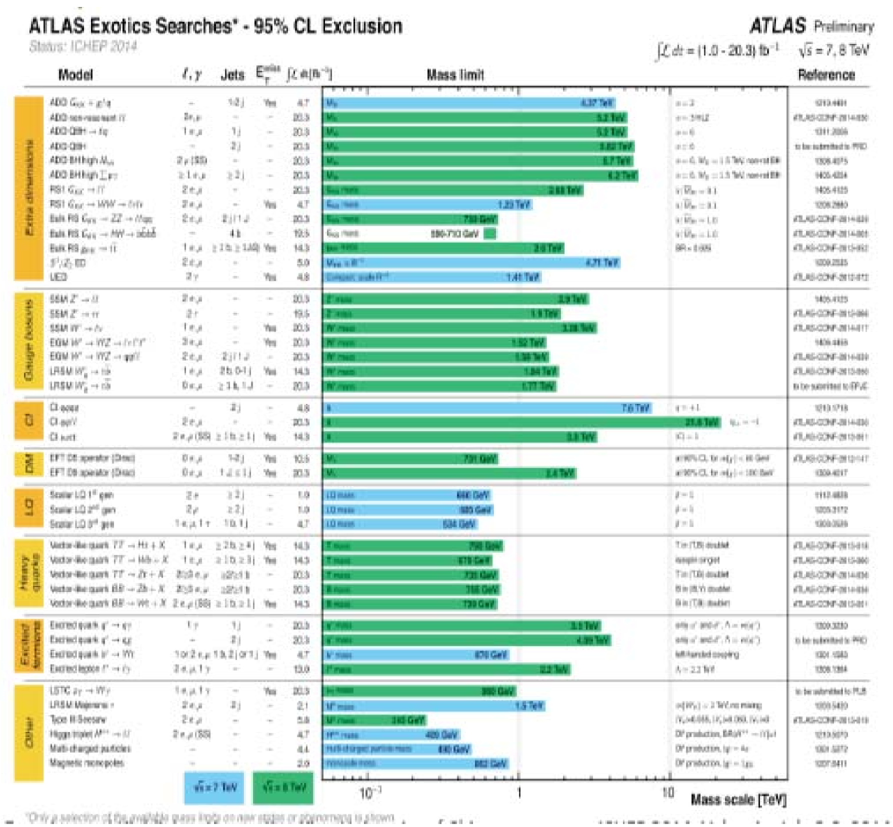
BSM STATUS

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

"TSUNAMI" EXCLUSION PLOTS



SUSY



EXOTICS

BSM STATUS

- Higgs discovered, close to SM-like

+

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

+

- Holding on to naturalness

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

HIGGS OUROBOROS

SM Higgs sector is the most ~~problematic~~ interesting

Affected by hierarchy problem

Calls for new physics at the TeV scale

It's very likely that the Higgs will depart from its SM properties

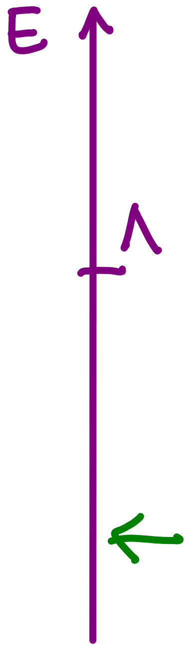
IMPORTANCE OF THE HIGGS

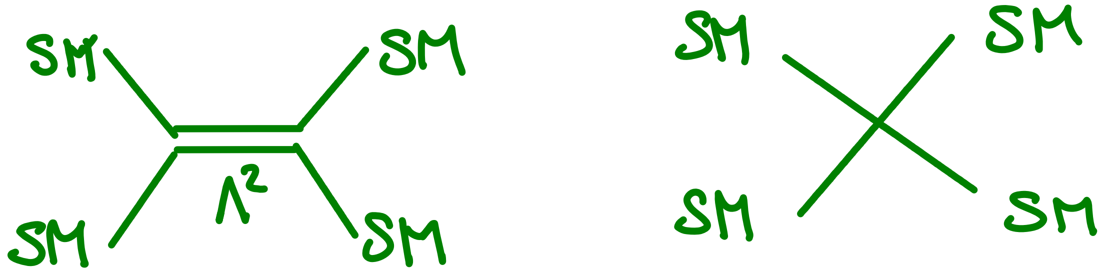
Not as the keystone
of the SM

but as the portal
to reveal the cracks
in the SM

EFFECTIVE THEORY APPROACH

$\Lambda \gg m_W$





$\sim \frac{1}{\Lambda^2}$

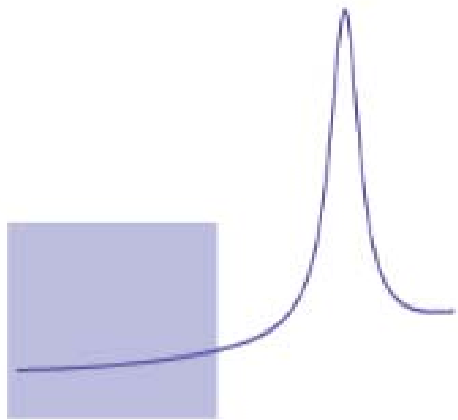
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots$$

$$\frac{y^2}{\Lambda}(L\cdot H)^2$$

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

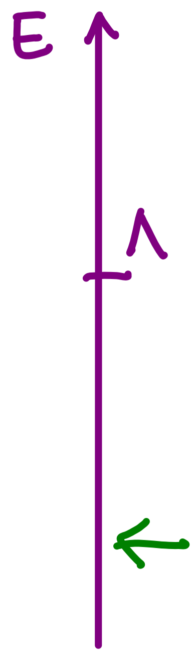
Neutrino masses

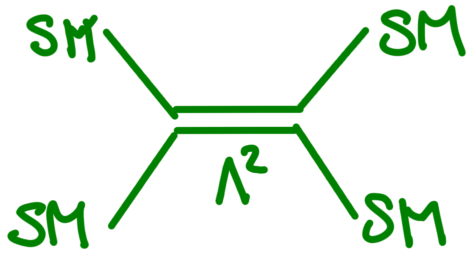
$(\Lambda \sim 10^{12}\,\mathrm{GeV} \gg \mathrm{TeV}) \rightarrow$ ignore

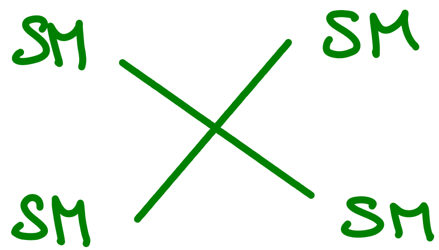


EFFECTIVE THEORY APPROACH

$$\Lambda \gg m_W$$







$$\sim \frac{1}{\Lambda^2}$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \mathcal{L}_{d=5} + \mathcal{L}_{d=6} + \ldots$$

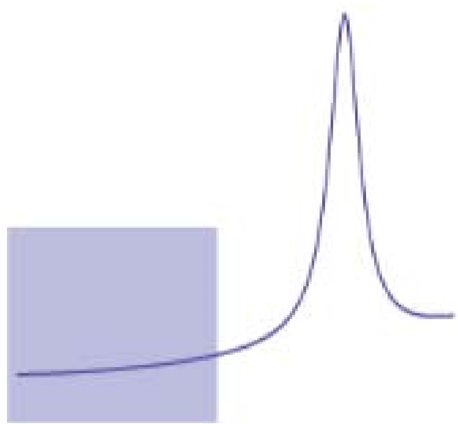
$$\frac{c_i}{\Lambda^2}\, \mathcal{O}_{d=6}$$

Wilson coeff. determined by NP

Scale of NP

$\Lambda \sim$ few TeV

made of SM fields



EFFECTIVE THEORY APPROACH

- What New Physics? Generic, but assuming

✓ B & L_i conservation ($\Lambda_{\cancel{B},\cancel{L}_i} \gg \text{TeV}$)

✓ H $SU(2)_L$ doublet

✓ Non generic flavor structure
(Minimal Flavor Violation)

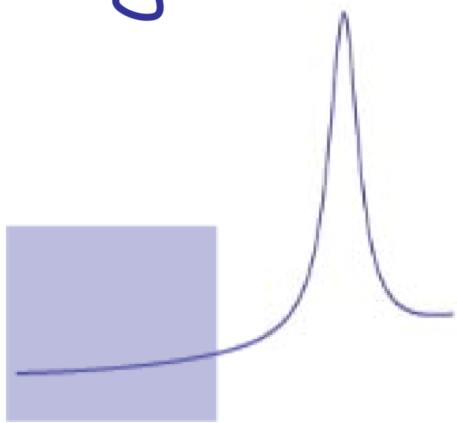
Deviations from SM ($\mathcal{L}_{d=6}$) can give crucial info.

VIRTUES OF EFT APPROACH

EFT approach well motivated by mass gap

$$\Lambda \gg M_W$$

- ✓ Model independent approach (complements analysis of concrete BSM models)
- ✓ Good guide to identify the most promising interactions that could show deviations
- ✓ Allows to probe (indirectly) higher energy scales than direct searches (complementary to them)



STRATEGY / GOAL

Look at the complete $\mathcal{L}_{d=6}$

Use all data from LHC + previous experiments (LEP I & II, Tevatron, ...) to determine what deviations from the SM (parametrized by $\mathcal{L}_{d=6}$) are still possible.

Main focus : Higgs physics

2. Power counting

Remember

determined by NP

$$\Delta\mathcal{L}_6 = \frac{c_i}{\Lambda^2}\,\mathcal{O}_{d=6}$$

Can we say something more precise about c_i's ?

E.g.

$$\frac{1}{\Lambda^2} g_i^2\, \mathcal{O}_i \longleftrightarrow \frac{1}{\Lambda^2} g_i^4\, \mathcal{O}_i \longleftrightarrow \frac{1}{\Lambda^2}\frac{g_i^2}{16\pi^2}\,\mathcal{O}_i \qquad (g_i \ll 1)$$

very different impact !

Some generic estimates for whole classes of theories are possible (and useful!)

※1 Use a sensible notation for your couplings:

Perturbative expansion in QFT is an expansion in powers of $\hbar$:

E.g.

$$\frac{S}{\hbar} = \frac{1}{\hbar}\int d^4x \left[\frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 - \frac{1}{4}g^2\phi^4\right]$$

$$\Big\downarrow \quad \phi \to \sqrt{\hbar}\,\phi'$$

$$\int d^4x \left[\frac{1}{2}(\partial\phi')^2 - \frac{1}{2}m^2\phi'^2 - \frac{1}{4}\hbar g^2\phi'^4\right]$$

Perturbative expansion: powers of $(\hbar g^2)$

Check that in SM the perturbative expansion is an expansion in

$$g_i^2\hbar, \qquad y_f^2\hbar, \qquad \lambda\hbar,$$

$\hookrightarrow Y, L, C$

We should call $\lambda = g_H^2$!

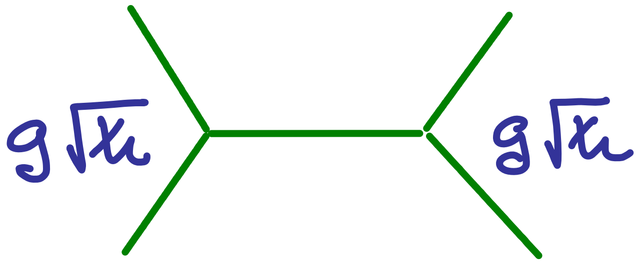
(Remember $\lambda = \frac{1}{4}(g^2+g'^2)\cos^2 2\beta$ in MSSM)

General Rule : $\delta\mathcal{L} = g_x^{n-2}\,\text{field}^n$

$$\left(\frac{1}{\hbar}\int d^4x\, g^{n-2}\,\text{field}^n \xrightarrow[\text{field}\to\sqrt{\hbar}\,\text{field}']{} \int d^4x\,(\hbar g^2)^{n/2-1}\,\text{field}'^n\right)$$

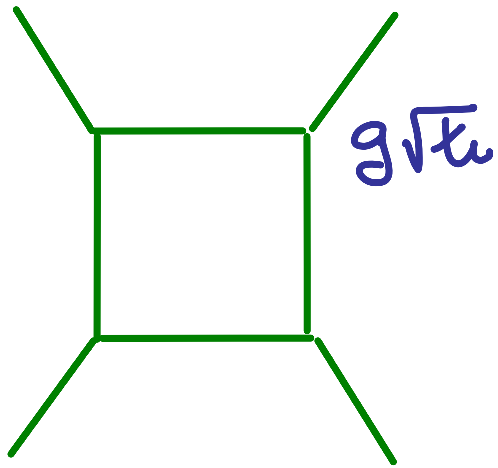
General Rule: $\delta\mathcal{L} = g_*^{n-2}\,\text{field}^n$

Rule holds when combining couplings:



$\sim \; g^2\hbar$

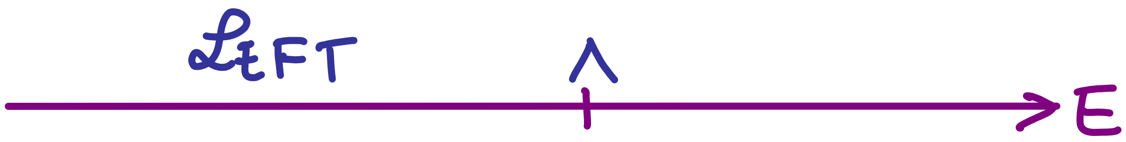
or



$$\sim \underbrace{(g^2\hbar)}_{\substack{\text{tree-level} \\ \text{counting for field}^4}} \overbrace{\left(\frac{\hbar g^2}{16\pi^2}\right)}^{\text{1-loop correction}}$$

Note: Strong coupling $g \sim 4\pi$

※2 Write the general EFT Lagrangian as



Λ BSM scale

$$\mathcal{L}_{EFT} = \frac{\Lambda^4}{g_*^2}\,\mathcal{L}\left(\frac{D_\mu}{\Lambda},\ \frac{g_H H}{\Lambda},\ \frac{g_{f_{L,R}} f_{L,R}}{\Lambda^{3/2}},\ \frac{g F_{\mu\nu}}{\Lambda}\right)$$

g_* generic coupling, $g^{n-2}\,\text{field}^n$ satisfied.

$$\left\{\begin{matrix} g_H \\ g_{f_L, f_R} \\ g \end{matrix}\right\} \text{ is a typical coupling of } \left\{\begin{matrix} \text{Higgs} \\ \text{fermions} \\ \text{gauge fields} \end{matrix}\right\} \text{ to the BSM sector}$$

From now on I'll take $g_H \sim g_{f_{L,R}} \sim g_*$

Gauge coupling to BSM, g, usual one (could be dif.)

#3 Aside: NDA power counting

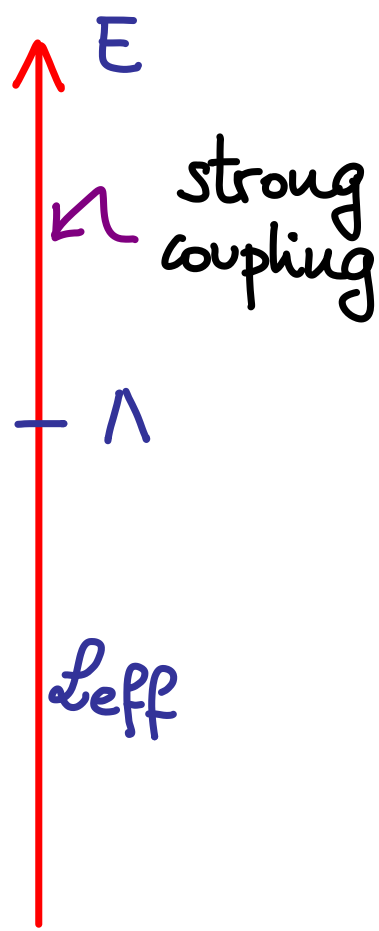
This power counting can be useful even when some coupling becomes strong.

E.g. take $g_* \sim g_H \sim g_{f_{L,R}} \sim 4\pi$ and introduce the quantity $f \equiv \Lambda/4\pi$

Generic term in $\mathcal{L}_{eff}$ below Λ:

$$f^2\Lambda^2 \left(\frac{\phi}{f}\right)^A \left(\frac{\psi}{f\sqrt{\Lambda}}\right)^B \left(\frac{gF_{\mu\nu}}{\Lambda^2}\right)^C \left(\frac{D}{\Lambda}\right)^D$$

reproduces the usual NDA counting.

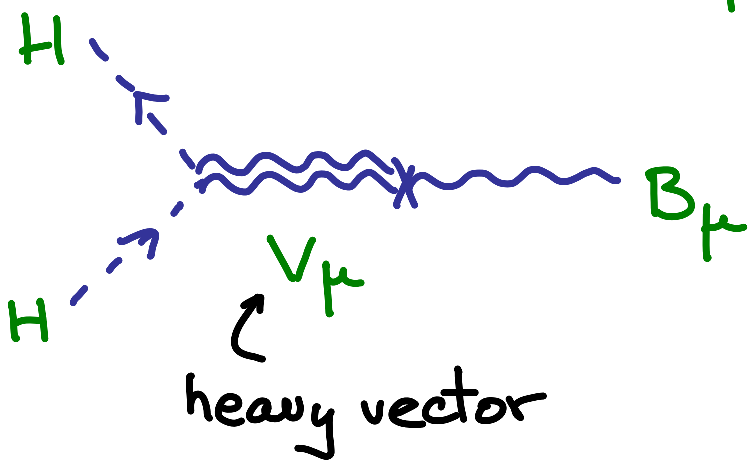


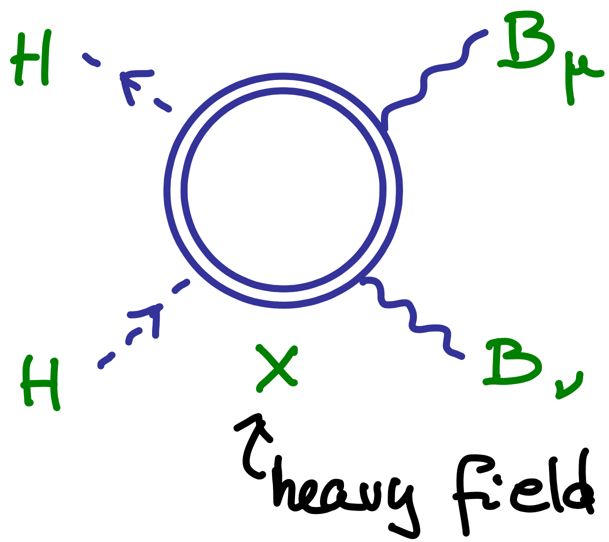
§4 Tree (or current-current) vs. Loop Operators

Not all operators are born equal Einhorn, Wudka '01

Ex :

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





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

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 ≤ 1 particles.

- As such, the classification is perfectly well-defined

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

CURRENT-CURRENT VS LOOP

- 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.

  Elias-Miró et al '12,'14
  Cheung et al '15

  c_{JJ} don't renormalize c_{loop}

(with very few exceptions)

⁂ Combine classifications

Type 1 Current-current with potential g_* enhancement.

$$\Delta\mathcal{L} = \frac{g_*^2}{\Lambda^2} c_i O_i$$

Type 2 Current-current w/o potential g_* enhancement.

$$\Delta\mathcal{L} = \frac{1}{\Lambda^2} c_i O_i$$

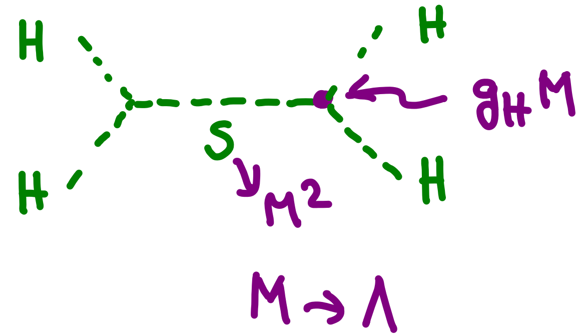
Type 3 Loop operator

$$\Delta\mathcal{L} = \frac{g_i^2}{16\pi^2} \frac{1}{\Lambda^2} c_i O_i$$

※ Combine classifications Examples

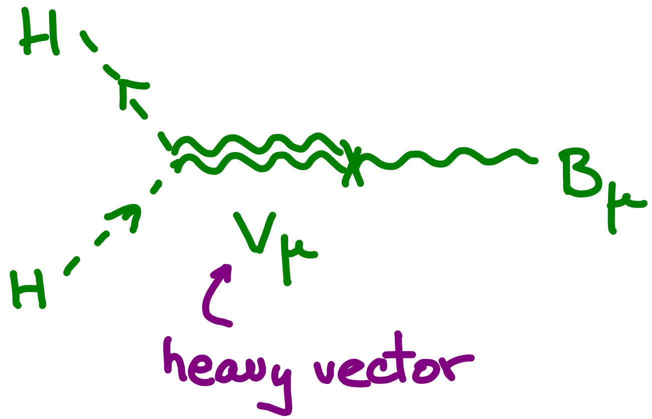
Type 1

$$\frac{g_H^2}{\Lambda^2}\underbrace{\frac{1}{2}\left(\partial_\mu |H|^2\right)^2}_{O_H} = -\frac{g_H^2}{2\Lambda^2}\underbrace{|H|^2}_{J_H}\,\partial^2\,\underbrace{|H|^2}_{J_H} \;:$$



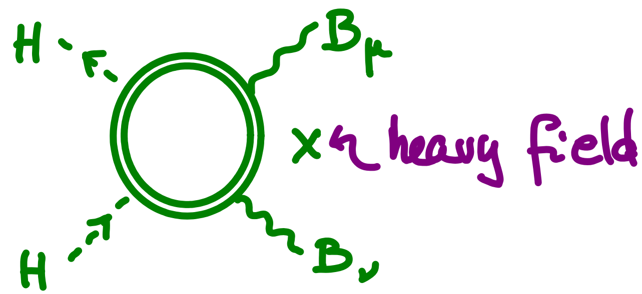
Type 2

$$O_B \equiv \frac{ig'}{2}\underbrace{\left(H^\dagger \overleftrightarrow{D}^\mu H\right)}_{J_H^\mu}\underbrace{\partial^\nu B_{\mu\nu}}_{J_{B\mu}}$$



Type 3

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



3. Operator bases

How many operators in $\mathcal{L}_{d=6} = \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$?

B & L_i Preserving : 59 * (single fermion family)

$\Rightarrow$ 59 ways of deviating from the SM

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

Naively, many more operators that can be ignored / eliminated.

*(Some c_i are complex $\Rightarrow$ 76 real parameters)

REDUNDANT OPERATORS

Operators that can be eliminated from $\mathcal{L}_{d=6}$ by field redefinitions (w/o changing S-matrix).

Example :

$$\Delta\mathcal{L}_6 = g_*^2 \frac{c_r}{\Lambda^2} |H|^2 |D_\mu H|^2$$

removable by $H \to H - \frac{1}{2} g_*^2 c_r H |H|^2 \frac{1}{\Lambda^2}$

REDUNDANT OPERATORS

Field redefinitions = use EoMs to simplify $\mathcal{L}_6$

$$S = \int d^4x \left[\mathcal{L}_4 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \dots \right]$$

Same physics

$$\varphi \to \varphi + \frac{1}{\Lambda^2} F(\varphi)$$

$$\int d^4x \left\{ \mathcal{L}_4 + \frac{1}{\Lambda^2}\left[\mathcal{L}_6 + \frac{\delta \mathcal{L}_4}{\delta \varphi} F(\varphi) \right] + \dots \right\}$$

⇨ Can drop terms in $\mathcal{L}_6$ of this form

⇨ use $\frac{\delta \mathcal{L}_4}{\partial \varphi} = 0$ EoM

BASES

Different ways of removing such operators

⇨ Different choices of operator basis

Same physics can be described by diff. op. subsets

"Physics cannot depend on the choice of basis, but which basis is the most convenient depends on the physics."

A. Zee

QFT in a Nutshell

Strongly Interacting Light Higgs

Giudice, Grojean, Pomarol, Rattazzi '07

A particular basis, well suited for PNGB Higgs

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

Type 1 (JJg_*^2)

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

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

Type 2 (JJ)

14 Bosonic ops

\+

6 CP-odd ones

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

Type 3 (Loop)

SILH BASIS

44 Fermionic (1 family)

			Type ↓
$\mathcal{O}_{y_u} = y_u\vert H\vert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d\vert H\vert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_l} = y_l\vert H\vert^2 \bar{L}_L H e_R$	
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_R^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L)$	
$\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$		$\mathcal{O}_L^{(3)\,l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu \sigma^a L_L)$	
$\mathcal{O}_{LR}^u = (\bar{Q}_L\gamma^\mu Q_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{LR}^d = (\bar{Q}_L\gamma^\mu Q_L)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{LR}^l = (\bar{L}_L\gamma^\mu L_L)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}_{LR}^{(8)\,u} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{u}_R\gamma^\mu T^A u_R)$	$\mathcal{O}_{LR}^{(8)\,d} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{d}_R\gamma^\mu T^A d_R)$		
$\mathcal{O}_{RR}^u = (\bar{u}_R\gamma^\mu u_R)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{RR}^d = (\bar{d}_R\gamma^\mu d_R)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_{RR}^l = (\bar{e}_R\gamma^\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	
$\mathcal{O}_{LL}^q = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma^\mu Q_L)$		$\mathcal{O}_{LL}^l = (\bar{L}_L\gamma^\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	1
$\mathcal{O}_{LL}^{(8)\,q} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma^\mu T^A Q_L)$			
$\mathcal{O}_{LL}^{ql} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{L}_L\gamma^\mu L_L)$			(JJg_*^2)
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L\gamma^\mu \sigma^a Q_L)(\bar{L}_L\gamma^\mu \sigma^a L_L)$			
$\mathcal{O}_{LR}^{ql} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{e}_R\gamma^\mu e_R)$			
$\mathcal{O}_{LR}^{lu} = (\bar{L}_L\gamma^\mu L_L)(\bar{u}_R\gamma^\mu u_R)$	$\mathcal{O}_{LR}^{ld} = (\bar{L}_L\gamma^\mu L_L)(\bar{d}_R\gamma^\mu d_R)$		
$\mathcal{O}_{RR}^{ud} = (\bar{u}_R\gamma^\mu u_R)(\bar{d}_R\gamma^\mu d_R)$			
$\mathcal{O}_{RR}^{(8)\,ud} = (\bar{u}_R\gamma^\mu T^A u_R)(\bar{d}_R\gamma^\mu T^A d_R)$			
$\mathcal{O}_{RR}^{ul} = (\bar{u}_R\gamma^\mu u_R)(\bar{e}_R\gamma^\mu e_R)$	$\mathcal{O}_{RR}^{dl} = (\bar{d}_R\gamma^\mu d_R)(\bar{e}_R\gamma^\mu e_R)$		
$\mathcal{O}_R^{ud} = y_u^\dagger y_d (i\tilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu d_R)$			
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}_L^i u_R)\epsilon_{ij}(\bar{Q}_L^j d_R)$			
$\mathcal{O}_{y_u y_d}^{(8)} = y_u y_d (\bar{Q}_L^i T^A u_R)\epsilon_{ij}(\bar{Q}_L^j T^A d_R)$			2
$\mathcal{O}_{y_u y_l} = y_u y_l (\bar{Q}_L^i u_R)\epsilon_{ij}(\bar{L}_L^j e_R)$			(JJ)
$\mathcal{O}'_{y_u y_l} = y_u y_l (\bar{Q}_L^{i\alpha} e_R)\epsilon_{ij}(\bar{L}_L^j u_R^\alpha)$			
$\mathcal{O}_{y_l y_d} = y_l y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$			
$\mathcal{O}_{DB}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} g' B_{\mu\nu}$	$\mathcal{O}_{DB}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}_{DB}^l = y_l \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$	
$\mathcal{O}_{DW}^u = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} g W_{\mu\nu}^a$	$\mathcal{O}_{DW}^d = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W_{\mu\nu}^a$	$\mathcal{O}_{DW}^l = y_l \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W_{\mu\nu}^a$	3
$\mathcal{O}_{DG}^u = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \tilde{H} g_s G_{\mu\nu}^A$	$\mathcal{O}_{DG}^d = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G_{\mu\nu}^A$		(Loop)

Many more for 3 families

SILH BASIS

SILH Operator counting : $14+6+44 = 64\ (>59)$

$\Rightarrow$ 5 redundant operators

Can live with them and remove them at will, depending on the physics.

OTHER BASES

- Hagiwara basis

  Hagiwara et al. Phys.Lett. B283 (1992) 353-359
  Phys.Rev. D48 (1993) 2182-2203

  Maximizes the number of ops. with bosons only.

- Polish/Warsaw basis

  Grzadkowski et al. http://arxiv.org/pdf/1008.4884.pdf

  Maximizes the number of ops. with derivatives

- BSM primaries

  Pomarol & Riva http://arxiv.org/pdf/1308.2803.pdf

  Minimizes correlations

BOSONIC OPS IN 3 BASES

$\mathcal{O}_W = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{WWW} = \mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}_\rho^{\mu}]$	$\mathcal{O}_{3W} = \frac{1}{3!} g\epsilon_{abc} W_\mu^{a\nu} W_{\nu\rho}^{b} W^{c\rho\mu}$
$\mathcal{O}_{\varphi W} = \varphi^\dagger\varphi W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$	—
$\mathcal{O}_{\varphi B} = \varphi^\dagger\varphi B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$	$\mathcal{O}_{BB} = g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{\varphi WB} = \varphi^\dagger\sigma^I\varphi W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$	—
—	$\mathcal{O}_W = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$
—	$\mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi)$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$
—	$\mathcal{O}_{DW} = \mathrm{Tr}\left([D_\mu,\hat{W}_{\nu\rho}][D^\mu,\hat{W}^{\nu\rho}]\right)$	$\mathcal{O}_{2W} = -\frac{1}{2}\left(D^\mu W^a_{\mu\nu}\right)^2$
—	$\mathcal{O}_{DB} = -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$	$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$
—	—	$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger\sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$
—	—	$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger\overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$
$\mathcal{O}_{\varphi D} = \left(\varphi^\dagger D^\mu\varphi\right)^*\left(\varphi^\dagger D_\mu\varphi\right)$	$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\Phi\Phi^\dagger(D^\mu\Phi)$	$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger\overleftrightarrow{D}_\mu H\right)^2$
$\mathcal{O}_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}_H = \frac{1}{2}(\partial^\mu|H|^2)^2$
$\mathcal{O}_\varphi = (\varphi^\dagger\varphi)^3$	$\mathcal{O}_{\Phi,3} = \frac{1}{3}(\Phi^\dagger\Phi)^3$	$\mathcal{O}_6 = \lambda|H|^6$
—	$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger(D^\mu\Phi)(\Phi^\dagger\Phi)$	—

"Warsaw" Hagiwara SiLH

Willenbrock & Zhang

THE ART OF CHOOSING A BASIS

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

Simple connection with UV physics that generates ops.

★ Respects possible symmetries of the BSM theory

Eg. shift symmetry for a PGB → SiLH basis

NO PERFECT BASIS

	Warsaw	SILH	BSM Primaries
Z-pole/TGC	✓ Separated	X Mixed	✓ Minimizes correlations
TGC/Higgs	X Mixed	✓ separated	✓
UV matching	✓ Composite fermions	✓ Universal (CH, MSSM)	X No easy UV match

New tool for basis translation ROSETTA
Falkowski et al '15

4. Experimental constraints

Generically, a measurement $q_i \to q_i^0 \pm \delta q_i$ constrains linear comb. of op. coefficients $\sum_i \alpha_i c_i$

Model-indep. constraints on the c_i's require

- Complete basis
- Care with possible correlations

⚠ Bounds obtained switching on one c_i at a time

- Ignores correlations (some due to basis choice!)
- Overestimates experimental constraints

Experimental constraints

Constraints in concrete models :

- incorporate correlations (model predictions)
- are stronger

⚠ In setting bounds we can forget about expected relative sizes of op. coefficients

→ these are only relevant for the theory ↔ ops. connection

Model-Independent global fits

Global fit of all 59 op. coefficients to all data is possible. Here I will focus only on those operators relevant for Higgs physics: just 20 operators (CP-even) List →

Elias-Miró et al '13

Operators relevant for Higgs Physics

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	Rescales H prop.
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	$h \to hh$
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$	
$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$	

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

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$	$h \to f\bar{f}$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$	$h \to Wf\bar{f}$, $Zf\bar{f}$
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L \sigma^a \gamma_\mu Q_L)(\bar{L}_L \sigma^a \gamma^\mu L_L)$		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$	

Potential BSM windows through Higgs physics

Model-Independent global fits

Global fit of all 59 op. coefficients to all data is possible. Here I will focus only on those operators relevant for Higgs physics: just 20 operators (CP-even)

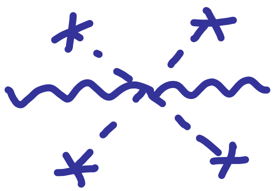
Many of these ops affect other processes/observables that don't require Higgs production, simply via $H \to \langle H \rangle$ Examples $\to$

Operators relevant for Higgs Physics

$M_W \Leftrightarrow M_Z \leftarrow$

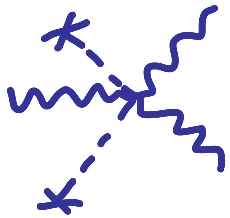
$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

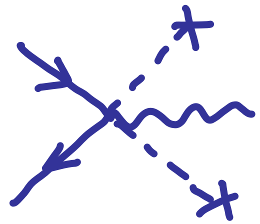
$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$



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

$\rightarrow$ TGCs



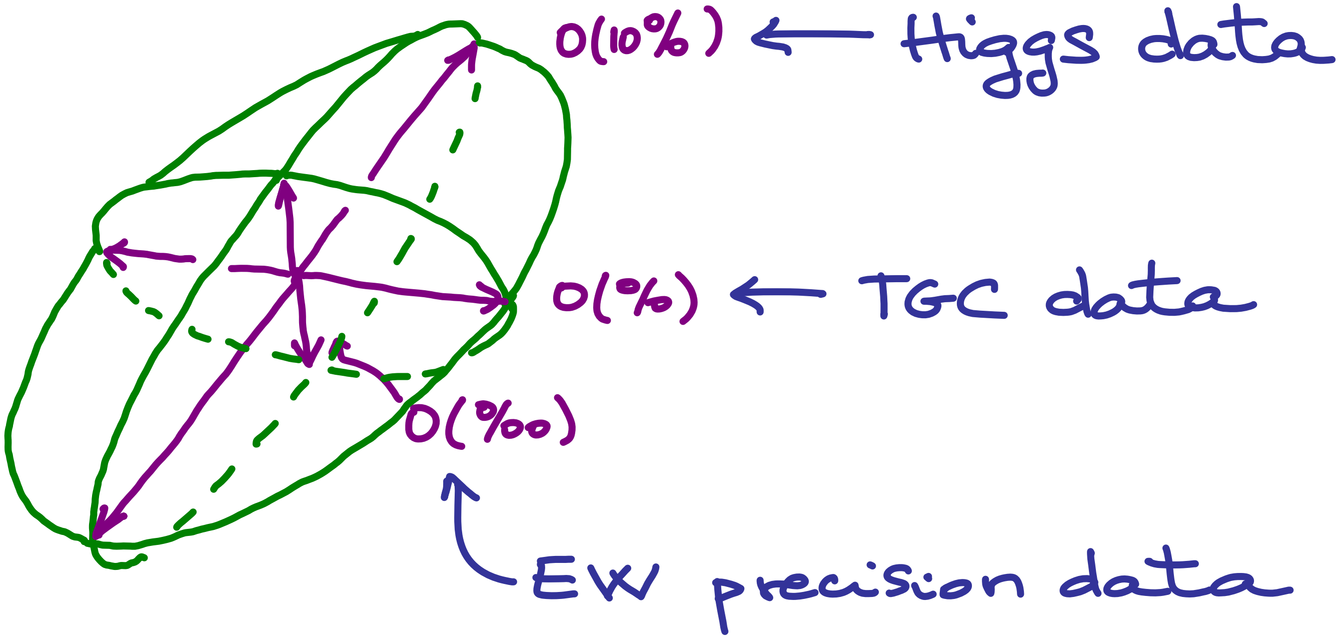
$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}^q_L = (iH^\dagger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

$\rightarrow$ ffV couplings

$\Rightarrow$ Pre-LHC data sets already some constraints.

Model-Independent global fits

To save effort and gain understanding, exploit the hierarchy of experimental bounds :



Align the op. basis to this structure.

Model-Independent global fits

$$\underbrace{\begin{bmatrix} q_i^{L} \\ q_i^{q} \\ q_i^{TGC} \end{bmatrix}}_{\text{observables}} = \begin{bmatrix} T_1 & 0 & 0 \\ \times & T_2 & 0 \\ \times & \times & T_3 \end{bmatrix} \cdot \underbrace{\begin{bmatrix} c_i^{a} \\ c_i^{b} \\ c_i^{c} \end{bmatrix}}_{\text{Wilson coefficients}}$$

Model-Independent global fits

$$\begin{bmatrix} g_i^{L} \\ g_i^{q} \\ g_i^{TGC} \end{bmatrix} = \begin{bmatrix} T_1 & 0 & 0 \\ \times & T_2 & 0 \\ \times & \times & T_3 \end{bmatrix} \cdot \begin{bmatrix} c_i^{a} \\ c_i^{b} \\ c_i^{c} \end{bmatrix}$$

$\}$ 4 c_i's

‰

LEP I Z-pole leptonic obs:

$Z \to \nu\nu,\ l_L l_L,\ l_R l_R$

Tevatron: m_W

$\}$ 4 measurements

$$\Rightarrow \quad c_i \frac{m_W^2}{\Lambda^2} \lesssim O(10^{-3})$$

NON-HIGGS CONSTRAINTS

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

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

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

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

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

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

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

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

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

$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

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

"Doors" closed to new physics at ‰ level

Model-Independent global fits

$$\begin{bmatrix} q_i^L \\ q_i^q \\ q_i^{TGC} \end{bmatrix} = \begin{bmatrix} T_1 & 0 & 0 \\ \times & T_2 & 0 \\ \times & \times & T_3 \end{bmatrix} \cdot \begin{bmatrix} \boxed{c_i^a} \\ c_i^b \\ c_i^c \end{bmatrix}$$

← can neglect

} 5 c_i's

‰

quark obs. LEP ($Zq\bar{q}$)

$\delta\Gamma_Z^{had}$, R_b, A_c, A_b

KLOE + β decays :

G_F^q / G_F^L

} 5 measurements

NON-HIGGS CONSTRAINTS

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

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

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$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
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$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \sigma^a \gamma_\mu Q_L)(\bar{L}_L \sigma^a \gamma^\mu L_L)$		$\mathcal{O}^{(3)\,l}_{LL} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

"Doors" closed to new physics at ‰ level

Model-Independent global fits

$$
\begin{bmatrix} g_i^{L} \\ g_i^{q} \\ g_i^{TGC} \end{bmatrix}
=
\begin{bmatrix} T_1 & 0 & 0 \\ \times & T_2 & 0 \\ \times & \times & T_3 \end{bmatrix}
\cdot
\begin{bmatrix} \boxed{\begin{matrix} c_i^{a} \\ c_i^{b} \end{matrix}} \\ c_i^{c} \end{bmatrix}
$$

can neglect

} 3 c_i's

%

LEP-II data

Triple Gauge Couplings

$g_1^{Z}, \kappa_\gamma, \lambda_\gamma$

} 3 measurements

NON-HIGGS CONSTRAINTS

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
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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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$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$

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

"Doors" closed to new physics at % level

5. Higgs physics

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu}B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu}G^{A\mu\nu}$
$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$	
$\mathcal{O}_6 = \lambda \lvert H\rvert^6$	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$ $\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$ $\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right)\partial^\nu B_{\mu\nu}$	$\mathcal{O}_{3W} = \frac{1}{3!} g\epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$

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

$\mathcal{O}_{y_u} = y_u \lvert H\rvert^2 \bar{Q}_L \tilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \lvert H\rvert^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \lvert H\rvert^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L\gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L\sigma^a\gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_{LL}^{(3)\,ql} = (\bar{Q}_L\sigma^a\gamma_\mu Q_L)(\bar{L}_L\sigma^a\gamma^\mu L_L)$		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L\sigma^a\gamma^\mu L_L)(\bar{L}_L\sigma^a\gamma_\mu L_L)$

Only 8 operators left!

8 Ops. left for Higgs physics

$$O_H = \frac{1}{2}(\partial_\mu |H|^2)^2 \qquad O_6 = \lambda (|H|^2)^3$$

$$O_{y_f} = y_f\, |H|^2 \bar{f}_L H f_R \qquad (f = t, b, \tau)$$

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

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

$$O_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\,\mu\nu}$$

All involve $|H|^2$ and $|H|^2 \to v^2/2$ gives SM d=4 ops.

$\Rightarrow$ Only Higgs physics can constrain them

8 Ops. left for Higgs physics

affects all h couplings

$$O_H = \frac{1}{2}(\partial_\mu |H|^2)^2 \qquad O_6 = \lambda (|H|^2)^3 \rightarrow h \to hh$$

$$O_{y_f} = y_f |H|^2 \bar{f}_L H f_R \qquad (f = t, b, \tau)$$

$h \to f\bar{f}$

(O_{y_t}) $h \to \gamma\gamma$

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

$$O_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\,\mu\nu} \rightarrow h \to Z\gamma$$

$$O_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\,\mu\nu} \rightarrow gg \to h$$

All involve $|H|^2$ and $|H|^2 \to v^2/2$ gives SM $d=4$ ops.

$\Rightarrow$ Only Higgs physics can constrain them

GLOBAL FIT TO LHC DATA

Only significant bounds from processes loop-suppressed in SM model :

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$$\frac{m_W^2}{\Lambda^2}\kappa_{GG} \in [-0.8, 0.8]\times 10^{-3}$$

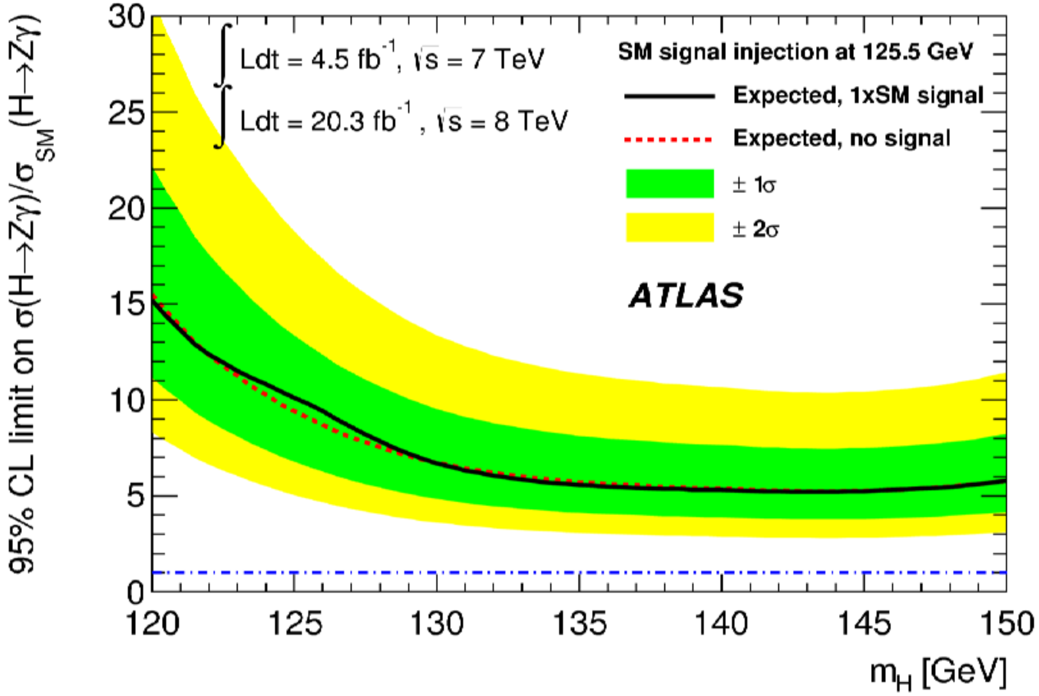
$$\frac{m_W^2}{\Lambda^2}\kappa_{BB} \in [-1.3, 1.8]\times 10^{-3} \qquad 95\%\,\text{C.L.}$$

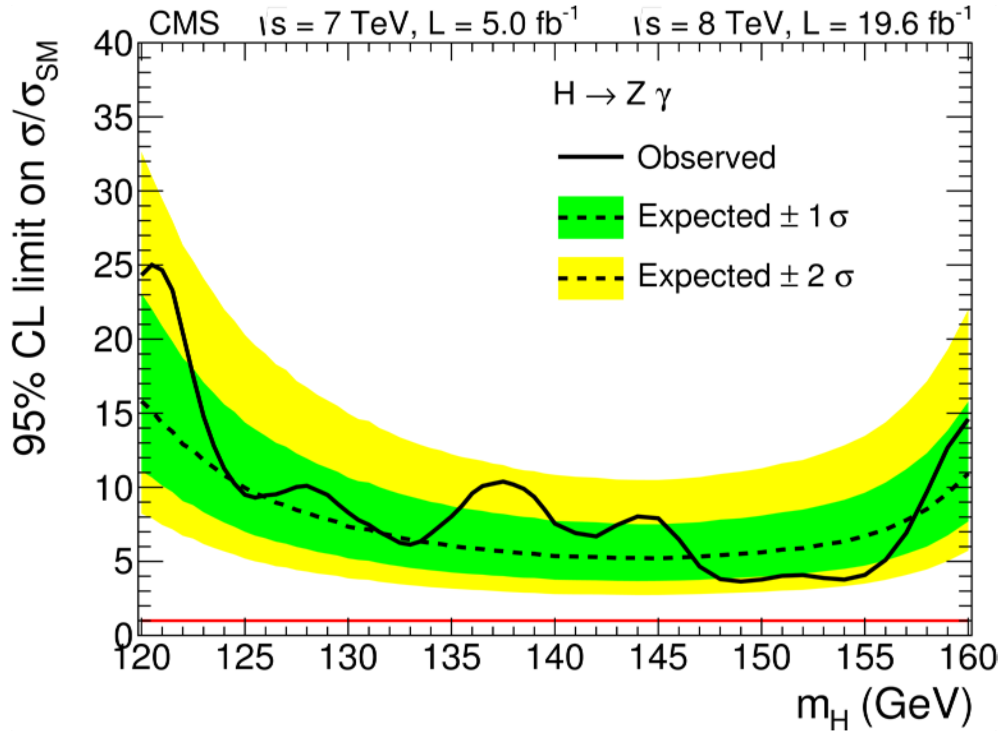
$$\frac{m_W^2}{\Lambda^2}\kappa_{Z\gamma} \in [-0.6, 1.2]\times 10^{-2}$$

with $\kappa_{Z\gamma} \equiv -\frac{1}{4}(\kappa_{HW}-\kappa_{HB}) - 2s_W^2\kappa_{BB}$.

GLOBAL FIT TO LHC DATA

- $\kappa_{Z\gamma}$ limit a bit weaker as $\sigma^{\lim}_{\exp} \gtrsim O(10)\,\sigma_{SM}$





GLOBAL FIT TO LHC DATA

- $\kappa_{Z\gamma}$ limit a bit weaker as $\sigma_{exp}^{lim} \lesssim O(10)\,\sigma_{SM}$
- Other Wilson coefficients constrained only very weakly or not at all, as c_{λ_6}
- Also c_{yf} for 1st & 2nd families totally unconstrained

Gilad's talk

Only 8 open doors for BSM-Higgs deviations

There's still room for significant deviations

EFT CONSTRAINTS

Many possible deviations are already constrained within this EFT framework:

Custodial symmetry test:

$$\lambda_{WZ}^2 = \frac{\Gamma(h\to WW)}{\Gamma^{SM}(h\to WW)} \cdot \frac{\Gamma^{SM}(h\to ZZ)}{\Gamma(h\to ZZ)}$$

Experimentally constrained to

$$\lambda_{WZ} - 1 \in (-0.2, 0.3) \qquad 95\%\ \text{C.L.}$$

d=6 EFT $\Rightarrow$ $\lambda_{WZ}^2 - 1 \simeq (0.6\,\delta g_1^Z - 0.5\,\delta\kappa_\gamma - 1.6\,\kappa_{Z\gamma})\,\frac{m_W^2}{\Lambda^2}$

TGC + $h\to Z\gamma$ $\Rightarrow$ $\lambda_{WZ} - 1 \in (-0.03, 0.04)$

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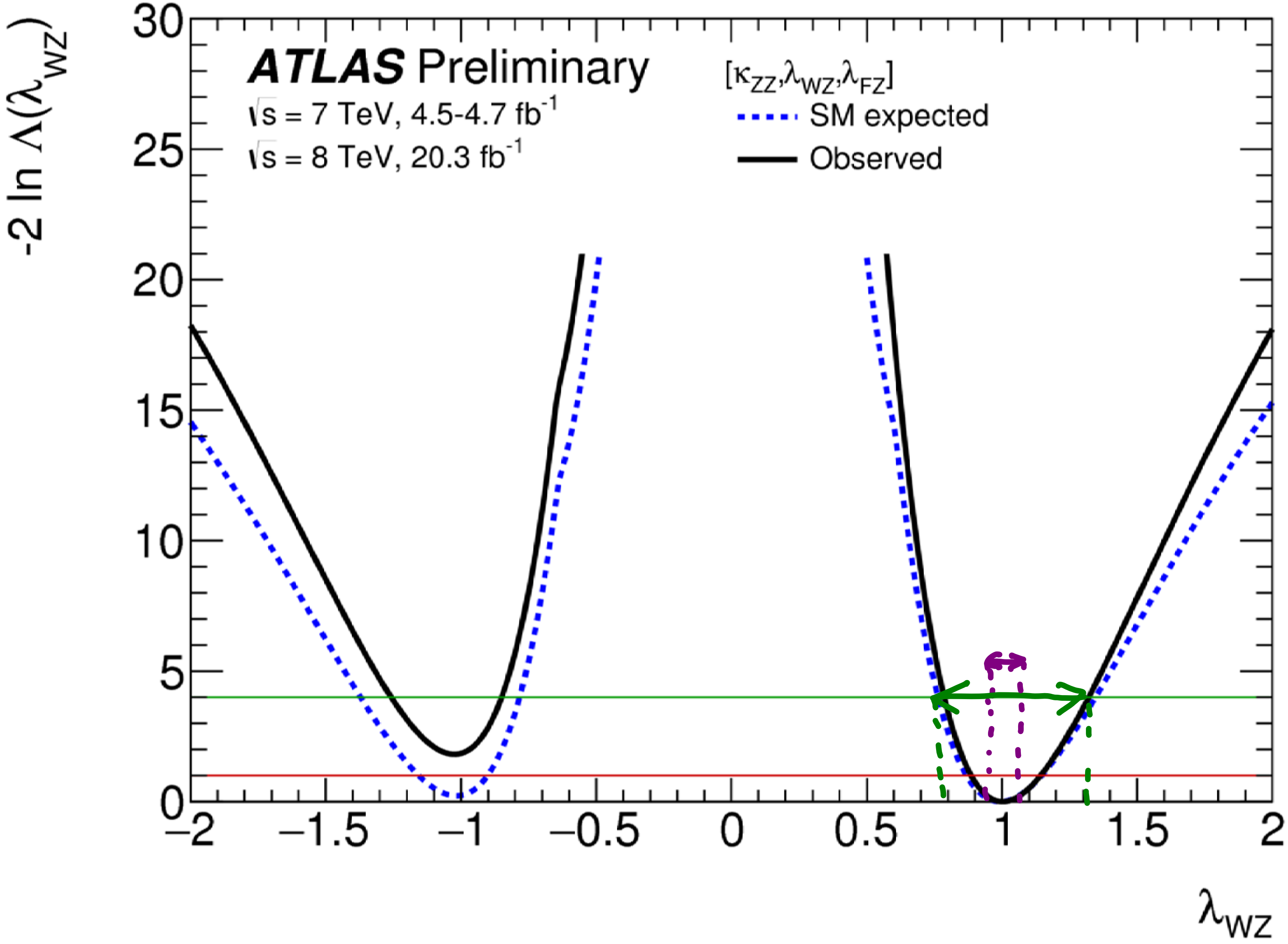
EFT CONSTRAINTS

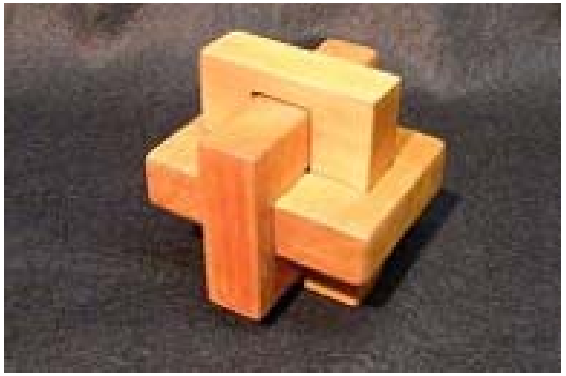


CONCLUSIONS

- The Higgs provides a very important window to probe BSM indirectly.
- Model-independent approach through $d=6$ operators very powerful.
- Still some room for deviations, but not as many as one would naively think.
- Nevertheless, we might be lucky to also have direct signals of BSM in LHC run 2!

AN AMUSING OPERATOR PUZZLE

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



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

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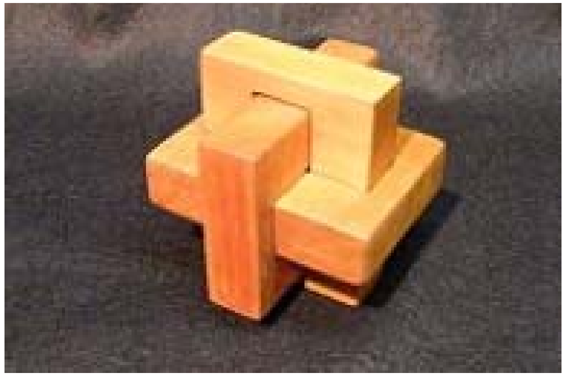

$$\underbrace{\frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial_\nu B^{\mu\nu}}_{O_B} = \underbrace{ig'(D_\mu H)^\dagger D_\nu H\, B^{\mu\nu}}_{O_{HB}} + \frac{1}{4}\underbrace{gg'(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}}_{O_{WB}} + \frac{1}{4}\underbrace{g'^2|H|^2 B_{\mu\nu}B^{\mu\nu}}_{O_{BB}}$$

and the same for O_W:

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

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.