

Effective Higgs Lagrangians

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Origin of the Higgs Particle in the Standard Model

- Gauge symmetry implies massless gauge bosons

$$m_W^2 W_\mu^+ W^{-\mu} \quad \text{Not Gauge invariant}$$

- Introduce scalar field

$$\mathcal{D}_\mu \Phi^\dagger \mathcal{D}_\mu \Phi = W_\mu^a W^{a\mu} \Phi^\dagger \Phi + \dots \quad \text{Gauge invariant}$$

- Spontaneous symmetry breaking

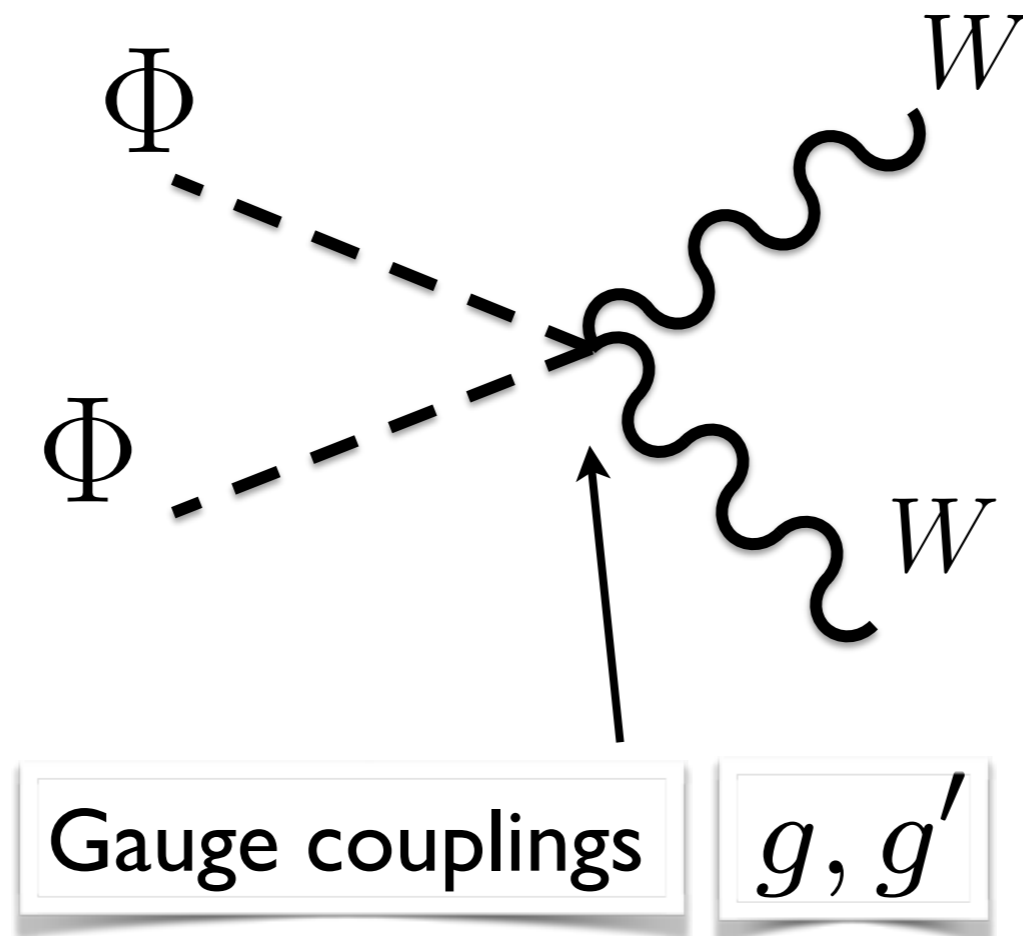
$$\Phi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \quad \frac{1}{2} g^2 v^2 = m_W^2$$

Origin of the Higgs Particle in the Standard Model

$$m_W^2 W_\mu^+ W^{-\mu} \left(1 + 2\frac{h}{v} + \frac{h^2}{v^2} \right)$$

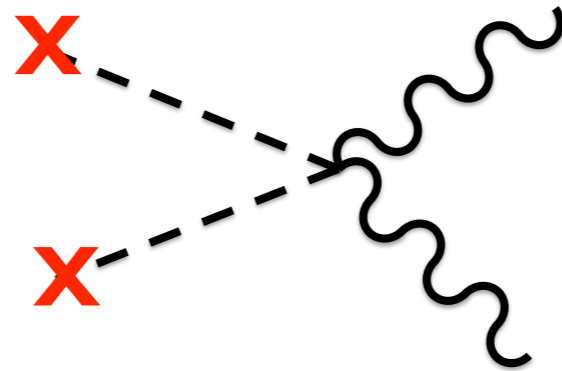
$$\frac{1}{2} m_Z^2 Z_\mu Z^\mu \left(1 + 2\frac{h}{v} + \frac{h^2}{v^2} \right)$$

Origin of the Higgs Particle in the Standard Model

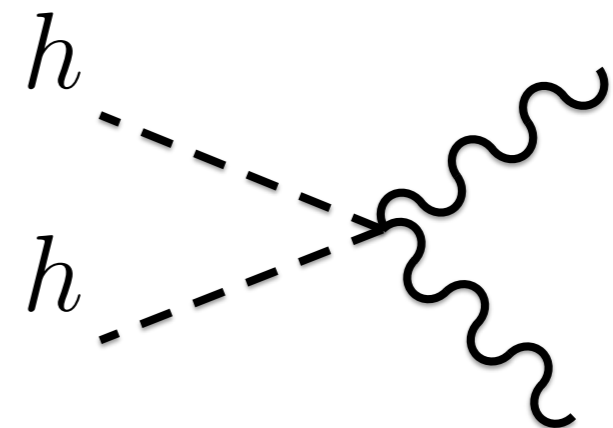
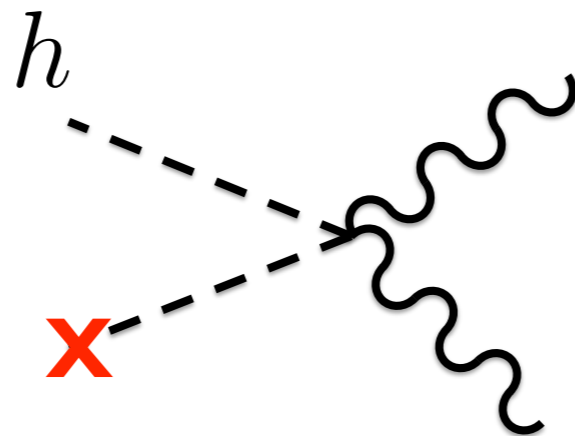


Origin of the Higgs Particle in the Standard Model

gauge boson masses



higgs couplings



Higgs in SM

Φ 4 New degrees of freedom: $4=3+1$

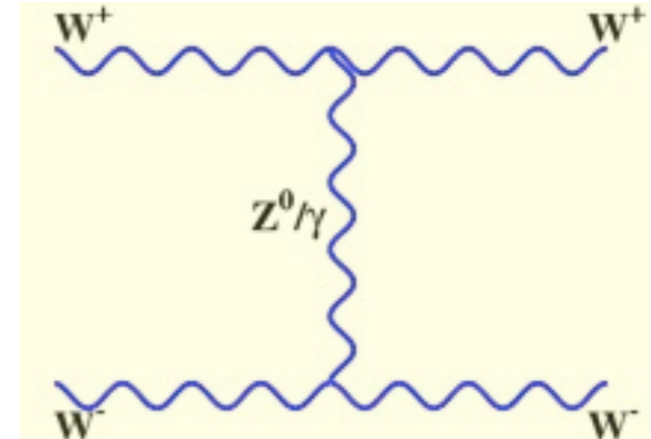
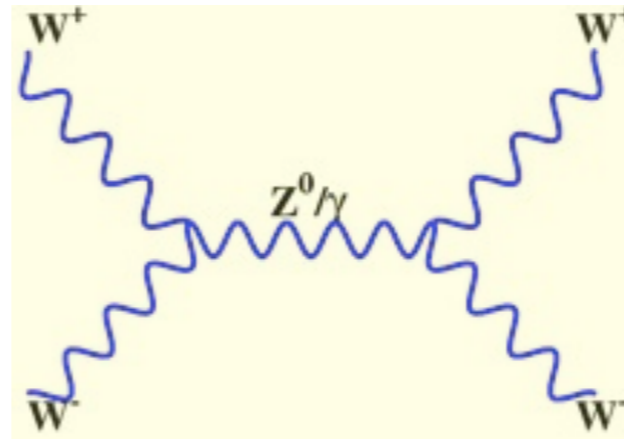
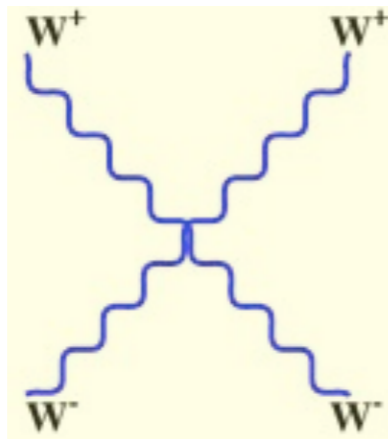
3 W_L^\pm, Z_L

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

1 Higgs scalar h

Unitary problem

$$WW \rightarrow WW$$

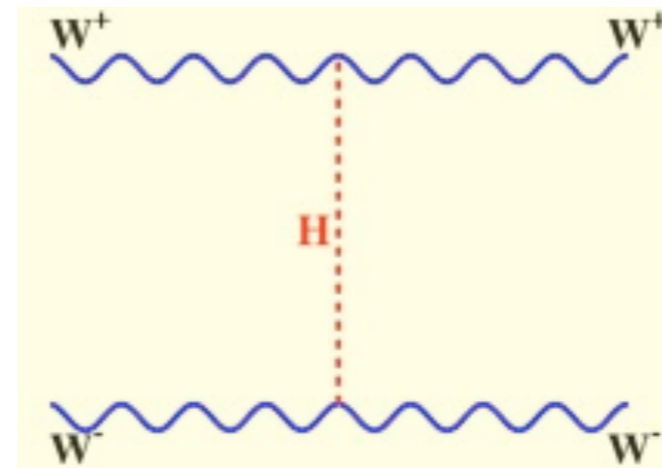
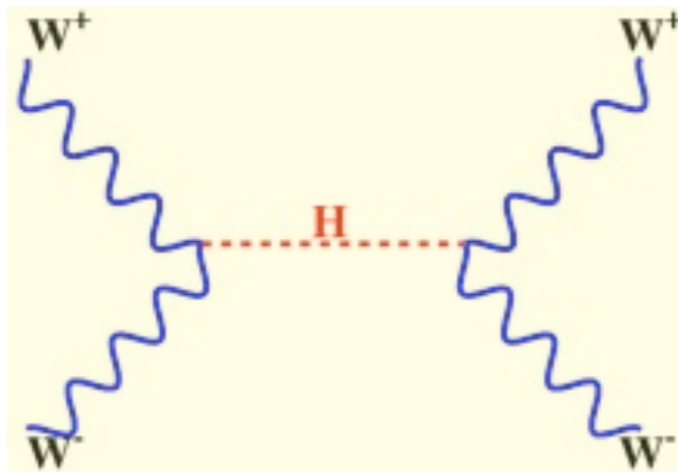


$$\mathcal{M}_{gauge} \sim \frac{s}{M_W^2}$$

$$s \gg M_W^2$$

Dominant contribution from W_L^\pm, Z_L

Unitary problem



Text

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

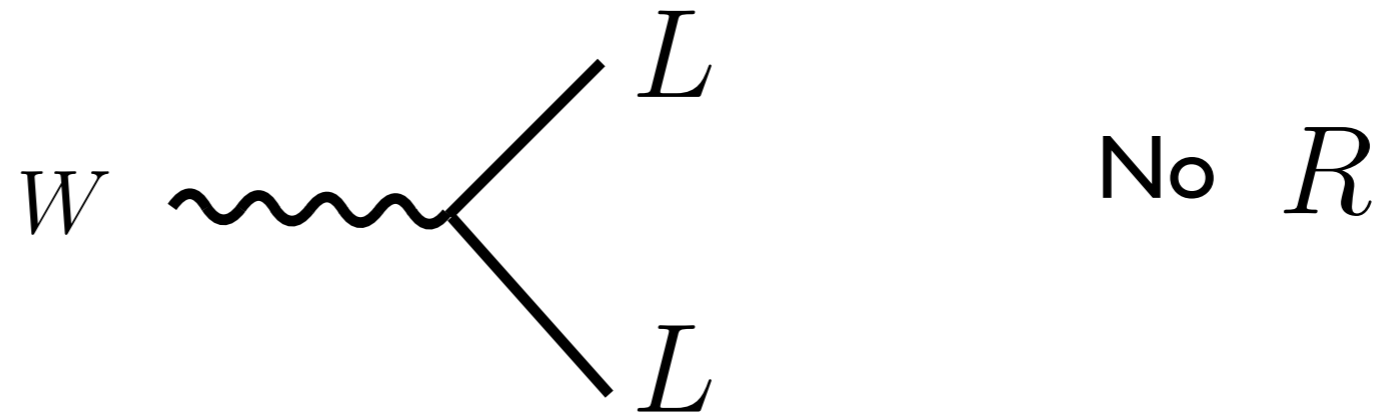
Cancellation
of linear growing

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

(for a light scalar)

Fermion masses

SM is a chiral theory



$SU(2)_L$

$$Q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R \quad d_R$$

$$m_d \bar{d}_L d_R + h.c.$$

Not Gauge invariant

Fermion masses

- Yukawa coupling with scalar field

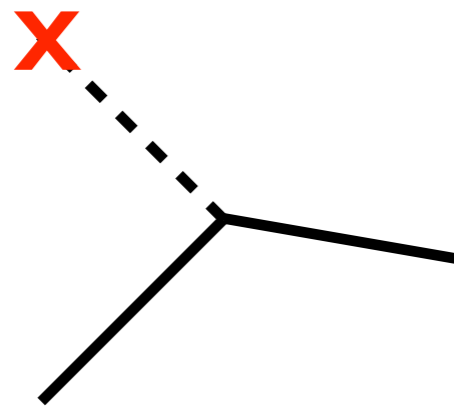
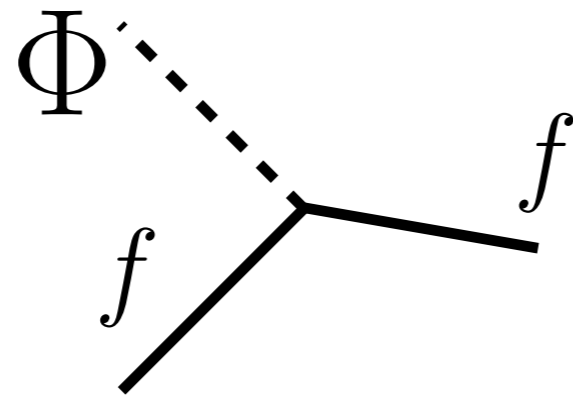
$$y_d \bar{Q}_L \Phi d_R + h.c.$$

Gauge invariant

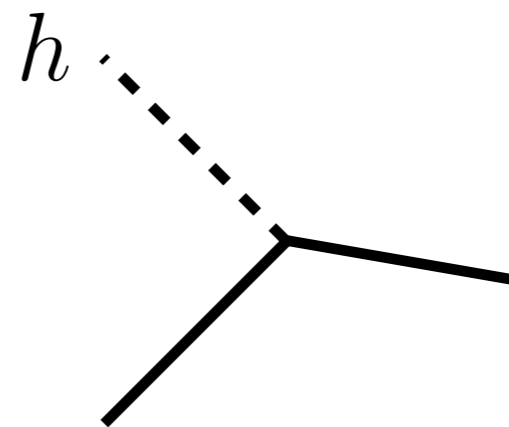
- **SSB** $\Phi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$

$$(m_d + h) \bar{d}_L d_R + h.c.$$

Higgs and fermion masses



fermion masses



higgs couplings

H couples to mass

- Without symmetry breaking
W, Z massless and massless fermions
- With symmetry breaking

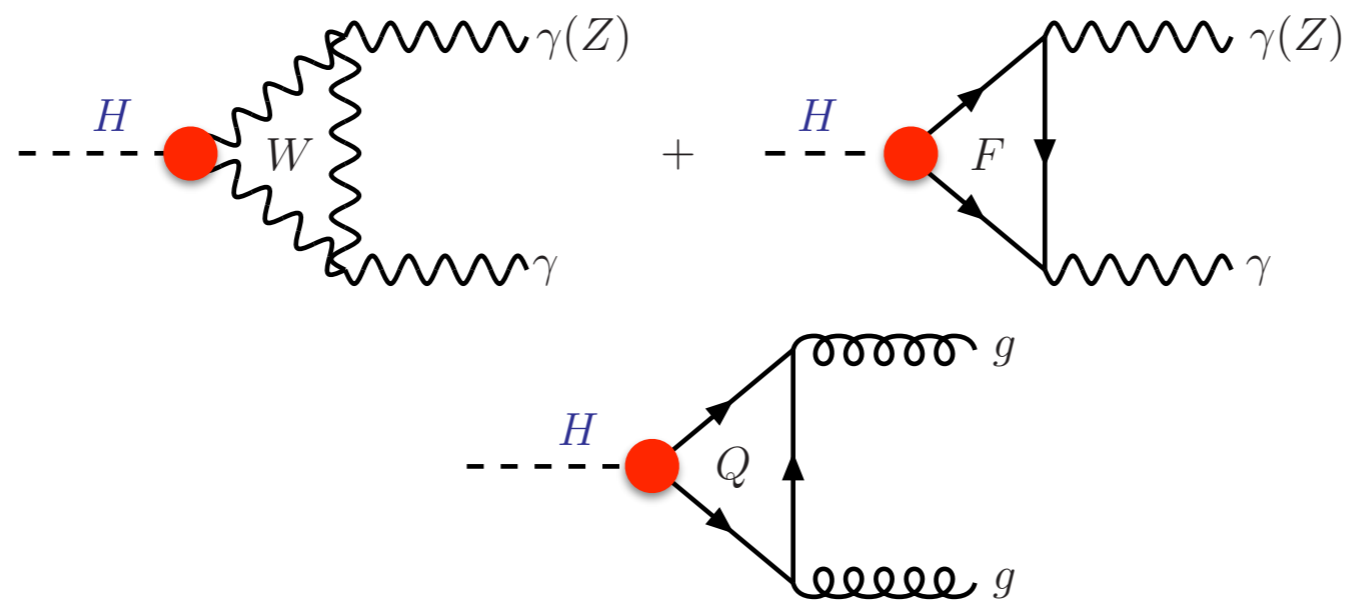
$$\Phi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$m_W^2 \left(WW + \frac{1}{2c_W^2} ZZ \right) \left(1 + \frac{2h}{v} + \frac{h^2}{v^2} \right)$$

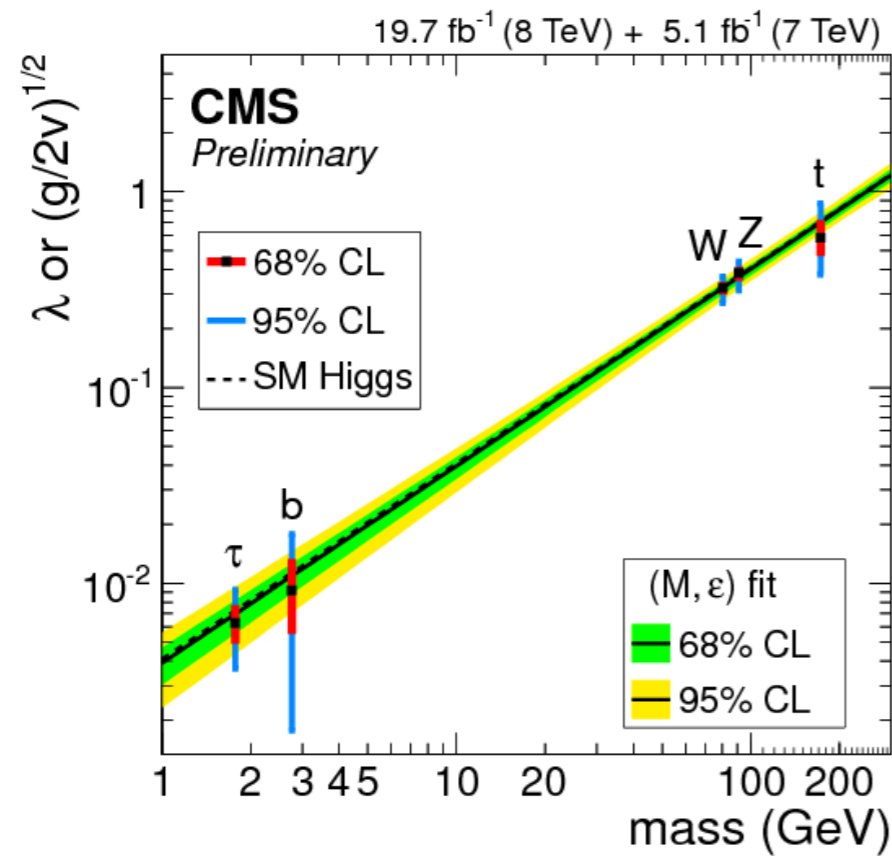
$$m_f \bar{f} f \left(1 + \frac{h}{v} \right)$$

H couples to photons and gluons

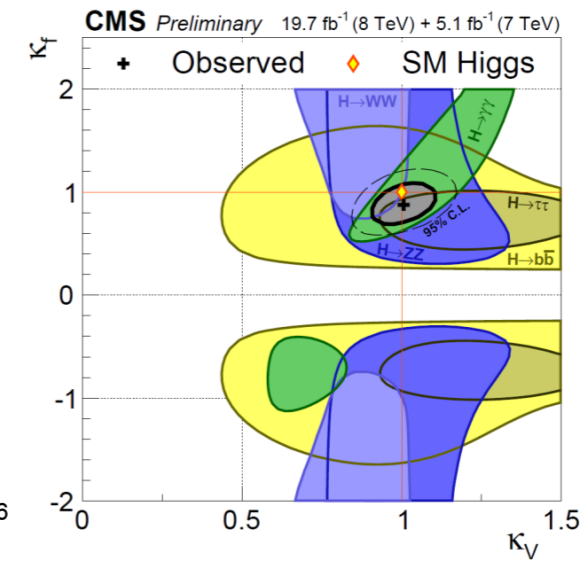
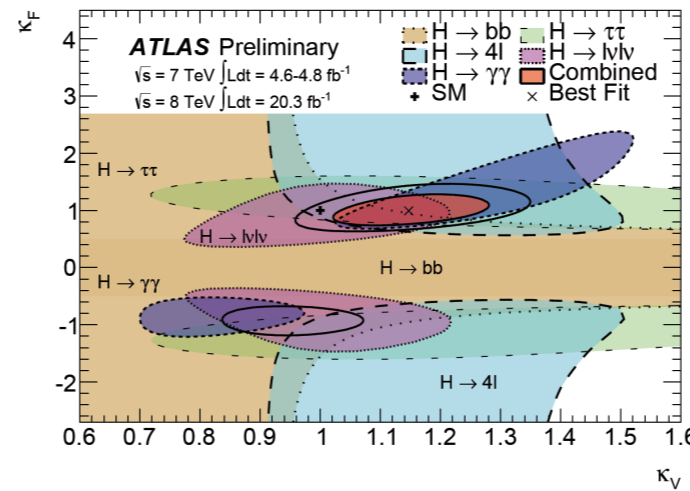
★ coupling through loops



Higgs Particle at LHC



$$\kappa_i \equiv g_i / g_i^{\text{SM}}$$



Higgs couples to masses (tree-level)

to photon-photon and gluon-gluon (loop-level)

Consistent with SM Higgs

Higgs Particle in PDG

H^0

$$J = 0$$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States = 1.17 ± 0.17 (S = 1.2)

$$W W^* = 0.87^{+0.24}_{-0.22}$$

$$Z Z^* = 1.11^{+0.34}_{-0.28} \quad (S = 1.3)$$

$$\gamma\gamma = 1.58^{+0.27}_{-0.23}$$

$$b\bar{b} = 1.1 \pm 0.5$$

$$\tau^+ \tau^- = 0.4 \pm 0.6$$

$$Z\gamma < 9.5, \text{ CL} = 95\%$$

Search for SUSY and other BSM Signatures

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

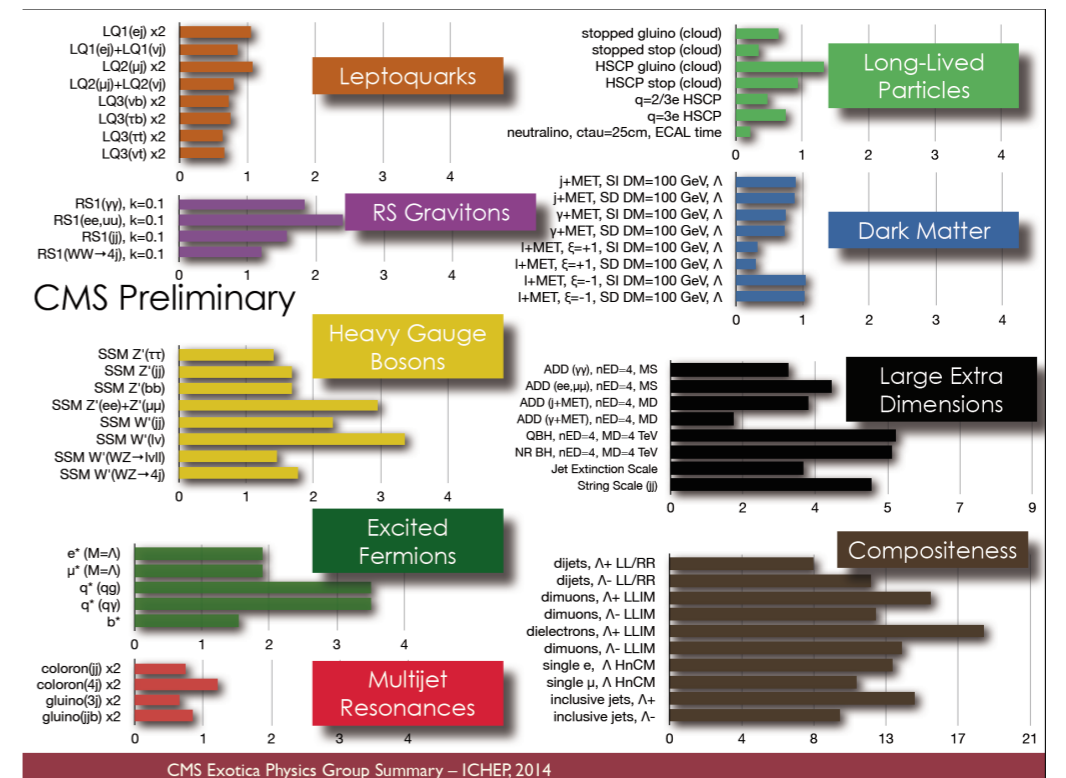
ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

| Model | e, μ, τ, γ | Jets | E_T^{miss} | $\int \mathcal{L} d\mathcal{L} [\text{fb}^{-1}]$ | Mass limit | Reference |
|---|------------------------|----------------|---------------------|--|---------------------------------|----------------------|
| Inclusive Searches | | | | | | |
| MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | \tilde{q}, \tilde{g} 1.7 TeV | 1405.7875 |
| MSUGRA/CMSSM | 1 e, μ | 3-6 jets | Yes | 20.3 | \tilde{g} 1.2 TeV | ATLAS-CONF-2013-062 |
| MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | any $m(\tilde{g})$ 1.1 TeV | 1308.1841 |
| $\tilde{q}\tilde{q}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$ | 0 | 2-6 jets | Yes | 20.3 | \tilde{q} 850 GeV | 1405.7875 |
| $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$ | 1 e, μ | 3-6 jets | Yes | 20.3 | \tilde{g} 1.33 TeV | 1405.7875 |
| $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{g}$ | 2 e, μ | 0-3 jets | - | 20.3 | \tilde{g} 1.18 TeV | ATLAS-CONF-2013-062 |
| GMSB (\tilde{t} NLSP) | 2 e, μ | 2-4 jets | Yes | 4.7 | \tilde{g} 1.12 TeV | ATLAS-CONF-2013-089 |
| GMSB (\tilde{t} NLSP) | 1-2 $\tau + 0-1 \ell$ | 0-2 jets | Yes | 20.3 | \tilde{g} 1.24 TeV | 1208.4688 |
| GGM (bino NLSP) | 2 γ | - | Yes | 20.3 | \tilde{g} 1.6 TeV | 1407.0603 |
| GGM (wino NLSP) | 1 $e, \mu + \gamma$ | - | Yes | 4.8 | \tilde{g} 1.28 TeV | ATLAS-CONF-2014-001 |
| GGM (higgsino-bino NLSP) | 2 e, μ | 1 b | Yes | 4.8 | \tilde{g} 619 GeV | ATLAS-CONF-2012-144 |
| GGM (higgsino NLSP) | 2 e, μ | 0-3 jets | Yes | 5.8 | \tilde{g} 900 GeV | 1211.1167 |
| Gravitino LSP | 0 | mono-jet | Yes | 10.5 | \tilde{g} 690 GeV | ATLAS-CONF-2012-152 |
| | | | | | \tilde{g} 645 GeV | ATLAS-CONF-2012-147 |
| $\tilde{3}^{\text{rd}}$ gen. \tilde{g} prod. | | | | | | |
| $\tilde{g} \rightarrow b\bar{b}\tilde{g}$ | 0 | 3 b | Yes | 20.1 | \tilde{g} 1.25 TeV | 1407.0600 |
| $\tilde{g} \rightarrow t\bar{t}\tilde{g}$ | 0 | 7-10 jets | Yes | 20.3 | \tilde{g} 1.1 TeV | 1308.1841 |
| $\tilde{g} \rightarrow \tau\bar{\tau}\tilde{g}$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.34 TeV | 1407.0600 |
| $\tilde{g} \rightarrow b\bar{b}\tilde{g}$ | 0-1 e, μ | 3 b | Yes | 20.1 | \tilde{g} 1.3 TeV | 1407.0600 |
| $\tilde{3}^{\text{rd}}$ gen. squarks direct production | | | | | | |
| $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{g}$ | 0 | 2 b | Yes | 20.1 | \tilde{b}_1 100-620 GeV | 1308.2631 |
| $\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow t\tilde{g}$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{b}_1 275-440 GeV | 1404.2500 |
| $\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{g}$ | 1-2 e, μ | 1-2 b | Yes | 4.7 | \tilde{t}_1 110-167 GeV | 1208.4305, 1209.2102 |
| $\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{g}$ | 2 e, μ | 0-2 jets | Yes | 20.3 | \tilde{t}_1 130-210 GeV | 1403.4853 |
| $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow b\tilde{g}$ | 2 e, μ | 2 jets | Yes | 20.3 | \tilde{t}_1 215-530 GeV | 1403.4853 |
| $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{g}$ | 1 e, μ | 0 | Yes | 20.1 | \tilde{t}_1 150-580 GeV | 1308.2631 |
| $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{g}$ | 1 e, μ | 1 b | Yes | 20 | \tilde{t}_1 210-640 GeV | 1407.0583 |
| $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{g}$ | 0 | 2 b | Yes | 20.1 | \tilde{t}_1 250-640 GeV | 1406.1122 |
| $\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{g}$ | 0 | mono-jet/c-tag | Yes | 20.3 | \tilde{t}_1 90-240 GeV | 1407.0608 |
| $\tilde{t}_1\tilde{t}_1$ (natural GMSB) | 2 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_1 150-580 GeV | 1403.5222 |
| $\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$ | 3 e, μ (Z) | 1 b | Yes | 20.3 | \tilde{t}_2 290-600 GeV | 1403.5222 |
| EW direct | | | | | | |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 2 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 90-325 GeV | 1403.5294 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 2 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 140-465 GeV | 1403.5294 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 2 τ | - | Yes | 20.3 | \tilde{t}_1 100-350 GeV | 1407.0350 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 3 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 700 GeV | 1402.7029 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 2-3 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 420 GeV | 1403.5294, 1402.7029 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 1 e, μ | 2 b | Yes | 20.3 | \tilde{t}_1 285 GeV | ATLAS-CONF-2013-093 |
| $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{g}$ | 4 e, μ | 0 | Yes | 20.3 | \tilde{t}_1 620 GeV | 1405.5086 |
| Long-lived particles | | | | | | |
| Direct $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ prod., long-lived $\tilde{\chi}_1^0$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^0$ 270 GeV | ATLAS-CONF-2013-069 |
| Stable, stopped \tilde{g} R-hadron | 0 | 1-5 jets | Yes | 27.9 | \tilde{g} 832 GeV | 1310.6584 |
| GMSB, stable $\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 + \tau(e, \mu)$ | 1-2 μ | - | - | 15.9 | $\tilde{\chi}_1^0$ 475 GeV | ATLAS-CONF-2013-058 |
| GMSB, $\tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^0 + \tau$ | 2 γ | - | - | 4.7 | $\tilde{\chi}_1^0$ 230 GeV | 1304.6310 |
| $\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\bar{q}\tilde{\chi}_1^0$ (RPV) | 1 μ , displ. vtx | - | - | 20.3 | \tilde{q} 1.0 TeV | ATLAS-CONF-2013-092 |
| RPV | | | | | | |
| LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e + \mu$ | 2 e, μ | - | - | 4.6 | $\tilde{\nu}_e$ 1.61 TeV | 1212.1272 |
| LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e(\mu) + \tau$ | 1 $e, \mu + \tau$ | - | - | 4.6 | $\tilde{\nu}_e$ 1.1 TeV | 1212.1272 |
| Bilinear RPV CMSSM | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{q}, \tilde{g} 1.35 TeV | 1404.2500 |
| $\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow e\tilde{\nu}_e, e\tilde{\nu}_e$ | 4 e, μ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 750 GeV | 1405.5086 |
| $\tilde{\chi}_1^0\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow \tau\tilde{\nu}_\tau, e\tilde{\nu}_e$ | 3 $e, \mu + \tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 450 GeV | 1405.5086 |
| $\tilde{g} \rightarrow q\bar{q}\tilde{g}$ | 0 | 6-7 jets | - | 20.3 | \tilde{g} 916 GeV | ATLAS-CONF-2013-091 |
| $\tilde{g} \rightarrow t\bar{t}\tilde{g}, \tilde{t}_1 \rightarrow b\tilde{g}$ | 2 e, μ (SS) | 0-3 b | Yes | 20.3 | \tilde{g} 850 GeV | 1404.250 |
| Other | | | | | | |
| Scalar gluon pair, $sgluon \rightarrow q\bar{q}$ | 0 | 4 jets | - | 4.6 | incl. limit from 1110.2693 | 1210.4826 |
| Scalar gluon pair, $sgluon \rightarrow t\bar{t}$ | 2 e, μ (SS) | 2 b | Yes | 14.3 | $sgluon$ 350-500 GeV | ATLAS-CONF-2013-051 |
| WIMP interaction (DS, Dirac χ) | 0 | mono-jet | Yes | 10.5 | M^{scale} 704 GeV | ATLAS-CONF-2012-147 |

$\sqrt{s} = 7 \text{ TeV}$ full data
 $\sqrt{s} = 8 \text{ TeV}$ partial data
 $\sqrt{s} = 8 \text{ TeV}$ full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



Still believe in BSM physics at high energies

$$\Lambda \gg M_W$$

BSM Signatures

★ Still believe BSM is there, at high energies
Expect effects on Higgs couplings

★ Analysis

- in specific BSM models

- using effective Lagrangians

Model independent,
but have their own assumptions

Effective Lagrangian Approach

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

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

Wilson coefficient

d=6 operator

High-energy scale
(suppresses effects)

The diagram illustrates the structure of a d=6 operator in an effective Lagrangian. The central term is $c \frac{1}{\Lambda^2} \mathcal{O}_6$. Three callout boxes with arrows point to its components: 'Wilson coefficient' points to the c , 'd=6 operator' points to \mathcal{O}_6 , and 'High-energy scale (suppresses effects)' points to the Λ^2 in the denominator.

quasi-SM Higgs

i.e. SM field with (slightly) modified couplings

$$\mathcal{L} = \mathcal{L}_4 + \mathcal{L}_6 + \dots$$



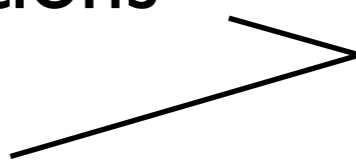
SM



neglect

This talk

Concentrate on the issues

- different basis can be used
 - correlations among physical predictions
 - connection with experiments
- 
- related

Based on work EM 1406.6376

see also

Gupta Pomarol Riva 1405.0181

Elias-Miro Espinosa EM Pomarol 1308.1879

Elias-Miro Grojean Gupta 1312.2928

.. others ...

Operator Basis

How many independent d=6 operators in \mathcal{L}_6 ? ?

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

59 (one family)

Buchmuller & Wyler 86

Grzadkowski, Iskrzynski, Misiak, Rosiek 10

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

Operator Basis

Grzadkowski, Iskrzynski, Misiak, Rosiek I 0

| X^3 | | φ^6 and $\varphi^4 D^2$ | | $\psi^2 \varphi^3$ | |
|--------------------------|--|---------------------------------|---|-----------------------|---|
| Q_G | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | Q_φ | $(\varphi^\dagger \varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$ |
| $Q_{\tilde{G}}$ | $f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$ |
| Q_W | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$ | $Q_{d\varphi}$ | $(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$ |
| $Q_{\tilde{W}}$ | $\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2 \varphi^2$ | | $\psi^2 X \varphi$ | | $\psi^2 \varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$ | Q_{eW} | $(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$ |
| $Q_{\varphi \tilde{G}}$ | $\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$ | Q_{eB} | $(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$ | Q_{uG} | $(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$ | $Q_{\varphi e}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$ |
| $Q_{\varphi \tilde{W}}$ | $\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$ | Q_{uW} | $(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$ | Q_{uB} | $(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi \tilde{B}}$ | $\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$ | Q_{dG} | $(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$ | $Q_{\varphi u}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$ | Q_{dW} | $(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$ | $Q_{\varphi d}$ | $(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$ |
| $Q_{\varphi \tilde{W}B}$ | $\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$ | Q_{dB} | $(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$ |

Table 2: Dimension-six operators other than the four-fermion ones.

| $(\bar{L}L)(\bar{L}L)$ | | $(\bar{R}R)(\bar{R}R)$ | | $(\bar{L}L)(\bar{R}R)$ | |
|---|--|------------------------|---|------------------------|--|
| Q_{ll} | $(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$ | Q_{ee} | $(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$ | Q_{le} | $(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$ | Q_{uu} | $(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$ | Q_{lu} | $(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | Q_{dd} | $(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$ | Q_{ld} | $(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$ | Q_{eu} | $(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$ | Q_{qe} | $(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$ | Q_{ed} | $(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$ |
| $(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$ | | B -violating | | | |
| Q_{ledq} | $(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$ | Q_{duq} | $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)^T C u_r^\beta] [(q_s^{\gamma j})^T C l_t^k]$ | | |
| $Q_{quqd}^{(1)}$ | $(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$ | Q_{qqq} | $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_t]$ | | |
| $Q_{quqd}^{(8)}$ | $(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$ | $Q_{qqq}^{(1)}$ | $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$ | | |
| $Q_{lequ}^{(1)}$ | $(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$ | $Q_{qqq}^{(3)}$ | $\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(q_s^{\gamma m})^T C l_t^n]$ | | |
| $Q_{lequ}^{(3)}$ | $(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$ | Q_{duu} | $\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$ | | |

Table 3: Four-fermion operators.

Operator Basis

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| |
|--|
| $\mathcal{O}_H = \frac{1}{2}(\partial^\mu H ^2)^2$ $\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2$ $\mathcal{O}_6 = \lambda H ^6$ |
| $\mathcal{O}_W = \frac{ig}{2} \left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H \right) D^\nu W_{\mu\nu}^a$ $\mathcal{O}_B = \frac{ig'}{2} \left(H^\dagger \overleftrightarrow{D}^\mu H \right) \partial^\nu B_{\mu\nu}$ |
| $\mathcal{O}_{2W} = -\frac{1}{2} (D^\mu W_{\mu\nu}^a)^2$ $\mathcal{O}_{2B} = -\frac{1}{2} (\partial^\mu B_{\mu\nu})^2$ $\mathcal{O}_{2G} = -\frac{1}{2} (D^\mu G_{\mu\nu}^A)^2$ |
| $\mathcal{O}_{BB} = g'^2 H ^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 H ^2 G_{\mu\nu}^A G^{A\mu\nu}$ $\mathcal{O}_{HW} = ig (D^\mu H)^\dagger \sigma^a (D^\nu H) W_{\mu\nu}^a$ $\mathcal{O}_{HB} = ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ $\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W_\mu^{a\nu} W_{\nu\rho}^b W^{c\rho\mu}$ $\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G_\mu^{A\nu} G_{\nu\rho}^B G^{C\rho\mu}$ |

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

Other basis:

Hagiwara Ishihara Szalapski Zeppenfeld 93

Corbett Eboli Gonzalez-Fraile Gonzalez-Garcia

Rosetta Stone



| X^2 | | ψ^6 and $\psi^4 D^2$ | $\psi^2 \psi^2$ | | |
|------------------|--|---------------------------|---|-----------------------|---|
| Q_{G^3} | $f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$ | Q_{ψ^6} | $(\psi^c \psi^c)^2$ | $Q_{\psi^2 \psi^2}$ | $(\psi^c \psi^c)(\bar{\psi}^c \psi^c)$ |
| Q_{G^2} | $f^{ABC} G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$ | $Q_{\psi^4 D^2}$ | $(\psi^c \psi^c) \square (\psi^c \psi^c)$ | $Q_{\psi^2 \psi^2}$ | $(\psi^c \psi^c)(\bar{\psi}^c \psi^c)$ |
| Q_{W^3} | $f^{IJK} W_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$ | $Q_{\psi^4 D^2}$ | $(\psi^c D_{\mu} \psi^c) (\psi^c D_{\mu} \psi^c)$ | $Q_{\psi^2 \psi^2}$ | $(\psi^c \psi^c)(\bar{\psi}^c \psi^c)$ |
| Q_{W^2} | $f^{IJK} \bar{W}_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$ | | | | |
| $X^2 \psi^2$ | | $\psi^2 X \psi$ | $\psi^2 \psi^2 D$ | | |
| $Q_{\psi^2 G^3}$ | $\psi^c \psi^c G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$ | $Q_{\psi^2 W^3}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 G^2}$ | $\psi^c \psi^c G_{\mu\nu}^A G_{\nu\rho}^B G_{\rho\mu}^C$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 W^3}$ | $\psi^c \psi^c W_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 W^2}$ | $\psi^c \psi^c W_{\mu\nu}^I W_{\nu\rho}^J W_{\rho\mu}^K$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 B^3}$ | $\psi^c \psi^c B_{\mu\nu} B_{\nu\rho} B_{\rho\mu}$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 B^2}$ | $\psi^c \psi^c B_{\mu\nu} B_{\nu\rho} B_{\rho\mu}$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 W B}$ | $\psi^c \psi^c W_{\mu\nu}^I B_{\nu\rho} B_{\rho\mu}$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |
| $Q_{\psi^2 W B}$ | $\psi^c \psi^c W_{\mu\nu}^I B_{\nu\rho} B_{\rho\mu}$ | $Q_{\psi^2 W^2}$ | $(\bar{\psi}^c \psi^c) (\psi^c W_{\mu\nu}^I W_{\nu\rho}^J)$ | $Q_{\psi^2 \psi^2 D}$ | $(\psi^c \bar{\psi}^c) (\bar{\psi}^c \psi^c)$ |

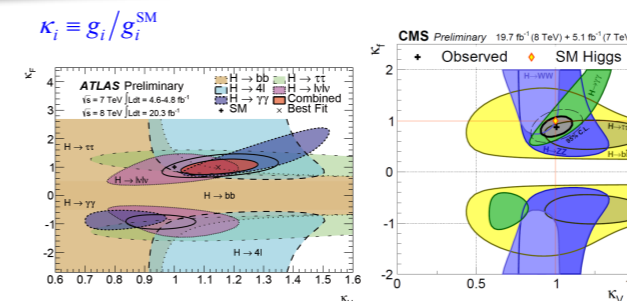
Table 2: Dimension-six operators other than the four-fermion ones.

d=6 operators



Looking for a clear relation

Experimental measurements



Coupling basis

Approaching the
Rosetta Stone



- Connection with experiment
- Correlations are clear

Correlations

Correlations among observables are expected

- gauge invariance restricts operator form
- not all possible operators are independent

Simple example:

In SM:

\mathcal{L}_4

$$m_W^2 \left(W^{+\mu} W_{\mu}^{-} + \frac{1}{2c_w^2} Z^{\mu} Z_{\mu} \right) \left(1 + \frac{2h}{v} + \frac{h^2}{v^2} \right)$$

In BSM:

$\mathcal{L}_4 + \mathcal{L}_6$

??

Relations preserved ?

Connection with Experiment

Coupling Basis

$$\mathcal{L}_6 = \sum_a \frac{c_a}{\Lambda^2} \mathcal{O}_a \quad \text{couplings } \{a\}$$

$$\frac{c_a}{\Lambda^2} \mathcal{O}_a^{unit} = \eta_a \left(\hat{\mathcal{D}}_a + \delta \mathcal{D}_a \right)$$

\nwarrow
 $V^3 \quad Zff \quad h\gamma\gamma \quad \dots$

independent $\{a\}$

$\{a\}$ define “directions” in operator space

- Start with monomial operators
- Combine them to get Coupling basis

Splitting

Can split

$$59 = 17 + 42$$



Can be further split

- Mix among themselves
- Relevant for Higgs physics (CP-even sector)

In this talk I will discuss these 17 operators

Higgs-only Sector

★ operators have form: $|\Phi|^2 \mathcal{O}_4 \rightarrow (v + h)^2 \mathcal{O}_4$

It can only be tested in Higgs physics: $v^2 \mathcal{O}_4 \rightarrow \mathcal{O}_{SM}$

Example:

$$\frac{1}{g_s^2} G_{\mu\nu}^2 + c \frac{|\Phi^2|}{\Lambda^2} G_{\mu\nu}^2 \xrightarrow{\text{vacuum}} \left(\frac{1}{g_s^2} + c \frac{v^2}{2\Lambda^2} \right) G_{\mu\nu}^2$$

8 operators/couplings in Higgs-only Sector

3 hff $f = t, b, \tau$ $\mathcal{O}_{y_u} = y_u |\Phi|^2 \bar{Q}_L \tilde{\Phi} u_R$, $\mathcal{O}_{y_d} = y_d |\Phi|^2 \bar{Q}_L \Phi d_R$,
 $\mathcal{O}_{y_e} = y_e |\Phi|^2 \bar{L}_L \Phi e_R$,

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

$h\gamma\gamma$

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

$h\gamma Z$

h^3

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

$h(VV)c = h(WW + \frac{1}{2c_W^2} ZZ)$

$\mathcal{O}_r = |\Phi|^2 |D_\mu \Phi|^2$ \mathcal{O}_6

Higgs-only Sector

$$h(VV)_c = h(WW + \frac{1}{2c_W^2} ZZ)$$

$$\mathcal{O}_r = |\Phi|^2 |D_\mu \Phi|^2 \quad \mathcal{O}_6$$

$$\mathcal{D}_{h(VV)_c} = v(hP_3) \left[W^{+\mu} W_\mu^- + \frac{1}{2c_w^2} Z^\mu Z_\mu \right] + \frac{m_f}{4m_W^2} (h^2 Q_1) \bar{f} f + \frac{m_h^2}{12m_W^2} (h^4 Q_2)$$

$$P_3 = 1 + \frac{2h}{v} + \frac{4h^2}{3v^2} + \frac{h^3}{3v^3},$$

$$Q_1 = 1 + \frac{h}{3v},$$

$$Q_2 = 1 + \frac{3h}{4v} + \frac{h^2}{8v^2}.$$

Higgs-only Sector

$$h(VV)_c = h(WW + \frac{1}{2c_W^2} ZZ)$$

$$\mathcal{O}_r = |\Phi|^2 |D_\mu \Phi|^2 \quad \mathcal{O}_6$$

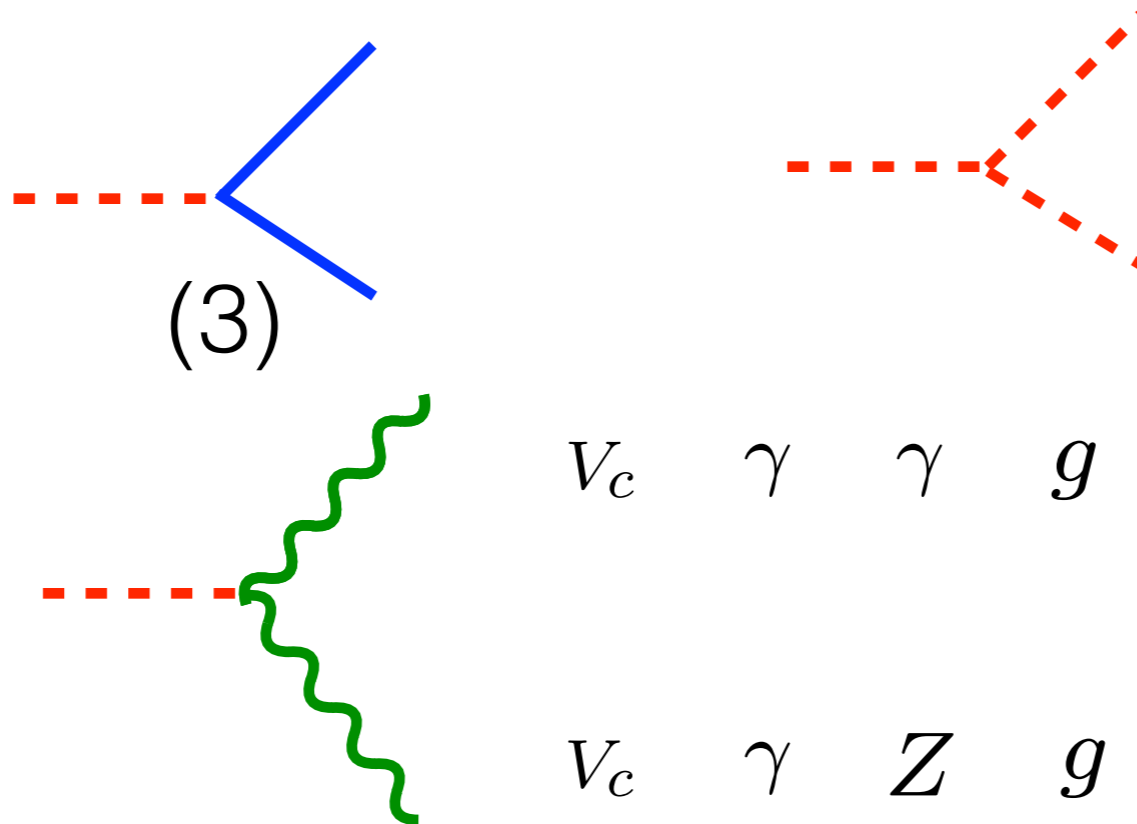
$$\mathcal{D}_{h(VV)_c} = v(hP_3) \left[W^{+\mu} W_\mu^- + \frac{1}{2c_w^2} Z^\mu Z_\mu \right] + \frac{m_f}{4m_W^2} (h^2 Q_1) \bar{f} f + \frac{m_h^2}{12m_W^2} (h^4 Q_2)$$

$$P_3 = 1 + \frac{2h}{v} + \frac{4h^2}{3v^2} + \frac{h^3}{3v^3},$$

$$Q_1 = 1 + \frac{h}{3v},$$

$$Q_2 = 1 + \frac{3h}{4v} + \frac{h^2}{8v^2}.$$

8 Higgs-only Couplings



Higgs-EWPT

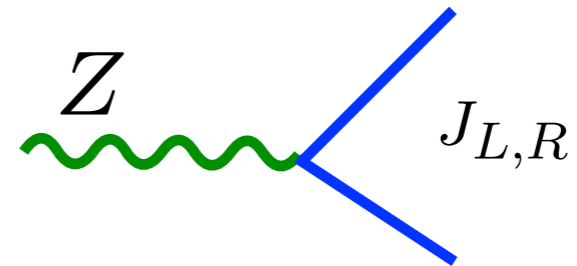
7 operators/couplings

$$Z f_R f_R$$

t, b, τ

$$Z f_L f_L$$

t, b, τ, ν



Example:

$$\mathcal{D}_{ZeL} = \left(1 + \frac{2h}{v} + \frac{h^2}{v^2}\right) \left[Z_\mu \bar{e}_L \gamma^\mu e_L - \frac{c_w}{\sqrt{2}} W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + \text{h.c.} \right]$$

Higgs-EWPT

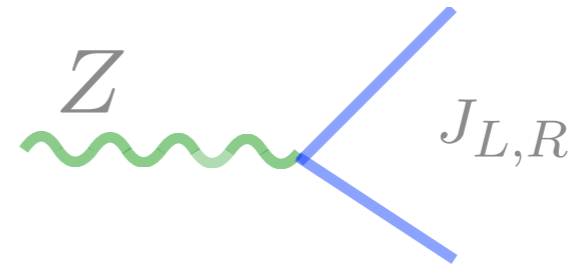
7 operators/couplings

$$Z f_R f_R$$

t, b, τ

$$Z f_L f_L$$

t, b, τ, ν



(Remember discussion on S-parameter)

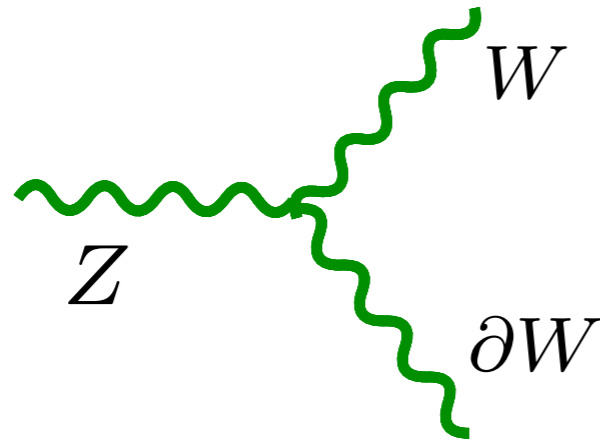
Example:

$$\mathcal{D}_{ZeL} = \left(1 + \frac{2h}{v} + \frac{h^2}{v^2} \right) \left[Z_\mu \bar{e}_L \gamma^\mu e_L - \frac{c_w}{\sqrt{2}} W_\mu^+ \bar{\nu}_L \gamma^\mu e_L + \text{h.c.} \right]$$

Higgs-TGC Operators

2 operators/couplings

g_Z^1

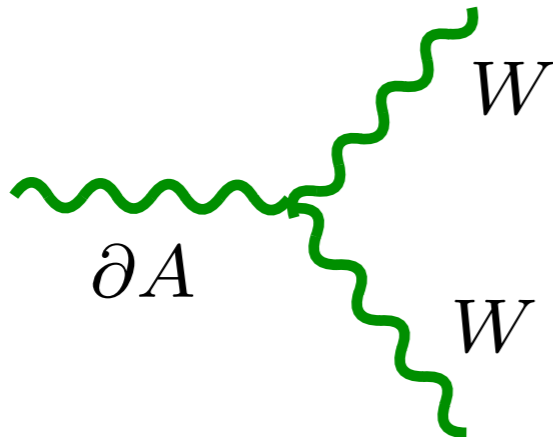


$$\mathcal{O}_B - \mathcal{O}_W = \frac{ig'}{2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi) \partial^\nu B_{\mu\nu} - \frac{ig}{2}(\Phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \Phi) D^\nu \mathcal{W}_{\mu\nu}^a$$

$$\mathcal{O}_r = |\Phi|^2 |D_\mu \Phi|^2$$

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

κ_γ



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

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

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

Summary

$$H = v + h$$

Higgs field

Physical Higgs boson

★ Measuring h-physics one probes v

- Higg-only (8)
- Higgs - Z pole
- Higgs - TGC

Only in the 8 only-Higgs
sth new is measured

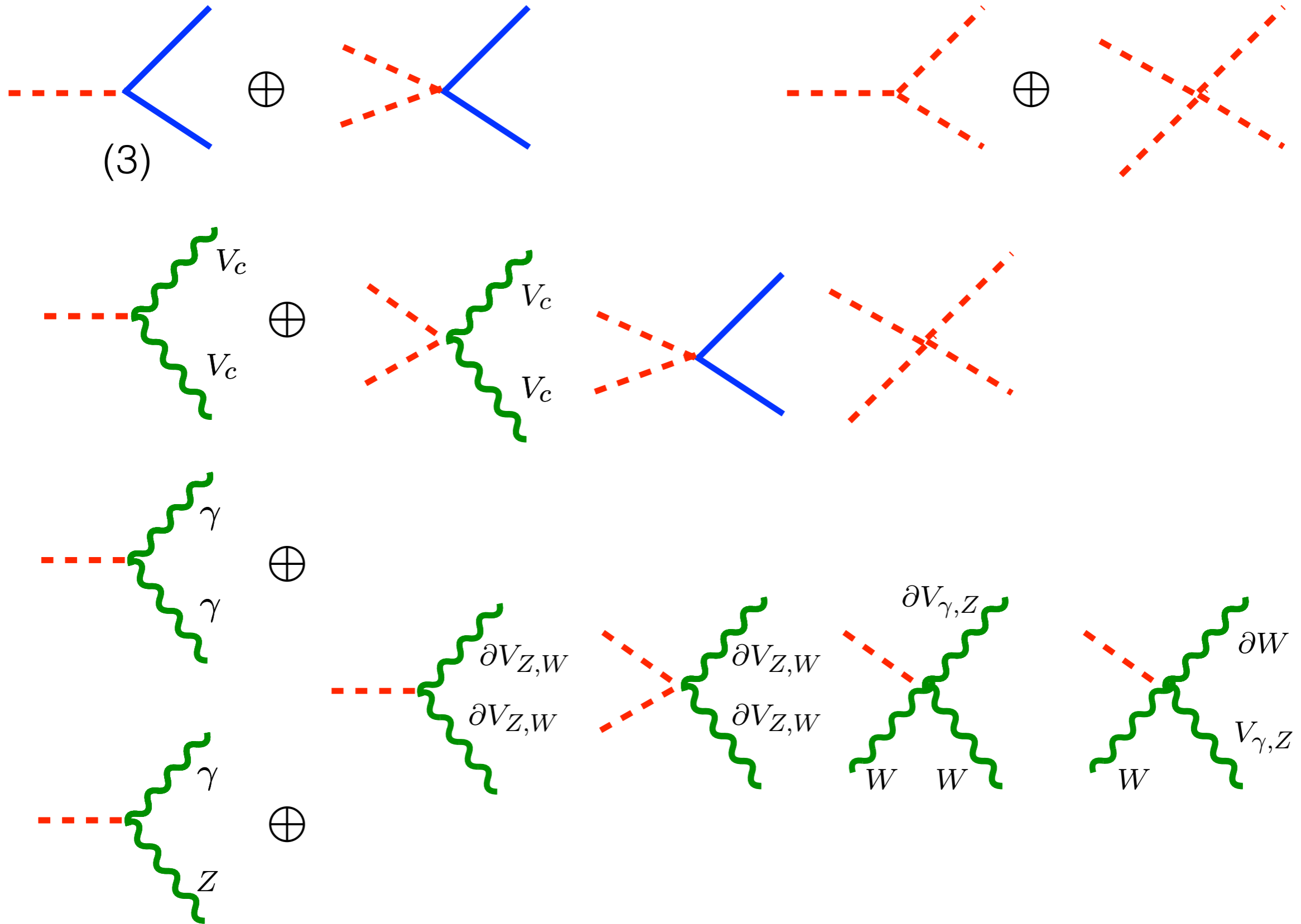
Directions

$$\frac{c_a}{\Lambda^2} \mathcal{O}_a^{unit} = \eta_a \left(\hat{\mathcal{D}}_a \oplus \delta \mathcal{D}_a \right)$$

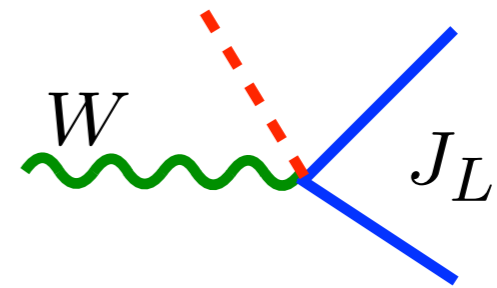
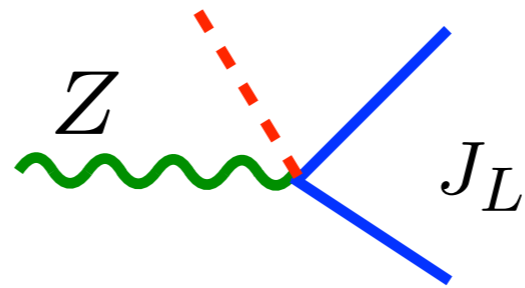
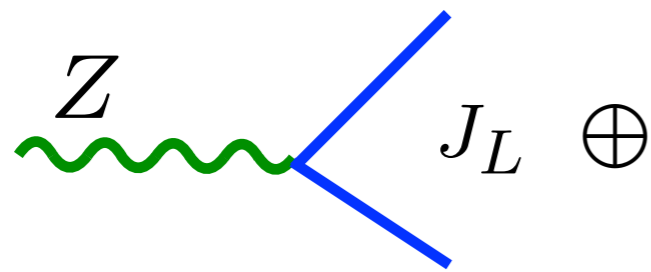
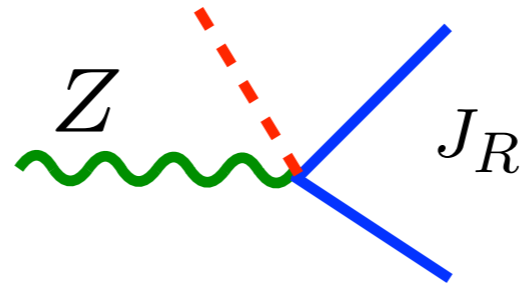
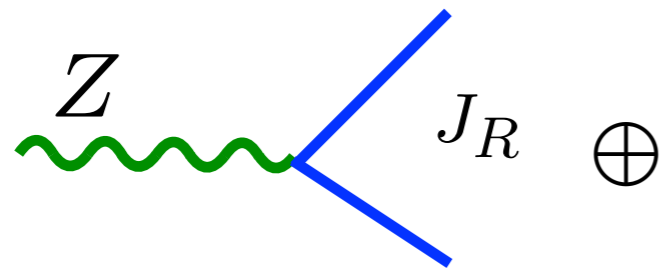
★ I will show correlations schematically

Exact expressions given
in EM 1406.6376

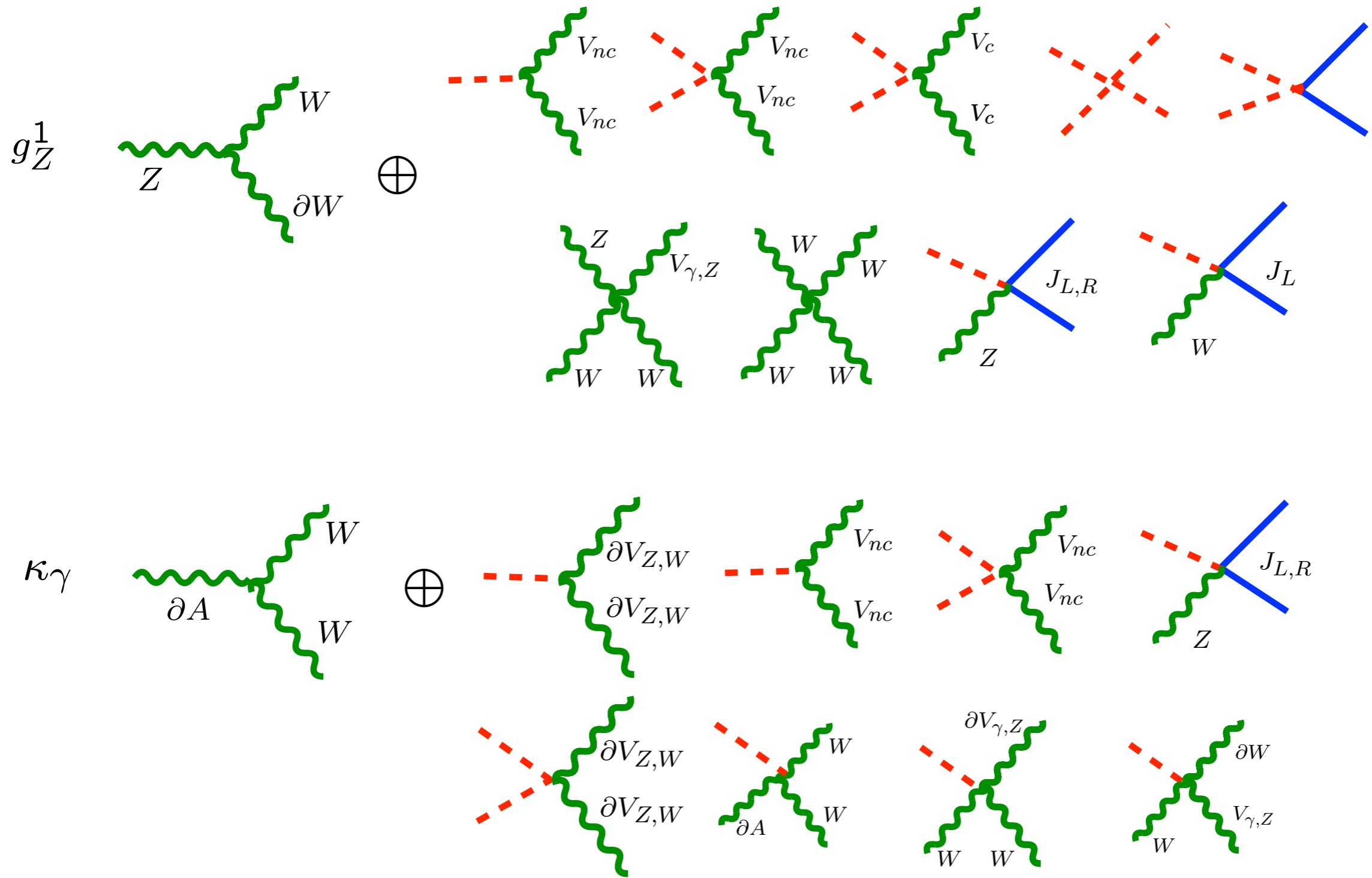
Higgs-only



Higgs-EWPT



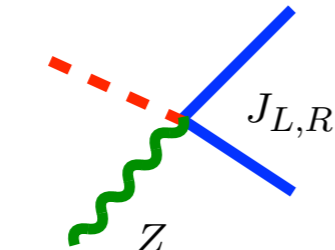
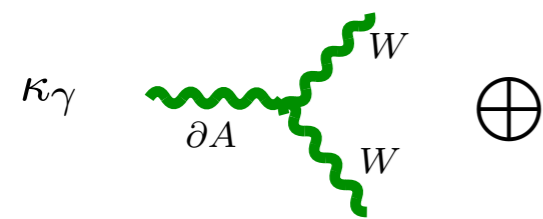
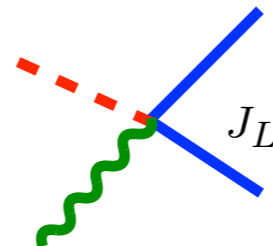
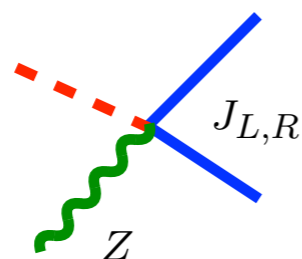
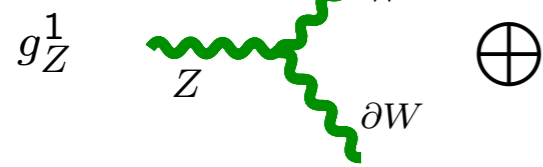
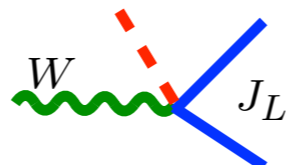
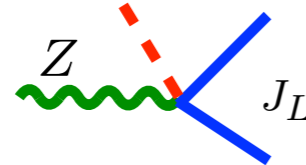
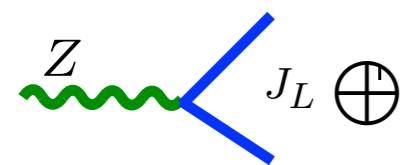
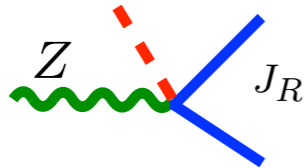
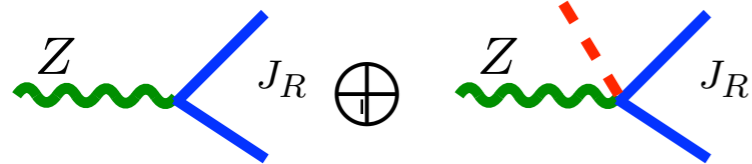
Higgs-TGC



Example of Correlations

contact term $hV_\mu \bar{f} \gamma^\mu f$

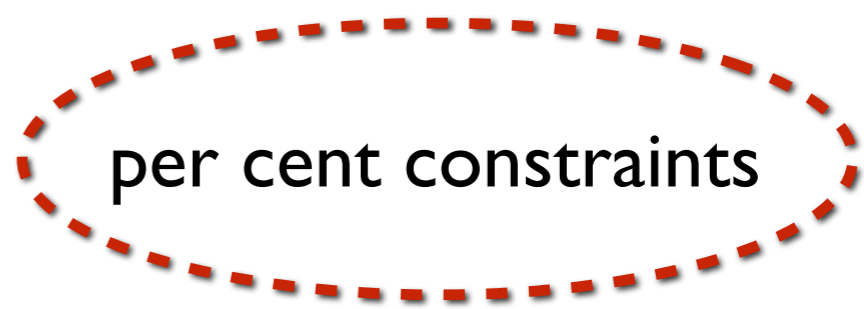
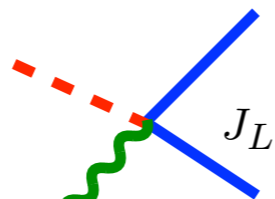
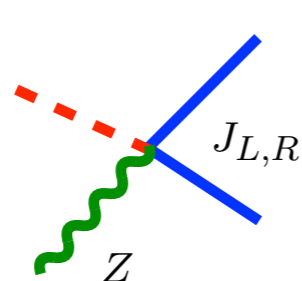
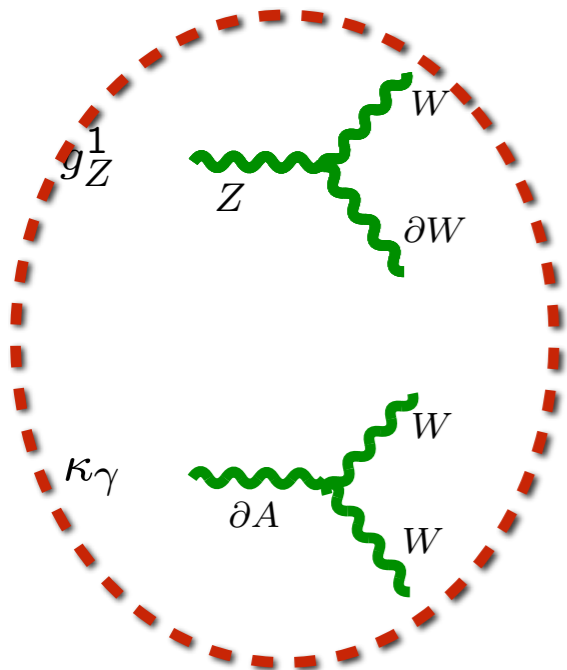
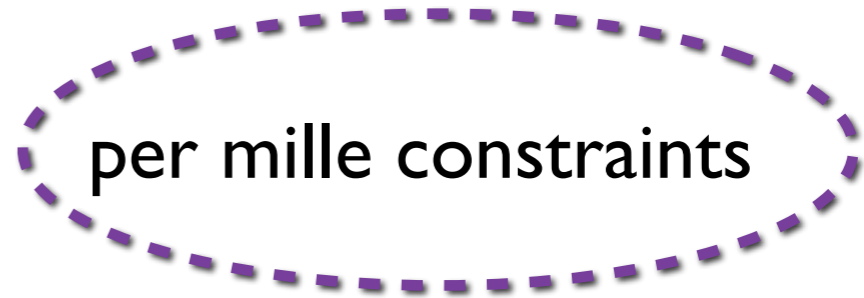
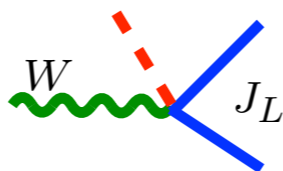
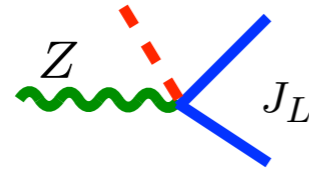
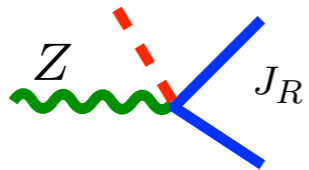
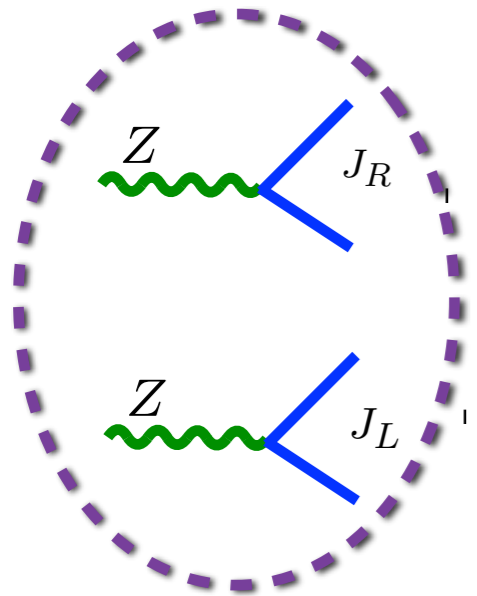
$h \rightarrow V f f$



Example of Correlations

contact term $hV_\mu \bar{f} \gamma^\mu f$

$h \rightarrow V f f$



CONCLUSIONS

- Effective Lagrangian approach is a model independent tool to analyse BSM physics

Assumptions: all new physics integrated at high energies, $d=6$ dominance, etc

- Coupling basis to clearly see presence (or absence) of correlations

back up

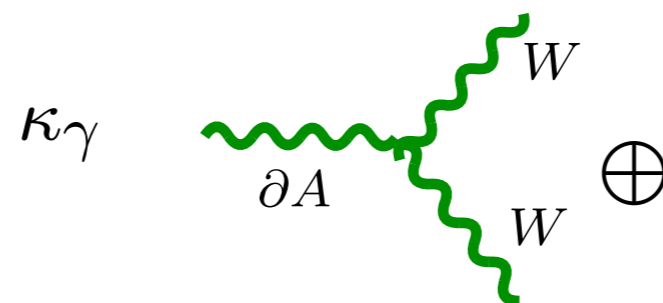
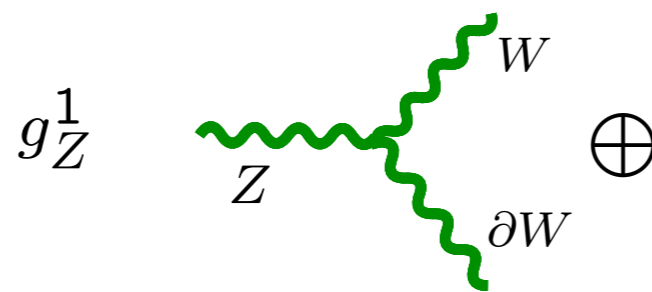
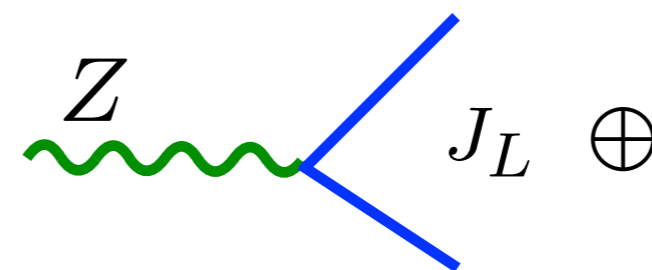
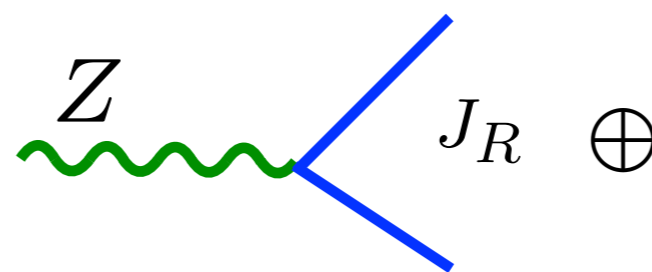
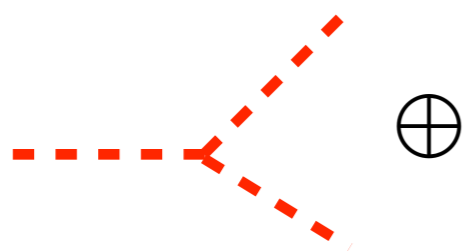
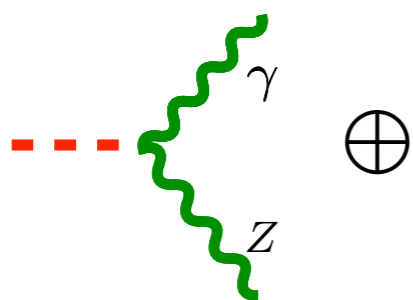
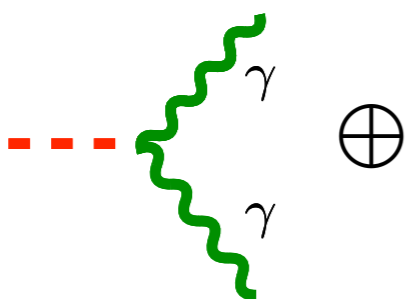
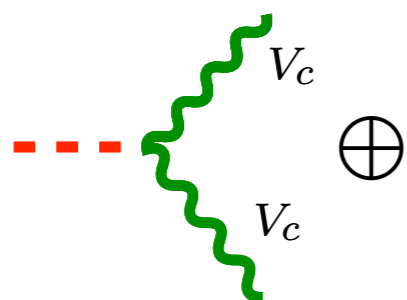
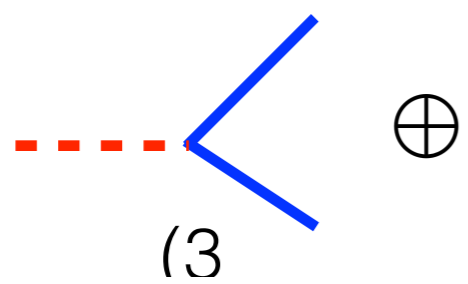
More Example of Correlations

● non custodial $V_\mu V^\mu$

$$V = W, Z$$

● form factor $V_{\mu\nu} V^{\mu\nu}$

Example of NO Correlations



Example Correlations (not involving Higgs)

★ from cubic to quartic

