Effective Higgs Lagrangians

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Origin of the Higgs Particle in the Standard Model

- Gauge symmetry implies massless gauge bosons

$$m_W^2 \; W_\mu^+ W^{-\,\mu}$$ Not Gauge invariant

- Introduce scalar field

$$\mathcal{D}_\mu \Phi^\dagger \mathcal{D}_\mu \Phi = W_\mu^a W^{a\mu} \; \Phi^\dagger \Phi \; + \; \ldots$$ Gauge invariant

- Spontaneous symmetry breaking

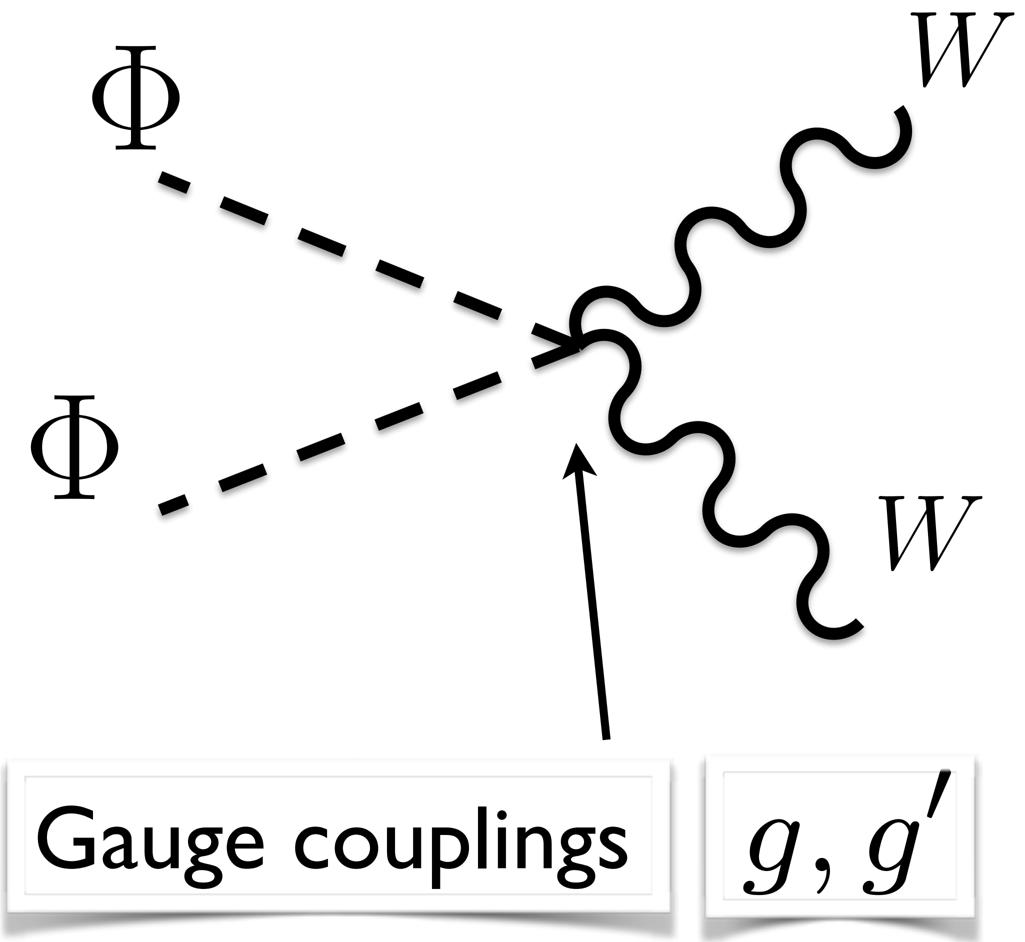
$$\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \frac{1}{2} \; g^2 v^2 = m_W^2$$

Origin of the Higgs Particle in the Standard Model

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

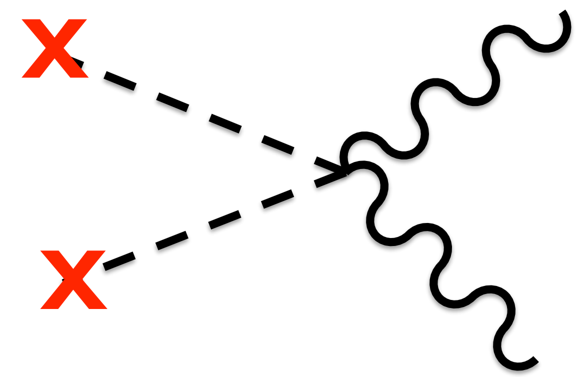
$$\frac{1}{2}\, m_Z^2 Z_\mu Z^\mu \;\left(1 + 2\frac{h}{v} + \frac{h^2}{v^2}\right)$$

Origin of the Higgs Particle in the Standard Model

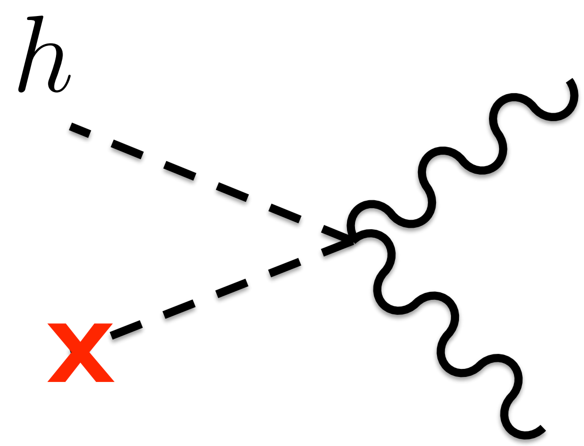


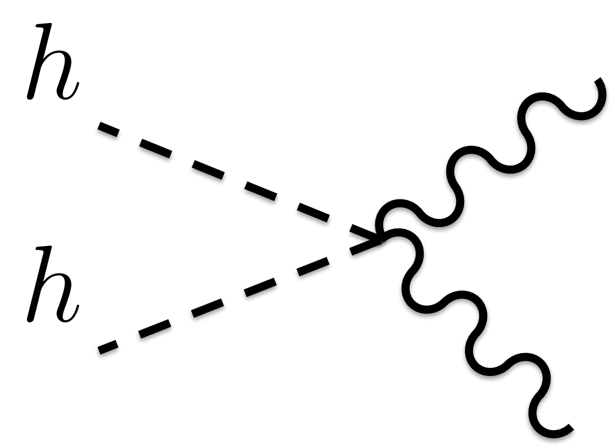
Origin of the Higgs Particle in the Standard Model

gauge boson masses



higgs couplings





Higgs in SM

Φ 4 New degrees of freedom: 4=3+1

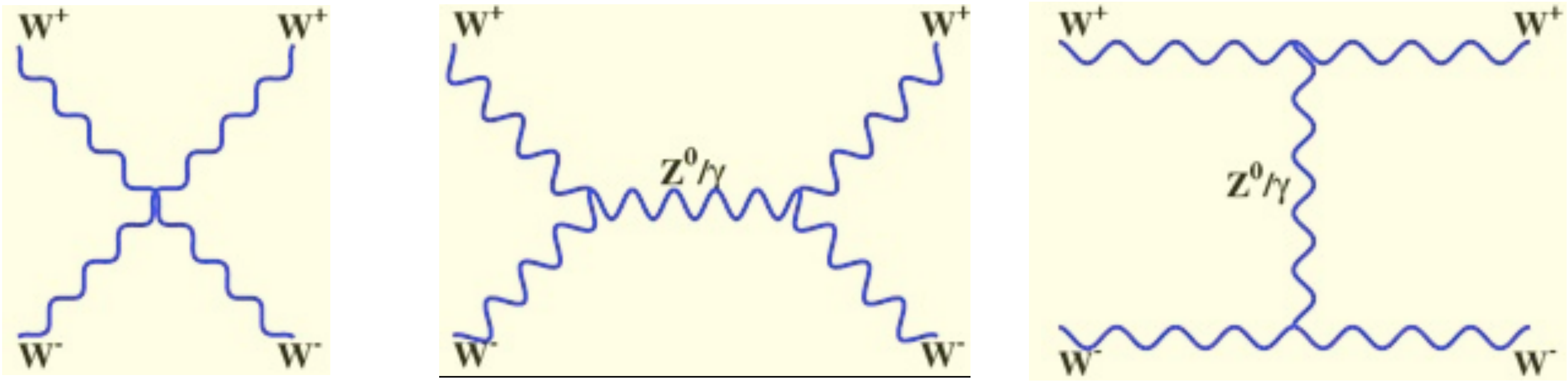
3 $W_L^{\pm}, Z_L$

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

1 Higgs scalar h

Unitary problem

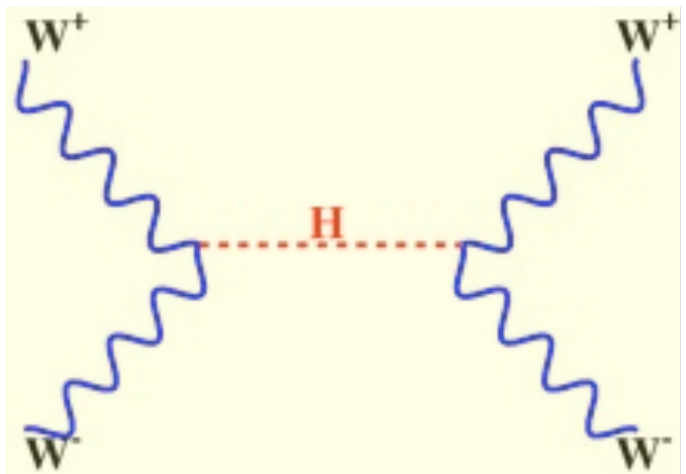
$$WW \to WW$$

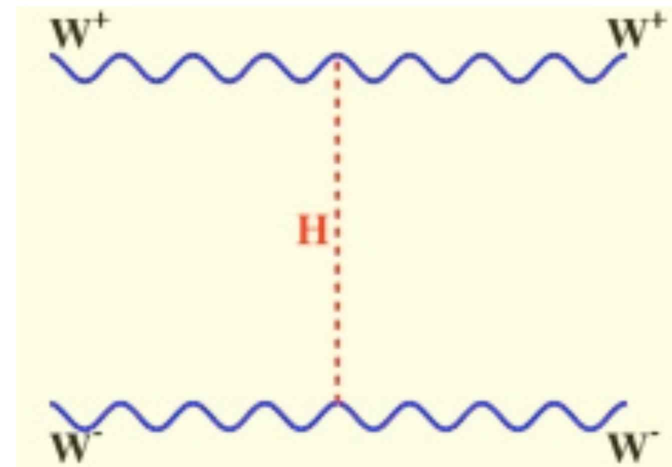


$$\mathcal{M}_{gauge} \sim \frac{s}{M_W^2} \qquad s \gg M_W^2$$

Dominant contribution from $W_L^{\pm}, Z_L$

Unitary problem





Text

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

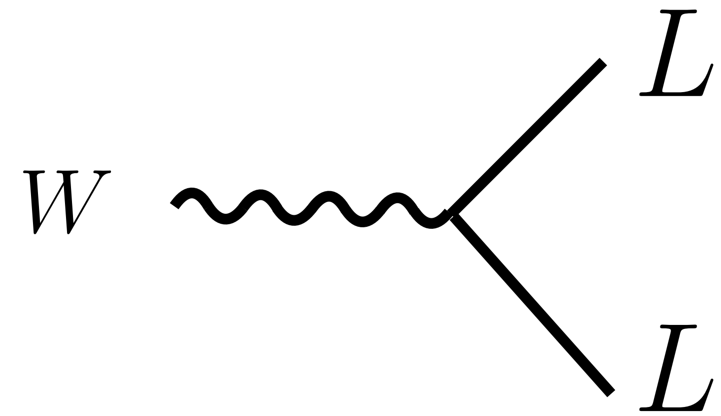
Cancellation
of linear growing

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

(for a light scalar)

Fermion masses

SM is a chiral theory



No R

$SU(2)_L$

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

$$m_d\, \bar{d}_L d_R \;+\; h.c.$$ Not Gauge invariant

Fermion masses

- Yukawa coupling with scalar field

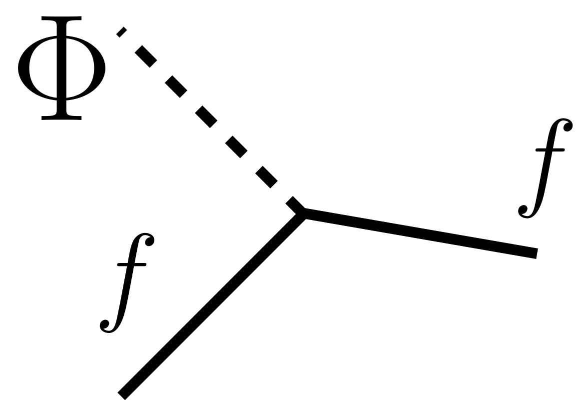
$$y_d \, \bar{Q}_L \Phi d_R \; + \; h.c.$$

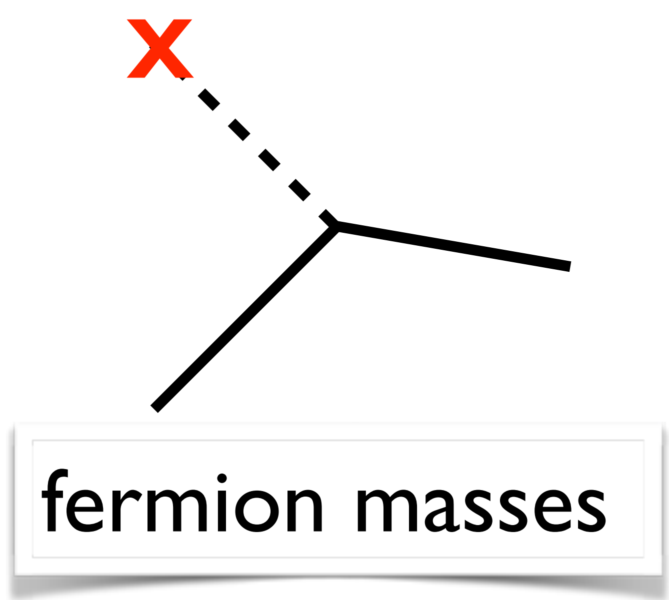
Gauge invariant

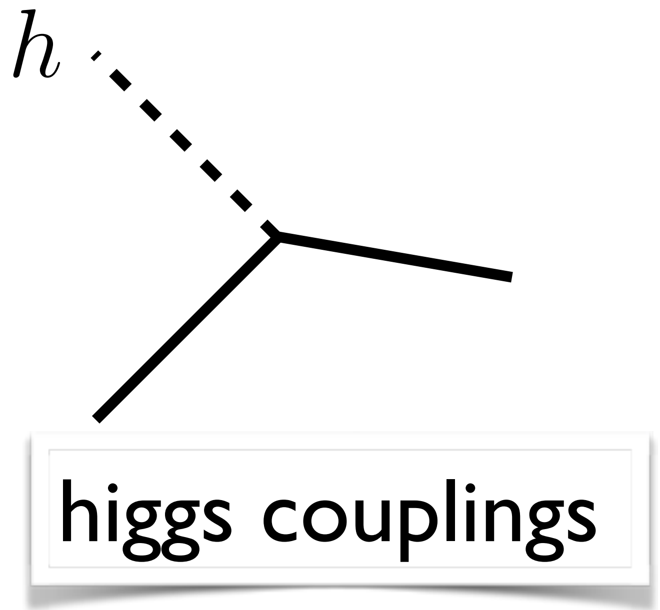
- SSB $\Phi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$

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

Higgs and fermion masses







H couples to mass

- Without symmetry breaking

  W, Z massless and massless fermions

- With symmetry breaking

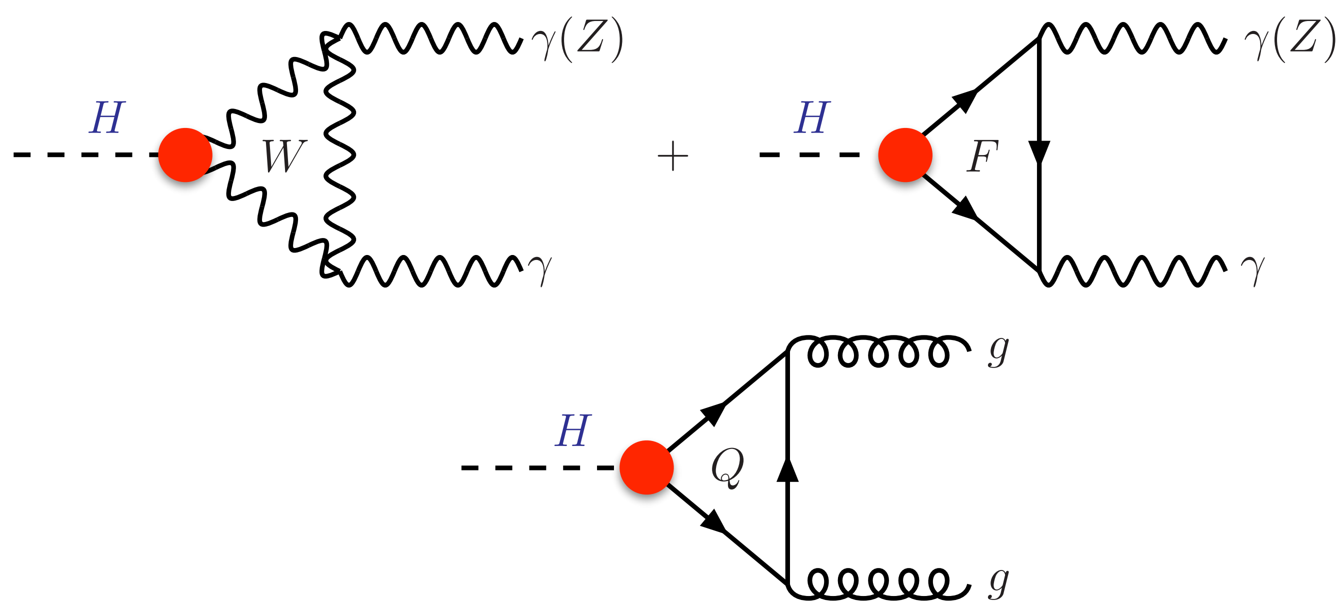
$$\Phi \to \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ H\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v+h\end{pmatrix}$$

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

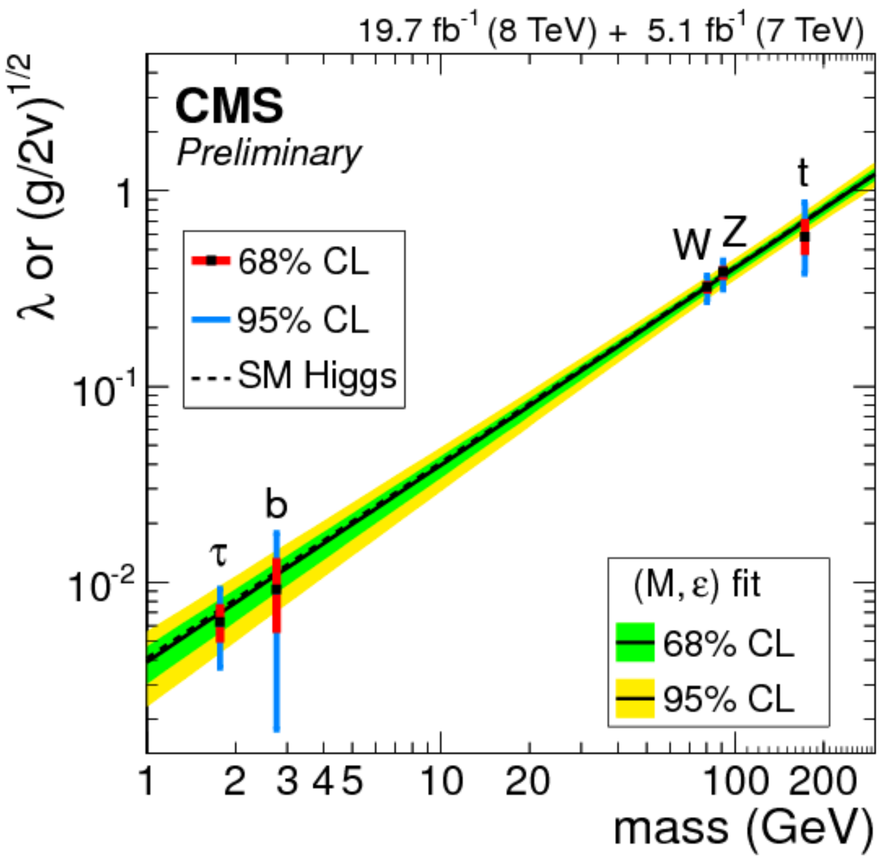
$$m_f\bar{f}f\left(1 + \frac{h}{v}\right)$$

H couples to photons and gluons

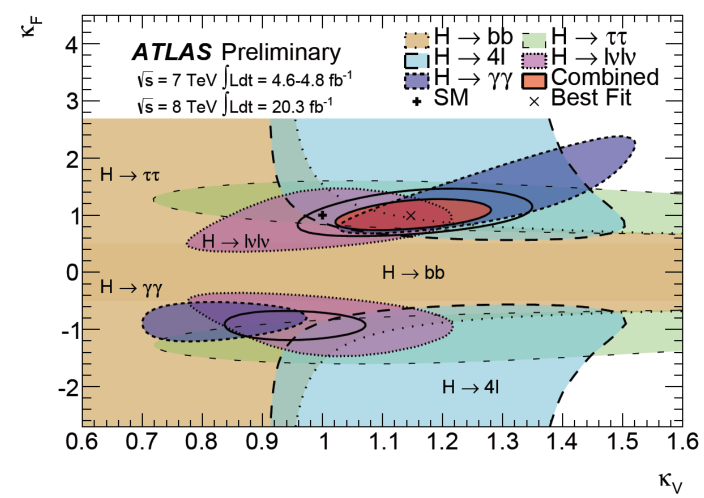
- coupling through loops

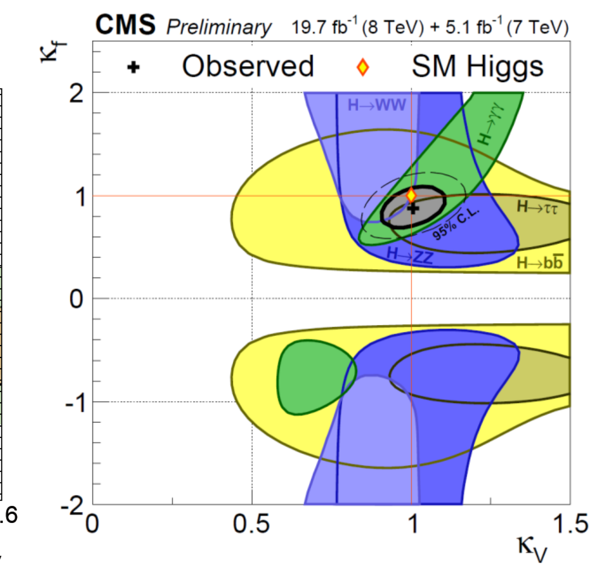


Higgs Particle at LHC



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





Higgs couples to masses (tree-level)

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

Consistent with SM Higgs

Higgs Particle in PDG

$\boxed{H^0}$

$J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

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

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

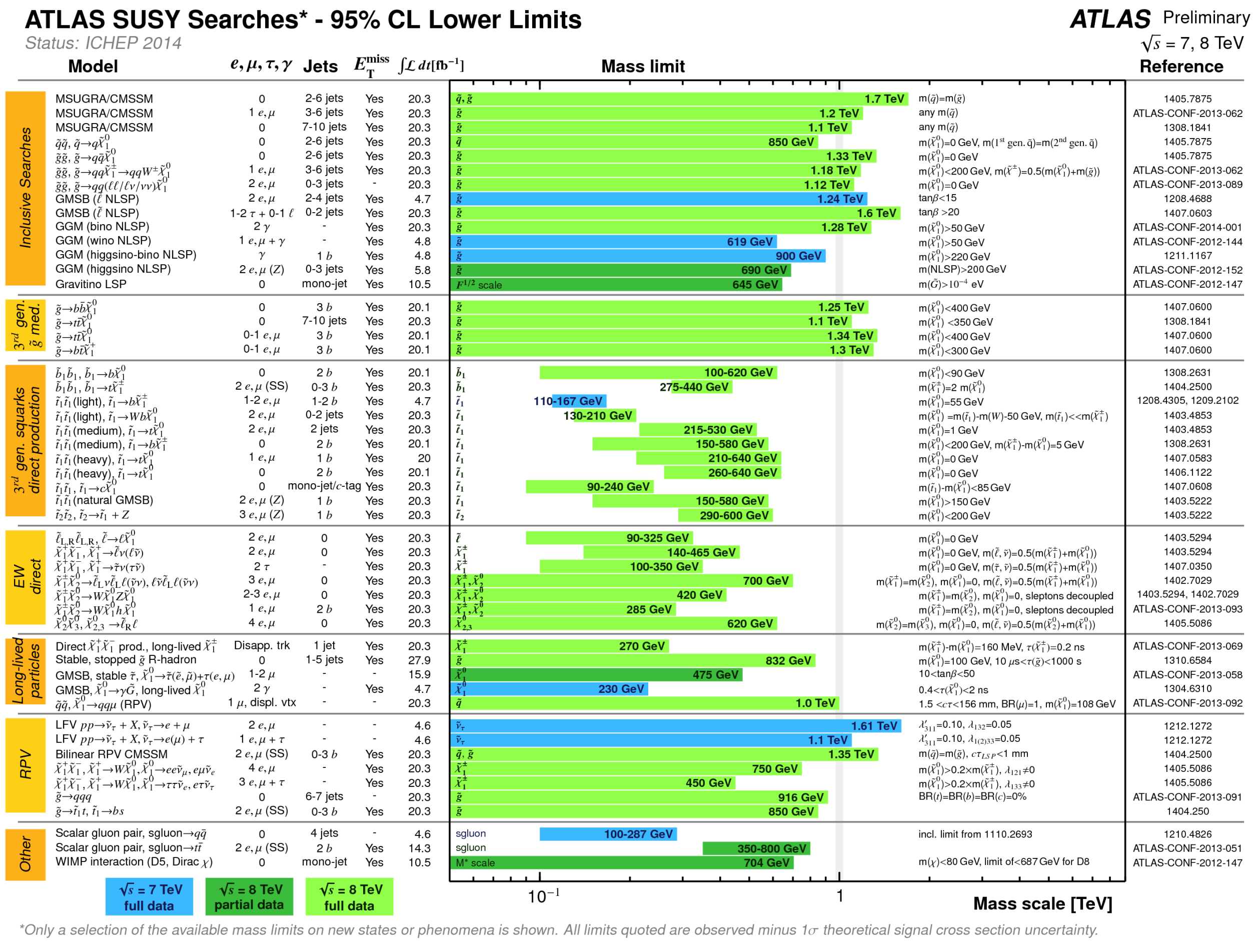
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

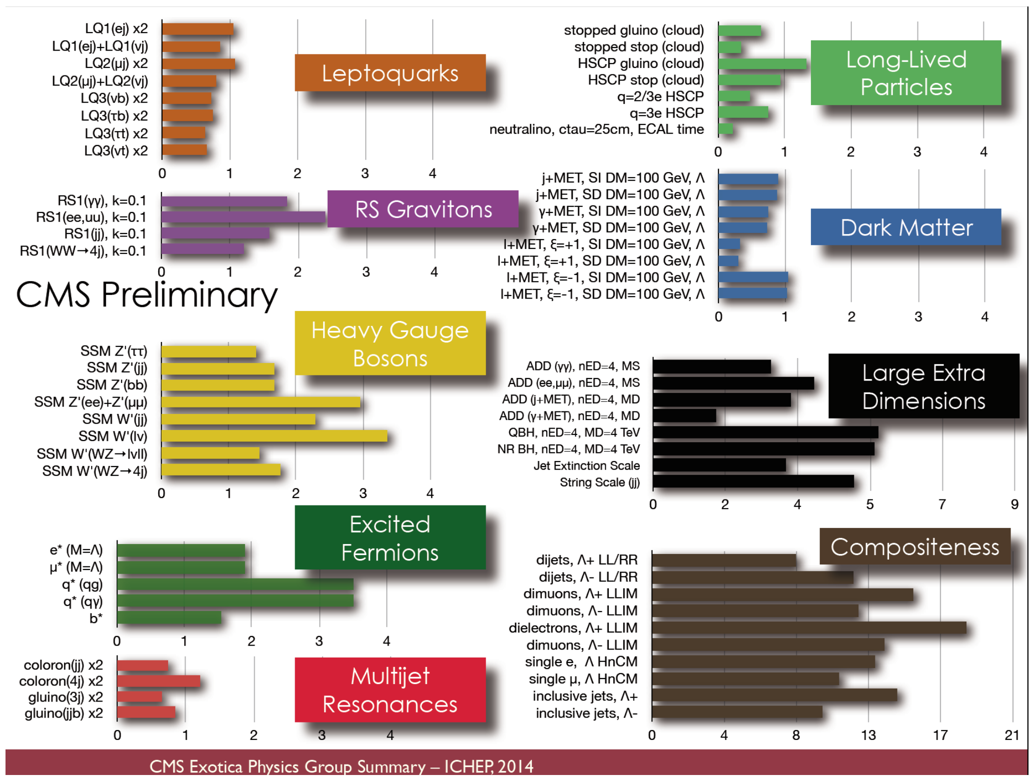
$b\overline{b} = 1.1 \pm 0.5$

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

$Z\gamma <$ 9.5, CL = 95%

Search for SUSY and other BSM Signatures





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-enery scale (suppresses effects)

quasi-SM Higgs

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

$$\mathcal{L} = \underbrace{\mathcal{L}_4}_{\text{SM}} + \mathcal{L}_6 + \underbrace{\ldots}_{\text{neglect}}$$

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, Rosiek10

<u>59 ways to modify the SM</u> !!
(many more for 3 families)

Operator Basis

Grzadkowski, Iskrzynski, Misiak, Rosiek10

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Table 3: Four-fermion operators.

Operator Basis

Giudice Grojean Pomarol Rattazzi 07

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

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

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

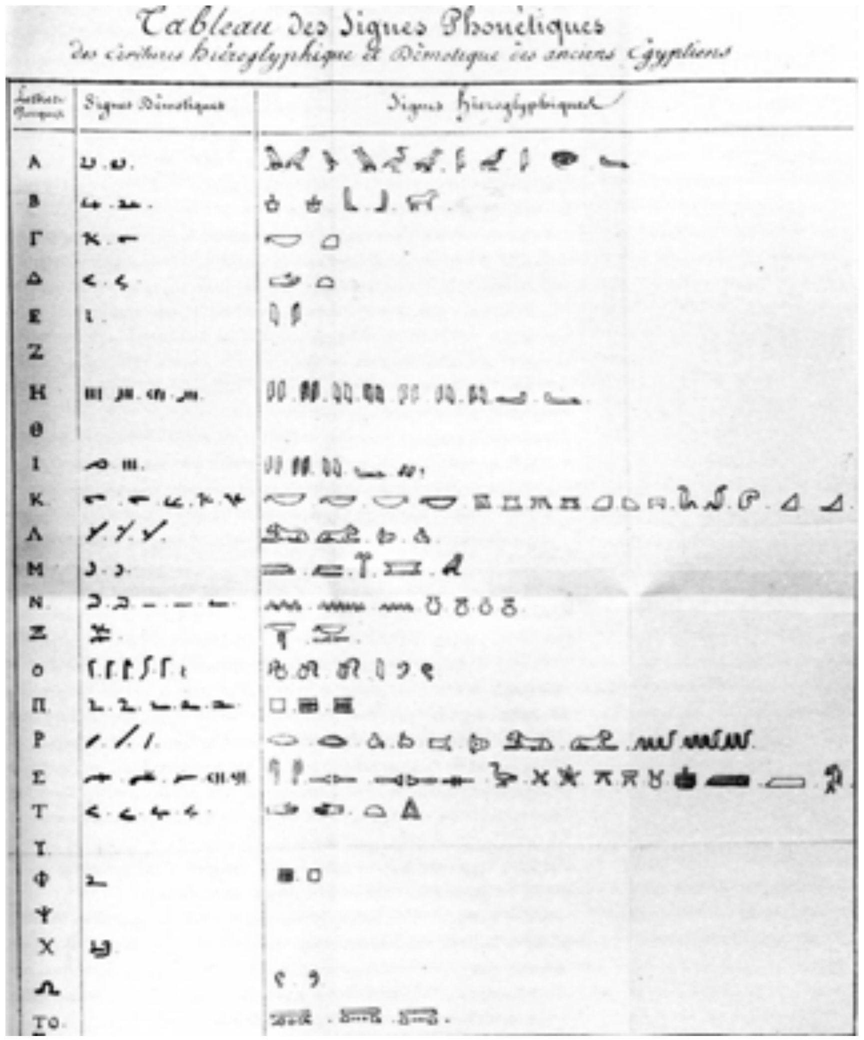
$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu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

Other basis:

Hagiwara Ishihara Szalapski Zeppenfeld 93

Corbett Eboli Gonzalez-Fraile Gonzalez-Garcia

Rosetta Stone



Allowed the understanding of Egiptian hieroglyphs

Rosetta Stone

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

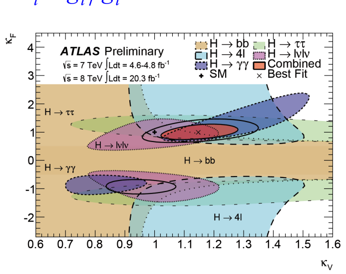
Table 2: Dimension-six operators other than the four-fermion ones.

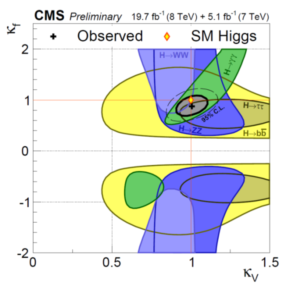
d=6 operators

Looking for a clear relation

Experimental measurements

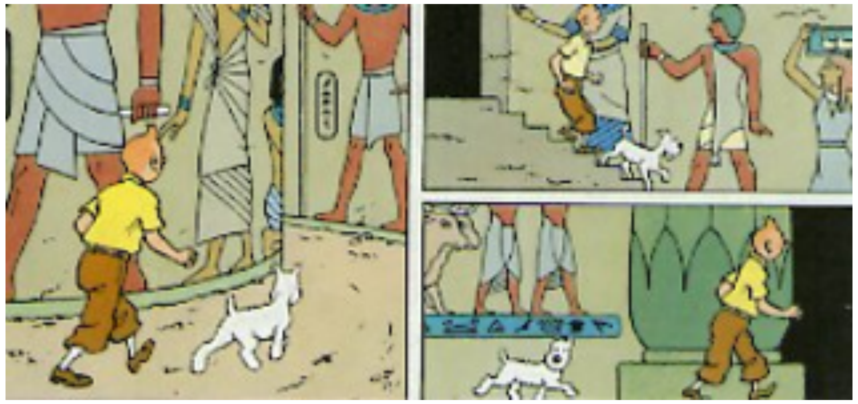
$\kappa_i \equiv g_i / g_i^{\rm SM}$





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: $\mathcal{L}_4$ $\quad m_W^2 \left(W^{+\mu} W^-_\mu + \frac{1}{2\, c_w^2} Z^\mu Z_\mu \right) \left(1 + \frac{2h}{v} + \frac{h^2}{v^2} \right)$

In BSM: $\mathcal{L}_4 + \mathcal{L}_6$ $\quad$ **? ?**

Relations preserved ?

Connection with Experiment
Coupling Basis

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

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

$V^3 \quad Zff \quad h\gamma\gamma \quad \ldots$ 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: $|\Phi|^2\,\mathcal{O}_4 \;\to\; (v+h)^2\,\mathcal{O}_4$

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

Example:

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

8 operators/couplings in Higgs-only Sector

3 hff $f = t, b, \tau$

$$\mathcal{O}_{y_u} = y_u|\Phi|^2 \bar{Q}_L \widetilde{\Phi} u_R \quad , \quad \mathcal{O}_{y_d} = y_d|\Phi|^2 \bar{Q}_L \Phi d_R \,,$$
$$\mathcal{O}_{y_e} = y_e|\Phi|^2 \bar{L}_L \Phi e_R \quad ,$$

hgg

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

$h\gamma\gamma$

$h\gamma Z$

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

h^3

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

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

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

Higgs-only Sector

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

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

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

$$\begin{aligned} P_3 &= 1 + \frac{2h}{v} + \frac{4h^2}{3v^2} + \frac{h^3}{3v^3}\ , \\ Q_1 &= 1 + \frac{h}{3v}\ , \\ Q_2 &= 1 + \frac{3h}{4v} + \frac{h^2}{8v^2}\ . \end{aligned}$$

Higgs-only Sector

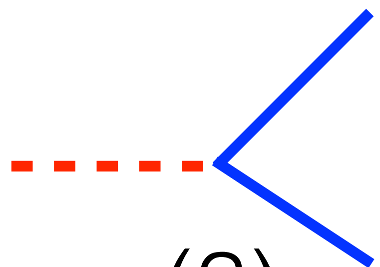
$$h(VV)c = h(WW + \frac{1}{2c_W^2}\ ZZ)$$

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

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

$$\begin{aligned}
P_3 &= 1 + \frac{2h}{v} + \frac{4h^2}{3v^2} + \frac{h^3}{3v^3}\ , \\
Q_1 &= 1 + \frac{h}{3v}\ , \\
Q_2 &= 1 + \frac{3h}{4v} + \frac{h^2}{8v^2}\ .
\end{aligned}$$

8 Higgs-only Couplings



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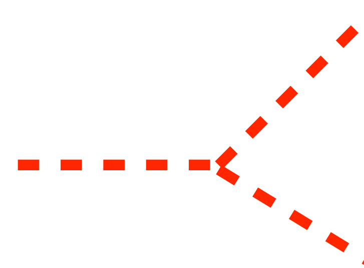
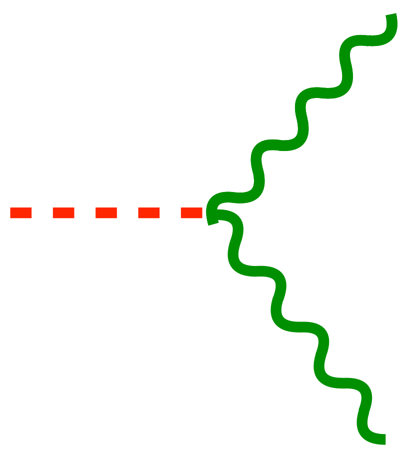




$V_c \quad \gamma \quad \gamma \quad g$

$V_c \quad \gamma \quad Z \quad g$

Higgs-EWPT

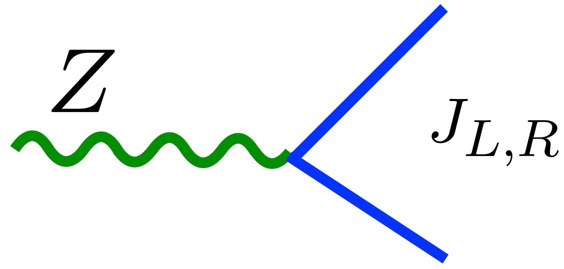
7 operators/couplings

$Z \; f_R f_R$

t, b, τ

$Z \; f_L f_L$

t, b, τ, ν



Example:

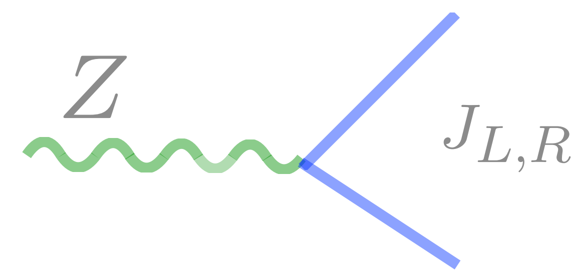
$$\mathcal{D}_{ZeL} = \left(1 + \frac{2h}{v} + \frac{h^2}{v^2}\right)\left[Z_\mu \; \bar{e}_L \gamma^\mu e_L - \frac{c_w}{\sqrt{2}} \; W_\mu^+ \; \bar{\nu}_L \gamma^\mu e_L + \text{h.c.}\right]$$

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)

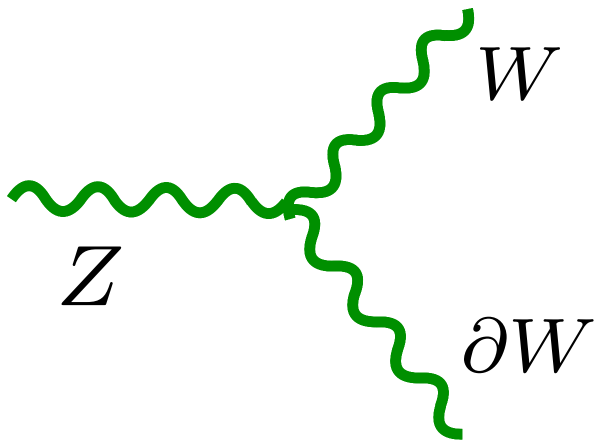
Example:

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

Higgs-TGC Operators

2 operators/couplings

g_Z^1

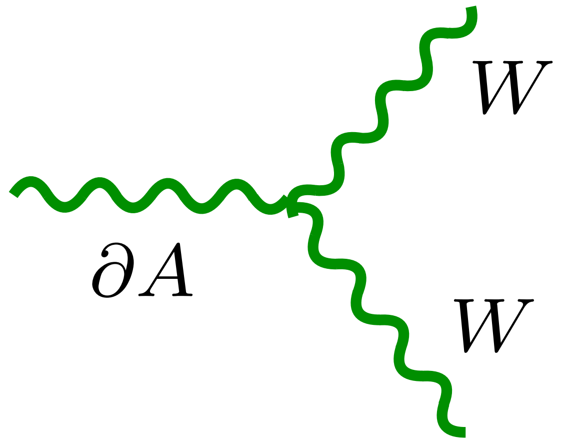


$$\mathcal{O}_B - \mathcal{O}_W = \frac{ig'}{2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)\partial^\nu B_{\mu\nu} - \frac{ig}{2}(\Phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \Phi) D^\nu \mathcal{W}^a_{\mu\nu}$$

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

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

κ_γ



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

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

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

Summary

vev

$$H = v + h$$

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

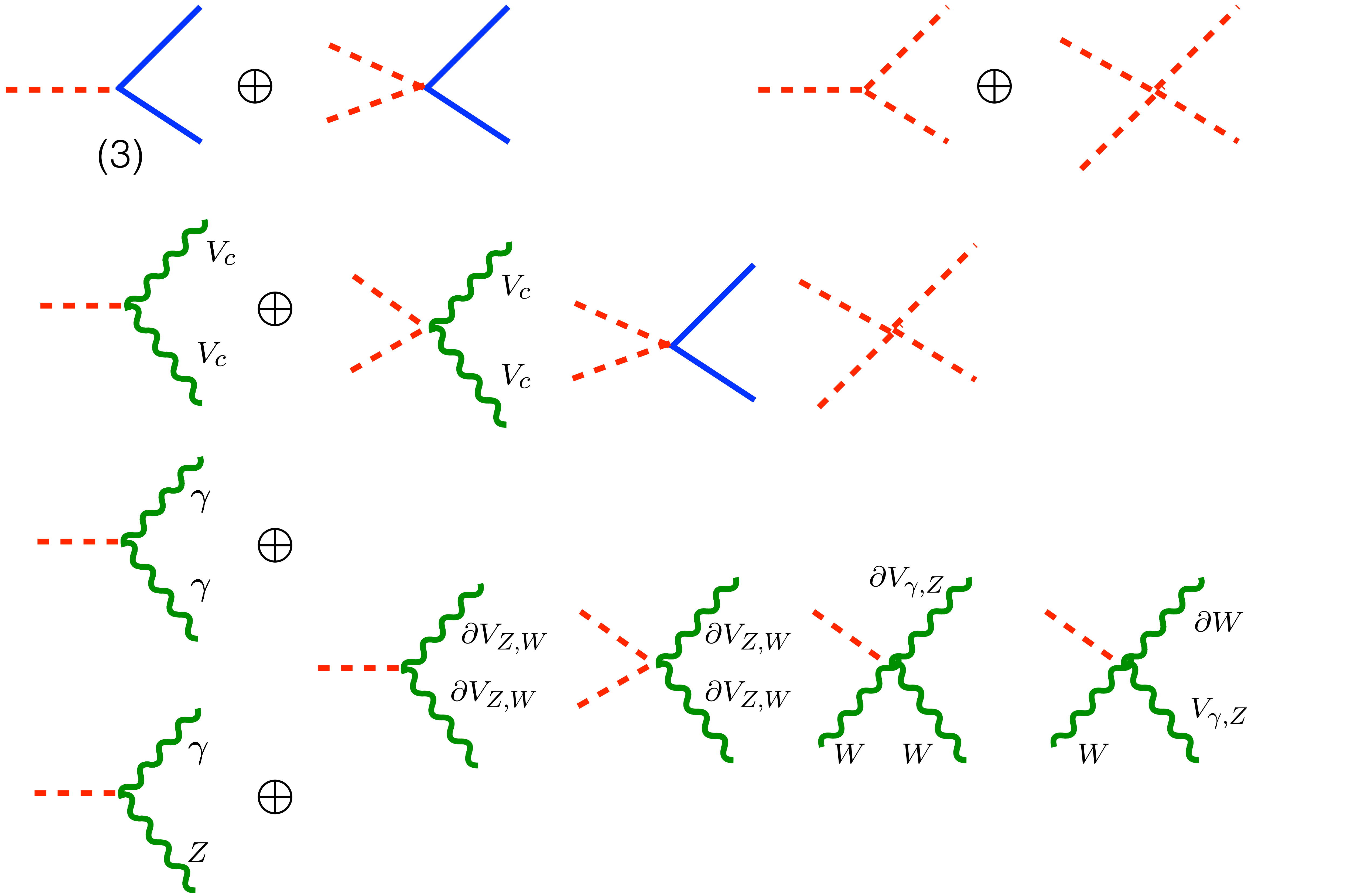
Directions

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

- I will show correlations schematicaly

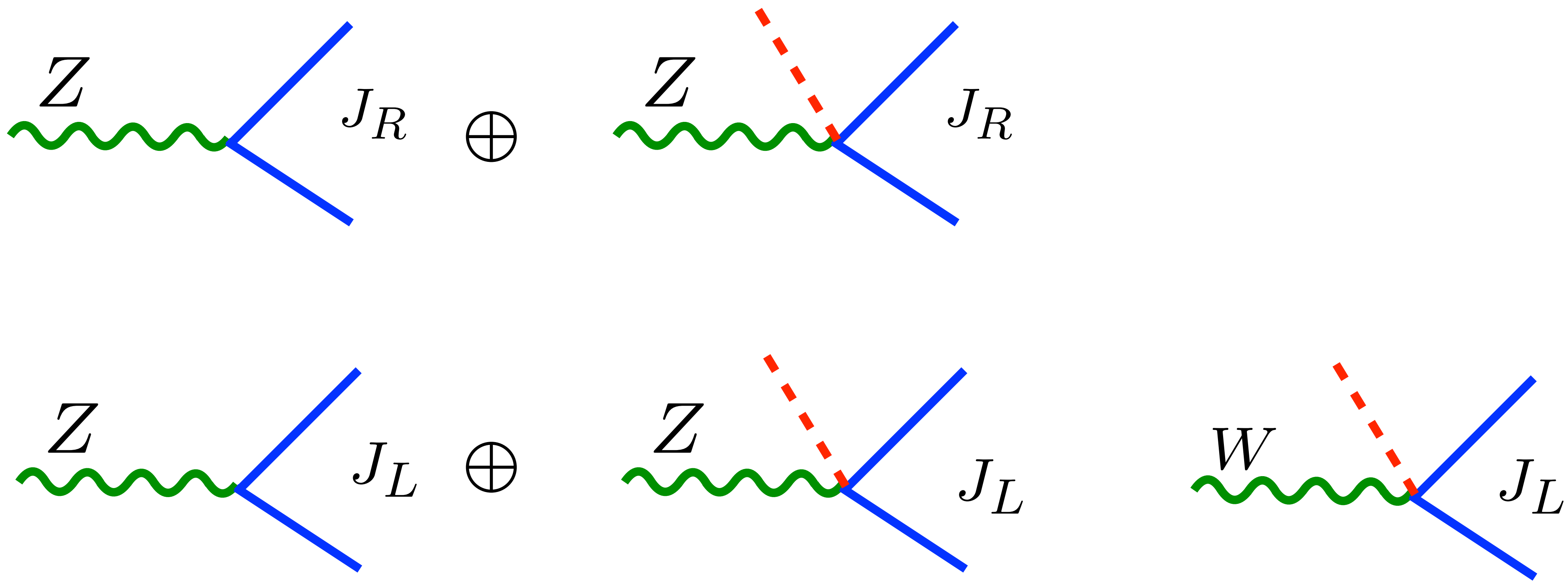
Exact expressions given
in EM 1406.6376

Higgs-only

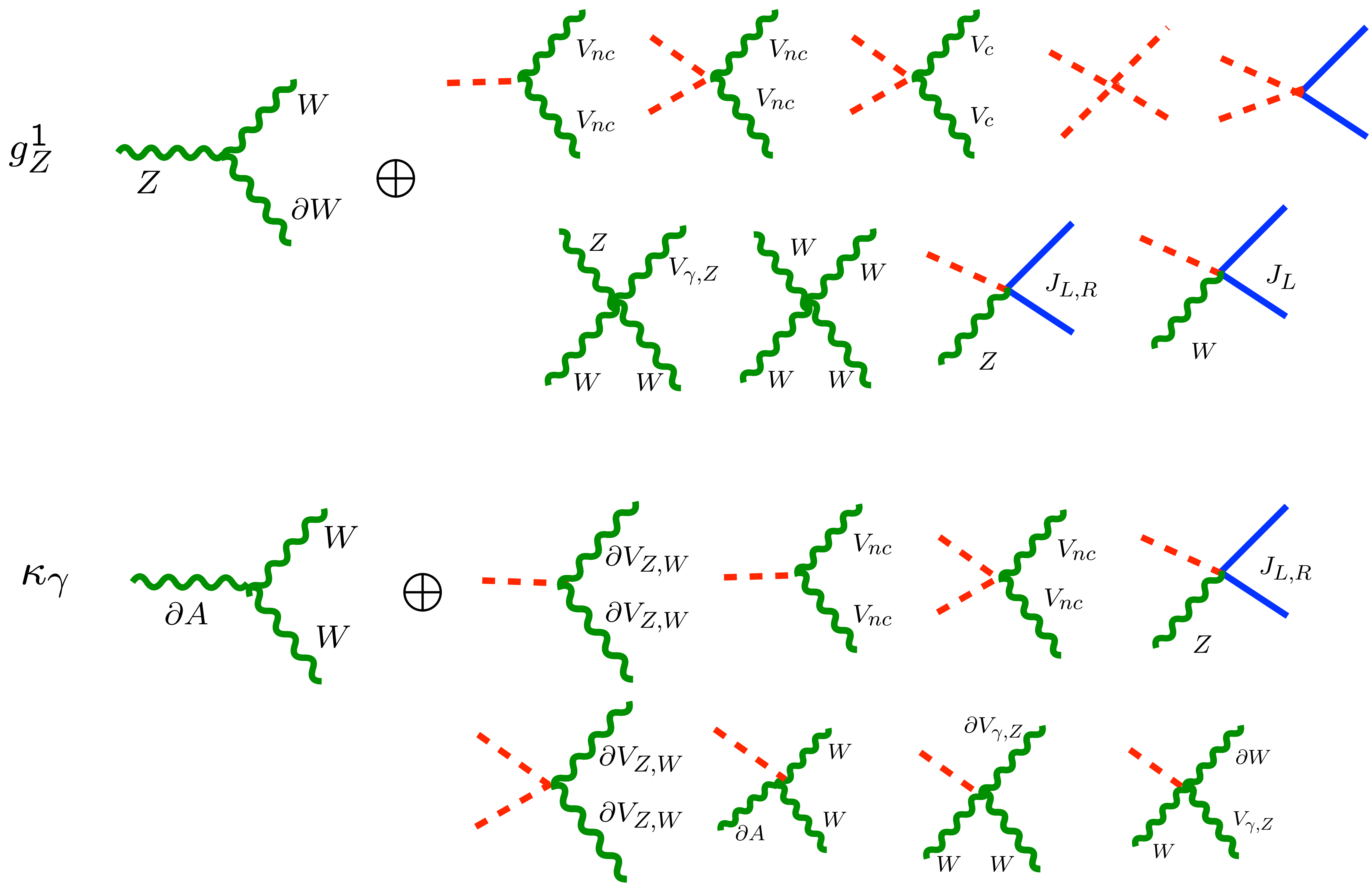


(3)
V_c
V_c
V_c
V_c
γ
γ
γ
Z
$\partial V_{Z,W}$
$\partial V_{Z,W}$
$\partial V_{Z,W}$
$\partial V_{Z,W}$
$\partial V_{\gamma,Z}$
W
W
∂W
$V_{\gamma,Z}$
W

Higgs-EWPT

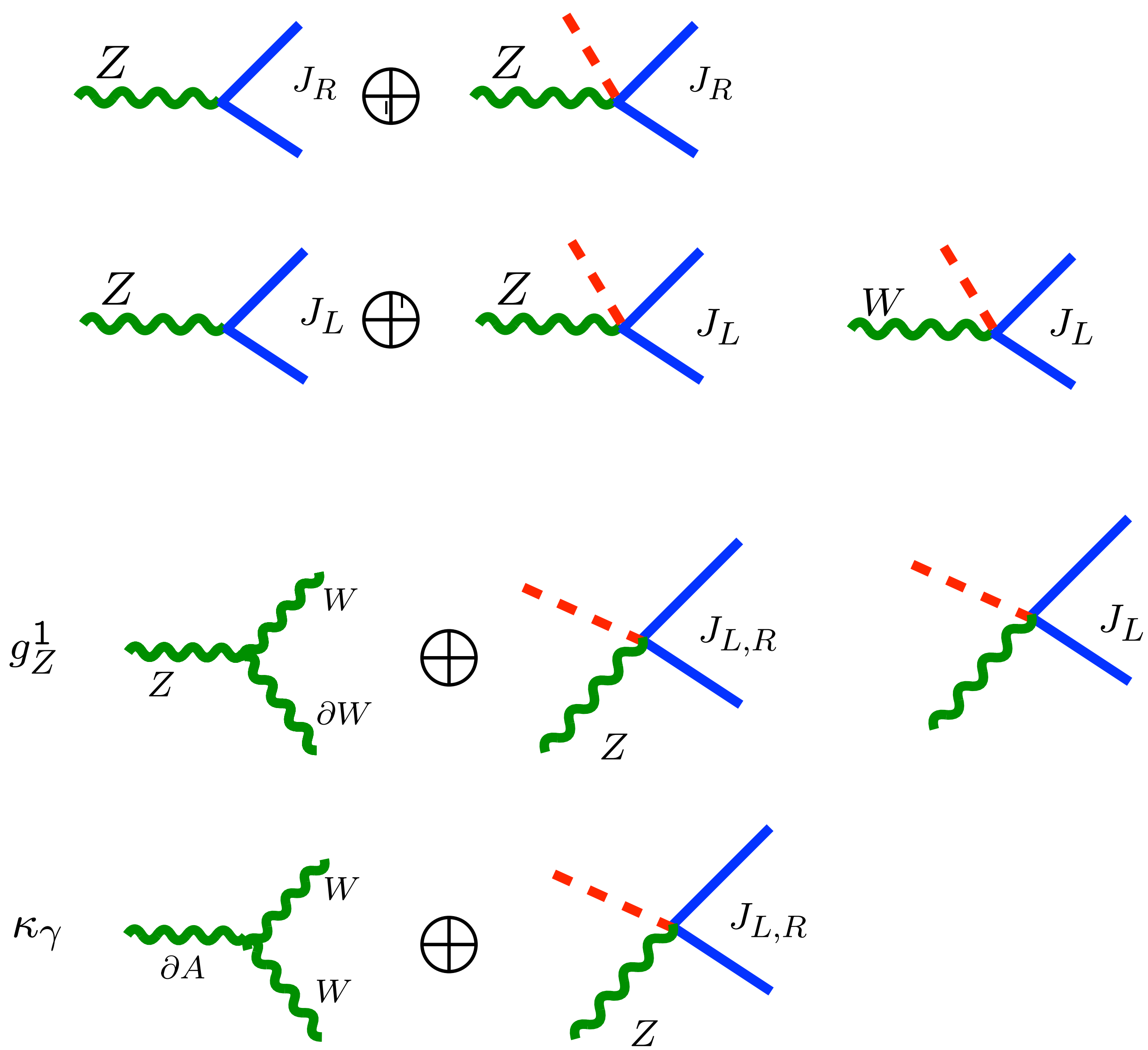


Higgs-TGC


g_Z^1
Z
W
∂W
$\oplus$
V_{nc}
V_{nc}
V_{nc}
V_{nc}
V_c
V_c
Z
$V_{\gamma,Z}$
W
W
W
W
W
W
$J_{L,R}$
Z
J_L
W
κ_γ
∂A
W
W
$\oplus$
$\partial V_{Z,W}$
$\partial V_{Z,W}$
V_{nc}
V_{nc}
V_{nc}
V_{nc}
$J_{L,R}$
Z
$\partial V_{Z,W}$
$\partial V_{Z,W}$
W
∂A
W
$\partial V_{\gamma,Z}$
W
W
∂W
$V_{\gamma,Z}$
W

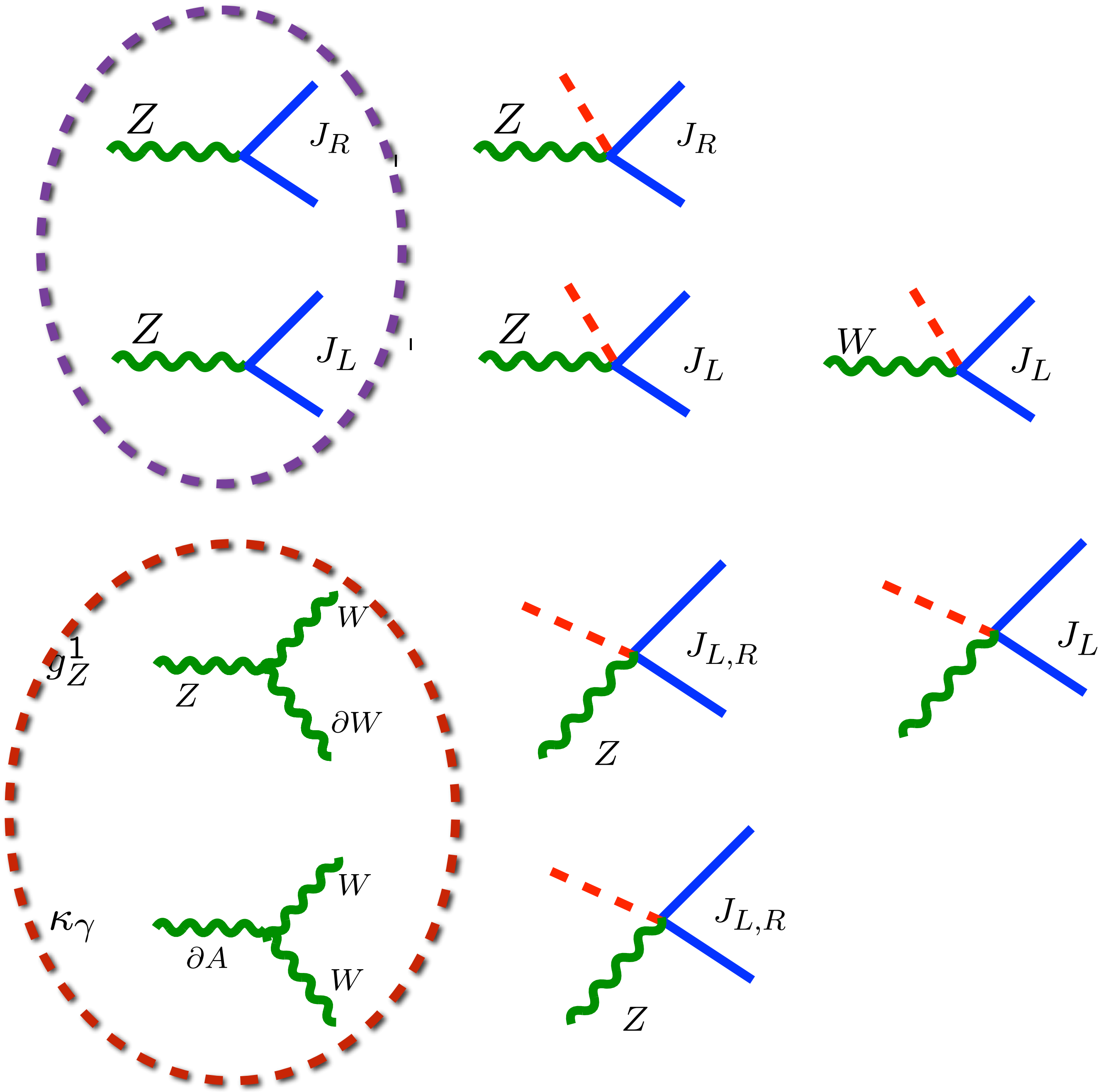
Example of Correlations

contact term $hV_\mu \bar{f}\gamma^\mu f$ $\qquad$ $h \to V f f$



Example of Correlations

contact term $hV_\mu \bar{f}\gamma^\mu f$ $\qquad h \to V f f$



per mille constraints

per cent constraints

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

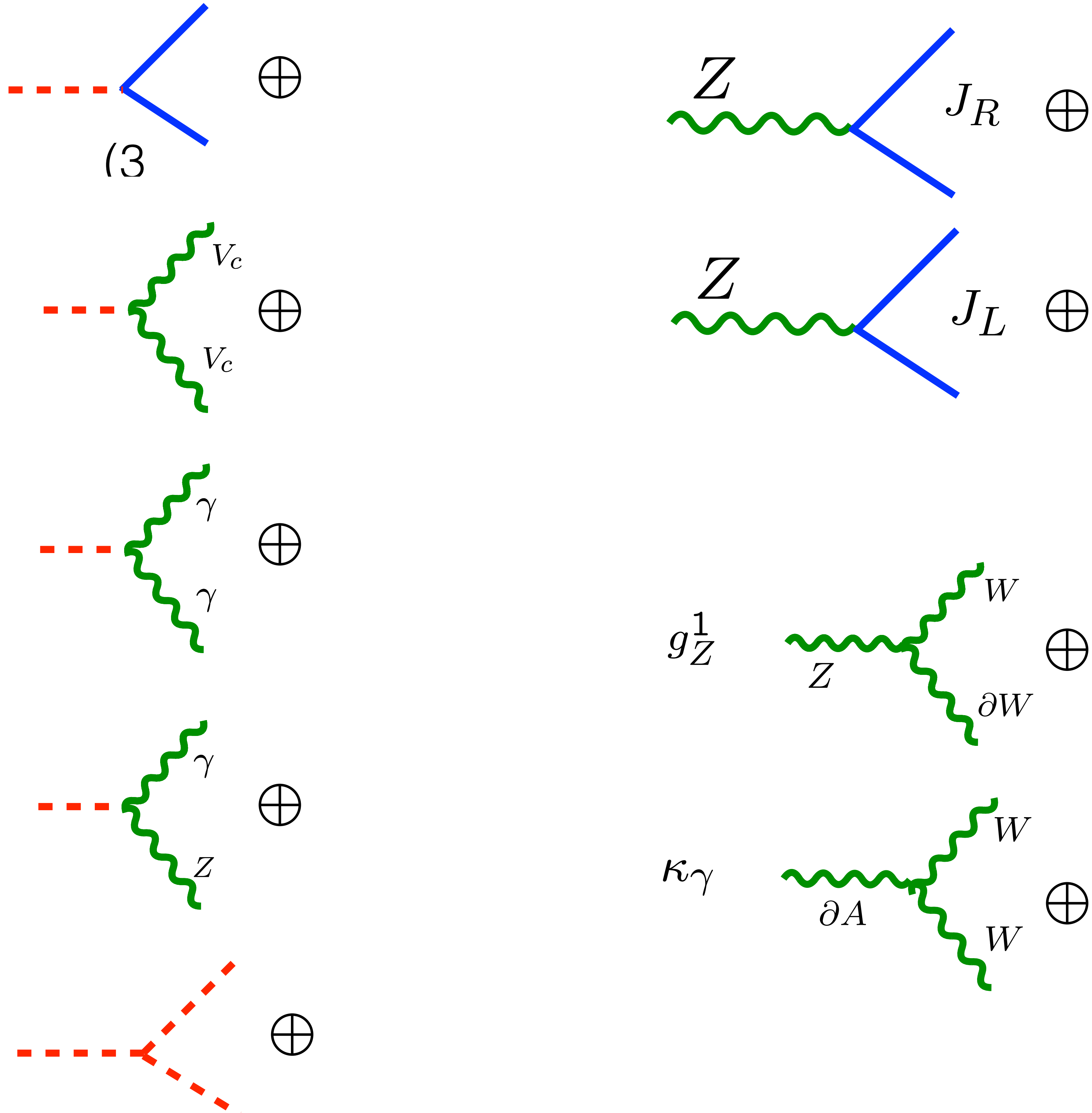
More Example of Correlations

- non custodial $V_\mu V^\mu$

$$V = W, Z$$

- form factor $V_{\mu\nu} V^{\mu\nu}$

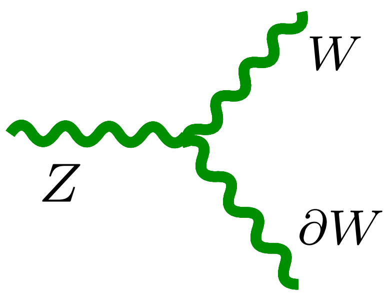
Example of NO Correlations



Example Correlations (not involving Higgs)

- from cubic to quartic

g_Z^1



$\oplus$