

What if $K_W \neq K_Z$?

– 0HDM (Zero Higgs Doublet Model) –

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Arxiv : 1410.xxxx

Work in progress in collaboration with H. Sugiyama (Maskawa Inst.)



SM (=1HDM)

Predictions of 1 Higgs doublet

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

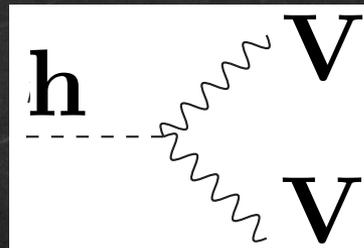
BEH mech.

$$M_W^2 = \frac{g^2}{4} v^2, M_Z^2 = \frac{g_Z^2}{4} v^2$$

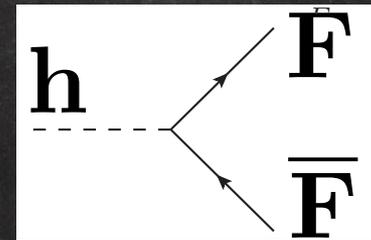
Fermion mass

$$M_F = Y_f \frac{v}{\sqrt{2}}$$

Higgs int. $v \rightarrow v+h$



$$\lambda_{hVV} = 2M_V^2/v$$



$$\lambda_{hF\bar{F}} = M_F/v$$

Non-minimal Higgs Sector ?

✓ SM Doublet + Singlet

Gauged B-L model

✓ SM Doublet + Doublet

SUSY Higgs Sector
2HDM

✓ SM Doublet + Triplet

Type-II seesaw for v

✓ SM Doublet + Septet

$\rho=1$ w/o custodial sym.

... 26-plet, 97-plet, ...

✓ SM Doublet + Doublets

Models based on flavor sym.

✓ SM Doublet + Triplets

Georgi-Machacek model
(Classical custodial sym.)

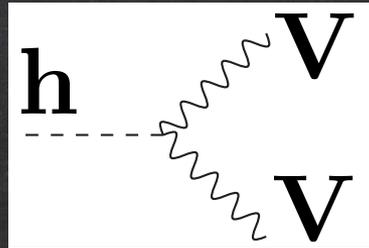
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SM + Singlet 1_0

- Singlet VEV does **not** contribute EWSB

(Electroweak Symmetry Breaking)

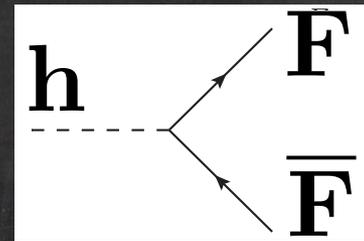
- Higgs-Mixing (h_{SM} -S) : **α**



$$\lambda_{hVV} = 2M_V^2/v$$

$$\times \cos \alpha$$

$$\equiv \kappa_V$$



$$\lambda_{hF\bar{F}} = M_F/v$$

$$\times \cos \alpha$$

$$\equiv \kappa_F$$

Higgs couplings are reduced by a factor **$\cos(\alpha)$**

SM + Doublet $2_{1/2}$

$$\tan \beta = v_2/v_1$$

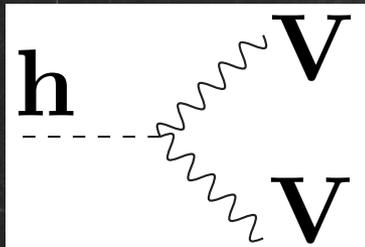
- Doublet VEV contributes EWSB (**VEV mixing**)

$$v^2 = v_1^2 + v_2^2$$

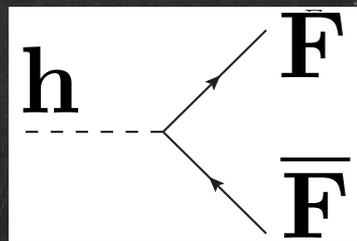
$$M_W^2 = \frac{g^2}{4}v^2, M_Z^2 = \frac{g_Z^2}{4}v^2$$

$$M_F = Y_f \frac{v_i}{\sqrt{2}} \quad (i = 1 \text{ and/or } 2)$$

- Higgs-Mixing (h_1 - h_2) : **α**



$$\kappa_V = \sin(\beta - \alpha)$$



$$\kappa_F = \sin(\beta - \alpha) - \xi \cos(\beta - \alpha)$$

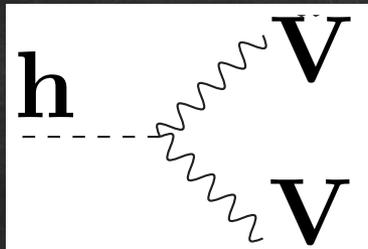
$$\xi = \begin{cases} \tan \beta \\ -\cot \beta \end{cases}$$

Higgs couplings depend on **α** and **β**

SM + Triplet 3_1

- Triplet VEV contributes EWSB differently

$$M_W^2 = \frac{g^2}{4}(v_2^2 + 2v_3^2), M_Z^2 = \frac{g_Z^2}{4}(v_2^2 + 4v_3^2)$$

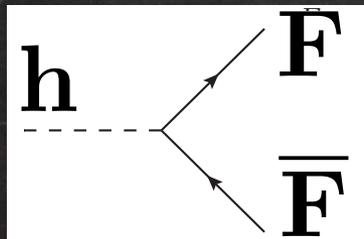


$$\kappa_V = \sin \beta_V \cos \alpha - \xi_V \cos \beta_V \sin \alpha$$

$$\xi_V = \begin{cases} \sqrt{2} & \text{for } W \\ 2 & \text{for } Z \end{cases}$$

$$\tan \beta_V = \frac{v_2}{\xi_V v_3}$$

$$(K_W \neq K_Z)$$



$$\kappa_F = \sin(\beta_W - \alpha) + \cot \beta_W \cos(\beta_W - \alpha)$$

Higgs couplings depend on α and β_V

SM + Triplet 3_1

- Triplet VEV contributes EWSB differently

$$M_W^2 = \frac{g^2}{4}(v_2^2 + 2v_3^2), \quad M_Z^2 = \frac{g_Z^2}{4}(v_2^2 + 4v_3^2)$$



$$\rho = \frac{M_W^2}{c_W^2 M_Z^2} \approx 1 - 2x^2, \quad x = \frac{v_3}{v_2}$$

VEV of exotic multiplet is constrained severely

$$\rho_{\text{exp}} = 1.0004^{+0.0003}_{-0.0004}$$

$$(K_W \approx K_Z)$$

SM + Triplets $3_1 + 3_0$

Georgi-Machacek Model
(Classical custodial sym.)

- Triplet VEVs contribute EWSB differently

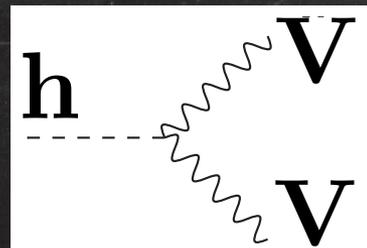
$$M_W^2 = \frac{g^2}{4}(v_2^2 + 2v_3^2), \quad M_Z^2 = \frac{g_Z^2}{4}(v_2^2 + 4v_3^2)$$

$$+2v_3'^2 \quad \downarrow \quad +0$$

$$\rho = \frac{M_W^2}{c_W^2 M_Z^2} = 1$$

VEV alignment

$$v_3 = v_3'$$



$$\kappa_V = \sin \beta \cos \alpha - 2\sqrt{2} \cos \beta \sin \alpha$$

κ_V can be as large as 1 (cf. septet)

$$K_W = K_Z$$

What we have learned?

- ✓ Higgs couplings are determined
by Higgs mixing α and VEV mixing β
- ✓ K_W and K_Z can be different
- ✓ VEV alignment accommodates “ $\rho = 1$ ” If so, $K_W = K_Z$

SM Doublet + something = “Extended” Higgs Sector

Can we predict $K_w \neq K_z$?

Non-minimal ~~Higgs Sector~~ ?

Standard Model

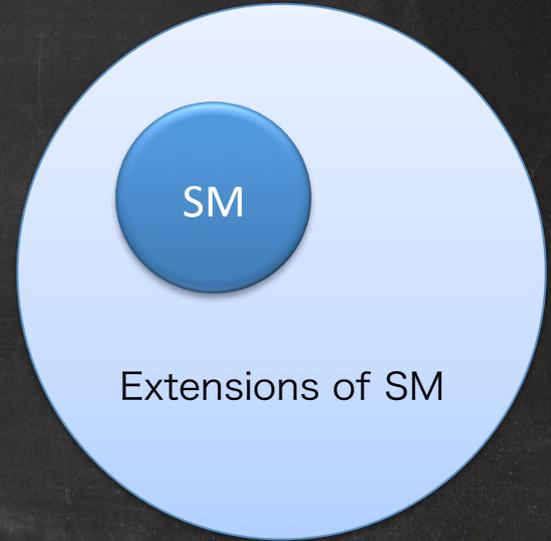
- ✓ SM Doublet + Singlet Gauged B-L model
- ✓ SM Doublet + Doublet SUSY Higgs Sector
2HDM
- ✓ SM Doublet + Triplet Type-II seesaw for ν
- ✓ SM Doublet + Septet $\rho=1$ w/o custodial sym.

... 26-plet, 97-plet, ...

- ✓ SM Doublet + Doublets Models based on flavor sym.
- ✓ SM Doublet + Triplets Georgi-Machacek model
(Classical custodial sym.)

...

~~SM Doublet~~ + "Higgs fields" = 0HDM



No SM limit



Rule of this Game

✓ No Higgs Doublet

- ✓ BEH mech. : Comb. of Higgs multiplets
(≥ 3 -plet is needed in order to break EW sym.)

Let's take **one 3-plet** (minimal)

- ✓ Fermion mass : Effective Higgs doublet ?



Without spoiling the success in the SM fermion sector

$$3 \otimes 4 = \boxed{2} \oplus 4 \oplus 6$$

Let's take **one 4-plet** (next minimal)

SM \ominus 2 \oplus 3 \oplus 4



EWSB Sector

Contrib. to M_V from $I_Y = \mathbf{3}_0, \mathbf{3}_1, \mathbf{4}_{1/2}, \mathbf{4}_{3/2}$ repr.

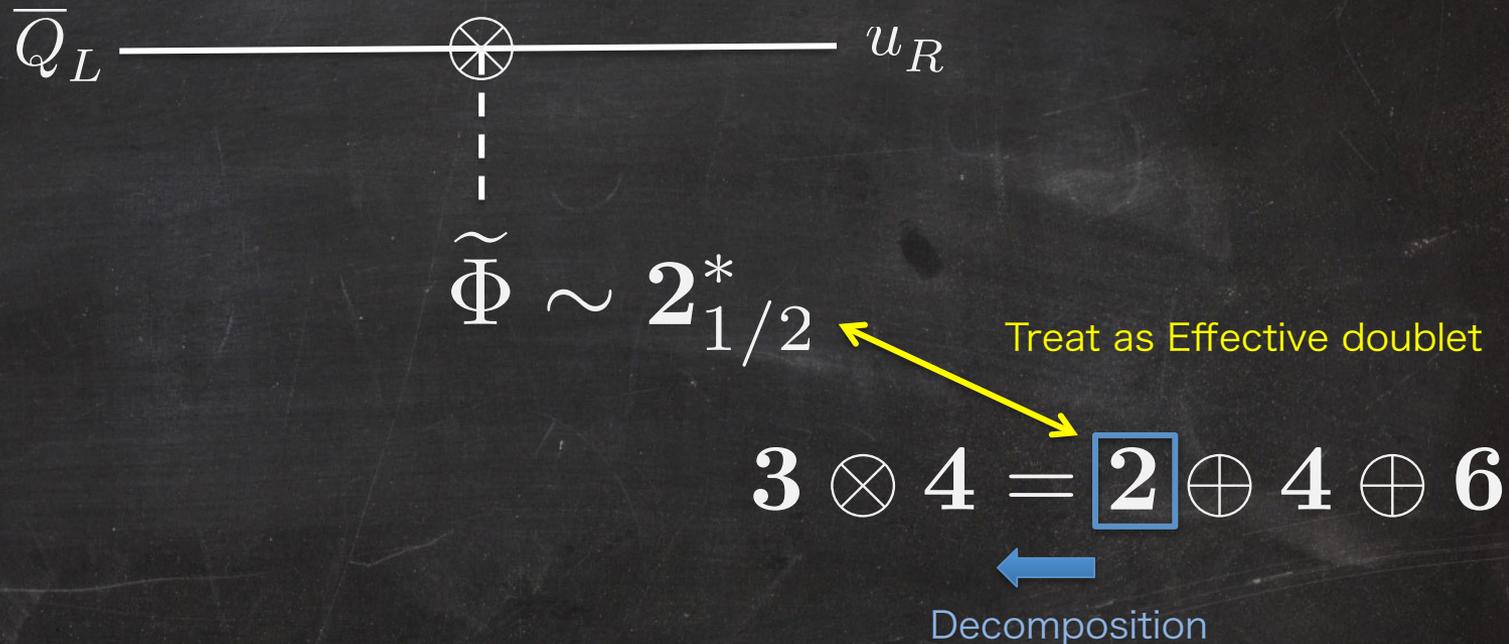
$$M_W^2 = g^2 \sum_{I,Y} [I(I+1) - Y^2] \frac{g^2}{4} v_{I,Y}^2, \quad M_Z^2 = g_Z^2 \sum_{I,Y} 2Y^2 v_{I,Y}^2$$

$\rho = \frac{M_W^2}{c_W^2 M_Z^2}$	$\mathbf{4}_{1/2}$	$\mathbf{4}_{3/2}$	
$\mathbf{3}_0$	$7 + 4x^2 \geq 7$	\times	$x = \frac{v_3}{v_4}$ Massless Fermions (mismatch of Y)
$\mathbf{3}_1$	$\frac{7 + 2x^2}{1 + 4x^2}$	$\frac{3 + 2x^2}{9 + 4x^2} \leq \frac{1}{2}$	

$\rho=1$ is realized if $x = \sqrt{3}$ ($v_3 \simeq 118\text{GeV}, v_4 \simeq 68\text{GeV}$)

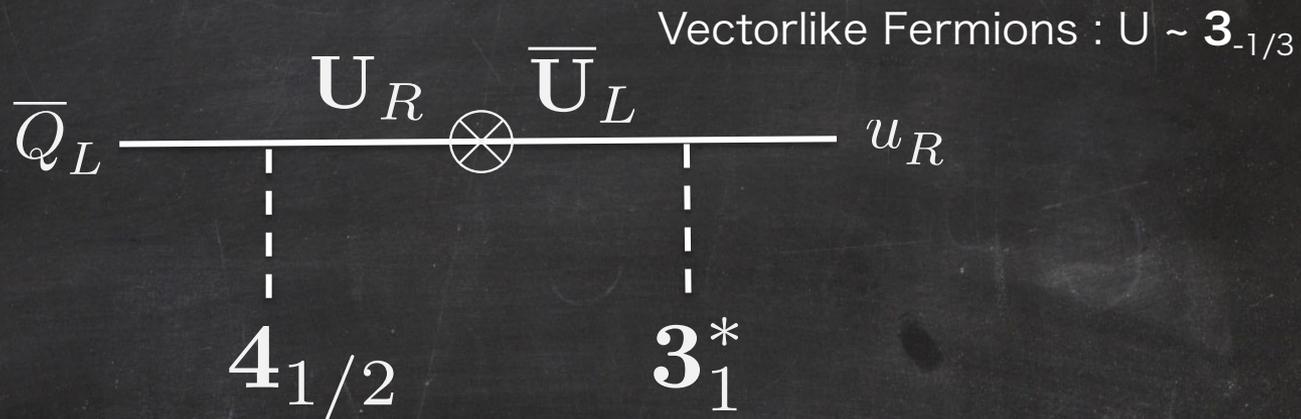
Fermion Mass Generation

The effective Yukawa int.



Fermion Mass Generation

The effective Yukawa int.



$$M_u = N_U \frac{y_3 y_4 v_3 v_4}{2M_U}$$

$$\mathbf{3} \otimes \mathbf{4} = \mathbf{2} \oplus \mathbf{4} \oplus \mathbf{6}$$

← Decomposition

Note 1 : $M_U \geq 700$ GeV

Note 2 : $\mathbf{3} \leftrightarrow \mathbf{4}$, then $U \sim \mathbf{4}$

Neutrino Mass

Type-II Seesaw mechanism



Higgs Coupling

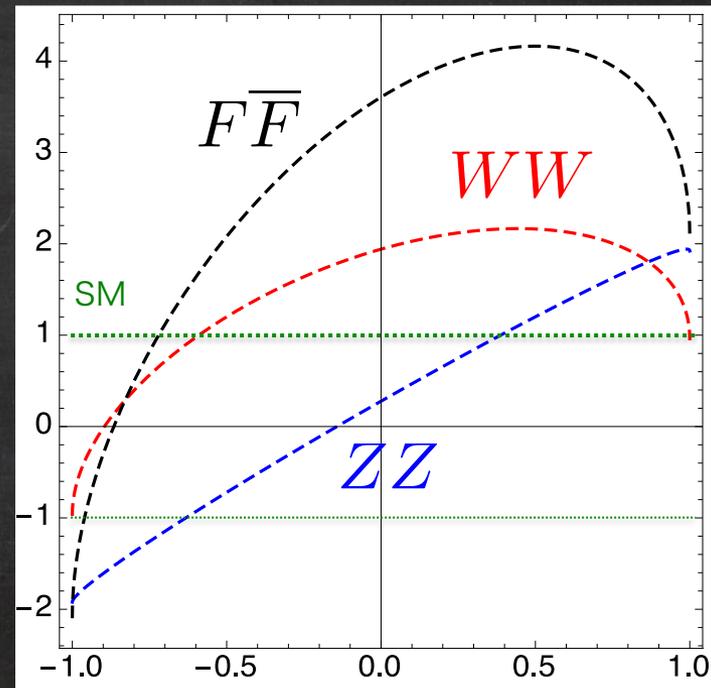
VEV mixing : $v_3/v_4=\sqrt{3}$ Higgs mixing (h_3-h_4) : Θ_0

κ_X

$$\kappa_W = \frac{1}{\sqrt{13}}(2\sqrt{3} \cos \theta_0 + 7 \sin \theta_0)$$

$$\kappa_Z = \frac{1}{\sqrt{13}}(4\sqrt{3} \cos \theta_0 + \sin \theta_0)$$

$$\kappa_F = \sqrt{13}\left(\frac{1}{\sqrt{3}} \cos \theta_0 + \sin \theta_0\right)$$



$\cos \theta_0$

Signal strength

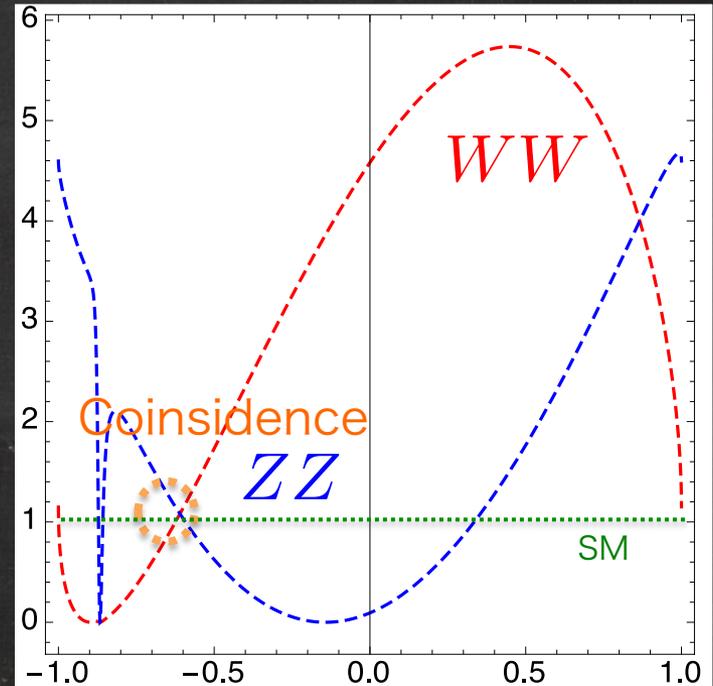
$gg \rightarrow h, h \rightarrow VV$ ($V=W,Z$)

$$\mu_{WW} \simeq \frac{\kappa_F^2 \kappa_W^2}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2} \quad \mu_{XX}$$

$$\mu_{ZZ} \simeq \frac{\kappa_F^2 \kappa_Z^2}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2}$$

$H \rightarrow ZZ^* \rightarrow 4l$	+0.35 -0.32 +0.20 -0.13 +0.17 -0.10		
$\mu = 1.44^{+0.40}_{-0.35}$			
$H \rightarrow WW^* \rightarrow l\nu$	+0.21 -0.21 +0.24 -0.19 +0.16 -0.08		
$\mu = 1.00^{+0.32}_{-0.29}$			

$H \rightarrow WW$ tagged	$\mu = 0.83 \pm 0.21$
$H \rightarrow ZZ$ tagged	$\mu = 1.00 \pm 0.29$



$\gamma\gamma$ is less predictive because of ambiguity in the Higgs potential

$\cos \theta_0$

Signal strength

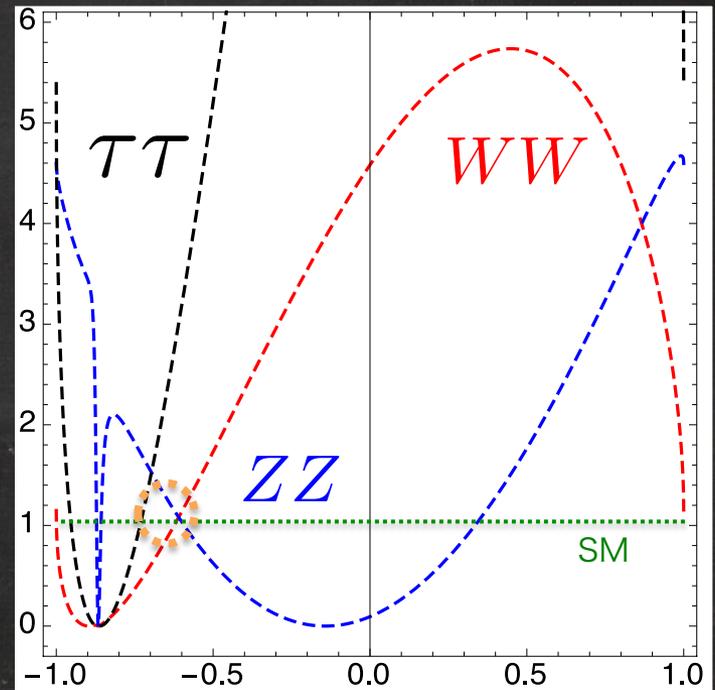
$gg \rightarrow h, h \rightarrow VV$ ($V=W,Z$)

$$\mu_{WW} \simeq \frac{\kappa_F^2 \kappa_W^2}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2} \quad \mu_{XX}$$

$$\mu_{ZZ} \simeq \frac{\kappa_F^2 \kappa_Z^2}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2}$$

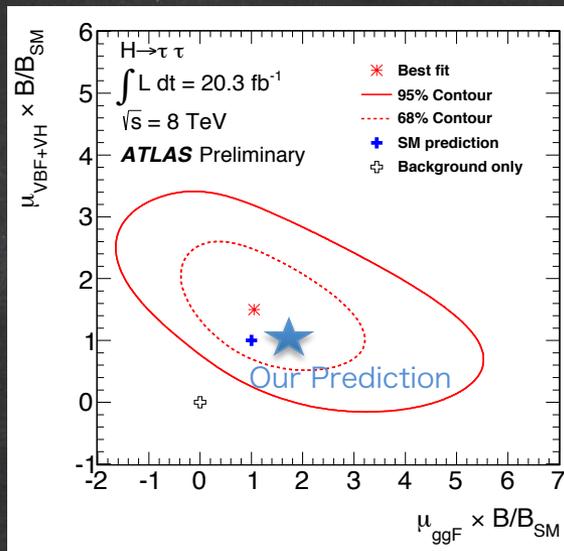
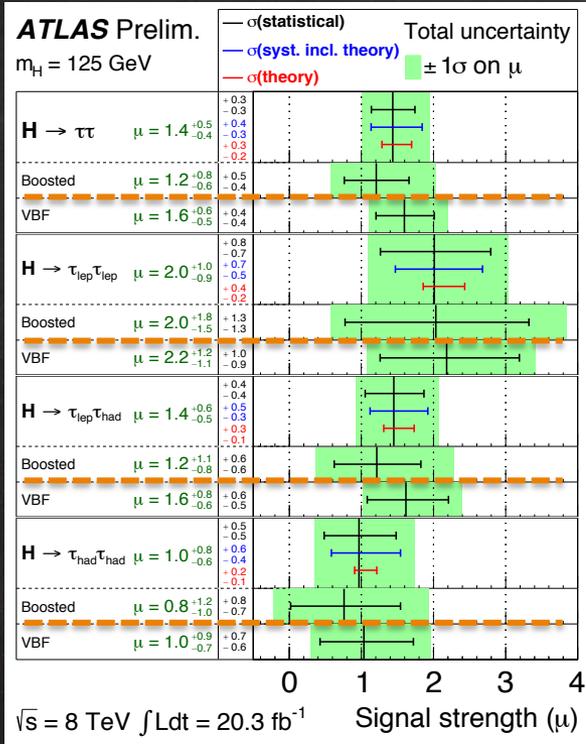
$gg \rightarrow h, h \rightarrow \tau\tau$

$$\mu_{\tau\tau} \simeq \frac{\kappa_F^4}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2}$$



$\cos \theta_0$

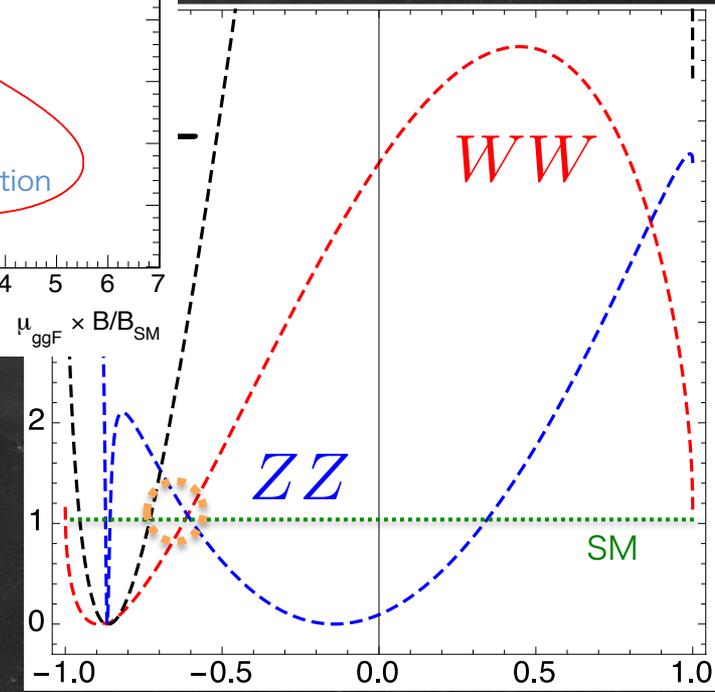
Signal strength



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$$gg \rightarrow h, h \rightarrow \tau\tau$$

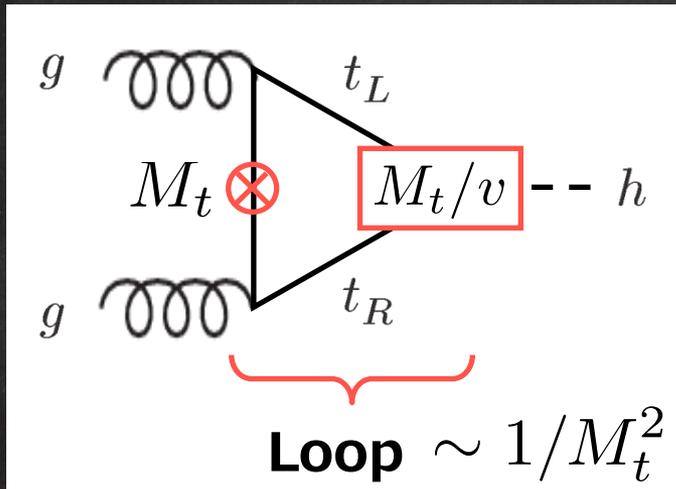
$$\mu_{\tau\tau} \approx \frac{\kappa_F^4}{(3/4)\kappa_F^2 + (1/4)\kappa_W^2}$$



$$\cos \theta_0$$

Decoupling

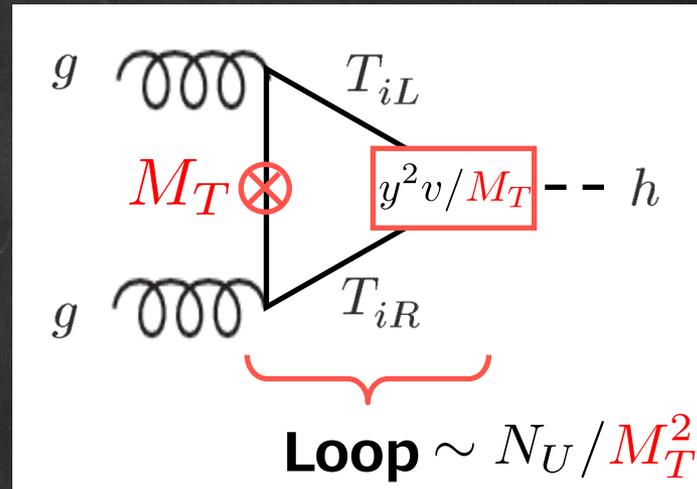
Top-loop $M_t \sim \frac{N_U y^2 v^2}{M_U}$



$$M_t \times \frac{M_t}{v} \times \frac{1}{M_t^2} \sim \frac{1}{v}$$

Non-decoupling for $M_t \rightarrow \infty$

Vector-Fermion-loop $M_T \sim M_U$

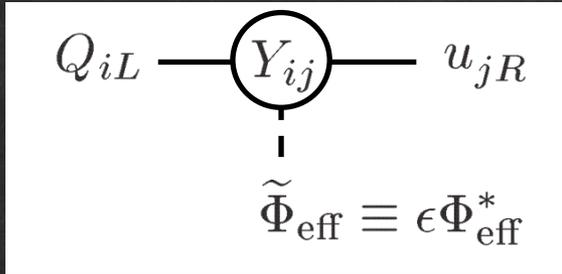


$$M_T \times \frac{y^2 v}{M_T} \times \frac{N_U}{M_T^2} \sim \frac{1}{v} \frac{M_t}{M_T} \rightarrow 0$$

Decoupling for $M_T \rightarrow \infty$

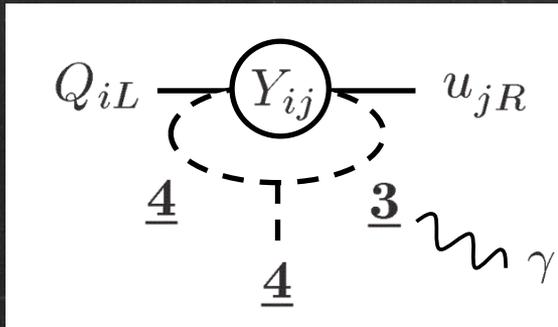
Flavor Changing Neutral Current

Tree level

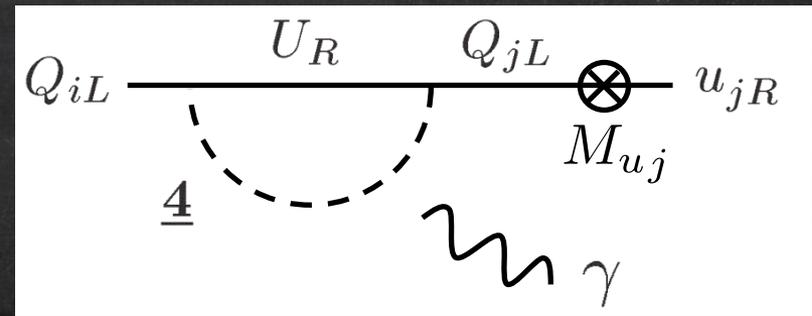


Diagonalized Simultaneously
with Mass Matrix
(Similar to the SM case)

Loop level



Diagonalized



Decoupling $\sim \frac{M_{uj}}{M_U^2} \rightarrow 0$

Summary

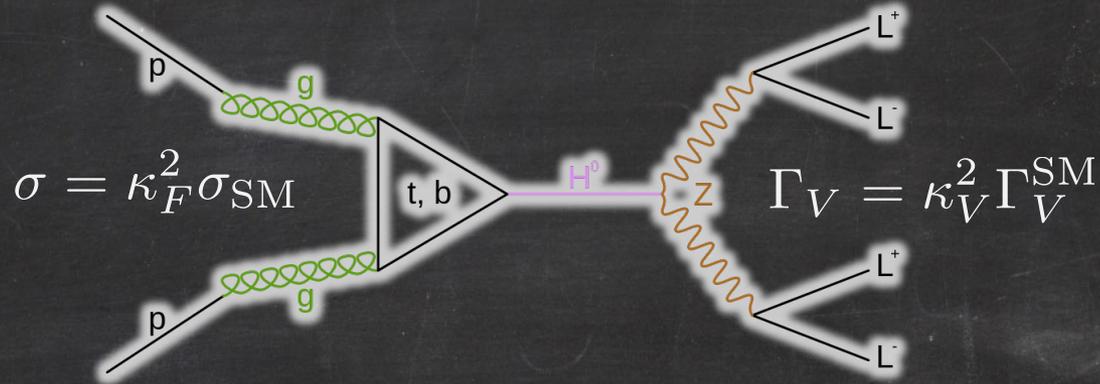
✓ SM-like Higgs boson can be realized **without Higgs doublet**

$$\text{OHDM}_{(\text{Minimal})} = 3\text{plet} + 4\text{plet} \quad (K_W \neq K_Z)$$

One has to pay the Price

- $\rho = 1$ VEV alignment
- M_F Vectorlike fermions
- K_X Higgs mixing

Relation between μ and Higgs Couplings



$$\mu \equiv \frac{\sigma \times \mathcal{B}}{\sigma_{SM} \times \mathcal{B}_{SM}} \simeq \frac{\kappa_F^2 \kappa_V^2}{(3/4)\kappa_F^2 + (1/4)\kappa_V^2}$$

$$\mathcal{B}_V \equiv \frac{\Gamma_V}{\Gamma_{tot}} = \frac{\kappa_V^2 \Gamma_V^{SM}}{\kappa_F^2 \Gamma_F^{SM} + \kappa_V^2 \Gamma_V^{SM}} = \frac{\kappa_V^2 \mathcal{B}_V^{SM}}{\kappa_F^2 \mathcal{B}_F^{SM} + \kappa_V^2 \mathcal{B}_V^{SM}}$$

Note : fermionic (& gluonic via Yukawa) decay dominate (~75%)

Relation between μ and Higgs Couplings

Production	Decay	LO SM
VH	$H \rightarrow bb$	$\sim (K_V^2 \times K_F^2) / (3/4 K_F^2 + 1/4 K_V^2)$
ttH	$H \rightarrow bb$	$\sim (K_F^2 \times K_F^2) / (3/4 K_F^2 + 1/4 K_V^2)$
VBF/VH	$H \rightarrow \tau\tau$	$\sim (K_V^2 \times K_F^2) / (3/4 K_F^2 + 1/4 K_V^2)$
ggH	$H \rightarrow \tau\tau$	$\sim (K_F^2 \times K_F^2) / (3/4 K_F^2 + 1/4 K_V^2)$
ggH	$H \rightarrow zz$	$\sim (K_F^2 \times K_V^2) / (3/4 K_F^2 + 1/4 K_V^2)$
ggH	$H \rightarrow ww$	$\sim (K_F^2 \times K_V^2) / (3/4 K_F^2 + 1/4 K_V^2)$
VBF/VH	$H \rightarrow ww$	$\sim (K_V^2 \times K_V^2) / (3/4 K_F^2 + 1/4 K_V^2)$
ggH	$H \rightarrow \gamma\gamma$	$\sim K_F^2 (8.6 K_V - 1.8 K_F + \text{Scalar})^2 / (3/4 K_F^2 + 1/4 K_V^2)$
VBF	$H \rightarrow \gamma\gamma$	$\sim K_V^2 (8.6 K_V - 1.8 K_F + \text{Scalar})^2 / (3/4 K_F^2 + 1/4 K_V^2)$

Need to be fixed scalar sector