New Physics Scale from Higgs Observables with Effective Dimension-6 Operators

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Goals

- Can we infer the scale of new physics from the current or future measurements of the Higgs observable at the LHC? How ?

  ** **Approach** : New physics at a scale M will appear as effective higher dimensional operator suppressed by suitable powers of M.

  - Introduce a new set of effective dimension-6 operators most relevant for Higgs observables.
  - Study the constraints imposed on this operators and new physics scale from the measured Higgs observables at the LHC.

Outline of Talk

- Brief Introduction
- Formalism
- Analysis of the Higgs observable for LHC measurements using effective dimension 6 operators
- Limits and predictions on the $t\bar{t}h$ and hh production cross-sections from the LHC data.
- Conclusions

Brief Introduction

- If there is new physics beyond the SM, it will manifest as effective interactions with a new mass scale.
- Simplest operators for new physics for Higgs observable are of dimension-6
- These operators arise in the Yukawa sector, EW gauge sector, strong sector, as well as the Higgs potential.

Brief Introduction

- We need to make judicious choice which are the most relevant for altering Higgs physics observables.

1. **Q1 :** After we have used the constraints, can be the $t\bar{t}h$ production be sufficiently enhanced or suppressed compare to SM predictions?

2. **Q2 :** Can the double-Higgs production be enhanced sufficiently to be observed in run II of LHC?

Formalism :

- Relevant Dimension-6 operators we use:
  - **EW Yukawa sector**:

$$\mathcal{L}^{(6)}_{Yuk} \supset \frac{y_t^{(6)}}{M^2}(\bar{t}_L, \bar{b}_L) t_R \tilde{H}(H^\dagger H) + \frac{y_b^{(6)}}{M^2}(\bar{t}_L, \bar{b}_L) b_R H(H^\dagger H) + \frac{y_\tau^{(6)}}{M^2}(\bar{\nu}_\tau, \bar{\tau}_L)\tau_R H(H^\dagger H) + h.c. \quad (1)$$

  - **Strong sector**:

$$\mathcal{L}^{(6)}_{Strong} \supset \frac{g^{(6)}}{M^2} G^{\mu\nu a} G_{\mu\nu a}(H^\dagger H) \quad (2)$$

Formalism :

- **EW gauge sector**:

$$\mathcal{L}^{(6)}_{EWgauge} \supset \frac{y_g^{(6)}}{M^2}(D^\mu H)^\dagger (D_\mu H)(H^\dagger H) \tag{3}$$

- **Scalar Potential**:

$$\mathcal{L}^{(6)}_{Scalar} \supset \frac{\lambda^{(6)}}{M^2}(H^\dagger H)^3 \tag{4}$$

- The relevant parameters in our analysis :

$$\left\{ y_t^{(6)},\ \ y_b^{(6)},\ \ y_g^{(6)},\ \ g^{(6)},\ \ \lambda^{(6)},\ \ M \right\} \tag{5}$$

Formalism :

- The operator $\mathcal{L}^{(6)}_{EWgauge}$ modifies the Higgs kinetic term $\frac{1}{2}\partial^\mu h \partial_\mu h$ to $\left(1 + \frac{y_g^{(6)} v^2}{2M^2}\right) \frac{1}{2}\partial^\mu h \partial_\mu h$. (Throughout our analysis, we use the convention $H = \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$ in unitary gauge).

- Hence, we need to redefine the Higgs field by dividing out with the factor $N = \left(1 + \frac{y_g^{(6)} v^2}{2M^2}\right)^{1/2}$ to get the canonically normalized form for the kinetic term $\frac{1}{2}\partial^\mu h \partial_\mu h$.

Formalism :

- This modifies the Higgs coupling to the SM by suitable factor, such as :

$$
\begin{aligned}
\kappa_V &= \left[\frac{1}{N^2} + \frac{y_g^{(6)} v^2}{M^2 N^4}\right], \\
\kappa_t &= \left[\frac{1}{N} + \frac{y_t^{(6)} v^3}{\sqrt{2} m_t M^2 N^3}\right], \\
\kappa_b &= \left[\frac{1}{N} + \frac{y_b^{(6)} v^3}{\sqrt{2} m_b M^2 N^3}\right], \\
\kappa_\tau &= \left[\frac{1}{N} + \frac{y_\tau^{(6)} v^3}{\sqrt{2} m_\tau M^2 N^3}\right], \\
\kappa_g &= \left[1.034\kappa_t + \epsilon_b \kappa_b + \frac{4\pi g^{(6)} v^2}{\alpha_s N^2 M^2}\right] / \left[1.034 + \epsilon_b\right], \\
\kappa_{\gamma\gamma} &= \left|\frac{\frac{4}{3}\kappa_t F_{1/2}(m_h) + \kappa_V F_1(m_h)}{\frac{4}{3} F_{1/2}(m_h) + F_1(m_h)}\right|, \\
\kappa_{Z\gamma} &= \left|\frac{\frac{2}{\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right)\kappa_t F_{1/2}(m_h) + \kappa_V F_1(m_h)}{\frac{2}{\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right) F_{1/2}(m_h) + F_1(m_h)}\right|
\end{aligned}
$$

Phenomenological analysis :

- We use the results for 36 fb^{-1} data for Higgs observable for the LHC.

- Parameter space we use

$$\left\{ y_t^{(6)},\ \ y_b^{(6)},\ \ y_g^{(6)},\ \ g^{(6)},\ \ \lambda^{(6)},\ \ M \right\} \tag{6}$$

- The signal strength μ, defined as the ratio of the measured Higgs boson rate to its SM prediction, is used to characterize the Higgs boson yields and it is given by :

$$\mu_f^i = \frac{\sigma^i \cdot BR_f}{(\sigma^i)_{SM} \cdot (BR_f)_{SM}} = \mu^i \cdot \mu_f . \tag{7}$$

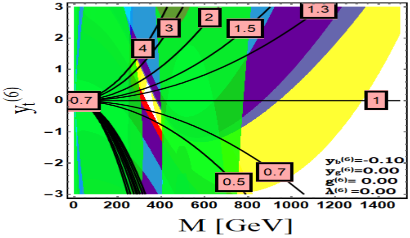
Signal Strength Constraints on Higgs Observables at LHC

Decay channel	Production Mode	CMS	ATLAS
$\gamma\gamma$	*ggF*	$1.05^{+0.19}_{-0.19}$	$0.80^{+0.19}_{-0.18}$
	VBF	$0.6^{+0.6}_{-0.5}$	$2.1^{+0.6}_{-0.6}$
	Wh	$3.1^{+1.50}_{-1.30}$	$0.7^{+0.9}_{-0.8}$
	Zh	$0.0^{+0.9}_{-0.0}$	$0.7^{+0.9}_{-0.8}$
$ZZ^\star$	*ggF*	$1.20^{+0.22}_{-0.21}$	$1.11^{+0.23}_{-0.27}$
	VBF	$0.05^{+1.03}_{-0.05}$	$4.0^{+2.1}_{-1.8}$
	Wh	$0.0^{+2.66}_{-0.00}$	< 3.8
	Zh	$0.0^{+2.66}_{-0.00}$	< 3.8
W^+W^-	*ggF*	$0.9^{+0.40}_{-0.30}$	$1.02^{+0.29}_{-0.26}$
	VBF	$1.4^{+0.8}_{-0.8}$	$1.7^{+1.1}_{-0.9}$
	Vh	$2.1^{+2.3}_{-2.2}$	$3.2^{+4.4}_{-4.2}$
	$ggF + VBF + Vh$	$1.05^{+0.26}_{-0.26}$	-
$b\bar{b}$	*Vh*	$1.0^{+0.5}_{-0.5}$	$0.9^{+0.28}_{-0.26}$
$\tau^+\tau^-$	*ggF*	$1.05^{+0.49}_{-0.46}$	$2.0^{+0.8}_{-0.8}$
	$VBF + Vh$	$1.07^{+0.45}_{-0.43}$	$1.24^{+0.58}_{-0.54}$
	$ggF + VBF + Vh$	$1.06^{+0.25}_{-0.24}$	$1.43^{+0.43}_{-0.37}$

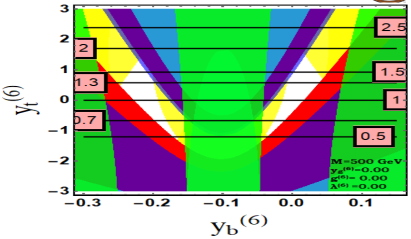
Analysis strategy:

- Effect of the Yukawa sector only, then add Yukawa plus EW gauge, then add strong, and finally add Higgs potential.
- : Yukawa sector only
  - Top $y_t^{(6)}$ and bottom Yukawa $y_b^{(6)}$ play key roles.
  - $y_t^{(6)} \Rightarrow$ Single Higgs production
  - $y_b^{(6)} \Rightarrow h \rightarrow b\bar{b}$ decay
- We include effect on all the Higgs observables.

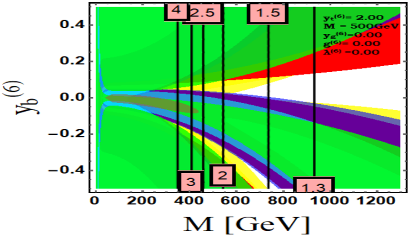
Results :



$y_t^{(6)}$
M [GeV]
$y_b^{(6)}$=-0.10
$y_g^{(6)}$=0.00
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00



$y_t^{(6)}$
$y_b^{(6)}$
M=500 GeV
$y_g^{(6)}$=0.00
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00

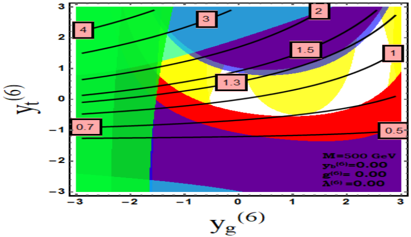


$y_b^{(6)}$
M [GeV]
$y_t^{(6)}$= 2.00
M = 500GeV
$y_g^{(6)}$=0.00
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00

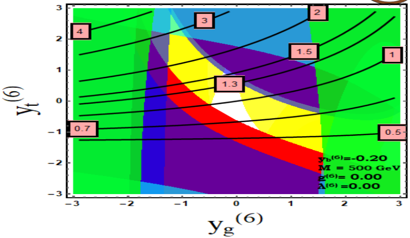
Analysis strategy:

- **Add the Effect from the EW gauge sector**
- Its impact is less than the dimension 6 Yukawa couplings.
- Because it plays lesser role in single Higgs production in ggF.
- It does modify $h \to WW, ZZ$ in a significant way.
- As $y_b^{(6)}$ gets larger values to enhance $h \to b\bar{b}$, $y_g^{(6)}$ has to get larger to satisfy the Higgs constraints.

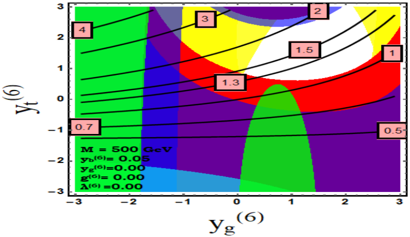
Results :



M=500 GeV
$y_b^{(6)}$=0.00
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00
4
3
2
1.5
1
1.3
0.7
0.5
$y_t^{(6)}$
$y_g^{(6)}$



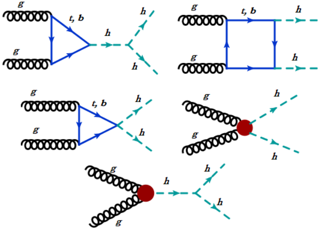
$y_b^{(6)}$=-0.20
M = 500 GeV
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00
4
3
2
1.5
1
1.3
0.7
0.5
$y_t^{(6)}$
$y_g^{(6)}$



M = 500 GeV
$y_b^{(6)}$= 0.05
$y_g^{(6)}$=0.00
$g^{(6)}$= 0.00
$\lambda^{(6)}$ =0.00
4
3
2
1.5
1
1.3
0.7
0.5
$y_t^{(6)}$
$y_g^{(6)}$

Analysis strategy:

- **Add the effect from the strong sector. Consider bothtin dividual and combined**
- Major effect ⇒ On single Higgs and di-Higgs productions
- With this, the diagram contributing to di-Higgs production is shown in following Figs.



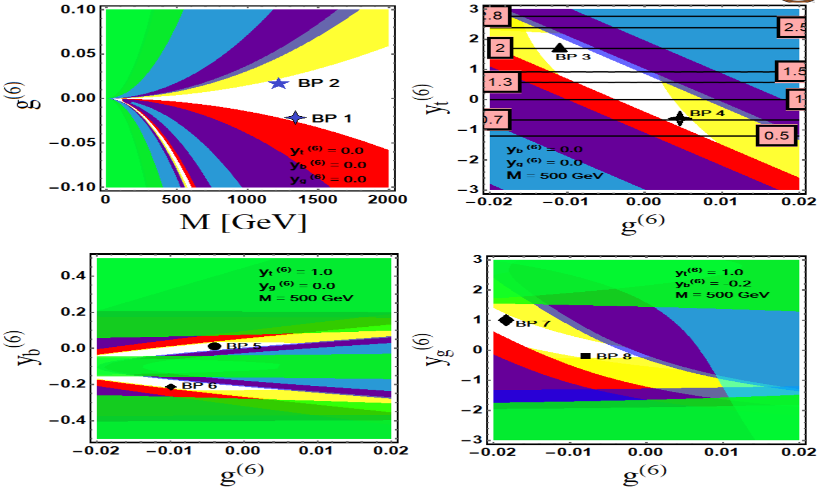
Analysis :

- In SM, $\sigma_{hh} \sim 33$ fb $\Rightarrow$ too small to be measured when we consider final state signal such as one $h \to b\bar{b}$, the other $h \to \gamma\gamma$.

- Addition of $g^{(6)} \Rightarrow$ can have big effect on di-Higgs production.

- We consider the signal strength for di-Higgs production relative to the SM expectation μ_{hh} as $\mu_{hh} = \frac{\sigma(pp \to hh)_{NewPhysics}}{\sigma(pp \to hh)_{SM}}$.

Results :



0.10
0.05
0.00
−0.05
−0.10
0
500
1000
1500
2000
M [GeV]
$g^{(6)}$
BP 2
BP 1
$y_t^{(6)} = 0.0$
$y_b^{(6)} = 0.0$
$y_g^{(6)} = 0.0$
.8
2.5
2
BP 3
1.5
1.3
1
.7
BP 4
0.5
$y_b^{(6)} = 0.0$
$y_g^{(6)} = 0.0$
M = 500 GeV
$y_t^{(6)}$
$g^{(6)}$
$y_t^{(6)} = 1.0$
$y_g^{(6)} = 0.0$
M = 500 GeV
BP 5
BP 6
$y_b^{(6)}$
$g^{(6)}$
$y_t^{(6)} = 1.0$
$y_b^{(6)} = -0.2$
M = 500 GeV
BP 7
BP 8
$y_g^{(6)}$
$g^{(6)}$

Results :

- If $y_t^{(6)} = y_b^{(6)} = 0 \Rightarrow g^{(6)}$ has to be very small ~ 0 unless the new mass scale > 2 TeV (BP1) to satisfy Higgs observables.

- However, when non-zero $y_t^{(6)}$ and $y_b^{(6)}$ are included, there are considerable region of parameter space which satisfy Higgs observable constraints and new physics scale can be much lower.

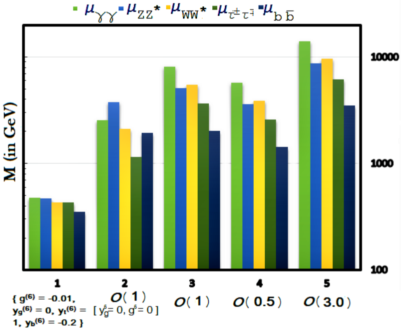
- For example, for BP's 3,4,5,6,7,8, $g^{(6)}$ can be as large as 0.06, and $\mu_{t\bar{t}h}$ can be as large as 2.5.

- In some of this allowed region, di-Higgs production can be as large as 6 times of the SM prediction.

Determination of new mass scale :

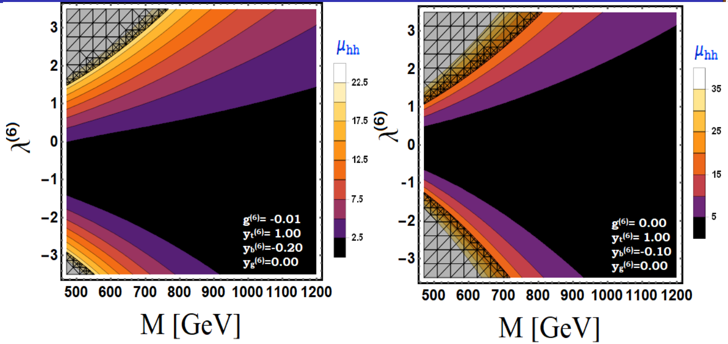
- The effect of dimension 6 operator depends on $(coupling^{(6)})^2/M^2$.
- Thus, we need to know $(coupling^{(6)})$ to determine the mass scale.
- We assume $(coupling^{(6)})^2/(4\Pi)$ satisfy the perturbativity limit so, $(coupling^{(6)}) < 3.5$.

Determination of new mass scale :



- Fig. shows the limit for the scan of the new physics scale satisfying constraints for the Higgs observables.
- We find that for a judicious choice of parameter space $(g^{(6)} = -0.01, y_g^{(6)} = 0, y_t^{(6)} = 1, y_b^{(6)} = -0.2)$, the new physics scale M can be as low as $\sim$500 GeV.

Effect of $\frac{\lambda^{(6)}}{M^2}(H^\dagger H)^3$:



- This gives large effect for di-Higgs production.
- For some region of the 6-dimensional parameter space, di-Higgs production cross-section can be as large as $\sim$ 10 or more times of the SM.
- This could make it potentially observable at the end of run II.

Conclusions :

- We explore the effect of relevant dimension-6 operators on the Higgs observables
- Included $\left\{ y_t^{(6)},\ \ y_b^{(6)},\ \ y_g^{(6)},\ \ g^{(6)},\ \ \lambda^{(6)},\ \ M \right\}$
- There are significant allowed region for which constarints for all the Higgs observable be satisfied.
- $t\bar{t}h$ production can be as large as 2.5 times the SM
- To estimate the mass scale, we have assumed perturbativity constraints, $(coupling^{(6)})^2/(4\Pi) < 1$.
- Mass scale as low as $\sim$ 500 GeV allowed.
- Di-Higgs production can be as large as $\sim$ 10 or more times of the SM.