New Physics in multi-Higgs boson final states[1]

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[1] arXiv:1702.03554 [hep-ph]

Outline

- Motivation
- Effective Field Theory (EFT) parameterization
- Analysis results of $pp \rightarrow hhh \rightarrow 2b2l^{\pm}4j + MET$
- New physics in $gg \rightarrow h$, $gg \rightarrow hh$, $gg \rightarrow hhh$
- Conclusion

Motivation

- The processes with multi-Higgs final states are important to understand the Higgs potential and electroweak symmetry breaking (EWSB).
- Deviations from the SM in double and triple Higgs final-state processes are expected by various new physics models. EFT is a suitable tools to study the new physics effects.
- $pp \rightarrow hhh \rightarrow 2b2l^{\pm}4j + MET$ is not well studied in the literature. What is the discovery potential of triple Higgs signal via this channel?

Motivation

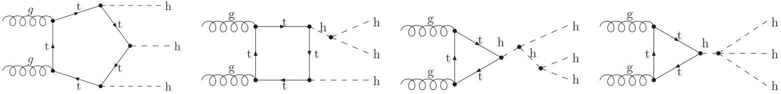
In the SM, the Higgs potential can be written as:

$$V(H^\dagger H) \;\; = \;\; -\mu^2 (H^\dagger H) + \frac{\lambda}{4}(H^\dagger H)^2,$$

After EWSB, we have the Higgs self-interation terms:

$$V_{\text{self}} \;\; = \;\; \frac{\lambda}{4} v h^3 + \frac{1}{16}\lambda h^4,$$

where $\lambda = 2m_h^2/v^2$.



Motivation

We compare the cross section of $gg \to hhh$ at the LHC and a 100 TeV machine:

E_{cm}	14 TeV	100 TeV
σ_{tot} (fb)	4.1×10^{-2}	3.2

If we can reduce the background and the integrated luminosity is high enough, it is possible to observe this process at a 100 TeV machine (SPPC).

EFT parameterization

A general way to parameterize the EFT Lagrangian is

$$
\begin{aligned}
\mathcal{L}_{EFT} &= \mathcal{L}_{SM} + \mathcal{L}_t + \mathcal{L}_h + \mathcal{L}_{ggh}, \\
\mathcal{L}_t &= -a_1 \frac{m_t}{v} \bar{t}t\, h - a_2 \frac{m_t}{2v^2} \bar{t}t\, h^2 - a_3 \frac{m_t}{6v^3} \bar{t}t\, h^3, \\
\mathcal{L}_h &= -\lambda_3 \frac{m_h^2}{2v} h^3 - \frac{\kappa_5}{2v} h\partial^\mu h \partial_\mu h - \lambda_4 \frac{m_h^2}{8v^2} h^4 - \frac{\kappa_6}{4v^2} h^2 \partial^\mu h \partial_\mu h, \\
\mathcal{L}_{ggh} &= \frac{g_s^2}{48\pi^2} \left(c_1 \frac{h}{v} + c_2 \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{a\,\mu\nu}
\end{aligned}
$$

where $a_1 = \lambda_3 = \lambda_4 = 1$ and $a_2 = a_3 = \kappa_5 = \kappa_6 = c_1 = c_2 = 0$ in the SM.

	$gg \to h$	$gg \to hh$	$gg \to hhh$
Parameters involved	$a_1,\ c_1$	$a_1,\ c_1$	$a_1,\ c_1$
	-	$a_2,\ c_2,\ \lambda_3,\ \kappa_5$	$a_2,\ c_2,\ \lambda_3,\ \kappa_5$
	-	-	$a_3,\ \lambda_4,\ \kappa_6$

EFT parameterization

- **Scenario 1:** Strong Interaction Light Higgs (SILH)
  [G. F. Giudice *et al.*, hep-ph/0703164]

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} \quad &= \frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{c_T}{2f^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \\
&- \frac{c_6 \lambda}{f^2}\left(H^\dagger H\right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \mathrm{h.c.}\right) \\
&+ \frac{c_g g_S^2}{16\pi^2 f^2}\frac{y_t^2}{g_\rho^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} + \frac{i c_W g}{2 m_\rho^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i \\
&+ \frac{i c_B g'}{2 m_\rho^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) + \frac{i c_{HW} g}{16\pi^2 f^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} \\
&+ \frac{i c_{HB} g'}{16\pi^2 f^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} + \frac{c_\gamma {g'}^2}{16\pi^2 f^2}\frac{g^2}{g_\rho^2} H^\dagger H B_{\mu\nu} B^{\mu\nu}.
\end{aligned}
$$

Two particular cases:

$$
\begin{aligned}
&\text{MCHM4:} \quad c_H = 1, \quad c_y = 0, \quad c_6 = 1 \\
&\text{MCHM5:} \quad c_H = 1, \quad c_y = 1, \quad c_6 = 0
\end{aligned}
$$

EFT parameterization

- **Scenario 2:** Higgs inflation
  [F. L. Bezrukov and M. Shaposhnikov, arXiv:0710.3755 [hep-th]]

$$S_{Jordan} = \int d^4x\sqrt{-g}\left\{-\frac{M^2+\xi h^2}{2}R+\frac{(\partial h)^2}{2}-\frac{1}{2}m_h h^2-\frac{\lambda}{4}h^4\right\}$$

One can define

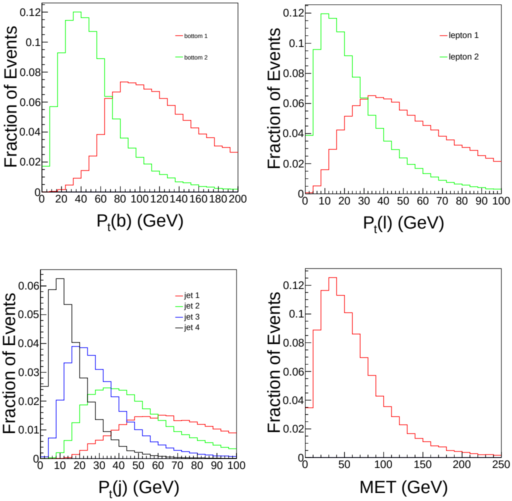
$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu} \quad \Omega^2 = 1+\xi h^2/M_{\text{Planck}}^2 \quad d\chi = \sqrt{\frac{\Omega^2+6\xi^2 h^2/M_{\text{Planck}}^2}{\Omega^4}}dh$$

And then the Lagrangian can be rewritten as Einstein frame

$$S_E = \int d^4x\sqrt{-\hat{g}}\Bigg\{-\frac{M_{\text{Planck}}^2}{2}\hat{R}+\frac{\partial_\mu h\partial^\mu h}{2\Omega^2}+\frac{3\xi}{M_{\text{Planck}}^2}\frac{h^2\partial_\mu h\partial^\mu h}{\Omega^4}$$
$$-(1-\frac{2\xi h^2}{M_{\text{Planck}}^2})\left[\frac{\lambda}{4}h(\chi)^4+\frac{1}{2}m_h h(\chi)^2\right]\Bigg\}.$$

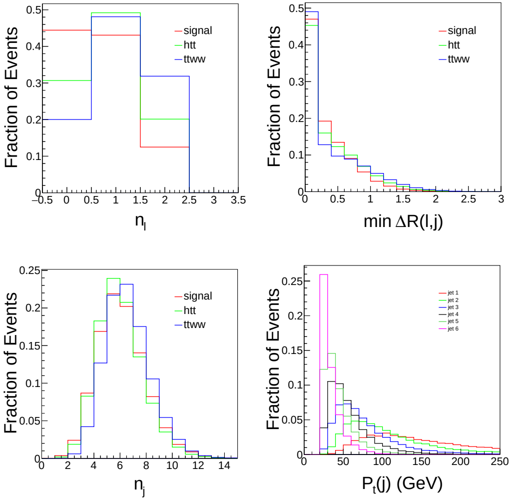
The Analysis results of $pp \to hhh \to 2b2l^{\pm}4j + MET$

Parton level:



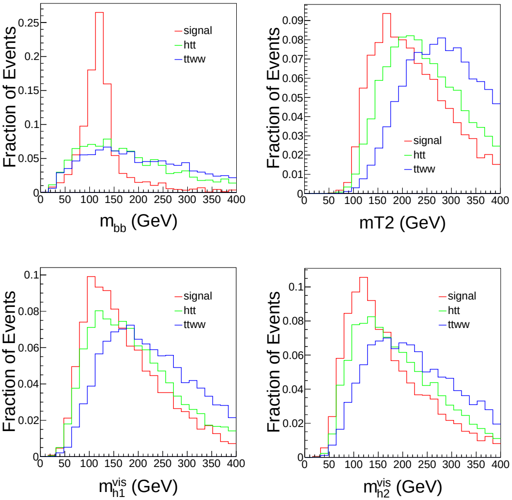
The Analysis results of $pp \rightarrow hhh \rightarrow 2b2l^{\pm}4j + MET$

Hadron level:



The Analysis results of $pp \to hhh \to 2b2l^{\pm}4j + MET$

Detector level:



New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

Here we switch on two operators

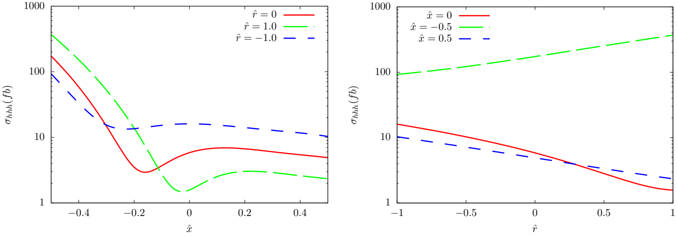
$$\begin{aligned} \mathcal{O}_1 &= \frac{x_1}{2v^2}\partial^\mu(H^\dagger H)\partial_\mu(H^\dagger H), \\ \mathcal{O}_2 &= \frac{x_2}{3v^2}(H^\dagger H)^3, \end{aligned}$$

And define $\hat{x} = x_1\zeta^2$ and $\hat{r} = -x_2\zeta^2\frac{2v^2}{3m_h^2}$, where $\zeta = (1+x_1)^{-1/2}$

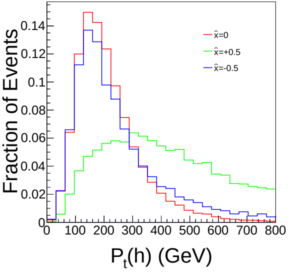
[H. J. He *et al.*, arXiv:1506.03302 [hep-ph]]

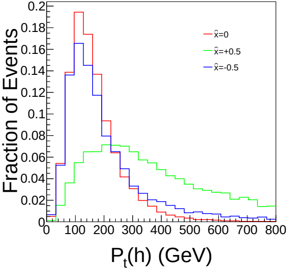
Our operators	Operators above	Relations
$-\frac{m_t}{v}a_1\bar{t}th$	$-\frac{m_t}{v}\zeta\bar{t}th$	$a_1 = \zeta$
$-\lambda_3\frac{m_h^2}{2v}h^3$	$-\frac{\zeta}{2v}(1+\hat{r})m_h^2h^3$	$\lambda_3 = \zeta(1+\hat{r})$
$-\lambda_4\frac{m_h^2}{8v^2}h^4$	$-\frac{\zeta^2}{8v^2}(1+6\hat{r})m_h^2h^4$	$\lambda_4 = \zeta^2(1+6\hat{r})$
$-\frac{1}{2v}\kappa_5 h(\partial h)^2$	$\frac{1}{v}\hat{x}\zeta h(\partial h)^2$	$\kappa_5 = -2\hat{x}\zeta$
$-\frac{\kappa_6}{4v^2}h^2(\partial h)^2$	$\frac{\hat{x}}{2v^2}\zeta^2h^2(\partial h)^2$	$\kappa_6 = -2\hat{x}\zeta^2$

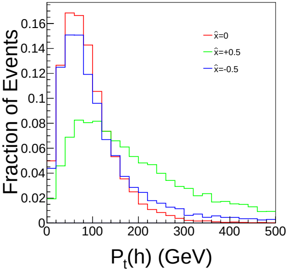
New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

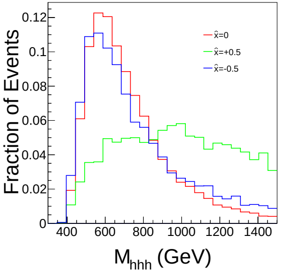


New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

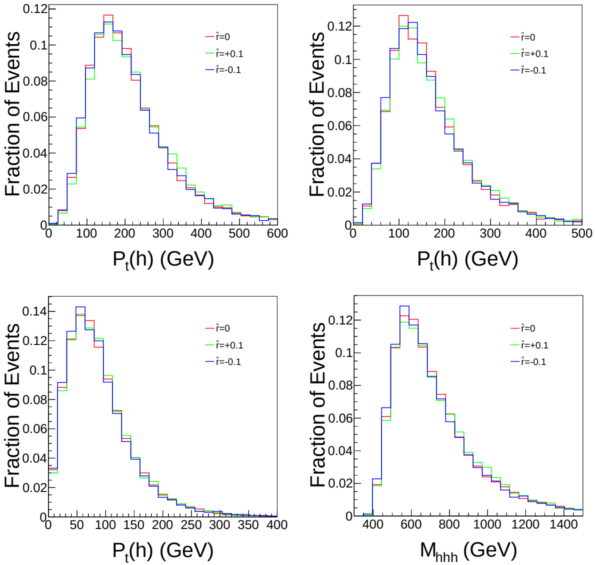




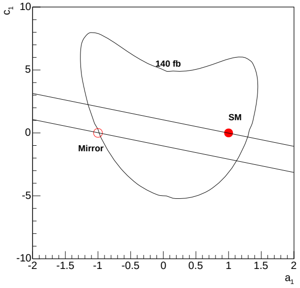




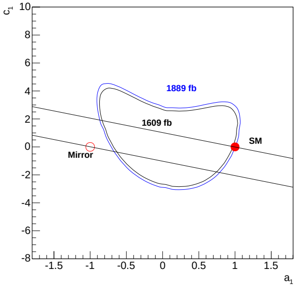
New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$



The processes $gg \to h$ and $gg \to hh$ give a strong constraint on a_1 and c_1 (assuming 30 ab^{-1} luminosity for 100 TeV)



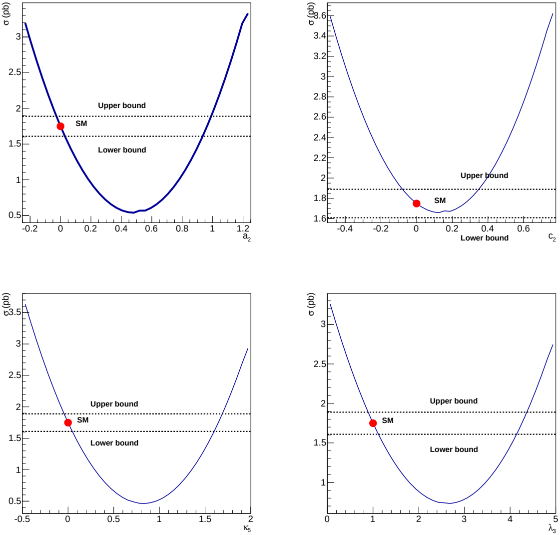
(a) 14 TeV



(b) 100 TeV

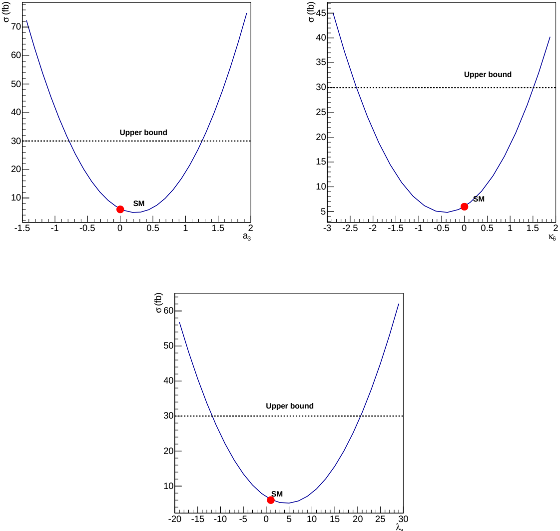
New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

$gg \to hh$ can constrain the a_2, λ_3 and κ_5 within 10% at a 100 TeV machine.



New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

The upper bounds of the parameters a_3, λ_4 and κ_6 can be obtained from $gg \to hhh$.



New physics in $gg \to h$, $gg \to hh$, $gg \to hhh$

Parameters	Constraints
a_1	1%
a_2	10%
a_3	40%
λ_3	10%
λ_4	$[-13, 20]$
κ_5	10%
κ_6	$[-2.3, 1.5]$
c_1	$\leq 1.0\%$
c_2	$[-0.1, 0.4]$

Conclusion

- The channel $pp \to hhh \to 2b2l^{\pm}4j + MET$ is studied at 100 TeV.
- We use the EFT method to discuss the new physics effects.
- The bounds on Yukawa couplings, trilinear and quartic self-coupling of Higgs via multi-Higgs final states are obtained at 100 TeV hadron collider.
- Our study can be applied to constrain the new physics model such as SILH and Higgs inflation.

Backup slides

Process	$\sigma(14\ TeV)$ (fb)	err.[th]	err.[exp]
$gg \to h$	4.968×10^4	$^{+7.5\%}_{-9.0\%}$	$\pm 1\%$
$gg \to hh$	45.05	$^{+7.3\%}_{-8.4\%}$	$< 120 fb$
$gg \to hhh$	0.0892	$^{+8.0\%}_{-6.8\%}$	$-$

	$\sigma(100\ TeV)$ (fb)	err.[th]	err. [exp]
$gg \to h$	8.02×10^5	$^{+7.5\%}_{-9.0\%}$	$\pm 0.1\%$
$gg \to hh$	1749	$^{+5.7\%}_{-6.6\%}$	$\pm 5\%$
$gg \to hhh$	4.82	$^{+4.1\%}_{-3.7\%}$	$< 30 fb$

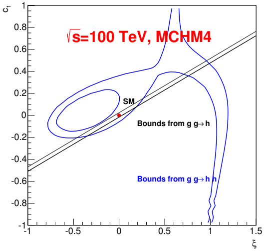
Triple-Higgs Decay Channel

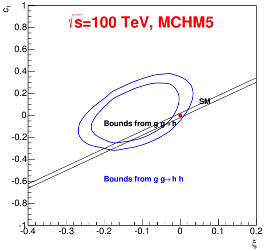
Decay channel	Branching ratio
$HHH \to b\bar{b}b\bar{b}W^+W^-$	22.34%
$HHH \to b\bar{b}b\bar{b}b\bar{b}$	20.30%
$HHH \to b\bar{b}W^+W^-W^+W^-$	8.20%
$HHH \to b\bar{b}b\bar{b}\tau^+\tau^-$	7.16%
$HHH \to b\bar{b}b\bar{b}gg$	6.54%
$HHH \to b\bar{b}b\bar{b}ZZ$	2.69%
$HHH \to W^+W^-W^+W^-W^+W^-$	1.00%
$HHH \to W^+W^-W^+W^-\tau^+\tau^-$	0.96%
$HHH \to W^+W^-W^+W^-gg$	0.88%
$HHH \to W^+W^-W^+W^-ZZ$	0.36%
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	0.29%

Parameter relationships of SILH, MCHM4 and MCHM5

	SILH	MCHM4	MCHM5
a_1	$(1-\frac{3}{2}c_y\xi)(1-\frac{1}{2}c_y\xi)^{-1}(1+c_H\xi)^{-1/2}$	$1-\frac{1}{2}\xi$	$1-\frac{3}{2}\xi$
a_2	$-3c_y\xi(1-\frac{1}{2}c_y\xi)^{-1}(1+c_H\xi)^{-1}$	0	-3ξ
a_3	$-3c_y\xi(1-\frac{1}{2}c_y\xi)^{-1}(1+c_H\xi)^{-3/2}$	0	-3ξ
c_1	$\frac{1}{4}c_g\xi\frac{y_t^2}{g_\rho^2}$	$\frac{1}{4}\xi\frac{y_t^2}{g_\rho^2}$	$\frac{1}{4}\xi\frac{y_t^2}{g_\rho^2}$
c_2	c_1	$c1$	$c1$
κ_5	$-2c_H\xi(1+c_H\xi)^{-3/2}$	-2ξ	-2ξ
κ_6	$-2c_H\xi(1+c_H\xi)^{-2}$	-2ξ	-2ξ
λ_3	$(1+\frac{5}{2}c_6\xi)(1+\frac{3}{2}c_6\xi)^{-1}(1+c_H\xi)^{-1/2}$	$1+\frac{\xi}{2}$	$1-\frac{1}{2}\xi$
λ_4	$(1+\frac{15}{2}c_6\xi)(1+\frac{3}{2}c_6\xi)^{-1}(1+c_H\xi)^{-1}$	$1+5\xi$	$1-\xi$

MCHM analysis





MCHM analysis