New Physics in multi-Higgs boson final states in 14 and 100 TeV colliders

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Based on a work to appear with
Wolfgang Kilian, Qi-Shu Yan, Xiaoran Zhao, and Zhijie Zhao[1, {]

Outline

- EFT parametrization of New Physics
    - SILH (strongly interacting light Higgs) of composite Higgses
    - Higgs inflation (Higgs gravity couplings)
- gg -> hhh in 2b2l4j+MET
- New physics in gg->h, gg->hh, gg->hhh
- Benchmark points for Models

Higgs potential

- In the Standard Model:

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

$$H = (G^+, \tfrac{1}{\sqrt{2}}(v+h+iG^0))^T \qquad v = 2|\mu|/\lambda \approx 246 \text{ GeV}$$

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

EFT for BSM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + ...$$

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i,$$

- The SM with BSM

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

$$a_1 = \lambda_3 = \lambda_4 = 1 \text{ and } a_2 = a_3 = \kappa_5 = \kappa_6 = c_1 = c_2 = 0.$$

UV theory I, SILH

- Strongly interacting Light Higgs,
- CP preserving part: up to dim-six, at least 2 Higgs fields.

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

$$MCHM4 : c_H = 1, \quad c_y = 0, \quad c_6 = 1\,,$$

$$MCHM5 : c_H = 1, \quad c_y = 1, \quad c_6 = 0\,.$$

Parameters	SILH with Eq. (9)	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	$(1+\frac{15}{2}c_6\xi)(1+\frac{3}{2}c_6\xi)^{-1}(1+c_H\xi)^{-1}$	$1+5\xi$	$1-\xi$

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

UV theory II, Higgs inflation

- Treat Higgs as an inflaton, coupled to Ricci Tensor:

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

$$\hat{g}_{\mu\nu} = \Omega^2 g_{\mu\nu}\ , \quad \Omega^2 = 1 + \xi h^2/M^2_{Planck}\ .$$

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

Pure Higgs term:

$$\frac{c_H}{2f^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) \to \frac{c_H}{2f^2}(v+h)^2\partial^\mu h\partial_\mu h.$$

$$\mathcal{L}_{kin} = \frac{1}{2}\left(1 + c_H\xi\right)\partial^\mu h\partial_\mu h,$$

- Higgs wavefunction renormalization: $\zeta = (1 + f_2 v^2/\Lambda^2)^{-1/2}$

$$\begin{aligned}
\mathcal{O}_1 &= (D^\mu H)^\dagger H H^\dagger (D_\mu H),\\
\mathcal{O}_2 &= \frac{1}{2}\partial^\mu (H^\dagger H)\partial_\mu (H^\dagger H),\\
\mathcal{O}_3 &= \frac{1}{3}(H^\dagger H)^3,\\
\mathcal{O}_4 &= (D^\mu H)^\dagger (D_\mu H)(H^\dagger H).
\end{aligned}$$

$$\begin{aligned}
\hat{x} &= x_2\zeta^2,\\
\hat{r} &= -x_3\zeta^2\frac{2v^2}{3m_h^2},
\end{aligned}$$

Our operators	Operators in Ref. [35]	Relations
$-\frac{m_t}{v}a_1\bar{t}th$	$-\frac{m_t}{v}\zeta\bar{t}th$	$a_1 = \zeta$
$-\lambda_3\frac{m_h^2}{2v}h^3$	$-\frac{\zeta}{2v}(1+\hat{r})m_h^2 h^3$	$\lambda_3 = \zeta(1+\hat{r})$
$-\lambda_4\frac{m_h^2}{8v^2}h^4$	$-\frac{\zeta^2}{8v^2}(1+6\hat{r})m_h^2 h^4$	$\lambda_4 = \zeta^2(1+6\hat{r})$
$-\frac{1}{2v}\kappa_5 h(\partial h)^2$	$\frac{1}{v}\hat{x}\zeta h(\partial h)^2$	$\kappa_5 = -2\hat{x}\zeta$
$-\frac{\kappa_6}{4v^2}h^2(\partial h)^2$	$\frac{\hat{x}}{2v^2}\zeta^2 h^2(\partial h)^2$	$\kappa_6 = -2\hat{x}\zeta^2$

- 1506.03302 by Hong-Jian He, Jing Ren, Weiming Yao

$$\mathcal{V}\left(H^{\dagger}H\right) = -\mu^2\left(H^{\dagger}H\right) + \lambda\left(H^{\dagger}H\right)^2 + \frac{c_6\lambda}{f^2}\left(H^{\dagger}H\right)^3$$

In this case, the VEV is given by

$$-\mu^2 + 2\lambda v^2 + \frac{3}{4}c_6\xi\lambda v^2 = 0,$$

and the corresponding Higgs mass is defined by

$$m_h^2 = 2\lambda v^2\left(1 + \frac{3}{2}c_6\xi\right)\zeta^2. \qquad \frac{1}{2}m_h^2 = -\frac{1}{2}\mu^2 + \frac{3}{2}\lambda v^2 + \frac{15}{8}c_6\xi\lambda v^2.$$

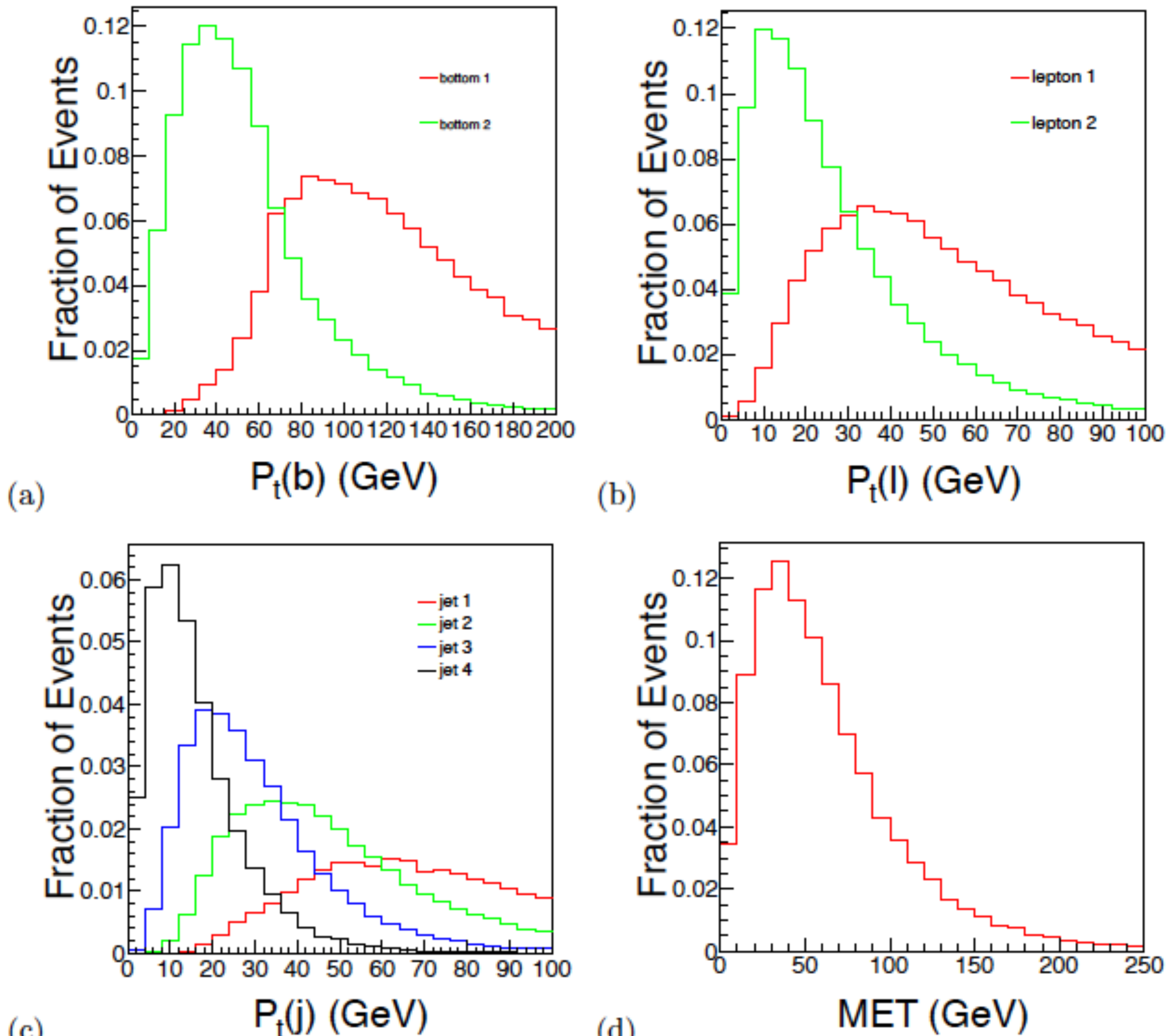
An alternative way is performing a non-linear transformation $h \to h - \frac{c_H\xi}{2}(h + \frac{h^2}{v} + \frac{h^3}{3v^2})$

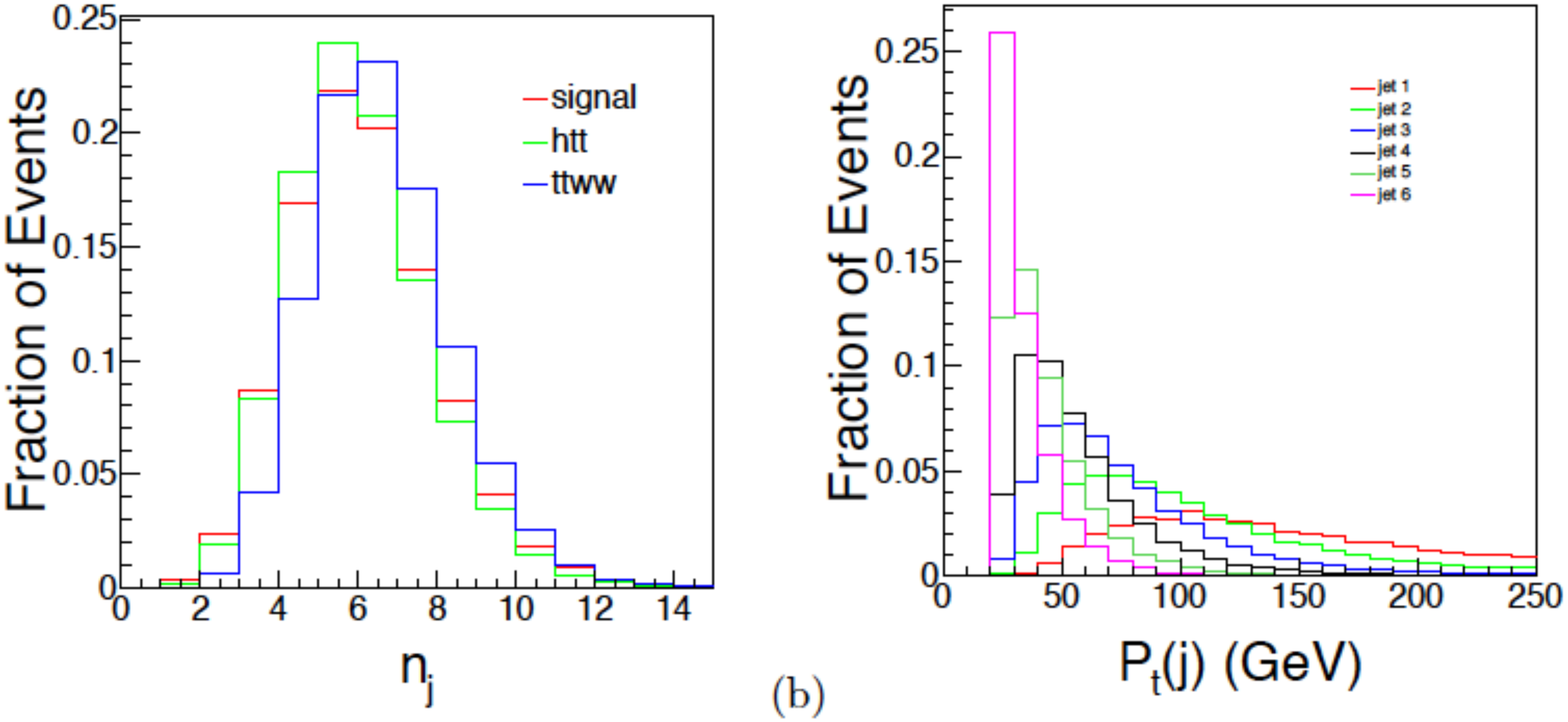
- To eliminate cH term, traditionally is through non-linear redefinition. ———-gives rise to the same result up to some order, but less sensitive to the derivative operators, and the Higgs kinematics

$2b2l^{\pm}4j + \not{E}$ CHANNEL IN THE SM

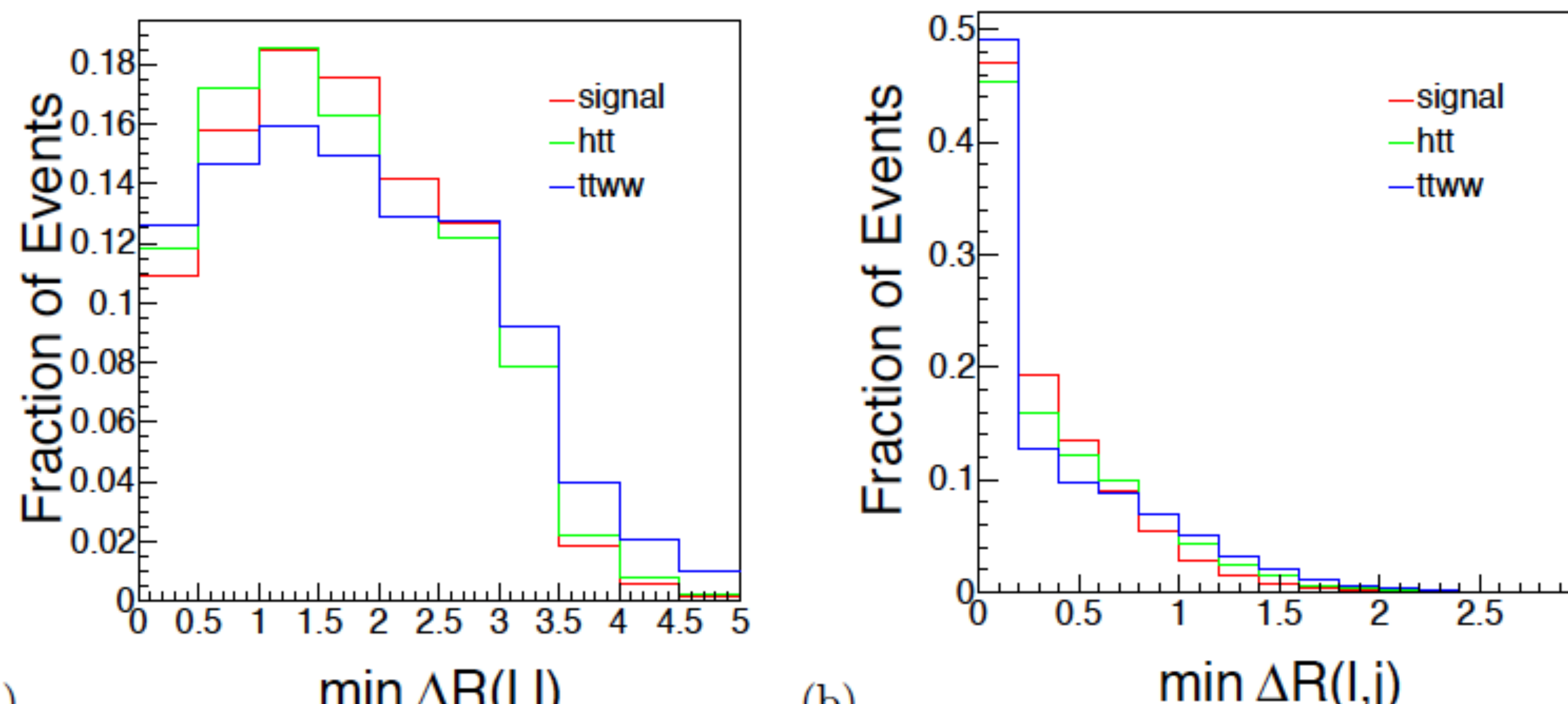
Process	$\sigma \times BR$ (ab)	K-factor	Expected number of events
Signal	10.71	2.0	642
$h(WW^*)t\bar{t}$	2.55×10^5	1.2	9.18×10^6
$t\bar{t}W^-W^+$	3.68×10^4	1.3	1.55×10^6

- gg -> hhh -> bbWWWW


Fraction of Events
bottom 1
bottom 2
Pt(b) (GeV)
(a)
Fraction of Events
lepton 1
lepton 2
Pt(l) (GeV)
(b)
Fraction of Events
jet 1
jet 2
jet 3
jet 4
Pt(j) (GeV)
(c)
Fraction of Events
MET (GeV)
(d)

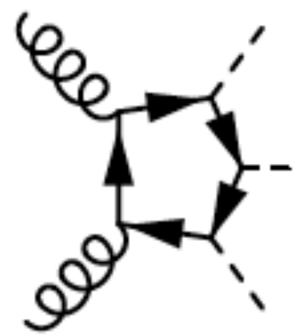

Fraction of Events
signal
htt
ttww
n_j
Fraction of Events
jet 1
jet 2
jet 3
jet 4
jet 5
jet 6
$P_t(j)$ (GeV)

(a) (b)


Fraction of Events
signal
htt
ttww
min ΔR(l,l)
Fraction of Events
signal
htt
ttww
min ΔR(l,j)

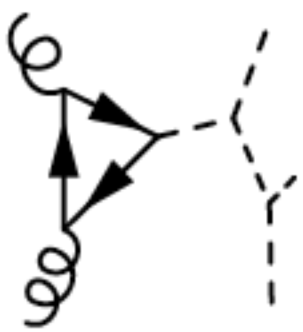
(a) (b)

New physics contributions

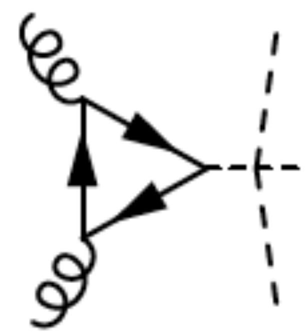


$\propto a_1^3$

$\propto a_1^2\lambda_3/a_1^2\kappa_5$



$\propto a_1\lambda_3^2/a_1\lambda_3\kappa_5/a_1\kappa_5^2$



$\propto a_1\lambda_4/a_1\kappa_6$

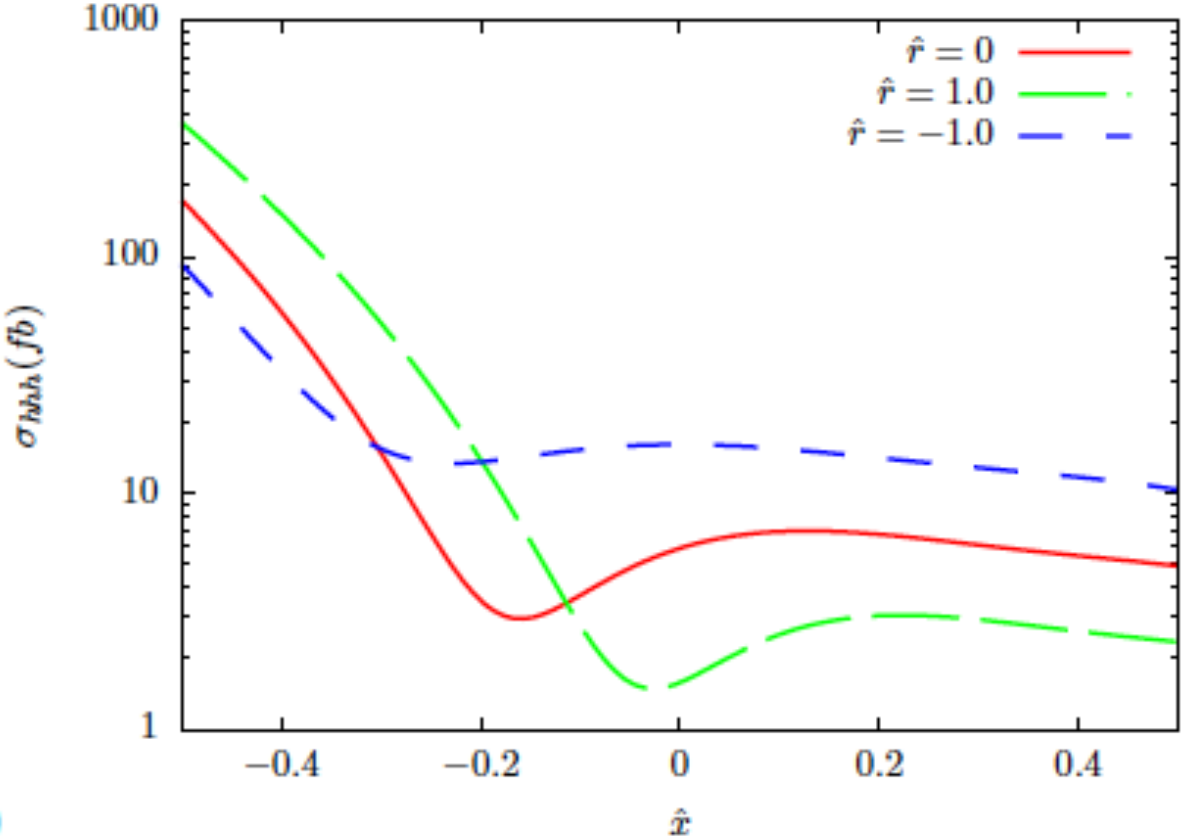
$$M(gg \to hhh) \propto f_1 a_1^3 + f_2 a_1^2\lambda_3 + f_3 a_1^2\kappa_5 + f_4 a_1\lambda_3^2 + f_5 a_1\lambda_3\kappa_5 \\ + f_6 a_1\kappa_5^2 + f_7 a_1\lambda_4 + f_8 a_1\kappa_6\,,$$

$$\sigma(pp \to hh) = f_1 a_1^4 + f_2 a_1^3\lambda_3 + f_3 a_1^3\kappa_5 + f_4 a_1^2\lambda_3^2 + f_5 a_1^2\lambda_3\kappa_5 \\ + f_6 a_1^2\kappa_5^2 + f_7 a_1^2 a_2 + f_8 a_1\lambda_3 a_2 + f_9 a_1\kappa_5 a_2 + f_{10} a_2^2\,.$$

	$gg \to h$	$gg \to hh$	$gg \to hhh$
Parameters	a_1, c_1	a_1, c_1	a_1, c_1
involved	-	a_2, c_2, λ_3, κ_5	a_2, c_2, λ_3, κ_5
	-	-	a_3, λ_4, κ_6

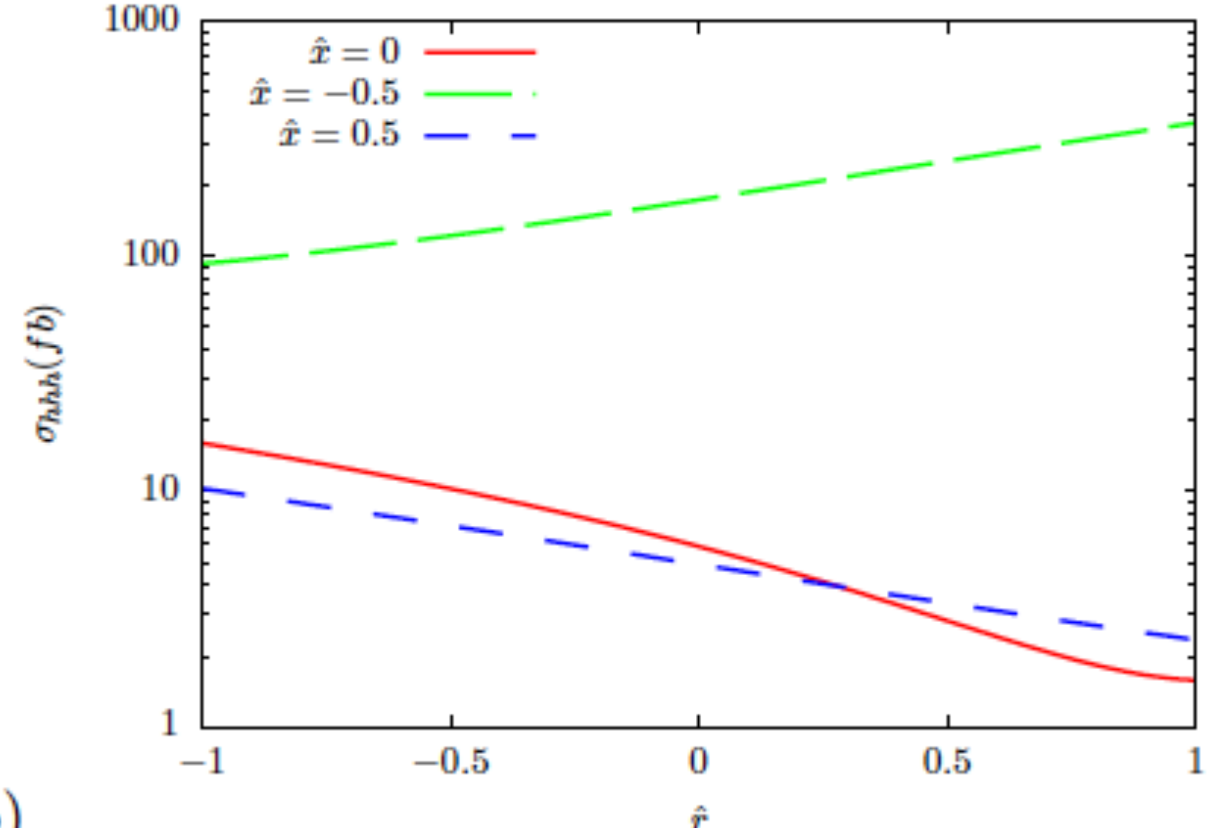
No.	a_1	c_1	$\sigma(gg \to h)$ [pb]	$\sigma(gg \to hh)$ [fb]	$\sigma(gg \to hhh)$ [fb]
1	0.99	-0.01	771	1710	5.90
2	-0.86	1.94	839.6	1685	29.7
3	0.78	-1.82	763	1747	6.23
4	-0.66	-0.37	817.8	1690	5.74

No.	ξ	c_1	$\sigma(gg \to h)[pb]$	$\sigma(gg \to hh)$ [fb]	$\sigma(gg \to hhh)$ [fb]
MCHM4	0.97	0.48	764	1618	321
MCHM5	-0.20	-0.30	817	1854	122
HGM	$\hat{x} = 0.02$	$\hat{r} = 3.2$	816	1786	37.78



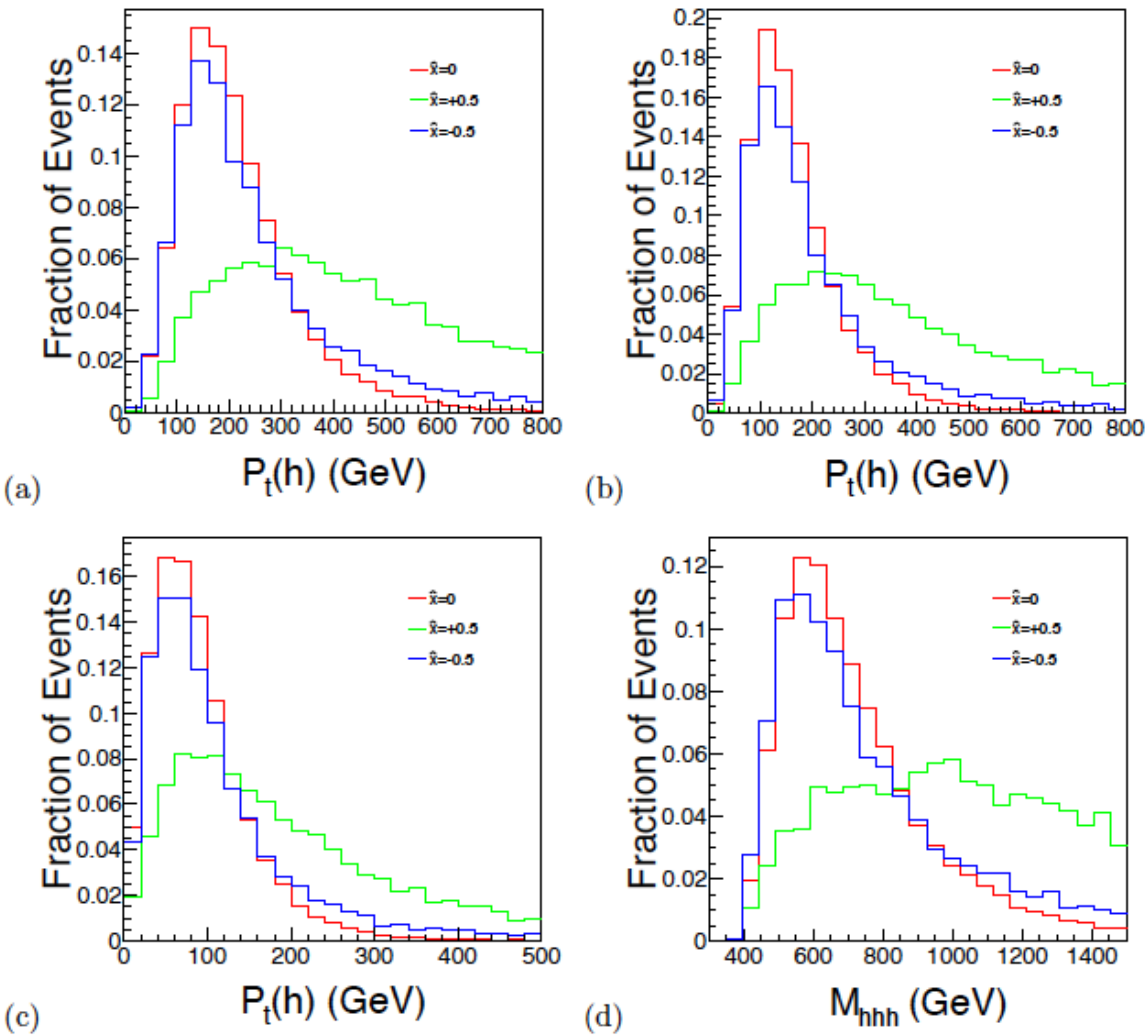
$\hat{r} = 0$
$\hat{r} = 1.0$
$\hat{r} = -1.0$
1000
100
10
1
$\sigma_{hhh}(fb)$
−0.4
−0.2
0
0.2
0.4
$\hat{x}$

(a)

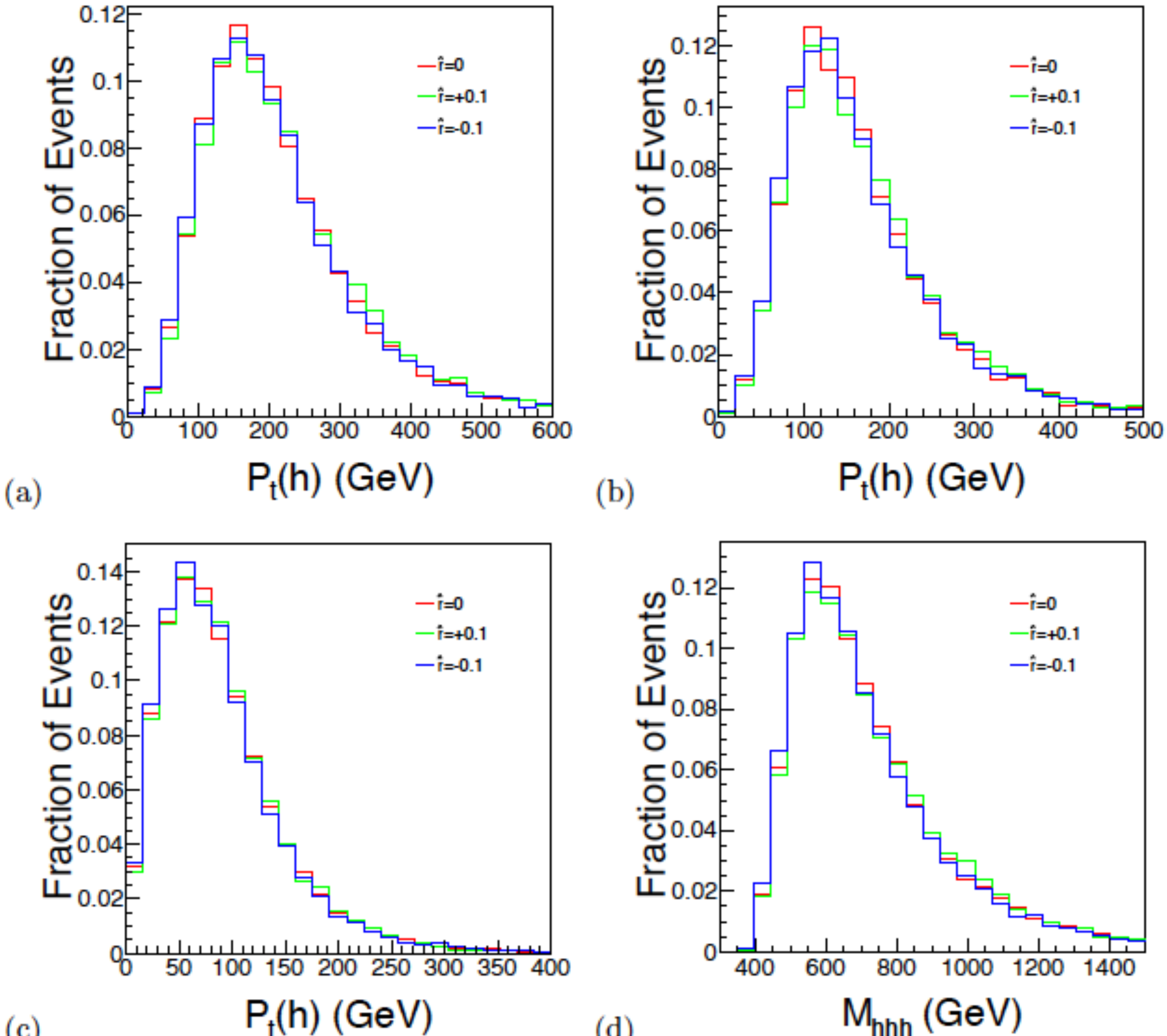


$\hat{x} = 0$
$\hat{x} = -0.5$
$\hat{x} = 0.5$
1000
100
10
1
$\sigma_{hhh}(fb)$
−1
−0.5
0
0.5
1
$\hat{r}$

(b)

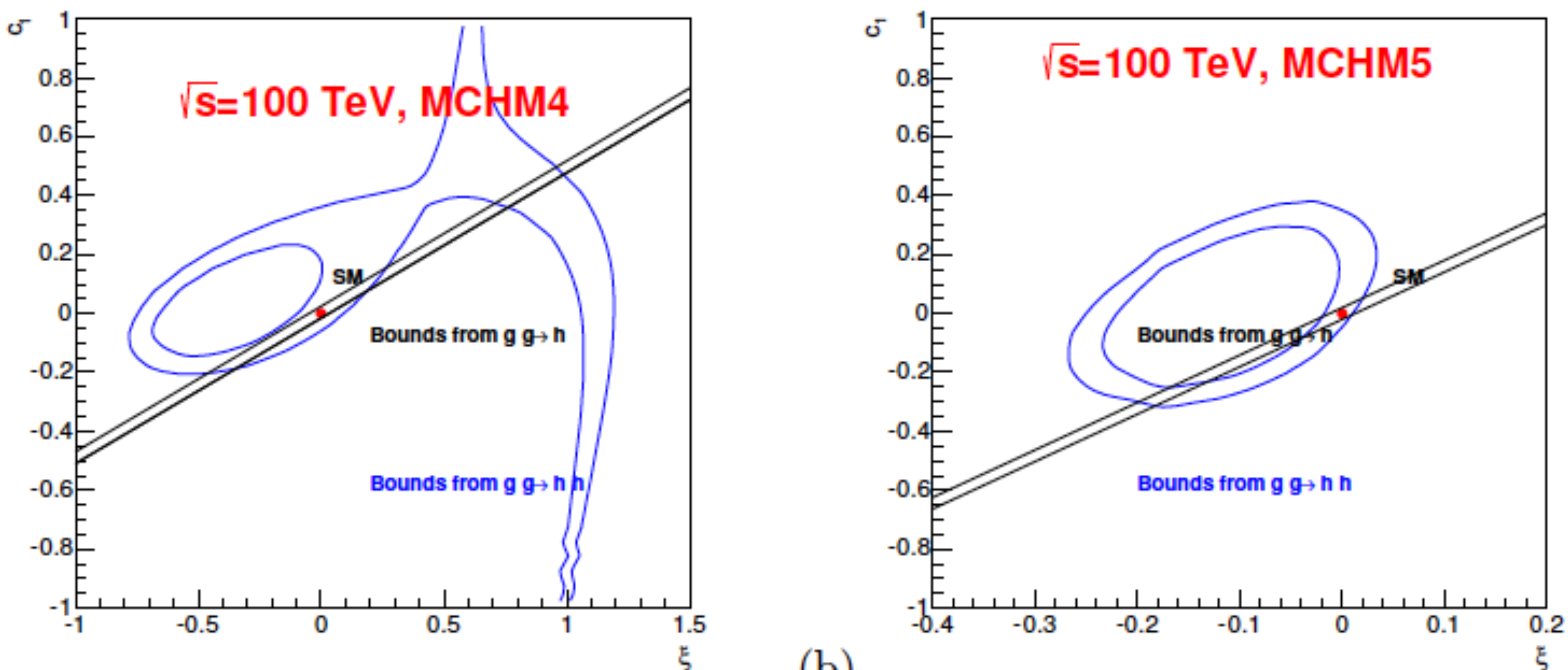


(a)
Fraction of Events
$P_t(h)$ (GeV)
$\hat{x}=0$
$\hat{x}=+0.5$
$\hat{x}=-0.5$
(b)
Fraction of Events
$P_t(h)$ (GeV)
$\hat{x}=0$
$\hat{x}=+0.5$
$\hat{x}=-0.5$
(c)
Fraction of Events
$P_t(h)$ (GeV)
$\hat{x}=0$
$\hat{x}=+0.5$
$\hat{x}=-0.5$
(d)
Fraction of Events
M_{hhh} (GeV)
$\hat{x}=0$
$\hat{x}=+0.5$
$\hat{x}=-0.5$

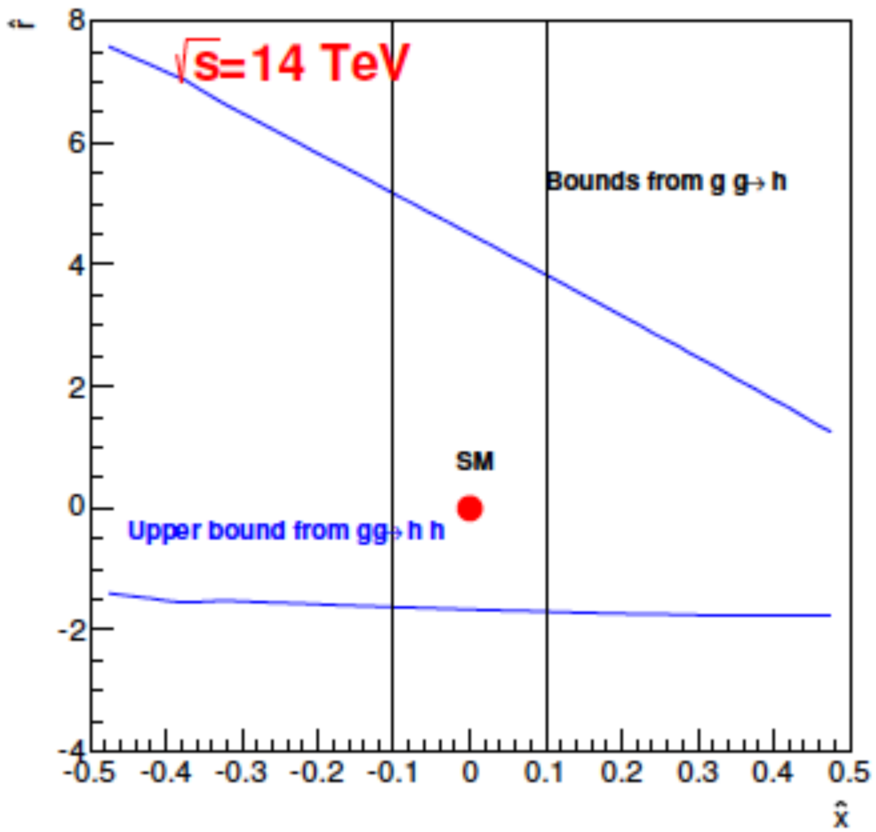


Fraction of Events
P_t(h) (GeV)
t̂=0
t̂=+0.1
t̂=-0.1
(a)
(b)
(c)
M_hhh (GeV)
(d)

Process	$\sigma(14\ TeV)$ (fb)	err.[th]	err.[exp]	$\sigma(100\ TeV)$ (fb)	err.[th]	err. [exp]
$gg \to h$	4.968×10^4	$^{+7.5\%}_{-9.0\%}$	$\pm 1\%$	8.02×10^5	$^{+7.5\%}_{-9.0\%}$	$\pm 0.1\%$
$gg \to hh$	45.05	$^{+7.3\%}_{-8.4\%}$	$< 120 fb$	1749	$^{+5.7\%}_{-6.6\%}$	$\pm 5\%$
$gg \to hhh$	0.0892	$^{+8.0\%}_{-6.8\%}$	–	4.82	$^{+4.1\%}_{-3.7\%}$	$< 30 fb$

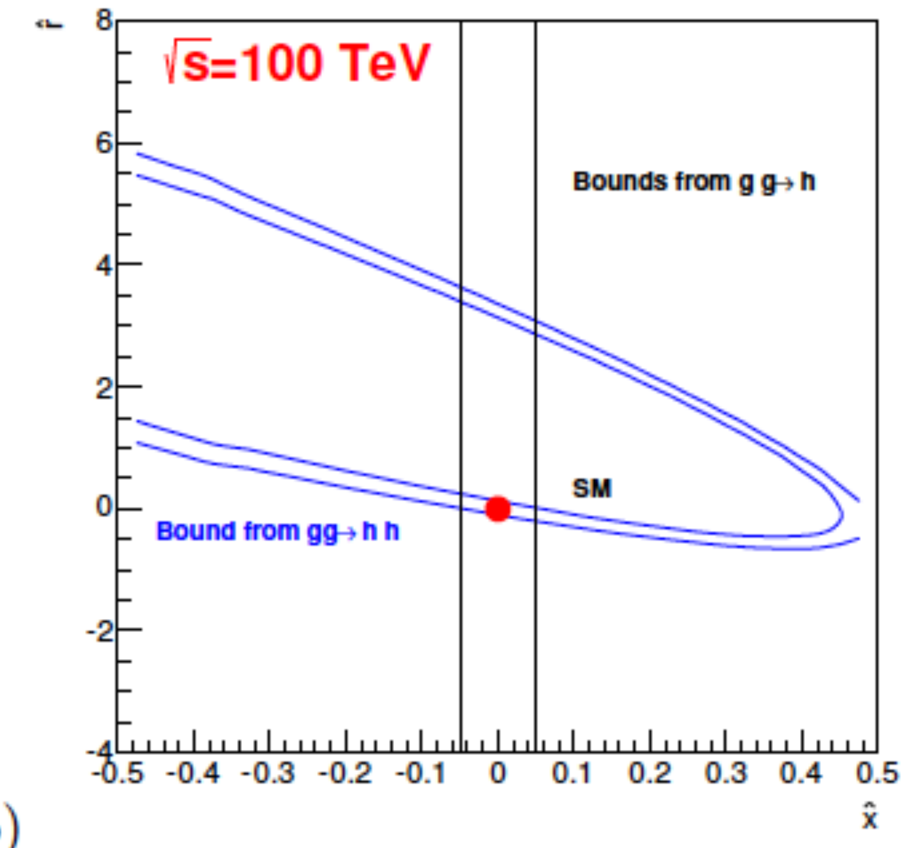


(a) (b)



√s=14 TeV
Bounds from g g→ h
SM
Upper bound from gg→ h h
r̂
x̂

(a)



√s=100 TeV
Bounds from g g→ h
SM
Bound from gg→ h h
r̂
x̂

(b)

Summary

- Study gg->hhh->bbWWWW channel both in 14 and 100 TeV colliders, in SM and BSM

- We clarified some points about non-linear redefinition in Higgs potential.

- Show how gg->h, gg->hh and gg->hhh constrains BSM:

    - composite Higgs

    - Higgs inflation

Thank you