Multi-Higgs boson production and Higgs couplings to the SM

晏启树, UCAS

In collaboration with

Kilian Wolfgang, Sichun Sun, Xiaoran Zhao, Zhijie Zhao,

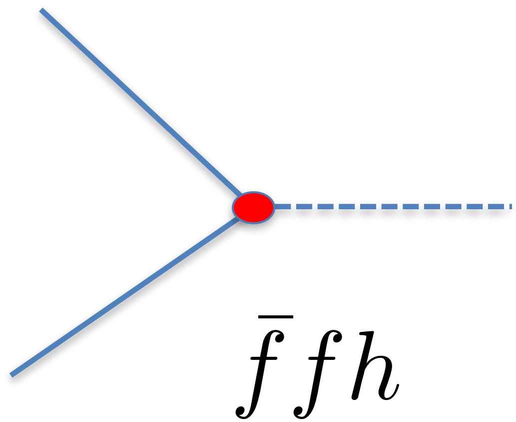
粒子物理前沿问题研讨会(广州), 21 – 25/January/2019

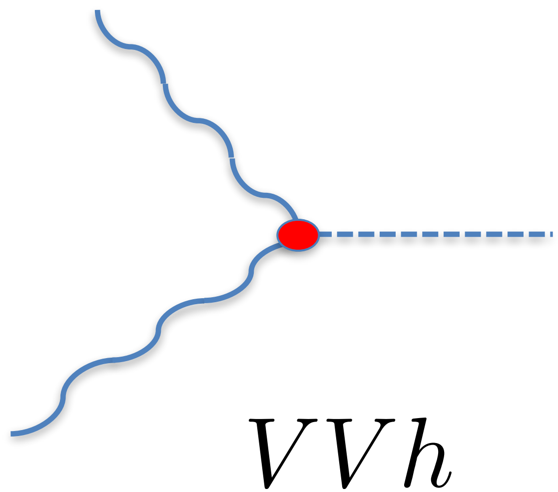
Outline

- Introduction
- EW Higgs interactions in the EFT
- Perturbative Unitarity constraint
- VBF Higgs bosons production in the EFT
- Conclusion

arXiv: 1808.05534

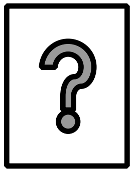
Those we know about Higgs Boson

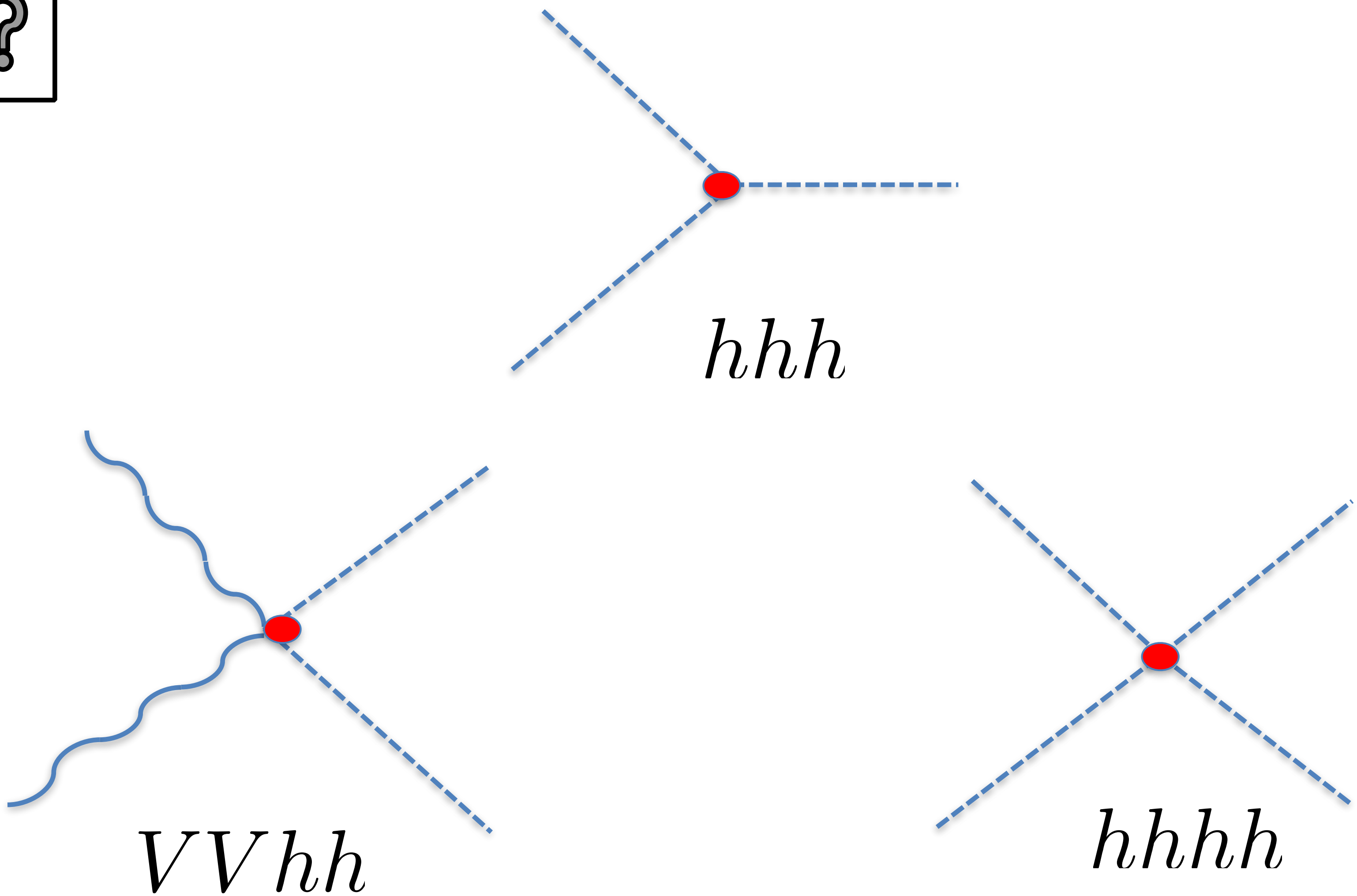




Production, decay, quantum corrections, …
Agreement with the SM, but …

Those we do not know up to now

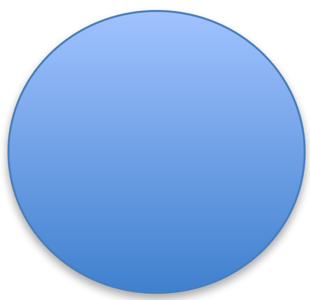


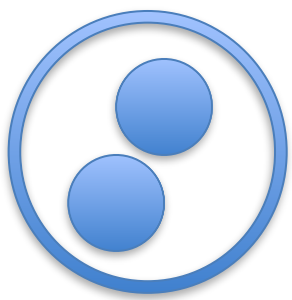


Questions to the Higgs boson

- What's the origin of Higgs boson's mass?
- Is it composite or fundamental?
- What's the shape of Higgs potential?
- How is EW symmetry broken?
- Whether there is only one Higgs boson?
- Can EW baryongensis work?
- …

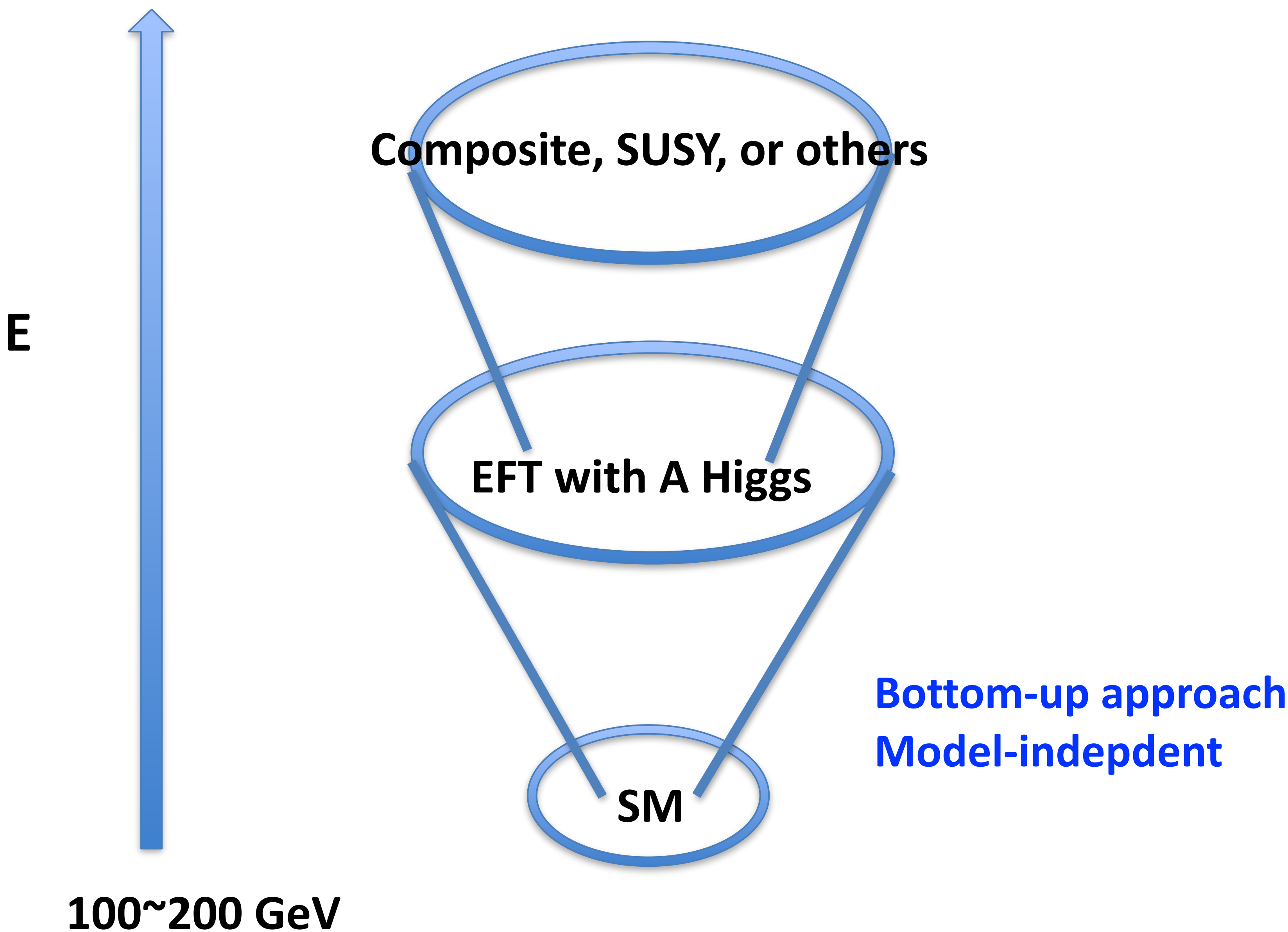
Fundamental? Composite?





To resolve the fine structure of Higgs boson, more measurements at the LHC, high precision and high energy machines are needed (Higgs factory, ILC, FCC-ee/pp, CEPC/SPPC). A new quest to the mystery just began.

A schematic view to EFT with a Hggs boson

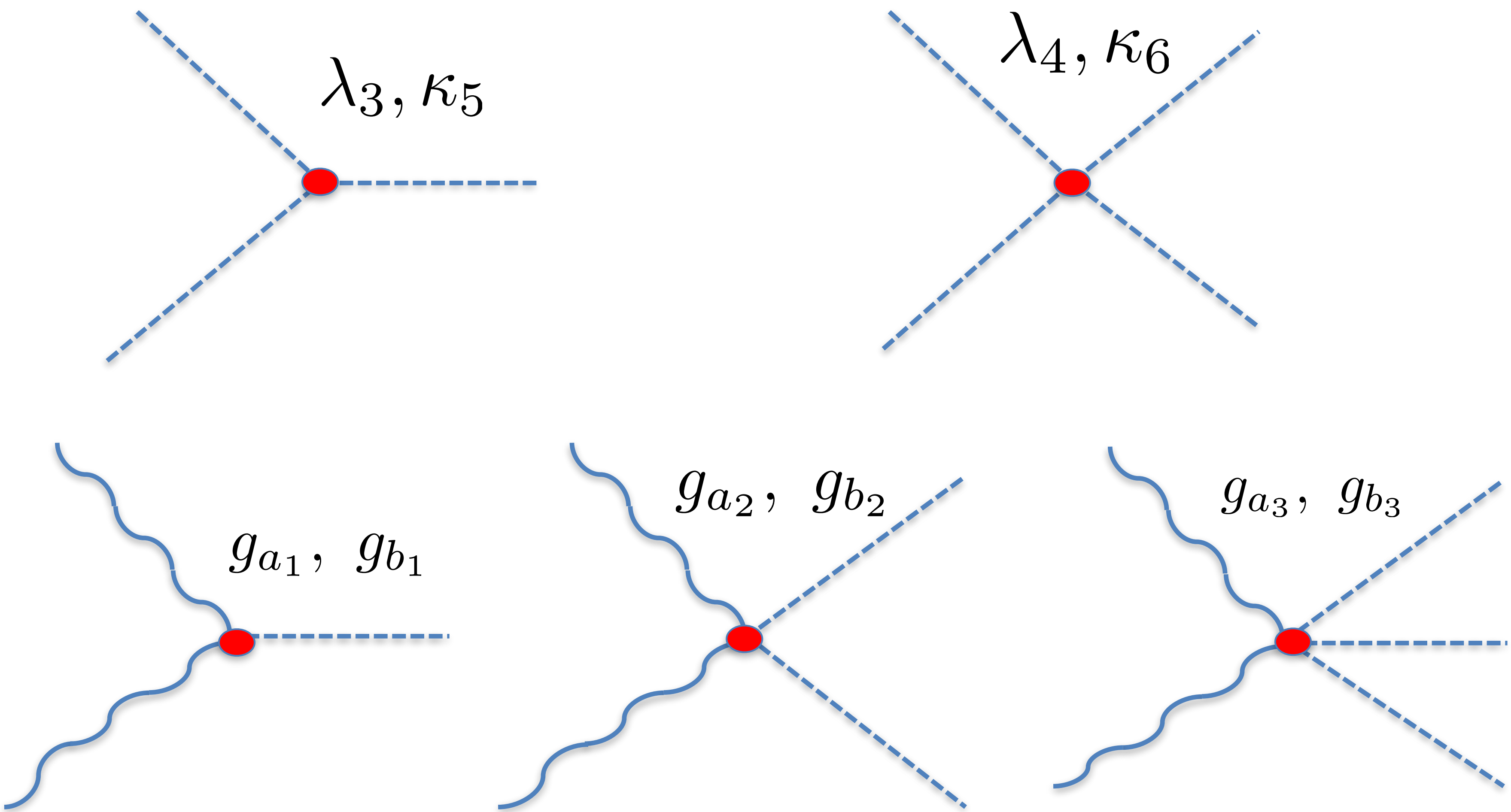


$$\mathcal{L}_{EFT} = \mathcal{L}_{\overline{SM}} + \mathcal{L}_h + \mathcal{L}_{VVh} + \mathcal{L}_{Vh},$$

$$\mathcal{L}_h = -\lambda_3 \frac{m_h^2}{2v} h^3 - \frac{\xi_5}{2v} h\partial^\mu h \partial_\mu h - \lambda_4 \frac{m_h^2}{8v^2} h^4 - \frac{\xi_6}{4v^2} h^2 \partial^\mu h \partial_\mu h + \cdots,$$

$$\begin{aligned}
\mathcal{L}_{VVh} = &- \left(g_{W,b1} \frac{h}{v} + g_{W,b2} \frac{h^2}{2v^2} + g_{W,b3} \frac{h^3}{6v^3} + \cdots \right) W^+_{\mu\nu} W^{-\mu\nu} \\
&- \left(g_{A,b1} \frac{h}{2v} + g_{A,b2} \frac{h^2}{4v^2} + g_{A,b3} \frac{h^3}{12v^3} + \cdots \right) F_{\mu\nu} F^{\mu\nu} \\
&- \left(g_{X,b1} \frac{h}{v} + g_{X,b2} \frac{h^2}{2v^2} + g_{X,b3} \frac{h^3}{6v^3} + \cdots \right) F_{\mu\nu} Z^{\mu\nu} \\
&- \left(g_{Z,b1} \frac{h}{2v} + g_{Z,b2} \frac{h^2}{4v^2} + + g_{Z,b3} \frac{h^3}{12v^2} + \cdots \right) Z_{\mu\nu} Z^{\mu\nu}
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{VH} = &g_{W,a1} \frac{2m_W^2}{v} h W^{+,\mu} W^-_\mu + g_{W,a2} \frac{m_W^2}{v^2} h^2 W^\mu W_\mu + g_{W,a3} \frac{m_W^2}{3v^3} h^3 W^\mu W_\mu \\
&+ g_{Z,a1} \frac{m_Z^2}{v} h Z^\mu Z_\mu + g_{Z,a2} \frac{m_Z^2}{2v^2} h^2 Z^\mu Z_\mu + g_{Z,a3} \frac{m_Z^2}{6v^3} h^3 Z^\mu Z_\mu + \cdots.
\end{aligned}$$



	$VV \to h$	$VV \to hh$	$VV \to hhh$
Parameters involved	$g_{V,a1}, g_{V,b1}$	$g_{V,a1}, g_{V,b1}$	$g_{V,a1}, g_{V,b1}$
	-	$g_{V,a2}, g_{V,b2}, \lambda_3, \kappa_5$	$g_{V,a2}, g_{V,b2}, \lambda_3, \kappa_5$
	-	-	$g_{V,a3}, g_{V,b3}, \lambda_4, \kappa_6$

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

The SILH model

$$
\begin{aligned}
S_{Jordan} = \int d^4x\sqrt{-g}\Bigg\{ & -\frac{M^2+2\xi HH^\dagger}{2}R-\frac{1}{4}W^{a\mu\nu}W^a_{\mu\nu}-\frac{1}{4}B^{a\mu\nu}B^a_{\mu\nu} \\
& +D_\mu H^\dagger D^\mu H-\lambda\left(HH^\dagger-\frac{v^2}{2}\right)^2\Bigg\}.
\end{aligned}
$$

Higgs Inflation model

	SILH	Higgs Inflation
λ_3	$(1+\frac{5}{2}c_6 v^2/f^2)(1+\frac{3}{2}c_6 v^2/f^2)^{-1}\zeta_h$	$(1+6\xi^2 v^2/M_p^2)^{-3/2}$
λ_4	$(1+\frac{15}{2}c_6 v^2/f^2)(1+\frac{3}{2}c_6 v^2/f^2)^{-1}\zeta_h^2$	$(1+6\xi^2 v^2/M_p^2)^{-2}$
ξ_5	$-2c_H v^2/f^2\zeta_h^3$	$-12v^2\xi^2/M_p^2(1+6\xi^2 v^2/M_p^2)^{-3/2}$
ξ_6	$-2c_H v^2/f^2\zeta_h^4$	$-12v^2\xi^2/M_p^2(1+6\xi^2 v^2/M_p^2)^{-2}$
$g_{W,b1}$	$c_{HW}\frac{g^2v^2}{32\pi^2 f^2}\zeta_h\zeta_W^2$	0
$g_{W,b2}$	$c_{HW}\frac{g^2v^2}{32\pi^2 f^2}\zeta_h^2\zeta_W^2$	0
$g_{W,a1}$	$\left[1-\left(c_W\frac{g^2v^2}{m_\rho^2}+c_{HW}\frac{g^2v^2}{16\pi^2 f^2}\right)\right]\zeta_h\zeta_W^2$	$(1+6\xi^2 v^2/M_p^2)^{-1/2}$
$g_{Z,a1}$	$\left[1-\left(c_W\frac{g^2v^2}{m_\rho^2}+c_B\frac{g'^2v^2}{m_\rho^2}+c_{HW}\frac{g^2v^2}{16\pi^2 f^2}+c_{HB}\frac{g'^2v^2}{16\pi^2 f^2}\right)\right]\zeta_h\zeta_Z^2$	$(1+6\xi^2 v^2/M_p^2)^{-1/2}$
$g_{W,a2}$	$\left[1-3\left(c_W\frac{g^2v^2}{m_\rho^2}+c_{HW}\frac{g^2v^2}{16\pi^2 f^2}\right)\right]\zeta_h^2\zeta_W^2$	$(1+6\xi^2 v^2/M_p^2)^{-1}$
$g_{Z,a2}$	$\left[1-3\left(c_W\frac{g^2v^2}{m_\rho^2}+c_B\frac{g'^2v^2}{m_\rho^2}+c_{HW}\frac{g^2v^2}{16\pi^2 f^2}+c_{HB}\frac{g'^2v^2}{16\pi^2 f^2}\right)\right]\zeta_h^2\zeta_Z^2$	$(1+6\xi^2 v^2/M_p^2)^{-1}$

A model corresponds to a specific corner of parameter space

3 Perturbative Unitarity Constraint

$$\mathcal{S}\mathcal{S}^\dagger = 1 \quad \mathcal{S} = 1 + i\mathcal{T} \quad -i(\mathcal{T} - \mathcal{T}^\dagger) = \mathcal{T}\mathcal{T}^\dagger$$

$$a^{\alpha\beta}_{AB} = \frac{1}{2}\int \mathrm{d}x_a\,\mathrm{d}x_b\,H^{\alpha*}_A(x_a)\,H^\beta_B(x_b)\,M^{\beta\alpha}(x_b, x_a)$$

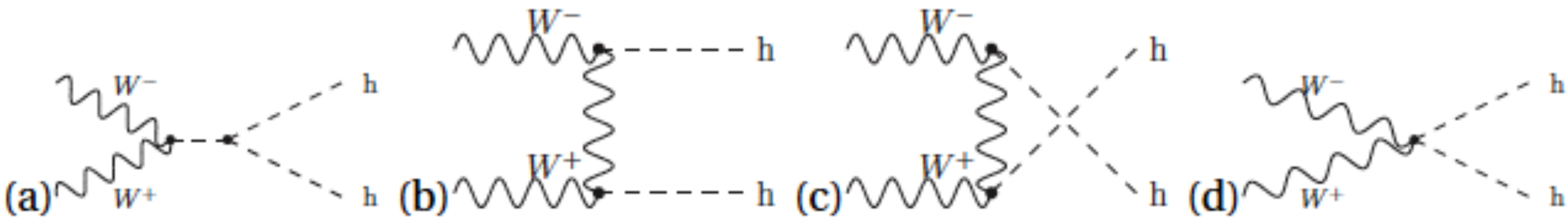
$$|\mathrm{Re}\,a^{\alpha\alpha}_{AA}|^2 + |\mathrm{Im}\,a^{\alpha\alpha}_{AA} - \frac{1}{2}|^2 + \sum_{C\neq A}|a^{\alpha\alpha}_{AC}|^2 + \sum_{\gamma\neq\alpha}\sum_C |a^{\alpha\gamma}_{AC}|^2 = \frac{1}{4}$$

$$|\mathrm{Re}\,a^{\alpha\alpha}_{AA}|^2 \leq \frac{1}{4}$$

$$|\mathrm{Im}\,a^{\alpha\alpha}_{AA} - \frac{1}{2}|^2 \leq \frac{1}{4}$$

$$\sum_{C\neq A}|a^{\alpha\alpha}_{AC}|^2 \leq \frac{1}{4}$$

$$\sum_{\gamma\neq\alpha}\sum_C |a^{\alpha\gamma}_{AC}|^2 \leq \frac{1}{4}$$



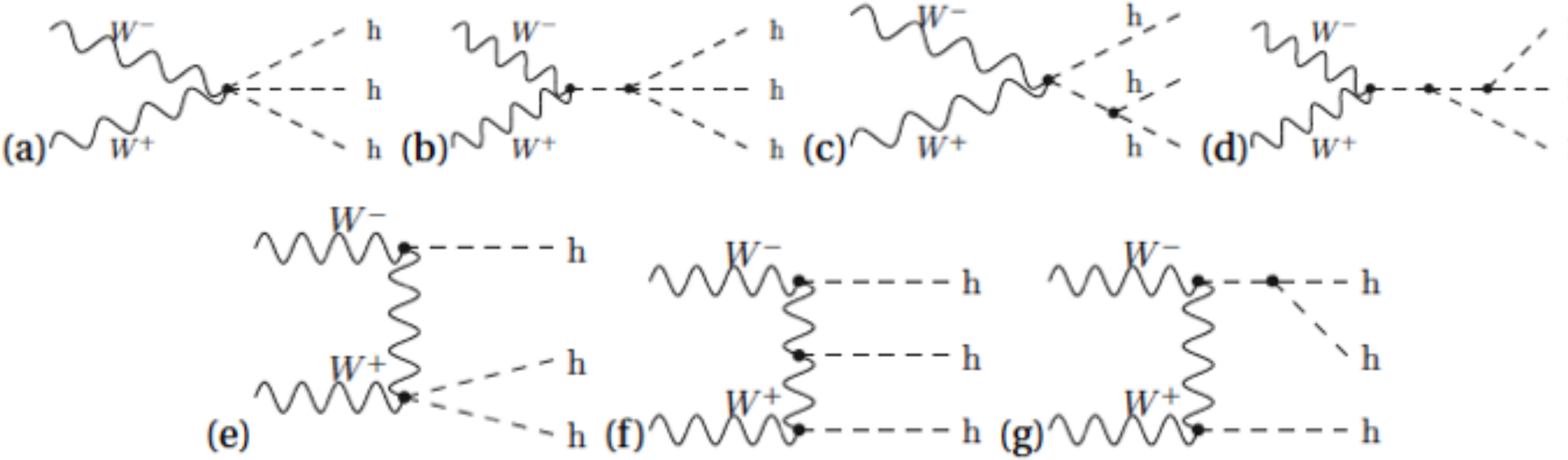
$$M(W^+W^- \to hh) = M_s + M_t + M_u + M_4.$$

$$M(W^+W^- \to hh) = \sum_{i=0}^{+\infty} m_i \left(\frac{\sqrt{s}}{v}\right)^{2-i}.$$

$$b_0(00) = \frac{s^2}{512\pi^2 v^4} |g_{W,a2} - g_{W,a1}^2 + \frac{1}{2}\kappa_5 g_{W,a1}|^2 \leq \frac{1}{4}$$

$$b_0(++) = \frac{s^2}{512\pi^2 v^4} |g_{W,b2} + 2g_{W,b1}^2 + \frac{1}{2}\kappa_5 g_{W,b1}|^2 \leq \frac{1}{4}$$

$$b_2(+-) = \frac{s^2}{3072\pi^2 v^4} g_{W,b1}^4 \leq \frac{1}{4}$$

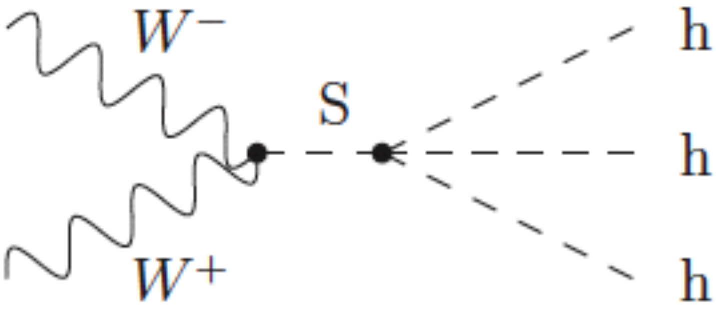


$$b_0(00) = \frac{s^3}{49152\pi^4 v^6} |g_{W,a3} + \frac{1}{2} g_{W,a1}\kappa_6 + \frac{3}{2} g_{W,a2}\kappa_5 + g_{W,a1}\kappa_5^2 - 4g_{W,a1}g_{W,a2} + 4g_{W,a1}^3 - 2g_{W,a1}^2\kappa_5|^2 \leq \frac{1}{4}$$

$$b_0(++) = \frac{s^3}{49152\pi^4 v^6} (|g_{W,b3} + \frac{1}{2} g_{W,b1}\kappa_6 + \frac{3}{2} g_{W,b2}\kappa_5 + g_{W,b1}\kappa_5^2 + 6g_{W,b1}g_{W,b2} + f_1 g_{W,b1}^3 - 3g_{W,b1}^2\kappa_5|^2 + f_2 g_{W,b1}^6) \leq \frac{1}{4}$$

4 Multi-Higgs boson final state via VBF Productions

Model Implement in Whizard

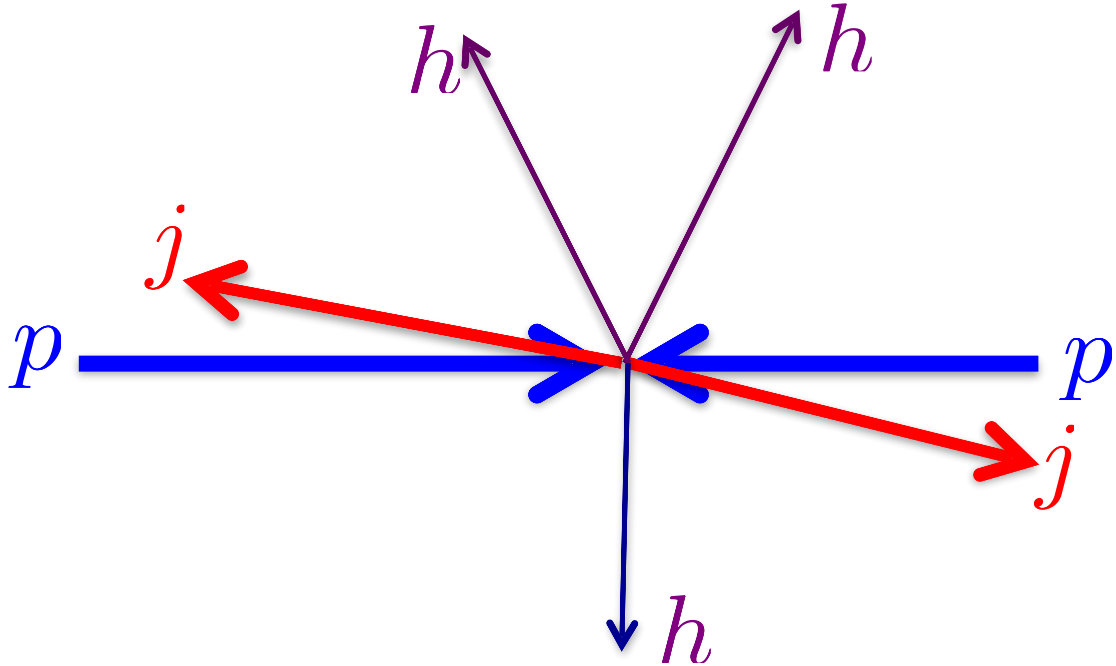


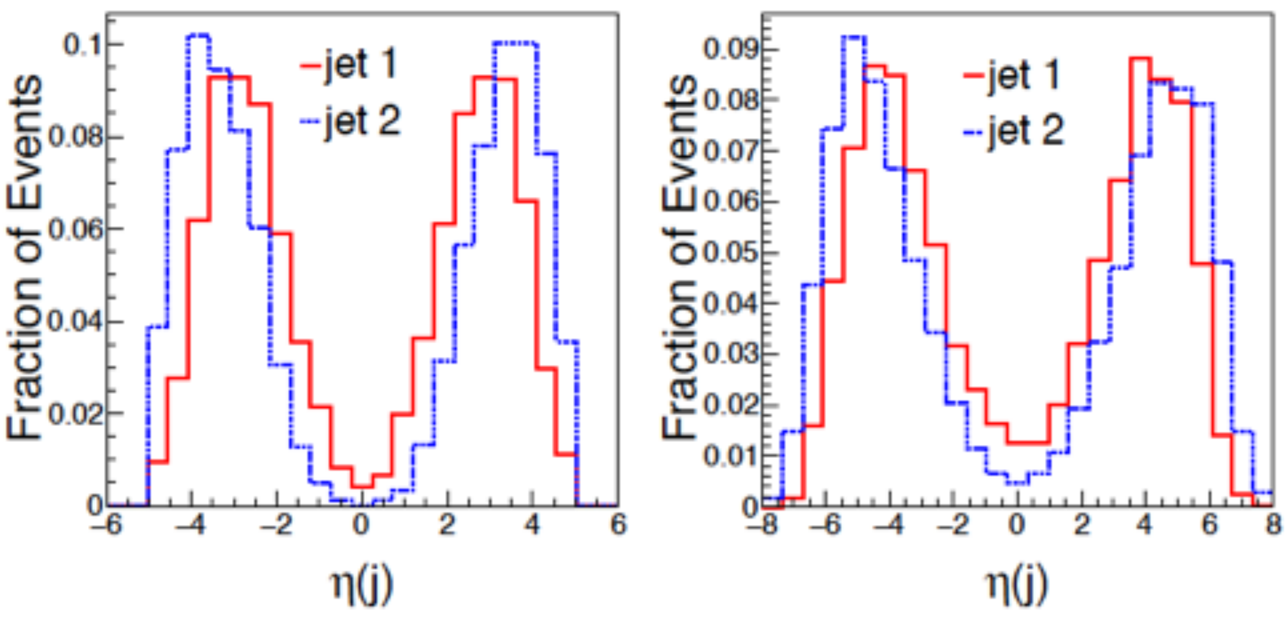
$$\mathcal{L}_S = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}M^2 S^2 - g_{Shhh}(\partial^2 S)h^3 + g_{w,a3}\frac{2m_W^2}{v^3}SW^\mu W_\mu - \frac{g_{w,b3}}{2v^3}SW^{\mu\nu}W_{\mu\nu}$$

Model Implement in Madgraph

$$\mathcal{L}_{hhh} = \frac{h^3}{3v^3}\left(g_{w,a3}m_W^2 W^\mu W_\mu - \frac{g_{w,b3}}{4}W^{\mu\nu}W_{\mu\nu}\right),$$

Agreement among Whizard, Madgraph, and VBFNLO is checked.

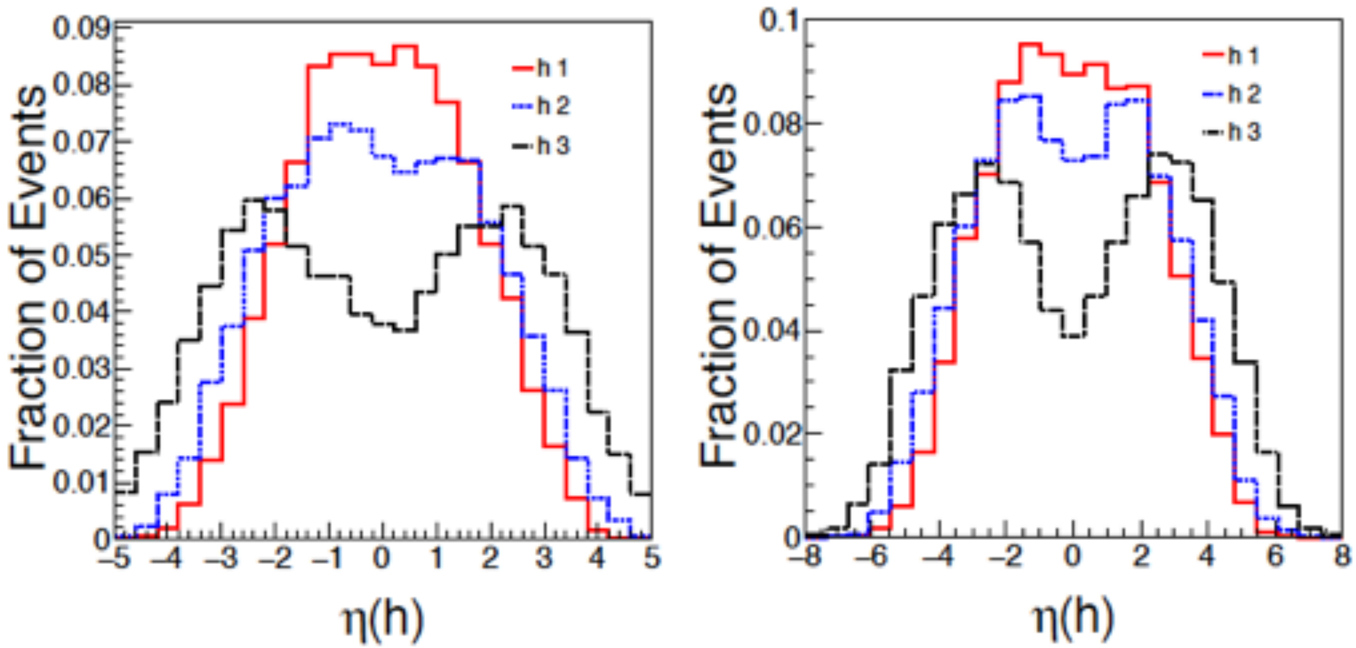




(a) 14 TeV

(b) 100 TeV

Cuts	$\sqrt{s} = 14$ TeV	$\sqrt{s} = 27$ TeV	$\sqrt{s} = 100$ TeV
$P_t(j)$	> 20 GeV	> 20 GeV	> 30 GeV
$\Delta R(j,j)$	> 0.8	> 0.8	> 0.8
$\|\eta(j)\|$	< 5.0	< 5.0	< 8.0
$\Delta\eta(j,j)$	> 3.6	> 3.6	> 4.0
$M(j,j)$	> 500 GeV	> 500 GeV	> 800 GeV

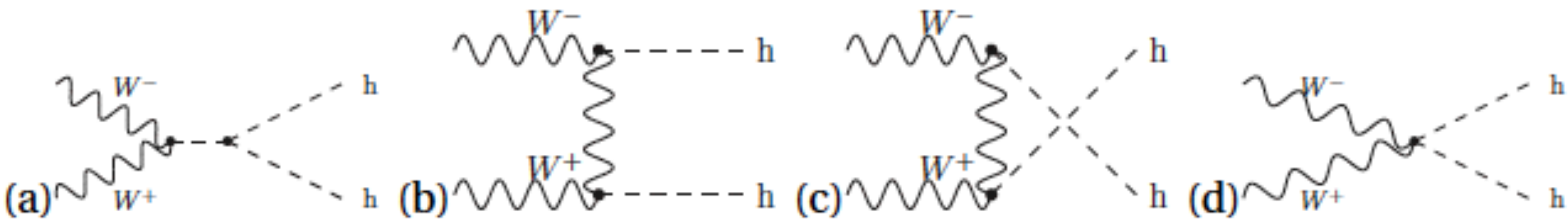


(a) 14 TeV

(b) 100 TeV

Process	σ(14TeV) [fb]	σ(100TeV) [fb]	$\frac{\sigma(100\text{TeV})}{\sigma(14\text{TeV})}$
$pp \to hjj$	1.64×10^3	2.60×10^4	15.9
$pp \to hhjj$	1.10	41.2	37.5
$pp \to hhhjj$	2.73×10^{-4}	4.50×10^{-2}	165

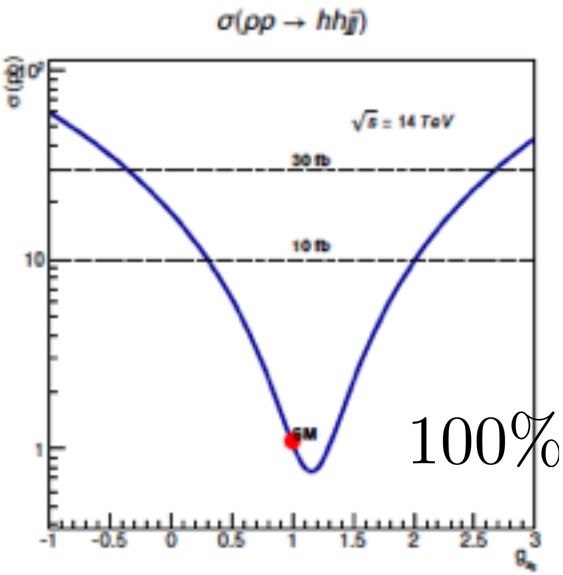
Results in the SM: gains with collision energy increase



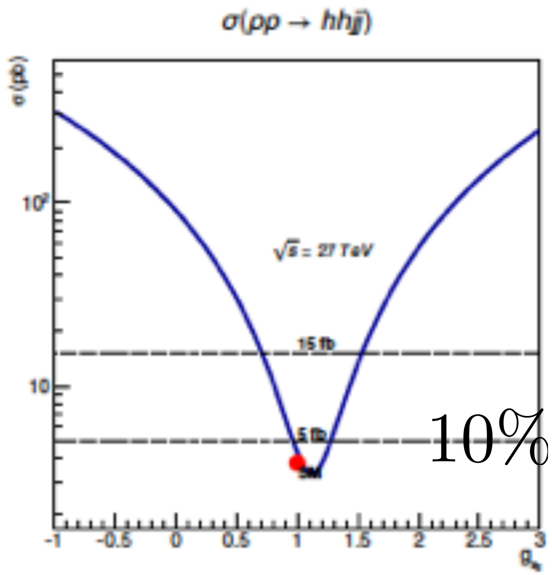
$$\sigma(pp \to hhjj) = K_0 + K_1 g_{W,a2} + K_2 g_{W,a2}^2 + K_3 g_{W,b2} + K_4 g_{W,a2} g_{W,b2} + K_5 g_{W,b2}^2 + K_6 \kappa_5 + K_7 g_{W,a2} \kappa_5 + K_8 g_{W,b2} \kappa_5 + K_9 \kappa_5^2 + K_{10} \lambda_3 + K_{11} g_{W,a2} \lambda_3 + K_{12} g_{W,b2} \lambda_3 + K_{13} \kappa_5 \lambda_3 + K_{14} \lambda_3^2$$

	K_0	K_1	K_2	K_3	K_4	K_5	K_6	K_7
14 TeV	23.37	-33.33	12.68	-0.88	1.97	106.8	-19.73	14.65
27 TeV	109.1	- 167.2	68.1	-5.27	10.5	1135.2	-94.96	74.48
100 TeV	1760	-3085	1401	-35.75	108.5	54070	-1630	1461

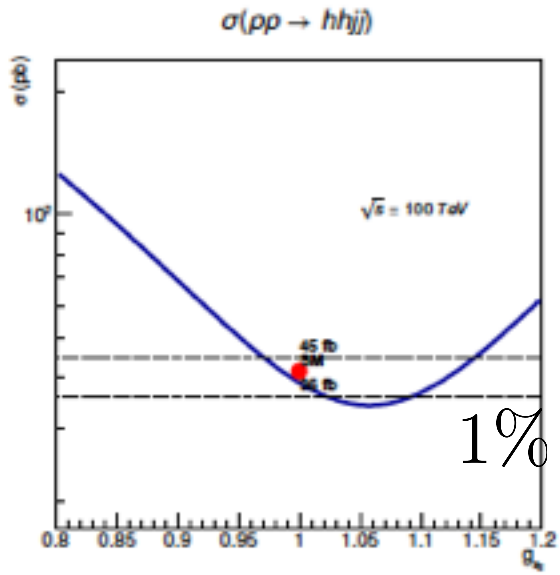
	K_8	K_9	K_{10}	K_{11}	K_{12}	K_{13}	K_{14}	
14 TeV	1.16	4.27	-6.39	4.00	0.43	2.70	0.73	
27 TeV	7.32	19.40	-23.4	14.99	1.74	10.04	2.61	
100 TeV	71.2	384.6	-175.1	121.2	10.33	76.91	16.3	



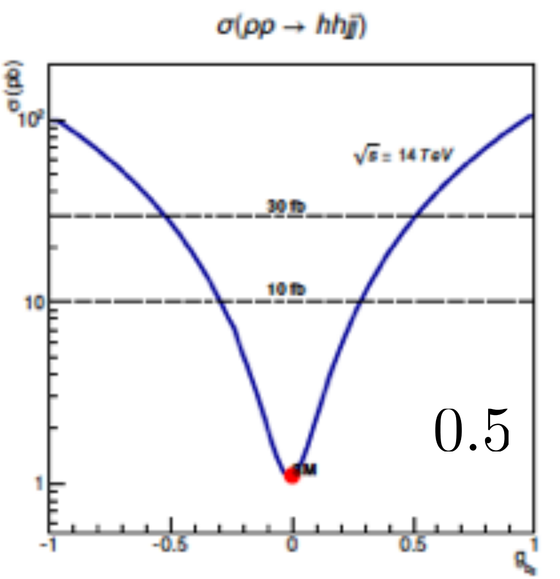
(a) 14 TeV



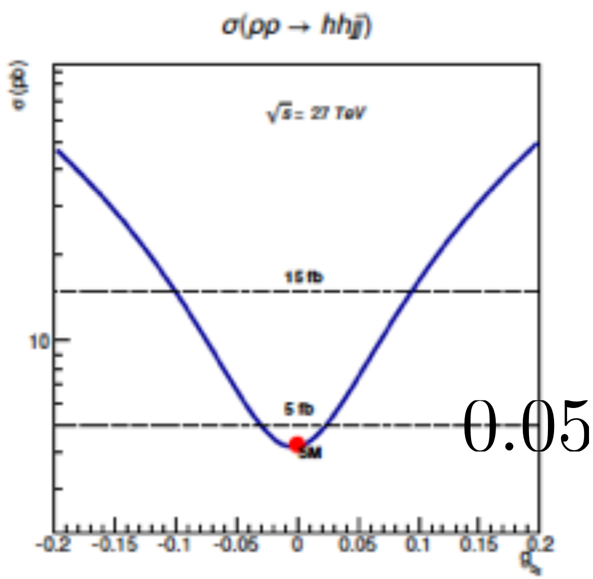
(b) 27TeV



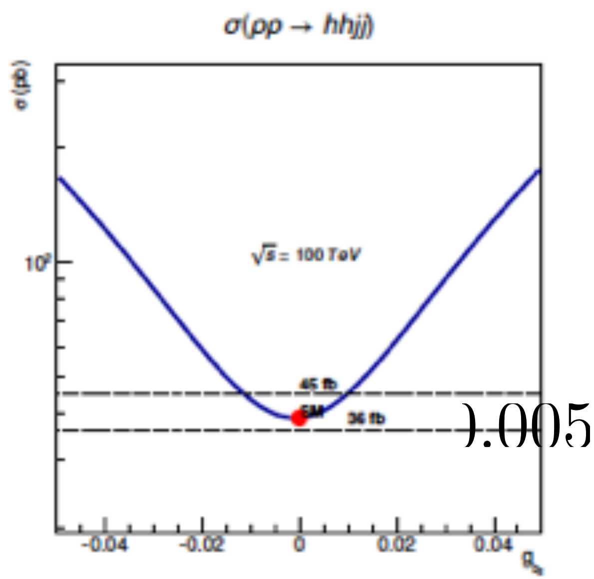
(c) 100 TeV



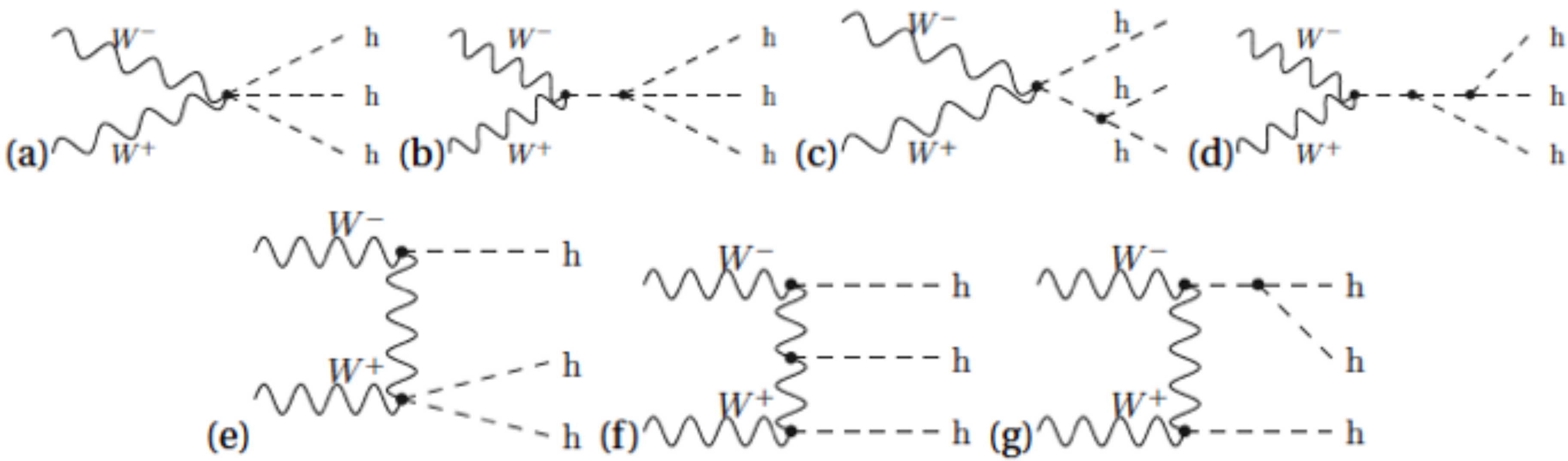
(d) 14 TeV



(e) 27 TeV



(f) 100 TeV



$$\sigma(pp \to VVjj \to hhhjj) = C_0 + C_1 g_{W,a3} + C_2 g_{W,a3}^2 + C_3 g_{W,b3} + C_4 g_{W,a3} g_{W,b3} + C_5 g_{W,b3}^2 + C_6 \kappa_6 + C_7 g_{W,a3}\kappa_6 + C_8 g_{W,b3}\kappa_6 + C_9 \kappa_6^2 + C_{10}\lambda_4 + C_{11} g_{W,a3}\lambda_4 + C_{12} g_{W,b3}\lambda_4 + C_{13}\kappa_6\lambda_4 + C_{14}\lambda_4^2$$

We assume other parameters can be determined to be close to those of the SM

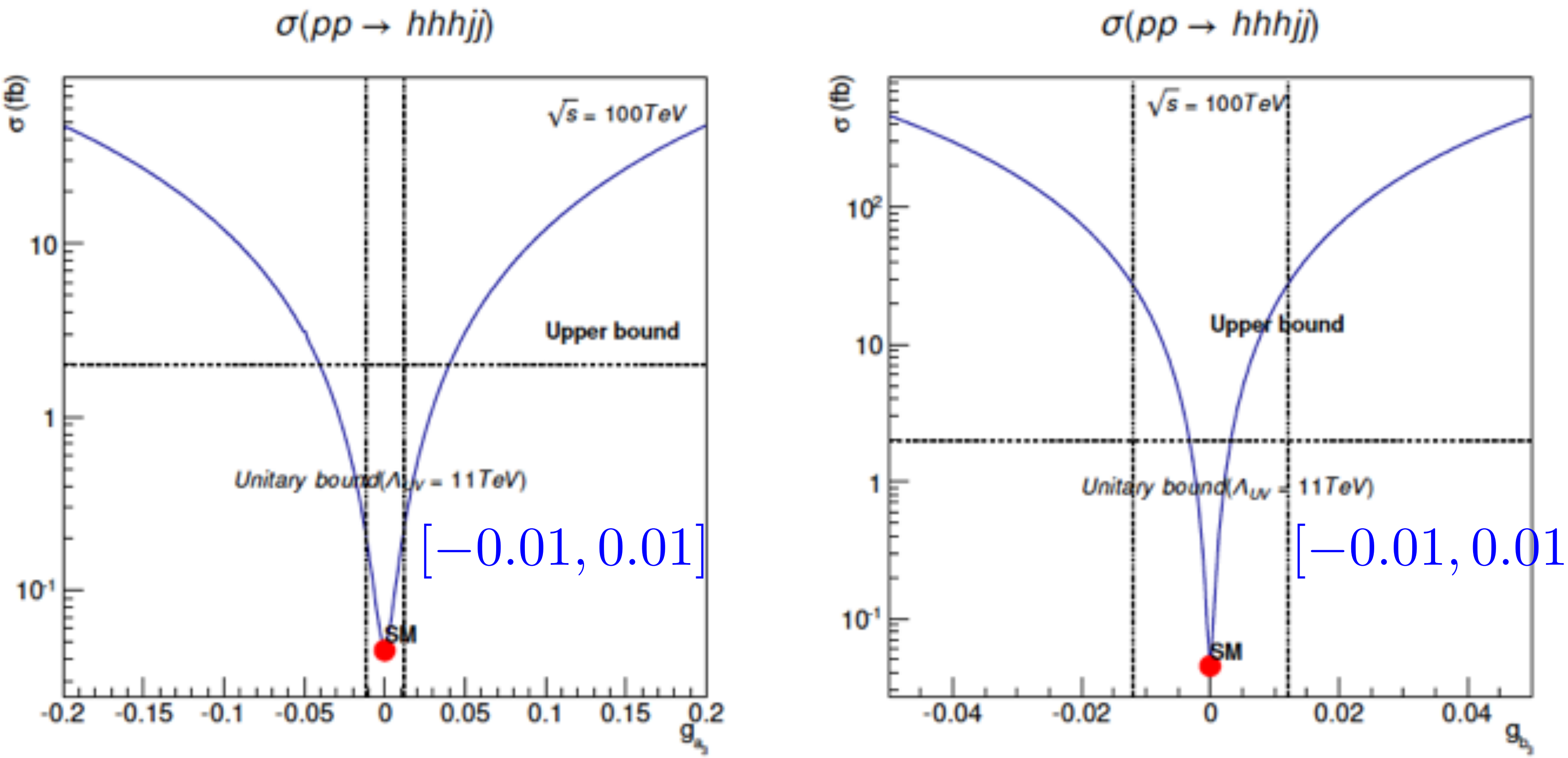
$$\sigma(pp\to VVjj\to hhhjj) = C_0 + C_1 g_{W,a3} + C_2 g_{W,a3}^2 + C_3 g_{W,b3} + C_4 g_{W,a3} g_{W,b3} + C_5 g_{W,b3}^2 + C_6\kappa_6 + C_7 g_{W,a3}\kappa_6 + C_8 g_{W,b3}\kappa_6 + C_9\kappa_6^2 + C_{10}\lambda_4 + C_{11} g_{W,a3}\lambda_4 + C_{12} g_{W,b3}\lambda_4 + C_{13}\kappa_6\lambda_4 + C_{14}\lambda_4^2$$

	C_0	C_1	C_2	C_3	C_4
14 TeV	6.18×10^{-4}	-9.42×10^{-3}	1.99×10^{-1}	-6.57×10^{-4}	2.11×10^{-2}
27 TeV	3.29×10^{-3}	-7.44×10^{-2}	2.974	-1.57×10^{-2}	3.02×10^{-1}
100 TeV	4.26×10^{-2}	- 1.74	6.01×10^{2}	-1.96	1.09×10^{2}

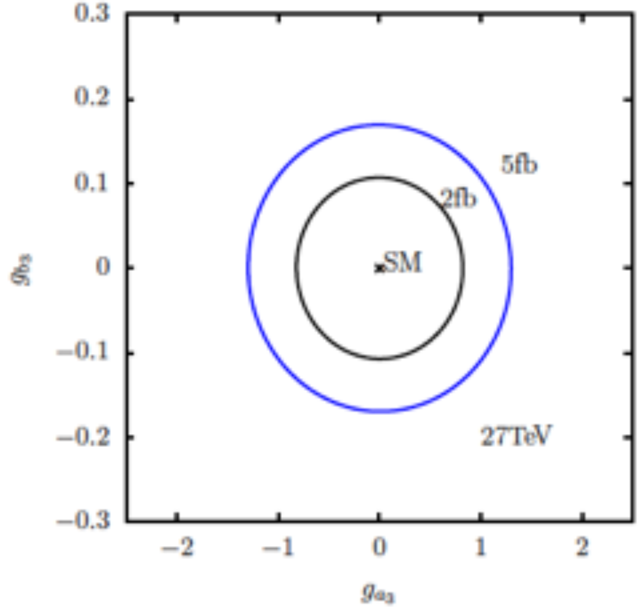
	C_5	C_6	C_7	C_8	C_9
14 TeV	4.80	-5.18×10^{-3}	2.05×10^{-1}	1.15×10^{-2}	5.30×10^{-2}
27 TeV	1.74×10^{2}	-3.92×10^{-2}	3.02	2.09×10^{-1}	7.66×10^{-1}
100 TeV	9.36×10^{4}	-1.13	6.08×10^{2}	1.82×10^{1}	1.53×10^{2}

	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}
14 TeV	-6.19×10^{-4}	9.38×10^{-3}	5.91×10^{-4}	5.03×10^{-2}	2.60×10^{-4}
27 TeV	-2.99×10^{-3}	6.44×10^{-2}	8.99×10^{-3}	3.38×10^{-2}	1.23×10^{-3}
100 TeV	-3.33×10^{-2}	1.88	1.29	9.75×10^{-1}	1.47×10^{-2}

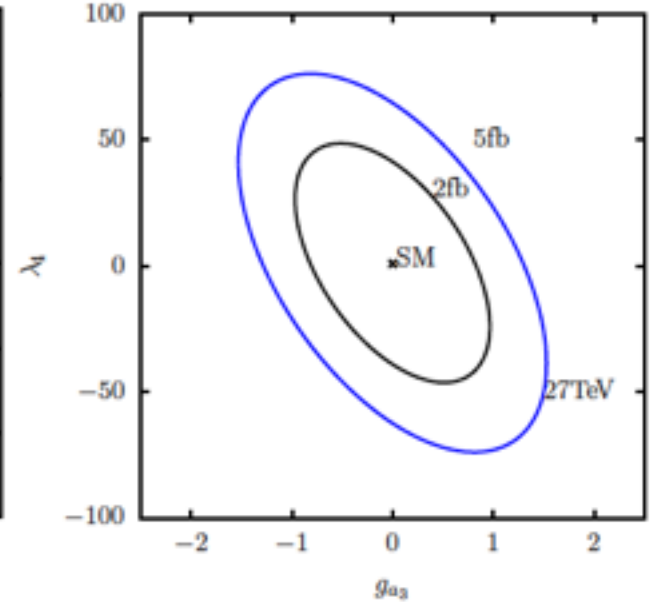
$$b_0(00) = \frac{s^3}{49152\pi^4 v^6}|g_{W,a3} + \frac{1}{2}g_{W,a1}\kappa_6 + \frac{3}{2}g_{W,a2}\kappa_5 + g_{W,a1}\kappa_5^2 - 4g_{W,a1}g_{W,a2} + 4g_{W,a1}^3 - 2g_{W,a1}^2\kappa_5|^2 \leq \frac{1}{4}$$



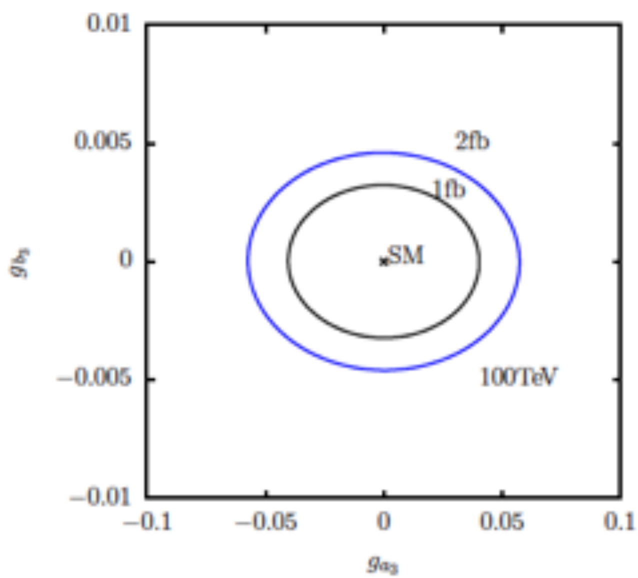
$$b_0(++) = \frac{}{49152\pi^4 v^6}(|g_{W,b3} + \frac{}{2}g_{W,b1}\kappa_6 + \frac{}{2}g_{W,b2}\kappa_5 + g_{W,b1}\kappa_5^2 + 6g_{W,b1}g_{W,b2} + f_1 g_{W,b1}^3 - 3g_{W,b1}^2\kappa_5|^2 + f_2 g_{W,b1}^6) \leq \frac{1}{4}$$



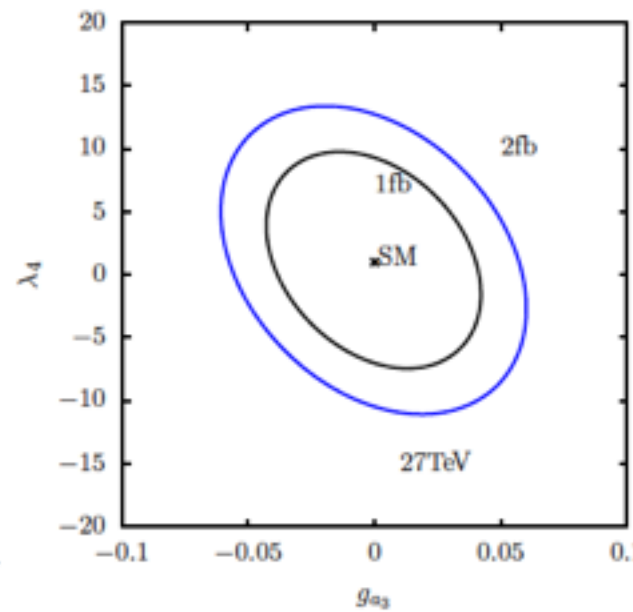
(a) 27 TeV



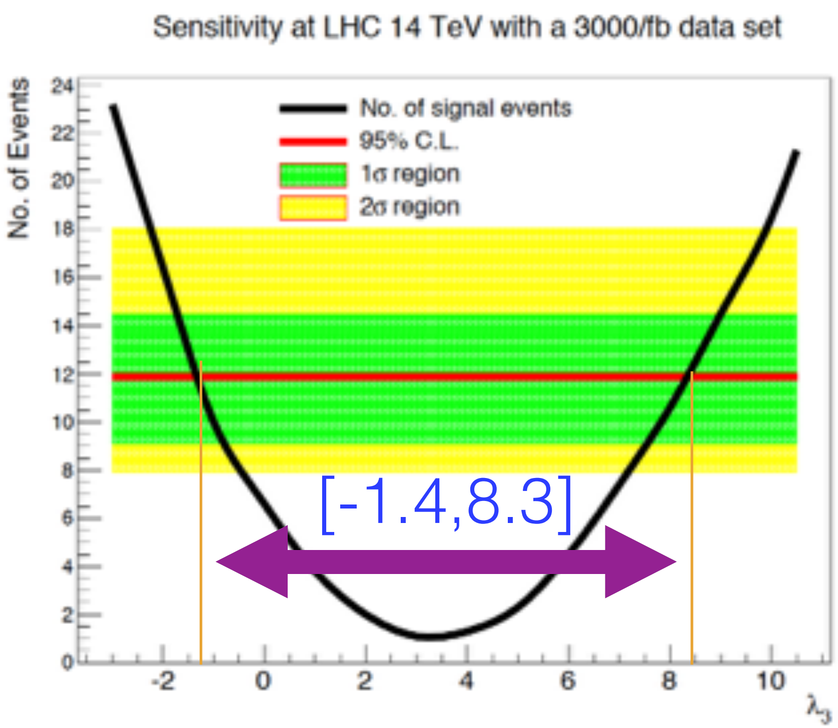
(b) 27 TeV

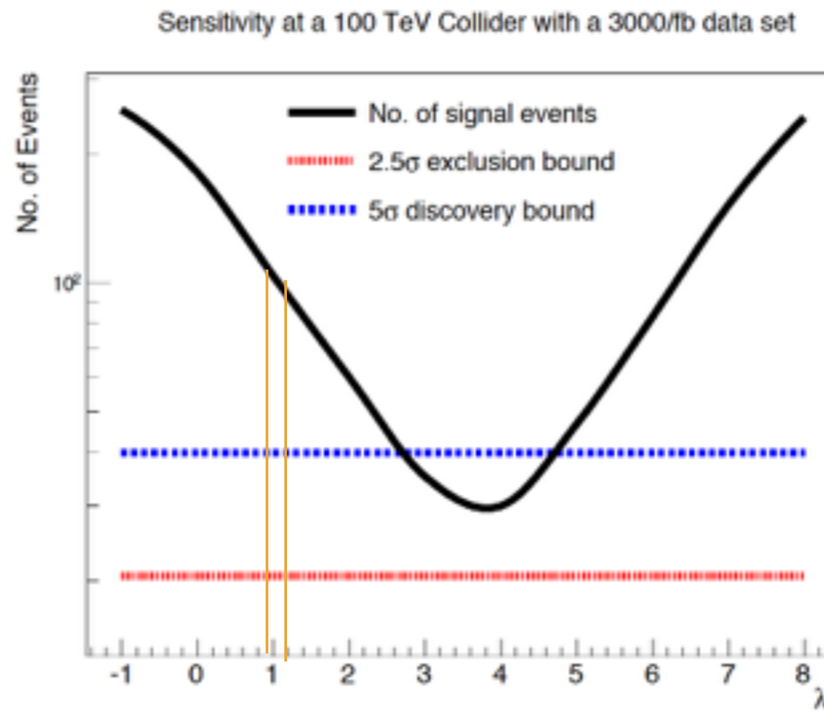


(c) 100 TeV



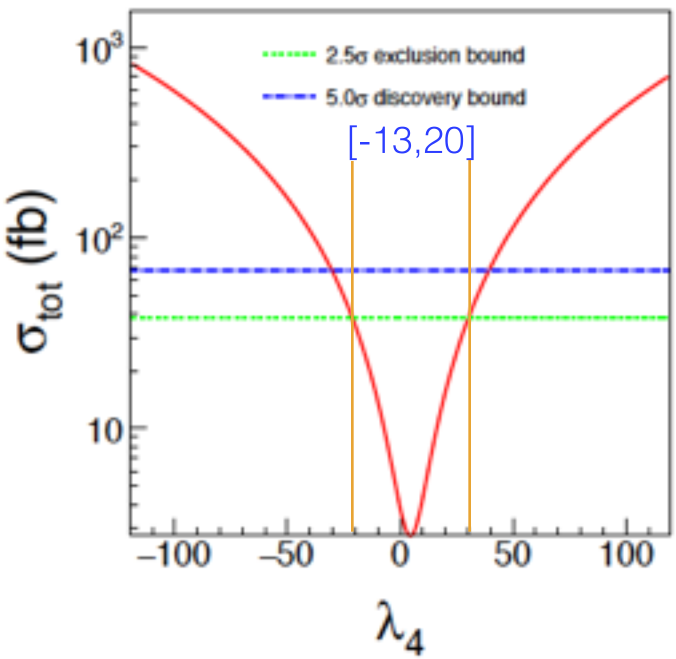
(d) 100 TeV



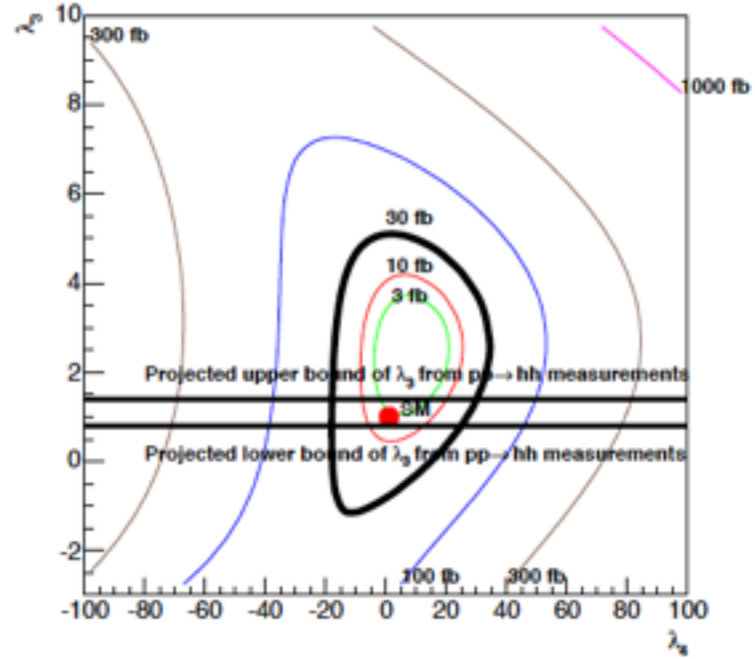


we can determine trilinear coupling to [0.9,1.2] at a 100 TeV collider with an integrated luminosity 30/ab, similar to a precision that ILC (1 TeV, 4/ab) can achieve

Q. Li, Z. Li, QY, X.R. Zhao, PRD92(2015)1,014015, arXiv:1503.07611



(a)The fitted cross section when λ_3 is fixed



(b)The feasibility of λ_3 and λ_4

C.Y. Chen,QY, X.R. Zhao, Z.J. Zhao, Y.M. Zhong, PRD93 (2016)1, 013007

EL for GF Processes

A general way to parameterize the EFT Lagrangian is (up to $O(p^6)$)

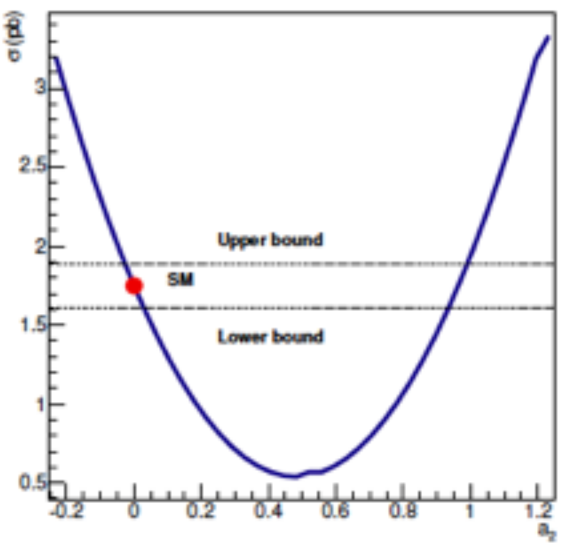
$$
\begin{aligned}
\mathcal{L}_{EFT} &= \mathcal{L}_{SM} + \mathcal{L}_t + \mathcal{L}_h + \mathcal{L}_{ggh}, \\
\mathcal{L}_t &= -a_1 \frac{m_t}{v} \bar{t}t\, h - a_2 \frac{m_t}{2v^2} \bar{t}t\, h^2 - a_3 \frac{m_t}{6v^3} \bar{t}t\, h^3, \\
\mathcal{L}_h &= -\lambda_3 \frac{m_h^2}{2v} h^3 - \frac{\kappa_5}{2v}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

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.

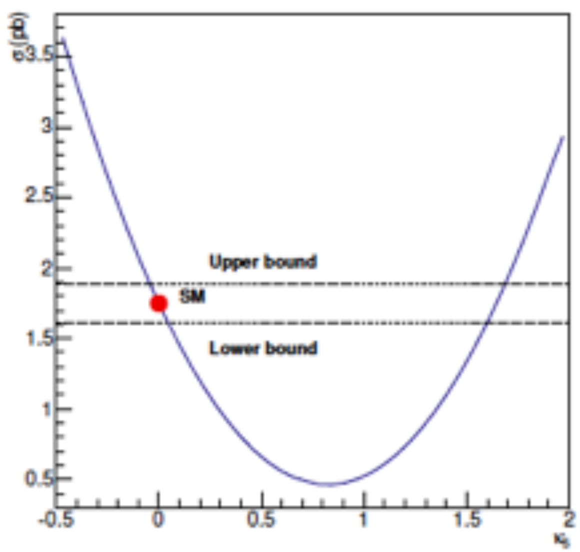
At leading order

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

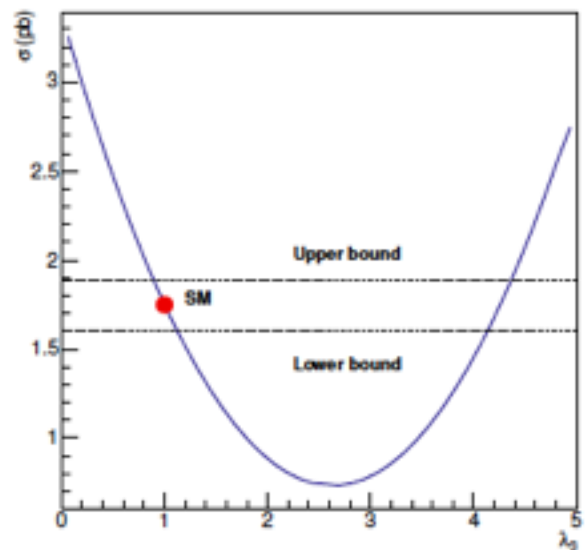
Effective Couplings at a 100 TeV collider



[0.99,1.01]



[-0.1,0.1]

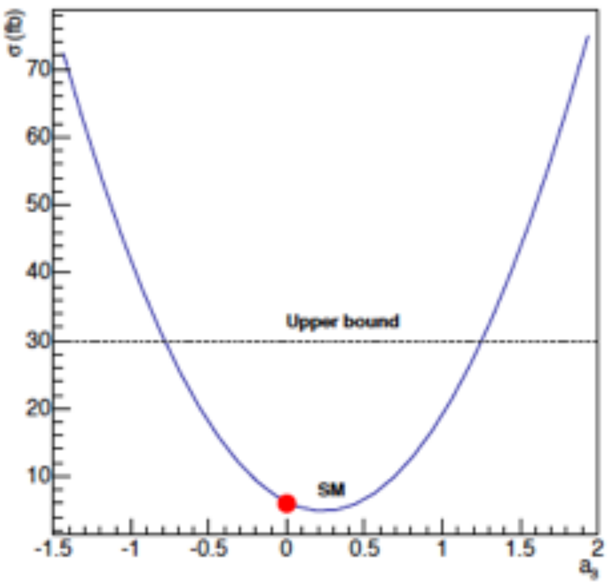


[0.9,1.1]

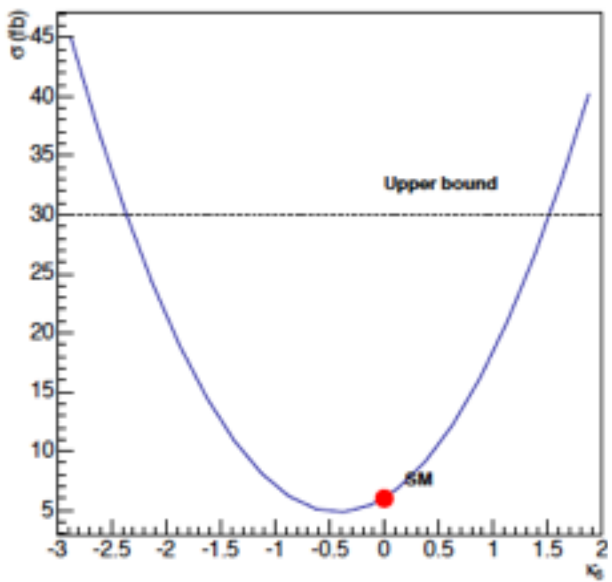
$$gg \to hh$$

W. Kilian, S. Sun, X. Zhao, and Z. Zhao, JHEP1706,145(2017)

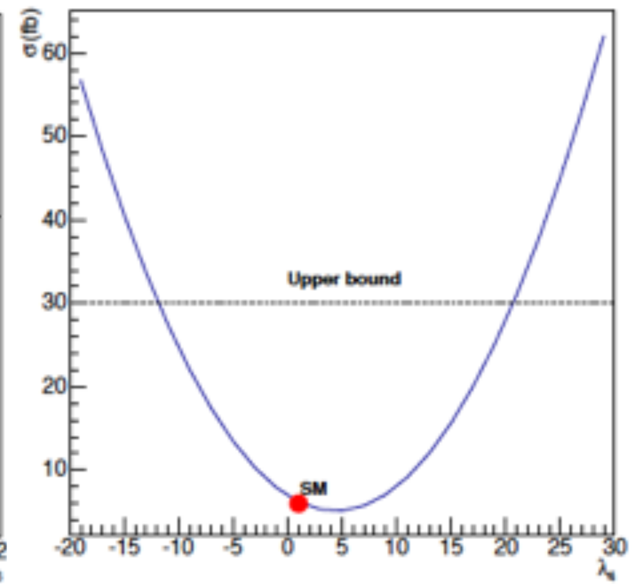
Higgs Quartic Couplings at a 100 TeV collider



[-0.8,1.3]



[-2.3,1.5]



[-13,20]

$$gg \to hhh$$

W. Kilian, S. Sun, X. Zhao, and Z. Zhao, JHEP1706,145(2017)

Parameters	LHC	LHC (projected)	ILC	CEPC	100 TeV
λ_3	$[-8.82, 15.04]$ [3]		27% [102]	28% [103]	10% [63]
λ_4					$[-13, 20]$ [63]
$g_{W,a1}$	$\leq 5.4\%$ [34, 35]		0.3% [102]	0.2% [108]	
$g_{W,b1}$		$[-0.008, 0.008]$ [107]		$[-0.30, 0.30]$ [108]	
$g_{X,b1}$				$\mathcal{O}(10^{-4})$ [109]	
$g_{Z,b1}$	$[0.098, 0.554]$ [34]	$[-0.011, 0.011]$ [107]		$\mathcal{O}(10^{-4})$ [109]	
$g_{W,a2}$		$[0.85, 1.19]$ [39]			$1^{+1\%}_{-1\%}$ [39]
$g_{W,b2}$		$[-0.008, 0.008]$ [107]			$0^{+1\%}_{-1\%}$
$g_{Z,b2}$		$[-0.011, 0.011]$ [107]			$0^{+2\%}_{-2\%}$
$g_{W,a3}$					$0^{+5\%}_{-5\%}$
$g_{W,b3}$					$0^{+0.5\%}_{-0.5\%}$
$g_{Z,b3}$					$0^{+1\%}_{-1\%}$

Conclusion

- EFT is a model independent way to describe new physics.
- **EFT with a Higgs boson** can serve as a useful tool to explore the potential of the LHC and future colliders.
- High energy hadron colliders and high precision machines can offer us the capability to address the fundamental questions about the Higgs sector at the TeV scale.

Backup

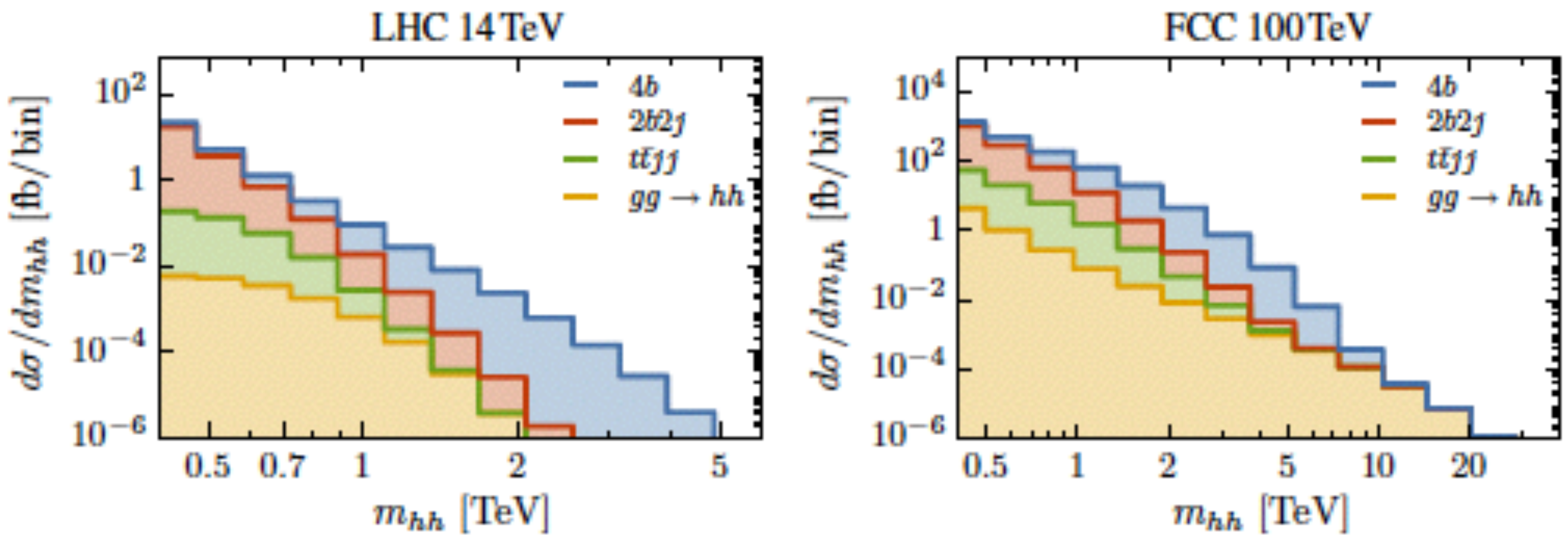
	Cross sections (fb)			
	Acceptance	VBF	Higgs reco.	m_{hh} cut
14 TeV				
Signal SM	0.011	0.0061	0.0039	0.0020
Signal $c_{2V} = 0.8$	0.035	0.020	0.017	0.011
Bkgd (total)	1.3×10^5	4.9×10^3	569	47
100 TeV				
Signal SM	0.22	0.15	0.11	0.033
Signal $c_{2V} = 0.8$	3.4	2.7	1.9	1.6
Bkgd (total)	1.9×10^6	1.9×10^5	9.5×10^3	212

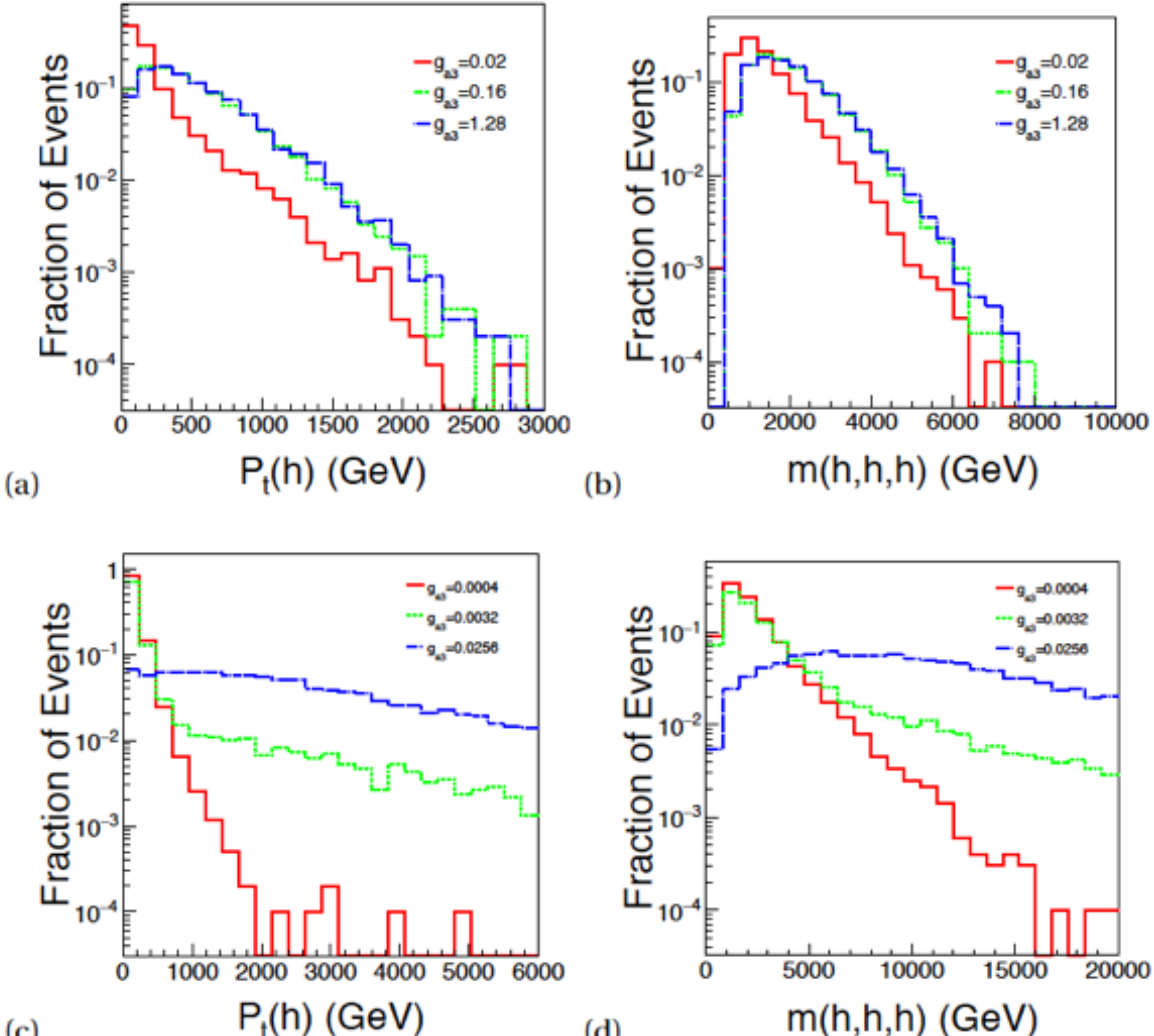
F. Bishara, R. Contino, and J. Rojo, EPJC(2017)77:481

Table 4 Same as Table 3, now listing separately each background process

	Acceptance	VBF	Higgs reco.	m_{hh} cut
LHC 14 TeV				
$4b$	1.18×10^4	613	54	4.45
$2b2j$	1.14×10^5	4.31×10^3	514	42.6
$t\bar{t}jj$	150	4.75	0.732	0.0706
$gg \to hh$	0.98	0.0388	0.0223	0.00857
Total	1.3×10^5	4.9×10^3	569	47
FCC 100 TeV				
$4b$	3.93×10^5	4.59×10^4	2.61×10^3	106
$2b2j$	1.52×10^6	1.46×10^5	6.88×10^3	104
$t\bar{t}jj$	9.76×10^3	832	55	1.47
$gg \to hh$	24.8	2.48	1.31	0.0892
Total	1.9×10^6	1.9×10^5	9.5×10^3	212

F. Bishara, R. Contino, and J. Rojo, EPJC(2017)77:481


LHC 14 TeV
FCC 100 TeV
4b
2b2j
tt̄jj
gg → hh
dσ/dm_hh [fb/bin]
m_hh [TeV]
10^2
1
10^-2
10^-4
10^-6
10^4
0.5
0.7
1
2
5
10
20



(a)
Fraction of Events
g_a3=0.02
g_a3=0.16
g_a3=1.28
P_t(h) (GeV)
0 500 1000 1500 2000 2500 3000
(b)
Fraction of Events
g_a3=0.02
g_a3=0.16
g_a3=1.28
m(h,h,h) (GeV)
0 2000 4000 6000 8000 10000
(c)
Fraction of Events
g_a3=0.0004
g_a3=0.0032
g_a3=0.0256
P_t(h) (GeV)
0 1000 2000 3000 4000 5000 6000
(d)
Fraction of Events
g_a3=0.0004
g_a3=0.0032
g_a3=0.0256
m(h,h,h) (GeV)
0 5000 10000 15000 20000