Investigating triple Higgs production in and beyond the SM at proton-proton colliders

Gilberto Tetlalmatzi-Xolocotzi

Based on:

A. Papaefstathiou, GTX, M. Zaro: 1909.09166/ Eur.Phys.J.C 79 (2019) 11, 947

A. Papaefstathiou, T. Robens, GTX: 2101.00037/ JHEP 05 (2021), 193

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Higgs Self-Interactions in the SM

$$\boxed{V\left(\Phi^\dagger\Phi\right)=\mu^2\Phi^\dagger\Phi+\lambda_{SM}\left(\Phi^\dagger\Phi\right)^2}$$

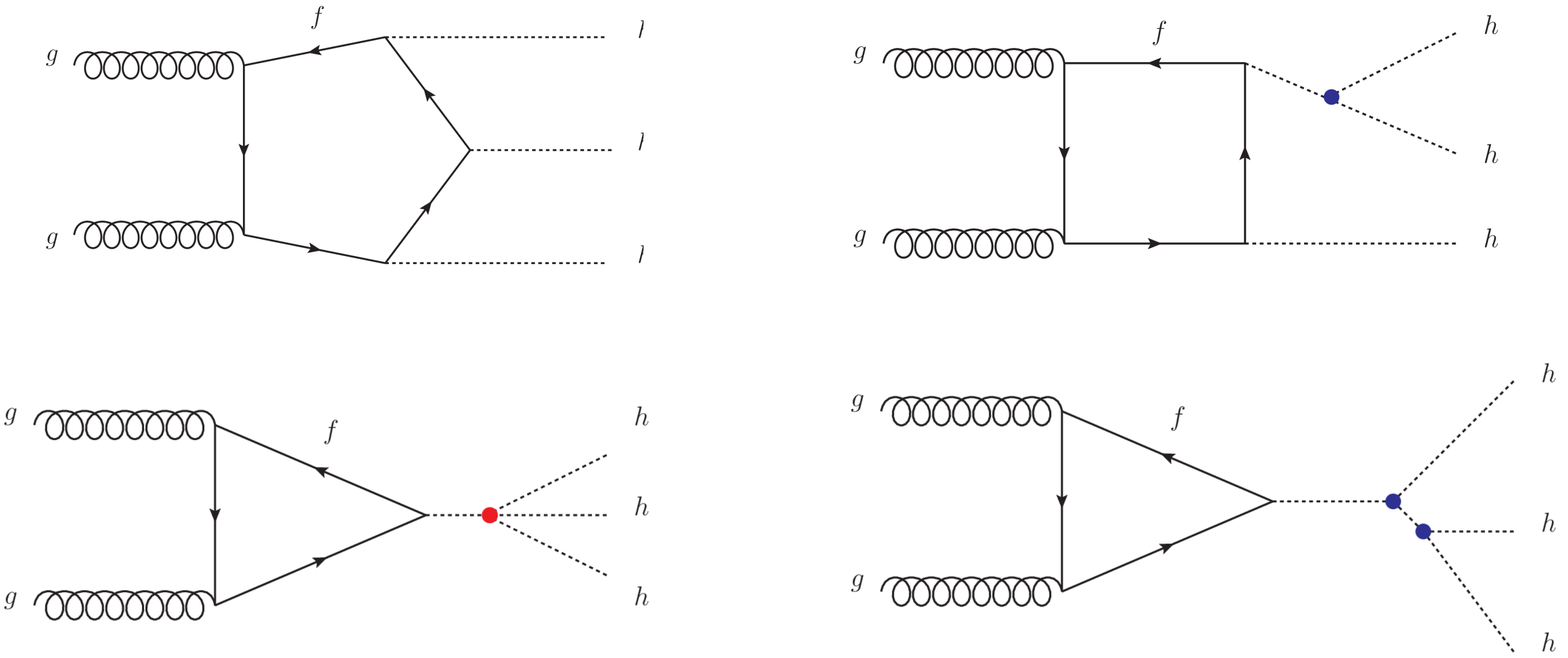
$$\Phi=\left(0,v_0+h\right)^T/\sqrt{2}$$

$$\boxed{V\left(\Phi^\dagger\Phi\right)\supset\tfrac{1}{2}m_h^2h^2+\lambda_{SM}v_0h^3+\frac{\lambda_{SM}}{4}h^4}$$

In the SM $m_h^2=\lambda_{SM}v_0^2/2$ $v_0^2=-\mu^2/\lambda_{SM}$

Triple Higgs production

$$g\,g \longrightarrow h\,h\,h$$



In the HL-LHC
(pp @ 14 TeV)

$$\sigma = 0.05\ fb$$

~*O(100)* events
Hopeless!

In the FCC
(pp @ 100 TeV)

$$\sigma \sim 5\ fb$$

Luminosity=*20 ab*$^{-1}$
~100 000 events.

de Florian, Fabre, Mazzitelli: 1912.02760

Why to study triple Higgs production?

- The triple Higgs self coupling is sensitive to New Particles.

- It allows to test the Higgs quartic self couplings.

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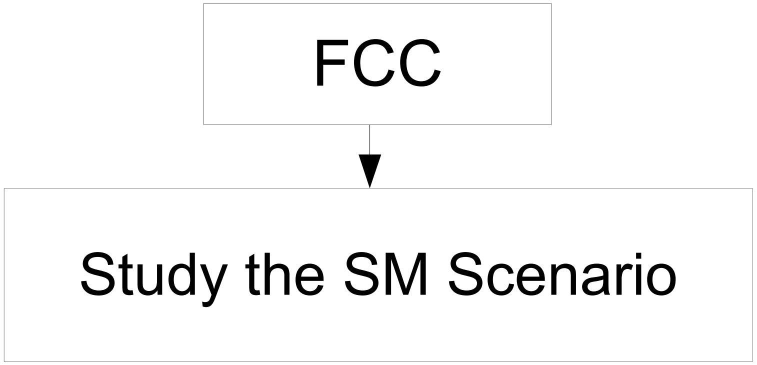

FCC

Study the SM Scenario

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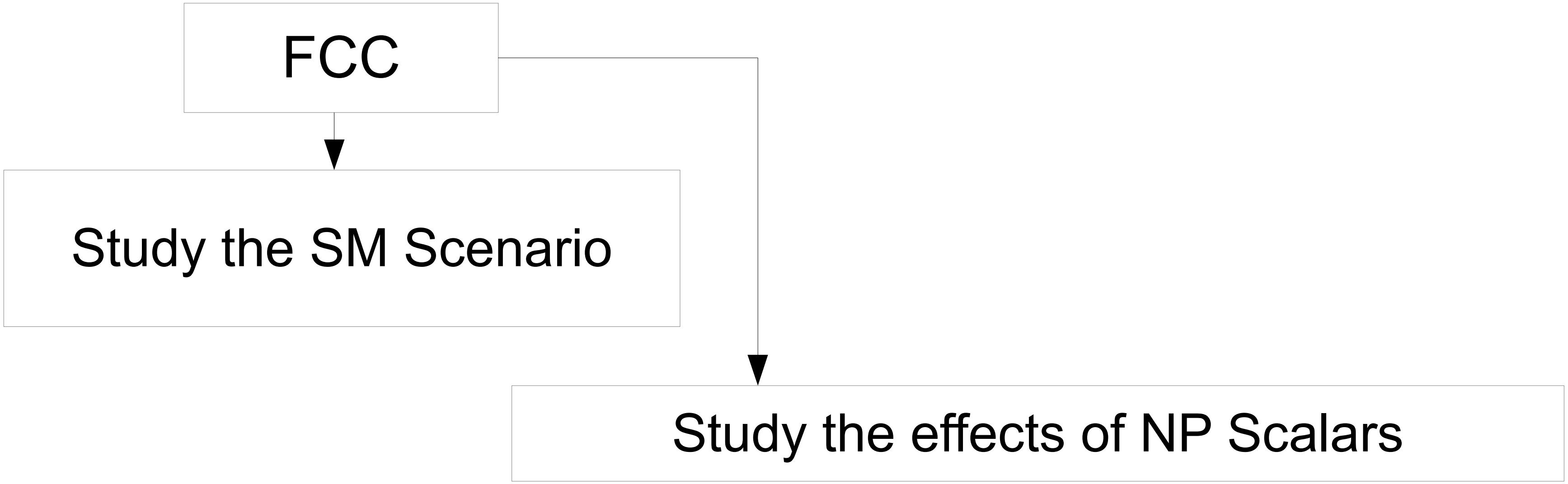

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Study the SM Scenario

Study the effects of NP Scalars

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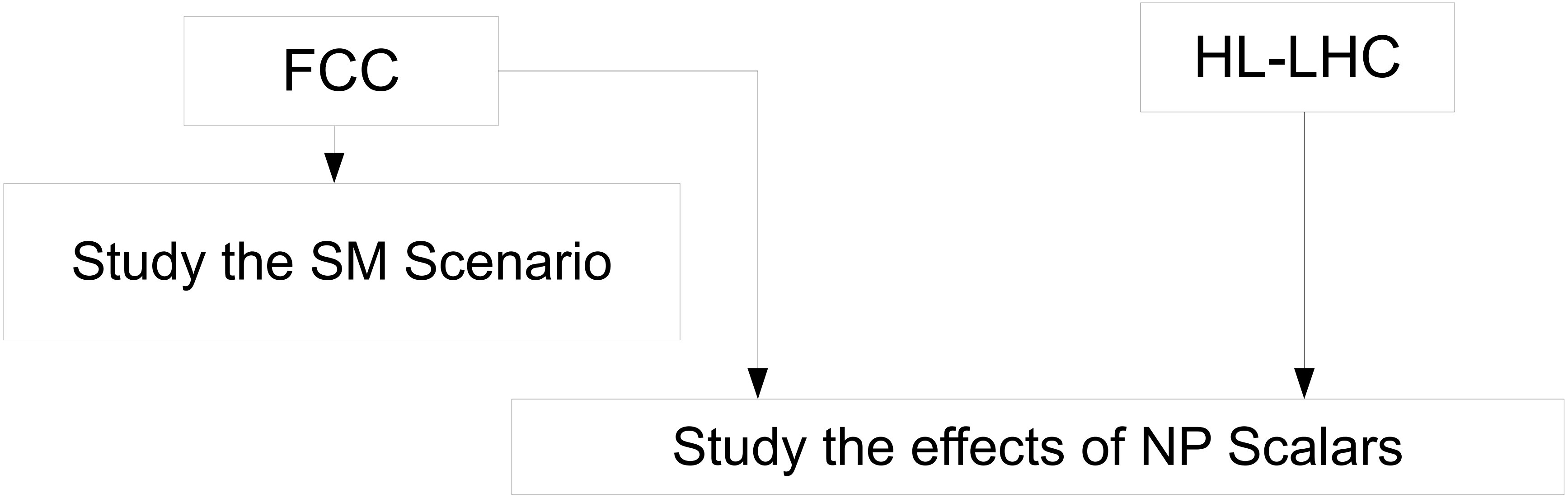


Final States

$$h\,h\,h \longrightarrow X$$

Assuming a K-factor of 2

Maltoni, Vryonidou, Zaro: 1408.6542

X (Final State)	*Br(%)*	*N(20 ab^{-1})*
$(b\bar{b})(b\bar{b})(b\bar{b})$	*19.21*	*22207*
$(b\bar{b})(b\bar{b})(WW_{1l})$	*7.20*	*8328*
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	*6.31*	*7297*
$(b\bar{b})(\tau\bar{\tau})(WW_{1l})$	*1.58*	*1824*
$(b\bar{b})(b\bar{b})(WW_{2l})$	*0.98*	*1128*
$(b\bar{b})(WW_{1l})(WW_{1l})$	*0.90*	*1041*
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	*0.69*	*799*
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	*0.23*	*263*

Papaefstathiou, GTX, Zaro: 1909.09166

Fuks, Kim, Lee: 1510.07697
1704.04298

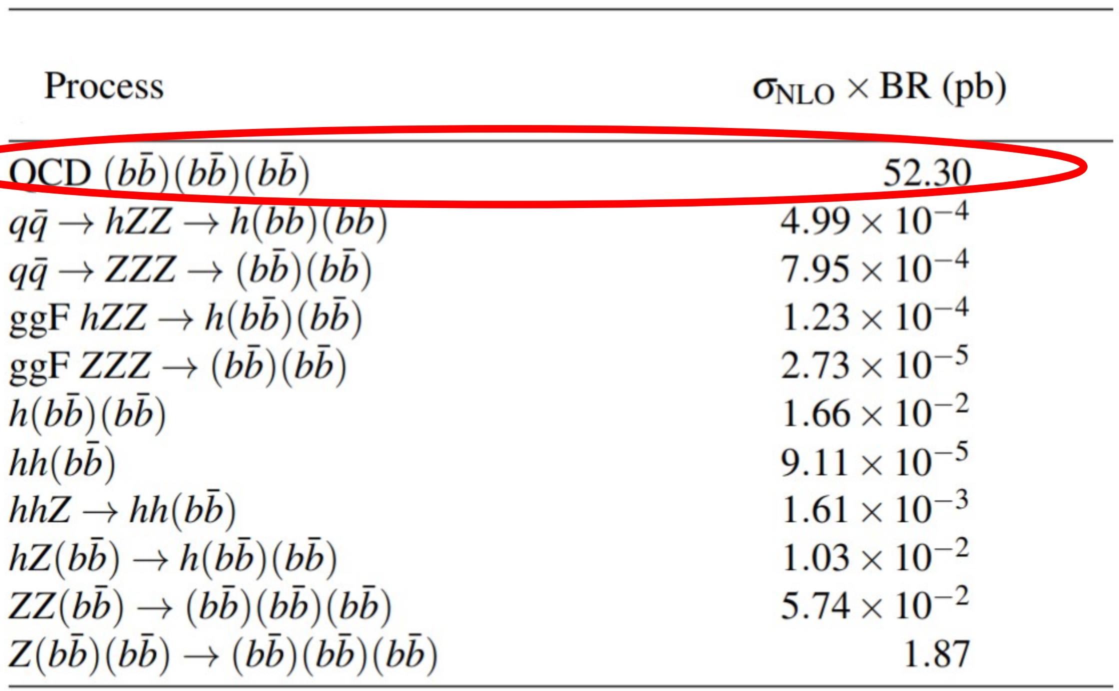
Killian et al.: 1702.03554

Papaefstathiou, Sakurai.: 1508.06524
Chen et al.:1510.04013
Fuks, Kim, Lee: 1510.07697

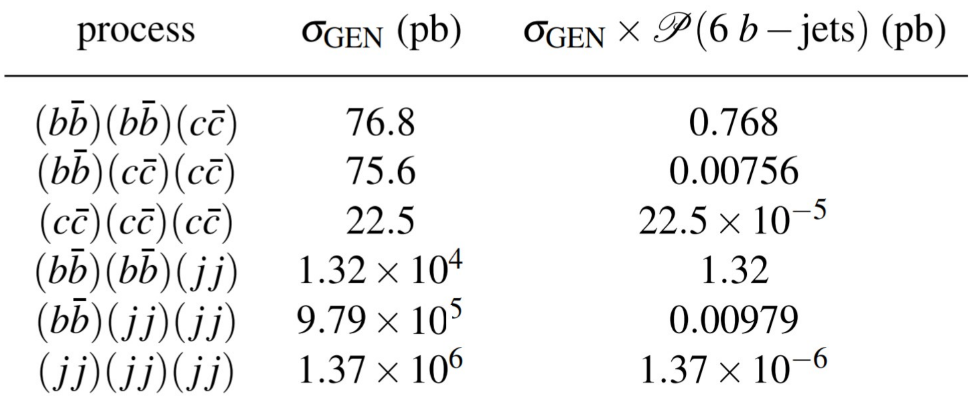
6-b final state has the largest Branching Fraction

This is the channel we are focusing on in this talk

Backgrounds



Process	$\sigma_{\mathrm{NLO}} \times \mathrm{BR}$ (pb)
QCD $(b\bar{b})(b\bar{b})(b\bar{b})$	52.30
$q\bar{q} \to hZZ \to h(bb)(bb)$	4.99×10^{-4}
$q\bar{q} \to ZZZ \to (b\bar{b})(b\bar{b})$	7.95×10^{-4}
ggF $hZZ \to h(b\bar{b})(b\bar{b})$	1.23×10^{-4}
ggF $ZZZ \to (b\bar{b})(b\bar{b})$	2.73×10^{-5}
$h(b\bar{b})(b\bar{b})$	1.66×10^{-2}
$hh(b\bar{b})$	9.11×10^{-5}
$hhZ \to hh(b\bar{b})$	1.61×10^{-3}
$hZ(b\bar{b}) \to h(b\bar{b})(b\bar{b})$	1.03×10^{-2}
$ZZ(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	5.74×10^{-2}
$Z(b\bar{b})(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	1.87



process	σ_{GEN} (pb)	$\sigma_{\mathrm{GEN}} \times \mathscr{P}(6\ b-\text{jets})$ (pb)
$(b\bar{b})(b\bar{b})(c\bar{c})$	76.8	0.768
$(b\bar{b})(c\bar{c})(c\bar{c})$	75.6	0.00756
$(c\bar{c})(c\bar{c})(c\bar{c})$	22.5	22.5×10^{-5}
$(b\bar{b})(b\bar{b})(jj)$	1.32×10^{4}	1.32
$(b\bar{b})(jj)(jj)$	9.79×10^{5}	0.00979
$(jj)(jj)(jj)$	1.37×10^{6}	1.37×10^{-6}

Includes miss-tagging factors

$$P_{c \to b} = 0.1$$

$$P_{j \to b} = 0.01$$

Details on the study of the 6b final state

- Parton level events (signal/background) generated with MadGraph5_aMC@NLO.

- The main source of background is QCD-6b-Jets.

- The production of the 6b-final state is challenging, it was generated in the NIKHEF and Siegen computer clusters using the gridpack option available in MadGraph5_aMC@NLO.

- Parton shower and non-perturbative effects included with Herwig 7.

- The analysis was performed using HwSim. [*Papaefsathiou*, https://bitbucket.org/andreasp/hwsim]

Selection Analysis

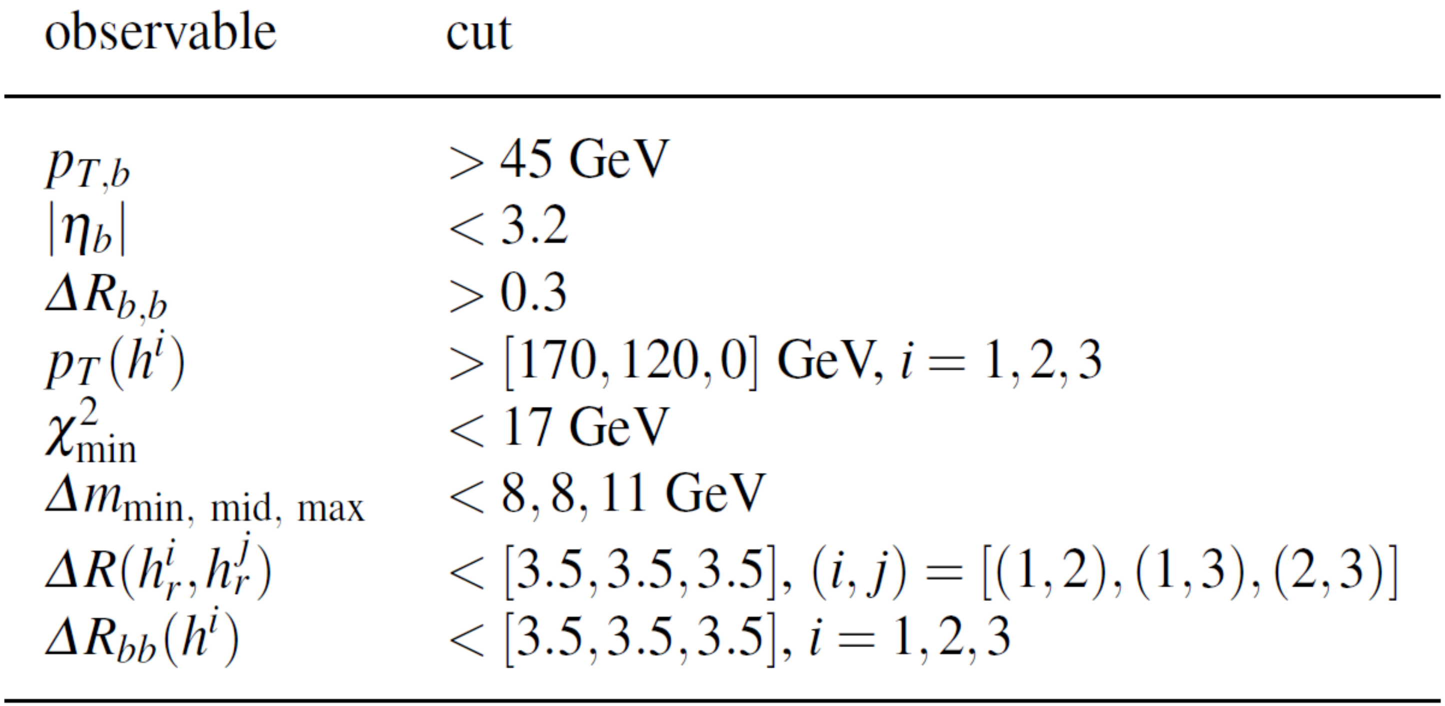
- *Require 6 b-tagged jets*
- *Construct all the possible combinations of 3-pairs of b-jets:* I.
- *For each combination* I calculate the observable

$$\chi^{2,(6)} = \sum_{qr \in I} \left(M_{qr} - m_h\right)^2$$

- *Select the event based on the value of the combination which minimizes* $\chi^{2,(6)}$
- *The combination determining* $\chi^{2,(6)}_{min}$ *defines the best candidates for the set of 3-Higgs* bosons in *the event.*

Selection Analysis

Set of observables and optimized cuts applied during the selection analysis



observable	cut
$p_{T,b}$	> 45 GeV
$\lvert\eta_b\rvert$	< 3.2
$\Delta R_{b,b}$	> 0.3
$p_T(h^i)$	$> [170, 120, 0]$ GeV, $i = 1, 2, 3$
χ^2_{min}	< 17 GeV
$\Delta m_{\text{min, mid, max}}$	$< 8, 8, 11$ GeV
$\Delta R(h^i_r, h^j_r)$	$< [3.5, 3.5, 3.5]$, $(i, j) = [(1,2), (1,3), (2,3)]$
$\Delta R_{bb}(h^i)$	$< [3.5, 3.5, 3.5]$, $i = 1, 2, 3$

h^i_r : Higgs boson candidate

$i = 1,2,3$

Sensitivity to quartic-self couplings

Consider a generalized version of the SM scalar potential

$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{SM}(1 + c_3) v_0 h^3 + \lambda_{SM} \frac{(1 + d_4)}{4} h^4$$

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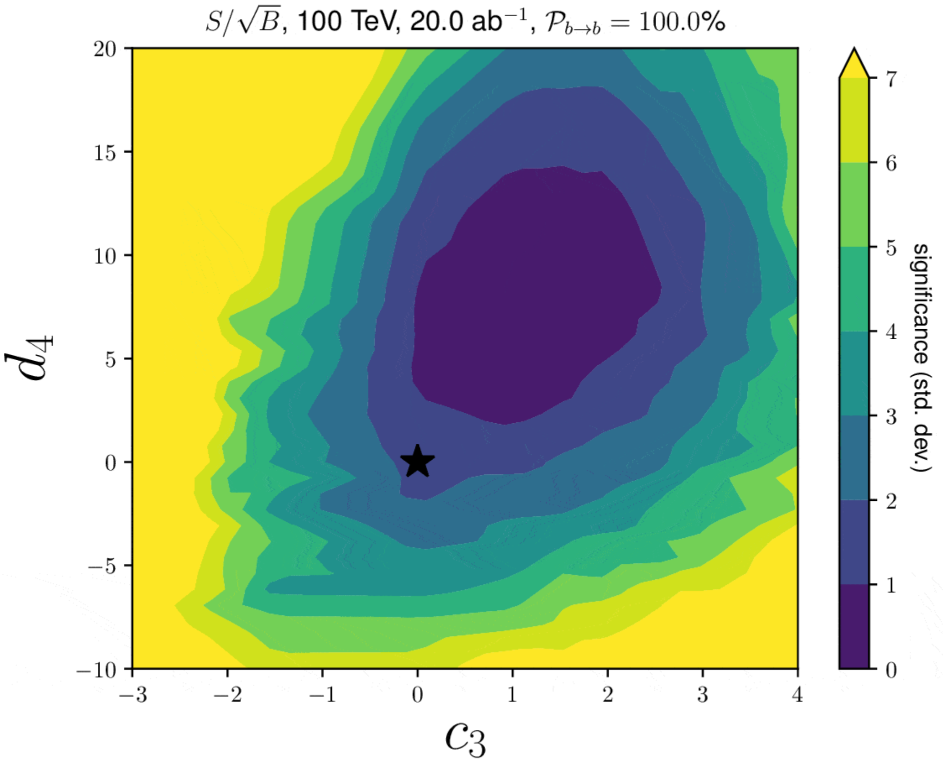

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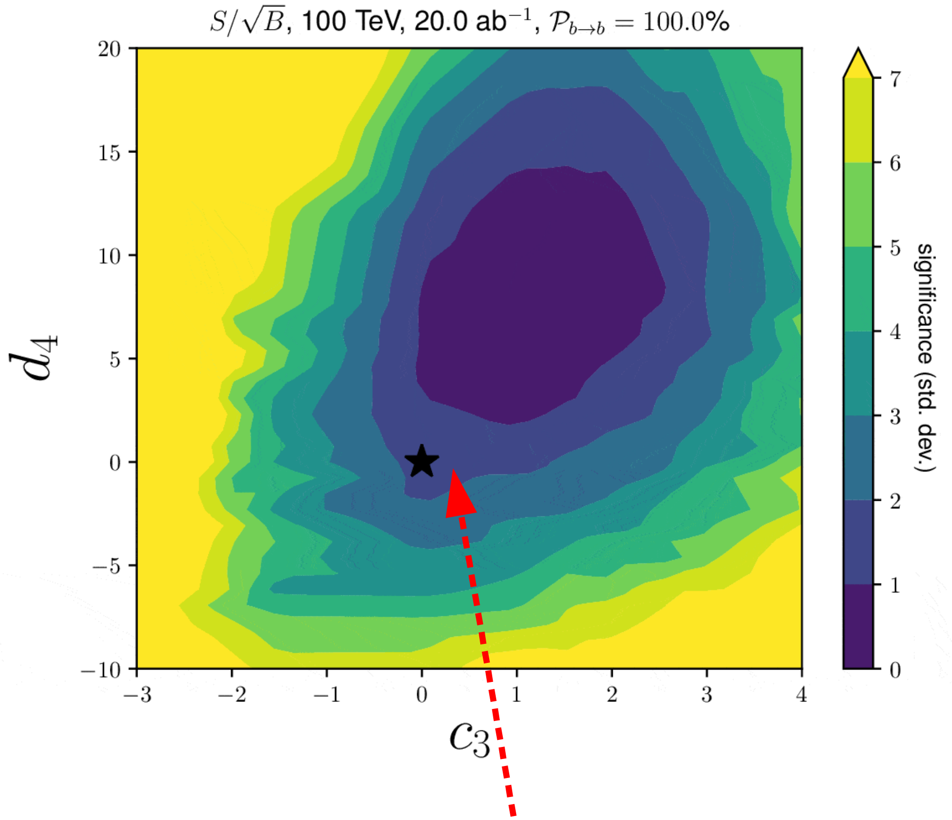

SM Significance ~1.7 σ

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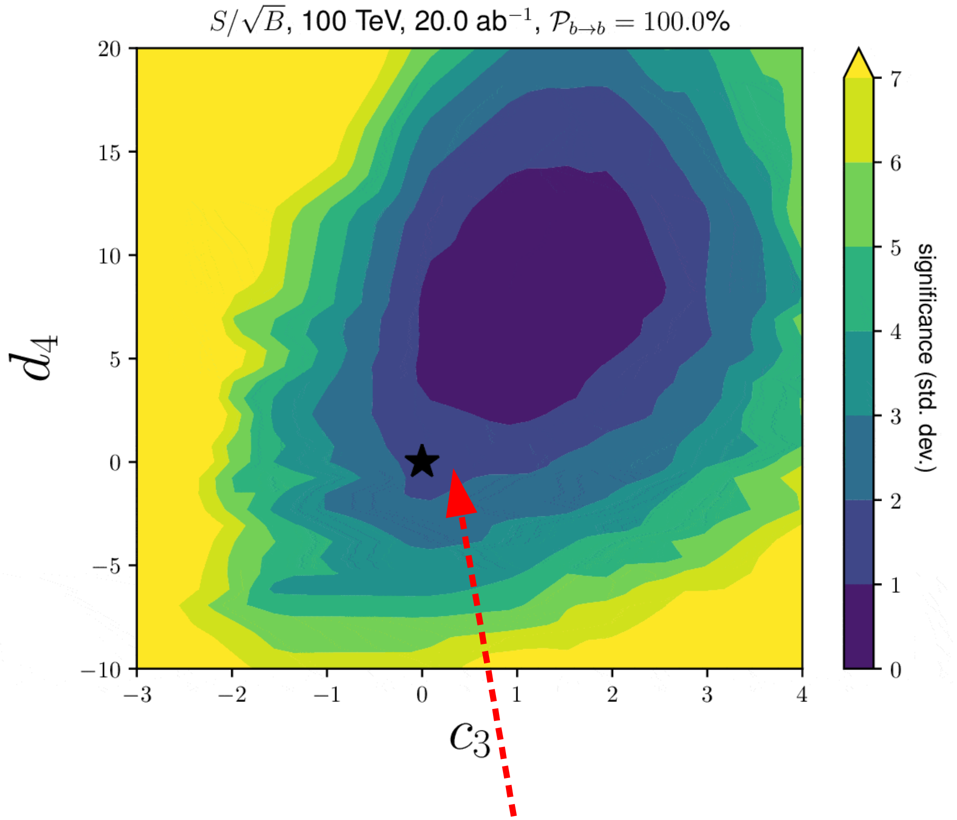

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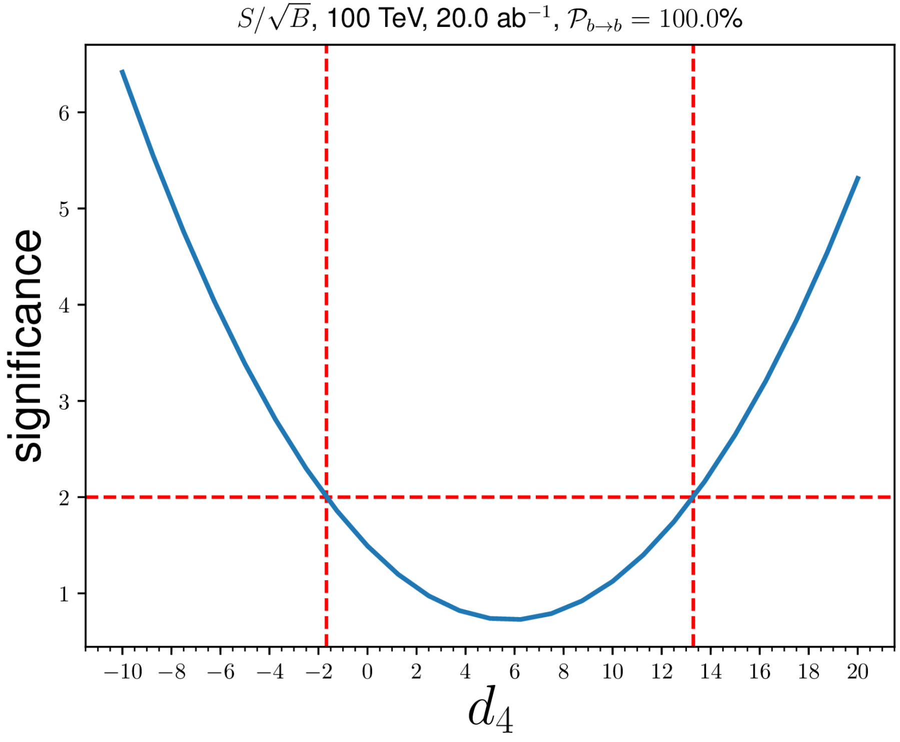


$c_3=0$

Adding an Extra-Scalar Singlet

The x-SM potential

$$V(\Phi, S) = \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \left(\frac{a_1}{2}\right)(\Phi^\dagger \Phi) S$$

$$+ \left(\frac{a_2}{2}\right)(\Phi^\dagger \Phi) S^2 + \left(\frac{b_2}{2}\right) S^2 + \left(\frac{b_3}{3}\right) S^3 + \left(\frac{b_4}{4}\right) S^4$$

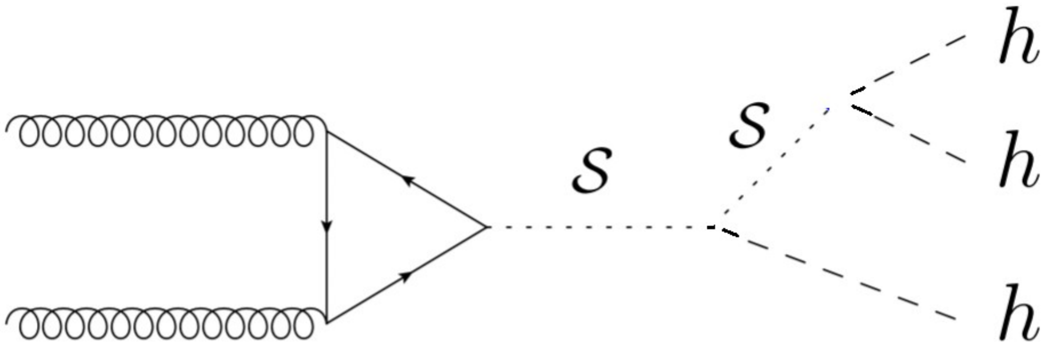
Kotwal et al. 1605.06123

Mass Eigenstates

$$h_1 = h \cos\theta + \phi_s \sin\theta$$

$$h_2 = -h \sin\theta + \phi_s \cos\theta$$

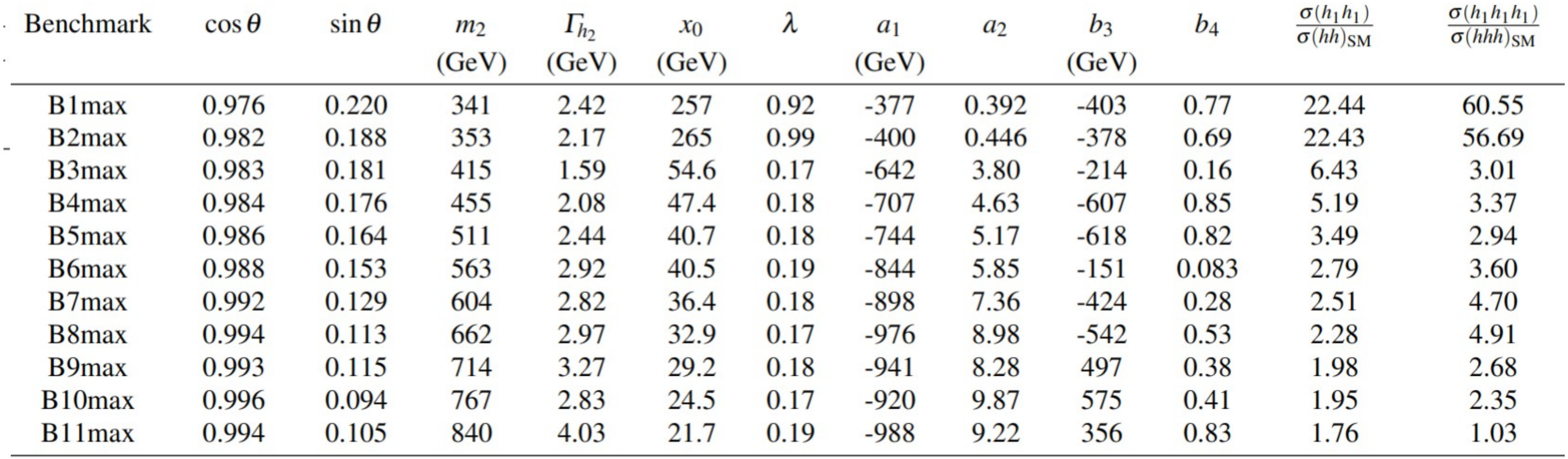
$$S = (\phi_S + v_S)/\sqrt{2}$$



Triple Higgs production in the presence of an extra-scalar

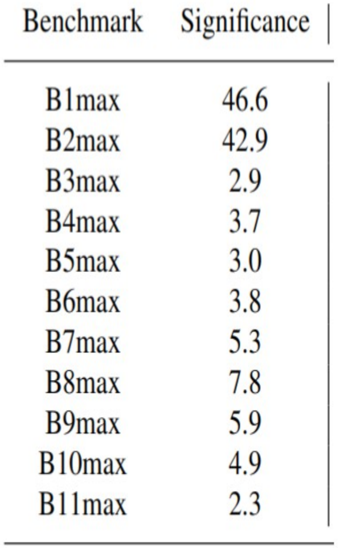
Analysis results

Benchmark points which lead to a Strong-First Order EW Phase Transition



Benchmark	$\cos\theta$	$\sin\theta$	m_2 (GeV)	Γ_{h_2} (GeV)	x_0 (GeV)	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	$\frac{\sigma(h_1h_1)}{\sigma(hh)_{SM}}$	$\frac{\sigma(h_1h_1h_1)}{\sigma(hhh)_{SM}}$
B1max	0.976	0.220	341	2.42	257	0.92	-377	0.392	-403	0.77	22.44	60.55
B2max	0.982	0.188	353	2.17	265	0.99	-400	0.446	-378	0.69	22.43	56.69
B3max	0.983	0.181	415	1.59	54.6	0.17	-642	3.80	-214	0.16	6.43	3.01
B4max	0.984	0.176	455	2.08	47.4	0.18	-707	4.63	-607	0.85	5.19	3.37
B5max	0.986	0.164	511	2.44	40.7	0.18	-744	5.17	-618	0.82	3.49	2.94
B6max	0.988	0.153	563	2.92	40.5	0.19	-844	5.85	-151	0.083	2.79	3.60
B7max	0.992	0.129	604	2.82	36.4	0.18	-898	7.36	-424	0.28	2.51	4.70
B8max	0.994	0.113	662	2.97	32.9	0.17	-976	8.98	-542	0.53	2.28	4.91
B9max	0.993	0.115	714	3.27	29.2	0.18	-941	8.28	497	0.38	1.98	2.68
B10max	0.996	0.094	767	2.83	24.5	0.17	-920	9.87	575	0.41	1.95	2.35
B11max	0.994	0.105	840	4.03	21.7	0.19	-988	9.22	356	0.83	1.76	1.03

Identification of the
Extra-scalar at *100 TeV*



Benchmark	Significance
B1max	46.6
B2max	42.9
B3max	2.9
B4max	3.7
B5max	3.0
B6max	3.8
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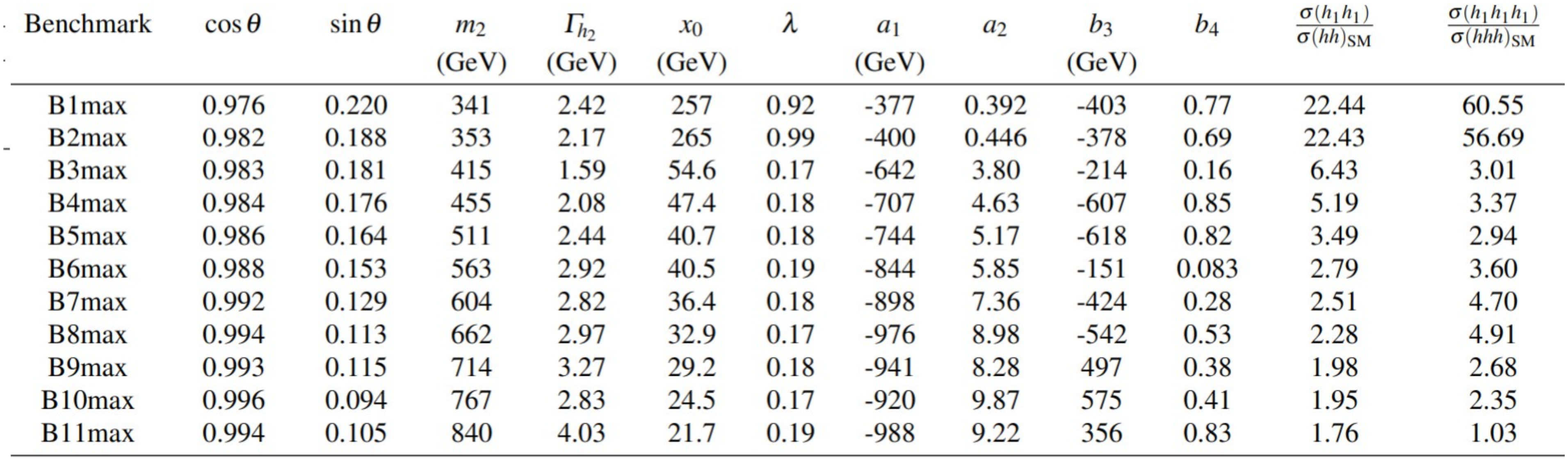

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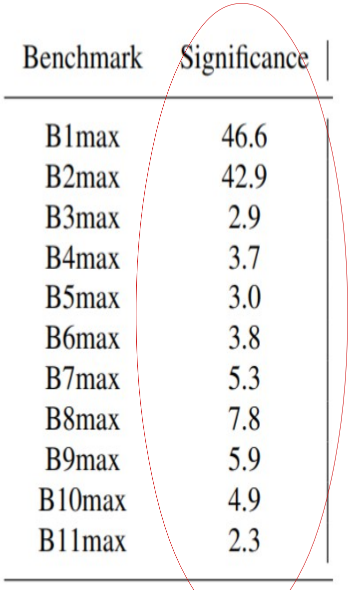

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Two Real Singlet Extension of the SM
TRSM

Robens, Stefaniak, Wittbrodt: 1908.08554

$$V(\Phi,\phi_i)=V_{SM}(\Phi)+V(\Phi,S,X)$$

Reduce the number of parameters by imposing

$$\mathbb{Z}_2^S : S\rightarrow -S\,,\; X\rightarrow X$$

$$\mathbb{Z}_2^X : S\rightarrow S\,,\; X\rightarrow -X$$

$$V(\Phi,X,S)=\mu_\Phi^2\Phi^{\dagger}\Phi+\lambda_\Phi(\Phi^{\dagger}\Phi)^2+\mu_S^2 S^2+\lambda_S S^4$$
$$+\mu_X^2 X^2+\lambda_X X^4+\lambda_{\Phi S}\Phi^{\dagger}\Phi X^2+\lambda_{SX} S^2 X^2$$

$$S=(\phi_S+v_S)/\sqrt{2}$$

$$X=(\phi_X+v_X)/\sqrt{2}$$

Change to the physical basis

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}=R(\theta_X,\theta_S)\begin{pmatrix} \phi_h \\ \phi_S \\ \phi_X \end{pmatrix}$$

$h_1=h$ *is the SM Higgs boson*

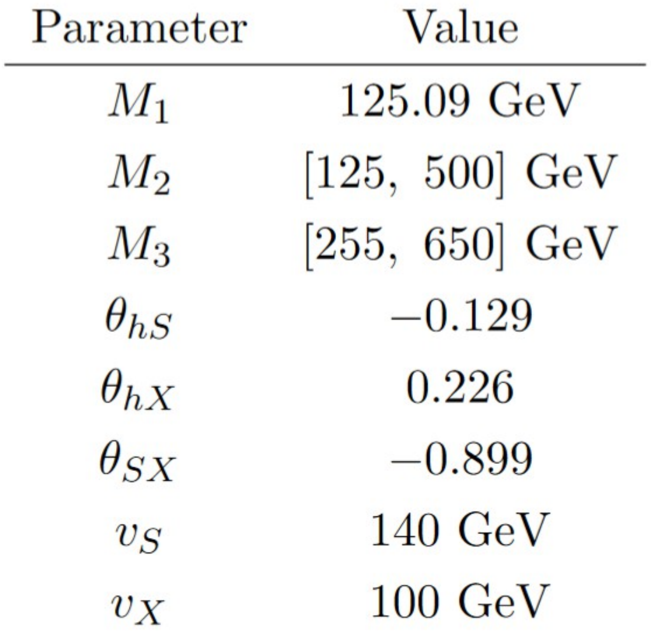
$$M_1=125\,GeV$$

Free independent parameters

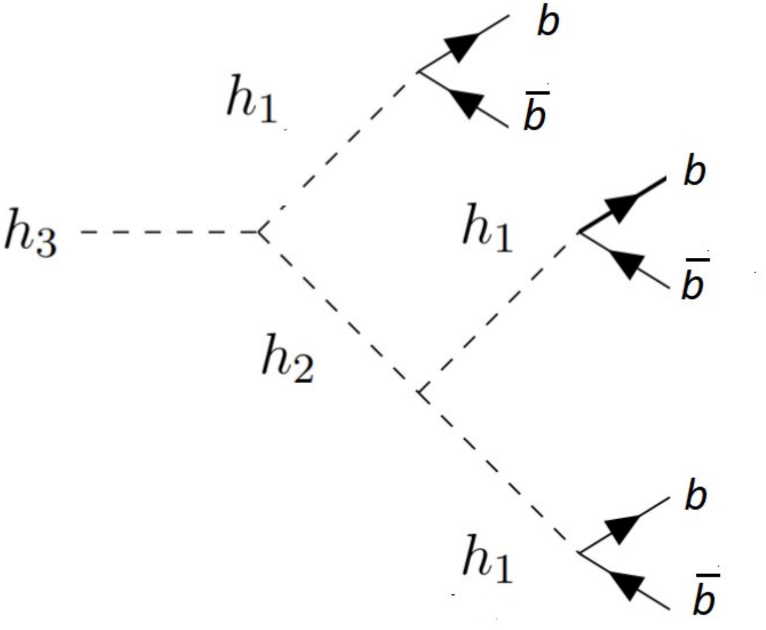
$$\boxed{M_2, M_3, \theta_{hS}, \theta_{hX}, \theta_{SX}, v_S, v_X}$$

Benchmark Scenario of Study BP3

Here we focus in the BP3 Scenario introduced in 1908.08554 which allows for a large $h_1 h_1 h_1$ *production while obeying current theoretical and experimental constraints.*

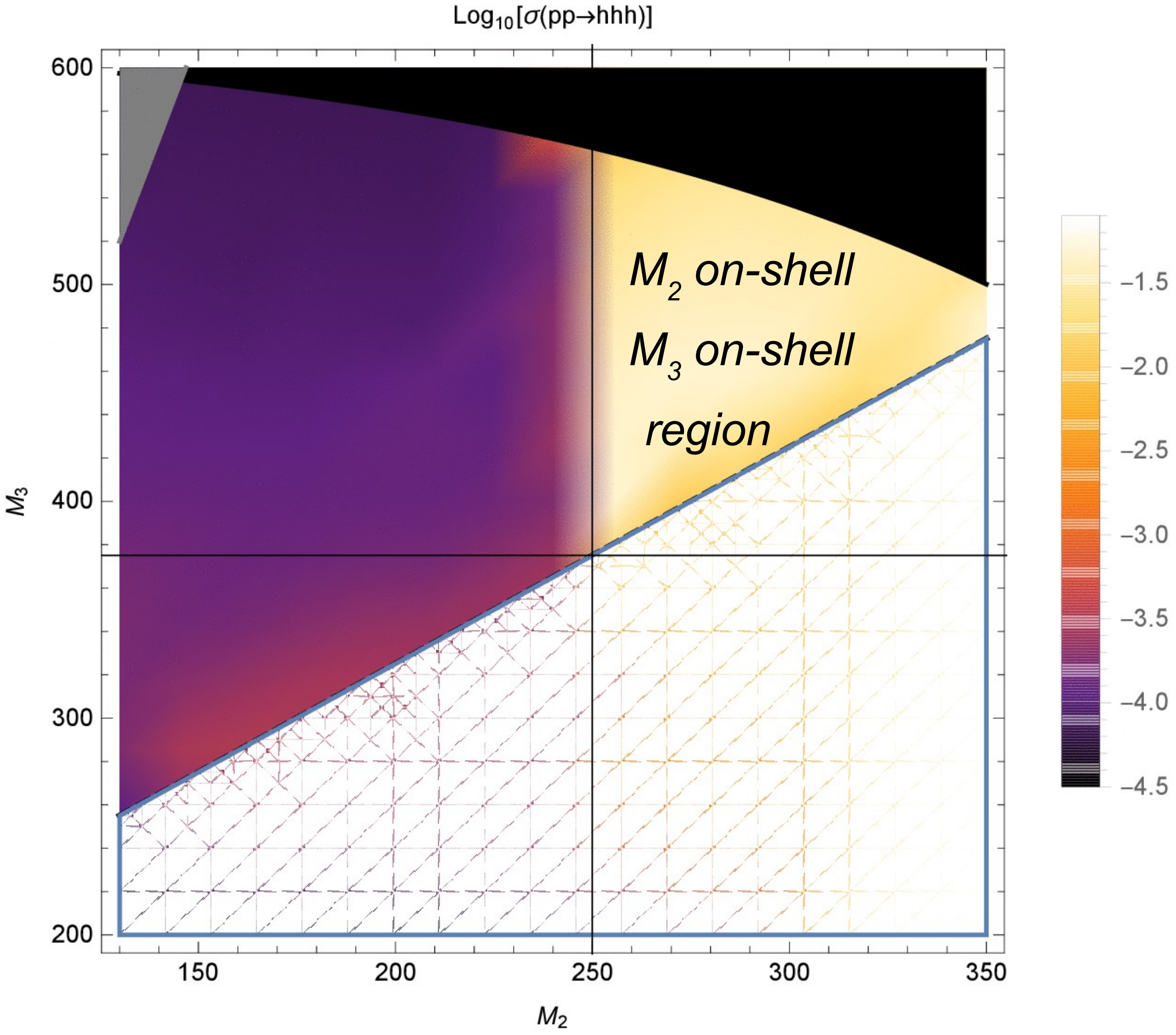


Parameter	Value
M_1	125.09 GeV
M_2	[125, 500] GeV
M_3	[255, 650] GeV
θ_{hS}	-0.129
θ_{hX}	0.226
θ_{SX}	-0.899
v_S	140 GeV
v_X	100 GeV



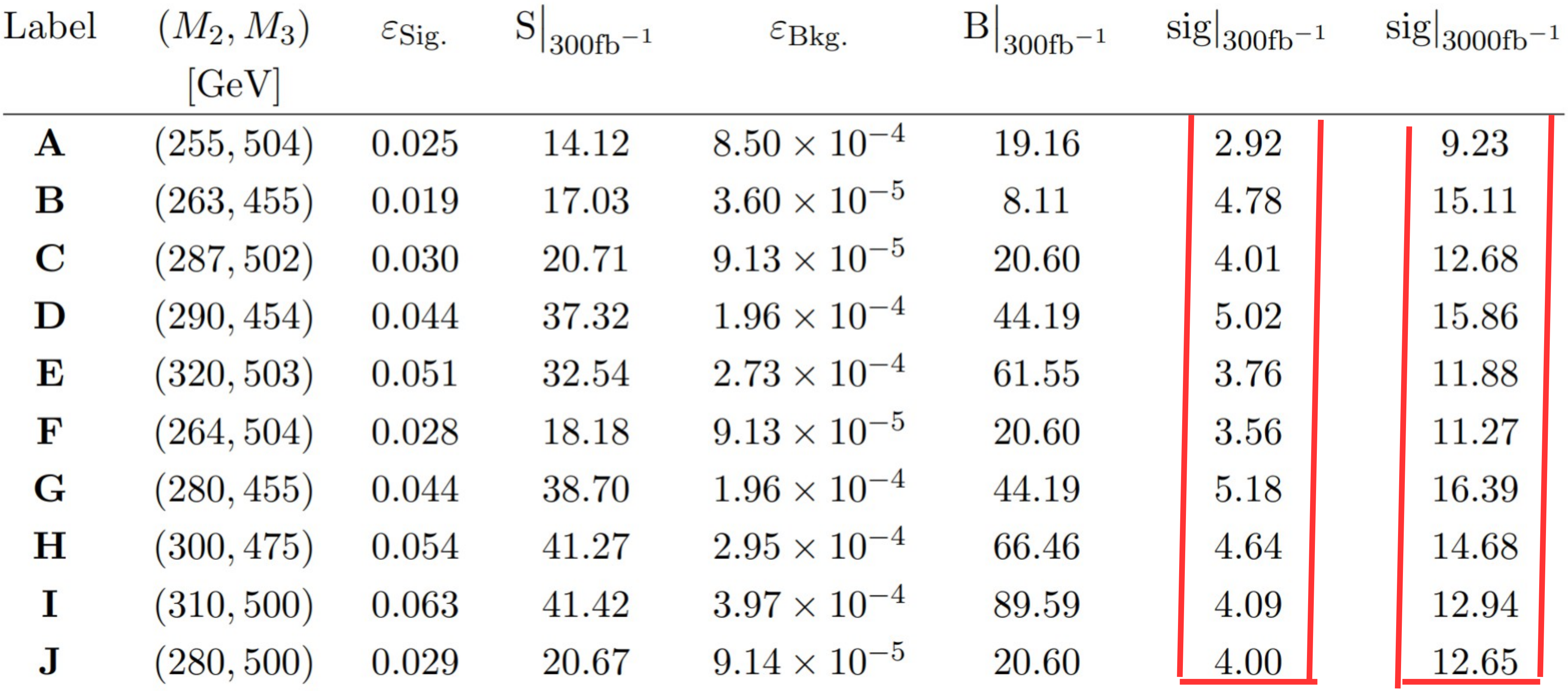
We consider the mass hierarchy $M_1 < M_2 < M_3$

Production cross section (LHC)



The X-Section can reach up to 50 fb for M_2~(263,280) GeV and M_3~450 GeV

Results



Label	(M_2, M_3) [GeV]	$\varepsilon_{\text{Sig.}}$	$\text{S}\|_{300\text{fb}^{-1}}$	$\varepsilon_{\text{Bkg.}}$	$\text{B}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
A	$(255, 504)$	0.025	14.12	8.50×10^{-4}	19.16	2.92	9.23
B	$(263, 455)$	0.019	17.03	3.60×10^{-5}	8.11	4.78	15.11
C	$(287, 502)$	0.030	20.71	9.13×10^{-5}	20.60	4.01	12.68
D	$(290, 454)$	0.044	37.32	1.96×10^{-4}	44.19	5.02	15.86
E	$(320, 503)$	0.051	32.54	2.73×10^{-4}	61.55	3.76	11.88
F	$(264, 504)$	0.028	18.18	9.13×10^{-5}	20.60	3.56	11.27
G	$(280, 455)$	0.044	38.70	1.96×10^{-4}	44.19	5.18	16.39
H	$(300, 475)$	0.054	41.27	2.95×10^{-4}	66.46	4.64	14.68
I	$(310, 500)$	0.063	41.42	3.97×10^{-4}	89.59	4.09	12.94
J	$(280, 500)$	0.029	20.67	9.14×10^{-5}	20.60	4.00	12.65

Performing the analysis for different points in the *M_2 -M_3 (on-shell, on-shell) region*

Closing Remarks

- Triple Higgs production $h_1 h_1 h_1$ as in the SM cannot be probed at the LHC due to its tiny cross section.
- The improved luminosity and center of mass energy of a 100 TeV collider can make the identification of the SM $h_1 h_1 h_1$ possible.
- The 6-b jets final state is a good candidate to search for $h_1 h_1 h_1$ *within and beyond the SM*
- *Extended scalar sectors can be probed through $h_1 h_1 h_1$ even in the HL-LHC (consider for instance the TRSM).*
- Moreover $h_1 h_1 h_1$ *can provide useful information on the quartic Higgs self couplings.*

Acknowledgements

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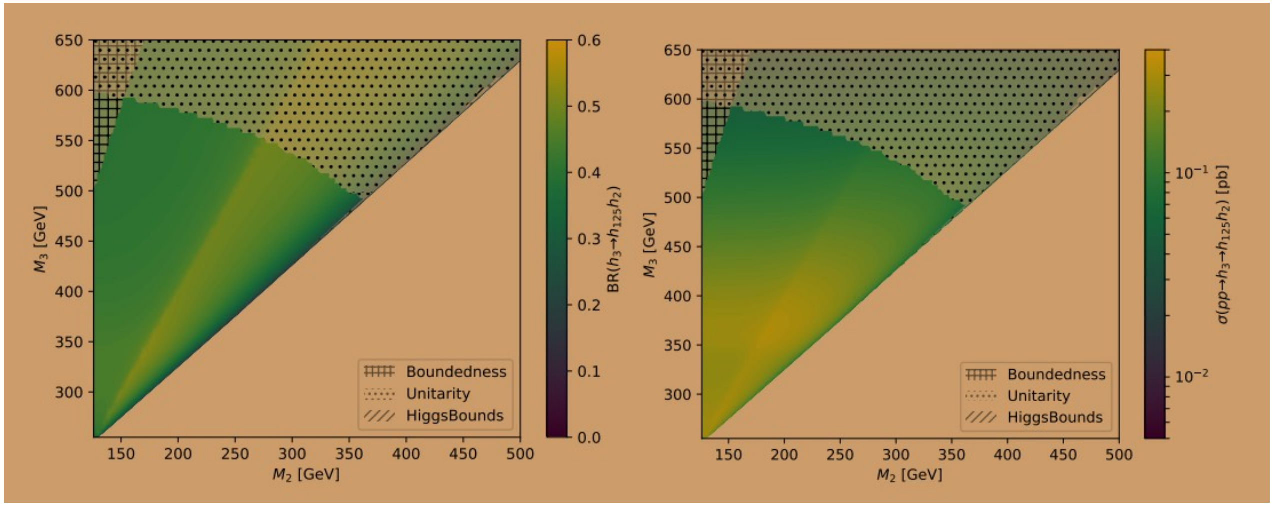
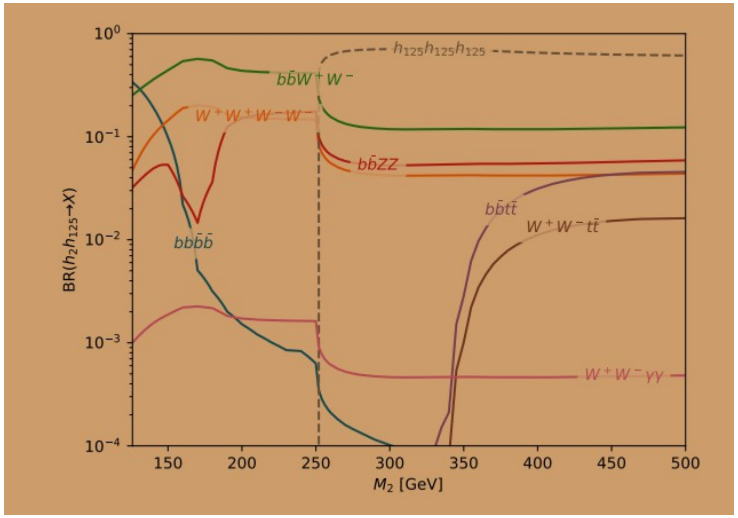
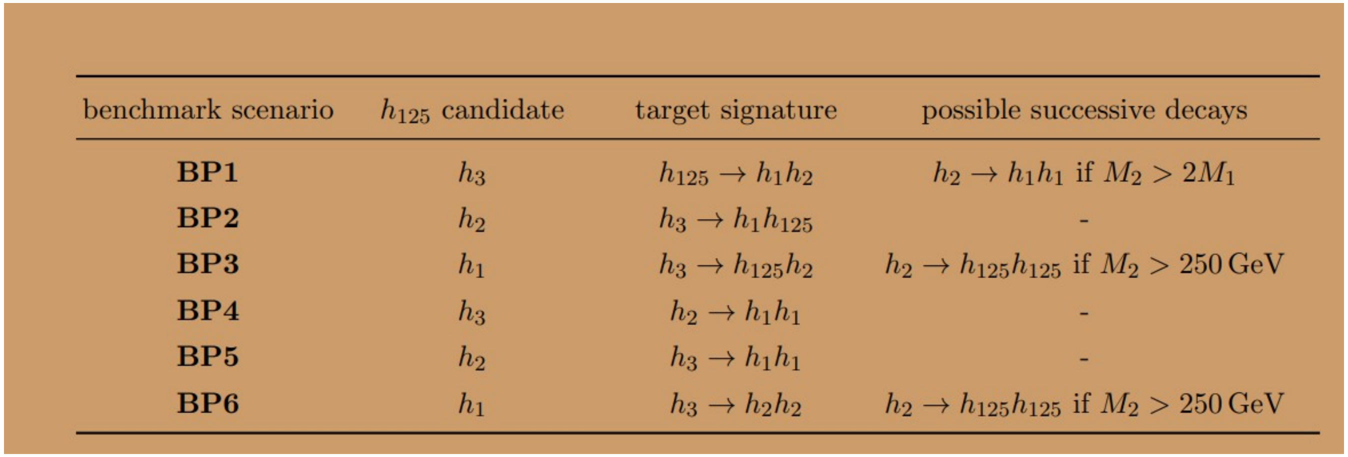
Backup

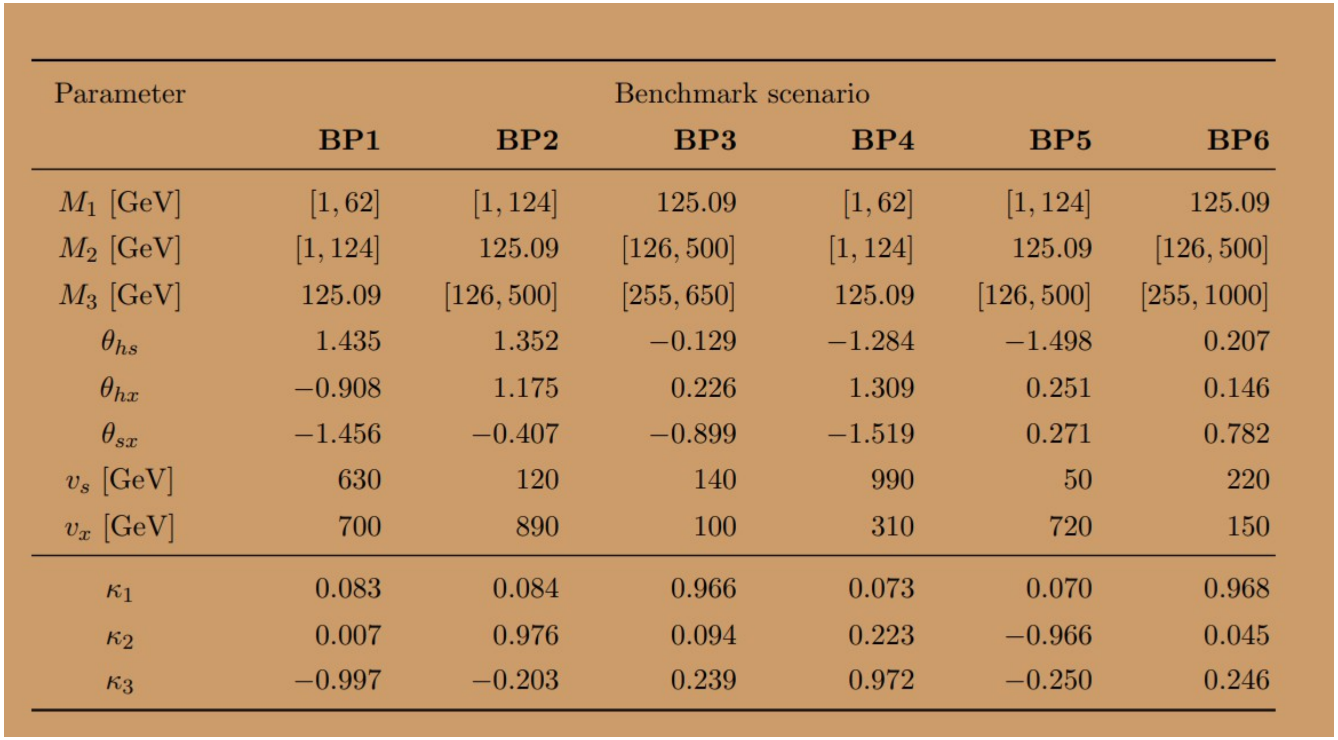

650
600
550
500
450
400
350
300
M_3 [GeV]
150
200
250
300
350
400
450
500
M_2 [GeV]
Boundedness
Unitarity
HiggsBounds
0.6
0.5
0.4
0.3
0.2
0.1
0.0
BR($h_3 \to h_{125} h_2$)
10^{-1}
10^{-2}
$\sigma(pp \to h_3 \to h_{125} h_2)$ [pb]


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
BR($h_2 h_{125} \to X$)
150
200
250
300
350
400
450
500
M_2 [GeV]
$h_{125}h_{125}h_{125}$
$b\bar{b}W^+W^-$
$W^+W^+W^-W^-$
$b\bar{b}ZZ$
$b\bar{b}t\bar{t}$
$W^+W^-t\bar{t}$
$bb\bar{b}\bar{b}$
$W^+W^-\gamma\gamma$

Backup



benchmark scenario	h_{125} candidate	target signature	possible successive decays
BP1	h_3	$h_{125} \to h_1 h_2$	$h_2 \to h_1 h_1$ if $M_2 > 2M_1$
BP2	h_2	$h_3 \to h_1 h_{125}$	-
BP3	h_1	$h_3 \to h_{125} h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\text{GeV}$
BP4	h_3	$h_2 \to h_1 h_1$	-
BP5	h_2	$h_3 \to h_1 h_1$	-
BP6	h_1	$h_3 \to h_2 h_2$	$h_2 \to h_{125} h_{125}$ if $M_2 > 250\,\text{GeV}$



Parameter	Benchmark scenario					
	BP1	**BP2**	**BP3**	**BP4**	**BP5**	**BP6**
M_1 [GeV]	$[1, 62]$	$[1, 124]$	125.09	$[1, 62]$	$[1, 124]$	125.09
M_2 [GeV]	$[1, 124]$	125.09	$[126, 500]$	$[1, 124]$	125.09	$[126, 500]$
M_3 [GeV]	125.09	$[126, 500]$	$[255, 650]$	125.09	$[126, 500]$	$[255, 1000]$
θ_{hs}	1.435	1.352	-0.129	-1.284	-1.498	0.207
θ_{hx}	-0.908	1.175	0.226	1.309	0.251	0.146
θ_{sx}	-1.456	-0.407	-0.899	-1.519	0.271	0.782
v_s [GeV]	630	120	140	990	50	220
v_x [GeV]	700	890	100	310	720	150
κ_1	0.083	0.084	0.966	0.073	0.070	0.968
κ_2	0.007	0.976	0.094	0.223	-0.966	0.045
κ_3	-0.997	-0.203	0.239	0.972	-0.250	0.246

Backup

$$\mathrm{sig}\,(S,B) = \sqrt{2\,[(S+B)\,\ln(1+S/B)-S]}.$$

$$\mathrm{sig}\,(S,B) = \sqrt{2\left(\left[S+B\right]\ln\left[\frac{(S+B)(B+\sigma_B^2)}{B^2+(S+B)\sigma_B^2}\right]-\frac{B^2}{\sigma_B^2}\ln\left[1+\frac{\sigma_B^2 S}{B(B+\sigma_B^2)}\right]\right)}$$

$$\chi^{2,(4)} = \sum_{qr\in I}\left(M_{qr}-M_1\right)^2 ,$$

$$\chi^{2,(6)} = \sum_{qr\in J}\left(M_{qr}-M_1\right)^2 .$$