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

CPPS, Theoretische Physik 1,
Universität Siegen

Center for Particle Physics Siegen

UNIVERSITÄT SIEGEN

Higgs Self-Interactions in the SM

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

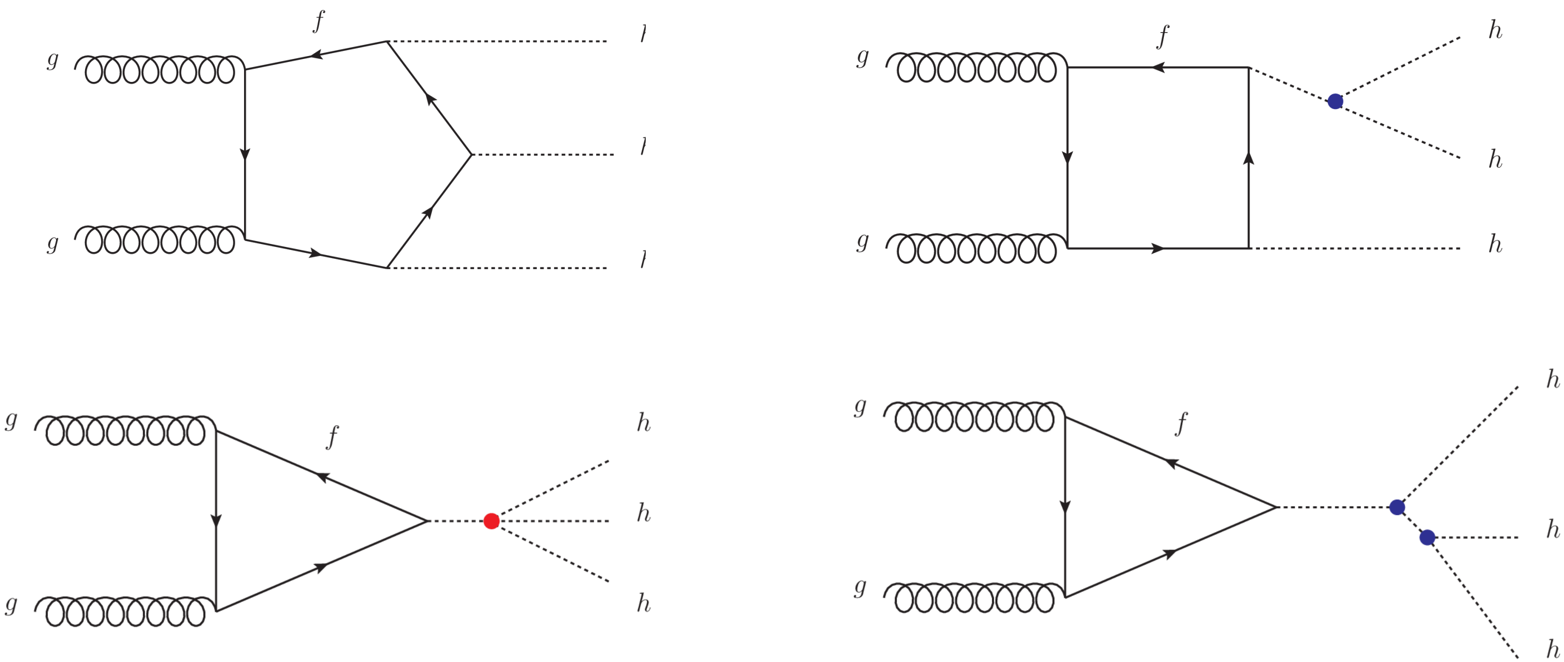
$$\Phi=\left(0,v_0+h\right)^T/\sqrt{2}$$

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

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

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)

$$\sigma \sim 5\ fb$$

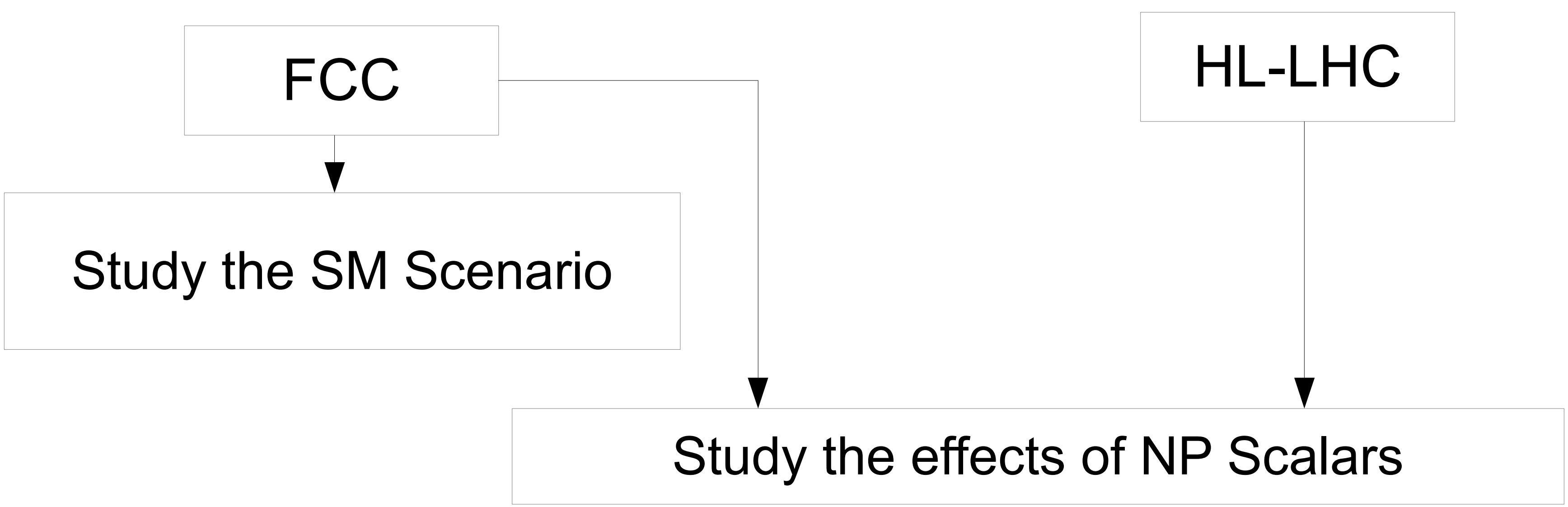
Luminosity=*20 ab⁻¹*
~100 000 events.

de Florian, Fabre, Mazzitelli: 1912.02760

Why to study triple Higgs production?

- The triple Higgs self coupling is sensitive to New Particles.
- It also gives the opportunity to test the Higgs quartic self couplings.

In view of the Low X-section for the SM Triple Higgs production in the LHC our approach is as follows



Final States

$$hhh \longrightarrow X$$

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
$q\bar{q} \to hZZ \to h(b\bar{b})(b\bar{b})$	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)	$\sigma_{\mathrm{GEN}} \times \mathscr{P}(6\ b-\mathrm{jets})$ (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

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

- *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
$\Delta R(h^i_r, h^j_r)$	$< [3.5, 3.5, 3.5]$, $(i, j) = [(1,2), (1,3), (2,3)]$
$\Delta R_{bb}(h^i)$	$< [3.5, 3.5, 3.5]$, $i = 1, 2, 3$

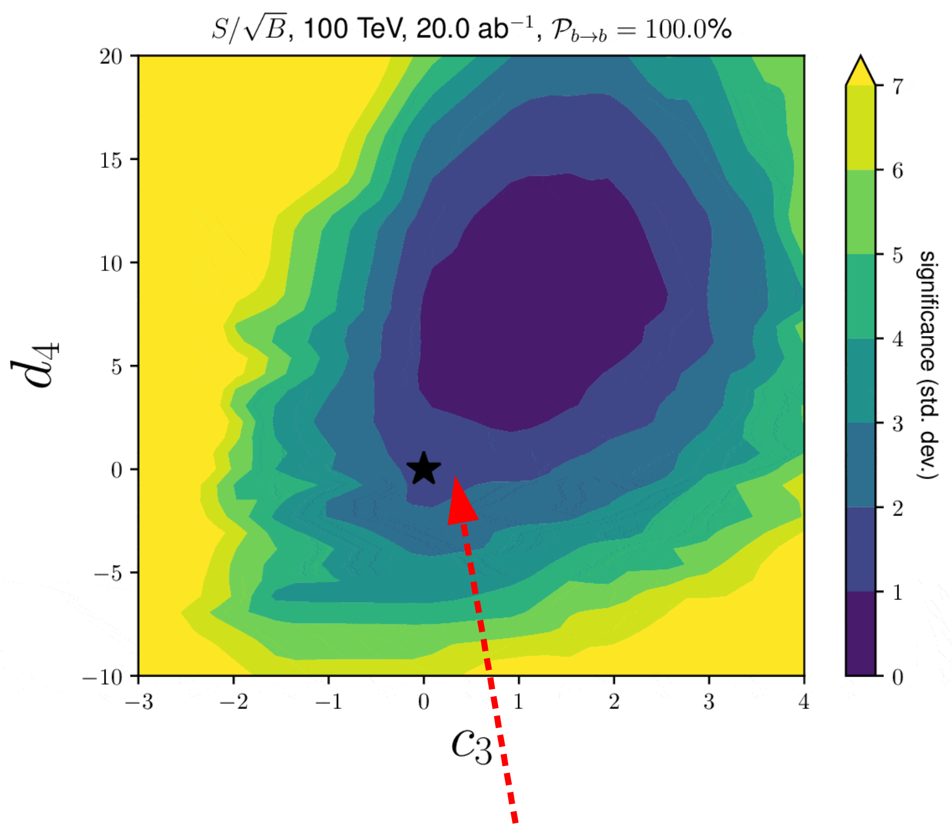
h^i_r : Higgs boson candidate

$i = 1,2,3$

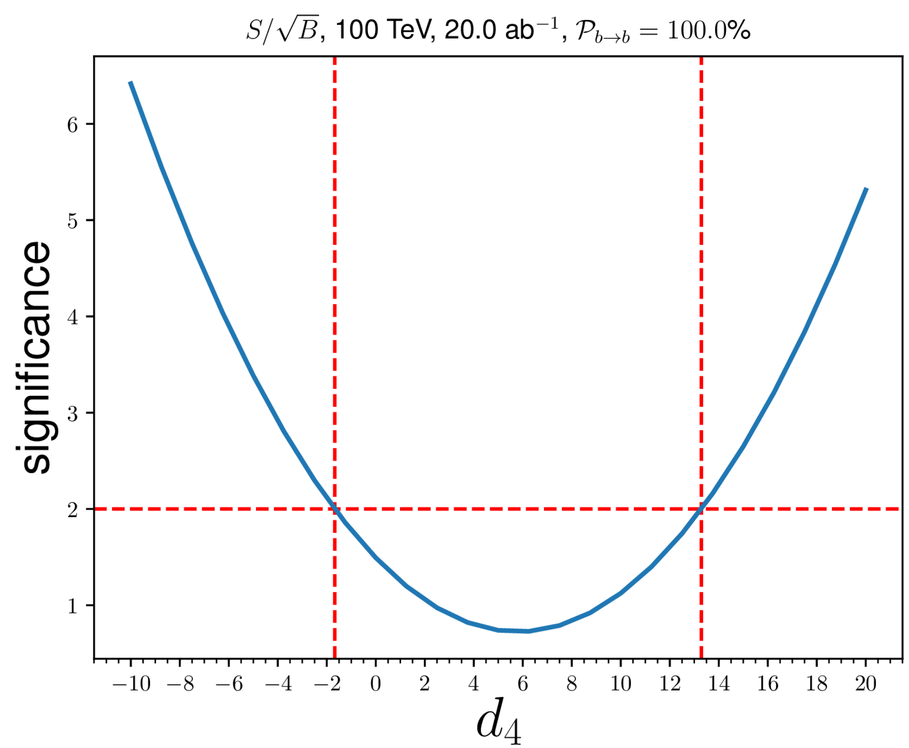
Sensitivity to quartic-self couplings

Consider a generalized version of the SM scalar potential

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



SM Significance ~1.7 σ



c_3=0

Adding an Extra-Scalar Singlet

The x-SM potential

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

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

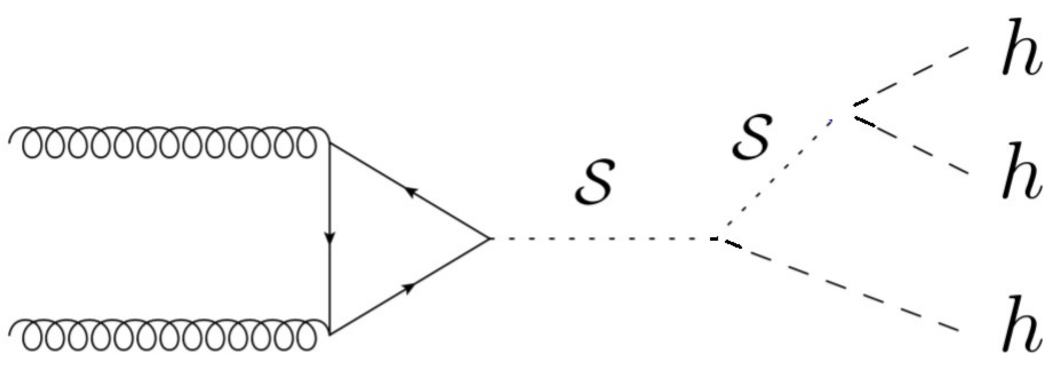
Kotwal et al. 1605.06123

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
B7max	5.3
B8max	7.8
B9max	5.9
B10max	4.9
B11max	2.3

Two Real Singlet Extension of the SM
TRSM

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

Reduce the number of parameters by imposing

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

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

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

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

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

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

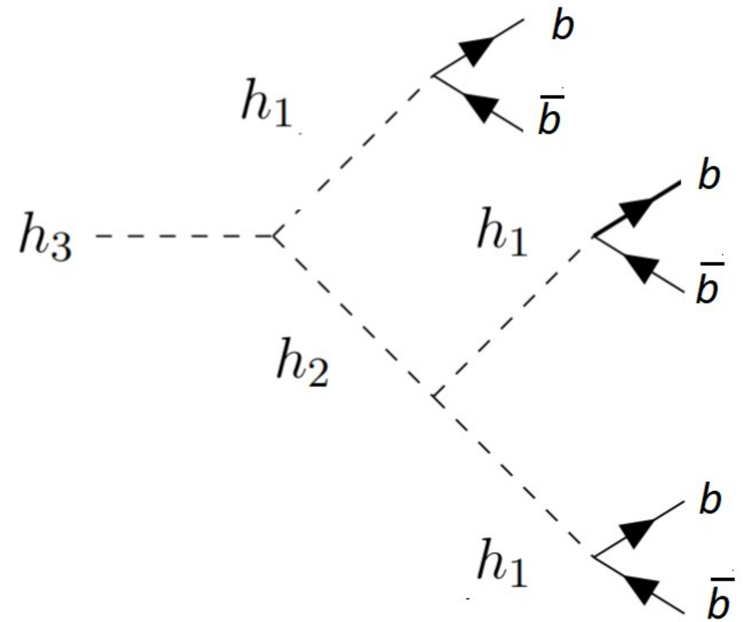
$$M_2, M_3, \theta_{hS}, \theta_{hX}, \theta_{SX}, v_S, v_X$$

Robens, Stefaniak, Wittbrodt: 1908.08554

Benchmark Scenario of Study BP3

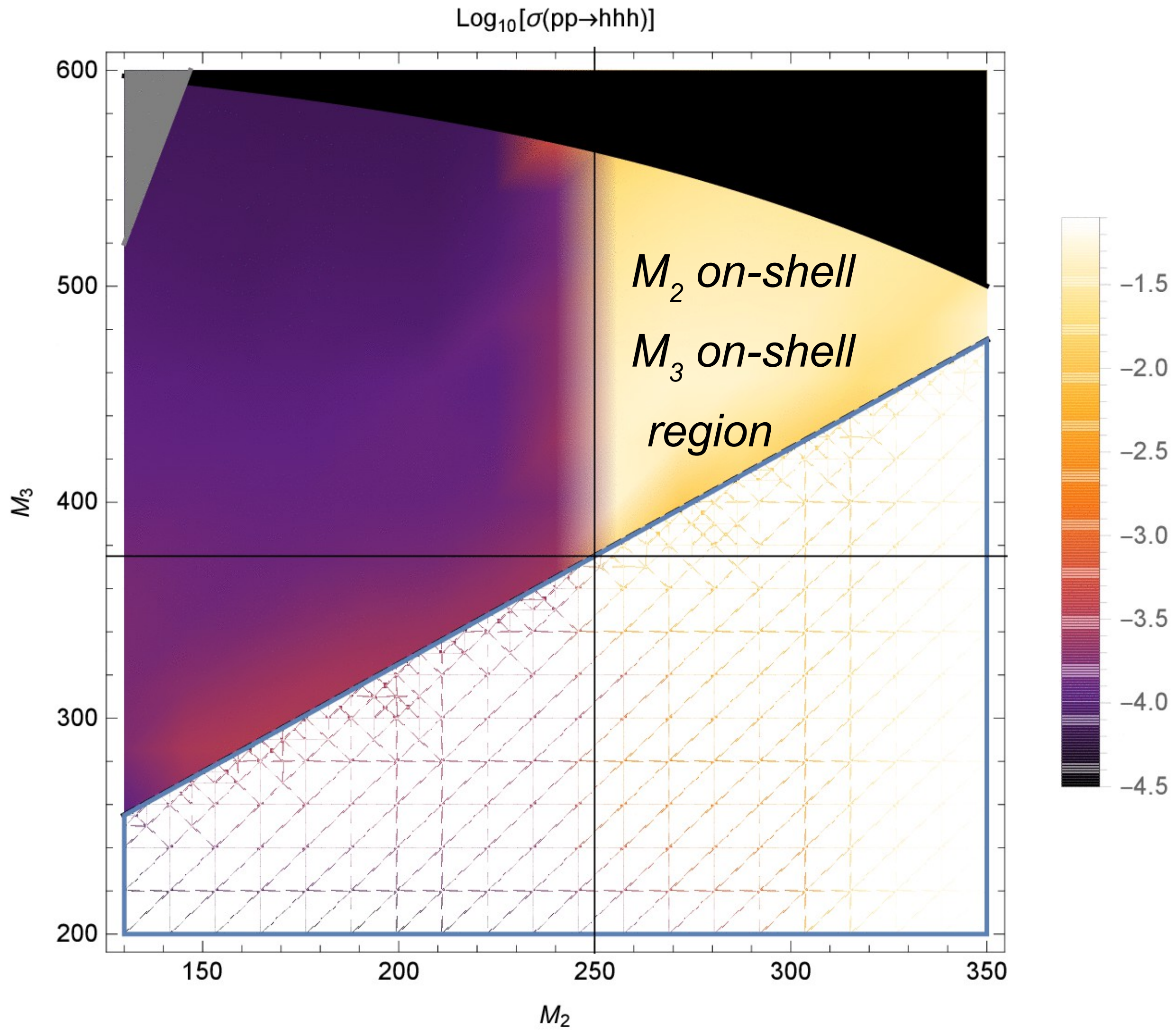
Here we focus in the BP3 Scenario introduced in 1908.08554 which allows for a large $h_1 h_1 h_1$ production while obeying current theoretical and experimental constraints.

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



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]	$\varepsilon_{\text{Sig.}}$	$S\|_{300\text{fb}^{-1}}$	$\varepsilon_{\text{Bkg.}}$	$B\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
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 $h_1h_1h_1$ 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 $h_1h_1h_1$ possible.

- The 6-b jets final state is a good candidate to search for $h_1h_1h_1$ *within and beyond the SM*

- *Extended scalar sectors can be probed through $h_1h_1h_1$ even in the HL-LHC (consider for instance the TRSM).*

- Moreover $h_1h_1h_1$ *can provide useful information on the quartic Higgs self couplings.*