Triple Higgs production at hadron colliders

Gilberto Tetlalmatzi-Xolocotzi

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

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

A. Papaefstathiou, GTX: JHEP 06 (2024) 124 (2312.13562)

O. Karkout, A. Papaefstathiou, M. Postma, GTX, J. van de Vis, T du Pree: JHEP 11 (2024) 077 (2404.12425)

A. Papaefstathiou, GTX: (2501.14866)

B. Fuks, A. Papaefstathiou, GTX: (2509.16364)

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Higgs Self-Interactions in the SM

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

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

$$V\left(\Phi^\dagger \Phi\right) \supset \tfrac{1}{2} m_h^2 h^2 + \lambda_{SM} v_0 h^3 + \tfrac{\lambda_{SM}}{4} h^4$$

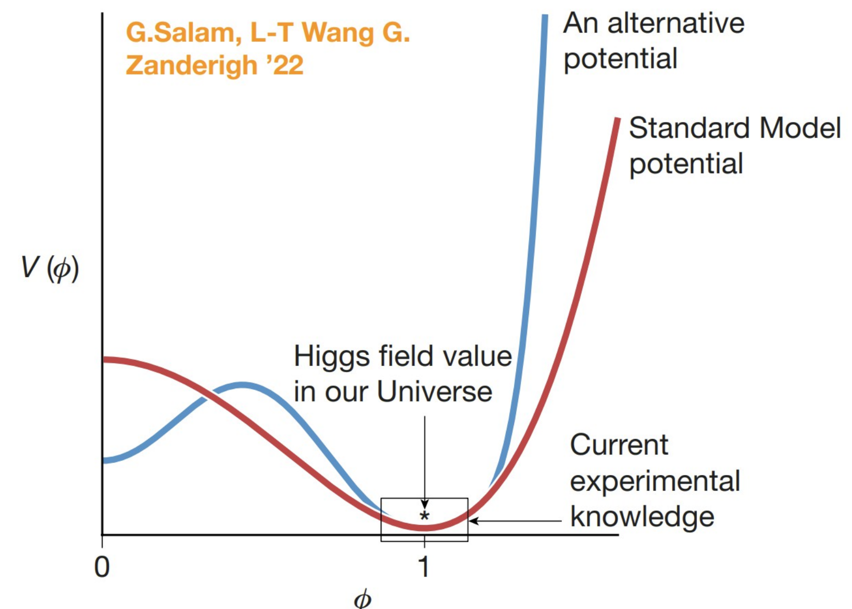
In the SM $\quad m_h^2 = \lambda_{SM} v_0^2 / 2 \qquad v_0^2 = -\mu^2 / \lambda_{SM}$

Why 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.

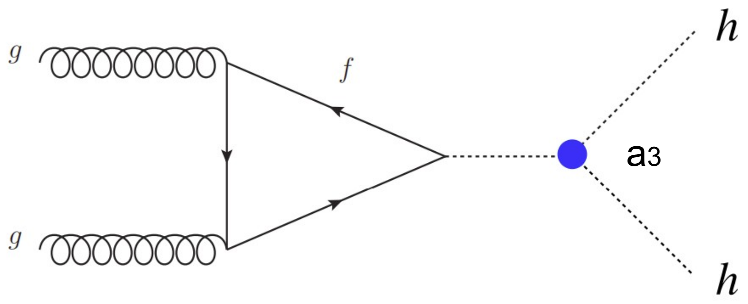
We do not know much about the shape of the Higgs potential.



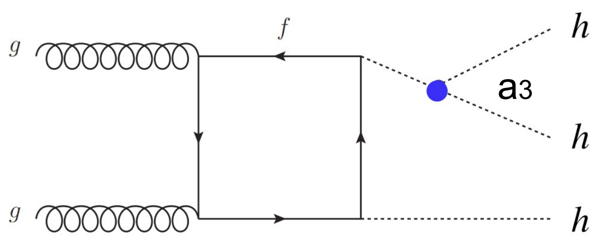
$$V\left(\Phi^{\dagger}\Phi\right) \supset \frac{1}{2} m_h^2 h^2 + a_3 h^3 + a_4 h^4$$

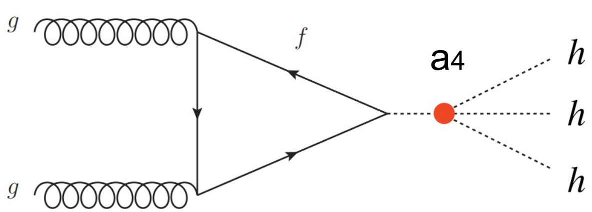
Why study triple Higgs production?

Double Higgs production is the lowest multiplicity to probe for a_3 .



Triple Higgs production is the lowest multiplicity to probe for a_4.





Possible Final states

$$hhh \longrightarrow X$$

X (Final State)	Br(%)
$(b\bar{b})(b\bar{b})(b\bar{b})$	19.21
$(b\bar{b})(b\bar{b})(WW_{1l})$	7.20
$(b\bar{b})(b\bar{b})(\tau\bar{\tau})$	6.31
$(b\bar{b})(\tau\bar{\tau})(WW_{1l})$	1.58
$(b\bar{b})(b\bar{b})(WW_{2l})$	0.98
$(b\bar{b})(WW_{1l})(WW_{1l})$	0.90
$(b\bar{b})(\tau\bar{\tau})(\tau\bar{\tau})$	0.69
$(b\bar{b})(b\bar{b})(\gamma\gamma)$	0.23

Papaefstathiou, GTX, Zaro: 1909.09166
A. Papaefstathiou, GTX: (2501.14866)
Fuks, Papaefstathiou, GTX: 2509.16364

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 vs Signal

In the FCC (pp @ 100 TeV)

Signal and Irreducible backgrounds

Process	$\sigma_{\text{GEN}} \times k_{\text{fac}} \times \text{BR} \times \mathcal{P}(6b)$ [fb]
hhh (SM)	4.29×10^{-1}
QCD $(b\bar{b})(b\bar{b})(b\bar{b})$	1.07×10^{4}
$q\bar{q} \to Z(b\bar{b})(b\bar{b})$	3.61×10^{2}
$q\bar{q} \to ZZb\bar{b}$	1.14×10^{1}
$q\bar{q} \to ZZZ$	1.80×10^{-1}
$q\bar{q} \to hZb\bar{b}$	2.04
$q\bar{q} \to hZZ$	1.48×10^{-1}
$q\bar{q} \to hhZ$	8.11×10^{-2}
$q\bar{q} \to hh(b\bar{b})$	1.80×10^{-2}
$q\bar{q} \to h(b\bar{b})(b\bar{b})$	7.25×10^{-1}
$gg \to ZZZ$	5.18×10^{-3}
$gg \to hZZ$	3.59×10^{-2}
$gg \to hhZ$	6.41×10^{-2}

Reducible backgrounds

Process	σ_{GEN} [fb]	$\sigma_{\text{GEN}} \times k_{\text{fac}} \times \mathcal{P}(6b)$ [fb]
$(b\bar{b})(b\bar{b})(c\bar{c})$	73.0×10^{3}	762
$(b\bar{b})(c\bar{c})(c\bar{c})$	72.0×10^{3}	10.4
$(c\bar{c})(c\bar{c})(c\bar{c})$	21.8×10^{3}	4.36×10^{-2}
$(b\bar{b})(b\bar{b})(jj)$*	3.09×10^{6}	161
$(b\bar{b})(jj)(jj)$*	1.07×10^{8}	1.54
$(c\bar{c})(c\bar{c})(jj)$*	1.73×10^{5}	3.46×10^{-3}
$(c\bar{c})(jj)(jj)$*	6.67×10^{7}	6.67×10^{-3}
$(jj)(jj)(jj)$*	3.04×10^{9}	6.08×10^{-3}

Assuming a K-factor of 2

Maltoni, Vryonidou, Zaro: 1408.6542

Details on the study of the 6b final state

- Parton level events (signal/background) generated with MadGraph5_aMC@NLO.
- The source of background with the highest XS is QCD-6b-Jets.
- The production of the 6b-final state is challenging, it was generated in the Siegen computer cluster 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].
- Two selection analysis approaches are followed: traditional cuts selection and gradient boosting using XGBoost.

Smearing effects

We introduce smearing effects based on ATLAS and CMS like scenarios

$$E_{\text{smeared}} = E + \Delta E\ , \qquad \Delta E \sim \mathcal{N}(0,\, \sigma_E)\ ,$$

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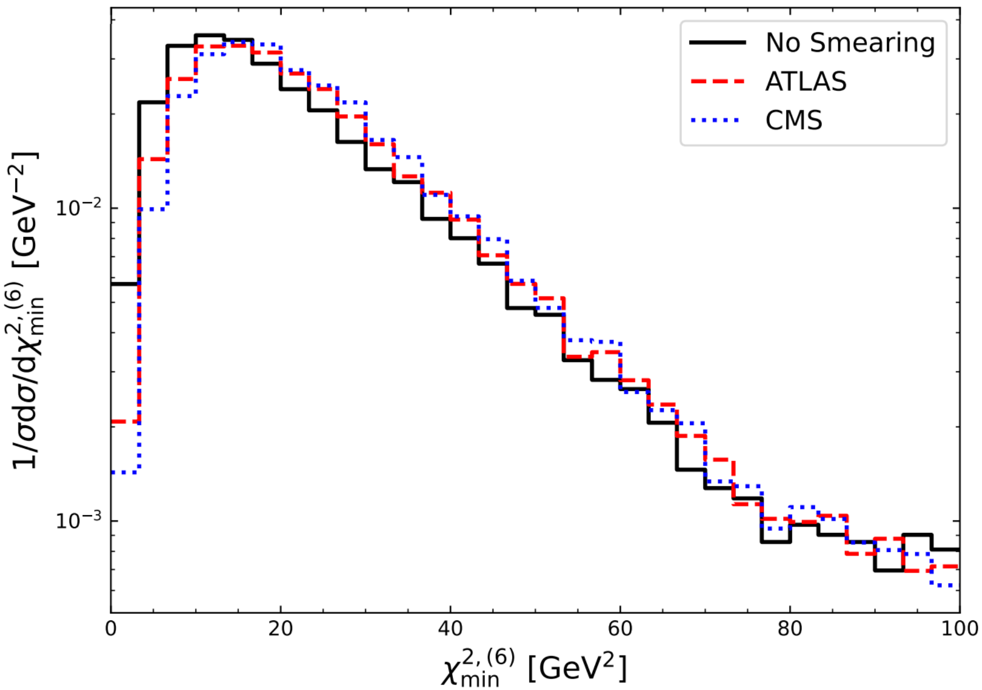
$$E_{\text{smeared}} = E + \Delta E \qquad p_{T,\text{smeared}} = \frac{E + \Delta E}{\cosh \eta}$$



$$\sigma_E^{\text{ATLAS}} = \begin{cases} \sqrt{(0.0302E)^2 + 0.5205^2 E + 1.59^2} & |\eta| \le 1.7 \\ \sqrt{(0.05E)^2 + 0.706^2 E} & |\eta| \in [1.7, 3.2] \\ \sqrt{(0.0942E)^2 + E} & |\eta| \in [3.2, 4.9] \end{cases}\ , \qquad \sigma_E^{\text{CMS}} = \begin{cases} \sqrt{(0.05E)^2 + 1.5^2 E} & |\eta| \le 3.0 \\ \sqrt{(0.130E)^2 + 2.7^2 E} & 3.0 < |\eta| \le 5.0 \end{cases}\ ,$$

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 *traditional* selection analysis (FCC)

Observable	Threshold
$p_{T,b}$ >	35.0 GeV
$\|\eta_b\|$ <	3.0
ΔR_{bb} >	0.3
p_{T,b_i} >	[170.0, 135.0, 35.0] GeV
$\chi^{2,(6)}$ <	26.0 GeV
Δm_i <	[8, 8, 8] GeV
$\Delta R_{bb}(h^i)$ <	[3.5, 3.5, 3.5]
$\Delta R(h^i, h^j)$ <	[3.5, 3.5, 3.5]
$p_T(h^i)$ >	[200.0, 190.0, 20.0] GeV

h^i : Higgs boson candidate

$i = 1,2,3$

Sensitivity to self couplings

We consider a generalized version of the SM scalar potential

$$\mathcal{L} \supset -\frac{m_h^2}{2v}\left(1 + c_3\right)h^3 - \frac{m_h^2}{8v^2}\left(1 + d_4\right)h^4$$

To asses the sensitivity towards the anomalous couplings we construct the following test statistic

$$\chi^2_{\rm tot}(c_3, d_4) = \chi^2(c_3, d_4) + \left(\frac{c_3}{\delta c_3}\right)^2 \qquad \chi^2(c_3, d_4) = \left[\frac{S_{\rm SM} - S(c_3, d_4)}{\delta_{\rm SM+B}}\right]^2$$

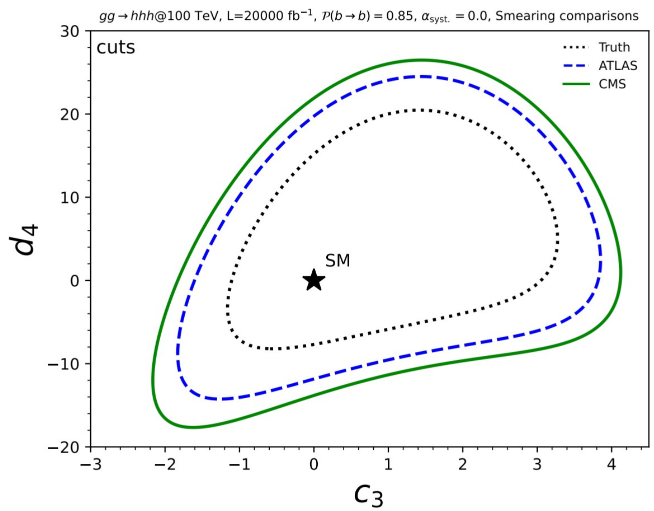
Gaussian prior to introduce information on the cubic coupling

Uncertainty in the number of expected SM events

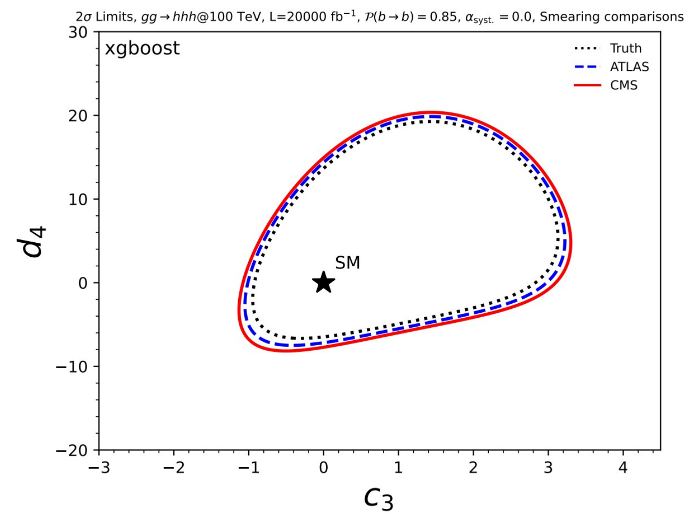
$$\delta_{\rm SM+B} = \sqrt{S_{\rm SM} + B + (\alpha B)^2}$$

Systematic uncertainties

Sensitivity to self couplings



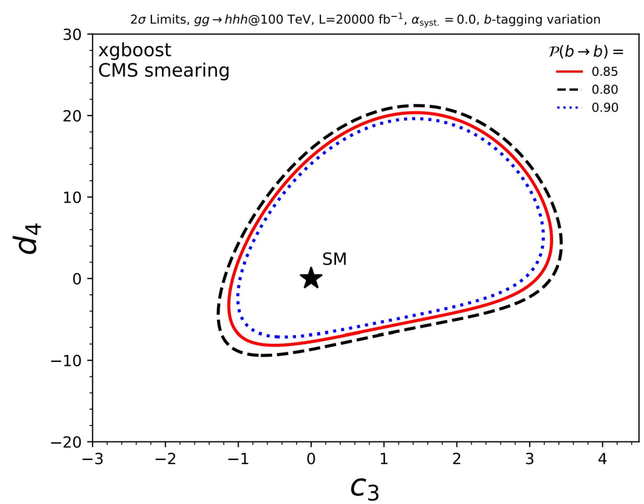
Traditional Cuts



XGBoost

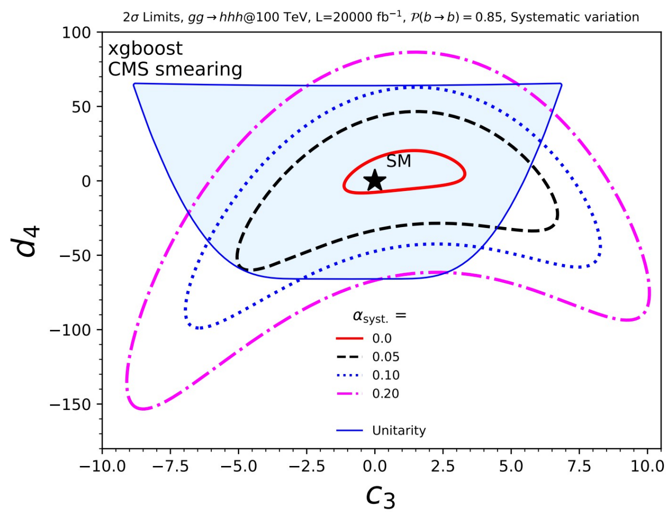
95% C. L. Regions

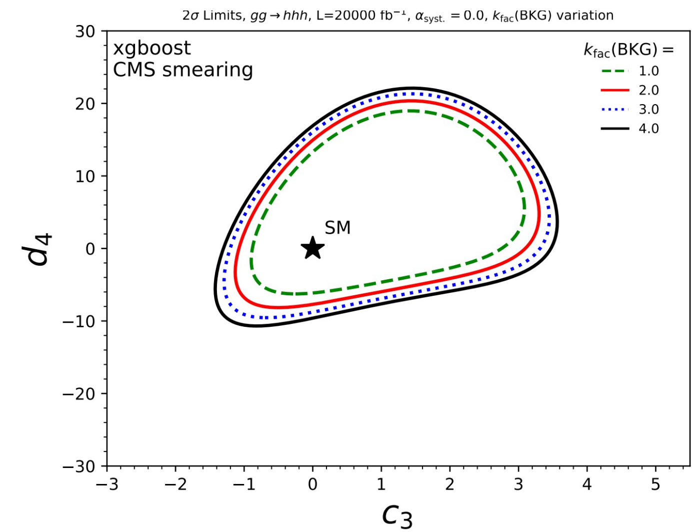
B. Fuks, A. Papaefstathiou, GTX: 2509.16364



b-Tagging impact

Sensitivity to self couplings





Systematic-error impact

K-factor impact

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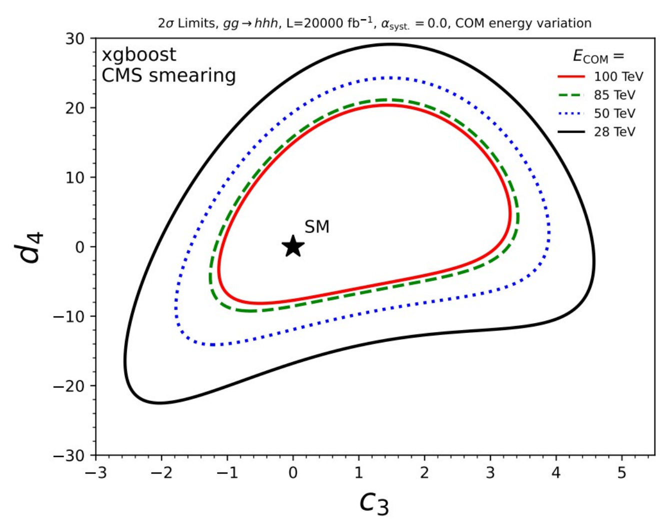
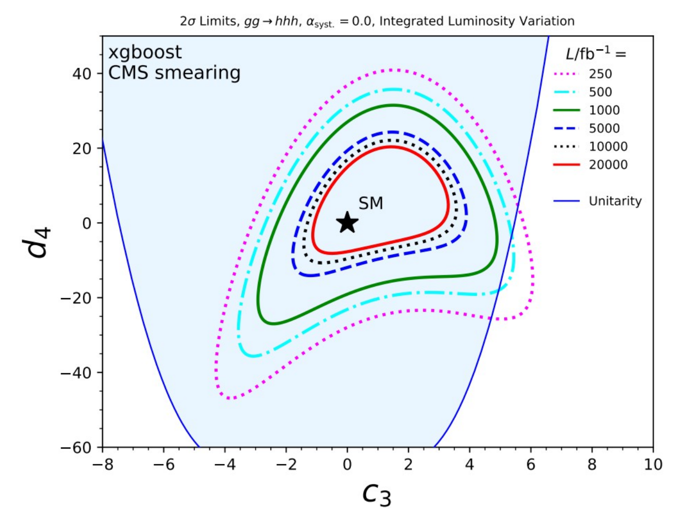
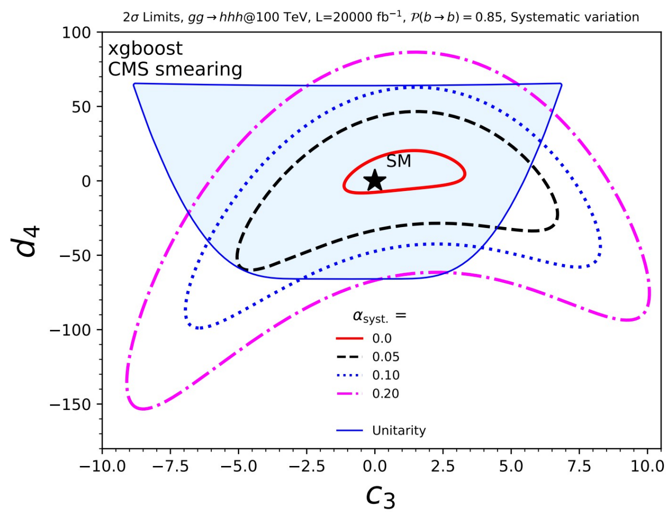




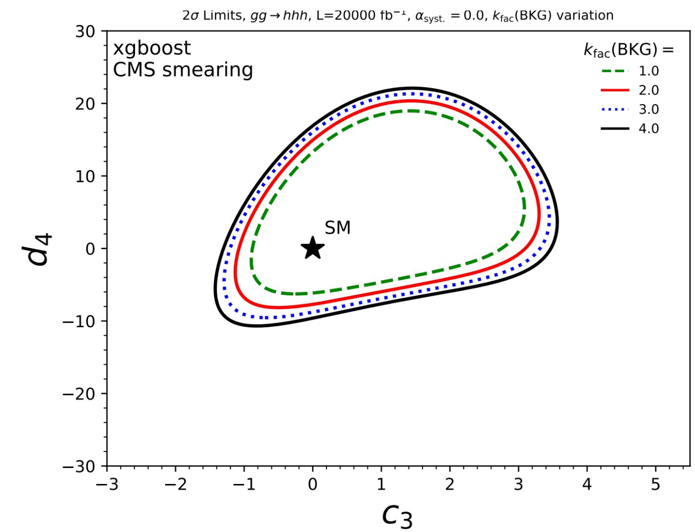
CM-impact

Luminosity impact

Sensitivity to self couplings



Systematic-error impact



K-factor impact

95% C. L. Regions

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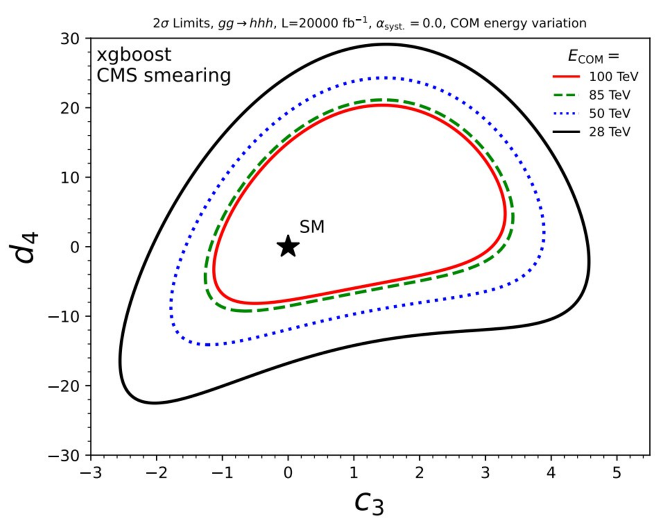
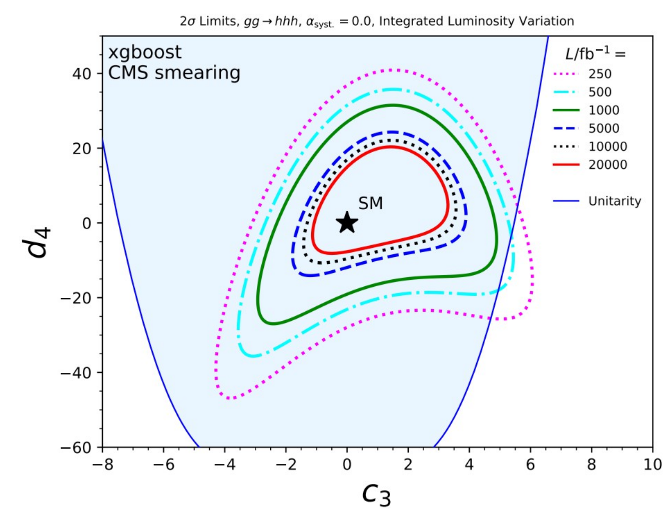


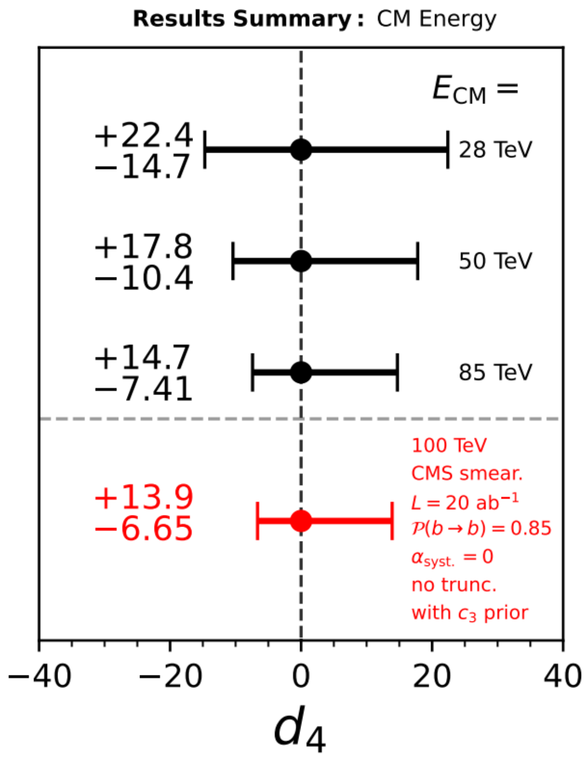
CM-impact

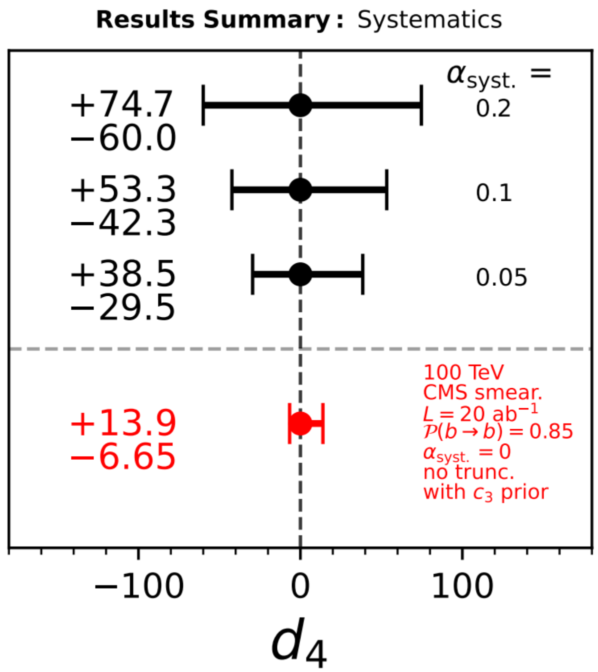


Luminosity impact

Sensitivity to self couplings

Summaries





$$\delta c_3 = 0.05$$

B. Fuks, A. Papaefstathiou, GTX: 2509.16364

Anomalous couplings

Relevant phenomenological Lagriangian
to test anomalous couplings

$$
\begin{aligned}
\mathcal{L}_{\mathrm{PhenoExp}} = & -\lambda_{\mathrm{SM}} v\,(1+d_3)\,h^3 - \frac{\lambda_{\mathrm{SM}}}{4}\,(1+d_4)\,h^4 \\
& + \frac{\alpha_s}{12\pi}\left(c_{g1}\frac{h}{v} - c_{g2}\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G^{\mu\nu}_a \\
& - \left[\frac{m_t}{v}\,(1+c_{t1})\,\bar{t}_L t_R h + \frac{m_b}{v}\,(1+c_{b1})\,\bar{b}_L b_R h + \mathrm{h.c.}\right] \\
& - \left[\frac{m_t}{v^2} c_{t2} \bar{t}_L t_R h^2 + \frac{m_b}{v^2} c_{b2} \bar{b}_L b_R h^2 + \mathrm{h.c.}\right] \\
& - \left[\frac{m_t}{v^3}\left(\frac{c_{t3}}{2}\right) \bar{t}_L t_R h^3 + \frac{m_b}{v^3}\left(\frac{c_{b3}}{2}\right) \bar{b}_L b_R h^3 + \mathrm{h.c.}\right],
\end{aligned}
$$

Obtained by considering D=6 EFT operators (SILH, 0703164) and breaking correlations (ATLAS and CMS)

Can also be obtained from the Electroweak chiral Lagrangian

Anomalous couplings

Relevant phenomenological Lagriangian
to test anomalous couplings

$$\begin{aligned}\mathcal{L}_{\text{PhenoExp}} =& - \lambda_{\text{SM}} v \, (1 + d_3) \, h^3 - \frac{\lambda_{\text{SM}}}{4} \, (1 + d_4) \, h^4 \\ &+ \frac{\alpha_s}{12\pi} \left(c_{g1} \frac{h}{v} - c_{g2} \frac{h^2}{2v^2} \right) G^a_{\mu\nu} G^{\mu\nu}_a \\ &- \left[\frac{m_t}{v} \, (1 + c_{t1}) \, \bar{t}_L t_R h + \frac{m_b}{v} \, (1 + c_{b1}) \, \bar{b}_L b_R h + \text{h.c.} \right] \\ &- \left[\frac{m_t}{v^2} c_{t2} \bar{t}_L t_R h^2 + \frac{m_b}{v^2} c_{b2} \bar{b}_L b_R h^2 + \text{h.c.} \right] \\ &- \left[\frac{m_t}{v^3} \left(\frac{c_{t3}}{2} \right) \bar{t}_L t_R h^3 + \frac{m_b}{v^3} \left(\frac{c_{b3}}{2} \right) \bar{b}_L b_R h^3 + \text{h.c.} \right],\end{aligned}$$

Obtained by considering D=6 EFT operators (SILH, 0703164) and breaking correlations (ATLAS and CMS)

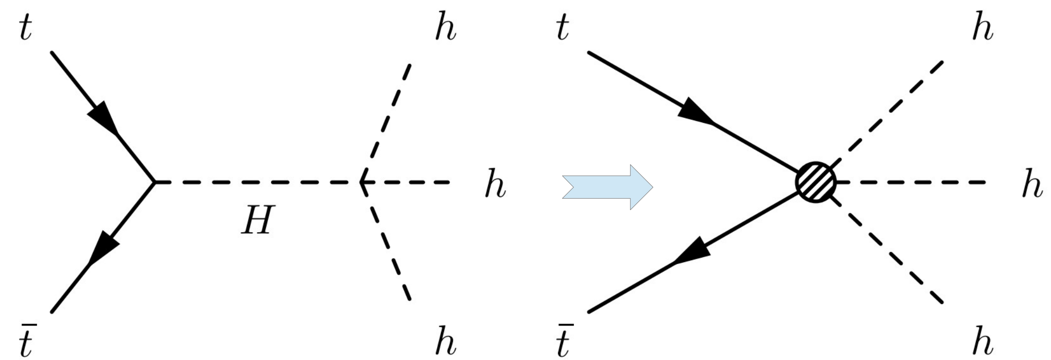
Can also be obtained from the Electroweak chiral Lagrangian

Anomalous couplings

Current and expected bounds on the anomalous couplings

Percentage uncertainties			
	HL-LHC	FCC-hh	Ref.
$\delta(d_3)$	50	5	[1905.03764]
$\delta(c_{g1})$	2.3	0.49	[1905.03764]
$\delta(c_{g2})$	5	1	[1502.00539]
$\delta(c_{t1})$	3.3	1.0	[1905.03764]
$\delta(c_{t2})$	30	10	[1502.00539]
$\delta(c_{b1})$	3.6	0.43	[1905.03764]
$\delta(c_{b2})$	30	10	[1502.00539]

$$\left(\frac{c_{t3}}{2}\right)\bar{t}_L t_R h^3$$

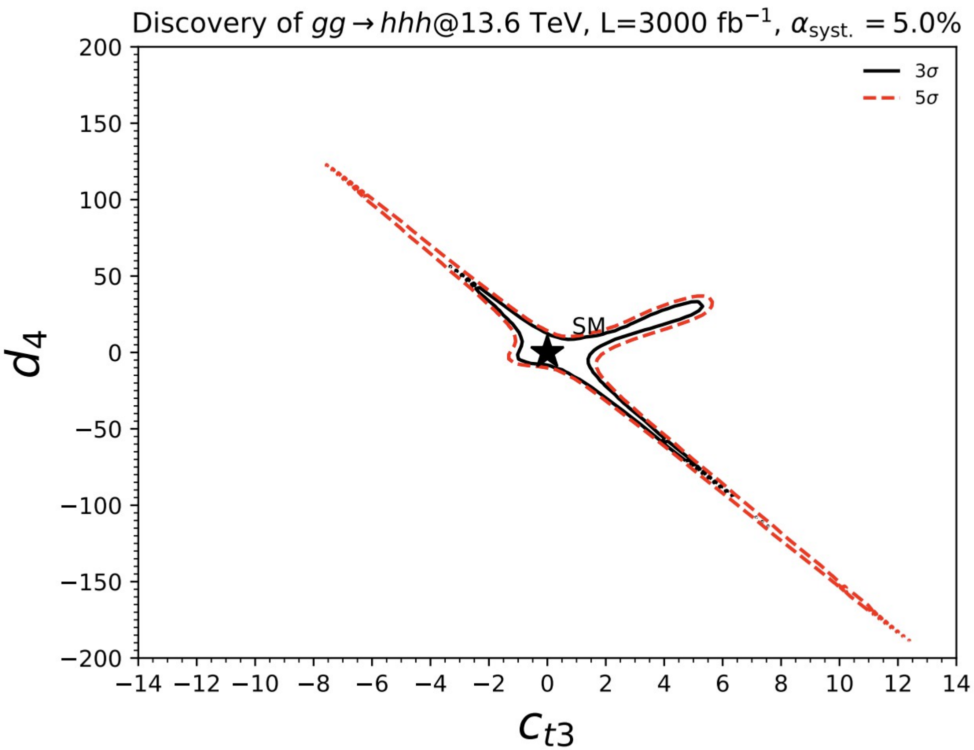


The couplings d_4 and c_{t3} can be bounded by triple Higgs production

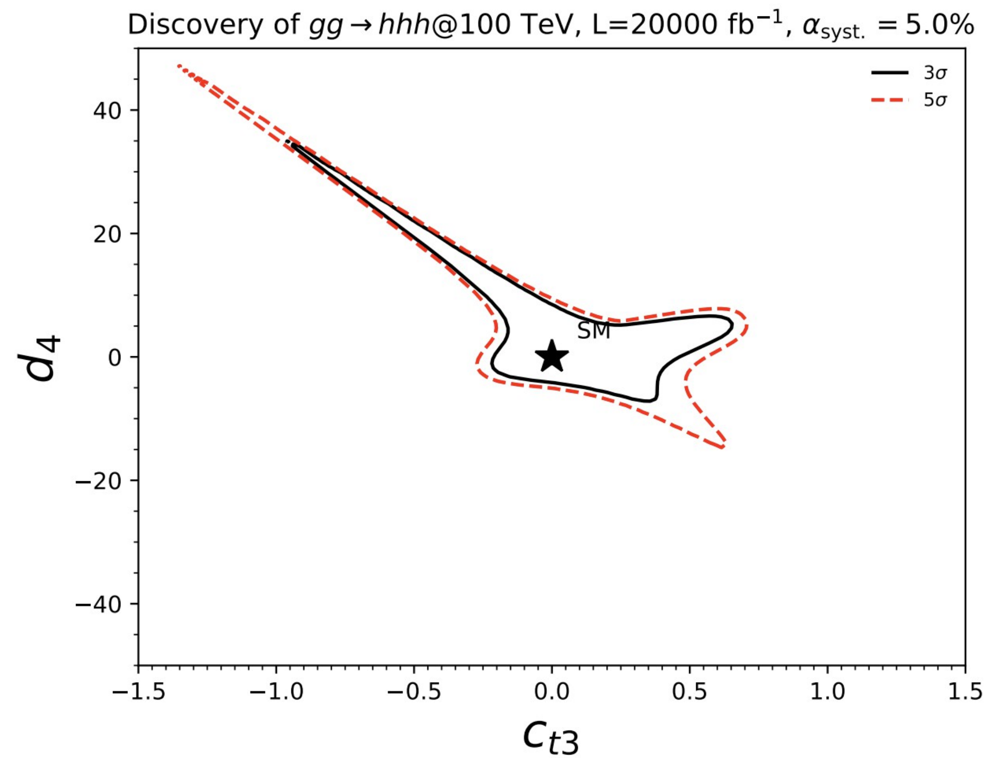
Anomalous couplings

Evidence and discovery regions for triple Higgs production at proton-proton colliders

HL-LHC



FCC



Evidence and discovery contours at proton colliders

A. Papaefstathiou, GTX: 2312.13562

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

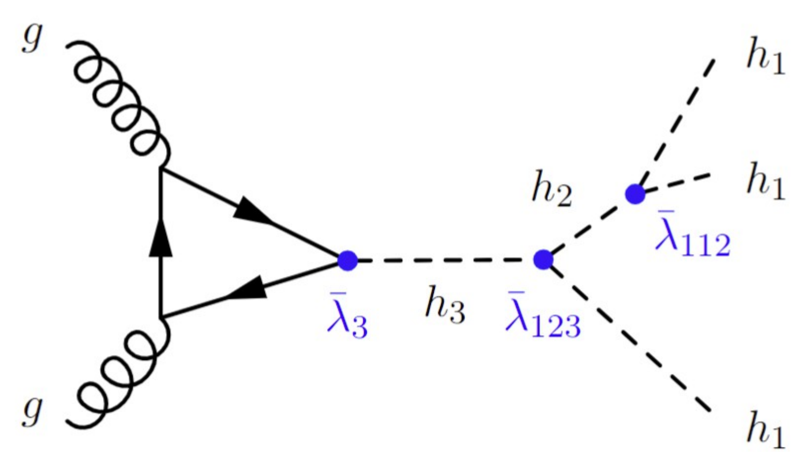
$$M_2, M_3, \theta_{hS}, \theta_{hX}, \theta_{SX}, v_S, v_X$$

Robens, Stefaniak, Wittbrodt: 1908.08554

Old Benchmark Scenario of Study BP3

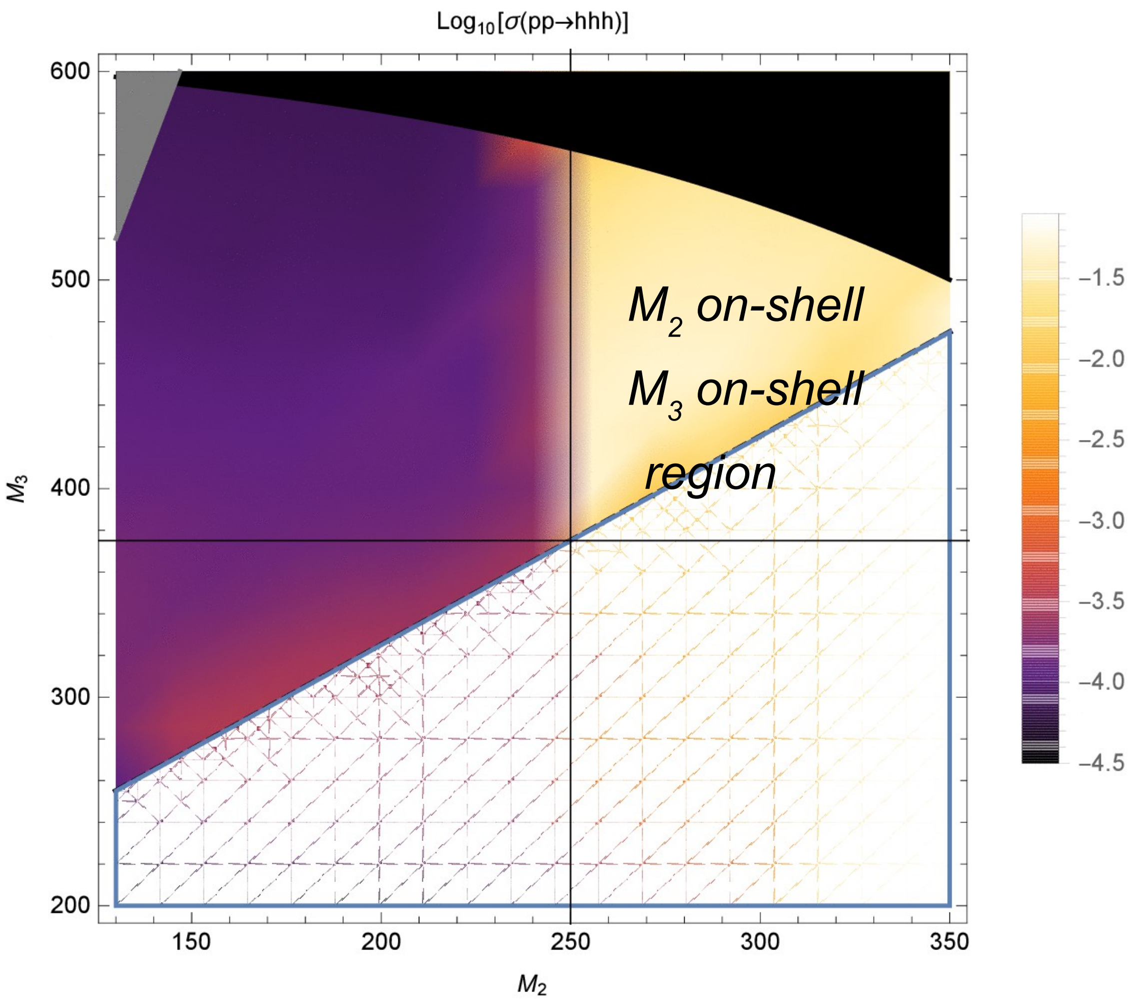
The BP3 Scenario introduced in 1908.08554 which allows for a large $h_1h_1h_1$ production while obeying current theoretical and experimental constraints.

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

A. Papaefstathiou, T. Robens, GTX: 2101.00037

Old benchmark points

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

These points are associated with large couplings which can break perturbativity at the energy scale MZ

A. Papaefstathiou, T. Robens, GTX: 2101.00037

New Benchmark points (LHC)

Determine phase space that enhances triple Higgs production in the TRSM based on

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Perturbative conditions

$$\lambda_{11} < \frac{\pi^2}{3} \approx 3.3, \quad \lambda_{22}, \lambda_{33} < \frac{4\pi^2}{9} \approx 4.4, \quad \lambda_{12}, \lambda_{13}, \lambda_{23} < 2\pi^2 \approx 20$$

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Boundedness from below

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$$\lambda_{11} < \frac{\pi^2}{3} \approx 3.3, \quad \lambda_{22}, \lambda_{33} < \frac{4\pi^2}{9} \approx 4.4, \quad \lambda_{12}, \lambda_{13}, \lambda_{23} < 2\pi^2 \approx 20$$

Boundedness from below

Experimental constraints from HiggsTools (HiggsSignals and HiggsBounds)

New Benchmark points (LHC)

Determine phase space that enhances triple Higgs production in the TRSM based on

Perturbative conditions

$$\lambda_{11} < \frac{\pi^2}{3} \approx 3.3, \quad \lambda_{22}, \lambda_{33} < \frac{4\pi^2}{9} \approx 4.4, \quad \lambda_{12}, \lambda_{13}, \lambda_{23} < 2\pi^2 \approx 20$$

Boundedness from below

Experimental constraints from HiggsTools (HiggsSignals and HiggsBounds)

Relevant HiggsBounds Experimental Analyses

Processes	Experiment	Int. Luminosity	arXiv ref.
$gg \to S \to W^+W^-, ZZ$	ATLAS	139 fb^{-1}	2004.14636 [57]
$gg \to S \to ZZ$	ATLAS	139 fb^{-1}	2009.14791 [58]
$gg \to S \to h_1 h_1 \to (b\bar{b})(\tau^+\tau^-)$	CMS	137 fb^{-1}	2106.10361 [59]
$(b\bar{b}, \tau^+\tau^-, W^+W^-, ZZ, \gamma\gamma)(b\bar{b})$		35.9 fb^{-1}	1811.09689 [60]
$gg \to S \to h_1 h_1 \to (b\bar{b}, \tau^+\tau^-, W^+W^-, \gamma\gamma)^2$	ATLAS	36.1 fb^{-1}	1906.02025 [61]
$gg \to S \to h_1 h_1 \to (b\bar{b})(\gamma\gamma)$	ATLAS	36.1 fb^{-1}	1807.04873 [62]
$gg \to S \to W^+W^-, ZZ$	ATLAS	36.1 fb^{-1}	1808.02380 [63]
$pp \to S \to ZZ$ (incl. VBF)	CMS	35.9 fb^{-1}	1804.01939 [64]
$gg \to S \to h_1 h_1 \to (b\bar{b})(b\bar{b})$	CMS	35.9 fb^{-1}	1806.03548 [65]
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New Benchmark points (LHC)

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Boundedness from below

Experimental constraints from HiggsTools (HiggsSignals and HiggsBounds)

We consider the threshold

$$\sigma_{3h_1} > 100\, \sigma_{3h_1}^{\mathrm{SM}},$$

Our analysis entailed 530,000 phase space points

Only 130 points fulfilled all the conditions

See Osama Karkout talk

New Benchmark points (LHC)

Benchmark points for enhanced triple Higgs production										
M_2	M_3	v_2	v_3	θ_{12}	θ_{13}	θ_{23}	$\frac{\sigma}{\sigma_{SM}}$	Res. Frac.	μ_{pert} GeV	$\frac{\mu_{\text{pert}}}{\mu_{\text{pole}}}$
259.0	495.0	215.8	180.8	6.191	0.163	5.691	306.025	0.955	2.7×10^2	7.3
270.6	444.7	122.4	847.2	0.268	0.030	0.522	302.361	0.929	1.8×10^2	7.4
268.6	452.7	137.8	784.8	0.263	0.023	0.645	275.616	0.954	2.4×10^2	7.3
272.6	480.7	928.3	143.7	3.098	2.9	2.375	267.245	0.948	1.4×10^2	7.3
269.0	409.8	138.0	599.4	0.244	0.004	0.773	266.439	0.976	2.4×10^2	7.4
269.1	486.9	227.5	307.9	0.074	6.149	2.631	157.583	0.956	4.3×10^2	7.3
259.2	577.0	289.0	275.6	0.137	6.148	2.324	145.470	0.781	1.2×10^4	7.3
283.7	575.0	259.4	330.4	0.137	6.152	2.299	122.546	0.779	3.0×10^3	7.3
264.3	469.3	207.3	359.5	0.285	6.277	0.692	119.121	0.999	5.4×10^3	7.3
266.5	461.9	653.1	229.0	2.889	3.046	1.015	112.794	0.863	5.3×10^4	7.4
259.2	399.7	444.5	217.0	2.917	3.046	1.047	103.717	0.973	1.2×10^5	7.4

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

O. Karkout, A. Papaefstathiou, M. Postma, GTX, J. van de Vis, T du Pree: 2404.12425

New Benchmark points (LHC)

Benchmark points for enhanced triple Higgs production

						…23	$\frac{\sigma}{\sigma_{SM}}$	Res. Frac.	$\mu_{\rm pert}$ GeV	$\frac{\mu_{\rm pert}}{\mu_{\rm pole}}$
						…691	306.025	0.955	2.7 $\times 10^2$	7.3
						…522	302.361	0.929	1.8 $\times 10^2$	7.4
						…645	275.616	0.954	2.4 $\times 10^2$	7.3
						…375	267.245	0.948	1.4 $\times 10^2$	7.3
						…773	266.439	0.976	2.4 $\times 10^2$	7.4
						…631	157.583	0.956	4.3 $\times 10^2$	7.3
						…324	145.470	0.781	1.2 $\times 10^4$	7.3
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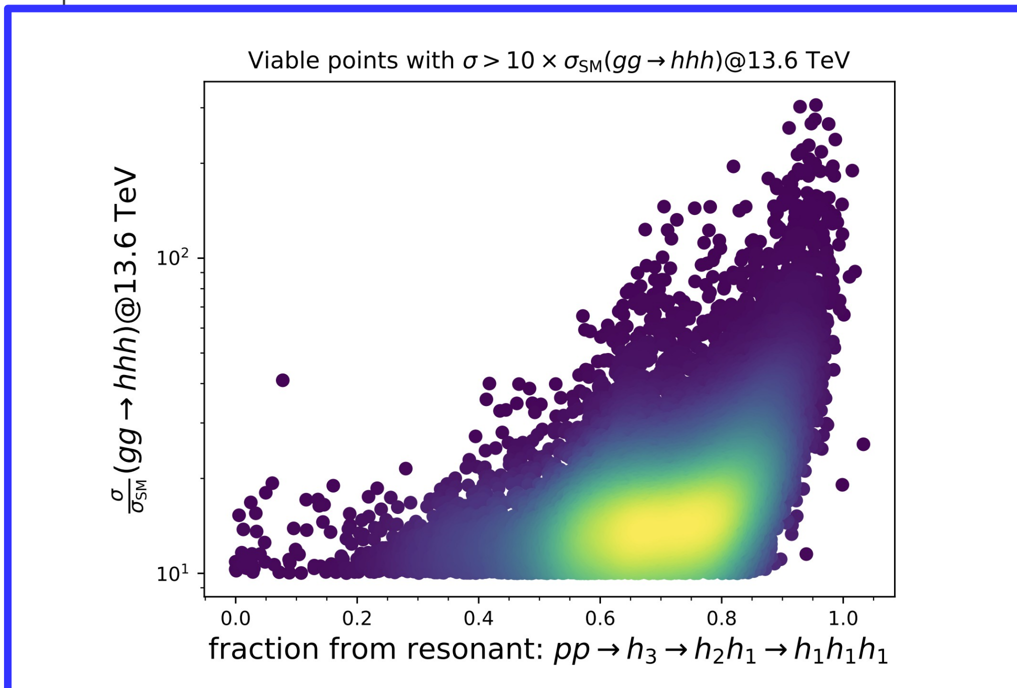

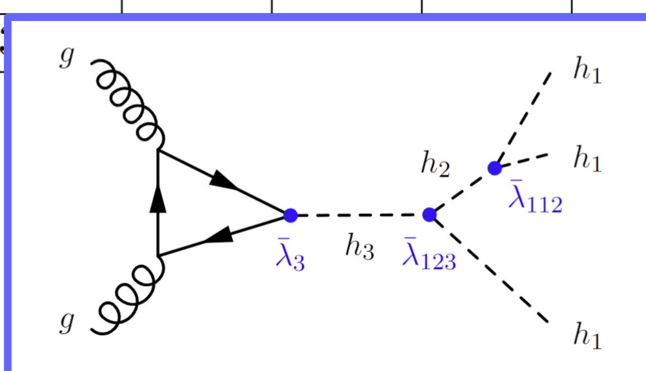

New Benchmark points (LHC)

Benchmark points for enhanced triple Higgs production

M_2	M_3	v_2	v_3	θ_{12}	θ_{13}	θ_{23}	$\frac{\sigma}{\sigma_{SM}}$	Res. Frac.	$\mu_{\rm pert}$ GeV	$\frac{\mu_{\rm pert}}{\mu_{\rm pole}}$
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New Benchmark points (LHC)

Benchmark points for enhanced triple Higgs production										
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259.2	399.7	444.5	217.0	2.917	3.046	1.047	103.717	0.973	1.2×10^5	7.4

In practice our points fulfil the following theoretical relationship

$$\ln(\mu_{\text{pole}}/\mu_{\text{pert}}) = 2$$

$$\mu_{\text{pole}} \approx 7.4\mu_{\text{pert}}$$

Closing Remarks

- 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).*

- *We have presented projections on the potential values that future hadron colliders can explore on the cubic and quartic self couplings.*

- *The double resonance dominance allows to find a universal simplified approach which allows to get bounds on potential optimal selection points in a model independent way.*

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 945422

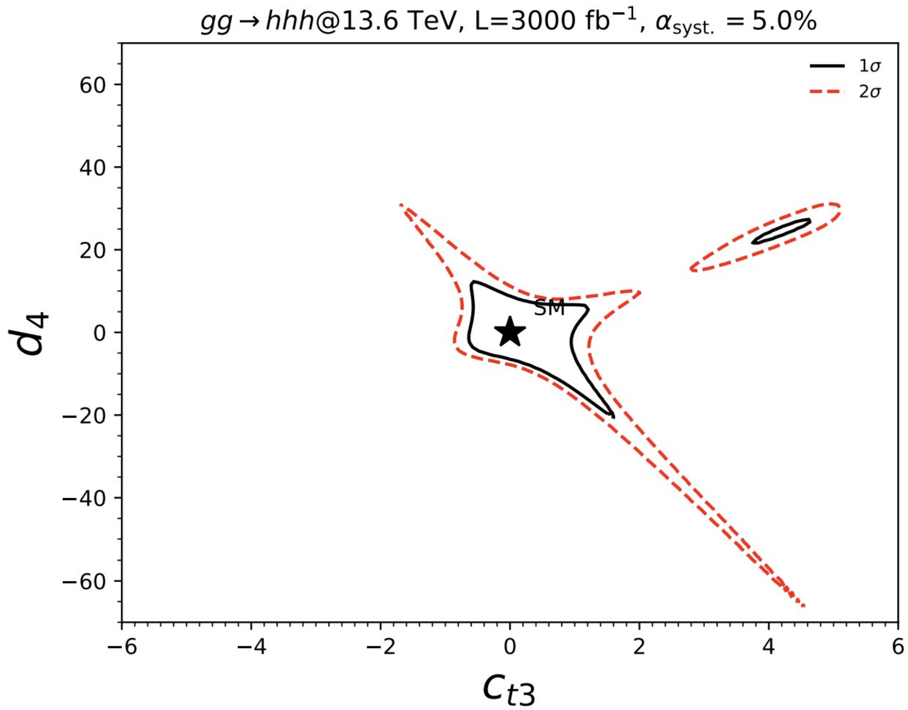
Backup

$$
\begin{aligned}
\mathcal{L}_{h^n} = & -\mu^2|H|^2 - \lambda|H|^4 - \left(y_t \bar{Q}_L H^c t_R + y_b \bar{Q}_L H b_R + \text{h.c.}\right) \\
& + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda_{\text{SM}}|H|^6 + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu} G_a^{\mu\nu} \\
& - \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar{Q}_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar{Q}_L H b_R + \text{h.c.}\right),
\end{aligned}
$$

Anomalous couplings

Confidence regions on the anomalous couplings at proton-proton colliders

HL-LHC



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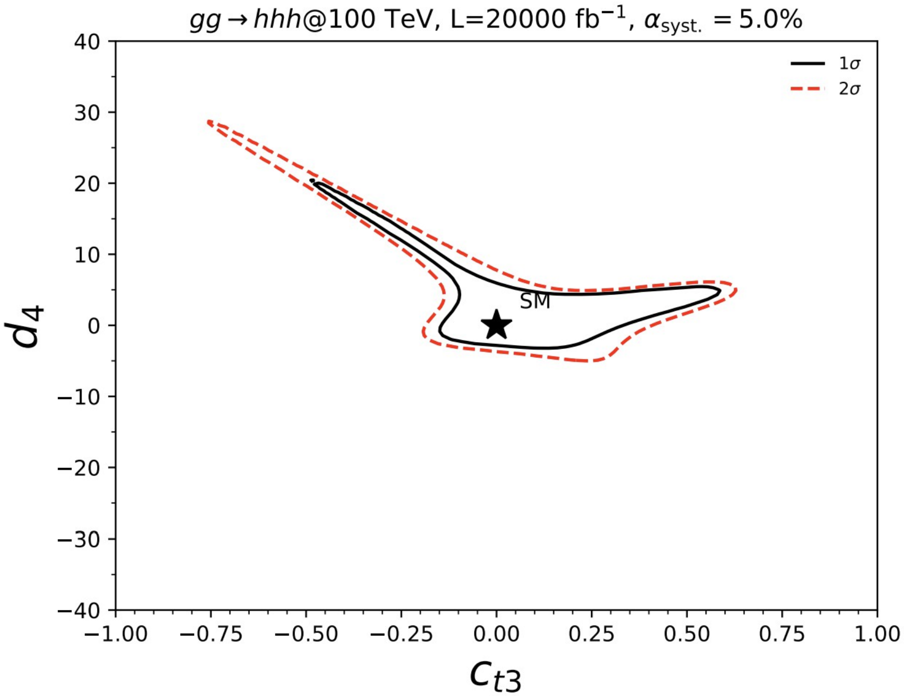


In this plot it is assumed that the SM is the underlying theory

Adding an Extra-Scalar Singlet

The x-SM potential

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

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

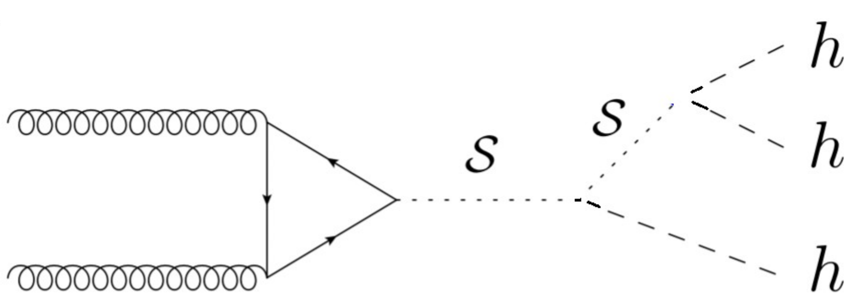
Kotwal et al. 1605.06123

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

A simplified approach to double resonant triple Higgs production (LHC)

When the double resonant channel is dominant

$$\sigma(m_2, m_3, \Gamma_2, \Gamma_3, \kappa_3, \lambda_{123}, \lambda_{112}) = \hat{\sigma}_u(m_2, m_3) \times \frac{\kappa_3^2 \lambda_{123}^2 \lambda_{112}^2}{\Gamma_2 \Gamma_3} = \hat{\sigma}_u(m_2, m_3) \times \rho^2$$

"Unity" cross section

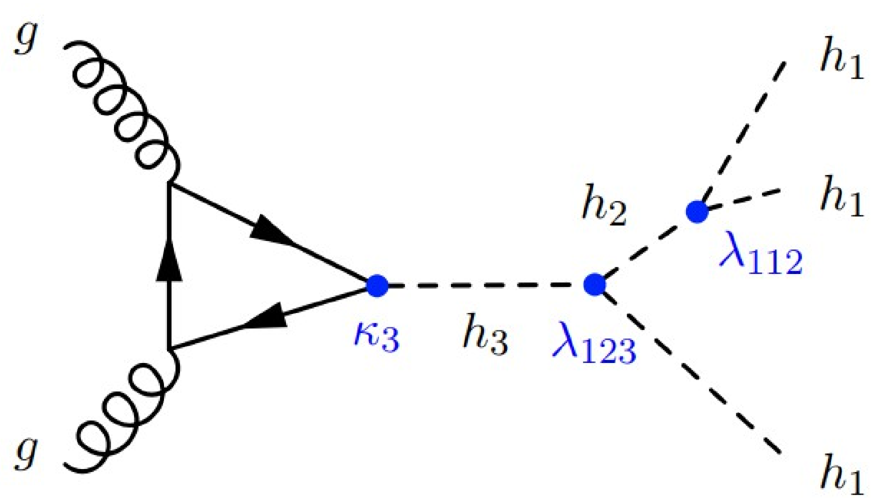
$$\kappa_3 = 1,\ \lambda_{123} = \lambda_{112} = 1\ \text{GeV}$$

$$\Gamma_2 = \Gamma_3 = 1\ \text{GeV}$$

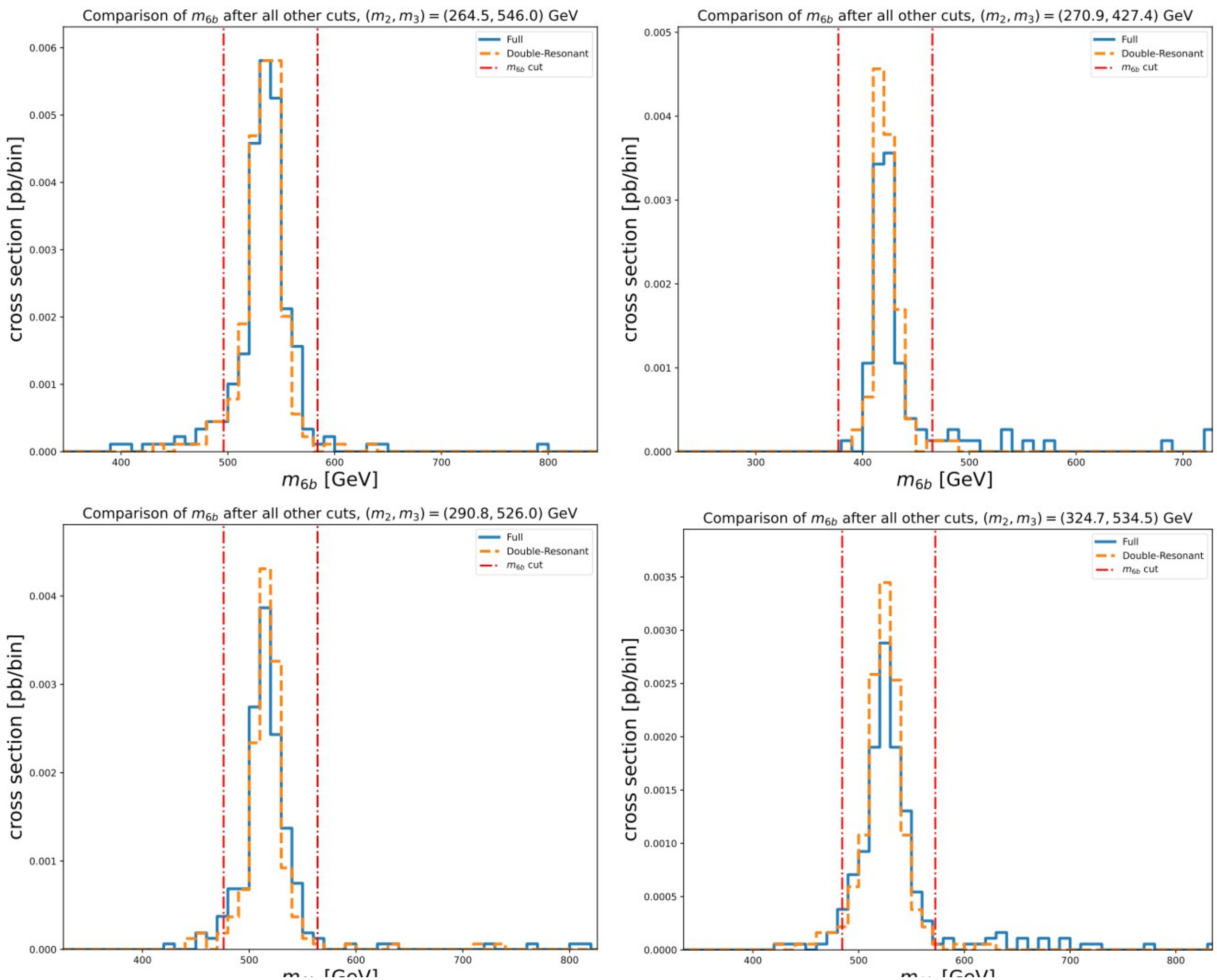
$$\Gamma_i \ll M_i$$

$$\rho^2 \equiv \kappa_3^2 \lambda_{123}^2 \lambda_{112}^2 / (\Gamma_2 \Gamma_3)\ .$$

Model dependent factor

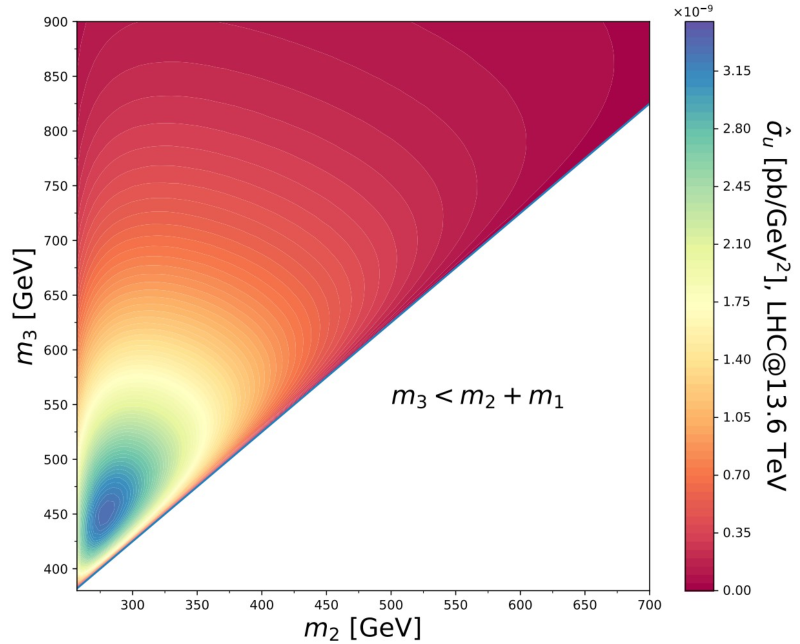


A simplified approach to double resonant triple Higgs production (LHC)



A. Papaefstathiou, GTX: 2501.14866

A simplified approach to double resonant triple Higgs production (LHC)



Define a “universal” set of selection cuts by optimizing

$$\Sigma_\Pi \equiv \prod_{i=1}^{N} \Sigma_i = \prod_{i=1}^{N} \frac{S_i}{\sqrt{B}} \quad \Rightarrow \quad \Sigma_\Pi = \left(\prod_{j=1}^{N} \frac{\sqrt{\mathcal{L}}\sigma_j}{\sqrt{\sigma_B}} \right) \left(\prod_{i=1}^{N} \frac{\varepsilon_i}{\sqrt{\varepsilon_{B,i}}} \right)$$

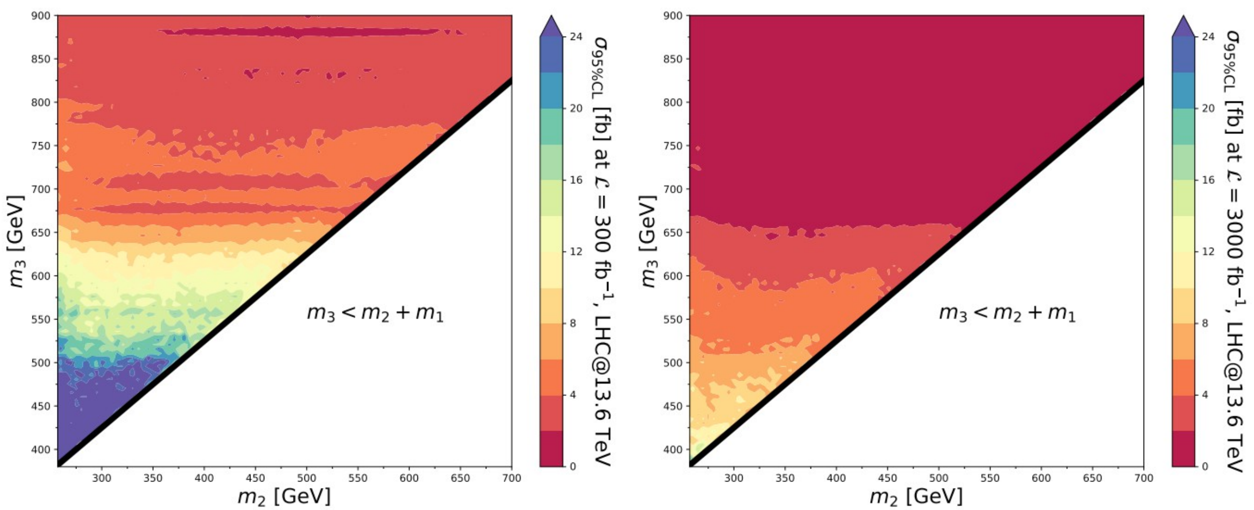
$$\Sigma = \frac{\varepsilon_S \sigma_S \mathcal{L}}{\sqrt{\varepsilon_B \sigma_B \mathcal{L}}} \quad \xrightarrow{\Sigma = 2} \quad \sigma_{95\%\mathrm{CL}} = 2 \frac{\sqrt{\varepsilon_B \sigma_B}}{\varepsilon_S \sqrt{\mathcal{L}}}$$

A. Papaefstathiou, GTX: 2501.14866

A simplified approach to double resonant triple Higgs production (LHC)

"Universal" set of selection cuts

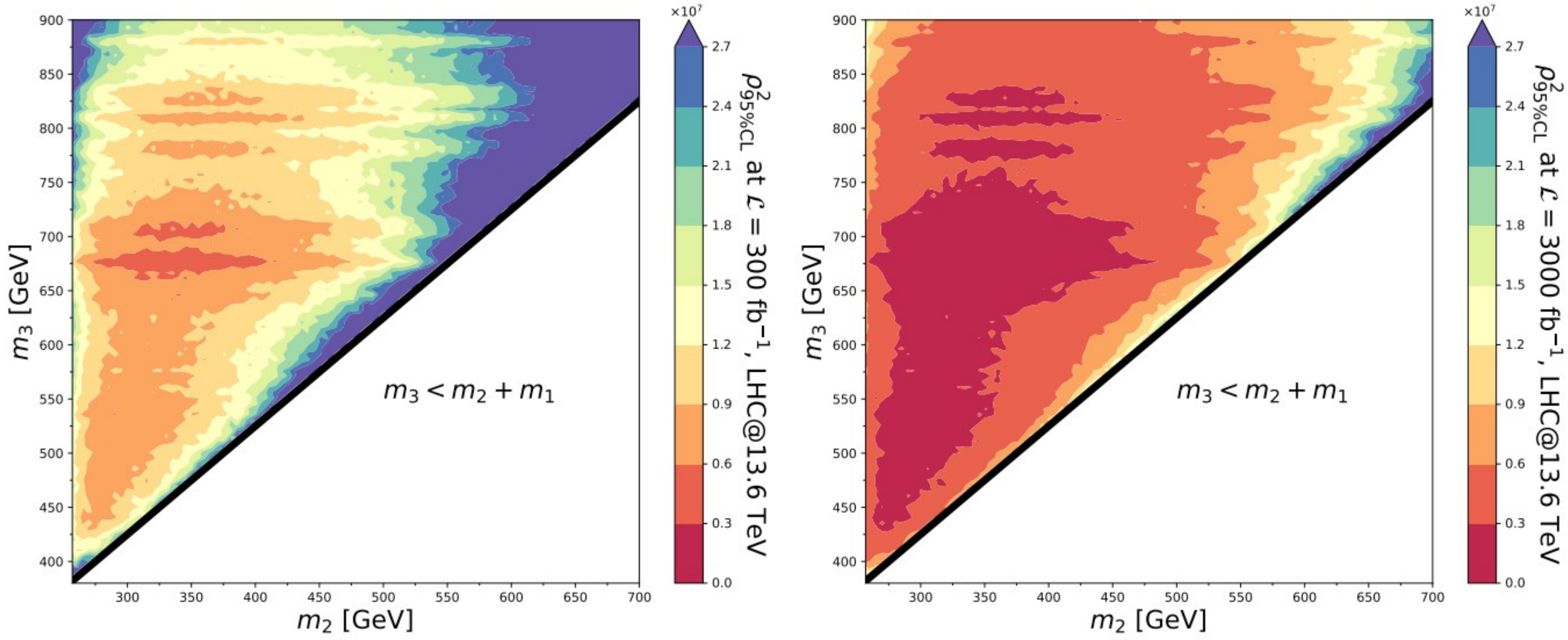
Observable	Constraint
$p_{T min,b}$	37.0
$\lvert\eta_{b,max}\rvert$	2.95
$\chi^{2,(6)}$	12.0
$\chi^{2,(4)}$	34.0
Δm_{6b}^{inv}	$^{+38.0}_{-50.0}$
m_{4b}^{inv}	$\leqslant m_3$
$p_T(h_1^i)$	$\geqslant [50, 50, 0]$
$\Delta m_{\text{min,med,max}}$	$\geqslant [15, 14, 20]$
$\Delta R(h_1^i, h_1^j)$	$\leqslant 3.5$
$\Delta R_{bb}(h_1)$	$\leqslant 3.5$



A. Papaefstathiou, GTX: 2501.14866

A simplified approach to double resonant triple Higgs production (LHC)

For the TRSM



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