

Di-Higgs production in the RxSM at the HL-LHC



Instituto de
Física
Teórica
UAM-CSIC



Author: Alain Verduras
Director: Sven Heinemeyer

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Motivation

SM predicts the same amount of particles and antiparticles

Where are the antiparticles?

Electroweak Baryogenesis can explain it

What do we need for Baryogenesis?

SFOEWPT

How can we obtain it?

BSM models that modify the Higgs sector of the SM

Which ones?

The simplest Higgs extended sector that allows a SFOEWPT: RxSM

Objectives

- Define a **benchmark plane** that allows a **SFOEWPT** for the RxSM.
- Check if the RxSM can be distinguished from the SM in the HL-LHC via the **di-Higgs production cross section** and **differential cross section distributions with respect to the invariant mass of the two Higgses**
- Check the **importance of taking into account the full calculation** for the total and differential di-Higgs production cross sections.

Real Singlet Extension

Potential

$$V(\mathcal{H}, \mathcal{S}) = -\mu^2(\mathcal{H}^\dagger \mathcal{H}) + \lambda(\mathcal{H}^\dagger \mathcal{H})^2 + \frac{a_1}{2}(\mathcal{H}^\dagger \mathcal{H})\mathcal{S} + \frac{a_2}{2}(\mathcal{H}^\dagger \mathcal{H})\mathcal{S}^2 + \frac{b_2}{2}\mathcal{S}^2 + \frac{b_3}{3}\mathcal{S}^3 + \frac{b_4}{4}\mathcal{S}^4$$

Doublet

Singlet

Mass matrix

Mixing matrix

$$\mathcal{H} = \begin{pmatrix} 0 \\ \frac{h'+v}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{S} = s + x$$

$$\begin{pmatrix} m_{h'}^2 & m_{h's}^2 \\ m_{h's}^2 & m_s^2 \end{pmatrix}$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} h' \\ s \end{pmatrix}$$

Real Singlet Extension

Triple Higgs couplings

$$\lambda_{hhh} = \frac{1}{v} \left[\left(\frac{a_1}{4} + \frac{a_2 x}{2} \right) \cos^2 \theta \sin \theta + a_2 v \cos \theta \sin^2 \theta + \left(\frac{b_3}{3} + b_4 x \right) \sin^3 \theta + \lambda v \cos^3 \theta \right]$$

$$\lambda_{hhH} = \frac{1}{4v} \left[(a_1 + 2a_2 x) \cos^3 \theta + 4v(a_2 - 3\lambda) \cos^2 \theta \sin \theta - 2(a_1 + 2a_2 x - 2b_3 - 6b_4 x) \cos \theta \sin^2 \theta - 2a_2 v \sin^3 \theta \right]$$

Mixing angle

$$\sin 2\theta = \frac{(a_1 + 2a_2 x)v}{m_H^2 - m_h^2}$$

Kappa lambda modifier

$$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\text{SM}}}$$

Real Singlet Extension: Constrains

Theoretical:

Vacuum stability:

$$0 < \lambda, \frac{a_2}{2}, \frac{b_4}{4} \quad a_2 > -2\sqrt{\lambda b_4}$$

Perturbativity:

$$\lambda, \frac{a_2}{2}, \frac{b_4}{4} < 4\pi$$

Experimental:

HiggsBounds:

BSM Higgs boson searches

HiggsSignals:

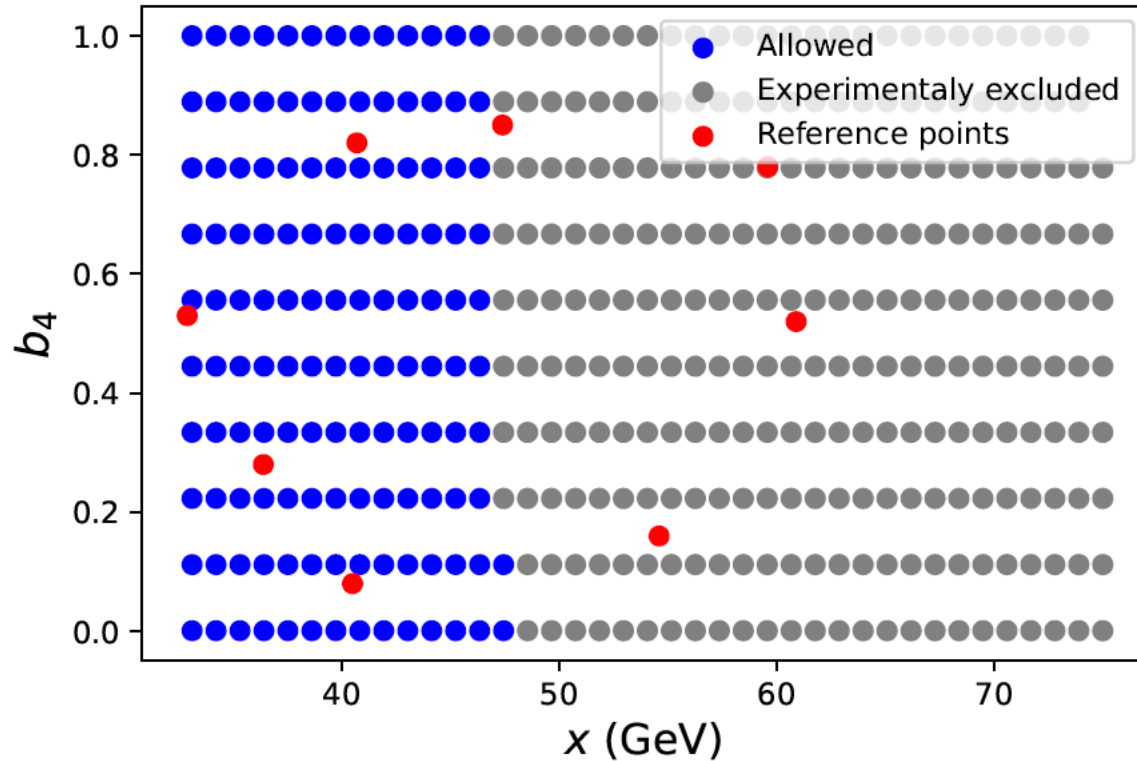
125 GeV Higgs boson measurements

Reference points

Benchmark	x	λ	a_1 (GeV)	a_2	b_3 (GeV)	b_4	κ_λ	λ_{hhH}
B1	60.9	0.17	-490	2.65	-361	0.52	1.42	0.25
B2	59.6	0.17	-568	3.26	-397	0.78	1.40	0.31
B3	54.6	0.17	-642	3.80	-214	0.16	1.41	0.34
B4	47.4	0.18	-707	4.63	-607	0.85	1.47	0.38
B5	40.7	0.18	-744	5.17	-618	0.82	1.47	0.37
B6	40.5	0.19	-844	5.85	-151	0.08	1.48	0.42
B7	36.4	0.18	-898	7.36	-424	0.28	1.43	0.48
B8	32.9	0.17	-976	8.98	-542	0.53	1.41	0.54

Ref: Hao-Lin Li, Michael Ramsey-Musolf, and Stéphane Willlocq. Probing a scalar singlet-catalyzed electroweak phase transition with resonant di-Higgs boson production in the 4b channel. Phys. Rev. D, 100(7):075035, 2019, 1906.05289.

Benchmark Plane: SFOEWPT

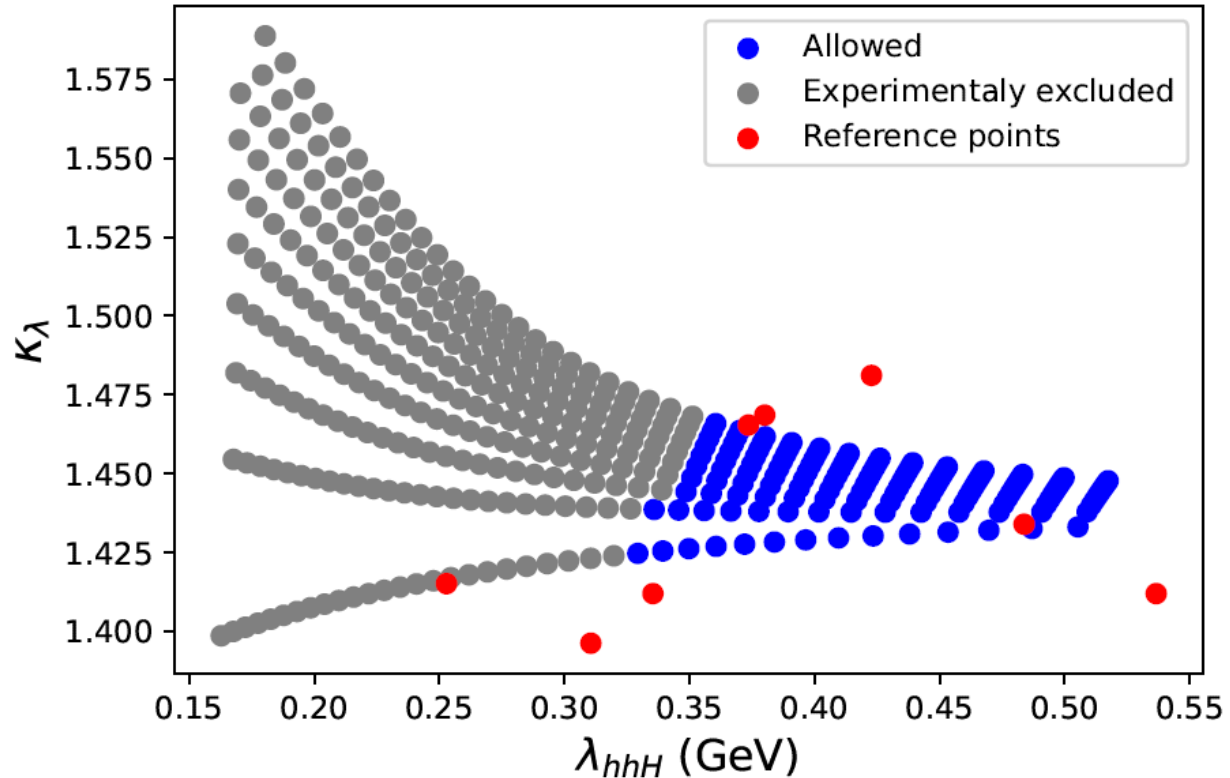


$$a_1 x = -32000 ,$$

$$\lambda = 0.18 ,$$

$$b_3 = -660\sqrt{b_4} .$$

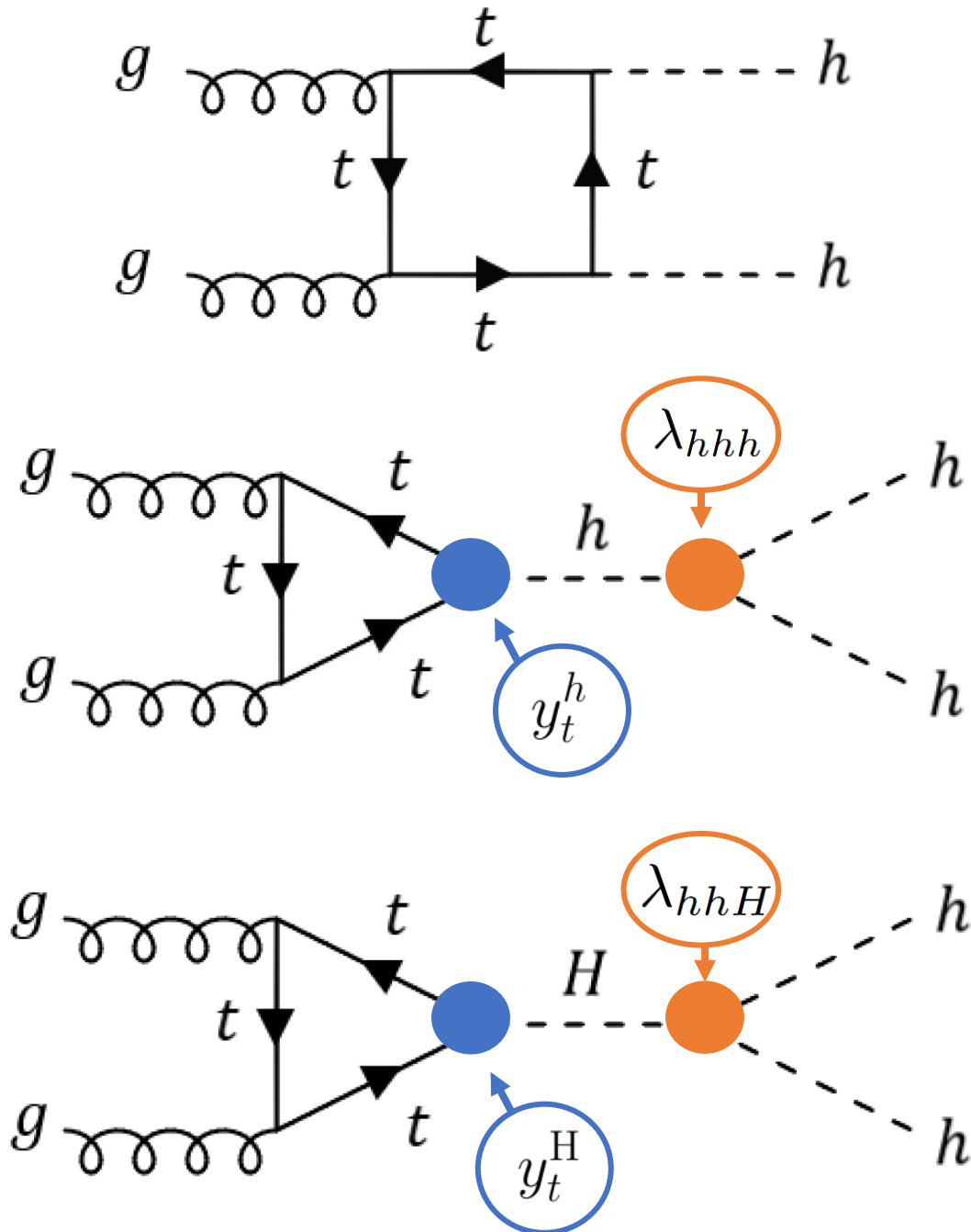
Benchmark Plane



Experimentally excluded:

2020 ATLAS search for a resonance of a heavy Higgs boson, which decays into two Z bosons and ultimately into four leptons

HPAIR

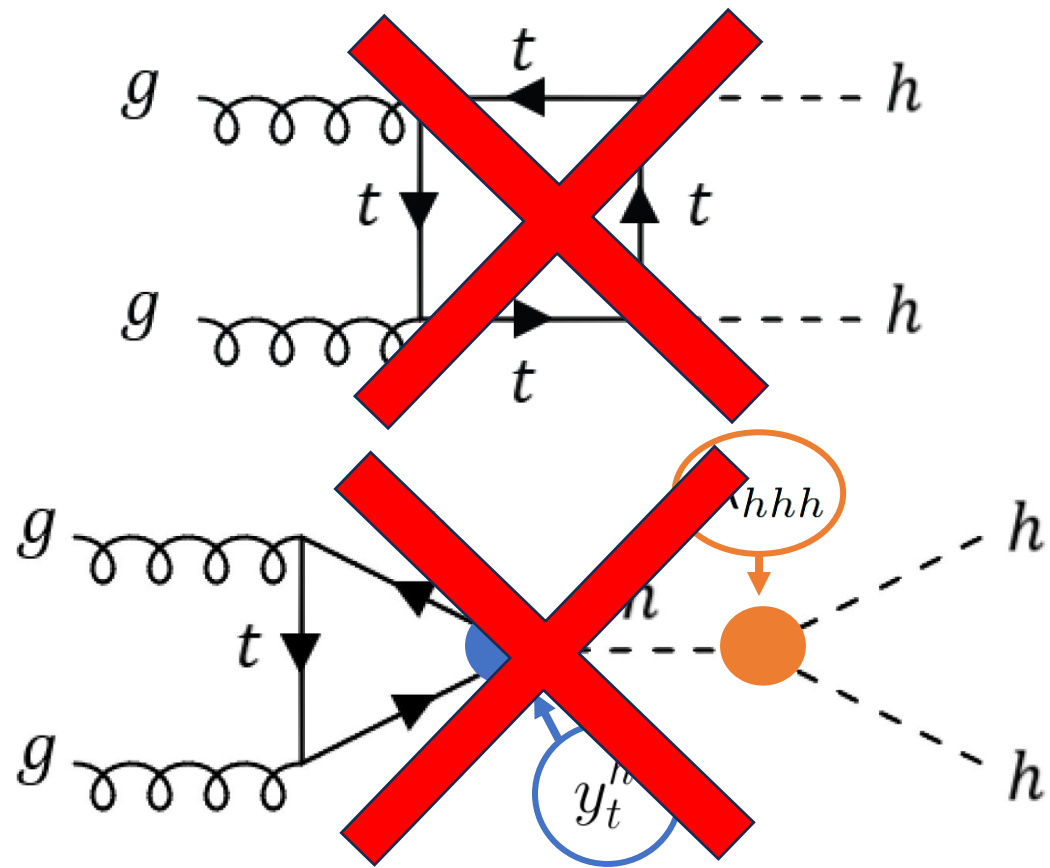


HPAIR is a private, model-dependent code that computes the production cross section of two neutral Higgs bosons at the HL-LHC and LHC by gluon fusion

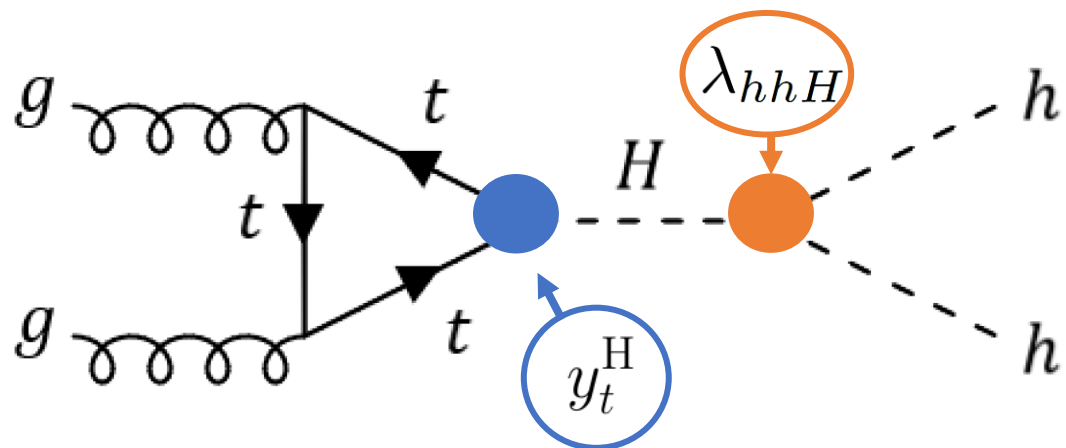
Fortran library **LHPDF6** has been used to perform the PDF calculations

Thanks to M. Muhlleitner (KIT) for developing the code

CMS/ATLAS ANALYSIS

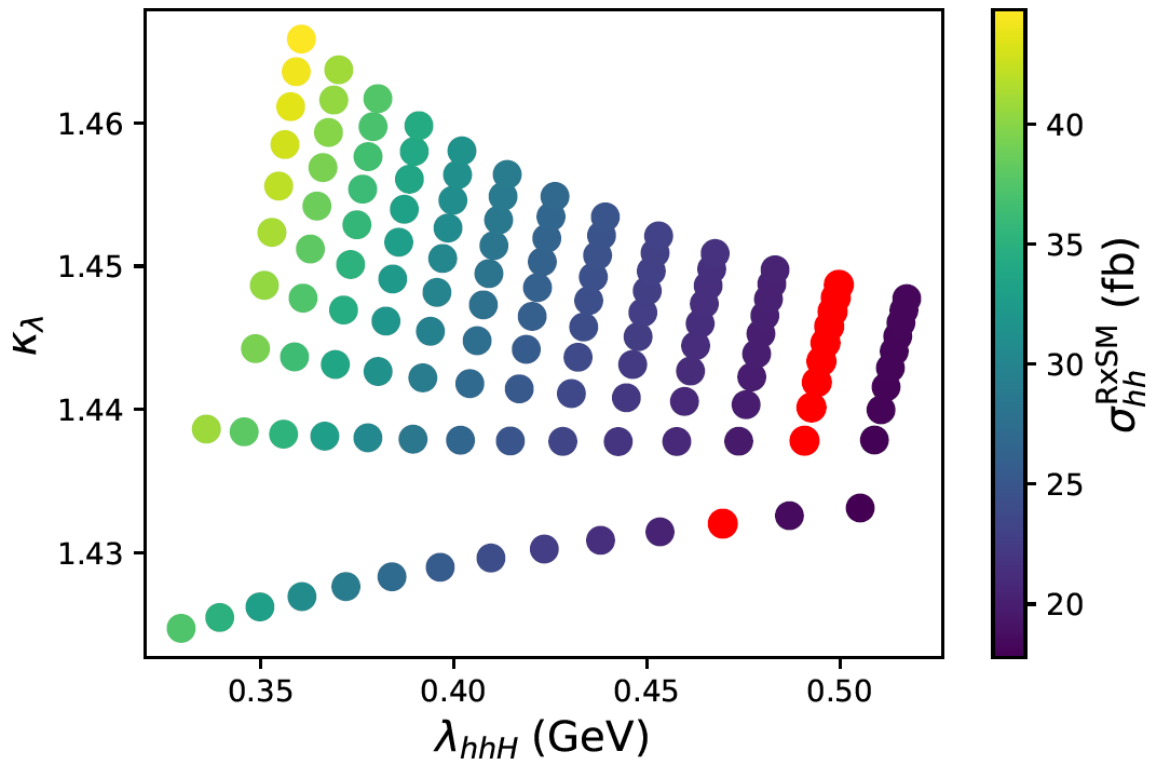


ONLY CONSIDER HEAVY HIGGS
S-CHANNEL CONTRIBUTION TO
THE CROSS SECTION

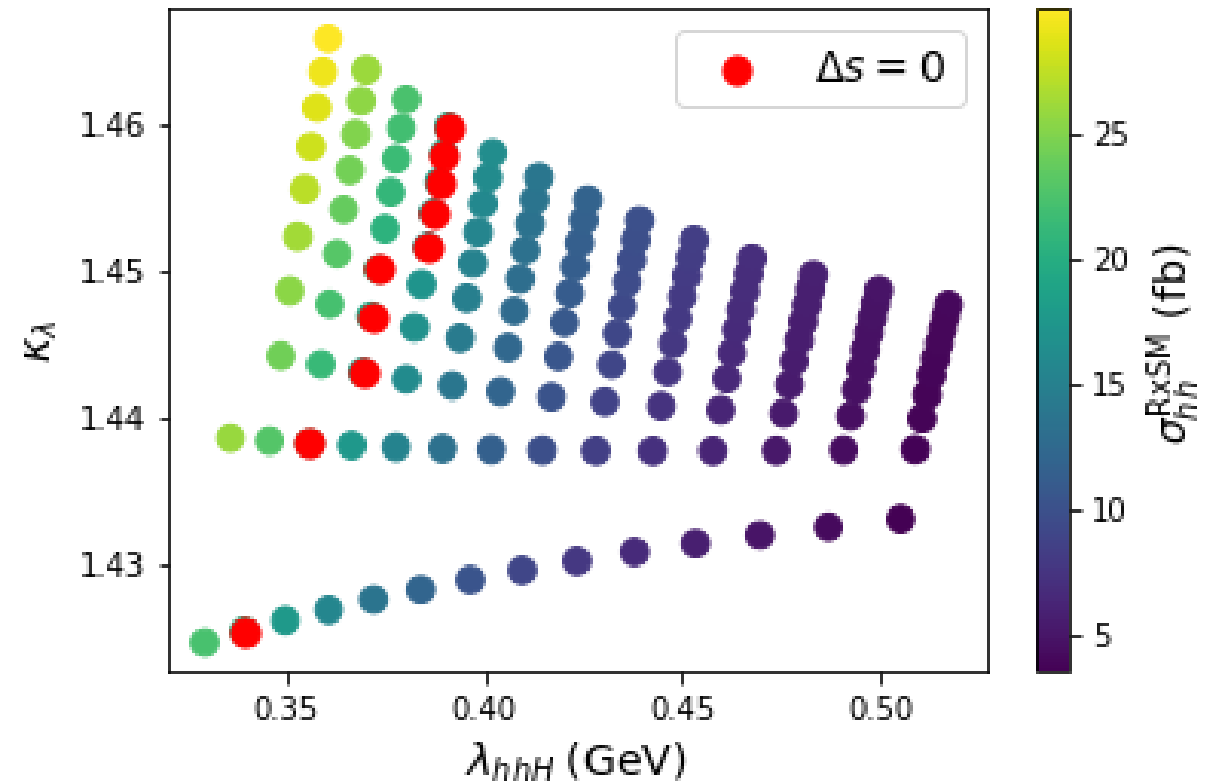


Di-Higgs production cross section

Full calculation:

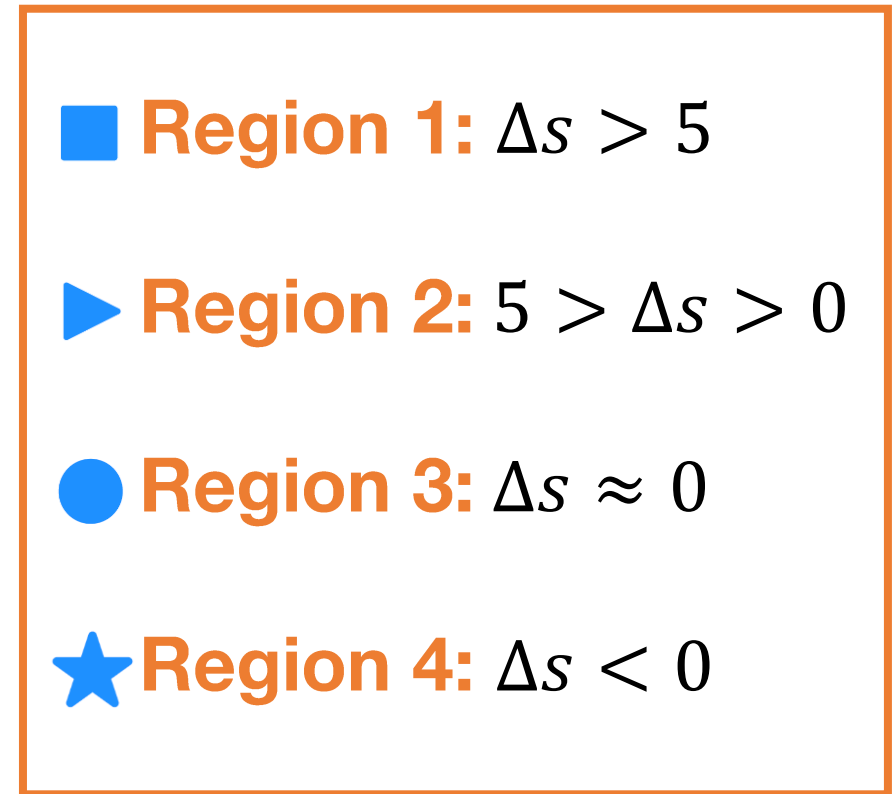
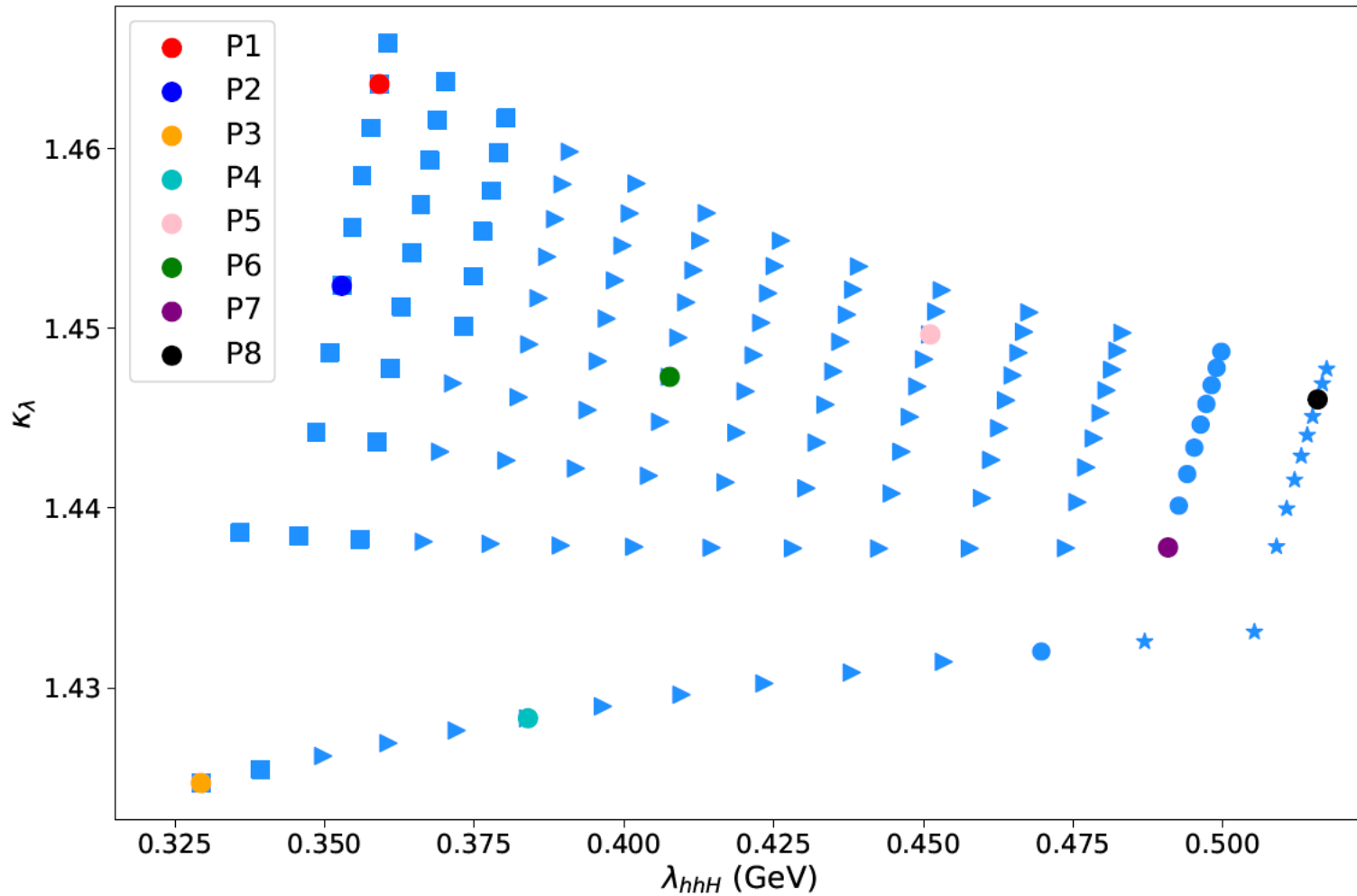


H resonant contribution:

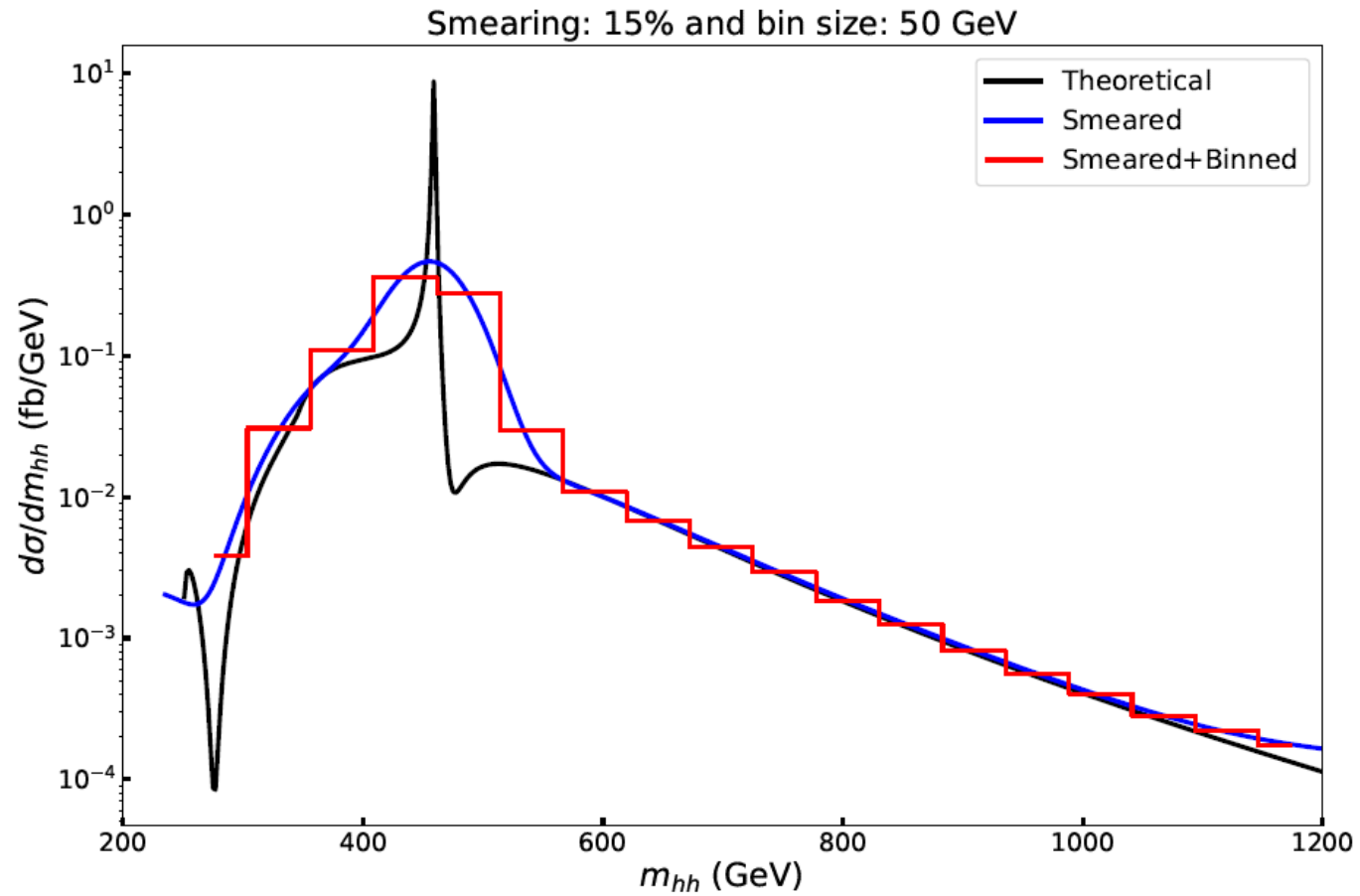


$$\sigma_{\text{SM}}^{\text{LO}}(\text{pp} \rightarrow \text{hh}) = 19.76 \text{ fb}$$

m_{hh} distribution



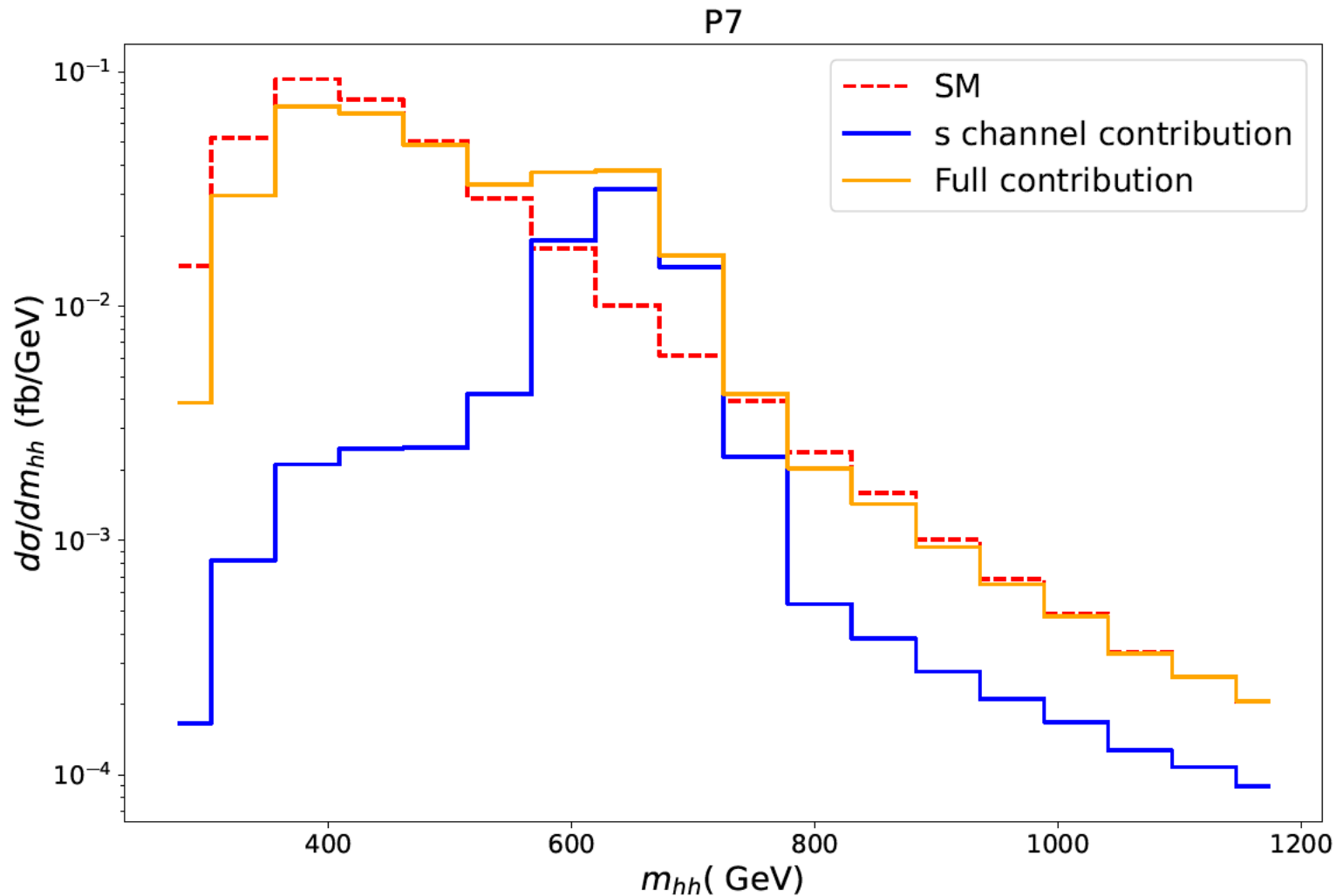
Experimental Uncertainties



Smearing: 15%

Binning: 50 GeV

m_{hh} distribution: results



$$m_H = 642,9 \text{ GeV}$$

$$x = 33,1 \text{ GeV}$$

$$\lambda_{hhH} = 0,49$$

$$\kappa_\lambda = 1,44$$

Conclusions

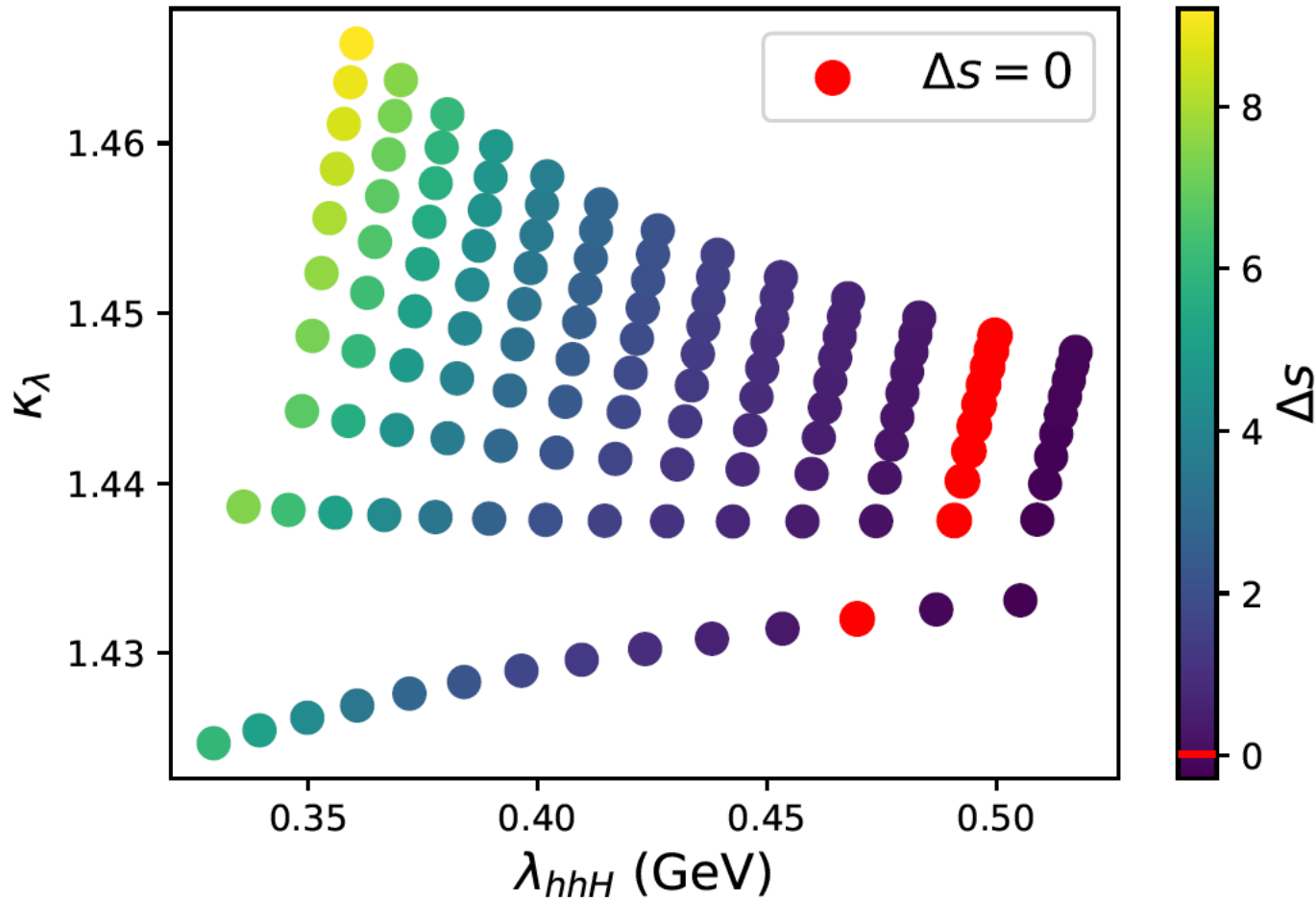
- A **benchmark** plane has been defined that allows **SFOEWPT** in the **RxSM**.
- Taking into account the **FULL CALCULATION** **the total and differential cross section can be used to distinguish the RxSM from the SM.**
- Limits obtained considering only resonant contributions are not reliable for the real model, cannot be used by theorists to interpret their data.

References

1. Hao-Lin Li, Michael Ramsey-Musolf, and Stéphanie Willocq. Probing a scalar singlet-catalyzed electroweak phase transition with resonant di-Higgs boson production in the 4b channel. *Phys. Rev. D*, 100(7):075035, 2019, 1906.05289.
2. CMS Collaboration, “A portrait of the Higgs boson by the {CMS} experiment ten years after the discovery”, *Nature* 607 (2022) 7917, arXiv: 2207.00043.
3. Henning Bahl, Thomas Biekötter, Sven Heinemeyer, Cheng Li, Steven Paasch, Georg Weiglein, and Jonas Wittbrodt. HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals. 10 2022, 2210.0933
4. Hamza Abouabid, Abdesslam Arhrib, Duarte Azevedo, Jaouad El Falaki, Pedro. M. Ferreira, Margarete Mühlleitner, and Rui Santos. Benchmarking di-Higgs production in various extended Higgs sector models. *JHEP*, 09:011, 2022, 2112.12515

Thanks for your
attention

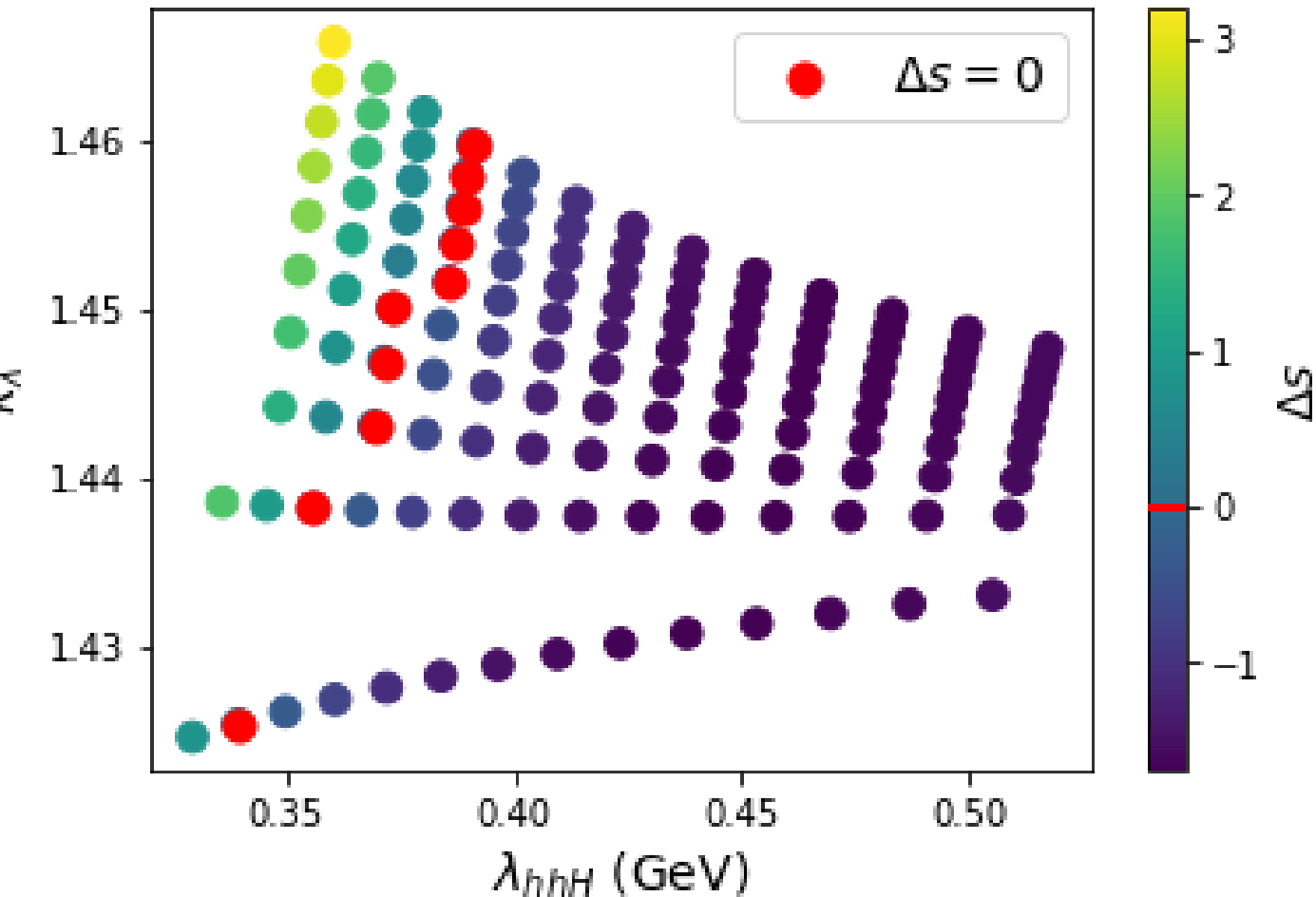
Statistical Significance wrt SM: full calculation



$$\Delta\sigma_{\text{RxSM}} = \frac{\sigma_{\text{RxSM}}}{s_{\text{SM}}} \frac{\sqrt{\sigma_{\text{SM}}}}{\sqrt{\sigma_{\text{RxSM}}}}$$

$$\Delta\mathcal{S} = \frac{\sigma_{\text{RxSM}} - \sigma_{\text{SM}}}{\Delta\sigma_{\text{RxSM}}}$$

Statistical Significance wrt SM: res-only



$$\Delta\sigma_{\text{RxSM}} = \frac{\sigma_{\text{RxSM}}}{s_{\text{SM}}} \frac{\sqrt{\sigma_{\text{SM}}}}{\sqrt{\sigma_{\text{RxSM}}}}$$

$$\Delta S = \frac{\sigma_{\text{RxSM}} - \sigma_{\text{SM}}}{\Delta\sigma_{\text{RxSM}}}$$

Real Singlet Extension II

Mass terms

$$m_{h,H}^2 = \frac{1}{2} \left(m_{h'}^2 + m_s^2 \mp |m_{h'}^2 - m_s^2| \sqrt{1 + \left(\frac{2m_{h's}^2}{m_{h'}^2 - m_s^2} \right)^2} \right)$$

BSM decay width

$$\Gamma_{H \rightarrow hh} = \frac{\lambda_{hhH}^2 \sqrt{1 - \frac{4m_h^2}{m_H^2}}}{8\pi m_H}$$

Total decay width

$$\Gamma_H = \Gamma^{\text{SM}}(m_H) \cdot \sin^2(\theta) + \Gamma_{H \rightarrow hh}$$

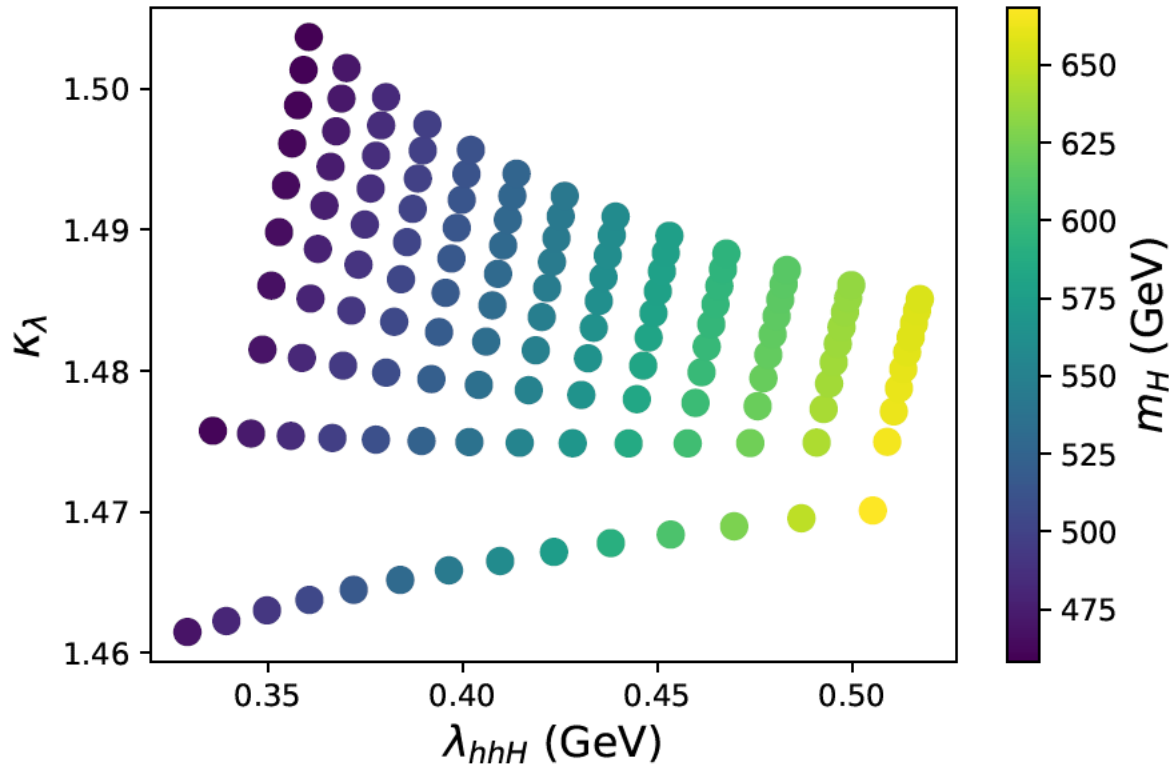
Decay width to SM:

$$\Gamma_{h \rightarrow ii}^{\text{RxSM}} = \Gamma_{h' \rightarrow ii}^{\text{SM}} \cdot \cos^2(\theta)$$

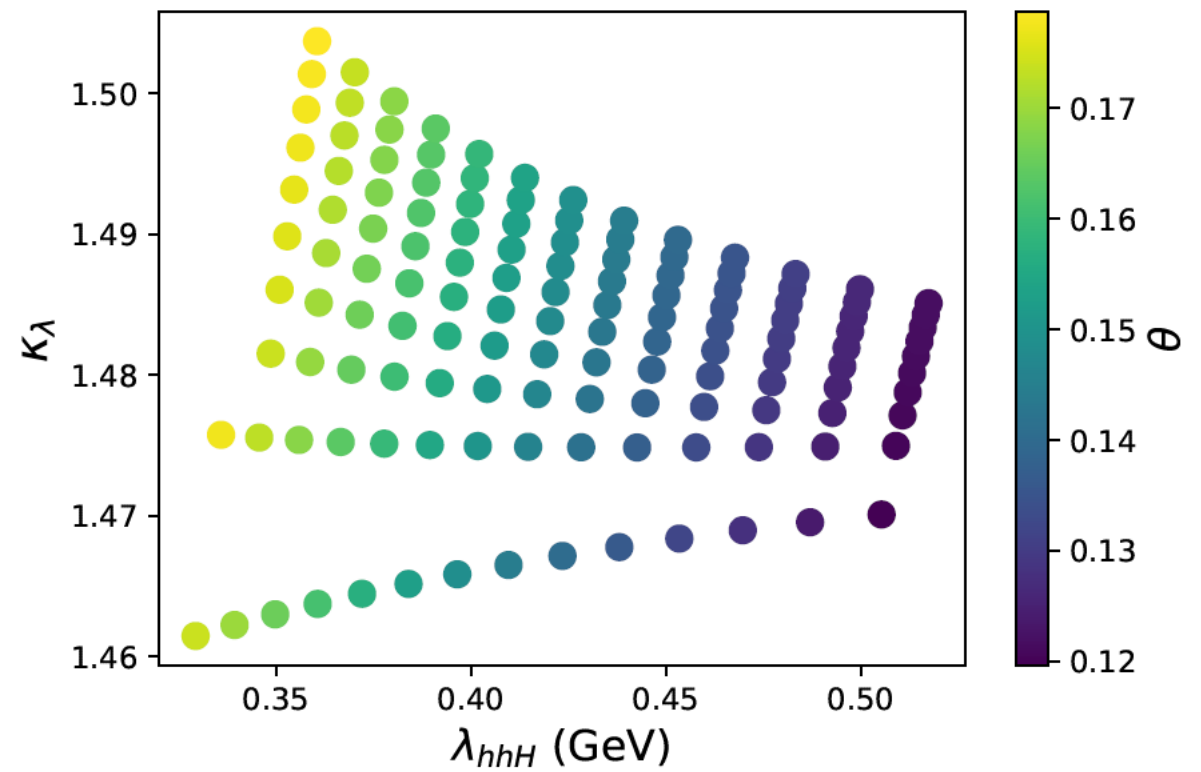
$$\Gamma_{H \rightarrow ii}^{\text{RxSM}} = \Gamma_{h' \rightarrow ii}^{\text{SM}} \cdot \sin^2(\theta)$$

Benchmark Plane

Heavy Higgs mass:



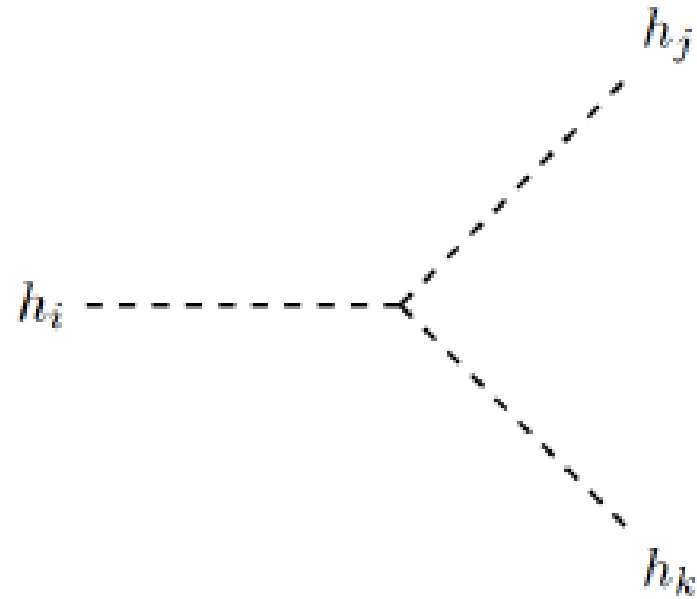
Mixing angle:



Benchmark points

Id	m_H (GeV)	θ	x (GeV)	b_4	λ_{hhH}	κ_λ	Γ_H (GeV)	$\sigma_{hh}^{\text{RxSM}}$ (fb)	Color
P1	459.2	0.178	46.3	0.89	0.36	1.47	2.07	44.15	red
P2	464.9	0.176	46.3	0.45	0.35	1.46	2.07	41.26	blue
P3	469.4	0.174	47.4	0.00	0.32	1.43	2.02	37.35	orange
P4	529.8	0.153	41.9	0.00	0.38	1.43	2.38	27.09	cyan
P5	577.5	0.139	37.5	0.78	0.45	1.45	2.72	22.88	pink
P6	531.7	0.152	40.8	0.45	0.40	1.45	2.46	27.72	green
P7	642.9	0.125	34.2	0.11	0.49	1.44	2.89	18.73	purple
P8	657.9	0.122	33.1	0.78	0.52	1.44	3.10	18.2	black

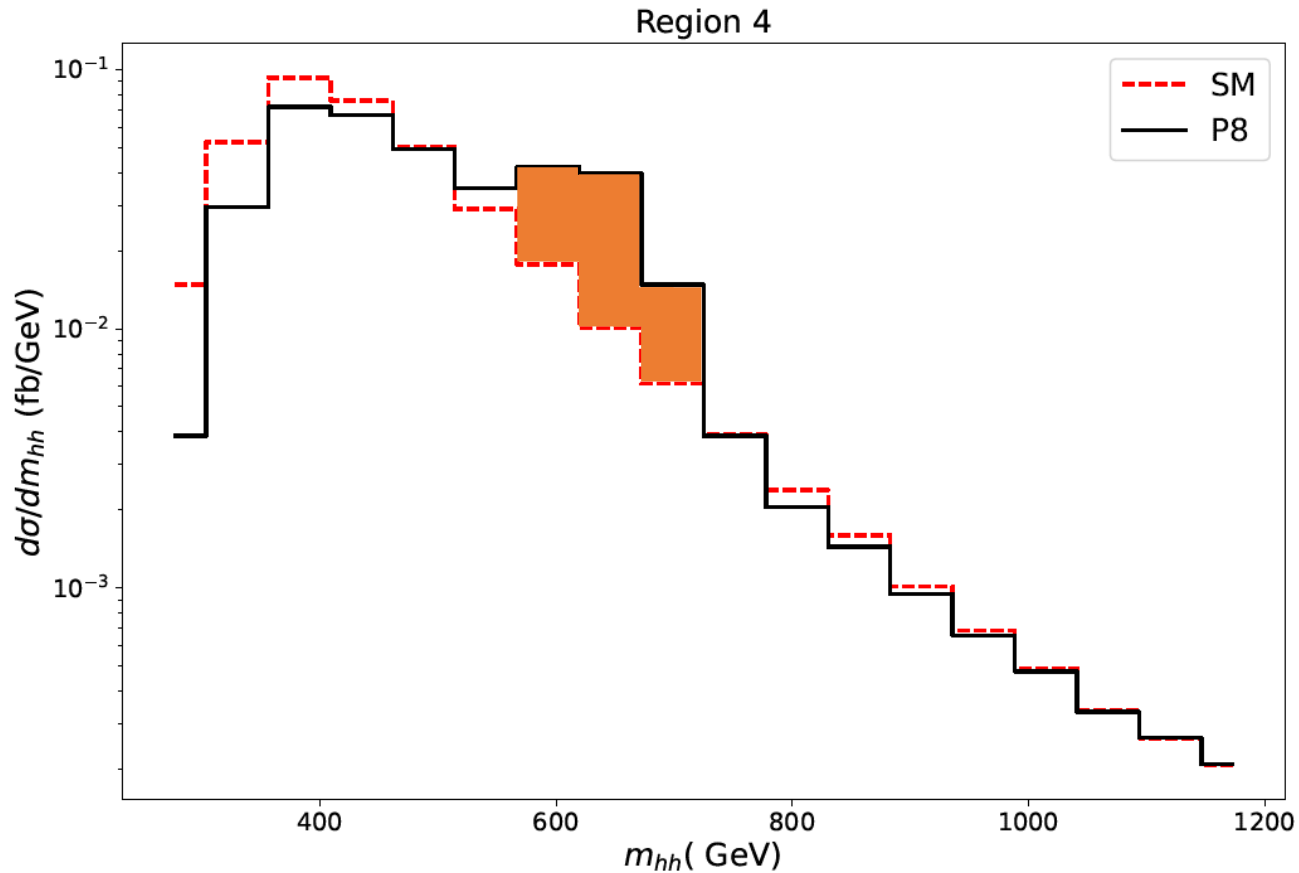
Triple Higgs coupling definition



A Feynman diagram representing a triple Higgs vertex. It consists of three dashed lines meeting at a central vertex. One line extends horizontally to the left and is labeled h_i . The other two lines extend upwards and downwards to the right, labeled h_j and h_k respectively.

$$= -i v n! \lambda_{h_i h_j h_k} ,$$

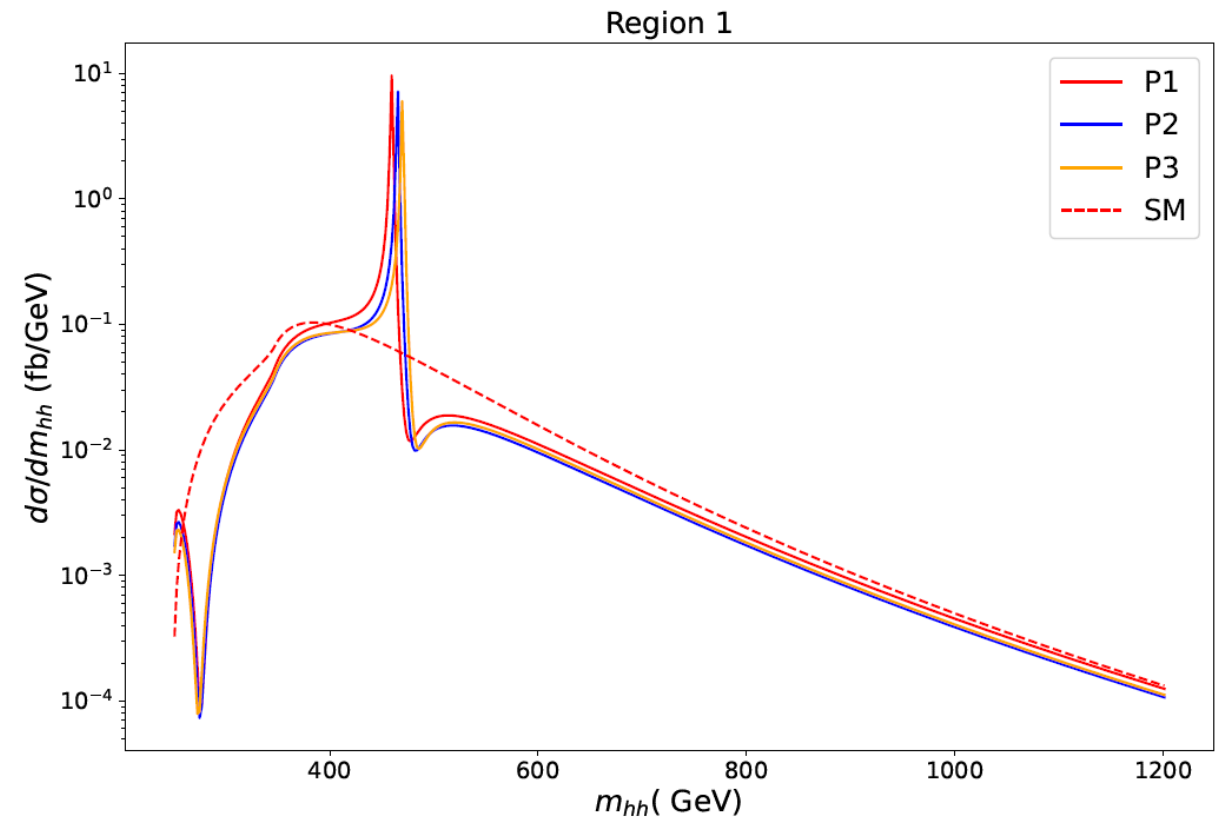
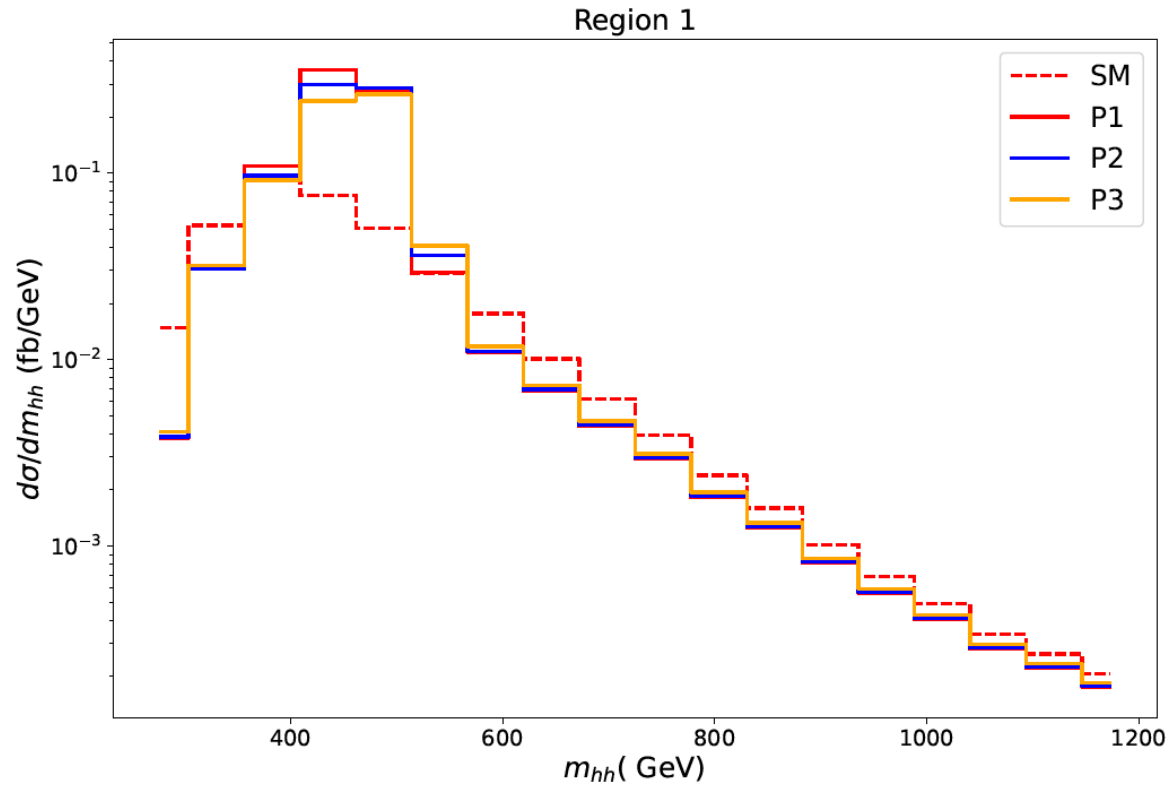
R parameter



$$R = \frac{\sum_i |N_i^R - N_i^C|}{\sqrt{\sum_i N_i^C}}$$

$$|N^R - N^C| > \text{bin size} \cdot 20 \text{ GeV}$$

Benchmark points



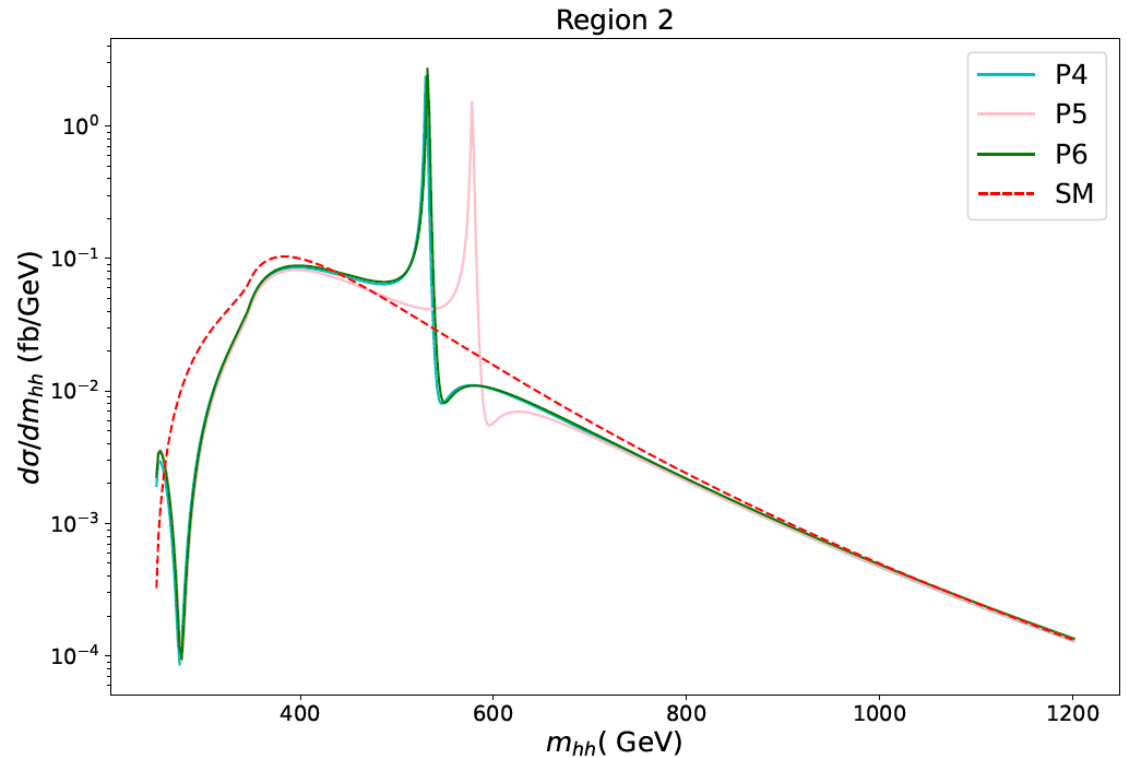
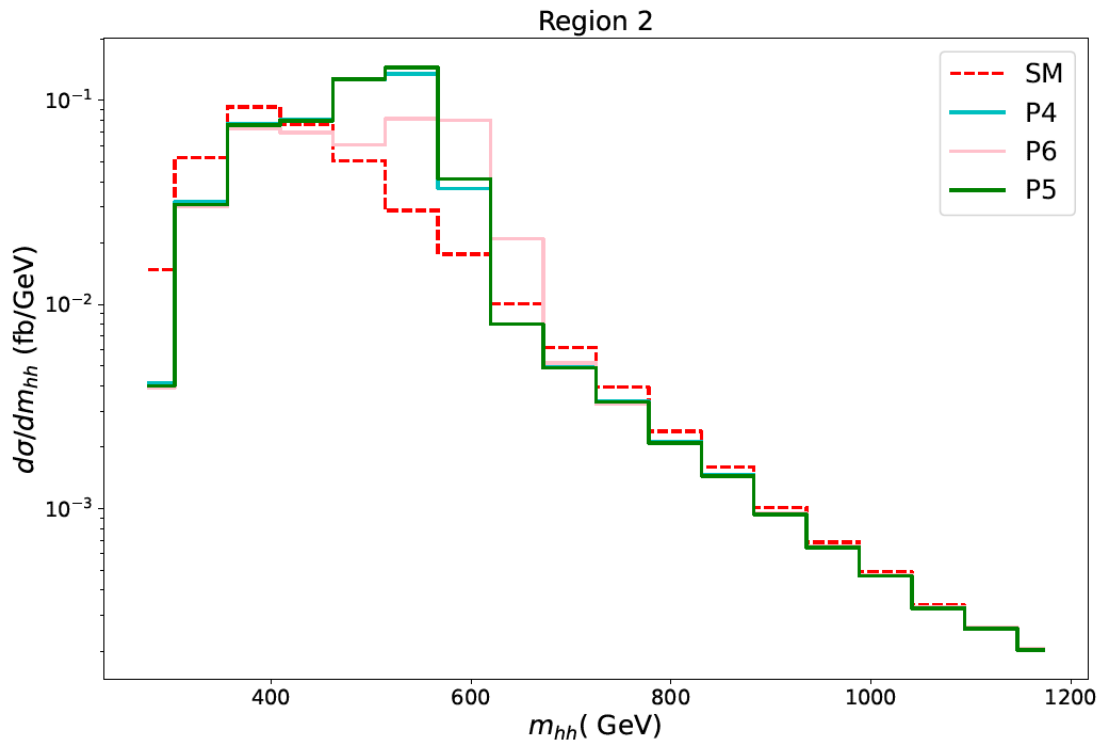
P1: $R = 348$

P2: $R = 319$

P3: $R = 320$

	P1	P2	P3
m_H (GeV)	459	465	469
λ_{hhh}	0.36	0.35	0.32
κ_λ	1.47	1.46	1.43

Experimental Uncertainties: Results

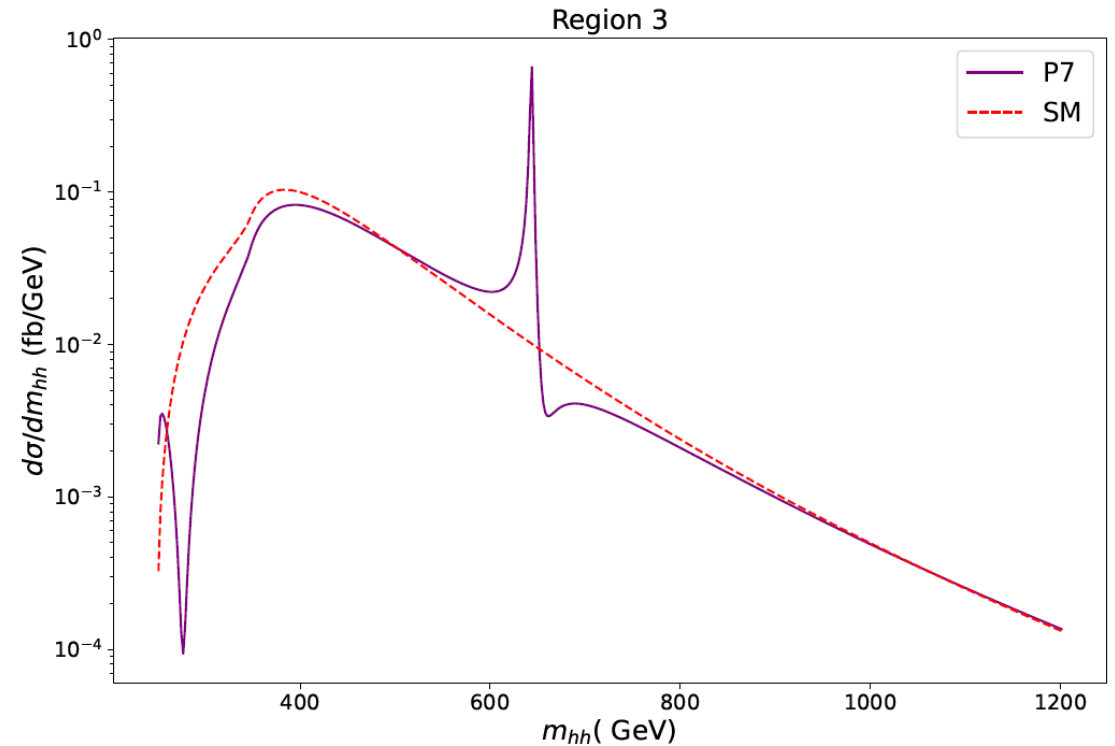
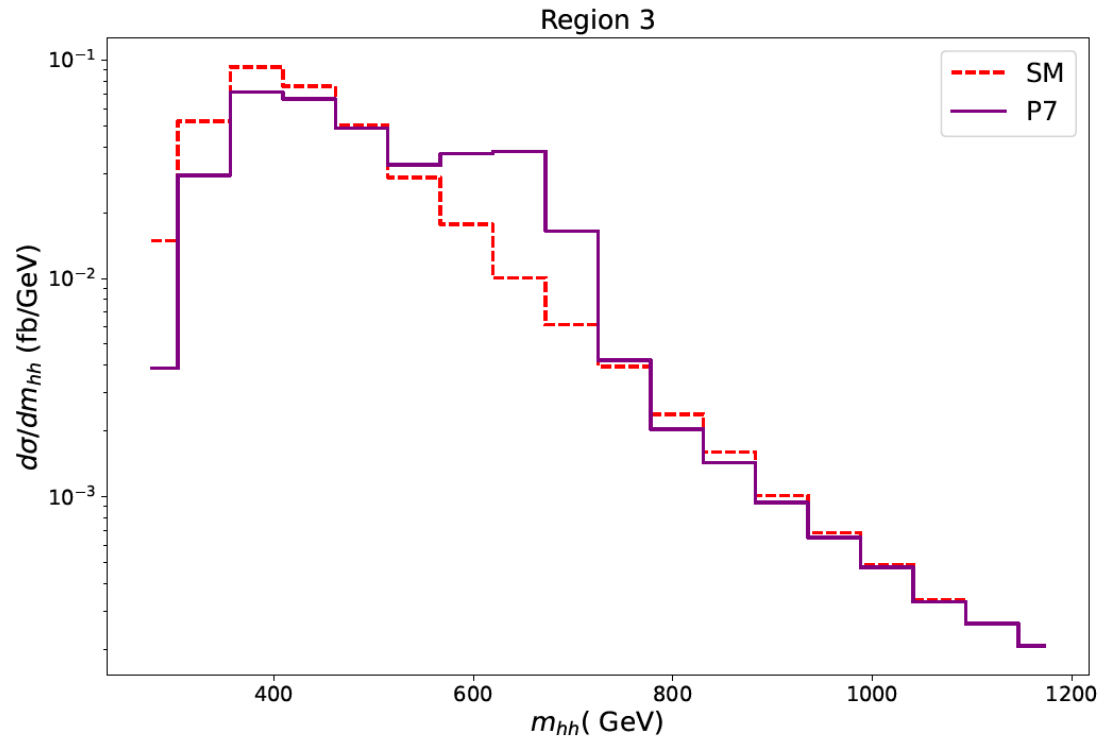


P4: $R = 198$
 P5: $R = 165$
 P6: $R = 172$

$$5 > \Delta s > 0$$

	P4	P5	P6
$m_H(\text{GeV})$	529	577	531
λ_{hhh}	0.38	0.45	0.40
κ_λ	1.43	1.45	1.45

Experimental Uncertainties: Results



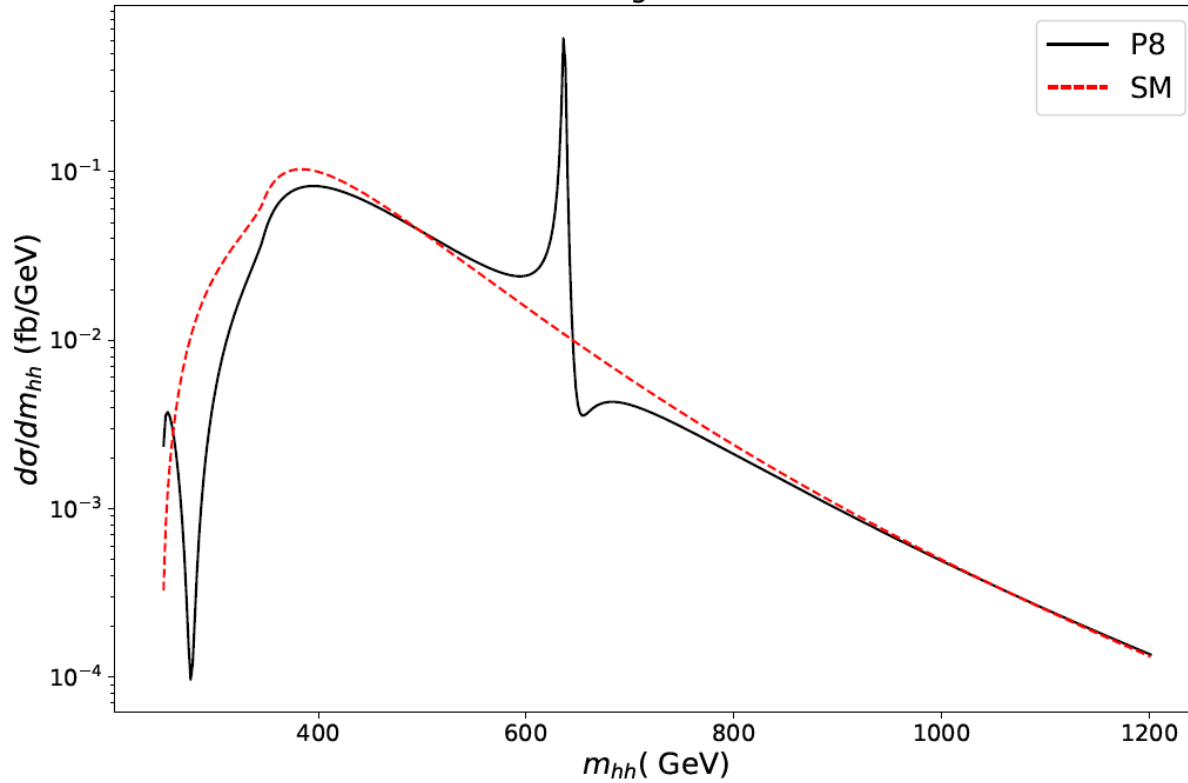
$$R = 128$$

$$\Delta s \approx 0$$

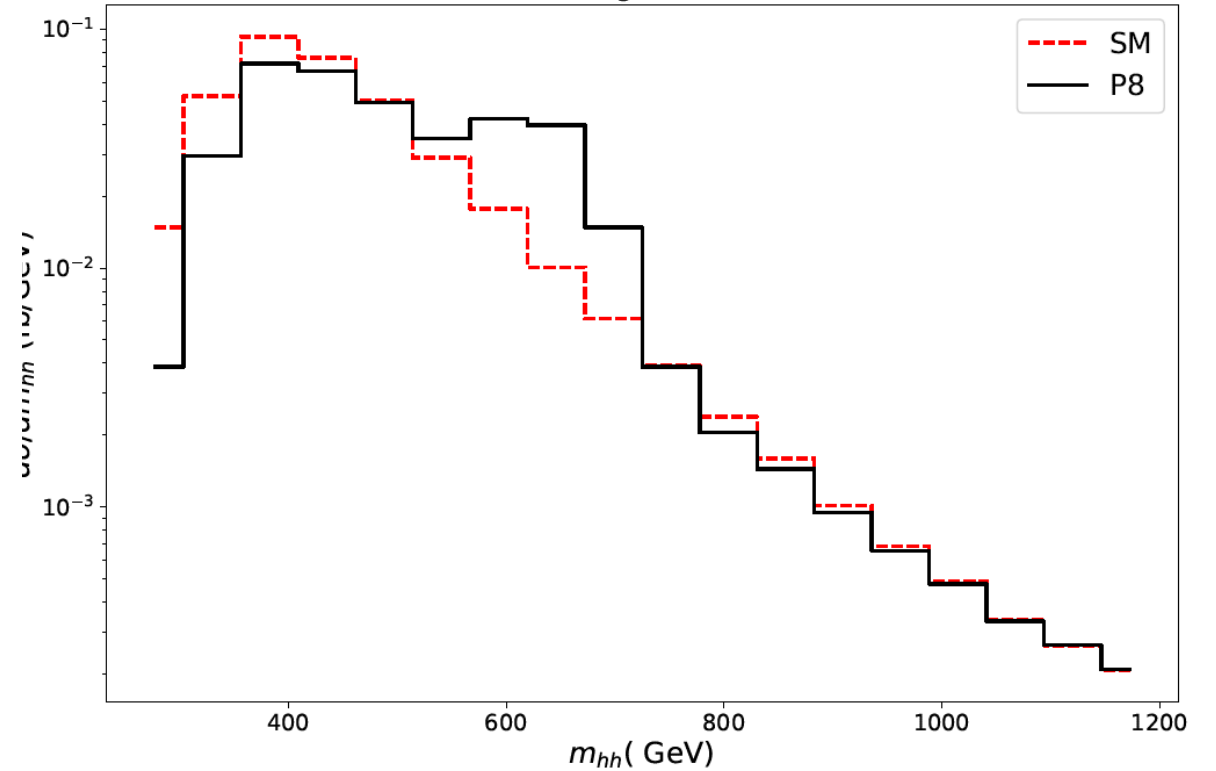
	P7
m_H (GeV)	643
λ_{hhH}	0.49
κ_λ	1.44

Benchmark points

Region 4



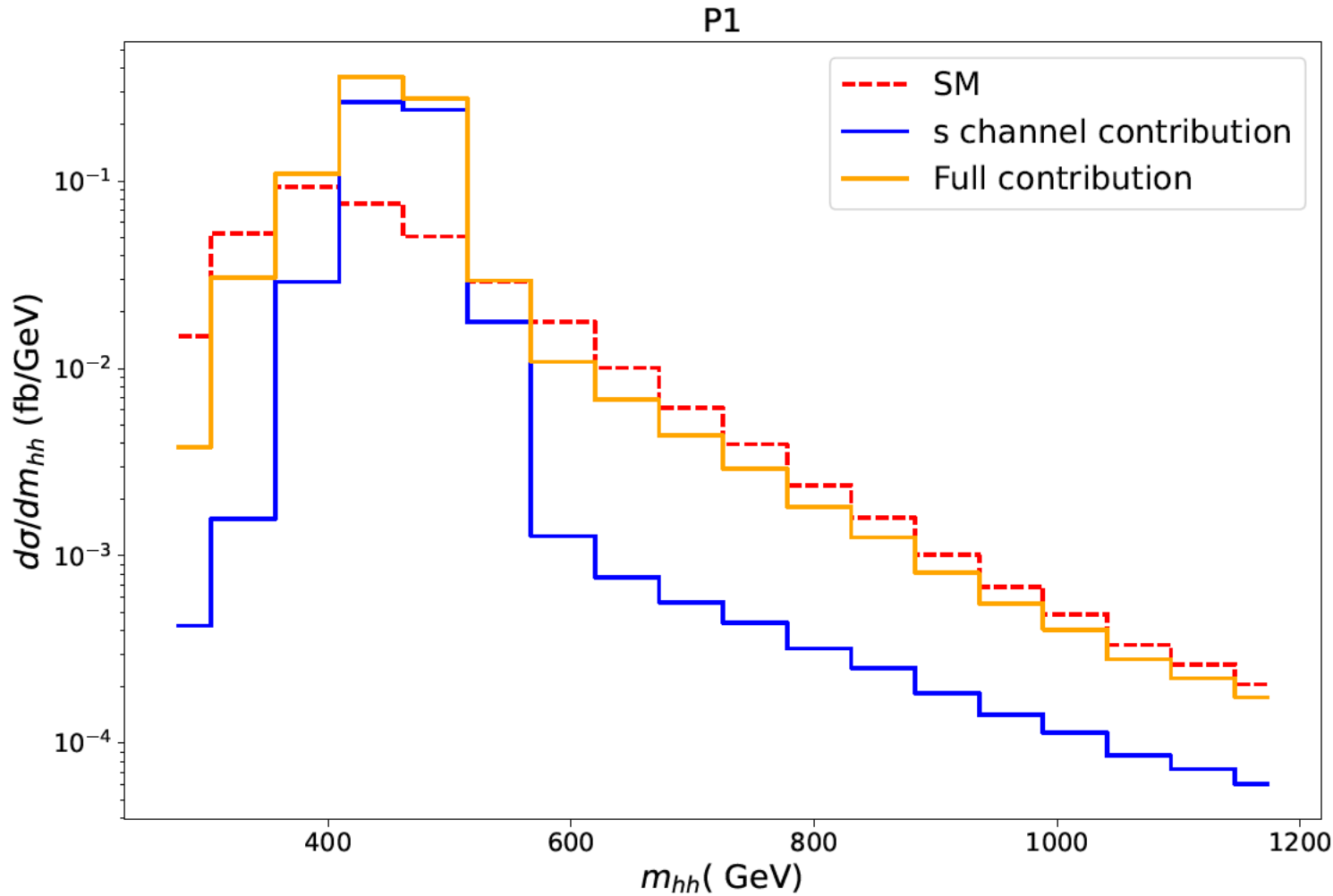
Region 4



	P8
m_H (GeV)	658
λ_{hhH}	0.52
κ_λ	1.44

$R = 132$

m_{hh} distribution: results



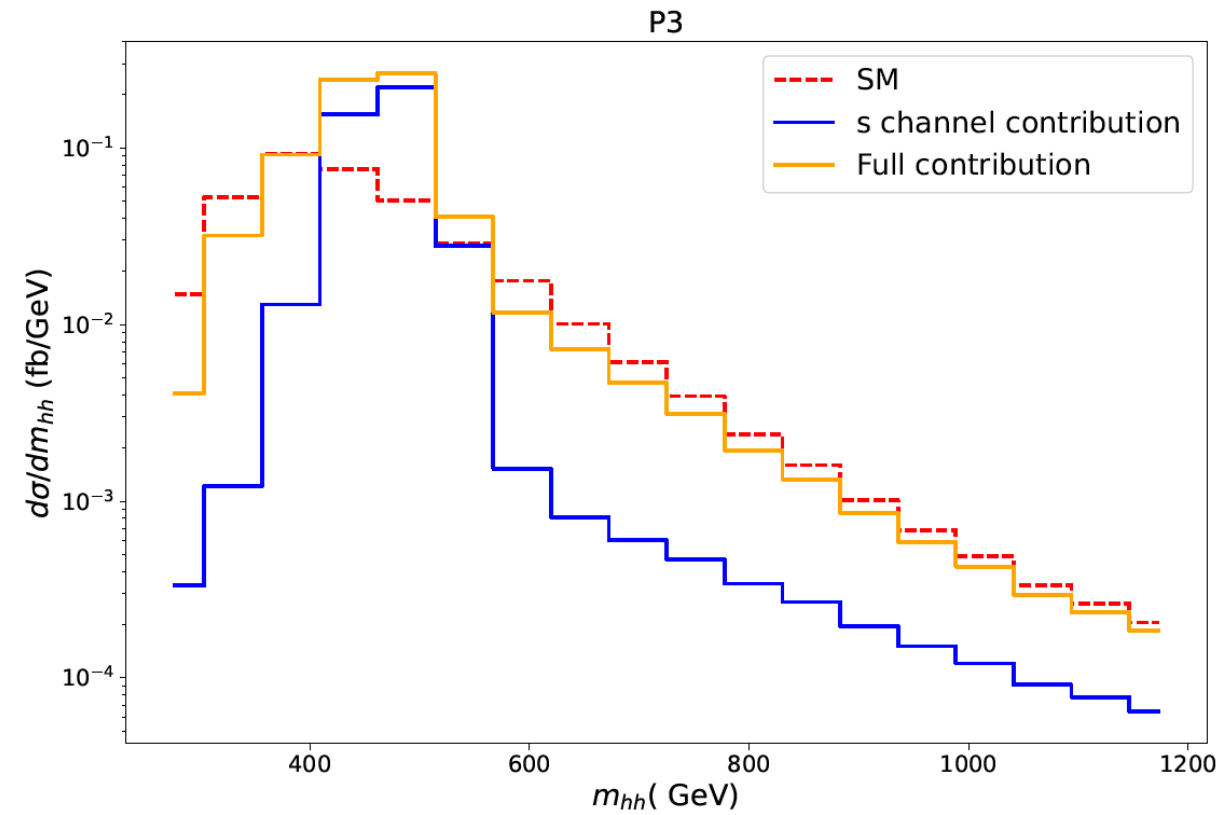
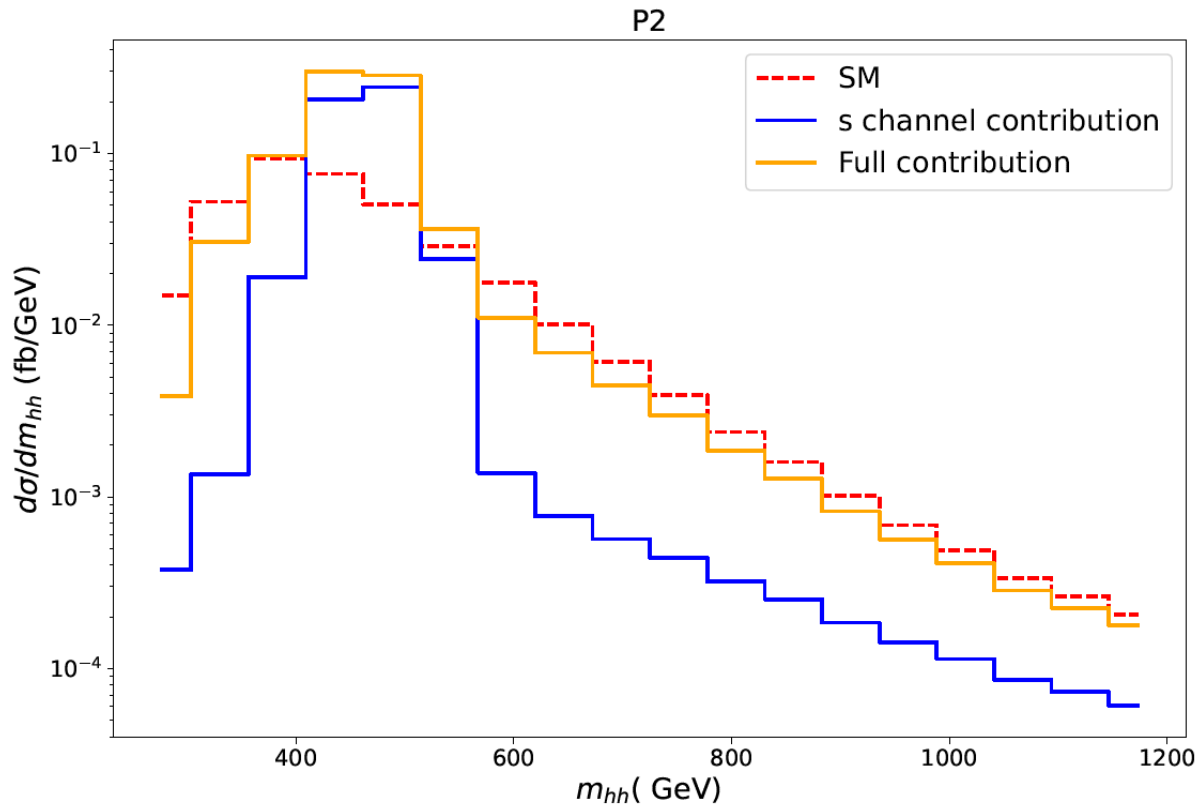
$$m_H = 459,7 \text{ GeV}$$

$$x = 46,3 \text{ GeV}$$

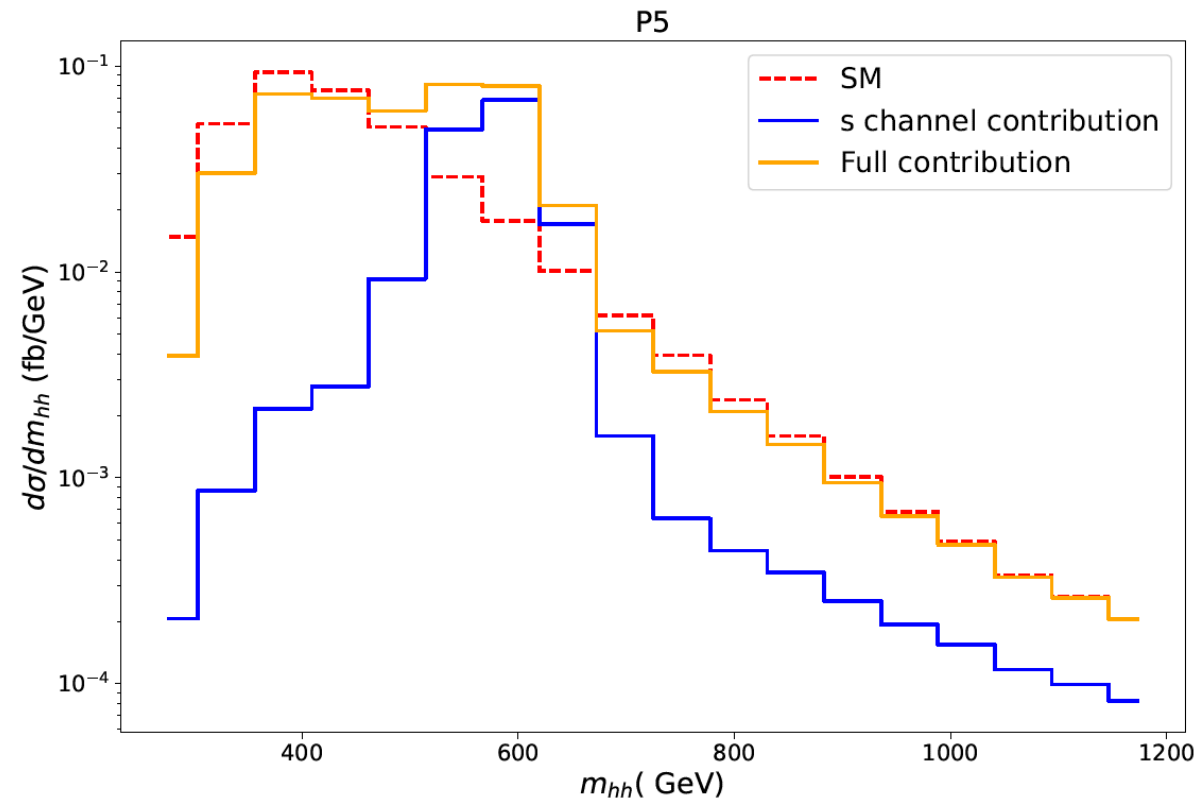
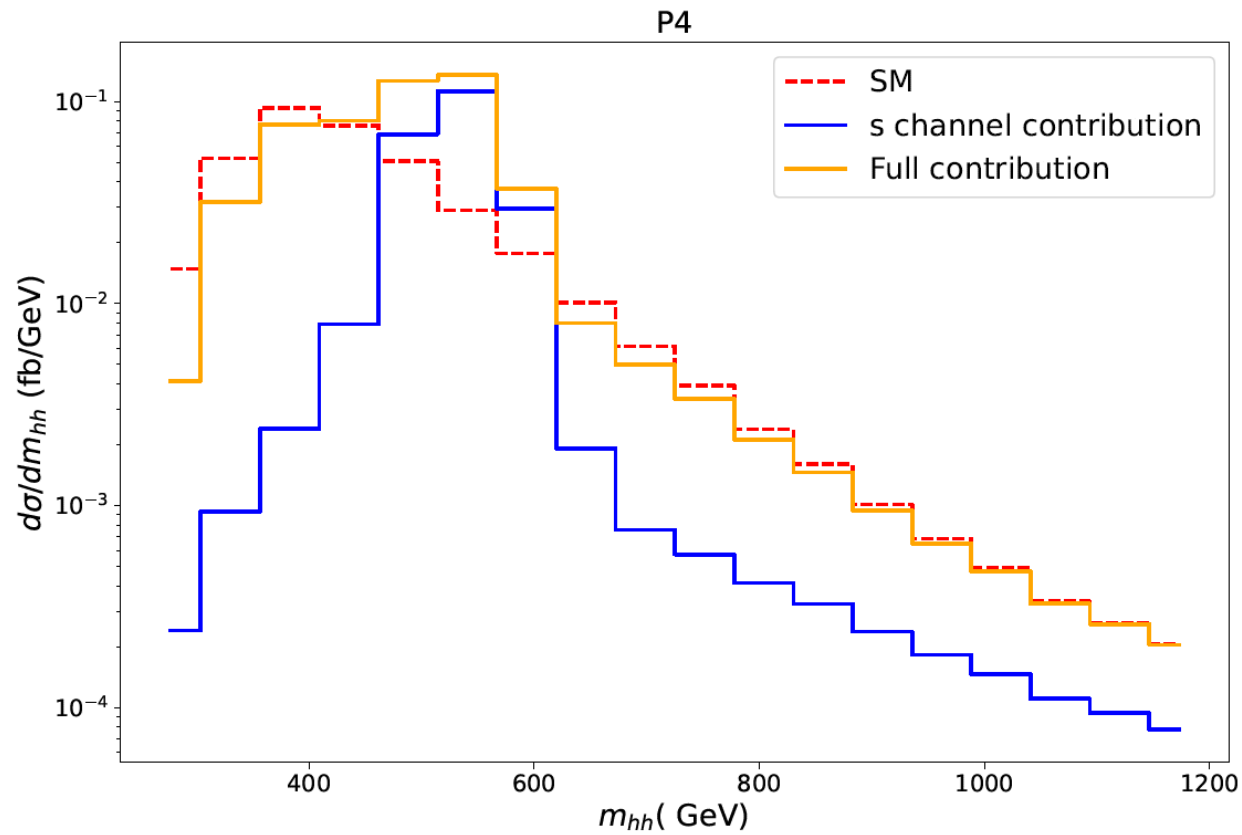
$$\lambda_{hhH} = 0,36$$

$$\kappa_\lambda = 1,47$$

Benchmark points



Benchmark points



Benchmark points

