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

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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

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

Doublet

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

Singlet

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

Mass matrix

$$\begin{pmatrix} m^2_{h'} & m^2_{h's} \\ m^2_{h's} & m^2_s \end{pmatrix}$$

Mixing matrix

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

Real Singlet Extension

Triple Higgs couplings

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

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

Mixing angle

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

Kappa lambda modifier

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

Real Singlet Extension: Constrains

Theoretical:

Vacuum stability:

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

Perturbativity:

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

Experimental:

HiggsBounds:

BSM Higgs boson searches

HiggsSignals:

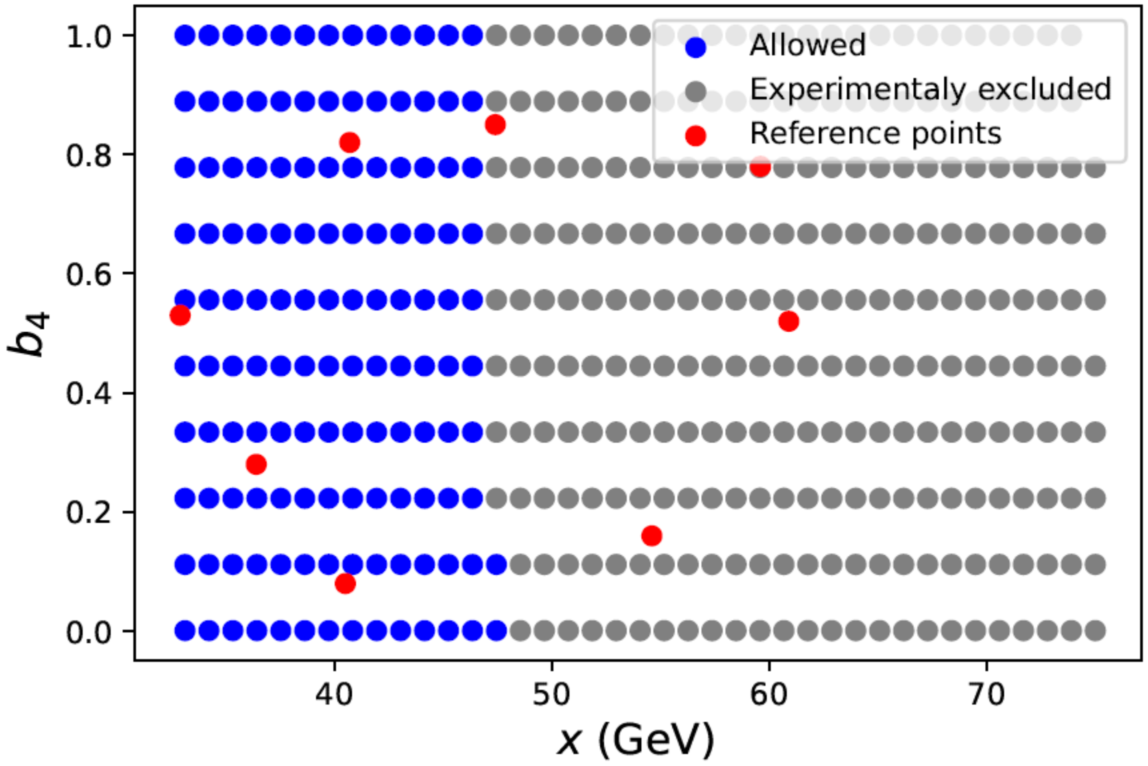
125 GeV Higgs boson measurements

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 St´ephane 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.

Benchmark Plane: SFOEWPT

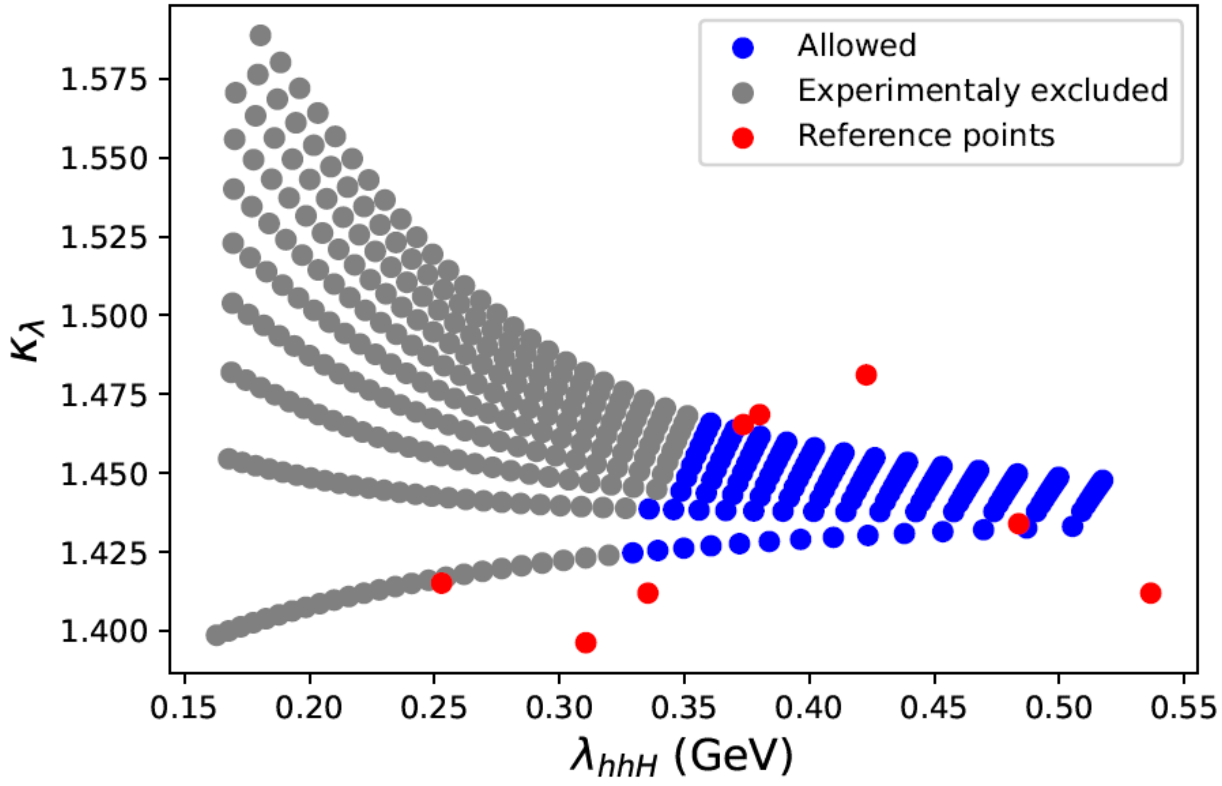


$$a_1 x = -32000 \,,$$

$$\lambda = 0.18 \,,$$

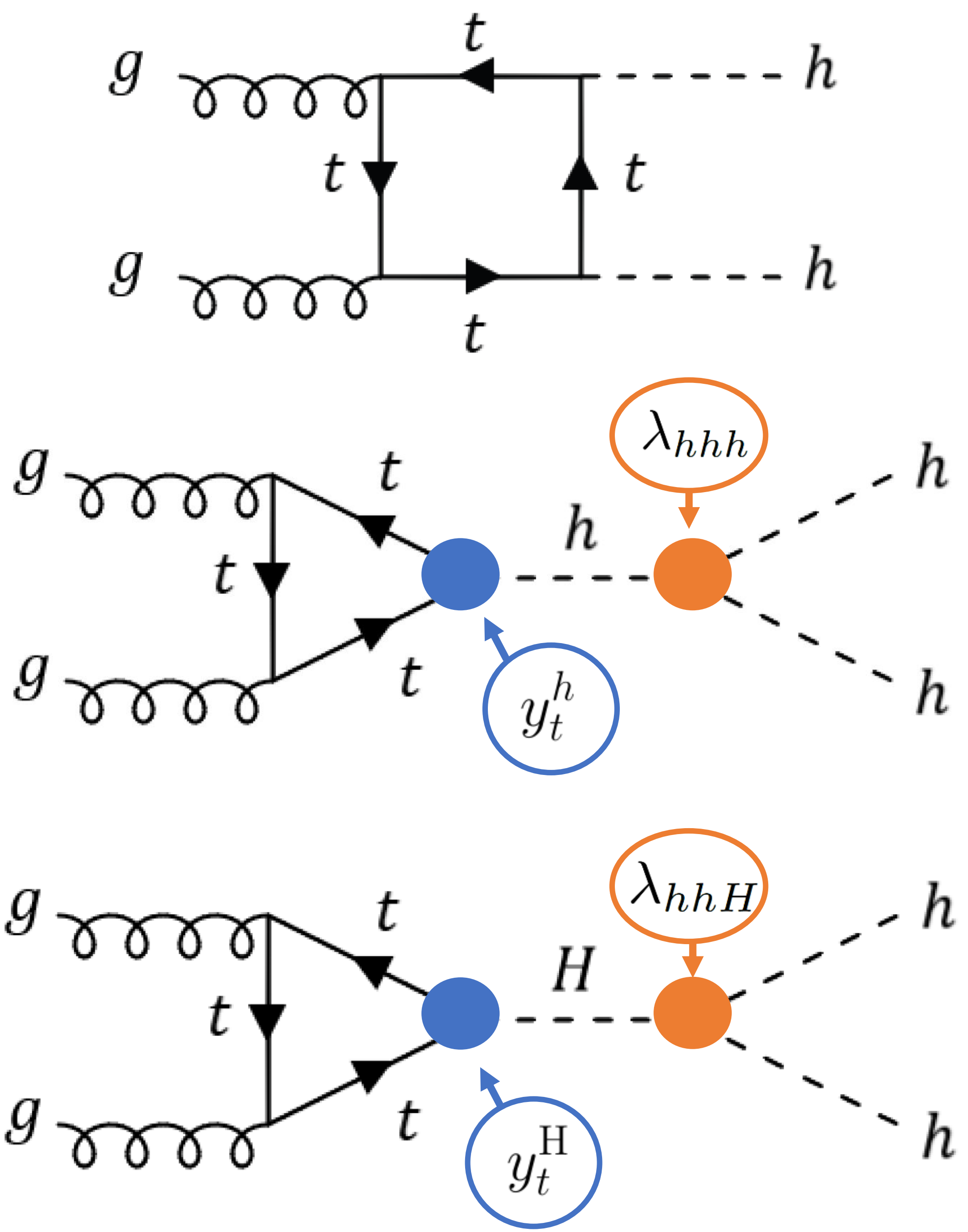
$$b_3 = -660\sqrt{b4} \,.$$

Benchmark Plane



Experimentaly excluded:

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

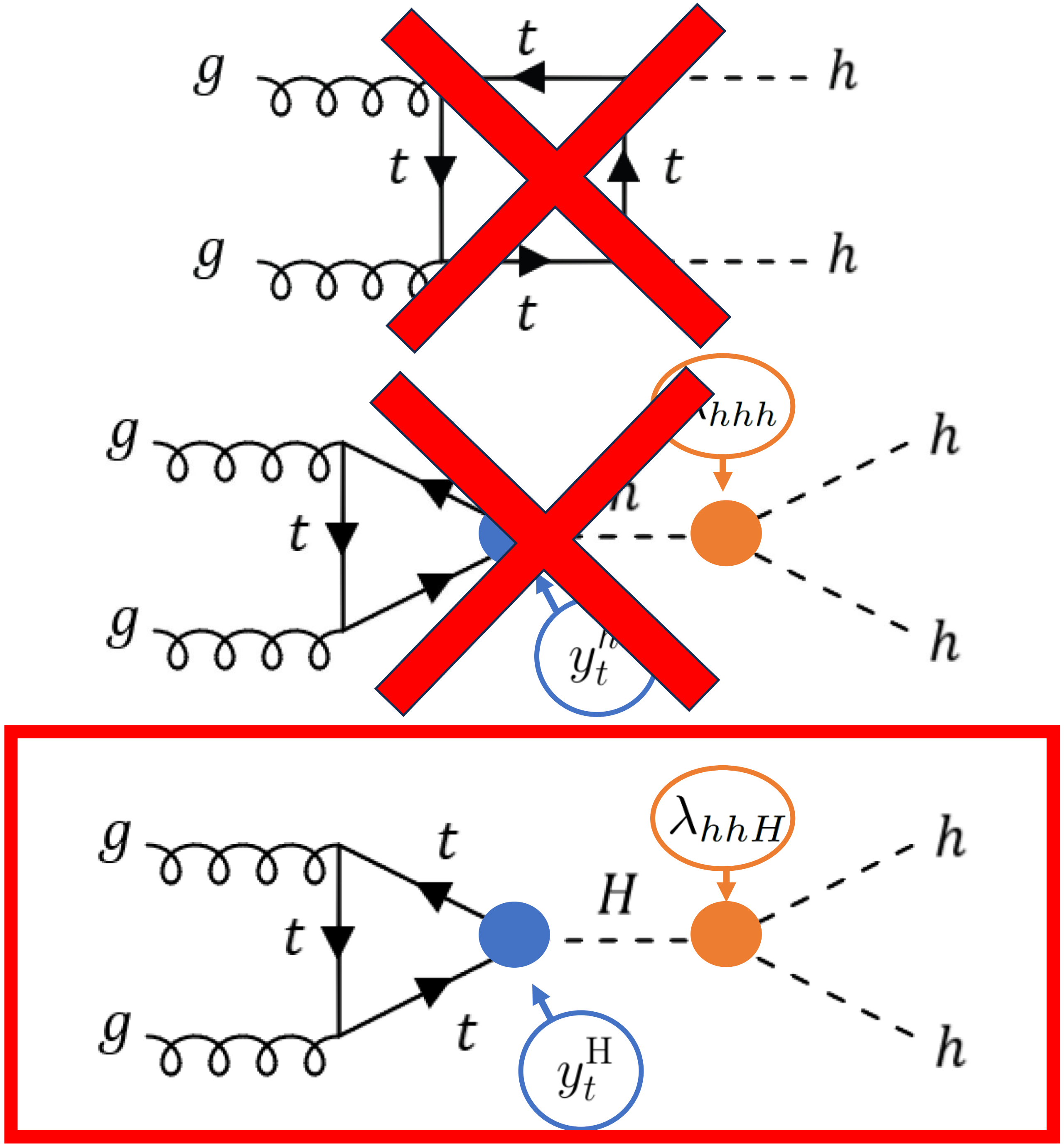


HPAIR

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

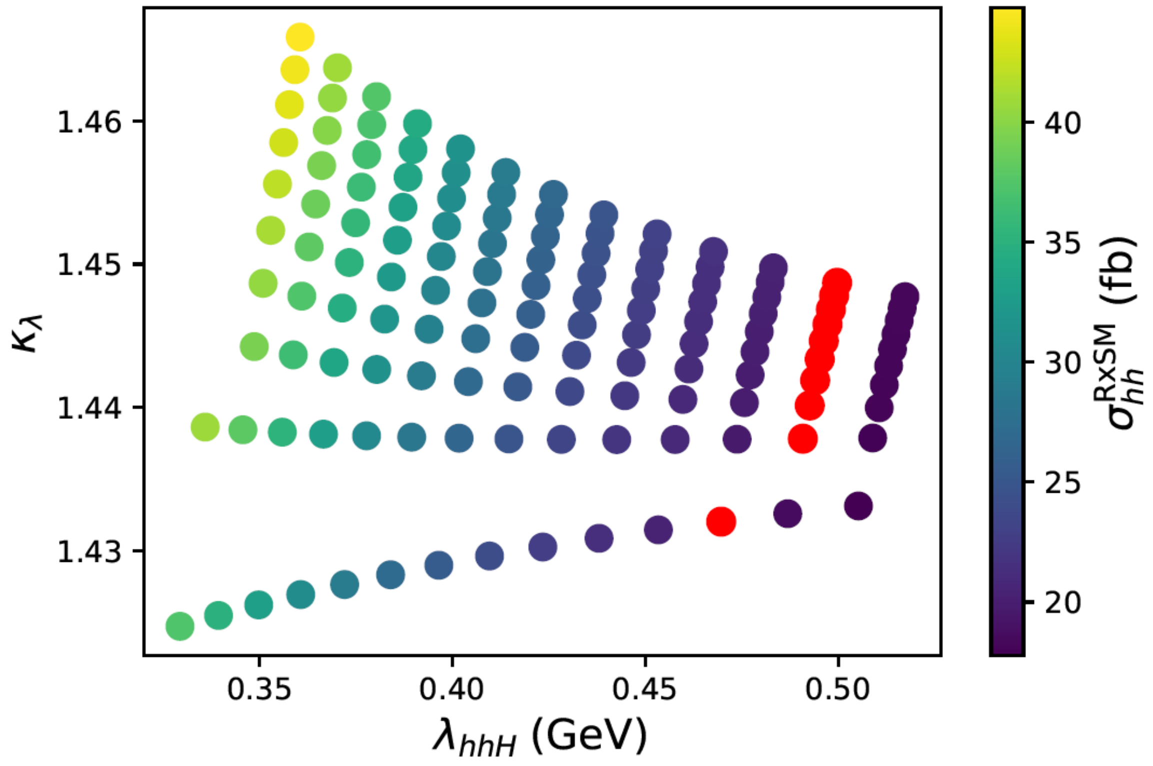


CMS/ATLAS ANALISIS

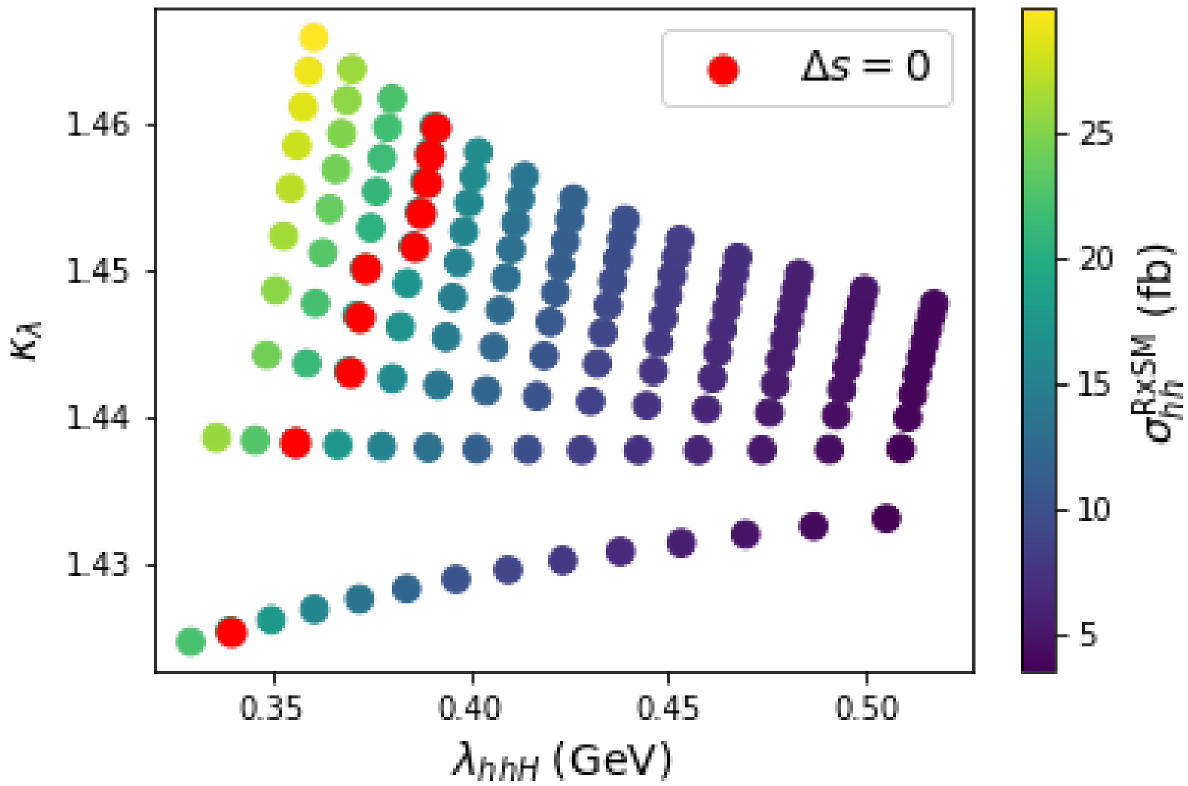
ONLY CONSIDER HEAVY HIGGS S-CHANNEL CONTRIBUTION TO THE CROSS SECTION

Di-Higgs production cross section

Full calculation:

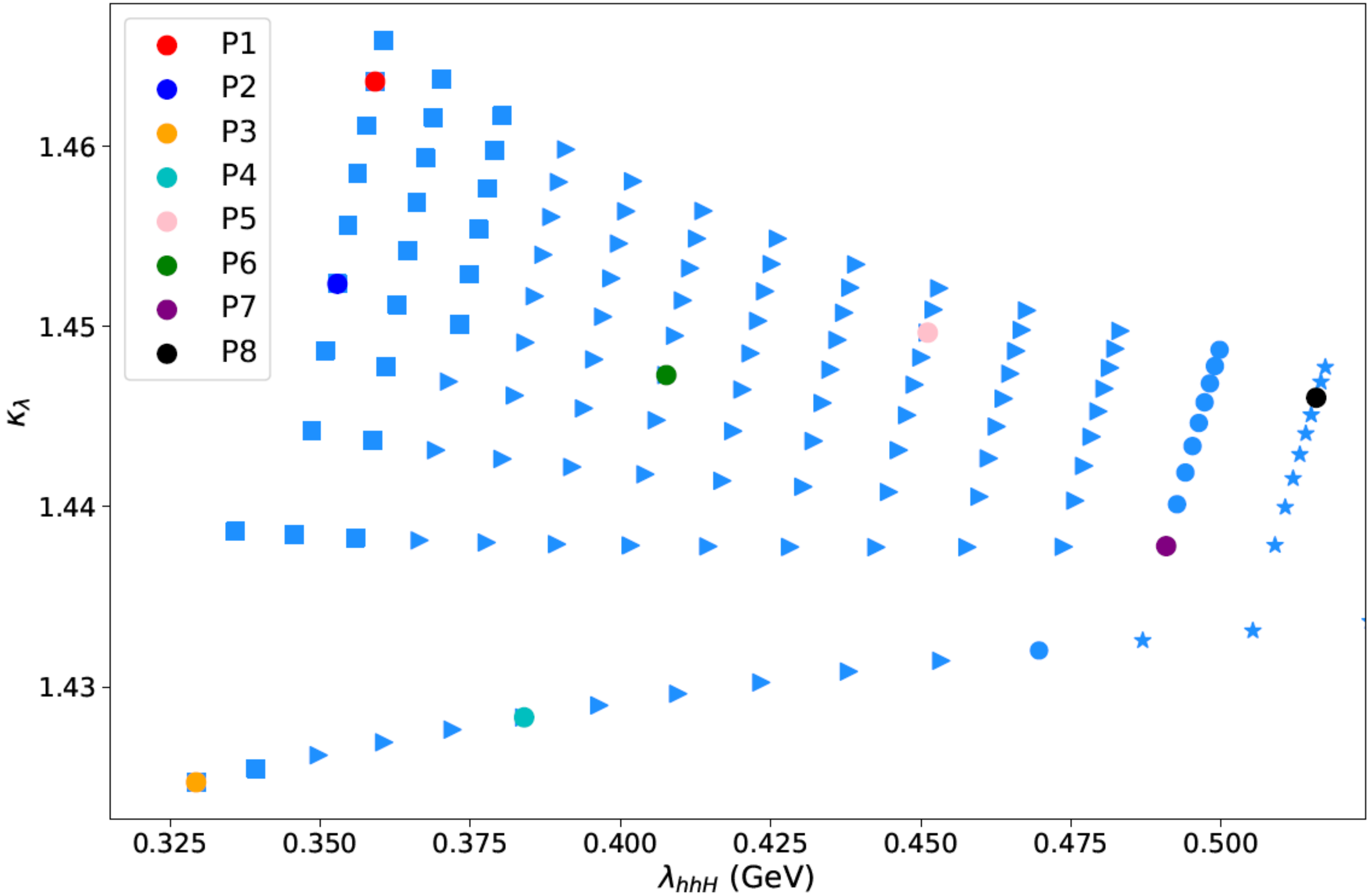


H resonant contribution:



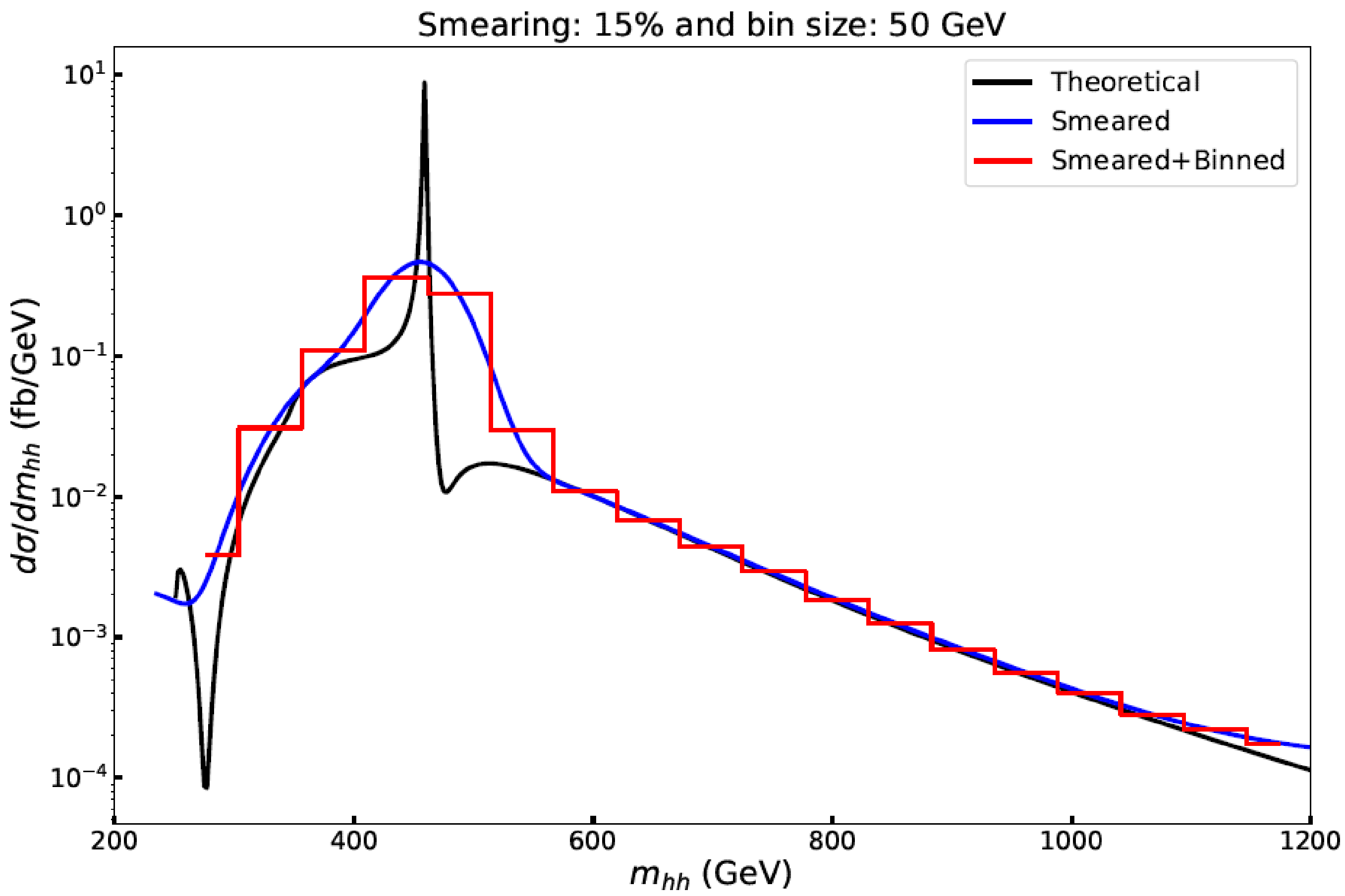
$$\sigma_{\rm SM}^{\rm LO}(\rm pp \to hh) = 19.76\ fb$$

m_{hh} distribution



- ■ **Region 1:** $\Delta s > 5$
- ▶ **Region 2:** $5 > \Delta s > 0$
- ● **Region 3:** $\Delta s \approx 0$
- ★ **Region 4:** $\Delta s < 0$

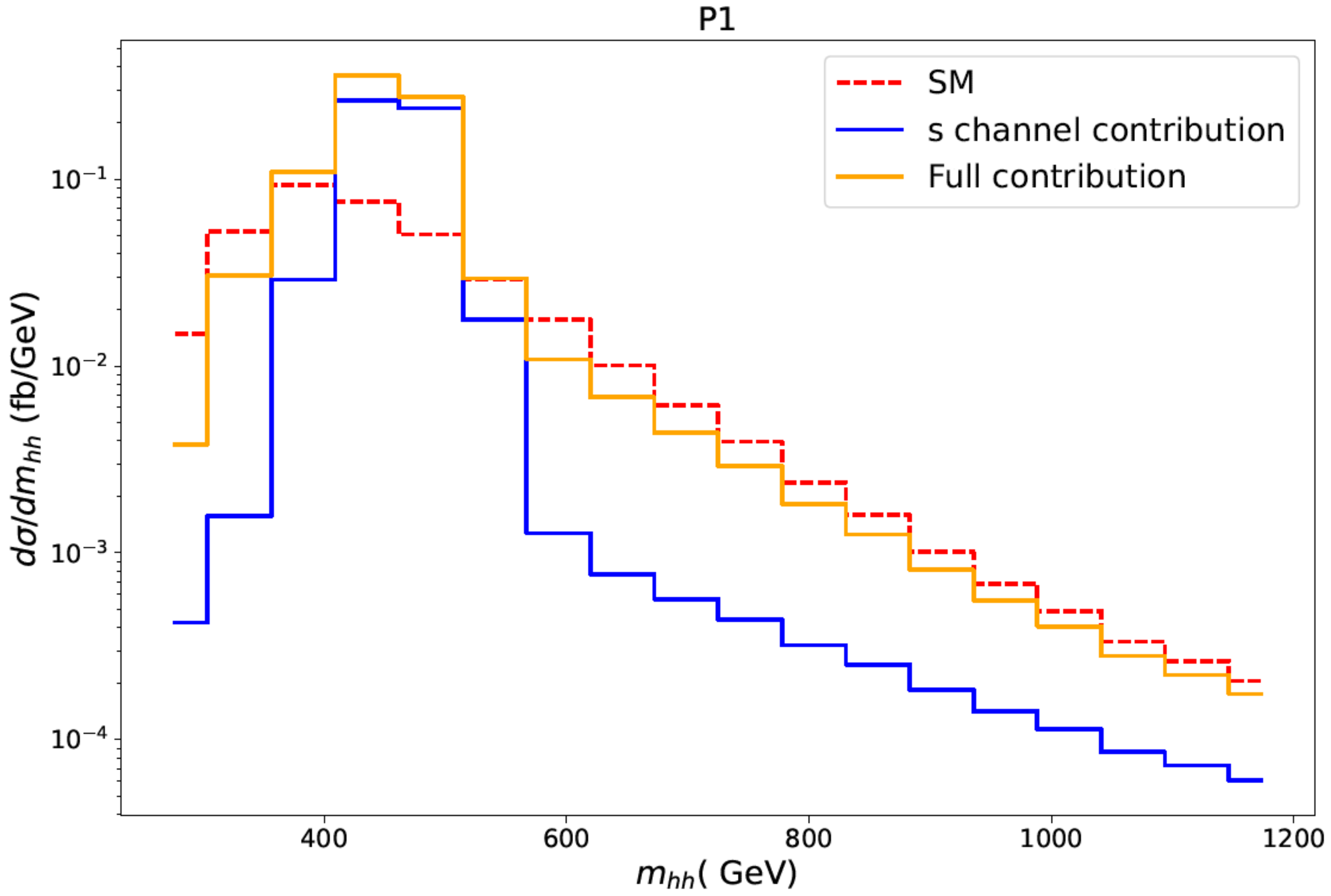
Experimental Uncertainties



Smearing: 15%

Binning: 50 GeV

m_{hh} distribution: results



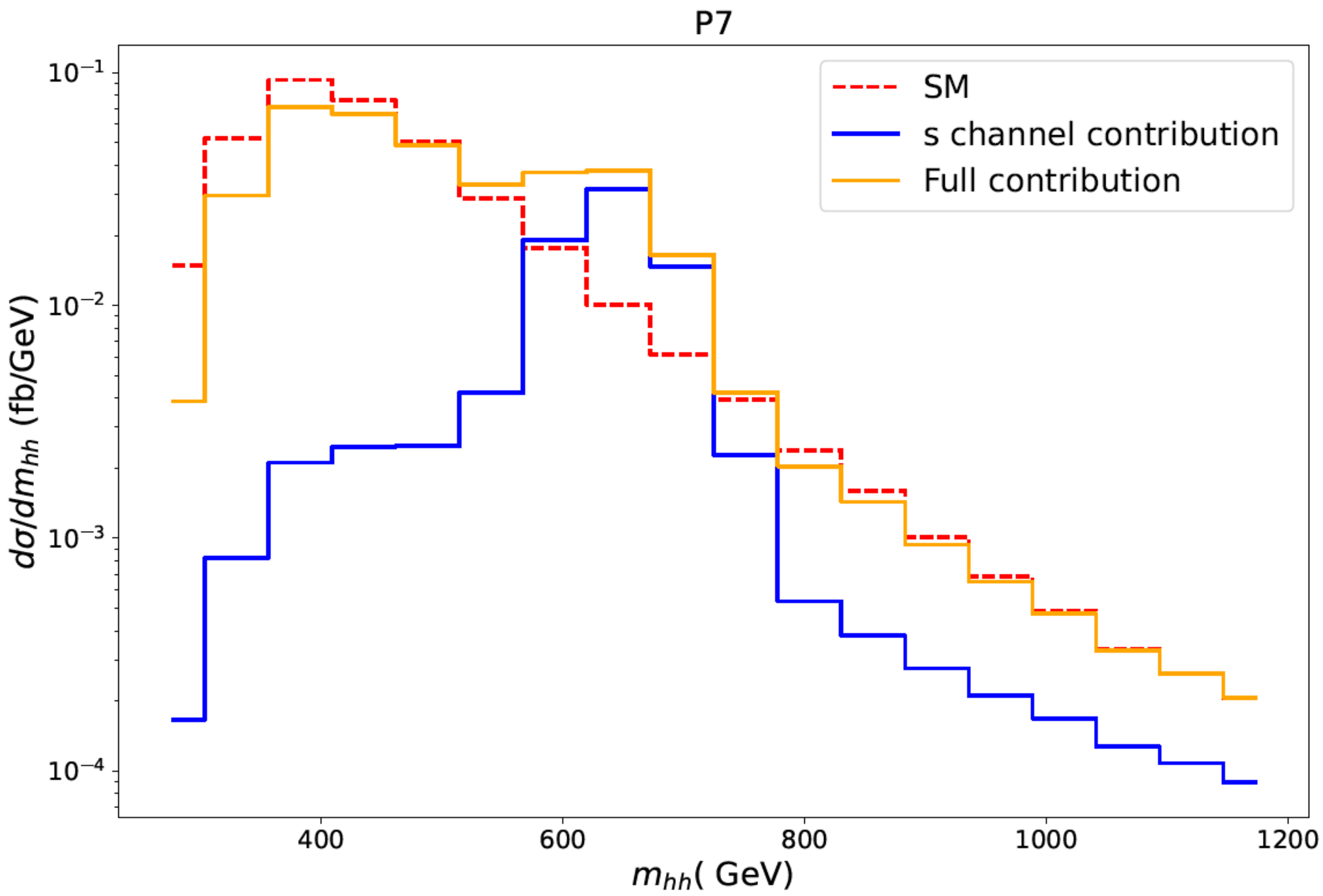
$$m_{\mathrm{H}} = 459{,}7 \text{ GeV}$$

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

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

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

m_{hh} distribution: results



$$m_{\mathrm{H}} = 642{,}9 \text{ GeV}$$

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

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

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

Conclusions

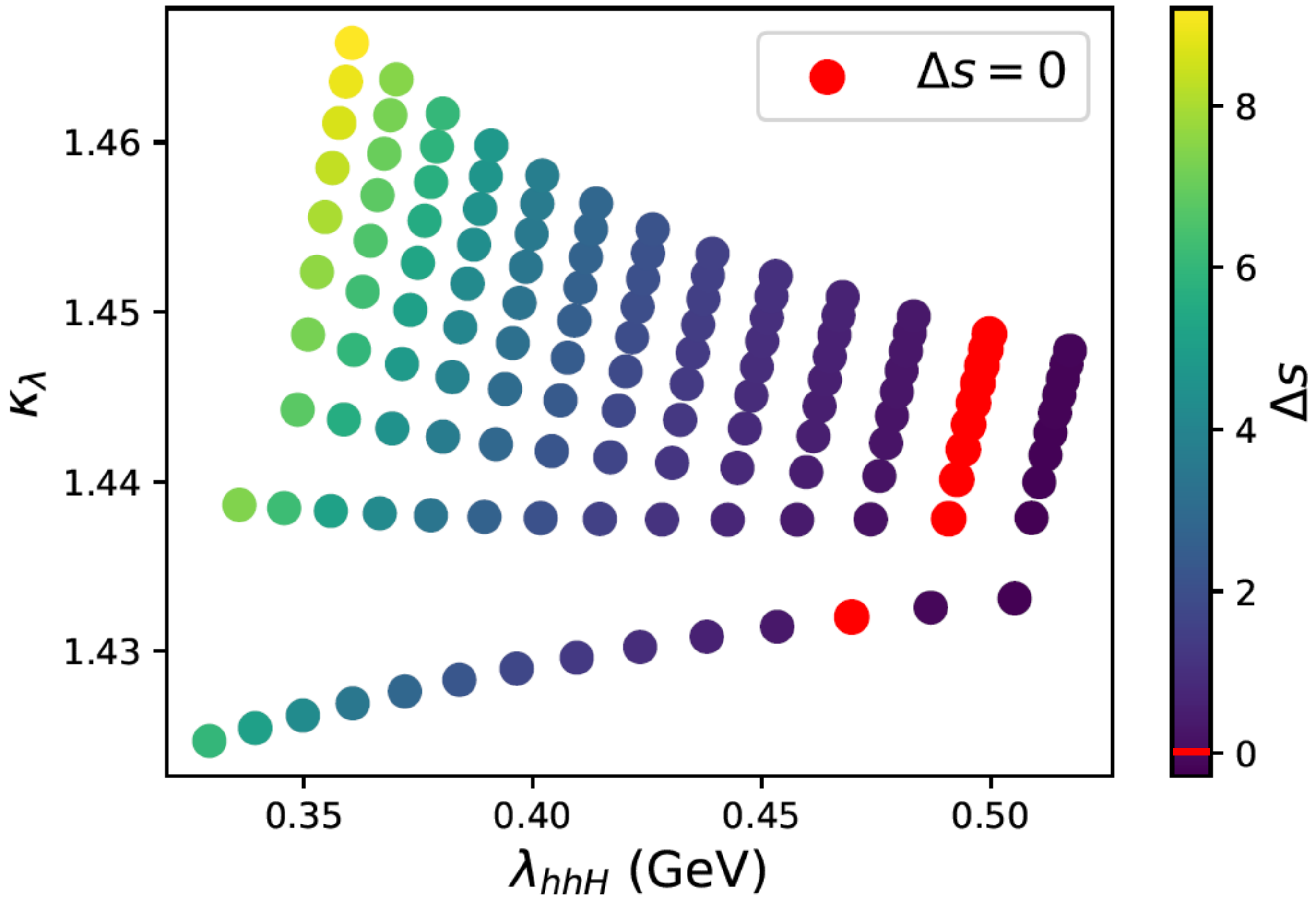
- A benchmark plane has been defined that allows SFOEWPT in the RxSM.
- Taking into account the FULL CALCULATION the total and differential cross section can be used to distinguish the RxSM from the SM.
- Limits obtained considering only resonant contributions are not reliable for the real model, cannot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

References

1. Hao-Lin Li, Michael Ramsey-Musolf, and St´ephane 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 Biek¨otter, Sven Heinemeyer, Cheng Li, Steven Paasch, Georg Weiglein, and Jonas Wittbrodt. HiggsTools: BSM scalar phenomenology with new versions of Higgs-Bounds and HiggsSignals. 10 2022, 2210.0933
4. Hamza Abouabid, Abdesslam Arhrib, Duarte Azevedo, Jaouad El Falaki, Pedro. M. Ferreira, Margarete M¨uhlleitner, and Rui Santos. Benchmarking di-Higgs production in various extended Higgs sector models. JHEP, 09:011, 2022, 2112.12515

Thanks for your attention

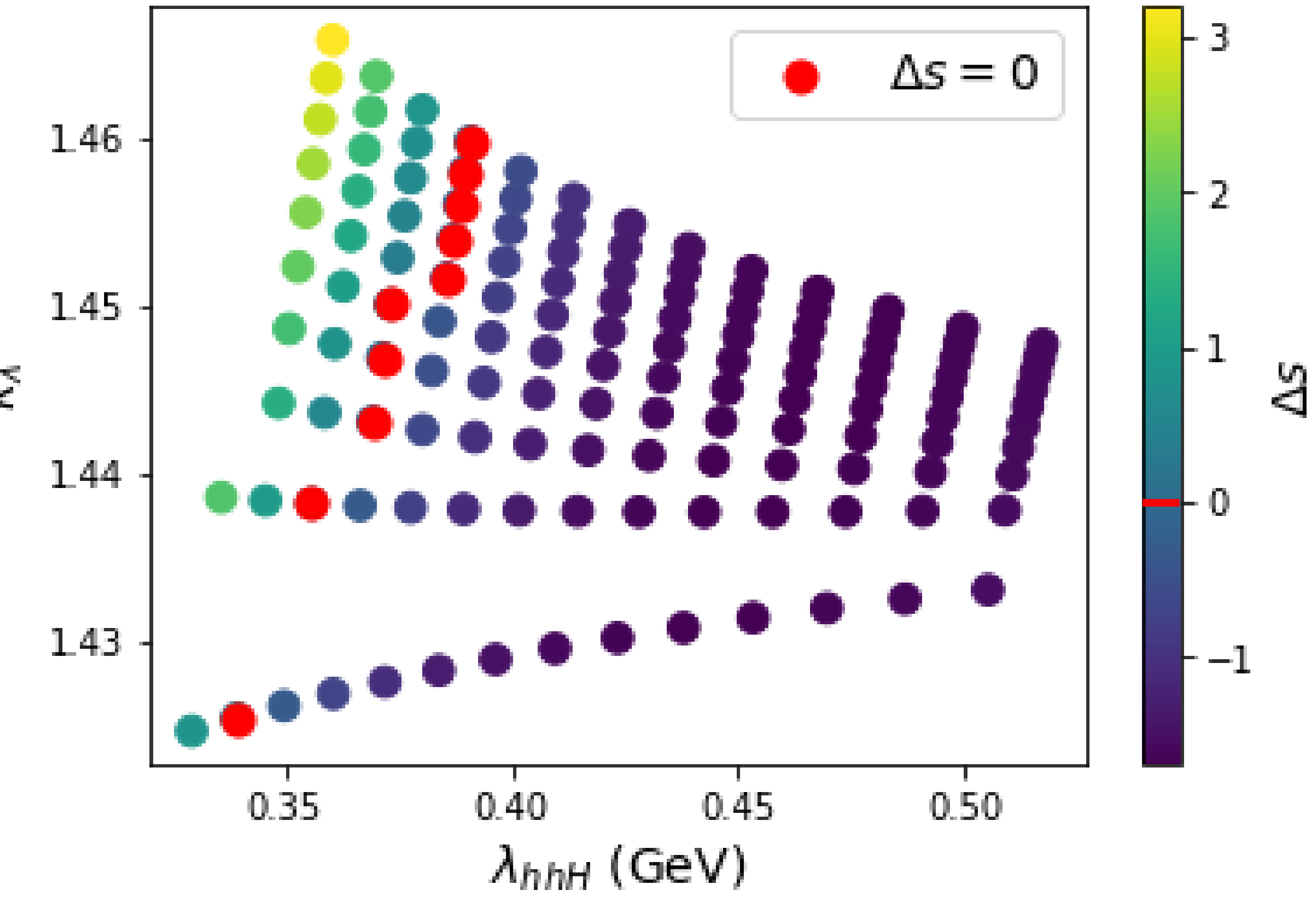
Statistical Significance wrt SM: full calculation



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

$$\Delta s = \frac{\sigma_{\rm RxSM} - \sigma_{\rm SM}}{\Delta\sigma_{\rm RxSM}}$$

Statistical Significance wrt SM: res-only



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

$$\Delta s = \frac{\sigma_{\rm RxSM} - \sigma_{\rm SM}}{\Delta\sigma_{\rm RxSM}}$$

Real Singlet Extension II

Mass terms

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

BSM decay width

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

Decay width to SM:

$$\Gamma^{\mathrm{RxSM}}_{h\to ii} = \Gamma^{\mathrm{SM}}_{h'\to ii} \cdot \cos^2(\theta)$$

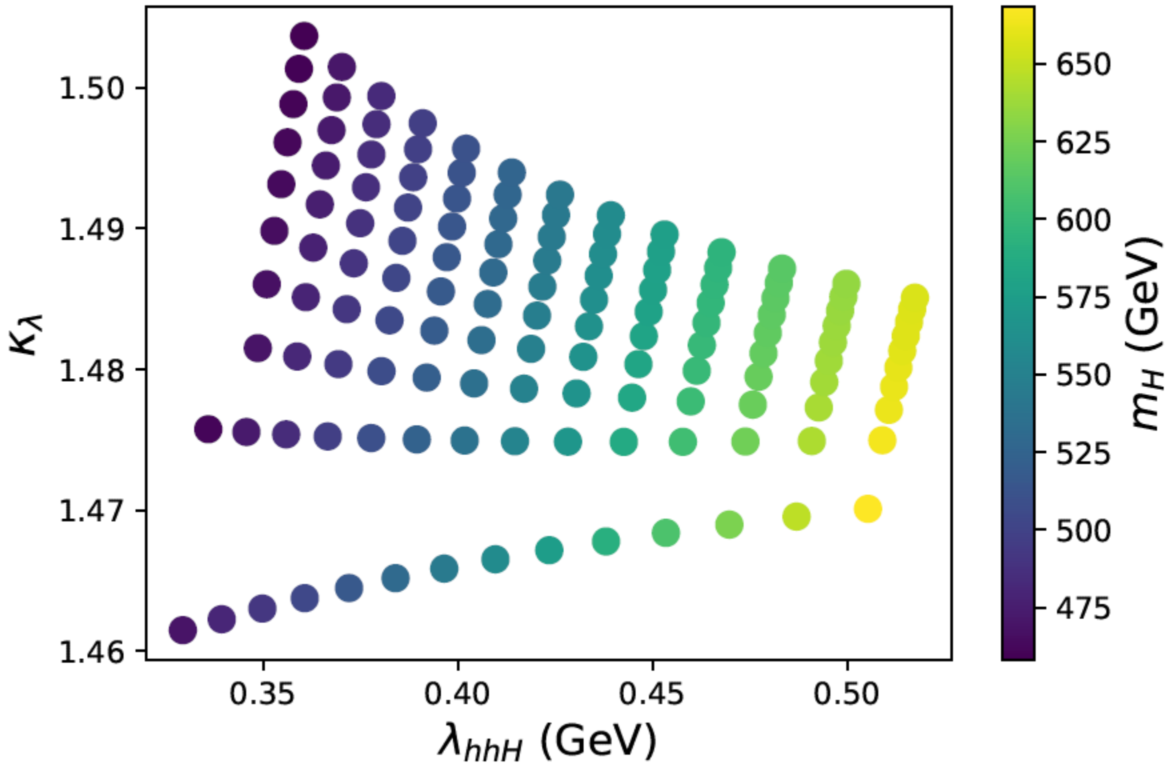
$$\Gamma^{\mathrm{RxSM}}_{H\to ii} = \Gamma^{\mathrm{SM}}_{h'\to ii} \cdot \sin^2(\theta)$$

Total decay width

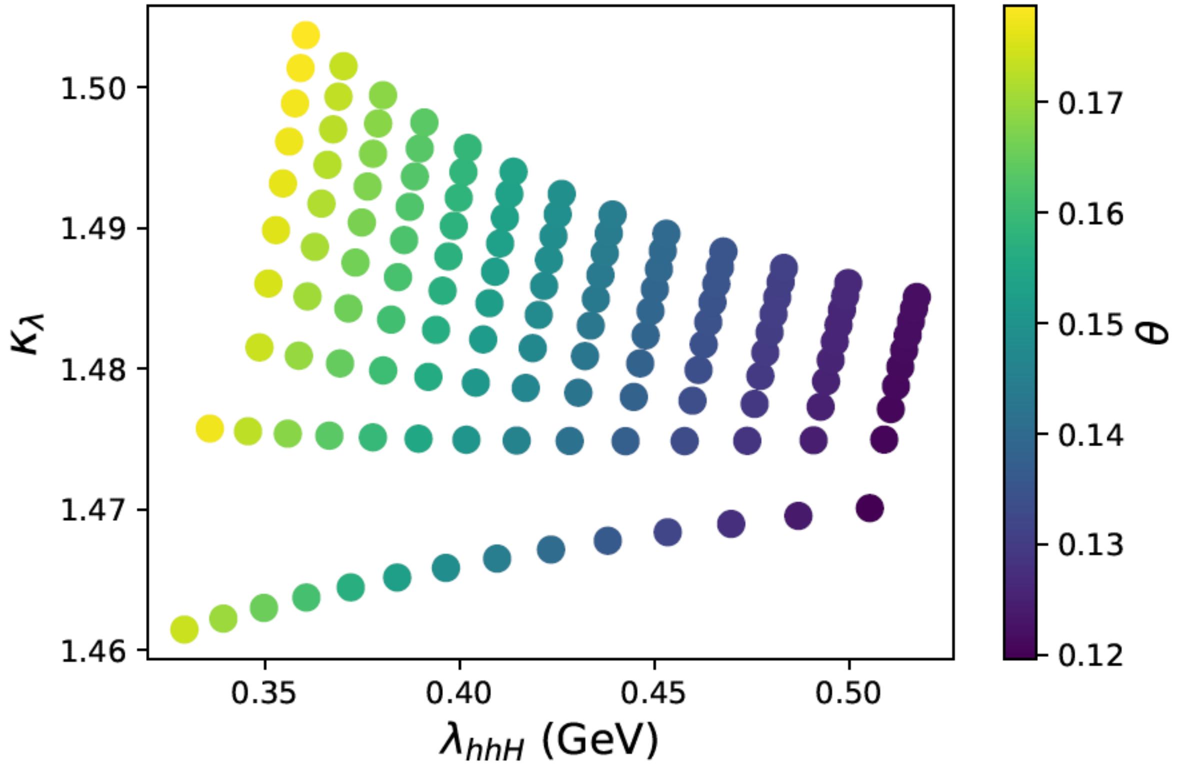
$$\Gamma_H = \Gamma^{\mathrm{SM}}(m_H) \cdot \sin^2(\theta) + \Gamma_{H\to hh}$$

Benchmark Plane

Heavy Higgs mass:



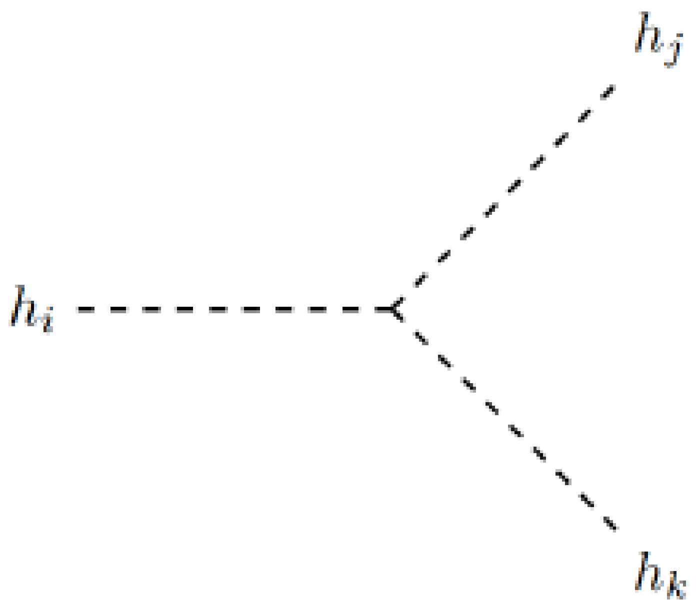
Mixing angle:



Benchmark points

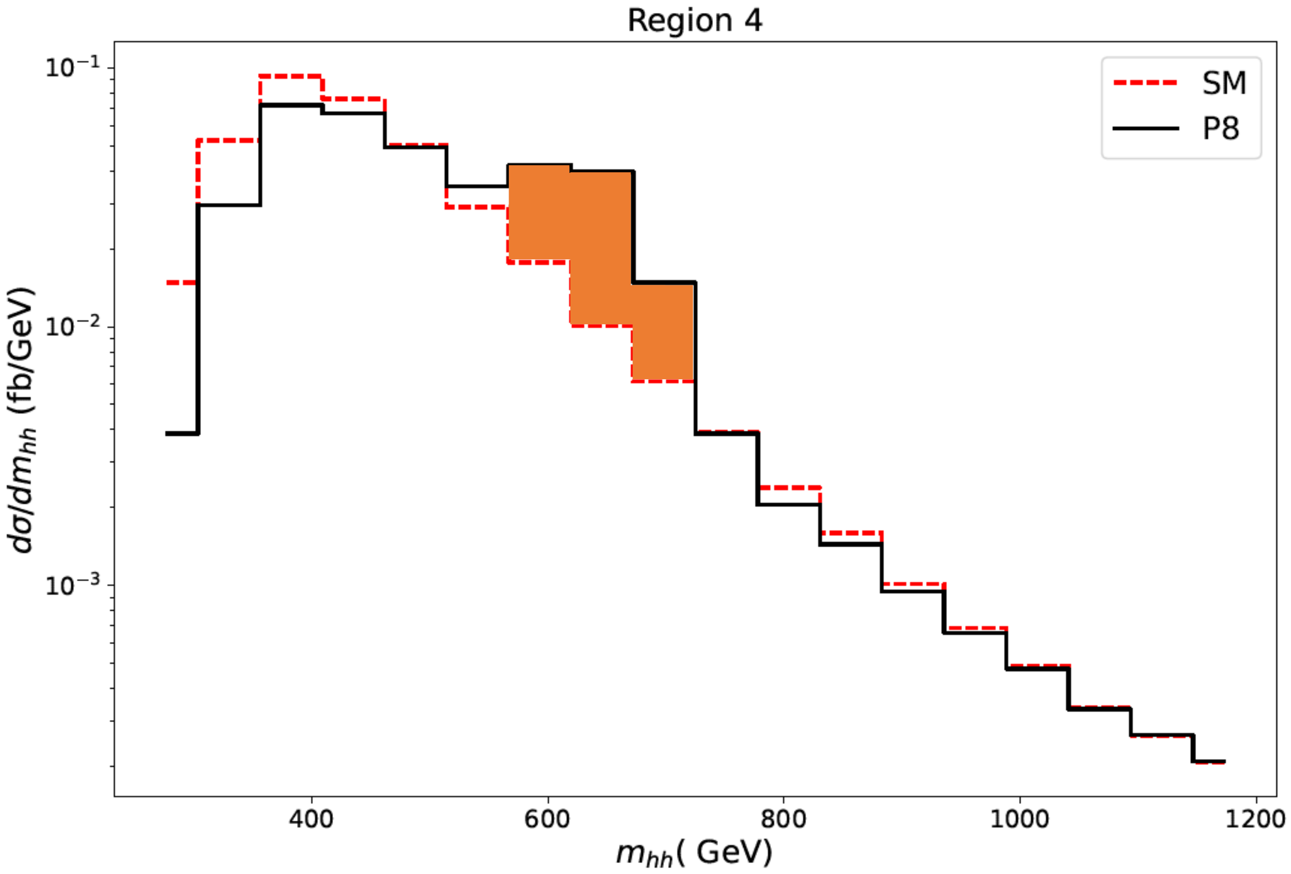
Id	m_H (GeV)	θ	x (GeV)	b_4	λ_{hhH}	κ_λ	Γ_H (GeV)	$\sigma_{hh}^{\mathrm{RxSM}}$ (fb)	Color
P1	459.2	0.178	46.3	0.89	0.36	1.47	2.07	44.15	red
P2	464.9	0.176	46.3	0.45	0.35	1.46	2.07	41.26	blue
P3	469.4	0.174	47.4	0.00	0.32	1.43	2.02	37.35	orange
P4	529.8	0.153	41.9	0.00	0.38	1.43	2.38	27.09	cyan
P5	577.5	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



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

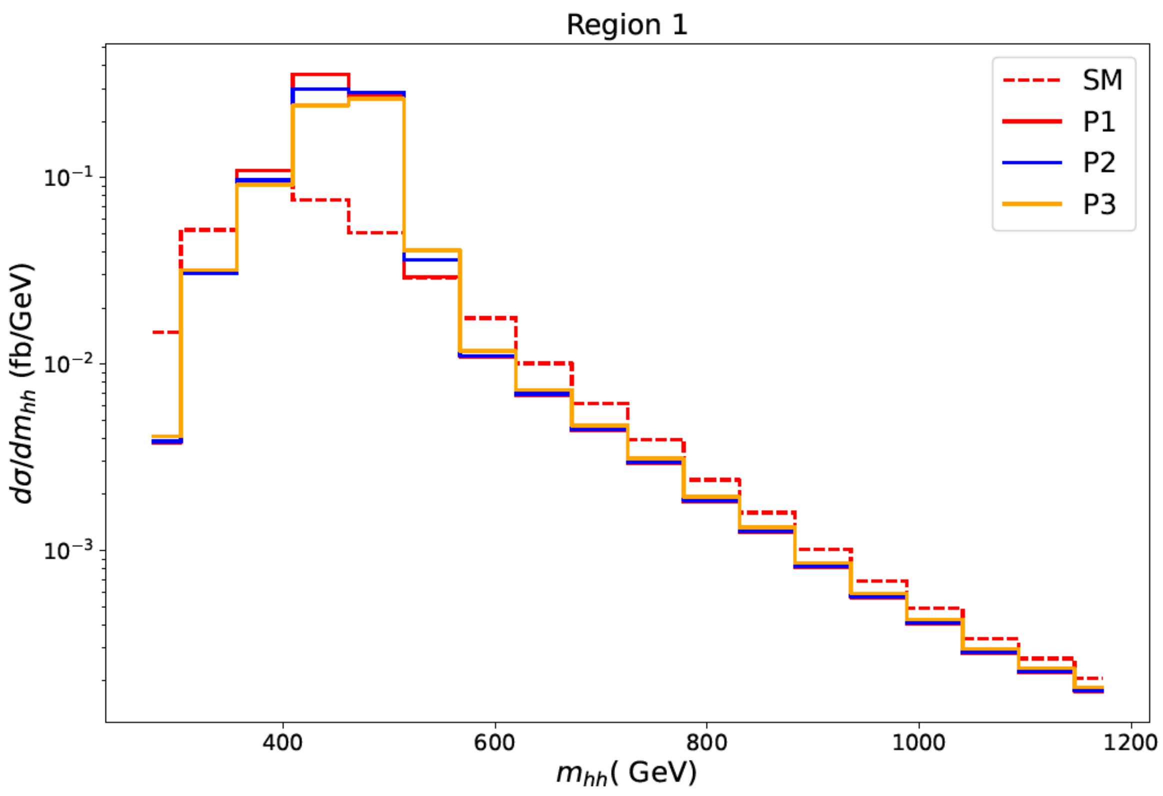
R parameter

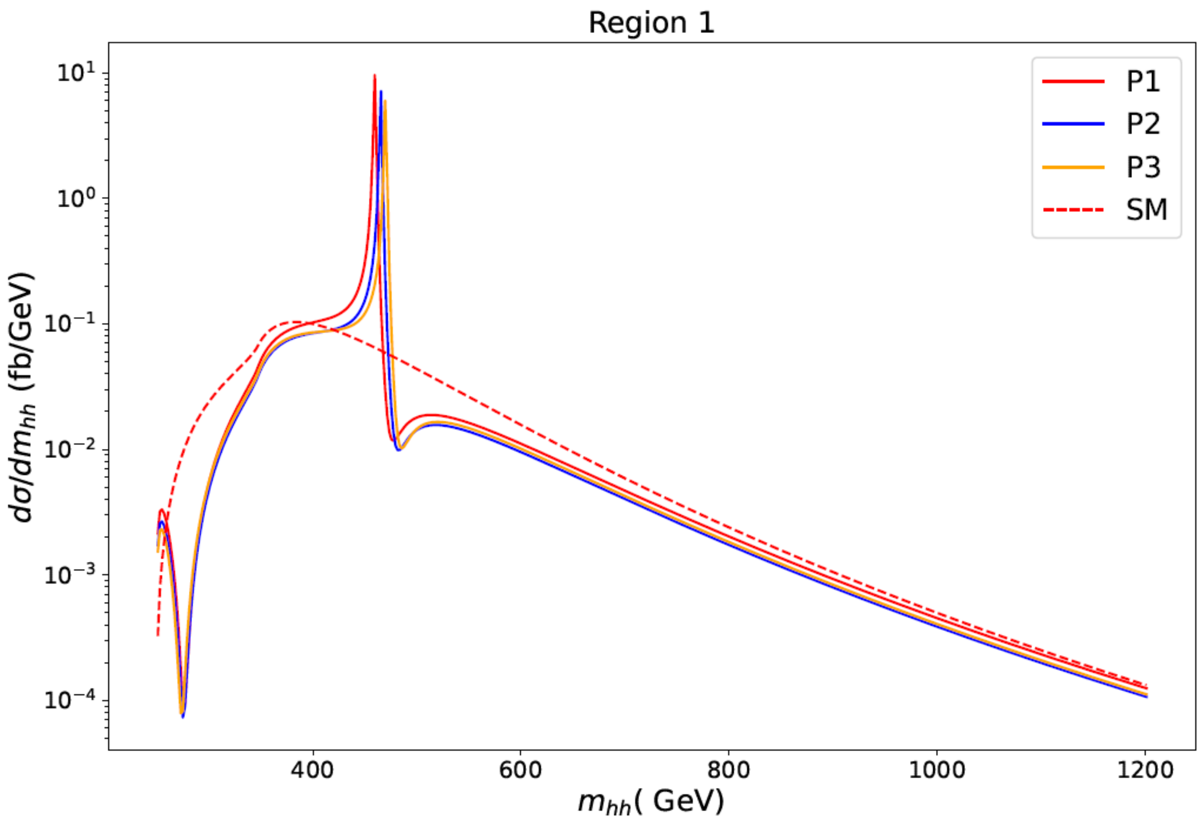


$$R = \frac{\sum_i |N_i^R - N_i^C|}{\sqrt{\sum_i N_i^C}}$$

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

Benchmark points

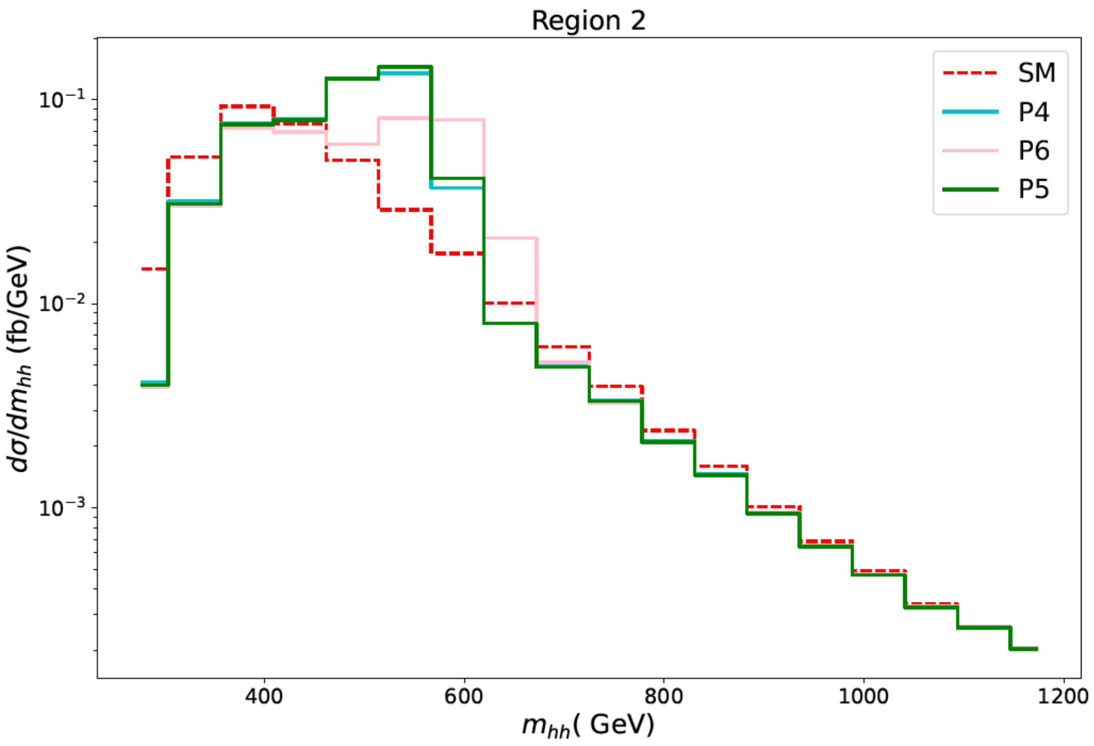


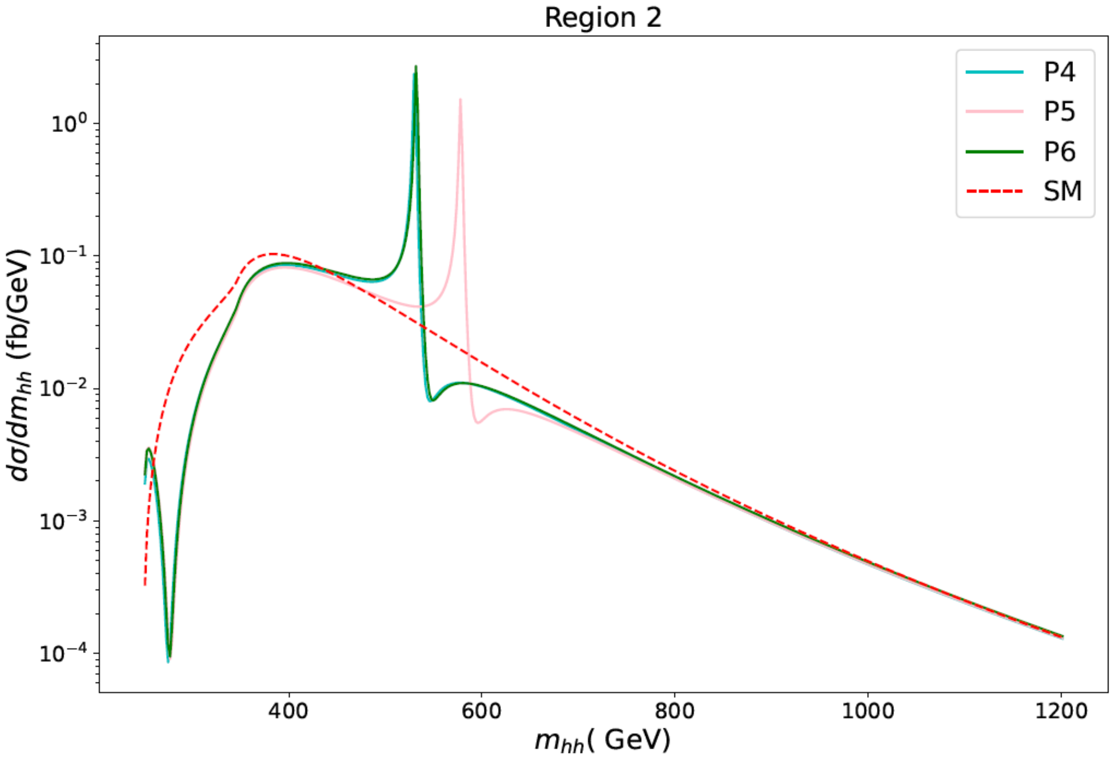


P1: $R = 348$
P2: $R = 319$
P3: $R = 320$

	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



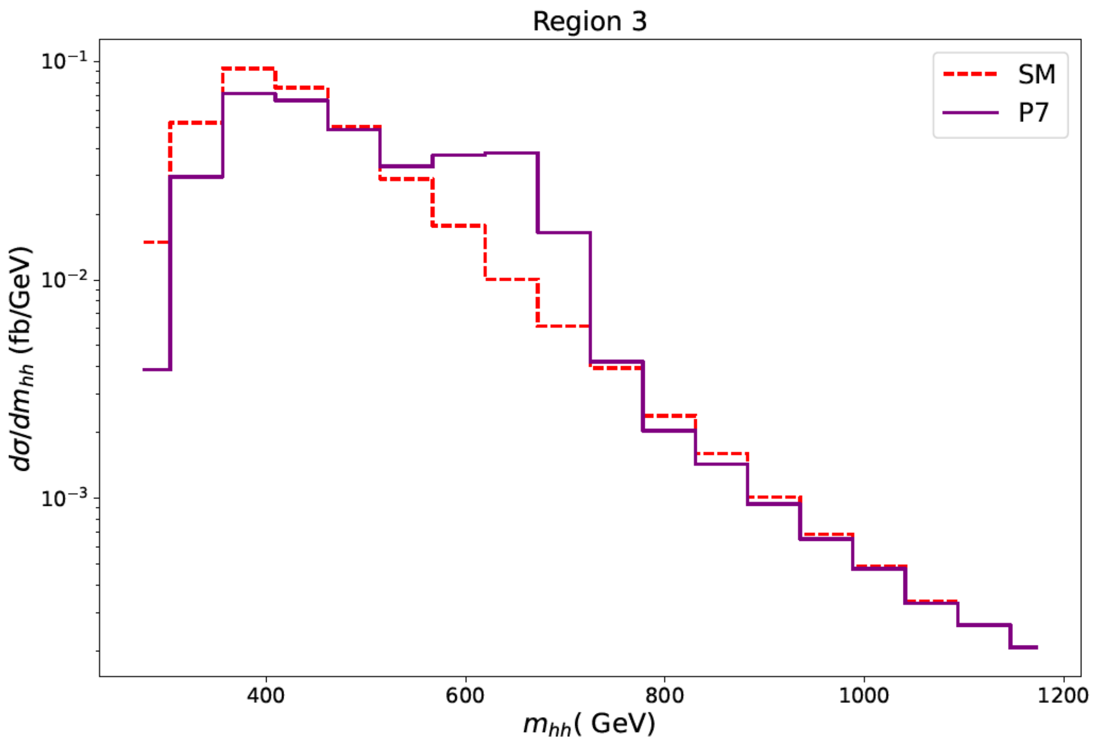


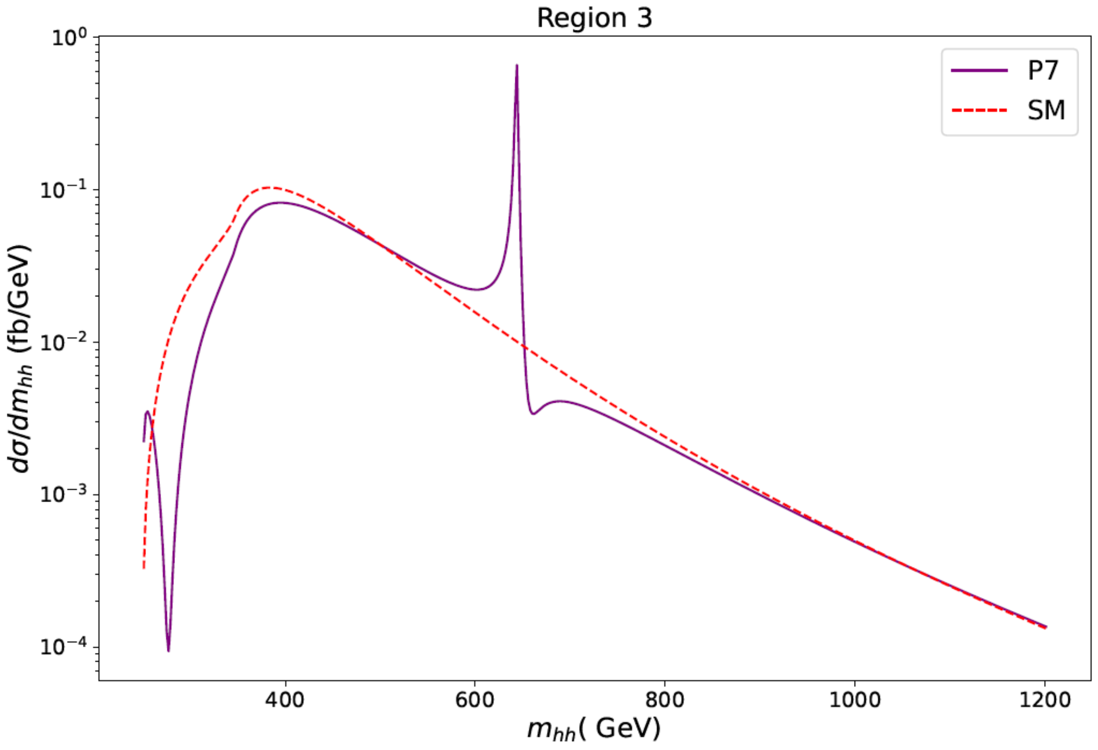
P4: $R = 198$
P5: $R = 165$
P6: $R = 172$

$5 > \Delta s > 0$

	P4	P5	P6
m_H(GeV)	529	577	531
λ_{hhH}	0.38	0.45	0.40
κ_λ	1.43	1.45	1.45

Experimental Uncertainties: Results



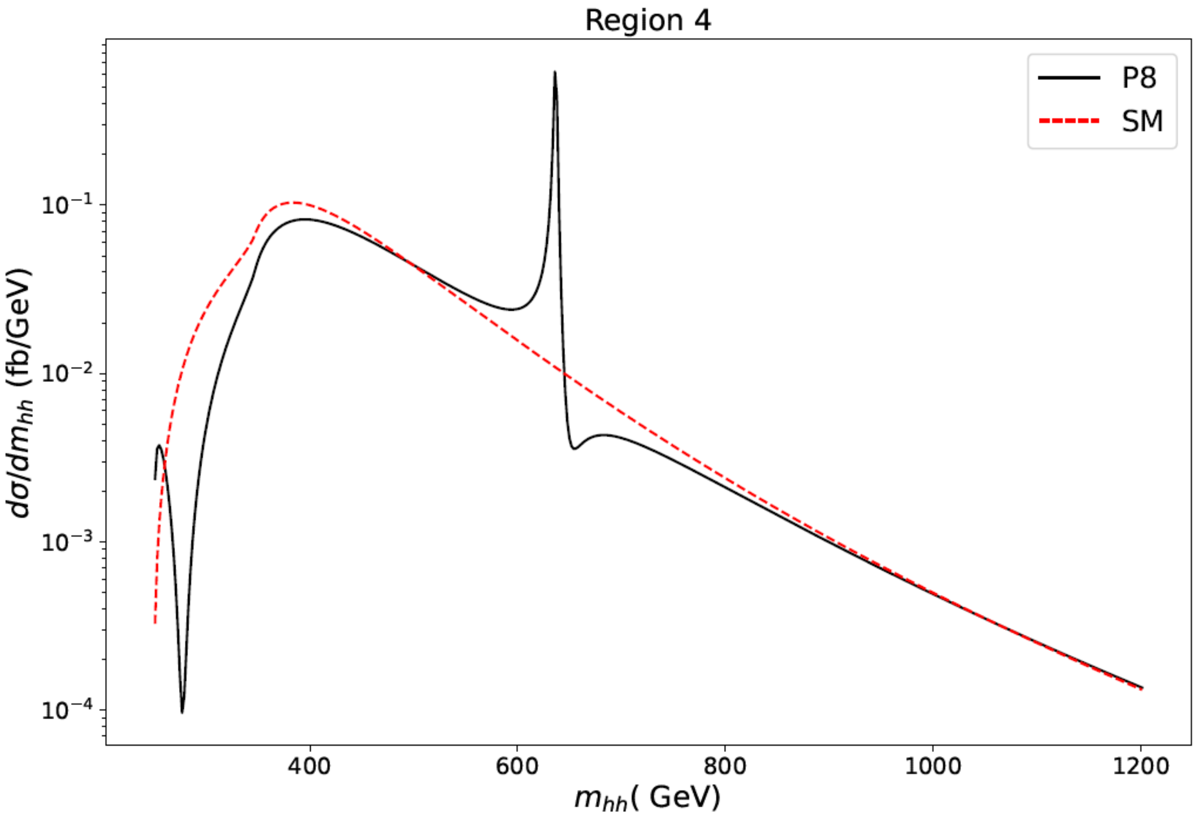


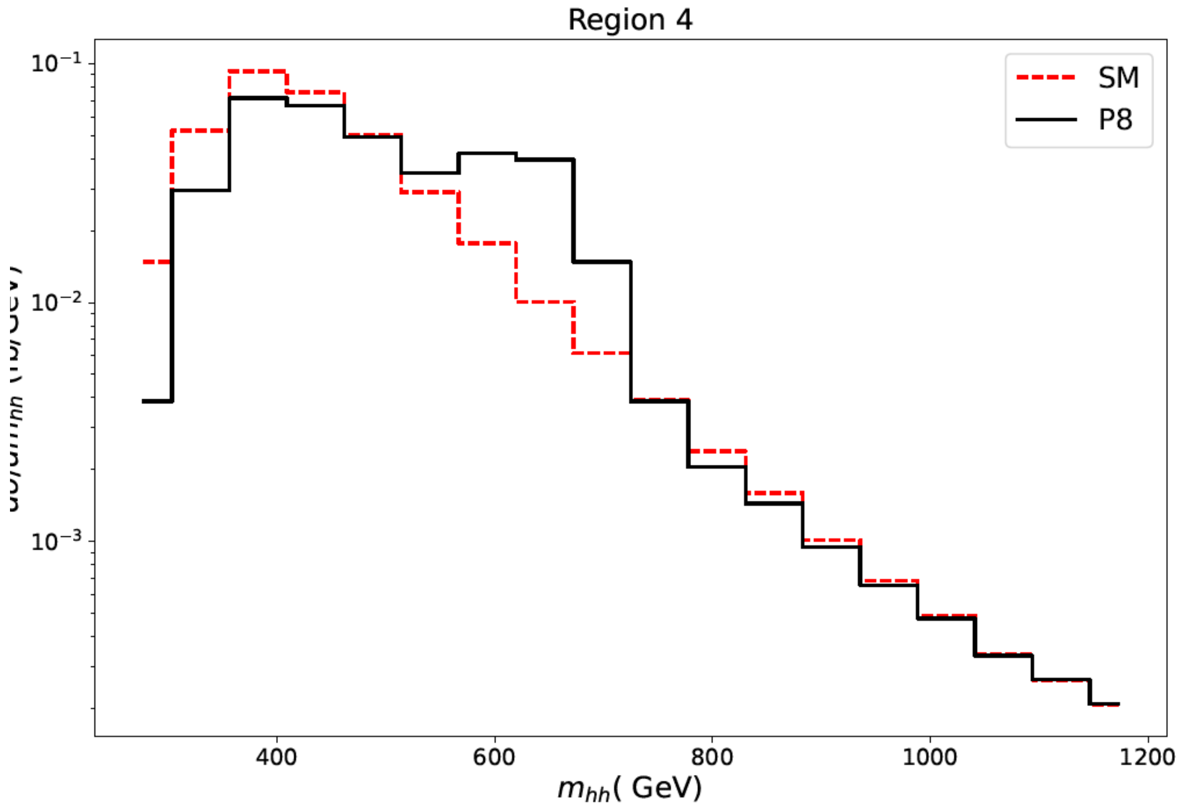
$R = 128$

$\Delta s \approx 0$

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

Benchmark points

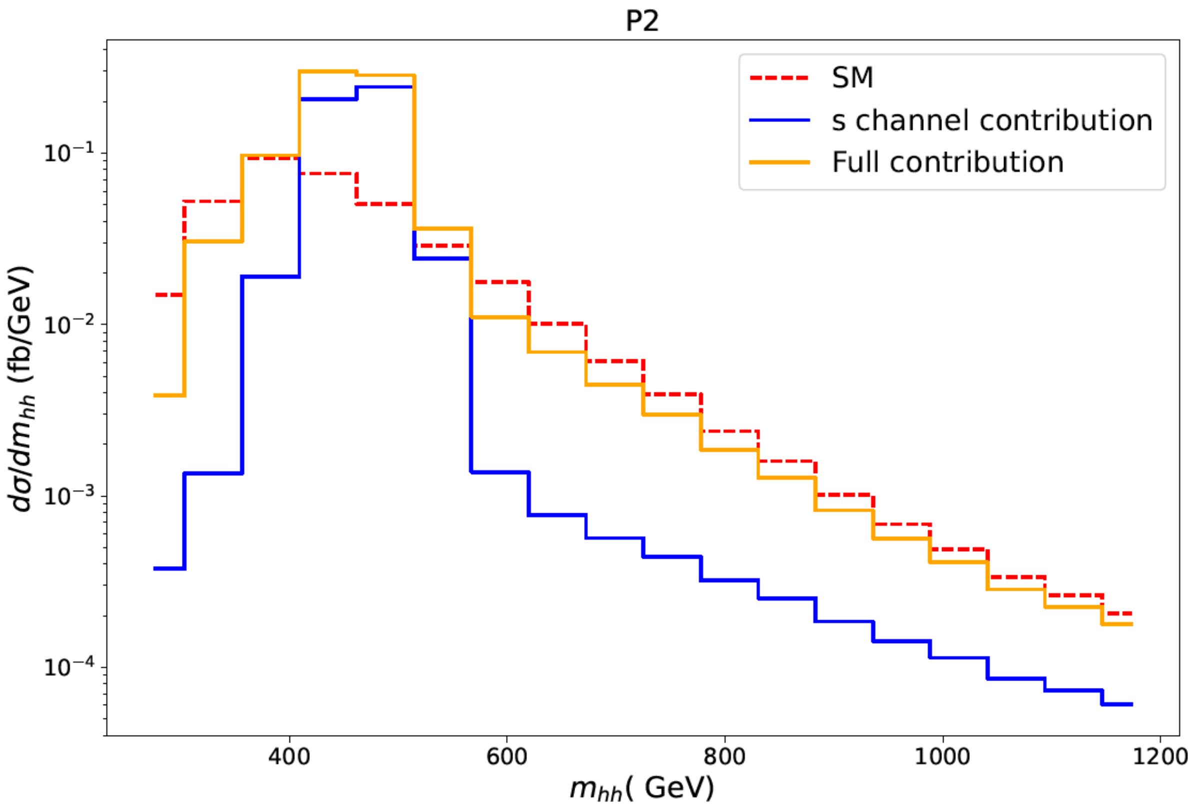


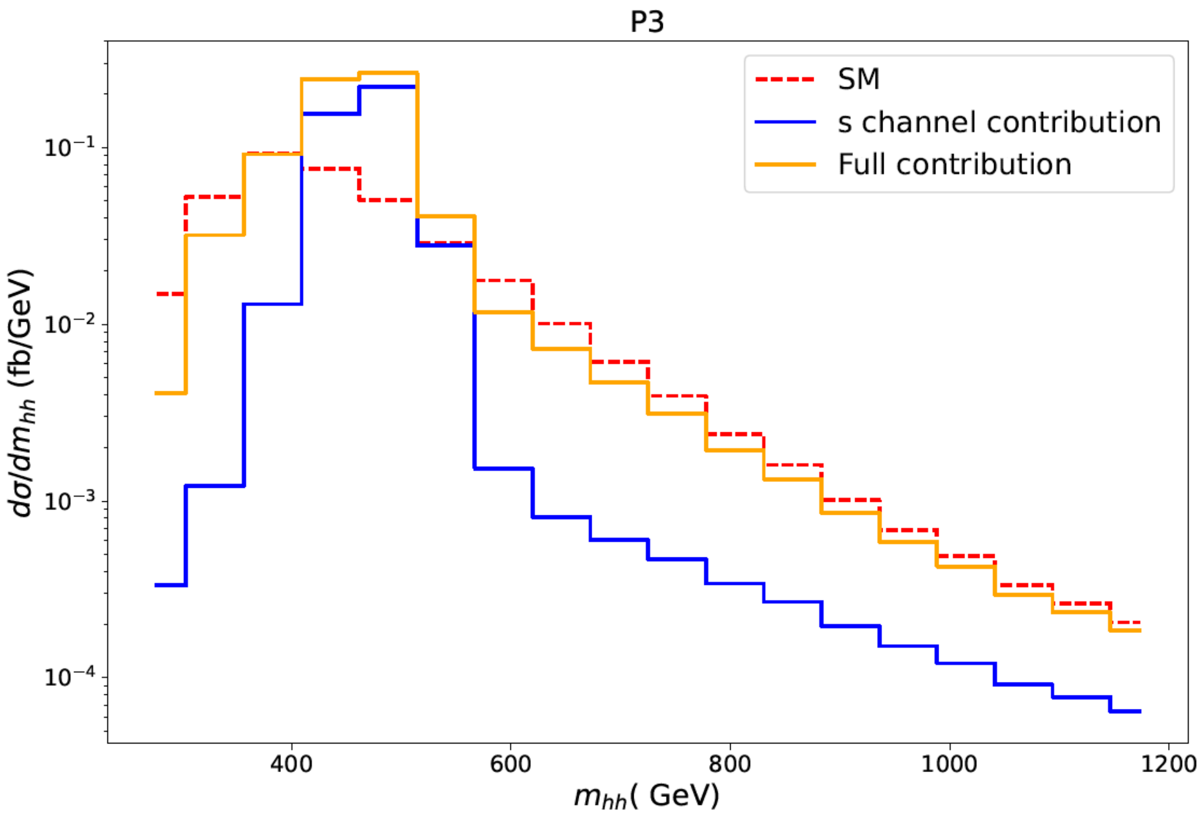


	P8
m_H(GeV)	658
λ_{hhH}	0.52
κ_λ	1.44

$R = 132$

Benchmark points





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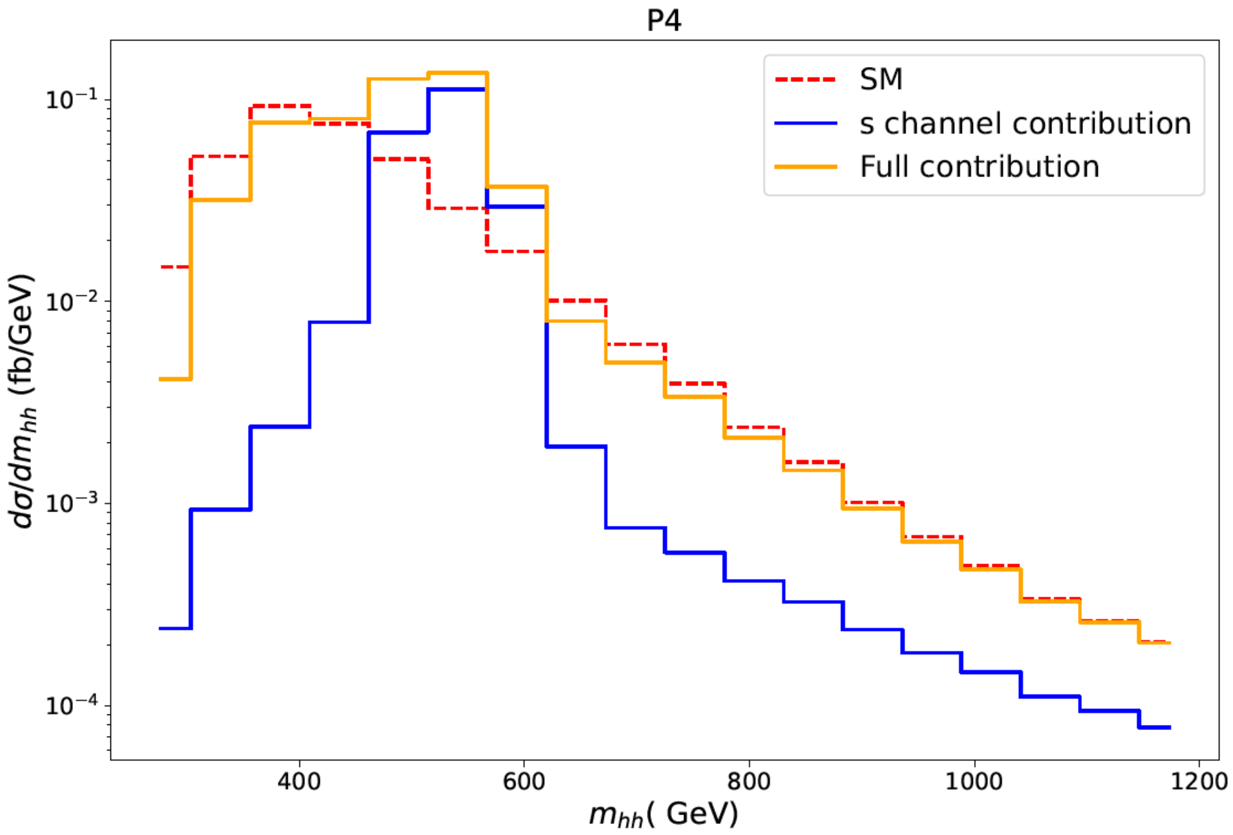

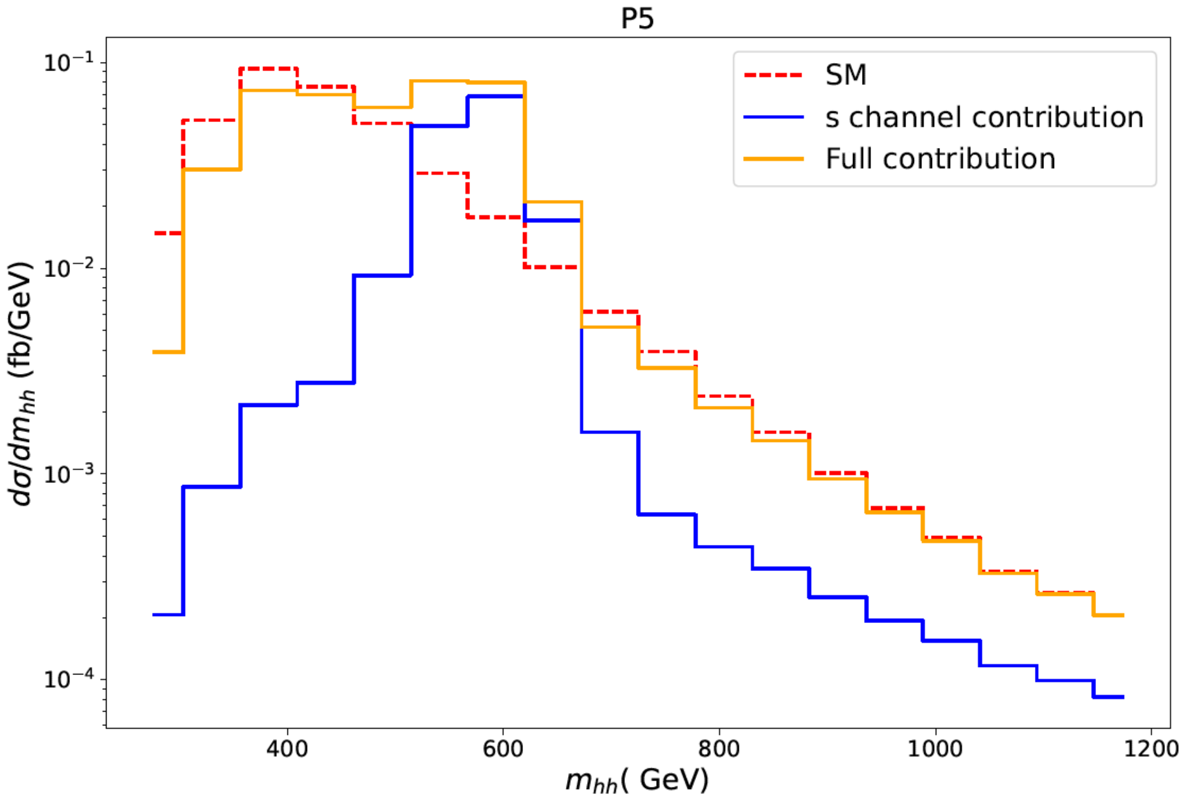

Benchmark points