Di-Higgs production in the RxSM in e^+e^- colliders

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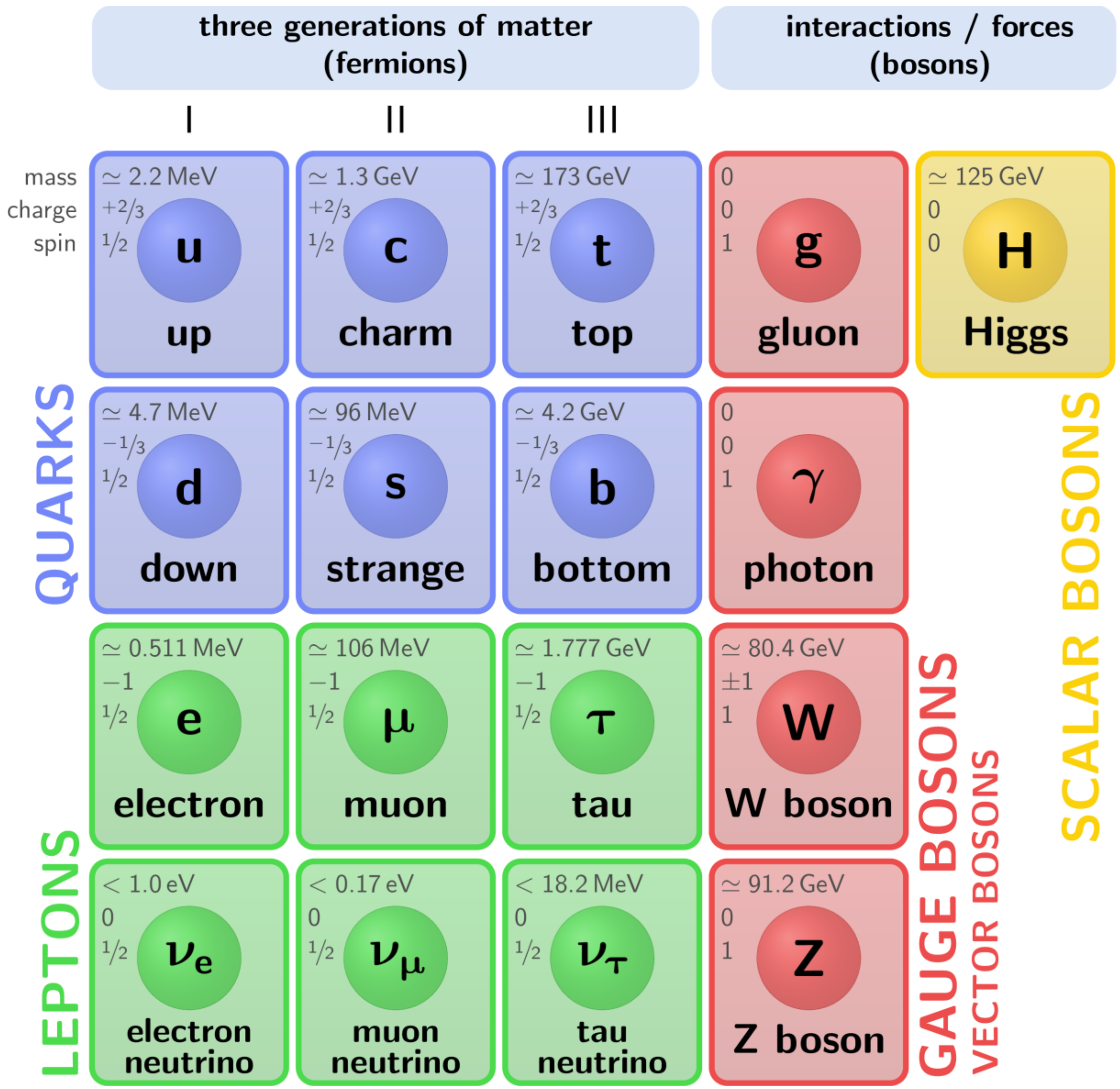
The Standard Model of Particle Physics (SM)



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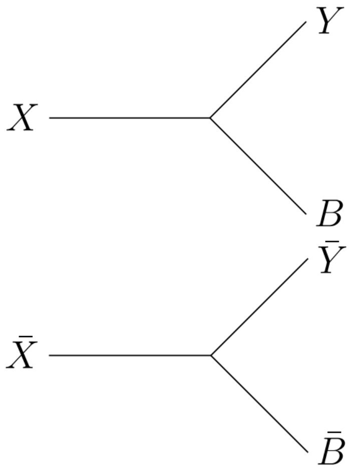
Motivation: Matter-Antimatter Asymmetry

The SM does not explain the **matter-antimatter asymmetry** in the universe $\eta = \frac{\eta_b}{s} \approx 6 \cdot 10^{-10}$

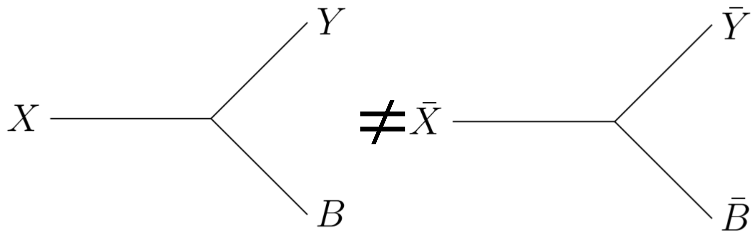
Proposal: **Electroweak Baryogenesis**:

- The three Shakarov conditions[1] must be fulfilled:

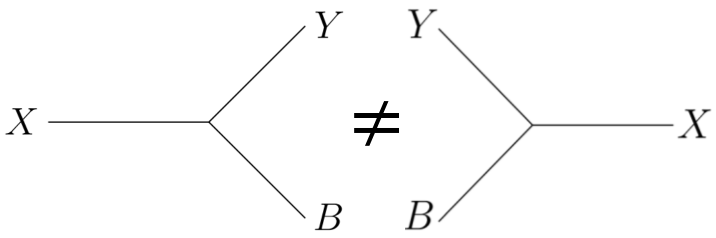
1) **Baryon Number Violation**



2) **C and CP Violations**



3) **Out of equilibrium**



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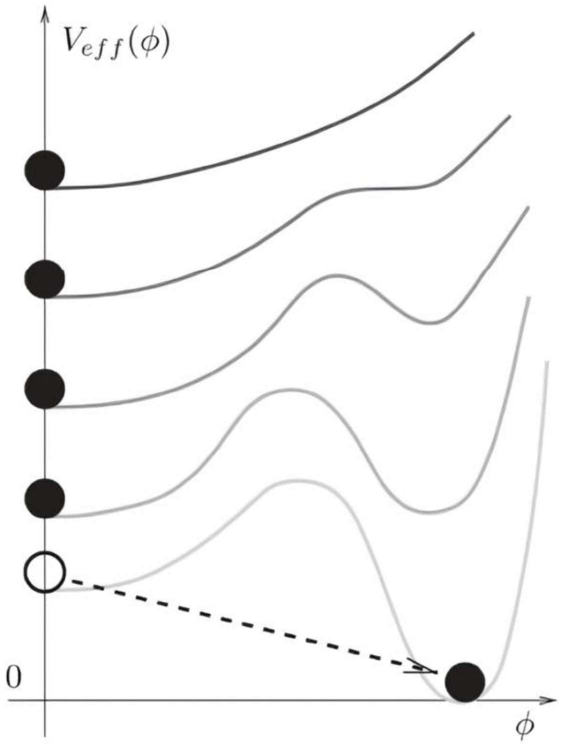
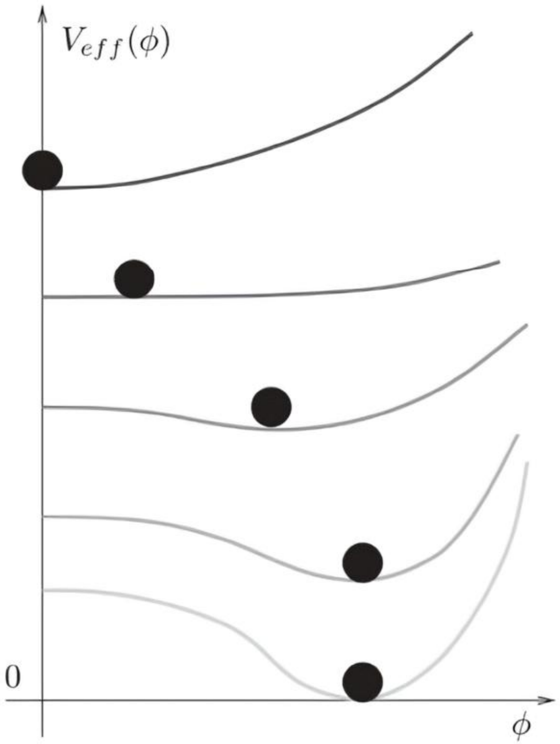
RxSM. SFOEWPT



SM



- Process out of termal equilibrium: **Strong First Order ElectroWeak Phase Transition (SFOEWPT)**
- **RxSM Model**, a BSM model where: SM + a new Higgs singlet, i. e., a new Higgs boson, H

Goals

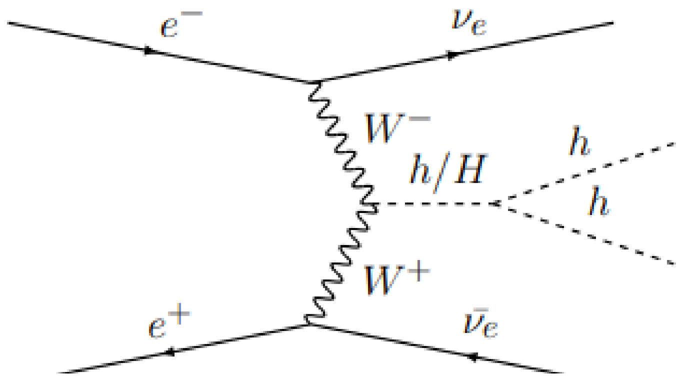
- Study of the **RxSM model**, formulation, benchmark plane…

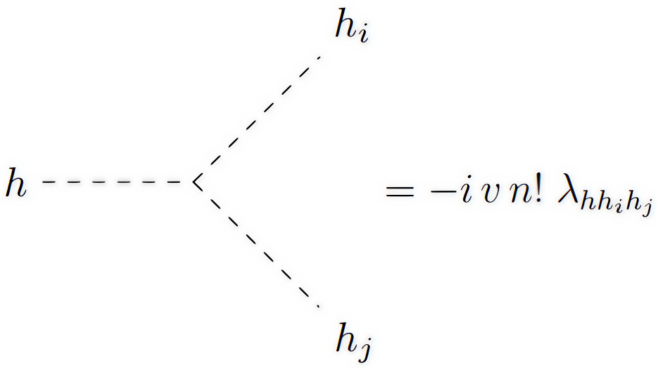
- Analysis of the process $\boldsymbol{e^+e^- \to hh\nu\bar{\nu}}$ with MadGraph for future e^+e^- colliders, e.g. **International Linear Collider (ILC).** We will apply cuts, smearing…

- Sentisivity to **Triple Higgs Couplings (THC)**, λ_{hhh}, λ_{hhH}

$$\left(\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}, -1.2 \leq \kappa_\lambda \leq 7.2 \; [2]\right)$$

ILC $(\sqrt{s} = 250 - 1000\ \mathbf{GeV})$





RxSM model, addition of a real singlet

Apart from the existent SM Higgs doublet, $\mathcal{H}$, we add a real singlet, $\mathcal{S}$,

$$\mathcal{H} = \begin{pmatrix} 0 \\ \frac{h'+v}{\sqrt{2}} \end{pmatrix}, \qquad \mathcal{S} = s + x$$

The Higgs potential is modified,

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

We obtain the mass matrix,

$$\mathcal{M}^2 = \begin{pmatrix} \frac{\partial^2 V}{\partial h'^2} & \frac{\partial^2 V}{\partial h' \partial s} \\ \frac{\partial^2 V}{\partial h' \partial s} & \frac{\partial^2 V}{\partial s^2} \end{pmatrix} \Bigg|_{h'=0,\, s=0} = \begin{pmatrix} m^2_{h'} & m^2_{h's} \\ m^2_{h's} & m^2_s \end{pmatrix} = \begin{pmatrix} 2\lambda v^2 & \frac{(a_1+2a_2x)v}{2} \\ \frac{(a_1+2a_2x)v}{2} & b_3 x + 2b_4 x^2 - \frac{a_1 v^2}{4x} \end{pmatrix}$$

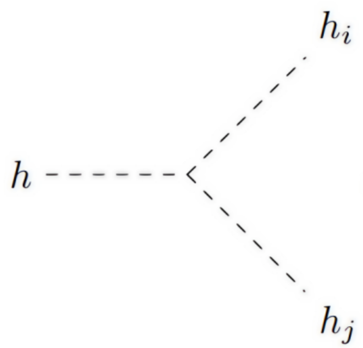
RxSM model, addition of a real singlet

Change of basis to diagonalise the mass matrix

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

Mass of the light Higgs, h, SM-like, and the heavy Higgs, H

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



$= -i\, v\, n!\, \lambda_{hh_ih_j}$

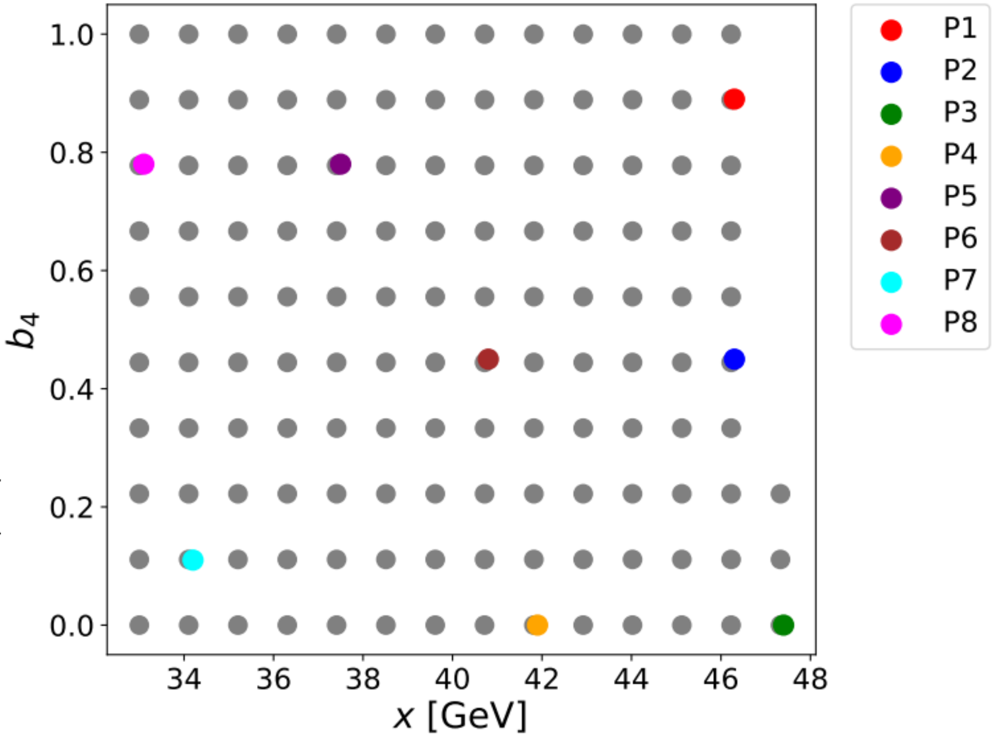
Triple Higgs Couplings

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

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

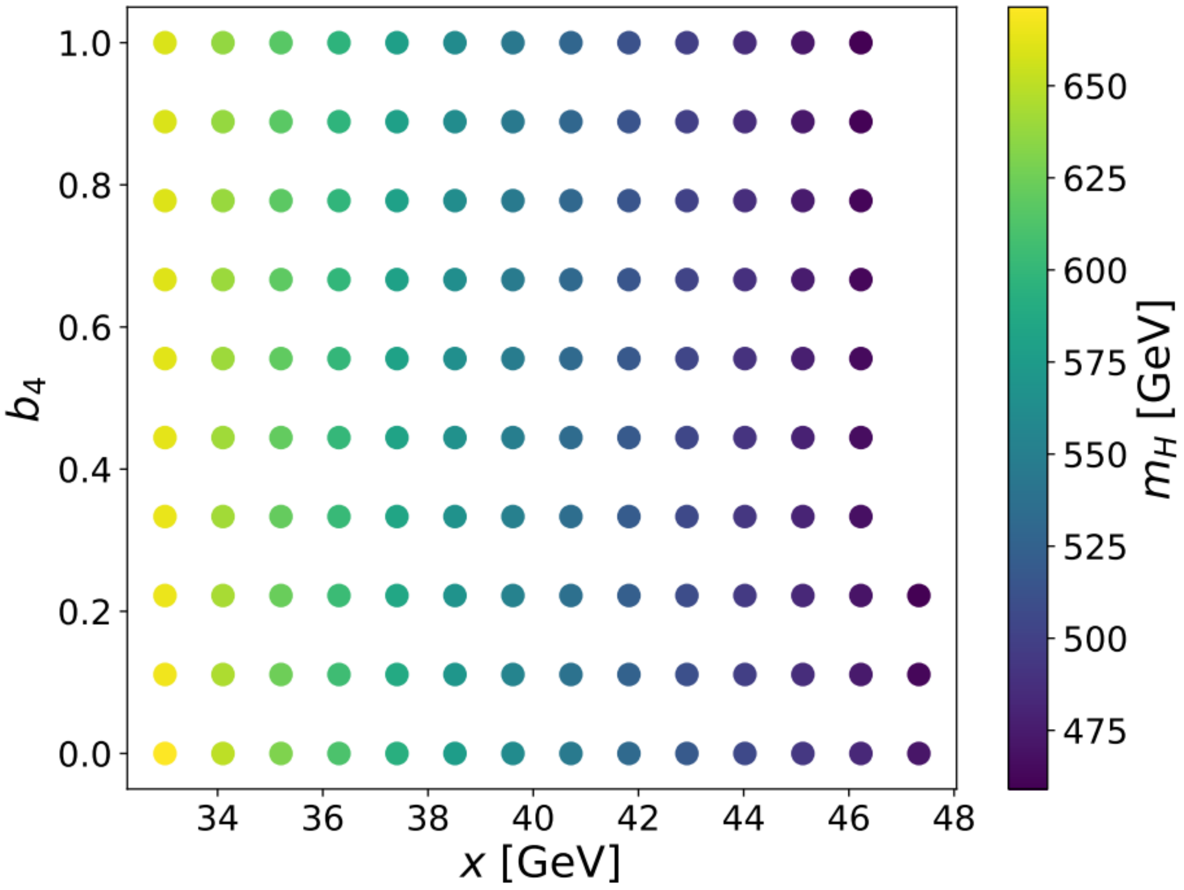
Benchmark Plane

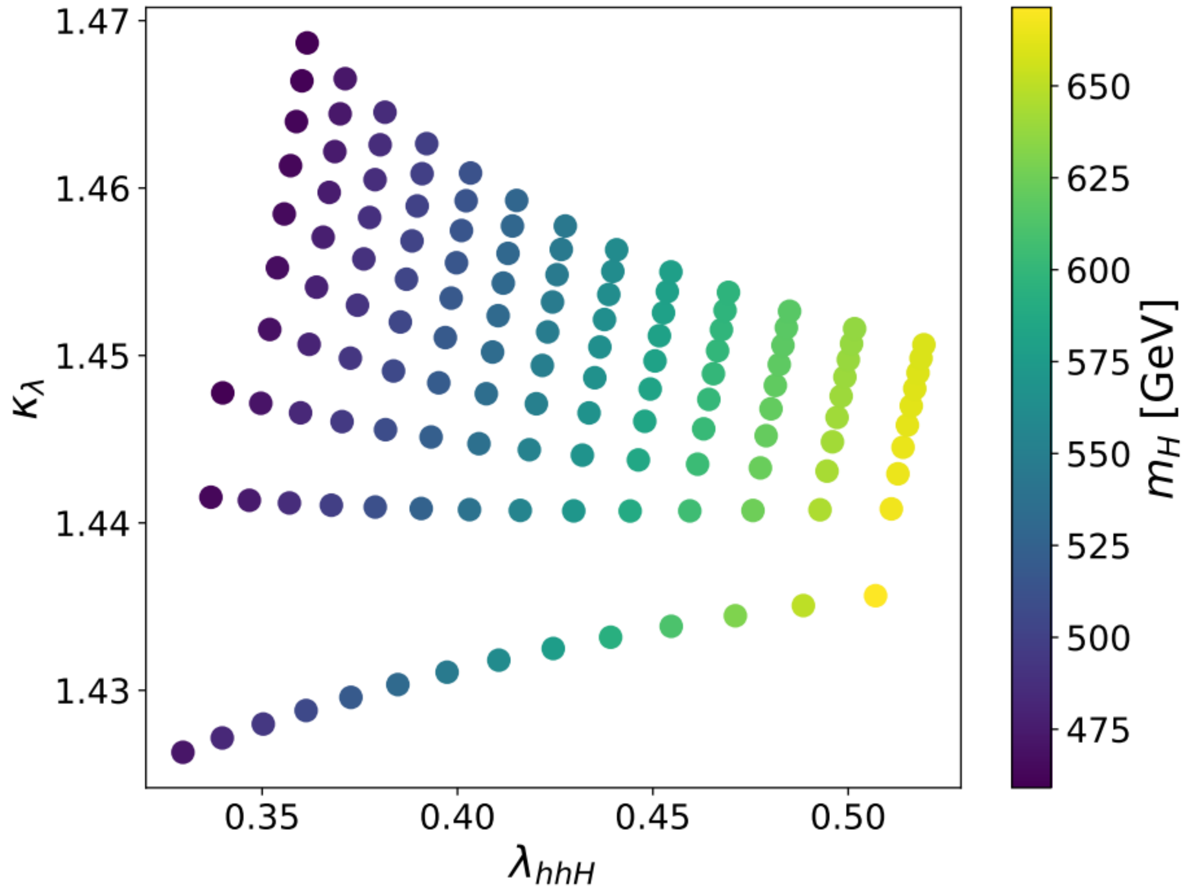
- After experimental and theoretical considerations, the plane is reduce to two independent variables, x y b_4. We define a plane that guarantees a **SFOEWPT**[3]
- 8 points[4] in the $x - b_4$ plane are chosen. We will also look at the $\kappa_\lambda - \lambda_{hhH}$ plane



Point	m_H [GeV]	θ	x	b_4	λ_{hhH}	$\lambda_{hhh}^{\mathrm{RxSM}}$	κ_λ	Γ_H [GeV]
P1	459.7	0.178	46.30	0.89	0.360	0.189	1.47	3.78
P2	465.3	0.176	46.30	0.45	0.353	0.188	1.46	3.71
P3	470.8	0.174	47.40	0.00	0.329	0.184	1.43	3.44
P4	530.9	0.152	41.90	0.00	0.384	0.185	1.43	4.15
P5	578.0	0.139	37.50	0.78	0.452	0.187	1.45	5.02
P6	532.1	0.152	40.80	0.45	0.408	0.187	1.45	4.46
P7	643.4	0.124	34.20	0.11	0.491	0.186	1.44	5.48
P8	658.3	0.122	33.10	0.78	0.516	0.187	1.45	5.81

Benchmark Plane. The heavy Higgs mass





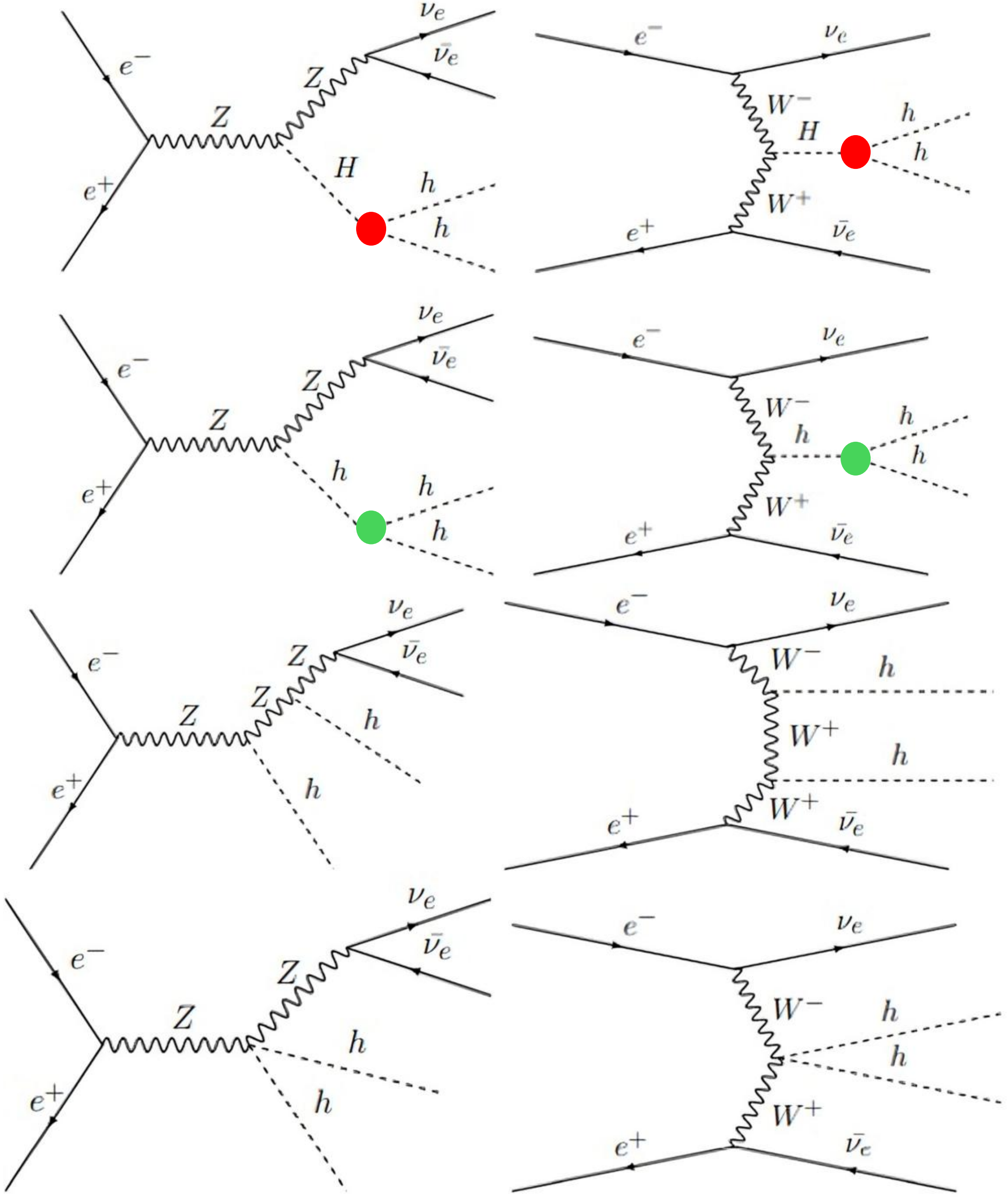
Process $e^+e^- \to hh\nu\bar{\nu}$

- Two kinds of Feynman Diagrams (FD), with Z or with $W^{\pm}$ bosons.

- In both FD with λ_{hhH}, a resonance of H is observed

- We obtain histograms of the cross sections as functions of m_{hh} at $\sqrt{s} = 1000\ \mathrm{GeV}$

- We obtain a **statistical significance** of the resonance for a luminosity of $L = 8000\ \mathrm{fb}^{-1}$



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  - RxSM

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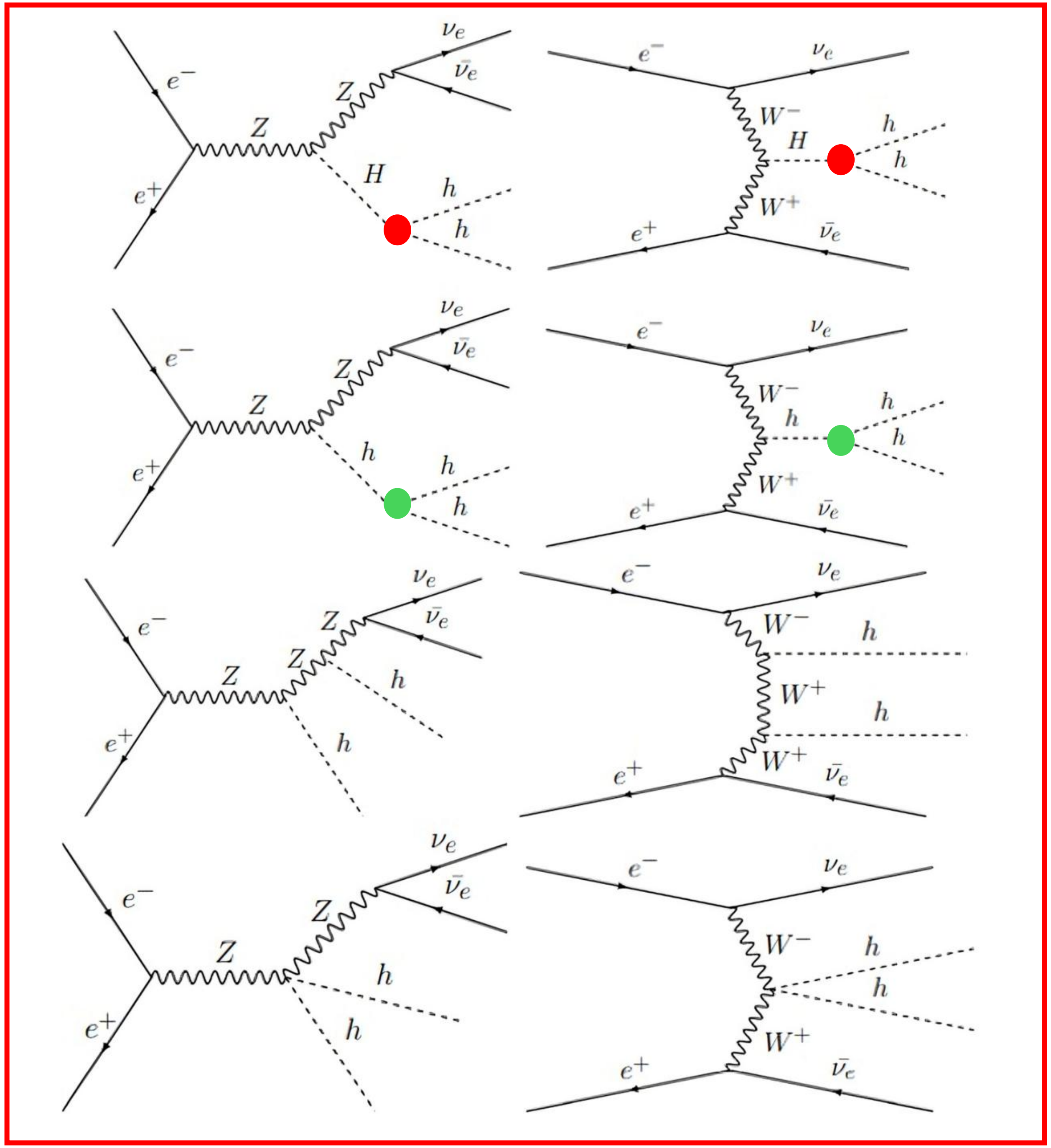

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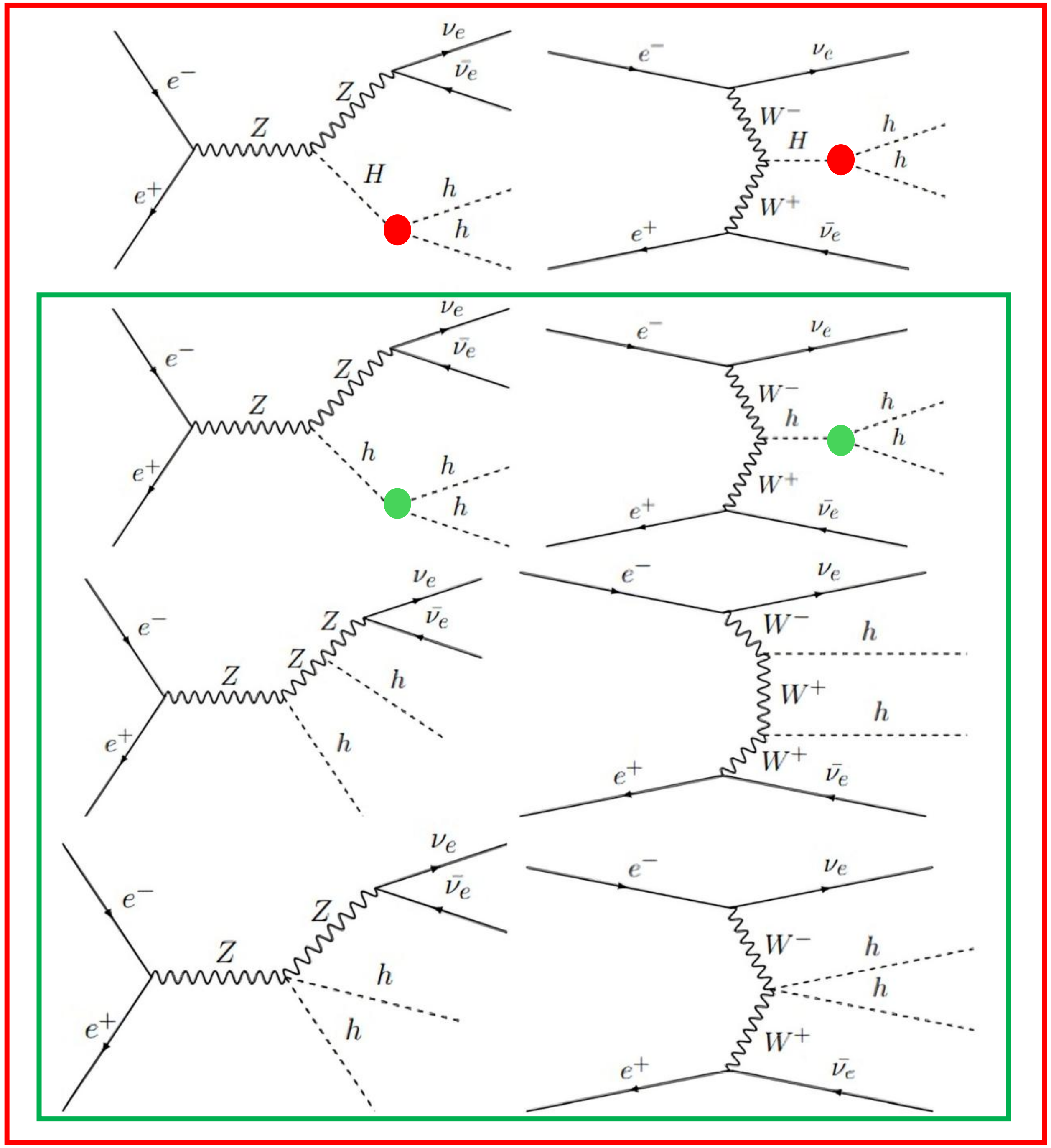

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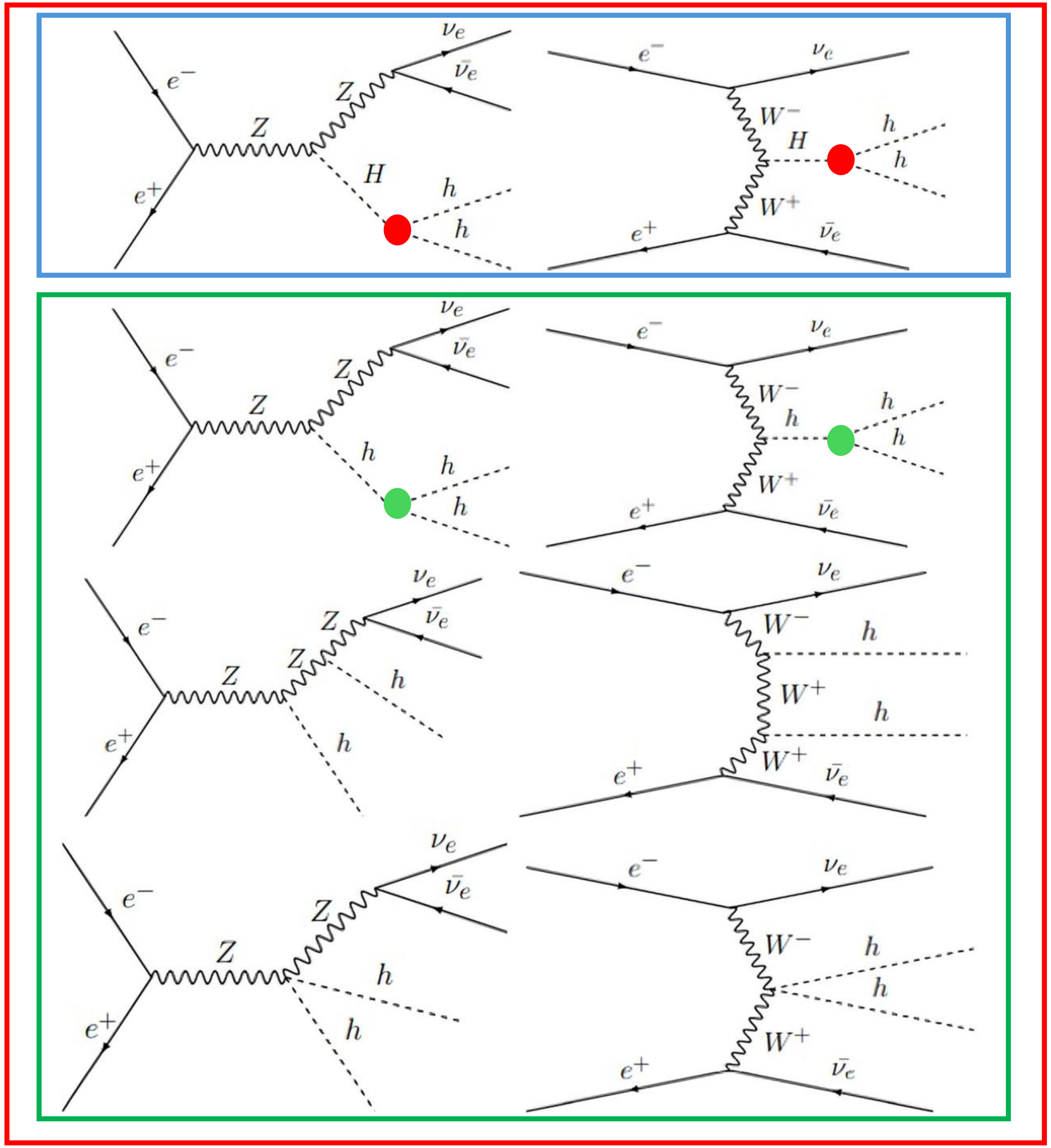

Process $e^+e^- \to hh\nu\bar{\nu}$

- Two kinds of Feynman Diagrams (FD), with Z or with $W^\pm$ bosons.
- In both FD with λ_{hhH}, a resonance of H is observed
- We obtain histograms of the cross sections as functions of m_{hh} at $\sqrt{s} = 1000\ \mathrm{GeV}$
  - RxSM
  - NoH
  - H
  - SM
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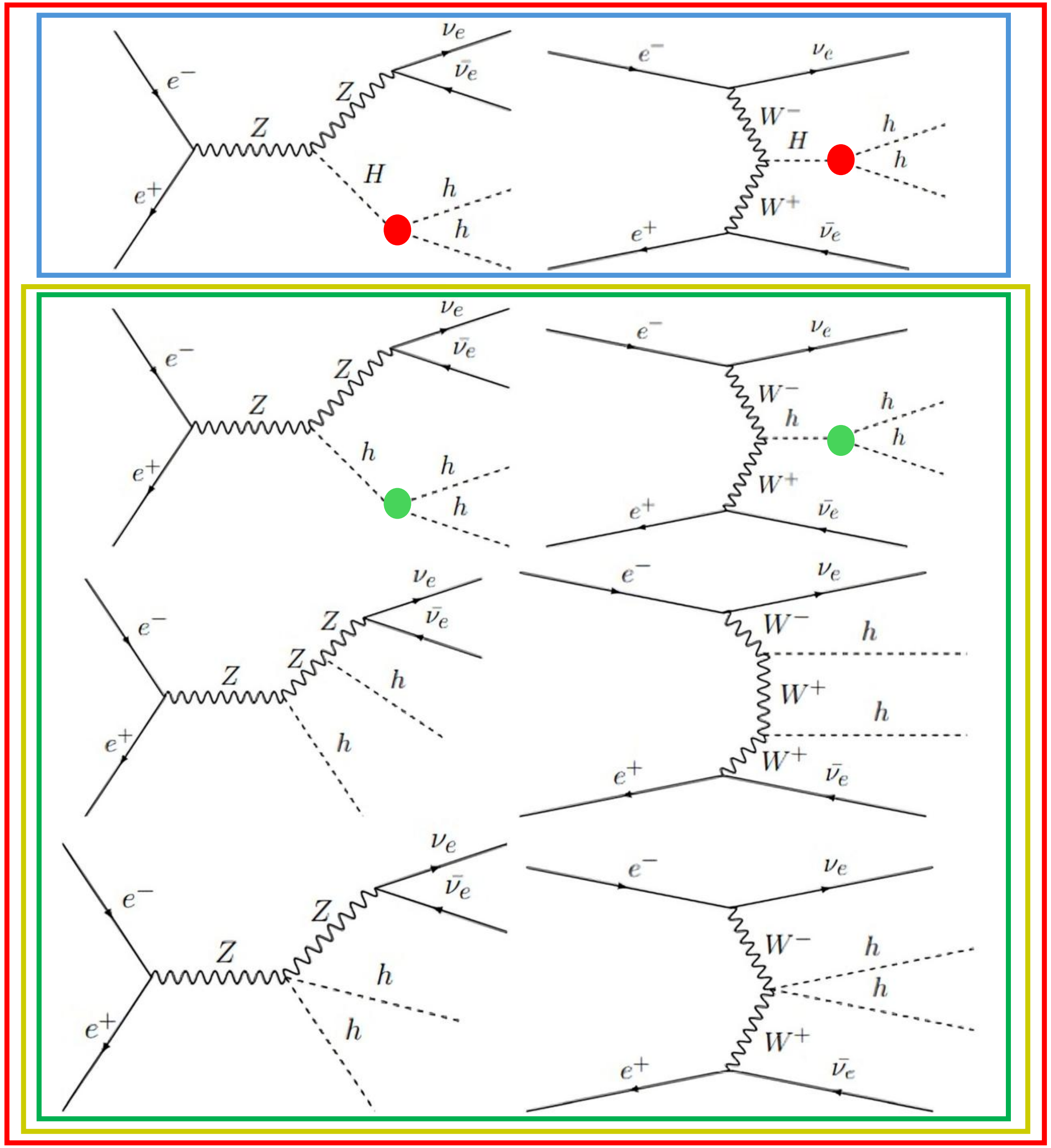
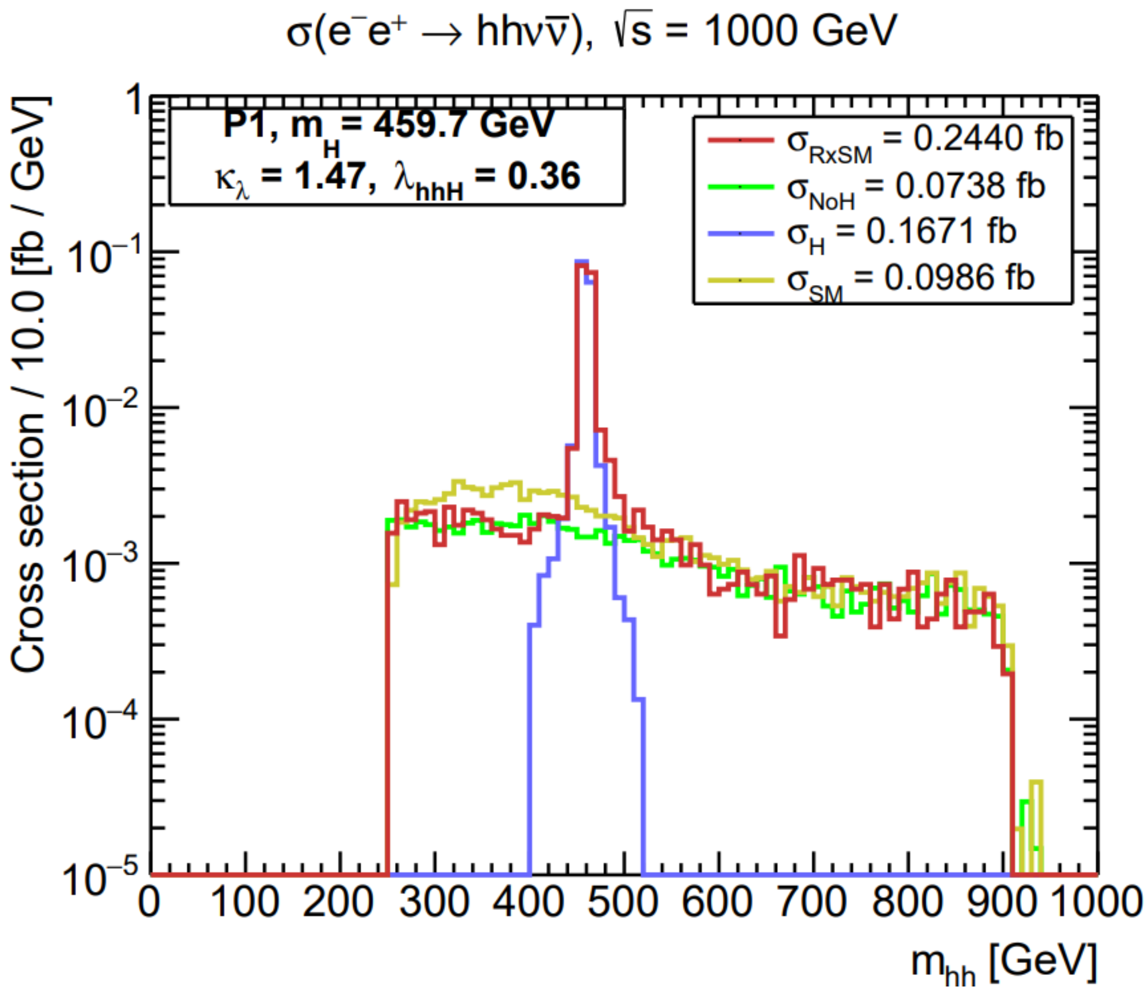
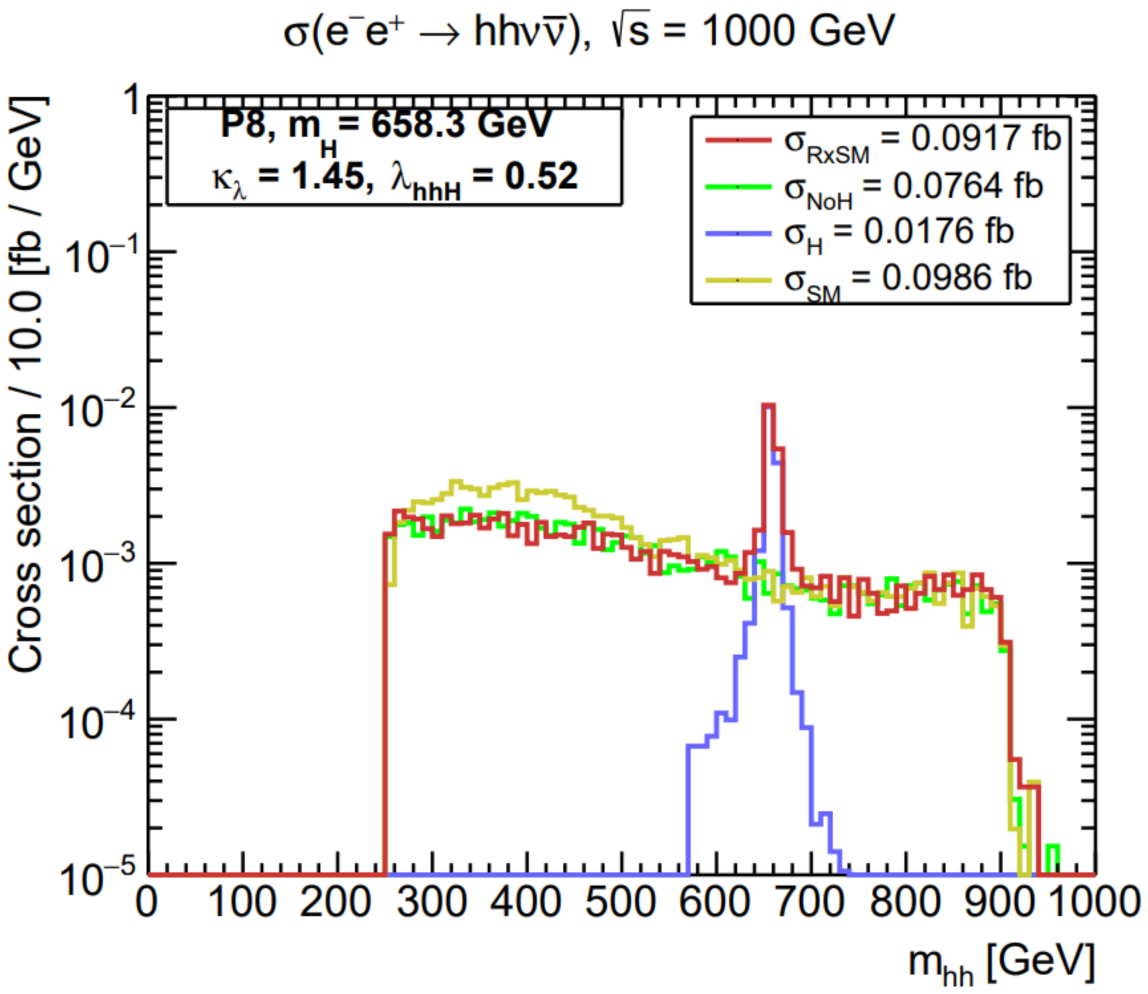


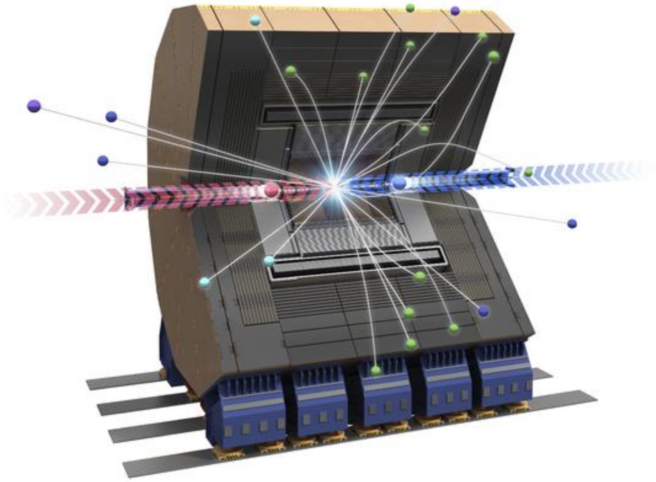
Distributions m_{hh}, $\sqrt{s} = 1000$ GeV



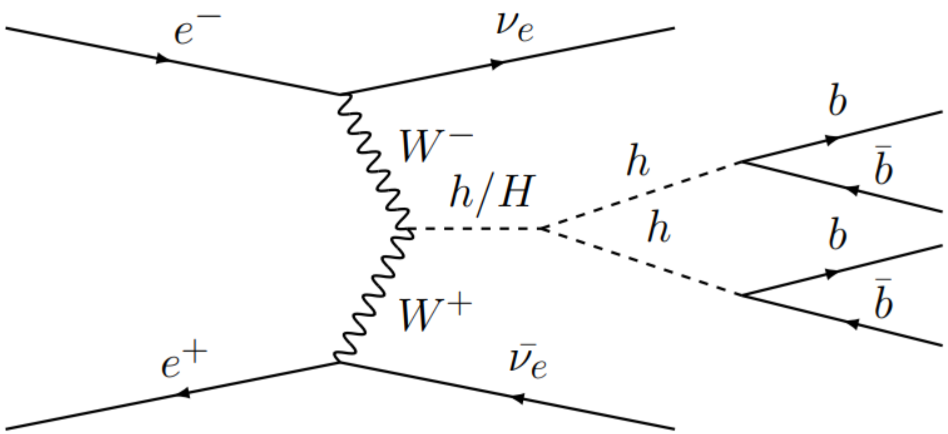


Process $e^+e^- \to hh\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$

Process calculations for colliders:



- Cuts for collider detection are applied
- **Acceptance** $\mathcal{A} = \frac{N_{\nu\bar{\nu}4b}^{\text{with cuts}}}{N_{\nu\bar{\nu}4b}^{\text{w/o cuts}}}$
- **Efficiency of b-tagged jets** $\epsilon_b = 0.85$
- **Branching ratio of the h to $b\bar{b}$** $\mathrm{BR}(h \to b\bar{b}) = 0.58$
- Without cuts $\bar{N}_{\nu\bar{\nu}4b}^{\text{w/o }\mathcal{A}\times\epsilon_b} = N_{hh\nu\bar{\nu}} \times (\mathrm{BR}(h \to b\bar{b}))^2$
- With cuts $\bar{N}_{\nu\bar{\nu}4b} = N_{hh\nu\bar{\nu}} \times (\mathrm{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$

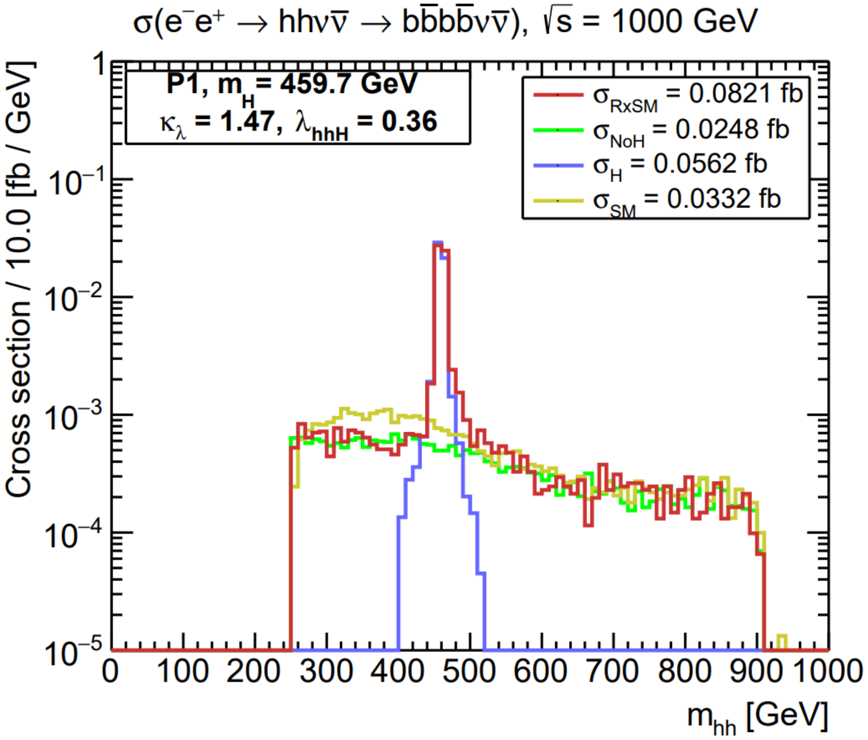


Process $e^+e^- \to hh\nu\bar{\nu} \to b\bar{b}b\bar{b}\nu\bar{\nu}$

Cuts in the detector:

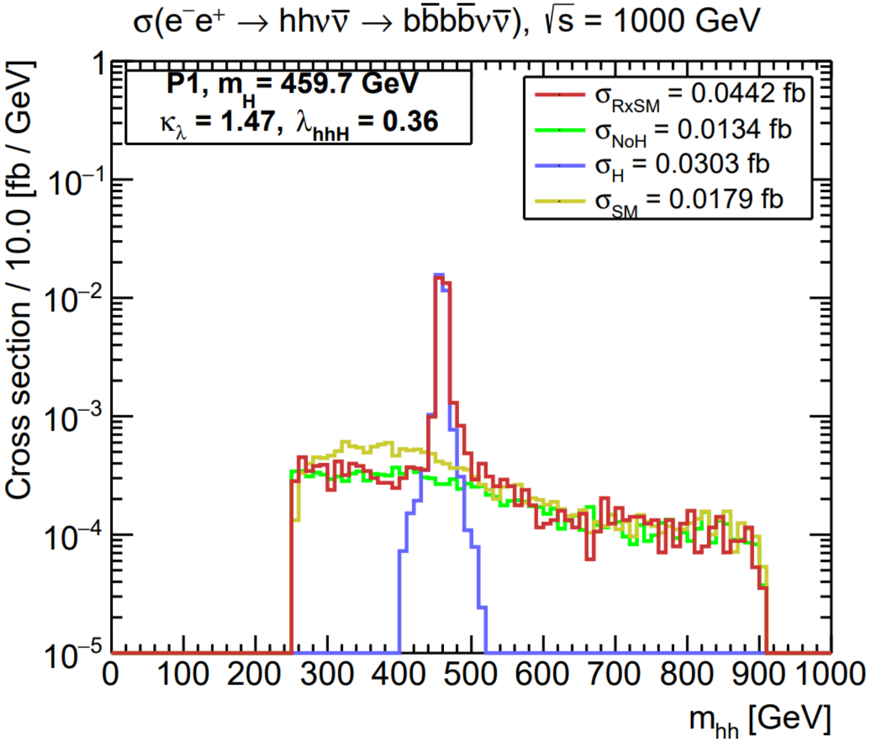
- $E_T^{miss} > 30$ GeV. Missing energy from the ν's
- $E_b > 20$ GeV. Minimum energy of the b-tagged jets
- $|\eta_b| < 2.5$. Pseudorapidity of the b-tagged jets
- $y_{bb} > 0.001$ at $\sqrt{s} = 1000$ GeV [5], for jet clustering

Without cuts



$$\bar{N}^{\mathrm{w/o}\ \mathcal{A}\times\epsilon_b}_{\nu\bar{\nu}4b} = N_{hh\nu\bar{\nu}} \times (\mathrm{BR}(h \to b\bar{b}))^2$$

With cuts

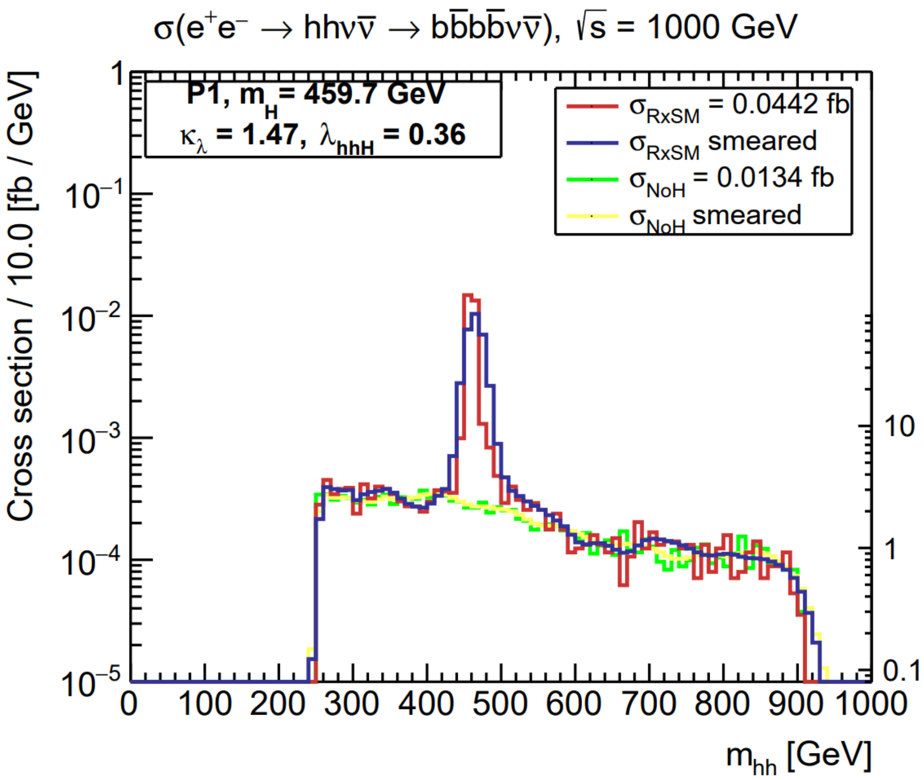


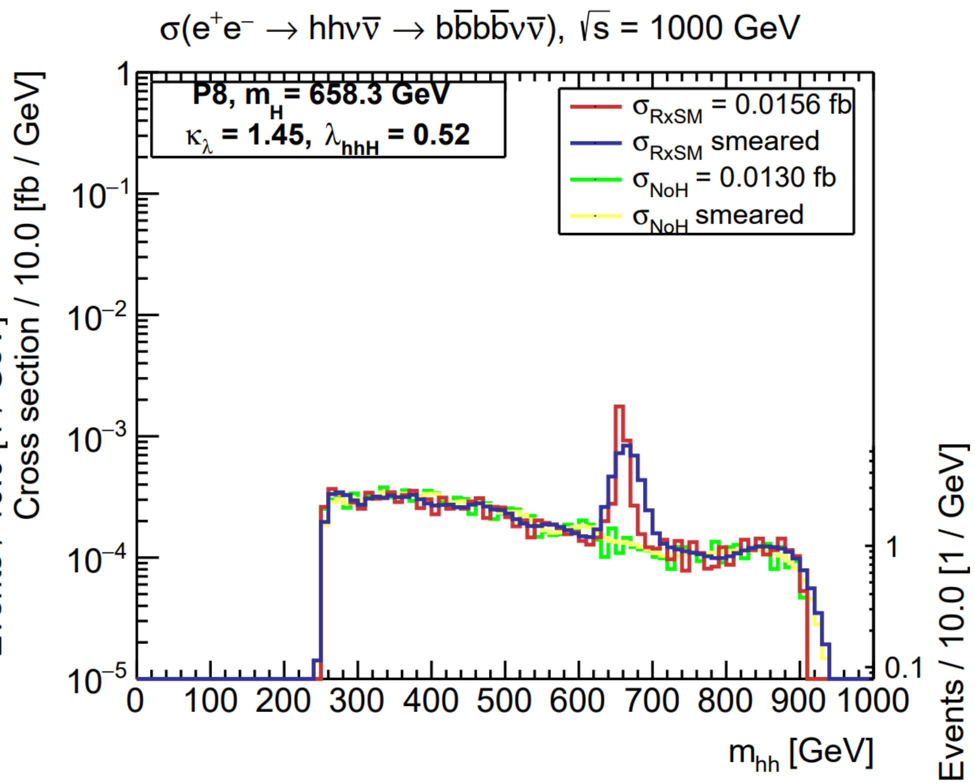
$$\bar{N}_{\nu\bar{\nu}4b} = N_{hh\nu\bar{\nu}} \times (\mathrm{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$$

Smearing

The **smearing** is an uncertainty due to the uncertainty in the experimental reconstruction of m_{hh}

- Each value of m_{hh} as a Gaussian centered in its value with a **FWHM** given by a percentage p of m_{hh}
- We consider the value $p = 5\%$ [6]





Significance of the resonance and sentisivity to λ_{hhH}

We obtain a value of the **statistical significance** of the resonance of H, called $\boldsymbol{Z}$. To do so, we follow [6]:

- With $\bar{N}_{\nu\bar{\nu}4b} = N_{hh\nu\bar{\nu}} \times (\mathrm{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$

- Obtain the next variables per bin

$$\begin{aligned} s_i &= \bar{N}_{i,\nu\bar{\nu}4b} - \bar{N}^C_{i,\nu\bar{\nu}4b} \\ b_i &= \bar{N}^C_{i,\nu\bar{\nu}4b} \ , \end{aligned} \quad , \quad Z_i = \sqrt{2\left((s_i + b_i)\log\left(1 + \frac{s_i}{b_i}\right) - s_i\right)}$$

($\bar{N}_{i,\nu\bar{\nu}4b}$ in RxSM and $\bar{N}^C_{i,\nu\bar{\nu}4b}$ in NoH)

- **Statistical significance** $\boldsymbol{Z} = \sqrt{\sum_i (Z_i)^2}$

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($\bar{N}_{i,\nu\bar{\nu}4b}$ in RxSM and $\bar{N}^C_{i,\nu\bar{\nu}4b}$ in NoH)

- **Statistical significance** $\boldsymbol{Z} = \sqrt{\sum_i (Z_i)^2}$

Points	m_H [GeV]	σ^{RxSM} [fb]	$\boldsymbol{Z}$	$\mathcal{A}$	$\mathcal{A} \times \epsilon_b$
P1	459.7	0.1567	**34.0**	63.3 %	53.9 %
P2	465.3	0.1475	31.9	63.6 %	54.0 %
P3	470.8	0.1344	29.4	63.4 %	54.0 %
P4	530.9	0.0920	18.4	61.8 %	52.5 %
P5	578.0	0.0750	13.7	61.0 %	51.9 %
P6	532.1	0.0948	19.6	62.2 %	52.9 %
P7	643.4	0.0592	7.50	60.0 %	51.0 %
P8	658.3	0.0571	**6.65**	59.5 %	50.6 %

To resolve the resonance, a experimental analysis is needed, $\boldsymbol{Z}$ is a theoretical significance

Conclusions

- We have introduce the **RxSM model** where a **SFOEWPT** takes place, a step to explain the **matter-antimatter asymmetry** in the universe

- We have studied the process $\boldsymbol{e^+e^- \to hh\nu\bar{\nu}}$ regarding future e^+e^- colliders such as the **ILC**

- We have obtained a **theoretical significance**, $\boldsymbol{Z}$, of the resonance of the new Higgs boson and a sensitivity of λ_{hhH}. To resolve the resonance, a experimental analysis is needed.

References

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[2] ATLAS Collaboration, Phys. Rev. Lett. 133, arXiv:2406.09971 [hep-ex], 101801 (2024).

[3] H.-L. Li, M. J. Ramsey-Musolf y S. Willocq, “Probing a scalar singlet-catalyzed electroweak phase transition with resonant di-Higgs boson production in the 4b channel”, Physical Review D 100, 10.1103/physrevd.100.075035, issn: 2470-0029 (2019) 10. 1103/physrevd.100.075035, http://dx.doi.org/10.1103/PhysRevD.100.075035.

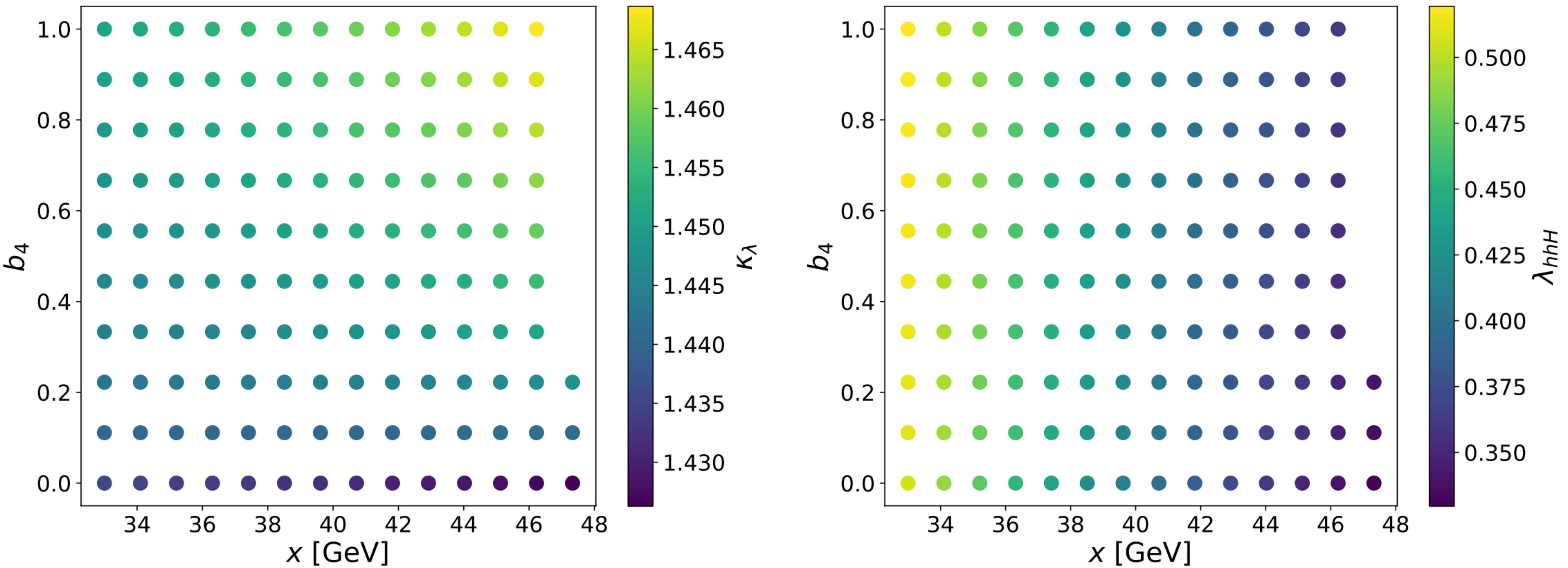
[4] A. V. Schaeidt y S. Heinemeyer, Di-higgs production in the rxsm at the hl-lhc, Trabajo de Fin de Master (IFT, UAM-CSIC), 2022.

[5] S. Catani, Y. L. Dokshitzer, M Olsson, G Turnock y B. R. Webber, “New clustering algorithm for multijet cross sections in e+ e- annihilation”, Physics Letters B 269, 432-438 (1991)

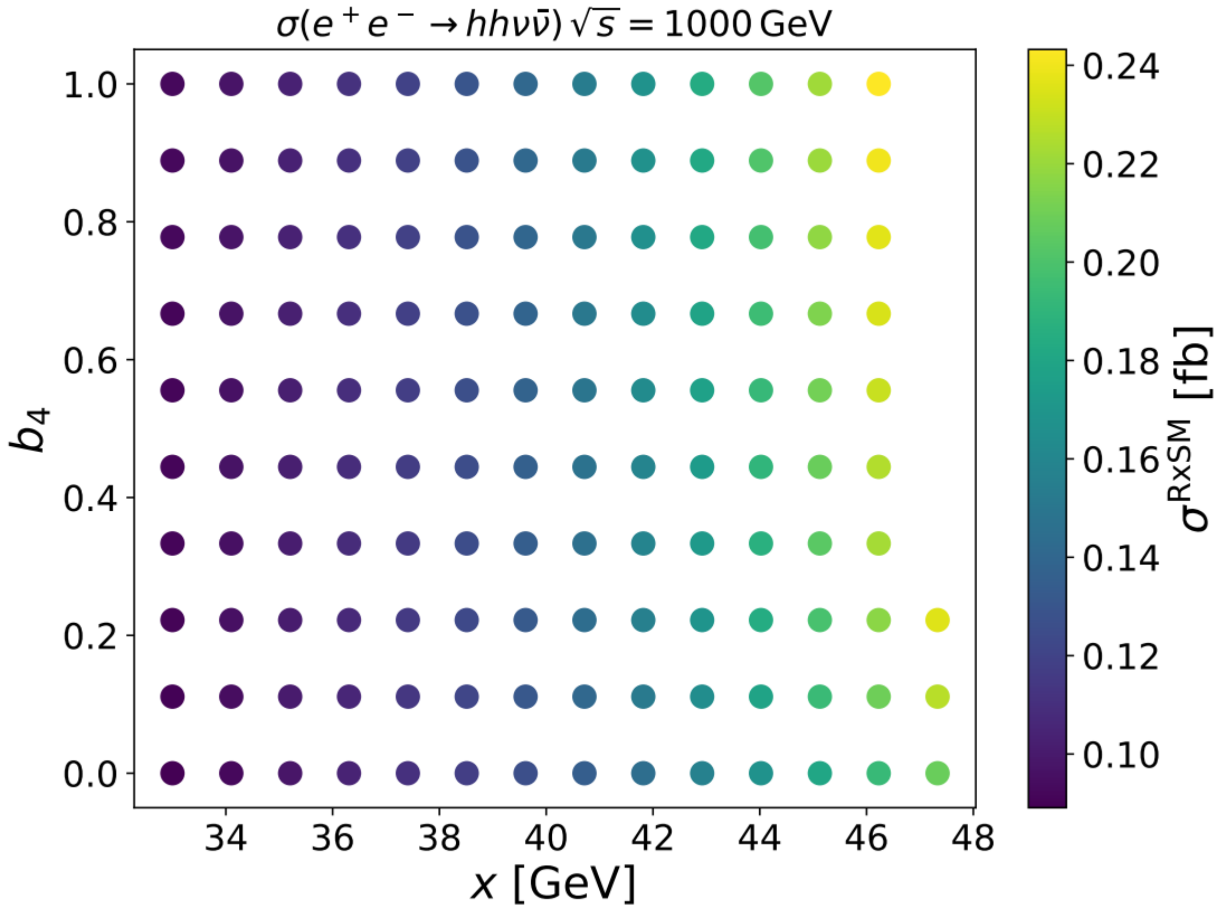
[6] F. Arco, S. Heinemeyer y M. M¨uhlleitner, “Large One-Loop Effects of BSM Triple Higgs Couplings on Double Higgs Production at e +e − Colliders”, (2025), arXiv:2505.02947 [hep-ph].

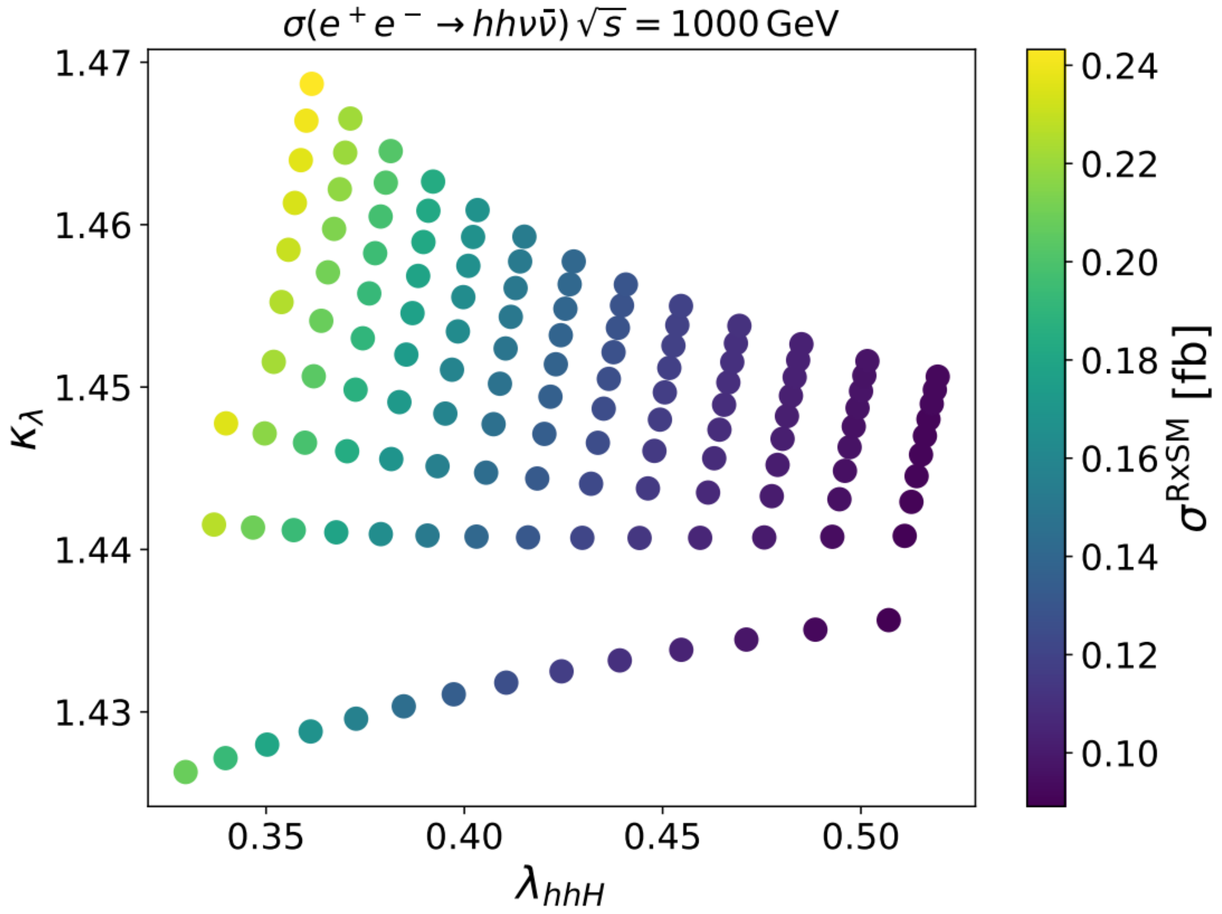
Extra

Benchmark Plane. The $x - b_4$ plane

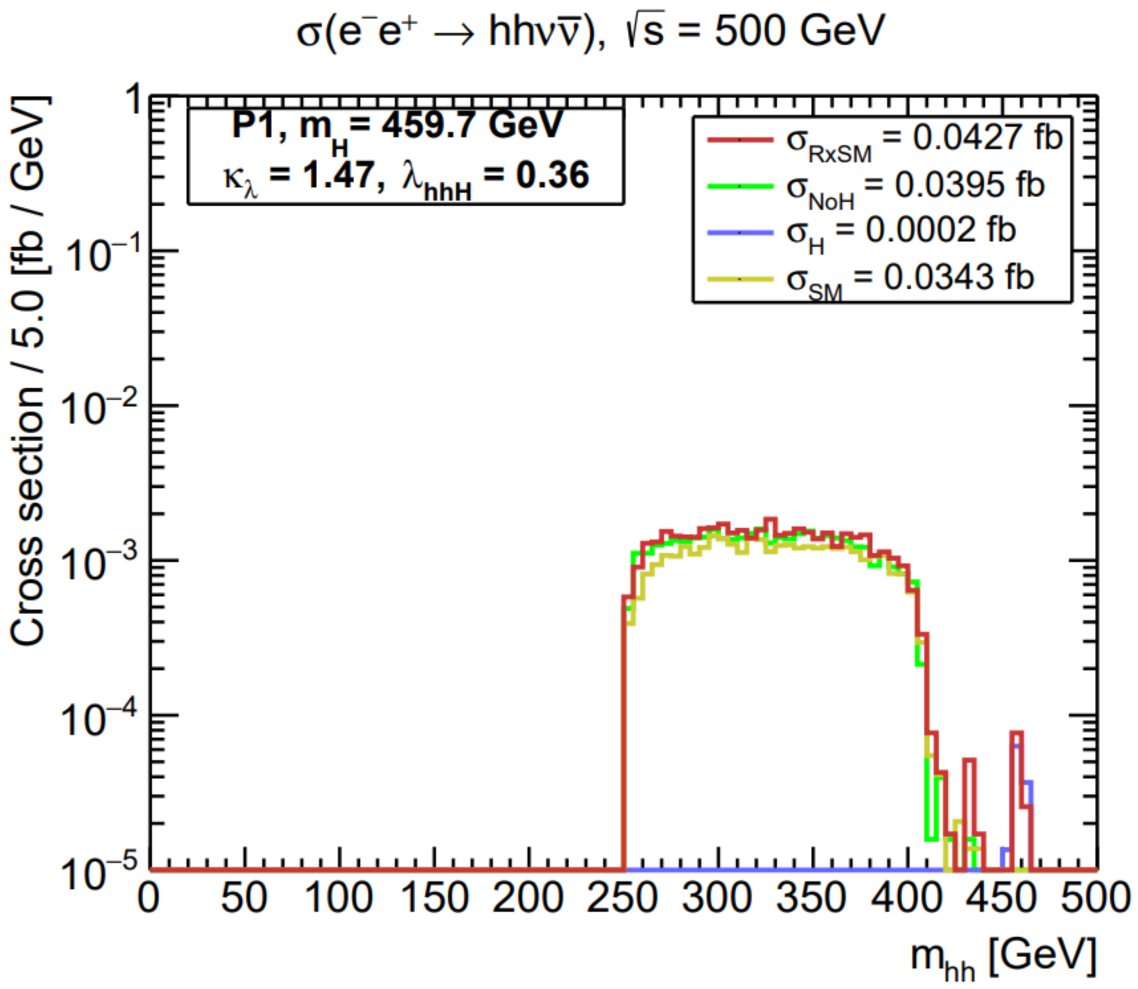


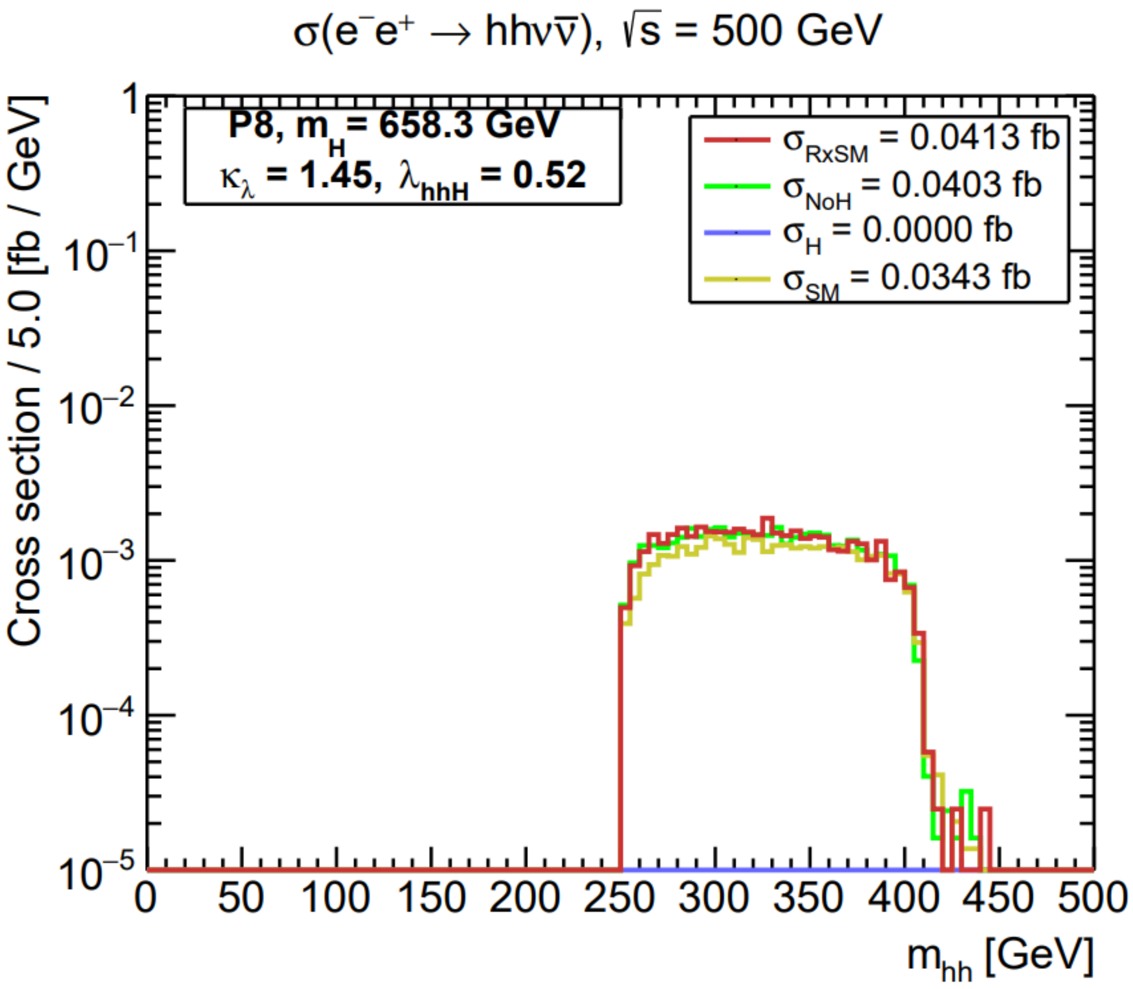
Benchmark Plane. Cross Sections



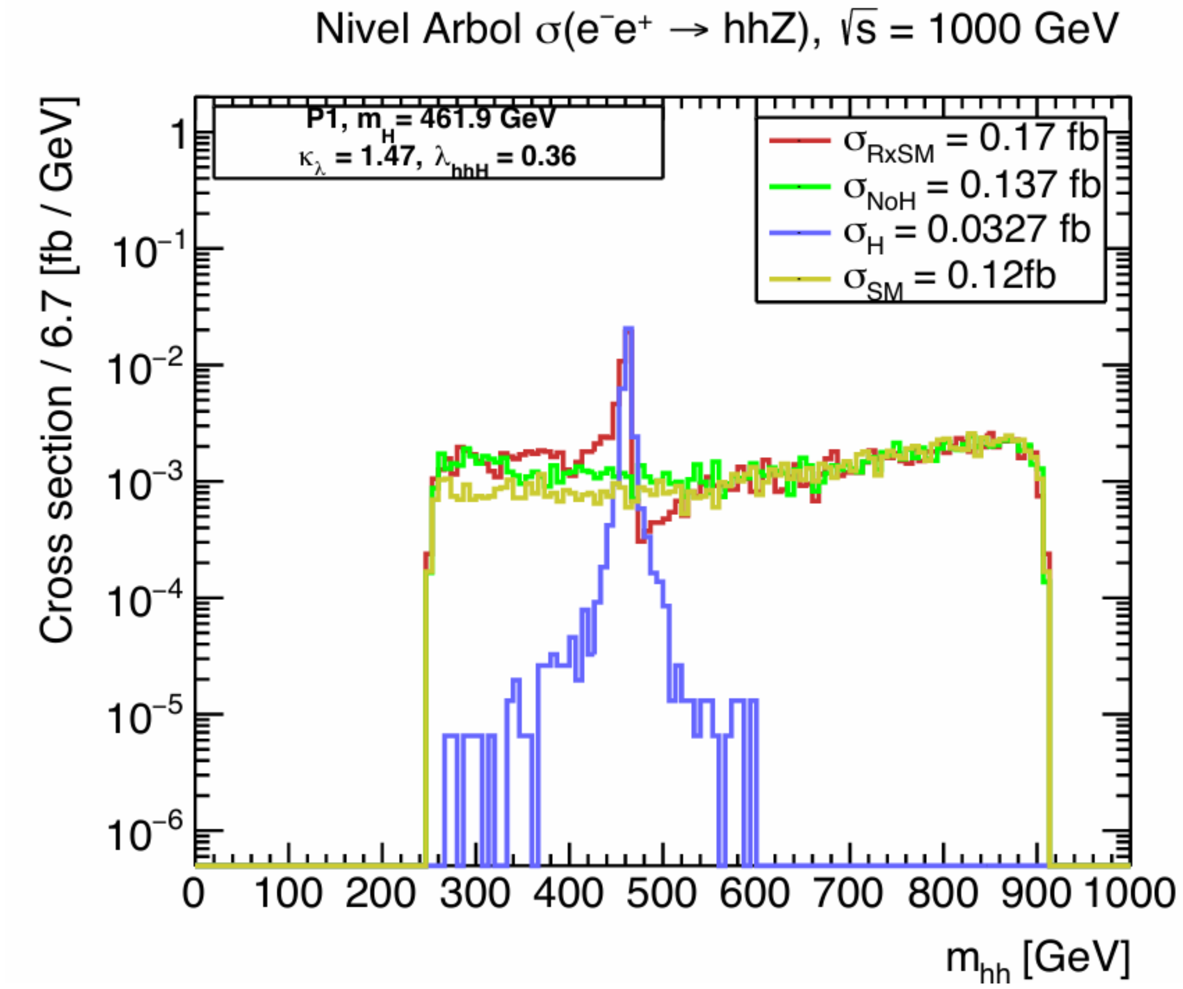


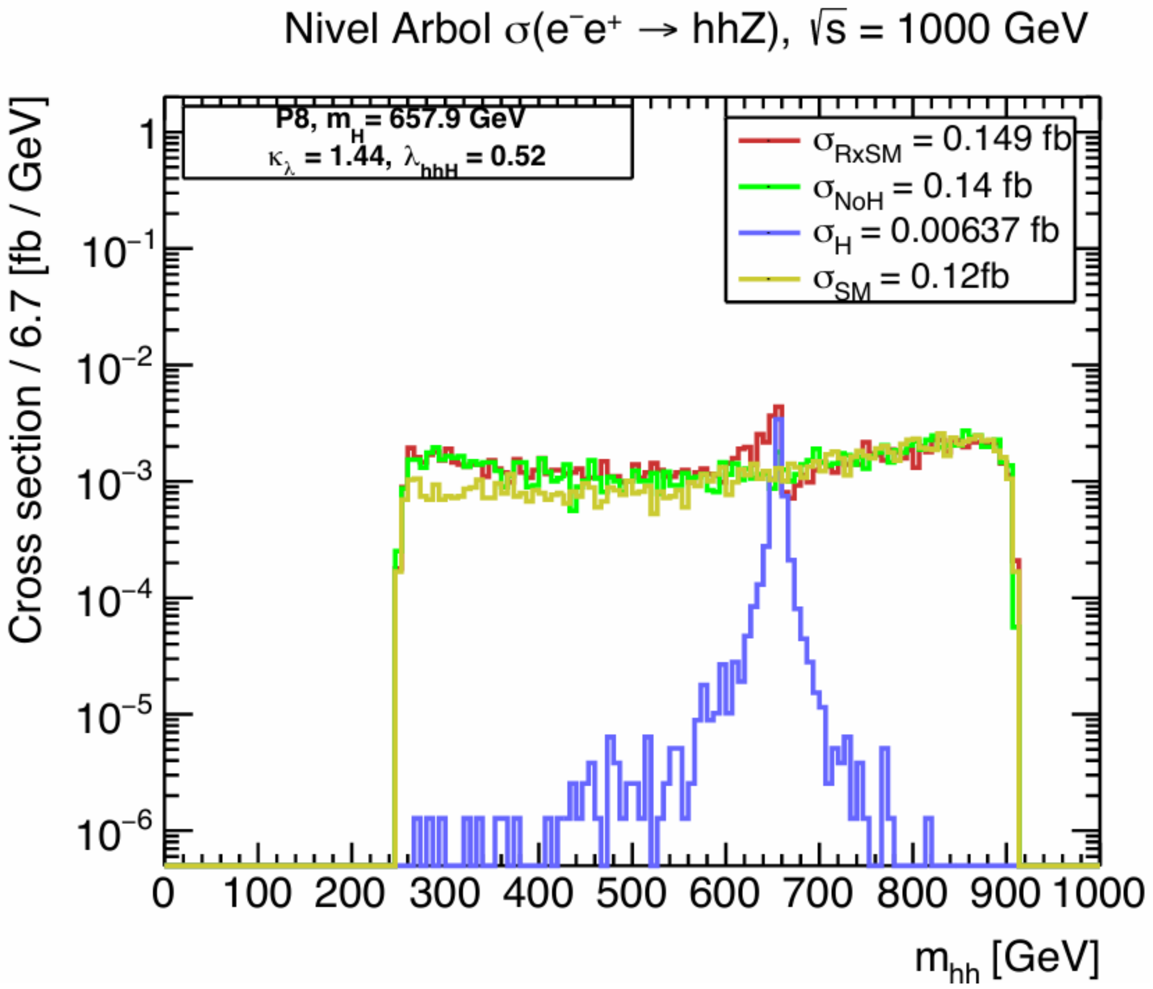
Distributions m_{hh}, $\sqrt{s} = 500$ GeV





Distribucions m_{hh} in hhZ channel, $\sqrt{s} = 1000$ GeV





Via: Andrea Parra Arnay. Producción de dos bosones de Higgs con Correcciones Cuánticas. Trabajo de Fin de Grado. (UAM) 2024