RxSM model with SFOEWPT. Di-Higgs production in e^+e^- colliders at one loop

DESY Summer Student Programme

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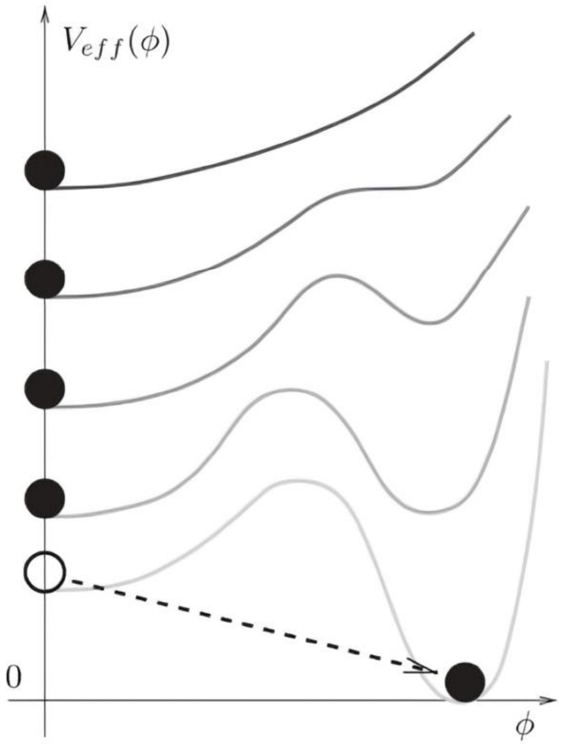
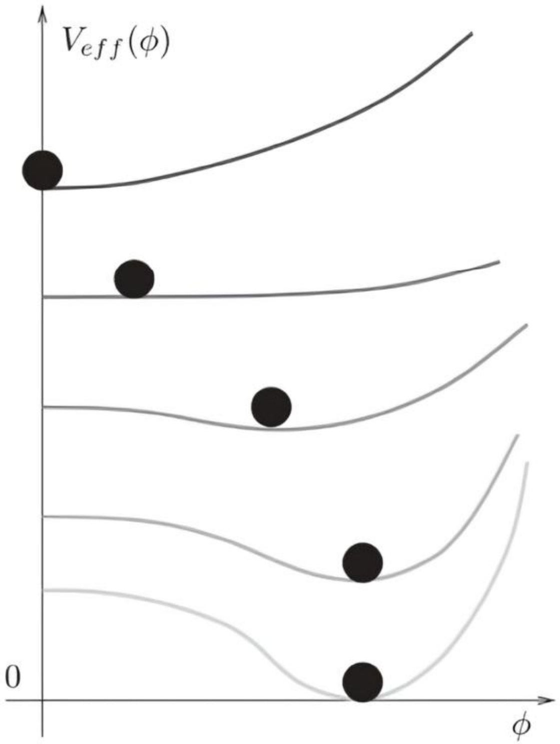
Motivation: Matter-Antimatter Asymmetry

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

RxSM. SFOEWPT



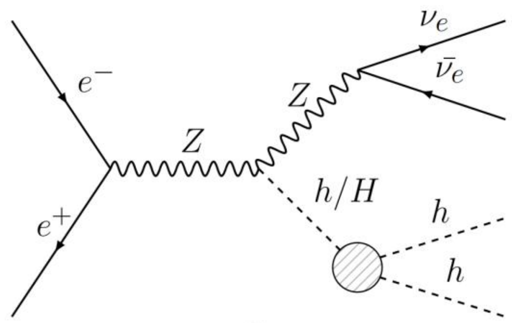
SM

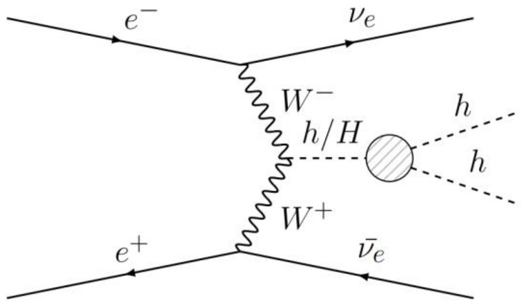


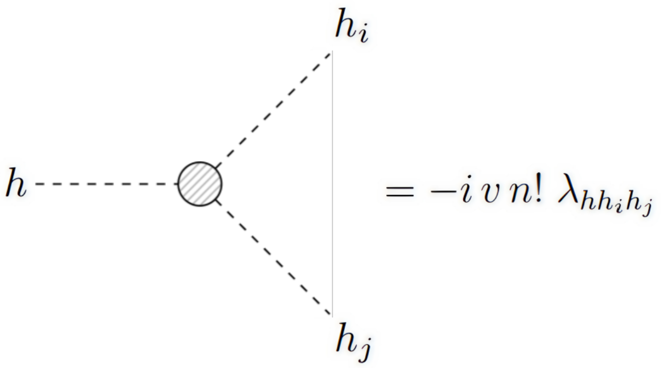
- Proposal: **Electroweak Baryogenesis**
- **Sakharov conditions**: Process out of termal equilibrium
- **Strong First Order ElectroWeak Phase Transition (SFOEWPT)**
- **RxSM Model**, a BSM model where: SM + a new Higgs singlet, i. e., a new Higgs boson, H

Goals

- Study of the **RxSM model** with a **SFOEWPT**
- Analysis of e^+e^- channels with **Triple Higgs Couplings (THC's)** in future e^+e^- colliders at $\sqrt{s} = 1$ **TeV**, e.g. **International Linear Collider (ILC), ILC1000:**
  - $\boldsymbol{e^+e^- \to Zhh}$
  - $\boldsymbol{e^+e^- \to \nu\bar{\nu}hh}$
- Corrections at **one loop (1L)** will be considered
- Behaviour of the **THC's**
- Implementing other models: the **CxSM model**







RxSM model, addition of a real singlet

Apart from the existent SM Higgs doublet, H, we add a real singlet, S,

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^+ \\ v + \phi + i\, G^0 \end{pmatrix}, \qquad S = s + v_S,$$

The Higgs potential is modified,

$$V^{(0)}(\Phi, S) = \underbrace{\mu^2 |\Phi|^2 + \frac{\lambda}{2} |\Phi|^4}_{\text{SM-like}} + \kappa_{SH} |\Phi|^2 S + \frac{\lambda_{SH}}{2} |\Phi|^2 S^2 + \frac{M_S^2}{2} S^2 + \frac{\kappa_S}{3} S^3 + \frac{\lambda_S}{2} S^4$$

Mass basis: h is the 125 GeV Higgs boson and H is a heavier Higgs boson with $m_H \geq 2m_h$

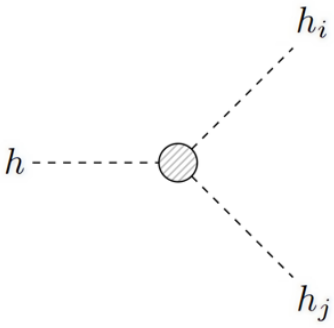
$$\begin{pmatrix} \phi \\ s \end{pmatrix} = R_\alpha \begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

Mass parameter basis:

$$m_h^2,\, m_H^2,\, \alpha,\, v,\, v_S,\, \kappa_S,\, \kappa_{SH}$$

Triple Higgs Couplings (THC's):

$$\lambda_{hhh}, \quad \lambda_{hhH}, \quad \lambda_{hHH}, \quad \lambda_{HHH}$$



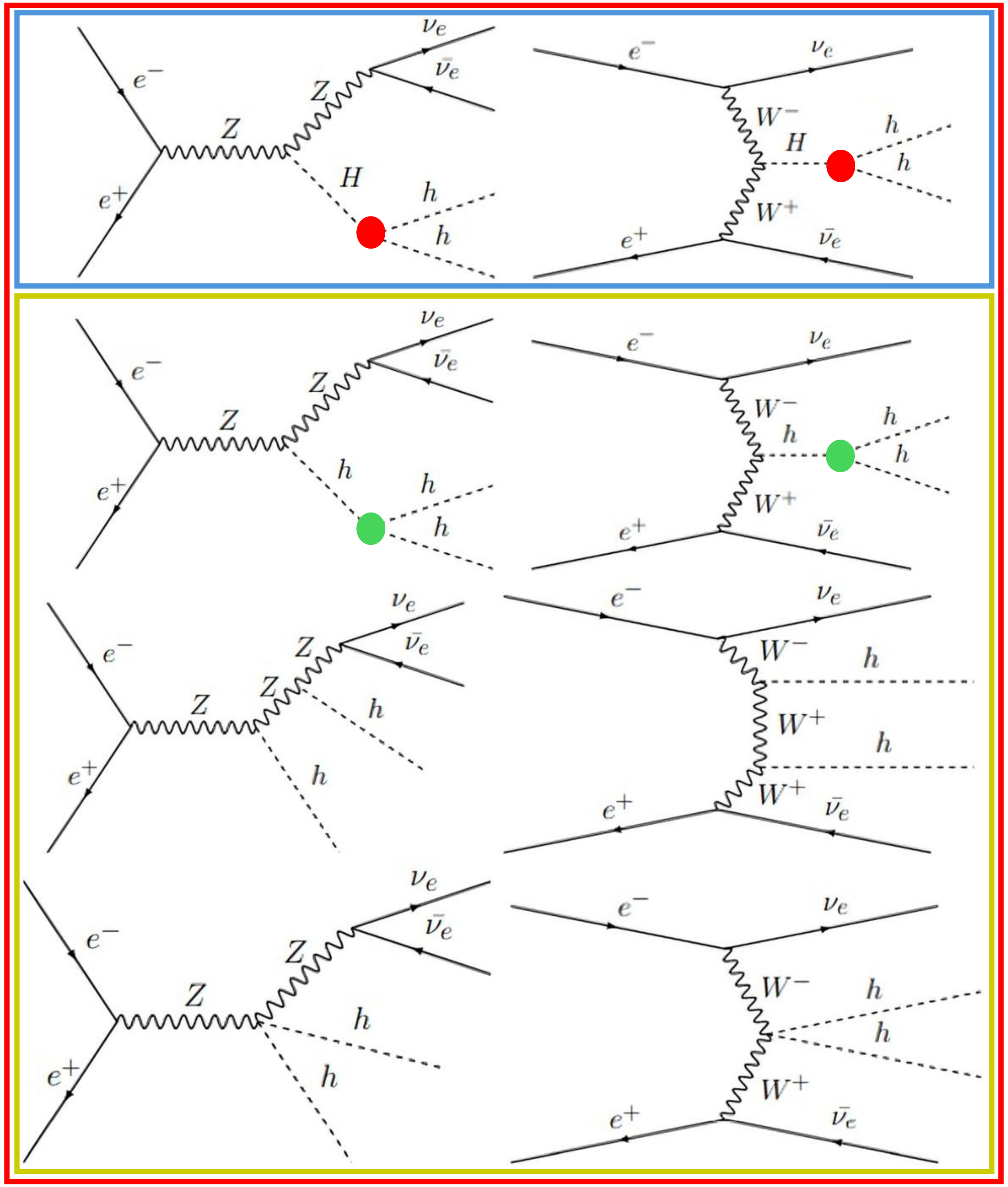
$$= -i\, v\, n!\, \lambda_{hh_ih_j}$$

Di-Higgs production

- Two channels:
  - e+e- $e^+e^- \to Zhh$
  - $e^+e^- \to \nu\bar{\nu}hh$

- We obtain histograms of the cross sections as function of m_{hh} at $\sqrt{s} = 1$ **TeV** including **1L** corrections.
  - RxSM
  - H
  - SM

- We obtain a **statistical significance** of the **RxSM** differential cross section with respect to the **SM** at a luminosity of $L = 8\ \mathrm{ab}^{-1}$



Benchmark Plane. Cross-section $\sigma(e^+e^- \to Zhh)$

We use a benchmark plane defined to maximise the strength of the **SFOEWPT,** which is given by:

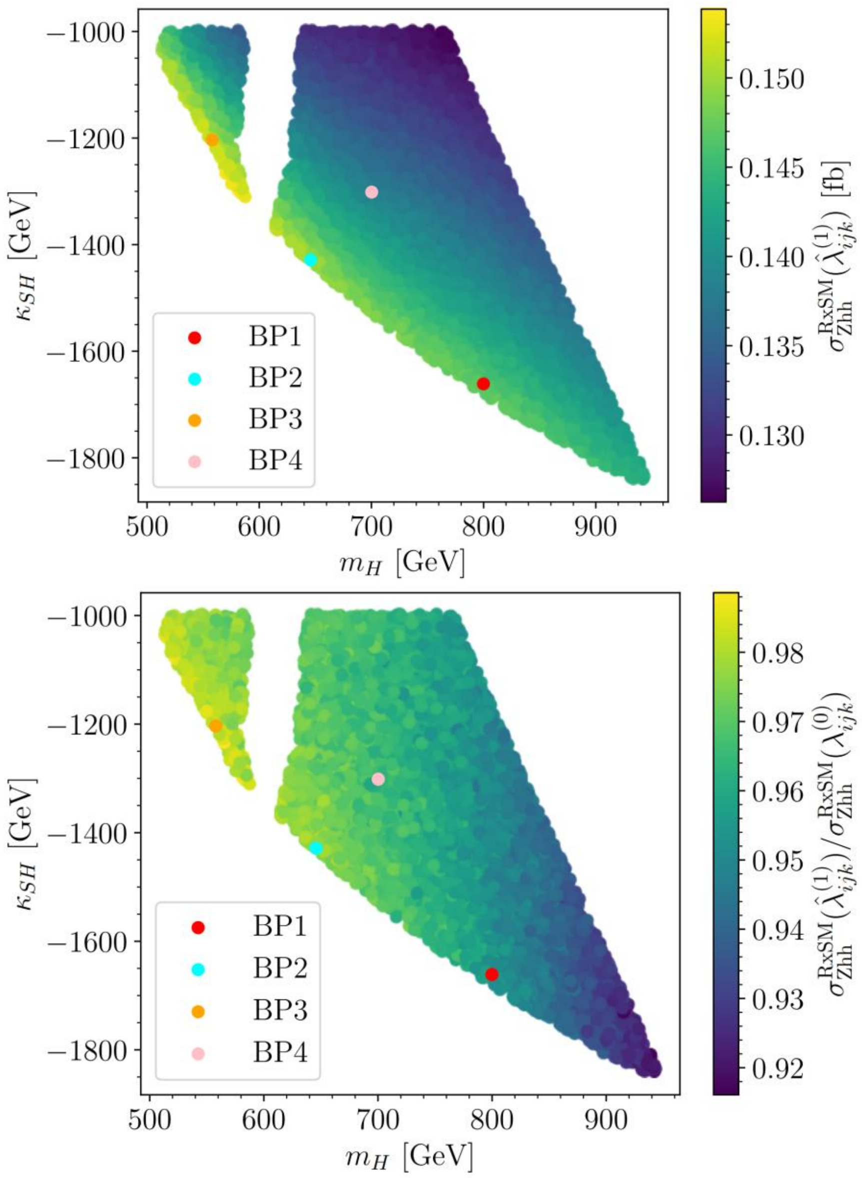
$$\cos\alpha = 0.98\,, \quad \kappa_S = -300\ \text{GeV}\,, \quad v_S = 280\ \text{GeV}\,.$$

Free parameters:

$$\kappa_{SH},\ m_H$$

We define 4 BP where we study the cross-sections in e^+e^- in this plane

BP	m_H [GeV]	$\cos\alpha$	v_S [GeV]	κ_S [GeV]	κ_{SH} [GeV]	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$ [GeV]	$\hat{\lambda}_{hhH}^{(1)}$ [GeV]
1	800	0.98	280	−300	−1601	1.8	1.7	72.1	38.6
2	646	0.98	280	−300	−1429	1.7	1.6	143.9	129.8
3	558	0.98	280	−300	−1204	1.6	1.5	145.0	137.4
4	700	0.98	280	−300	−1301	1.6	1.5	61.5	40.0



Cross-sections in e^+e^- colliders

- **Cuts in e^+e^- colliders (ILC1000) [1]:**

$e^+e^- \to Zhh \to Zb\bar{b}b\bar{b}$	$e^+e^- \to \nu\bar{\nu}hh \to \nu\bar{\nu}b\bar{b}b\bar{b}$
$E_b > 20$ GeV, $\lvert\eta_Z\rvert < 2.5$, $\lvert\eta_b\rvert < 2.5$, $y_{bb} > 0.001$	$E_b > 20$ GeV, $E_T^{\text{miss}} > 30$ GeV, $\lvert\eta_b\rvert < 2.5$, $y_{bb} > 0.001$

- **Acceptance:** $\mathcal{A} = \dfrac{N^{\text{w/ cuts}}}{N^{\text{w/o cuts}}}$

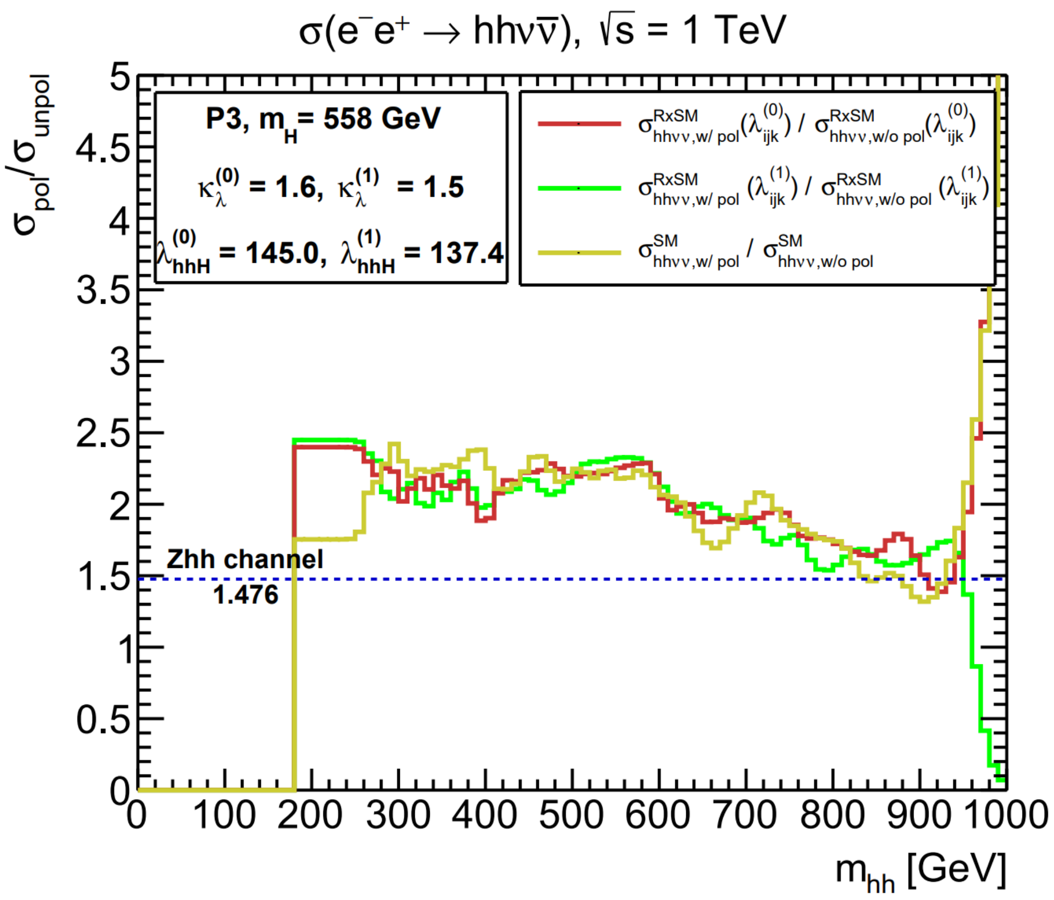
- **Efficiency of b-tagged jets:** $\epsilon_b = 0.85$ [1]

- **Smearing:** 5%[1]

- **Polarization:**

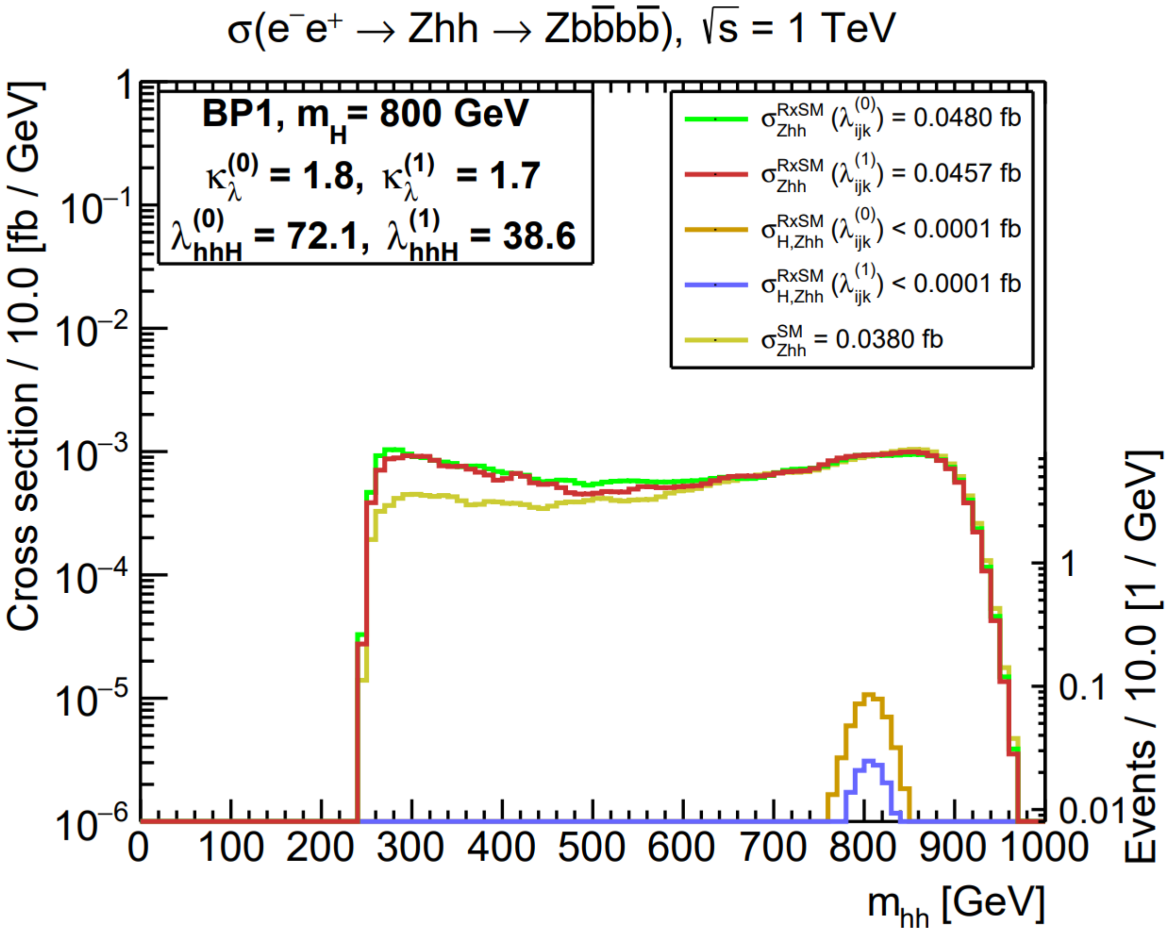
Zhh channel	$\nu\bar{\nu}hh$ channel
$\sigma_{pol} \approx 1.476\sigma_{unpol}$[1]	Madgraph5_aMC v3.5.9⟶ $\sim 1.5 - 2.5$

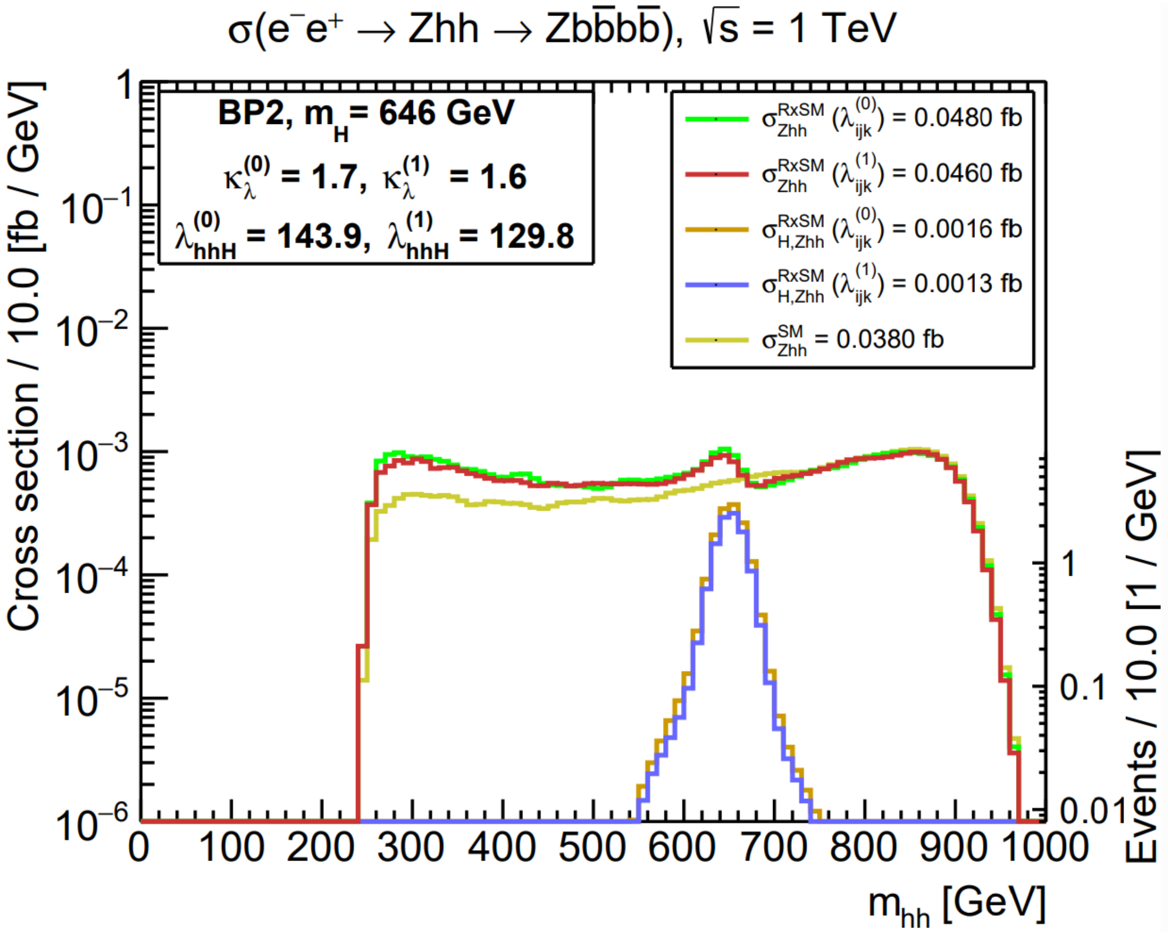
- $N_{4b} = N_{hh} \times (\text{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$



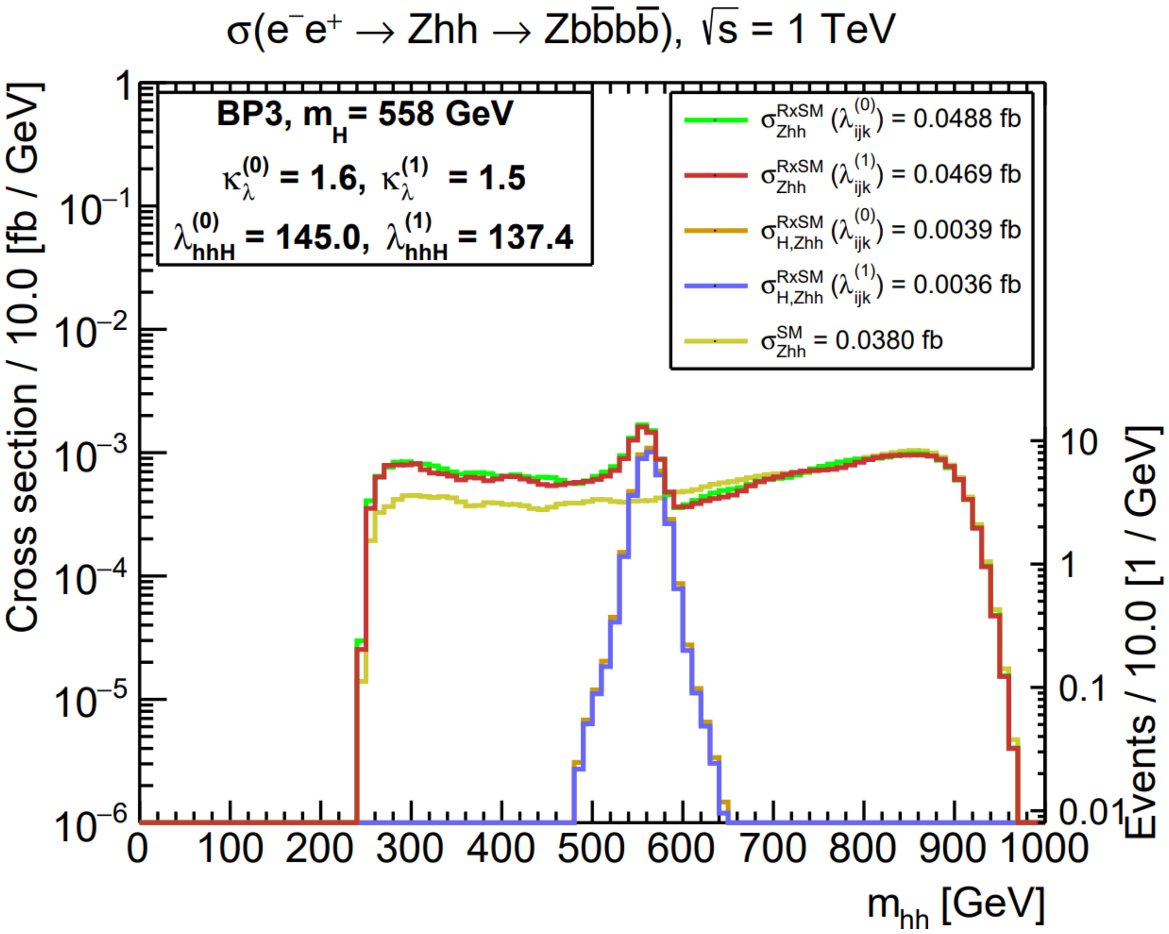
[1] 2505.02947

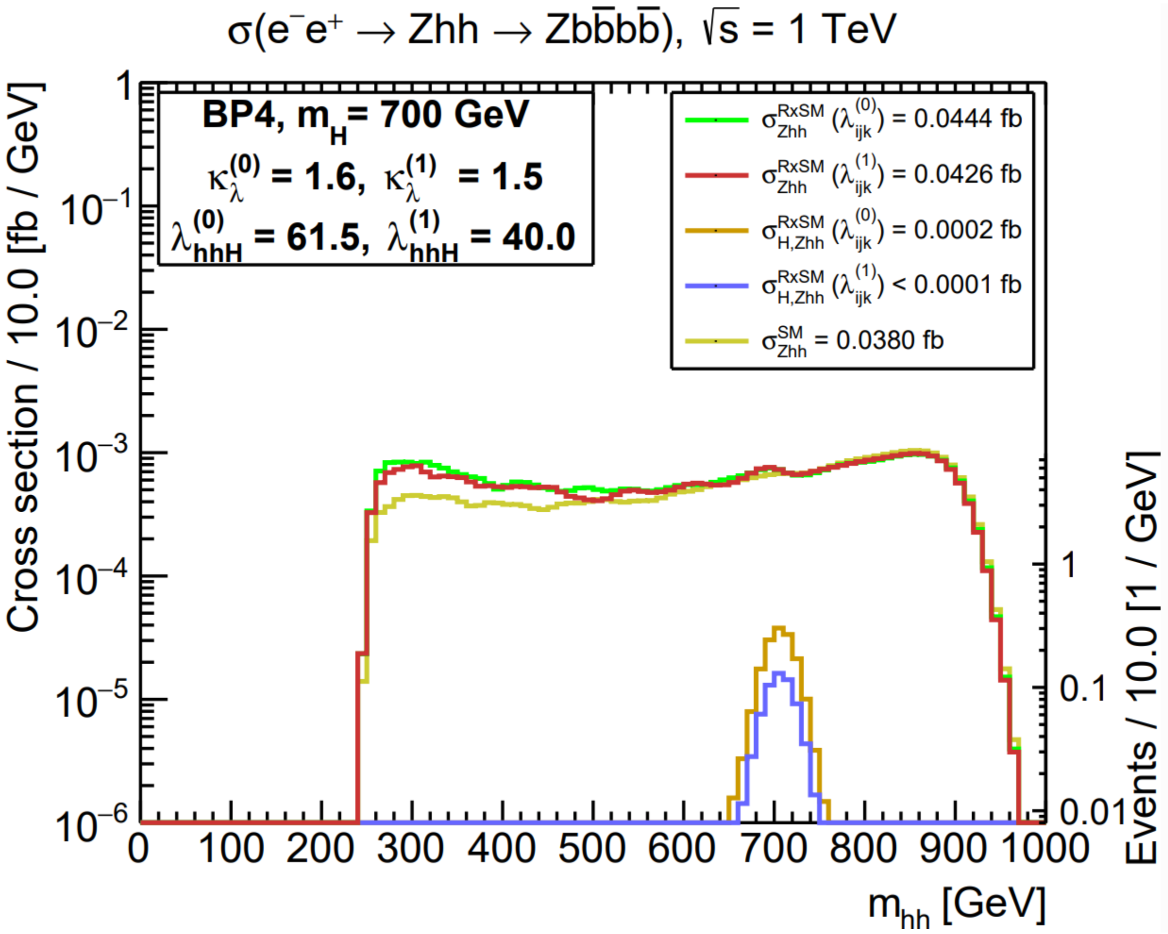
m_{hh} distributions in $e^+e^- \to Zhh \to Zb\bar{b}b\bar{b}$



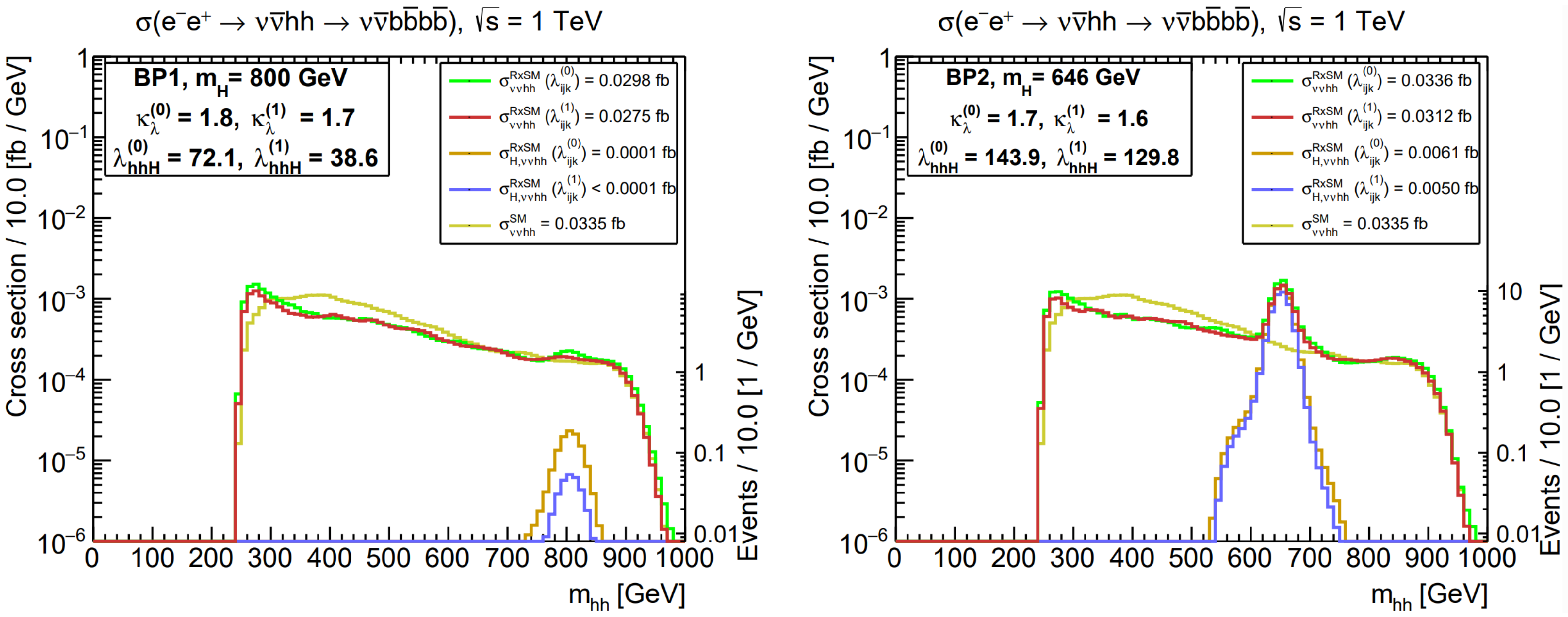


m_{hh} distributions in $e^+e^- \to Zhh \to Zb\bar{b}b\bar{b}$

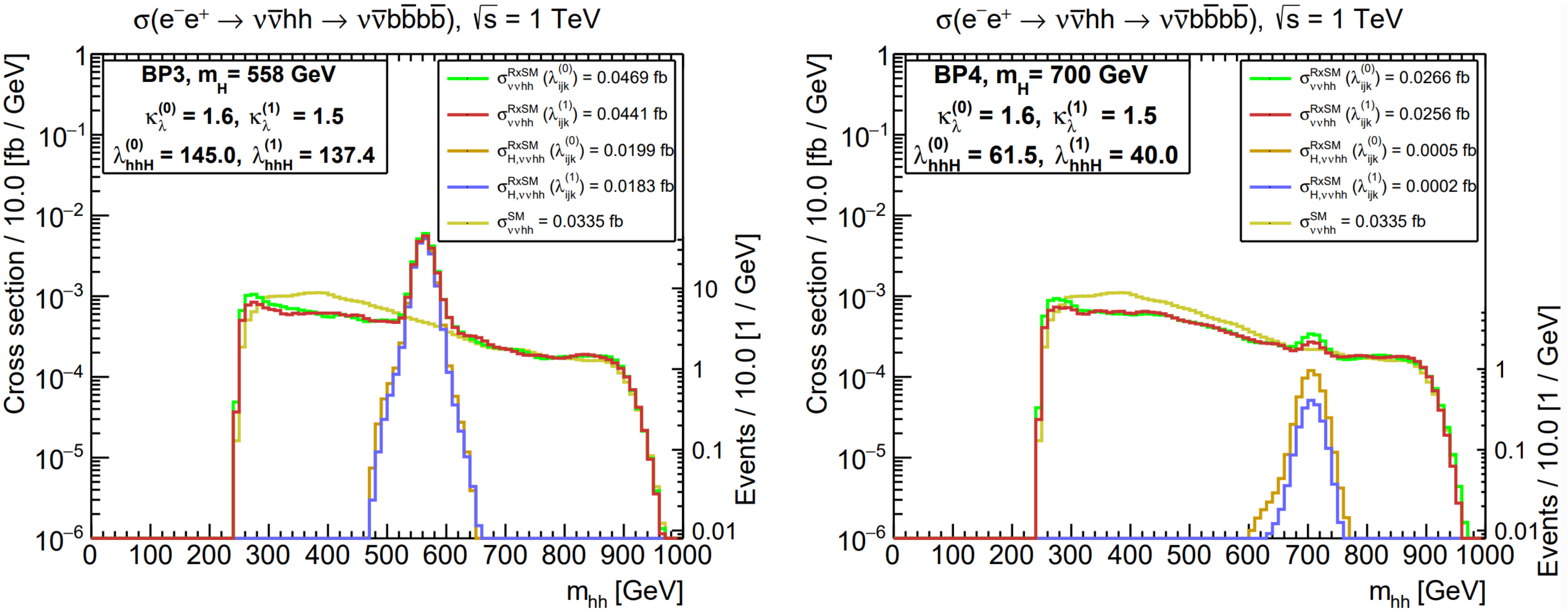




m_{hh} distributions in $e^+e^- \to \nu\bar{\nu}hh \to \nu\bar{\nu}b\bar{b}b\bar{b}$



m_{hh} distributions in $e^+e^- \to \nu\bar{\nu}hh \to \nu\bar{\nu}b\bar{b}b\bar{b}$



Significance of the RxSM differential cross-section

Statistical significance of the RxSM with respect to the SM, called $\boldsymbol{Z}$ [1]:

- With $N_{4b} = N_{hh} \times (\mathrm{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$ at $L = 8\ \mathrm{ab}^{-1}$

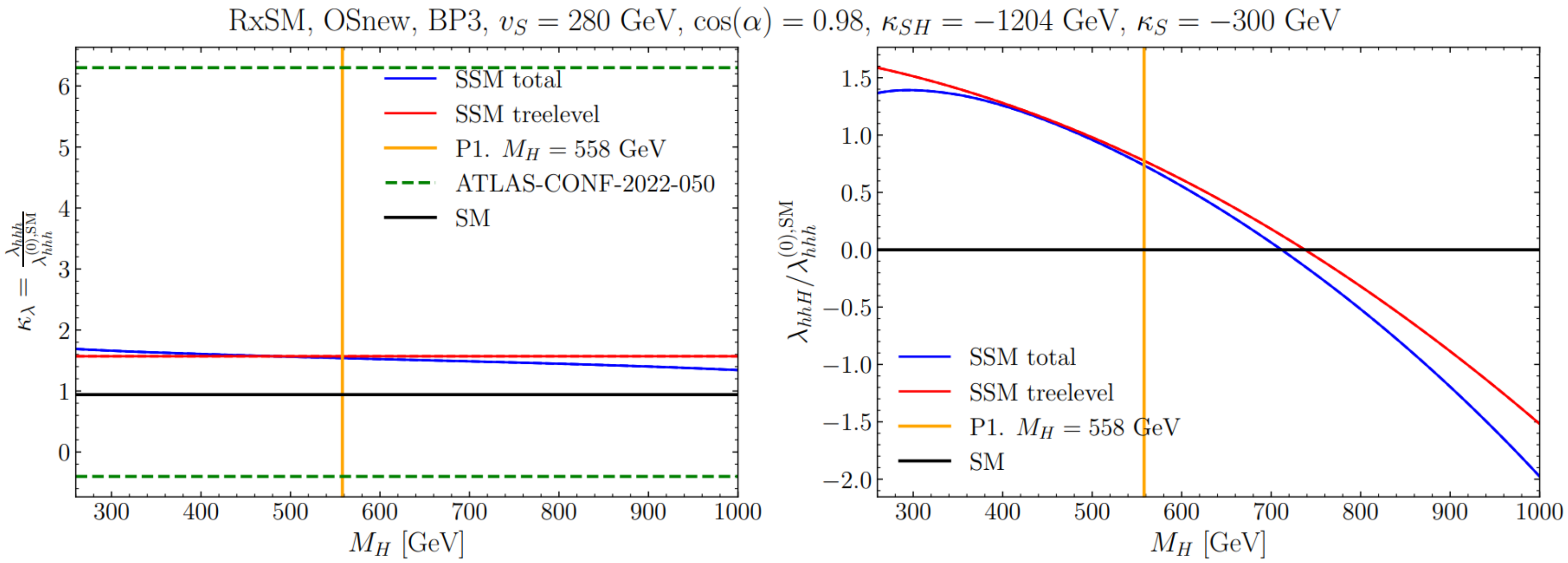
$$\boldsymbol{Z} = \sqrt{\sum_i (Z_i)^2}$$

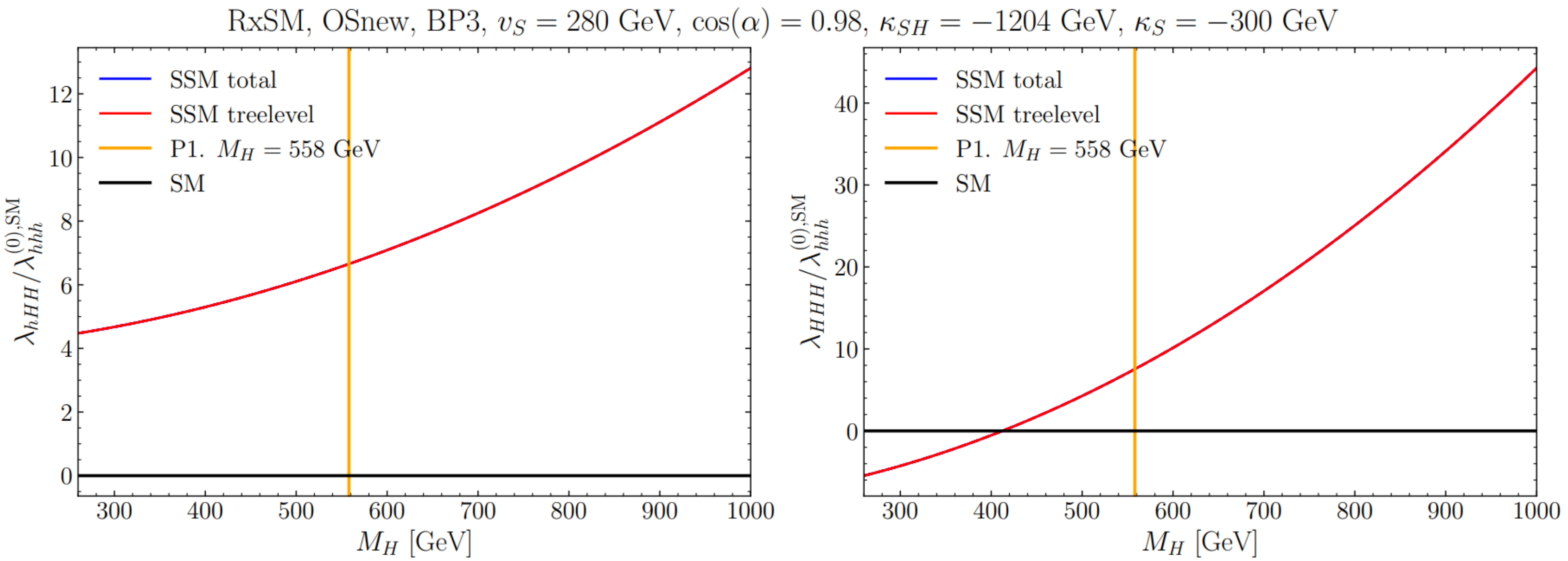
Points	$\sigma^{\mathrm{RxSM}}_{Zhh}(\lambda^{(0)}_{ijk})$ [fb]	$\sigma^{\mathrm{RxSM}}_{Zhh}(\lambda^{(1)}_{ijk})$ [fb]	$Z^{(0)}_{Zhh}$	$Z^{(1)}_{Zhh}$	$\mathcal{A}^{(0)}_{Zhh} \times \epsilon_b$	$\mathcal{A}^{(1)}_{Zhh} \times \epsilon_b$
BP1	0.0480	0.0457	7.59	6.33	63.4%	63.2%
BP2	0.0480	0.0460	7.64	6.25	63.2%	63.2%
BP3	0.0488	0.0469	9.49	8.81	63.4%	63.6%
BP4	0.0444	0.0426	5.53	4.29	63.2%	63.2%

Points	$\sigma^{\mathrm{RxSM}}_{\nu\nu hh}(\lambda^{(0)}_{ijk})$ [fb]	$\sigma^{\mathrm{RxSM}}_{\nu\nu hh}(\lambda^{(1)}_{ijk})$ [fb]	$Z^{(0)}_{\nu\nu hh}$	$Z^{(1)}_{\nu\nu hh}$	$\mathcal{A}^{(0)}_{\nu\nu hh} \times \epsilon_b$	$\mathcal{A}^{(1)}_{\nu\nu hh} \times \epsilon_b$
BP1	0.0298	0.0275	6.44	5.94	52.4%	51.3%
BP2	0.0336	0.0312	9.78	8.77	51.7%	51.3%
BP3	0.0469	0.0441	21.49	20.33	52.2%	51.8%
BP4	0.0266	0.0256	5.55	5.23	50.7%	49.8%

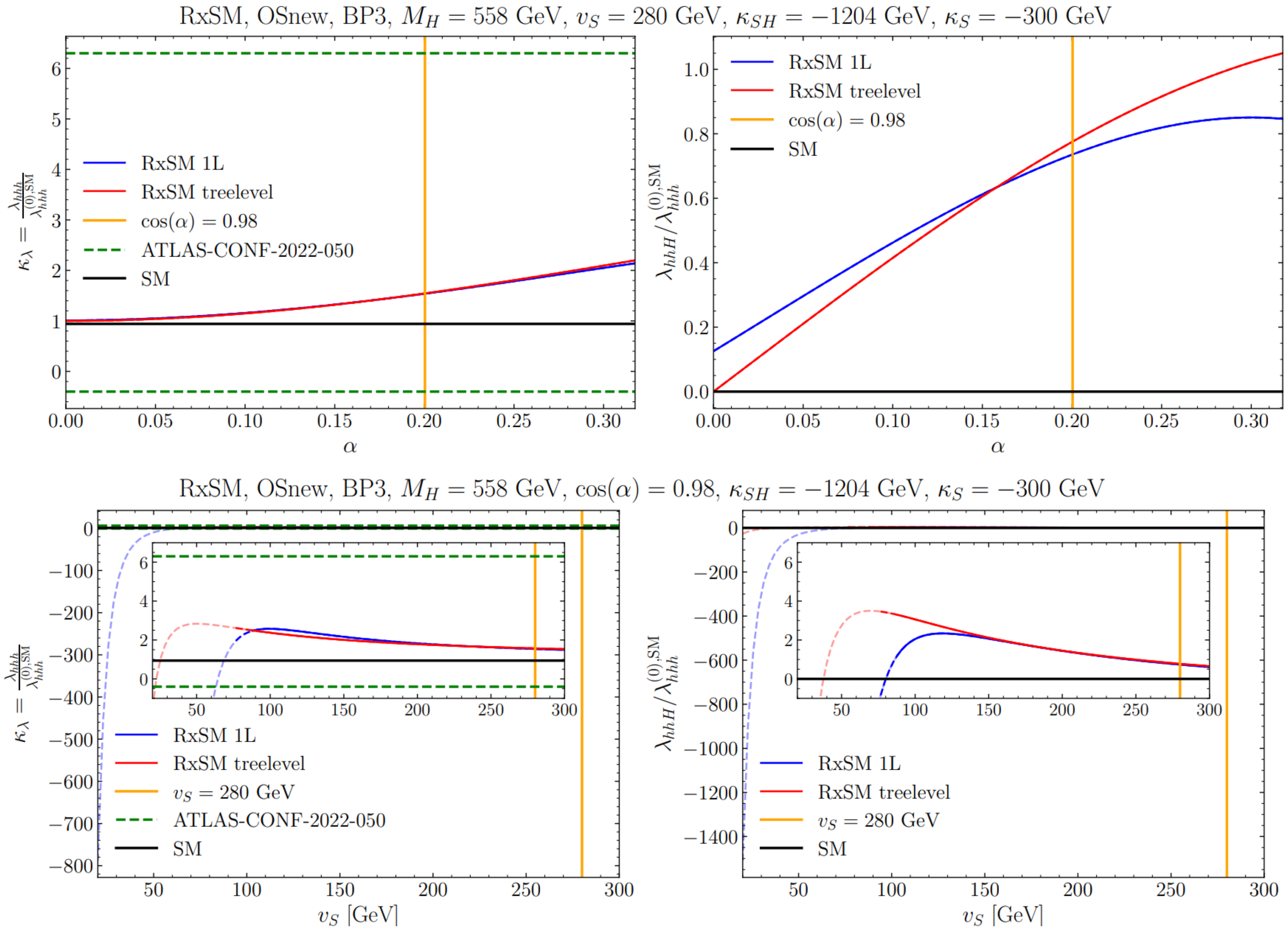
[1] 2505.02947

THC's in the RxSM

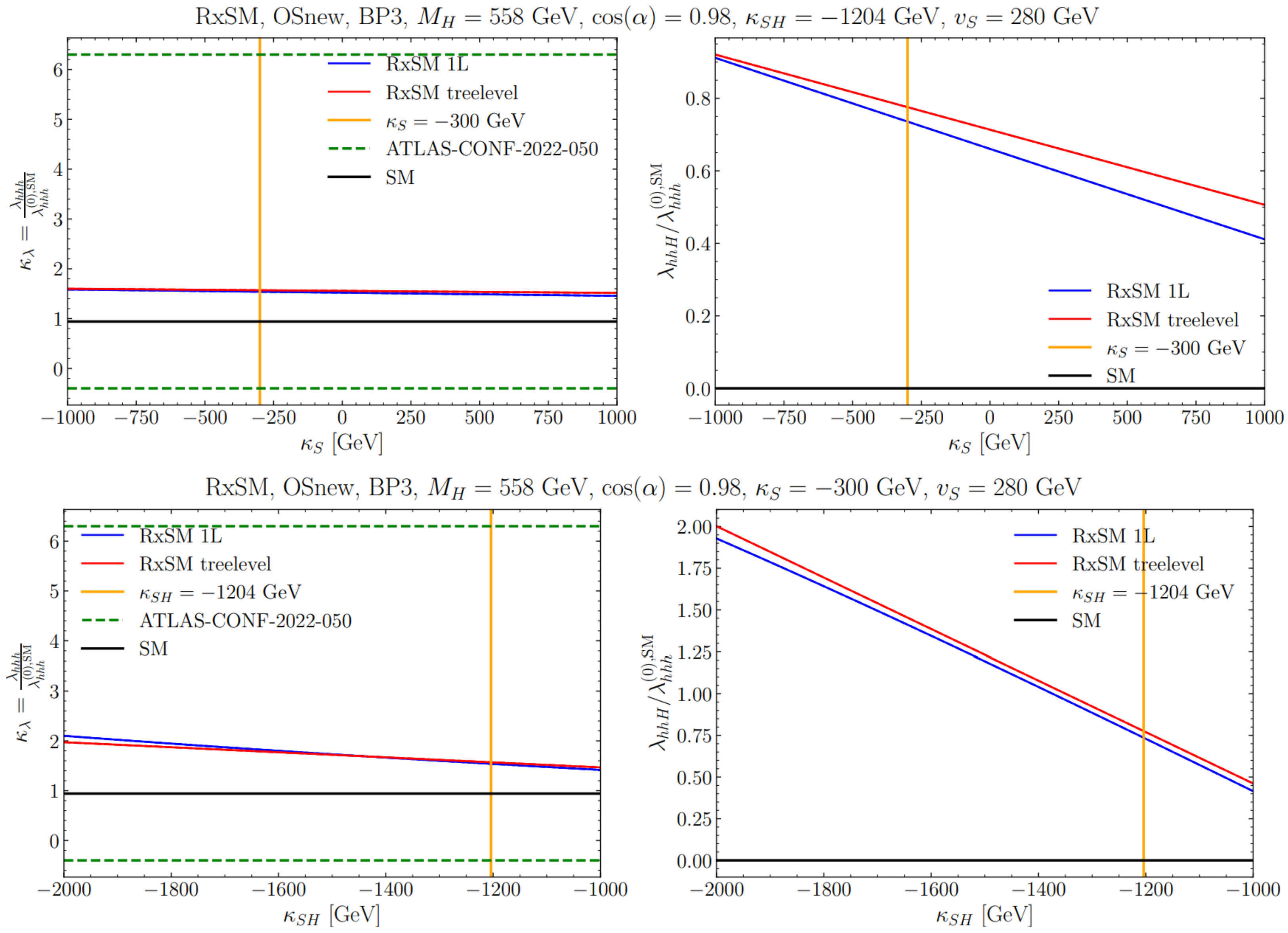




THC's in the RxSM



THC's in the RxSM



Other singlet extensions: The CxSM model

In the **CxSM** model a complex singlet, S, is added, apart from the SM Higgs doublet, H

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^+ \\ v + \phi + i\, G^0 \end{pmatrix}, \qquad S = \frac{1}{\sqrt{2}}(s + v_S + iA),$$

We consider a model with a global $U(1)$ symmetry in S softly broken and a Z_2 symmetry in A

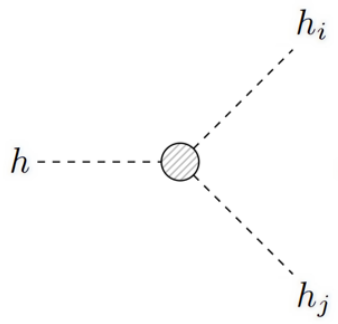
$$V(\Phi, S) = \underbrace{\frac{m^2}{2}\,\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2}_{\text{SM-like}} + \frac{\delta_2}{2}\,\Phi^\dagger\Phi\,|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(\frac{b_1}{4}S^2 + a_1 S + \text{c.c.}\right)$$

Mixing between the ϕ and S fields:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix}$$

Mass parameter basis:

$$m_h^2,\; m_H^2,\; m_A^2,\; \alpha,\; v,\; v_S,\; a_1$$



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

Triple Higgs Couplings (THC's):

$$\lambda_{hhh},\; \lambda_{hhH},\; \lambda_{hHH},\; \lambda_{HHH},\; \lambda_{hAA},\; \lambda_{HAA},$$

SFOEWPT? A as **DM**?...

An implementation of this model was made in `SARAH` (use in programs like `anyBSM`)

Other singlet extensions: The other CxSM model

However… due to technical problems, in these results another version of the **CxSM** model was used:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\,G^+ \\ v+\phi+i\,G^0 \end{pmatrix}, \qquad S = \frac{1}{\sqrt{2}}(s+iA),$$

We consider a model with a Z_2 symmetry in S

$$V(\Phi,S) = \underbrace{\frac{m^2}{2}\,\Phi^\dagger\Phi + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2}_{\text{SM-like}} + \frac{\delta_2}{2}\,\Phi^\dagger\Phi\,|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4,$$

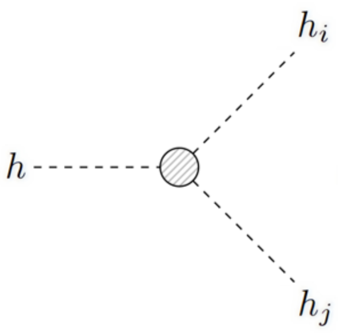
There is no mixing between the fields: S^+ and S^- are particle and antiparticle and are charged

Mass parameter basis:

$$m_h^2,\ m_s^2,\ v,\ d_2,\ \delta_2$$

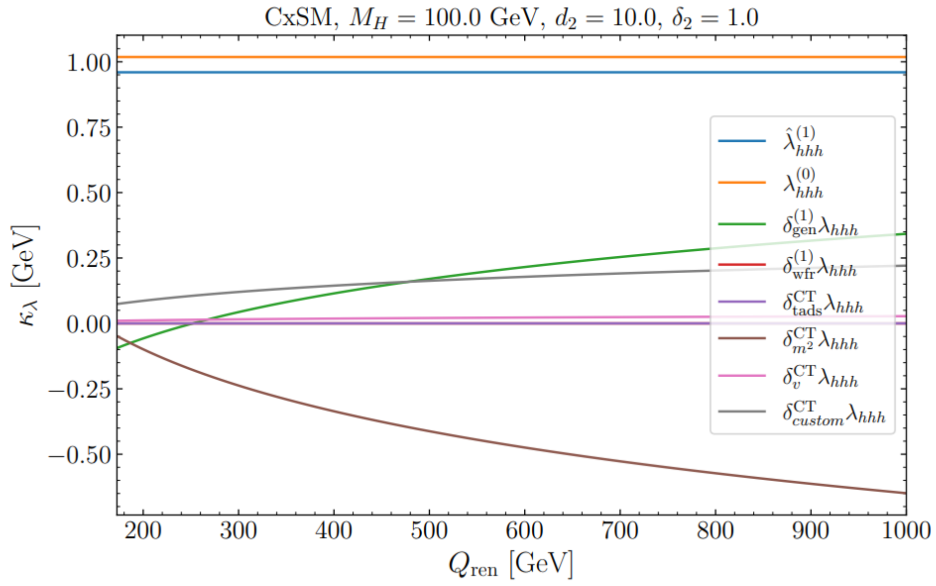
Triple Higgs Couplings (THC's):

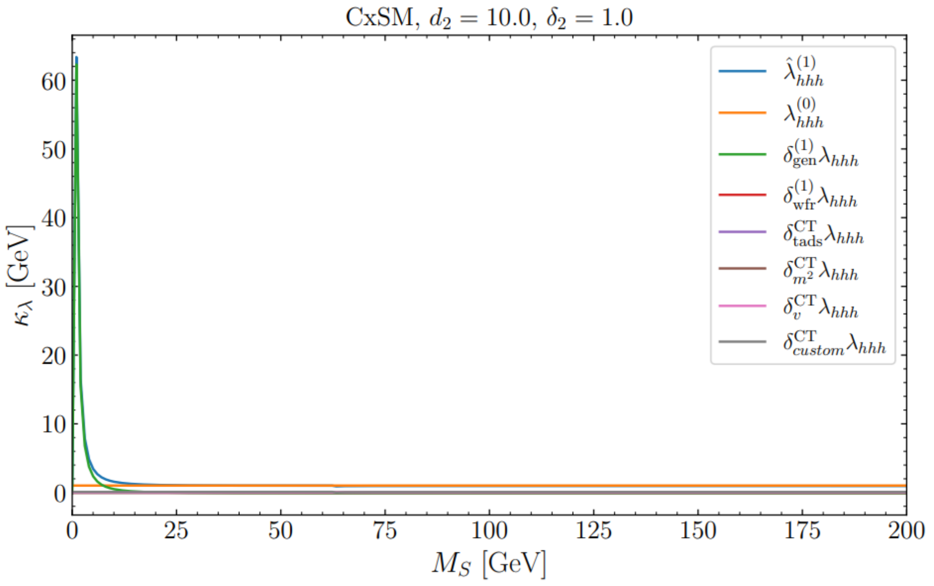
$$\lambda_{hhh},\ \lambda_{hS^+S^-},$$

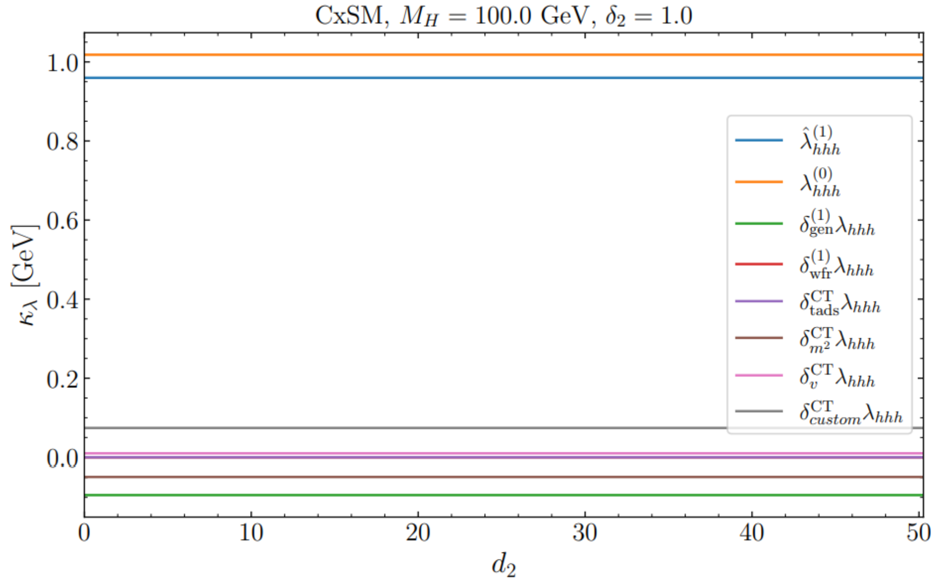


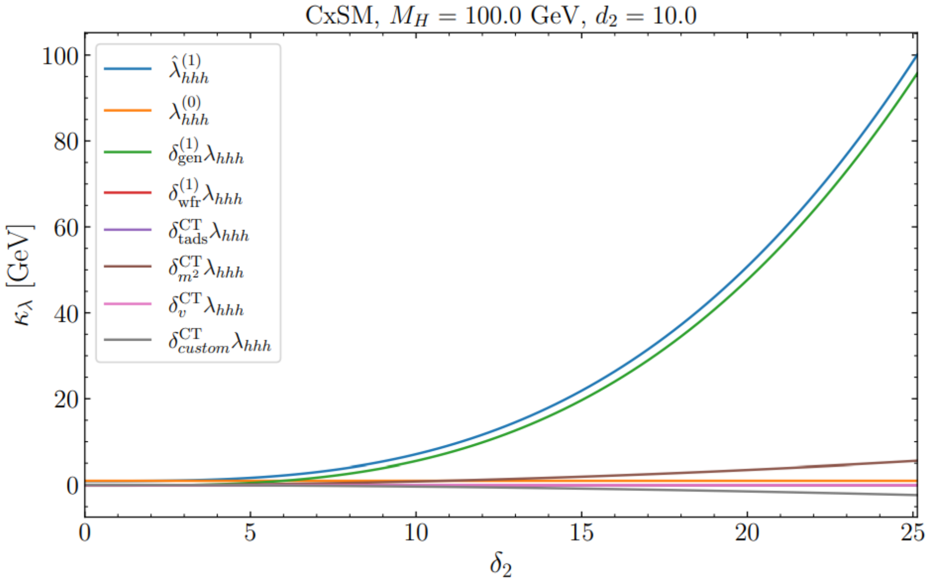
$$= -i\,v\,n!\,\lambda_{hh_ih_j}$$

1L corrections to λ_{hhh} in the CxSM model





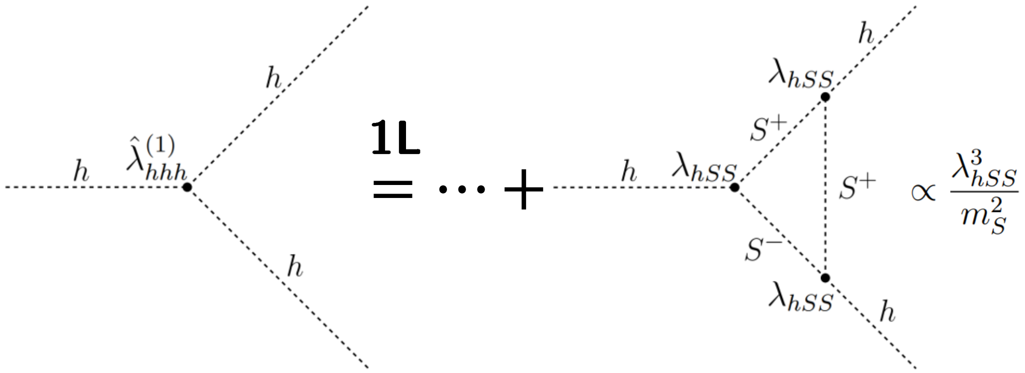


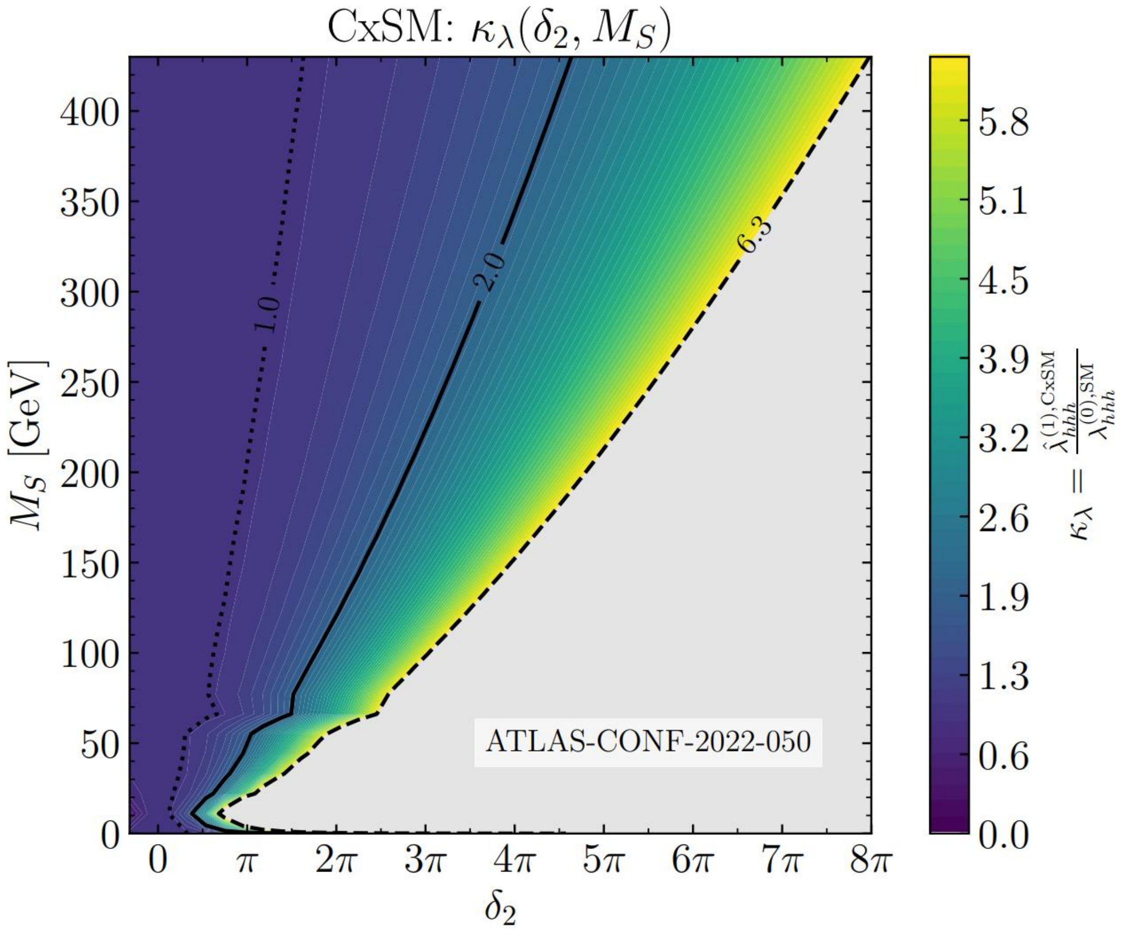


1L corrections to λ_{hhh} in the CxSM model

Increase if the **1L** corrections of λ_{hhh}

Dependance of other **THC's** of **1L** through other Feynman diagrams





Conclusions

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

- We have analyse the main channel in Di-Higgs production in $e^{+}e^{-}$ channels in future colliders, **ILC1000**

- We have obtained a **theoretical significance**, Z, of the model with respect to the **SM**

- Conclusion for the future, keeps working on the **CxSM** model

Extra

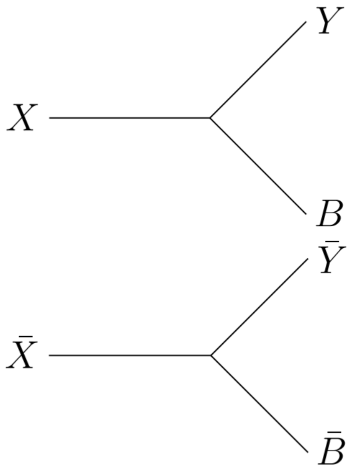
Motivation: Matter-Antimatter Asymmetry

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

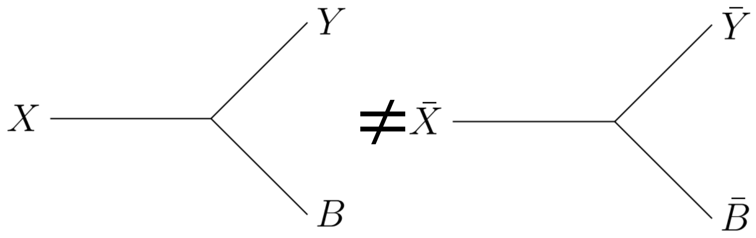
Proposal: **Electroweak Baryogenesis**:

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

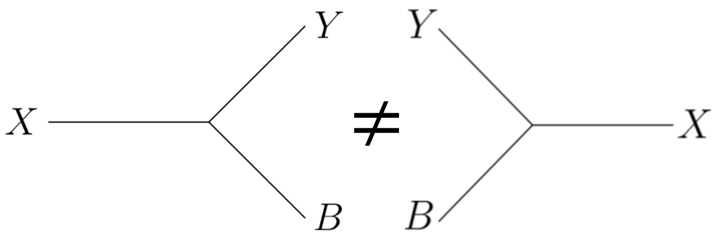
1) **Baryon Number Violation**



2) **C and CP Violations**

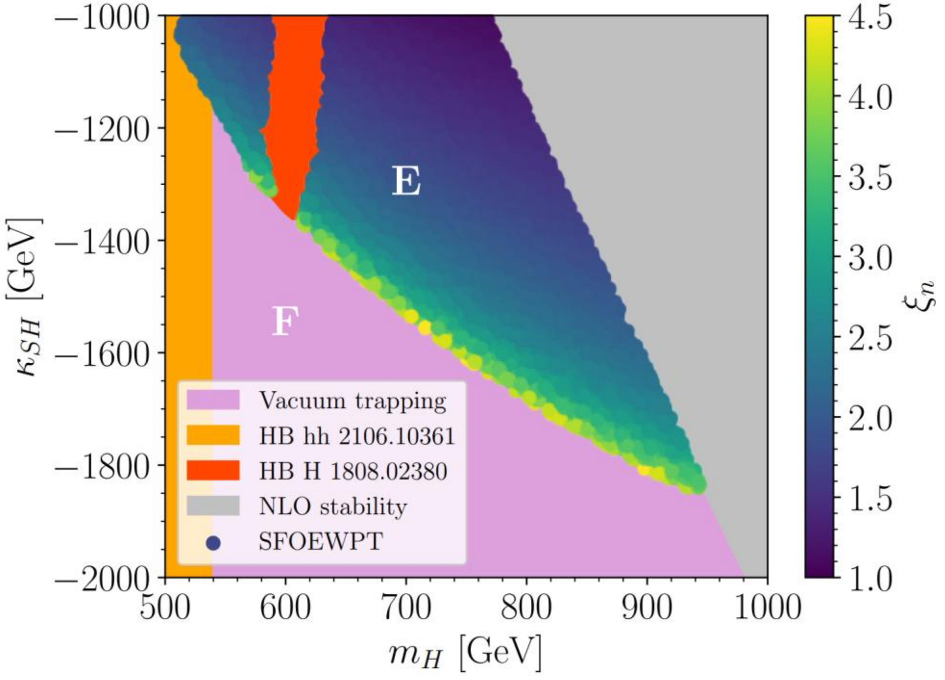


3) **Out of equilibrium**

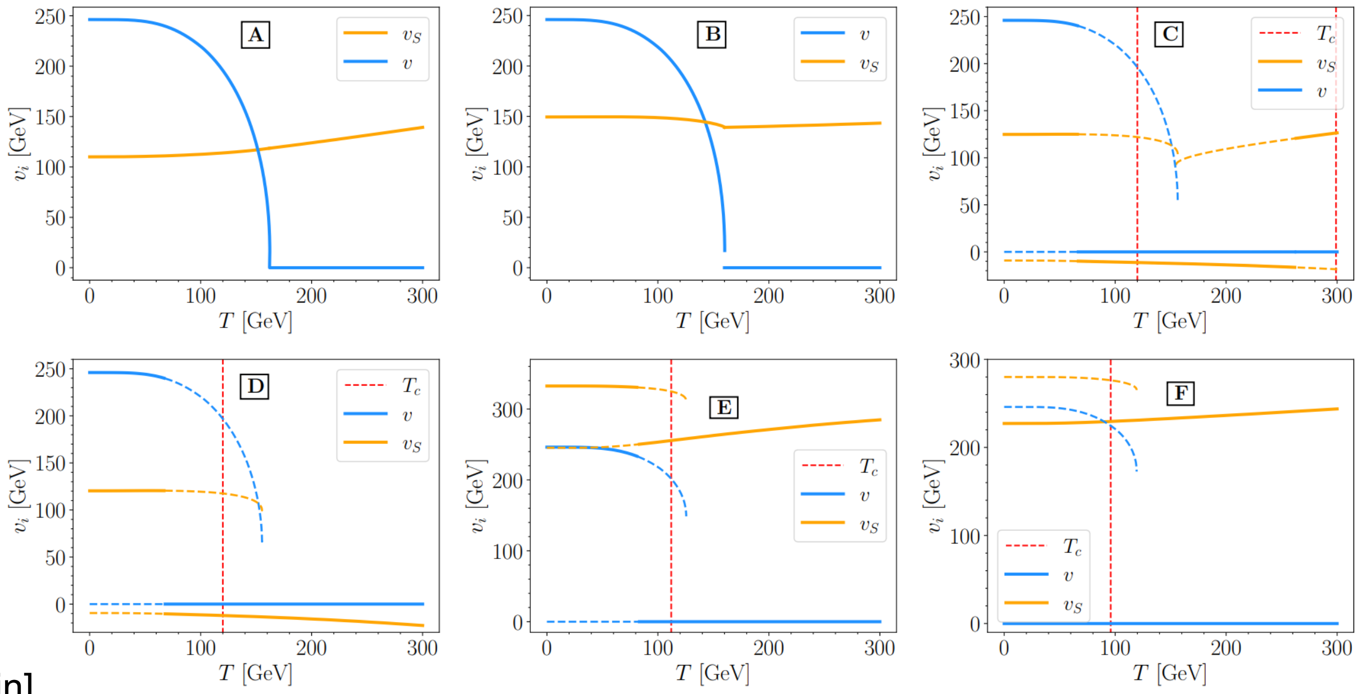


Benchmark plane. SFOEWPT

We define $\xi_n = \frac{v(T_n)}{T_n} \gtrsim 1$, where T_n is the temperatura of nucleation, as the conditions for **SFOEWPT**



Different kind of **EWPT**



[Alain]

Red and Orange areas are excluded areas from Di-Higgs researches

Cross-sections in e^+e^- colliders

- Cuts in e^+e^- colliders (ILC1000):

$e^+e^- \to Zhh \to Zb\bar{b}b\bar{b}$
$E_b > 20$ GeV, $\lvert\eta_Z\rvert < 2.5$, $\lvert\eta_b\rvert < 2.5$, $y_{bb} > 0.001$

$e^+e^- \to \nu\bar{\nu}hh \to \nu\bar{\nu}b\bar{b}b\bar{b}$
$E_b > 20$ GeV, $E_T^{miss} > 30$ GeV, $\lvert\eta_b\rvert < 2.5$, $y_{bb} > 0.001$

- **Acceptance:** $\mathcal{A} = \frac{N^{\text{w/ cuts}}}{N^{\text{w/o cuts}}}$

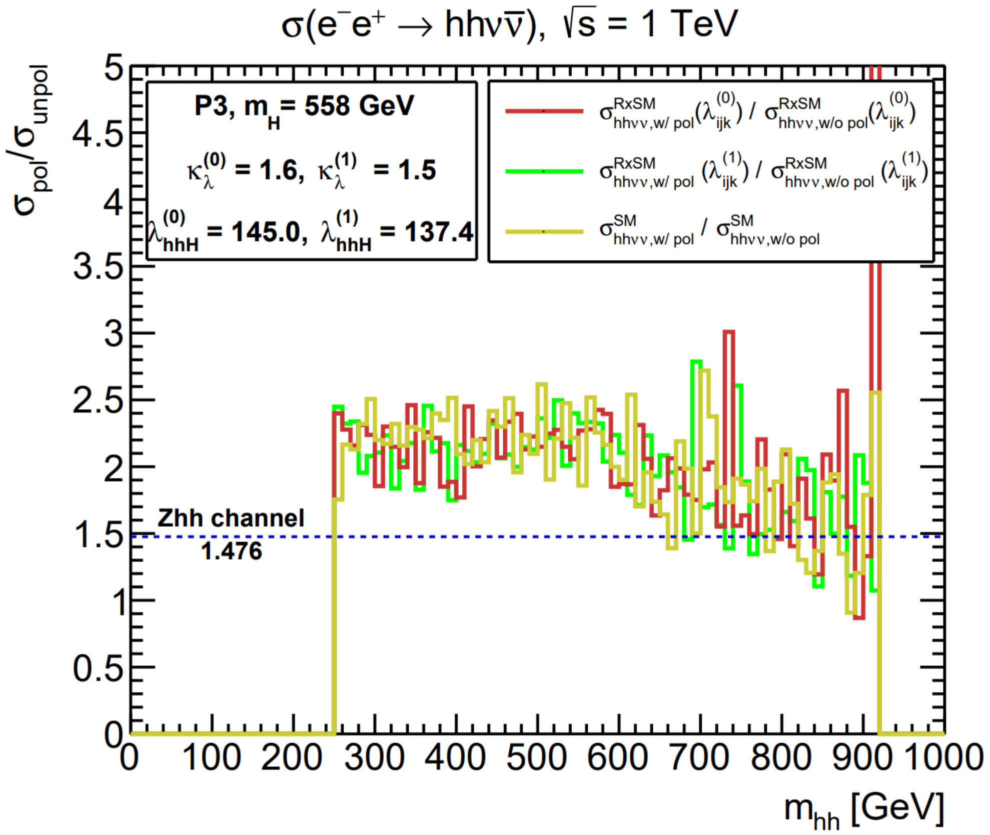
- **Efficiency of b-tagged jets:** $\epsilon_b = 0.85$

- **Smearing:** 5%[]

- **Polarization:**

Zhh channel	$\nu\bar{\nu}hh$ channel
$\sigma_{pol} \approx 1.476\sigma_{unpol}$[1]	Madgraph5_aMC v3.5.9

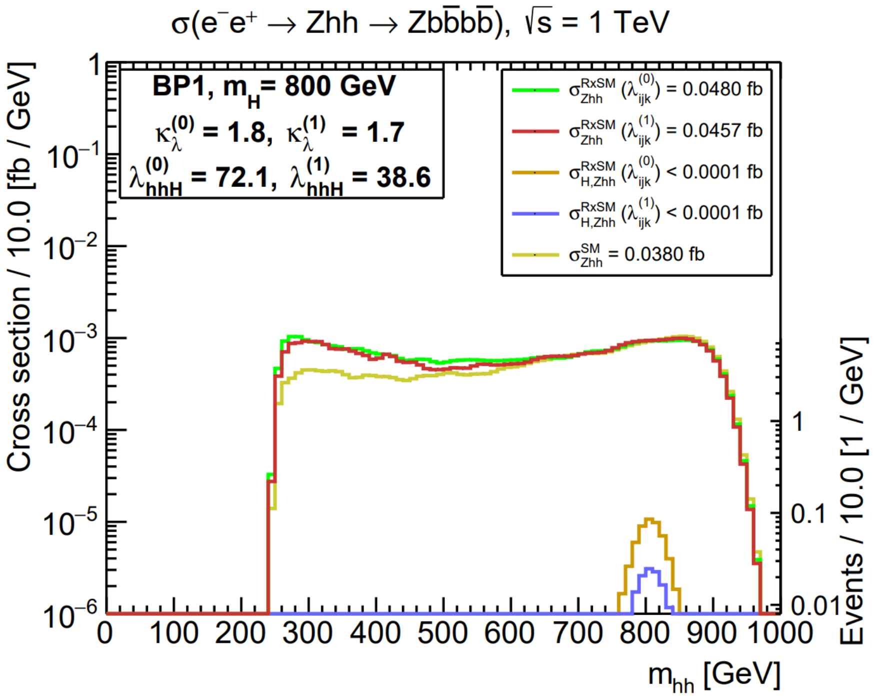
- $N_{4b} = N_{hh} \times (\text{BR}(h \to b\bar{b}))^2 \times \mathcal{A} \times \epsilon_b$

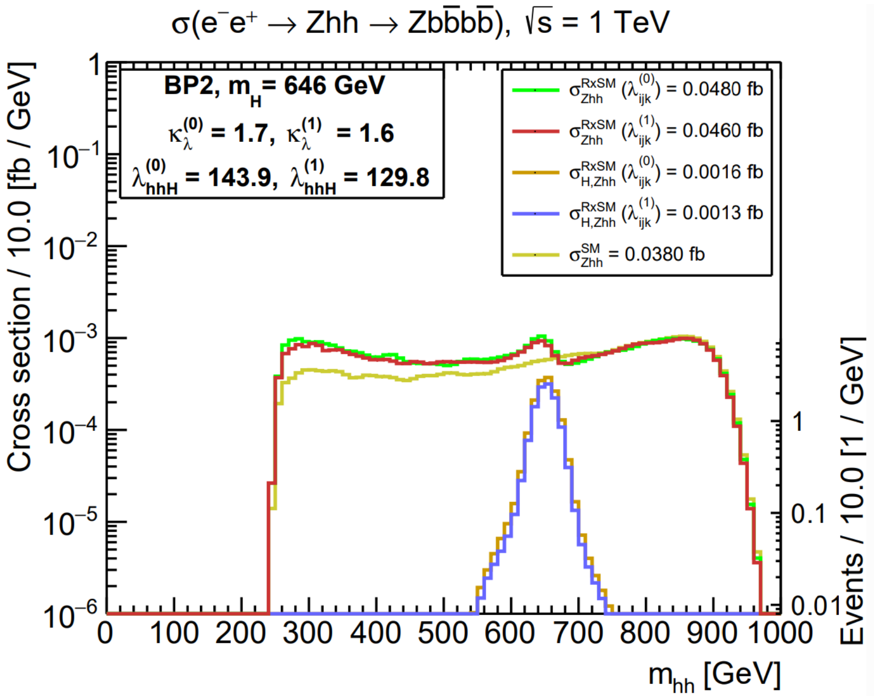


Smearing

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}

Statistical significance of the resonance of H, called $\boldsymbol{Z}$[6]:

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

- Obtain the next variables per bin, $s_i = \bar{N}_{i,\nu\bar{\nu}4b} - \bar{N}^C_{i,\nu\bar{\nu}4b}$, $b_i = \bar{N}^C_{i,\nu\bar{\nu}4b}$, $Z_i = \sqrt{2\left((s_i + b_i)\log\left(1 + \frac{s_i}{b_i}\right) - s_i\right)}$

  ($\bar{N}_{i,\nu\bar{\nu}4b}$ in RxSM at 1L and $\bar{N}^C_{i,\nu\bar{\nu}4b}$ in SM)

- **Statistical significance**

$$\boldsymbol{Z} = \sqrt{\sum_i (Z_i)^2}$$

Points	$\sigma^{\mathrm{RxSM}}_{Zhh}(\lambda^{(0)}_{ijk})$ [fb]	$\sigma^{\mathrm{RxSM}}_{Zhh}(\lambda^{(1)}_{ijk})$ [fb]	$Z^{(0)}_{Zhh}$	$Z^{(1)}_{Zhh}$	$\mathcal{A}^{(0)}_{Zhh} \times \epsilon_b$	$\mathcal{A}^{(1)}_{Zhh} \times \epsilon_b$
BP1	0.0480	0.0457	7.59	6.33	63.4%	63.2%
BP2	0.0480	0.0460	7.64	6.25	63.2%	63.2%
BP3	0.0488	0.0469	9.49	8.81	63.4%	63.6%
BP4	0.0444	0.0426	5.53	4.29	63.2%	63.2%

Points	$\sigma^{\mathrm{RxSM}}_{\nu\nu hh}(\lambda^{(0)}_{ijk})$ [fb]	$\sigma^{\mathrm{RxSM}}_{\nu\nu hh}(\lambda^{(1)}_{ijk})$ [fb]	$Z^{(0)}_{\nu\nu hh}$	$Z^{(1)}_{\nu\nu hh}$	$\mathcal{A}^{(0)}_{\nu\nu hh} \times \epsilon_b$	$\mathcal{A}^{(1)}_{\nu\nu hh} \times \epsilon_b$
BP1	0.0298	0.0275	6.44	5.94	52.4%	51.3%
BP2	0.0336	0.0312	9.78	8.77	51.7%	51.3%
BP3	0.0469	0.0441	21.49	20.33	52.2%	51.8%
BP4	0.0266	0.0256	5.55	5.23	50.7%	49.8%