Di-Higgs production at e^+e^- colliders with quantum corrections

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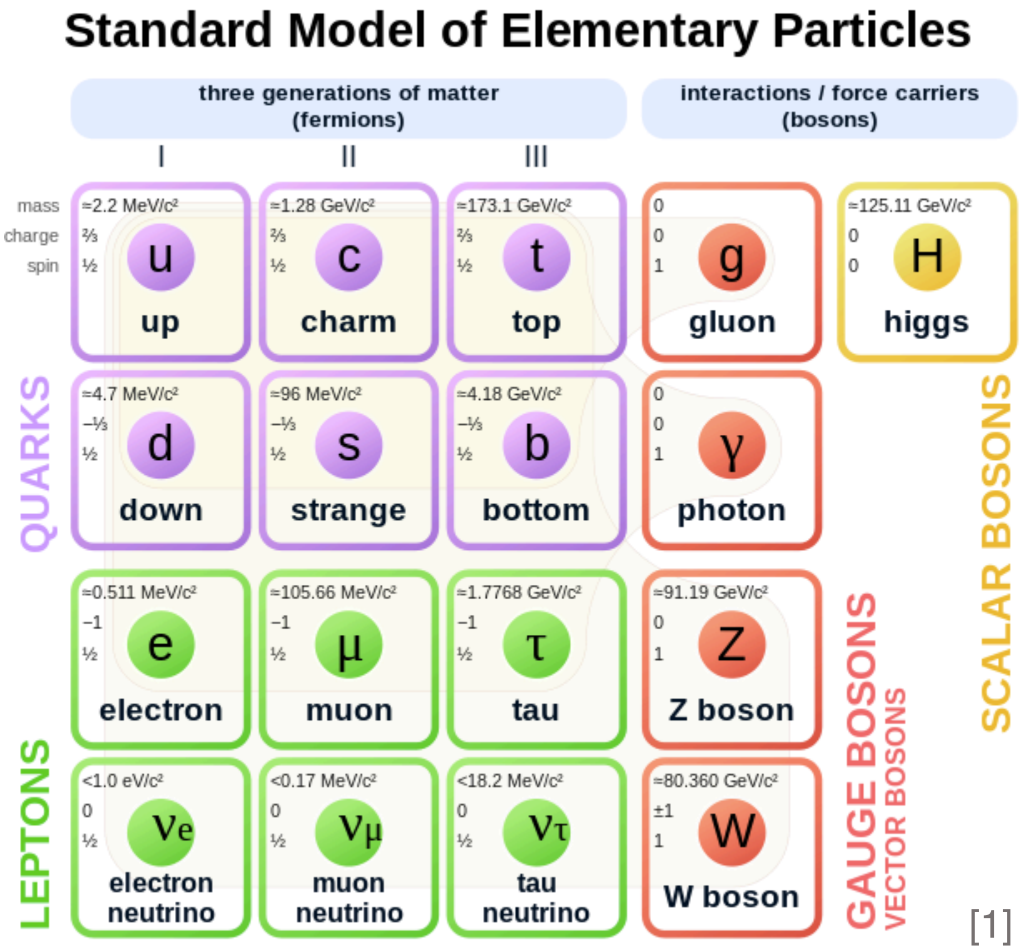
Introduction



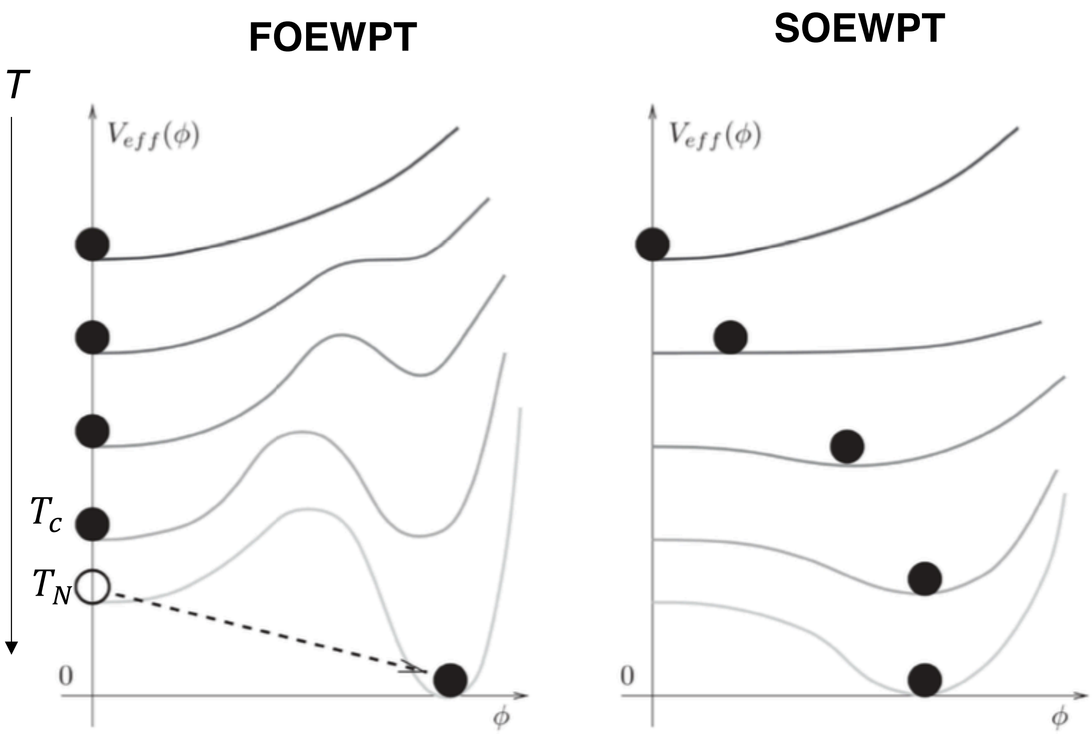
[1]

Standard Model (SM)

- Problem: SM doesn't explain the matter-antimatter asymmetry in the early Universe (BAU)

BAU could be explained with Electroweak Baryogenesis → we should include it in new models BSM *(Beyond Standard Model)* with enlarged Higgs sectors..

What BSM we should choose?



[2]

How to introduce Electroweak Baryogenesis?

- Our model needs to meet the three Sakharov conditions ⟶ processes out of thermal equilibrium

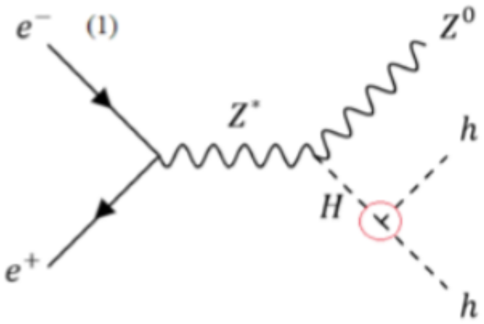
How to introduce processes out of thermal equilibirum?

- With a FOEWPT *(First Order Electroweak Phase Transition).*

⬇

Chosen model that lets FOEWPT:
RxSM (*Real Singlet Extension*)

Objectives



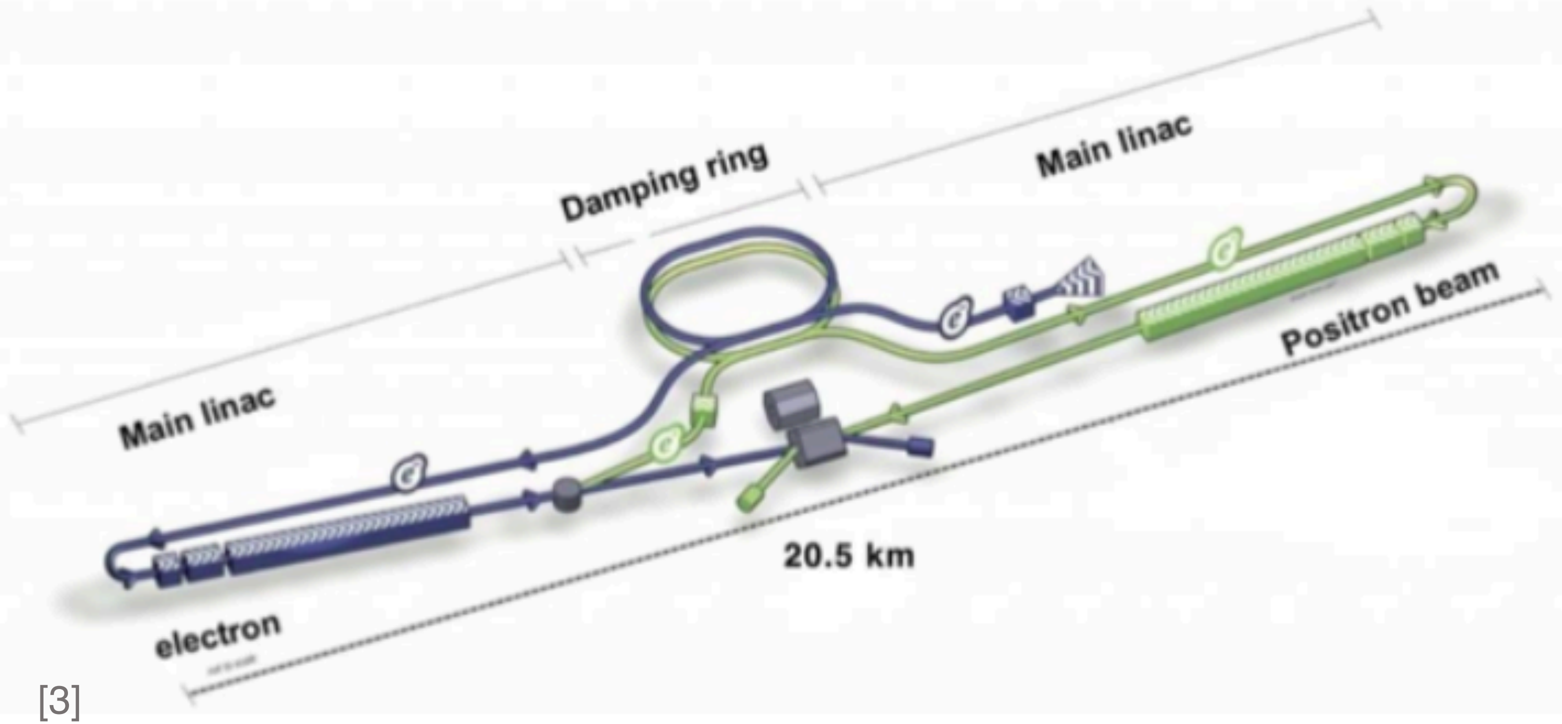
- Analyze the form of $V(\phi)$ in RxSM:

1) Measure **THC's** (*Triple Higgs Couplings*): λ_{hhH} and λ_{hhh}.

2) Analyze the process $e^+e^- \longrightarrow h\,h\,Z$.

3) Analyze the differences between a tree level analysis and including **one loop corrections** $\longrightarrow$ more realistic.

ILC: *International Linear Collider*



[3]

$\sqrt{s}$ =250-1000 GeV

New Model: RxSM *(Real Singlet Extension) I*

- **Higgs fields:** doublet + singlet

$$\phi = \begin{pmatrix} 0 \\ \frac{\bar{h}+v}{\sqrt{2}} \end{pmatrix}, \qquad S = h' + x.$$

- **Higgs potential:** no Z_2 imposition

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

- **Mass matrix:**

$$\begin{pmatrix} m^2_{\bar{h}} & m^2_{\bar{h}h'} \\ m^2_{h'\bar{h}} & m^2_{h'} \end{pmatrix} = \begin{pmatrix} 2\lambda v^2 & \frac{v}{2}(a_1 + 2a_2 s) \\ \frac{v}{2}(a_1 + 2a_2 s) & b_3 s + 2b_4 s^2 - \frac{a_1 v^2}{4s} \end{pmatrix}$$

→ h' and $\bar{h}$ aren't mass eigenstates.

RxSM II

- **Mixing matrix:**

Light Higgs (m_h = 125,09 GeV)

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} cos\alpha & -sin\alpha \\ sin\alpha & cos\alpha \end{pmatrix} \begin{pmatrix} \bar{h} \\ h' \end{pmatrix}$$

Heavy Higgs

Diagonalize mass matrix

- **Mass terms:**

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

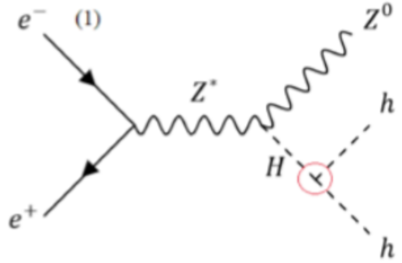
- **Mixing angle:**

$$\sin 2\alpha = \frac{2m^2_{\bar{h},h'}}{m^2_H - m^2_h}$$

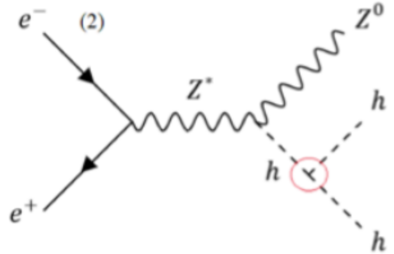
RxSM III

- **THC:**

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



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



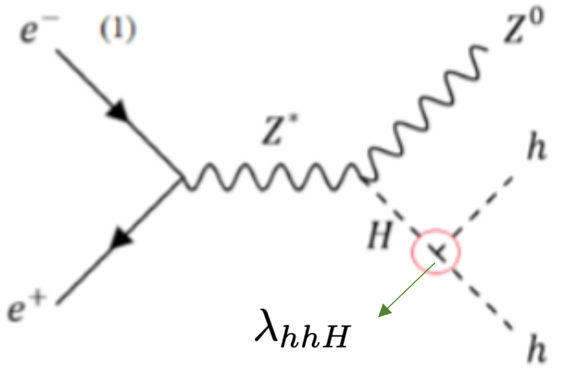
- **Higgs-SM couplings:** $g_{Hi}^{RxSM} = g_{hi}^{SM}\sin\alpha, \quad g_{hi}^{RxSM} = g_{hi}^{SM}\cos\alpha.$

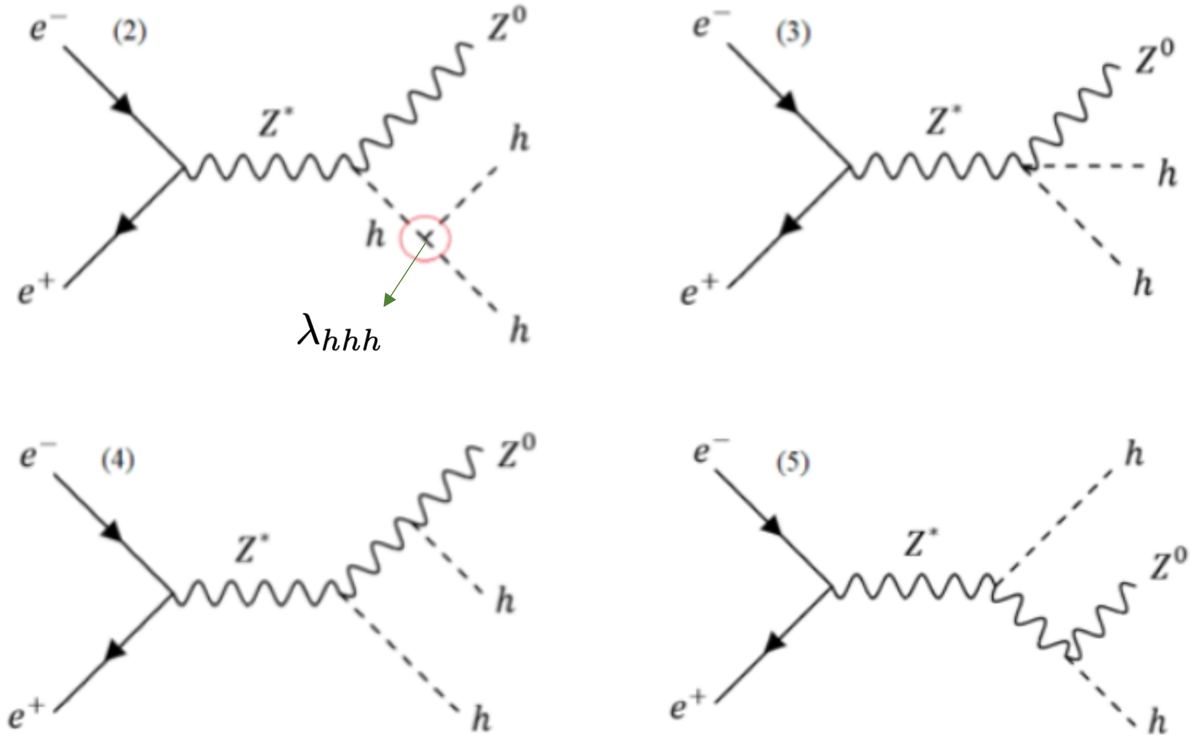
- **Higgs-SM disintegration width:** $\Gamma_{H\to ii}^{RxSM} = \Gamma_{h\to ii}^{SM}\sin^2\alpha, \quad \Gamma_{h\to ii}^{RxSM} = \Gamma_{h\to ii}^{SM}\cos^2\alpha.$

- **Total disintegration width of H :** $\Gamma_{H,total}\sum_i \Gamma_{H\to ii}\sin\alpha^2 + \Gamma_{H\to hh}$ ⟶ $\Gamma_{H\to hh} = \lambda_{hhH}^2\frac{\sqrt{1-\frac{4m_h^2}{m_H^2}}}{8\pi m_H}$

Feynman diagrams: Tree level

$$e^+e^- \longrightarrow h\,h\,Z$$



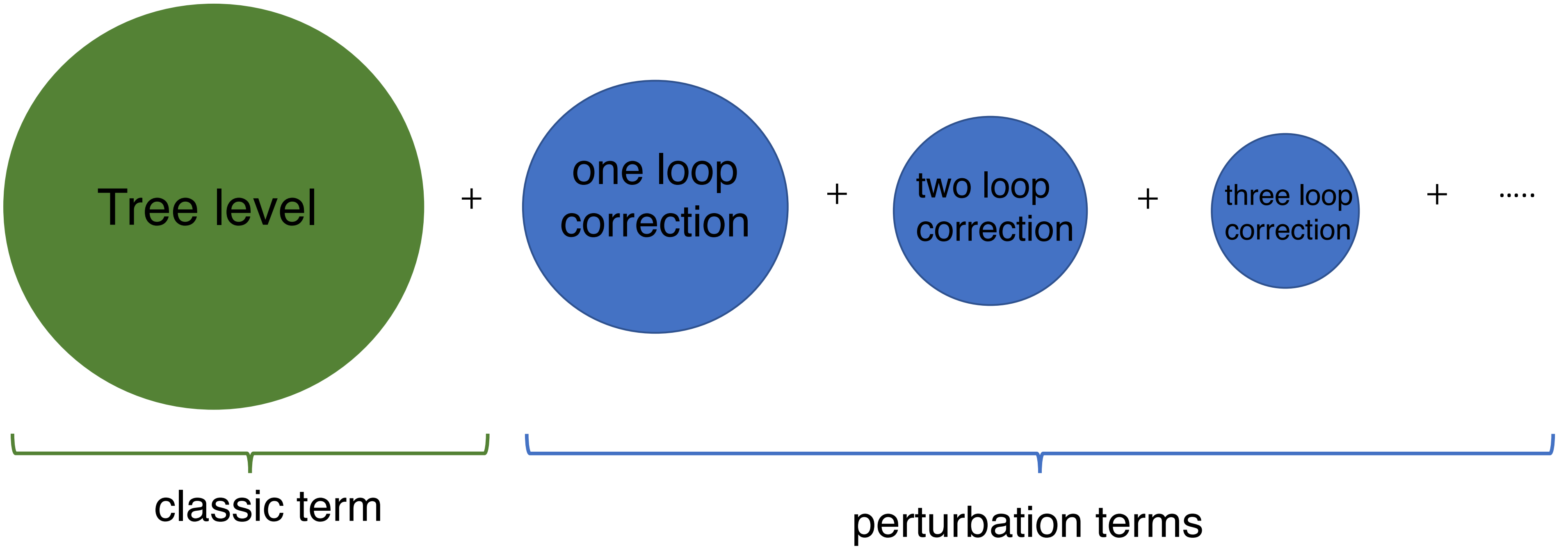


[4]

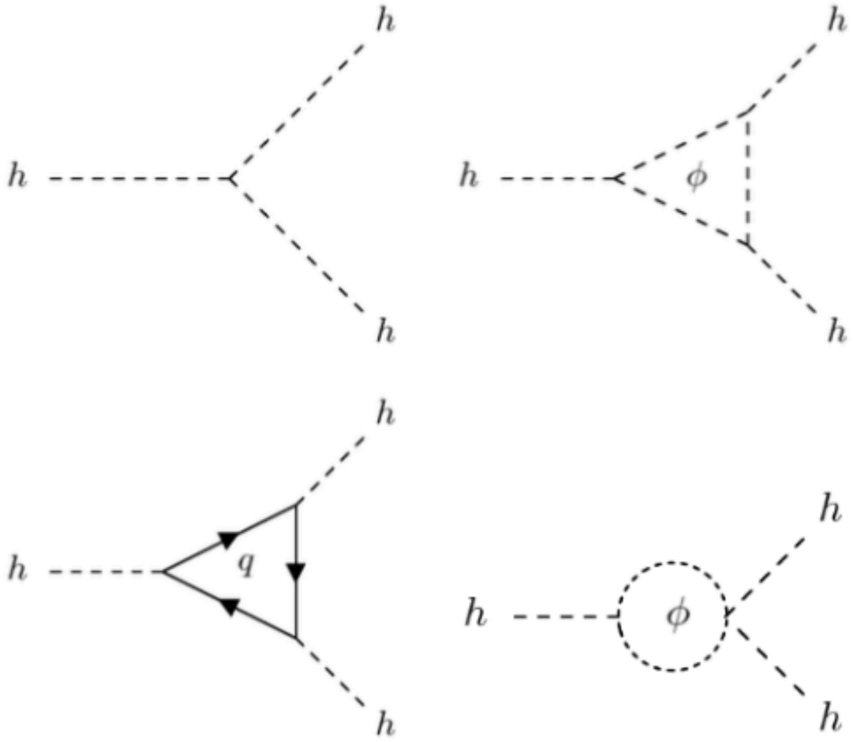
Resonant diagram

Non-resonant diagrams

Feynman diagrams: Corrections I



Feynman diagrams: Corrections



- **Simplifications:**

-One loop.

-Applied only to THC's.

Work space I

Punto	m_H[GeV]	x[GeV]	b_4	b_3	a_1	a_2	α
P1	461.9	46.3	0.89	-622.6	-691.10	4.50	0.180
P2	470.8	46.3	0.45	-442.70	-691.10	4.45	0.177
P3	469.4	47.4	0.00	0.00	-675.10	4.11	0.174
P4	530.9	41.9	0.00	0.00	-763.7	5.23	0.153
P5	575.10	37.5	0.78	-582.90	-853.30	6.65	0.140
P6	529.60	40.8	0.45	-442.70	-784.30	5.63	0.153
P7	642.50	34.2	0.11	-218.90	-935.70	7.85	0.125
P8	656.10	33.1	0.78	-582.90	-966.80	8.44	0.122

[4] y [5]

$$a_1 x = -32000,$$

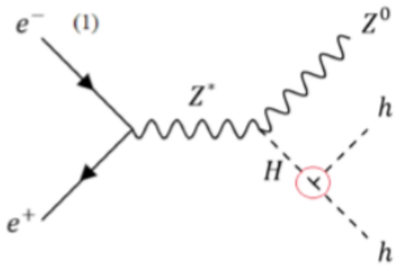
$$b_3 = 660\sqrt{b_4},$$

$$\lambda = 0{,}18.$$

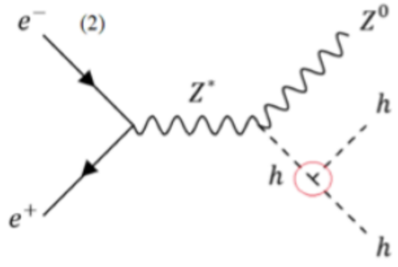
[5]

Two free parameters:
x and b_4

FOEWPT assured in the plane:
$x \in [33, 48]$ GeV and $b_4 \in [0.1\,, 1]$

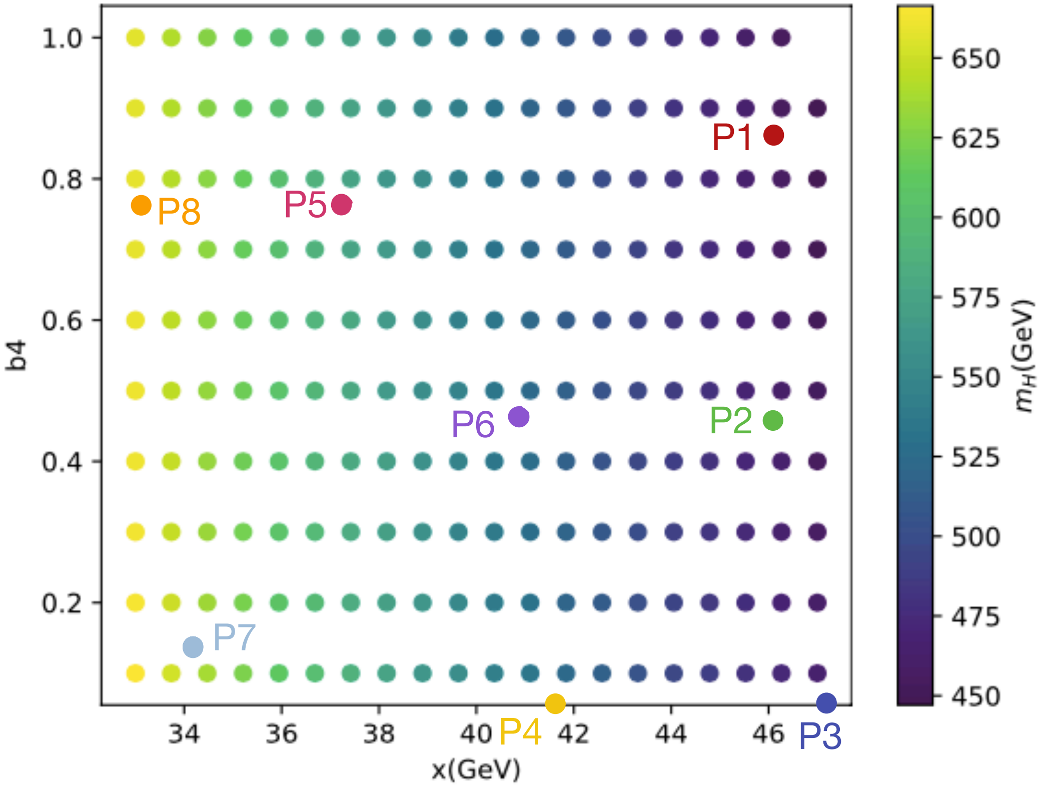


Work space II



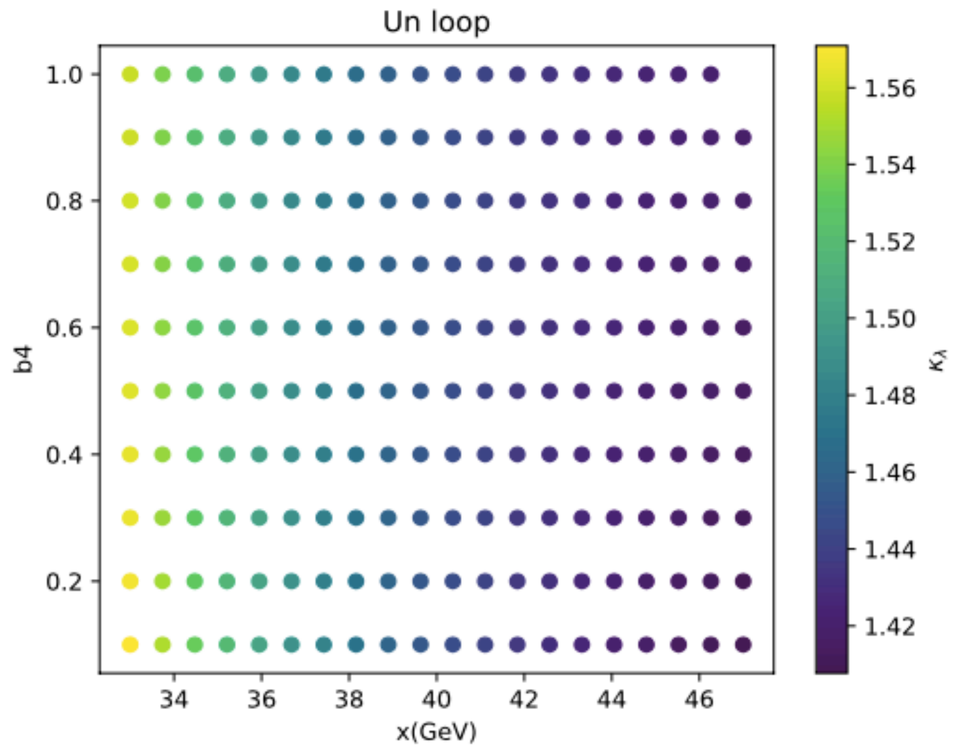
Punto	$\lambda_{hhH}^{árbol}$	$\kappa_{\lambda}^{árbol}$	$\Gamma_{H}^{árbol}$[GeV]	λ_{hhH}^{loop}	κ_{λ}^{loop}	Γ_{H}^{loop}[GeV]	$\cos\alpha\lambda_{hhh}^{árbol}$	$\sin\alpha\lambda_{hhH}^{árbol}$	$\cos\alpha\lambda_{hhh}^{loop}$	$\sin\alpha\lambda_{hhH}^{loop}$
P1	0.36	1.47	3.81	0.26	1.26	3.14	0.187	0.064	0.150	0.047
P2	0.35	1.46	3.73	0.26	1.41	3.18	0.185	0.061	0.168	0.046
P3	0.33	1.43	3.48	0.28	1.40	3.25	0.182	0.057	0.167	0.048
P4	0.38	1.43	4.15	0.31	1.43	3.48	0.182	0.058	0.171	0.047
P5	0.45	1.46	5.05	0.28	1.48	3.48	0.186	0.063	0.178	0.039
P6	0.40	1.45	4.49	0.29	1.44	3.32	0.185	0.069	0.173	0.044
P7	0.49	1.44	5.50	0.31	1.54	3.47	0.184	0.061	0.185	0.039
P8	0.52	1.44	5.84	0.27	1.46	3.16	0.184	0.063	0.176	0.033

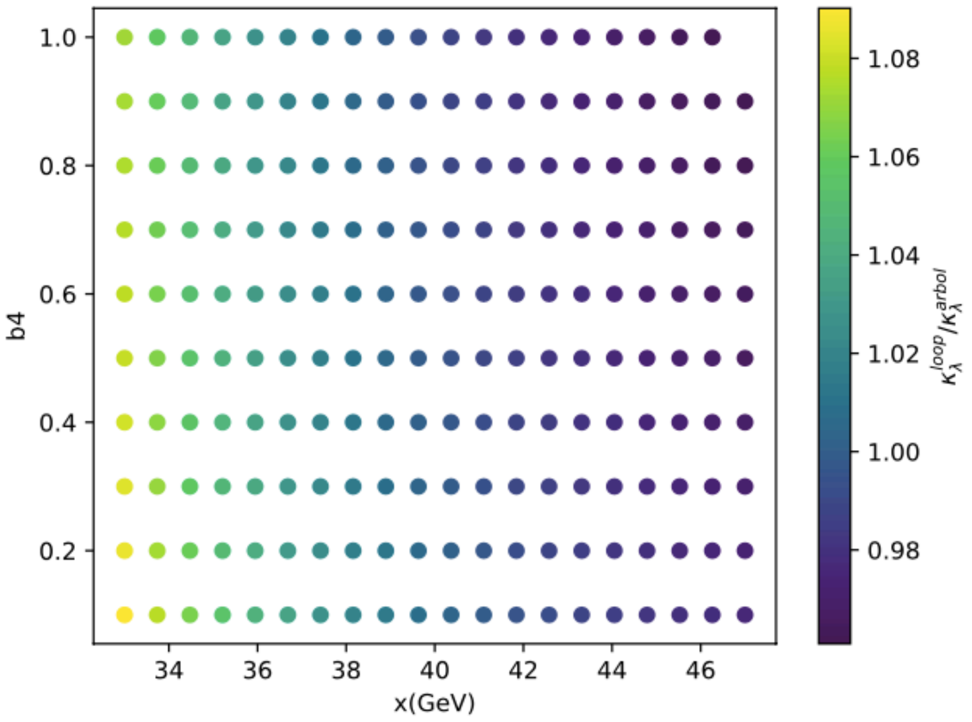
Heavy Higgs mass (m_H) and points in the plane

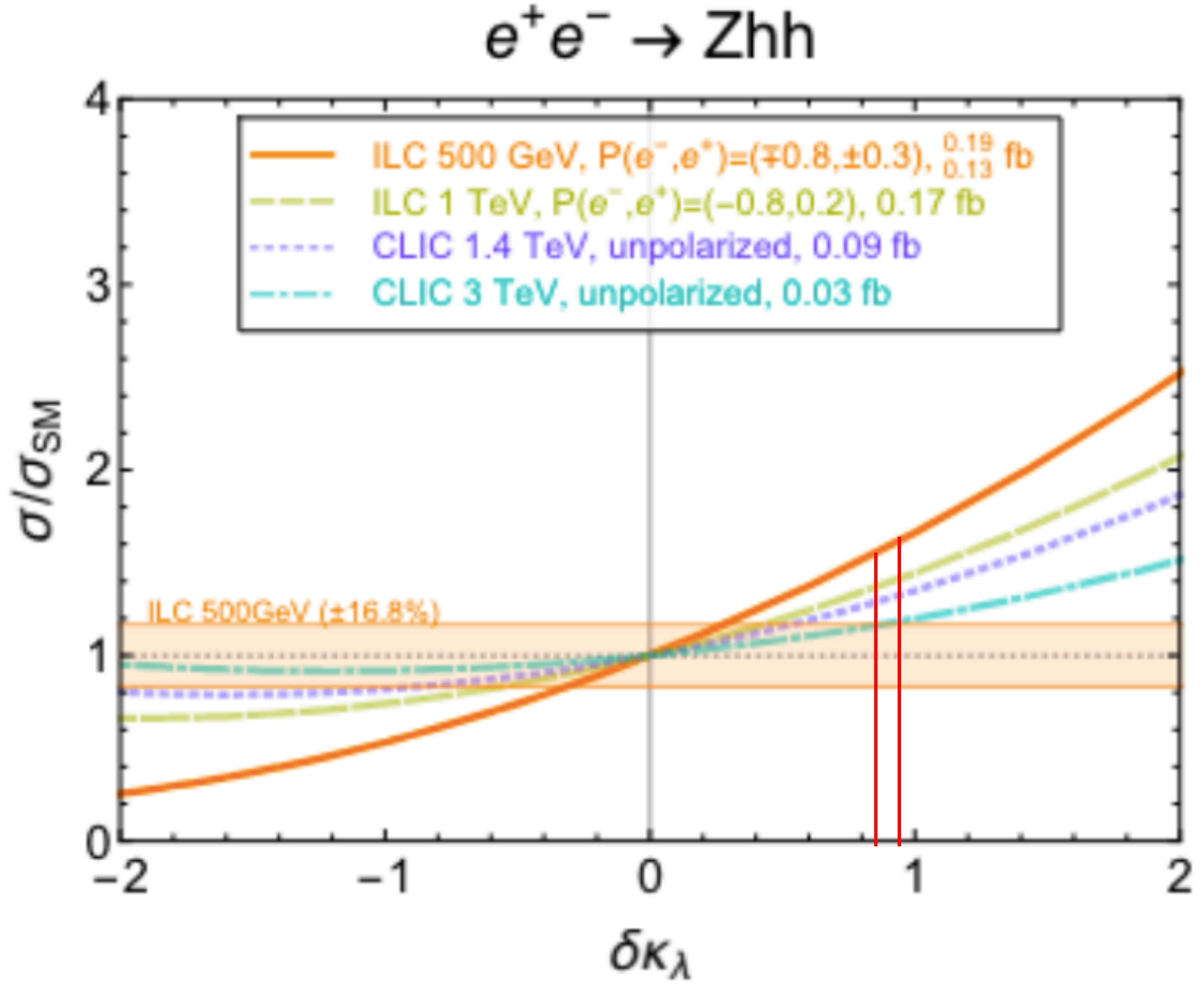


κ_λ analysis

$$\kappa_\lambda = \lambda_{hhh}^{loop,RxSM} \Big/ \lambda_{hhh}^{tree,SM}$$



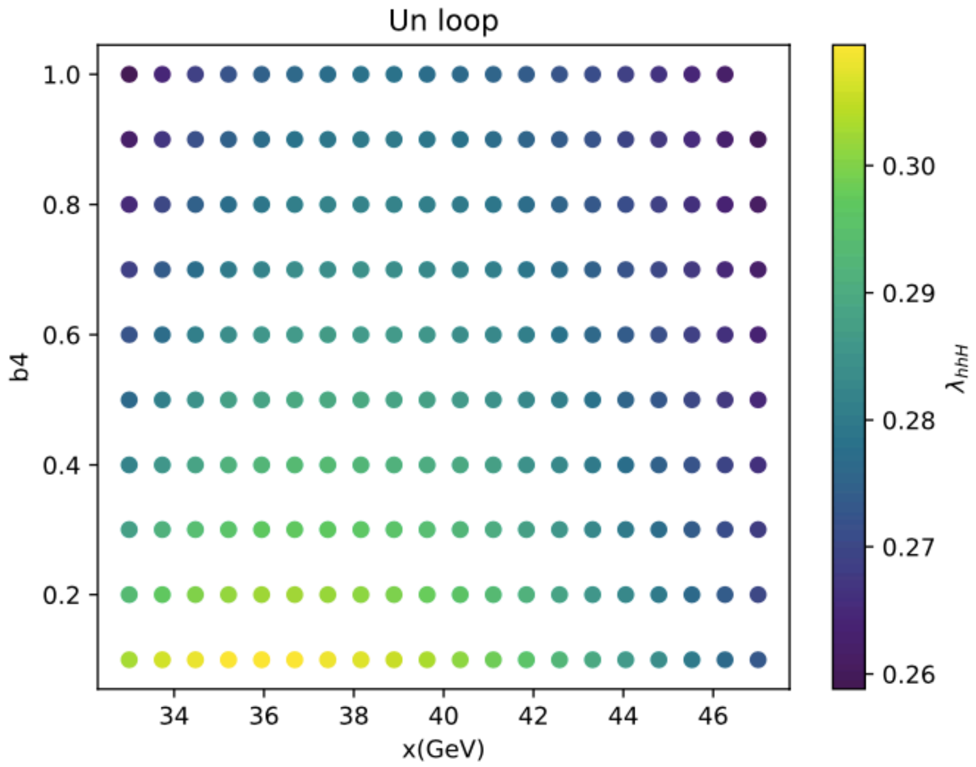


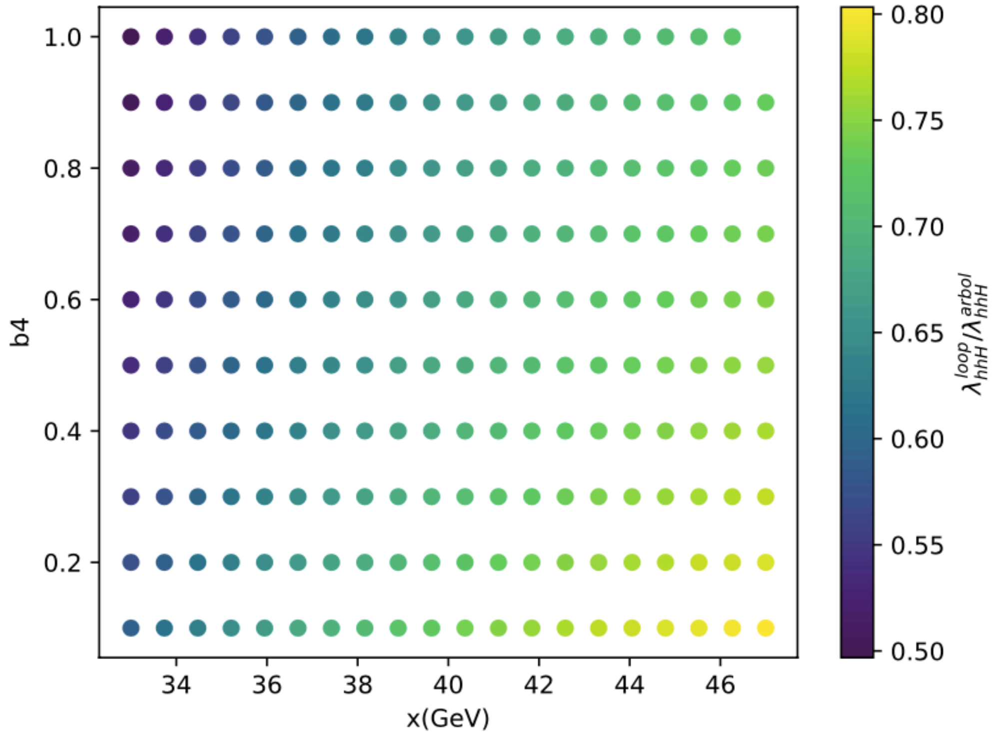


[6]

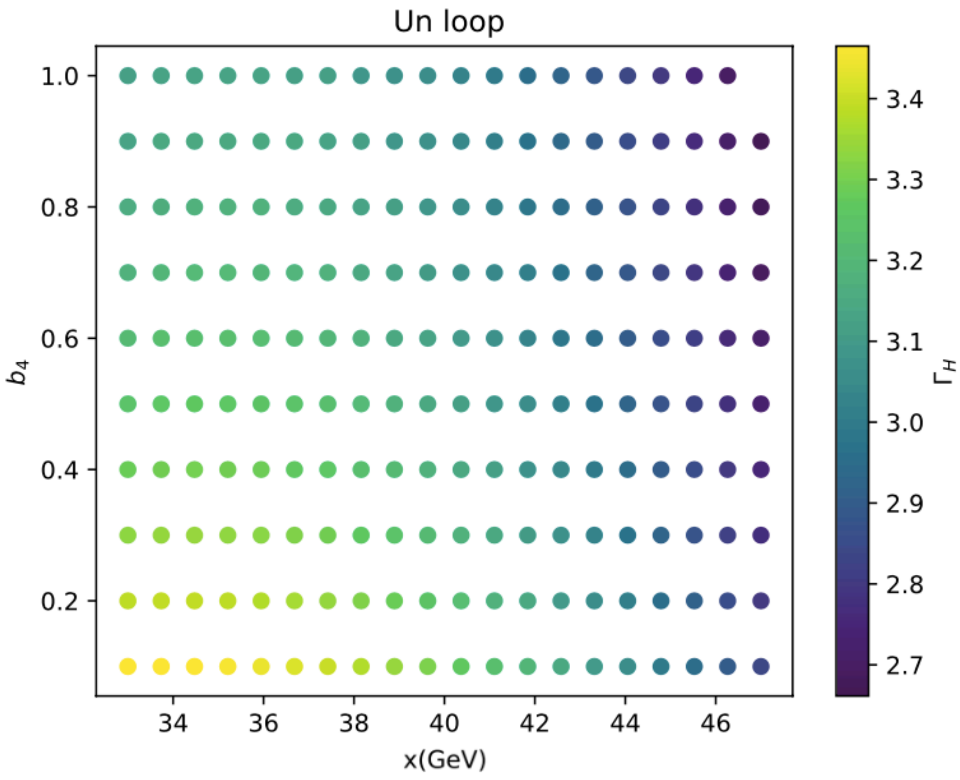
$$\delta\kappa_\lambda = \kappa_\lambda - 1$$

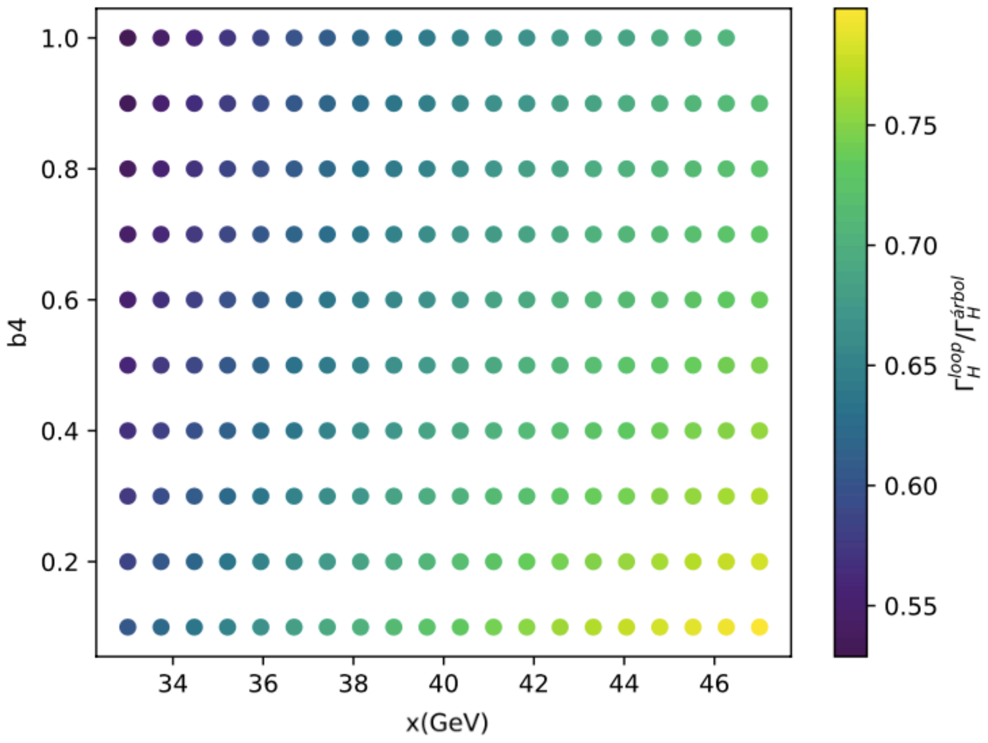
λ_{hhH} analysis





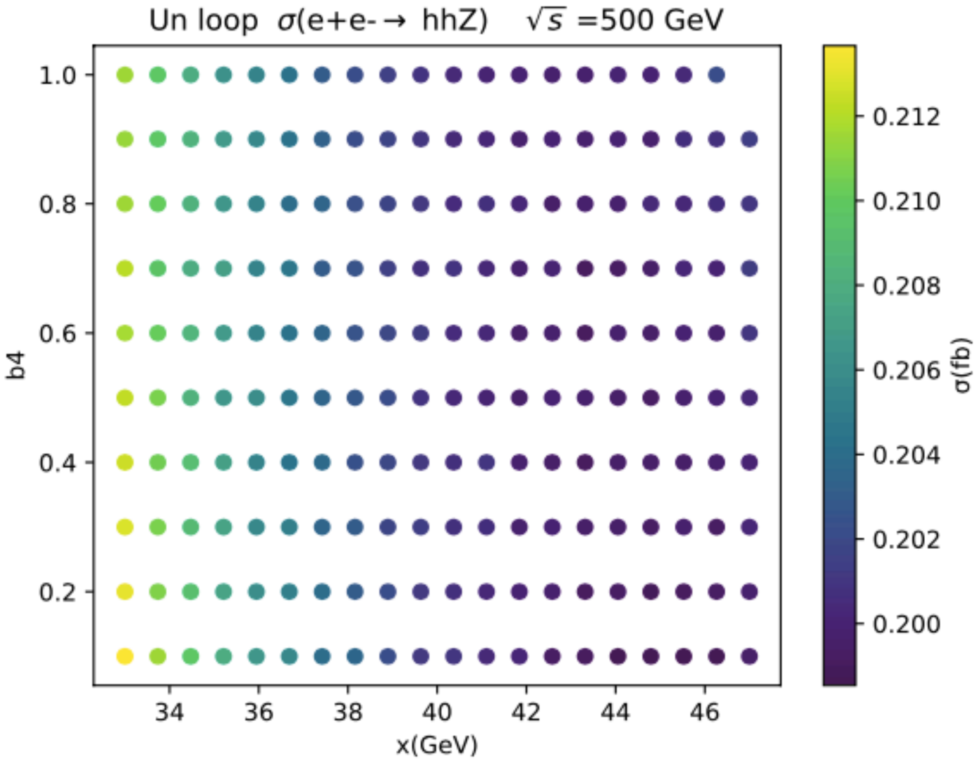
Γ_H analysis



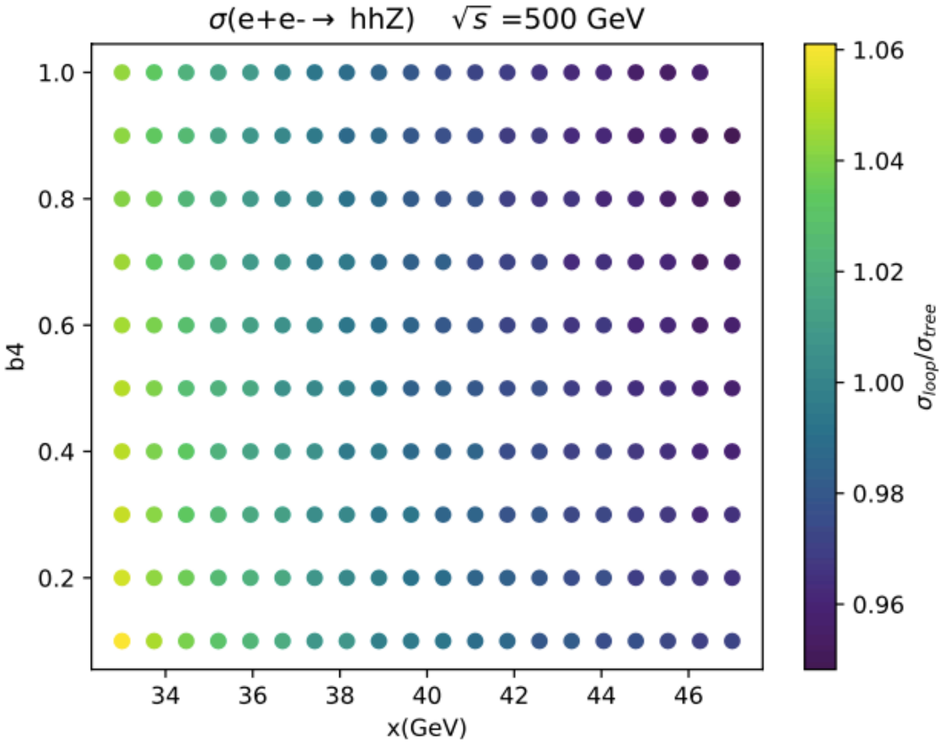


Cross section in the $x - b_4$ plane

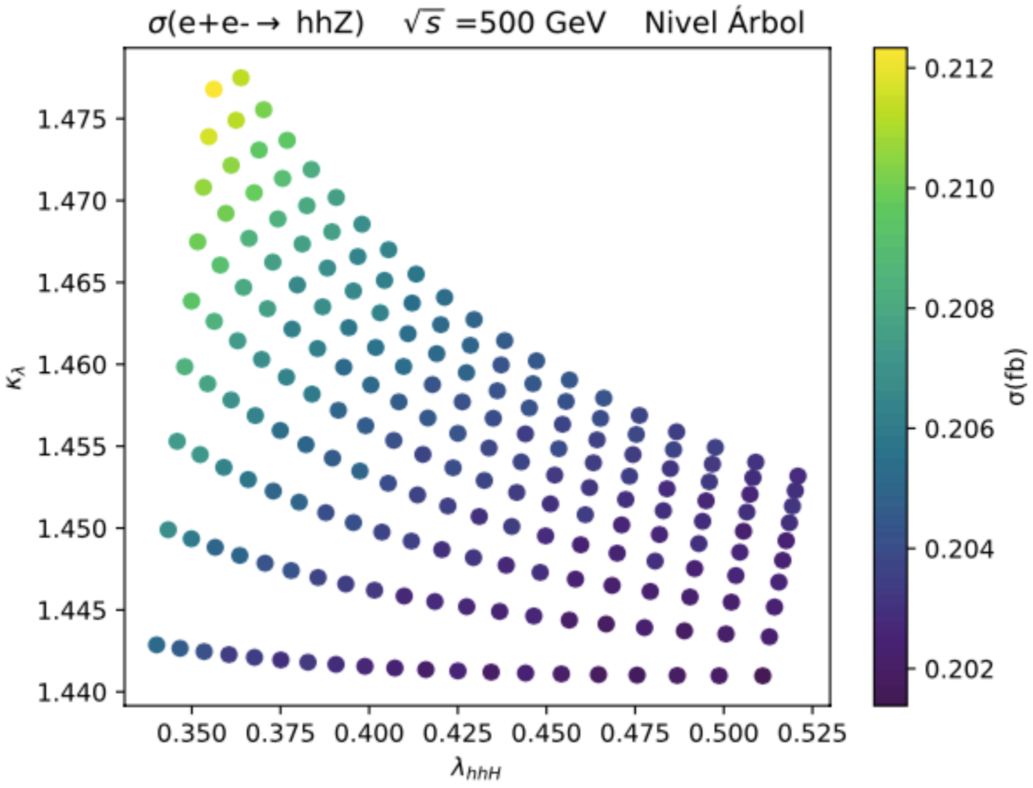
$(\sqrt{s} = 500\ GeV)$

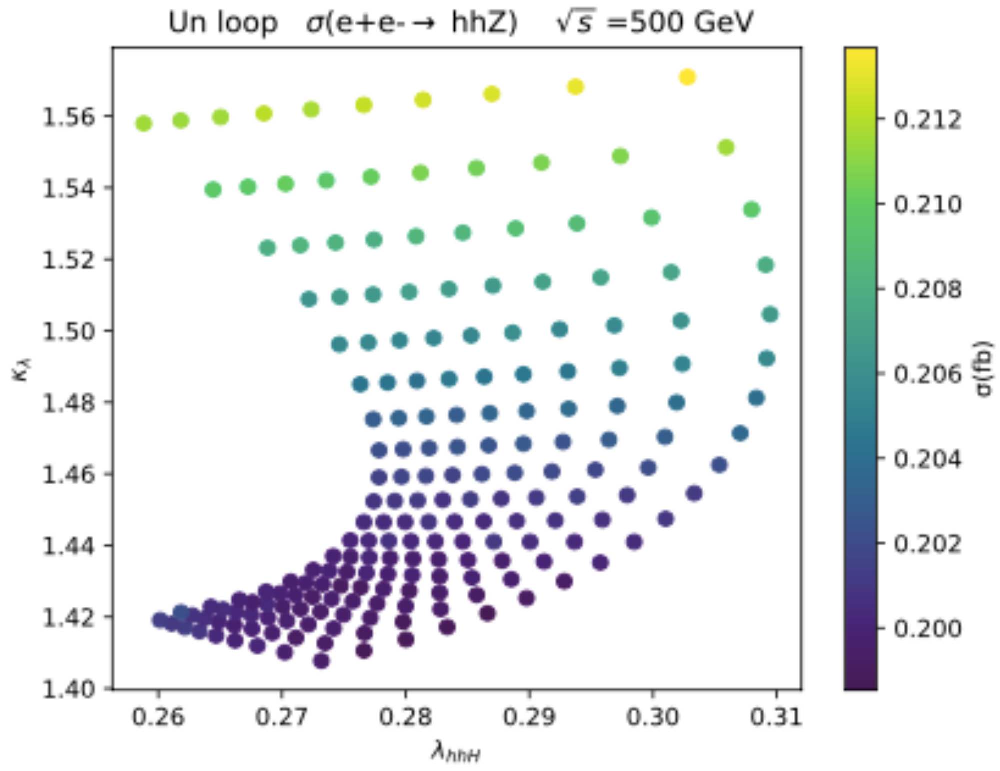


$\sigma_{SM} = 0.158$ fb

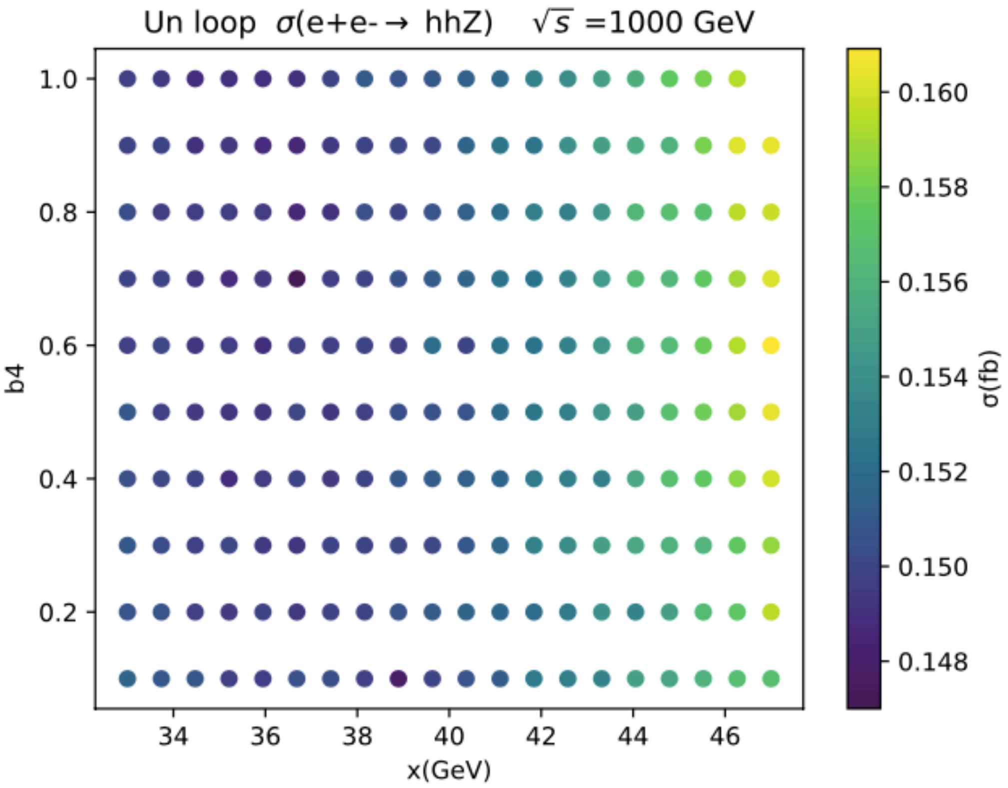


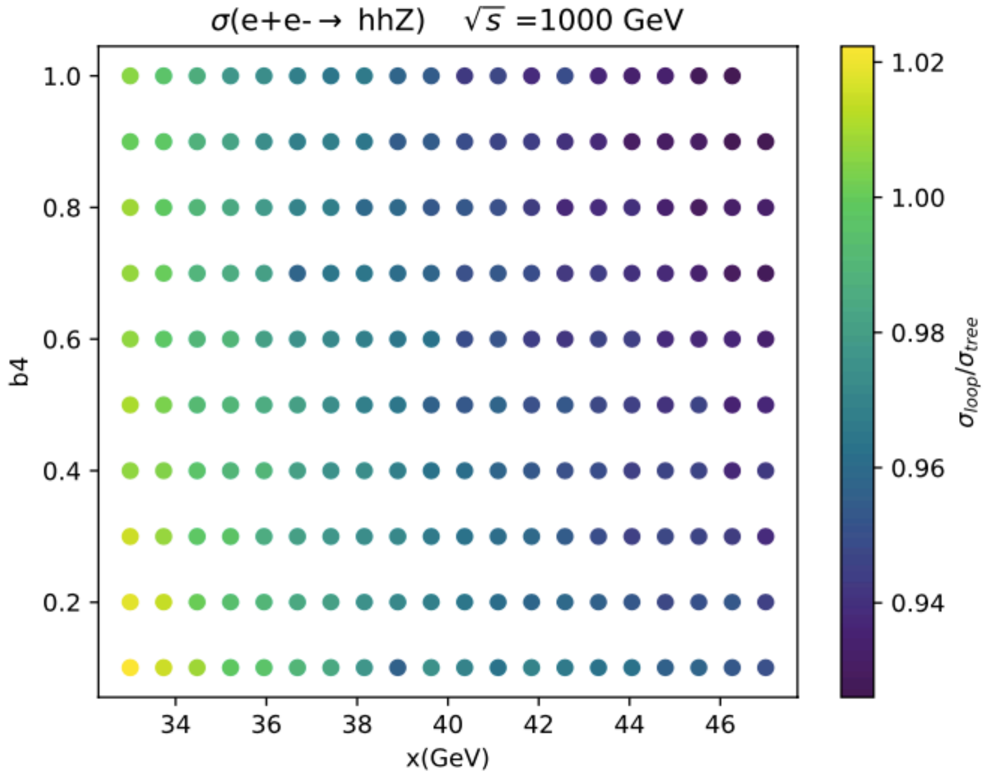
Cross section in the $\kappa_\lambda - \lambda_{hhH}$ plane
$(\sqrt{s} = 500\ GeV)$





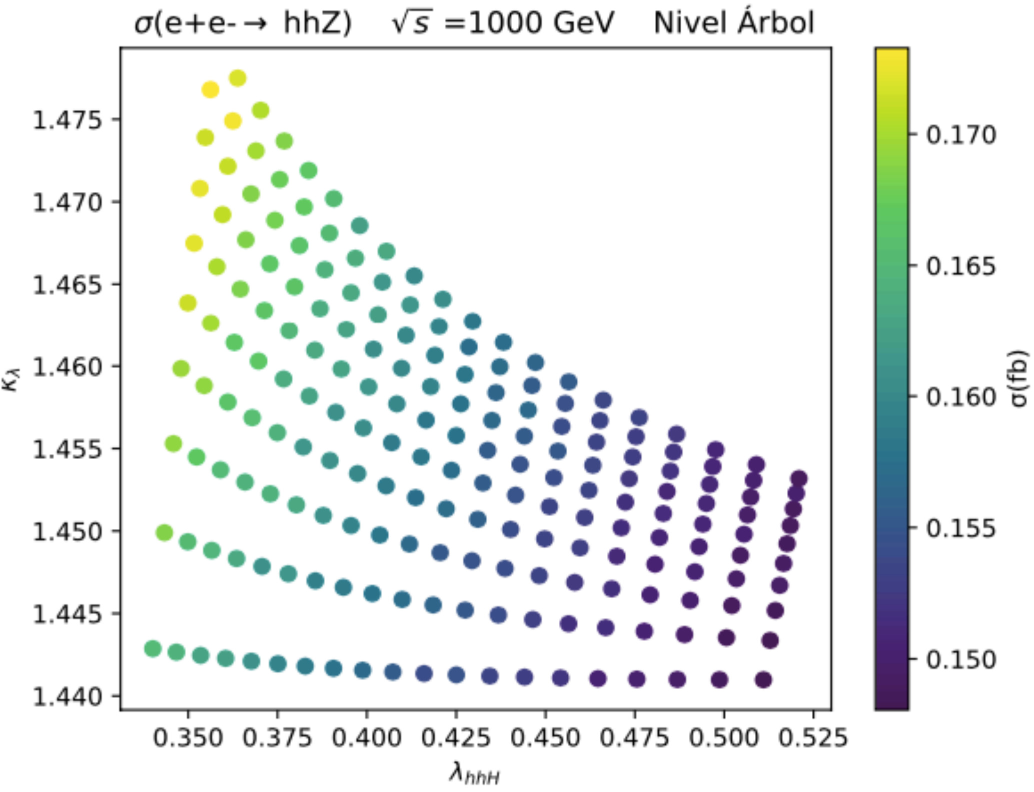
Cross section in the $x - b_4$ plane
$(\sqrt{s} = 1000\ GeV)$

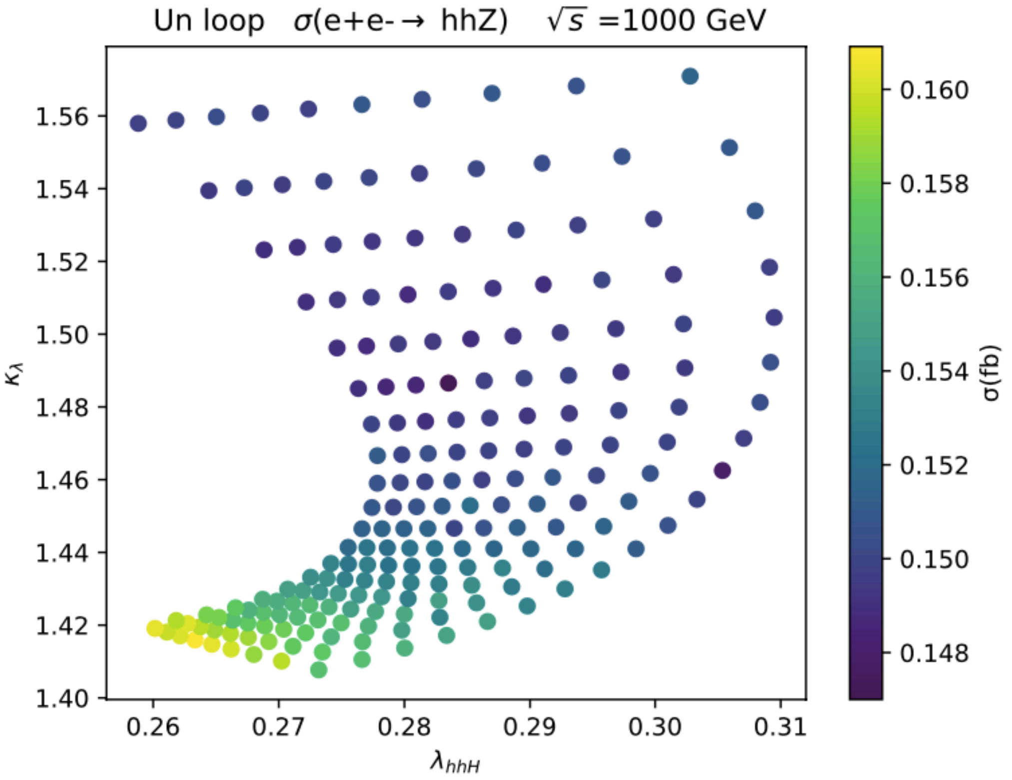




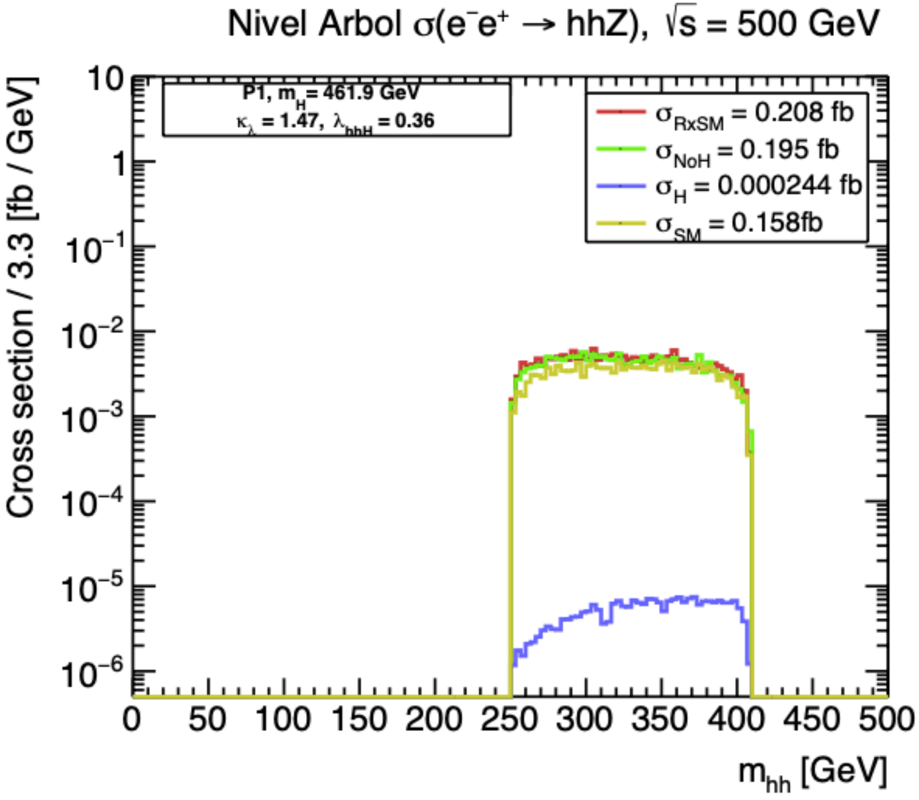
$\sigma_{SM} = 0.120$ fb

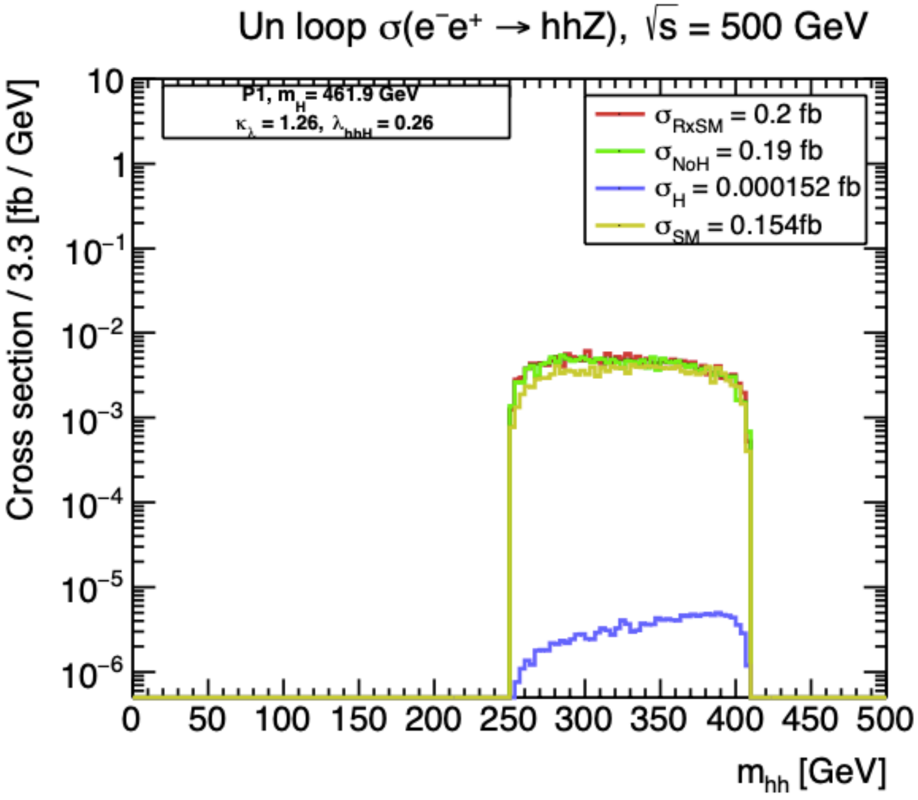
Cross section in the $\kappa_\lambda - \lambda_{hhH}$ plane
$(\sqrt{s} = 1000\ GeV)$





m_{hh} distributions
$(\sqrt{s} = 500\ GeV, P1)$

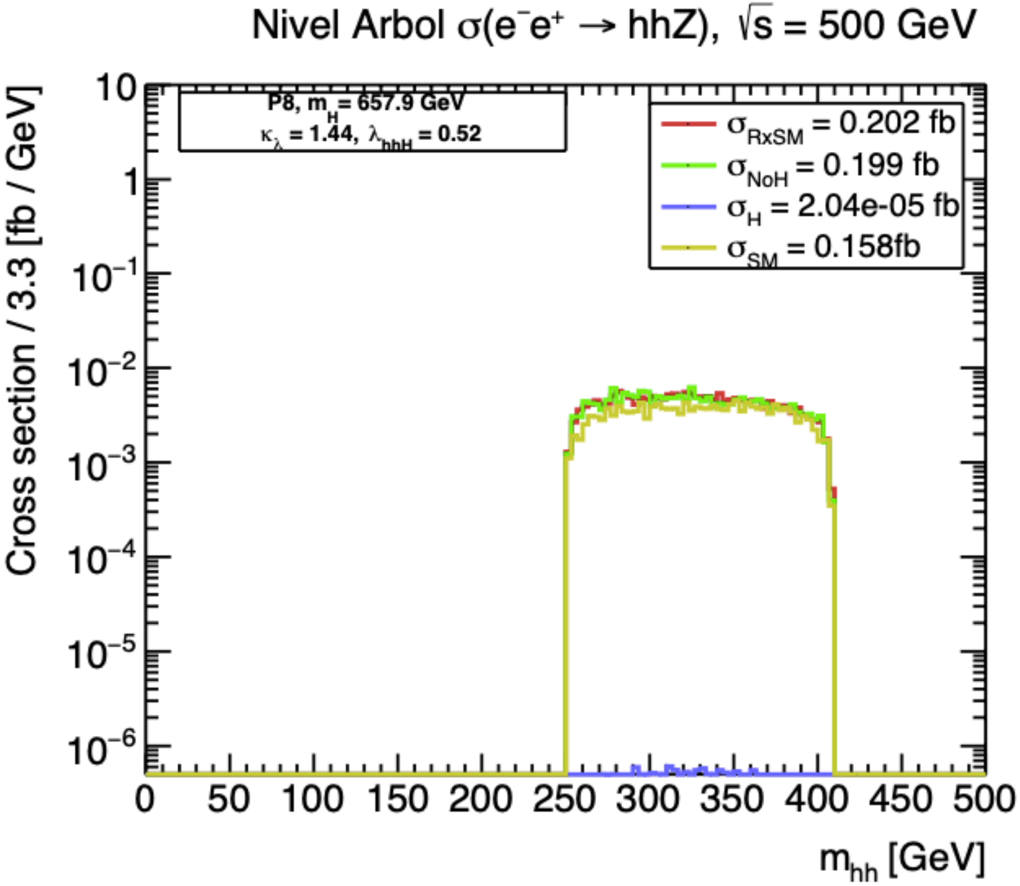


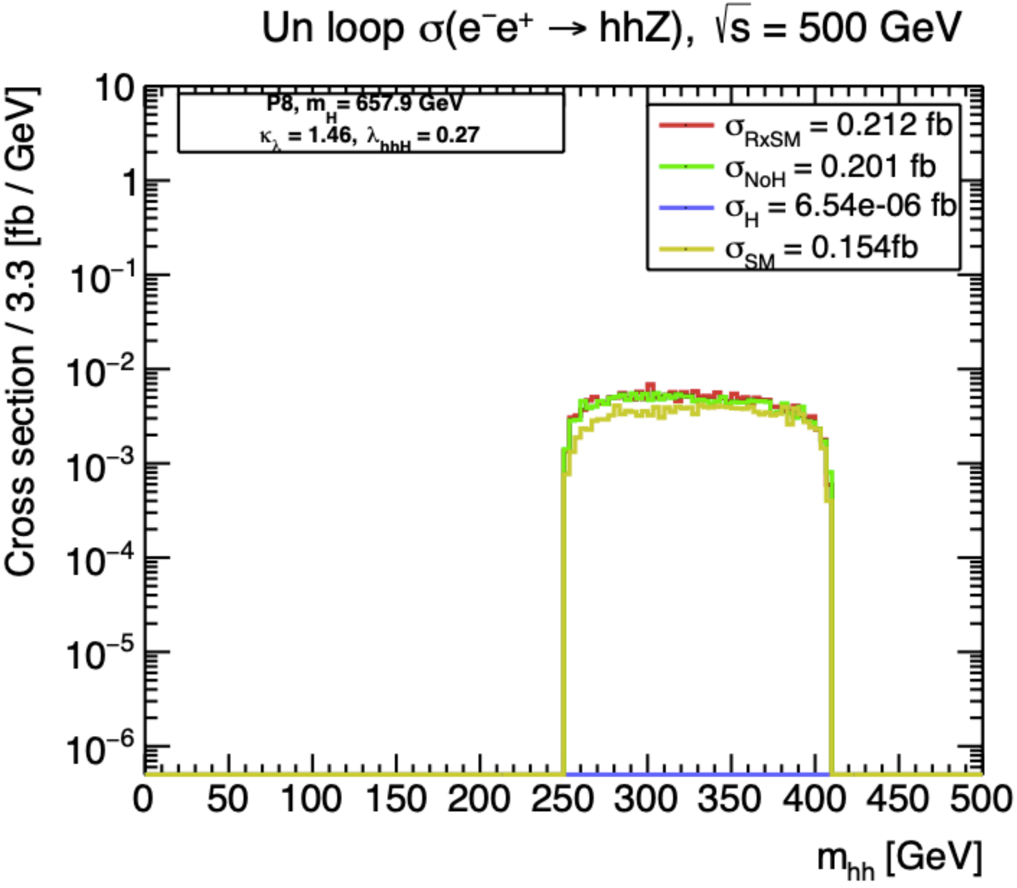


$\lambda_{hhh}^{árbol,\,SM} = 0{,}129$

$\lambda_{hhh}^{loop,\,SM} = 0{,}94\ \lambda_{hhh}^{árbol,\,SM} = 0{,}121$

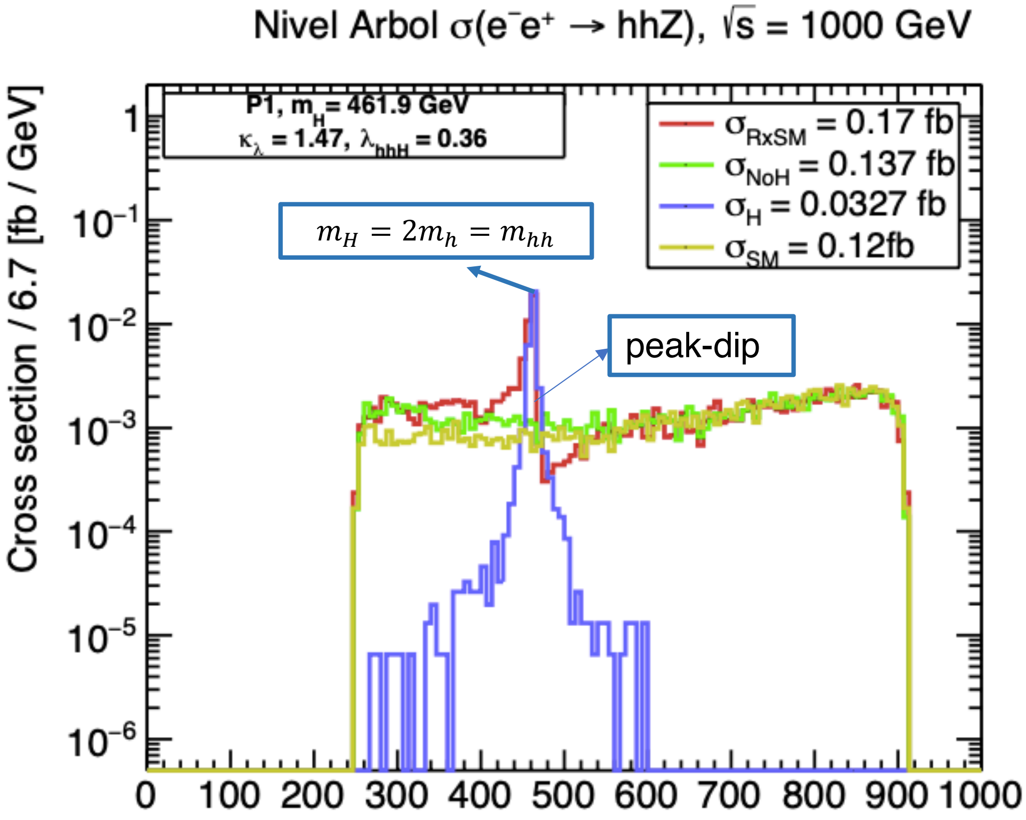
m_{hh} distributions
$(\sqrt{s} = 500\ GeV, P8)$



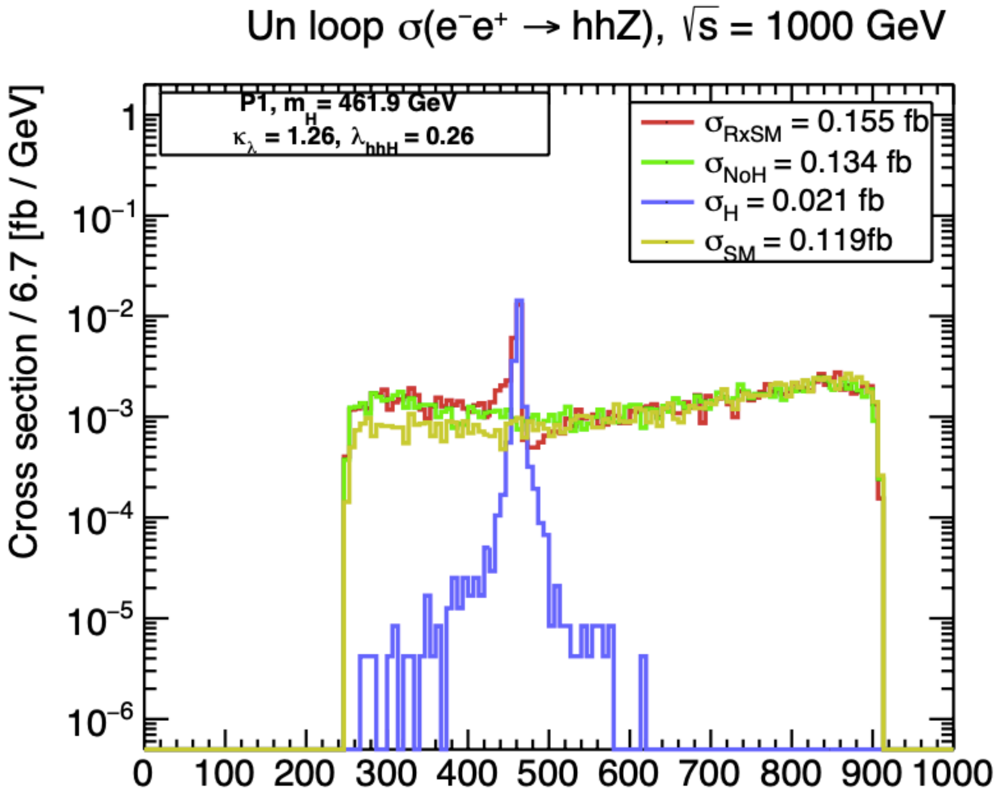


m_{hh} distributions

$(\sqrt{s} = 1000\ GeV, P1)$

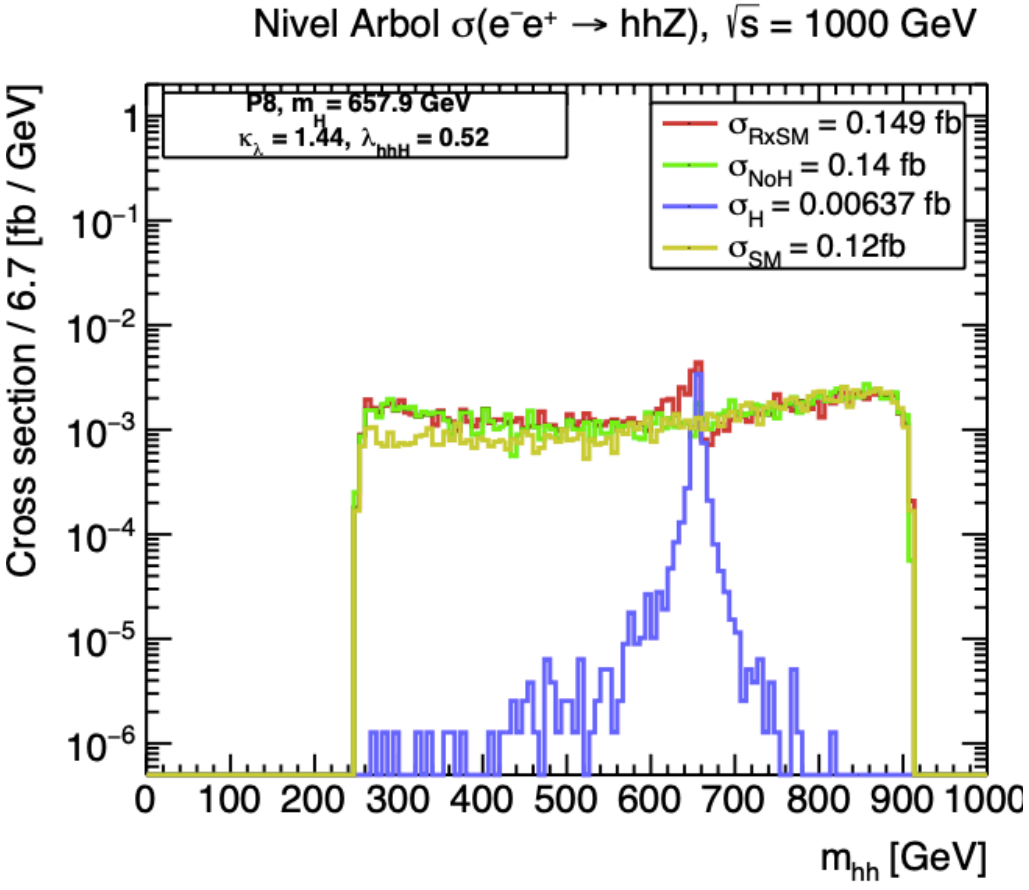


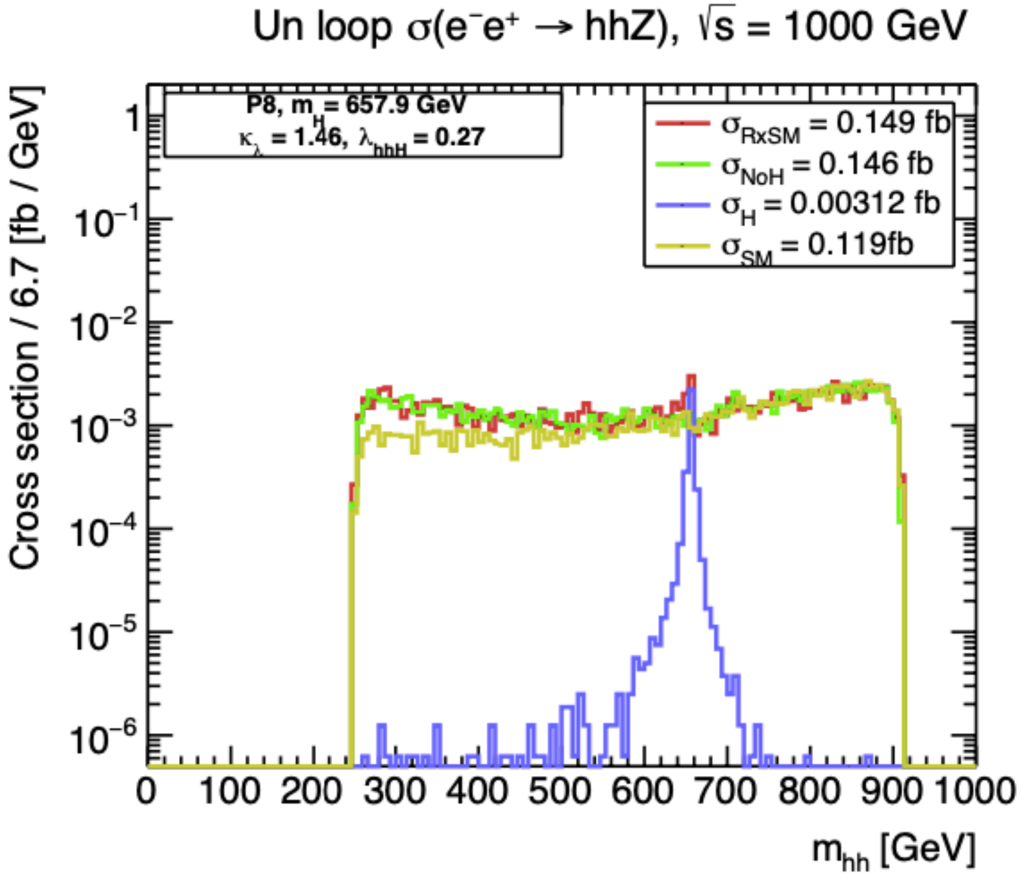
$\lambda_{hhh}^{tree,SM} = 0{,}129$



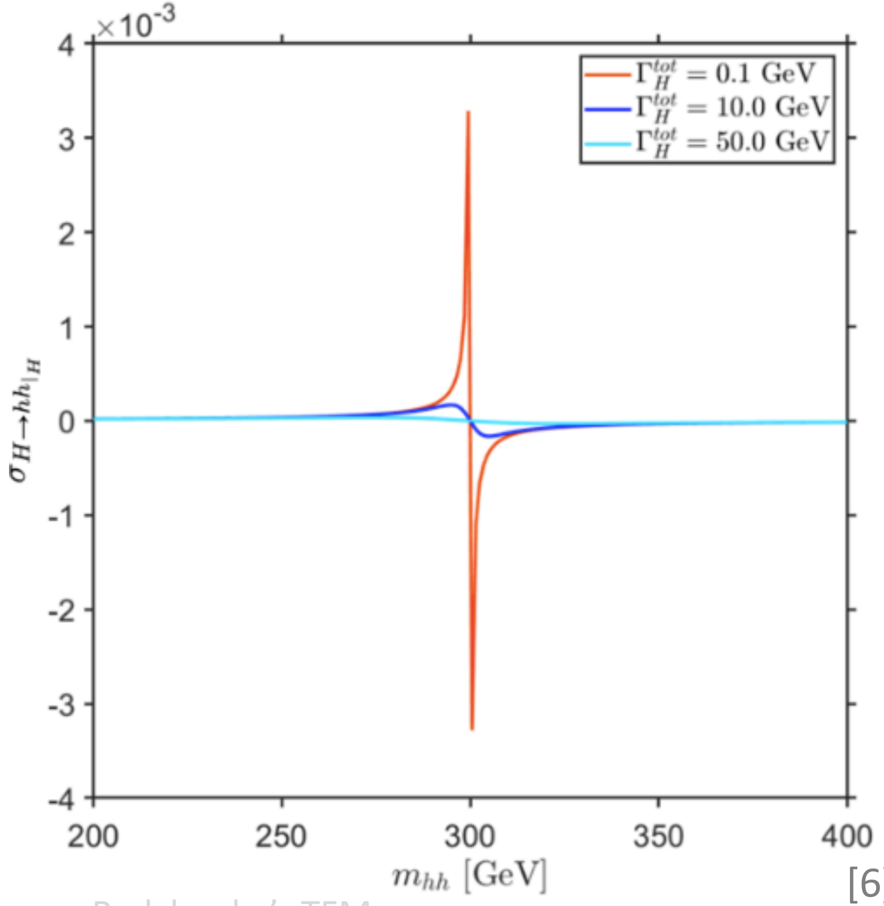
$\lambda_{hhh}^{loop,SM} = 0{,}94\ \lambda_{hhh}^{árbol,SM} = 0{,}121$

m_{hh} distributions
$(\sqrt{s} = 1000\ GeV, P8)$





Peak-dip effect



[6]

$$\sigma_{interf} \propto \frac{Q^2 - m_H^2}{(Q^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}.$$

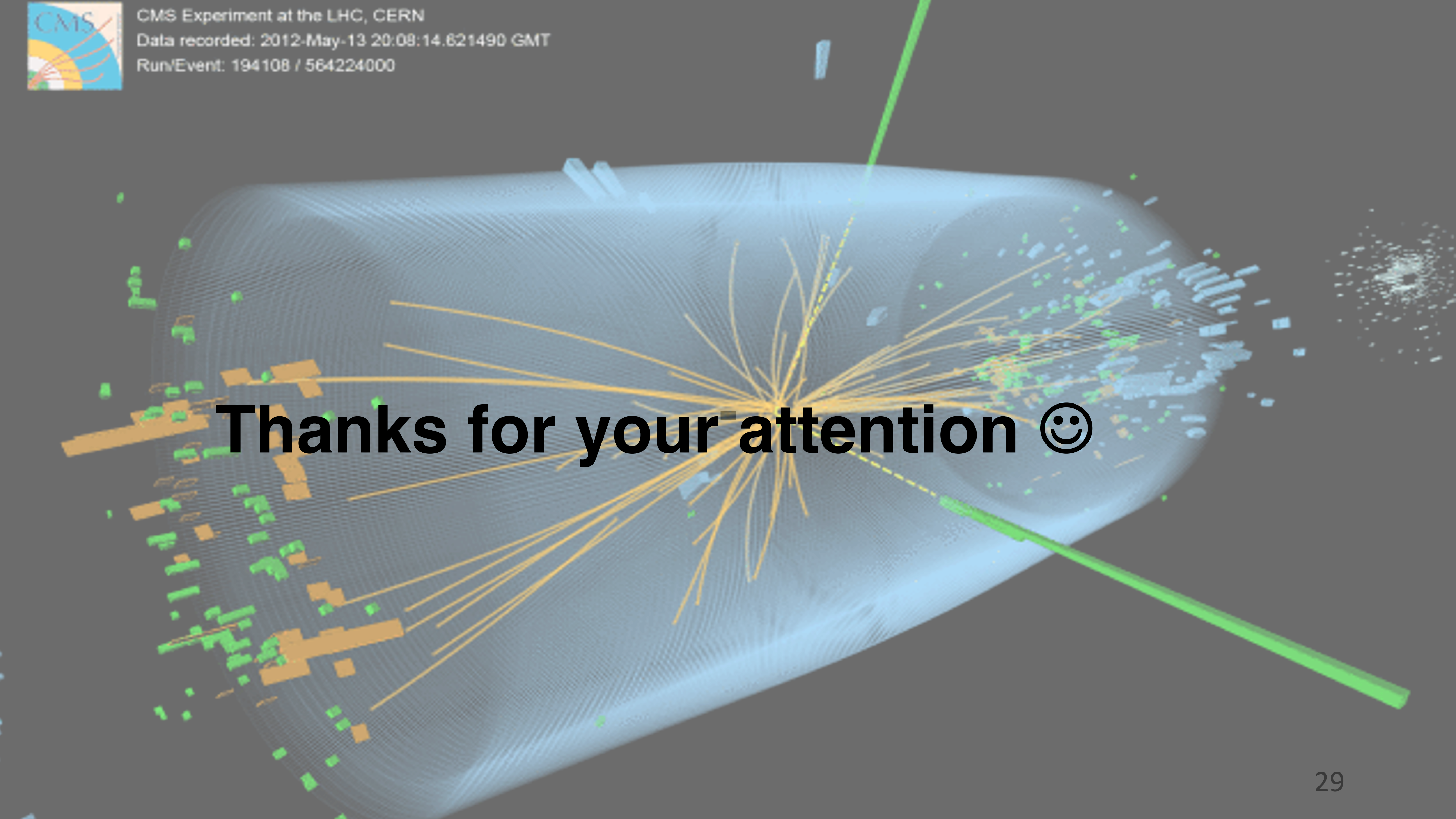
Conclusions

- We can study the FOEWPT with RxSM → Electroweak Baryogenesis → **matter-antimatter asymmetry** in the early Universe and the $V(\phi)$ form.

- Quantum one loop corrections in THC's are important for $\boldsymbol{\lambda_{hhH}}$ → $\lambda_{hhH}^{loop} < \lambda_{hhH}^{tree}$.

- In the process $e^{+}e^{-} \longrightarrow h\,h\,Z$
  - **Quantum one loop corrections** aren't important ($\sigma_{loop}/\sigma_{tree} \sim 1$) (in our plane).
  - RxSM produces an increase ~ 30 % → in the total cross section.

- Outlook: more quantitative analysis of λ_{hhH} sensitivity.



Thanks for your attention ☺

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