Karlsruhe Institute of Technology

Institute for Theoretical Physics

Impact of One-Loop Triple Higgs Couplings on Double Higgs Production at e^+e^- Colliders

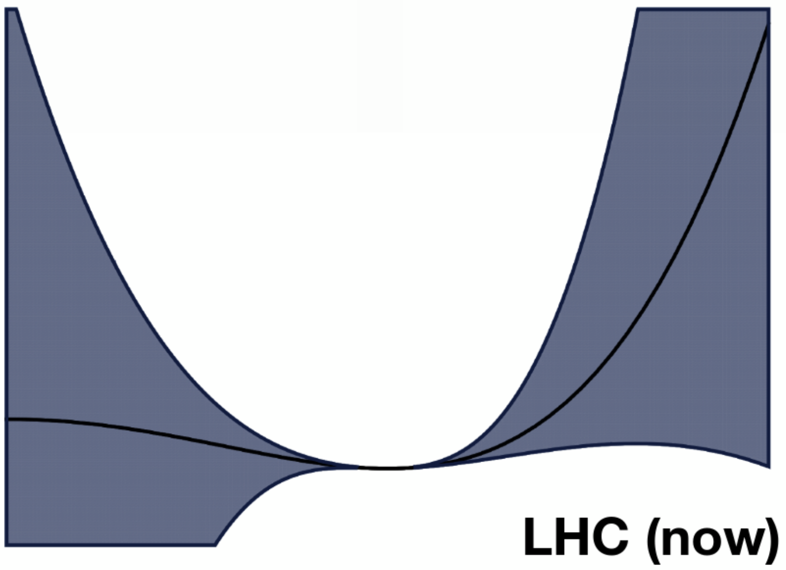
Francisco Arco *(he/him)*

SUSY 2024 – Higgs Parallel Session
Madrid (IFT) – June 13, 2024

Ongoing work with S. Heinemeyer and M. Mühlleitner

Motivation: BSM in the Higgs Sector

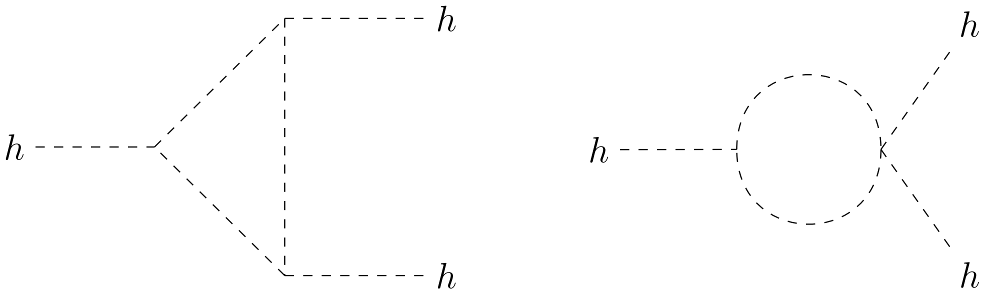
- The Higgs boson potential is essentially ***untested***
- Extended Higgs sectors can solve (at least some) of the SM problems
  - Dark matter, baryon asymmetry…
- Framework: **Two Higgs doublet model (2HDM)**
  - 5 Higgs bosons $h, H, A, H^{\pm}$ + new scalar interactions



Sketch of the current uncertainty in the (SM) Higgs potential, by Nathaniel Craig

Large 1-loop corrections in BSM!

- Large couplings of SM-like Higgs to other Higgs bosons *still allowed*! *[FA, Heinemeyer, Herrero, 21, 22]*
- The 1-loop Higgs self-coupling $\lambda_{hhh}^{(1)}$ can receive corrections well above 100% w.r.t. the tree-level prediction *[Kanemura, Kiyoura, Okada, Senaha, Yuan, 02]*
- Main contributions from **large scalar couplings**:



- Important contributions could happen in other triple Higgs couplings (THCs)

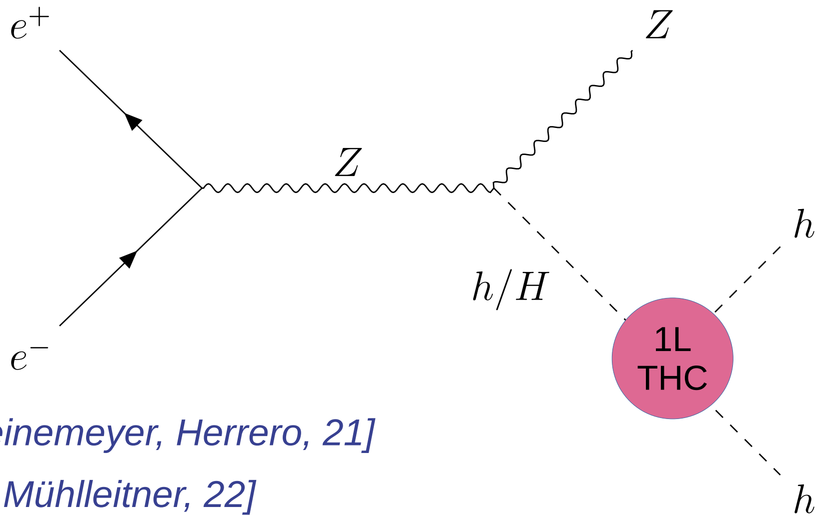
Where to look? At e^+e^- colliders!

- Our computation:

Tree level $e^+e^- \to hhZ$
+
1L corrected $\lambda_{hhh}^{(1)}$ and $\lambda_{hhH}^{(1)}$

- Includes the main corrections:

$$\mathcal{O}\left(\lambda_{3\text{Higgs}}\lambda_{4\text{Higgs}}\right),\ \mathcal{O}\left(\lambda_{3\text{Higgs}}\right)^3$$



- Computation of 1L THCs:
  1. Effective potential for $\lambda_{hhh}^{(1)}$ and $\lambda_{hhH}^{(1)}$
  2. Diagramatic calculation for $\lambda_{hhh}^{(1)}$

- Tree-level THCs @ e^+e^- colliders *[FA, Heinemeyer, Herrero, 21]* and @(HL-)LHC *[FA, Heinemeyer, Radchenko, Mühlleitner, 22]*
- 1 and 2L THCs @(HL-)LHC *[Bahl, Braathen, Weiglein, 22] [Heinemeyer, Mühlleitner, Radchenko, Wieglein, 23]*

Two Higgs Doublet Model (2HDM)

Karlsruhe Institute of Technology

- SM + **second Higgs doublet**

$$V^{(0)}_{\mathrm{2HDM}} = m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) - \left[m_{12}^2\left(\Phi_1^\dagger\Phi_2\right) + \mathrm{h.c.}\right] + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left[\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \mathrm{h.c.}\right]$$

5 physical Higgs bosons: h, H: (CP-even) A: (CP-odd) and $H^\pm$

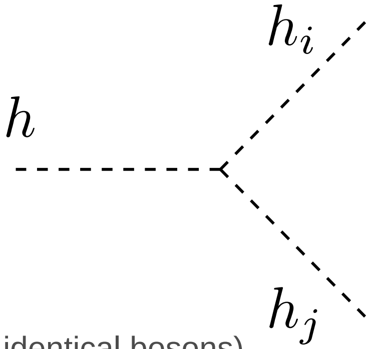
- Z_2 symmetry to avoid FCNC (sofly broken by m_{12}^2) $\Rightarrow$ Four 2HDM types!
- Input parameters:

$$m_h\ (\sim 125\ \mathrm{GeV}),\ m_H, m_A, m_{H^\pm},\ \tan\beta, \cos(\beta-\alpha) \equiv c_{\beta-\alpha},\ m_{12}^2 \equiv \bar{m}^2 s_\beta c_\beta$$

- ***Alignment limit:*** for $c_{\beta-\alpha} = 0$ the SM interactions for h are recovered

Triple Higgs Couplings at tree level

- Notation for THCs:



$$= -ivn!\lambda^{(0)}_{hh_ih_j}$$

(n = # identical bosons)

- Ratio to the SM tree-level coupling:

$$\kappa_\lambda^{(0,1)} \equiv \frac{\lambda^{(0,1)}_{hhh}}{\lambda^{(0)}_{\text{SM}}}$$

with $\lambda^{(0)}_{\text{SM}} = \frac{m_h^2}{2v^2} \simeq 0.13$

- Scalar (triple and quartic) couplings enter at the one-loop (1L) predictions for $\lambda^{(1)}_{hhh}, \lambda^{(1)}_{hhH}$
- Can be very large for large Higgs masses! *[FA, Heinemeyer, Herrero, 21, 22]*
  - For instance: $\lambda_{hH^+H^-} = \lambda_{hhH^+H^-} \lesssim 15$

One-Loop Effective Potential

- Add the 1L Coleman-Weinberg (CW) + counterterm (CT) to the potential

$$V_{\text{2HDM}}^{\text{Eff.}(1)} = V_{\text{2HDM}}^{(0)} + V_{\text{2HDM}}^{(1),\text{CW}} + V_{\text{2HDM}}^{(1),\text{CT}}$$

- **'On-shell'** renormalization scheme:
  - Loop corrected masses and mixing angles are equal to the tree-level values
- **1L THCs** $\lambda^{(1)}_{h_i h_j h_k}$ given by:

$$\boldsymbol{\lambda^{(1)}_{h_i h_j h_k} = \frac{1}{n!v} \frac{\partial^3 V_{\text{2HDM}}^{\text{Eff.}(1)}}{\partial h_i \partial h_j \partial h_k}\bigg|_{\text{min}}}$$

($n =$ # identical bosons)

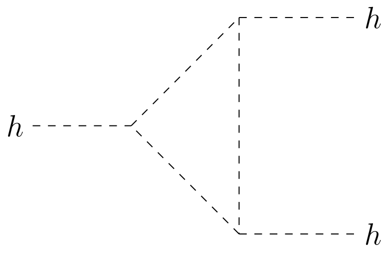
- BSMPT *[Basler, Biermann, Mühlleitner, Müller, Santos, 24]*

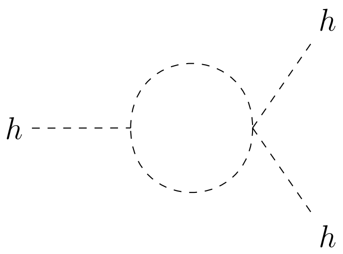
Diagramatic Computation for κ_λ

- All 1L contibutions: WFR + 1PI + tadpoles + counterterms

$$\lambda_{hhh}^{(1)} = \lambda_{hhh}^{(0)} + \delta_{\text{1PI}}^{(1)}\lambda_{hhh} + \delta_{\text{tadpoles}}^{(1)}\lambda_{hhh} + \delta_{\text{WFR}}^{(1)}\lambda_{hhh} + \delta_{\text{CT}}^{(1)}\lambda_{hhh}$$

- **On-shell** renormalization for masses and the angles α and β *[Kanemura, Okada, Senaha, Yuan, 04]*
- m_{12}^2 in the MS bar (small μ dependence)
- Three external legs corrections (WFRs) evaluated at $p_{\text{ext}}^2 = m_h^2$ (OS condition)
- All contributions considered: **full momentum dependence** $\lambda_{hhh}^{(1)}\left(p^2 = m_{hh}^2\right)$
- `anyBSM` *[Bahl, Braathen, Gabelmann, Weiglein, 23]*





(fermion and gauge boson contributions are also included!)

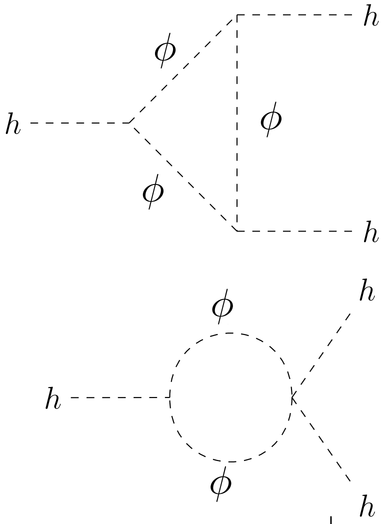
THCs: tree vs 1loop

Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

- Scan of the parameter space
- Applied ***constraints*** to the 2HDM
  - EWPO
  - Tree-level unitarity + potential stability
  - BSM Higgs boson searches
  - Properties of the SM-like Higgs boson
    - *Close to the alignment!*
  - Flavor Observables

[ScannerS + HiggsTools + HDECAY]

κ_λ: tree level vs 1 loop



$\phi = H, A, H^\pm$

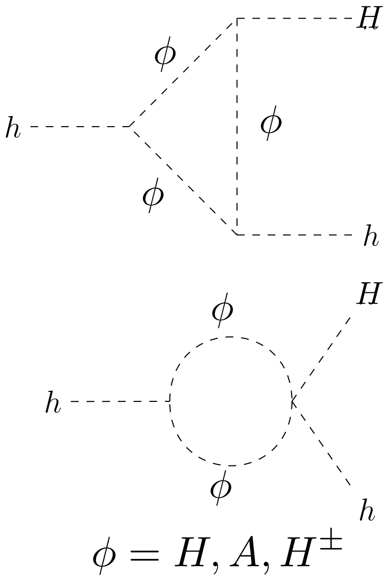
Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- h couplings to heavy Higgs bosons can be large ($\lambda_{h\phi\phi} \sim 15$)
  - Even at the ***alignment limit*** !!!

(In the SM, top-loops are ~ -8%)

λ_{hhH}: tree level vs 1 loop



Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.6]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 5.6]	[-1.7, 1.7]	[-2.0, 2.1]
FL	[0.7, 1.0]	[0.8, 5.6]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- 1L corrections are *not as significant* as for λ_{hhh}
- Still interesting results: $\lambda_{hhH}^{(1)} \gtrsim \lambda_{hhh}^{(0)} \sim 0$ or change of sign in λ_{hhH}

What can we learn from $e^+e^- \to hhZ$?

Karlsruhe Institute of Technology

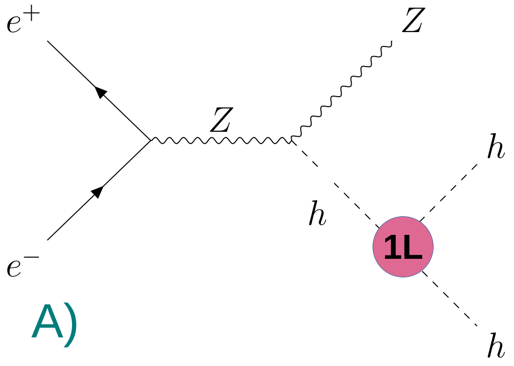
- **Effect of the 1L THCs**, with all pure-scalar contributions (expected to be the larger ones)
- In the case of $\kappa_\lambda^{(1)}$:
  - Very different from the SM even in the alignment! Potential access to BSM physics!
  - Is momentum dependence important?
    - Effective potential has zero external momentum, but $p = m_{hh} \gg 0$
- In the case of $\lambda_{hhH}^{(1)}$:
  - How does the 1L effects affect the H resonant peak?
  - Can we see something at the ILC?

Effects from THCs at $e^+e^- \to hhZ$

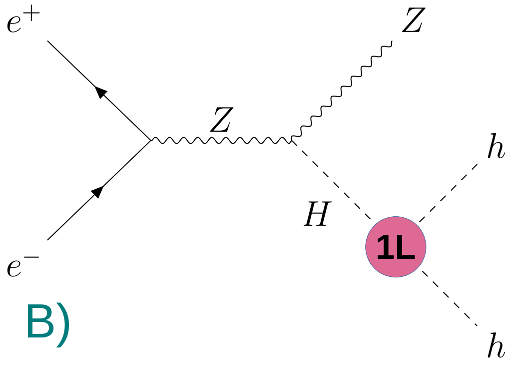
A) **Non-resonant** diagram with $\boldsymbol{\kappa_\lambda}$ → at low m_{hh}

B) **Resonant $\boldsymbol{H}$** diagram with $\boldsymbol{\lambda_{hhH}}$ → at $m_{hh} \simeq m_H$

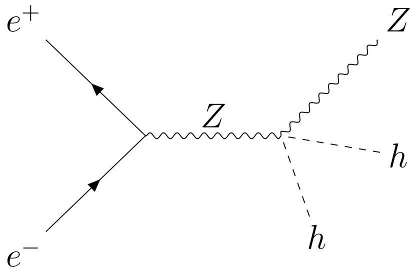
C) Resonant A diagram (no THC)

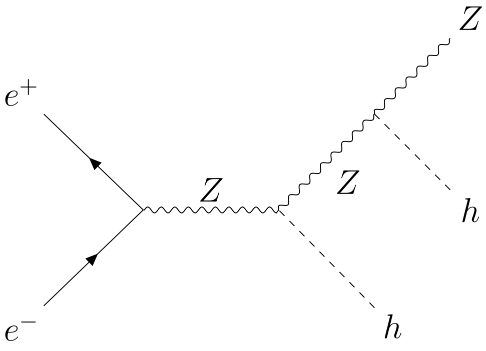


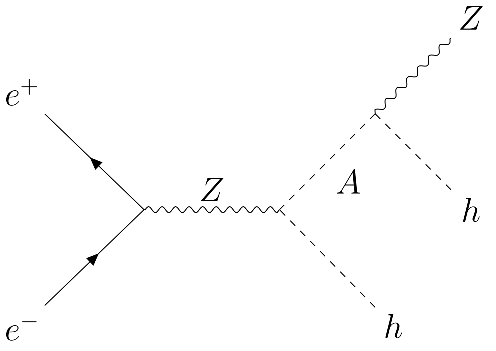
A)



B)







C)

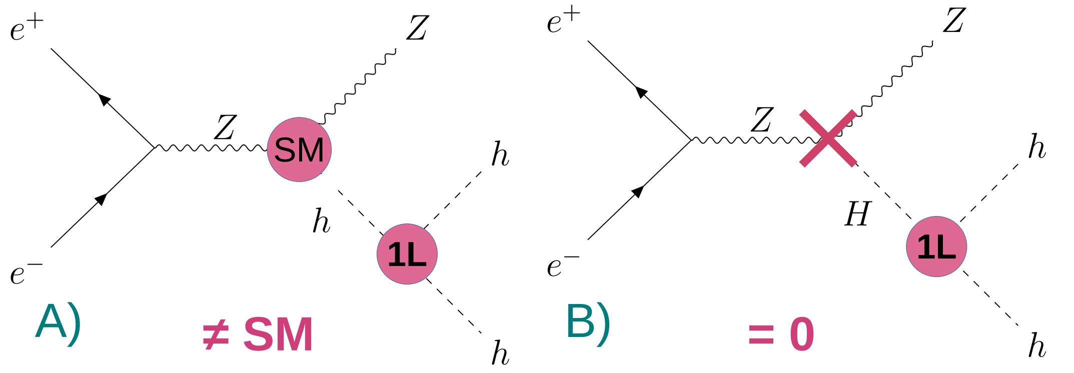
In the alignment limit ($c_{\beta-\alpha}=0$)

A) **Non-resonant** diagram
wit ... h

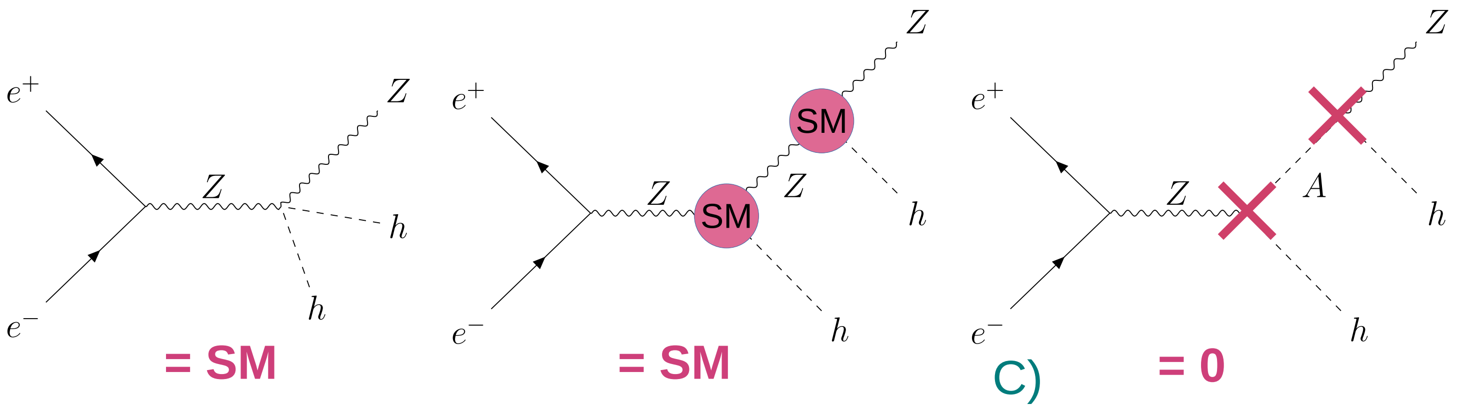
B) **Re** ... am
wit ... $\simeq m_H$

C) Re ... am
(no THC)

Only BSM effects in $\kappa_\lambda^{(1)}$



$$\kappa_\lambda^{(0)} = 1,$$
$$\lambda_{hhH}^{(0)} = 0$$

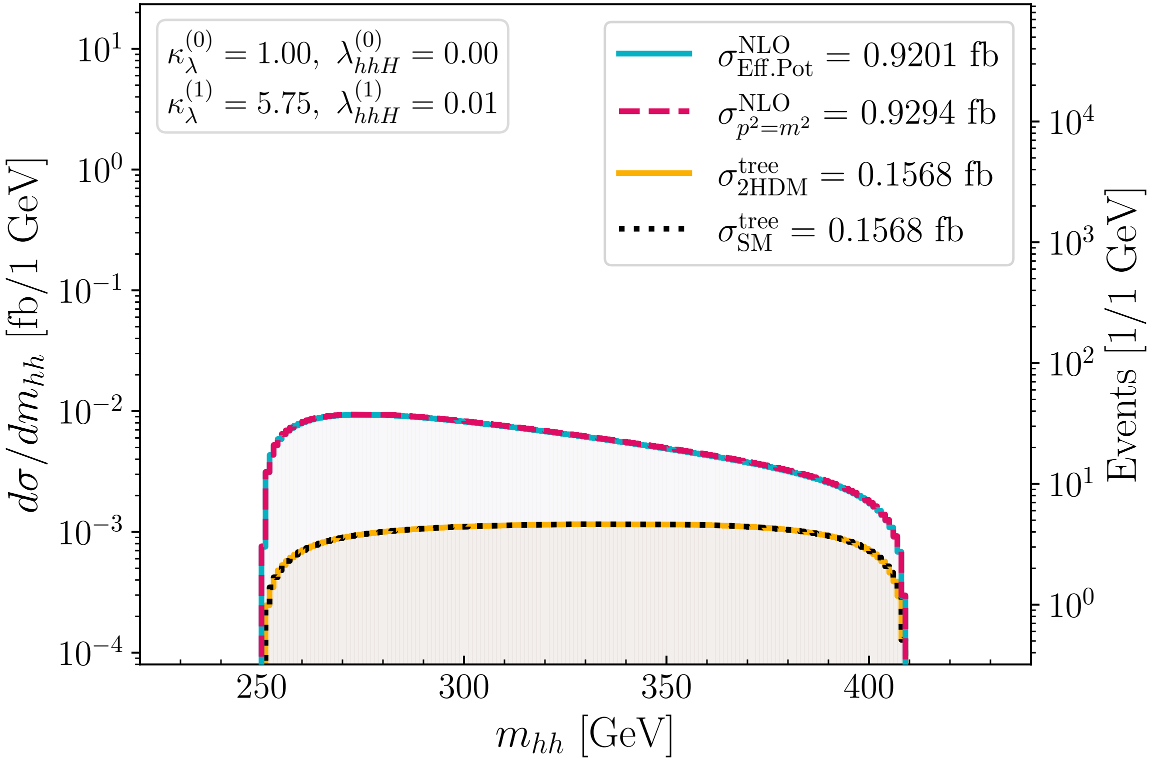


Large 1L κ_λ @ILC500GeV

BPal, all types!

$$m_H = \bar{m} = 400\ \text{GeV},$$
$$m_A = m_{H^\pm} = 800\ \text{GeV},$$
$$\tan\beta = 3,\ \cos(\beta-\alpha) = 0$$

- Cross section 6 times larger than the tree-level prediction !!!
- Momentum effects on $\kappa_\lambda(m_{hh})$ not larger than 1-2%



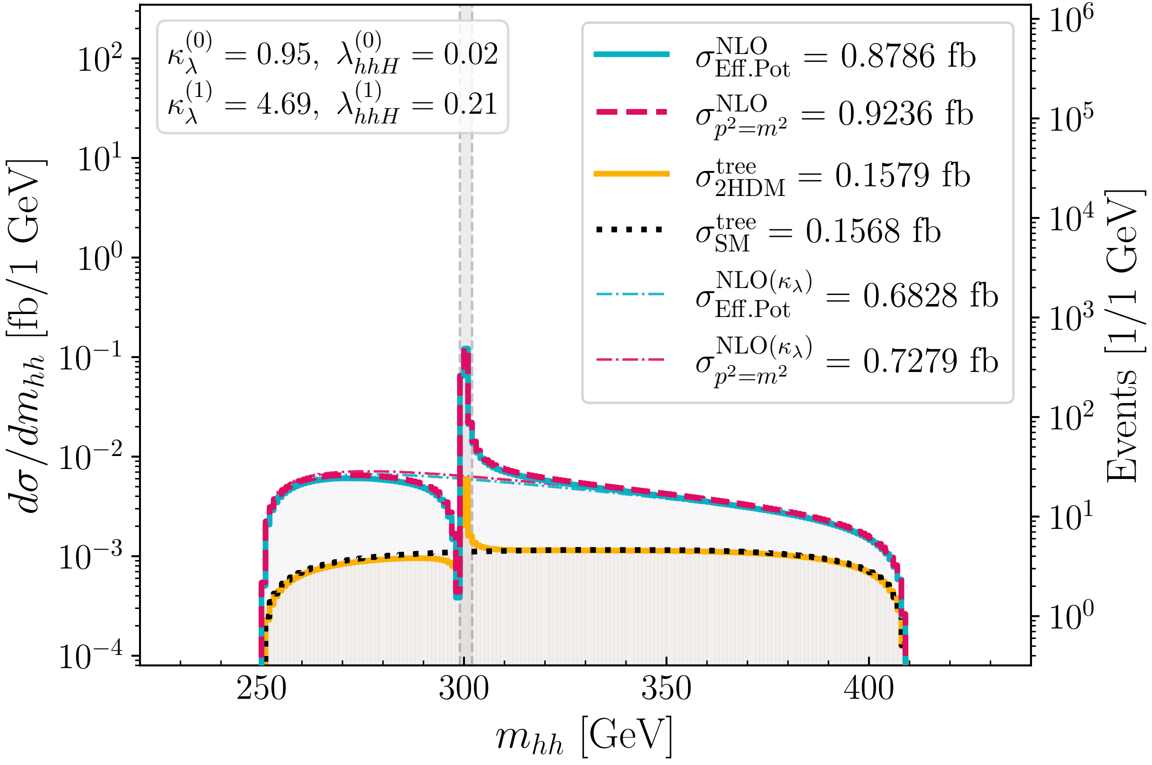
Large 1L λ_{hhH} @ILC500GeV

BPlahhH-1, type I

$$m_H = \bar{m} = 300 \text{ GeV},$$
$$m_A = m_{H^\pm} = 650 \text{ GeV},$$
$$\tan\beta = 12,\ \cos(\beta-\alpha) = 0.12$$

- Large effect from $\kappa_\lambda^{(1)}$
- For this point $\lambda_{hhH}^{(0)} \ll \lambda_{hhH}^{(1)}$

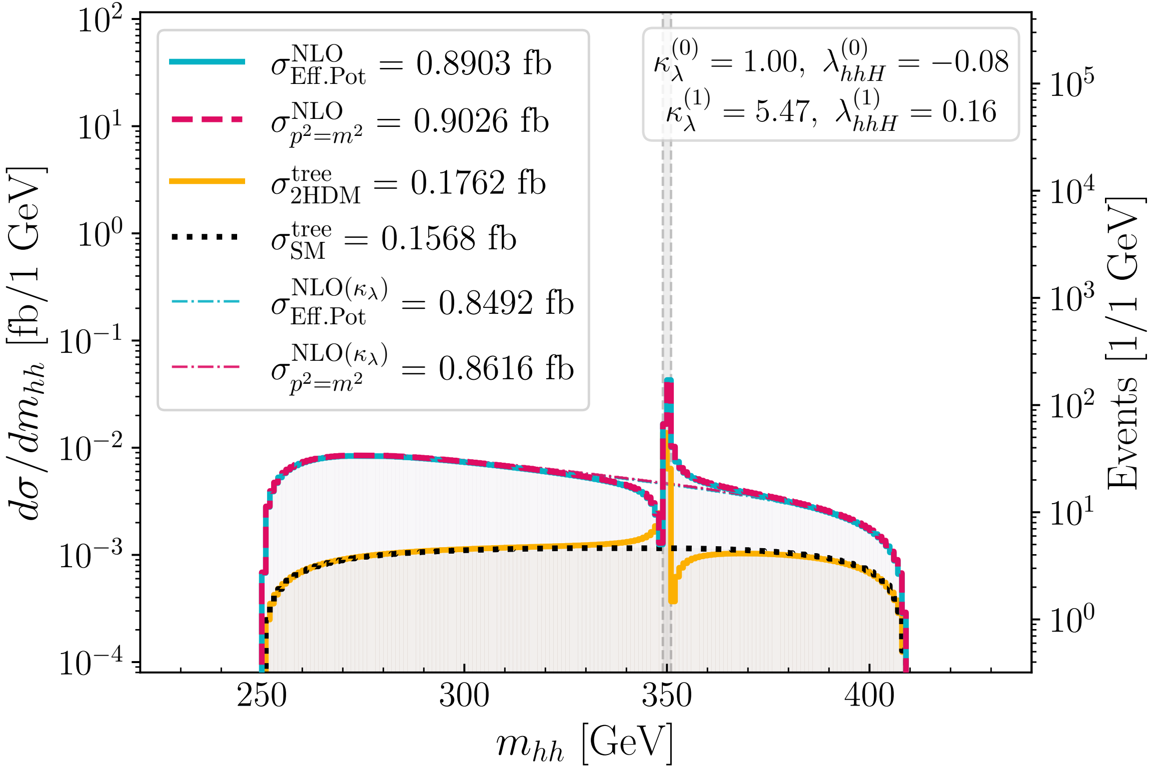
$\Rightarrow$ the H resonance is more prominent



1L λ_{hhH} with different sign @ILC500

$$\text{BPsign, type I}$$
$$m_H = \bar{m} = 350 \text{ GeV},$$
$$m_A = m_{H^\pm} = 650 \text{ GeV},$$
$$\tan\beta = 20,\ \cos(\beta-\alpha) = 0.1$$

- In this point:
  $$\text{sign}\left(\lambda^{(1)}_{hhH}\right) \neq \text{sign}\left(\lambda^{(0)}_{hhH}\right)$$
- $\Rightarrow$ changes the dip-peak structure of the resonance !
- Large effect from $\kappa^{(1)}_\lambda$

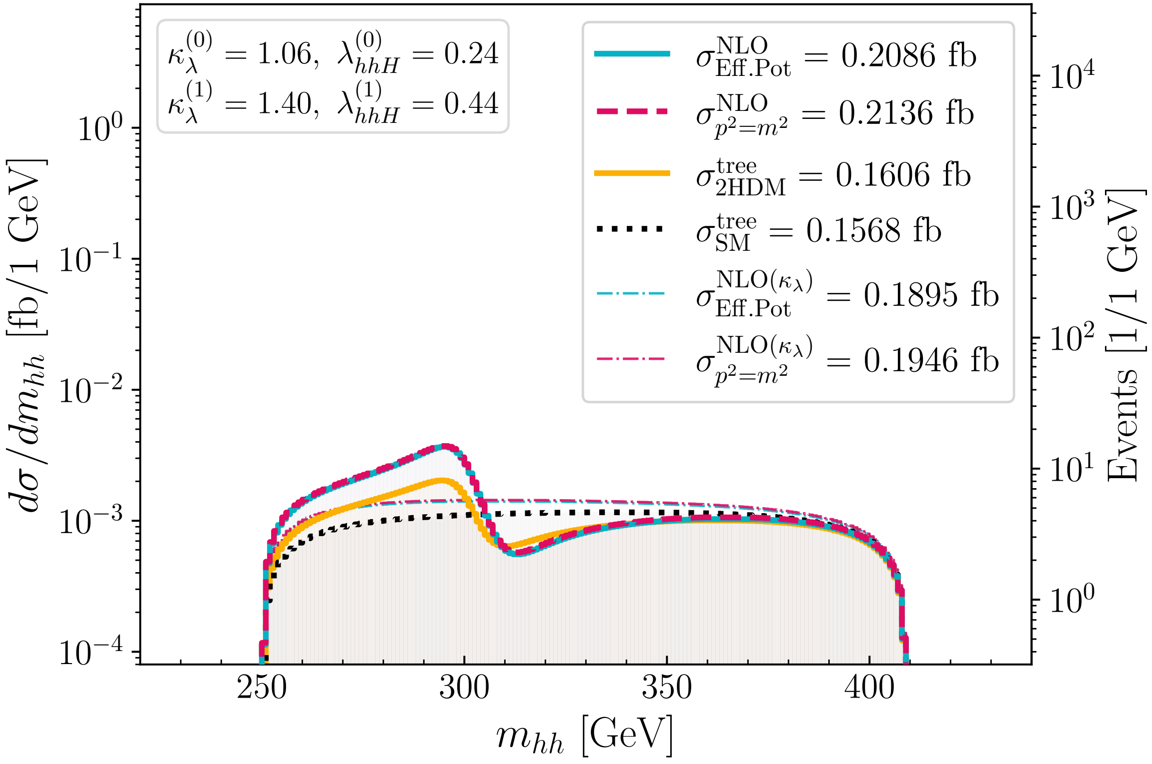


Large 1L λ_{hhH} + large Γ_H @ILC500

BPlahhH-3, type I

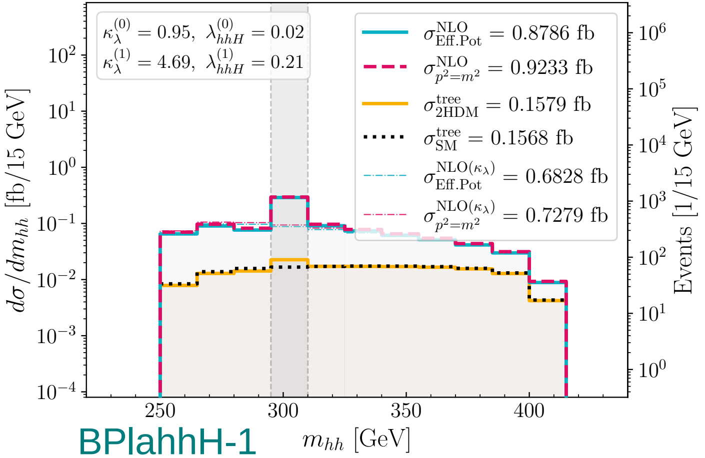
$$m_H = m_{H^\pm} = \bar{m} = 300 \text{ GeV},$$
$$m_A = 100 \text{ GeV},$$
$$\tan\beta = 2.5,$$
$$\cos(\beta - \alpha) = -0.18$$

- In this point, $\lambda^{(1)}_{hhH} \simeq 2\lambda^{(0)}_{hhH}$ but Γ_H = 16 GeV $\Rightarrow$ very broad resonance!
- Not large effects from $\kappa_\lambda^{(1)}$

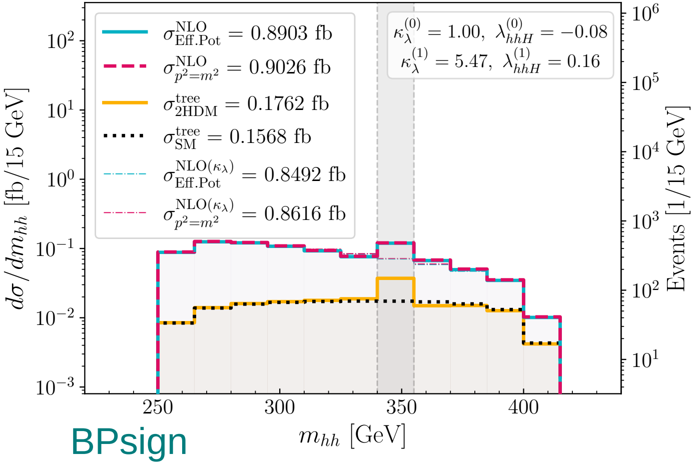


A more realistic bin size: 15 GeV

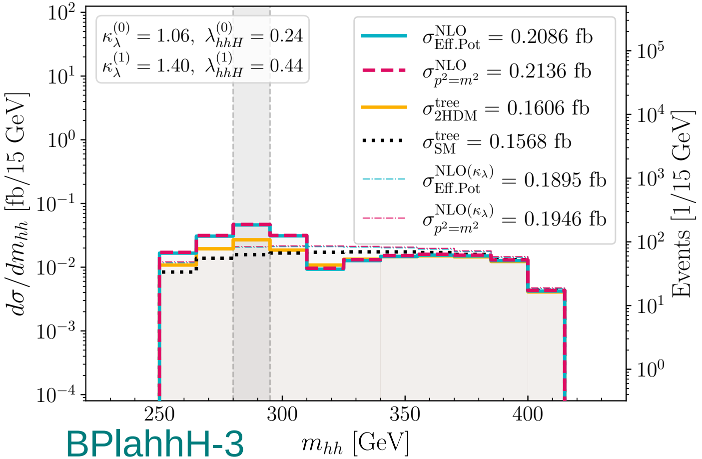
- All the previous features are more difficult to see now…
- Can we quantify this?



BPlahhH-1



BPsign



BPlahhH-3

‘Sensitivity’ to the H resonance

- **Theoretical ‘estimator’** to the sensitivity to the H resonance with the **final $4b$-jet events** from the resonance (R) and the ‘continuum’ (C):

$$R = \sqrt{2\left(\left(s+b\right)\log\left(1+\frac{s}{b}\right)-s\right)}$$

$$\bar{N}_{4bZ} = N_{hhZ} \times \mathrm{BR}\left(h\to b\bar{b}\right)^2 \times \epsilon_b^4 \times \mathcal{A}$$

$$s = \sum_i \left|\bar{N}^R_{i,4bZ} - \bar{N}^C_{i,4bZ}\right|$$

$$b = \sum_i \bar{N}^C_{i,4bZ}$$

(Sum over the bins where R and C are at least 3σ away)

- Correction factors:
  - b-tagging efficiency: ϵ_b = 80%
  - Detector acceptance $\mathcal{A}$ with detection cuts:

$$\mathrm{p}_T^Z > 20\ \mathrm{GeV}\,,\ p_T^b > 20\ \mathrm{GeV}\,, \eta_b < 2\,,\ \Delta R_{bb} > 0.4$$

Similar analysis to
[FA, Heinemeyer, Herrero,21]
[FA, Heinemeyer, Radchenko, Mühlleitner, 22]

Warning! This is not an experimental analysis! No backgrounds, detection simulation, hadronization...

Results for R :

- Large bin size decreases R by 5-6 units
  - Still optimistic results
- BPlahhH-3 (broad peak) is challenging
  - Small bins have no events and large bins give small sensitivity

Point	$\sqrt{s}$	Bin size	# of bins	s	b	b_{tree}	b_{SM}	$\mathcal{A}$	R_2
BPlahhH-1	500	15	1	76.3	35.6	8.6	6.3	0.688	10.2
BPlahhH-1	500	1	3	72.3	7.2	3.6	1.2	0.688	15.4
BPlahhH-1	1000	15	1	64.5	19.4	3.3	1.4	0.613	10.8
BPlahhH-1	1000	1	3	60.9	3.9	2.2	0.3	0.613	15.6
BPlahhH-2	500	15	1	42.1	8.1	31.3	6.6	0.69	9.9
BPlahhH-2	500	1	3	40.7	1.5	26.8	1.2	0.69	14.2
BPlahhH-2	1000	15	1	65.8	2.4	40.4	1.4	0.672	18.0
BPlahhH-2	1000	1	6	65.2	1.2	39.8	0.6	0.672	20.1
BPlahhH-3	500	15	1	9.6	7.9	10.1	5.9	0.679	2.9
BPlahhH-3	500	1	0	0	0	0	0	0.679	-
BPlahhH-3	1000	15	1	6.0	2.6	3.9	1.5	0.675	2.9
BPlahhH-3	1000	1	0	0	0	0	0	0.675	-
BPsign	500	15	1	18.4	27.0	14.0	6.5	0.684	3.2
BPsign	500	1	2	19.0	3.5	7.6	0.8	0.684	6.8
BPsign	1000	15	1	27.3	18.1	11.6	1.3	0.626	5.4
BPsign	1000	1	2	27.0	2.4	9.8	0.2	0.626	9.7
BPext	500	15	1	83.7	38.9	27.7	3.1	0.678	10.7
BPext	500	1	2	79.9	6.3	24.8	0.6	0.678	17.1
BPext	1000	15	1	53.3	19.8	16.4	0.8	0.587	9.2
BPext	1000	1	2	50.6	3.3	15.6	0.2	0.587	14.1

Summary & Conclusions

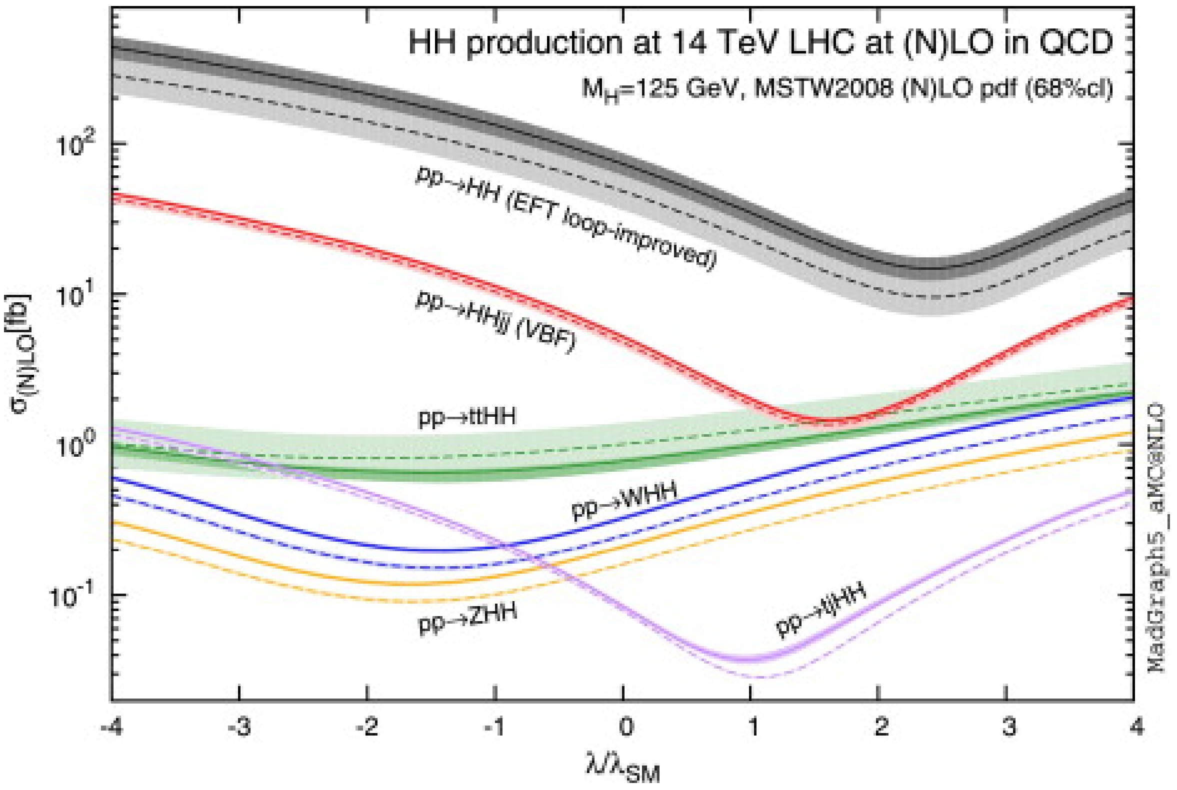
Karlsruhe Institute of Technology

- Analysis of the **1L corrected triple Higgs couplings κ_λ and λ_{hhH}**, and their impact in **double Higgs production** at e^+e^- colliders in the 2HDM, specifically $e^+e^- \to hhZ$ at ILC
- **1L corrections to κ_λ can be very large**, *even in the alignment limit!!!*
  - Very distinct prediction even for a very SM-like Higgs boson!
- **1L corrected λ_{hhH} can lead to interesting pheno!**
  - Access to this effect via the H resonance peak
    - Analysis of the **final 4b-jet events**: access to the resonance peak may be challenging *(but an experimental analysis is needed)*
    - Resolution in the m_{hh} distributions will be crucial

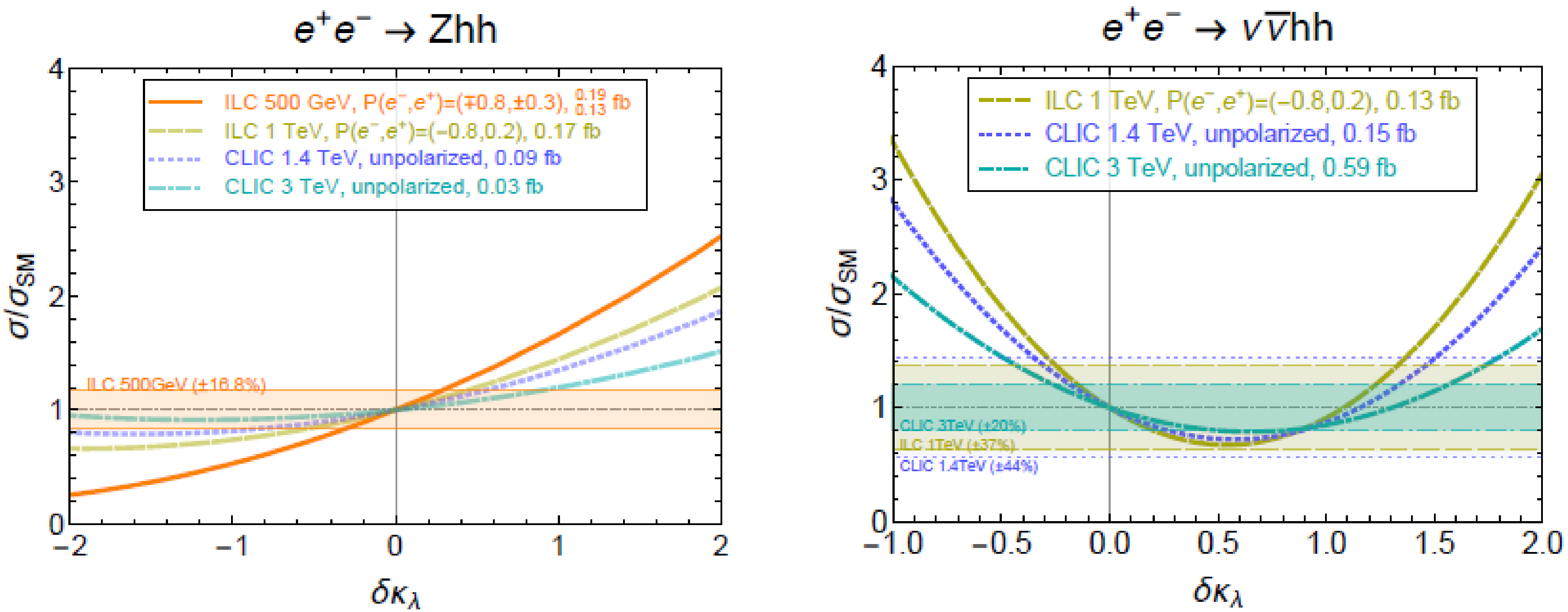
Thanks for your attention! :)

Back up

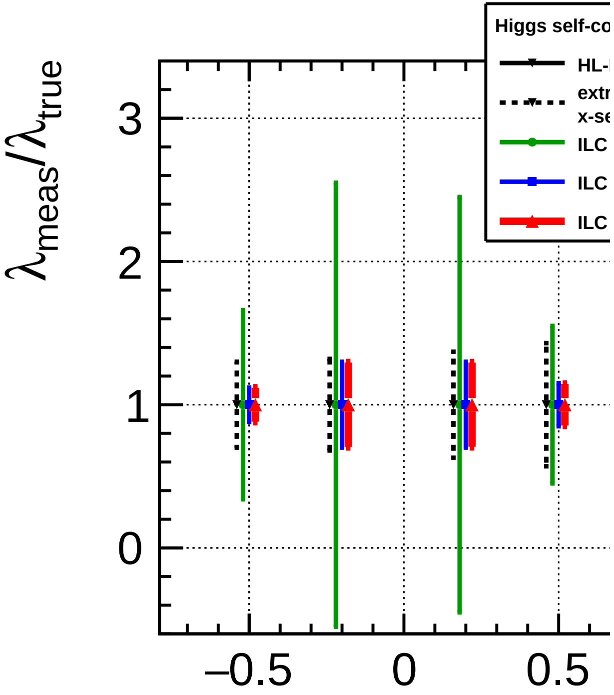
XS vs κ_λ in the SM at LHC



XS vs κ_λ in the SM at e^+e^- colliders



$\kappa_\lambda \neq 1$ at HL-LHC and e^+e^- colliders



[Torndal, List, Ntounis, Vernieri, 23]

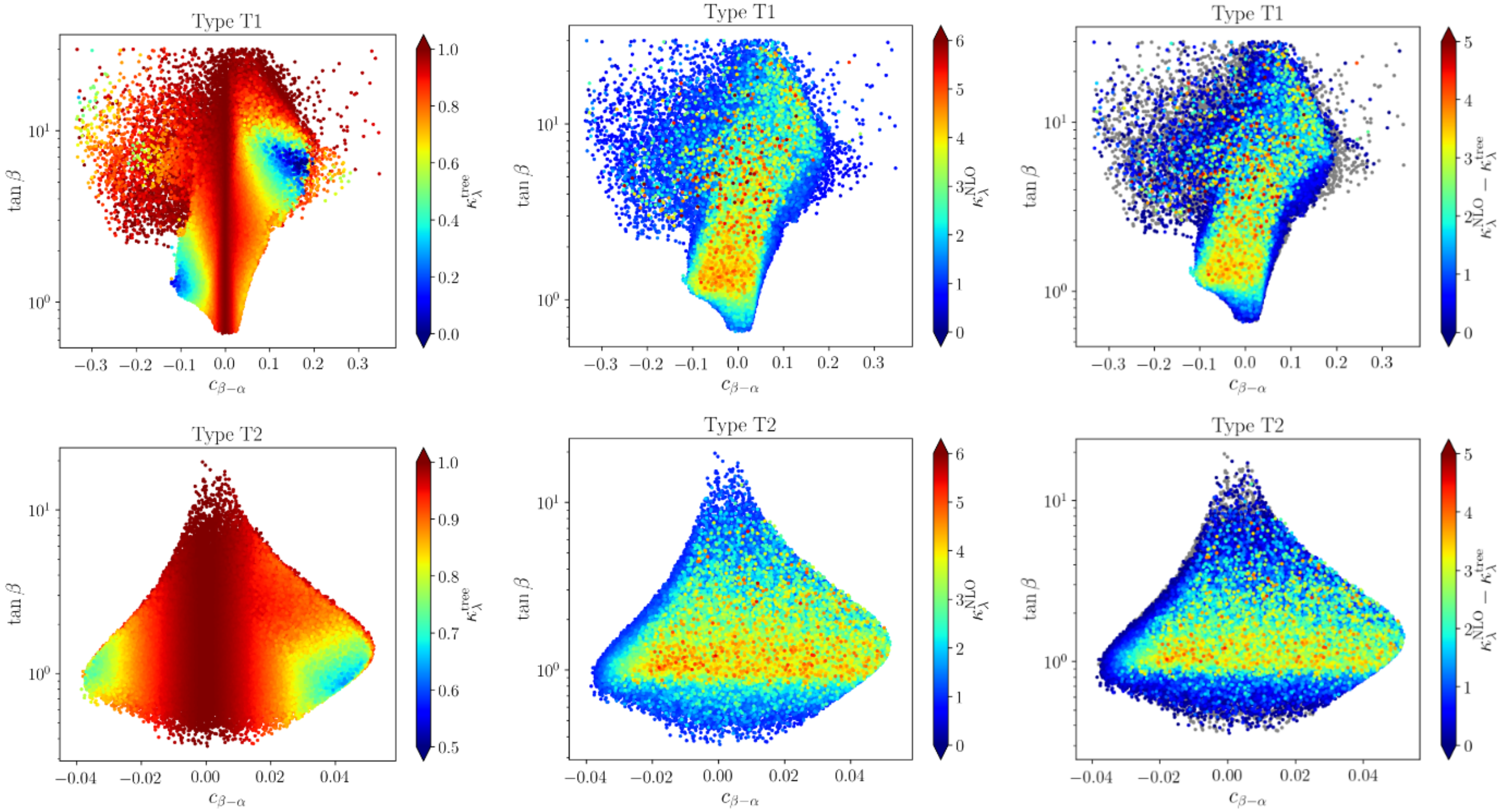
Main corrections to κ_λ

[Kanemura,Kiyoura,Okada,Senaha,Yuan,02]

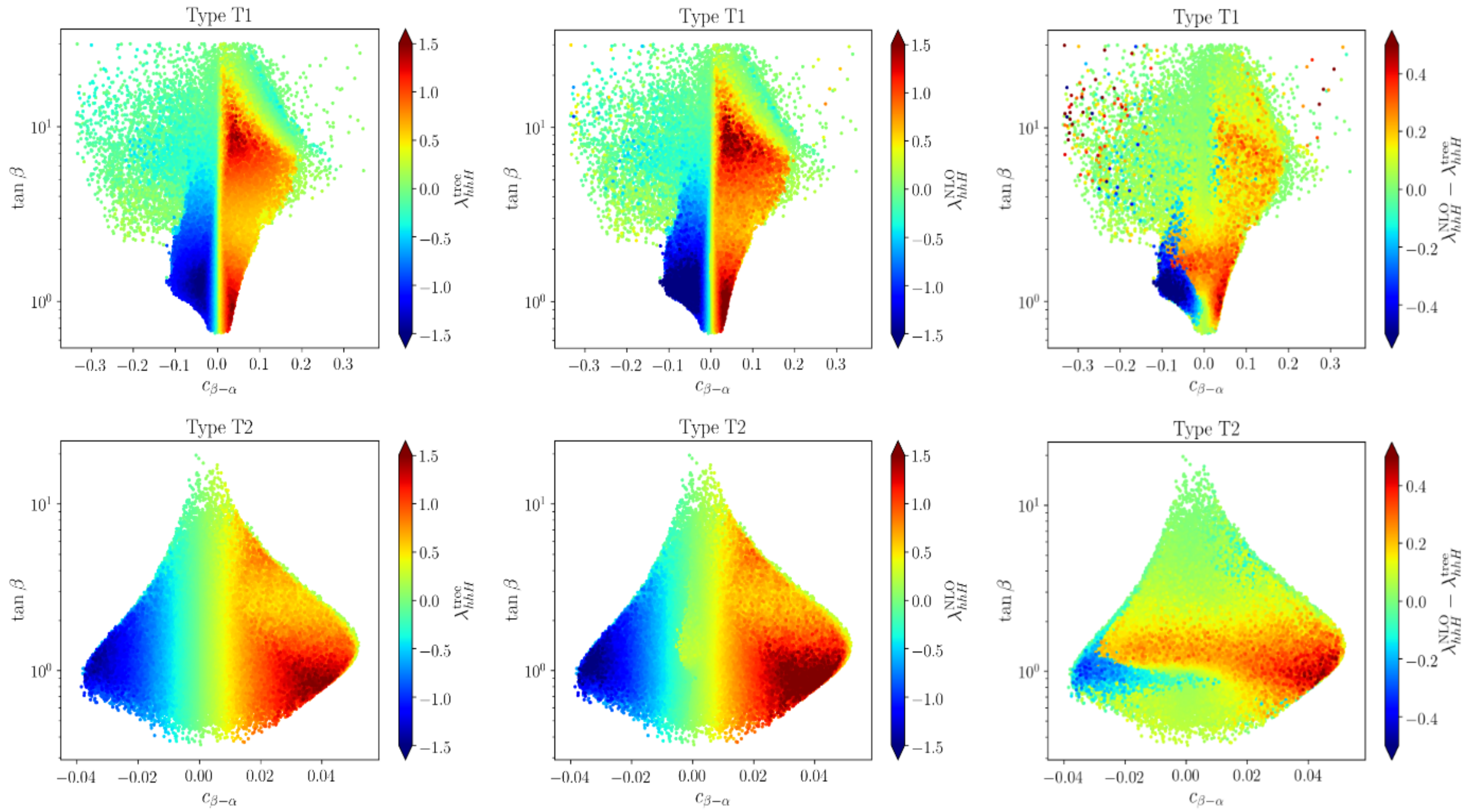
$$\kappa_\lambda^{(1)} \equiv \frac{\lambda_{hhh}^{(1)}}{\lambda_{\rm SM}^{(0)}} \simeq 1 + \sum_{\phi=H,A,H^\pm} \frac{m_\phi^4}{12\pi^2 m_h^2 v^2}\left(1 - \frac{\bar{m}^2}{m_\phi^2}\right)^3$$

$$\lambda_{\rm SM}^{(1)} \simeq \lambda_{\rm SM}^{(0)}\left(1 - \frac{m_t^4}{\pi^2 m_h^2 v^2}\right) \qquad \lambda_{\rm SM}^{(0)} = \frac{2m_h^2}{v^2} \simeq 0.13$$

Results for κ_λ



Results for λ_{hhH}

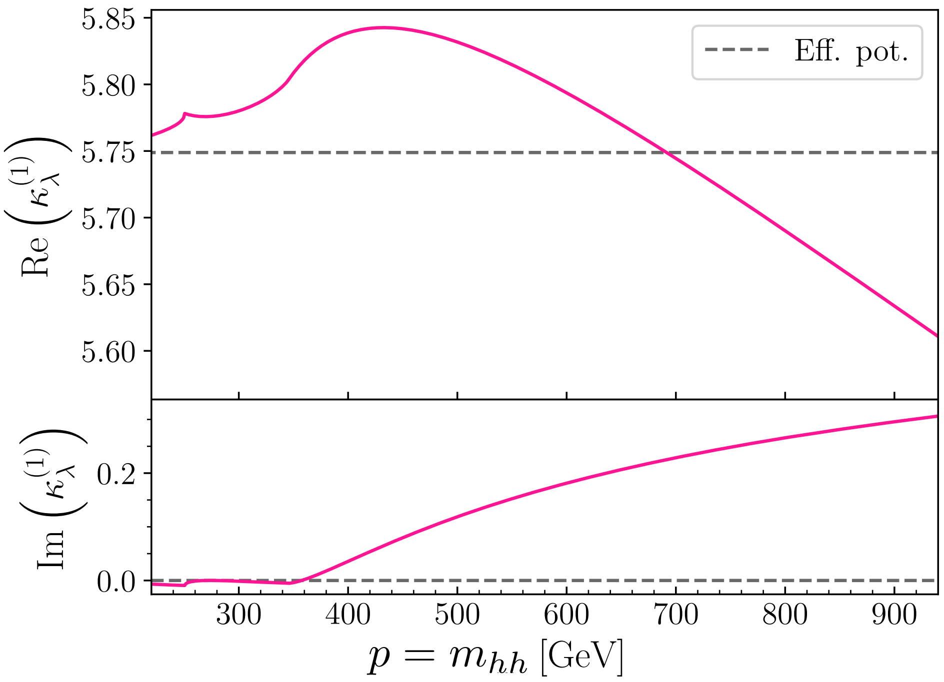


Example for large κ_λ at 1 loop

BPal, all types!

$$m_H = \bar{m} = 400 \text{ GeV},$$
$$m_A = m_{H^\pm} = 800 \text{ GeV},$$
$$\tan\beta = 3,\ \cos(\beta - \alpha) = 0$$

- Large $\kappa_\lambda^{(1)}$ due to large $\lambda^{(0)}_{hAA}$ and $\lambda^{(0)}_{hH^+H^-}$
- Good agreement between effective potential and diagramatic computation
  - Momentum dependence more important for large momentum



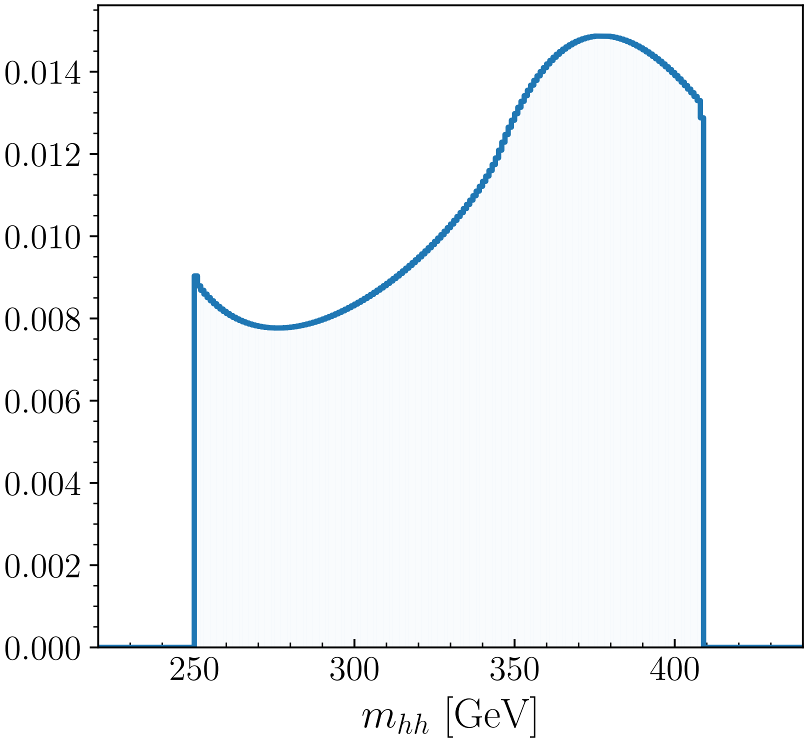
Relative difference w/ and wo/ p

BPal, all types!

$$m_H = \bar{m} = 400 \text{ GeV},$$

$$m_A = m_{H^\pm} = 800 \text{ GeV},$$

$$\tan\beta = 3,\ \cos(\beta - \alpha) = 0$$



2HDM Yukawa couplings

Karlsruhe Institute of Technology

$$\mathrm{L}_{\text{Yukawa}} \supset -\sum_{f=u,d,l} \frac{m_f}{v} \left[\xi_f^h \bar{f} f h + \xi_f^H \bar{f} f H + \xi_f^A \bar{f} \gamma_5 f A \right]$$

$$- \frac{\sqrt{2}}{v} \left[\bar{u} \left(\xi_d V_{\text{CKM}} m_d P_R - \xi_u m_u V_{\text{CKM}} P_L \right) d H^+ + \xi_l \bar{\nu} m_l P_R l H^+ + \text{h.c.} \right]$$

	Type I	Type II	Type III	Type IV
ξ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_d	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$
ξ_l	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$

with $\xi_f^h = s_{\beta-\alpha} + \xi_f c_{\beta-\alpha}\,, \xi_f^H = c_{\beta-\alpha} - \xi_f s_{\beta-\alpha}\,, \xi_u^A = -i\xi_u\,, \xi_{d,l}^A = i\xi_{d,l}$