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Institute for Theoretical Physics

BSM (one-loop) Triple Higgs Couplings at Future e^+e^- Colliders

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Virtual Overflow Session of 3rd ECFA Workshop
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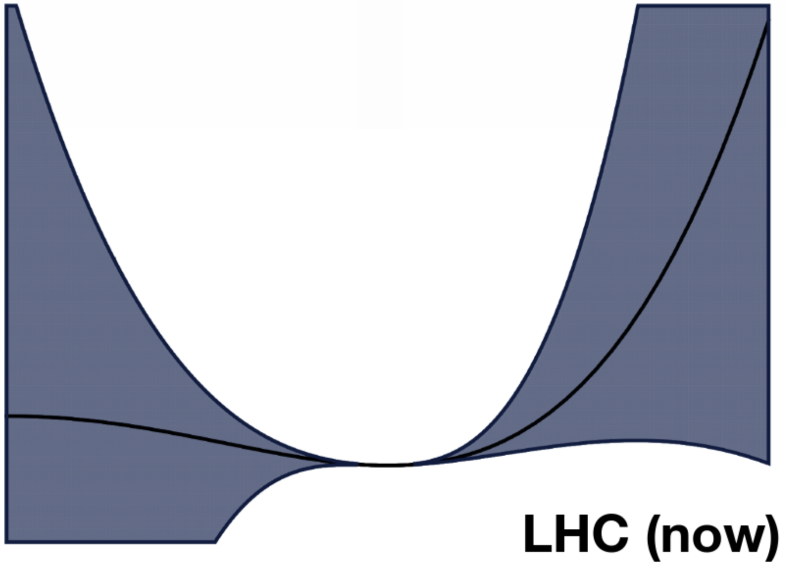
Ongoing work with S. Heinemeyer and M. Mühlleitner

Motivation: BSM in the Higgs Sector

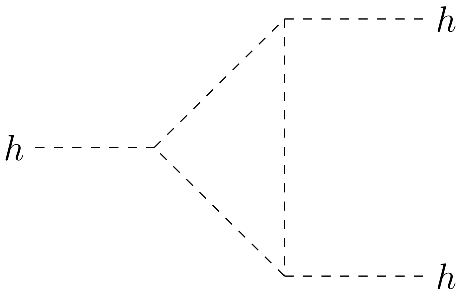
- The Higgs boson potential is essentially ***untested***
- Extended Higgs sectors can solve (at least some) of the SM problems
  - Baryon asymmetry
  - Dark matter
  - Hierarchy problem
  - ...
- ***Many, many room for BSM physics!***

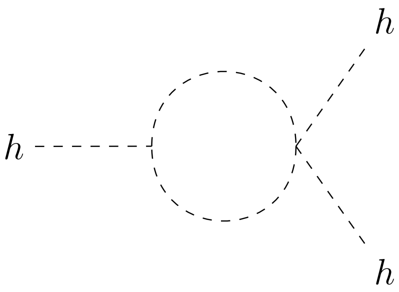


Sketch of the current uncertainty in the (SM) Higgs potential, by Nathaniel Craig

Large 1L corrections @BSM models!

- Framework: **Two Higgs doublet model (2HDM)**
  - 5 Higgs bosons $h, H, A, H^{\pm}$ + new scalar interactions
  - **Large scalar couplings** are still allowed! *[FA, Heinemeyer, Herrero, 21, 22]*
- Large scalar couplings can lead to **large 1L corrections** to $\lambda_{hhh}^{(1)}$ (well above 100% w.r.t. the tree level) *[Kanemura, Kiyoura, Okada, Senaha, Yuan, 02]*



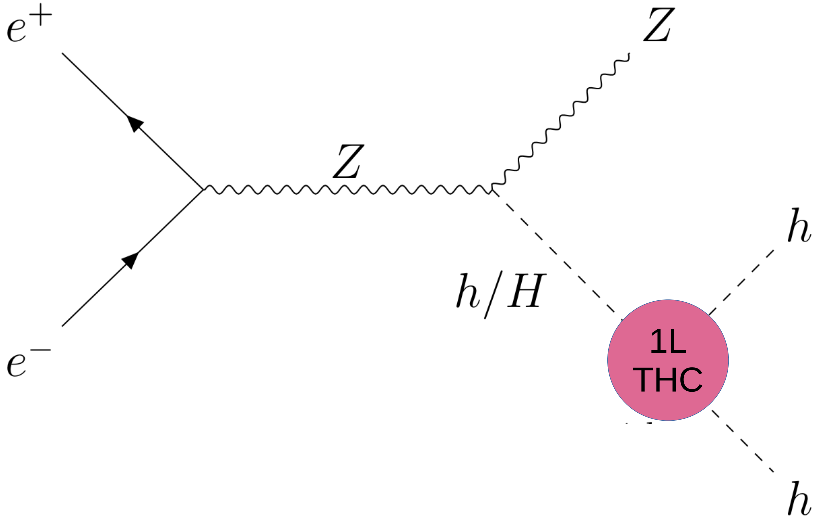


- Other triple Higgs couplings (THCs) could receive similar contributions

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

- Our computation of the xs (@ ILC):

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



- Computation of 1L THCs:
  1. Effective potential for λ_{hhh} and λ_{hhH}
  2. Diagramatic calculation for λ_{hhh}
- Includes the expected main EW corrections

Two Higgs Doublet Model (2HDM)

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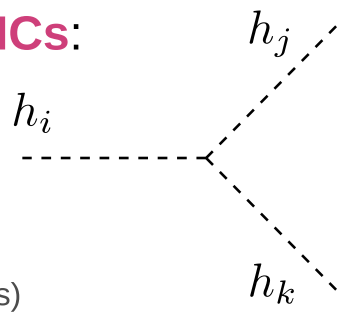
- SM + **second Higgs doublet** (CP-conserving)

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

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

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

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



$$= -ivn!\lambda^{(0)}_{h_i h_j h_k}$$

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

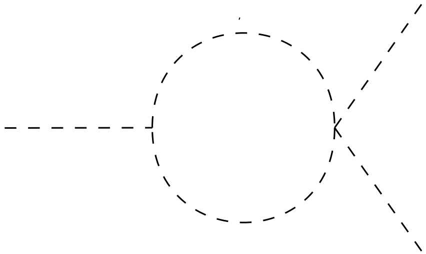
with

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

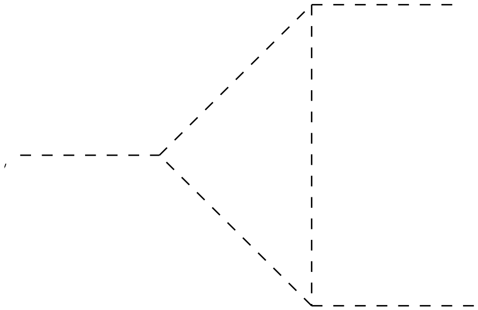
($n =$ # identical bosons)

Triple Higgs Couplings at 1 Loop

- **Effective potential** for $\lambda^{(1)}_{hhh}$ and $\lambda^{(1)}_{hhH}$
  - 'On-shell' renormalization: 1L parameters are set equal to their tree-level values
  - `BSMPTv3` *[Basler, Biermann, Mühlleitner, Müller, Santos, Viana, 24]*



- **Full diagramatic** approach, only for $\lambda^{(1)}_{hhh}$
  - On-shell conditions for masses, angles, and WFRs MS-bar for m^2_{12}
  - The *finite momentum* effects are included!
  - `anyH3/anyBSM` *[Bahl, Braathen, Gabelmann, Weiglein, 23]*



- They will capture the pure scalar 1L corrections to $e^+e^- \to hhZ$ *(expected to be the main EW ones)*

THCs: tree vs 1loop with constraints

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, 5.7]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 6.3]	[-1.7, 1.7]	[-2.2, 2.1]
FL	[0.7, 1.0]	[0.8, 5.8]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Scan of the parameter space (550,000 points) *[ScannerS + HiggsTools + HDECAY]*
- 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

κ_λ: tree level vs 1 loop

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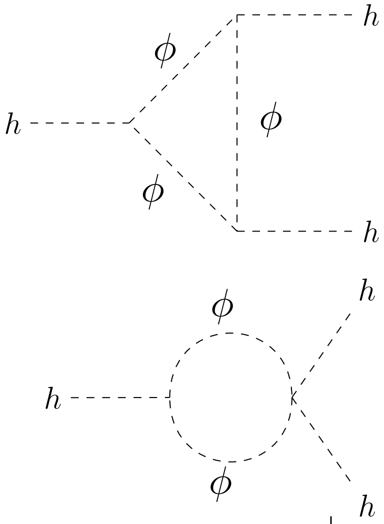


$\phi = H, A, H^\pm$

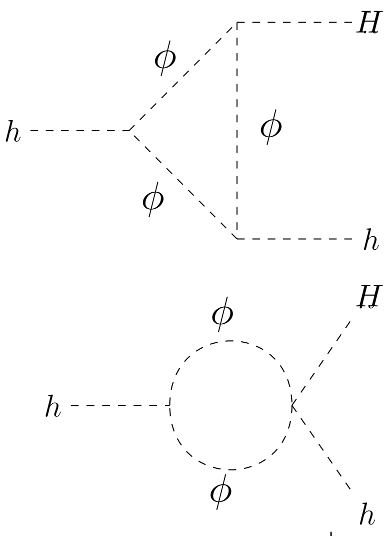
Type	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$	$\lambda_{hhH}^{(0)}$	$\lambda_{hhH}^{(1)}$
I	[-0.2, 1.2]	[0.2, 6.8]	[-1.6, 1.5]	[-2.1, 1.9]
II	[0.6, 1.0]	[0.7, 5.7]	[-1.5, 1.6]	[-1.7, 2.0]
LS	[0.5, 1.0]	[0.6, 6.3]	[-1.7, 1.7]	[-2.2, 2.1]
FL	[0.7, 1.0]	[0.8, 5.8]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- Very large corrections are possible! $\lambda_{hhh}^{(1)} >> \lambda_{hhh}^{(0)}$
- Reason: h couplings to heavy Higgs bosons can be large
  - Even at the *alignment limit* !!! $m_H \sim \bar{m} < m_A \sim m_{H^\pm}$

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

λ_{hhH} : 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, 5.7]	[-1.5, 1.6]	[-1.7, 2.0]
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FL	[0.7, 1.0]	[0.8, 5.8]	[-1.6, 1.3]	[-1.9, 1.5]

(results from the effective potential)

- 1L corrections for λ_{hhH} can also yield interesting results!
- Example: $\lambda_{hhH}^{(1)} \gtrsim \lambda_{hhH}^{(0)} \sim 0$ or change of sign in λ_{hhH}

At e^+e^- colliders

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

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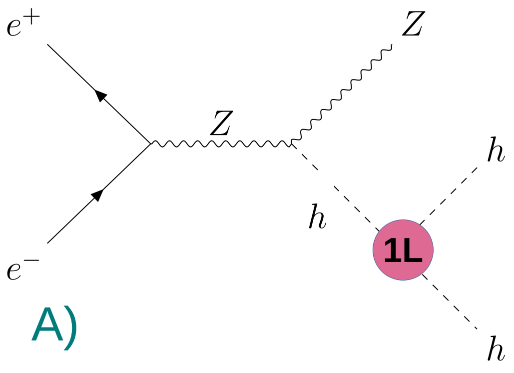
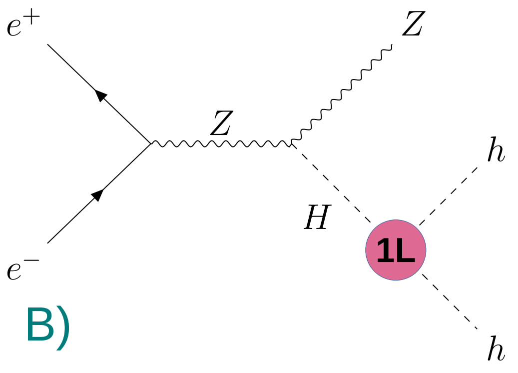
A) **Non-resonant** diagram with $\boldsymbol{\kappa_\lambda}$ $\Rightarrow$ at low m_{hh}

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

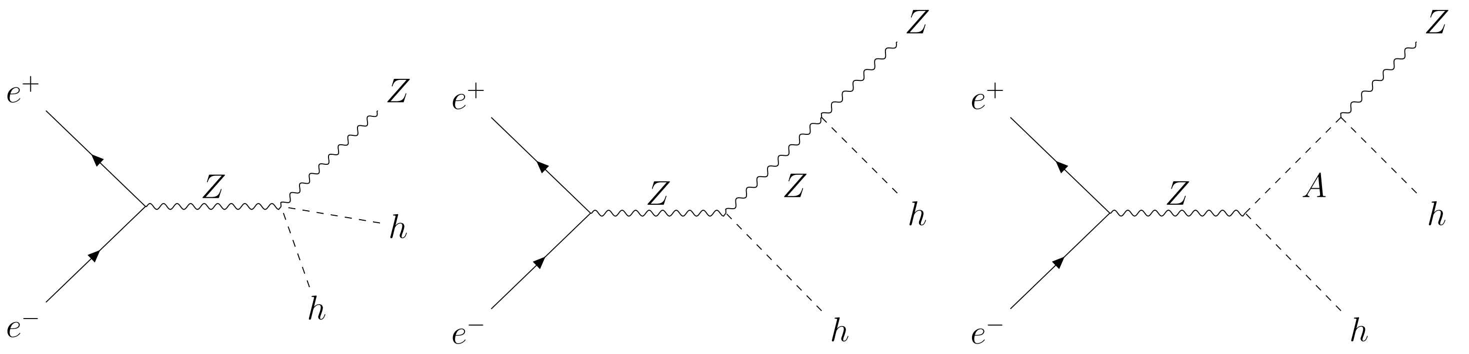
C) Resonant A diagram (no THC)



A)



B)



C)

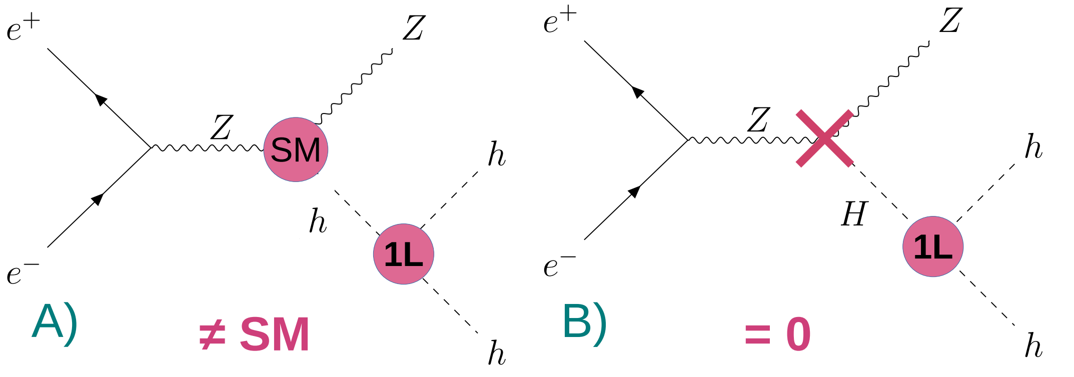
In the alignment limit ($c_{\beta-\alpha} = 0$)

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

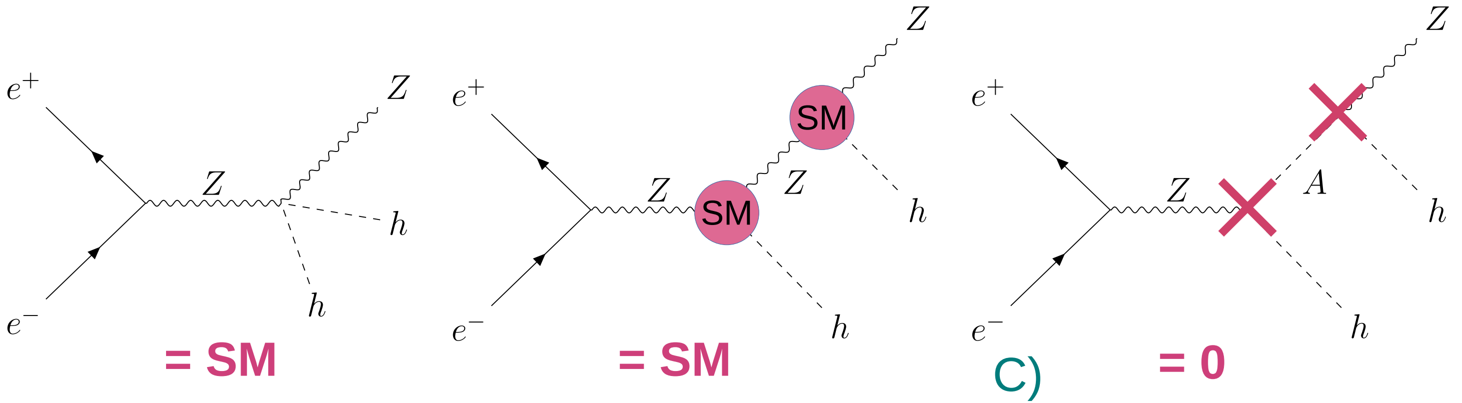
B) **Re**... ...am
wit... $\simeq m_H$

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

C) Resonant A diagram
(no THC)



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



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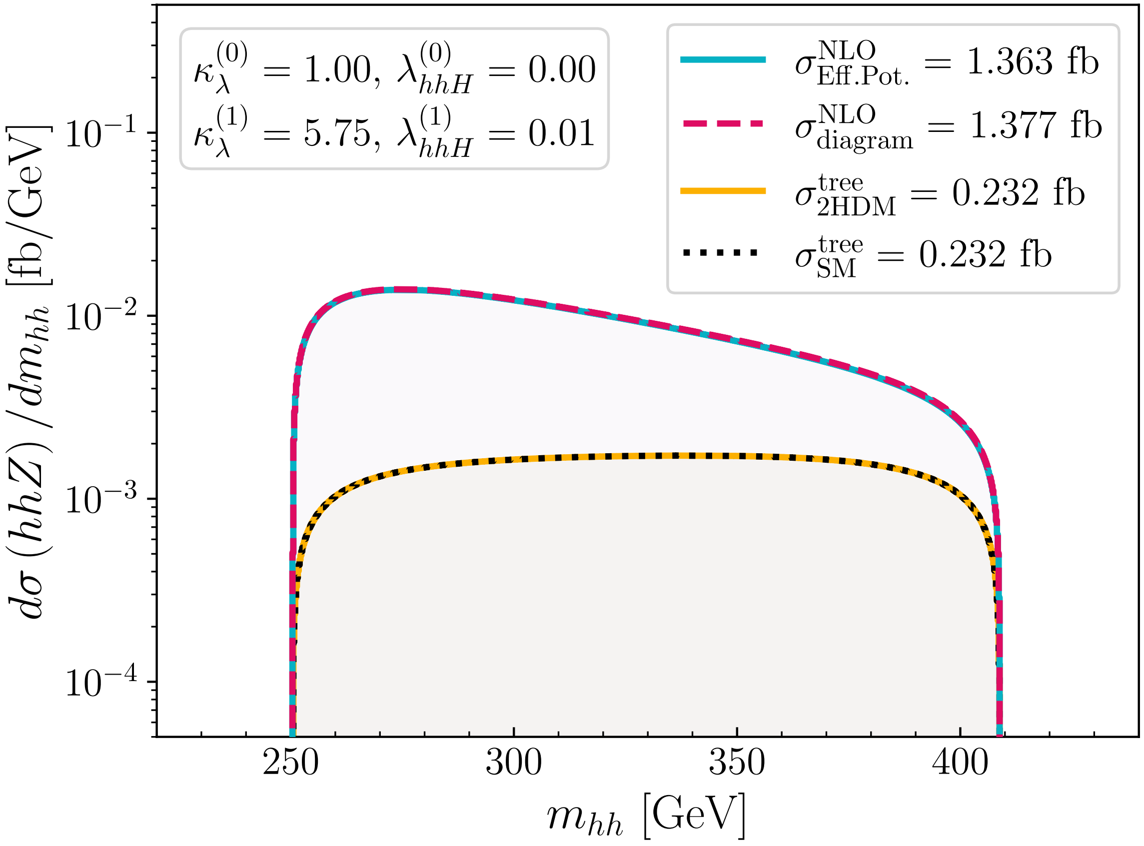
Access to $\kappa_\lambda^{(1)}$ (at ILC)

Large 1L κ_λ @ILC500GeV

BPal, all types!

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

- XS 6 times larger than the tree-level !!!
- Momentum effects on $\kappa_\lambda^{(1)}(m_{hh})$ around 1-2%
- Better access, and sensitivity, to $\kappa_\lambda^{(1)}$ than in the SM!



Large 1L κ_λ @ILC1TeV

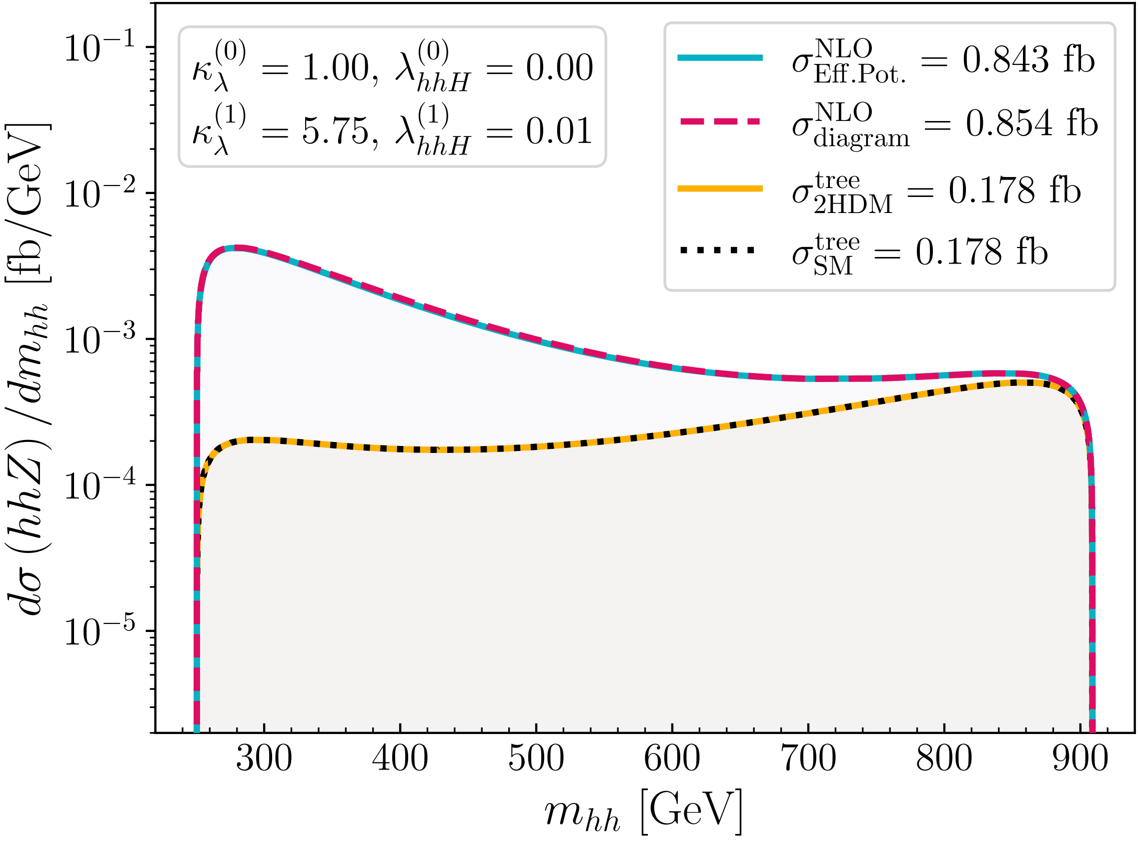
BPal, all types!

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

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

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

- Similar to the 500 GeV case
- All points with large scalar couplings can potentially lead to large κ_λ at 1L !!!



Access to $\lambda^{(1)}_{hhH}$ (at ILC 500 GeV)

‘Sensitivity’ to the H resonance

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- **Theoretical ‘sensitivity’:** significance Z from a likelihood profile ratio testing the H resonance peak vs. the no resonance (i.e. $\lambda_{hhH} = 0$)
- Expected **final 4b-jet events**: $\bar{N}_{4bZ} = N_{4bZ} \times \mathcal{A} \times \epsilon_b$
  - 4b-jet tagging efficiency: ϵ_b = 85% *[Dürig PhD Thesis, 16]*
  - Acceptance $\mathcal{A}$ after the preselection cuts (around 75%):

$$|\eta_{b,Z}| < 2.5,\ \ E_b > 20\,\mathrm{GeV},\ \ y_{b_1 b_2} = \frac{2\min\left(E_1^2, E_2^2\right)(1 - \cos\theta_{12})}{s} > 0.0025$$

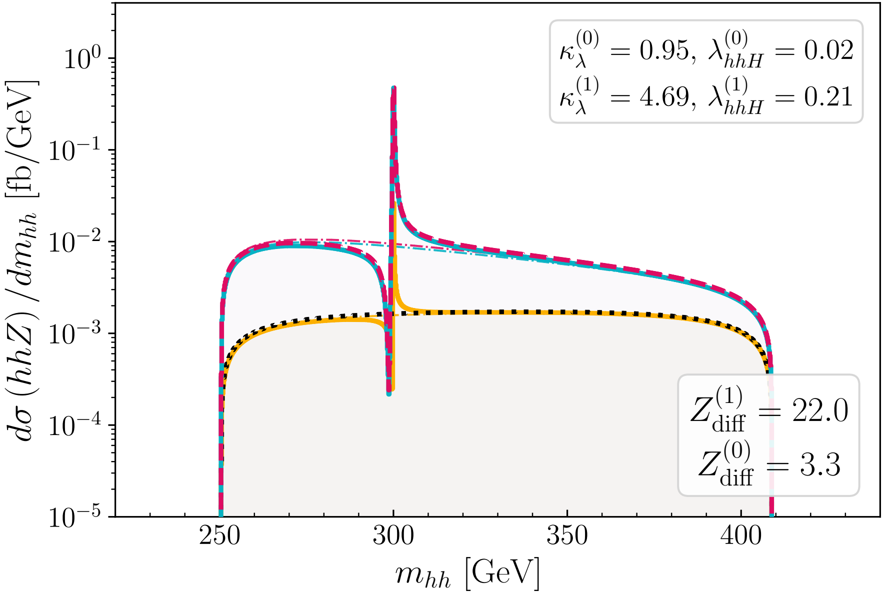
- **Smearing** of the m_{hh} distributions due to finite detector resolution
  - We consider 2% and 5% Gaussian smearing
- **Size of the bin**: bins with at least 2 events inside the kinematically allowed region

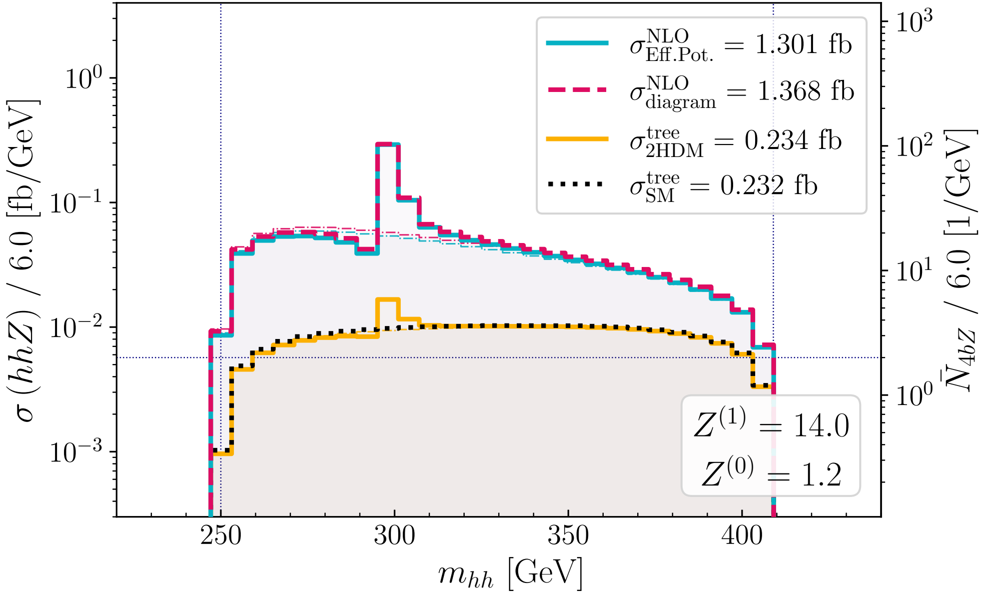
Large 1L λ_{hhH} (no smear)

BP1, type I
$m_H = \bar{m} = 300$ GeV,
$m_A = m_{H^\pm} = 650$ GeV,
$\tan\beta = 12,\ \cos(\beta-\alpha) = 0.12$

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

$\Rightarrow$ More prominent H resonance (greater Z)

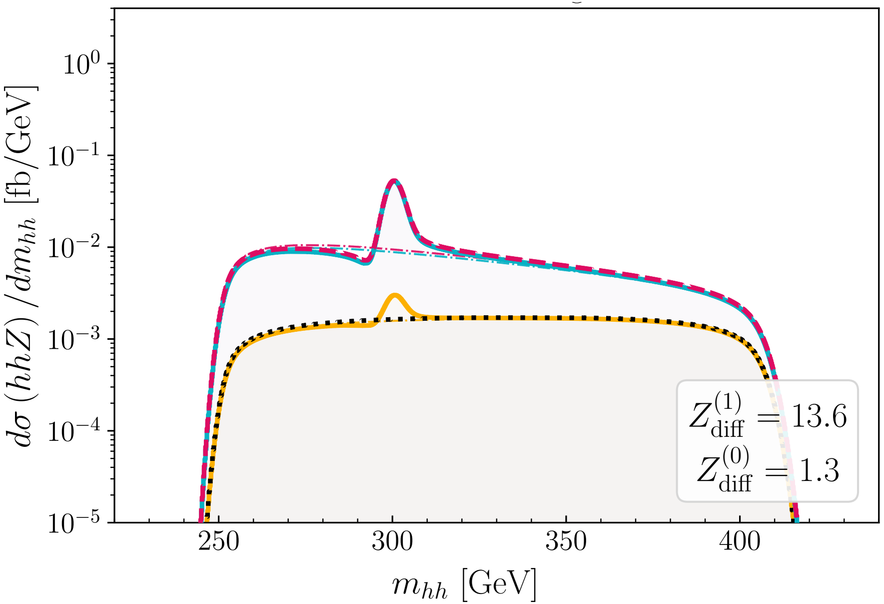


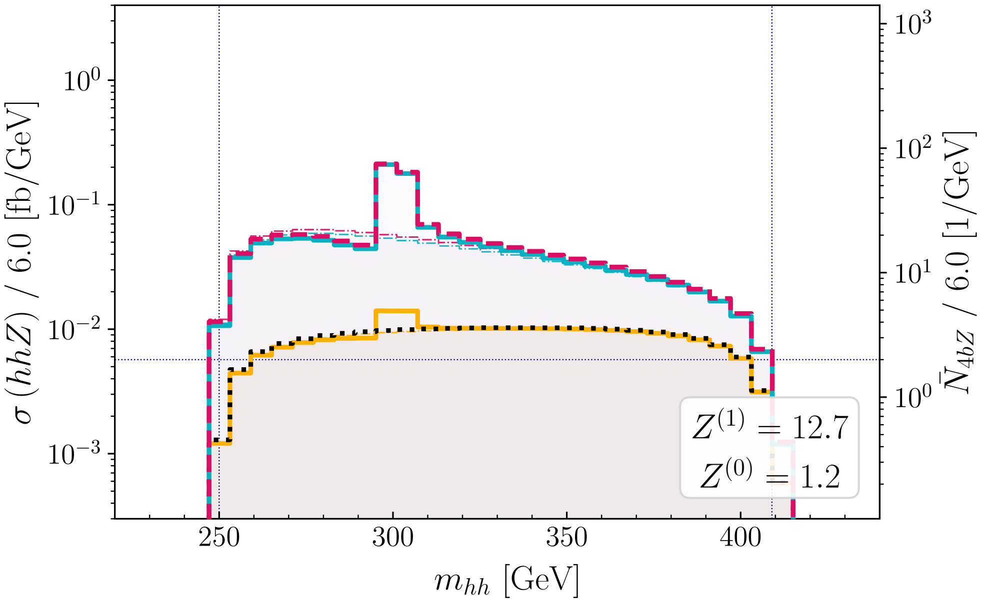


Large 1L λ_{hhH} + 2% smear

BP1, type I
$m_H = \bar{m} = 300$ GeV,
$m_A = m_{H^\pm} = 650$ GeV,
$\tan\beta = 12,\ \cos(\beta - \alpha) = 0.12$

- The resonance gets 'smeared'
- Values for Z get worst





Large 1L λ_{hhH} + 5% smear

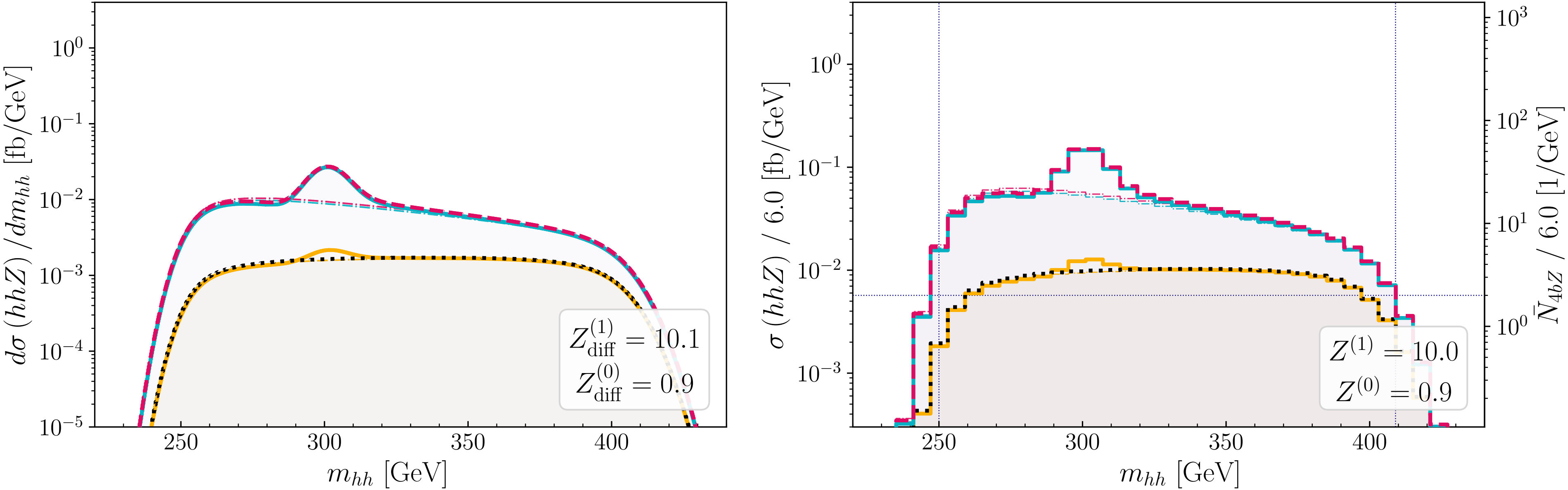
BP1, type I

$m_H = \bar{m} = 300$ GeV,

$m_A = m_{H^\pm} = 650$ GeV,

$\tan\beta = 12, \ \cos(\beta - \alpha) = 0.12$

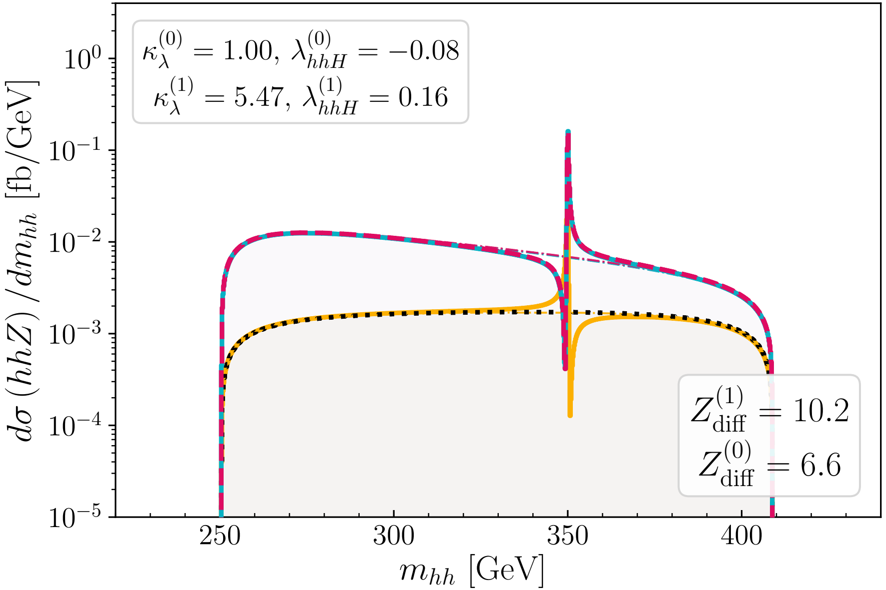
- The resonance gets even more ‘smeared’
- Values for Z get even worst

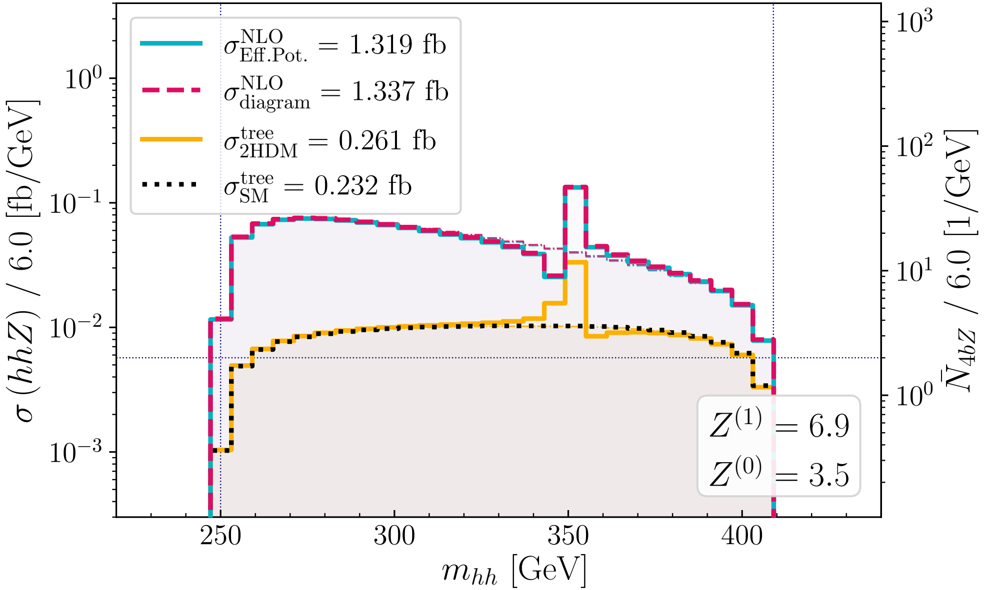


1L λ_{hhH} with different sign (no smear)

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

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

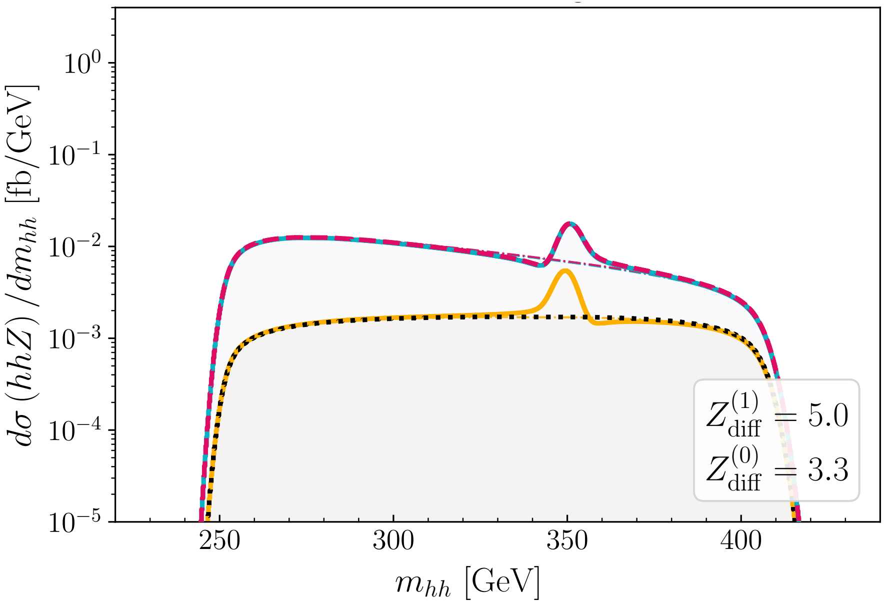


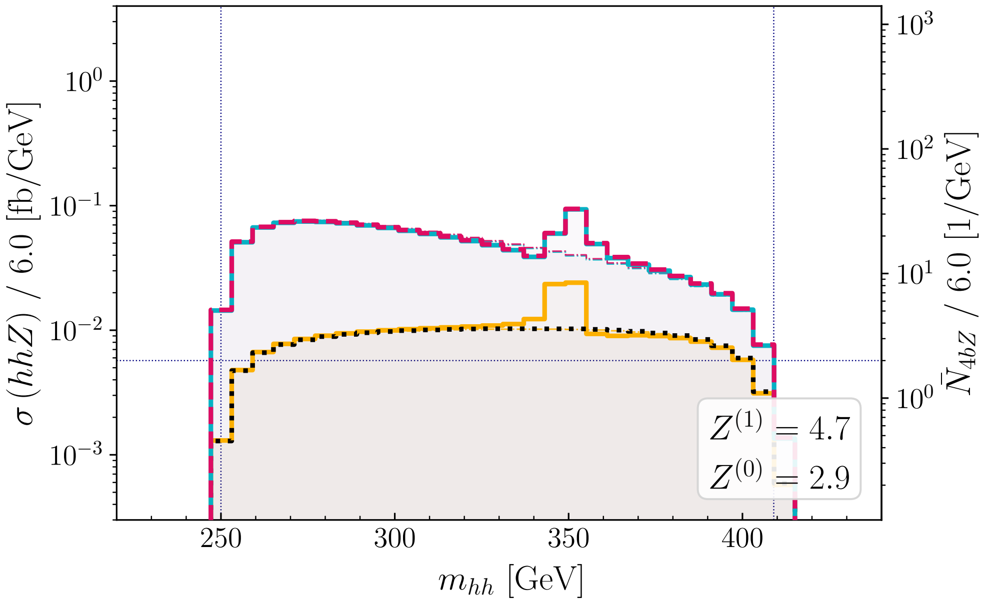


1L λ_{hhH} with different sign + 2% smear

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

- The dip-peak structure gets washed out
  - No apparent sensitivity to the coupling sign

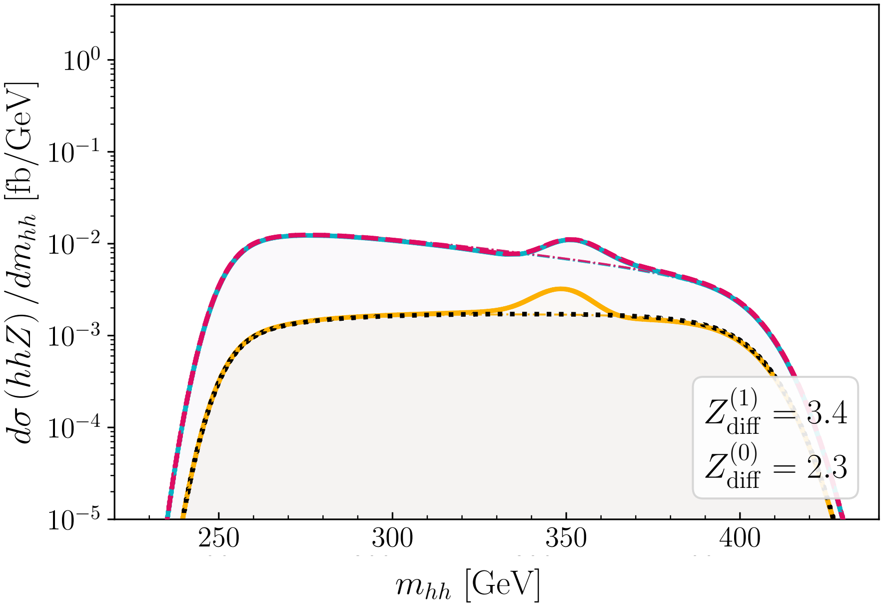


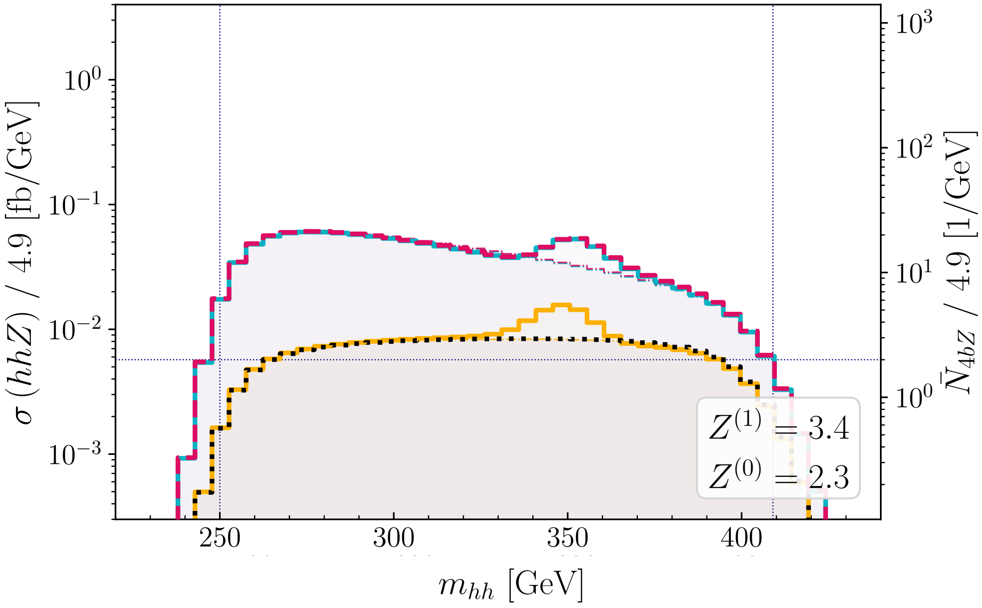


1L λ_{hhH} with different sign + 5% smear

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

- The resonance peak gets very difficult to detect :(





Results for Z :

- Larger values of Z at 1L vs. tree-level
- Smearing decreases the value of Z
  - Still optimistic results: the κ_λ enhancement helps
- Challenging access to resonance H peaks and dip-peak/peak-dip structures
- Still a full experimental analysis is needed!

BP	Smearing	Bin (loop)	$Z^{(1)}_{\text{diff}}$	$Z^{(1)}$	Bin (tree)	$Z^{(0)}_{\text{diff}}$	$Z^{(0)}$
BP1	0%	6.0	22.0	14.0	11.4	3.3	1.2
BP1	2%	6.0	13.6	12.7	11.4	1.3	1.2
BP1	5%	6.0	10.1	10.0	11.4	0.9	0.9
BP1	10%	4.8	7.8	7.8	10.8	0.6	0.6
BP2	0%	8.4	18.0	12.2	11.4	14.4	8.8
BP2	2%	8.4	13.4	12.2	11.4	9.5	8.0
BP2	5%	8.4	10.6	10.4	11.4	7.3	7.1
BP2	10%	8.1	8.5	8.4	10.9	5.7	5.7
BP3	0%	10.1	4.6	4.4	10.8	2.3	2.2
BP3	2%	10.1	4.5	4.3	10.8	2.2	2.2
BP3	5%	10.1	4.2	4.1	10.8	2.0	2.0
BP3	10%	10.1	3.6	3.6	10.8	1.7	1.7
BPsign	0%	6.0	10.2	6.9	11.4	6.6	3.5
BPsign	2%	6.0	5.0	4.7	11.4	3.3	2.9
BPsign	5%	4.9	3.4	3.4	10.8	2.3	2.3
BPsign	10%	3.9	2.5	2.5	10.8	1.8	1.7
BPext	0%	6.0	24.9	17.2	11.4	17.1	11.0
BPext	2%	6.0	15.0	13.8	9.5	11.1	10.3
BPext	5%	4.9	11.9	11.9	9.5	9.3	9.1
BPext	10%	3.9	10.4	10.4	9.3	8.2	8.1

Summary & Conclusions

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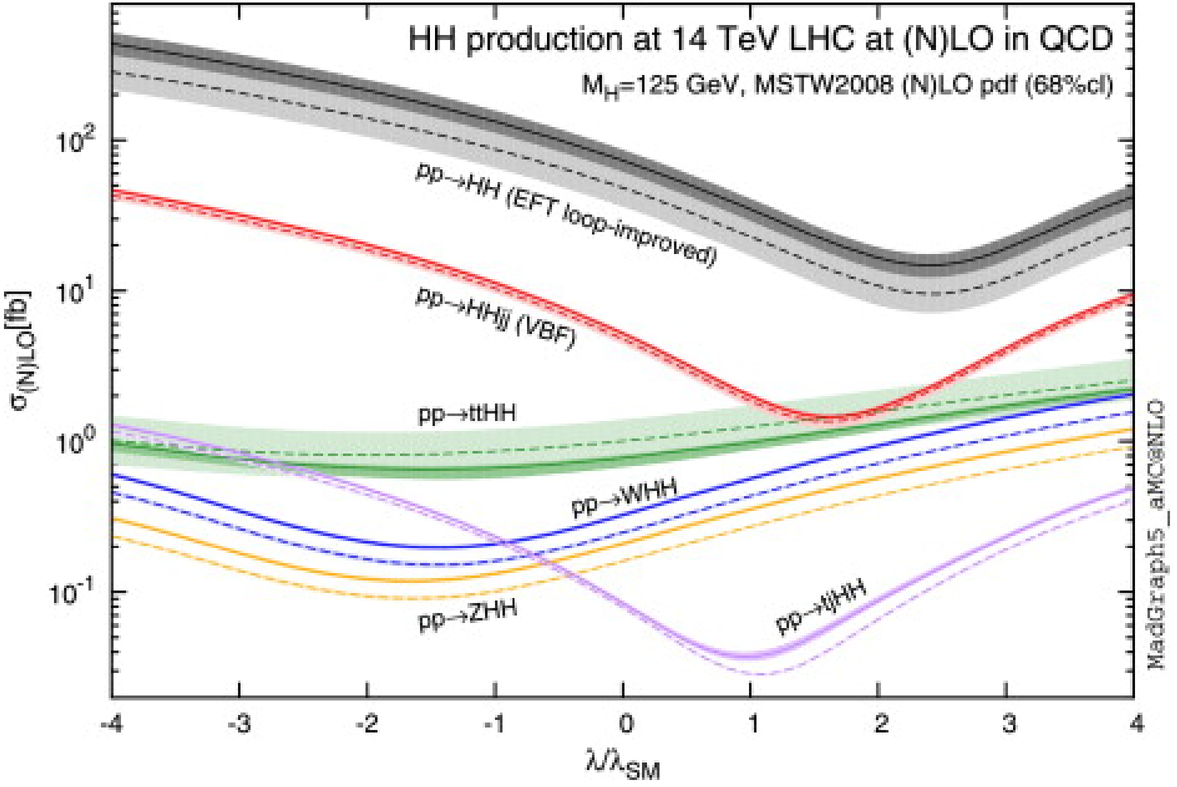
- Analysis of the **1L corrected triple Higgs couplings κ_λ and λ_{hhH}**, and their impact in **double Higgs production** at e^+e^- colliders in the 2HDM, specifically $e^+e^- \to hhZ$ at ILC
- **1L corrections to κ_λ can be very large**, *even in the alignment limit !!!*
  - Very distinct prediction even for a very SM-like Higgs boson!
  - No relevant effects from finite momentum
- **1L corrected λ_{hhH} can lead to interesting pheno!** Access via the H resonance peak
  - Analysis of the **final 4b-jet events + smearing + bin size**: 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! :)

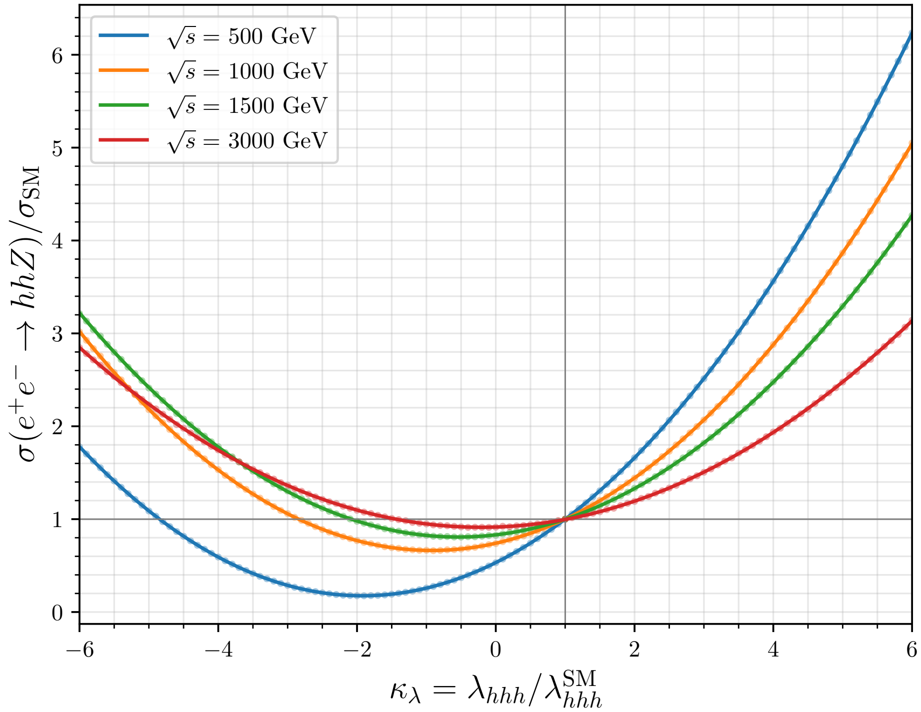
Back up

XS vs κ_λ in the SM at LHC



Di-Higgs production @e^+e^- colliders

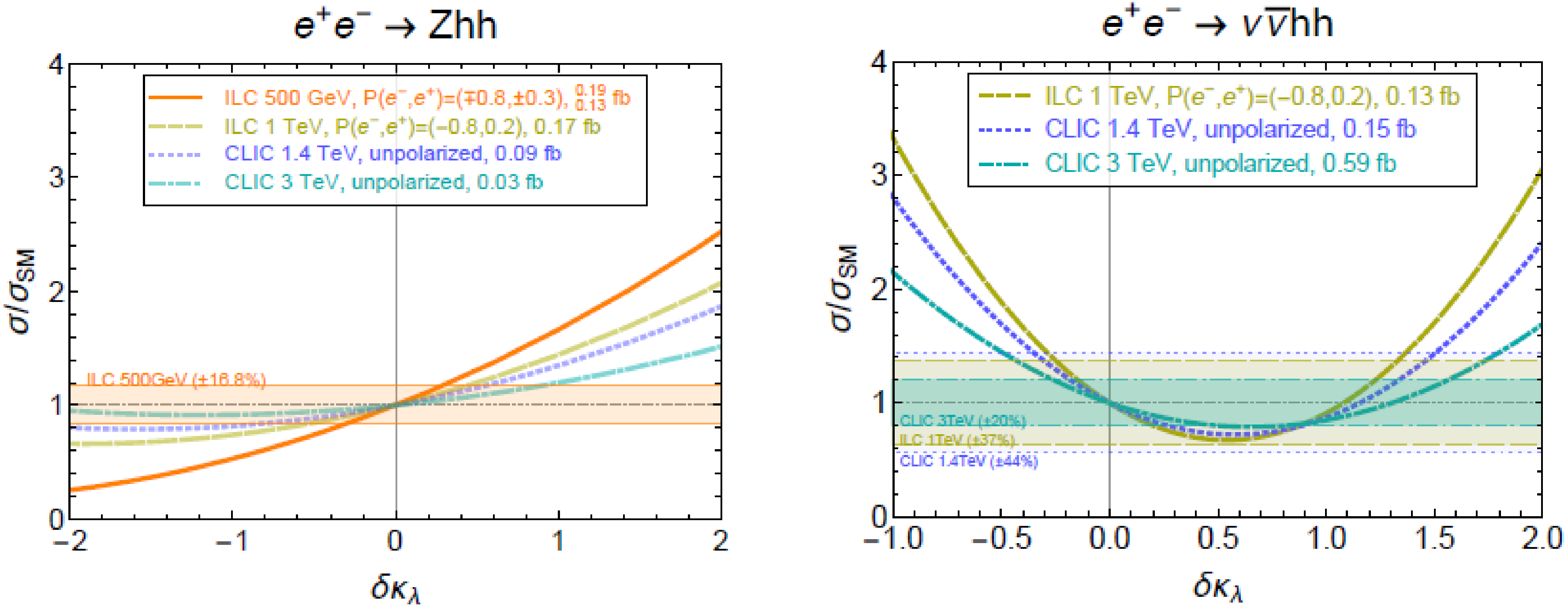
- Main production channel is the double Higgs-strahlung $e^+e^- \to hhZ$



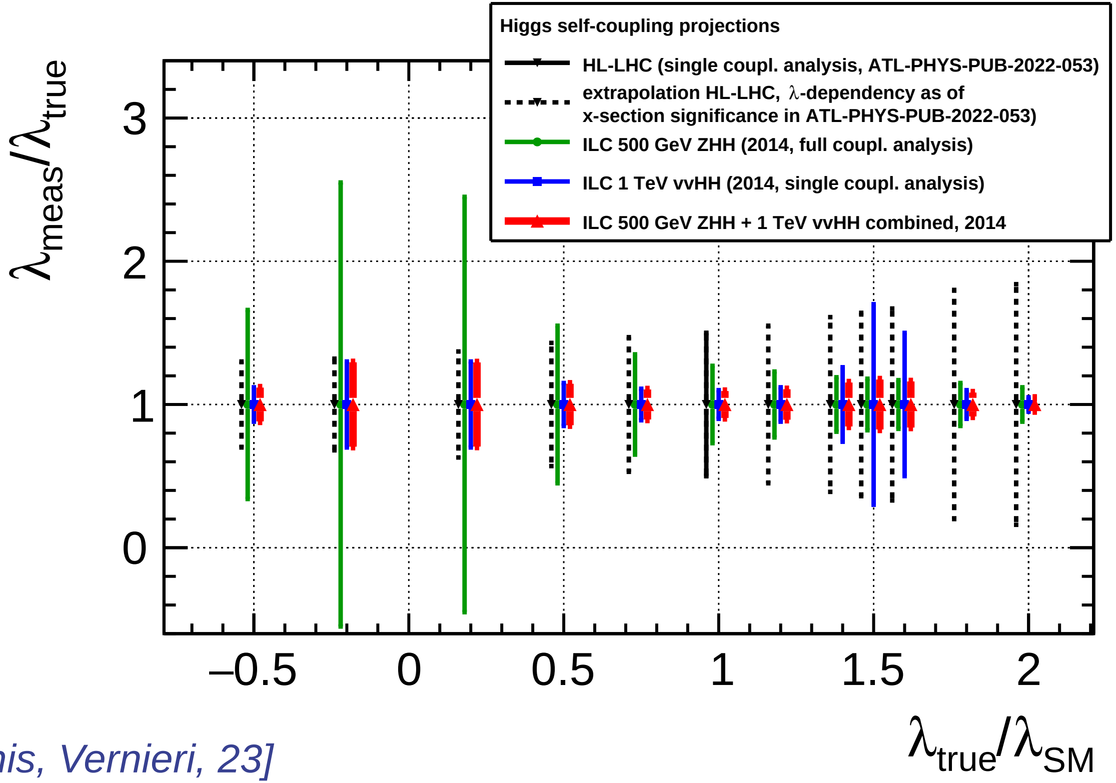
- We expect ***larger cross sections*** for larger values of κ_λ !

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

[Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon, 18]



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



[Torndal, List, Ntounis, Vernieri, 23]

Feynman Rules @tree level @alignment

$$hhh: \quad \frac{-3im_h^2}{v} = -6iv\lambda_{\rm SM}^{(0)},$$

$$hhH = hhhH: \quad 0,$$

$$hHH/v = hhHH: \quad \frac{-i\left(m_h^2 + 2m_H^2 - 2\bar{m}^2\right)}{v^2},$$

$$h\phi\phi/v = hh\phi\phi: \quad \frac{-i\left(m_h^2 + 2m_\phi^2 - 2\bar{m}^2\right)}{v^2},$$

$$HHH/(3v) = hHHH = H\phi\phi/v = hH\phi\phi: \quad \frac{2i\left(m_H^2 - \bar{m}^2\right)\cot 2\beta}{v^2},$$

$$HHHH/3 = HH\phi\phi: \quad \frac{-i\left(m_h^2 + 4\left(m_H^2 - \bar{m}^2\right)\cot^2 2\beta\right)}{v^2},$$

Main corrections to κ_λ

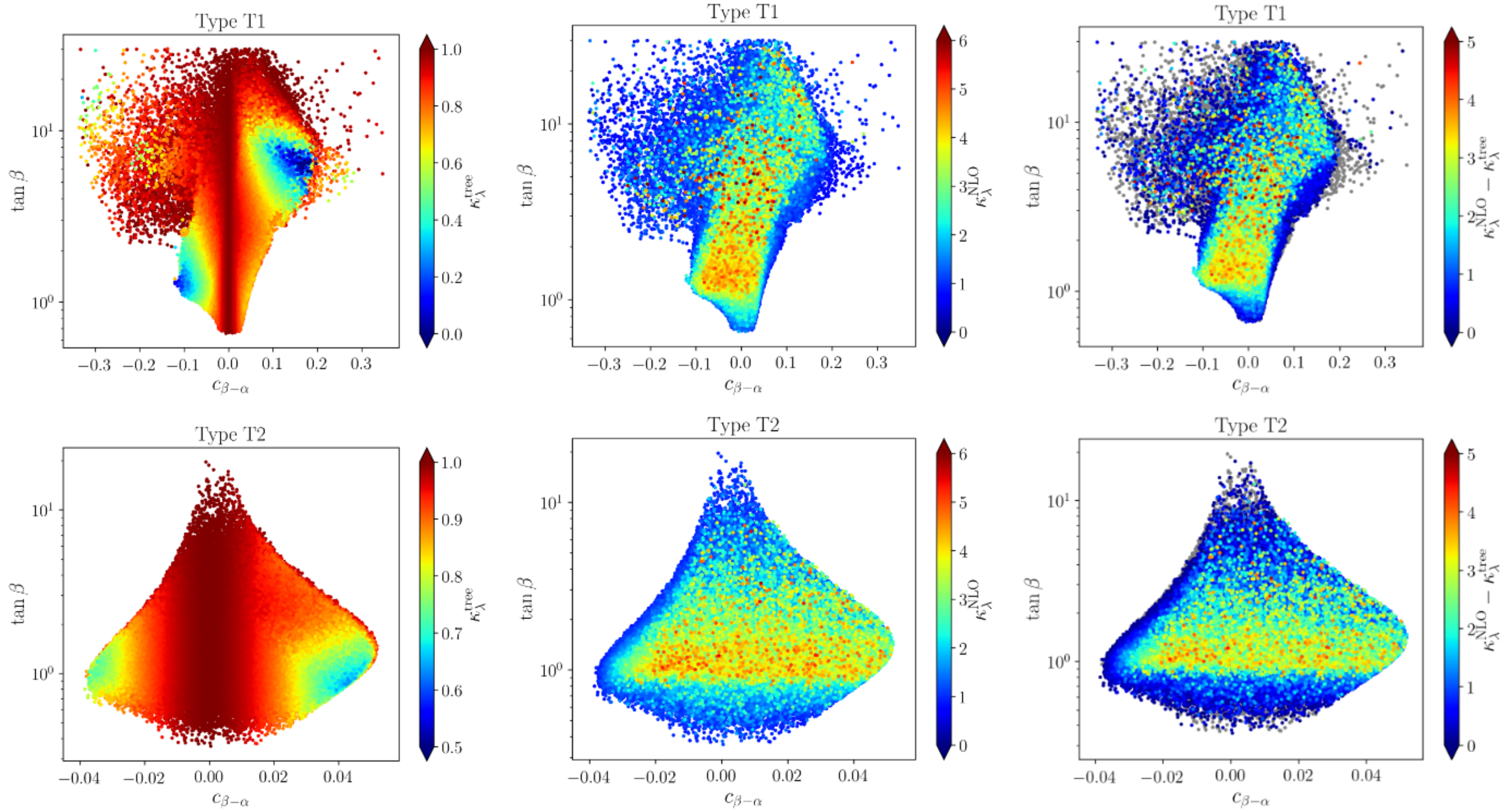
[Kanemura,Kiyoura,Okada,Senaha,Yuan,02]

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

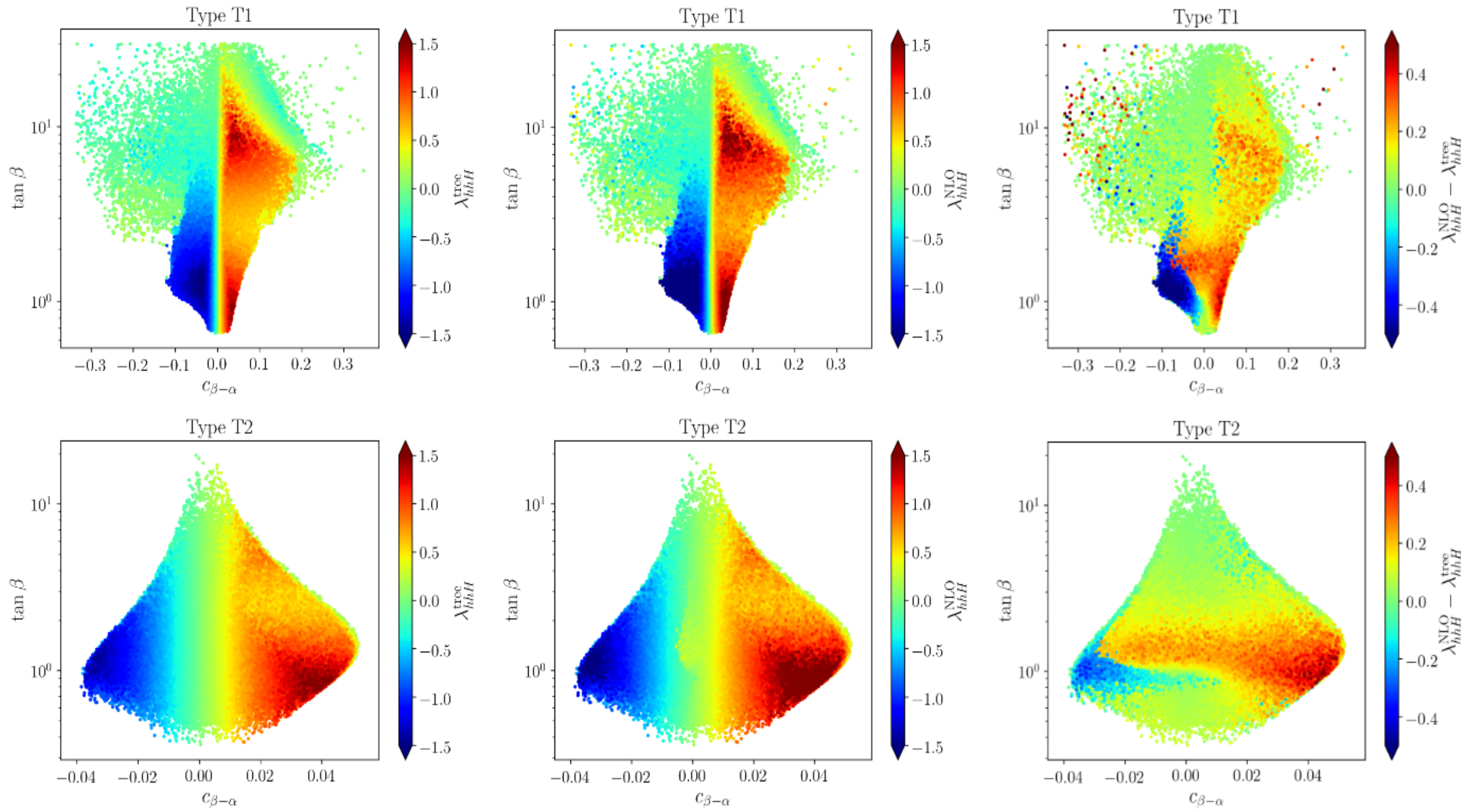
$$\lambda_{\mathrm{SM}}^{(1)} \simeq \lambda_{\mathrm{SM}}^{(0)}\left(1 - \frac{m_t^4}{\pi^2 m_h^2 v^2}\right)$$

$$\lambda_{\mathrm{SM}}^{(0)} = \frac{2m_h^2}{v^2} \simeq 0.13$$

Results for κ_λ



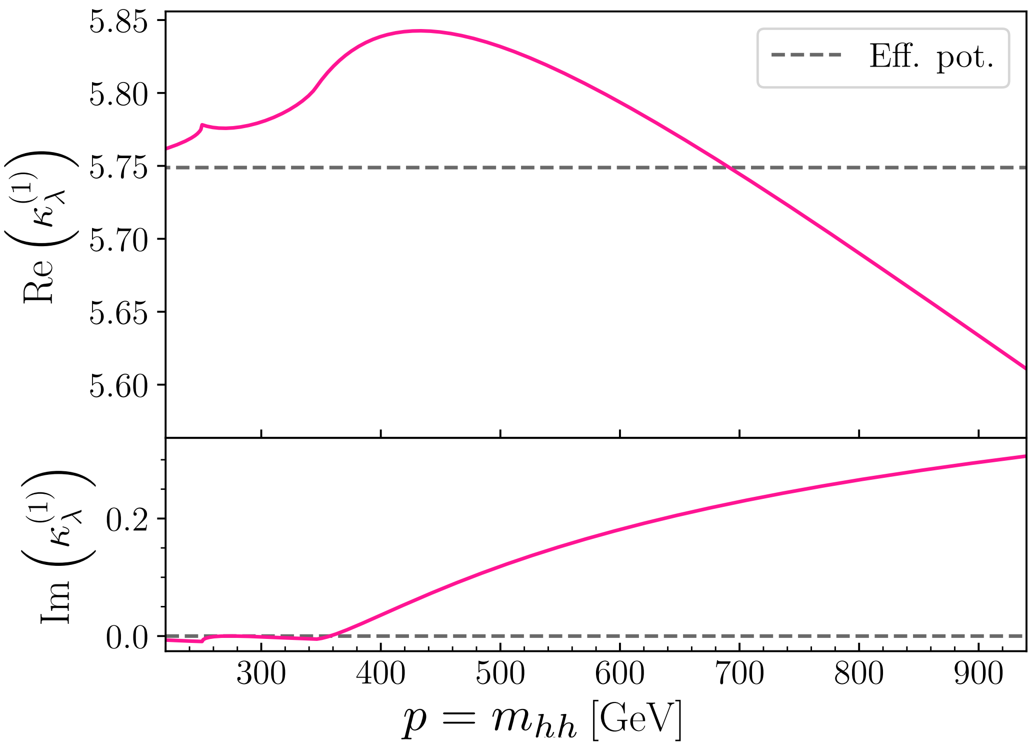
Results for λ_{hhH}



Example for large κ_λ at 1 loop

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

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



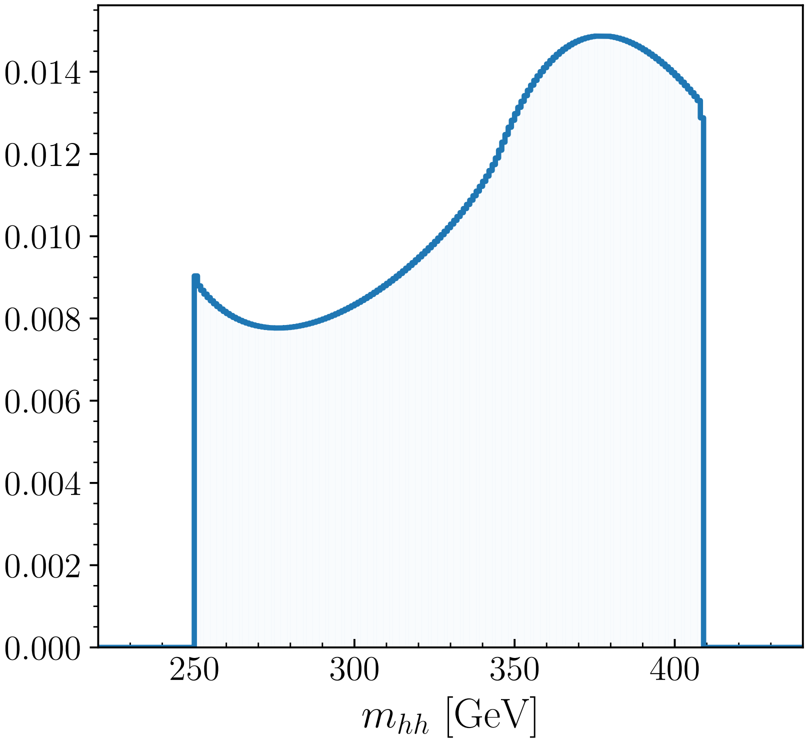
Relative difference w/ and wo/ p

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

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

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

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

‘Sensitivity’ to the H resonance

[Cowan, Cranmer, Gross, Vitells, 13]

- Our **theoretical ‘estimator’**:
  - Significance Z from a likelihood profile ratio statistical test: H resonance vs no resonance (i.e. $\lambda_{hhH} = 0$, the ‘continuum’)
- Notion of the *‘sensitivity’* to the H resonance and hence to λ_{hhH}

$$L(\mu) = \prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)}$$

$$s_i = \bar{N}_{i,4bZ} - \bar{N}^C_{i,4bZ}$$

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

$$n_i = s_i + b_i$$

$$Z = \sqrt{-2\log\left(\frac{L(0)}{L(1)}\right)} \equiv \sqrt{\sum_i (Z_i)^2}$$

$$Z_i = \sqrt{2\left((s_i + b_i)\log\left(1 + \frac{s_i}{b_i}\right) - s_i\right)}$$

<u>Disclaimer!</u> This is *NOT* an experimental significance!