Large BSM One-Loop Triple Higgs Couplings in Di-Higgs Production at e^+e^- Colliders.

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[he/him]

Based on 2505.02947 with S. Heinemeyer and M. Mühlleitner

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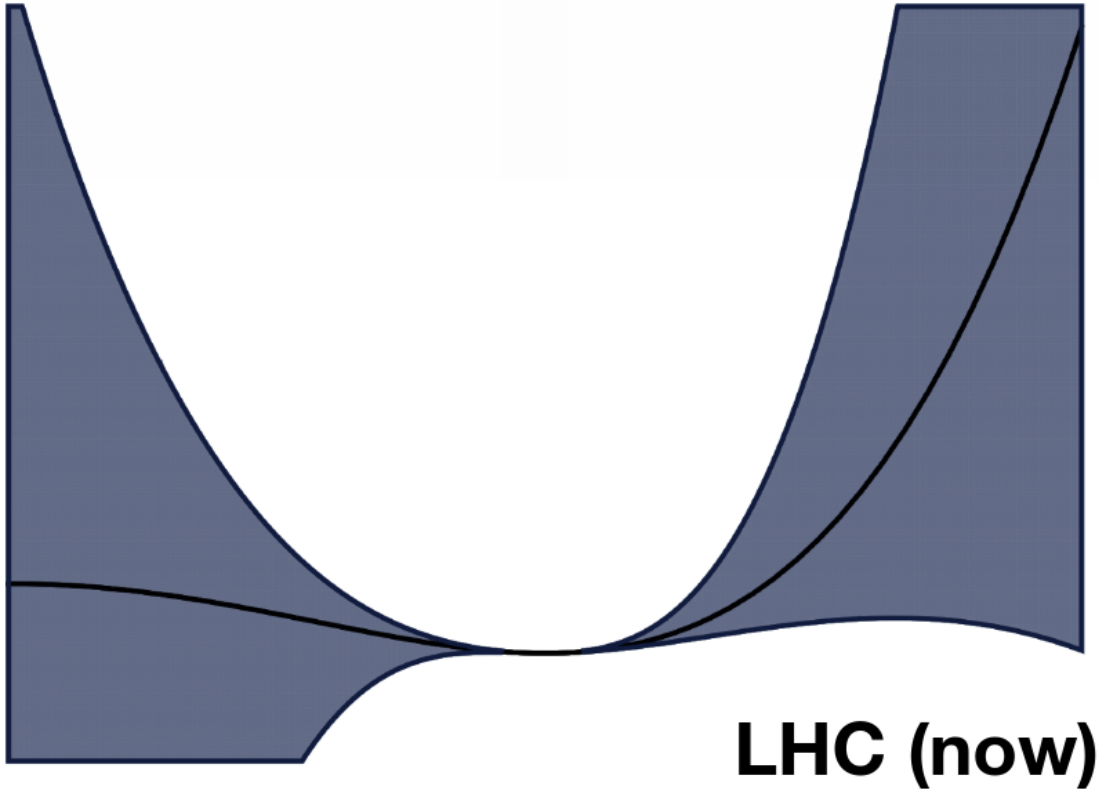
HELMHOLTZ

DESY.

Motivation: BSM in the Higgs Sector

Testing the Higgs potential!

- At present, the Higgs boson potential is essentially ***untested***
- Extended Higgs sectors can solve (at least some) of the **SM problems**
  - Baryon asymmetry, dark matter, …
- **Much, much room for BSM physics**
- This talk/our work:
  - How big can **one-loop corrected triple Higgs couplings (THCs)** be?
  - What is their impact in **di-Higgs production** at **high energy e^+e^- colliders**



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

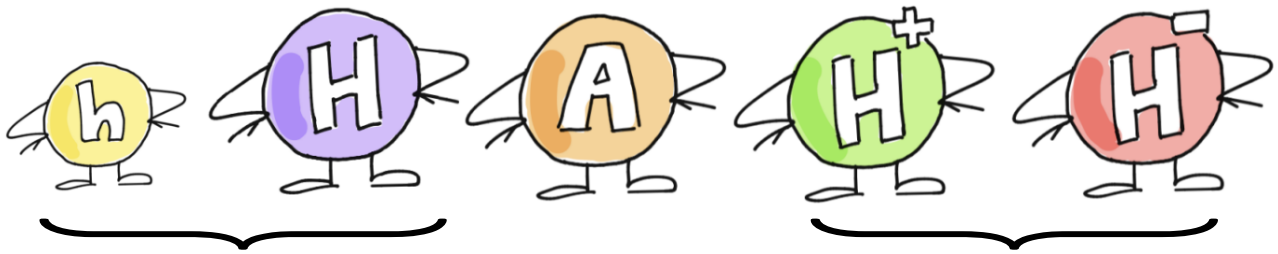
Follow-up from tree-level analysis *[FA, Heinemeyer, Herrero, 21]*

Two Higgs Doublet Model (2HDM)

SM + second Higgs doublet

- Five physical Higgs bosons:

Image by K. Radchenko



SM-like

Neutral CP even

Neutral CP odd

Charged

$$\bar{m}^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

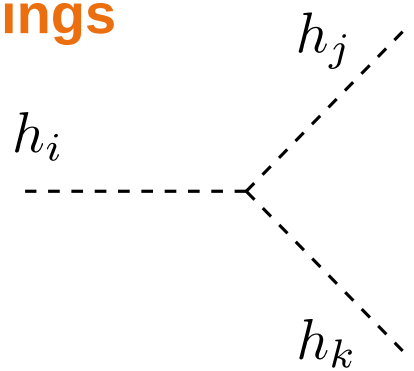
(softly breaks Z_2 symmetry)

- Input parameters:

$$m_h = 125\ \text{GeV},\quad m_H,\quad m_A,\quad m_{H^\pm},\quad \tan\beta = v_2/v_1,\quad \cos(\beta-\alpha),\quad \bar{m}^2$$

- ***Alignment limit*** $(\cos(\beta-\alpha)=0)$ ⇒ the tree-level SM interactions for h are recovered!

- **Triple Higgs couplings** (THCs):



$$= -ivn!\lambda^{(0)}_{h_i h_j h_k} \qquad \kappa_\lambda^{(0,1)} \equiv \frac{\lambda^{(0,1)}_{hhh}}{\lambda^{(0)}_{\text{SM}}}$$

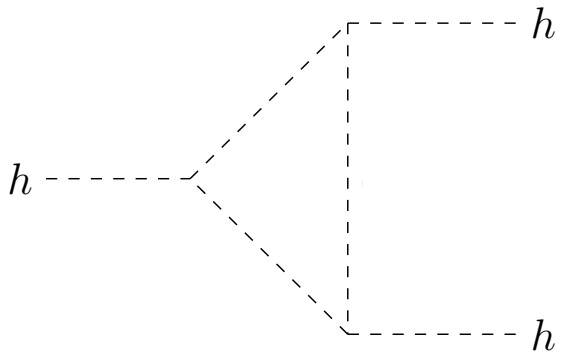
with

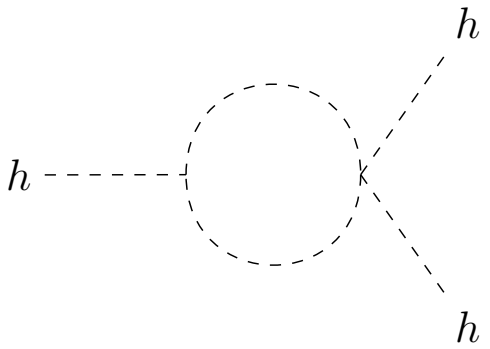
$$\lambda^{(0)}_{\text{SM}} = \frac{m_h^2}{2v^2} \simeq 0.13$$

Large one-loop corrections to THCs at BSM models!

Concrete example: 2HDM

- **Large scalar couplings** (triple and quartic) between Higgs bosons can *still* be large in the 2HDM *[FA, Heinemeyer, Herrero, 21, 22]*
- These large scalar can lead to **large one-loop corrections** to the SM-like Higgs boson self-coupling *[Kanemura, Kiyoura, Okada, Senaha, Yuan, 02] ...* ⇒ **non-decoupling effects**
  - Corrections can be well above 100% w.r.t. the tree level prediction !!!





In general, other THCs can receive similar contributions

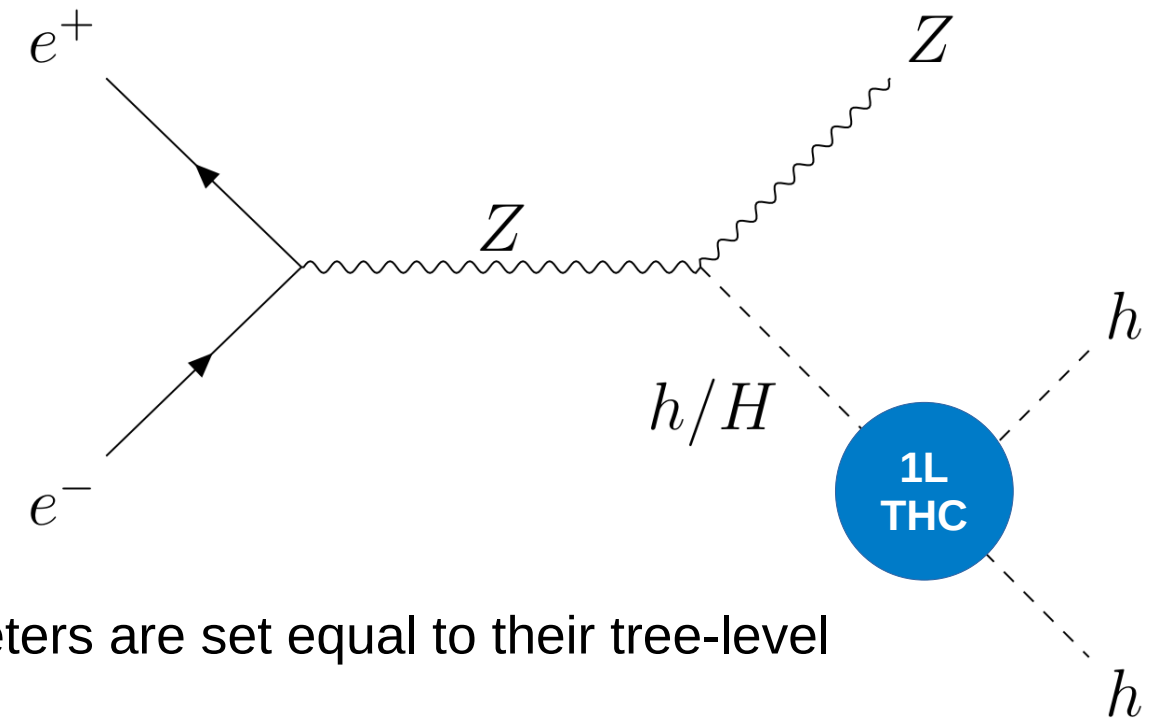
One-loop THCs in di-Higgs production at e^+e^- colliders

Our xs and THCs computation

Tree-level xs $e^+e^- \to Zhh$

+

One-loop THCs $\lambda^{(1)}_{hhh}$ and $\lambda^{(1)}_{hhH}$



Two approaches for the **one-loop THCs**:

1) **Effective potential** for λ_{hhh} and λ_{hhH}
   - 'On-shell' renormalization: one-loop parameters are set equal to their tree-level values
   - `BSMPTv3` *[Basler, Biermann, Mühlleitner, Müller, Santos, Viana, 24]*

2) **Full diagramatic** approach, (only for λ_{hhh}) ⇒ finite *momentum effects* included!
   - On-shell renormalization for masses, angles, and WFRs and $\overline{\text{MS}}$ for m^2_{12}
   - `anyH3/anyBSM` *[Bahl, Braathen, Gabelmann, Weiglein, 23]*

Note: gluon fusion + 1L THC: *[Heinemeyer, Mühlleitner, Radchenko, Weiglein, 24]*

Allowed ranges for THCs at tree level vs one loop

Considering the relevant theoretical and experimental constraints

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

In the alignment limit:

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

$\lambda_{hhH}^{(0)} = 0$

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, 5.8]	[-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]

For κ_λ :

- Very large corrections are possible!
  - Even *at the alignment limit* !!!
- Larger non-resonant $\sigma(Zhh)$ wrt in the SM!

For λ_{hhH} :

- One-loop corrections can lead to $\lambda_{hhH}^{(1)} \neq \lambda_{hhH}^{(0)} \simeq 0$ or a change of sign in λ_{hhH}
- Changes the H resonance!

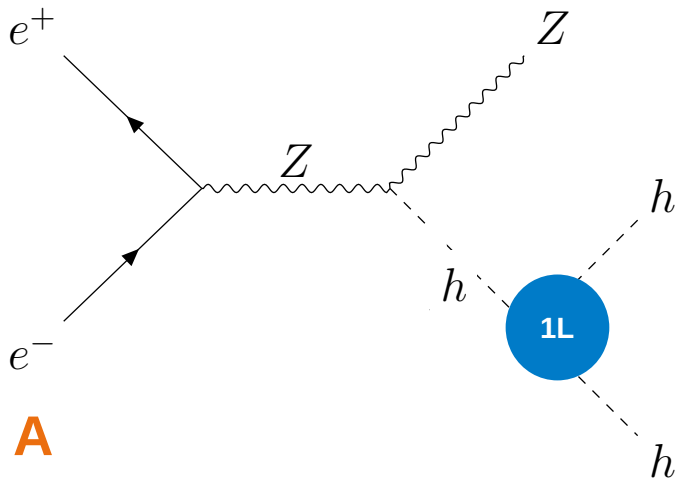
Effects from THCs at di-Higgs production

Main BSM contributions

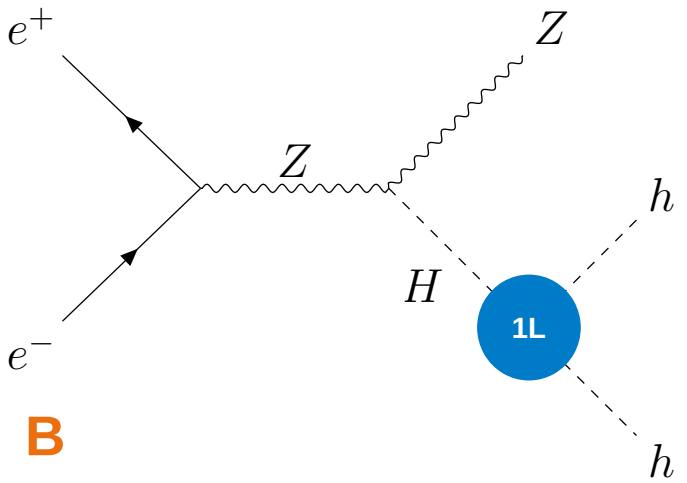
A **Non-resonant diagram with κ_λ**
at low m_{hh}

B **Resonant H diagram with λ_{hhH}**
at $m_{hh} \simeq m_H$

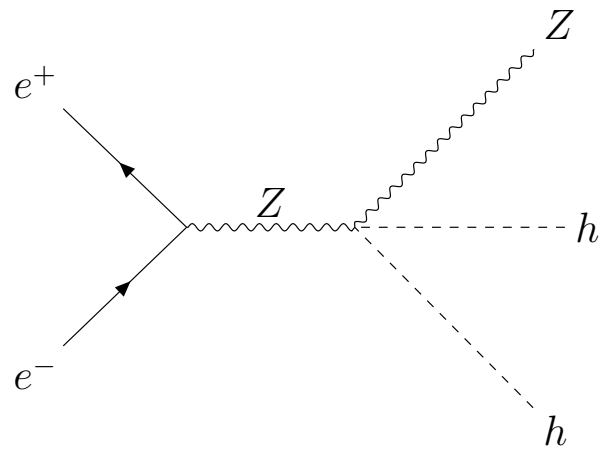
C Resonant A diagram (no THC)

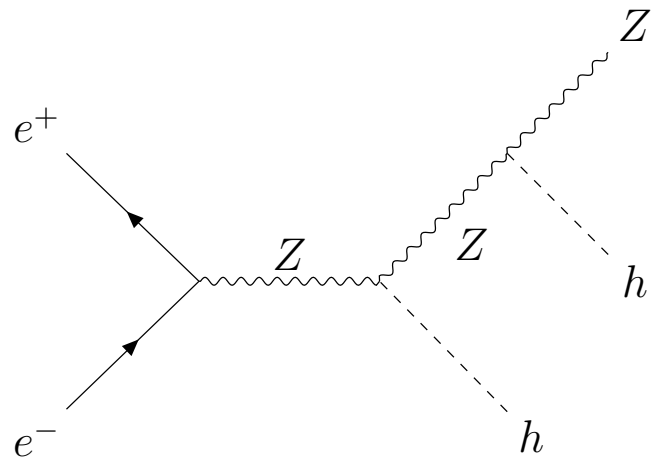


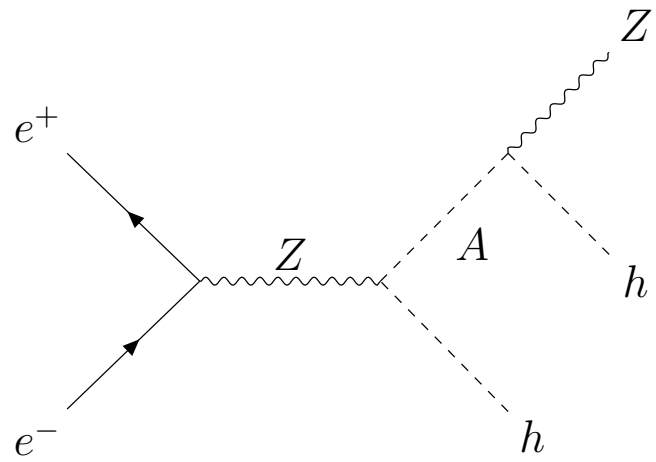
A



B







C

Effects from THCs at di-Higgs production

In the alignment limit

A **Non-resonant diagram with κ_λ**

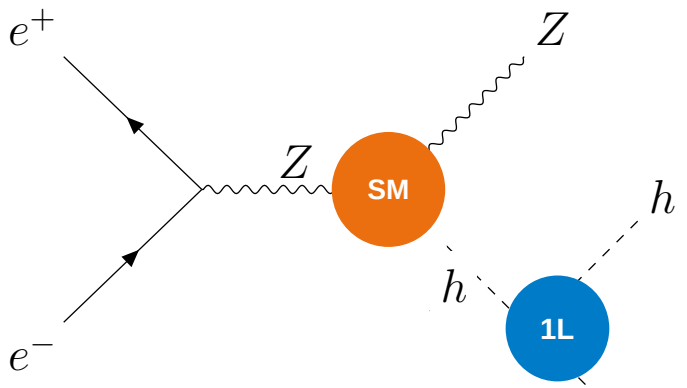
at low m

B **Reson** **h λ_{hhH}**

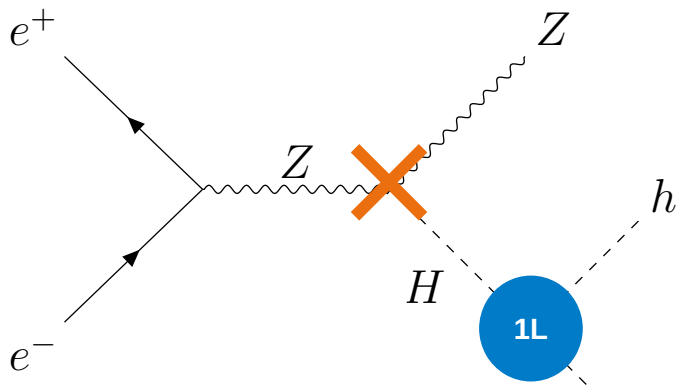
at m_{hh} ≈

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

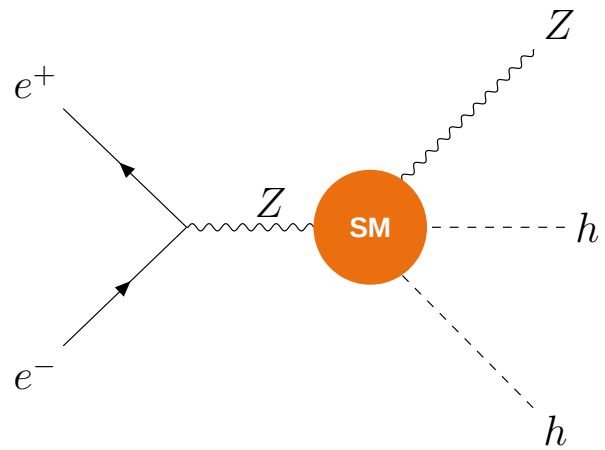
C Resonant A diagram (no THC)



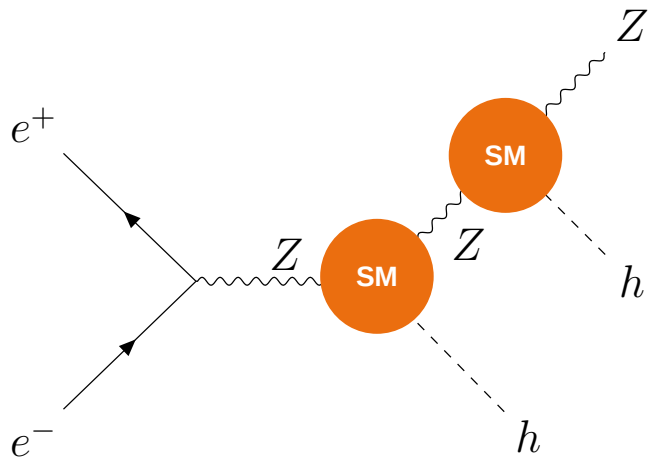
A **≠ 0 nor SM**



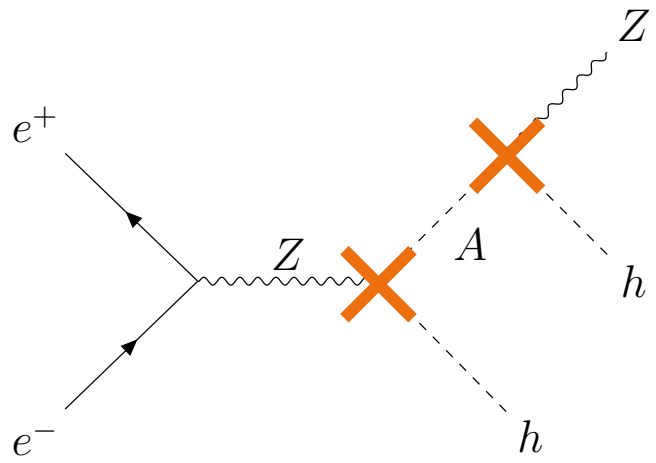
B **= 0**



= SM



= SM



C **= 0**

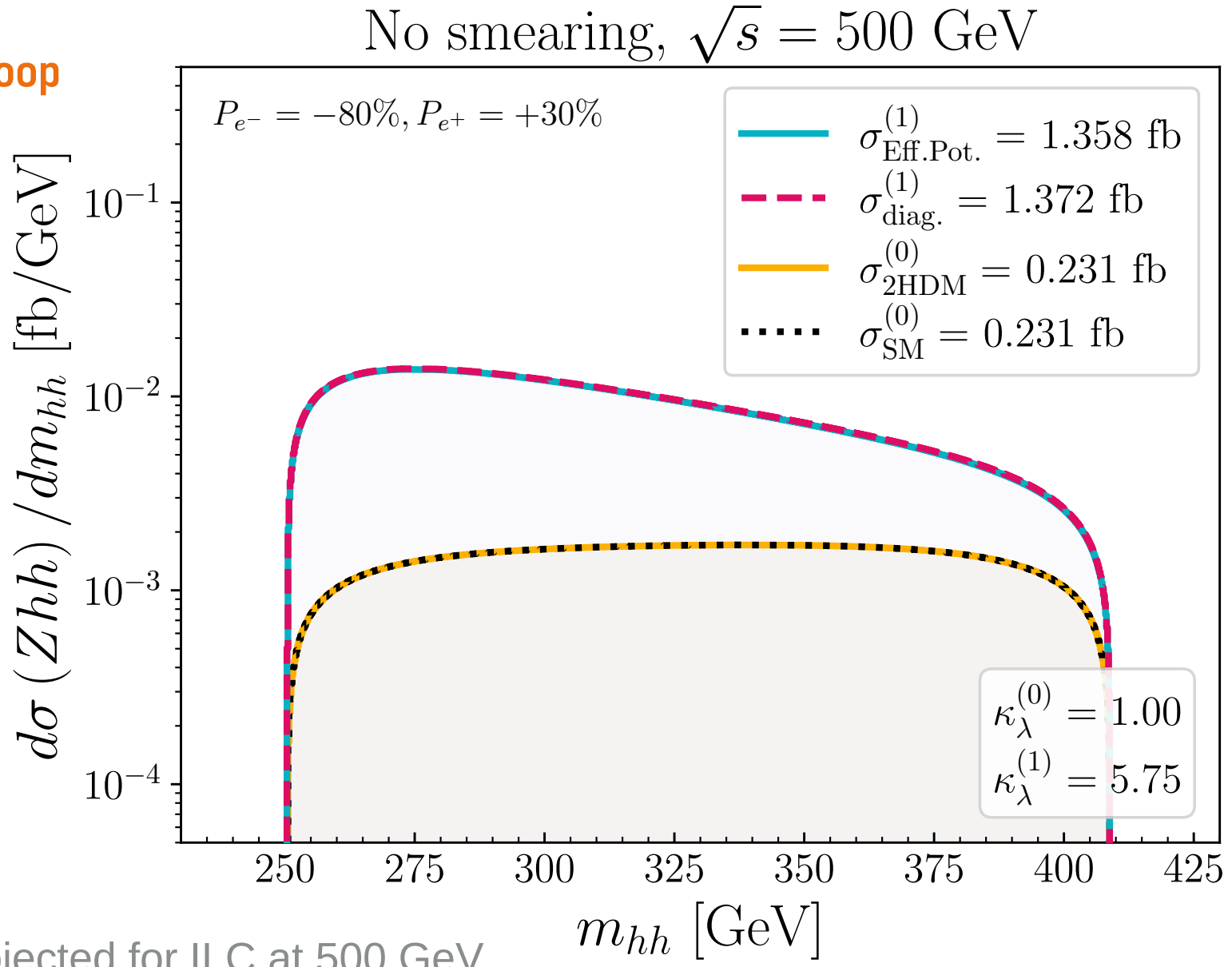
Access to κ_λ @500 GeV

Benchmark point with large κ_λ at one loop

BPal, all types!

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

- Cross section **6 times larger** than at the tree level !!!
  - Expected precision on κ_λ ~10% *[LCVision, LCF, 25]*
- **Momentum effects** from $\kappa_\lambda(m_{hh})$ around 1-2%



Note: luminosity and polarization projected for ILC at 500 GeV

Access to κ_λ @500 GeV

Benchmark point with large κ_λ at one loop

BPal, all types!

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

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

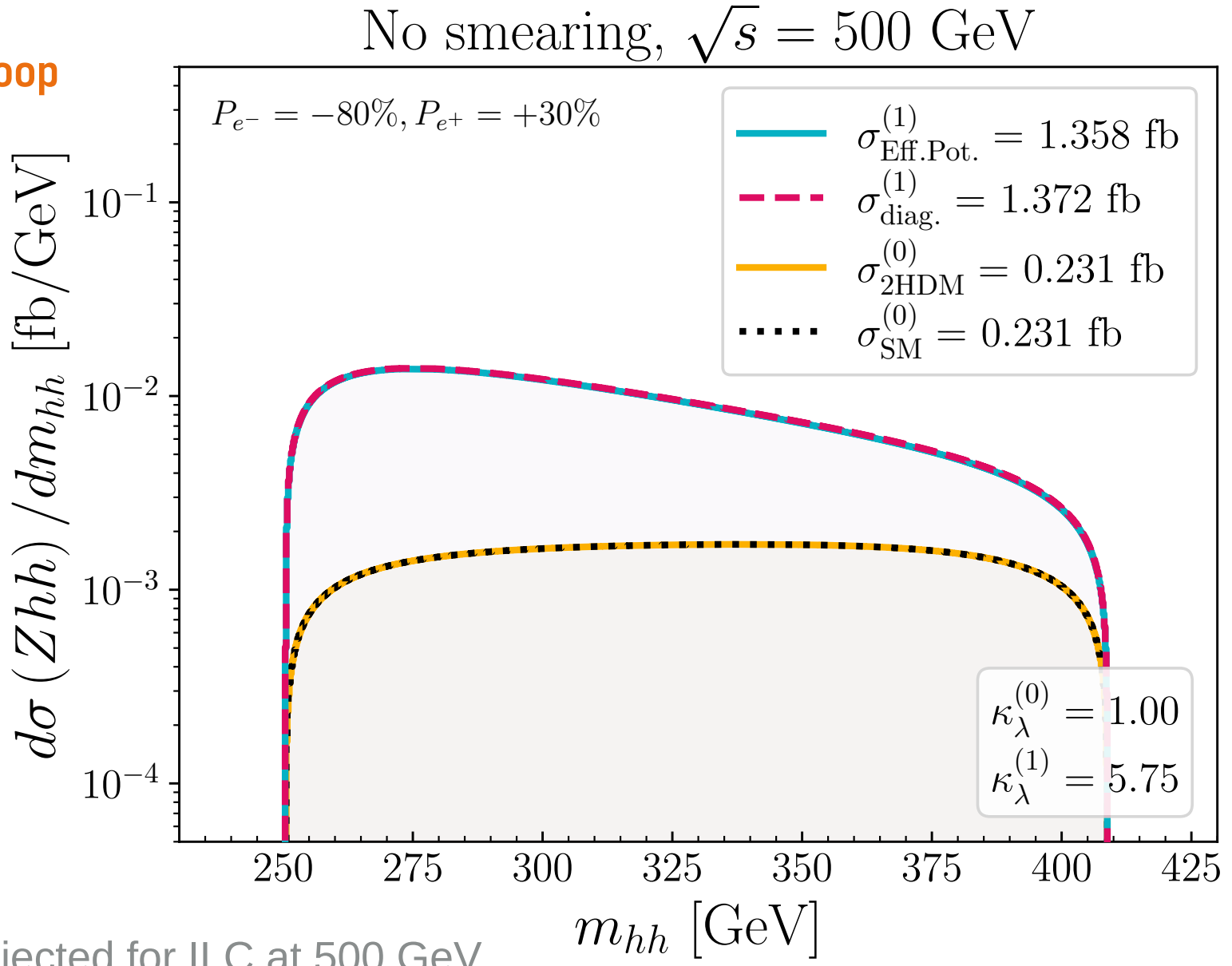
Take-home message:

Necessary to consider one-loop corrected THCs in BSM predictions!

- (

~10% *[LCVision, LCF, 25]*

- **Momentum effects** from $\kappa_\lambda(m_{hh})$ around 1-2%



Note: luminosity and polarization projected for ILC at 500 GeV

Sensitivity to the H resonance and access to λ_{hhH}

Several experimental considerations

- **Theoretical 'sensitivity':** significance Z testing the **H resonance vs the no resonance** (i.e. $\lambda_{hhH} = 0$) hypothesis *(no backgrounds are considered)*
- Expected final **$4b$-jet events**:
  - Efficiency of reconstructing the $4b$ jets of 85% *[C. Dürig PhD Thesis, 16]*
  - Acceptance after the preselection cuts (around 75%):

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

- **Smearing of the m_{hh} distributions** to mimic the finite detector resolution
  - We consider 2%, 5% and 10% of Gaussian smearing (currently 5% is expected) *[LCVision, 25]*
- **Size of the bin**: at least 2 events within the kinematically allowed region

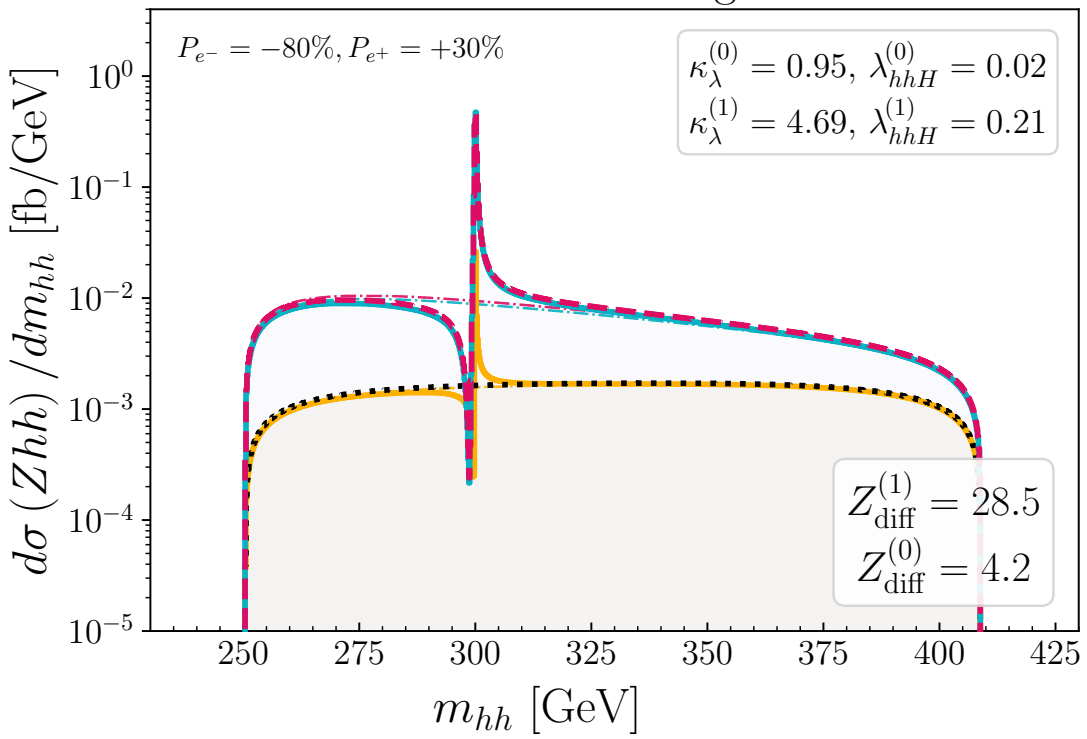
Access to λ_{hhH} (no smearing) - BP1

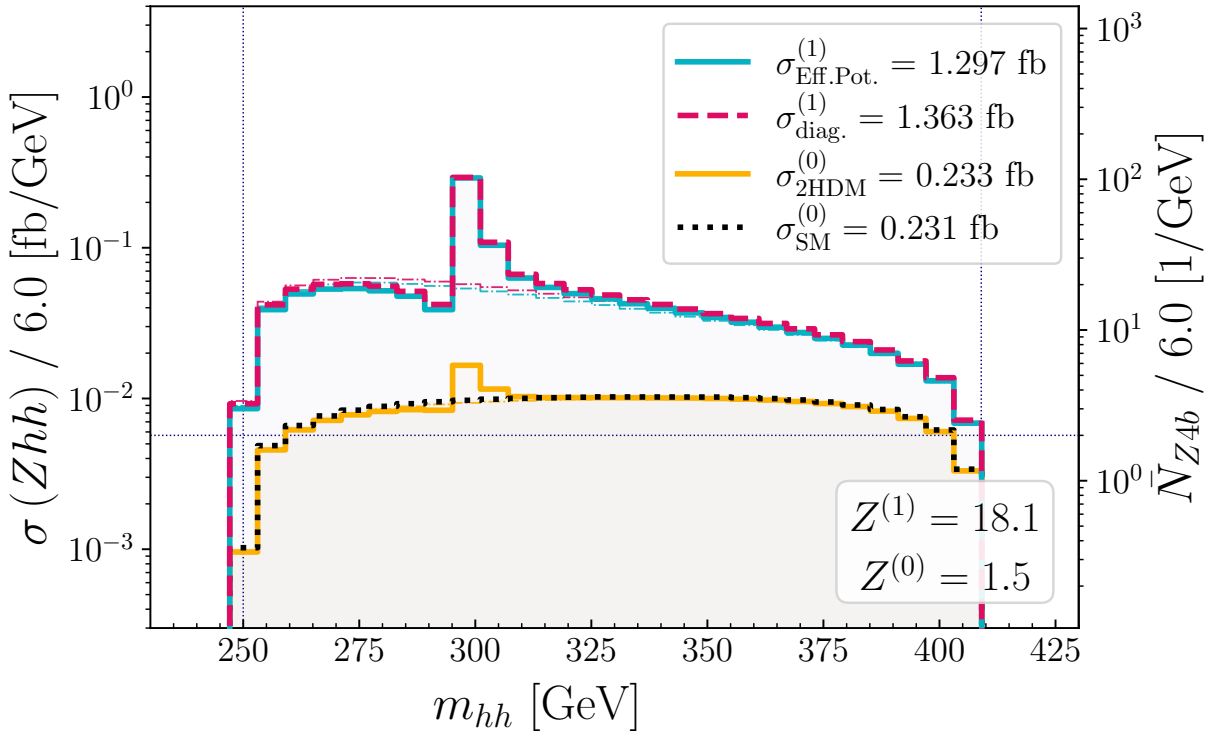
Benchmark point with λ_{hhH} twice at one loop vs tree level

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

- Large effect from $\kappa_\lambda^{(1)} \simeq 4.7$
- For this point $\lambda_{hhH}^{(0)} \sim 0 \ll \lambda_{hhH}^{(1)}$
  - More prominent H resonance, so greater Z

No smearing





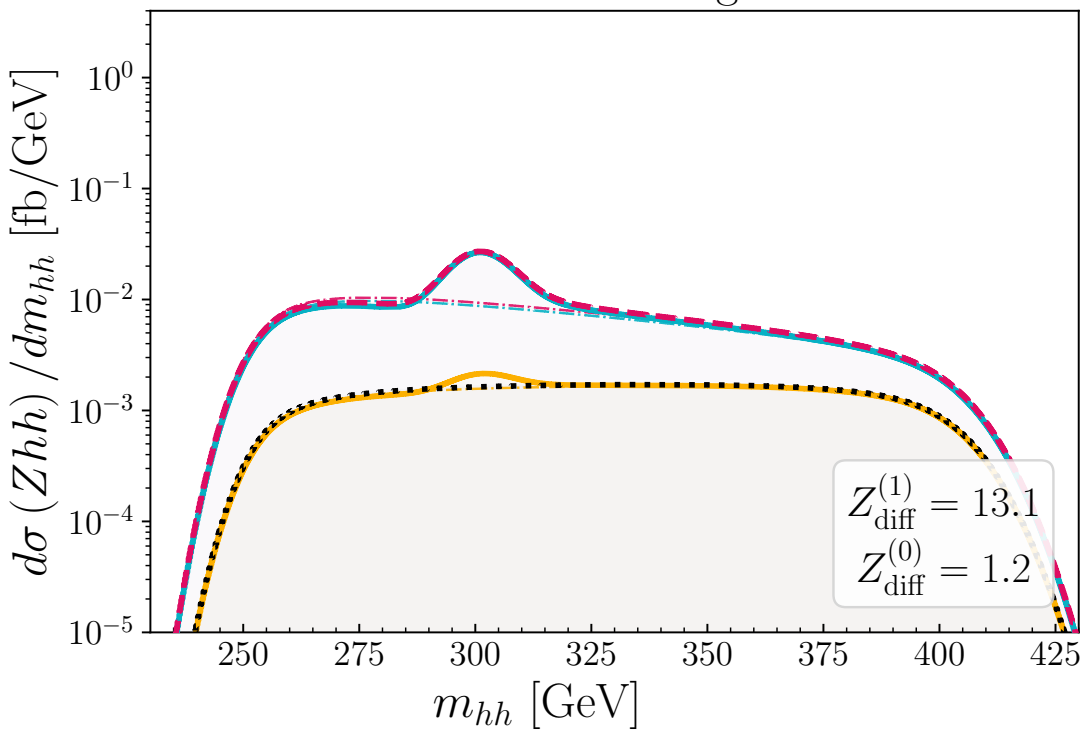
Access to λ_{hhH} (5% smearing) - BP1

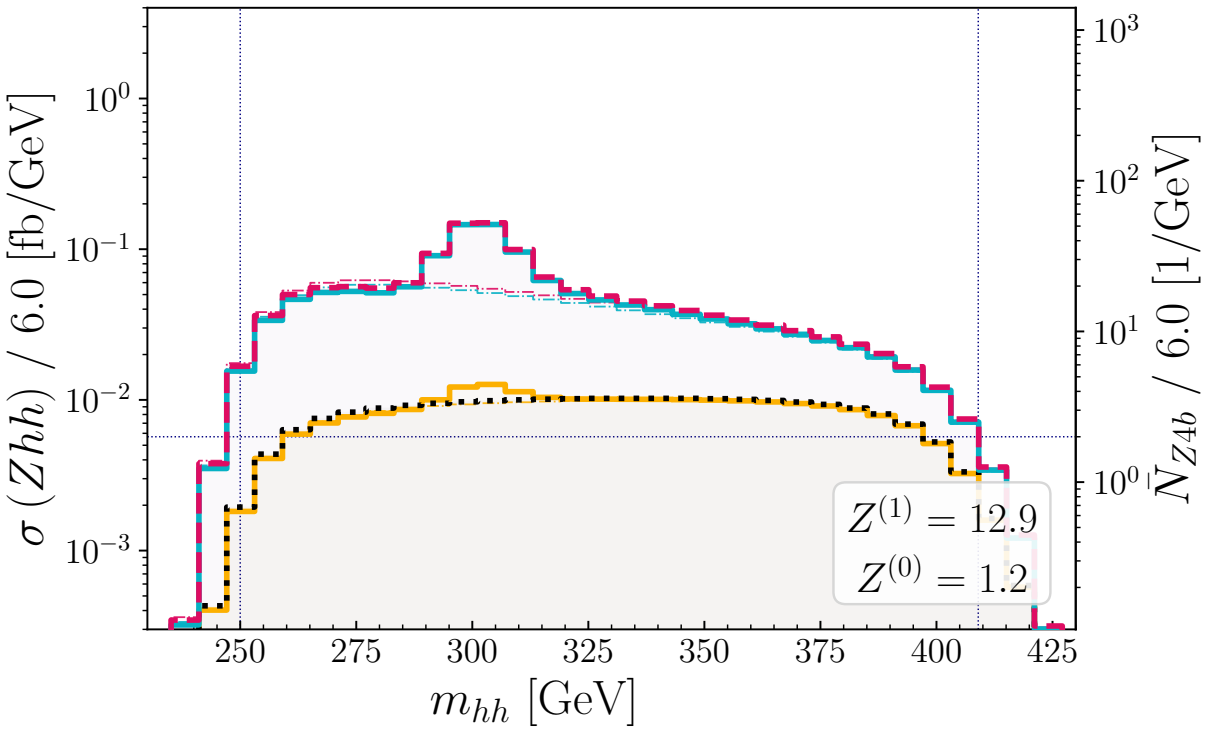
Benchmark point with λ_{hhH} twice at one loop vs tree level

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

- The H resonance peak gets even more smeared
- Values of Z get even worst
- Sensitivity to the sign of λ_{hhH} becomes challenging

5% smearing





Access to λ_{hhH} (no smearing) - BPsign

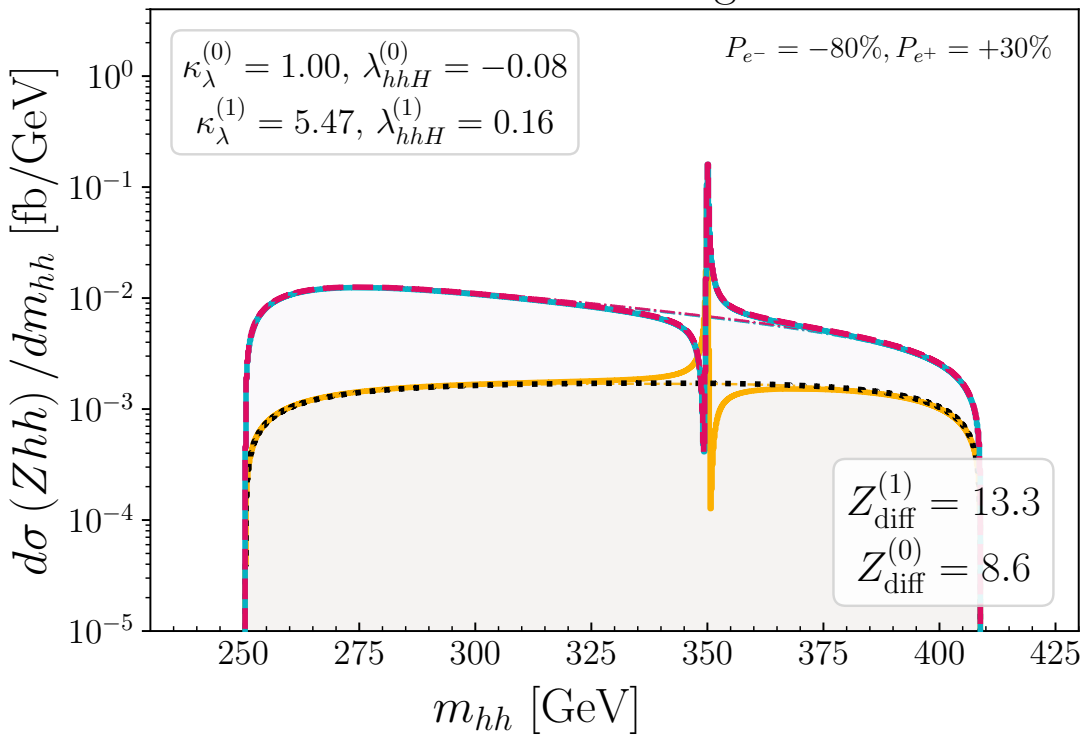
Benchmark point with λ_{hhH} changing sign at one loop vs tree level

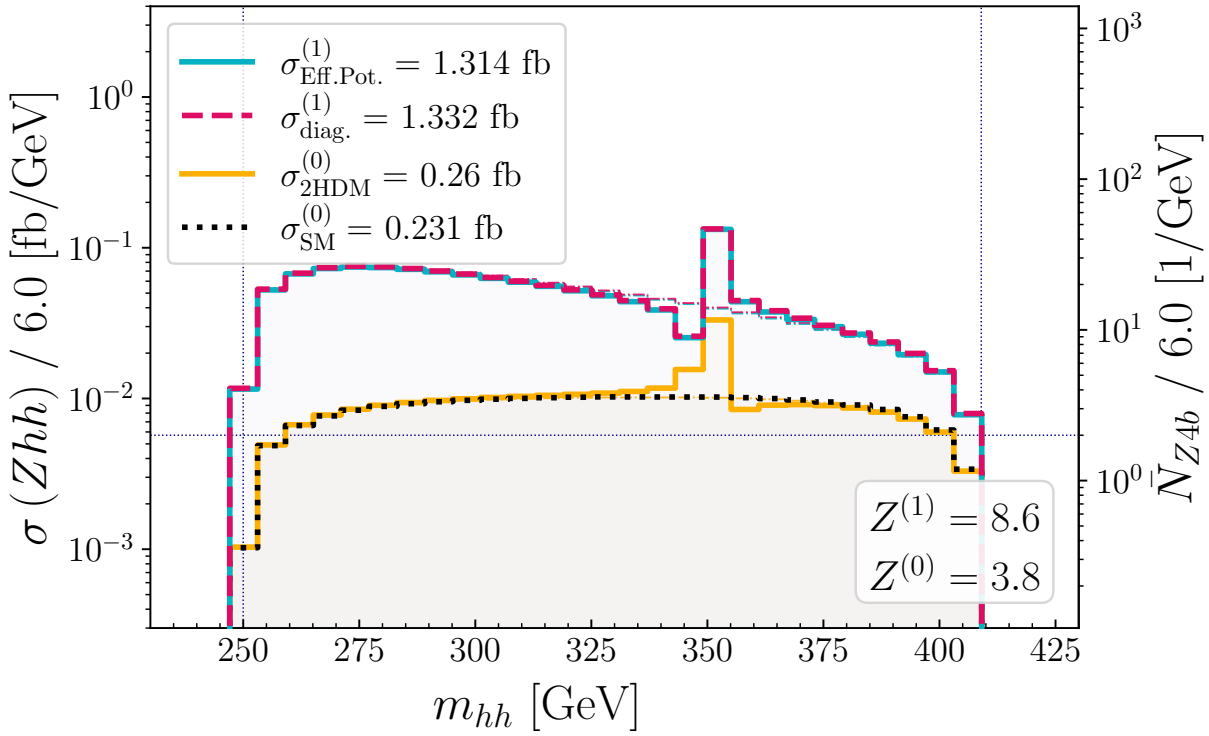
$$\text{BPsign, type I}$$
$$m_H = \bar{m} = 350 \text{ GeV},$$
$$m_A = m_{H^\pm} = 650 \text{ GeV},$$
$$\tan\beta = 20, \ \cos(\beta - \alpha) = 0.1$$

- 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 peak!
- Large effect from $\kappa^{(1)}_\lambda$

No smearing



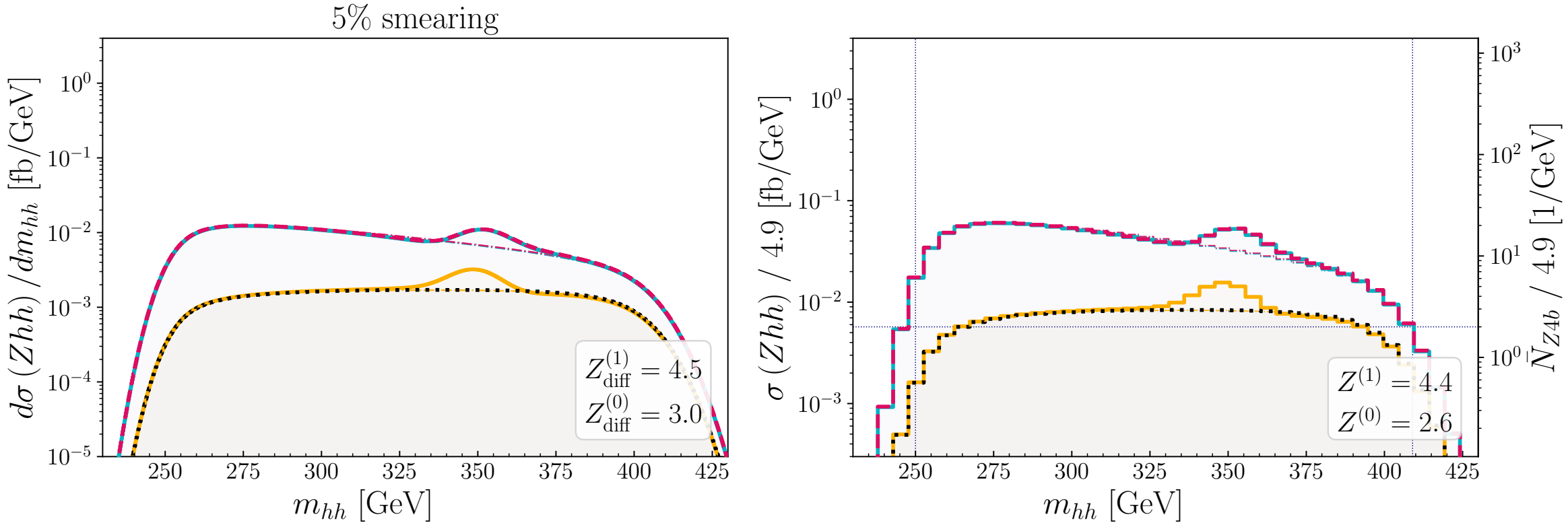


Access to λ_{hhH} (5% smearing) - BPsign

Benchmark point with λ_{hhH} changing sign at one loop vs tree level

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

- The dip-peak structure gets diluted wrt no smearing
- Challenging access to the sign of λ_{hhH}



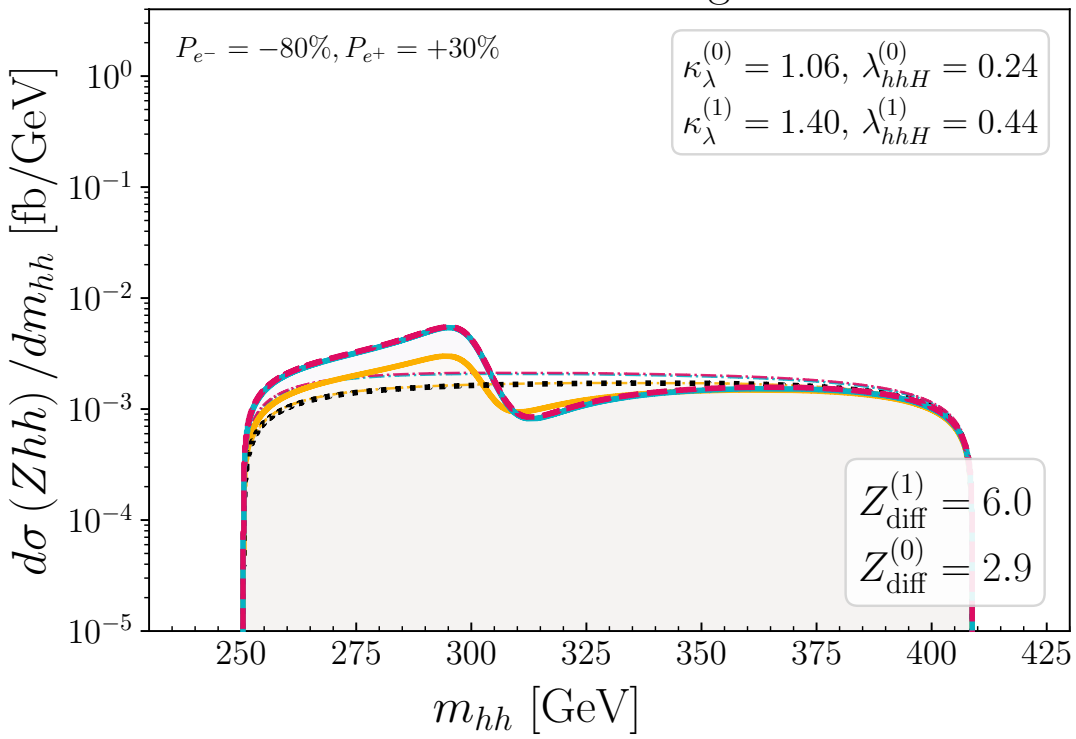
Access to λ_{hhH} (no smearing) - BP3

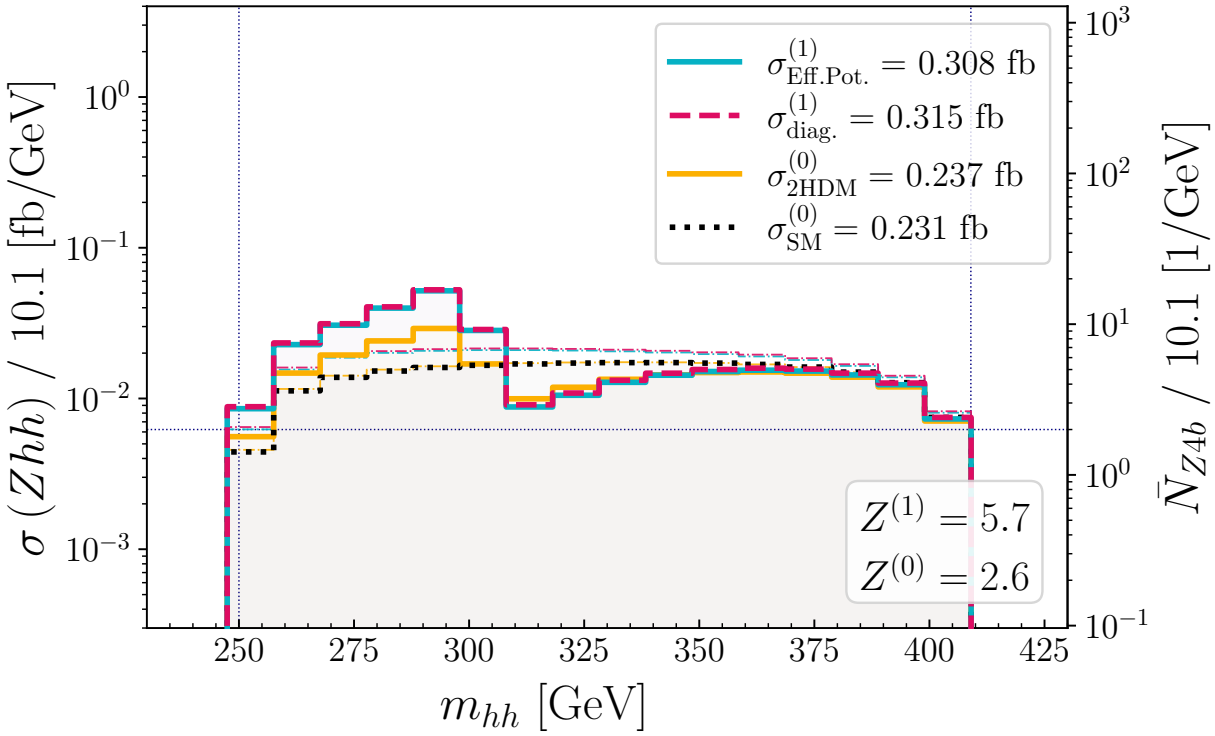
Benchmark point with a large H width

$$\text{BP3, type I}$$
$$m_H = m_{H^\pm} = 300 \text{ GeV},$$
$$m_A = 100 \text{ GeV}, \bar{m} = 0$$
$$\tan\beta = 2.5, \ \cos(\beta - \alpha) = -0.18$$

- Large one-loop λ_{hhH} wrt tree level
- Γ_H ~ 16 GeV because $H \to AA$ is open

No smearing



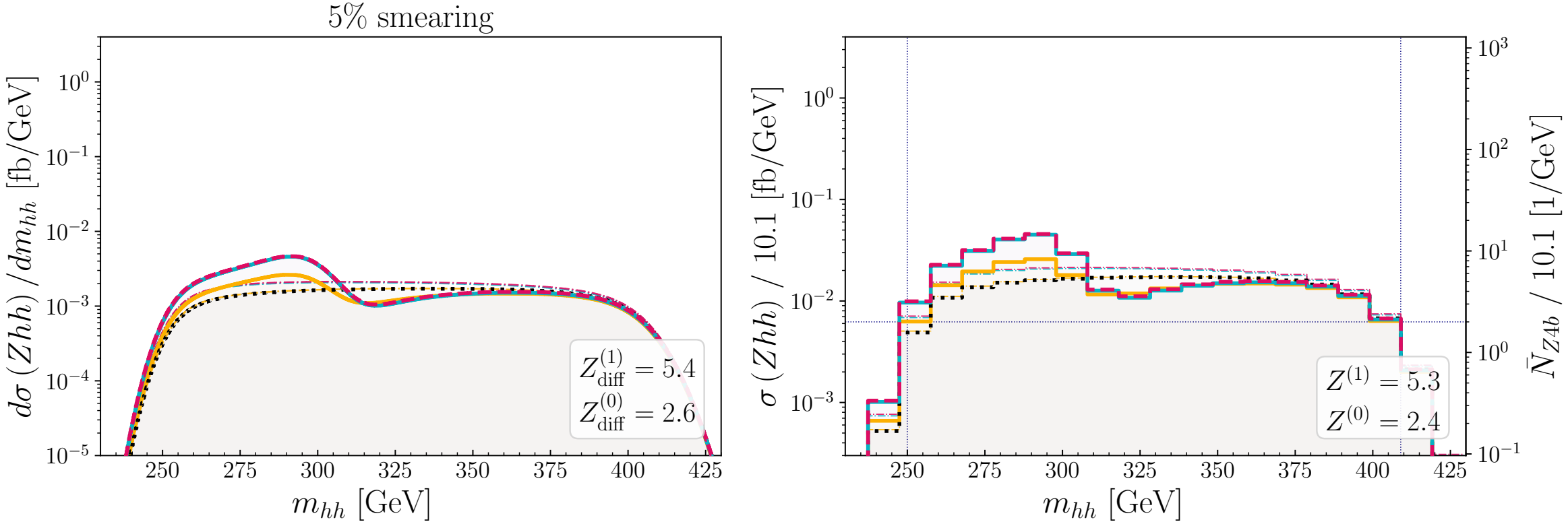


Access to λ_{hhH} (5% smearing) - BP3

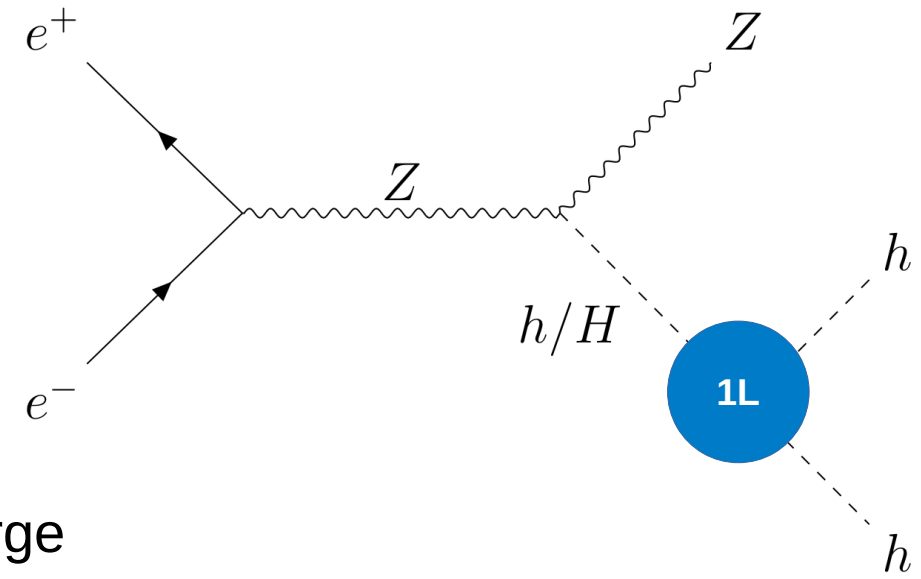
Benchmark point with a large H width

$$\text{BP3, type I}$$
$$m_H = m_{H^\pm} = 300 \text{ GeV},$$
$$m_A = 100 \text{ GeV}, \bar{m} = 0$$
$$\tan\beta = 2.5, \ \cos(\beta - \alpha) = -0.18$$

- Smearing is only important for narrow resonances
- Still challenging access to these point



Summary and conclusions



- **One-loop corrected triple Higgs couplings (THCs)** can *significantly* impact the **double Higgs production at e^+e^- colliders** in the 2HDM, $e^+e^- \to Zhh$ at 500 GeV

- **One-loop corrections to λ_{hhh}** (alternatively κ_λ) can be large
  - *Even in the alignment limit!* ⇒ Very distinct prediction even for a very SM-like Higgs boson!
  - No relevant effects from finite momentum
- **One-loop corrections to λ_{hhH}** can lead to interesting pheno! Access via the **H resonance** peak
- Analysis of the final **4b-jet events + smearing + bin size**: promising access to the H peak *(but an experimental analysis is needed)*
  - Resolution in the m_{hh} distributions will be crucial

Thanks for your attention