
I FOUND THE HUGS BISON.
MINIMUMBLE.COM
©2012 CHRIS HALLBECK

# Corrections to BSM Triple Higgs Couplings and their phenomenological consequences

*Sven Heinemeyer, IFT (CSIC, Madrid)*

Wittenberg, 04/2024

1. Introduction: (BSM) di-Higgs production at the (HL-)LHC
2. Calculation
3. Phenomenological impact
4. BSM di-Higgs production at $e^+e^-$ colliders
5. Conclusions

# 1. Introduction: (BSM) di-Higgs production at the (HL-)LHC

# 1. Introduction: (BSM) di-Higgs production at the (HL-)LHC

## 1. Introduction: (BSM) di-Higgs production at the (HL-)LHC


⇒ Why is there more matter than antimatter? ⇒ (EW) baryogenesis

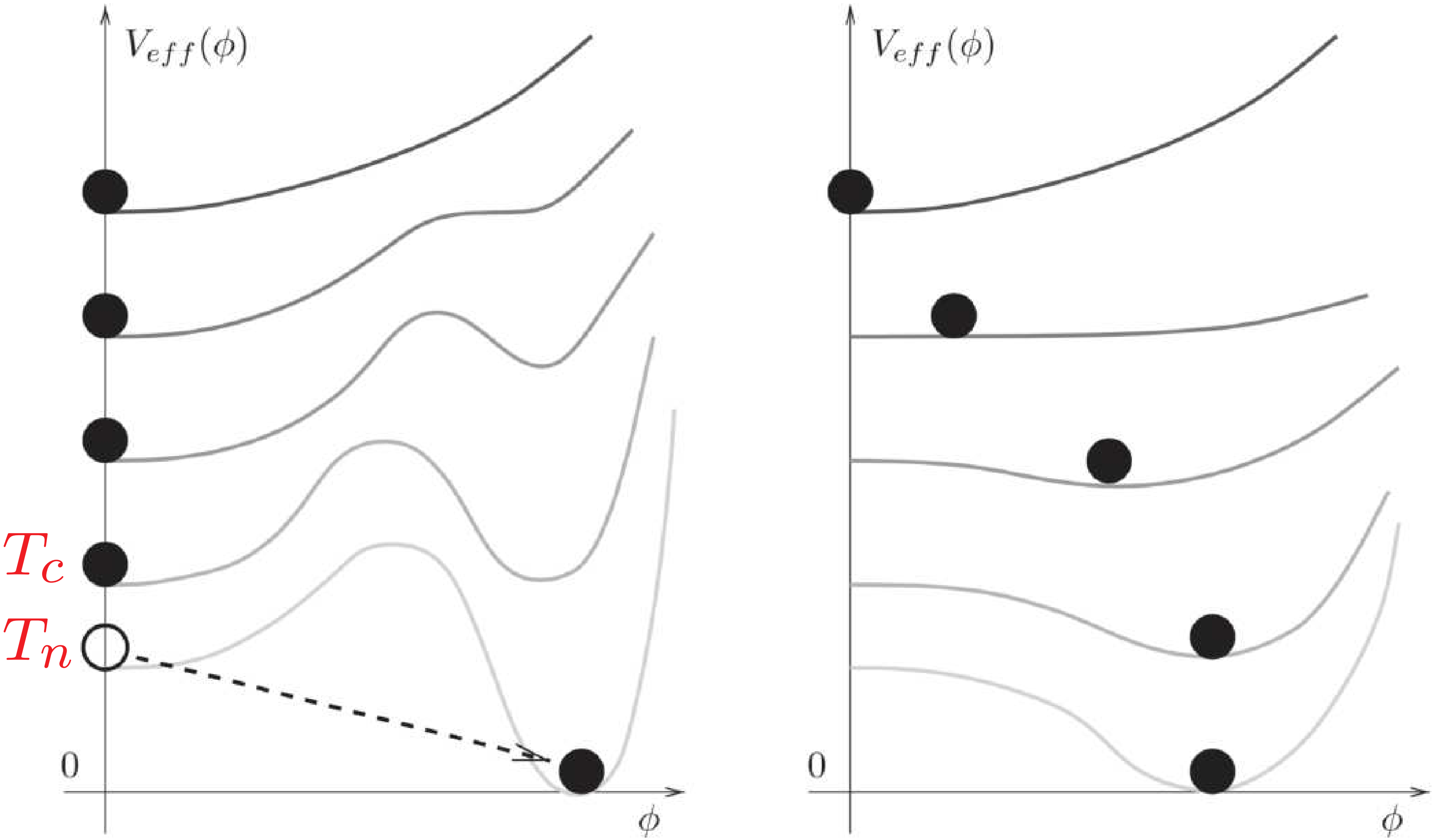
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

FOEWPT can cause Gravitational Waves (GW), detectable with LISA, . . .

## Phase transition: BSM vs. SM

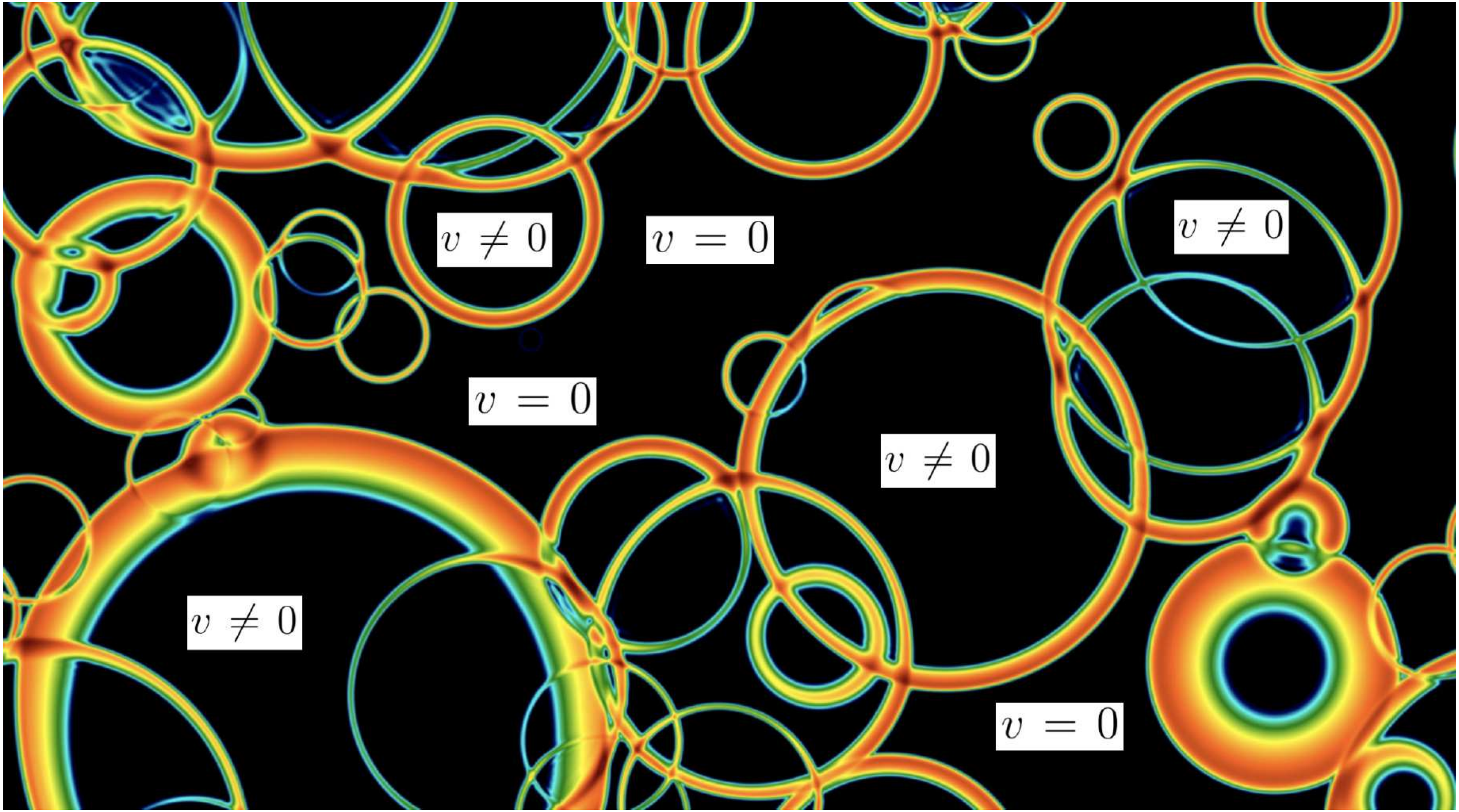
[*taken from V. A. Rubakov and D. S. Gorbunov*]




$\Rightarrow$ BSM Higgs sector (large THCs) required to realize FOEWPT

# Bubble formation can lead to Gravitational Waves

[*taken from D. Weir*]




$\Rightarrow$ BSM Higgs sector (large THCs) required to realize FOEWPT

# Our choice for BSM Higgs sectors: Two Higgs Doublet Model (2HDM):

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \end{aligned}$$

Physical states: $h$, $H$, ($\mathcal{CP}$-even), $A$ ($\mathcal{CP}$-odd), $H^\pm$ (charged)

"Physical" input parameters:

$$c_{\beta-\alpha}\,, \quad \tan\beta\,, \quad v\,, \quad M_h, \quad M_H\,, \quad M_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Alignment limit: $c_{\beta-\alpha} \to 0$ (for $M_h \sim 125$ GeV)

Many triple Higgs couplings: $\lambda_{hhh}$, $\lambda_{hhH}$, $\lambda_{hHH}$, $\lambda_{hH^+H^-}$, $\lambda_{HAA}$, ...

Assumption: $h \sim h_{125}$

$Z_2$ symmetry to avoid FCNC:

$$\Phi_1 \to \Phi_1 \, , \; \Phi_2 \to -\Phi_2$$

Extension of the $Z_2$ symmetry to fermions determines four types:

| | $u$-type | $d$-type | leptons | |
|---|---|---|---|---|
| type I | $\Phi_2$ | $\Phi_2$ | $\Phi_2$ | |
| type II | $\Phi_2$ | $\Phi_1$ | $\Phi_1$ | $\to$ SUSY type |
| type III (lepton-specific) | $\Phi_2$ | $\Phi_2$ | $\Phi_1$ | |
| type IV (flipped) | $\Phi_2$ | $\Phi_1$ | $\Phi_2$ | |

Sum rule (with $h$ SM-like): $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) \approx 0$

Unitarity/perturbativity and EWPO : $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

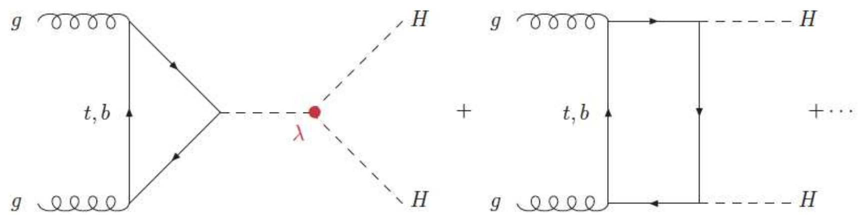
## 2. Calculation

### Basics on di-Higgs production at the (HL-)LHC

[*taken from M. Spira*]

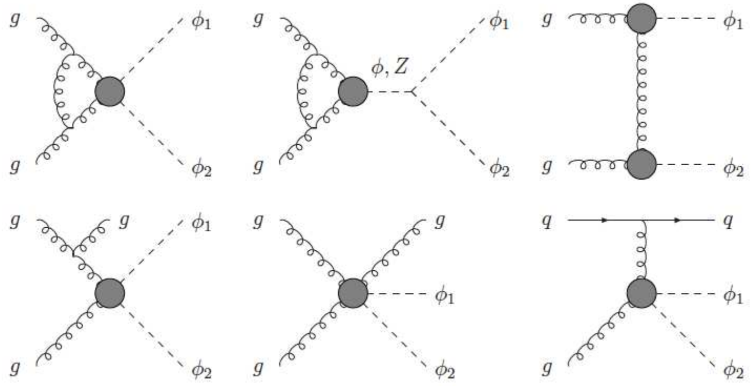
$gg \to HH$

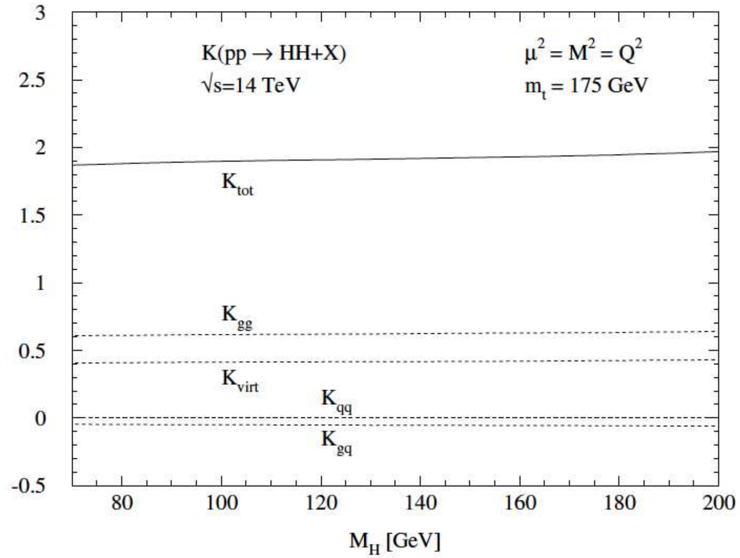
(B)SM




- third generation dominant $\to t, b$

- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$

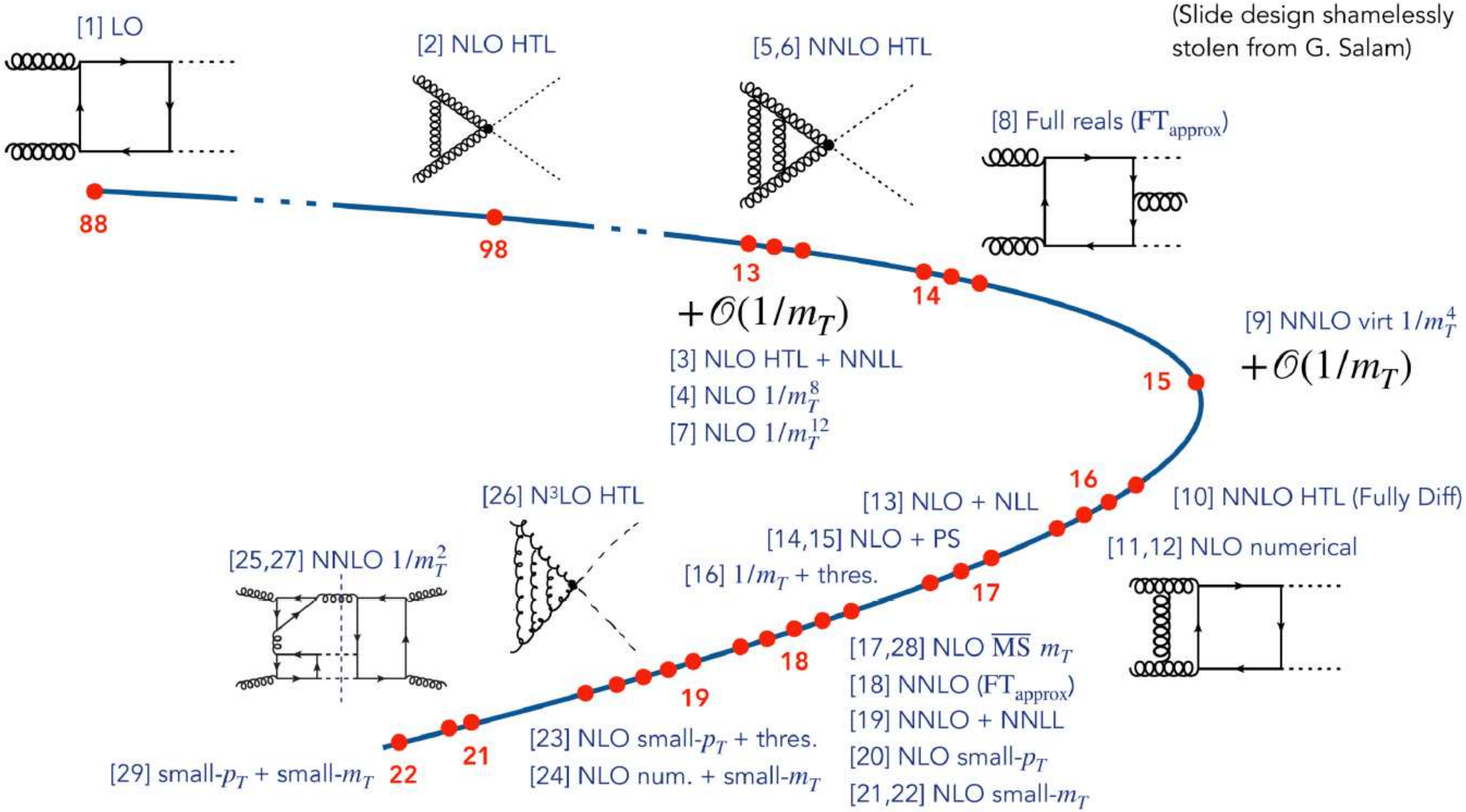



Dawson, Dittmaier, S.

$\Rightarrow$ predictions "easily" available in NLO QCD (heavy top limit)

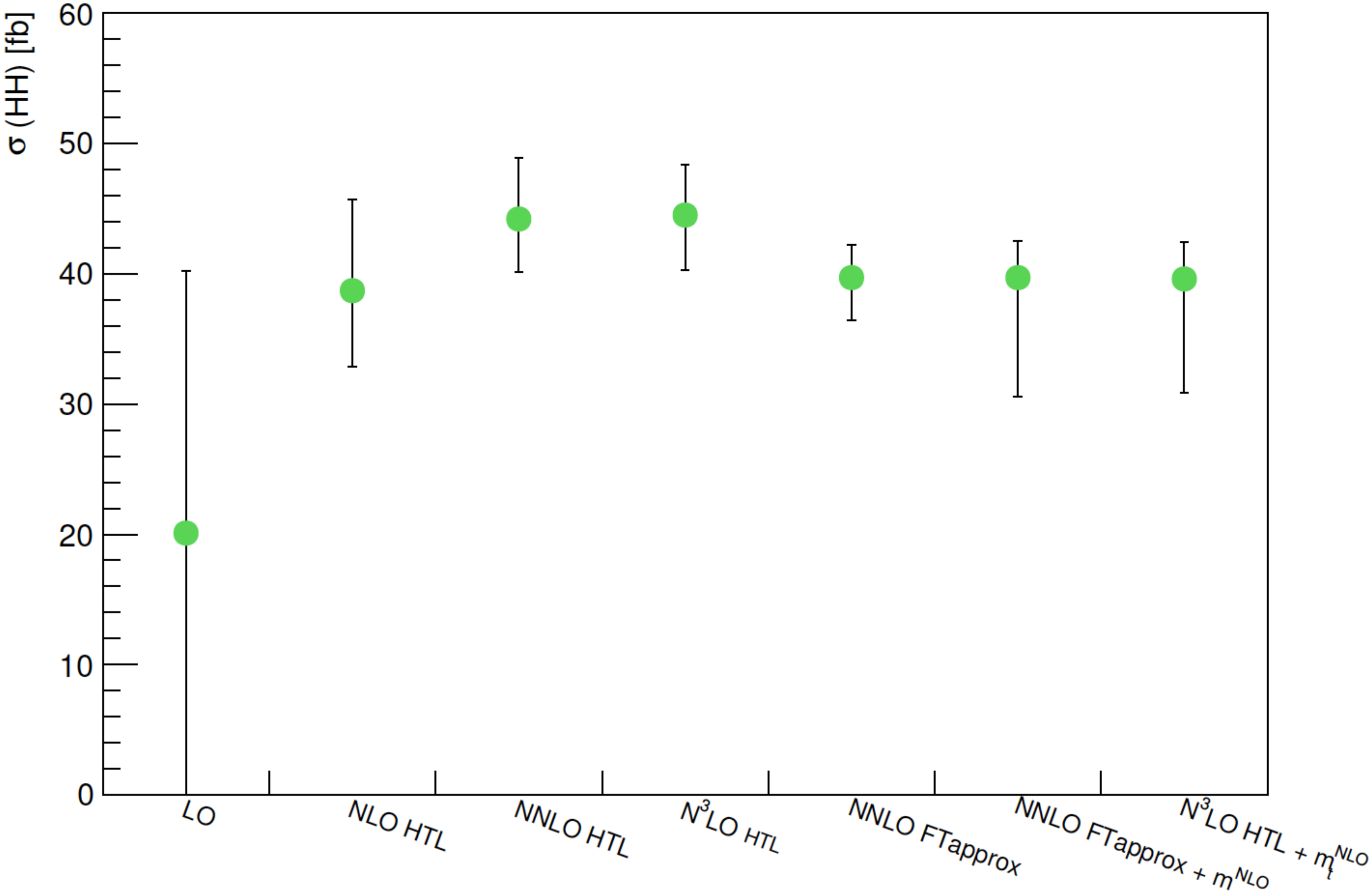
## In the SM there is much more available:




[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

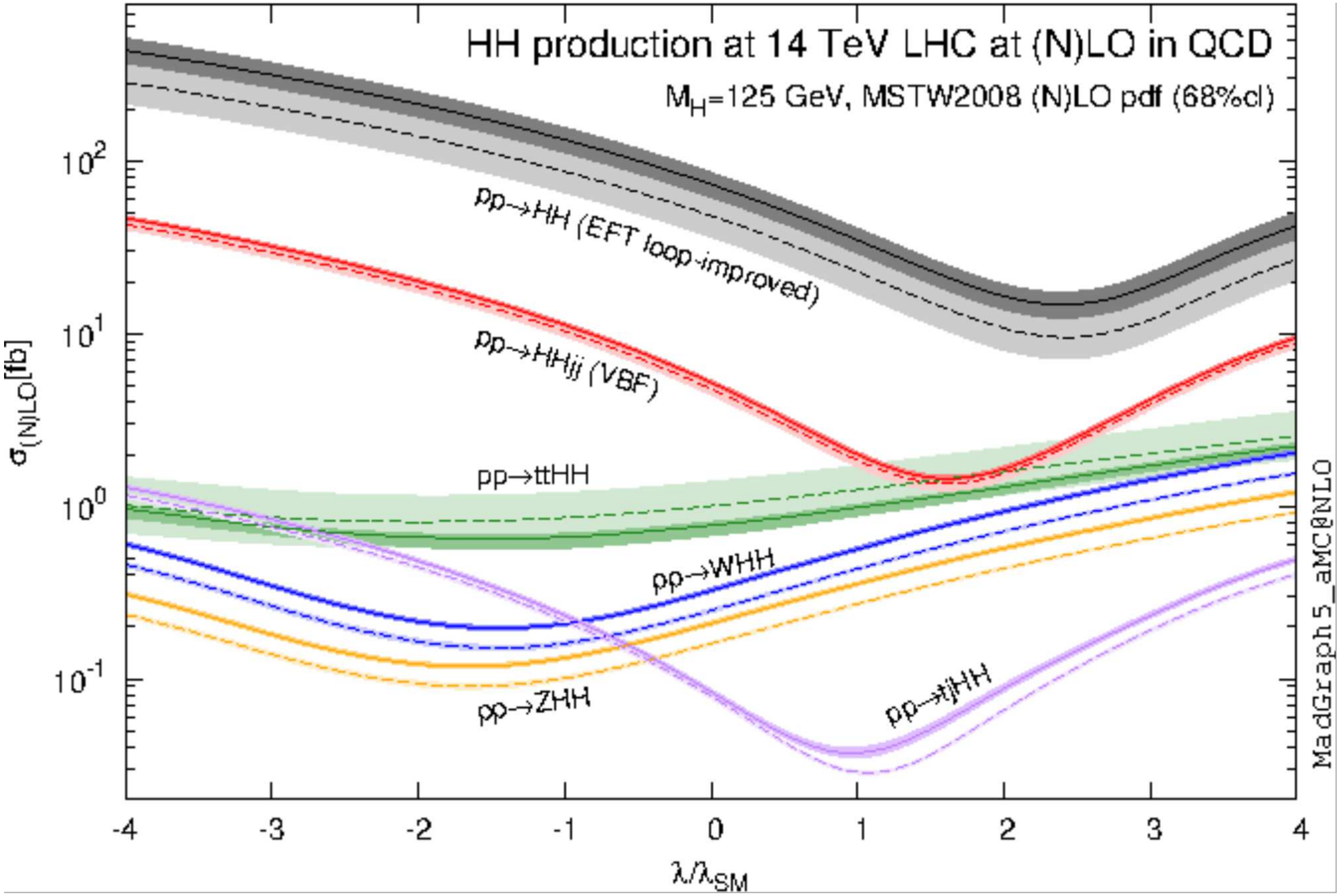
S. Jones

## Size of the SM corrections has stabilized (albeit with uncertainties)



# Di-Higgs production at the LHC: $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$

$\Rightarrow$ strong interference of "box" and "SM-like Higgs"

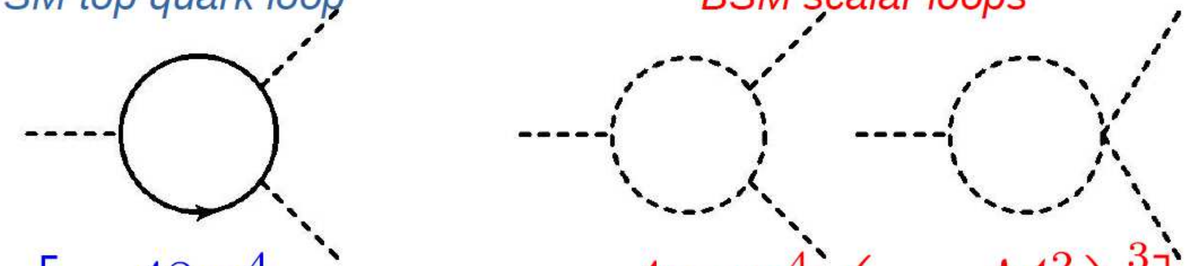



$\Rightarrow$ higher-order corrections to $\kappa_\lambda$ potentially very important

# One-loop non-decoupling effects

- **Leading one-loop** corrections to $\lambda_{hhh}$ in models with extended sectors (like 2HDM):

*SM top quark loop* *BSM scalar loops*



$$\delta^{(1)}\lambda_{hhh} \supset \frac{1}{16\pi^2}\left[-\frac{48m_t^4}{v^3} + \sum_\Phi \frac{4n_\Phi m_\Phi^4}{v^3}\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3\right]$$

*First found in 2HDM:*
[Kanemura, Kiyoura, Okada, Senaha, Yuan '02]

$\mathcal{M}$ : **BSM mass scale**, e.g. soft breaking scale M of $Z_2$ symmetry in 2HDM
$n_\Phi$ : # of d.o.f of field Φ

- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda}v^2$

$$\left(1-\frac{\mathcal{M}^2}{m_\Phi^2}\right)^3 \longrightarrow \begin{cases} 0, \text{ for } \mathcal{M}^2 \gg \tilde{\lambda}v^2 \\ 1, \text{ for } \mathcal{M}^2 \ll \tilde{\lambda}v^2 \end{cases} \longrightarrow$$ **Huge BSM effects possible!**

⇒ effects of 500% - 1000% found . . .

# Higher-order correction to BSM THCs:

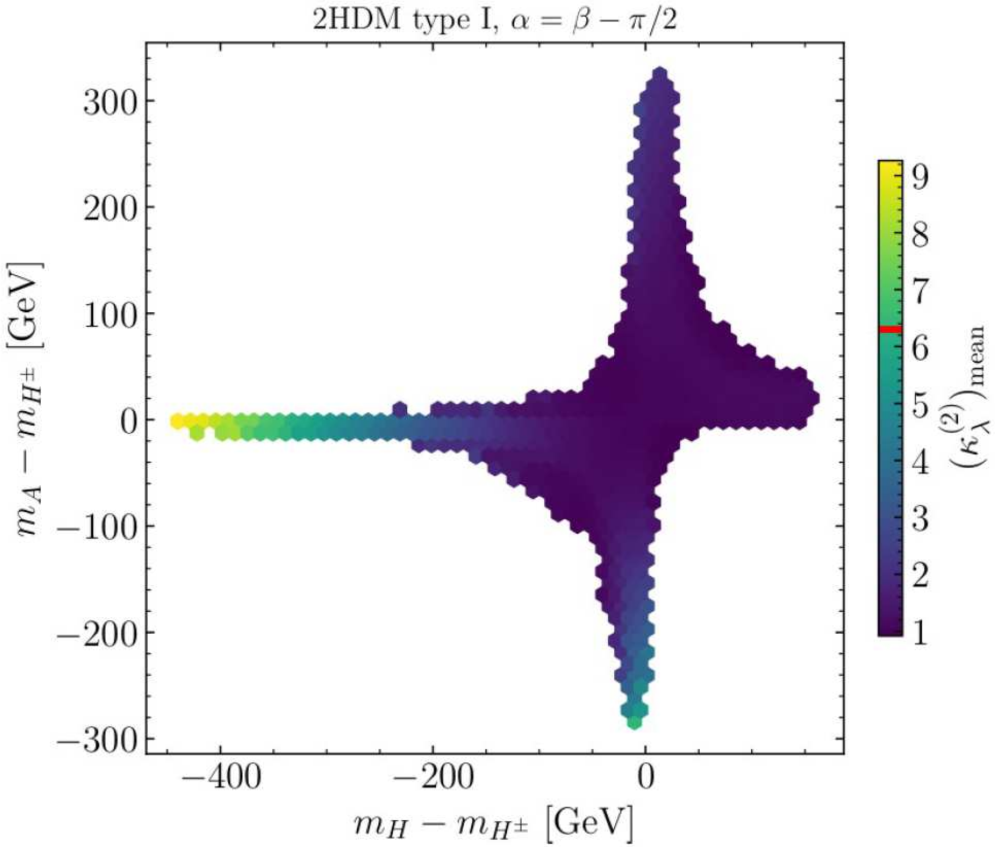
*[taken from J. Braathen]*

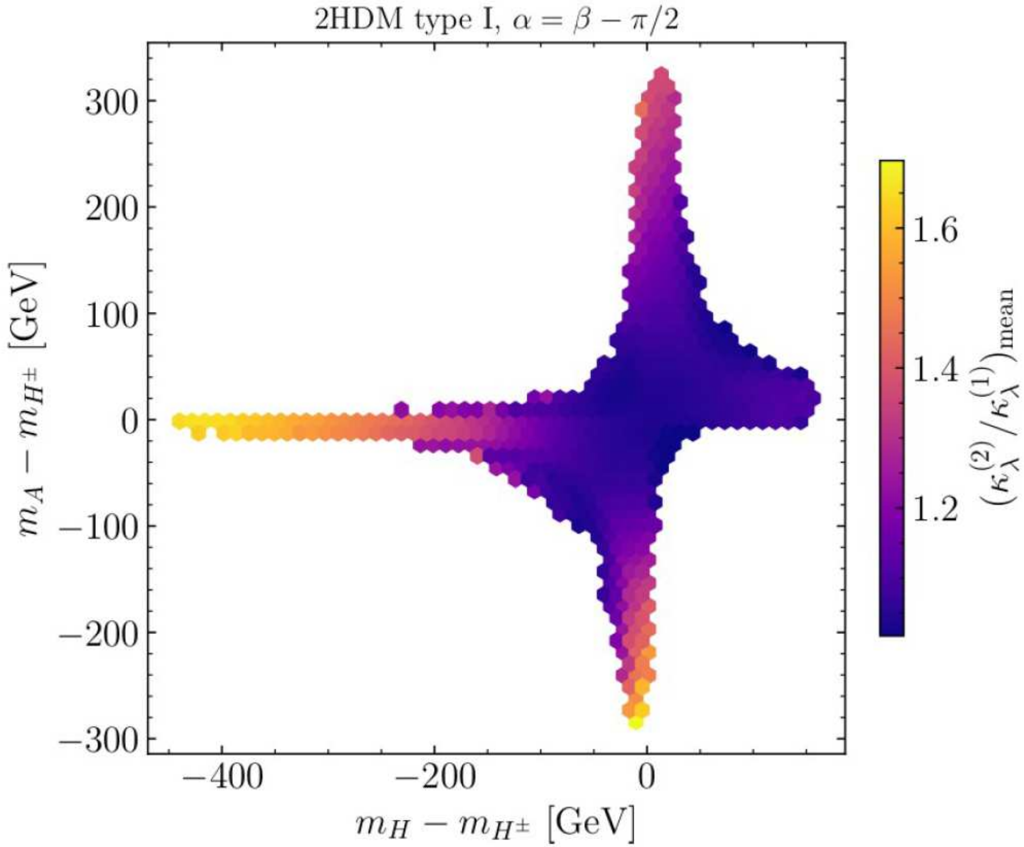
⇒ effects of 500% - 1000% found . . . ⇒ perturbativity??

## Parameter scan results

[Bahl, JB, Weiglein 2202.03453]

**Mean value for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(1)})^{2HDM}$ [right] in ($m_H$-$m_{H\pm}$, $m_A$-$m_{H\pm}$) plane**



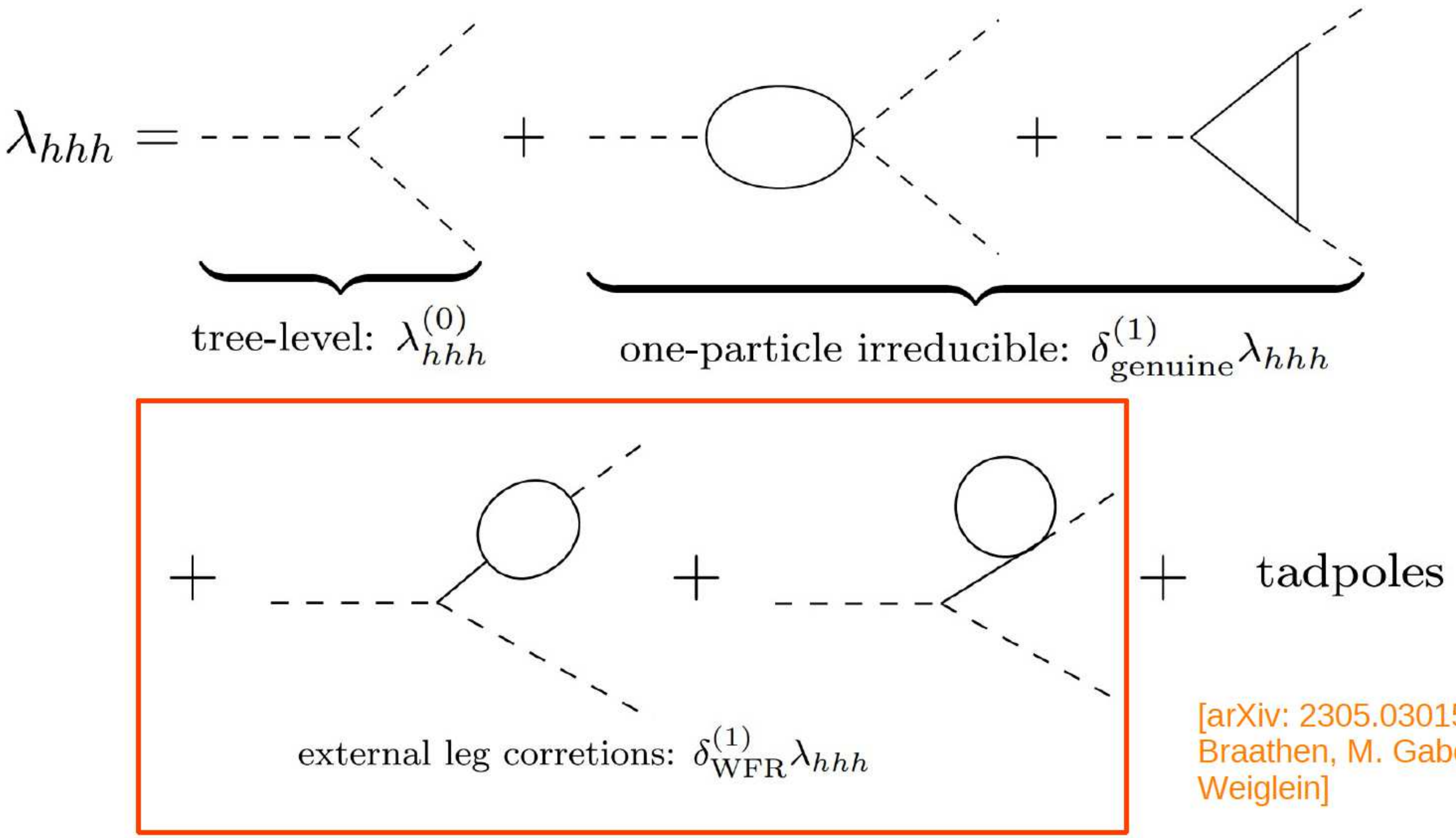

*NB: all previously mentioned constraints are fulfilled by the points shown here*

⇒ Perturbativity is found going from 1L to 2L

# Details of possible higher-order correction to BSM THCs:

*[taken from A. Verduras]*

## External leg corrections




[arXiv: 2305.03015 H. Bahl, J. Braathen, M. Gabelmann, G. Weiglein]

[*taken from A. Verduras*]

# External leg corrections

- The external leg corrections depend on the momentum of the external legs

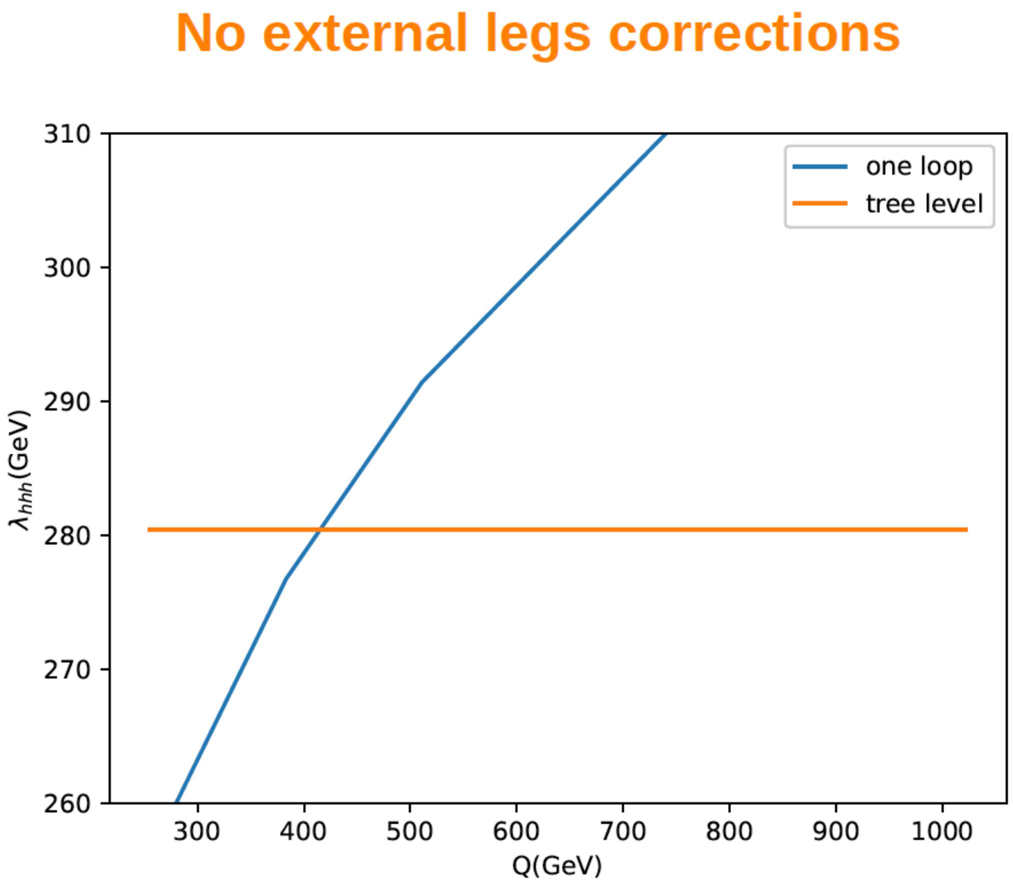
$$\delta^{(1)}\lambda_{hhh}^{\mathrm{WFR}} = \sum_i \left( \frac{1}{2}\Sigma'_{hh}(p_i^2)\lambda_{hhh}^{(0)} + \sum_{j,h_j \neq h} \frac{\Sigma_{hh_j}(p_i^2)}{p_i^2 - m_{h_j}^2}\lambda_{h_j hh}^{(0)} \right)$$

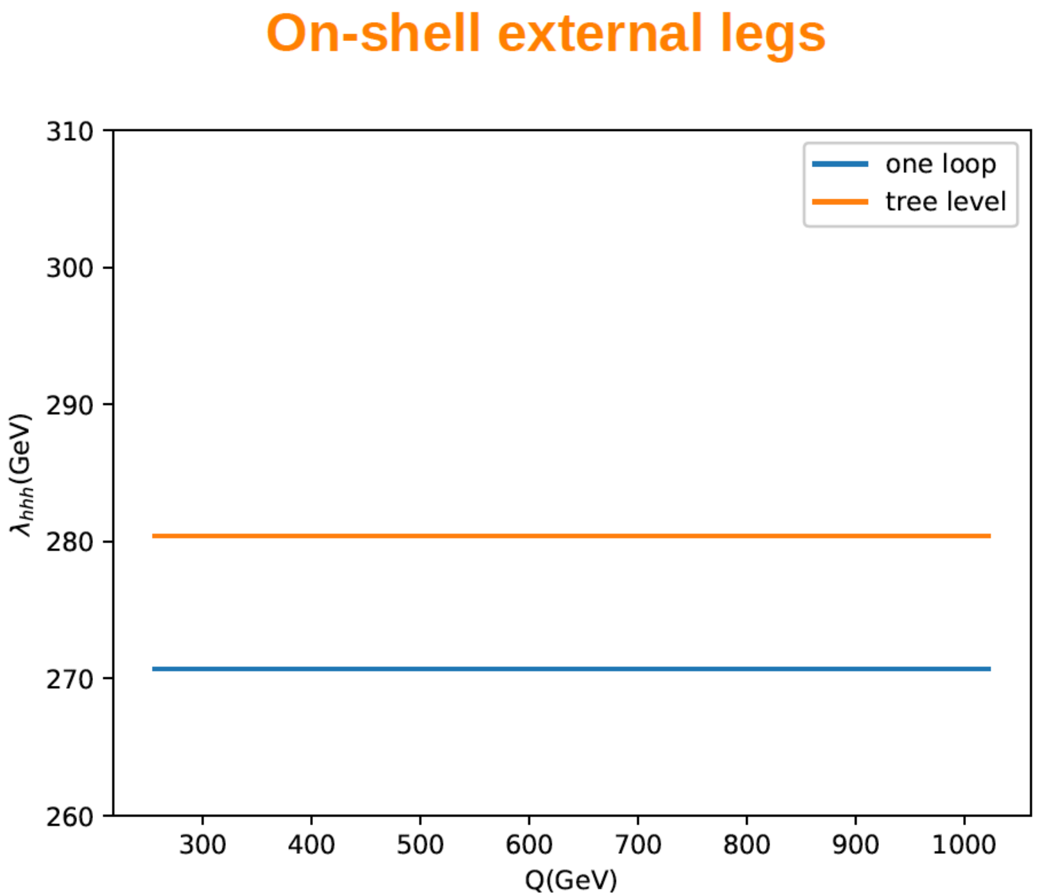
$$\equiv \sum_i \left( \frac{1}{2}\delta^{(1)} Z_h(p_i^2)\lambda_{hhh}^{(0)} + \sum_{j,h_j \neq h} \delta^{(1)} Z_{hh_j}(p_i^2)\lambda_{h_j hh}^{(0)} \right)$$

[arXiv: 2305.03015 H. Bahl, J, Braathen, M. Gabelmann, G. Weiglein]

For "no full-OS" renormalization: [*taken from A. Verduras*]

# External leg correction effect



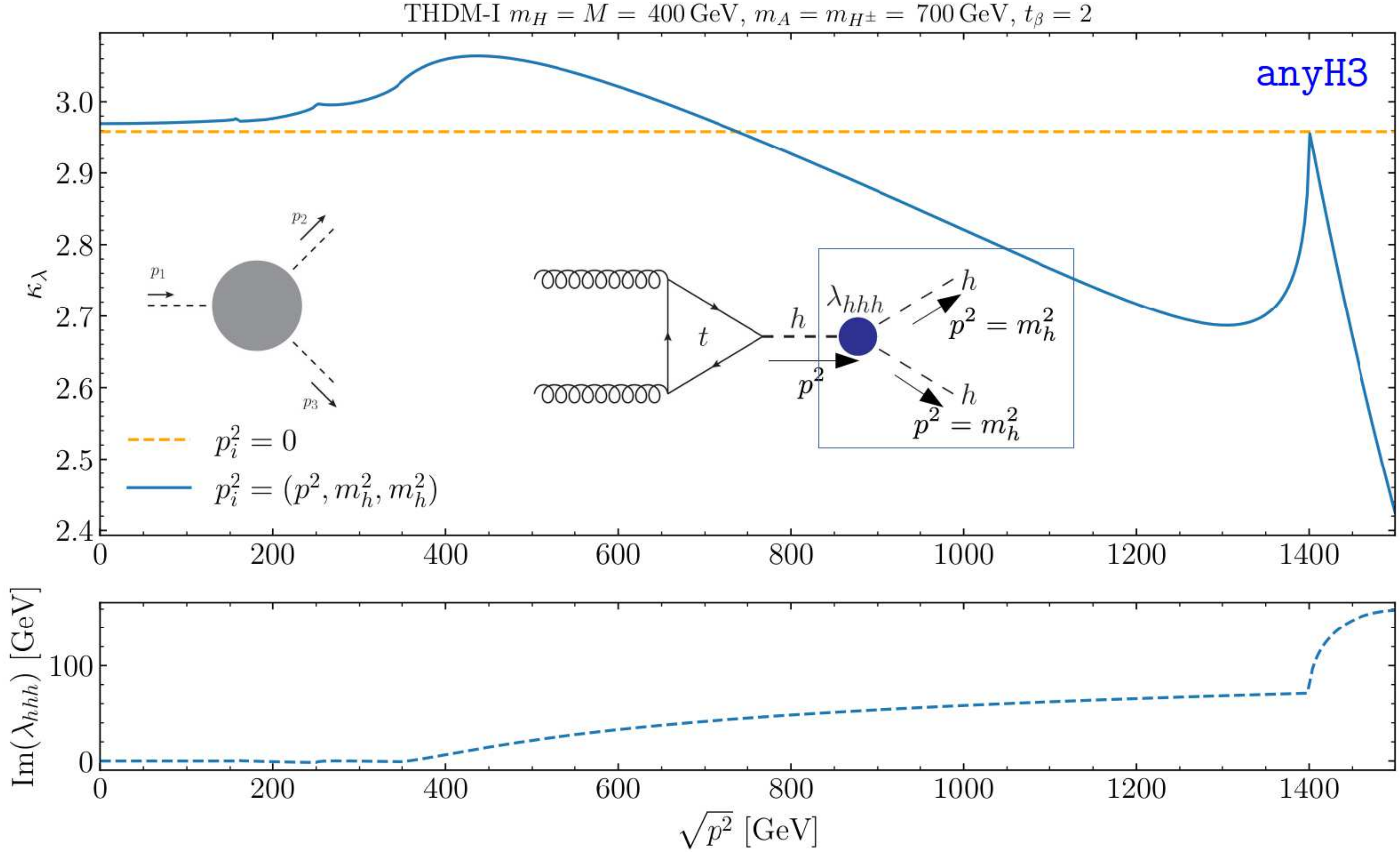

$\Rightarrow$ full calculation, or good/well justified scale choice

# Details of possible higher-order correction to BSM THCs:

[*taken from J. Braathen*]

Momentum dependent effects:

**anyH3: momentum dependence in the 2HDM (1L)**

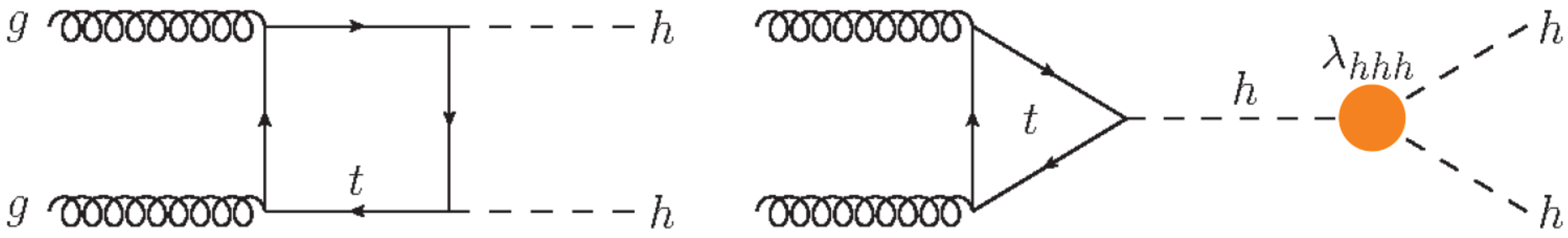



$\Rightarrow$ induce numerically sub-leading effect

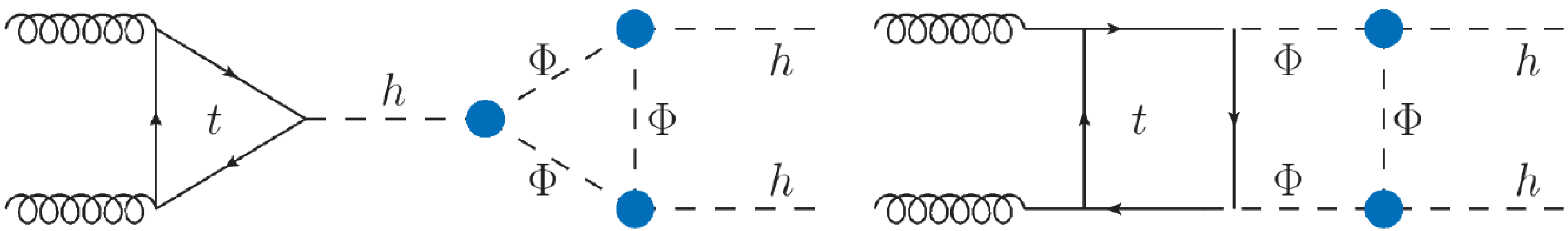
## Higher-order correction to BSM THCs:

*[taken from J. Braathen]*

### Box vs. $s$ channel Higgs:




### Inclusion of one-loop corrections to THCs:




$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$ $\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$

***Correction to $\lambda_{hhh}$ → included*** ***not included***

⇒ always closed subset, dominant for large THCs

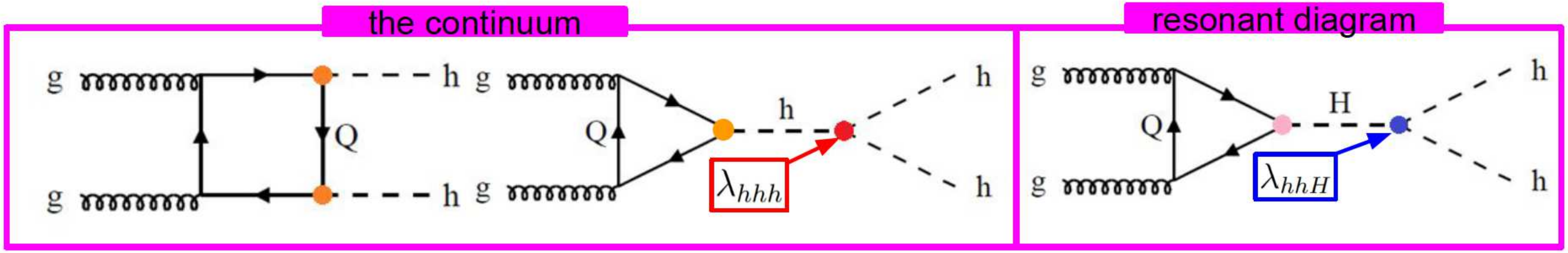
⇒ see also M. Kerner's talk yesterday

BSM effects that can only be captured by explicite calculations

# Di-Higgs production ($gg \to hh$)

[Plehn, Spira, Zerwas : arXiv: 9603205]

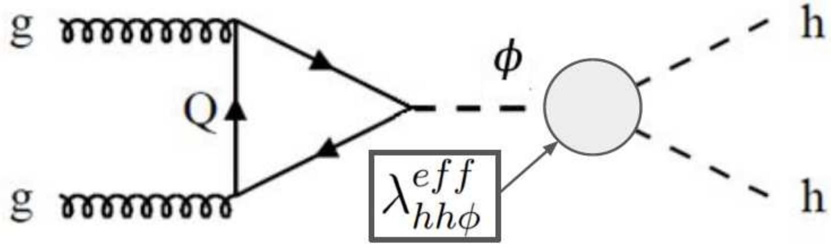
- Dominant process at the LHC **gluon fusion** via quark loop (mostly the top): $\sigma_{SM}$ ~ 38 fb (NLO QCD)




We include corrections to this process by means of effective trilinear Higgs couplings assuming that the largest contribution comes from this type of diagrams and others can be neglected (eg. double box diagram):

- Is this reasonable? -> modifications of $\lambda_{hhh}$ are the leading source of deviations of non resonant hh production cross section

[Bahl, Braathen, Weiglein : arXiv: 2202.03453]



# Genuine BSM THC effects:

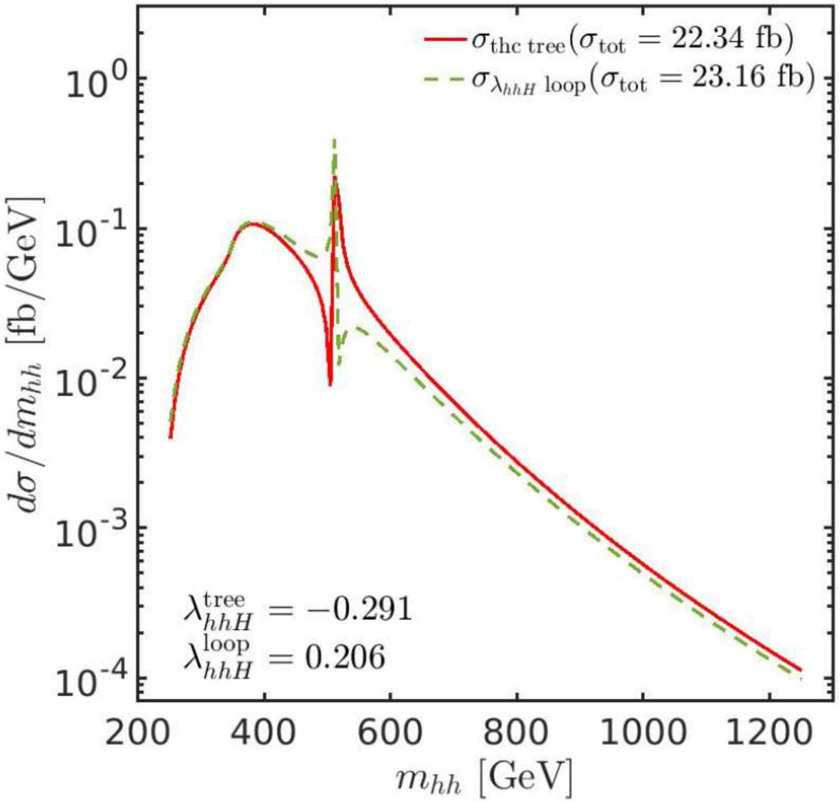
[*taken from K. Radchenko*]

BSM effects that can only be captured by explicite calculations

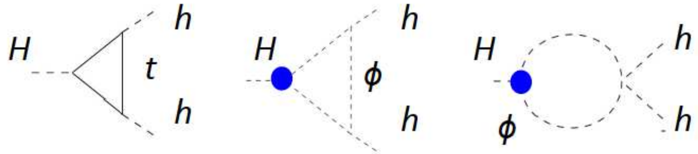
## Effect of changes of $\lambda_{hhH}$ in $m_{hh}$

[Arco, Heinemeyer, Mühlleitner, Radchenko: arXiv: 2212.11242 ]

- Such a different phenomenology can be induced by the inclusion of loop corrections to the trilinears




- One loop corrections to $\lambda_{hhH}$ in general are subleading in the allowed regions. However, in scenarios with mass splitting the sign of $\lambda_{hhH}$ can change.




● $\lambda_{h\phi\phi} \propto (M^2 - m_\phi^2)$ [Braathen, Kanemura: arxiv: 1911.11507]

- Smaller enhancement in the total cross section
- The corrections on $\lambda_{hhH}$ lead to a completely different phenomenology in invariant mass distributions compared to the tree level coupling

[taken from K. Radchenko]

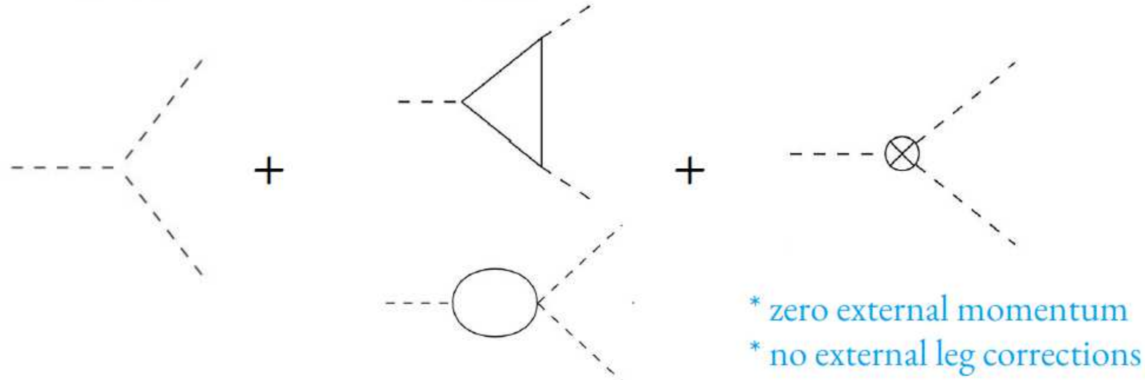
# Radiative corrections to the trilinear couplings

- Crucial for first order electroweak phase transition
- We use the effective potential approach and implement an effective coupling in the di-Higgs production

[Coleman, Weinberg: (1973) Physical Review]

$$V_{\text{eff}} = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}$$

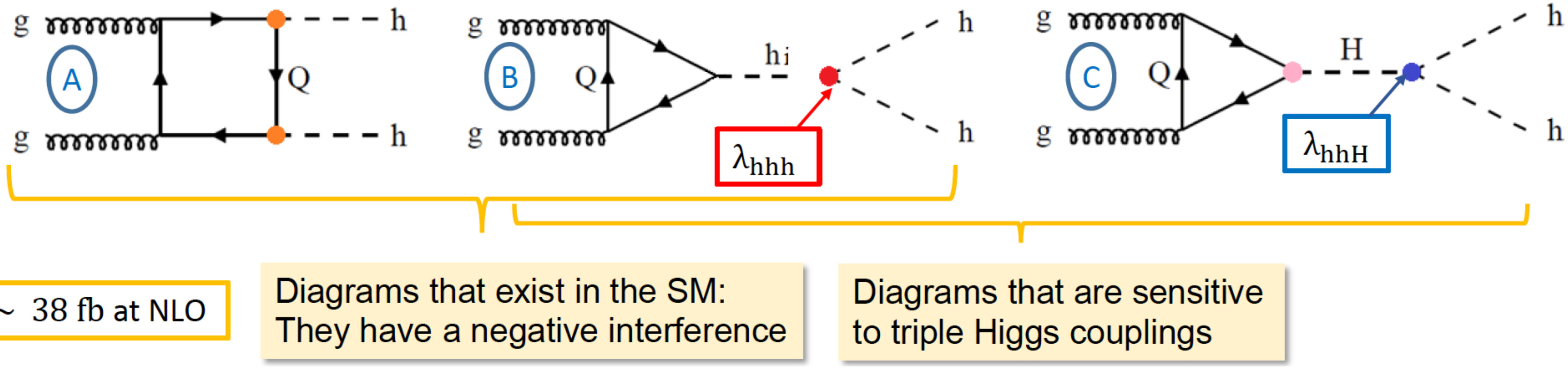
$$\lambda^{\text{eff}}_{hhh} = \frac{\partial^3 V_{\text{eff}}}{\partial h^3}\bigg|_{h=0} =$$




- The calculation is done by means of the public code BSMPT: [Basler, Mühlleitner: arXiv: 1803.02846]
- It is performed in the limit of zero external momentum
- Physical masses and mixing angles are renormalized on shell to their tree level value
- An alternative approach would be to compute the corrections diagrammatically: anyH3

# 3. Phenomenological impact

⇒ all calculated with HPAIR




$\sigma_{SM} \sim$ 38 fb at NLO

Case 1: Non-resonant BSM di-Higgs production

Case 2: Resonant BSM di-Higgs production

**Q:** effects of higher-order corrections to THCs?

Important: experimental limtis are obtained for

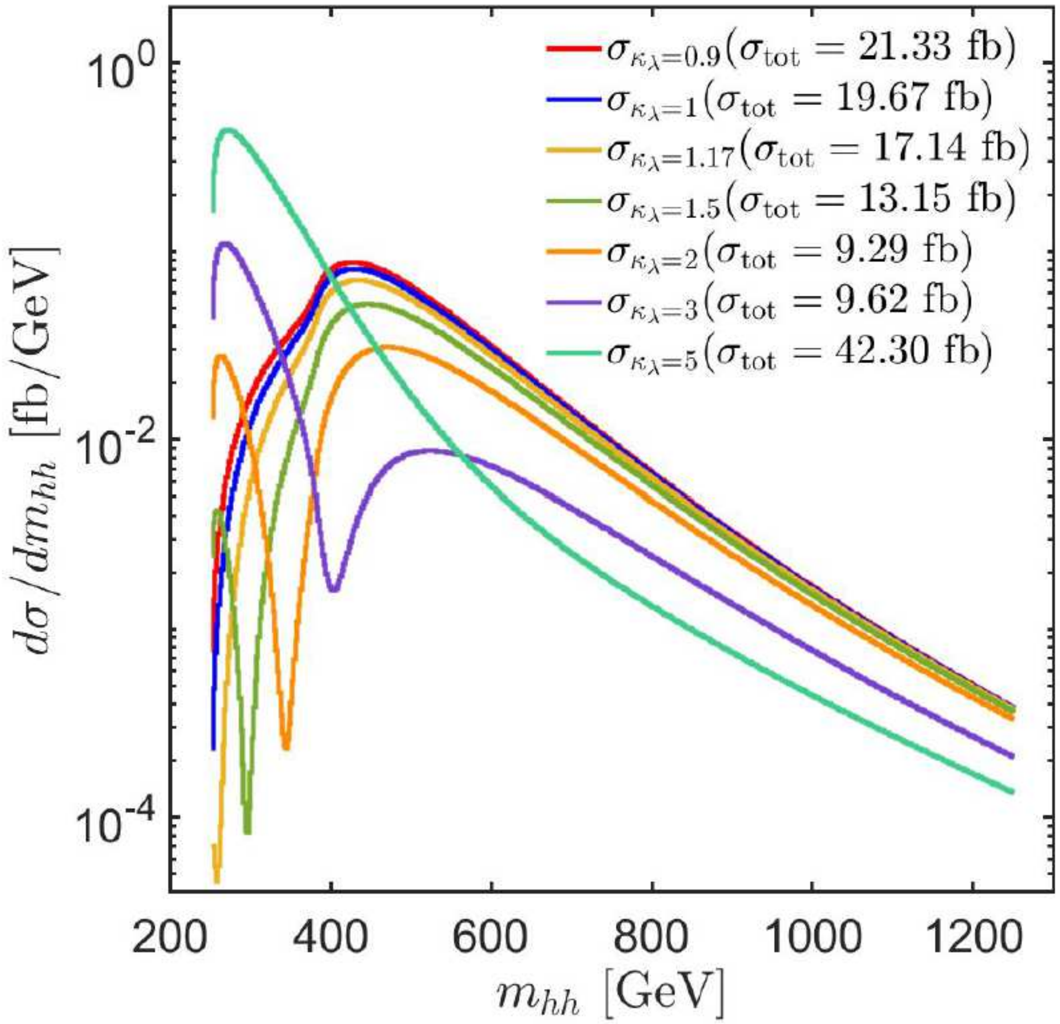
– non-resonant production

– purely resonant production

⇒ no limits available for mixed scenarios :-(

# Non-resonant BSM di-Higgs production

[*S.H., M. Mühlleitner, K. Radchendo, G. Weiglein – PRELIMINARY*]



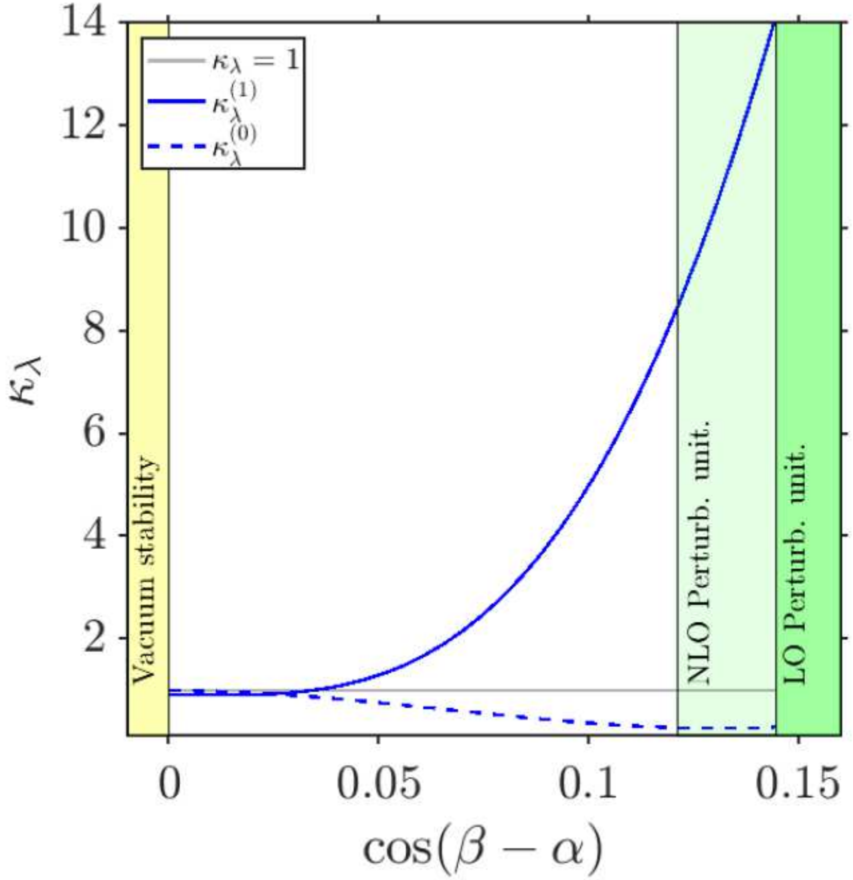

$\Rightarrow$ higher-order effects in $\kappa_\lambda$

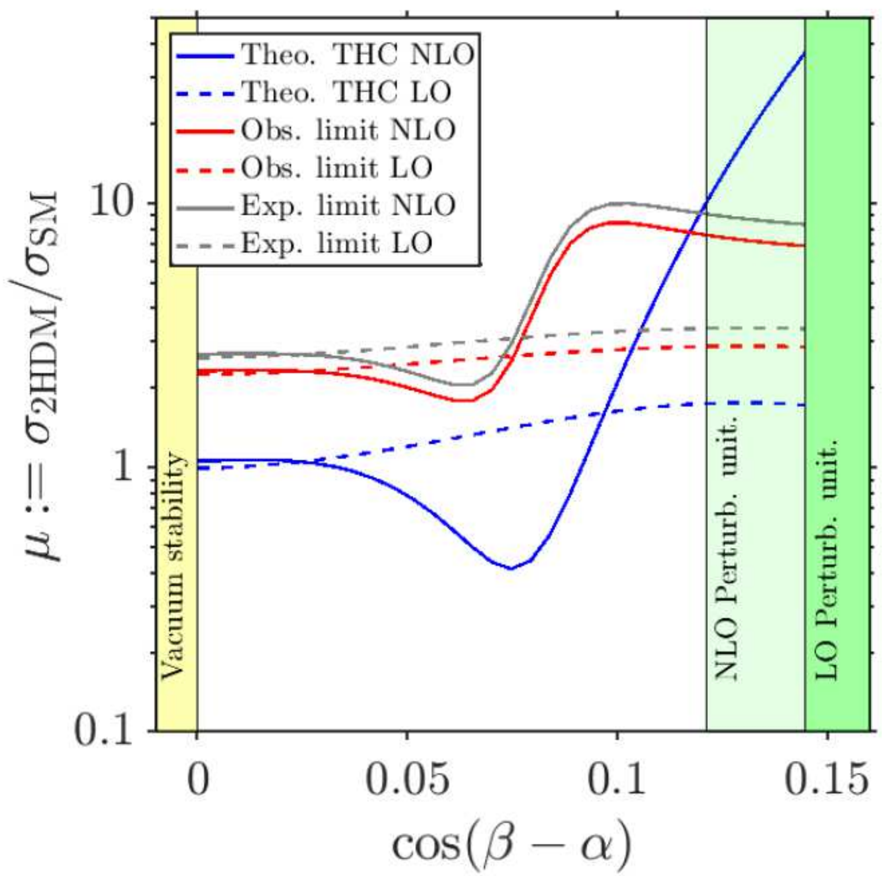
$\Rightarrow$ huge effects on $m_{hh}$ distributions $\Rightarrow$ effects on search limits?

# Non-resonant BSM di-Higgs production

[*S.H., M. Mühlleitner, K. Radchendo, G. Weiglein '24*]

$\tan\beta = 10$, $c_{\beta-\alpha}$ varied, $m_H = m_A = m_{H^\pm} = 1000$ GeV, $m_{12}^2 = m_H^2 \cos^2\alpha / \tan\beta$



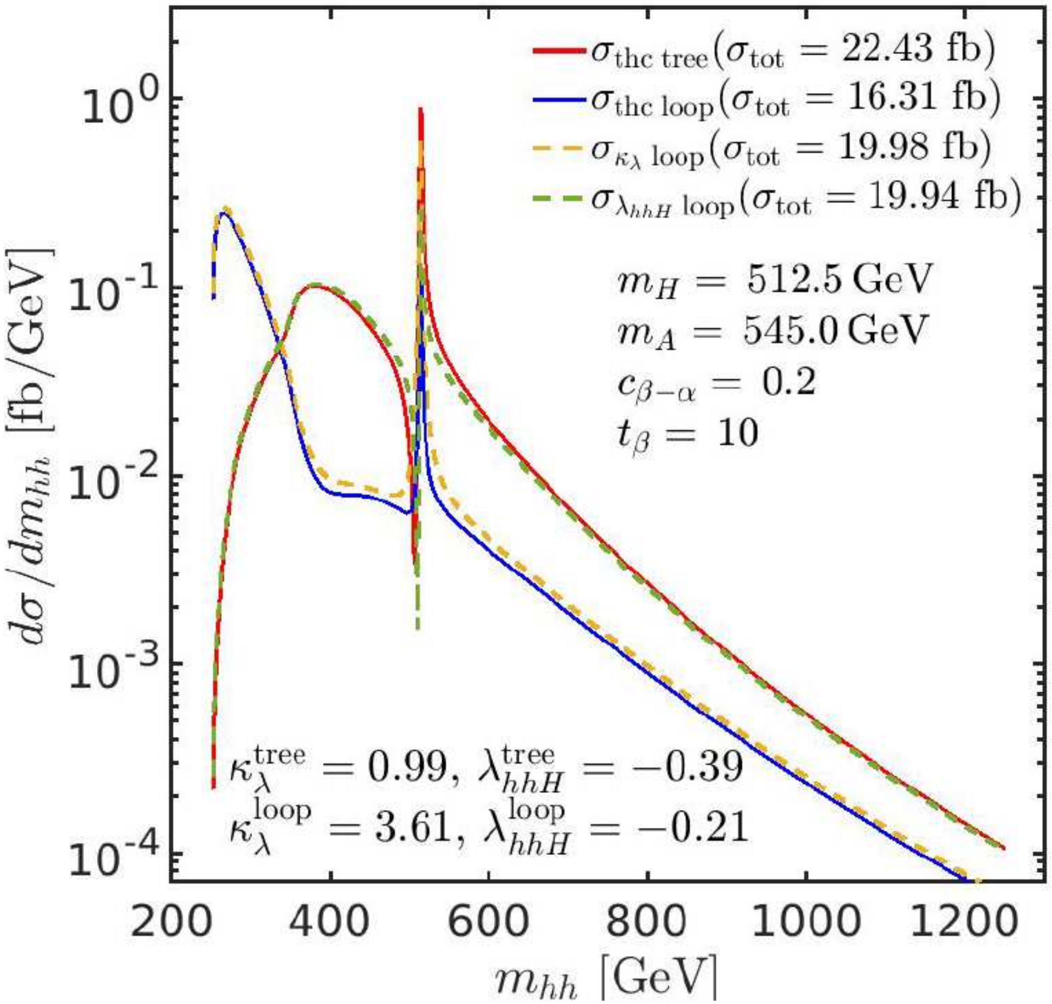




⇒ higher-order effects in $\kappa_\lambda$

⇒ visible effect on allowed parameter space

# Resonant BSM di-Higgs production

[S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]



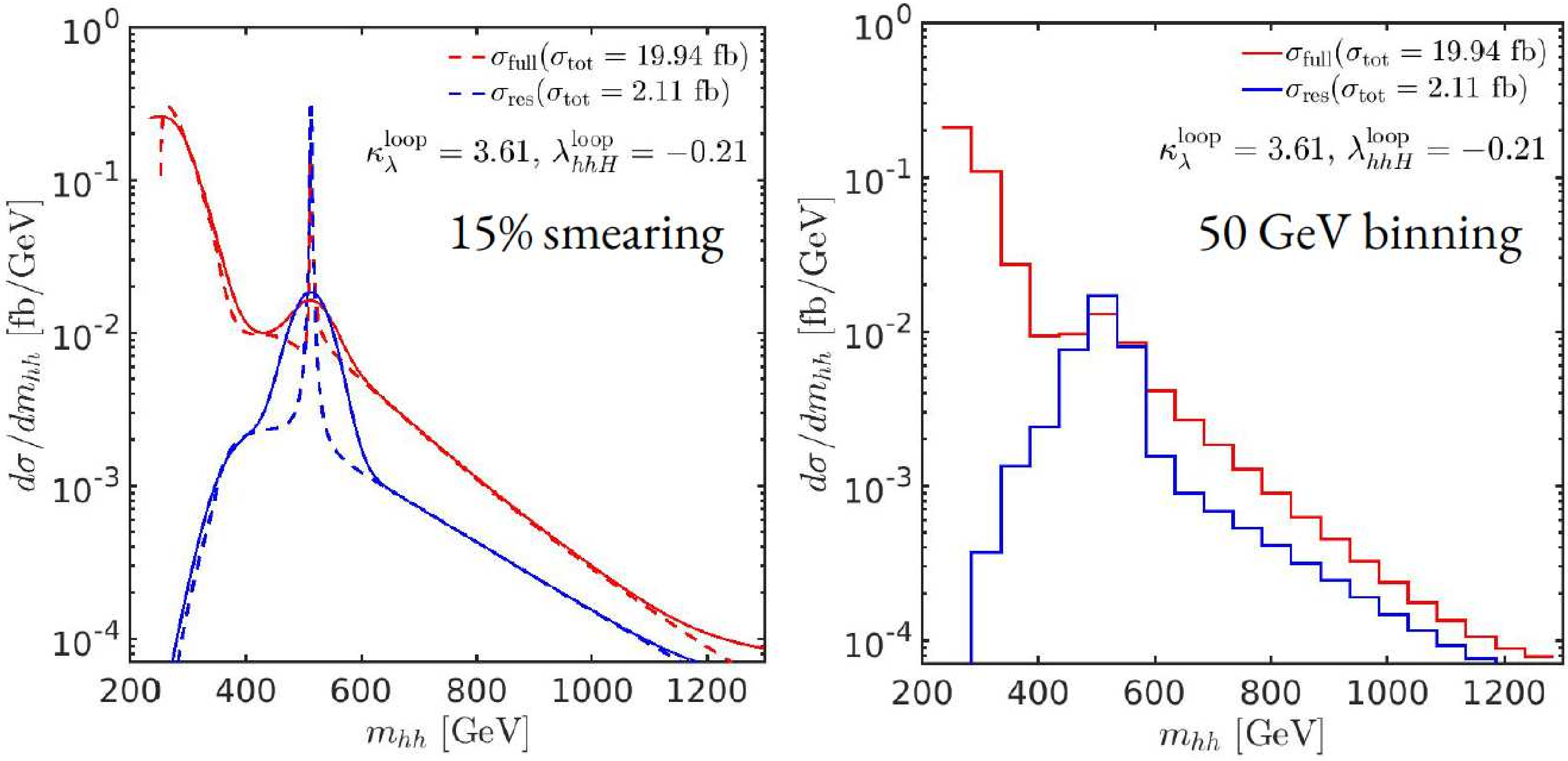

⇒ higher-order effects in $\kappa_\lambda$ and $\lambda_{hhH}$

⇒ huge effects on $m_{hh}$ distributions ⇒ effects on search limits?

# Experimental analysis vs. reality:

[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein – PRELIMINARY*]

## Experimental reality: smearing and binning (THCs at 1L)

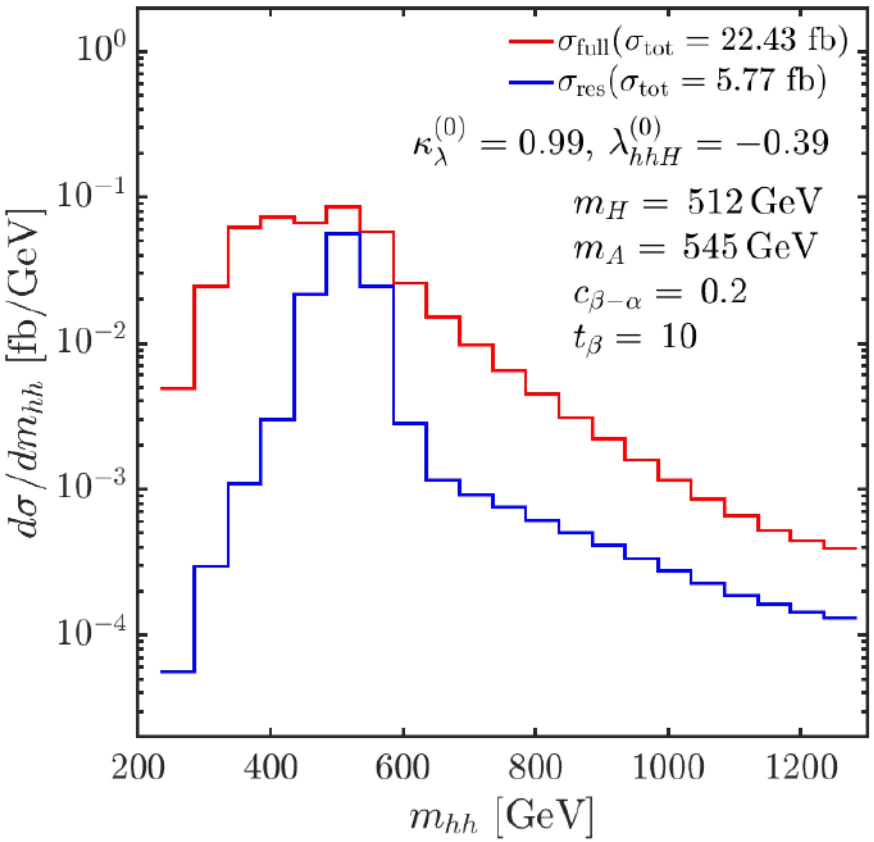



⇒ experimental analysis ⇒ full calculation

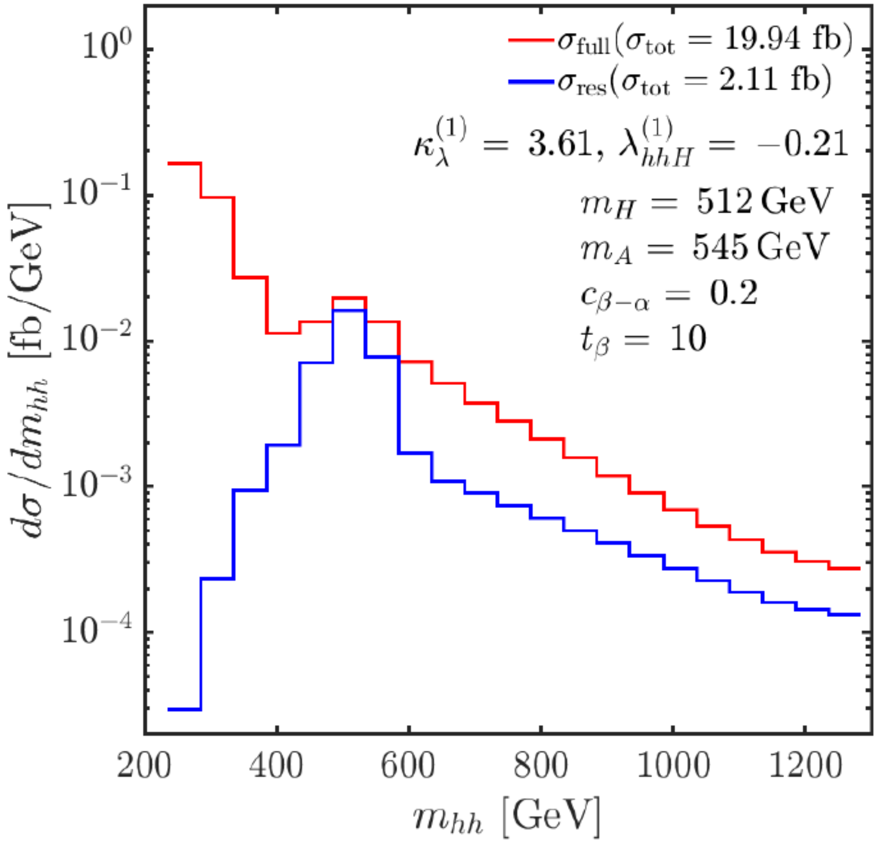
# Experimental analysis vs. reality:

[S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]

THC tree-level



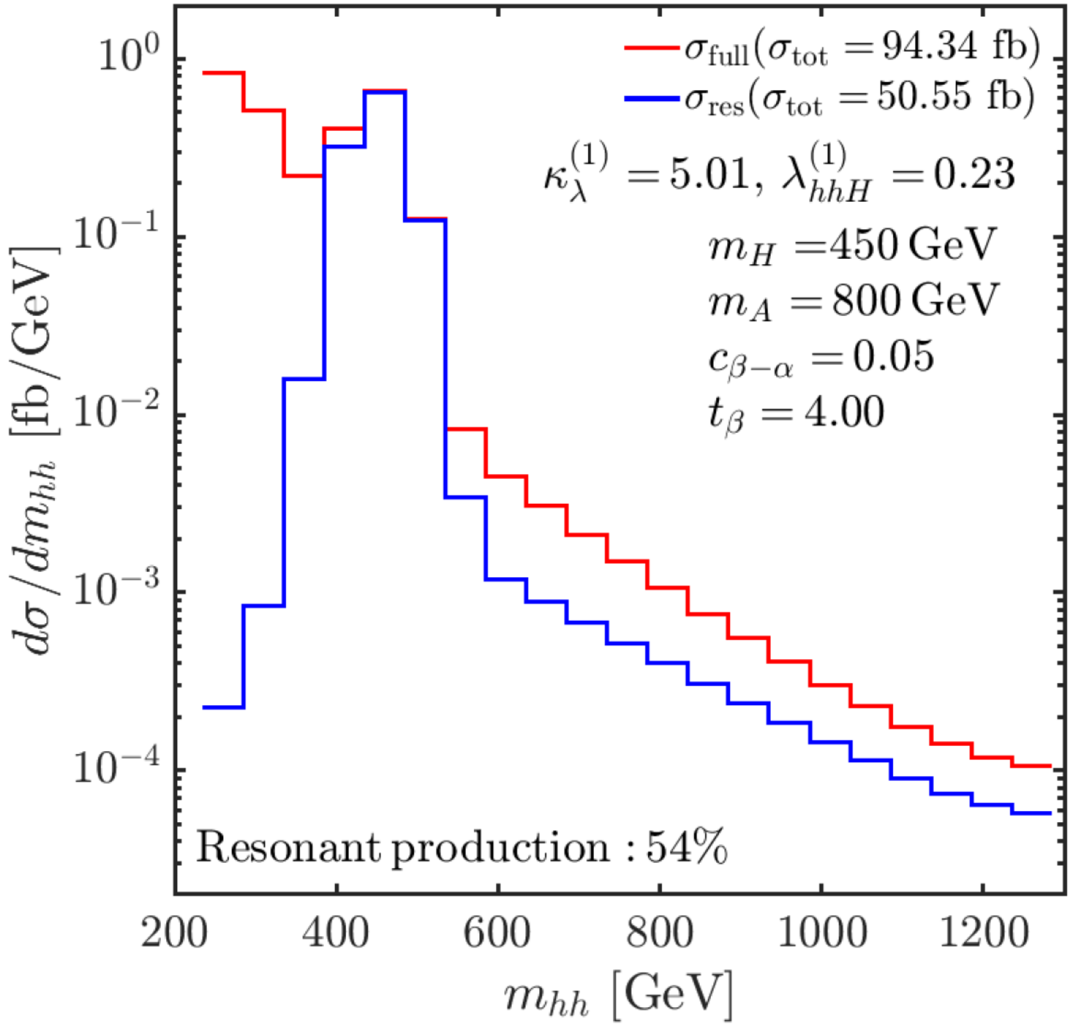

THC one-loop




$\Rightarrow$ experimental analysis $\Rightarrow$ full calculation

## Experimental analysis vs. reality:

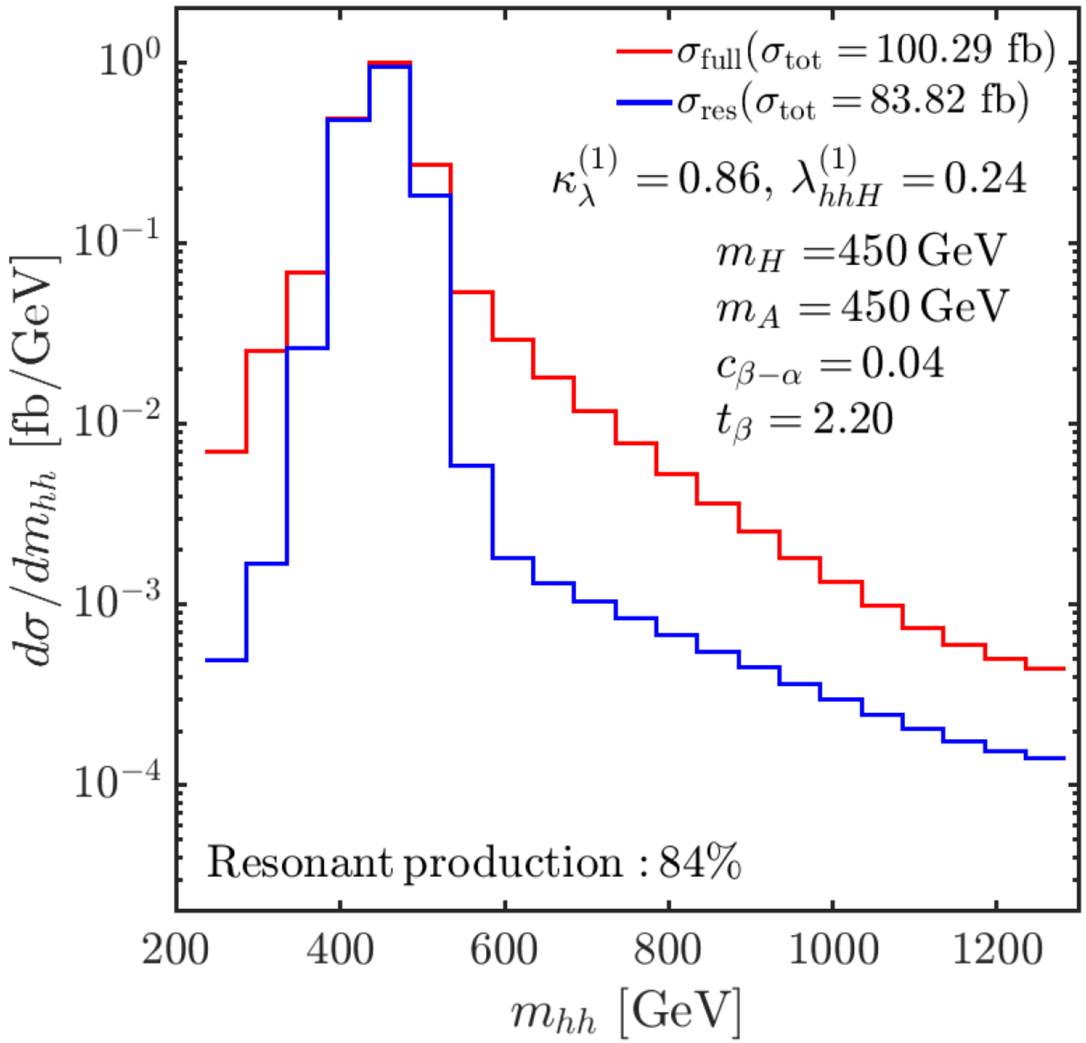
[S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]




$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

# Experimental analysis vs. reality:

[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]

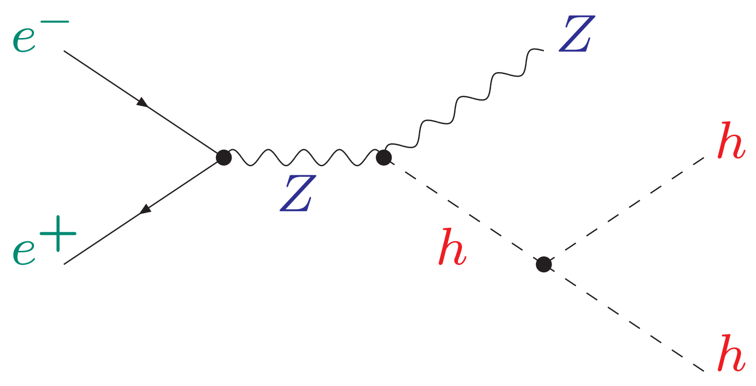



$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

# 4. BSM di-Higgs production at $e^+e^-$ colliders

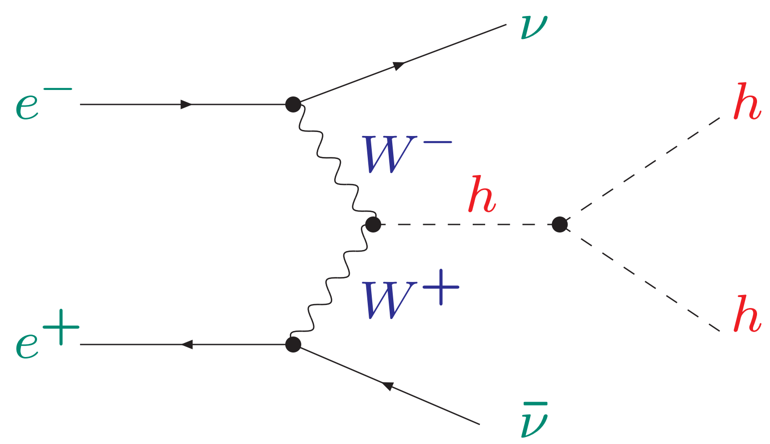
Higgs-strahlung:

$e^+e^- \to Z^* \to Zhh$

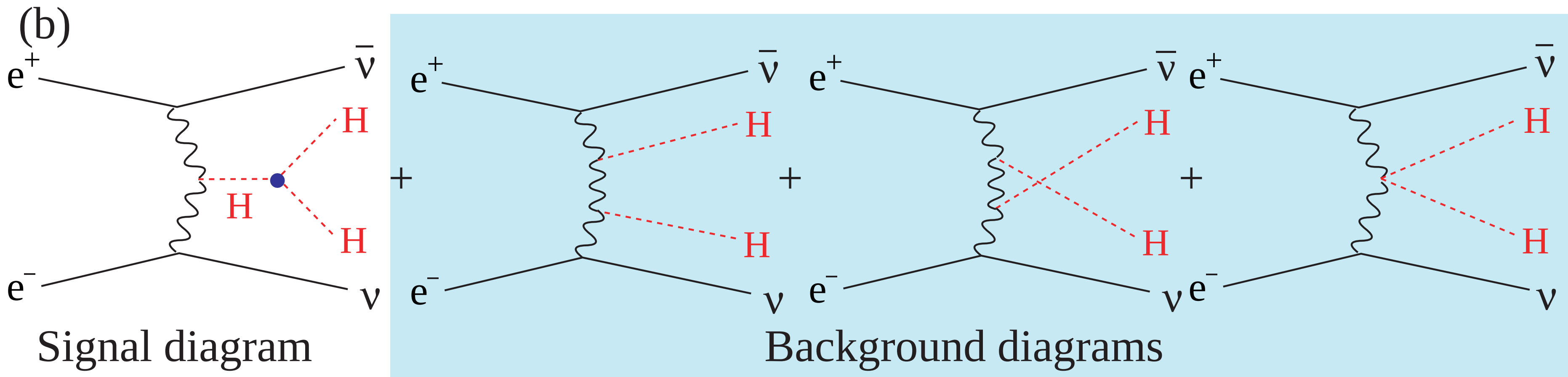



weak boson fusion (WBF):

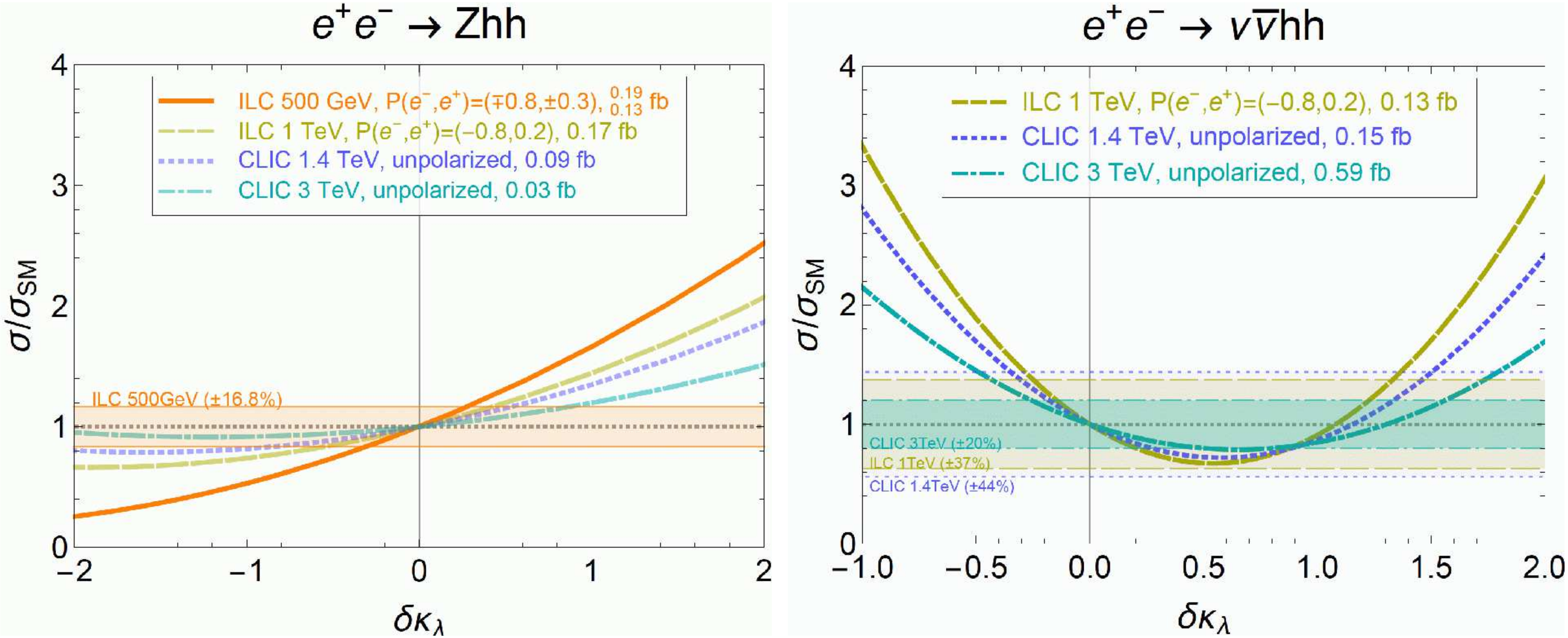
$e+e- \to \nu\bar{\nu}hh$




Signal and background interference:



# Di-Higgs production at ILC/CLIC:

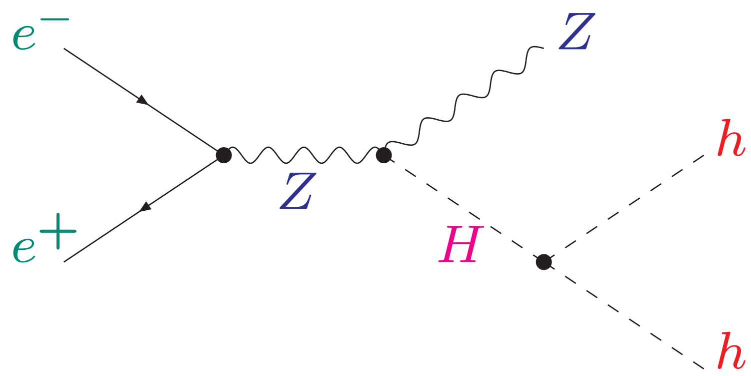



$\kappa_\lambda := 1 + \delta\kappa_\lambda$

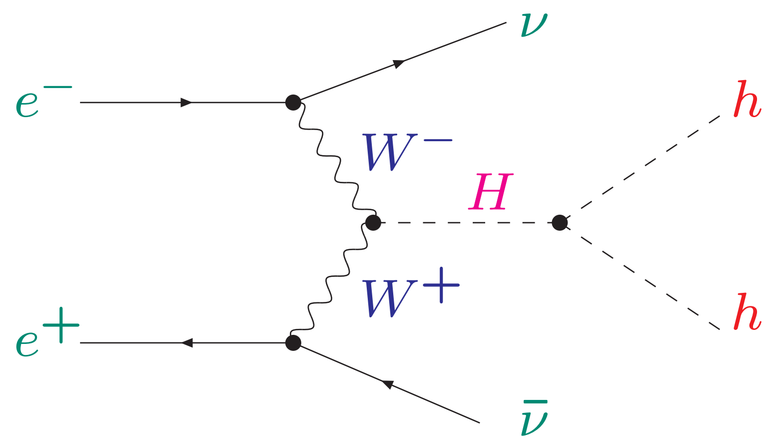
$\Rightarrow$ strong and different dependence on $\kappa_\lambda$

# Heavy Higgs enters also in $e^+e^-$ di-Higgs production:

Higgs-strahlung:
$e^+e^- \to Z^* \to Zhh$




weak boson fusion (WBF):
$e+e- \to \nu\bar{\nu}hh$




## Difference w.r.t. $gg \to hh$:

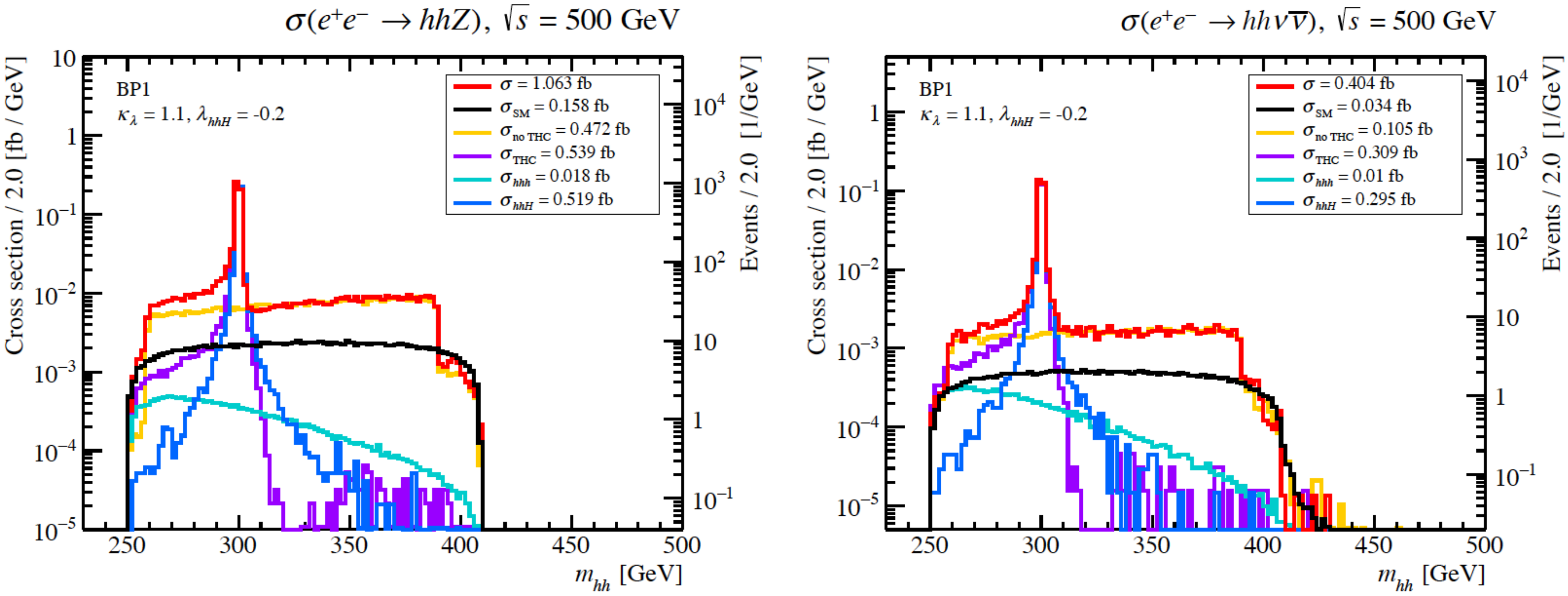
– alignment limit gives the SM result for $e^+e^-$

– $\mathcal{CP}$-odd Higgs bosons enter into the calculation (but not with THCs)

## Di-Higgs production at the ILC: [F. Arco, S.H., M. Herrero '21]

Example: 2HDM type I $e^+e^- \to Zhh/\nu\bar{\nu}hh$ with MadGraph

$m_{H,A,H^\pm} = 300$ GeV, $t_\beta = 10, c_{\beta-\alpha} = 0.25, m_{12}^2 = m_H^2 c_\alpha^2/t_\beta \Rightarrow \kappa_\lambda = 1.1, \lambda_{hhH} = -0.2$




theory analysis: $R := (\bar{N}^R - \bar{N}^C)/\sqrt{\bar{N}^C}$

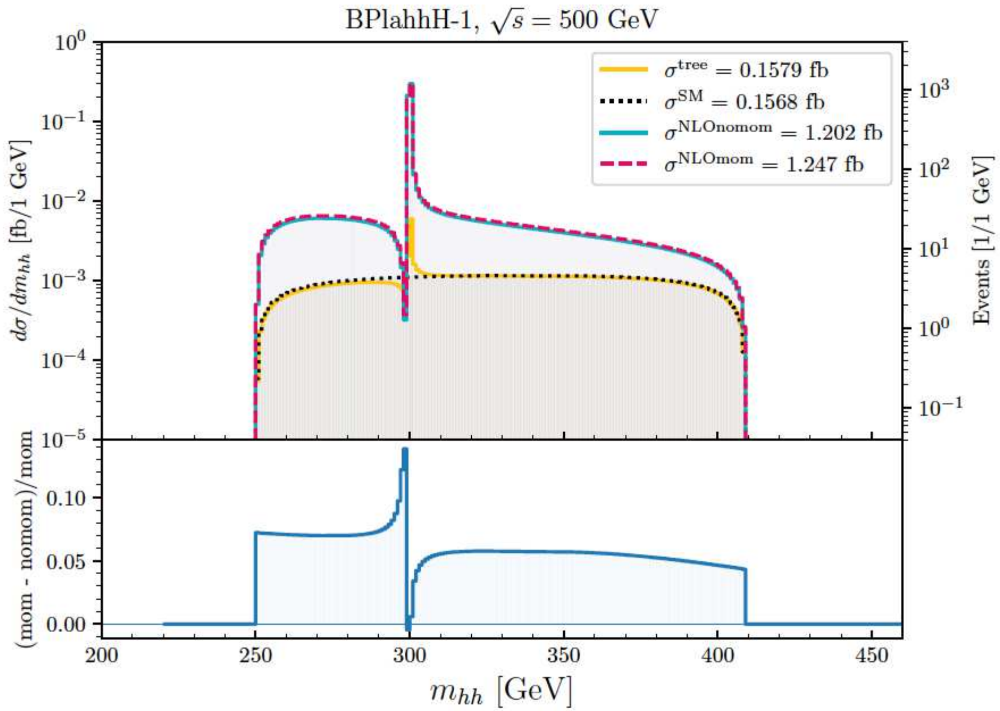
R = "resonance", C = "continuum", $\bar{N}$ incl. cuts and $b$-tagging efficiencies

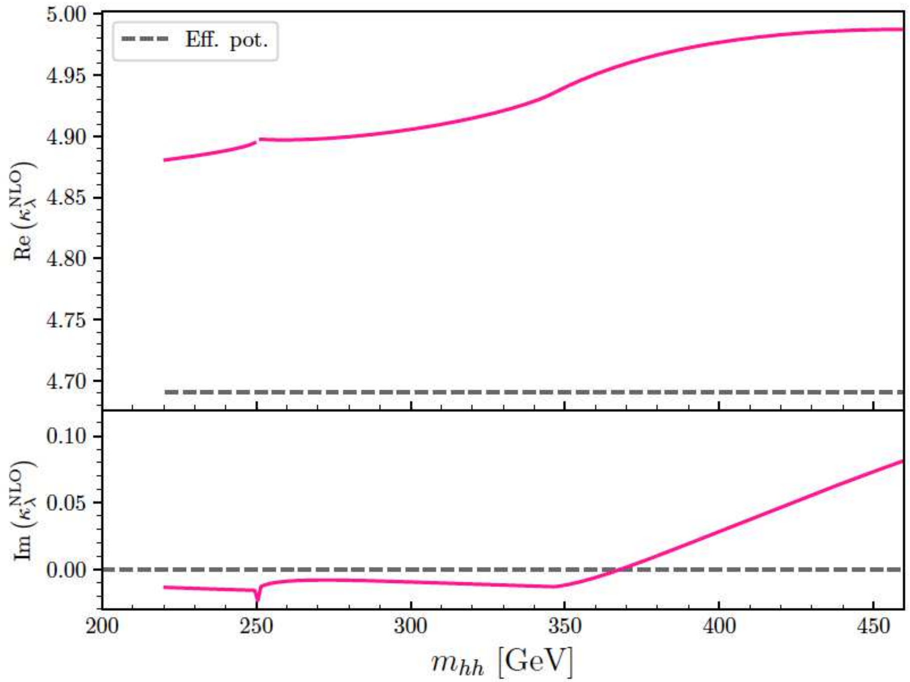
$$\sqrt{s} = 500\ (1000)\ \text{GeV} \quad \Rightarrow \quad R = 58\ (205)$$

experimental analysis: crucially needed!

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



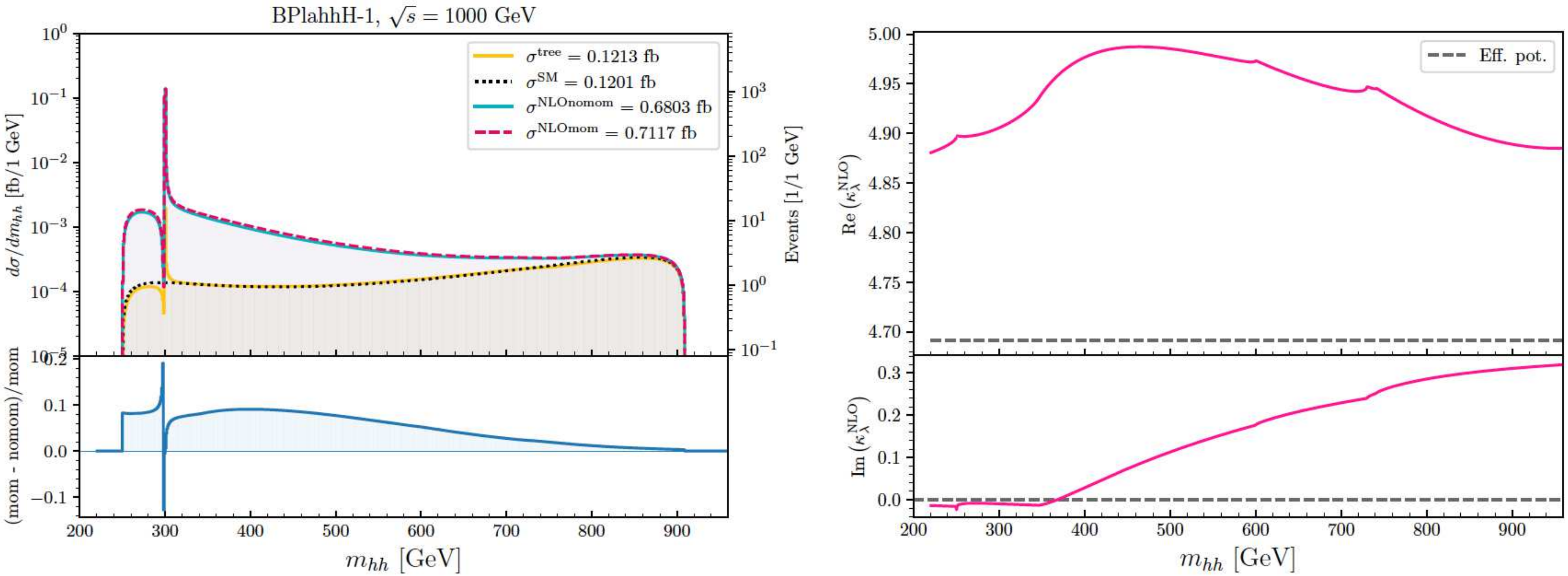

$\tan\beta = 12$, $c_{\beta-\alpha} = 0.12$, $m_H = \bar{m} = 300$ GeV, $m_A = m_{H^\pm} = 650$ GeV

$\kappa_\lambda^{\rm tree} = 0.95$, $\kappa_\lambda^{\rm NLO} = 4.69$

$\lambda_{hhH}^{\rm tree} = 0.02$, $\lambda_{hhH}^{\rm NLO} = 0.21$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



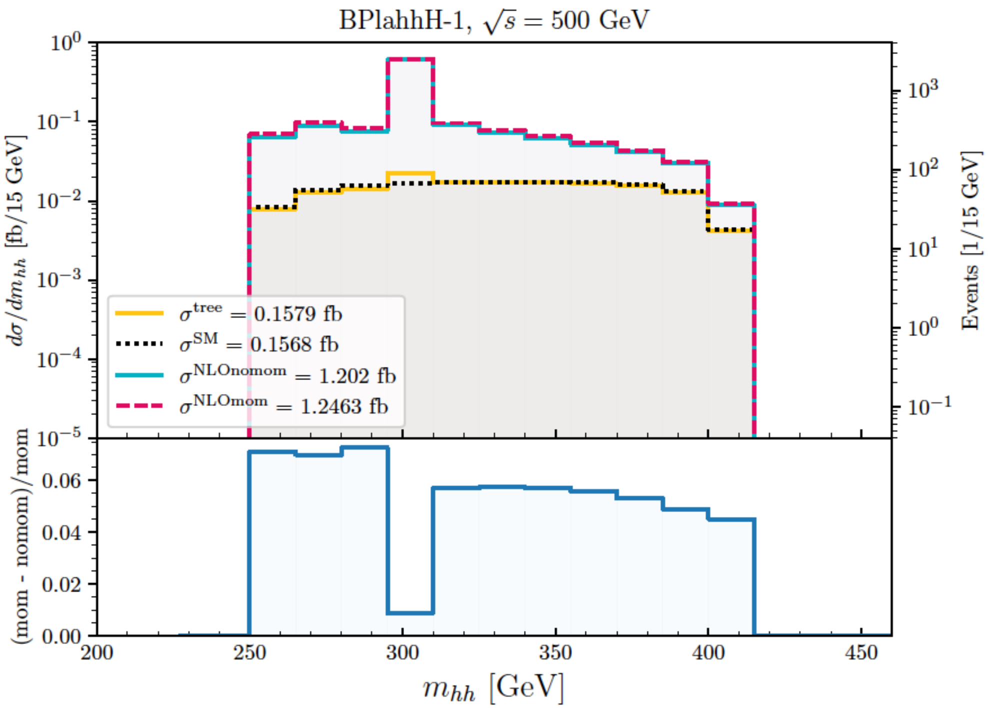

$\tan\beta = 12$, $c_{\beta-\alpha} = 0.12$, $m_H = \bar{m} = 300$ GeV, $m_A = m_{H^\pm} = 650$ GeV

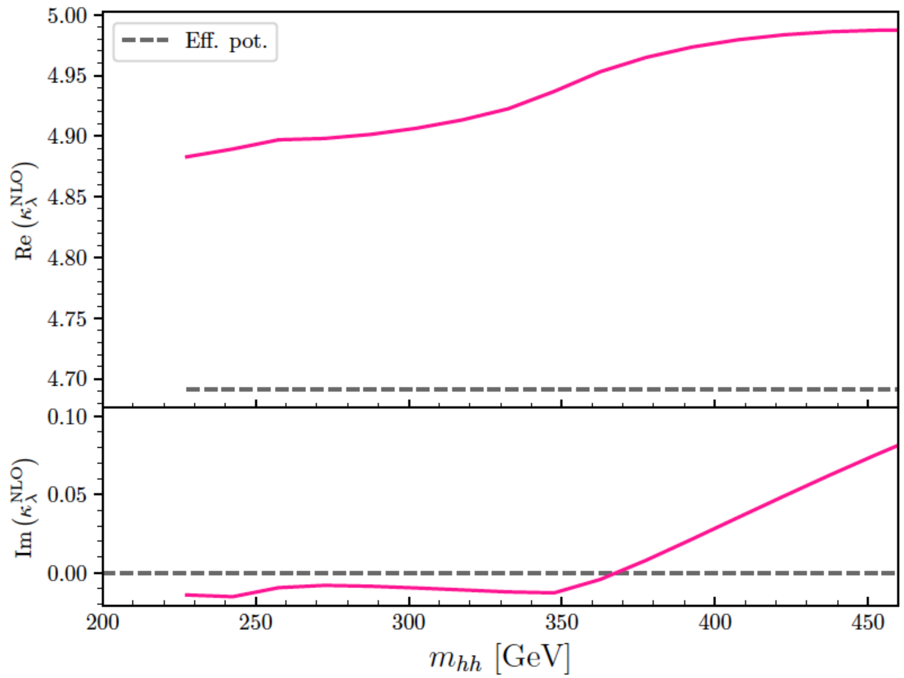
$\kappa_\lambda^{\text{tree}} = 0.95$, $\kappa_\lambda^{\text{NLO}} = 4.69$

$\lambda_{hhH}^{\text{tree}} = 0.02$, $\lambda_{hhH}^{\text{NLO}} = 0.21$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



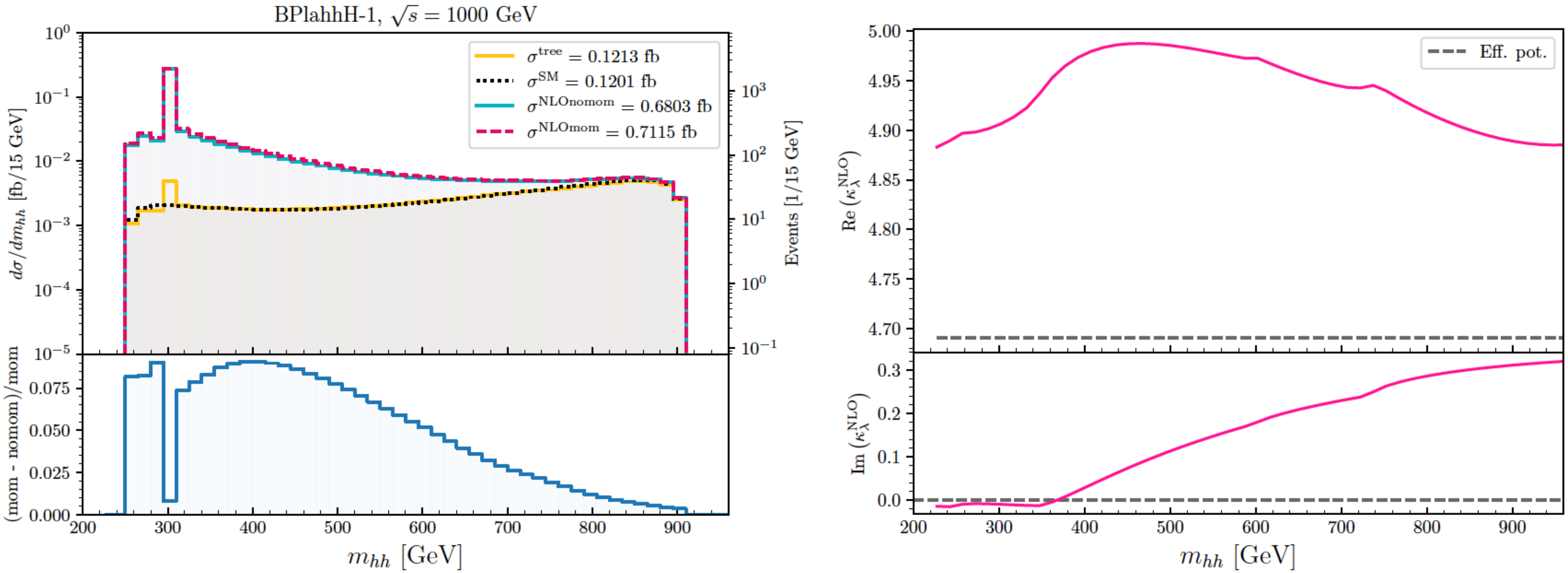

$\tan\beta = 12$, $c_{\beta-\alpha} = 0.12$, $m_H = \bar{m} = 300$ GeV, $m_A = m_{H^\pm} = 650$ GeV

$\kappa_\lambda^{\text{tree}} = 0.95$, $\kappa_\lambda^{\text{NLO}} = 4.69$

$\lambda_{hhH}^{\text{tree}} = 0.02$, $\lambda_{hhH}^{\text{NLO}} = 0.21$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



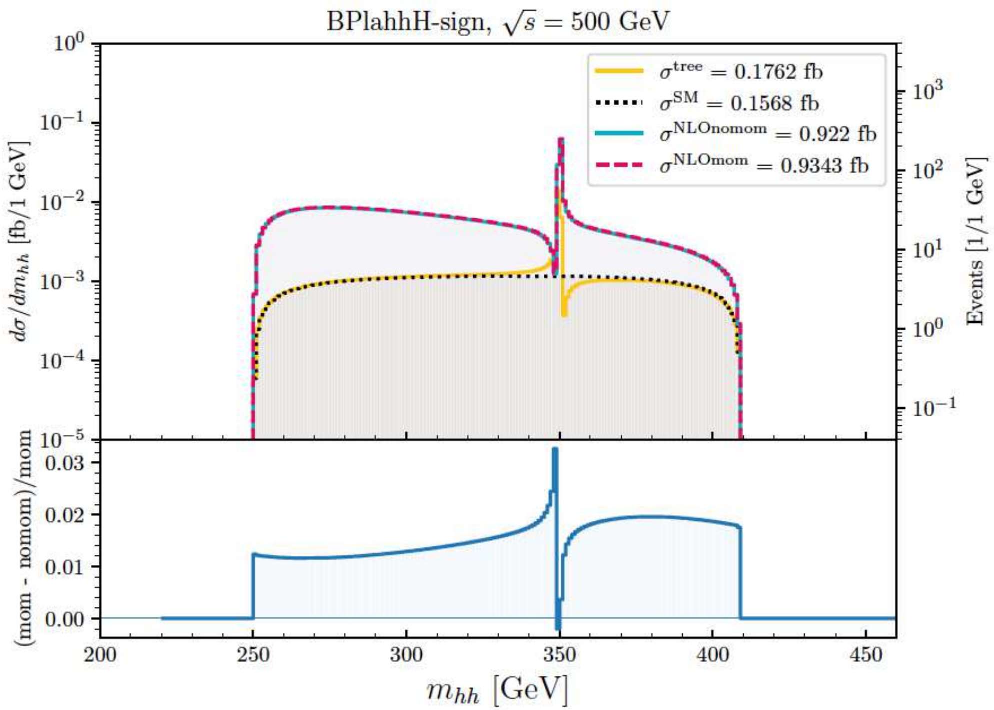

$\tan\beta = 12$, $c_{\beta-\alpha} = 0.12$, $m_H = \bar{m} = 300$ GeV, $m_A = m_{H^\pm} = 650$ GeV

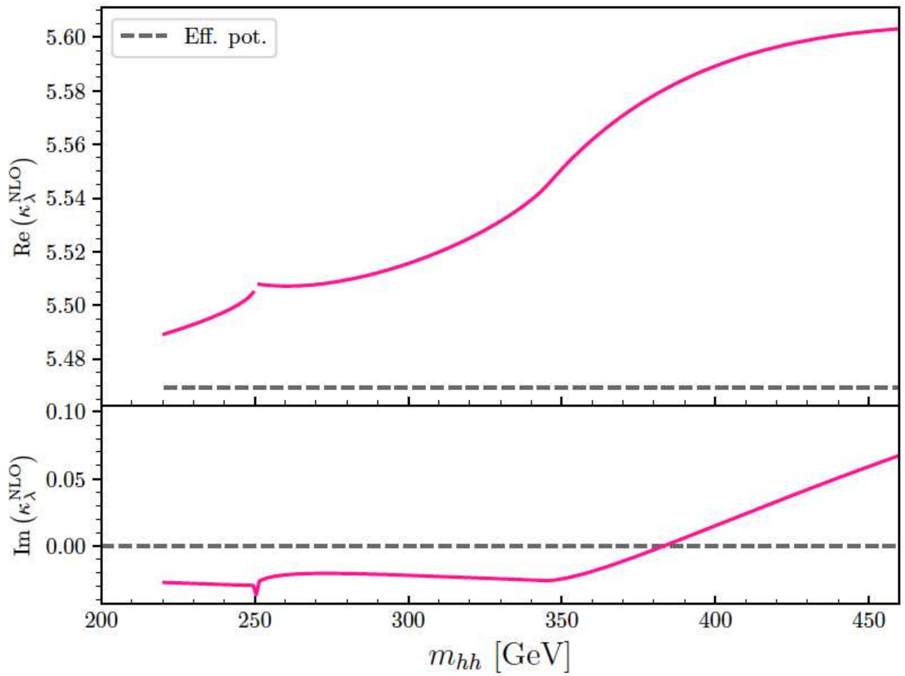
$\kappa_\lambda^{\text{tree}} = 0.95$, $\kappa_\lambda^{\text{NLO}} = 4.69$

$\lambda_{hhH}^{\text{tree}} = 0.02$, $\lambda_{hhH}^{\text{NLO}} = 0.21$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



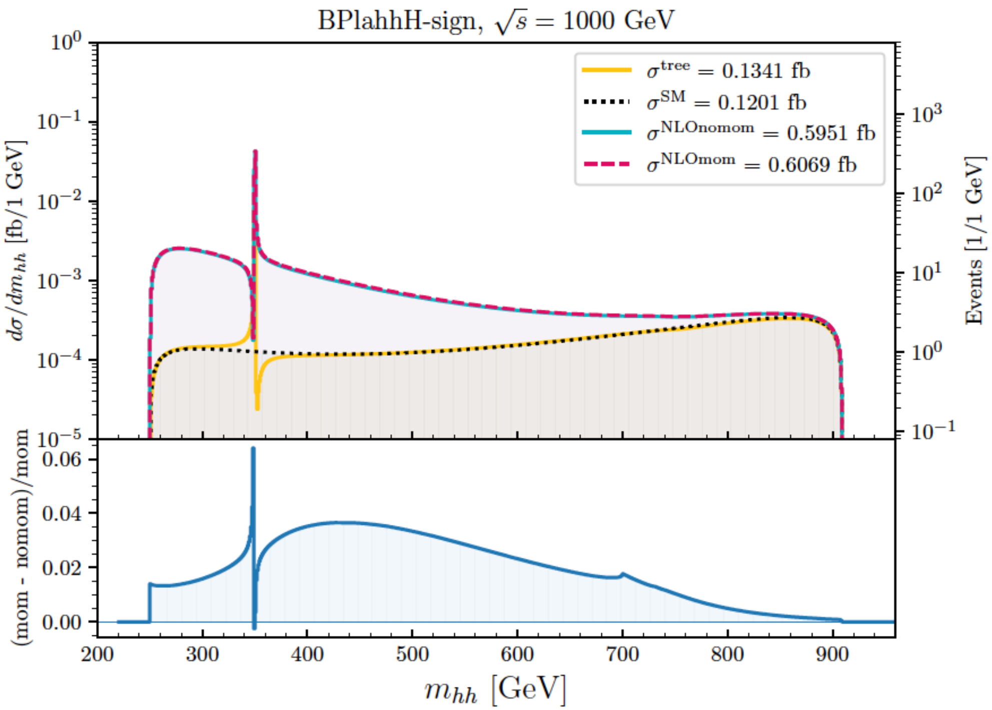

$\tan\beta = 20$, $c_{\beta-\alpha} = 0.10$, $m_H = \bar{m} = 350$ GeV, $m_A = m_{H^\pm} = 650$ GeV

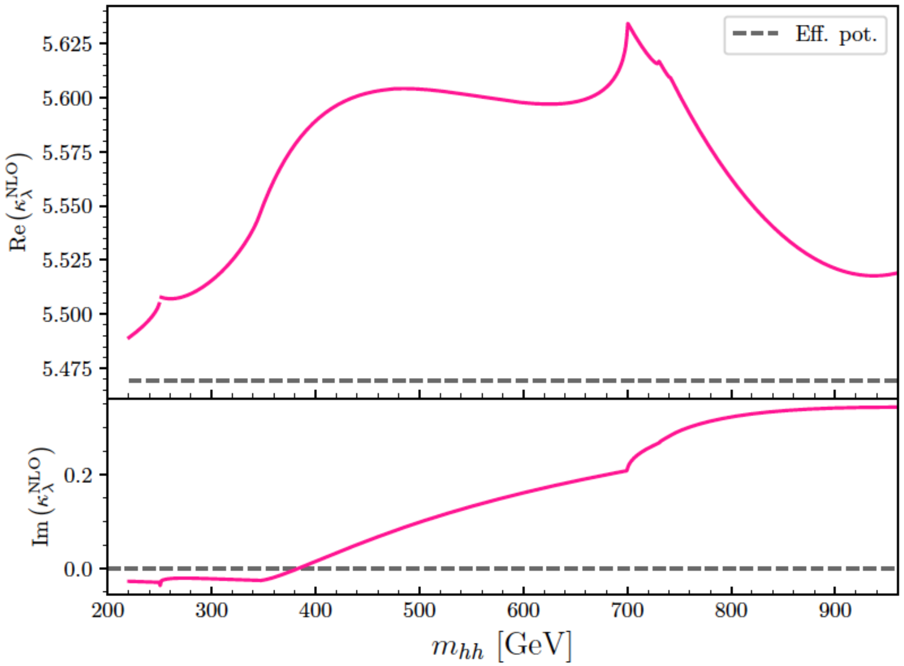
$\kappa_\lambda^{\rm tree} = 0.995$, $\kappa_\lambda^{\rm NLO} = 5.47$

$\lambda_{hhH}^{\rm tree} = -0.07$, $\lambda_{hhH}^{\rm NLO} = 0.16$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*



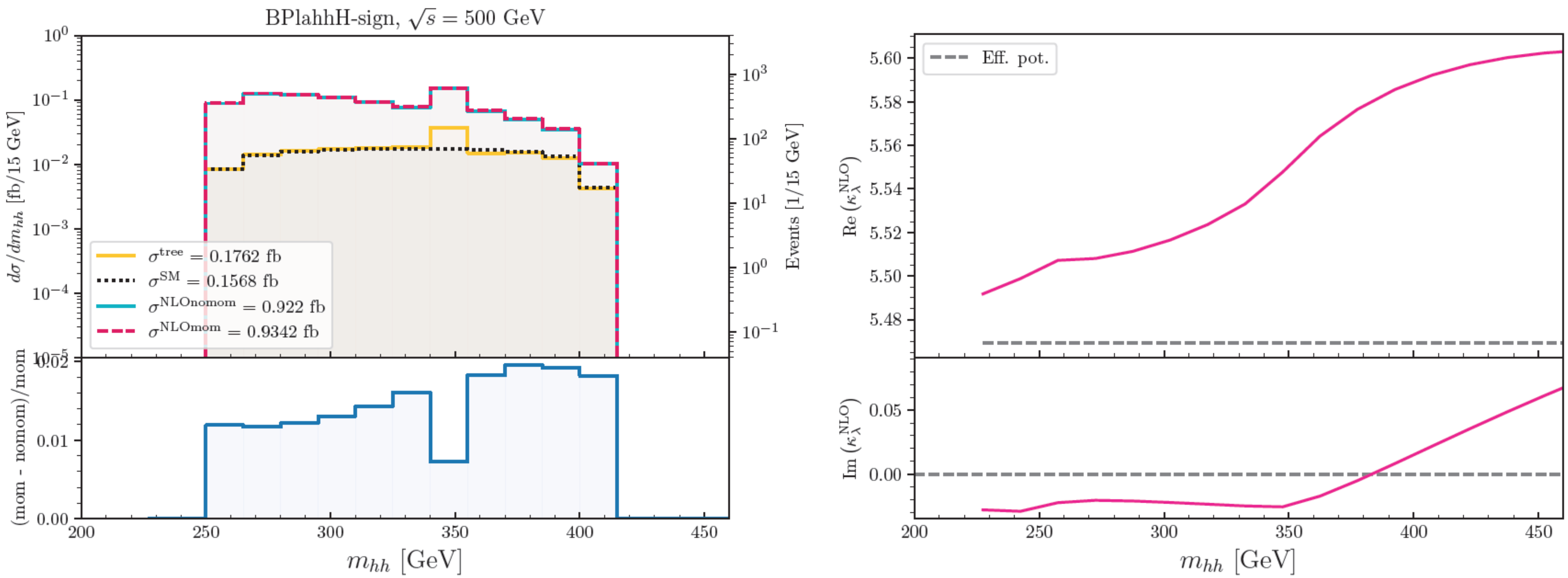

$\tan\beta = 20$, $c_{\beta-\alpha} = 0.10$, $m_H = \bar{m} = 350$ GeV, $m_A = m_{H^\pm} = 650$ GeV

$\kappa_\lambda^{\rm tree} = 0.995$, $\kappa_\lambda^{\rm NLO} = 5.47$

$\lambda_{hhH}^{\rm tree} = -0.07$, $\lambda_{hhH}^{\rm NLO} = 0.16$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]



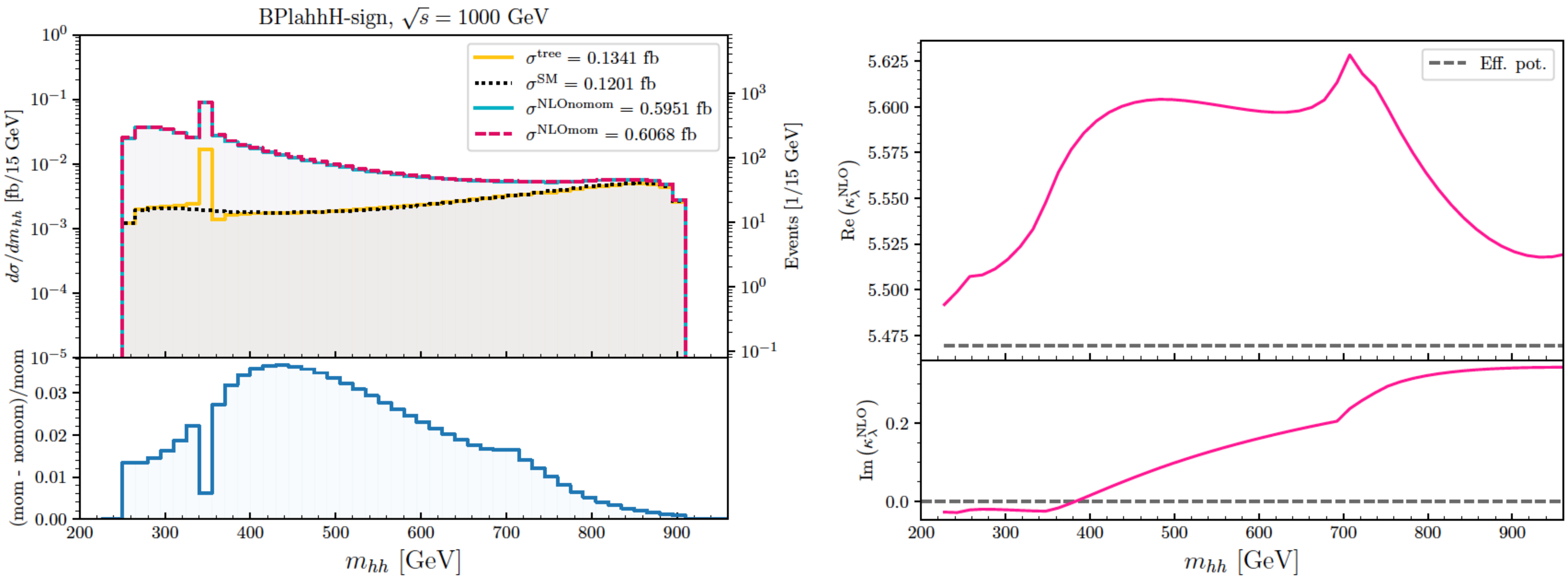

$\tan\beta = 20$, $c_{\beta-\alpha} = 0.10$, $m_H = \bar{m} = 350$ GeV, $m_A = m_{H^\pm} = 650$ GeV

$\kappa_\lambda^{\text{tree}} = 0.995$, $\kappa_\lambda^{\text{NLO}} = 5.47$

$\lambda_{hhH}^{\text{tree}} = -0.07$, $\lambda_{hhH}^{\text{NLO}} = 0.16$

# Impact of NLO corrections to THCs at $e^+e^-$ colliders

*[F. Arco, S.H., M. Mühlleitner – PRELIMINARY]*




$\tan\beta = 20$, $c_{\beta-\alpha} = 0.10$, $m_H = \bar{m} = 350$ GeV, $m_A = m_{H^\pm} = 650$ GeV

$\kappa_\lambda^{\rm tree} = 0.995$, $\kappa_\lambda^{\rm NLO} = 5.47$

$\lambda_{hhH}^{\rm tree} = -0.07$, $\lambda_{hhH}^{\rm NLO} = 0.16$

# 5. Conclusions

- ⇒ Why is there more matter than antimatter? ⇒ (EW) baryogenesis
  ⇒ requires First Order EW Phase Transition (FOEWPT)
  FOEWPT not possible in the SM ⇒ BSM Higgs sector required
  FOEWPT can cause Gravitational Waves (GW), detectable with LISA

- 2HDM:
  Many triple Higgs couplings: $\lambda_{hhh}$, $\lambda_{hhH}$, $\lambda_{hHH}$, $\lambda_{hH^+H^-}$, $\lambda_{HAA}$, ...
  ⇒ large loop corrections to $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\rm SM}$ possible
  (many sublteties can be taken into account)

- $gg \to hh$:
  – large corrections to $\kappa_\lambda$ have a drastic effect on the XS
  (large destructive interference of box and $h$ resonance)
  – $\lambda_{hhH}$ enters via resonant $H$ exchange
  – loop corrections to THCs form a closed – and often leading – subset

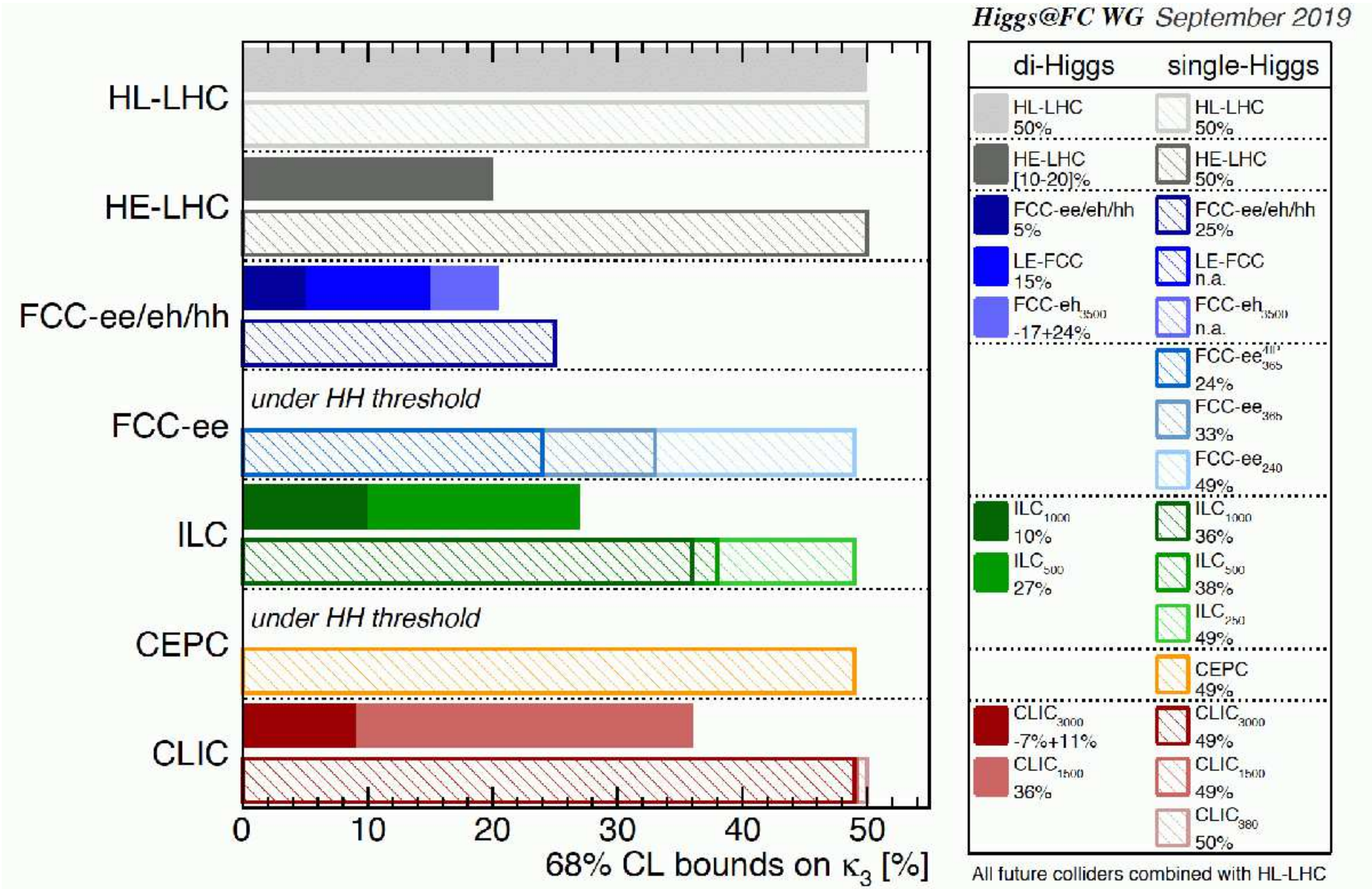
- Experimental limits from non-resonant di-Higgs searches:
  – limits depend on the value of $\kappa_\lambda$
  – one-loop corrections can rule out otherwise allowed parameter space

- Experimental limits from non-resonant di-Hiiggs searches:
  ⇒ exp. analyses leave out interferences ⇒ results not reliable


Katharsis of Ultimate Theory Standards
Meeting 2.2 @ DESY (Hamburg)
26 – 28 June 2024
indico.desy.de/event/43627
Organized by:
S. Heinemeyer, P. Slavich
Local organizers:
J. Braathen, G. Weiglein
DESY.
Emmy
Noether-
Programm
DFG
Deutsche
Forschungsgemeinschaft


Further Questions?

## SM triple Higgs coupling: comparison of all colliders:



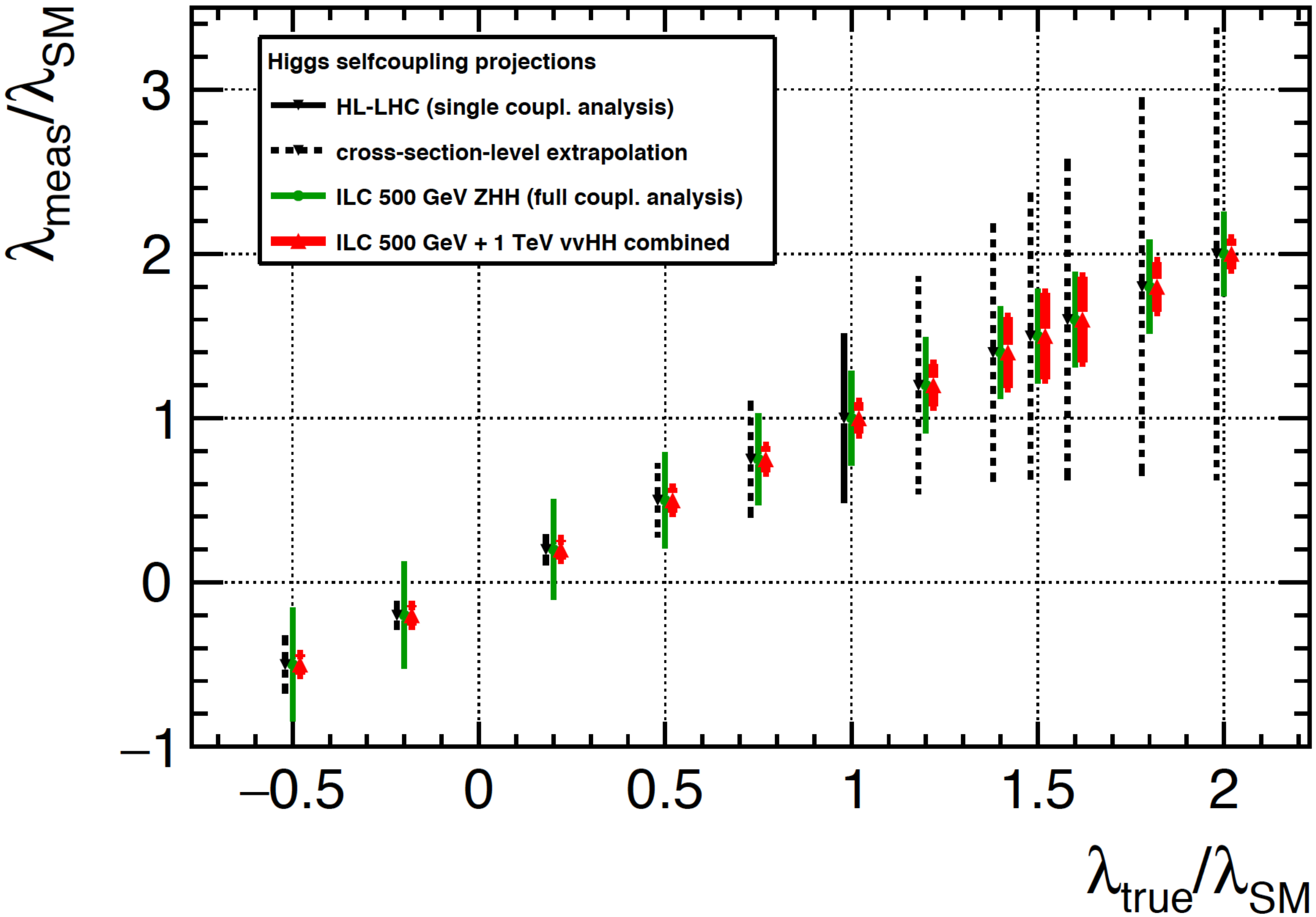

⇒ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM}}$

BSM case 1: $\kappa_\lambda \neq 1$

BSM case 2: THC that involves BSM Higgses: $\lambda_{hhH}, \ldots$

## Measurement of $\kappa_\lambda$ selfcoupling at HL-LHC/ILC:

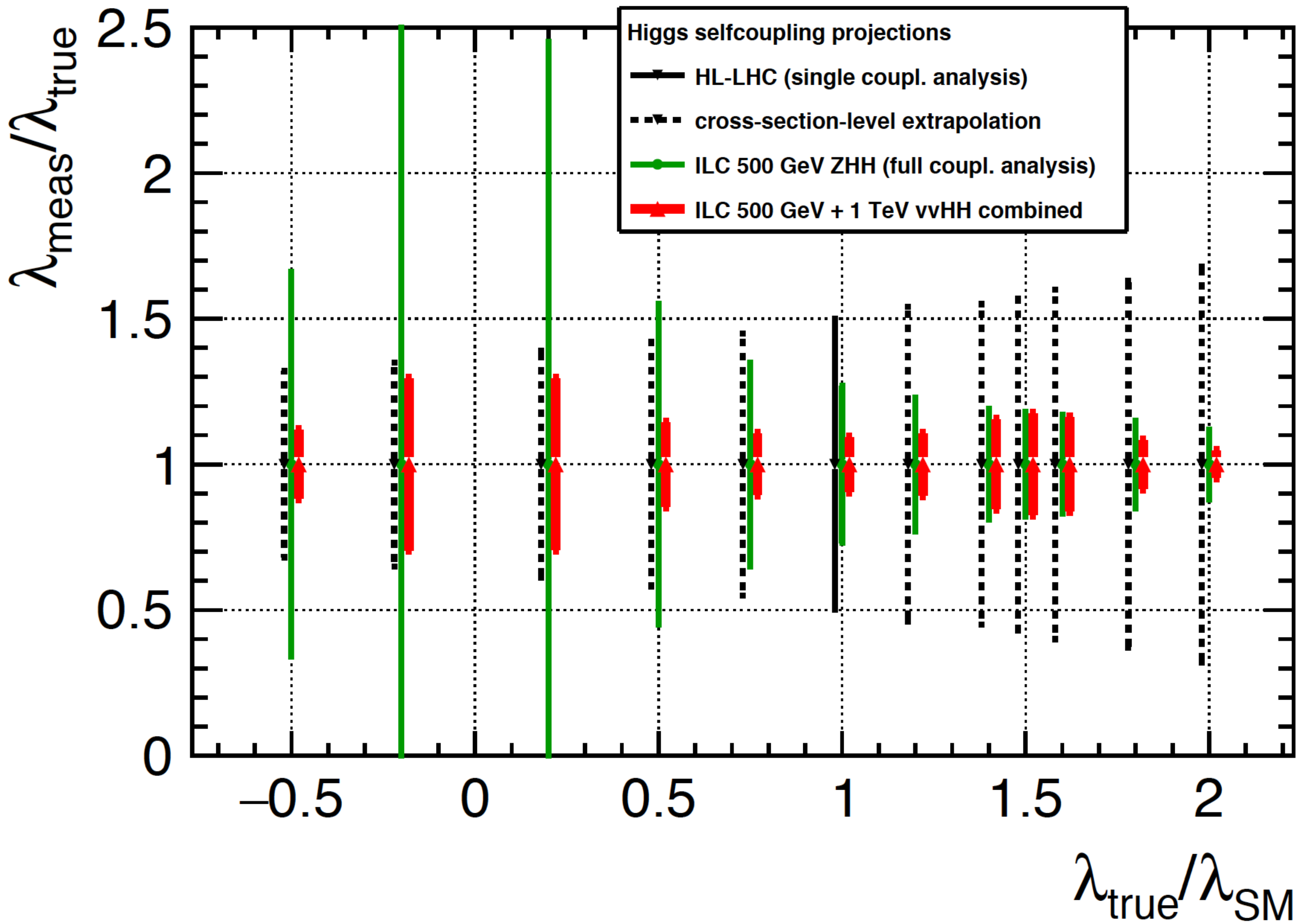
[*J. List et al. – PRELIMINARY*]




FOEWPT/GW: $\lambda_{hhh} \lesssim 2 \Rightarrow$ bad for HL-LHC, good for ILC

# Measurement of $\kappa_\lambda$ selfcoupling at HL-LHC/ILC:

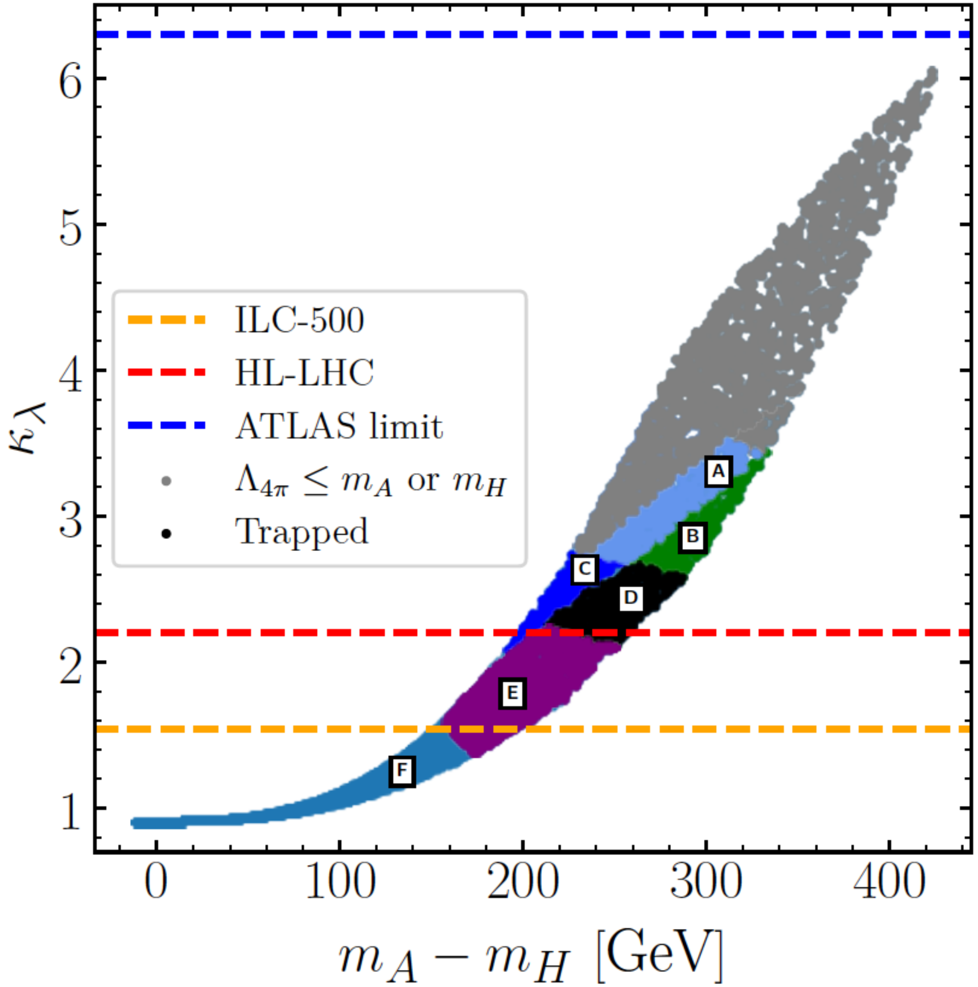
[J. List et al. – PRELIMINARY]

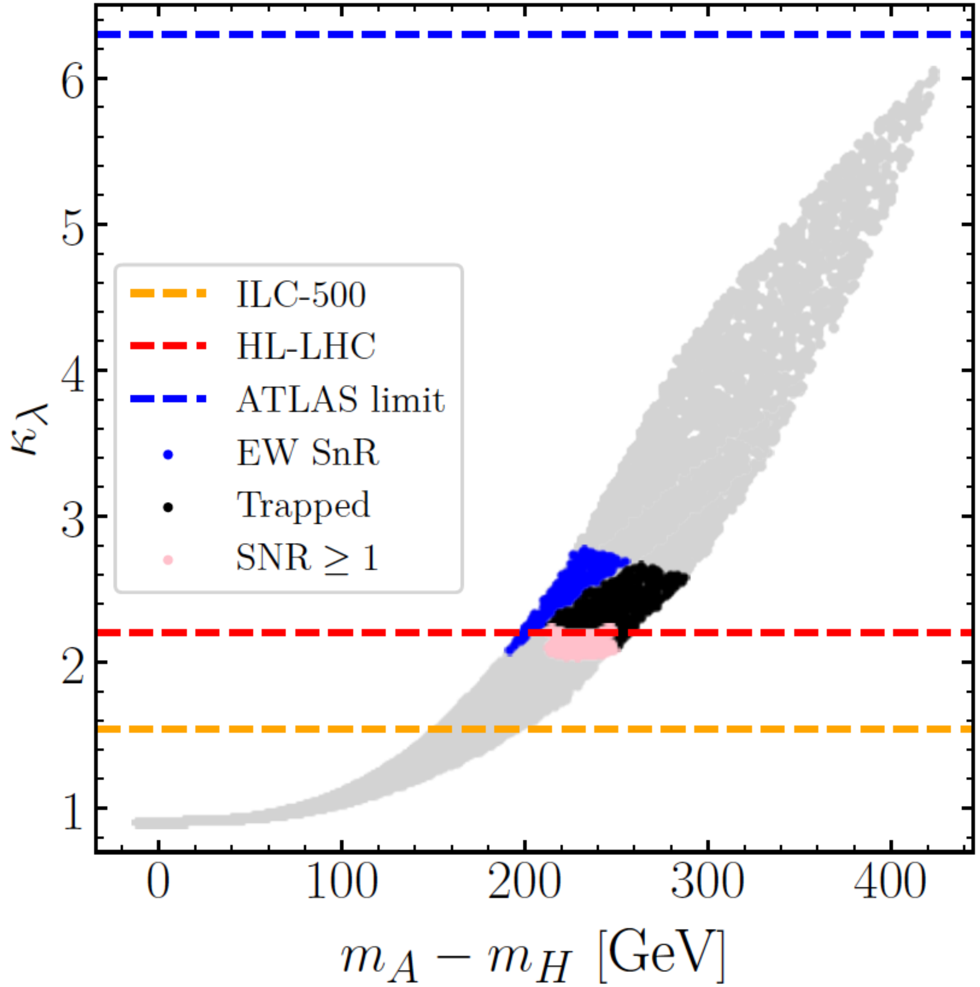



⇒ over most of the parameter space ILC is clearly superior to HL-LHC

# 2HDM parameter scan to yield FOEWPT:

[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



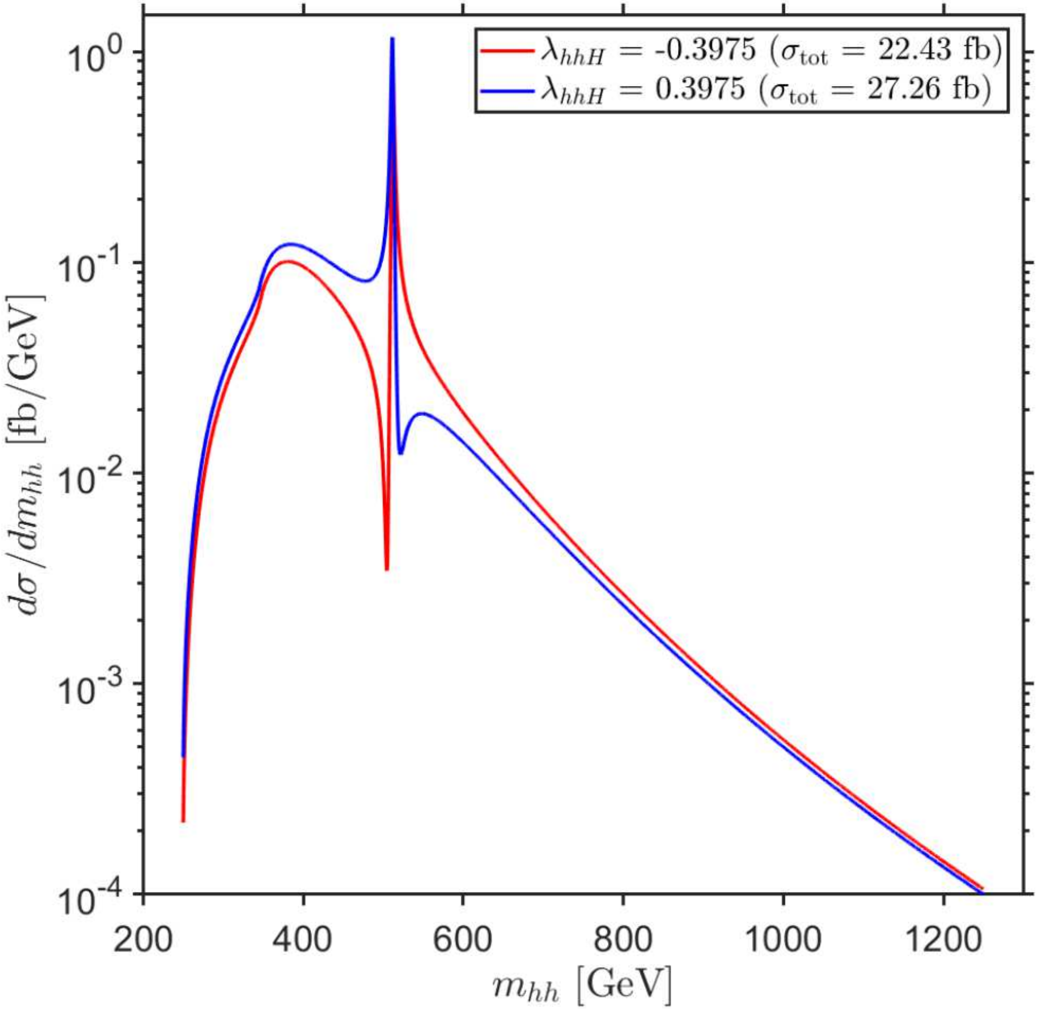

$\Rightarrow$ FOEWPT requires $\kappa_\lambda \lesssim 2$

$\Rightarrow$ GW signal requires $\kappa_\lambda \sim 2$

# Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

## Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV$, m_H = 515$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

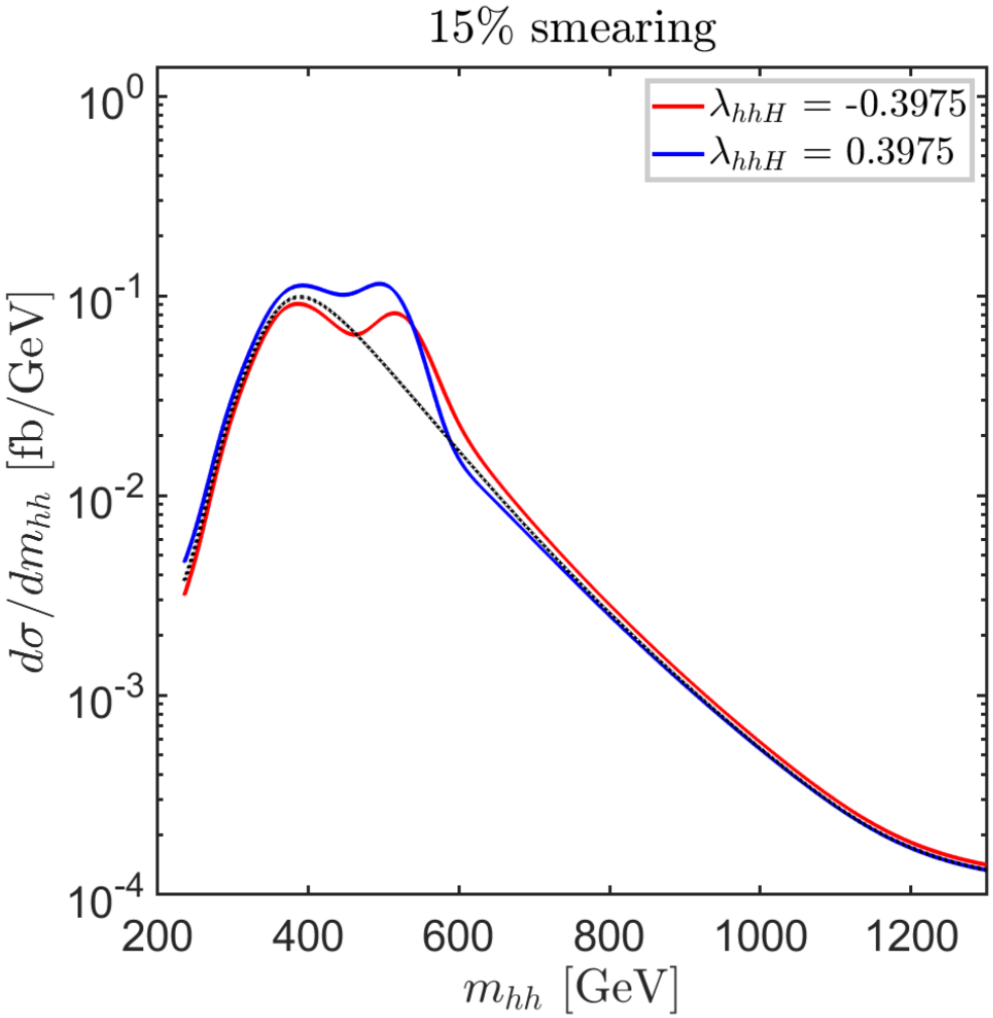



⇒ dip-peak / peak-dip from resonant $H$-exchange ⇒ access to $\lambda_{hhH}$?

## Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV, $m_H = 515$ GeV, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

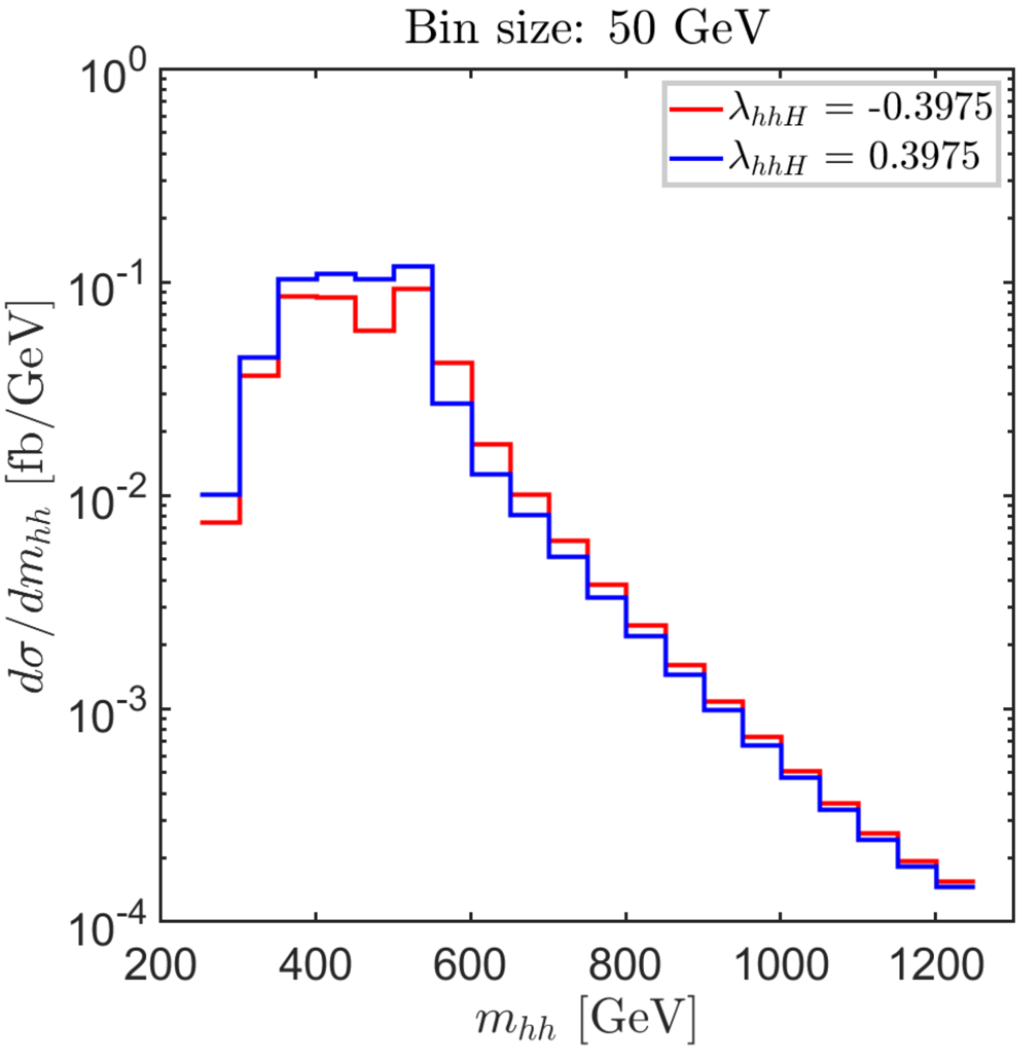



⇒ smearing of 15% applied (optimistic?) ⇒ access to $\lambda_{hhH}$?

## Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

$m_{A,H^\pm} = 545$ GeV$, m_H = 515$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$



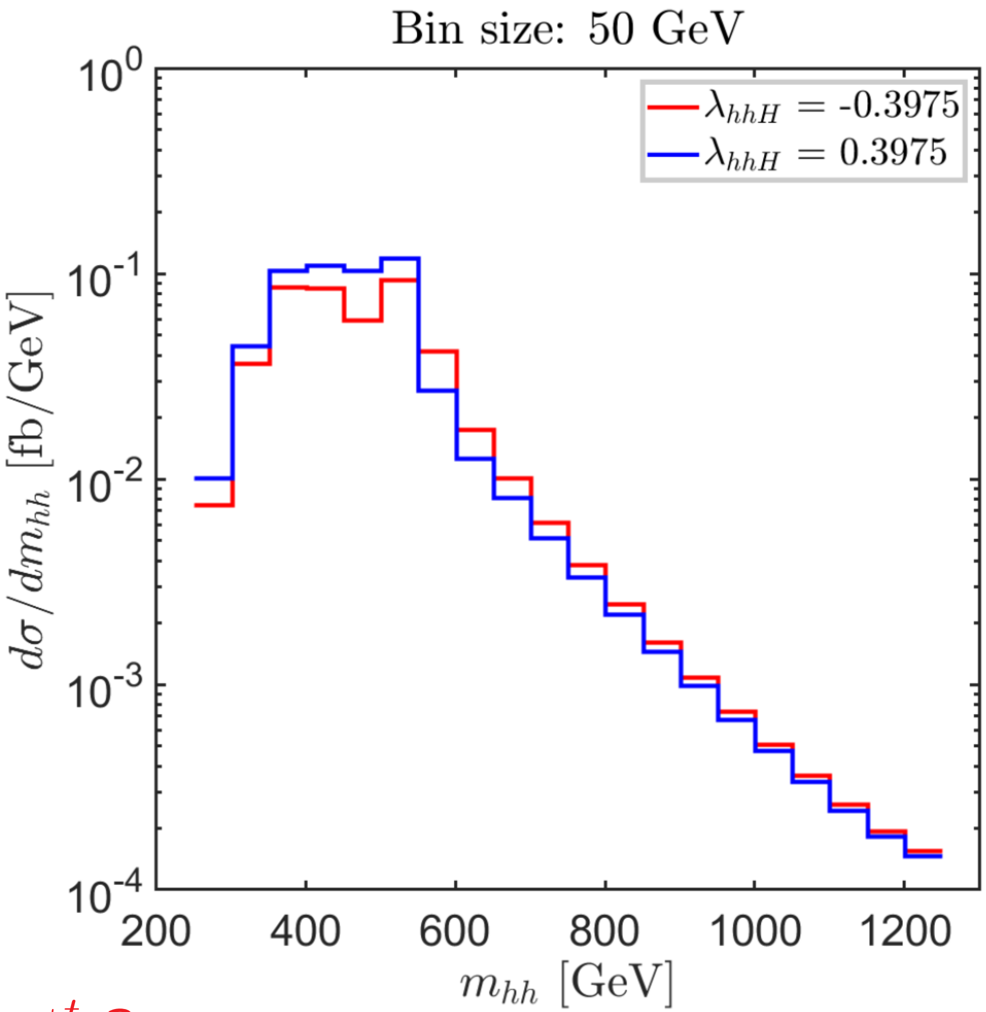

⇒ binning of 50 GeV applied (realistic?) ⇒ access to $\lambda_{hhH}$?

# My first neural network analysis

Di-Higgs production at the HL-LHC: [F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

Benchmark point: 2HDM type I,

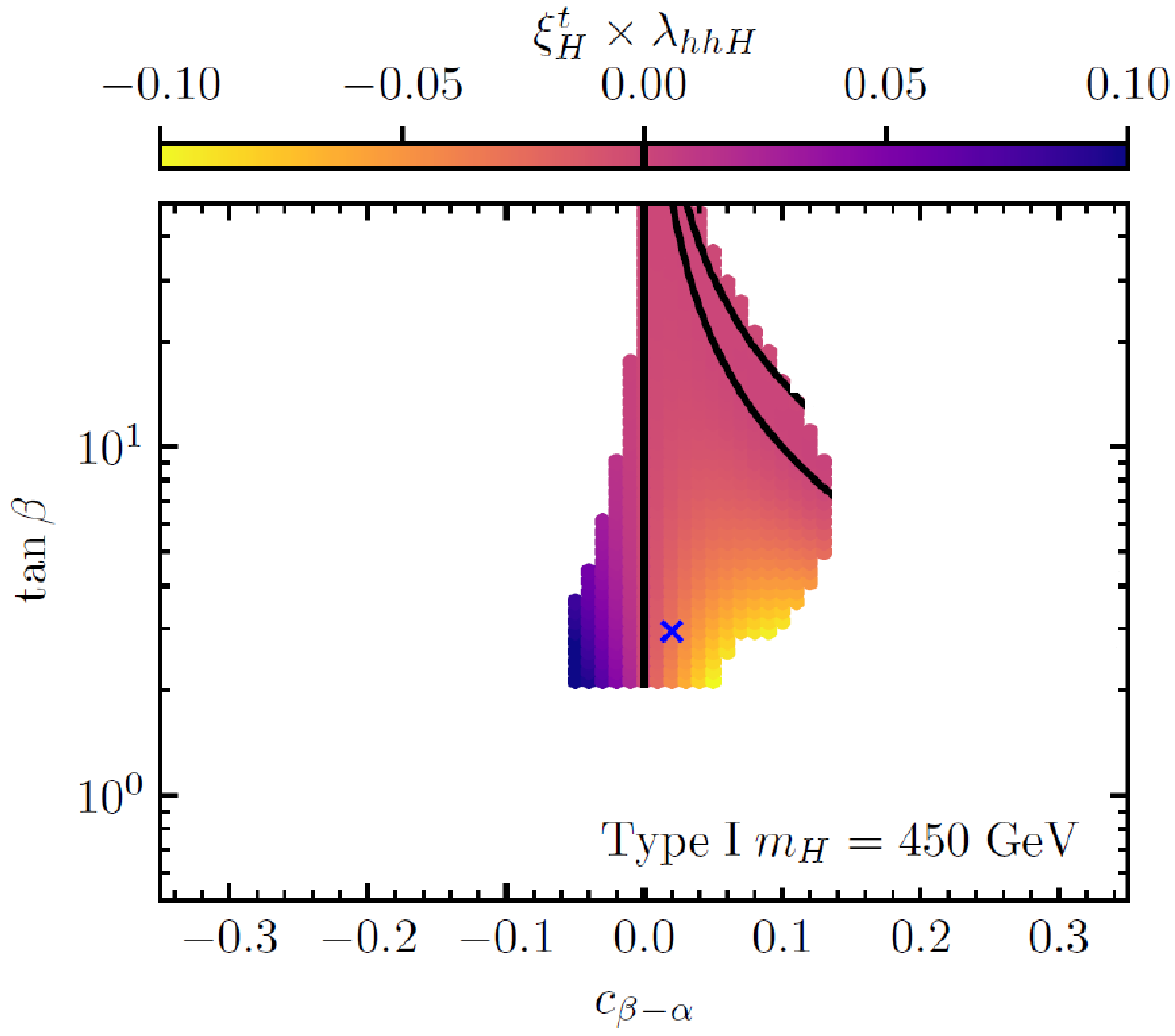
$m_{A,H^\pm} = 545$ GeV$, m_H = 515$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$




$\Rightarrow$ access to $\lambda_{hhH} \times \xi_H^t$?

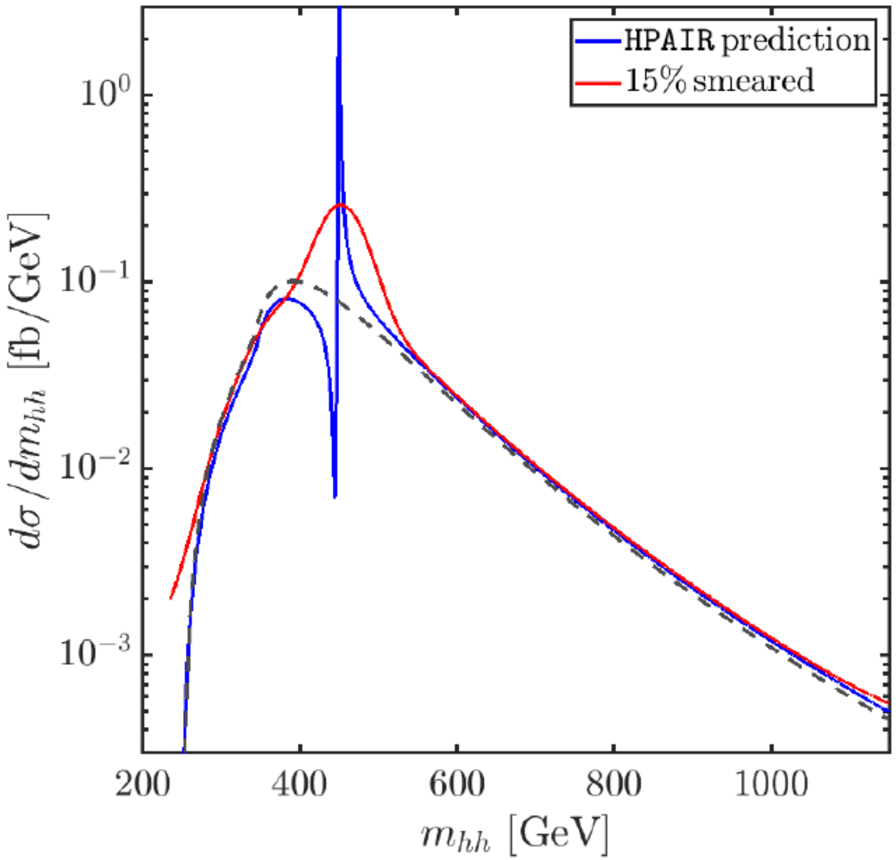
# Parameter plane to train the NN:

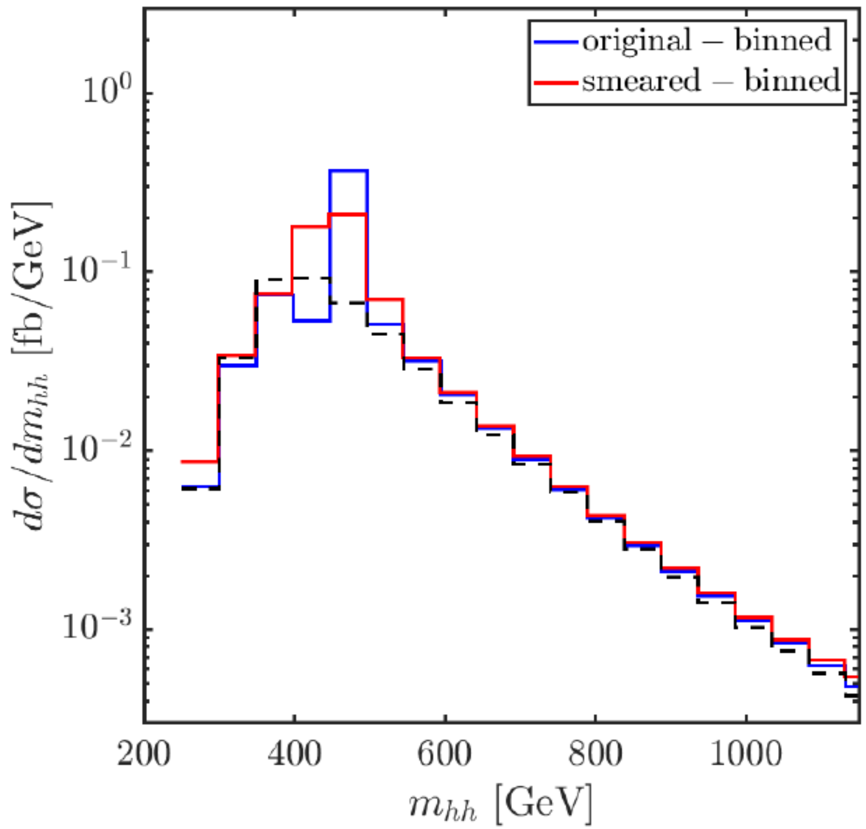
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



# Each point yields an $m_{hh}$ distribution $\Rightarrow$ fed to the NN

*[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]*

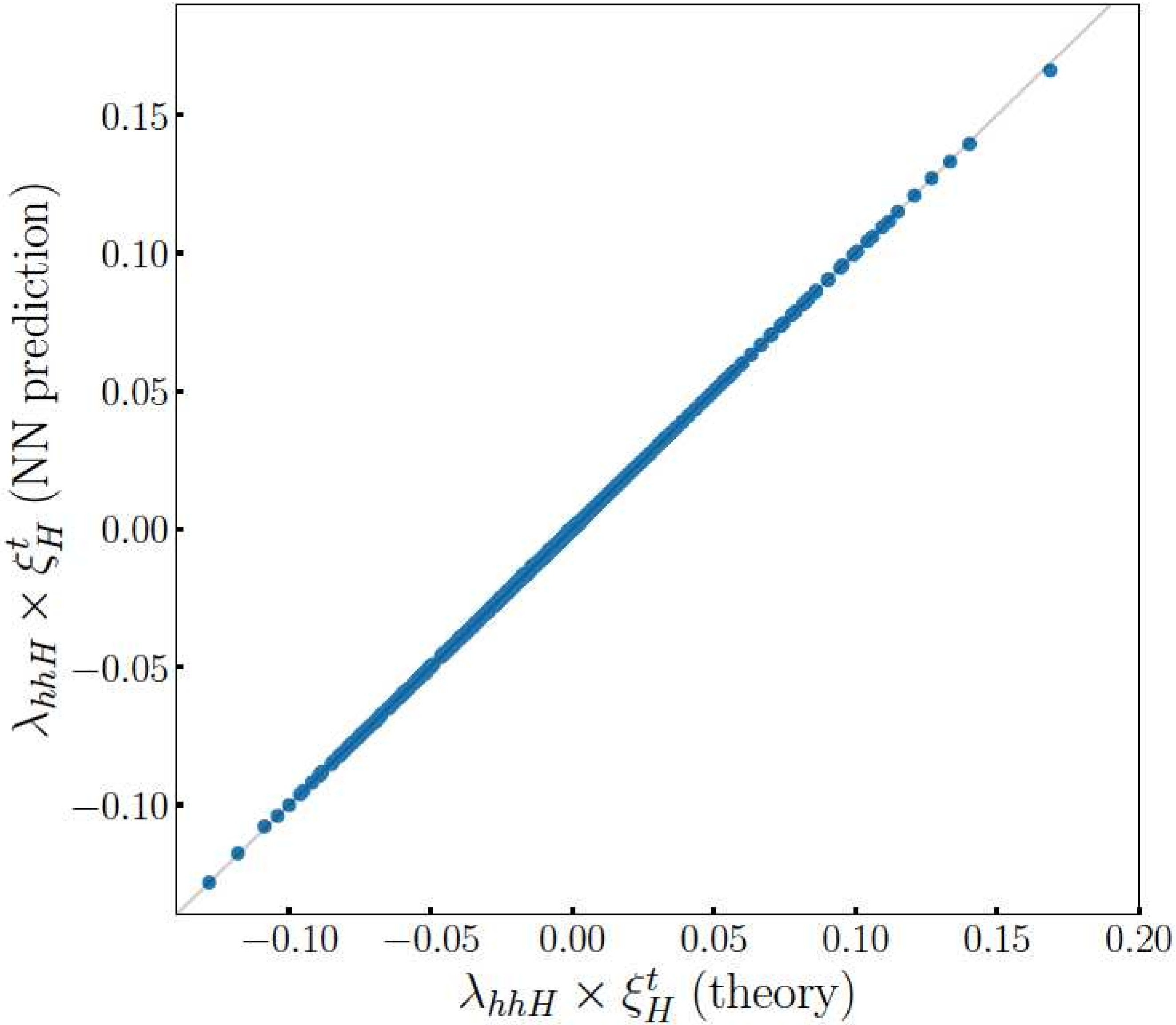



– 15 input values (smeared and binned)
– 3 hidden layers with 128 nodes
– output layer to yield $\lambda_{hhH} \times \xi^t_H$
– training with 3/4 of $m_{hh}$ distribution (randomly chosen)
– "measure" the remaining 1/4 (or . . . )

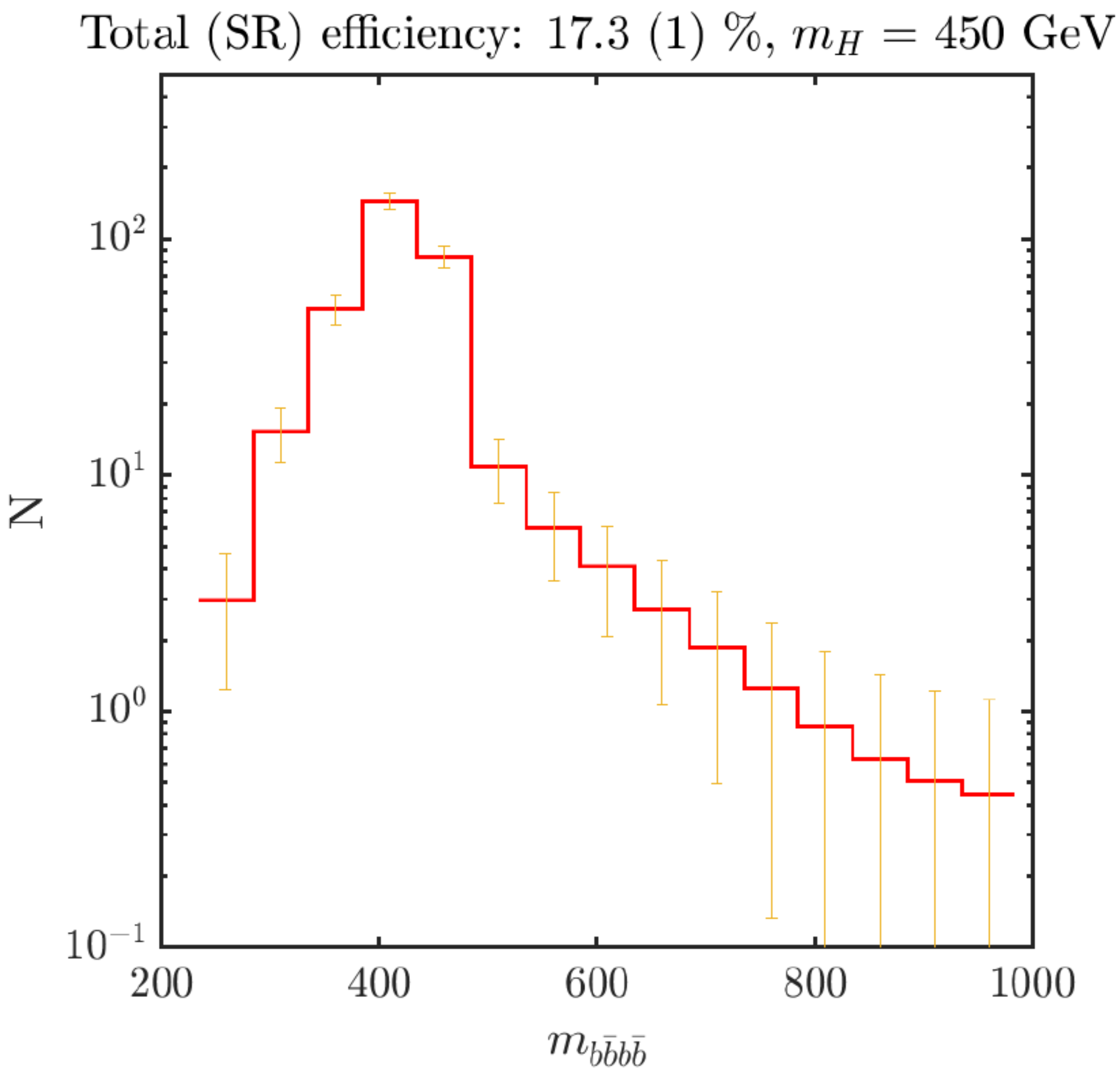
# Train with the correct $m_{hh}$ distributions: ⇒ perfect result

[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



## “Realistic result” has statistical uncertainties ($b\bar{b}\,b\bar{b}$ final state):

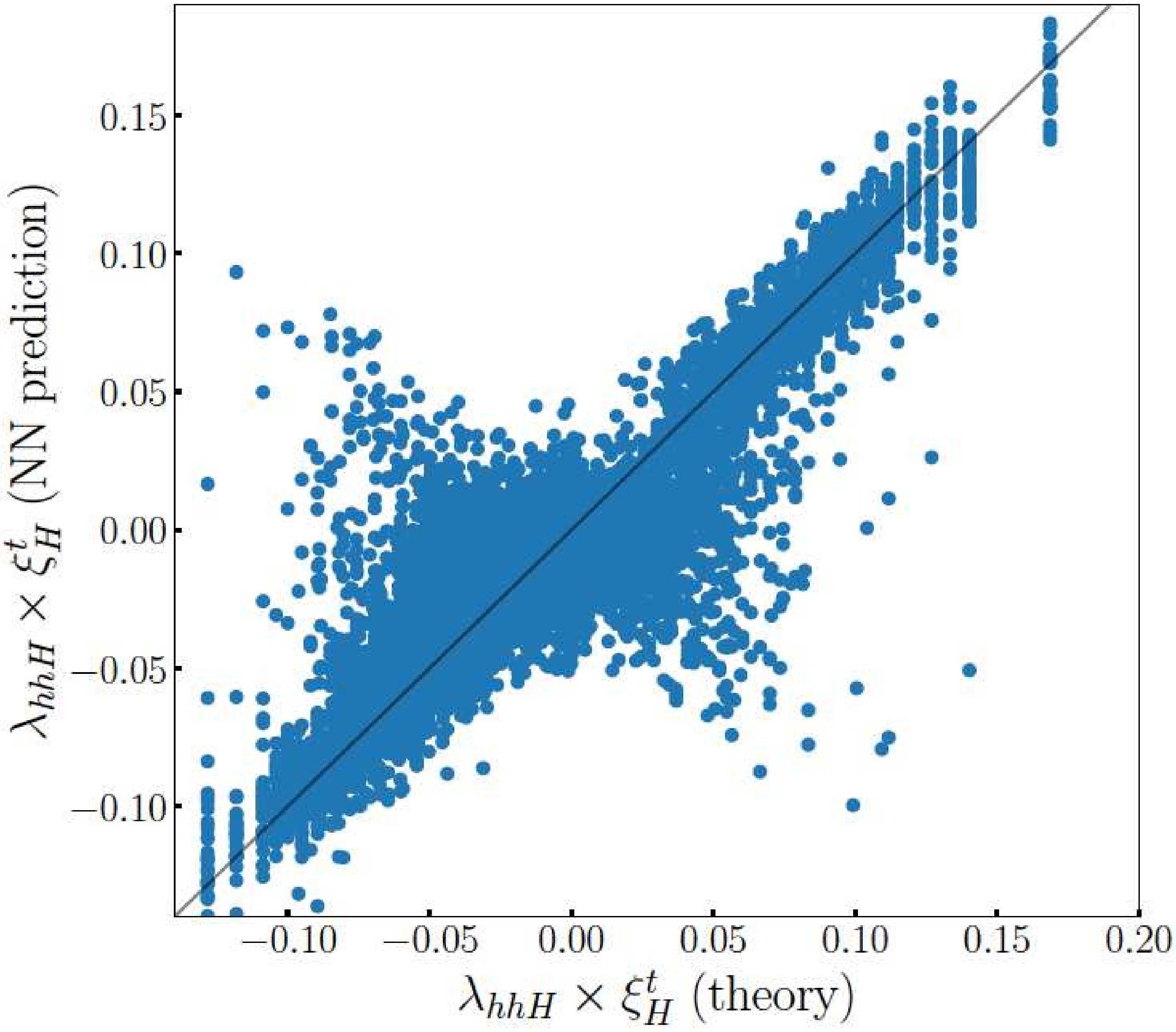
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]




$\Rightarrow$ for each point in the plane test an $m_{hh}$ distribution statistically smeared

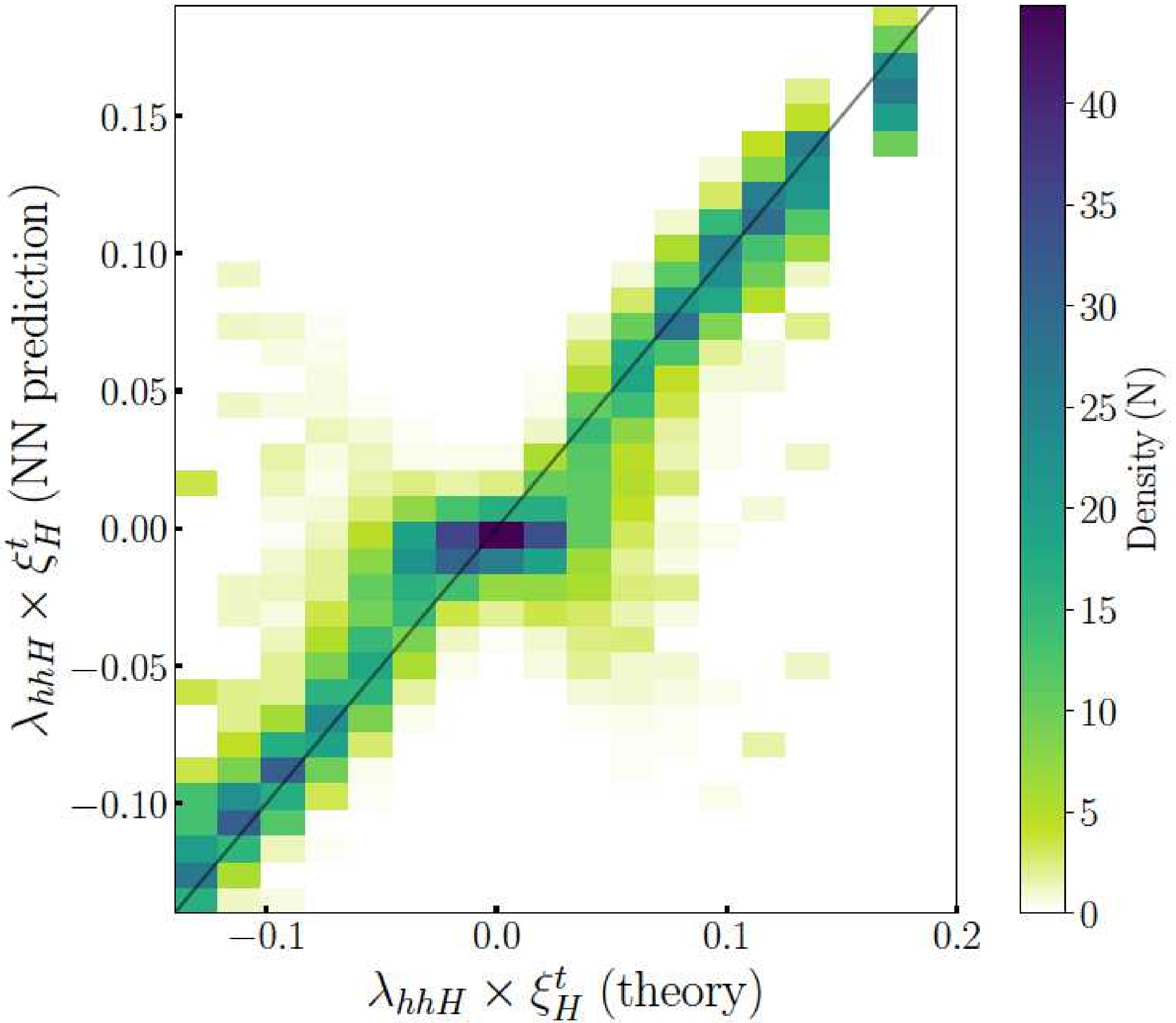
## "Realistic" determination of $\lambda_{hhH} \times \xi_H^t$:

[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]



## “Realistic” determination of $\lambda_{hhH} \times \xi^t_H$:

[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



# Hypothetical improvement in the efficiencies by $\times 2$:

[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]