
I FOUND THE HUGS BISON.
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Di-Higgs Production at the LHC: Theory vs. Experiment

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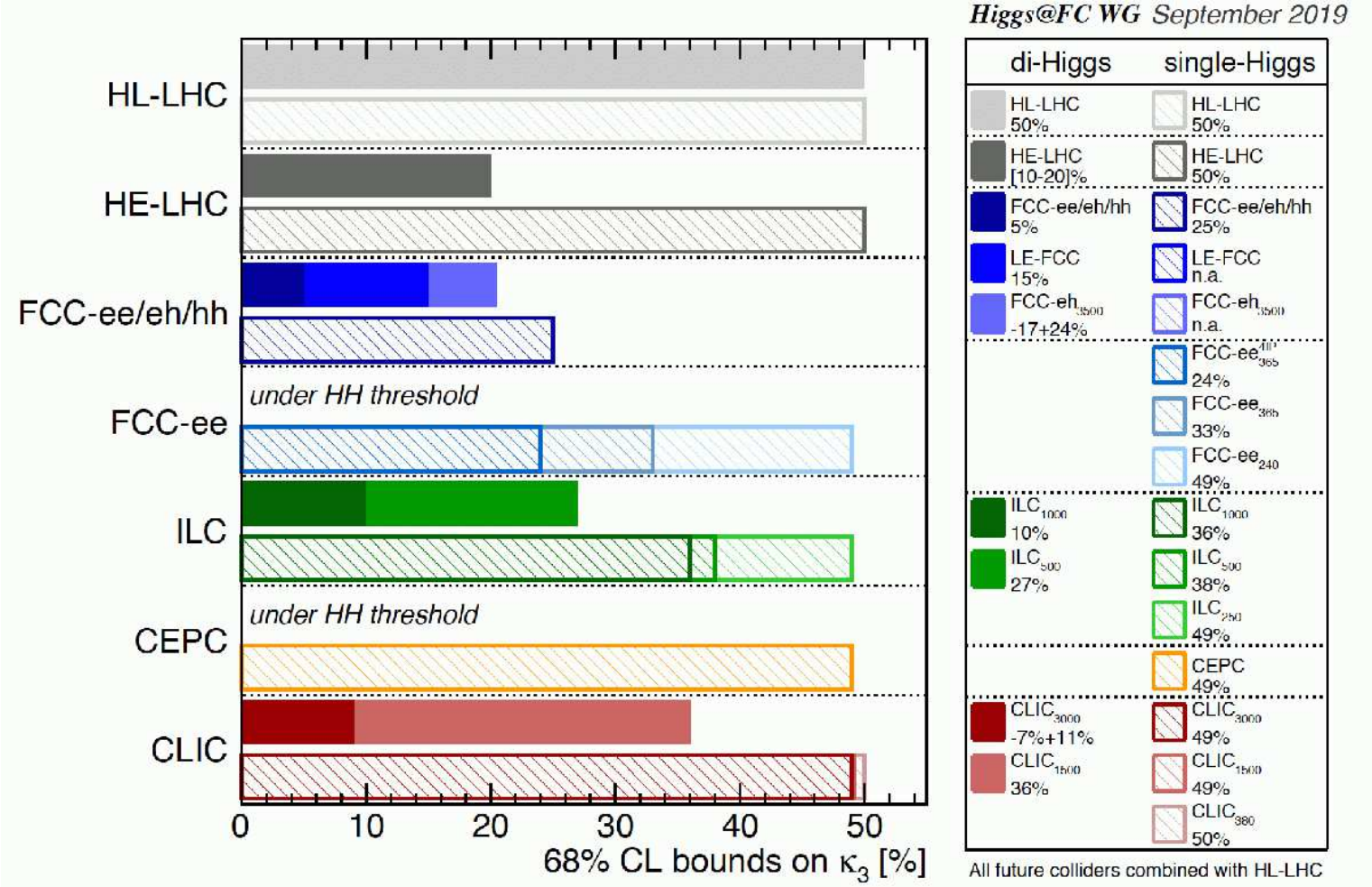
1. Introduction
2. Resonant di-Higgs production: theory vs. experiment
3. My first Neural Network analysis
4. Conclusions

1. Introduction

SM triple Higgs coupling: comparison of all colliders:

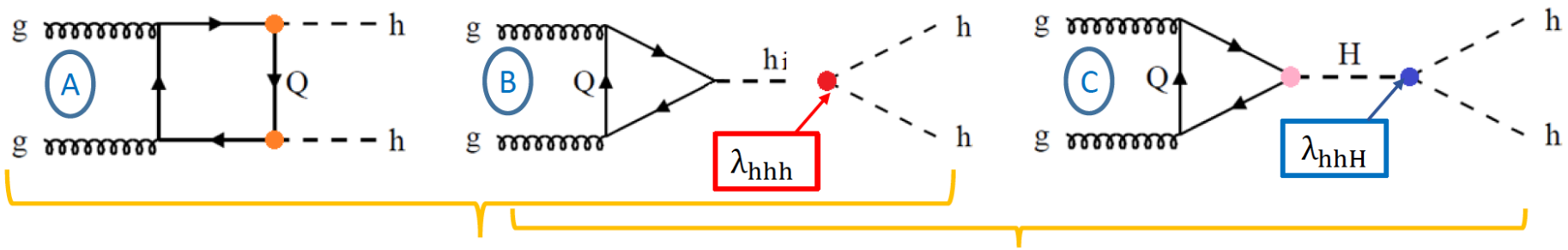


$\Rightarrow$ focus on "SM triple Higgs coupling", $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM,tree}}$

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

BSM case 2: THC that involves BSM Higgses: λ_{hhH}, ...

Di-Higgs production at the LHC:

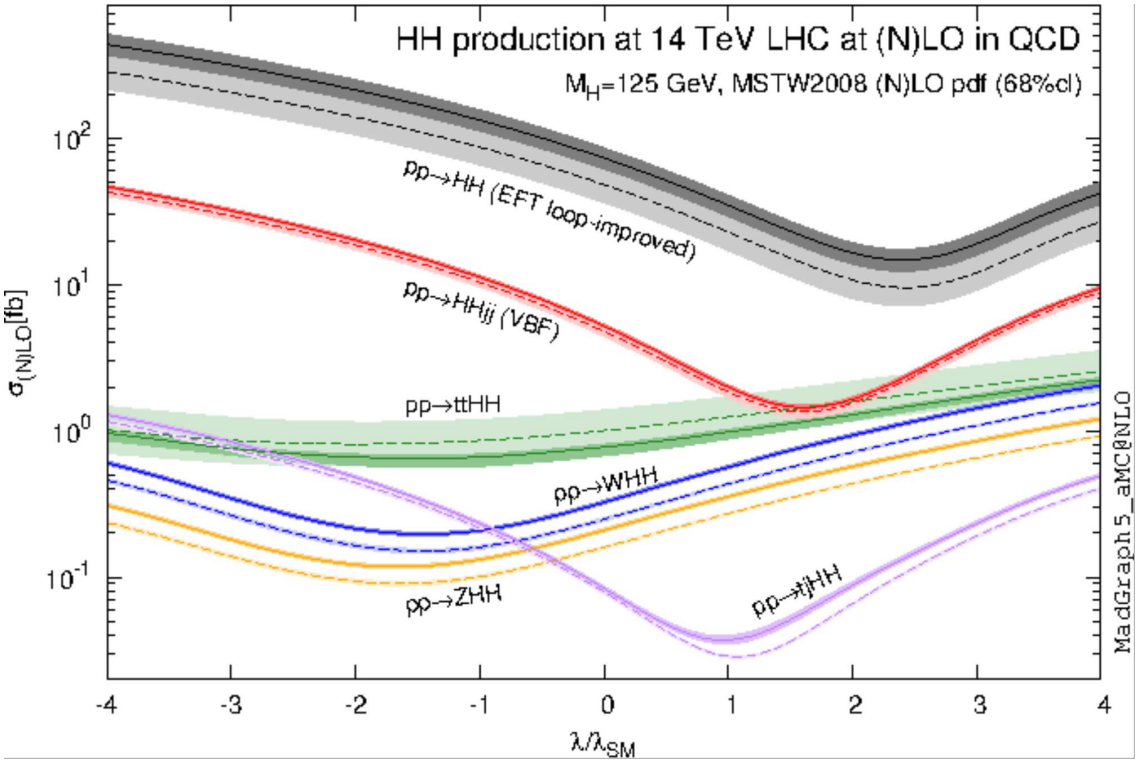


$\sigma_{SM} \sim$ 38 fb at NLO

Diagrams that exist in the SM:
They have a negative interference

Diagrams that are sensitive
to triple Higgs couplings

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



Resonant di-Higgs production requires BSM physics

Resonant di-Higgs production requires BSM physics

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: λ_{hhh}, λ_{hhH}, λ_{hHH}, $\lambda_{hH^+H^-}$, λ_{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:

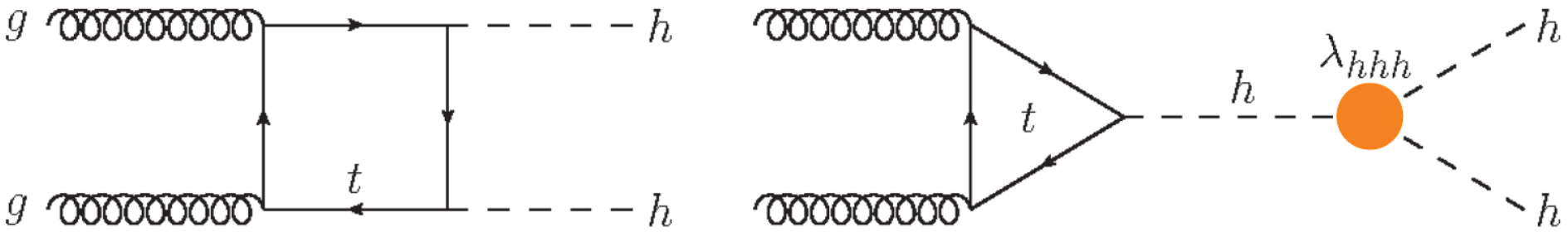
	u-type	d-type	leptons	
type I	Φ_2	Φ_2	Φ_2	
type II	Φ_2	Φ_1	Φ_1	$\to$ SUSY type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

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

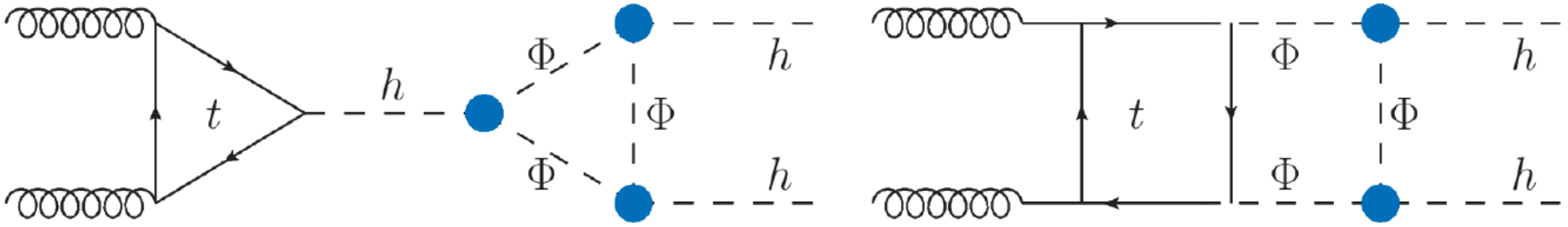
Unitarity/perturbativity and EWPO : $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

Higher-order correction to the THCs in the 2HDM: [taken from J. Braathen]

Box vs. s-channel Higgs:



Inclusion of one-loop corrections to THCs:



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

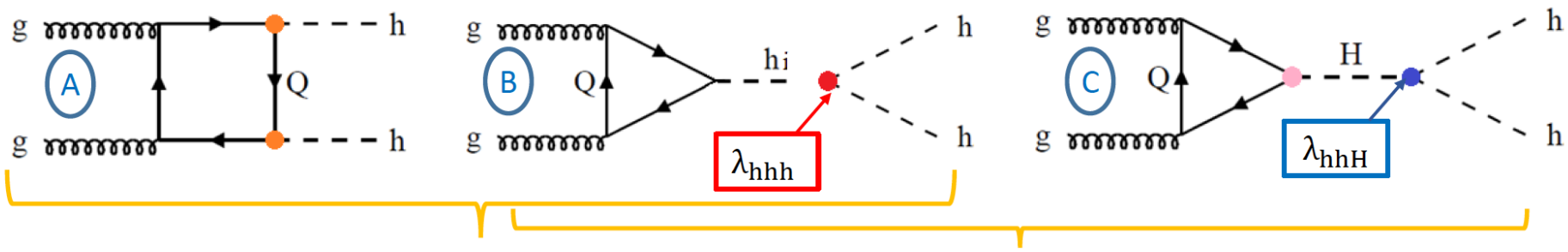
Correction to λ_{hhh} → included

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

not included

$\Rightarrow$ always closed subset, dominant for large THCs

BSM THCs at the HL-LHC



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

Diagrams that exist in the SM:
They have a negative interference

Diagrams that are sensitive
to triple Higgs couplings

⇒ possible strong resonance with BSM Higgs

Important: experimental limtis are obtained for

– non-resonant production

– purely resonant production

⇒ no limits available for mixed scenarios :-(

⇒ existing exclusion bounds questionable!

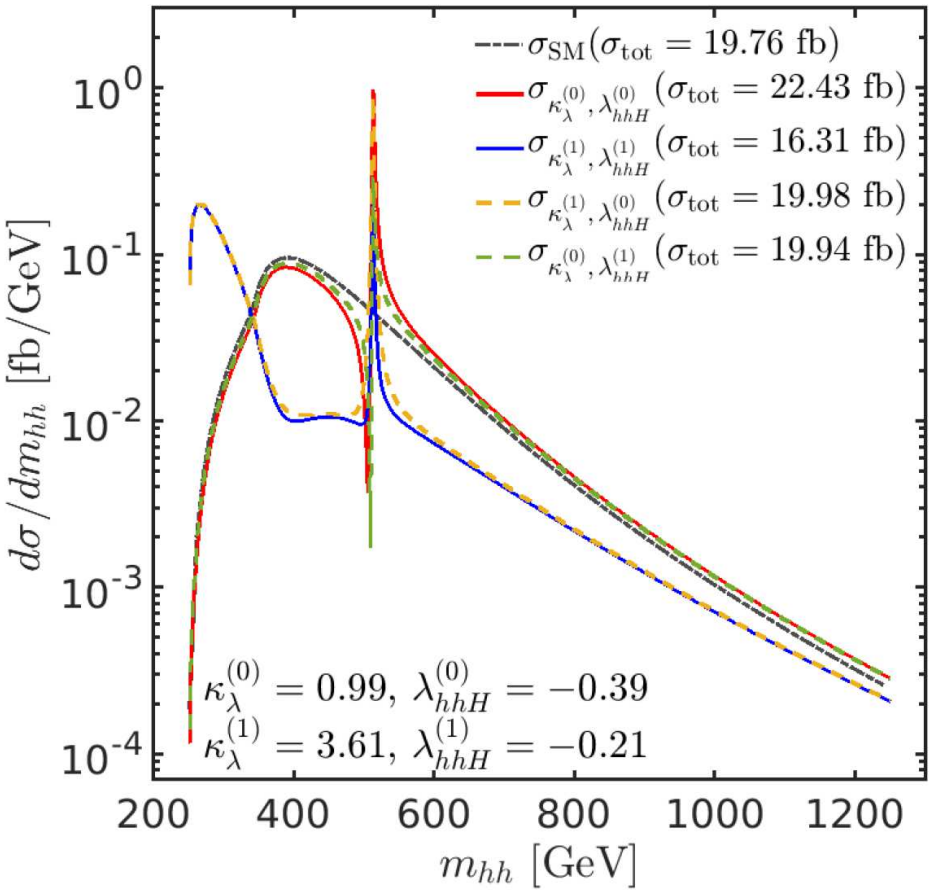
Example model in this talk: 2HDM
Similar results exist also for RxSM (Higgs singlet extension)

[S.H., A. Verduras PRELIMINARY]

2. Resonant di-Higgs production: theory vs. experiment:

$\Rightarrow$ analyses so far focus on "SM THC": $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\text{SM,tree}} \equiv 1$
BSM case 1: $\kappa_\lambda \neq 1$
BSM case 2: THC that involves BSM Higgses: λ_{hhH}, ...

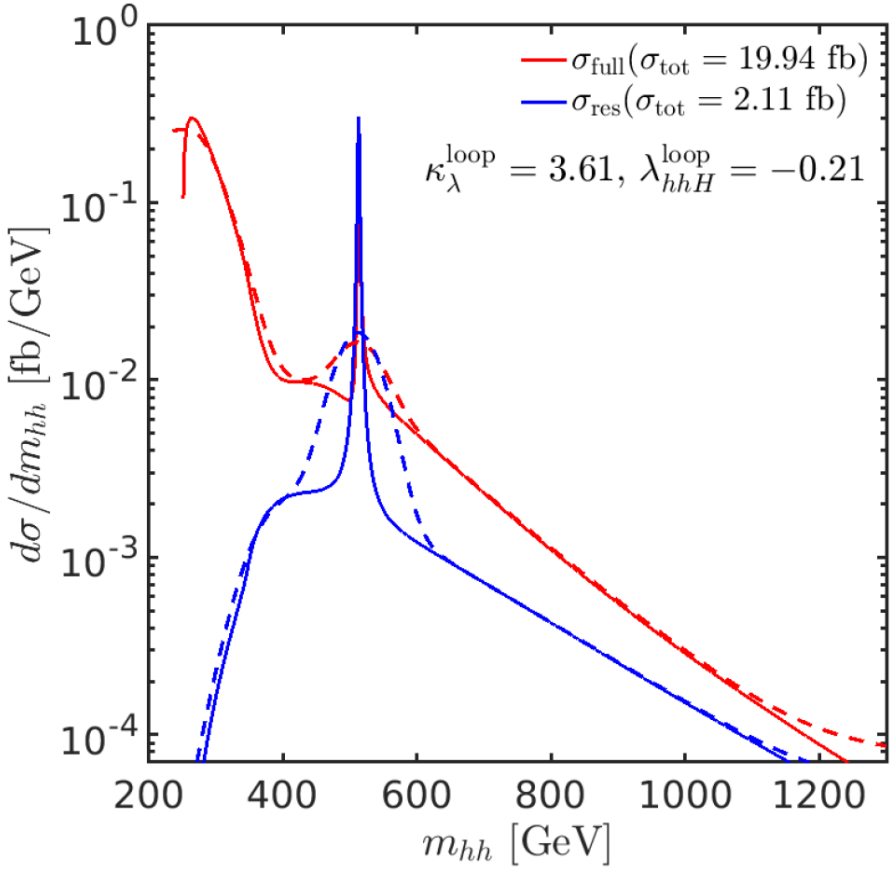
Example of m_{hh} distortions: [S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24]



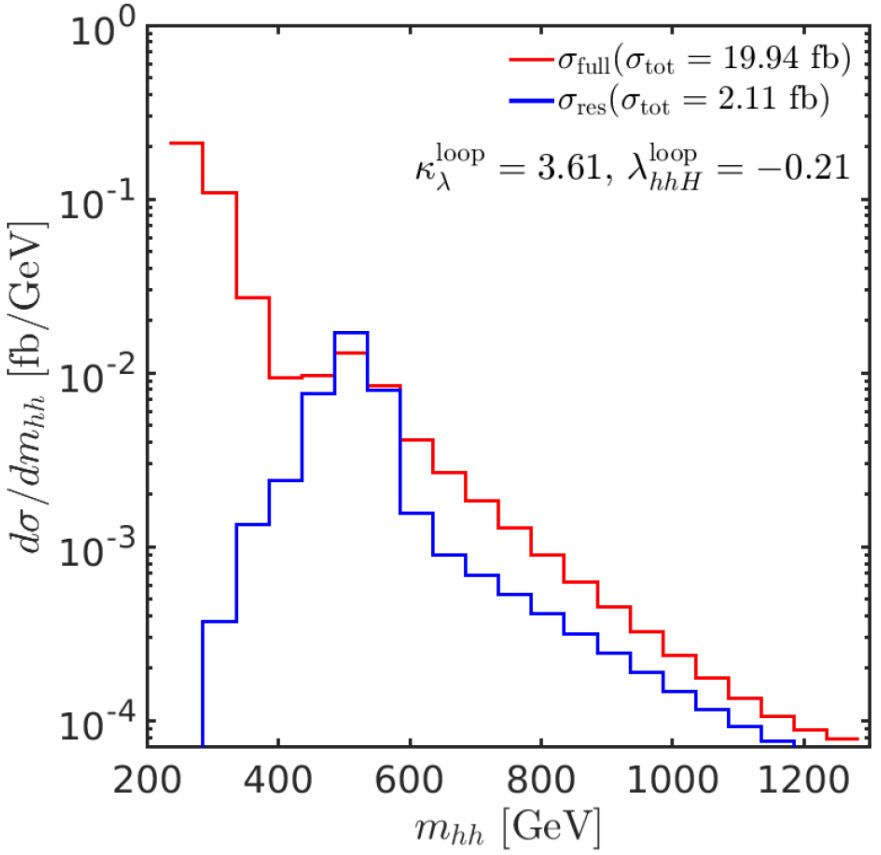
Experimental analysis vs. reality: including exp. uncertainties

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

smeared



$\oplus$ binned

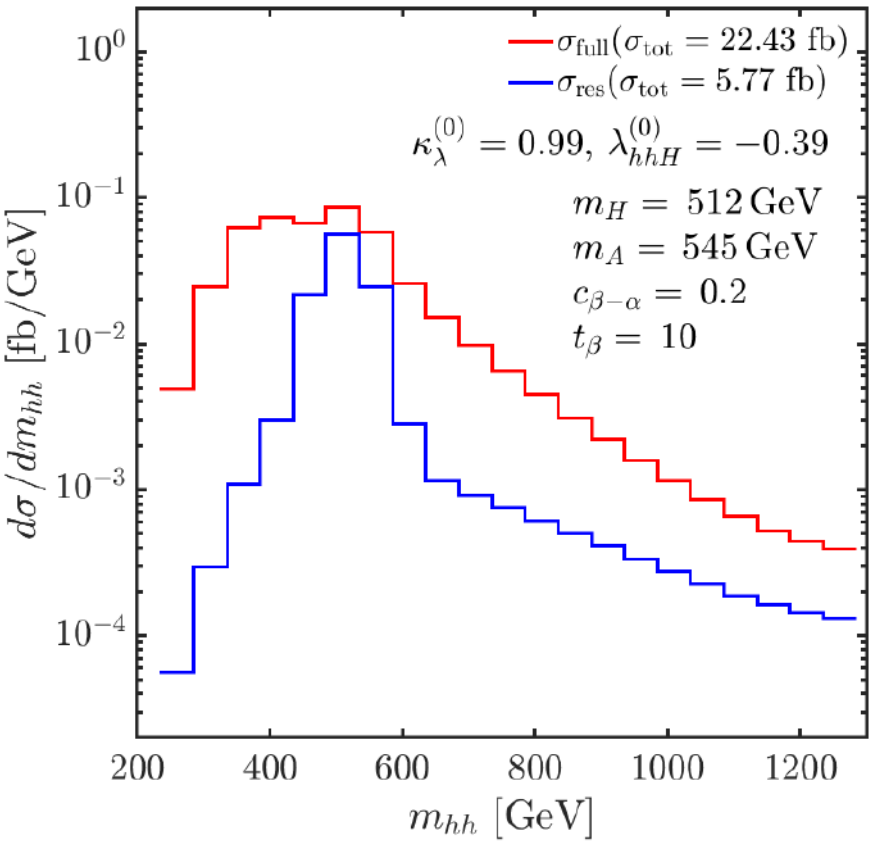


$\Rightarrow$ experimental analysis $\Rightarrow$ full calculation

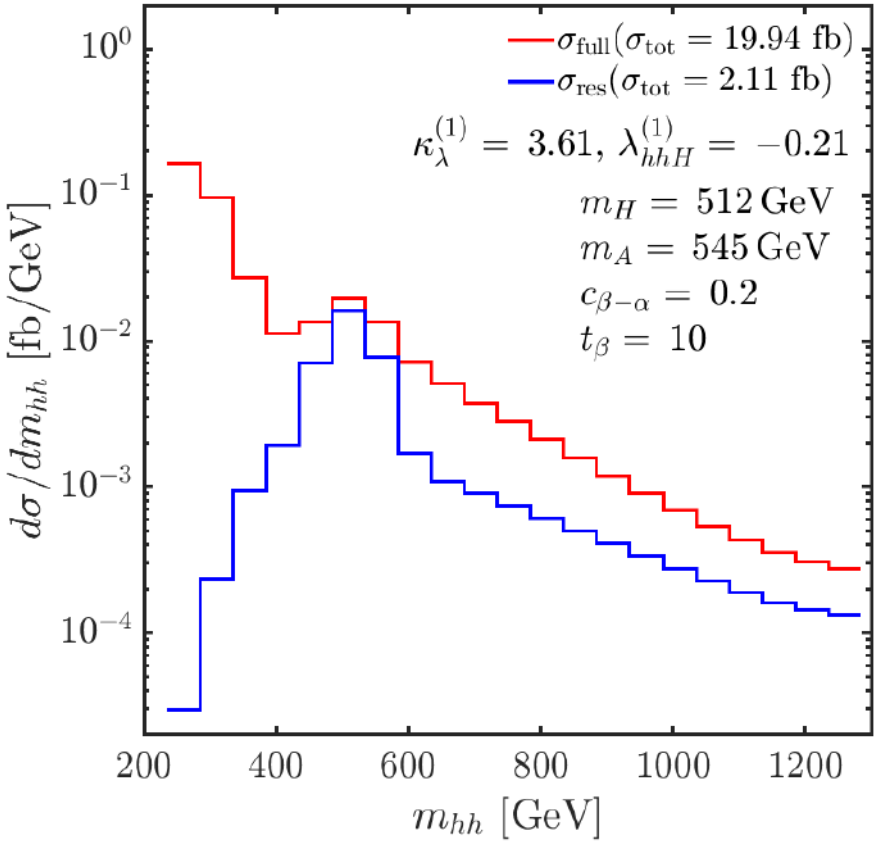
Experimental analysis vs. reality: relevance of loop corrections

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

THC tree-level



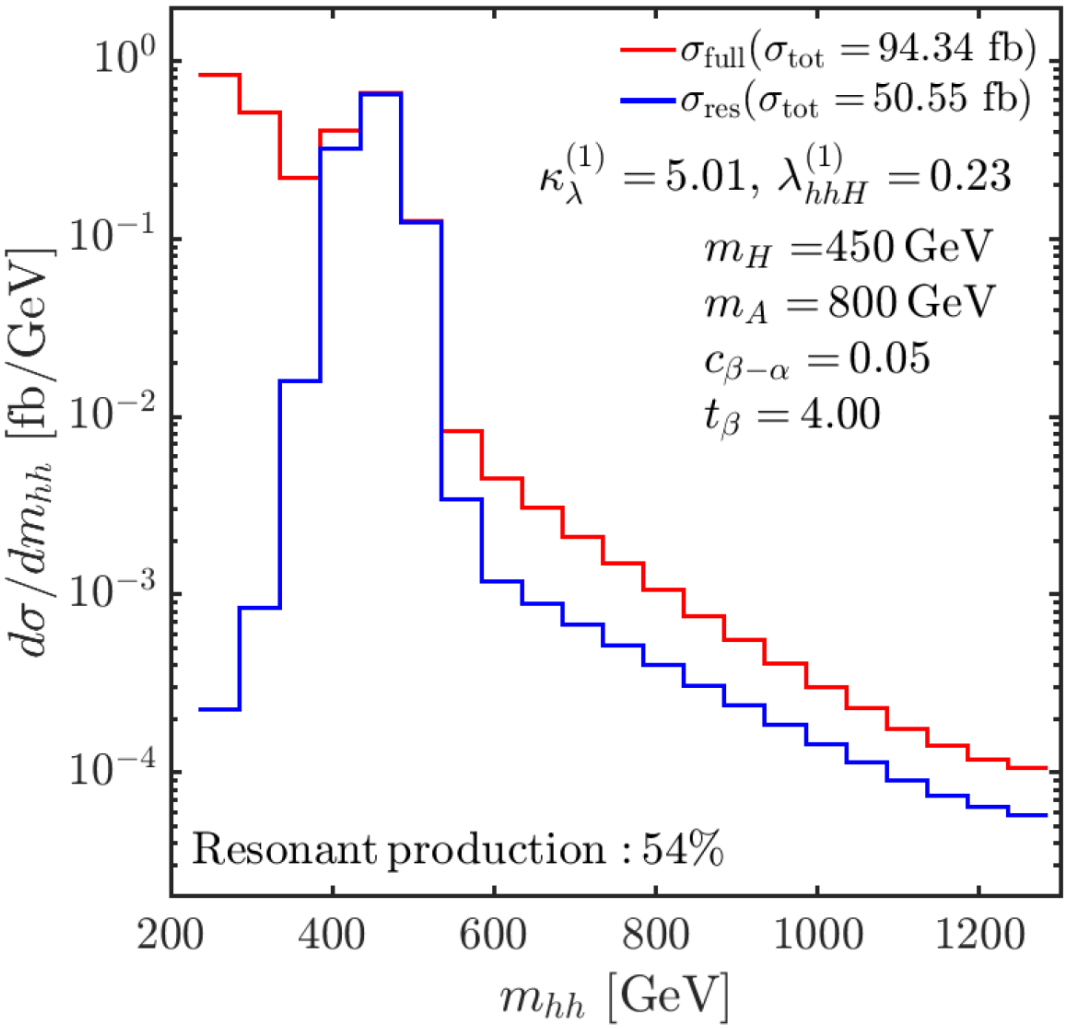
THC one-loop



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

Experimental analysis vs. reality: real point (I)

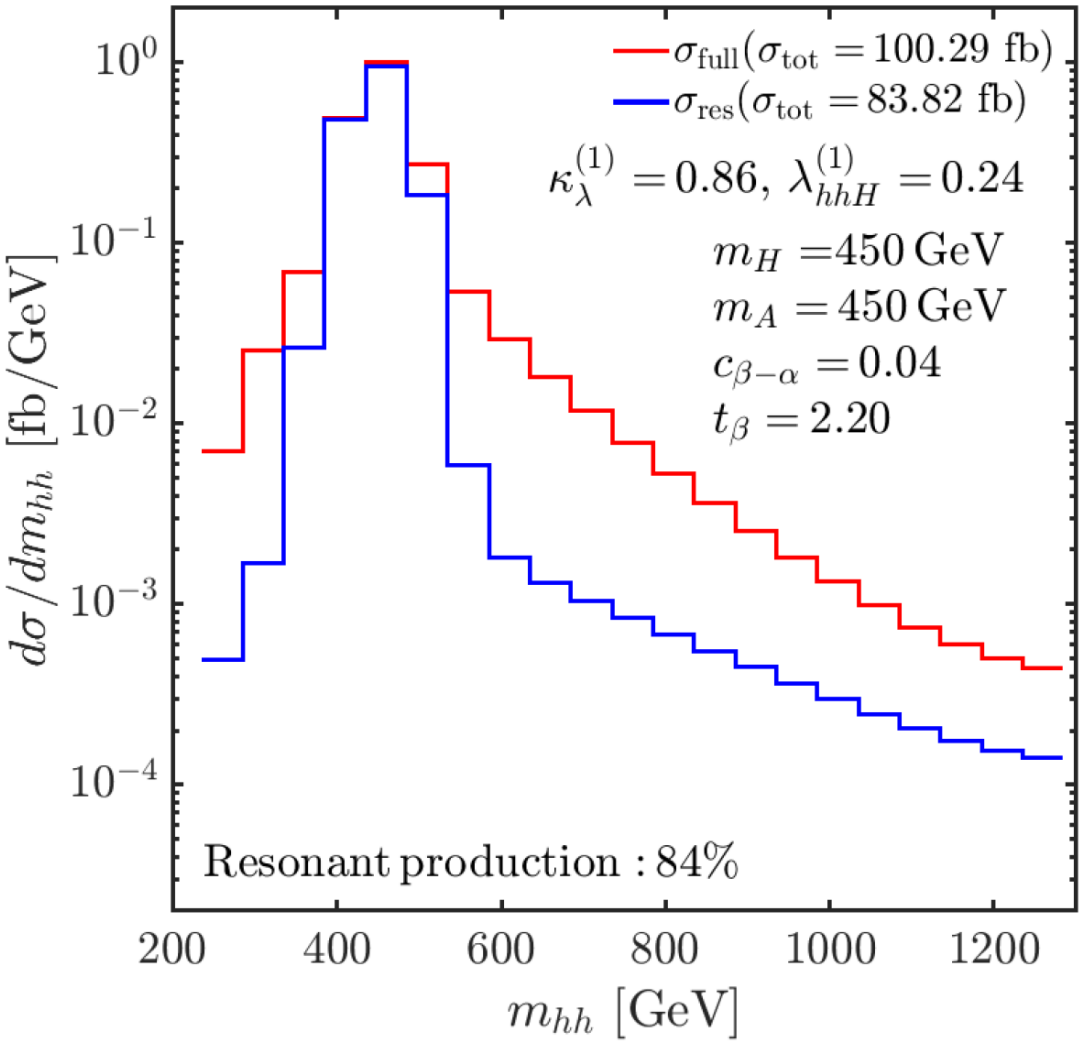
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



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

Experimental analysis vs. reality: real point (II)

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

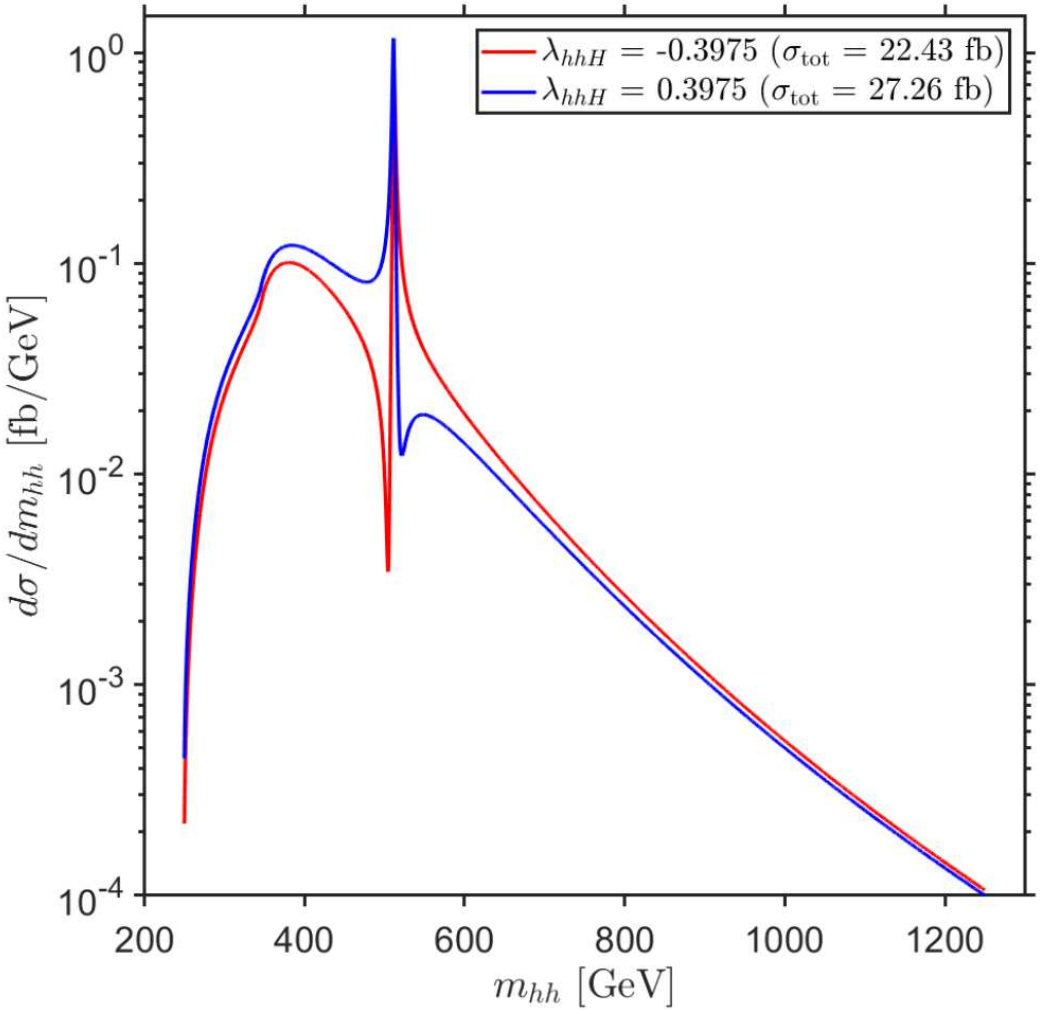


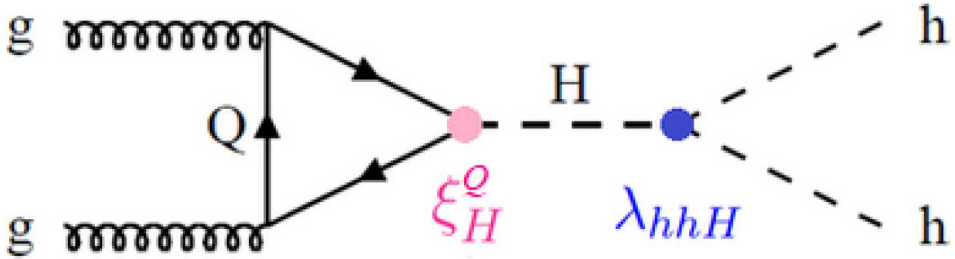
$\Rightarrow$ excluded by ATLAS resonant searches $\Leftrightarrow$ reality: exclusion?

3. My first neural network analysis

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

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



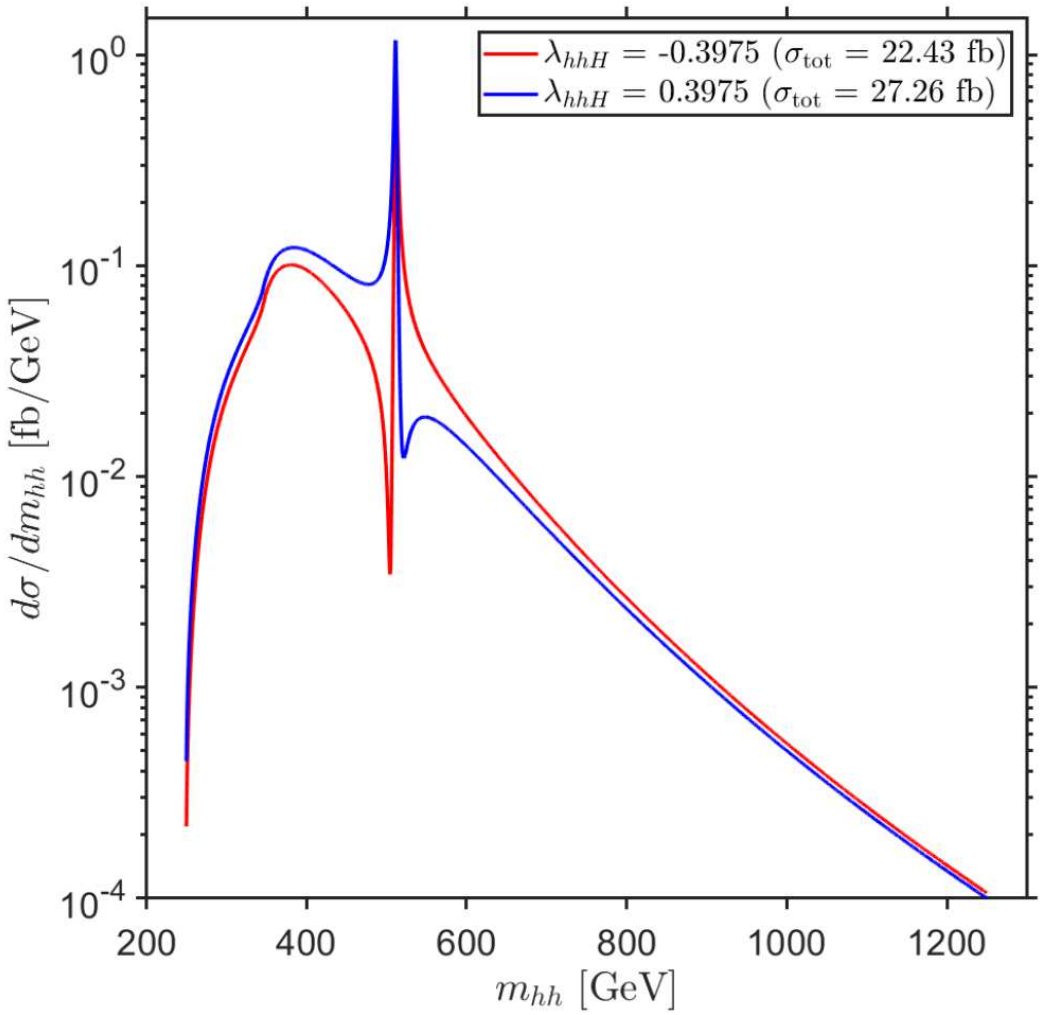


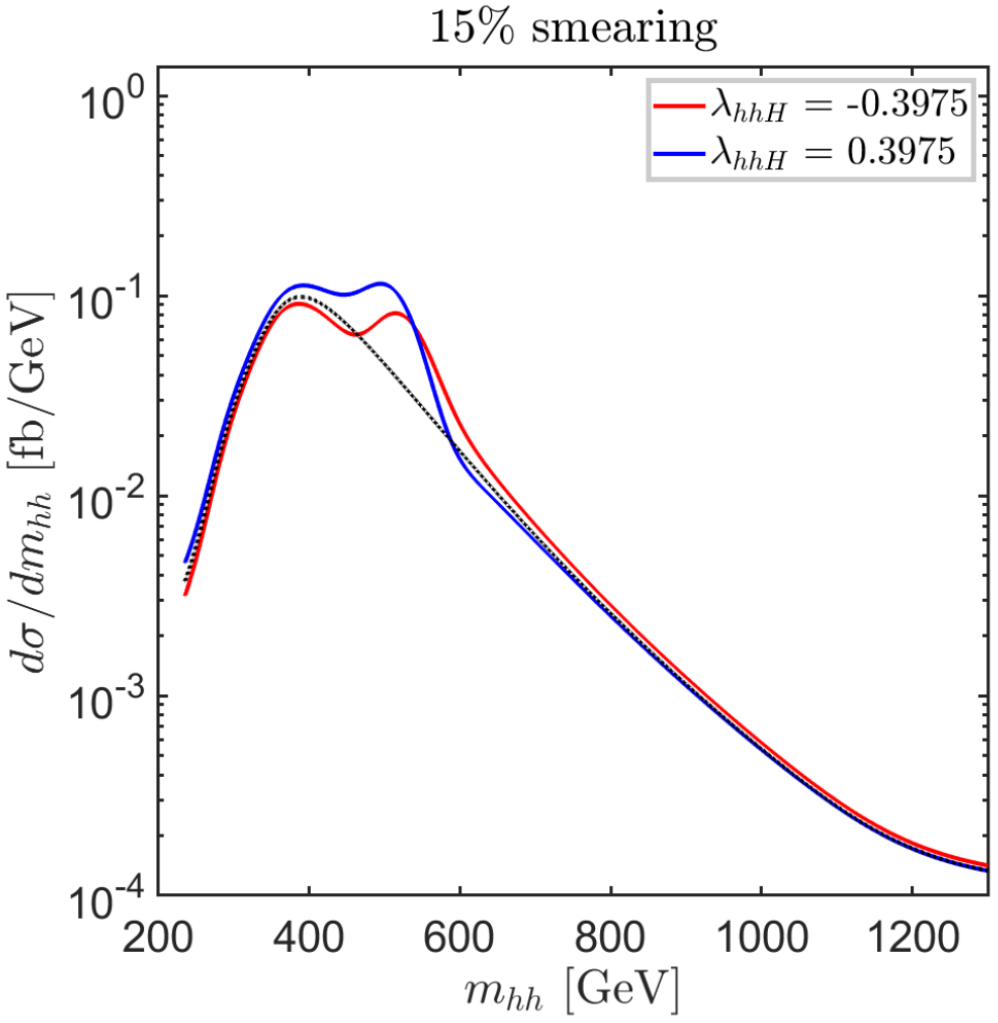
$\Rightarrow$ dip-peak / peak-dip from resonant H-exchange $\Rightarrow$ access to $\xi_H^t \times \lambda_{hhH}$?

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, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$



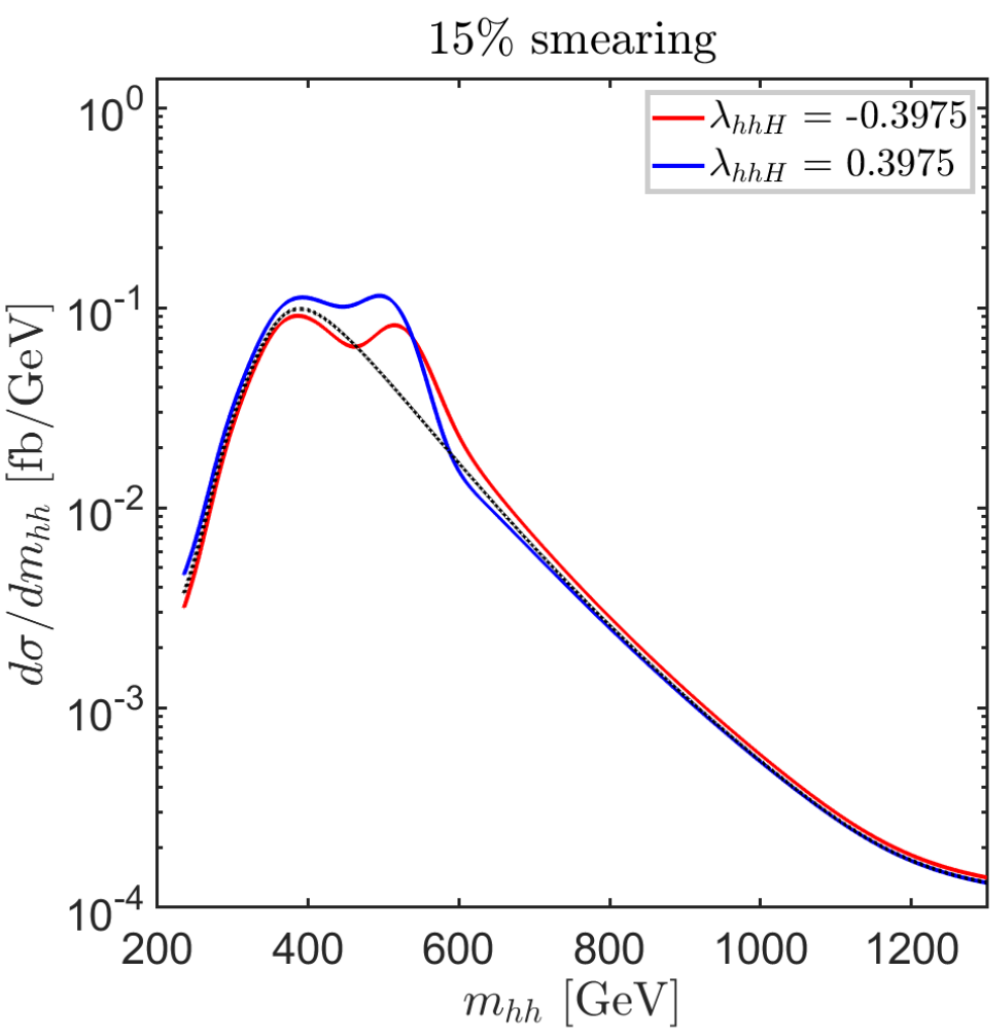


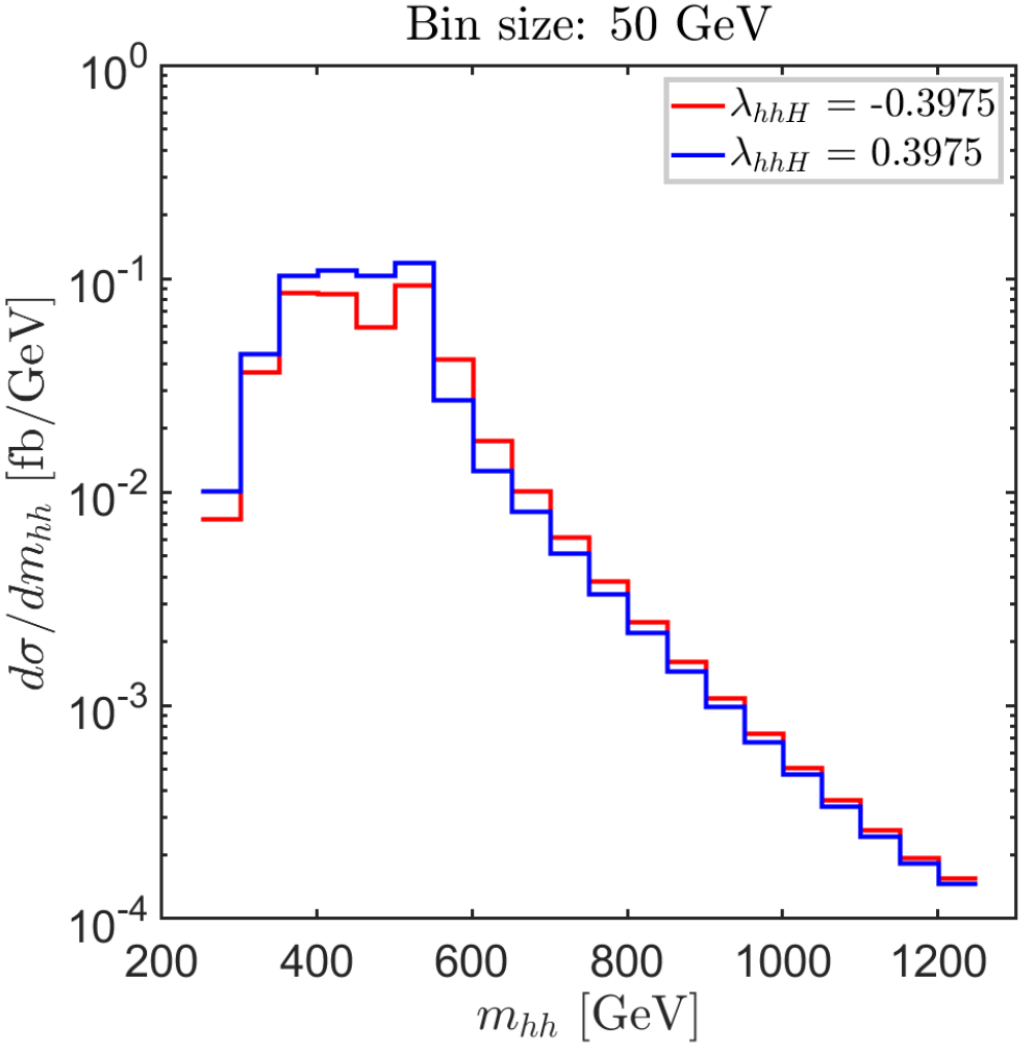
$\Rightarrow$ smearing of 15% applied (optimistic?) $\Rightarrow$ access to $\xi_H^t \times \lambda_{hhH}$?

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, $t_\beta = 10$, $c_{\beta-\alpha} = 0.2$, $m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$

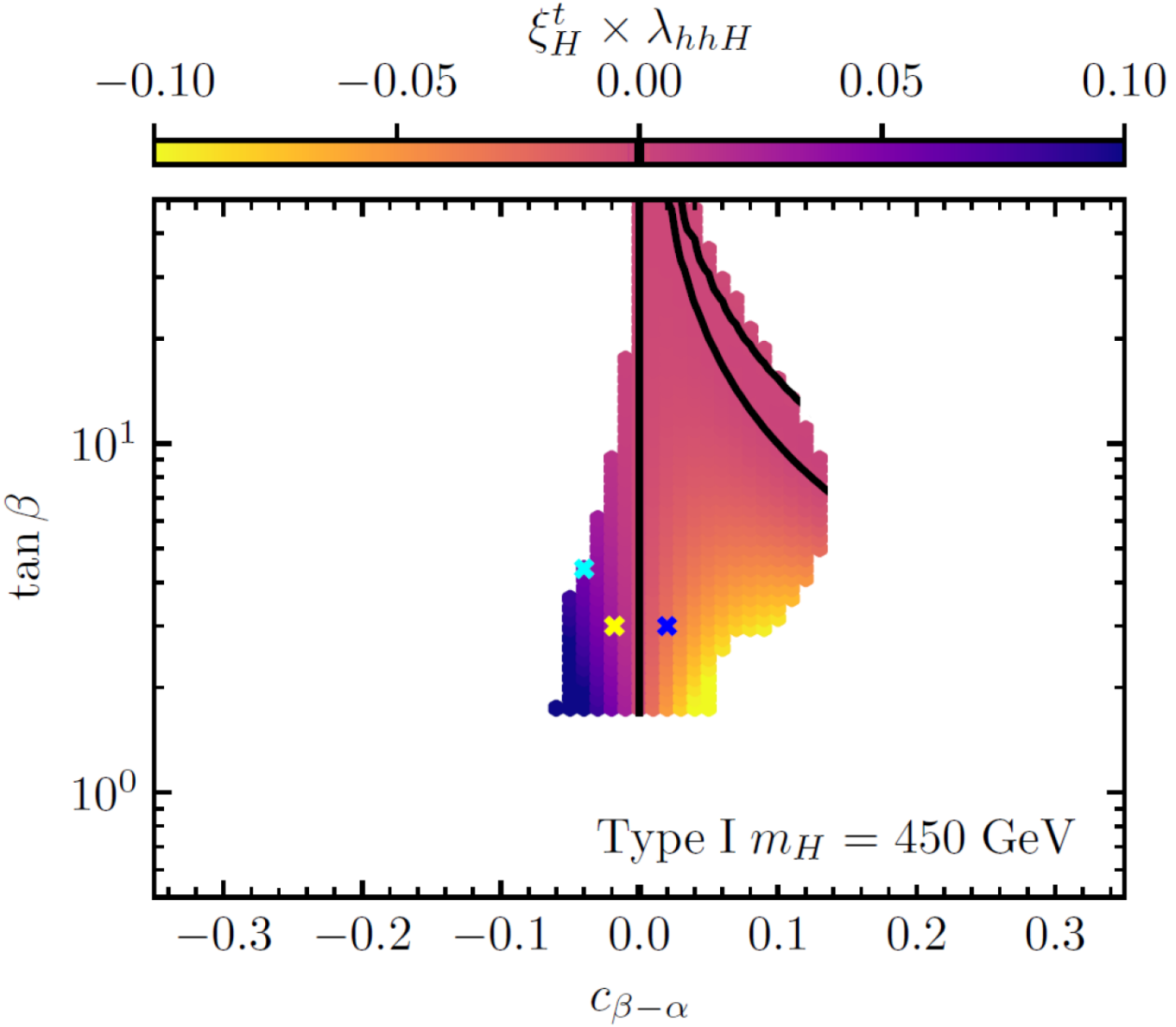




$\Rightarrow$ binning of 50 GeV applied (realistic?) $\Rightarrow$ access to $\xi_H^t \times \lambda_{hhH}$?

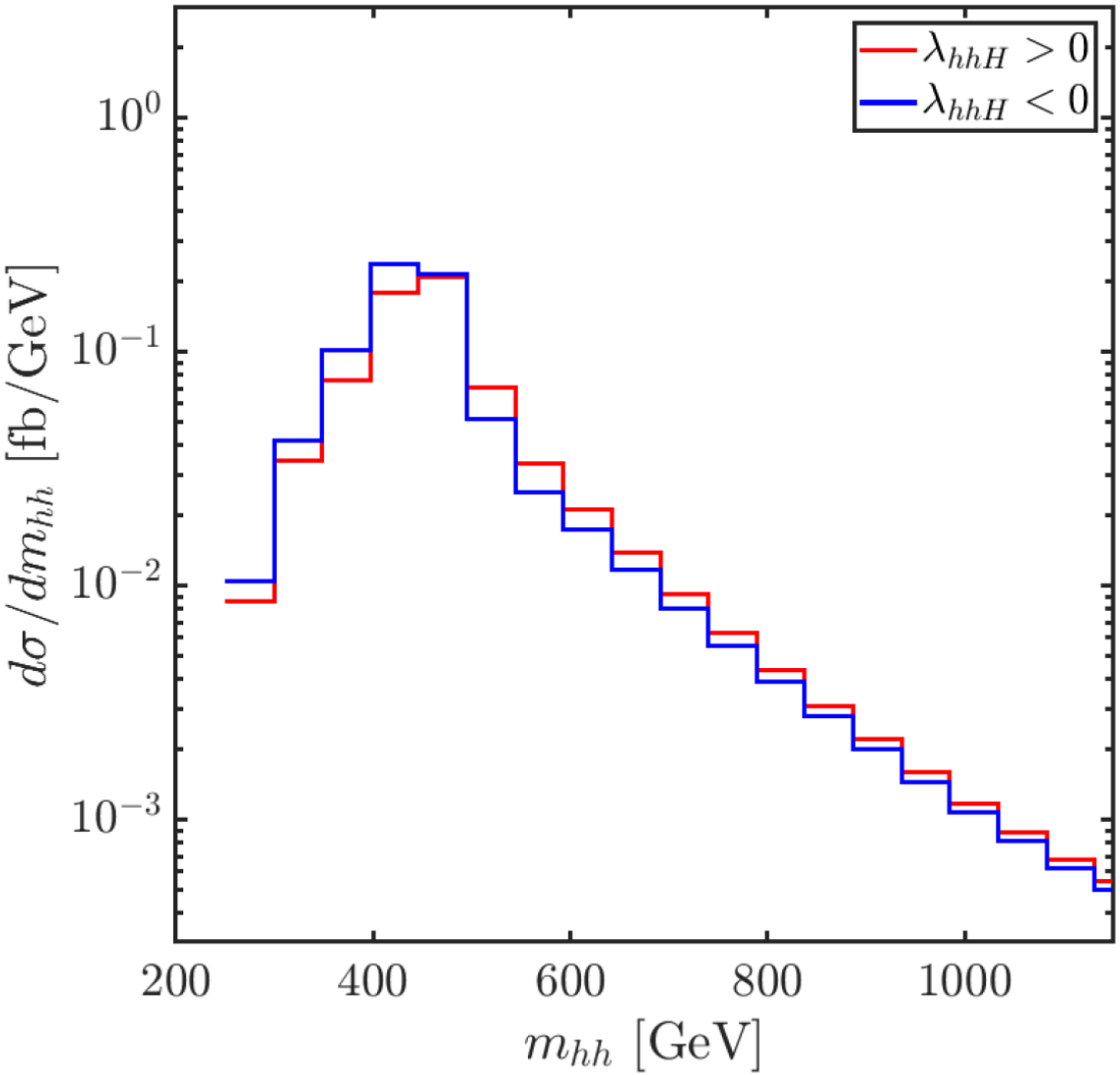
Parameter plane to train the NN:

[*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]

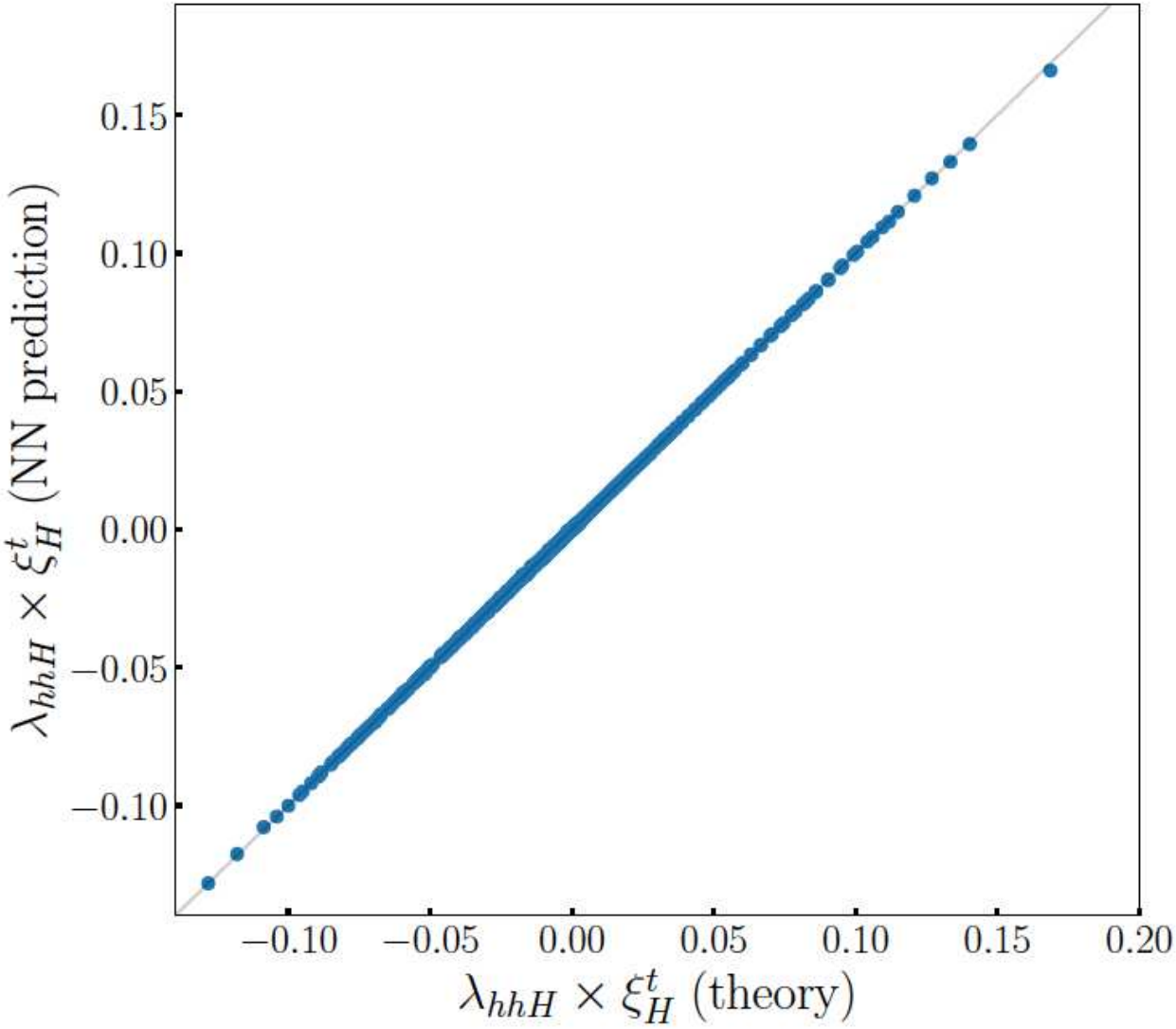


NN set-up:

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

Train with the correct m_{hh} distributions: $\Rightarrow$ perfect result

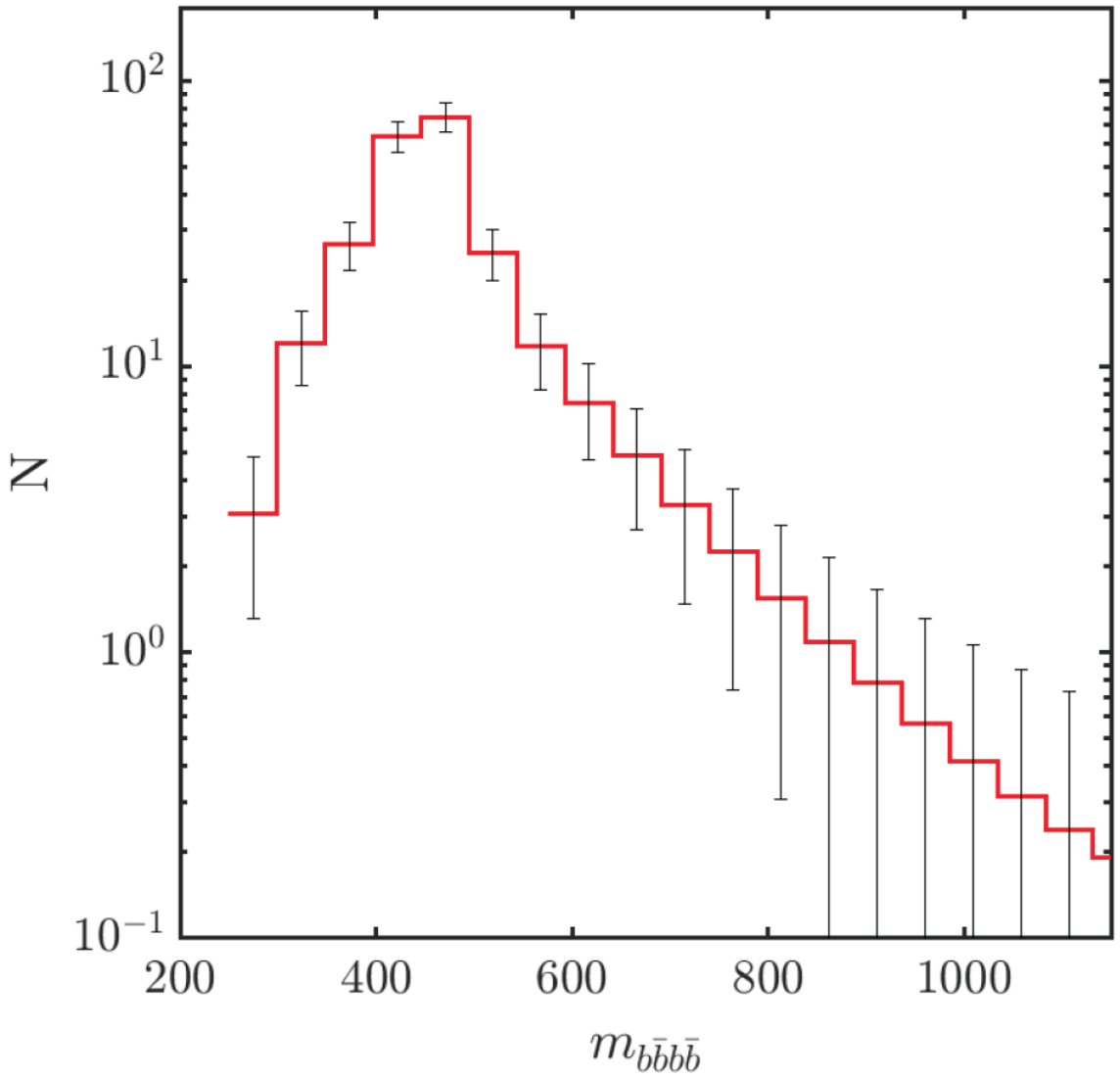
[M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]



$\Rightarrow$ but not realistic . . .

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

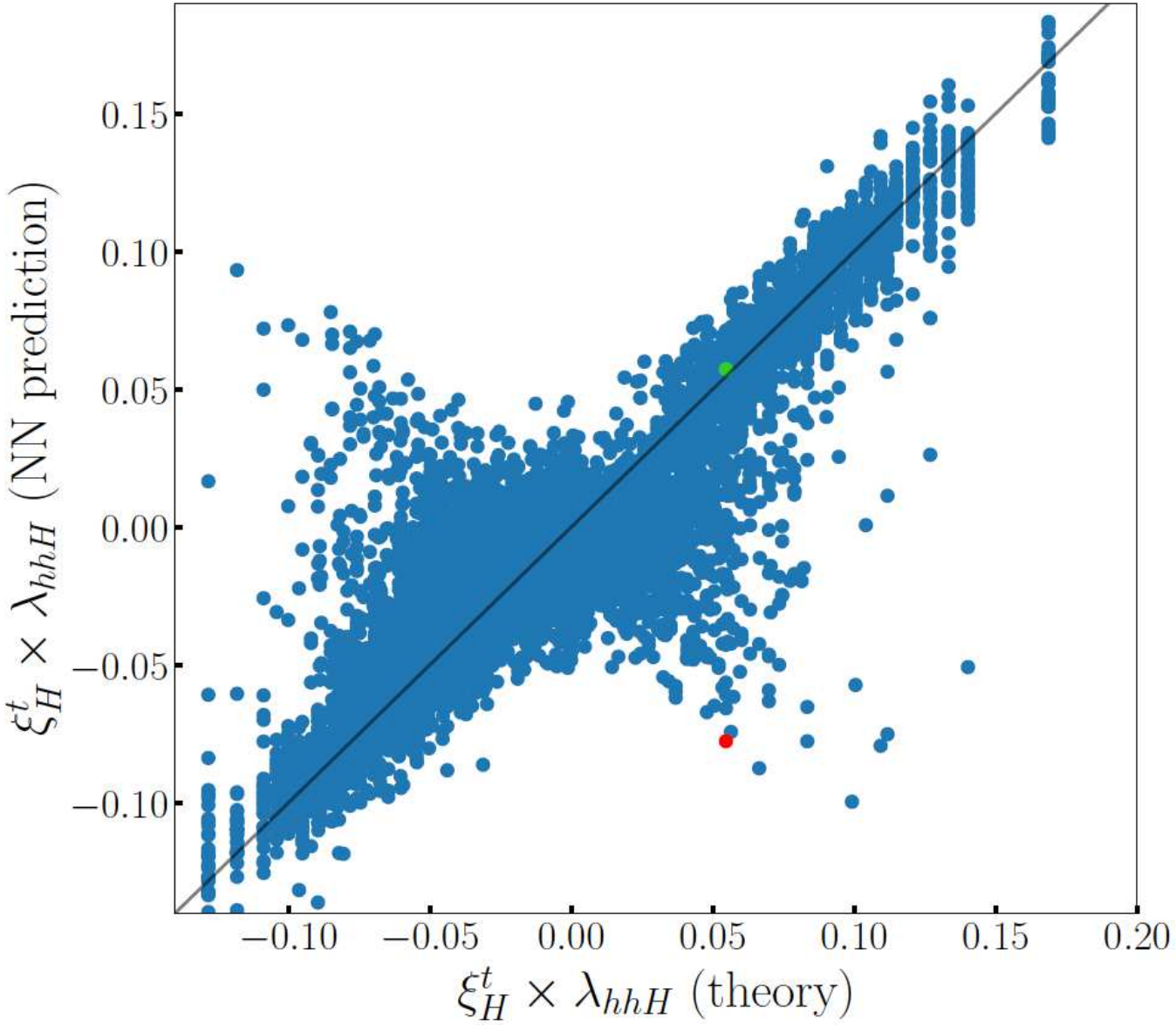
(and corr. exp. efficiencies) [*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



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

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

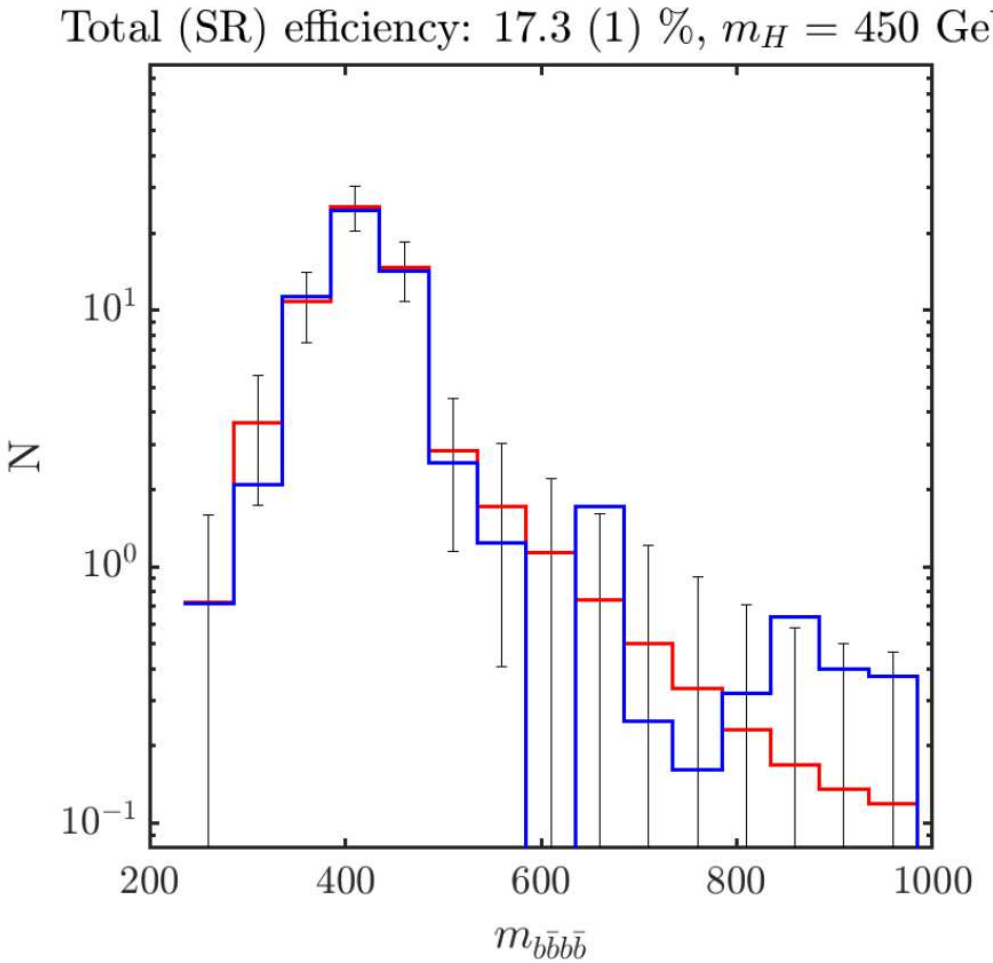
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



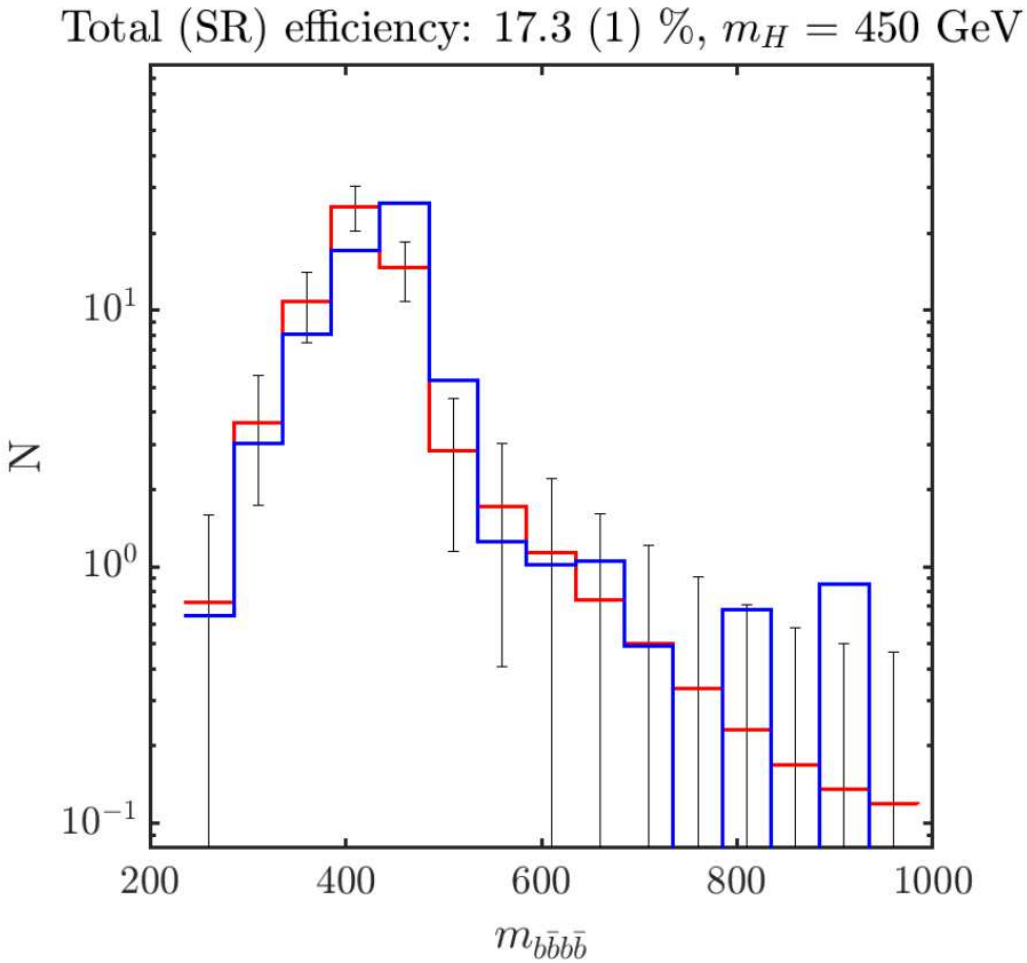
"Realistic" determination of $\xi_H^t \times \lambda_{hhH}$:

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

"good" point



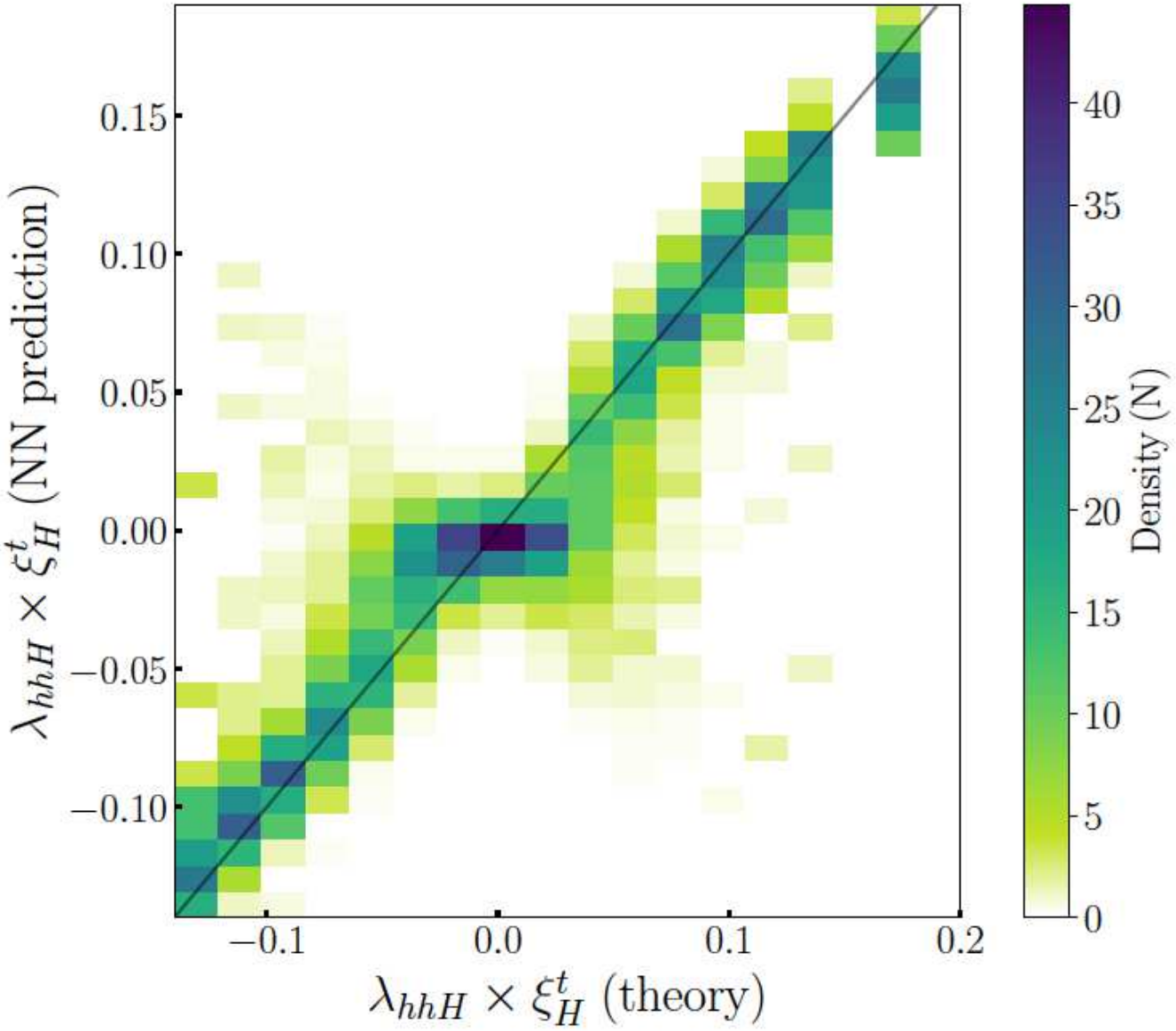
"bad" point



$\Rightarrow$ "good" point much more likely than "bad" points

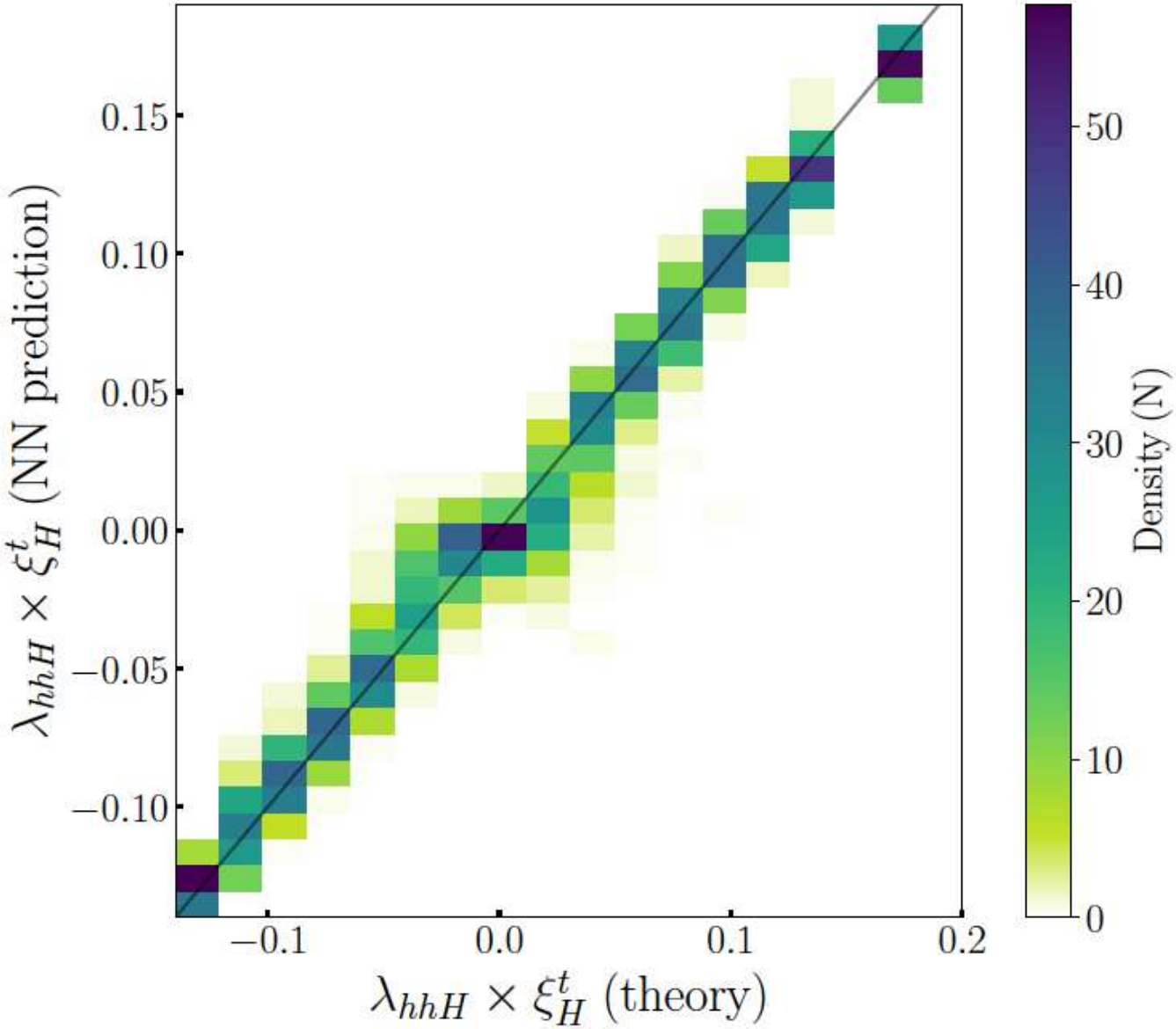
"Realistic" determination of $\lambda_{hhH} \times \xi_H^t$:

[*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*]



4. Conclusions

- Tripe Higgs couplings are in the focus of current and future colliders
  $\Rightarrow$ focus so far 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: λ_{hhH}, ...

  $\Rightarrow$ Both can have a strong impact on $\sigma(gg \to hh)$ and m_{hh}

- BSM model: 2HDM: spectrum: h, H, A, $H^\pm$ with λ_{hhh}, λ_{hhH}, ...
  $\Rightarrow$ large one-loop corrections to κ_λ of 100% ... 1000%

- Experimental searches for resonant di-Higgs production:

  $\Rightarrow$ exp. analyses leave out interferences with non-res. diagrams
  $\Rightarrow$ strong impact on m_{hh} $\Rightarrow$ results not reliable

- Access to $\xi_H^t \times \lambda_{hhH}$ at the HL-LHC:

  interference of res. H with non-res. diagrams $\Rightarrow$ peak-dip structure
  $\Rightarrow$ diluted by smearing (15%) and binning (50 GeV)

- Solution: deep NN trained on realistic set of m_{hh}'s
  $\Rightarrow$ biggest challenge: statistical uncertainty in m_{hh}
  $\Rightarrow$ taken into account, incl. exp. efficiencies for $hh \to b\bar{b}b\bar{b}$
  $\Rightarrow$ NN analysis shows remarkable sensitivity
  $\Rightarrow$ extraction of $\xi_H^t \times \lambda_{hhH}$ possible


Further Questions?