
I FOUND THE HUGS BISON.

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BSM Higgs Lecture

Sven Heinemeyer, IFT (CSIC, Madrid)

Daejeon, 09-10/2025

1. The SM Higgs & Motivation for BSM Higgs
2. BSM Higgs sectors: RxSM, 2HDM, N2HDM, MSSM . . .
3. BSM Higgs sectors: collider phenomenology & more
4. Anomalies and possible explanations

BSM Higgs Lecture

BSM Higgs sectors: collider phenomenology & more

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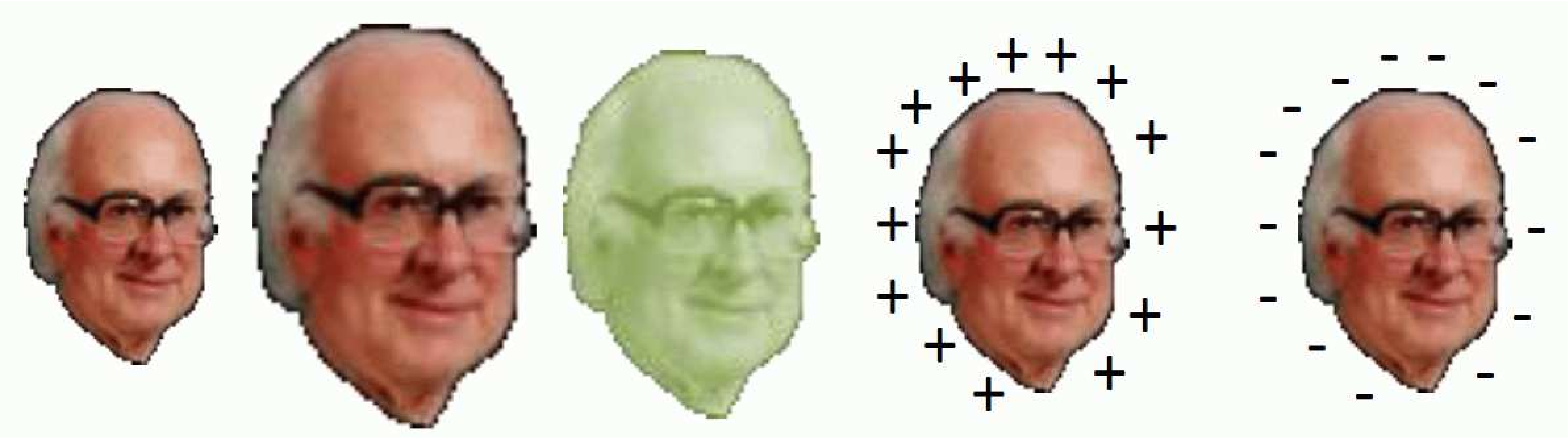
1. Heavy BSM Higgs searches at the LHC
2. Triple Higgs Couplings (THCs) at the (HL-)LHC
3. m_{hh} measurements at the HL-LHC
4. BSM THCs at the ILC
5. Measurements of BSM THCs
6. FOEWPT and GWs in the 2HDM

1. Heavy BSM Higgs searches at the LHC



The MSSM Higgs sector:

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$ Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$t_\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (t_\beta + \cot\beta)$$

Search for the MSSM Higgs bosons:

Smart choice of MSSM parameters?

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

[*E. Bagnaschi, H. Bahl, E. Fuchs, T. Hahn, S.H., S. Liebler, S. Patel, P. Slavich, T. Stefaniak, C. Wagner, G. Weiglein '18*]

1. M_h^{125} scenario: 2HDM-like model
2. $M_h^{125}(\tilde{\tau})$ scenario: light staus: $h \to \gamma\gamma$, $H/A \to \tilde{\tau}\tilde{\tau}$
3. $M_h^{125}(\tilde{\chi})$ scenario: light EW-inos: $H/A \to \tilde{\chi}_i^0\tilde{\chi}_j^0, \tilde{\chi}_k^\pm\tilde{\chi}_l^\mp$
4. M_h^{125} (alignment) scenario: h SM-like for very low M_A
5. M_H^{125} scenario: $M_H \sim 125$ GeV, all Higgses light
6. $M_{h_1}^{125}$ (CPV) scenario: complex phases, h_2-h_3 interference

Additional set for very heavy scalar tops:

Set of benchmarks for low $\tan\beta$

[*H. Bahl, S. Liebler, T. Stefaniak '19*]

– use 2HDM as low-energy model

– (mainly) EFT calculation, RGE running to M_{SUSY}

– implemented in FeynHiggs 2.16.0

7. $M_{h,\mathsf{EFT}}^{125}$ scenario: all SUSY particles very heavy

8. $M_{h,\mathsf{EFT}}^{125}(\tilde{\chi})$ scenario: SUSY particles very heavy, but light EW-inos

Data to be taken into account:

- Higgs boson mass (LHC) ⇒ FeynHiggs

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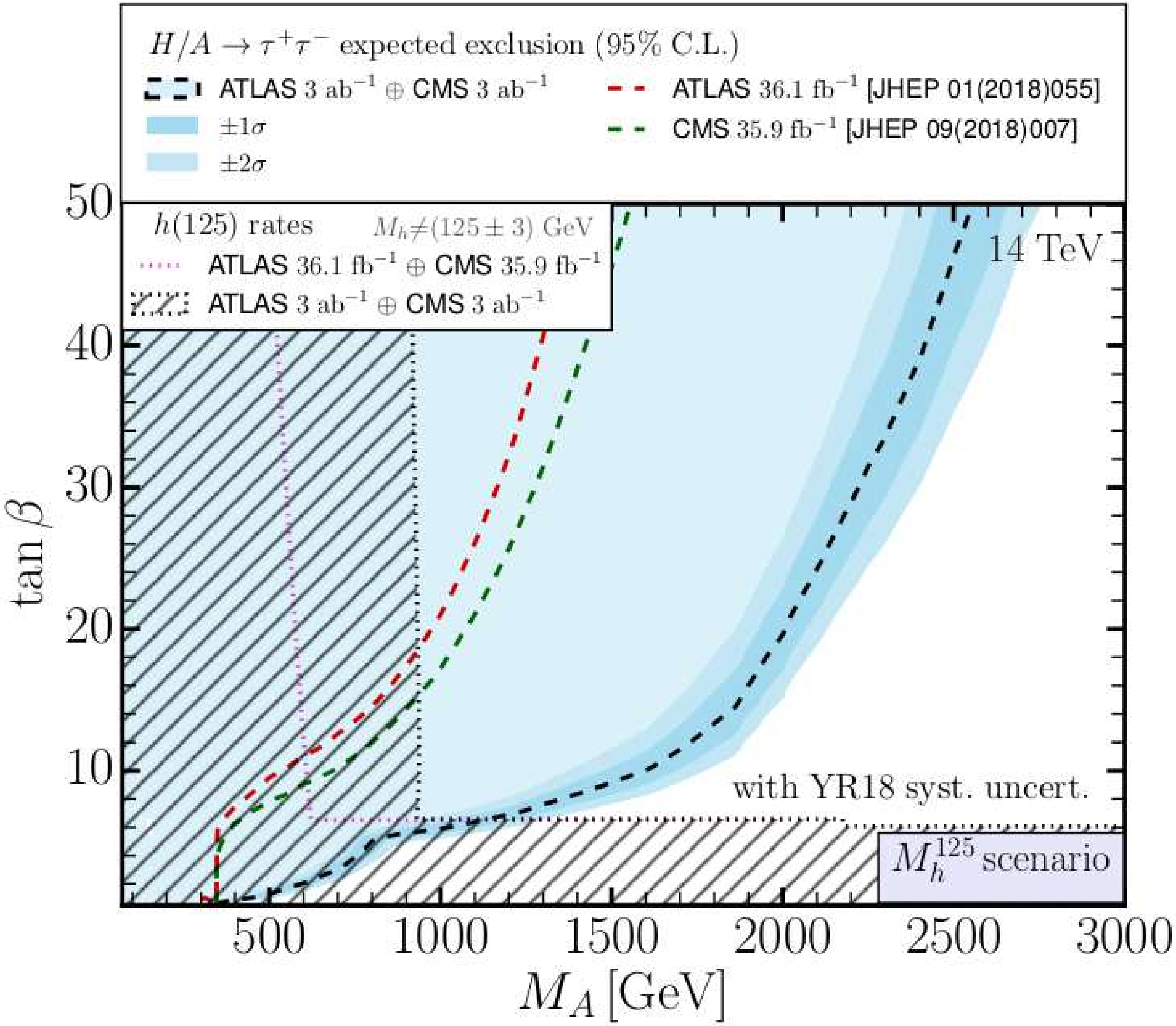
Data on purpose not to be taken into account:

- electroweak precision data
- flavor data
- astrophysical data (DM properties)

HL-LHC reach in M_h^{125} scenario

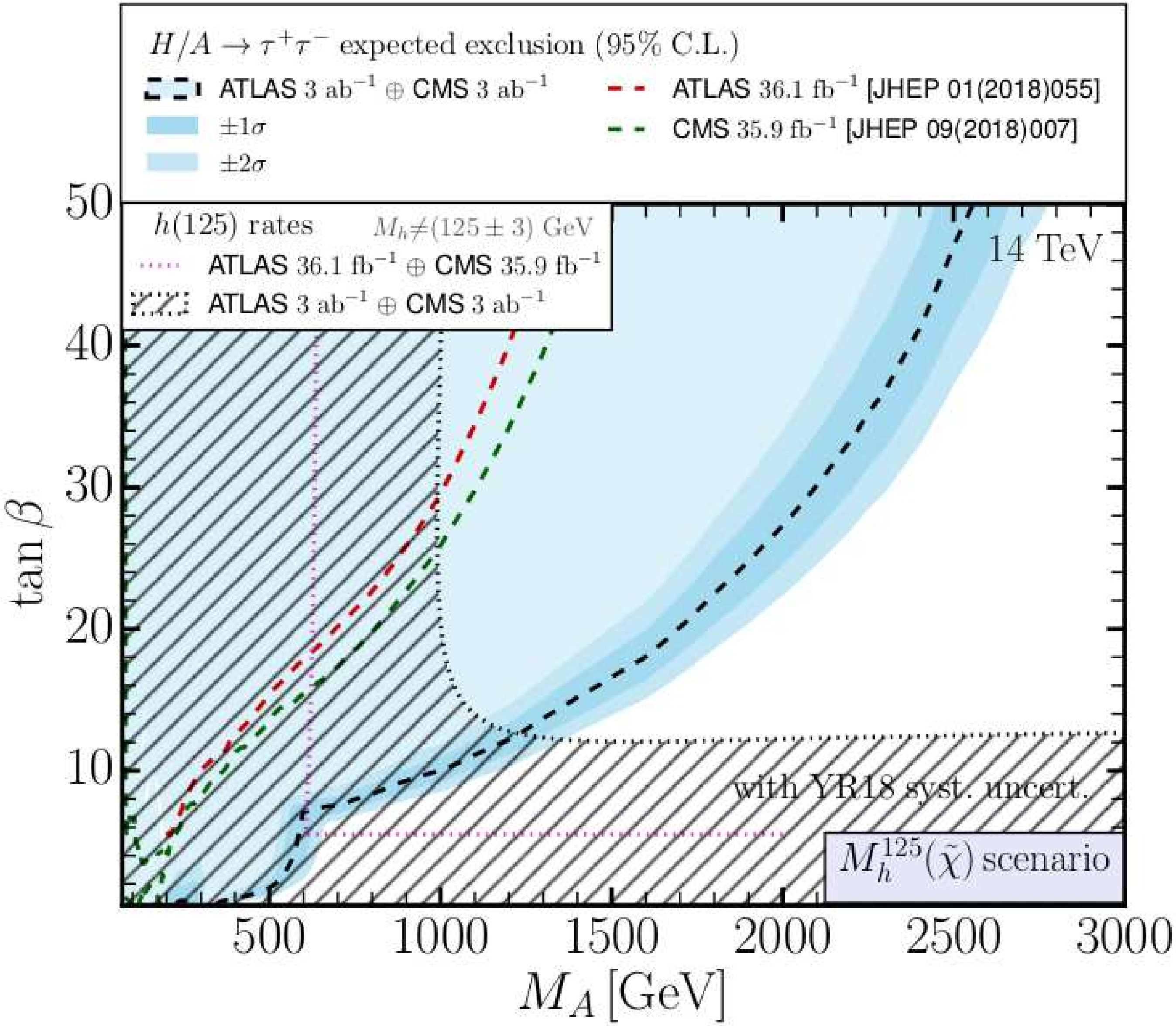
[H. Bahl et al., '20]



⇒ direct and indirect measurements: $M_A \gtrsim$ 1200 GeV

HL-LHC reach in $M_h^{125}(\tilde{\chi})$ scenario

[H. Bahl et al., '20]

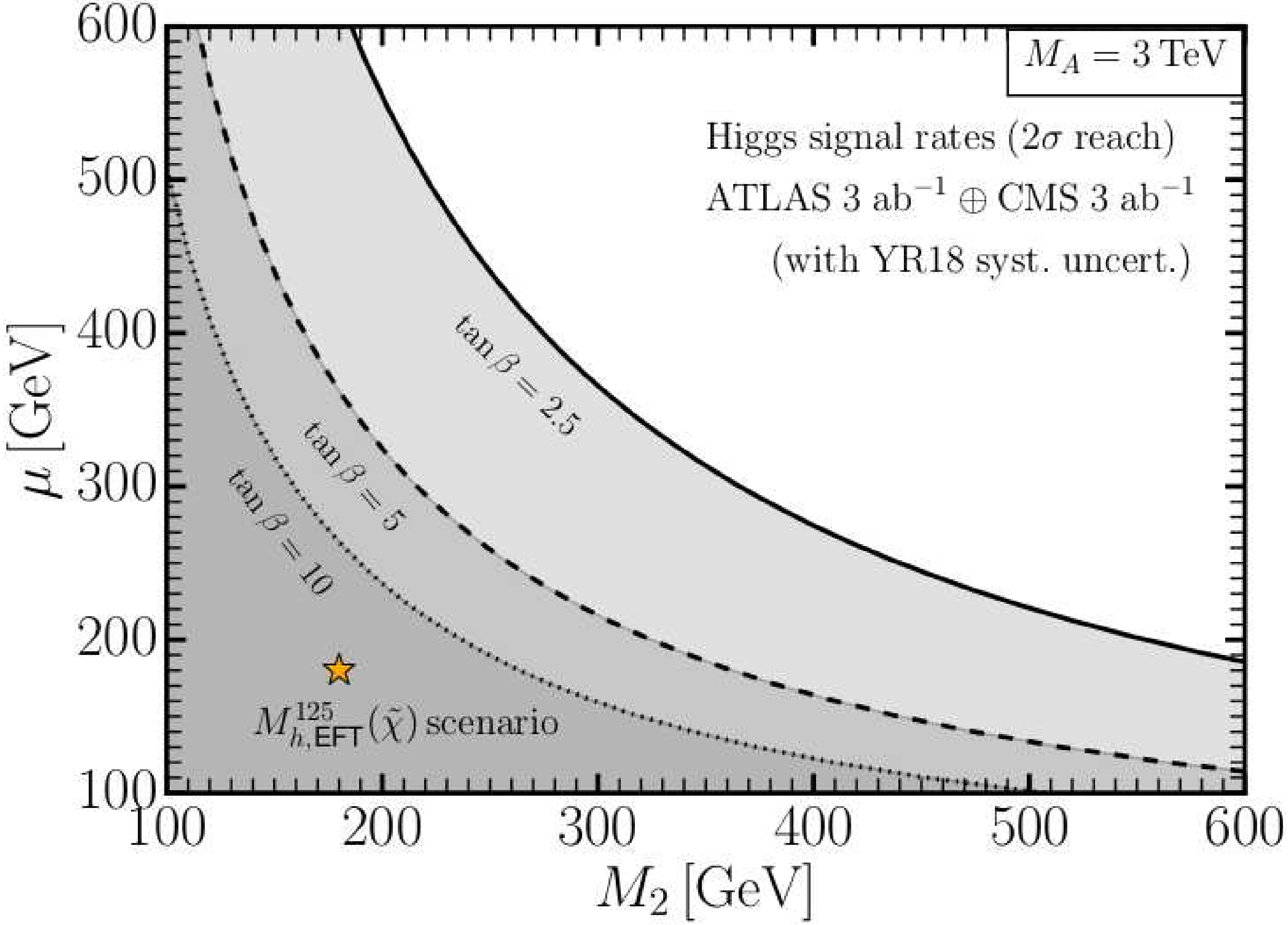


⇒ direct and indirect measurements: $M_A \gtrsim 1200$ GeV

Indirect HL-LHC reach in $M_{h,\mathrm{EFT}}^{125}(\tilde{\chi})$ scenario

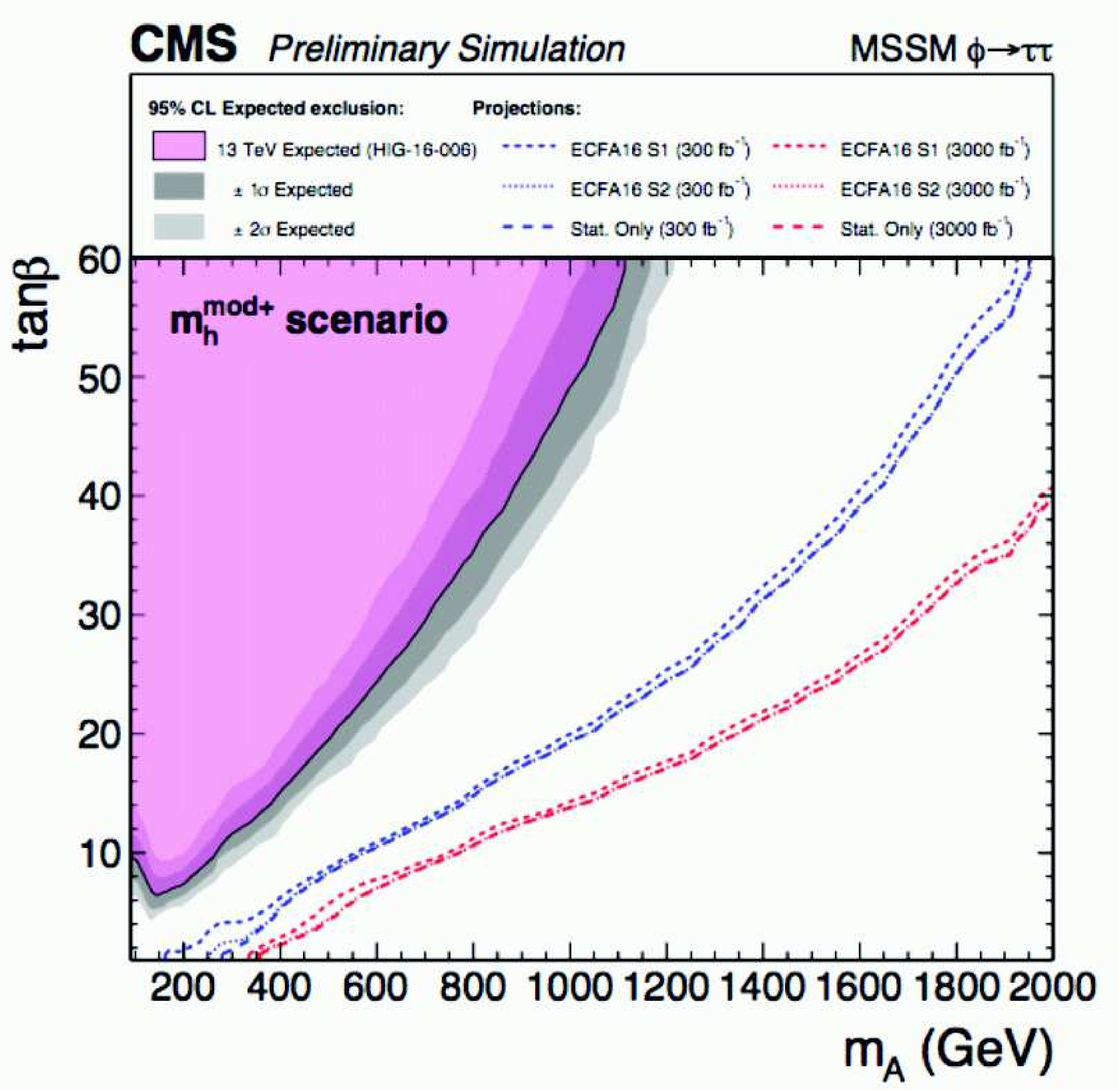
[*H. Bahl et al., '20*]

⇒ reach for charginos (mainly) via $h \to \gamma\gamma$:



⇒ strong reach for low $\tan\beta$

Prospects for e^+e^- colliders

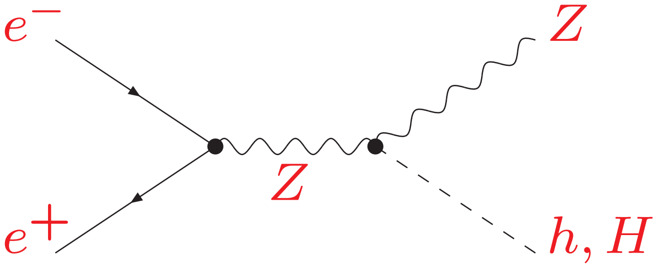


⇒ strong (HL-)LHC limits

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

Search for neutral SUSY Higgs bosons:

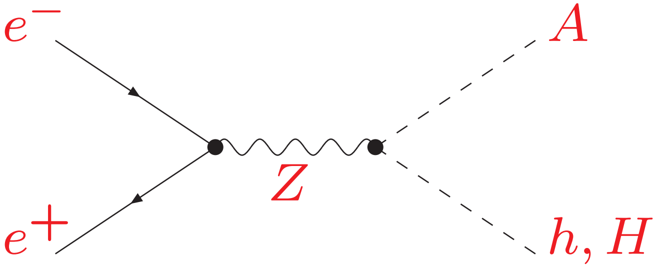
$e^+e^- \to Zh, ZH$



$$\sigma_{hZ} \approx \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HZ} \approx \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$e^+e^- \to Ah, AH$



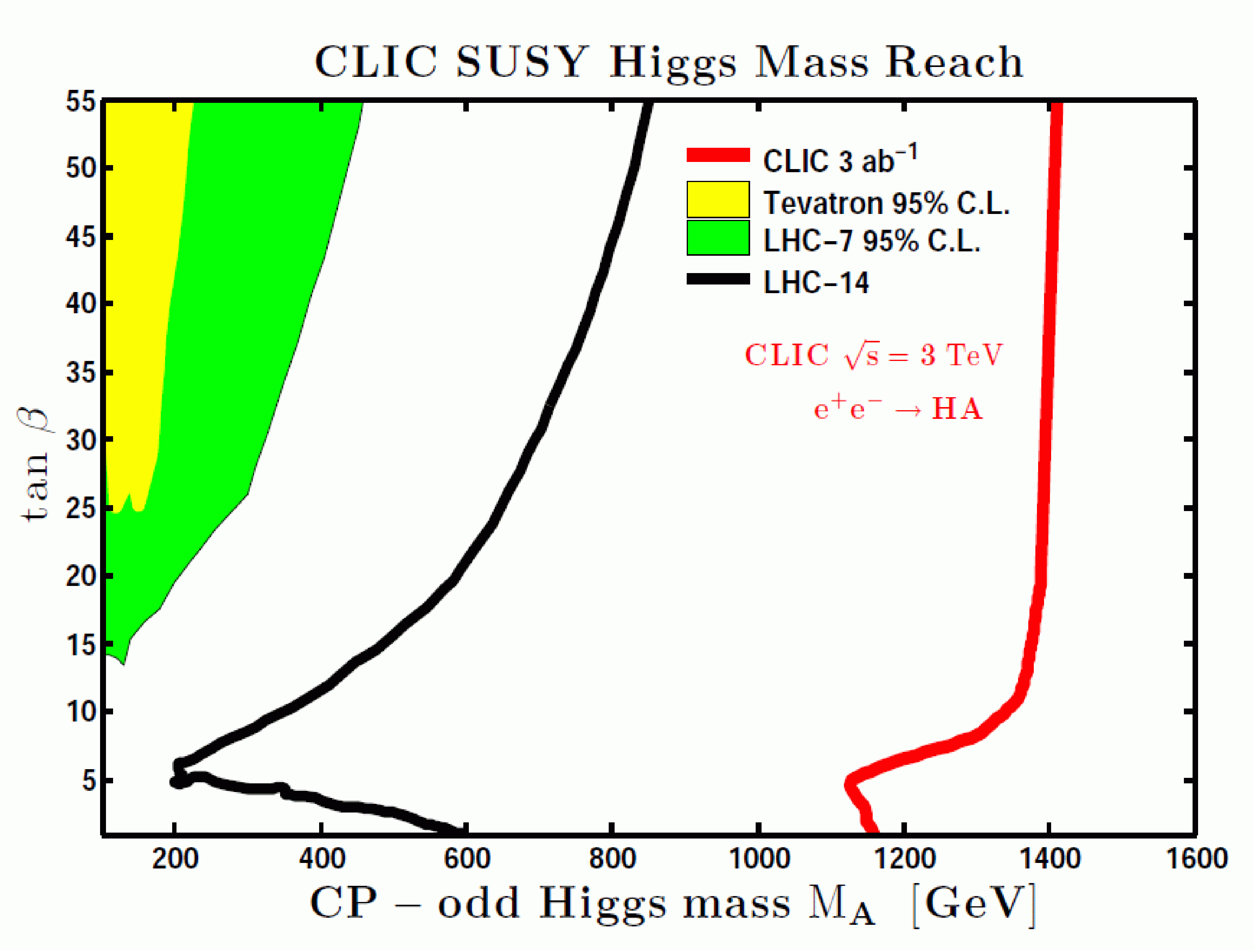
$$\sigma_{hA} \propto \cos^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$$\sigma_{HA} \propto \sin^2(\beta - \alpha_{\text{eff}})\sigma_{hZ}^{\text{SM}}$$

$\Rightarrow$ only pair production of heavy Higgs bosons! reach: $M_A \lesssim \sqrt{s}/2$

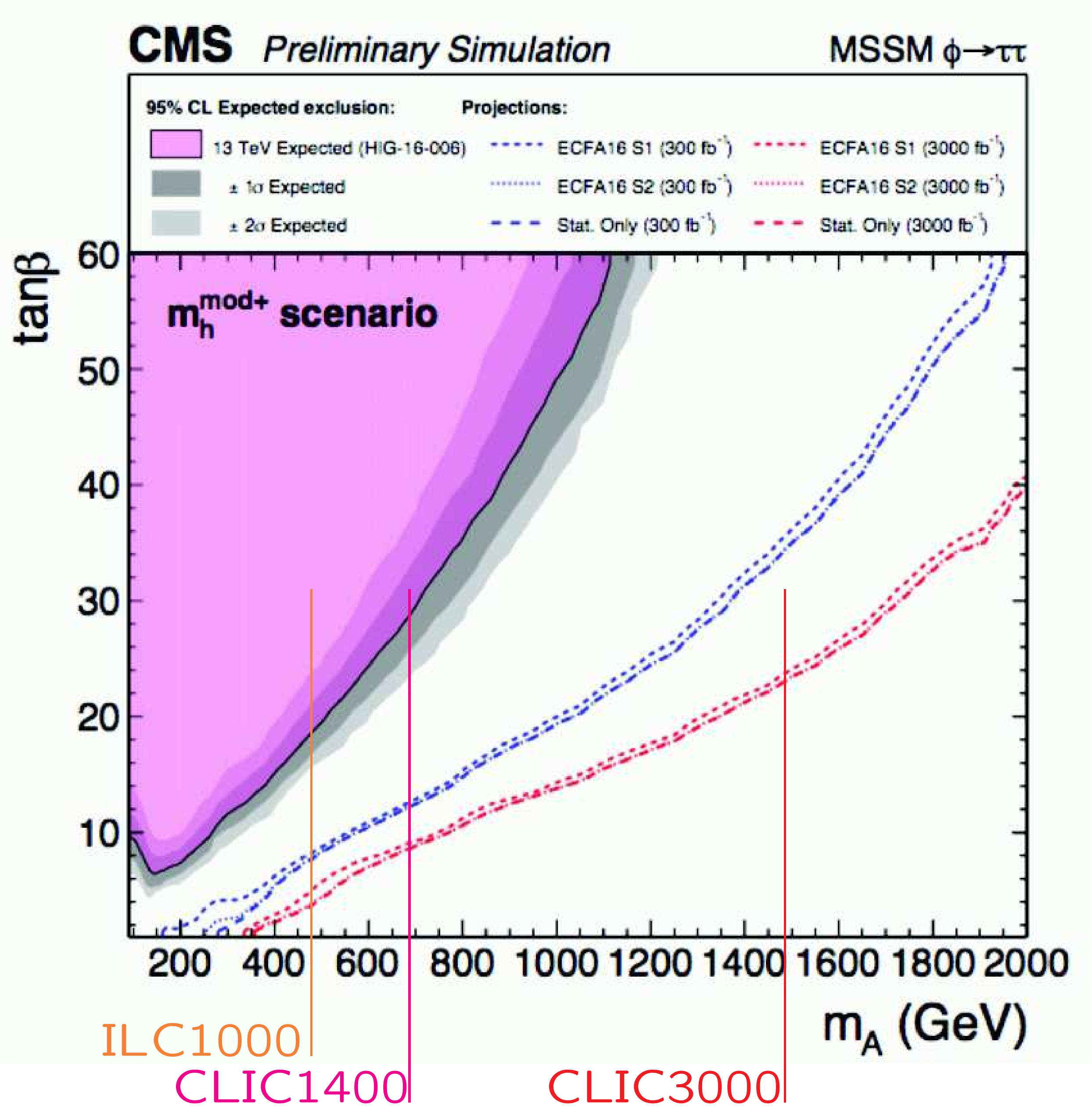
CLIC reach:

[*L. Linssen et al. '12*]



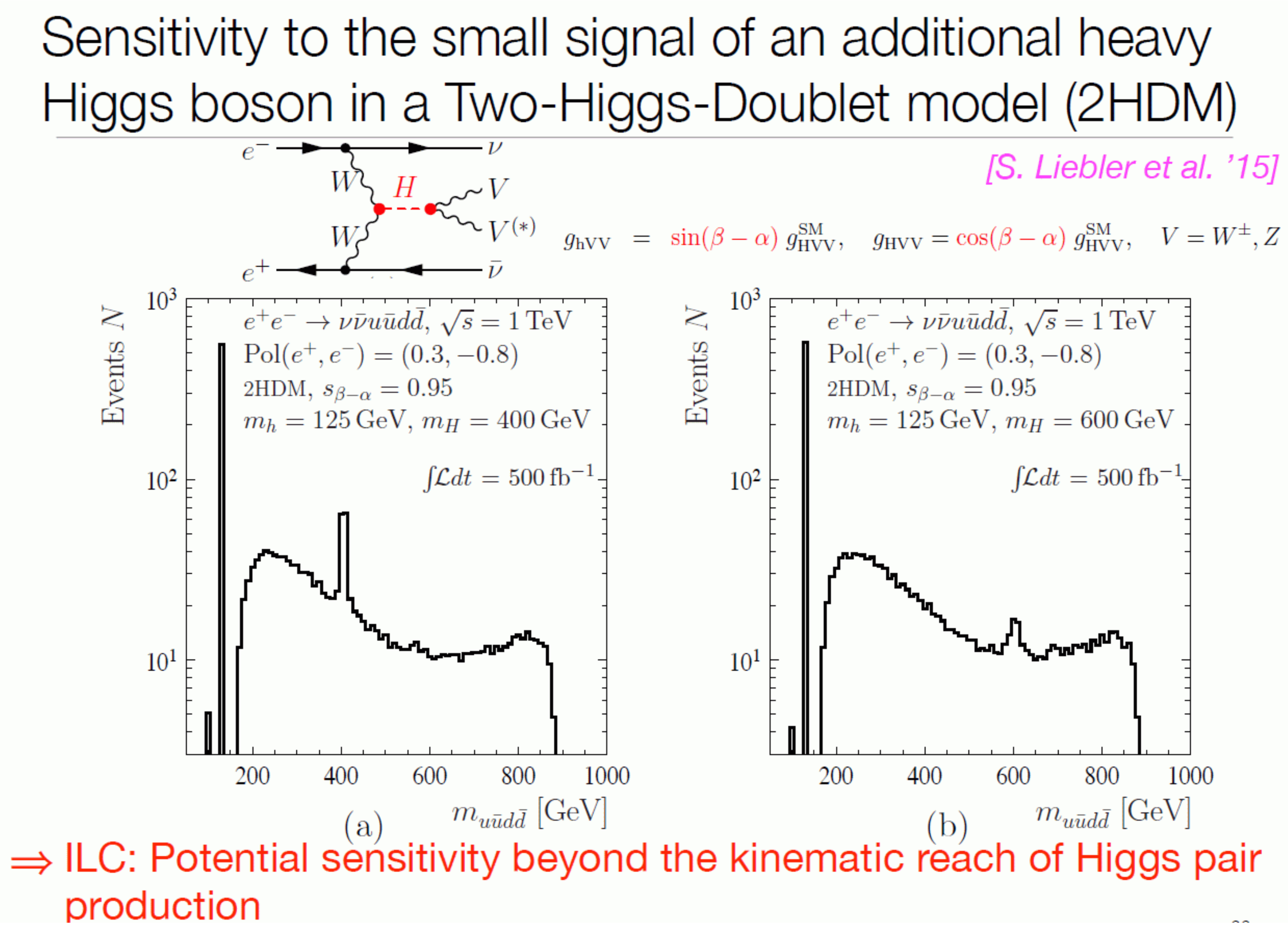
⇒ close to kinematic limit

“Simple” LC reach in the MSSM (neglecting $t\bar{t}$ final states)



⇒ unique opportunities!

Single heavy Higgs production beyond kinematic reach:



Sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)

[S. Liebler et al. ’15]

$$g_{\mathrm{hVV}} \;=\; \sin(\beta-\alpha)\; g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad g_{\mathrm{HVV}} = \cos(\beta-\alpha)\; g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad V = W^{\pm}, Z$$

⇒ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

[*Taken from G. Weiglein ’18*]

2. Triple Higgs couplings (THCs) at the (HL-)LHC

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

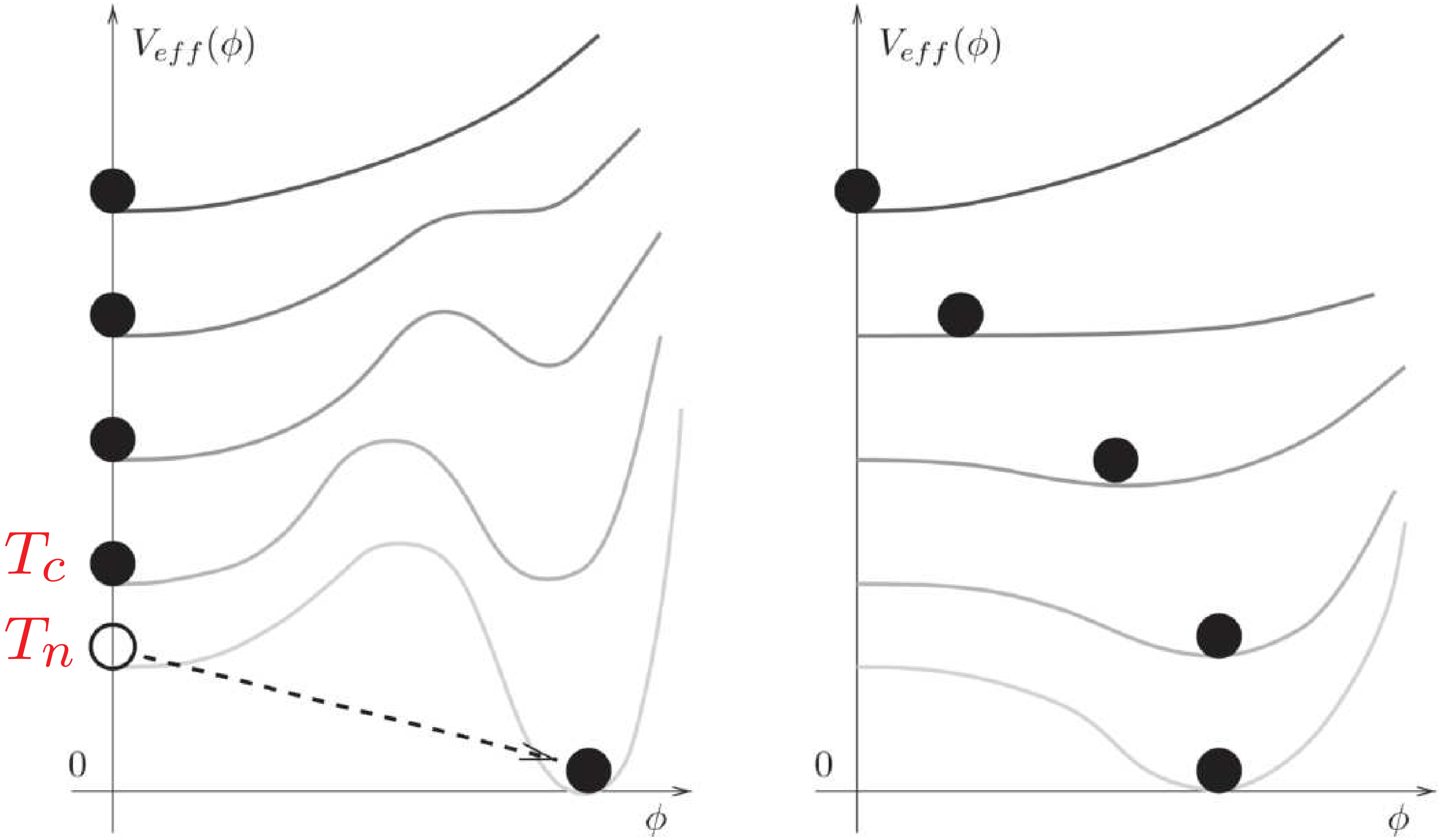
⇒ requires First Order EW Phase Transition (FOEWPT)

FOEWPT not possible in the SM ⇒ BSM Higgs sector required

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

Phase transition: BSM vs. SM

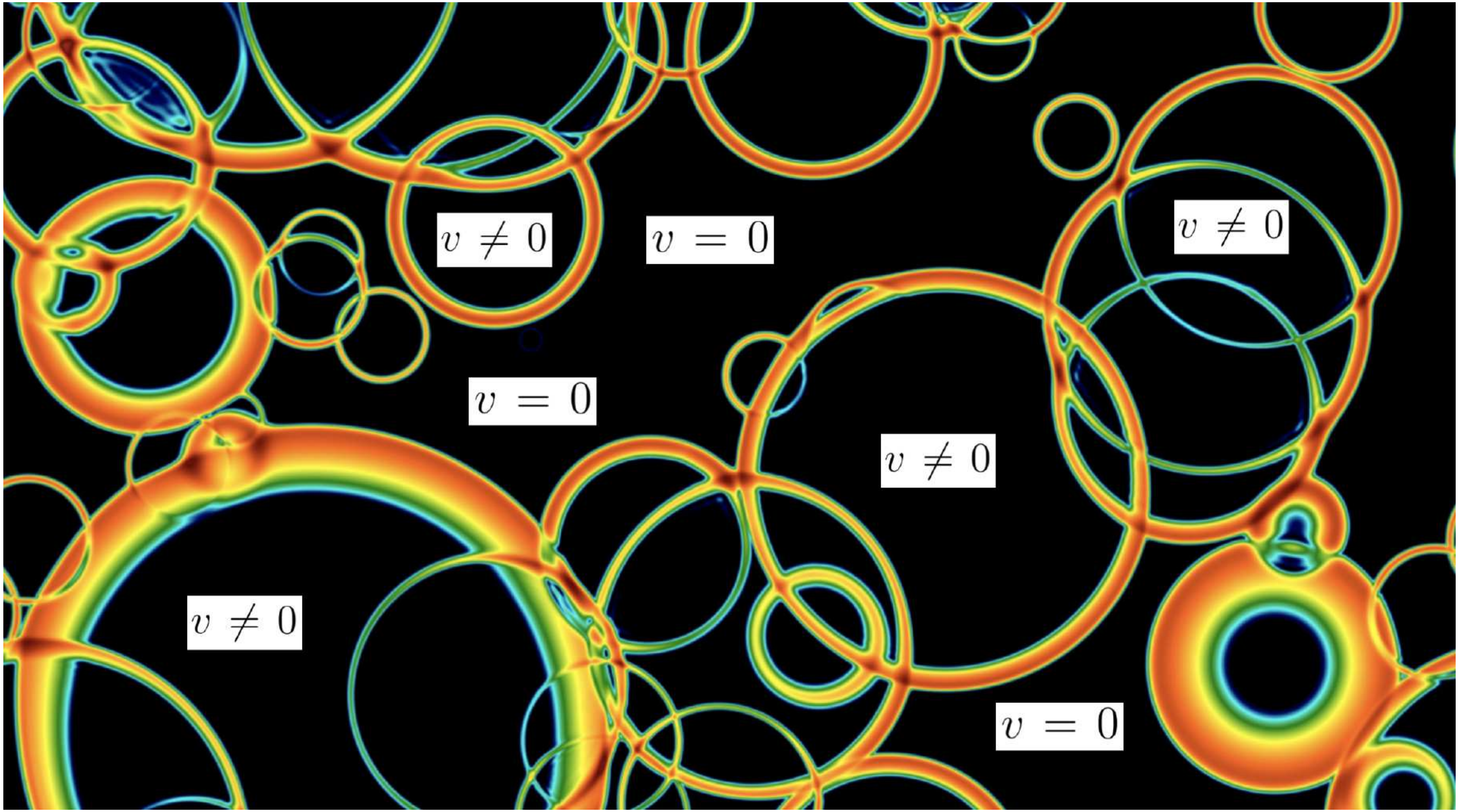
[*taken from V. A. Rubakov and D. S. Gorbunov*]



$\Rightarrow$ BSM Higgs sector required to realized FOEWPT

Bubble formation can lead to Gravitational Waves

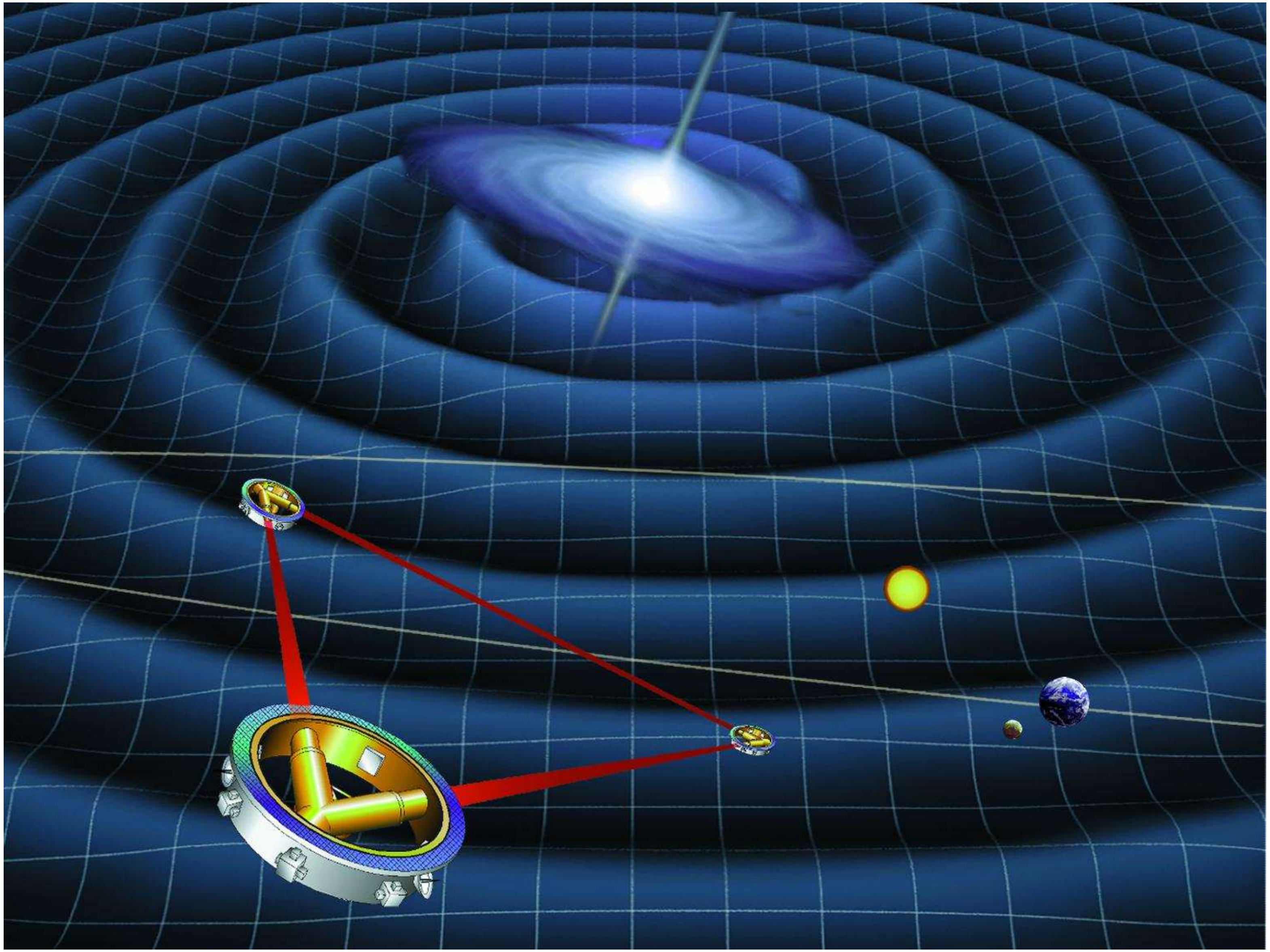
[*taken from D. Weir*]



⇒ Interesting interplay of Higgs physics and Gravitational Waves!

GW observatory: LISA

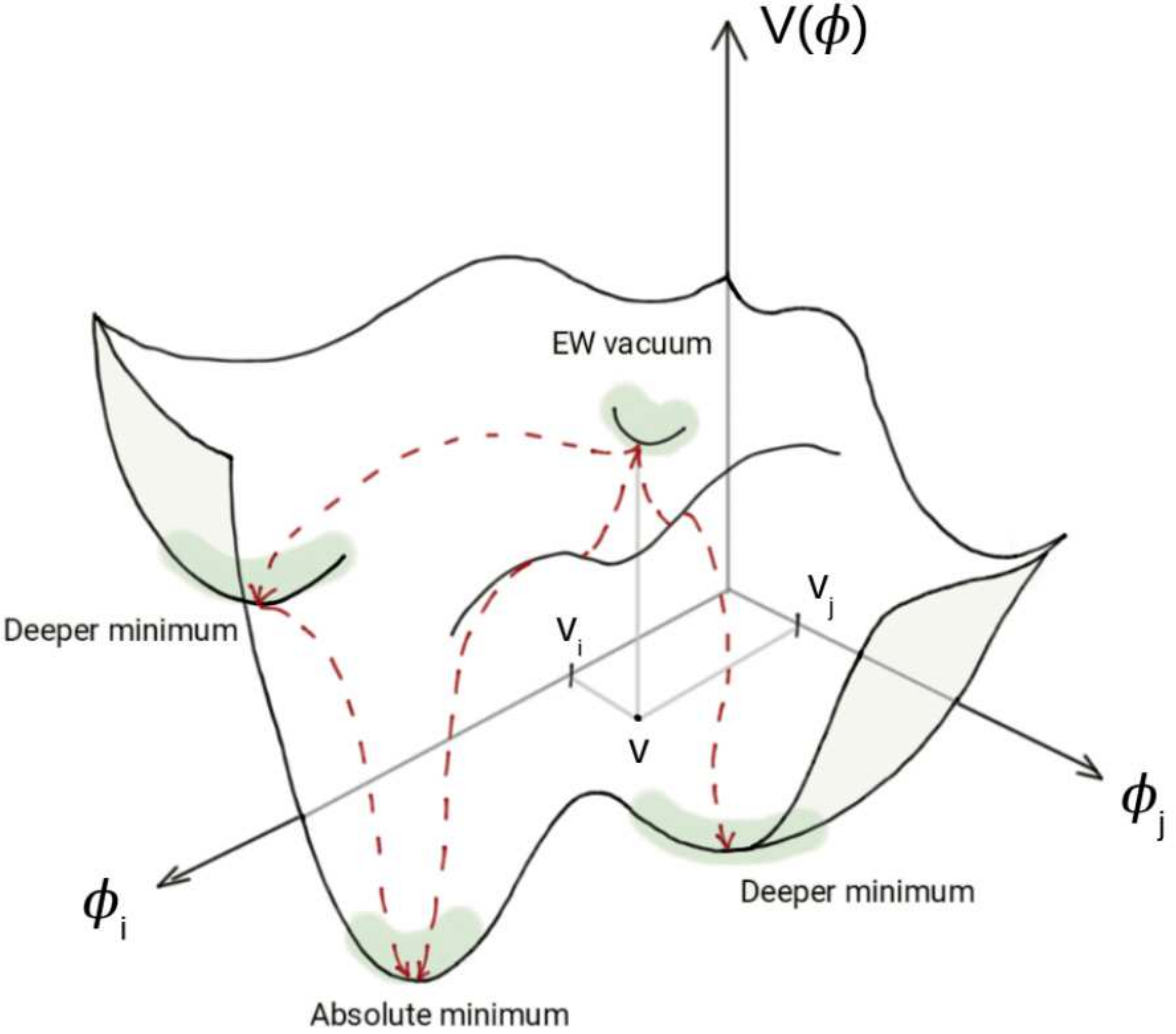
[NASA]



Approved launch date: $\sim$ 2035

BSM Higgs sectors can (should) behave very different from SM Higgs

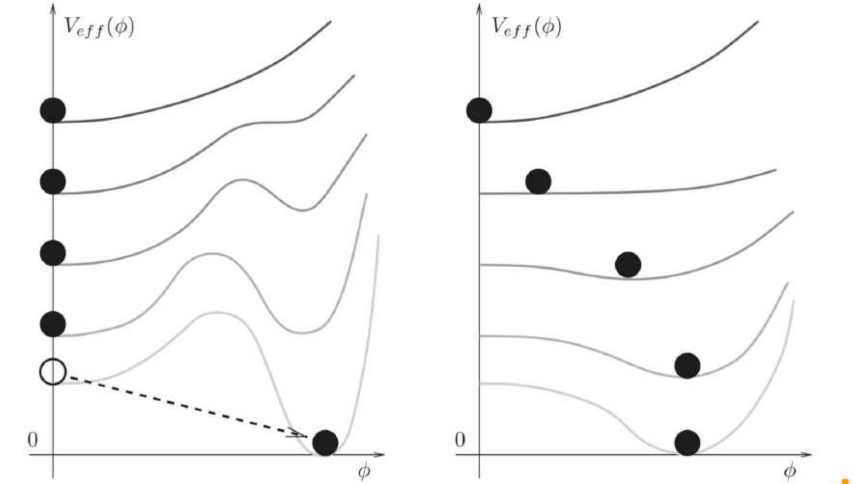
[K. Radchenko '24]



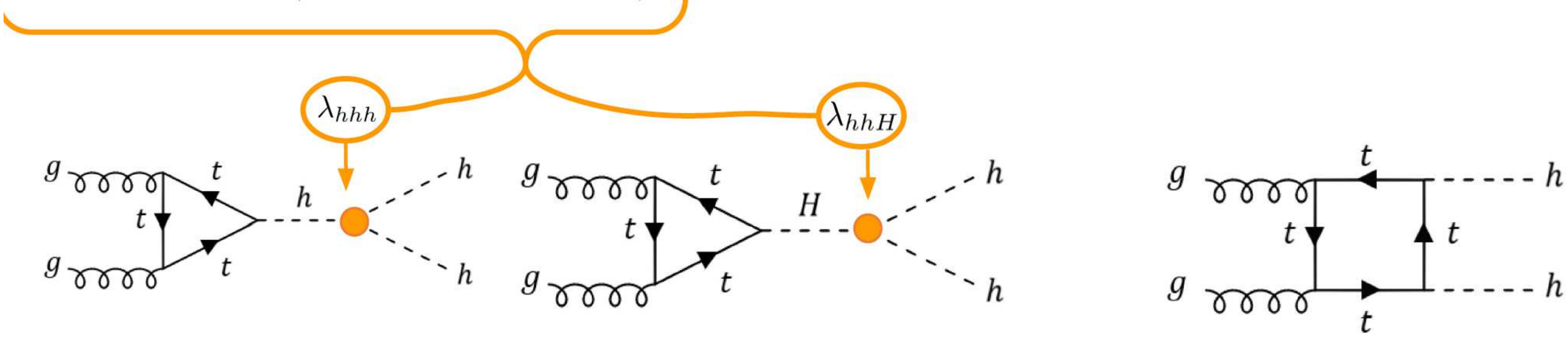
$\Rightarrow$ much more complicated structure, very^2 little known . . .

Extended Higgs sectors and Triple Higgs Couplings (THCs):

[taken from A. Verduras '24]



- THC determine the formation of the barrier
- The computation of the **EWPT dynamics is done at the one-loop level**
- To capture this effects in the di-Higgs production **we need one-loop THC**



$\Rightarrow$ Measurement of all THCs crucial!

$\Rightarrow \kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}, \quad \lambda_{hhH}, \ldots$

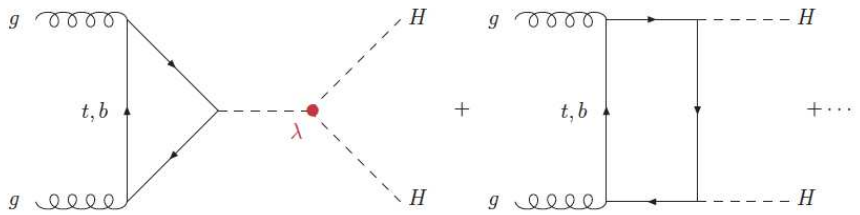
Calculation in the SM

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

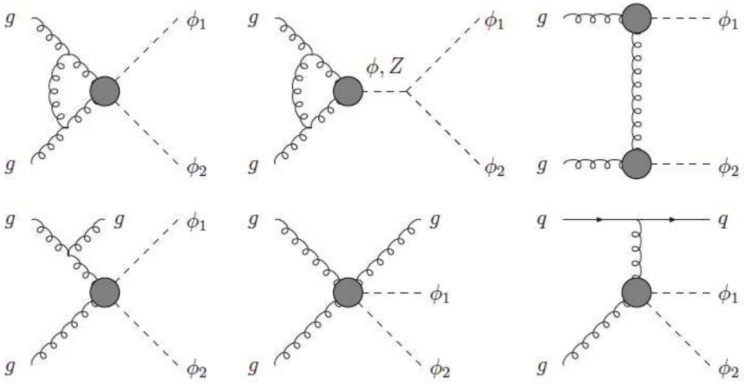
[taken from M. Spira]

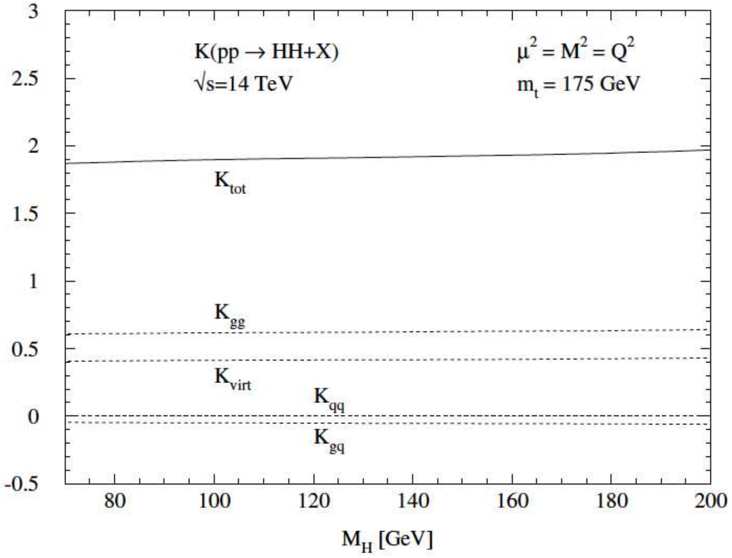
$gg \to HH$

(B)SM



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





Dawson, Dittmaier, S.

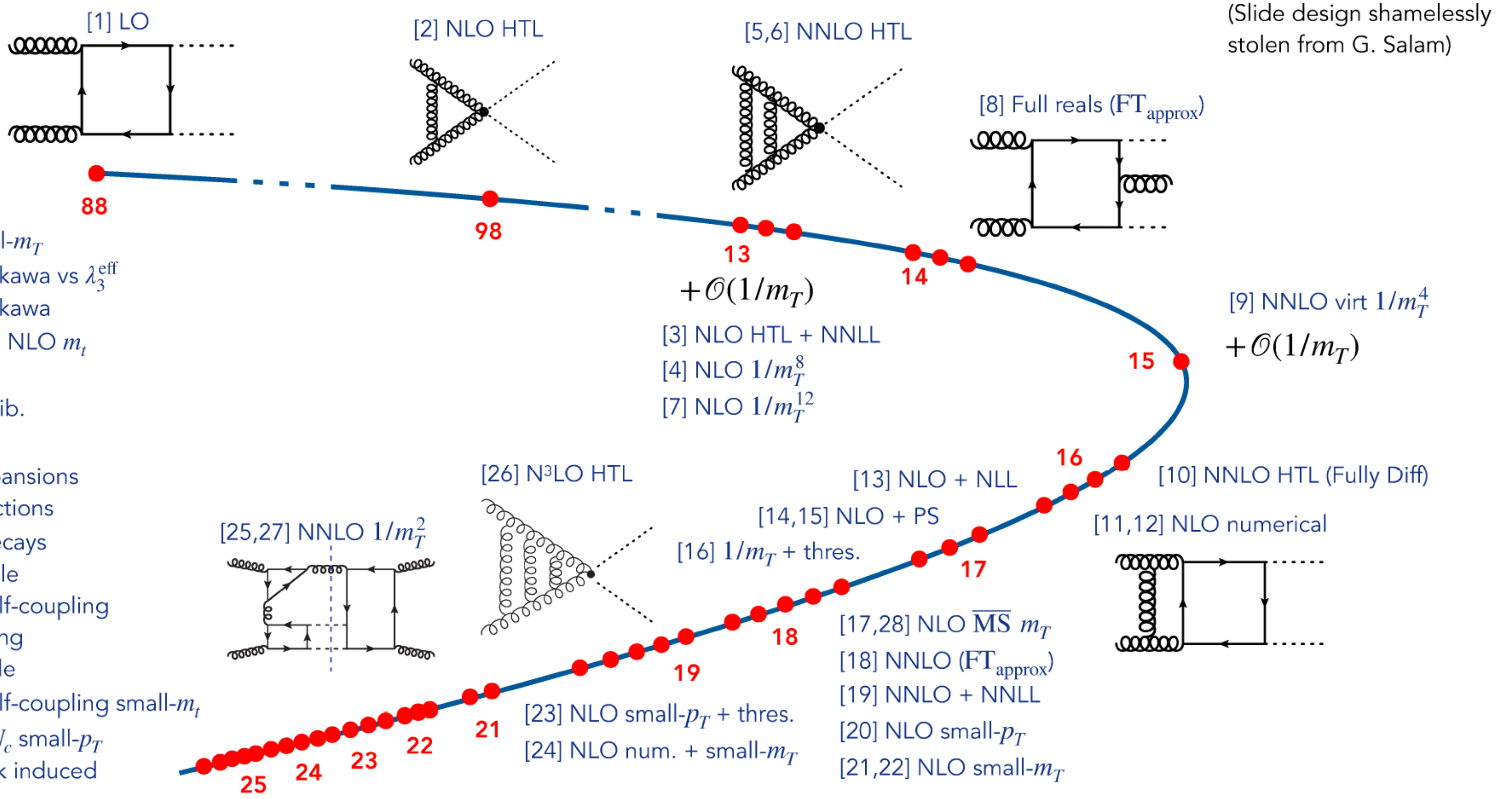
⇒ predictions "easily" available in NLO QCD (heavy top limit)

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

[taken from M. Spira]

In the SM there is much more available:

(Slide design shamelessly stolen from G. Salam)



[1] LO

[2] NLO HTL

[5,6] NNLO HTL

[8] Full reals ($\mathrm{FT}_{\mathrm{approx}}$)

$+\mathcal{O}(1/m_T)$

[3] NLO HTL + NNLL

[4] NLO $1/m_T^8$

[7] NLO $1/m_T^{12}$

[9] NNLO virt $1/m_T^4$

$+\mathcal{O}(1/m_T)$

[10] NNLO HTL (Fully Diff)

[11,12] NLO numerical

[13] NLO + NLL

[14,15] NLO + PS

[16] $1/m_T$ + thres.

[26] N³LO HTL

[25,27] NNLO $1/m_T^2$

[17,28] NLO $\overline{\mathrm{MS}}$ m_T

[18] NNLO ($\mathrm{FT}_{\mathrm{approx}}$)

[19] NNLO + NNLL

[20] NLO small-p_T

[21,22] NLO small-m_T

[23] NLO small-p_T + thres.

[24] NLO num. + small-m_T

[29] small-p_T + small-m_T
[30] EW: leading Yukawa vs λ_3^{eff}
[31] EW: leading Yukawa
[32] N^{3}LO + N^{3}LL + NLO m_t
[33] small-t
[34] NNLO: n_f contrib.
[35] EW: $1/m_T$
[36] NLO comb expansions
[37] NLO EW corrections
[38] NLO + $b\bar{b}\gamma\gamma$ decays
[39] NNLO: reducible
[40] EW: Yukawa/self-coupling
[42] EW: self-coupling
[43] EW: Factorizable
[44] EW: Yukawa/self-coupling small-m_t
[45] NNLO: Large-N_c small-p_T
[46] EW: Light quark induced

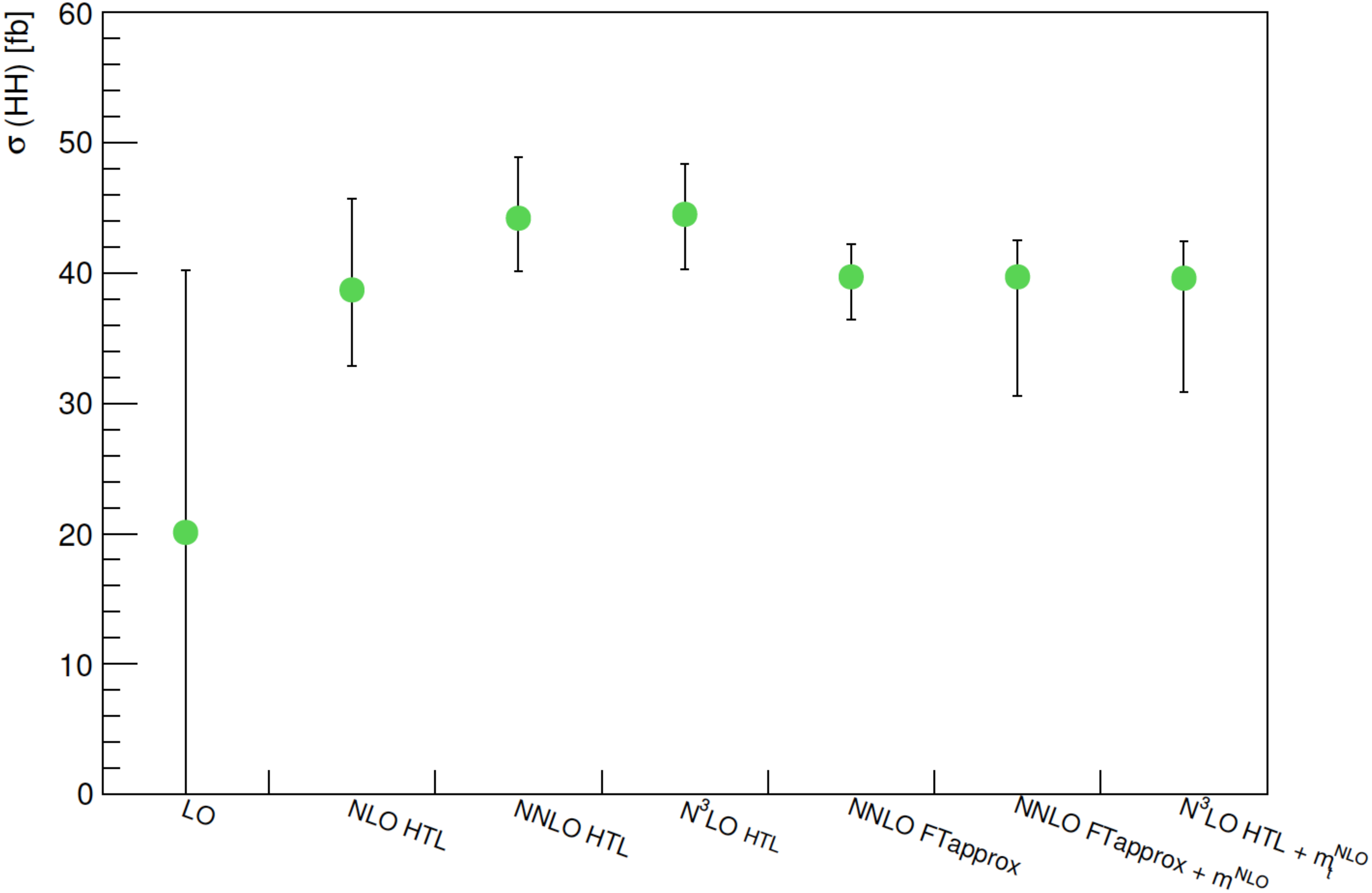
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, 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; [30] Mühlleitner, Schlenk, Spira 22; [31] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [32] Ajjath, Shao 22; [33] Davies, Mishima, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser 23; [35] Davies, Schönwald, Steinhauser, Zhang 23; [36] Bagnaschi, Degrassi, Gröber 23; [37] Bi, Huang, Huang, Ma Yu 23 [38] Li, Si, Wang, Zhang, Zhao 24; [39] Davies, Schönwald, Steinhauser, Vitti 24; [40] Heinrich, SPJ, Kerner, Stone, Vestner [41] Li, Si, Wang, Zhang, Zhao 24; [42] Davies, Schönwald, Steinhauser, Zhang 24; [43] Davies, Schönwald, Steinhauser, Zhang 25; [44] Davies, Schönwald, Steinhauser 25; [45] Bonetti, Rendler, Bobadilla 25;

S. Jones

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

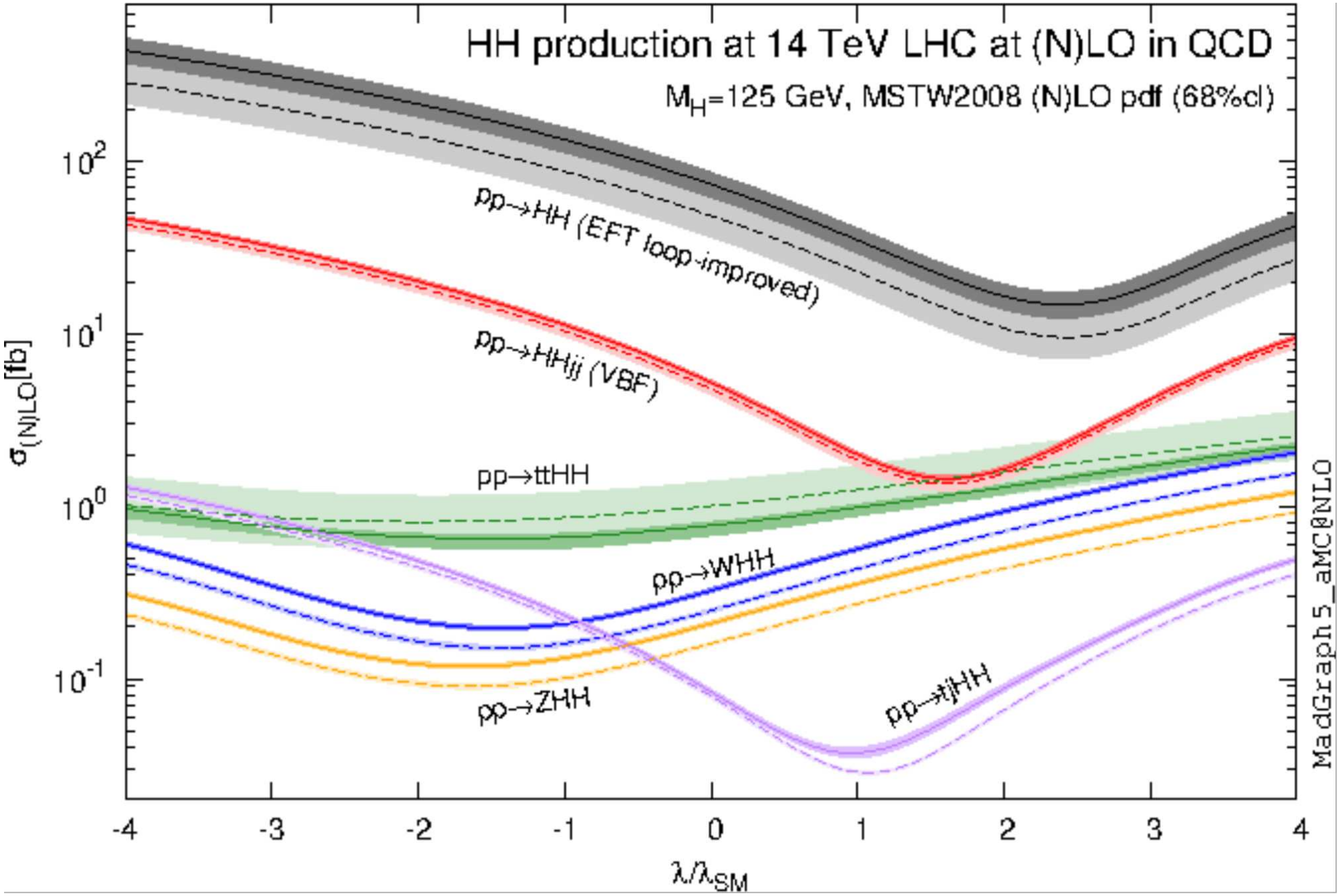
[*taken from M. Spira*]

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



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

⇒ strong interference of "box" and "SM-like Higgs"



⇒ higher-order corrections to κ_λ potentially very important

Higher-order correction to BSM THCs:

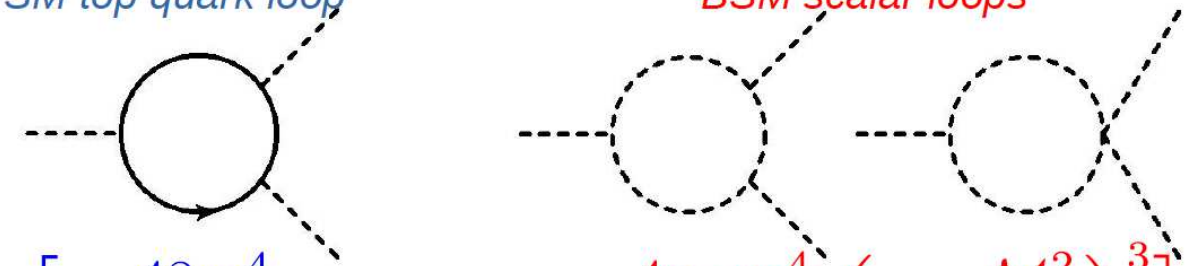
[taken from J. Braathen]

One-loop non-decoupling effects

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

SM top quark loop

BSM scalar loops



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

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_Φ : # of d.o.f of field Φ

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

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

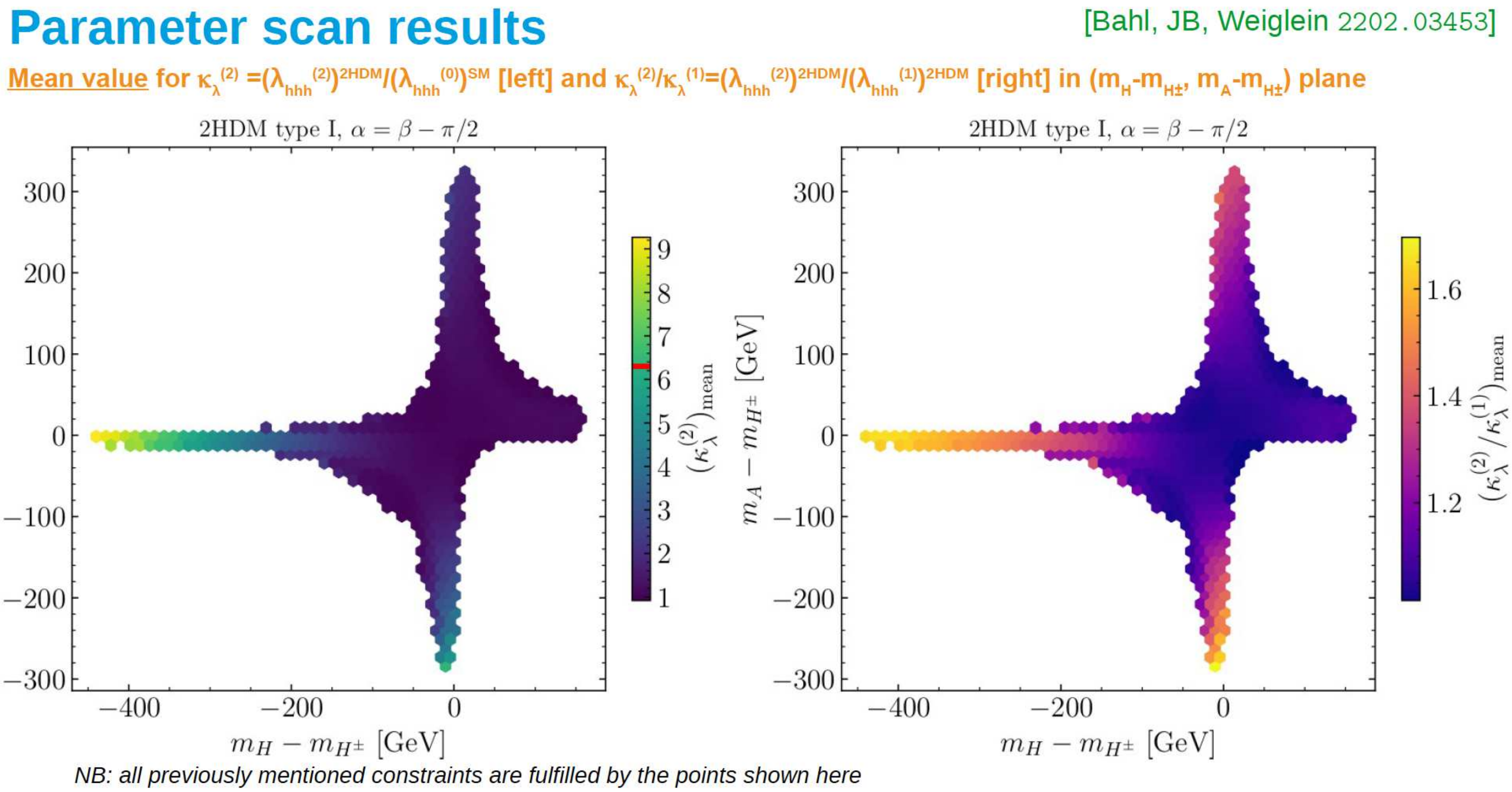
Huge BSM effects possible!

⇒ 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

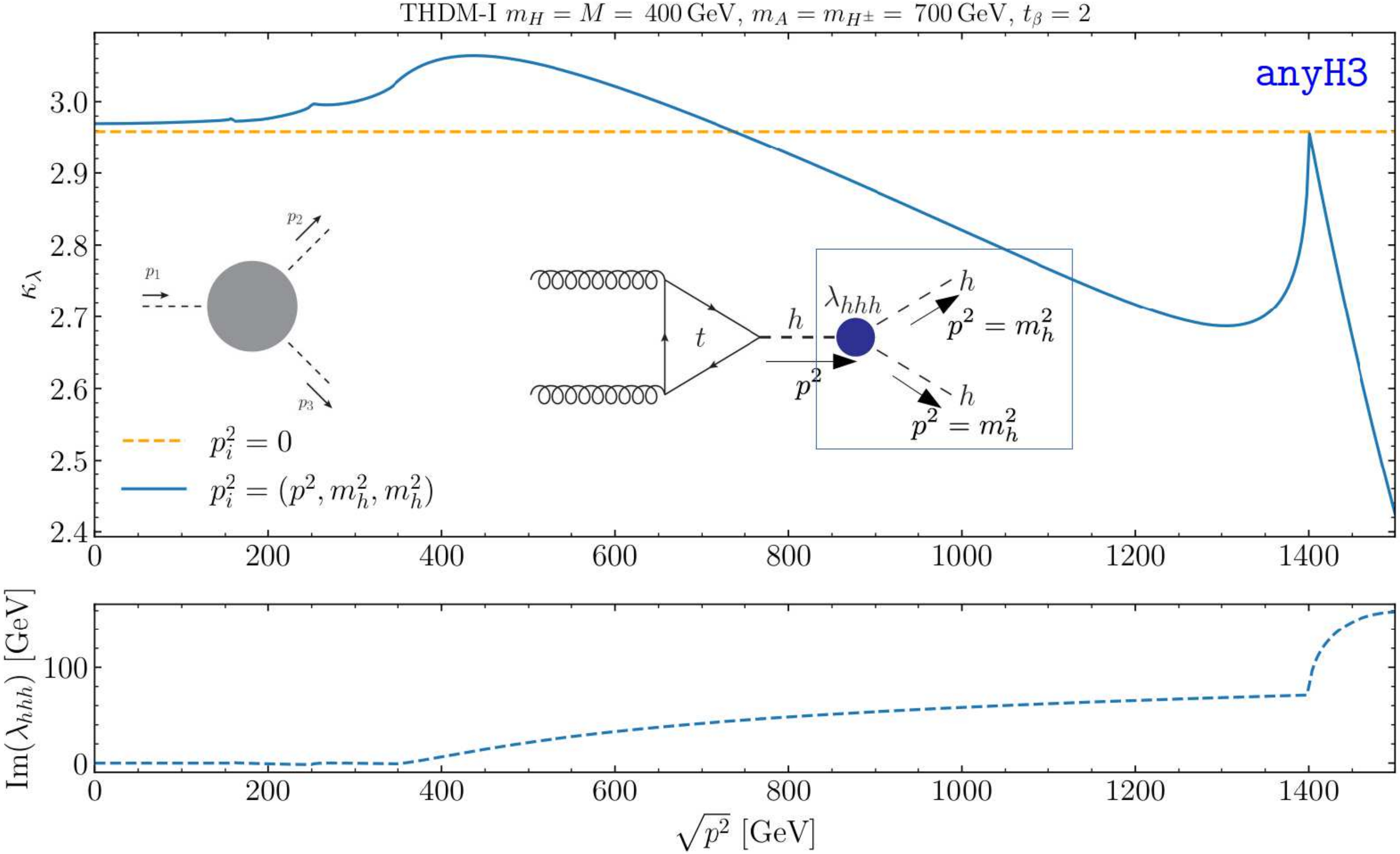
⇒ Perturbativity is found going from 1L to 2L

Details of possible higher-order correction to BSM THCs:

[*taken from J. Braathen*]

Momentum dependent effects:

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

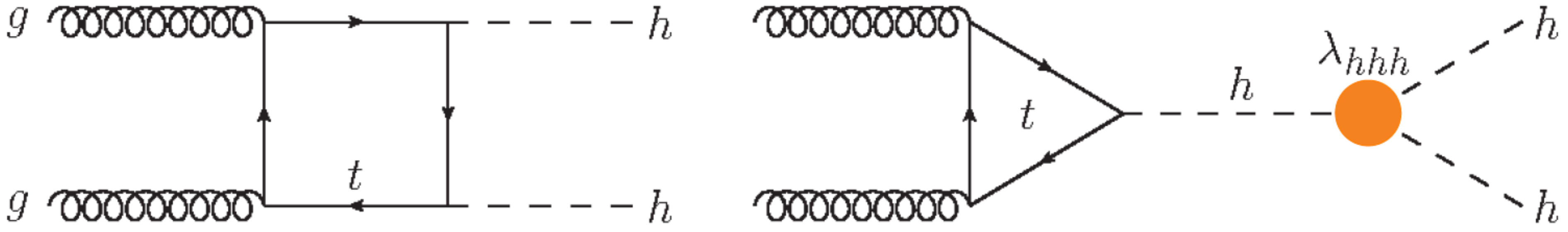


$\Rightarrow$ induce numerically sub-leading effect

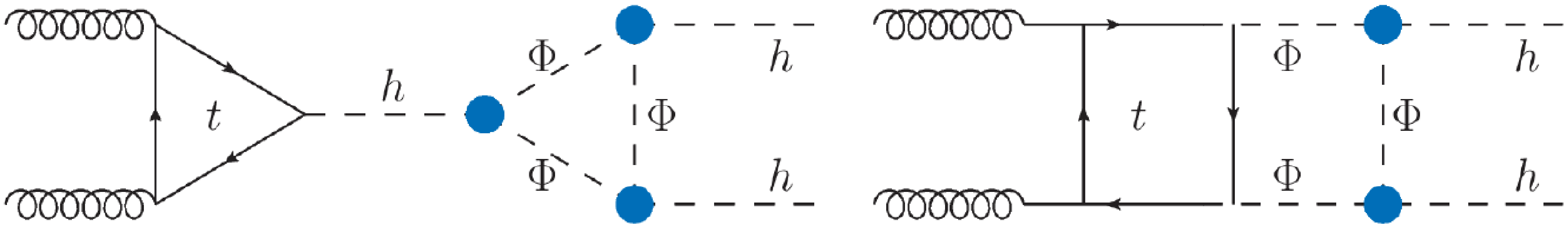
Higher-order correction to BSM THCs:

[*taken from J. Braathen*]

Box vs. s channel Higgs:



Inclusion of one-loop corrections to THCs:



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

Correction to λ_{hhh} → included

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

not included

⇒ always closed subset, dominant for large THCs

(Theory) Tool development:

[*taken from J. Braathen '24*]

Generic predictions for λ_{hhh}

anyH3

Based on

`arXiv:2305.03015` (EPJC) + WIP

in collaboration with Henning Bahl, Martin Gabelmann, Kateryna Radchenko Serdula and Georg Weiglein

⇒ crucially needed

⇒ links to MadGraph, . . .

Exploration of possible ranges of κ_λ using anyH3:

[*taken from J. Braathen '24*]

New results I: mass-splitting effects in various BSM models

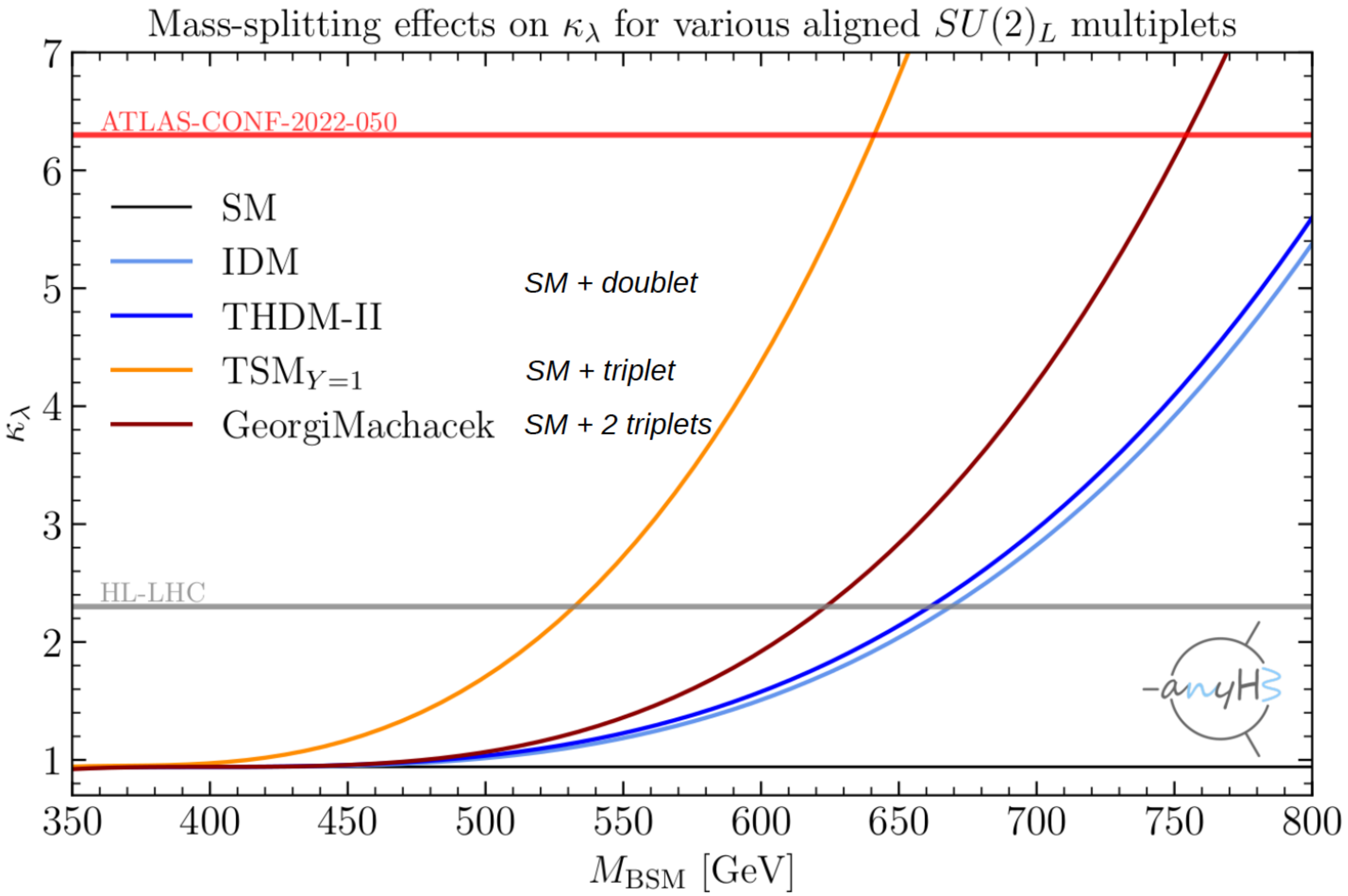
- Consider the non-decoupling limit in several BSM models

$$M_{\rm BSM}^2 = \mathcal{M}^2 + \tilde{\lambda} v^2$$

- Increase $M_{\rm BSM}$, keeping $\mathcal{M}$ fixed
  → large mass splittings
  → **large BSM effects!**

- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**



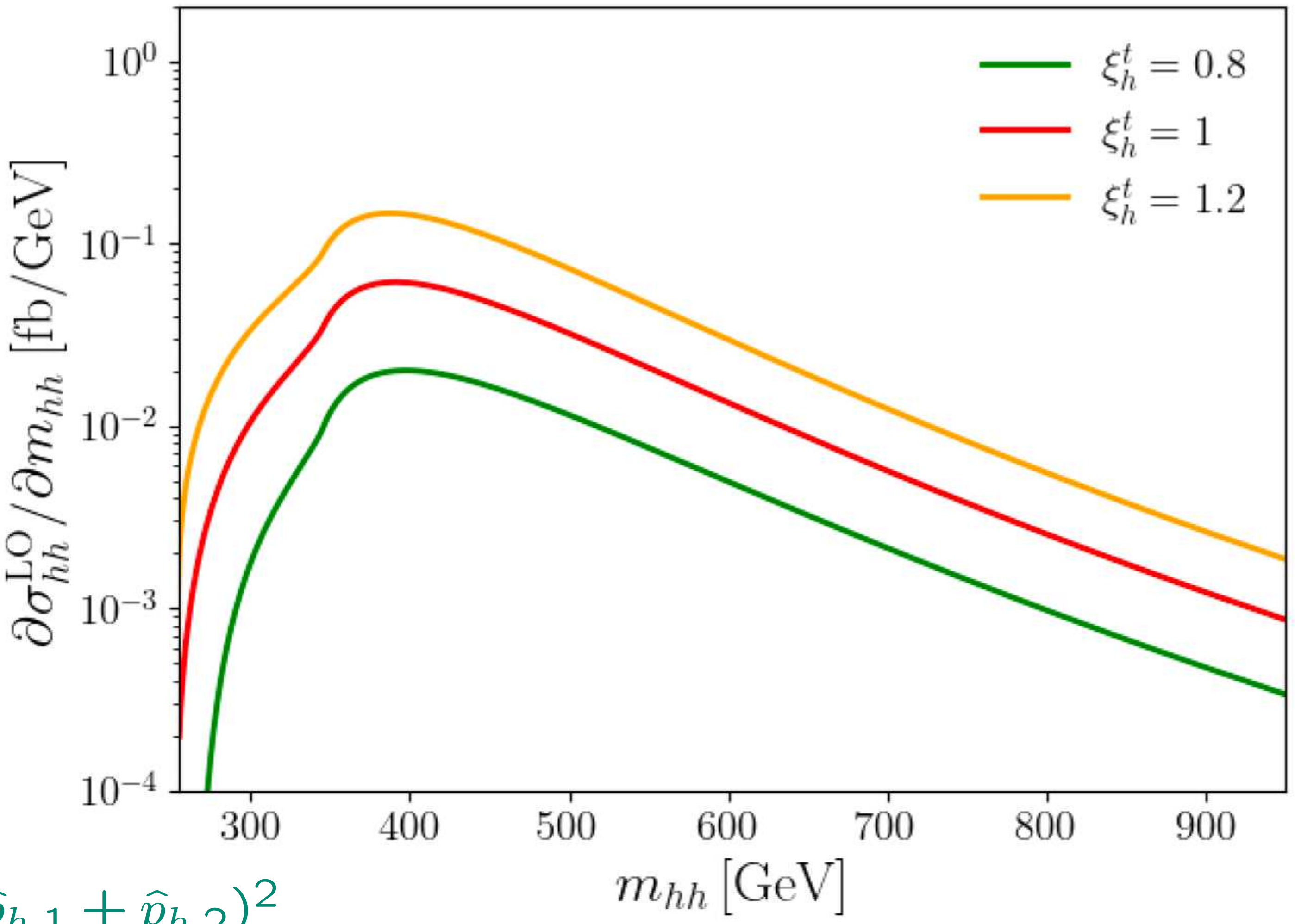
Here: scenarios with lightest BSM scalar mass + BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

(HL-)LHC di-Higgs searches rely on m_{hh}

[PhD K. Radchenko '25]

m_{hh}: invariant mass distribution of the di-Higgs system

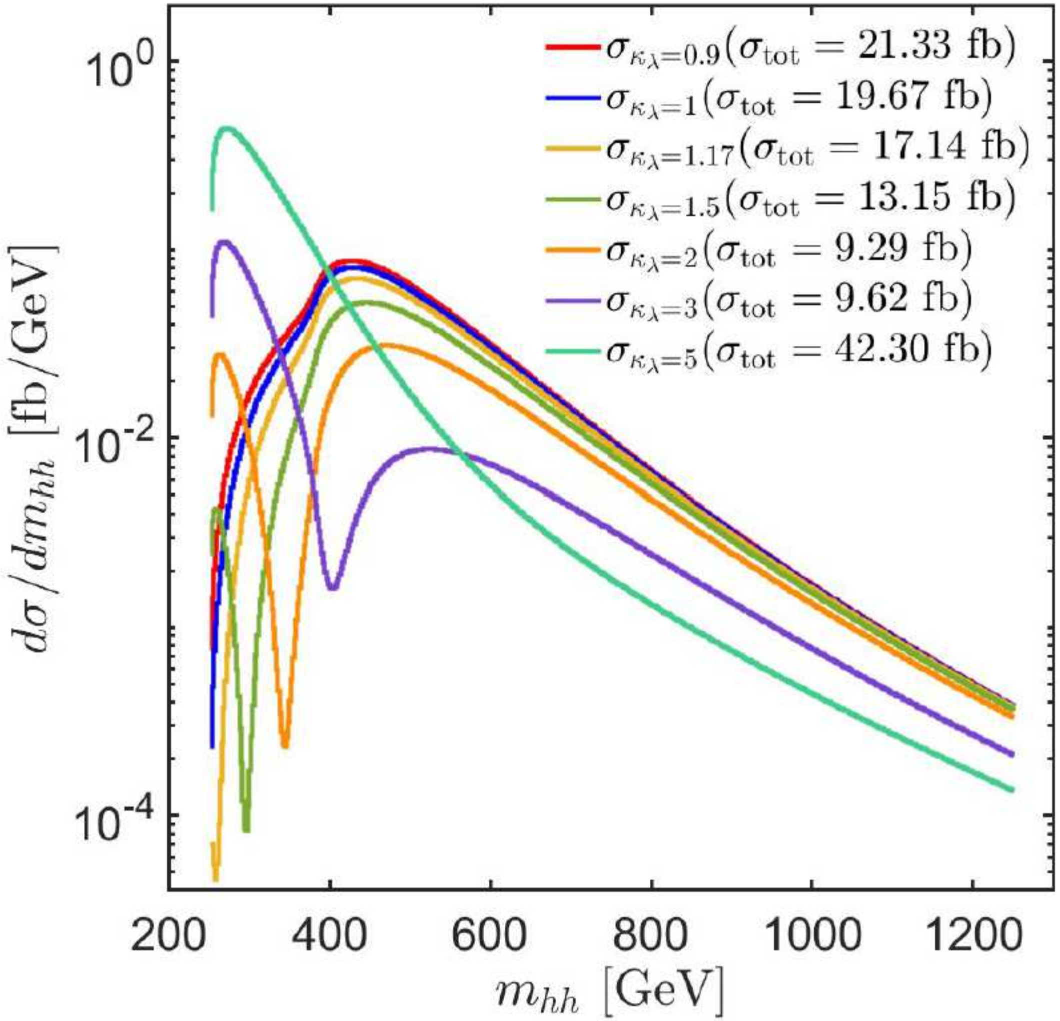
SM case with ξ_h^t varied:



$\Rightarrow m_{hh}^2 = (\widehat{p}_{h,1} + \widehat{p}_{h,2})^2$

Non-resonant BSM di-Higgs production $\Rightarrow$ all calculated with HPAIR

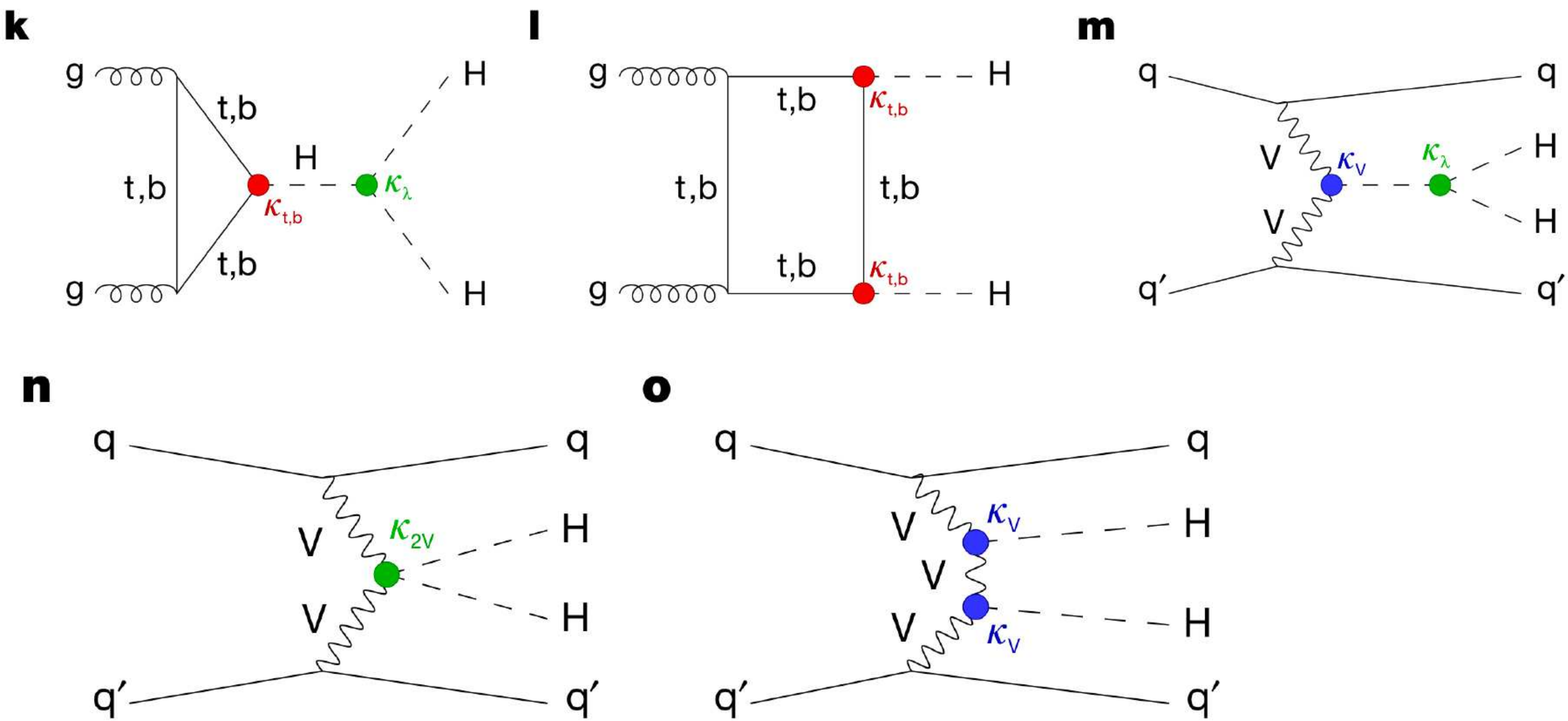
[*S.H., M. Mühlleitner, K. Radchendo, G. Weiglein – PRELIMINARY*]



$\Rightarrow$ higher-order effects in κ_λ

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

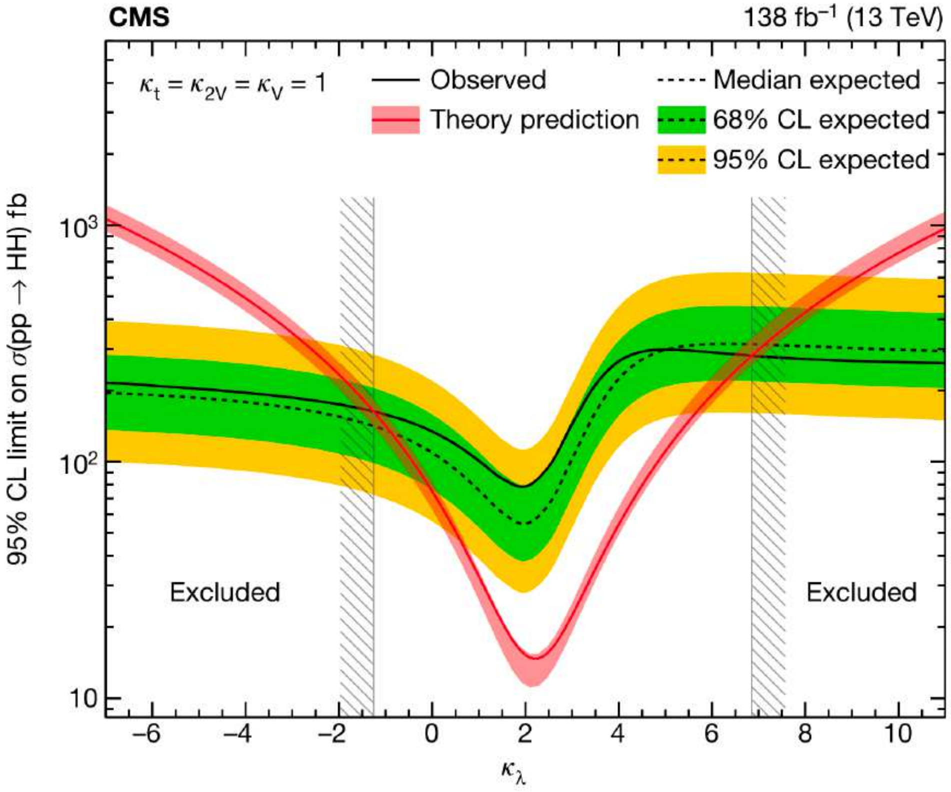
Experimental limits on κ_λ and κ_{2V}

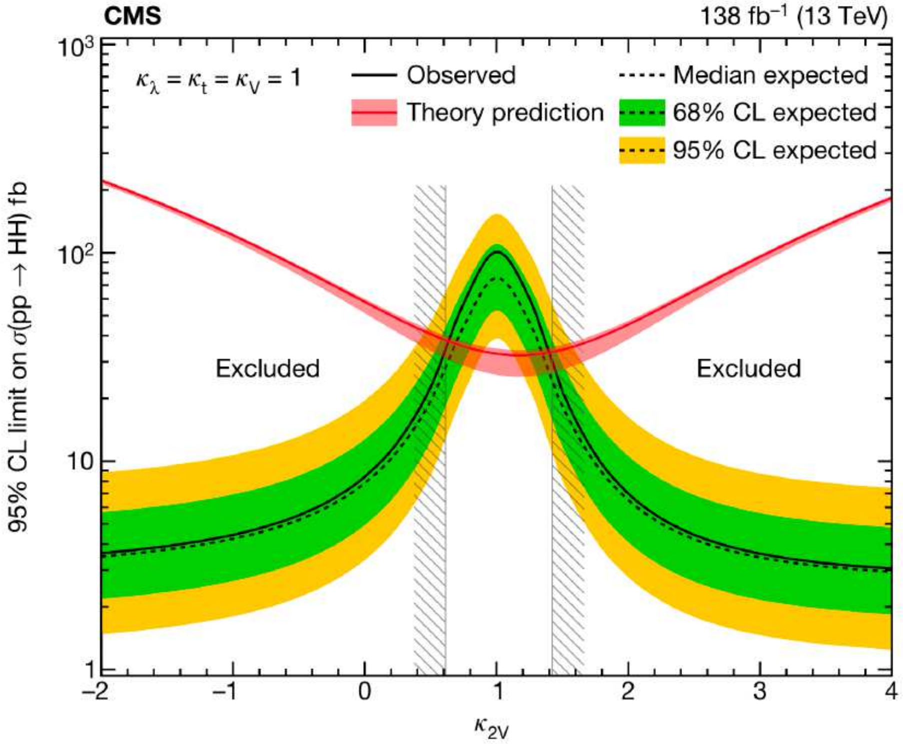


⇒ all κ's should be varied simultaneously

⇒ sensitivity to κ_λ and κ_{2V}?!

Experimental limits on κ_λ and κ_{2V}

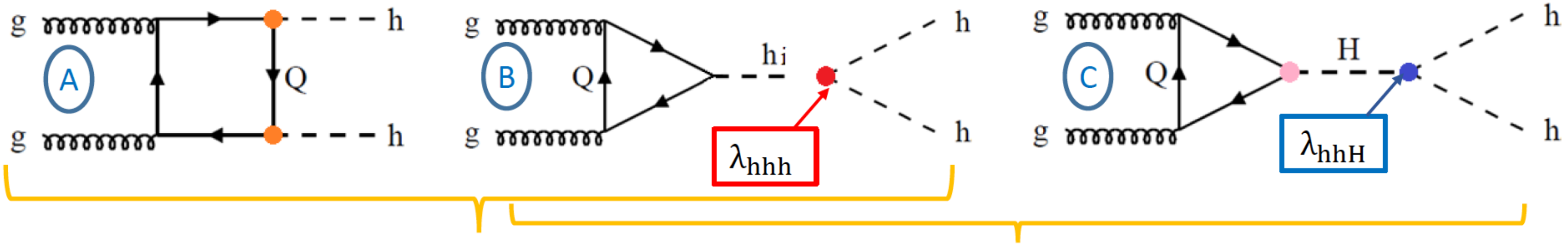




⇒ shape of expected limits from m_{hh} distributions

⇒ limits getting stronger, improvement getting difficult

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 :-(

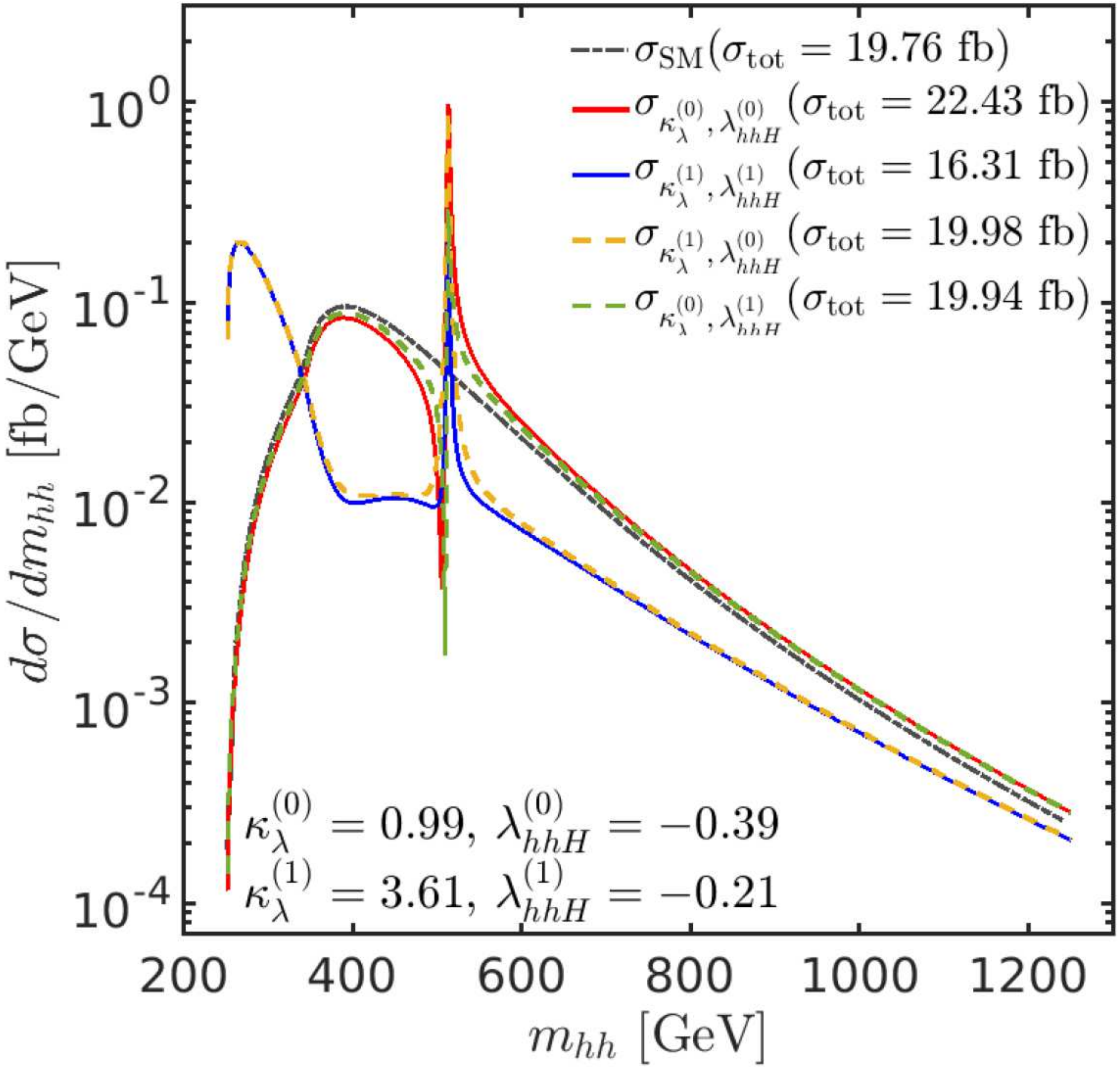
⇒ existing exclusion bounds questionable!

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

[F. Arco, S.H., M. Mühlleitner, A. Parra Arnay, N. Rivero González, A. Verduras Schaeidt '25]

Resonant di-Higgs production at the (HL-)LHC:

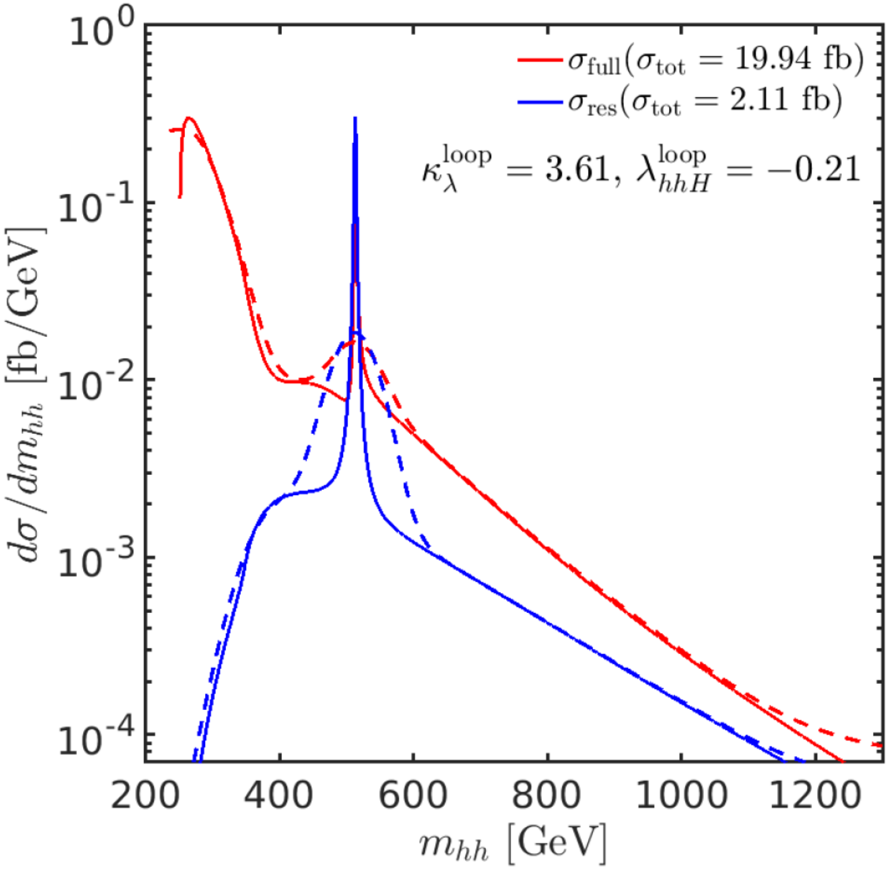
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



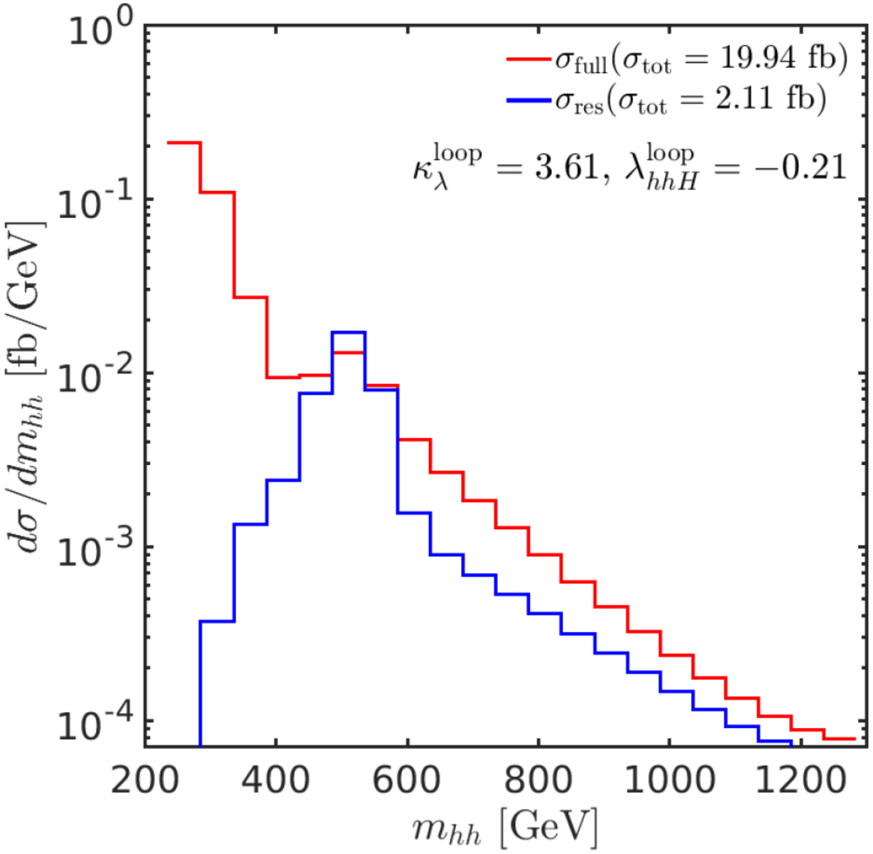
Experimental analysis vs. reality:

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

smeared



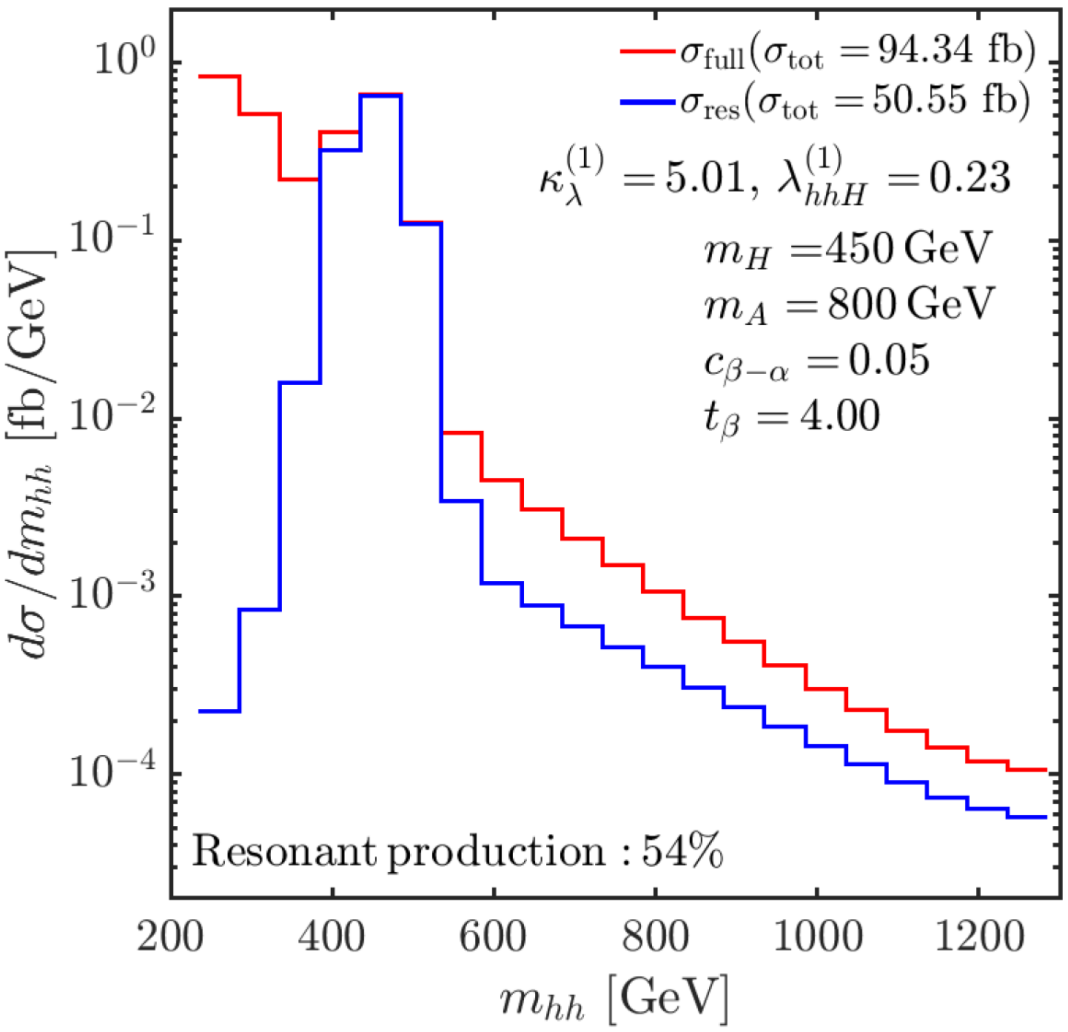
⊕ binned



⇒ experimental analysis   ⇒ full calculation

Experimental analysis vs. reality:

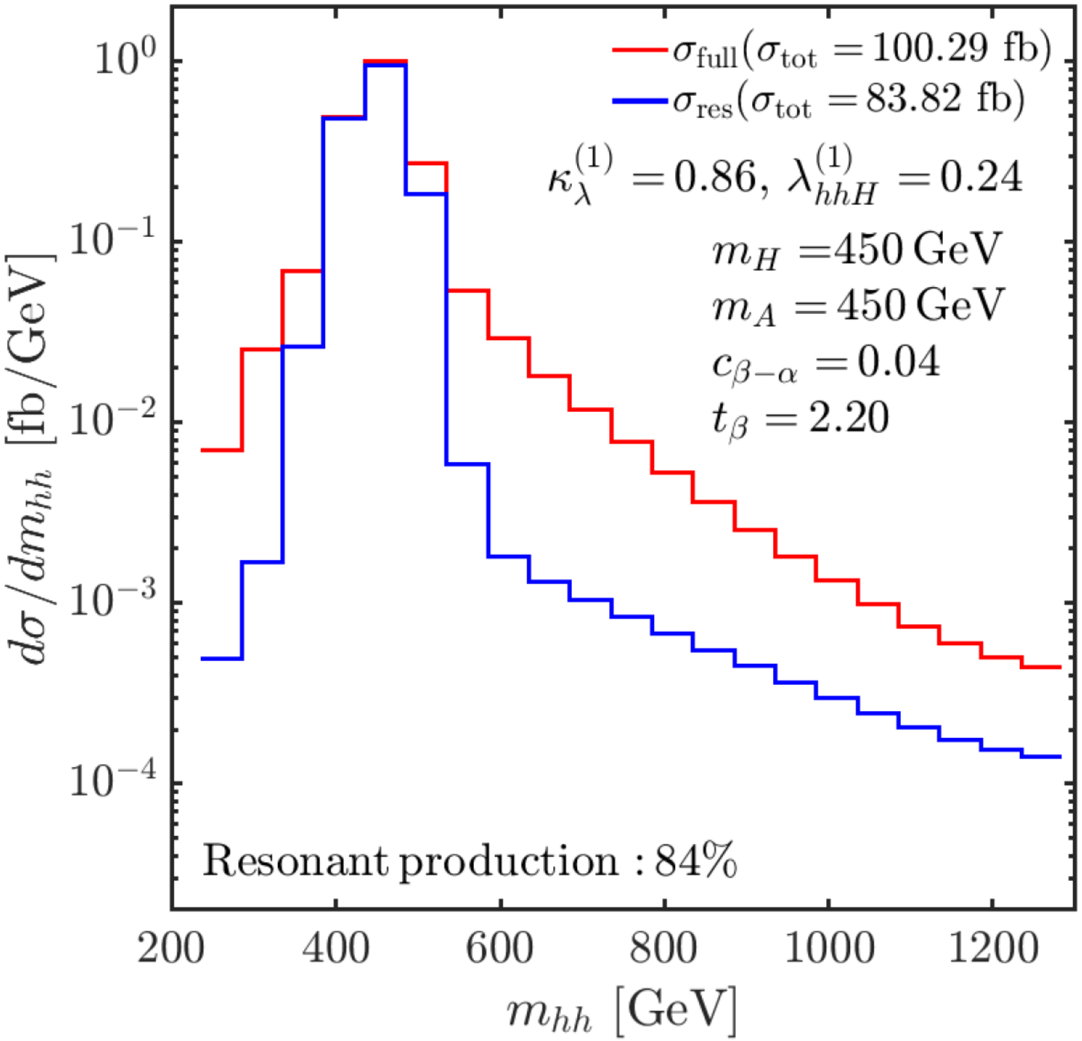
[*S.H., M. Mühlleitner, K. Radchenko, G. Weiglein '24*]



$\Rightarrow$ 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?

3. m_{hh} measurements at the HL-LHC?

[*F. Arco, S.H., M. Mühlleitner, A. Parra Arnay, N. Rivero González, A. Verduras Schaeidt '25*]

Model: RxSM

Benchmark plane features:
- FOEWPT
- large “pure resonant di-Higgs production” at the LHC based on [*M. Ramsey-Musolf et al. '19*]

⇒ first look at total cross section

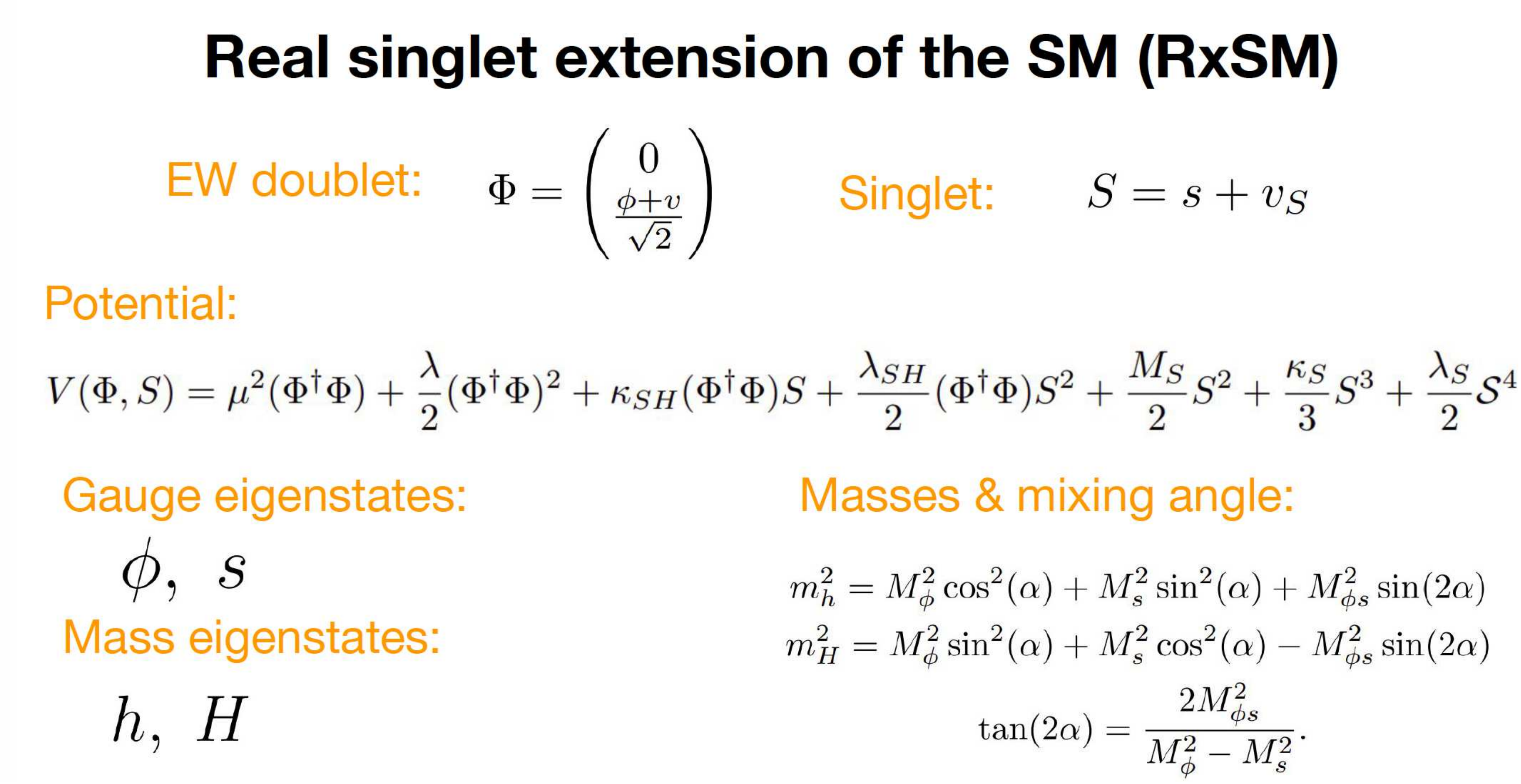
⇒ then at differential cross section (m_{hh} distribution)

⇒ effects of $\kappa_\lambda \neq 1$

⇒ effects of H resonance, λ_{hhH}

Our model:

[*taken from A. Verduras '24*]



Real singlet extension of the SM (RxSM)

EW doublet: $\Phi = \begin{pmatrix} 0 \\ \frac{\phi+v}{\sqrt{2}} \end{pmatrix}$

Singlet: $S = s + v_S$

Potential:

$$V(\Phi,S) = \mu^2(\Phi^\dagger\Phi) + \frac{\lambda}{2}(\Phi^\dagger\Phi)^2 + \kappa_{SH}(\Phi^\dagger\Phi)S + \frac{\lambda_{SH}}{2}(\Phi^\dagger\Phi)S^2 + \frac{M_S}{2}S^2 + \frac{\kappa_S}{3}S^3 + \frac{\lambda_S}{2}S^4$$

Gauge eigenstates:

$\phi, \; s$

Mass eigenstates:

$h, \; H$

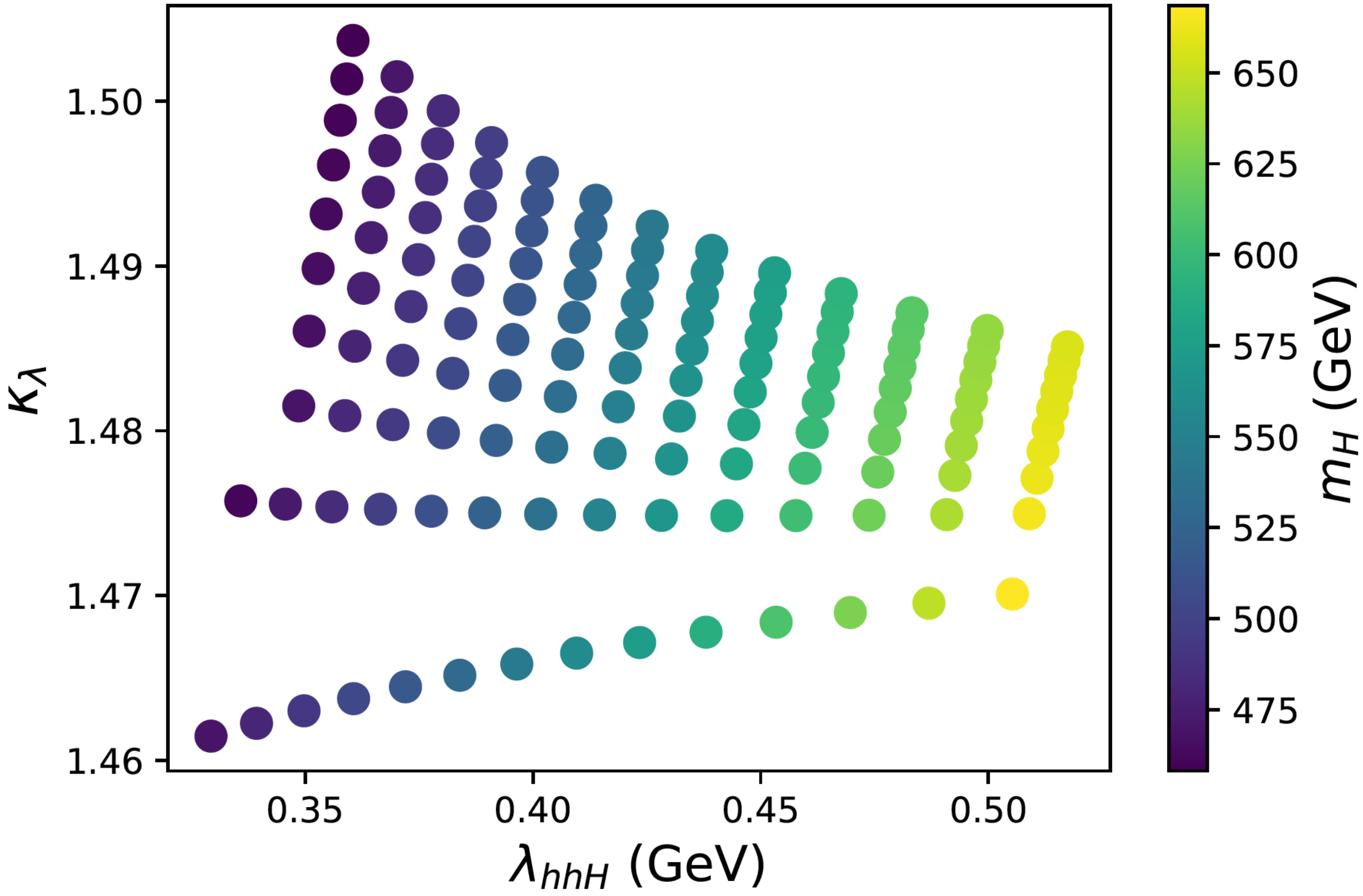
Masses & mixing angle:

$$m_h^2 = M_\phi^2\cos^2(\alpha) + M_s^2\sin^2(\alpha) + M_{\phi s}^2\sin(2\alpha)$$
$$m_H^2 = M_\phi^2\sin^2(\alpha) + M_s^2\cos^2(\alpha) - M_{\phi s}^2\sin(2\alpha)$$
$$\tan(2\alpha) = \frac{2M_{\phi s}^2}{M_\phi^2 - M_s^2}.$$

⇒ note slight difference w.r.t. RxSM introduced yesterday?

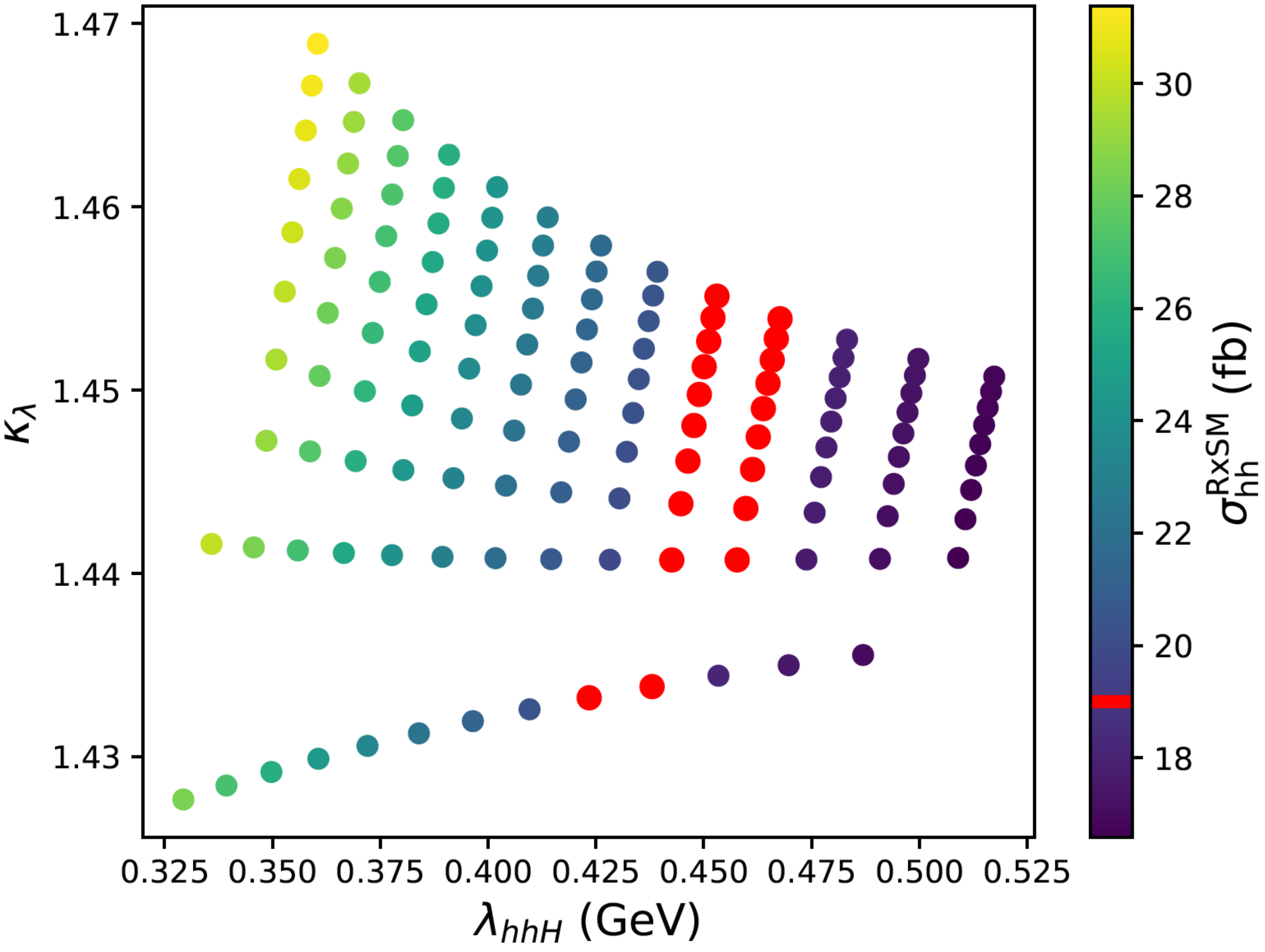
⇒ simplest Higgs-sector extension that features strong FOEWPT

RxSM anaysis in parameter plane featuring a FOEWPT



⇒ interesting range of m_H

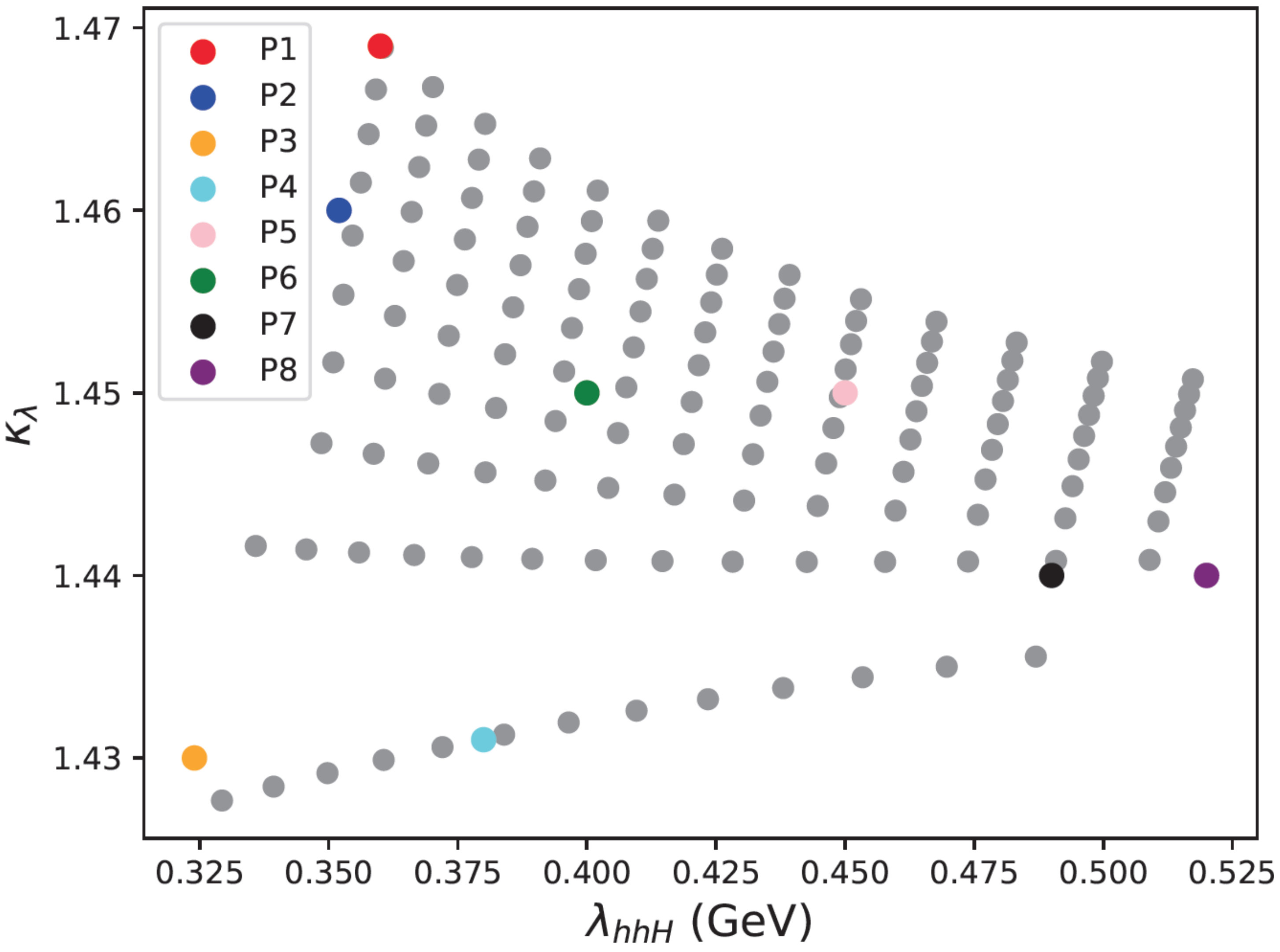
RxSM anaysis in parameter plane featuring a FOEWPT



$\Rightarrow$ deviations from SM possible, but not guaranteed

$\Rightarrow$ not alignment, but compensation of $\kappa_\lambda \approx 1.45$ and H contribution!

Define benchmark points for detailed analysis:



$\Rightarrow$ covering the whole plane/relevant phenomenology

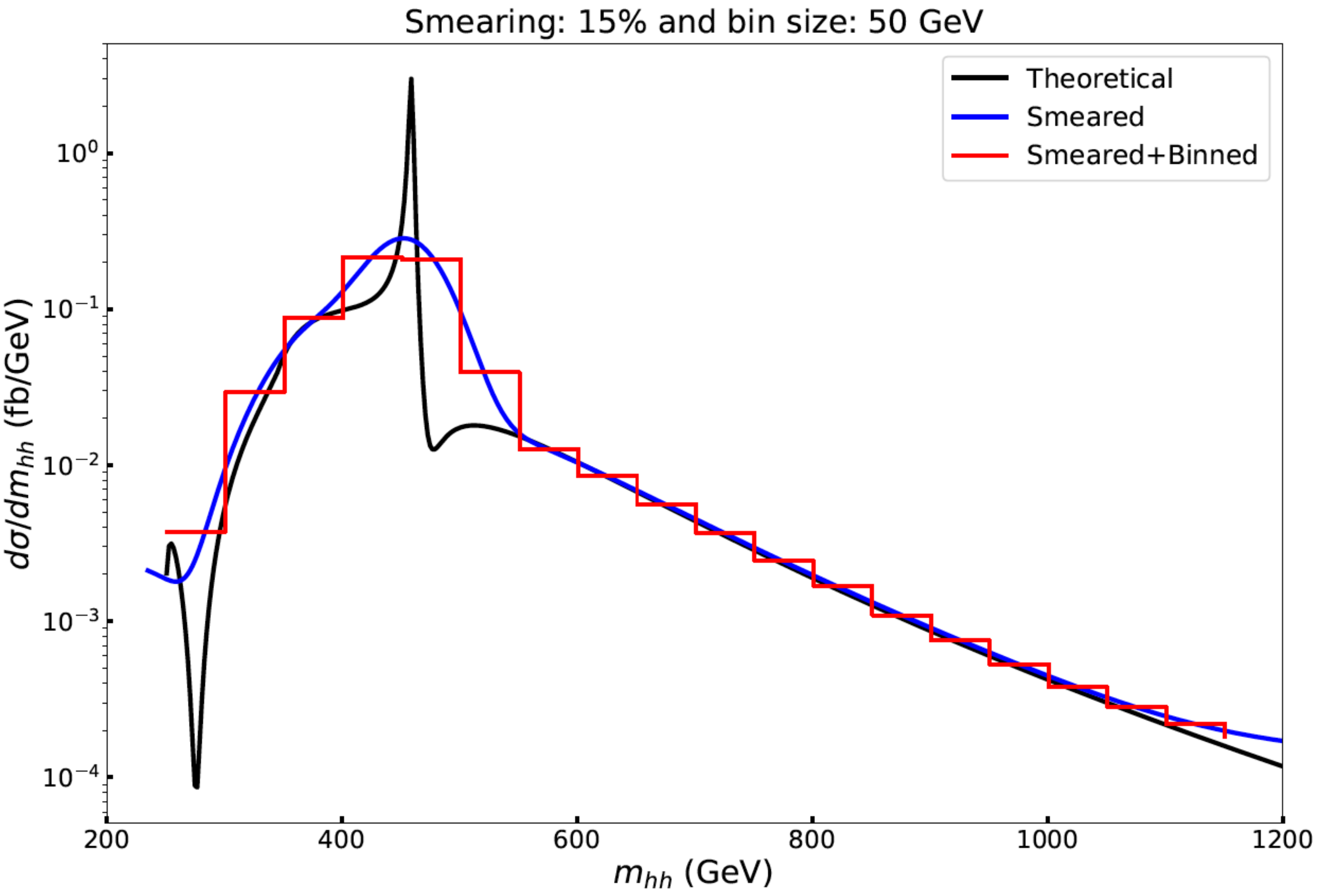
Define benchmark points for detailed analysis:

Point	x [GeV]	λ	a_1 [GeV]	a_2	b_3 [GeV]	b_4	κ_λ	λ_{hhH}	λ_{hHH}	λ_{HHH}
P1	46.3	0.18	-691.10	4.50	-622.6	0.89	1.47	0.36	0.41	0.80
P2	46.3	0.18	-691.10	4.45	-442.70	0.45	1.46	0.35	0.46	0.37
P3	47.4	0.18	-675.10	4.11	0.00	0.00	1.43	0.33	0.44	0.67
P4	41.9	0.18	-763.70	5.23	0.00	0.00	1.43	0.38	0.55	0.82
P5	37.5	0.18	-853.30	6.65	-582.90	0.78	1.46	0.45	0.84	0.45
P6	40.8	0.18	-784.30	5.63	-442.70	0.45	1.45	0.40	0.60	0.42
P7	34.2	0.18	-935.70	7.85	-218.90	0.11	1.44	0.49	0.88	0.96
P8	33.1	0.18	-966.80	8.44	-582.90	0.78	1.44	0.52	0.92	0.98

Variation of:

- κ_λ: negligible
- λ_{hhH}: 50%
- λ_{hHH}: 100%
- λ_{HHH}: 100%

Analysis of m_{hh} distributions:



$\Rightarrow$ smearing and binning crucial - as expected

How to determine the significance of the H resonance?

Theoretical estimator:

$$R := \frac{\sum_i \left| N_i^R - N_i^C \right|}{\sqrt{\sum_i N_i^C}}$$

N_i^R : # of events in bin i under the resonance
N_i^C : # of events in bin i in the continuum/SM

under the condition:

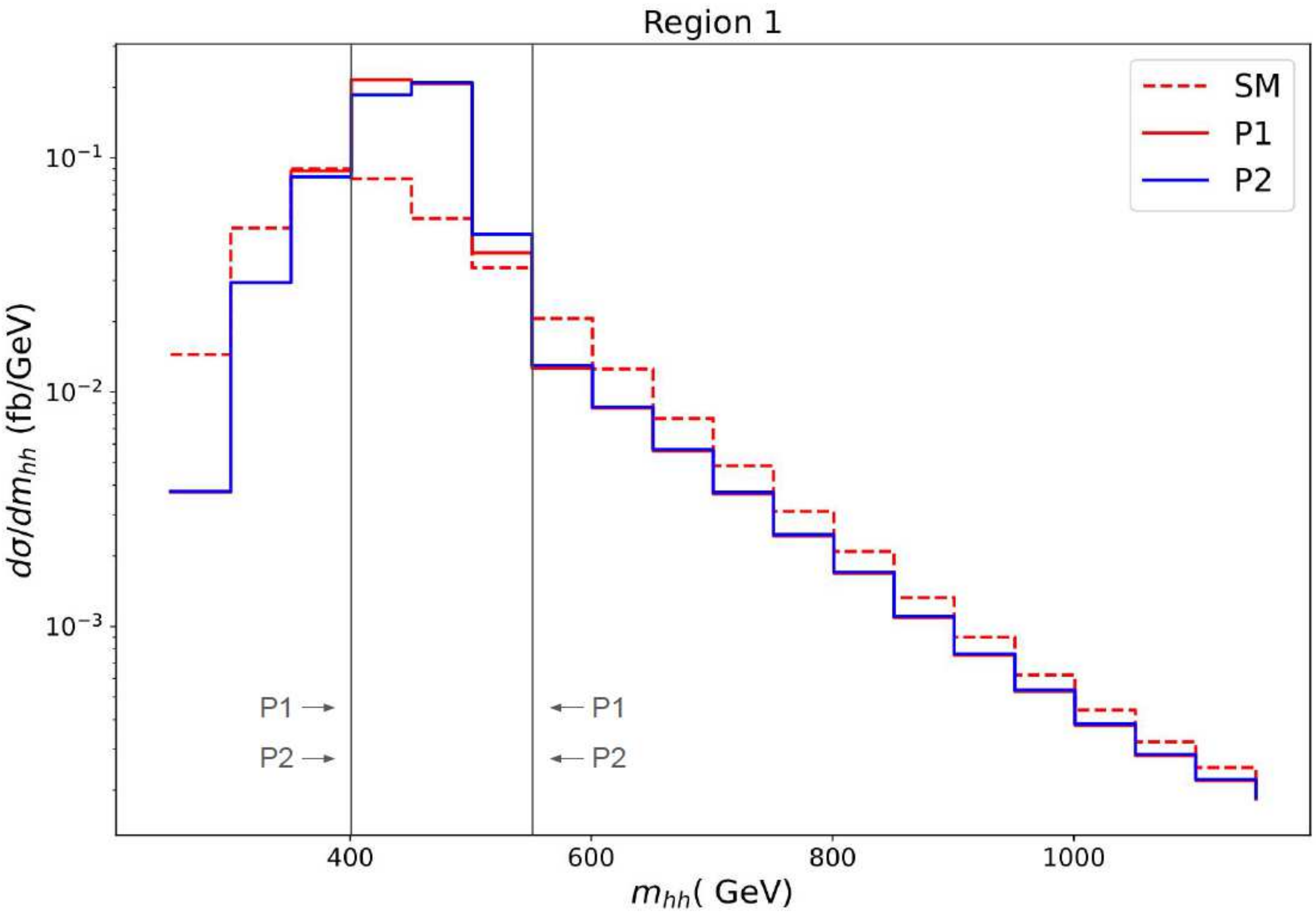
$$\left| N_i^R - N_i^C \right| \geq 100 \quad \text{in bin } i$$

Assumed final state: $gg \to hh \to b\bar{b}\, b\bar{b}$

Assumed luminosity: $\mathcal{L}_{\text{int}} = 3000\,\text{fb}^{-1} \times 2$ (for ATLAS $\oplus$ CMS)

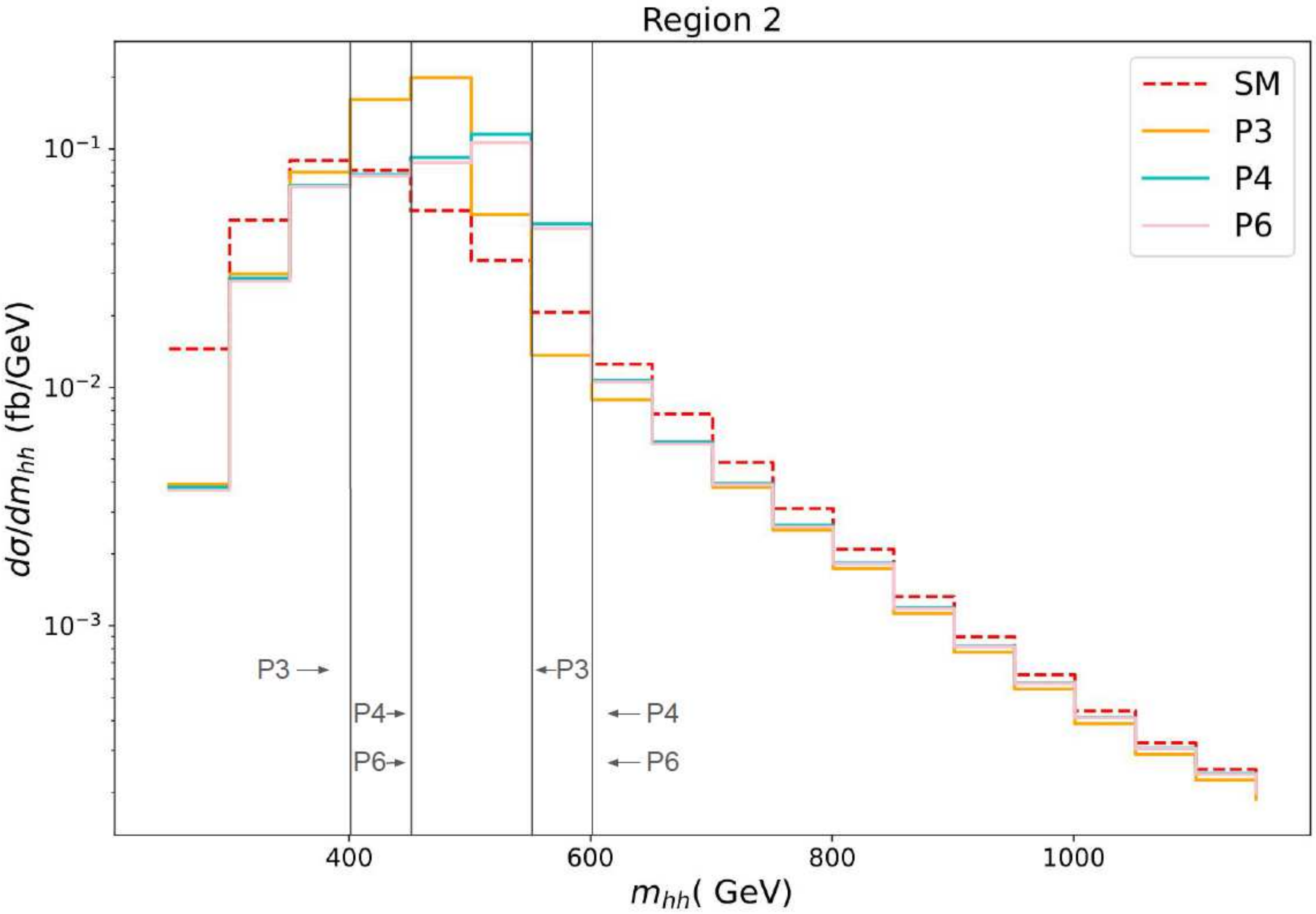
NOTE: this is to compare parameter points, it does NOT correspond to an experimental significance. But it helps. :-)

BPs with large deviation in $\sigma(gg \to hh)$ wrt. SM:



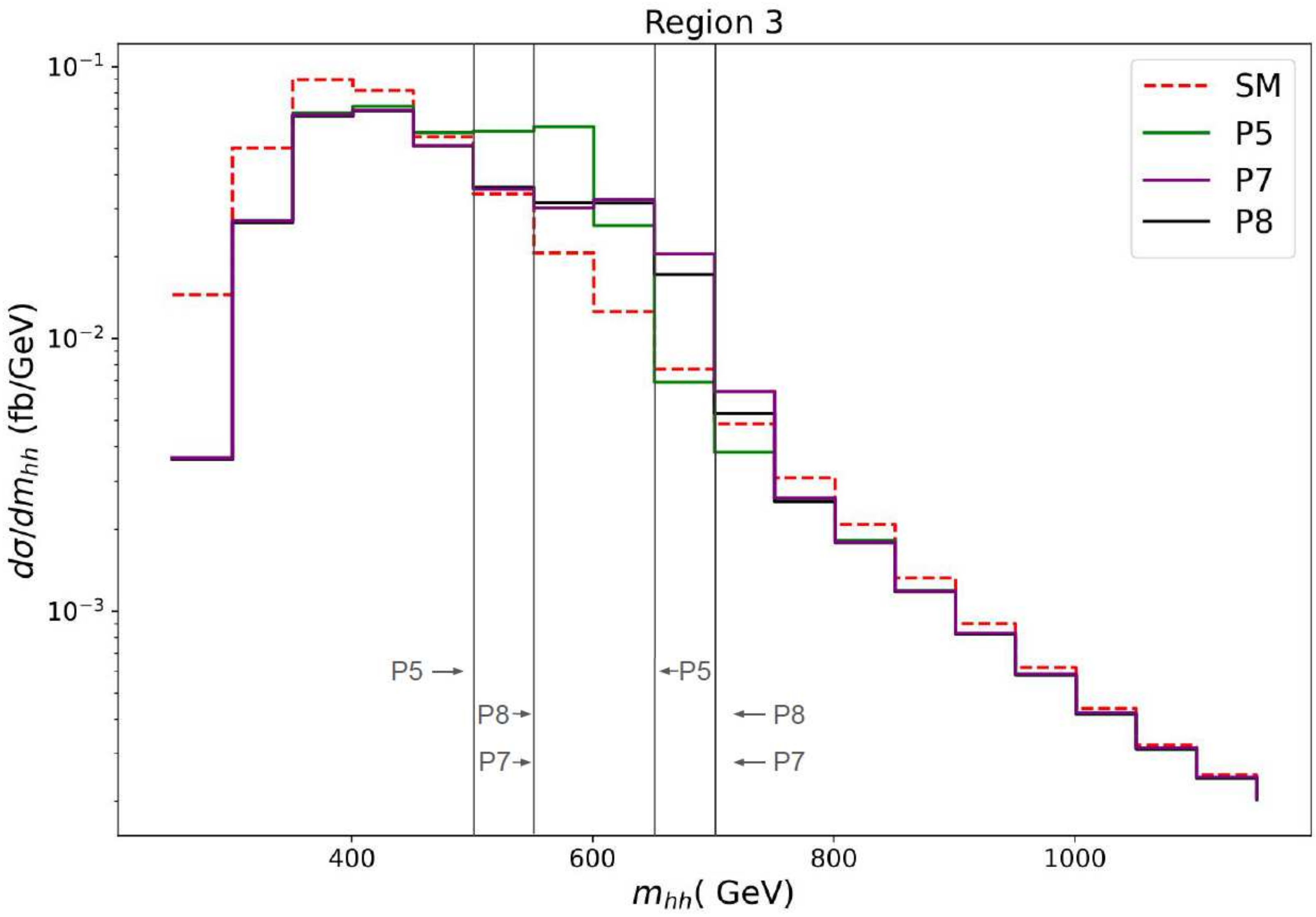
$\Rightarrow R_{1,2} \approx 230 \Rightarrow$ good prospects (full exp. analysis needed!)

BPs with small deviation in $\sigma(gg \to hh)$ wrt. SM:



$\Rightarrow R_{3,4,6} \approx 150..200 \Rightarrow$ good prospects?? (full exp. analysis needed!)

BPs with vanishing deviation in $\sigma(gg \to hh)$ wrt. SM:



$\Rightarrow R_{5,7,8} \approx 75..110 \Rightarrow$ good prospects???? (full exp. analysis needed!)

Mini-summary of BSM Higgs bosons/THCs at the LHC:

– large parameter spaces with relatively low masses allowed

– BSM Higgs sectors predict $\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$ different from 1
FOEWPT favors $\kappa_\lambda \sim 1.5 - 2$

– BSM Higgs sectors predict BSM triple Higgs couplings: $\lambda_{hhH}, \ldots$

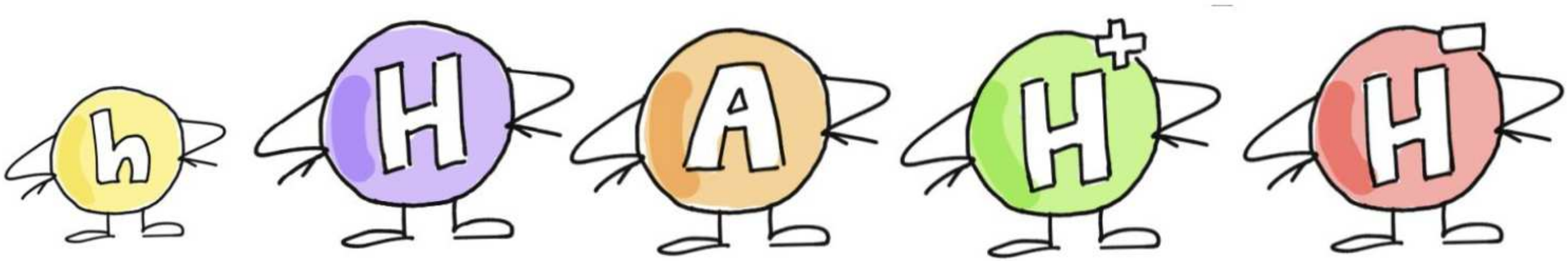
– access to κ_λ and λ_{hhH} via $gg \to hh$
crucial: m_{hh} distributions

– low m_{hh}: affected by changes in κ_λ

– $m_{hh} \sim m_H$: peak-dip resonance structure caused by λ_{hhH}
crucial: smearing and binning

– RxSM analysis suggests experimental sensitivity at the HL-LHC

4. BSM THCs at the ILC



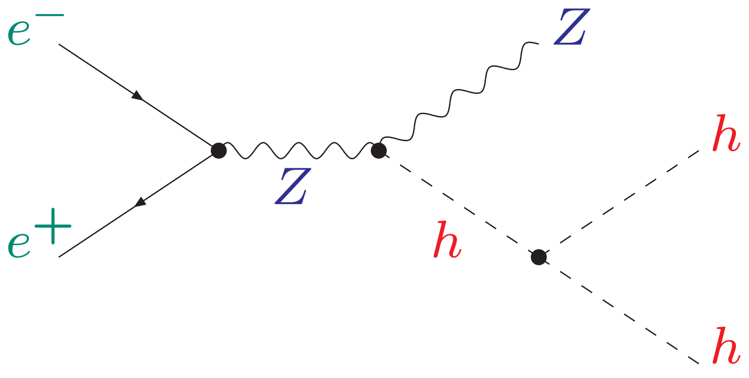
[*K. Radchenko*]


cherheit-Gesundheit-Umweltschutz
Einbahnstraße!
One Way Street!
Einbahnstraße
Always think safety!
HAHH

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

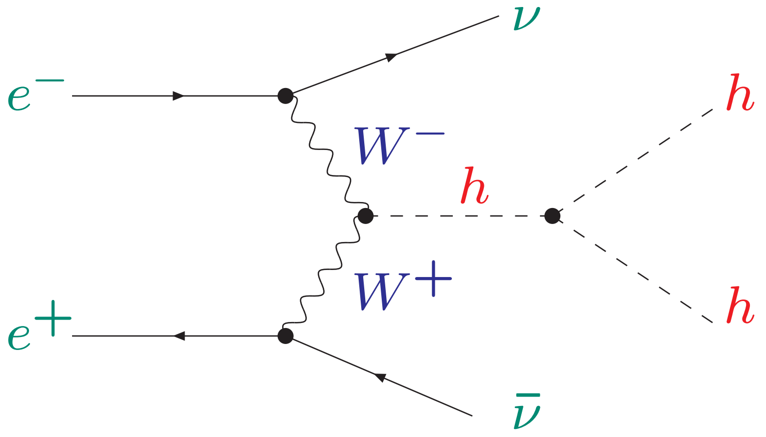
Higgs-strahlung:

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

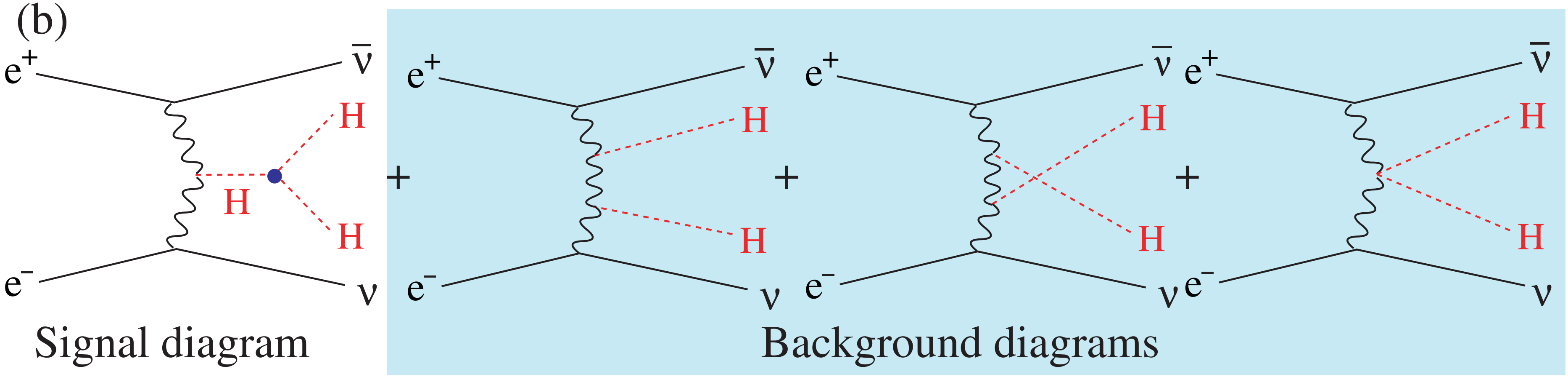


weak boson fusion (WBF):

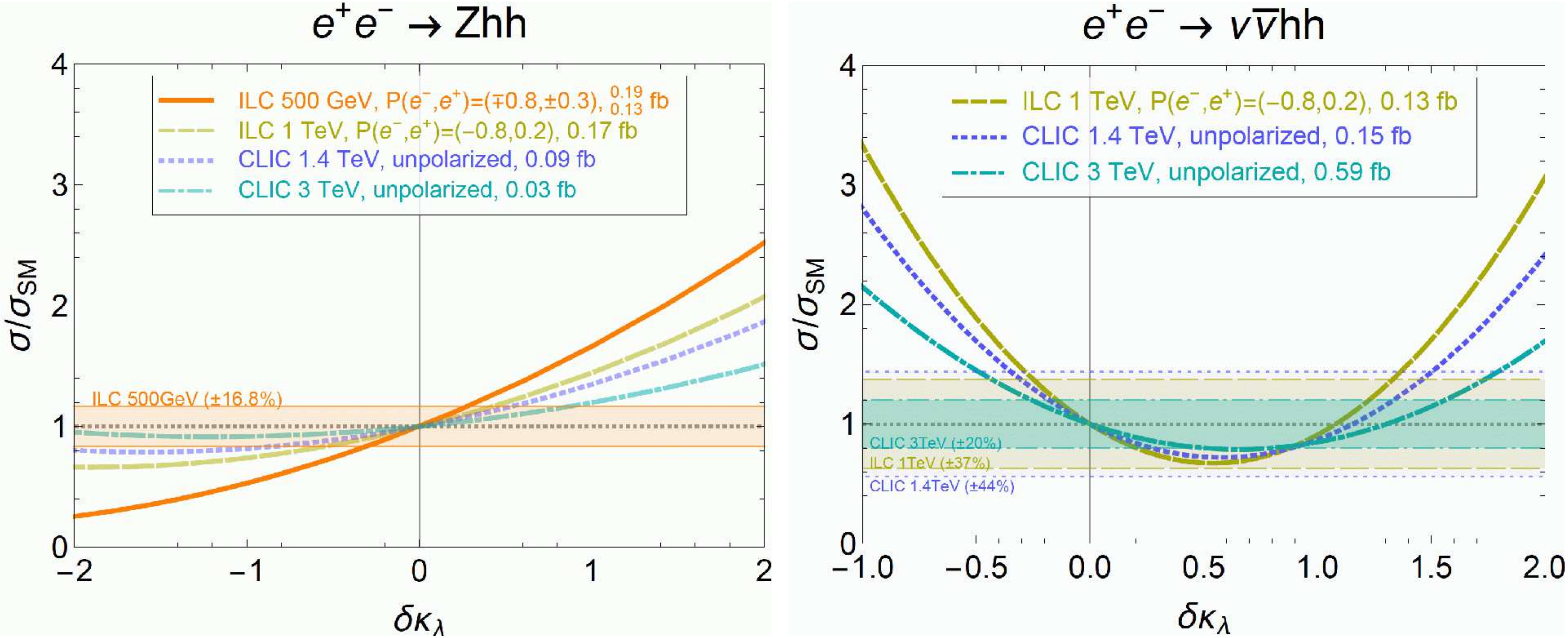
$e + e- \to \nu\bar{\nu}hh$



Signal and background interference:



Di-Higgs production at ILC/CLIC:

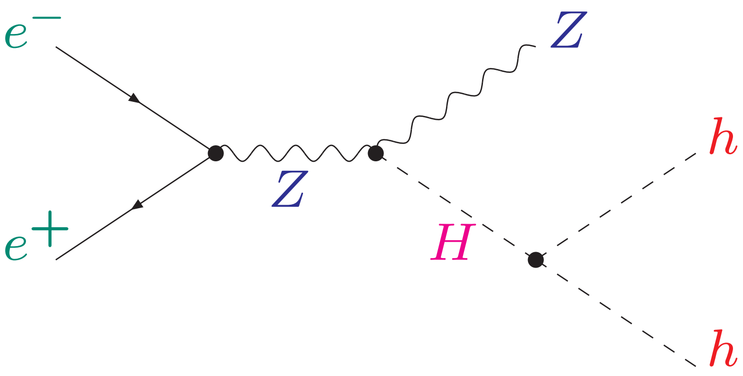


$\kappa_\lambda := 1 + \delta\kappa_\lambda$

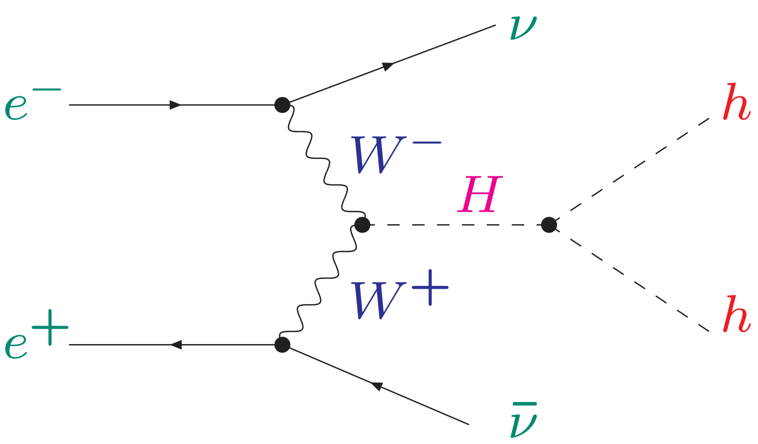
⇒ strong and different dependence on κ_λ

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)

Two Higgs Doublet Model (2HDM):

Fields:

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

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:

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

Assumption (for now): $h \sim h_{125}$

Z_2 symmetry to avoid FCNC:

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

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	→ MSSM 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: $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

Possible effects (beyond tree-level) on 2HDM THCs:

[*taken from F. Arco '24*]

Parameter scan in the 2HDM (all types):

[*F. Arco, S.H., M. Mühlleitner '25*]

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

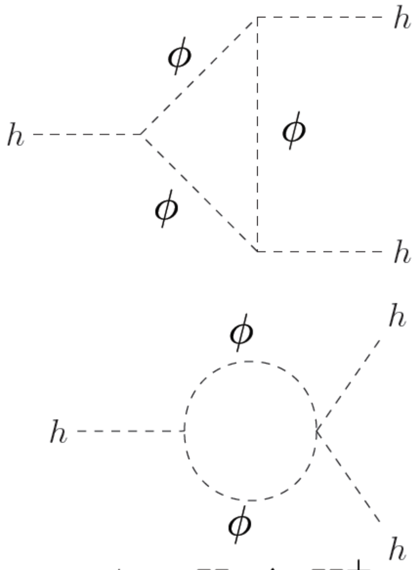
[ScannerS + HiggsTools + HDECAY]

Possible effects (beyond tree-level) on 2HDM THCs:

[*taken from F. Arco '24*]

Parameter scan in the 2HDM (all types):

[*F. Arco, S.H., M. Mühlleitner '25*]



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

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]
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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*** !!!

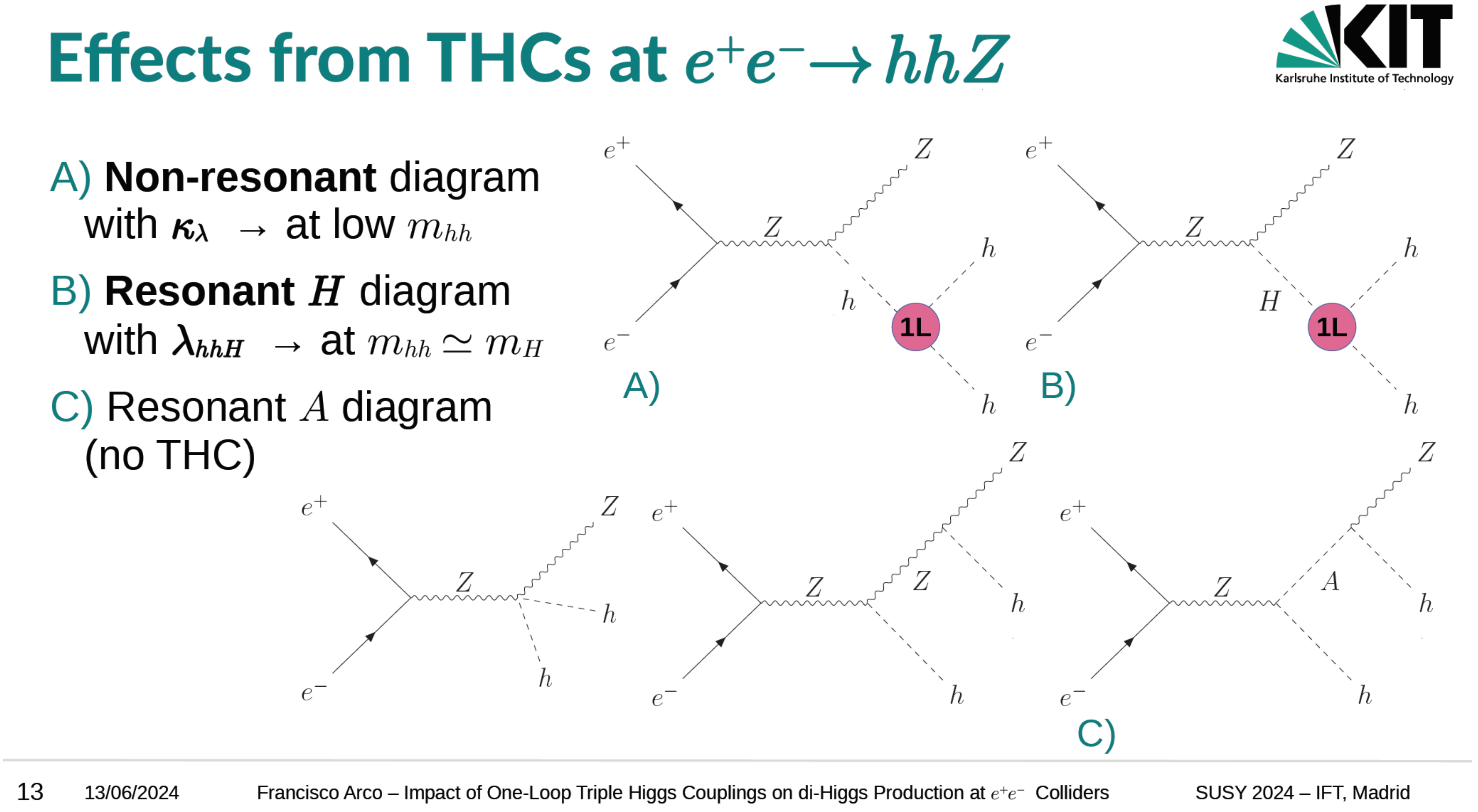
(In the SM, top-loops are ~ -8%)

⇒ effect of the extended BSM Higgs sector!

Effects on THC determination at the ILC:

[taken from F. Arco '24]

[F. Arco, S.H., M. Mühlleitner '25]



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)

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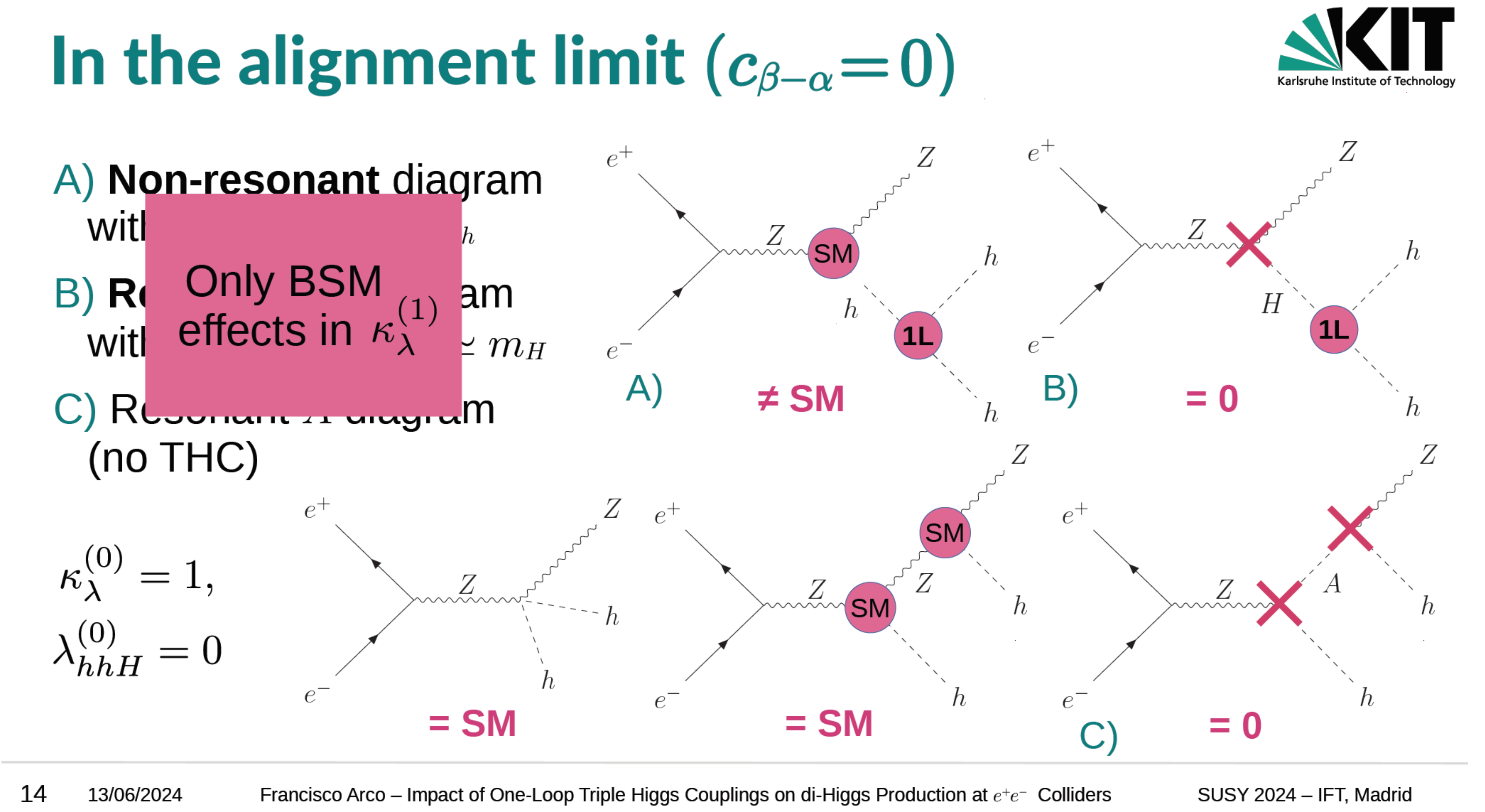
Effects on THC determination at the ILC:

[*taken from F. Arco '24*]

[*F. Arco, S.H., M. Mühlleitner '25*]



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

A) **Non-resonant** diagram
wit

B) **R**
wit

C) R diagram
(no THC)

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

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

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How to determine the significance of the H resonance?

Theoretical estimator:

$$R := \frac{\sum_i \left|\bar{N}_i^R - \bar{N}_i^C\right|}{\sqrt{\sum_i \bar{N}_i^C}}$$

$\bar{N}_i^R$: # of events in bin i under the resonance

$\bar{N}_i^C$: # of events in bin i in the continuum/SM

under the condition:

$$\left|\bar{N}_i^R - \bar{N}_i^C\right| \geq 2 \quad \text{in bin } i$$

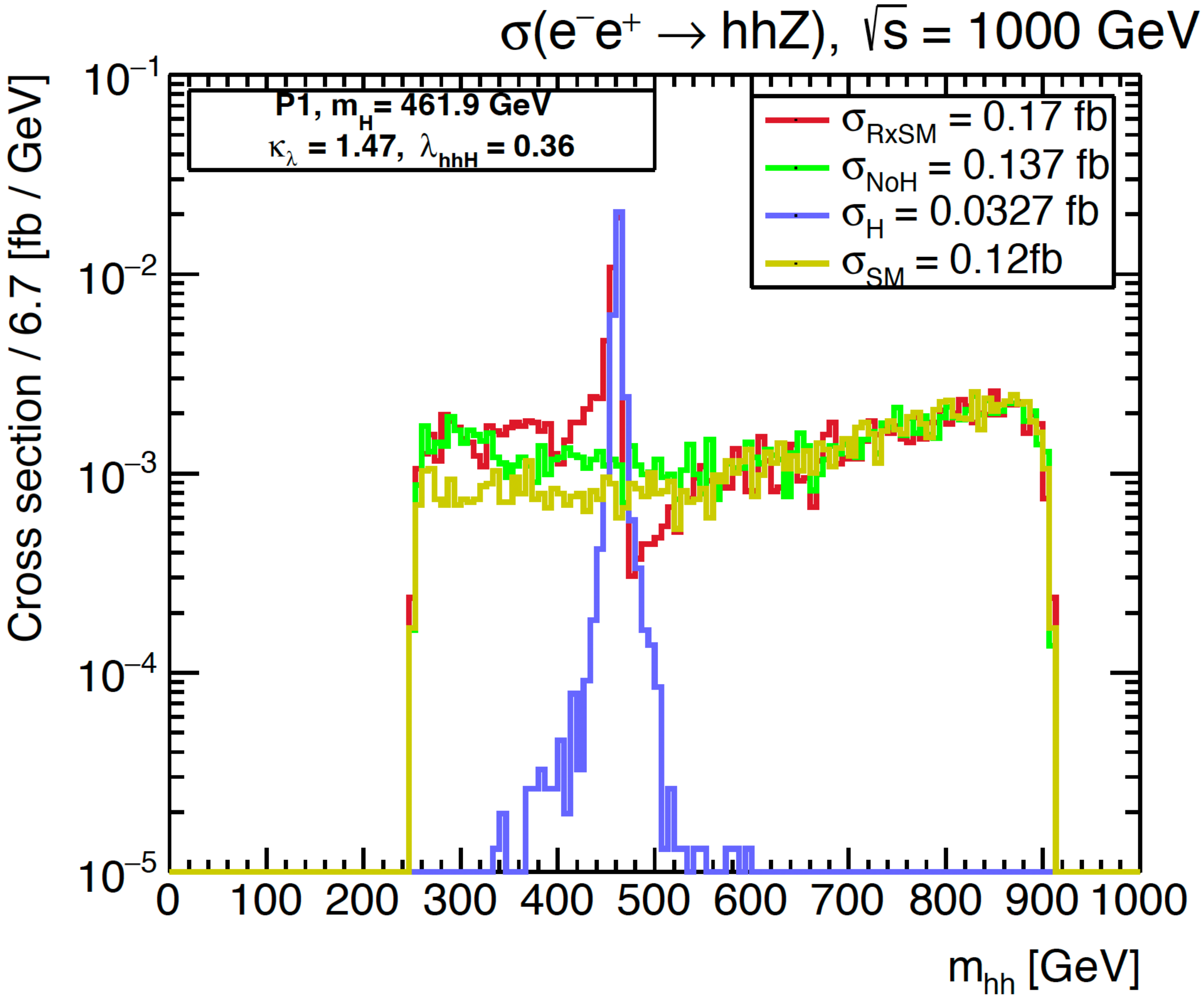
$\bar{N}$:= $N \times \left(\mathrm{BR}(h \to b\bar{b})\right)^2 \times \mathcal{A} \times {\varepsilon_b}^4$

$\mathcal{A}$: $p_T^Z > 20$ GeV, $p_T^b > 20$ GeV, $|\eta_b| > 2$, $\Delta R_{bb} > 0.4$ ≈ 0.75

$\varepsilon_b = 0.8$

$\mathcal{L} = 8\,\mathrm{ab}^{-1}$

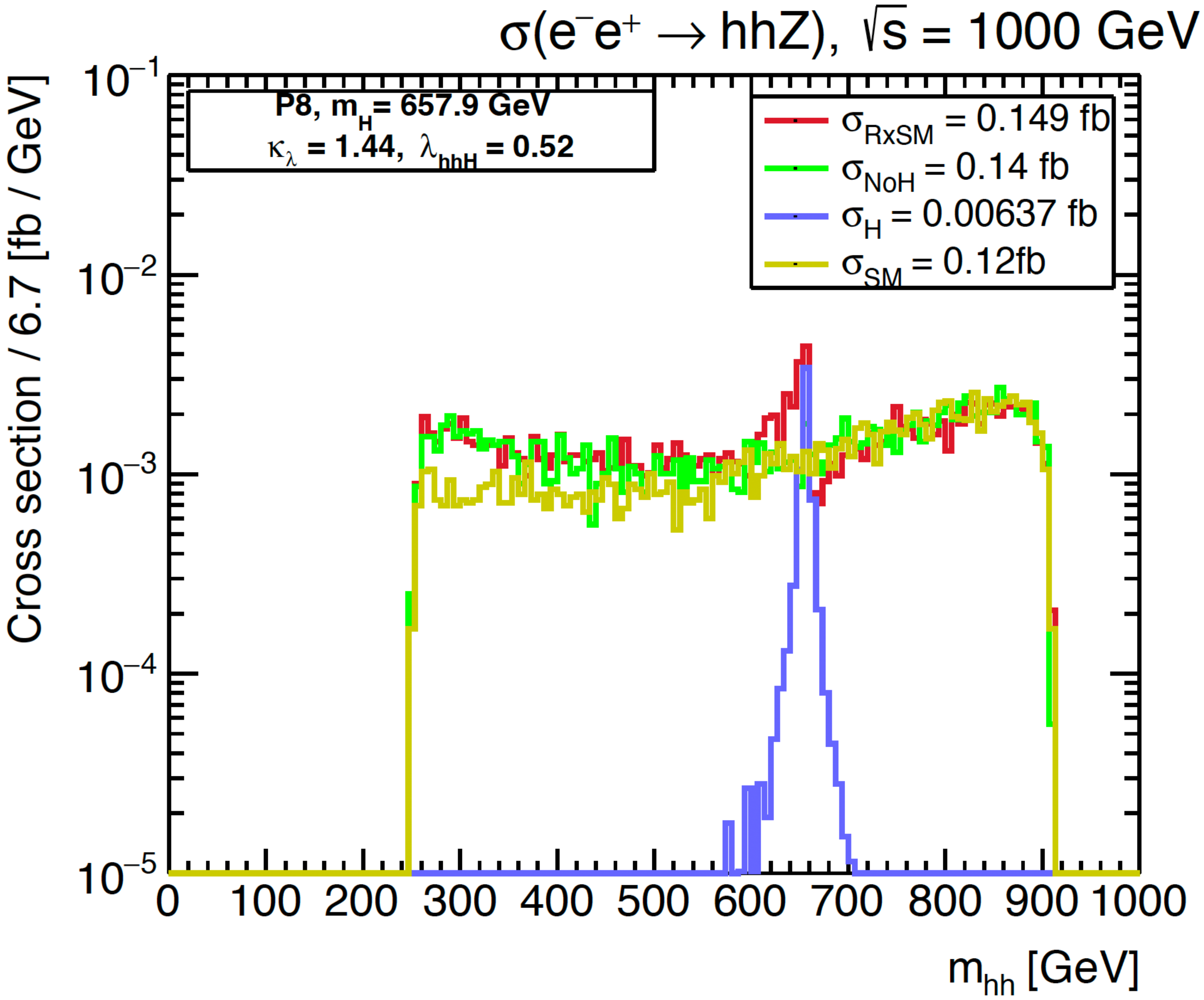
RxSM: m_{hh} for BP1 (lowest m_H)



Effects of κ_λ: low m_{hh}

Effects of λ_{hhH}: at $m_{hh} \sim m_H$ $\Rightarrow$ clear peak-dip structure

RxSM: m_{hh} for BP8 (highest m_H)



Effects of κ_λ: low m_{hh}

Effects of λ_{hhH}: at $m_{hh} \sim m_H$ ⇒ less clear peak-dip structure

RxSM: Summary of sensitivities:

	P1	P2	P3	P4	P5	P6	P7	P8
R	13.59	14.35	10.54	7.16	5.75	7.26	3.39	3.70
m_H [GeV]	461.9	470.8	469.4	530.9	575.1	529.6	642.5	656.1
λ_{hhH}	0.36	0.35	0.33	0.38	0.45	0.40	0.49	0.52

Benchmark plane artefact:

lower λ_{hhH} $\Leftrightarrow$ lower m_H $\Leftrightarrow$ higher R

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Q: Can we actually measure λ_{hhH}?

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Benchmark plane artefact:

lower λ_{hhH} $\Leftrightarrow$ lower m_H $\Leftrightarrow$ higher R

Q: Can we actually measure λ_{hhH}?

A: Yes! Either with NNs , or at high-energy lepton colliders

5. Measurement of BSM THCs

You can choose:

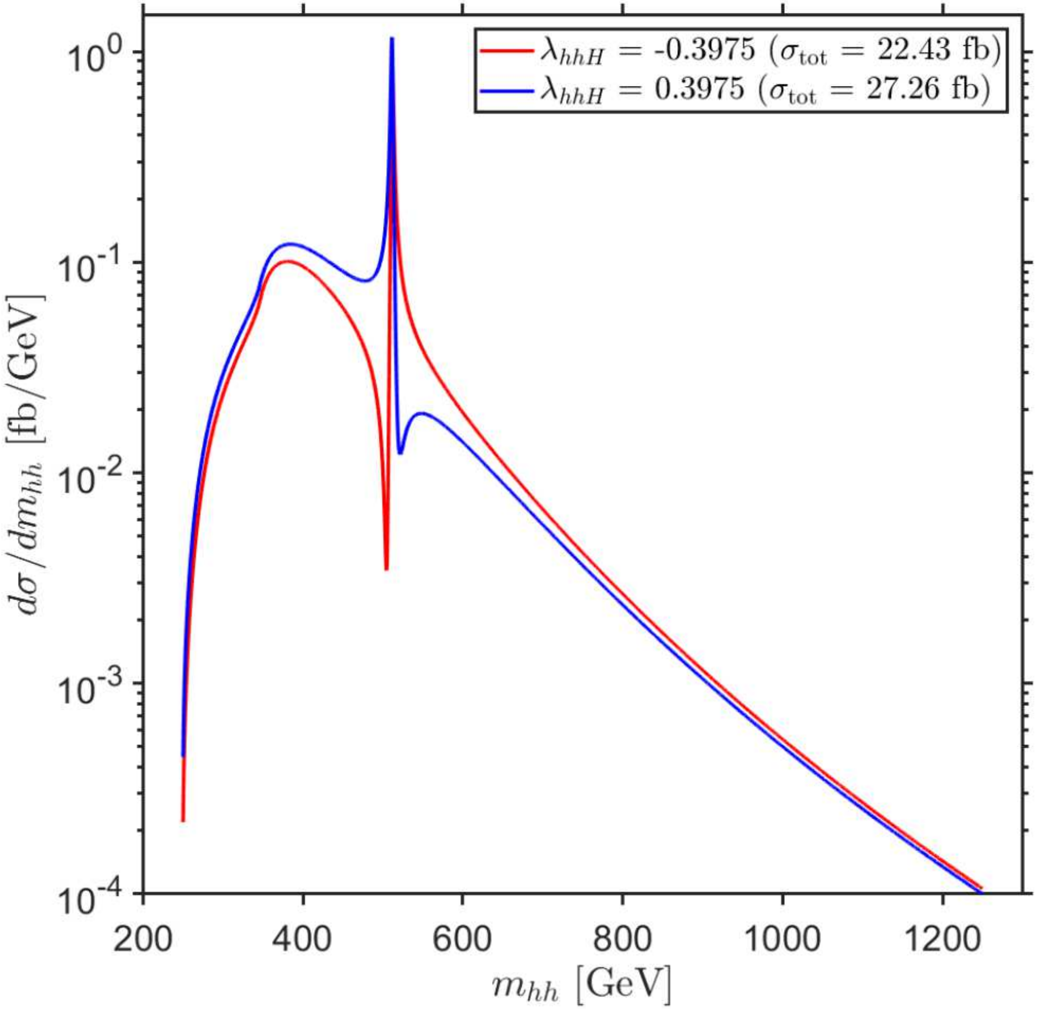
1. THC BSM measurement at the HL-LHC with NNs

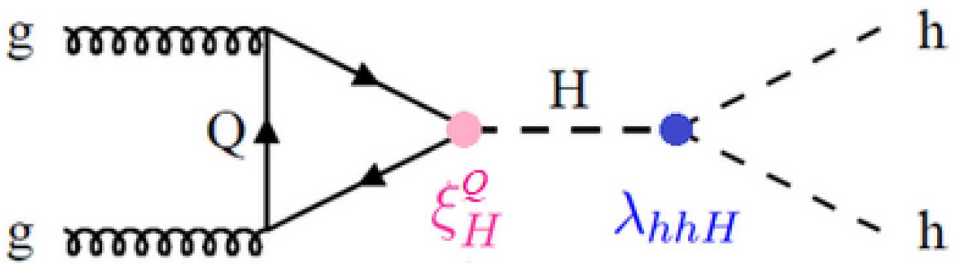
2. BSM THC measurements at a μC

THC BSM measurement at the HL-LHC with NNs

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

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





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

Di-Higgs production at the HL-LHC:

[F. Arco, S.H., M. Mühlleitner, K. Radchenko '22]

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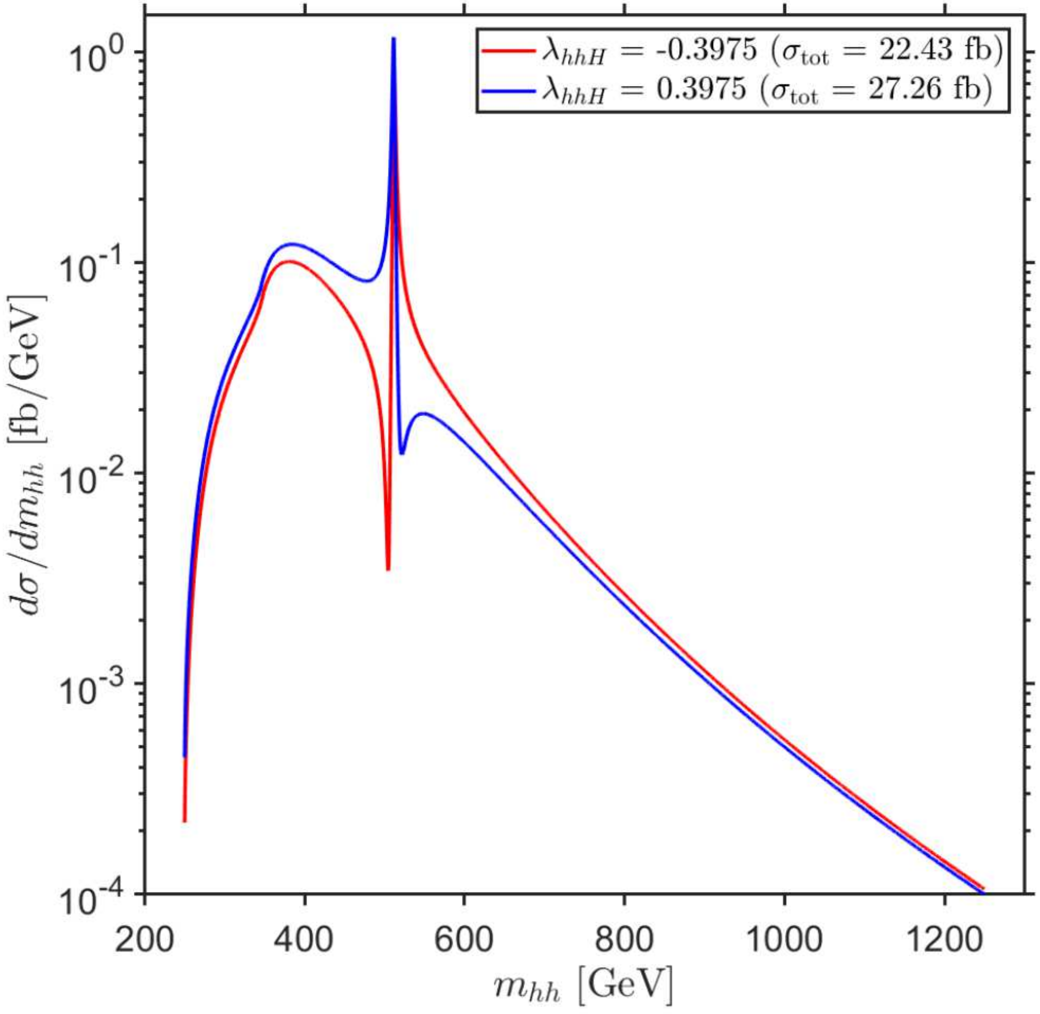
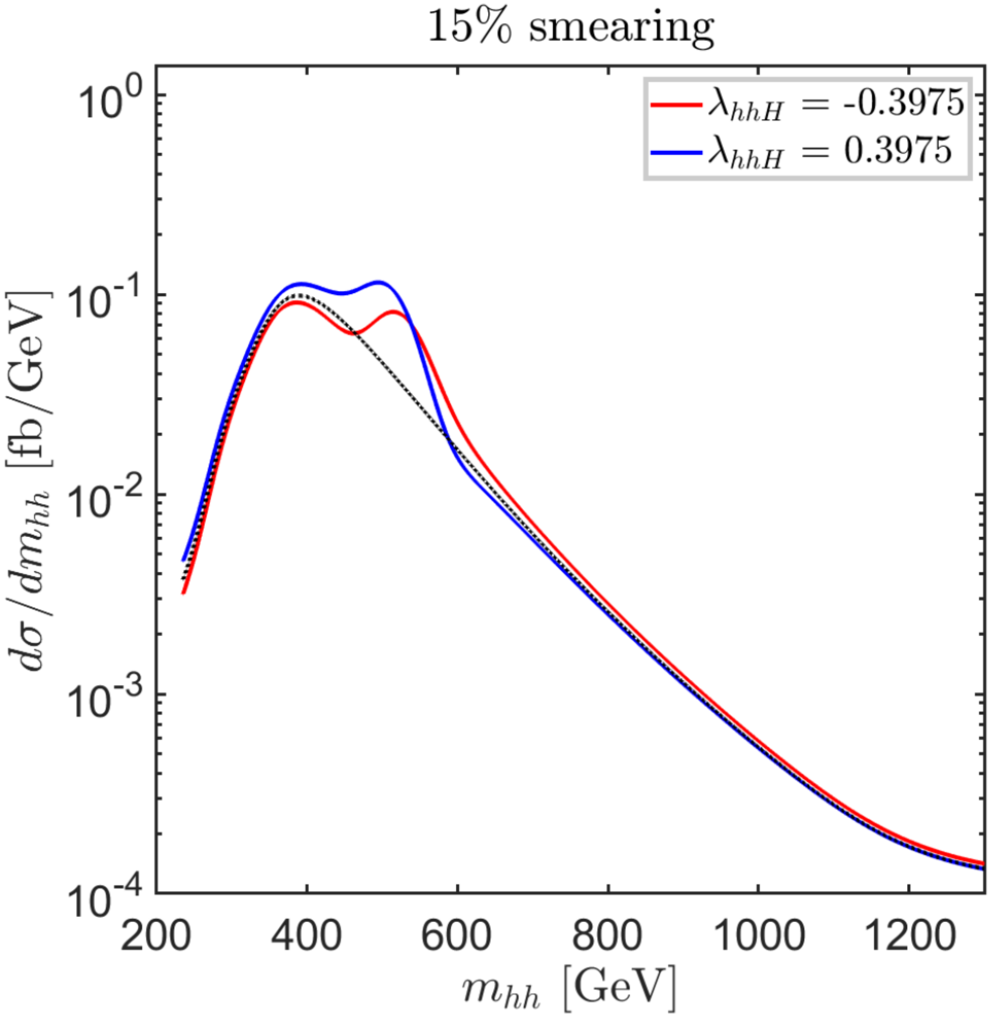


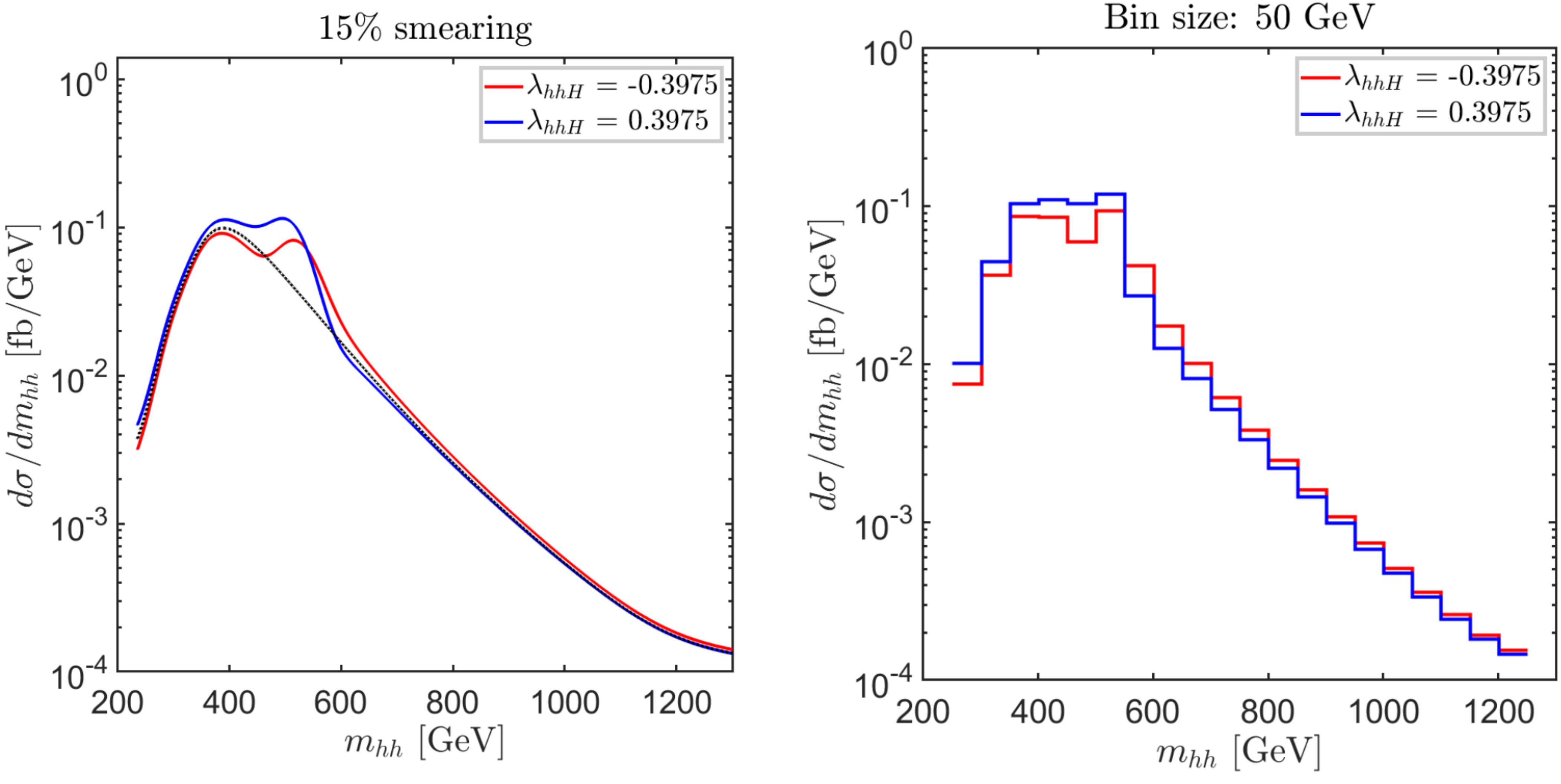


⇒ smearing of 15% applied (optimistic?) ⇒ access to $\xi_H^t \times \lambda_{hhH}$?

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

Benchmark point: 2HDM type I,

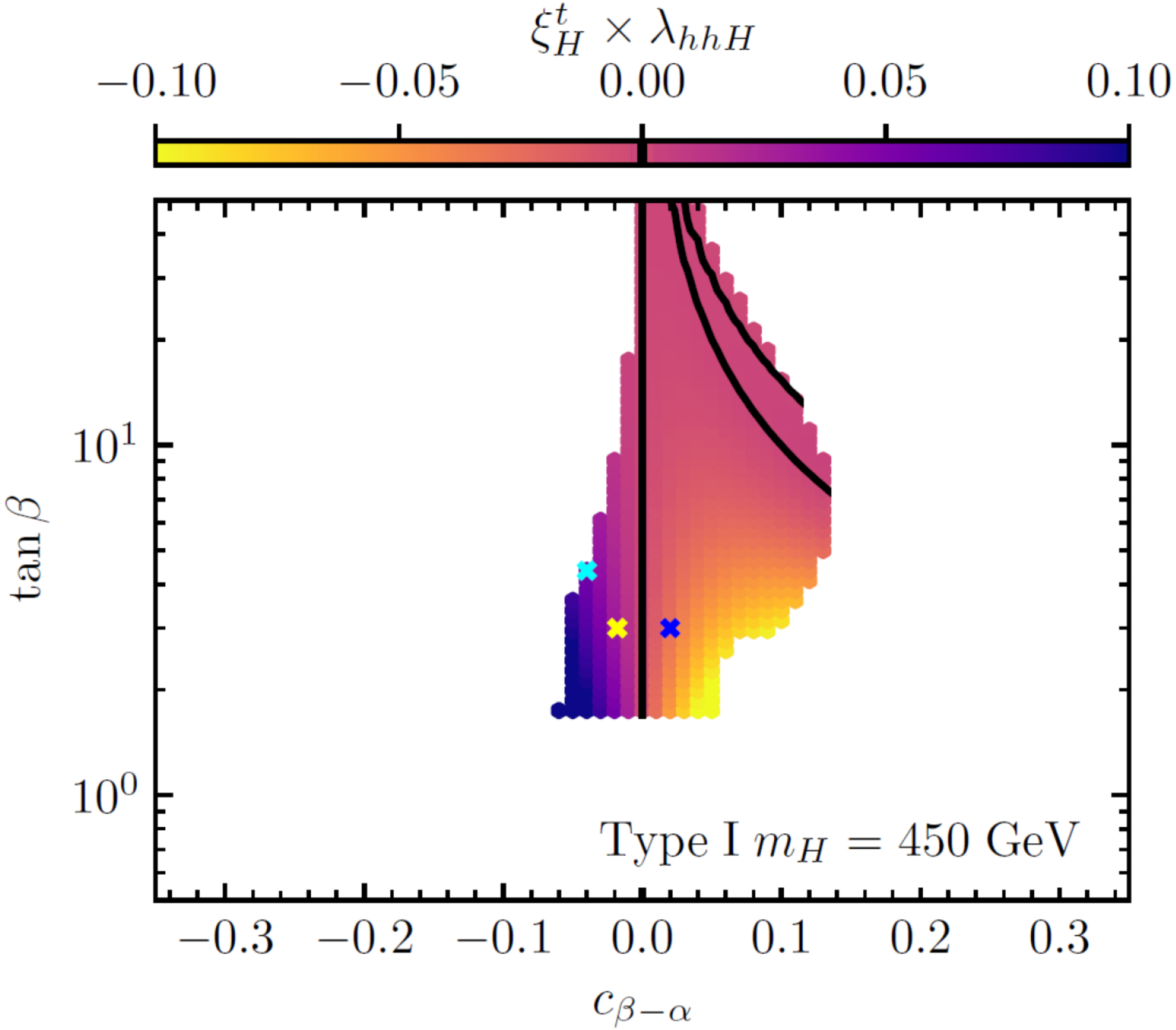
$m_{A,H^\pm} = 545$ GeV$, m_H = 515$ GeV$, t_\beta = 10, c_{\beta-\alpha} = 0.2, m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$



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

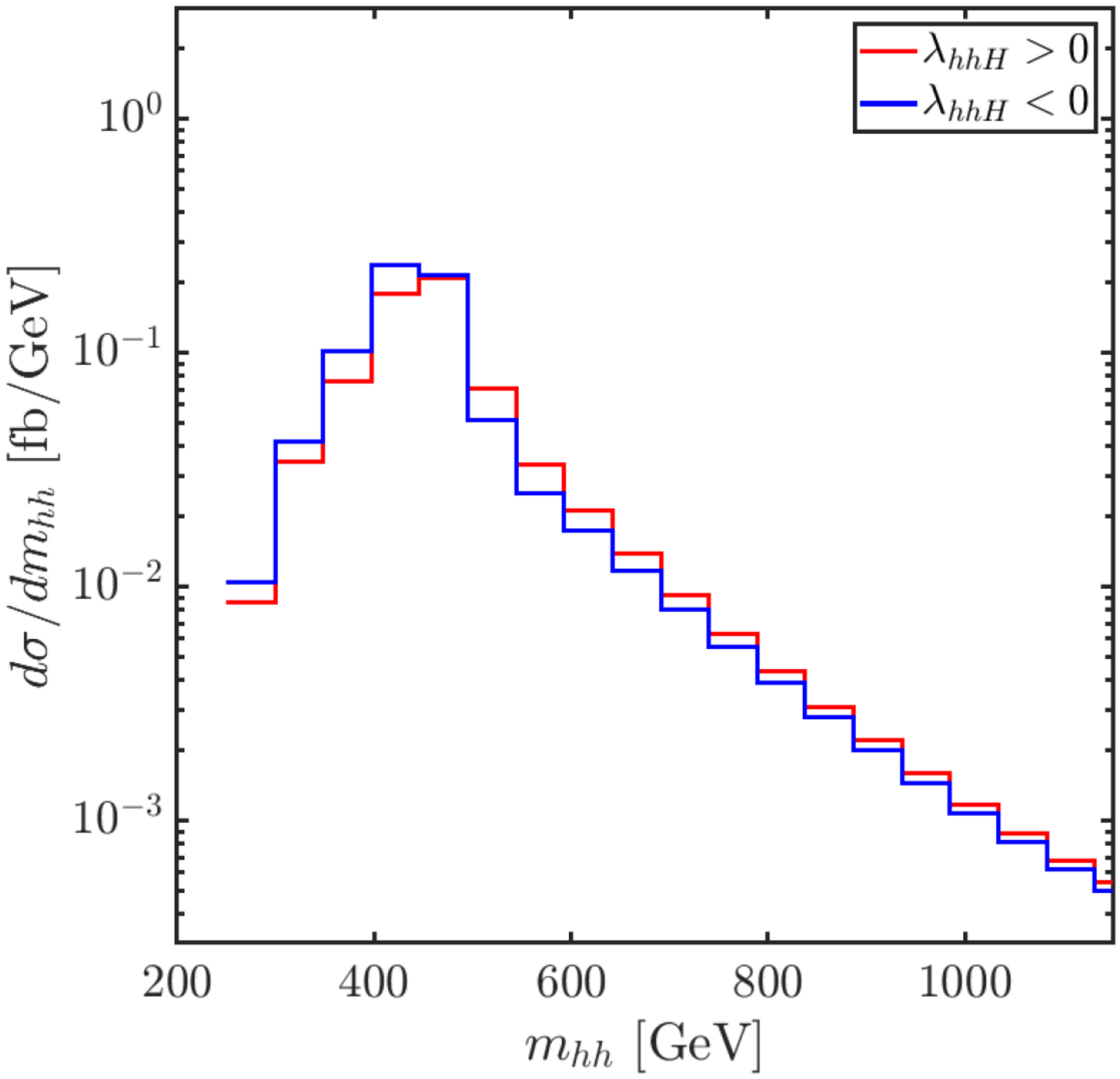
Parameter plane to train the NN:

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



Each point yields an m_{hh} distribution ⇒ fed to the NN

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

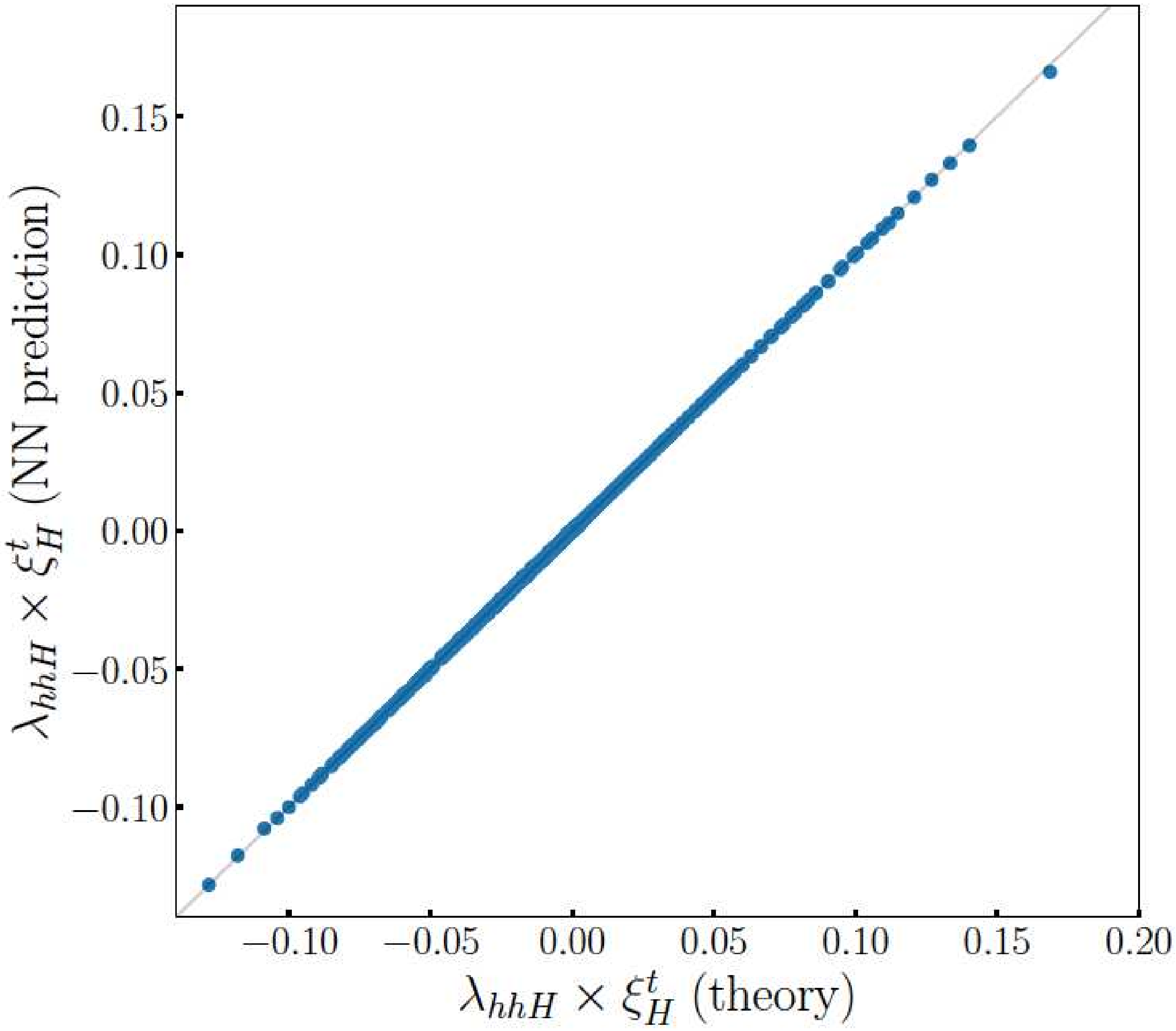


NN set-up:

- 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

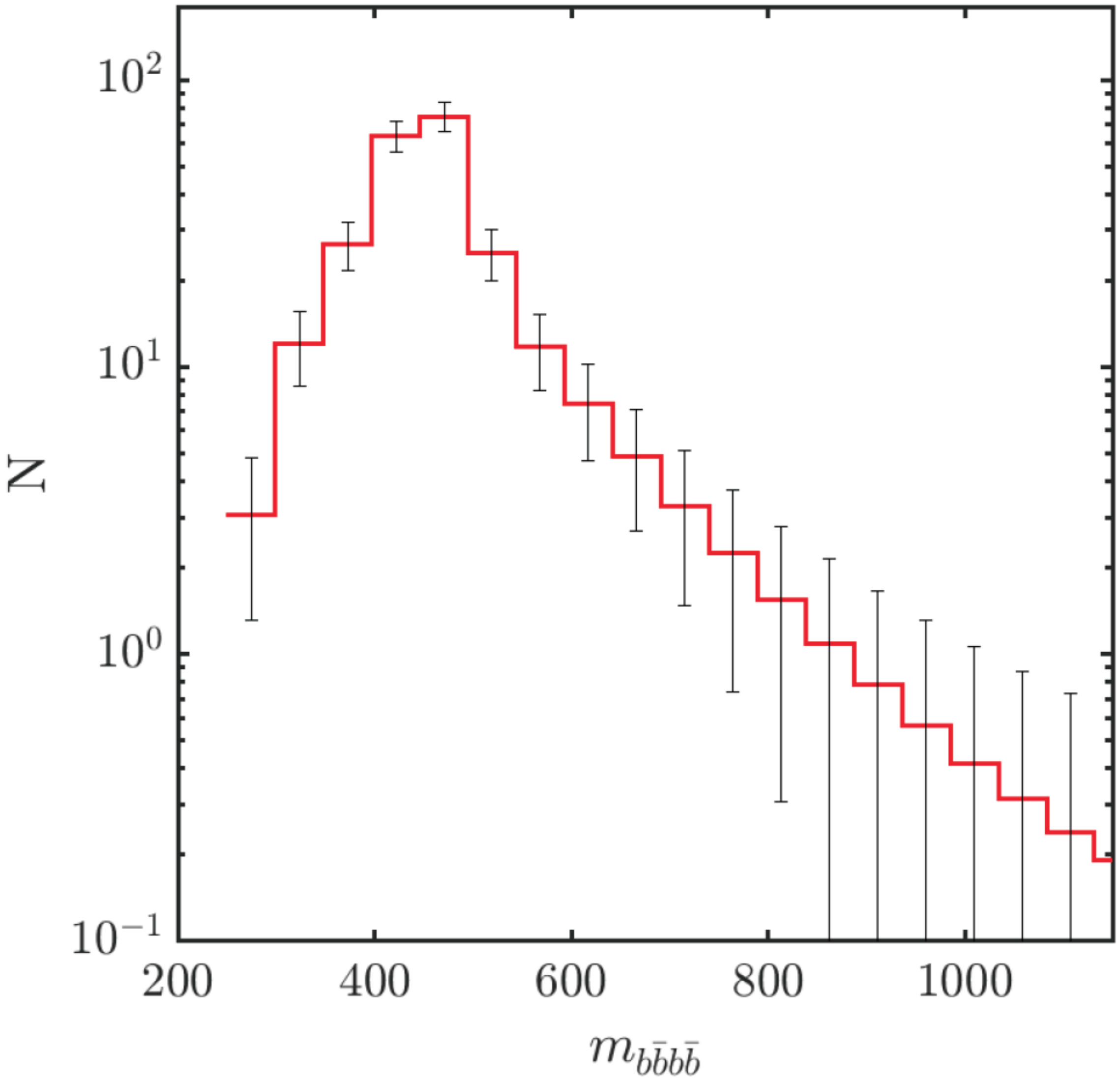
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



$\Rightarrow$ but not realistic . . .

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

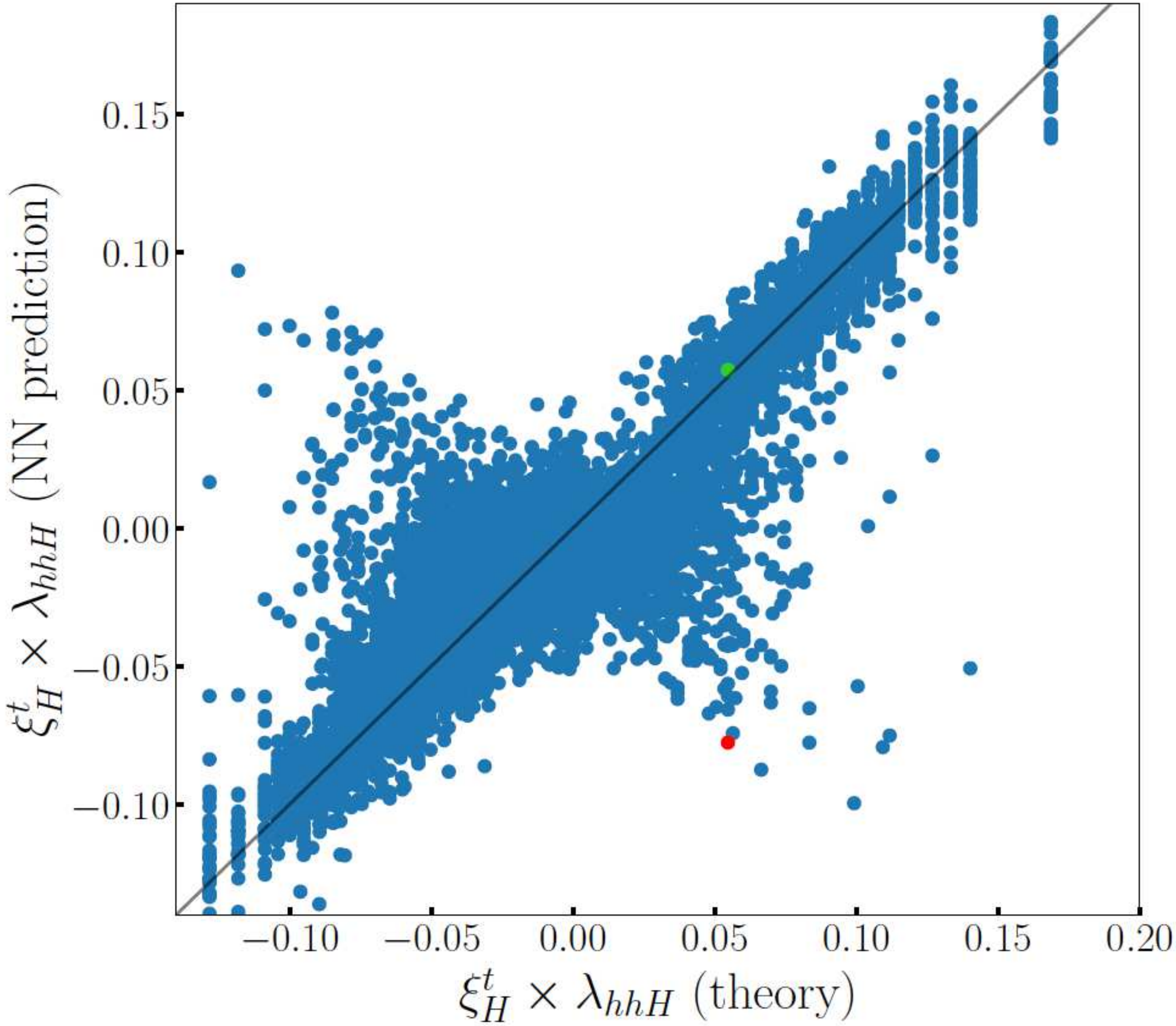
(and corr. exp. efficiencies) [M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY]



⇒ for each point in the plane test an m_{hh} distribution statistically smeared

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

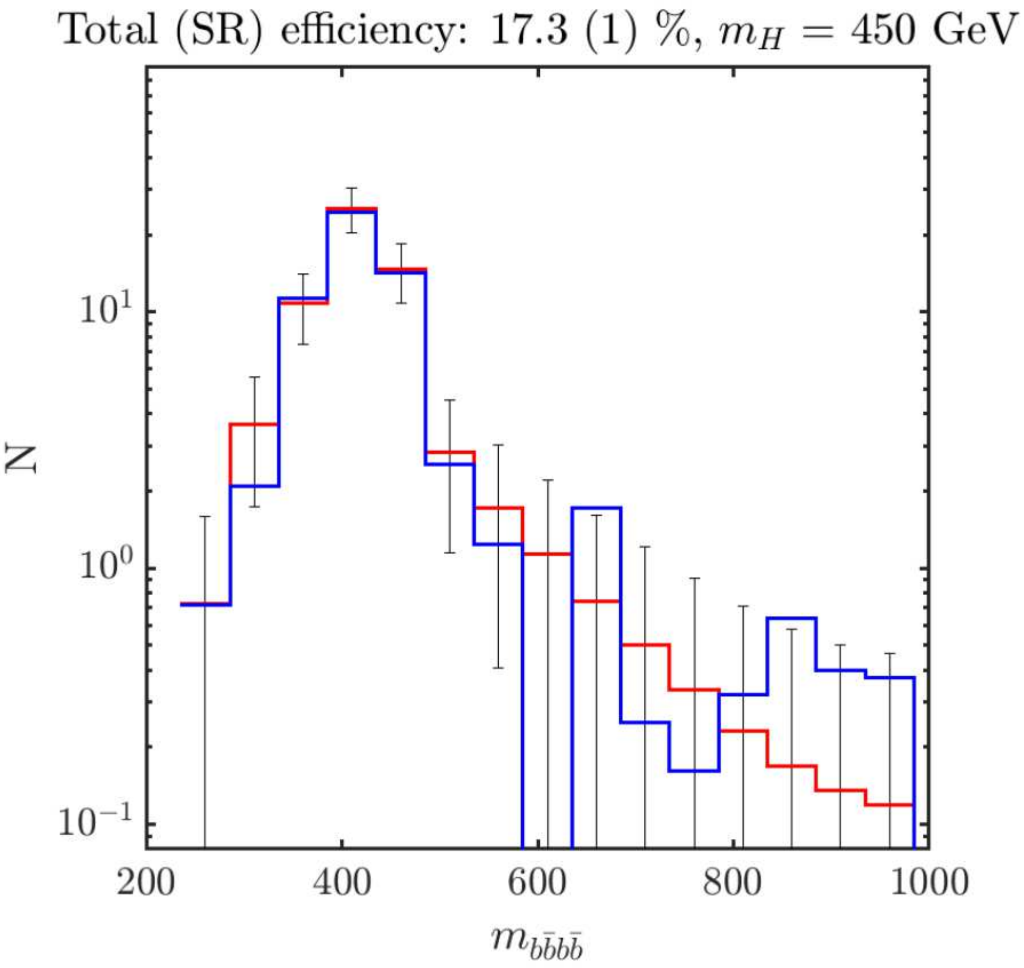
[*M. Frank, S.H., M. Mühlleitner, K. Radchenko, PRELIMINARY*]



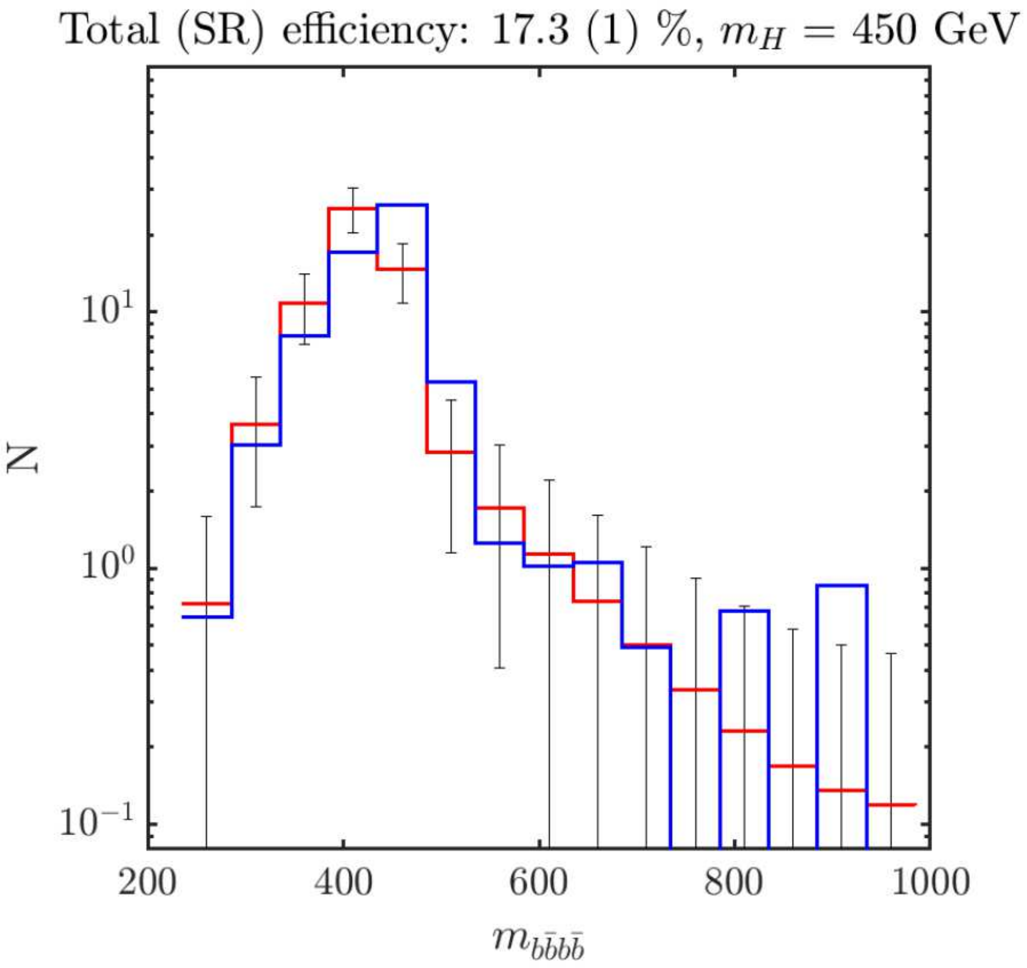
“Realistic” determination of $\xi_H^t \times \lambda_{hhH}$:

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

“good” point



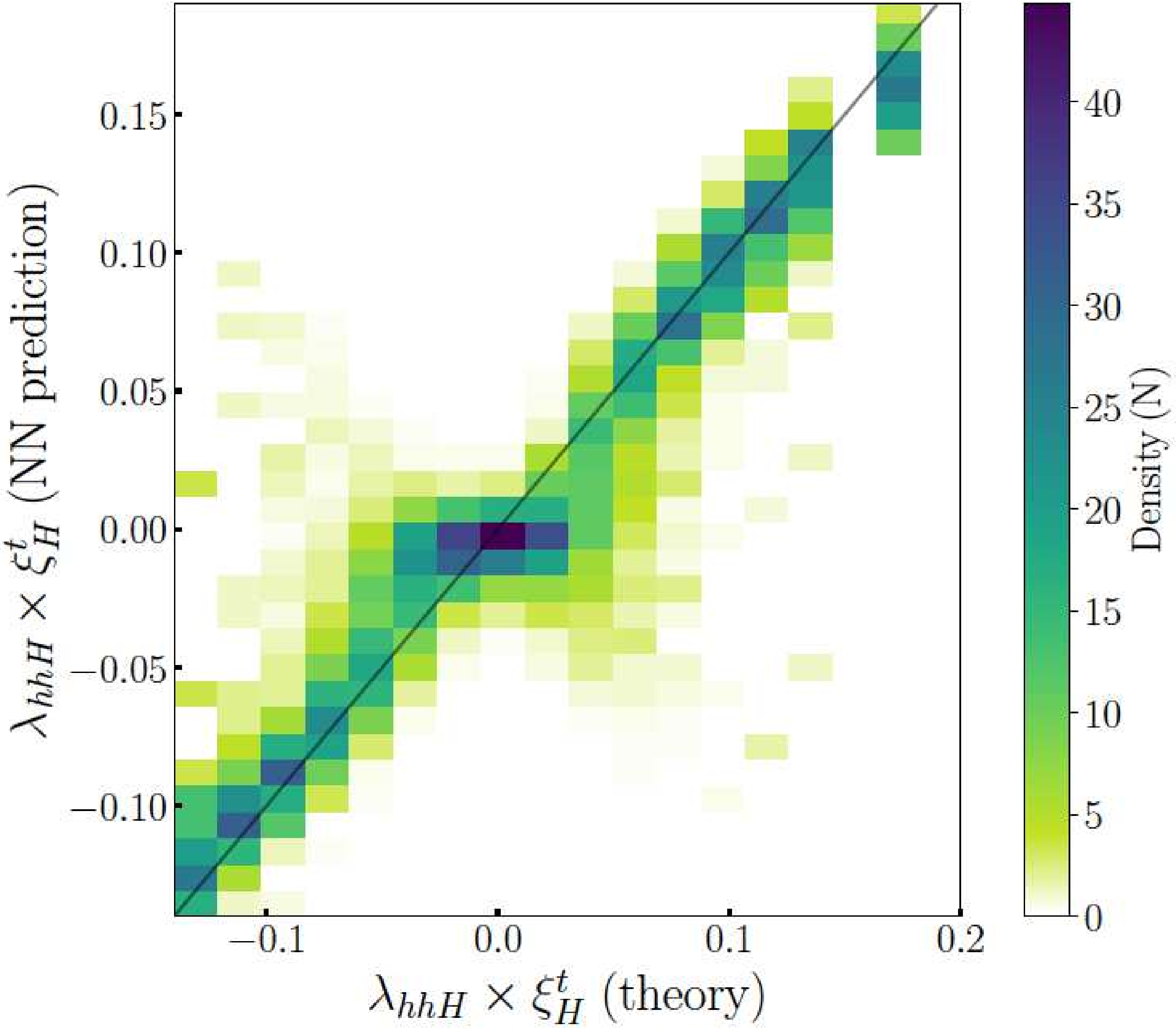
“bad” point



$\Rightarrow$ “good” point much more likely than “bad” points

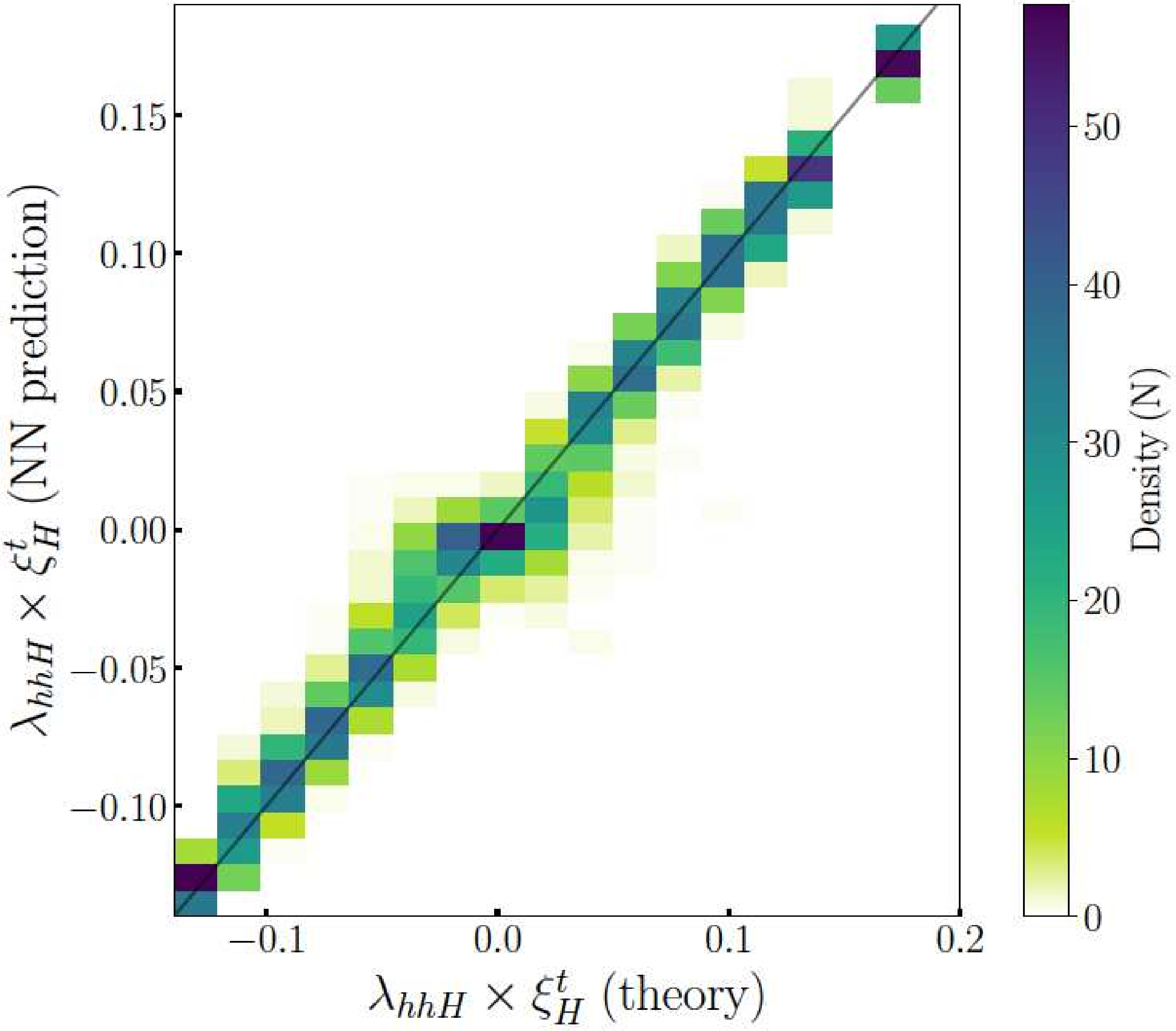
“Realistic” determination of $\lambda_{hhH} \times \xi^t_H$:

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



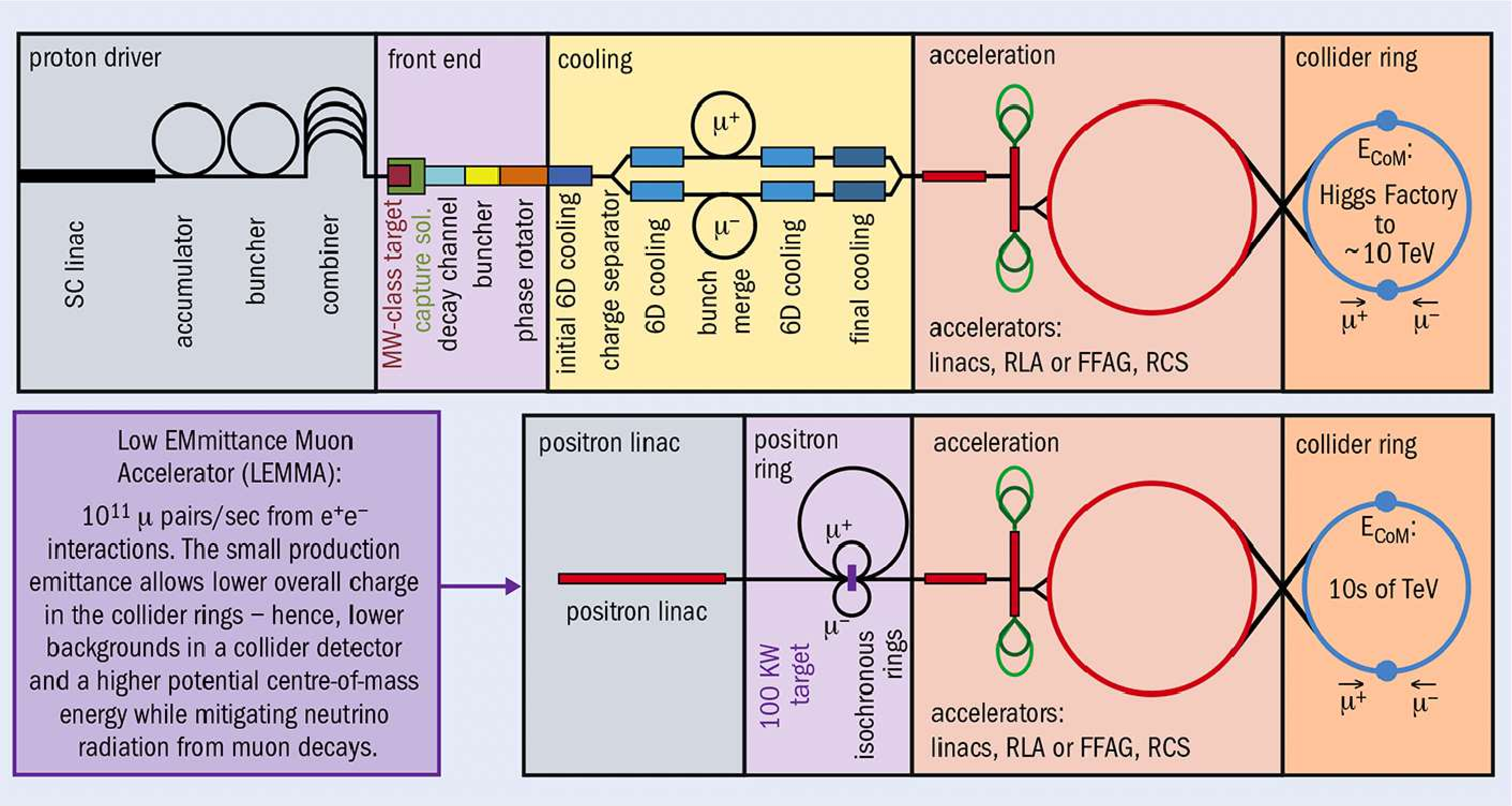
Hypothetical improvement in the efficiencies by $\times 2$:

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



BSM THC measurements at a μC [*M. Fernández-Monzón Aguilar, S.H. '25*]

Several proposals exists:

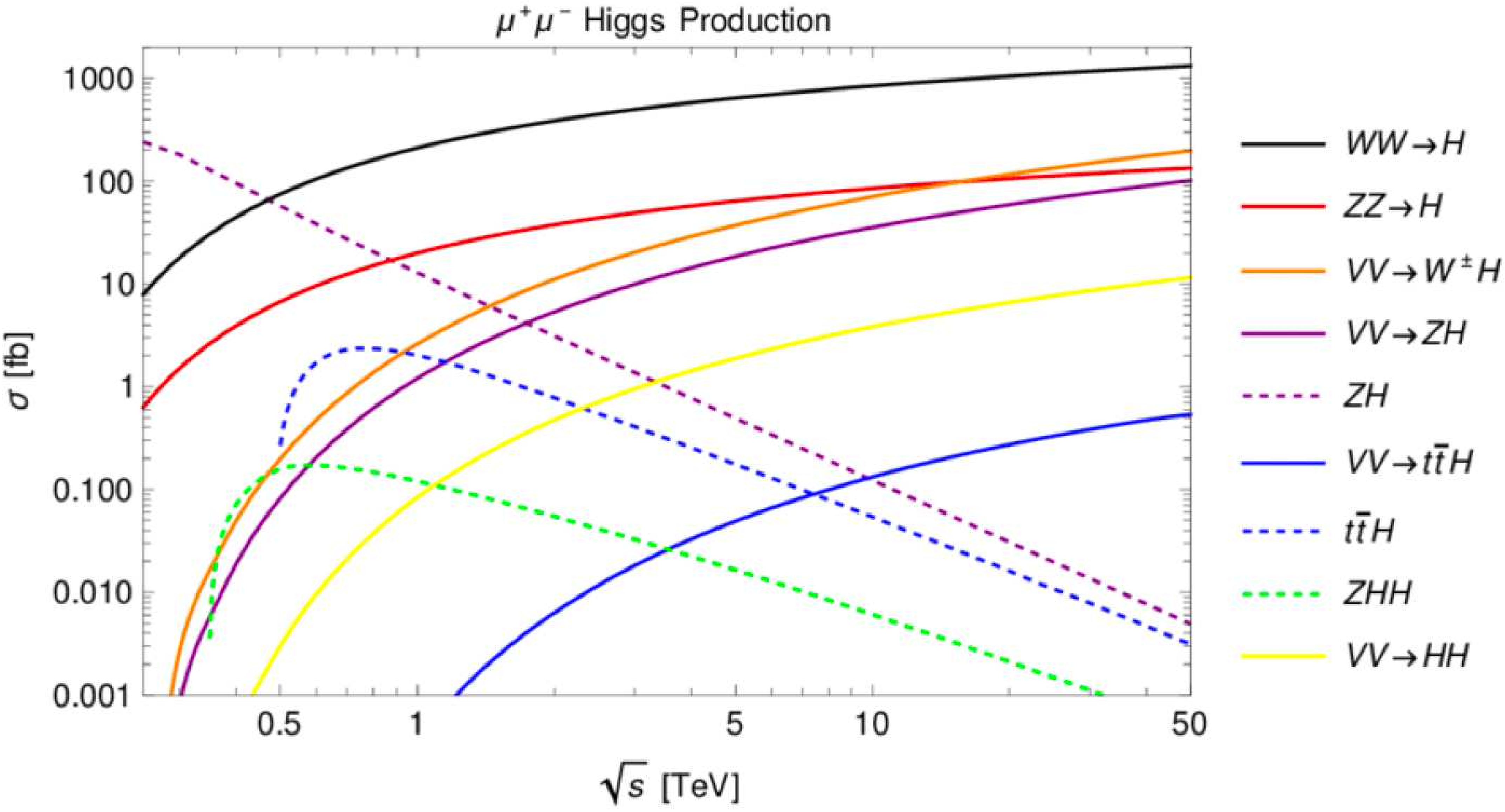


Low EMmittance Muon Accelerator (LEMMA):

10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential centre-of-mass energy while mitigating neutrino radiation from muon decays.

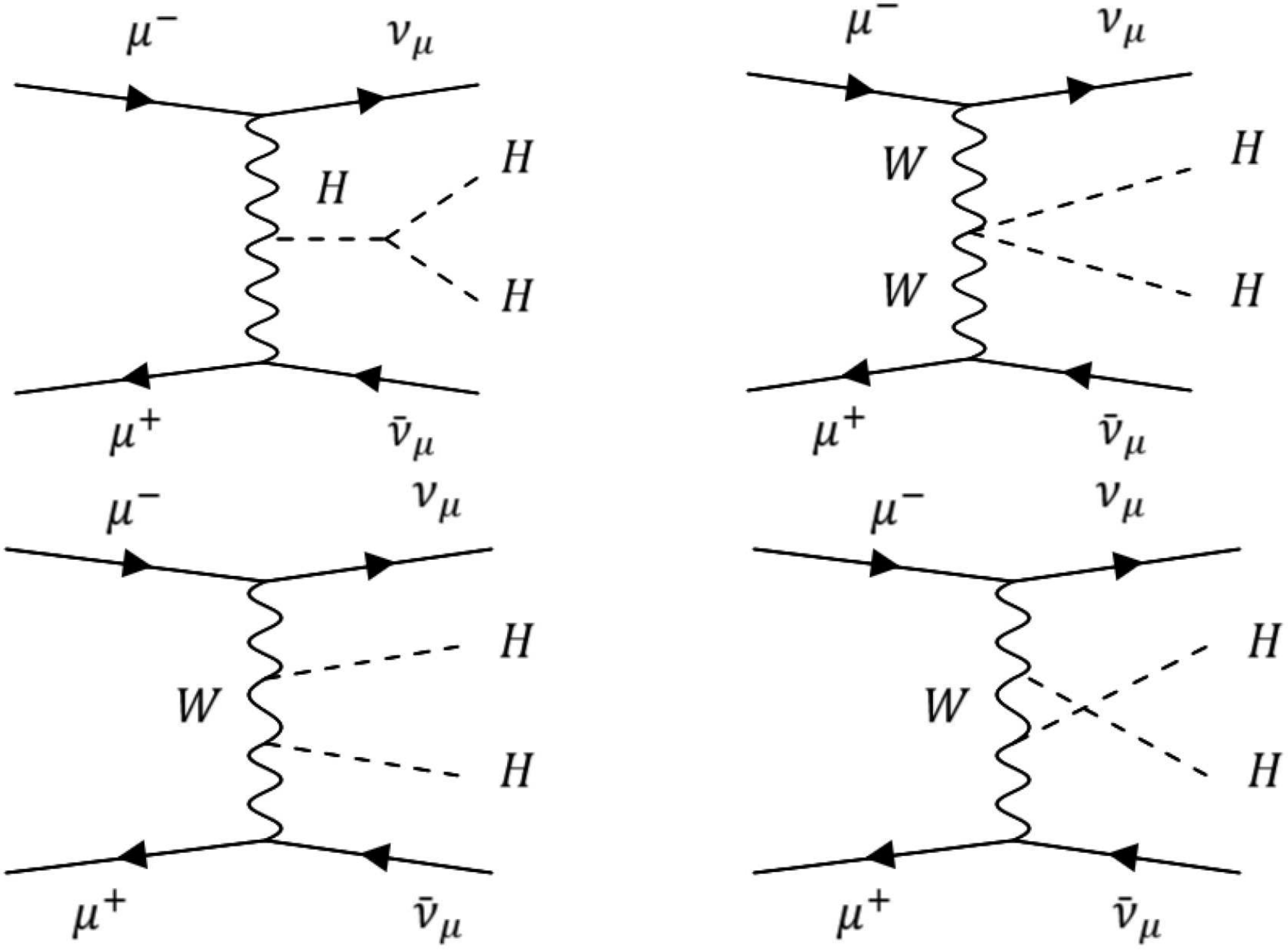
We assume: $\sqrt{s} = 3$ TeV, $\mathcal{L} = 5\,\text{ab}^{-1}$

Higgs cross sections:



$\Rightarrow \mu^+\mu^- \to \nu\nu hh/hH/HH$ is a good choice

Feynman diagrams (in the SM):



⇒ calculated with MadGraph

BSM THC measurements at the μC

Objective I

Calculate the total di-Higgs production cross section via **MadGraph** at a **3 TeV Muon Collider (MuC)** via the **VBF channel** for the following final states:

- $\mu^+\mu^- \to \boldsymbol{hh\nu\bar{\nu} \to (b\bar{b})(b\bar{b})\nu\bar{\nu}}$
- $\mu^+\mu^- \to \boldsymbol{hH\nu\bar{\nu} \to (b\bar{b})(ZZ/W^+W^-} \to \text{jets}\boldsymbol{)\nu\bar{\nu}}$
- $\mu^+\mu^- \to \boldsymbol{HH\nu\bar{\nu} \to (ZZ/W^+W^-} \to \text{jets}\boldsymbol{)(ZZ/W^+W^-} \to \text{jets}\boldsymbol{)\nu\bar{\nu}}$

Objective II

Estimate the experimental uncertainty in the cross section measurement for each process at $\sqrt{s} = 3$ TeV and an integrated luminosity of $\mathcal{L}_{\text{int}} = 5\ \text{ab}^{-1}$.

Objective III

Extract the trilinear Higgs couplings (THCs) and evaluate their associated uncertainties.

Analysis flow

Generate signal events $\mu^+\mu^- \to h_i h_j \nu\bar{\nu}$ using `MadGraph`.

↓

Shower and hadronise with `Pythia8`.

↓

Apply detector smearing and cuts to events generated by `Pythia8`.

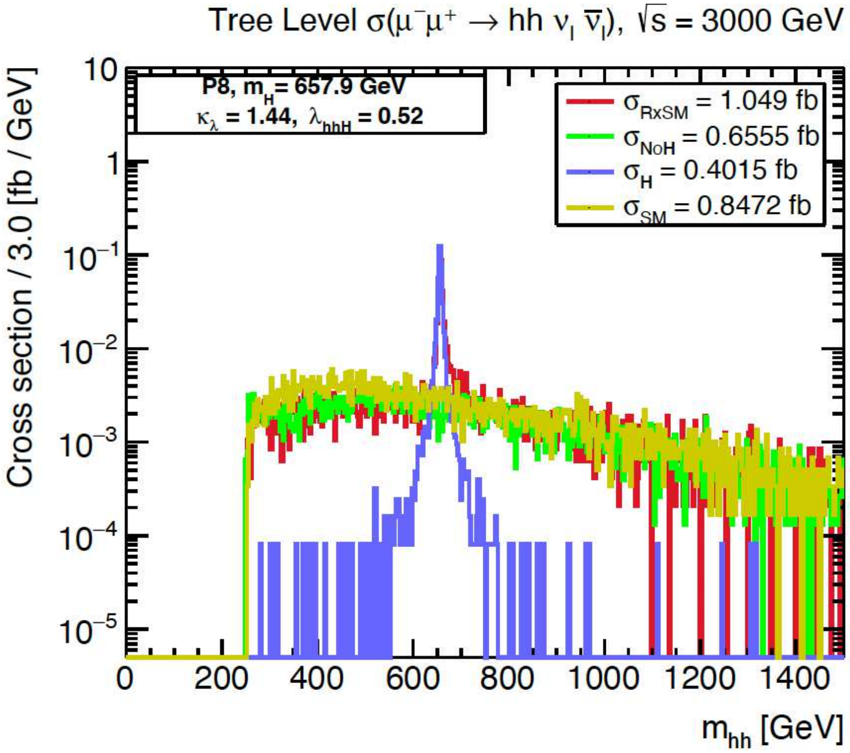
↓

Jet reconstruction using `FastJet` and apply final cuts.

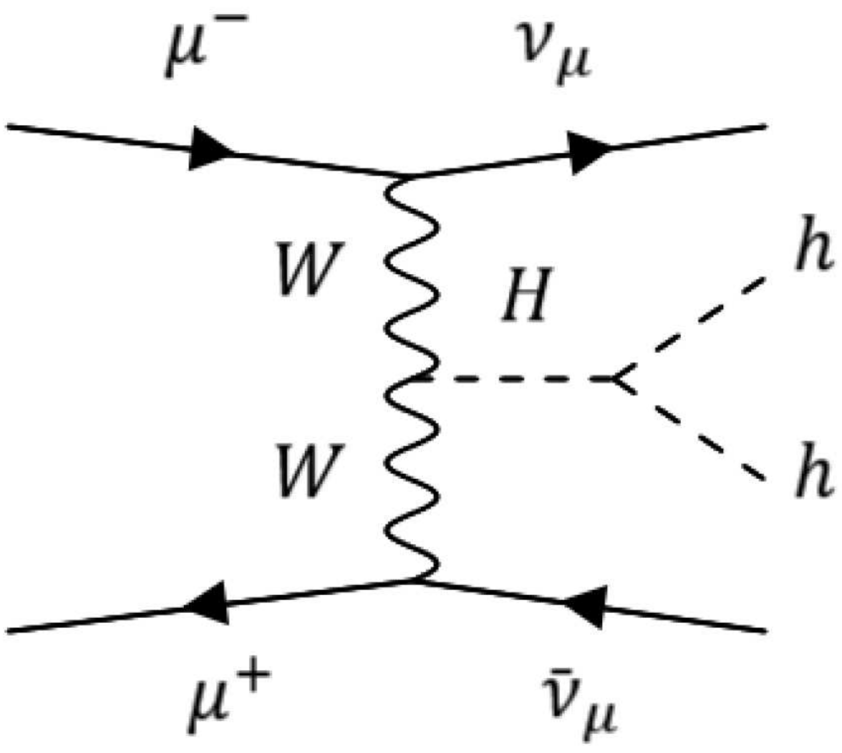
Observable (O)	$\frac{\Delta O}{O}$ [%]
$\sigma(\mu^+\mu^- \to hh\,\nu\bar{\nu} \to b\bar{b}b\bar{b}\,\nu\bar{\nu})$	9.43
$\sigma(\mu^+\mu^- \to hH\,\nu\bar{\nu} \to b\bar{b}qqqq\,\nu\bar{\nu})$	26.11
$\sigma(\mu^+\mu^- \to HH\,\nu\bar{\nu} \to qqqq\,qqqq\,\nu\bar{\nu})$	18.59

⇒ experimental uncertainties obtained

Differential distributions I:



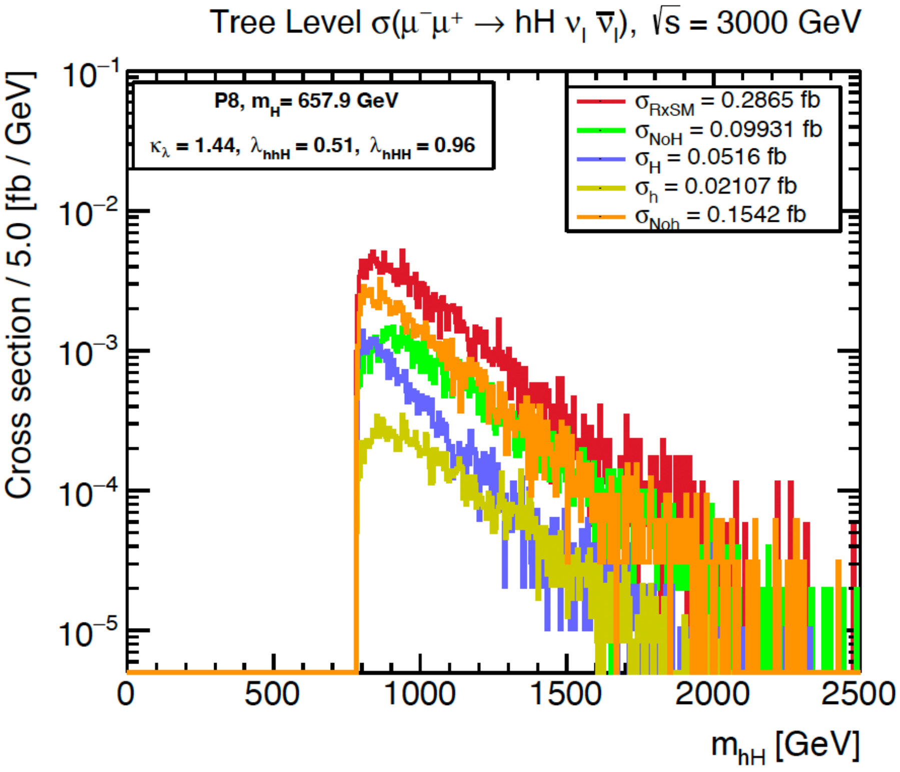
SM-like di-Higgs production for BP8



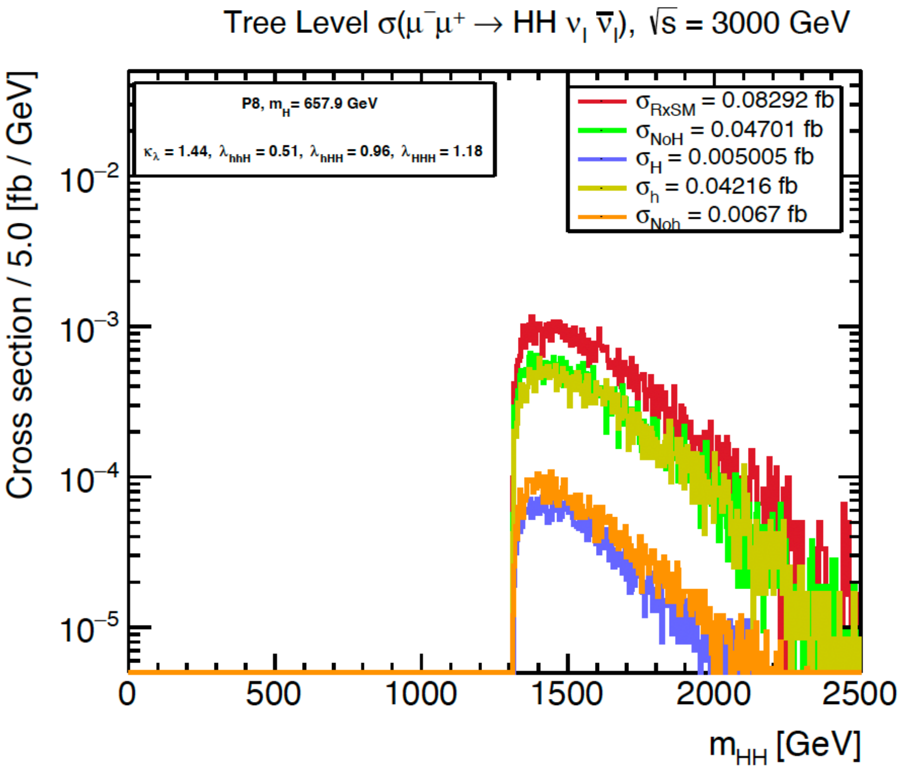
Resonant diagram

⇒ resonance peak as in e^+e^- (obvious)

Differential distributions II:



hH di-Higgs production for BP8



HH di-Higgs production for BP8

⇒ no resonance peaks (obvious)

Determination of all THCs:

⇒ λ_{hhh}, λ_{hhH}, λ_{hHH}, λ_{HHH}

⇒ three production cross sections: hh, hH, HH

⊕ κ_λ measurement as at CLIC (11%)

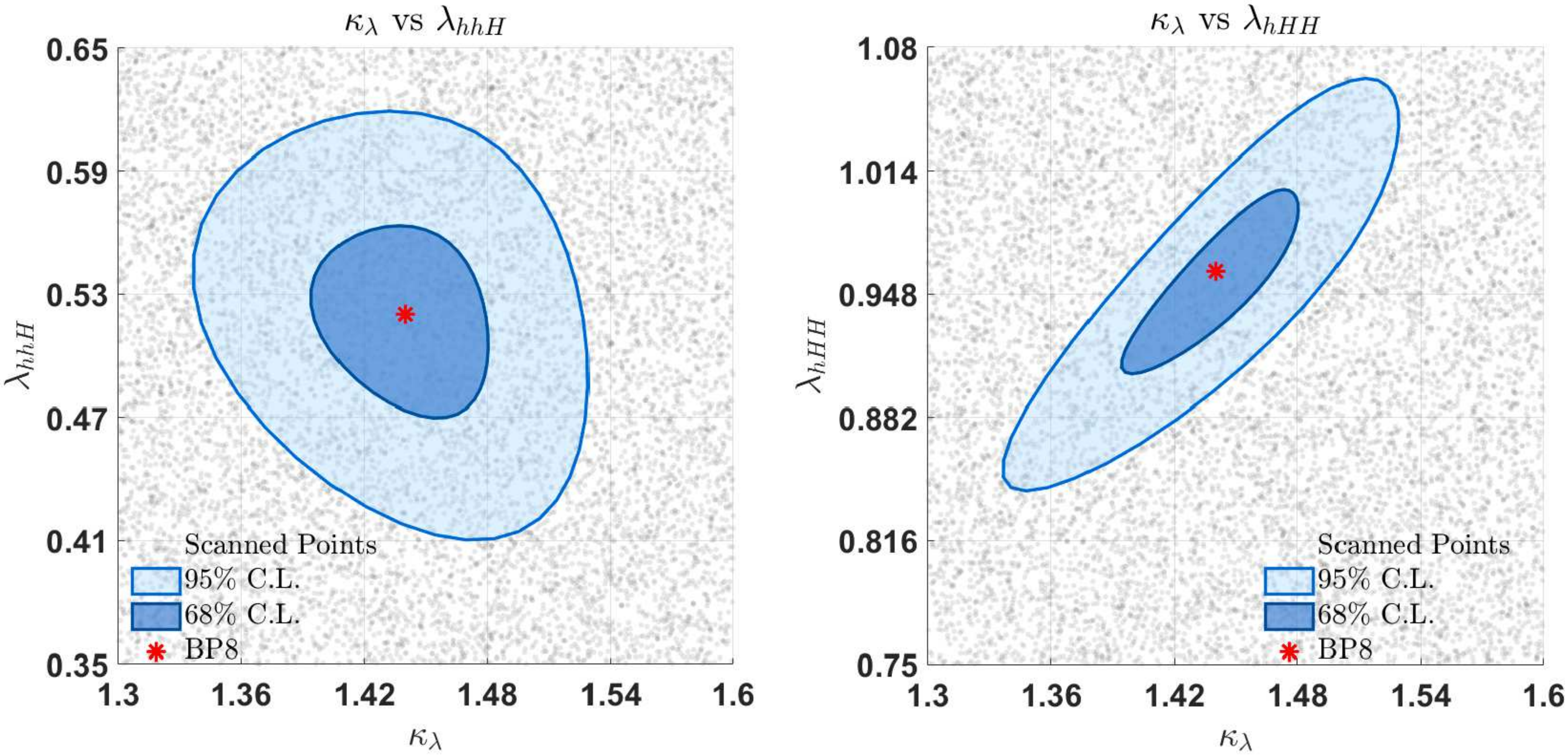
$$\chi^2 = \left(\frac{\kappa_\lambda^{\rm BP} - \kappa_\lambda}{\Delta\kappa_\lambda^{\rm prior}}\right)^2 + \left(\frac{\sigma(\mu^+\mu^- \to hh\nu_\ell\bar\nu_\ell)^{\rm BP} - \sigma(\mu^+\mu^- \to hh\nu_\ell\bar\nu_\ell)}{\Delta\sigma(\mu^+\mu^- \to hh\nu_\ell\bar\nu_\ell)}\right)^2$$
$$+ \left(\frac{\sigma(\mu^+\mu^- \to hH\nu_\ell\bar\nu_\ell)^{\rm BP} - \sigma(\mu^+\mu^- \to hH\nu_\ell\bar\nu_\ell)}{\Delta\sigma(\mu^+\mu^- \to hH\nu_\ell\bar\nu_\ell)}\right)^2$$
$$+ \left(\frac{\sigma(\mu^+\mu^- \to HH\nu_\ell\bar\nu_\ell)^{\rm BP} - \sigma(\mu^+\mu^- \to HH\nu_\ell\bar\nu_\ell)}{\Delta\sigma(\mu^+\mu^- \to HH\nu_\ell\bar\nu_\ell)}\right)^2$$

– scan (randomly) around the true point in all parameters

– find regions with $\chi^2 \le 4.72\,(9.72)$ ⇒ find 68 (95) % CL regions

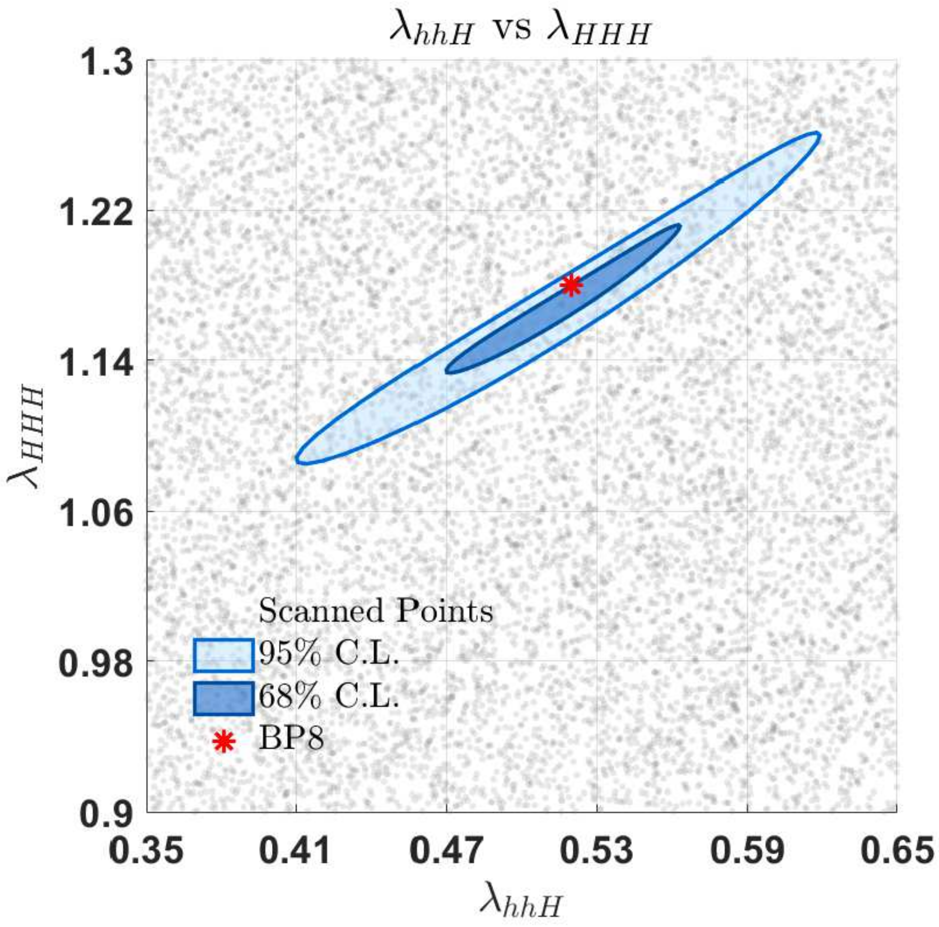
⇒ first determination of all THCs of a model

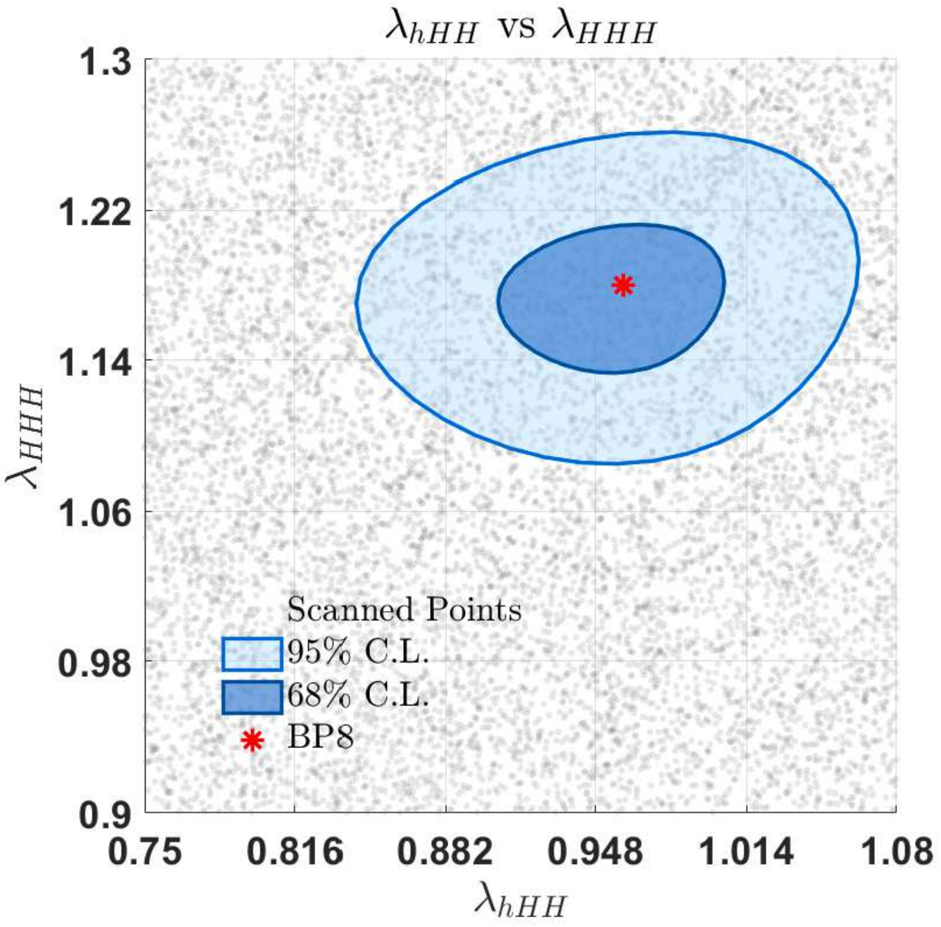
BP8 projection I:



⇒ good determination of THCs

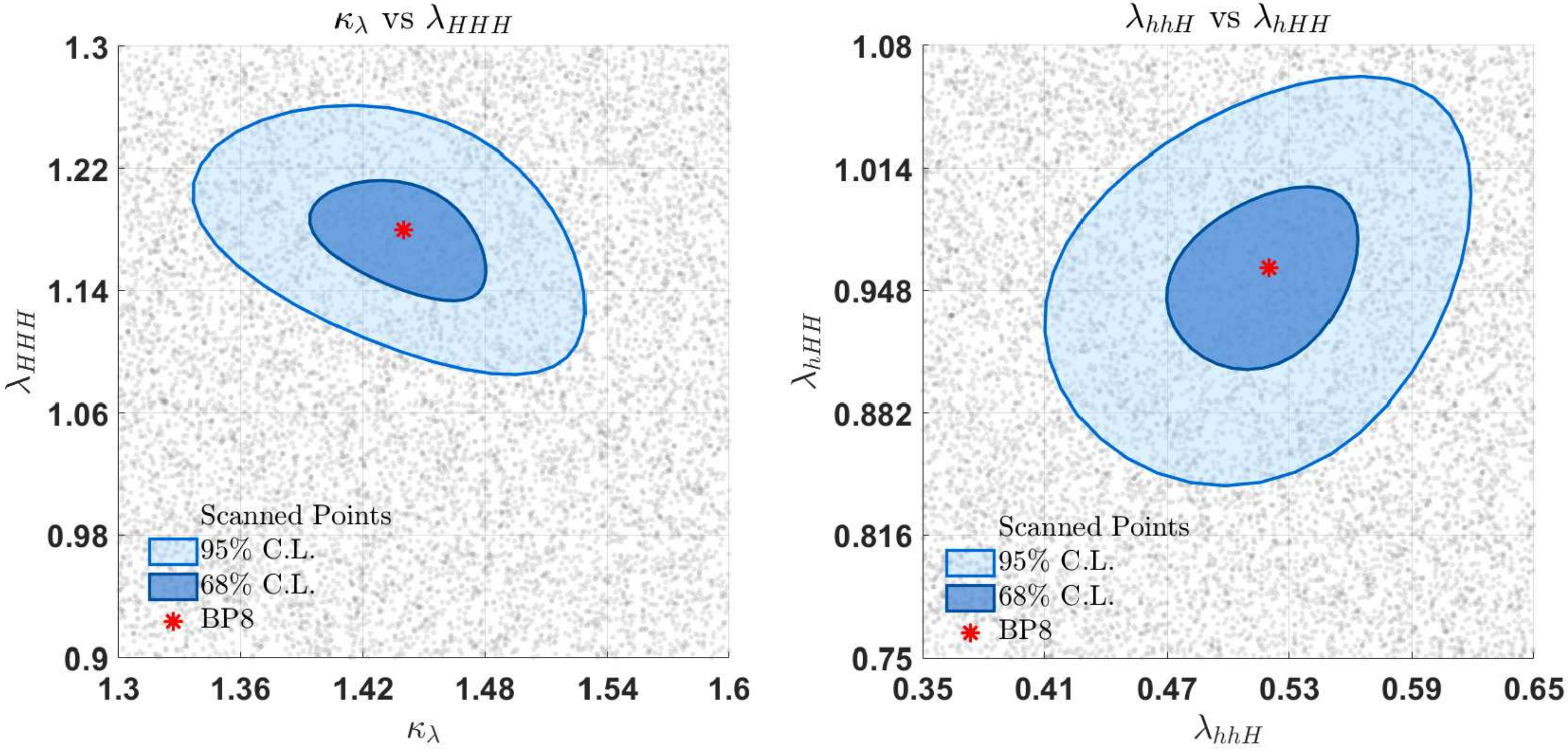
BP8 projection II:





$\Rightarrow$ good determination of THCs

BP8 projection III:



⇒ good determination of THCs

Results for all BPs: 68% CL ranges:

Point	κ_λ	λ_{hhH}	λ_{hHH}	λ_{HHH}
P1	$[1.44, 1.53]$	$[0.34, 0.38]$	$[0.39, 0.44]$	$[0.75, 0.84]$
P2	$[1.41, 1.52]$	$[0.31, 0.41]$	$[0.42, 0.49]$	$[0.34, 0.40]$
P3	$[1.39, 1.51]$	$[0.29, 0.41]$	$[0.38, 0.49]$	$[0.62, 0.71]$
P4	$[1.36, 1.50]$	$[0.30, 0.45]$	$[0.47, 0.61]$	$[0.77, 0.87]$
P5	$[1.42, 1.50]$	$[0.41, 0.53]$	$[0.74, 0.87]$	$[0.39, 0.51]$
P6	$[1.38, 1.53]$	$[0.35, 0.46]$	$[0.50, 0.68]$	$[0.38, 0.46]$
P7	$[1.36, 1.55]$	$[0.46, 0.57]$	$[0.83, 0.92]$	$[0.87, 1.04]$
P8	$[1.39, 1.48]$	$[0.46, 0.56]$	$[0.85, 0.94]$	$[0.93, 1.01]$

$\Rightarrow$ good determination all THCs

Results for all BPs: 95% CL ranges:

Point	κ_λ	λ_{hhH}	λ_{hHH}	λ_{HHH}
P1	$[1.35, 1.58]$	$[0.32, 0.40]$	$[0.34, 0.47]$	$[0.67, 0.91]$
P2	$[1.38, 1.56]$	$[0.28, 0.43]$	$[0.39, 0.51]$	$[0.30, 0.44]$
P3	$[1.37, 1.53]$	$[0.26, 0.44]$	$[0.35, 0.52]$	$[0.59, 0.73]$
P4	$[1.32, 1.53]$	$[0.26, 0.50]$	$[0.43, 0.64]$	$[0.75, 0.91]$
P5	$[1.40, 1.52]$	$[0.37, 0.57]$	$[0.68, 0.91]$	$[0.30, 0.57]$
P6	$[1.35, 1.57]$	$[0.32, 0.49]$	$[0.46, 0.73]$	$[0.36, 0.49]$
P7	$[1.32, 1.59]$	$[0.43, 0.60]$	$[0.80, 0.94]$	$[0.82, 1.09]$
P8	$[1.35, 1.50]$	$[0.43, 0.58]$	$[0.84, 0.98]$	$[0.90, 1.03]$

⇒ good determination all THCs, even at 95 % CL

6. FOEWPT and GWs in the 2HDM

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	→ 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 : $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

$\Rightarrow$ Parameter scan in the 2HDM type II $\Rightarrow$ ScannerS

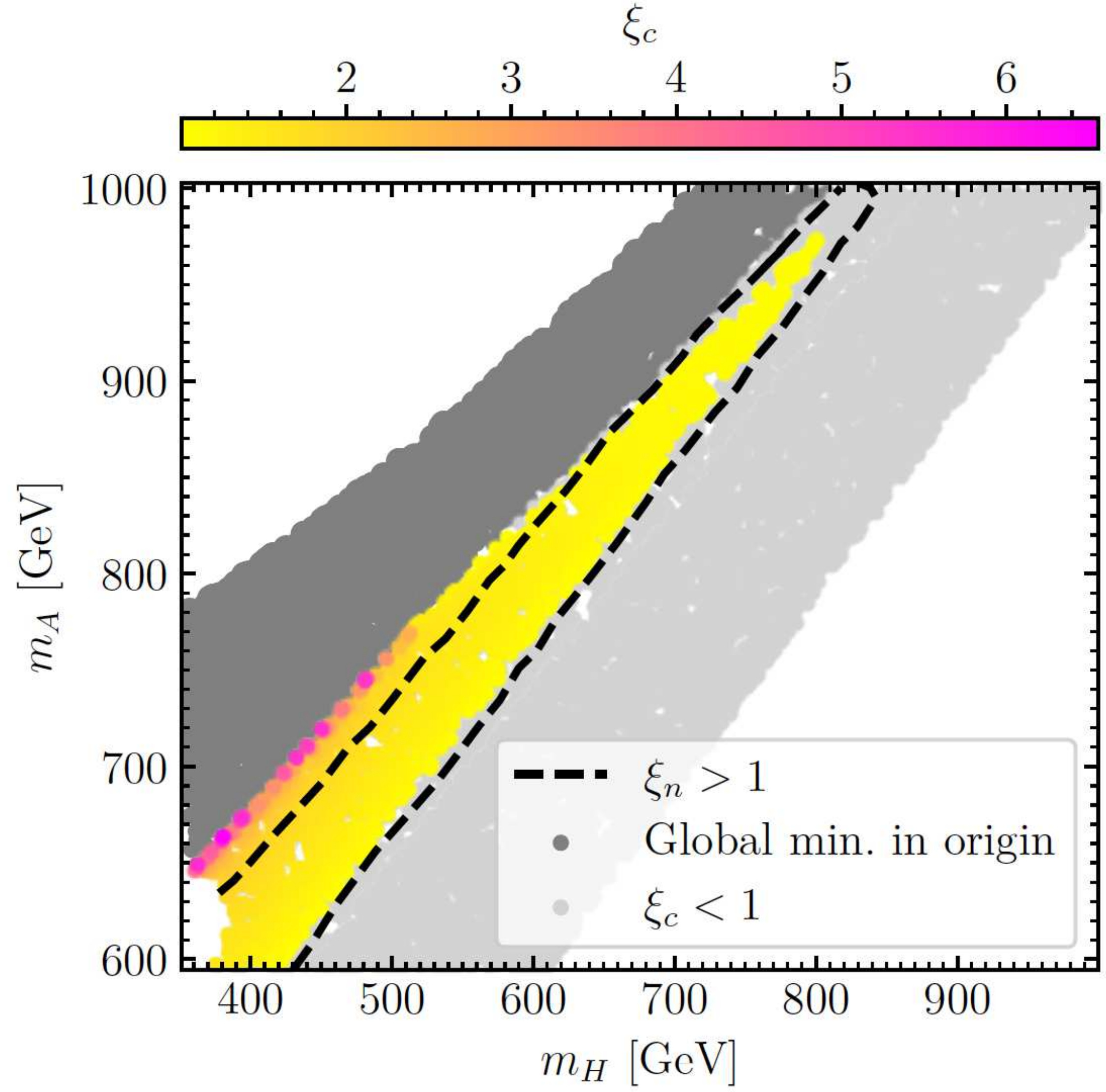
$\tan\beta = 3$, $c_{\beta-\alpha} = 0$, $m_{12}^2 = m_H^2 s_\beta c_\beta$
0.2 TeV $\leq m_H \leq$ 1 TeV, 0.6 TeV $\leq m_A = m_{H^\pm} \leq$ 1.2 TeV

Constraints:

- Tree-level perturbativity $\Rightarrow$ ScannerS
- Minimum of potential is global minimum $\Rightarrow$ ScannerS
  ... or sufficiently long-lived $\Rightarrow$ Evade
- Higgs searches at LEP, Tevatron, LHC $\Rightarrow$ HiggsBounds
- SM-like Higgs properties $\Rightarrow$ HiggsSignals (2HDECAY, SusHi)
  $\Rightarrow \chi^2_{125}$ (with $\chi^2_{\text{SM},125} = 84.4$)
- Flavor physics (mainly BR($B_s \to X_s\gamma$), ΔM_{B_s}) $\Rightarrow$ SuperIso bounds
- Electroweak precision data (T and S) $\Rightarrow$ ScannerS

GWs in the 2HDM: $\xi_c := v_c/T_c \gtrsim 1$

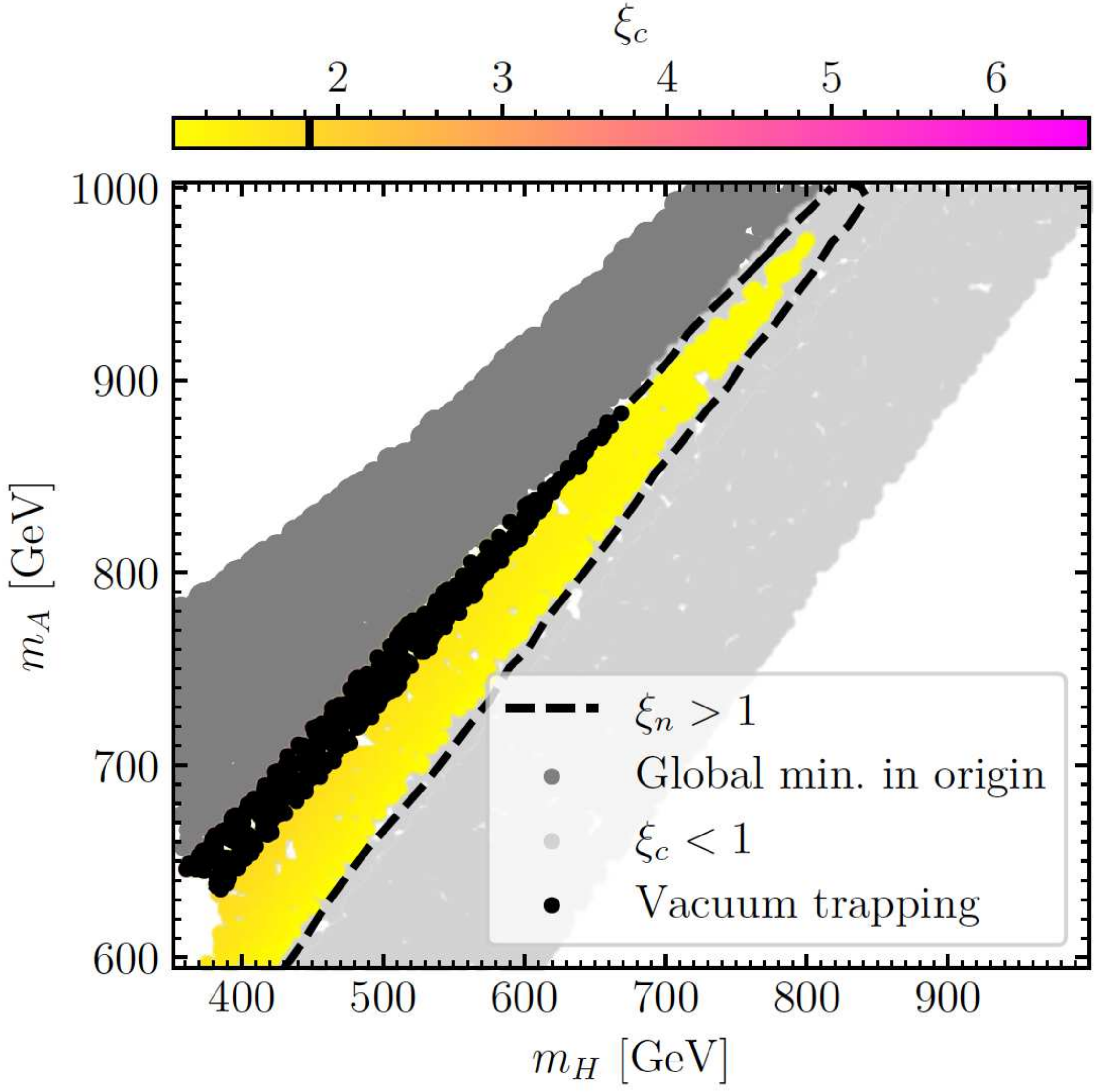
[T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22]



$\Rightarrow$ large ξ_c found in the 2HDM $\Rightarrow$ strong GW signal?

GWs in the 2HDM: $\xi_n := v_n/T_n \gtrsim 1$

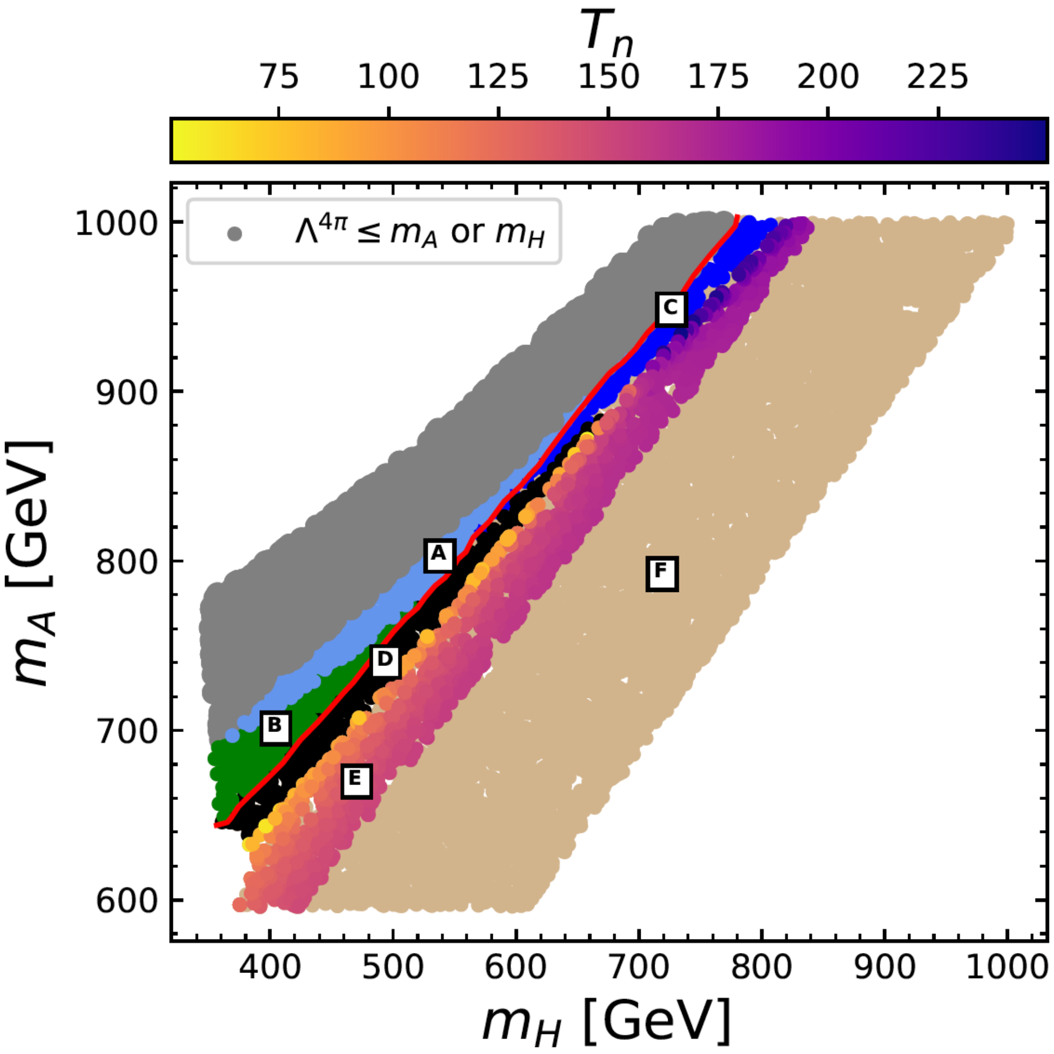
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



⇒ potentially strongest GW signal: forbidden by vacuum trapping

Six thermal histories in the 2HDM:

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



E: viable for FOEWPT, GWs are induced (detectable?)

F: no FOEWPT, no GWs are induced

Six thermal histories in the 2HDM:

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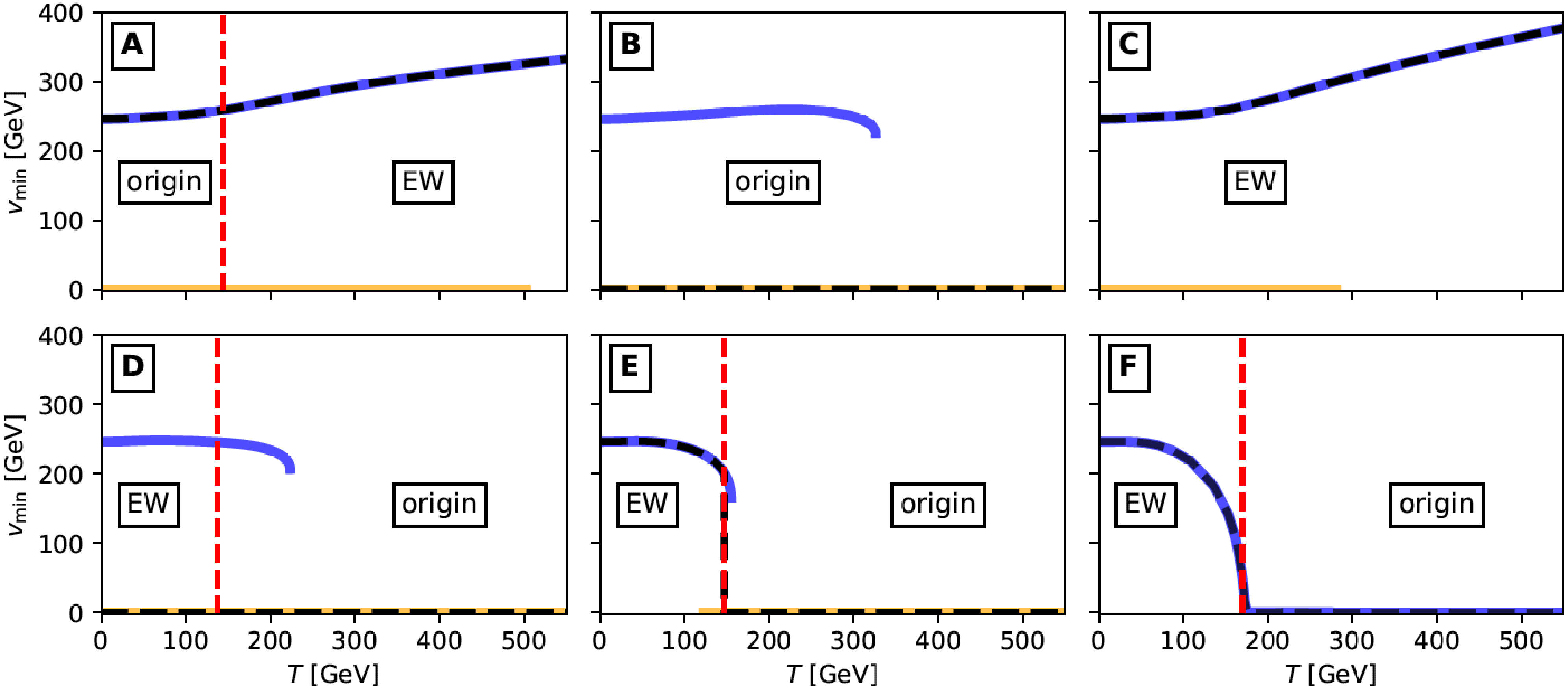

⇒ Zone E preferred by phenomenology/FOEWPT

GWs vs. LISA: ($m_H = 419$ GeV, $m_A = m_{H^\pm} = 663$ GeV)

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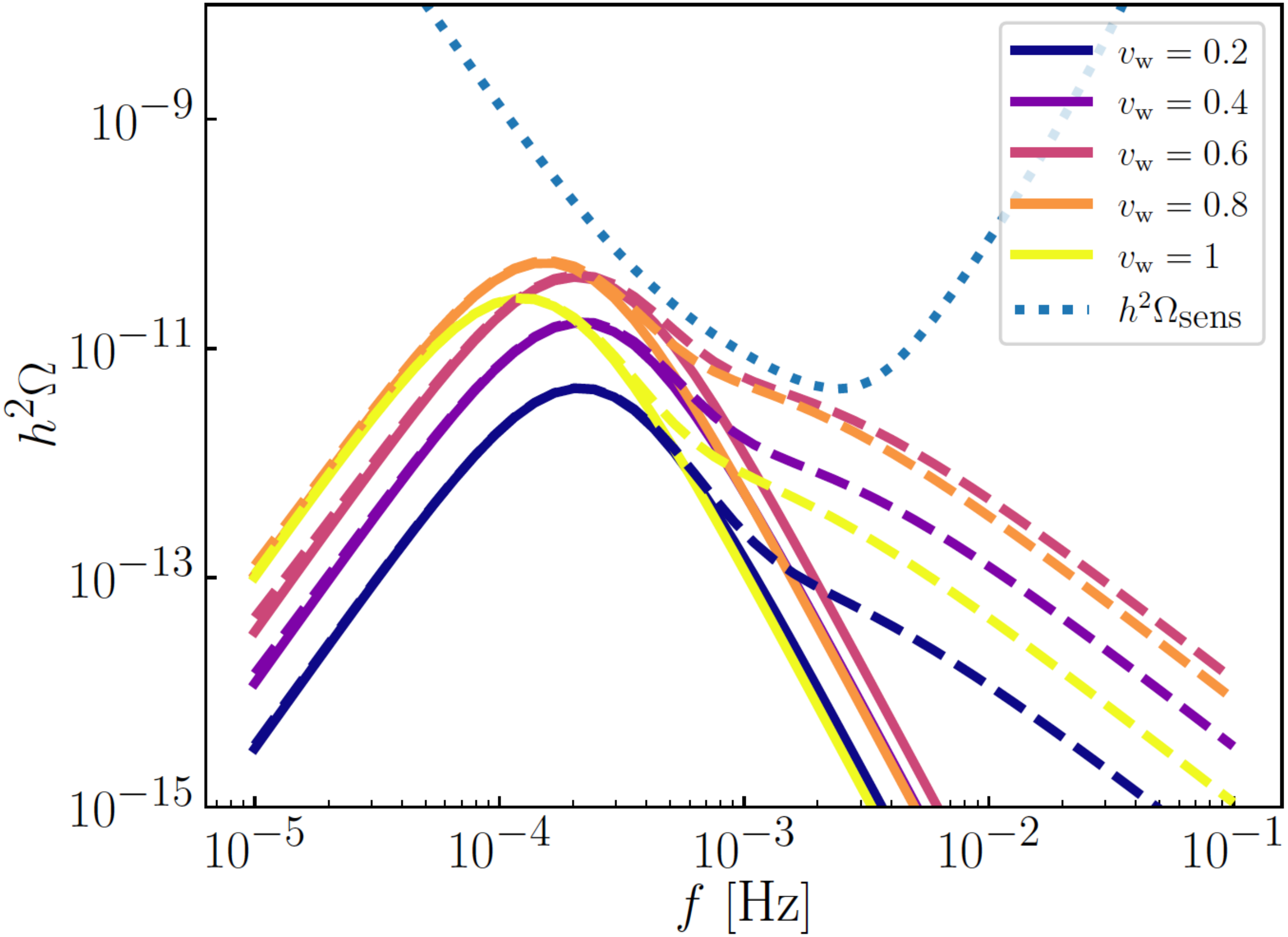

⇒ bubble wall velocity and turbulence important

GWs vs. LISA: ($v_\mathrm{w} = 0.6$, 7 years of LISA data)

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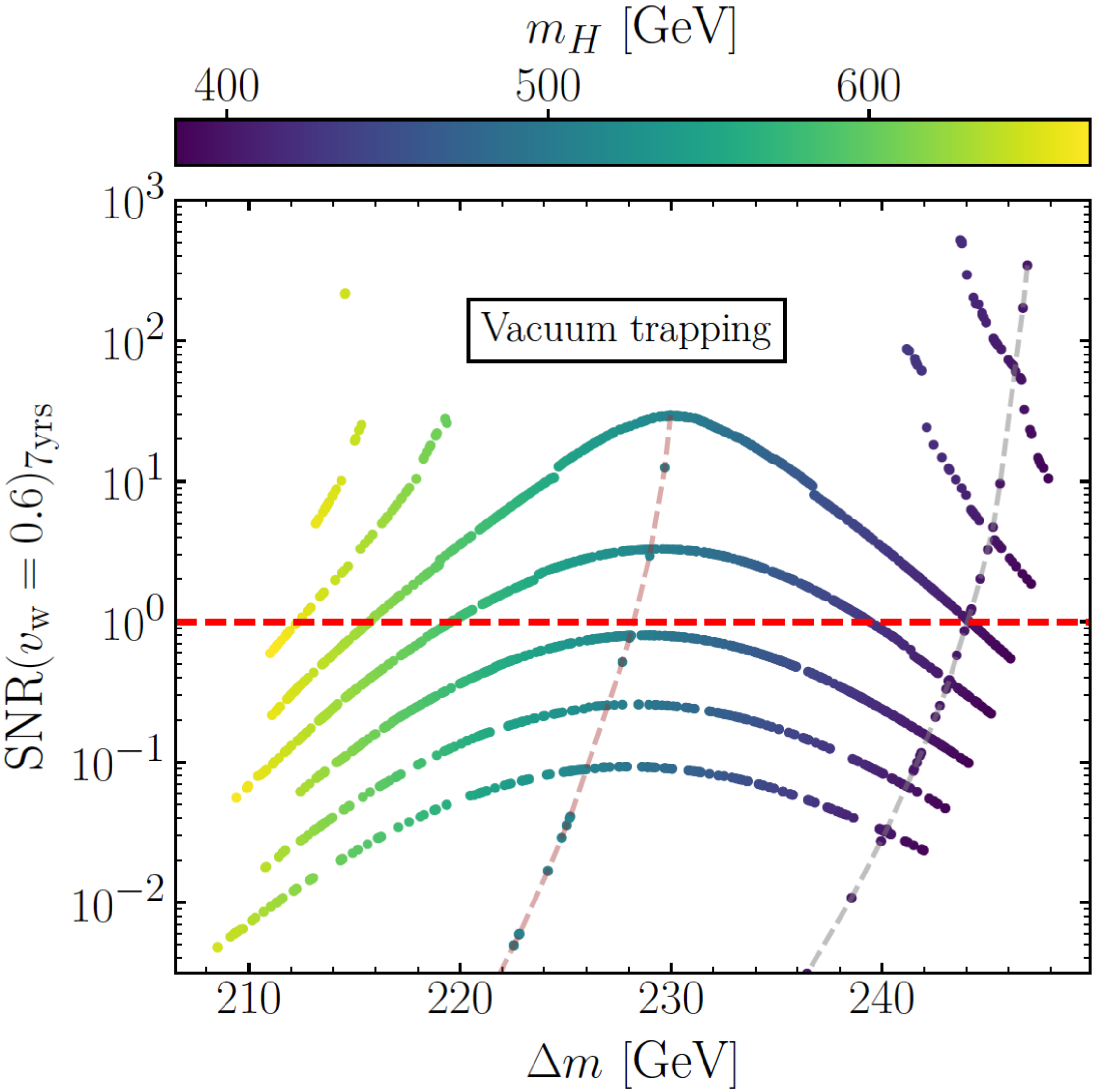
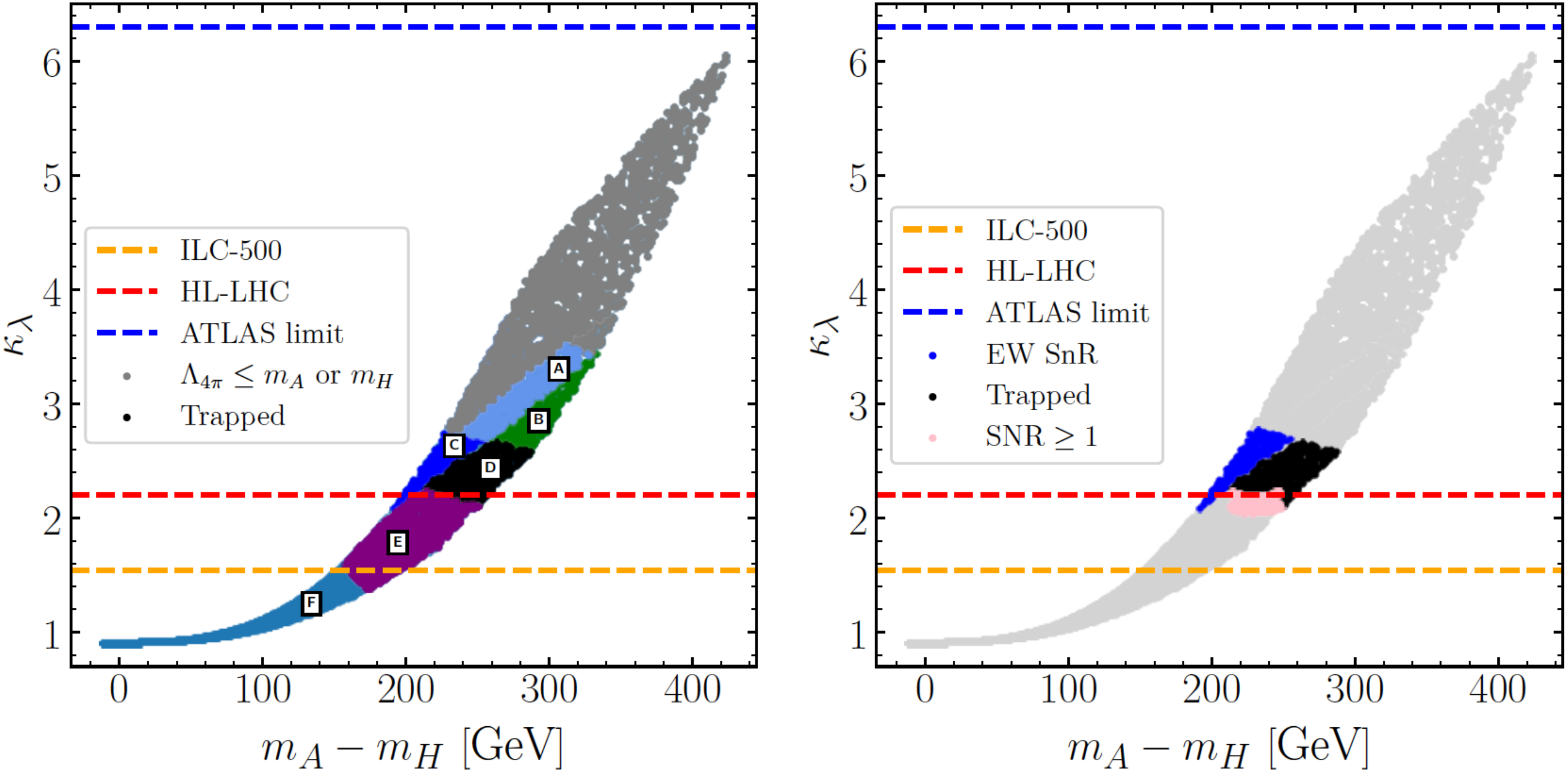


$\Rightarrow$ detectable GWs only in a very small zone close to VT

7. Signs of a FOEWPT at the LHC?

2HDM parameter scan to yield FOEWPT:

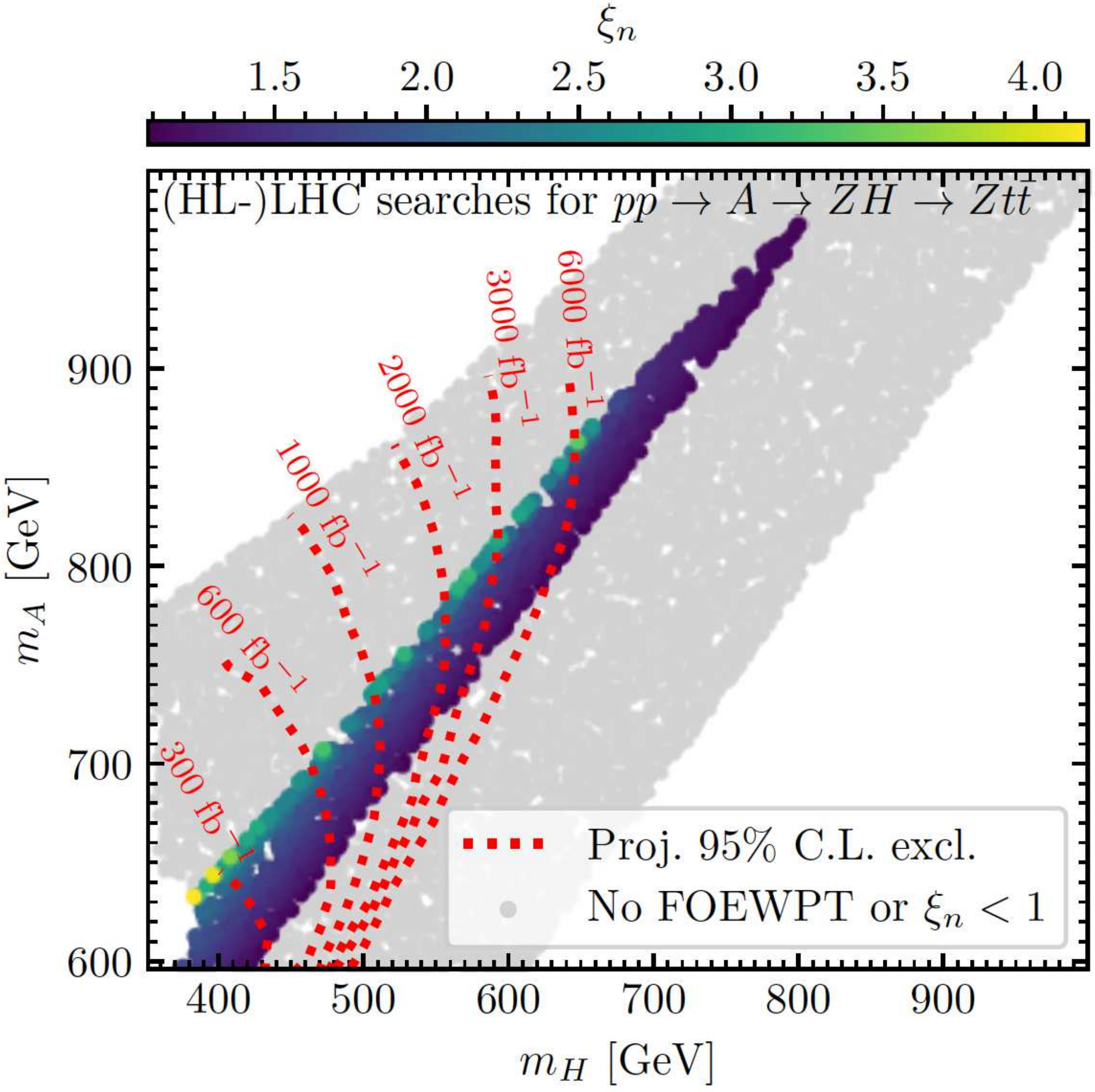
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



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

Smoking gun signature: gap between m_A and m_H

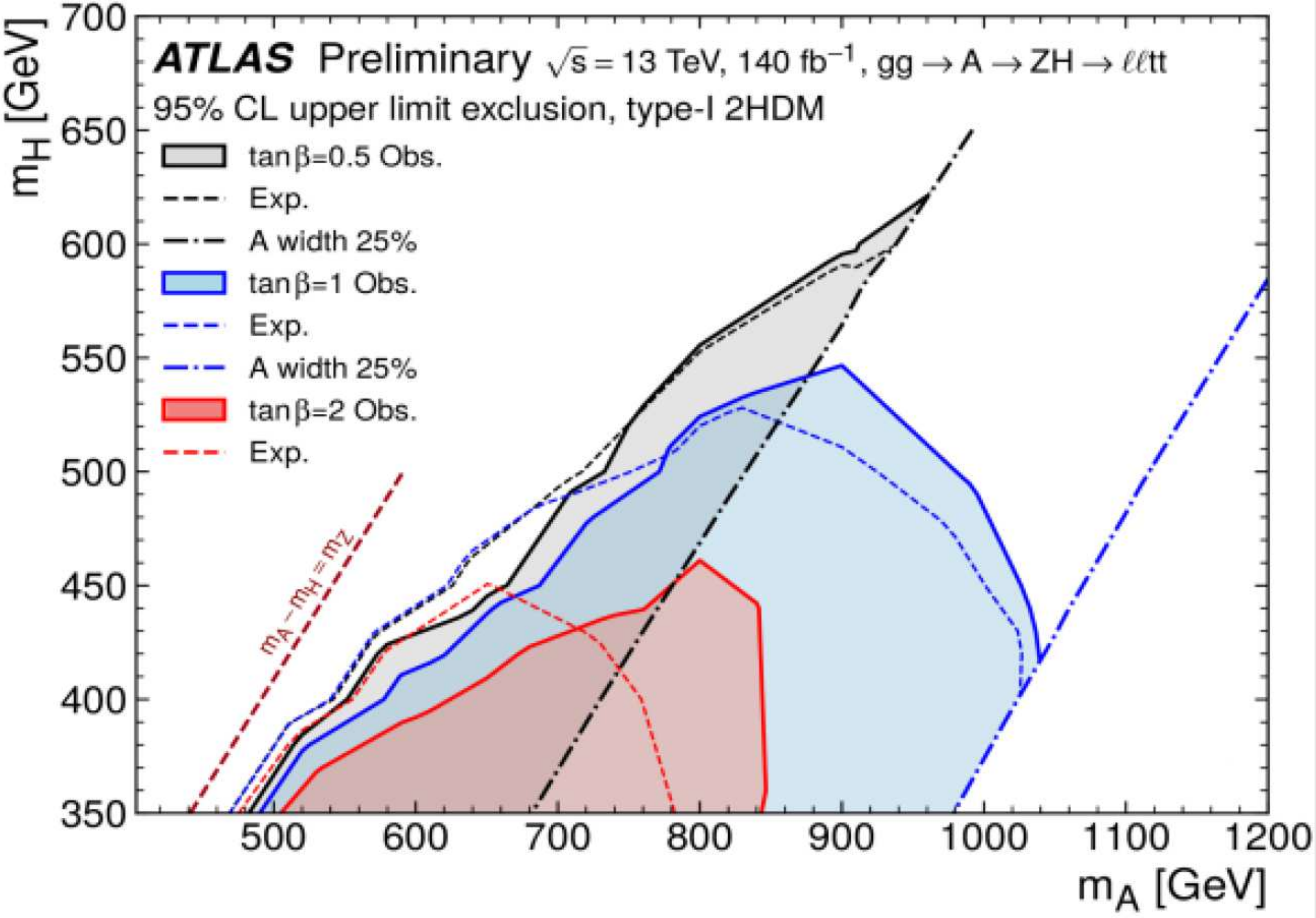
[*T. Biekötter, S.H., J. No, O. Olea, G. Weiglein '22*]



⇒ GW zone can be covered at the HL-LHC

Latest experimental results: ATLAS at LHCP23

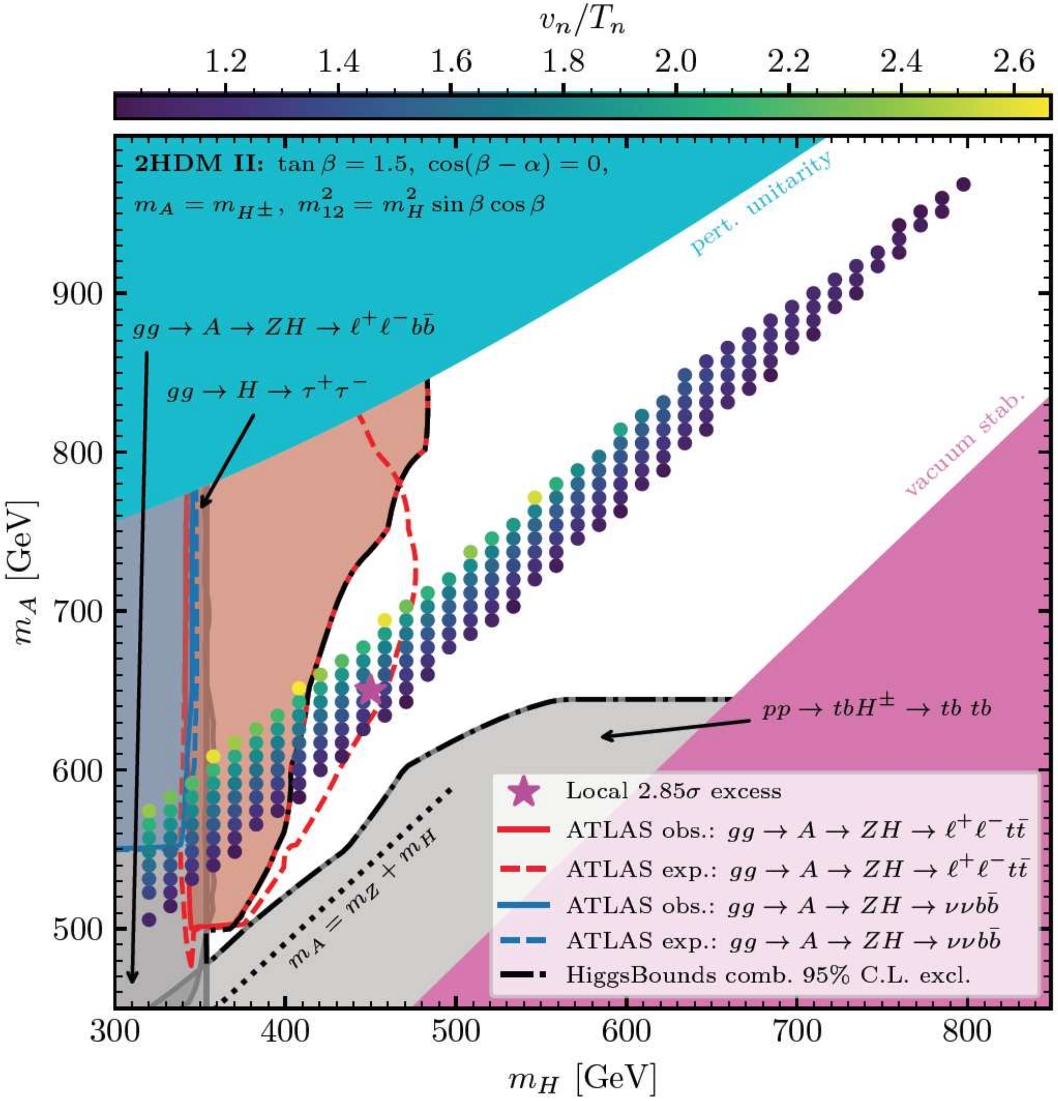
[*ATLAS '23*]



⇒ interesting excess in the "right spot" :-) ($m_H = 450$ GeV, $m_A = 650$ GeV)

Smoking gun signature: highest excess for $\tan\beta = 1.5$

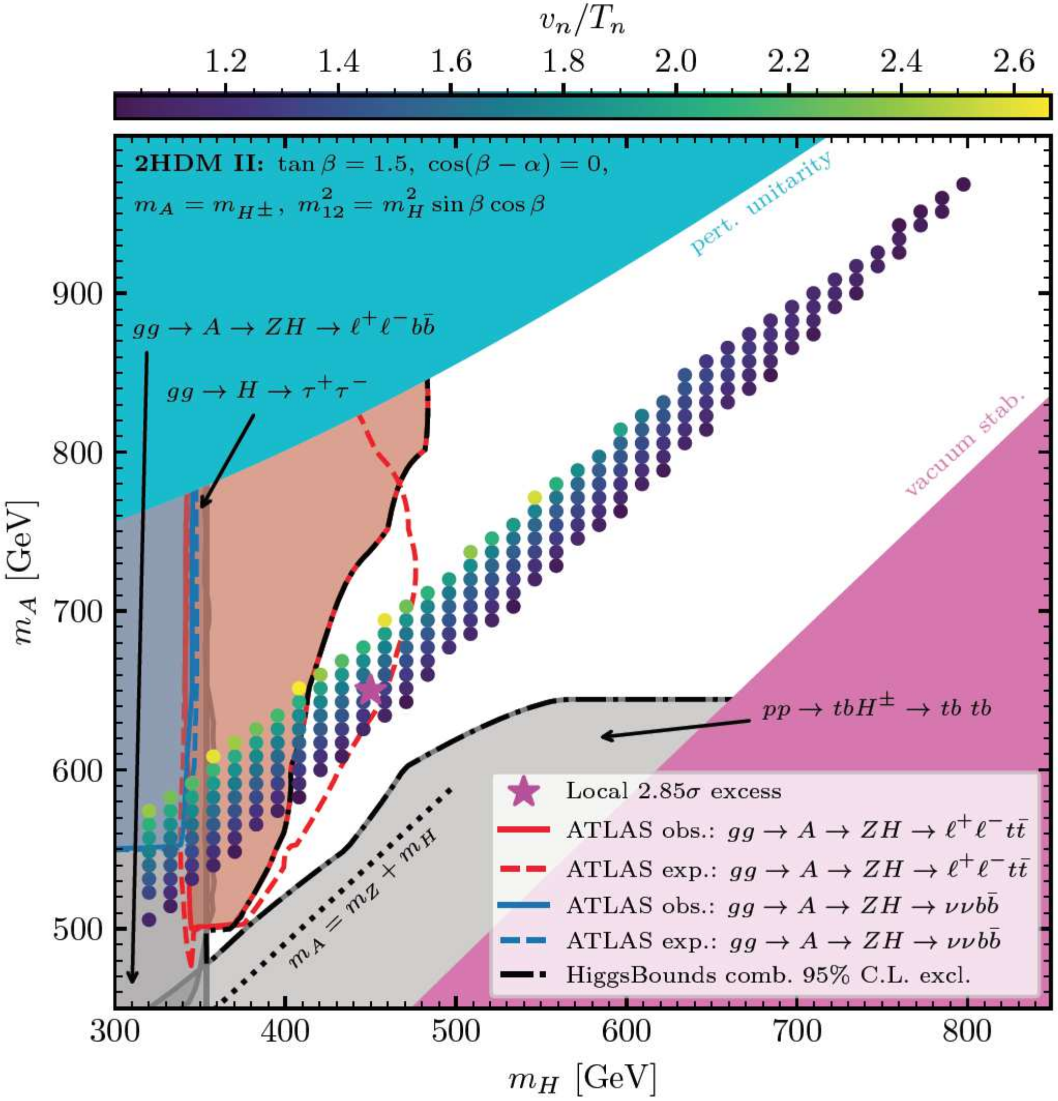
[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein '23*]



⇒ excess in the sweet spot

Smoking gun signature: highest excess for $\tan\beta = 1.5$

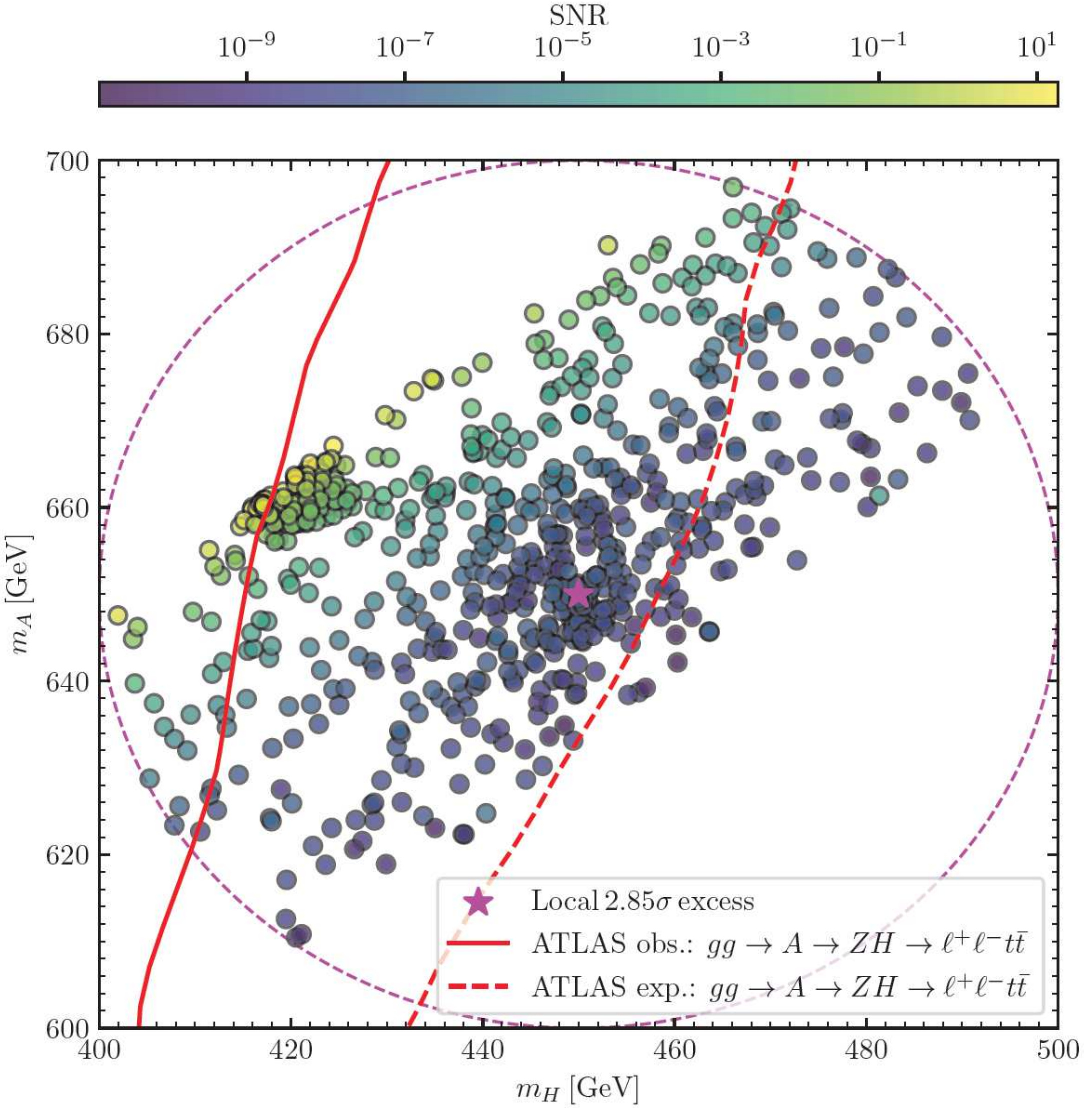
[T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein ’23]



⇒ excess in the sweet spot ⇒ not confirmed by CMS Run 2 analysis :-(

Smoking gun signature: GW signal at LISA?

[*T. Biekötter, S.H., J. No, O. Olea, K. Radchenko, G. Weiglein ’23*]



⇒ GW signal at LISA possible, but not guaranteed