Probing the nature of Higgs physics with the latest experimental results

Georg Weiglein,

DESY & UHH, 10 / 2022

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DESY.

Finally: Dark Matter produced in the laboratory!

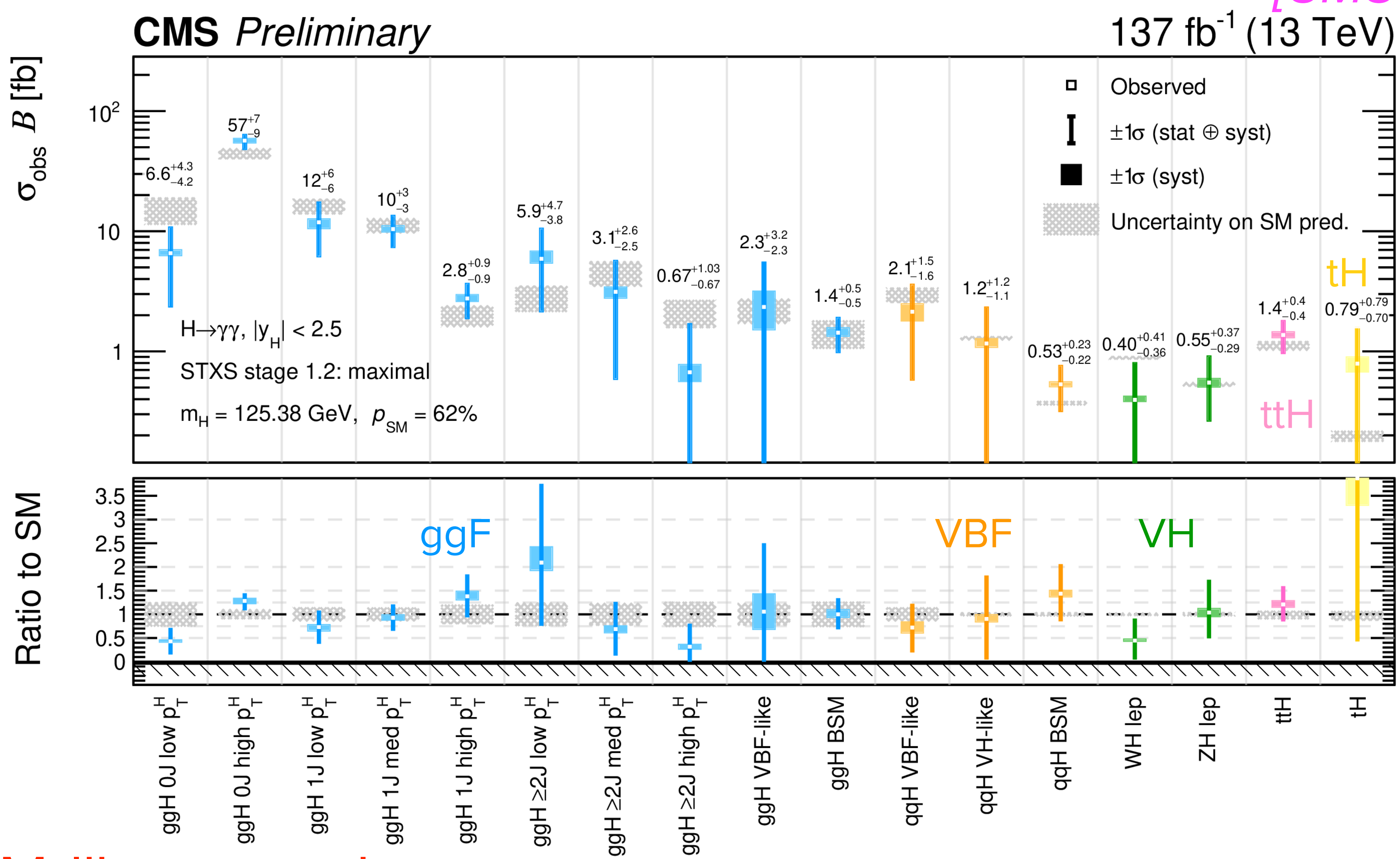
Outline

- Introduction
- Properties of the observed Higgs boson at 125 GeV
- Analysis of possible hints from searches for additional Higgs bosons
- Conclusions

Introduction

A bit more than 10 years after the discovery of the Higgs boson at 125 GeV (h125): high-precision measurement of the mass, detailed investigations of inclusive and differential rates

[CMS Collaboration '22]

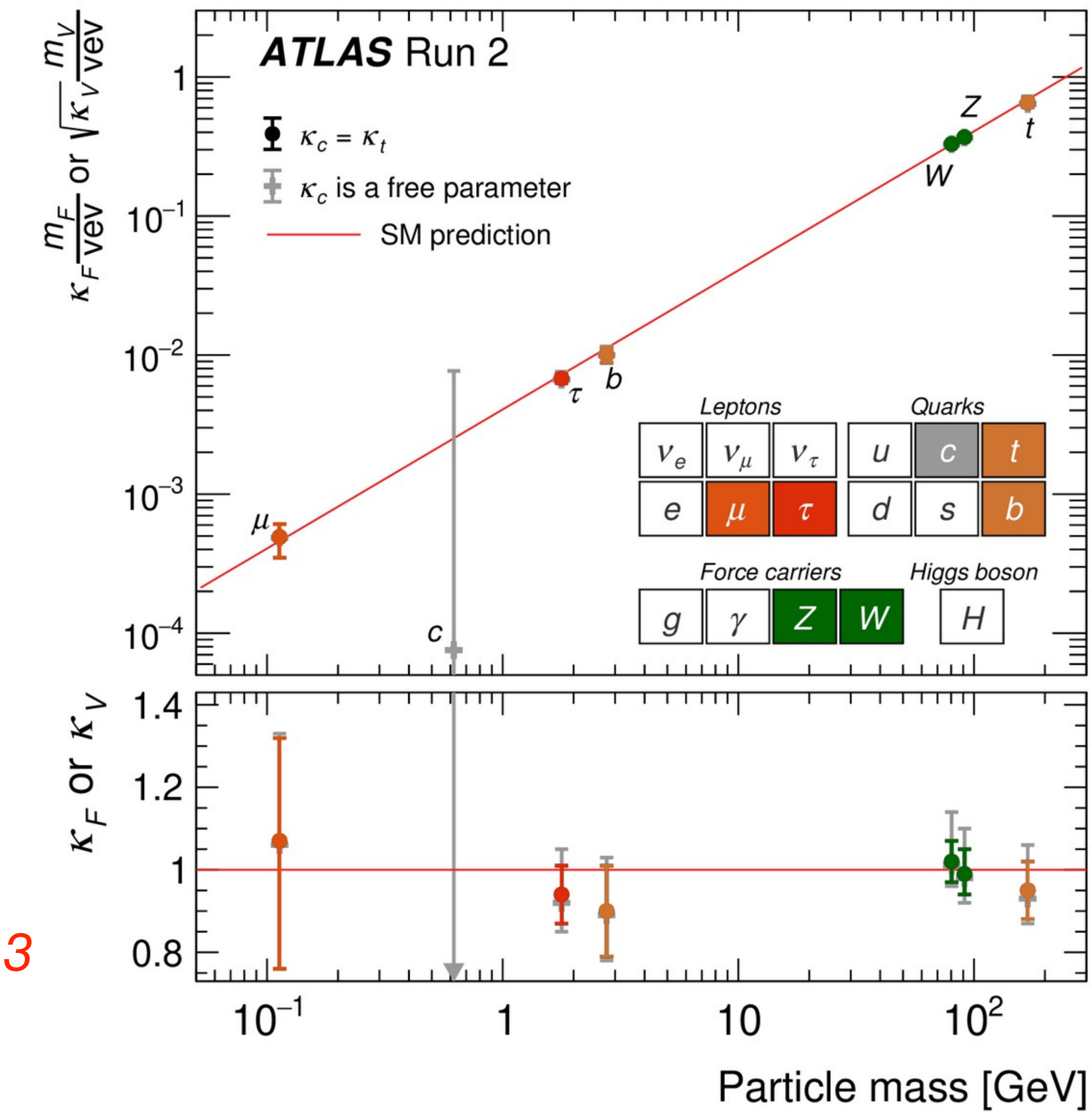


⇒SM-like properties

Properties of the detected Higgs boson (h125)

Couplings to other particles:

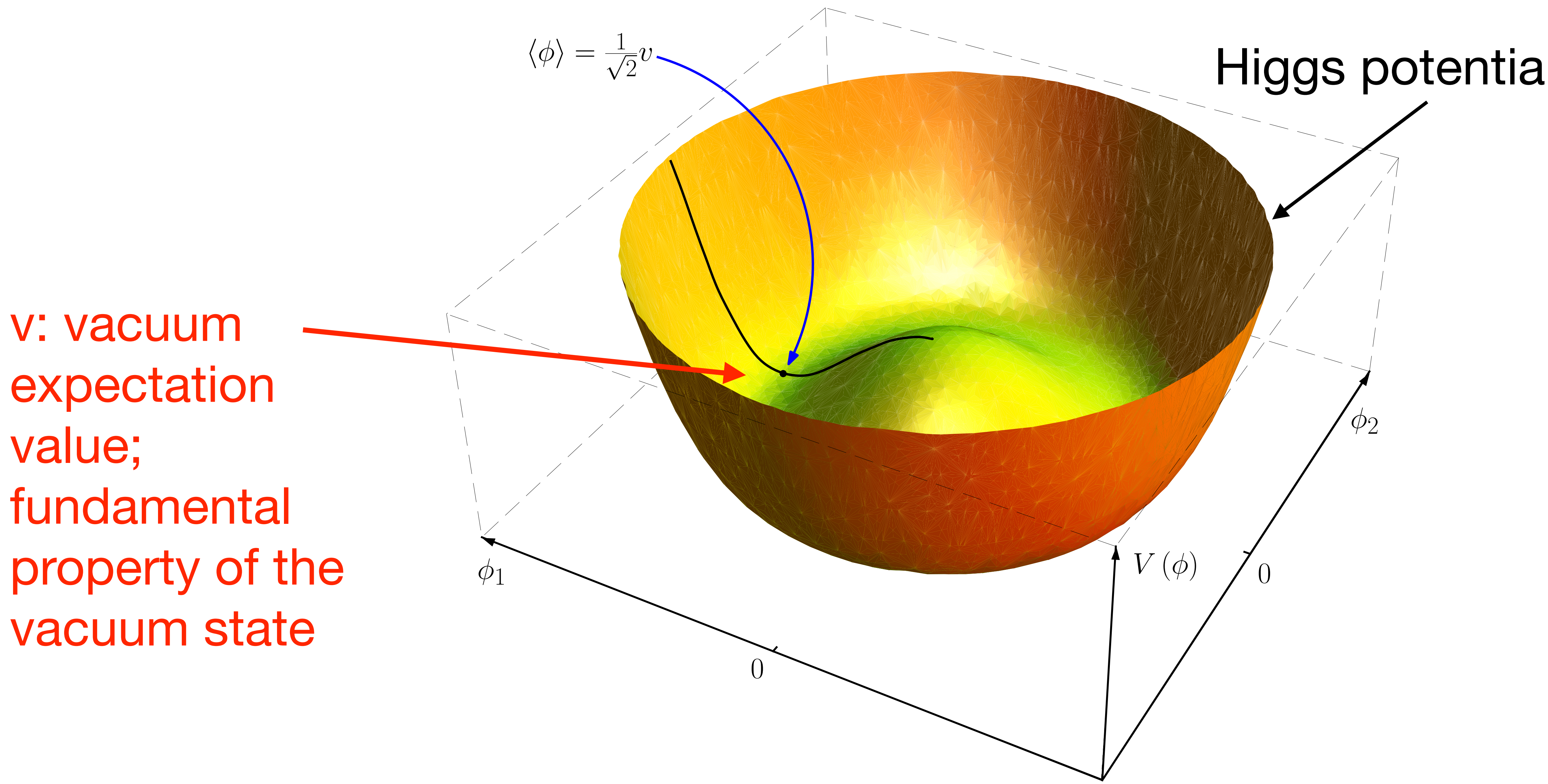
[ATLAS Collaboration '22]



Nobel Prize 2013

⇒ Agrees with predictions of the Brout-Englert-Higgs (BEH) mechanism

The Brout-Englert-Higgs (BEH) mechanism and the structure of the vacuum

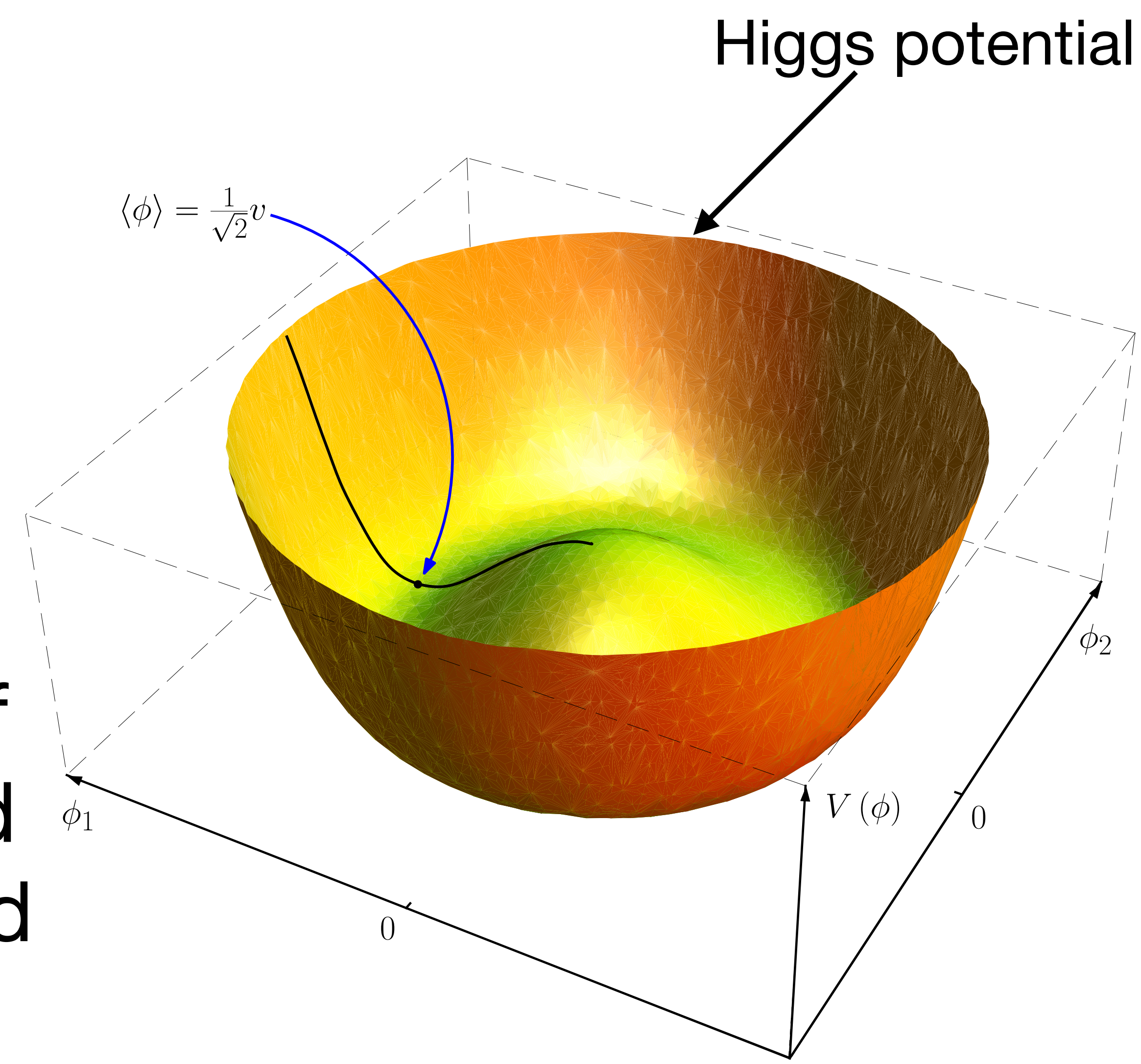


BEH mechanism, spontaneous symmetry breaking: vacuum state does not obey the underlying symmetry principle (gauge invariance)

BEH mechanism ⇔ non-trivial structure of the vacuum

What is the underlying dynamics of electroweak symmetry breaking?

The vacuum structure is caused by the Higgs field through the Higgs potential. We lack a deeper understanding of this!



We do not know where the Higgs potential that causes the structure of the vacuum actually comes from and which form of the potential is realised in nature. Experimental input is needed to clarify this!

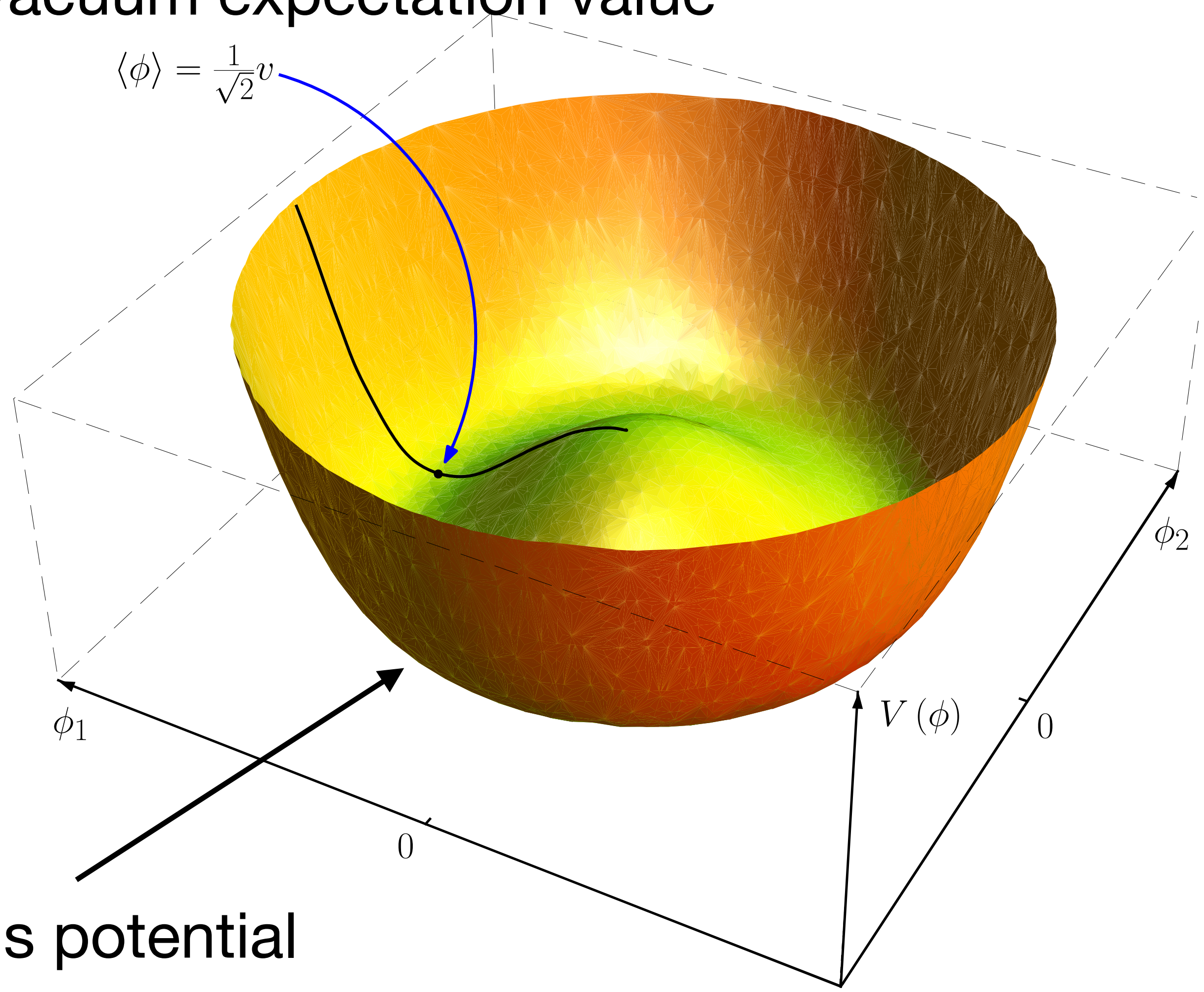
Single doublet or extended Higgs sector? (new symmetry?)

Fundamental scalar or compositeness? (new interaction?)

Higgs potential: the "holy grail" of particle physics

Crucial questions related to electroweak symmetry breaking: what is the form of the Higgs potential and how does it arise?

Vacuum expectation value



Higgs potential

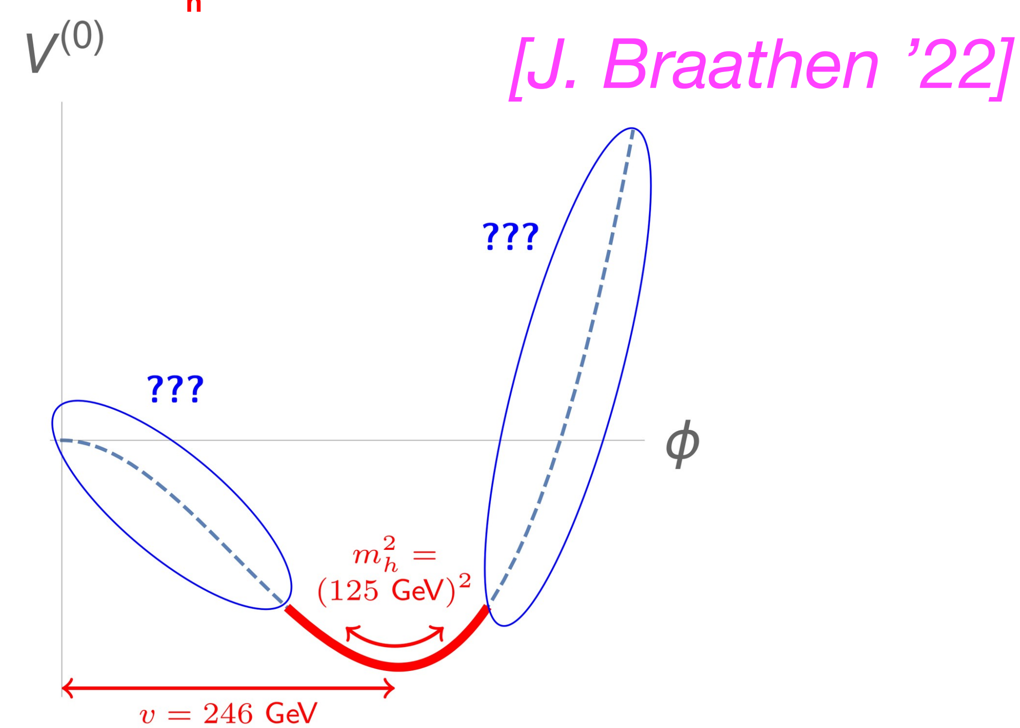
Only known so far:

→ the location of the EW minimum:

v = 246 GeV

→ the curvature of the potential around the EW minimum:

m_h = 125 GeV



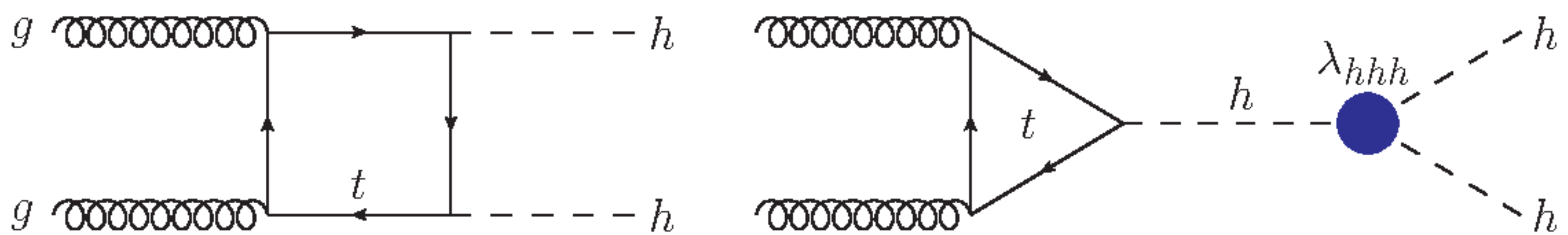
Information about these questions can be obtained from the trilinear Higgs self-coupling, which will be a main focus of the experimental and theoretical activities in particle physics during the coming years

Trilinear Higgs self-coupling: experimental situation

The measurement of the trilinear Higgs self-coupling λ_{hhh} is a prime experimental goal, but a coupling by itself is not a physical observable

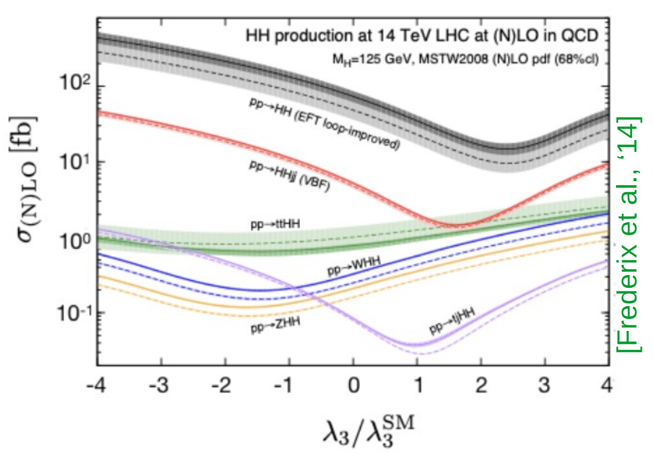
Experimental access via Higgs pair production (or indirectly via loop contributions involving λ_{hhh}):

- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

Box and triangle diagrams interfere destructively
⇒ Small cross section in the SM, can be much enhanced if λ_{hhh} deviates from the SM value

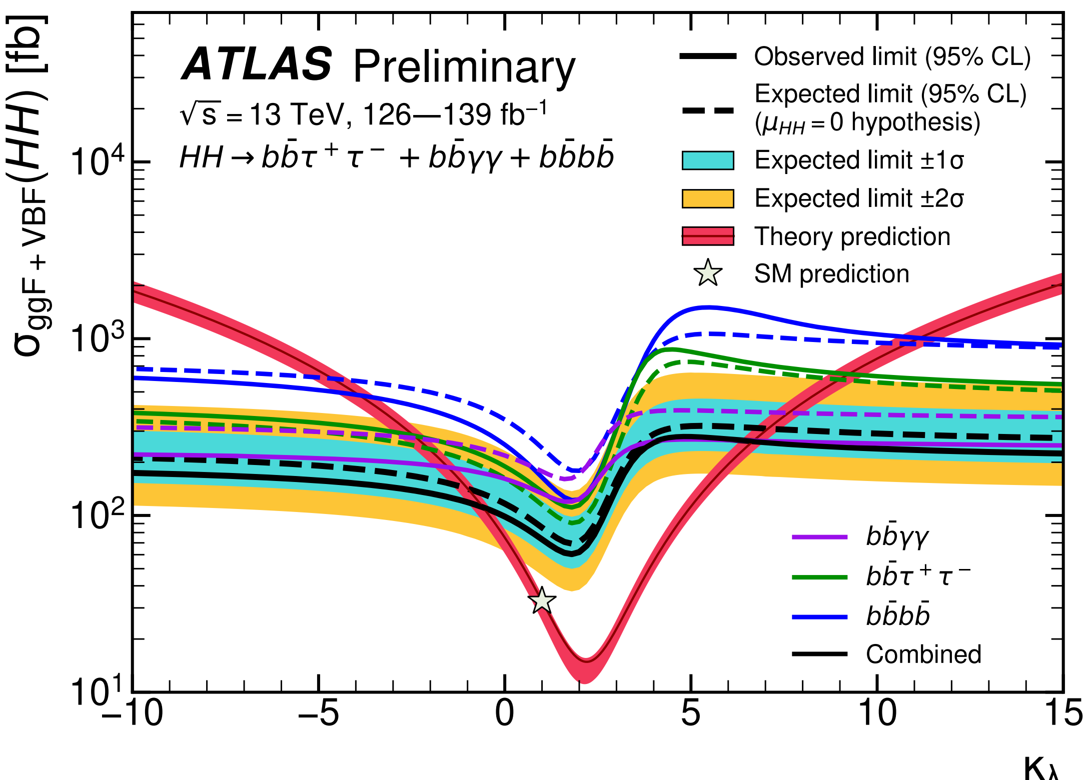


Trilinear Higgs self-coupling: experimental situation

Current experimental bound on the signal strength of Higgs pair production: $\mu_{hh} < 2.4$ *[ATLAS Collaboration '22]*

Experimental limit on Higgs pair production has been translated (taking into account also indirect information from single-Higgs production) into a limit on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$ under the assumption that new physics only affects the trilinear Higgs self-coupling:

$-0.4 < \varkappa_\lambda < 6.3$ at 95% C.L.



Comparison, latest CMS limit: $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L. *[CMS Collab. '22]*

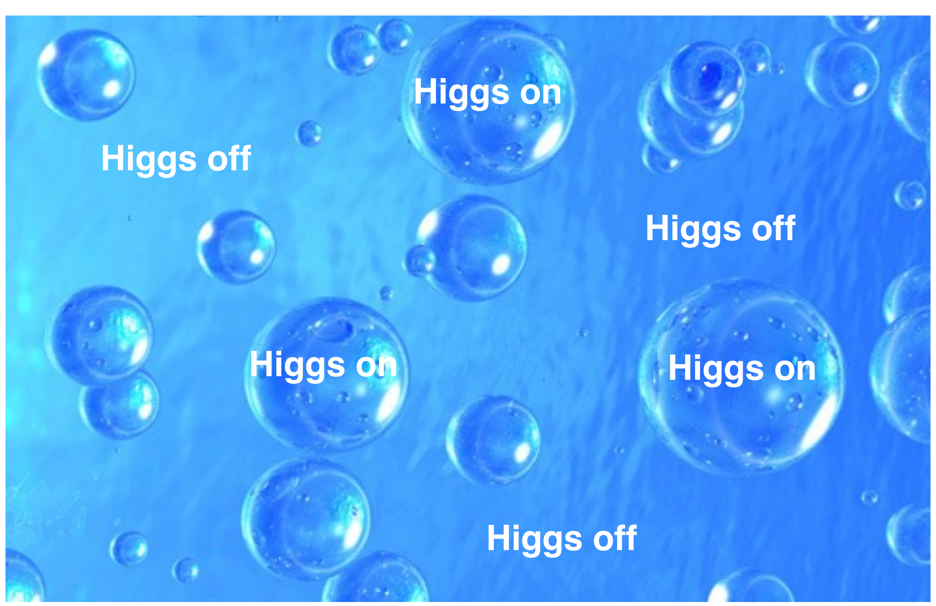
The Higgs potential and the electroweak phase transition (EWPT)

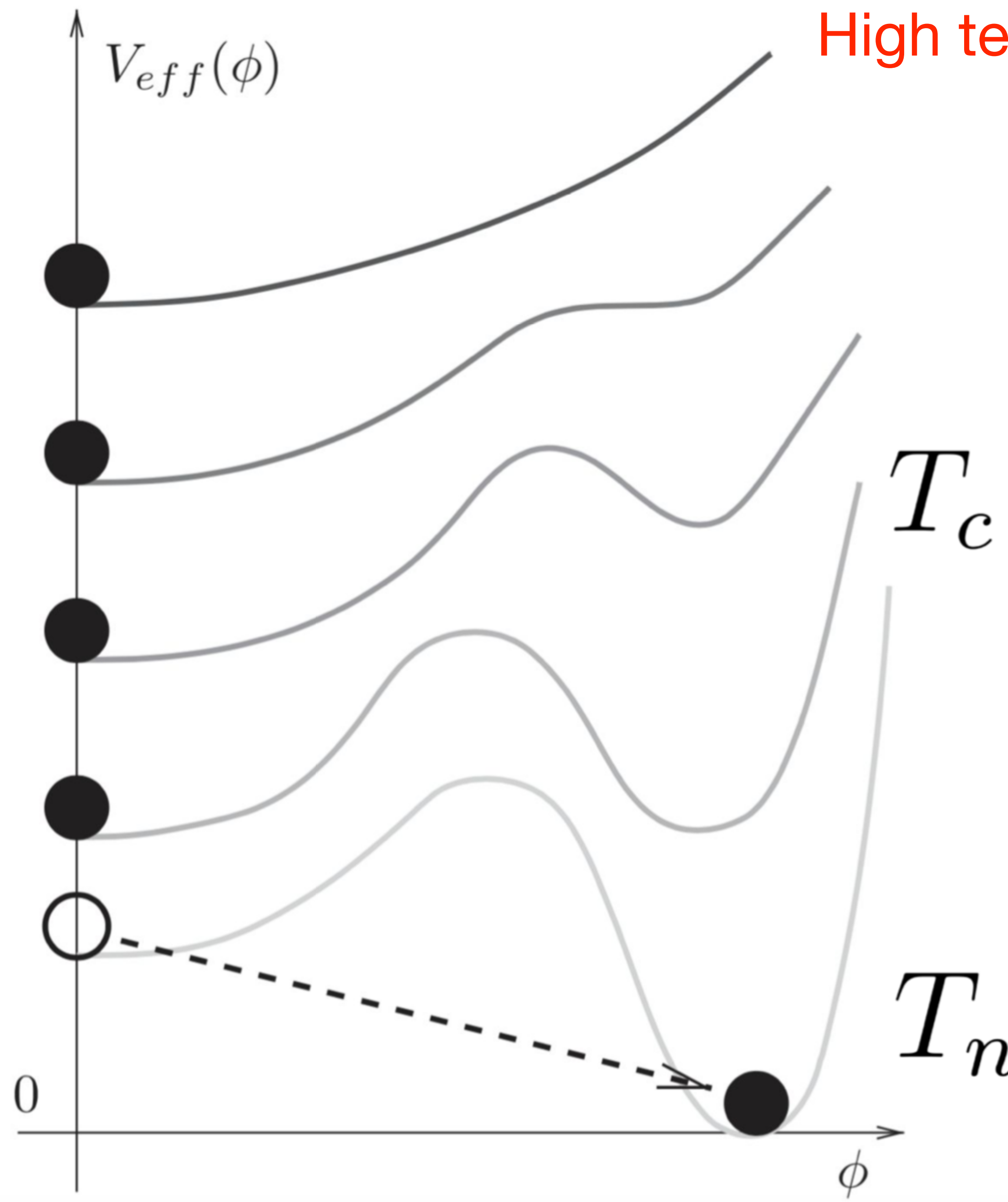
Temperature evolution of the Higgs potential in the early universe:

$$V(\phi, T) = V_0(\phi) + V^{loop}(\phi, T)$$

V. Rubakov, 1955-2022

[D. Gorbunov, V. Rubakov]





High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

EWPT: are there additional sources for CP violation in the Higgs sector?

Baryogenesis: creation of the asymmetry between matter and anti-matter in the universe requires a strong first-order electroweak phase transition (EWPT)

First-order EWPT does not work in the SM
The amount of CP violation in the SM (induced by the CKM phase) is not sufficient to explain the observed asymmetry between matter and anti-matter in the universe

First-order EWPT can be realised in extended Higgs sectors
could give rise to detectable gravitational wave signal

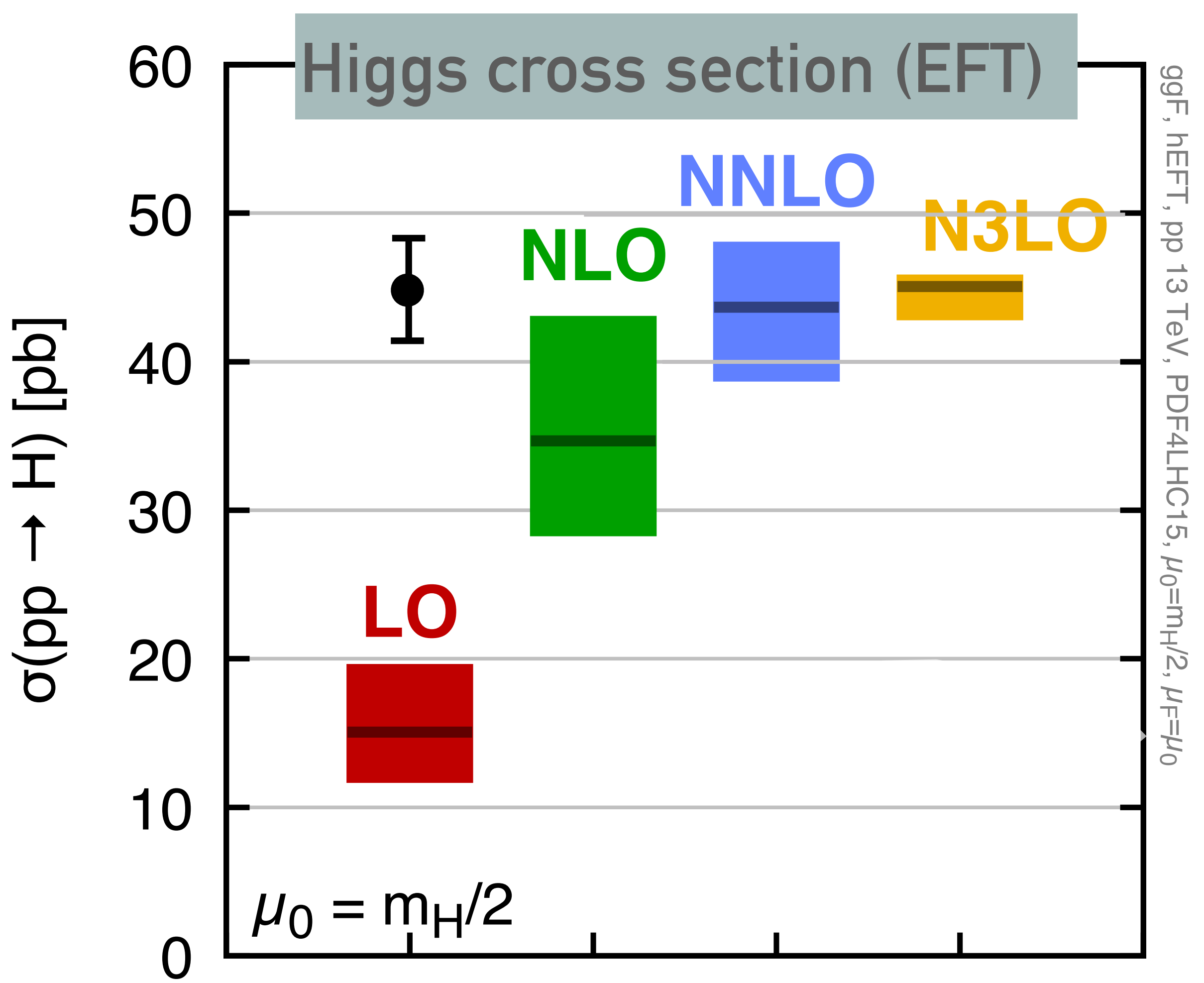
⇒ Search for additional sources of CP violation

But: strong experimental constraints from limits on electric dipole moments (EDMs)

Comparison between experiment and theory

Comparison between experiment and theory for the properties of h125 requires a high level of sophistication in the predictions for signal and background processes at the LHC

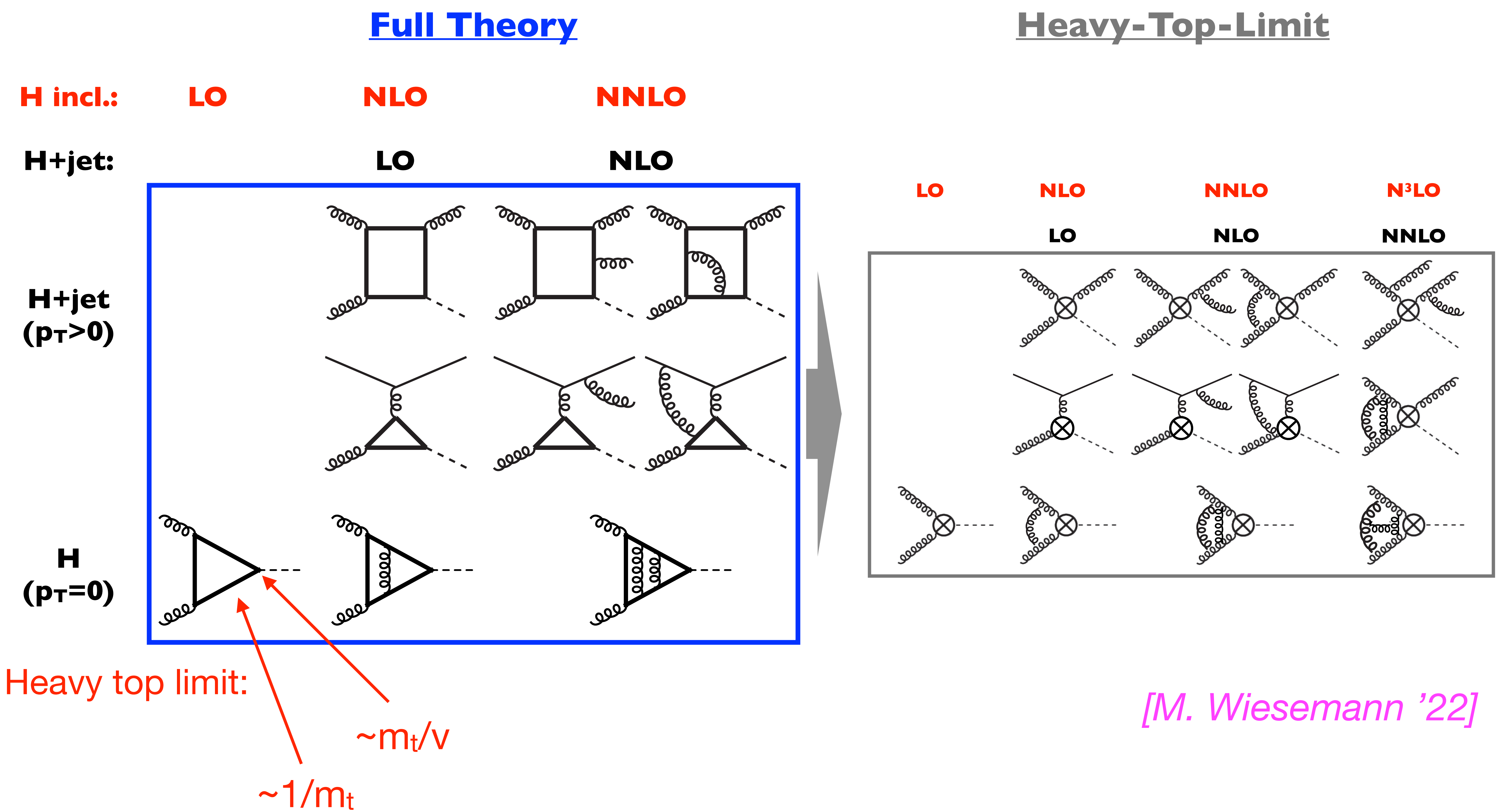
Example: inclusive Higgs production, total cross section (heavy top limit)



[Anastasiou et al. '15], [Mistlberger '18]

[M. Wiesemann '22]

Full theory vs. heavy top limit: H inclusive and H + jet



[M. Wiesemann '22]

Renormalisation scheme uncertainties

Amplitude with massive internal particles (e.g. full theory result for the top loops) depends on the scheme chosen for the mass renormalisation

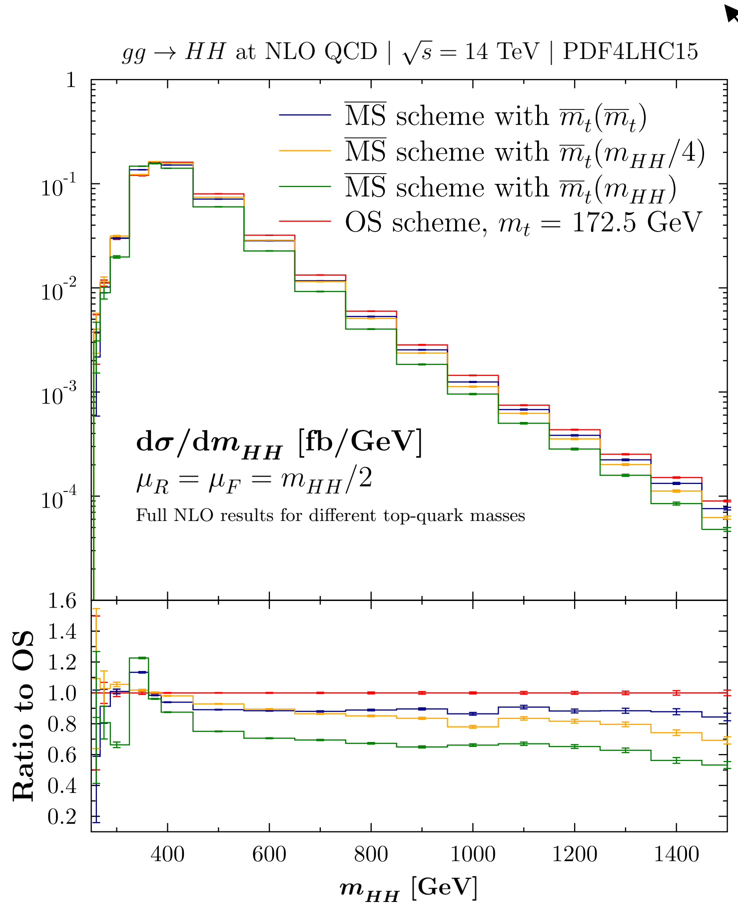
Higher-order uncertainty can be estimated by comparing on-shell scheme with $\overline{\mathrm{MS}}$ scheme

[M. Kerner '22]

HH production [Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 19,20]

$$\frac{d\sigma(gg\to HH)}{dQ}\Big|_{Q=300\text{ GeV}} = 0.0312(5)^{+9\%}_{-23\%}\text{ fb/GeV}$$

$$\frac{d\sigma(gg\to HH)}{dQ}\Big|_{Q=1200\text{ GeV}} = 0.000435(4)^{+0\%}_{-30\%}\text{ fb/GeV}$$



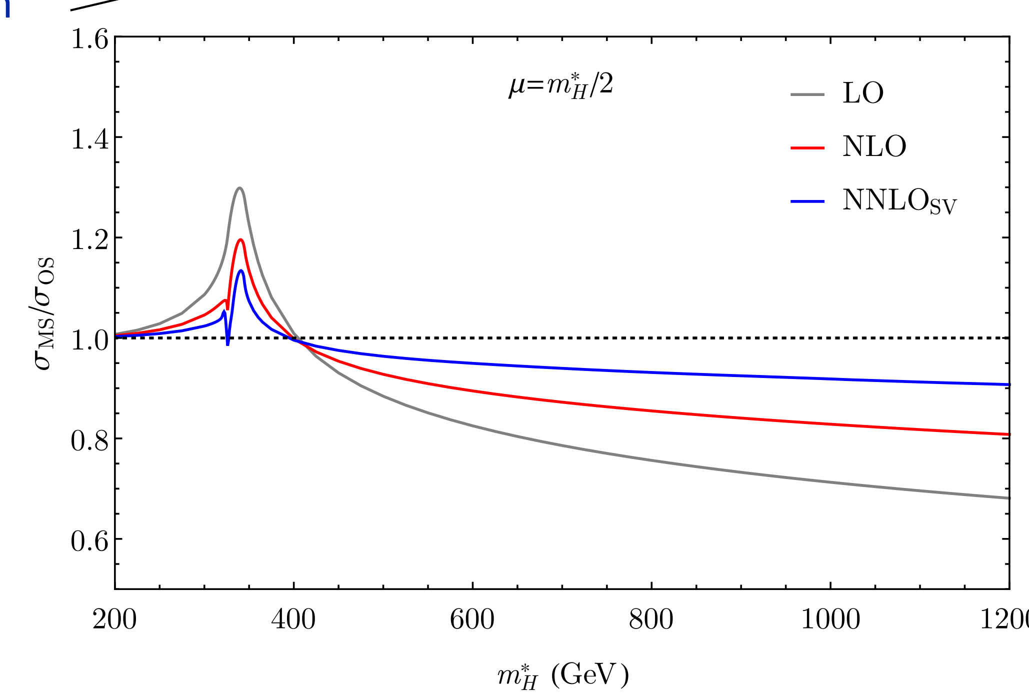
Dependence on mass-renormalization scheme can be large for large $\sqrt{s}$

off-shell H production [see Jones, Spira in Les Houches `19 Mazzitelli 22]

$$\sigma(gg\to H^*)\Big|_{Q=125\text{ GeV}} = 42.17^{+0.4\%}_{-0.5\%}\text{ pb}$$

$$\sigma(gg\to H^*)\Big|_{Q=600\text{ GeV}} = 1.97^{+0.0\%}_{-15.9\%}\text{ pb}$$

Only small dependence for physical m_H



Renormalisation scheme uncertainties

Scheme uncertainties of similar size also for other processes:

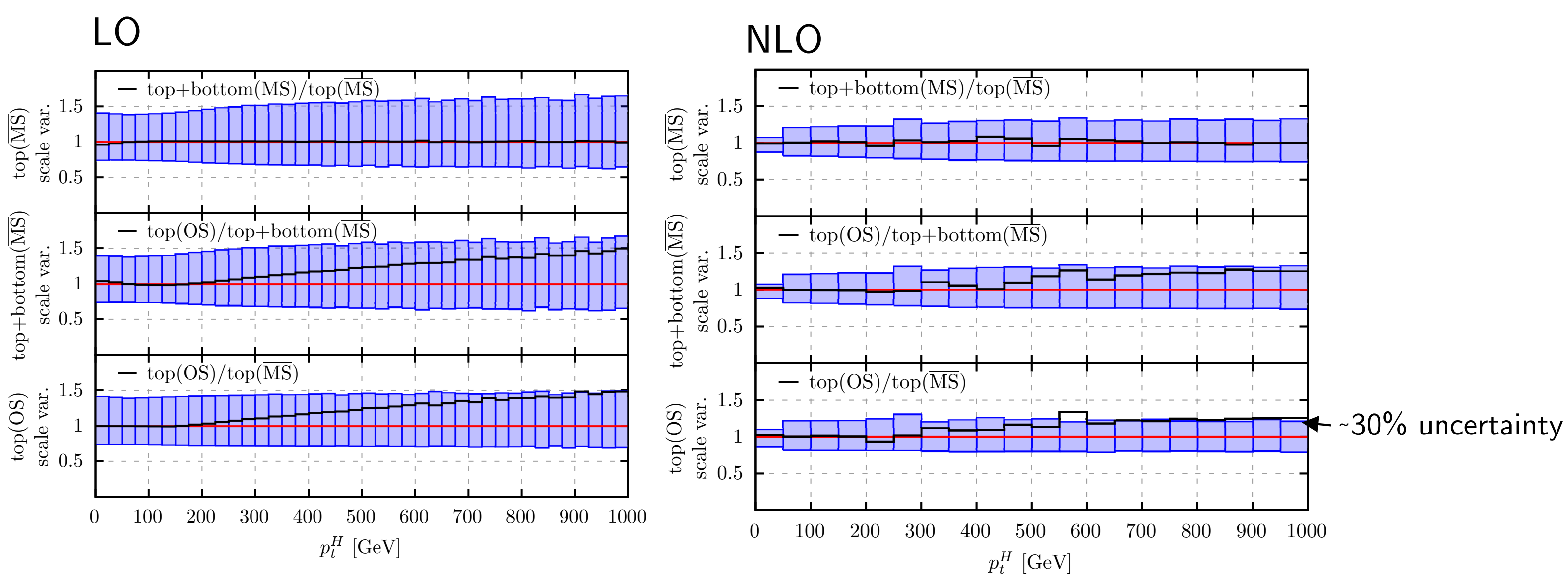
[M. Kerner '22]

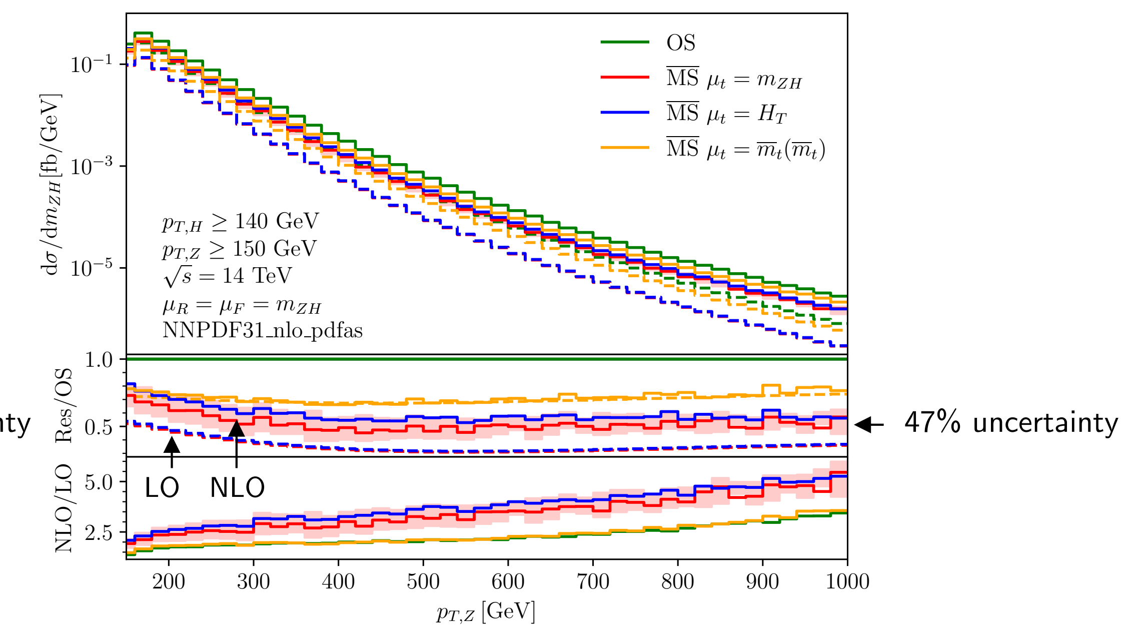
HJ production (using DiffExp approach)

Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22

ZH production (using SecDec & HE expansion)

Chen, Davies, Heinrich, Jones, MK, Mishima, Schlenk, Steinhauser 22

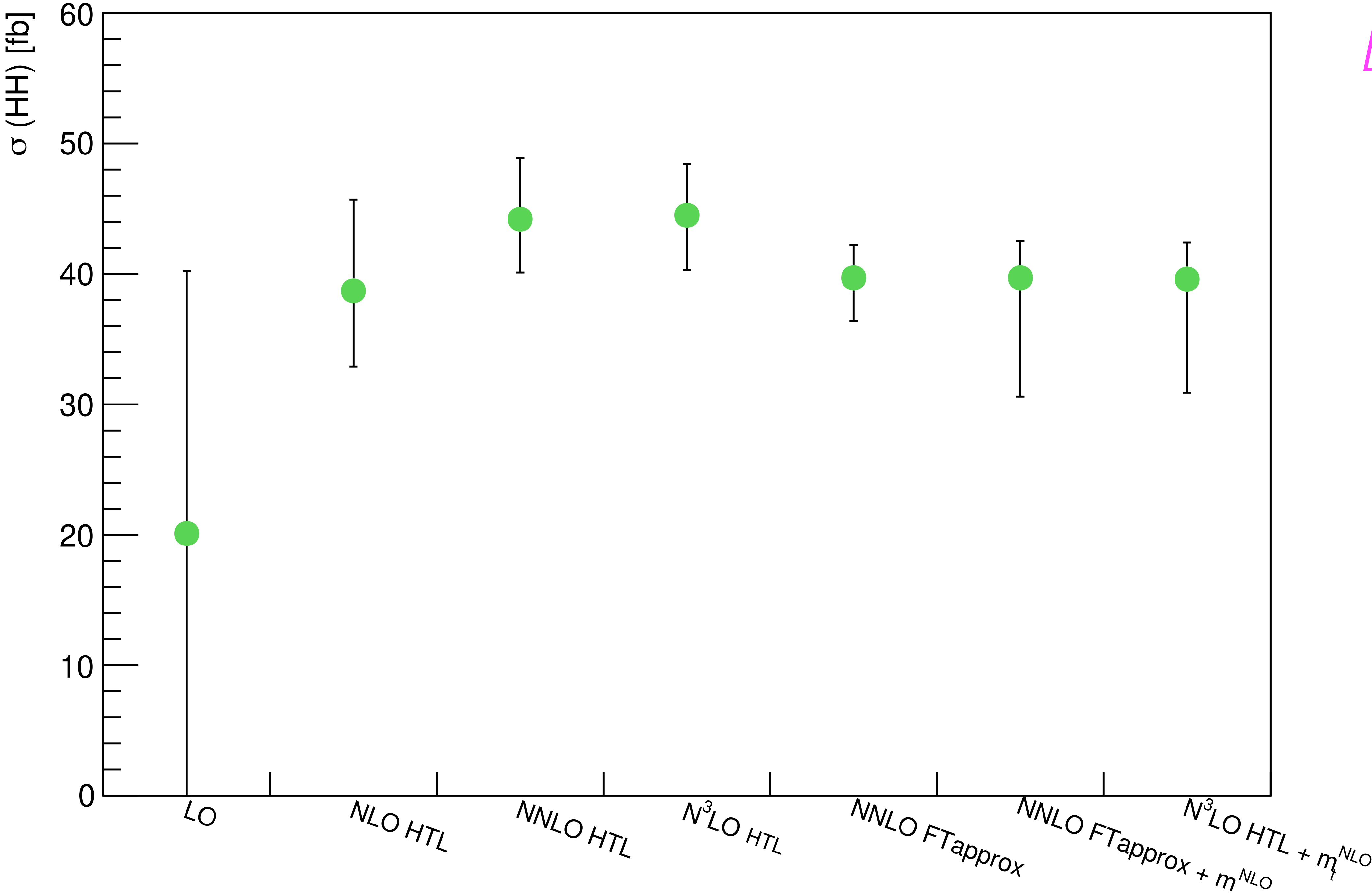




Scheme uncertainty typically reduced by factor of ~2 going from LO to NLO,
but still O(20-50%) at large $\sqrt{s}$, p_T

Estimate of electroweak corrections: parameterisation in terms of G_F vs. α, etc.

Higgs pair production, prediction and uncertainties



[M. Spira '22]

Electroweak corrections: top-Yukawa contributions

[M. Mühlleitner, J. Schlenk, M. Spira '22] [J. Davies et al. '22]

Comparison between experiment and theory

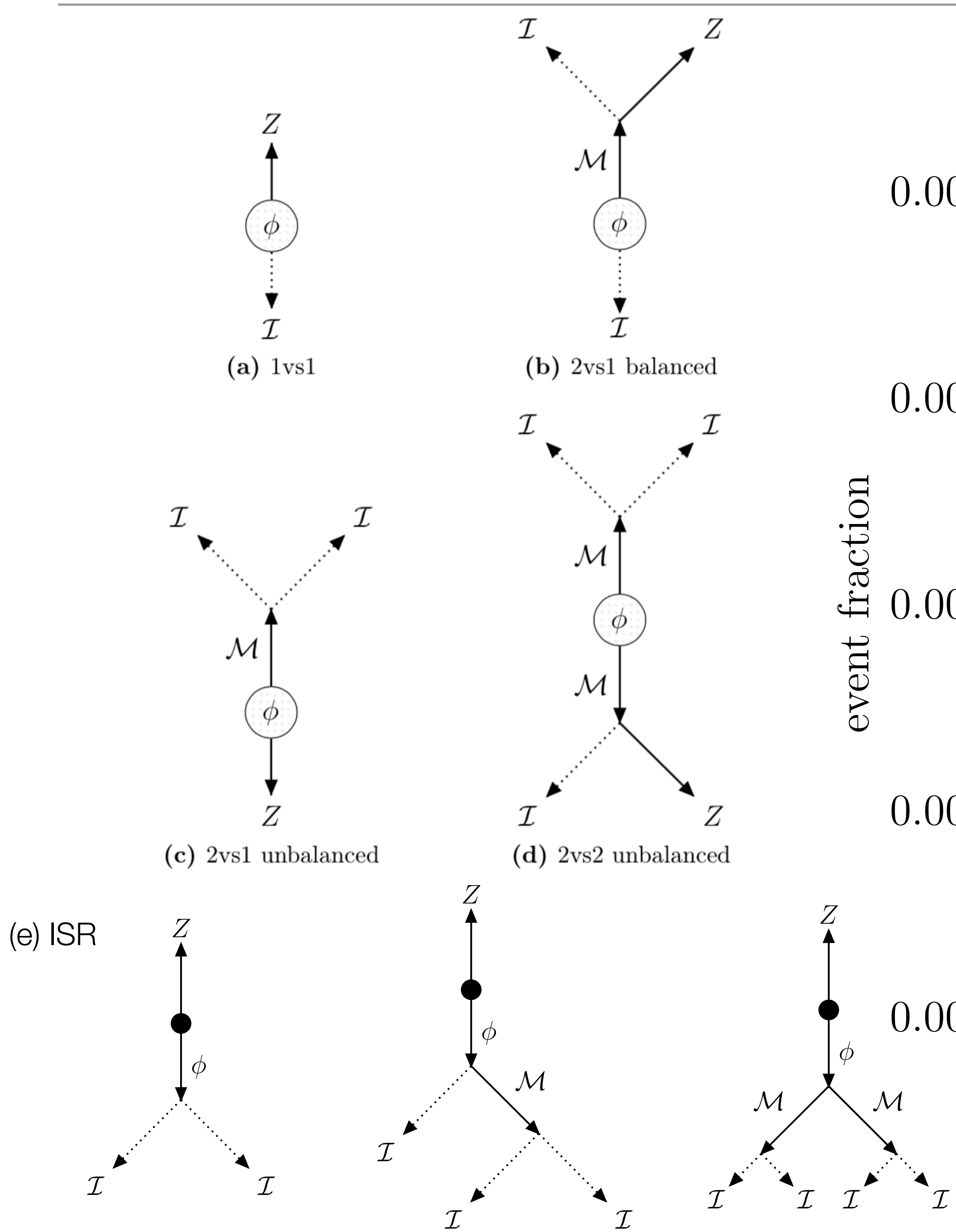
- Properties of h125:
  The comparison between experiment and theory is carried out at the level of signal strengths, STXS, fiducial cross sections, … , and to a lesser extent for $\varkappa$ parameters (signal strength modifiers; see example of $\varkappa_\lambda$ below) and coefficients of EFT operators

  Public tools for confronting the experimental results with model predictions: *HiggsSignals* (signal strengths, STXS), *Lilith* (signal strengths), …

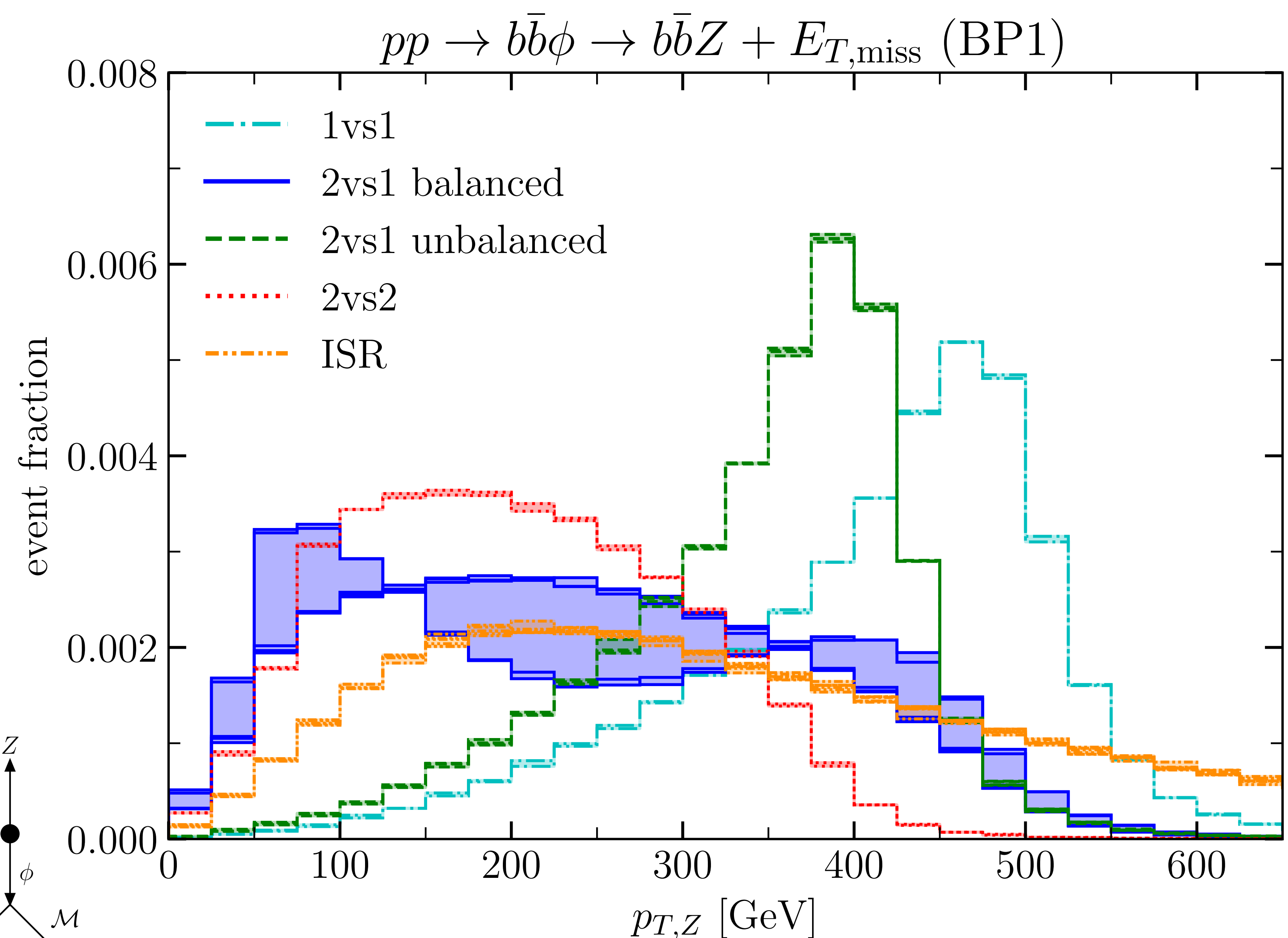
  New versions: *HiggsTools* *[H. Bahl et al. '22]*

- Limits from the searches for additional Higgs bosons:
  Public tools for reinterpretation / recasting of experimental results:
  HiggsBounds (limits on σ x BR, full likelihood information incorporated where provided by exp. collaborations)
  Recasting tools:
  MadAnalysis 5, *Rivet*, *ColliderBit*, *RECAST* (ATLAS-internal), …

Simplified models for BSM Higgs searches



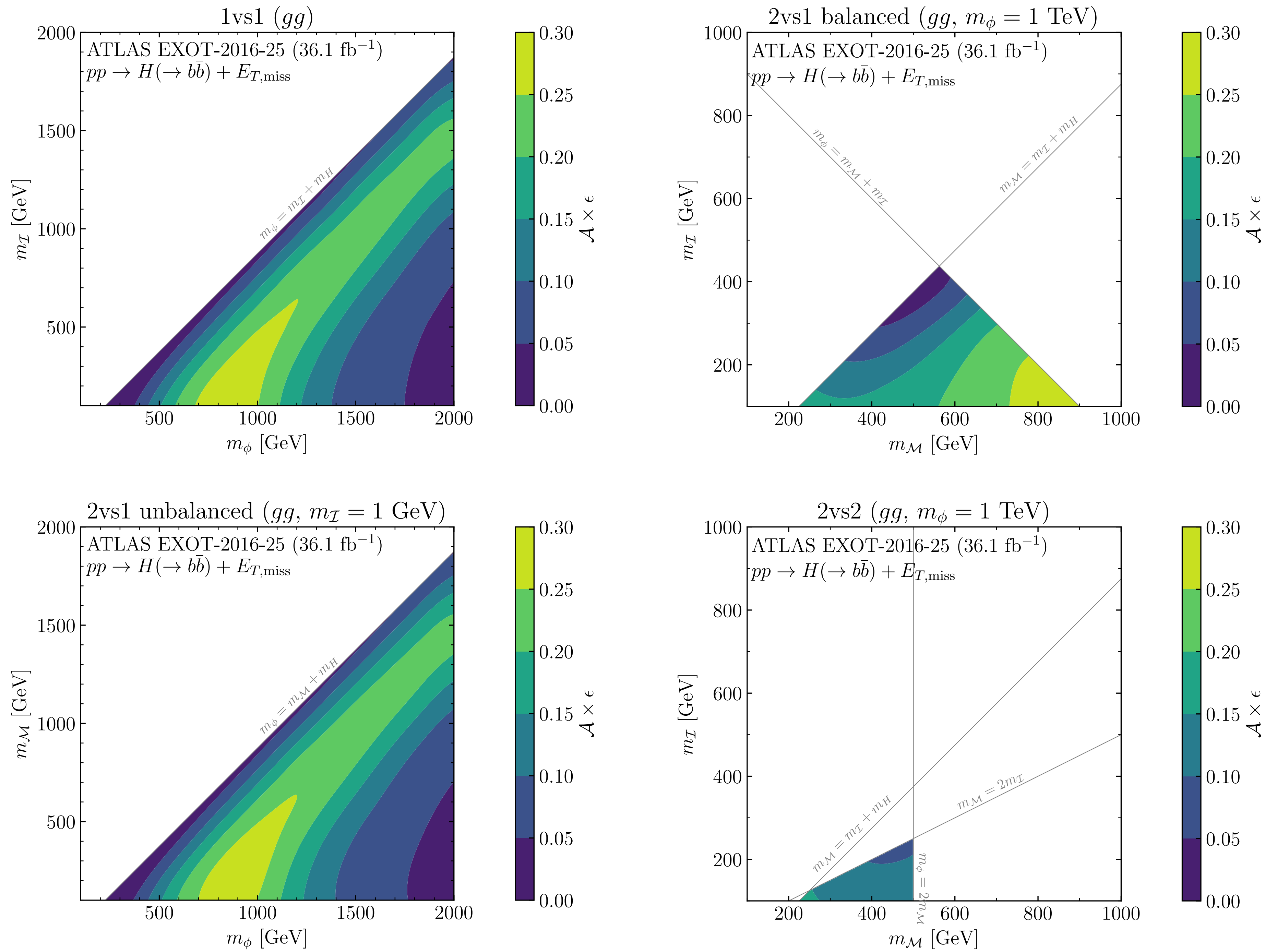
[H. Bahl, V. Martin Lozano, G. W. ’21]



⇒ High sensitivity to different simplified model topologies, spins of mediators and invisible particles have relatively small impact

Simplified models for BSM Higgs searches

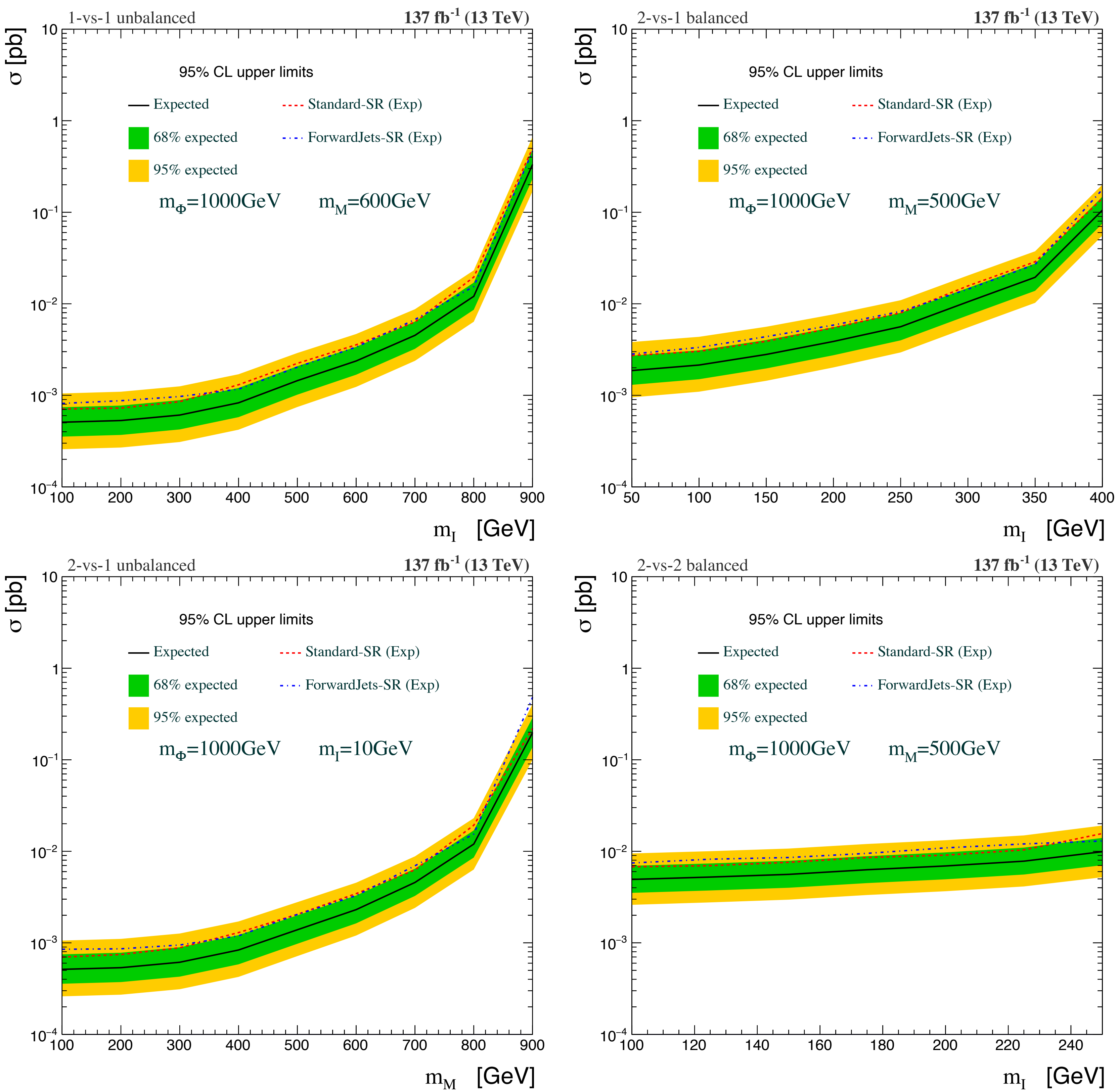
[H. Bahl, V. Martin Lozano, G. W. '21]



⇒ (Acceptance x efficiency) maps, can easily be utilised to obtain exclusion limits for a wide range of models

Application: expected limits for simplified model topologies from search in bbZ + E_T^{miss} final state

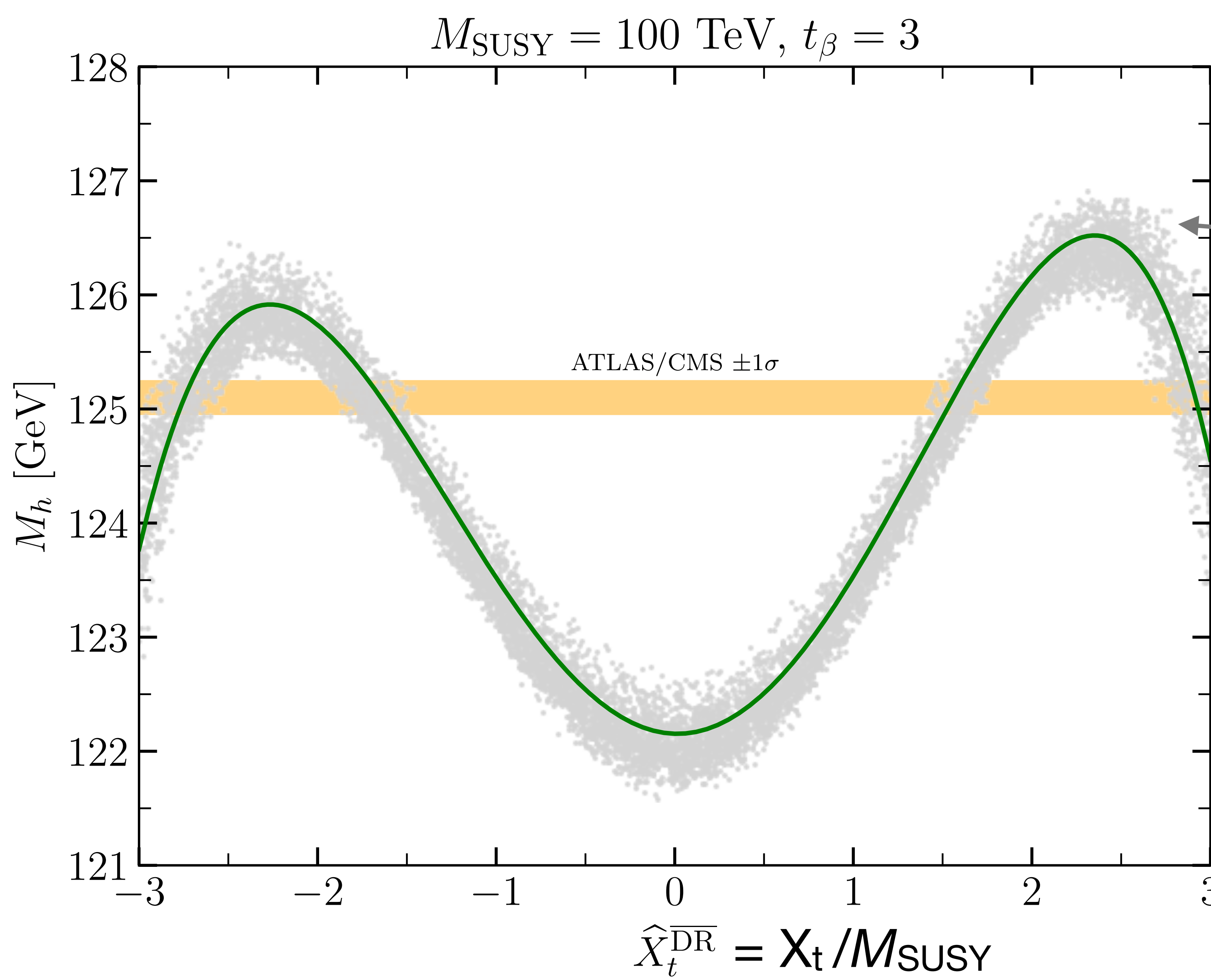
[D. P. Adan et al. '22]



⇒ Signal region with forward jets has sizeable impact

Properties of the observed Higgs boson at 125 GeV

Higgs mass as a precision observable: M_{h125} = 125.25 ± 0.17 GeV
Comparison: M_h prediction for heavy SUSY (M_{SUSY} = 100 TeV)



= X_t / M_{SUSY}

[H. Bahl, J. Braathen, G. W. '22]

Mass parameters and trilinear couplings varied in [1/2 M_{SUSY}, 2 M_{SUSY}]

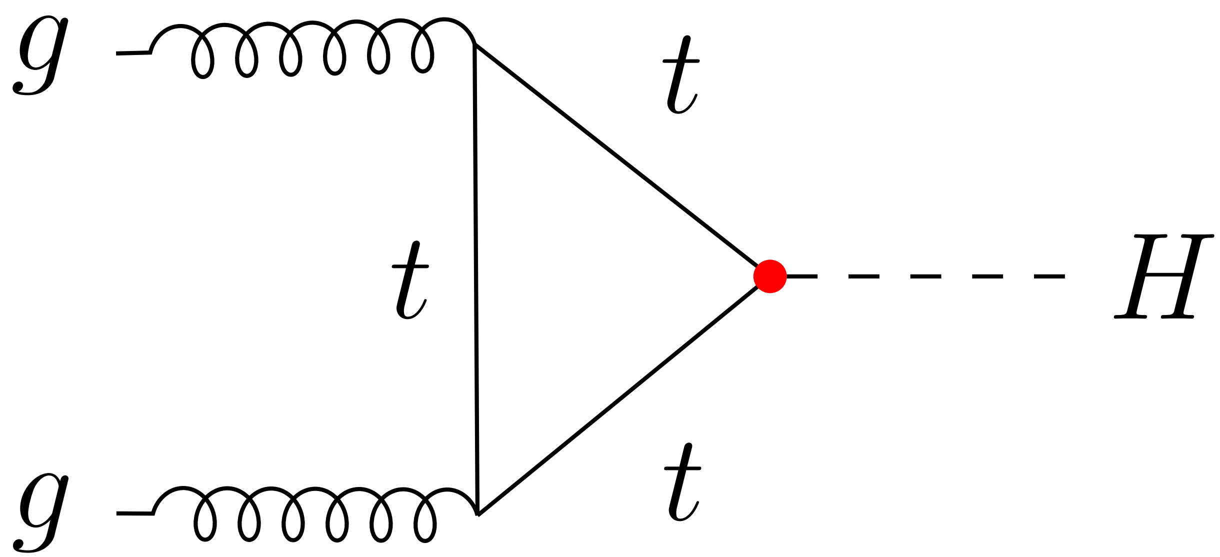
X_t : mixing in the scalar top sector

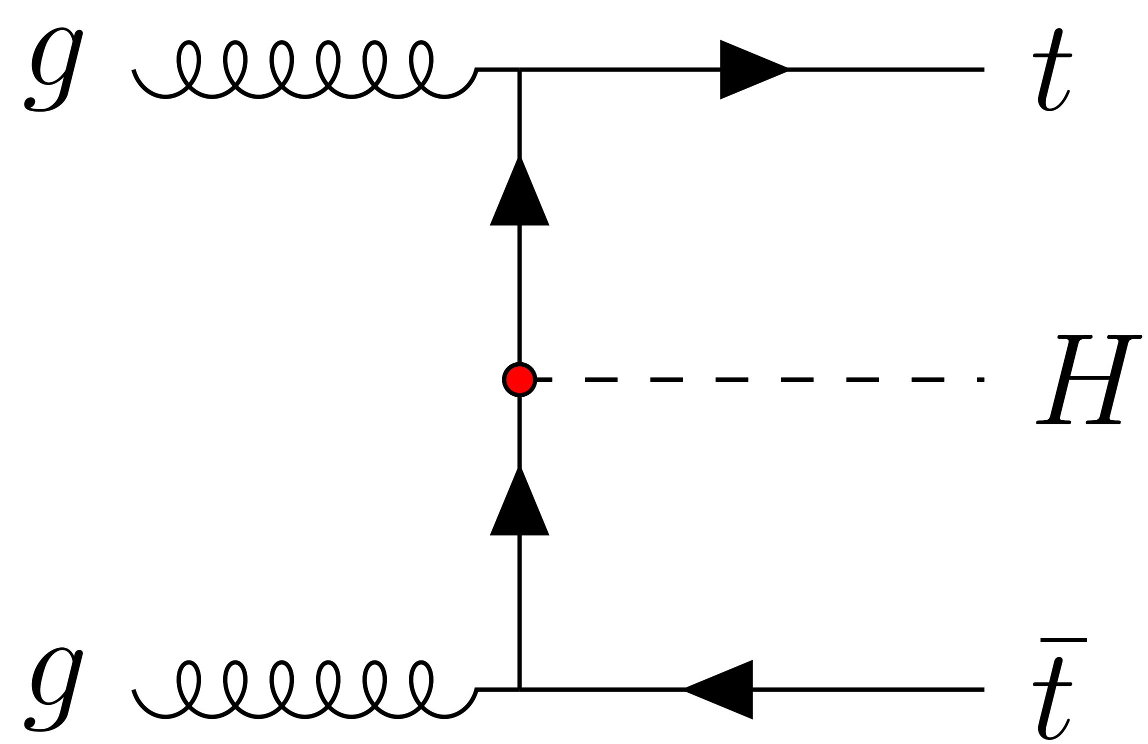
⇒ High-precision measurement of the Higgs mass puts important constraints on BSM physics even if new physics scale is very high!

CP properties of h125

It has been experimentally verified that h125 is not a pure CP-odd state, but it is by no means clear that it is a pure CP-even state

The main testing ground are processes involving only Higgs couplings to fermions



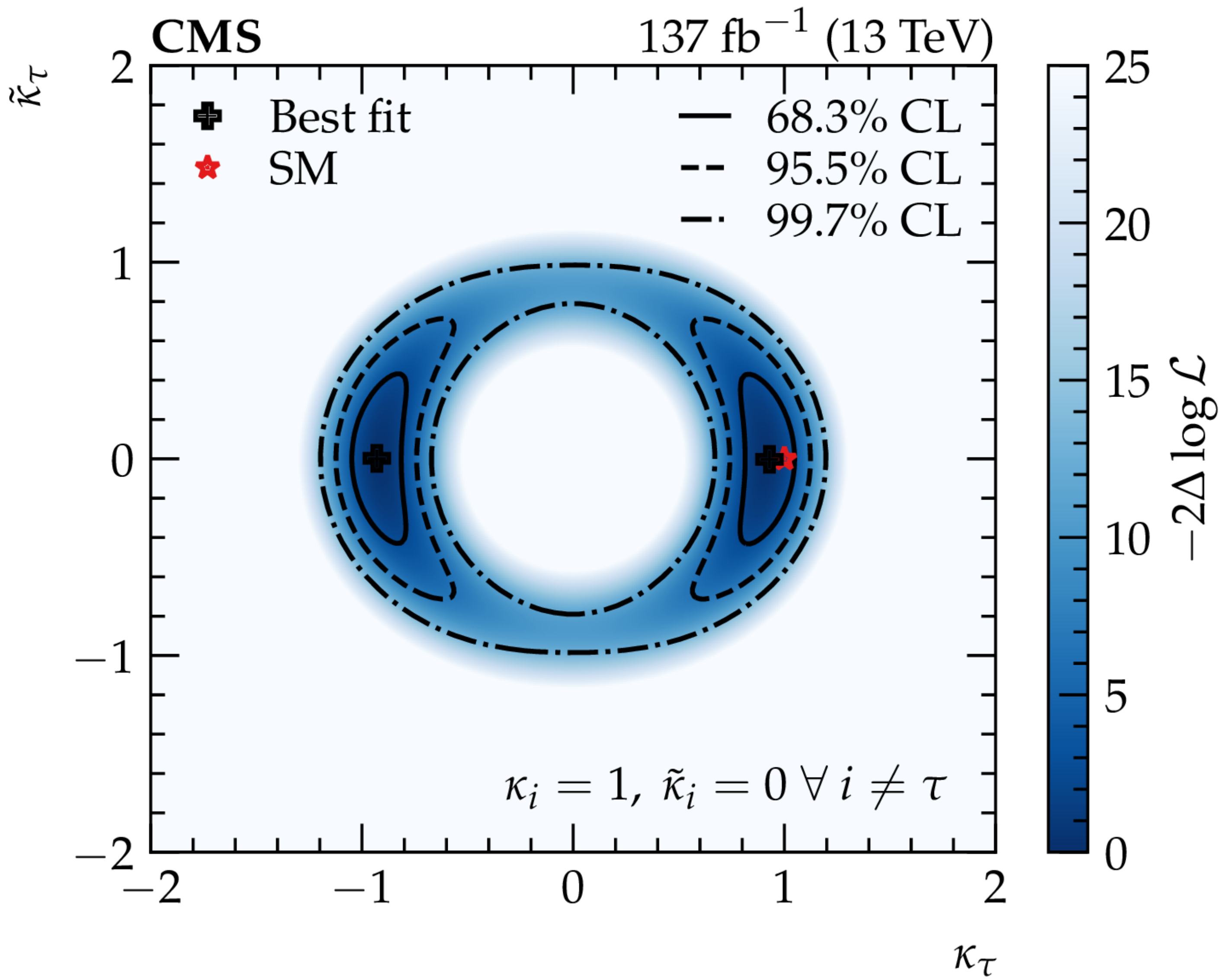


with H → $\tau\tau$, bb, …

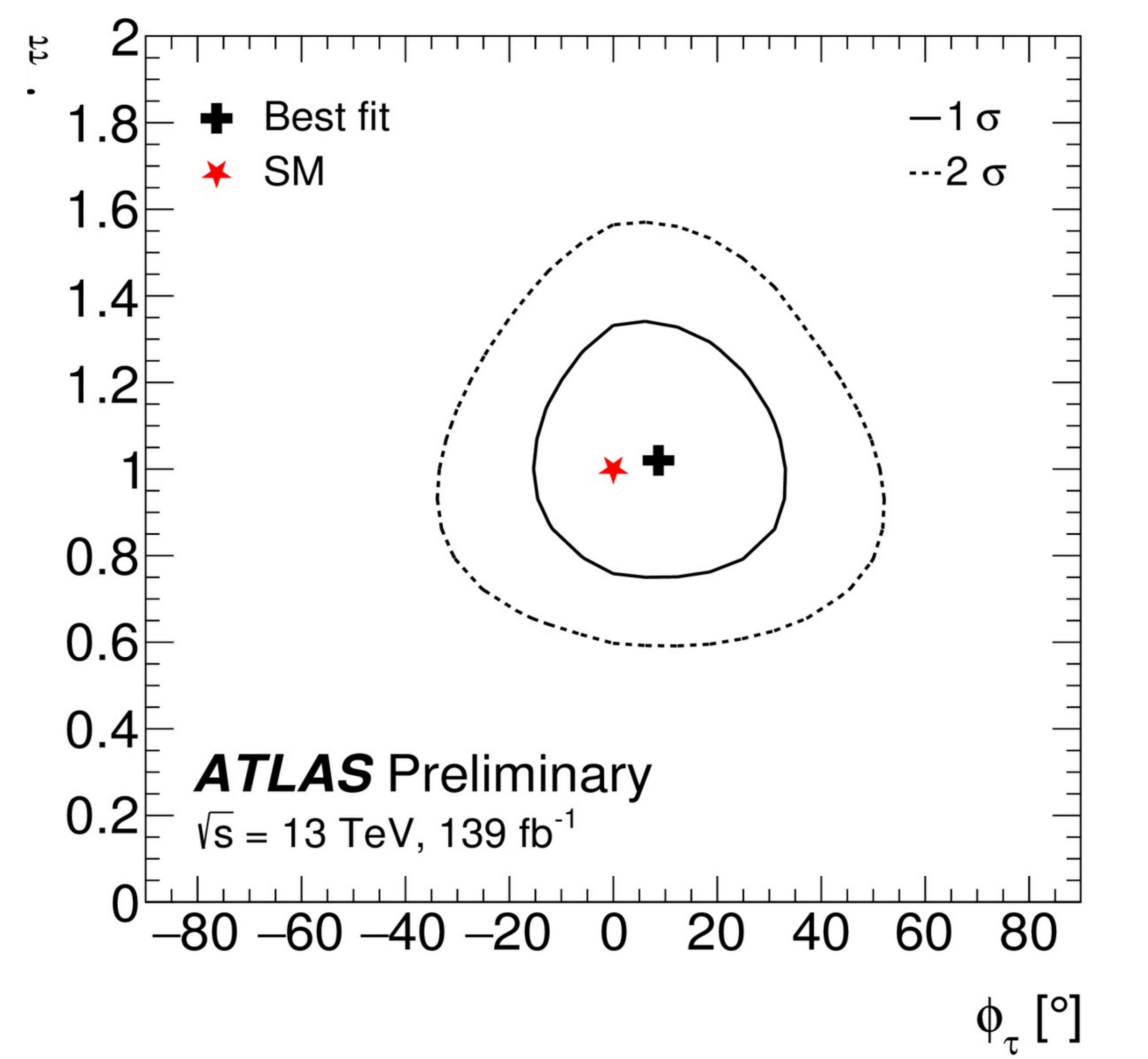
Test of CP violation in the tau Yukawa coupling

Constraints on the CP structure of the tau Yukawa coupling from h125 → $\tau\tau$ decays using angular correlation between decay products:

[CMS Collaboration ’21]



[ATLAS Collaboration ’22]



Effect on global CP analysis of Higgs-fermion couplings

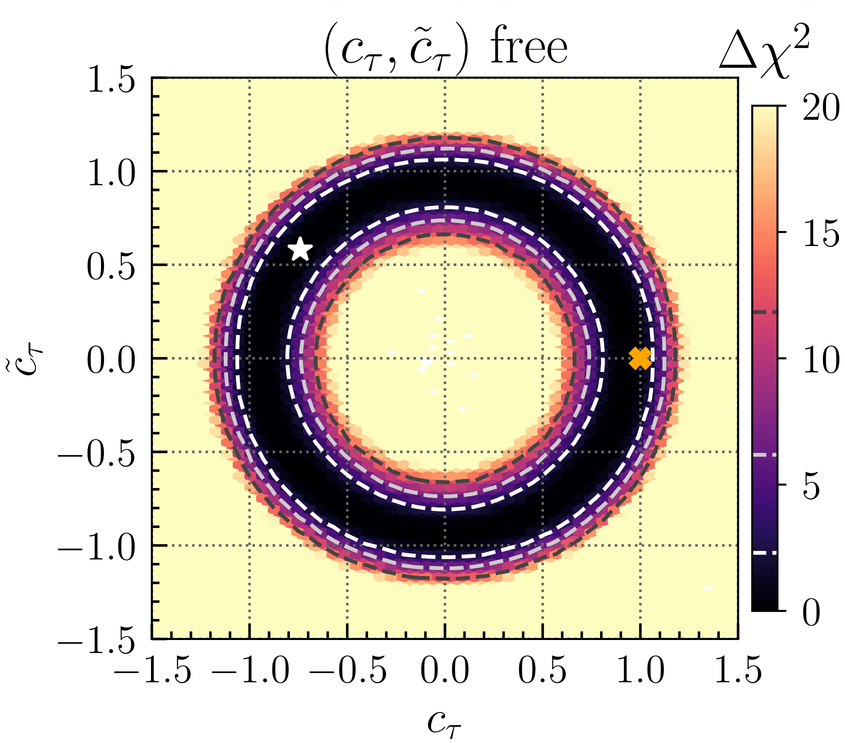
[H. Bahl et al. '22]

Incorporation of recent CMS result on the CP structure of the tau Yukawa coupling from h125 → $\tau\tau$ decays using angular correlation between the decay products

$$\mathcal{L}_{\rm Yuk} = -\sum_f \frac{y_f}{\sqrt{2}} \bar{f} \left(c_f + i\gamma_5 \tilde{c}_f \right) f h,$$

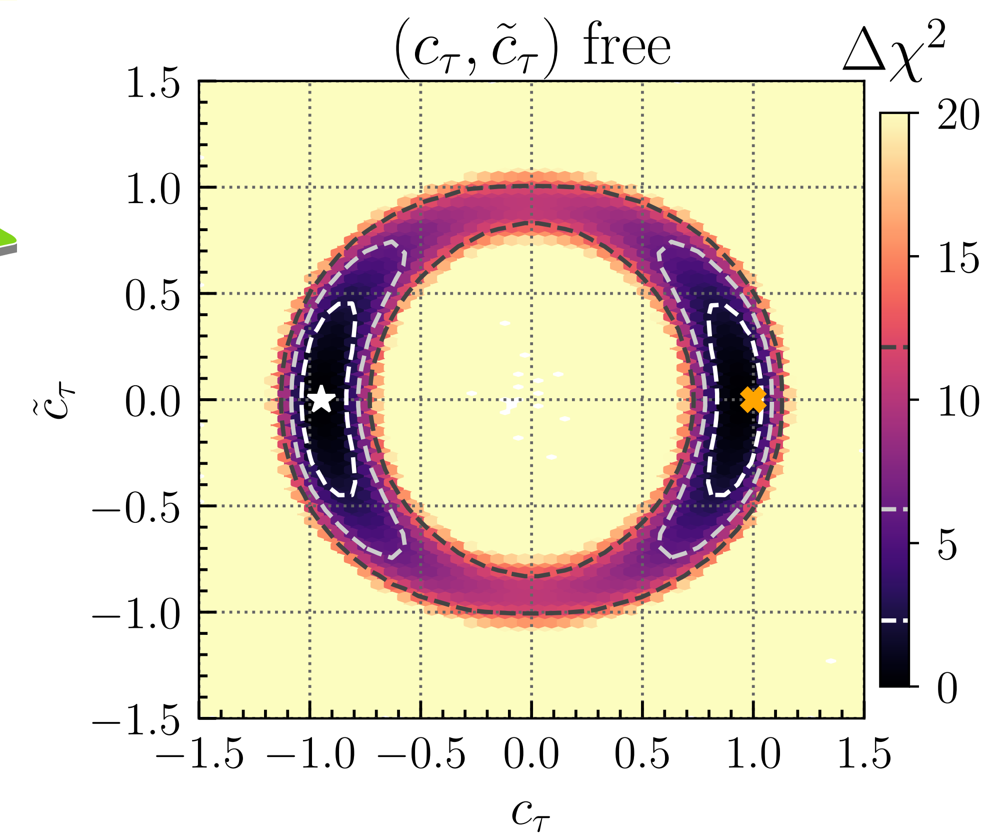
can also be analyzed in EFT

Global fit using **HiggsSignals** + recent analyses



CMS 2110.04836
h→ ττ CPV analysis

$c_\tau \simeq \pm 1$ almost degenerate minima of $\Delta\chi^2$



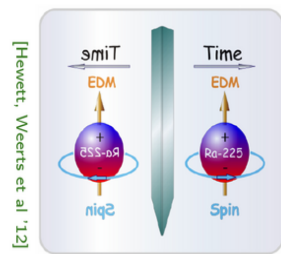
Ring-structure from upper/lower bound on BR

CMS analysis excludes large $\tilde{c}_\tau$

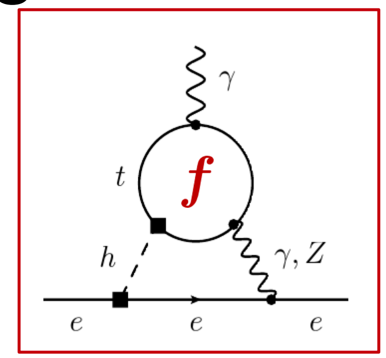
CP structure of the Higgs-fermion couplings

[H. Bahl et al. '22]

Comparison with the existing EDM constraints



EDM violates $\mathcal{T}$ and $\mathcal{P}$ $\Rightarrow \not{C}\not{P}$



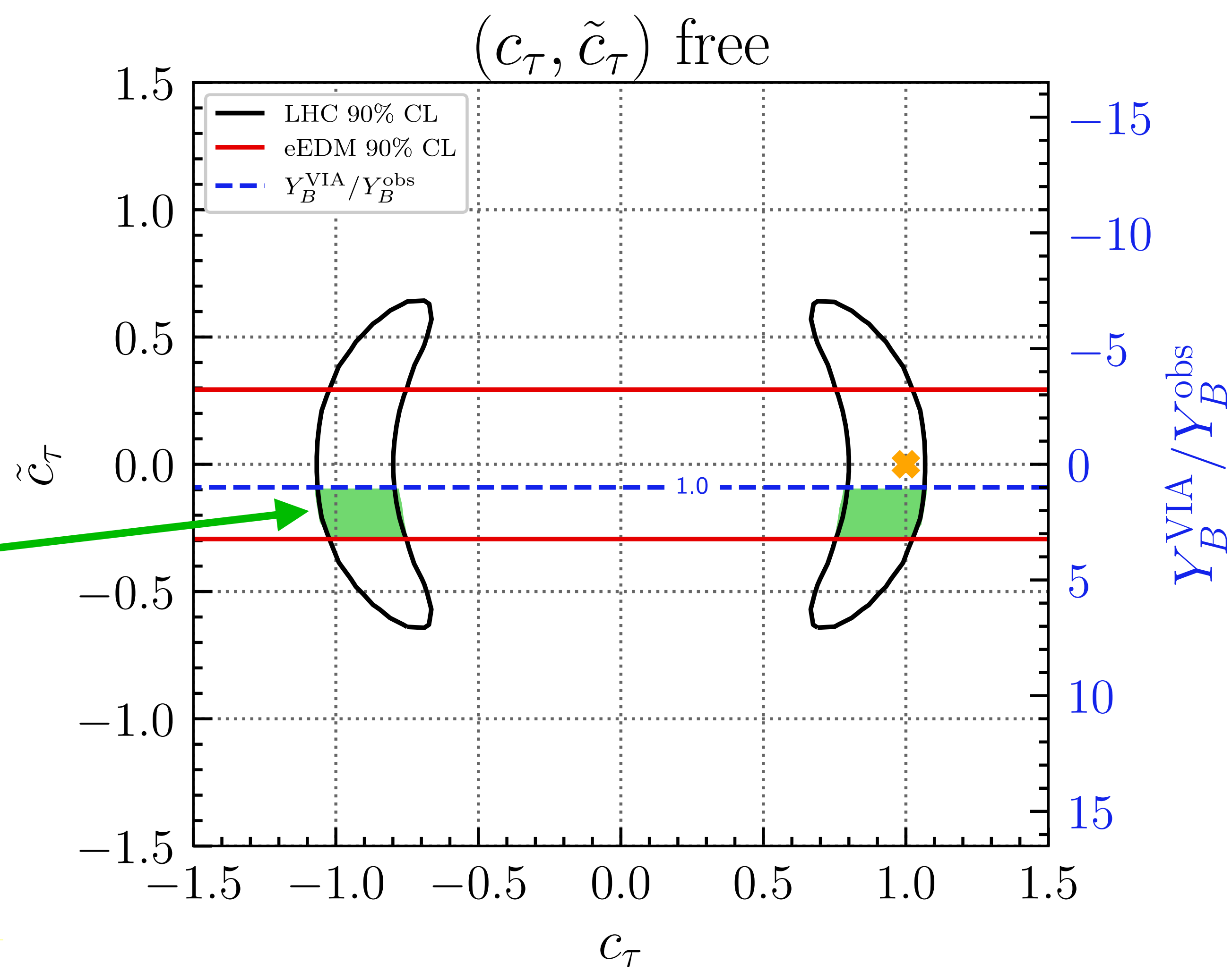
ACME [Nature '18]:

$$d_e \leq 1.1 \times 10^{-29}\, e\,\mathrm{cm} \text{ at } 90\%\ \mathrm{CL}$$

Using [Panico, Pomarol, Riembau '18], [Brod, Haisch, Zupan '13], [Brod, Stamou '18],...

Analysis of the resulting amount of baryon asymmetry in the universe

Electron electric dipole moment $d_e \propto \tilde{c}_f$



Allowed by LHC, EDM constraints and baryogenesis!

Could work even for the case where CP violation occurs just in the τ coupling (in optimistic scenario)!

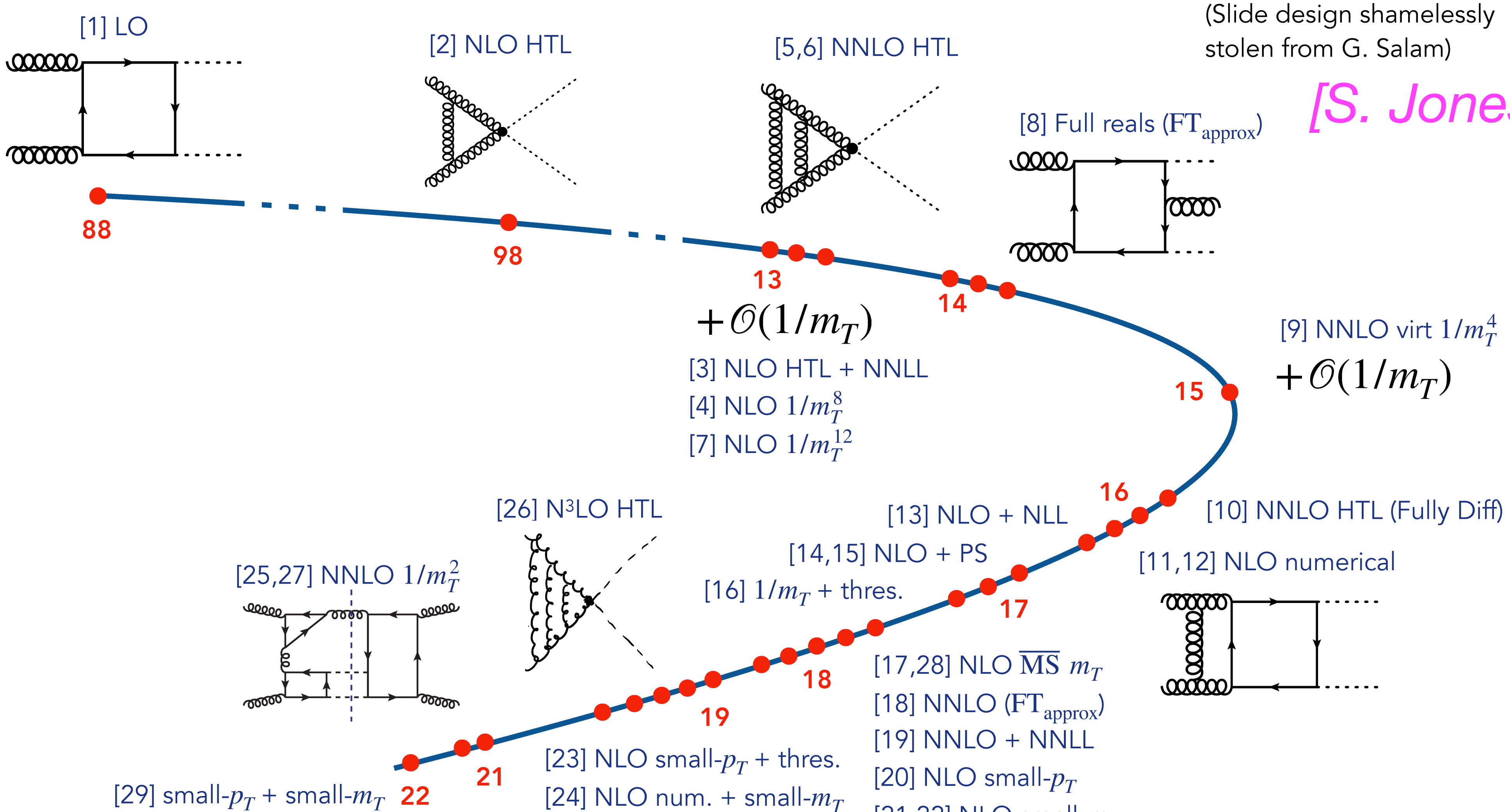
$\Rightarrow$ CP violation in τ coupling could yield correct baryon asymmetry!

Higgs pair production: theory predictions

An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)

[S. Jones, G. Salam]



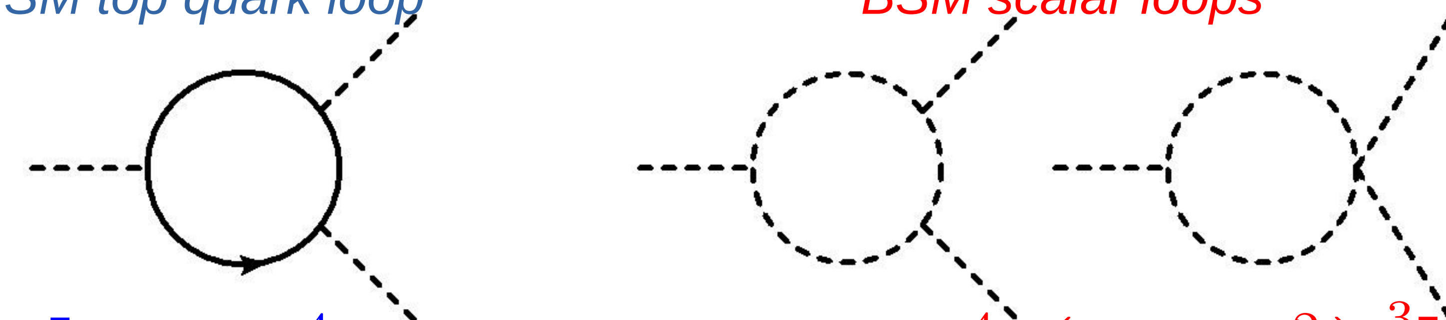
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, 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;

Effects of BSM particles on the trilinear Higgs coupling

Trilinear Higgs coupling in extended Higgs sectors: potentially large loop contributions

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

SM top quark loop *BSM scalar loops*



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

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: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda} v^2$

⇒ Large effects possible for sizeable splitting between m_Φ and $\mathcal{M}$

Simple example of extended Higgs sector: 2HDM

- 2 $SU(2)_L$ doublets $\Phi_{1,2}$ of hypercharge ½
- CP-conserving 2HDM, with softly-broken Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) to avoid tree-level FCNCs

$$V^{(0)}_{\text{2HDM}} = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_2) + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_2^\dagger\Phi_1|^2 + \frac{\lambda_5}{2}\Big((\Phi_2^\dagger\Phi_1)^2 + \text{h.c.}\Big)$$

- m_1,m_2 eliminated with tadpole equations, and $v_1^2 + v_2^2 = v^2 = (246\text{ GeV})^2$
- 7 free parameters in scalar sector: m_3, λ_i (i=1,..,5), $\tan\beta \equiv v_2/v_1$
- Mass eigenstates: h, H: CP-even Higgses, A: CP-odd Higgs, $H^\pm$: charged Higgs, α: CP-even Higgs mixing angle
- λ_i (i=1,..,5) traded for mass eigenvalues m_h, m_H, m_A, $m_{H\pm}$ and angle α
- m_3 replaced by a Z_2 soft-breaking mass scale

$$M^2 = \frac{2m_3^2}{s_{2\beta}}$$

- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

In alignment limit, α = β - π/2 : h couplings are SM-like at tree level

Two-loop predictions for the trilinear Higgs coupling in the 2HDM vs. current experimental bounds

[H. Bahl, J. Braathen, G. W. '22]

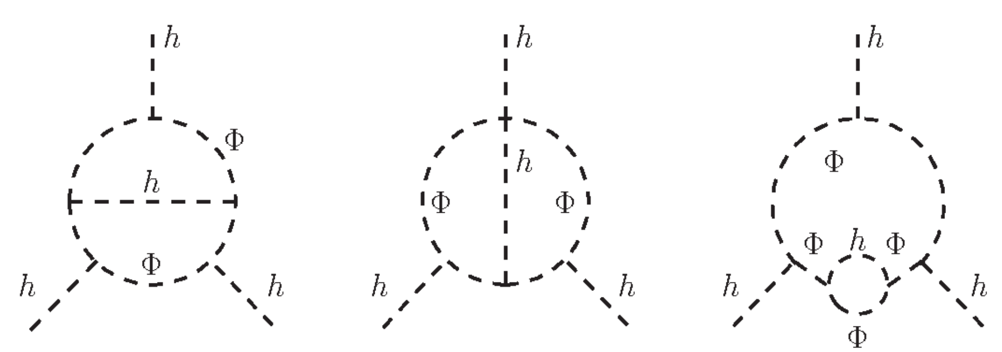
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2} \qquad \Phi \in \{H, A, H^\pm\}$$

Leading two-loop corrections involving heavy BSM Higgses and the top quark in the effective potential approximation

[J. Braathen, S. Kanemura '19, '20]

⇒Incorporation of the highest powers in $g_{hh\phi\phi}$



Analysis is carried out in the alignment limit of the 2HDM (α = β - π/2)

⇒h has SM-like tree-level couplings

Check of applicability of the experimental limit on $\varkappa_\lambda$

The assumption that new physics only affects the trilinear Higgs self-coupling is expected to hold at most approximately in realistic models

BSM models can modify Higgs pair production via resonant and non-resonant contributions

The current experimental limit can only probe scenarios with large deviations from the SM

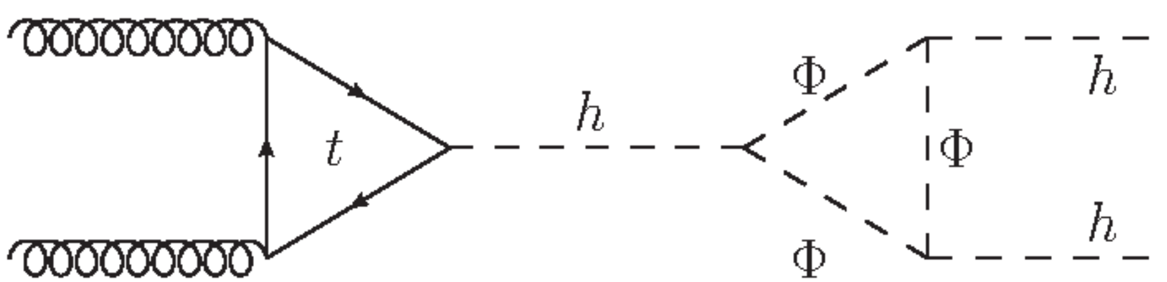
$\Rightarrow$ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

Check of applicability of the experimental limit on $\varkappa_\lambda$

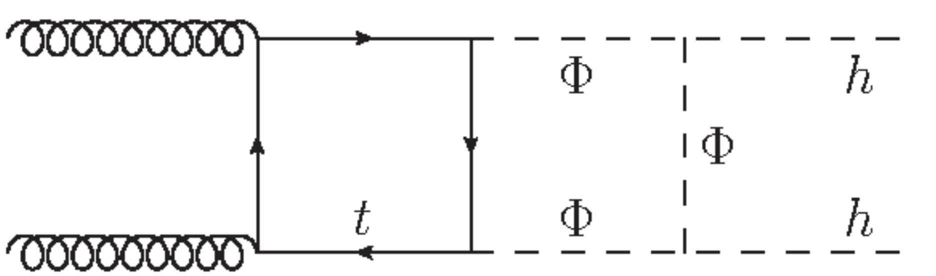
Alignment limit: h has SM-like tree-level couplings

Resonant contribution to Higgs pair production with H or A in the s channel is absent in the alignment limit

The dominant new-physics contributions enter via trilinear coupling



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



$\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

⇒The leading effects in $g_{hh\Phi\Phi}$ to the Higgs pair production process are correctly incorporated at the 1- and 2-loop order via the corrections to the trilinear Higgs coupling!

Two-loop prediction for the trilinear Higgs coupling Parameter scan with exp. and theoretical constraints

[H. Bahl, J. Braathen, G. W. '22]

- Our strategy:
  1. **Scan BSM parameter space**, keeping only points passing various theoretical and experimental constraints (*see below*)
  2. Identify regions with **large BSM deviations in λ_{hhh}**
  3. Devise a **benchmark scenario** allowing large deviations and investigate impact of experimental limit on λ_{hhh}
- *Here*: we consider an **aligned 2HDM of type-I**, but similar results expected for other 2HDM types, or other BSM models with extended Higgs sectors
- Constraints in our parameter scan:

  experimental
  - SM-like Higgs measurements with `HiggsSignals`
  - Direct searches for BSM scalars with `HiggsBounds`
  - b-physics constraints, using results from [Gfitter group 1803.01853]

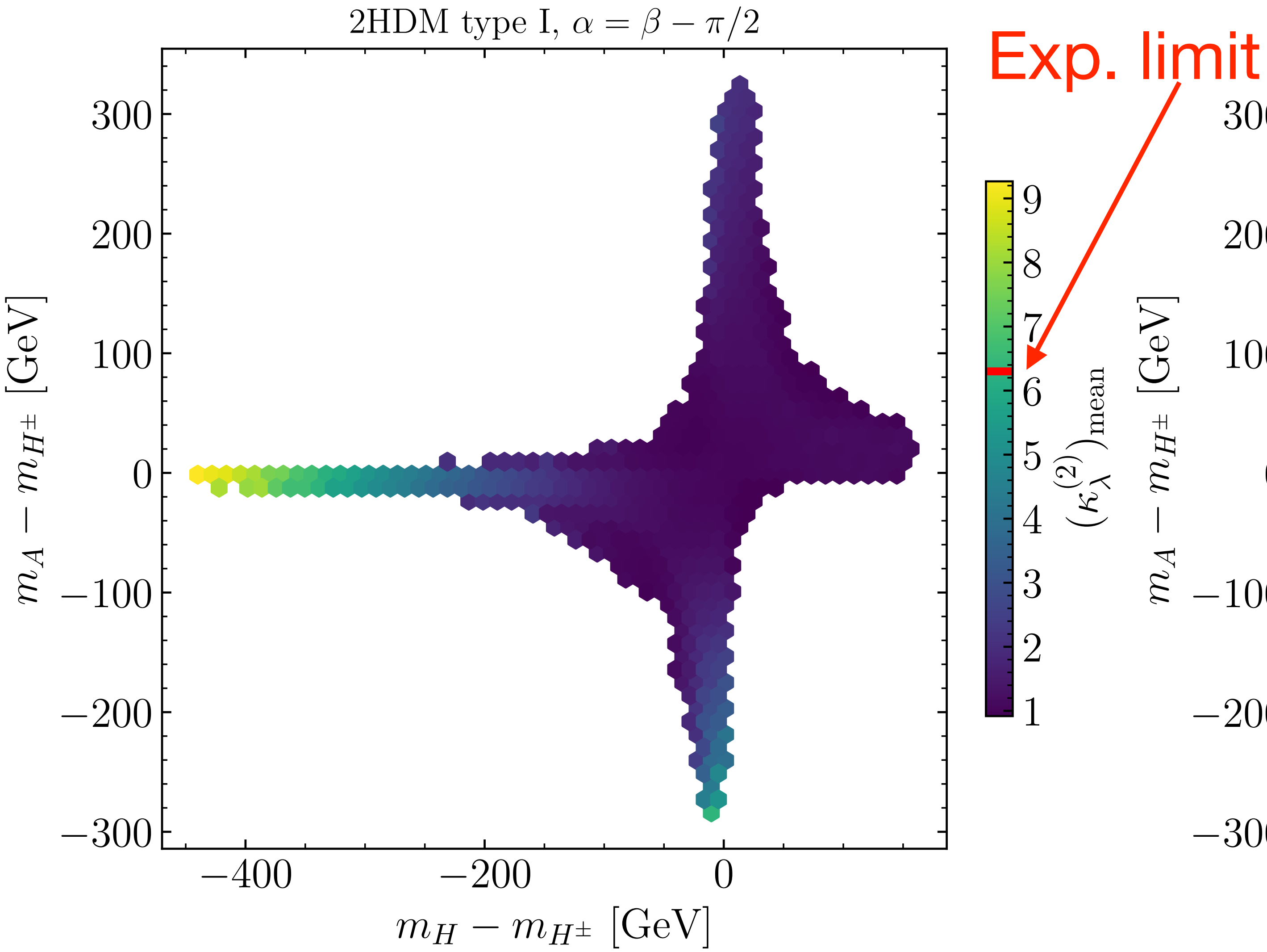
  theoretical
  - Vacuum stability
  - Boundedness-from-below of the potential
  - EW precision observables, computed at two loops with `THDM_EWPOS` [Hessenberger, Hollik '16]
  - NLO perturbative unitarity, using results from [Grinstein et al. 1512.04567], [Cacchio et al. 1609.01290]

  Checked with `ScannerS` (applies to the first five constraints)
- For points passing these constraints, we compute κ_λ at 1L and 2L, using results from [JB, Kanemura '19]

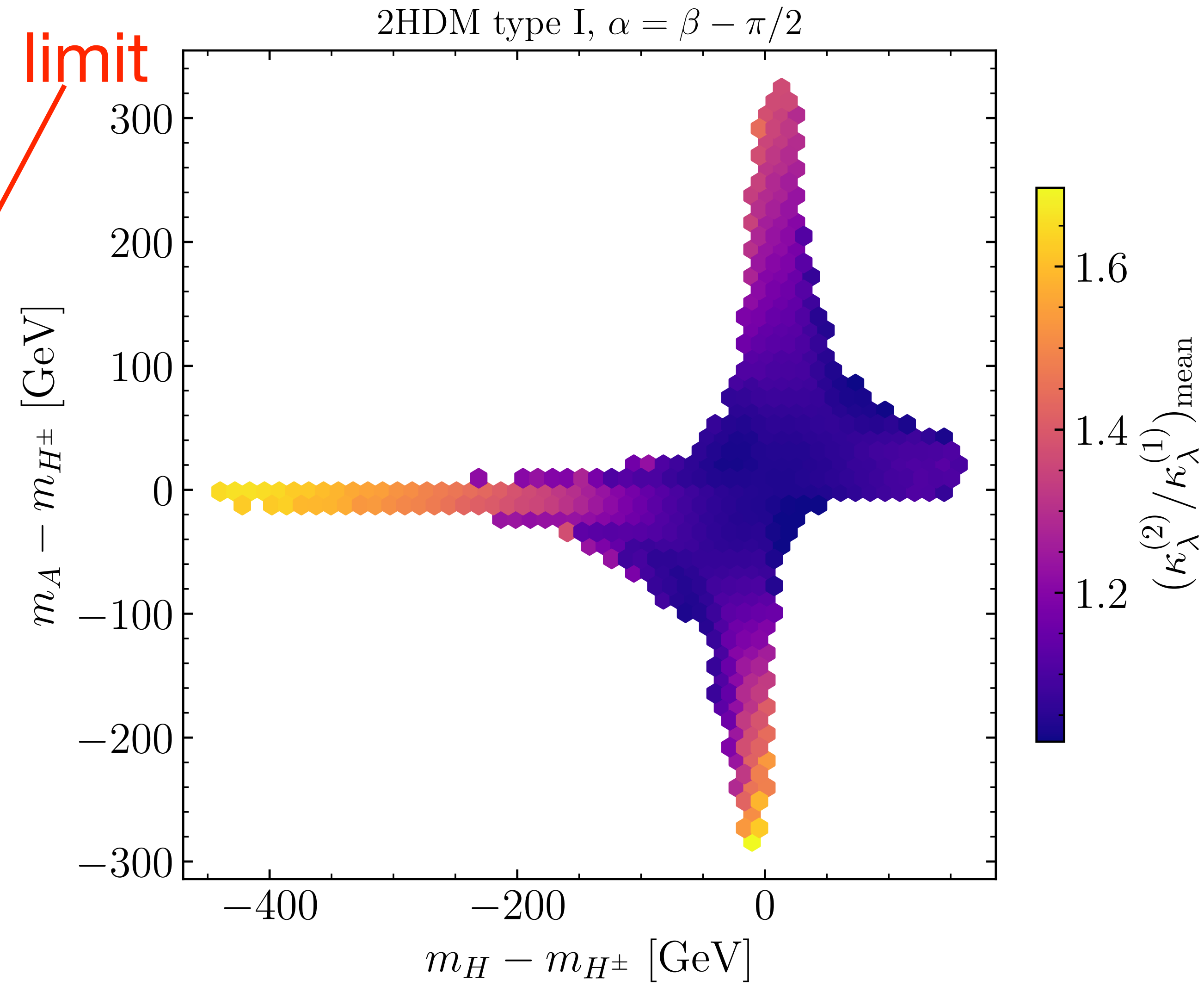
Results for the Two-Higgs doublet model (2HDM)

[H. Bahl, J. Braathen, G. W. '22]

Two-loop prediction for κ_λ:



Comparison with one-loop result:



Displayed points are in agreement with the exp. and theo. constr.

Enhancement up to factor 10 w.r.t. SM possible

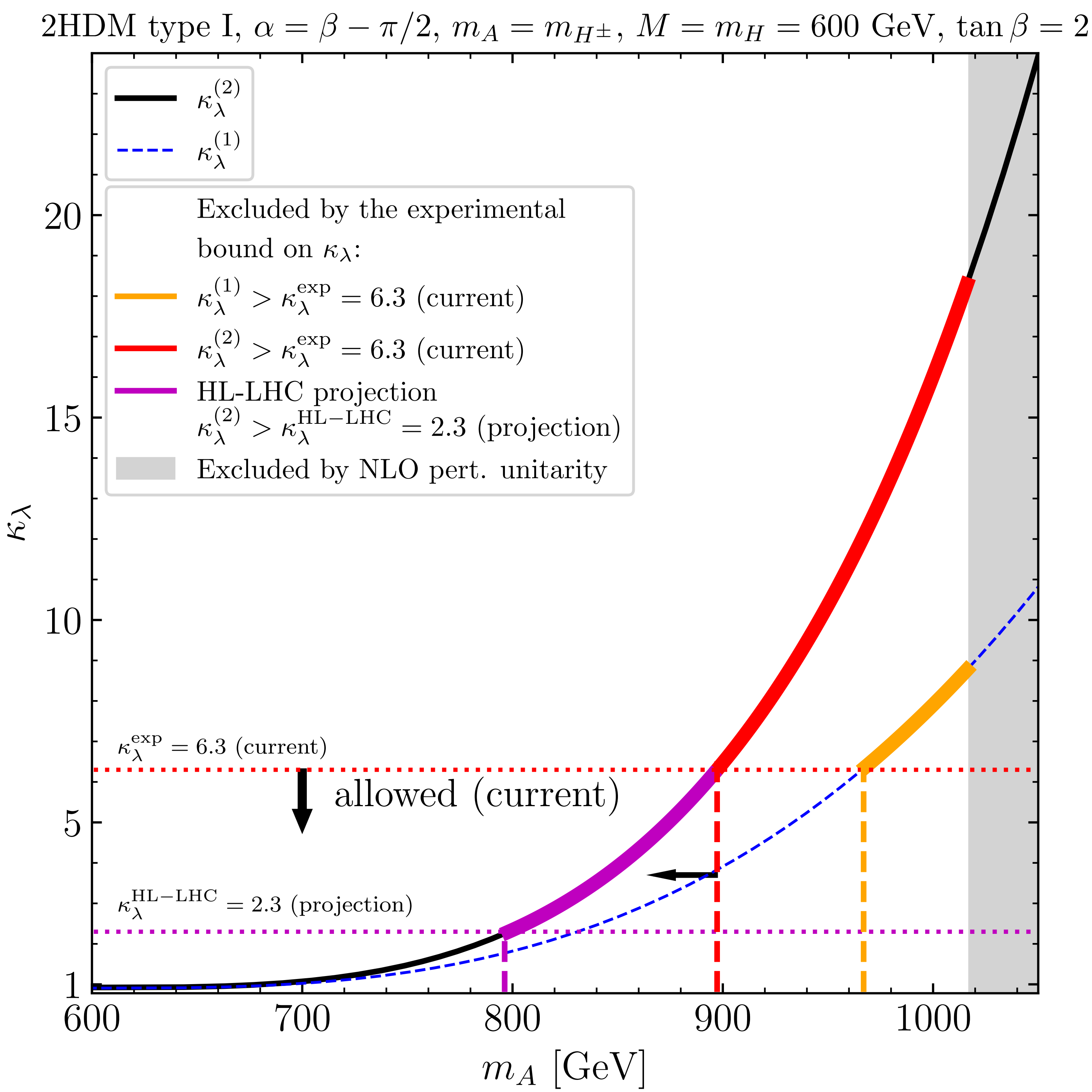
2-loop corrections can reach 70% of the 1-loop effects

⇒ Large effects possible, can be probed with the LHC limits!

Results for the Two-Higgs doublet model (2HDM)

Prediction for $\varkappa_\lambda$ up to the two-loop level:

[H. Bahl, J. Braathen, G. W. '22, to appear in Phys. Rev. Lett.]

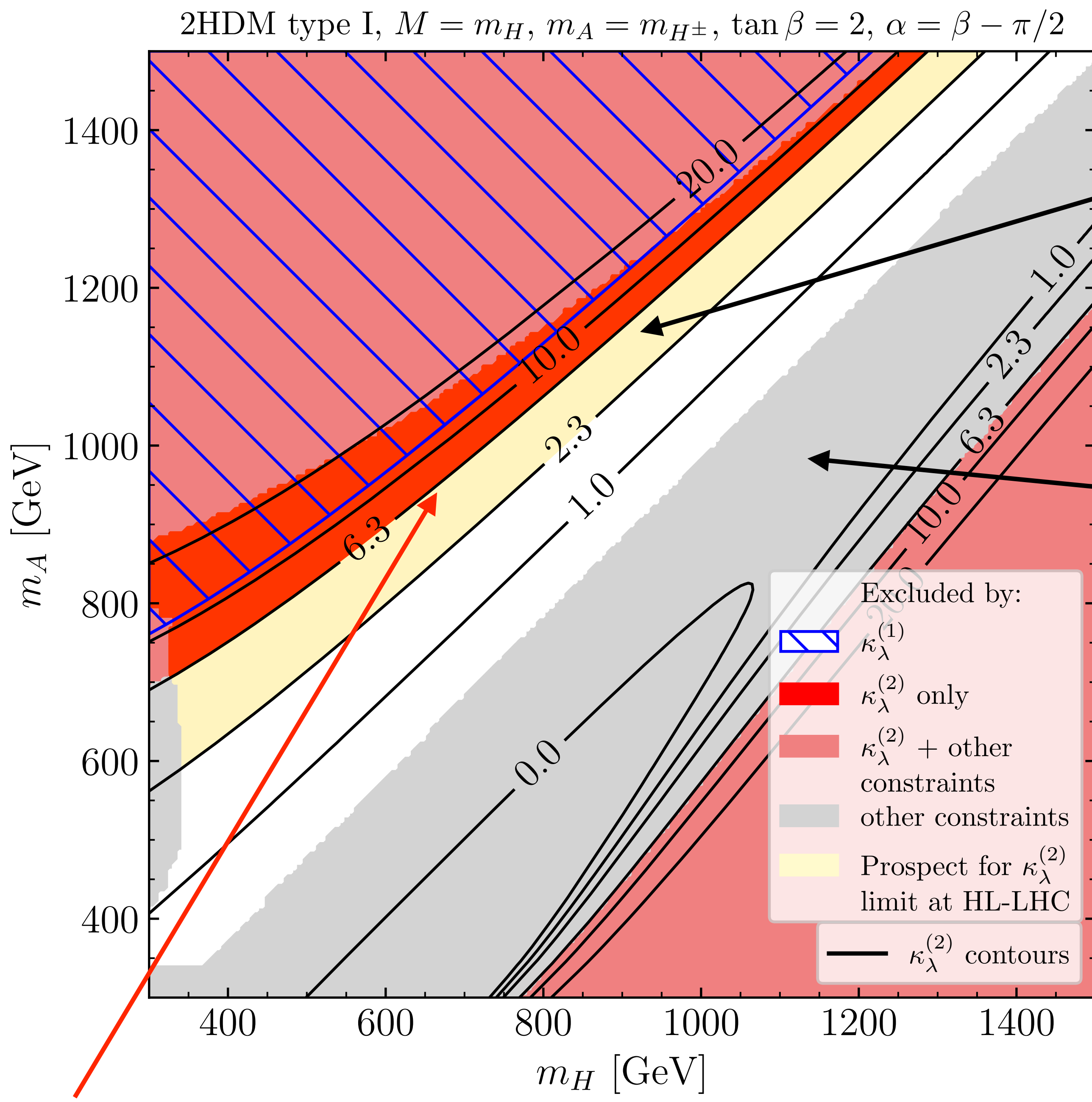


⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

Experimental limit on the trilinear Higgs coupling already has sensitivity to probe extended Higgs sectors!

Constraints in the mass plane of H and A

[H. Bahl, J. Braathen, G. W. '22]



Sensitivity to $\varkappa_\lambda$ at the HL-LHC

Excluded by other constraints:
Higgs physics,
boundedness from below,
NLO perturbative unitarity, …

⇒ LHC limits exclude parameter regions that would be allowed by all other constraints; high sensitivity of future limits / measurements!

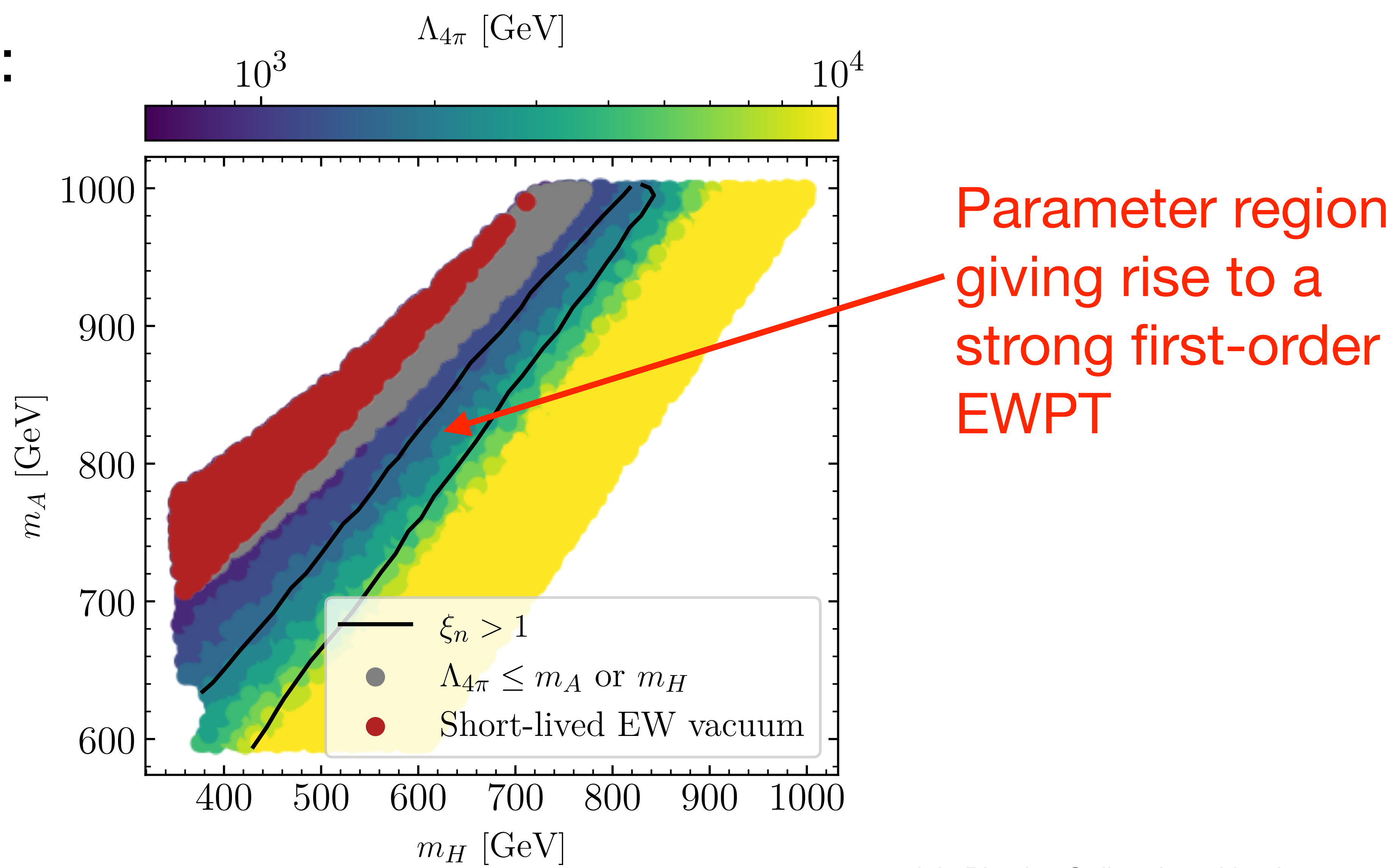
Connection between the trilinear Higgs coupling and the evolution of the early universe

2HDM, N2HDM, … : the parameter region giving rise to a strong first-order EWPT, which may cause a detectable gravitational wave signal, is correlated with an enhancement of the trilinear Higgs self-coupling and with ``smoking gun” signatures at the LHC

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. ’22]

2HDM of type II:

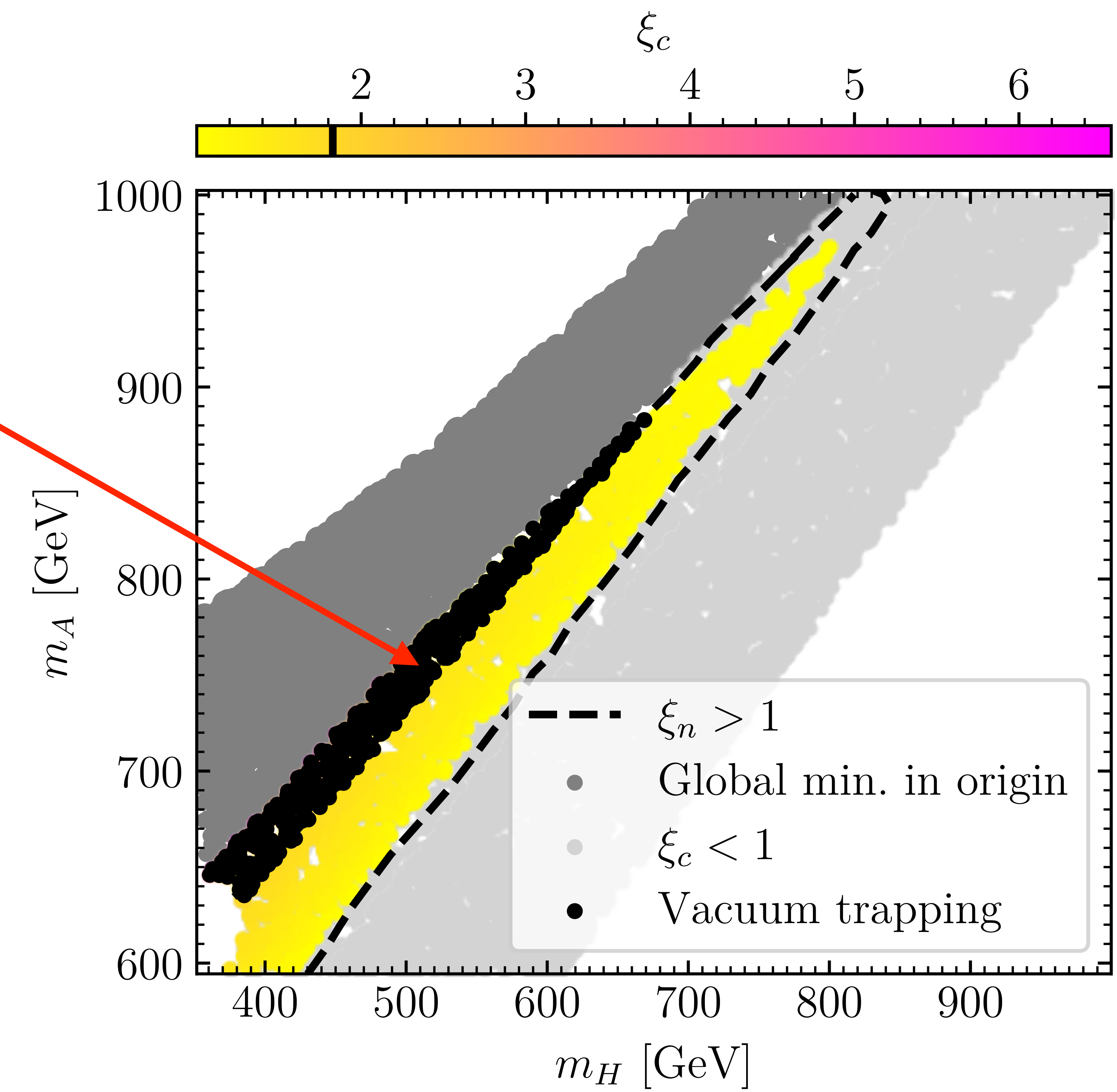
alignment limit,
tanβ = 3



2HDM of type II: region of strong first-order EWPT

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

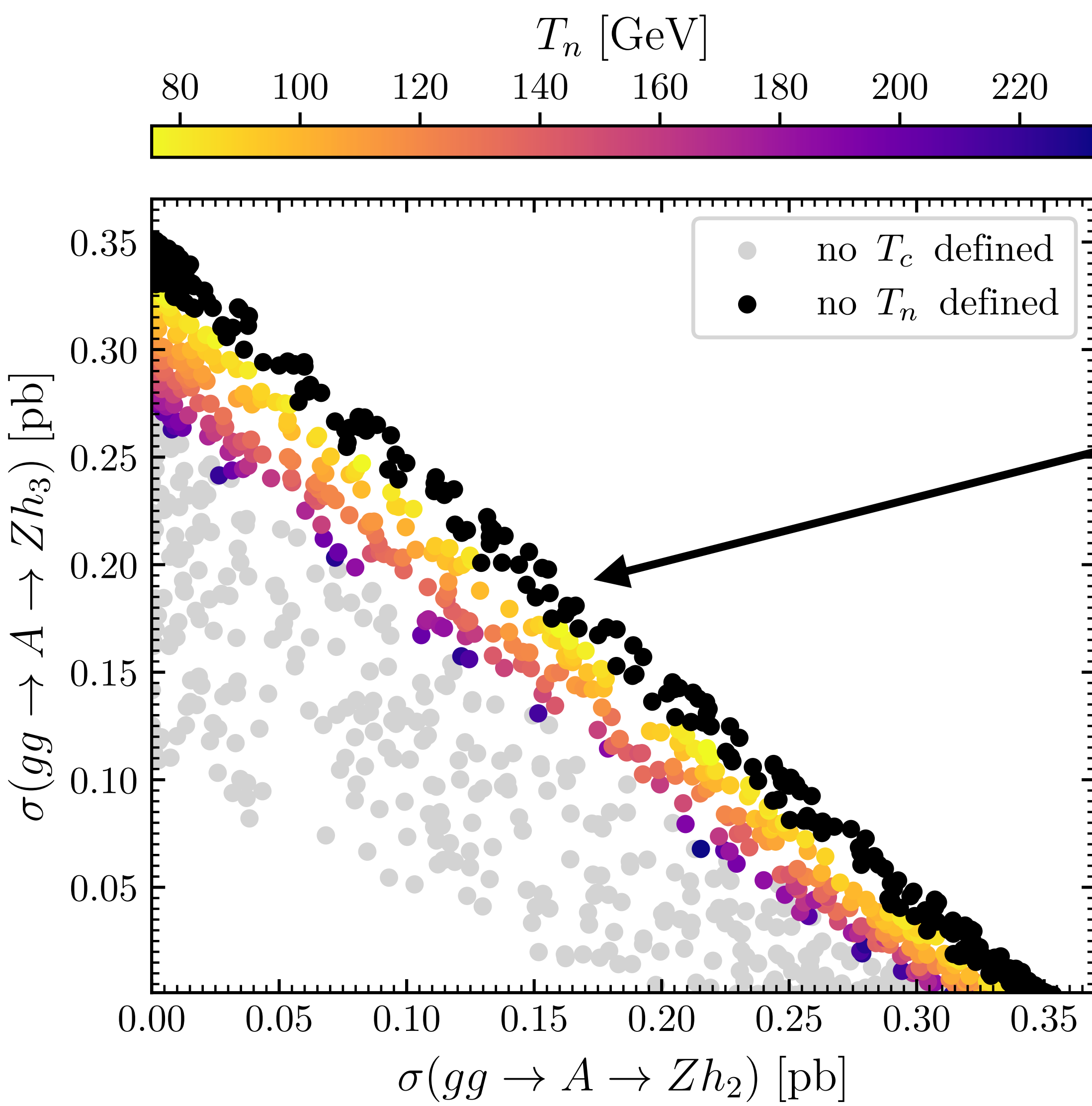
Constraints from "vacuum trapping": the universe may remain "trapped" in a symmetry-conserving vacuum at the origin, because the conditions for a transition into the deeper EW-breaking minimum are not fulfilled



N2HDM (two doublets + real singlet) example

``Smoking gun" collider signatures: A → Z h_2, A → Z h_3
Nucleation temperature for the first-order EWPT, N2HDM scan:

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '21]

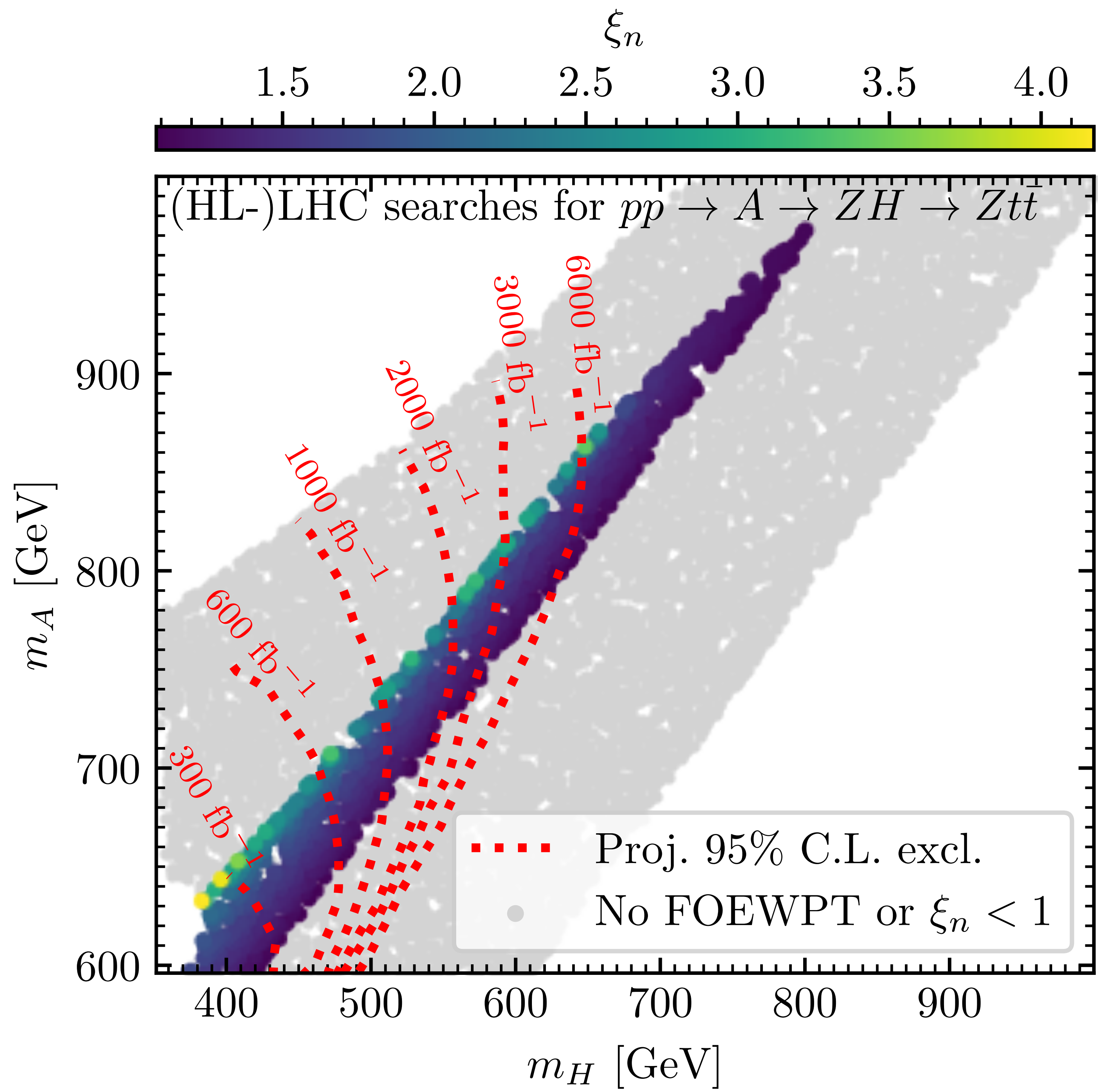


No first-order EWPT: universe is trapped in a ``false" vacuum

⇒ Lower nucleation temperatures, i.e. stronger first-order EWPTs, are correlated with larger signal rates at the LHC!

2HDM, projections for pp → A → ZH → Ztt search

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]



alignment limit,
tanβ = 3

⇒ Good prospects for probing the regions giving rise to strongest first-order EWPTs and to a potentially observable gravitational wave signal

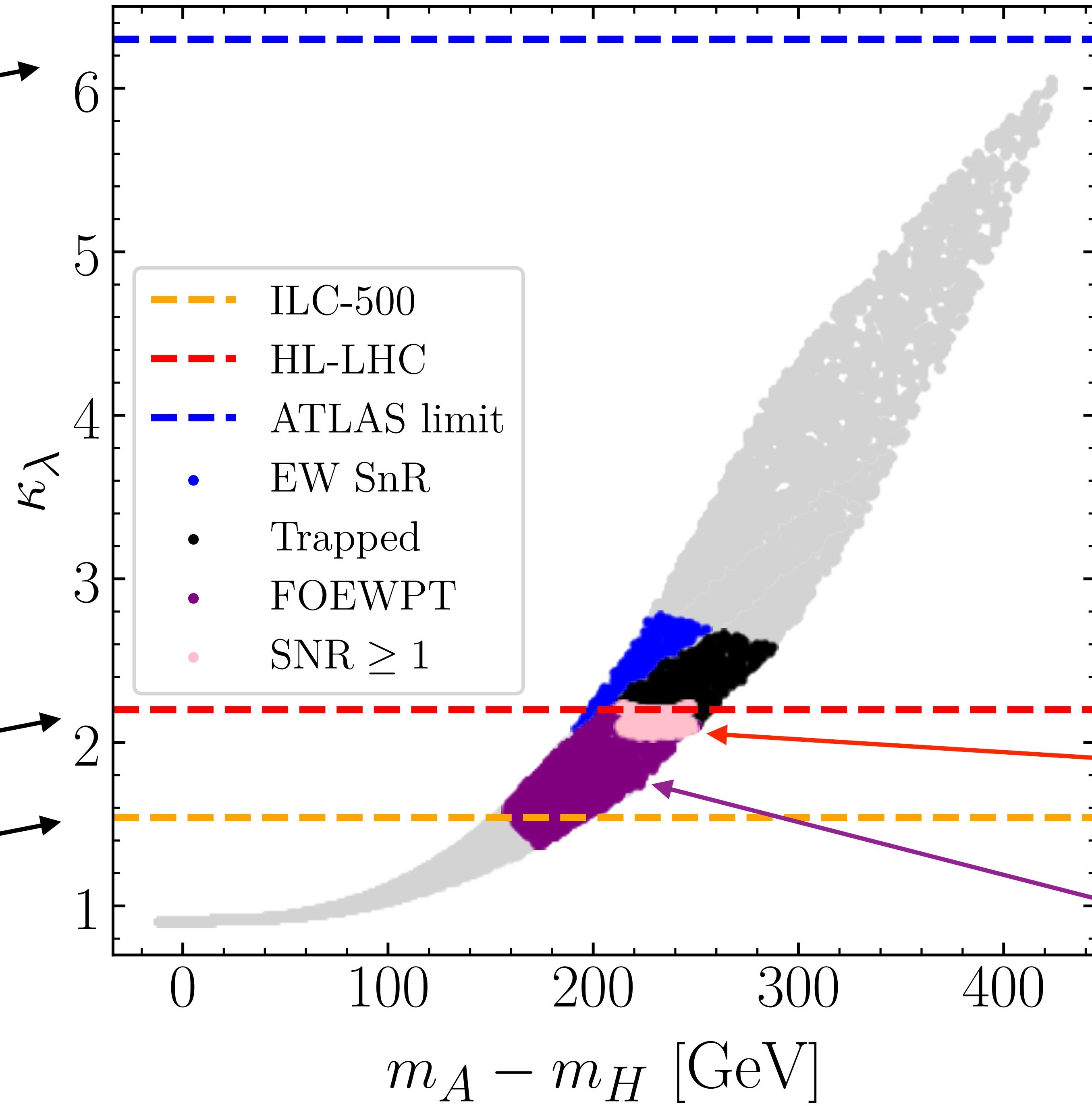
2HDM, 1-loop predictions for the trilinear Higgs coupling vs. current bound and future sensitivities

[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, G. W. '22]

current bound

HL-LHC sensitivity

ILC sensitivity



alignment limit, tanβ = 3

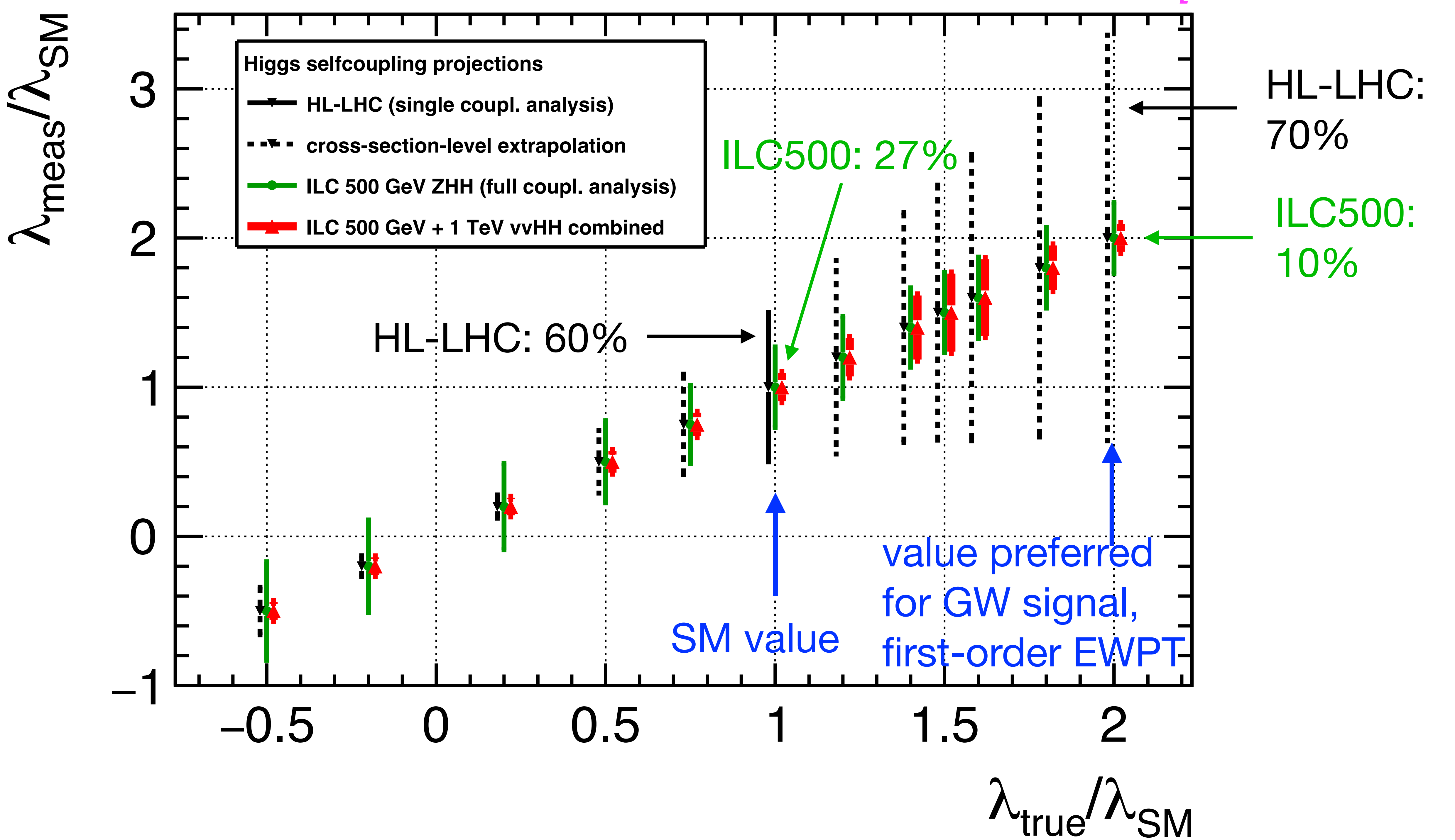
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

⇒ Region with potentially detectable GW signal and strong first-order EWPT is correlated with significant deviation of $\varkappa_\lambda$ from SM value

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC

[J. List et al. '21]



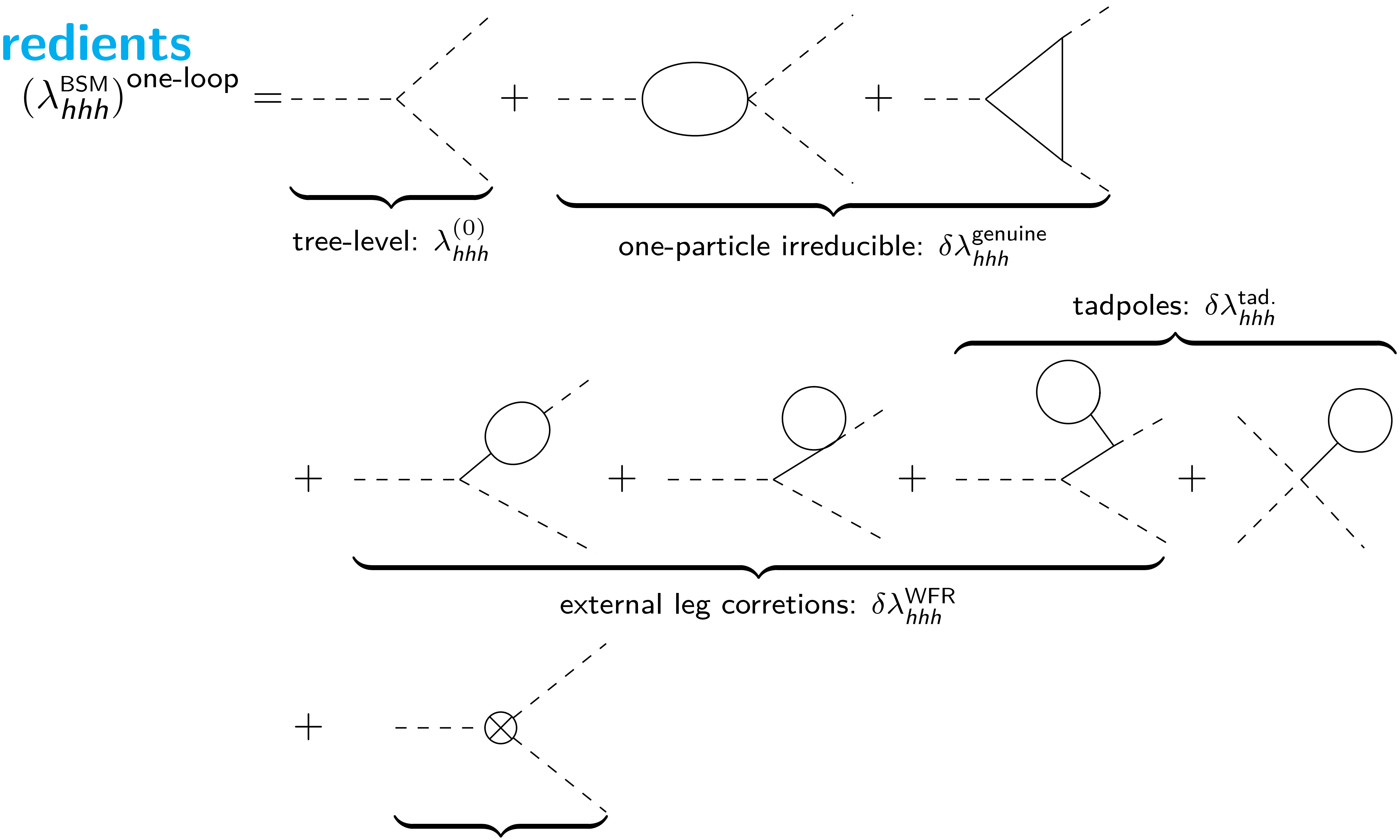
⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC500 than for HL-LHC

Reason: different interference contributions

anyH3: automated one-loop predictions for λ_{hhh}

[H. Bahl, J. Braathen, M. Gabelmann, G. W. ’22]

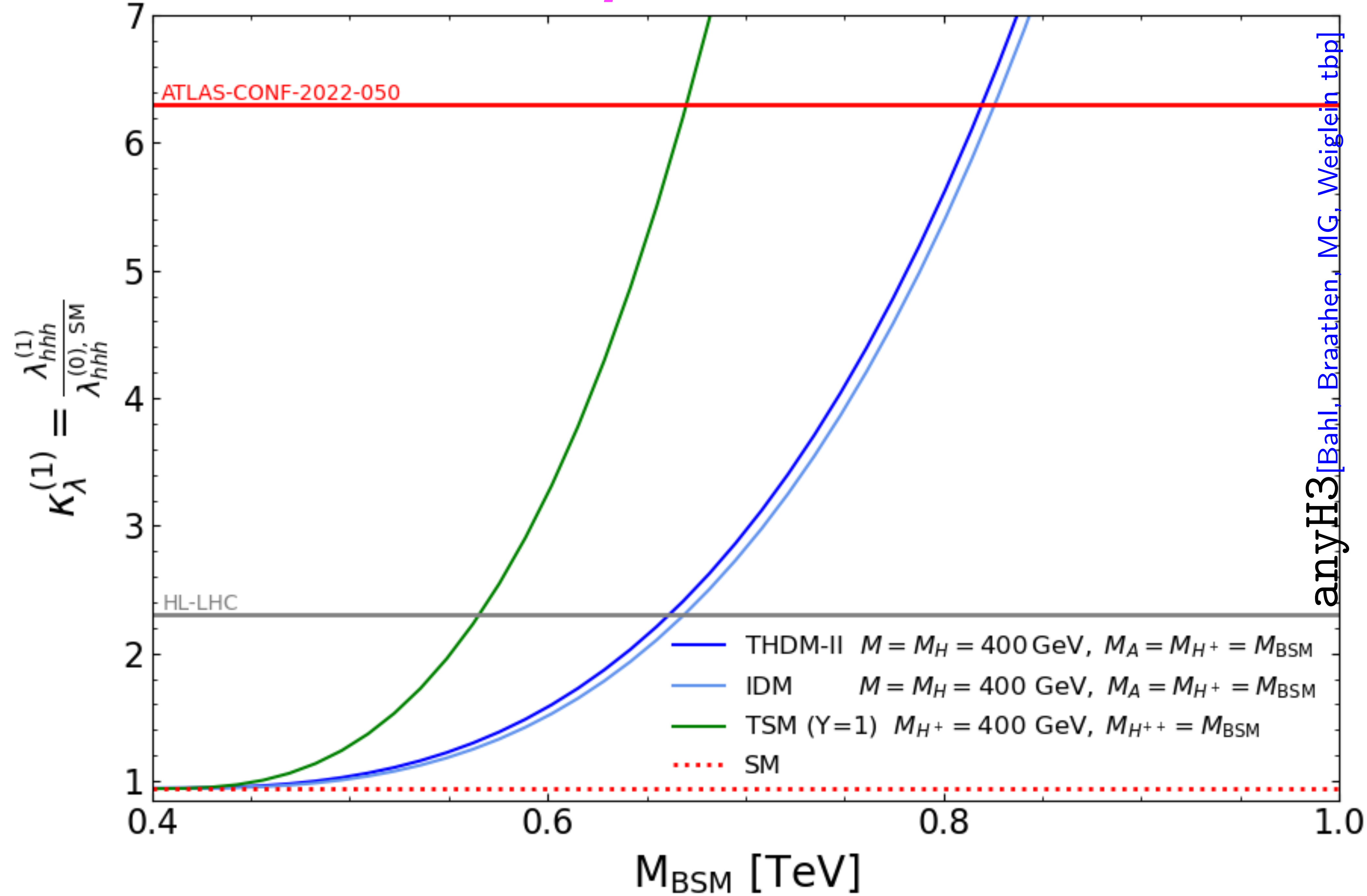
Ingredients



renormalisation: $\delta\lambda_{hhh}^{CT}$, different choices for SM-type and BSM parameters

Example: doublet and triplet extensions of the SM

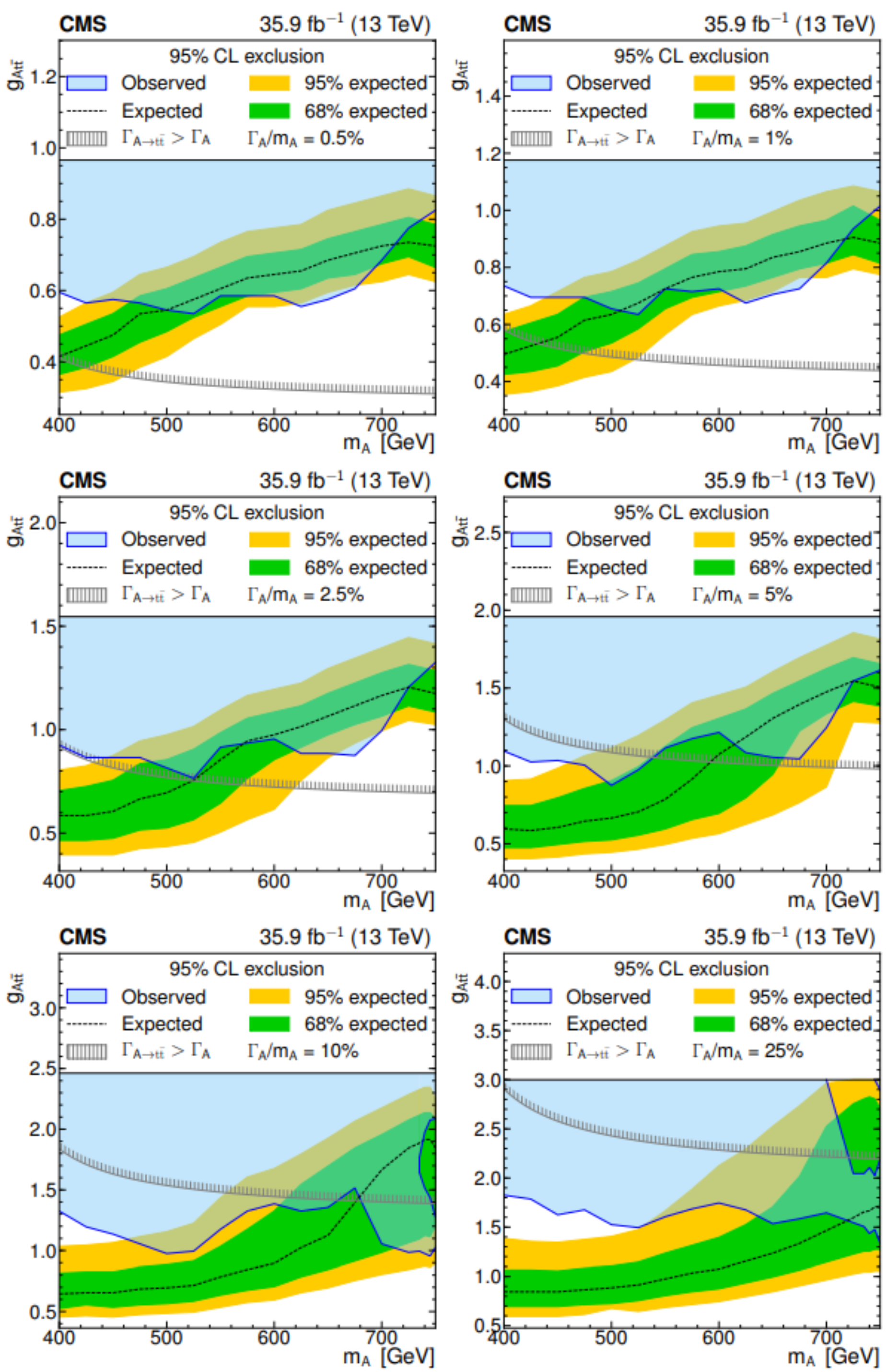
[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]



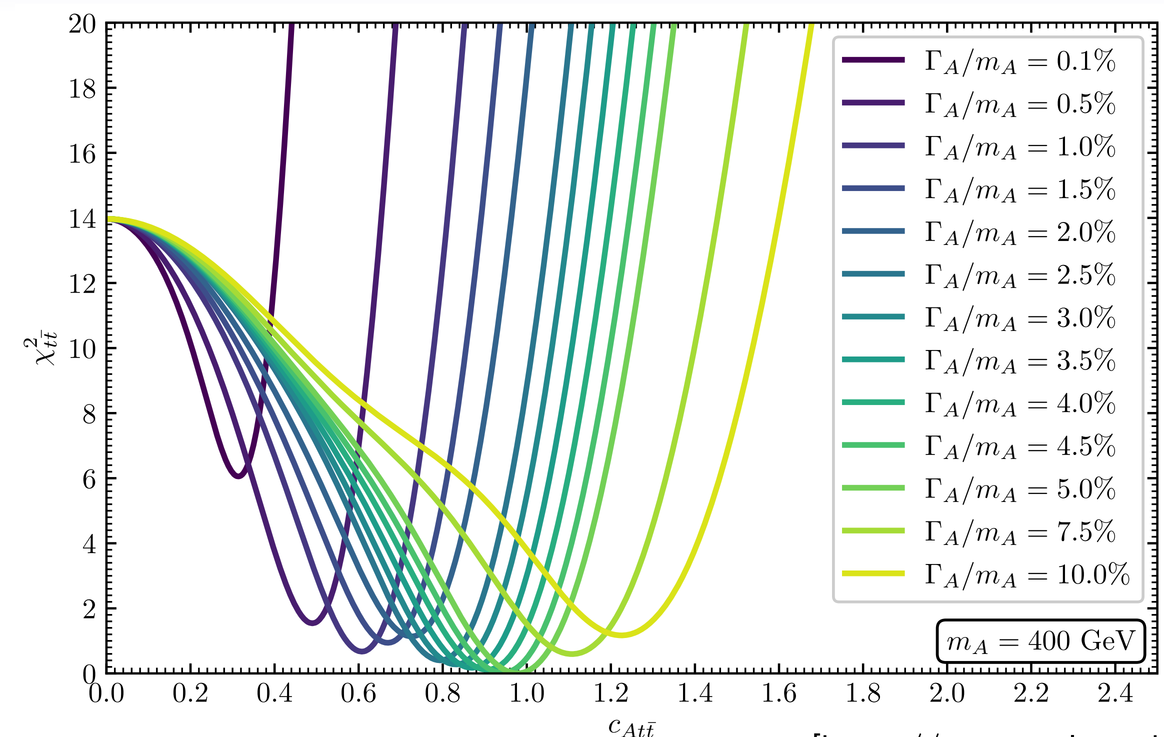
⇒ Mass splitting within the same multiplet yields large loop corrections for large values of M_{BSM}

Possible hints from searches for additional Higgses

Excess in the CMS search for A → tt at about 400 GeV:



[CMS: 1908.01115]



[https://cms-results.web.cern.ch]

Local excess of 3.5σ at ~ 400 GeV
Global significance below 2σ

Consistent with a pseudoscalar Higgs boson at ~ 400 GeV

Most significant for $\Gamma_A/m_A = 4\%$ and $c_{At\bar{t}} \sim 1$, but also consistent with slightly different m_A and Γ_A/m_A $\rightarrow \chi^2_{t\bar{t}}(m_A, \Gamma_A/m_A, c_{At\bar{t}})$

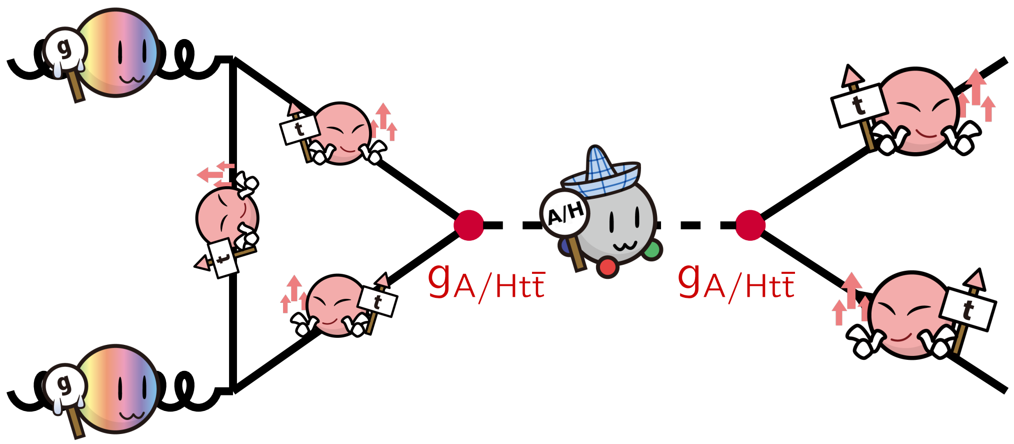
Corresponding ATLAS limits only for $m_A > 500$ GeV and only 8 TeV data

[ATLAS: 1707.06025]

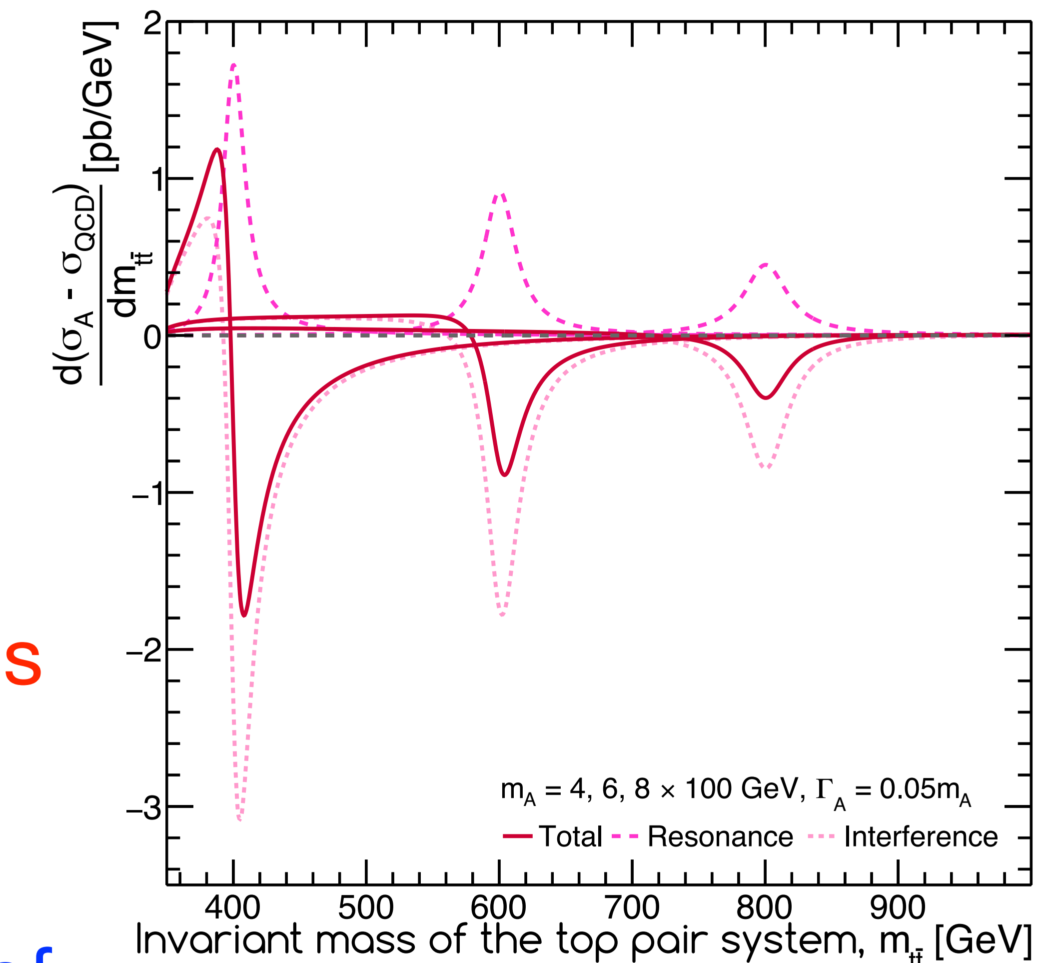
[CMS Collaboration '19]

CMS: excess in search for A → tt at about 400 GeV

[A. Anuar '21]



Interference ⇒

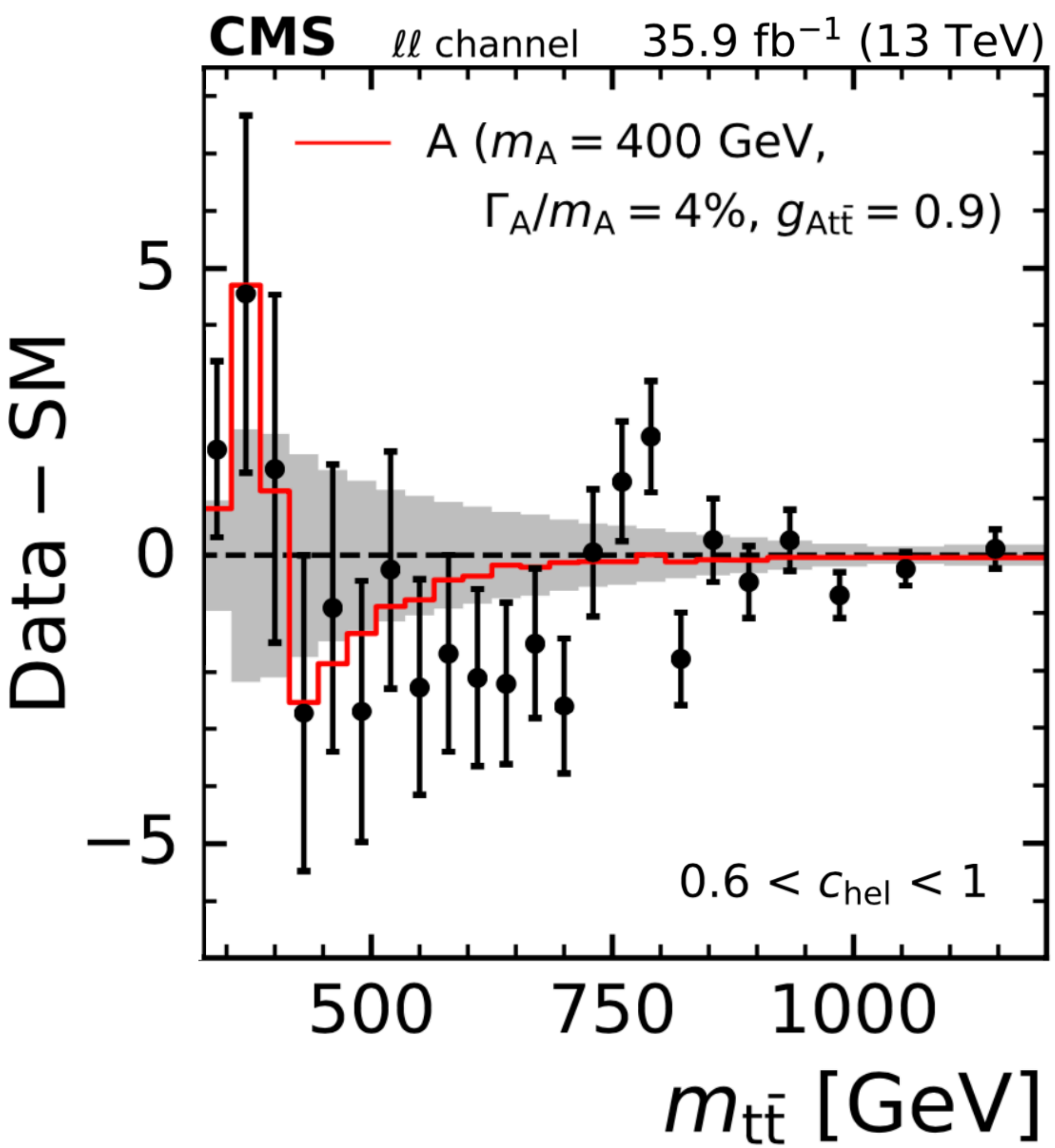


Signal-background interference yields peak-dip structure

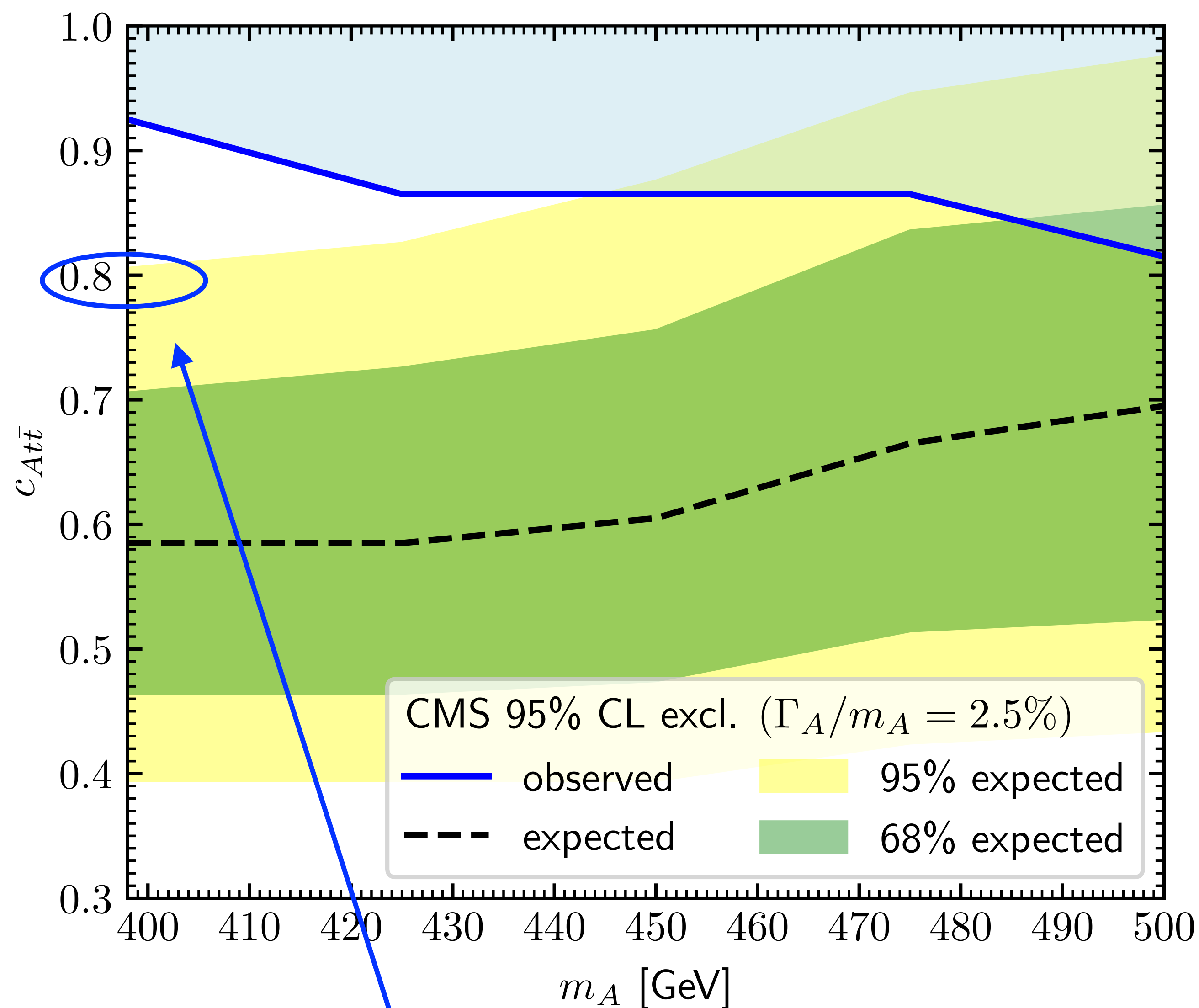
Analysed using angular correlations of the top and anti-top decay products

Search for additional Higgs bosons: H, A → tt

Excess in CMS search at about 400 GeV:



[CMS Collaboration '19]

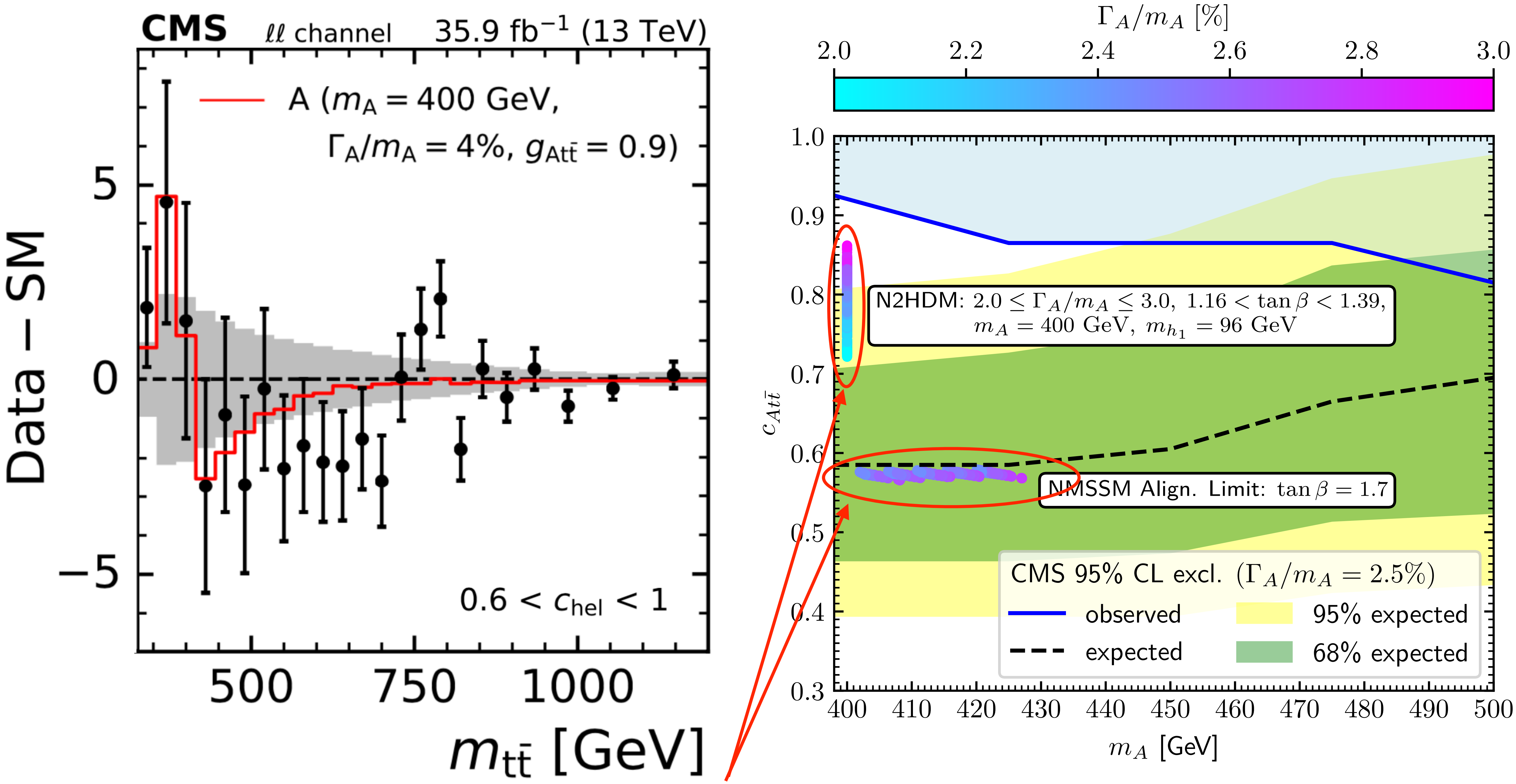


CMS, best fit value for $\Gamma_A/m_A = 2.5\%$

Search for additional Higgs bosons: H, A → tt

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

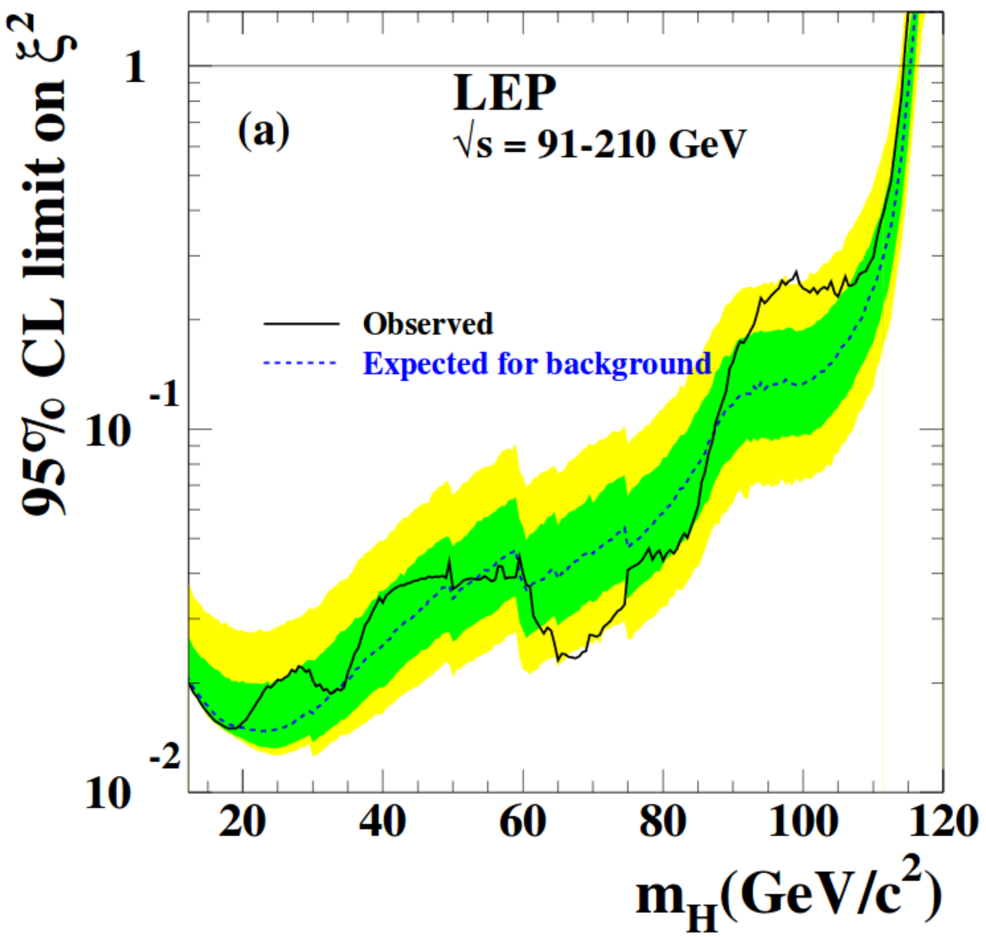
Excess in CMS search at about 400 GeV:



⇒ Good description of the A → tt excess at 400 GeV in models with extended Higgs sectors (N2HDM, NMSSM)

Further hints for an additional light Higgs boson: excesses at about 95 GeV at LEP and CMS

[LEP Higgs Combination ’06]

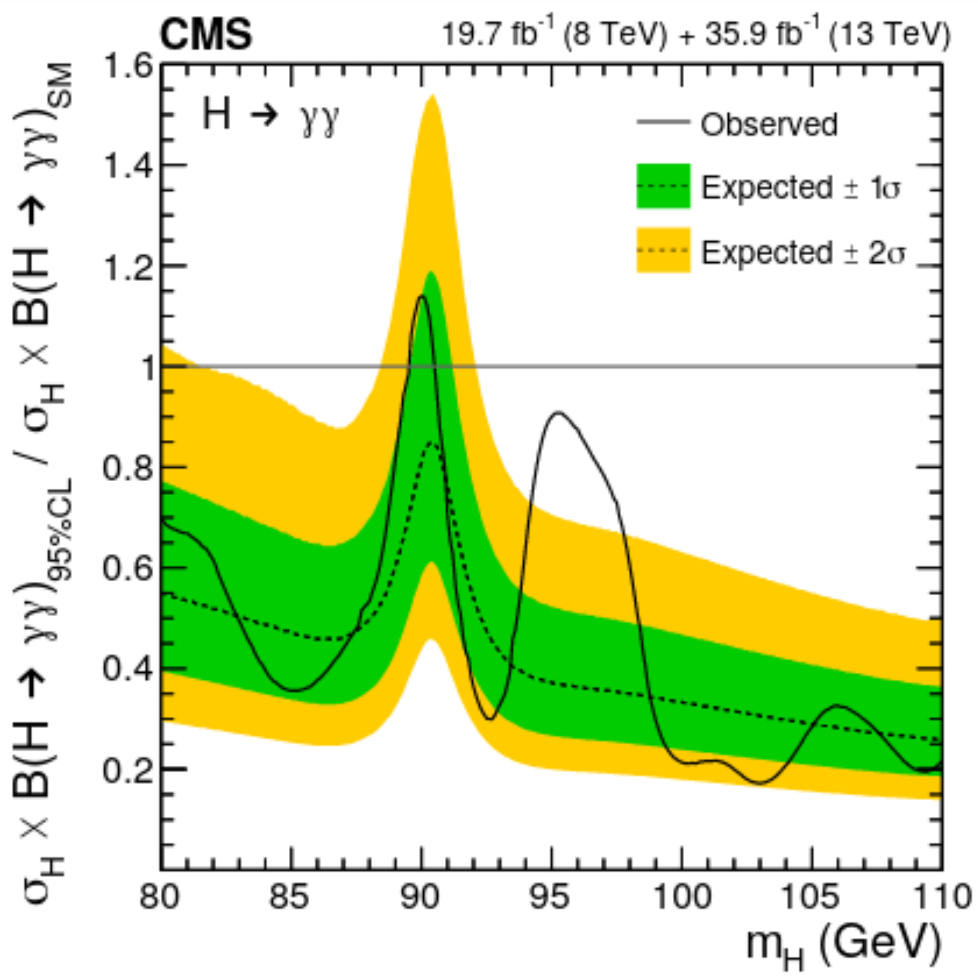


[LEP: hep-ex/0306033]

$\sim 2\sigma$ local excess at 96 - 98GeV

Extracted signal strength:
$\mu_{\rm LEP}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$ [1612.08522]

[CMS Collaboration ’18]



[CMS: 1811.08459]

Run I/II data: Local excess of $\gtrsim 3\sigma$

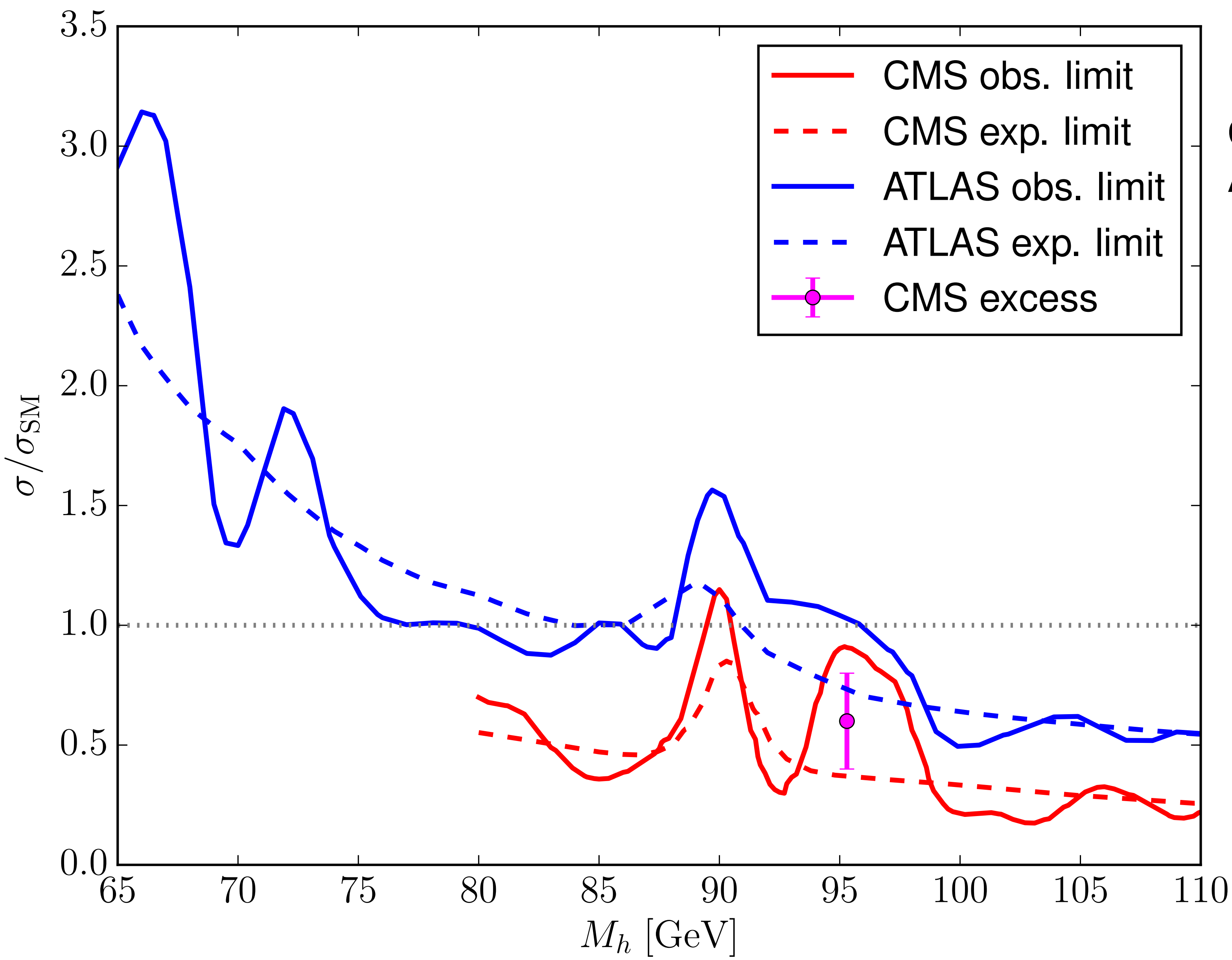
Extracted signal strength:
$\mu_{\rm CMS}\left(gg \to h \to \gamma\gamma\right) = 0.6 \pm 0.2$

$\to \chi^2_{96}(\mu_{\rm LEP}, \mu_{\rm CMS})$ assuming no correlation between $\mu_{\rm LEP}$ and $\mu_{\rm CMS}$

Many model interpretations with common origin of both excesses, including N2HDM and NMSSM

Possible hint for an additional light Higgs boson: CMS excess in $h \longrightarrow \gamma\gamma$ search vs. ATLAS limit

[T. Stefaniak '18]



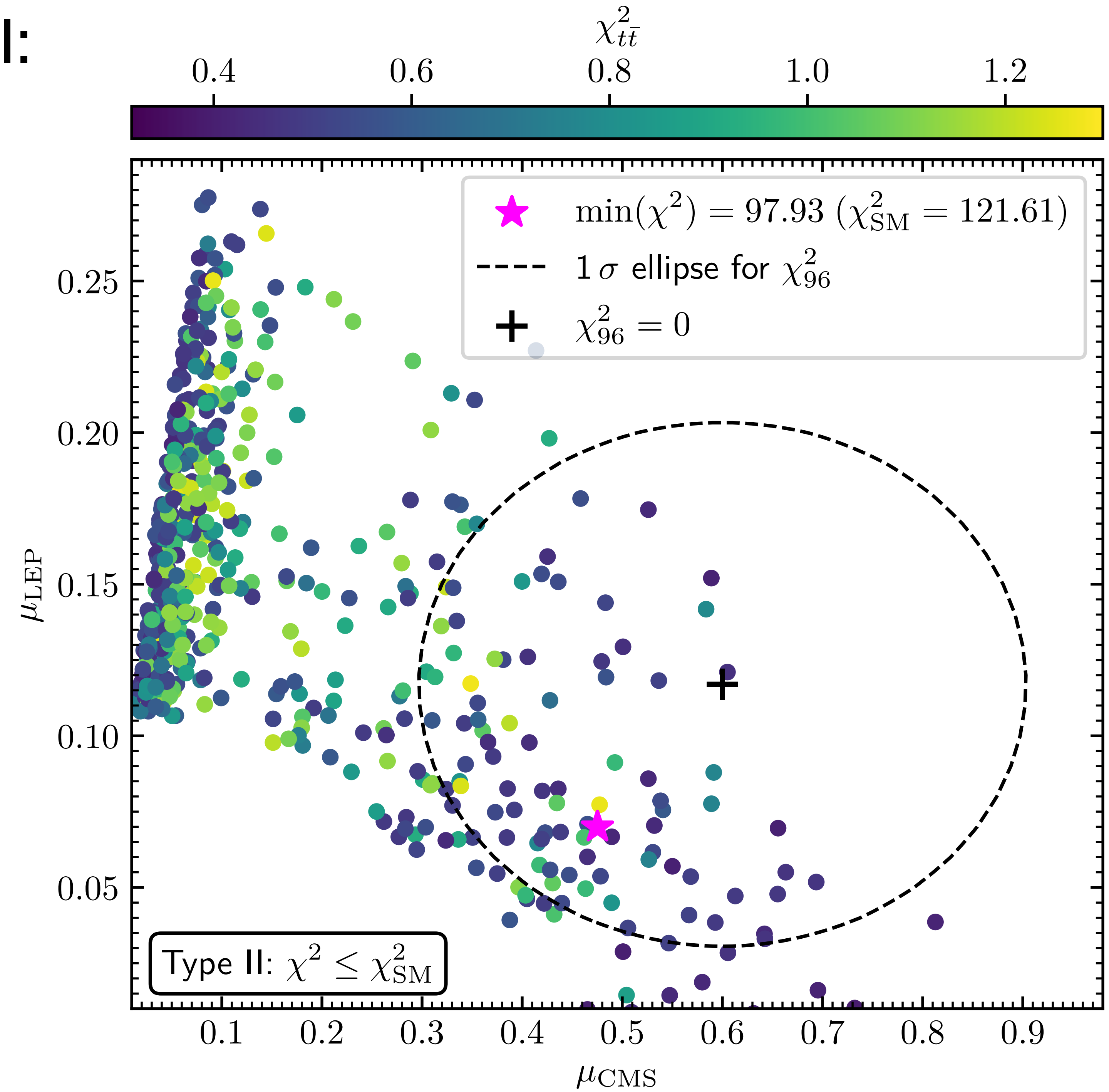
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

Could these excesses in the search for light additional Higgs bosons also be accommodated in the considered models?

Combined interpretation of excesses at 400 GeV (tt) + 95 GeV

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

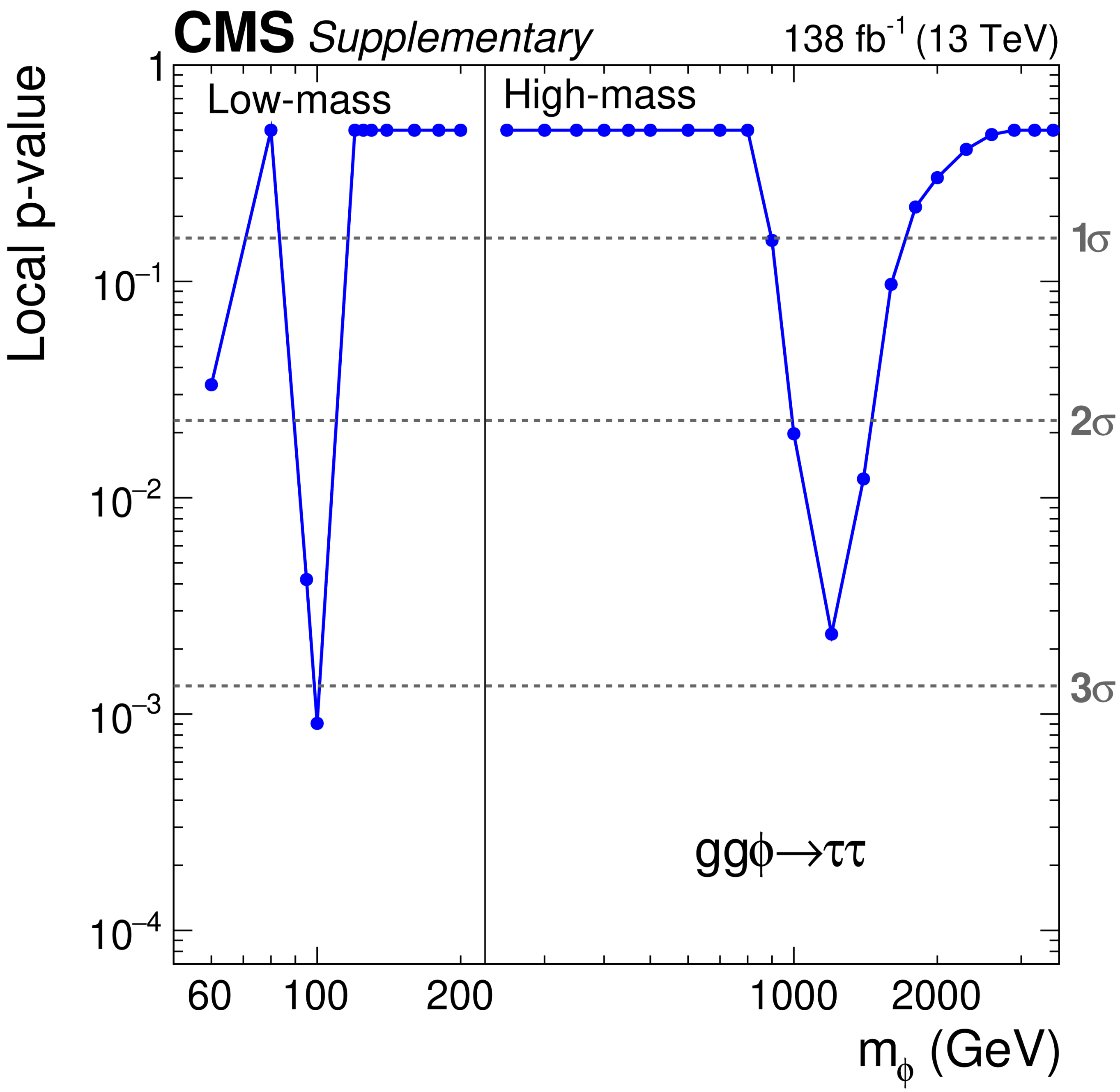
N2HDM, type II:

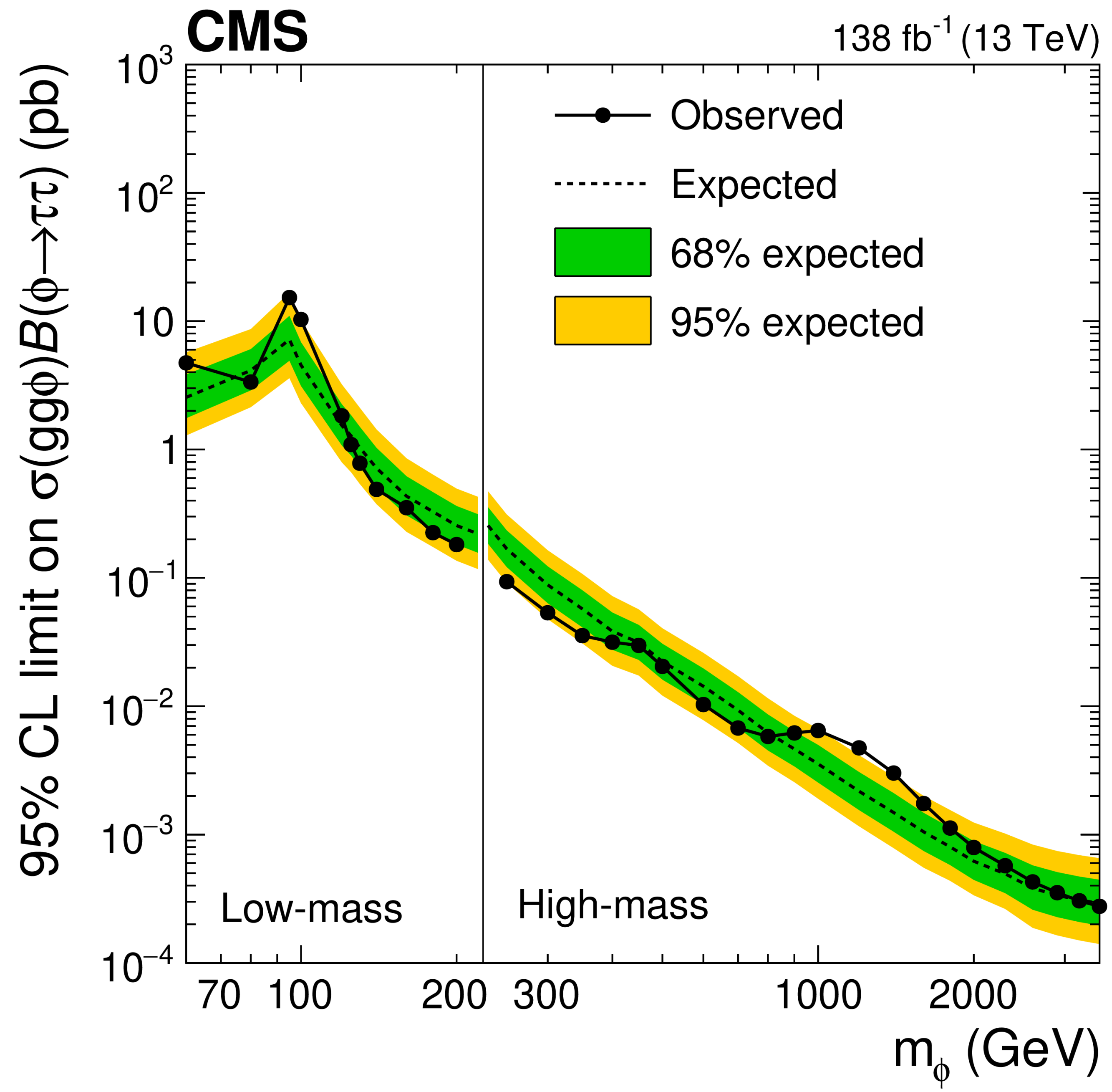


⇒ The A → tt excess at 400 GeV and the CMS $\gamma\gamma$ and LEP excesses at about 95 GeV can be described very well simultaneously!

Latest news: CMS result for the $\tau\tau$ channel

[CMS Collaboration '22]





⇒ The low-mass search shows an excess near 95 GeV that is compatible with the one observed in the $\gamma\gamma$ channel at Run I and II

Can the CMS $\gamma\gamma$, CMS $\tau\tau$ and the LEP excess near 95 GeV all be described simultaneously?

Next-to-Two-Higgs doublet model (N2HDM):

[T. Biekötter, S. Heinemeyer, G. W. '22]

$$\begin{aligned}\text{N2HDM} &= \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s) \\ &= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s)\end{aligned}$$

Higgs sector

$$\begin{aligned}V = {} & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \\ & + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2\end{aligned}$$

Symmetries: Z_2: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$ and $\phi_s \to \phi_s$, only softly broken by m_{12}^2
Z_2': $\phi_1 \to \phi_1$, $\phi_2 \to \phi_2$ and $\phi_s \to -\phi_s$, spontaneously broken by v_s

Extension of Z_2 to Yukawa sector $\Rightarrow$ 4 types of the (N)2HDM

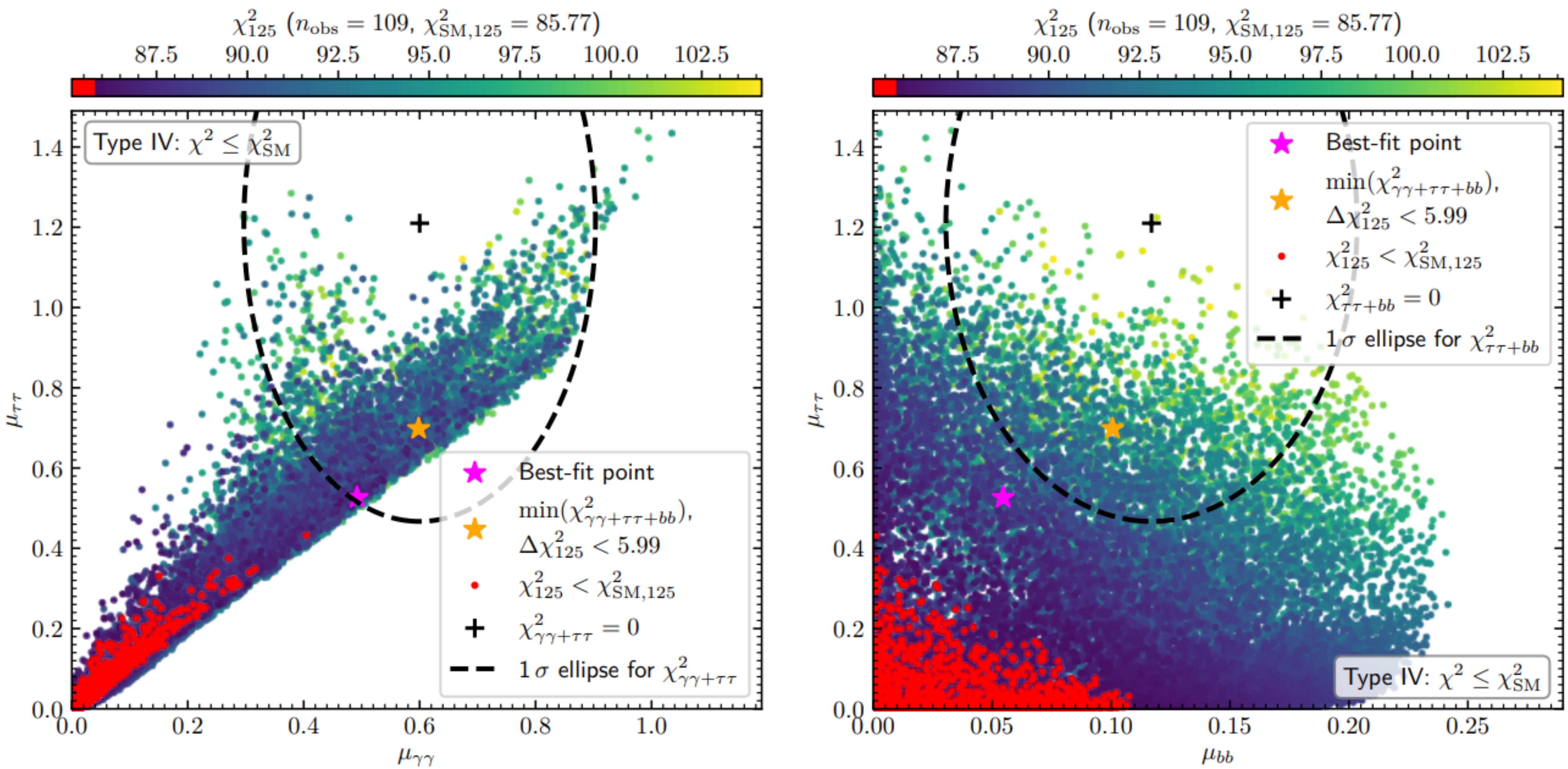
$$-\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{2} \frac{\sqrt{2} m_f}{v} c_{h_i f \bar{f}} \overline{\Psi}_f \Psi_f h_i$$

Type	u-quarks	d-quarks	leptons
I	ϕ_2	ϕ_2	ϕ_2
II (Susy-like)	ϕ_2	ϕ_1	ϕ_1
III (lepton-specific)	ϕ_2	ϕ_2	ϕ_1
IV (flipped)	ϕ_2	ϕ_1	ϕ_2

N2HDM vs. excesses in Higgs searches near 95 GeV

N2HDM, type IV:

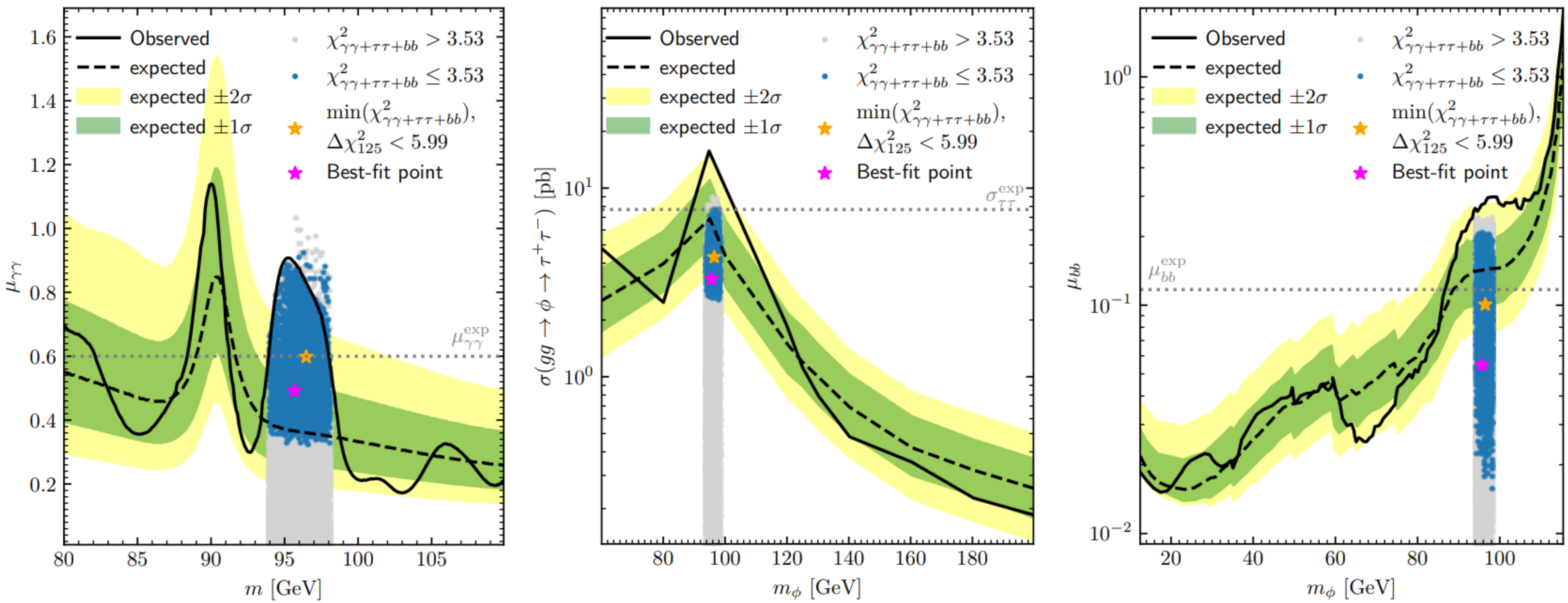
[T. Biekötter, S. Heinemeyer, G. W. '22]



⇒ Good compatibility with all three excesses!

N2HDM vs. excesses in Higgs searches near 95 GeV

N2HDM, type IV: *[T. Biekötter, S. Heinemeyer, G. W. '22]*



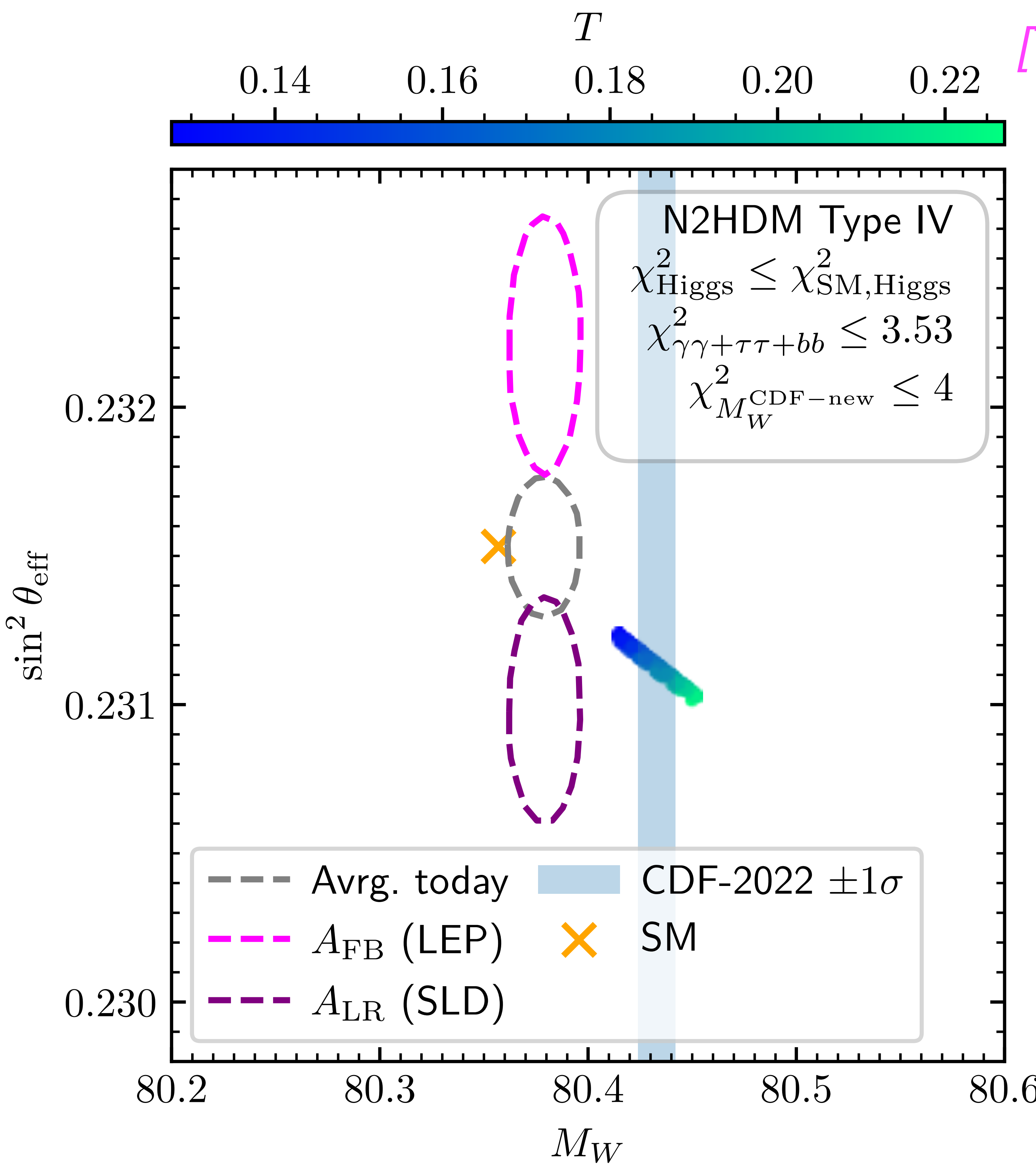
[2203.13180]

$$\chi^2 = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau} + \chi^2_{bb} + \chi^2_{125}$$

χ^2_{125}: HiggsSignals

⇒ Good compatibility with all three excesses!

N2HDM: a 95 GeV Higgs and the CDF value of M_W



[T. Biekötter, S. Heinemeyer, G. W. '22]

$\Rightarrow$ The N2HDM of type IV can simultaneously accommodate the three excesses in the Higgs searches near 95 GeV and an M_W value that agrees with the new CDF measurement!

Conclusions

Observed Higgs boson at 125 GeV: LHC and EDM constraints are compatible with sizeable amount of CP violation in fermion couplings

The constraints on the trilinear Higgs coupling from the LHC have already sensitivity to the physics of extended Higgs sectors

Predictions for the trilinear Higgs coupling are closely related to the electroweak phase transition and the thermal evolution of the early universe, and have an impact on potentially detectable gravitational wave signals and ``smoking gun" signatures at the LHC

Excesses in BSM Higgs searches at 95 GeV and 400 GeV are well described in models with extended Higgs sectors (N2HDM, …)

$\Rightarrow$ Much progress expected during the next years from more data and improved theoretical predictions

A bit of advertisement

Museum der Arbeit, 26.10.2022 bis 10.04.2023

Wissenschaft hautnah: Der Exzellenzcluster „Quantum Universe“ der Universität Hamburg zeigt gemeinsam mit dem Forschungszentrum DESY und dem Museum der Arbeit die Sonderausstellung Wie alles begann. Von Galaxien, Quarks und Kollisionen über den Ursprung und die Entwicklung des Universums.

Backup

Experimental constraints on $\varkappa_\lambda$

[ATLAS Collaboration '22]

Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Higgs self-coupling λ

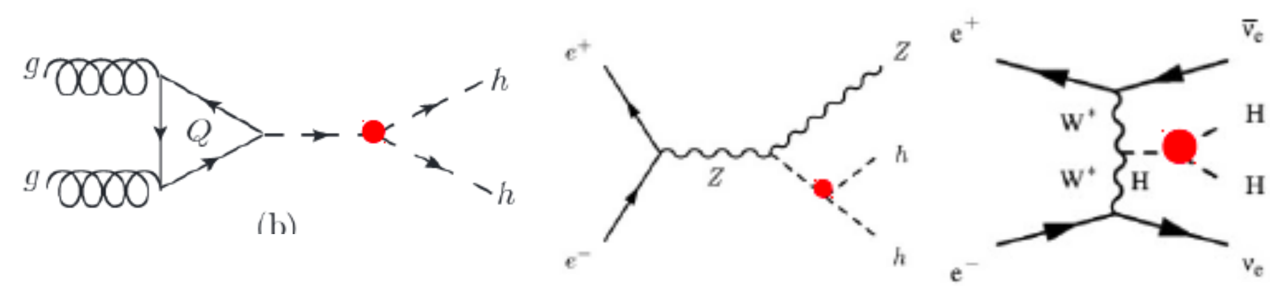
Self-coupling λ of h125: experimental access to the Higgs potential

Sensitivity of different processes crucially depends on the actual value of λ

[B. Heinemann '19]

Di-Higgs processes at hadron colliders:

- $\sigma(HH) \approx 0.01 \times \sigma(H)$
- Important to use differential measurements

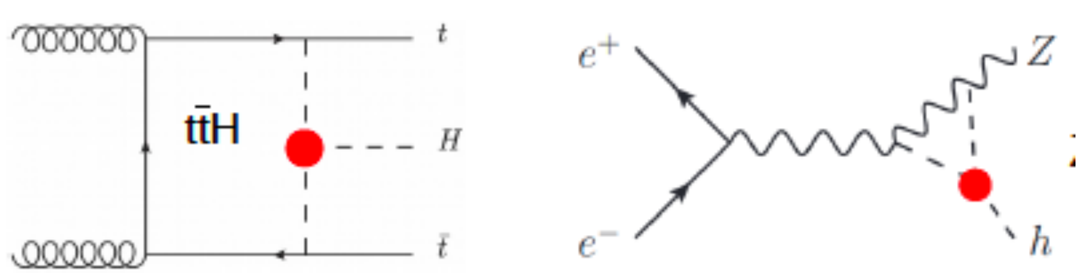


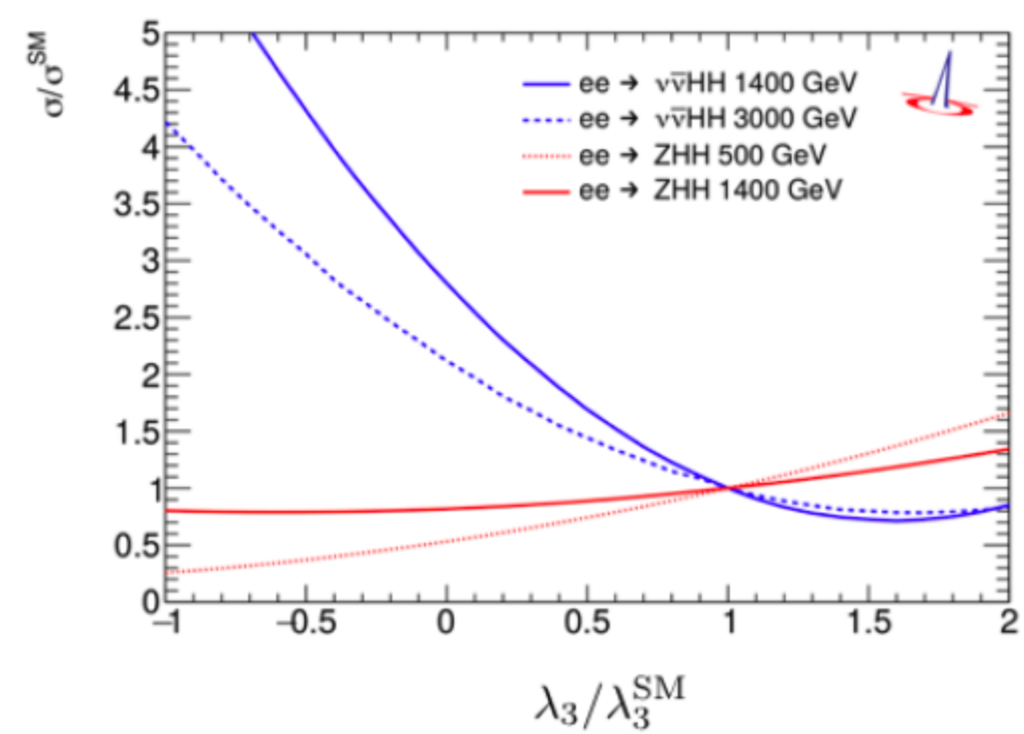
Di-Higgs processes at lepton colliders

- ZHH or VBF production complementary

Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$:

- Hadron colliders: ~3%
- Lepton colliders: ~1%





NLO electroweak corrections

Generic size $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \;\Rightarrow\;$ NLO EW $\sim$ NNLO QCD

typical: few per cent for inclusive observables

[A. Denner '22]

systematic enhancements

- by (soft and/or collinear) photon emission:
  kinematic effects, radiative tails
  mass-singular logarithms $\propto \alpha \ln(m_\mu/Q)$ for bare muons
  $\Rightarrow$ huge effects ($> 100\%$) possible (in radiative tails)
- at high energies:
  EW Sudakov logarithms $\propto (\alpha/s_w^2)\ln^2(M_W/Q)$ and subleading logs
  $\Rightarrow$ EW corrections of several 10% in high-energy tails of distributions or cross sections dominated by high scales

$\Rightarrow$ NLO EW corrections can be sizeable

$\Rightarrow$ must be included in theoretical predictions

Combination of electroweak and QCD corrections in additive / factorised form

anyH3: one-loop predictions for the trilinear Higgs coupling in (essentially) any model

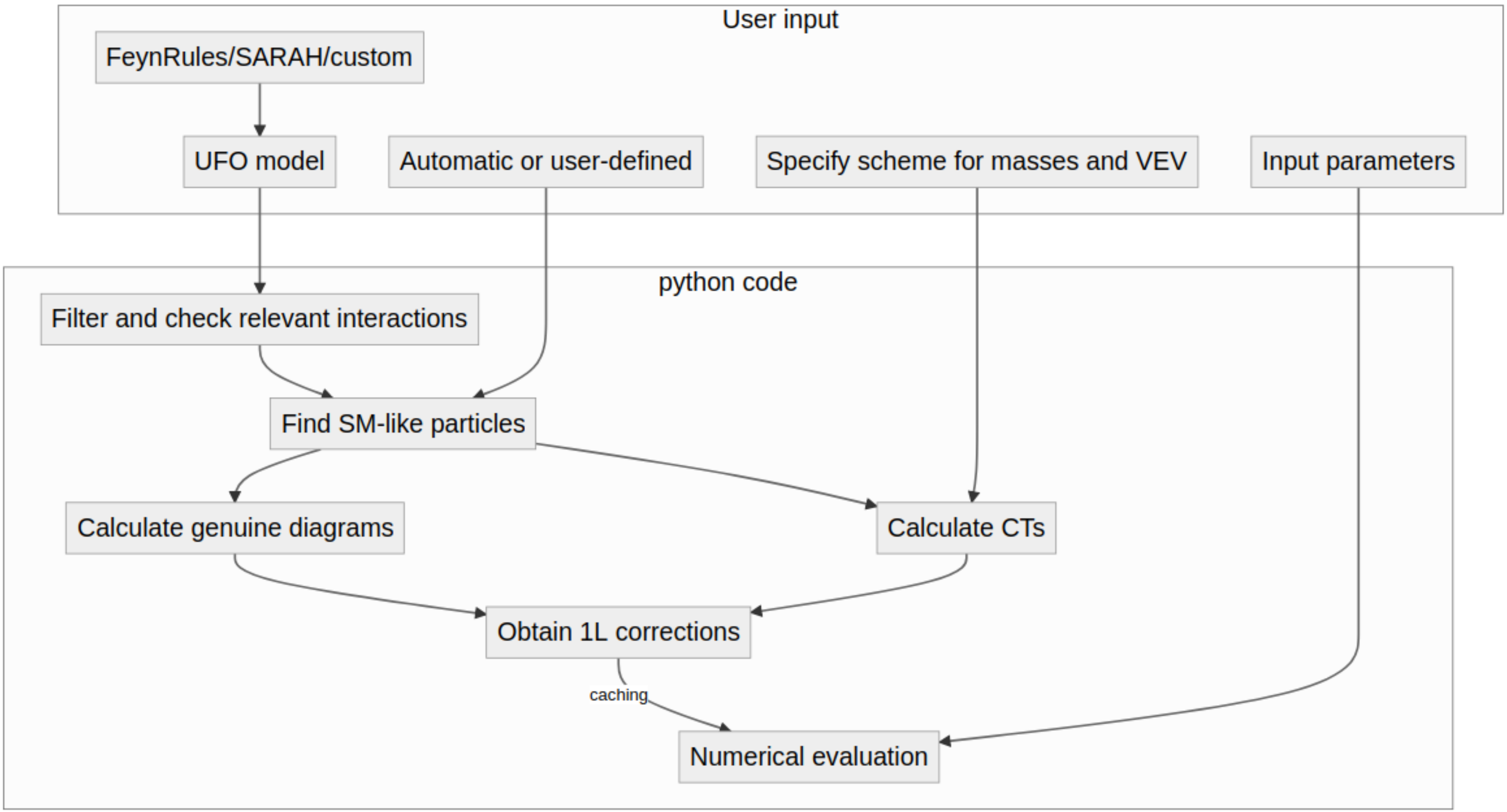
Because of the importance of the trilinear Higgs coupling for constraining BSM scenarios, which will further grow during the next years, a tool providing in a quick and convenient way a one-loop prediction for $\varkappa_\lambda$ in a wide variety of models may be useful

This was the idea that led to the development of the Python code *anyH3* *[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]*

Disclaimer: the trilinear Higgs coupling is not a physical observable (see above); the provided result should be understood as a building block that contributes to the Higgs pair production process; the user needs to determine whether the experimental bounds on $\varkappa_\lambda$ are applicable to the considered model

anyH3 workflow

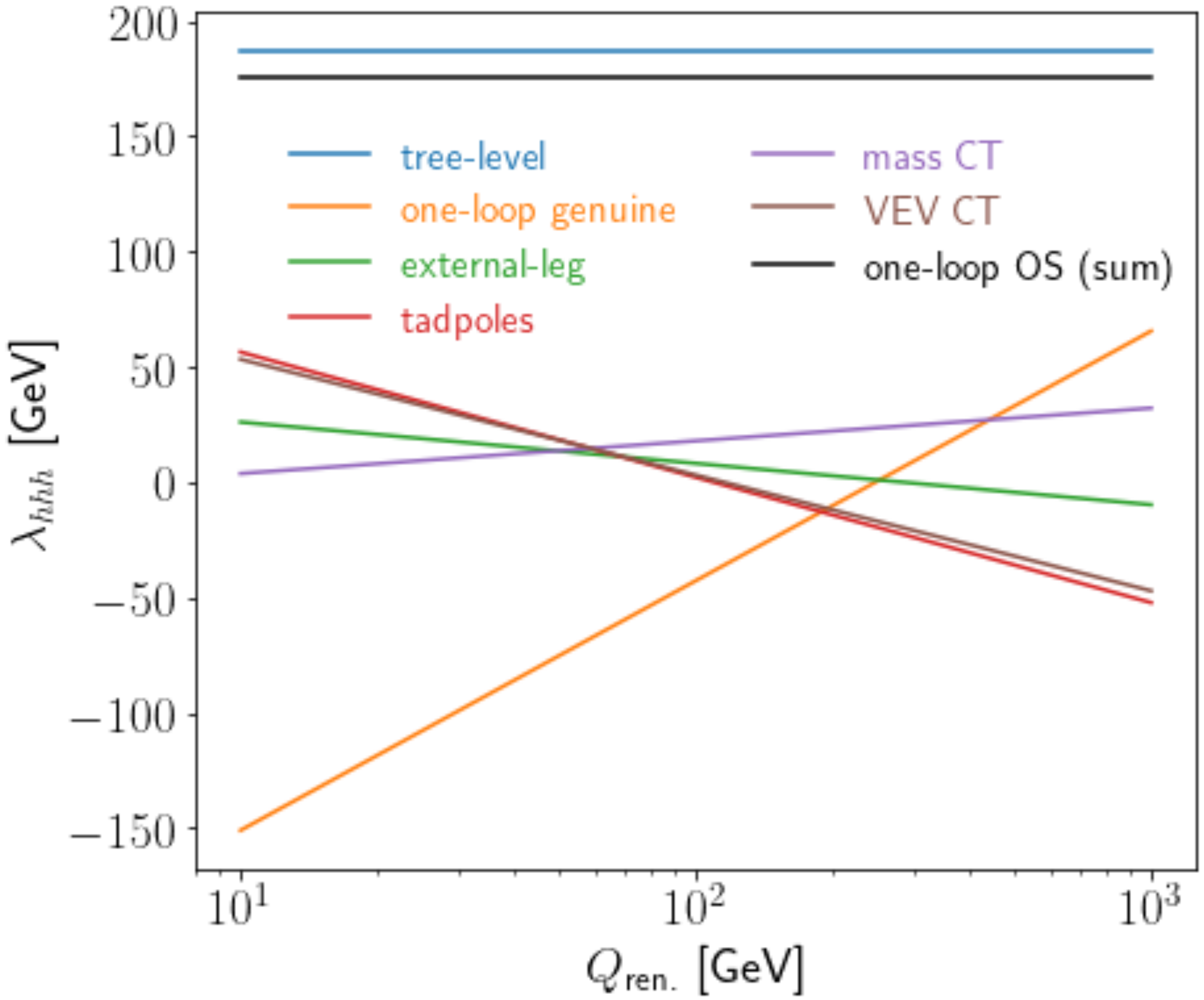
[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]

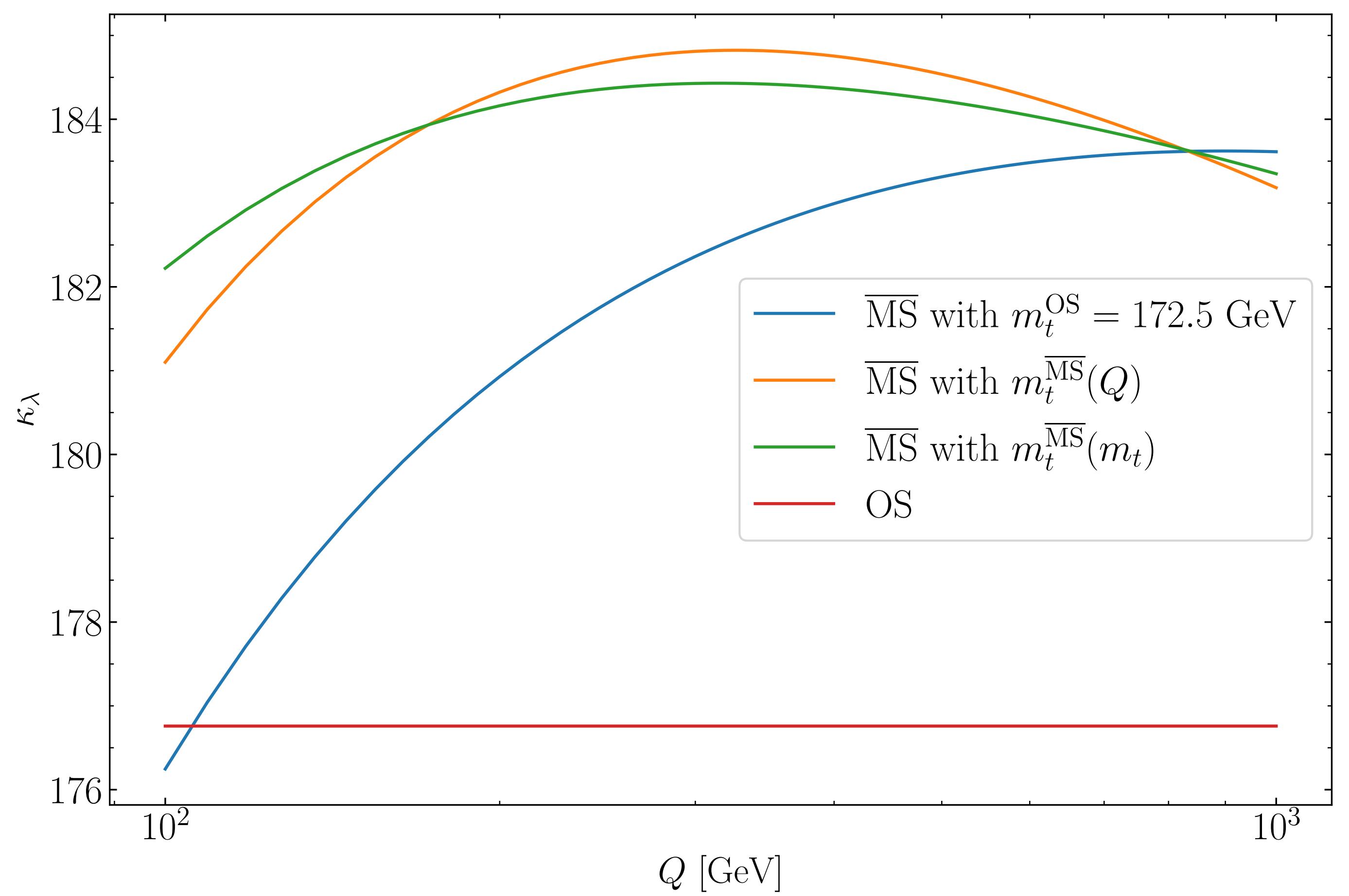


SM result

Individual contributions / scheme comparison as function of renormalisation scale:

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]



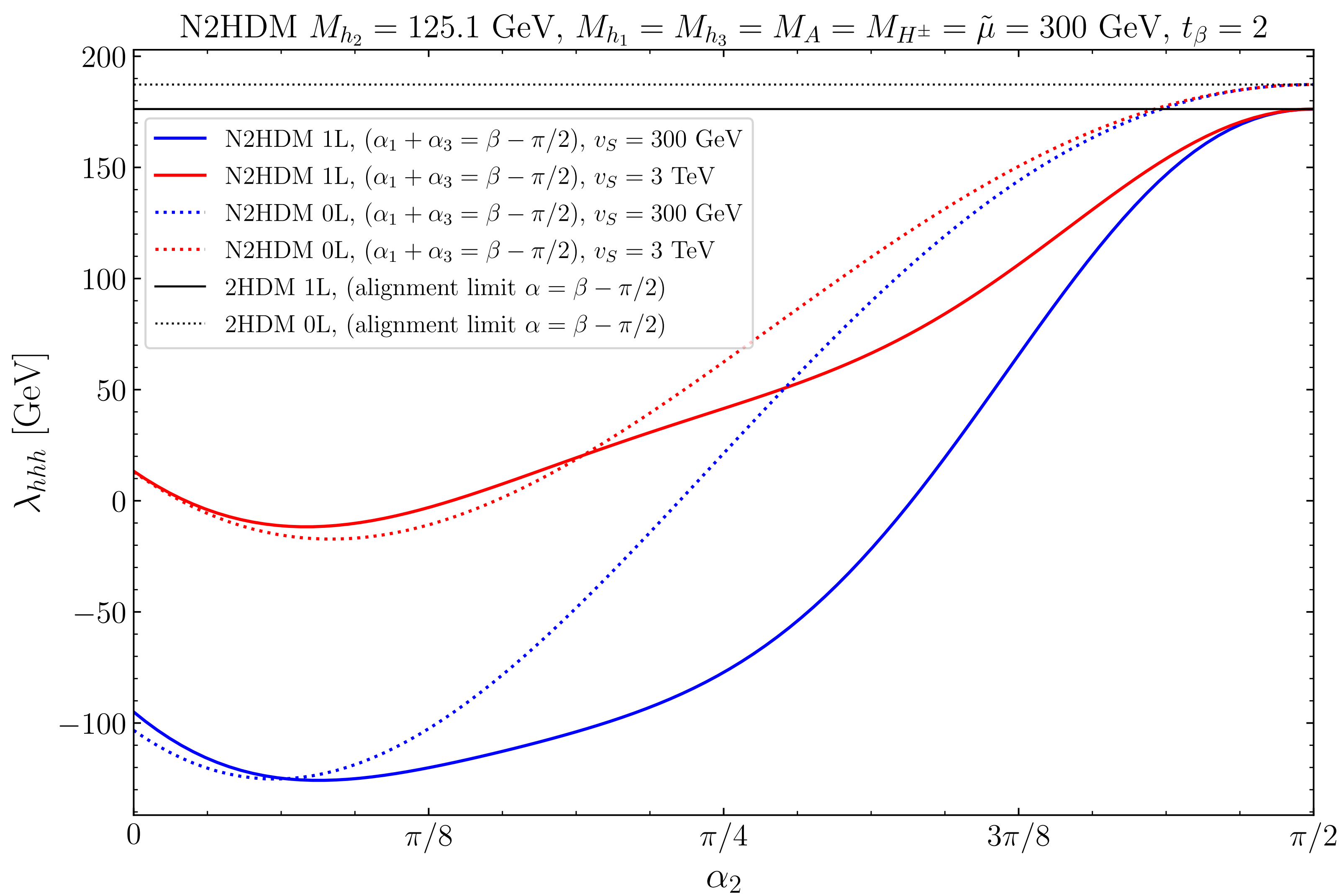


N2HDM vs. 2HDM

Prediction for λ_{hhh} in the N2HDM as function of the mixing angle α_2
No further constraints applied; $\alpha_2 \to \pi/2$: 2HDM in the alignment limit

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]

Example 1: 2HDM limit corresponds to SM limit



⇒ Significant deviations between SM / 2HDM and N2HDM possible

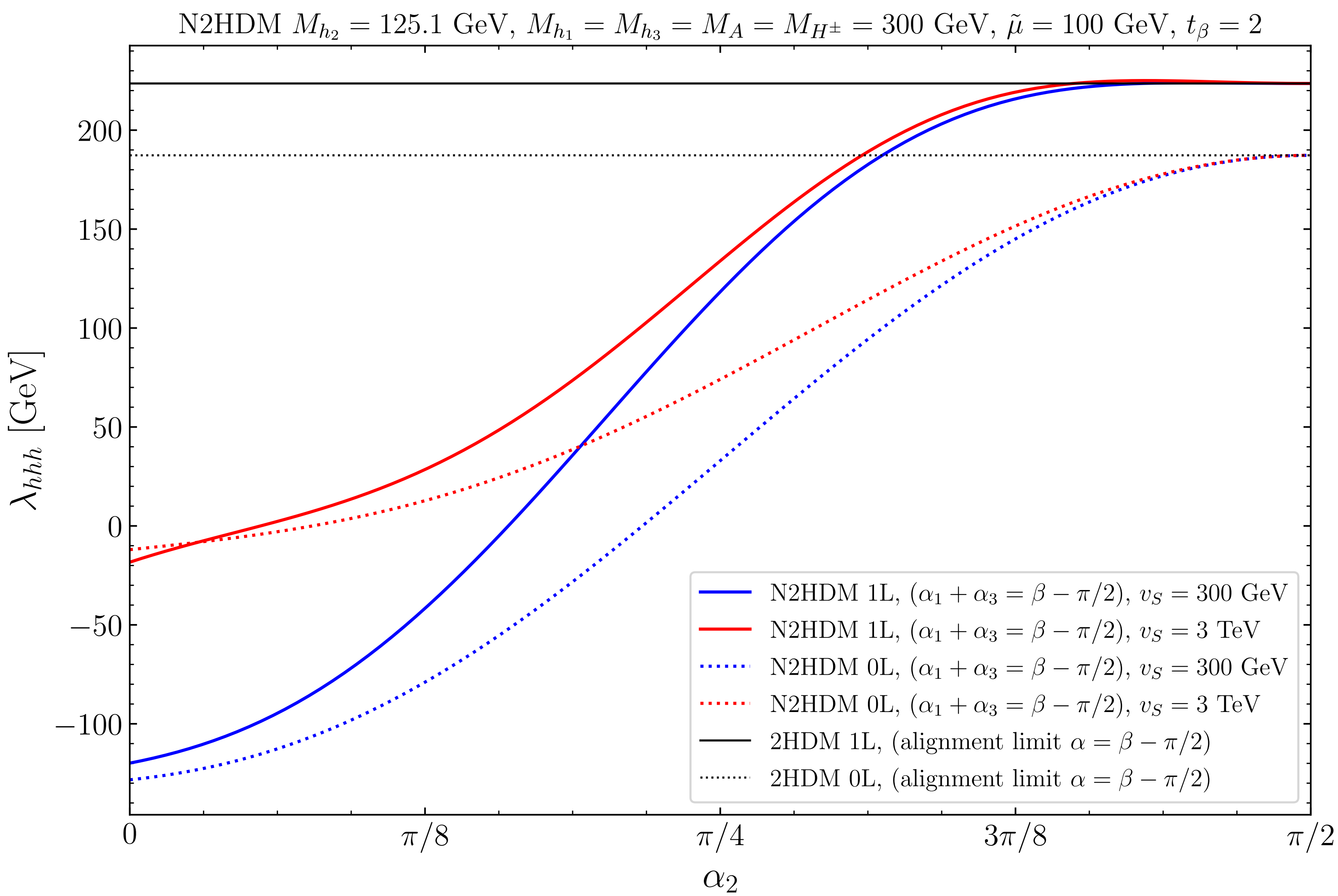
N2HDM vs. 2HDM

Prediction for λ_{hhh} in the N2HDM as function of the mixing angle α_2

No further constraints applied; $\alpha_2 \to \pi/2$: 2HDM in the alignment limit

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]

Example 2: BSM Higgs bosons of the N2HDM are heavy



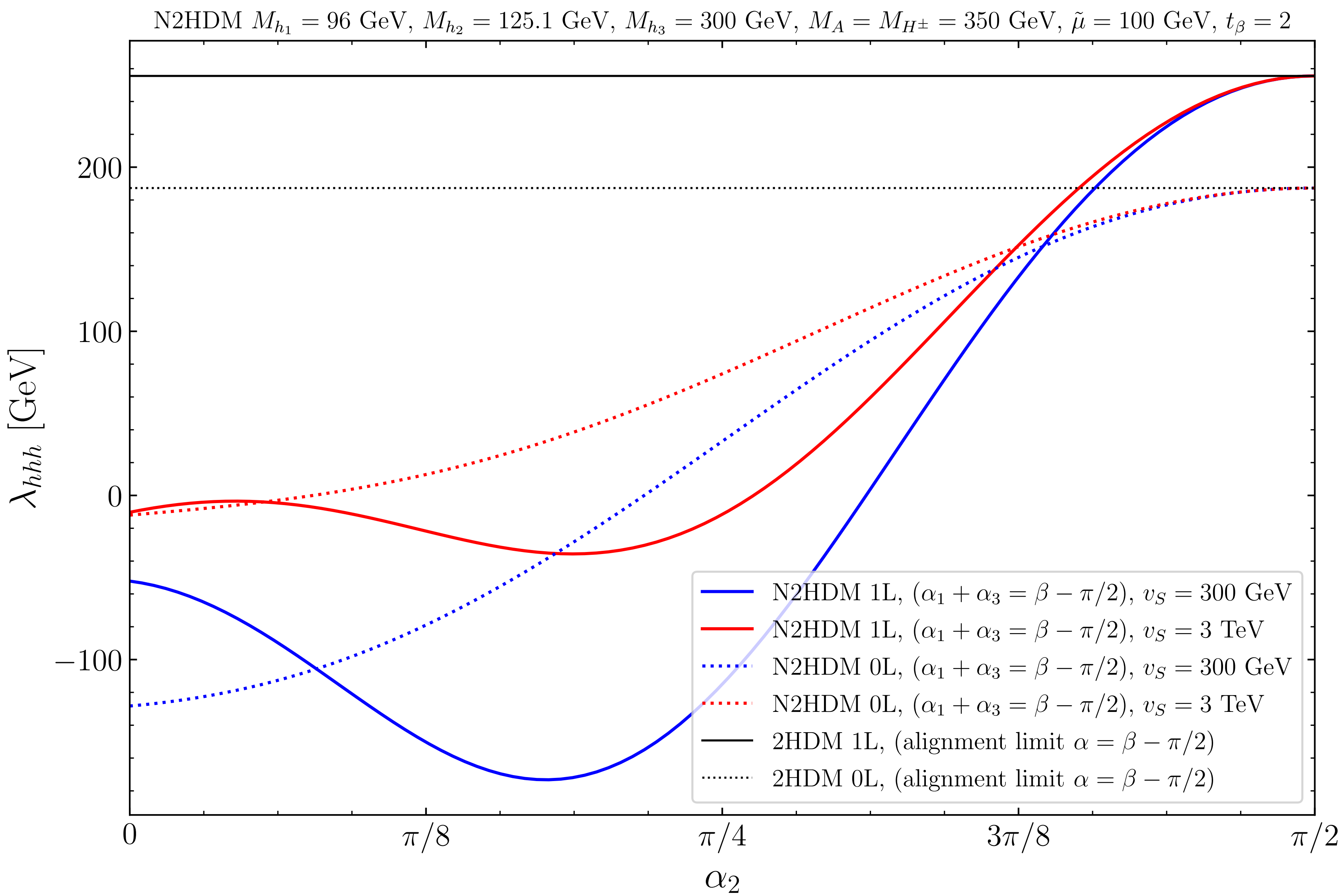
⇒ Significant deviations between 2HDM and N2HDM possible

N2HDM vs. 2HDM

Prediction for λ_{hhh} in the N2HDM as function of the mixing angle α_2
No further constraints applied; $\alpha_2 \to \pi/2$: 2HDM in the alignment limit

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '22]

Example 3: N2HDM with a Higgs boson at 96 GeV



$\Rightarrow$ Significant deviations between 2HDM and N2HDM possible

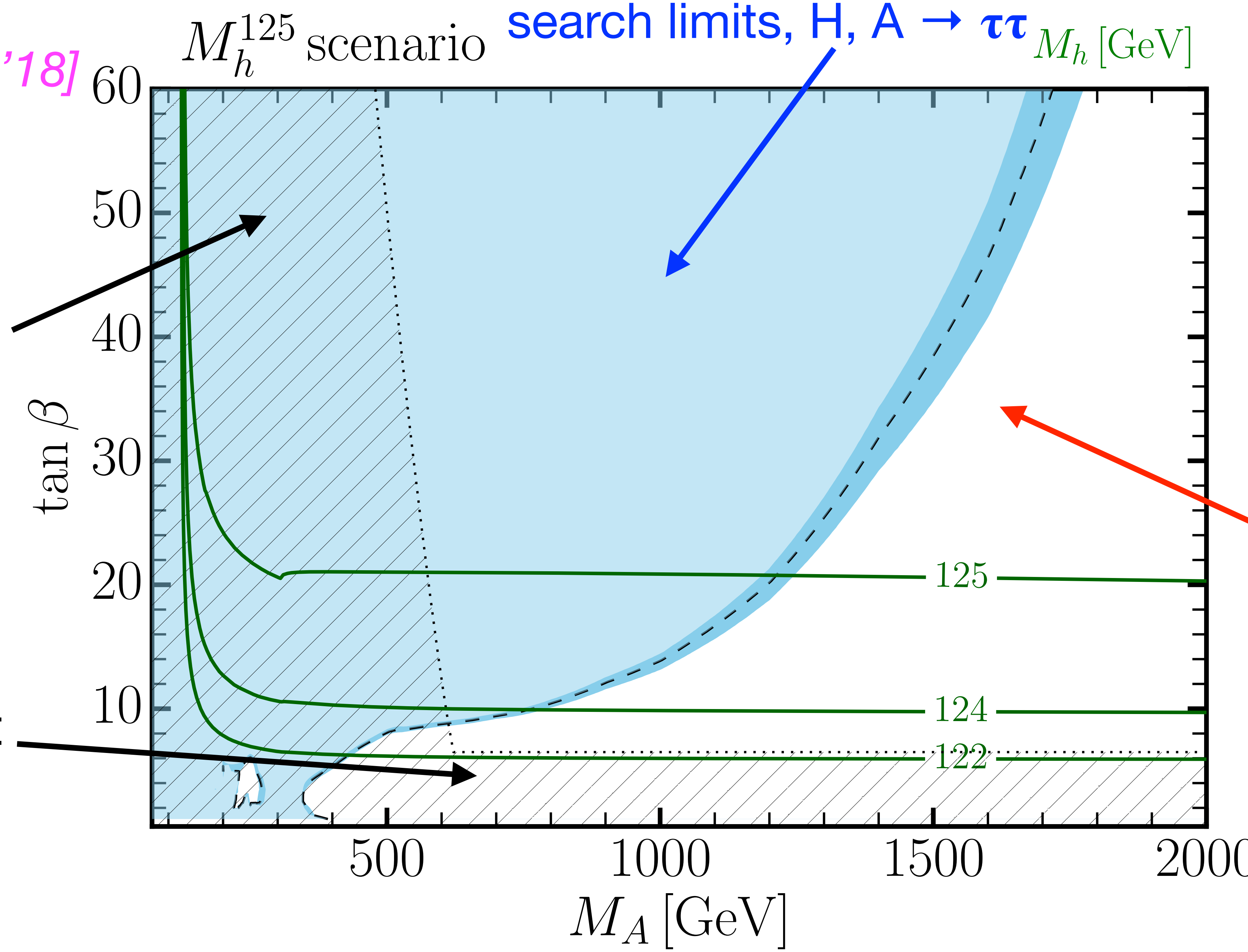
Higgs physics at the LHC (Run 3, HL-LHC)

Search for additional Higgs bosons (+ vector boson scattering): MSSM example

HiggsBounds: area excluded by Higgs search limits, H, A → **ττ**

[H. Bahl et al. '18]

HiggsSignals: area is not compatible with the properties of the detected Higgs signal h125 (indirect sensitivity)

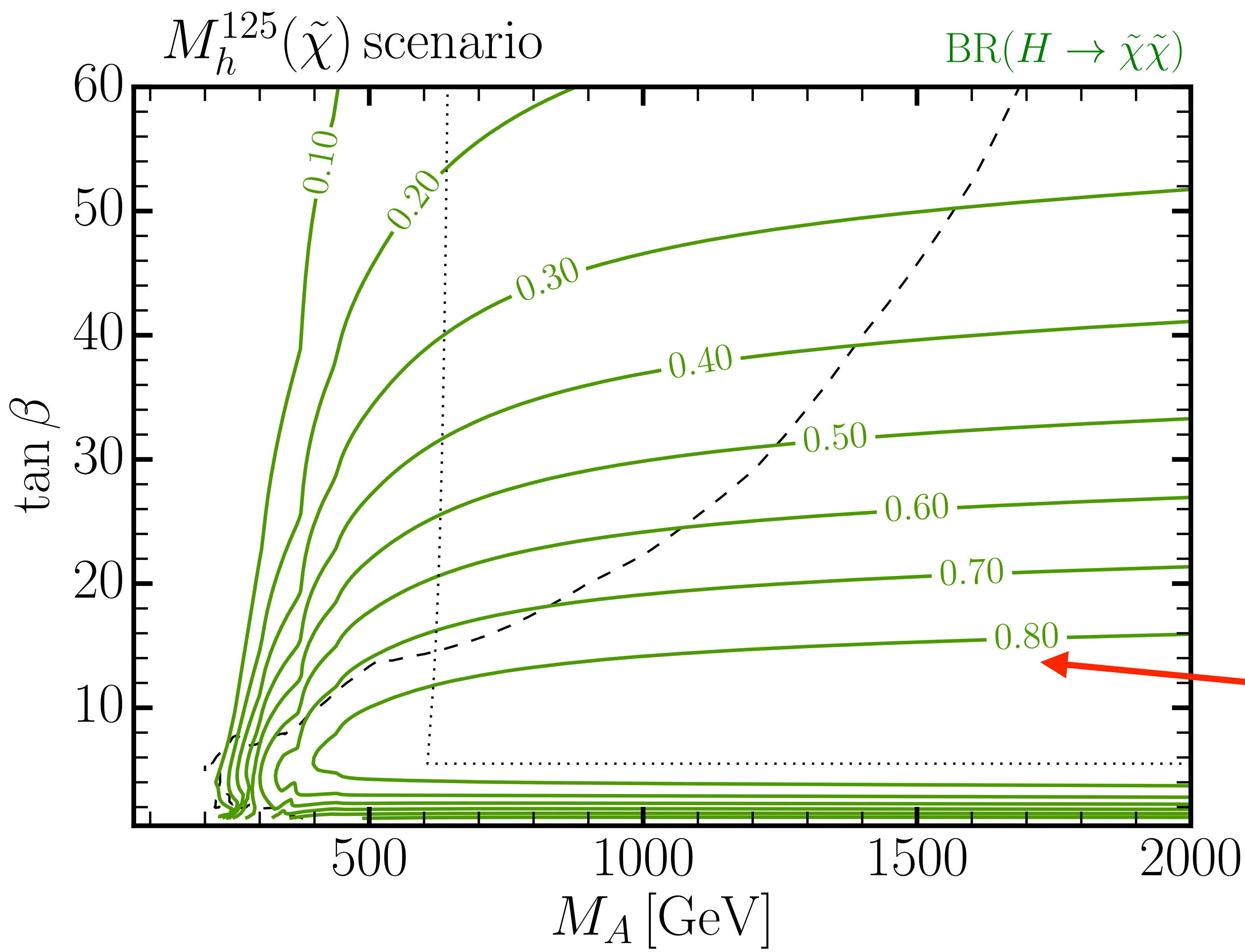


Allowed region, could be probed by dedicated searches for H, A → BSM part.

Non-standard decays of heavy Higgses, e.g. $H \to \tilde{\chi}\tilde{\chi}$

[H. Bahl et al. '18]

Decays of heavy Higgs bosons *H, A* into charginos and neutralinos:



Branching ratios of more than 80% possible!

⇒ Dedicated searches for heavy Higgs decays into SUSY particles could probe the ``LHC wedge" region

Theoretical description: N2HDM and NMSSM

[T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. W. '21]

Scans in the N2HDM (Higgs sector consists of two doublets and a real singlet) and the NMSSM (MSSM + Higgs singlet + superpartners), taking into account the constraints from collider searches, the signal rates of the Higgs at 125 GeV, flavour physics, electroweak precision observables, vacuum stability and perturbative unitarity

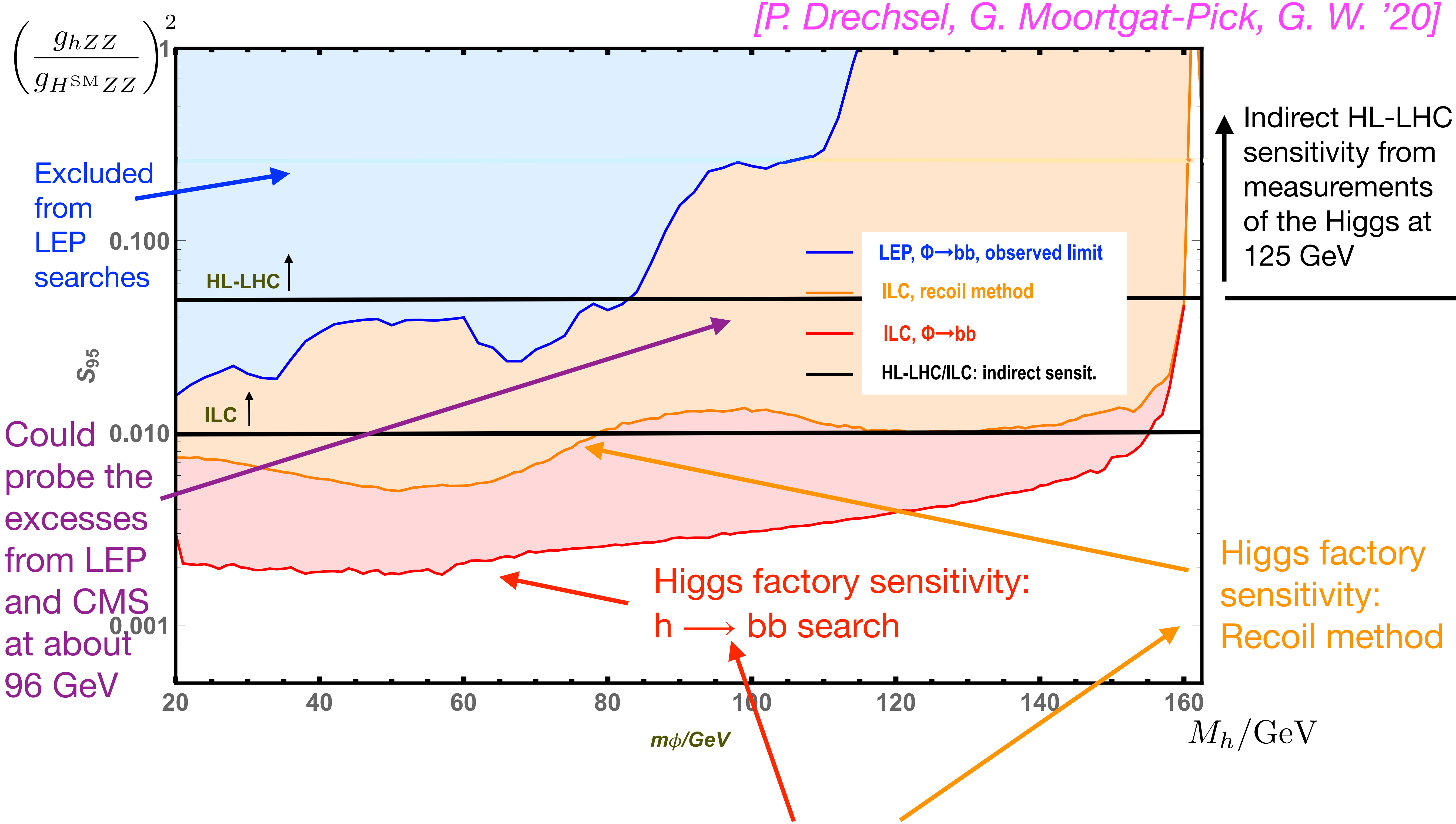
NMSSM with M_A = 400 GeV and low tanβ: ``alignment without decoupling" region

$$\chi^2 = \chi^2_{125} + \chi^2_{tt} + \dots$$

Require: $\chi^2 \leqq \chi^2_{SM}$

Higgs factory: discovery potential for a low-mass Higgs; Sensitivity at 250 GeV with 500 fb^{-1}

[P. Drechsel, G. Moortgat-Pick, G. W. '20]

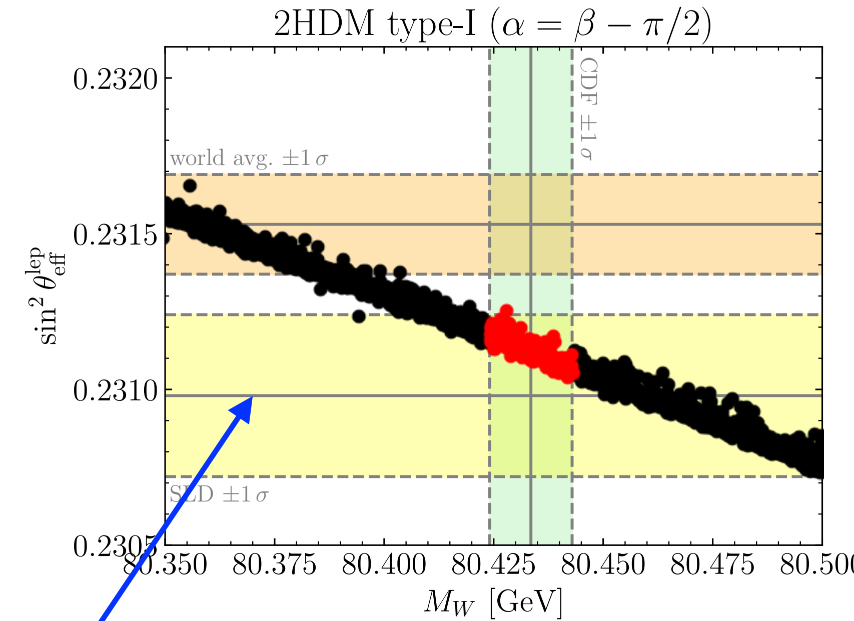


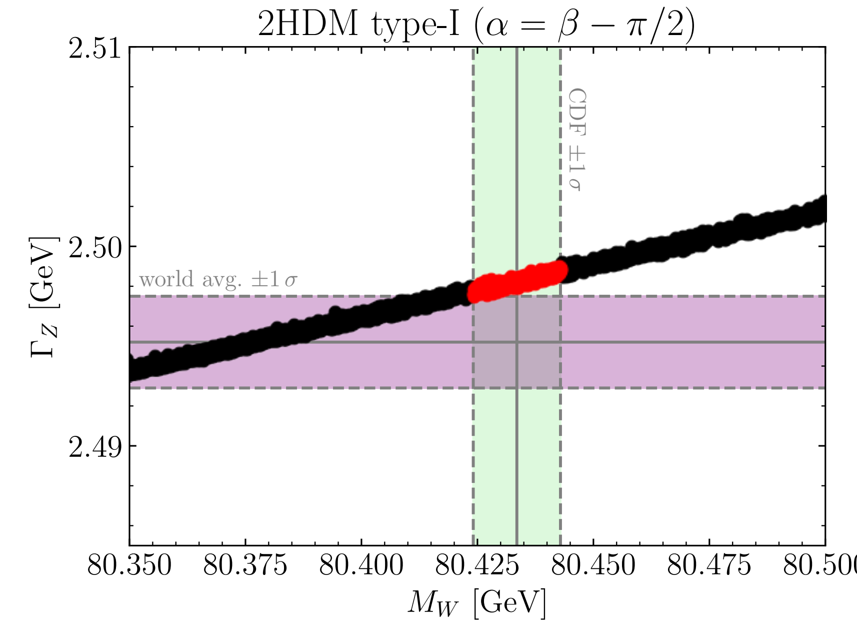
⇒ Higgs factory at 250 GeV will explore a large untested region!

Large corrections to M_W in the 2HDM

[H. Bahl, J. Braathen, G. W. '22]

All displayed points are in agreement with other relevant experimental and theoretical constraints

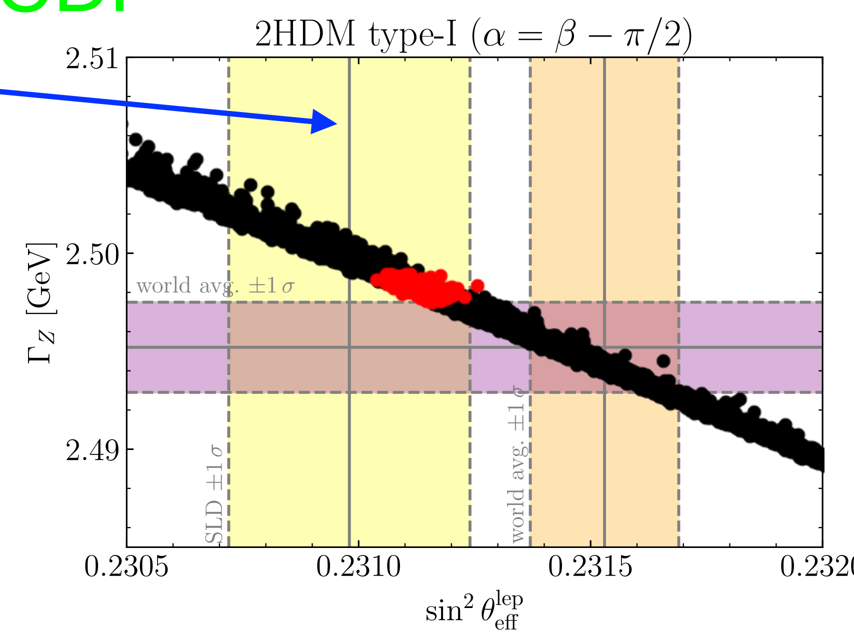




CDF

CDF

SLD value



Red: points in the 1-sigma range of the CDF measurement

M_W values as large as the CDF one can be accommodated in the 2HDM without violating other constraints
Better agreement with SLD value for $\sin^2\theta_{\rm eff}$

Results for the 2HDM (alignment limit)

Leading BSM one-loop contribution: $\Delta M_W \simeq \frac{1}{2} M_W \frac{c_W^2}{c_W^2 - s_W^2} \Delta\rho$

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2} \Bigg\{ \frac{m_A^2 m_H^2}{m_A^2 - m_H^2} \ln \frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H^\pm}^2}{m_A^2 - m_{H^\pm}^2} \ln \frac{m_A^2}{m_{H^\pm}^2} - \frac{m_H^2 m_{H^\pm}^2}{m_H^2 - m_{H^\pm}^2} \ln \frac{m_H^2}{m_{H^\pm}^2} + m_{H^\pm}^2 \Bigg\}$$

⇒ Large contribution possible for sizeable splitting between the BSM Higgs bosons

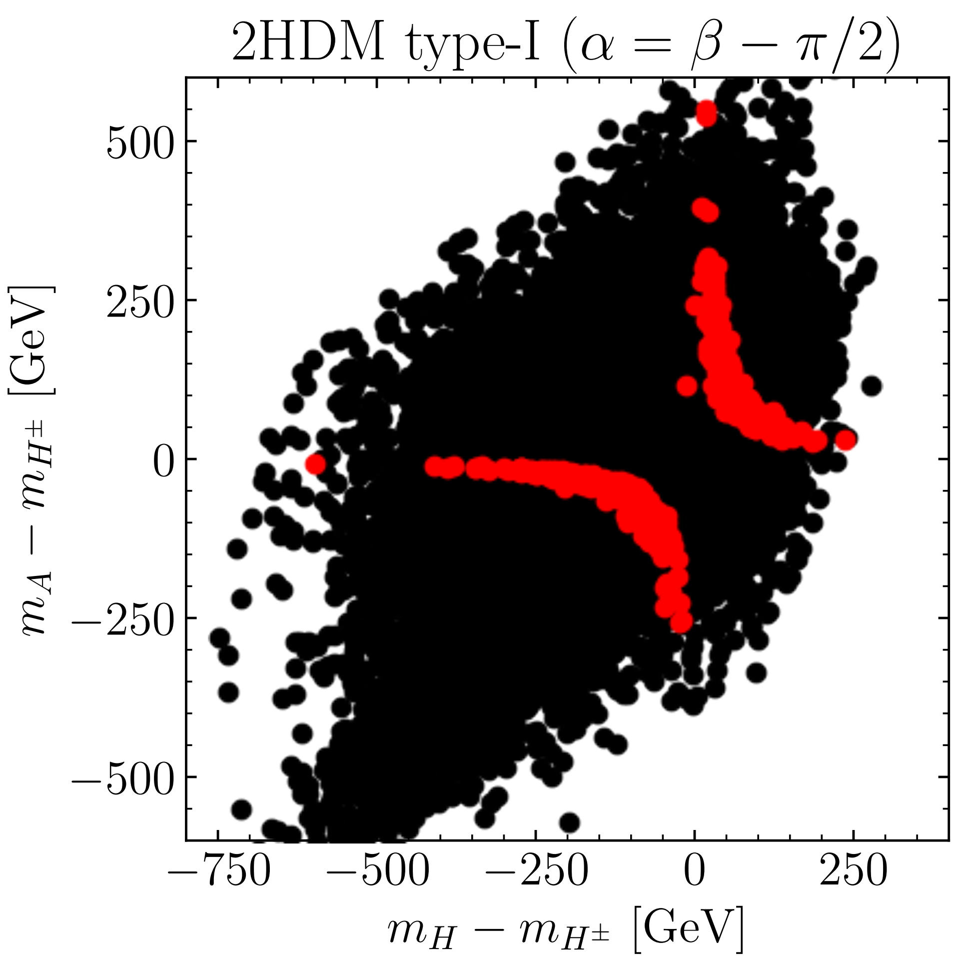
⇒ Prediction for the electroweak precision observables in the 2HDM (alignment limit) at 2-loop order *[H. Bahl, J. Braathen, G. W. '22]*
THDM_EWPOS *[S. Hessenberger, W. Hollik '16]*

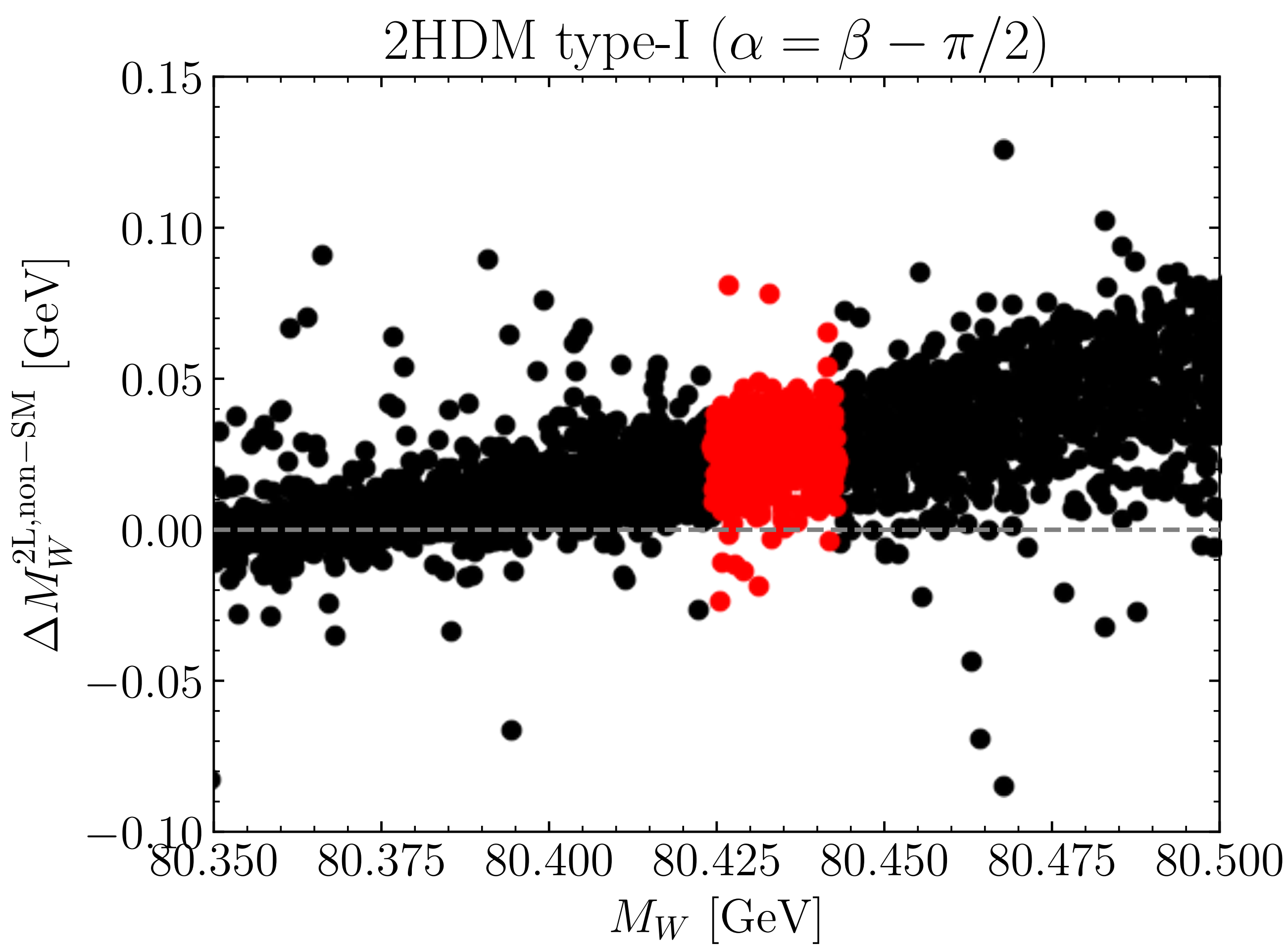
Plots on next slides:
All displayed points are in agreement with other relevant experimental and theoretical constraints
Red: points in the 1-sigma range of the CDF measurement

Large corrections to M_W in the 2HDM

[H. Bahl, J. Braathen, G. W. '22]

Prediction for the electroweak precision observables at 2-loop order, 2HDM in the alignment limit; example type I





⇒ Large effects on M_W arise from mass splitting between heavy Higgses
2-loop effects can be very important!
No significant impact on results for trilinear Higgs coupling (see above)