Searches for New Physics at the (HL-)LHC – Selected theory topics

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

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DFG Deutsche Forschungsgemeinschaft

Outline and disclaimer

- Introduction
- Direct searches for New Physics
- BSM via precision Higgs measurements
- Di-Higgs production in BSM models

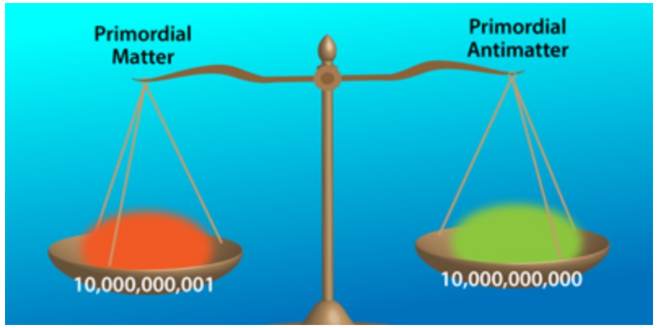
Disclaimer: the selection of what I present is of course biased by my own research interests, and there are plenty more exciting directions that I can't mention because of time!

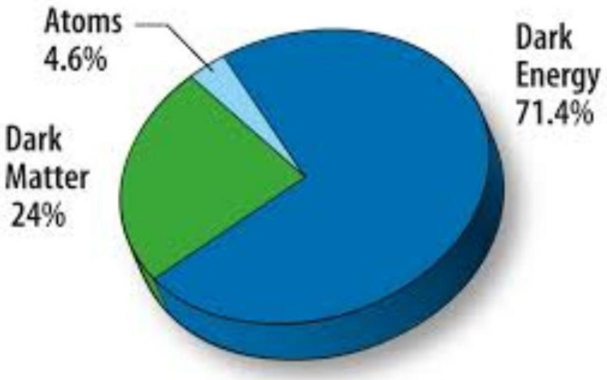
BSM searches as of 2025

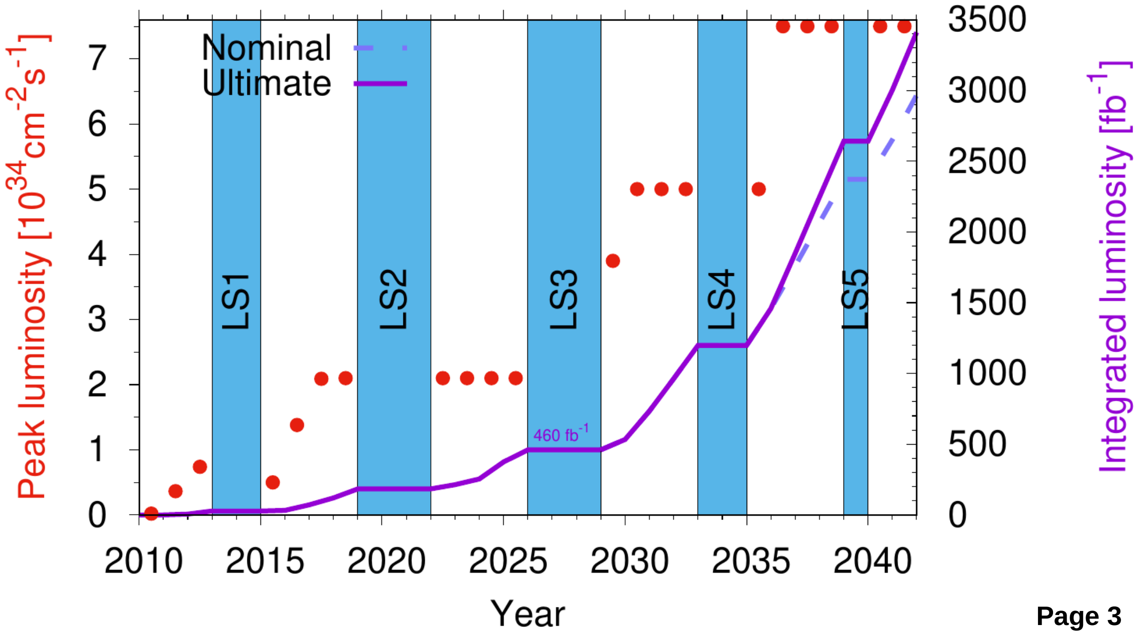
- No confirmed sign of Beyond-the-Standard-Model (BSM) Physics in LHC searches yet

- However, the **motivation for BSM remains intact**:
  → matter-antimatter asymmetry
  (or bayon asymmetry of the Universe, BAU)
  → dark matter
  → origin of electroweak symmetry breaking
  → naturalness and hierarchy problem(s)
  → neutrino masses
  → strong CP-problem
  … and many more!

- **Only ~15% of total (HL-)LHC data collected so far!**







Some avenues to search for New Physics at (HL-)LHC

- **Increased luminosity**
  → search for rare processes (e.g. rare decays of top quark, or of Higgs boson; di-Higgs production, etc.)

- **New search ideas and strategies, and new analysis techniques**
  (*c.f. also talks of T. Vasquez Schröder and S. Lowette*)
  → consider new final states, new/forgotten channels, different regions of phase space
  → improved data analysis, e.g. with machine learning techniques
  → $\sqrt{\mathcal{L}}$ scaling is at best overly conservative [Belvedere, Englert, Kogler, Spannowsky '24]

- **Increased precision on properties of known particles**
  → precision measurements programme ongoing (more later on case of Higgs boson)
  → finding a deviation from SM would give us information about scale of BSM

- **More global analyses** (e.g. EFT) → *see e.g. talk of E. Vryonidou*

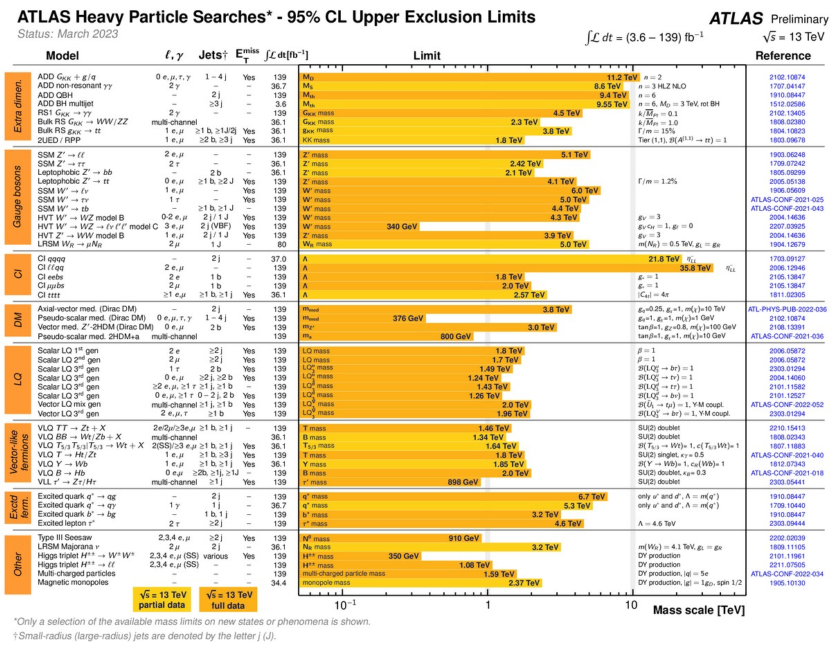
Direct searches for New Physics

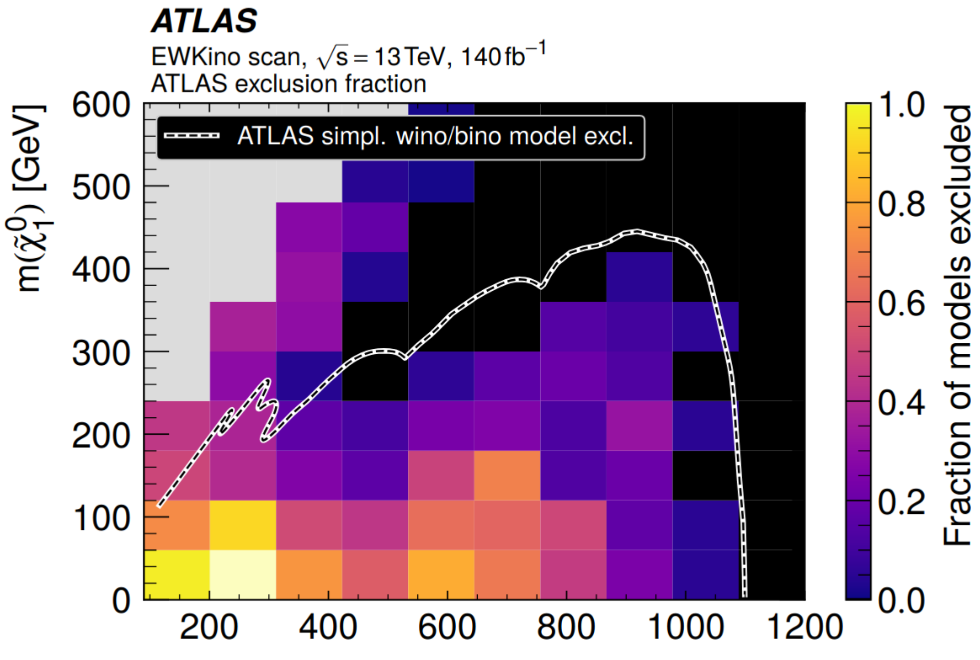
Search limits and interpretations

- **Increasingly stringent limits on BSM states**,
  e.g. → stops/sbottoms > 1.3 TeV
  → gluinos and 1st/2nd family squarks > 2.4 TeV
  → Z' > ~ 2 TeV (at least)
  → scalar leptoquarks > 1.2 TeV
  etc.

- Interpretation of searches often given in terms of simplified models/scenarios → **care is then needed to draw general conclusions!** *(c.f. pMSSM example)*

- **Different approaches for (re)interpretations:**
  - recasting, e.g. with `MadAnalysis 5` [Conte et al. '12-'18], [Araz et al. '20, '21], `CheckMATE` [Drees et al. '13], [Dercks et al. '16], [Desai et al. '21], `RIVET` [Buckley et al. '10], [Bierlich et al. '19] with `Contour` [Buckley et al. '21], `ColliderBit` [Balázs et al. '17], [Athron et al '18] (from GAMBIT), or `HackAnalysis` [Goodsell '24]
  - map BSM model/scenario onto simplified model search limits
    → e.g. `SModelS` [Kraml et al. '13], [Alguero et al. '21]
  - identify most sensitive BSM search channel to compare model to
    → e.g. `HiggsBounds` [Bechtle et al '08-'20], [Bahl et al. '22]

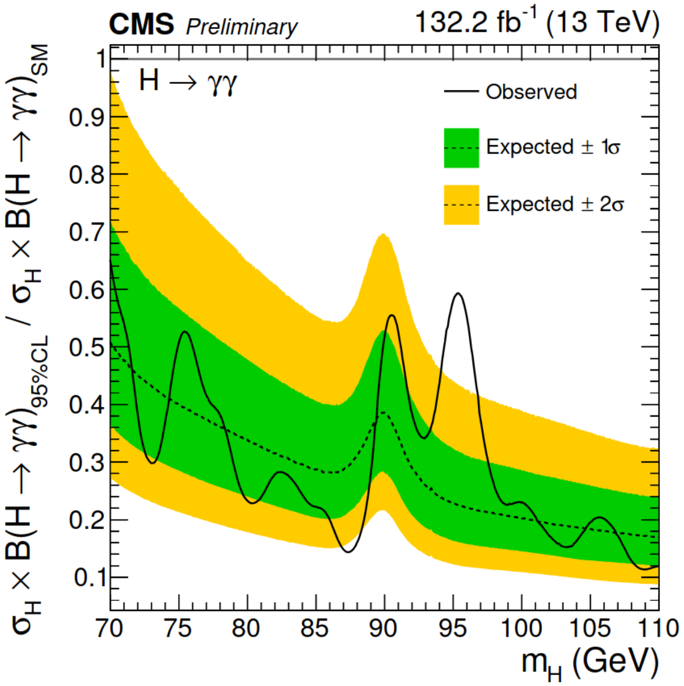




ATLAS results for pMSSM
[ATLAS `2402.01392`]

Some reasons for excitement?

- Some tentalising excesses worth mentioning:
  - **A Higgs boson at 95 GeV?**
    → excesses seen by ATLAS and CMS in low mass $\Phi \to \gamma\gamma$ searches
    + CMS search for $\Phi \to \tau^+\tau^-$ + LEP excess in $\Phi \to b\bar{b}$ (debated)
    → numerous possible BSM interpretations (w. or w/o $\tau^+\tau^-$ and $b\bar{b}$)
    (*far too many references to fit on this slide*)



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    → numerous possible BSM interpretations (w. or w/o $\tau^+\tau^-$ and $b\bar{b}$)
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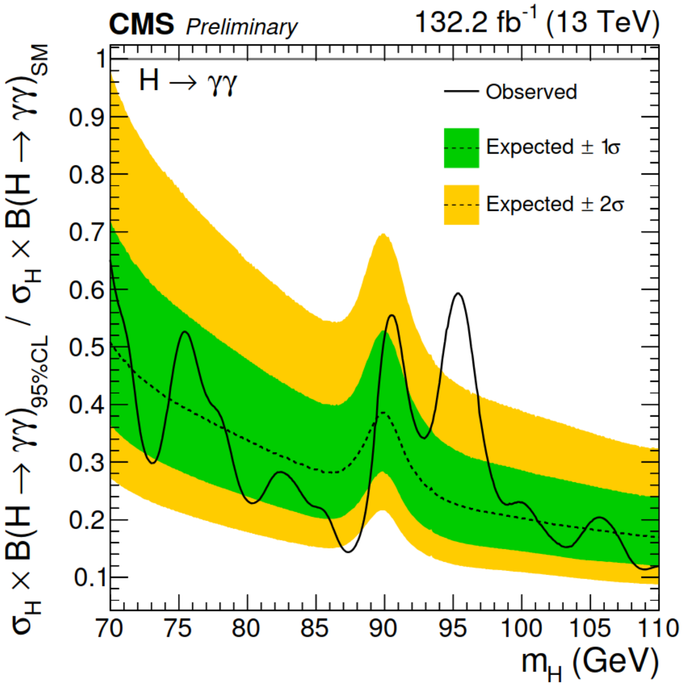
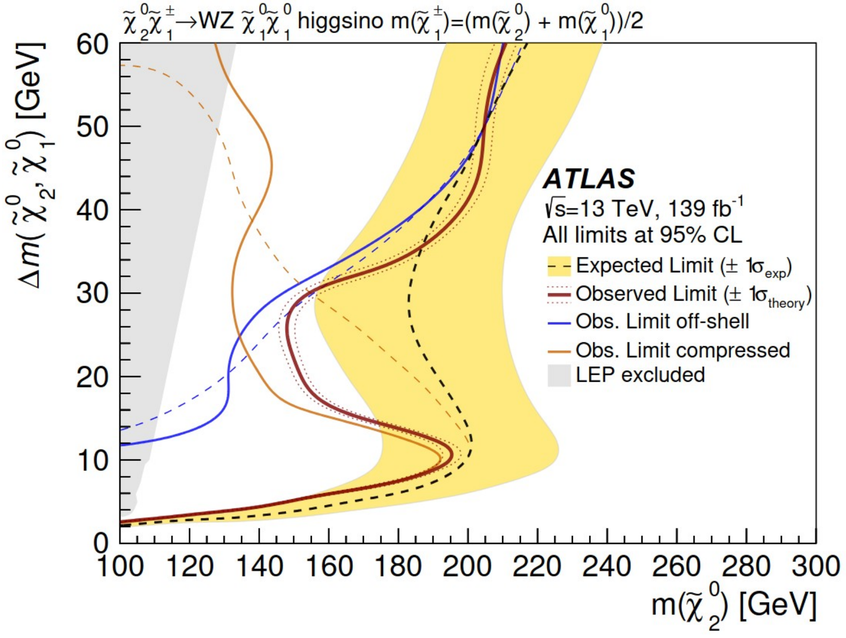
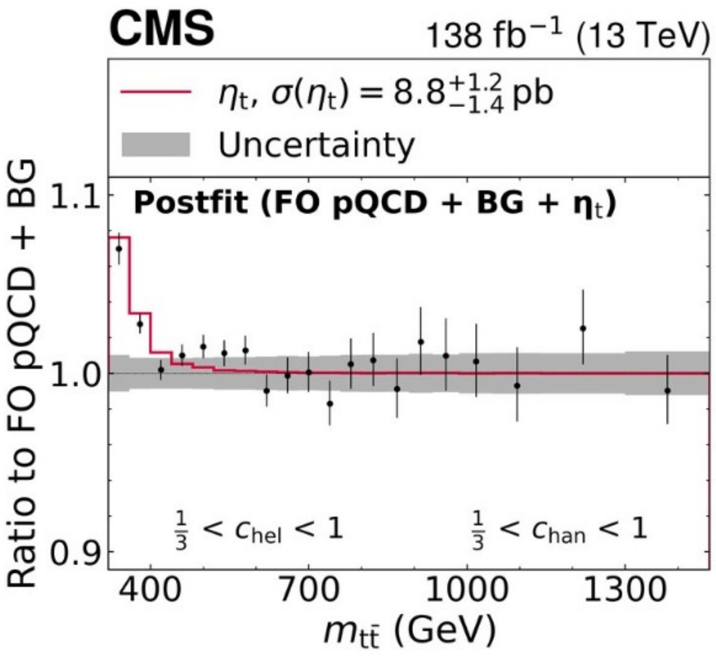
  - **Excesses in soft lepton and monojet searches**
    → excesses seen by ATLAS ([ATLAS-SUSY-2018-16], [ATLAS-SUSY-2019-09]) and CMS ([CMS-SUS-18-004]) in searches for 2 or 3 soft leptons + MET
    → recasting of ATLAS and CMS results ([ATLAS-EXOT-2018-06], [CMS-EXO-20-004]) finds corresponding excesses in searches for monojet + MET [Agin et al. ‘23]
    → interpretations possible in MSSM, NMSSM, Dirac gaugino models, with or without DM and/or h_{95} , see e.g. [Agin et al. ‘23, ‘24, ‘25], [Chakraborti et al. ‘24], [Ellwanger et al. ‘24], [Fuks et al. ‘25], [Araz et al. ‘25]





Some reasons for excitement?

- Some tentalising excesses worth mentioning:
  - **A Higgs boson at 95 GeV?**
  - **Excesses in soft lepton and monojet searches**
  - **Excess at $t\bar{t}$ threshold** → *see talk of S. Lowette yesterday*
    → *clear excess* above SM prediction for non-resonant $t\bar{t}$ production: CMS >> 5σ [CMS-TOP-24-007], confirmed by ATLAS [ATLAS-CONF-2025-008]
    → signal compatible with ***toponium bound state*** (predicted in SM) or(and?) with ***BSM pseudoscalar***
    → only toponium (most likely, see e.g. [CMS-HIG-22-013] which uses NRQCD model from [Fuks et al. '21, '24]) or could it be both? (see [Djouadi, Ellis, Quevillon '24], [Bahl, Kumar, Weiglein '25])
    → inclusion of precise theory predictions (c.f. [Garzelli et al '24]) needed and underway
    → *see talk of M. Garzelli on Friday*



Some reasons for excitement?

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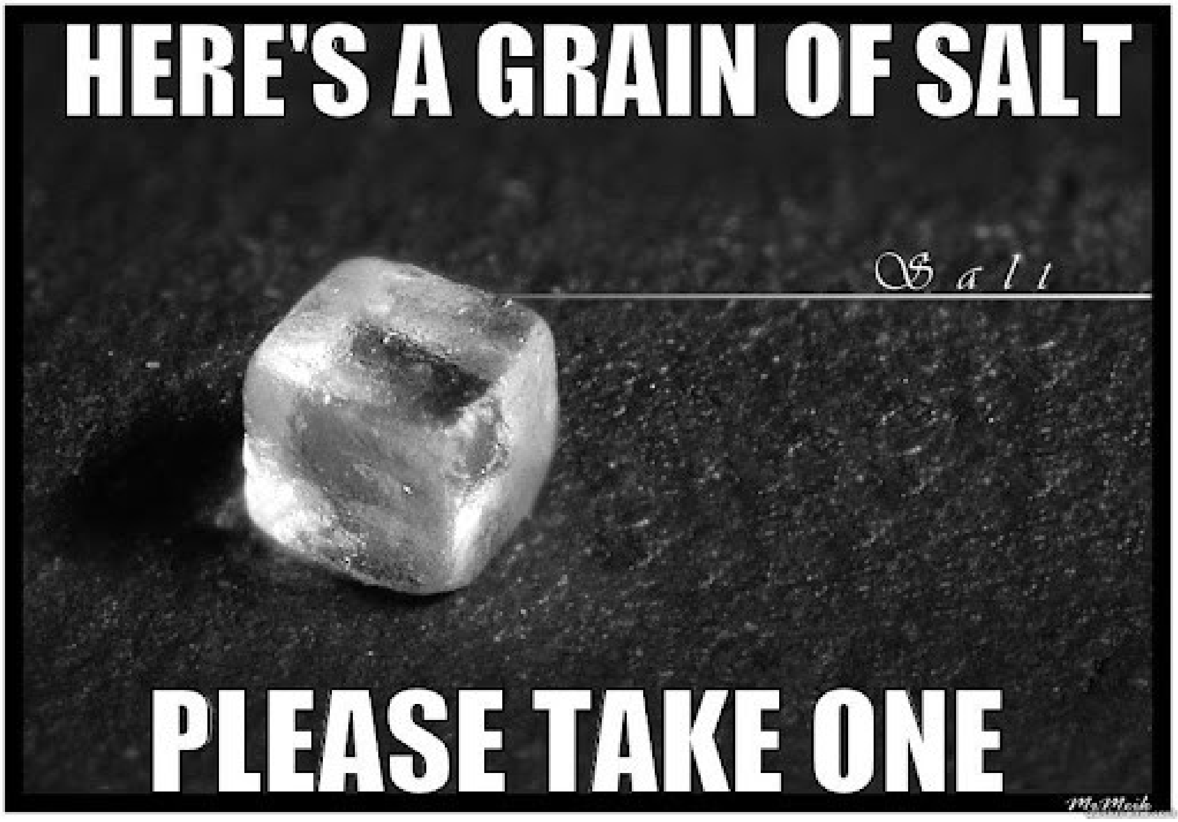
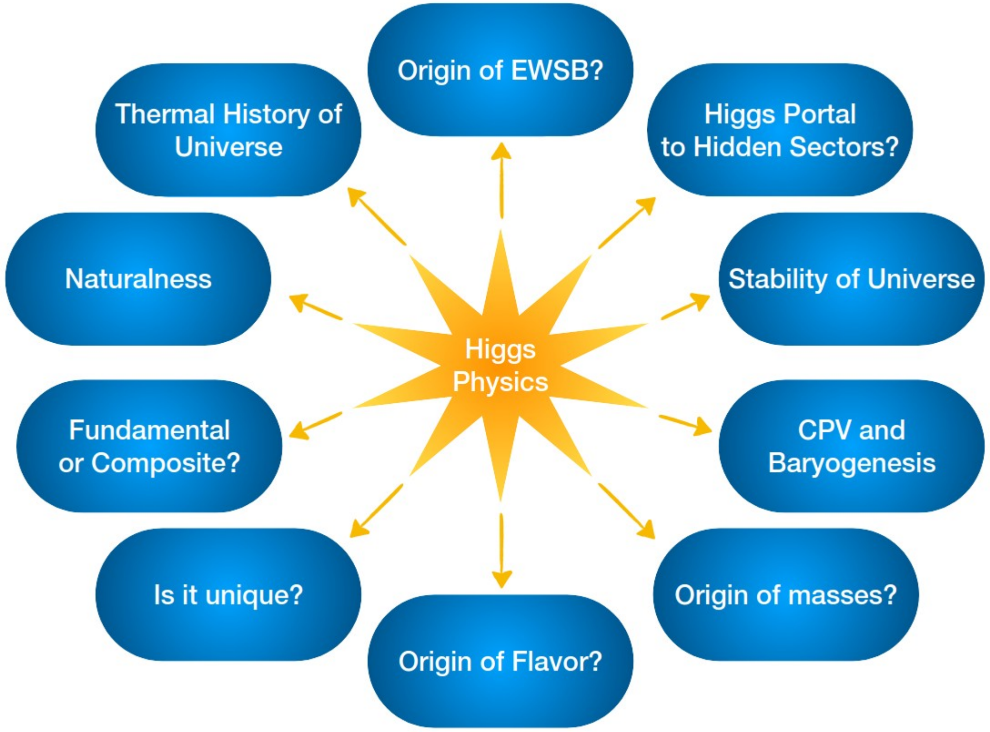


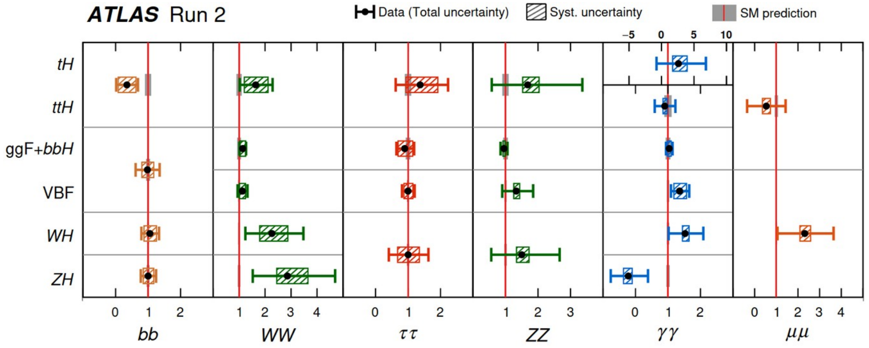
*NB: I am **not claiming that any of the following are confirmed to be BSM** yet, but:*
*→ these examples show that there is **still ample room for direct discoveries**!*
→ while most of these will (likely) disappear or find an explanation within the SM,
***it suffices that one remain** to have a discovery of New Physics!*

BSM searches via Higgs precision measurements

The central role of the Higgs to search for New Physics

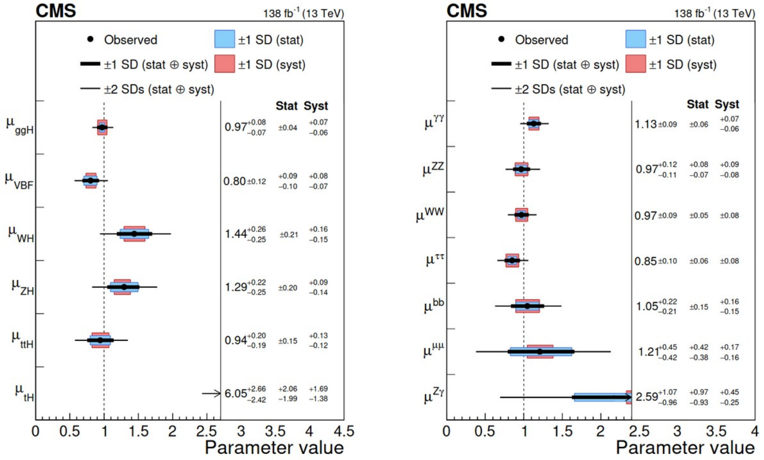


[Snowmass report on Higgs Physics 2209.07510]



[ATLAS Nature '22] σ × B normalized to SM prediction

[CMS Nature '22]



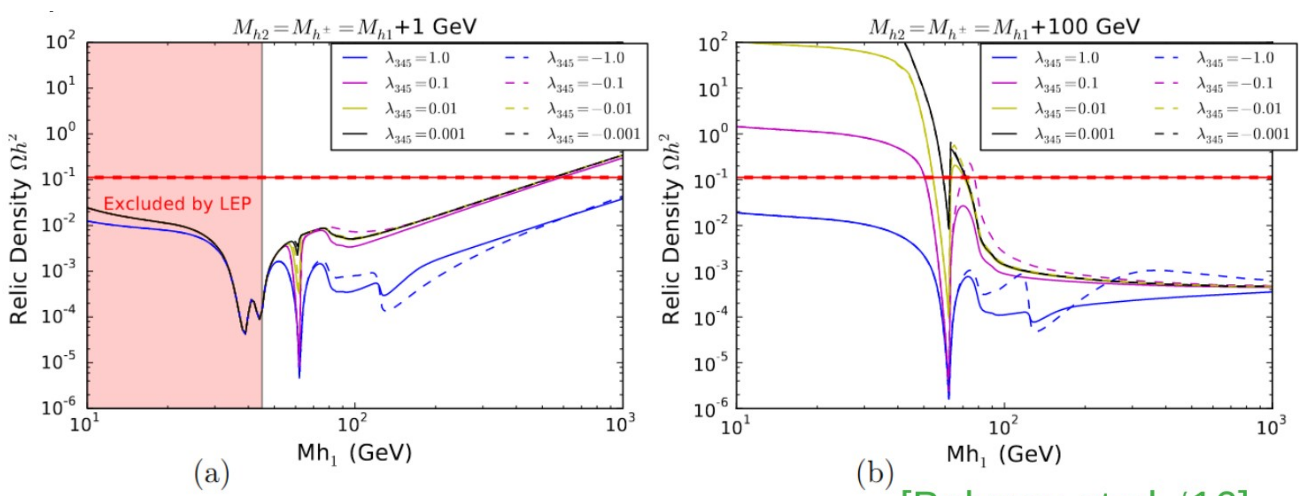
- The Higgs boson is **related to many of the open questions of HEP**
- BSM theories commonly feature extended Higgs/scalar sectors, or states that couple to the detected Higgs boson → **can modify properties of h_{125}**
- Ongoing and future programme of precision measurements of Higgs properties at (HL-)LHC, see e.g. [ATLAS Nature '22], [CMS Nature '22]
  Results in terms of κ-framework, signal strengths, STXS, EFT operators, etc. (→*c.f. talk of S. Lowette*)

Example: dark matter in the Inert Doublet Model

- **Inert Doublet Model (IDM):**
  add 2nd doublet to SM, charged under unbroken Z_2 symmetry

Inert BSM scalars

  → **lightest inert scalar H = DM candidate**

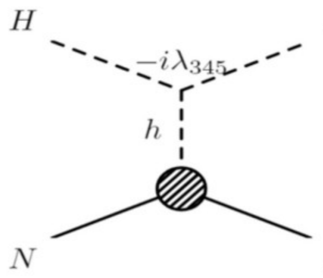


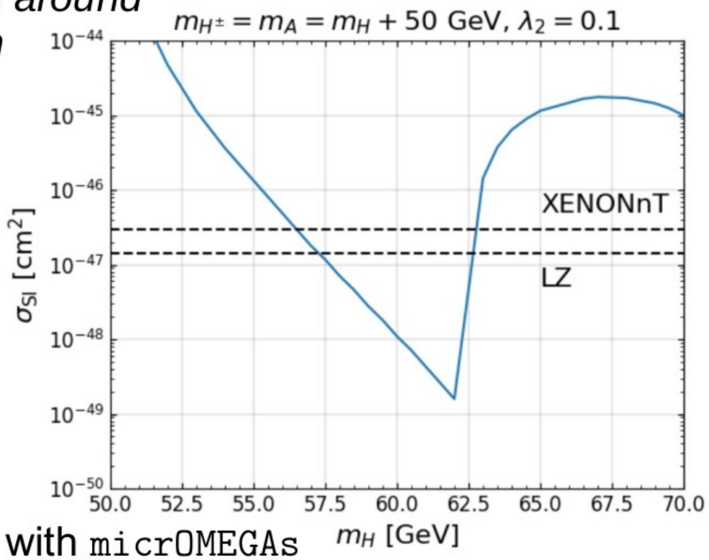
[Belyaev et al. '16]

- DM relic density obtained via freeze-out, while evading current detection bounds

- **Higgs portal DM models like IDM testable** via:
  - DM direct and indirect searches
  - direct searches at colliders
  - precision/indirect tests, e.g. properties of h_{125}
    - **$h \to$ invisible**
      (only if $m_H < m_h/2$; can also be evaded by tuning portal coupling)
    - **$h \to \gamma\gamma$**

Direct detection bounds around Higgs resonance region (i.e. $m_H \sim m_h/2$)

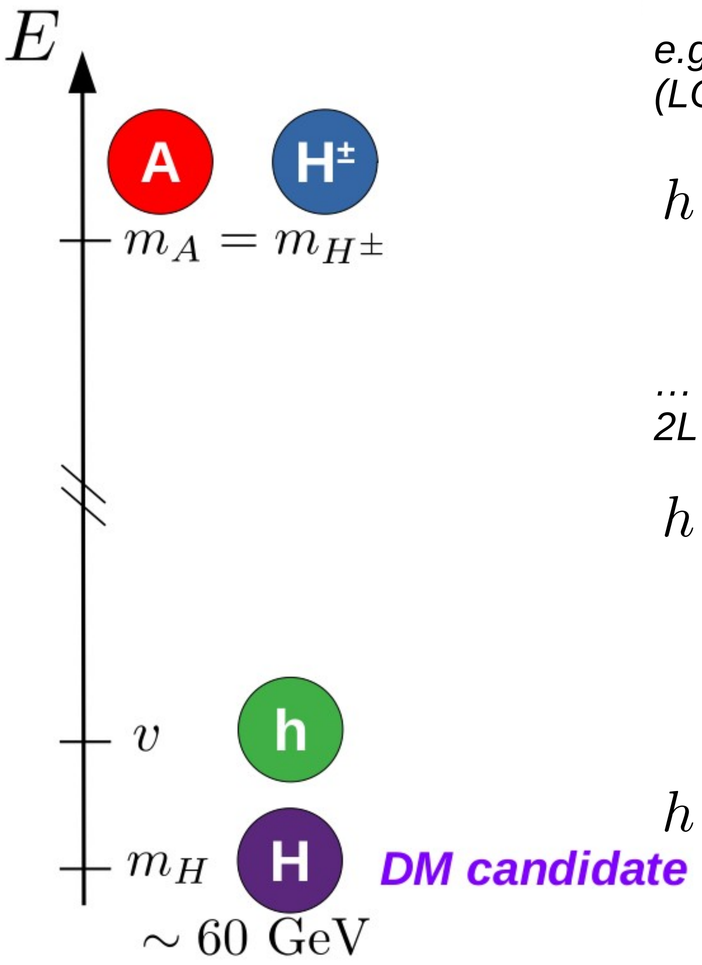




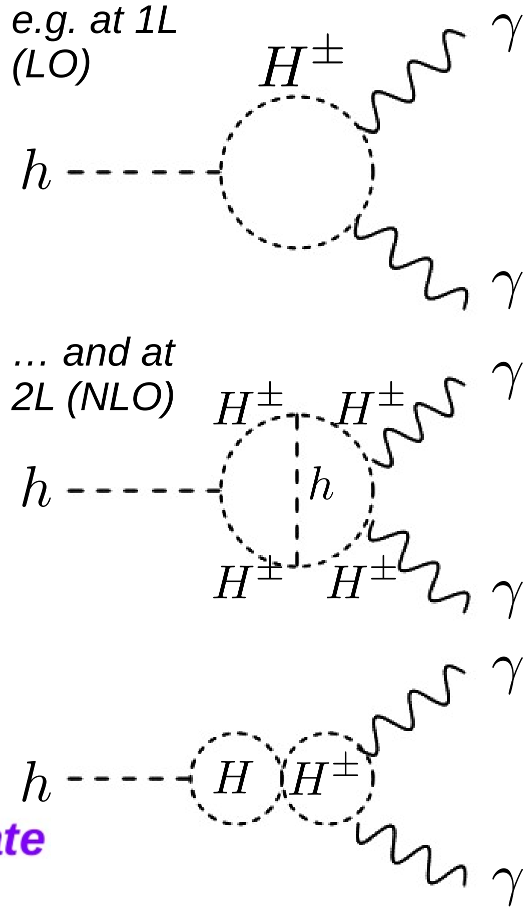
Plot made with `micrOMEGAs`
[Bélanger et al. '18]

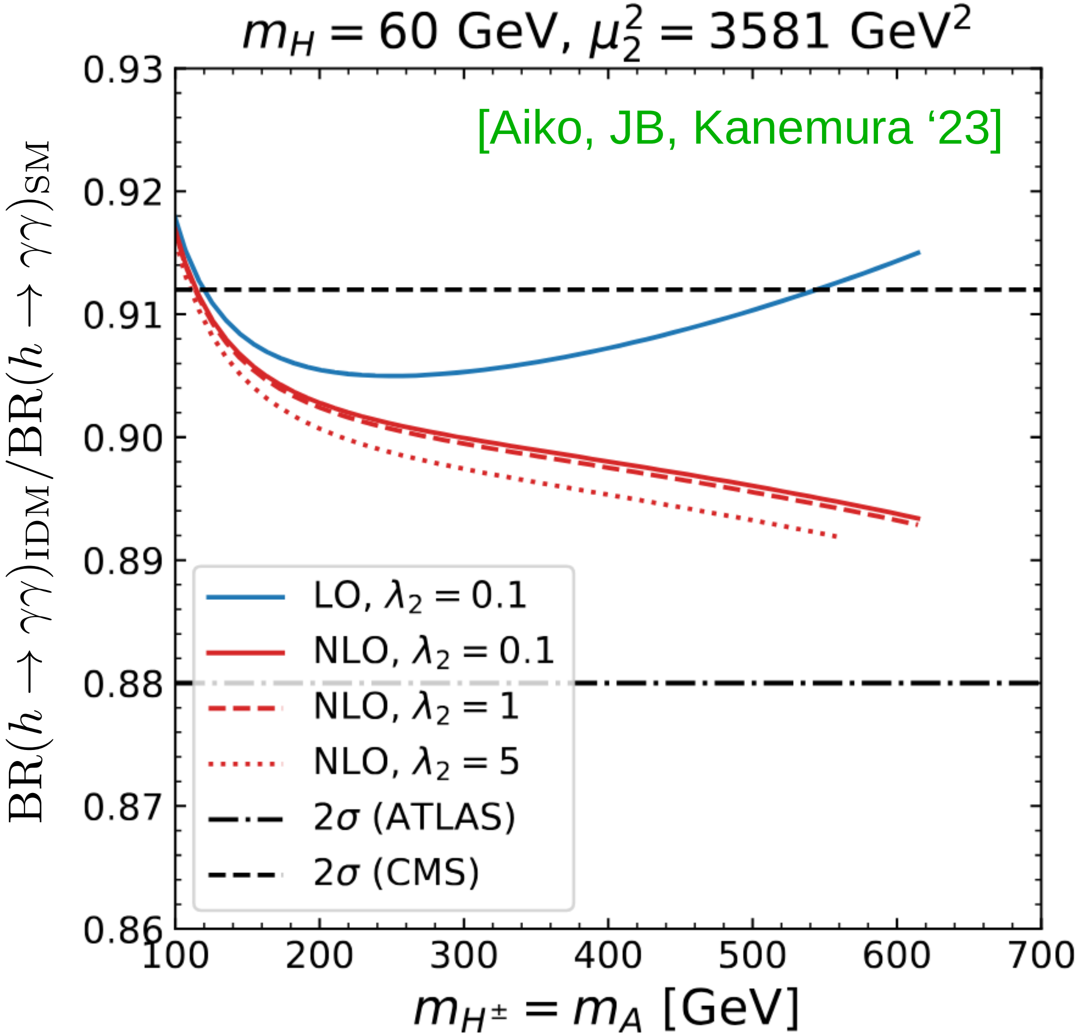
Probing dark matter in the Inert Doublet Model with h→γγ

"Higgs resonance" scenario of IDM: *DM candidate at ~$m_h/2$*



Charged Higgs boson gives a BSM contribution to h→γγ



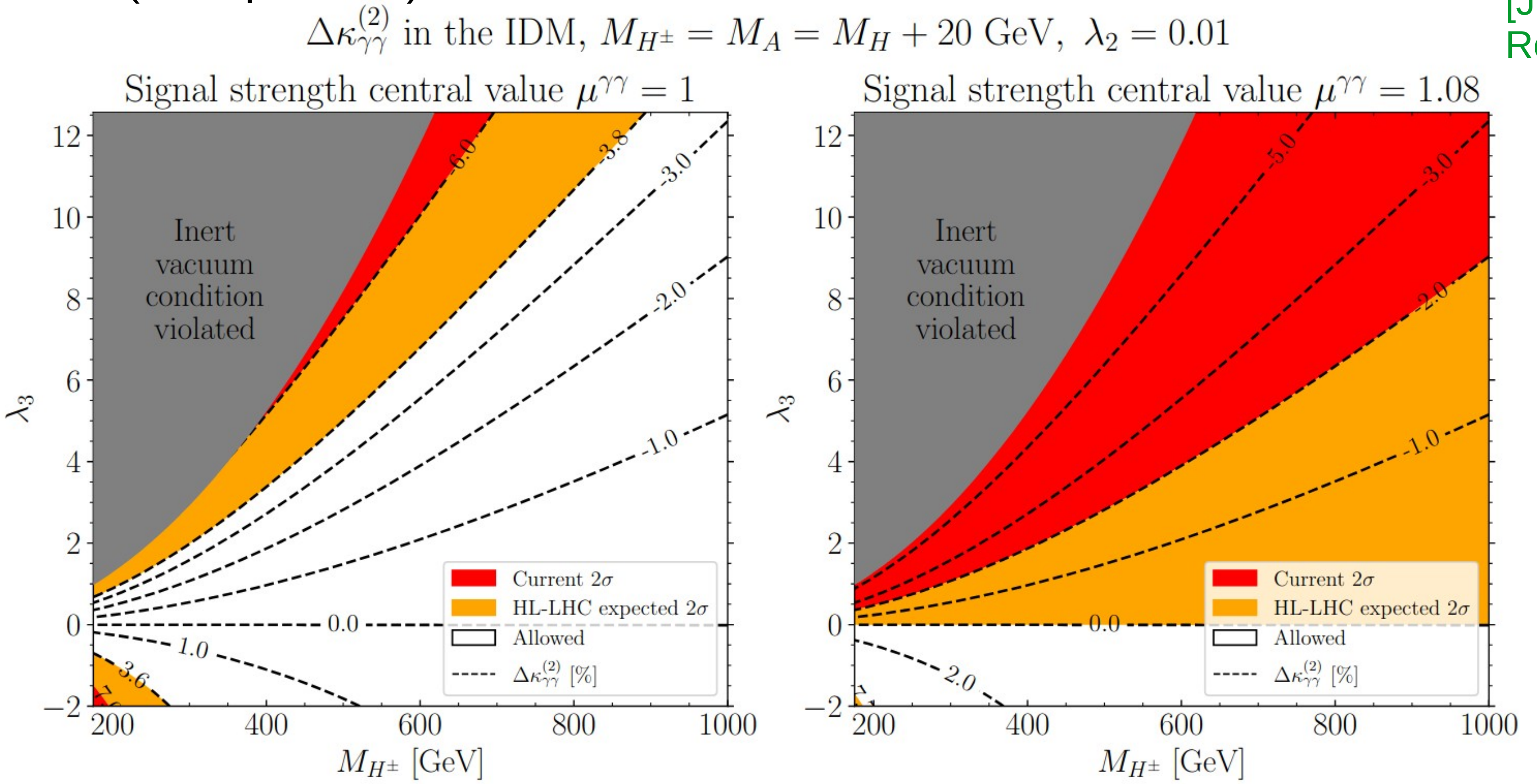


- **Almost entire "Higgs resonance" scenario ($m_A = m_{H\pm} > 120$ GeV) could be excluded by h→γγ!**
- **Two-loop analysis crucial for this**

Probing the Inert Doublet Model with h→γγ

- Significant contraints on IDM parameter space from Γ(h→γγ) at HL-LHC, especially if central value of signal strength remains > 1 (now: $\mu^{\gamma\gamma}$=1.08)

[JB, Gabelmann, Robens, Stylianou '24]



- Tension in a single measurement is of course **not enough**
  → **combined analysis of Higgs properties needed**, e.g. with `HiggsSignals` [Bechtle et al. '13, ;20], [Bahl et al. '22] or `Lilith` [Bernon, Dumont '15], [Kraml et al. '19]

Precise predictions for Higgs properties in BSM models

- Public tools including NLO QCD and EW/BSM corrections for Higgs decays in specific models, e.g.:
  - `HDecay` [Djouadi et al., '98, '10] and variants like [Mühlleitner et al. '17], [Krause et al. '18], [Krause and Mühlleitner '19] (MSSM, 2HDM, N2HDM, composite Higgs, etc.)
  - `Prophecy4f` [Bredenstein et al. '06], [Altenkamp, Dittmaier, Rzehak '17], [Altenkamp, Boggia, Dittmaier '18], [Denner, Dittmaier, Mück '19] (2HDM, HSM)
  - `H-COUP` [Kanemura et al., '17, '19], [Aiko et al., '23] (HSM, 2HDM, IDM)

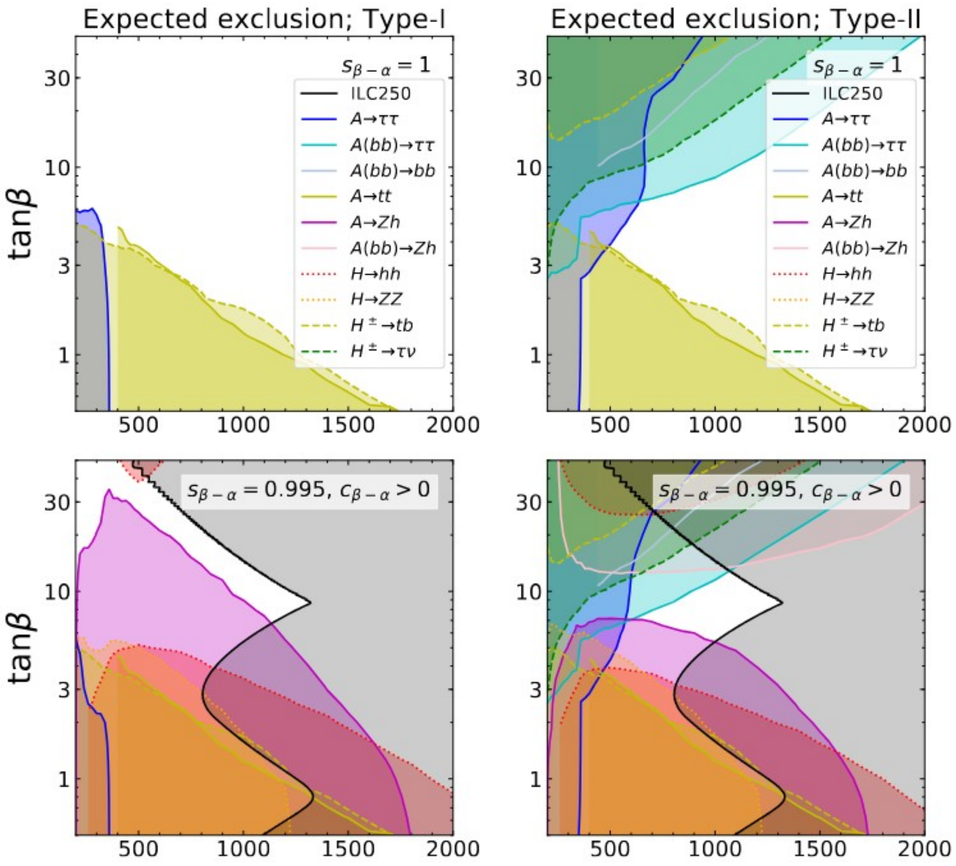
- Public tools for Higgs/scalar decays beyond LO, in general renormalisable theories
  - `SARAH`/`SPheno` [Staub '08-'15], [Porod '03], [Staub, Porod '11] based on [Goodsell, Liebler, Staub '17]
  - `FlexibleDecay` [Athron et al., '21] (part of `FlexibleSUSY` [Athron et al., '14, '17]; see also `NPointFunctions` [Khasianevich et al., '24])

- Inclusion of known higher-order SM contributions is **crucial for reliable comparisons with experimental data**

- Higgs production at LHC dominantly via gluon fusion, less affected by BSM if not charged under $SU(3)_c$, but other production channels can also be affected

Interplay of Higgs measurements with other BSM searches

- ***Example 1***: Complementary cover of BSM parameter space (here for 2HDM [Aiko et al. ‘20]) from direct searches and indirect constraints from precision measurements of Higgs properties (finding a deviation sets upper bound on BSM mass scale)



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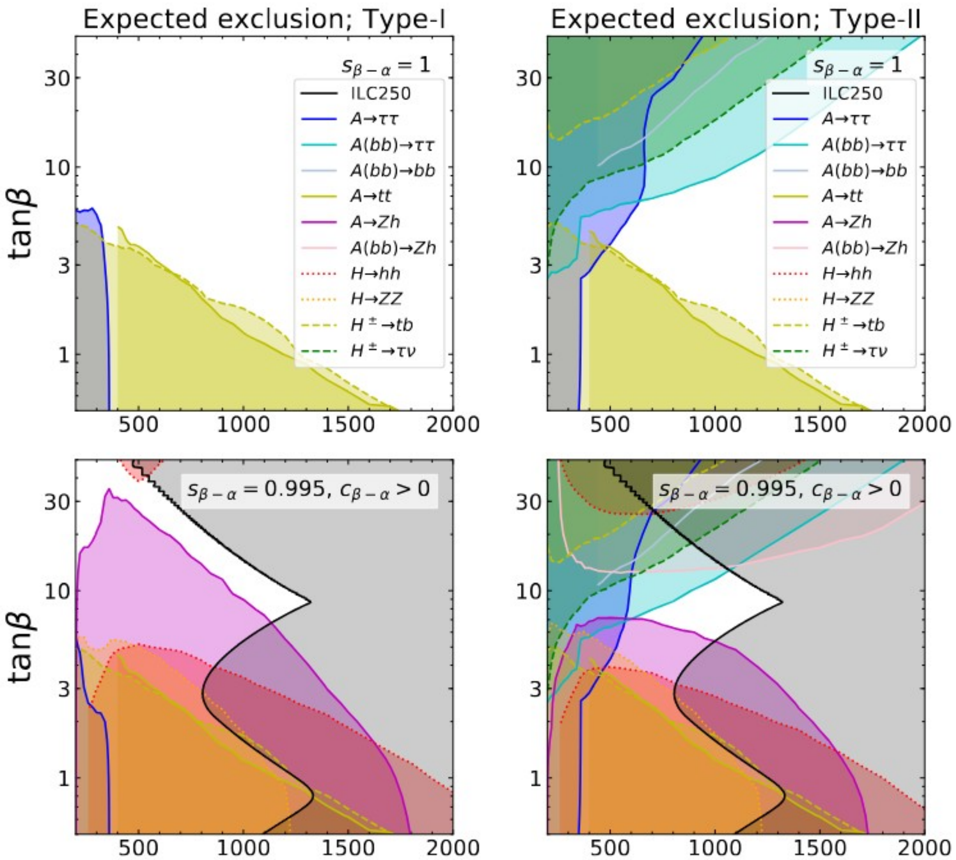
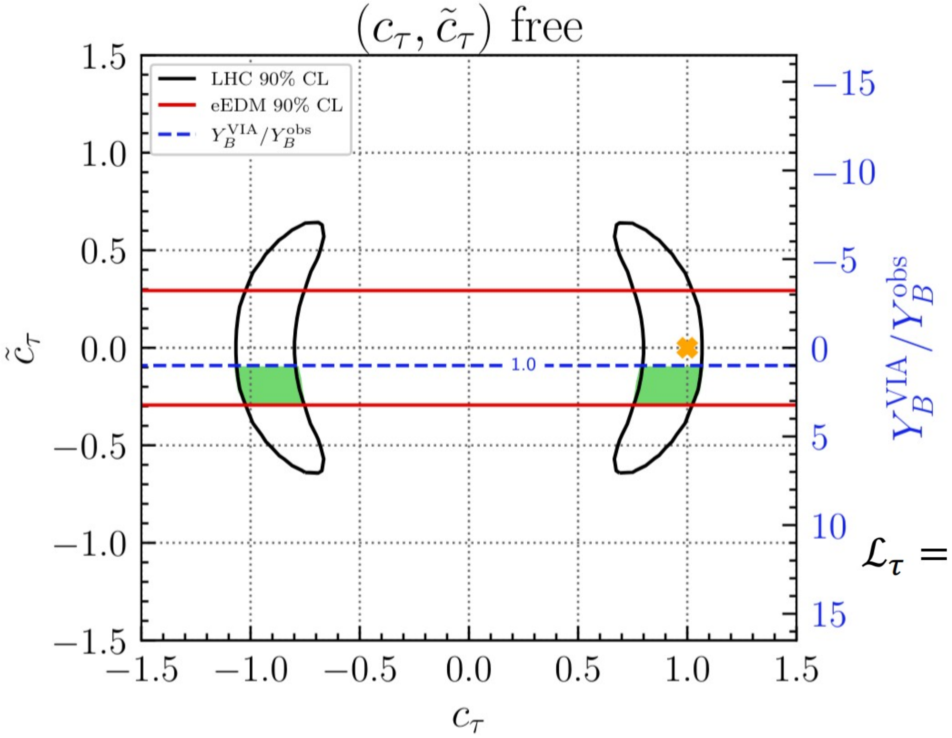


- ***Example 2***: CP violation (needed for baryogenesis, c.f. [Sakharov '67]) in Higgs-fermion interactions so far not very constrained (unlike in Higgs-gauge-boson interactions) → probed via **angular distributions of Higgs processes at colliders**, via **electric dipole moments**, and related to **prediction of BAU**, e.g. here global analysis of CPV in Higgs-tau sector [Bahl et al. '22]



Higgs characterisation model

$$\mathcal{L}_\tau = \frac{y_\tau^{SM}}{\sqrt{2}} \bar{\tau}(c_\tau + i\gamma_5 \tilde{c}_\tau)\tau H$$

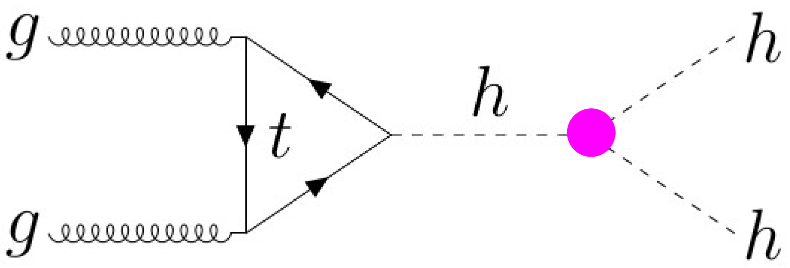
See also [Miralles et al. '24] for CPV in top/Higgs sector (studied within SMEFT)

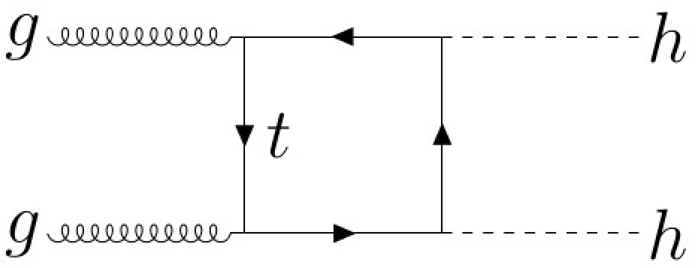
Di-Higgs production

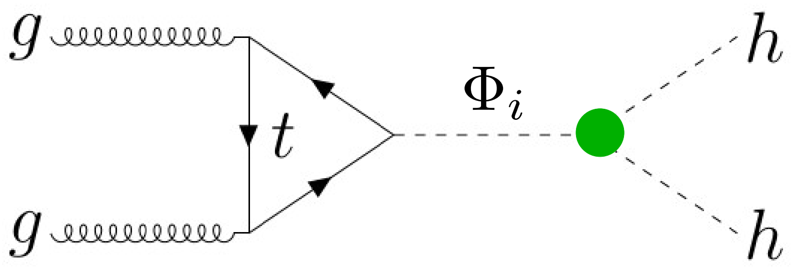
Di-Higgs production

h ≡ h_{125}
[discovered Higgs boson]

➢ Dominant channel for di-Higgs production at (HL-)LHC: **gluon fusion**
Here, leading order (LO) diagrams, involving top quark (dominant contribution among quark loops)





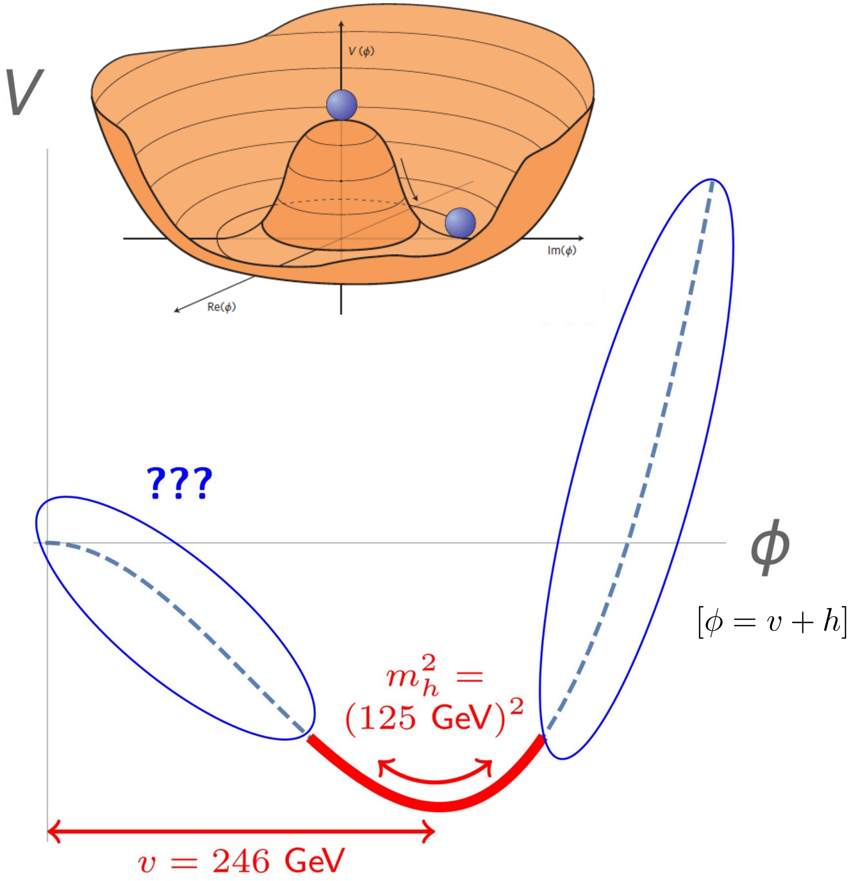


"Non-resonant contributions"
- Standard Model (SM)-like diagrams
- Involves the trilinear self-coupling of h_{125} – λ_{hhh}
  → **probe of the Higgs potential**
- Large destructive interference between triangle and box diagram
  → **suppression of cross-section in SM**
  → **large changes in di-Higgs cross-section possible from BSM effects in λ_{hhh}**

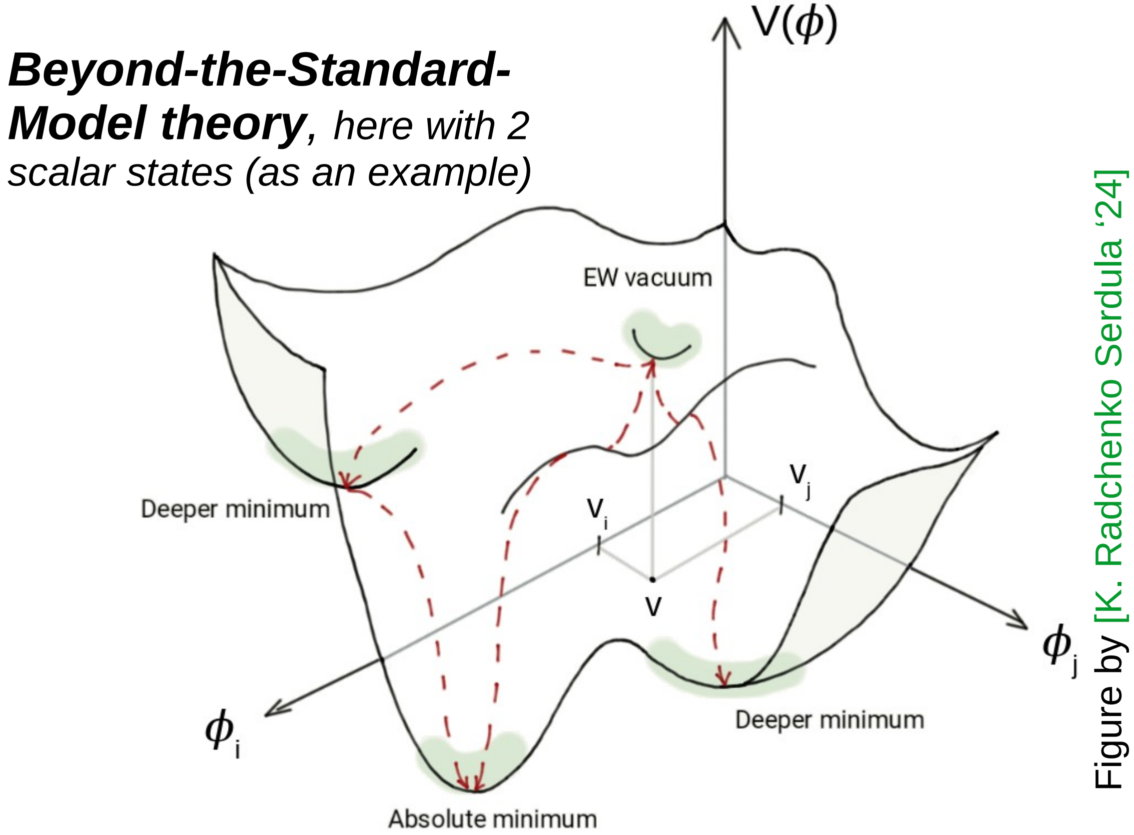
"Resonant contributions"
- Diagrams involving BSM scalars in s-channel
(here generically denoted Φ_i)
→ **collider searches for BSM scalars**
- Involve BSM trilinear scalar couplings λ_{ijk} → **probe of Higgs potential in extended scalar sectors**

*NB: in the following, I focus on **higher-order BSM corrections to gg->$h_i h_j$***
Higher-order QCD/EW corrections to ggF and other channels are of course crucial → see talk of S. Jones!

Form of the Higgs potential and trilinear scalar couplings



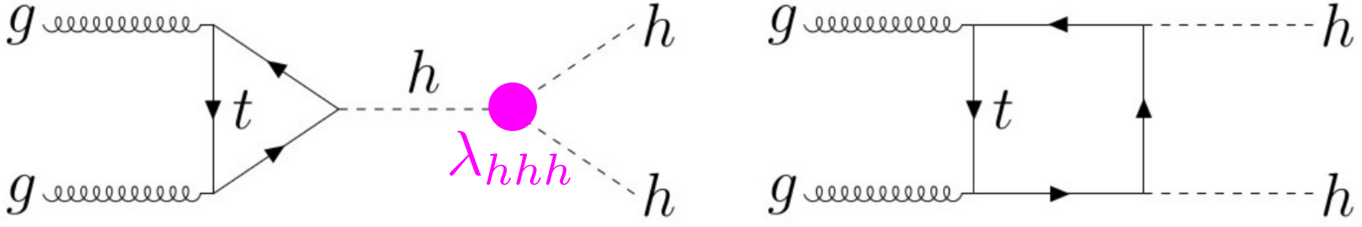
One field direction
↔ shape of potential away from EW minimum is related to λ_{hhh}



Extended scalar sectors
→ more complex Higgs potentials
→ more trilinear scalar couplings needed to reconstruct potential

- **Form of Higgs potential related to how EWPT took place in early Universe**

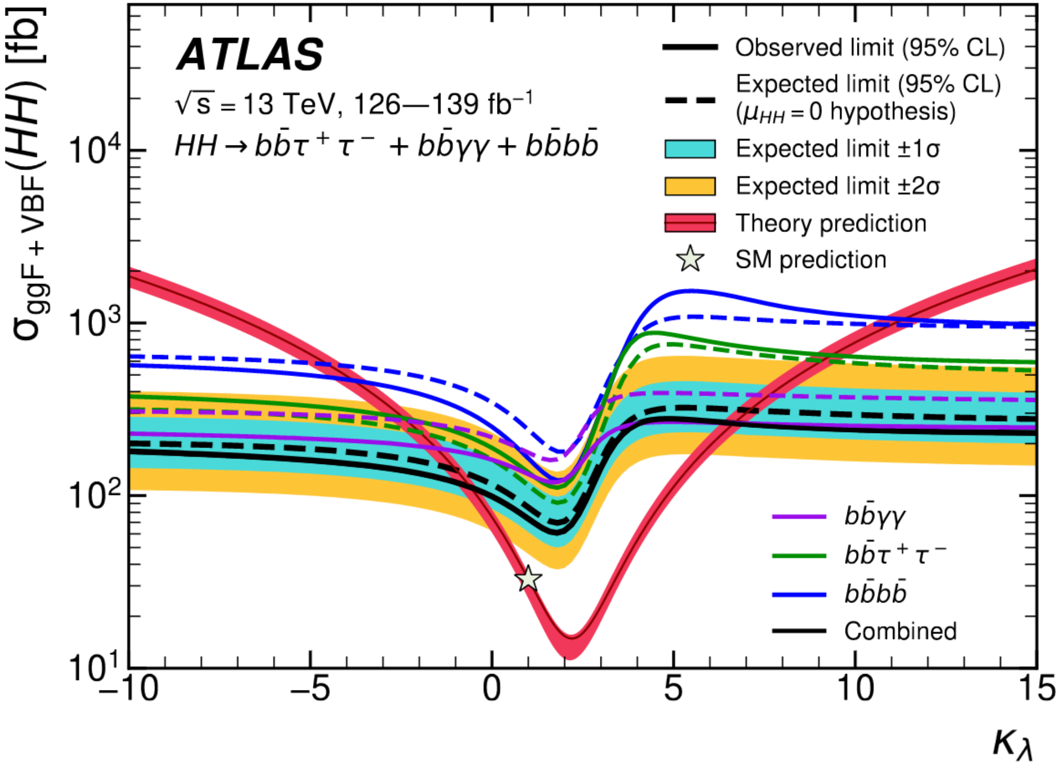
Interference in non-resonant di-Higgs production



Coupling modifier:

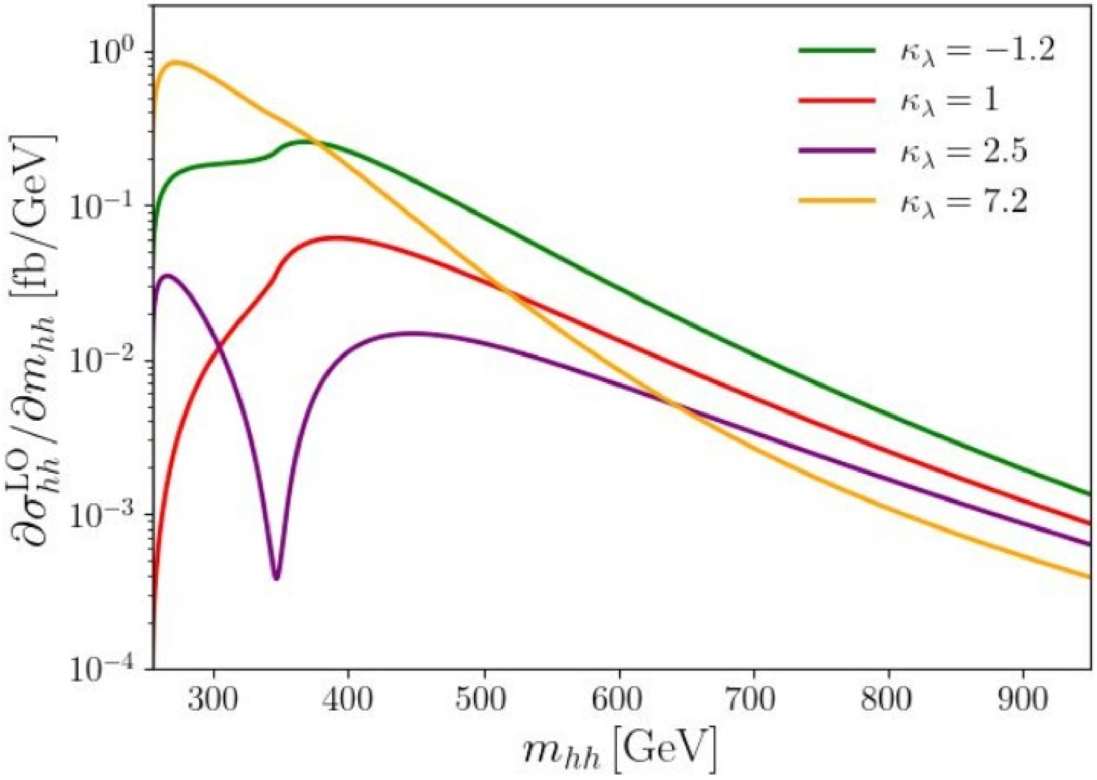
$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}}$$

Relative change in total cross-section for varying κ_λ



[ATLAS 2211.01216]

Differential m_{hh} distributions for varied κ_λ



Plot by [K. Radchenko Serdula '24]

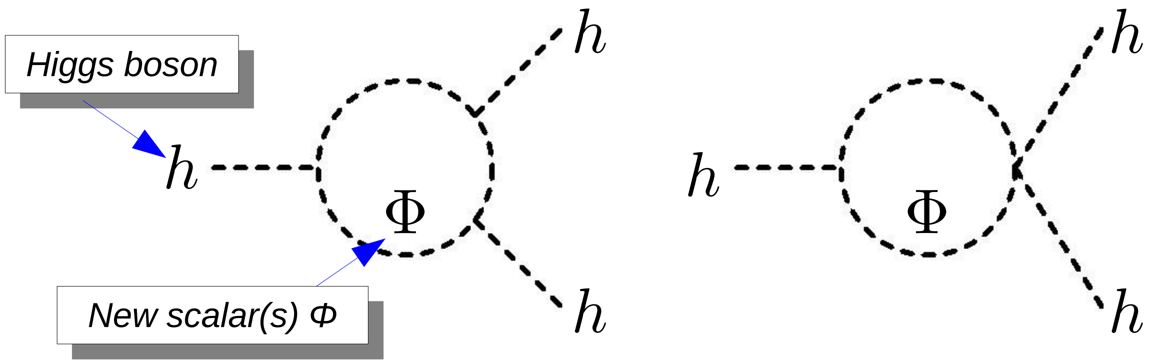
Note: impact of change in top Yukawa → overall shift (up/down) of distribution

Mass-splitting effects in the trilinear Higgs coupling

- Latest bounds on λ_{hhh} [ATLAS PRL '24]

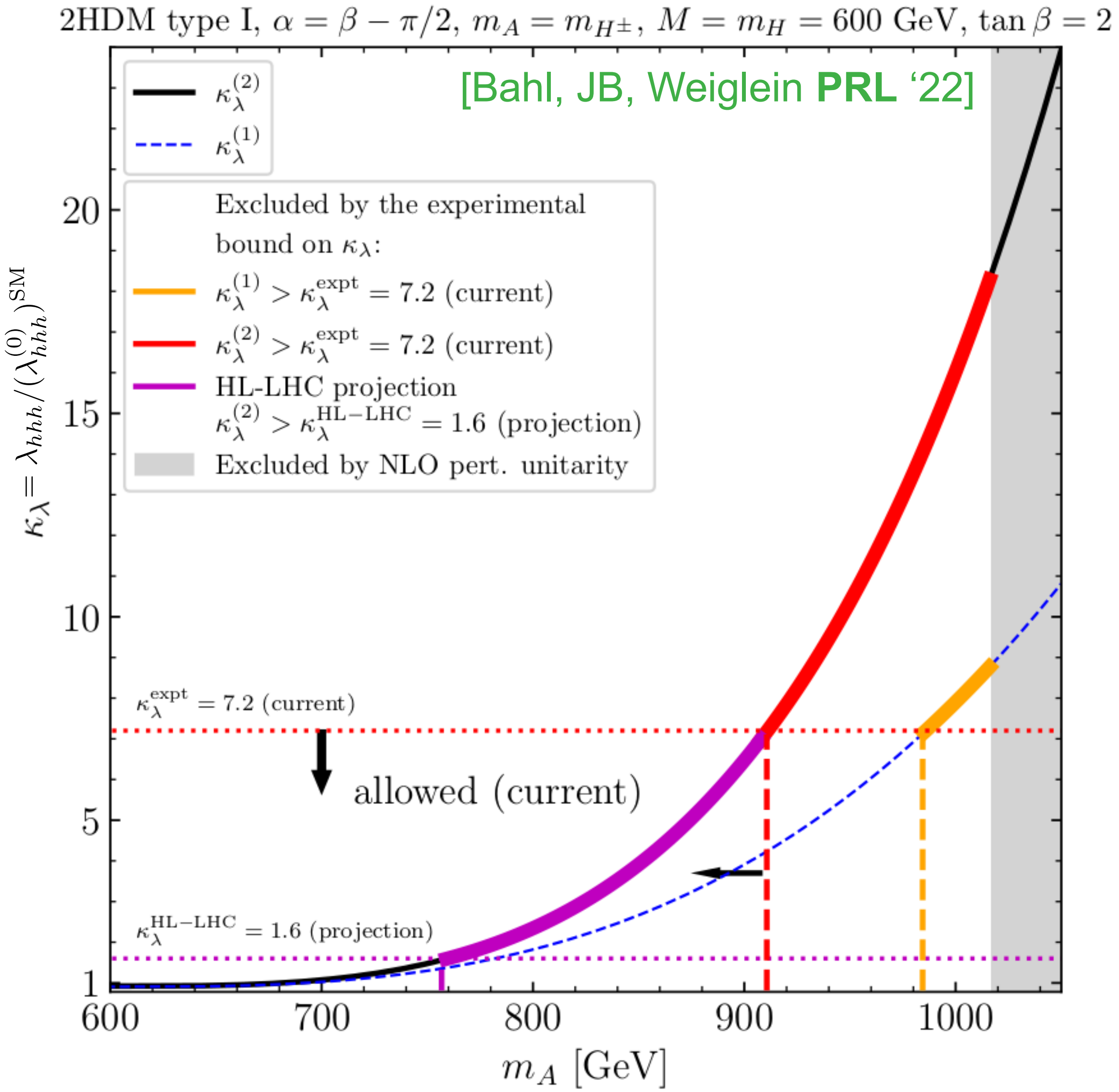
$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda^{(0)}_{hhh})^{\text{SM}}} < 7.2$$

- **Large effects from New Physics possible in λ_{hhh}**, due to radiative corrections from extra scalars, e.g. at leading order (one loop)



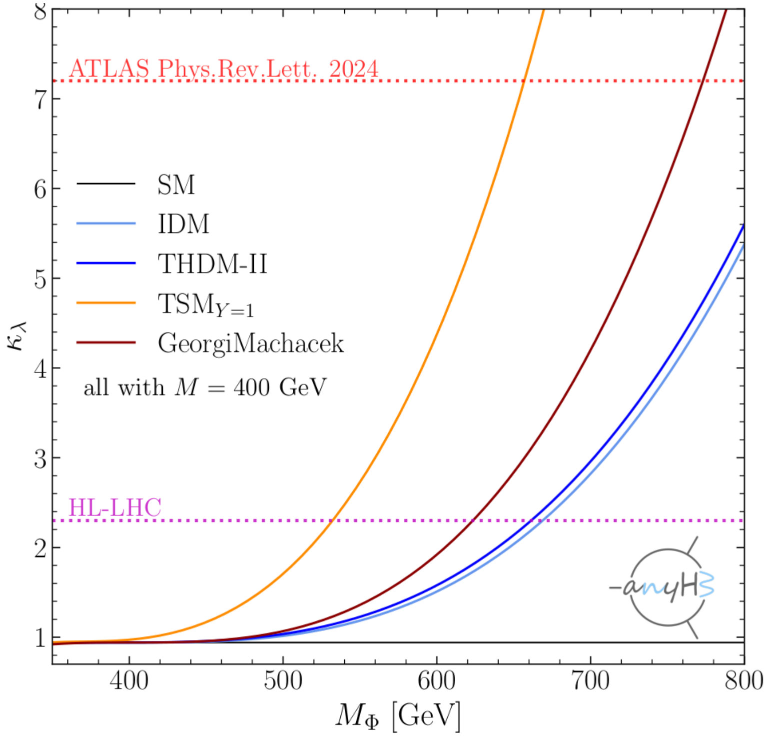
Physical nature of these large BSM effects **confirmed by explicit two-loop calculations**, e.g. [JB, Kanemura '19]

- BSM deviations in κ_λ ***can*** also be **motivated from the point of view of early-Universe evolution, e.g. strong first-order EW phase transition** (*more in a few slides*)



Large corrections to trilinear scalar couplings

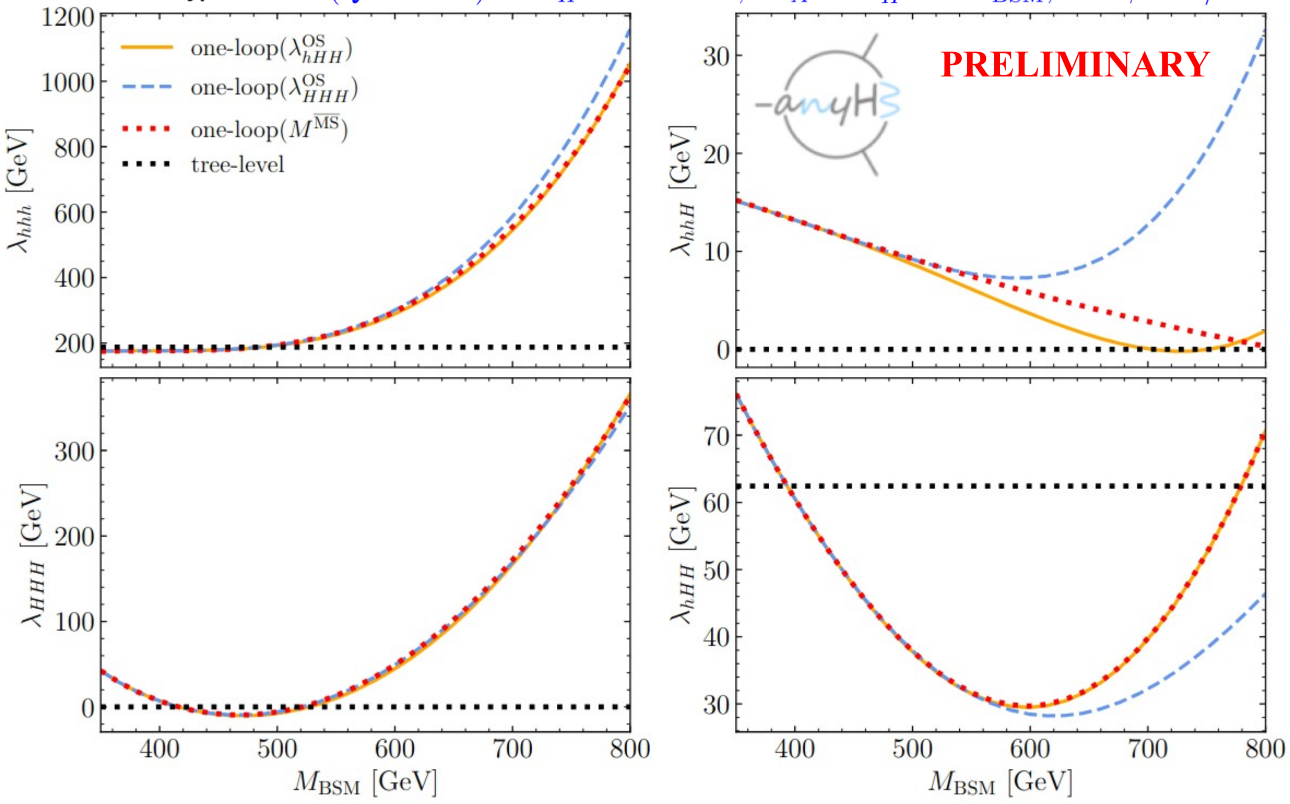
Mass-splitting effects in various BSM models:
`anyH3` v1 [Bahl, JB, Gabelmann, Weiglein '23]
public tool for full one-loop calculation of λ_{hhh} in arbitrary renormalisable models, using UFO inputs



Many more examples with model-specific calculations:
at 1L: [Kanemura et al. '04, '16], [Hollik, Penaranda '04], [Aoki et al. '12], [Dao et al. '13], [Hashino, Kanemura, Orikasa '16], [Basler et al. '17, '19], [Chiang et al. '18];
… and at 2L: [Brucherseifer et al. '13], [Dao et al. '15], [Senaha '18], [JB, Kanemura '19], [JB, Kanemura, Shimoda '20], [Borschensky et al '22], etc.

Mass-splitting effects in trilinear scalar couplings:
`anyH3` v2 [Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein WIP] → calculation extended to generic λ_{ijk}
Here for a benchmark example in an aligned 2HDM and with different renormalisation schemes

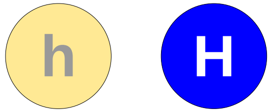
2HDM type-II: $M^{\overline{\mathrm{MS}}}(Q = M^{\overline{\mathrm{MS}}}) = M_H = 400$ GeV, $M_A = M_{H^\pm} \equiv M_{\mathrm{BSM}}$, $\alpha = \beta - \pi/2$



See also e.g. [Arco, Heinemeyer, Mühlleitner, '25]

Two example models to investigate di-Higgs production

- **RxSM: general singlet extension of the SM**
  (without a Z_2 symmetry)
  → add a real singlet to SM
  → 2 CP-even Higgs bosons

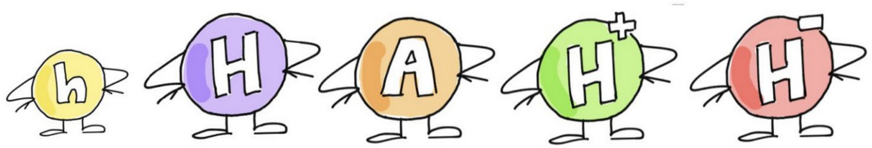


- Scalar sector parametrised in terms of:

$$\underbrace{m_h^2,\, v}_{\text{known}},\, \underbrace{m_H^2,\, \alpha,\, v_S,\, \kappa_S,\, \kappa_{SH}}_{\text{free}}$$

with
$m_h,\ m_H$: masses of detected and BSM Higgs bosons
α : CP-even mixing angle
$v,\ v_S$: EW and singlet VEVs
$\kappa_S,\ \kappa_{SH}$: Lagrangian trilinear couplings

- **2HDM: Two-Higgs-Doublet Model**
  (here CP-conserving variant)



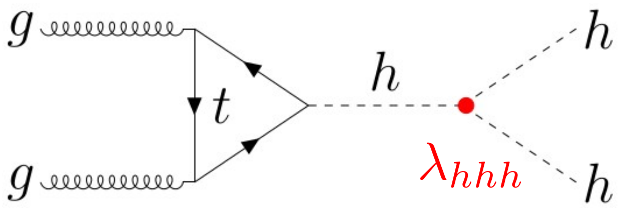
Drawing by [K. Radchenko Serdula]

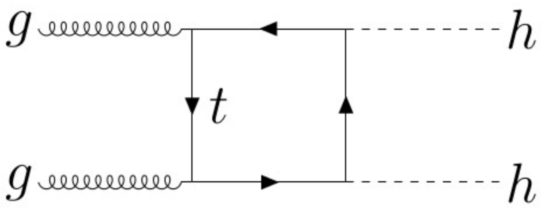
- Scalar sector parametrised in terms of:

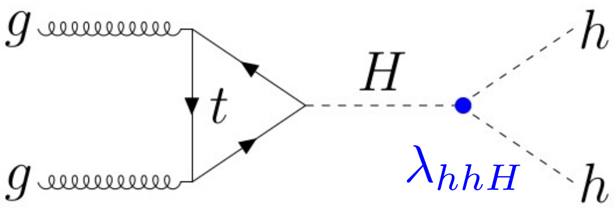
$$\underbrace{m_h^2,\, v}_{\text{known}},\, \underbrace{m_H^2,\, m_A^2,\, m_{H^\pm}^2,\, M,\, \alpha,\, \tan\beta}_{\text{free}}$$

with
$m_{h,H,A,H^\pm}$: masses of detected and BSM Higgs bosons
α : CP-even mixing angle
$\tan\beta \equiv v_2/v_1$: ratio of VEV of 2 doublets
v : EW VEV
M : BSM mass scale (controls decoupling)

- Three **leading diagrams** in di-Higgs production, with **significant dependence on 2 relevant trilinears: λ_{hhh} and λ_{hhH}**







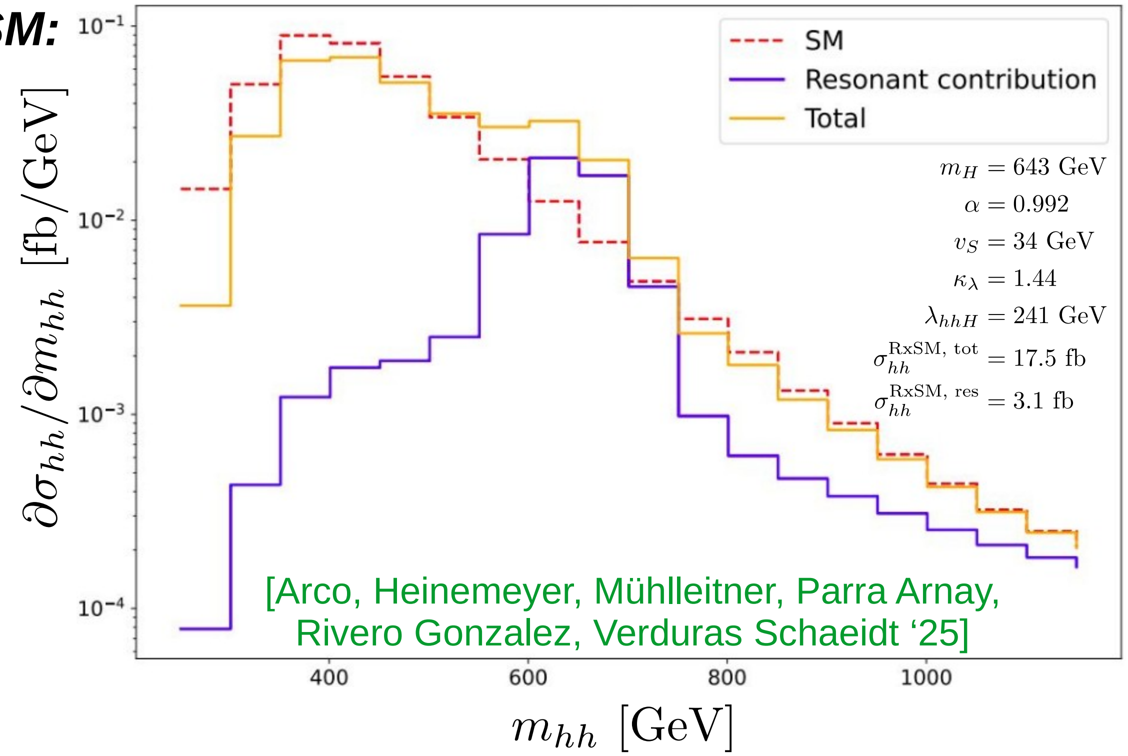
Interference effects: resonant contributions vs full distributions

- Including interference between non-resonant and resonant contributions can **drastically change di-Higgs invariant mass distributions**
- Distributions computed with `HPAIR` ([Plehn, Spira, Zerwas ‘96], [Dawson, Dittmaier, Spira ‘98], [Abouabid et al. ‘22], [Arco et al., ‘25]), shown here after experimental effects taken into account (15% smearing and 50 GeV binning)
- Relatively good agreement between peak of resonant and total distributions, but **away from peak they can differ by up to 2 orders of magnitude**

→ large impact of interference effects **warrants analysis of these scenarios with full predictions**

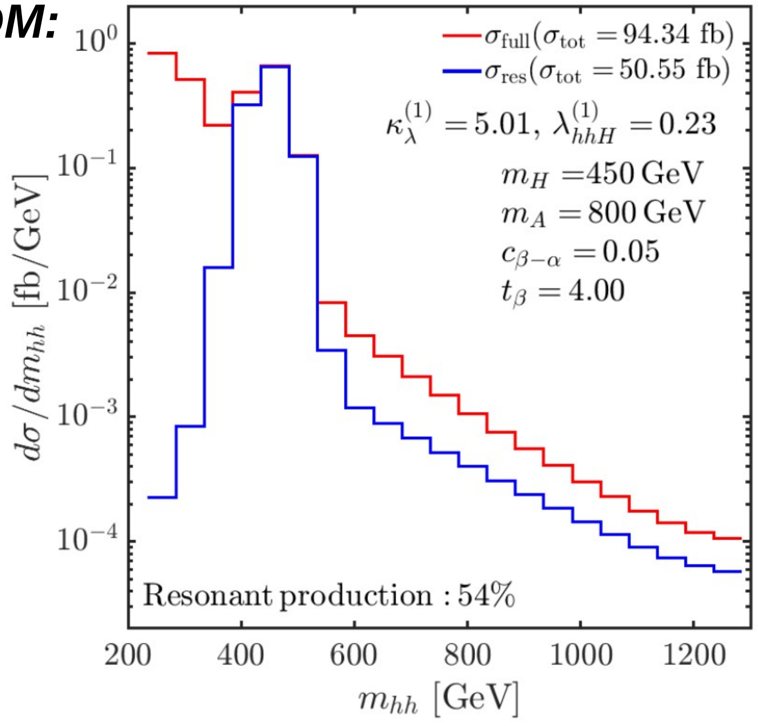
→ possible with codes for di-Higgs predictions (e.g. `HPAIR`, `anyHH`), or reweighting tools, e.g. `HHReweighter` [Feuerstake et al ‘24]

RxSM:



[Arco, Heinemeyer, Mühlleitner, Parra Arnay, Rivero Gonzalez, Verduras Schaeidt ‘25]

2HDM:



NB: this 2HDM scenario is excluded by resonant searches but allowed by non-resonant searches

[Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein ‘24]

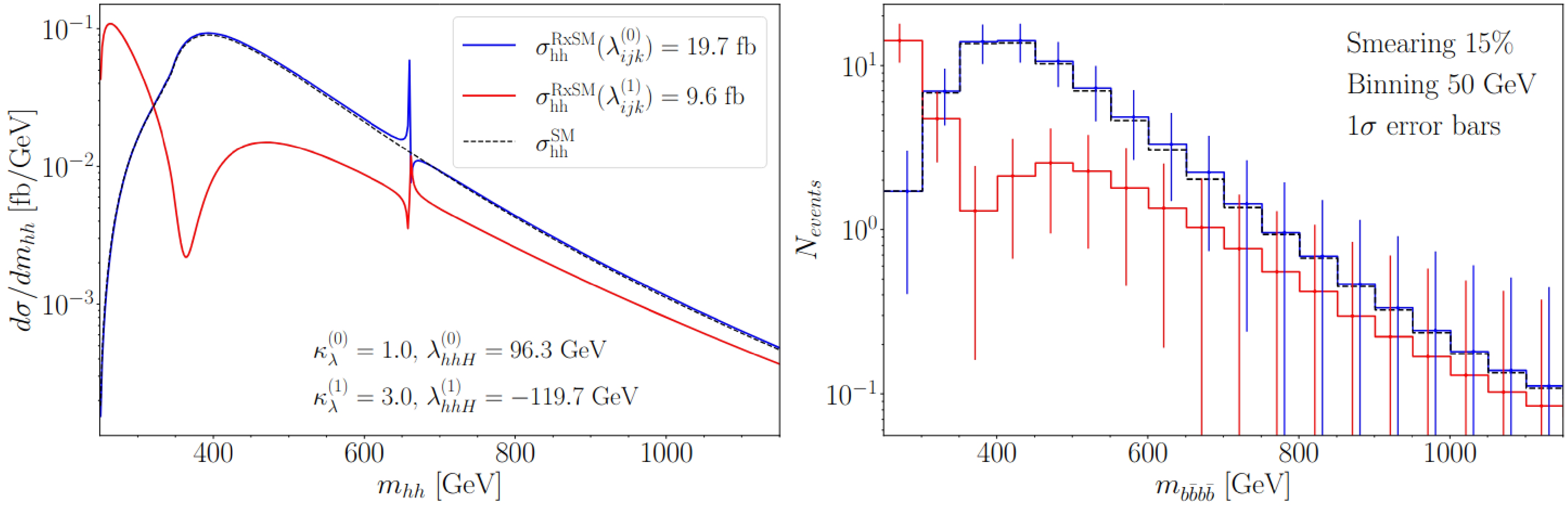
Impact of NLO corrections in the RxSM

[JB, Heinemeyer, Parra Arnay, Verduras Schaeidt ‘25]

Impact on di-Higgs invariant mass distributions

BP1: $m_H = 659.4$ GeV, $\cos\alpha = 0.99$, $v_S = 56.1$ GeV, $\kappa_S = -880$ GeV, $\kappa_{SH} = -880$ GeV, $Z^{(0)} = 0.3$, $Z^{(1)} = 9.3$

NB: total cross-section is SM-like!

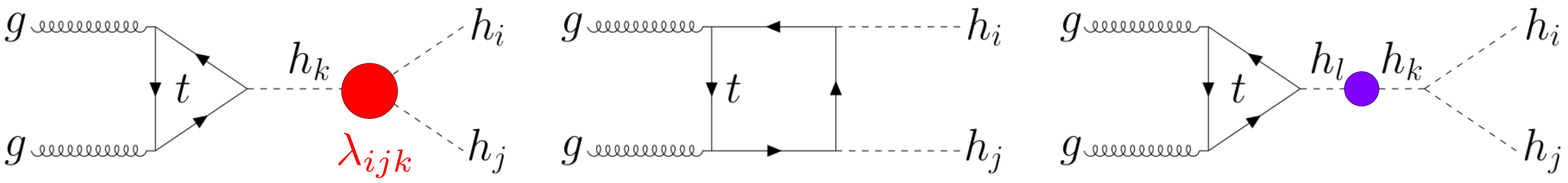


- Cross-sections computed with RxSM-specific version of `HPAIR` [Arco et al. ‘25]; results shown at LO in QCD
- Large radiative corrections to both trilinear couplings, λ_{hhh} and λ_{hhH}, modify the interference pattern and shift the dip from m_{hh} ~ 250 GeV to 350 GeV + change the peak-dip structure at m_H into dip-peak
- After taking into account experimental effects (with smearing and binning), an analysis with tree-level trilinears ($Z^{(0)}=0.3$) would not be able to find a deviation from the SM, but an analysis with one-loop ones would ($Z^{(1)}=9.3$)

Di-Higgs production in arbitrary models: anyHH

[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

- **anyHH: Total and differential cross-sections** (so far, at LO in QCD) for $gg \to h_i h_j$ including:
  - **1L corrections to λ_{ijk}** (computed by anyH3)
  - **BSM contributions in s-channel diagrams**
  - **momentum-dependence** both in vertex corrections and in propagators



- Takes UFO model files as inputs, as anyH3. So far limited to models without additional coloured particles.

- Good agreement found with existing results in the literature – e.g. HPAIR (*details in backup*)

See also parallel talk of M. Gabelmann tomorrow!

Impact of NLO corrections in the 2HDM

[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

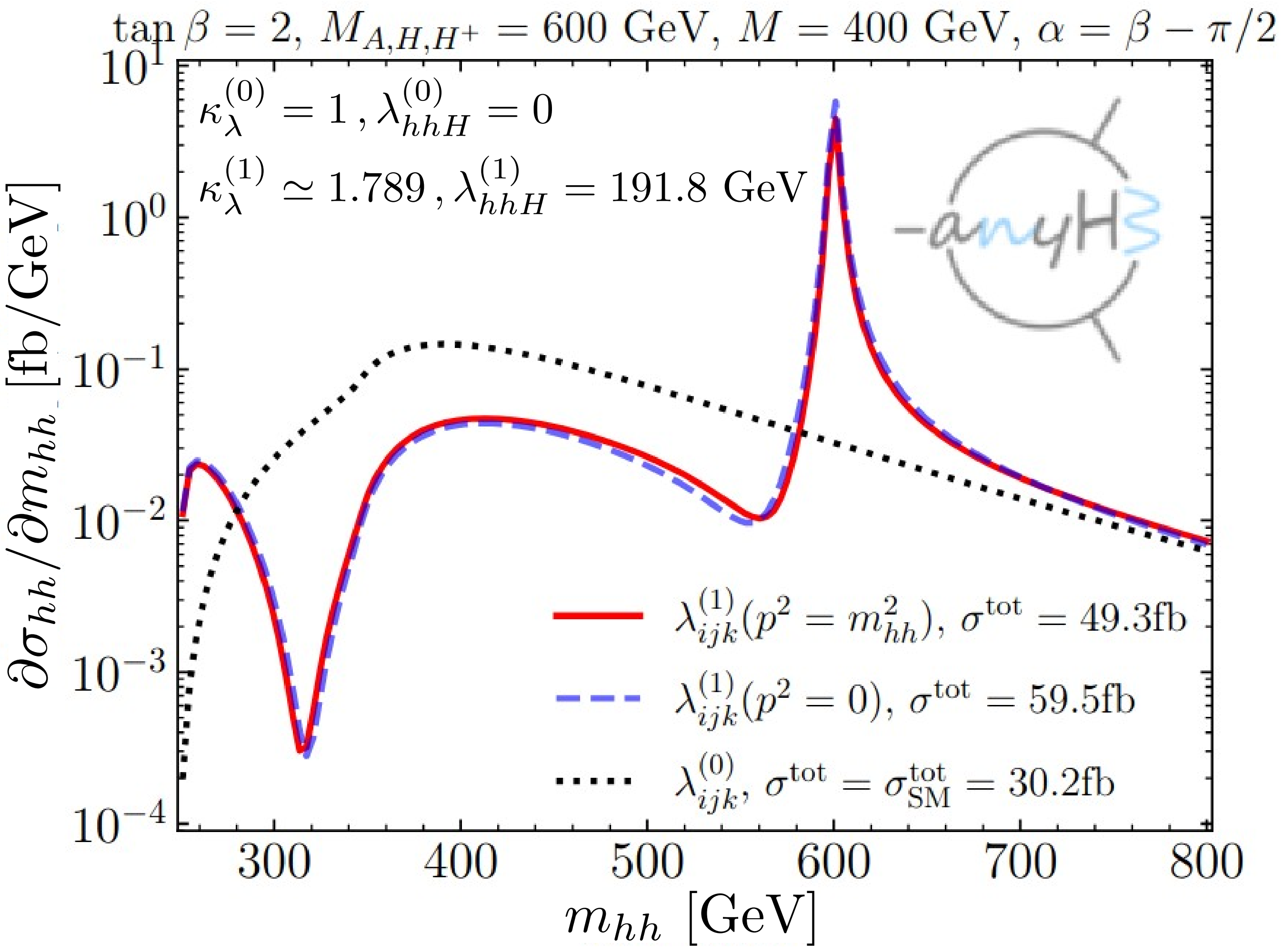
Example in **aligned 2HDM**, with di-Higgs cross-section and m_{hh} distributions computed with `anyHH`
→ $\kappa_\lambda^{(0)} = 1;\ \lambda_{hhH}^{(0)} = 0$ (due to alignment limit)

Impact of loop corrections to trilinear couplings

Black vs red curves → huge impact of loop corrections to λ_{ijk} on both cross-section and distributions

Impact of momentum in s-channel diagrams

Blue vs red curves → O(20%) impact of momentum in λ_{ijk}

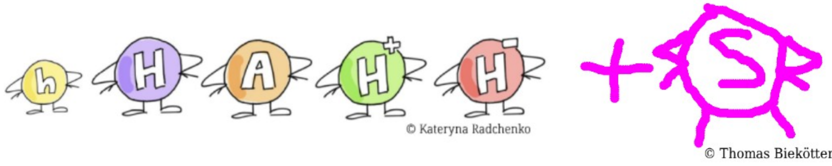


Note: similar results for impact of loop corrections also found [Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein ‘24]

Results in the N2HDM with `anyHH`

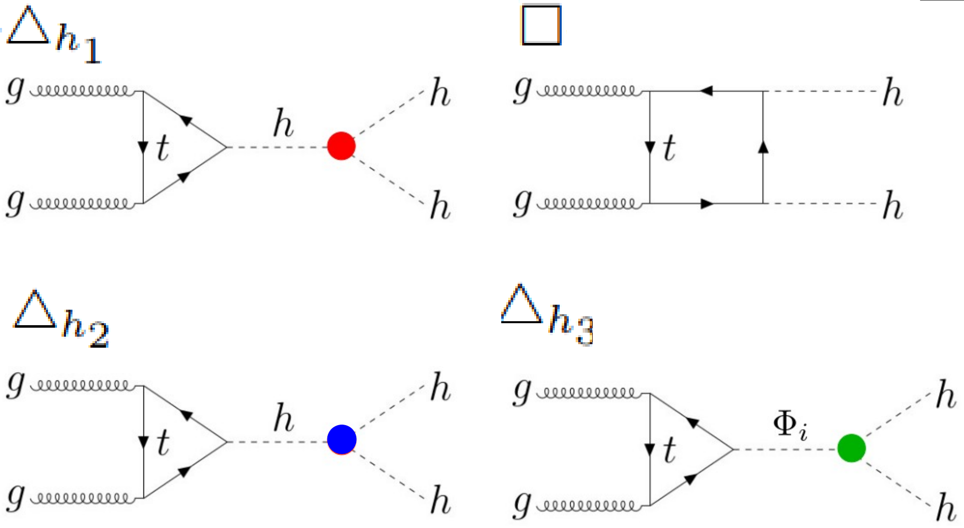
[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

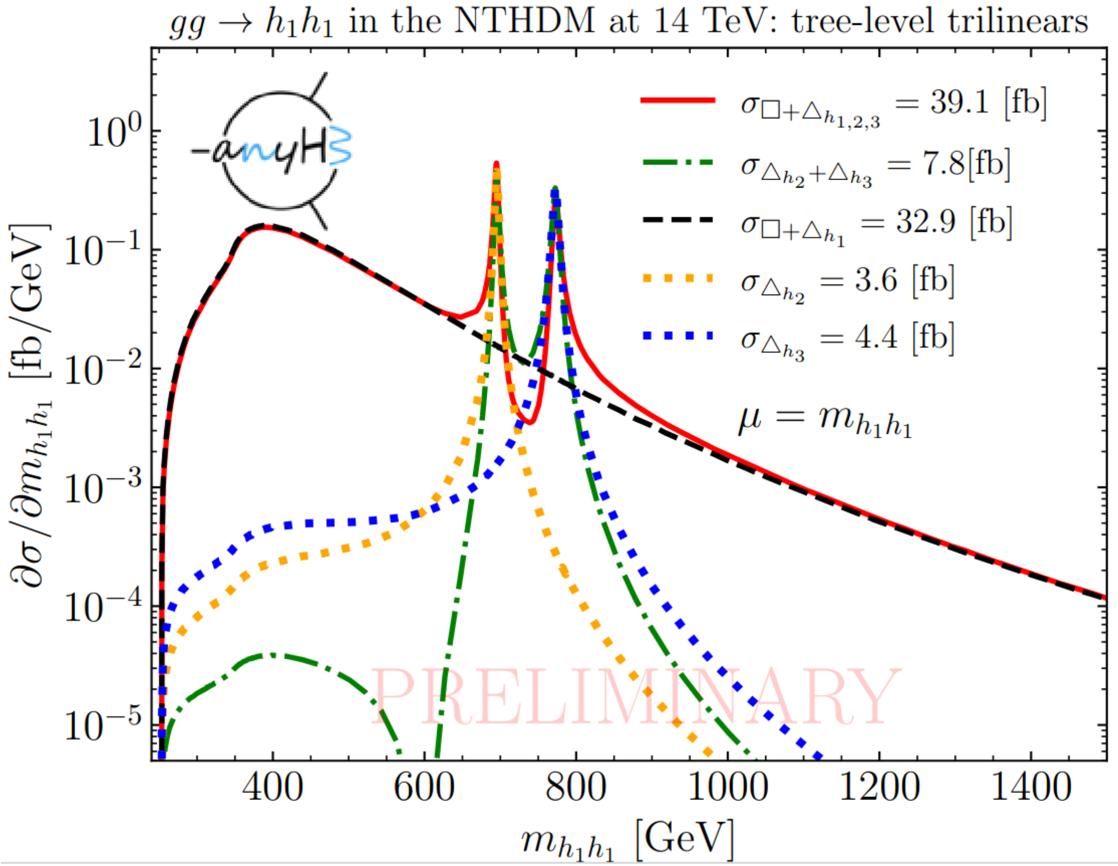
- **N2HDM = 2HDM + real singlet**
  → 3 CP-even mass eigenstates
  h_1, h_2, h_3



- `anyHH` allows computing contributions to di-Higgs production together or separately
  → *find impact of interference*
- Here first with tree-level trilinear scalar couplings

$\kappa_\lambda^{(0)}$	0.97
$\kappa_\lambda^{(1)}$	2.18
$\lambda^{(0)}_{h_1h_1h_2}$ [GeV]	93.5
$\lambda^{(1)}_{h_1h_1h_2}$ [GeV]	40.3
$\lambda^{(0)}_{h_1h_1h_3}$ [GeV]	160.5
$\lambda^{(1)}_{h_1h_1h_3}$ [GeV]	342.8





N2HDM benchmark definition:

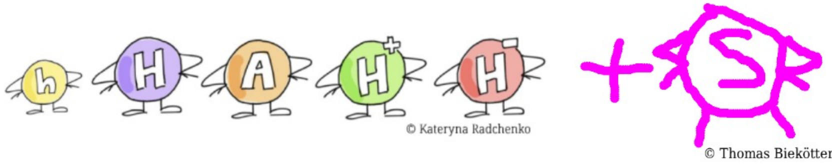
$\alpha_1 = 1.019$, $\alpha_2 = -0.076$, $\alpha_3 = 0.960$,
$M_{h_1} = 125\,\text{GeV}$, $M_{h_2} = 695\,\text{GeV}$, $M_{h_3} = 773\,\text{GeV}$,
$M_A = 673\,\text{GeV}$, $M_{H^\pm} = 762\,\text{GeV}$, $M_{12} = 367\,\text{GeV}$,
$\tan\beta = 1.53$, $v_S = 415.4\,\text{GeV}$.

Allowed by flavour, Higgs phys. EWPO, vacuum stability, perturbative unitarity

Results in the N2HDM with anyHH

[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

- **N2HDM = 2HDM + real singlet**
  → 3 CP-even mass eigenstates
  h_1, h_2, h_3
- anyHH allows computing contributions to di-Higgs production together or separately
  → *find impact of interference*
- Here first with **loop-corrected trilinear scalar couplings**



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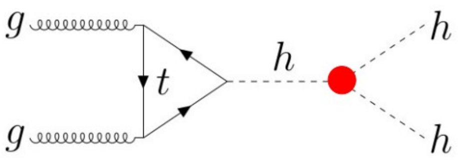
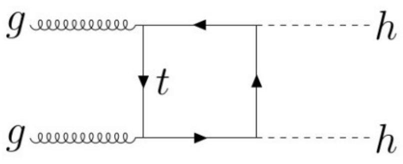
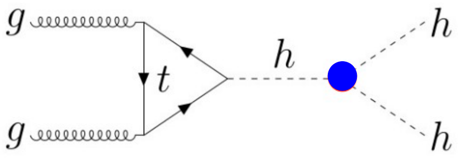
$\triangle_{h_1}$



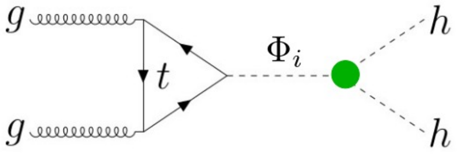
$\square$

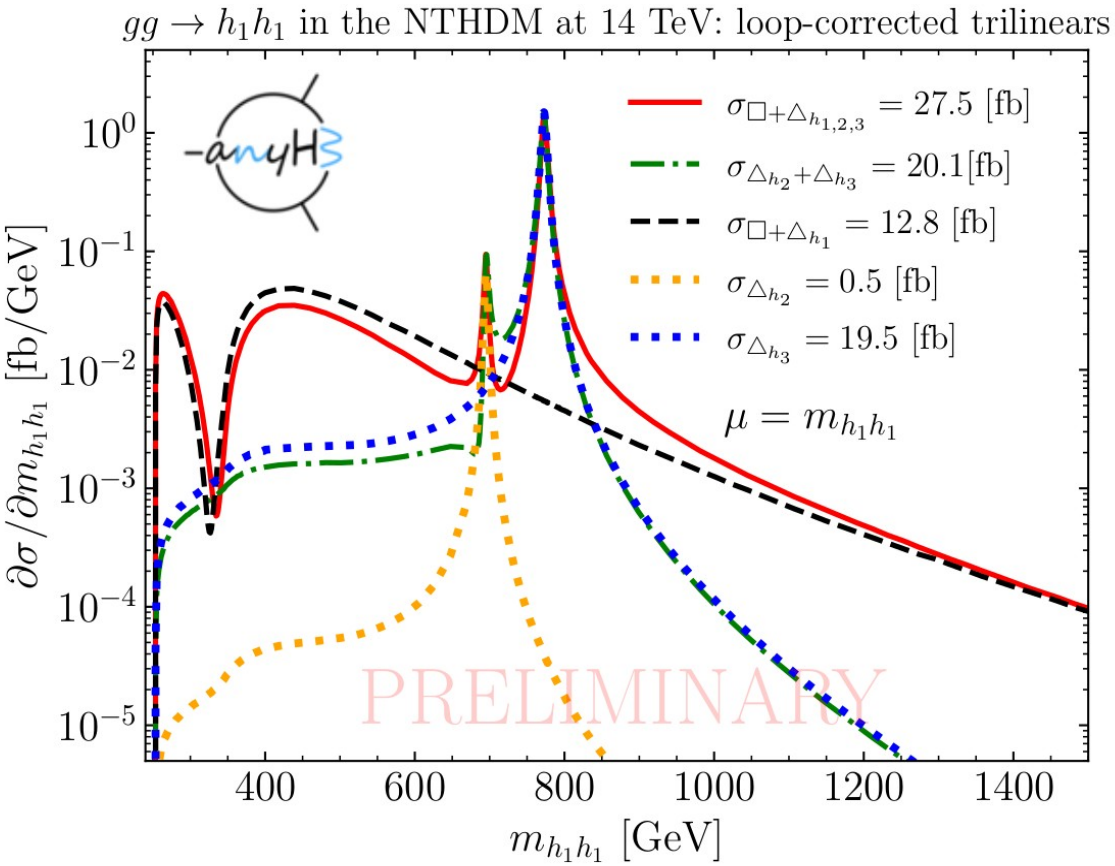


$\triangle_{h_2}$



$\triangle_{h_3}$





<u>*N2HDM benchmark definition*</u>:

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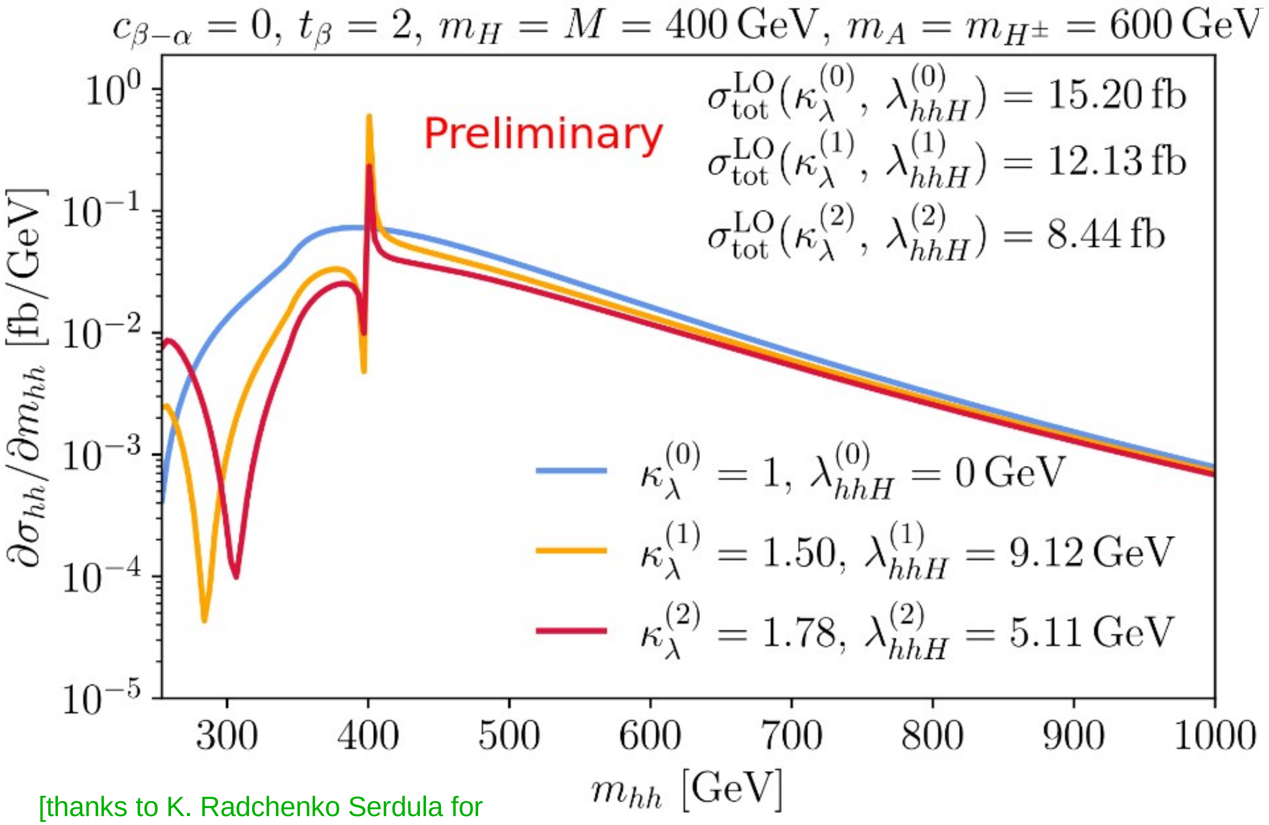
$$\tan\beta = 1.53, \quad v_S = 415.4\,\text{GeV}.$$

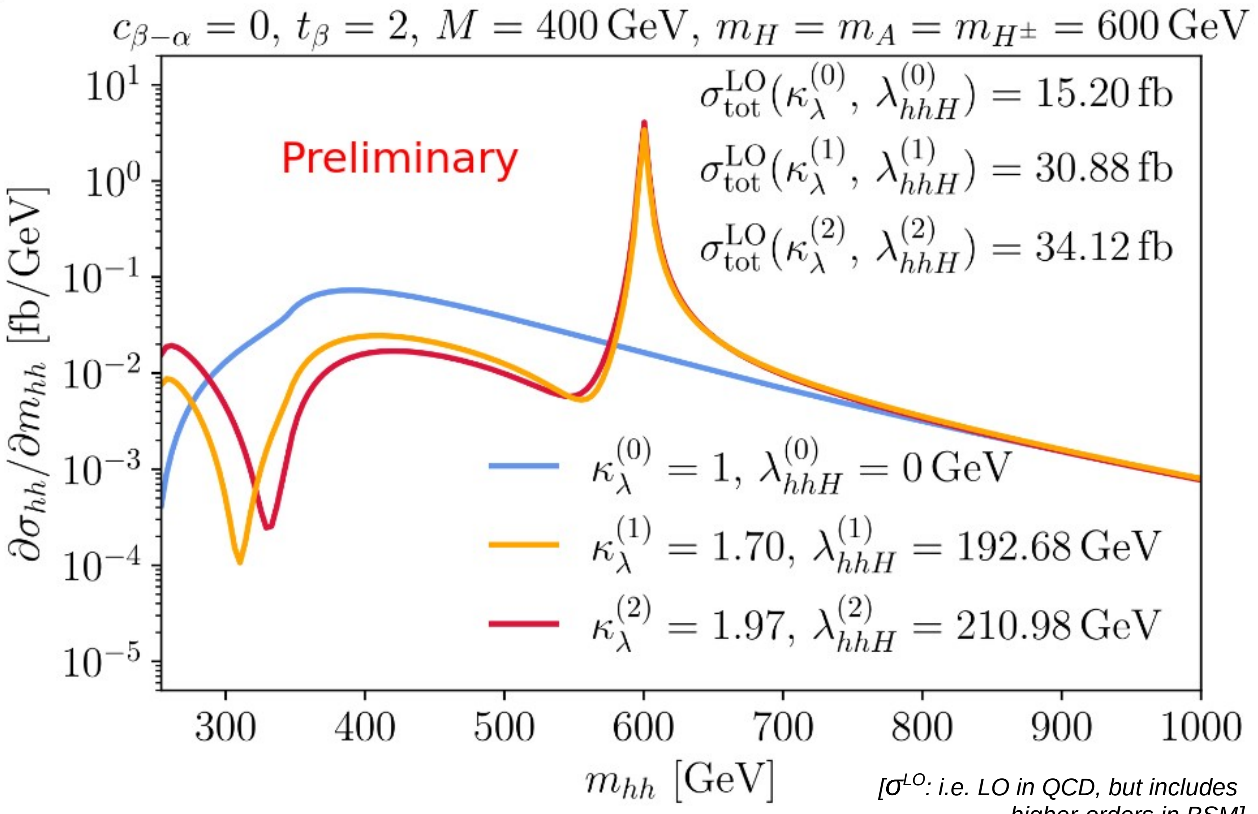
Allowed by flavour, Higgs phys. EWPO, vacuum stability, perturbative unitarity

Impact of NNLO BSM corrections in the 2HDM

What about higher orders?

Here: example in **aligned 2HDM**, with di-Higgs cross-section and m_{hh} distributions computed with `anyHH` and with 2L corrections to λ_{hhh} and λ_{hhH} from [JB, Egle, Verduras Schaeidt WIP]





[thanks to K. Radchenko Serdula for running the plots!]

[σ^{LO}: i.e. LO in QCD, but includes higher-orders in BSM]

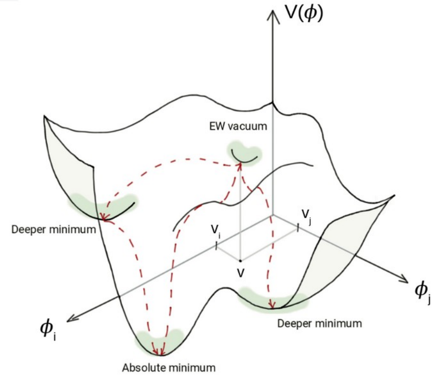
Note: see also [Degrassi, Gröber, Slavich ‘25] for NNLO BSM corrections to λ_{hhh}, λ_{hhH} and total di-Higgs cross-section

Complementary probes of SFOEWPT

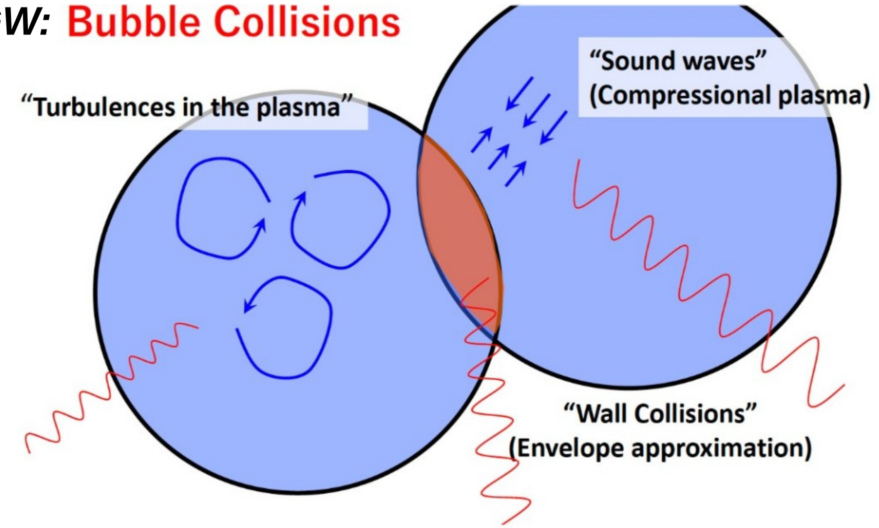
- SFOEWPT motivated by scenario of **electroweak baryogenesis**, as a possible solution to BAU,
  → needed fulfill 3rd Sakharov condition [Sakharov '67]
  (departure from thermal equilibrium)
  c.f. talk by L. Biermann tomorrow

- **Probes of SFOEWPT**:
  - *reconstruct form of Higgs potential realised in Nature*
    → access **trilinear Higgs/scalar coupling(s)**, e.g. at (HL-)LHC via di-Higgs production processes

  - *search for **cosmological relics** of a strong first-order phase transition*
    - stochastic background of **gravitational waves** (GW) → probed with space-based GW interferometers like LISA
    - **primordial black holes** (PBHs) → densities of PBHs constrained by micro-lensing observations (e.g. OGLE)
    - **primordial magnetic fields** (PMFs) → lower bounds on PMFs from X-ray observations (e.g. MAGIC or Fermi/LAT)



GW:



PBH production:

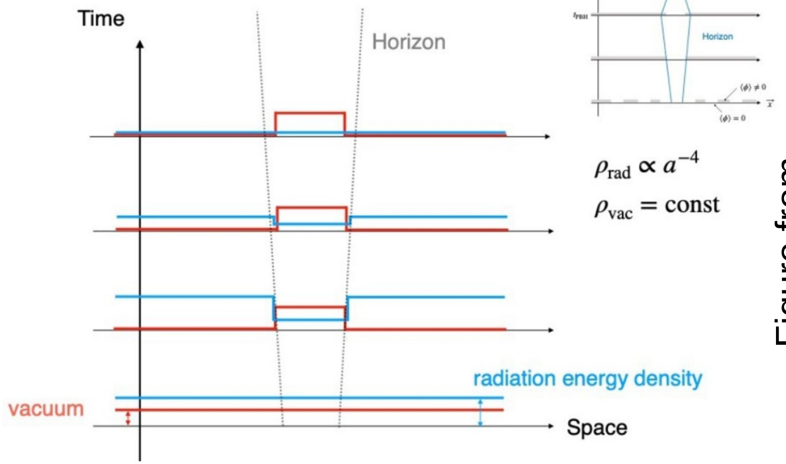
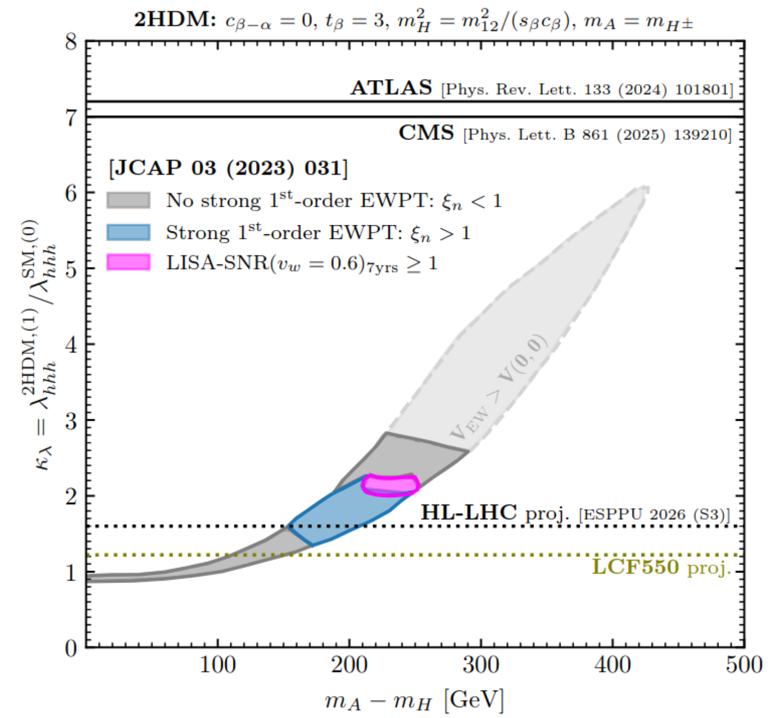


Figure from [Kanemura '23]

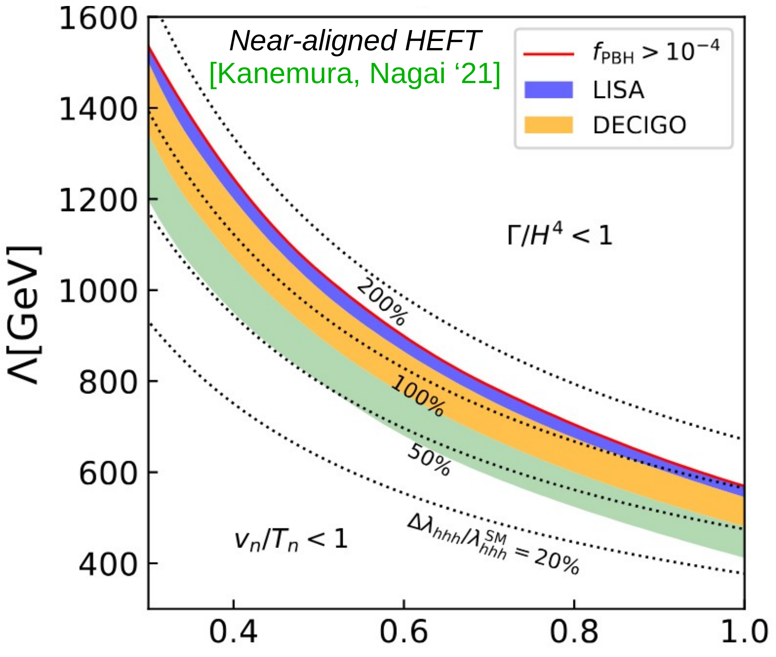
Complementary probes of SFOEWPT

- **Probes of SFOEWPT**:
  - *reconstruct form of Higgs potential realised in Nature*
  - *search for **cosmological relics** of a strong first-order phase transition*
- Many examples, e.g. for
  - ***models with extended scalar sectors*** *(singlet model variants, 2HDMs, classical scale invariant models, etc.)* [Hashino et al., '16, '18, '19], [Huang, Long, Wang, '16], [Artymowski et al. '17], [Chala, Ramos, Spannowsky '18], [Alves et al. '19,'20], [Chen, Li, Wu, Bian '19], [Biekötter et al. '22]
  - ***composite Higgs models*** [Bruggisser et al., '18]
  - ***EFTs*** *(SMEFT/HEFT/naHEFT)* [Hashino et al. '22, '25]
  - ***Warped extra-dimensions*** [Ghoshal et al. '25]

  … and many more
  See also review [Athron et al '23]



[Biekötter et al., '22, '25]



r = fraction of BSM scalar mass from Higgs VEV

[Hashino et al., '22]

Synergies between di-Higgs and gravitational waves in RxSM

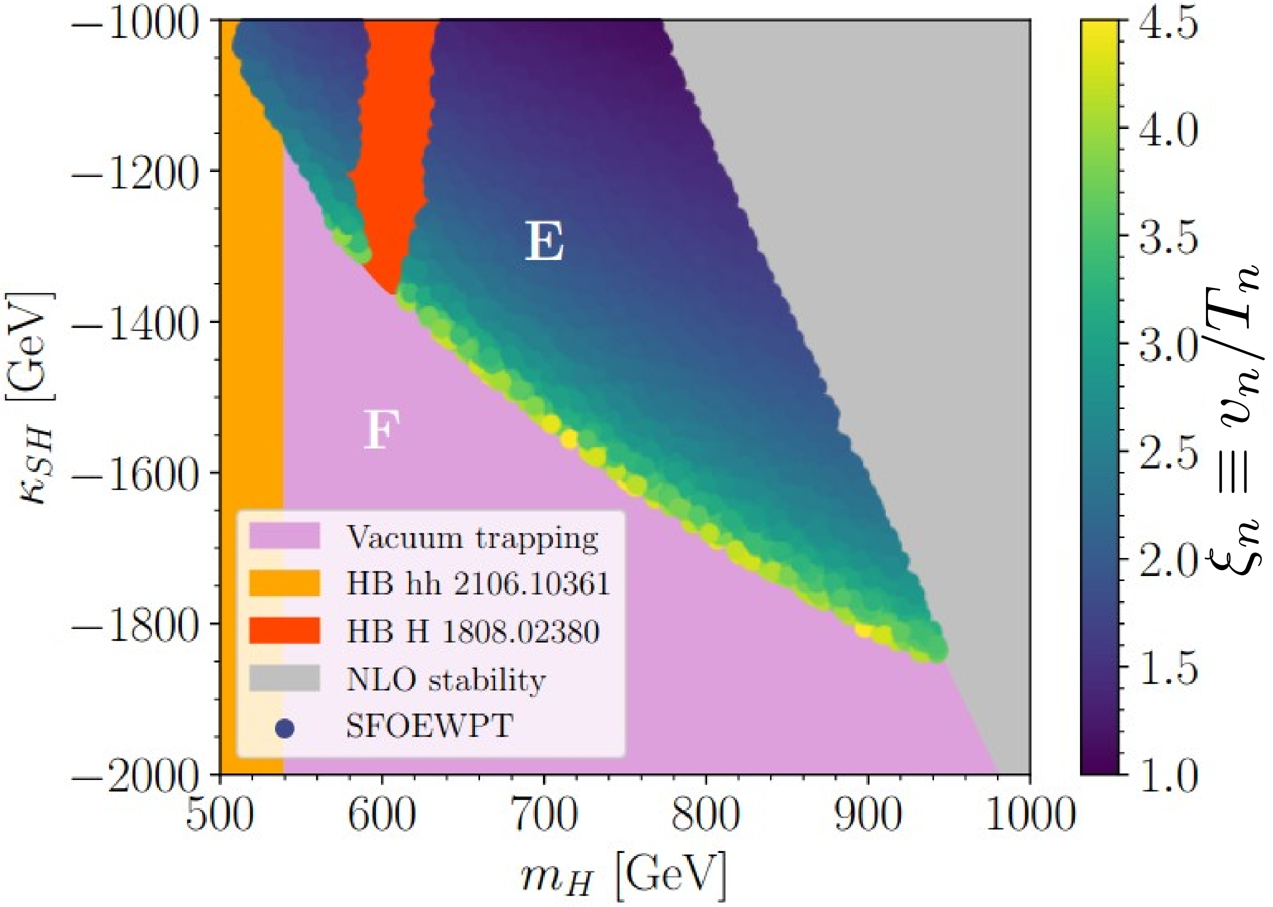
[JB, Heinemeyer, Pulido Boatella, Verduras Schaeidt *WIP*]

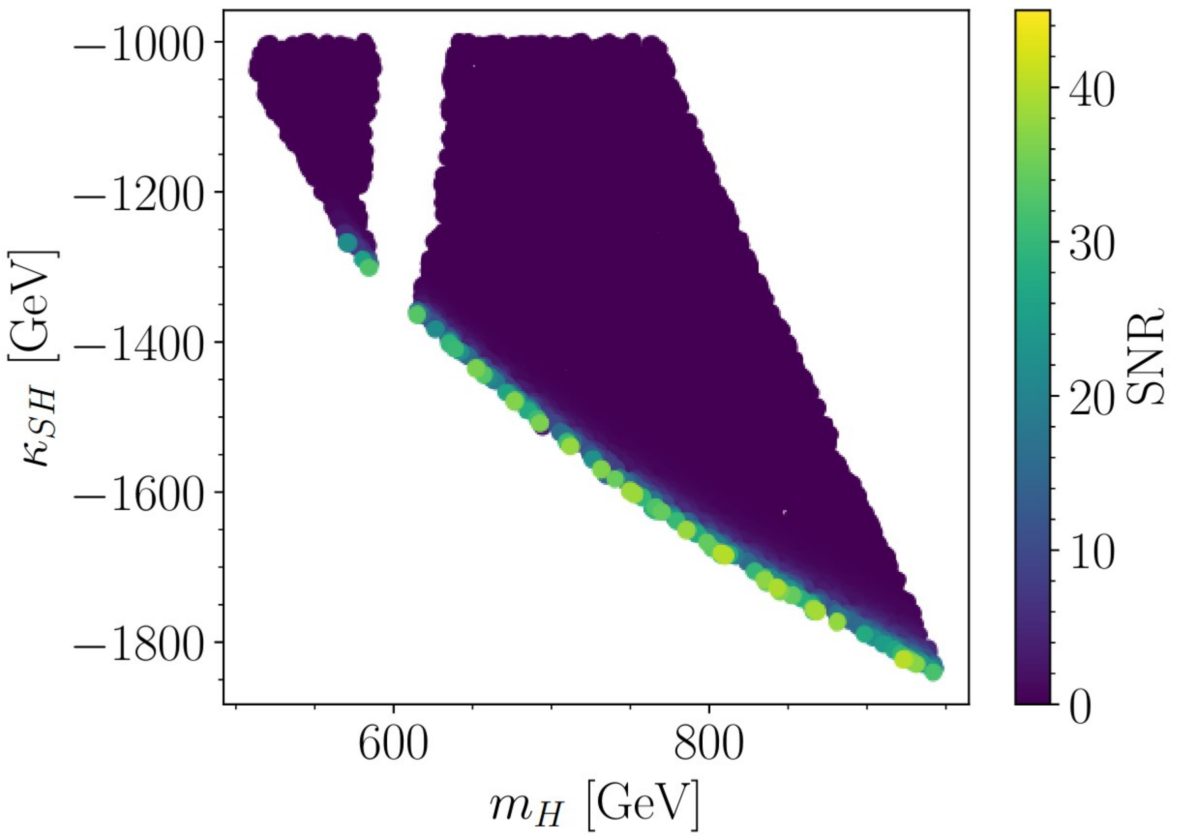
Thermal histories in RxSM

Here: benchmark plane with:

$c_\alpha = 0.98$, $\kappa_S = -300$ GeV, $v_S = 280$ GeV

Region E → SFOEWPT



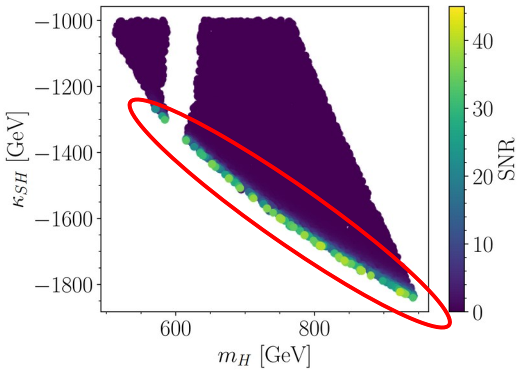


For a band in this plane, one finds a **stochastic background of gravitational waves** (GW) **detectable with LISA** (w. 3 yrs. data taking, $v_w = 0.6$)

→ *could we probe this region at (HL-)LHC?*

Synergies between di-Higgs and gravitational waves in RxSM

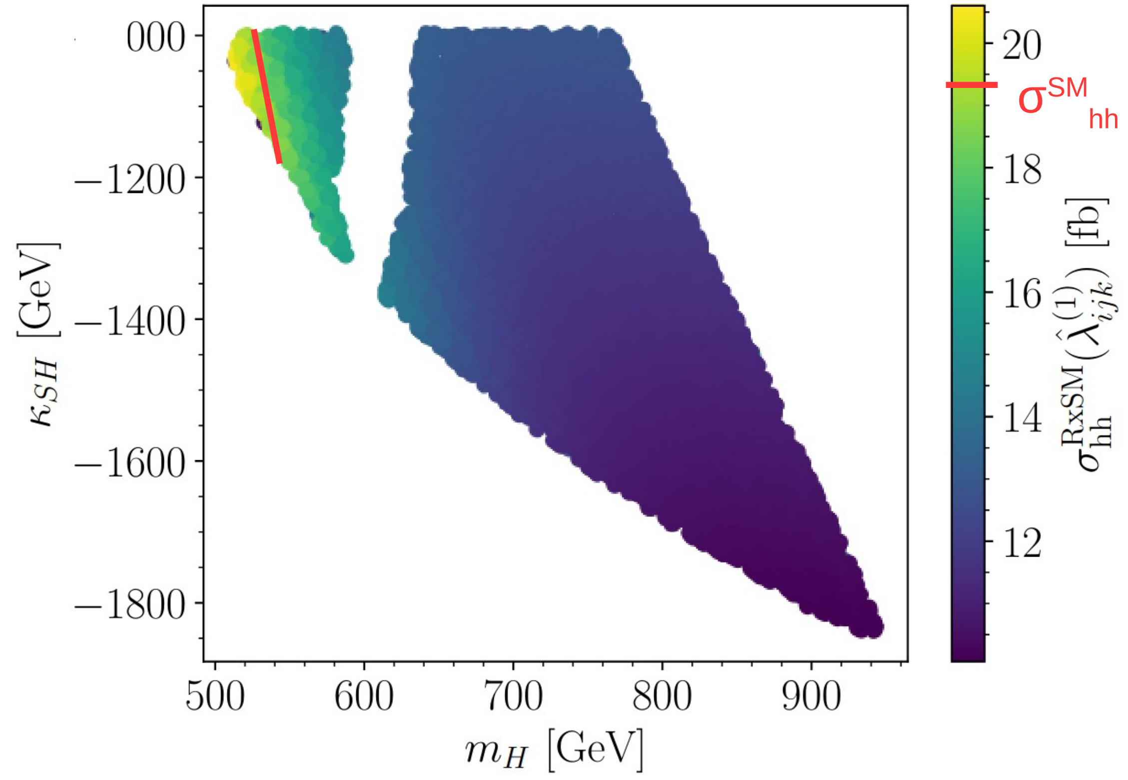
[JB, Heinemeyer, Pulido Boatella, Verduras Schaeidt *WIP*]



Region with observable GW signal at LISA:

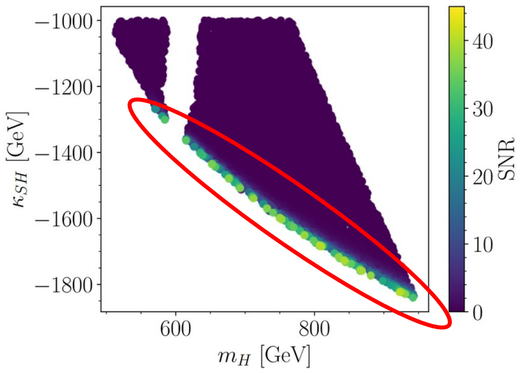
- di-Higgs cross-section below SM prediction

→ difficult to probe this region using total cross-section



Synergies between di-Higgs and gravitational waves in RxSM

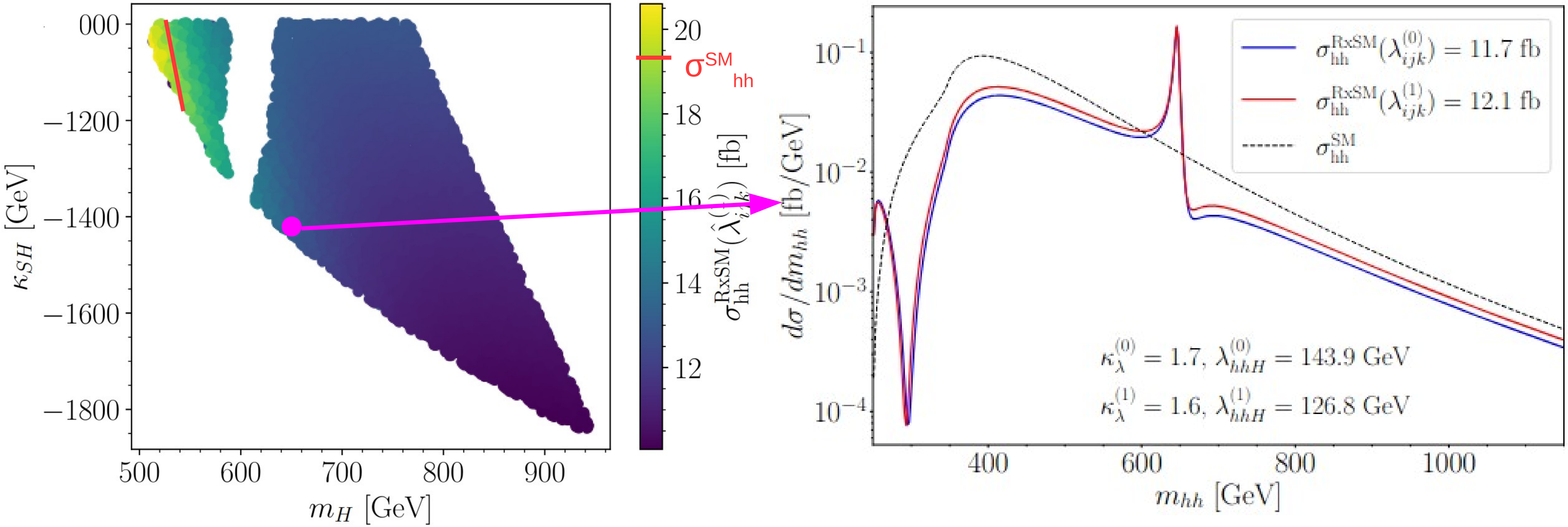
[JB, Heinemeyer, Pulido Boatella, Verduras Schaeidt *WIP*]



Region with observable GW signal at LISA:

- di-Higgs cross-section below SM prediction
  → difficult to probe this region using total cross-section

… but **m_{hh} distribution can be distinguished from SM!**

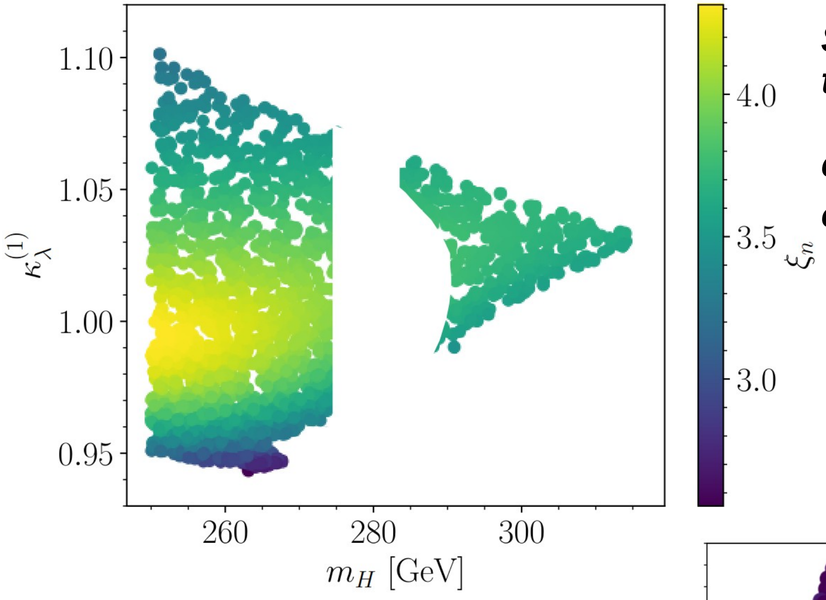


Complementary probes of SFOEWPT in RxSM

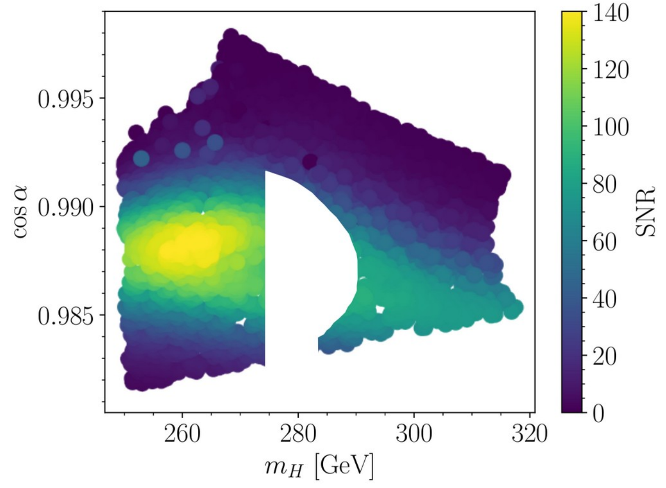
[JB, Heinemeyer, Pulido Boatella, Verduras Schaeidt *WIP*]

- No guarantee that SFOEWPT scenarios in RxSM can all be probed with gg→hh or GW
  → **complementarity needed to cover as much as possible of the RxSM parameter space**

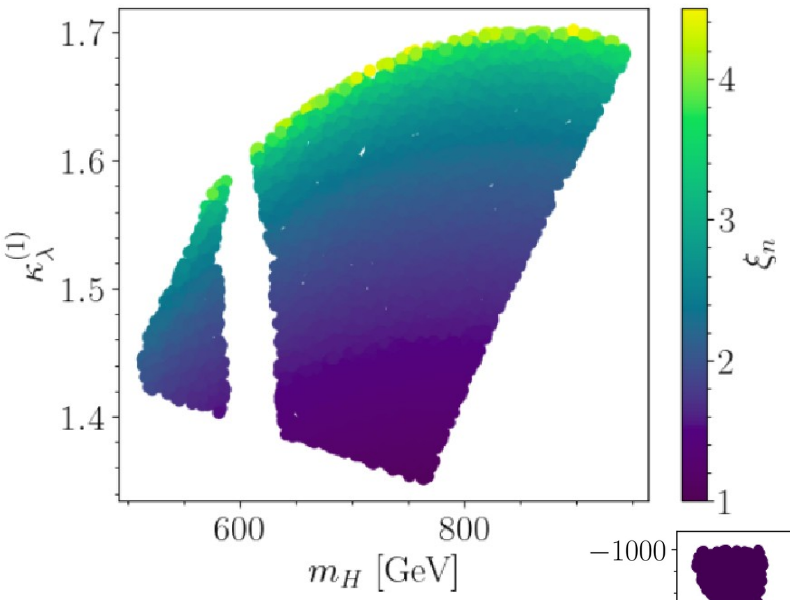
BP with SFOEWPT driven by singlet field



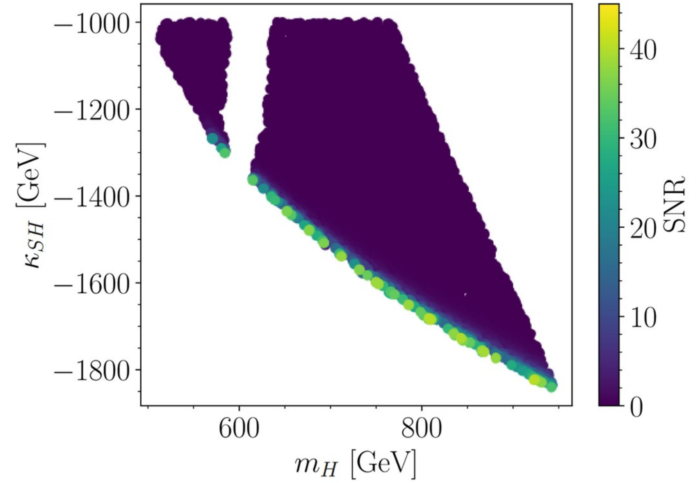
SFOEWPT caused by tree-level barrier → small loop corrections to κ_λ and other Higgs couplings



BP for SFOEWPT driven by doublet field



SNR shown for 3 years data taking, and v_w = 0.6



Complementary probes of SFOEWPT in RxSM

[JB, Heinemeyer, Pulido Boatella, Verduras Schaeidt *WIP*]

- No guarantee that SFOEWPT scenarios in RxSM can all be probed with gg→hh or GW
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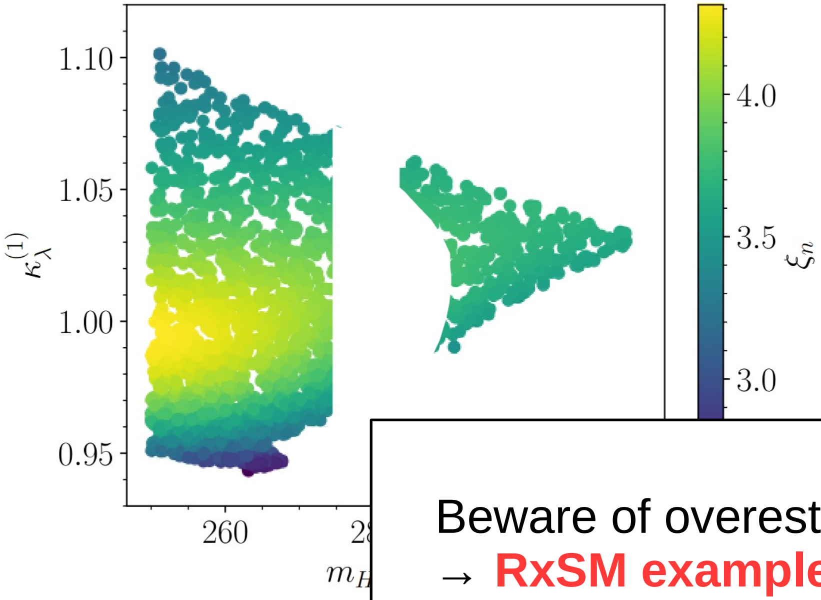
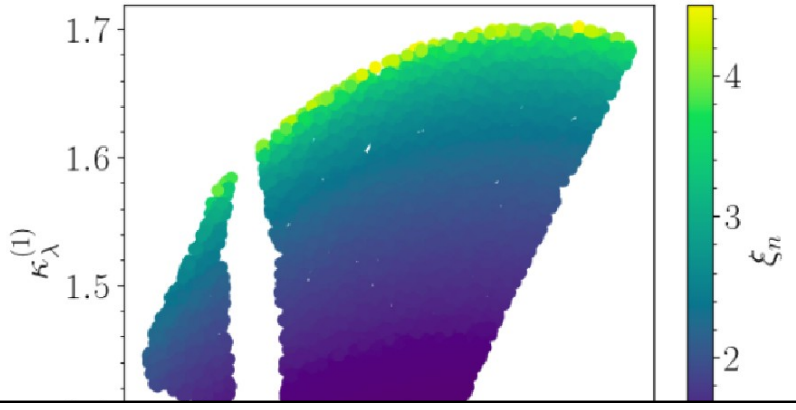
BP with SFOEWPT driven by singlet field



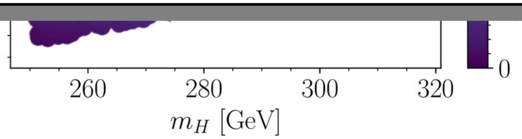
SFOEWPT caused by tree-level barrier → small loop corrections to κ_λ and other Higgs couplings

BP for SFOEWPT driven by doublet field

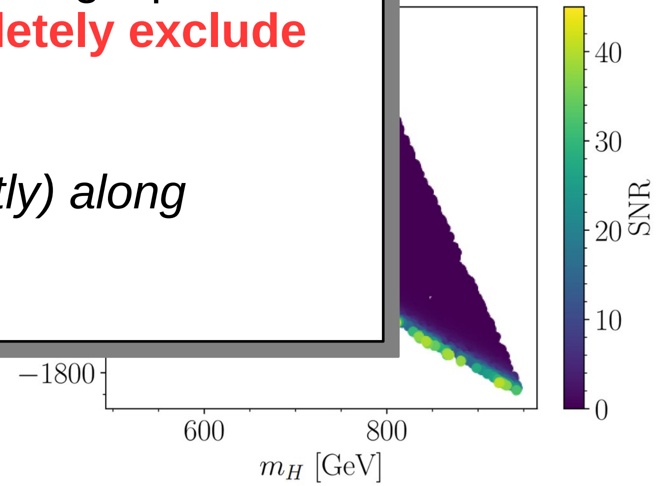


Beware of overestimating/overstating reach of single measurement/single process
→ **RxSM example shows that HL-LHC will not be able to completely exclude the possibility of a SFOEWPT**

Note: EFT treatments cannot be applied if EWPT occurs (partly) along BSM field direction(s) that is(are) integrated out



and v_w = 0.6



Summary

- 85% of (HL-)LHC data remains to be taken → **plenty of room left for BSM discoveries!**
- **Significant progress to come in direct searches**, thanks to ingenuity in terms of new search strategies, analysis techniques, etc.
- Some tentalising excesses
  → more data from Run 3 and beyond might clarify this
  → **it suffices that one of them materialises to have a BSM discovery!**
- **Precision measurements of properties of Higgs boson** (or of other known particles) have strong potential to probe or constrain BSM
  → **high precision theory predictions (QCD/EW/BSM) are needed**
  → combined/global analyses
- Intense theory efforts to prepare for di-Higgs production searches, one of the flagship measurements at HL-LHC
  → **BSM higher-order effects could be very significant**

Thank you very much for your attention!

Contact

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Backup slides

RxSM

The RxSM

General singlet extension of the SM (no Z_2 symmetry)

- **Potential**

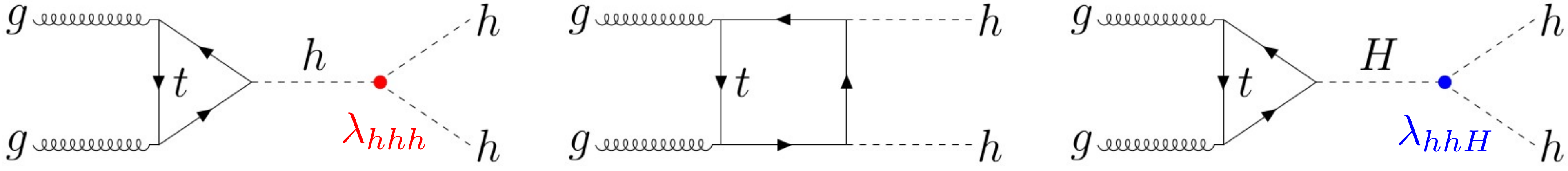
$$V(\Phi,S)=\mu^2(\Phi^\dagger\Phi)+\frac{\lambda}{2}(\Phi^\dagger\Phi)^2+\kappa_{SH}(\Phi^\dagger\Phi)S+\frac{\lambda_{SH}}{2}(\Phi^\dagger\Phi)S^2+\frac{M_S^2}{2}S^2+\frac{\kappa_S}{3}S^3+\frac{\lambda_S}{2}S^4.$$

- Field content (after EWSB) $\Phi=\frac{1}{\sqrt{2}}\begin{pmatrix}\sqrt{2}G^+\\ v+\phi+iG^0\end{pmatrix}, \qquad S=s+v_S$

- Mixing among 2 CP-even Higgs bosons: $\text{Gauge basis: }\phi,\, s \xrightarrow{\text{mixing angle }\alpha} \text{Mass basis: } h,\, H$

- **RxSM scalar sector parametrised in terms of** $\underbrace{m_h^2,\, v}_{\text{known}},\, \underbrace{m_H^2,\, \alpha,\, v_S,\, \kappa_S,\, \kappa_{SH}}_{\text{free}}$

- Three **leading diagrams** in di-Higgs production, with **significant dependence on 2 relevant trilinears: λ_{hhh} and λ_{hhH}**



Full on-shell renormalisation of the RxSM

[JB, Heinemeyer, Parra Arnay, Verduras Schaeidt *WIP*]

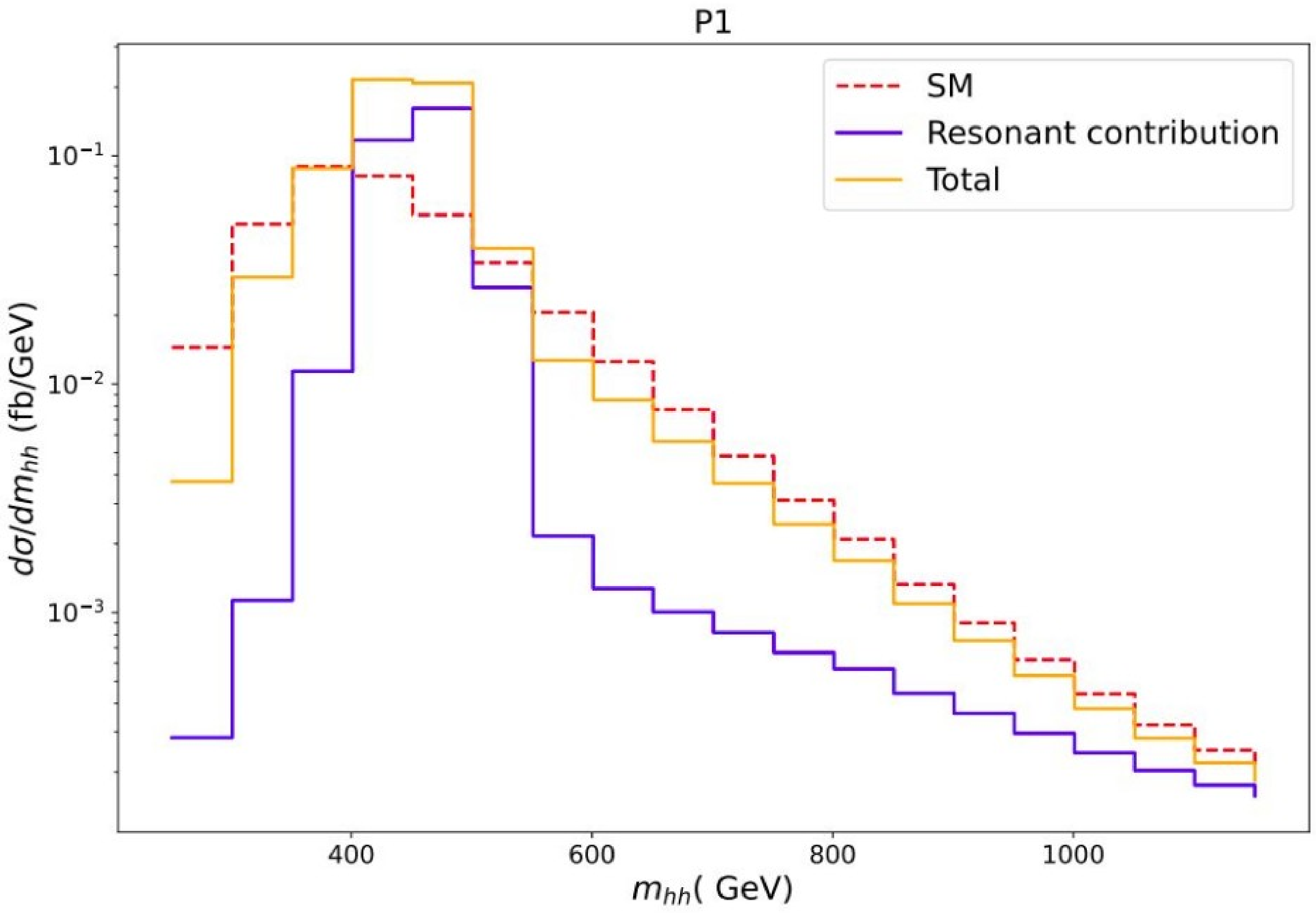
- Masses: m_h^2, m_H^2 — Renormalization of two-point functions
- EW VEV: v — SM-like electroweak sector
- Singlet VEV: v_S — No divergences
- Mixing angle: α — Rotation matrix: [Kanemura, Kikuchi, Yagyu, '15]
- Tadpoles: $t_\phi,\ t_s$ — OS/Standard scheme
- Kappas: κ_S, κ_{SH} — $\hat{\lambda}^{(1)}_{hHH} \overset{!}{=} \lambda^{(0)}_{hHH} \quad \hat{\lambda}^{(1)}_{HHH} \overset{!}{=} \lambda^{(0)}_{HHH}$

Slide by A. Verduras Schaeidt

Interference effects in the RxSM

[Arco, Heinemeyer, Mühlleitner, Parra Arnay, Rivero Gonzalez, Verduras Schaeidt '25]

Di-Higgs production differential distributions: total result vs resonant only



Benchmark P1

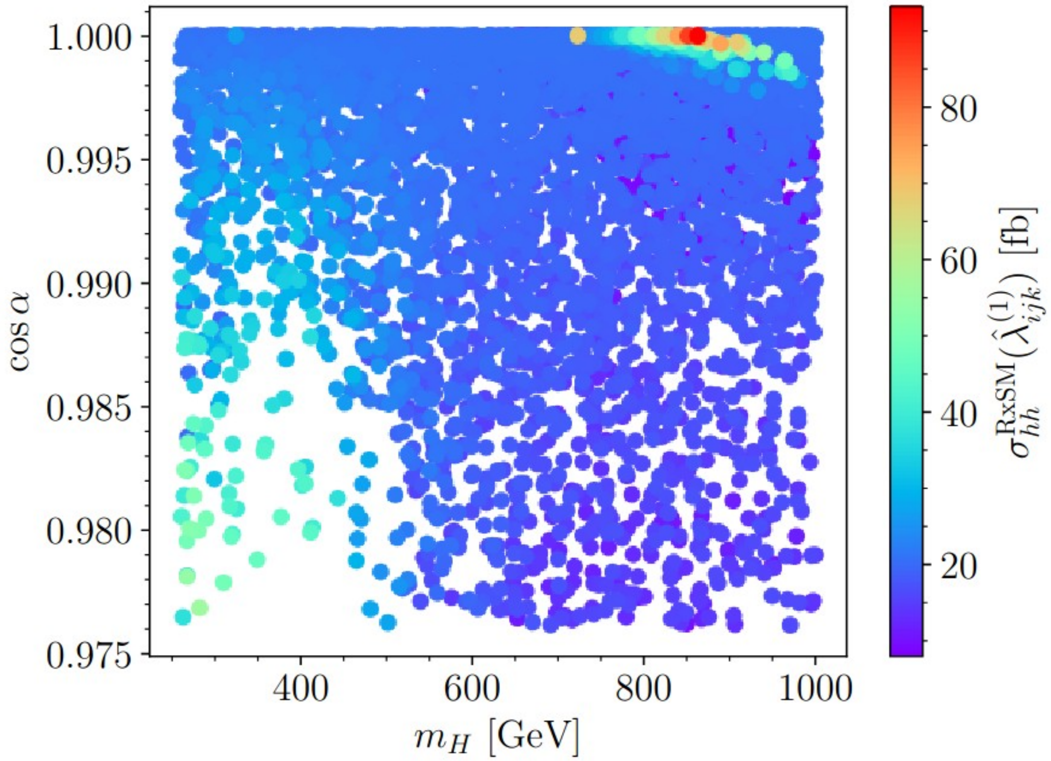
$$m_H = 459 \text{ GeV}$$
$$\alpha = 0.984$$
$$v_S = 46 \text{ GeV}$$
$$\kappa_\lambda = 1.47$$
$$\lambda_{hhH} = 177 \text{ GeV}$$
$$\sigma_{hh}^{\text{RxSM, tot}} = 31.1 \text{ fb}$$
$$\sigma_{hh}^{\text{RxSM, res}} = 16.3 \text{ fb}$$

- Distributions shown here after **experimental effects** are taken into account (**15% smearing and 50 GeV binning**)
- **Relatively good agreement between peak of resonant and total distributions, but tails are far apart**

Impact of NLO corrections in the RxSM

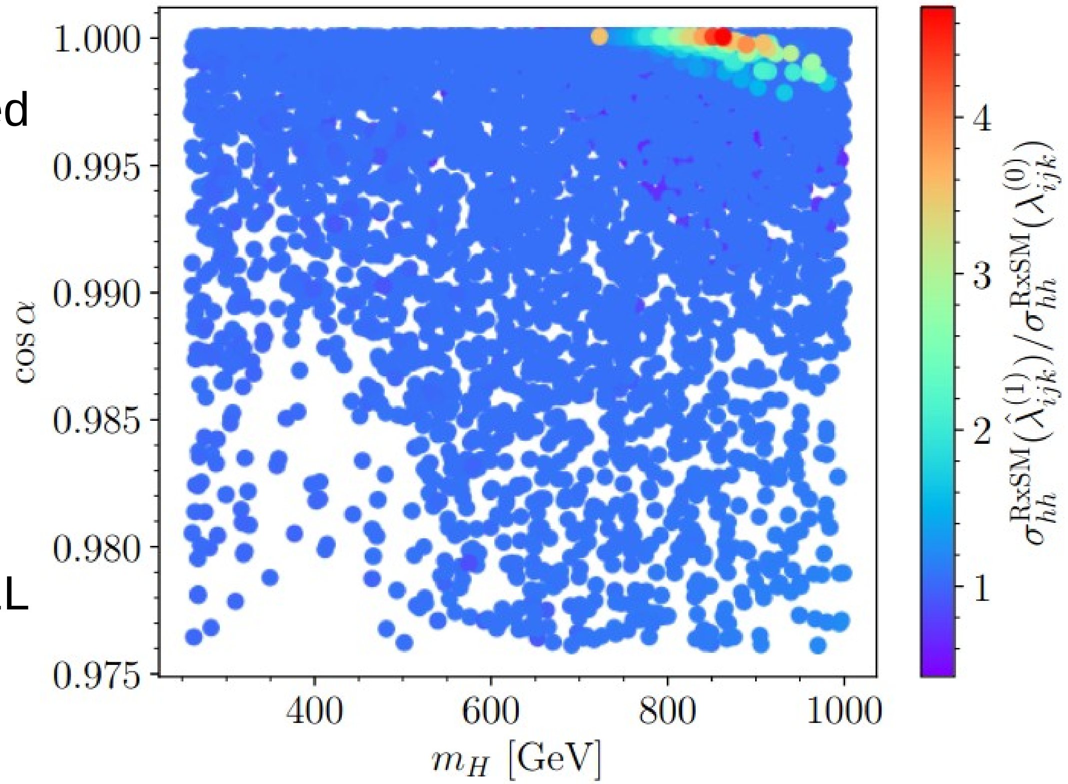
[JB, Heinemeyer, Parra Arnay, Verduras Schaeidt '25]

Parameter scans



Left: cross-section computed with 1L trilinears

Right: ratio of cross-sections computed with 1L and 0L trilinears

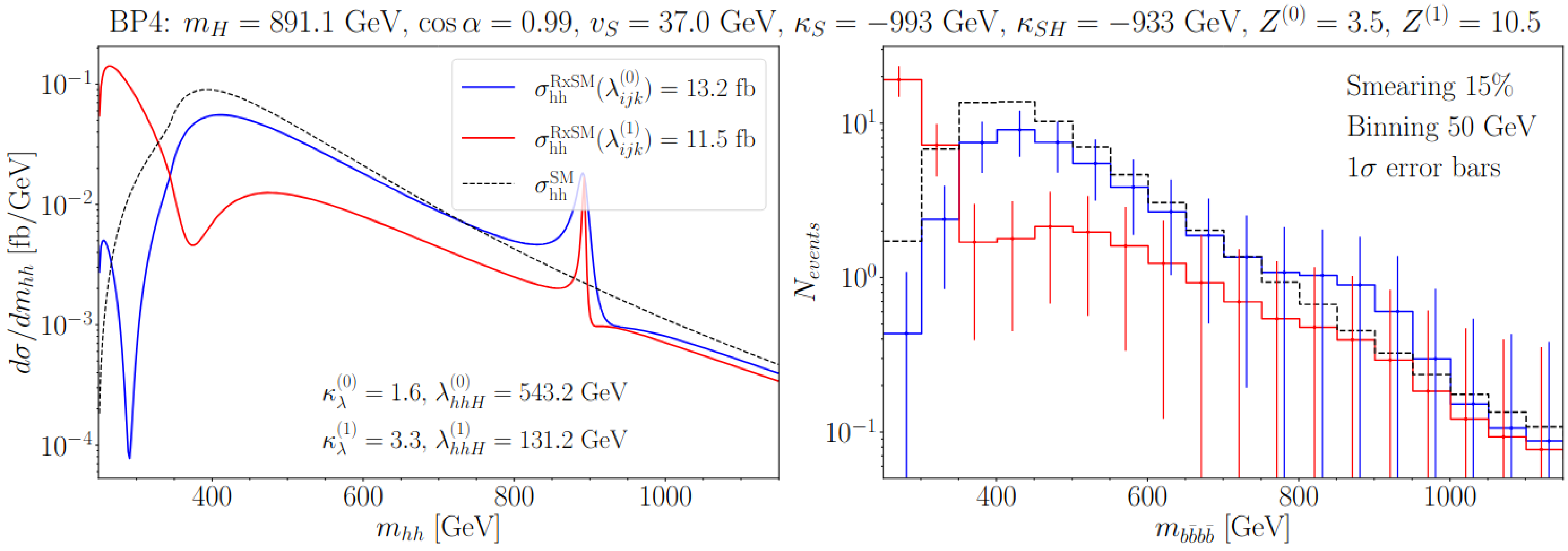


- Largest increases in σ_{hh}^{RxSM} w.r.t. SM for m_H > 750 GeV, v_S < 50 GeV and small mixing → **loop induced effects**
- Points with smaller increases in σ_{hh}^{RxSM} (up to ~2.5 σ_{hh}^{SM}) for low m_H → **effect from resonant H contribution (already at tree level)**

Impact of NLO corrections in the RxSM

[JB, Heinemeyer, Parra Arnay, Verduras Schaeidt '25]

Impact on di-Higgs invariant mass distributions

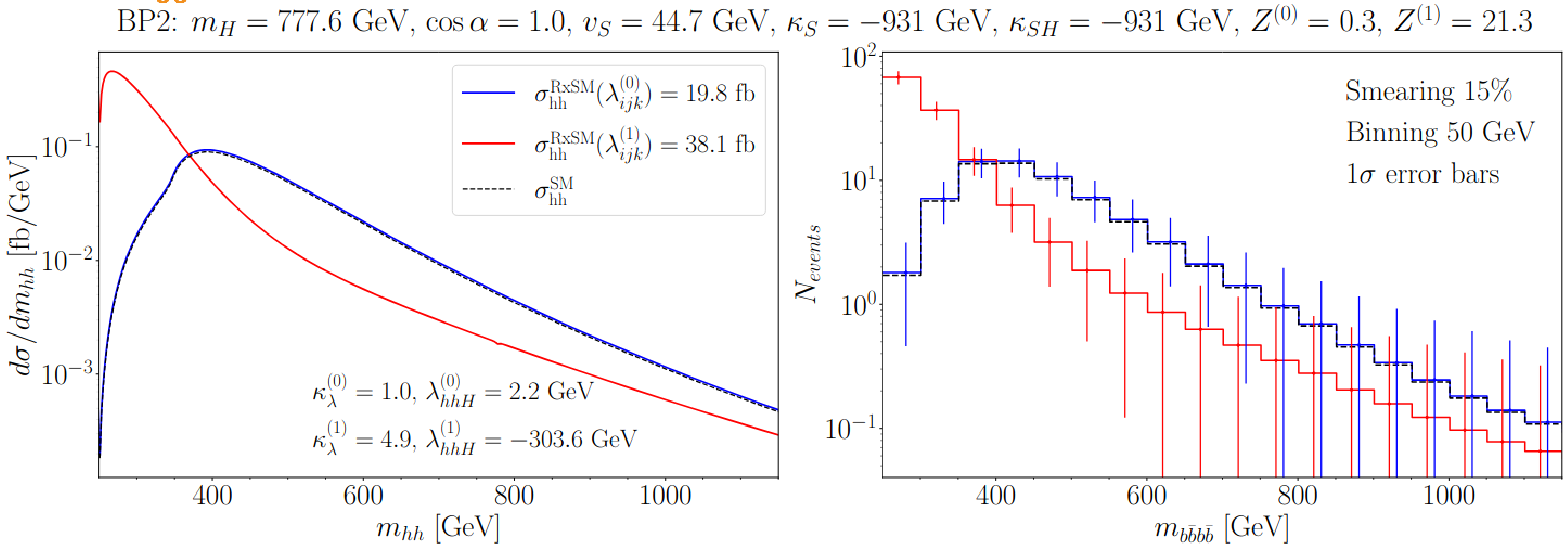


- Total cross-section is not modified very significantly
- Large (positive) correction to λ_{hhh} changes the distribution drastically for low m_{hh}, while large negative correction to λ_{hhH} makes the peak at m_H narrower
- Change at low m_{hh} is substantial enough to allow distinguishing the RxSM from the SM with an analysis using one-loop trilinear scalar couplings

Impact of NLO corrections in the RxSM

[JB, Heinemeyer, Parra Arnay, Verduras Schaeidt *WIP*]

Impact on di-Higgs invariant mass distributions



- Similar to BP1, main effect from loop correction to κ_λ (resonant peak suppressed by high m_H)
- As for BP1, for BP2, an analysis with tree-level trilinears ($Z^{(0)}=0.3$) would not be able to show a deviation from the SM, but an analysis with one-loop ones would ($Z^{(1)}=21.3$)

2HDM

The Two-Higgs-Doublet Model

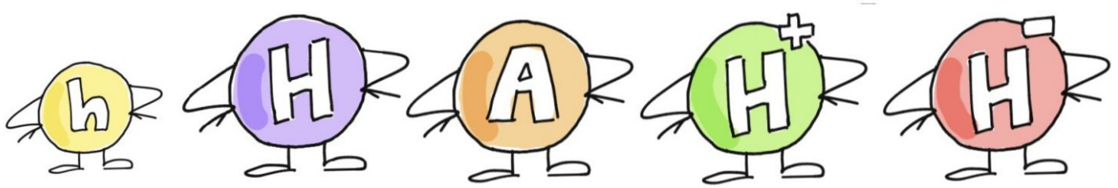


Figure by [K. Radchenko Serdula '24]

- 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

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

$$v_1^2 + v_2^2 = v^2 = (246\ \text{GeV})^2$$

- **Mass eigenstates**:
  h, H: CP-even Higgs bosons *(h → 125-GeV SM-like state);* A: CP-odd Higgs boson;
  $H^\pm$: charged Higgs boson

- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv 2m_3^2/s_{2\beta}$), angles α (CP-even Higgs mixing angle) and β (defined by $\tan\beta = v_2/v_1$)

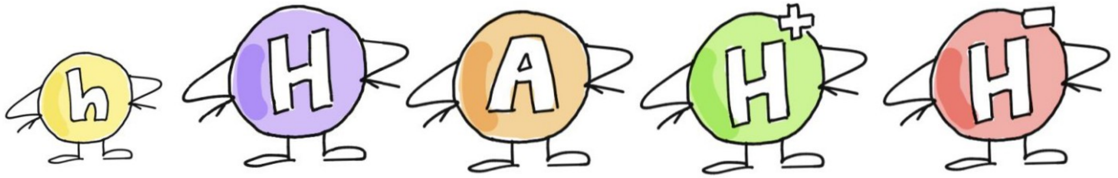
- **BSM-scalar masses** take form $m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2\,, \quad \Phi \in \{H, A, H^\pm\}$

- We take the **alignment limit α = β - π/2** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data

Interference effects in the 2HDM

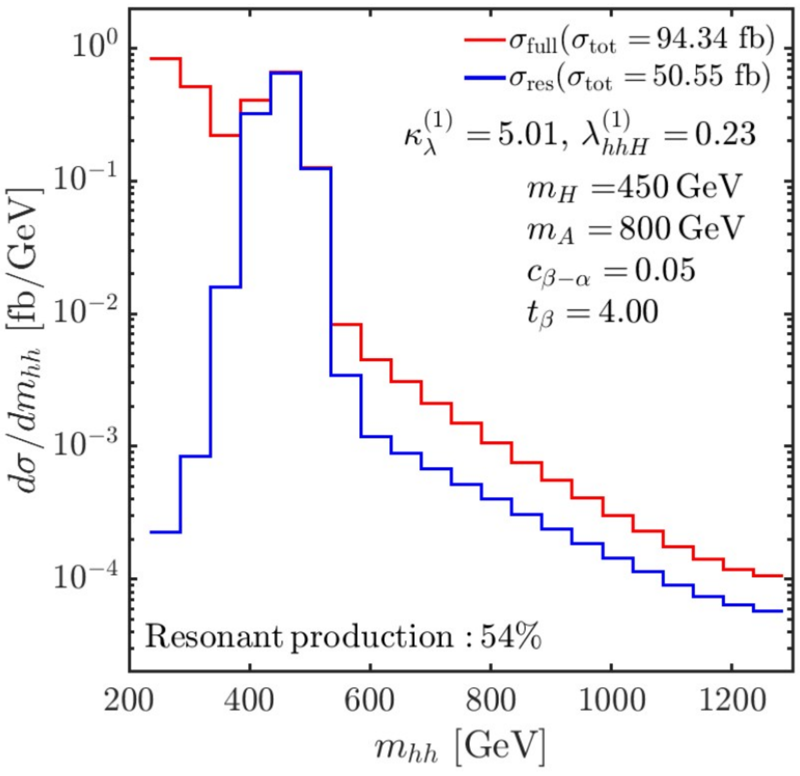
[Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein ‘24]

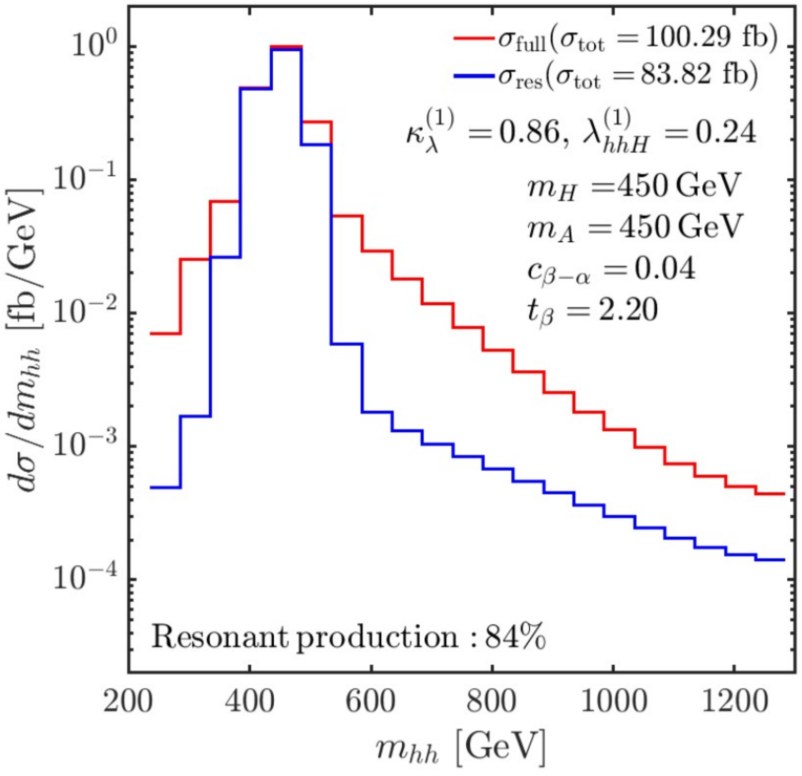
Resonant only vs total distributions



Drawing by [K. Radchenko Serdula ‘24]

- 2HDM adds second doublet to SM
- Interference between non-resonant and resonant contributions as well as loop corrections to trilinear scalar couplings can again drastically change di-Higgs invariant mass distributions
- 2 benchmark scenarios *excluded by resonant searches but allowed by non-resonant searches* [ATLAS ‘22]
  → large impact of interference effects **warrants analysis of these scenarios with full calculation**

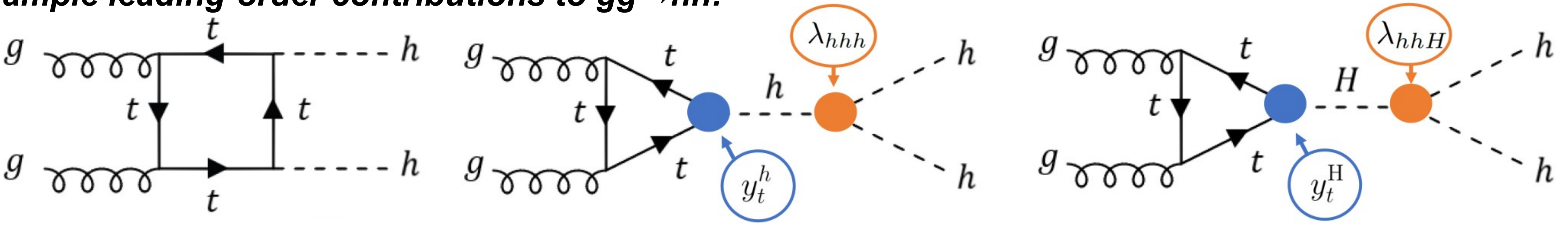




anyH3 (v2) / anyHH

Ongoing developments in `anyBSM`: `anyLambdaijk` and `anyHH`

Example leading-order contributions to gg→hh:

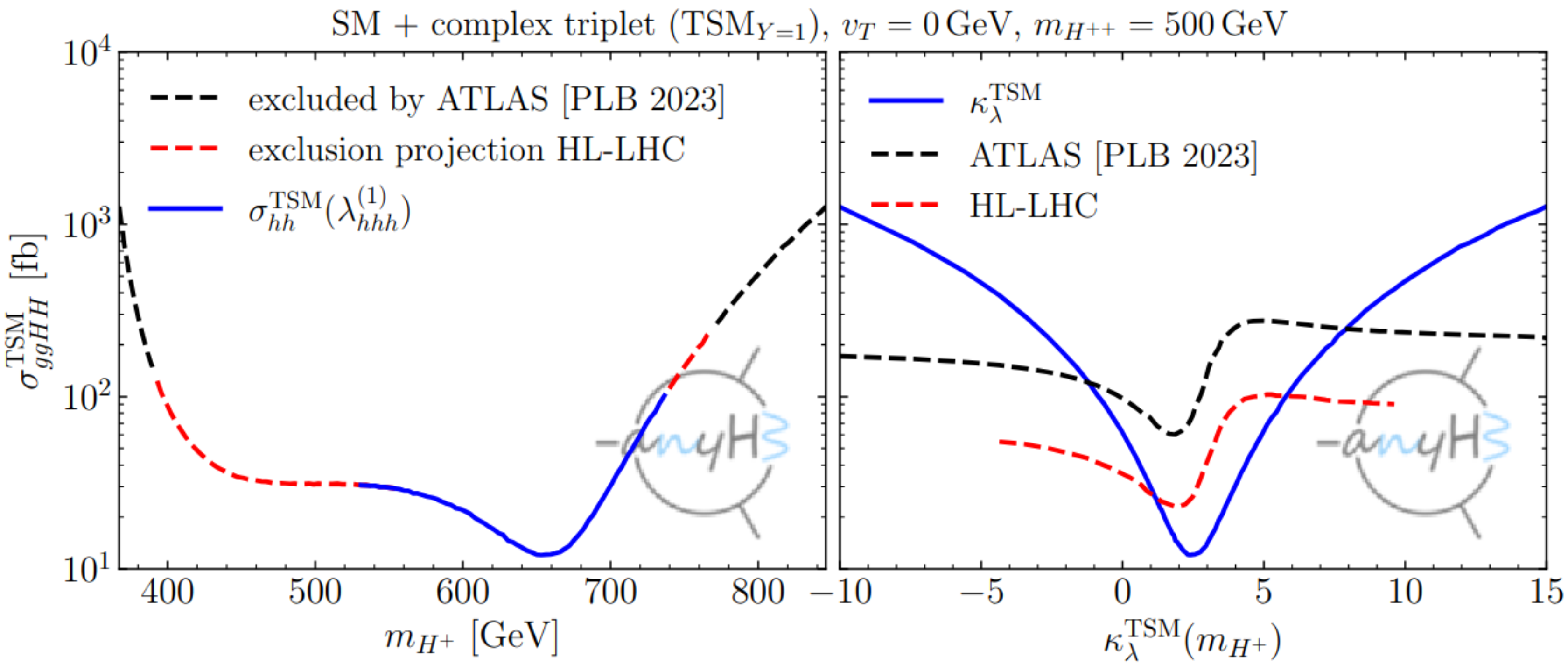


[Diagrams by A. Verduras Schaeidt]

Having predictions for di-Higgs production, including **all (i.e. resonant + non-resonant) contributions + 1L corrections to trilinear scalar couplings** in **arbitrary models** would be highly desirable

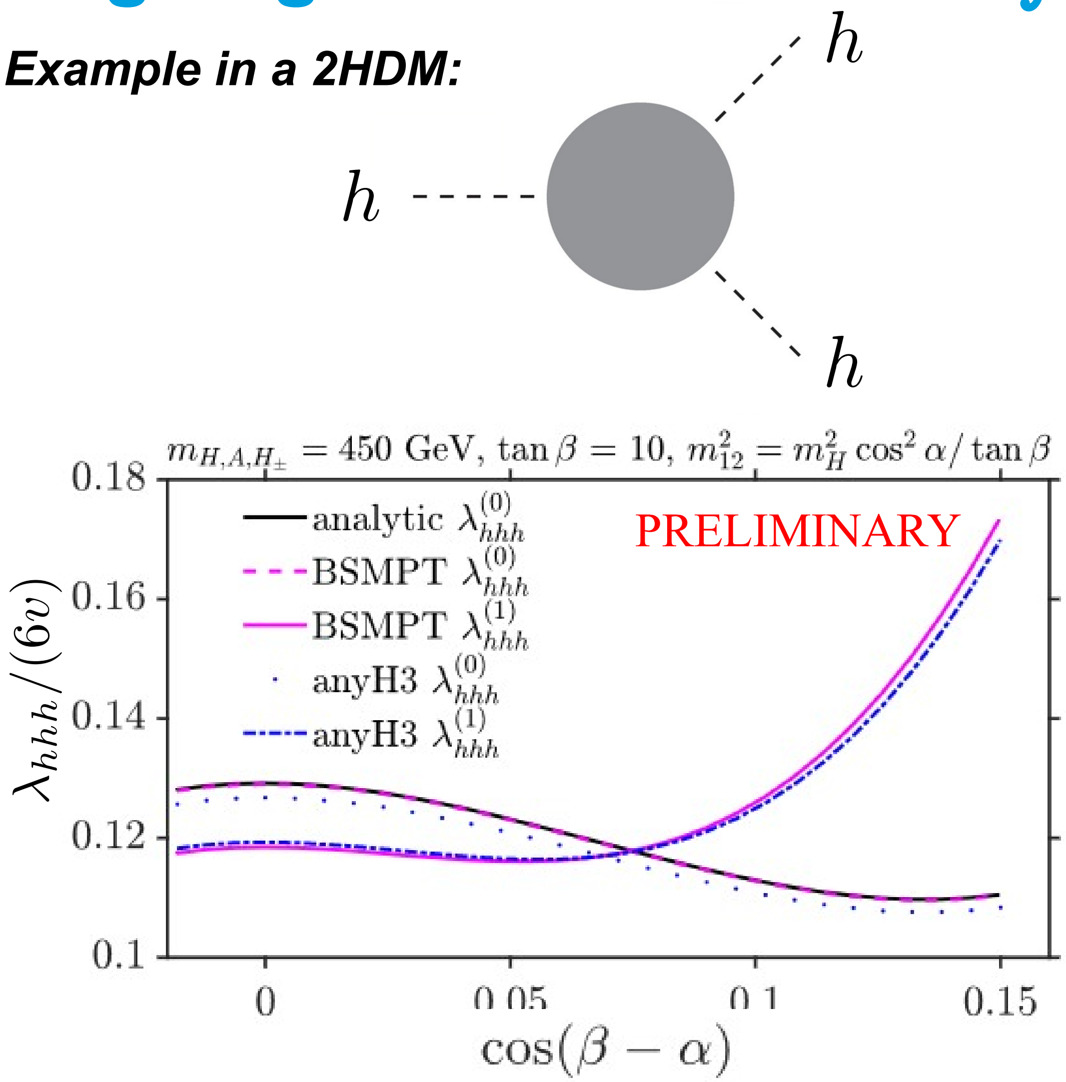
→ new modules `anyLambdaijk` and `anyHH`

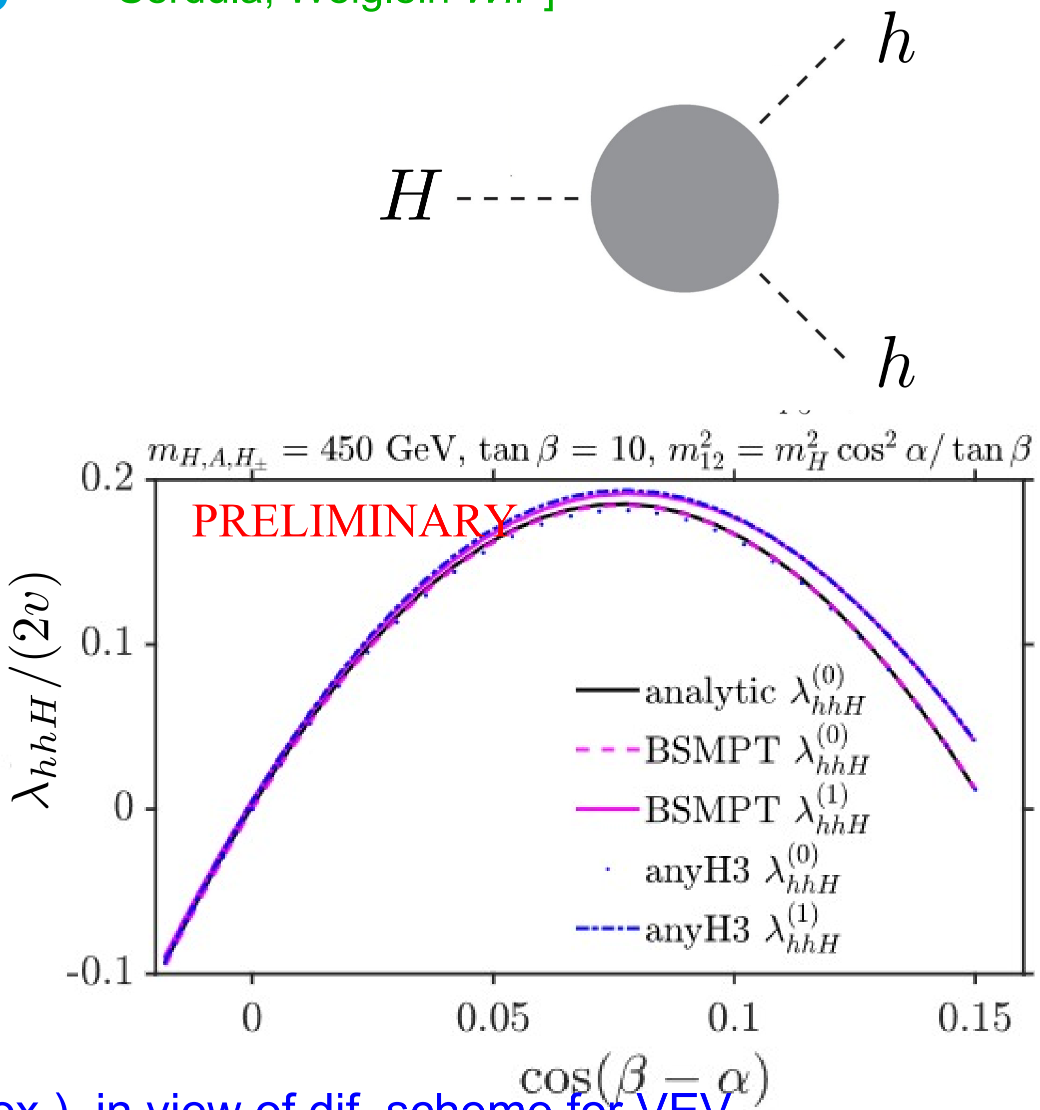
[Bahl, Braathen, Gabelmann, Radchenko Serdula, GW *WIP*]



Ongoing developments: `anyLamijk` [Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]

Example in a 2HDM:



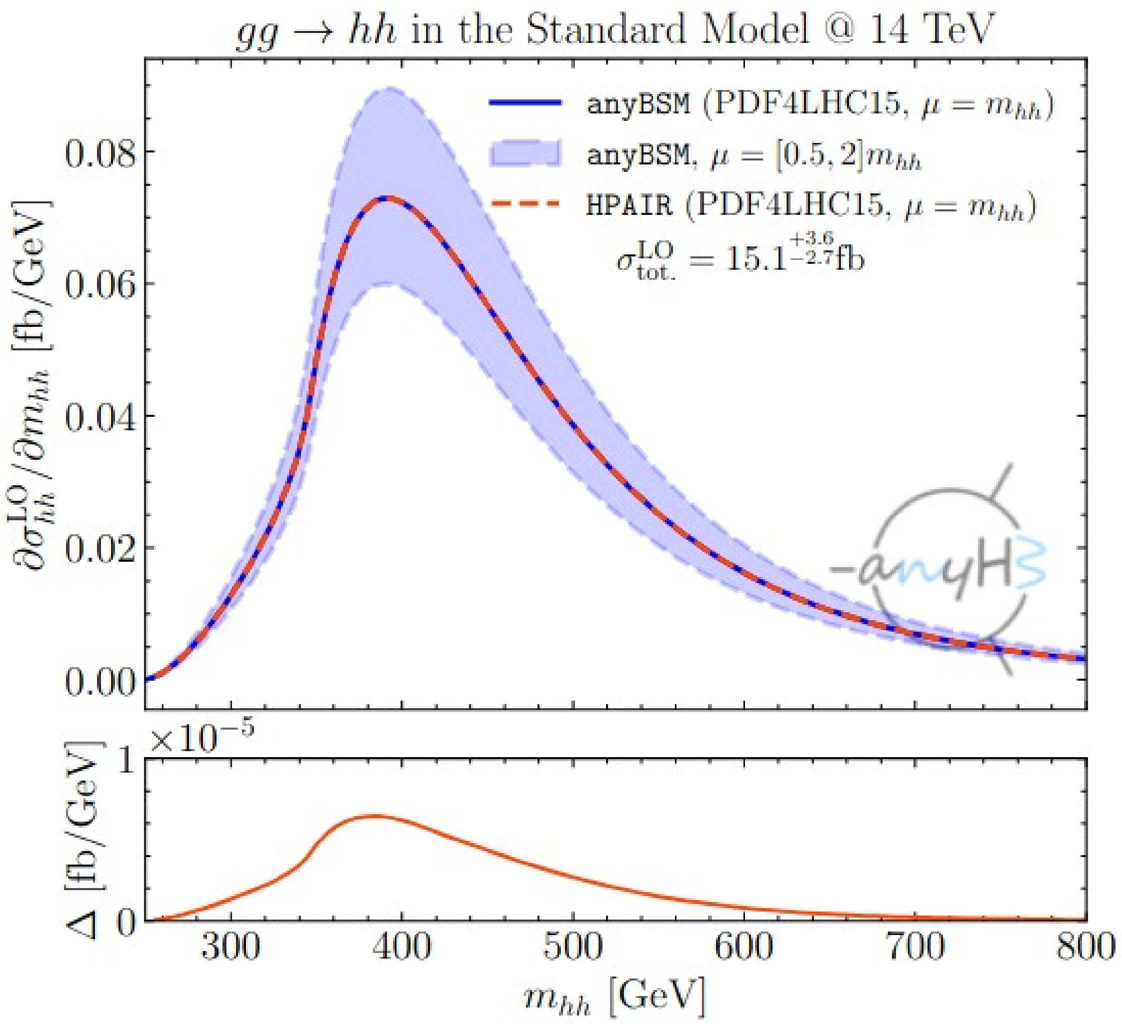


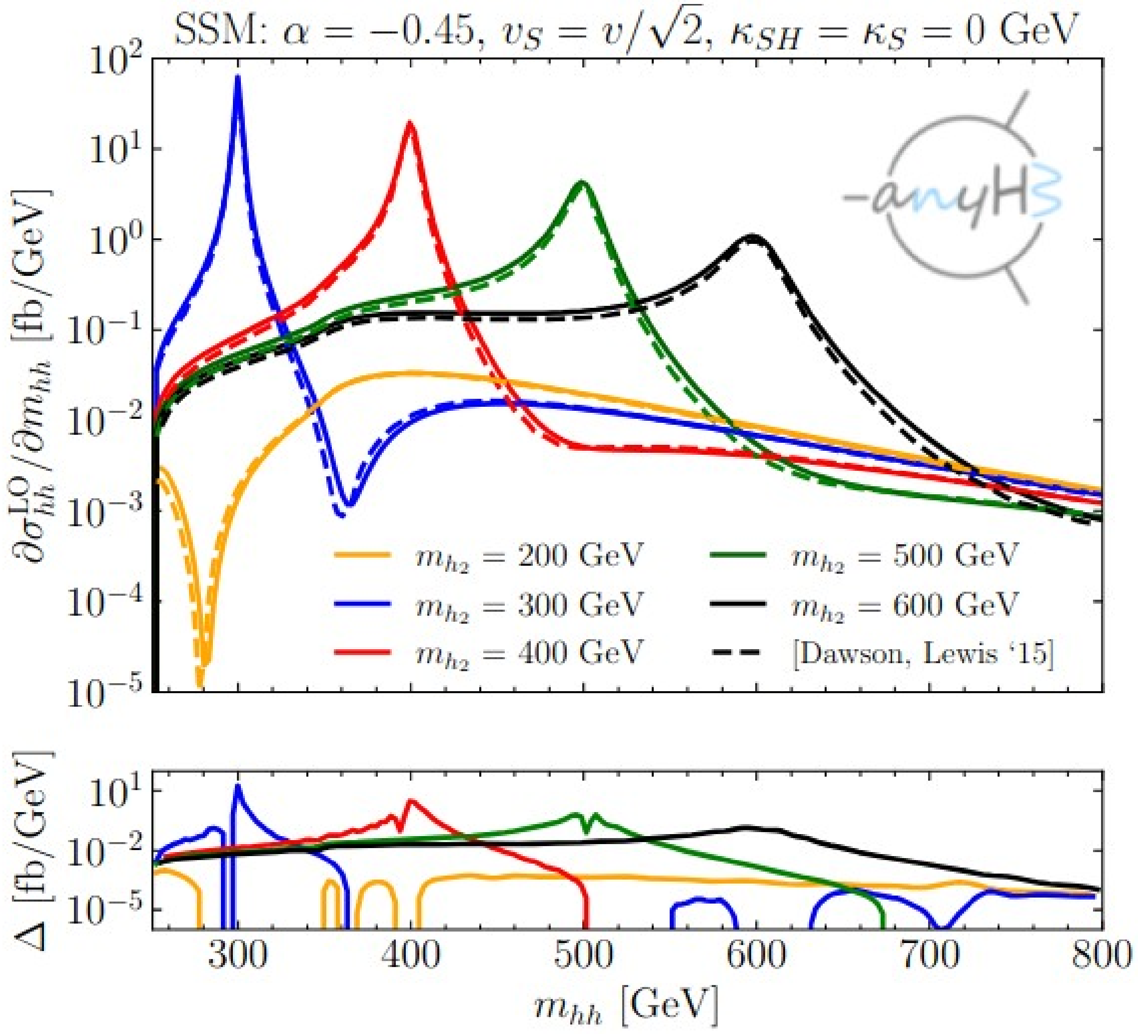
→ excellent agreement with BSMPT results (in eff. pot. approx.), in view of dif. scheme for VEV

→ full OS schemes for λ_{hhh} and λ_{hhH} couplings worked out in 2HDM [Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein], RxSM [JB, Heinemeyer, Verduras Schaeidt], and more [Bosse, JB, Gabelmann, Hannig, Weiglein]!

Ongoing developments: tests of `anyHH` with leading order trilinear couplings

$$\Delta \equiv |\partial\sigma_{hh}^{\text{LO}}/\partial m_{hh}(\texttt{HPAIR}) - \partial\sigma_{hh}^{\text{LO}}/\partial m_{hh}(\texttt{anyHH})|$$

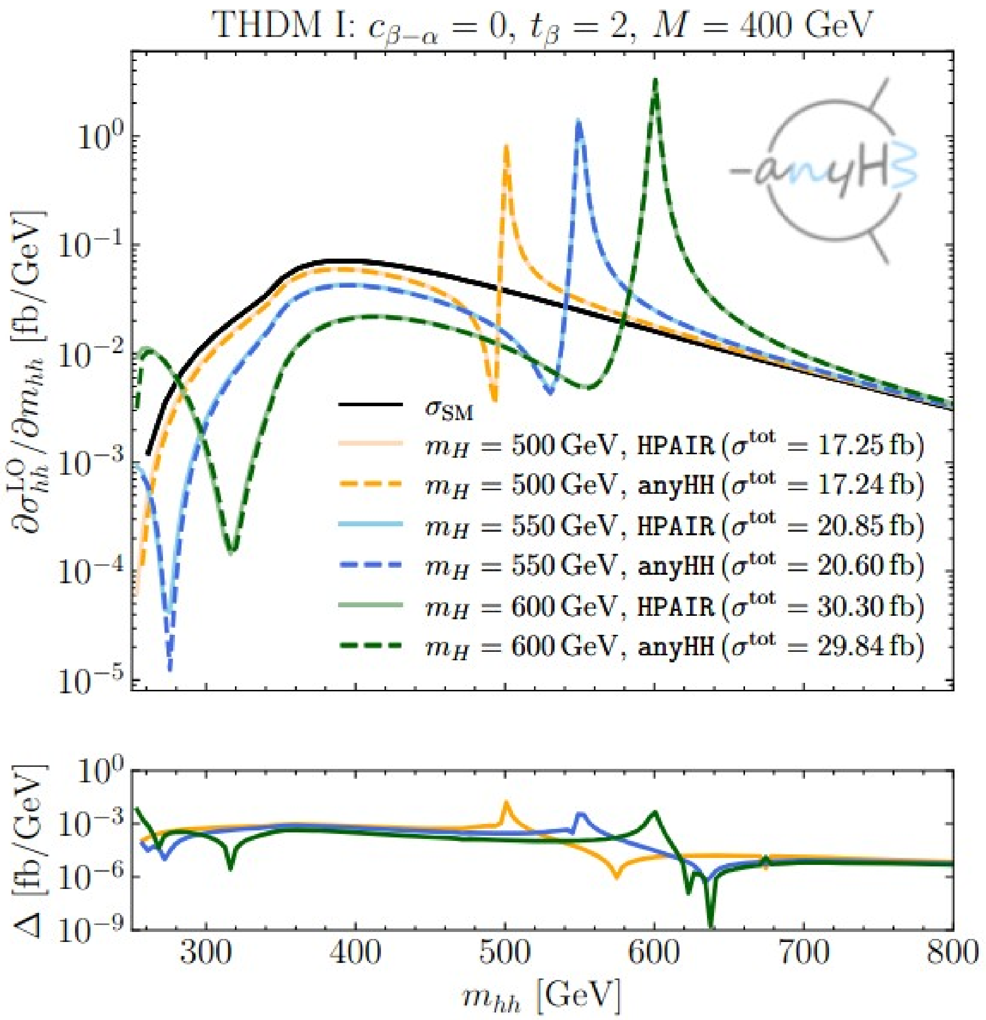


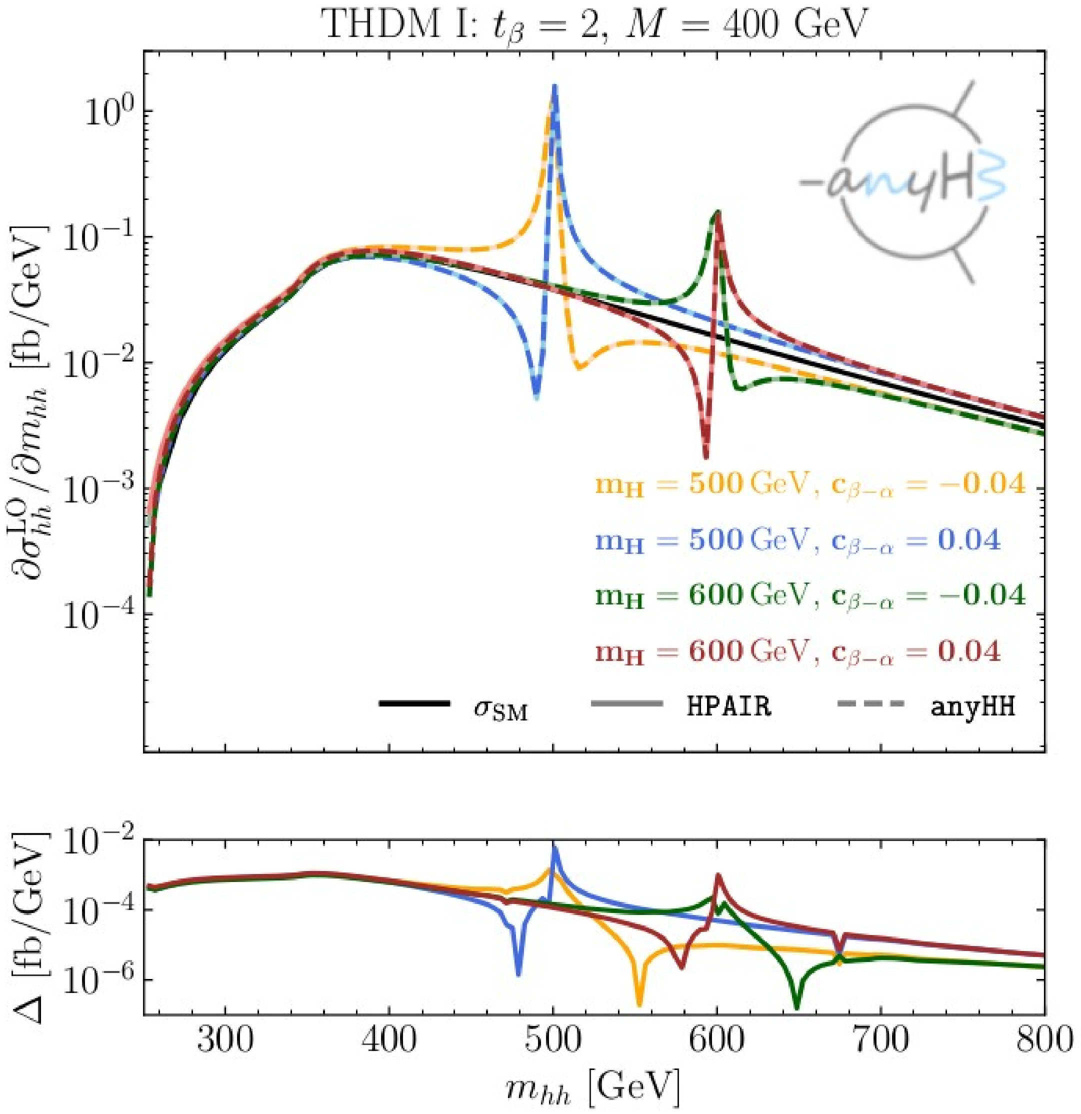


- Excellent agreement with LO HPair result, once one ensures that running of α_s + choice of PDFs are same

- Very good agreement results of [Dawson, Lewis ‘15] for singlet extension of SM (remaining difference because PDF sets can’t be taken to be the same)

Ongoing developments: comparisons with HPAIR in the 2HDM

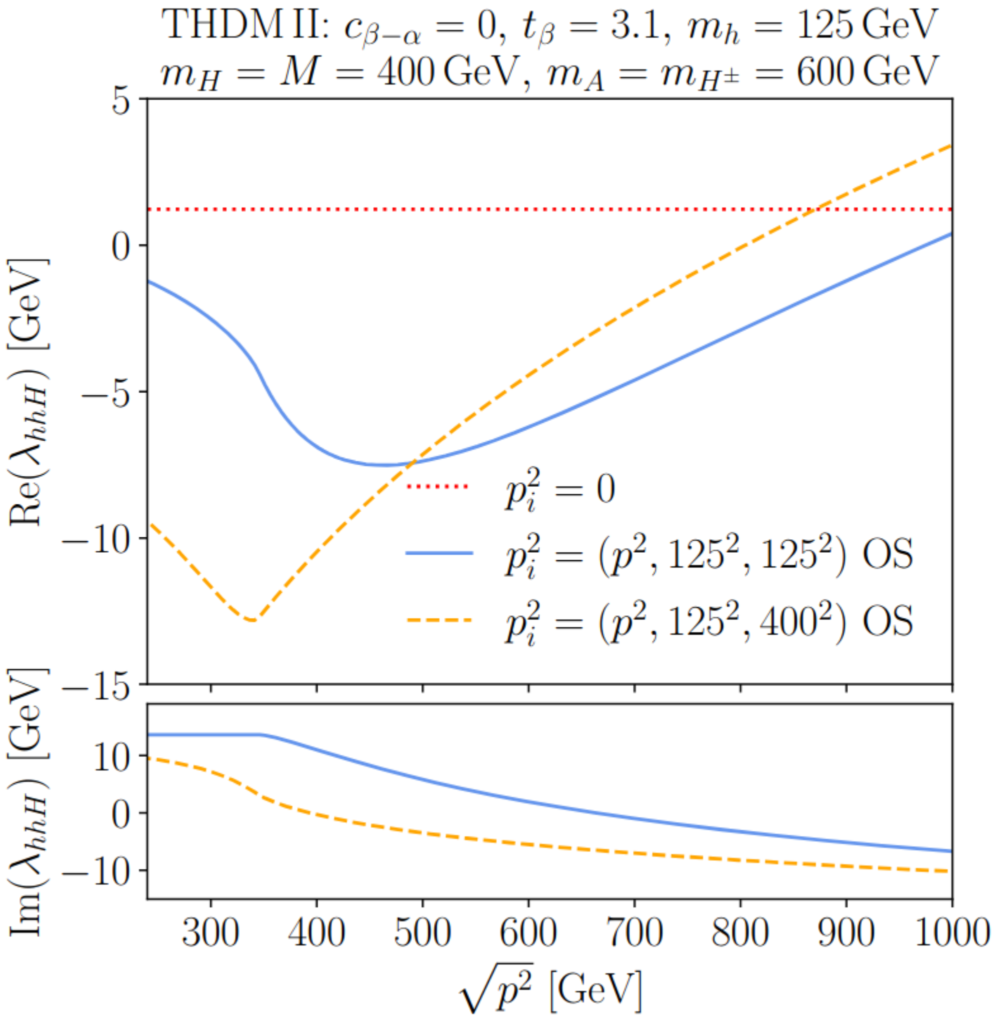


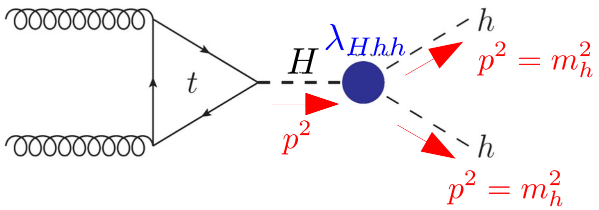


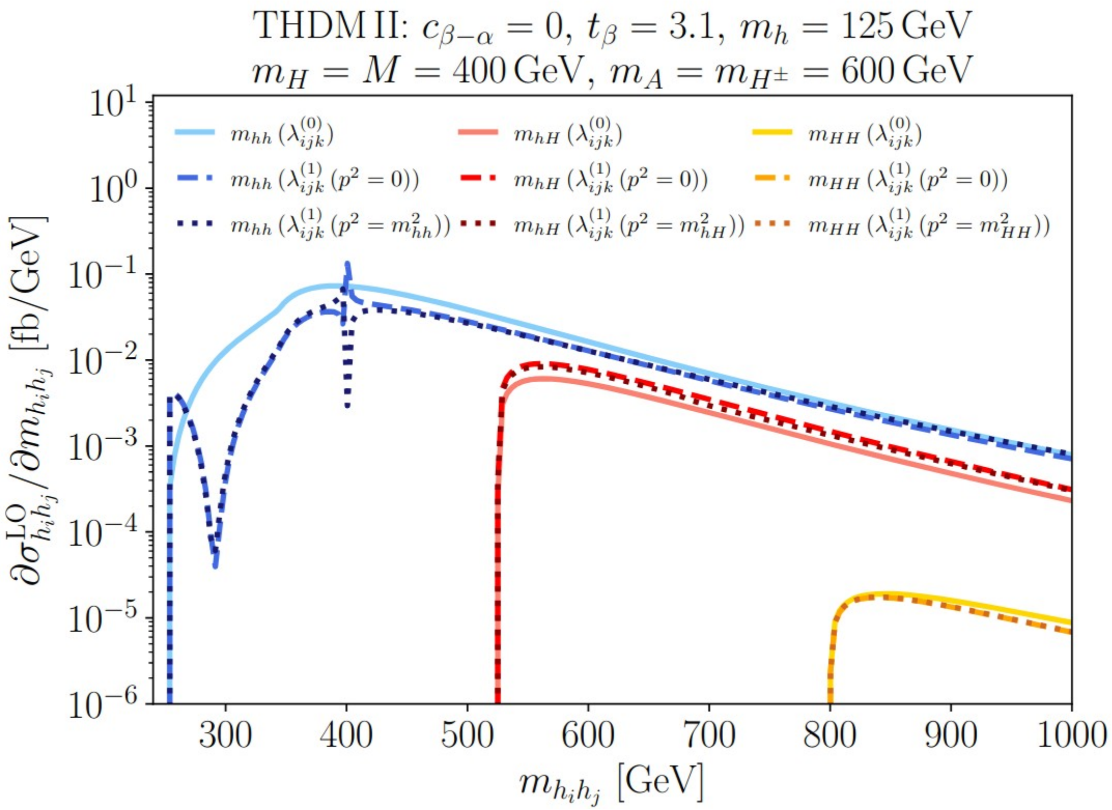
- Very good agreement with HPair, using one-loop trilinear scalar couplings computed by anyH3/anyLambdaijk, for 2HDM benchmarks (here in alignment limit)

Momentum effects

[Bahl, JB, Gabelmann, Radchenko Serdula, Weiglein *WIP*]







Peak around $m_{hh} = m_H$ depends on λ_{hhH} and $\Gamma^{\mathrm{tot.}}_H$

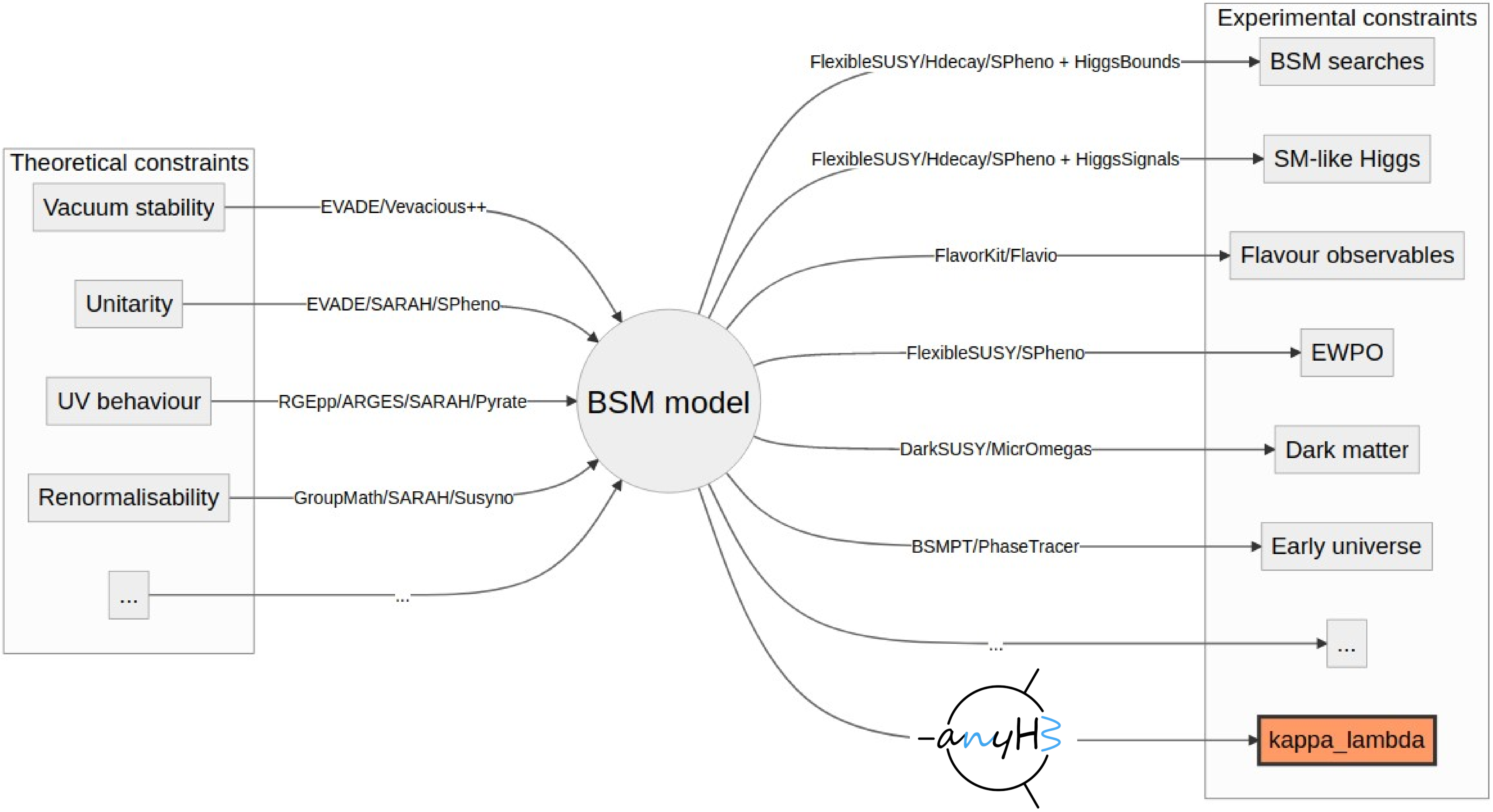
- Here: alignment limit, so at tree level: $\lambda^{(0)}_{hhH} = 0$
- However at loop level: $\lambda^{(1)}_{hhH}(0,0,0) \sim 1\ \mathrm{GeV} > 0$

  but $\lambda^{(1)}_{hhH}(m^2_{hh}, m^2_h, m^2_h) < 0$

Consequence: **'dip-peak' → 'peak-dip' structure**

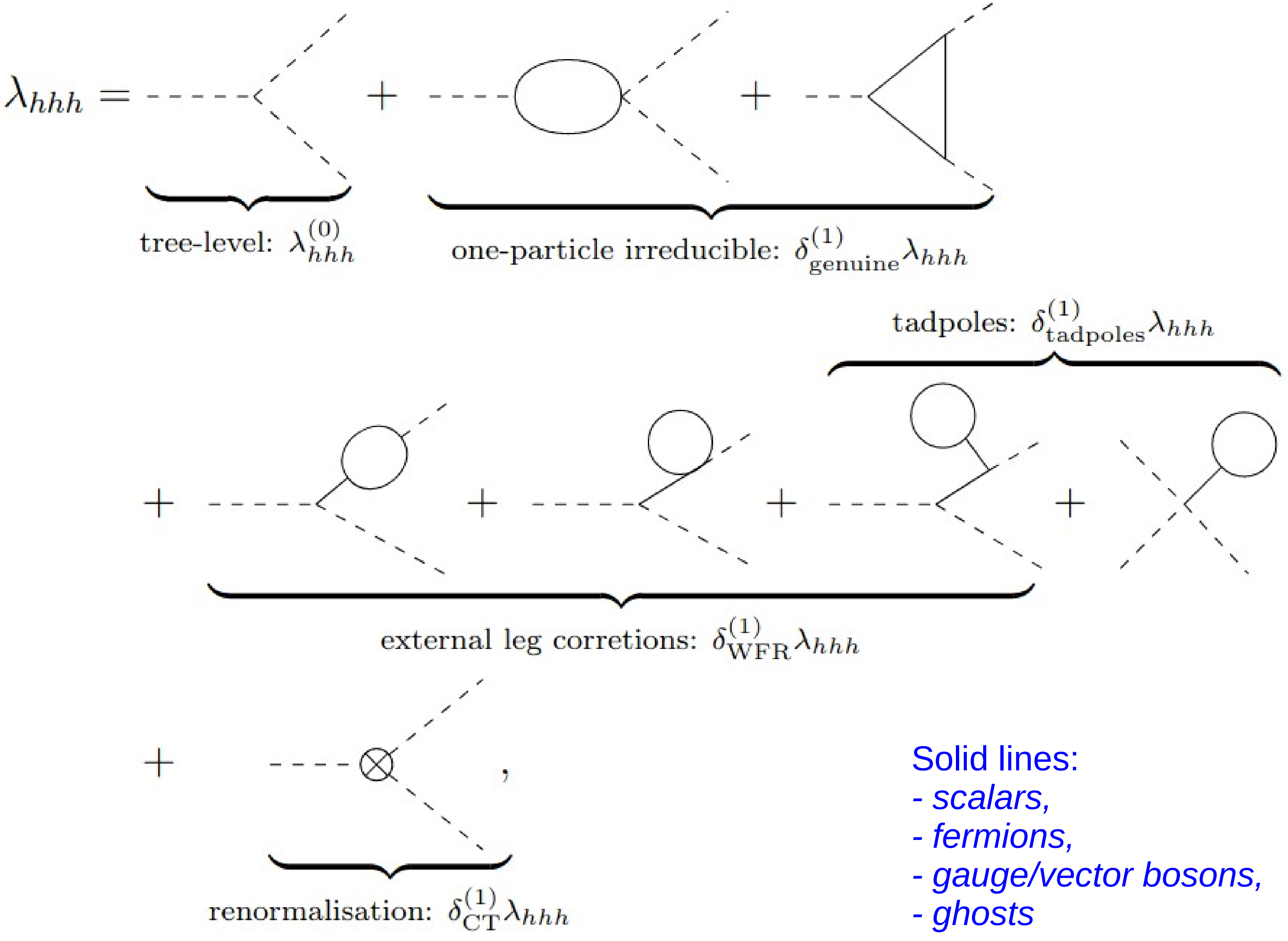
anyH3 (v1)

λ_{hhh} within the landscape of automated tools



Full one-loop calculation of λ_{hhh} with `anyH3`: how does it work?

- Generic results applied to concrete (B)SM model, using inputs in `UFO` format [Degrande et al., '11], [Darmé et al. '23]
- Loop functions evaluated via `COLLIER` [Denner et al '16] interface, `pyCollier`
- Restrictions on **particles** and/or **topologies** possible
- **Renormalisation performed automatically** (*more in backup*)

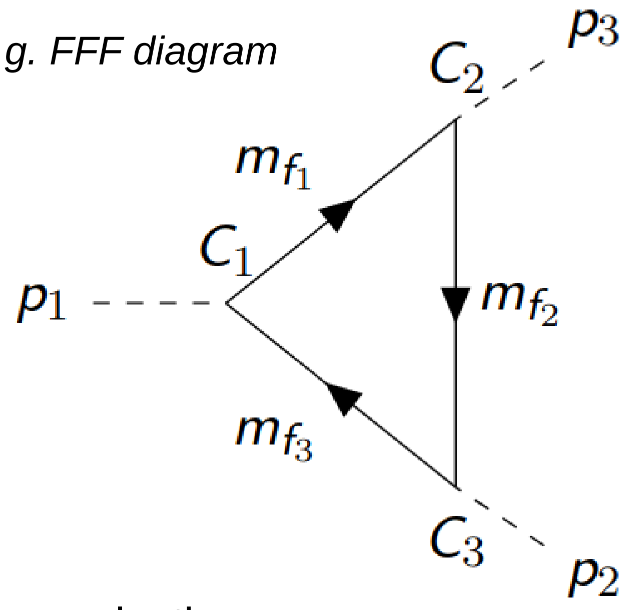


Solid lines:
- *scalars,*
- *fermions,*
- *gauge/vector bosons,*
- *ghosts*

Computing λ_{hhh} in general renormalisable theories: method

Our method: we derive and implement analytic results for **generic diagrams**, i.e. assuming generic

e.g. FFF diagram



- Couplings $C_i = C_i^L P_L + C_i^R P_R,\ \text{where } P_{L,R} \equiv \frac{1}{2}(1 \mp \gamma_5)$
- Masses on the internal lines m_{f_i}, i=1,2,3
- External momenta p_i, i=1,2,3

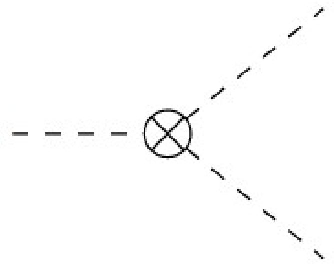
$$\begin{aligned}
&= 2\mathbf{B0}(p_3^2, m_2^2, m_3^2)(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + \\
&C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3})) + m_{f_1} \mathbf{C0}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((C_1^L C_2^L C_3^R + \\
&C_1^R C_2^R C_3^L)(p_1^2 + p_2^2 - p_3^2) + 2(C_1^L C_2^L C_3^L + C_1^R C_2^R C_3^R) m_{f_2} m_{f_3} + \\
&2m_{f_1}(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + \\
&C_2^L C_3^R m_{f_3}))) + \mathbf{C1}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)(2p_2^2(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + \\
&C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + (p_1^2 + p_2^2 - p_3^2)((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L) m_{f_1} + \\
&(C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3})) + \mathbf{C2}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((p_1^2 + p_2^2 - \\
&p_3^2)(C_1^L C_3^R(C_2^L m_{f_1} + C_2^R m_{f_2}) + C_1^R C_3^L(C_2^R m_{f_1} + C_2^L m_{f_2})) + 2p_1^2((C_1^L C_2^L C_3^R + \\
&C_1^R C_2^R C_3^L) m_{f_1} + (C_1^L C_2^R C_3^L + C_1^R C_2^L C_3^R) m_{f_3}))
\end{aligned}$$

For evaluation:

- Apply to concrete (B)SM model, using inputs in `UFO` format [Degrande et al., ‘11], [Darmé et al. ‘23]
- Evaluate loop functions via `COLLIER` [Denner et al ‘16] interface, `pyCollier`
- All included in public tool `anyH3` [Bahl, JB, Gabelmann, Weiglein ‘23]

(**B0**, **C0**, **C1**, **C2**: loop functions)

Flexible choice of renormalisation schemes

$\delta^{(1)}_{\mathrm{CT}}\lambda_{hhh} =$  $= \,?$

- **1L calculation** → renormalisation of all parameters entering λ_{hhh} at tree-level
- In general:

$$(\lambda^{(0)}_{hhh})^{\mathrm{BSM}} = (\lambda^{(0)}_{hhh})^{\mathrm{BSM}}(\underbrace{m_h \simeq 125\text{ GeV}, v \simeq 246\text{ GeV}}_{\text{SM sector}},\ \underbrace{m_{\Phi_i}}_{\substack{\text{BSM}\\ \text{masses}}},\ \underbrace{\alpha_i}_{\substack{\text{BSM}\\ \text{mixing angles}}},\ \underbrace{v_i}_{\substack{\text{BSM}\\ \text{VEVs}}},\ \underbrace{g_i}_{\substack{\text{indep.}\\ \text{BSM coups.}}})$$

- Most automated codes: $\overline{\text{MS}}/\overline{\text{DR}}$ only
- **`anyH3`**: much more flexibility, following **user choice**:
  - **SM sector** (m_h, v): fully OS or $\overline{\text{MS}}/\overline{\text{DR}}$
  - **BSM masses**: OS or $\overline{\text{MS}}/\overline{\text{DR}}$
  - **Additional couplings/vevs/mixings**: by default $\overline{\text{MS}}$, but **user-defined ren. conditions** also possible!

$$\delta^{(1)}_{\mathrm{CT}}\lambda_{hhh} = \sum_x \left(\frac{\partial}{\partial x}(\lambda^{(0)}_{hhh})^{\mathrm{BSM}}\right)\delta^{\mathrm{CT}}x\,, \qquad \text{with } x \in \{m_h, v, m_{\Phi_i}, v_i, \alpha_i, g_i, \text{etc.}\}$$

Renormalised in $\overline{\text{MS}}$, OS, in custom schemes, etc.

(Default) Renormalization choice of $(v^{\text{SM}})^{\text{OS}}$ and $(m_i^2)^{\text{OS}}$

- $v^{\text{OS}} \equiv \frac{2M_W^{\text{OS}}}{e}\sqrt{1-\frac{M_W^{2\,\text{OS}}}{M_Z^{2\,\text{OS}}}}$ with
  - $\delta^{(1)} M_V^{2\,\text{OS}} = \frac{\Pi_V^{(1),T}}{M_V^{2\,OS}}(p^2 = M_V^{2\,OS})\,,\, V = W, Z$
  - $\delta^{(1)} e^{\text{OS}} = \frac{1}{2}\dot{\Pi}_\gamma(p^2=0) + \text{sign}(\sin\theta_W)\frac{\sin\theta_W}{M_Z^2\cos\theta_W}\Pi_{\gamma Z}(p^2=0)$
- attention *(i)*: $\rho^{\text{tree-level}} \neq 1 \to$ further CTs needed (depends on the model)

  $\longrightarrow$ ability to define *custom* renormalisation conditions
- scalar masses: $m_i^{\text{OS}} = m_i^{\text{pole}}$
  - $\delta^{\text{OS}} m_i^2 = -\widetilde{\text{Re}}\Sigma_{h_i}^{(1)}|_{p^2=m_i^2}$
  - $\delta^{\text{OS}} Z_i = \widetilde{\text{Re}}\frac{\partial}{\partial p^2}\Sigma_{h_i}^{(1)}|_{p^2=m_i^2}$
- attention *(ii)*: scalar mixing may also require further CTs/tree-level relations

All bosonic one- & two-point functions and their derivatives for general QFTs are required for flexible OS renormalisation.

Features of `anyH3`, so far

- Import/conversion of any UFO model
- Definition of renormalisation schemes

```
# schemes.yml
```

(extract from schemes.yml for 2HDM)

```yaml
renormalization_schemes:
  MS:
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: MS
    mass_counterterms:
      h1: MS
      h2: MS
  OS:
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: OS
    custom_CT_hhh: 'dbetaH =
f"({Sigma(''Hm1'',''Hm2'',momentum=''0'')} +
{Sigma(''Hm1'',''Hm2'',momentum=''MHm2**2'')})/-
(2*MHm2**2)"

      dTanBeta = f"({dbetaH})/cos(betaH)**2"
```

...

- Analytical / numerical / LaTeX outputs
- **3 user interfaces**:
  - Python library

```python
from anyBSM import anyH3
myfancymodel = anyH3('path/to/UFO/model')
result = myfancymodel.lambdahhh()
```

  - Command line
  - Mathematica interface
- **Perturbative unitarity checks** available (at tree level and in high-energy limit for now)
- Can be used together with a spectrum generator and **handles SLHA format**
- Efficient **caching** available
- Lots more!

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

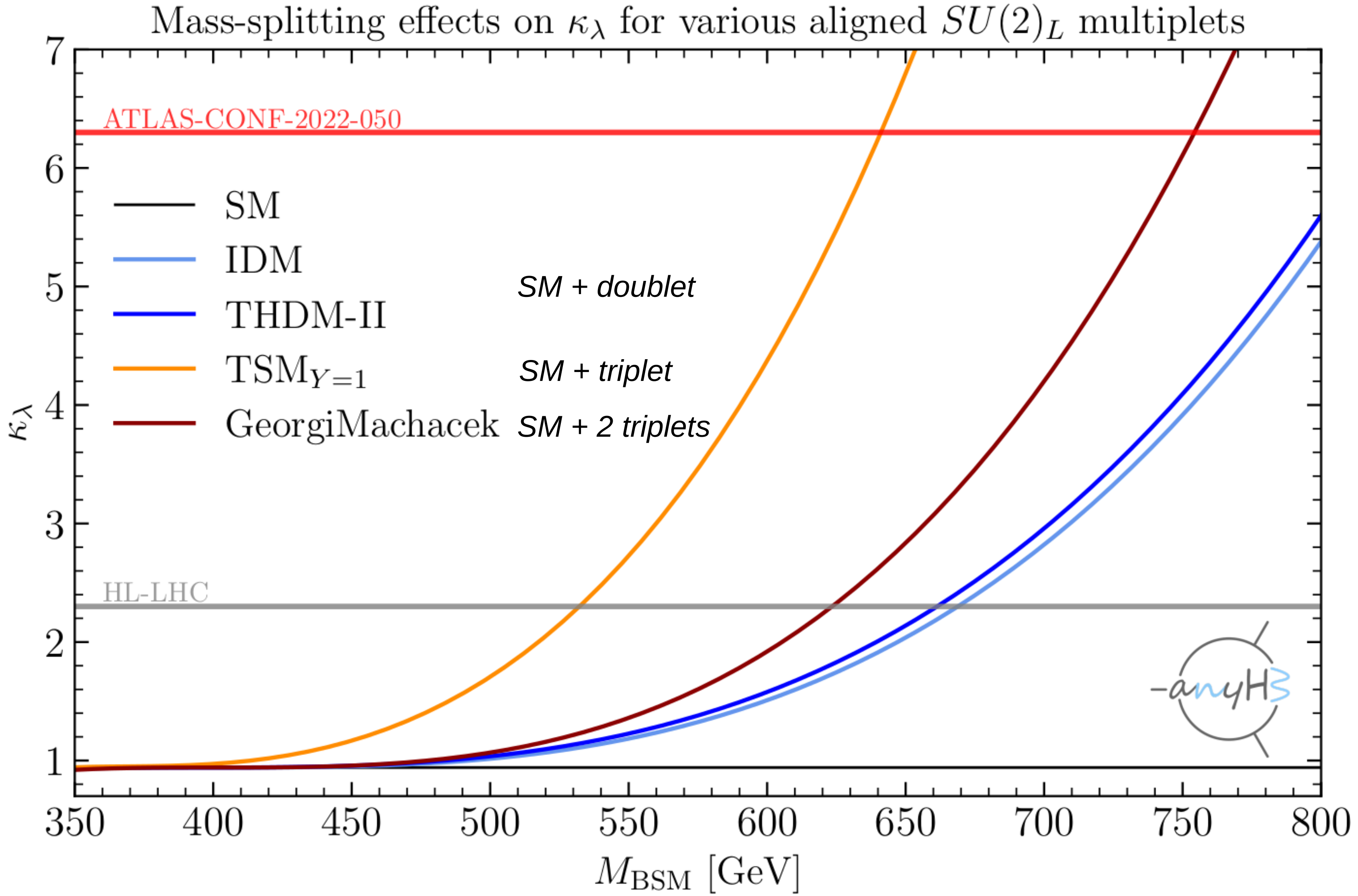
- Consider the non-decoupling limit in several BSM models

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

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

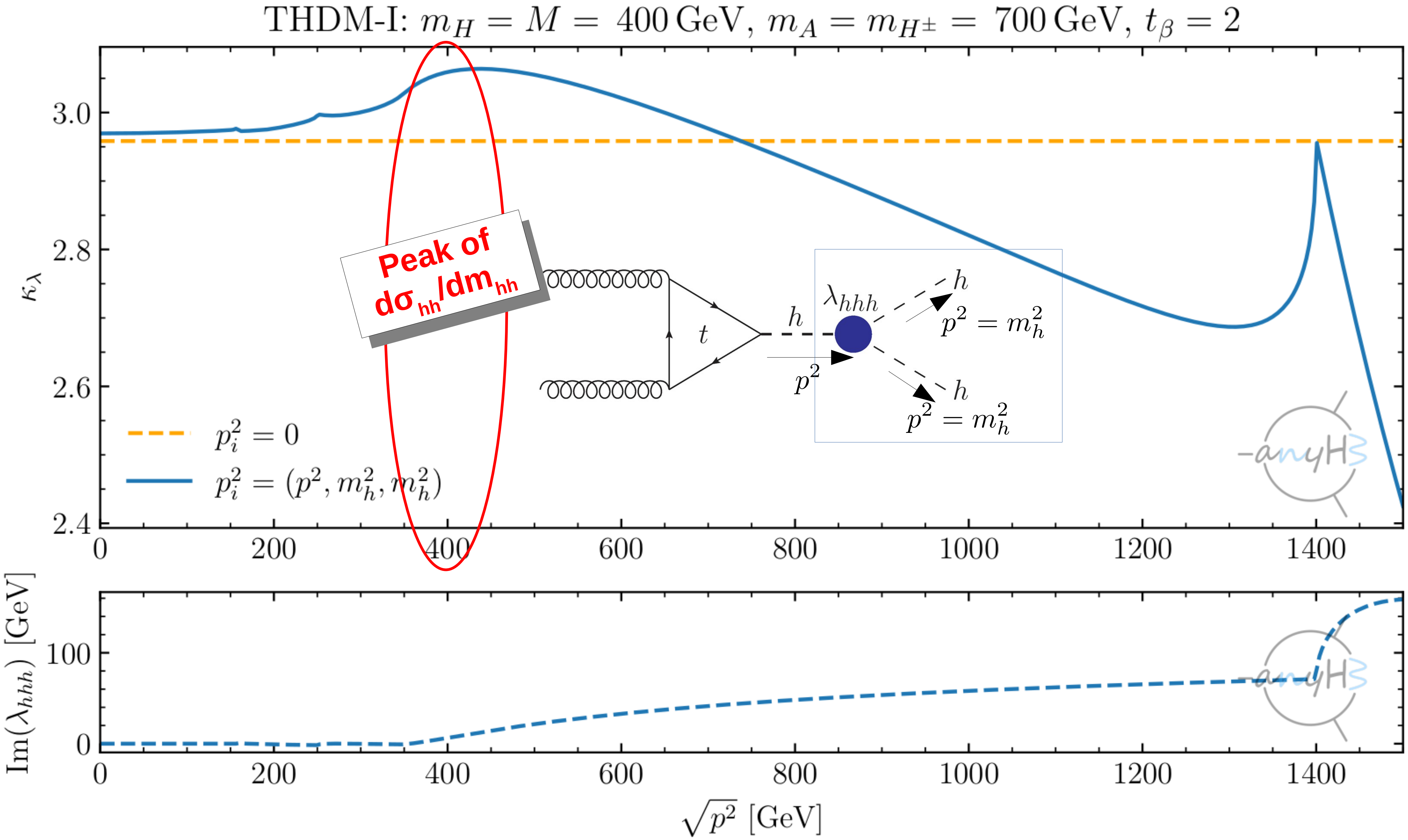
- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**



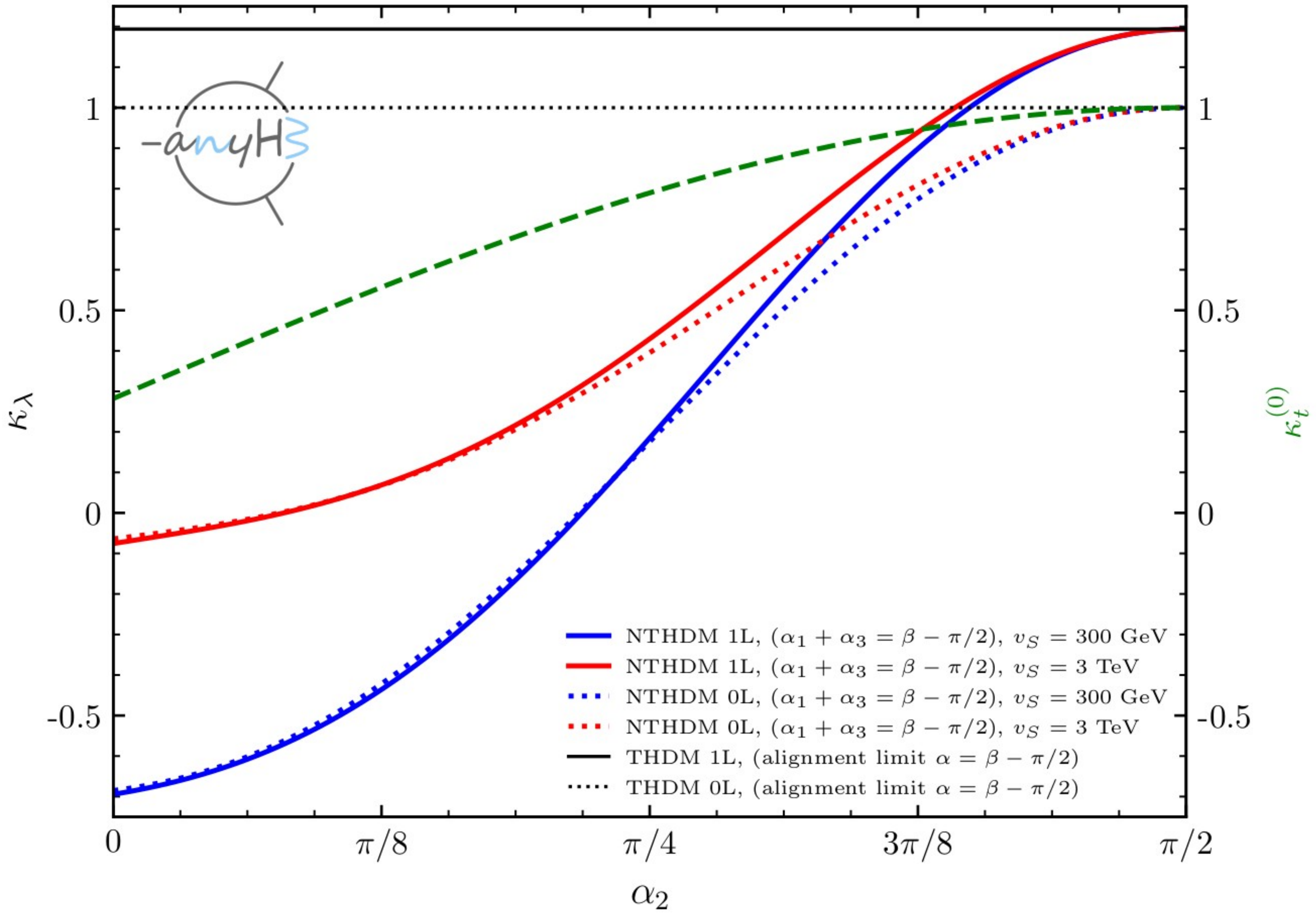
Here: scenarios with lightest BSM scalar mass & BSM mass param. at 400 GeV; other BSM scalar masses = M_{BSM}

New results II: momentum dependence in the 2HDM



More new results with `anyH3`: an example in the N2HDM

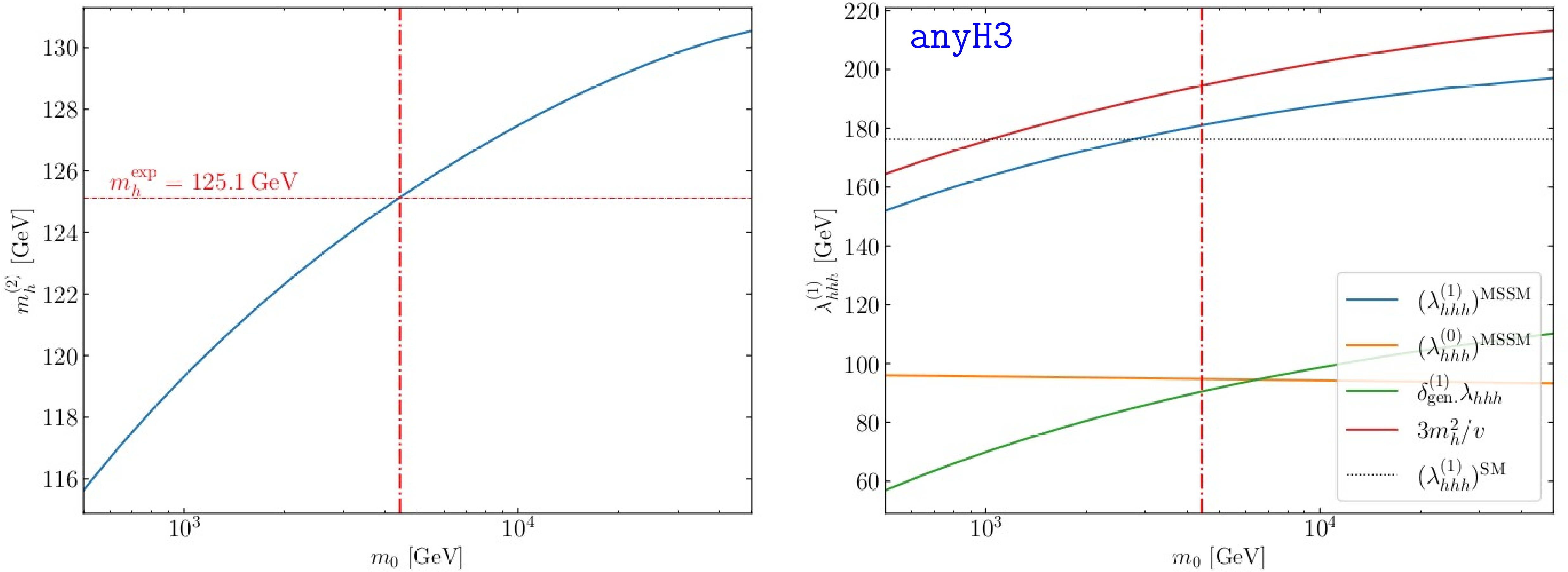
NTHDM: $m_{h_2} = 125.1$ GeV, $m_{h_1} = m_{h_3} = m_A = m_{H^\pm} = 300$ GeV, $\tilde{\mu} = 100$ GeV, $t_\beta = 2$



- **N2HDM = 2HDM + real singlet**
- CP-even sector: 3 states h_1, h_2, h_3, with 3 mixing angles α_1, α_2, α_3
- Here $\alpha_2 \to \pi/2$ → recover 2HDM (itself in alignment limit)
- We can study e.g. the relative sign of κ_λ and κ_t → affects double-Higgs production
- κ_t too far away from 1 excluded

Full one-loop calculation of λ_{hhh} in the MSSM

CMSSM, $m_0 = m_{1/2} = -A_0$, $\tan\beta = 10$, $\mathrm{sgn}(\mu) = 1$, with m_h computed at 2L in SPheno

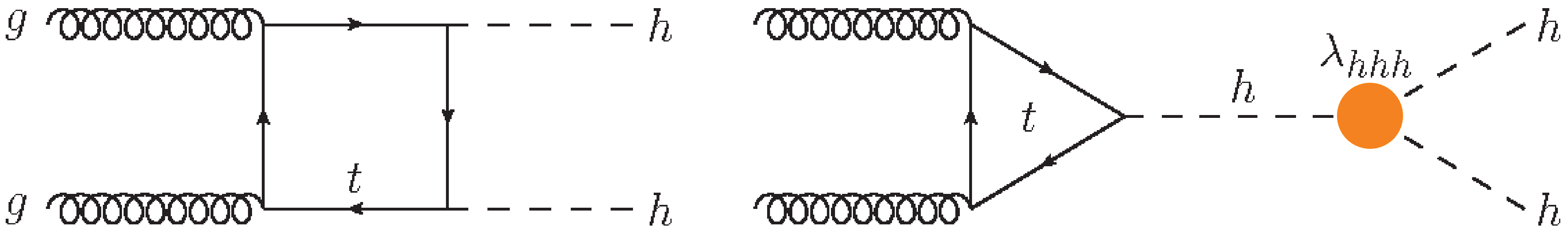


- Example for a very simple version of the constrained MSSM → BSM parameters m_0, $m_{1/2}$, A_0, sgn(μ), tanβ
- For each point, M_h computed at 2L with SPheno, and SLHA output of SPheno used as input of anyH3

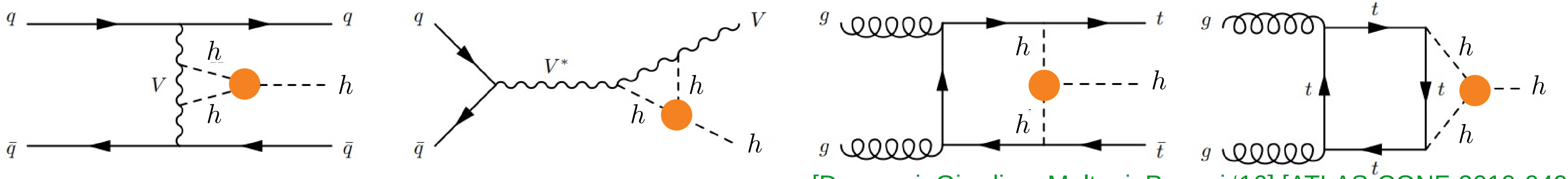
Trilinear Higgs self-coupling

Experimental probes of λ_{hhh}

- **Double-Higgs production** → λ_{hhh} enters at leading order (LO) → **most direct probe!**

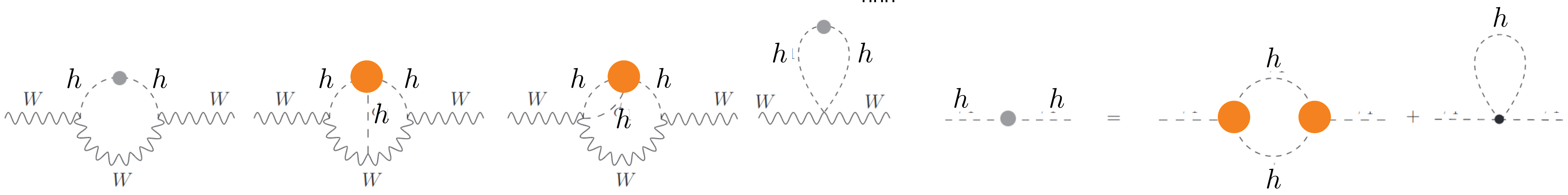


- **Single-Higgs production** → λ_{hhh} enters at NLO



[Degrassi, Giardino, Maltoni, Pagani '16] [ATLAS-CONF-2019-049]

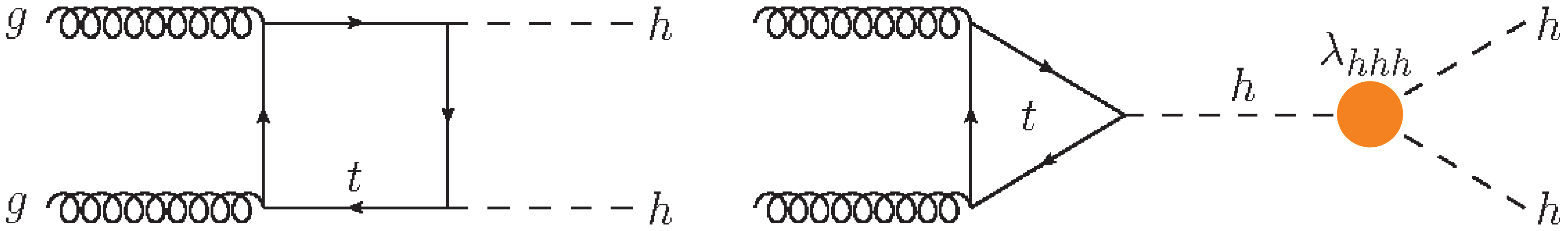
- **Electroweak Precision Observables** (EWPOs) → λ_{hhh} enters at NNLO



[Degrassi, Fedele, Giardino '17]

Accessing λ_{hhh} via di-Higgs production

- **Di-Higgs production** → λ_{hhh} enters at leading order (LO) → **most direct probe of λ_{hhh}**



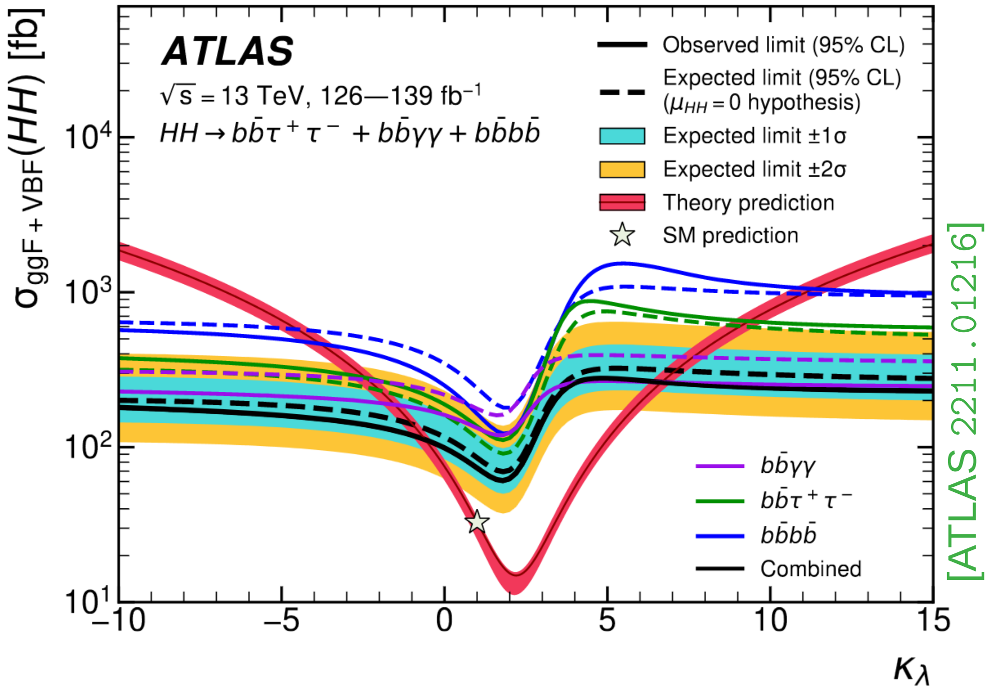
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

- Box and triangle diagrams **interfere destructively**
  → small di-Higgs cross-section σ_{hh} in SM

  → BSM deviation in λ_{hhh} can **significantly alter di-Higgs production!**

- Upper limit on di-Higgs cross-section
  → **limits on $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$**

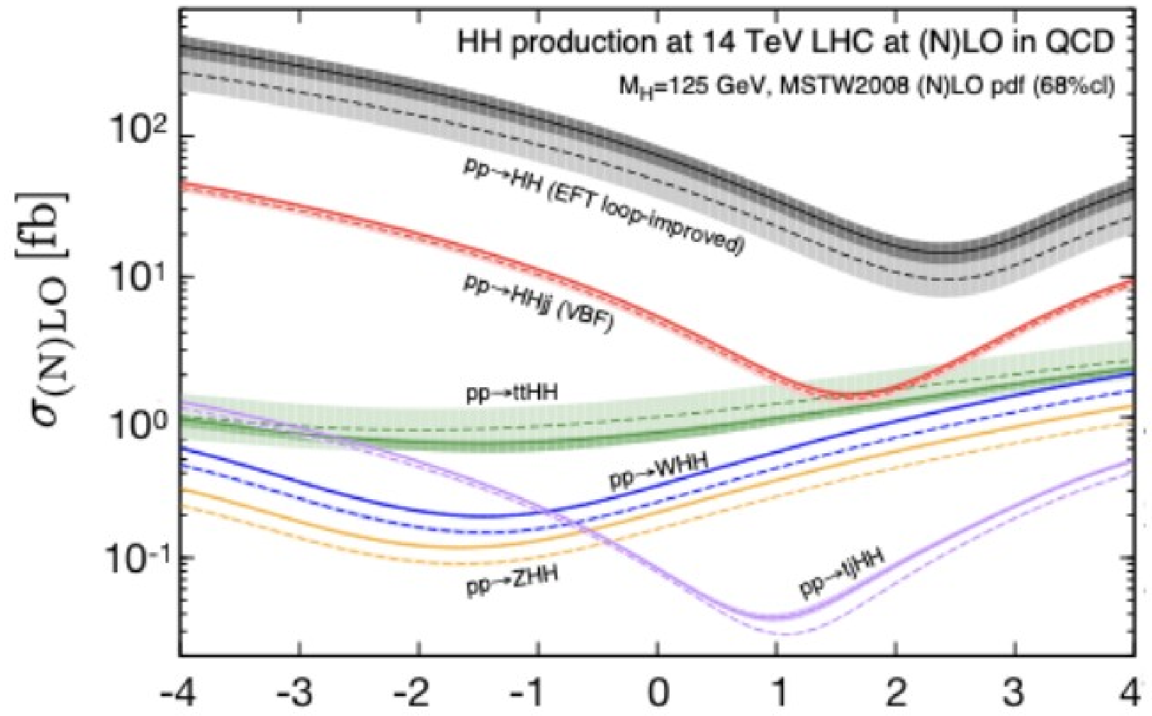
- κ_λ as an *effective coupling*: $\mathcal{L} \supset -\kappa_\lambda \times \frac{3m_h^2}{v^2} \cdot h^3 + \cdots$



Di-Higgs production cross-sections as a function of λ_{hhh}

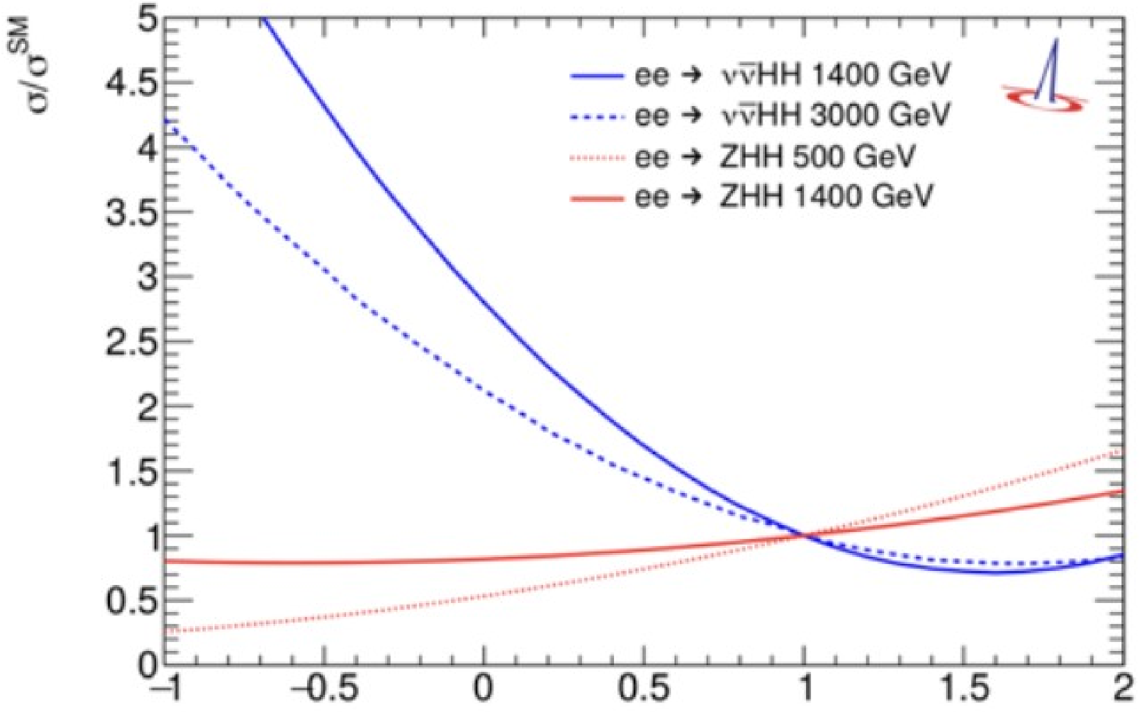
Plots taken from
[de Blas et al., 1905.03764]

Hadron collider



[Frederix et al., 1401.7340] $\lambda_3/\lambda_3^{SM} = \kappa_\lambda$

e^+e^- collider

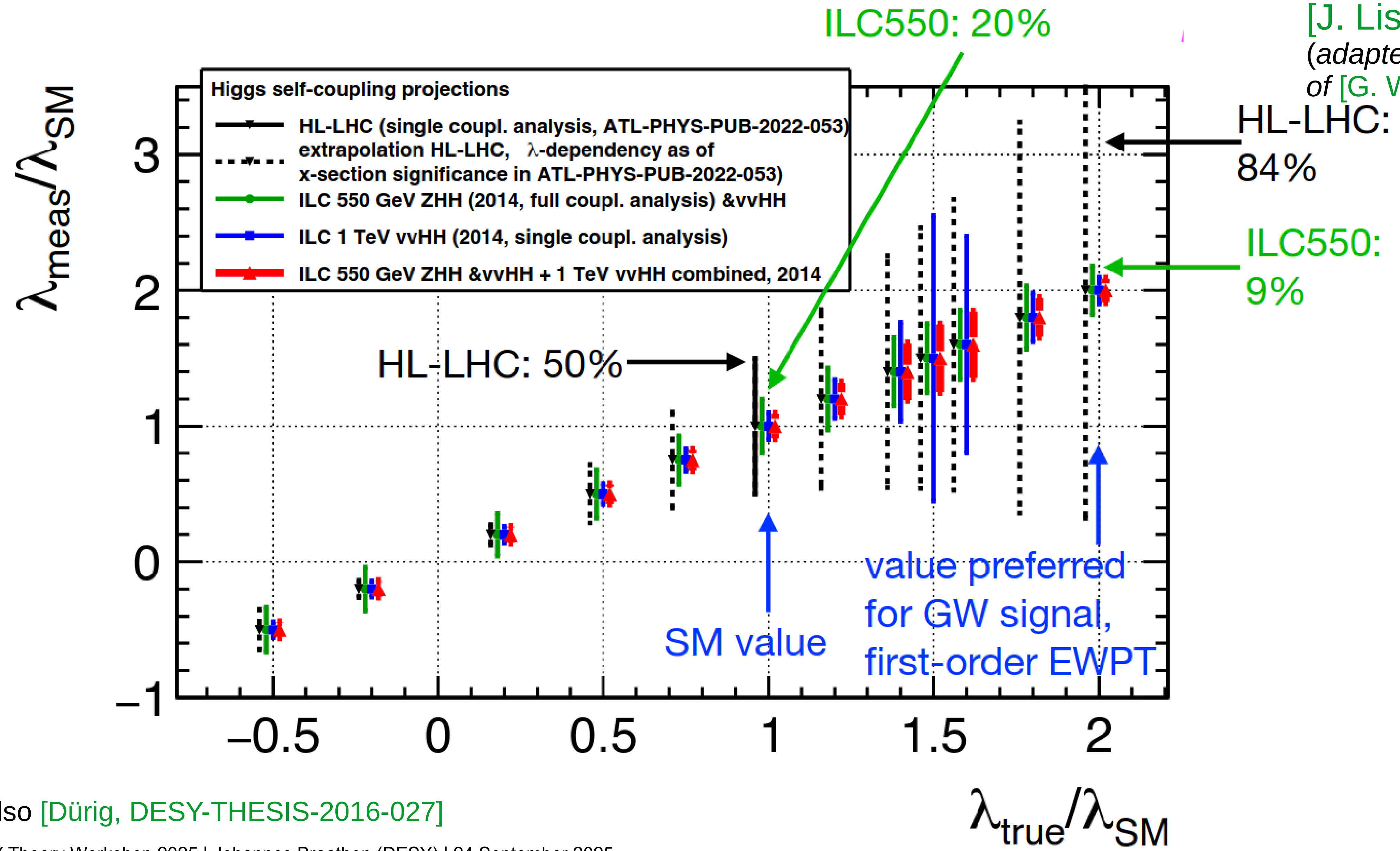


$\lambda_3/\lambda_3^{SM} = \kappa_\lambda$ [Reuter '19]

- **BSM deviation in κ_λ modifies the interference between different contributions to di-Higgs production**
- Strong impact on total cross-sections (and also on differential distributions, see later slides)

Precision on the determination of λ_{hhh} as a function of λ_{hhh}

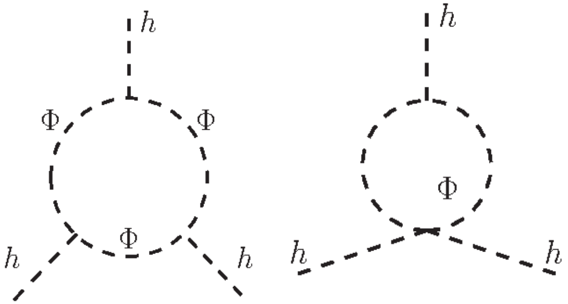
[J. List et al '24]
(*adapted from slide of* [G. Weiglein '24])



See also [Dürig, DESY-THESIS-2016-027]

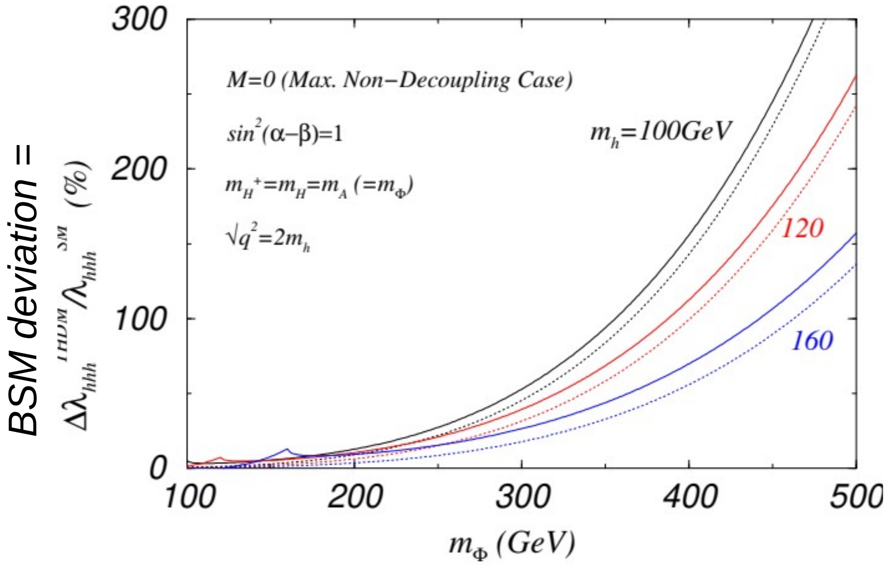
Mass splitting effects in λ_{hhh}

- First investigation of 1L BSM contributions to λ_{hhh} in 2HDM: [Kanemura, (Kiyoura), Okada, Senaha, Yuan '02, '04]



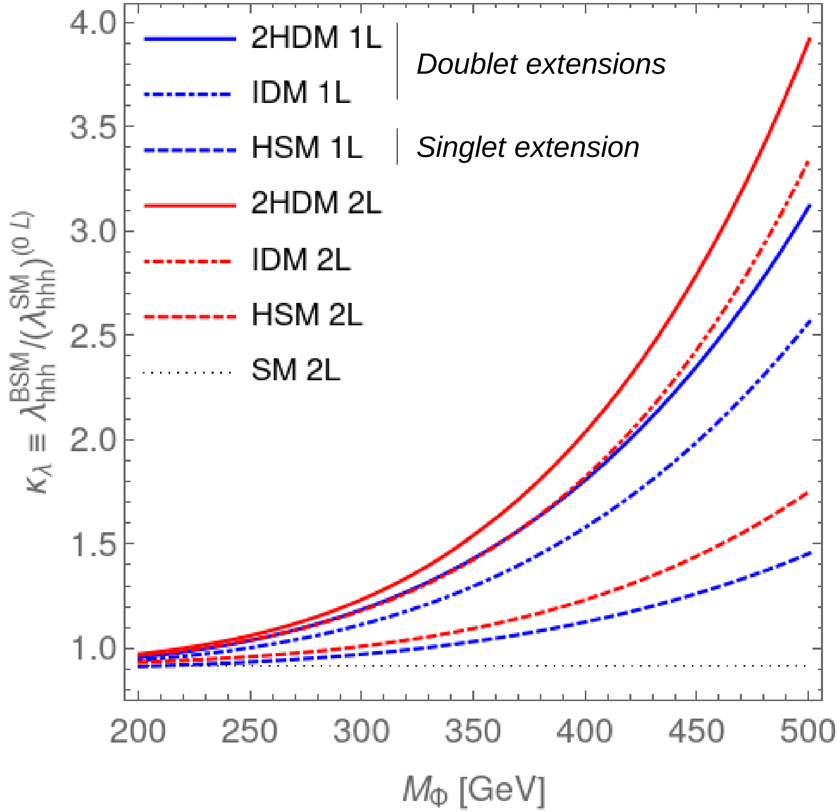
$$g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

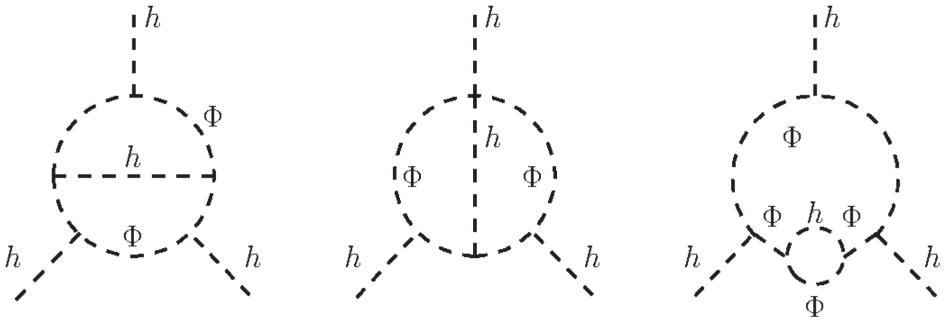
$$(\Phi \in \{H, A, H^\pm\})$$



- **Deviations of tens/hundreds of % from SM possible,** for **large $g_{h\Phi\Phi}$ or $g_{hh\Phi\Phi}$ couplings**
- **Mass splitting effects**, now found in various models (2HDM, inert doublet model, singlet extensions, etc.)

- Large effects **confirmed at 2L** in [JB, Kanemura '19]
→ **leading 2L corrections involving BSM scalars (H,A,H±) and top quark**, computed in effective potential approximation

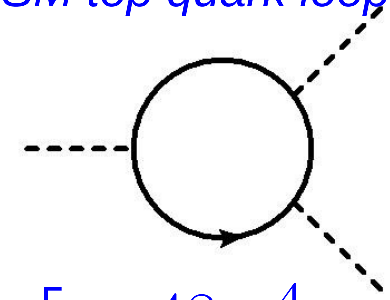




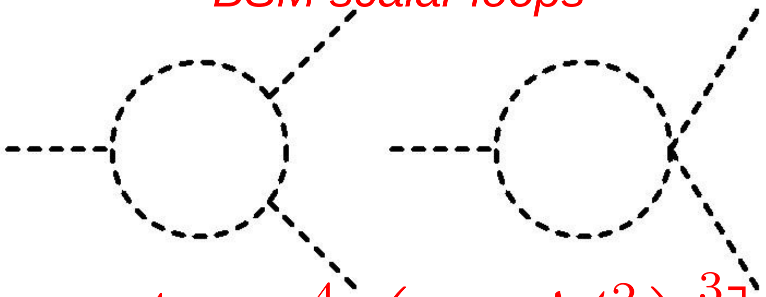
One-loop mass-splitting effects

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

SM top quark loop



BSM scalar loops



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

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

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

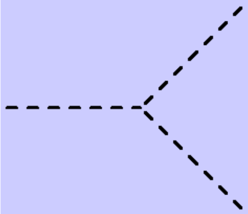
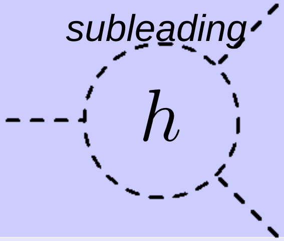
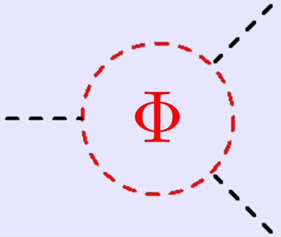
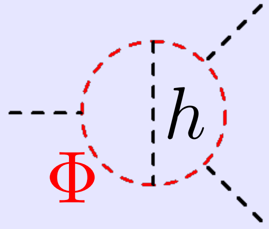
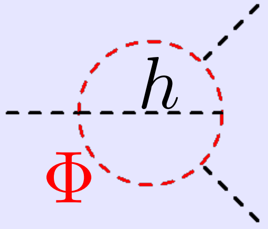
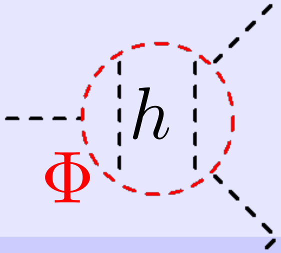
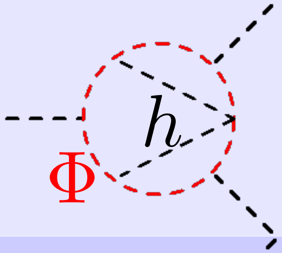
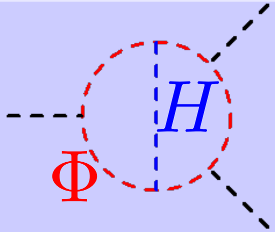
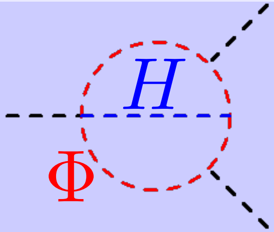
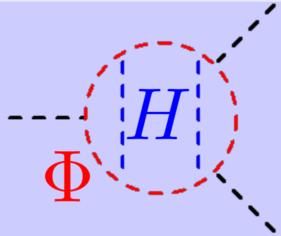
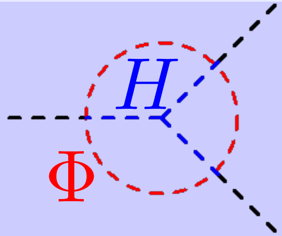
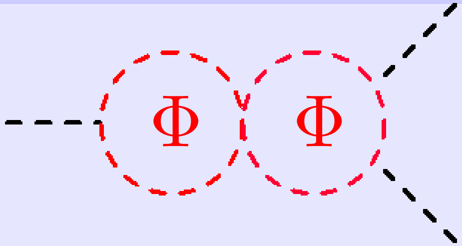
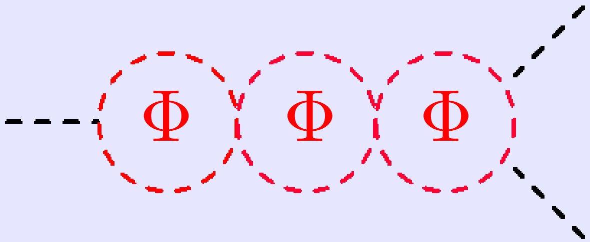
- Size of new effects depends on how the BSM scalars acquire their mass: $m_\Phi^2 \sim \mathcal{M}^2 + \tilde{\lambda}v^2$

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

→ **Huge BSM effects possible!**

Examples of scalar contributions to λ_{hhh} in aligned 2HDM

BSM scalars:
$\Phi \in \{H, A, H^{\pm}\}$
$m_\Phi^2 = M^2 + \tilde{\lambda}_\Phi v^2$

Coupling/Order	0L	1L	2L	3L
g_{hhhh}		*subleading* 	*subleading*	*subleading*
$g_{(h)h\Phi\Phi}$ $\left[g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}\right]$	-		 	 
$g_{(h)H\Phi\Phi'}$ [$g_{(h)G\Phi\Phi'}$ case similar]	-	-	 	 
$g_{\Phi\Phi\Phi'\Phi'}$ [2 BSM scalars of species Φ, 2 of species Φ']	-	-		

[NB: 1 h can be replaced by a VEV]

→ *no further type of coupling entering after 2L*

→ *for each class of diagrams, perturbative convergence can be checked!*

e.g. in [Bahl, JB, Weiglein PRL '22]

Constraining BSM models with λ_{hhh}

i. Can we apply the limits on κ_λ, extracted from experimental searches for di-Higgs production, for BSM models?

ii. Can large BSM deviations occur for points still allowed in light of theoretical and experimental constraints? If so, how large can they become?

As a concrete example, we consider an aligned 2HDM

Based on

arXiv:2202.03453 **(Phys. Rev. Lett.) in collaboration with Henning Bahl and Georg Weiglein**

Can we apply di-Higgs results for the aligned 2HDM?

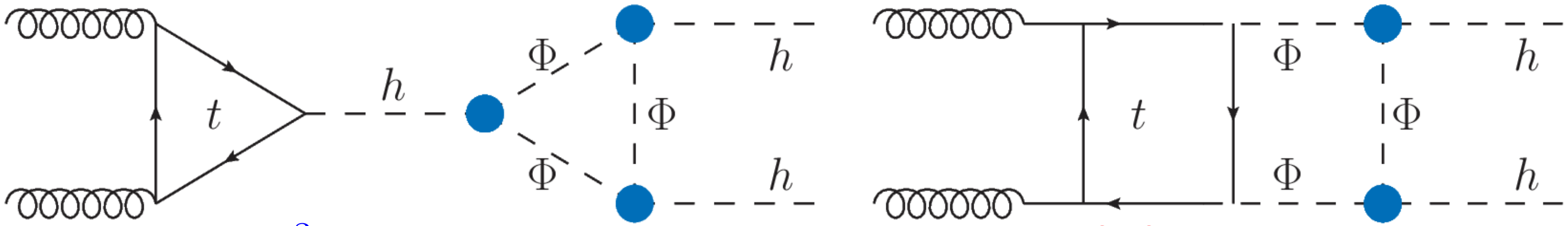
- Current strongest limits on κ_λ from ATLAS di-Higgs searches

  $-1.2 < \kappa_\lambda < 7.2$ [ATLAS-CONF-2024-006]

  [where $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$]

- What are the *assumptions* for the ATLAS limits?
  - All other Higgs couplings (to fermions, gauge bosons) are SM-like

    → this is **ensured by the alignment** ✓
  - The modification of λ_{hhh} is the only source of deviation of the *non-resonant Higgs-pair production cross section* from the SM



$\propto \mathcal{O}(y_t g^3_{hh\Phi\Phi})$ ***included*** $\propto \mathcal{O}(y_t^2 g^2_{hh\Phi\Phi})$ *not included*

→ We **correctly include all leading BSM effects to di-Higgs production, in powers of $g_{hh\Phi\Phi}$, up to NNLO!** ✓

- **We can apply the ATLAS limits to our setting!**

A parameter scan in the aligned 2HDM

[Bahl, JB, Weiglein PRL '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
- 125-GeV Higgs measurements with `HiggsSignals`
- Direct searches for BSM scalars with `HiggsBounds`
- b-physics constraints, using results from [Gfitter group 1803.01853]

] Checked with `ScannerS` [Mühlleitner et al. `2007.02985`]

- EW precision observables, computed at two loops with `THDM_EWPOS` [Hessenberger, Hollik '16, '22]

theoretical
- Vacuum stability
- Boundedness-from-below of the potential

] Checked with `ScannerS`

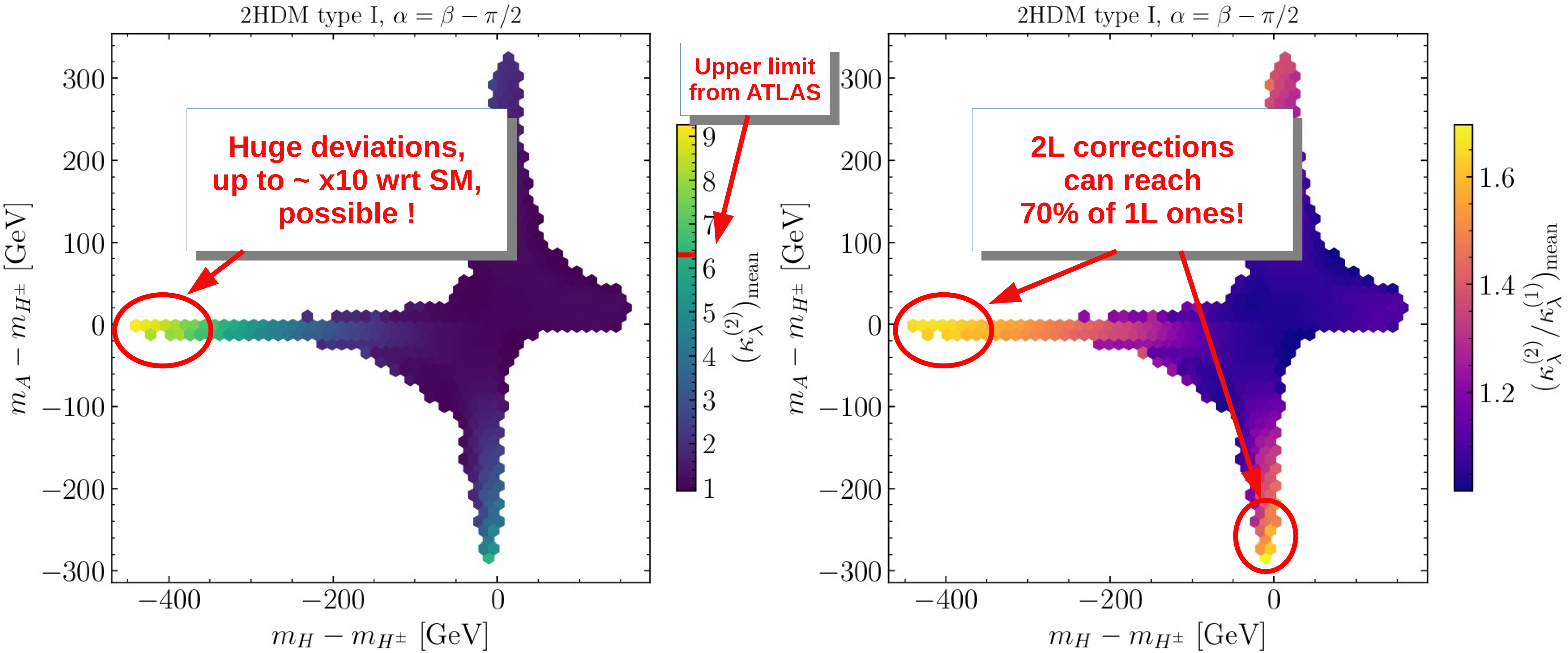
- NLO perturbative unitarity, using results from [Grinstein et al. `1512.04567`], [Cacchio et al. `1609.01290`]

- For points passing these constraints, we **compute κ_λ at 1L and 2L**, using results from [JB, Kanemura '19]

Parameter scan results

[Bahl, JB, Weiglein PRL '22]

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



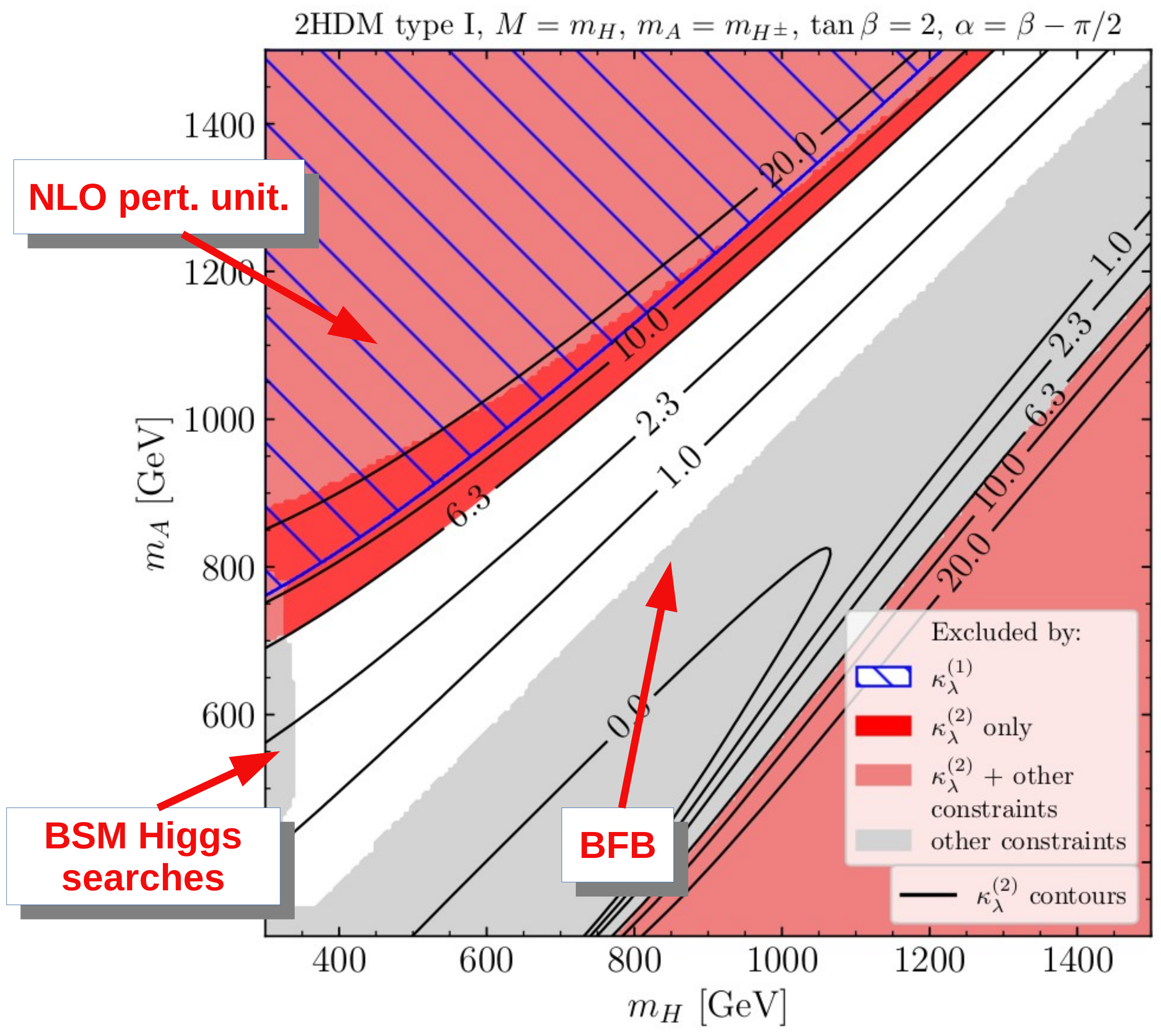
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark scenario in the aligned 2HDM

[Bahl, JB, Weiglein PRL '22]

Results shown for aligned 2HDM of type-I, similar for other types (*available in backup*)

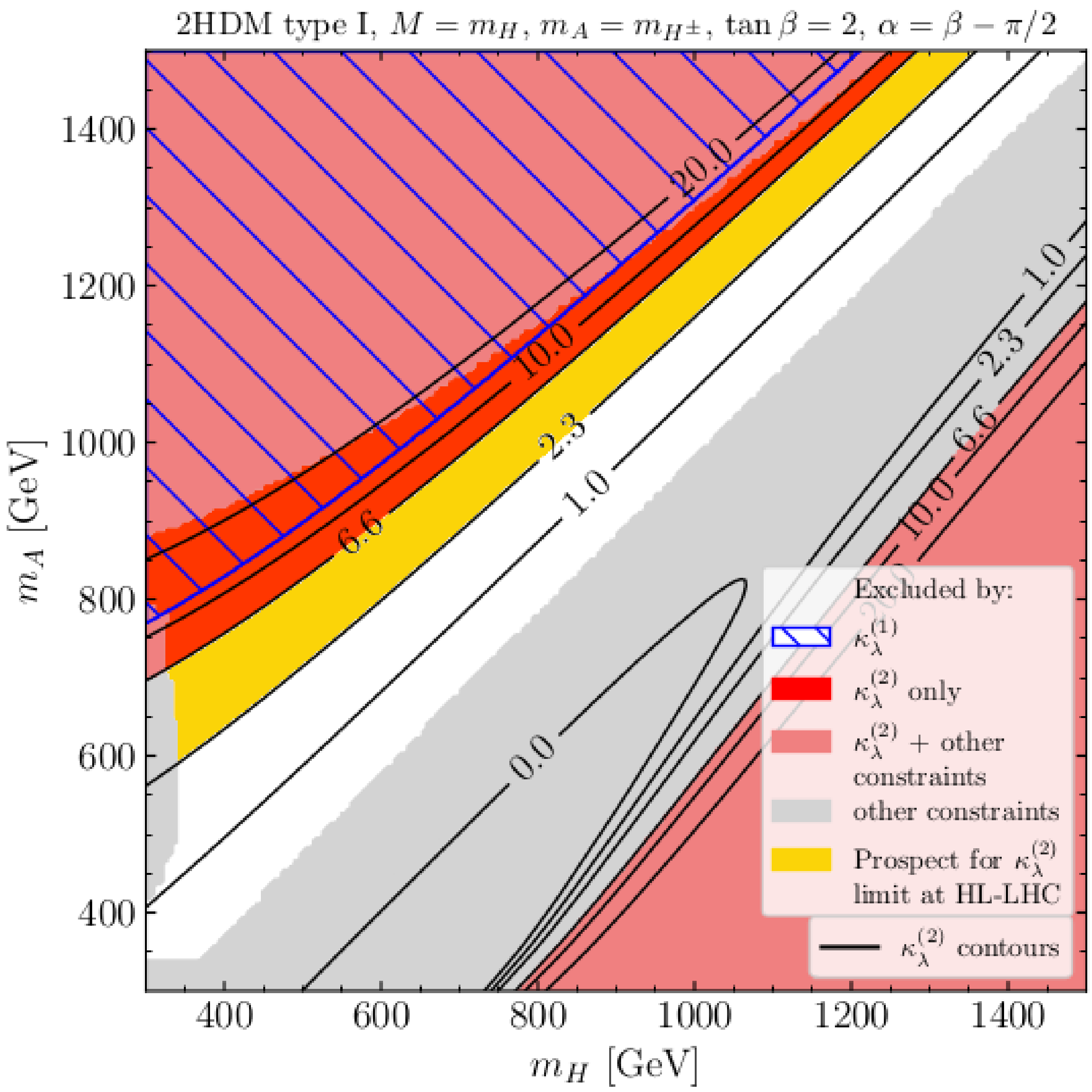
We take $m_A = m_{H\pm}$, $M = m_H$, $\tan\beta = 2$



- ***Grey area:*** area excluded by other constraints, in particular BSM Higgs searches, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.3$ [in region where $\kappa_\lambda^{(2)} < -0.4$ the calculation isn't reliable]
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.3$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.3$ → impact of including 2L corrections is significant!

A benchmark scenario in the aligned 2HDM – future prospects

Suppose for instance the upper bound on κ_λ becomes $\kappa_\lambda < 2.3$



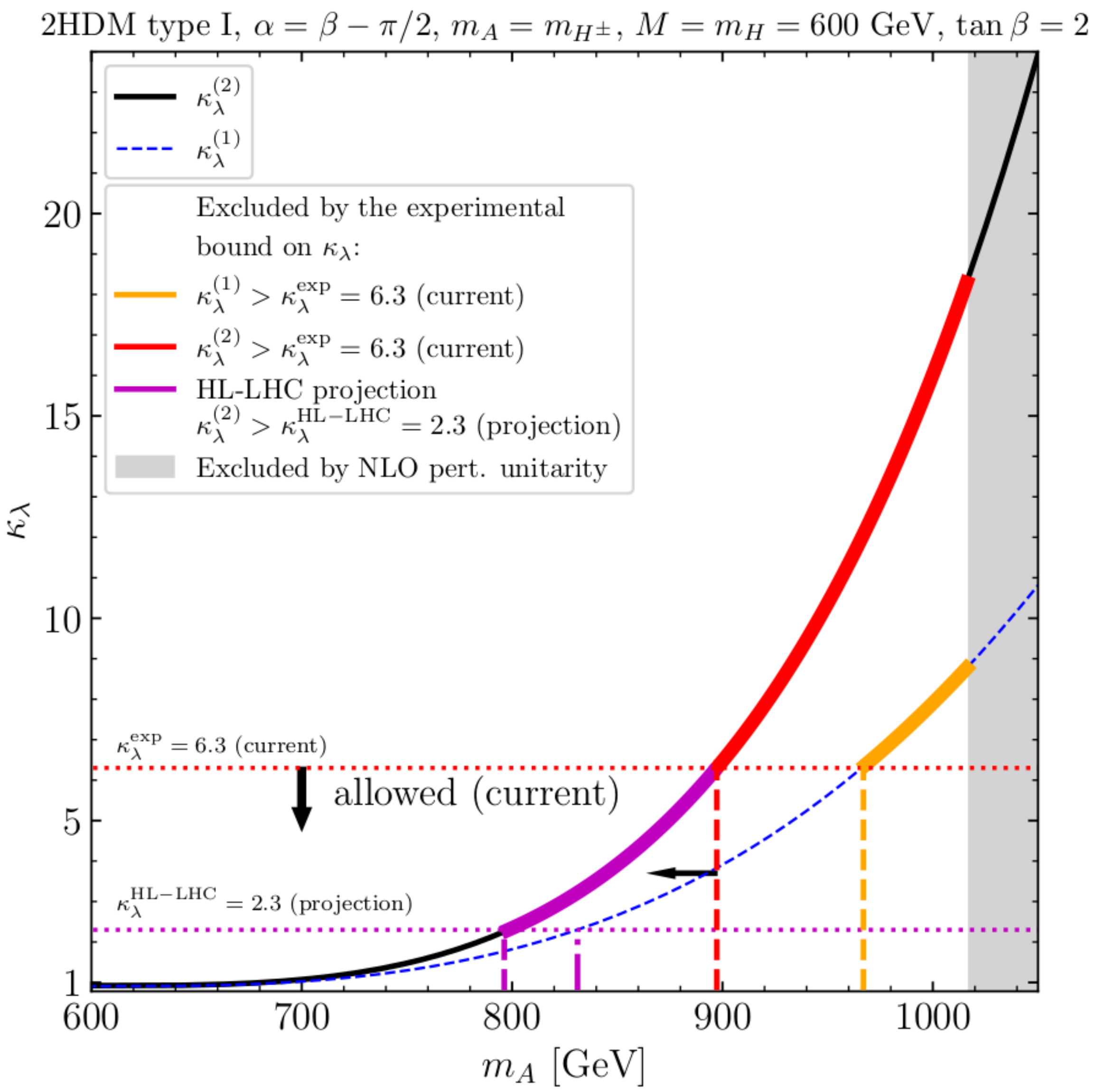
[Bahl, JB, Weiglein '23]

- ***Golden area:*** additional exclusion if the limit on κ_λ becomes $\kappa_\lambda^{(2)} < 2.3$ (achievable at HL-LHC)
- Of course, **prospects even better with an e^+e^- collider!**
- Experimental constraints, such as Higgs physics, may also become more stringent, however **not** theoretical constraints (like BFB or perturbative unitarity)

A benchmark scenario in the aligned 2HDM – 1D scan

Within the previously shown plane, we fix $M=m_H=600$ GeV, and vary $m_A=m_{H\pm}$

[Bahl, JB, Weiglein PRL '22]

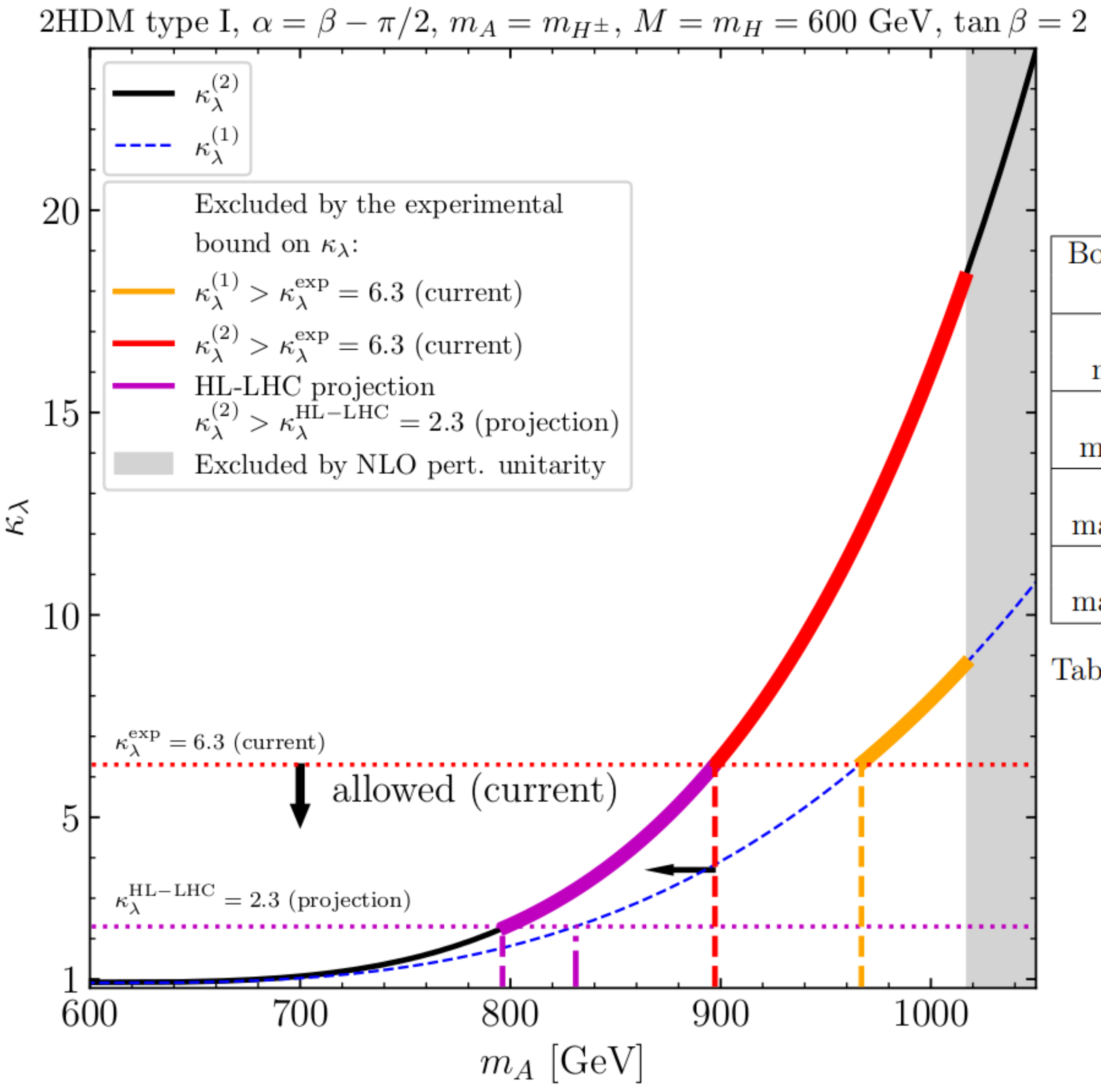


- Illustrates the significantly improved reach of the experimental limit when including **2L corrections** in calculation of κ_λ

- A stricter choice for the perturbative unitarity constraint (grey) does not significantly change the region excluded by $\kappa_\lambda^{(2)}$

A benchmark scenario in the aligned 2HDM – 1D scan

[Bahl, JB, Weiglein PRL '22]



Bound on eigenvalues	$\max(m_A)$ with LO pert. unit.	$\max(m_A)$ with NLO pert. unit.	$\max(m_A)$ with with finite $\sqrt{s} \in [3\text{ TeV}, 10\text{ TeV}]$
$\max(\lvert a_i \rvert) < 1$	1161 GeV	1017 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 1$	1161 GeV	1033 GeV	1260 GeV
$\max(\lvert a_i \rvert) < 0.5$	917 GeV	937 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.5$	917 GeV	958 GeV	929 GeV
$\max(\lvert a_i \rvert) < 0.49$	911 GeV	933 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.49$	911 GeV	956 GeV	922 GeV
$\max(\lvert a_i \rvert) < 0.45$	889 GeV	912 GeV	–
$\max(\lvert \mathfrak{Re}(a_i) \rvert) < 0.45$	889 GeV	948 GeV	897 GeV

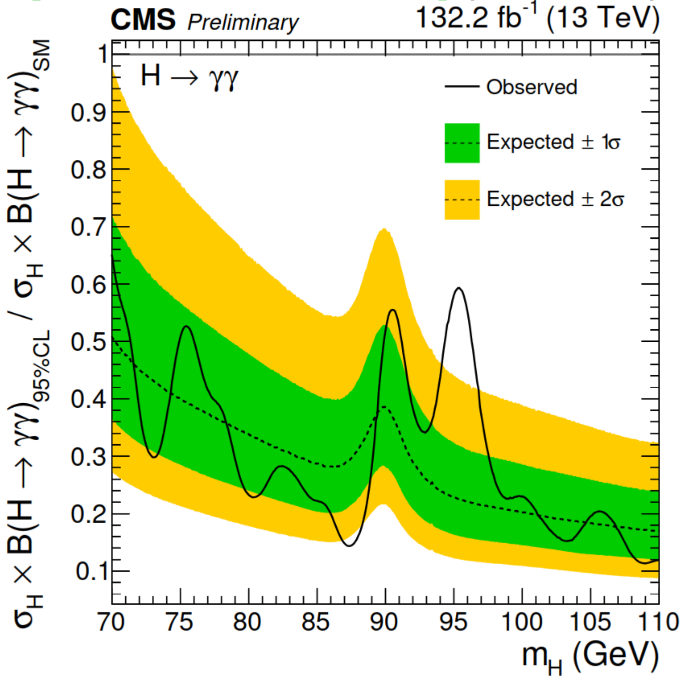
Table 1: Maximal values of m_A allowed in the benchmark scenario under the constraint of perturbative unitarity, at LO and NLO, and for different upper bounds on the $2 \to 2$ scattering eigenvalues used in the perturbative unitarity constraint. Note that tree-level scattering eigenvalues are all real, so there is no difference between using max or $\mathfrak{Re}$(max) for the left column.

LHC excesses

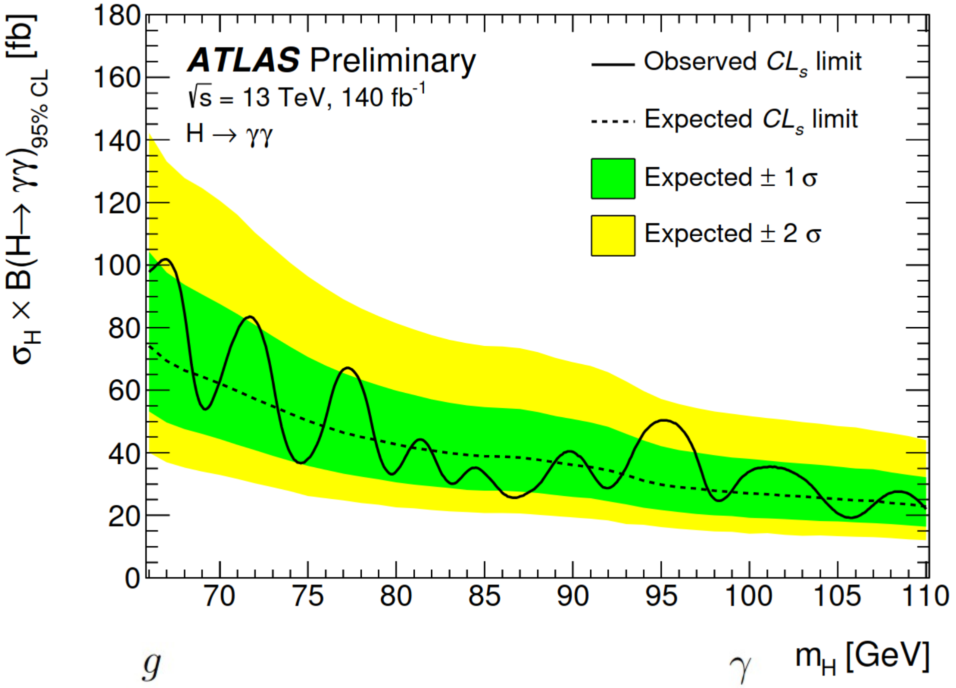
A Higgs boson at 95 GeV?

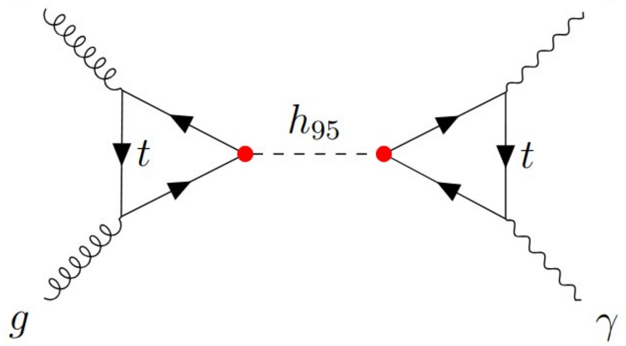
- Excesses at 95 GeV in ATLAS and CMS low mass searches for $\Phi \to \gamma\gamma$

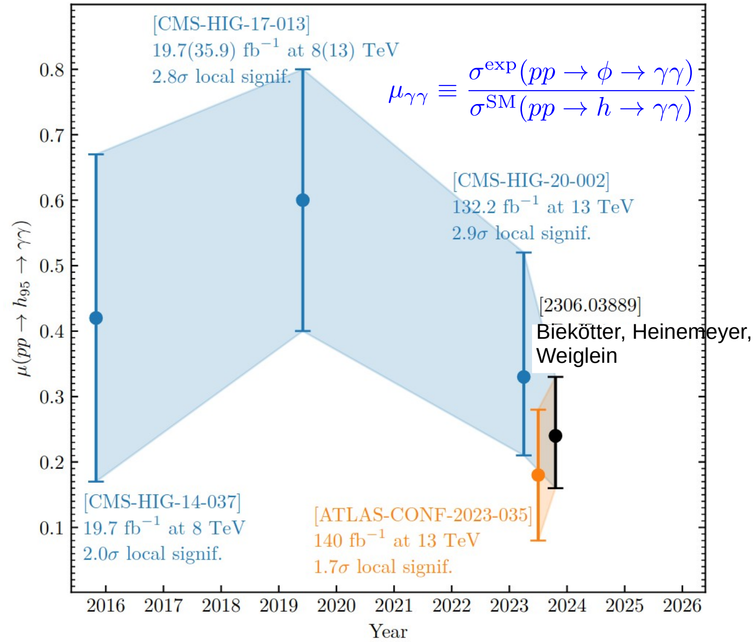
[CMS PAS HIG-20-002] (2.9σ local)



[ATLAS-CONF-2023-035] (1.7σ local)

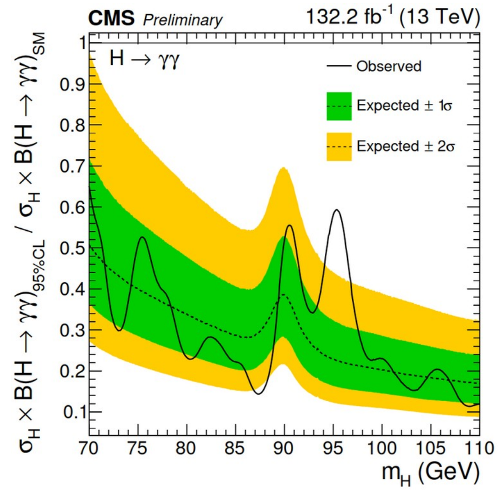




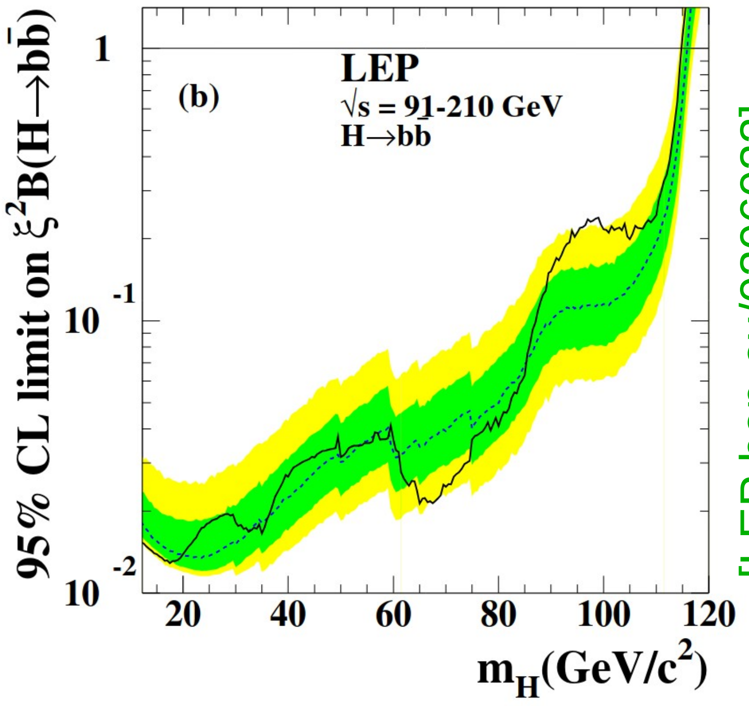


[Biekötter '24]

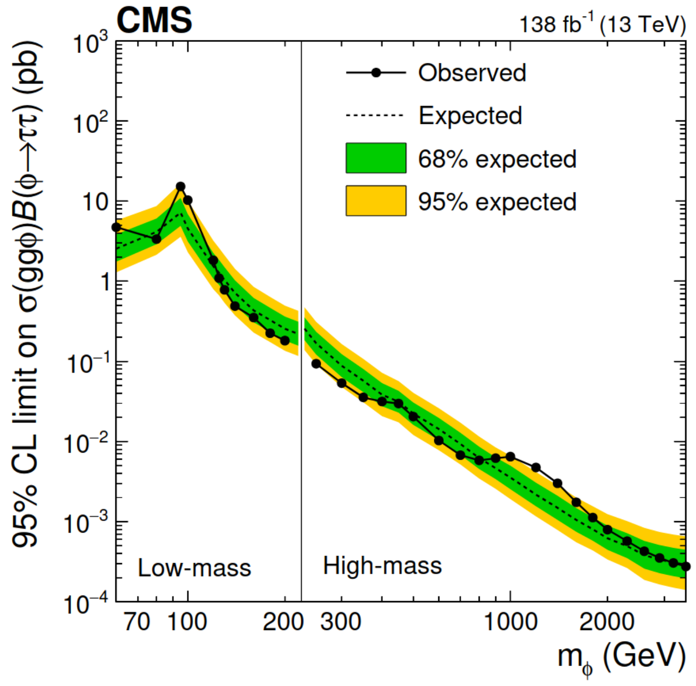
A Higgs boson at 95 GeV?



- Excesses at 95 GeV in ATLAS and CMS low mass searches for $\Phi \to \gamma\gamma$
- Could correspond to LEP data in $\Phi \to b\bar{b}$ (but debated, see [Janot ‘24])
- CMS also found a broad excess (run 2) in $\Phi \to \tau^+\tau^-$, around 95-100 GeV
  However, only observed in ggF, and not in other production modes, in particular $t\bar{t}h$ (although it should have); also no corresponding ATLAS run 2 result so far



[LEP hep-ex/0306033]



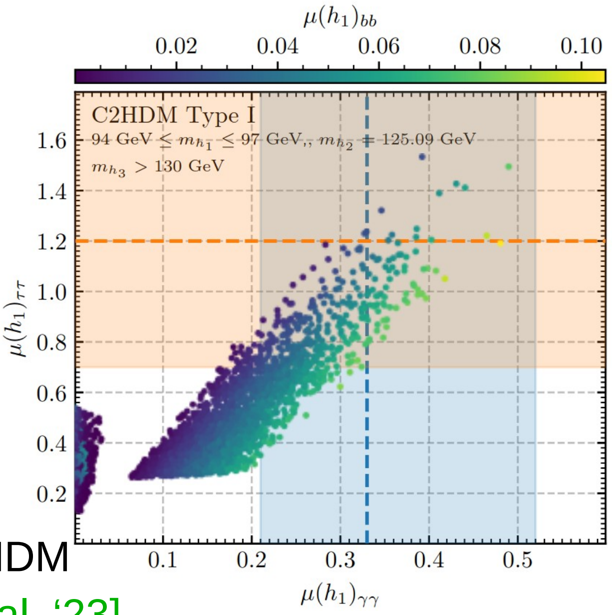
[CMS-HIG-21-001]

A Higgs boson at 95 GeV? – a few possible interpretations

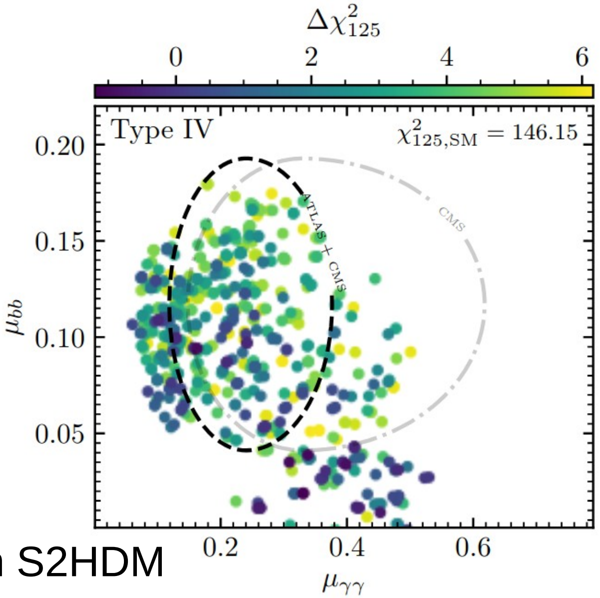
- Main classes of models accommodating h_{95}:
  1) h_{95} belongs to an $SU(2)_L$ multiplet, e.g. 2HDM variants, Y=0 triplet, etc.

  2) h_{95} comes from a singlet field mixing with h_{125}
  e.g. N2HDM, S2HDM, NMSSM, μνSSM, etc.

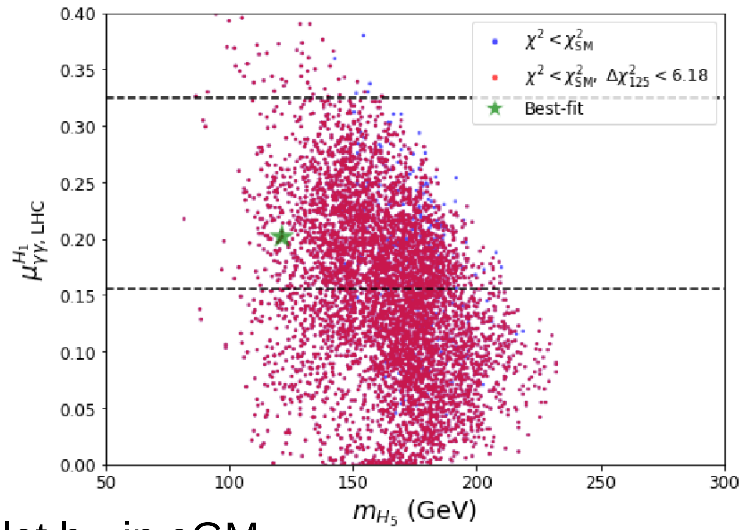
  3) h_{95} is singlet-like, but $\mu(h_{95} \to \gamma\gamma)$ is explained by additional charged states, e.g. extended Georgi-Machacek model, etc.



1) A_{95} in C2HDM
[Azevedo et al. '23]



2) h_{95} in S2HDM
[Biekötter et al. '23]



3) Singlet h_{95} in eGM
[Chen et al. '23]

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  2) h_{95} comes from a singlet field mixing with h_{125}
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  3) h_{95} is singlet-like, but $\mu(h_{95} \to \gamma\gamma)$ is explained by additional charged states, e.g. extended Georgi-Machacek model, etc.

What next?

→ wait for ATLAS $\Phi \to \tau^+\tau^-$ run 2 results, and ATLAS and CMS run 3 results

→ look for additional states (e.g. $H^\pm$, $H^{\pm\pm}$, ...) of models explaining h_{95} – directly, via effects on properties of h_{125} (like $h_{125} \to \gamma\gamma$), or via mixing effects

Excesses in soft-lepton and monojet searches