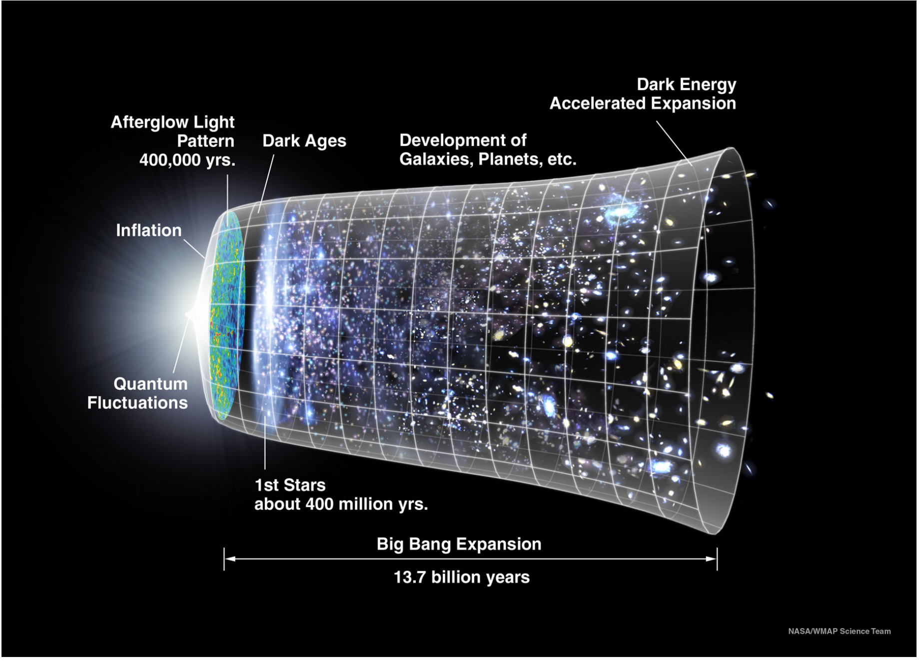
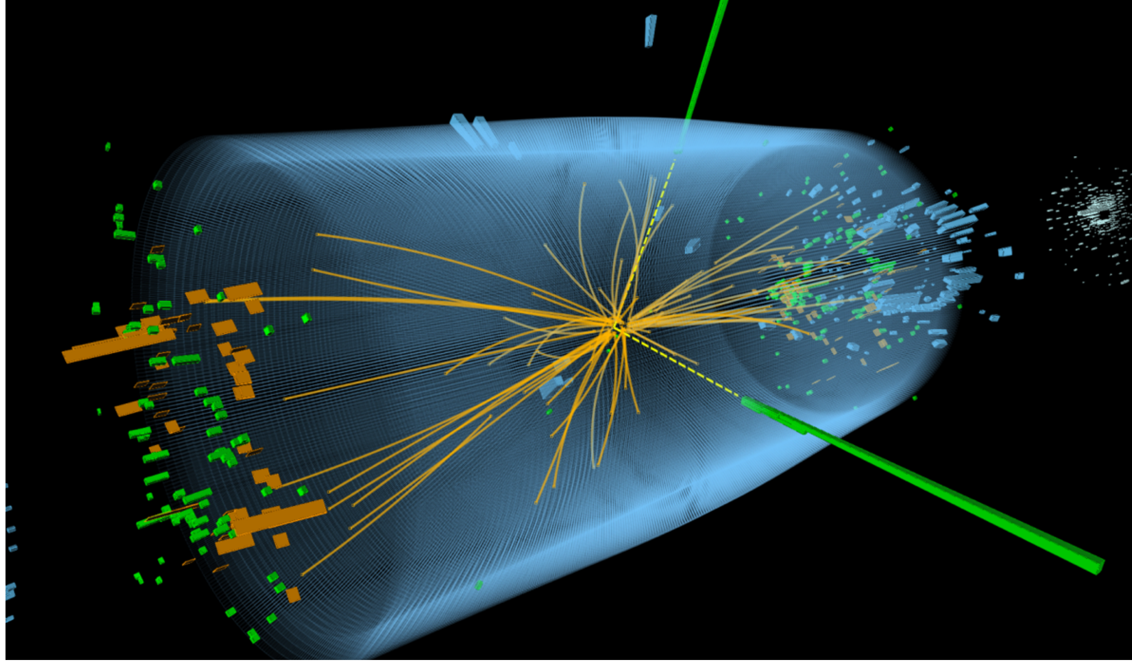
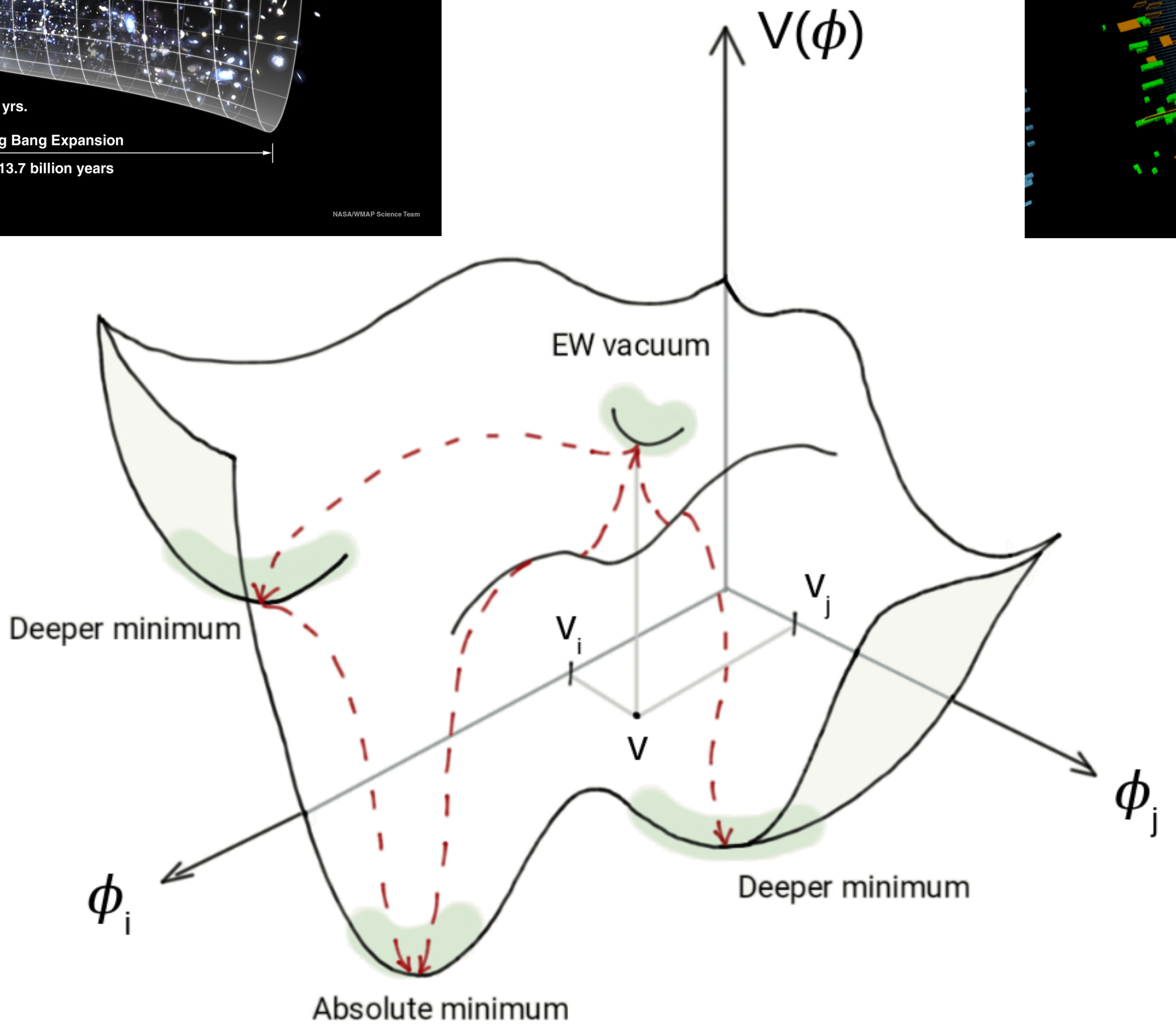
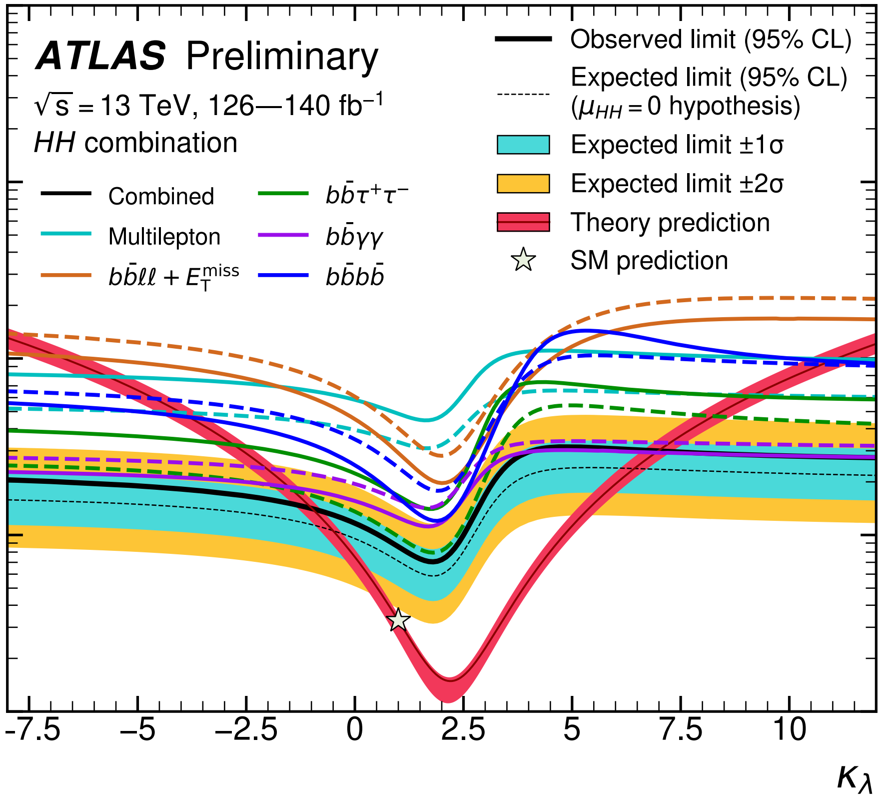








Bridging the gap: Requests from Theory to Experiment

Georg Weiglein, DESY & UHH

CERN, 10 / 2024

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

My adaptation of the title:

Requests

→ Needs / Wishes / Suggestions / Room for improvements …

Please note:

For illustration I will use a few slides from Halil Saka’s talk on Monday

If I make remarks where I see room for improvements, these remarks are not directed to Halil but to the discussed analyses from ATLAS and CMS!

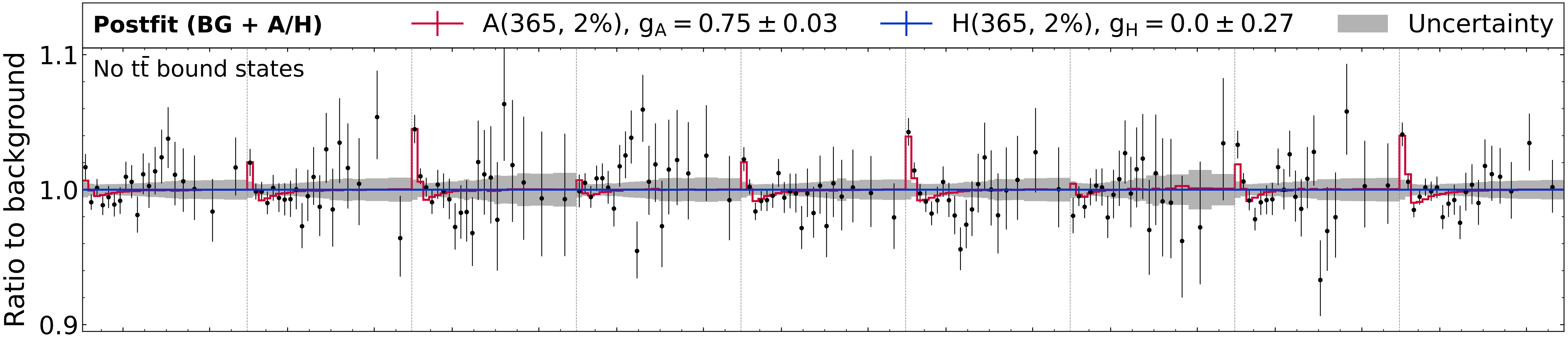
Theory wishes: a discovery would be nice …

Theory wishes: a discovery would be nice …

Did a discovery actually just happen? Of what?

Recent CMS result on BSM Higgs searches in the tt final state: ϕ = H, A, η_t (tt bound state), using spin correlations (variables c_{hel} and c_{han}), di-lepton channel, different bins of the two variables:

[CMS Collaboration '24]

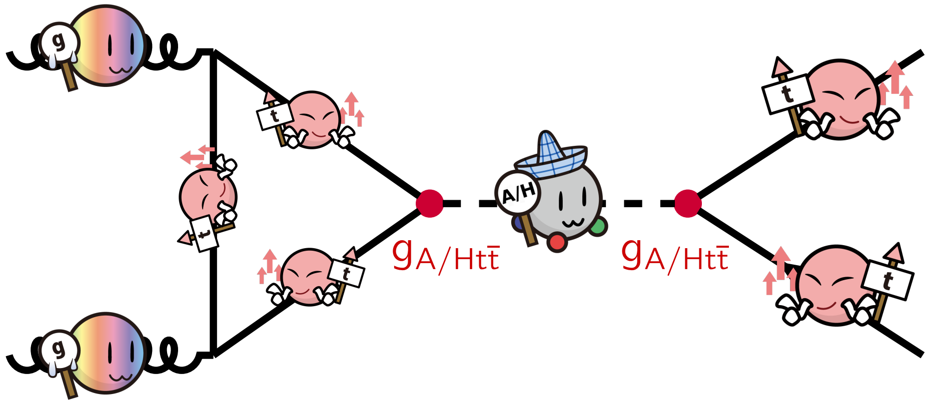


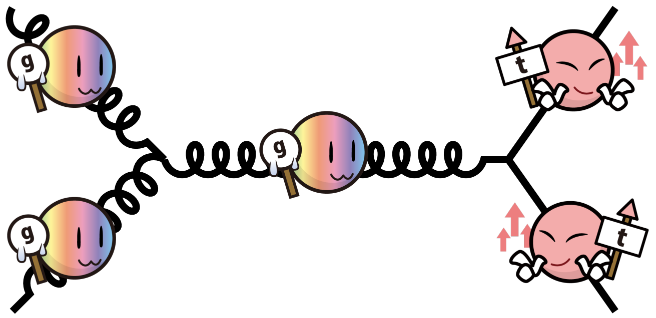
Results are well compatible with CP-odd Higgs boson A at 365 GeV or tt bound state at 343 GeV; excess of (much) more than 5 σ compared to SM background from perturbative QCD

Previous CMS analysis (first year of Run 2)

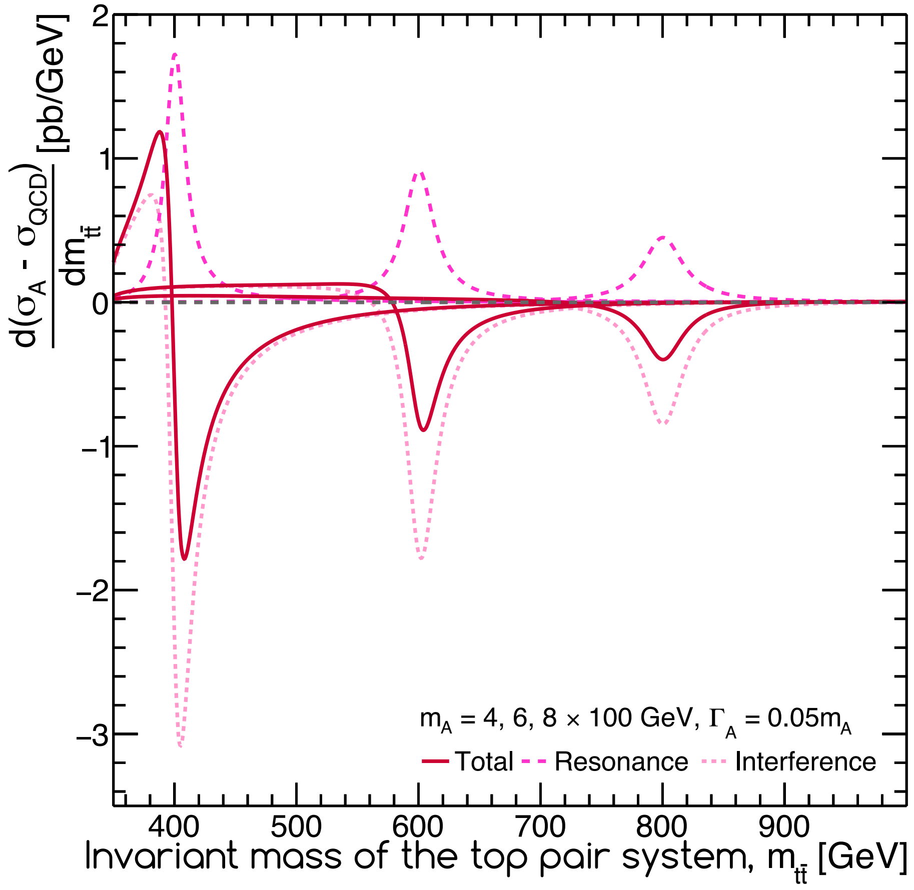
H, A → tt search in CMS

[A. Anuar '21]





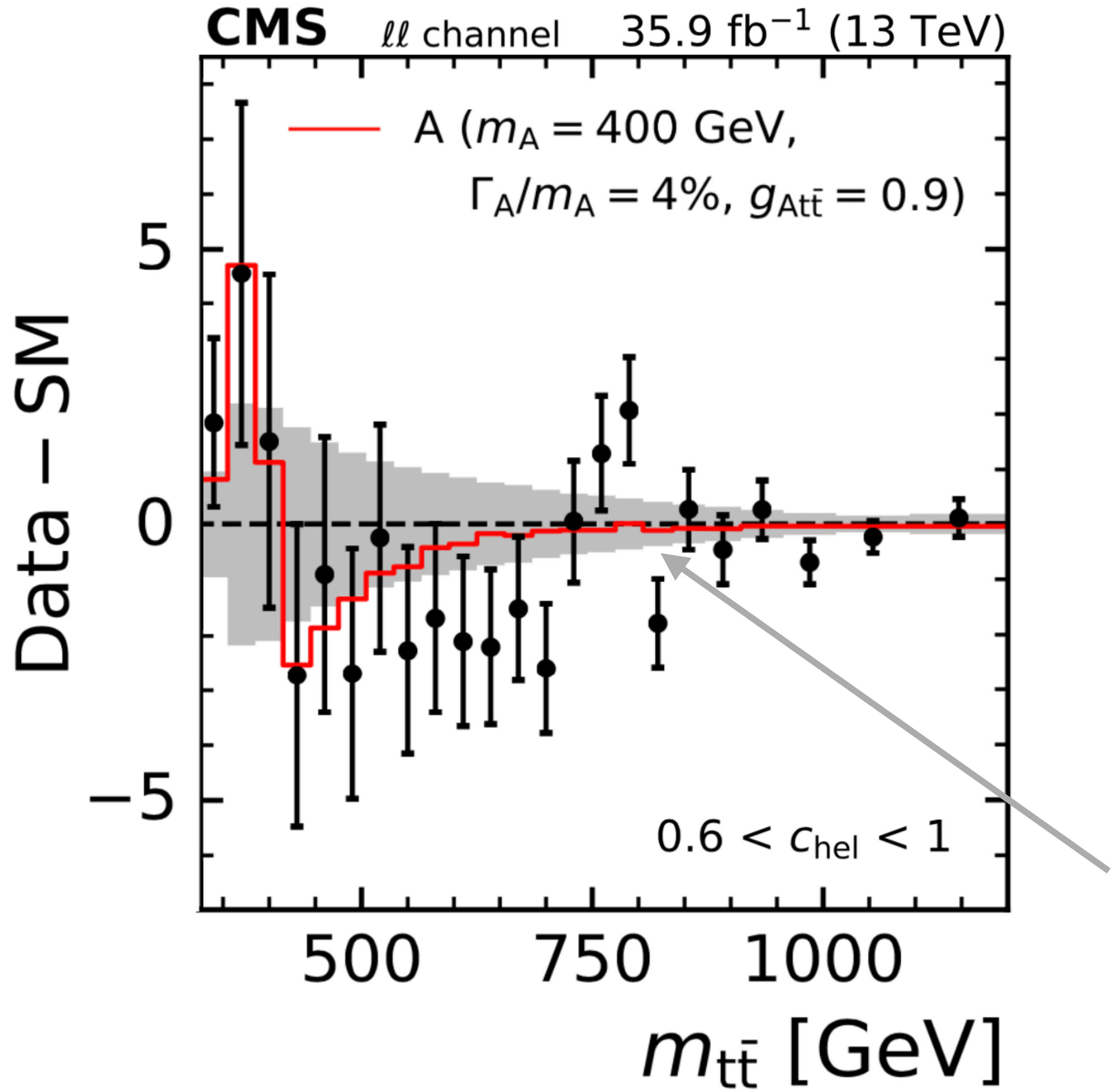
Interference ⇒



Signal-background interference yields peak-dip structure

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

H, A → tt search in CMS (first year of Run 2)



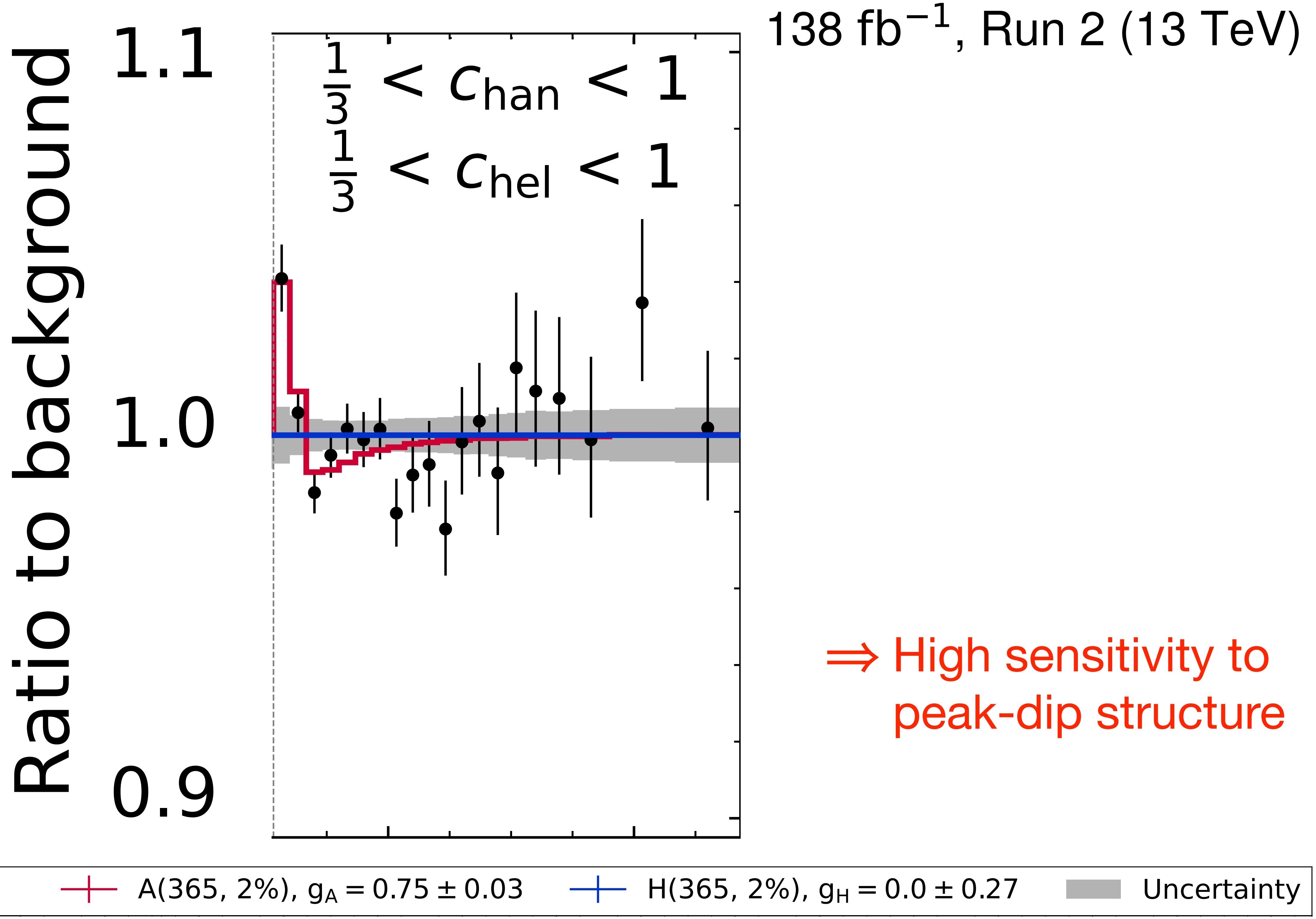
[CMS Collaboration ’19]

⇒CMS analysis has sensitivity to the peak-dip structure caused by a signal-background interference

Observed excess is compatible with CP-odd Higgs at about 400 GeV

New result: full Run 2 data

[CMS Collaboration ’24]



⇒ High sensitivity to peak-dip structure

Interpretation of observed excess near tt threshold?

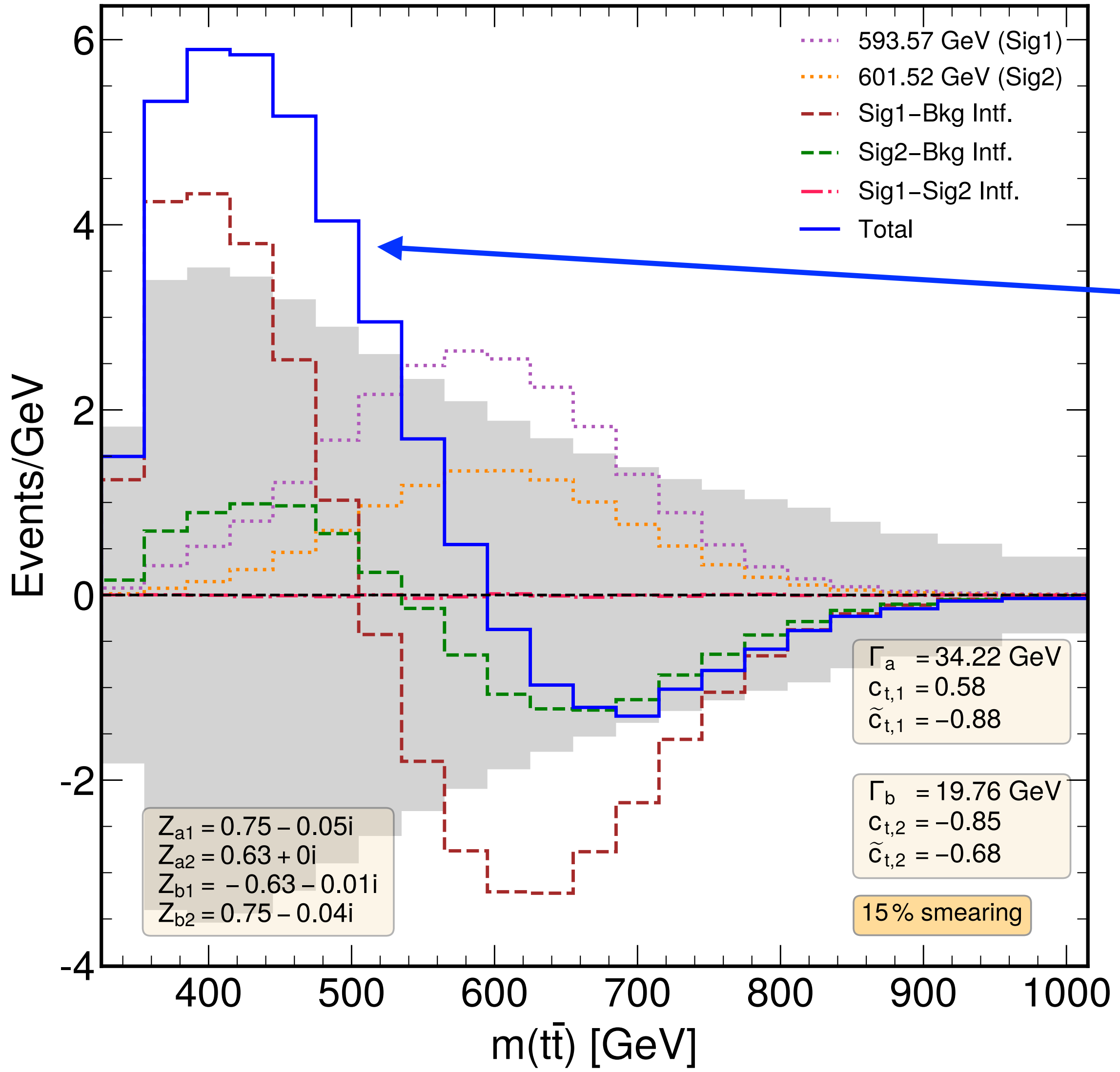
[CMS Collaboration '24]

tt bound state? Which rate? tt + …? CP-odd Higgs? ALP?
Overlap of two heavier CP-mixed states (here: ≈600 GeV)? …

C2HDM, result for BP 3 of *[P. Basler, S. Dawson, C. Englert, M. Mühlleitner '20]*

[H. Bahl, R. Kumar, G. W. '24]

[see talk by R. Kumar]



Total result

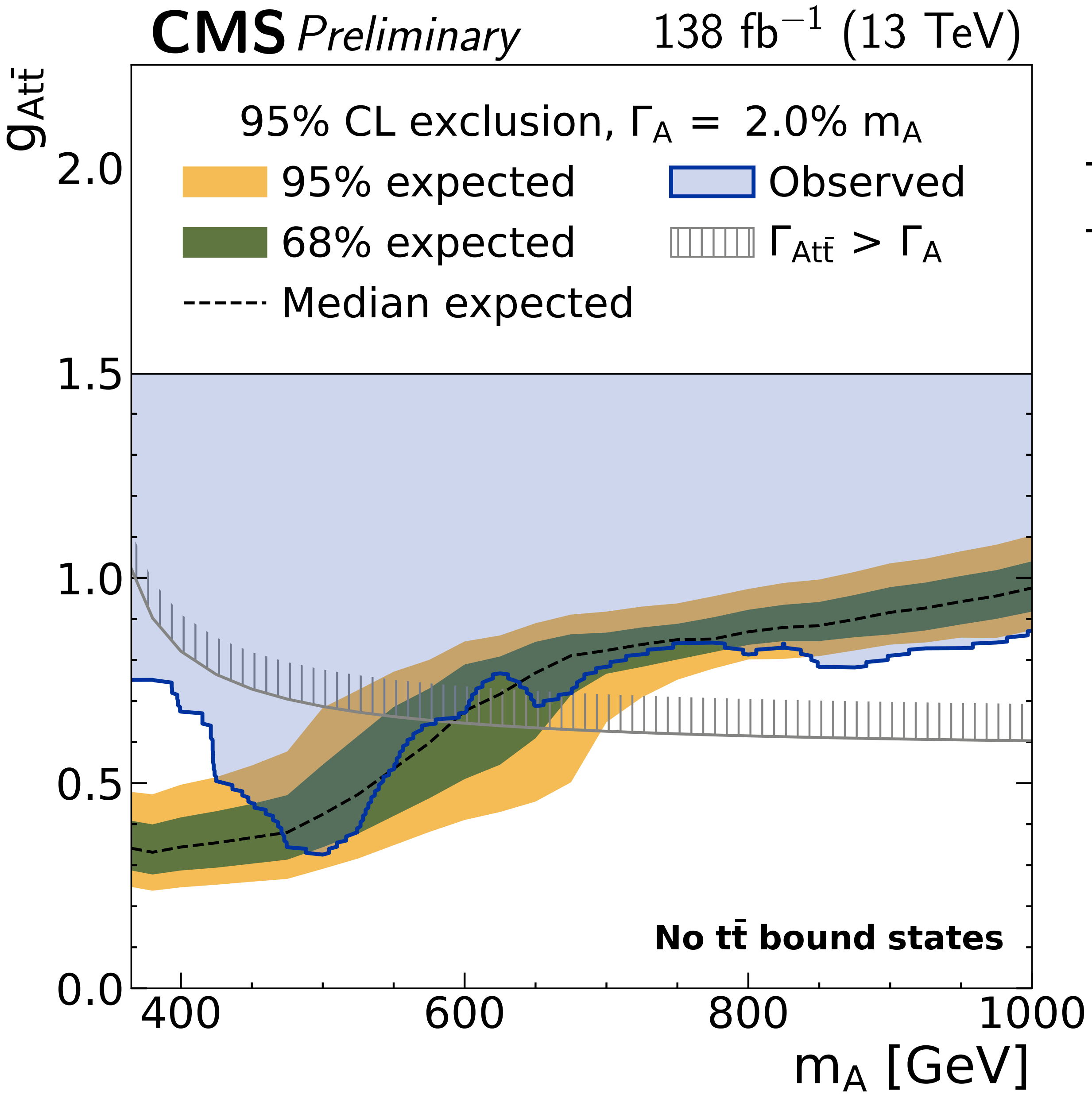
Resembles shape for a single particle at lower mass; highest sensitivity in the region just above the tt threshold!

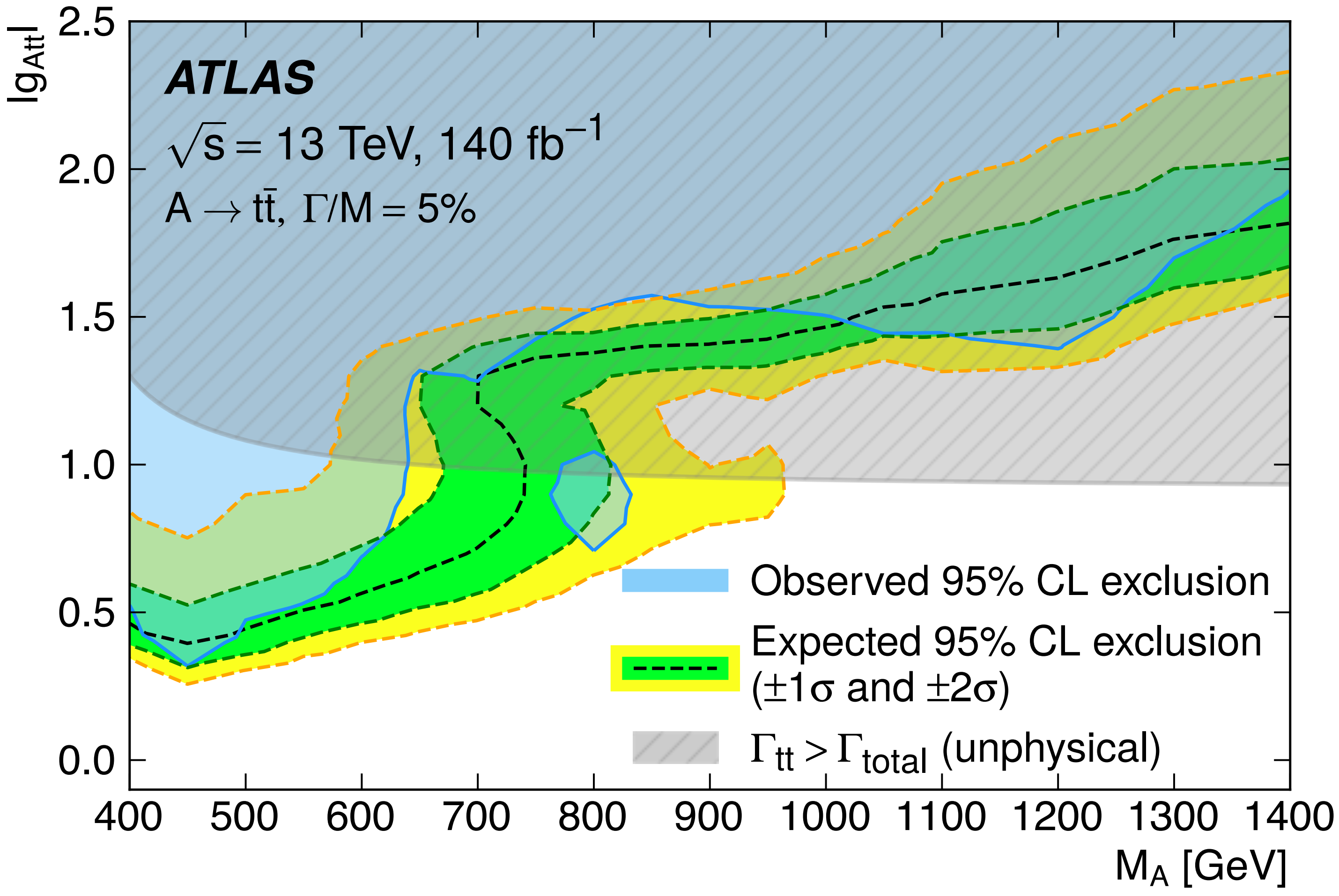
⇒ BSM effects tend to manifest themselves at the tt threshold, even for much higher BSM masses

Compatibility between CMS and ATLAS results?

[CMS Collaboration ’24]

[ATLAS Collaboration ’24]

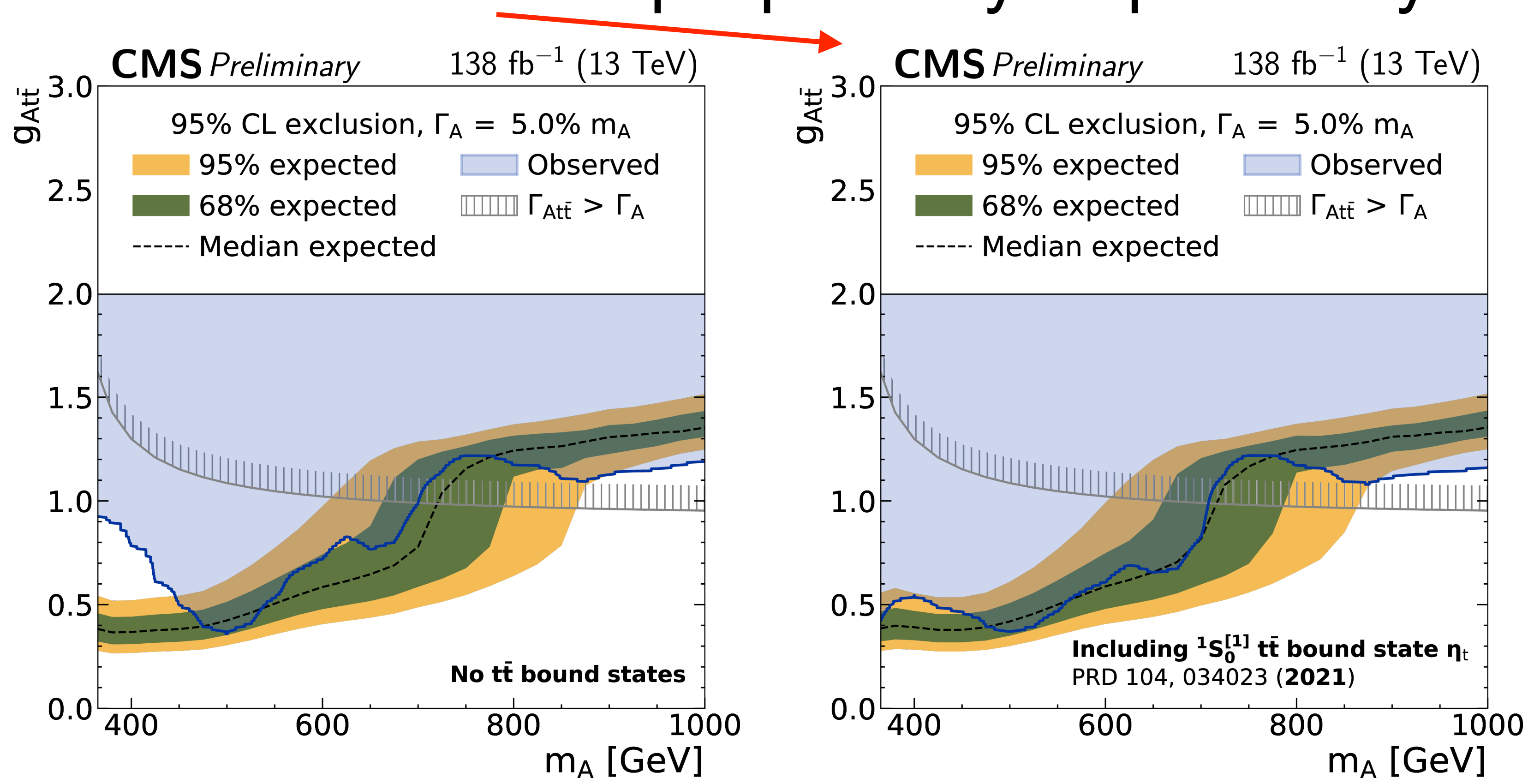




My (theory) wishes to CMS

- Quote the actual statistical significance, not just ``above 5 σ" (a non-zero cross section has been quoted with 11% uncertainty, so it is obvious that the actual value is around 9 σ)

- I don't think that this is a proper way to present your results:



[H. Saka, talk on Monday]

Data is consistent with SM expectations once/if the potential bound state is taken into account *(with unconstrained normalization).*

As far as I can tell this means you are fitting your data (in the signal region) and put the result into the background!?!

My (theory) wishes / questions to ATLAS

- CMS sees a very significant excess over the perturbative QCD background, but the situation whether or not ATLAS sees something seems to be rather unclear. How is this possible?

- Please try to exploit the spin correlation information as much as possible. I understand that your ongoing ``quantum entanglement” analysis essentially contains this information?

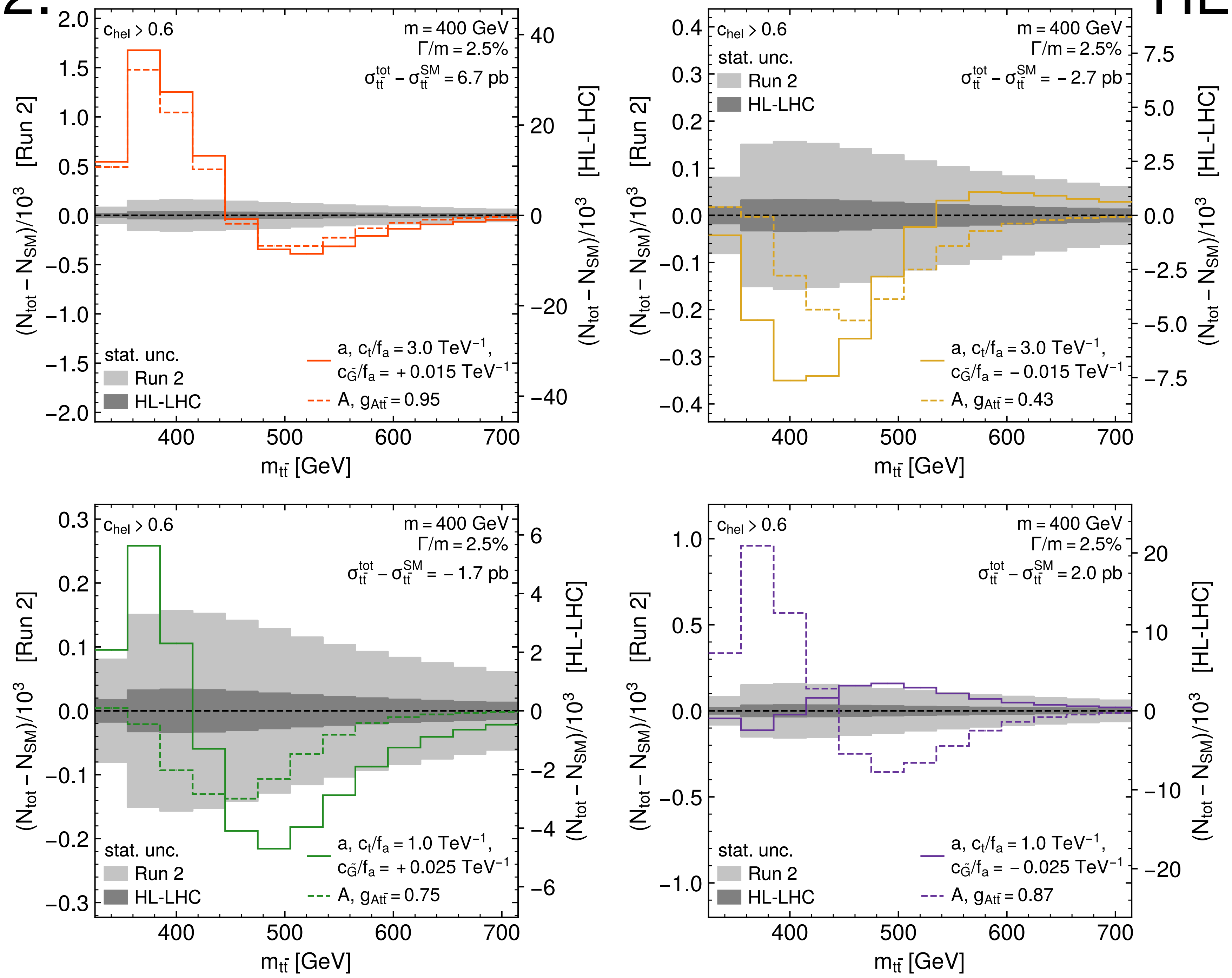
- How does your result in the tt threshold region look like?

- How do you treat your background and how does this differ from what CMS does?

Axion-like particle (ALP) ($c_{\tilde{G}} \neq 0$) vs. CP-odd Higgs boson, same total cross section

[A. Anuar et al. '24]

LHC Run 2: HL-LHC:



⇒High sensitivity for detecting a signal, good prospects for distinguishing ALP from CP-odd Higgs

Where should experiment and theory meet?

- 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 κ parameters (signal strength modifiers; see example of κ_λ below) and coefficients of EFT operators

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

New framework: *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), …

Comparison between experiment and theory

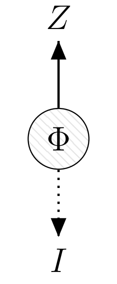
Making the results on Higgs measurements and Higgs searches from ATLAS and CMS available in such a way that they can be confronted with theoretical predictions in different models is an issue that is very important both for the theory and the experimental community

Maintaining the public tools that can be used for this purpose and keeping them up to date is a very time-consuming and often tedious task

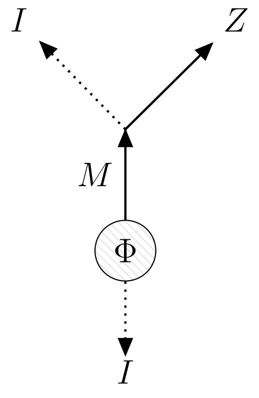
Help from ATLAS and CMS in this context is highly appreciated!

Simplified models for BSM Higgs searches

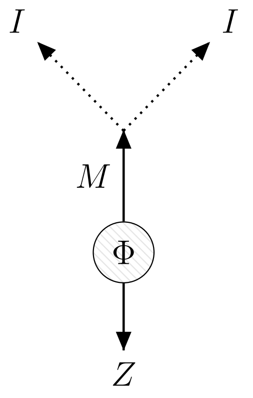
[H. Bahl, V. Martin Lozano, G. W. '21]



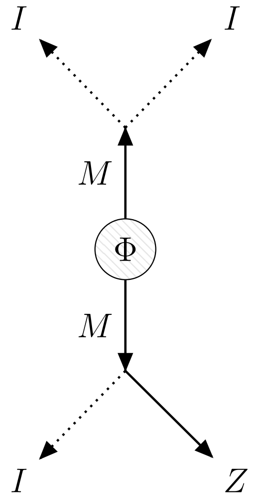
(a) 1-vs-1 unbalanced



(b) 2-vs-1 balanced

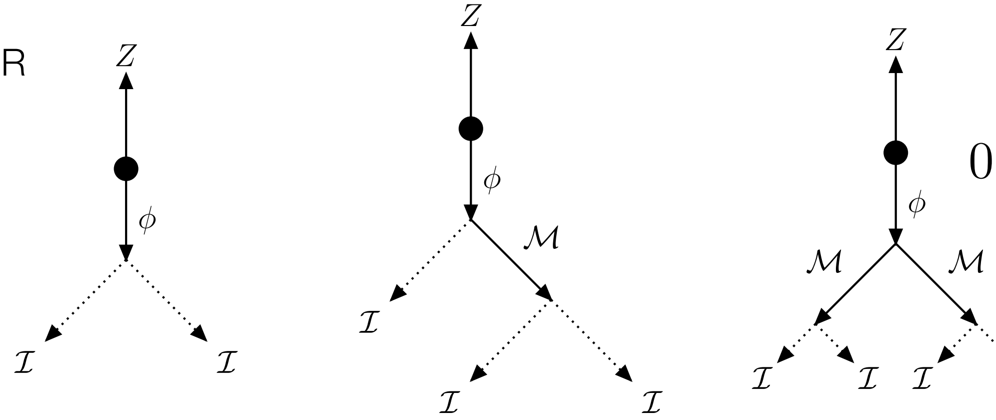


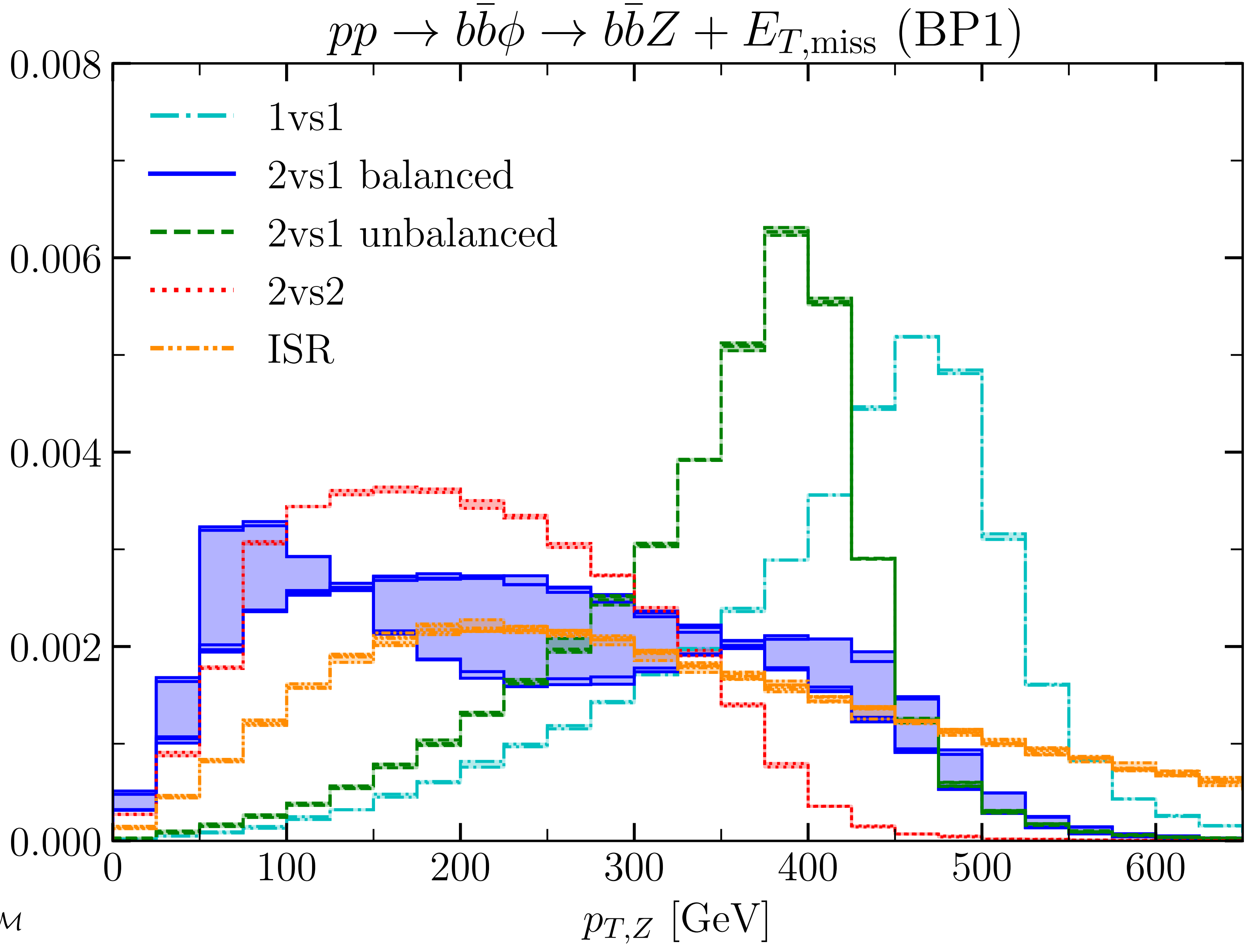
(c) 2-vs-1 unbalanced



(d) 2-vs-2 balanced

(e) ISR

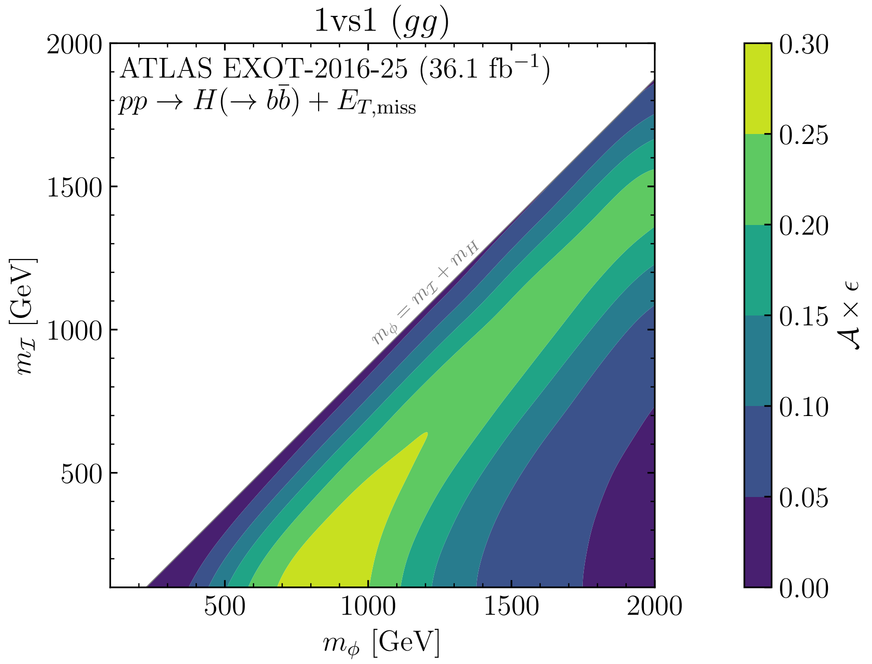


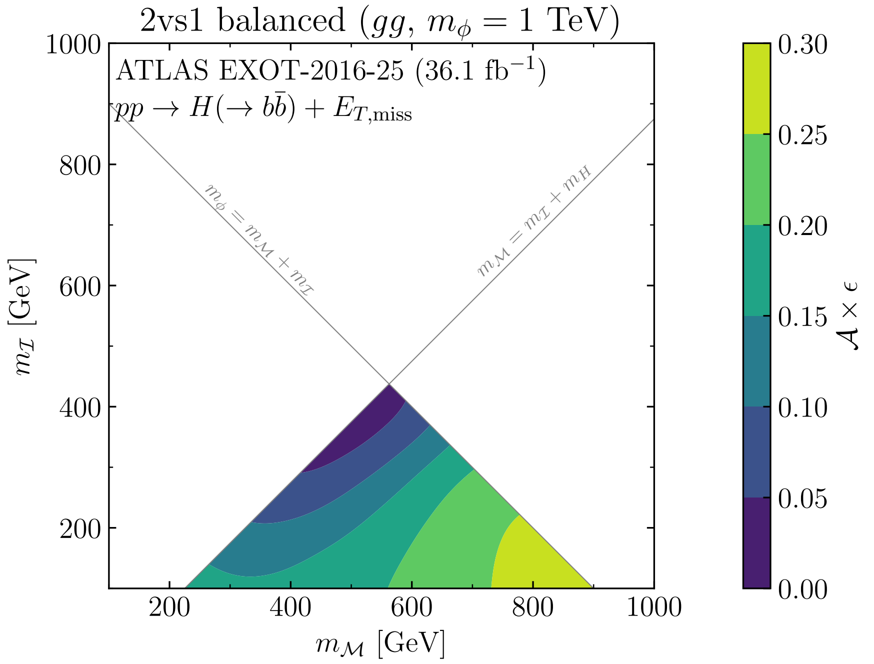


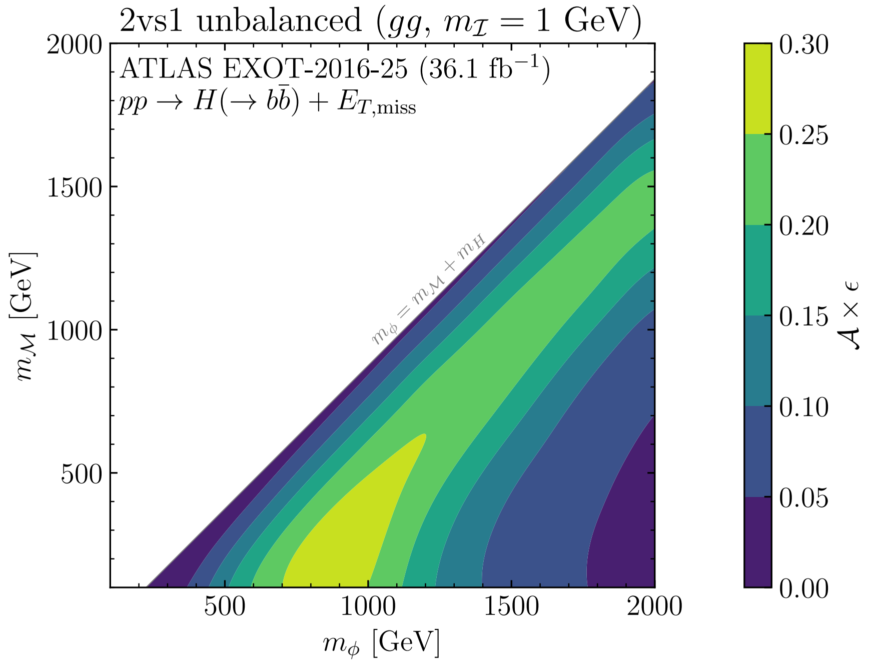
⇒ High sensitivity to different simplified model topologies, spins of mediators and invisible particles have relatively small impact

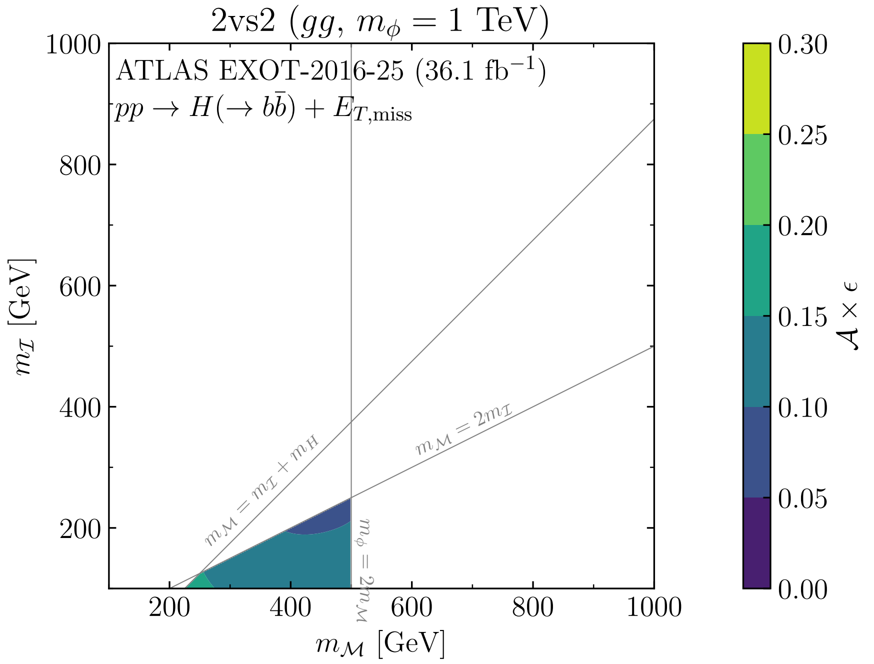
Simplified models for BSM Higgs searches

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





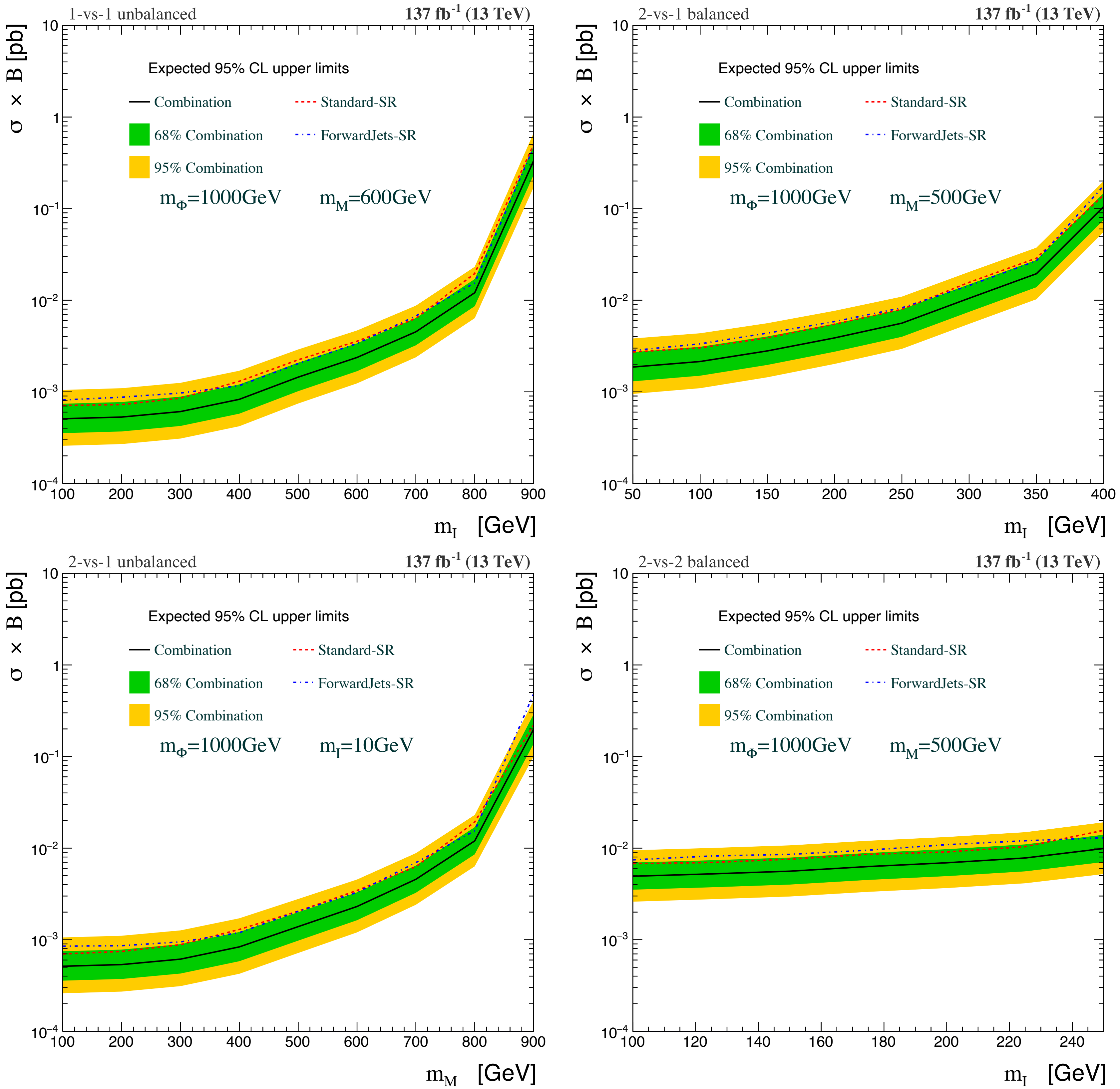




⇒ (Acceptance x efficiency) maps, can easily be utilised to obtain exclusion limits for a wide range of models

Application: expected limits for simplified model topologies from search in bbZ + $E_{T\mathrm{miss}}$ final state

[D. P. Adan et al. ’23]

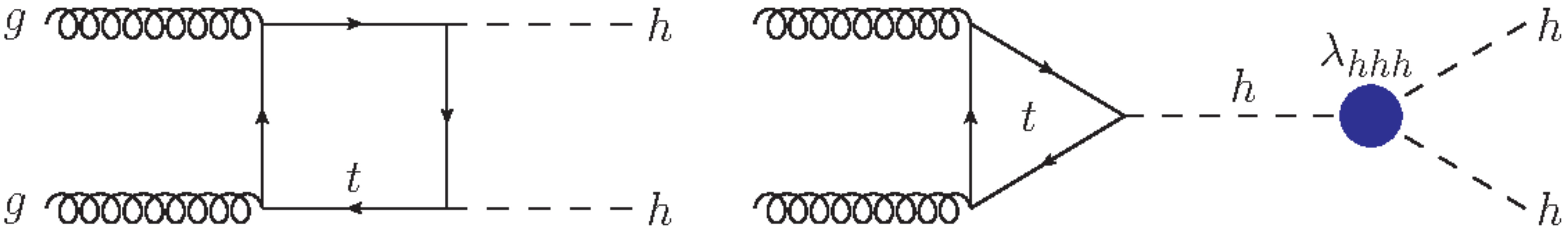


⇒ Signal region with forward jets has sizeable impact

Trilinear Higgs self-coupling, λ_{hhh}, di-Higgs production

Sensitivity to λ_{hhh} from Higgs pair production: *[see talk by C. Pandini]*

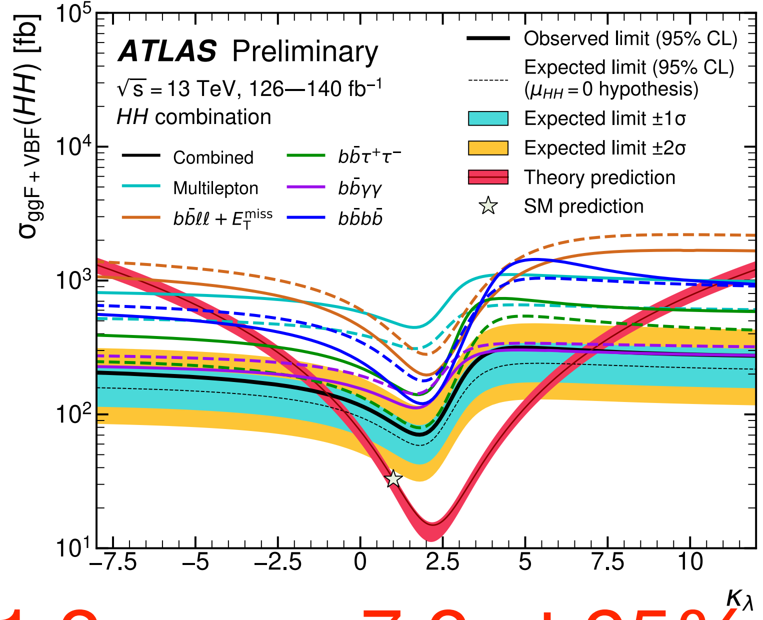
- **Double-Higgs production** → λ_{hhh} enters at LO → **most direct probe of λ_{hhh}**



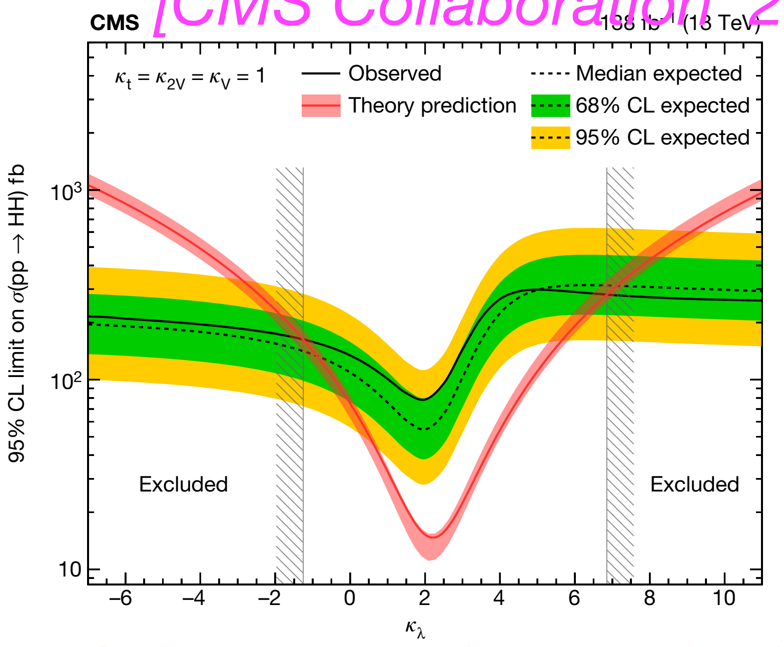
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

Note: the ``non-resonant" experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$

[ATLAS Collaboration '24]



[CMS Collaboration '22]



Using only information from di-Higgs production and assuming that new physics only affects λ_{hhh}

$-1.2 < \varkappa_\lambda < 7.2$ at 95% C.L. $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L.

Higgs potential: the “holy grail” of particle physics

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

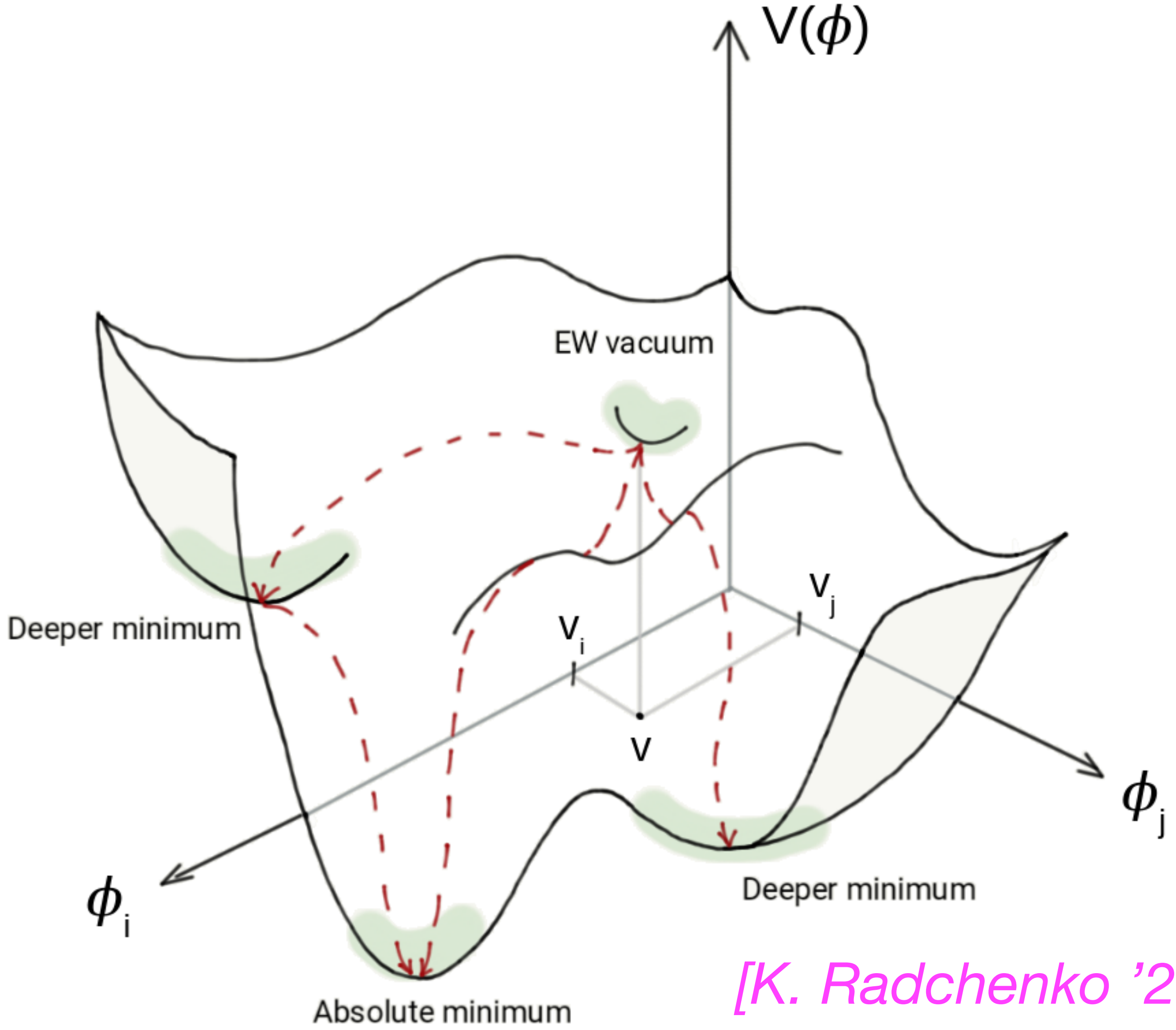
Trilinear coupling Quartic coupling Possible couplings involving additional scalars

$$V = 1/2\, m_h^2\, h^2 + v\, \lambda_{hhh}\, h^3 + \lambda_{hhhh}\, h^4 + \ldots + v\, \lambda_{hhH}\, h^2 H + v\, \lambda_{HHH}\, H^3 + \ldots$$

Known so far:
(h: detected Higgs at 125 GeV)

Distance of EW minimum from origin of field space: v

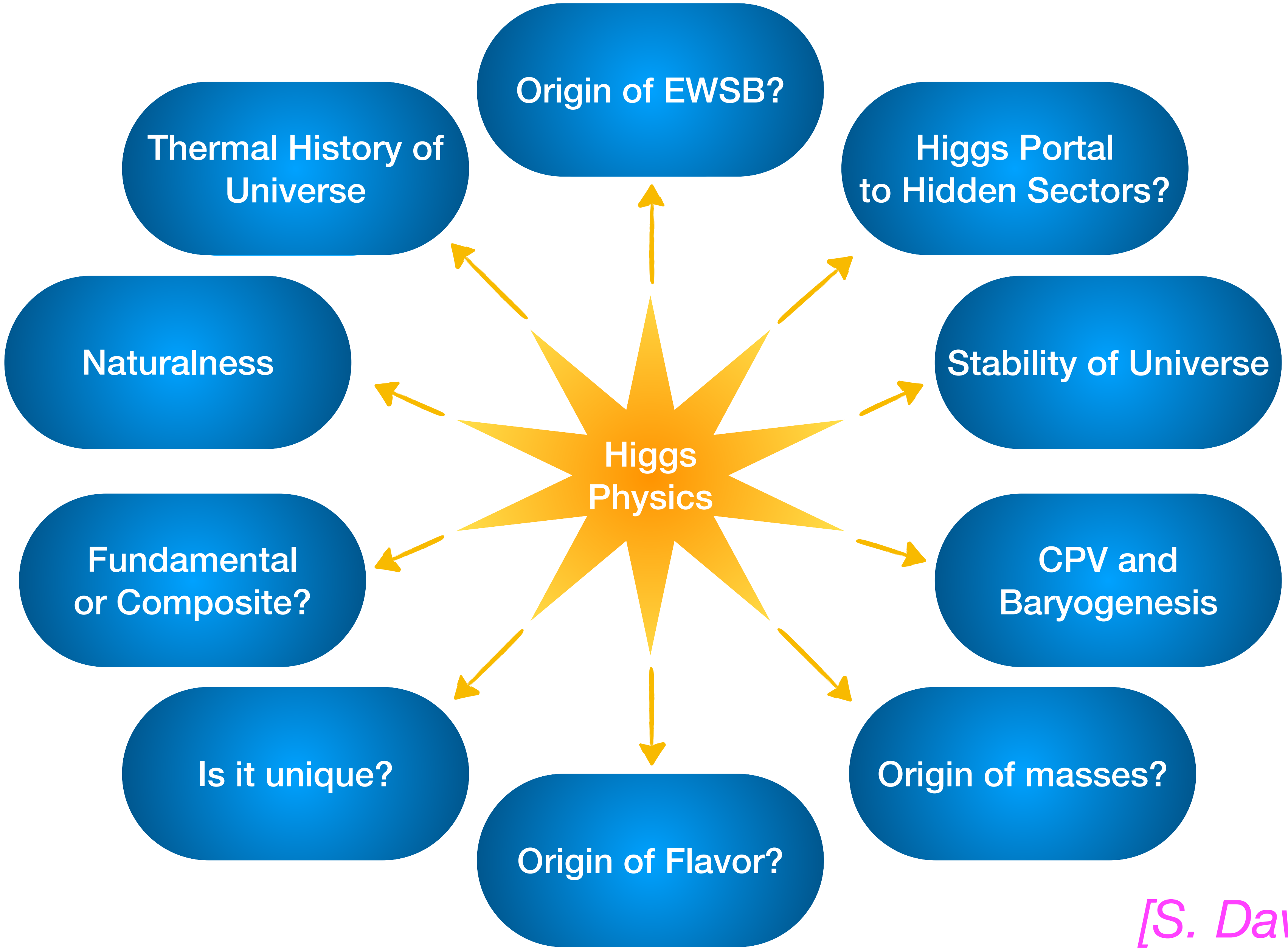
Curvature of the potential around the EW minimum: m_h



[K. Radchenko ’24]

Higgs potential: the “holy grail” of particle physics

Most of the open questions of particle physics are directly related to Higgs physics and in particular to the Higgs potential



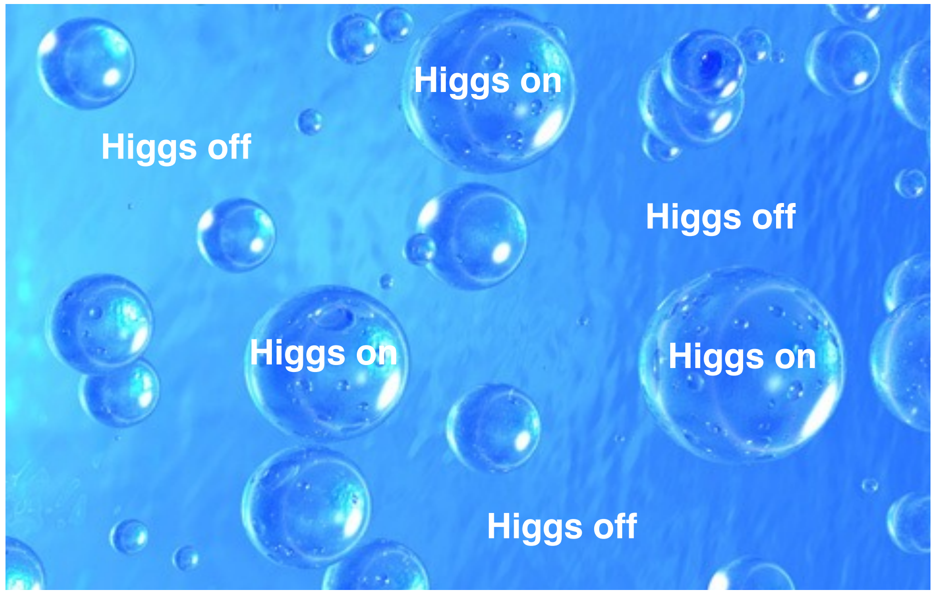
[S. Dawson et al. ’22]

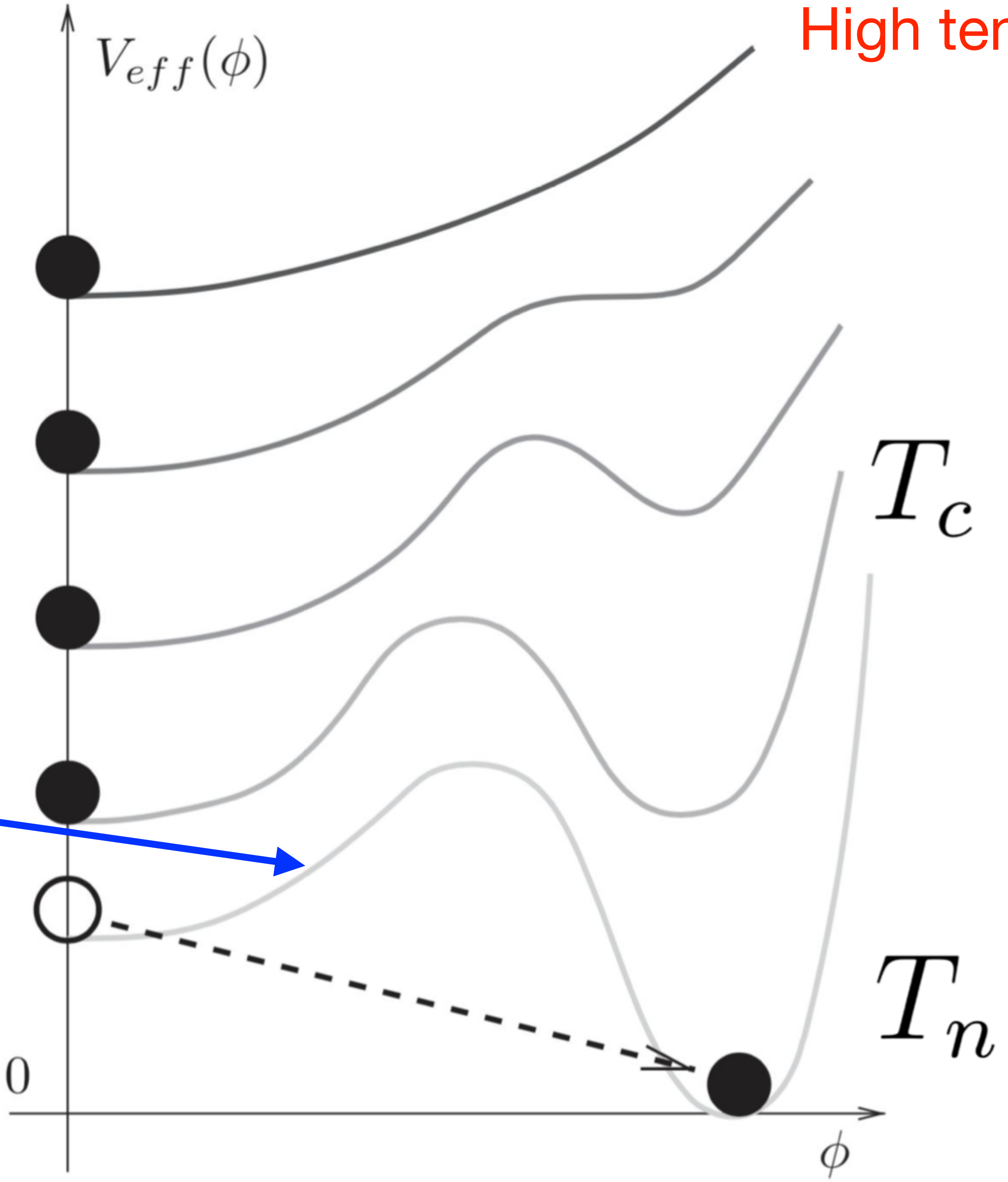
The Higgs potential and the electroweak phase transition (EWPT)

[D. Gorbunov, V. Rubakov]

Temperature evolution of the Higgs potential in the early universe:

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





High temperature

Critical temperature (degenerate minima)

Transition temperature (strong first-order EWPT)

Potential barrier depends on trilinear Higgs coupling(s)

Baryogenesis: creation of the asymmetry between matter and antimatter in the universe requires strong first-order EWPT

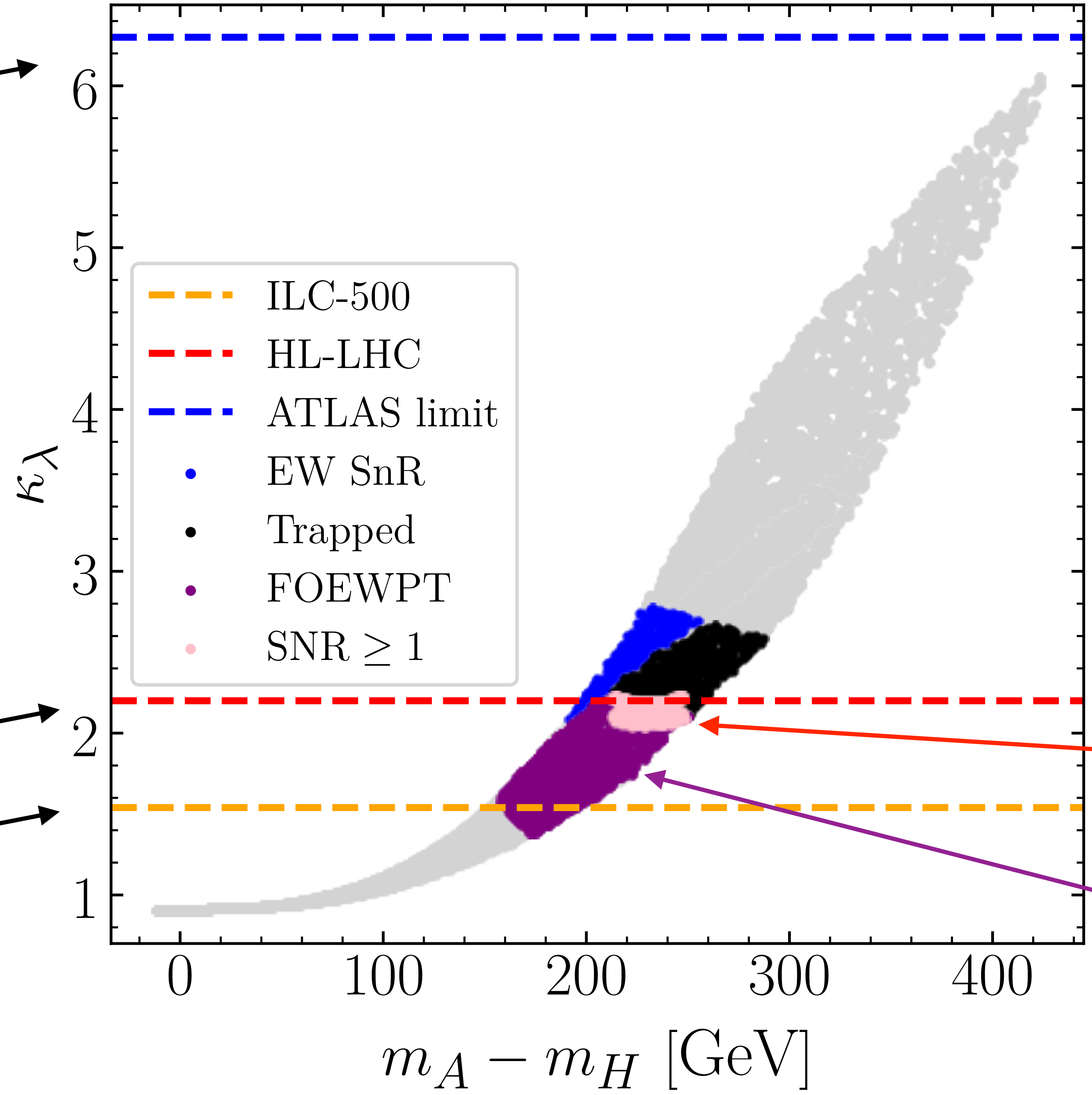
Relation between trilinear Higgs coupling and strong first-order EWPT with potentially observable GW signal

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

current bound

HL-LHC sensitivity

ILC sensitivity



alignment limit,
tanβ = 3,
1-loop prediction

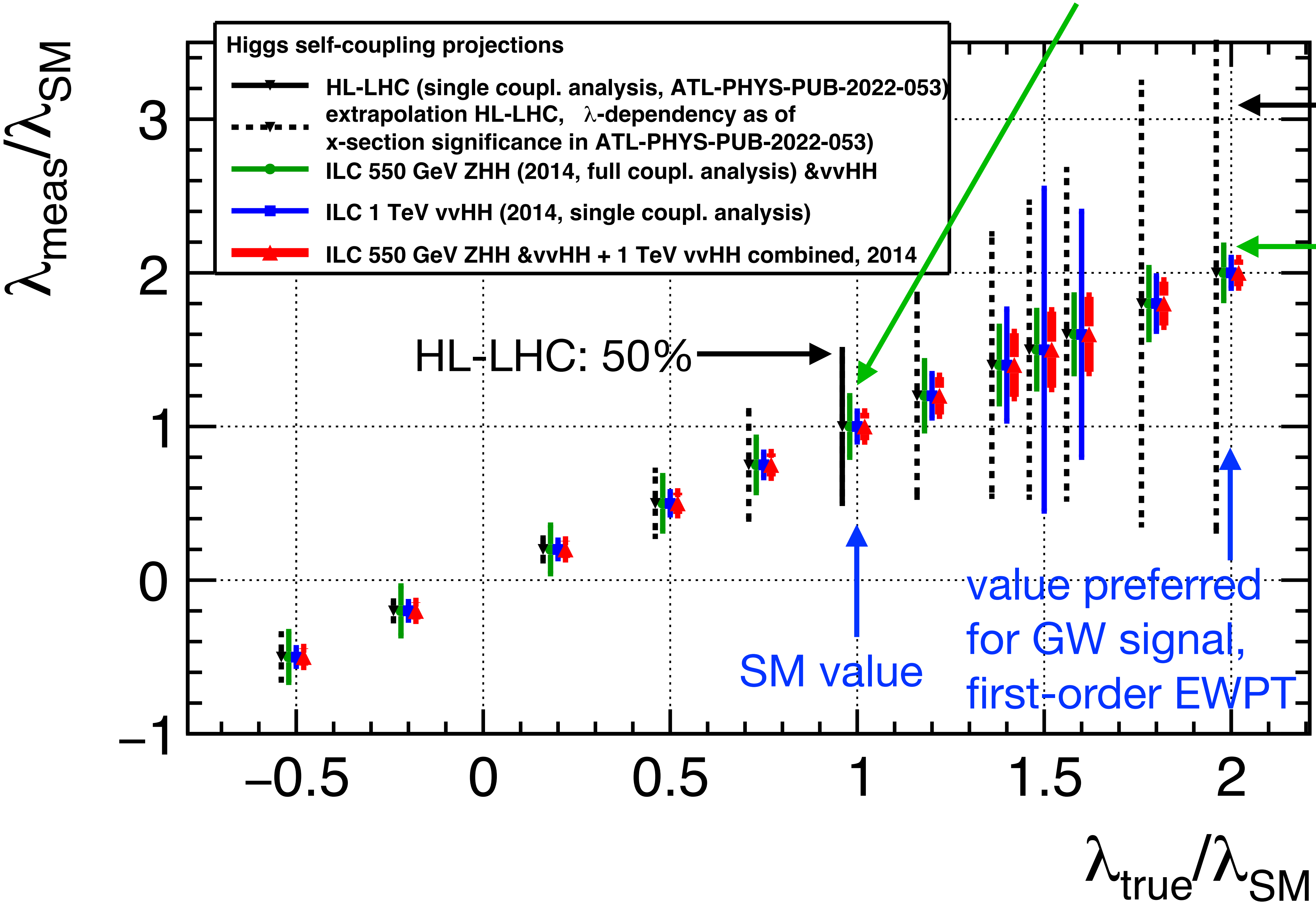
region with potentially observable gravitational wave (GW) signal

region with strong first-order EWPT

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

Prospects for measuring the trilinear Higgs coupling: HL-LHC vs. ILC (550 GeV, Higgs pair production)

[J. List et al. '24]



ILC550: 20%

HL-LHC: 50%

HL-LHC: 84%

ILC550: 9%

SM value

value preferred for GW signal, first-order EWPT

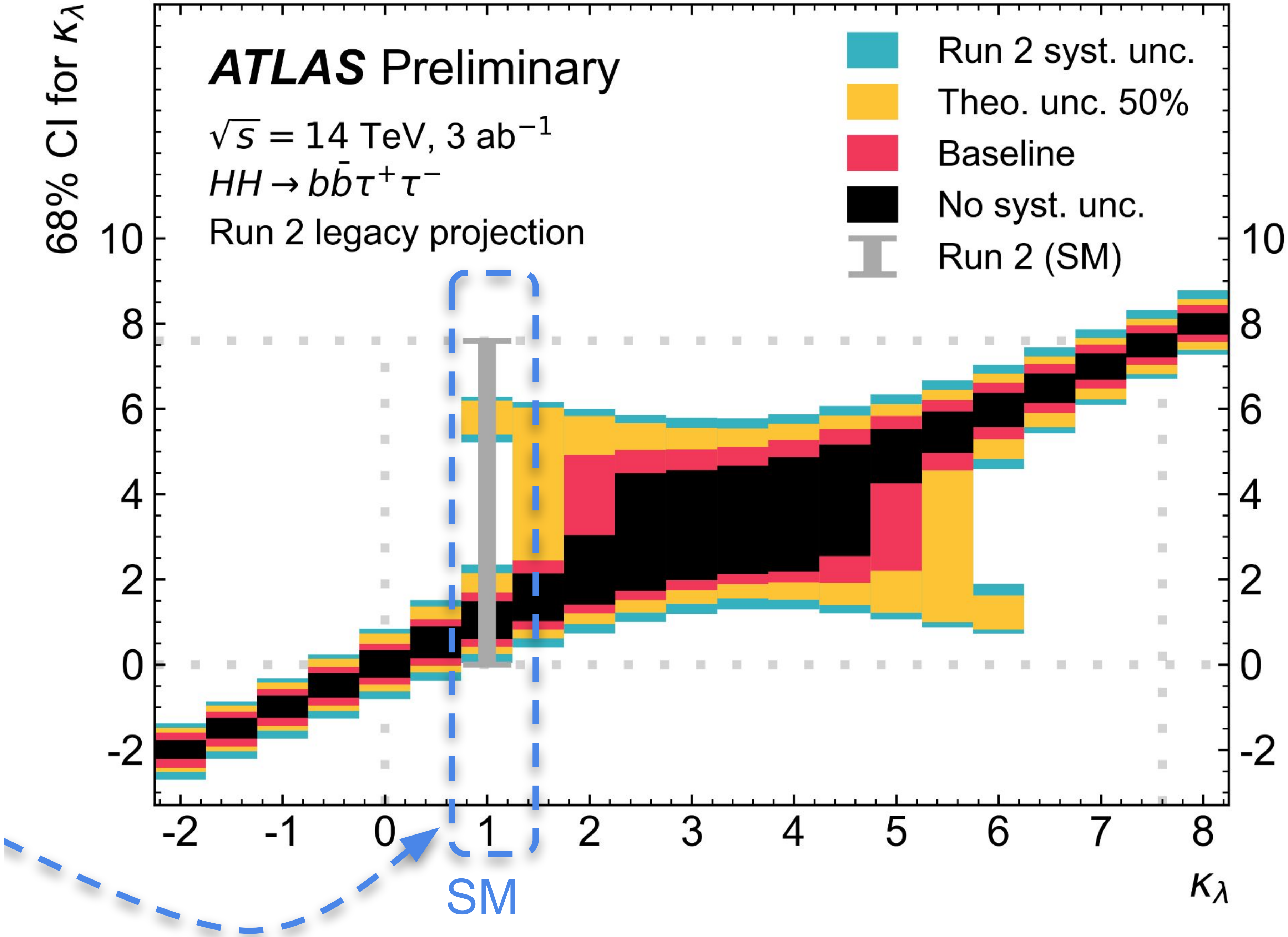
⇒ For $\varkappa_\lambda \approx 2$: much better prospects for ILC550 than for HL-LHC

Reason: different interference contributions

Recent ATLAS projection going beyond the assumption of $\varkappa_\lambda = 1$

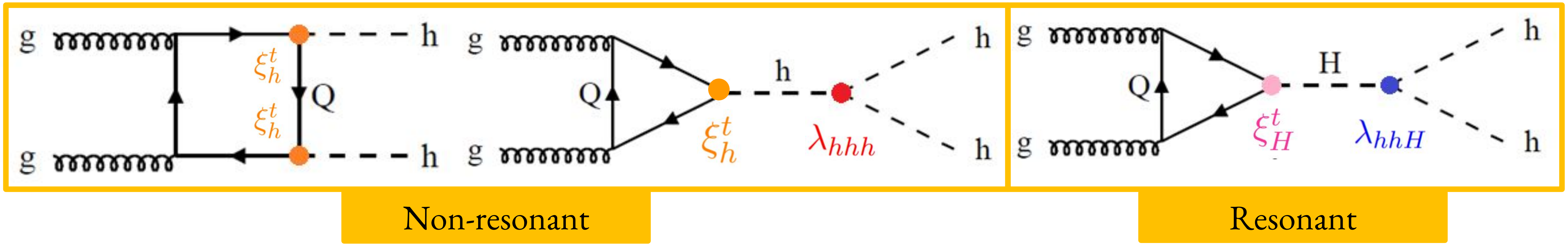
[ATLAS Collaboration ’24]

68% CI for $\boldsymbol{\kappa_\lambda}$ at **3000 fb^{-1}** varying κ_λ



⇒ Large dependence on actual value of $\varkappa_\lambda$

Pair production of the detected Higgs boson (h)



Non-resonant

Resonant

- Depends on trilinear Higgs self-coupling, $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$, and therefore provides experimental access to the Higgs potential

- SM-type contributions (non-resonant): large interference effects between box (left) and vertex (right) contributions

- In extended Higgs sectors: mass splitting between BSM Higgs bosons induces very large loop effects to $\varkappa_\lambda$, while the couplings of h to gauge bosons and fermions can be very close to the SM values

- Process is sensitive to resonant contributions of BSM states, e.g. additional Higgs boson H

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hVV}, g_{hff} couplings)

[H. Bahl et al.'24]

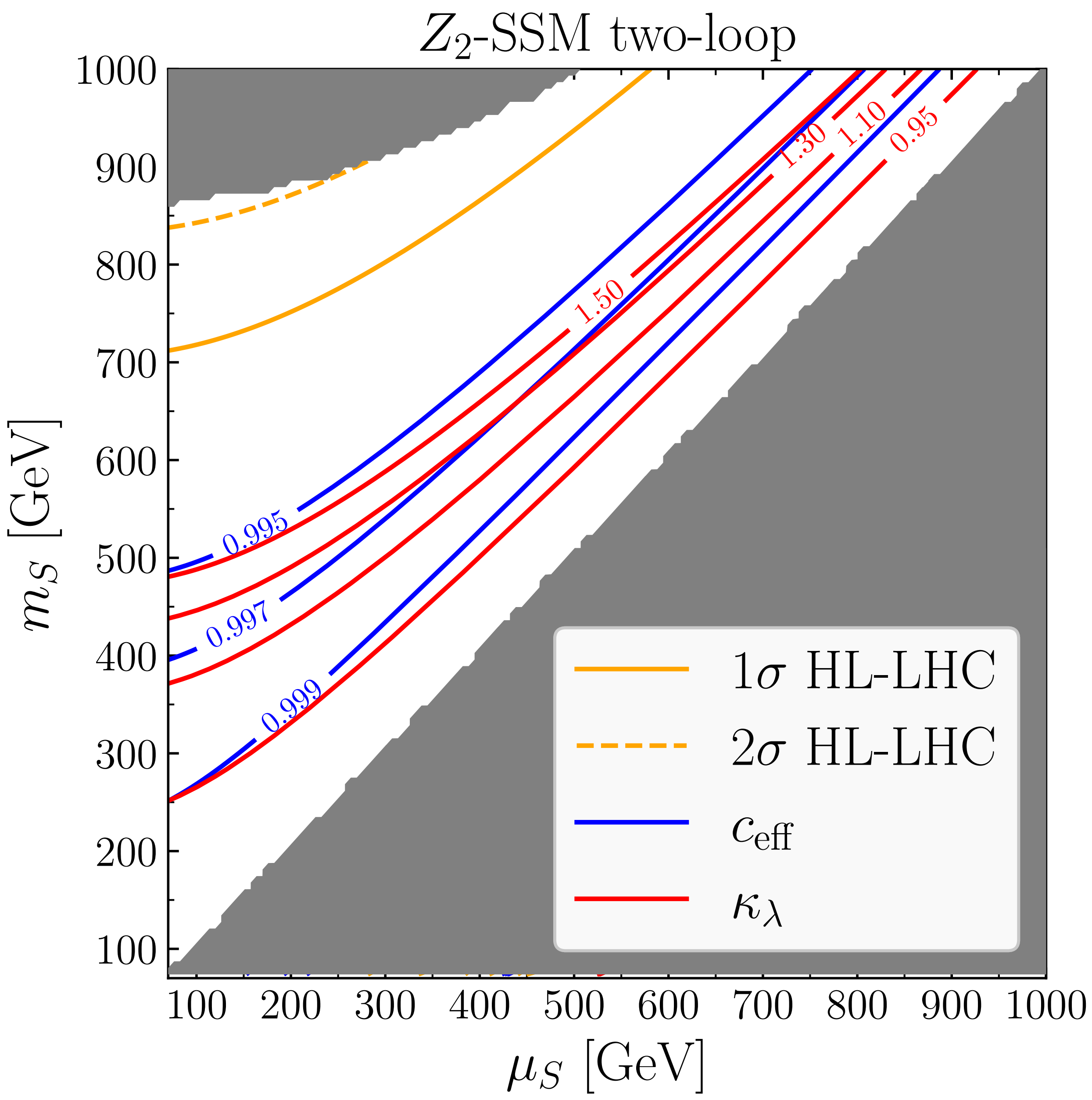


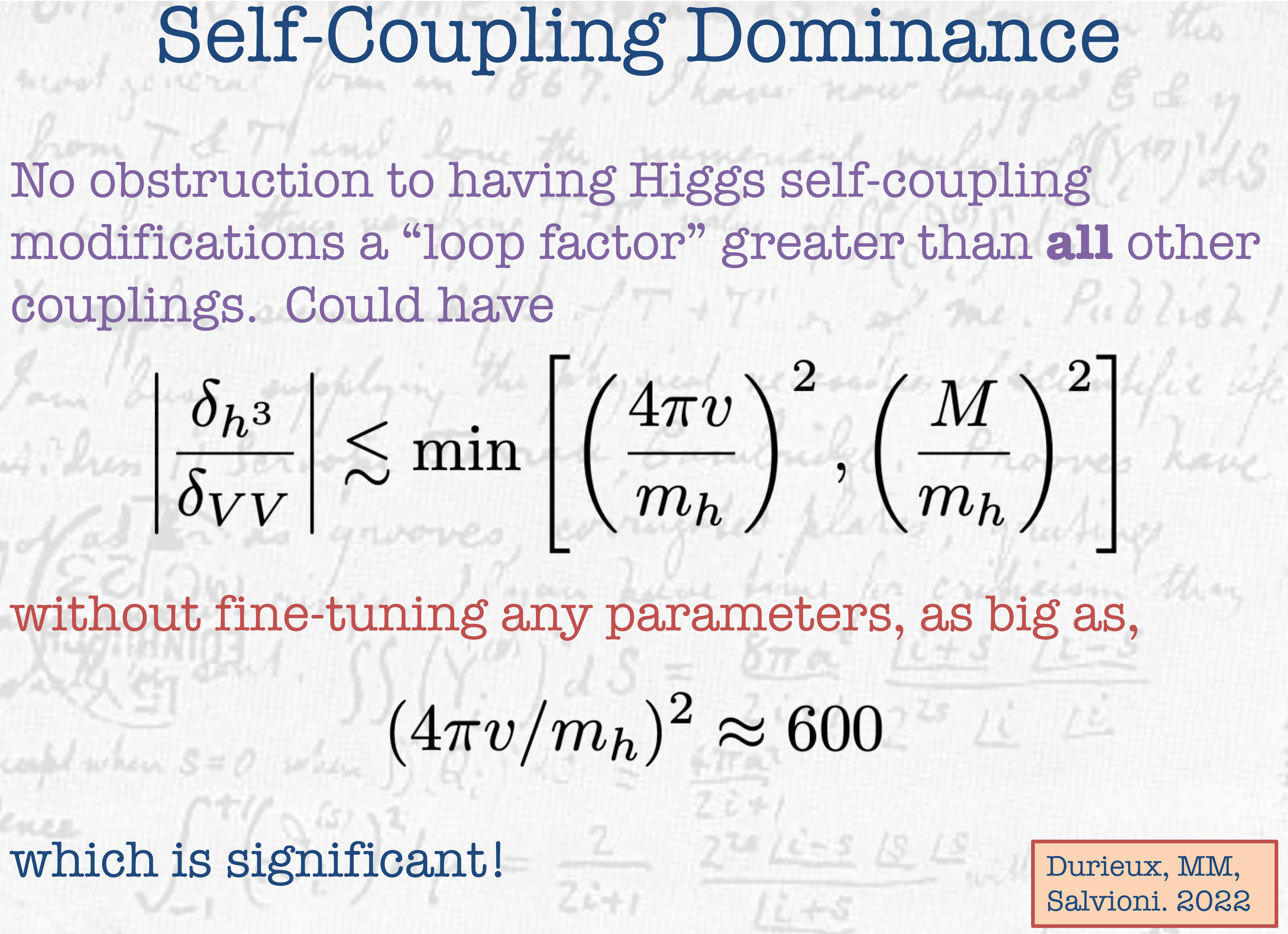
Figure 2: Contour lines of κ_λ (red) and c_{eff} (blue), computed at two loops, in the $\{\mu_S, m_S\}$ parameter plane of the Z_2-SSM (with $\lambda_S = 0$). The orange solid and dashed lines indicate the regions of parameter space probed by single-Higgs measurements at the HL-LHC (assuming SM-like central values) at the 1σ and 2σ levels respectively.

⇒ Large effects possible in λ_{hhh} while the couplings of h to gauge bosons and fermions are very close to the SM value!

Effects in λ_{hhh} vs. g_{hZZ} (and other g_{hVV}, g_{hff} couplings)

EFT perspective:

[M. McCullough, ICHEP 2024]



Self-Coupling Dominance

No obstruction to having Higgs self-coupling modifications a “loop factor” greater than **all** other couplings. Could have

$$\left|\frac{\delta_{h^3}}{\delta_{VV}}\right| \lesssim \min\left[\left(\frac{4\pi v}{m_h}\right)^2, \left(\frac{M}{m_h}\right)^2\right]$$

without fine-tuning any parameters, as big as,

$$(4\pi v/m_h)^2 \approx 600$$

which is significant!

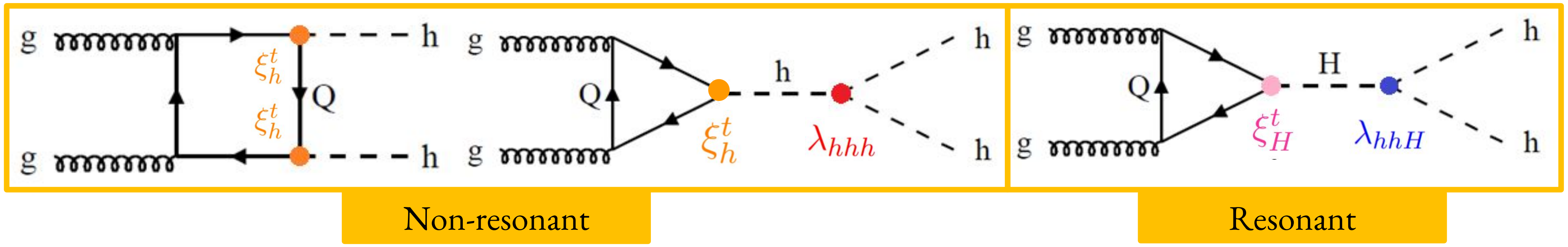
Durieux, MM, Salvioni. 2022

``Higgs self-coupling, … arguably the most important of them all!”

Resonant Higgs pair production: loop contributions and interference effects

Up to now ATLAS and CMS present the limits from their ``resonant" di-Higgs searches for a signal model that does not take into account the non-resonant and interference contributions

In all realistic scenarios the resonant contribution, involving H, is accompanied by the non-resonant SM-like contribution, involving h, giving rise to potentially large interference contributions



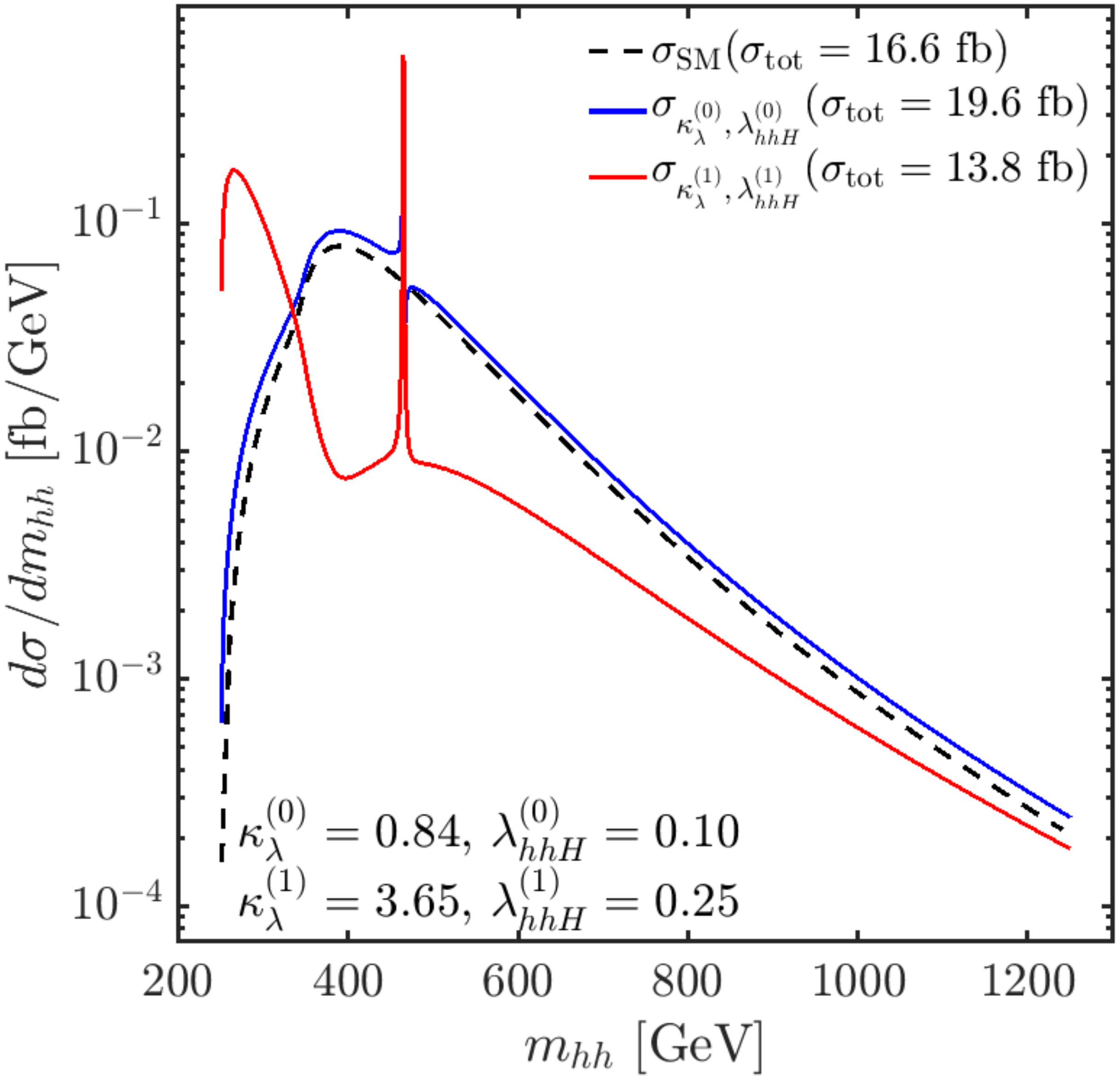
Assumption made by ATLAS and CMS: at the current level of sensitivity the non-resonant contributions and the interference effects can be ignored

However, this assumption made by ATLAS and CMS is in general not valid!

Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

2HDM example, m_{hh} invariant mass distribution:
theoretical prediction, experimental effects will be discussed below



$$t_\beta = 10,\ c_{\beta-\alpha} = 0.13\ (s_{\beta-\alpha} > 0)\ m_H = 465\ \text{GeV},$$
$$m_A = m_{H^\pm} = 660\ \text{GeV}\ m_{12}^2 = m_H^2 c_\alpha^2/t_\beta$$

- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

- Drop in the m_{hh} ~ 400 GeV region due to a shift in the cancellation of form factors

- Change in the dip peak structure of the resonance

[see talk by K. Radchenko]

⇒ Tree-level result: suppression at threshold (cancellation of vertex and box contrib.), close to SM result + resonance (peak-dip structure)

Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

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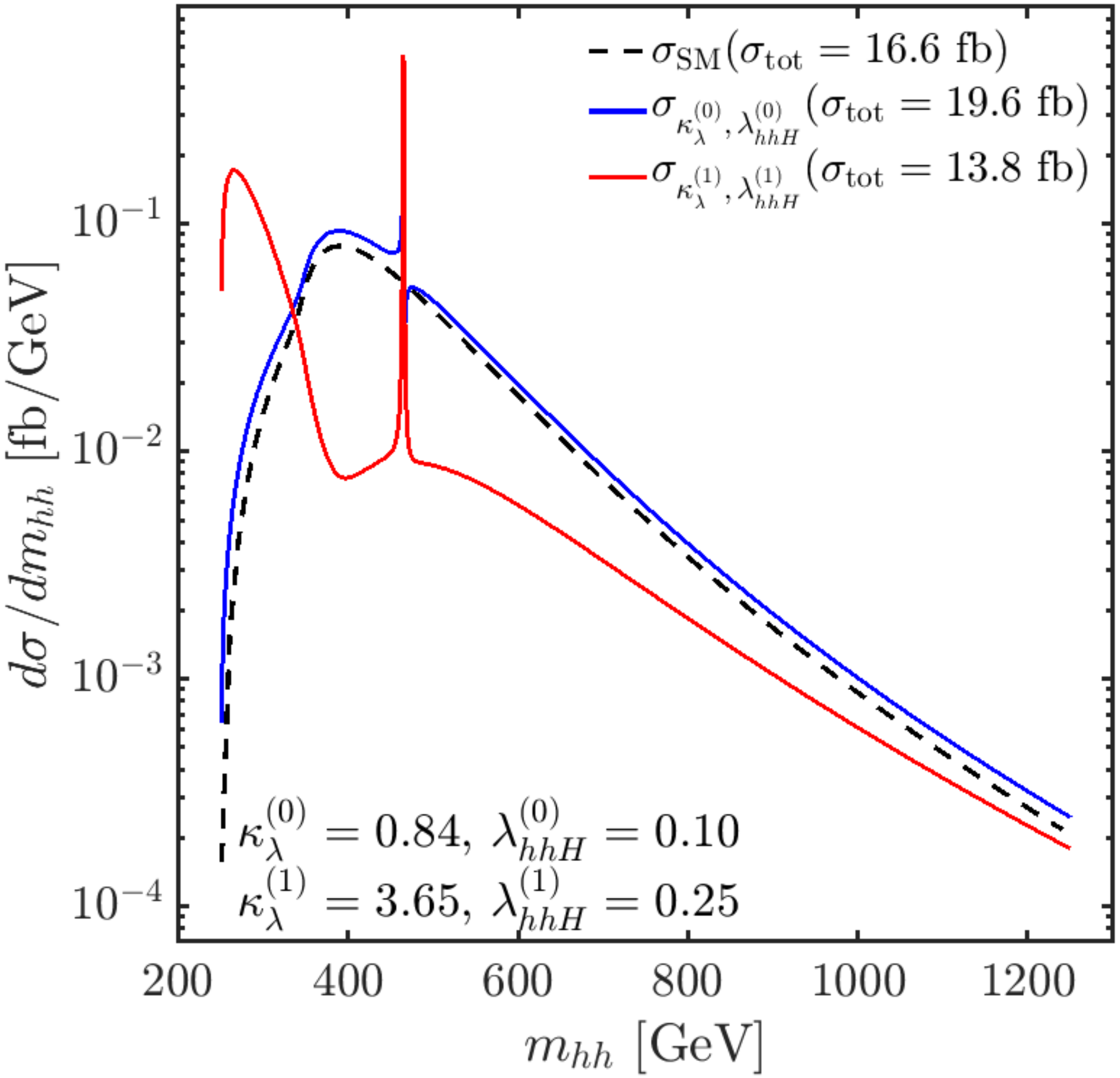
theoretical prediction, experimental effects will be discussed below



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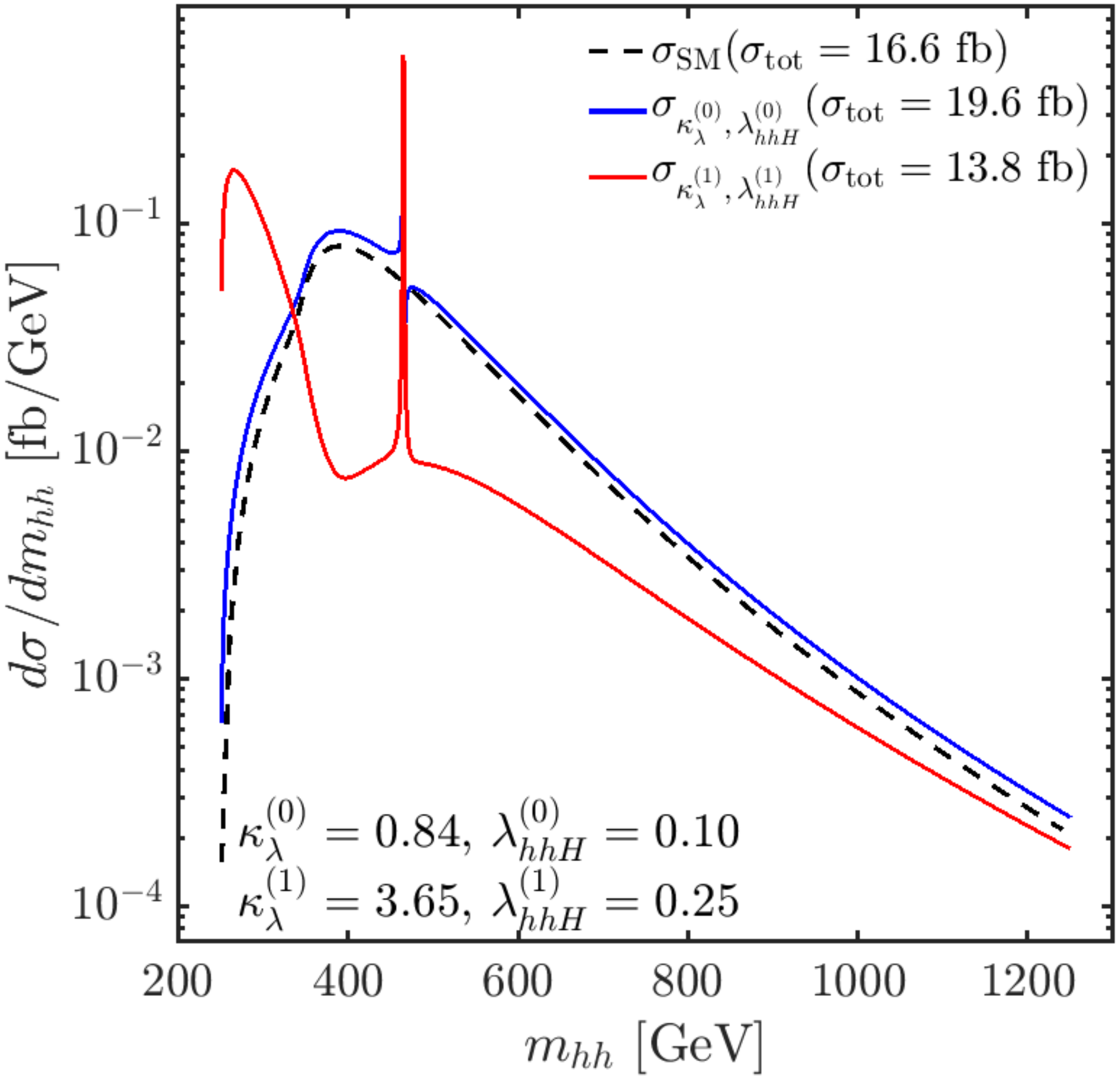
[see talk by
K. Radchenko]

⇒ Inclusion of loop contributions to λ_{hhh} ($\varkappa_\lambda$) and λ_{hhH}: cancellation at higher m_{hh} values, resonance peak, large impact on shape of distribut.

Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. ’24]

2HDM example, m_{hh} invariant mass distribution:
theoretical prediction, experimental effects will be discussed below



$$t_\beta = 10,\ c_{\beta-\alpha} = 0.13\ (s_{\beta-\alpha} > 0)\ m_H = 465\ \text{GeV},$$
$$m_A = m_{H^\pm} = 660\ \text{GeV}\ m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$$

- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

- Drop in the m_{hh} ~ 400 GeV region due to a shift in the cancellation of form factors

- Change in the dip peak structure of the resonance

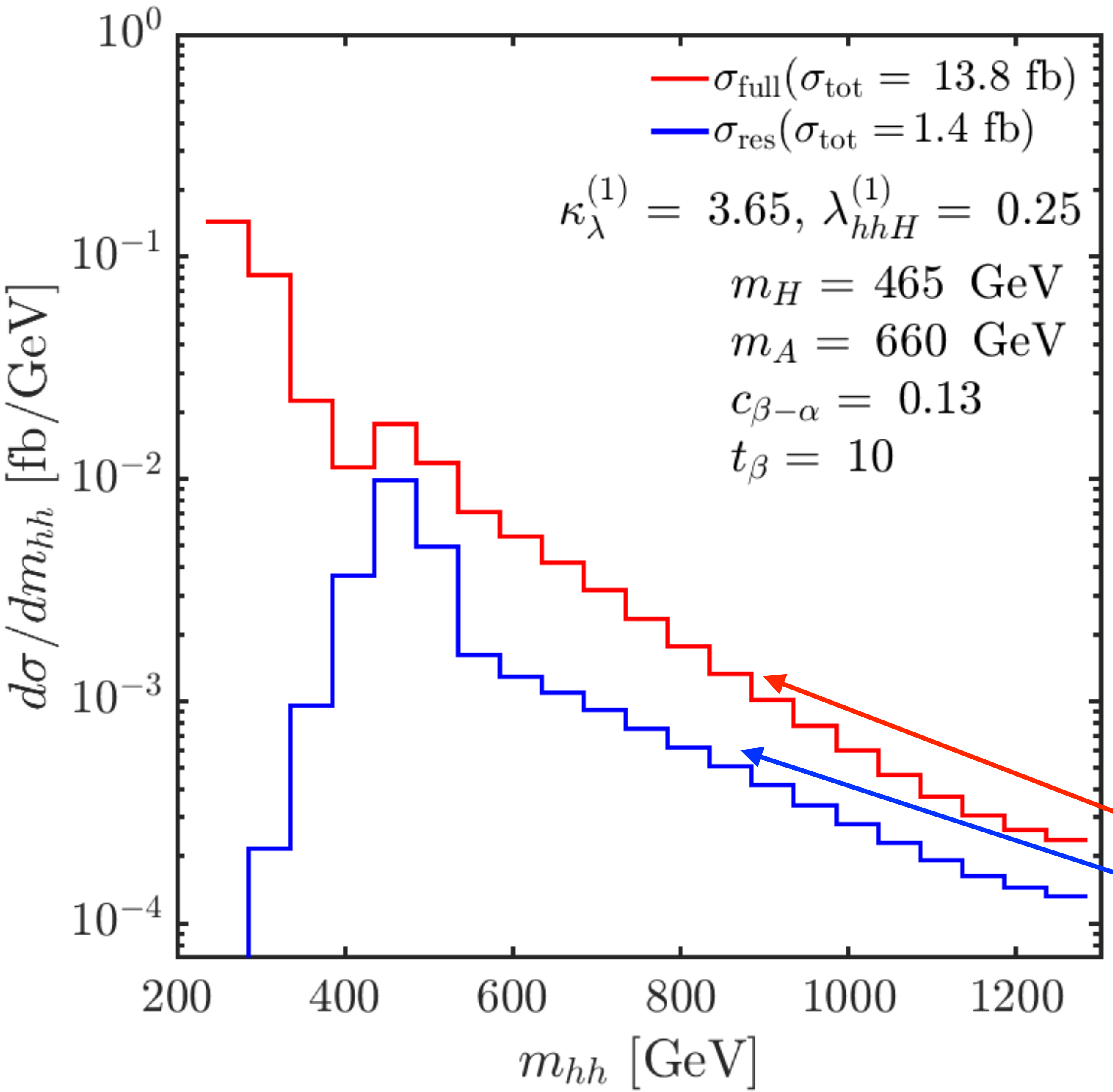
[see talk by
K. Radchenko]

⇒ Inclusion of loop contributions (mainly from κ_λ) has drastic impact on invariant mass distribution, large interference effects

Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

2HDM example, m_{hh} invariant mass distrib.: effects of smearing (15%) and binning (50 GeV) incorporated to account for finite exp. resolution



Same scenario as above:

$$t_\beta = 10,\ c_{\beta-\alpha} = 0.13\ (s_{\beta-\alpha} > 0)\ m_H = 465\ \mathrm{GeV},$$
$$m_A = m_{H^\pm} = 660\ \mathrm{GeV}\ m_{12}^2 = m_H^2 c_\alpha^2 / t_\beta$$

- Larger sensitivity to κ_λ in the low m_{hh} region (because of a cancellation between the box and triangle diagrams in the SM)

- Drop in the m_{hh} ~ 400 GeV region due to a shift in the cancellation of form factors

- Change in the dip peak structure of the resonance

full result

resonant contribution only

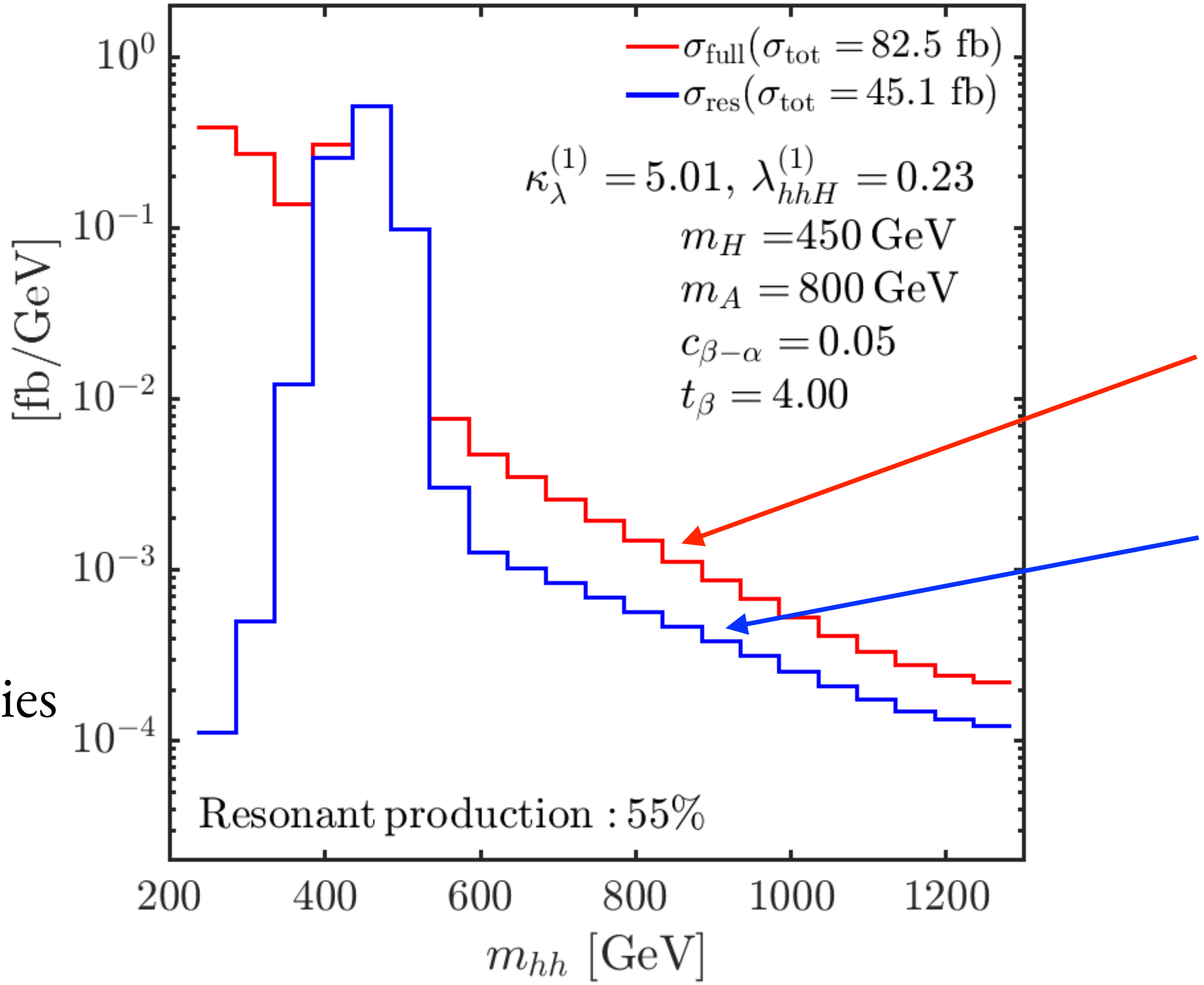
⇒ Loop corrections (mainly from κ_λ) and interference with non-resonant contributions has drastic impact on the shape of the m_{hh} distribution

Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. '24]

2HDM example, exp. smearing included, scenario that is claimed to be excluded by the resonant LHC searches, full result vs. resonant contrib.

15 % smearing
50 GeV binning
applied to account for
experimental uncertainties



full result

resonant contribution only

[see talk by K. Radchenko]

⇒ m_{hh} distribution depends very sensitively on $\varkappa_\lambda$, important interference effects, large deviation between resonant contribution and full result; limits using resonant contribution may be too optimistic

How to proceed?

In order to confront the experimental limits from resonant di-Higgs searches with the predictions from realistic models, appropriate tools are needed that make it possible to properly incorporate loop contributions to the trilinear Higgs couplings λ_{hhh} and λ_{hhH} as well as interference contributions between the resonant and the non-resonant contributions

[see talk by D. Winterbottom]

In the following: ongoing developments of the public code *anyH3* and link to the *MadGraph* event generator

[see talk by M. Gabelmann]

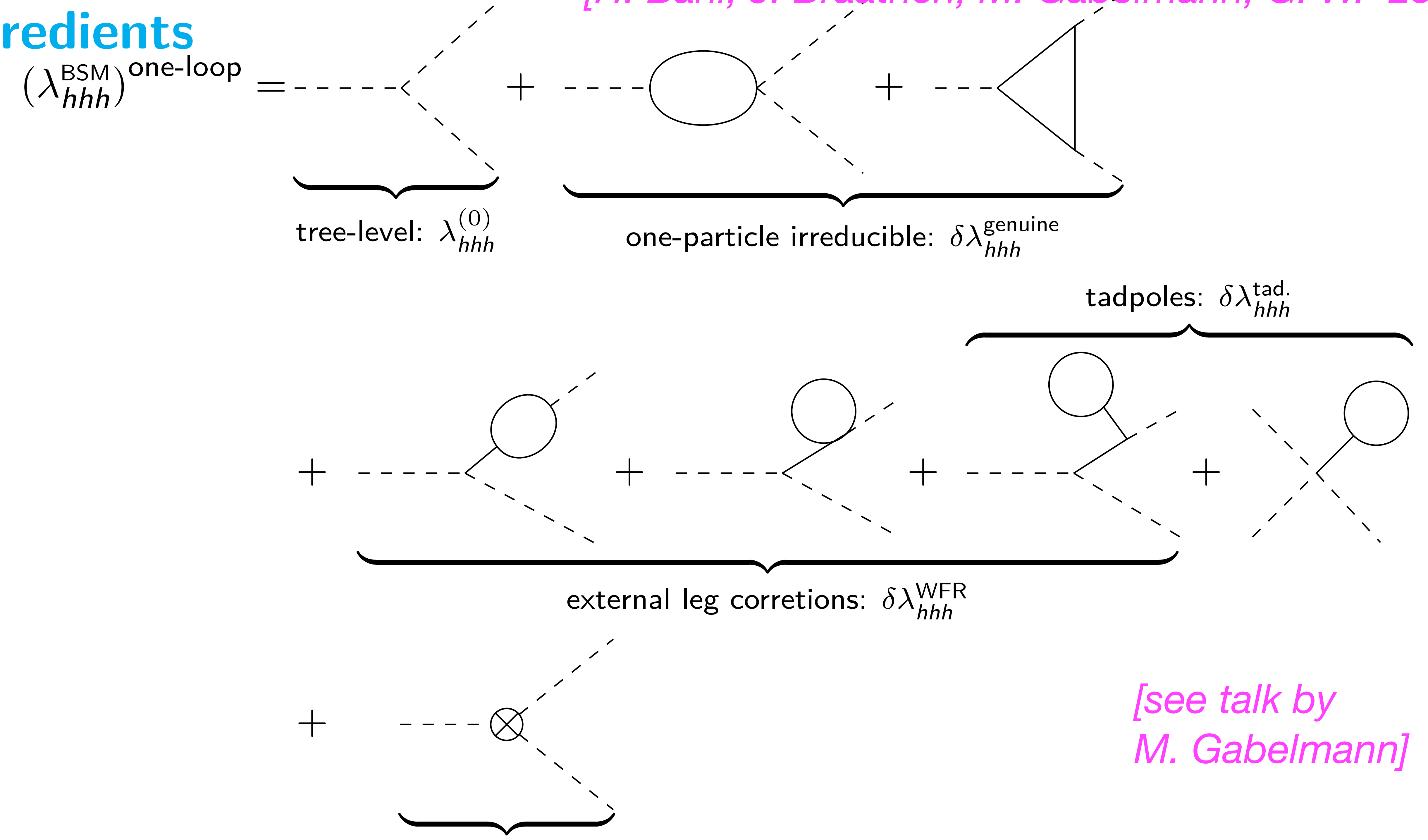
The public code *anyH3*: ongoing developments

https://anybsm.gitlab.io/

One-loop predictions for λ_{hhh} in arbitrary renormalisable models

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '23]

Ingredients



[see talk by M. Gabelmann]

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

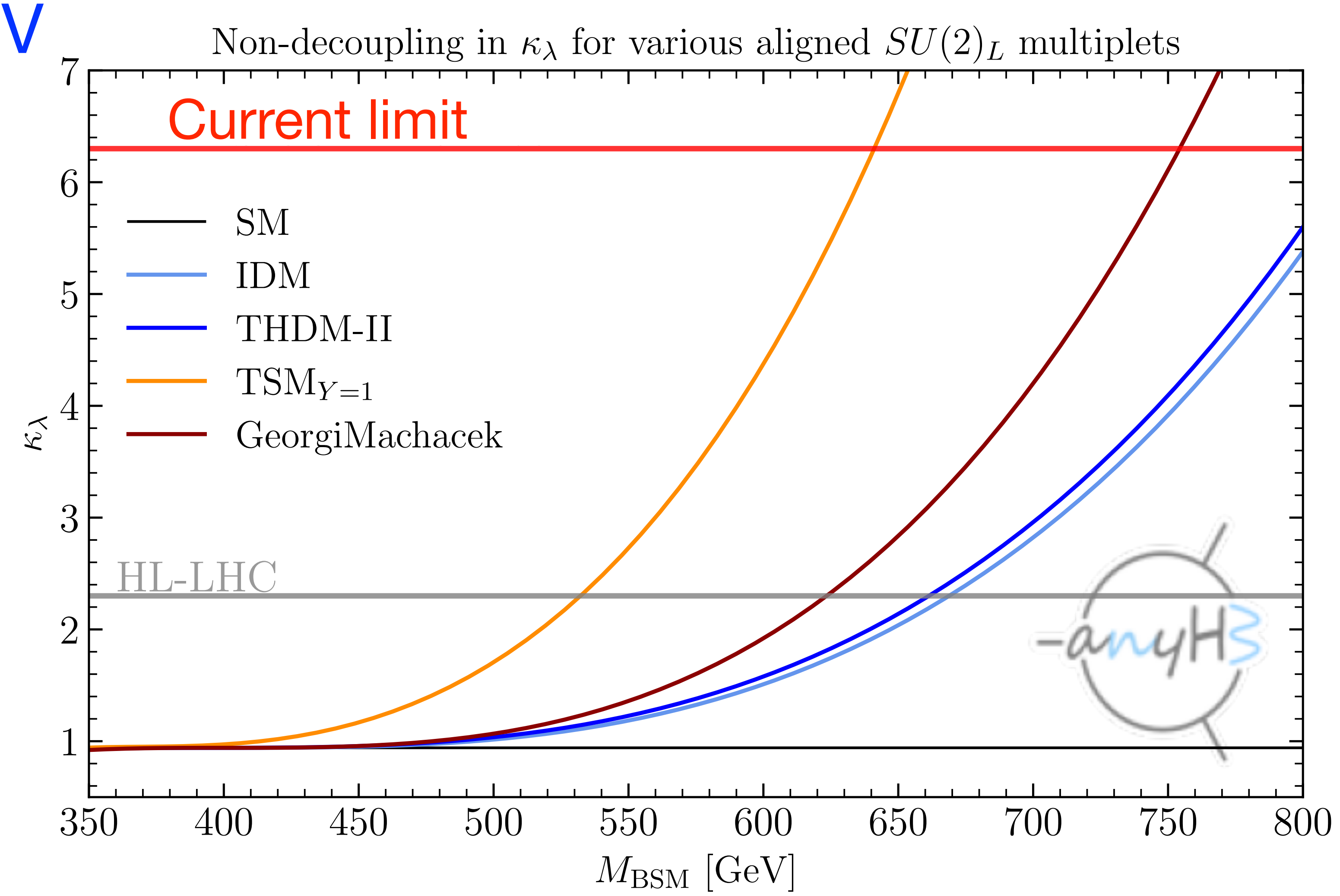
Higgs self-couplings in extended Higgs sectors

Effect of splitting between BSM Higgs bosons:

Very large corrections to the Higgs self-couplings, while all couplings of h_{125} to gauge bosons and fermions are SM-like (tree-level couplings agree with the SM in the alignment limit)

[H. Bahl, J. Braathen, M. Gabelmann, G. W. '23]

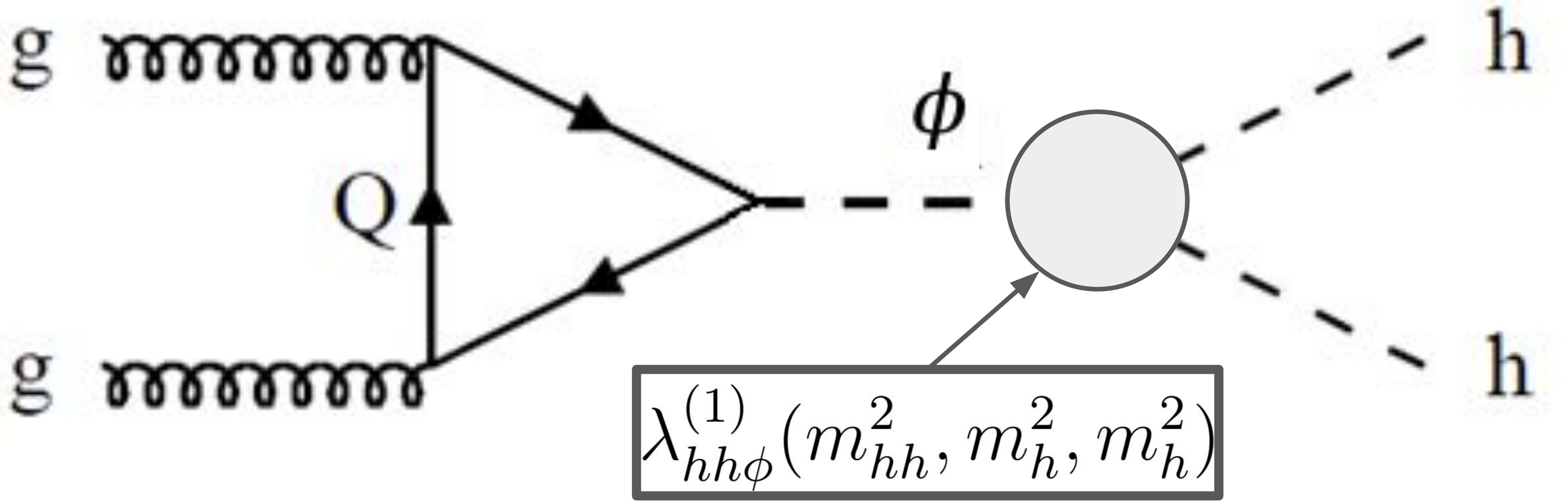
M_L = 400 GeV



Ongoing developments

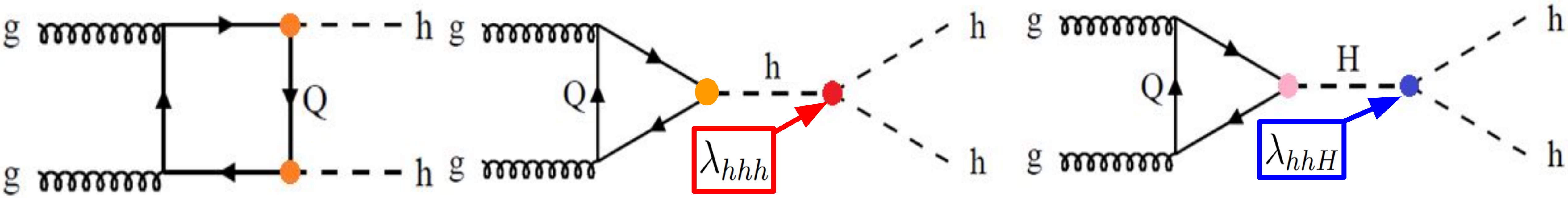
[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '24]

- Generalisation to trilinear couplings involving BSM Higgses: λ_{hhH}, …



[see talk by M. Gabelmann]

- Prediction for di-Higgs production involving resonant and non-resonant contributions and loop-corrected trilinear couplings

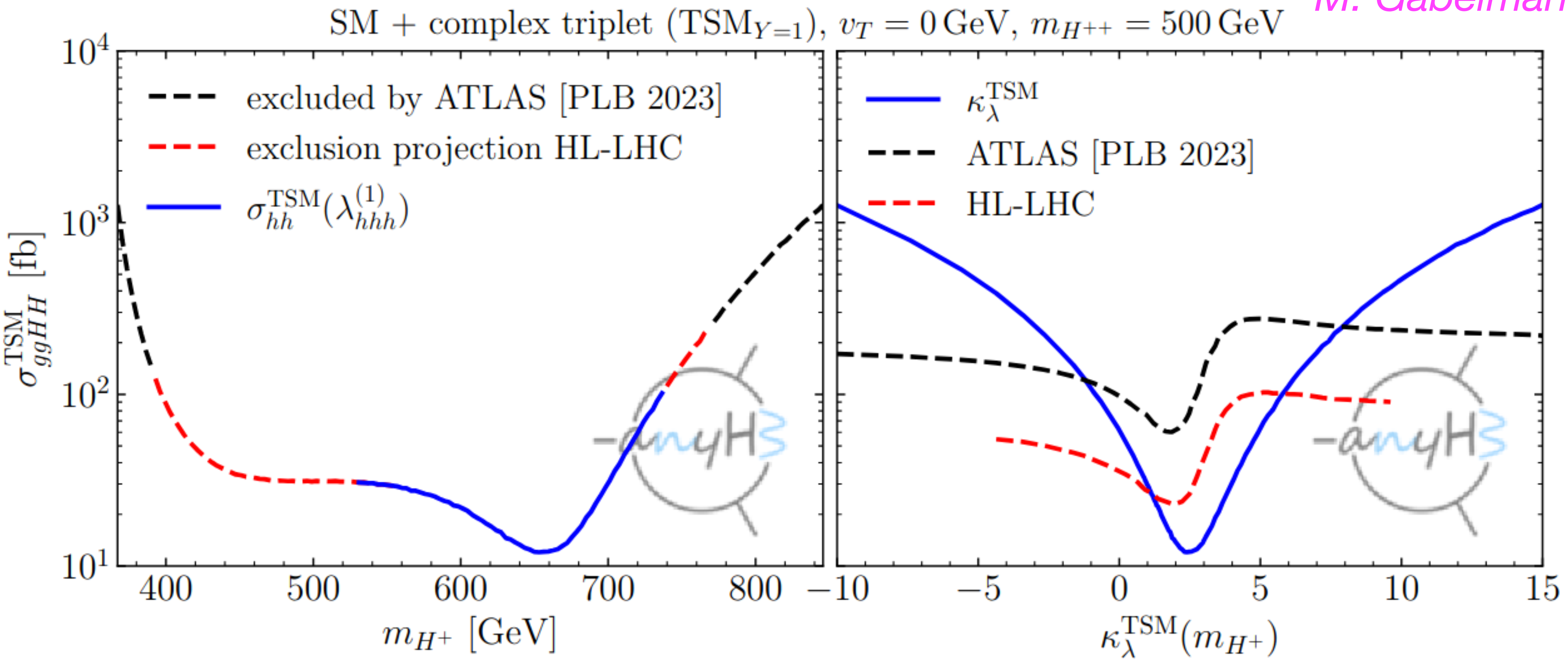


Di-Higgs production (*anyHH*)

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. ’24]

Example: SM + complex triplet (TSM)

[see talk by M. Gabelmann]



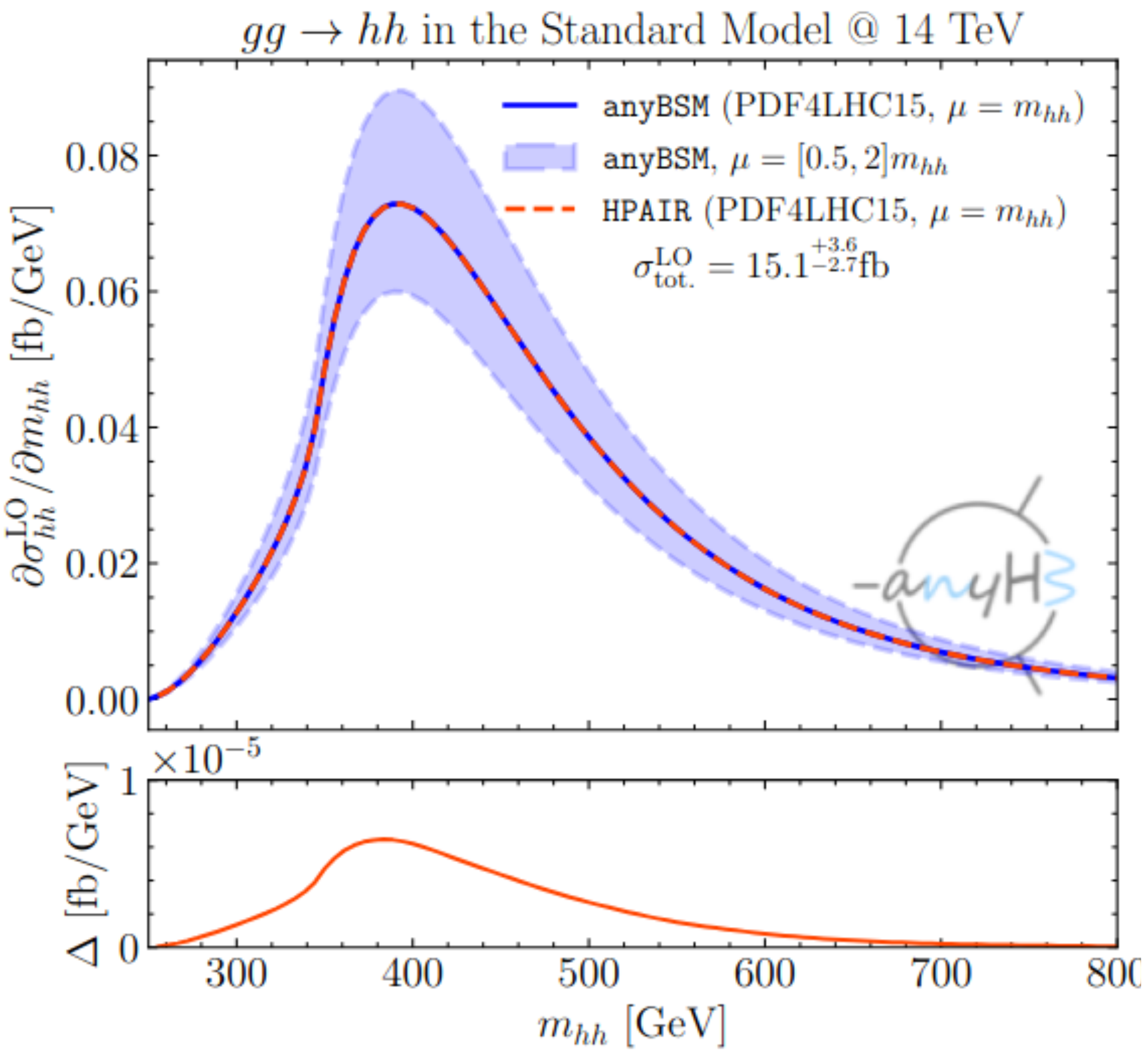
⇒ Present bounds from non-resonant searches already put important constraints

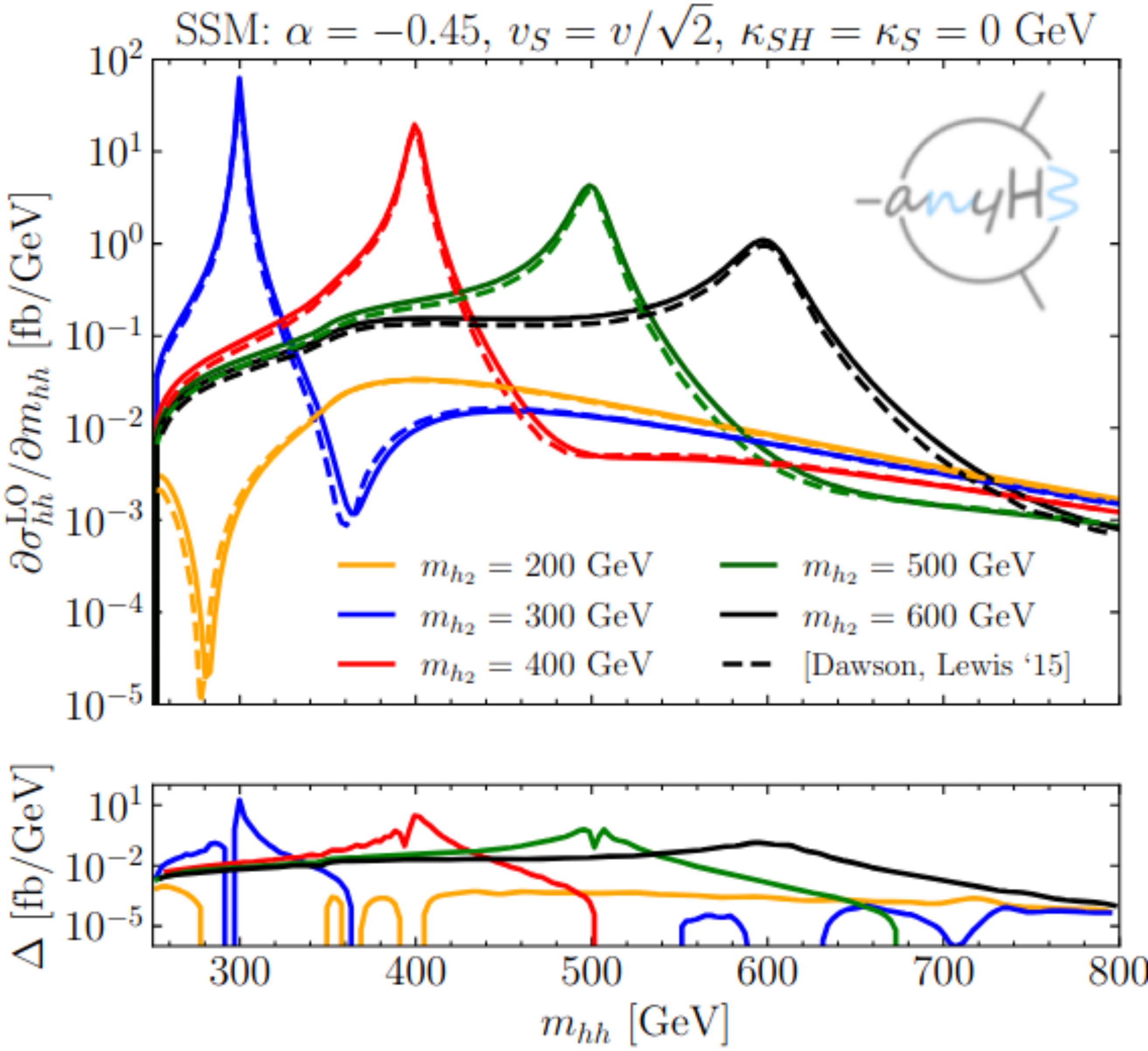
Tests of *anyHH* with leading-order trilinear couplings

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '24]

Comparison with *HPAIR*:
[M. Mühlleitner, M. Spira, et al.]

$$\Delta \equiv |\partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{HPAIR}) - \partial\sigma^{\rm LO}_{hh}/\partial m_{hh}(\texttt{anyHH})|$$





⇒ Excellent agreement with LO *HPAIR* result, once one ensures that running of α_s + choice of PDFs are same

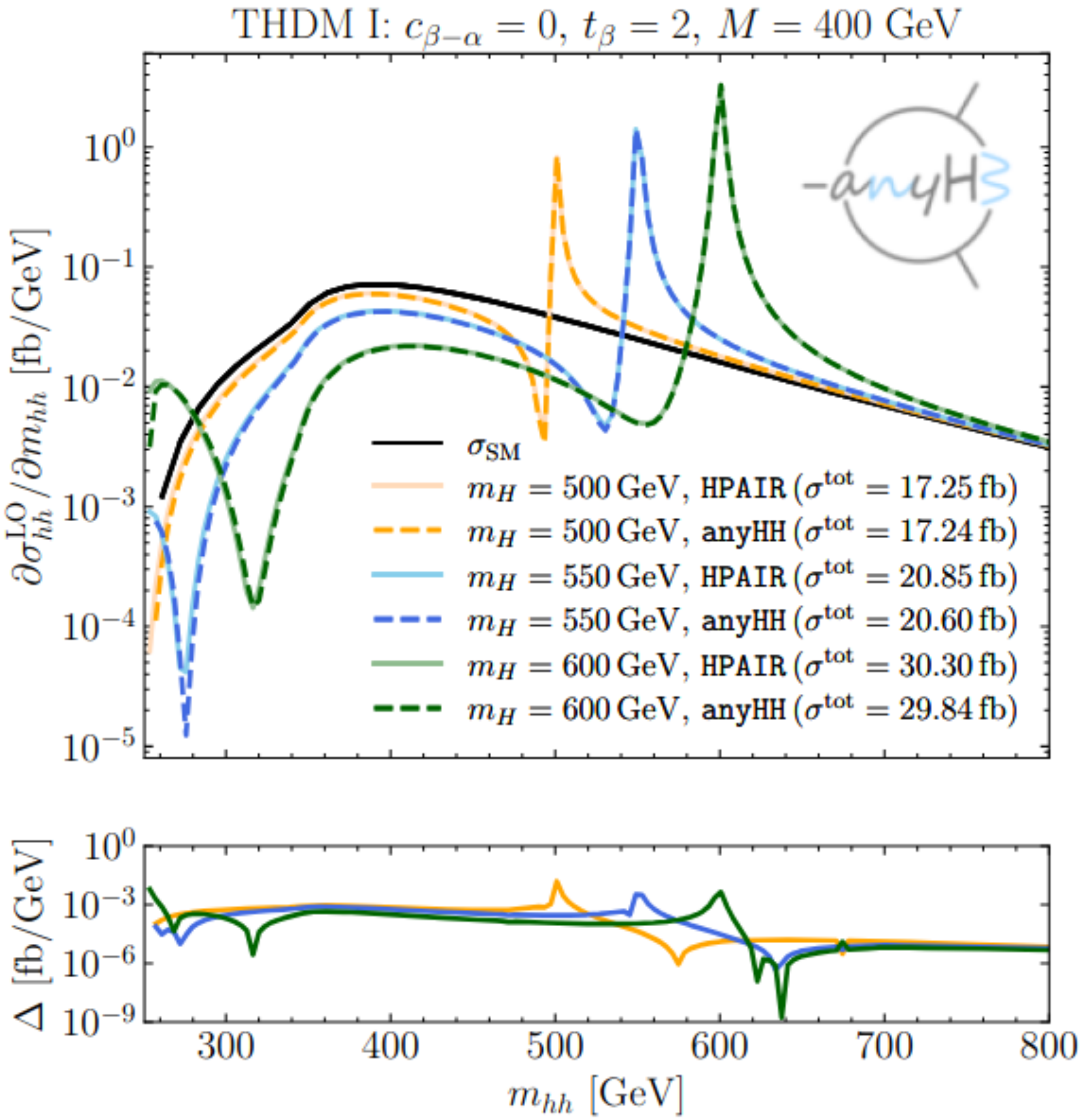
Very good agreement with results of *[S. Dawson, I. Lewis '15]* for singlet extension of SM (up to PDF sets)

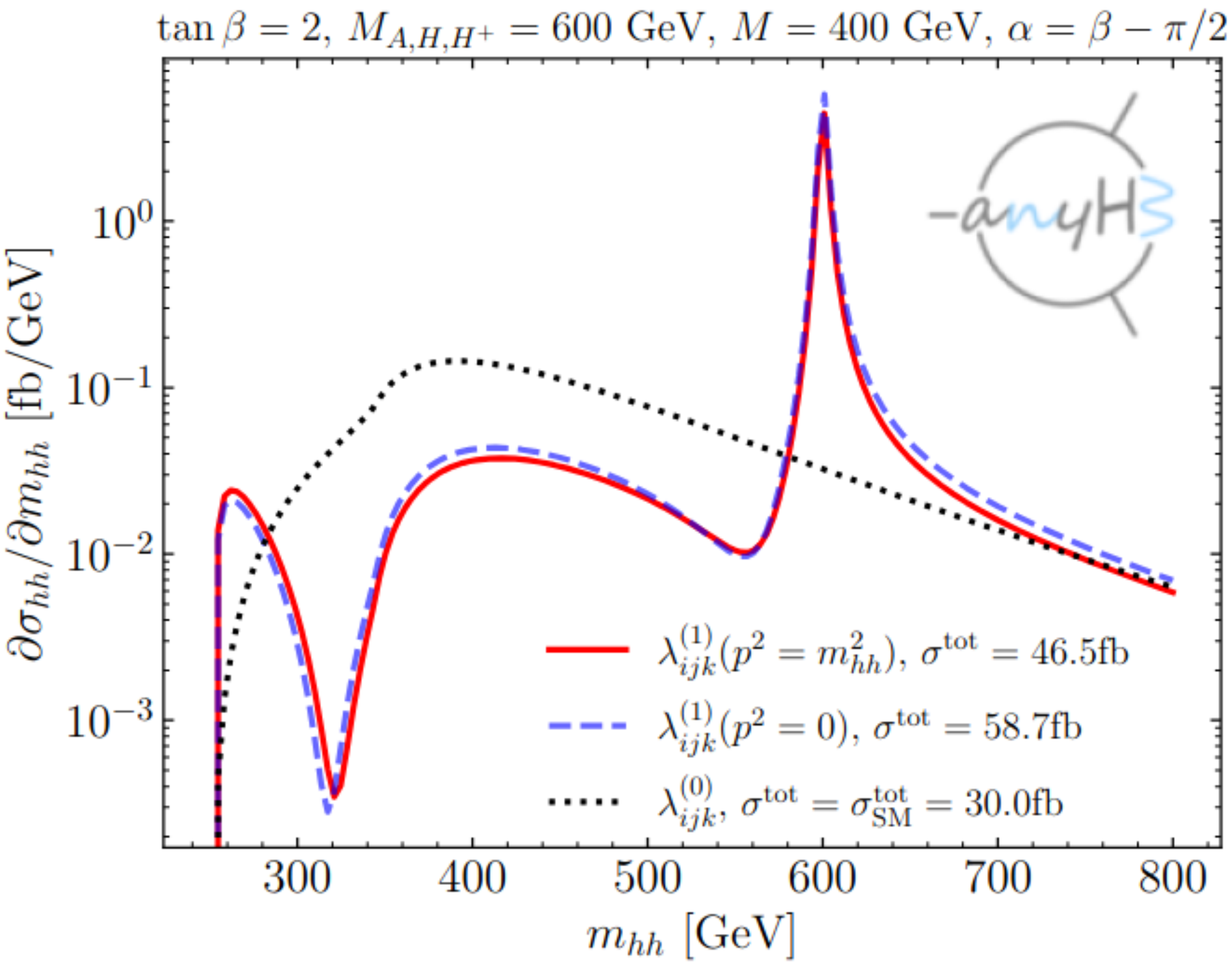
anyHH: 2HDM results

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. ’24]

Comparison with *HPAIR*:

[M. Mühlleitner, M. Spira, et al.]





⇒ Very good agreement with *HPAIR*, using one-loop trilinear scalar couplings computed by *anyH3* for 2HDM benchmarks (here: alignment limit)

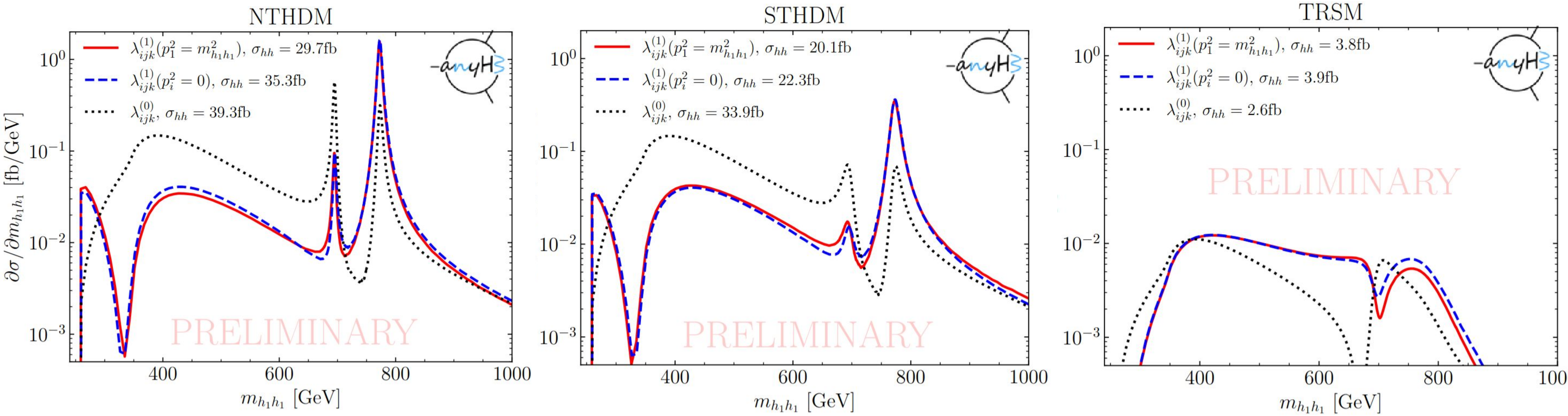
One-loop corrections to trilinear Higgs couplings have large impact on differential distribution

Moderate effect of momentum dependence of trilinear couplings (up to 20% on total cross-section)

anyHH results and link to *MadGraph*

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. '24]

Examples: NTHDM = 2HDM + real singlet; STHDM = 2HDM + complex singlet DM; TRSM: two-real singlet model



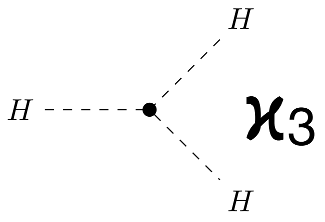
Under development: link to the *MadGraph* event generator

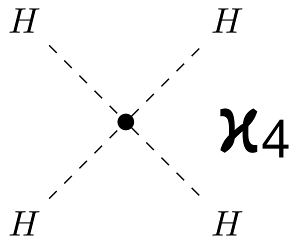
[see talk by M. Gabelmann]

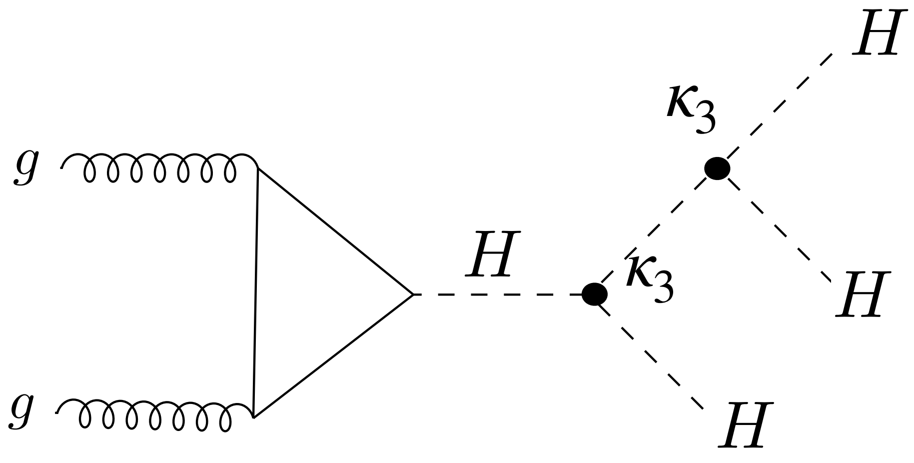
Export analytical expressions for loop-corrected trilinear couplings λ_{ijk} (with momentum dependence) from *anyHH* to UFO format, so that loop-corrected trilinear couplings can be used directly in *MadGraph* simulations

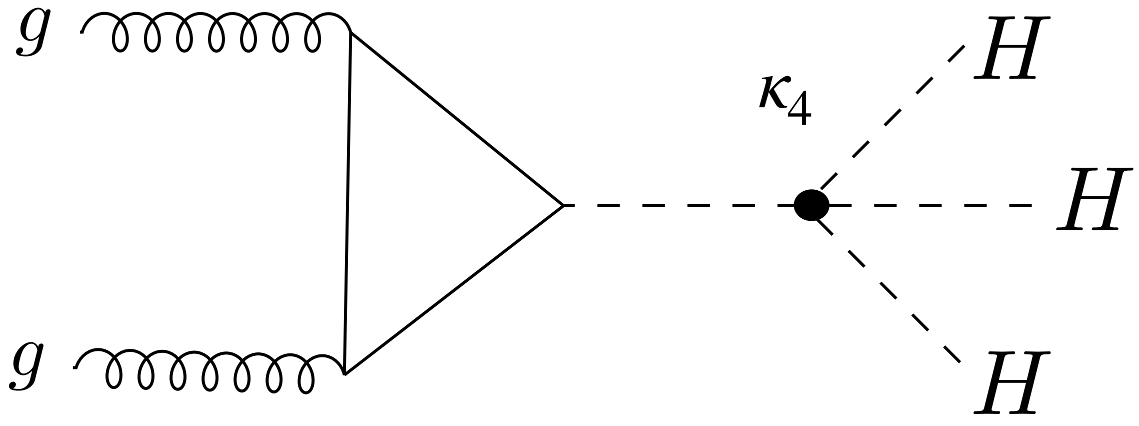
HHH production and Higgs self-couplings

Triple Higgs production depends on $\varkappa_3$ and $\varkappa_4$!









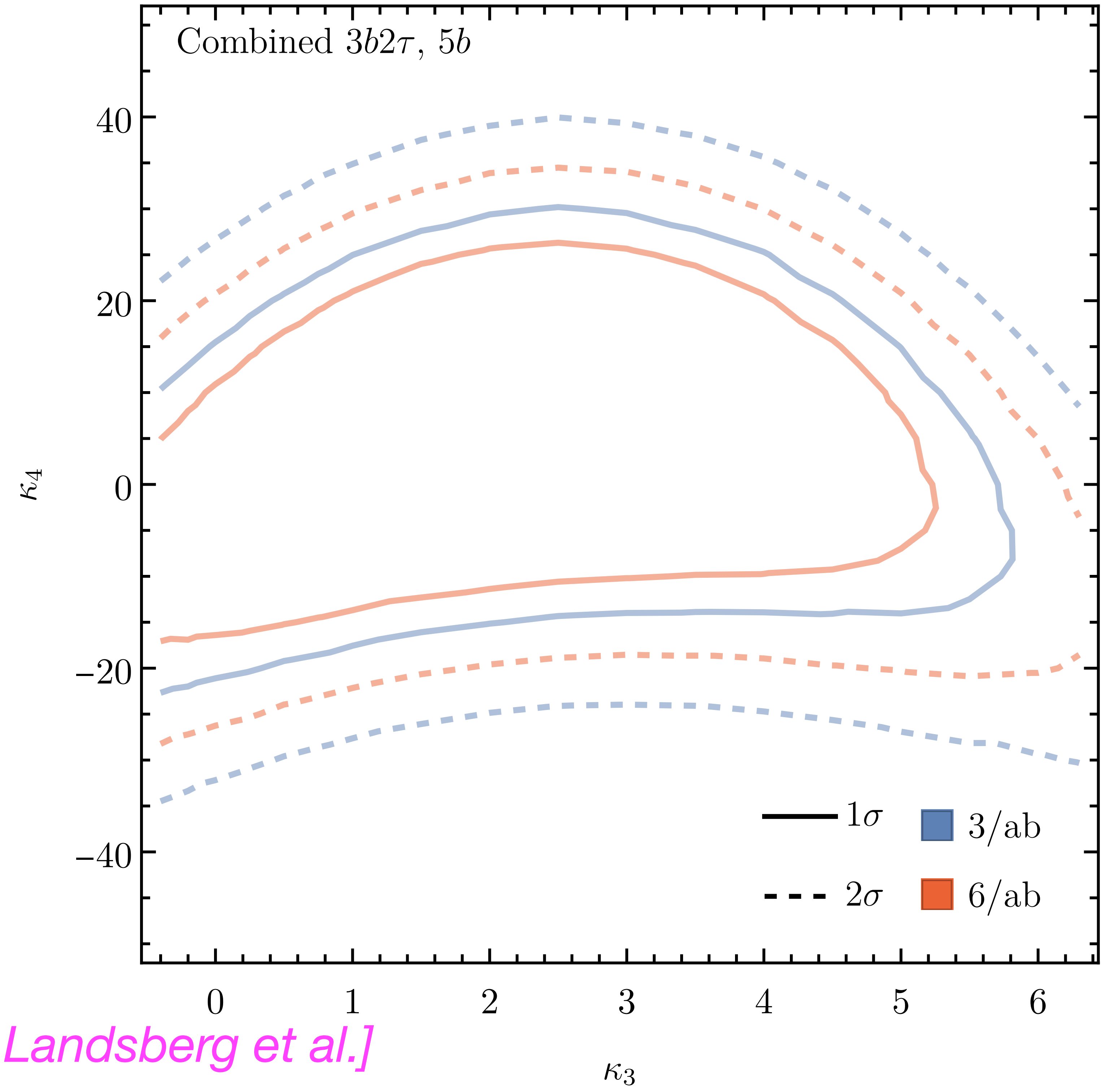
Is it possible to obtain bounds from triple Higgs production on $\varkappa_3$ and $\varkappa_4$ that go beyond the existing theoretical bounds from perturbative unitarity? Potential for $\varkappa_3$ constraints beyond the ones from di-Higgs production?

How big could the deviations in $\varkappa_4$ from the SM value (= 1) be in BSM scenarios?

Prospects for the HL-LHC: 6b and 4b2τ channels comb.

[P. Stylianou, G. W. '24]

- **Assumption:** No correlations



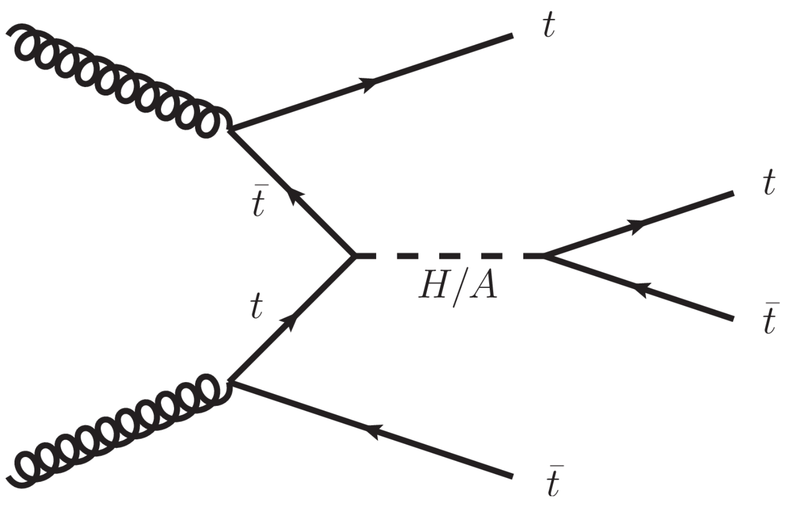
Combination of further channels and improvements of **tagging/reconstruction** methods could enhance results further

[see talk by C. Pandini] *[G. Landsberg et al.]*

Theory question: first ATLAS and CMS results on HHH searches?

ATLAS 4 top search

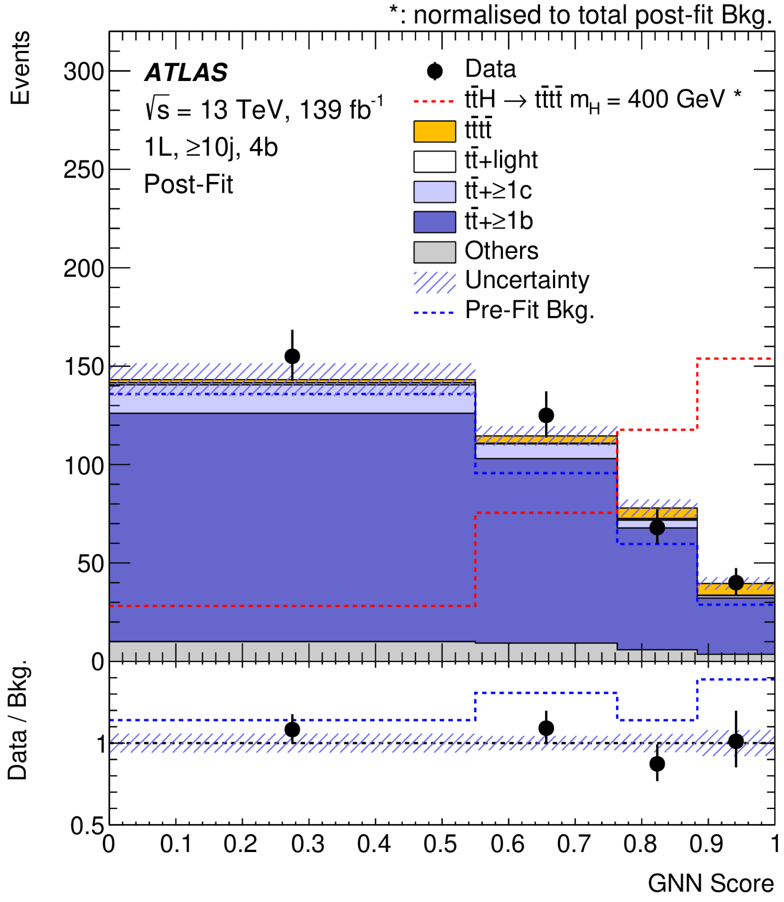
ttH/A→tttt

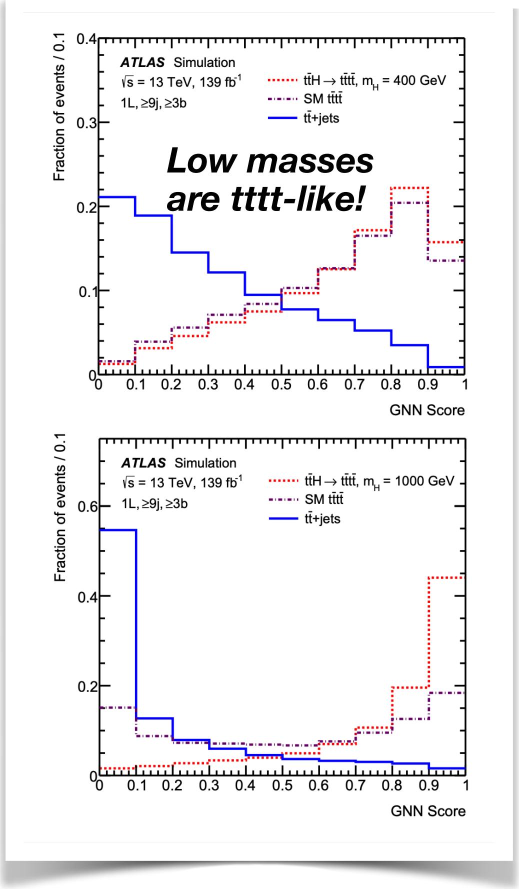


[H. Saka, talk on Monday]

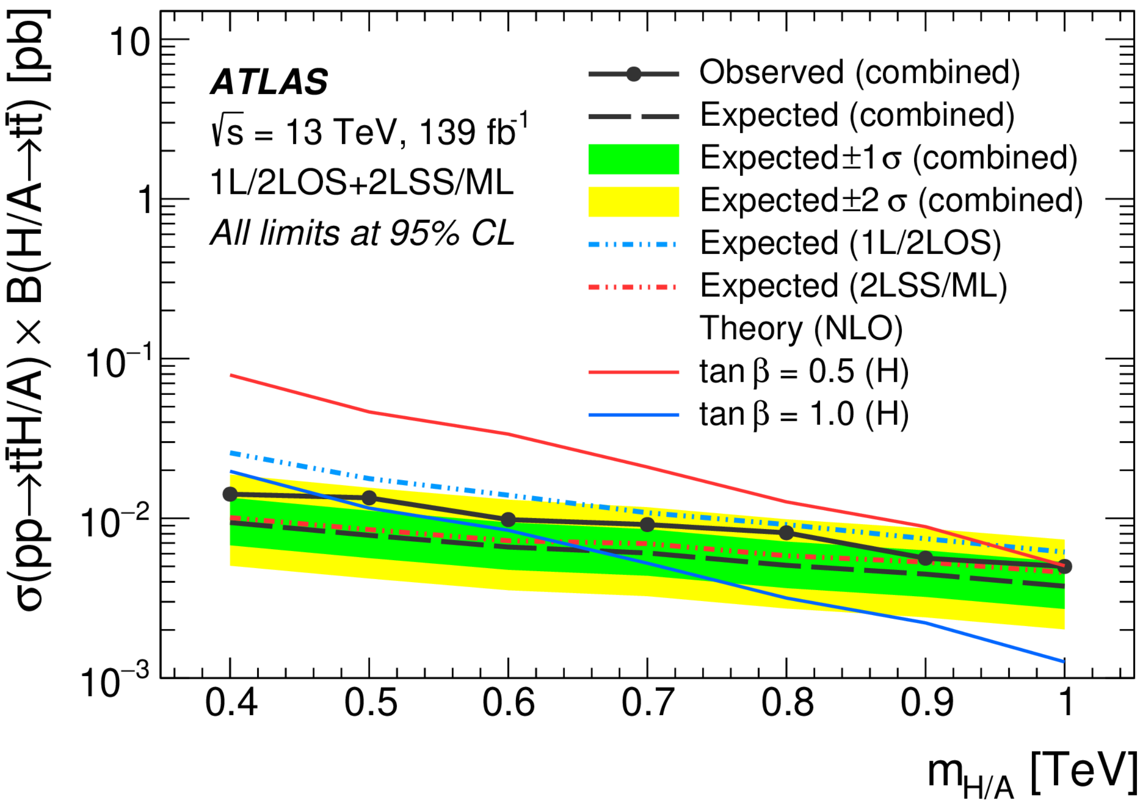
ATLAS EXOT-2022-13

arXiv:2408.17164





Low masses are tttt-like!



A parametrized GNN is used to separate S from B for a given mass hypothesis.

*Results **combined with the earlier 2LSS and ML** analysis.*
→ significant improvement at lower masses.

Near identical kinematics and acceptance between A and H.

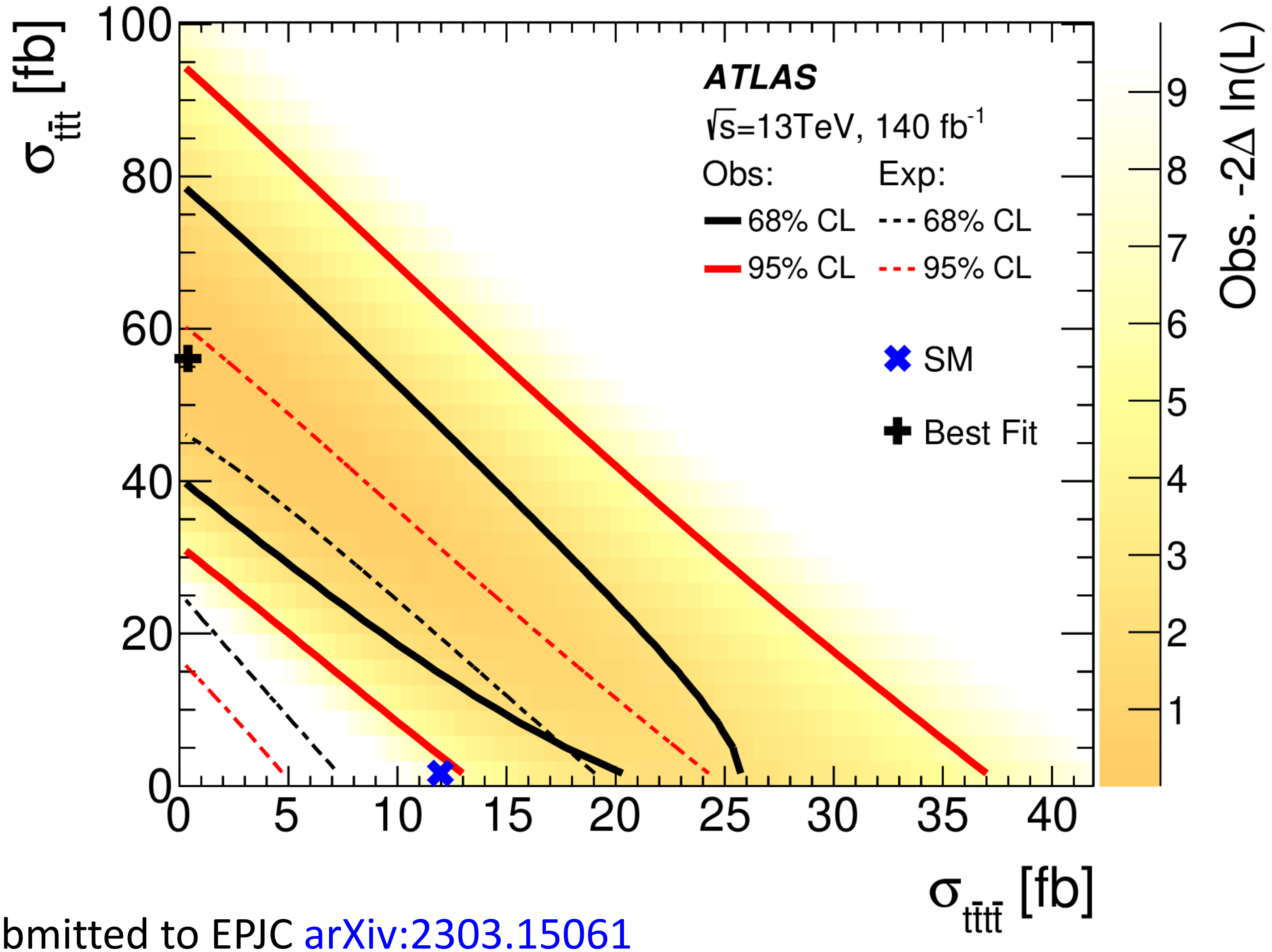
How about the A cross section?

How about the ttt final state?

ATLAS cross section measurement: 3-top vs. 4-top final states

[ATLAS Collaboration '23]

ATLAS: three tops?



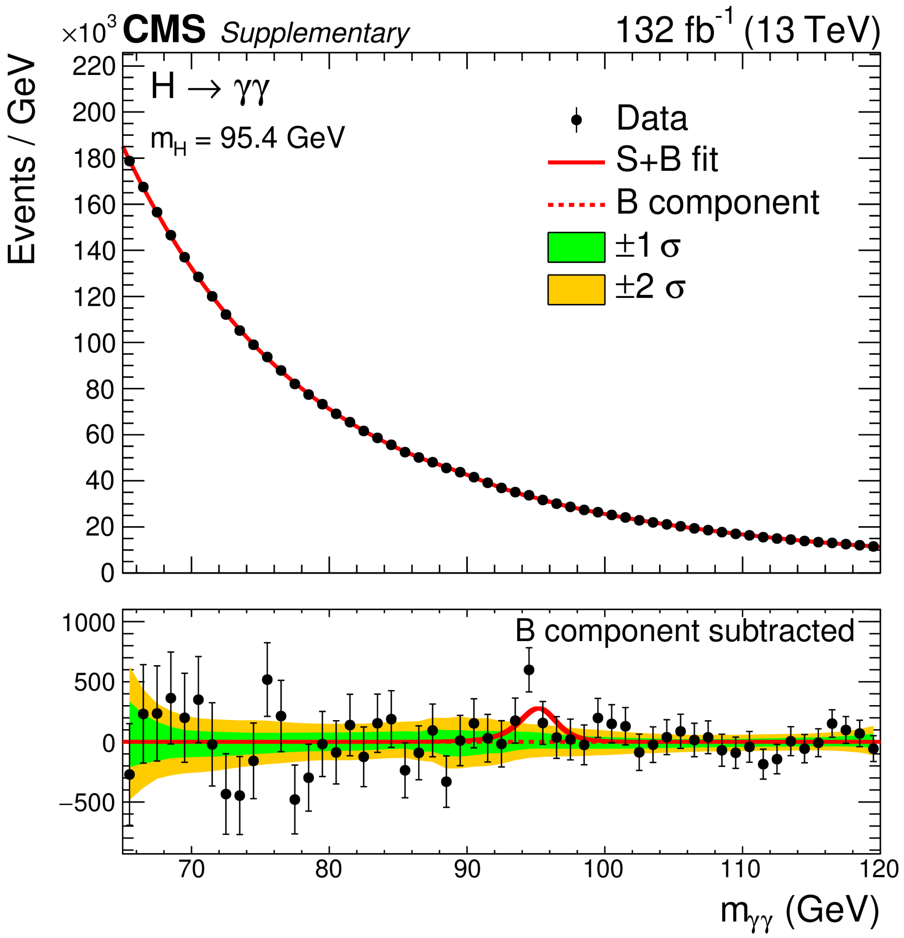
Submitted to EPJC arXiv:2303.15061

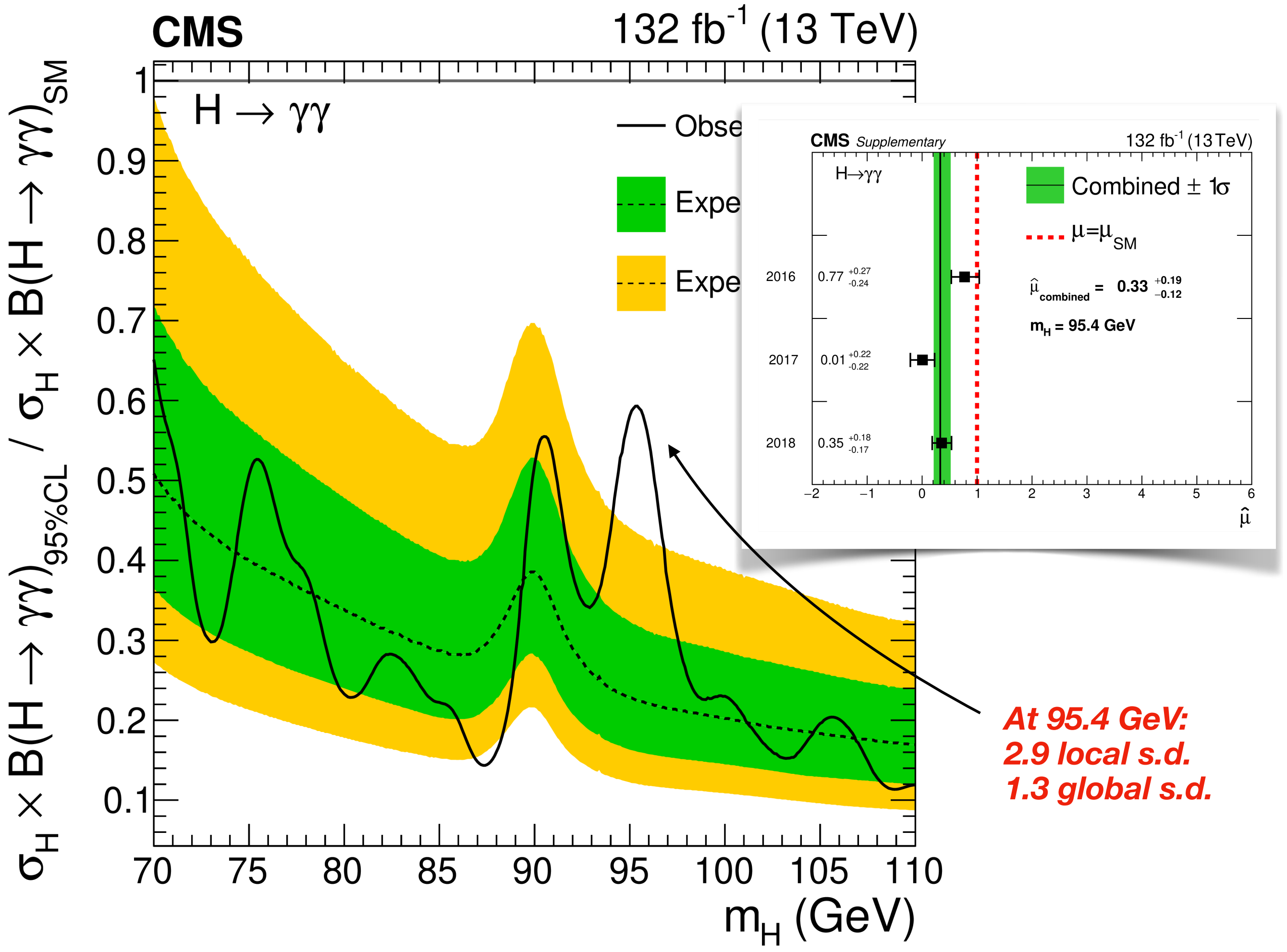
freyablekman FH physics discussion

A possible light Higgs at 95 GeV?

$H \to \gamma\gamma$ (low mass)

CMS HIG-20-002
arXiv:2405.18149





At 95.4 GeV:
2.9 local s.d.
1.3 global s.d.

Multiple MVA discriminants *are used for* ***photon energy, ID, and event classification*** *(also uses vertex information)****.***

Search for narrow signal peak over ***smoothly-falling background (parametric fit).***

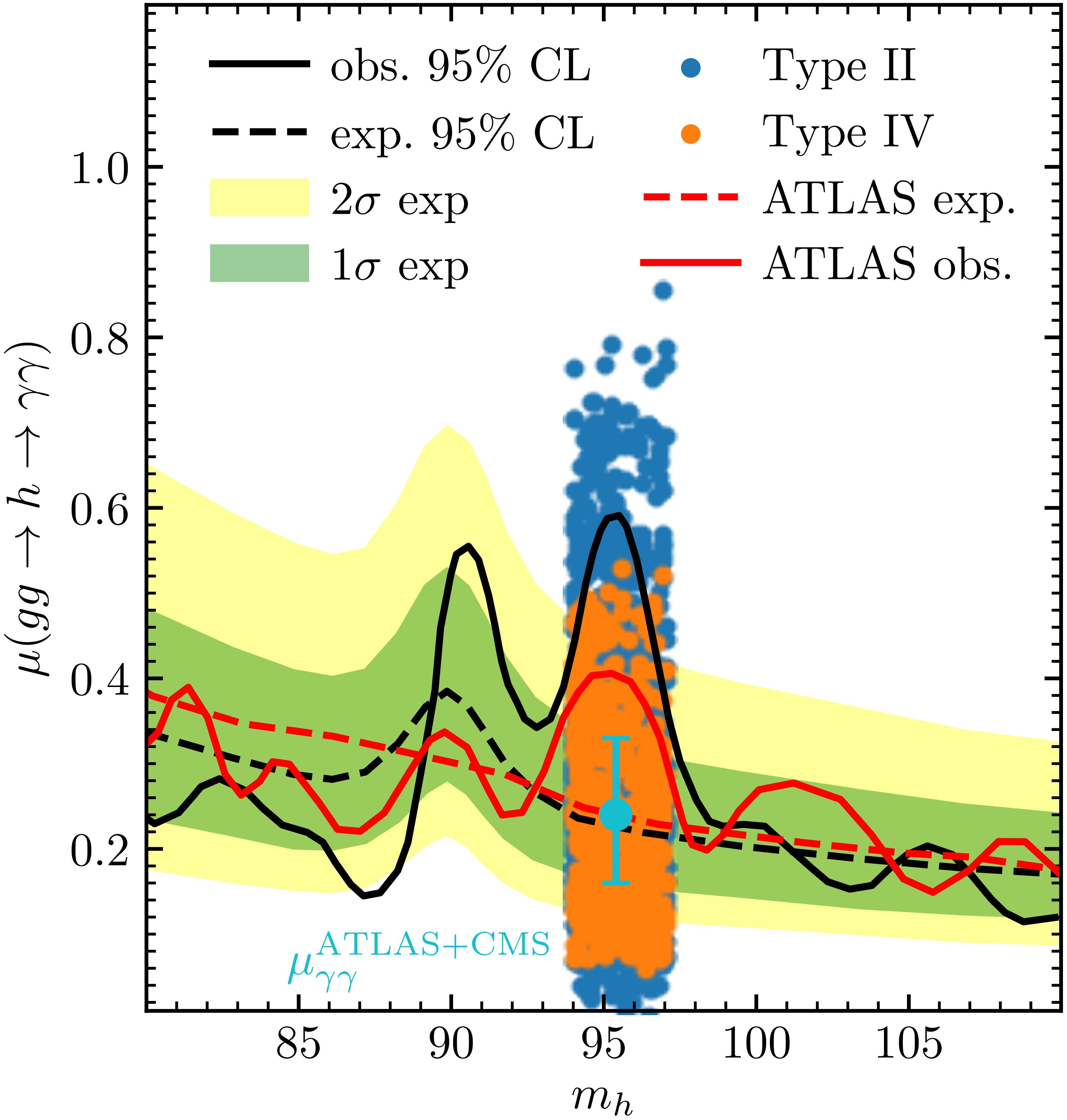
Targets ggF, VBF, ttH, VH modes*, via the Class MVA and jet multiplicity variables.*

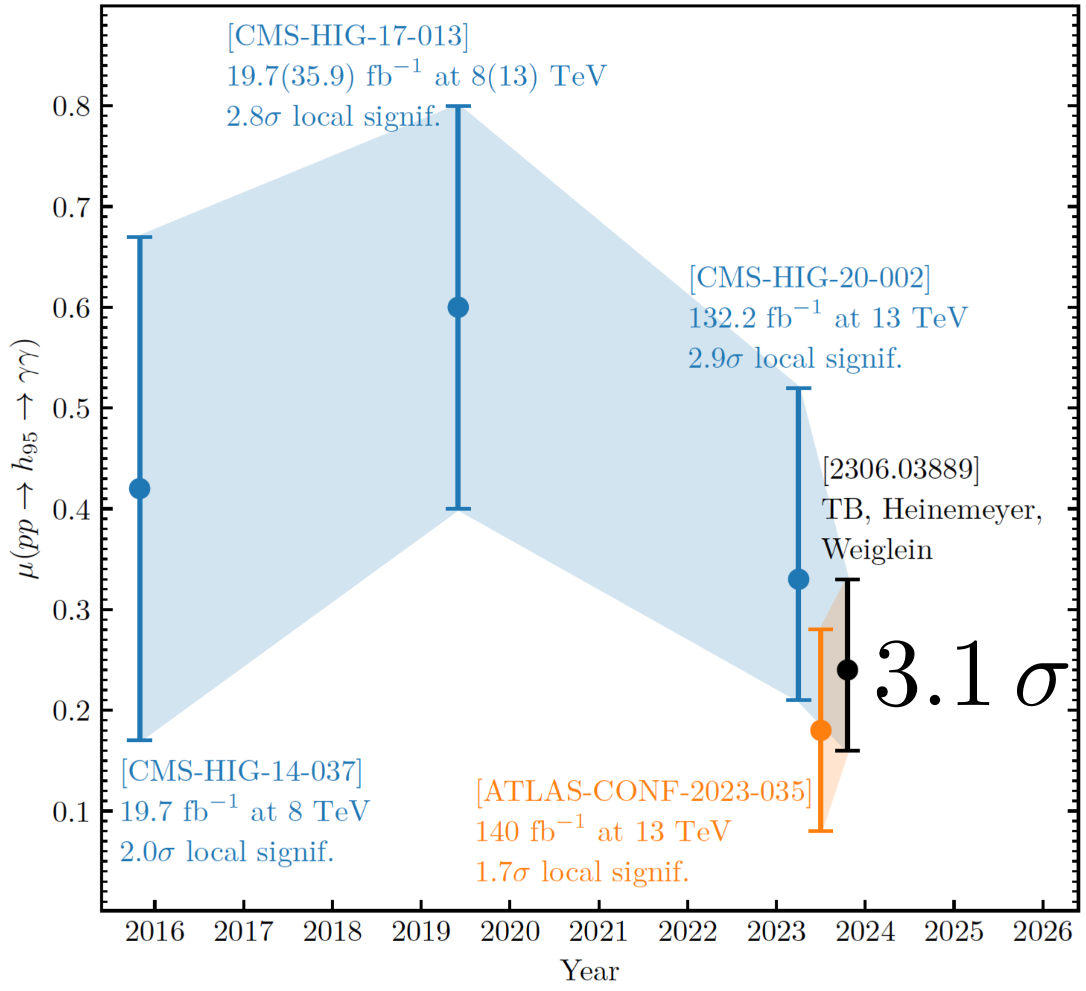
[H. Saka, talk on Monday]

A possible light Higgs at 95 GeV?

[T. Biekötter, S. Heinemeyer, G. W. '23]

CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV: $\mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08}$





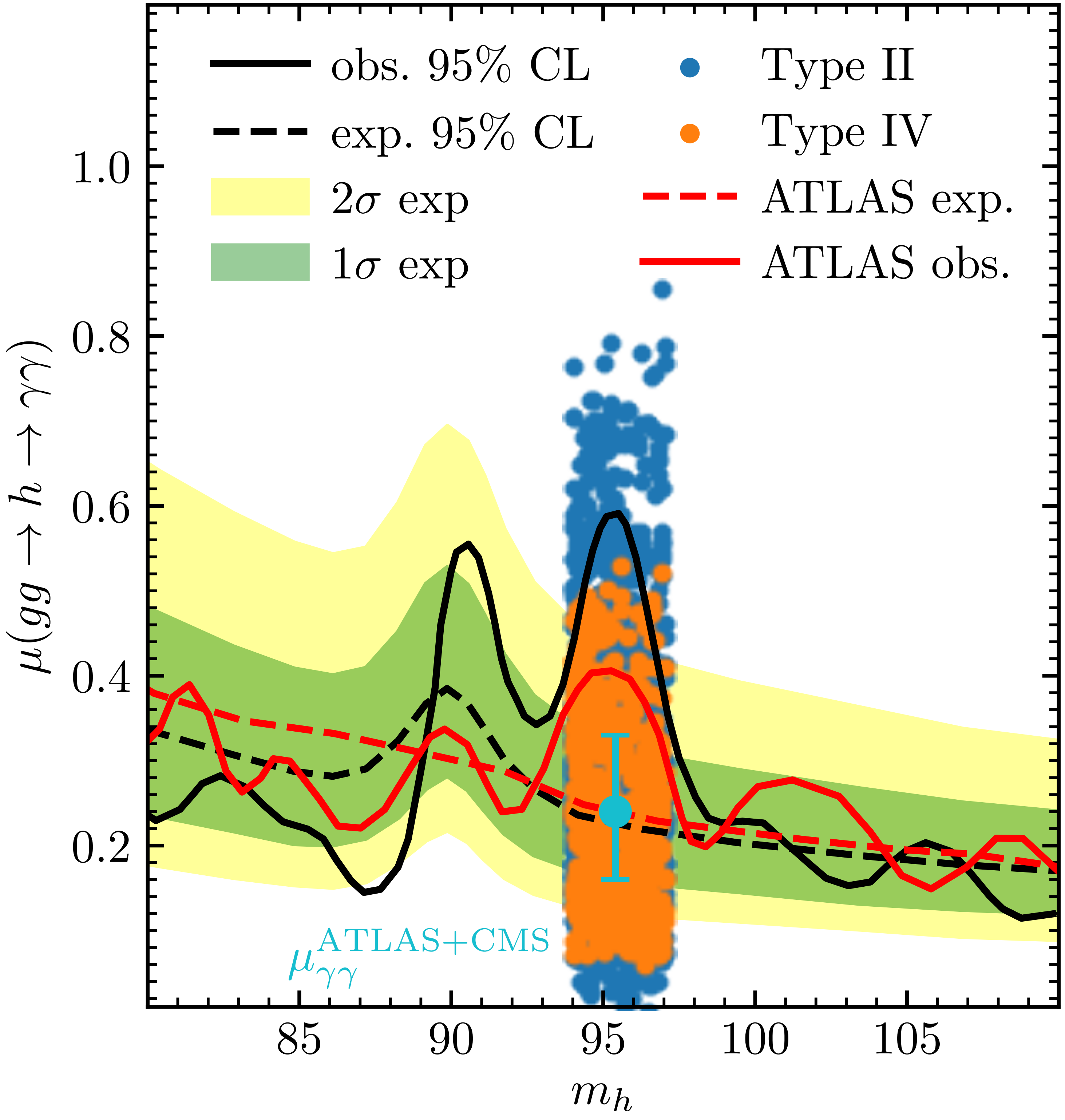
Example interpretation:
S2HDM, type II and IV

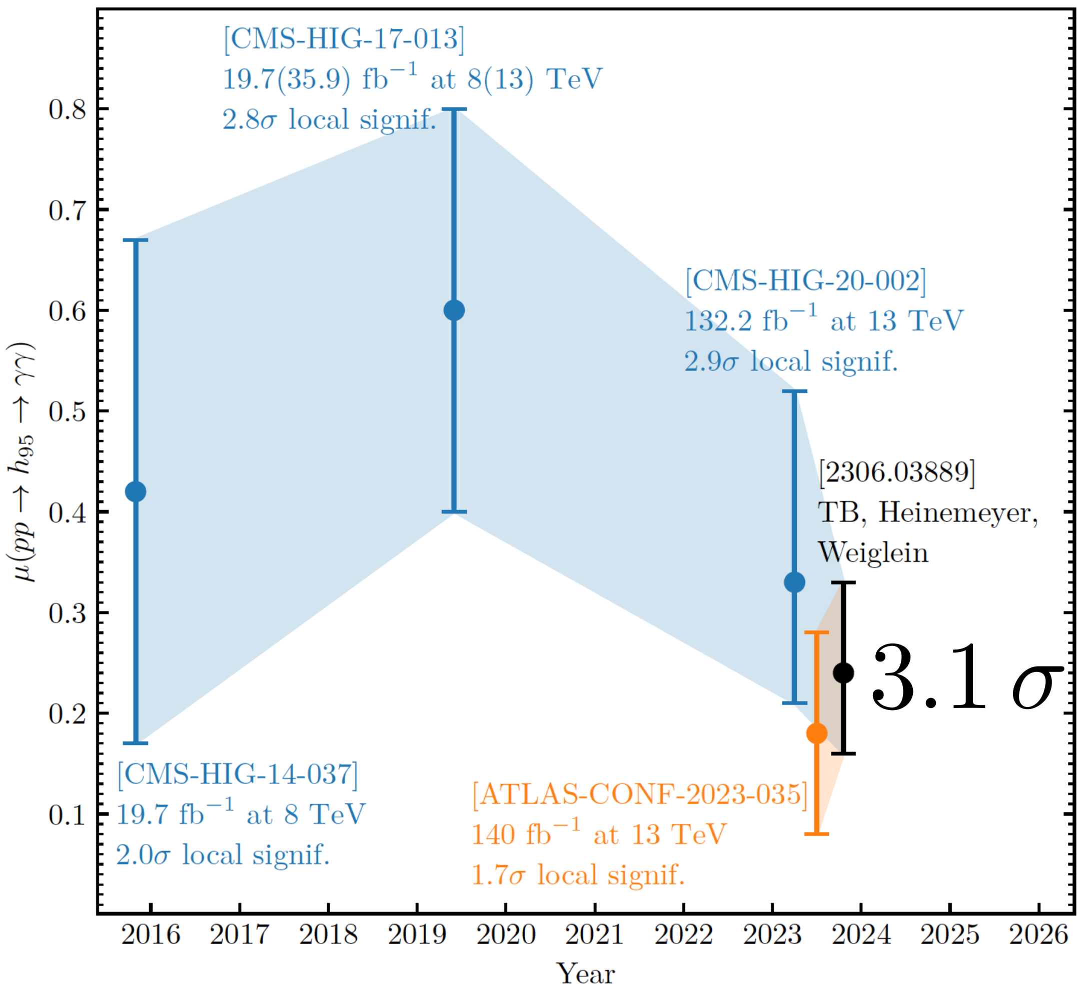
⇒ Good description in extended Higgs sectors with additional doublet and singlet

A possible light Higgs at 95 GeV?

[T. Biekötter, S. Heinemeyer, G. W. ’23]

CMS + ATLAS excess in $\gamma\gamma$ channel at 95 GeV: $\mu_{\gamma\gamma}^{\text{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08}$





Theory question: how about the tth$_{95}$, h$_{95}$ → $\gamma\gamma$ channel?

Conclusions

The physics of extended Higgs sectors at the LHC has reached a stage where, because of the high precision of the measurements and the investigated signatures, the comparison between the experimental results and the theory predictions requires a careful incorporation of a variety of effects (higher orders, interferences, …)

A joint effort between experiment and theory will be instrumental for fully exploiting the LHC capabilities!

Backup

Electroweak phase transition and baryon asymmetry

Observed Baryon Asymmetry of the Universe (BAU)

$$\eta \equiv \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.1 \times 10^{-10}$$ [Planck '18]

n_b: baryon no. density
$n_{\bar{b}}$: antibaryon no. density
n_γ: photon no. density

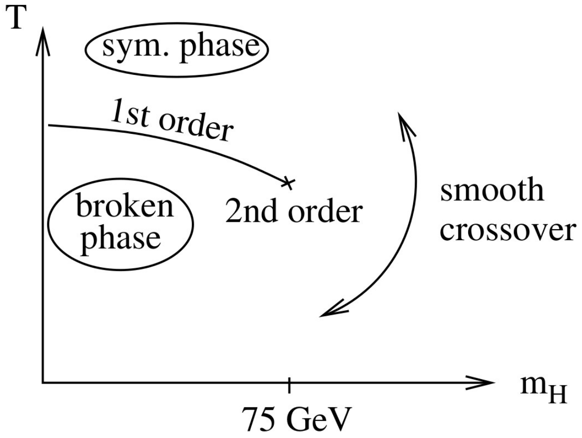
[J. M. No '23]

Sakharov Conditions

(*for dynamical generation of baryon asymmetry*)

- B Violation
- C/CP Violation ✘ not enough in SM
- Departure from Thermal Equilibrium

SM phase diagram



SM CP Violation insufficient by ~ 10 orders of magnitude

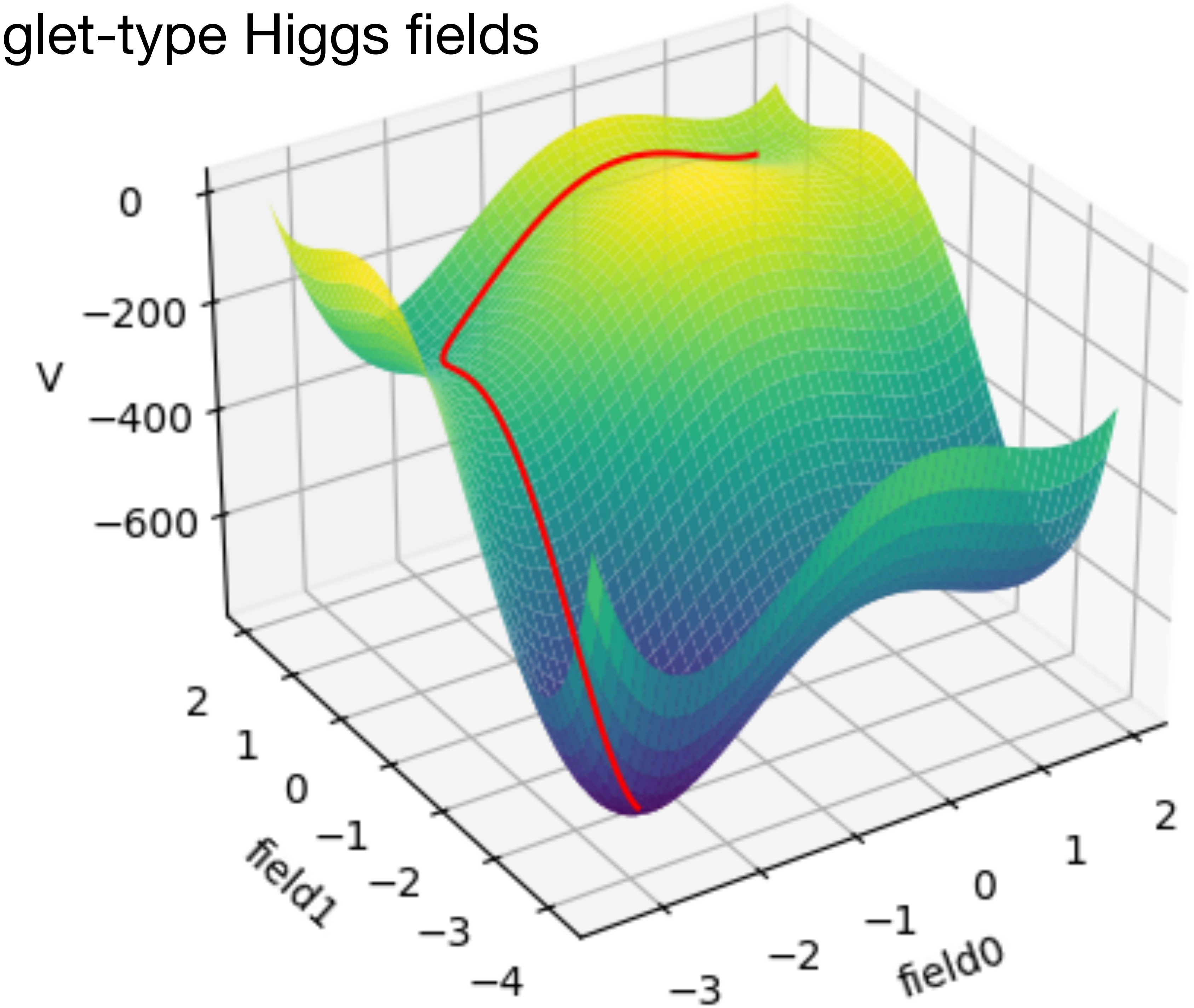
via 3-family fermion mixing
(CKM matrix)

Sakharov conditions:
- baryon (or lepton) number violation starting from symmetric state
- treat baryons and anti-baryons differently (to remove anti-matter)
- suppress inverse processes

The Higgs potential and vacuum stability

[T. Biekötter, F. Campello, G. W. '24]

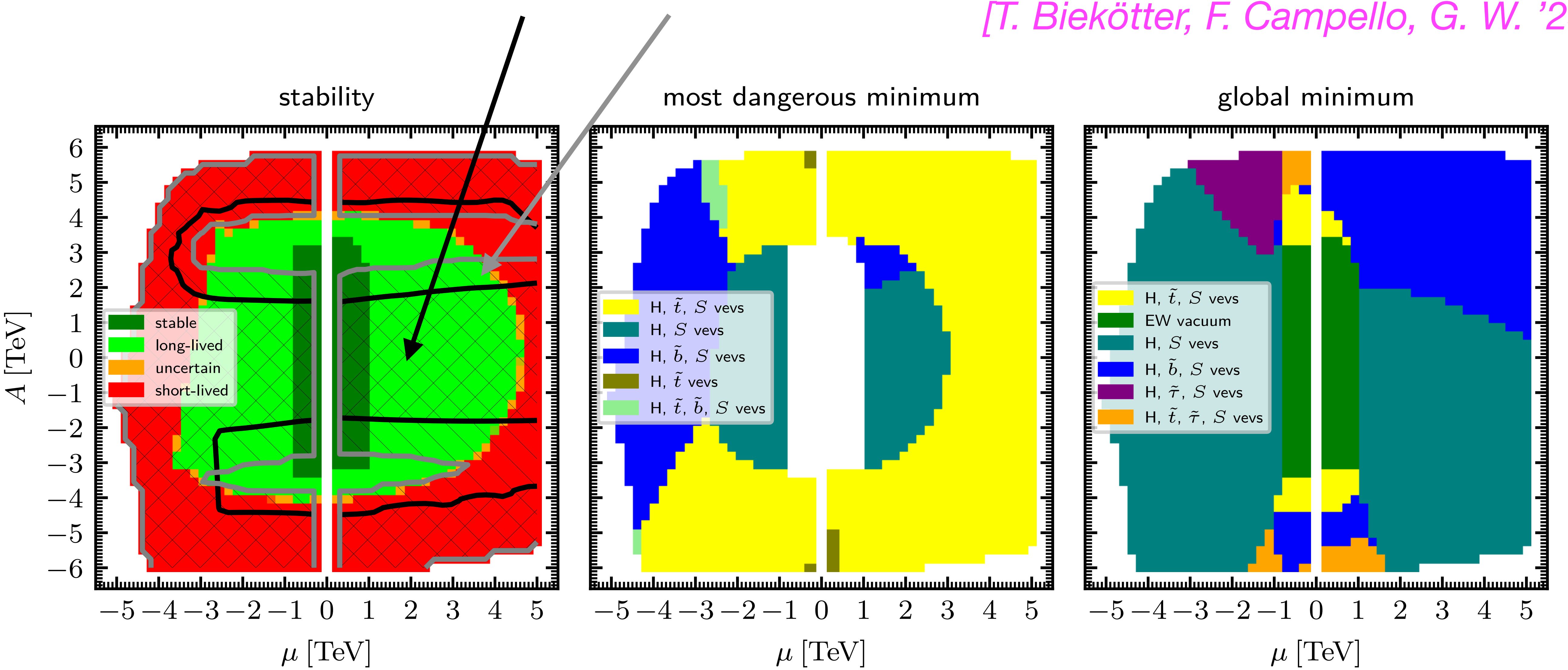
Tunneling from a local minimum into the global minimum: toy example, two singlet-type Higgs fields



⇒ Proceeds via intermediate local minimum

Vacuum stability constraints in the NMSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt ’18]*
Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*



HiggsBounds *HiggsSignals*

[T. Biekötter, F. Campello, G. W. ’24]

Character of most-dangerous minimum differs from global minimum

Strongly first-order EWPT in the 2HDM

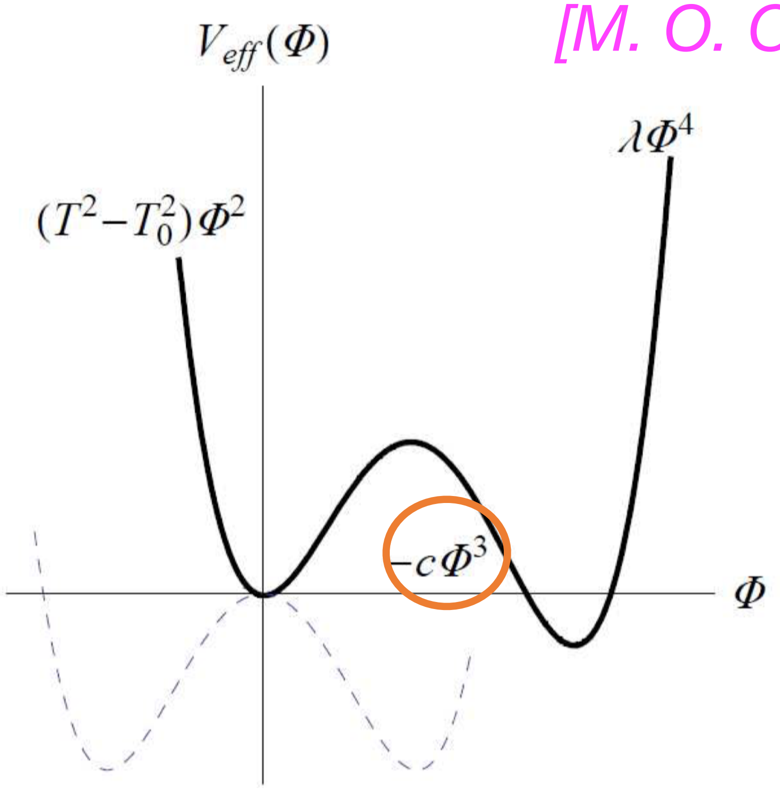
Barrier is related to a cubic term in the effective potential

Arises from higher-order contributions and thermal corrections to the potential, in particular:

$$-\frac{T}{12\pi}\left[\mu_S^2+\boxed{\lambda_{HS}h^2}+\Pi_S\right]^{\boxed{3/2}}$$

⇒ For sizeable quartic couplings an effective cubic term in the Higgs potential is generated

⇒ Yields mass splitting between the BSM Higgs bosons and sizeable corrections to the trilinear Higgs coupling



[M. O. Olea '23]

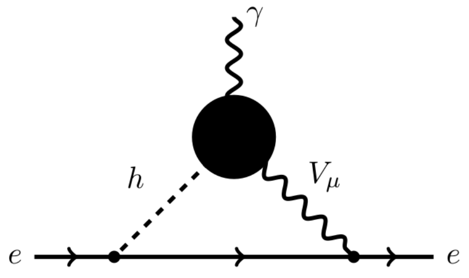
EWPT: are there additional sources for CP violation in the Higgs sector?

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

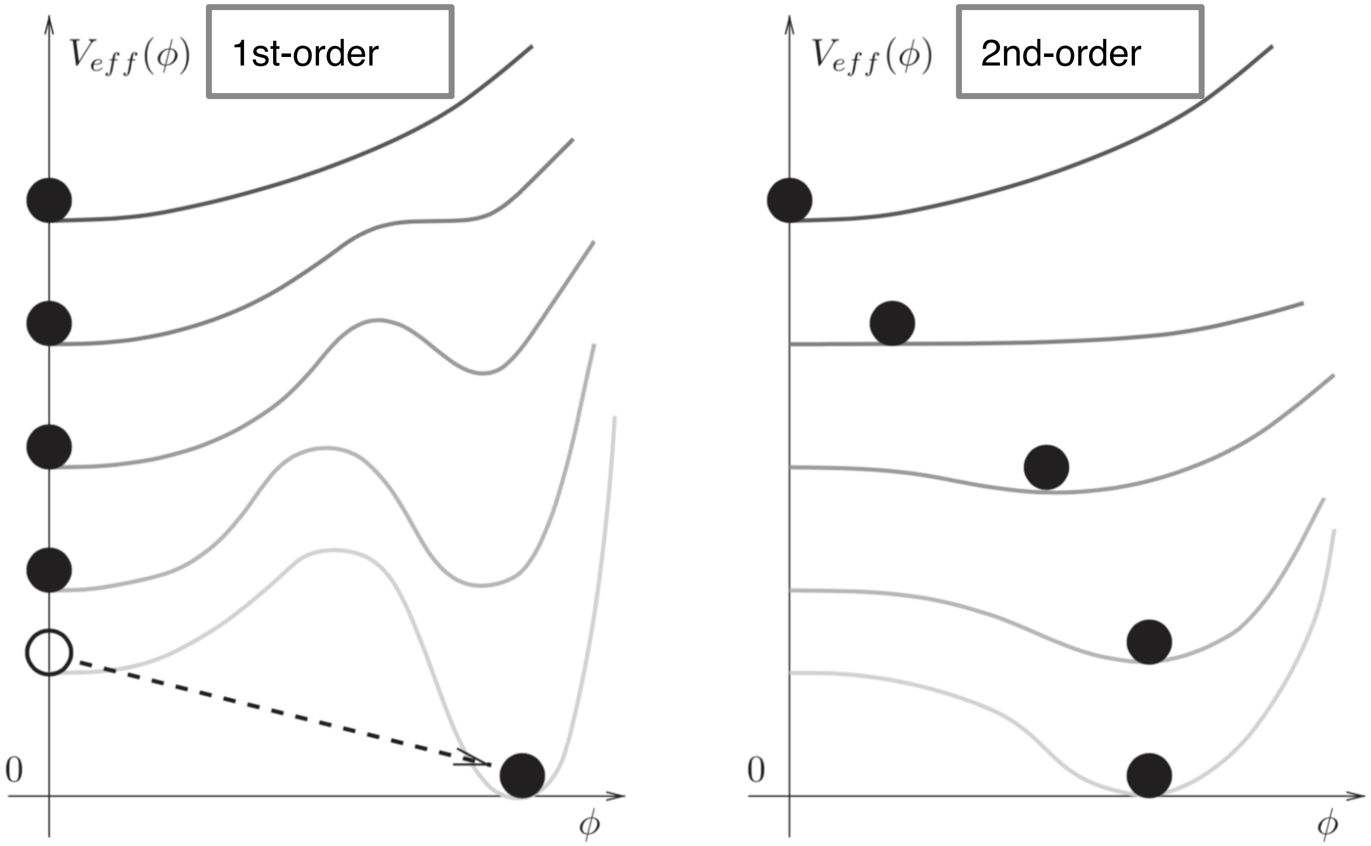


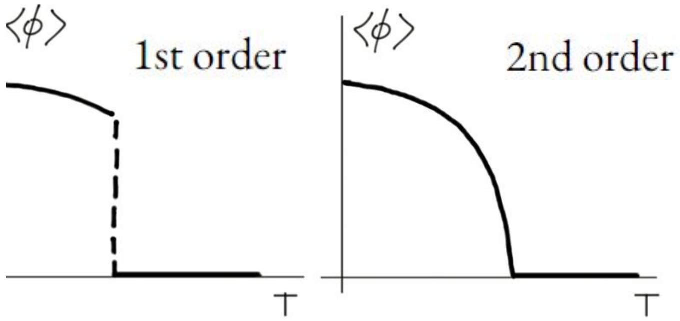
Two-loop "Barr-Zee"
electron EDM contribution

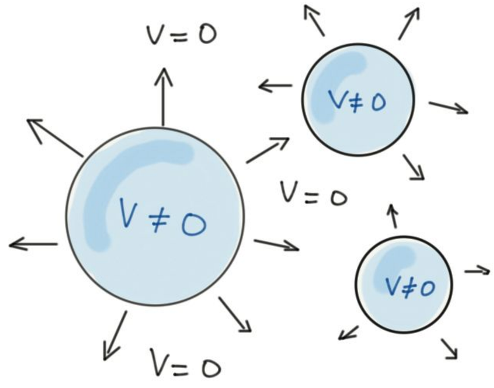
But: strong experimental constraints from limits on electric dipole moments (EDMs)

First-order vs. second order EWPT

[D. Gorbunov, V. Rubakov]







[K. Radchenko ’23]

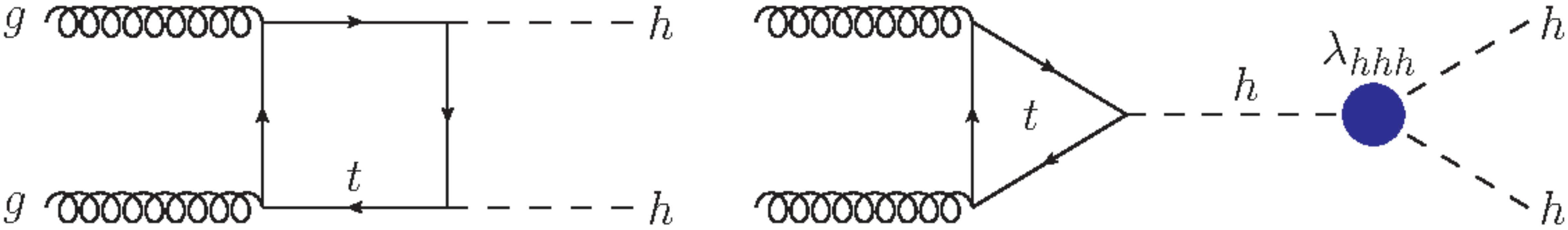
Potential barrier needed for first-order EWPT, depends on trilinear Higgs coupling(s)

Deviation of trilinear Higgs coupling from SM value is a typical feature of a strong first-order EWPT

Non-resonant di-Higgs production and the trilinear Higgs self-coupling

Sensitivity to the trilinear Higgs self-coupling from Higgs pair production:

- **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)]

Note: the ``non-resonant” experimental limit on Higgs pair production obtained by ATLAS and CMS depends on $\varkappa_\lambda = \lambda_{hhh} / \lambda_{hhh}^{SM,\,0}$

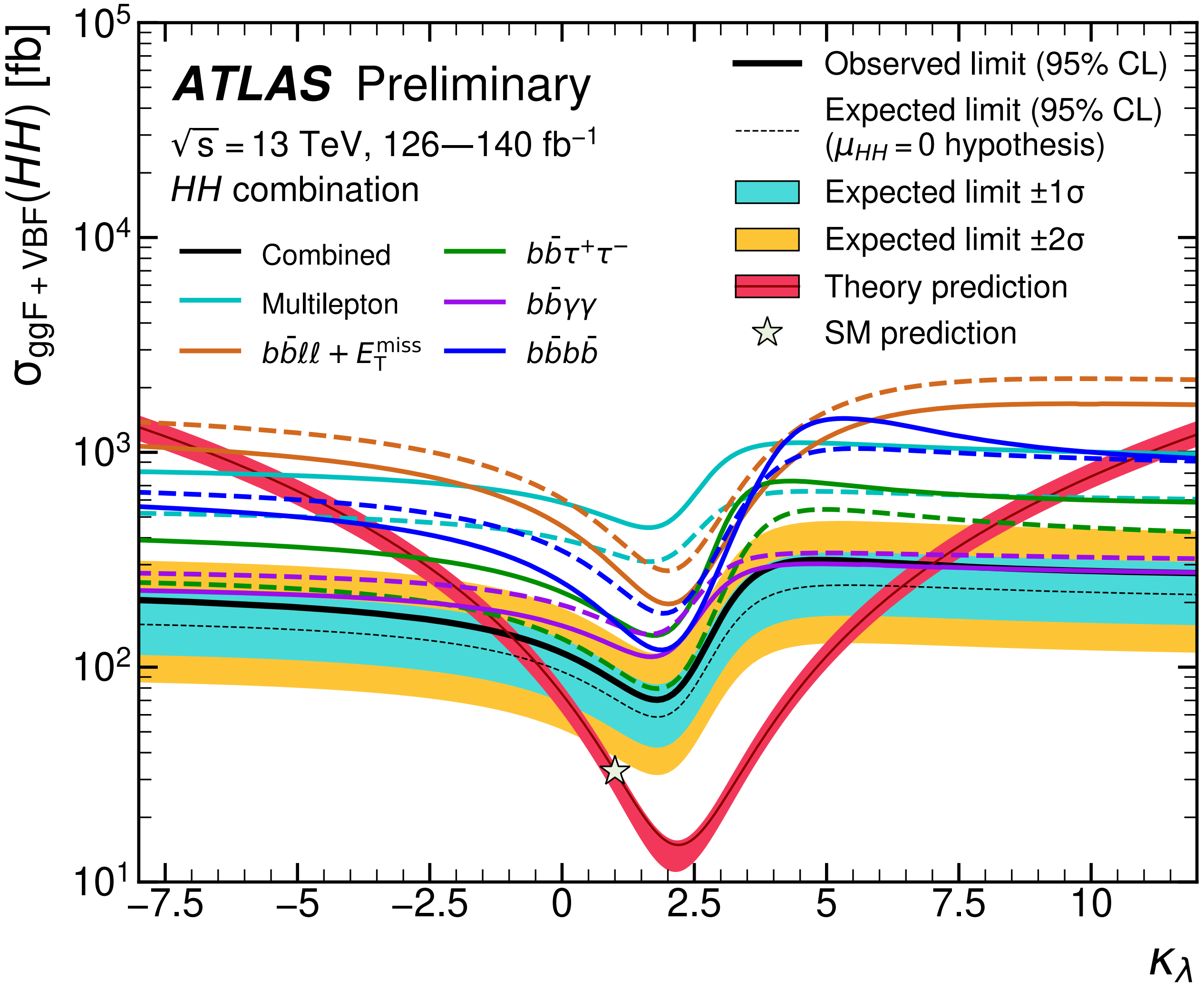
e^+e^- Higgs factory:

Indirect constraints from measurements of single Higgs production and electroweak precision observables at lower energies are not competitive

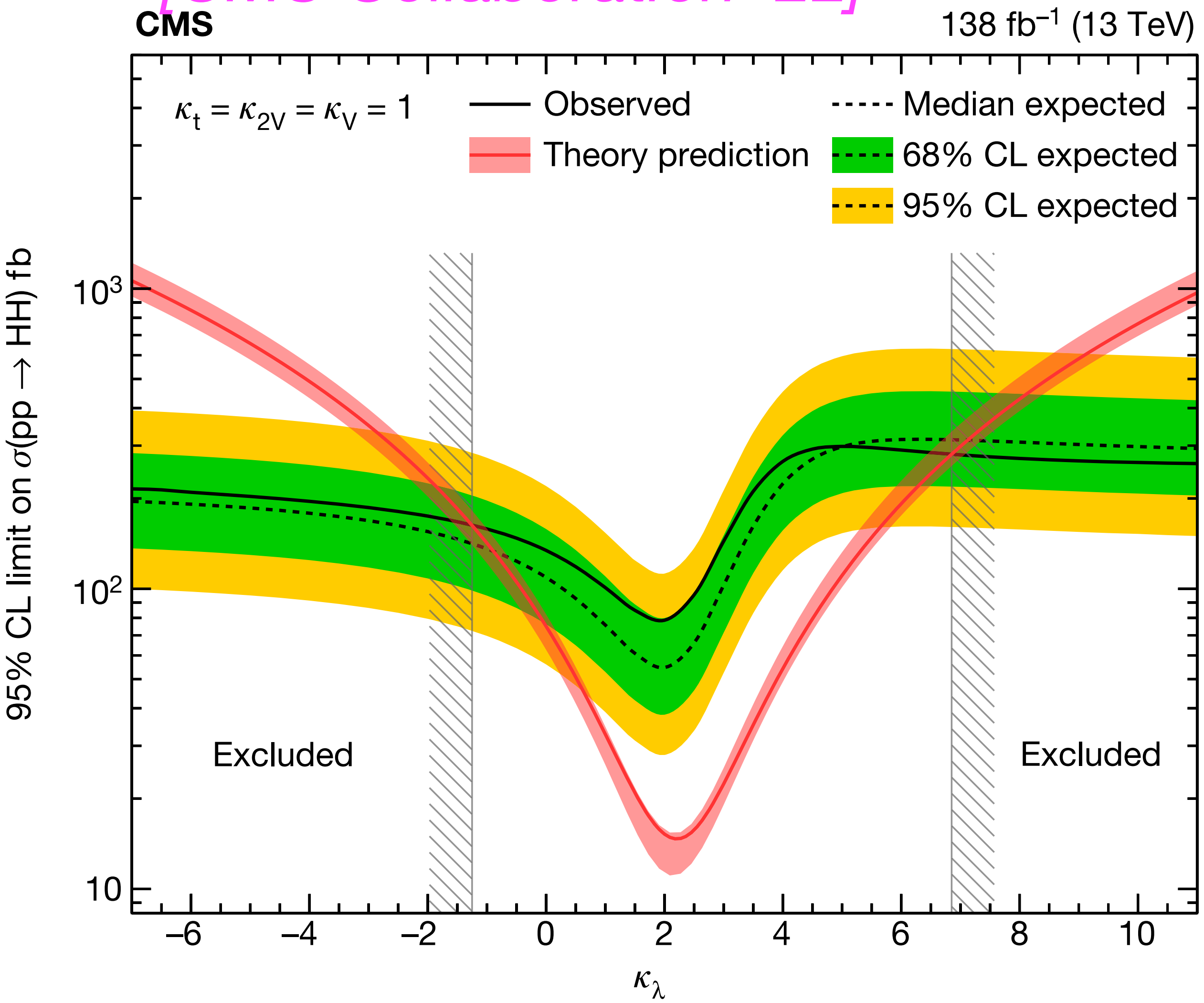
Direct measurement of trilinear Higgs self-coupling is possible at a lepton collider with at least 500 GeV c.m. energy

LHC, bound on the trilinear Higgs self-coupling: $\varkappa_\lambda$

[ATLAS Collaboration '24]



[CMS Collaboration '22]



Using only information from di-Higgs production and assuming that new physics only affects the trilinear Higgs self-coupling, this limit on the cross section translates to:

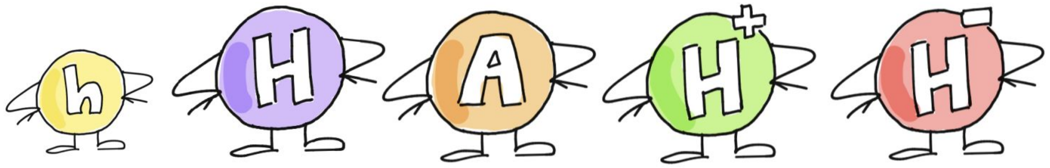
ATLAS: $-1.2 < \varkappa_\lambda < 7.2$ at 95% C.L. *[ATLAS Collaboration '24]*

CMS: $-1.2 < \varkappa_\lambda < 6.5$ at 95% C.L. *[CMS Collaboration '22]*

Simple example of extended Higgs sector: 2HDM

Two Higgs doublet model (2HDM):

- **CP conserving** 2HDM with two complex doublets: $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1+\rho_1+i\eta_1}{\sqrt{2}} \end{pmatrix}, \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2+\rho_2+i\eta_2}{\sqrt{2}} \end{pmatrix}$



[K. Radchenko '23]

- **Softly broken $\mathbb{Z}_2$ symmetry** ($\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$) entails 4 Yukawa types

- Potential:

$$\boxed{\begin{aligned} V_{\text{2HDM}} = m_{11}^2(\Phi_1^\dagger\Phi_1) + m_{22}^2(\Phi_2^\dagger\Phi_2) - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \\ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}((\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2), \end{aligned}}$$

- Free parameters: m_h, m_H, m_A, $m_{H^\pm}$, m_{12}^2, $\tan\beta$, $\cos(\beta-\alpha)$, v

$$\boxed{\begin{aligned} &\tan\beta = v_2/v_1 \\ &v^2 = v_1^2 + v_2^2 \sim (246\ \text{GeV})^2 \end{aligned}}$$

In alignment limit, $\cos(\beta - \alpha) = 0$: h couplings are as in the SM at tree level

Masses of the BSM Higgs fields

$$m_A^2 = [m_{12}^2/(v_1 v_2) - 2\lambda_5]\,(v_1^2 + v_2^2) \qquad m_+^2 = [m_{12}^2/(v_1 v_2) - \lambda_4 - \lambda_5]\,(v_1^2 + v_2^2)$$

In general: BSM Higgs fields receive contributions from two sources:

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

where $M^2 = 2\, m_{12}{}^2 / \sin(2\beta)$

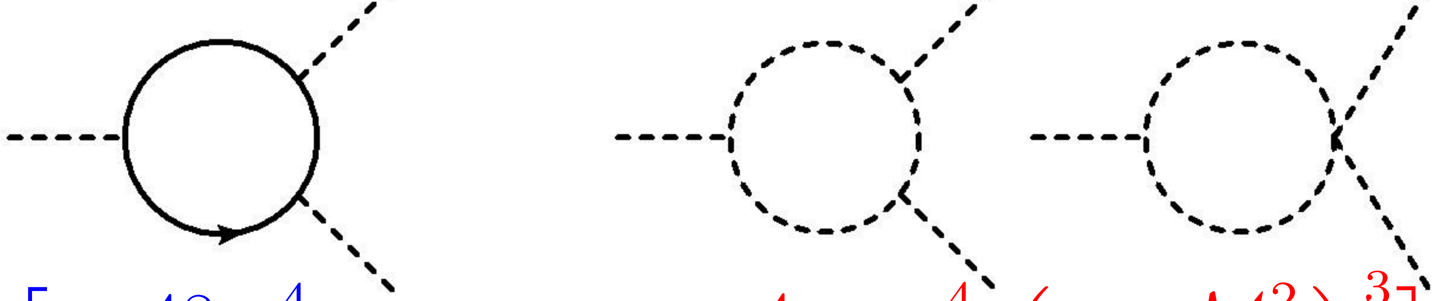
Sizeable splitting between m_Φ and M induces large BSM contributions to the Higgs self-couplings

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*



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

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

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

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

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

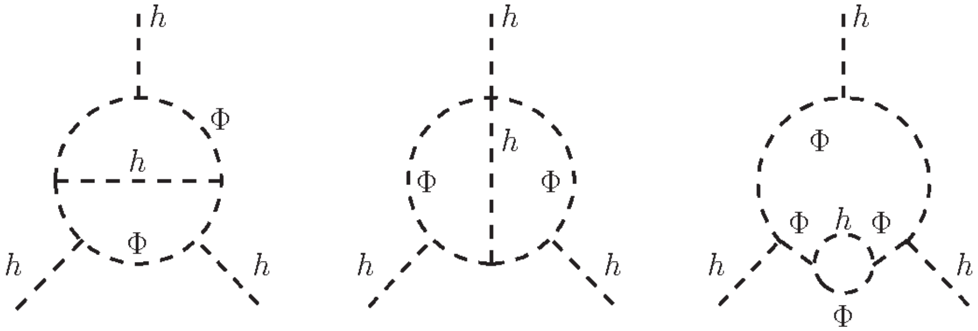
The largest loop corrections to λ_{hhh} in the 2HDM are induced by the quartic couplings between two SM-like Higgs bosons h (where one external Higgs is possibly replaced by its vacuum expectation value) and two BSM Higgs bosons ϕ of the form

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

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 $g_{hh\phi\phi}$



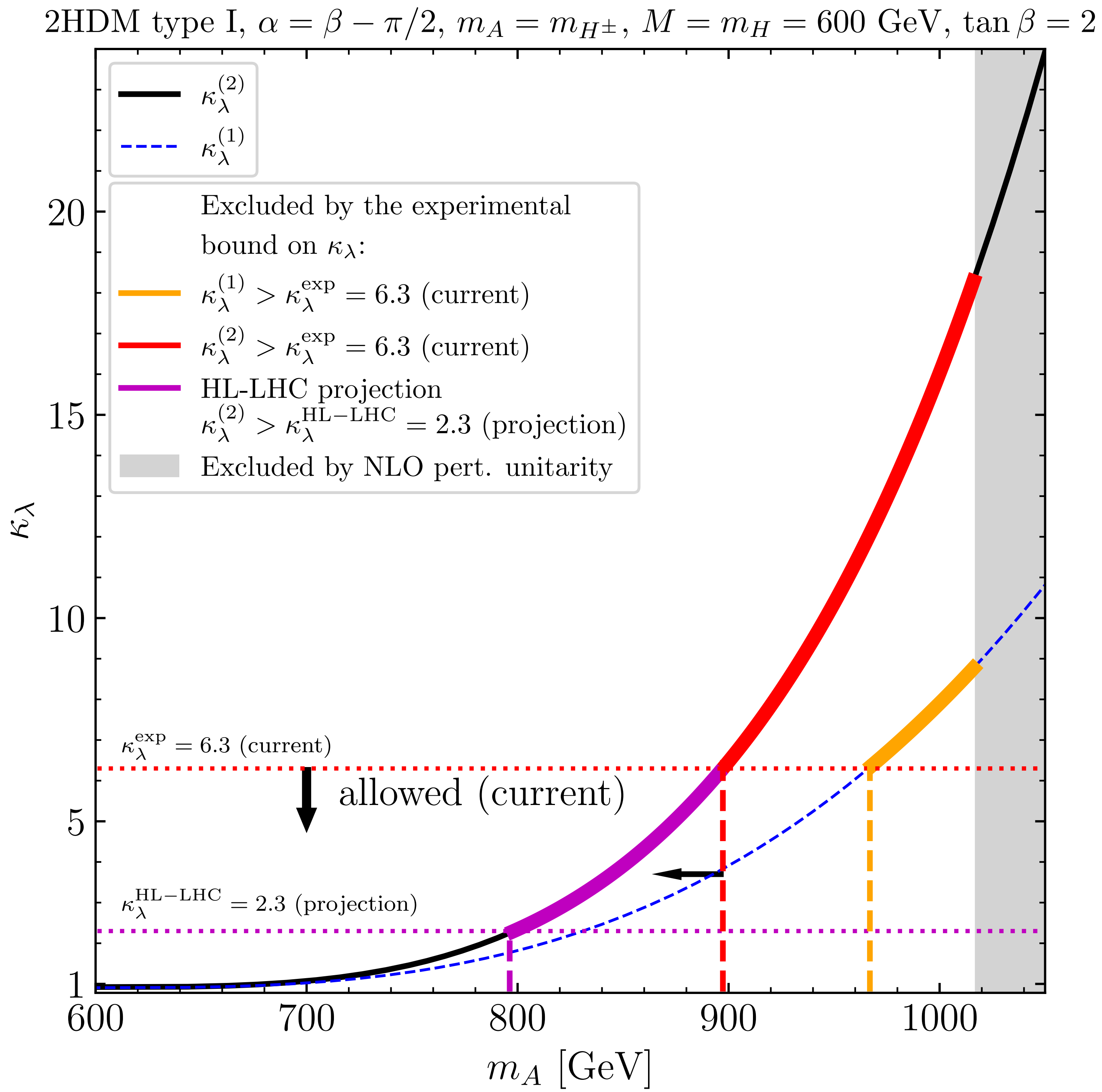
Analysis is carried out in the alignment limit of the 2HDM ($\alpha = \beta - \pi/2$)

⇒h has SM-like tree-level couplings

Trilinear Higgs coupling: current experimental limit vs. prediction from extended Higgs sector (2HDM)

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

[H. Bahl, J. Braathen, G. W. '22, Phys. Rev. Lett. 129 (2022) 23, 231802]

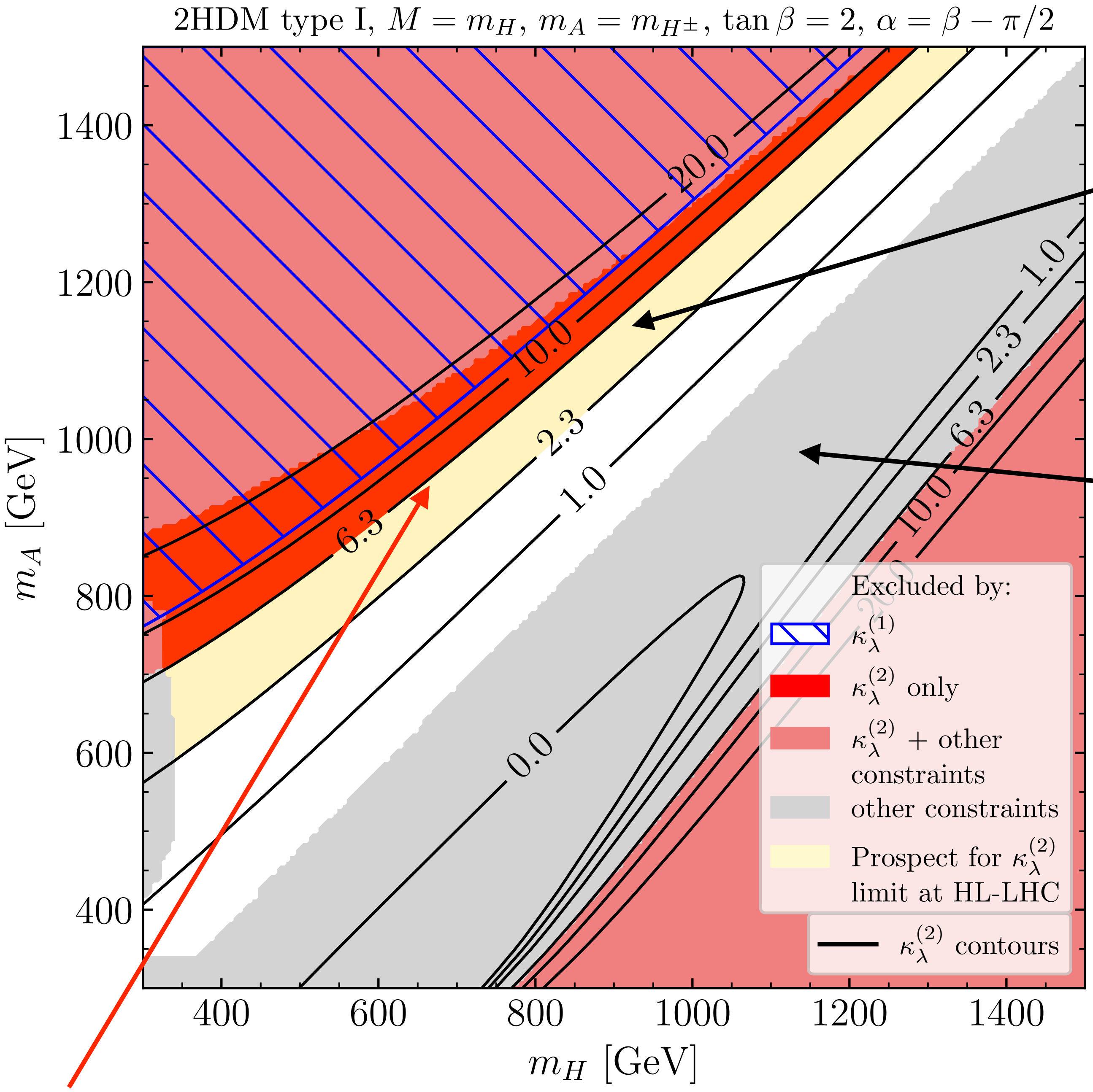


⇒ Current experimental limit excludes important parameter region that would be allowed by all other constraints!

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, …

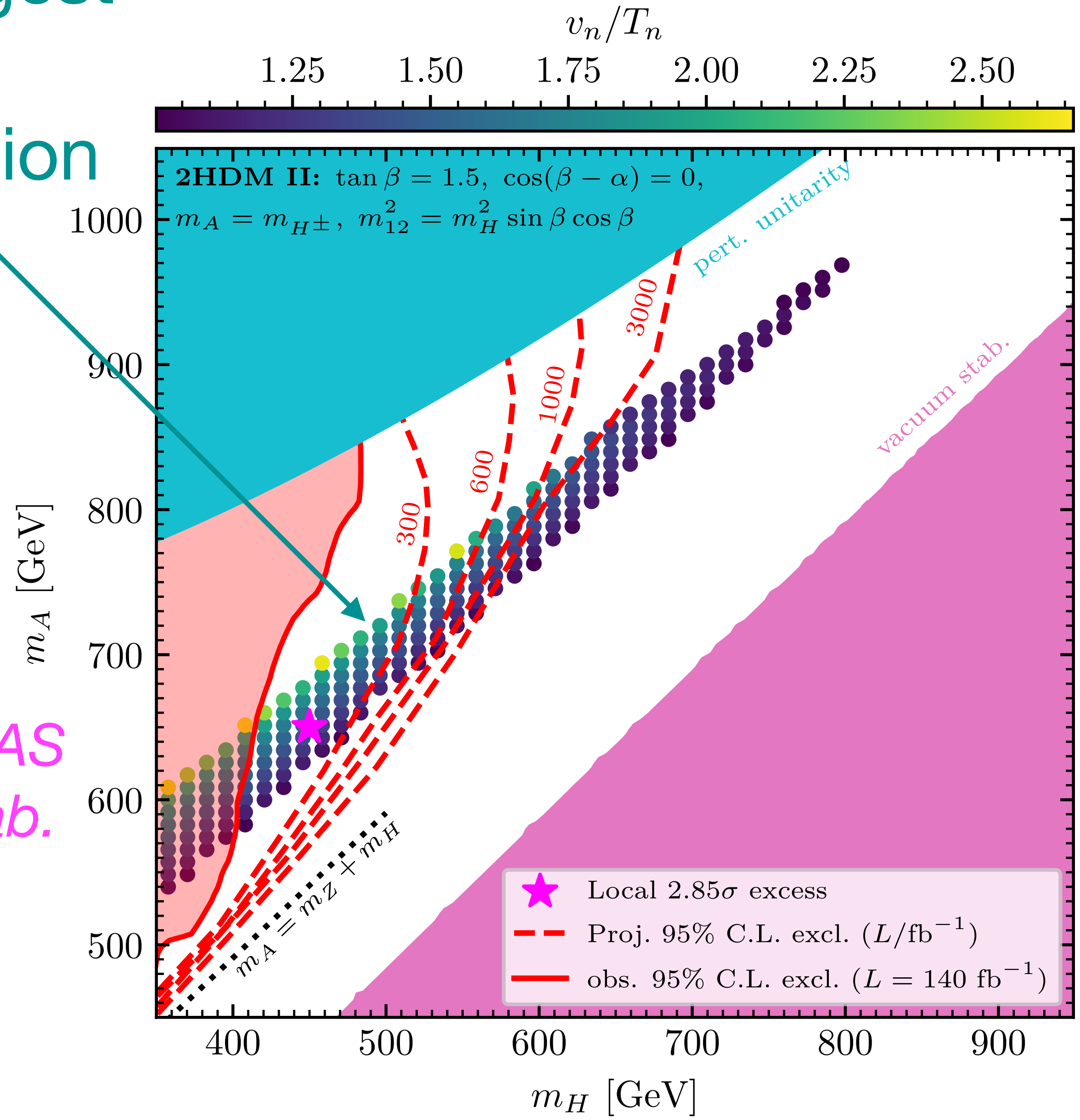
⇒ LHC limits exclude parameter regions that would be allowed by all other constraints; high sensitivity of future limits / measurements!

Probing the electroweak phase transition with the “smoking gun” signature pp → A → ZH → Ztt

Projection for future sensitivity based on ATLAS result, 2HDM, tanβ =1.5:

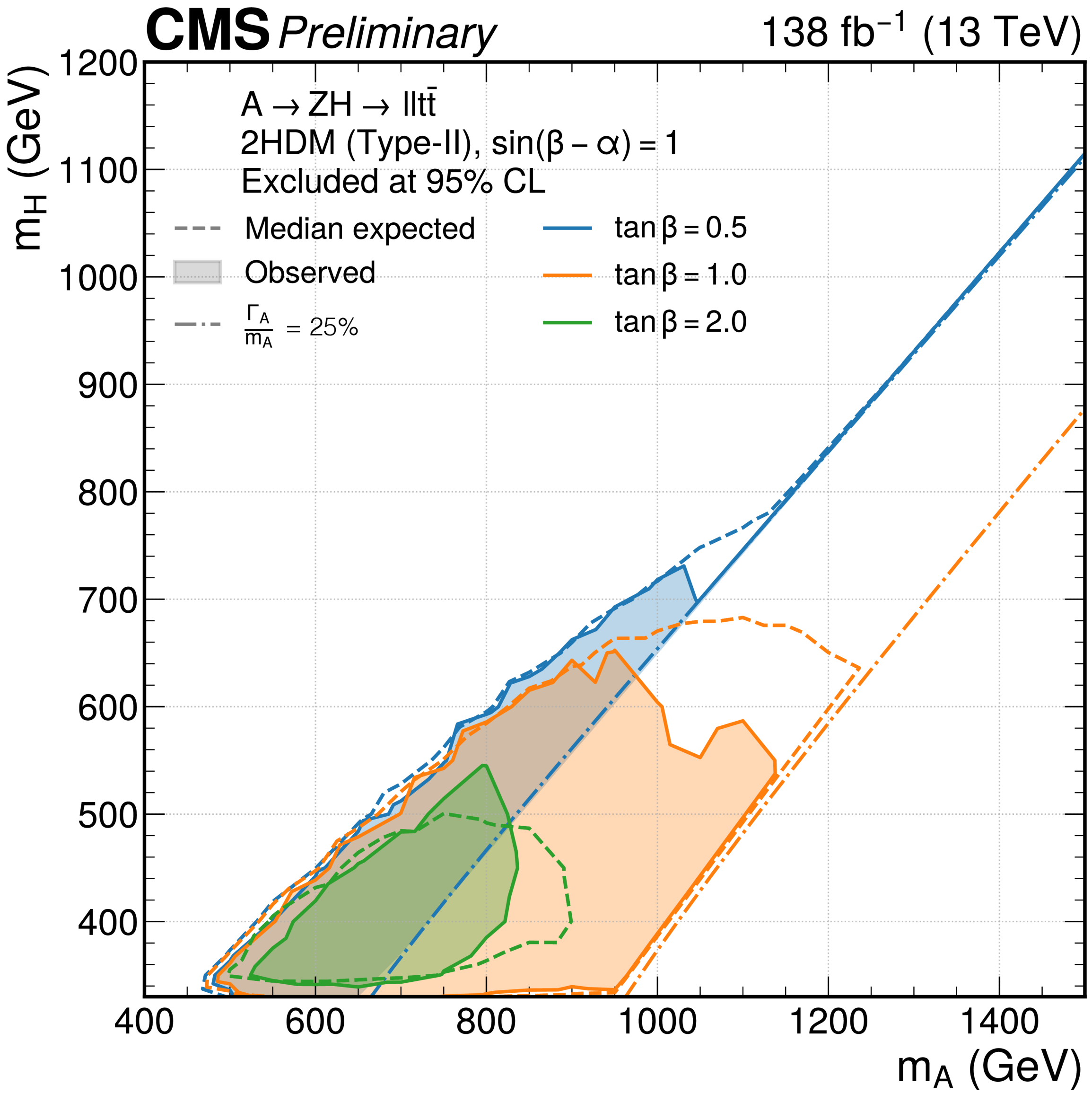
[T. Biekötter, S. Heinemeyer, J. M. No, M. O. Olea, K. Radchenko, G. W. ’23]

Strongest phase transition



[ATLAS Collab. ’23]

[CMS Collaboration ’24]



⇒LHC searches start probing the region giving rise to a strong FOEWPT

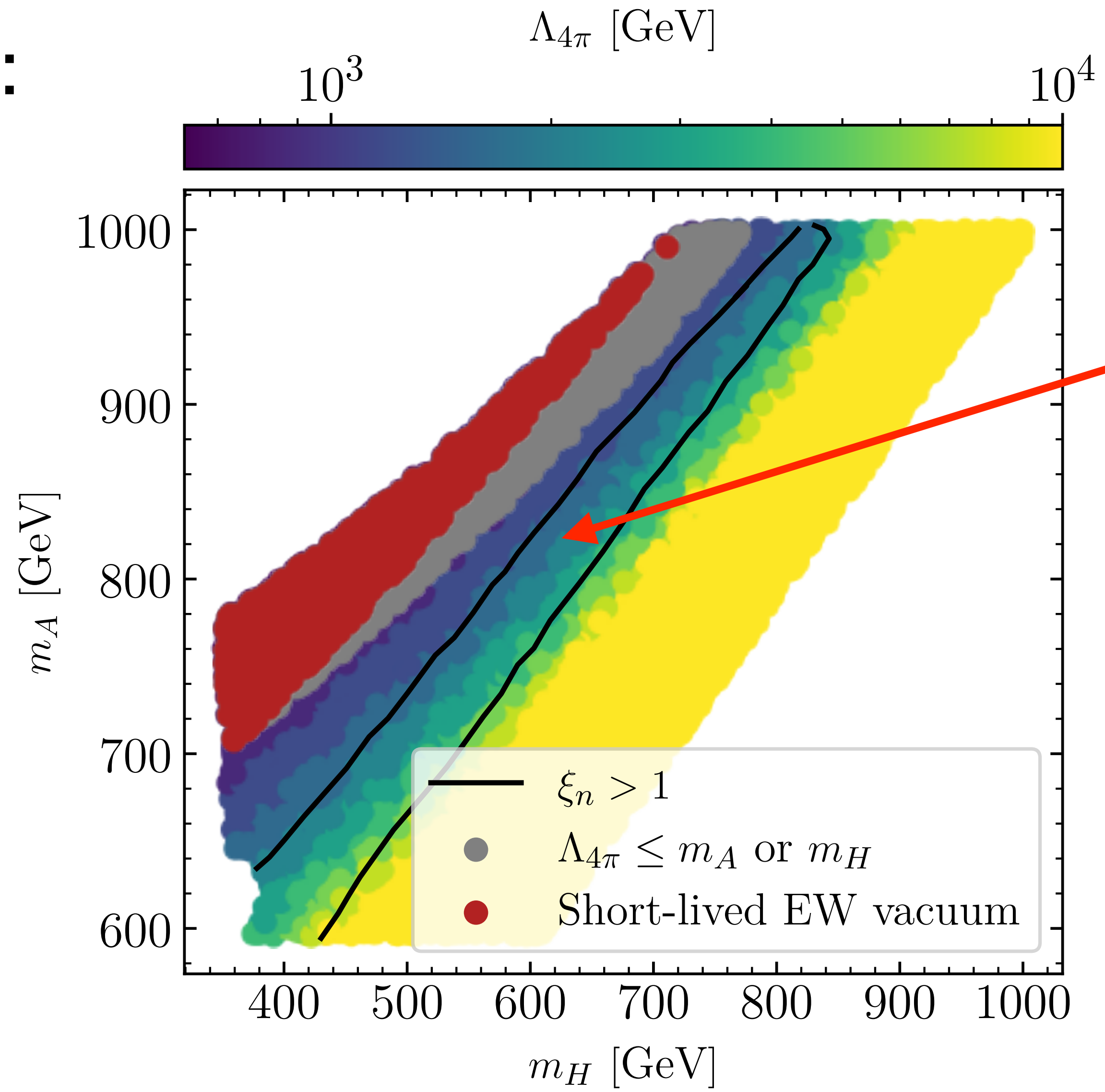
Connection between the trilinear Higgs coupling and the evolution of the early Universe

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

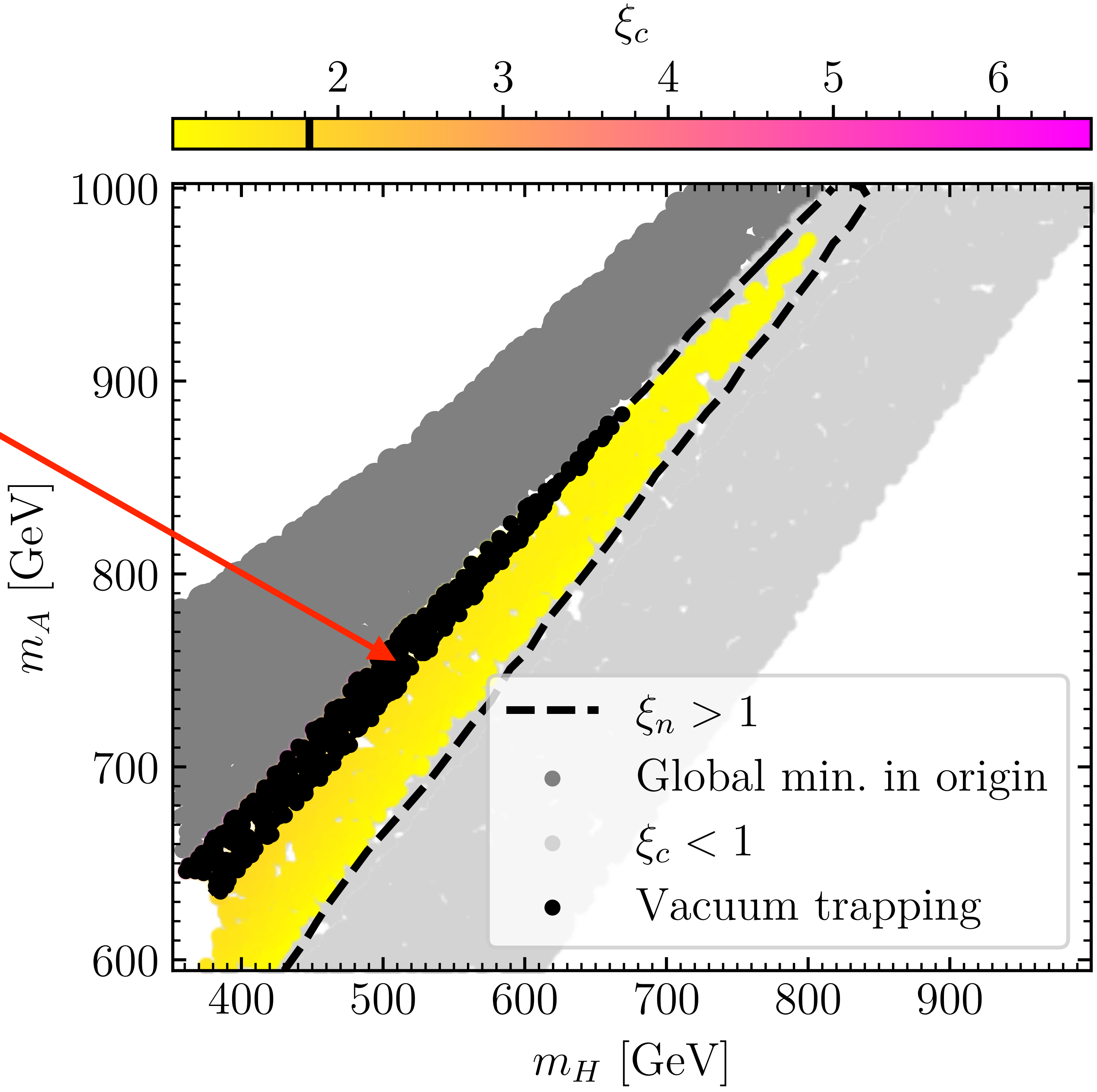


Parameter region giving rise to a strong first-order EWPT

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



``$\varkappa$ framework” and EFT approach for coupling analyses

Simplified framework for coupling analyses: deviations from SM parametrised by ``scale factors” $\varkappa_i$, where $\varkappa_i \equiv g_{Hii}/g^{SM,\,(0)}_{Hii}$

Assumptions inherent in the $\varkappa$ framework: signal corresponds to only one state, no overlapping resonances, etc., zero-width approximation, only modifications of coupling strengths (absolute values of the couplings) are considered
⇒ Assume that the observed state is a CP-even scalar

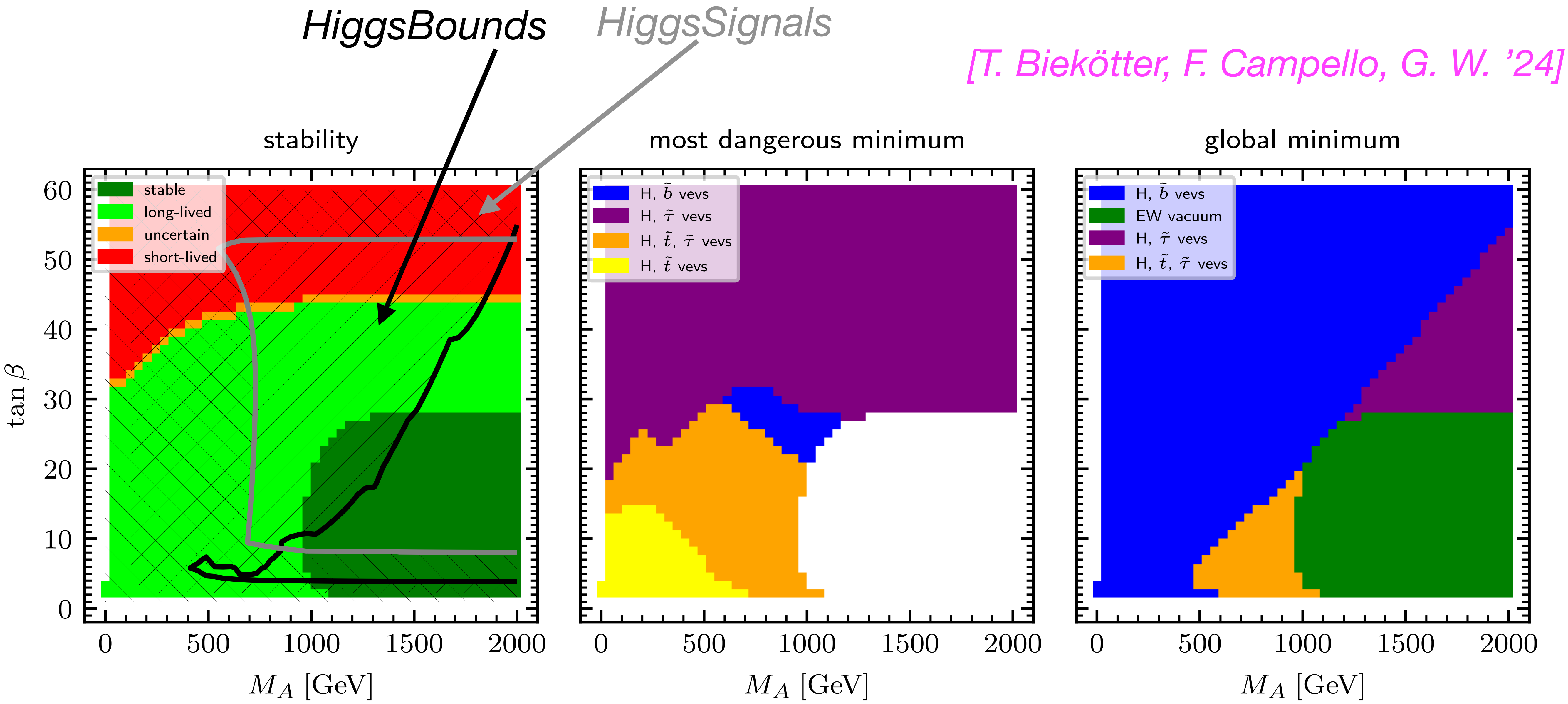
Theoretical assumptions in determination of the $\varkappa_i$:
$\varkappa_V \leqq 1$, no invisible / undetectable decay modes, …

EFT: fits for Wilson coefficients of higher-dimensional operators in SMEFT Lagrangian, …

Vacuum stability constraints in the MSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt ’18]*
Example: constraints from vacuum stability in the MSSM on the region allowed by *HiggsBounds* and *HiggsSignals*

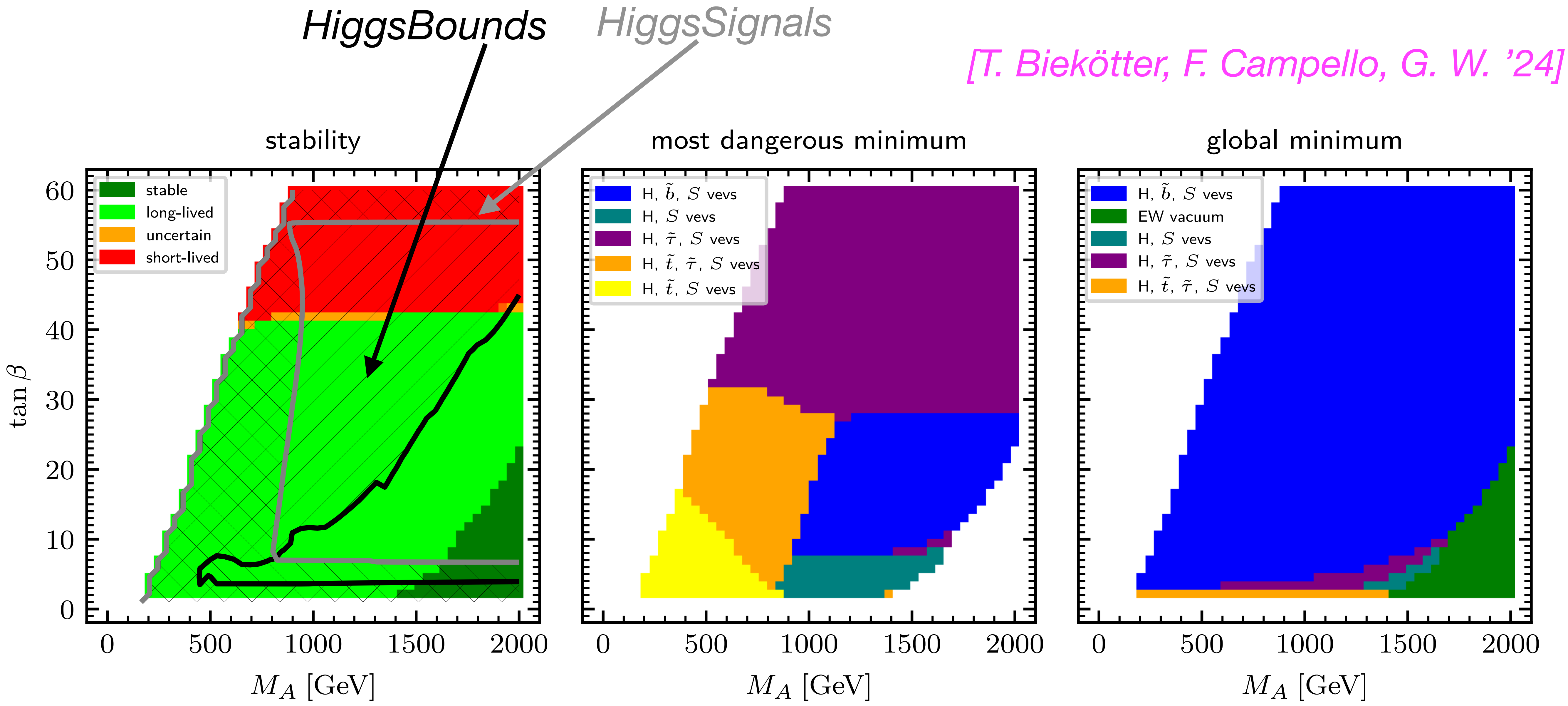
[T. Biekötter, F. Campello, G. W. ’24]



Character of most-dangerous minimum differs from global minimum

Vacuum stability constraints in the NMSSM

Improved version of the public code *Evade* *[W.G. Hollik, G. W., J. Wittbrodt ’18]*
Example: constraints from vacuum stability in the NMSSM on the region allowed by *HiggsBounds* and *HiggsSignals*



HiggsBounds

HiggsSignals

[T. Biekötter, F. Campello, G. W. ’24]

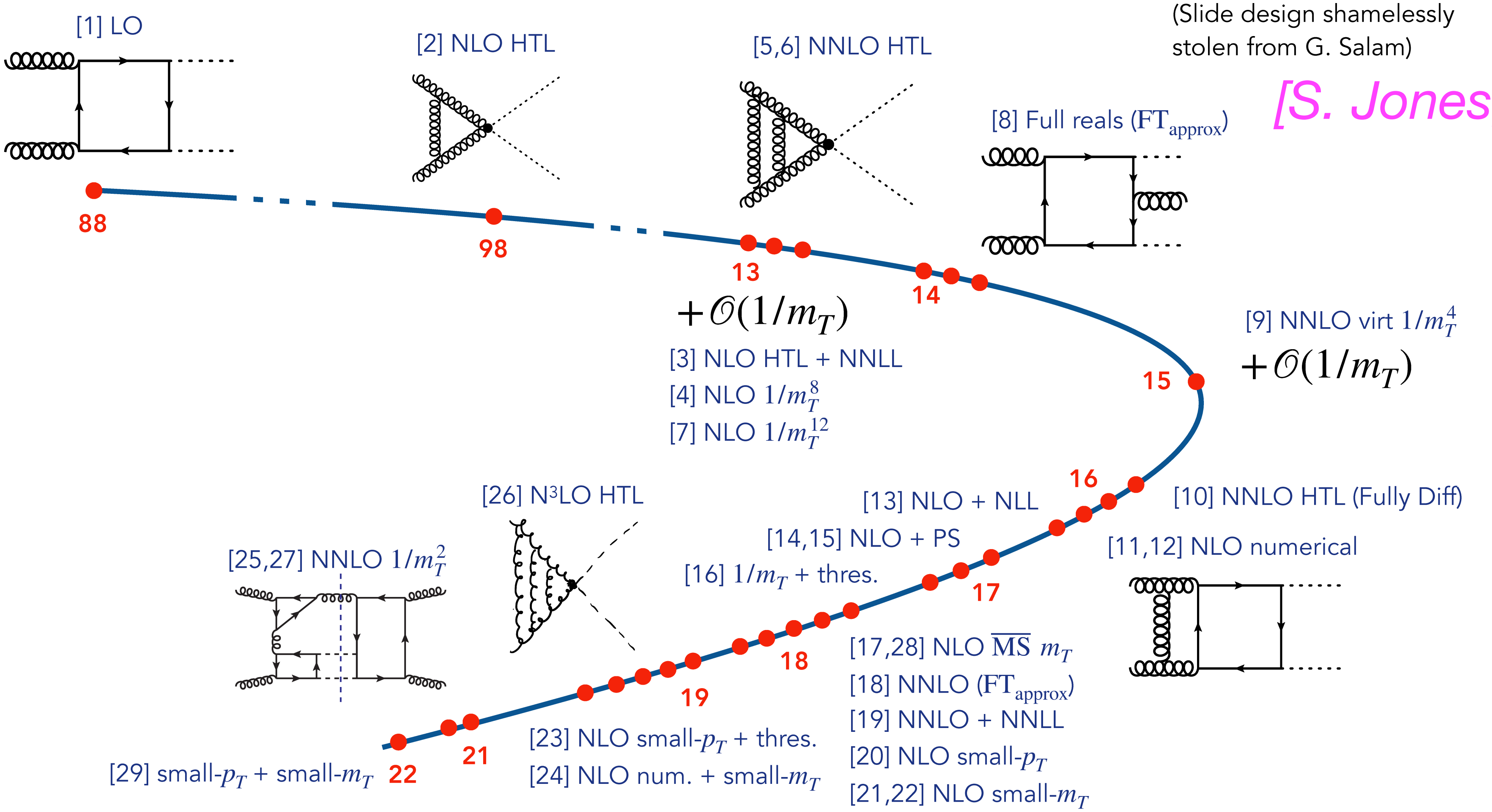
Character of most-dangerous minimum differs from global minimum

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] LO

[2] NLO HTL

[5,6] NNLO HTL

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

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

[3] NLO HTL + NNLL

[4] NLO $1/m_T^8$

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

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

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

[10] NNLO HTL (Fully Diff)

[13] NLO + NLL

[14,15] NLO + PS

[16] $1/m_T$ + thres.

[11,12] NLO numerical

[26] N³LO HTL

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

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

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

[19] NNLO + NNLL

[20] NLO small-p_T

[21,22] NLO small-m_T

[23] NLO small-p_T + thres.

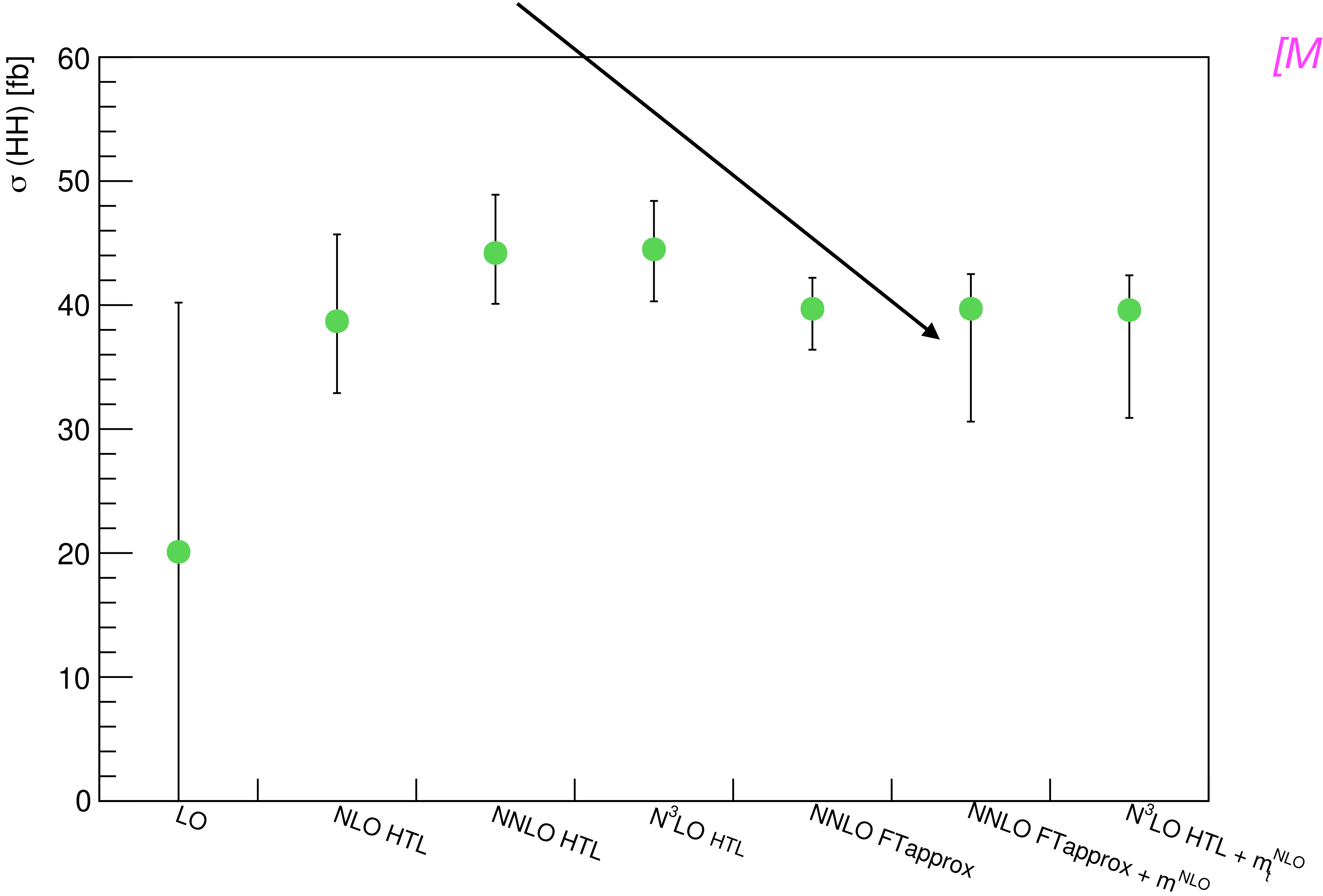
[24] NLO num. + small-m_T

[29] small-p_T + small-m_T

[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;

Higgs pair production, prediction and uncertainties

Impact of the renormalisation-scheme dependence of the top mass:



[M. Spira '22]

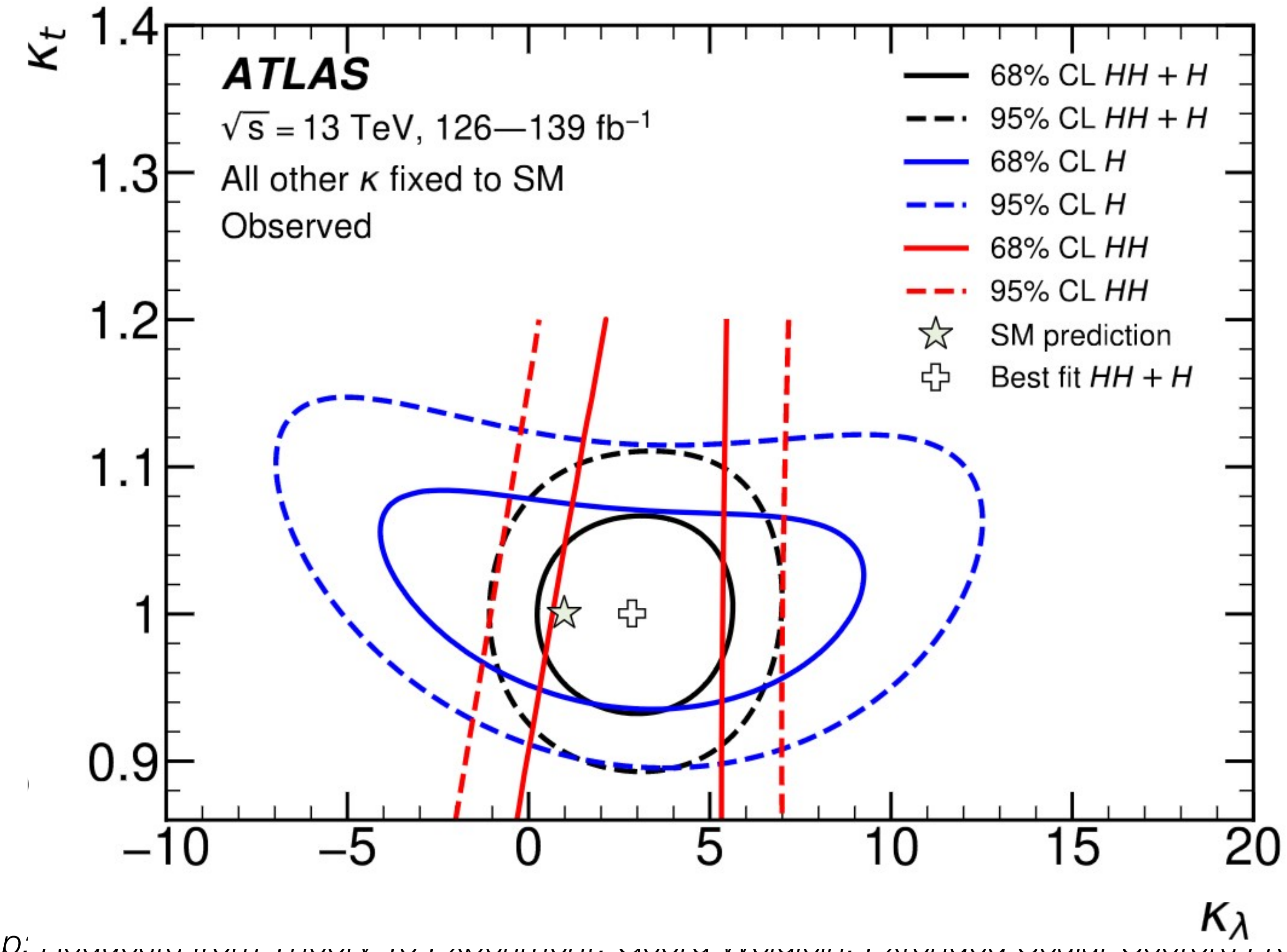
Electroweak corrections: top-Yukawa contributions

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

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	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

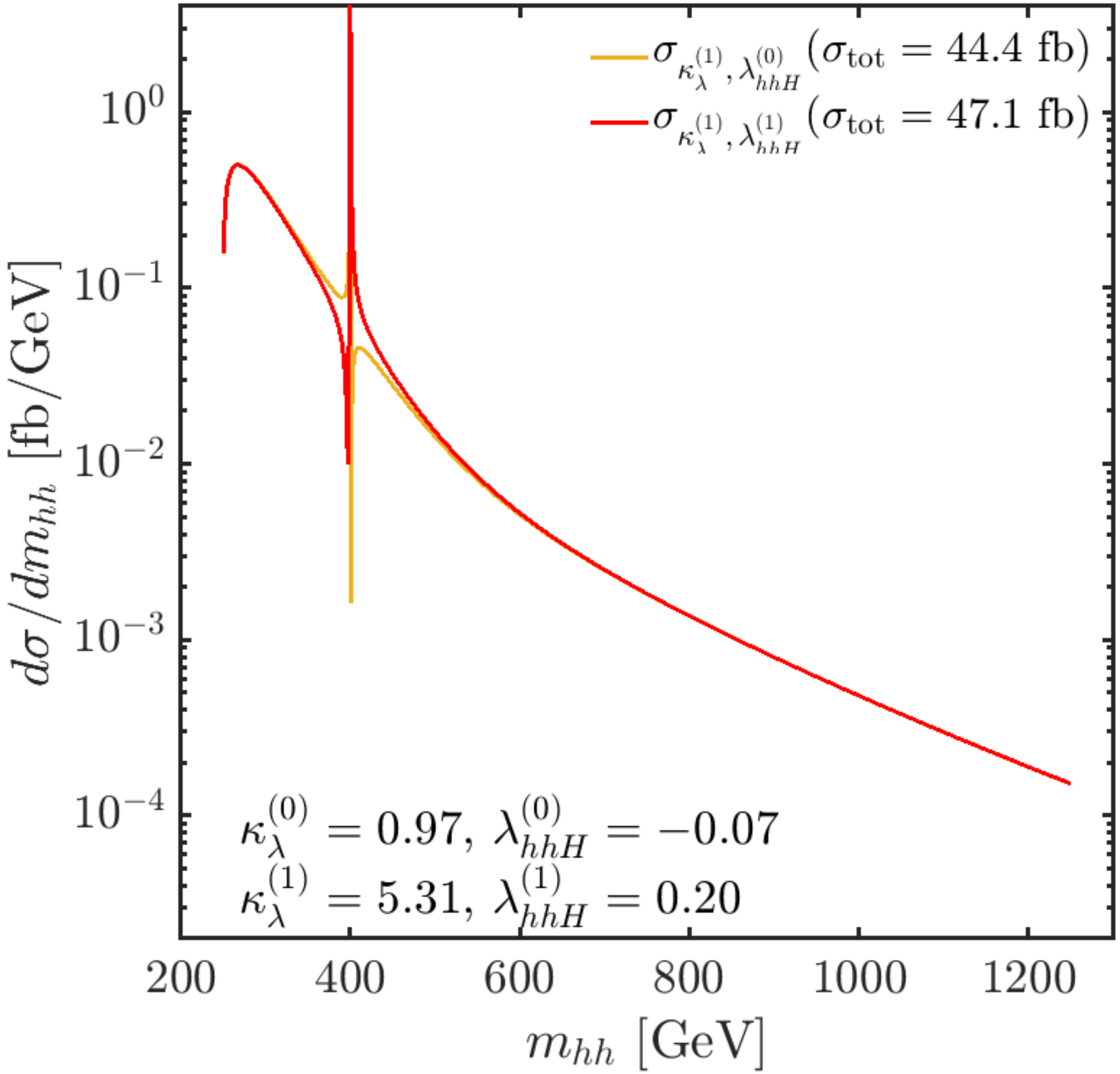


Interference effects in resonant Higgs pair production

[S. Heinemeyer, M. Mühlleitner, K. Radchenko, G. W. ’24]

2HDM example, m_{hh} invariant mass distribution:
theoretical prediction, experimental effects will be discussed below

Example of impact of loop contributions to λ_{hhH}:



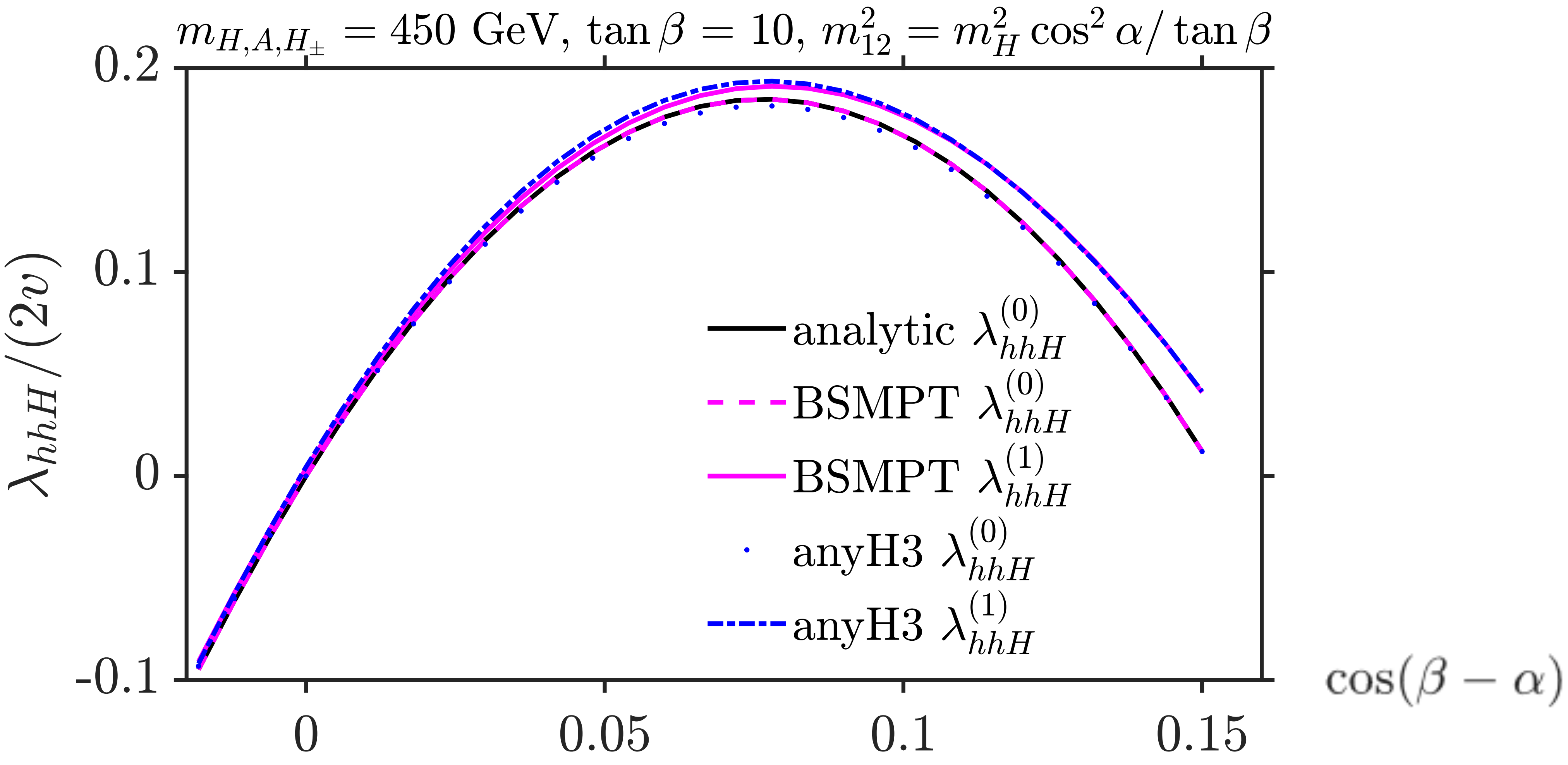
⇒ Peak-dip structure changed into dip-peak structure

General trilinear couplings

[H. Bahl, J. Braathen, M. Gabelmann, K. Radchenko, G. W. ’24]

Comparison with *BSMPT* *[P. Basler et al. ’18, ’20 ’24]*

Different scheme for vev renormalisation used



⇒ Very good agreement

Full on-shell renormalisation scheme for λ_{hhh} and λ_{hhH} worked out for a variety of models

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

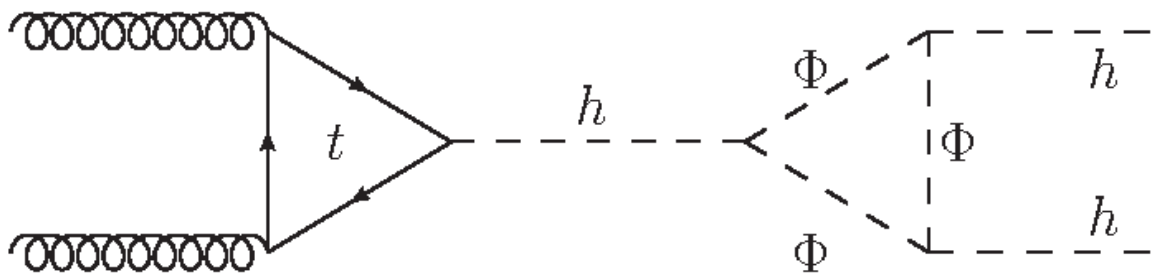
The current experimental limit can only probe scenarios with large deviations from the SM
⇒ Direct application of the experimental limit on $\varkappa_\lambda$ is possible if sub-leading effects are less relevant

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

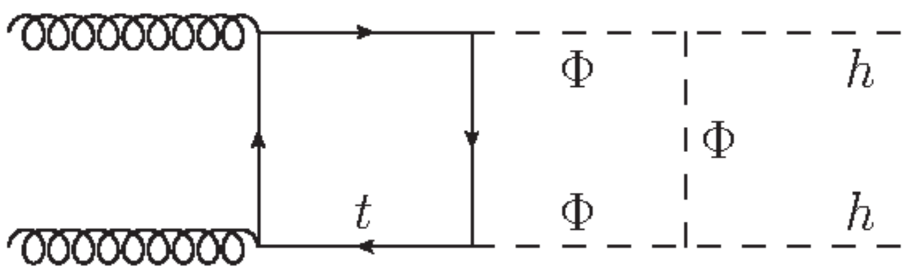
Alignment limit: h has SM-like tree-level couplings

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



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



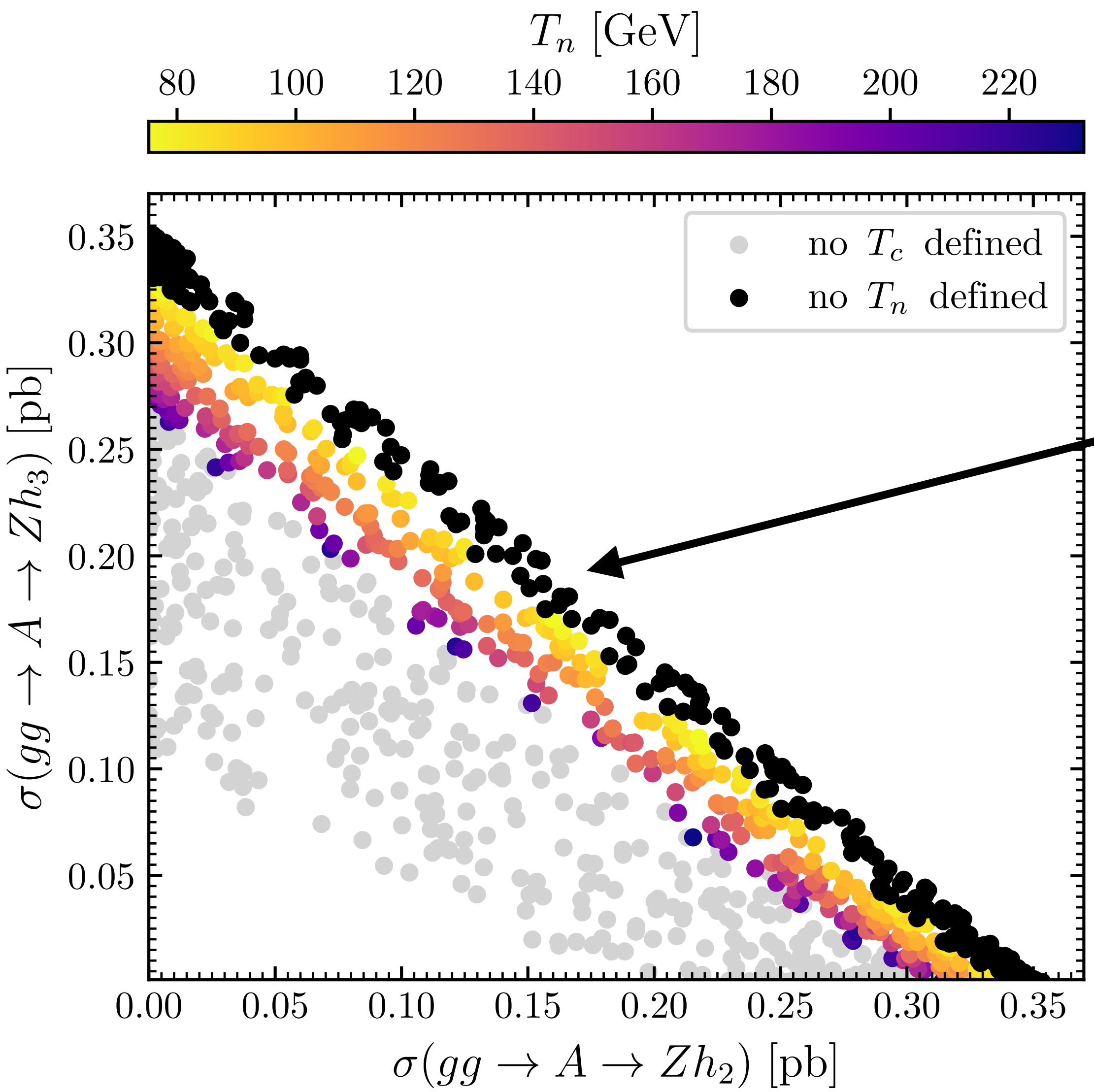
$\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ *not included*

⇒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!

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]

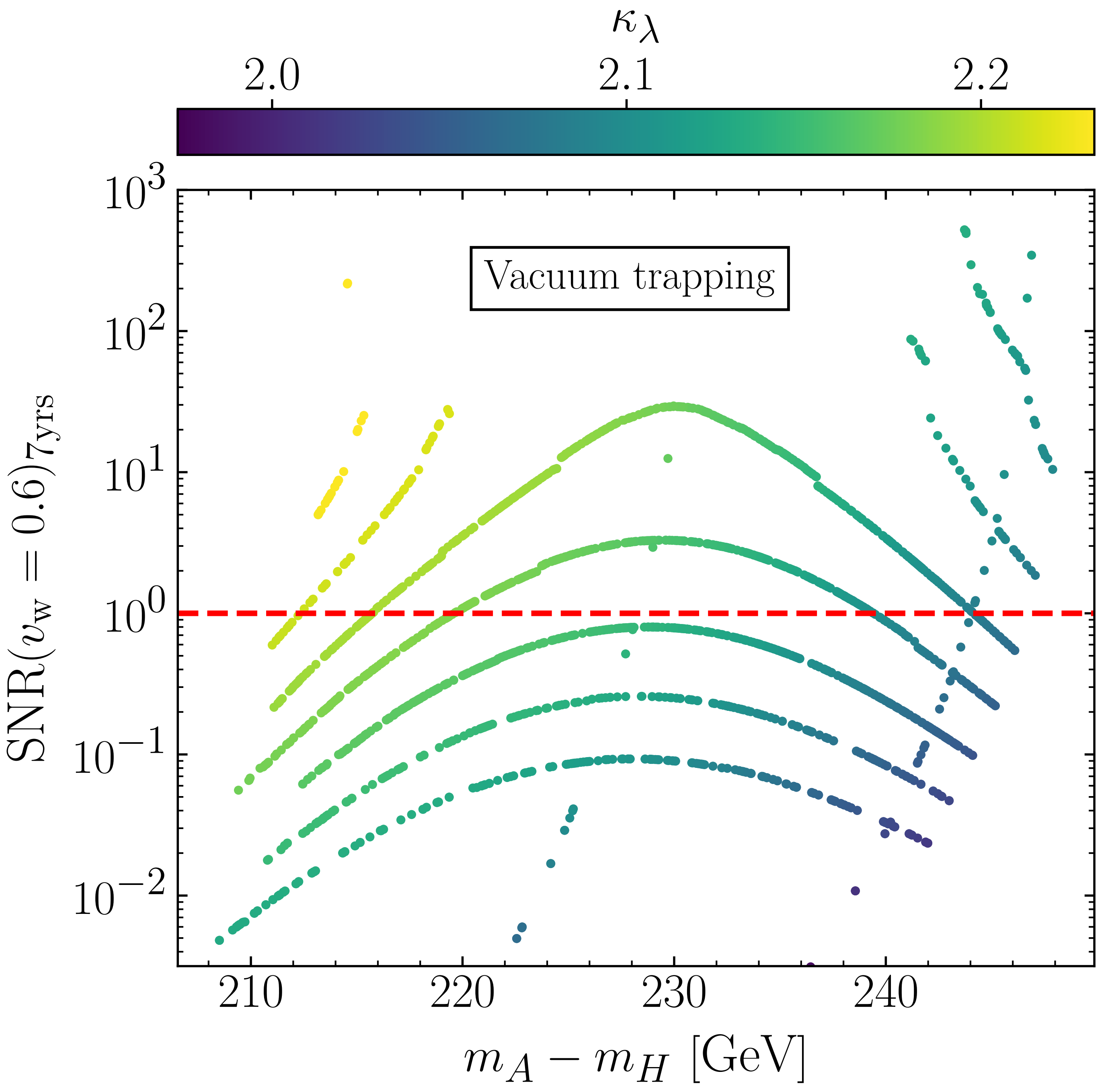


No first-order EWPT: universe is trapped in a ``false” vacuum

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

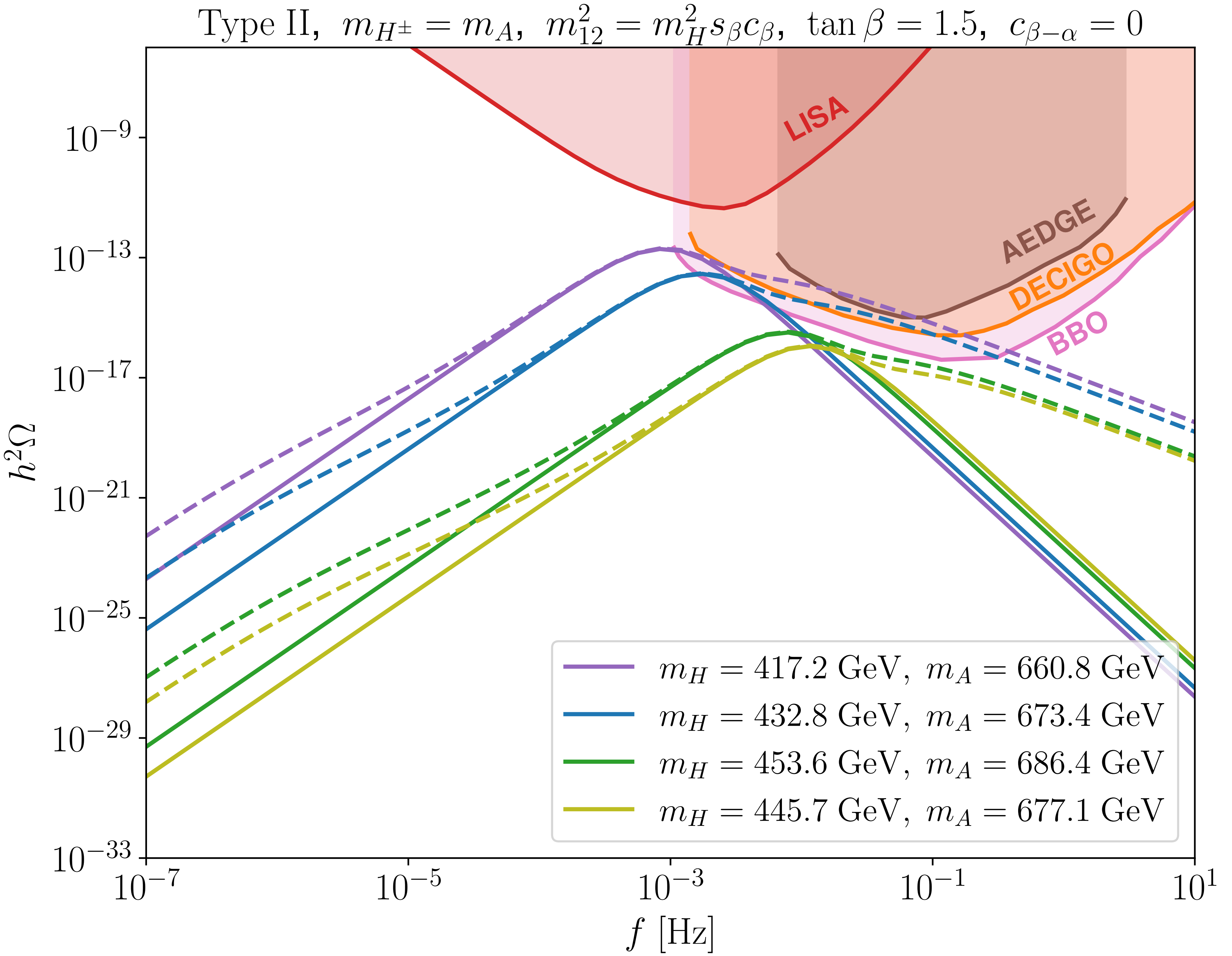
Correlation of $\varkappa_\lambda$ with the signal-to-noise ratio (SNR) of a gravitational wave signal at LISA

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



⇒Region with potentially detectable gravitational wave signal: significant enhancement of $\varkappa_\lambda$ and non-vanishing mass splitting

GW spectra of scenarios fitting the excess



[T. Biekötter,
S. Heinemeyer,
J. M. No,
M. O. Olea,
K. Radchenko,
G. W. '23]

⇒ Prospects for GW detection depend very sensitively on the precise details of the mass spectrum of the additional Higgs bosons

Bounds from perturbative unitarity

[P. Stylianou, G. W. '24]

- Process relevant for κ_3, κ_4 is $HH \to HH$ scattering (see also [Liu et al ` 18])

- Jacob-Wick expansion allows to extract partial waves

$$\boxed{\beta(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz}$$

Wigner functions

$$a^J_{fi} = \frac{\beta^{1/4}(s, m^2_{f_1}, m^2_{f_1})\beta^{1/4}(s, m^2_{i_1}, m^2_{i_1})}{32\pi s} \int_{-1}^{1} \mathrm{d}\cos\theta\, \mathcal{D}^J_{\mu_i\mu_f}\, \mathcal{M}(s, \cos\theta)$$

- Tree level unitarity:

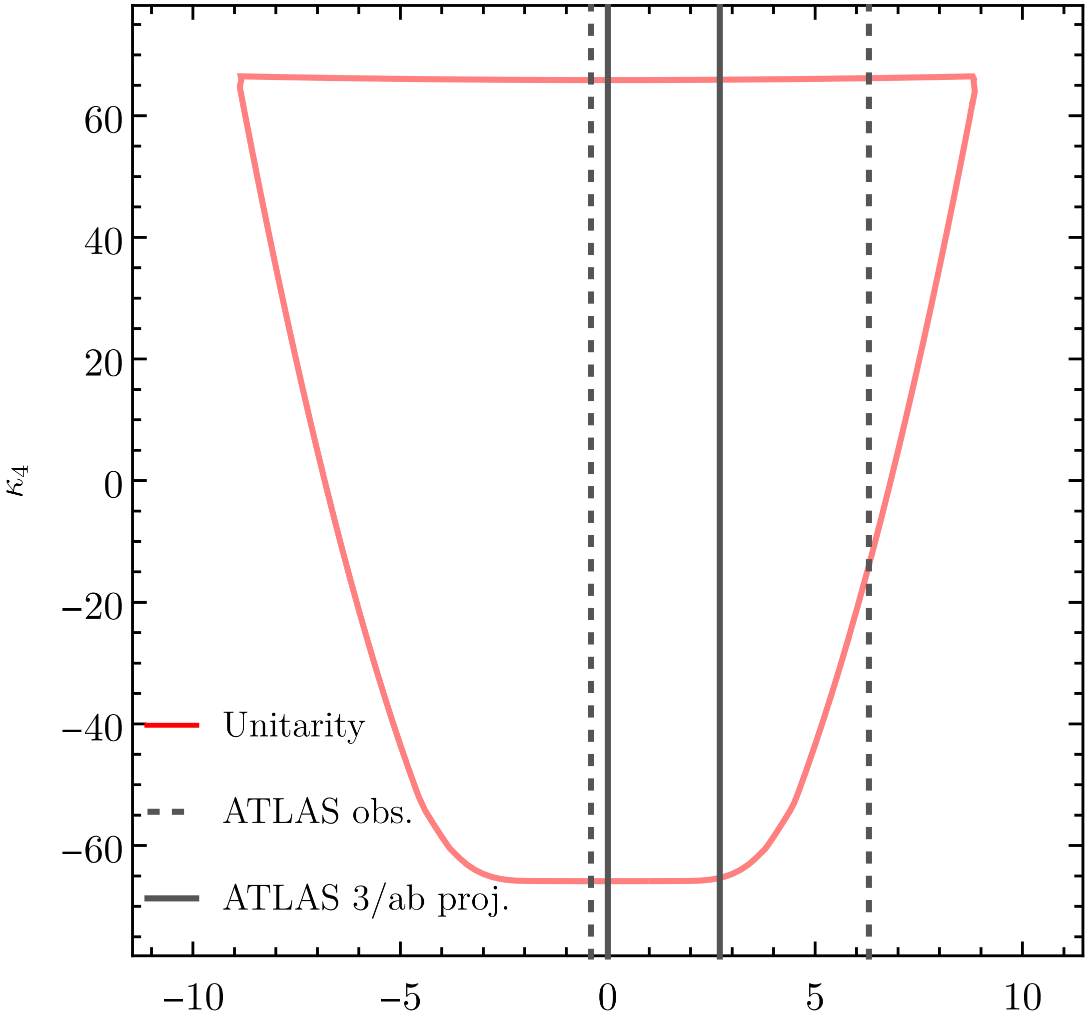
$$\mathrm{Im} a^0_{ii} \geq |a^0_{ii}|^2 \implies |\mathrm{Re} a^0_{ii}| \leq \frac{1}{2}$$

95 % CL

ATLAS current bounds: $[-0.4, 6.3]$

CMS & ATLAS HH projections: $[0.1, 2.3]$

[ATLAS 2211.01216]
[CERN Yellow Rep. 1902.00134]



Possible size of BSM contributions: SMEFT: effects of higher-dimensional operators

Linear power expansion for higher order terms in Λ^{-1} orders:

[Boudjema, Chopin `96]
[Maltoni, Pagani, Zhao `18]

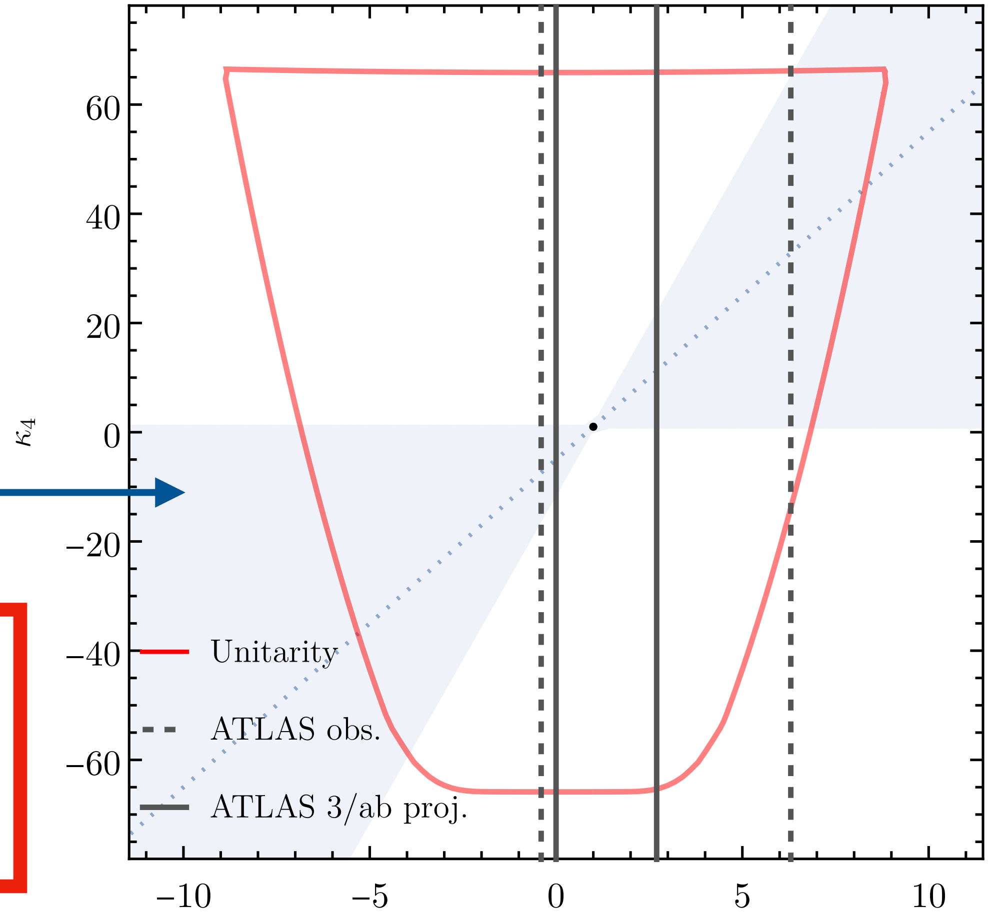
$$V_{\mathrm{BSM}} = \frac{C_6}{\Lambda^2}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^3 + \frac{C_8}{\Lambda^4}\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^4 + \ldots$$

Contributions to κ_3, κ_4:

$$\begin{aligned}(\kappa_3 - 1) &= \frac{C_6 v^2}{\lambda\Lambda^2}\,,\\ (\kappa_4 - 1) &= \frac{6C_6 v^2}{\lambda\Lambda^2} + \frac{4C_8 v^4}{\lambda\Lambda^4}\\ &\simeq 6(\kappa_3 - 1) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)\end{aligned}$$

vanishing dimension-8 →

Shaded region: $\frac{4C_8 v^4}{\lambda\Lambda^4} < \frac{6C_6 v^2}{\lambda\Lambda^2}$ →



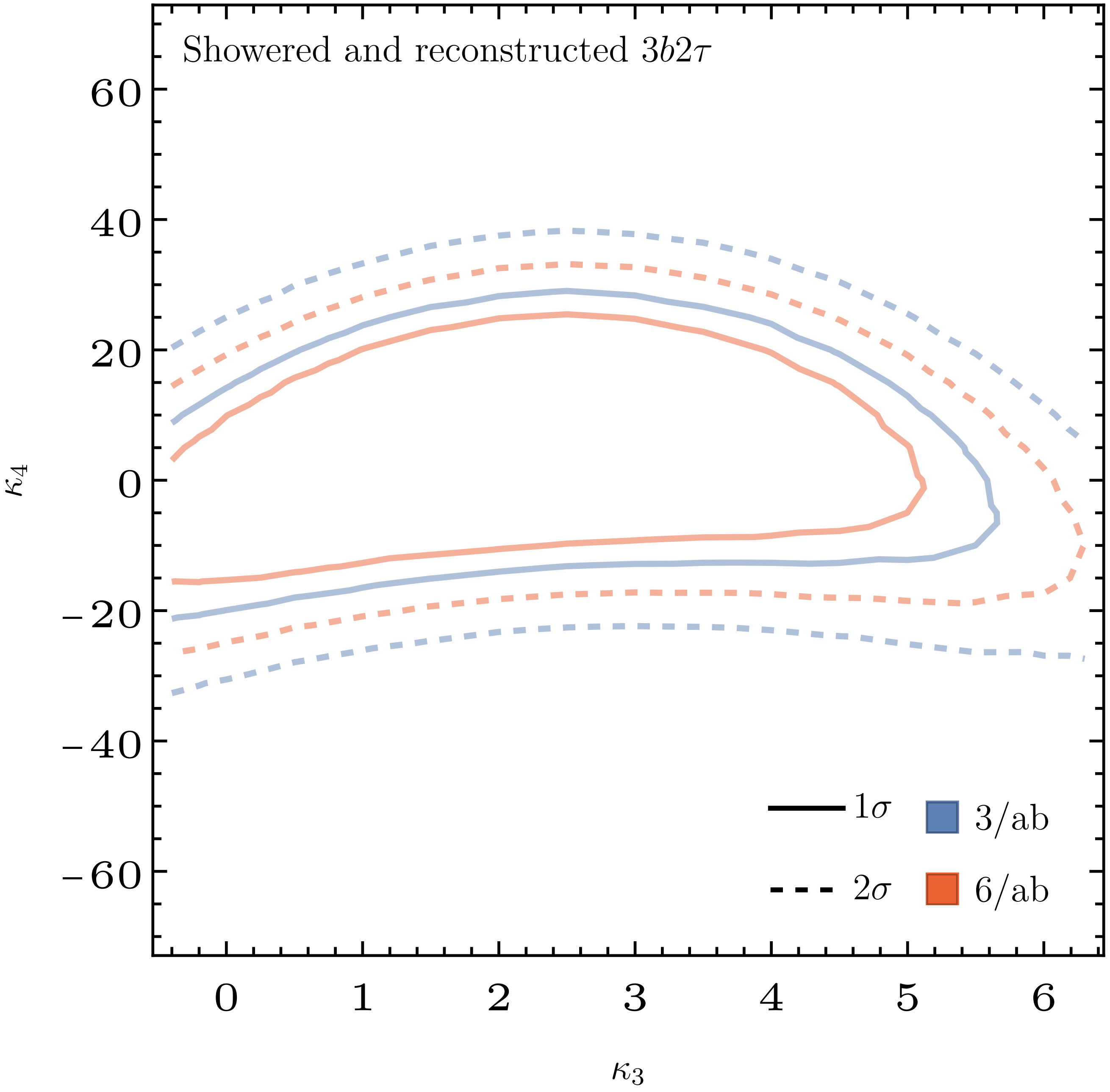
Electroweak Chiral Lagrangian (HEFT):
Higgs introduced as singlet and κ_3 and κ_4 are **free parameters** →probes **non-linearity**

⇒Deviation in $\varkappa_4$ enhanced by factor 6!

Showered and reconstructed results: 3b2$\boldsymbol{\tau}$

[P. Stylianou, G. W. '24]

- $3b2\tau$ more complicated due to multiple backgrounds → multi-class classification
- Train on backgrounds: $W^+W^-b\bar{b}b\bar{b},\ Zb\bar{b}b\bar{b},\ t\bar{t}(H\to\tau^+\tau^-)$



Higgs pair production at e⁺e⁻ colliders

[S. di Vita et al. ’18]