Probing BSM physics via the trilinear Higgs coupling

Henning Bahl

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

BSM seminar, Karlsruhe, 7.5.2025

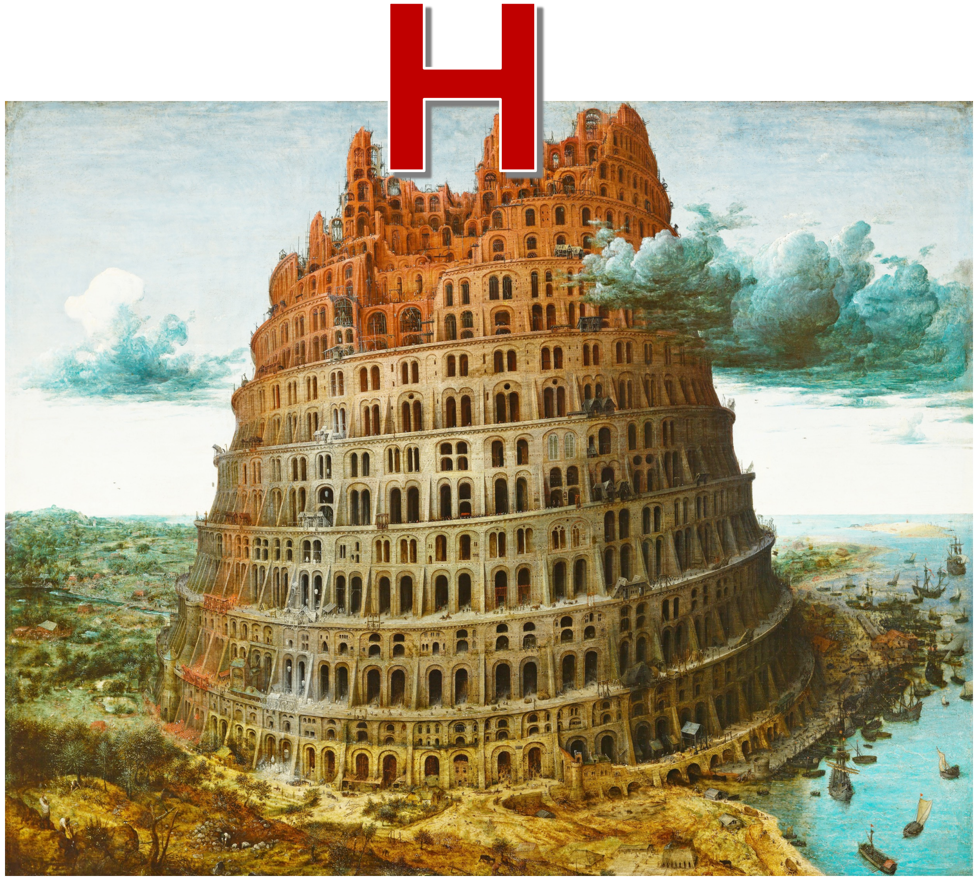
The Higgs discovery

After decades of work, the Higgs discovery was a big success for particle physics.

→ Where are we more than 10 years later?

→ What have we learned about the Higgs in the mean time?

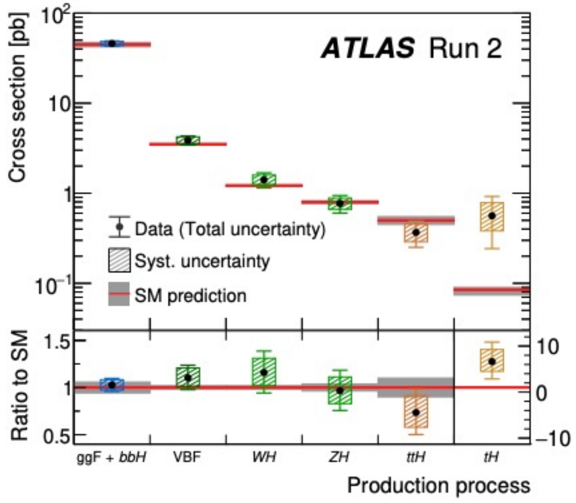
→ What is still left to explore?

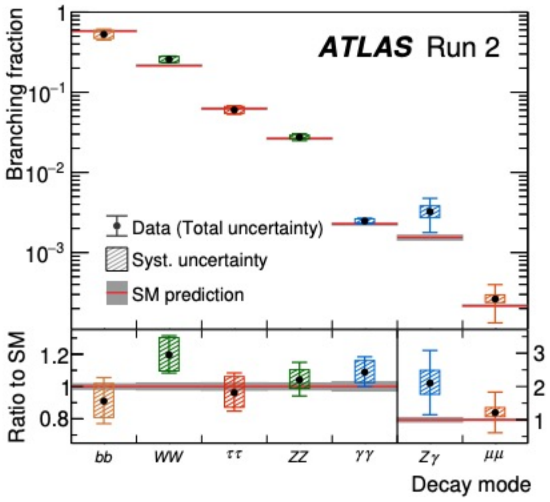


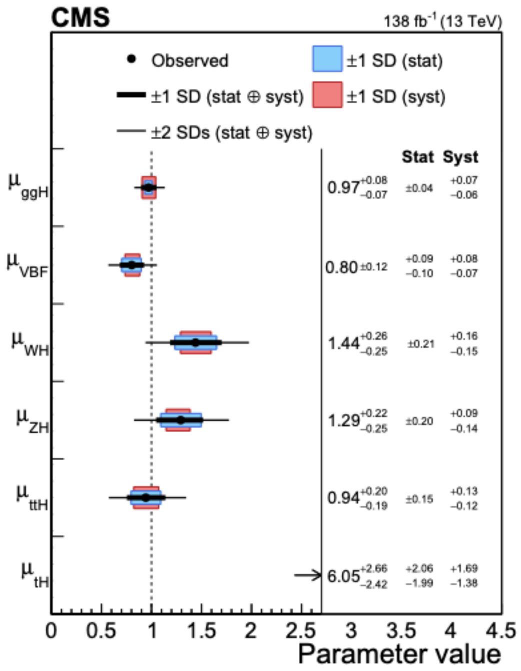
Tower of ~~Babel~~ *the SM*

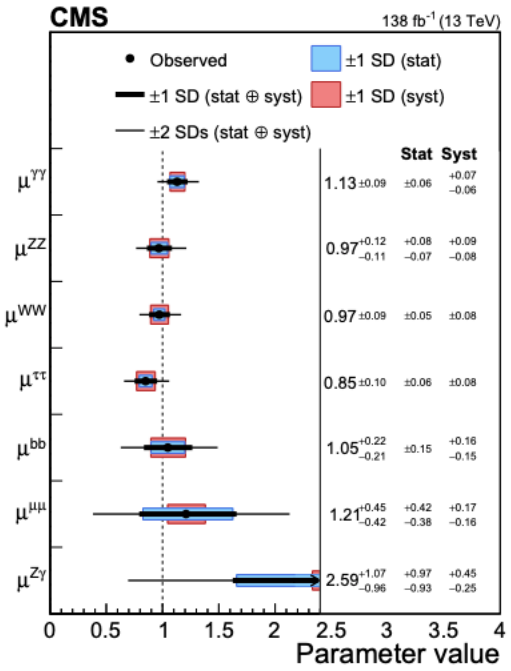
The Higgs 10 years later

[ATLAS 2207.00092, CMS 2207.00043]









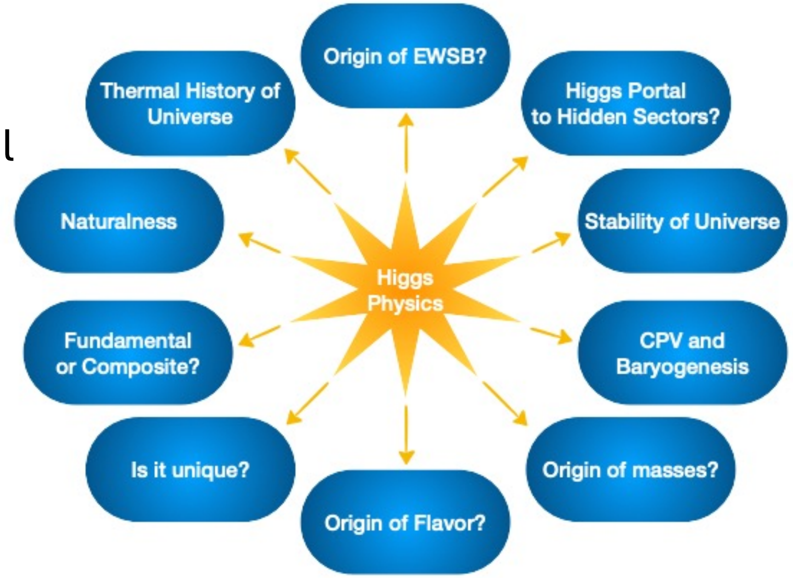
- Ten years later, we have entered the Higgs precision era.
- So far, all Higgs measurements agree with the SM predictions within the experimental and theoretical uncertainties.

So, everything left to do is to confirm the SM with even more precision?

Motivation for future Higgs measurements

So, everything left to do is to confirm the SM with even more precision? $\rightarrow$ **No!**

- Most couplings are measured with $\sim 10\%$ precision.
  $\rightarrow$ BSM effects could be hidden within the uncertainties.
- Some Higgs properties are only weakly constrained.
- Existing measurements already provide strong guidance for BSM model building.
- Many types of BSM physics can be linked to the Higgs.



[Snowmass 2209.07510]

$\Rightarrow$ Strong motivation for on-going and future Higgs precision programs.

What we don’t know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

What we don't know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

- Higgs width/BSM decay channels,

  SM: $\Gamma_h \simeq 4.1\ \mathrm{MeV}$,

What we don't know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

- Higgs width/BSM decay channels,

  SM: $\Gamma_h \simeq 4.1\ \mathrm{MeV}$,

- Higgs potential,

  SM: $V(\Phi) = -\frac{1}{2} m_h^2 \Phi^\dagger \Phi + \frac{m_h^2}{2v^2} \left(\Phi^\dagger \Phi\right)^2$,

What we don't know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

- Higgs width/BSM decay channels,

  SM: $\Gamma_h \simeq 4.1\ \text{MeV}$,

- Higgs potential,

  SM: $V(\Phi) = -\frac{1}{2} m_h^2 \Phi^\dagger \Phi + \frac{m_h^2}{2v^2} \left(\Phi^\dagger \Phi\right)^2$,

- light Yukawas,

  SM: $y_f \propto m_f / v$,

What we don't know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

- Higgs width/BSM decay channels,

  SM: $\Gamma_h \simeq 4.1\ \mathrm{MeV}$,

- Higgs potential,

  SM: $V(\Phi) = -\frac{1}{2} m_h^2 \Phi^\dagger \Phi + \frac{m_h^2}{2v^2}\left(\Phi^\dagger \Phi\right)^2$,

- light Yukawas,

  SM: $y_f \propto m_f/v$,

- Higgs CP properties,

  SM: Higgs is CP-even (at least almost).

What we don't know about the Higgs (yet)

Many Higgs properties only weakly constrained, e.g.:

- Higgs width/BSM decay channels,

  SM: $\Gamma_h \simeq 4.1\ \mathrm{MeV}$,

- Higgs potential,

  SM: $V(\Phi) = -\frac{1}{2}m_h^2\Phi^\dagger\Phi + \frac{m_h^2}{2v^2}\left(\Phi^\dagger\Phi\right)^2$,

- light Yukawas,

  SM: $y_f \propto m_f/v$,

- Higgs CP properties,

  SM: Higgs is CP-even (at least almost).

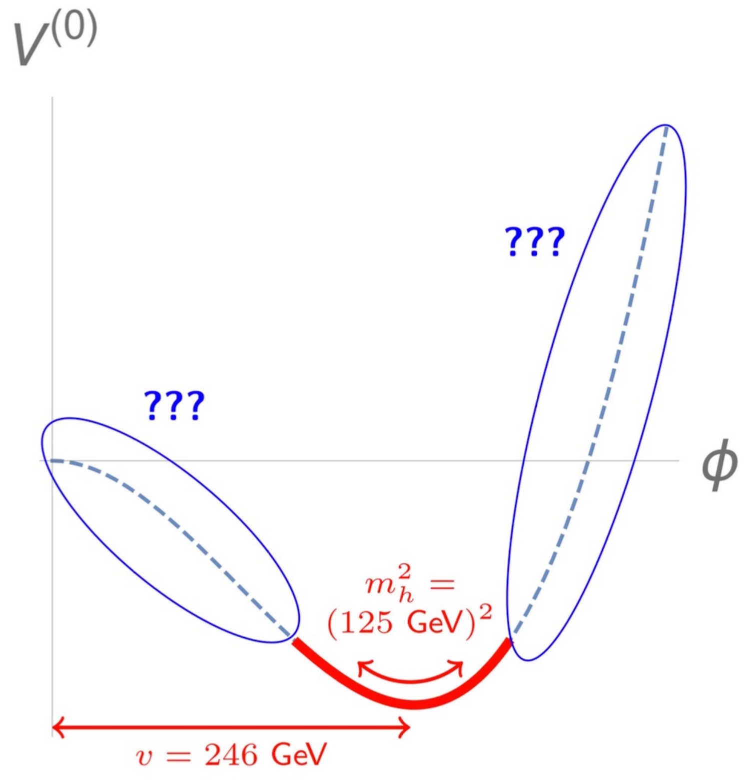
We should test all these predictions!

What do we know about the Higgs potential?

- After the Higgs discovery, we know
  - the location of the EW minimum: $v = 246$ GeV
  - the curvature of the potential close to the minimum

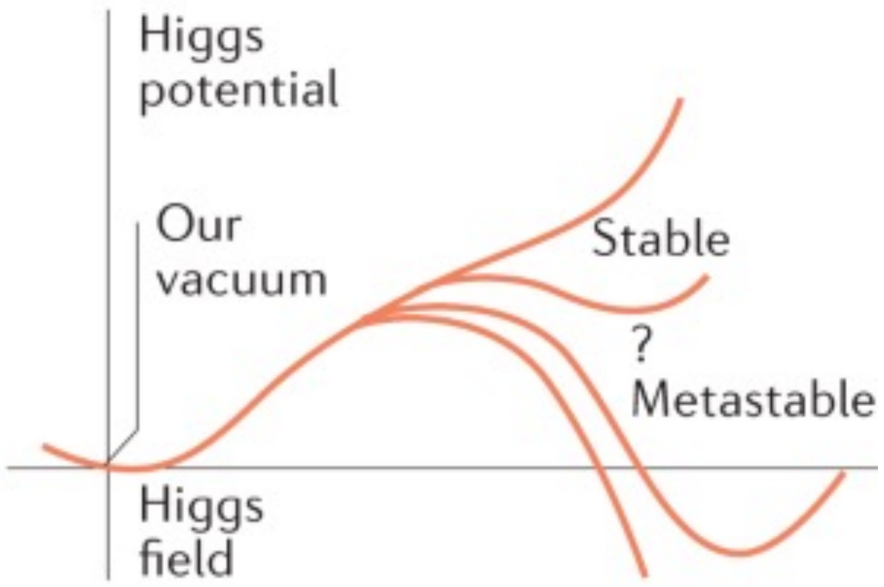
- Away from the minimum, the shape of the potential is, however, unknown so far.

➡ Determination of trilinear Higgs coupling λ_{hhh} crucial



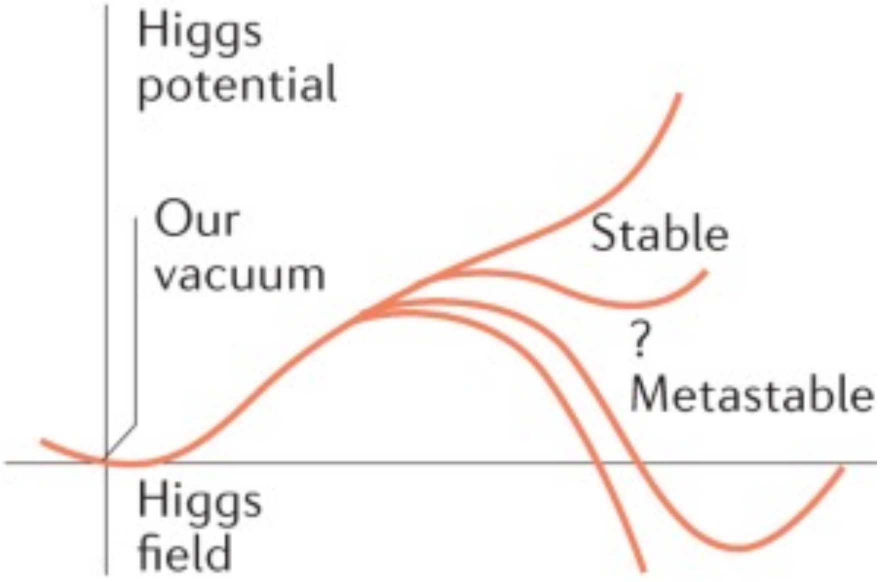
[figure by J. Braathen]

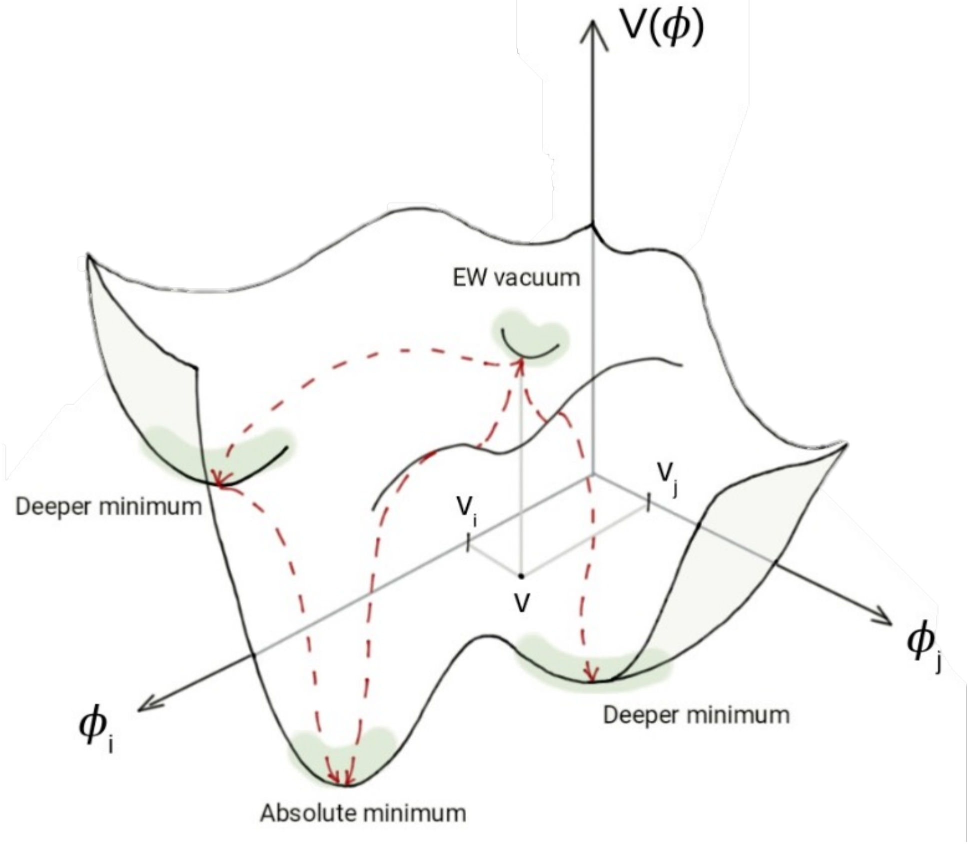
What is the shape of the Higgs potential?



λ_{hhh} closely linked to stability of EW vacuum & nature of EW phase transition

What is the shape of the Higgs potential?





[figure by K. Radchenko Serdula]

λ_{hhh} closely linked to stability of EW vacuum & nature of EW phase transition

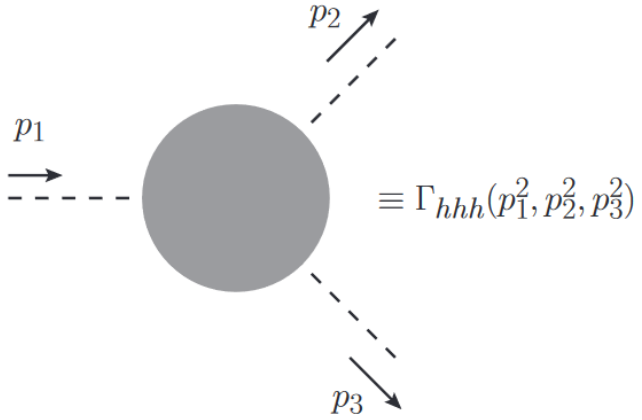
BSM effects in the trilinear Higgs coupling

How large can they get within existing constraints?

→ focus on BSM extensions of the SM Higgs sector

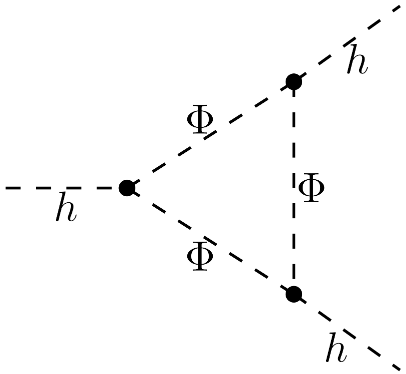
Calculating BSM corrections to κ_λ

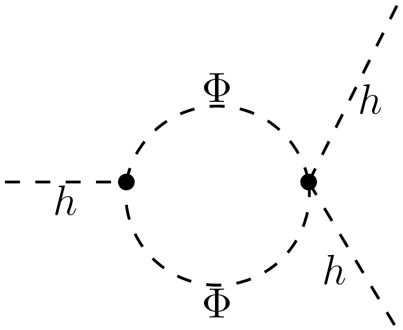
- Need to calculate Higgs three-point function:



- define $\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\left(\lambda_{hhh}^{(0)}\right)^{\mathrm{SM}}}$ with $\lambda_{hhh} = -\Gamma_{hhh}(p_1^2, p_2^2, p_3^2)$

- at the tree-level, $\kappa_\lambda \sim 1$ due to Higgs precision measurements





- but BSM loop corrections can be large if large couplings of h to BSM scalars Φ

Calculating BSM corrections to κ_λ

- In many models with extended Higgs sectors:

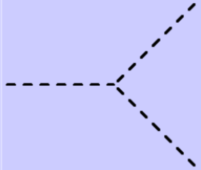
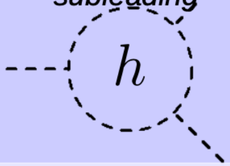
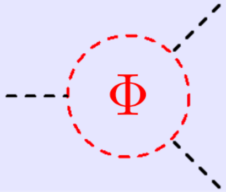
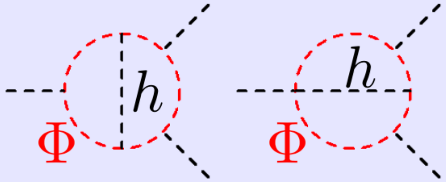
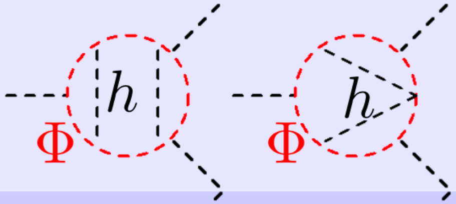
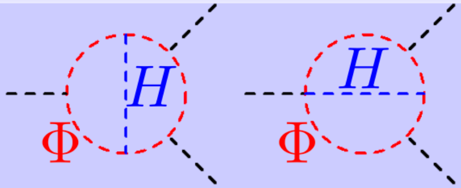
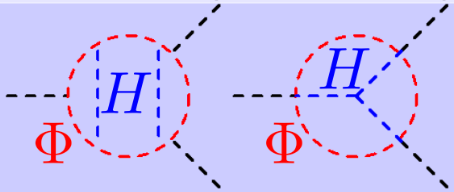
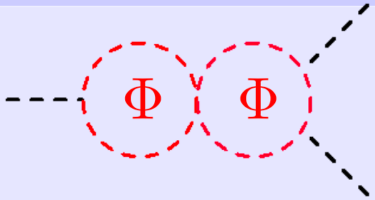
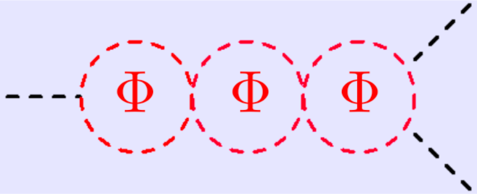
$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$$

- m_Φ: masses of BSM states,
- M^2: BSM mass parameter in the Lagrangian,
- $g_{hh\Phi\Phi}$: combination of Lagrangian quartic couplings

⇒ Large couplings if large splitting between M^2 and m_Φ^2 or between BSM scalars

Consider e.g. the case of the 2HDM in the alignment limit: $\Phi = \{H, A, H^\pm\}$

2HDM loop corrections to Higgs trilinear

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']	-	-		

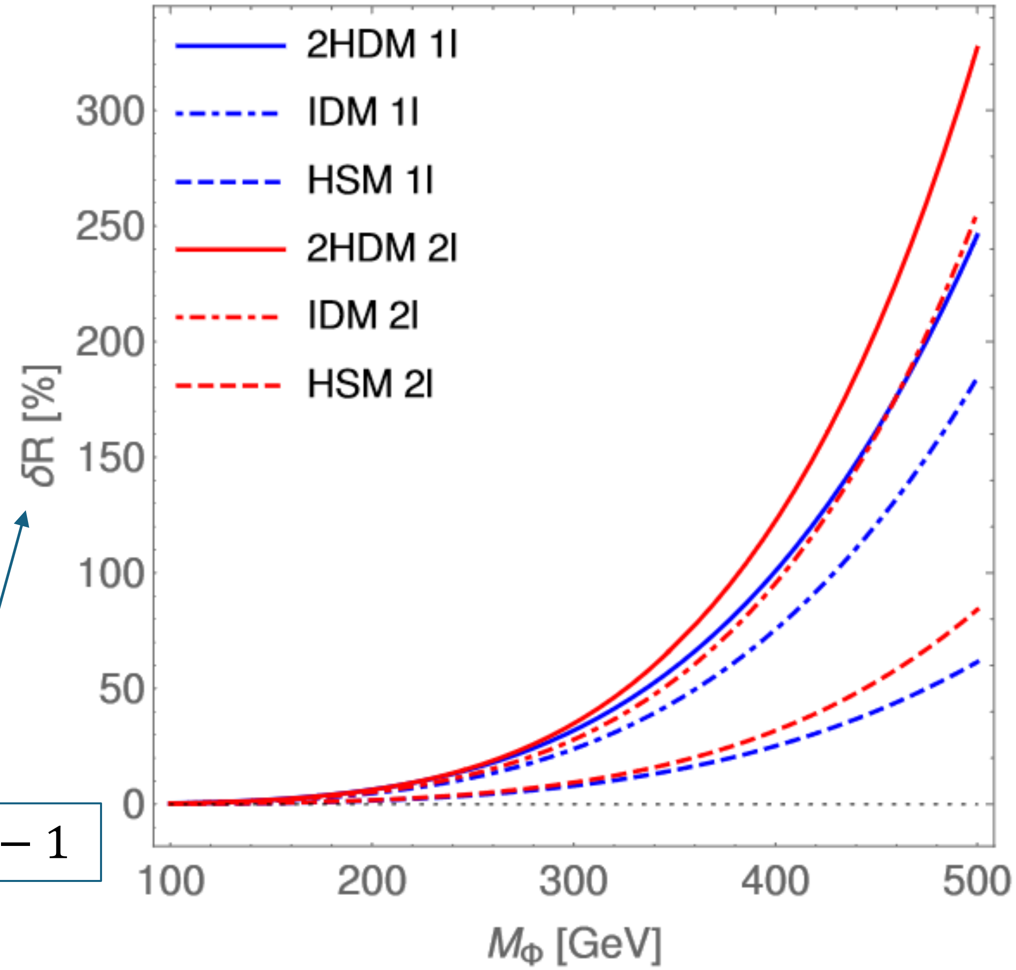
[table by J. Braathen '24]

Loop corrections in degenerate limit

[Braathen,Kanemura,1911.11507]

- $\delta^{(1)}\lambda_{hhh} = \sum_{\Phi} \frac{4n_{\Phi}m_{\Phi}^4}{v^3}\left(1 - \frac{M^2}{m_{\Phi}^2}\right)^3$
- all BSM masses degenerate
- $M^2 = 0$
- no violation of perturbative unitarity

$\delta R = \kappa_\lambda - 1$



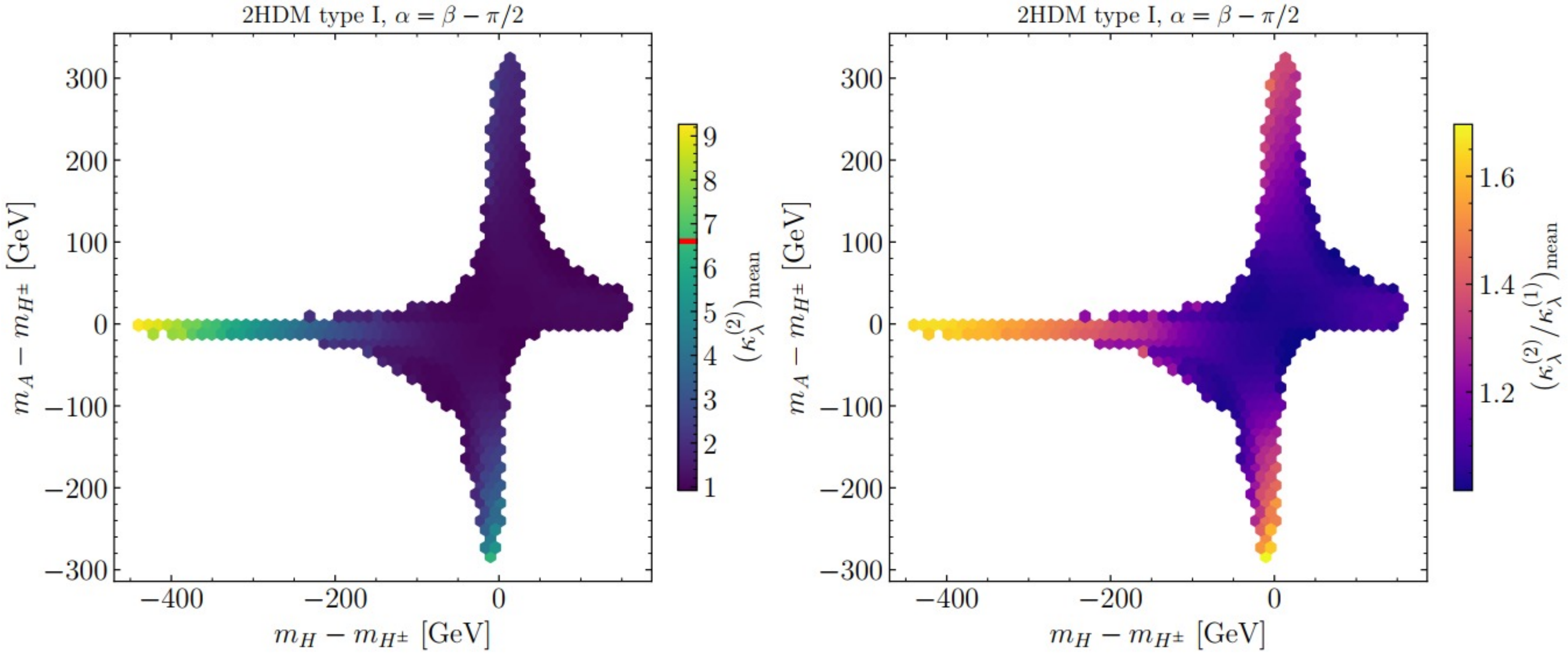
Full 2HDM parameter scan

[HB,Braathen,Weiglein, 2202.03453]

- Checked for
  - vacuum stability and boundedness-from-below,
  - NLO perturbative unitarity, [Grinstein et al., 1512.04567; Cacchio et al., 1609.01290]
  - electroweak precision observables (calculated at the 2L level using THDM_EWPOS), [Hessenberger & Hollik,1607.04610,2207.03845]
  - SM-like Higgs measurements via HiggsSignals, [Bechtle et al., 2012.09197]
  - direct searches for BSM scalars via HiggsBounds, [Bechtle et al., 2006.06007]
  - b-physics constraints.
- Most constraints checked using ScannerS. [Mühlleitner et al., 2007.02985]
- For each point passing the constraints, calculate κ_λ at the 1L and 2L level ($\kappa_\lambda^{(1)}$ and $\kappa_\lambda^{(2)}$). [Braathen,Kanemura,1911.11507]

2HDM scan results

[HB,Braathen,Weiglein, 2202.03453]



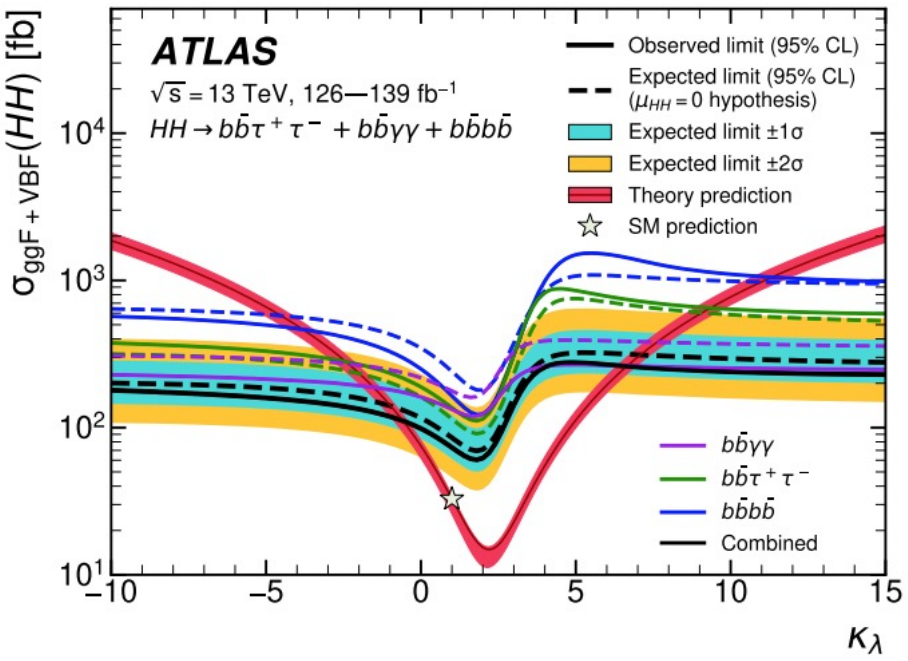
- Largest corrections for $m_A \simeq m_{H^\pm}, m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}, m_A$
- 2L corrections have sizeable impact (up to 70%).

Experimental bound on $\kappa_\lambda \equiv \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$

Current strongest limit: $-0.4 < \kappa_\lambda < 6.1$ at 95% CL [ATLAS 2211.01216].

Assumptions:

- Simplest analysis assumes that all other Higgs couplings are SM-like.
- Non-resonant Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling (i.e., no heavy resonances).



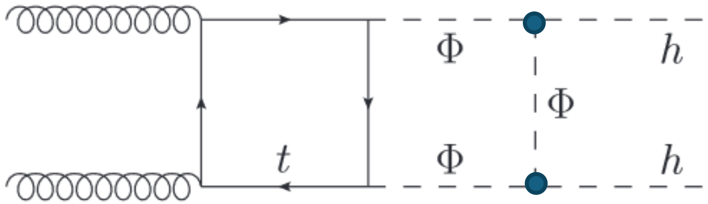
Can we use this seemingly weak limit to constrain the 2HDM?

Can we apply the experimental constraints on κ_λ?

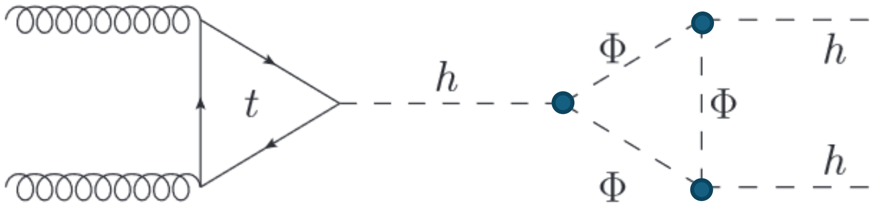
[HB,Braathen,Weiglein, 2202.03453]

Assumptions of experimental bound:

- All other Higgs couplings are SM-like.
  - ➢ 2HDM in the alignment limit with heavy BSM masses.
- Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling.
  - ➢ No resonant contribution because Hhh coupling is zero in alignment limit.
  - ➢ Other BSM contributions to hh production?



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



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

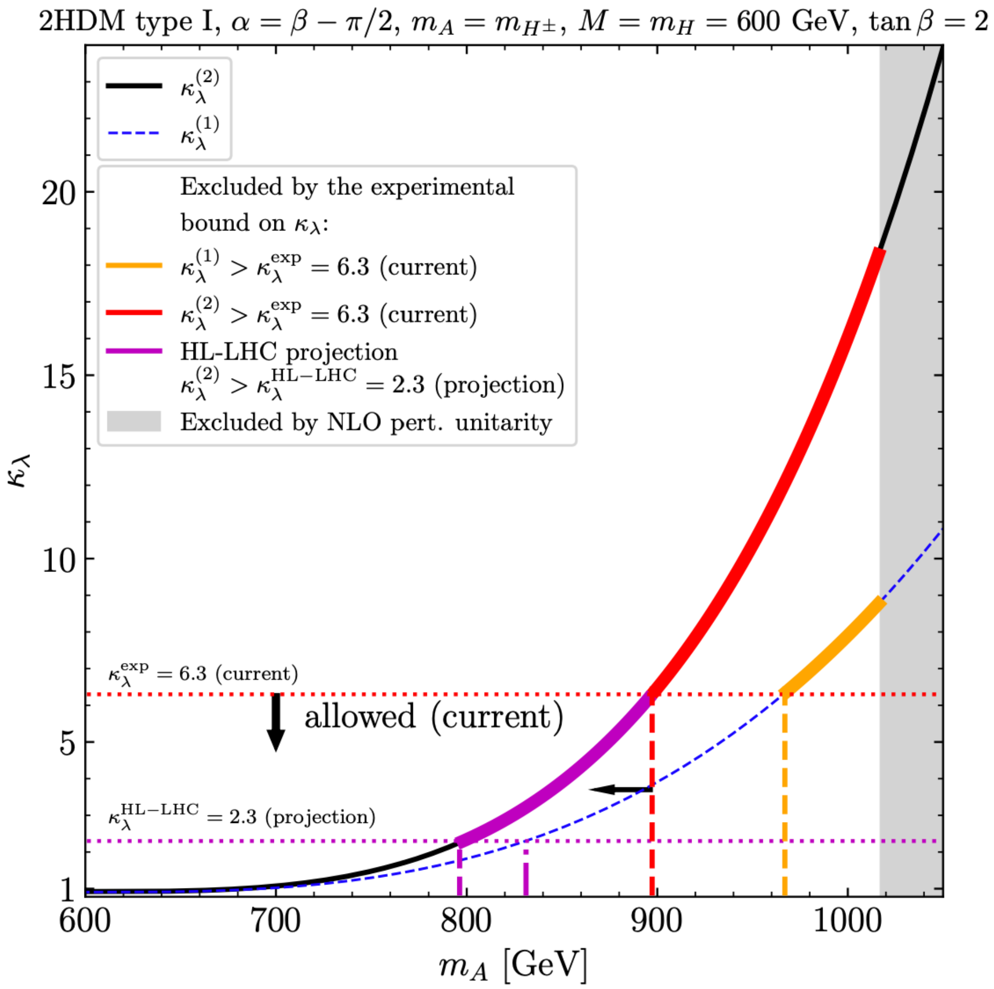
  - ➢ We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level.

2HDM benchmark scenario

[HB,Braathen,Weiglein, 2202.03453]

- κ_λ bound already now stronger than perturbative unitarity
- 2L corrections to κ_λ crucial for accurate bounds
- only high m_A region constrained by pert. unitarity

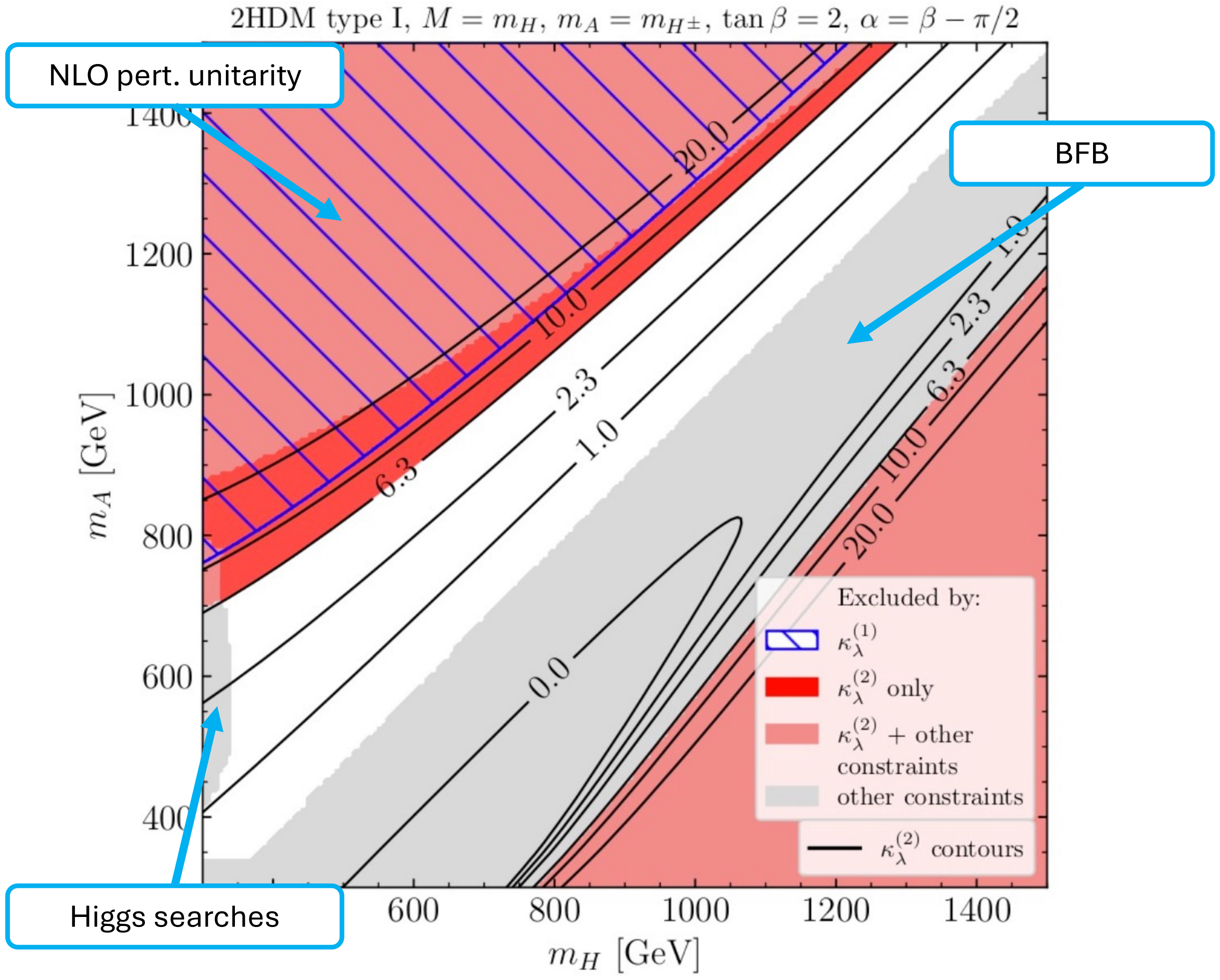
Already current experimental limits on κ_λ probe so-far unconstrained BSM parameter space!



[HB,Braathen,Weiglein, 2202.03453]

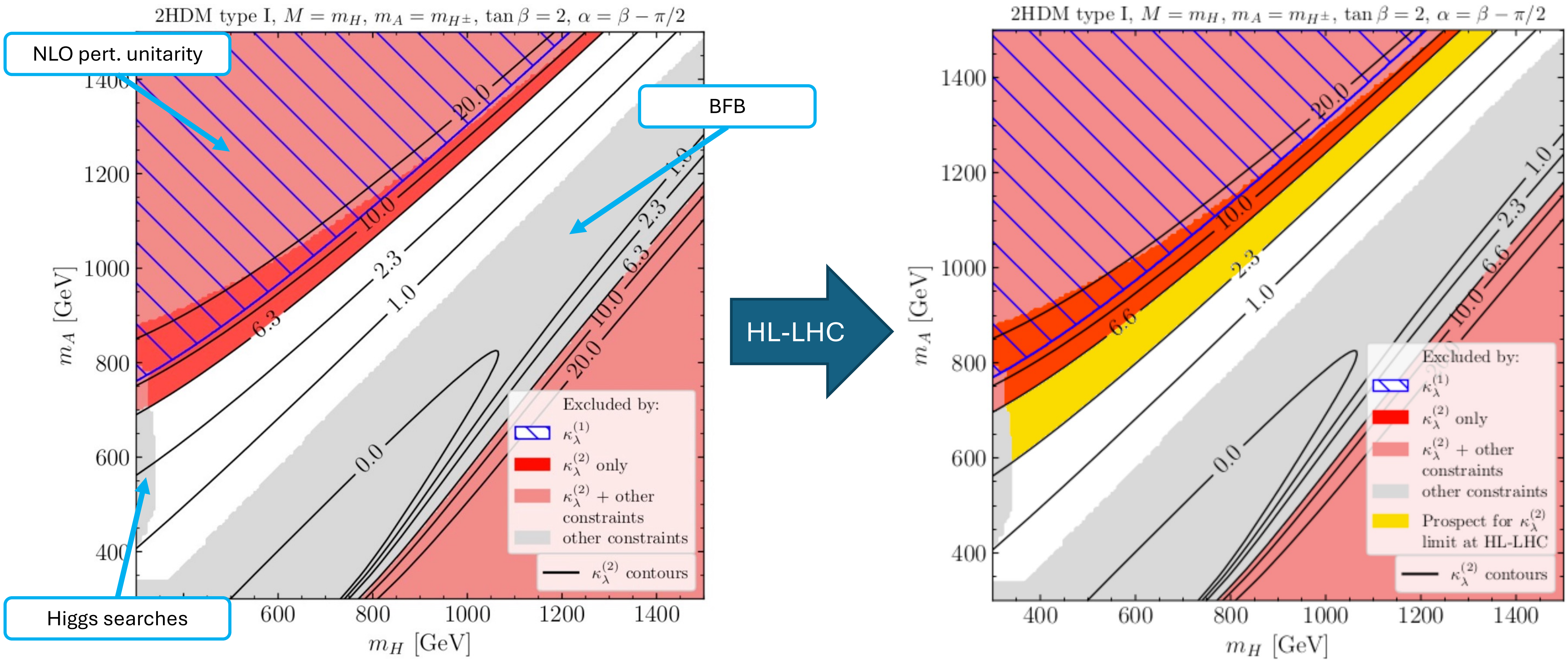
Constraints on κ_λ — benchmark plane

[HB,Braathen,Weiglein, 2202.03453]



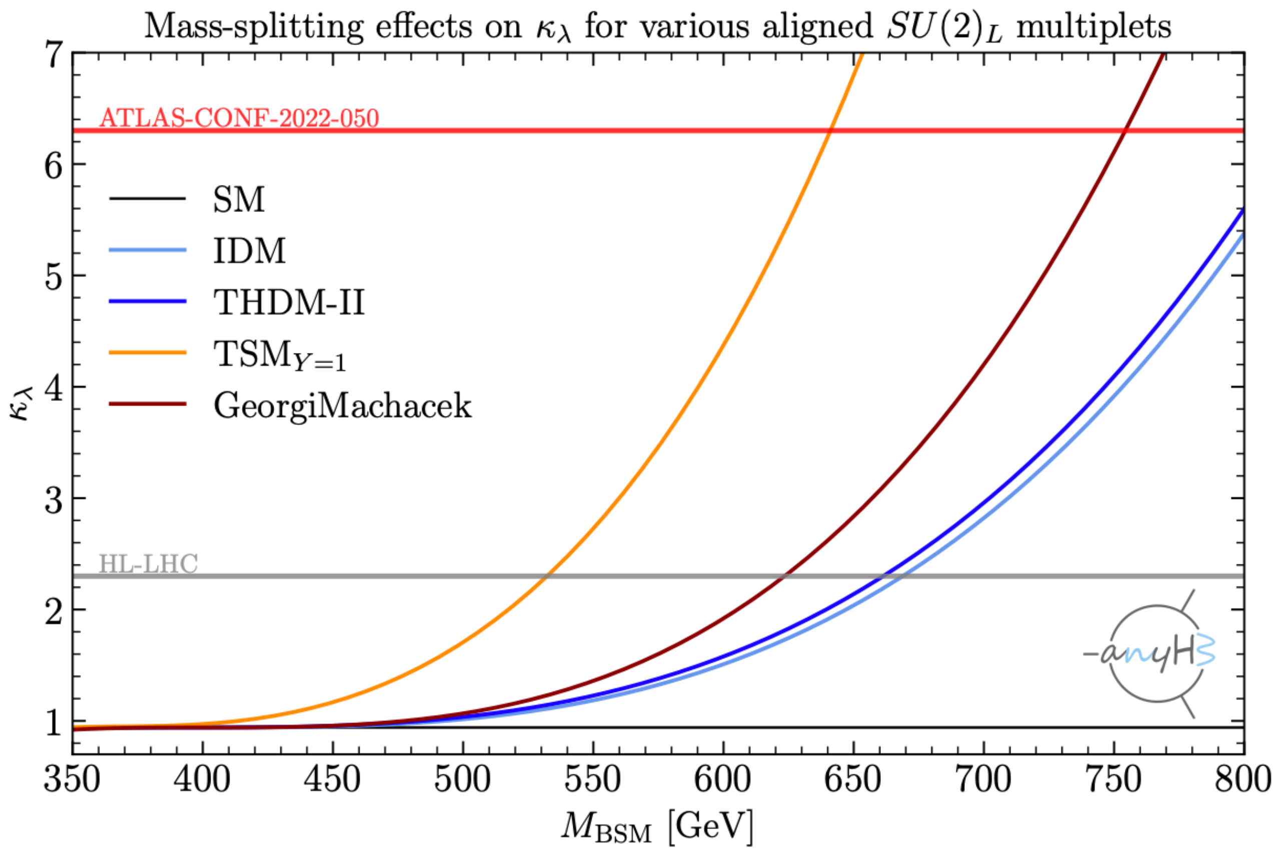
Constraints on κ_λ — benchmark plane

[HB,Braathen,Weiglein, 2202.03453]



Other extension of SM Higgs sector

[HB,Braathen,Gabelmann,Weiglein,2305.03015]



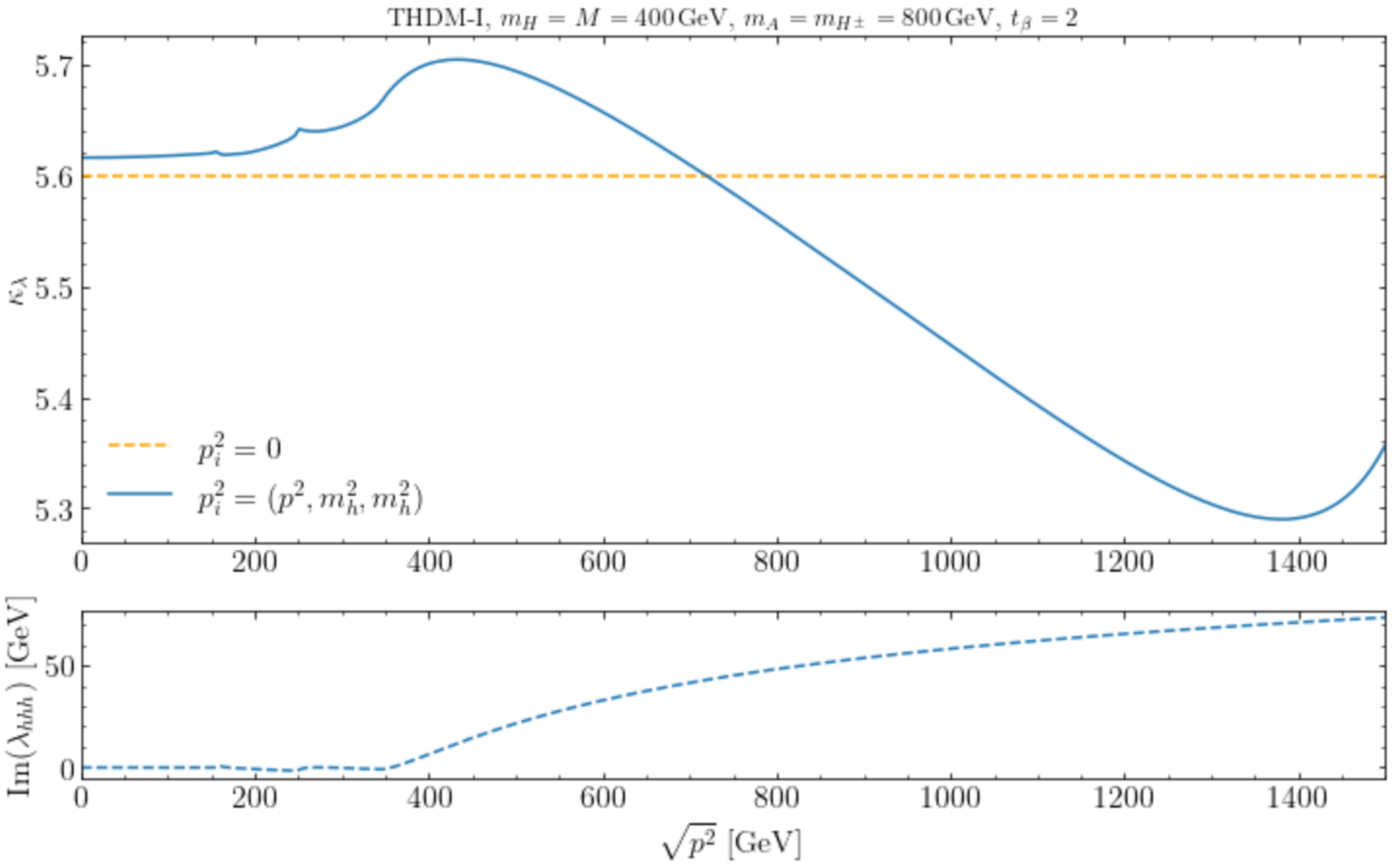
- Large loop corrections to κ_λ possible in various models.
- κ_λ very sensitive to BSM scalar couplings.
- Automatized calculation of κ_λ available in Python package anyH3.
- Uses UFO models as input.
- See also [1704.01953,1902.05936,2209.00666] for non-Higgs models, EFT discussion, etc.

Momentum dependence

[HB,Braathen,Gabelmann,Weiglein,2305.03015]

- Typical assumption: zero momentum ($p_1^2 = p_2^2 = p_3^2 = 0$)
- Using anyH3, check validity

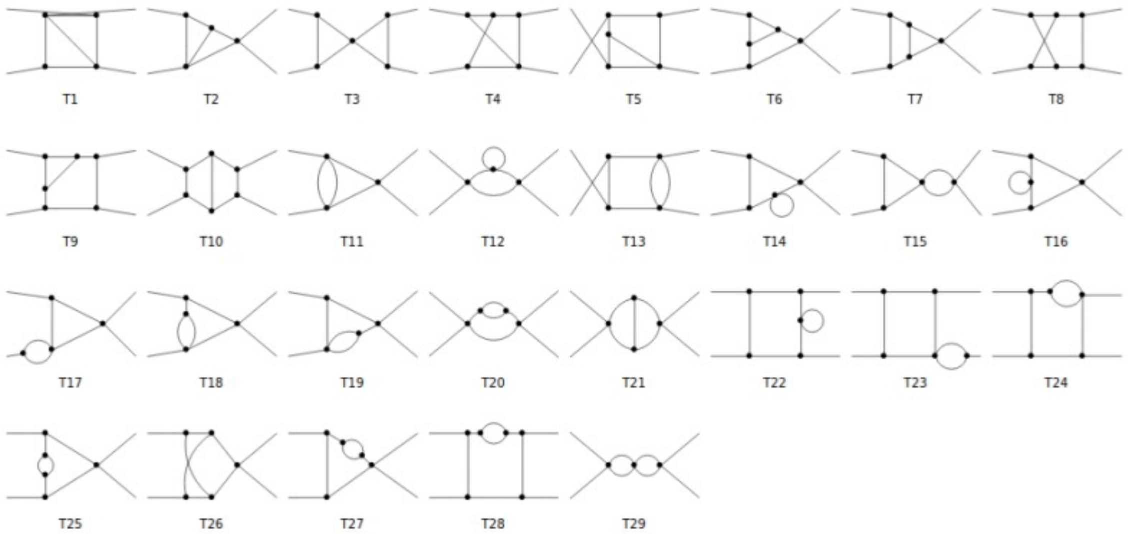
Zero-momentum correction captures bulk of correction



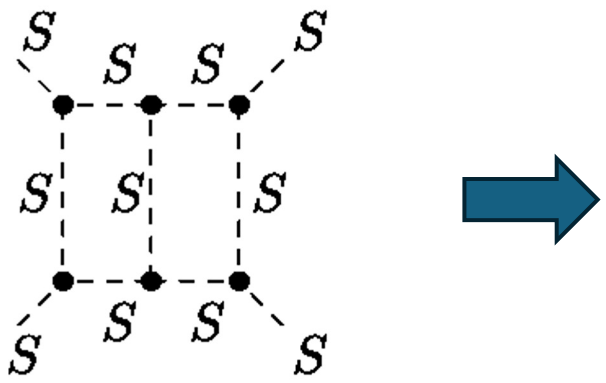
Generic 2L results for λ_{hhh}

[HB,Braathen,Gabelmann,Paßehr,2503.15645]

- 1L predictions full automated: anyH3 and BSMPT [Basler et al.,1803.02846,...]
- next step: automation for 2L
- building blocks: scalar 0,1,2,3,4-point functions
- work in zero-momentum approximation
- write down all possible Feynman diagrams with generic fields/couplings
- reduce number of diagrams using known symmetries



Exemplary result



Unique edge list defining diagram

```
{
  {1, 1, 1},
  {
   edge[iv[1], v[5], S[i3]], edge[iv[2], v[6], S[i4]],
   edge[iv[3], v[7], S[i1]], edge[iv[4], v[8], S[i2]],
   edge[v[5], v[6], -S[i9]], edge[v[5], v[7], -S[i6]],
   edge[v[5], v[8], -S[i8]], edge[v[6], v[7], -S[i5]],
   edge[v[6], v[8], -S[i7]]
  },
  -((lfac^2*SSS[i1, -i5, -i6, 1]*SSS[i2, -i7, -i8, 1]*
     SSSS[i3, i6, i8, i9, 1]*SSSS[i4, i5, i7, -i9, 1]*
     T[Df[k1, MS[i7]]*Df[k1, MS[i8]]*Df[k3, MS[i5]]*
       Df[k3, MS[i6]]*Df[k4, MS[i9]]]
    )/SF[1, 1/6, 1])
},
```

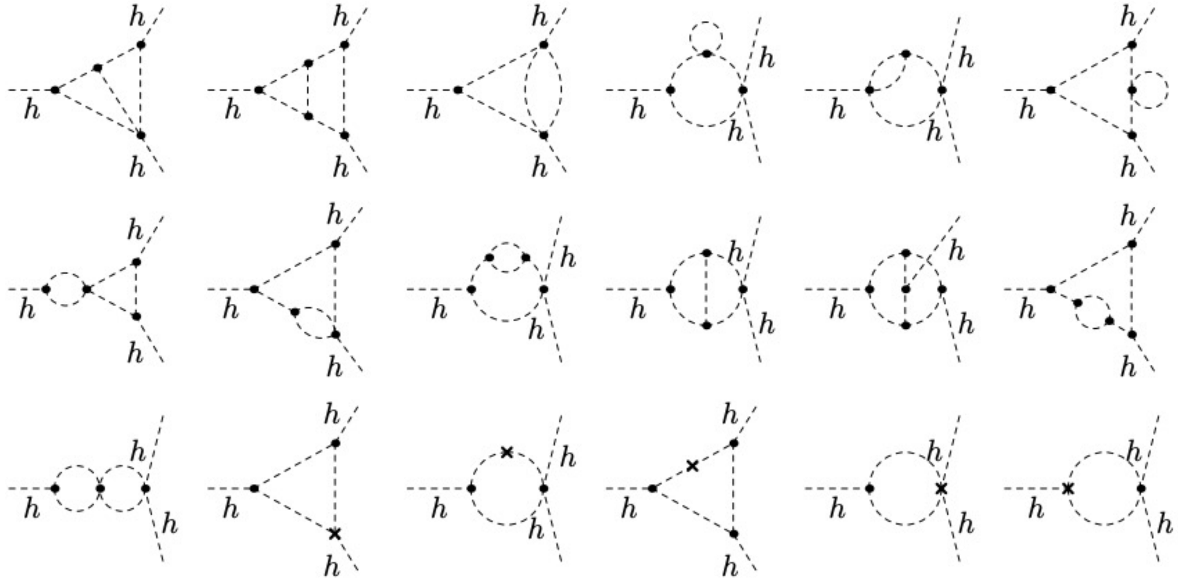
Generic couplings

T-integral
[Weiglein,Scharf,Böhm,hep-ph/9310358]

Symmetry factor

Application to concrete model

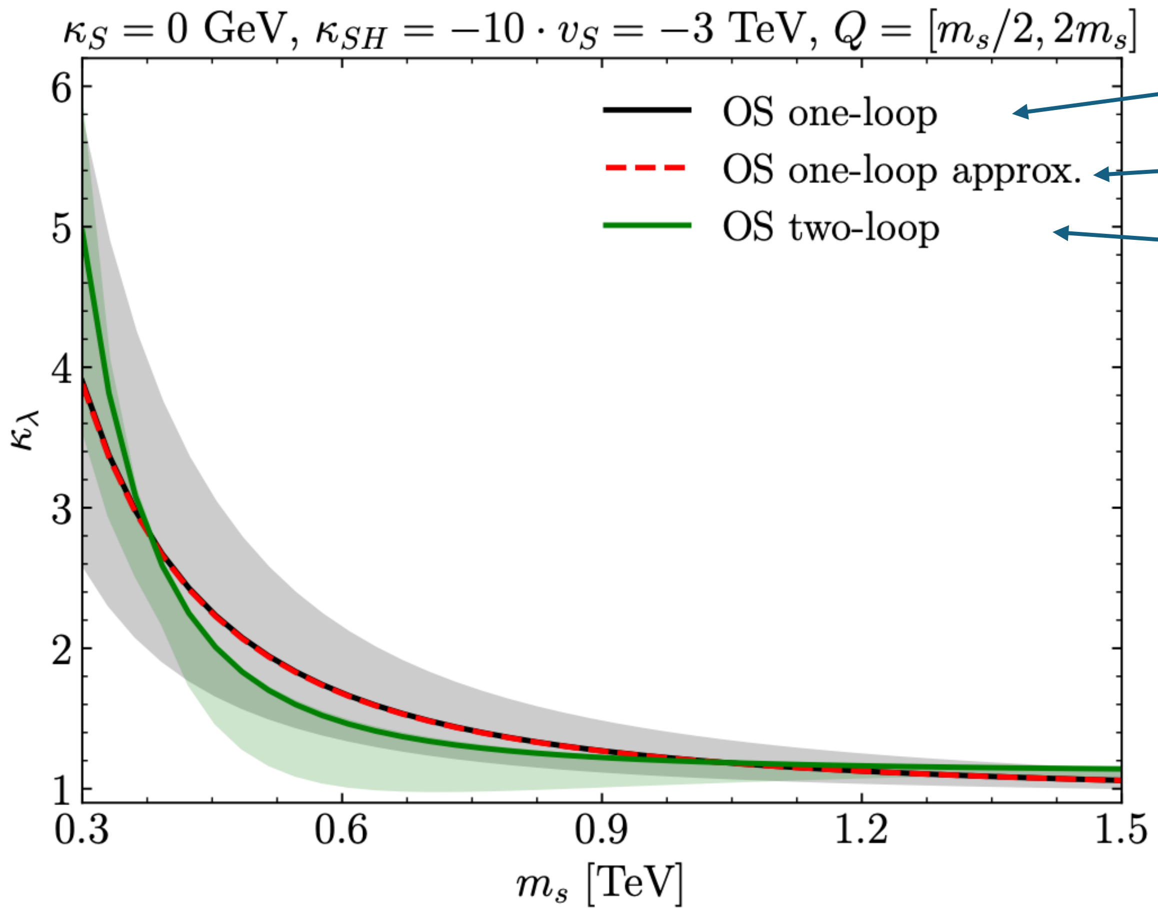
- map generic results to concrete model using FeynArts [Hahn et al.,hep-ph/0012260]
- numerical evaluation of loop integrals: on-the-fly reduction using new Python package Tintegrals
- cross-checked against many known results in the literature



- **new 2L result**: general singlet extension in alignment limit
- All parameters OS renormalized apart from $\overline{\text{MS}}$ $v_S, \kappa_S, \kappa_{SH}$

$$V_{SSM} = \mu^2|\Phi|^2 + \frac{\lambda_H}{2}|\Phi|^4 + \frac{m_S^2}{2}S^2 + \frac{\lambda_S}{2}S^4 + \frac{\lambda_{SH}}{2}S^2|\Phi|^2 + \kappa_{SH}S|\Phi|^2 + \frac{\kappa_S}{3}S^3$$

2L corrections in SSM



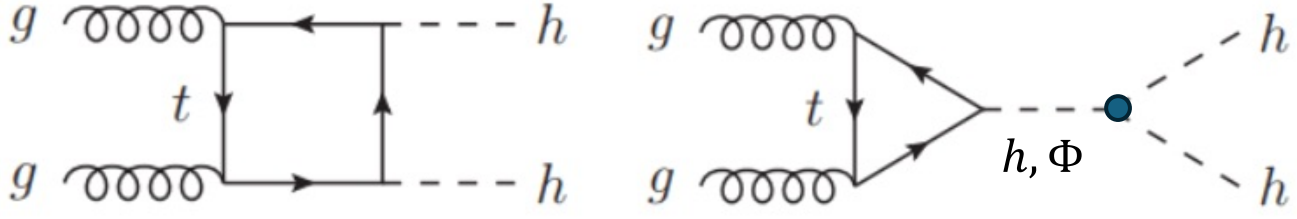
full 1L result

1L result with $m_h = 0$

2L result with $m_h = 0$

all building blocks for automated 2L prediction now available!

Large trilinear couplings and di-HH production



Di-Higgs production in a nutshell

- λ_{hhh} is not a physical observable but σ_{hh} is

external Higgs

trilinear Higgs couplings

top-coupling modifiers

di-HH formfactors

$$\frac{d\sigma_{h_i h_j}}{d\hat{t}} = \frac{\gamma}{256\pi}\frac{\alpha_s^2}{(4\pi)^2}\left\{\left|\sum_k \frac{-c_{t,h_k}\lambda_{h_i h_j h_k} v_{\text{EW}}}{s - m_{h_k}^2 + i m_{h_k}\Gamma_{h_k}} F_\triangle^e + c_{t,h_i} c_{t,h_j} F_\Box^{ee} + \tilde{c}_{t,h_i}\tilde{c}_{t,h_j} F_\Box^{oo}\right|^2 \right.$$
$$+ \left|\sum_k \frac{-\tilde{c}_{t,h_k}\lambda_{h_i h_j h_k} v_{\text{EW}}}{s - m_{h_k}^2 + i m_{h_k}\Gamma_{h_k}} F_\triangle^o + c_{t,h_i}\tilde{c}_{t,h_j} F_\Box^{eo}\right|^2$$
$$\left. + \left|c_{t,h_i} c_{t,h_j} G_\Box^{ee} + \tilde{c}_{t,h_i}\tilde{c}_{t,h_j} G_\Box^{oo}\right|^2 + \left|c_{t,h_i}\tilde{c}_{t,h_j} G_\Box^{eo}\right|^2 \right\}$$

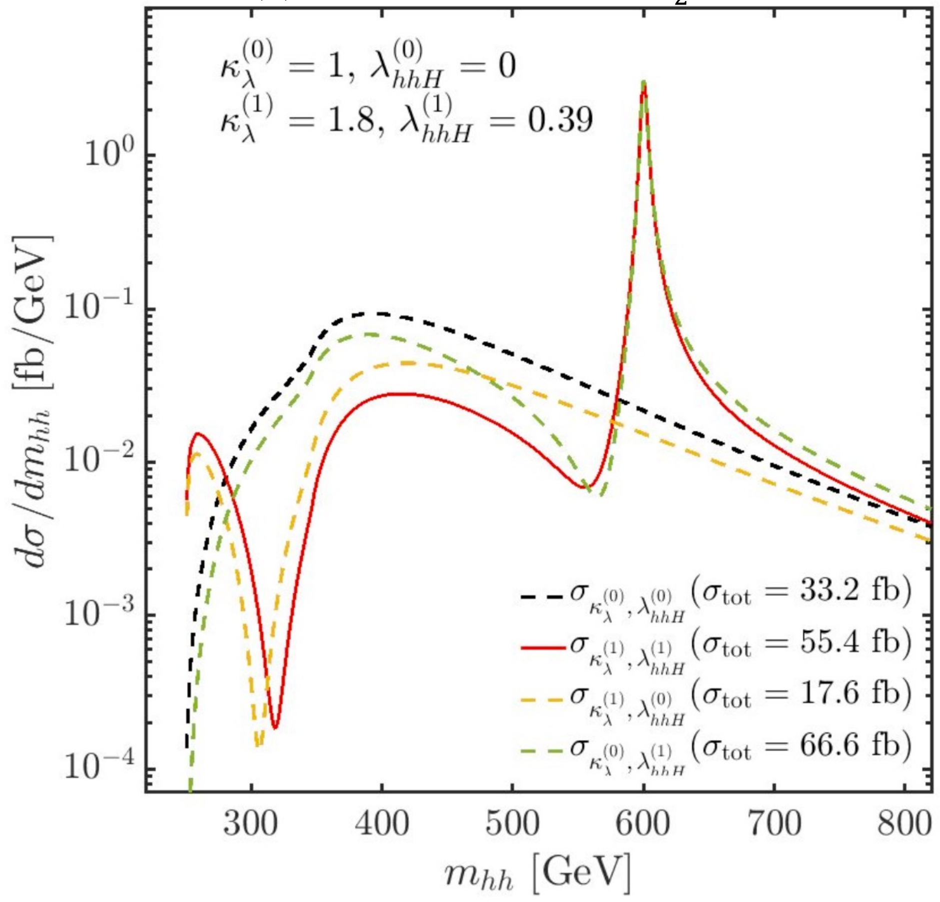
- implement generic LO QCD differential XS into anyH3 → new anyHH subpackage
  [Plehn,Spira,Zerwas,hep-ph/9603205]

- also available in HPAIR (+ NLO QCD) [Mühlleitner et al.,2112.12515,...]

Effect on invariant mass distribution in 2HDM

[Heinemeyer,Mühlleitner,Radchenko,Weiglein,2403.14776]

$M_{H,A,H^\pm} = 400\ GeV, \alpha = \beta - \frac{\pi}{2}, t_\beta = 2$

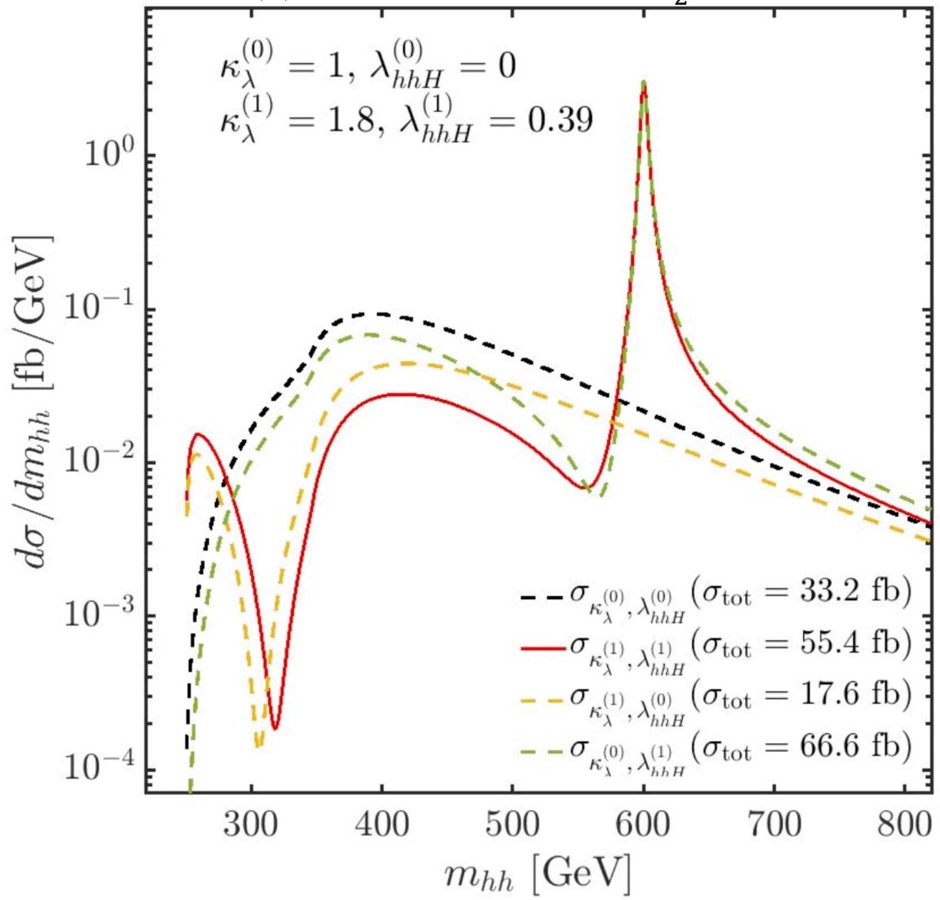


➡ Significant distortion of distribution; loop corrections to BSM trilinears important.

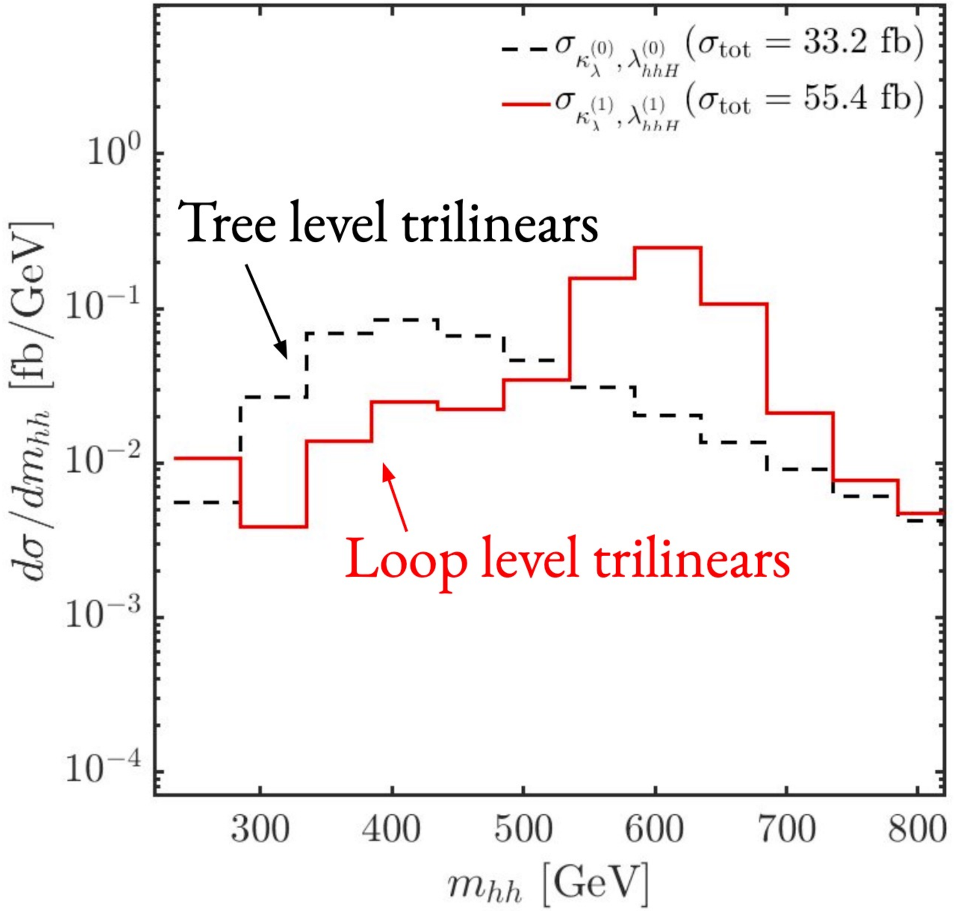
Effect on invariant mass distribution in 2HDM

[Heinemeyer,Mühlleitner,Radchenko,Weiglein,2403.14776]

$M_{H,A,H^\pm} = 400\ GeV, \alpha = \beta - \frac{\pi}{2}, t_\beta = 2$



smearing + binning



Significant distortion of distribution; loop corrections to BSM trilinears important.

Momentum effects

[HB,Braathen,Gabelmann,Radchenko,Weiglein,WIP]

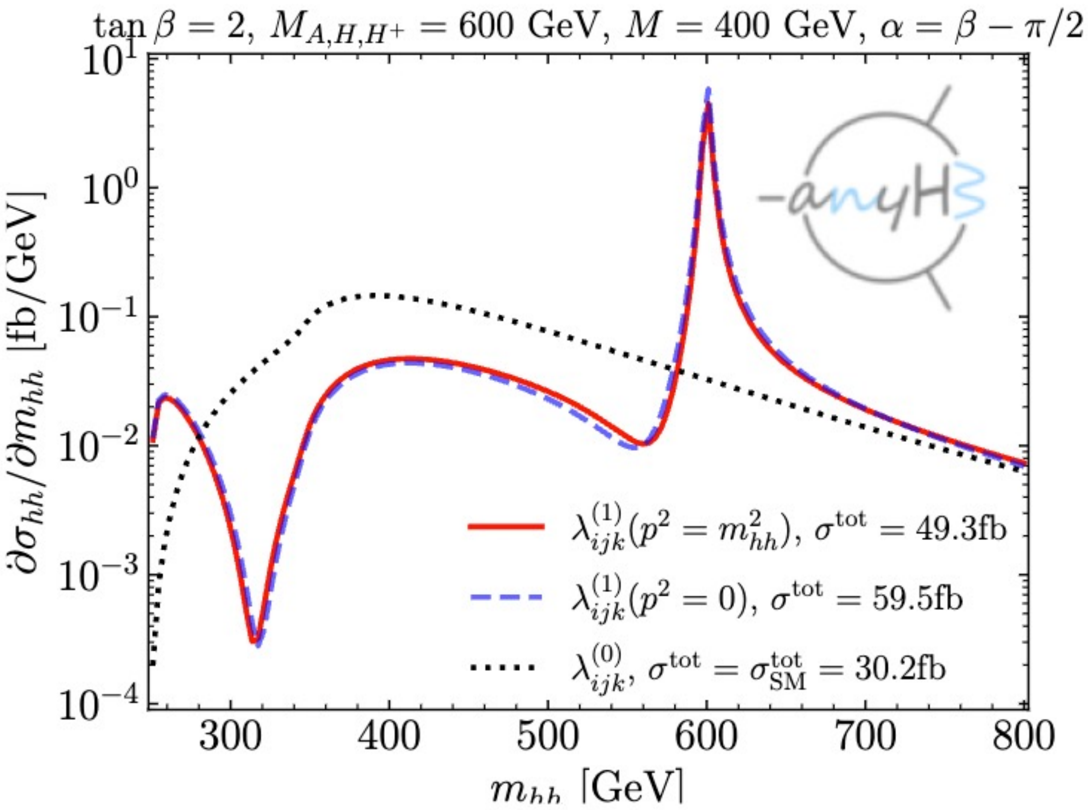
- momentum effects seemingly small

- but large impact on total XS due to p^2-dependence of λ_{hhH}

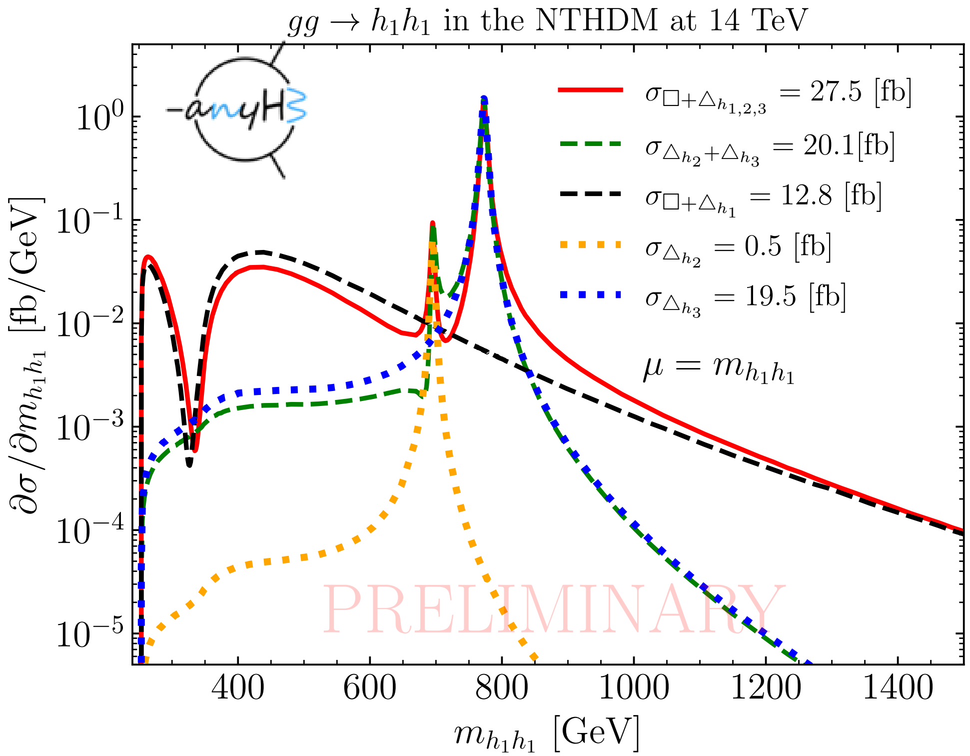
Future improvements:

- link to MC generators

- subleading corrections



Going beyond the 2HDM – multiple resonances



anyHH: automated di-HH results for models without colored BSM states including loop corrected trilinears.

Can we discover BSM first in di-Higgs?

Or are the other Higgs coupling/BSM searches always more sensitive?

Exemplary scenario: SSM ”nightmare” scenario

$$V_{\mathrm{SSM}}(\Phi, S) = V_{\mathrm{SM}}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi$$

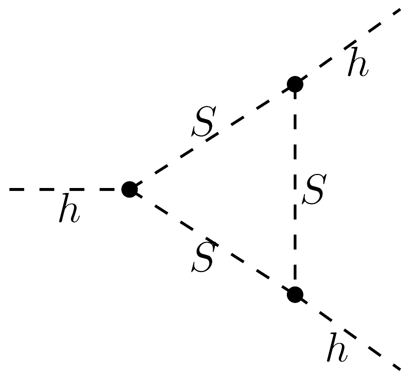
If there is an exact $S \to -S$ symmetry, S does not get a vev.

- No mixing with SM Higgs.
- All Higgs couplings are SM-like at the tree level.
- Also searches very difficult, since S has to be pair produced via the 125 GeV Higgs.

What about loop-level effects on the Higgs couplings?

Case study: Z_2 SSM

$$V(\Phi, S) = V_{\rm SM}(\Phi) + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4!}\lambda_S S^4 + \lambda_{S\Phi} S^2 \Phi^\dagger \Phi$$



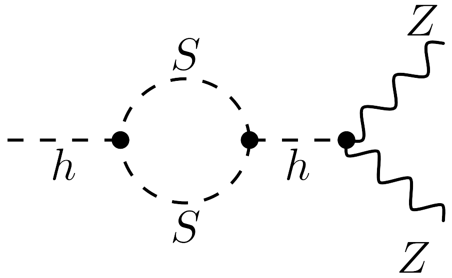
If S does not get a vev, $\lambda_{hhh} = \lambda_{hhh}^{\rm SM}$ at the tree-level ($m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$).

The 1L correction to λ_{hhh} scales like

$$\lambda_{hhh}^{1L} \propto \frac{g_{hSS}^3}{(4\pi)^2} C_0(\ldots) \propto \frac{g_{hSS}^3}{(4\pi)^2}\frac{1}{m_S^2} \propto \frac{1}{(4\pi)^2}\frac{m_S^4}{v^3}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3 \Rightarrow \kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{\rm SM}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^4}{v^4 \lambda_\Phi^{\rm SM}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$$

whereas the dominant correction to other Higgs couplings scale like

$$g^{1L} \propto \frac{g_{hSS}^2}{(4\pi)^2} B_0'(\ldots) \cdot g_{\rm tree} \propto \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2 \Rightarrow c_{\rm eff} \equiv \frac{g}{g^{\rm SM}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

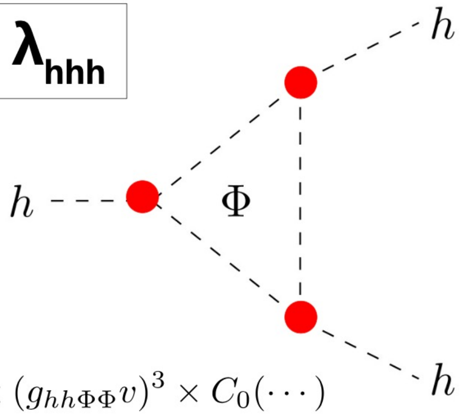


➡ Deviation in λ_{hhh} enhanced by a factor $\frac{m_S^2}{v^2 \lambda_\Phi^{\rm SM}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)$ w.r.t. to other Higgs couplings!

Higgs couplings: power counting

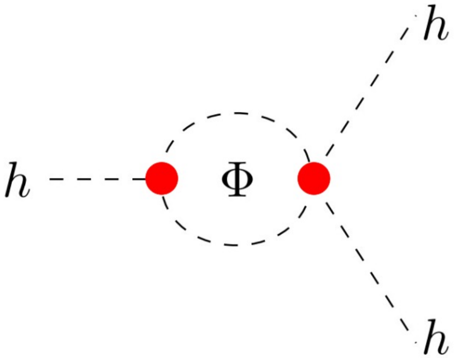
$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2$$

λ_{hhh}



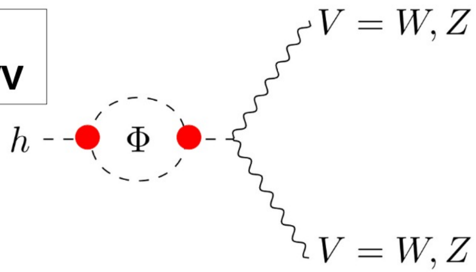
$$\propto (g_{hh\Phi\Phi} v)^3 \times C_0(\cdots)$$

$$\sim \frac{(g_{hh\Phi\Phi} v)^3}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi}^2)$$



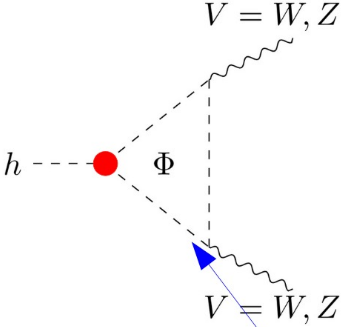
$$\propto g_{hh\Phi\Phi}^2 v \times \underbrace{B_0(\cdots)}_{\text{mass. dim. } 0} \sim \mathcal{O}(g_{hh\Phi\Phi}^2)$$

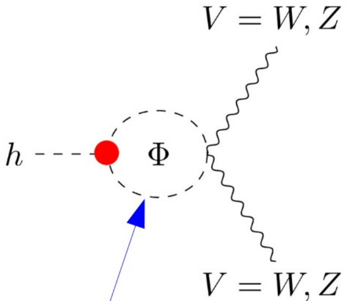
g_{hVV}



$$\propto (g_{hh\Phi\Phi} v)^2 \times g_{\mathrm{EW}} \times B_0'(\cdots)$$

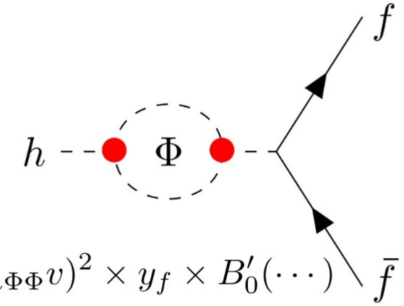
$$\propto \frac{(g_{hh\Phi\Phi} v)^2}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi})$$





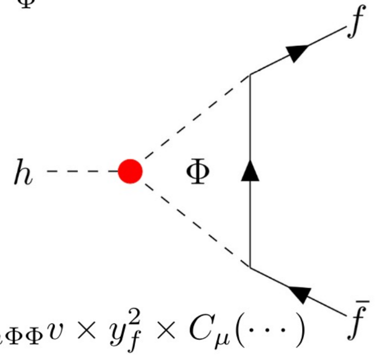
$$\propto g_{hh\Phi\Phi} v \times g_{\mathrm{EW}}^2 \times \underbrace{\{C_{\mu\nu}(\cdots) \text{ or } B_0(\cdots)\}}_{\text{mass. dim. } 0} \sim \mathcal{O}(g_{hh\Phi\Phi})$$

$g_{hf\bar{f}}$



$$\propto (g_{hh\Phi\Phi} v)^2 \times y_f \times B_0'(\cdots)$$

$$\propto \frac{(g_{hh\Phi\Phi} v)^2}{m_\Phi^2} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} \mathcal{O}(g_{hh\Phi\Phi})$$



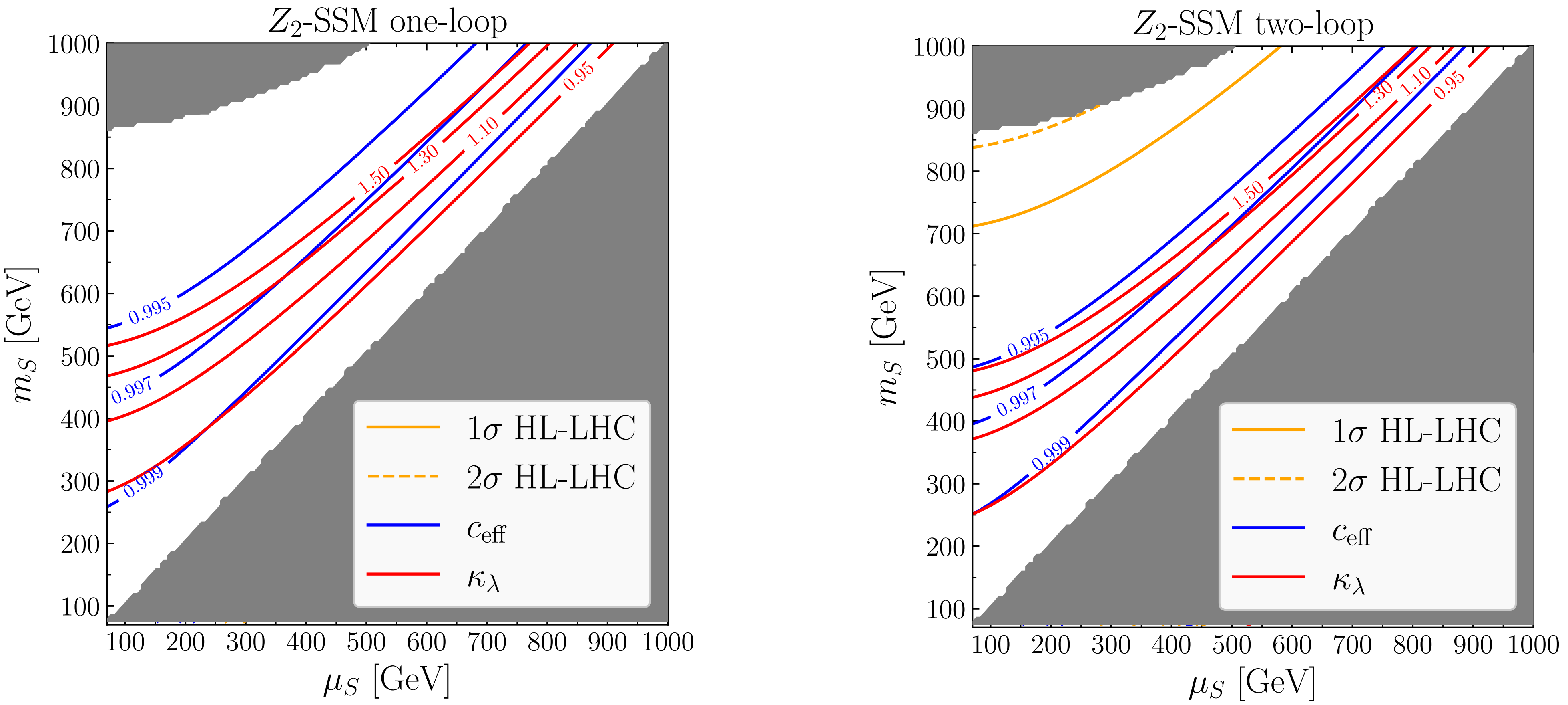
$$\propto g_{hh\Phi\Phi} v \times y_f^2 \times C_\mu(\cdots)$$

$$\sim \frac{g_{hh\Phi\Phi} v}{m_\Phi} \xrightarrow{g_{hh\Phi\Phi} v^2 \gg \mathcal{M}^2} O(g_{hh\Phi\Phi}^{1/2})$$

[overview by J. Braathen]

Z_2 SSM benchmark plane

[HB et al.,WIP]

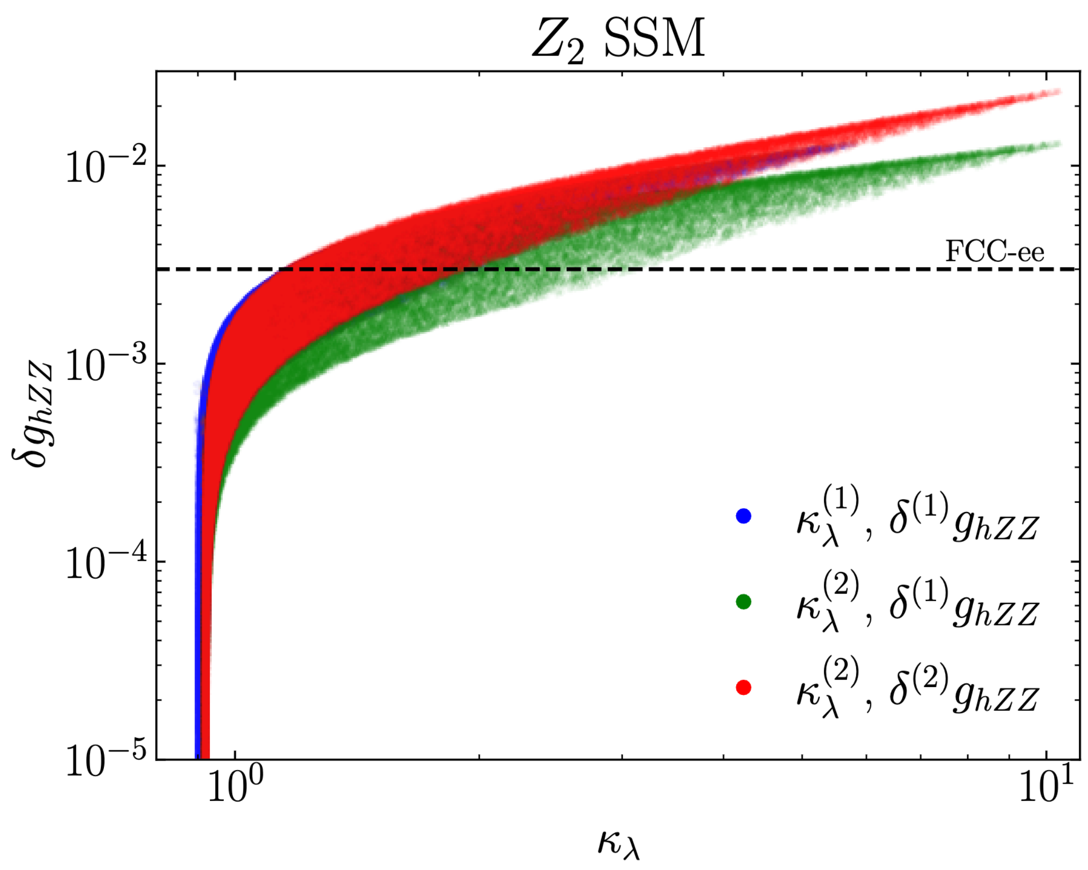


Large deviations in κ_λ possible while other Higgs couplings very SM-like

Parameter scan

[HB et al.,WIP]

Deviation of hZZ coupling w.r.t. SM



- all points pass experimental and theoretical bounds
- $\kappa_\lambda \lesssim 2$ feasible within FCC-ee bounds on δg_{hZZ}
- Projected future collider sensitivity on κ_λ: $\mathcal{O}(10)\%$
- similar results in the other models (i.e., IDM, 2HDM)

Trilinear Higgs coupling can be discovery tool!

Conclusions

Conclusions

- precise determination of λ_{hhh} crucial to probe
  - shape of the Higgs potential
  - nature of EW phase transition
  - search for BSM physics

- radiative corrections in extended Higgs sectors can significantly enhance λ_{hhh} within theoretical and experimental bounds

➡ λ_{hhh} as a new precision probe of BSM parameter space

- loop-corrected trilinear can significantly distort invariant mass spectrum in di-HH

- BSM physics could be found first in λ_{hhh}!

Conclusions

- precise determination of λ_{hhh} crucial to probe
  - shape of the Higgs potential
  - nature of EW phase transition
  - search for BSM physics

- radiative corrections in extended Higgs sectors can significantly enhance λ_{hhh} within theoretical and experimental bounds

➡ λ_{hhh} as a new precision probe of BSM parameter space

- loop-corrected trilinear can significantly distort invariant mass spectrum in di-HH

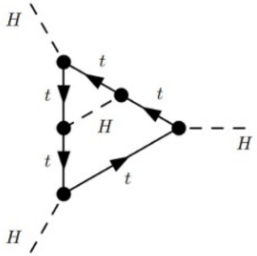
- BSM physics could be found first in λ_{hhh}!

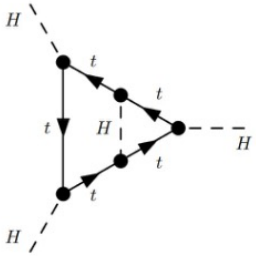
Thanks for your attention!

Appendix

Reduction algorithm

Automating the reduction



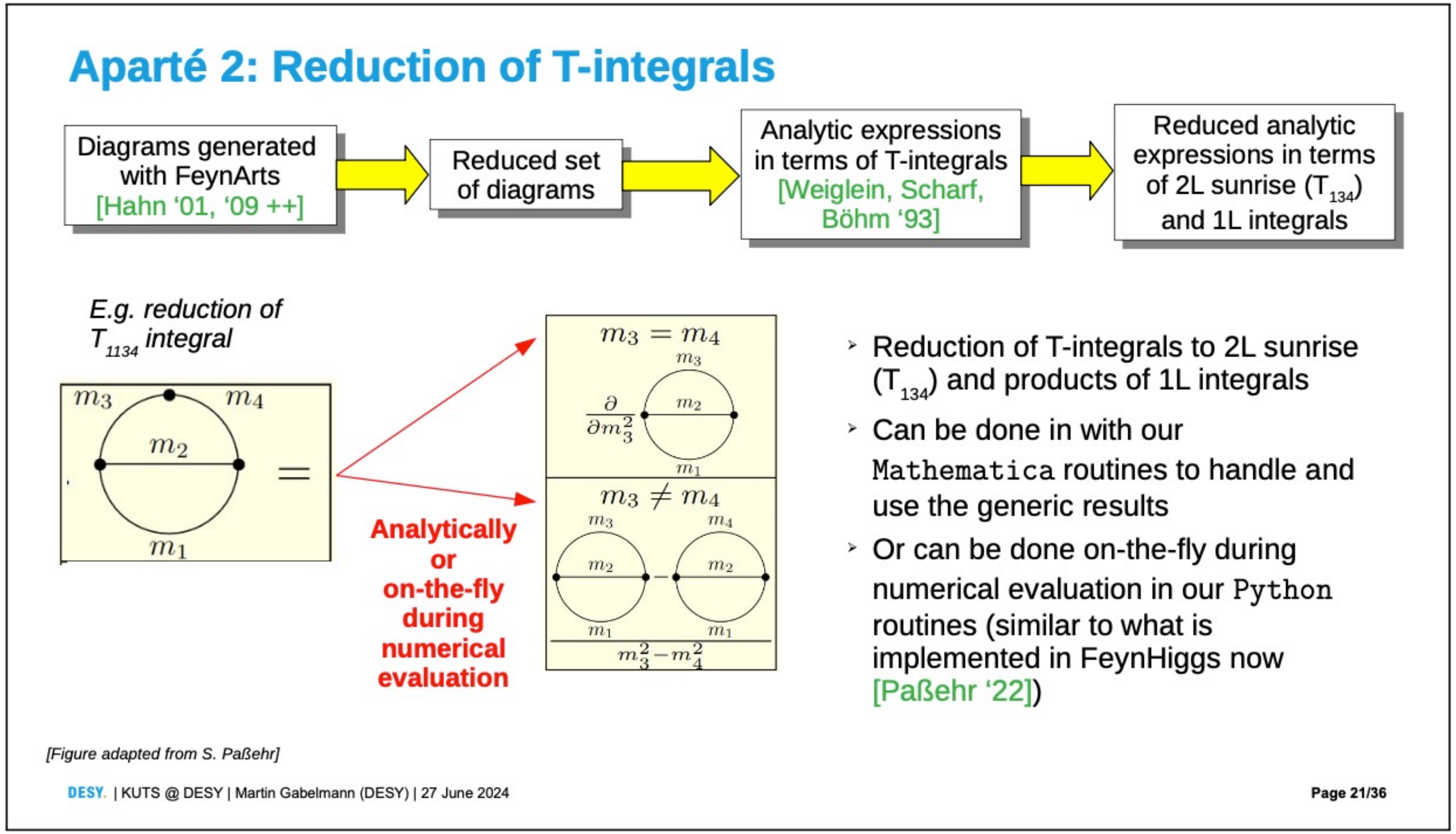



```
edgelist1 = {edge[v[1], v[4],  S[1]], edge[v[2], v[5],  S[1]],
             edge[v[3], v[6],  S[1]], edge[v[4], v[7], -F[3]],
             edge[v[4], v[8],  F[3]], edge[v[5], v[6],  F[3]],
             edge[v[5], v[8], -F[3]], edge[v[6], v[7],  F[3]],
             edge[v[7], v[8],  S[1]]}
edgelist2 = {edge[v[1], v[4],  S[1]], edge[v[2], v[5],  S[1]],
             edge[v[3], v[6],  S[1]], edge[v[4], v[5],  F[3]],
             edge[v[4], v[7], -F[3]], edge[v[5], v[8],  F[3]],
             edge[v[6], v[7],  F[3]], edge[v[6], v[8], -F[3]],
             edge[v[7], v[8],  S[1]]}
```

Unique representation of diagram
→ ”***canonical edges***”
- list of ”edges” (= lines in diagram)
- identical diagrams ↔ permutations of edges
- canonical form = one particular choice of ordering

Reduction algorithm with “canonical edges” in pseudo code:
- identify internal and external indices
- generate permutations of external indices
- generate permutations of internal indices
- combine permutations of internal and external indices
- permute edge list following the combined list of permutations
- sort list of permuted edge lists
- return first element of sorted list of “edge lists”

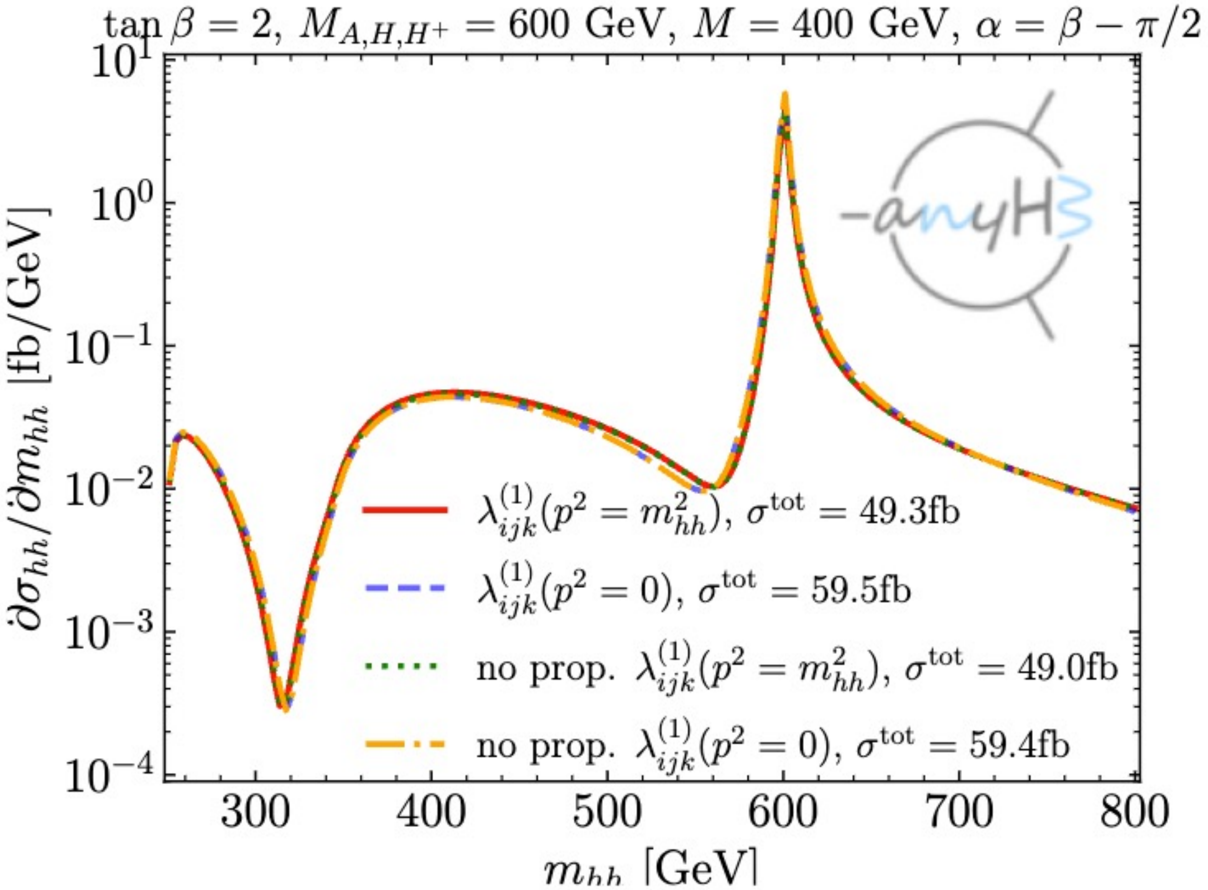
T-integral reduction

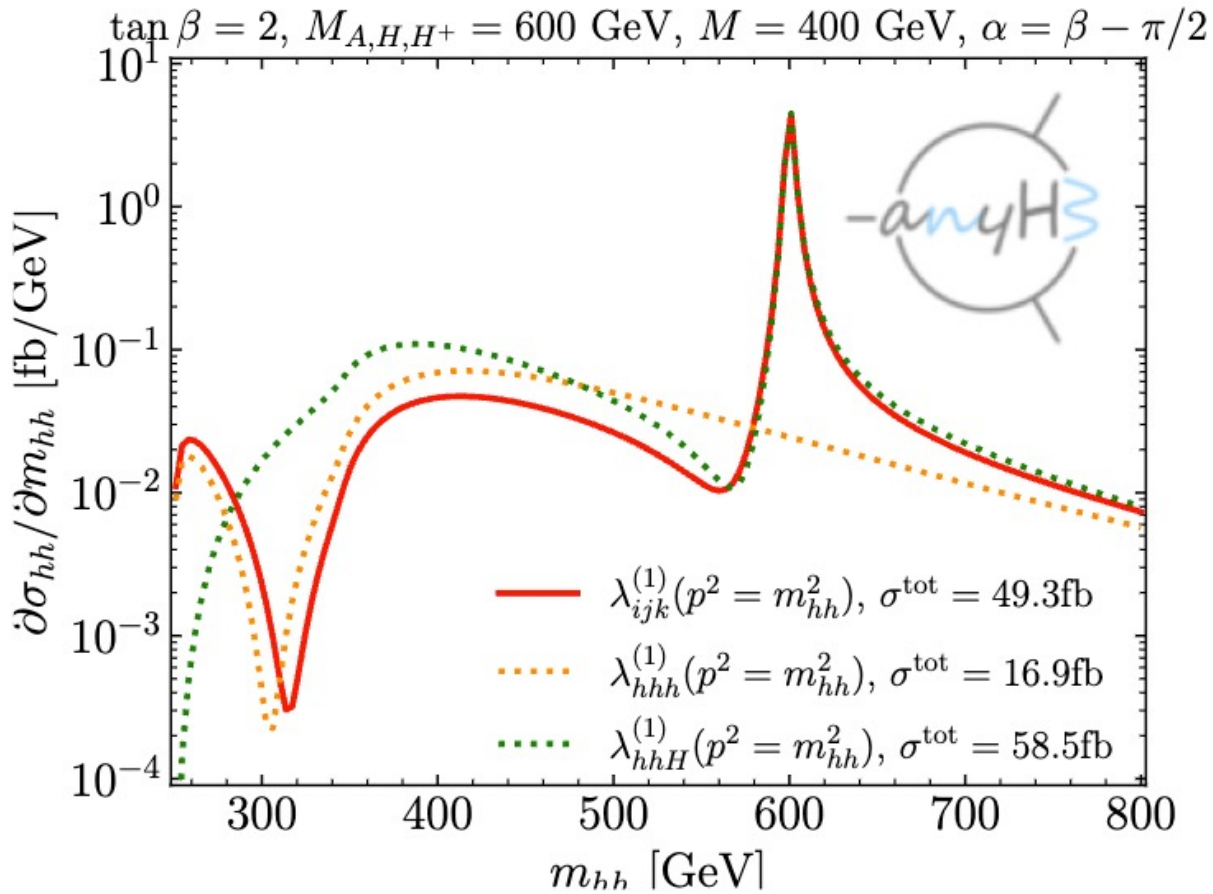


New: release of "Tintegrals"

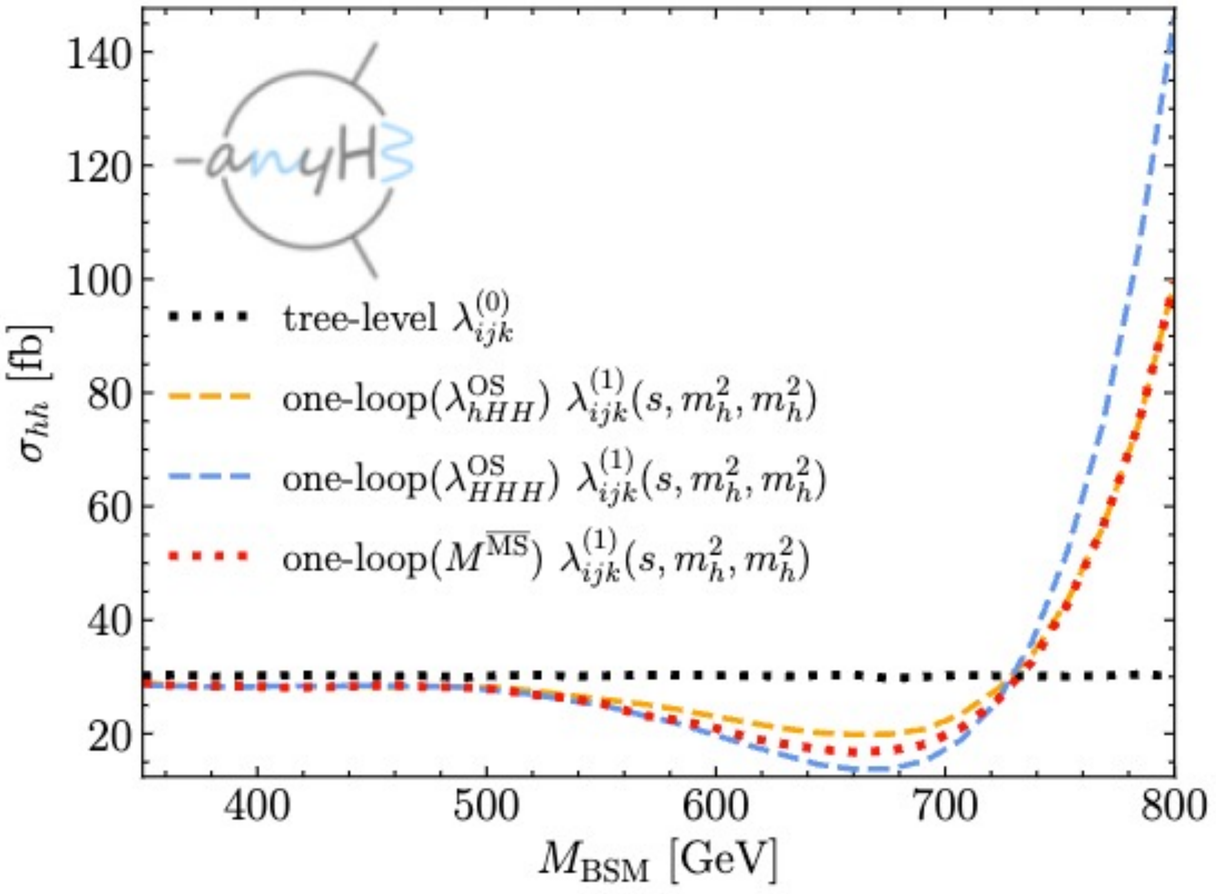
```
pip install Tintegrals
```

```python
import Tintegrals as T
x,y=125.**2,250.**2
T.setMudim(x)
T.T1134fin(x,y,x,y)
T.T1134fin(x,x,y,y)
```

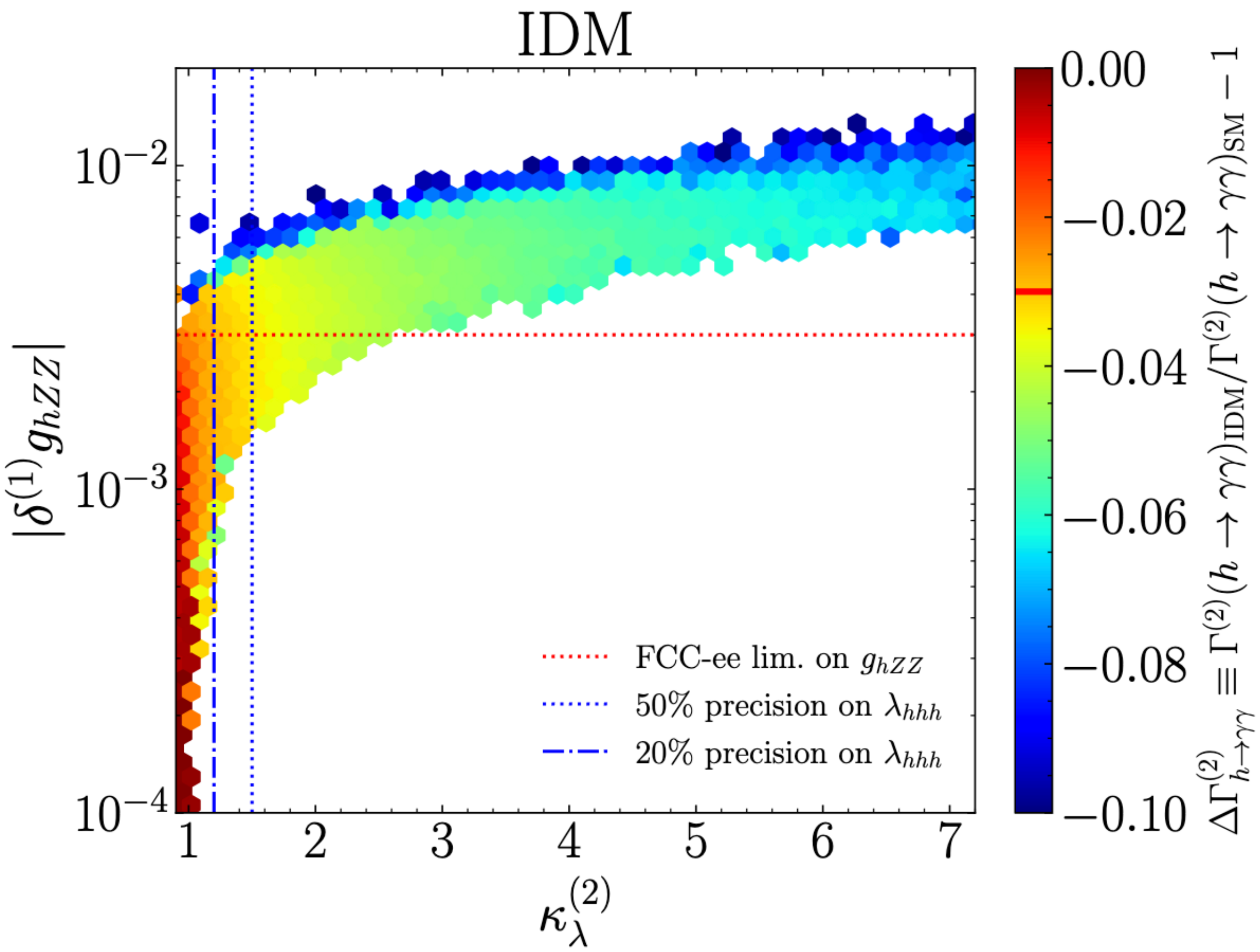

$\tan\beta = 2,\ M_{A,H,H^+} = 600$ GeV, $M = 400$ GeV, $\alpha = \beta - \pi/2$
$\partial\sigma_{hh}/\partial m_{hh}$ [fb/GeV]
m_{hh} [GeV]
$\lambda^{(1)}_{ijk}(p^2 = m^2_{hh})$, $\sigma^{\text{tot}} = 49.3$fb
$\lambda^{(1)}_{ijk}(p^2 = 0)$, $\sigma^{\text{tot}} = 59.5$fb
no prop. $\lambda^{(1)}_{ijk}(p^2 = m^2_{hh})$, $\sigma^{\text{tot}} = 49.0$fb
no prop. $\lambda^{(1)}_{ijk}(p^2 = 0)$, $\sigma^{\text{tot}} = 59.4$fb
anyH3



$\tan\beta = 2,\ M_{A,H,H^+} = 600$ GeV, $M = 400$ GeV, $\alpha = \beta - \pi/2$
$\partial\sigma_{hh}/\partial m_{hh}$ [fb/GeV]
m_{hh} [GeV]
$\lambda^{(1)}_{ijk}(p^2 = m^2_{hh})$, $\sigma^{\mathrm{tot}} = 49.3$fb
$\lambda^{(1)}_{hhh}(p^2 = m^2_{hh})$, $\sigma^{\mathrm{tot}} = 16.9$fb
$\lambda^{(1)}_{hhH}(p^2 = m^2_{hh})$, $\sigma^{\mathrm{tot}} = 58.5$fb
anyH3



140
120
100
80
60
40
20
400
500
600
700
800
σ_{hh} [fb]
M_{BSM} [GeV]
tree-level $\lambda_{ijk}^{(0)}$
one-loop($\lambda_{hHH}^{\mathrm{OS}}$) $\lambda_{ijk}^{(1)}(s, m_h^2, m_h^2)$
one-loop($\lambda_{HHH}^{\mathrm{OS}}$) $\lambda_{ijk}^{(1)}(s, m_h^2, m_h^2)$
one-loop($M^{\overline{\mathrm{MS}}}$) $\lambda_{ijk}^{(1)}(s, m_h^2, m_h^2)$


IDM
10^{-2}
10^{-3}
10^{-4}
$|\delta^{(1)} g_{hZZ}|$
1
2
3
4
5
6
7
$\kappa_\lambda^{(2)}$
FCC-ee lim. on g_{hZZ}
50% precision on λ_{hhh}
20% precision on λ_{hhh}
0.00
−0.02
−0.04
−0.06
−0.08
−0.10
$\Delta\Gamma^{(2)}_{h\to\gamma\gamma} \equiv \Gamma^{(2)}(h\to\gamma\gamma)_{\mathrm{IDM}}/\Gamma^{(2)}(h\to\gamma\gamma)_{\mathrm{SM}} - 1$