Precise predictions for the trilinear Higgs coupling in arbitrary models with anyH3

Based on
Eur.Phys.J.C 83 (2023) 12, 1156 [arXiv:2305.03015]
in collaboration with Henning Bahl, Martin Gabelmann and Georg Weiglein

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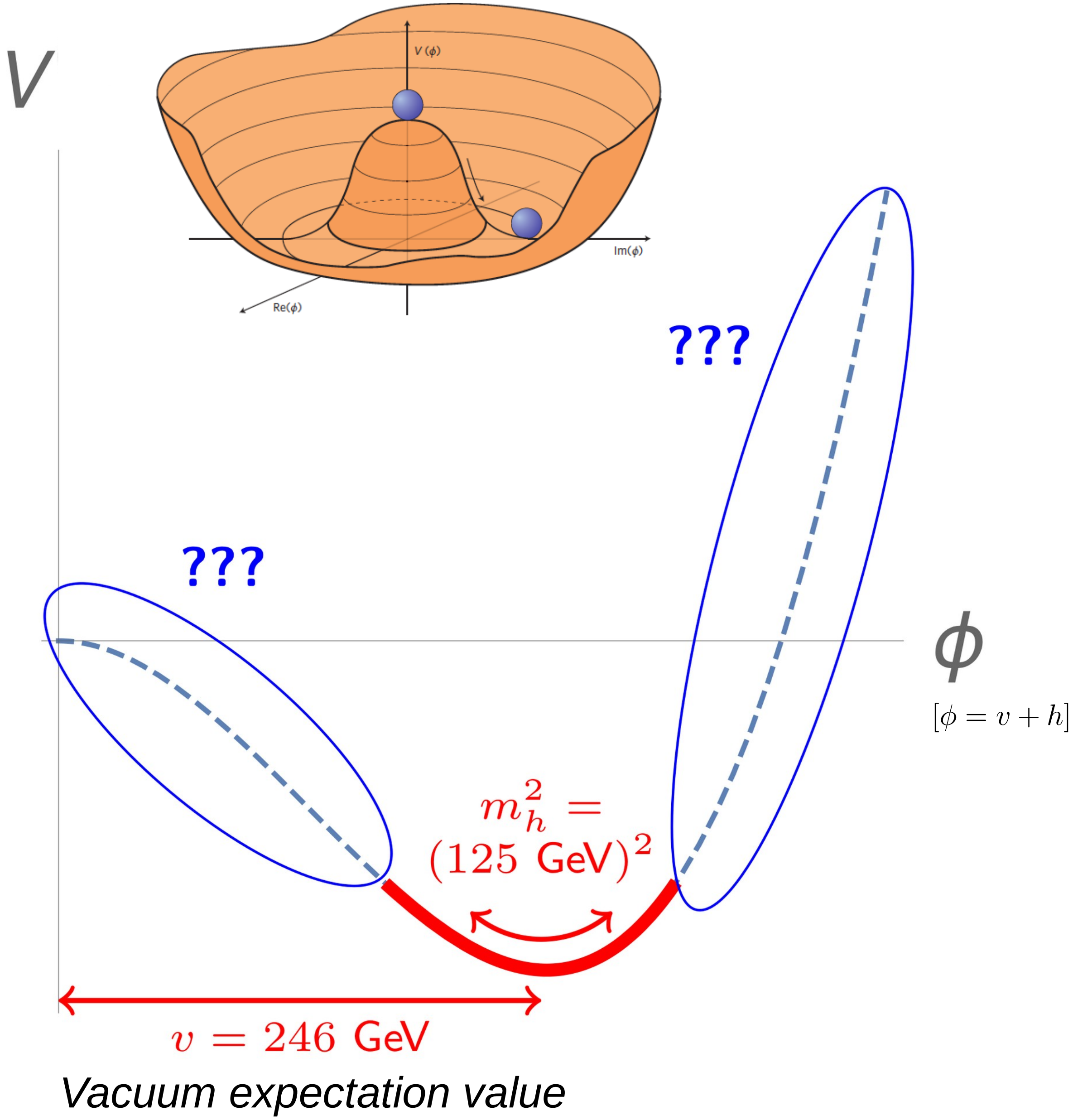
Rencontres de Physique des Particules 2024
Sorbonne Université, Paris, France | 26 January 2024

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft
DESY.
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DESY.

Why investigate λ_{hhh} ?

Form of the Higgs potential and trilinear Higgs coupling

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition



Form of the Higgs potential and trilinear Higgs coupling

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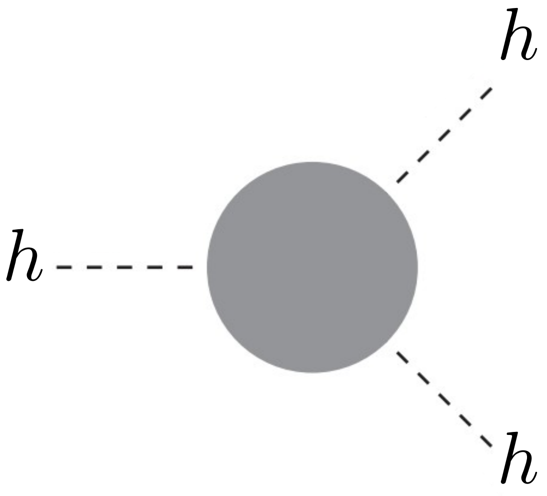
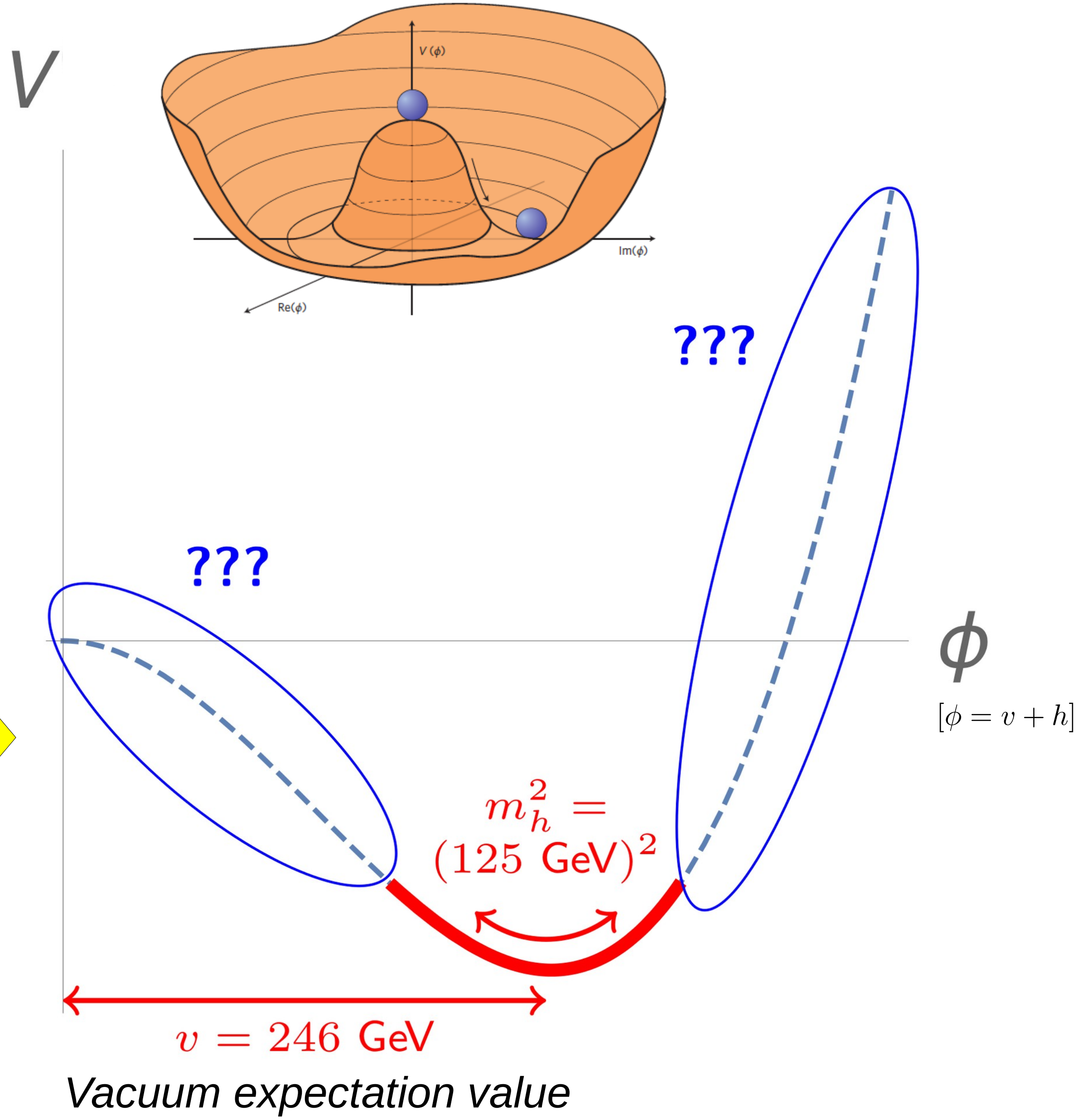
- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**



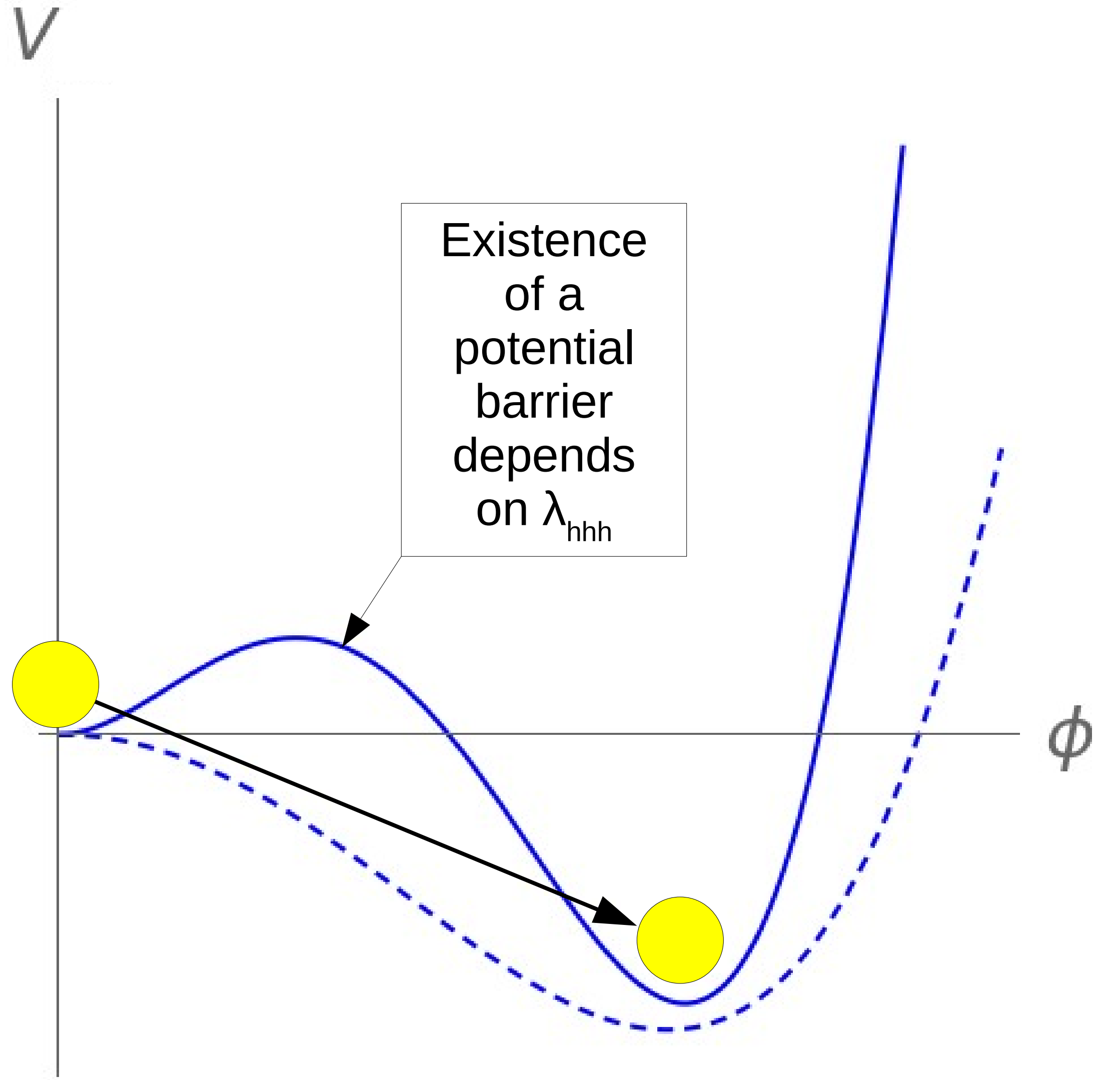


Form of the Higgs potential and baryon asymmetry

- Brout-Englert-Higgs mechanism = **origin of electroweak symmetry breaking** ...
  … but very little known about the **Higgs potential** causing the phase transition

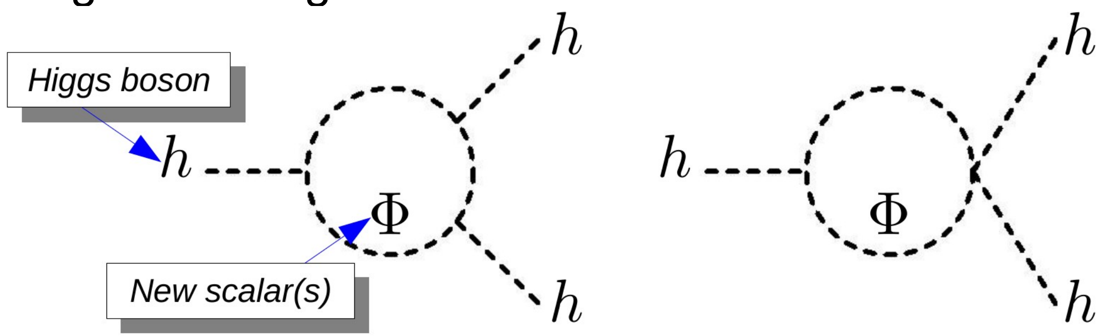
- Shape of the potential determined by **trilinear Higgs coupling λ_{hhh}**

- Among **Sakharov conditions** necessary to explain **baryon asymmetry via electroweak phase transition** (EWPT):
  - ***Strong first-order EWPT***
    → barrier in Higgs potential
    → typically significant deviation in λ_{hhh} from SM



Probing New Physics with the trilinear Higgs coupling

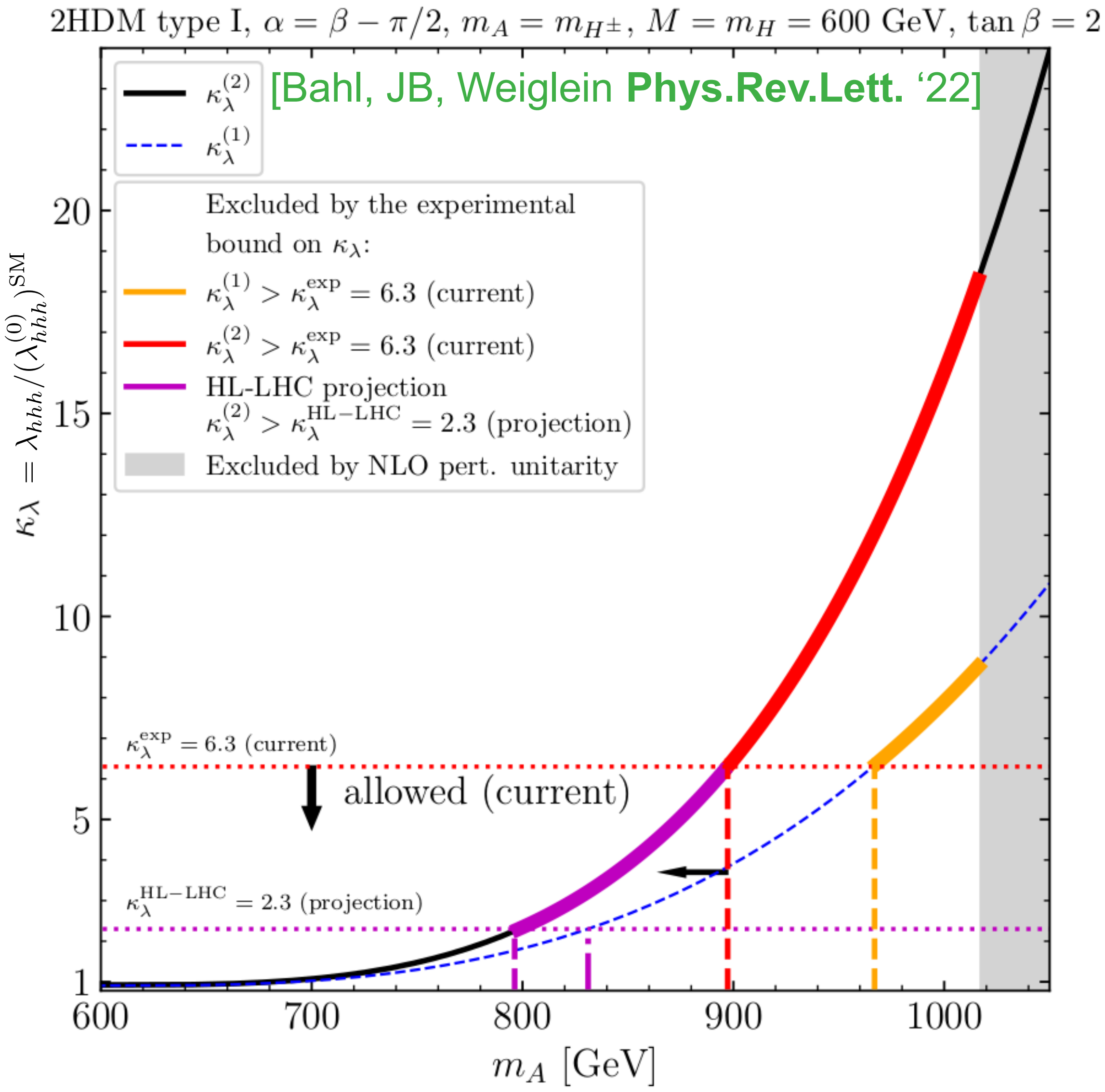
- **Large effects from New Physics possible in λ_{hhh},** due to radiative corrections from extra scalars, e.g. at leading order



- Comparing latest exp. bounds

$$-0.4 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}} < 6.3$$

[ATLAS PLB 2023]
with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models**
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



Computing λ_{hhh} in BSM theories

- Calculations of λ_{hhh} are important, and receive increasing attention
  - More and more model specific results at 1L

    SM + singlet [Kanemura et al. '16]; ***2HDMs*** [Kanemura et al. '04], [Basler et al. '17]; ***N2HDM (2HDM + singlet)*** [Basler et al. '19]; ***triplet extensions*** [Aoki et al. '12], [Chiang et al. '18]; ***MSSM*** [Hollik, Penaranda '04]; ***NMSSM*** [Dao et al. '13]; ***models with classical scale invariance*** [Hashino, Kanemura, Orikasa '16], etc.

    … and at 2L

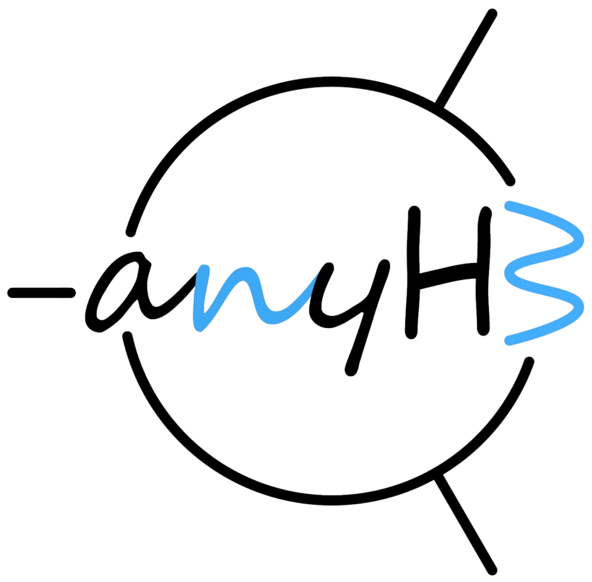
    SM + singlet [JB, Kanemura '19]; ***2HDMs*** [Senaha '18], [JB, Kanemura '19]; ***MSSM*** [Brucherseifer et al. '13]; ***NMSSM*** [Dao et al. '15], [Borschensky et al '22] ; ***models with classical scale invariance*** [JB, Kanemura, Shimoda '20], etc.

    but many more models to investigate!

- For many (pseudo-)observables, automated tools exist
  (e.g. micrOMEGAs for DM observables → c.f. talk of Andreas Goudelis on Wednesday)

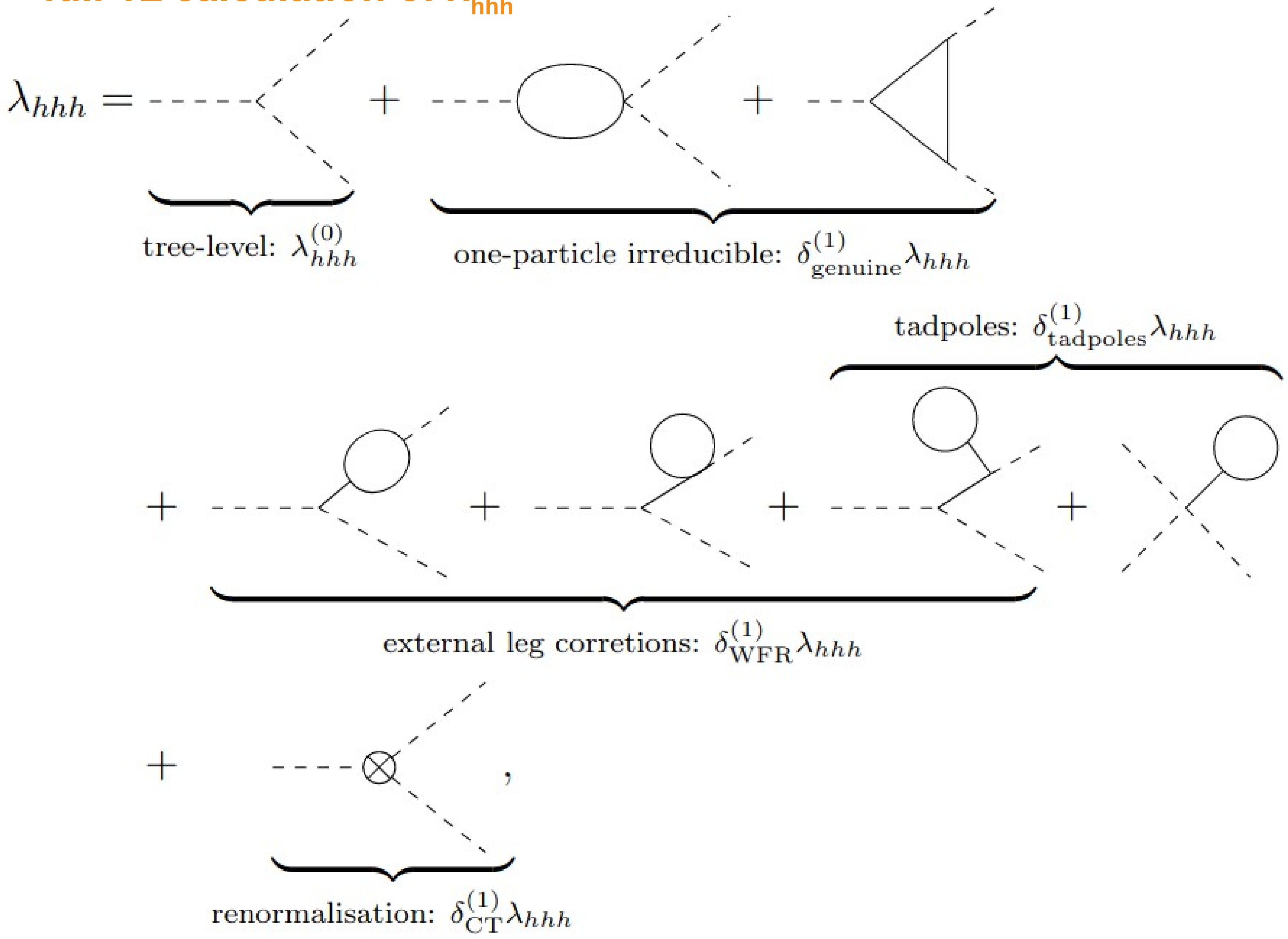
- What about for the trilinear Higgs coupling?
  → none so far
  → `anyH3` [Bahl, JB, Gabelmann, Weiglein `2305.03015`]

Generic predictions for λ_{hhh}



Computing λ_{hhh} in general renormalisable theories: ingredients

anyH3 → full 1L calculation of λ_{hhh}

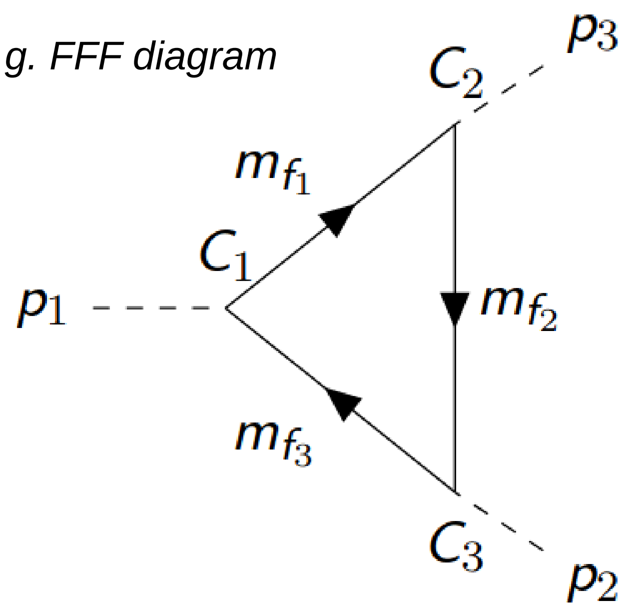


- Solid lines:
  - *scalars,*
  - *fermions,*
  - *gauge/vector bosons,*
  - *ghosts*
- Restrictions on particles and/or topologies possible

Computing λ_{hhh} in general renormalisable theories: method

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

e.g. FFF diagram



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

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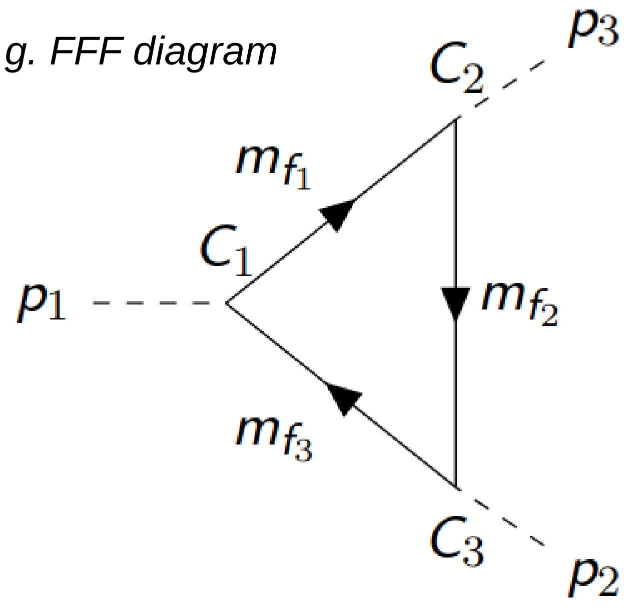

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- Masses on the internal lines m_{f_i}, i=1,2,3
- External momenta p_i, i=1,2,3

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

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

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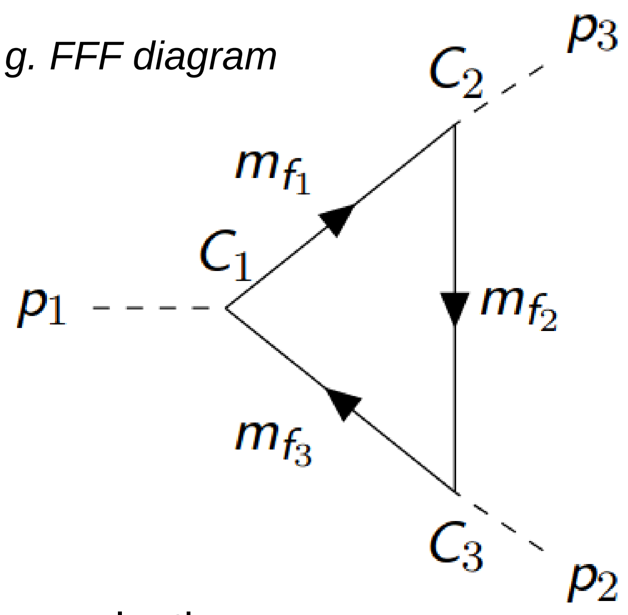
e.g. FFF diagram



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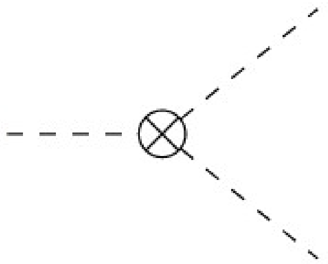
$$= 2\mathbf{B0}(p_3^2, m_2^2, m_3^2)(C_1^L(C_2^L C_3^R m_{f_1} + C_2^R C_3^R m_{f_2} + C_2^R C_3^L m_{f_3}) + C_1^R(C_2^R C_3^L m_{f_1} + C_2^L C_3^L m_{f_2} + C_2^L C_3^R m_{f_3})) + m_{f_1}\mathbf{C0}(p_2^2, p_3^2, p_1^2, m_1^2, m_3^2, m_2^2)((C_1^L C_2^L C_3^R + C_1^R C_2^R C_3^L)(p_1^2 + p_2^2 -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

For evaluation:

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

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

Flexible choice of renormalisation schemes

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

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

- In general:

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

- Most automated codes: $\overline{\text{MS}}/\overline{\text{DR}}$ only

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

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

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

Example results from anyH3

A cross-check: the decoupling limit

- Consider the decoupling limit in several BSM models

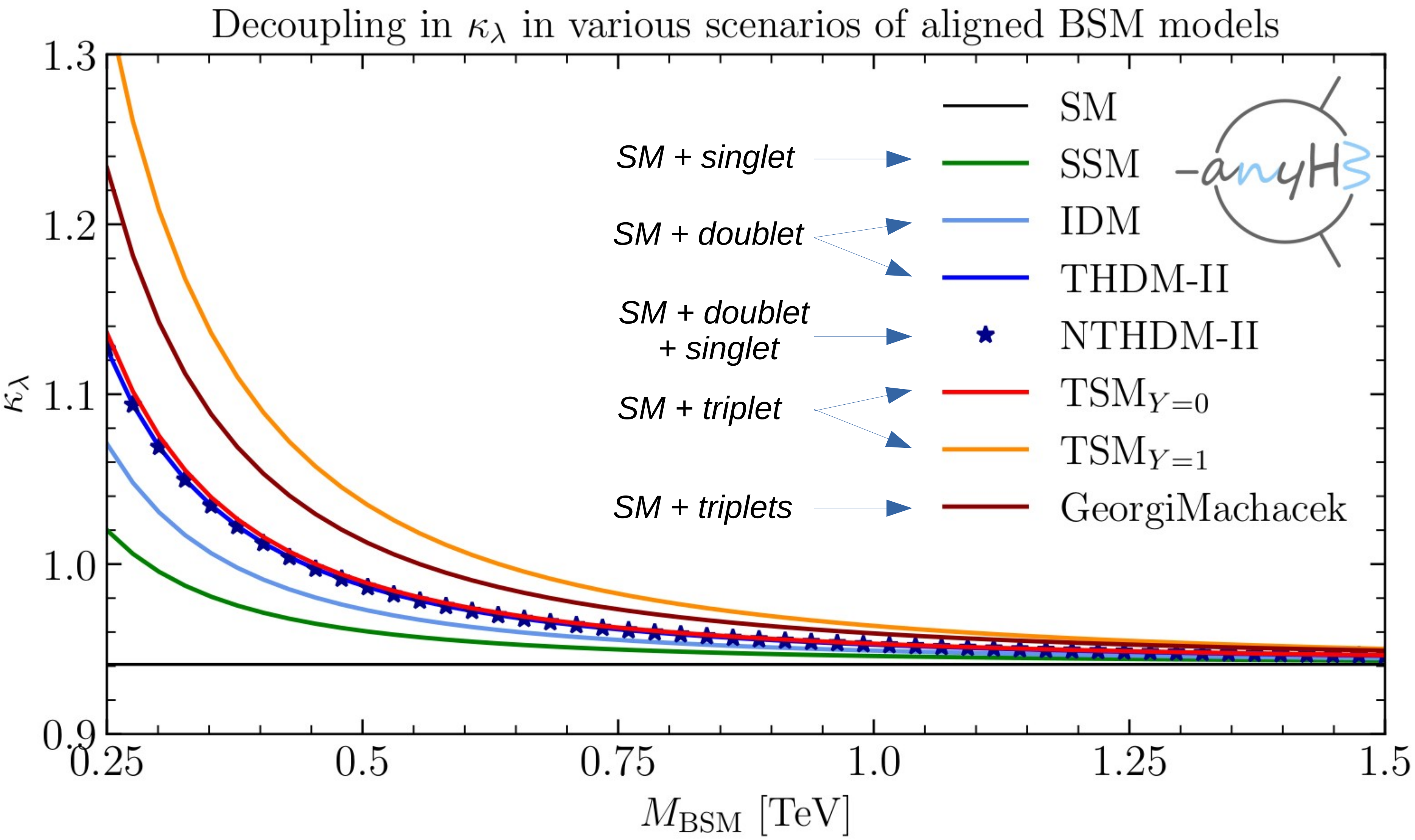
$$M^2_{\text{BSM}} = \mathcal{M}^2 + \tilde{\lambda} v^2$$

$\mathcal{M}$: BSM mass scale
$\tilde{\lambda}$: Quartic couplings

- Increase BSM mass scale

$$\mathcal{M} \to \infty$$

- BSM corrections to should vanish (c.f. decoupling theorem [Appelquist, Carrazone '75])



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

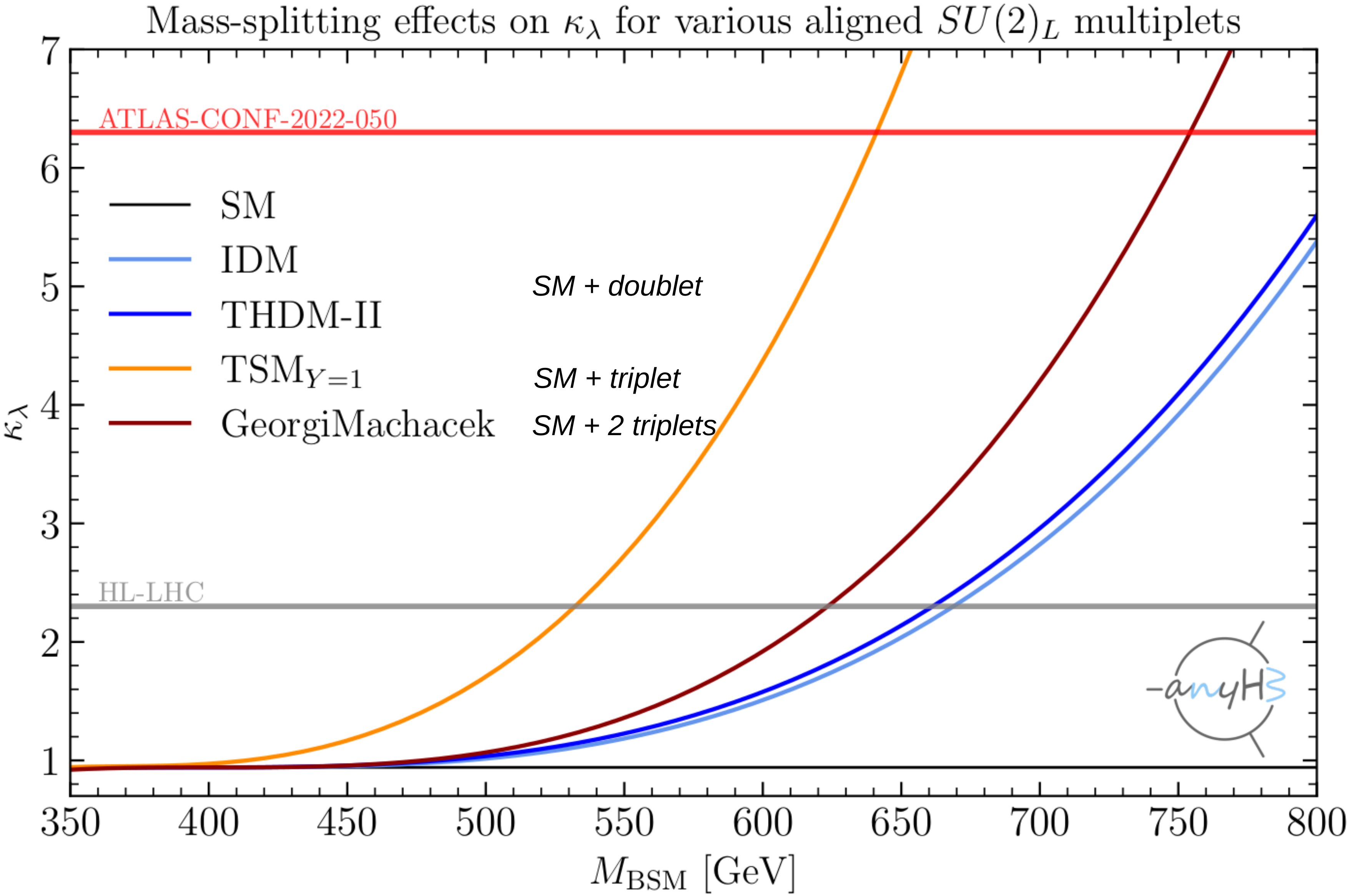
- Consider the non-decoupling limit in several BSM models

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

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

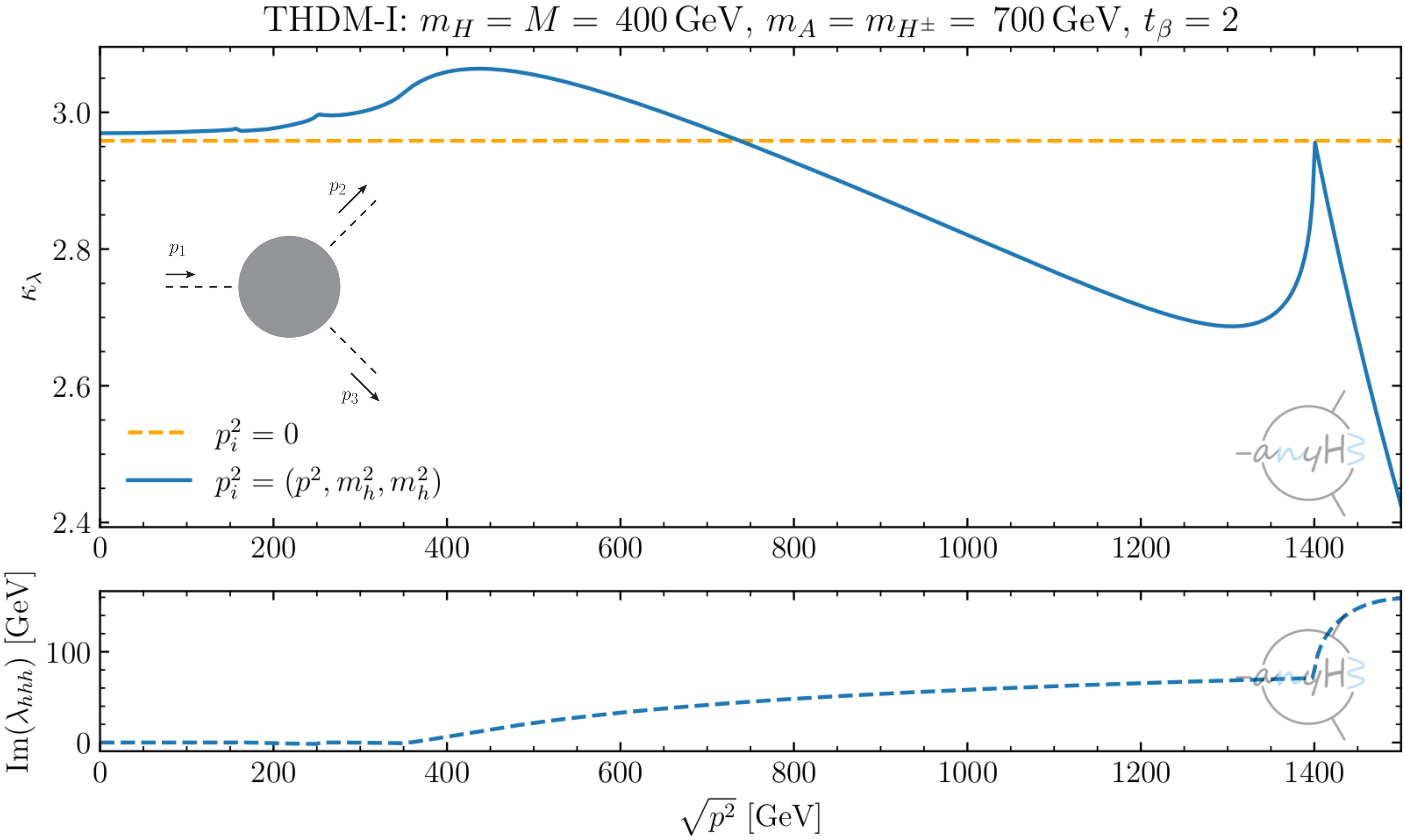
- Perturbative unitarity checked with `anyPerturbativeUnitarity`

- **Constraints on BSM parameter space!**



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

New results II: momentum dependence in the 2HDM



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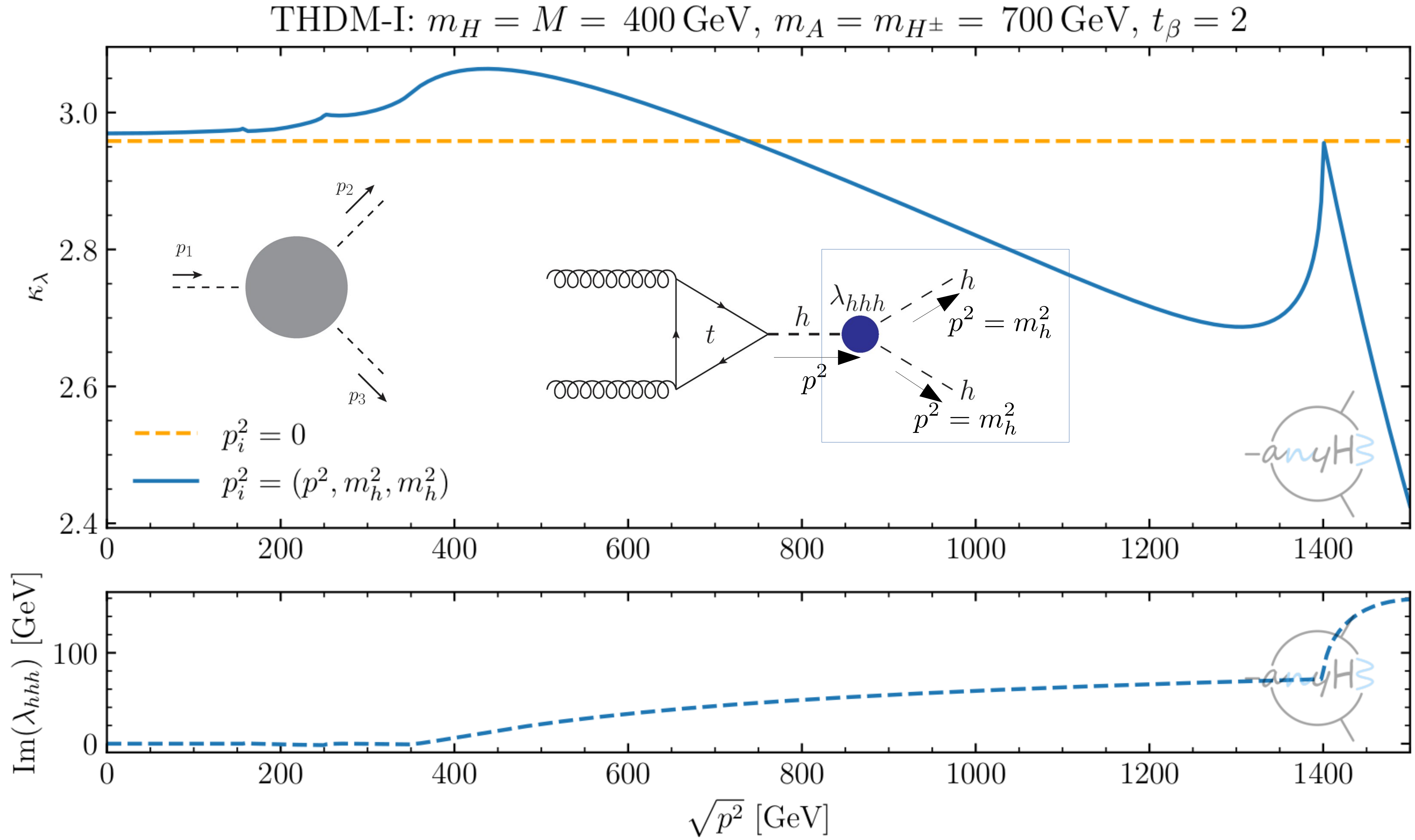

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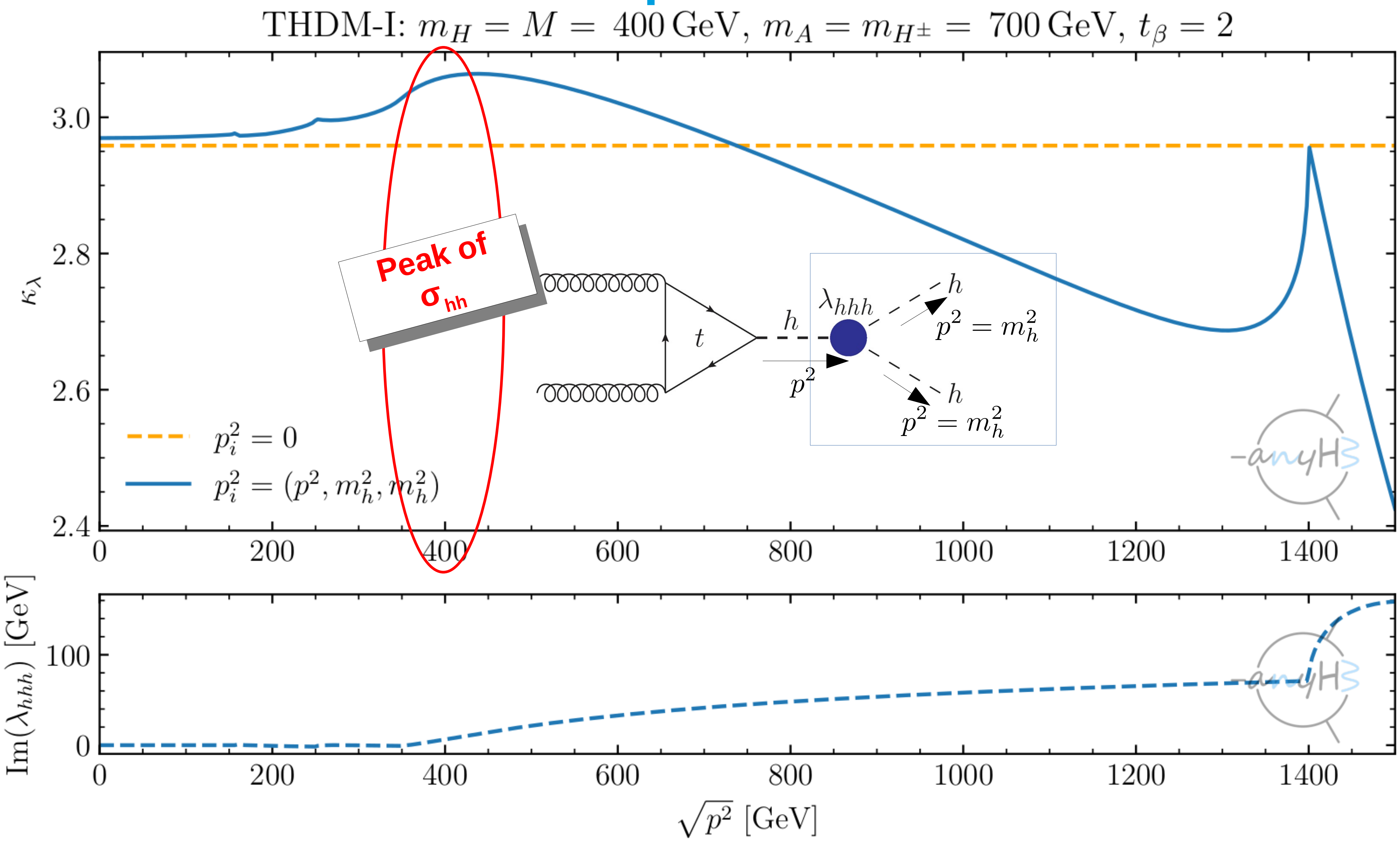
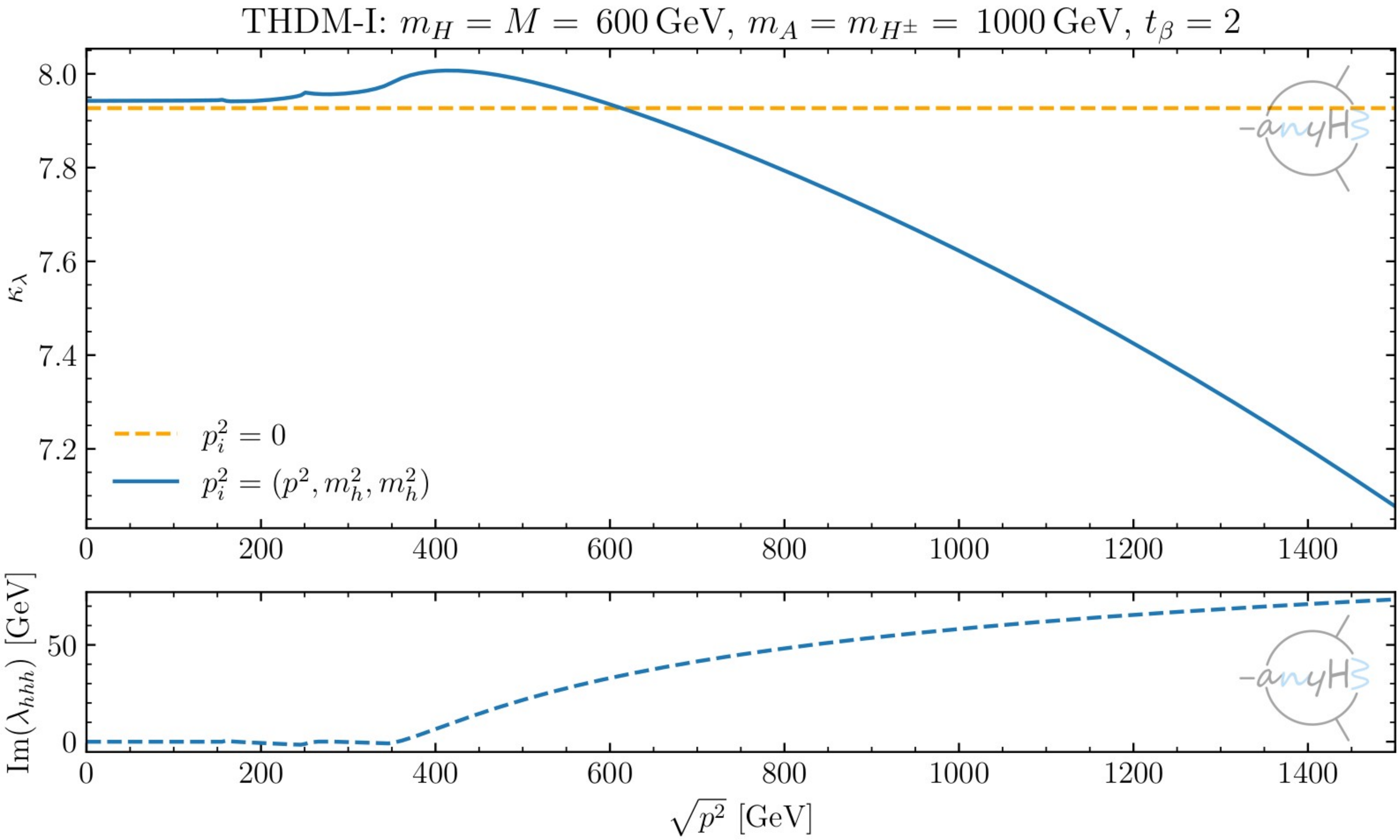
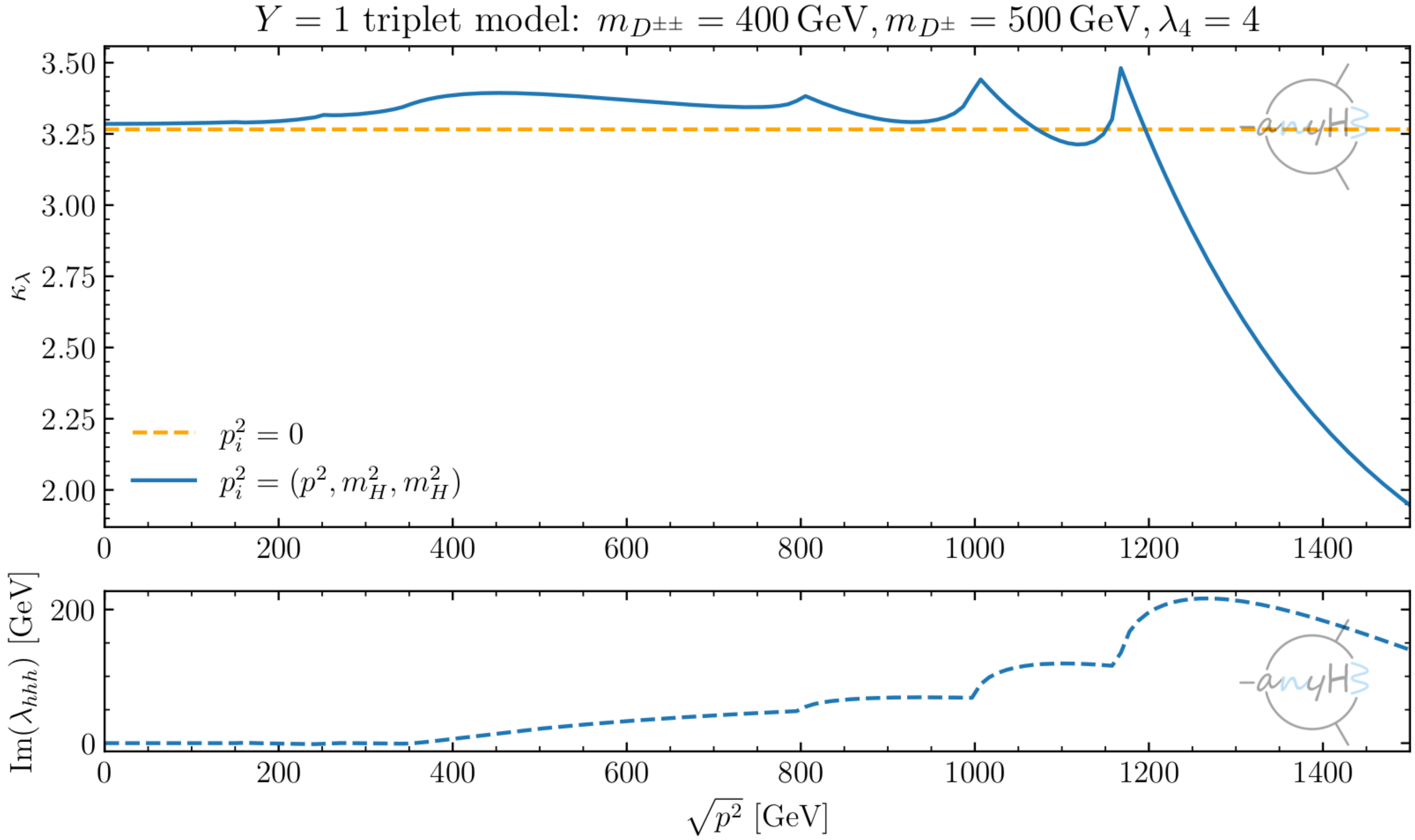


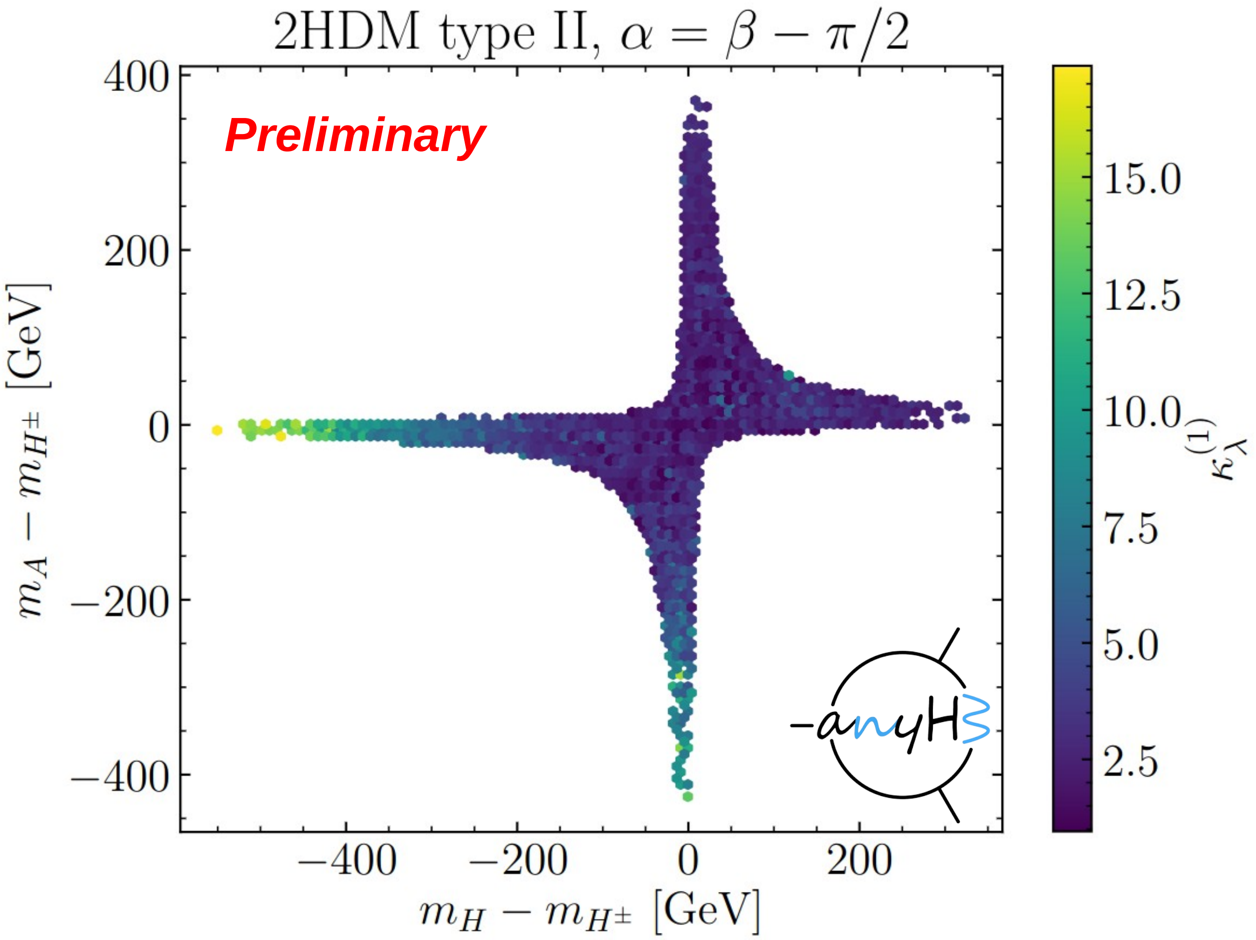
New results II’: momentum dependence in the 2HDM

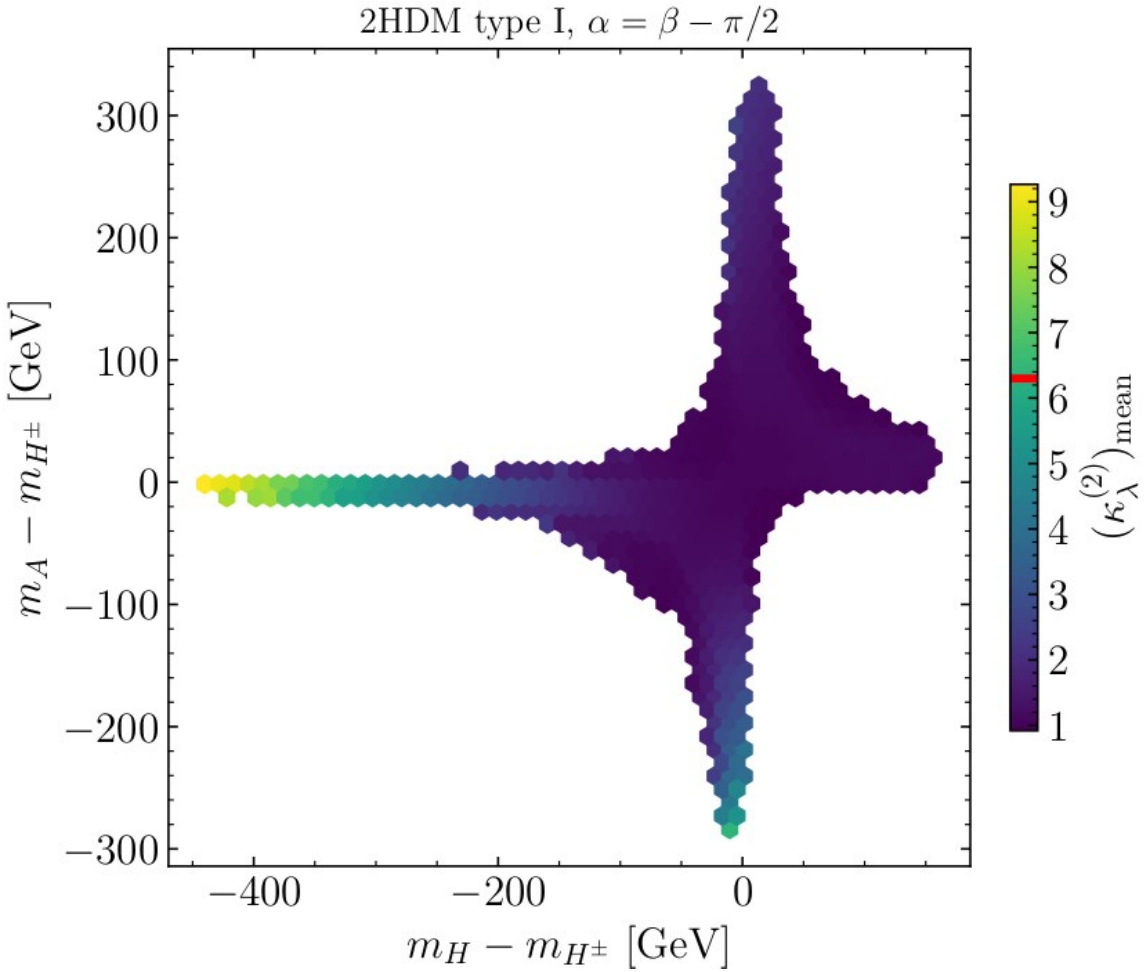


New results III: momentum dependence in a Y=1 triplet extension



New results IV: parameter scans including λ_{hhh}

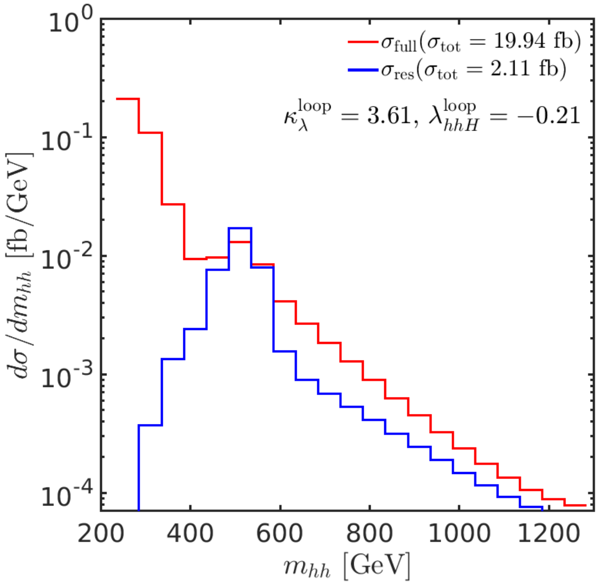




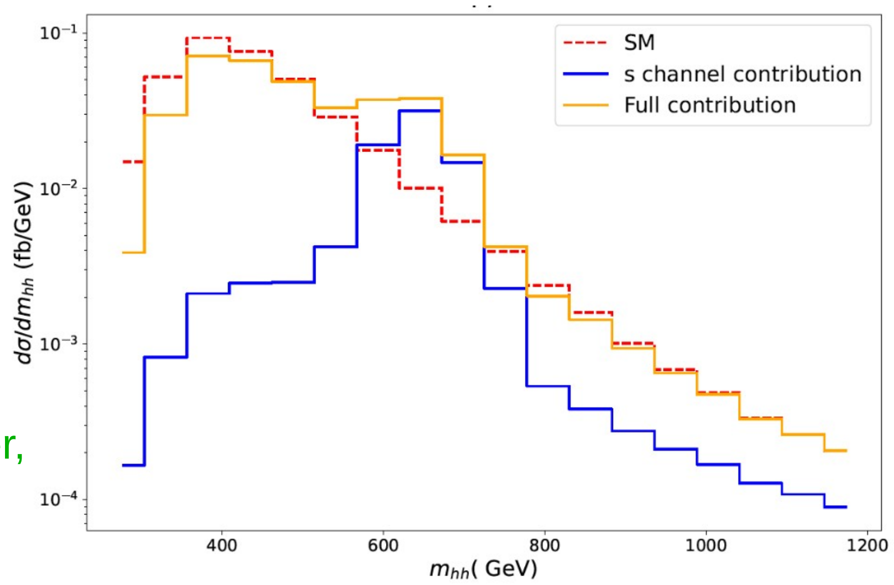
- Scan with anyH3, linked to scanning tool BSMArt [Goodsell, Joury '23] – preliminary results from [Bosse, JB, Gabelmann, Hannig, Weiglein *WIP*] using active learning

- Scan with ScannerS [Mühlleitner et al. '20] + 2L results for κ_λ from [JB, Kanemura '19]

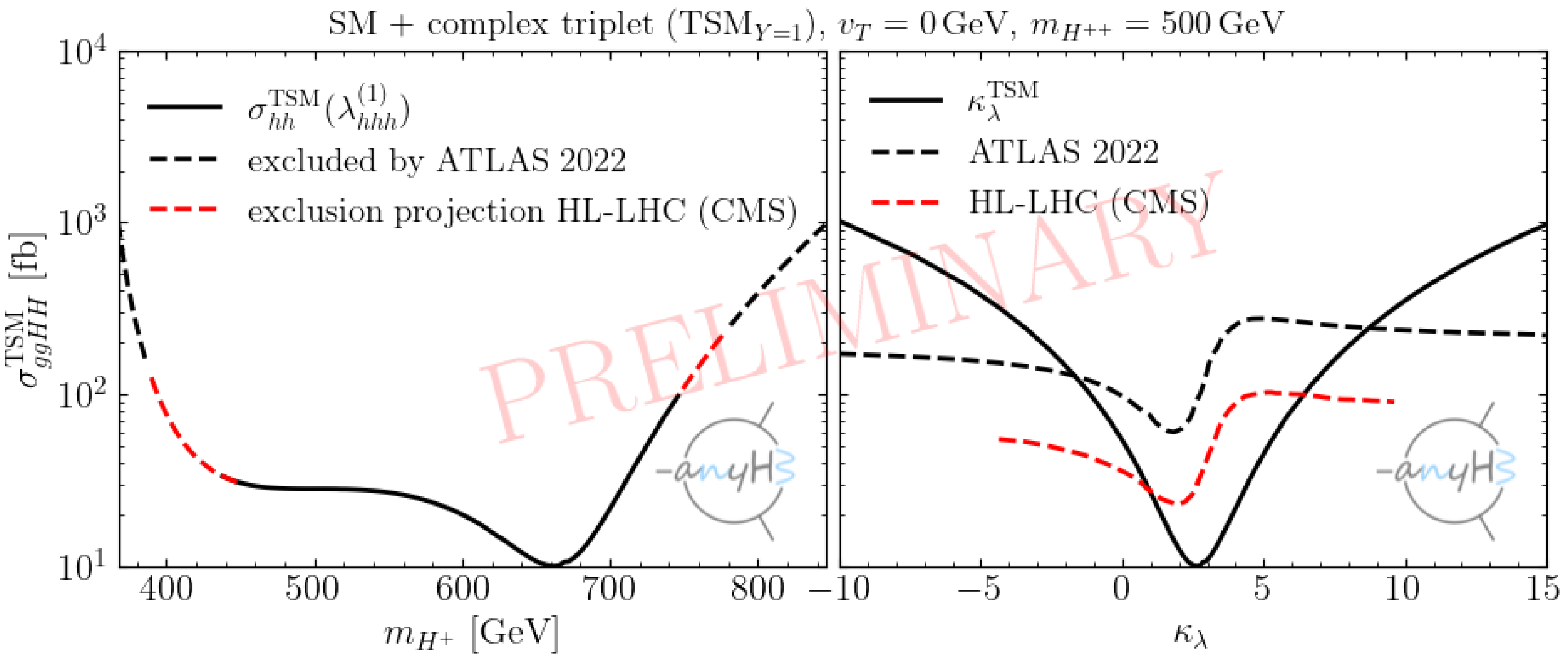
Ongoing developments in anyBSM



Left: 2HDM
[Heinemeyer, Mühlleitner, Radchenko Serdula, Weiglein *WIP*]
plot from talk of K. Radchenko Serdula at 20th LHC Higgs WG workshop



Right: singlet extension
[Arco, Heinemeyer, Mühlleitner, Rivero, Verduras *WIP*]
→ **c.f talk by Alain Verduras**



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

→ new module in anyBSM

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

Summary

- λ_{hhh} plays a crucial role to understand the **shape of the Higgs potential**, and probe indirectly **signs of New Physics**
- **Python package `anyH3` allows calculation of λ_{hhh} for arbitrary renormalisable theories** with
  - Full 1L effects including p^2 dependence
  - Highly flexible choices of renormalisation schemes → predefined or by user
- Uses **UFO** model inputs (generated with SARAH, FeynRules or using custom ones)
- Analytical results (Python, Mathematica)
- Fast numerical results (with caching): SM → O(0.2s); MSSM → O(0.5s)
- Part of wider **anyBSM framework**, under development
- Currently 14 models included, easy inclusion of further models → **new ideas/requests welcome!**

Get started at https://anybsm.gitlab.io/
or directly in terminal with
`pip install anyBSM` **&** `anyBSM --help` **!**

Thank you very much for your attention!

Contact

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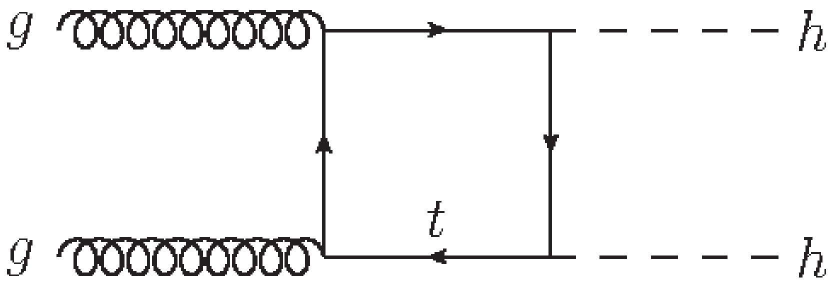
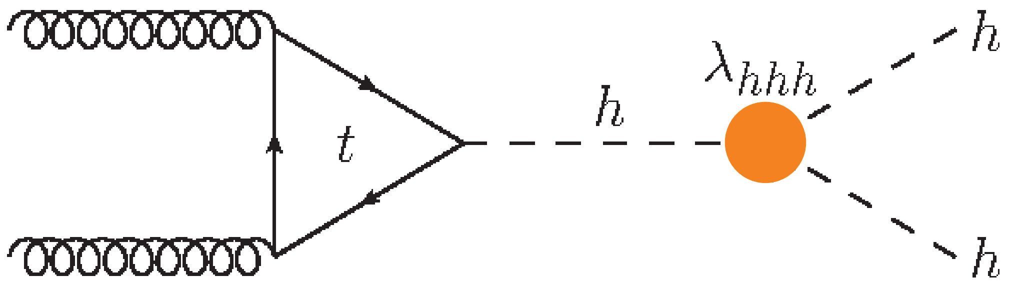
Backup

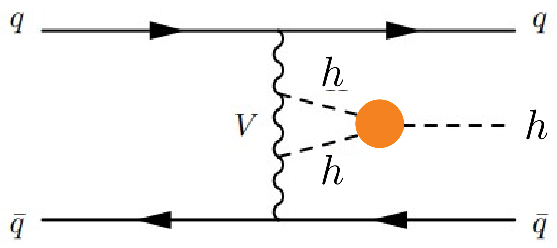
Experimental probes of λ_{hhh}

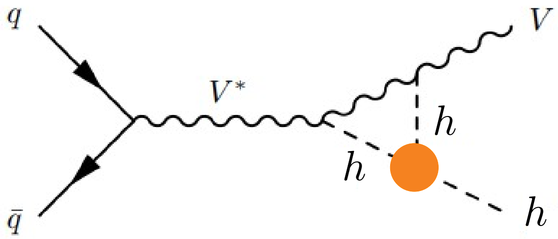
- **Double-Higgs production** → λ_{hhh} enters at <u>leading order (LO)</u> → **most direct probe!**

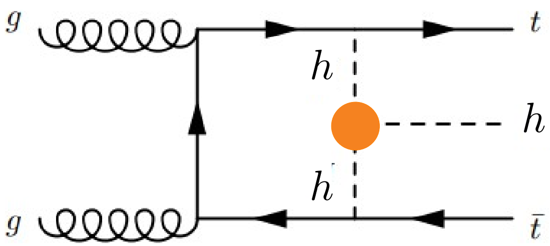


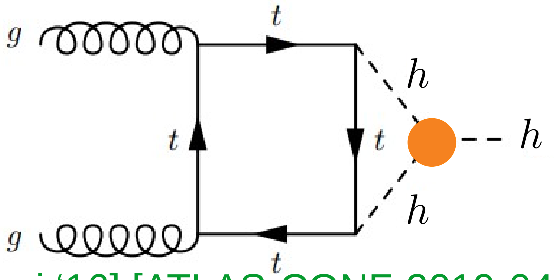


- **Single-Higgs production** → λ_{hhh} enters at <u>NLO</u>



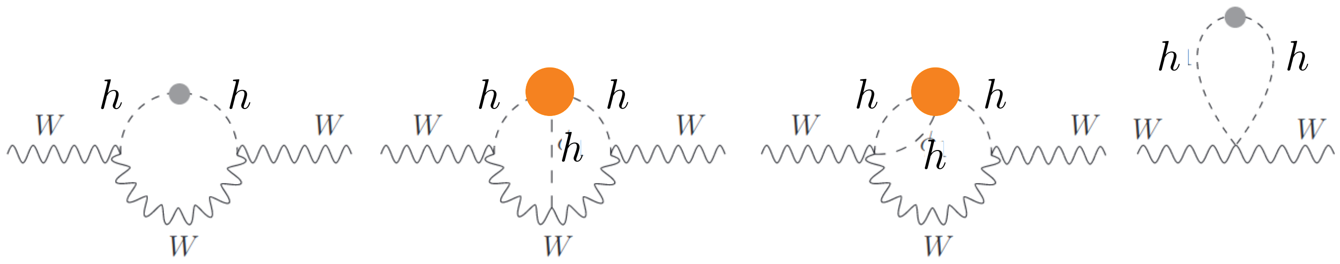


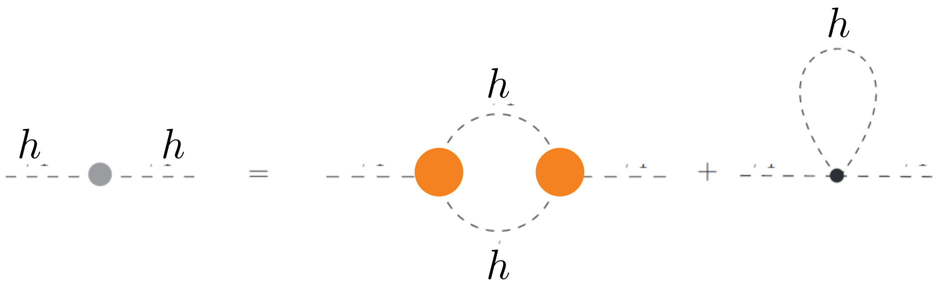




[Degrassi, Giardino, Maltoni, Pagani ‘16] [ATLAS-CONF-2019-049]

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

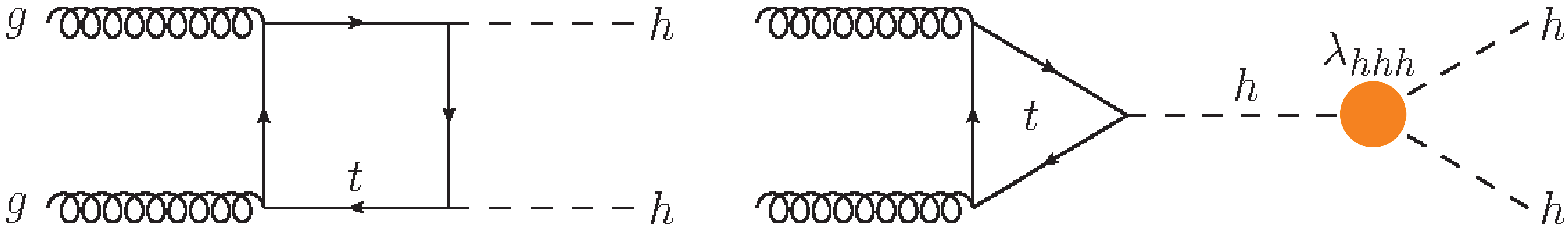




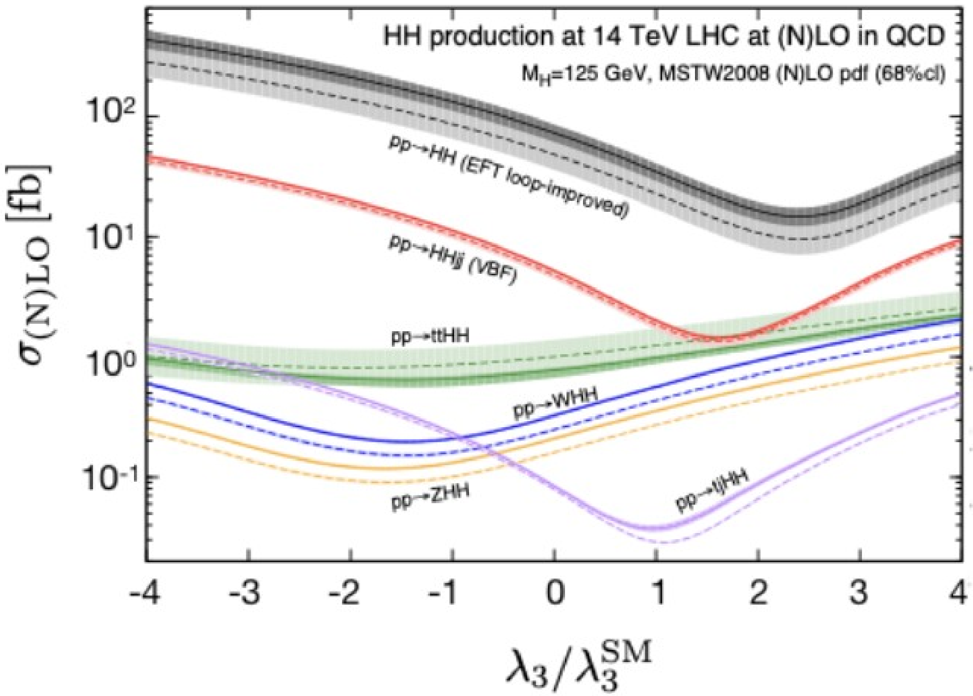
[Degrassi, Fedele, Giardino ‘17]

Accessing λ_{hhh} experimentally

- **Double-Higgs production** $\rightarrow \lambda_{hhh}$ enters at LO $\rightarrow$ **most direct probe of λ_{hhh}**



- Box and triangle diagrams **interfere destructively**
  $\rightarrow$ small prediction in SM
  $\rightarrow$ BSM deviation in λ_{hhh} can **significantly alter double-Higgs production!**



[Frederix et al., '14]

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

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

Accessing λ_{hhh} via double-Higgs production

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

Recent results from ATLAS hh-searches [ATLAS-CONF-2022-050]
yield the limits:

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

→ factor ~2 improvement compared to
pre-2021 best ATLAS limits (from single-h prod.)
$-3.2 < \kappa_\lambda < 11.9$ at 95% C.L. [ATLAS-PHYS-PUB-2019-009]

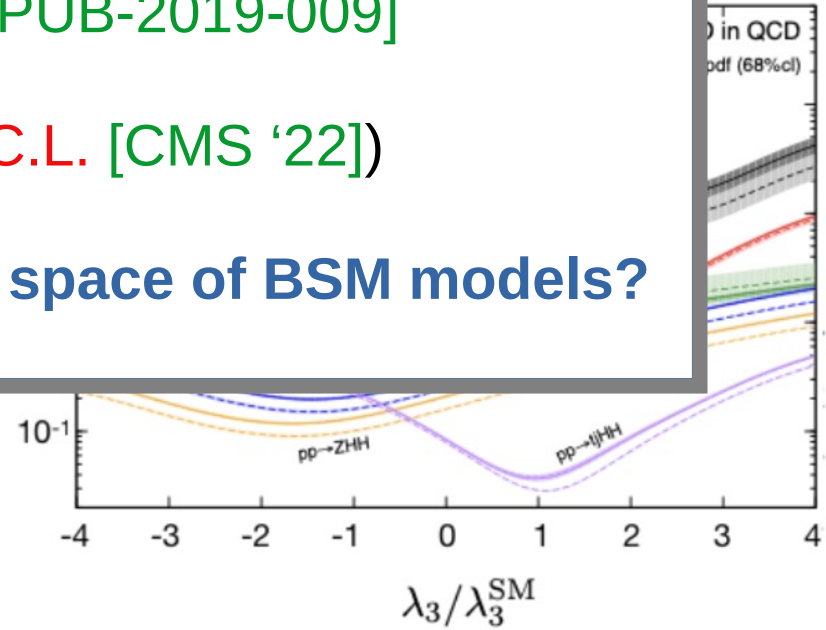
(CMS recently gave **$-1.2 < \kappa_\lambda < 6.5$** at 95% C.L. [CMS '22])

→ **Can κ_λ now be used to constrain the parameter space of BSM models?**

- Box ...
  → sr...
  → B...
  hh-p...

- Uppe...
  $\kappa_\lambda \equiv \lambda$...

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



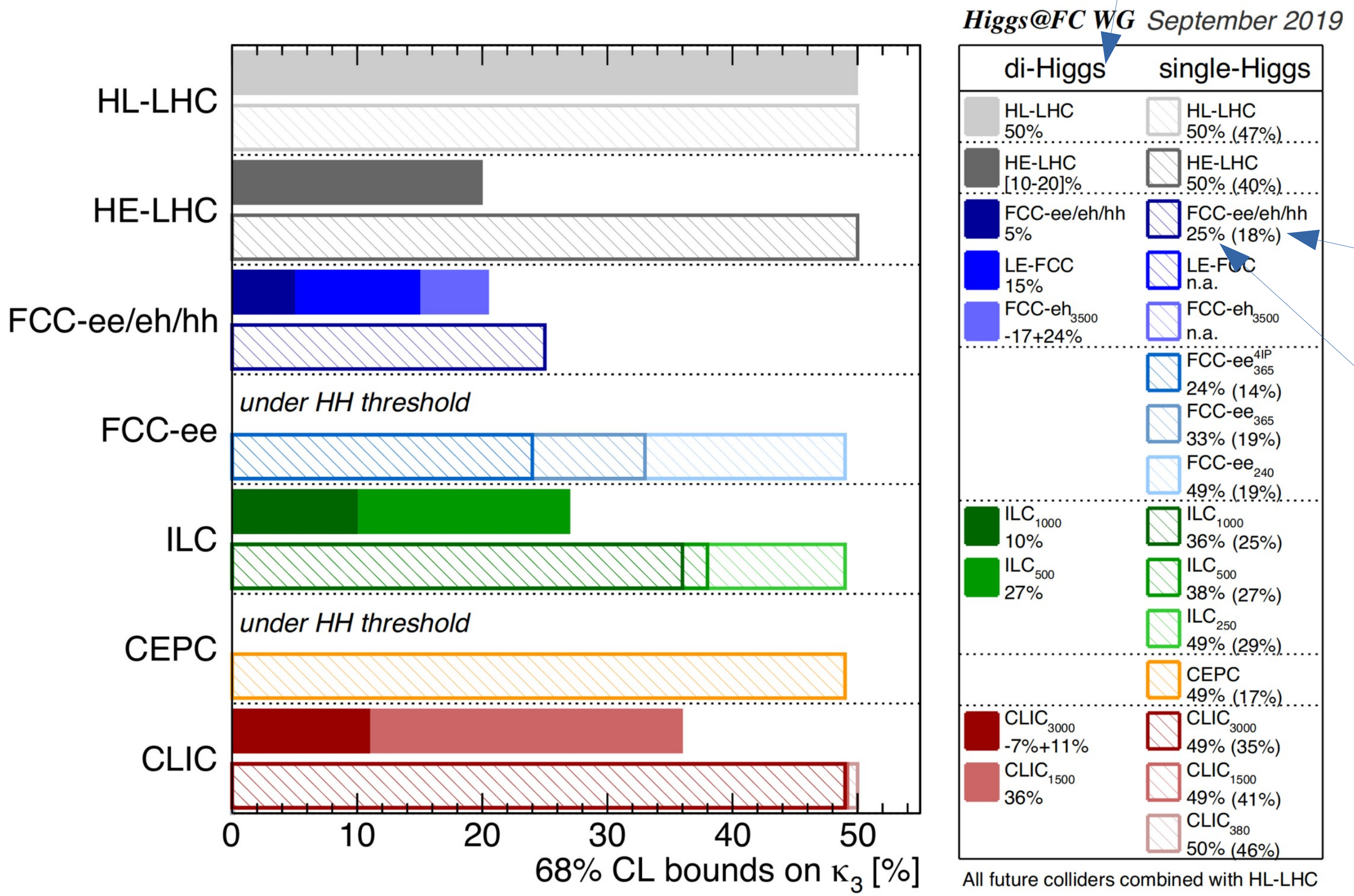
[Frederix et al., '14]

Future determination of λ_{hhh}

Expected sensitivities in literature, assuming $\lambda_{hhh} = (\lambda_{hhh})^{SM}$

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

di-Higgs exclusive result



single-Higgs exclusive

single-Higgs global

see also [Cepeda et al., 1902.00134], [Di Vita et al.1711.03978], [Fujii et al. 1506.05992, 1710.07621, 1908.11299], [Roloff et al., 1901.05897], [Chang et al. 1804.07130,1908.00753], *etc.*

Future determination of λ_{hhh}

Higgs production cross-sections (here double Higgs production) depend on λ_{hhh}

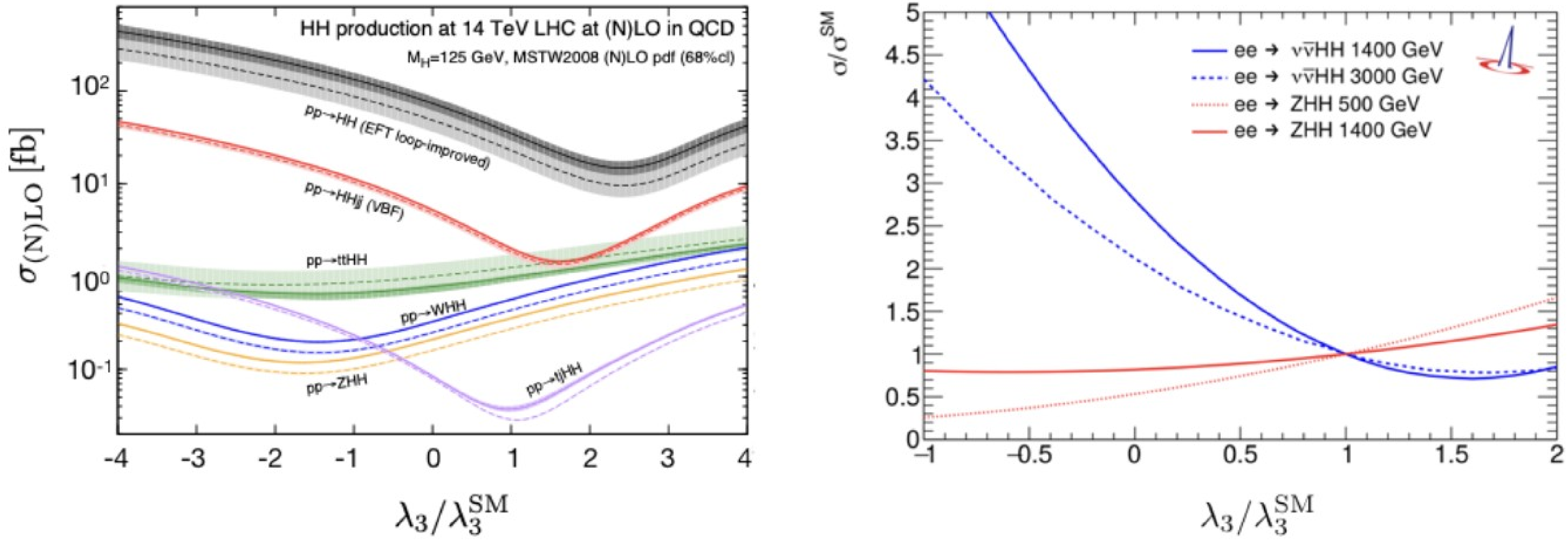


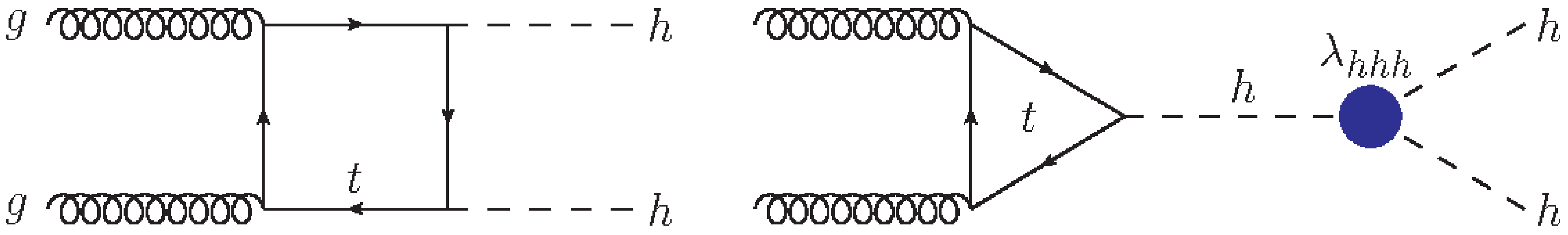
Figure 10. Double Higgs production at hadron (left) [65] and lepton (right) [66] colliders as a function of the modified Higgs cubic self-coupling. See Table 18 for the SM rates. At lepton colliders, the production cross sections do depend on the polarisation but this dependence drops out in the ratios to the SM rates (beam spectrum and QED ISR effects have been included).

[Frederix et al., 1401.7340]

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

Experimental situation for λ_{hhh}

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



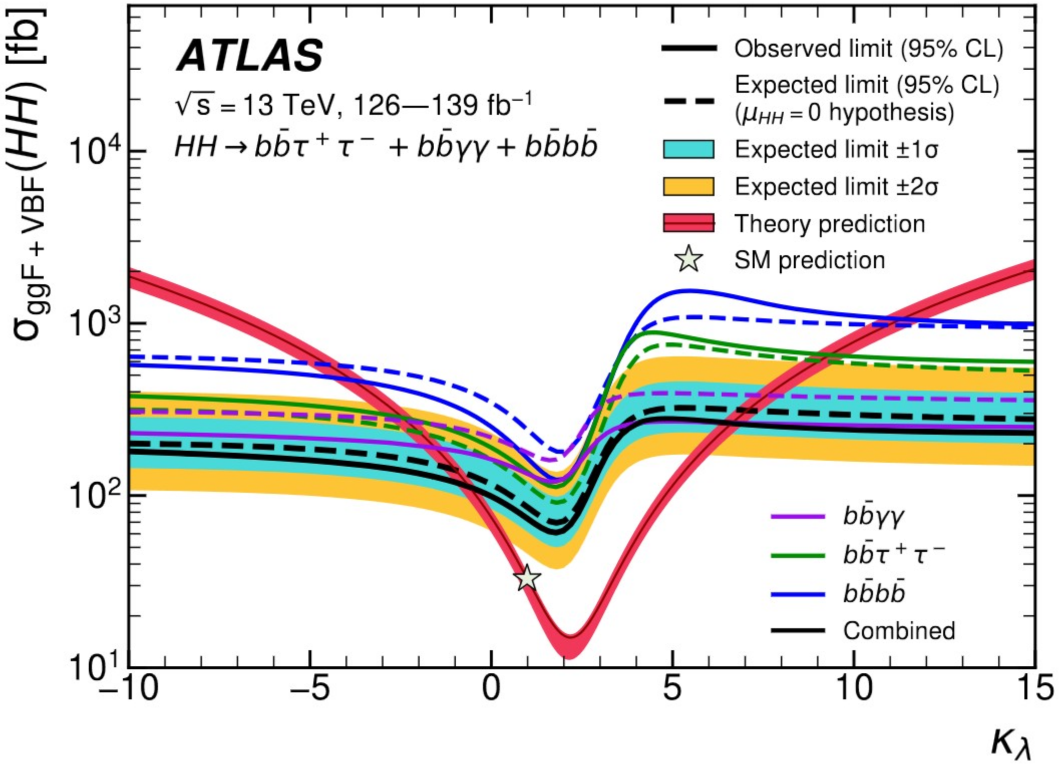
[Note: Single-Higgs production (EW precision observables) → λ_{hhh} enters at NLO (NNLO)]

- Box and triangle diagrams **interfere destructively**
  → small prediction in SM
  → BSM deviation in λ_{hhh} can **significantly enhance double-Higgs production!**

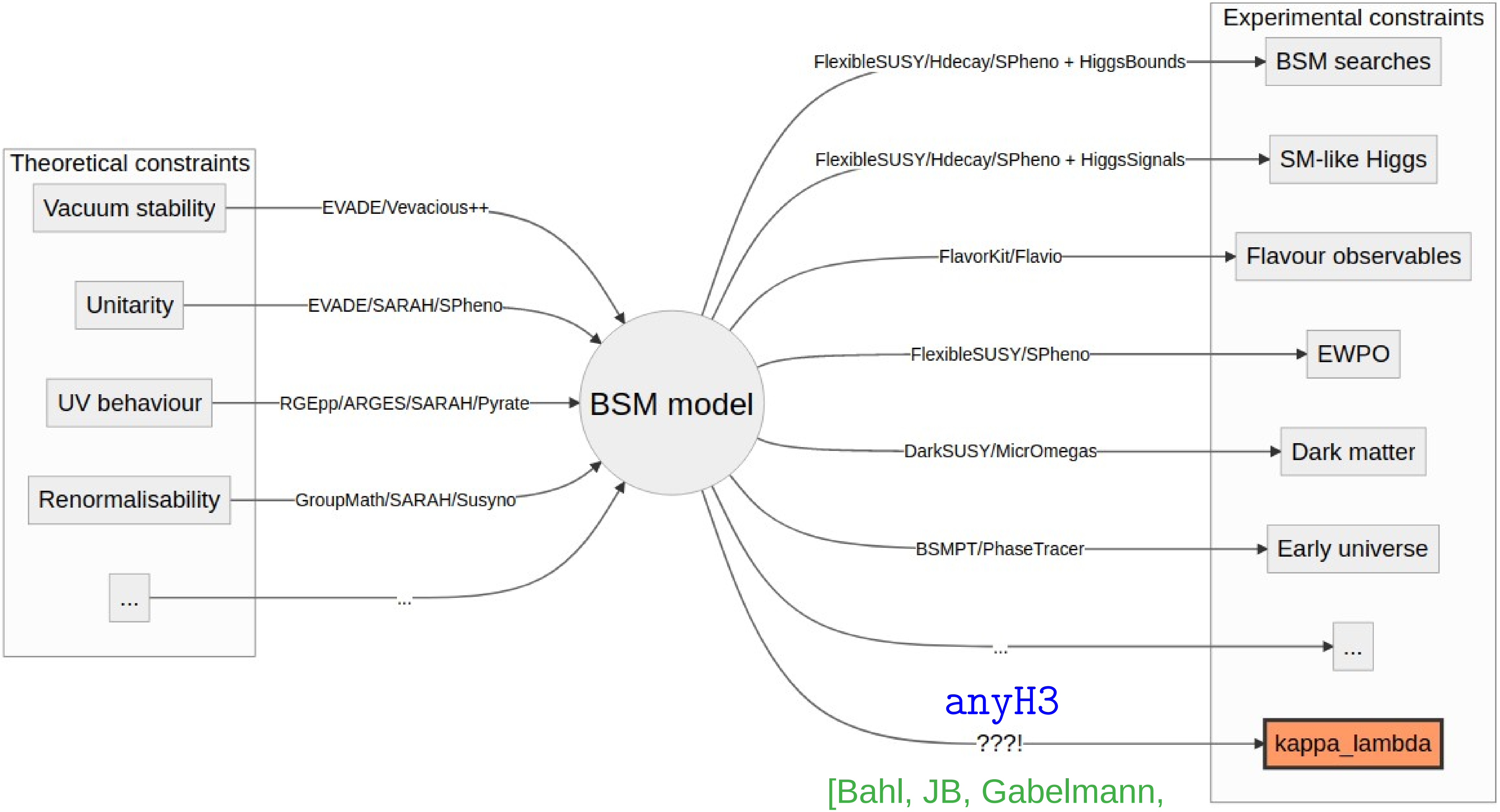
- Search limits on double-Higgs production
  → **limits on effective coupling $\kappa_\lambda \equiv \lambda_{hhh}/(\lambda_{hhh}^{(0)})^{SM}$**

$$-0.4 < \kappa_\lambda < 6.3$$

[ATLAS PLB '23]

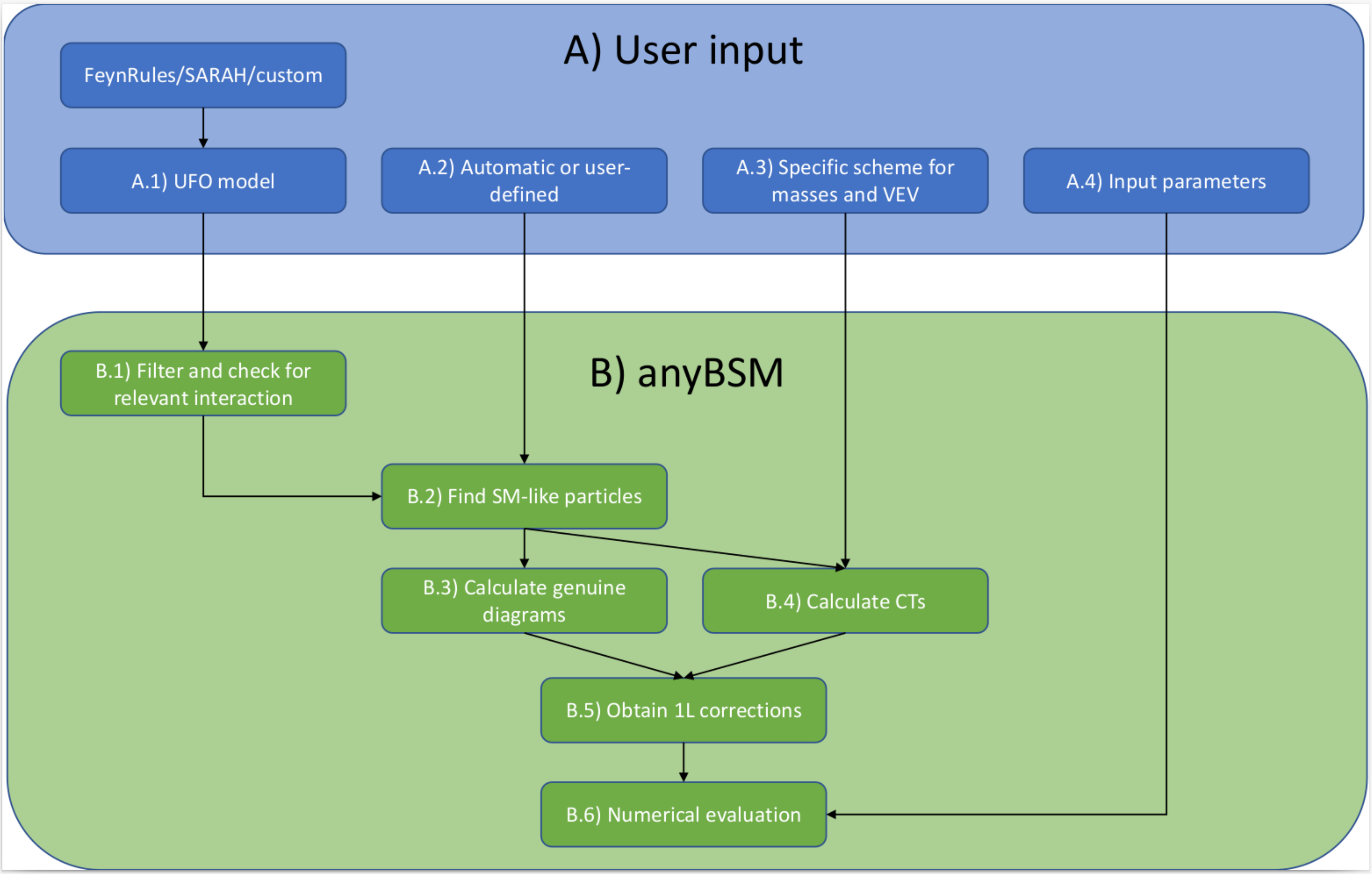


λ_{hhh} within the landscape of automated tools



[Bahl, JB, Gabelmann, Weiglein 2305.03015]

Workflow of anyH3



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

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

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

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

Features of anyH3, so far

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

schemes.yml:

Example for 2HDM

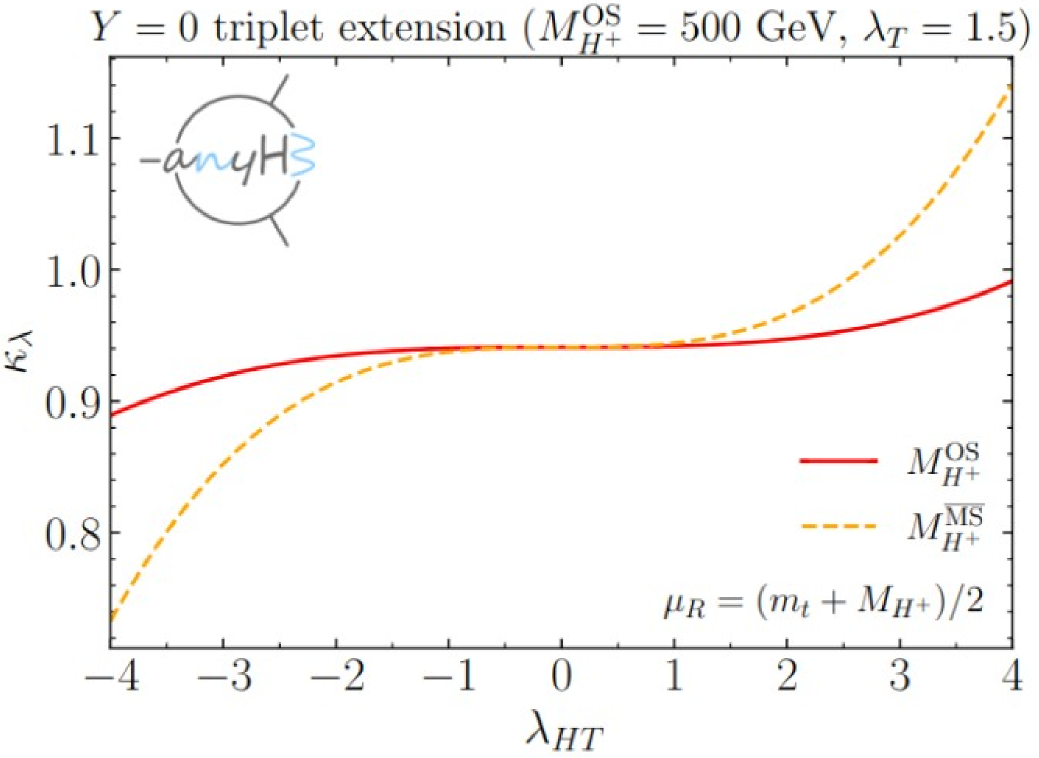
```yaml
default_scheme: OSalignment

renormalization_schemes:
  MS:
    description: all (B)SM parameters MS
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: MS
    mass_counterterms:
      h1: MS
      h2: MS

  OSalignment:
    description: $\overline{\mathrm{MS}}$ mixing angles
and OS masses i.e. fully on-shell $\lambda_{hhh}$ for $
\sin {\beta-\alpha}=1$
    SM_names:
      Higgs-Boson: h1
    VEV_counterterm: OS
    mass_counterterms:
      h1: OS
      h2: OS

  OS:
    description: OS conditions for scalar masses as well
```

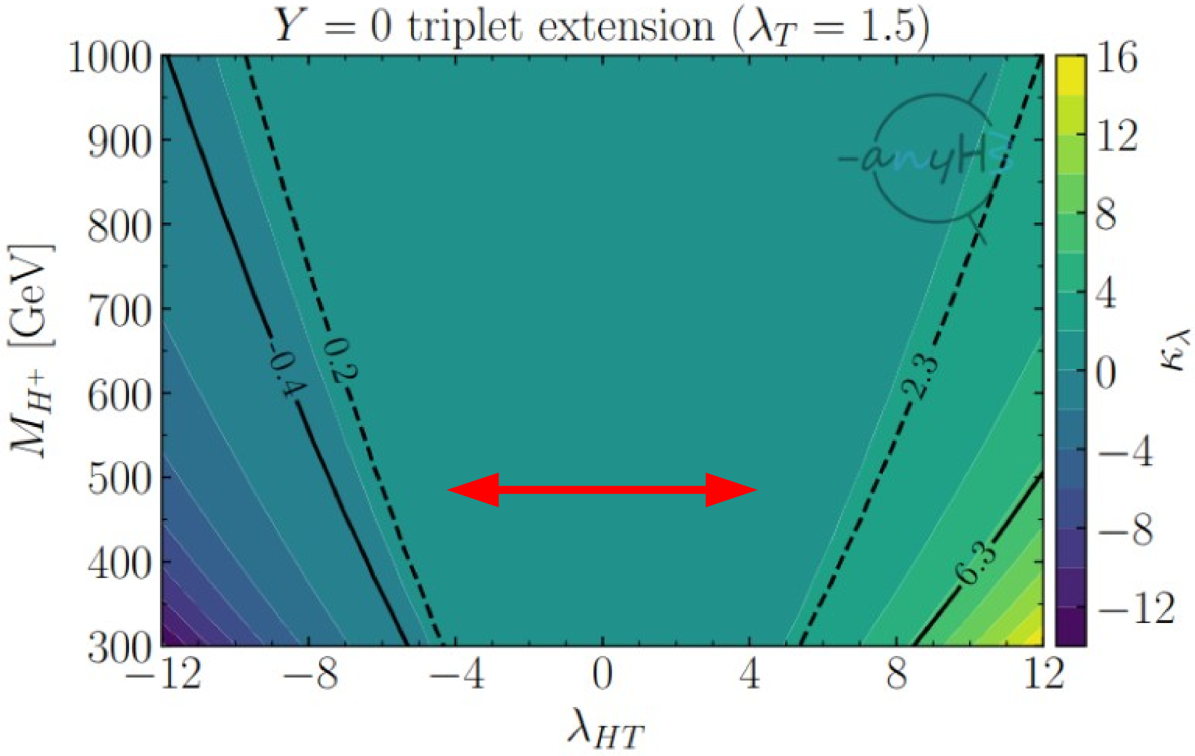
- Analytical / numerical / LaTeX outputs
- Restrictions on topologies or on considered particles possible
- **3 user interfaces**:
  - Python library
  - Command line
  - Mathematica interface
- **Perturbative unitarity checks** available (at tree level and in high-energy limit for now)
- Can be used together with a spectrum generator and **handles SLHA format**
- Efficient **caching** available
- Etc.

New results IV: renormalisation scheme comparisons

Real (VEV-less) triplet model:

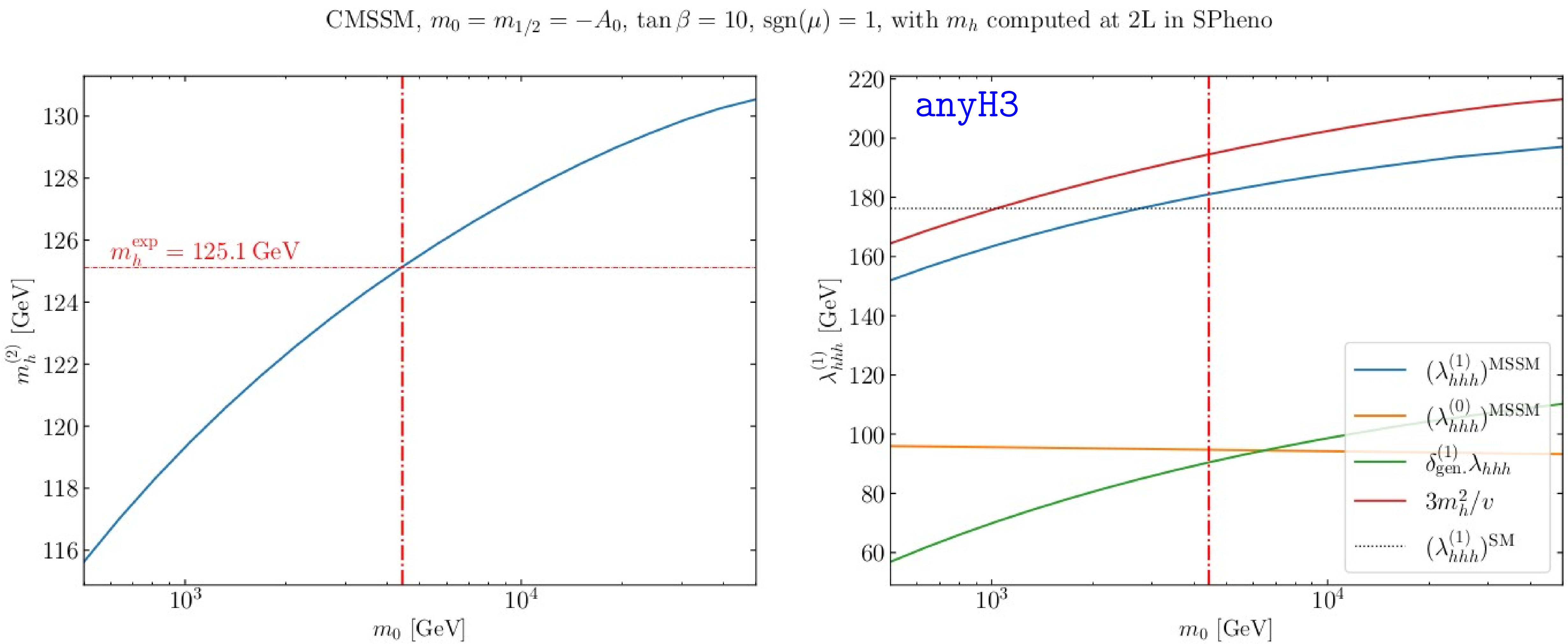
$$V(\Phi, T) = \mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4 + \frac{M_T^2}{2}|T|^2 + \frac{\lambda_T}{2}|T|^4 + \frac{\lambda_{HT}}{2}|T|^2|\Phi|^2, \ \langle T\rangle = 0, \langle\Phi\rangle = v_{SM}$$





- *Left*: scheme variation of charged triplet mass $M_{H\pm}$ (enters λ_{hhh} from 1L) → estimate of theoretical uncertainty from missing 2L corrections
- *Right*: κ_λ @ 1L in plane of $M_{H\pm}$ and λ_{HT} (portal coupling)

New results VI: full one-loop calculation of λ_{hhh} in the MSSM



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