BSM phenomenology at future accelerators

Henning Bahl

Corfu 2024 Workshop on Future Accelerators, 21.5.2024

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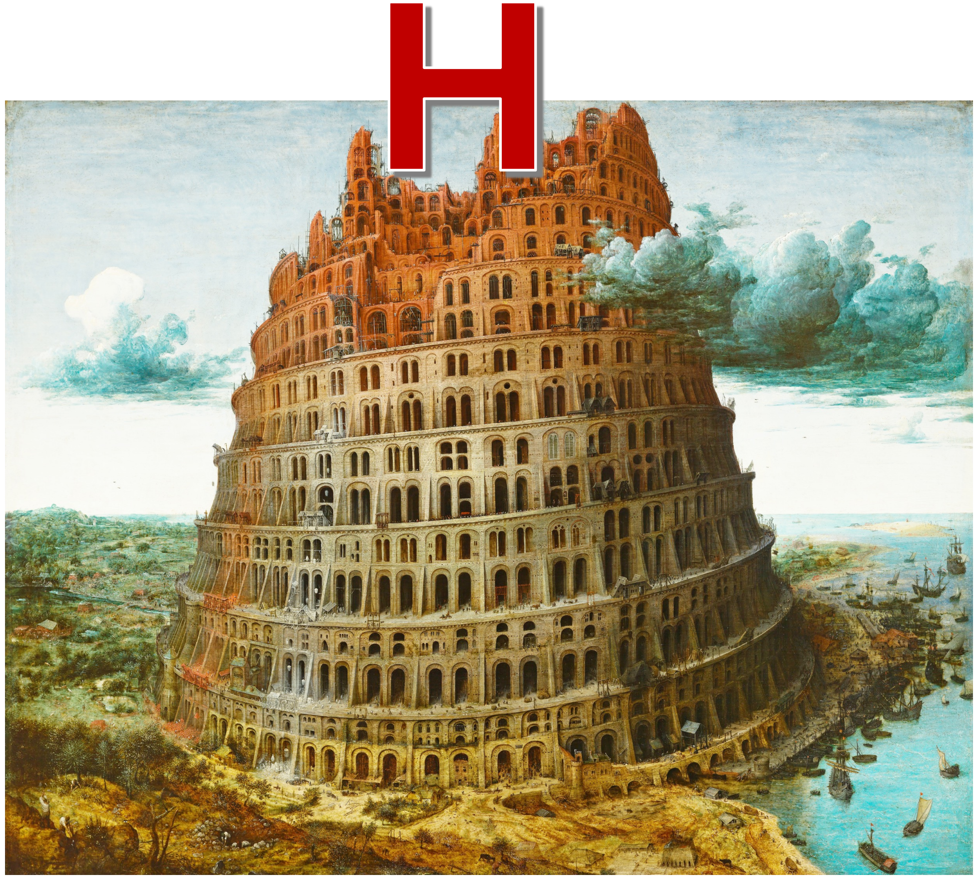

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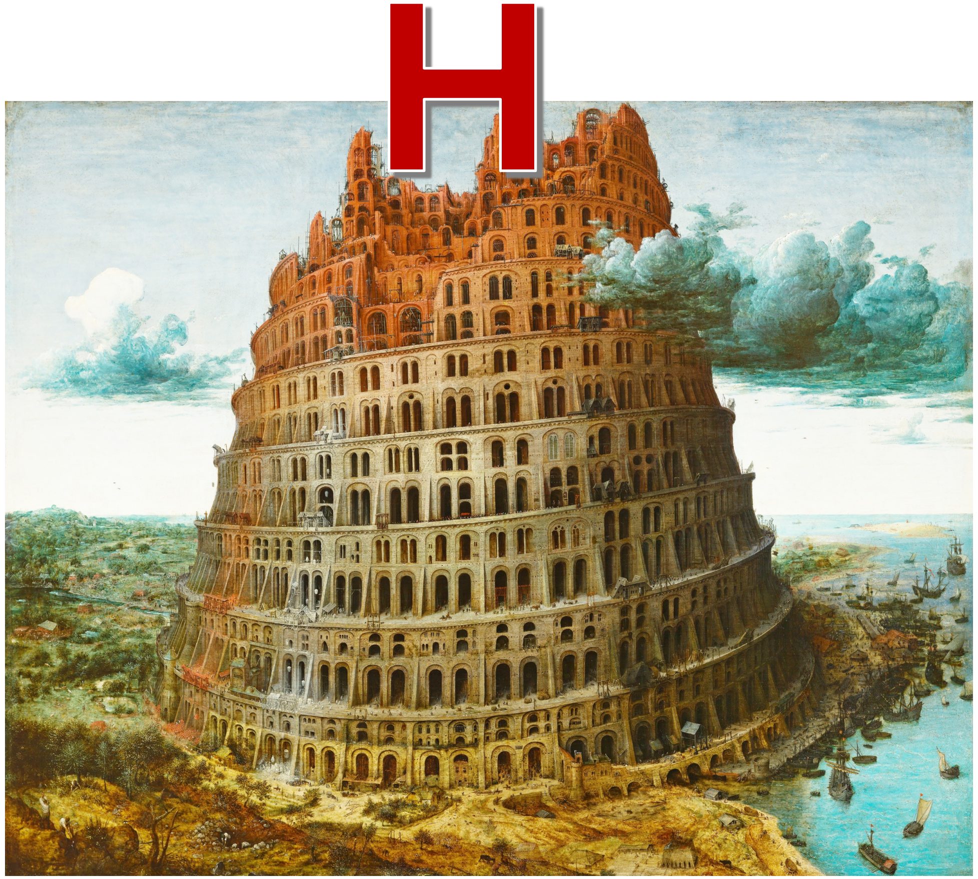

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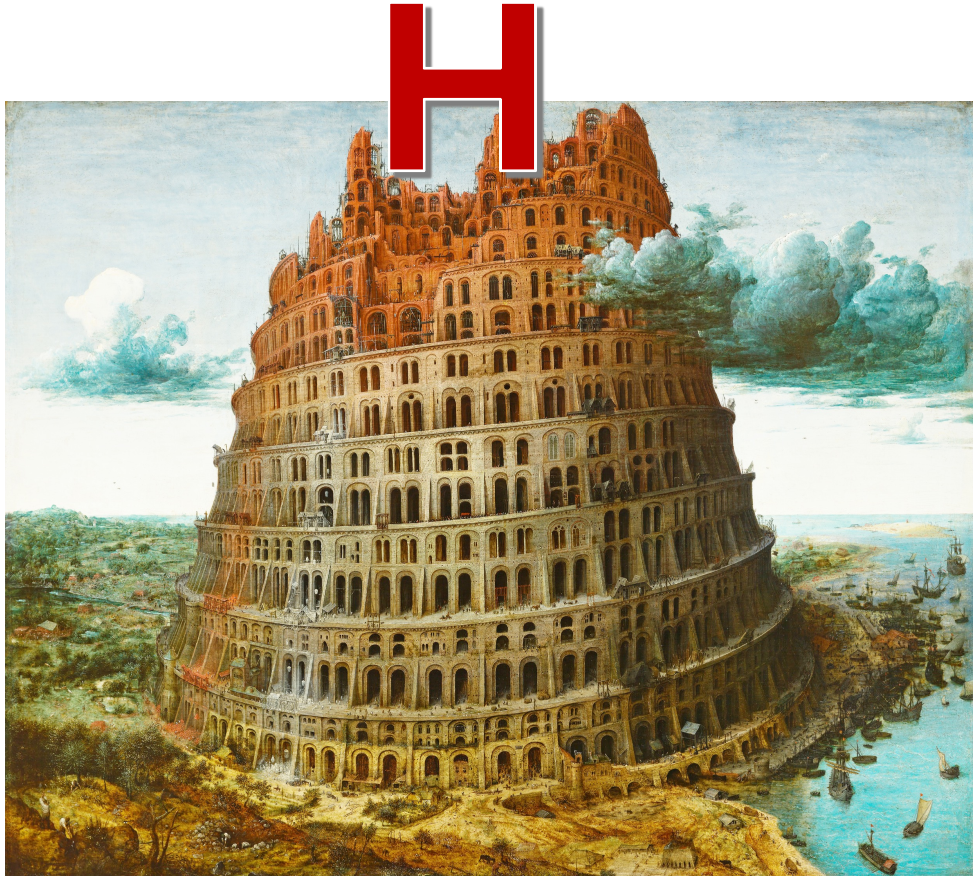

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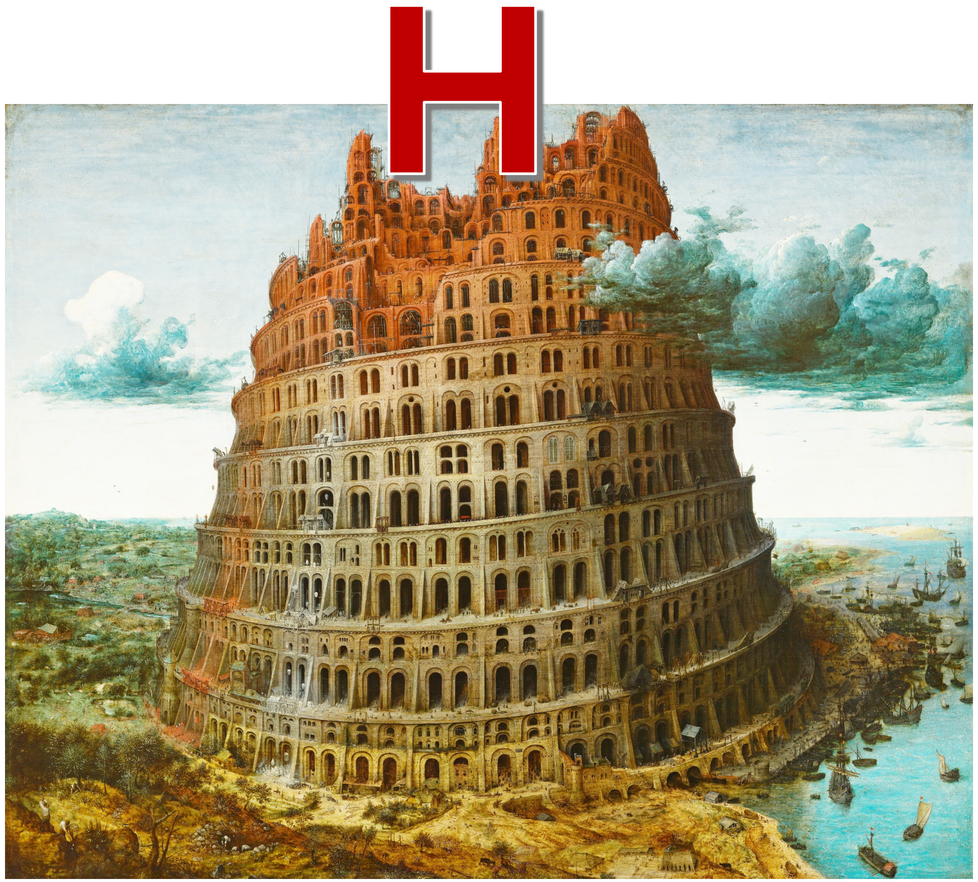
- More and more precision measurements and searches.
- The SM precisely describes a large variety of processes over many order of magnitudes.
- So, particle physics is doing great?!



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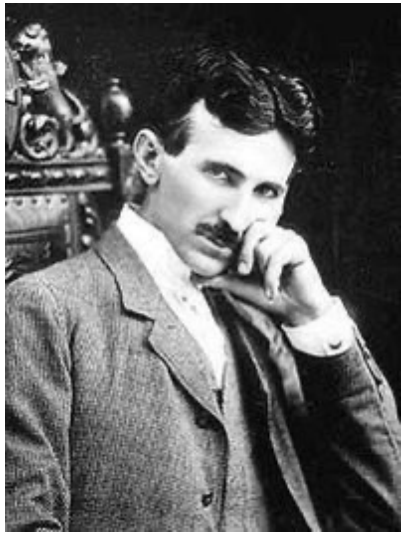

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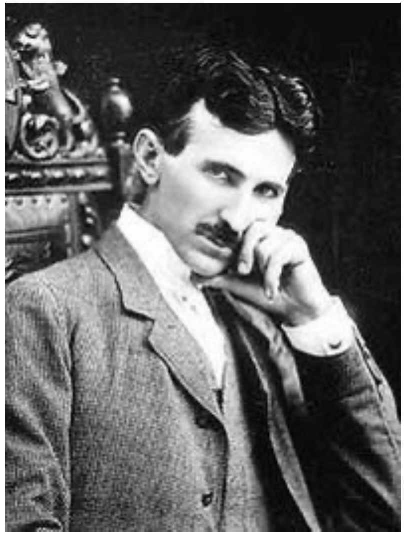

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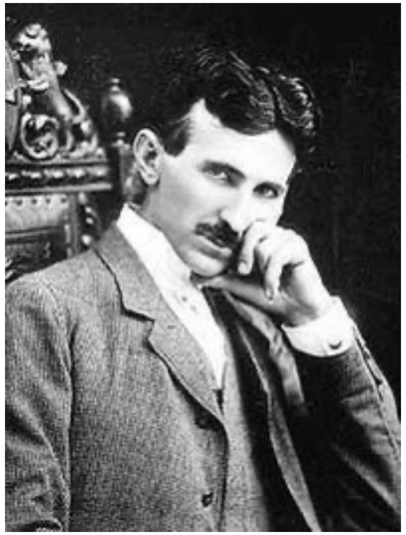

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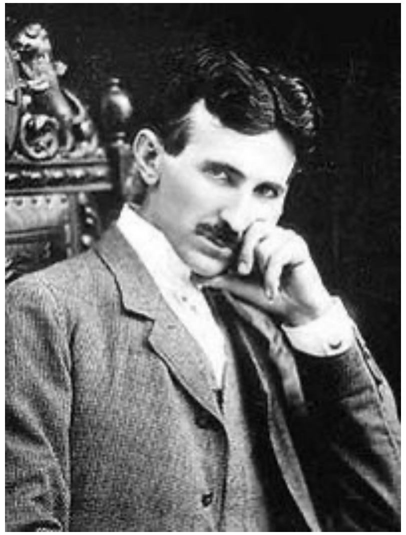

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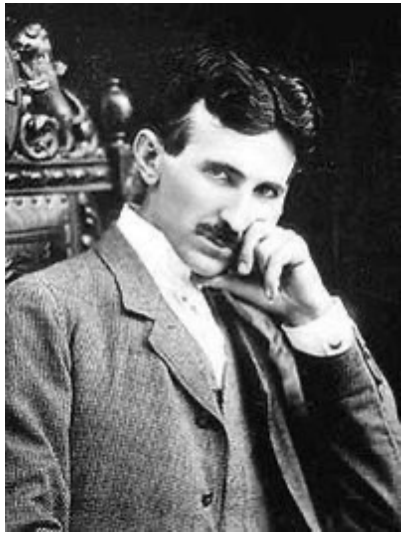

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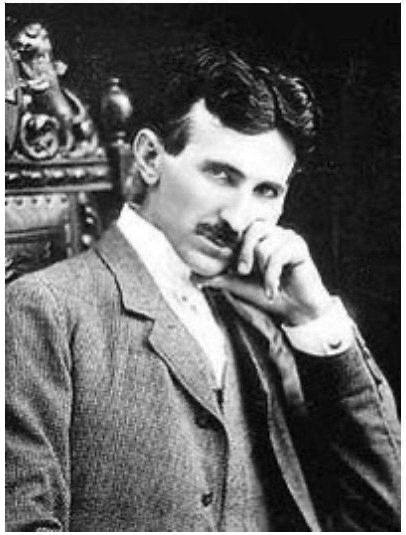

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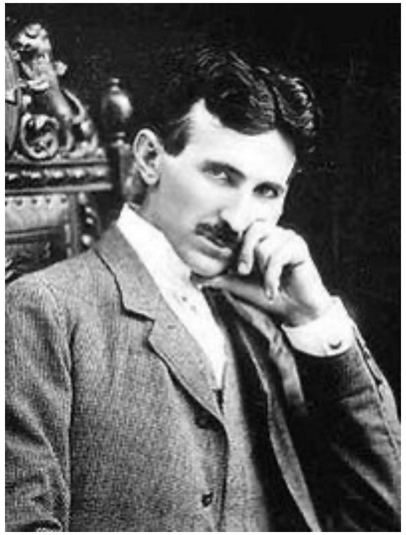

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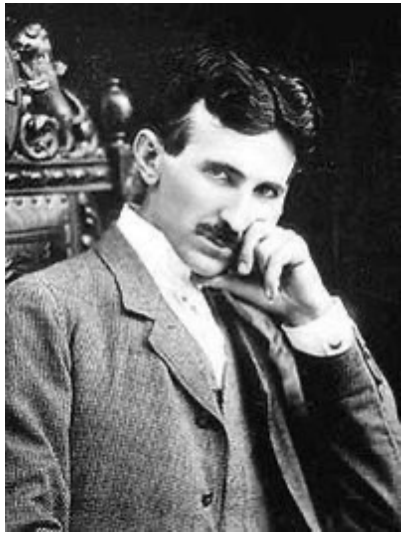

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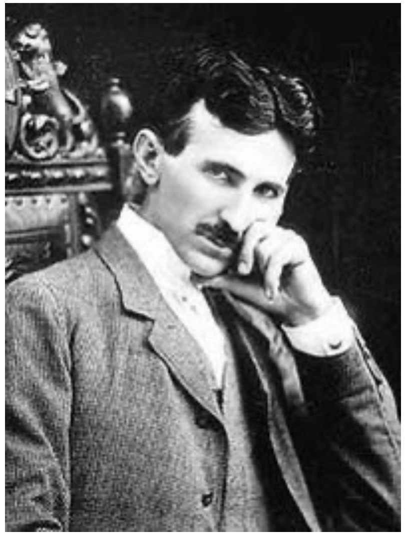

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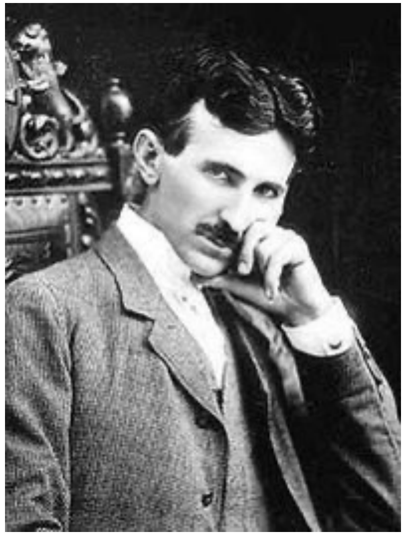

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Goal for future collider: Bring as closer to answering these questions!

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Where can we go from here?

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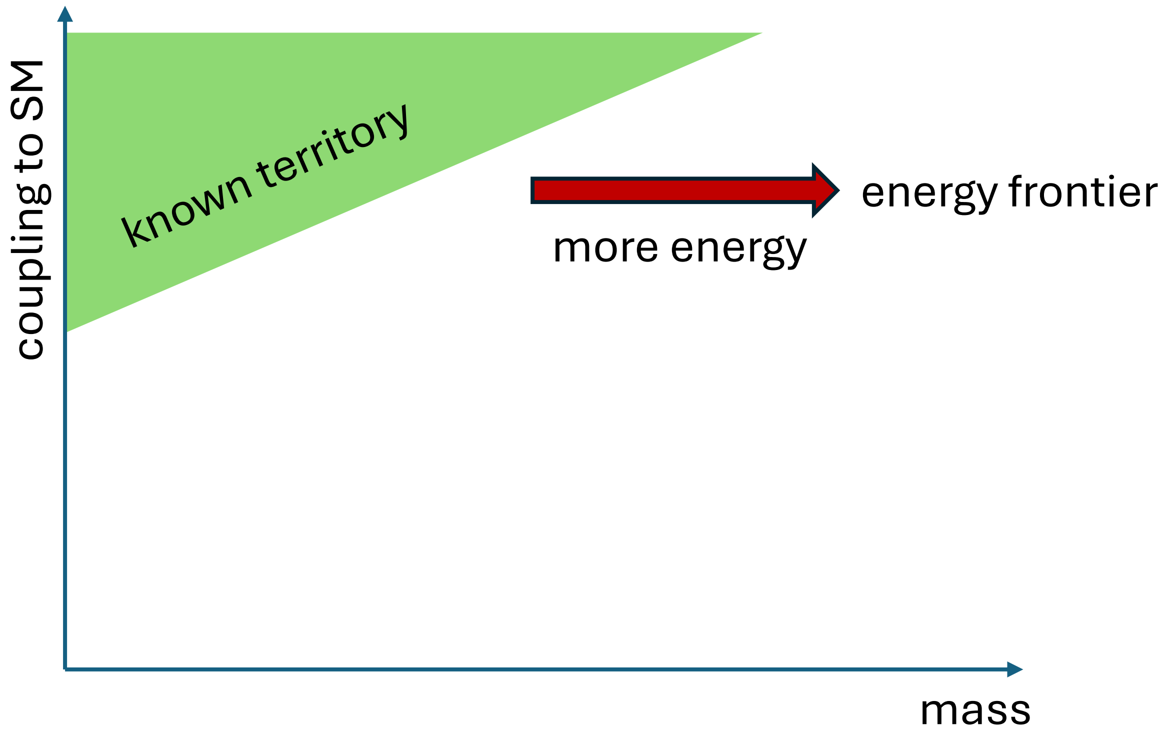

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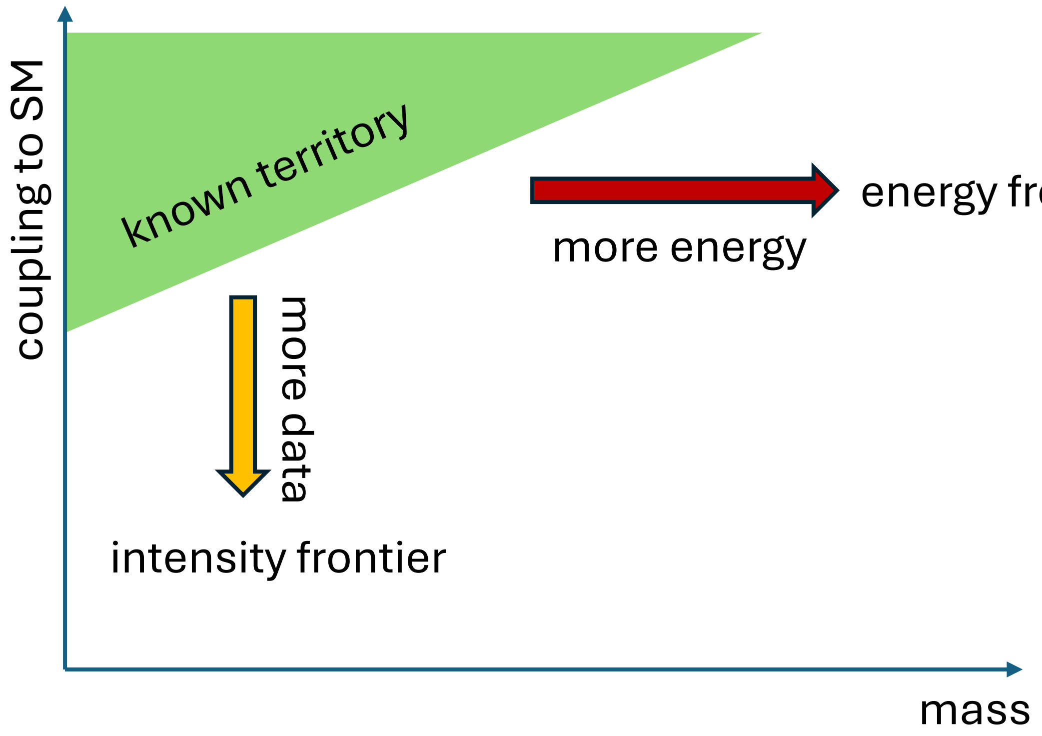

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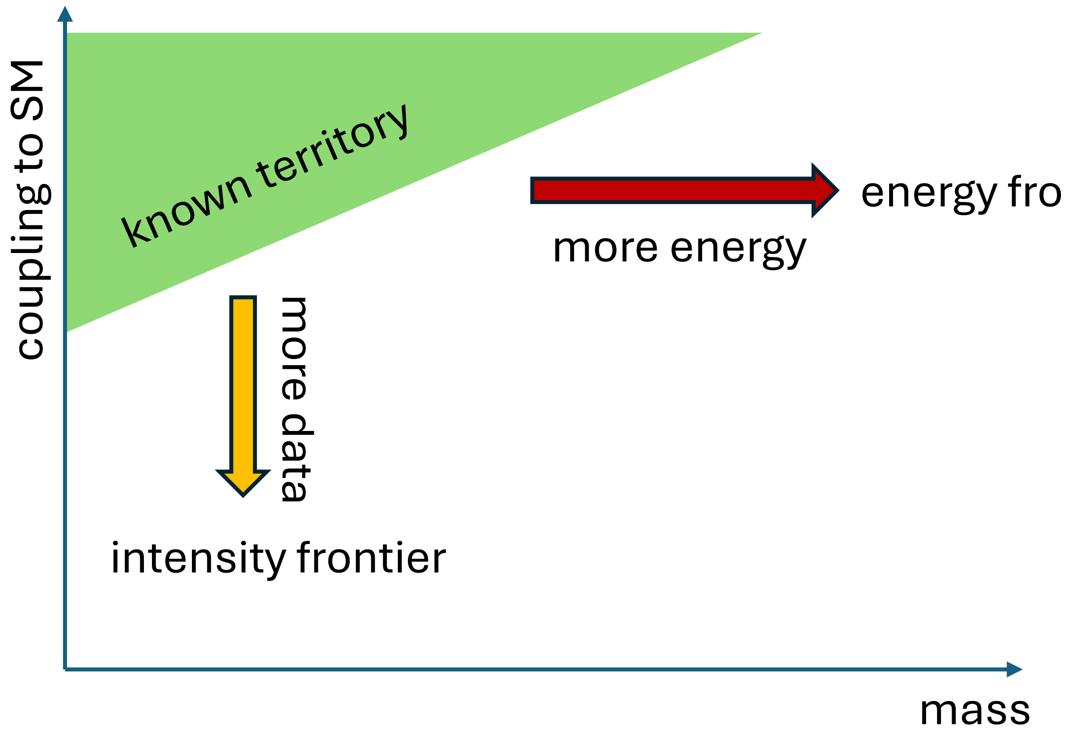

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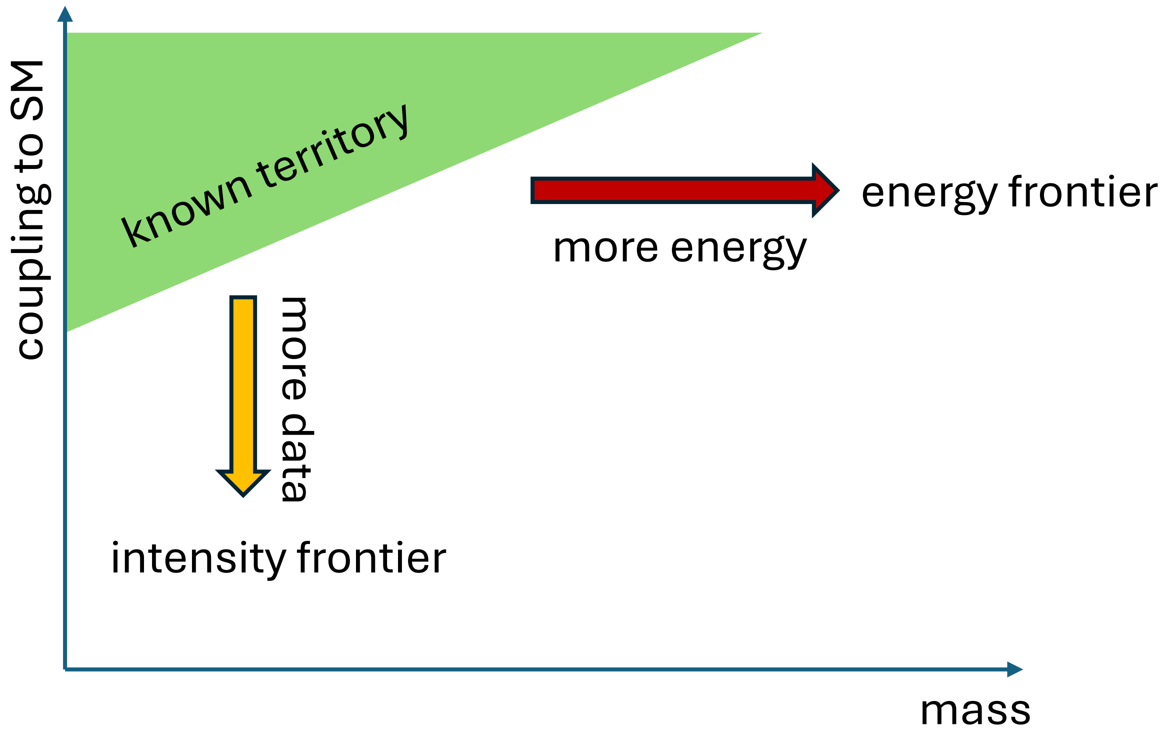

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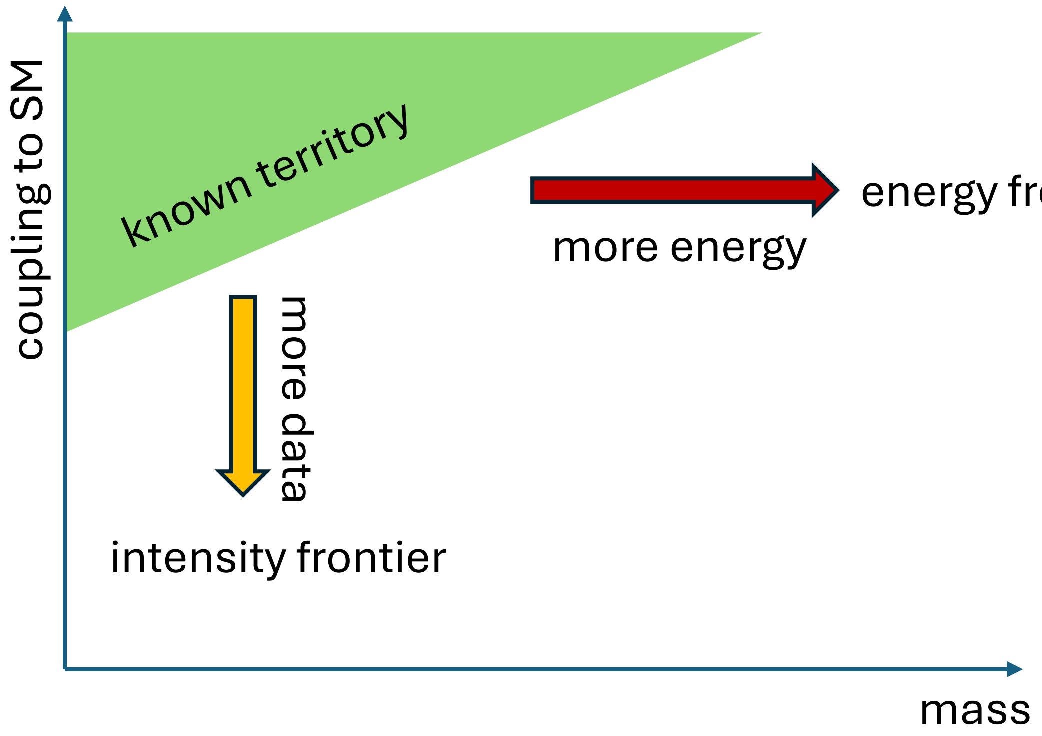

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Side note: the LHC was such an experiment, since without the Higgs the SM is inconsistent.

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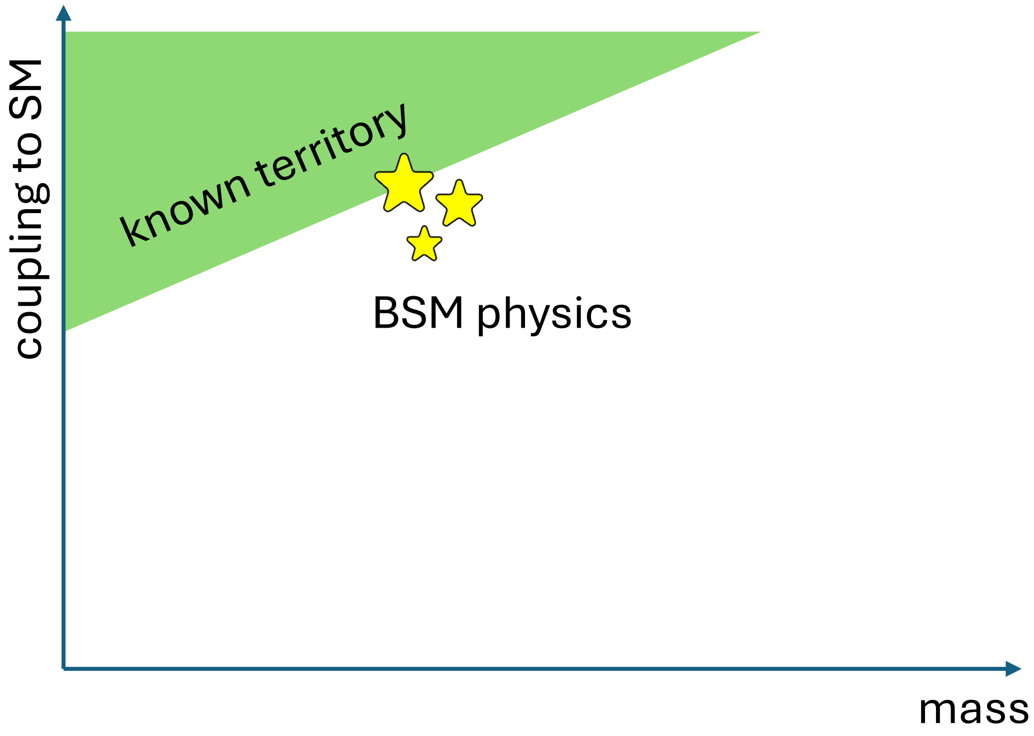

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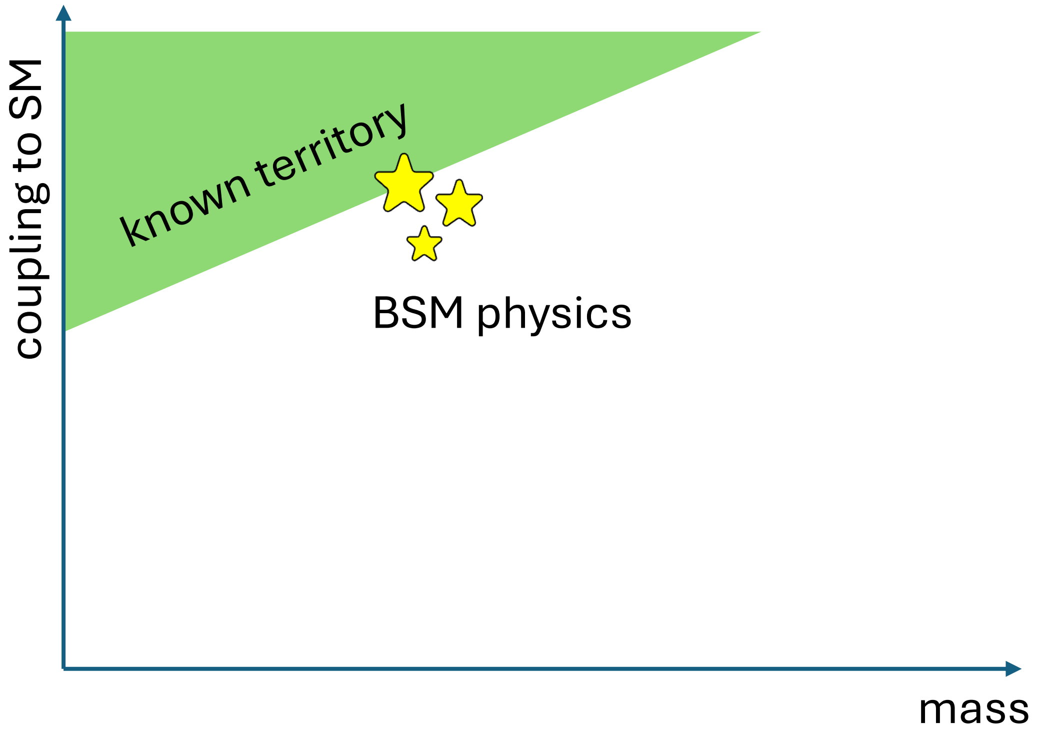

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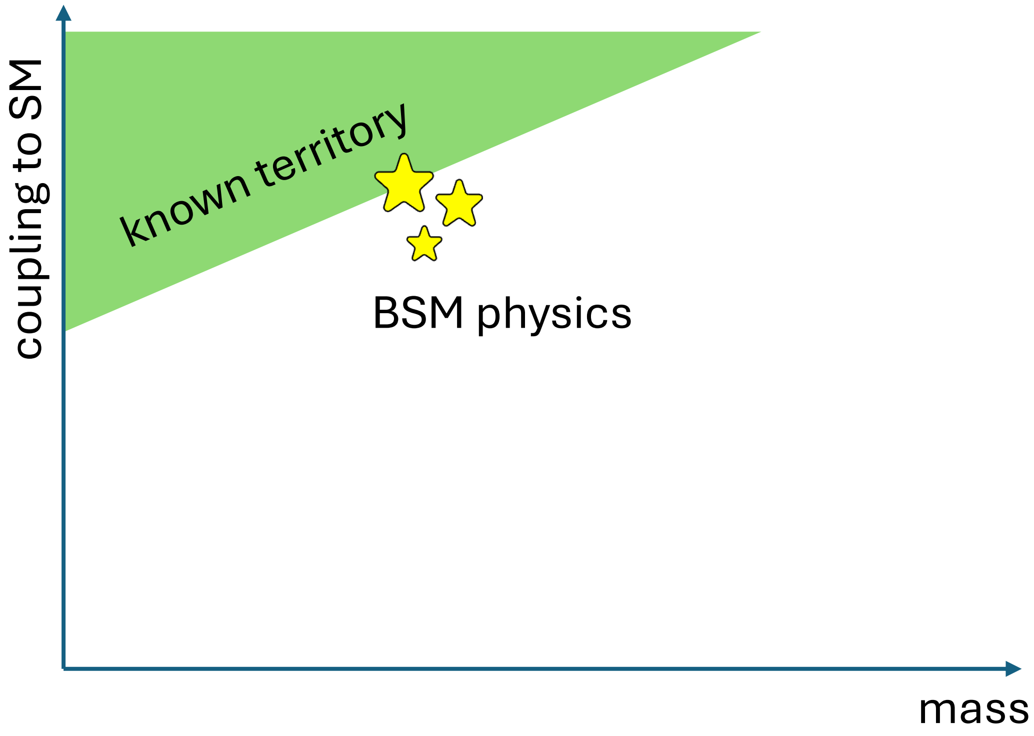

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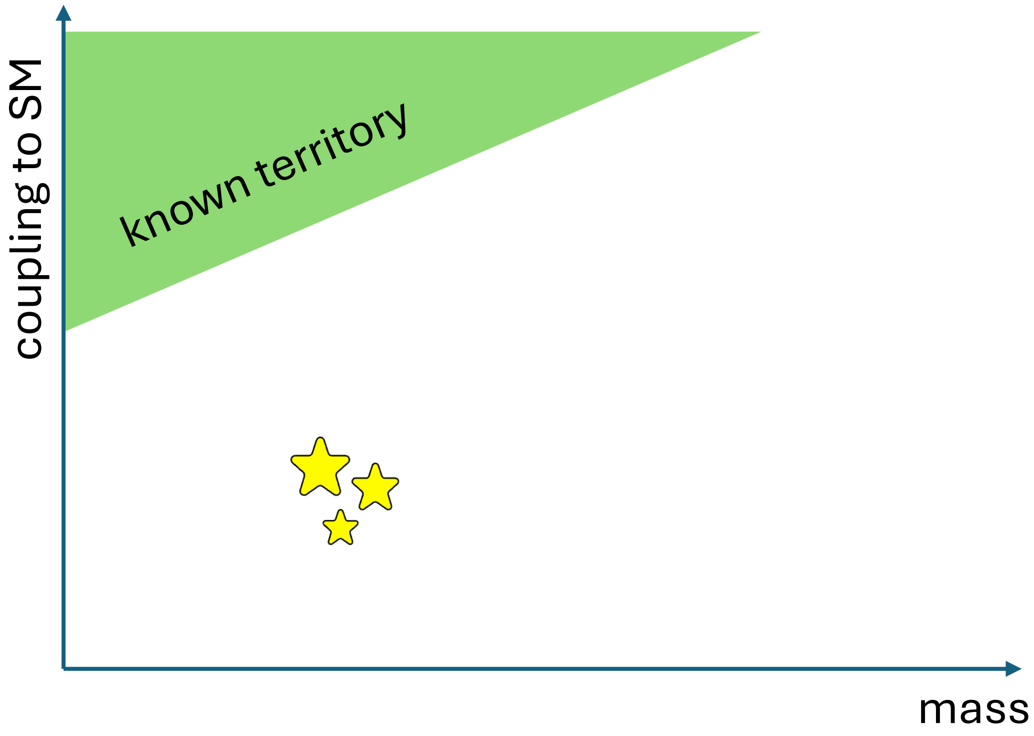

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→ talk outline: discuss examples for both.

Constraining light BSM physics

The top lamppost and rare decays [HB,Koren,Wang, 2307.11154]

Searching for light BSM physics: rare top decays

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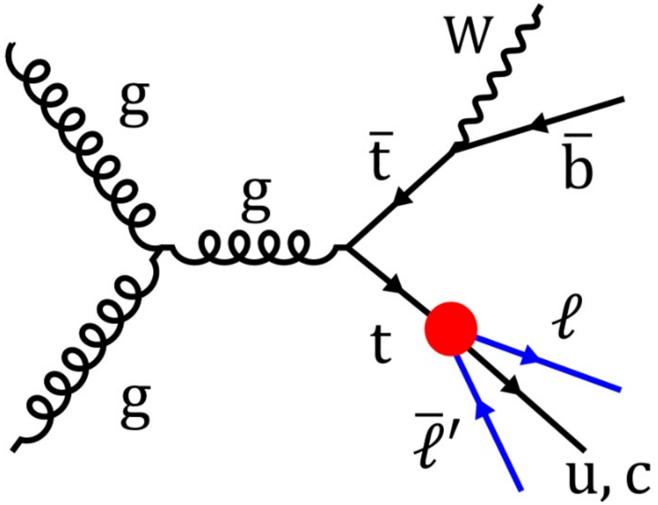

[CMS 2201.07859]

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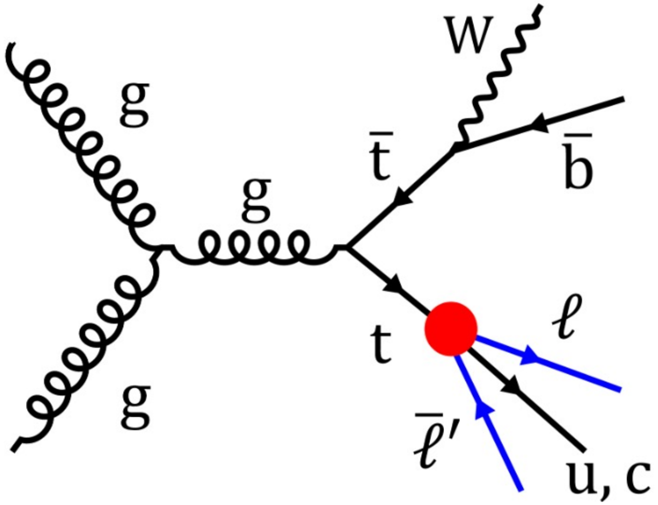

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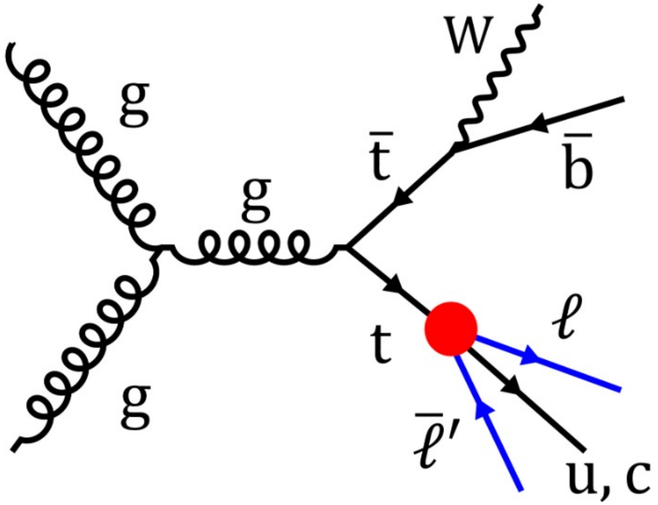

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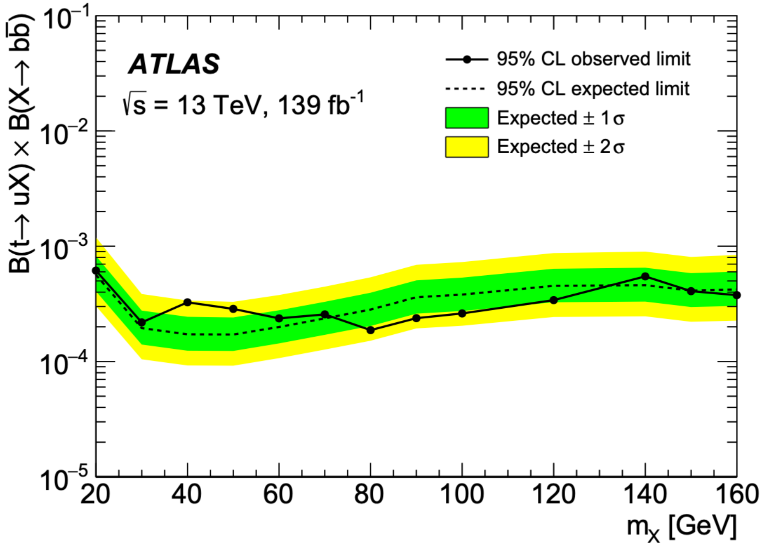

Can we do this in a more systematic manner?

Rare top decays — EFT classification

- Rare top-quark decays with SM final state can be parameterized using SMEFT (see e.g. [Bradshaw & Chang 2304.06063]).

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{i,n} \frac{c_n}{\Lambda^i} \mathcal{O}_i^n$$

SM dim 6	
$Q_{quqd}^{(1)}$	$\left(\bar{Q}_{Li}^a u_{Rj}\right) \varepsilon_{ab} \left(\bar{Q}_{Lk}^b d_{Rl}\right)$
$\mathcal{O}_{lequ}^{(1)}$	$\left(\bar{Q}_{Li}^a u_{Rj}\right) \varepsilon_{ab} \left(\bar{L}_{Lk}^b e_{Rl}\right)$
$Q_{u\Phi}$	$(\Phi^\dagger \Phi)(\bar{Q}_{Li} u_{Rj} \tilde{\Phi})$
$Q_{\Phi q}^{(1)}$	$(\Phi^\dagger i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}_{Li} \gamma^\mu Q_{Lj})$
Q_{uG}	$(\bar{Q}_{Li} \sigma^{\mu\nu} \mathcal{T}^A u_{Rj}) \widetilde{\Phi} G_{\mu\nu}^A$
Q_{uW}	$(\bar{Q}_{Li} \sigma^{\mu\nu} u_{Rj}) \tau^I \widetilde{\Phi} W_{\mu\nu}^I$
Q_{uB}	$(\bar{Q}_{Li} \sigma^{\mu\nu} u_{Rj}) \widetilde{\Phi} B_{\mu\nu}$

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- Additionally, we also consider the possibility of light BSM particles:
  - scalar singlet S (e.g. ALP),
  - fermionic singlet N (e.g. sterile neutrino),
  - light gauge boson Z' (e.g. from gauging $B_3 - L_3$),
  - not discussed here: light charged Higgs boson.

⇒ New operators and final states.

BSM dim 5	
Q_{SqD}	$S(\bar{Q}_{Li} \not{D} Q_{Lj})$
$Q_{Su\Phi}$	$S(\bar{Q}_{Li} u_{Rj} \widetilde{\Phi})$
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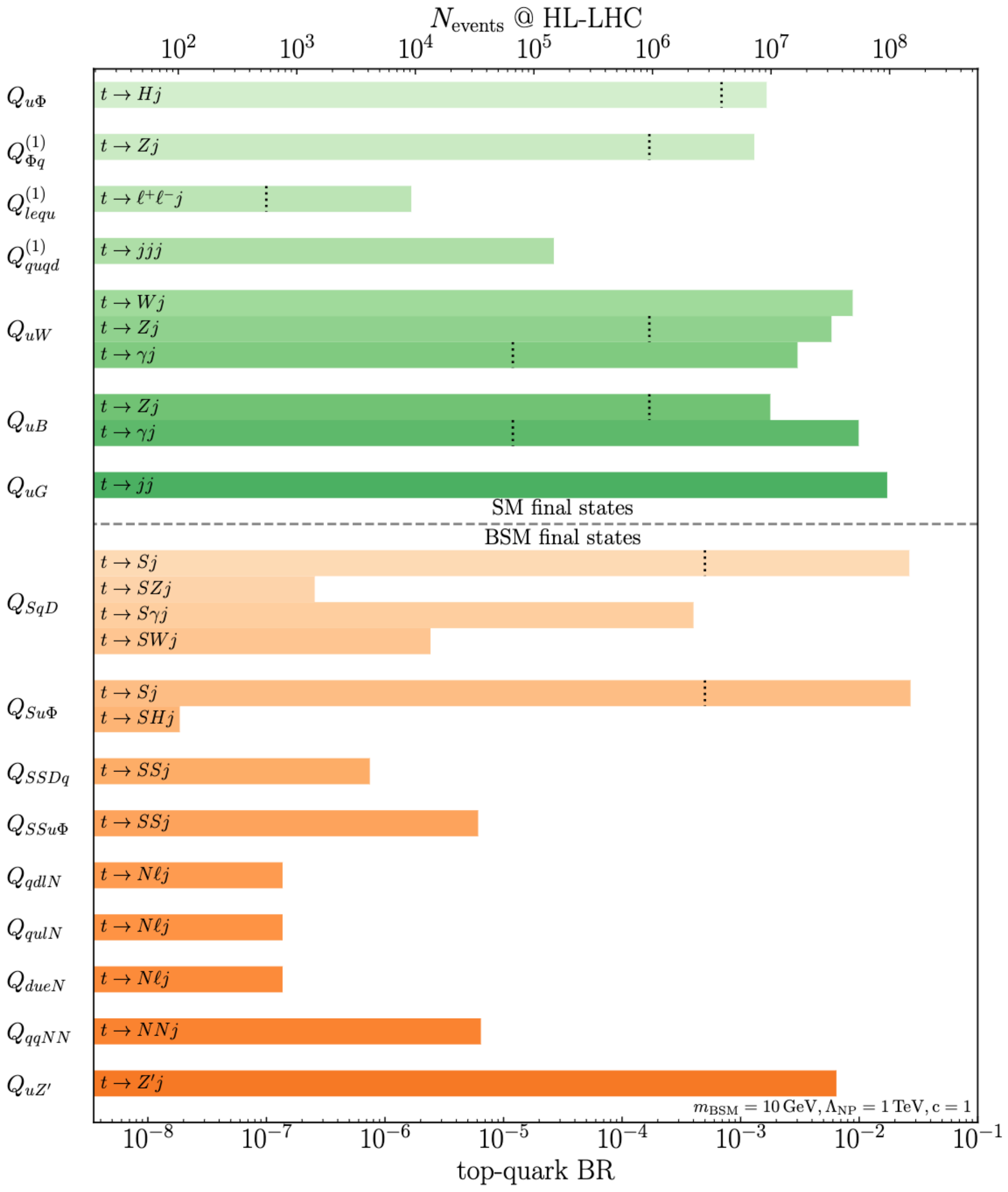
Q_{qdlN}	$(\bar{Q}^a_{Li} d_{Rj})\, \varepsilon_{ab}\, (\bar{L}^b_{Lk} N)$
Q_{qulN}	$(\bar{Q}_{Li} u_{Rj})\, (\bar{N} L_{Lk})$
Q_{dueN}	$(\bar{e}^c_{Rj} u_{Rj})\, (\bar{d}_{Rk} N)$
Q_{qqNN}	$(\bar{Q}_{Li} \gamma_\mu Q_{Lj})\, (\bar{N} \gamma^\mu N)$
Q_{SSDq}	$S^2(\bar{Q}_{Li} \not{D} Q_{Lj})$
$Q_{SSu\Phi}$	$S^2(\bar{Q}_{Li} u_{Rj} \widetilde{\Phi})$
$Q_{uZ'}$	$(\bar{Q}_{Li} \sigma^{\mu\nu} u_{Rj}) \widetilde{\Phi} F'_{\mu\nu}$

Rare top-quark decays I

- Investigate operators individually.
- Set $\Lambda = 1$ TeV, $c_i^n = 1$, and $m_S = m_N = m_{Z'} = 10$ GeV as a benchmark.
- Calculate branching ratio for different final states.



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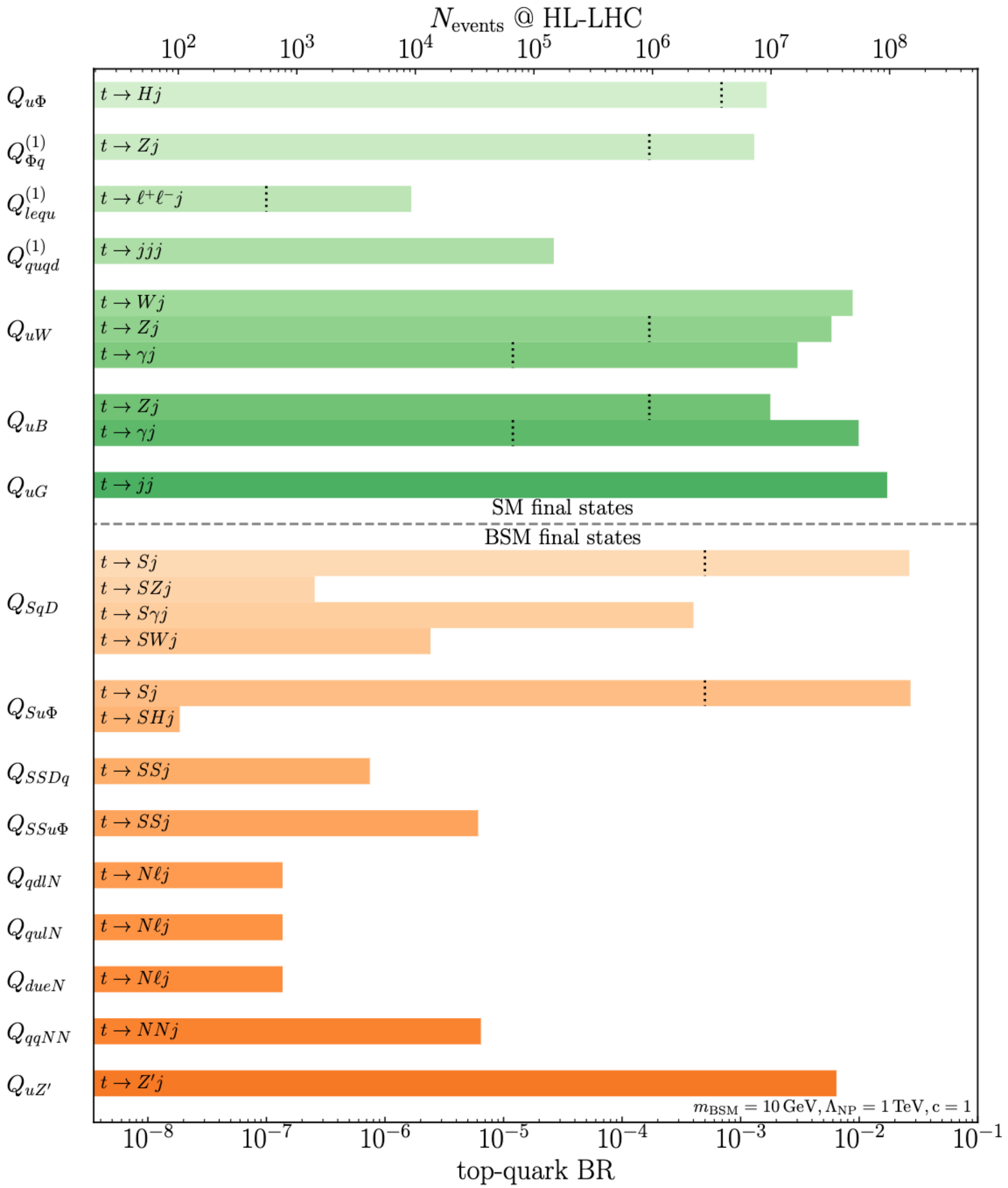

- Sizeable branching ratios/number of events for various operators.
- Various final states which can be probed with current and future data.

$\Rightarrow$ Huge potential for future searches!

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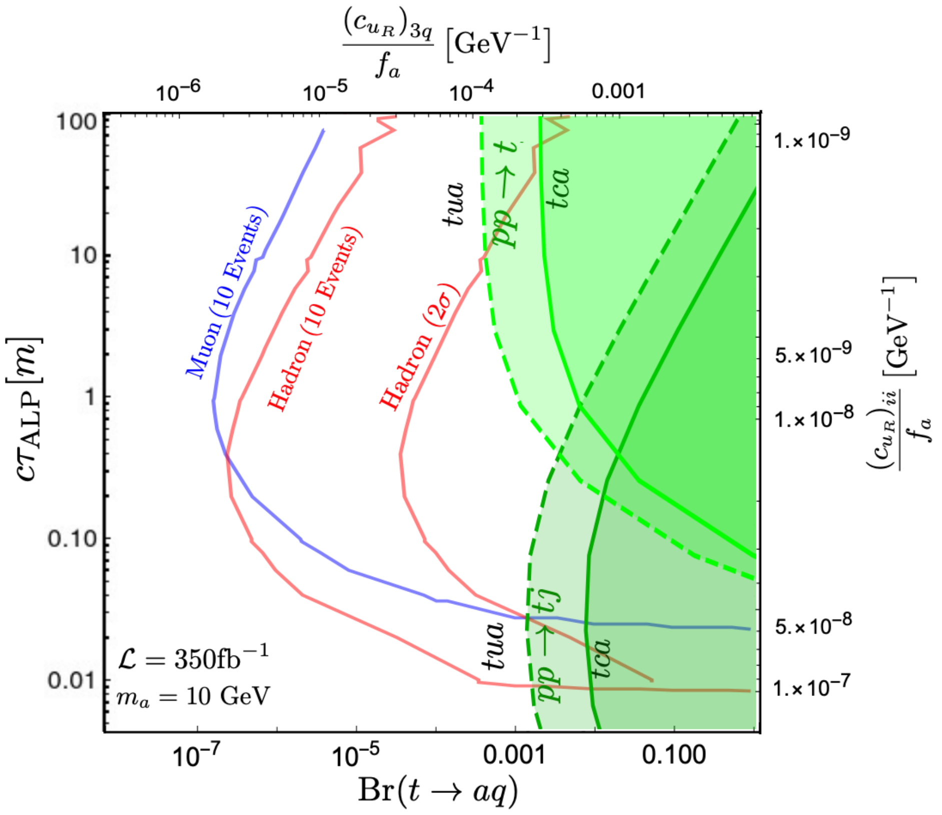

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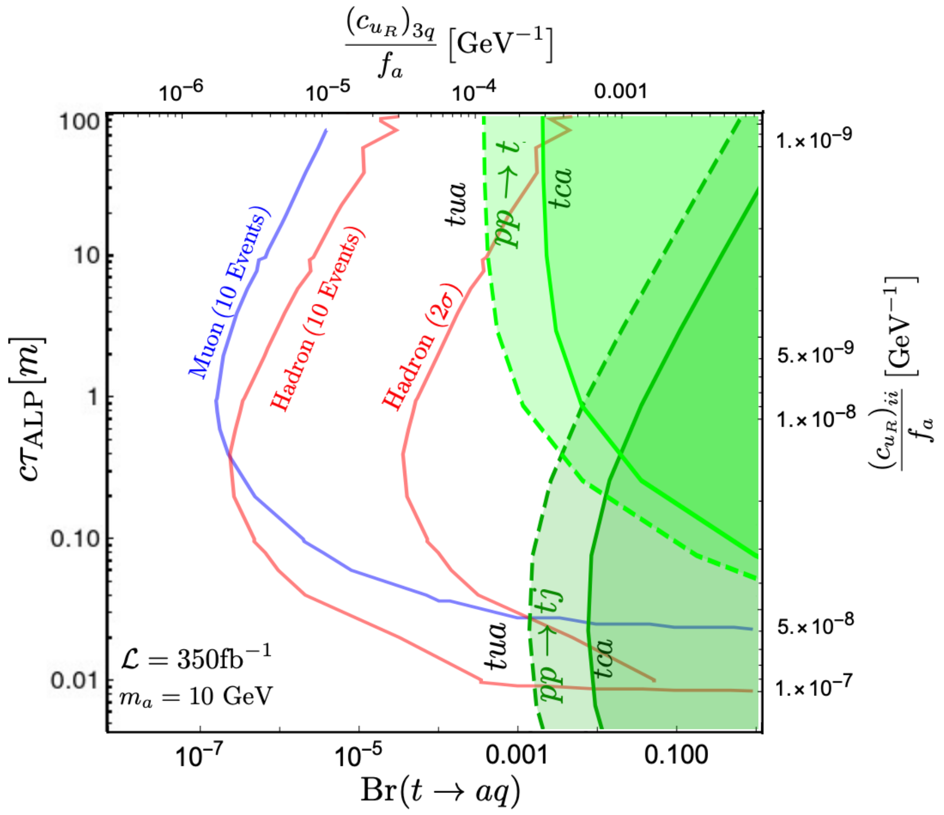

[Carmona et al. 2202.09371]

→ What if we just have top-decay operators?

Rare top-quark decays III

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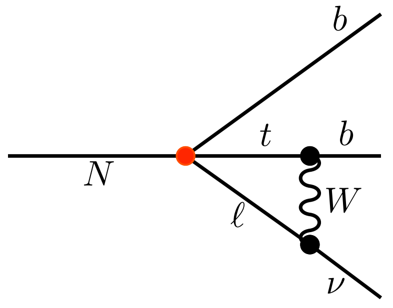

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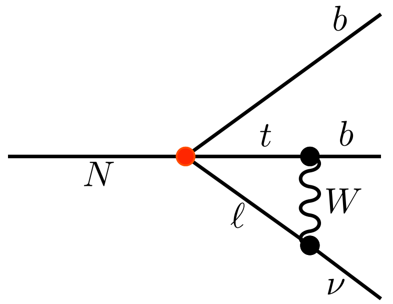

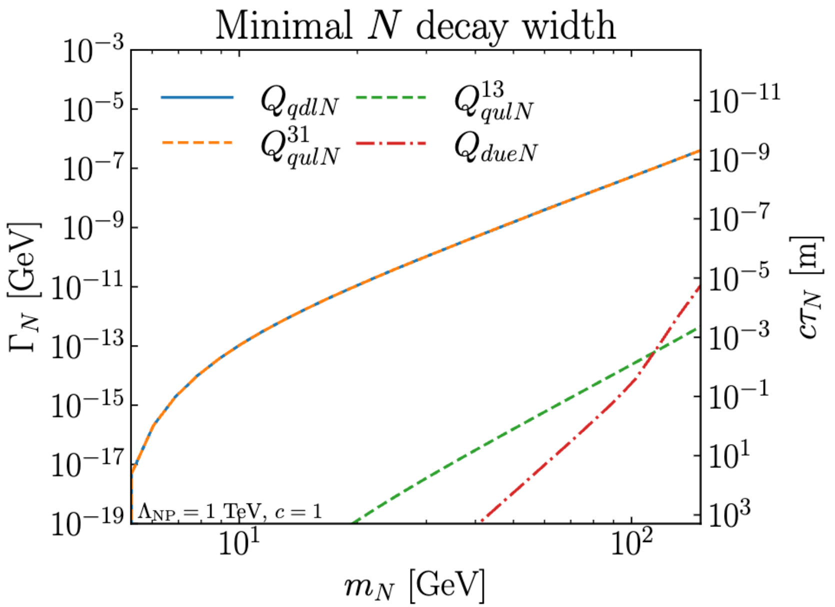

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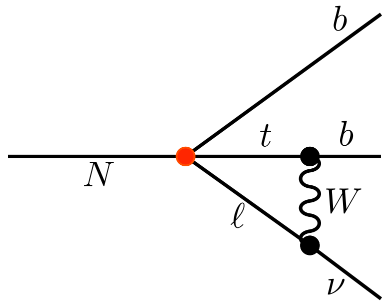

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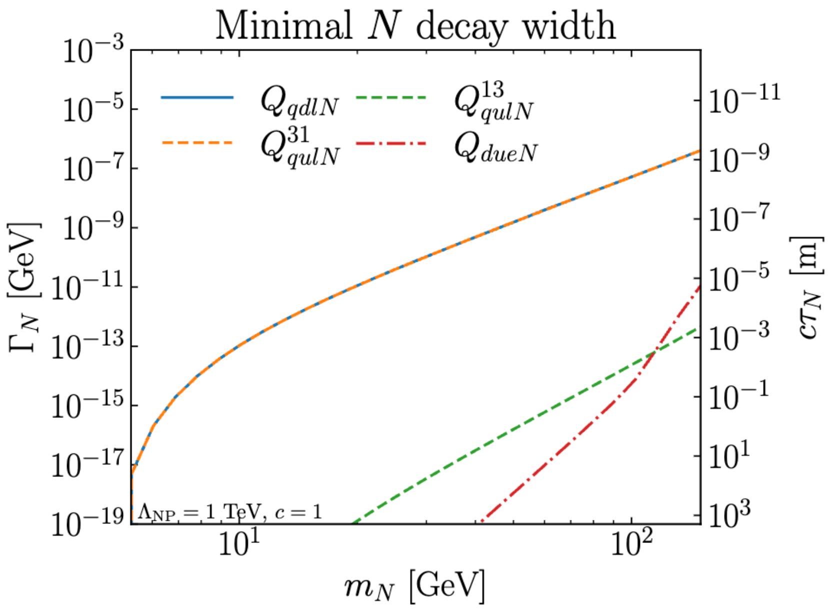

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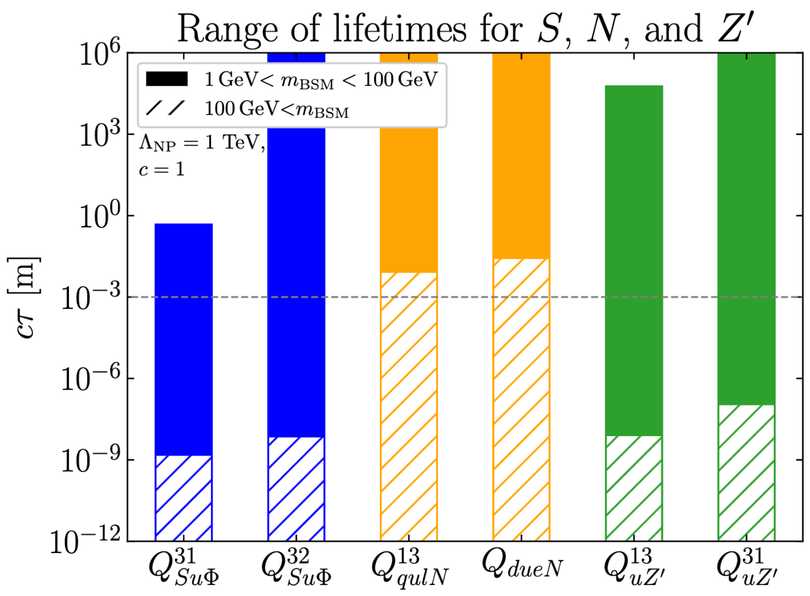

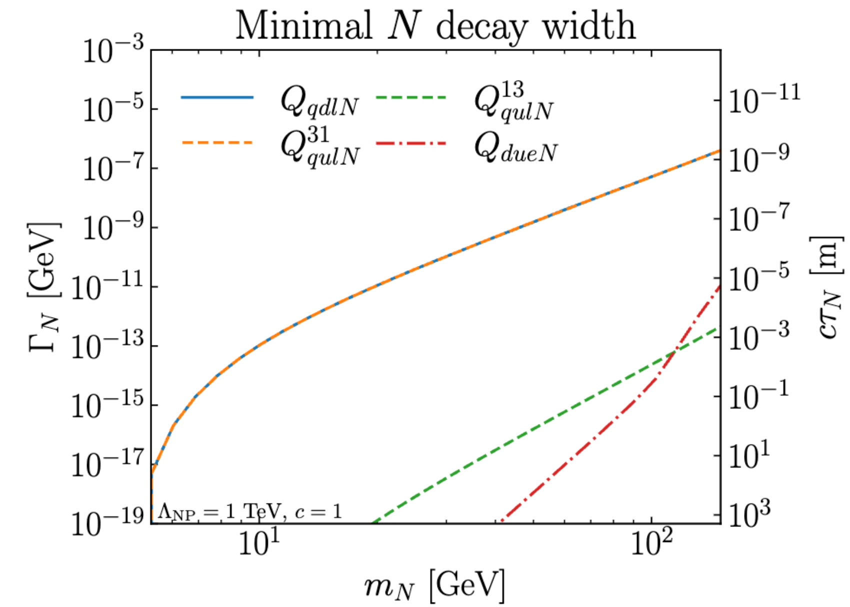

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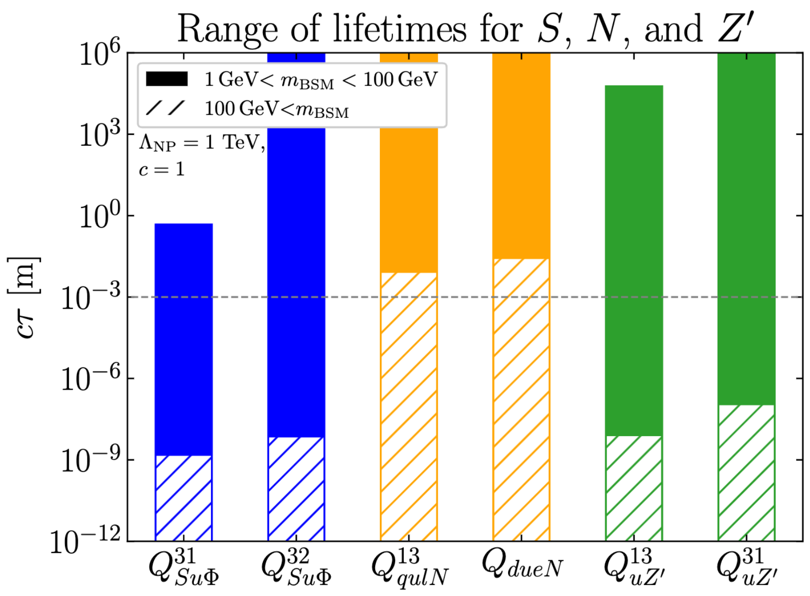

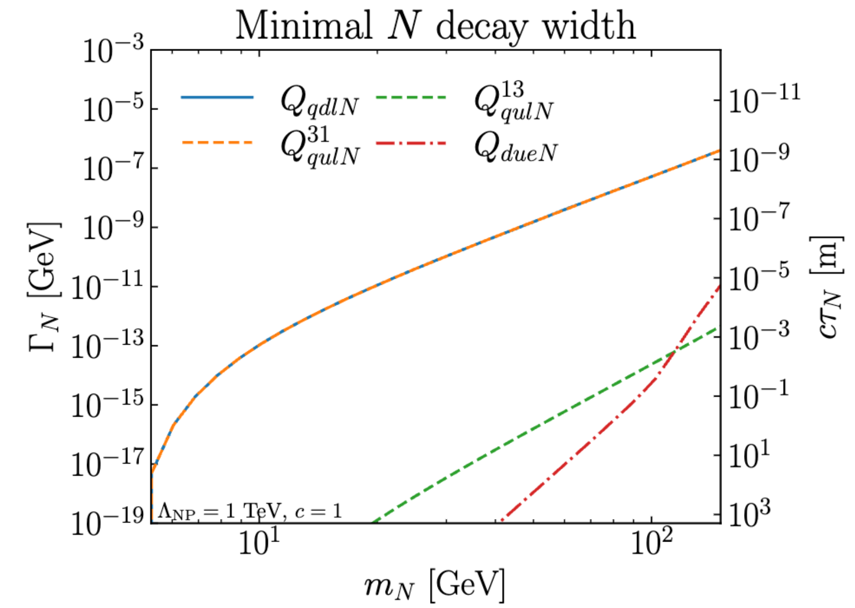

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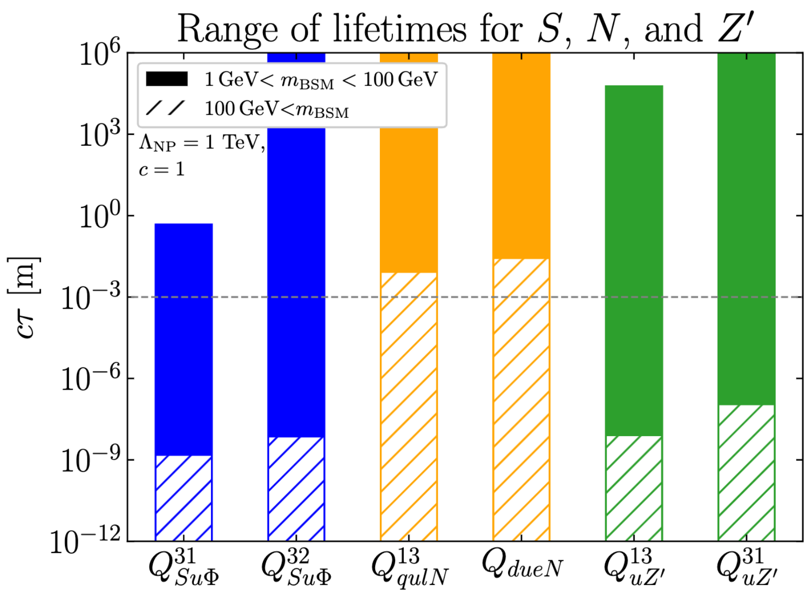

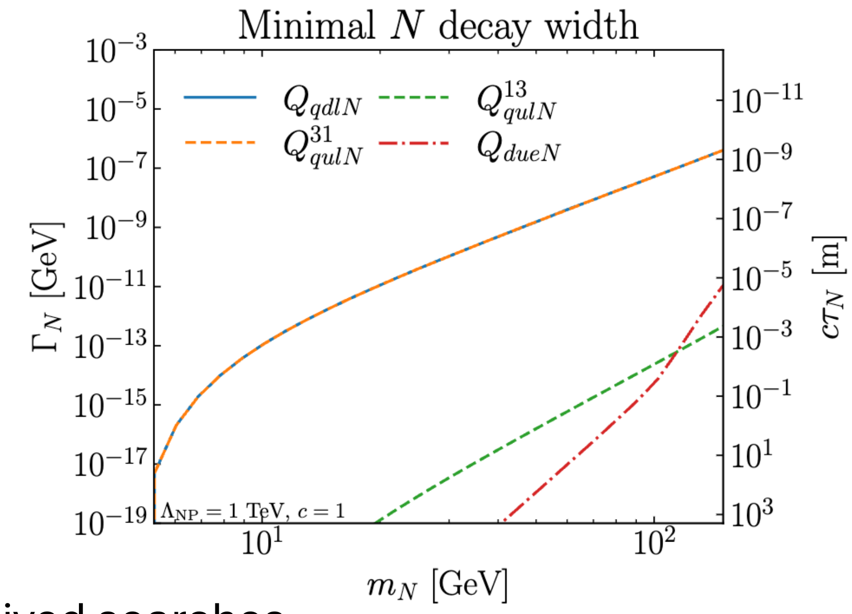

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→ Many interesting unexplored signatures for prompt and long-lived searches.

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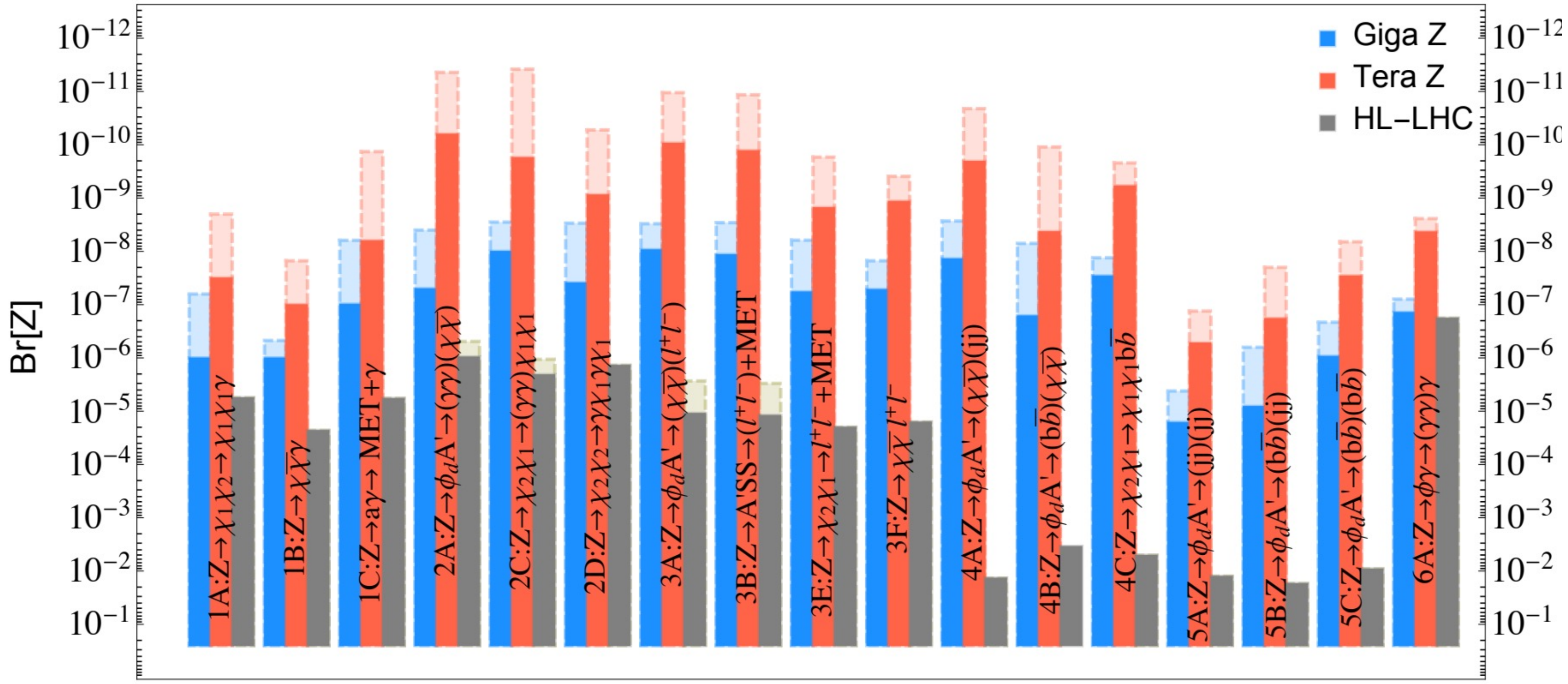

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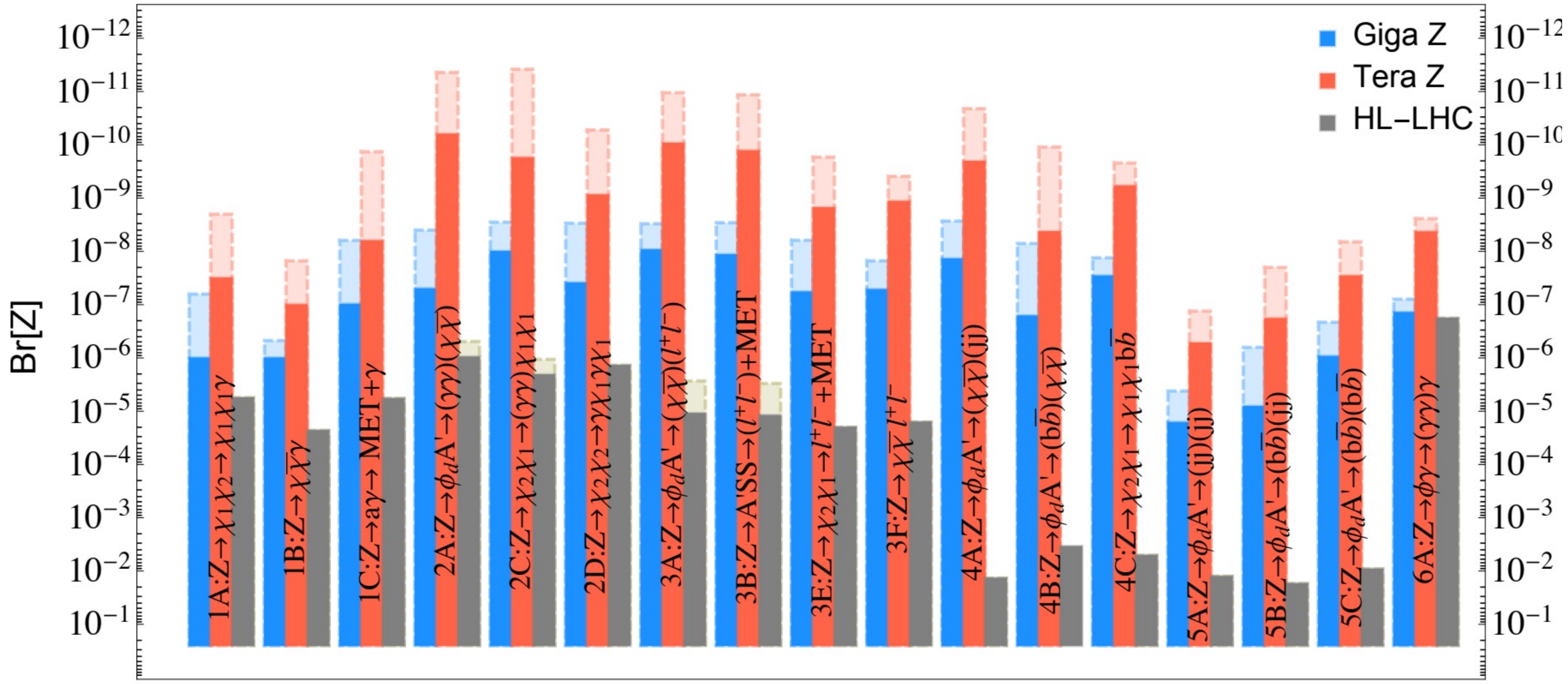

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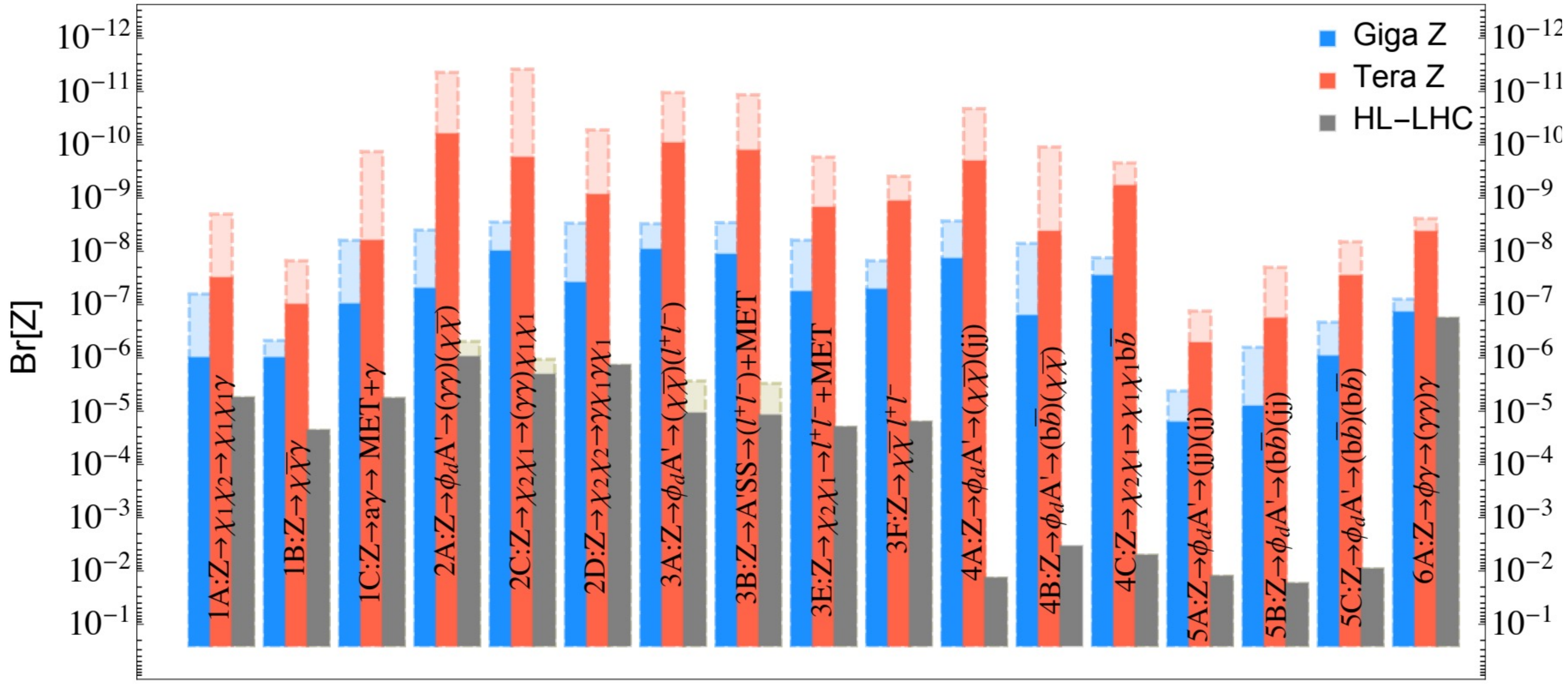

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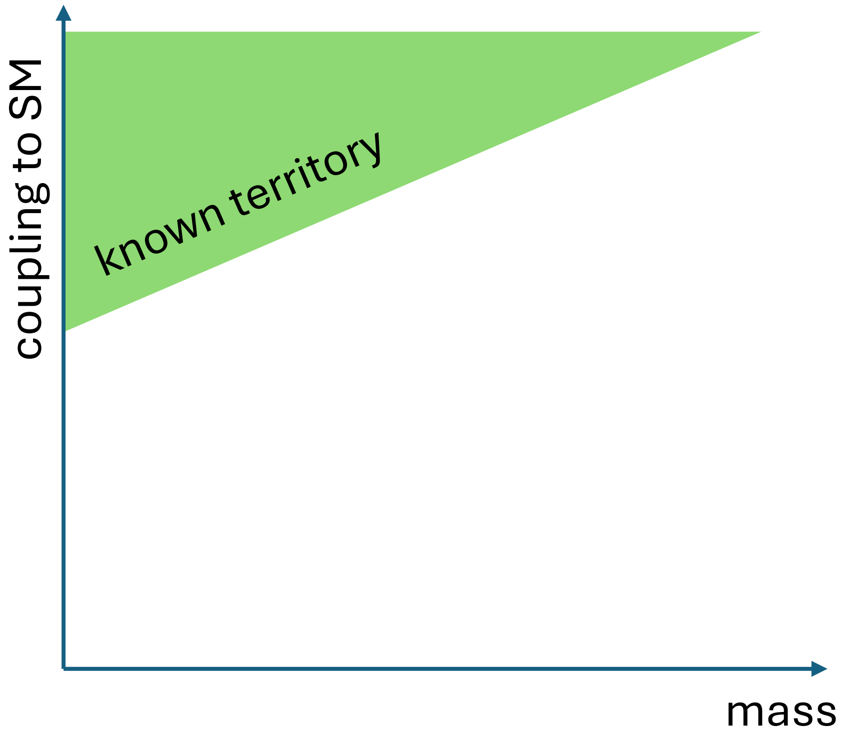
Constraining heavy BSM physics

The Higgs lamppost and the interplay with precision measurements

What to learn from Higgs precision measurements?



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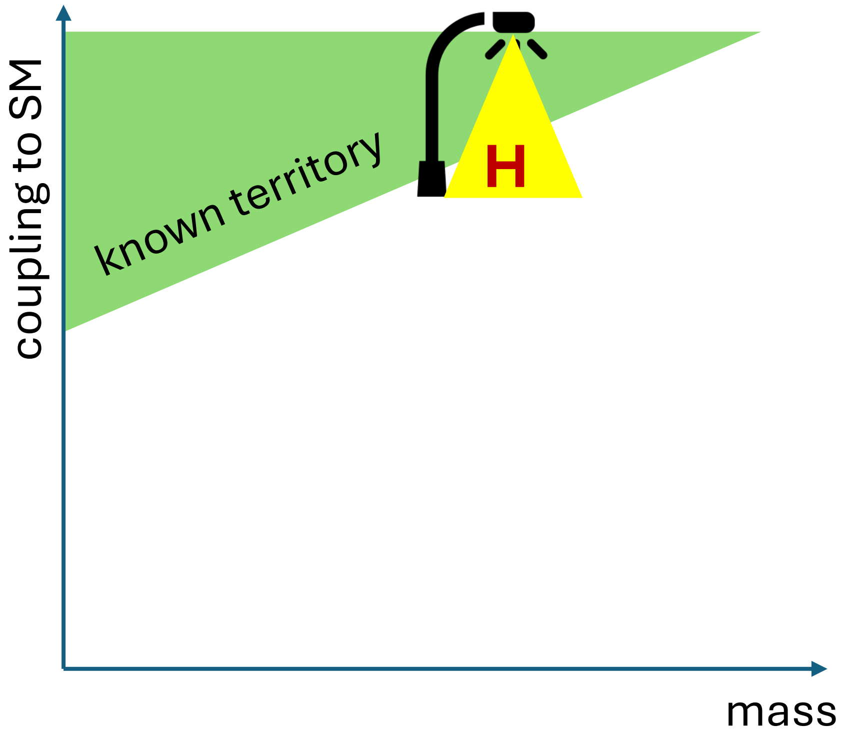

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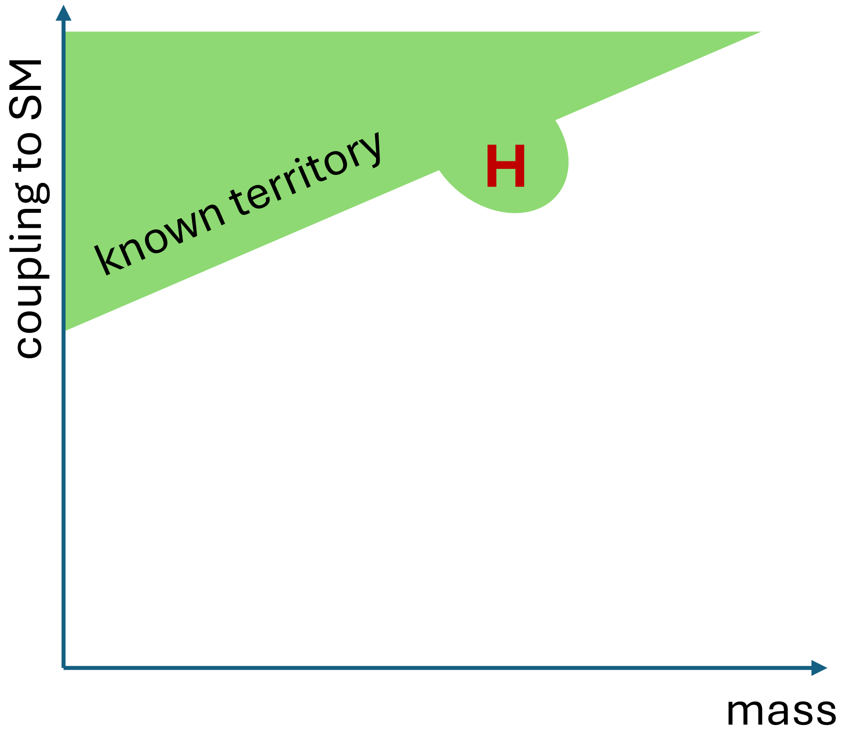

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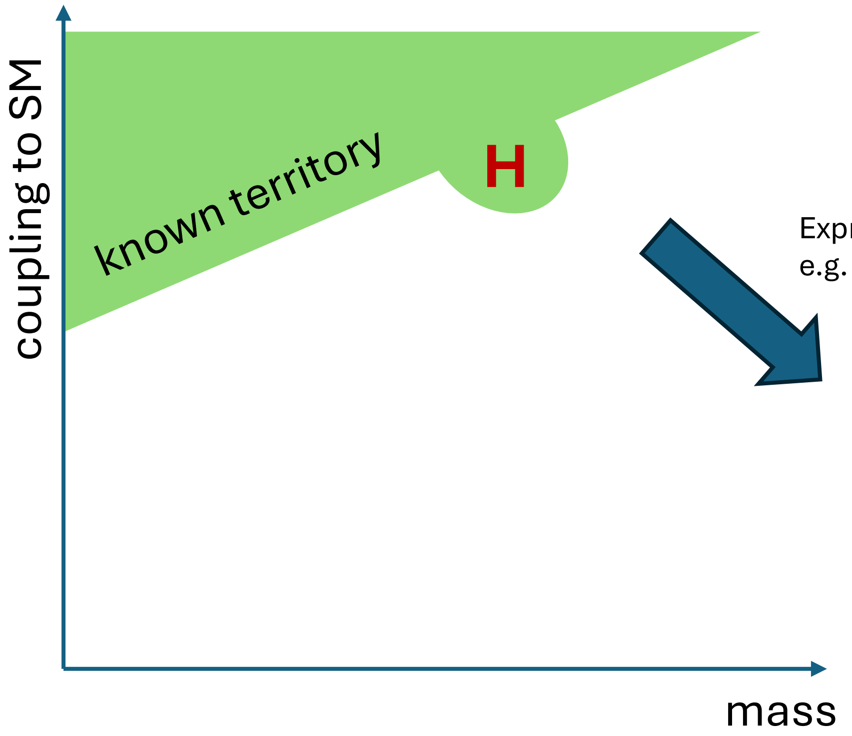
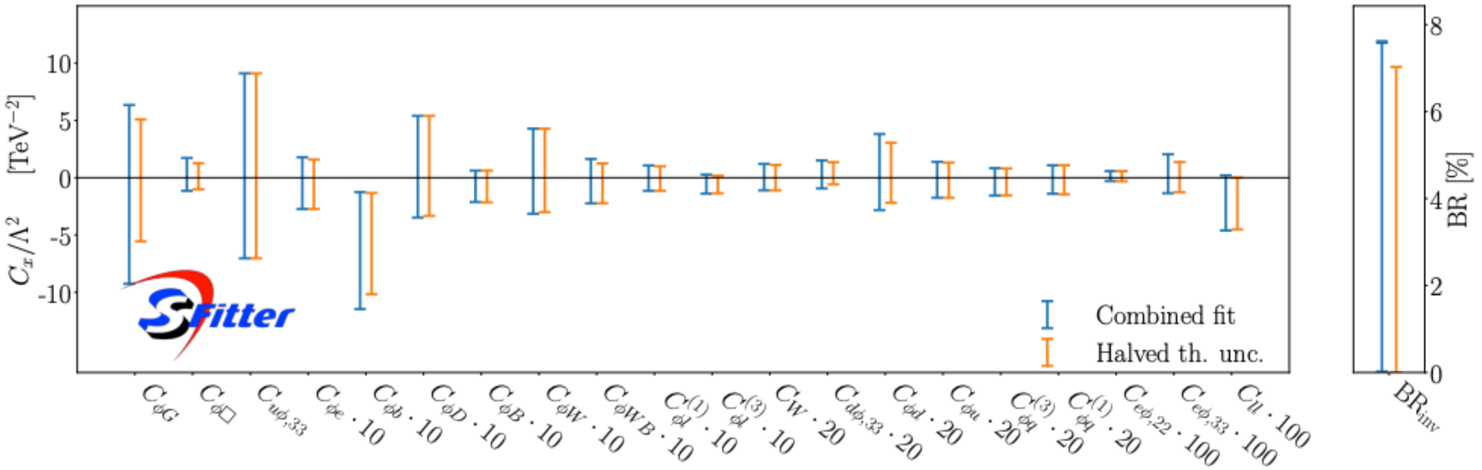


Express these constraint
e.g. using SMEFT



[Elmer et al., 2312.12502]

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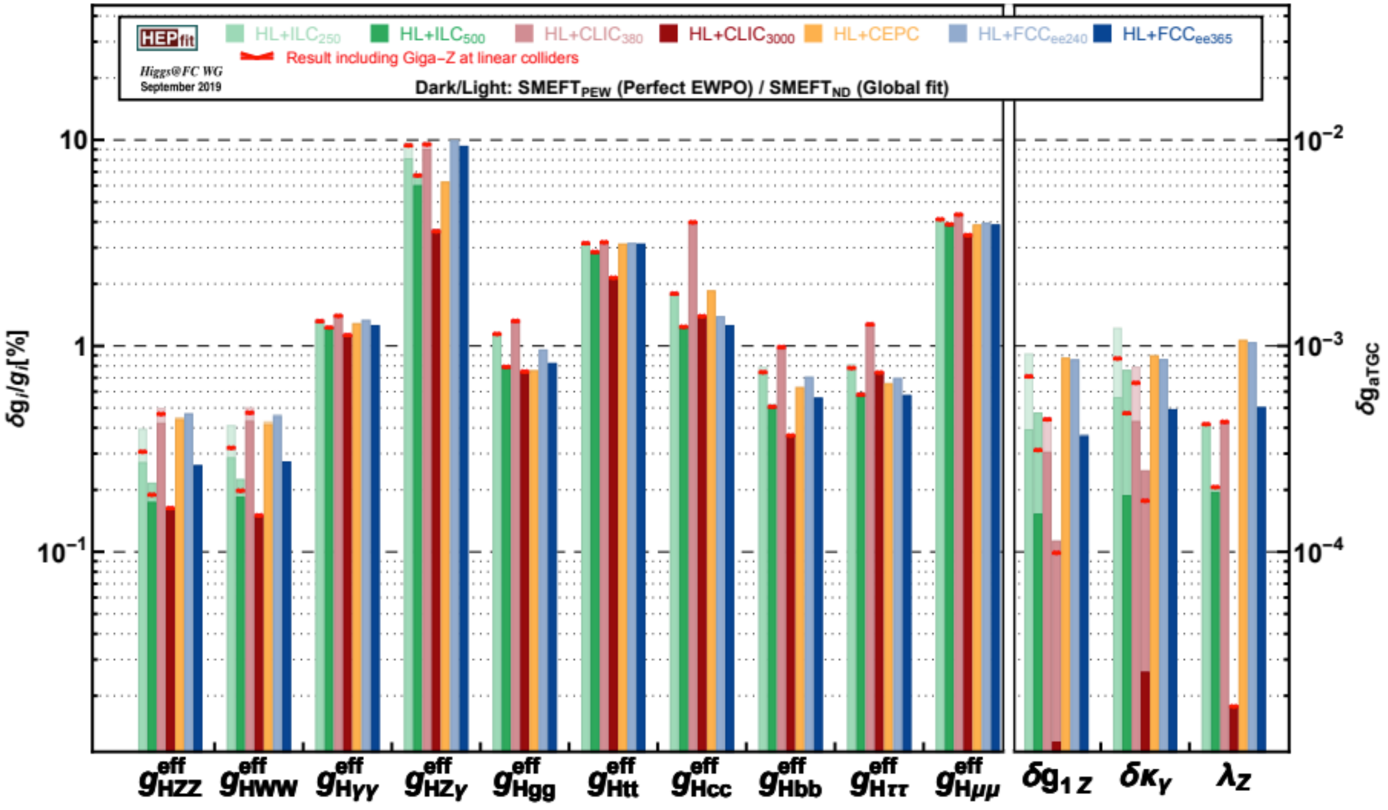

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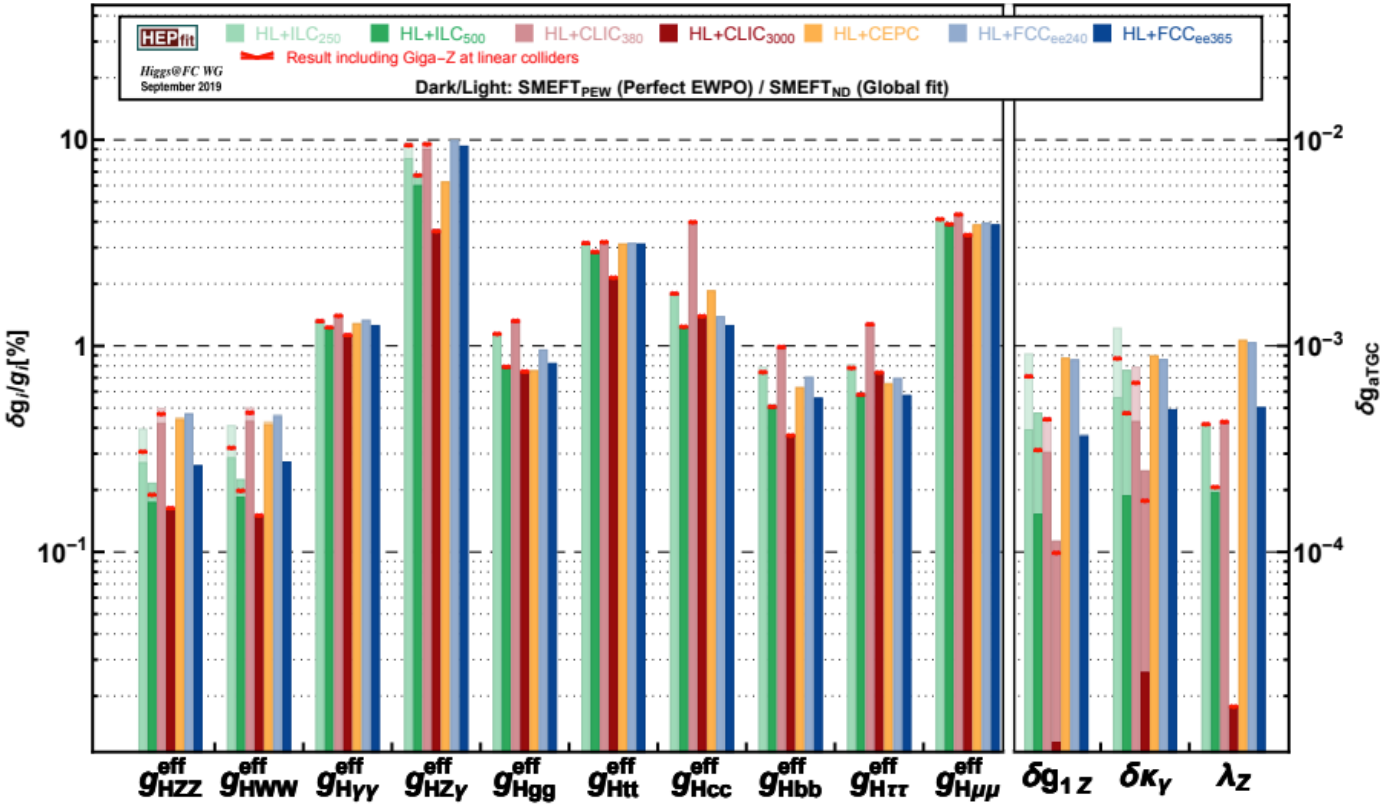

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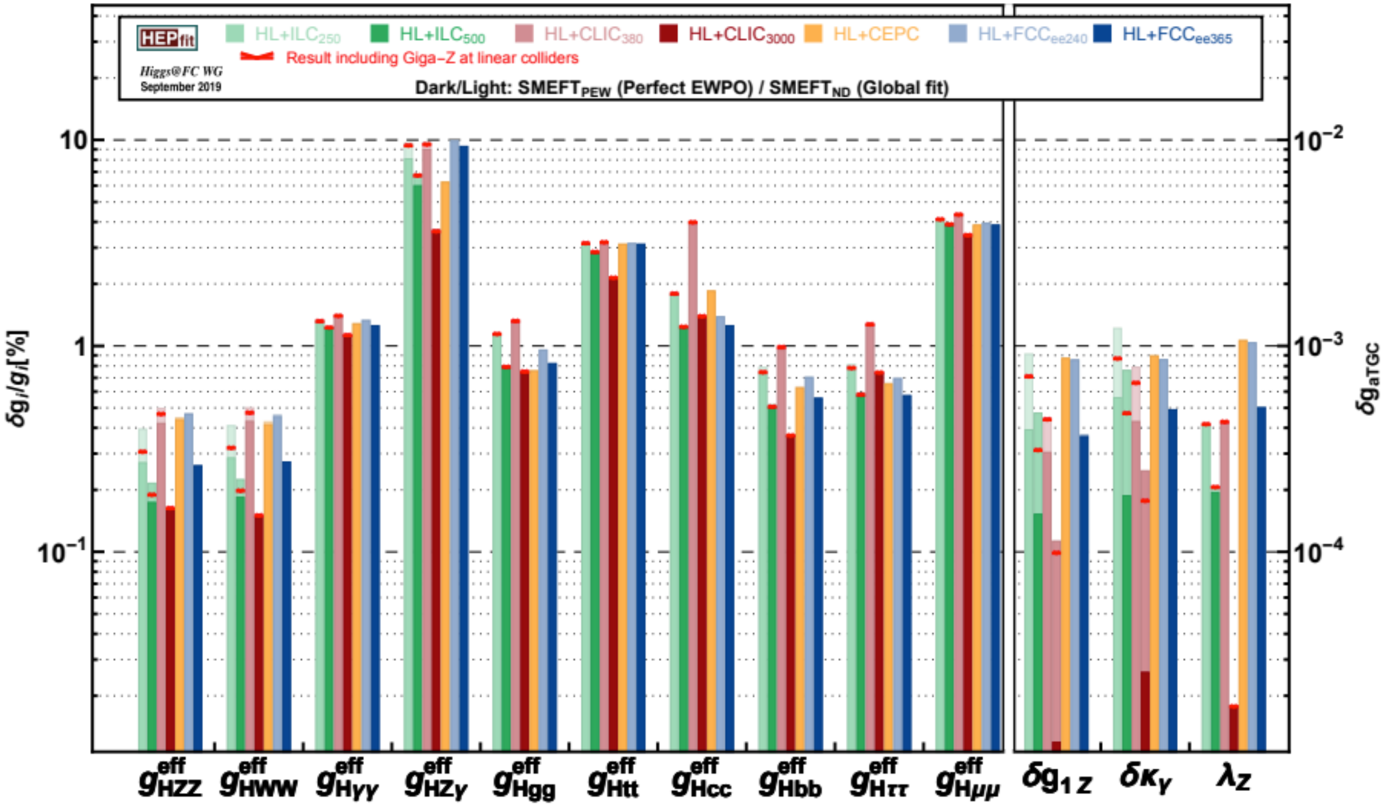

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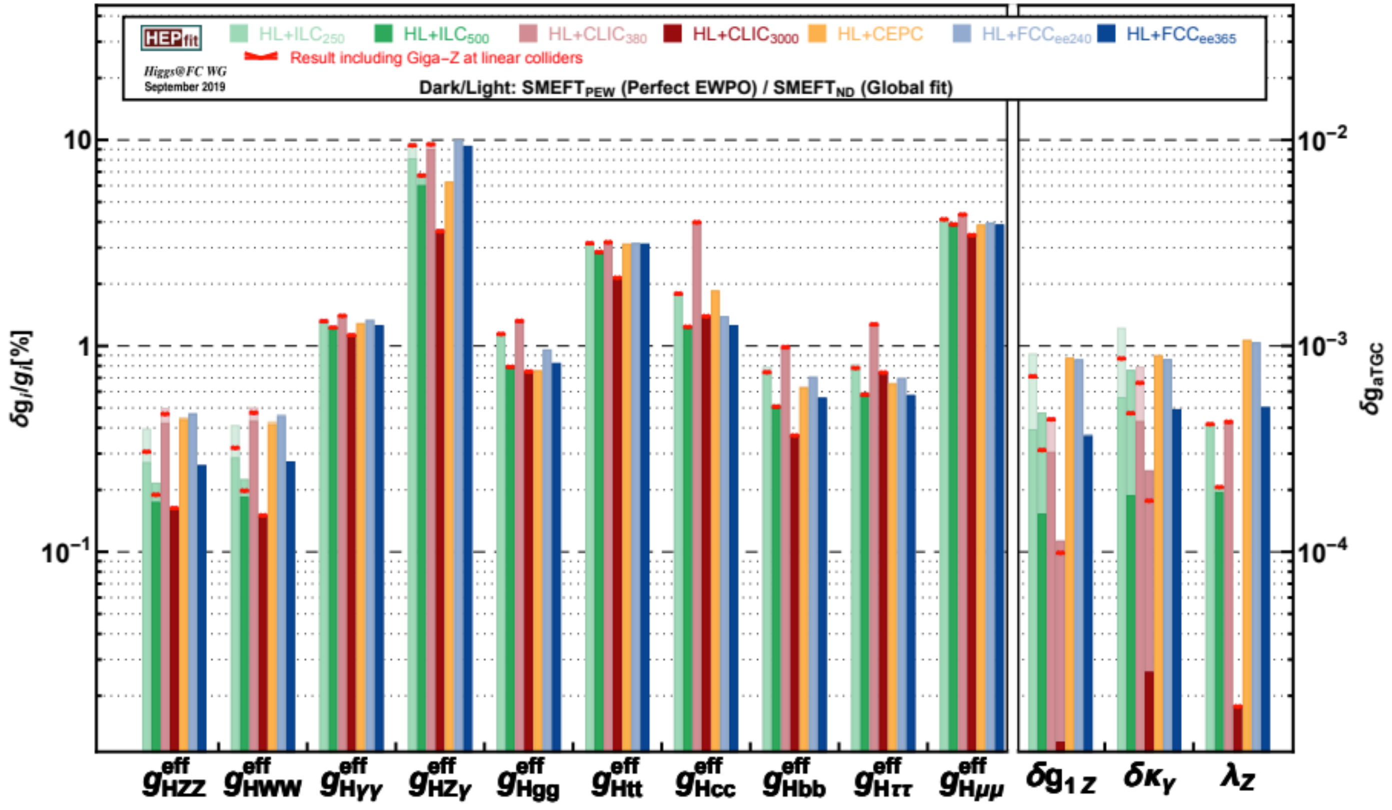

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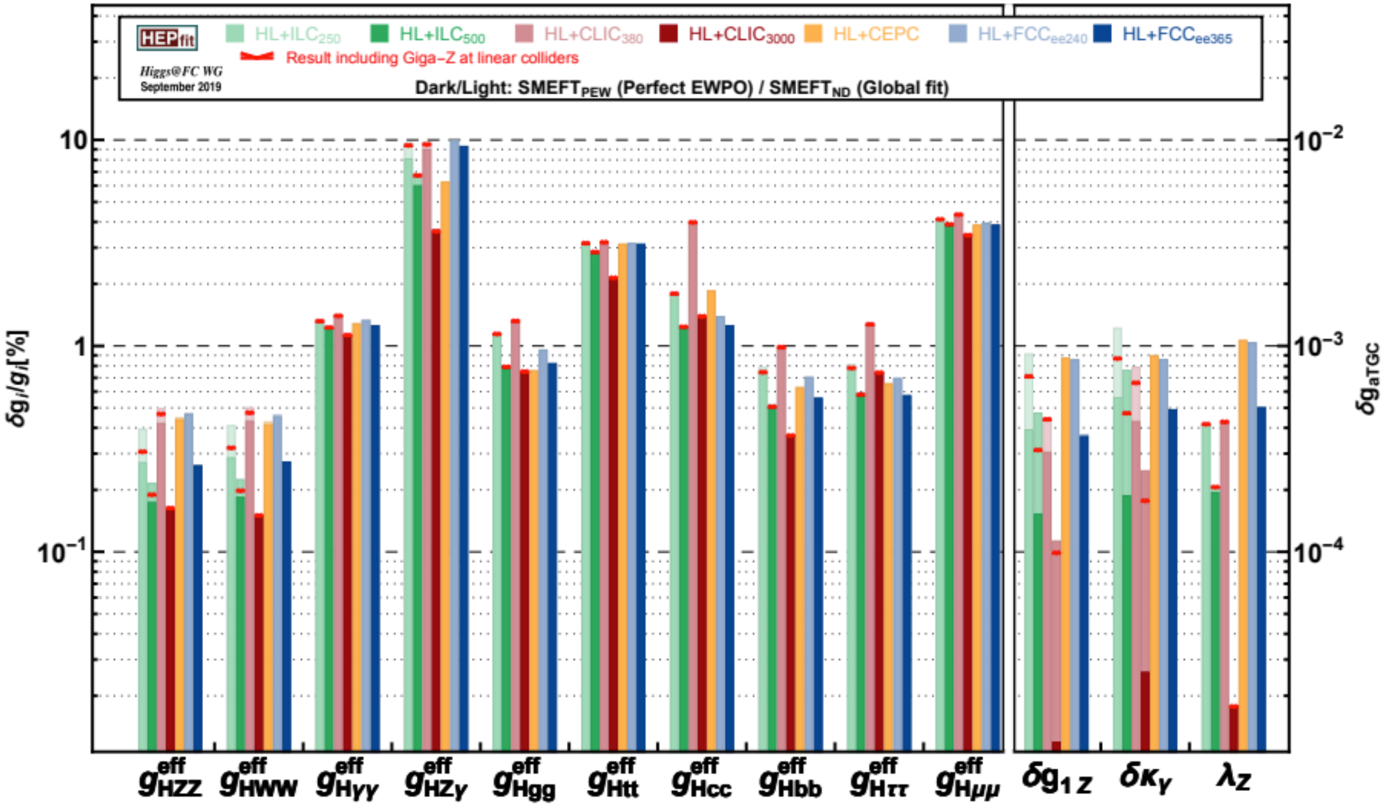

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Consider simple BSM extensions of the SM!

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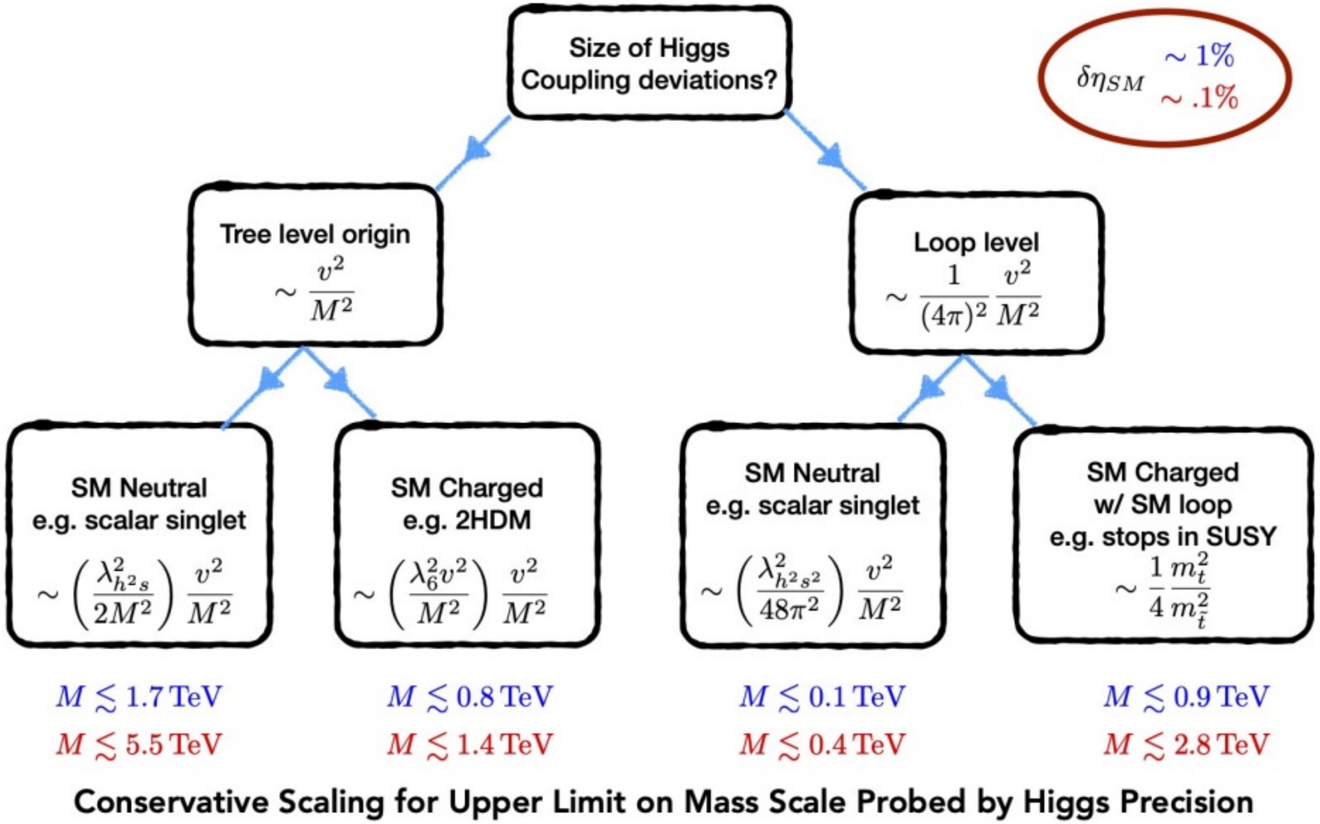

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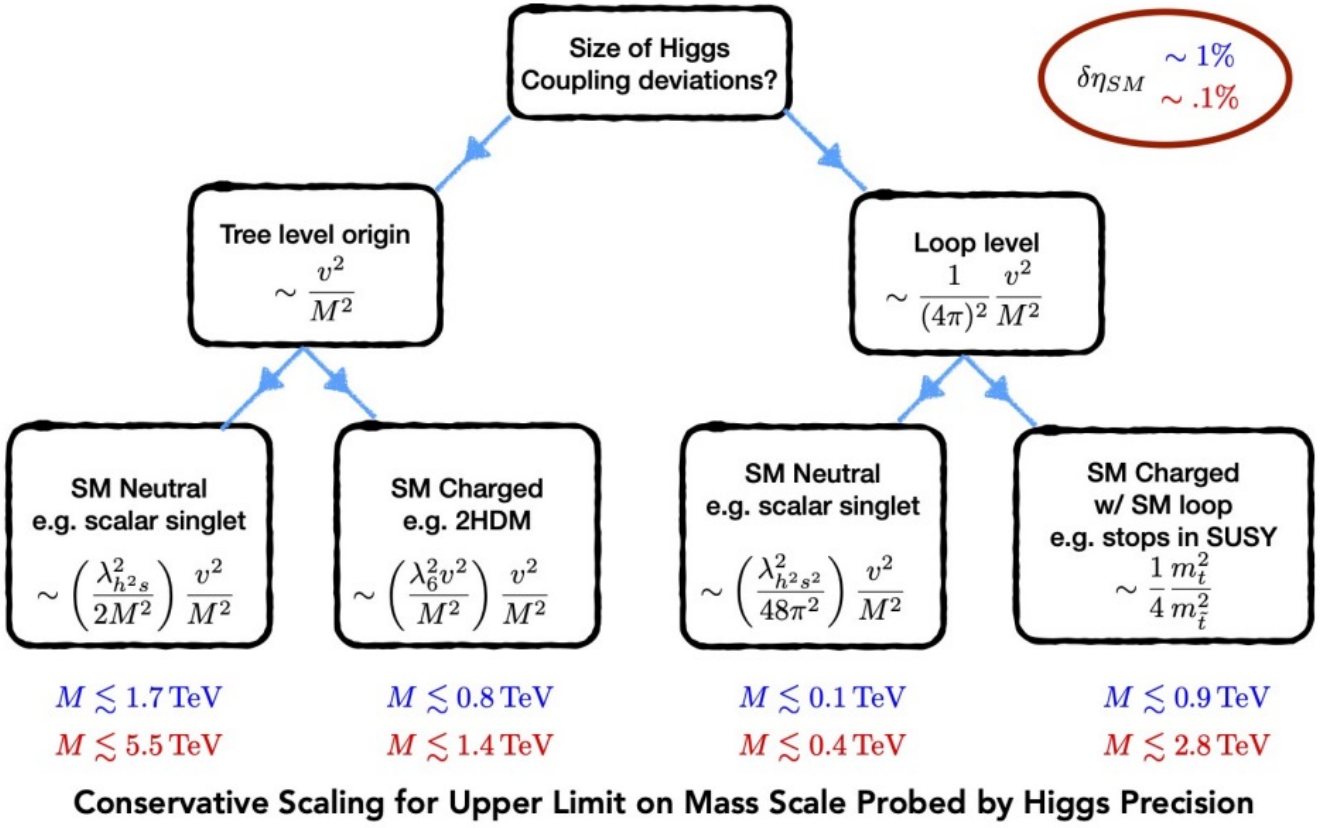

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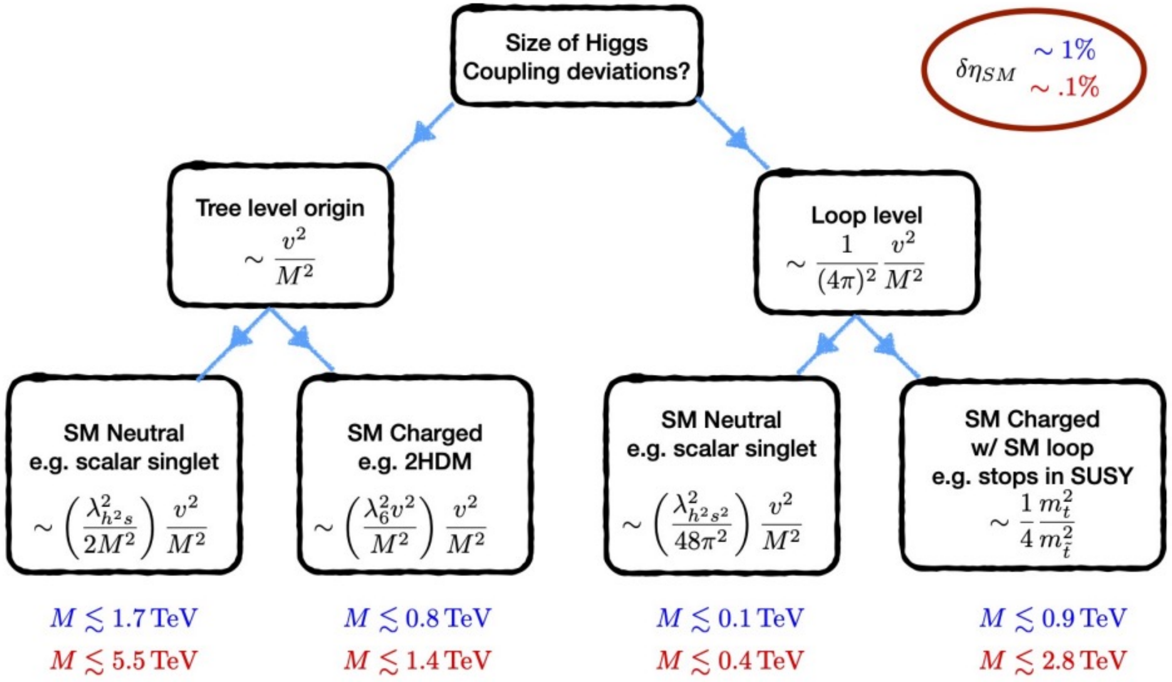
Simplified scaling analysis:

- 1% precision constrains BSM particles with mass from 100 GeV to several TeV.

Case study: Higgs singlet extension



Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

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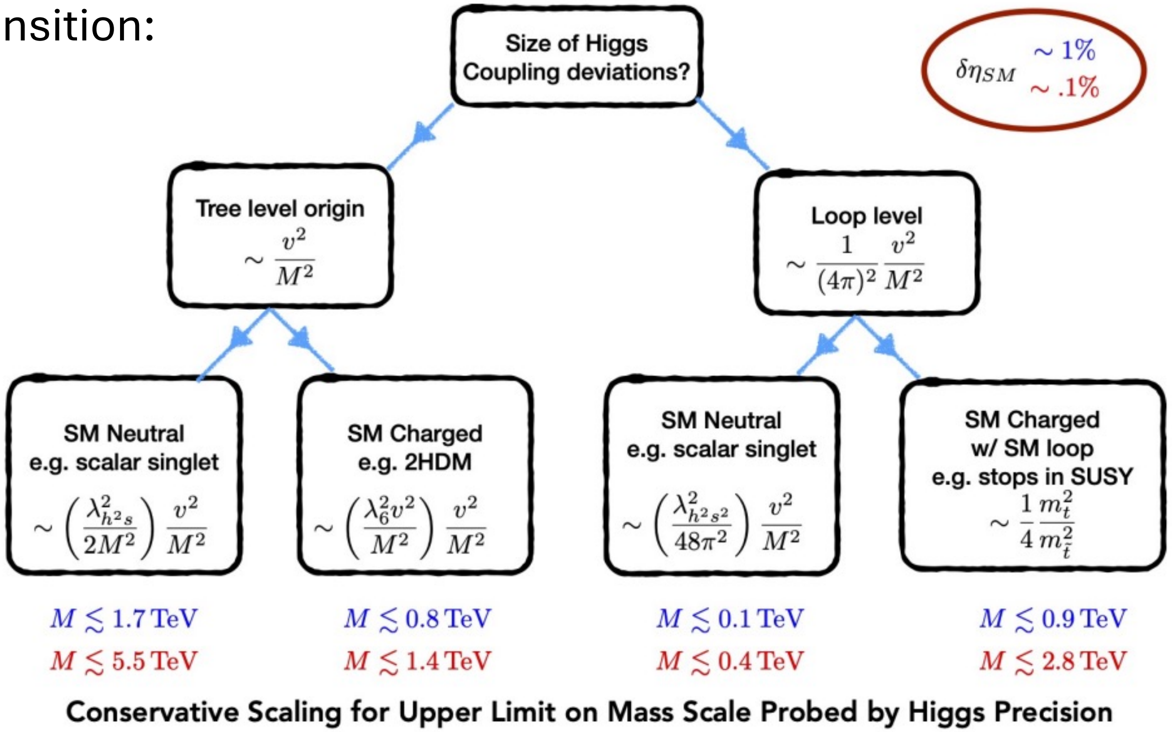
Very simple model allowing for strong 1st order phase transition:



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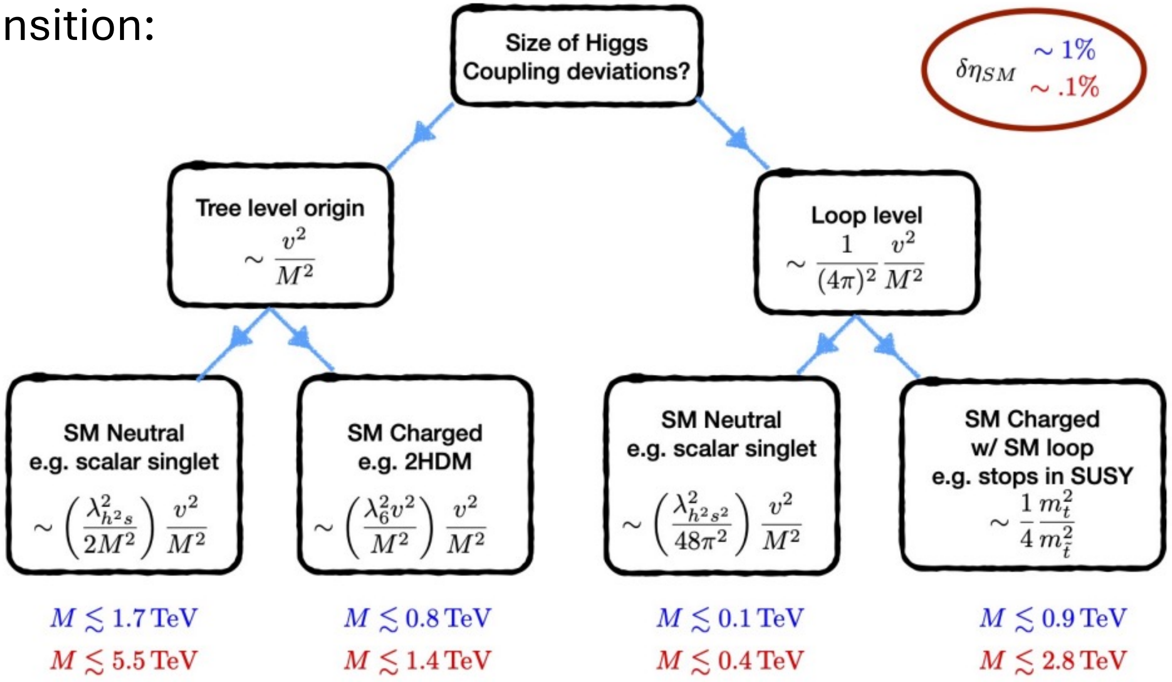

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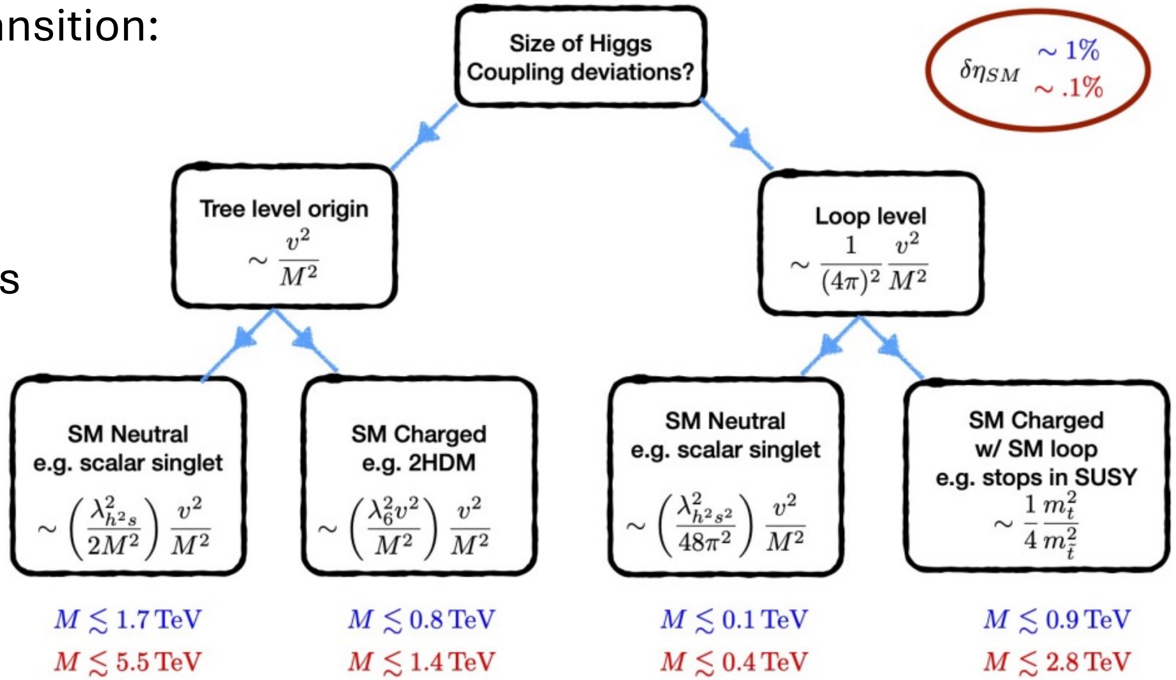

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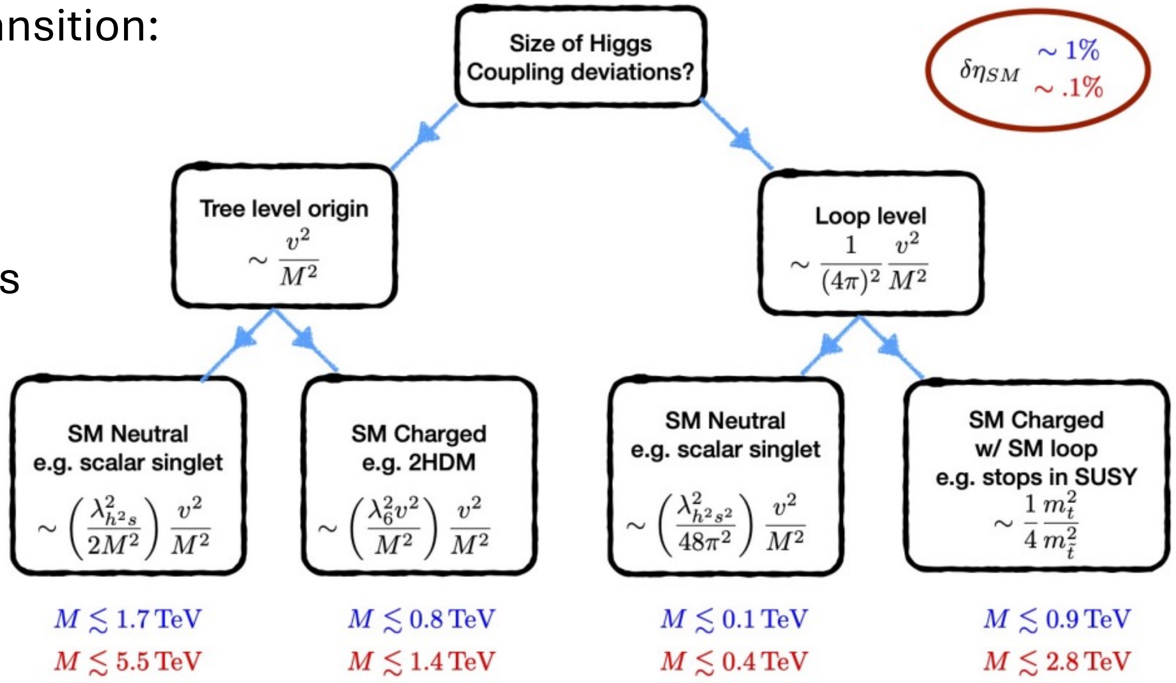

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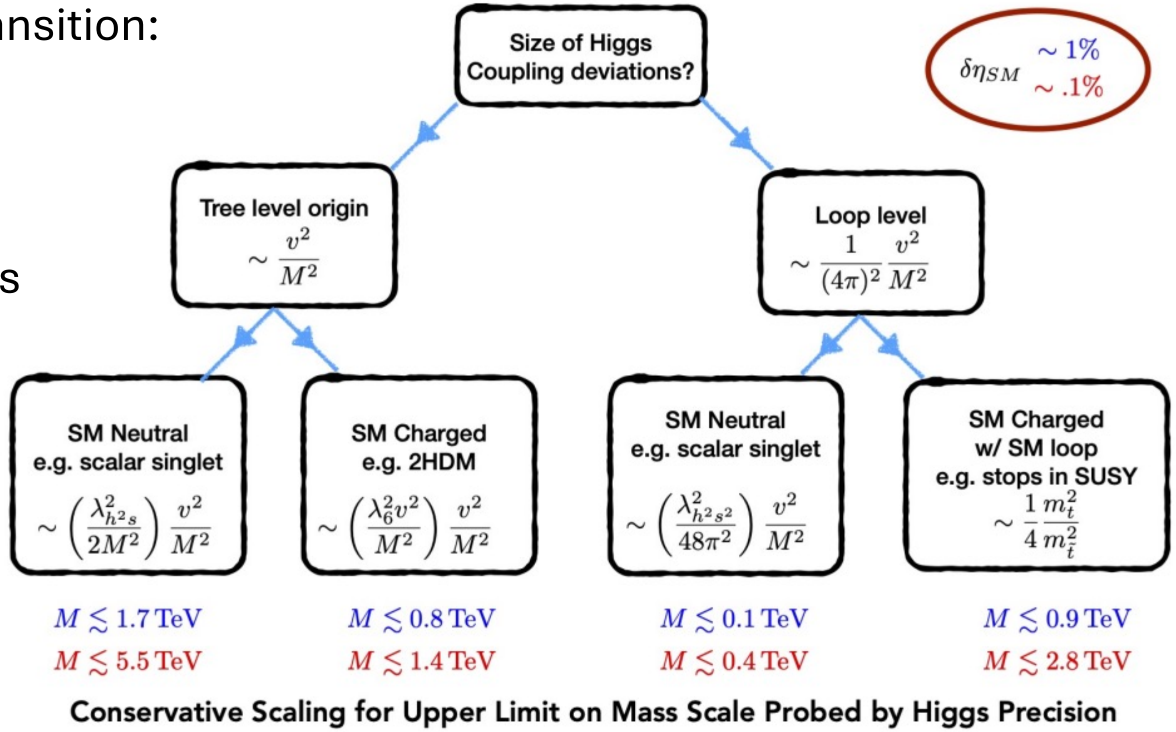

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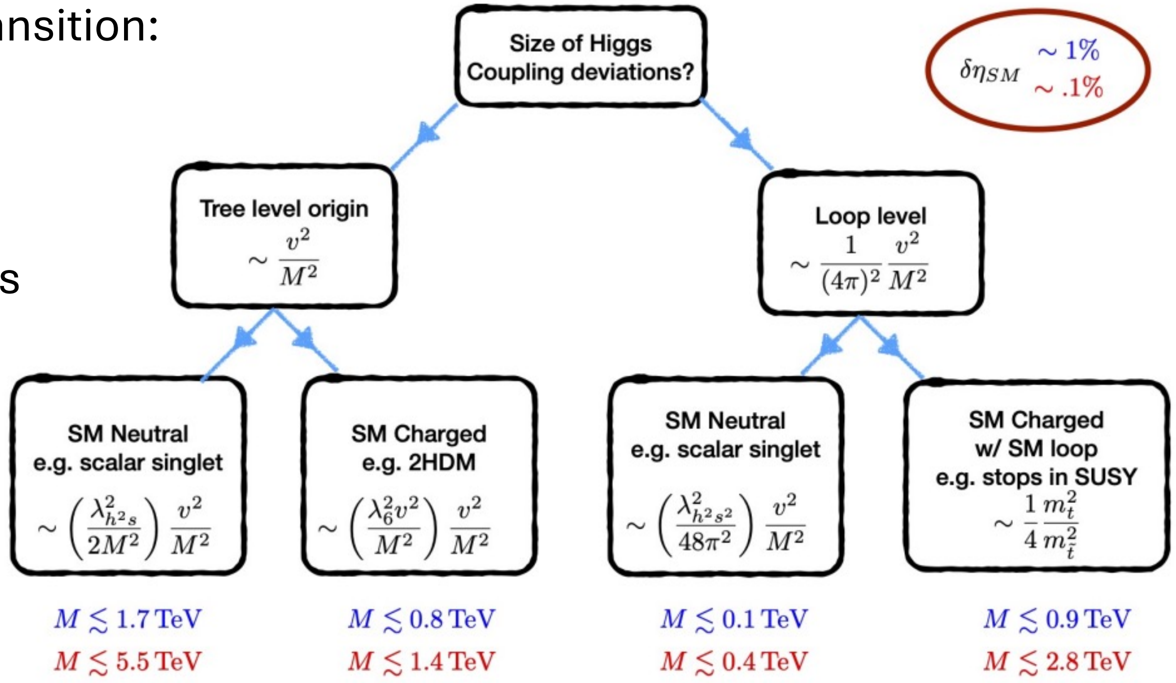

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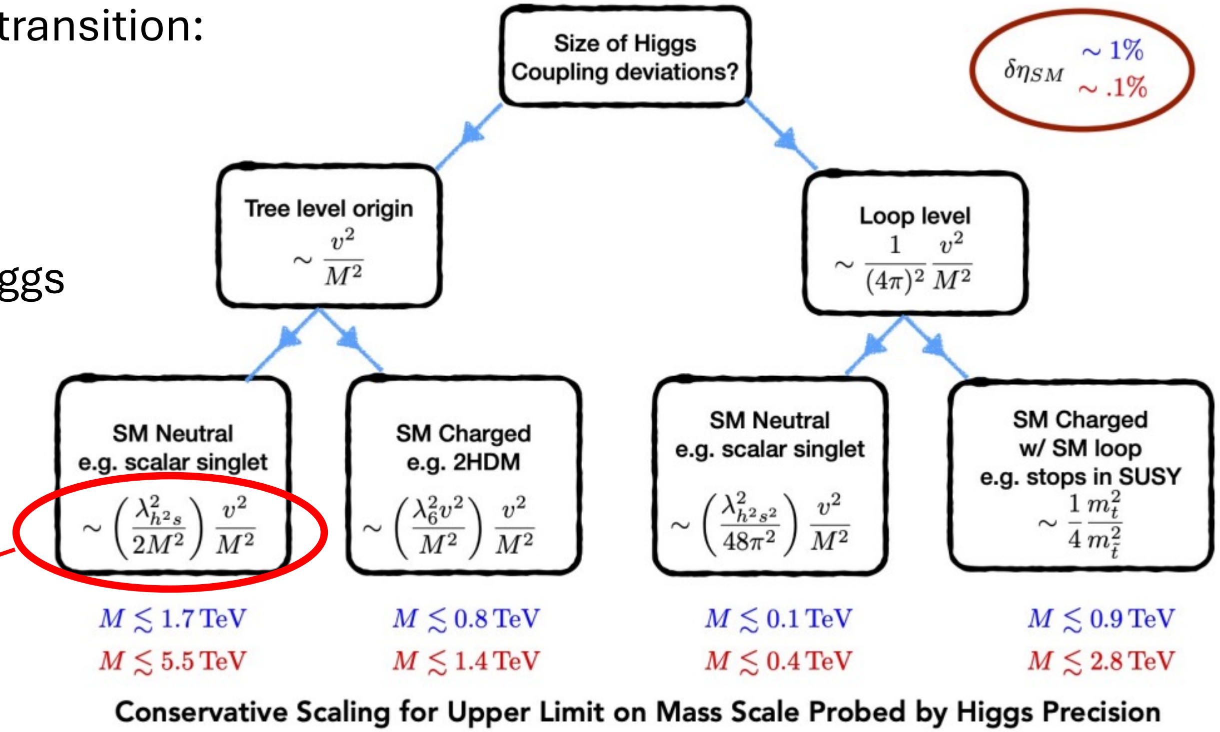

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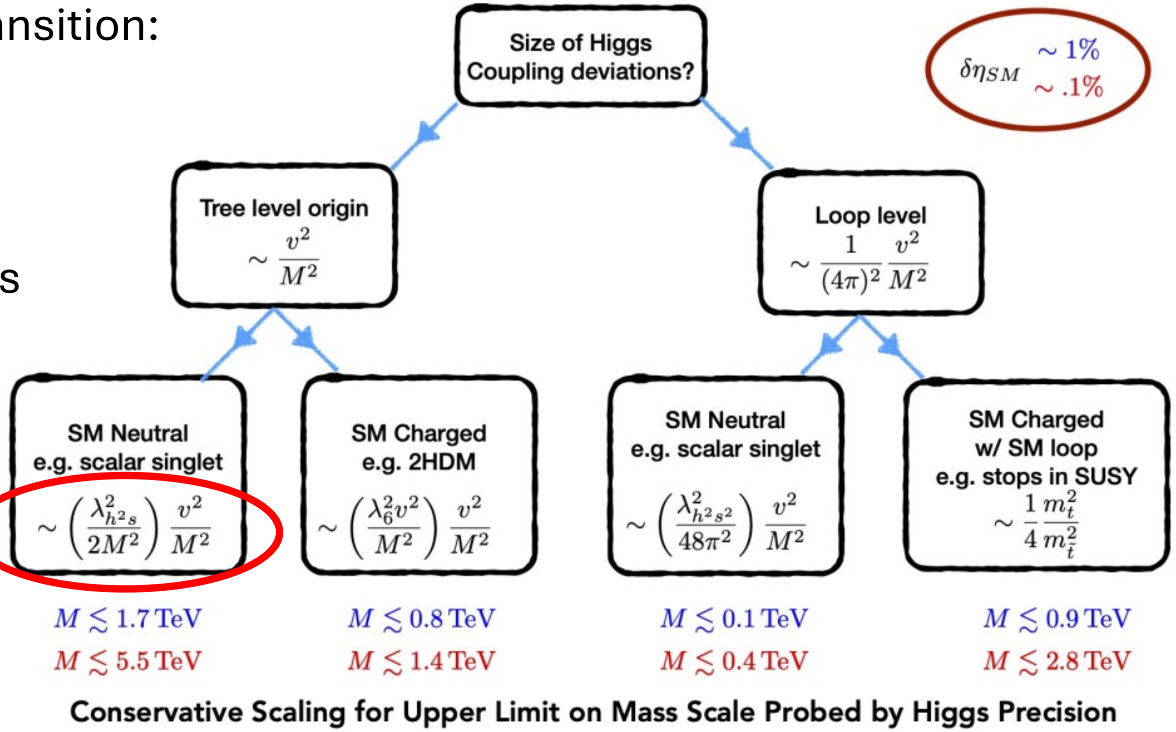

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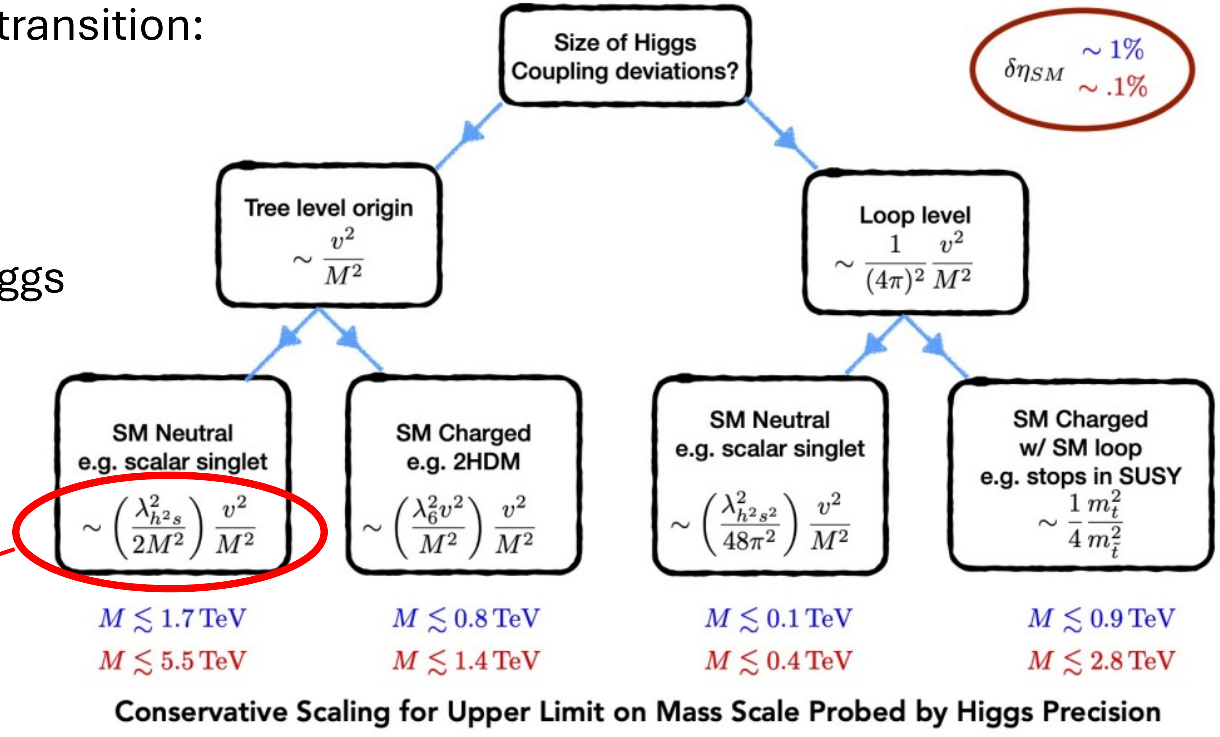

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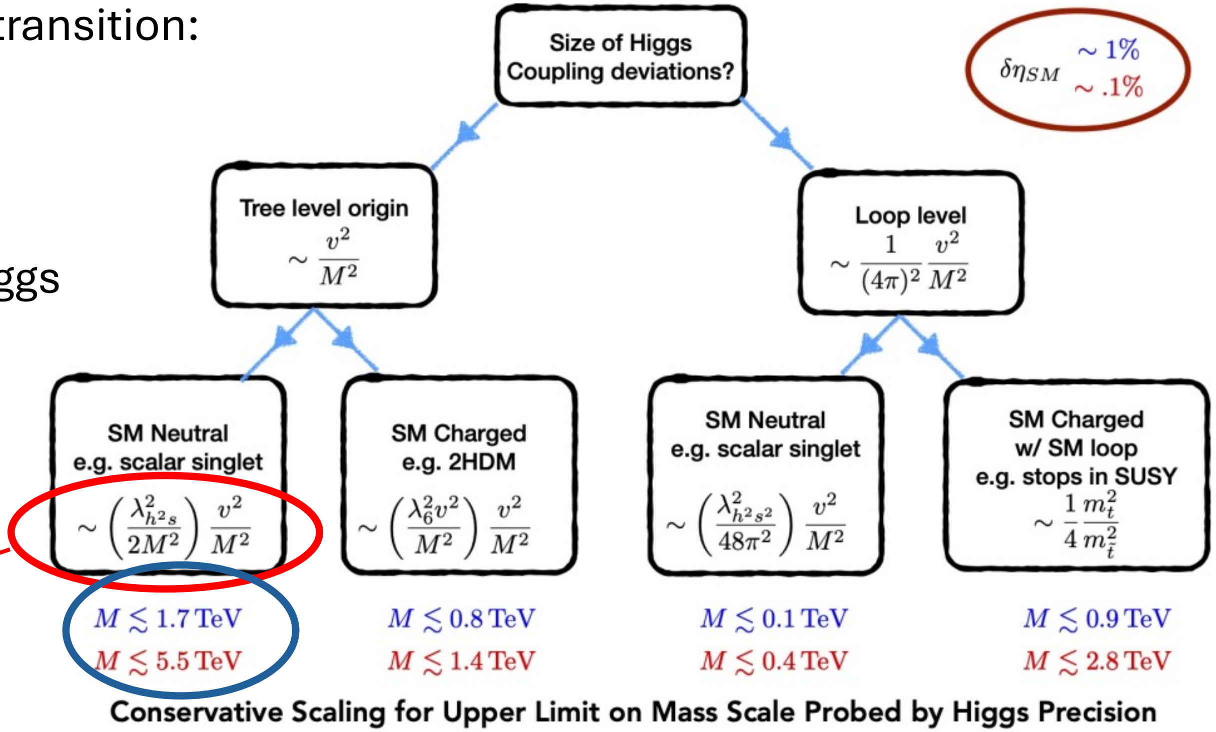

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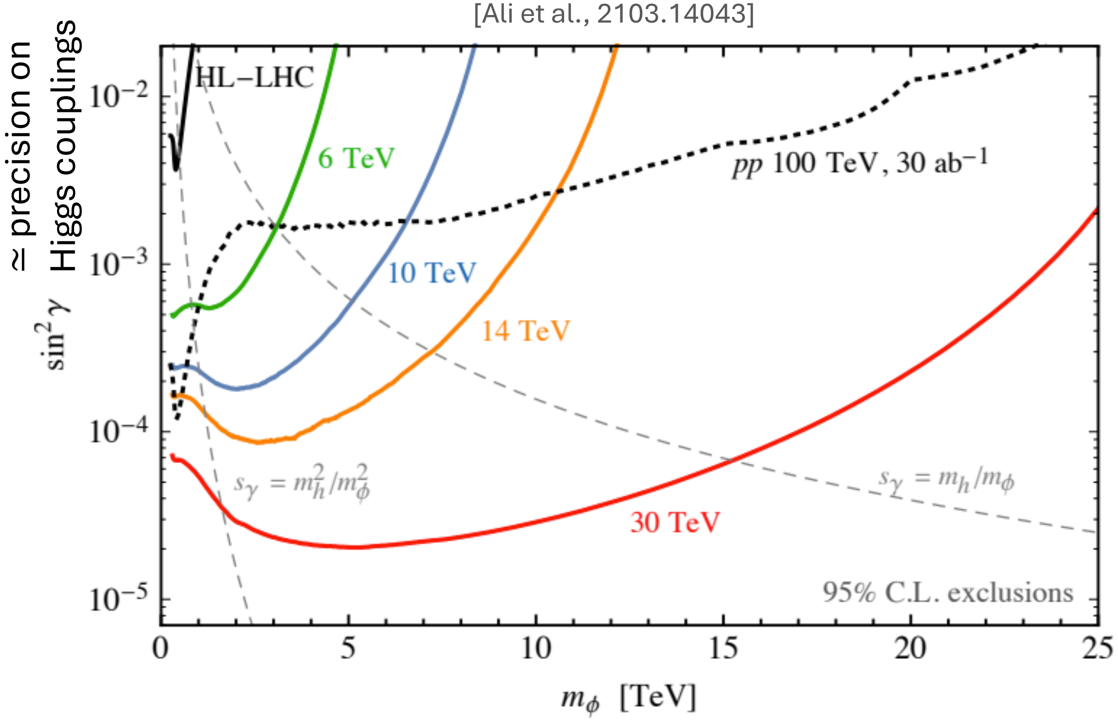
[Ali et al., 2103.14043]



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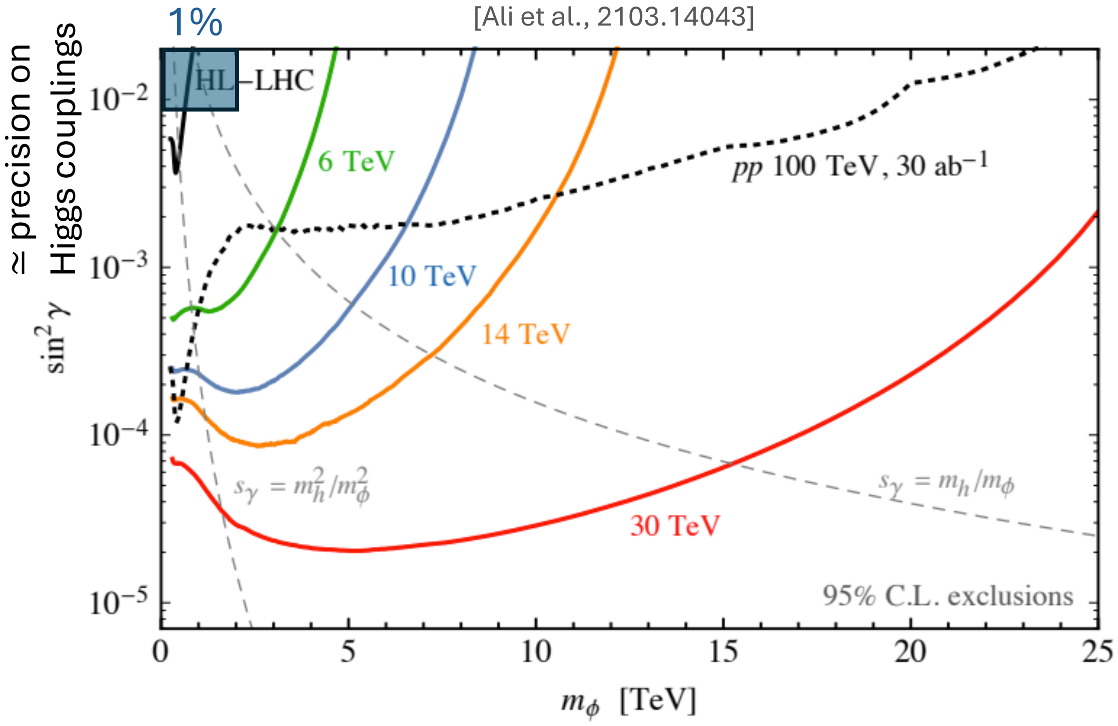

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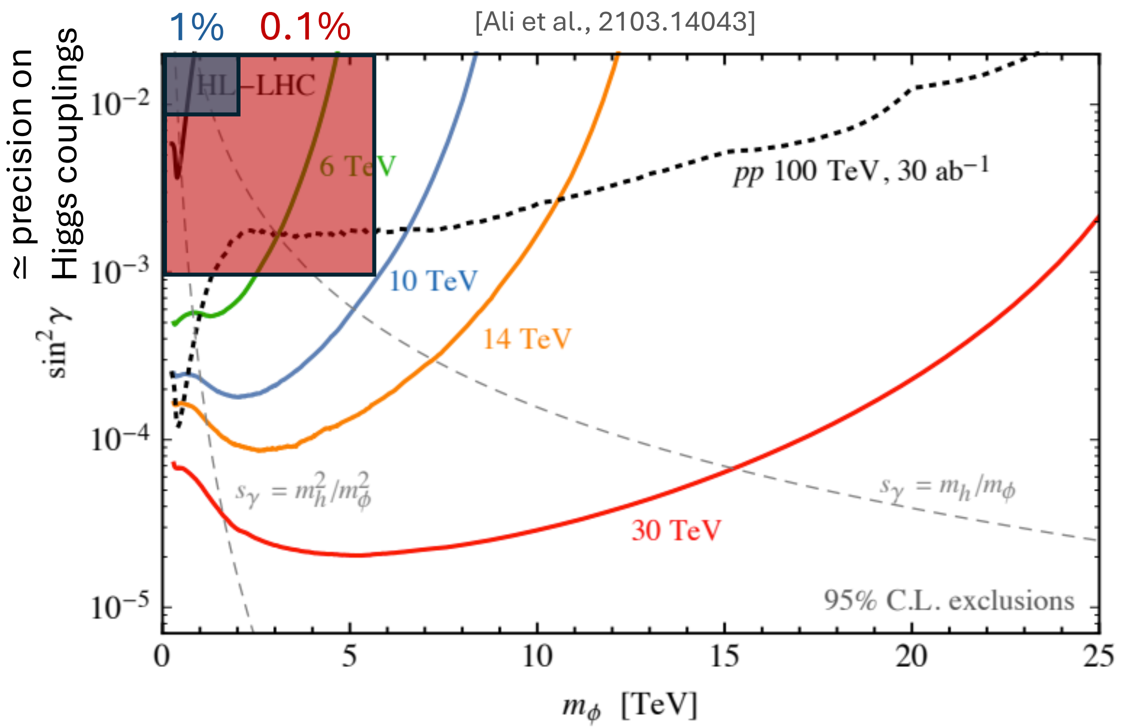

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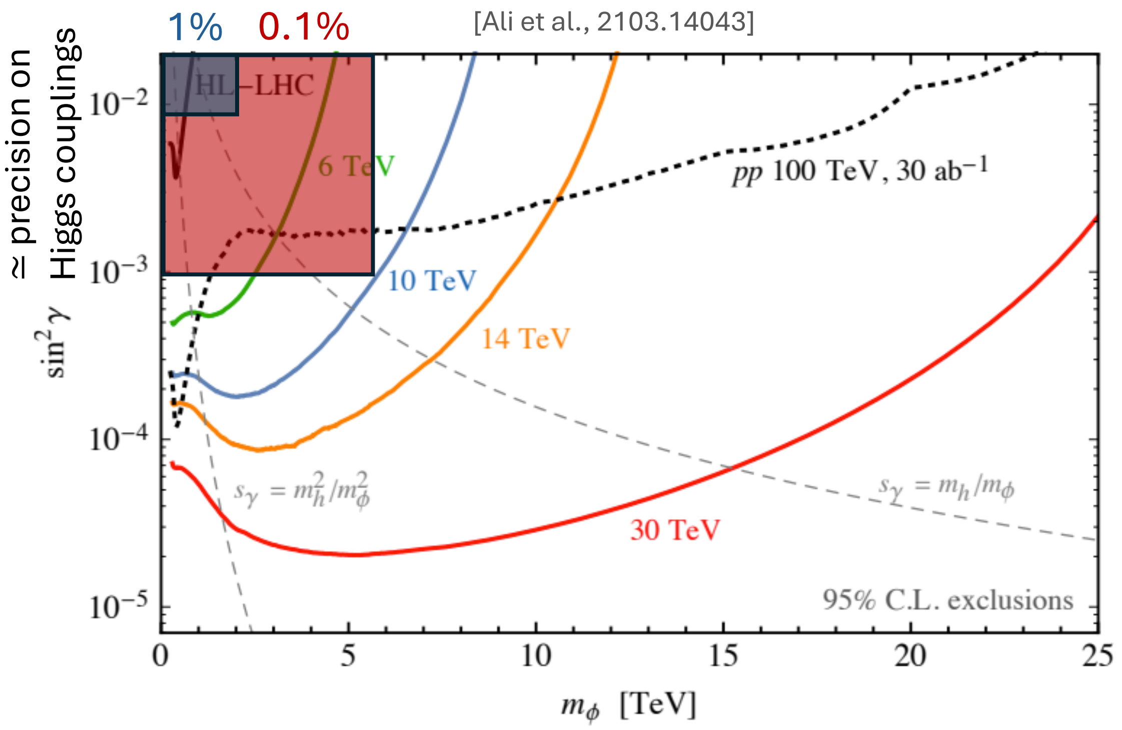

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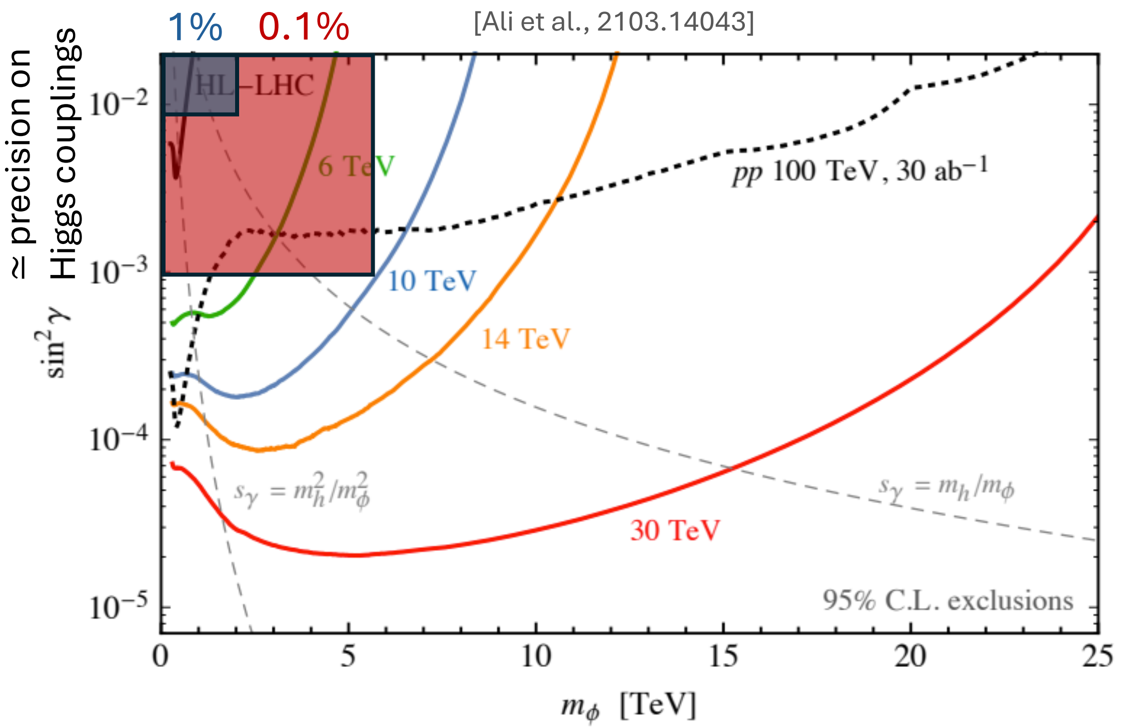

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Also true at the LHC and holds also for other models!

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[HB et al., 2005.14536]

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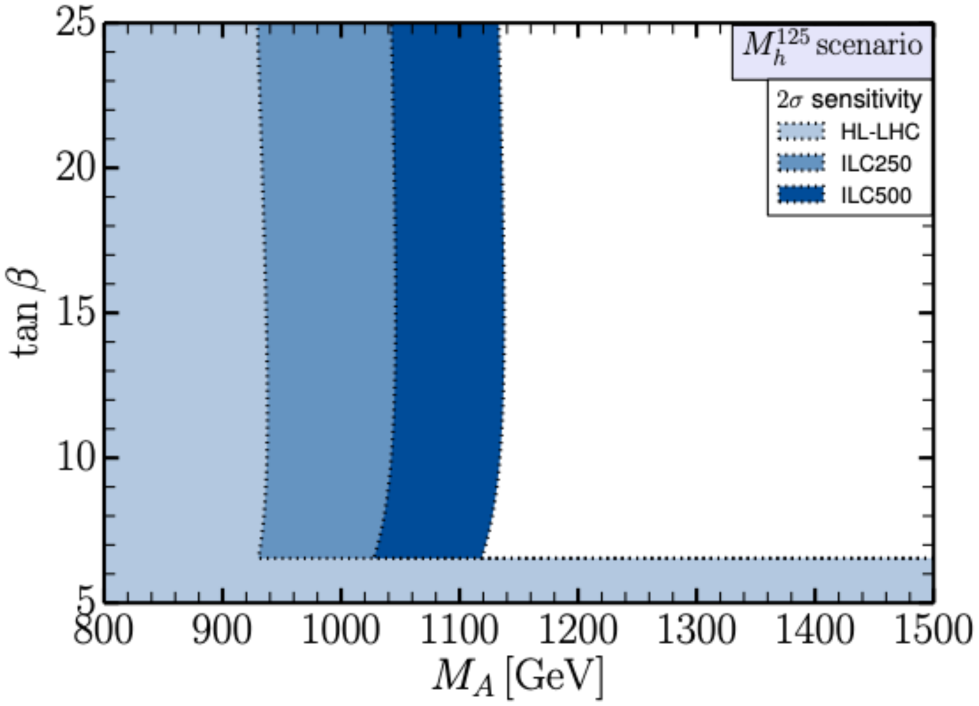

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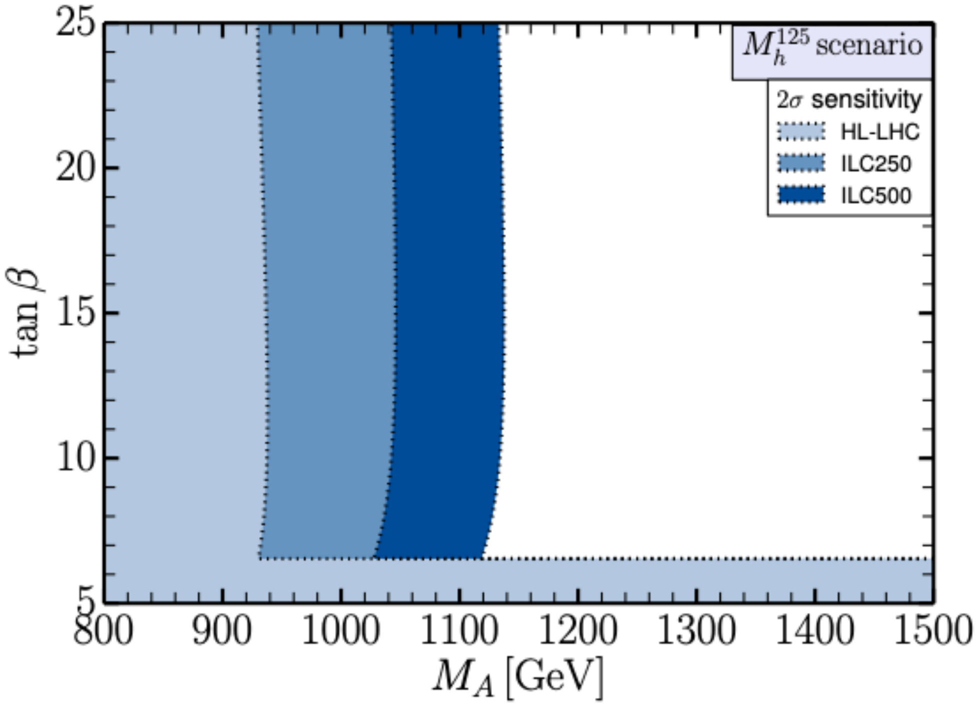
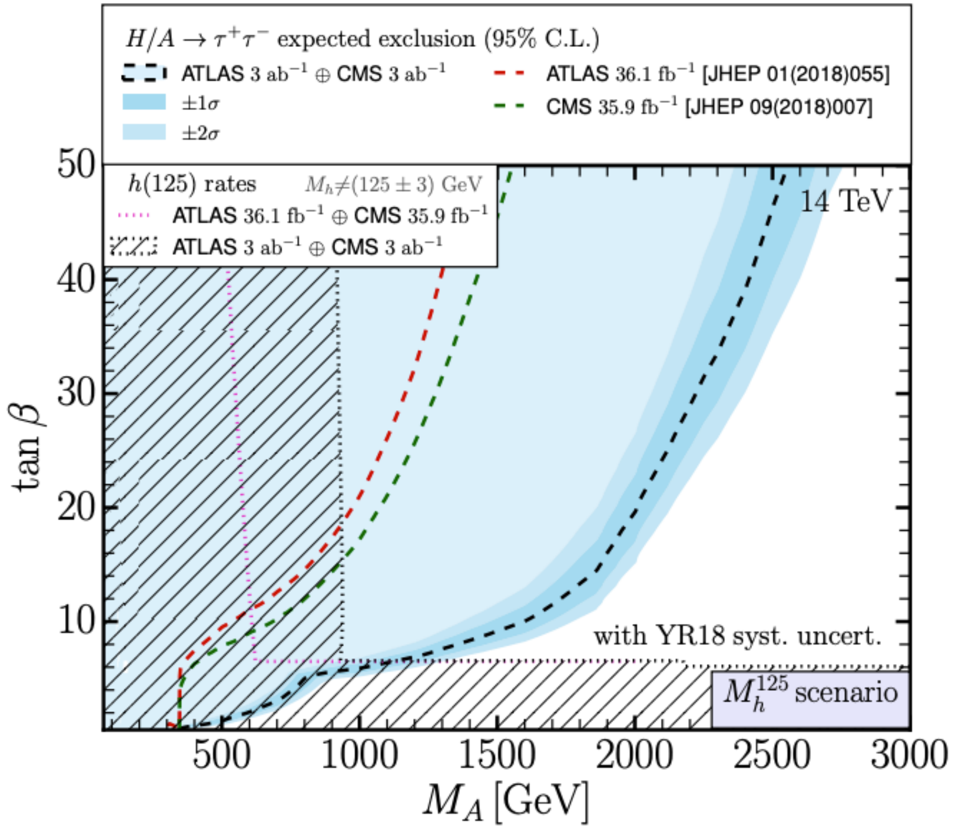
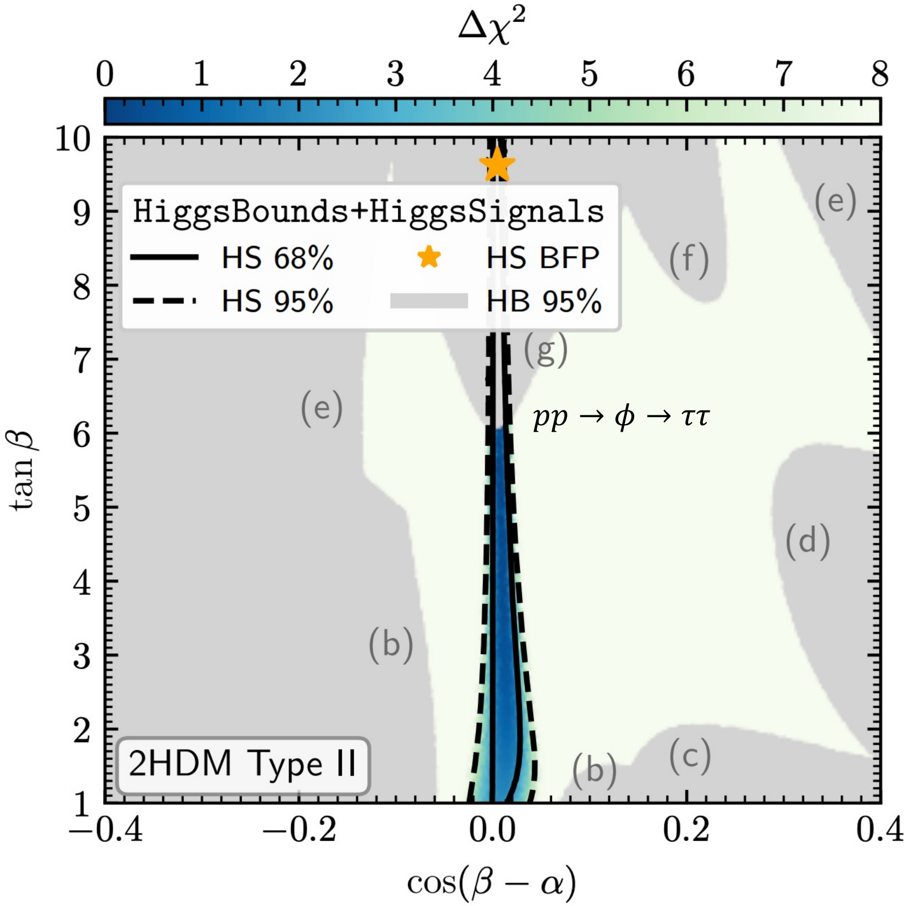




What about direct searches? — 2HDM



[HB et al., 2210.09332]

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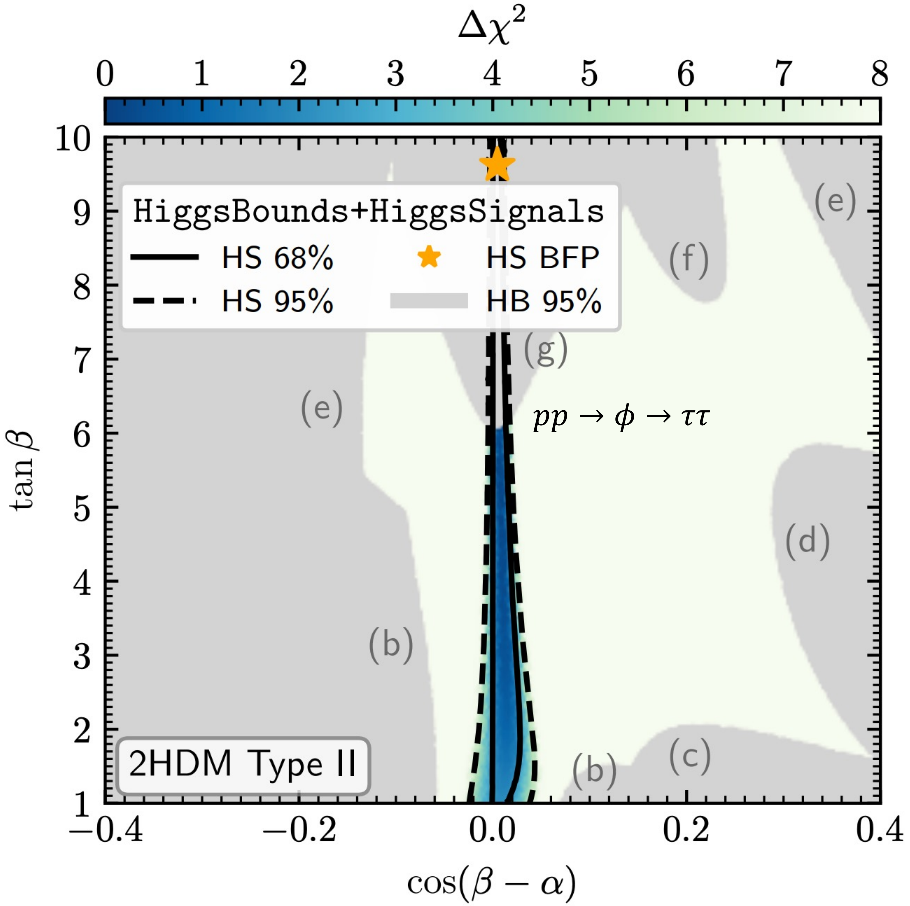

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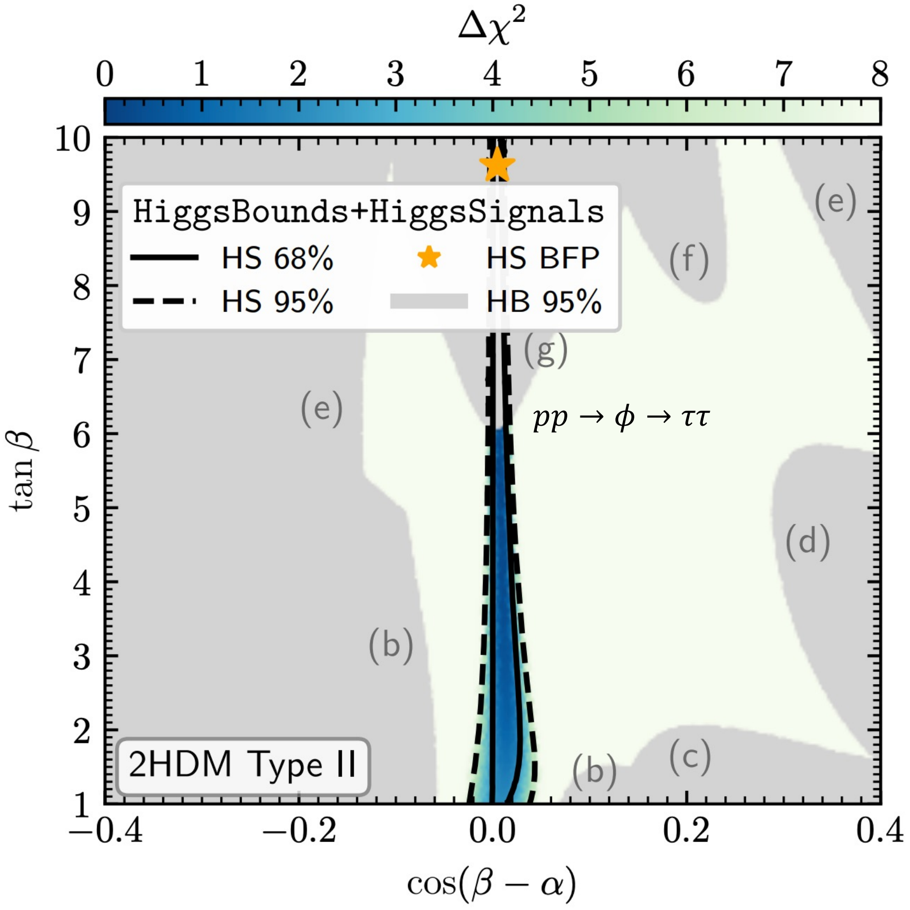

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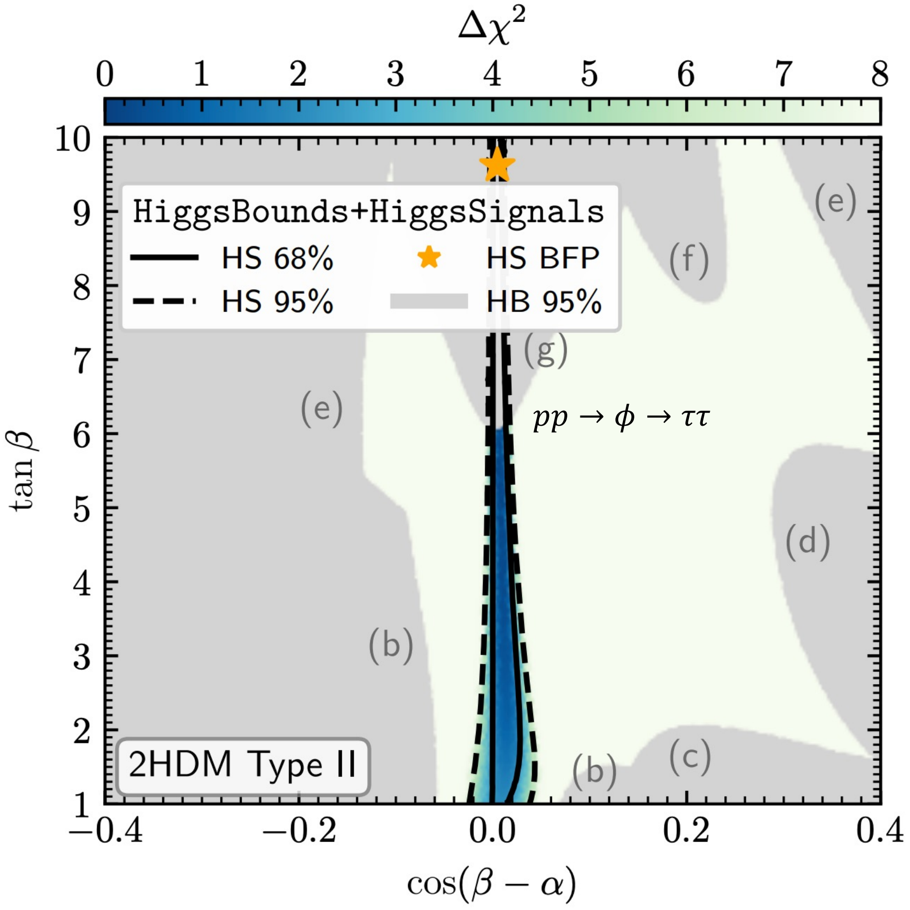

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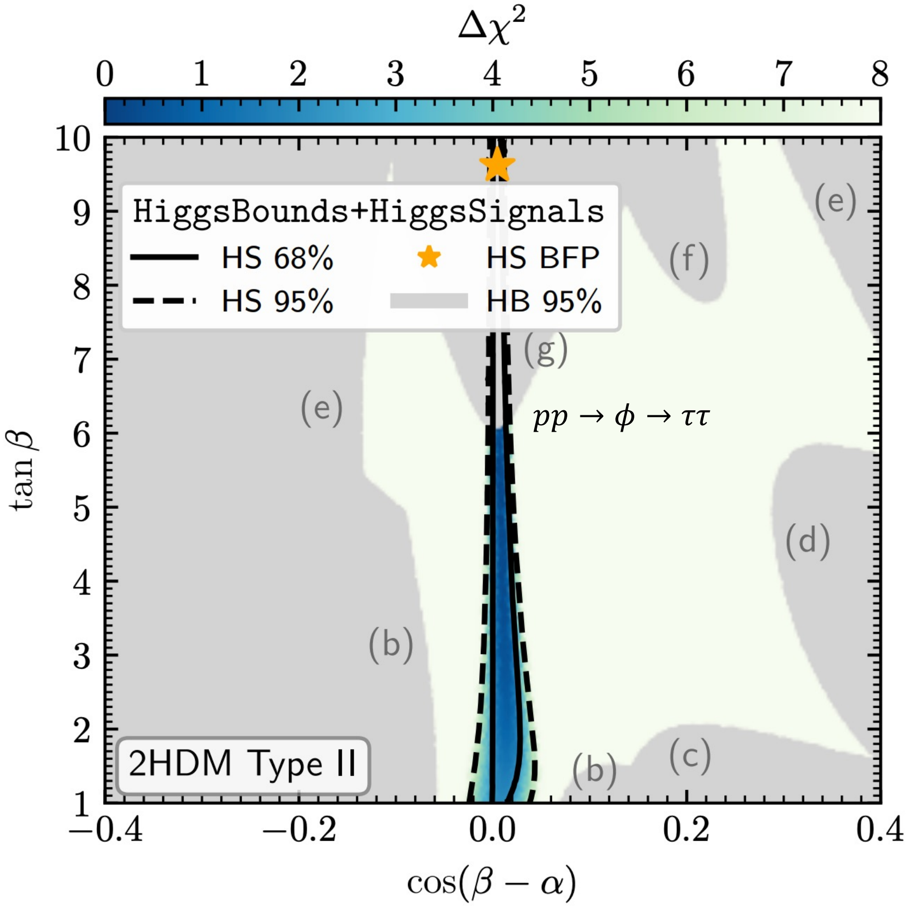

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What if the BSM sector is protected by a Z_2 symmetry?

The SSM ”nightmare” scenario

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

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

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What about loop-level effects on the Higgs couplings?

Loop-level deviations in the SSM

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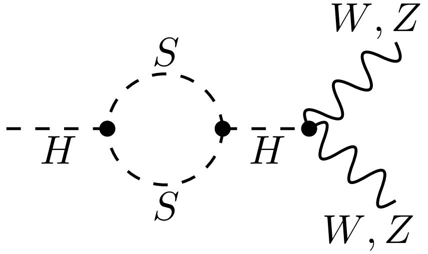

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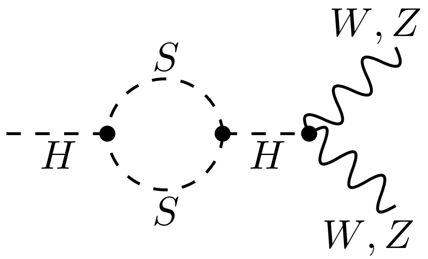

$$g^{1L} \propto \frac{g_{HSS}^2}{(4\pi)^2} B_0'(\dots) \cdot g_{\text{tree}} \propto \frac{1}{(4\pi)^2} \frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2 \Rightarrow c_{\text{eff}} \equiv \frac{g}{g^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2} \frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

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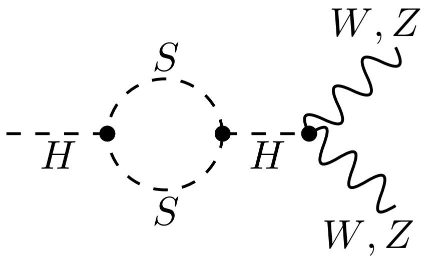

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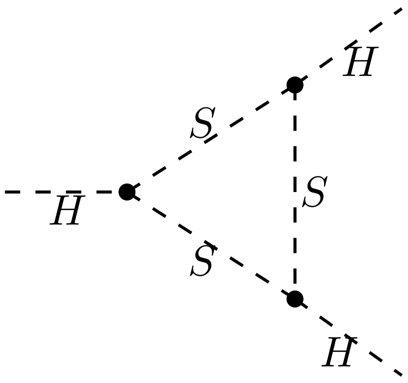

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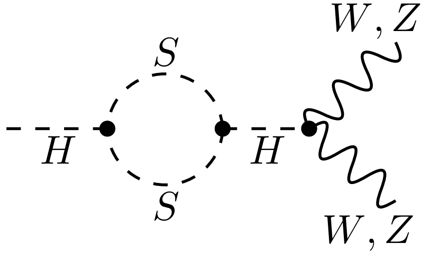

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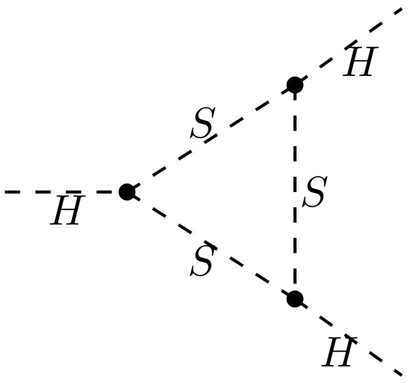

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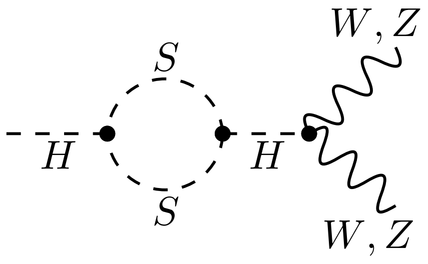

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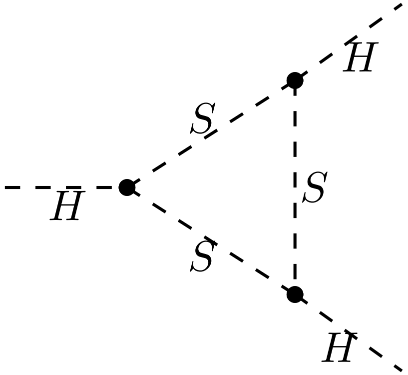

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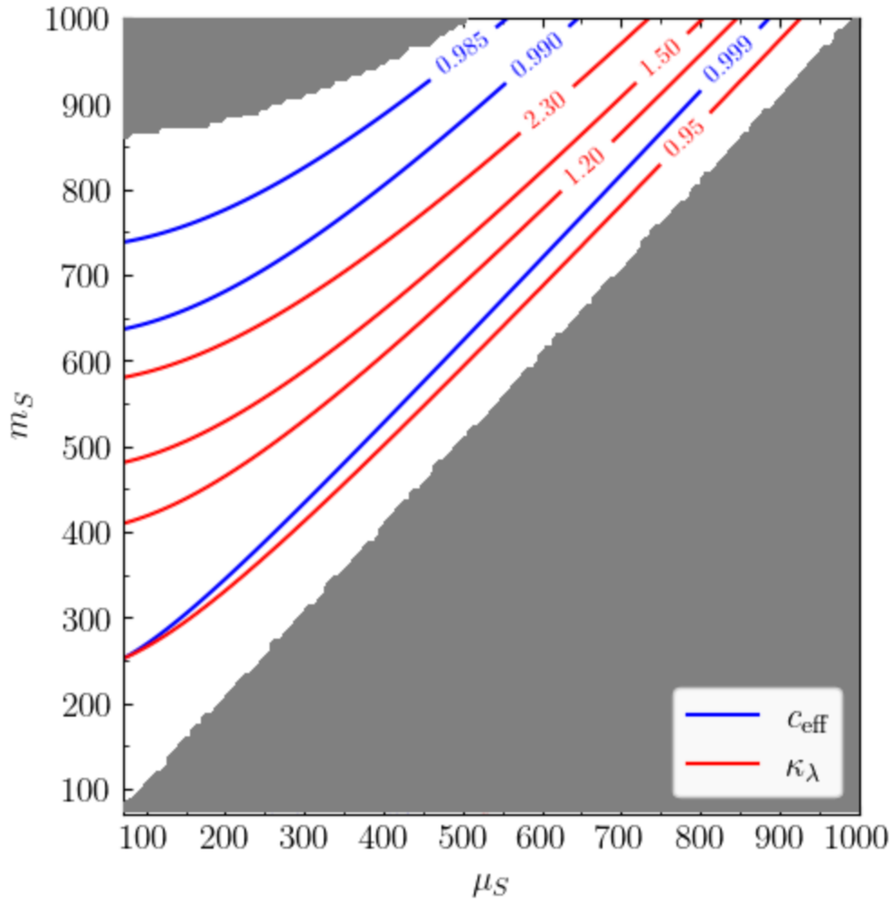
⇨ Deviation in λ_{HHH} enhanced by a factor $\frac{m_S^2}{v^2 \lambda_\Phi^{\text{SM}}} \left(1 - \frac{\mu_S^2}{m_S^2}\right)$ w.r.t. to other Higgs couplings!

The Higgs trilinear as a precision probe



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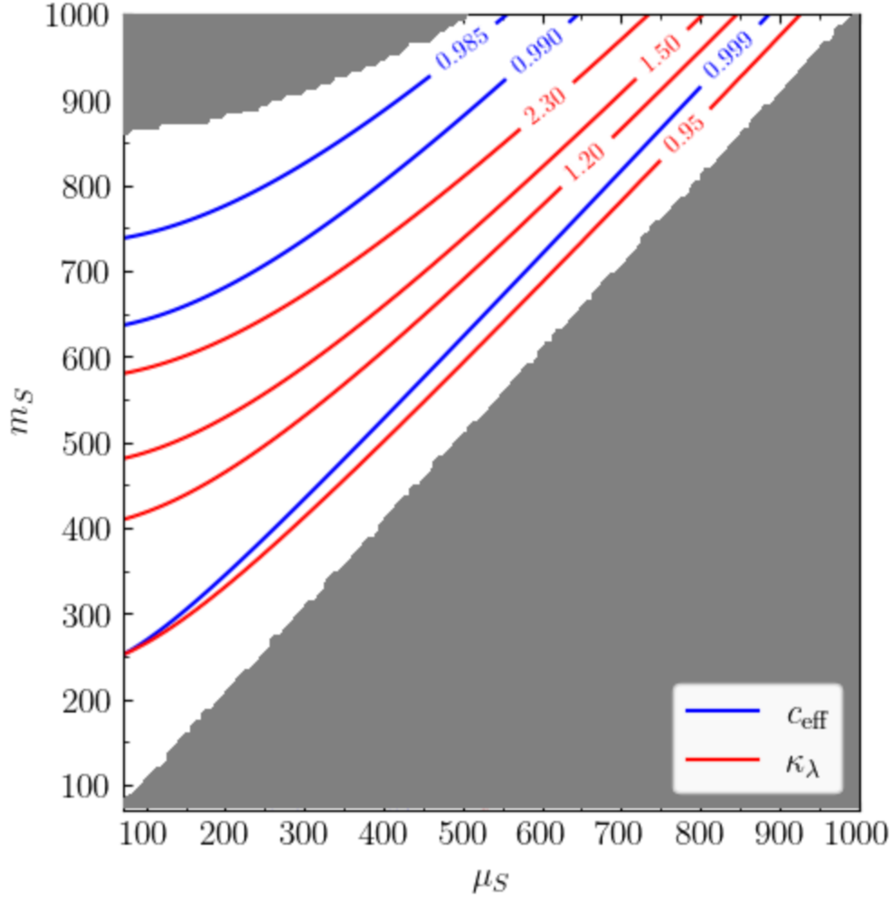
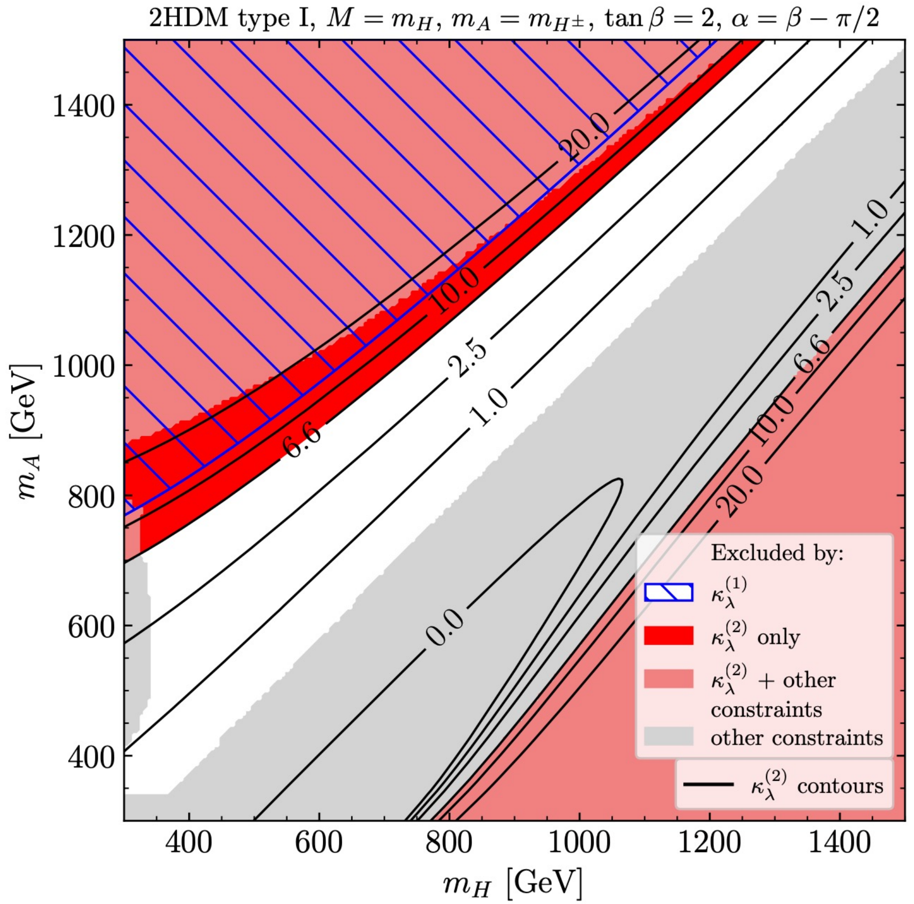
[HB,Braathen,Weiglein, 2202.03453]



Similar results in other models.



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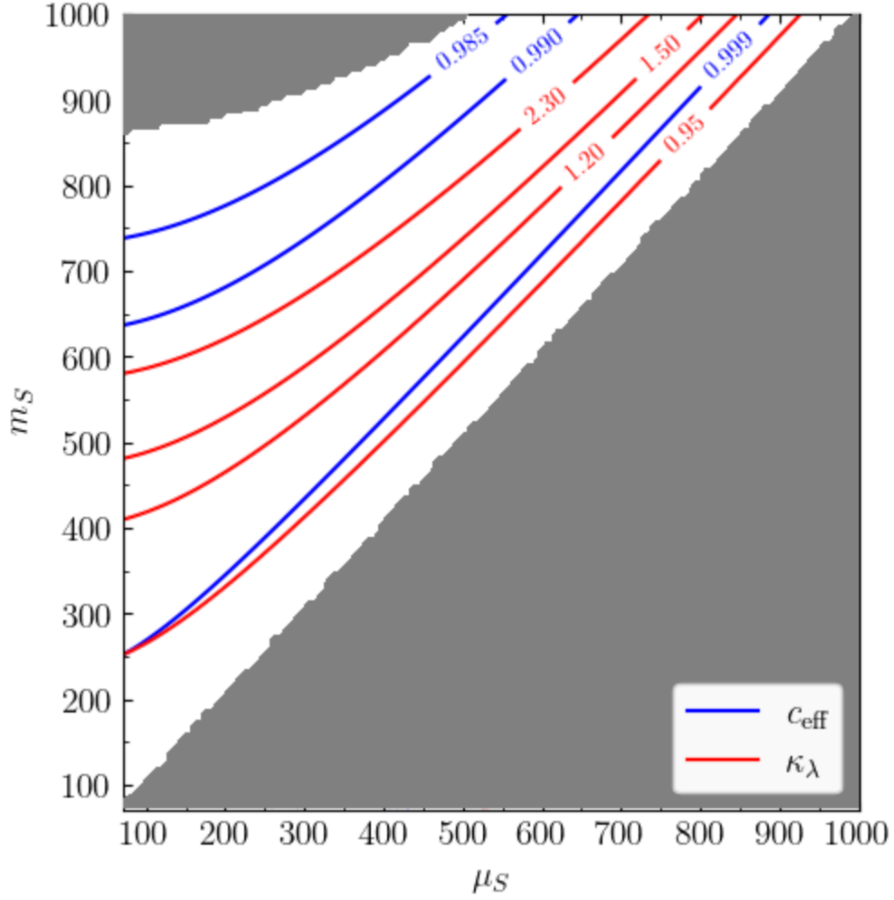

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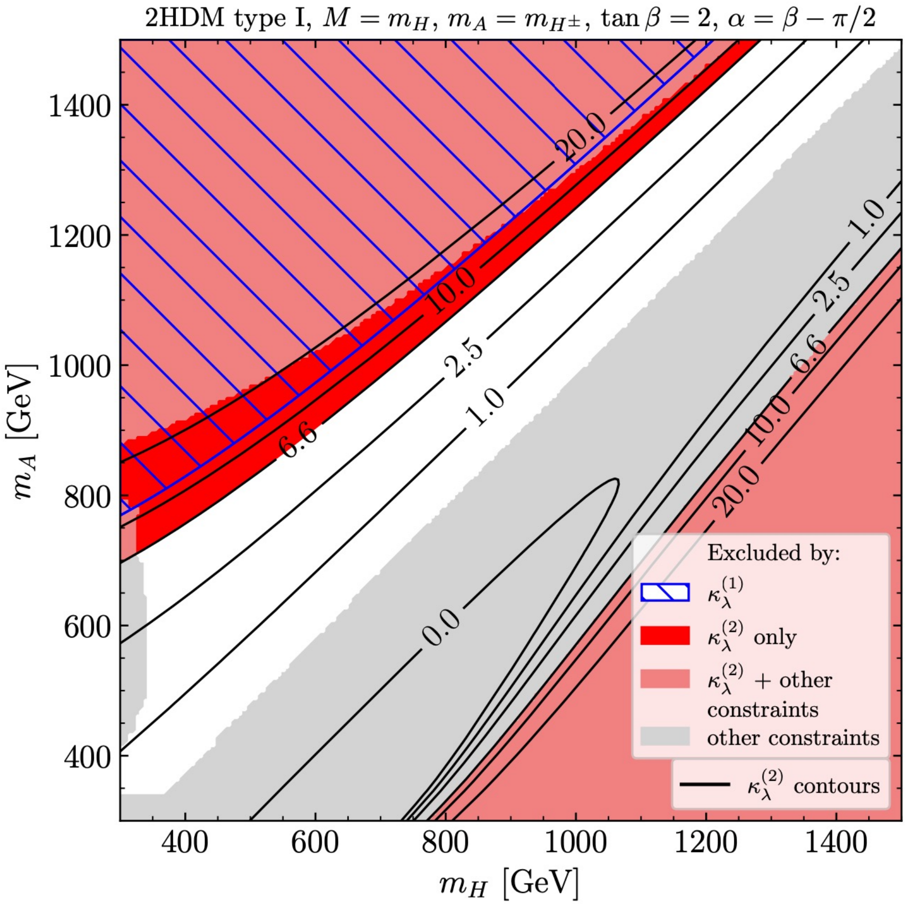

The Higgs trilinear is not only an indicator for a strong 1st order phase transition but also probes parameter regions not accessible by other measurements/searches!

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Thanks for your attention!