BSM effects in Higgs precision measurements

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THE UNIVERSITY OF CHICAGO

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The Higgs discovery

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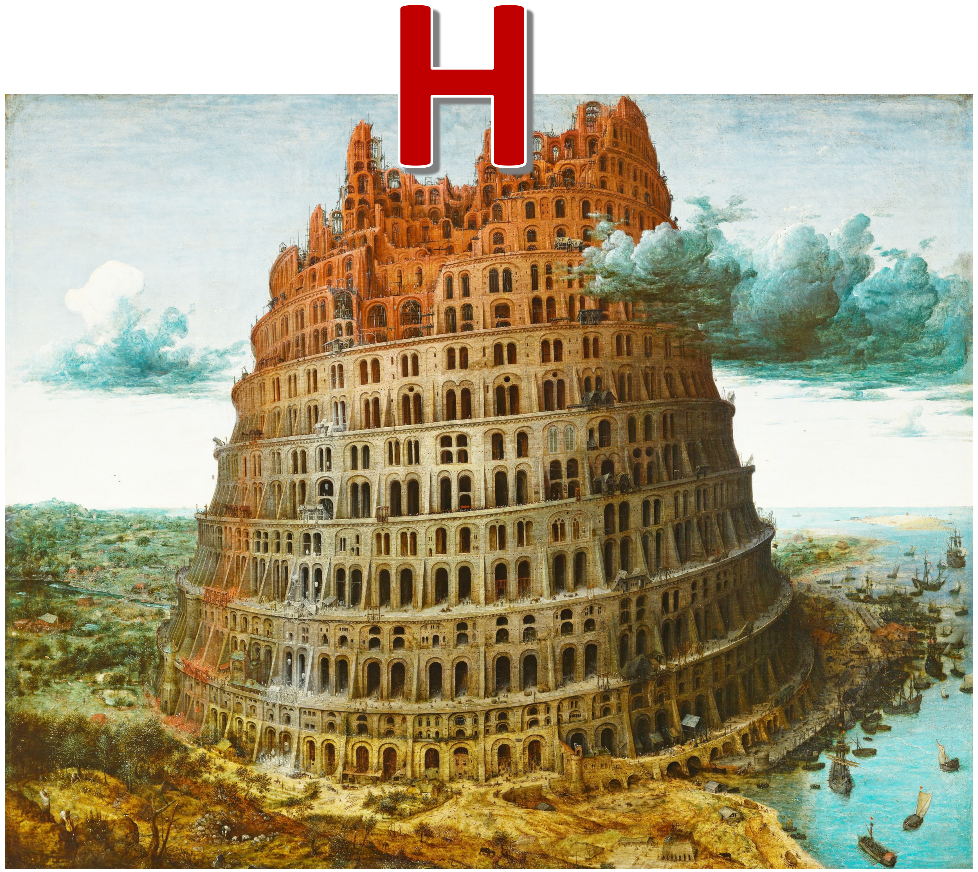

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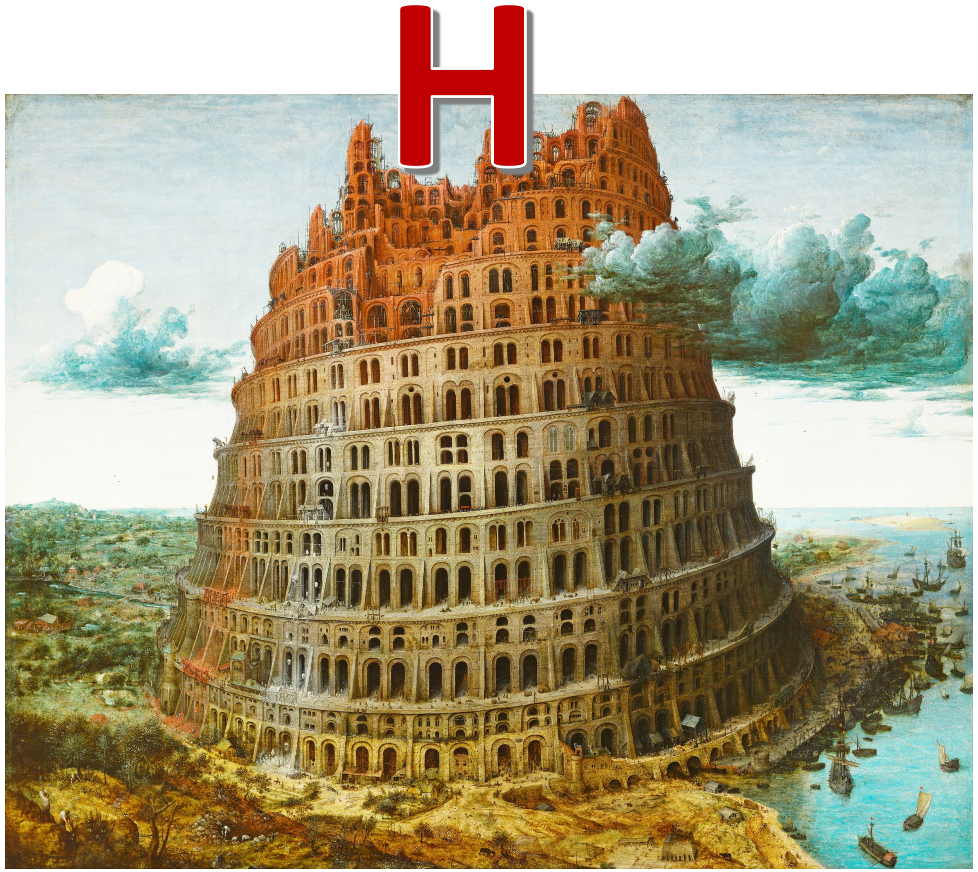

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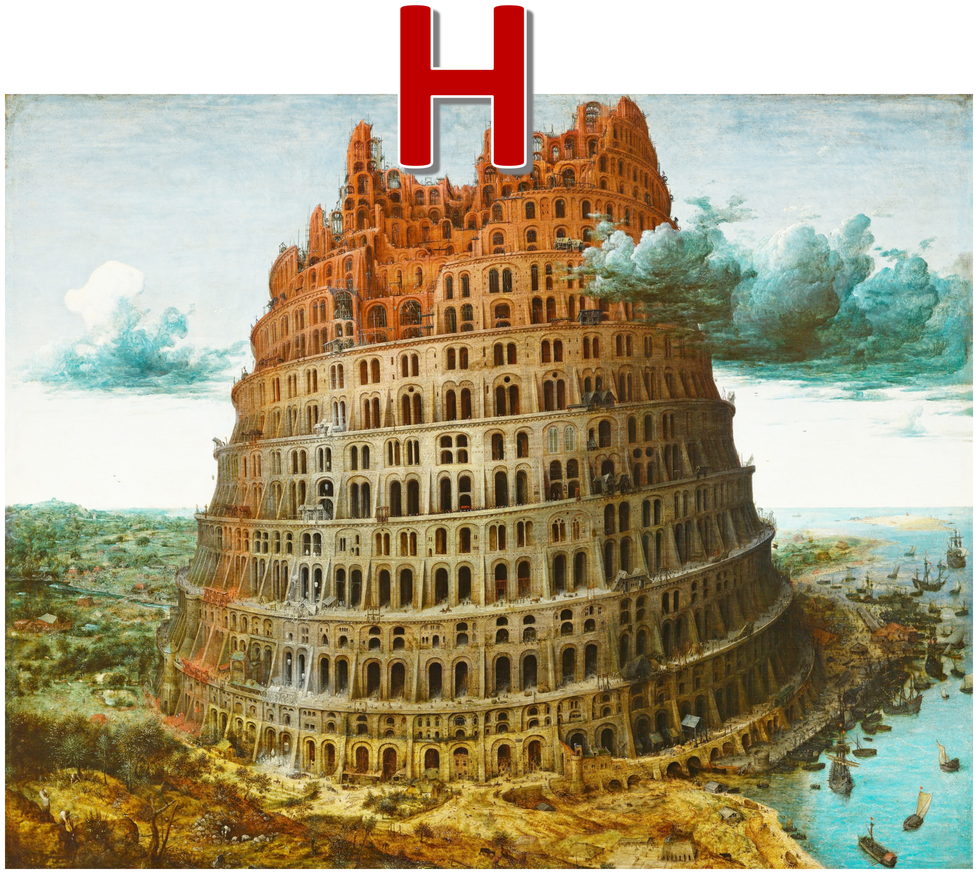

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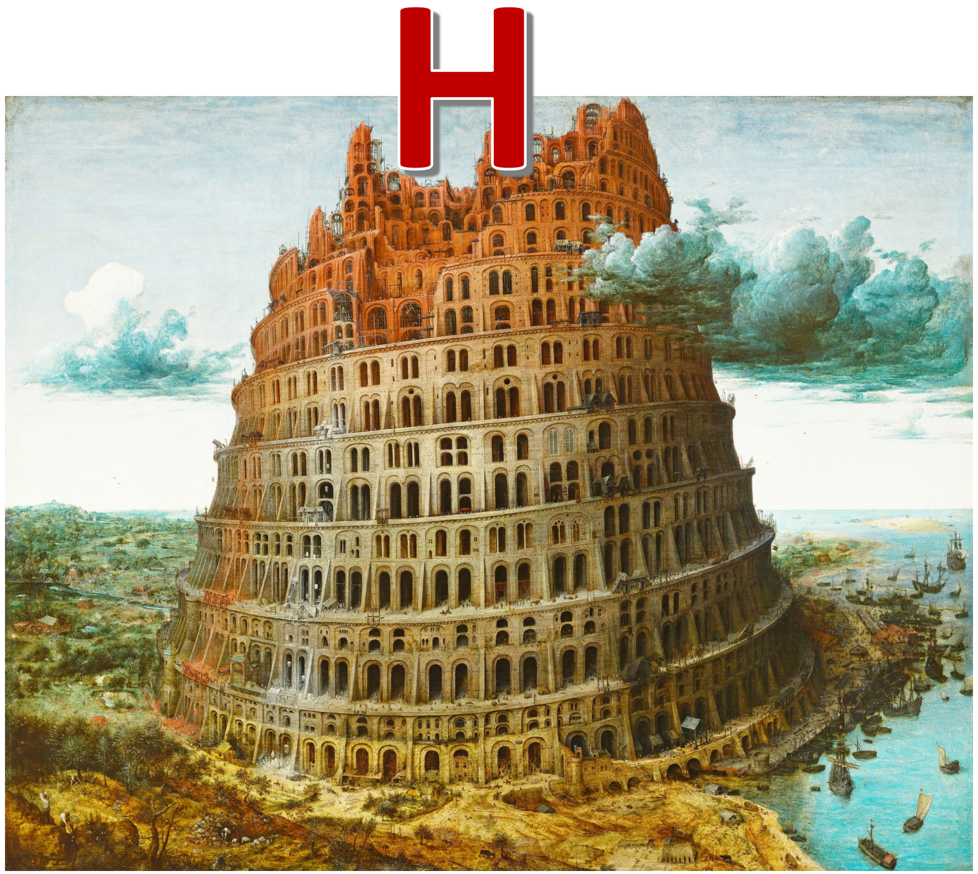
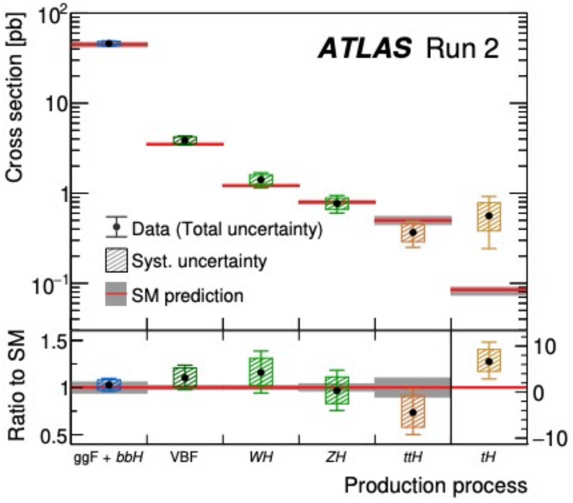
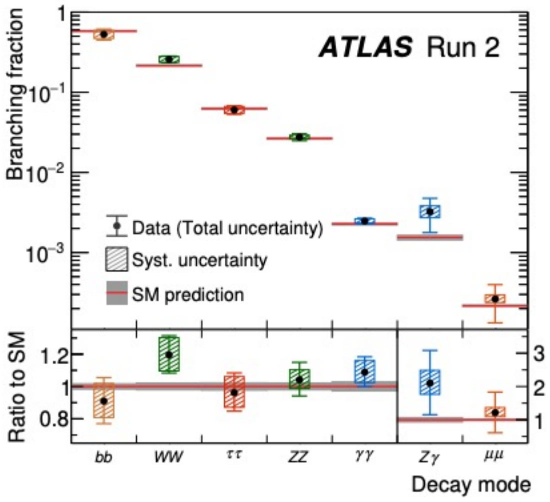
→ What is still left to explore?

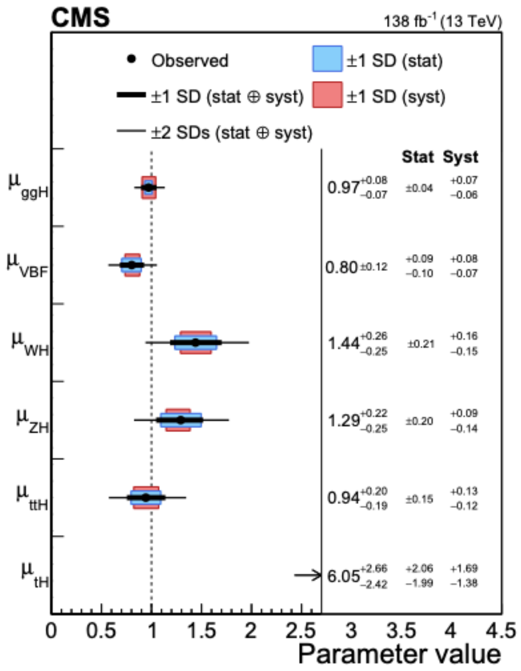


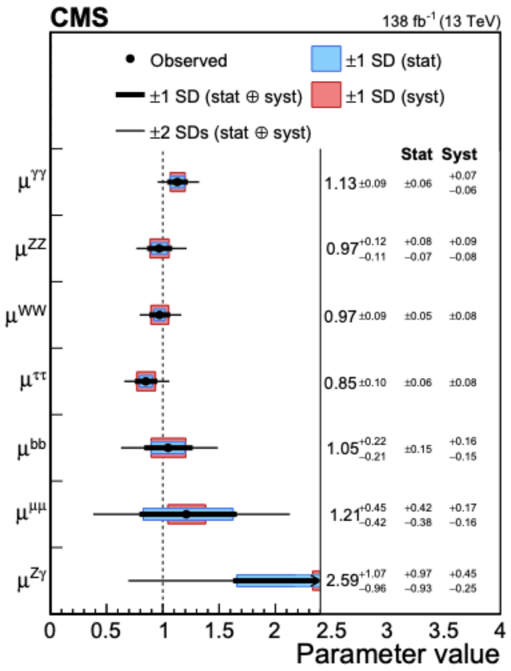
The Higgs 10 years later

[ATLAS 2207.00092, CMS 2207.00043]









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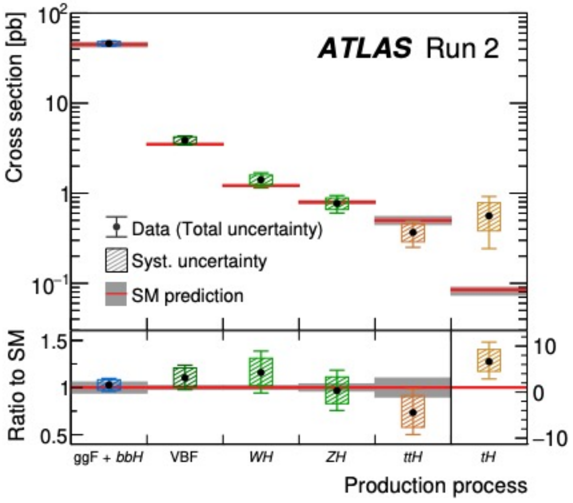

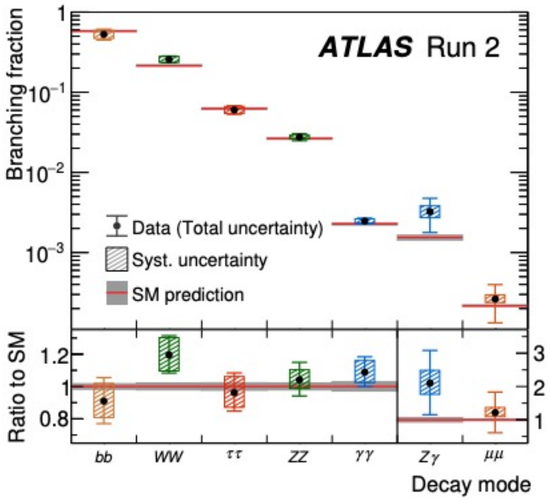

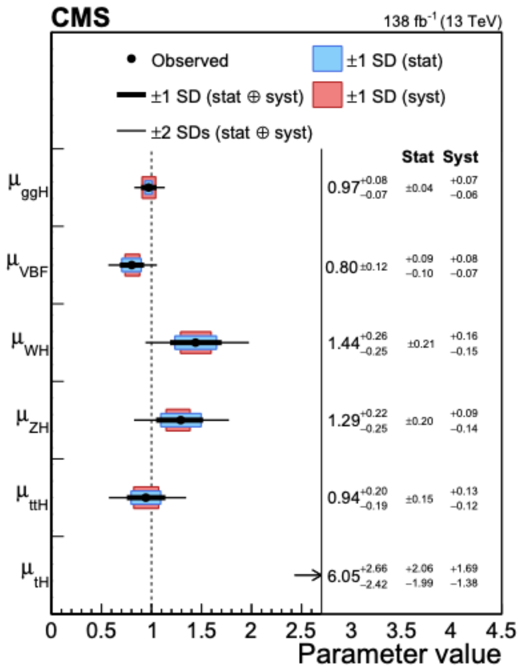

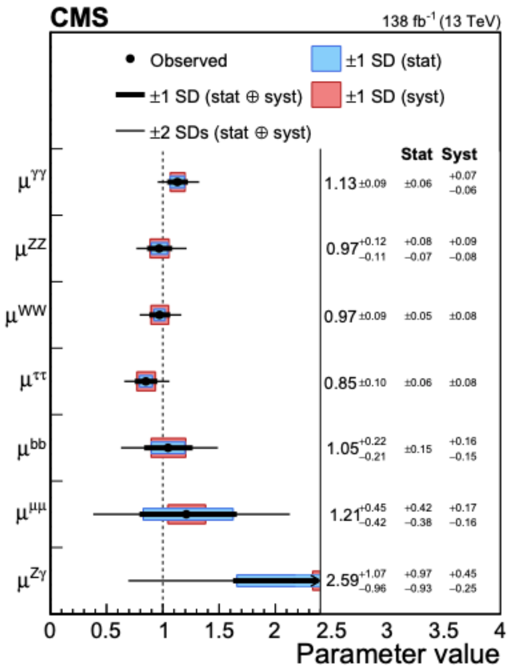

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[Snowmass 2209.07510]

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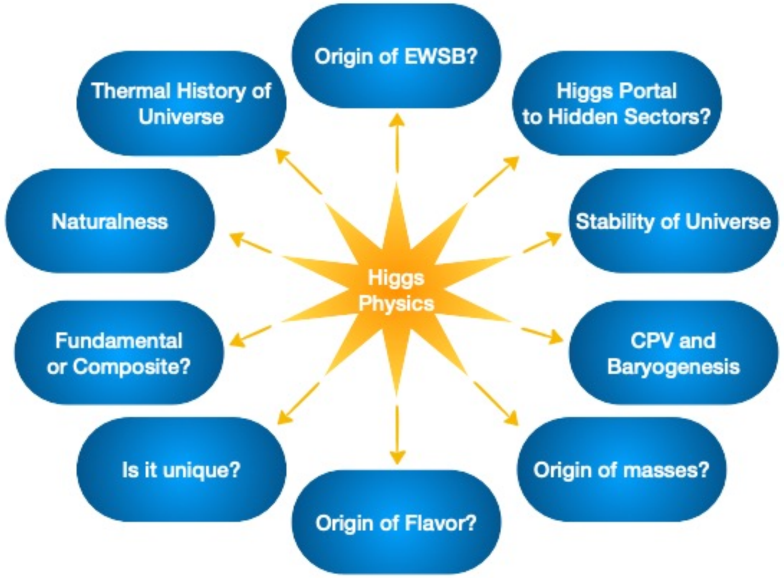

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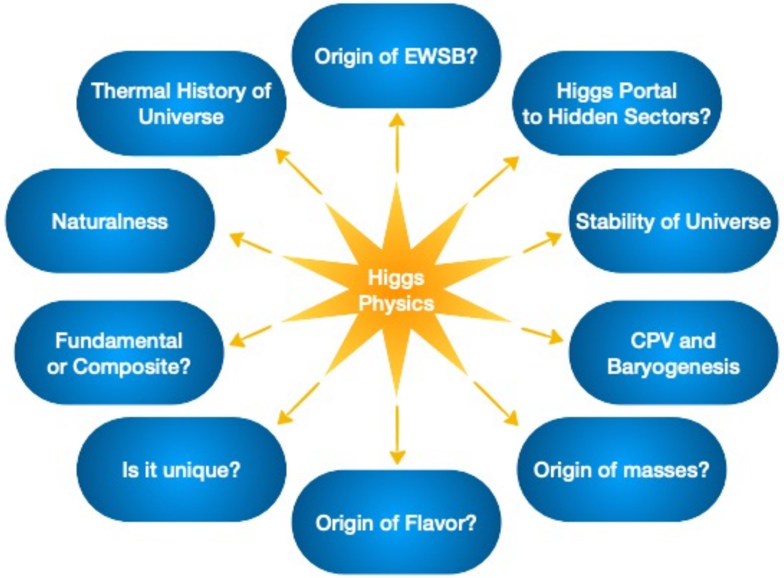
⇒ Strong motivation for on-going and future Higgs precision programs.



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What can we learn from existing measurements?

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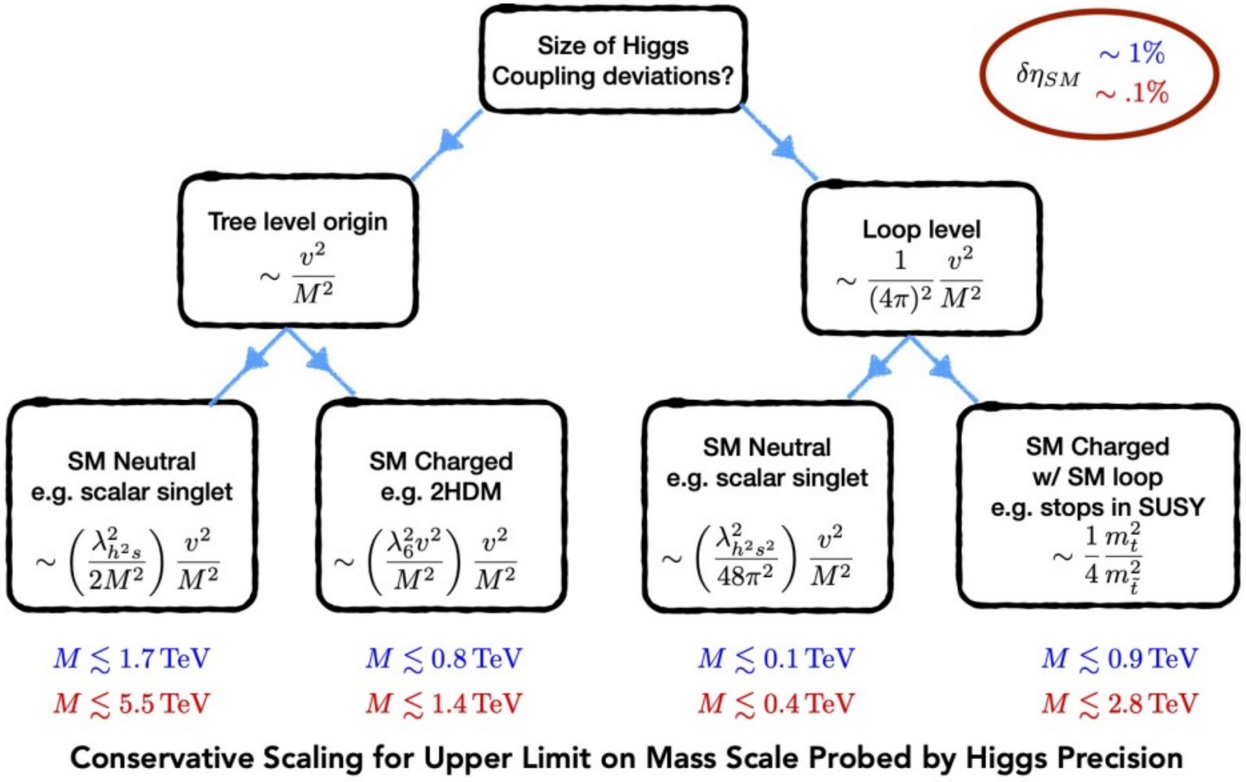
- Higgs precision measurements put stringent constraints on many BSM scenarios.

Simplified scaling analysis:

- 1% precision level can constrain BSM particles with mass from 100 GeV to several TeV (within reach of the LHC or future colliders).

→ More on EFT perspective in Duarte's talk.



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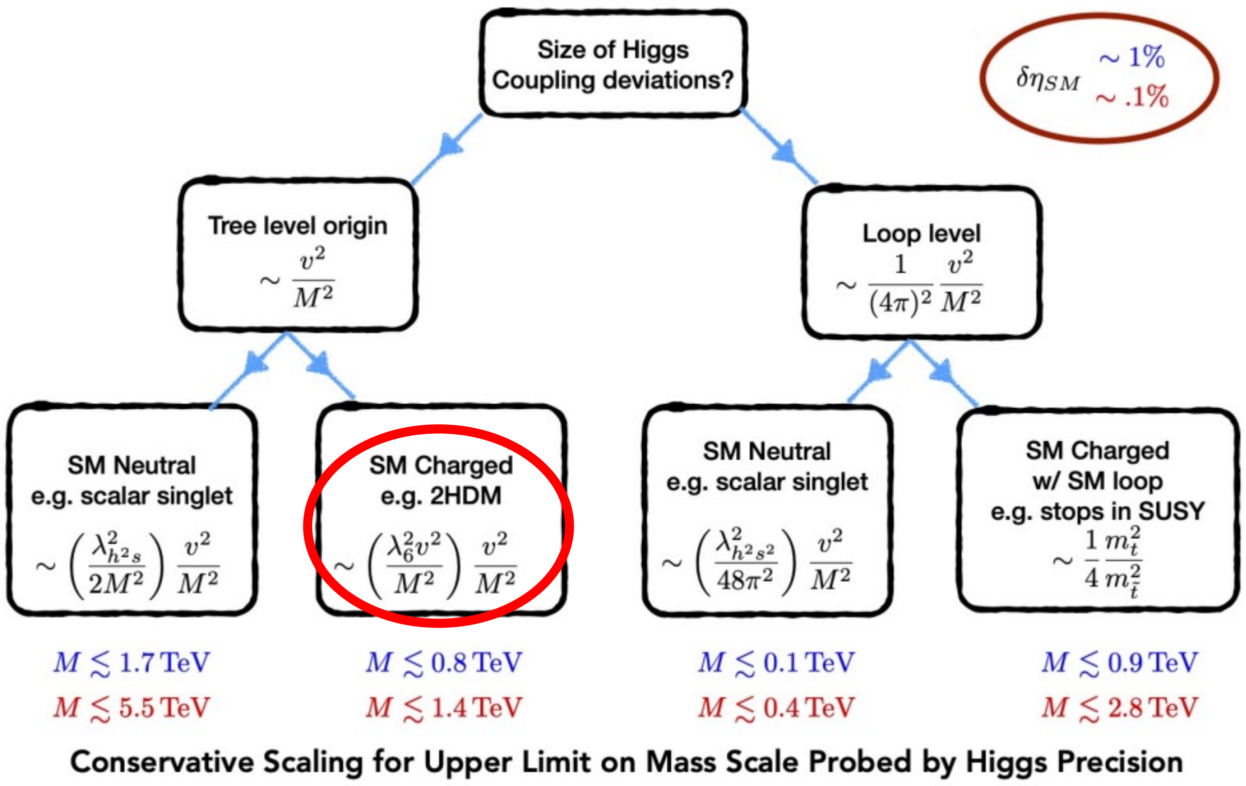


[Snowmass 2209.07510]

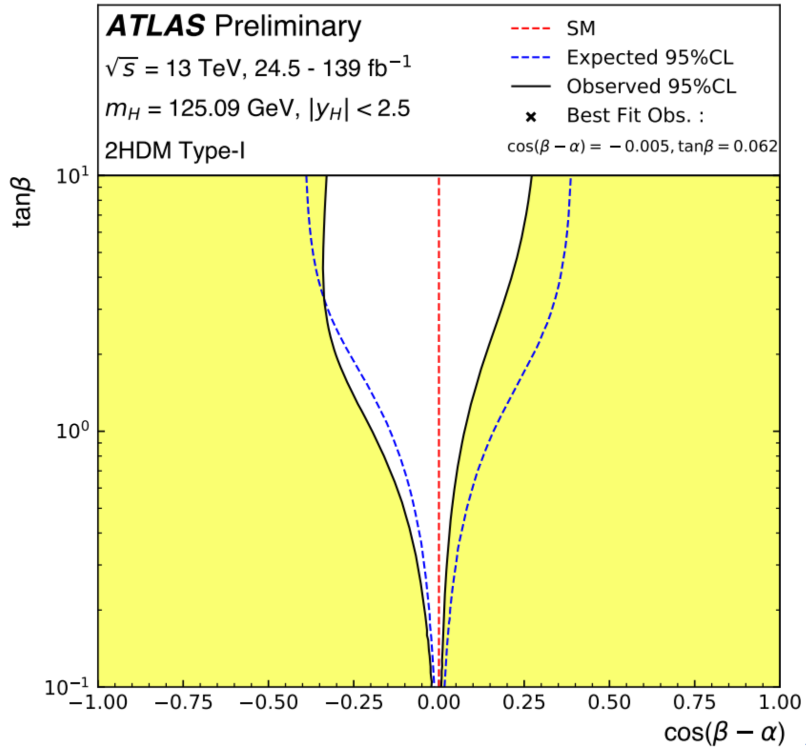
Impact of Higgs precision measurements on 2HDM

- BSM benchmark model: 2HDM type-I

- Two Higgs doublets → CP-even h_1, h_2 (and $A, H^{\pm}$)
  - $\tan\beta$: ratio of vevs
  - α: mixing angle
  - $m_{h_1} < m_{h_2}$
- Scaling of vector boson couplings

$$c(h_1VV) \propto \sin(\beta - \alpha)$$
$$c(h_2VV) \propto \cos(\beta - \alpha)$$

→ Measurements enforce approximate alignment of the SM-like Higgs with the electroweak vacuum.



[ATLAS-CONF-2020-027]

assumes that h_1 is h_{125}

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$$\sin(\beta - \alpha) \sim 1 \text{ if } h_1 \text{ is } h_{125} \text{ or}$$
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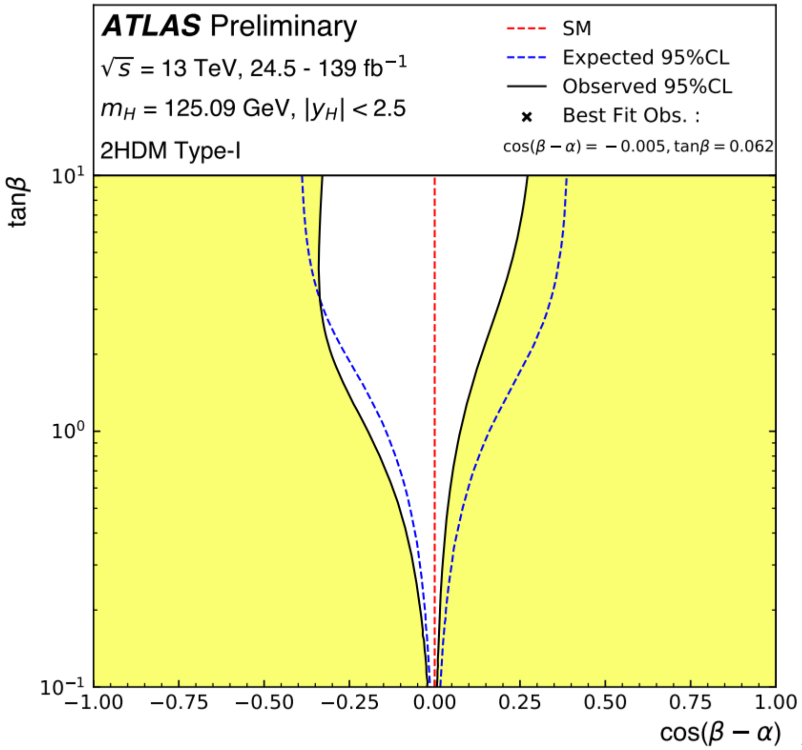

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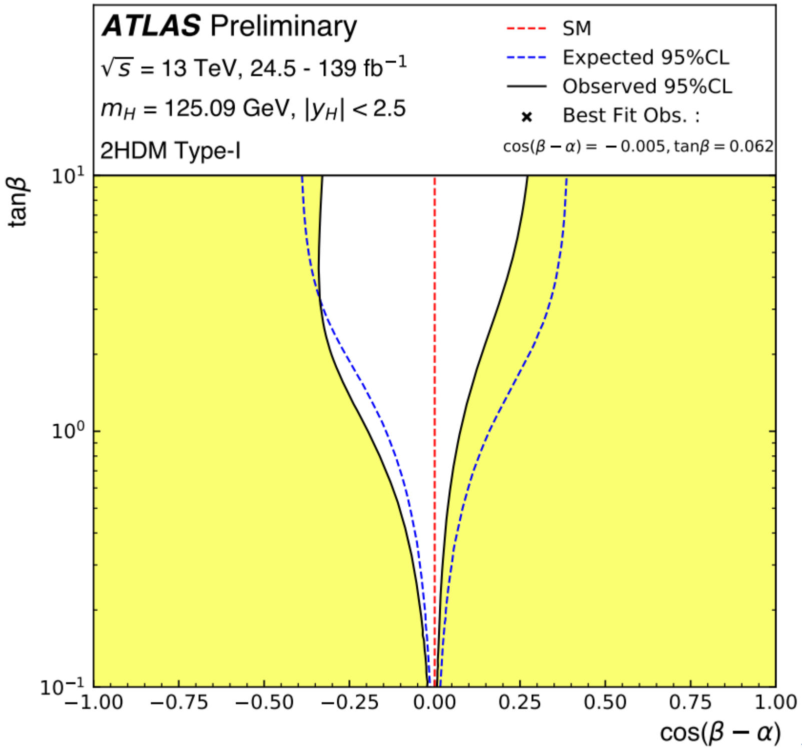

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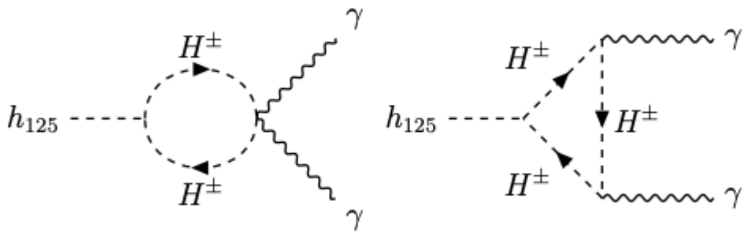
assumes that h_1 is h_{125}

How can we distinguish the two cases?

Interplay with $H\gamma\gamma$ coupling

- Also loop effects can be important as evident in the di-photon decay channel.

- Charged Higgs yields sizeable contribution:



Coupling: $g_{h_{125}H^+H^-} \to -\frac{1}{v}\left[m^2_{h_{125}} + 2(m^2_{H^\pm} - \overline{m}^2)\right]$

Loop suppression: $v^2/m^2_{H^\pm}$

Higgs potential parameter.
Pert. unitarity enforces $m^2_{h_2} \sim m^2_{H^\pm} \sim \overline{m}^2$

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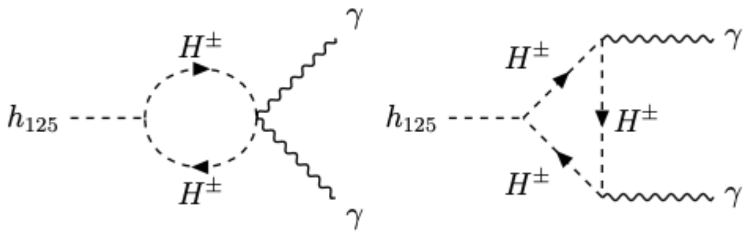

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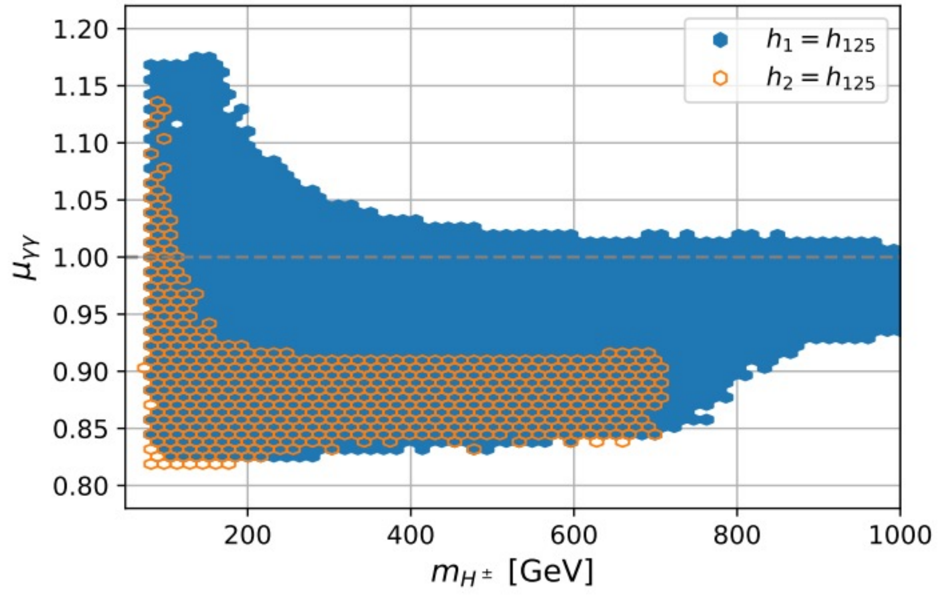
⇒ Lower di-photon signal rate predicted if heavier CP-even Higgs H is h_{125}

2HDM type-I



[HB et al. 2103.07484, see also Bernon et al 1511.03682]

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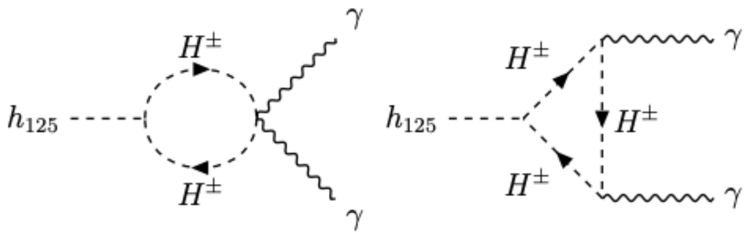

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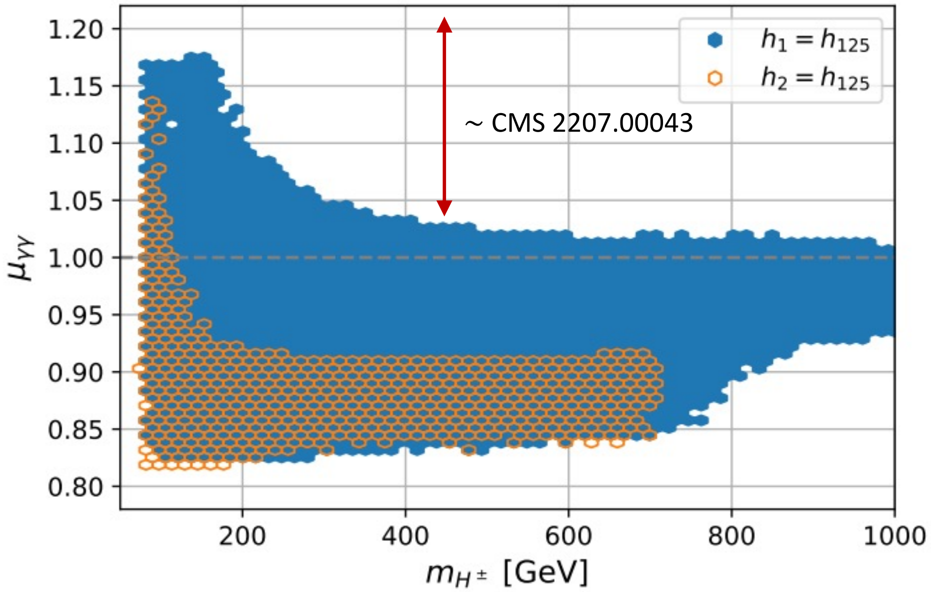

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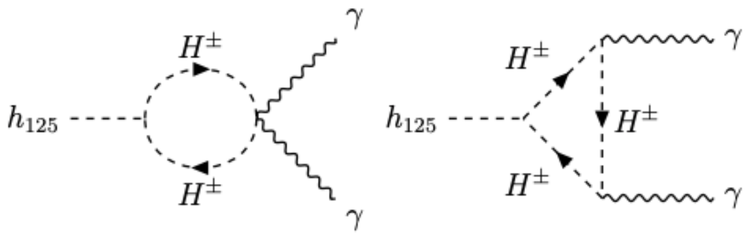

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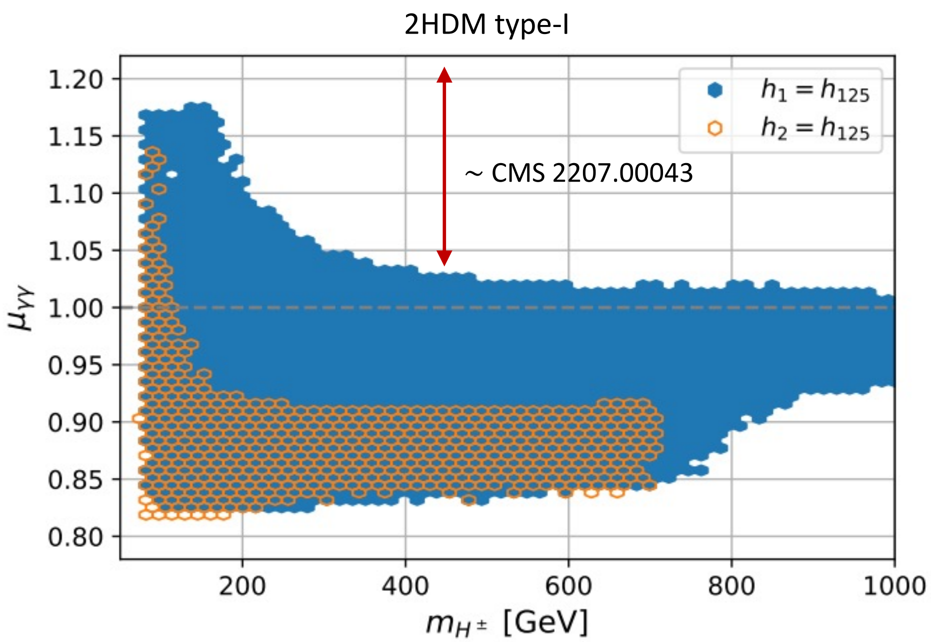


[HB et al. 2103.07484, see also Bernon et al 1511.03682]

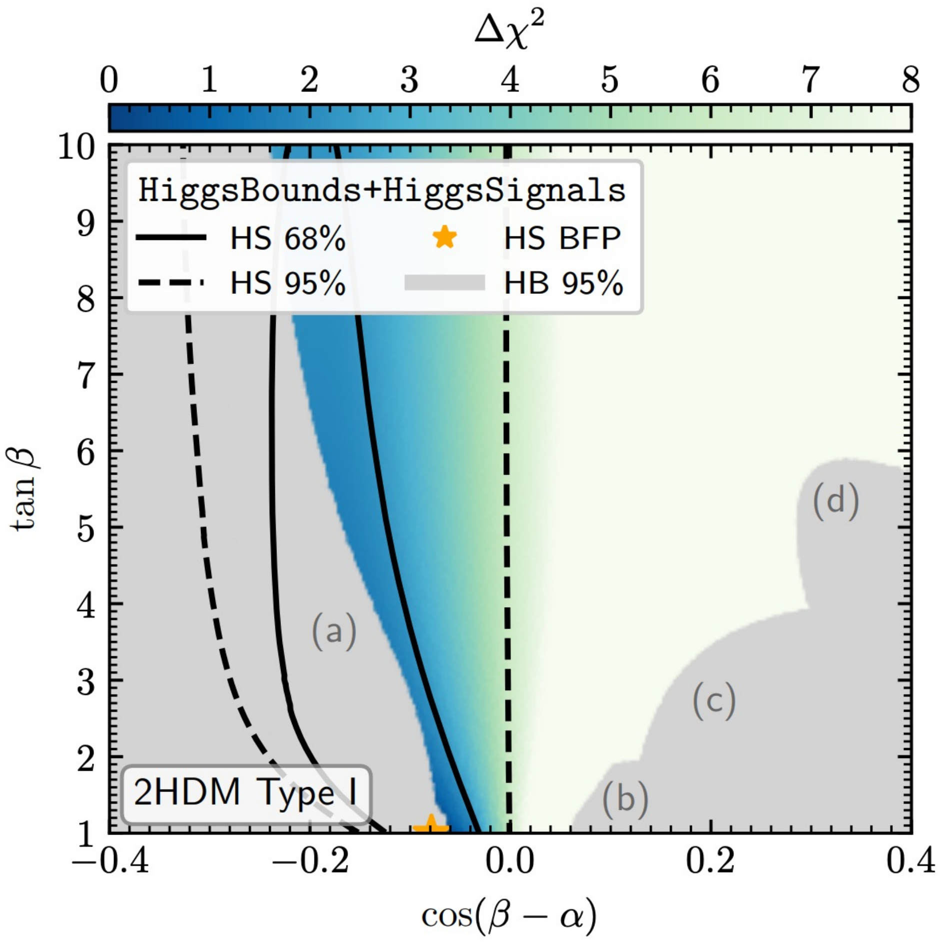
Important interplay between different Higgs couplings!

Interplay with direct searches

- Important interplay between Higgs precision measurements and direct searches for BSM particles.

- BSM searches:
  a) CMS: $pp \to \phi \to h_{125}h_{125}$
  b) CMS: $pp \to \phi_1 \to h_{125}\phi_2 \to bb\tau\tau$
  c) CMS: $pp \to \phi \to Zh_{125}$
  d) ATLAS: $pp \to \phi \to WW, ZZ, WZ$

- Deviations from $\cos(\beta-\alpha) = 0$ due to $t\bar{t}H$ measurements affected by $t\bar{t}W$ theory unc.
  $\Rightarrow$ Experimentally precision should be met by theoretical precision.



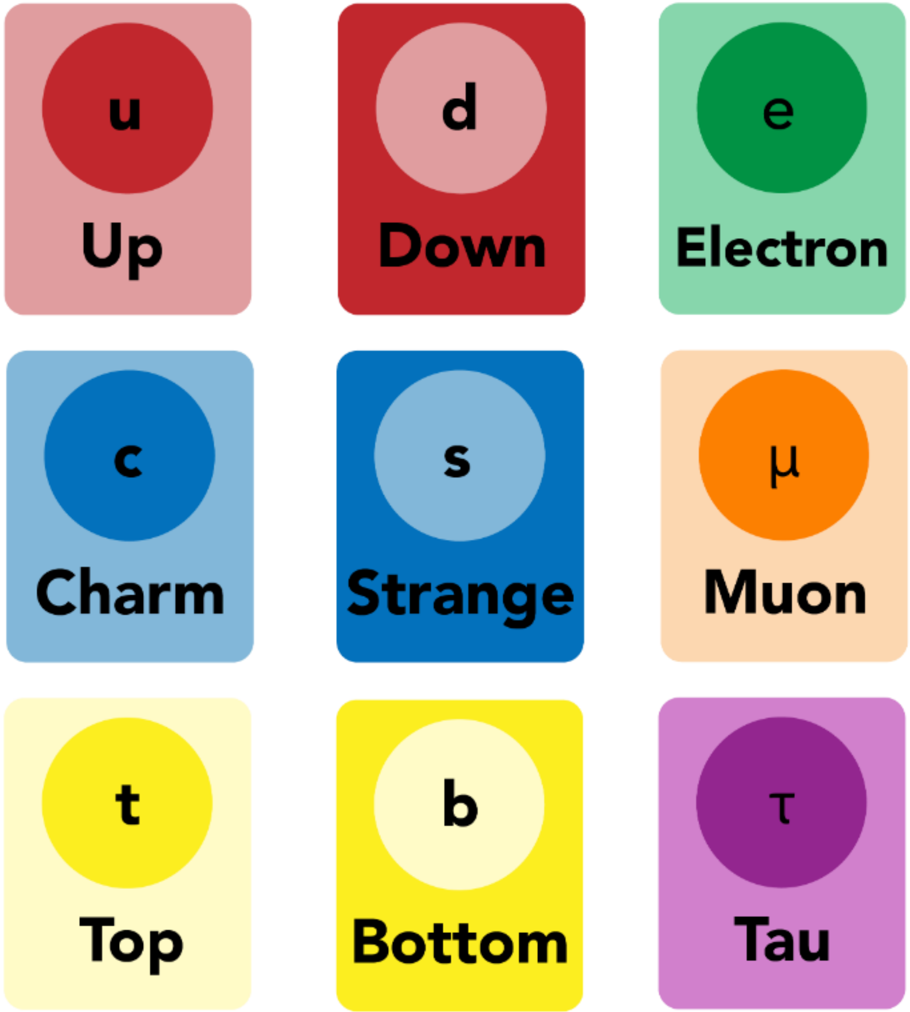
$m_H = m_A = m_{H^\pm} = \sqrt{m_{12}^2/(\sin\beta\cos\beta)} = 800$ GeV

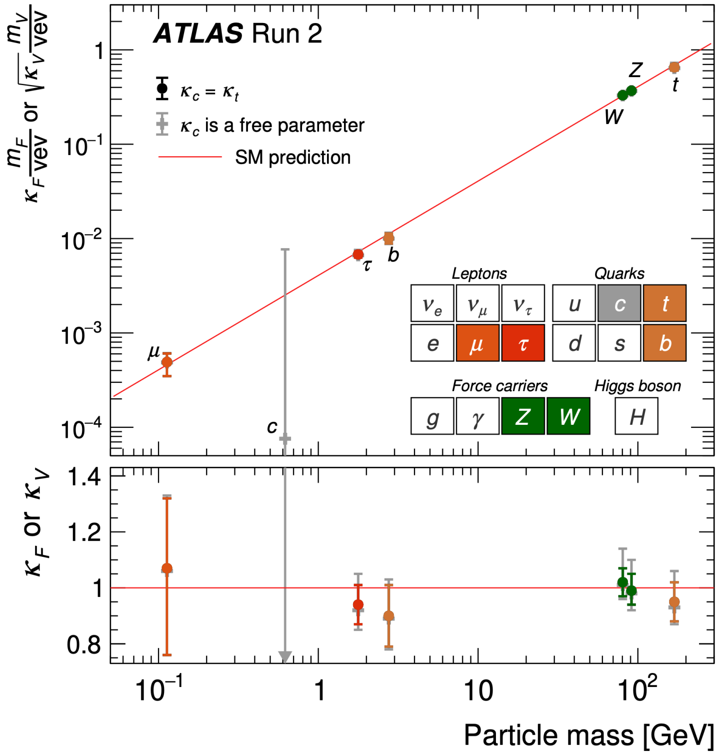
[HB et al. 2210.09332]

What is still left to explore?

Yukawa couplings (and their CP character)

Yukawa couplings





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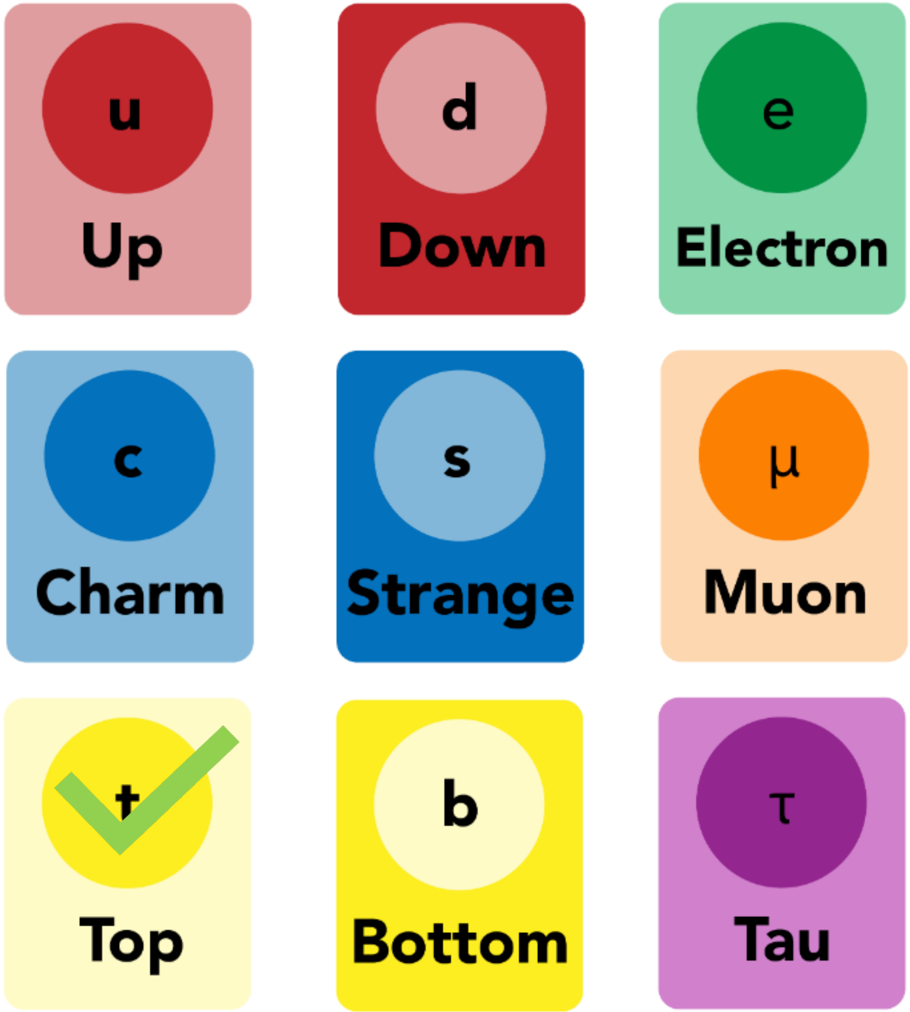

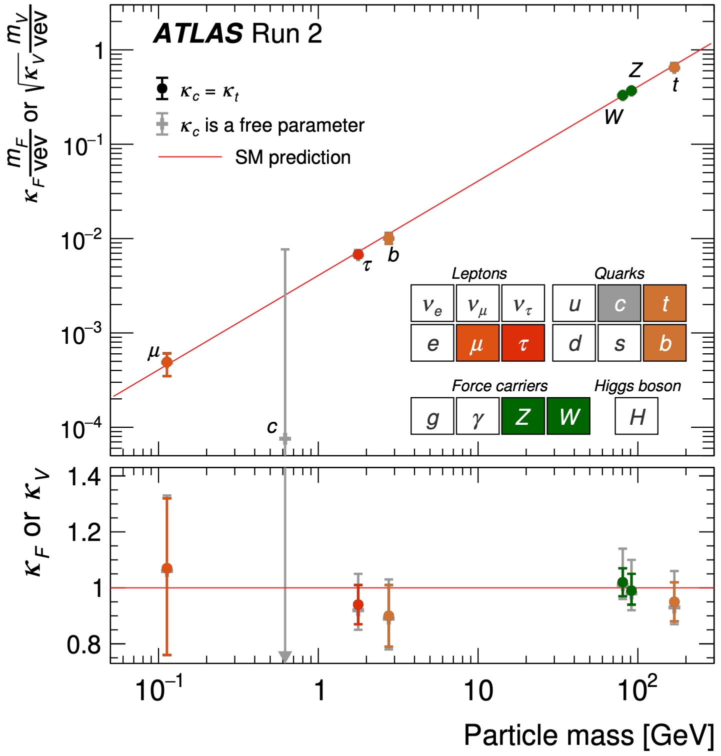

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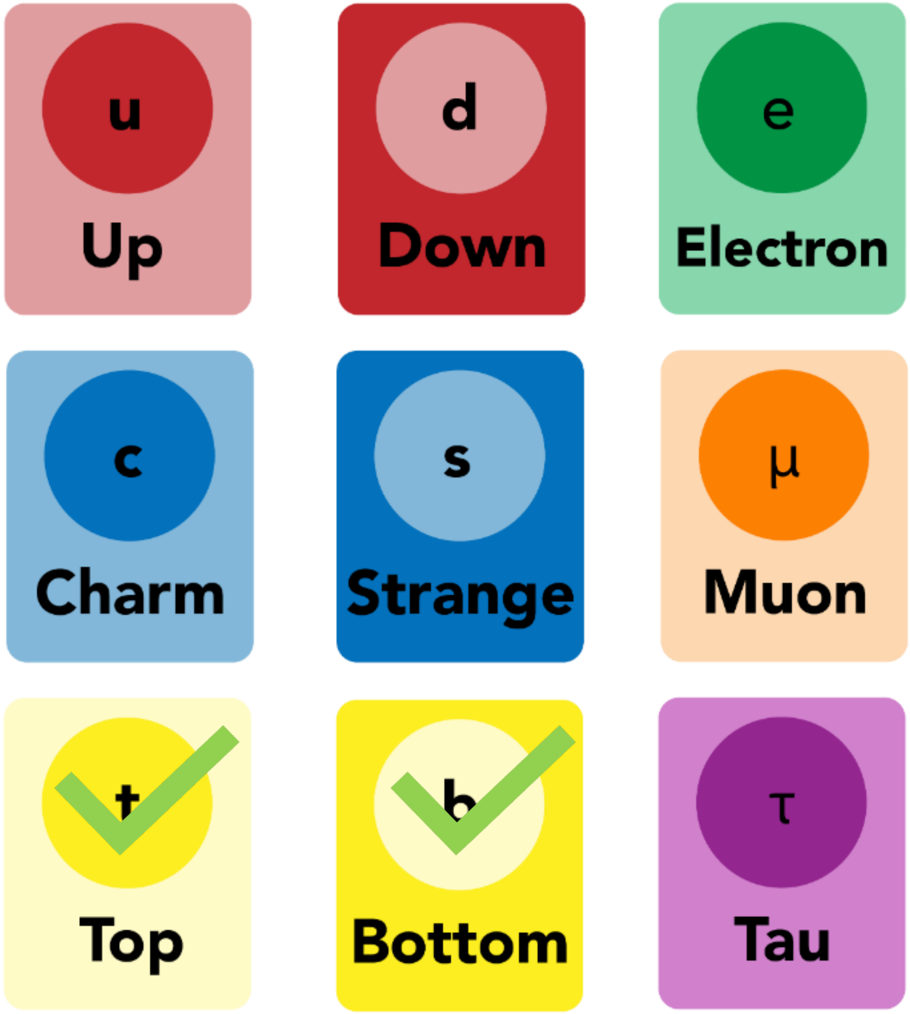

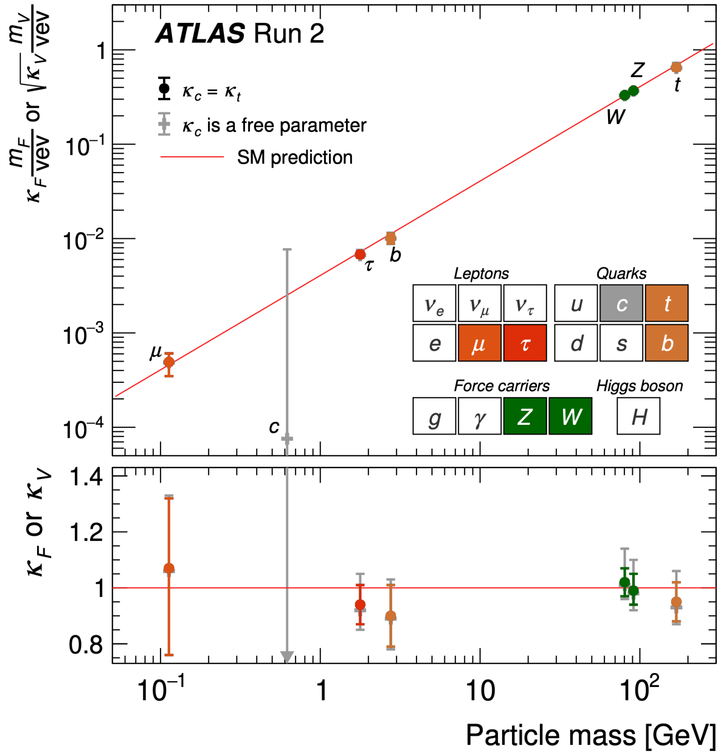

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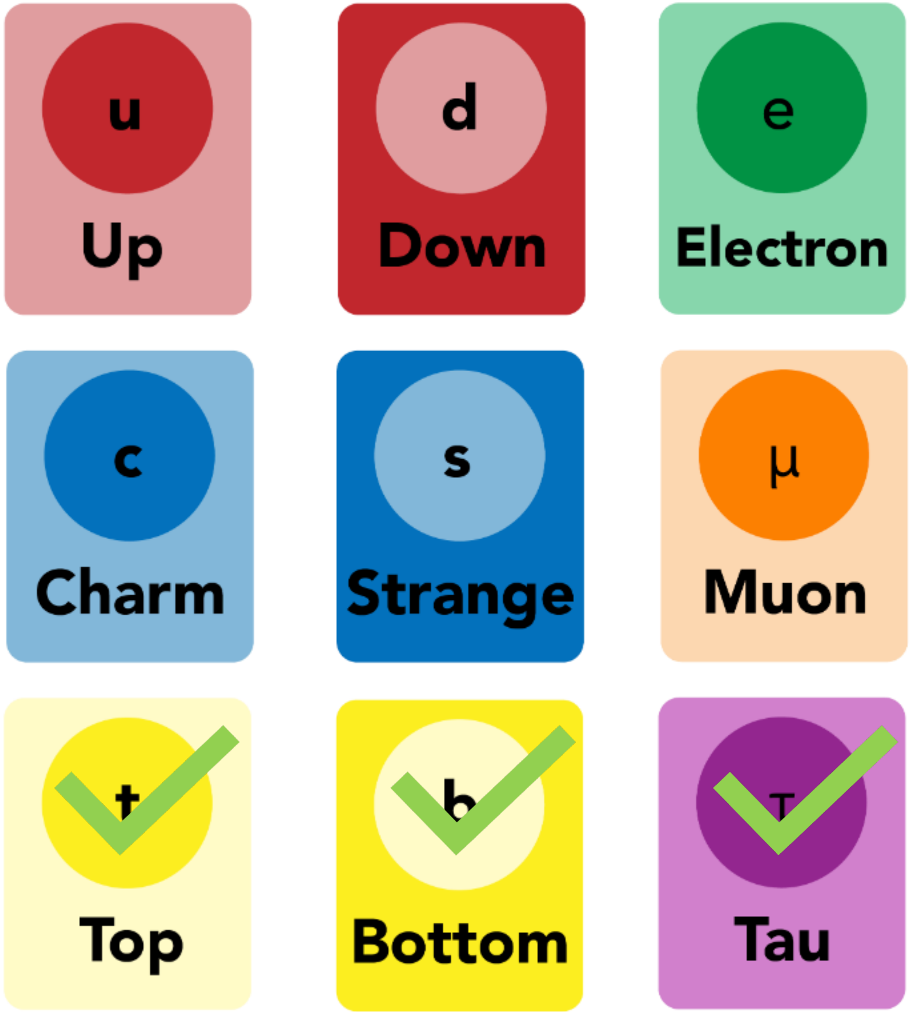

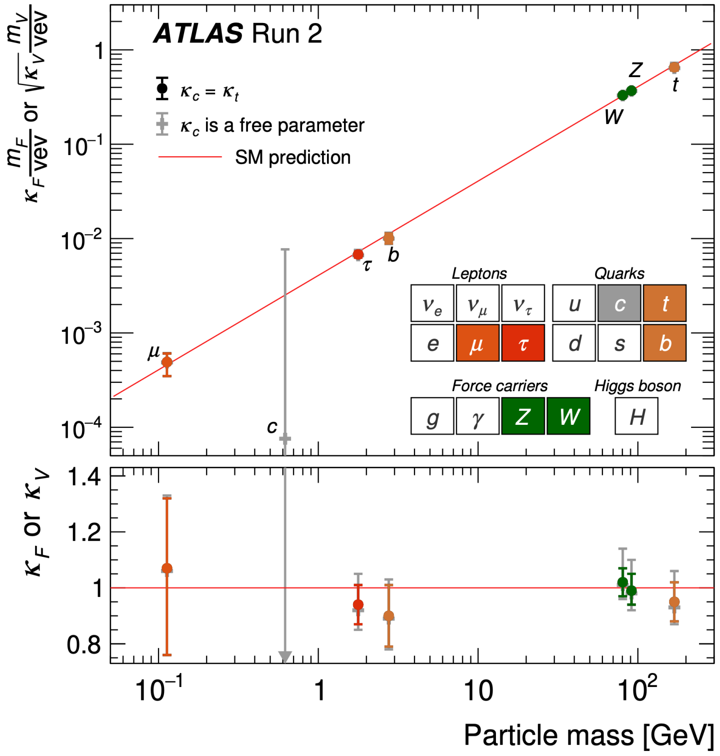

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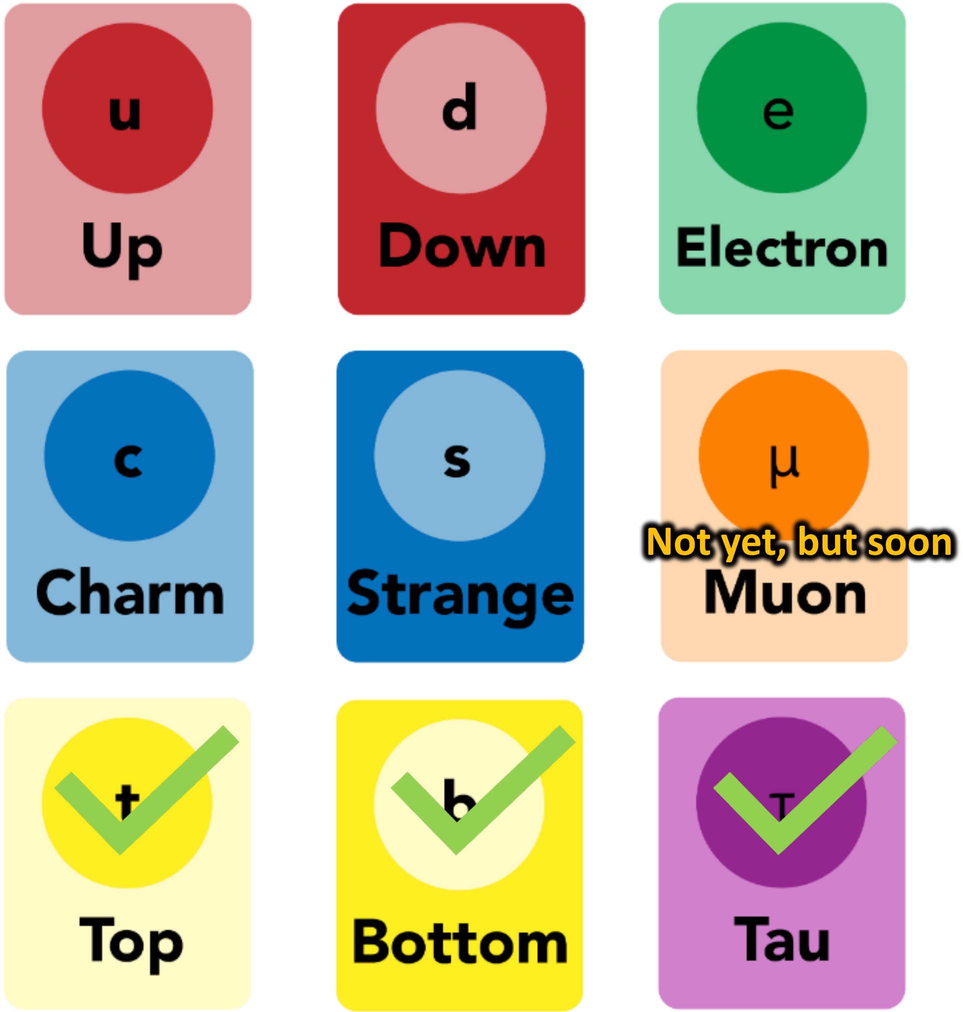

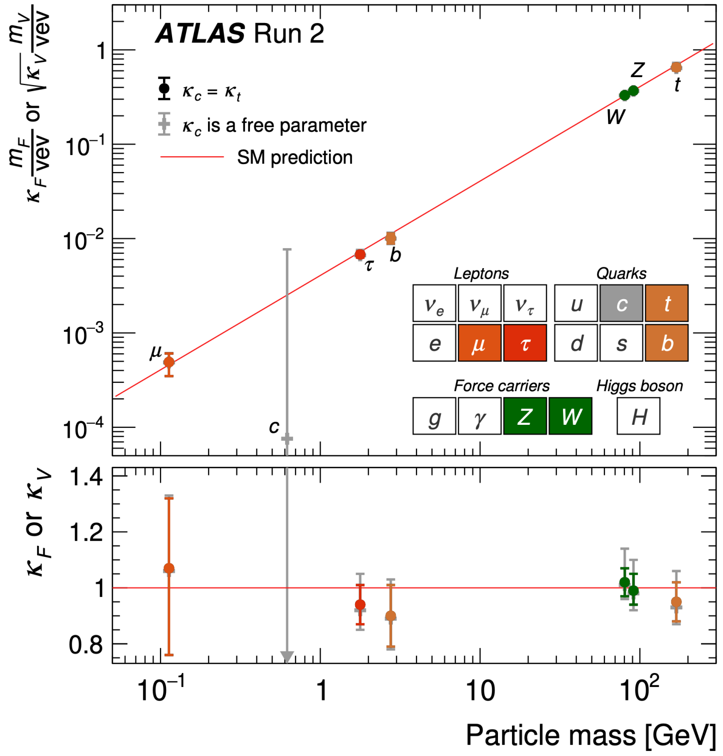

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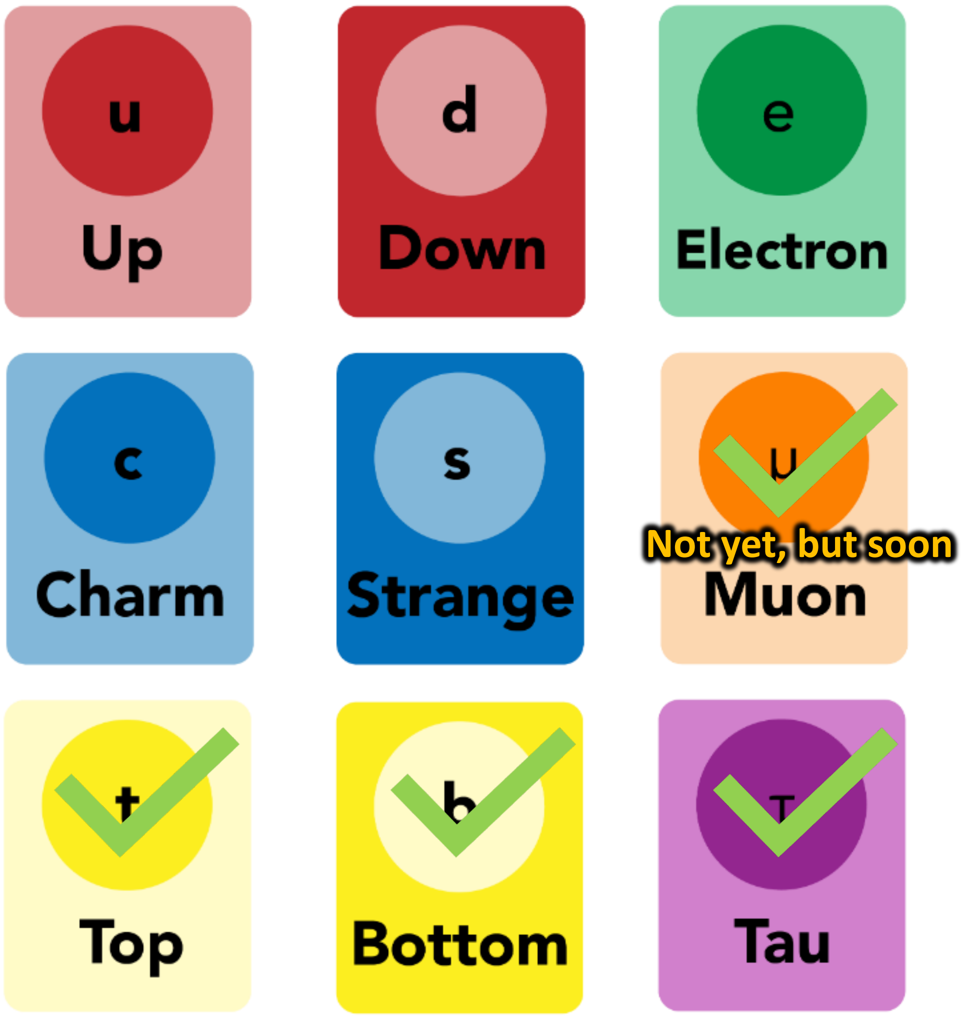

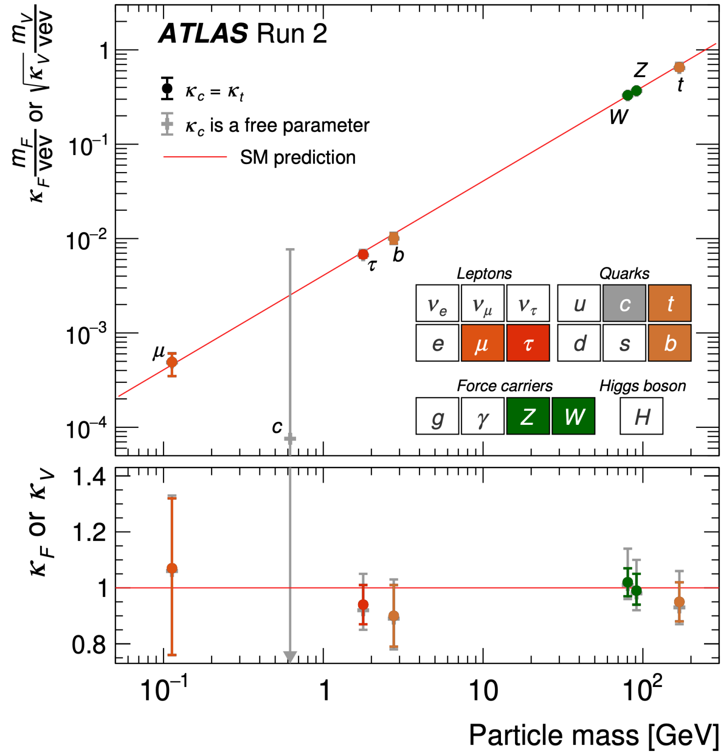

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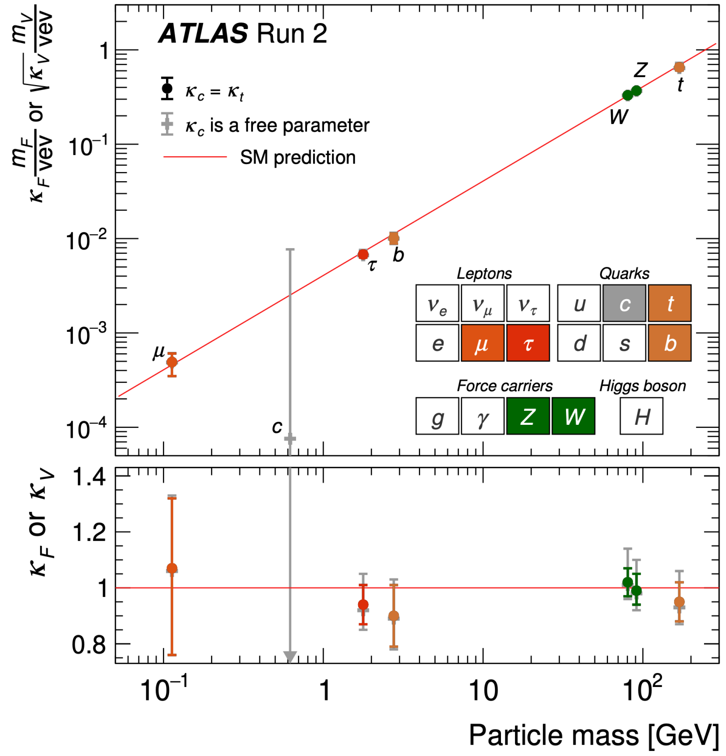

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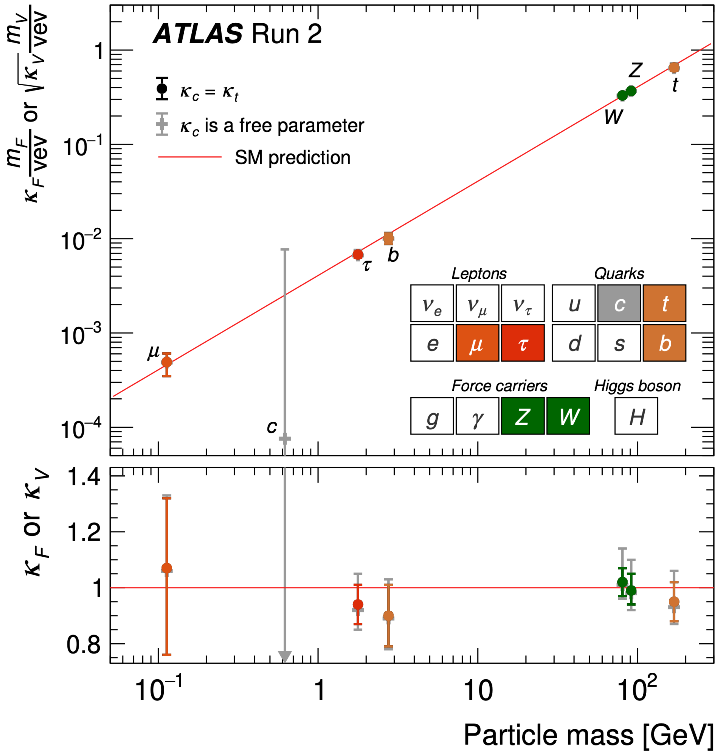

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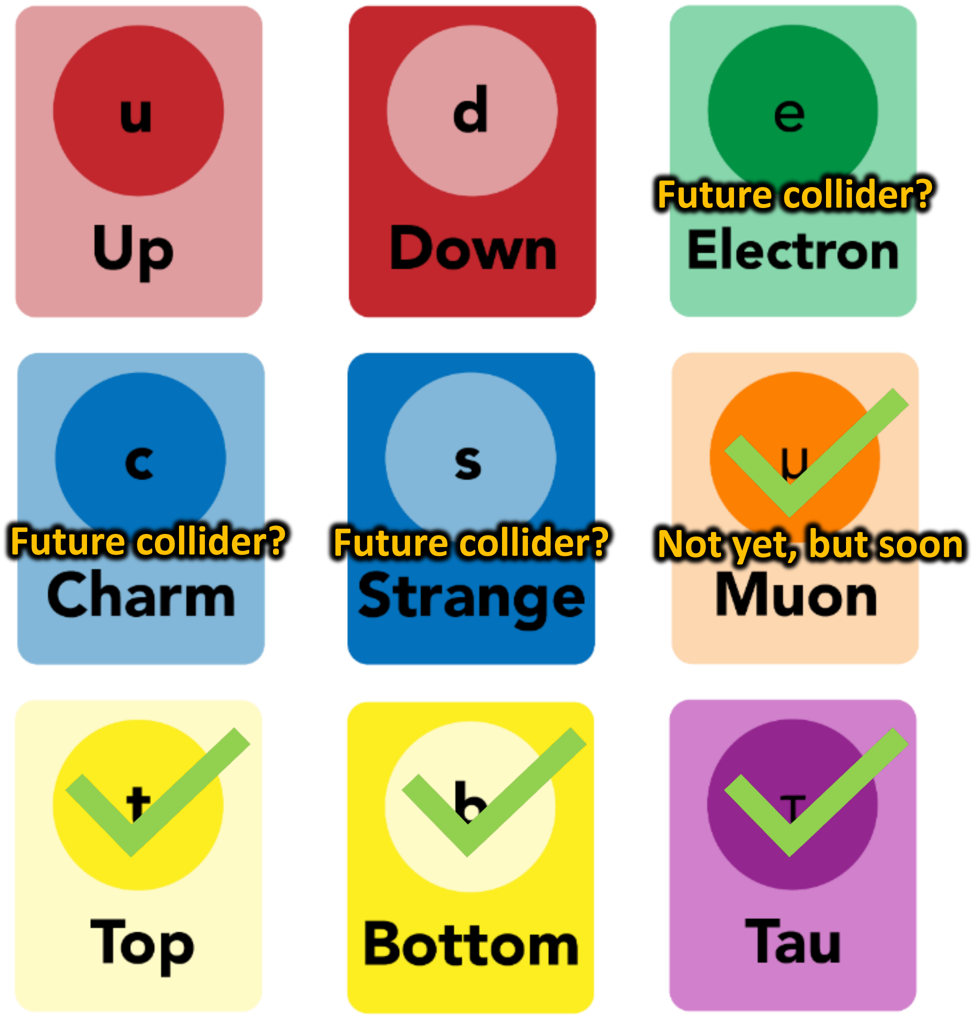

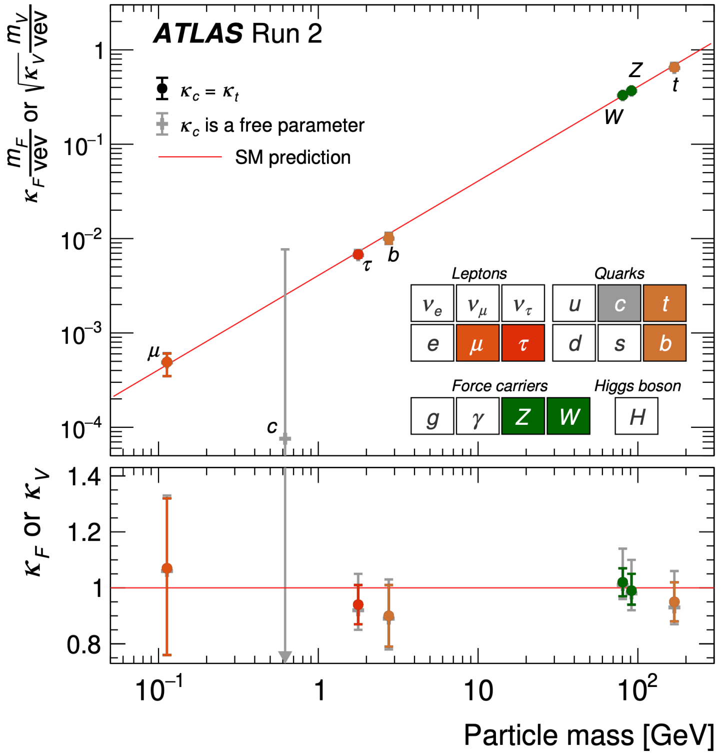

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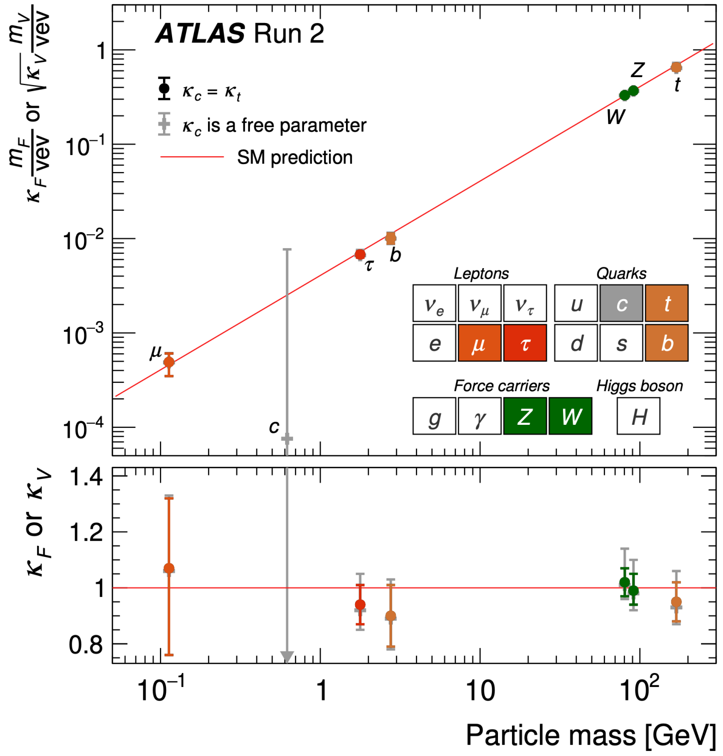

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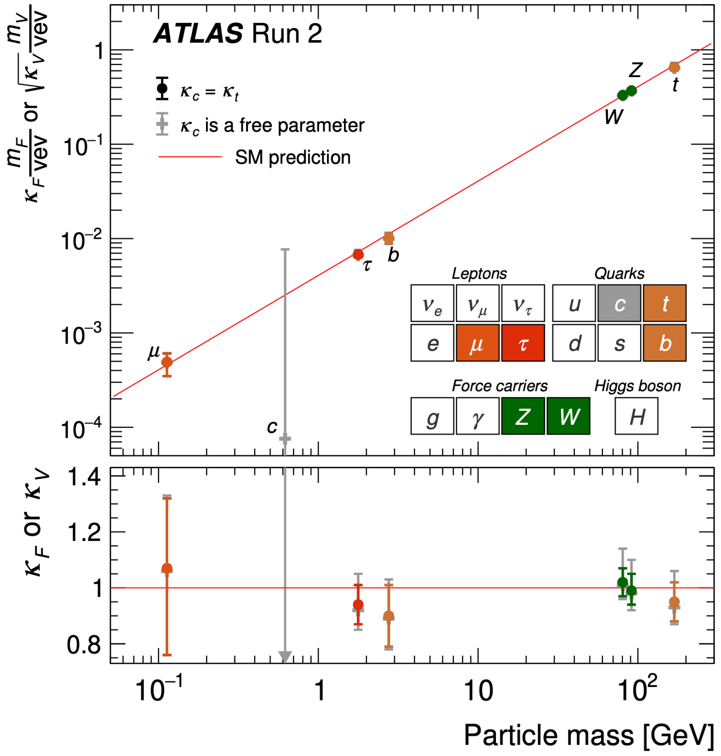

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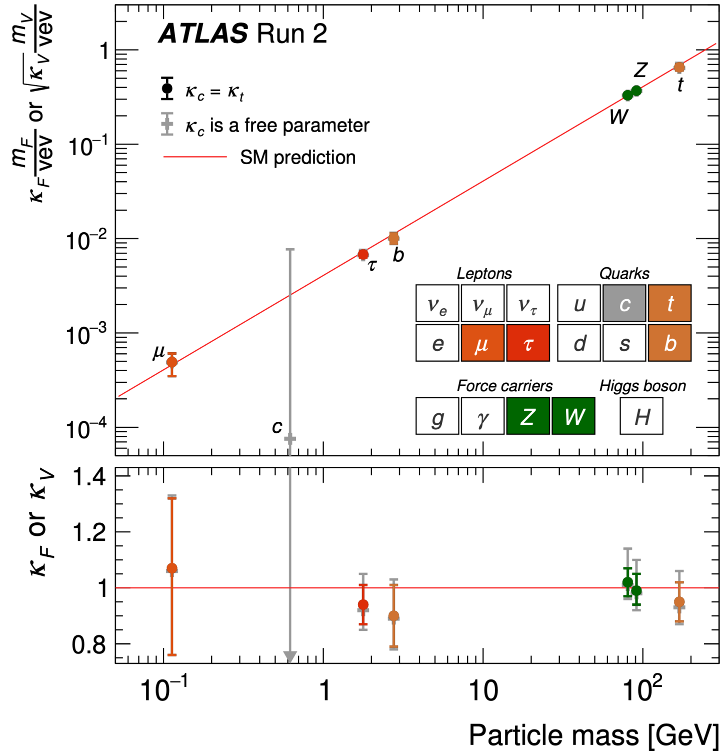

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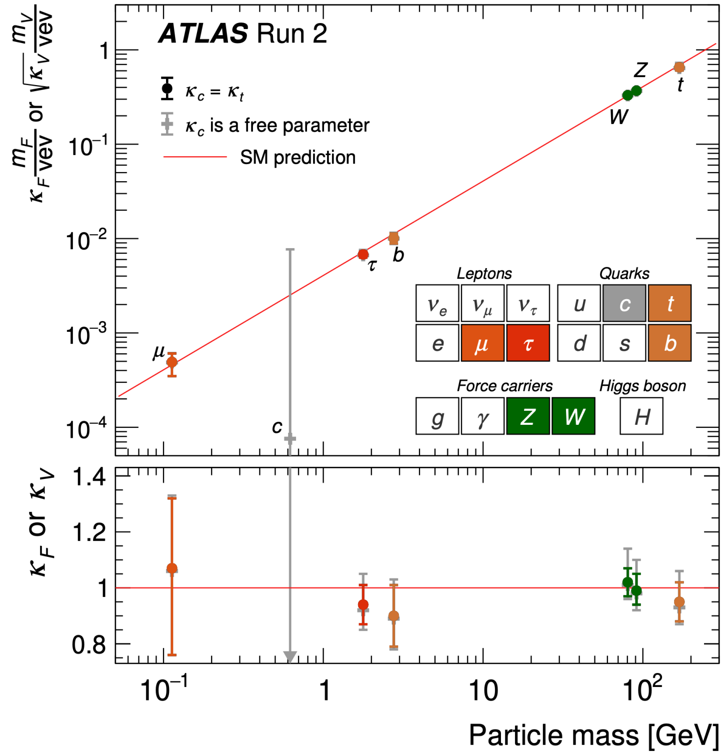

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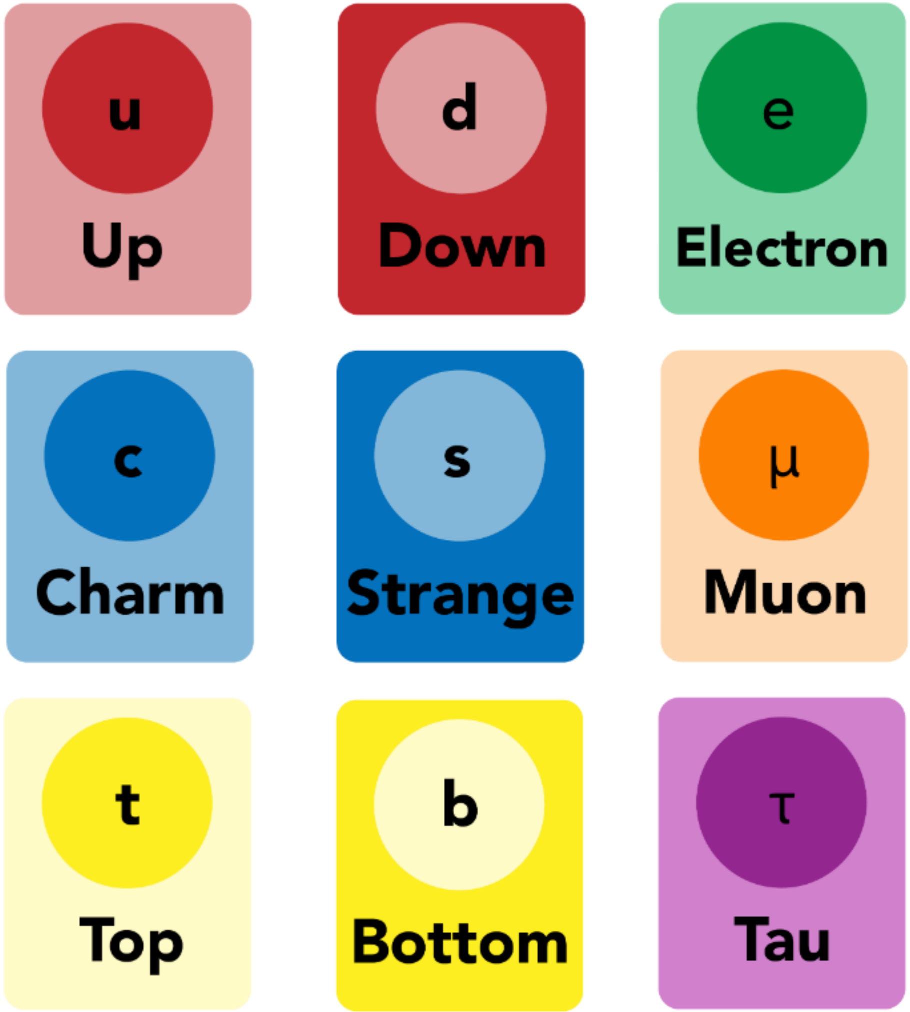
→ Dedicated charm session on Wednesday!

CP structure of Yukawa couplings



- While CP structure of HVV interactions is already comparably well-constrained, the CP structure of the $Hf\bar{f}$ interactions is far less (similar for Hgg and $H\gamma\gamma$).

$$\mathcal{L}_{\text{yuk}} = -\sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f}\left(c_f + i\gamma_5 \tilde{c}_f\right) f H,$$

- Most BSM theories, however, predict largest CP violation in $Hf\bar{f}$ couplings.

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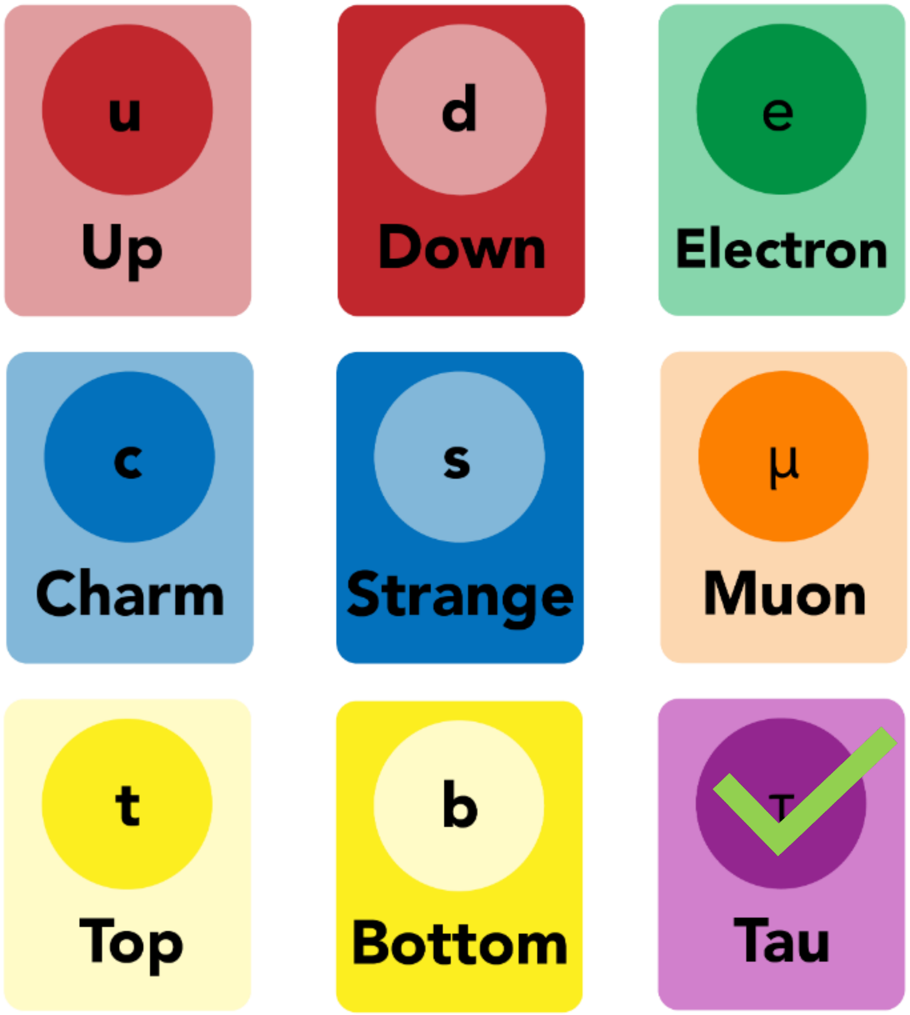

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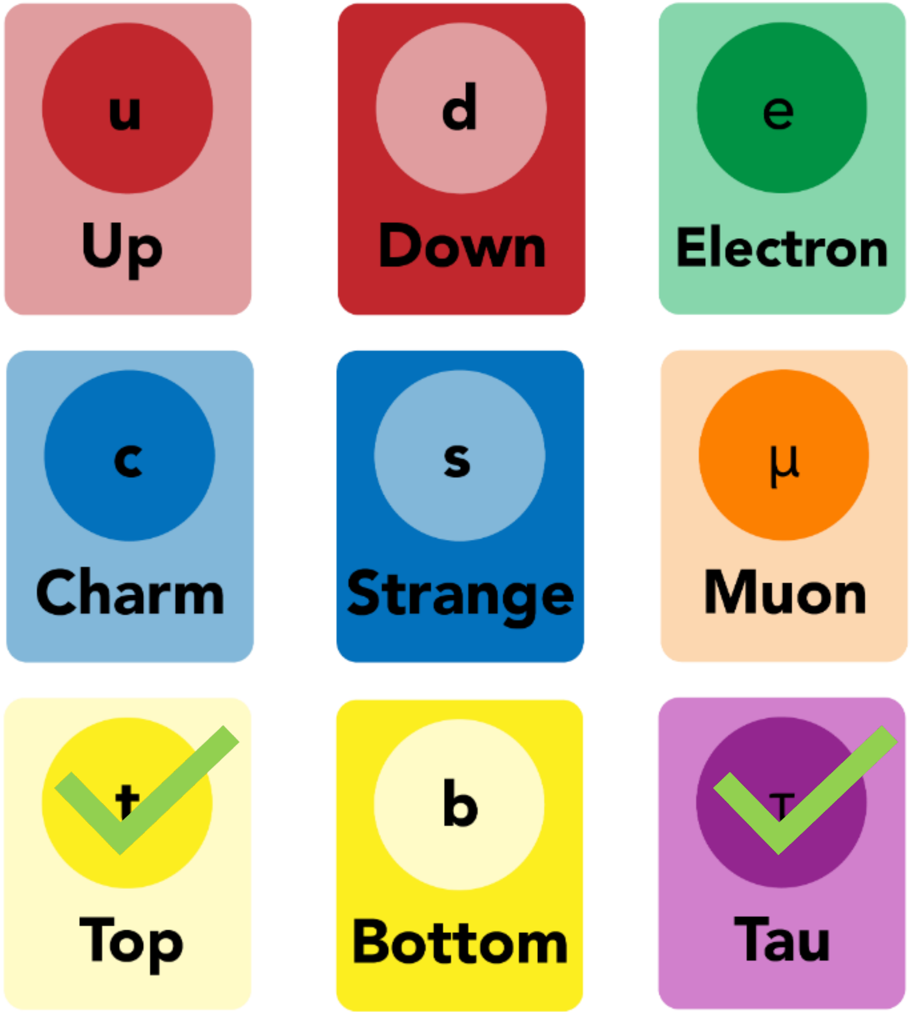

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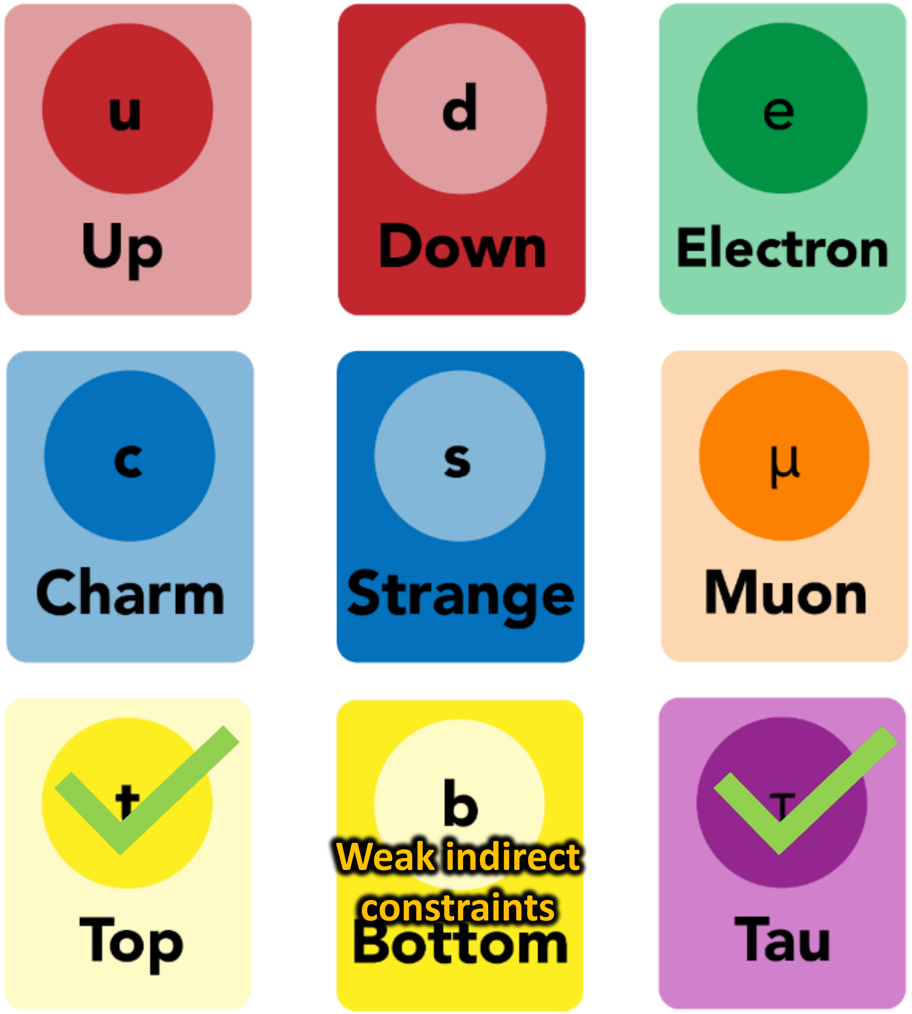

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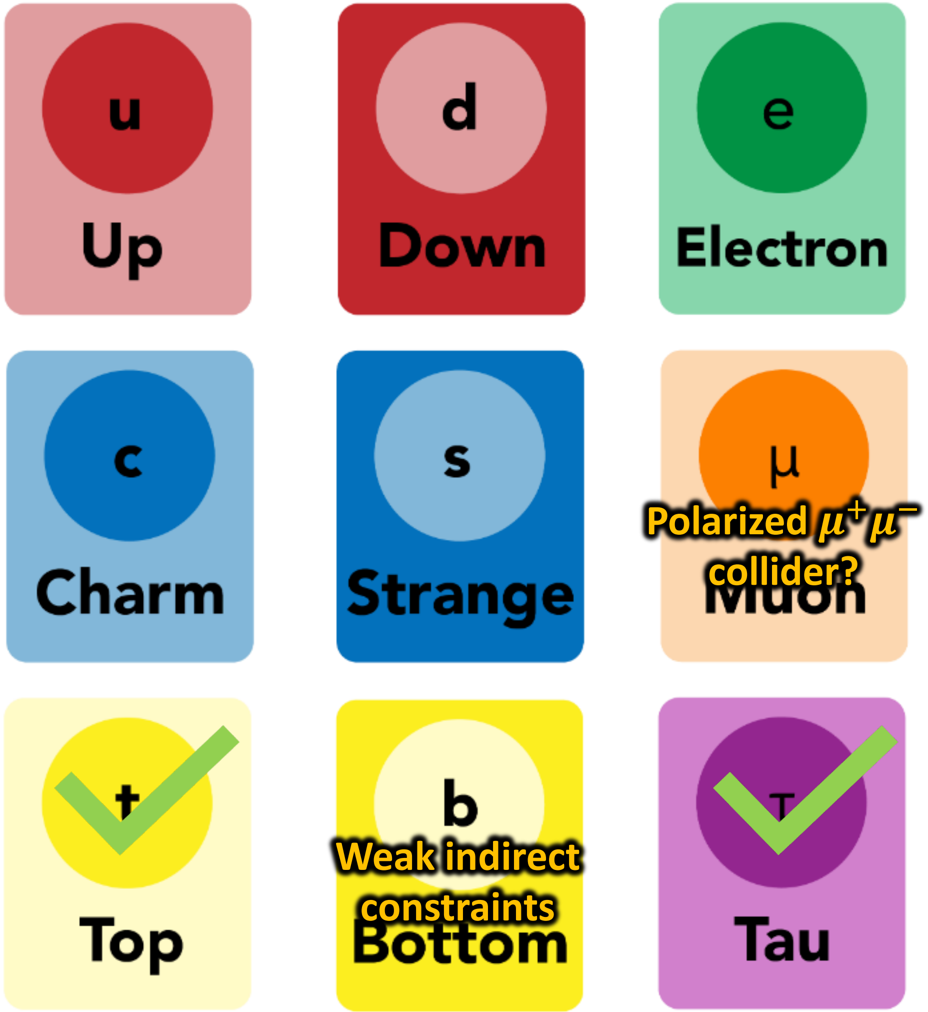

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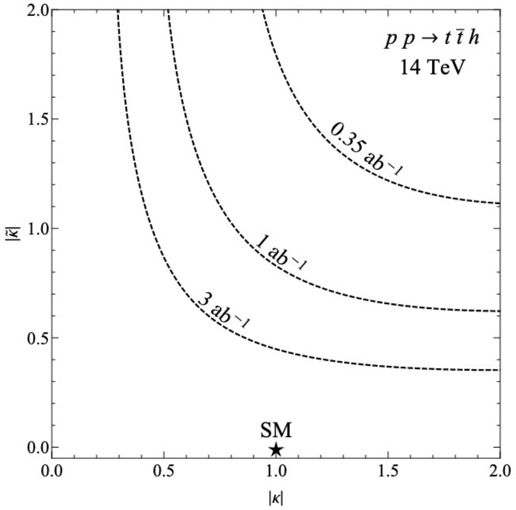
- How can we improve on this situation?
  - Direct constraints: CP-odd observables.
  - Indirect constraints: CP-even observables.
  - Kinematic information: potentially mixing CP-odd and CP-even observables.
  - Complementarity with electric dipole moments (EDMs).

Constraining CP violation: top-Yukawa example

CP-odd observables:
- Clean interpretation.
- Difficult experimentally since top-quark polarization needs to be measured.



[Faroughy et al.,1909.00007]

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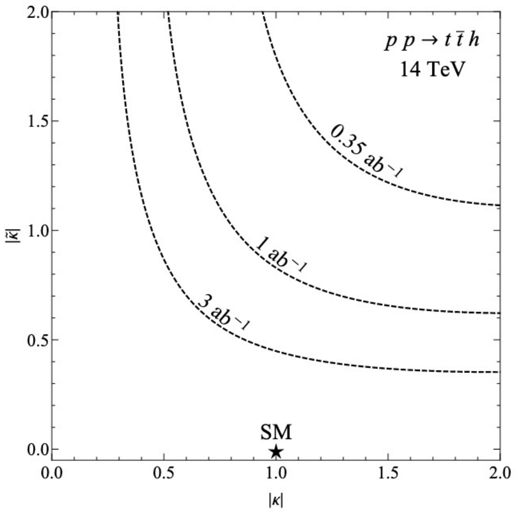
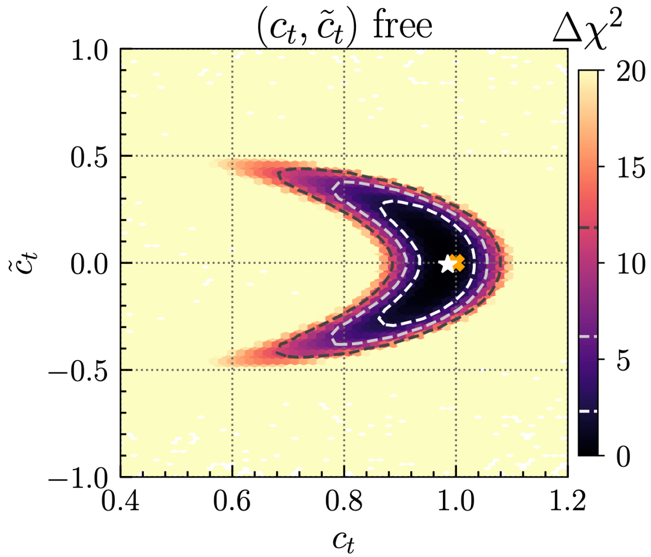


[Faroughy et al.,1909.00007]

Indirect constraints:

- Strong constraints from ggH and $H\gamma\gamma$ rate measurements. ✓
- Constraints very model-dependent. ✗



[HB et al., 2007.08542]

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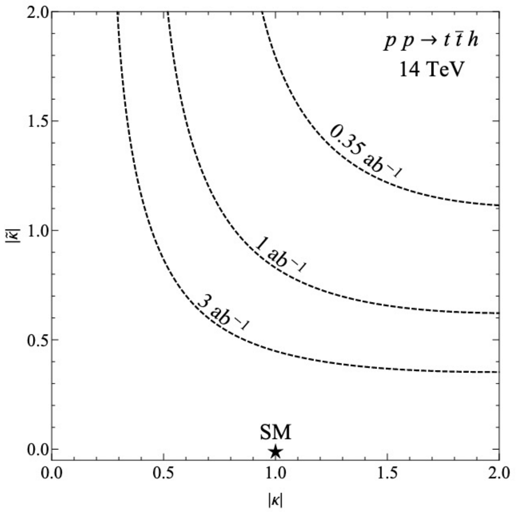

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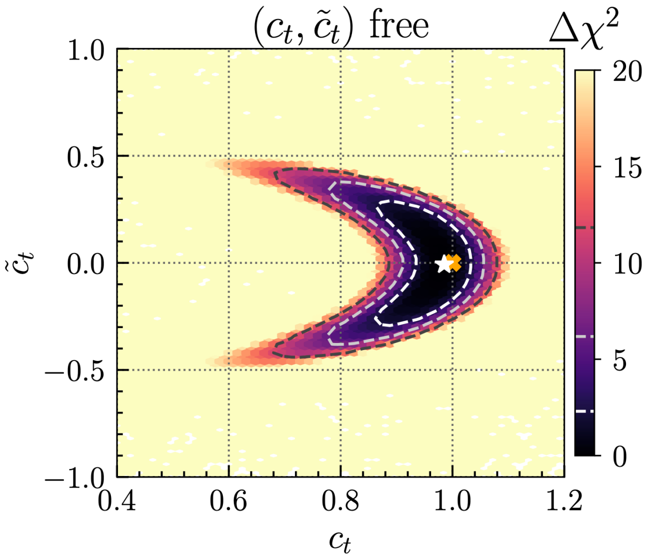
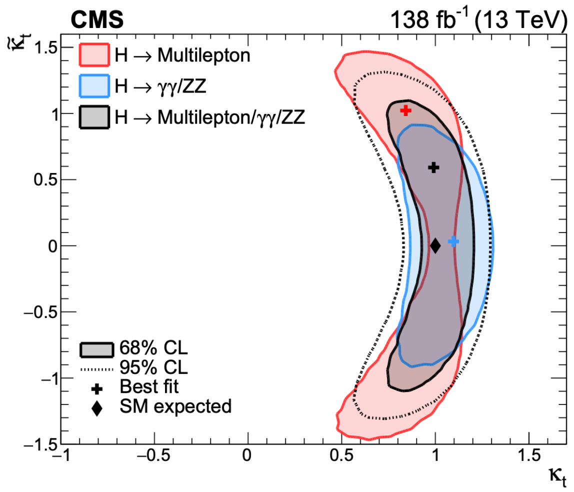


[HB et al., 2007.08542]

Kinematic information:
- Focus on comparably model-independent $t\bar{t}H$ production.
- Combination of different decay channels and across experiments difficult.



[CMS, 2208.02686]

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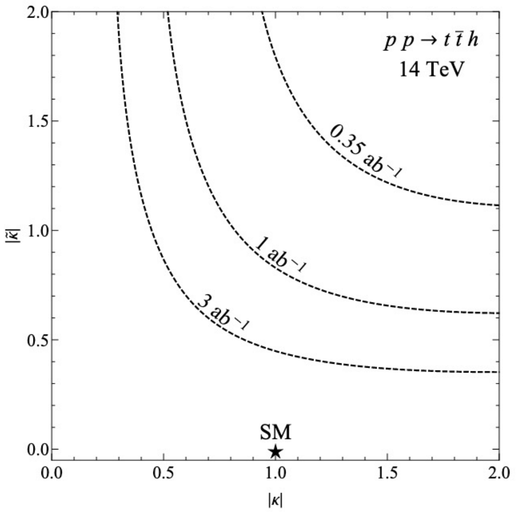

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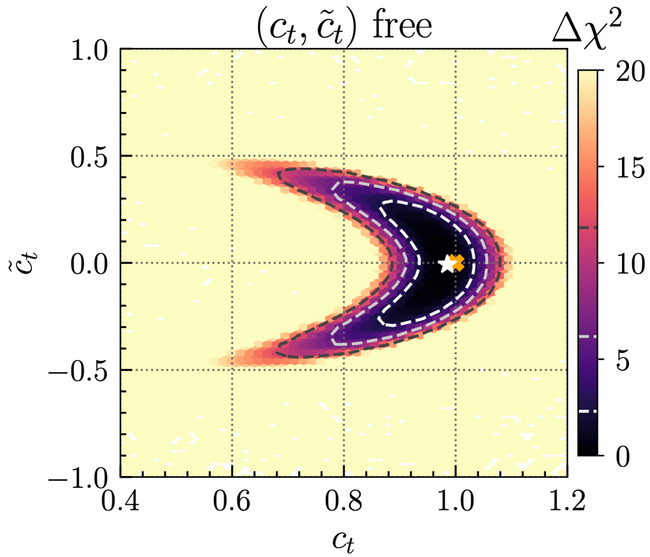

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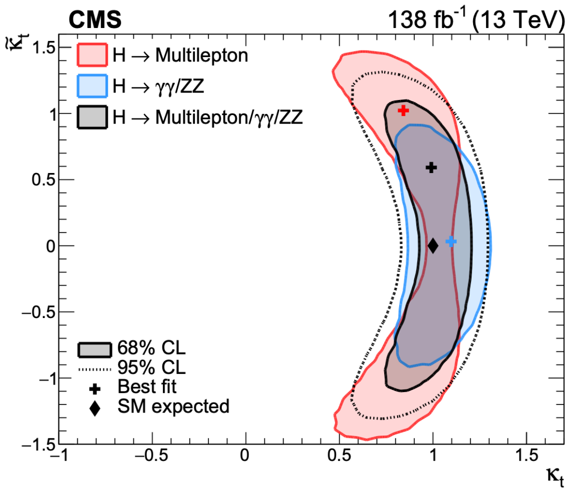

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Exploit complementarity of different approaches!

Next steps: CP-sensitive STXS, degeneracies with CP-violation in non-Higgs couplings, other processes, …

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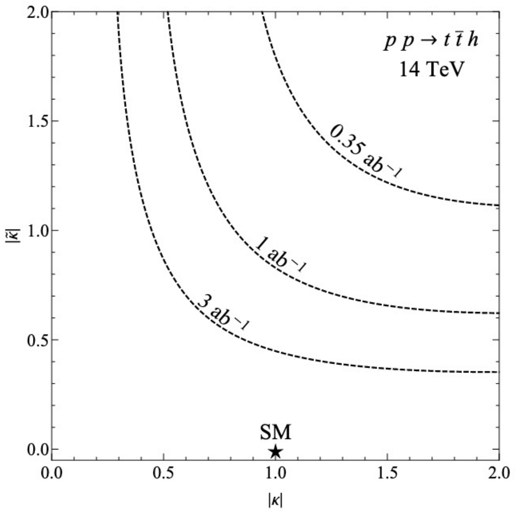

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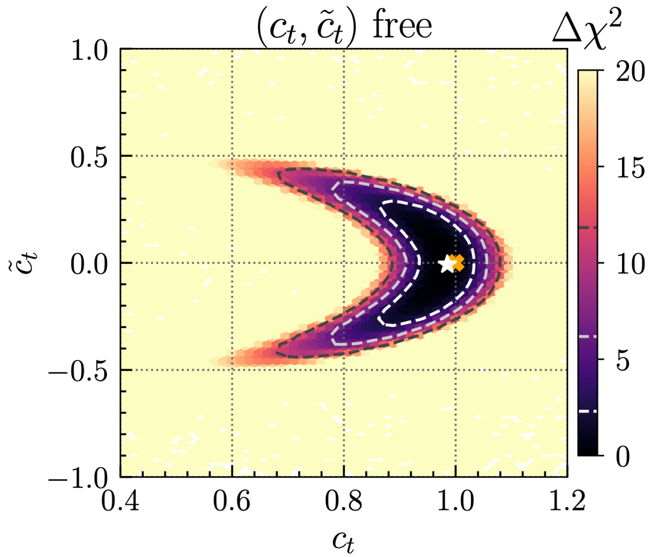

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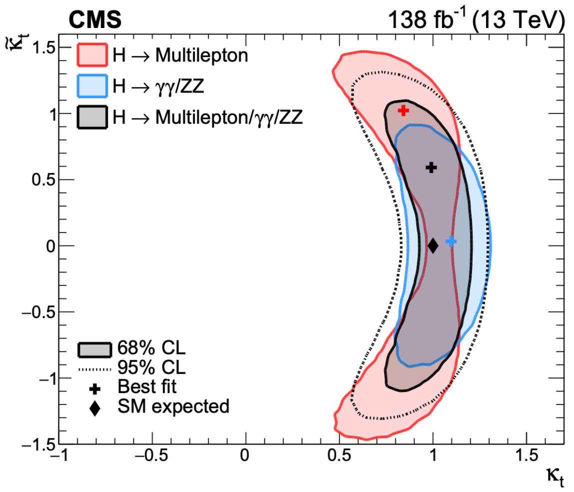

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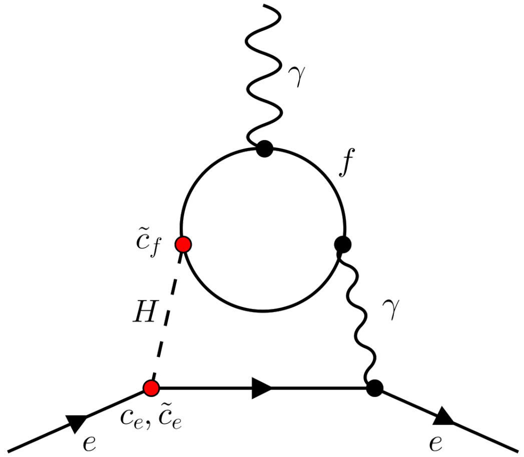
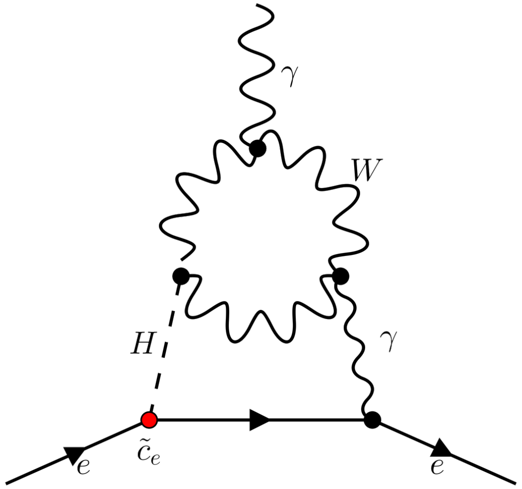
➡ **Exploit complementarity of different approaches!**

Next steps: CP-sensitive STXS, degeneracies with CP-violation in non-Higgs couplings, other processes, …

→ See also Savvas' talk on Thursday!

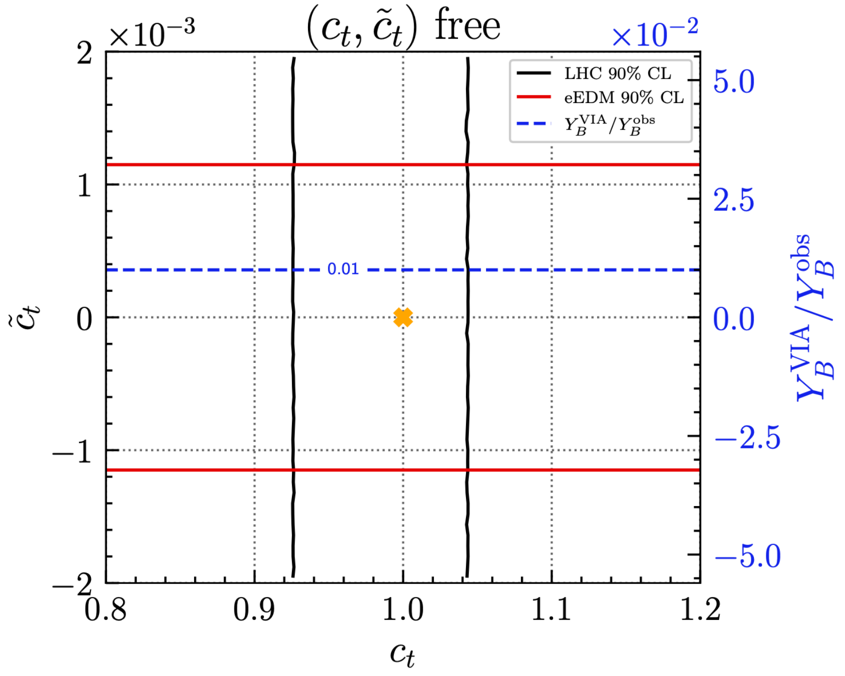
Complementarity with EDM constraints



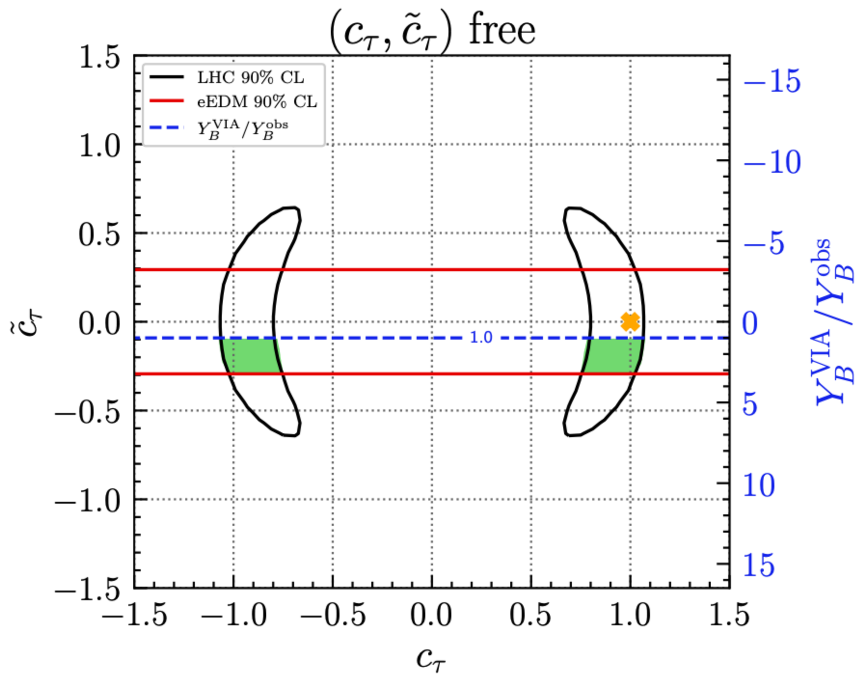


- Several EDMs are sensitive to CP violation in the Higgs sector.
- Consider here only constraints from theoretically cleanest EDM: the electron EDM.
  [Brod et al.,1310.1385,1503.04830, 1810.12303, 2203.03736;Panico et al.,1810.09413;Altmannshofer et al.,2009.01258]
- Limit by ACME collaboration: $d_e^{\text{ACME}} = 1.1 \cdot 10^{-29} e$ cm at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]
- $\frac{d_e}{d_e^{\text{ACME}}} \simeq c_e(870.0\tilde{c}_t + 3.9\tilde{c}_b + 3.4\tilde{c}_\tau + \cdots) + \tilde{c}_e(610.1c_t + 3.1c_b + 2.8c_\tau - 1082.6c_V + \cdots)$
- Bounds strongly depend on assumptions about electron-Yukawa coupling.

Complementarity with EDM constraints: t and τ



Very strong constraints on CP-odd top-Yukawa coupling.



CP-odd τ coupling can contribute significantly to baryon asymmetry.

EDM > LHC?

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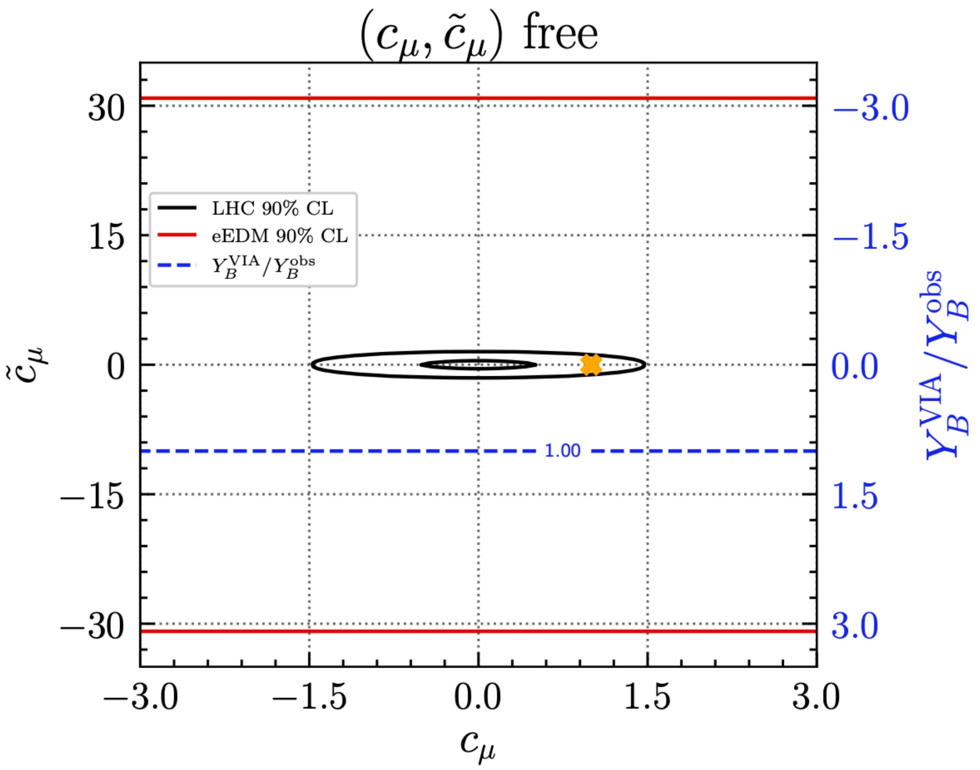
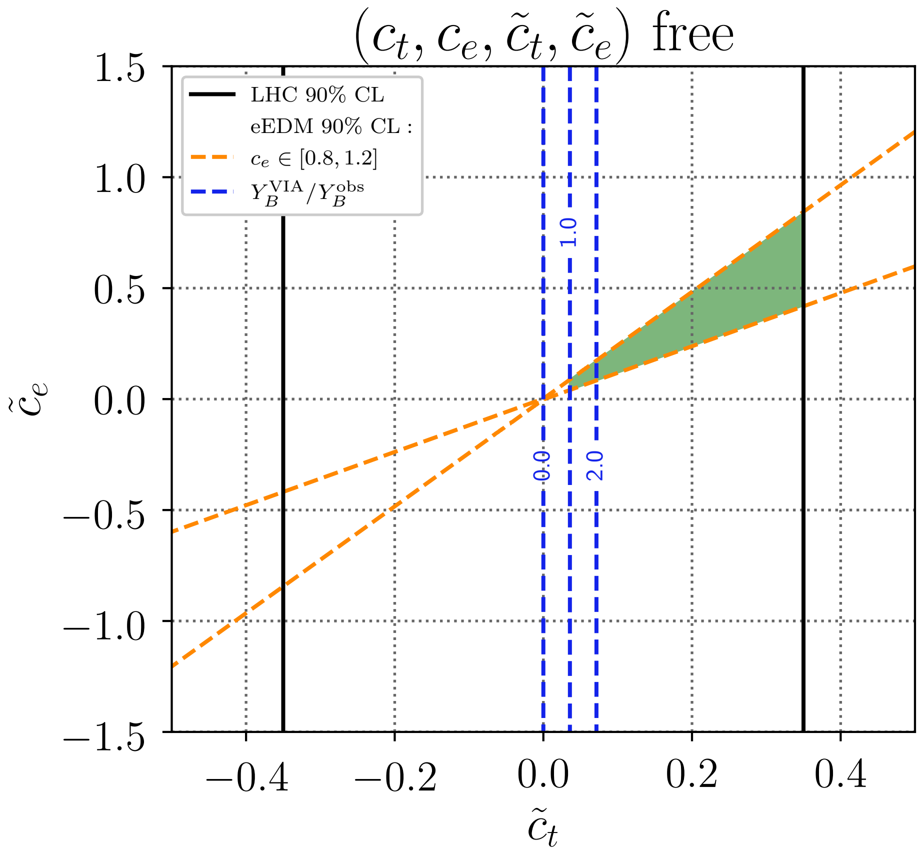


CP-insensitive $H \to \mu^+\mu^-$ rate measurement outperforms EDM constraint.

Dependence on electron-Yukawa coupling

[HB et al.,2202.11753]



- Electron Yukawa-coupling only very weakly constrained ($g_e \leq 268$ at 95% CL).
- If c_e smaller, eEDM significantly weakened.
- Moreover, we can fine-tune CP-odd electron-Yukawa coupling such that $d_e < d_e^{\rm ACME}$.
- Neutron EDM has similar dependence on first-generation quark-Yukawa couplings.

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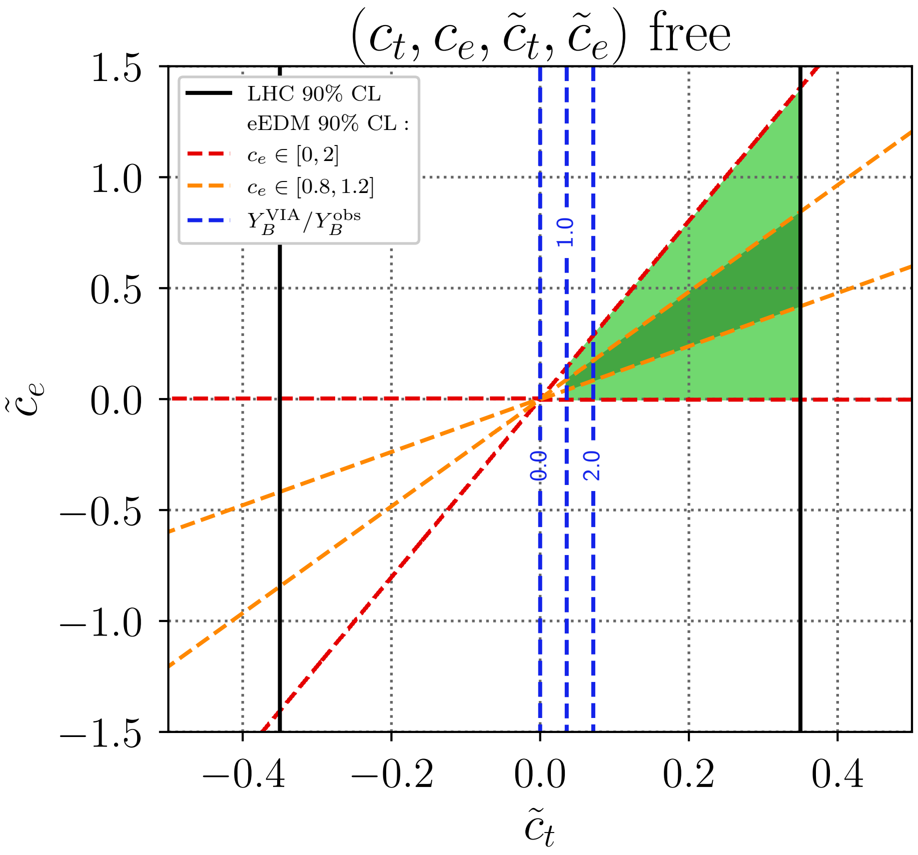

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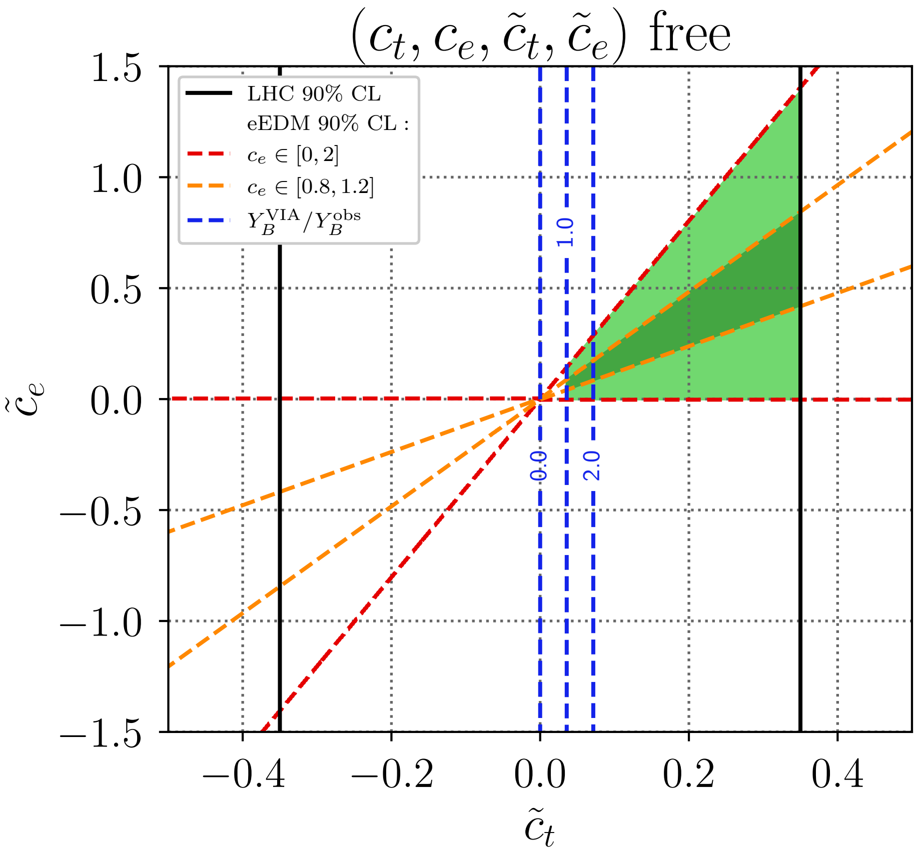

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→ LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

What is still left to explore?

- Yukawa couplings (and their CP character)
- Higgs potential

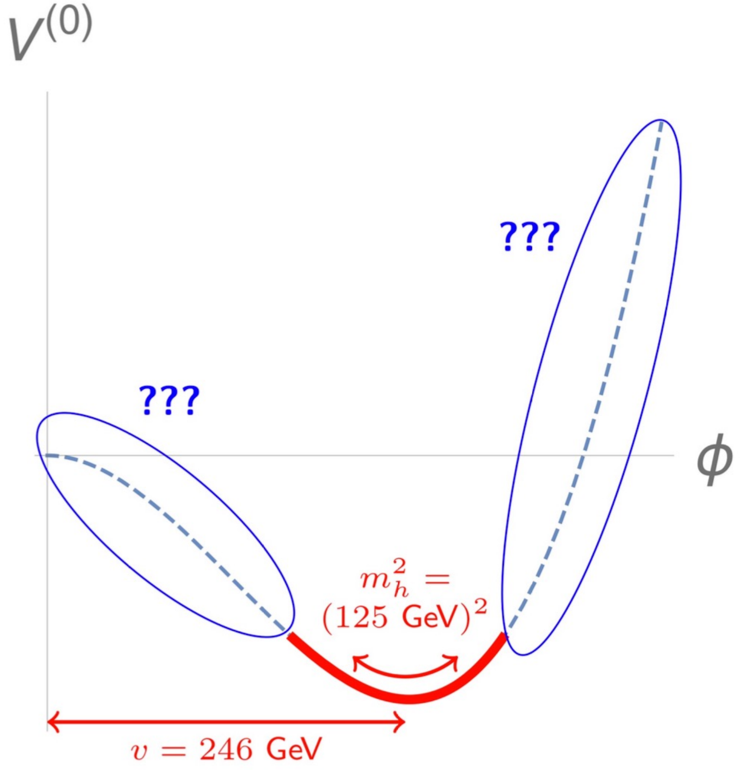
What do we know about the Higgs potential?

- After the Higgs discovery, we know
  - the location of the EW minimum: $v = 246$ GeV,
  - the curvature of the potential close to the minimum: $m_h = 125$ GeV.

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

  → Determination of trilinear Higgs coupling λ_{hhh} crucial (dedicated session on Wednesday).

- λ_{hhh} closely linked to
  - stability of EW vacuum
  - nature of EW phase transition (→ EW baryogenesis?).



[figure by J. Braathen]

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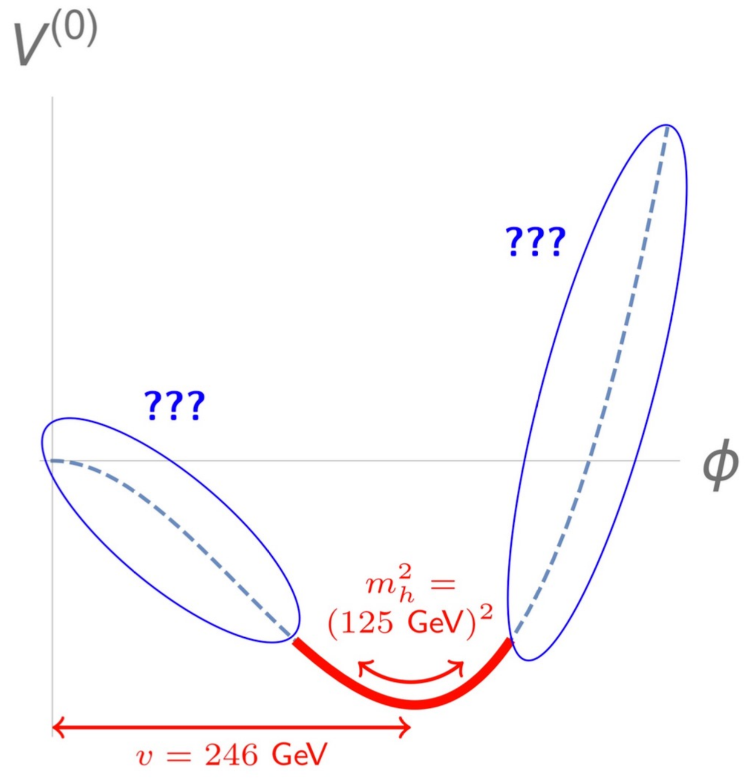
➡ Is the Higgs trilinear also a discovery tool?

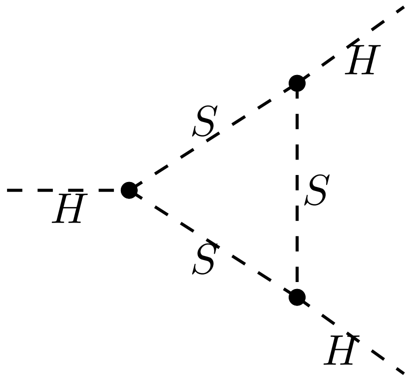


[figure by J. Braathen]

Case study: real singlet extension of the SM

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

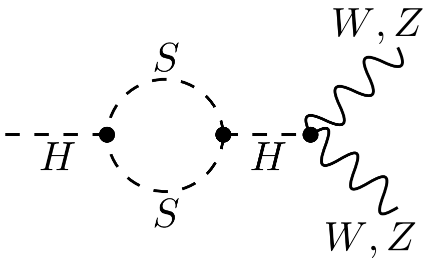
If S does not get a vev, $\lambda_{HHH} = \lambda_{HHH}^{\mathrm{SM}}$ at the tree-level ($m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$).



The 1L correction to λ_{HHH} scales like ($\lambda_\Phi^{\mathrm{SM}} \sim 0.25$)

$$\kappa_\lambda \equiv \frac{\lambda_{HHH}}{\lambda_{HHH}^{\mathrm{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^4}{v^4 \lambda_\Phi^{\mathrm{SM}}}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3$$

whereas the dominant correction to other Higgs couplings scale like



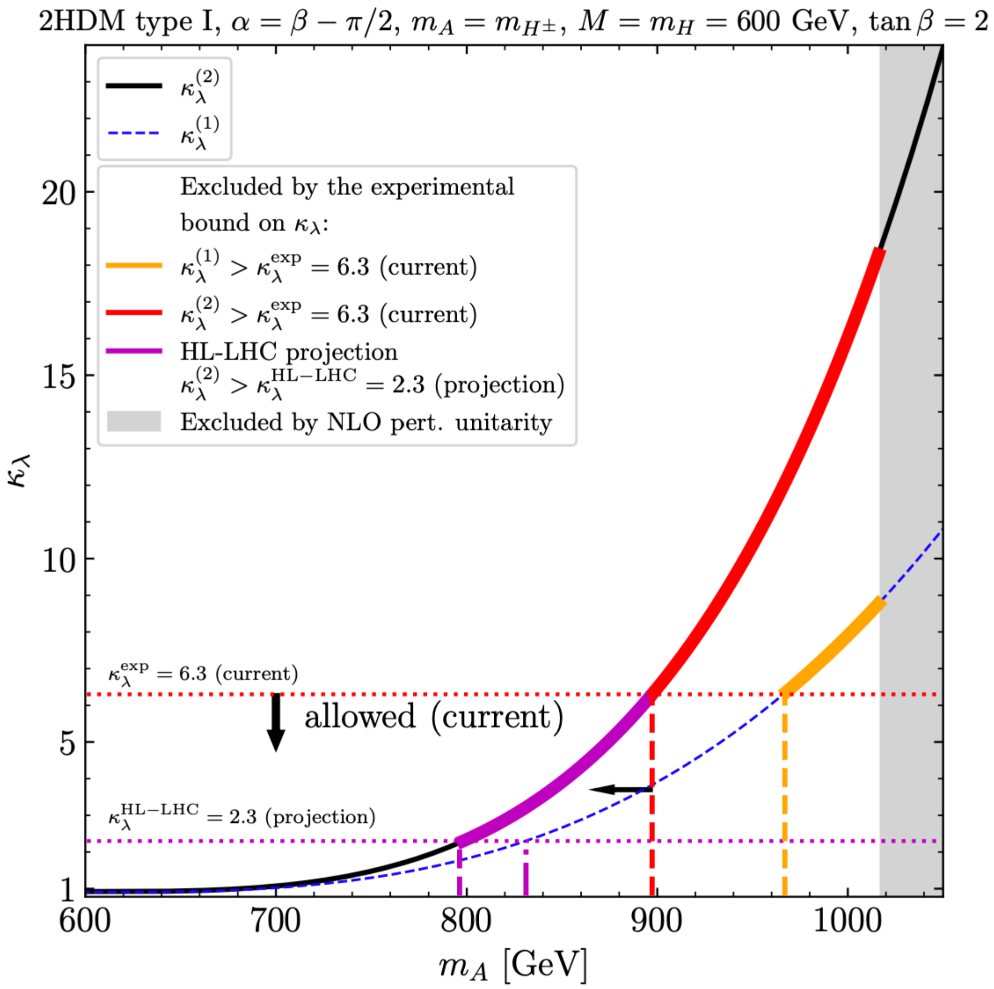
$$\kappa_g \equiv \frac{g}{g^{\mathrm{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

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

Trilinear Higgs coupling in the 2HDM

- Even larger deviations possible in the 2HDM (more BSM particles).
- Additional enhancement by 2L corrections.
- Maximal size bounded by perturbative unitarity.
- Currently strongest experimental limit on κ_λ:

  $-0.4 < \kappa_\lambda < 6.3$ at 95% CL [ATLAS-CONF-2022-050]



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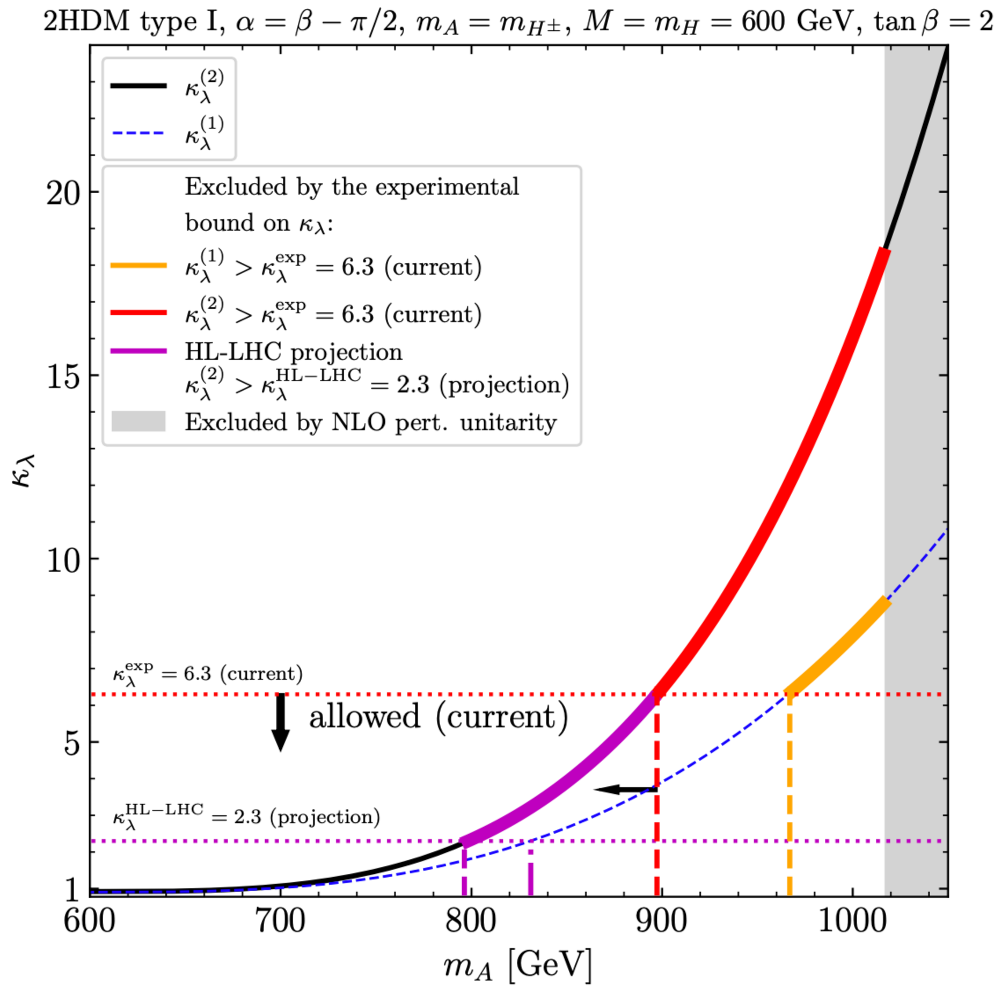
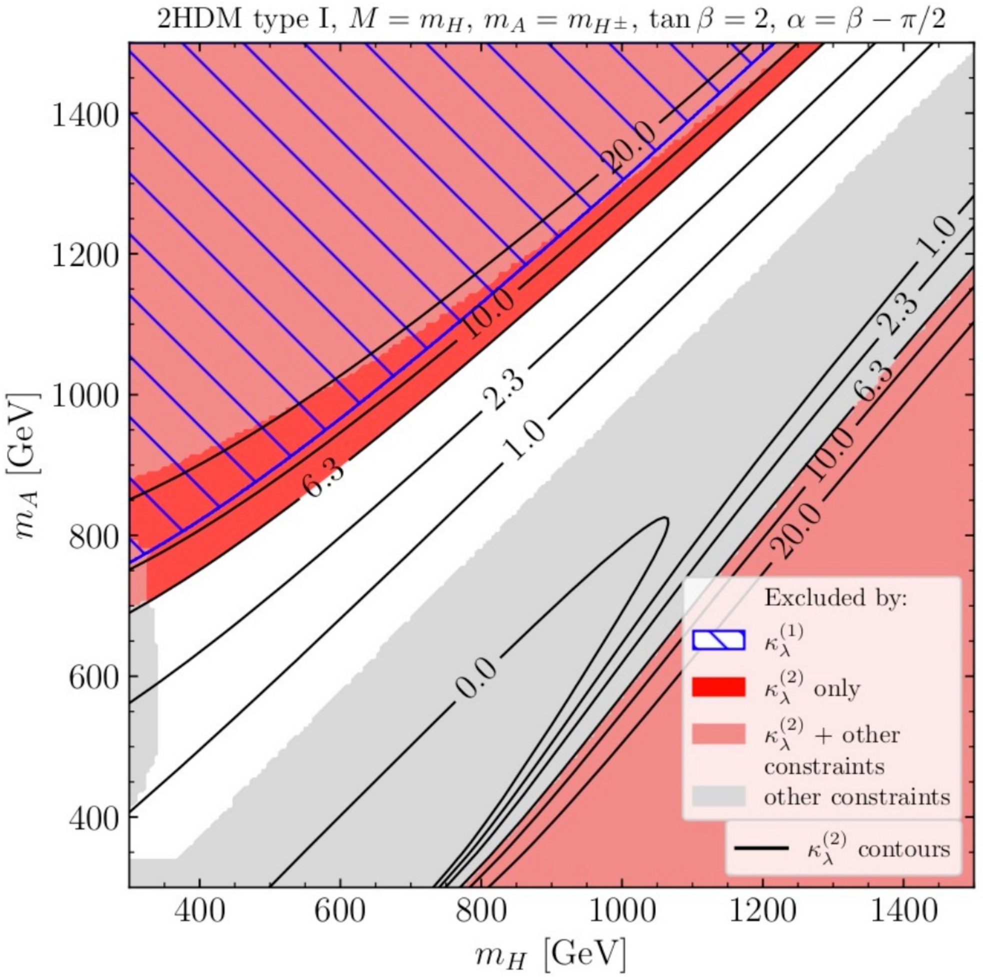
Already current experimental limits on κ_λ probe so-far unconstrained BSM parameter space!



Constraints on κ_λ — benchmark scenario



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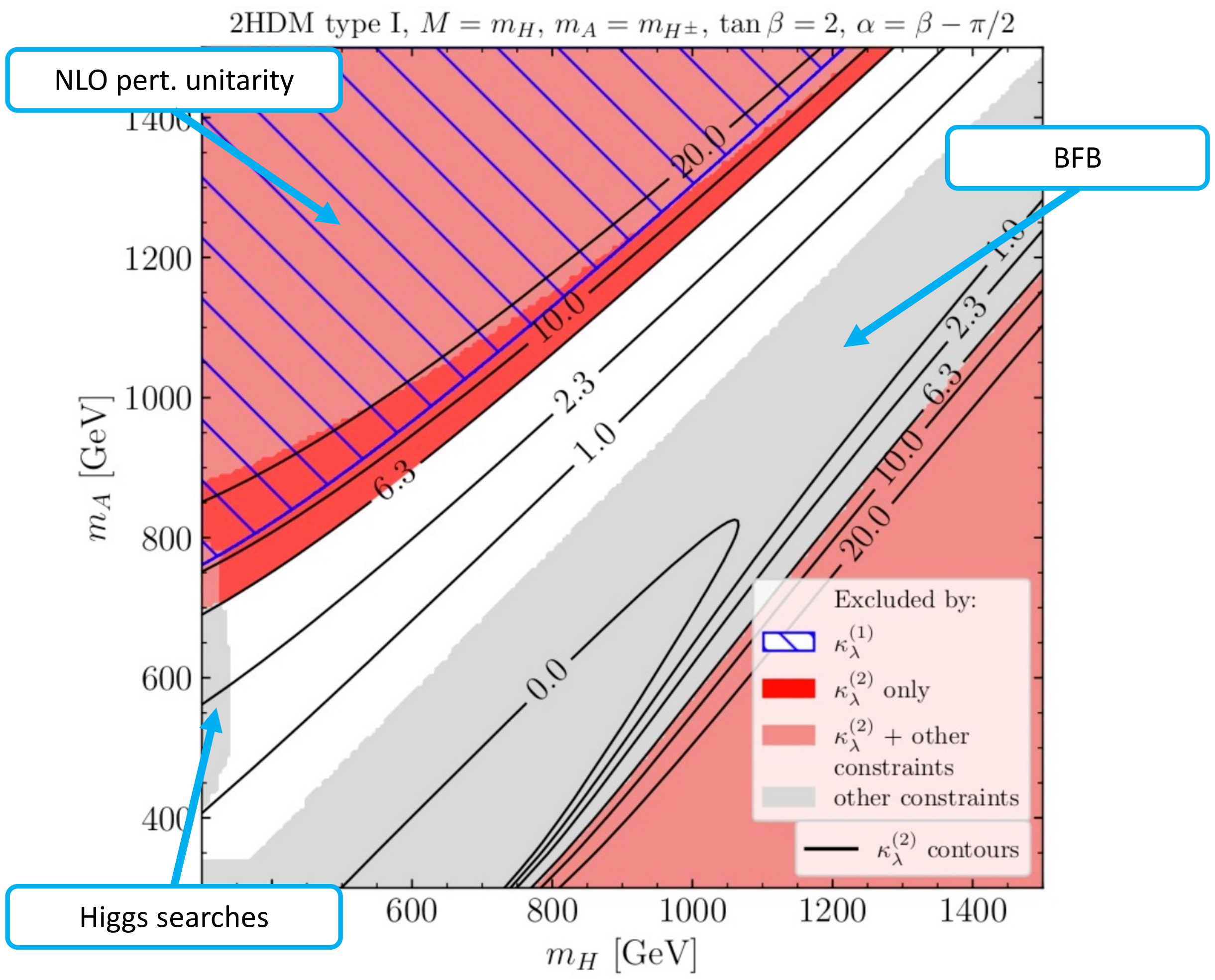

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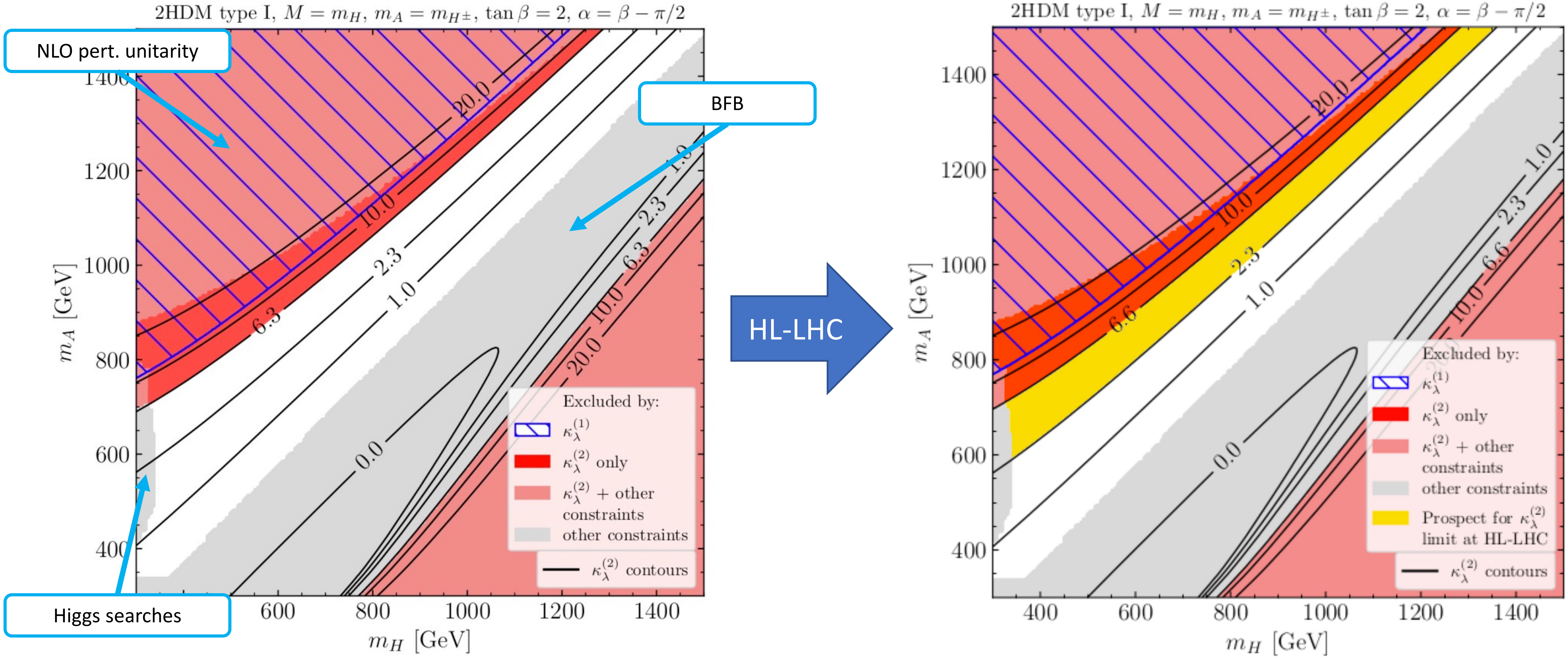

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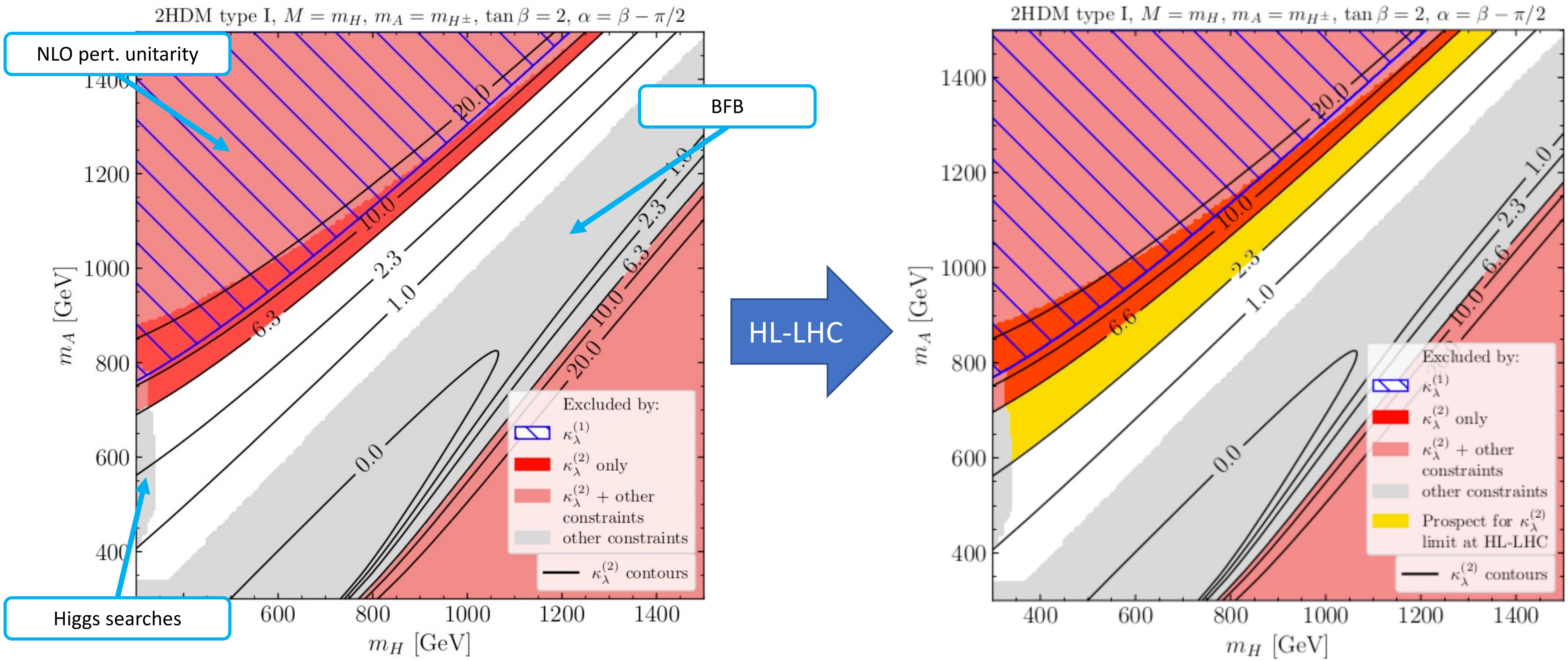
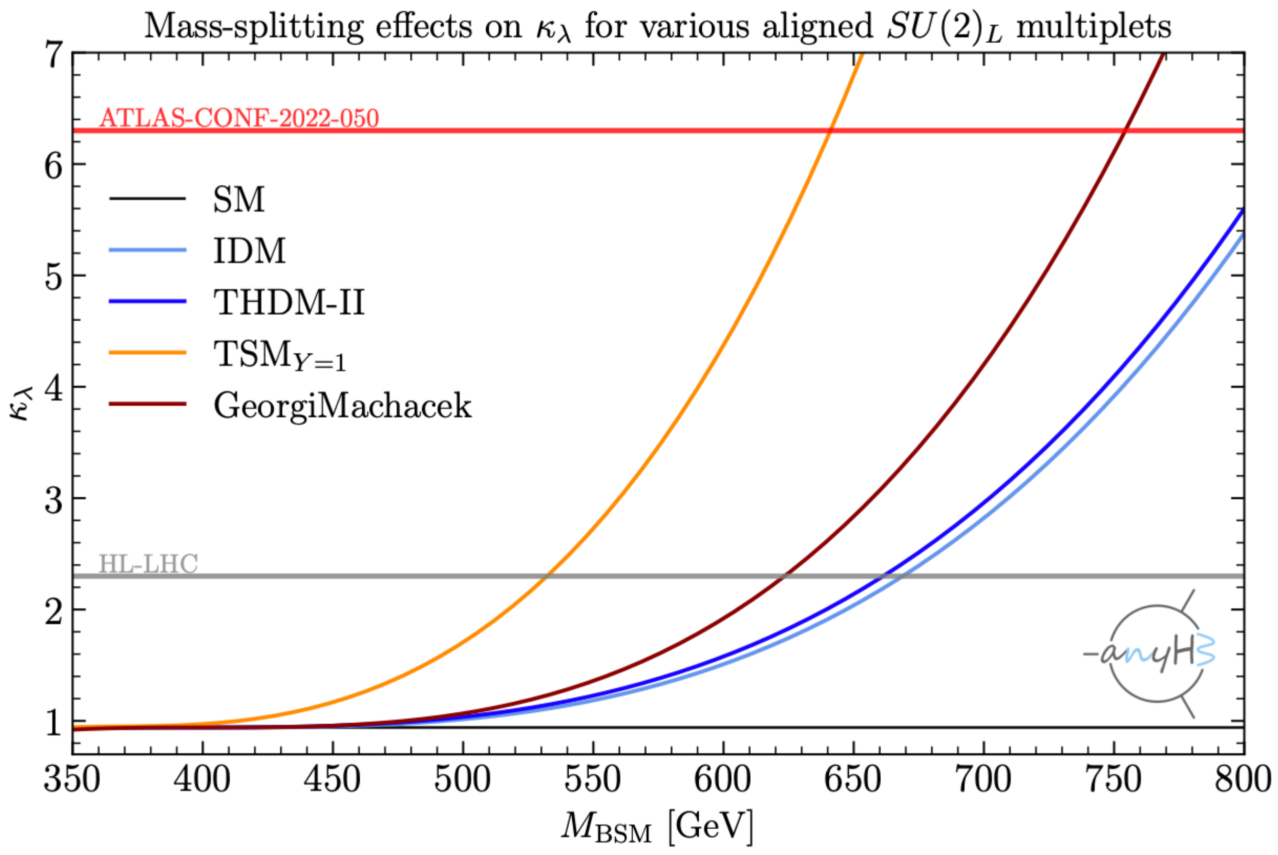


Other extension of SM Higgs sector

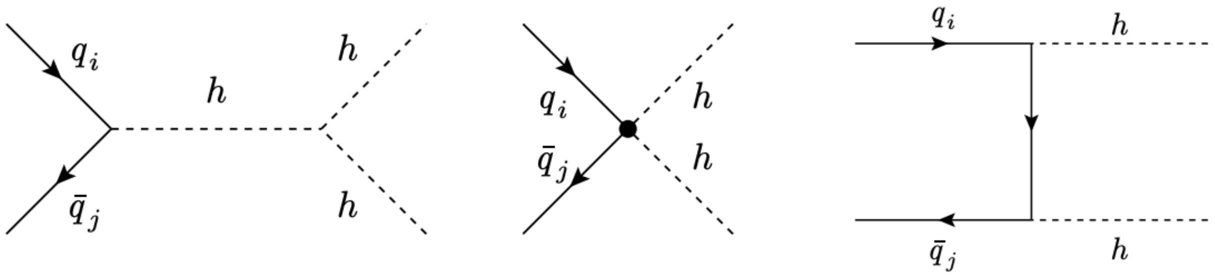


- Large loop corrections to κ_λ possible in various models.
- κ_λ very sensitive to BSM scalar couplings.
- Automatized calculation of κ_λ available in Python package anyH3.
- See also [1704.01953,1902.05936,2209.00666] for other models/more discussion.

Strong motivation for the experimental di-Higgs program!

Interplay between trilinear Higgs coupling and light Yukawas [Alasfar et al.,1909.05279 ,2207.04157]

Quark-induced hh production sensitive to size of 1st-gen Yukawas.



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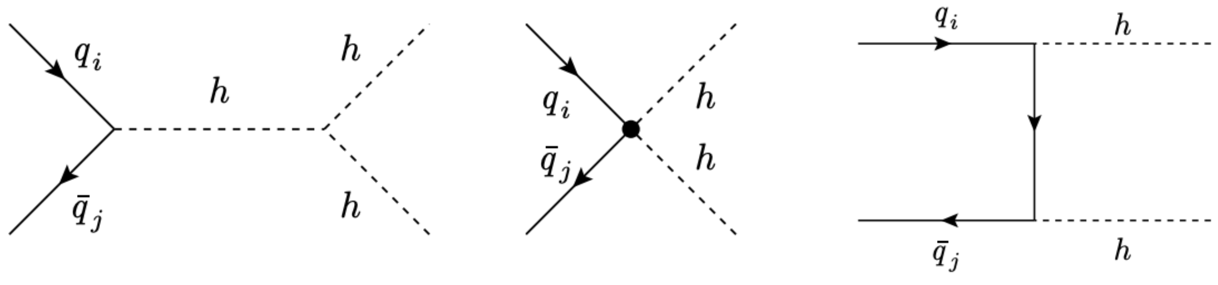

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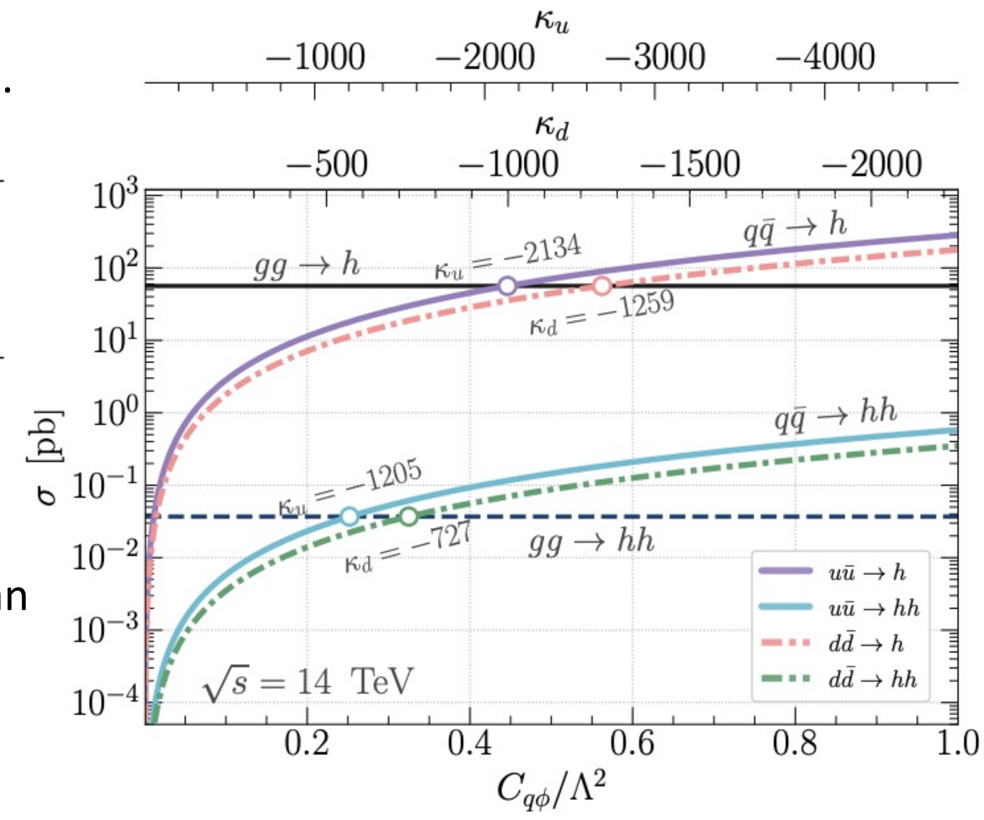
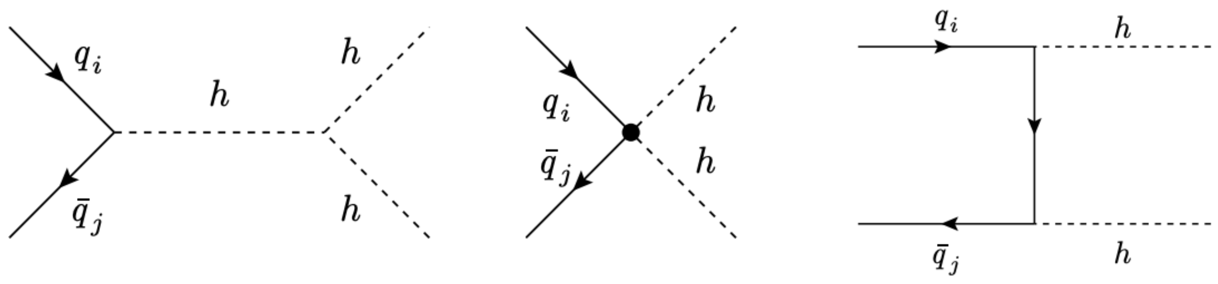
- Quark-induced channel more important for hh production than for single h production.



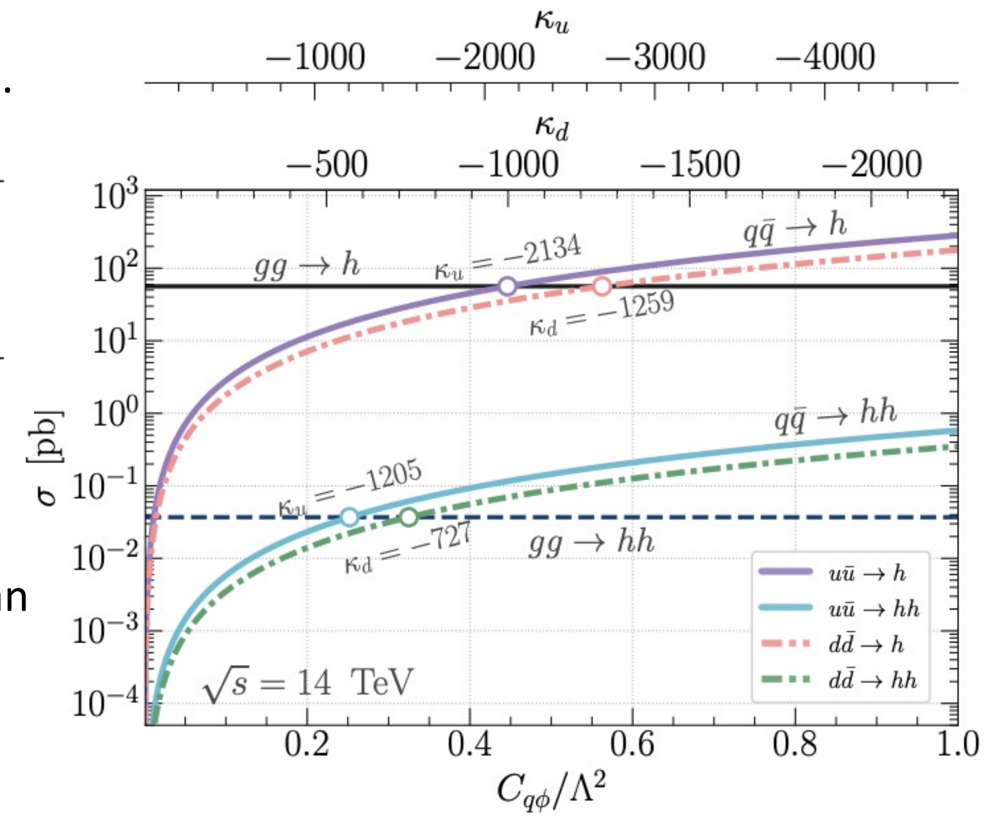
Interplay between trilinear Higgs coupling and light Yukawas [Alasfar et al.,1909.05279 ,2207.04157]

Quark-induced hh production sensitive to size of 1st-gen Yukawas.



$$\mathcal{L} \supset \frac{\phi^\dagger\phi}{\Lambda^2}\left((C_{u\phi})_{ij}\bar{q}_L^i\tilde{\phi}u_R^j + (C_{d\phi})_{ij}\bar{q}_L^i\phi d_R^j + h.c.\right)$$

- Quark-induced channel more important for hh production than for single h production.
- Freely floating κ_u and κ_d has significant impact on expected HL-LHC bounds on κ_λ from [0.53, 1.7] to [0.79, 2.3] (using 6 ab^{-1}).



What is still left to explore?

- Yukawa couplings (and their CP character)
- Higgs potential
- Higgs width/BSM decay channels → See also Christina’s and Yingjie’s talks on Tuesday!
- Flavour structure
- ….

Conclusions

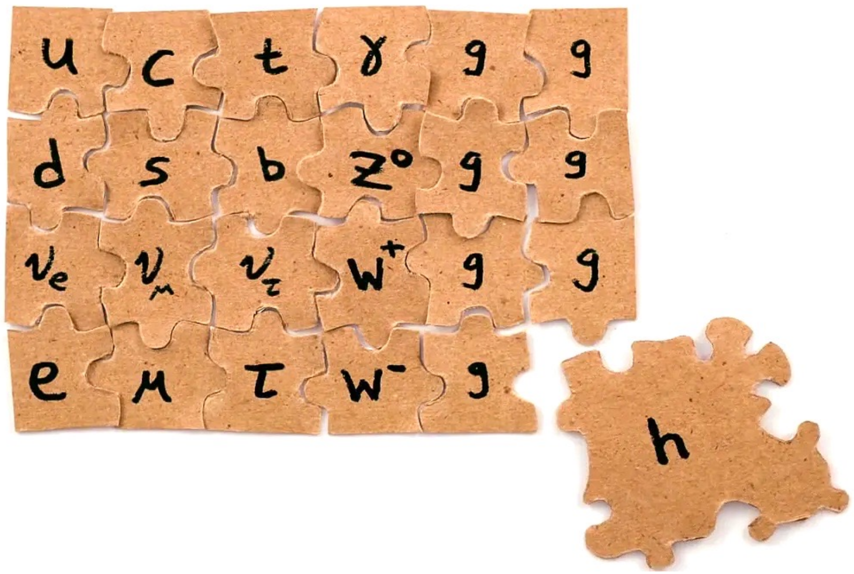
Conclusions

- The Higgs is not the last missing puzzle piece of the SM but could be the link to many BSM scenarios.

- Higgs precision measurements and precision predictions are crucial to understand electroweak symmetry breaking.

- Existing measurements already teach us a lot about possible BSM extensions.

- Much work still left to do:
  - Light Yukawas,
  - Higgs CP structure,
  - Higgs potential,
  - Higgs width,
  - …



Conclusions

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- Higgs precision measurements and precision predictions are crucial to understand electroweak symmetry breaking.
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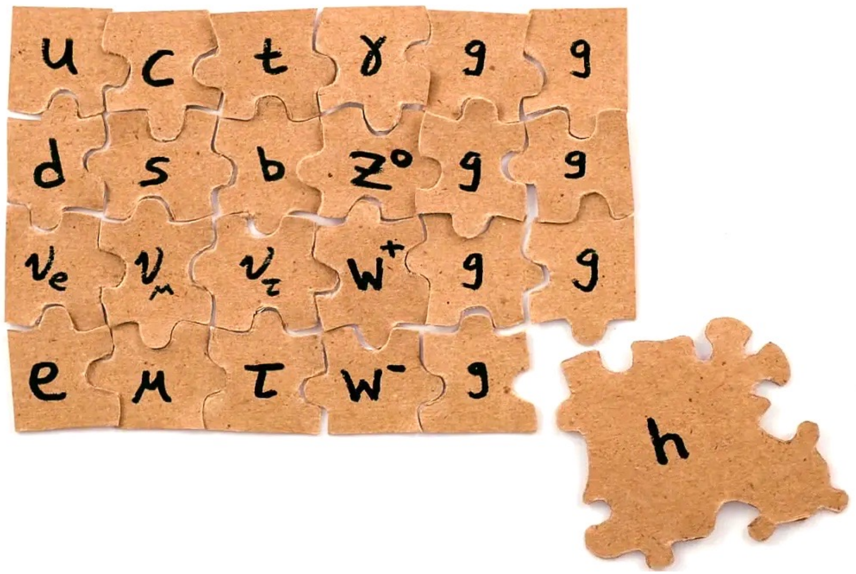


The Higgs will keep us busy for many decades to come!

Appendix

Interlude: HiggsTools

[HB et al., 2210.09332]

HiggsTools is a complete and extended rewrite of **HiggsBounds** and **HiggsSignals** in modern C++.

HiggsPredictions-1

- Handles user input (model predictions).
- Provides tabulated cross sections and BRs.
- Common process definitions and clustering.

HiggsBounds-6

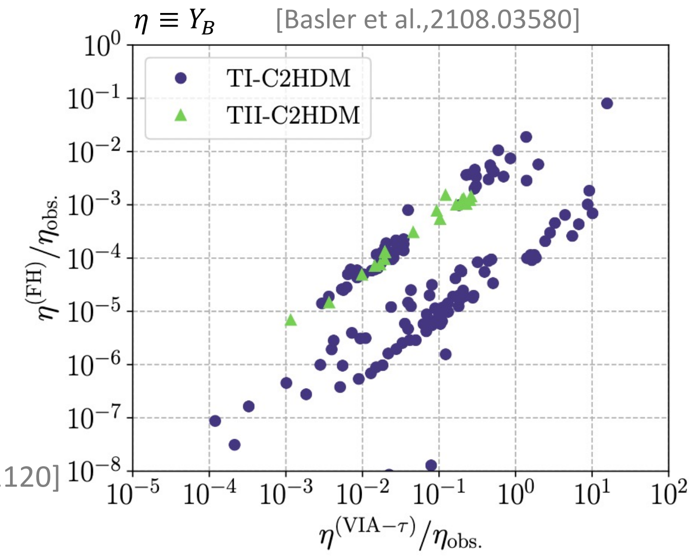
current status: 258 limits

HiggsSignals-3

current status: 131 measurements

➡ C++ interface for high performance; Python and Mathematica interfaces for ease of use.

Baryon asymmetry of the Universe



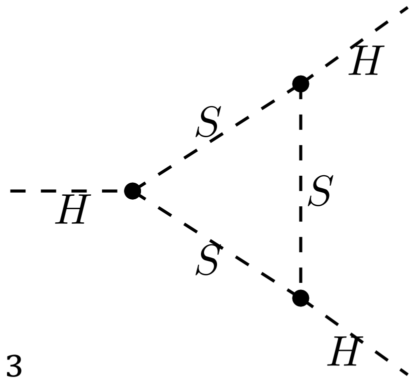
- Different techniques used in the literature to calculate BAU Y_B:
  - Vev-insertion approach (VIA),
    [Huet&Nelson,9504427,9506477;Carena et al., 9603420;Riotto, 9712221;Lee et al.,0412354;Postma et al.,2206.01120]
  - WKB (or FH) approximation.
    [Joecy et al.,9410282;Kainulainen et al.,0105295, 0202177;Prokopec et al., 0312110, 0406140;Konstandin et al.,1302.6713, 1407.3132]
- VIA approach yields consistently higher results by orders of magnitude.
- We use VIA approach with bubble wall parameters close to optimal values for Y_B:
  [de Vries,1811.11104;Fuchs et al.,2003.00099,2007.06940;Shapira,2106.05338]

$$\frac{Y_B}{Y_B^{\mathrm{obs}}} \simeq 28\tilde{c}_t - 0.2\tilde{c}_b - 11\tilde{c}_\tau + \cdots$$

Y_B values should be regarded as **upper bound** on what is theoretically achievable.

Case study: real singlet extension of the SM

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



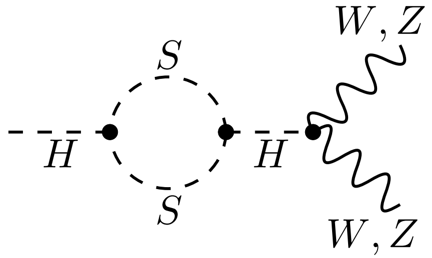
If S does not get a vev, $\lambda_{HHH} = \lambda_{HHH}^{\rm SM}$ at the tree-level ($m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$).

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

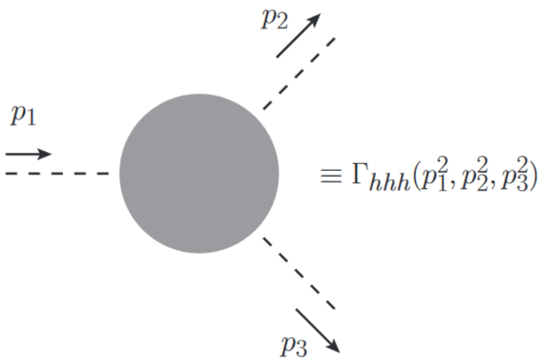
$$g^{1L} \propto \frac{g_{HSS}^2}{(4\pi)^2} B_0'(\ldots) \cdot g_{\rm tree} \propto \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2 \Rightarrow \kappa_g \equiv \frac{g}{g^{\rm SM}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$



➡ 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!

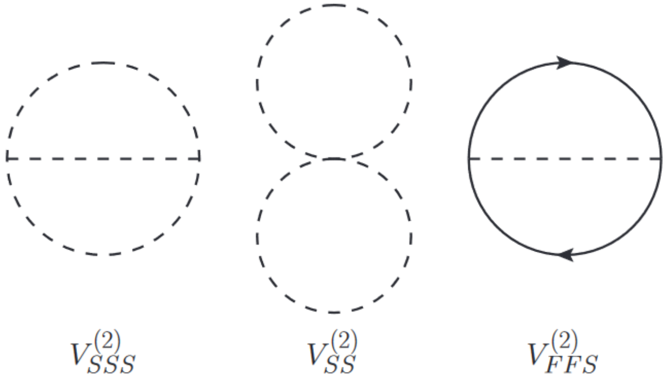
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



- Alternatively, employ zero momentum approximation and then use effective potential:

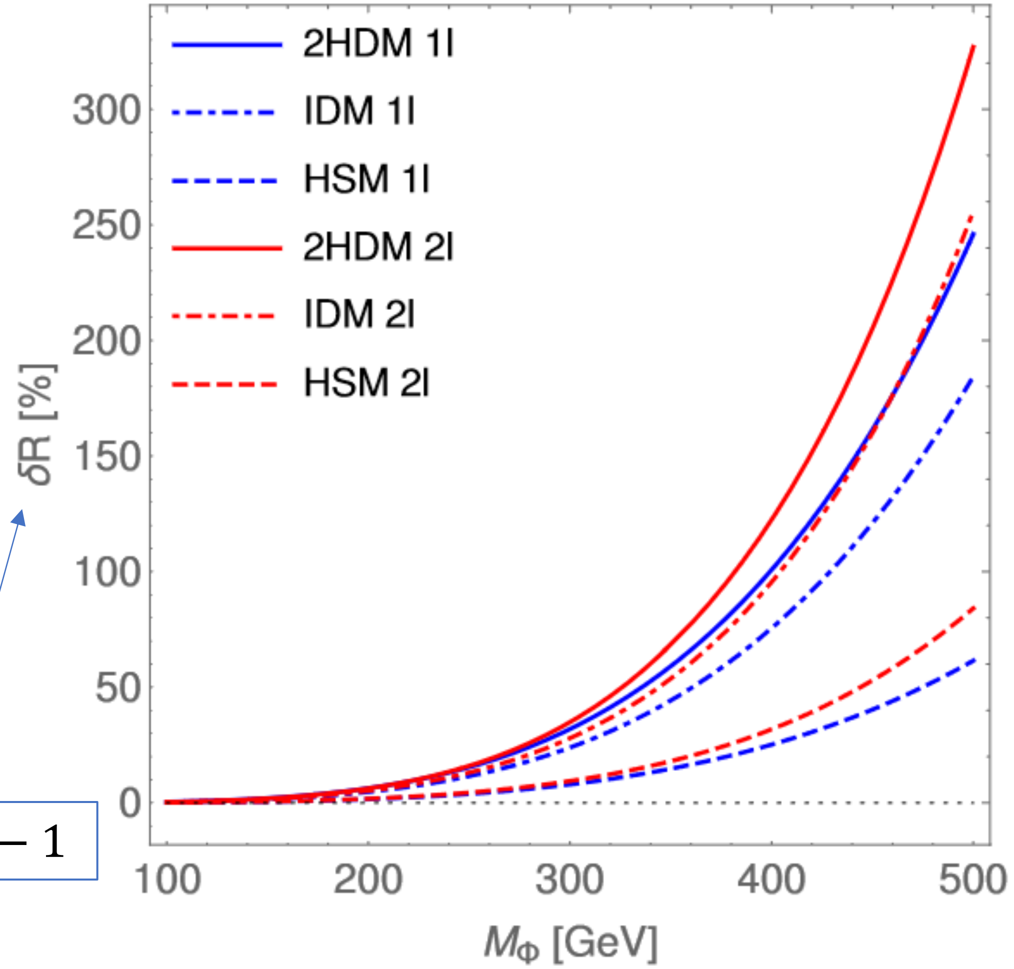
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda_{hhh}^{(0)} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- Using V_{eff}, 1L and 2L corrections have been calculated in various BSM Higgs models (see e.g. [Braathen,Kanemura,1911.11507]).

Calculating BSM corrections to κ_λ

[Braathen,Kanemura,1911.11507]



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

- Large non-decoupling corrections found in several BSM models.
- Analysis assumed that all BSM masses are equal M_Φ.
- No phenomenological analysis has been performed.

Idea of this work:

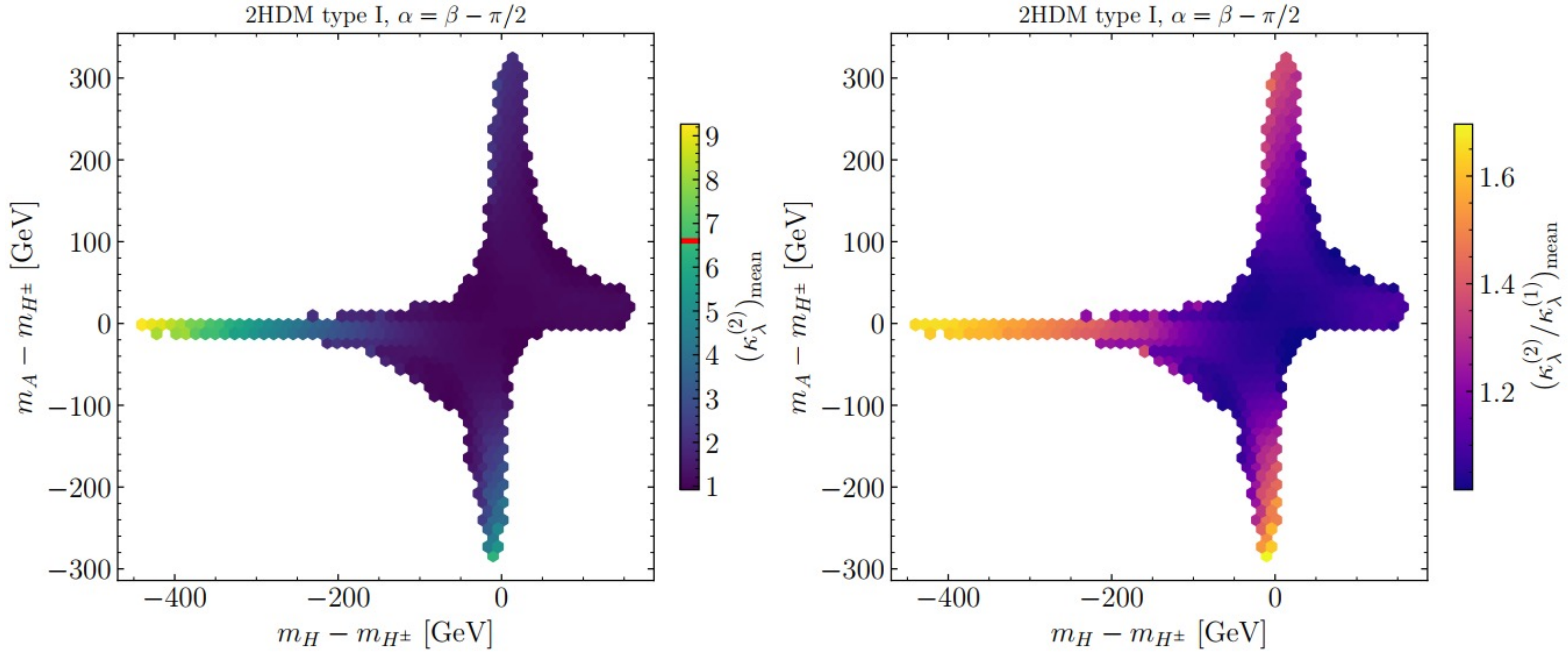
Can we constrain these models based on the large corrections to κ_λ?

2HDM parameter scan

- We 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, we calculate κ_λ at the 1L and 2L level ($\kappa_\lambda^{(1)}$ and $\kappa_\lambda^{(2)}$). [Braathen,Kanemura,1911.11507]

2HDM parameter scan — results

(showing only points passing all constraints mentioned on previous slide)

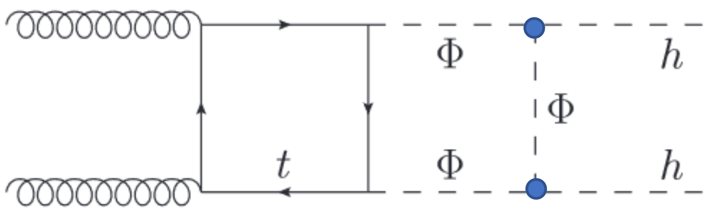


- Largest corrections for $m_A \simeq m_{H^\pm}$, $m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}$, $m_A < m_{H^\pm}$ (κ_λ of up to 9).
- 2L corrections have sizeable impact (up to 70%).

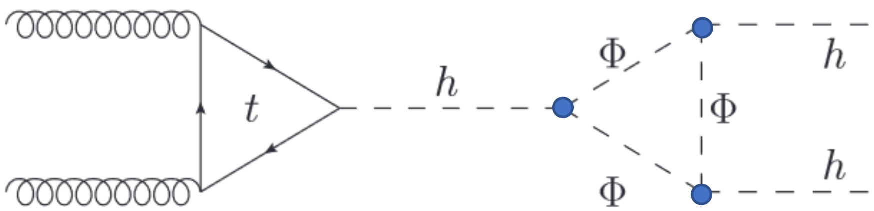
Can we apply the experimental constraints on κ_λ?

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?



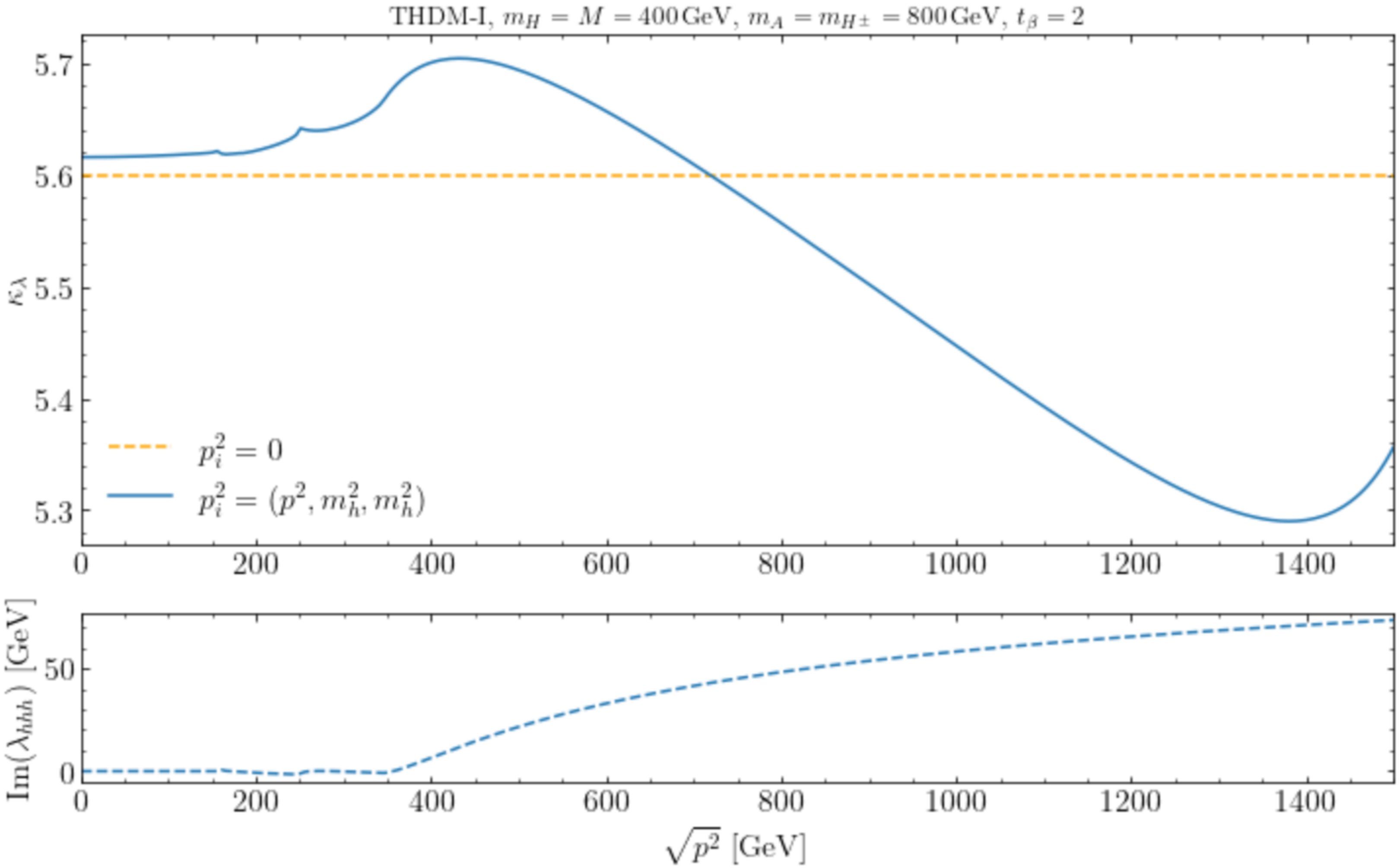
$\propto \mathcal{O}(y_t^2 g_{hh\Phi\Phi}^2)$ (not included)



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

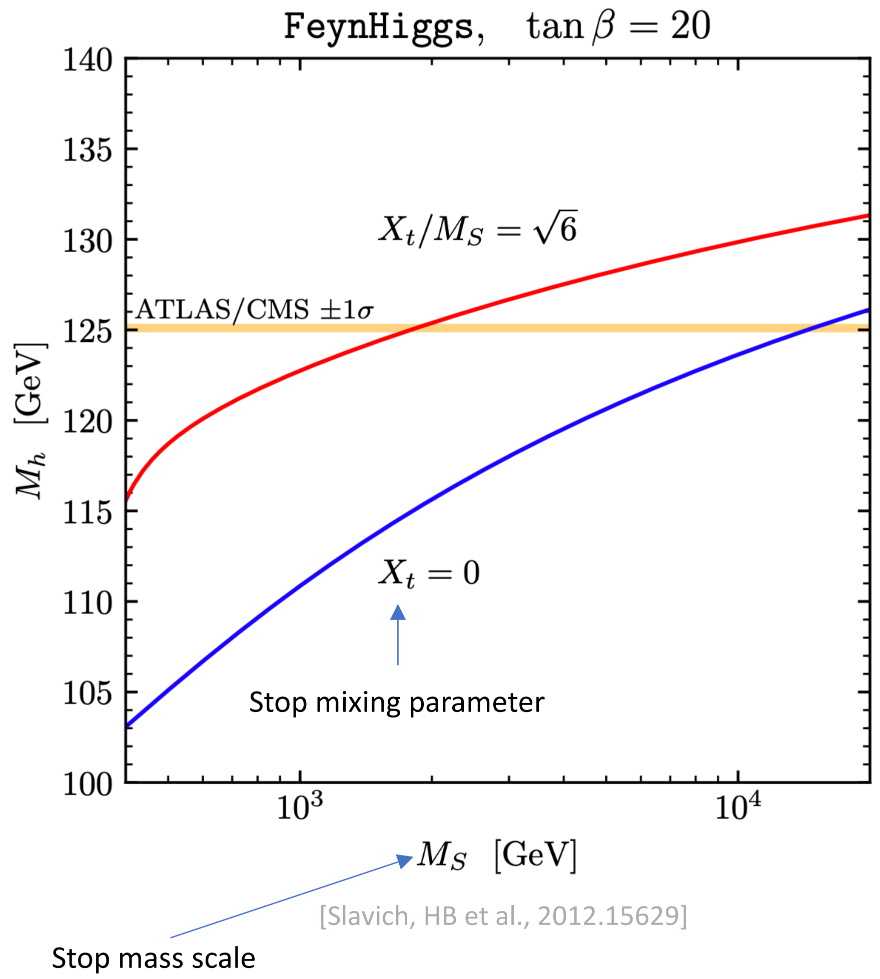
- ➢ We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level.

Momentum dependence



The Higgs mass as a precision observable

- Also the Higgs mass is a precision observable useful for BSM phenomenology.
- In SUSY models, the Higgs mass can be predicted in terms of the model parameters.
- MSSM: $M_h \sim 125$ GeV ⇒ stop masses $\gtrsim$ 2 TeV.
- Experimental precision significantly better than remaining theoretical uncertainty.
  (~ 0.5 GeV for $X_t/M_S = 0$ and ~ 1 GeV for $X_t/M_S = \sqrt{6}$)



[Slavich, HB et al., 2012.15629]