Deciphering the Nature of the Higgs Boson

Henning Bahl

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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The Higgs mechanism in a nutshell

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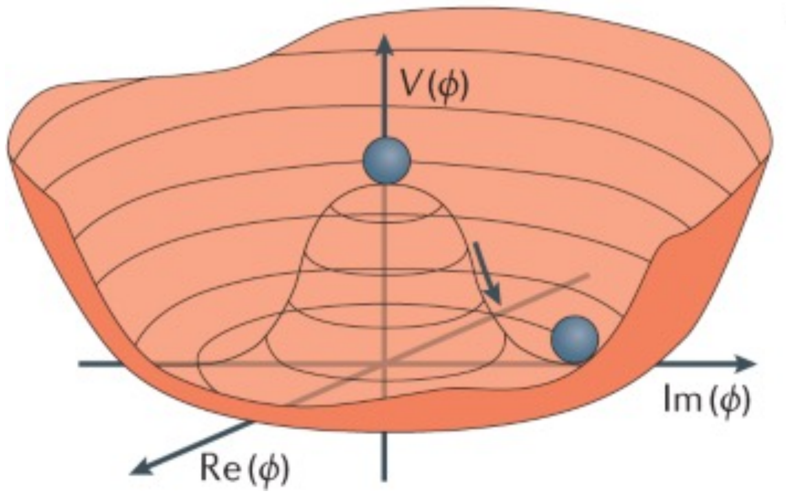

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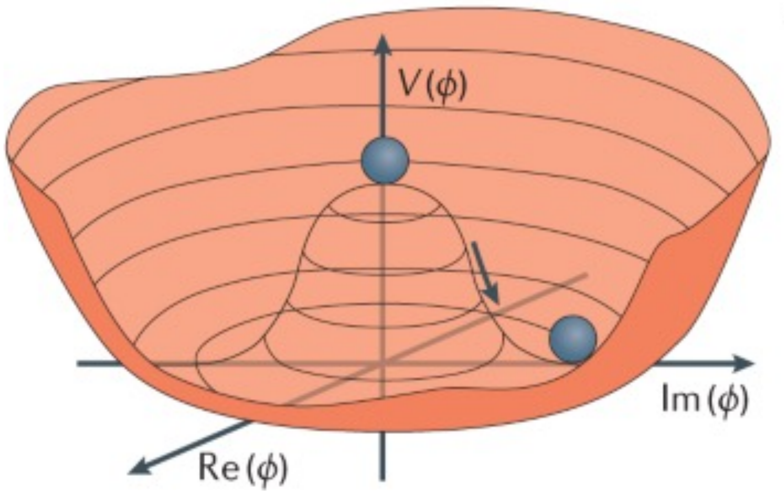

$$\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma)e^{\frac{i\pi(x)}{F_\pi}}$$

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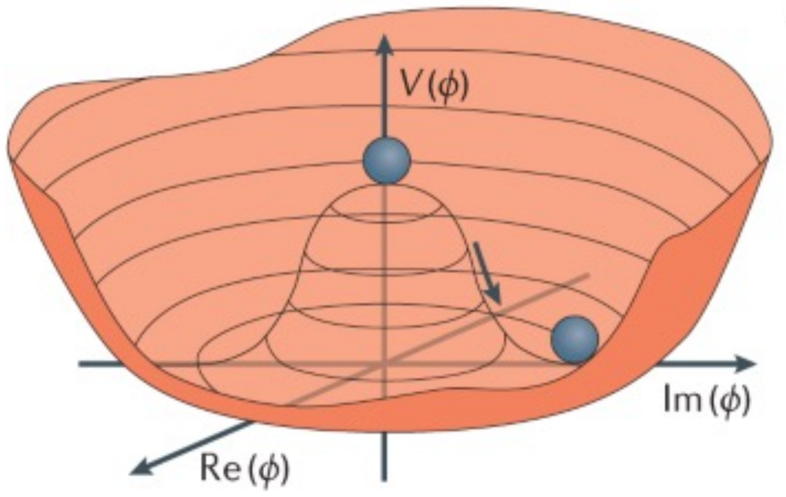

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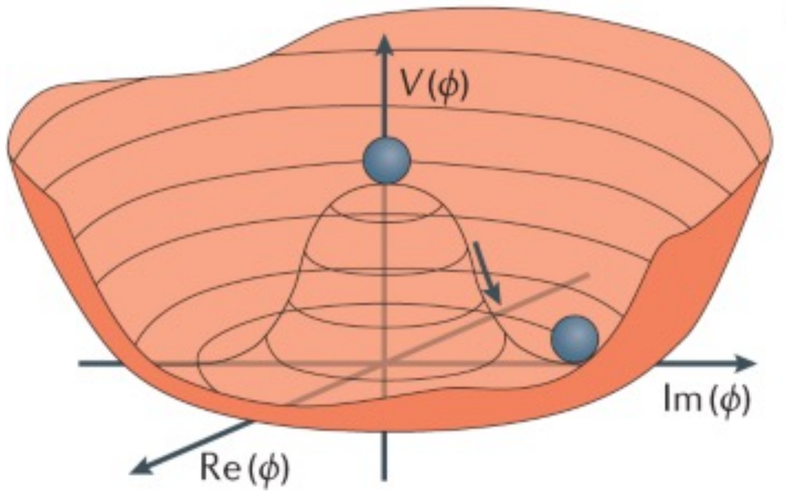

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- Model also used for describing super-conductivity (→ Ginzburg-Landau theory)

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\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
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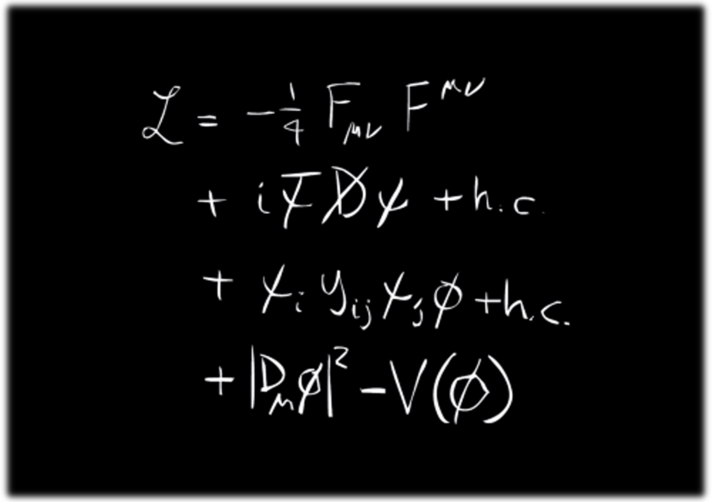

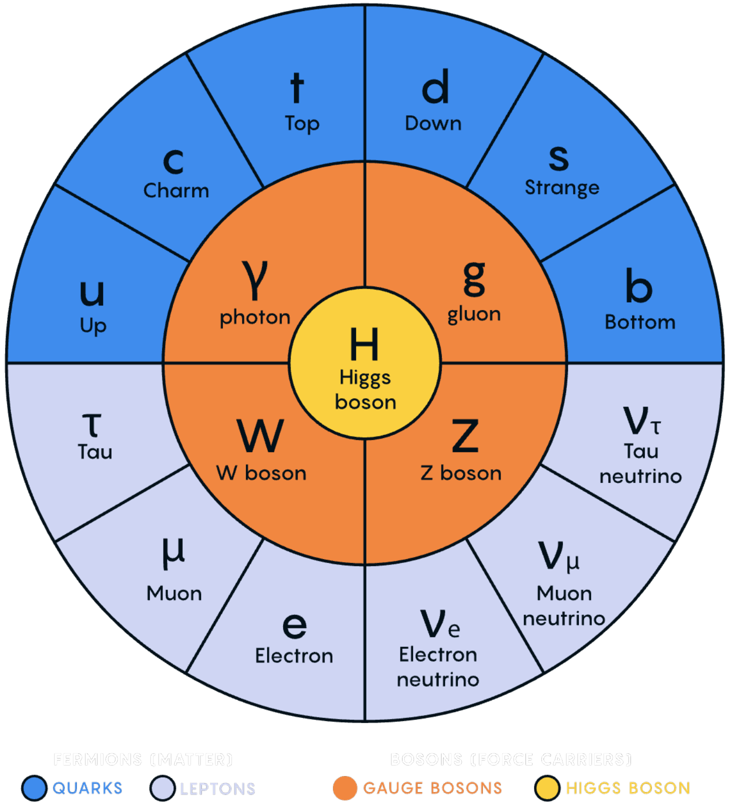

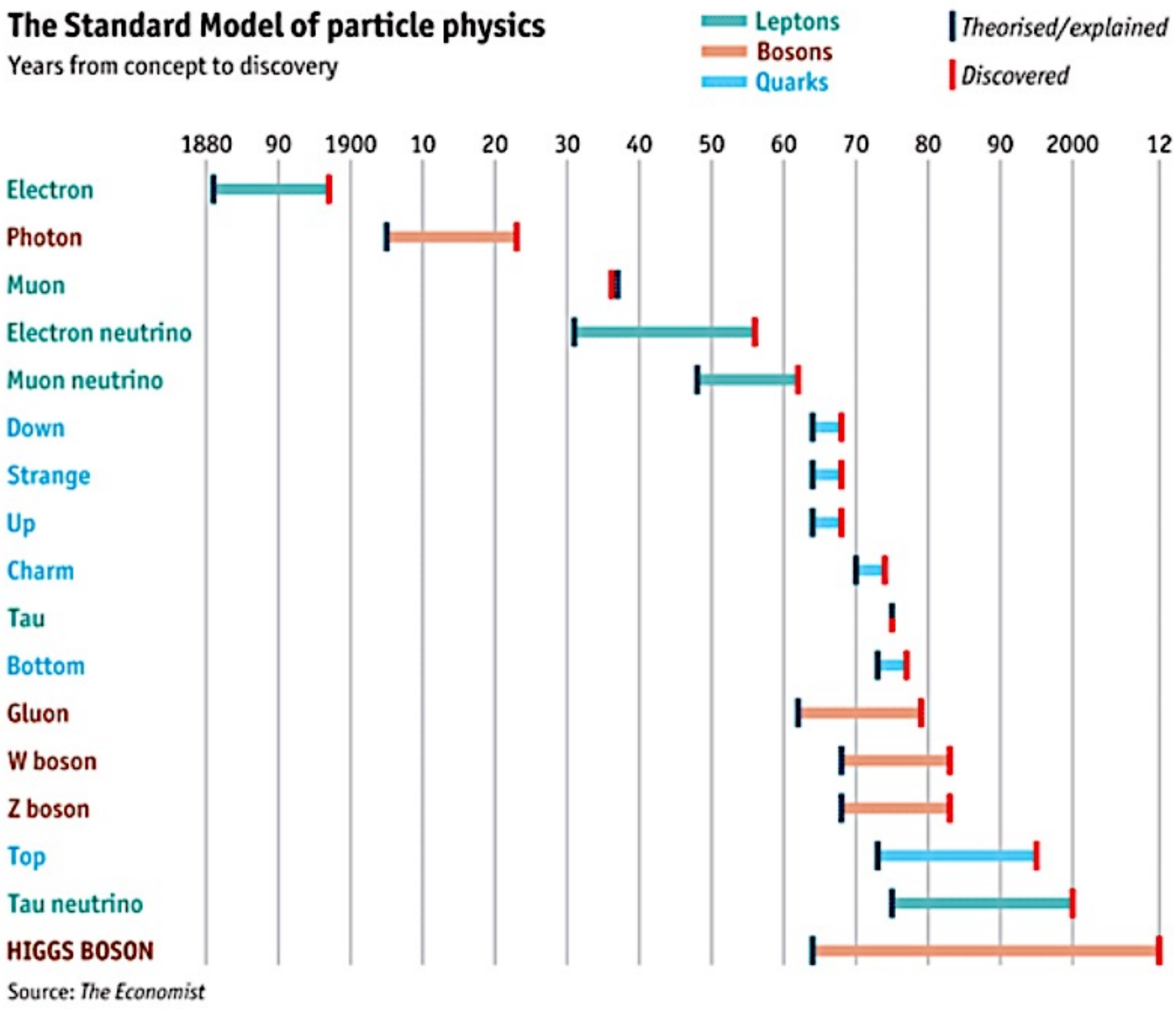
The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
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1900
10
20
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40
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60
70
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2000
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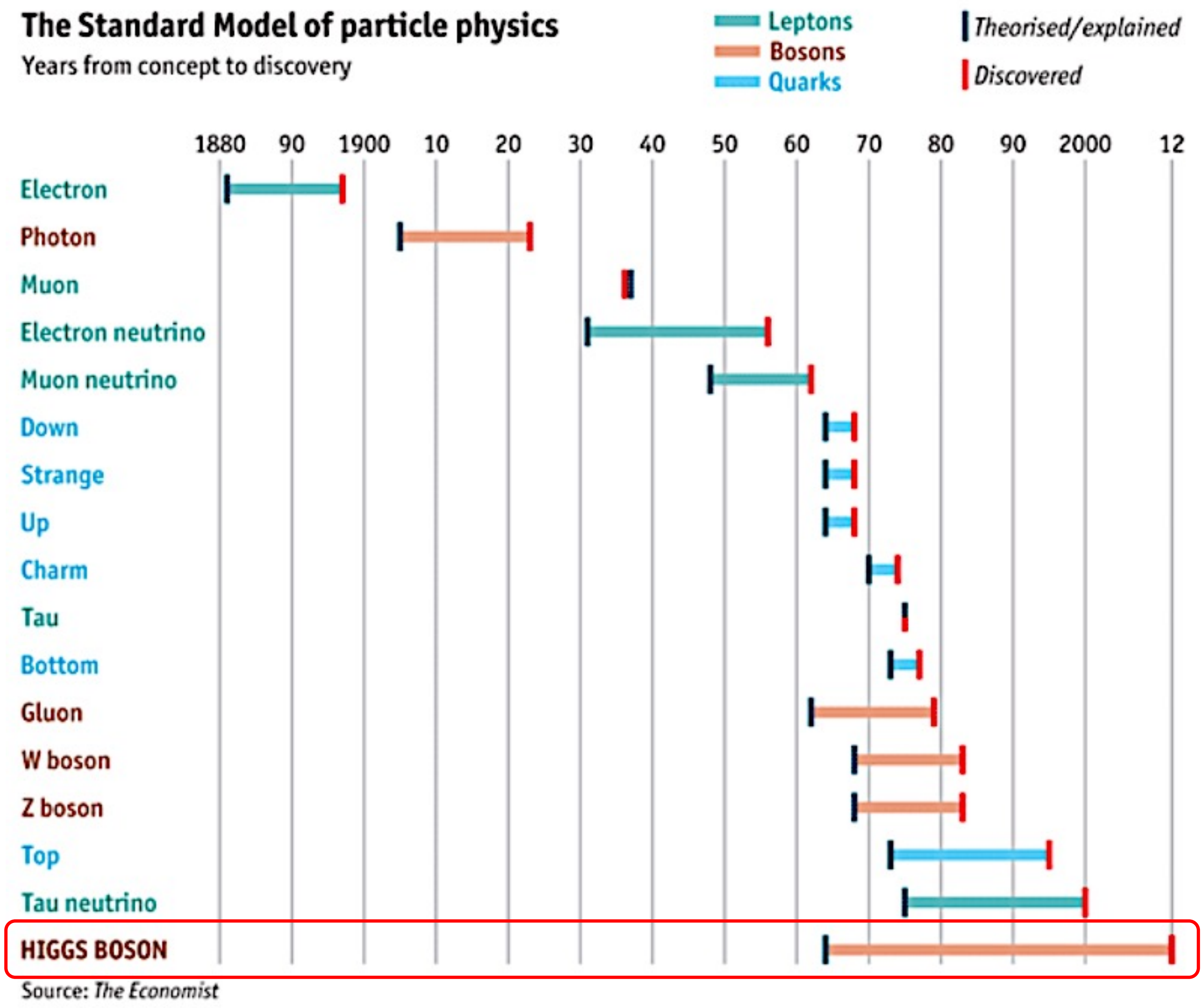
Source: The Economist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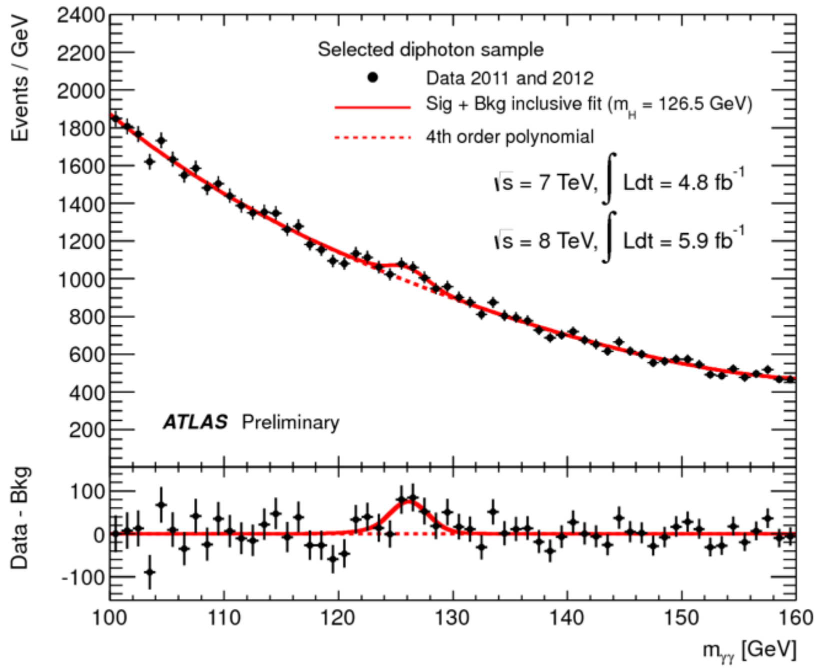
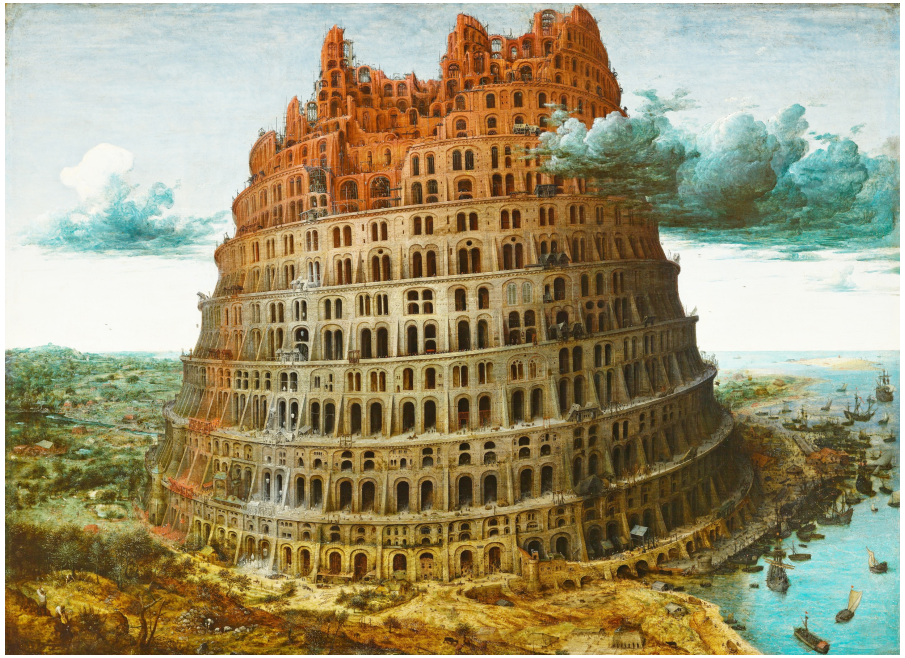
The Higgs discovery

2012





Tower of Babel

After decades of work, the Higgs discovery was a big success for particle physics ($m_h = 125$ GeV).

The Higgs discovery

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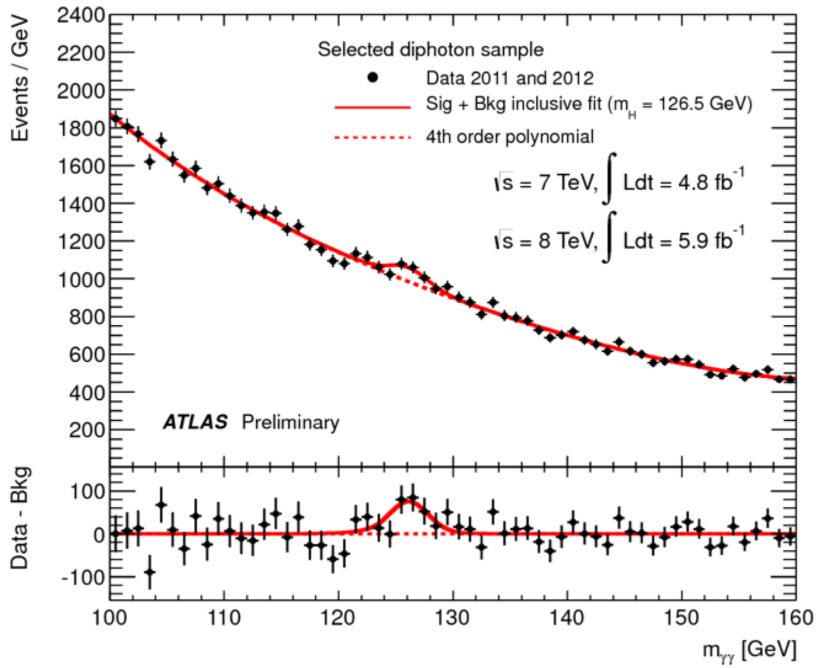

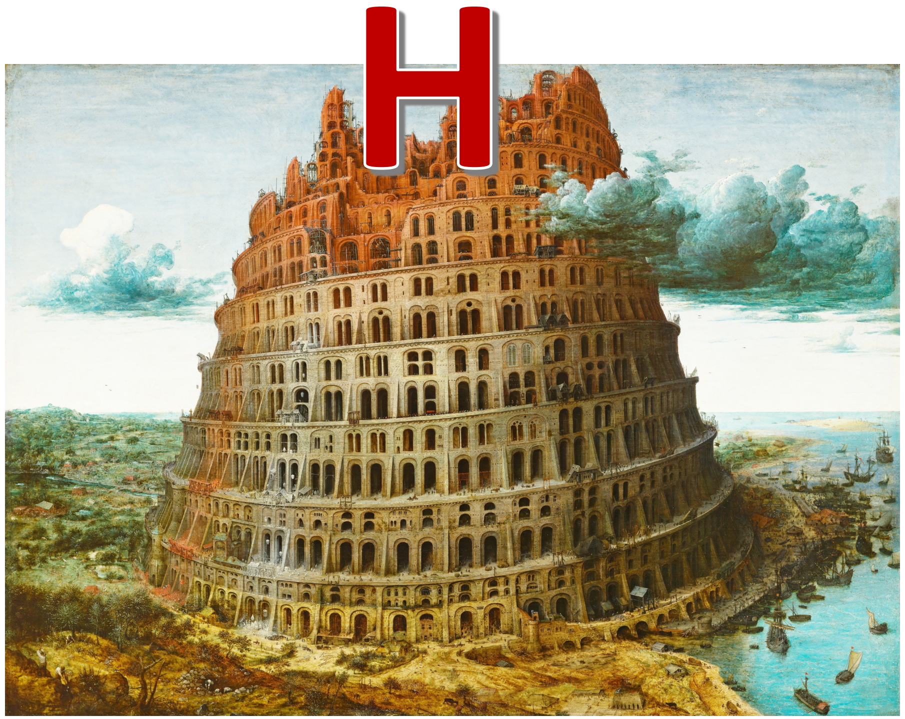

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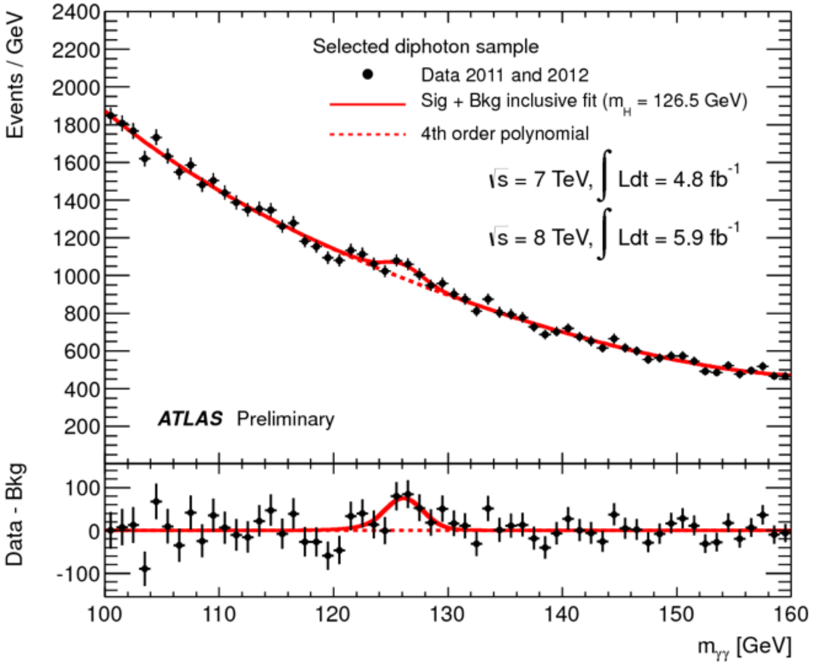

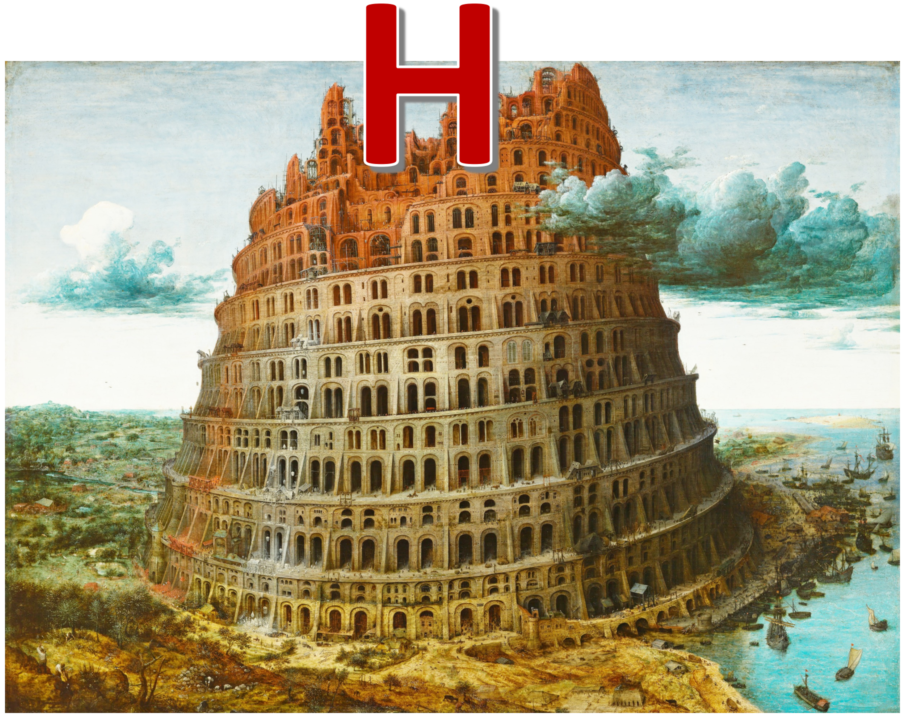

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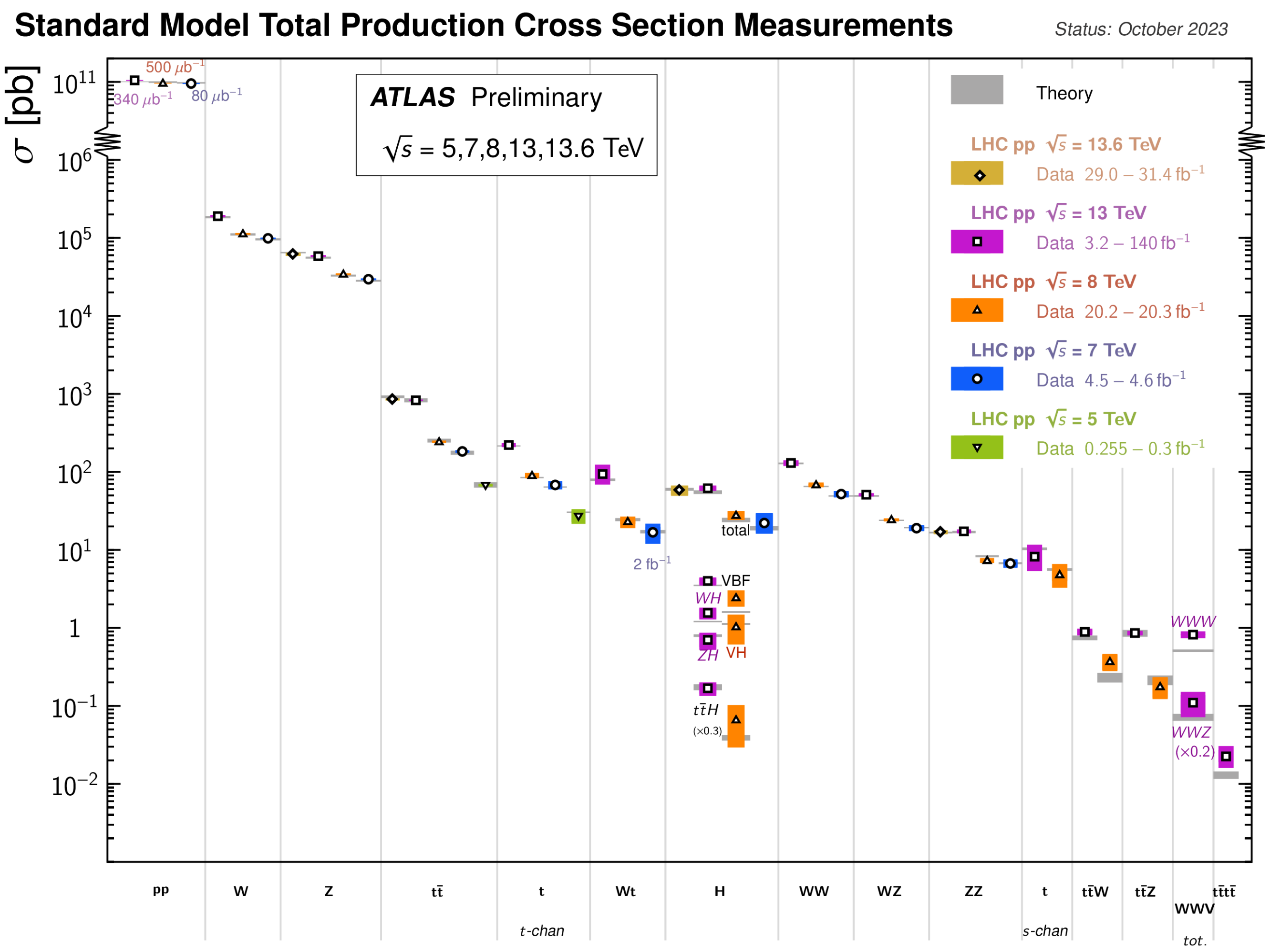
→ So, have we *completed* the SM?

The SM at the LHC



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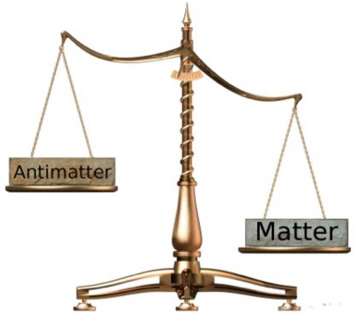

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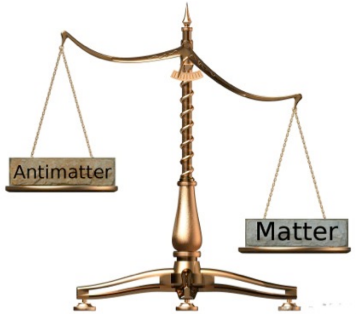

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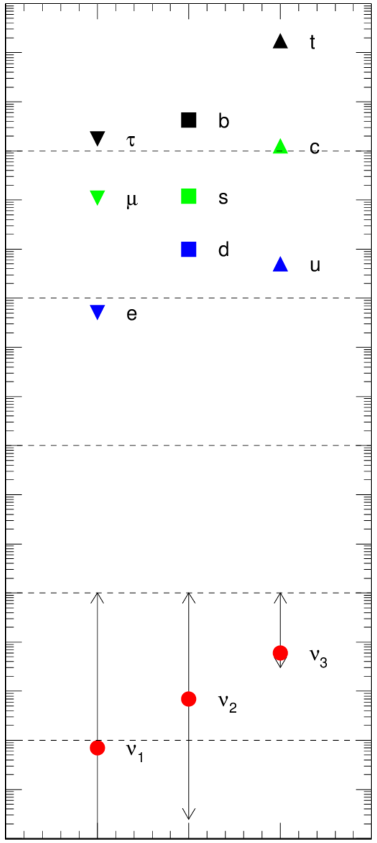

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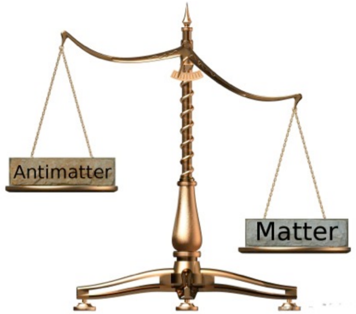

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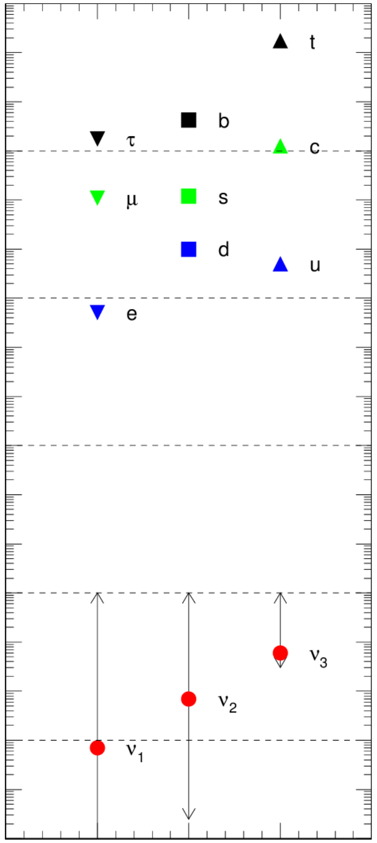

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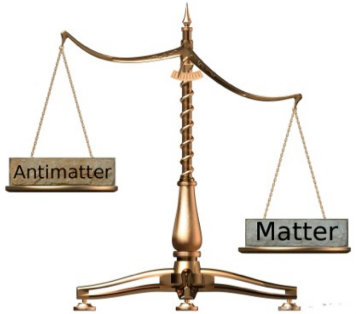

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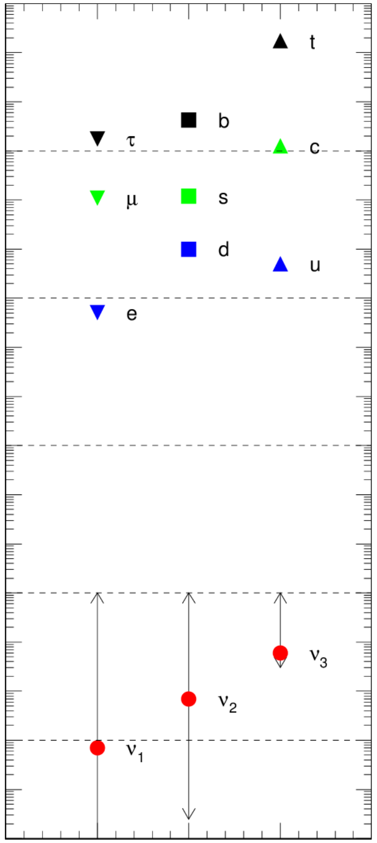

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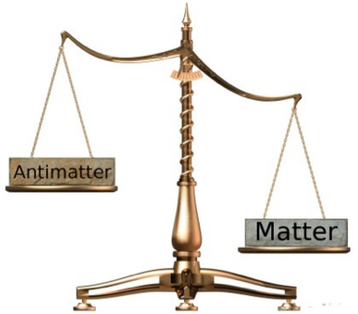

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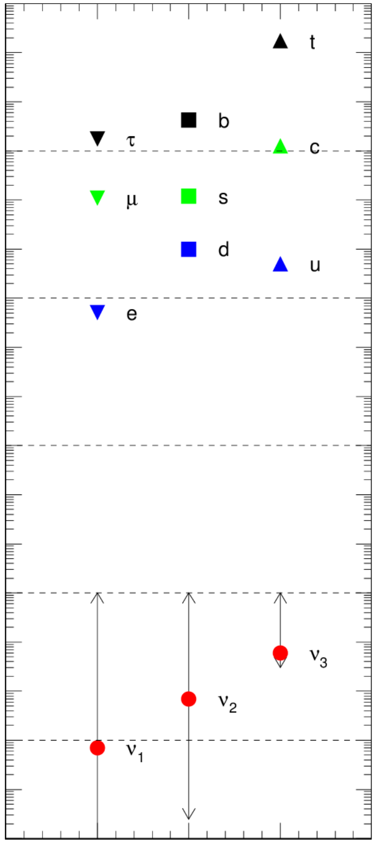

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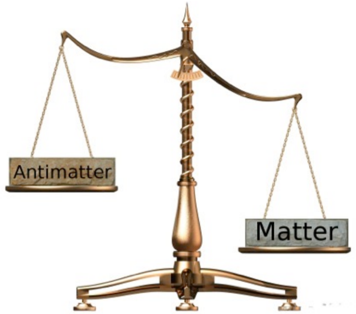

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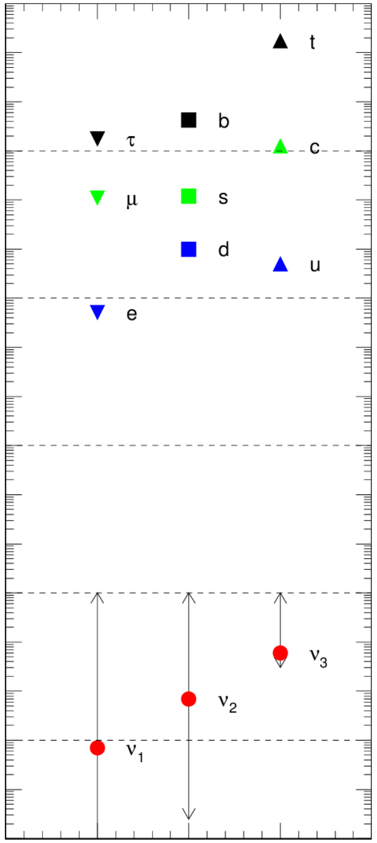

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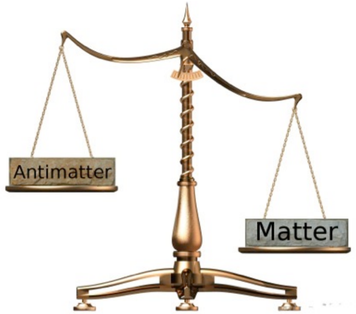

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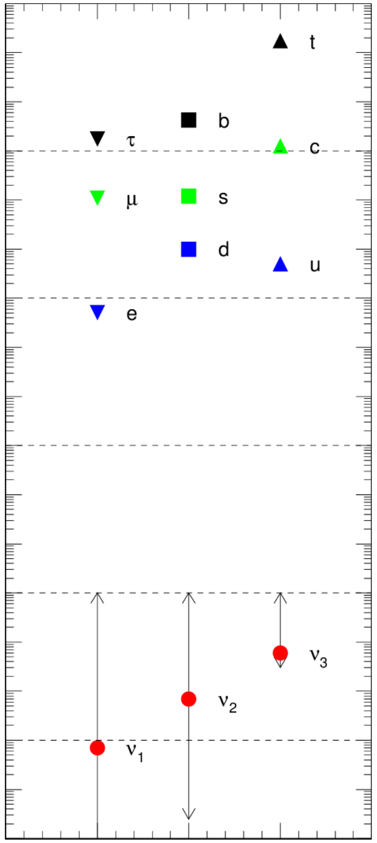

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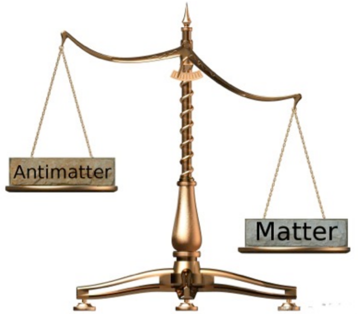

The Higgs as a window to new physics

$$\mathcal{L}_{\text{Higgs}} = (D^\mu H)^\dagger \left(D_\mu H\right) + y_{ij} H f_i \bar{f}_j + \mu^2 |H|^2 - \lambda |H|^4 - V_0$$

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

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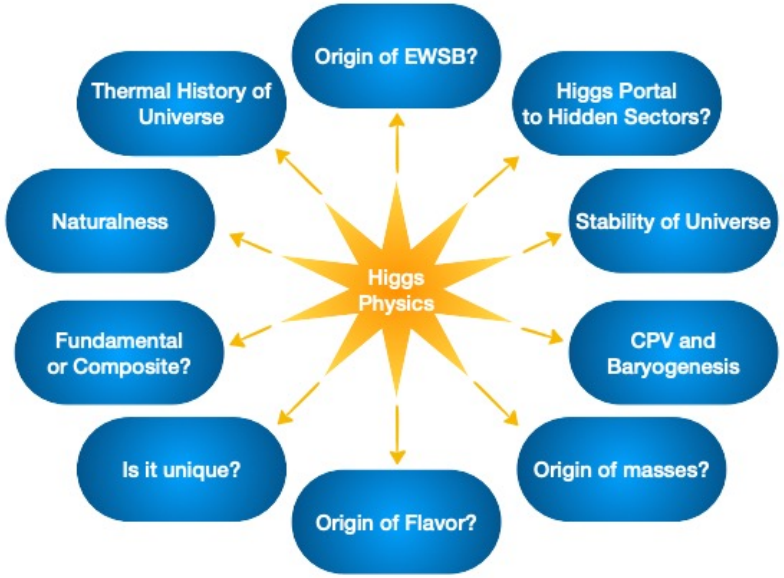

[Snowmass 2209.07510]

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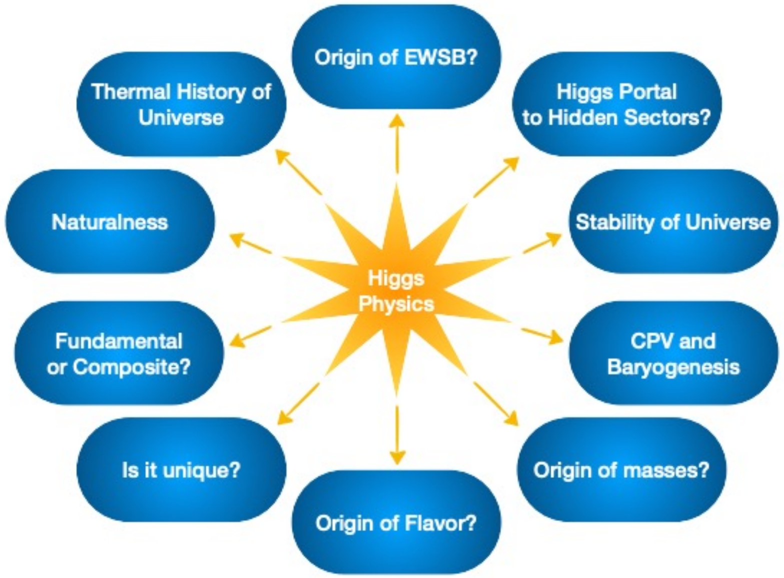

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→ Where are we more than a decade after the Higgs discovery?

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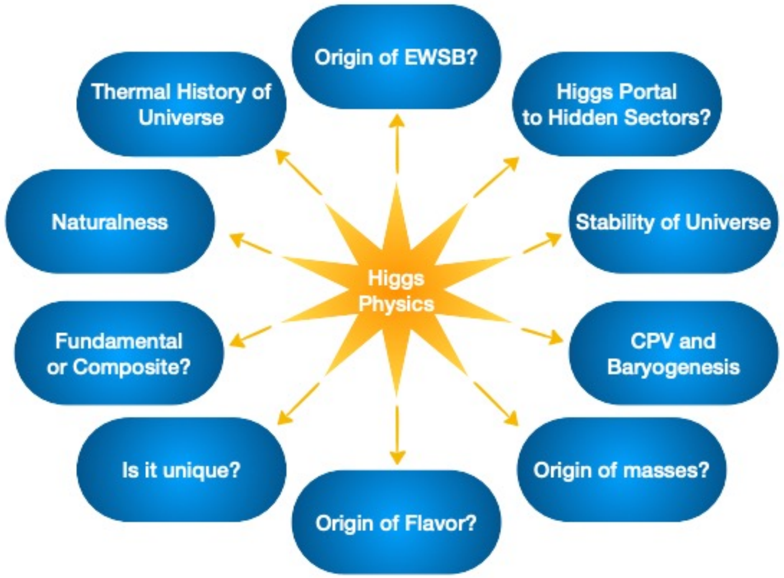

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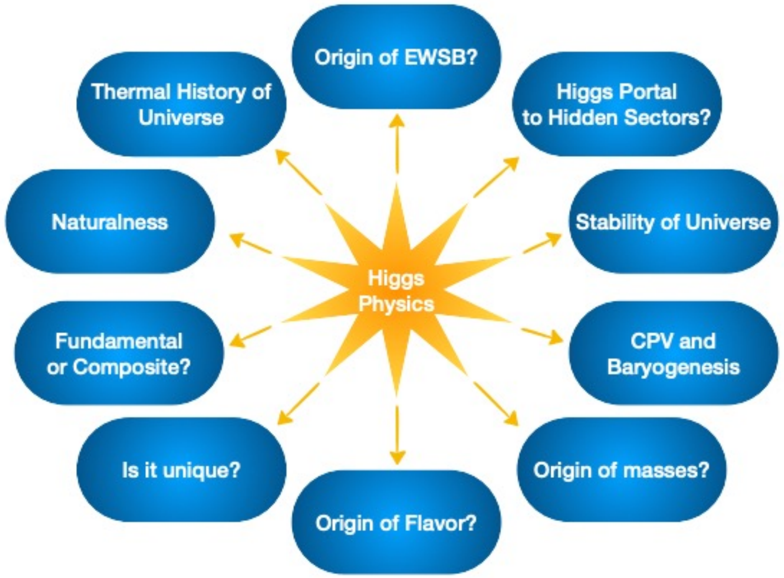

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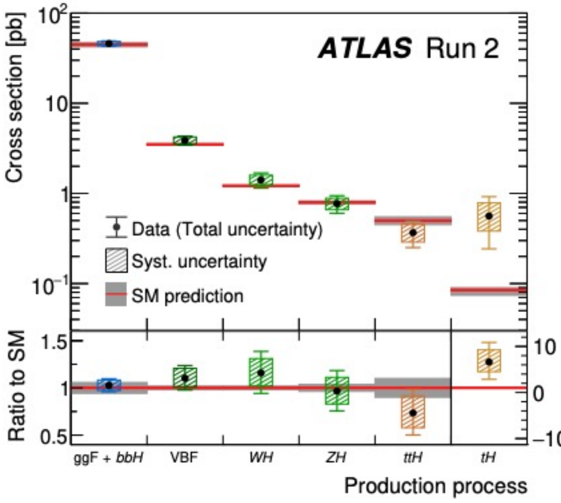
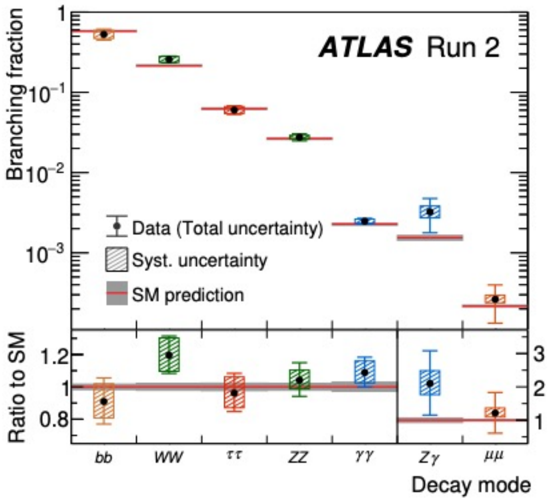
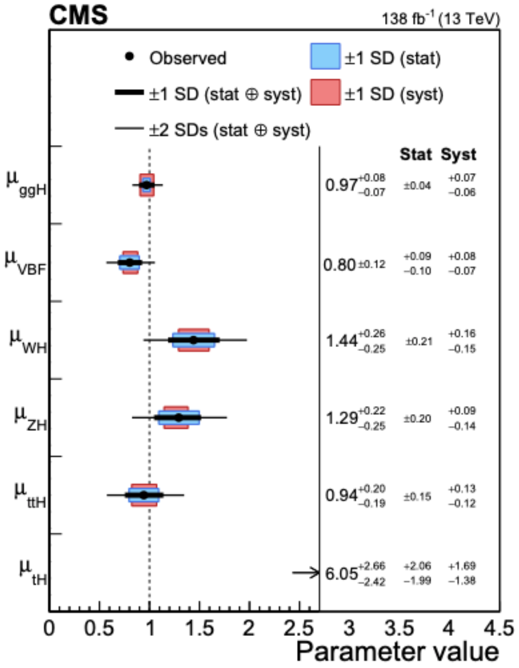
→ What is still left to explore?

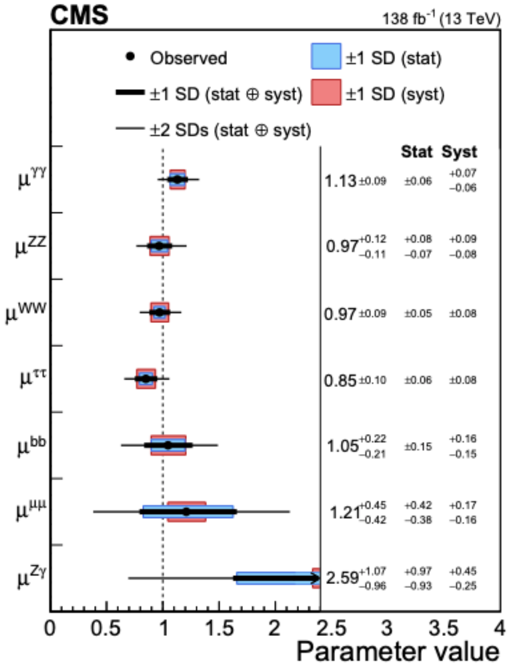
The Higgs 10 years later

[ATLAS 2207.00092, CMS 2207.00043]



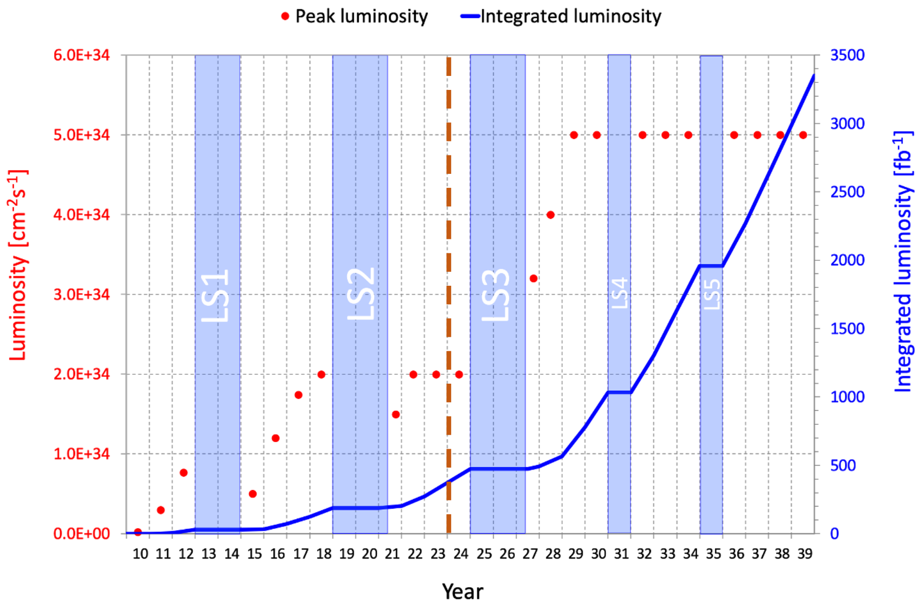






- Ten years later, we have entered the Higgs precision era.
- So far, all Higgs measurements agree with the SM predictions within the experimental and theoretical uncertainties.

LHC Run-3 and beyond



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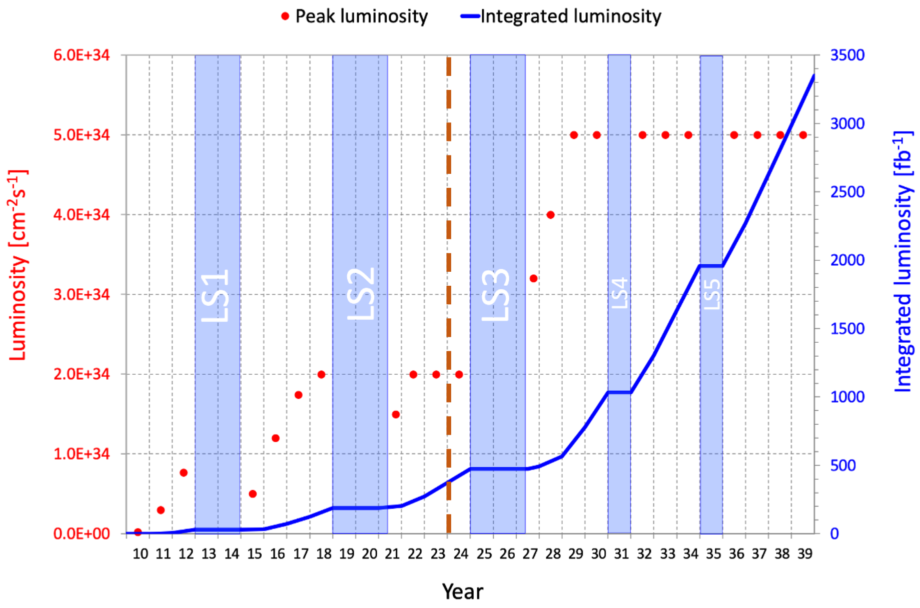

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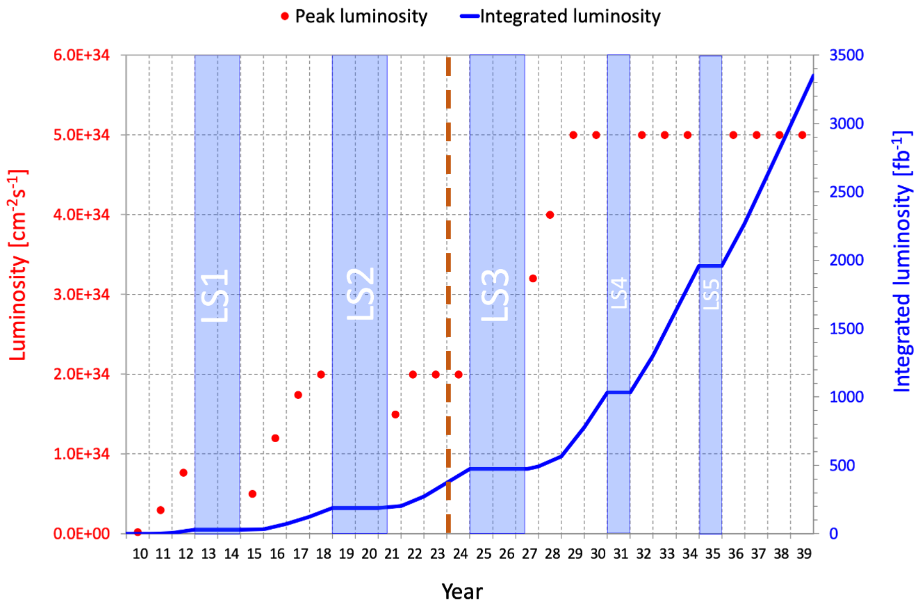


Much more data will be collected in the next years.

→ The LHC program has just started.

- What can we learn from existing measurements?
- What is still left to explore?
- Have we found **the** SM Higgs?

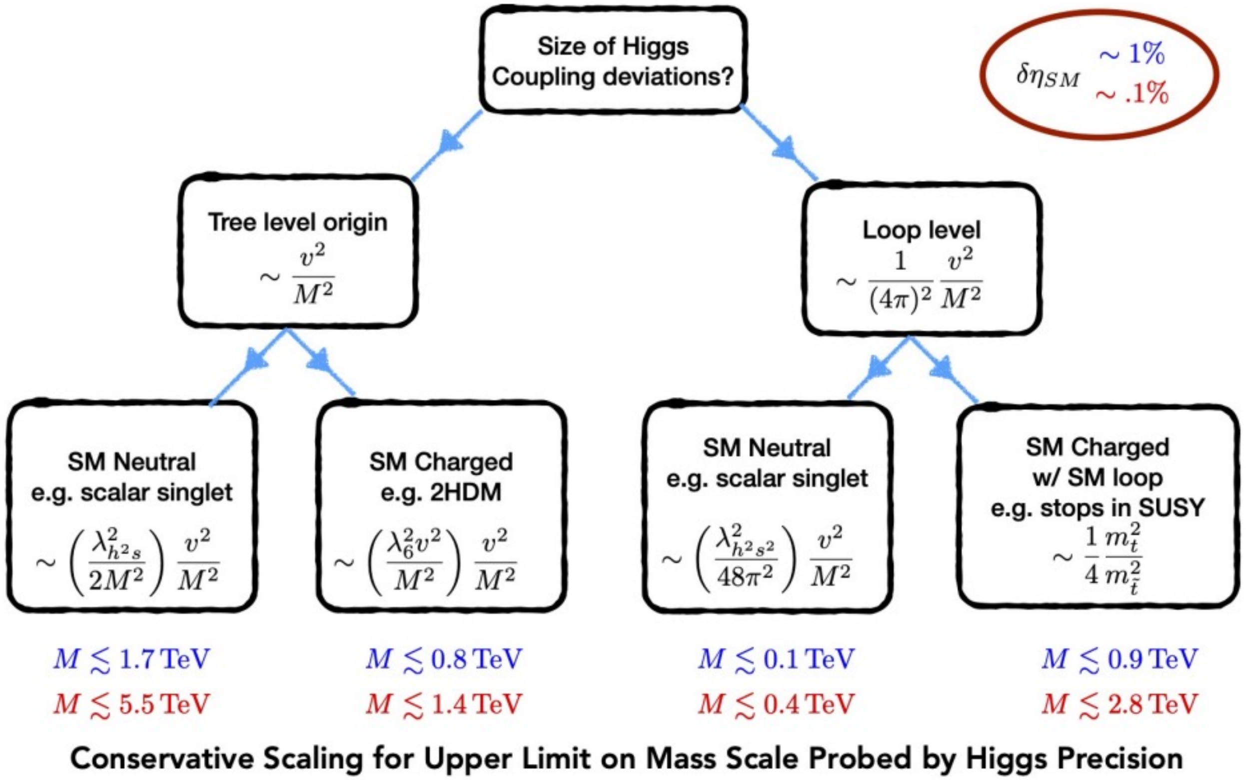
What can we learn from existing measurements?

What can we learn from Higgs precision measurements?

- 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).



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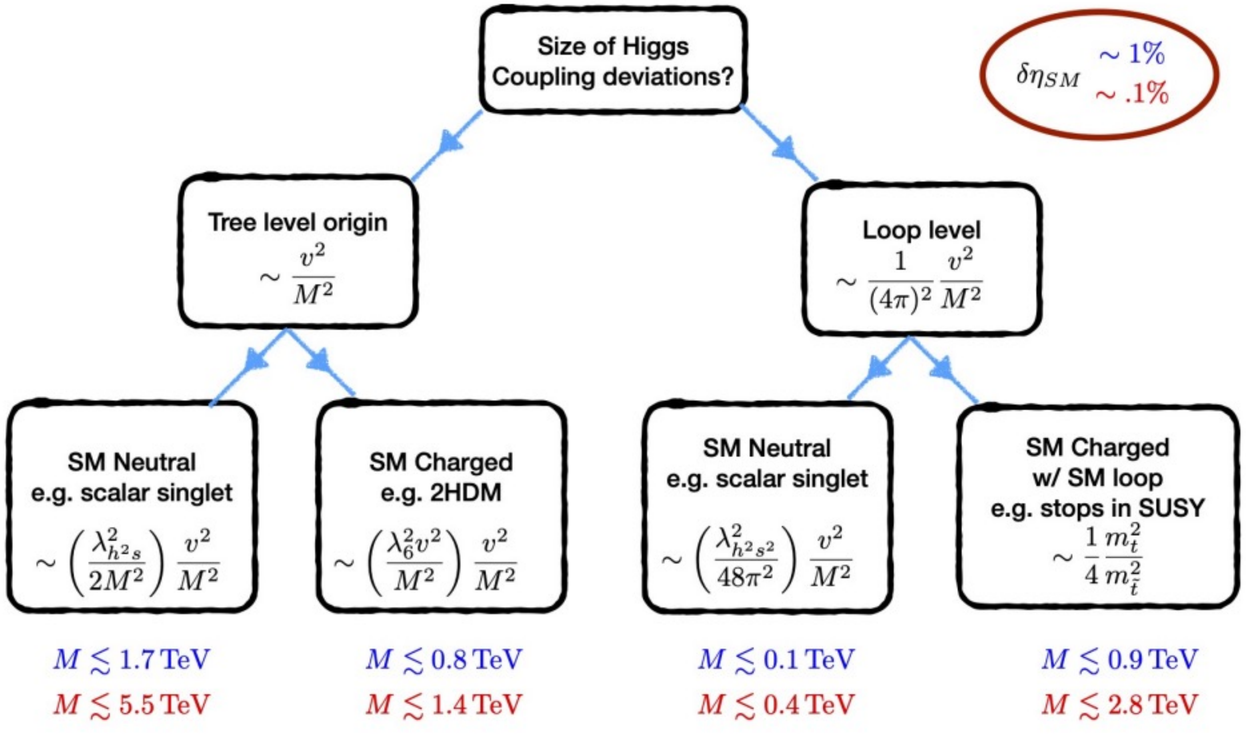

Conservative Scaling for Upper Limit on Mass Scale Probed by Higgs Precision

[Snowmass 2209.07510]

We also shouldn't forget about the interplay with direct searches!

Interplay with direct searches

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

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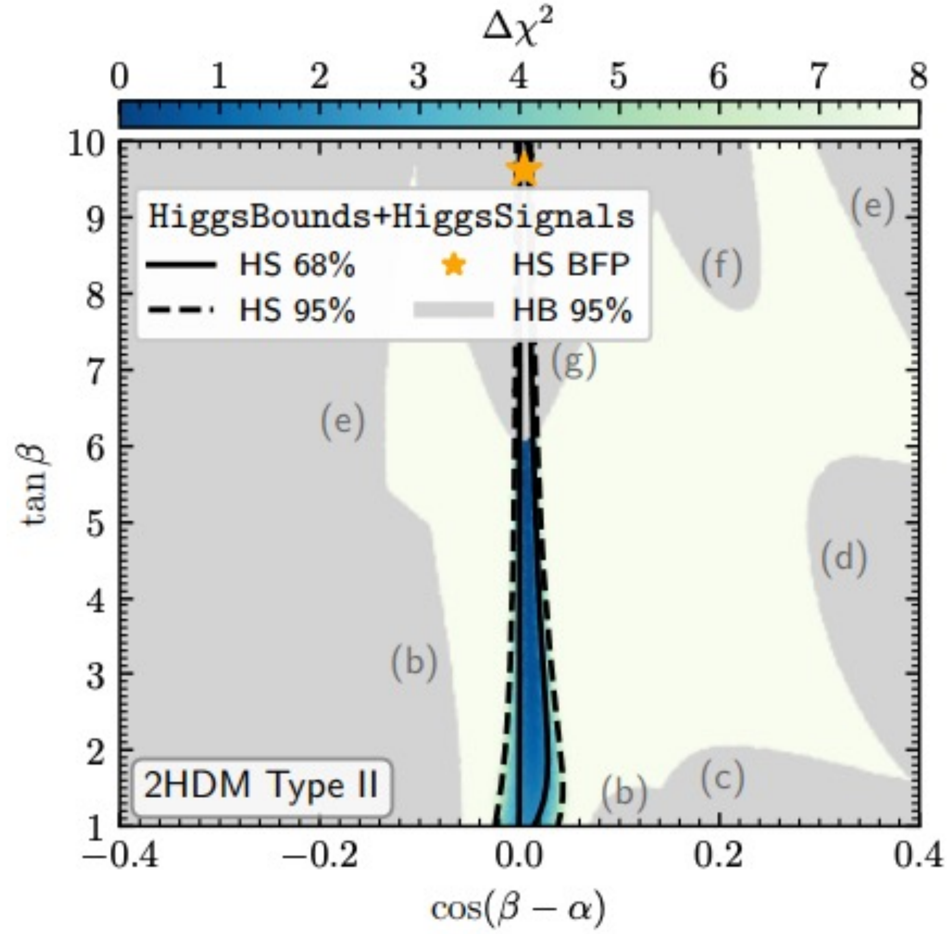
- BSM searches:
  b) CMS: $pp \to \phi_1 \to h_{125}\phi_2 \to bb\tau\tau$
  c) CMS: $pp \to \phi \to Zh_{125}$
  d) ATLAS: $pp \to \phi \to WW, ZZ, WZ$
  e) ATLAS: $pp \to \phi \to h_{125}h_{125}$
  f) ATLAS: $pp \to \phi \to VV, Vh_{125}$
  g) ATLAS: $pp \to \phi \to \tau\tau$



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

[HB et al. 2210.09332]

What is still left to explore?

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

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

- Higgs width/BSM decay channels,
  SM: $\Gamma_h \simeq 4.1\ \mathrm{MeV}$,
- light Yukawas,
  SM: $y_f \propto m_f/v$,
- Higgs potential,
  SM: $V(\Phi) = -\frac{1}{2}m_h^2\Phi^\dagger\Phi + \frac{m_h^2}{2v^2}\left(\Phi^\dagger\Phi\right)^2$,
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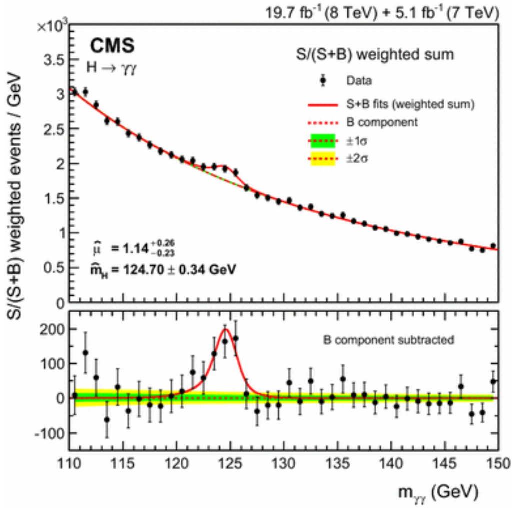

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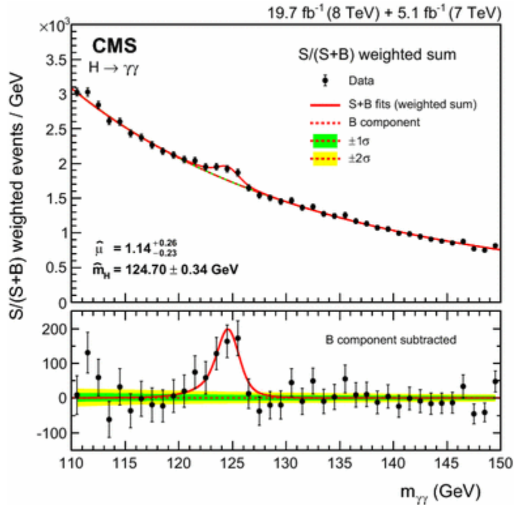

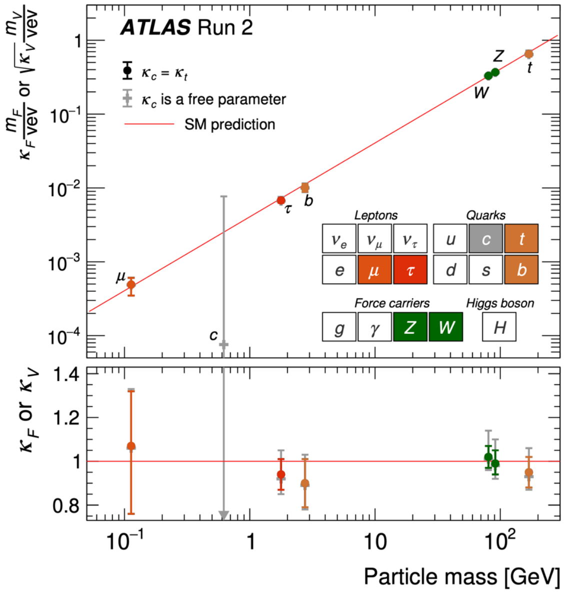

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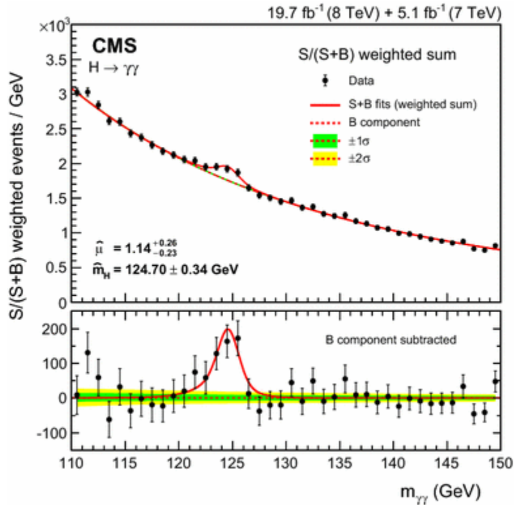
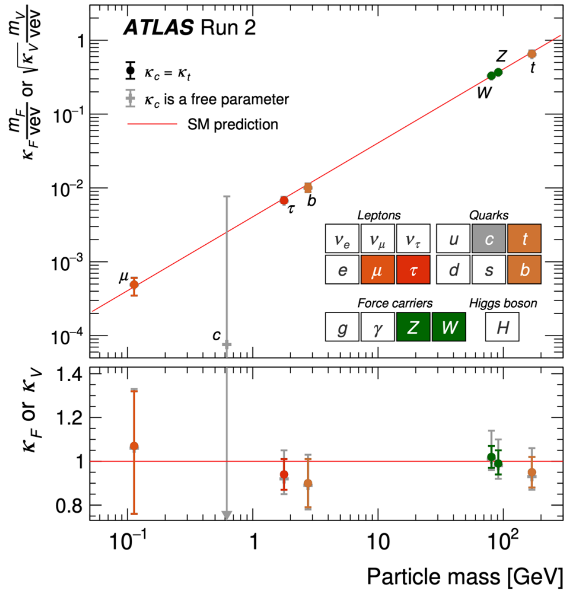




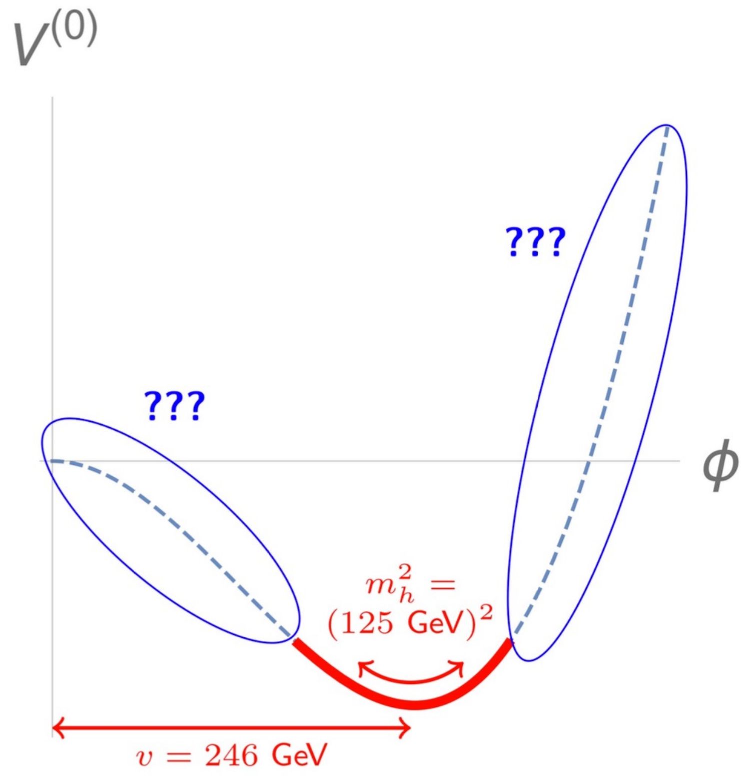
The Higgs potential

The Higgs potential

Is it really a Mexican hat?

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.



[figure by J. Braathen]

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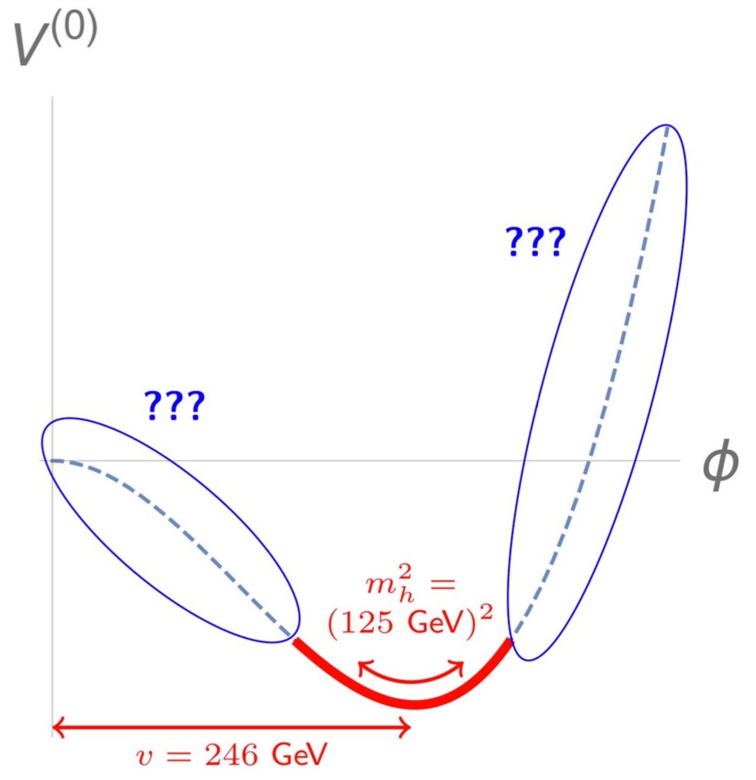

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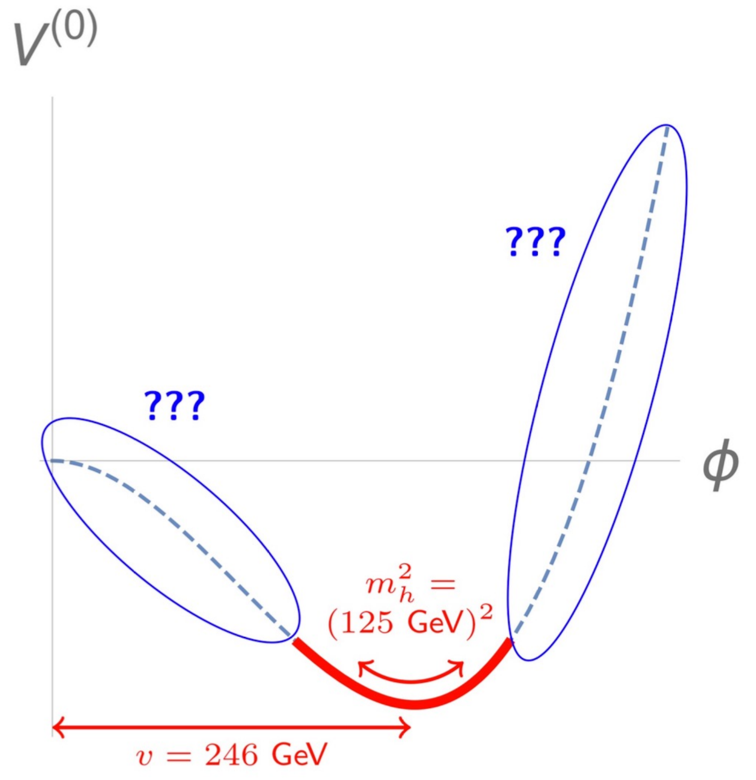
- λ_{hhh} closely linked to
  - stability of EW vacuum,
  - nature of EW phase transition (→ EW baryogenesis?).



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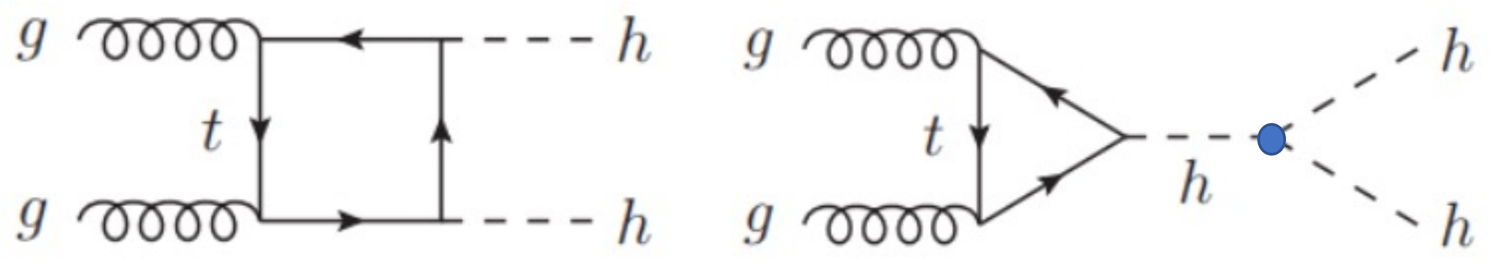
Probing λ_{hhh} via double-Higgs production

Most direct probe of trilinear Higgs coupling: double-Higgs production via gluon fusion.



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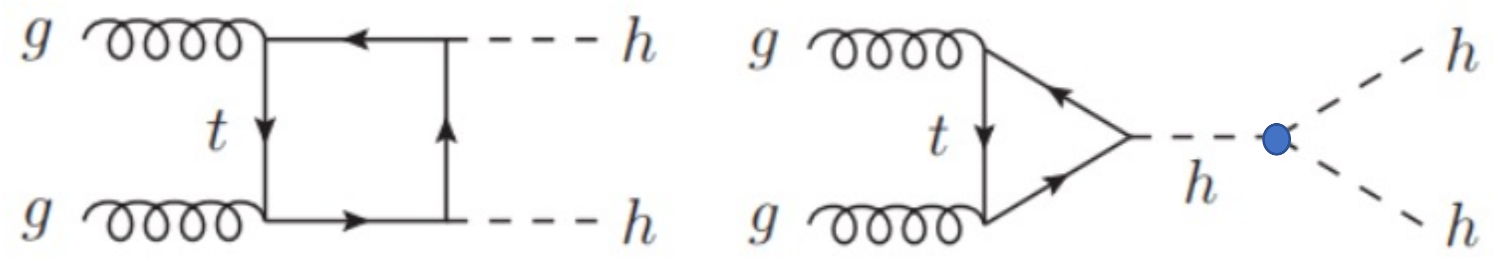


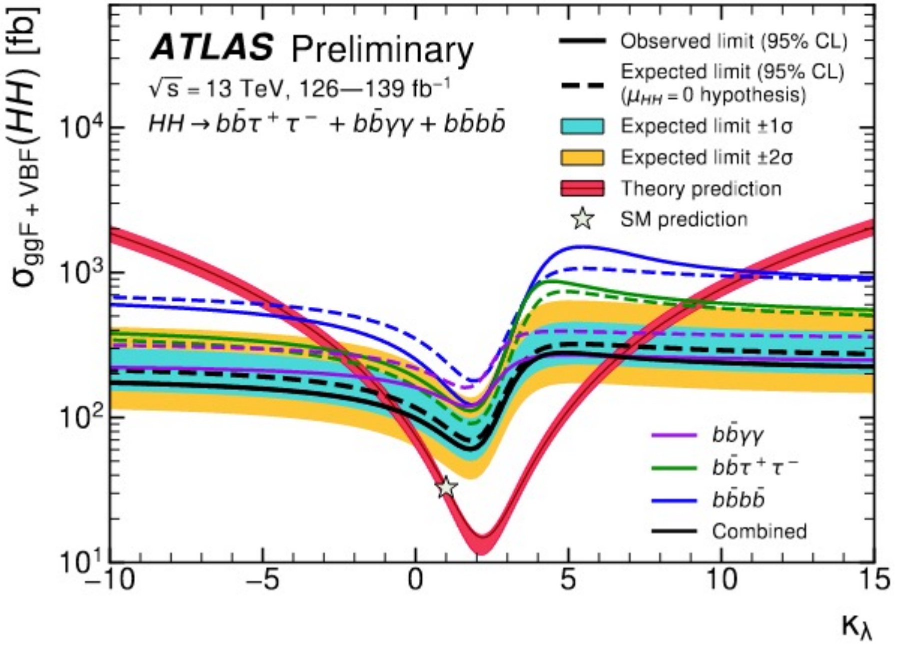
In the SM: large destructive interference between box and triangle contribution.

⇒ Deviations from SM trilinear Higgs coupling can significantly enhance the hh cross section.

Interpret experimental upper limits on hh cross section as limits on κ_λ.

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

Current strongest limit: $-0.4 < \kappa_\lambda < 6.3$ at 95% CL [ATLAS-CONF-2022-050].



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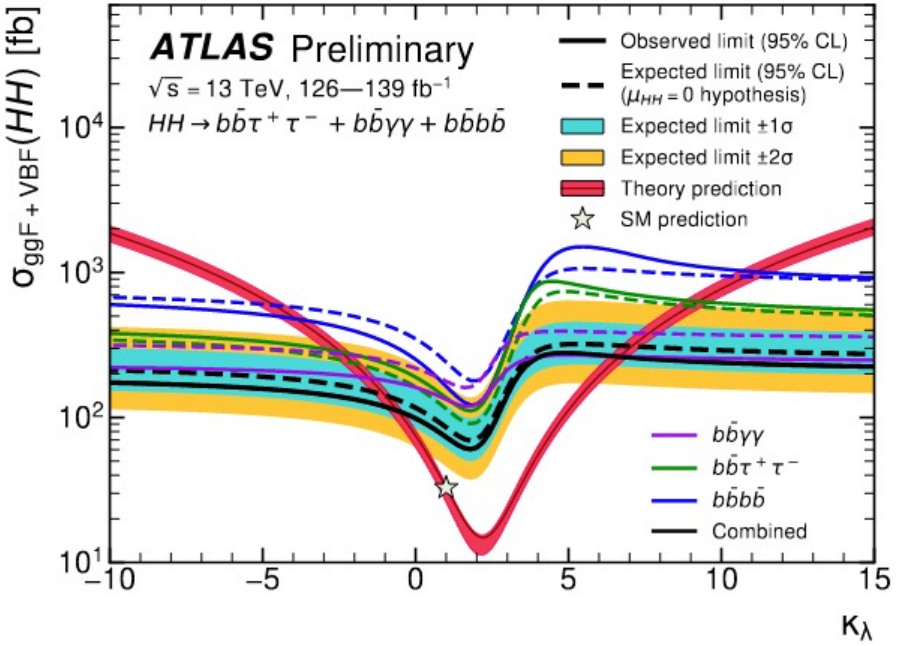

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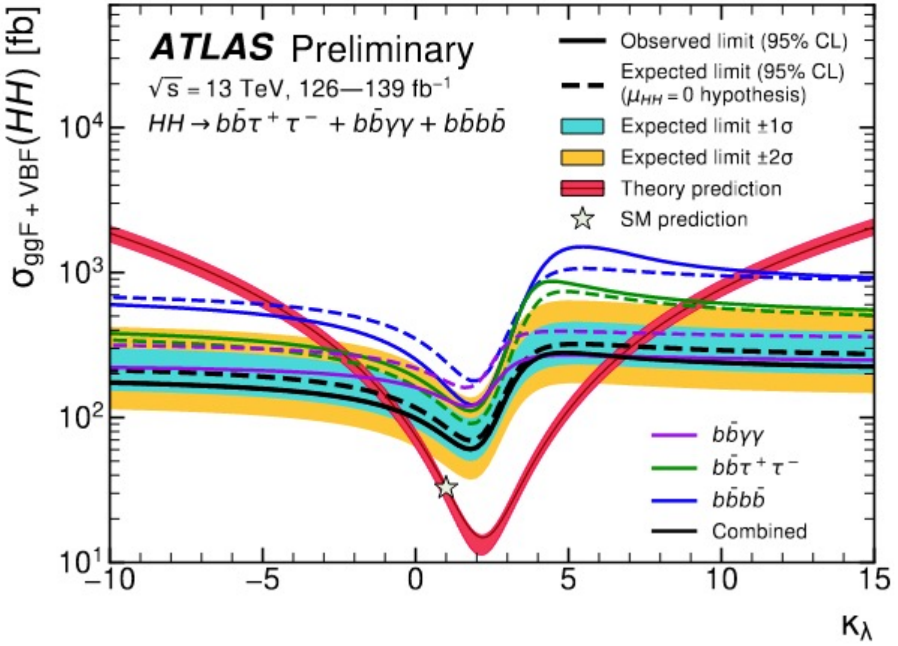
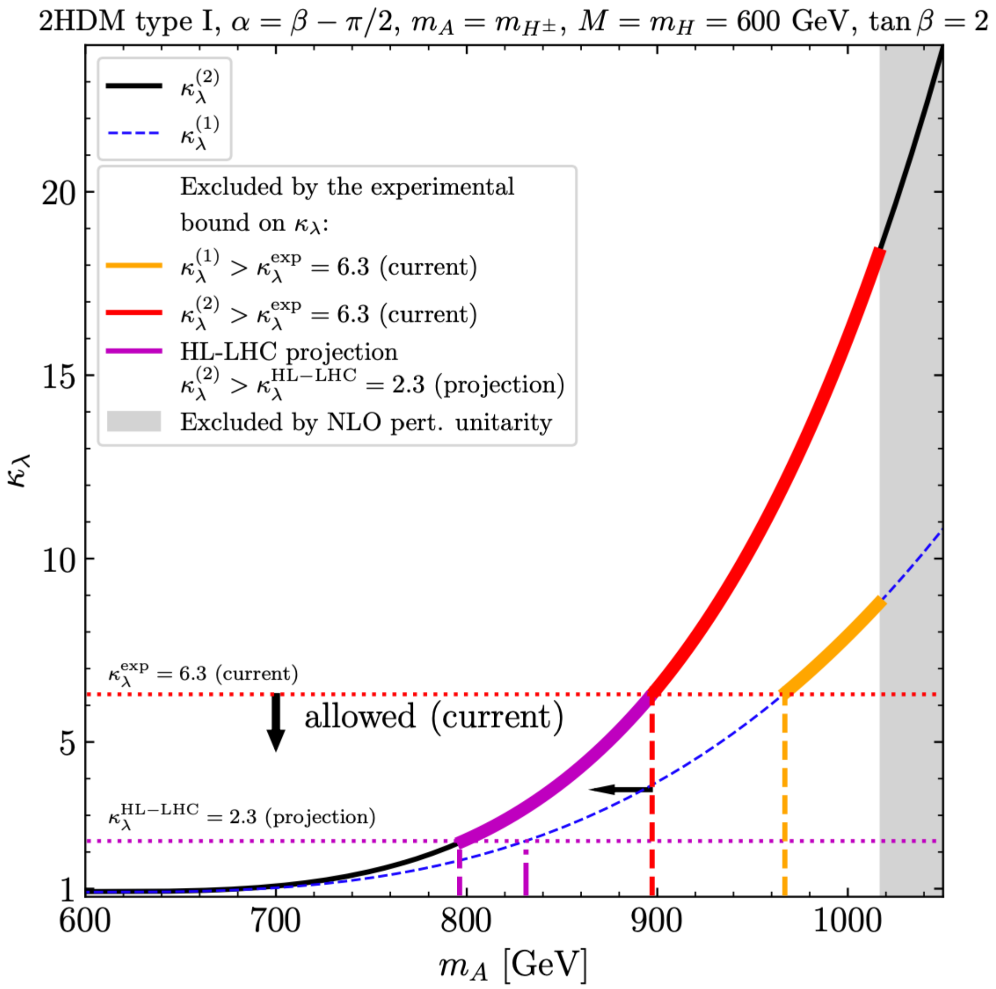


- Can we use this seemingly weak limit to constrain BSM models?
- Can large BSM deviations occur given other theoretical and experimental constraints?

Trilinear Higgs coupling in the 2HDM

- Large deviations possible in the 2HDM without being in conflict with other measurements.
- Additional enhancement by 2L corrections.
- Maximal size bounded by perturbative unitarity.



[HB,Braathen,Weiglein, 2202.03453]

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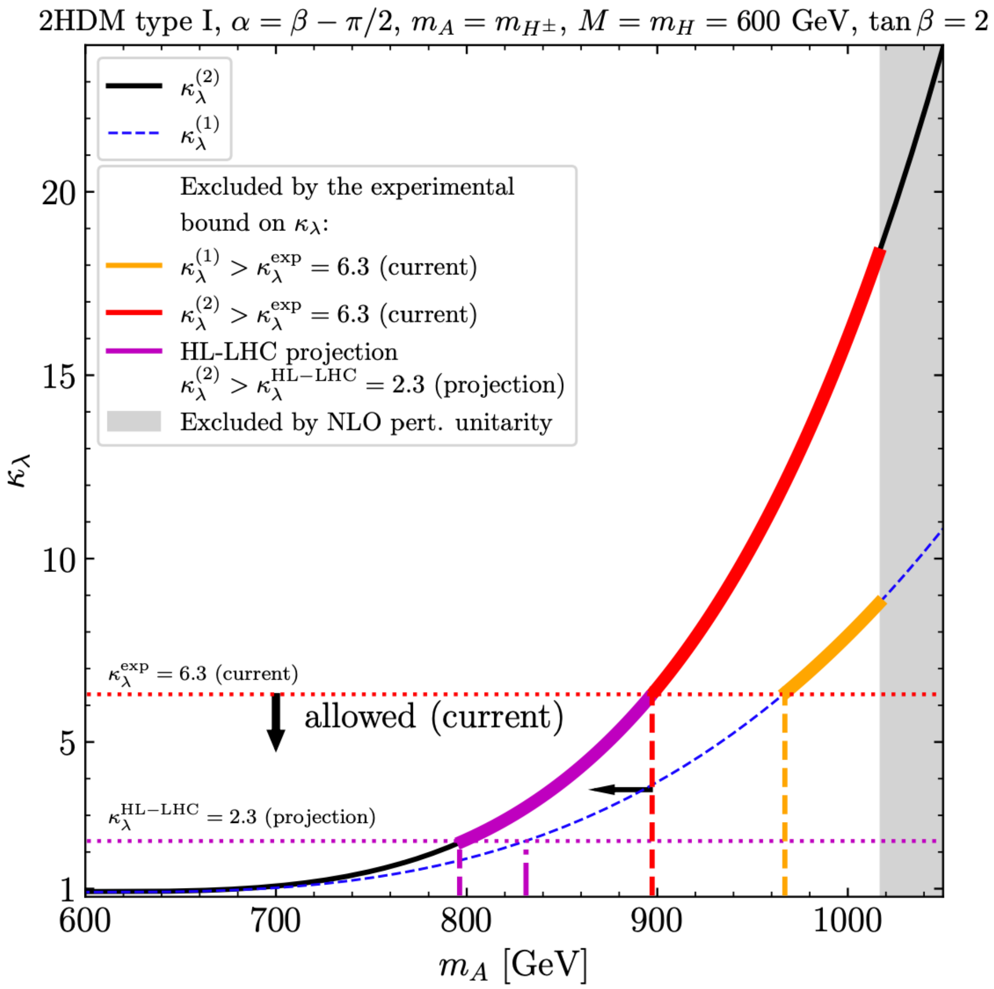
Already current experimental limits on κ_λ probe so-far unconstrained BSM parameter space!



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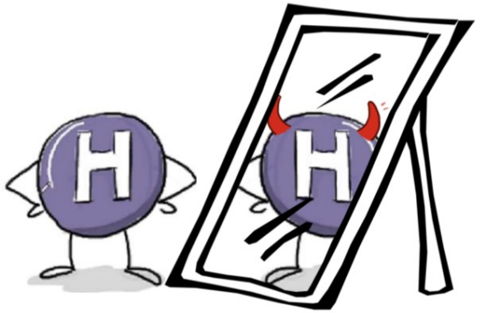
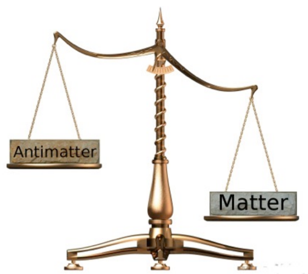


The CP nature of the Higgs boson

Does the Higgs sector provide additional sources of CP violation?

The CP nature of the Higgs boson



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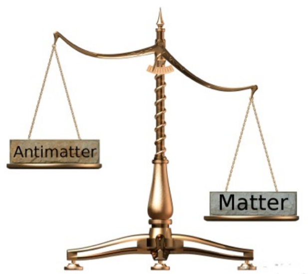

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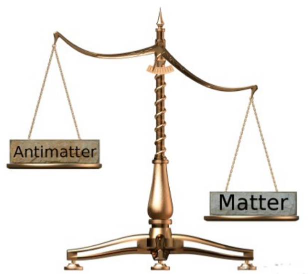

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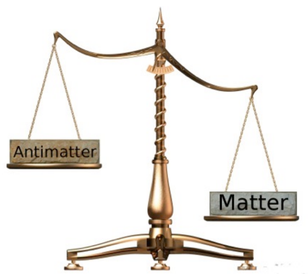

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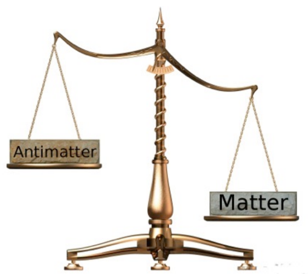

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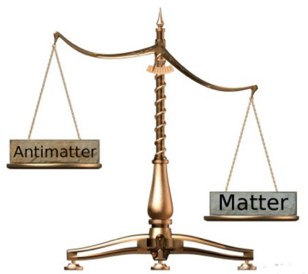

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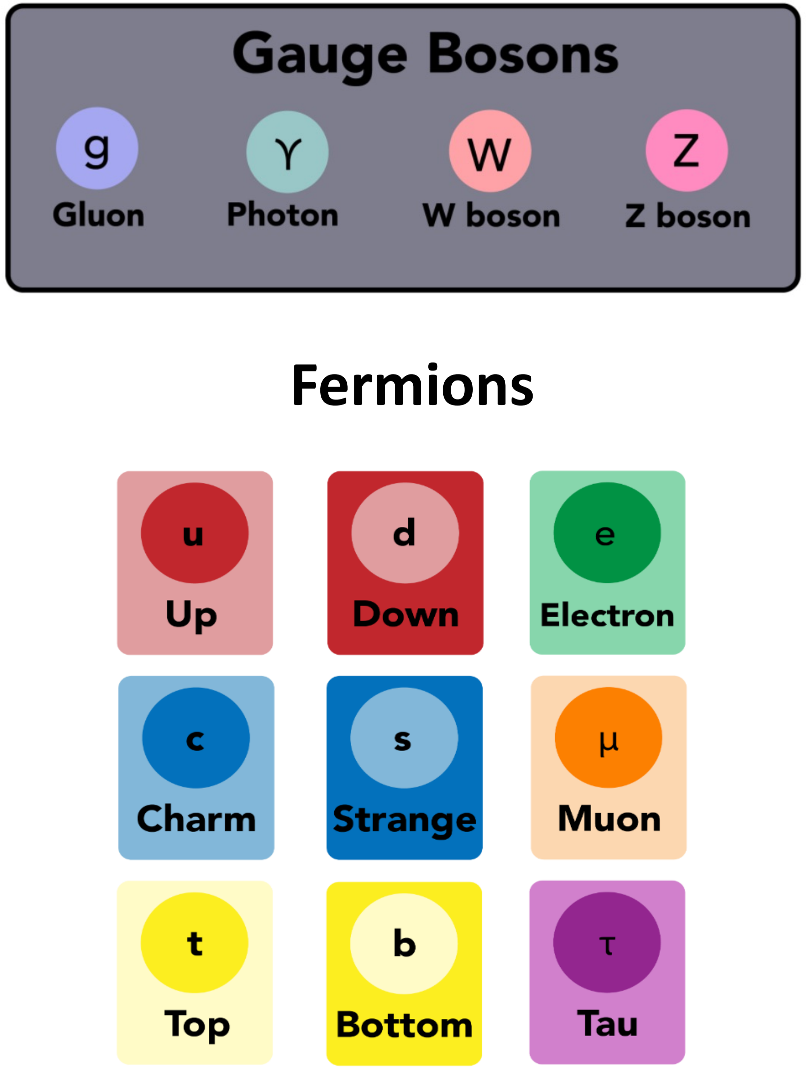
What is the current status?

Which CP structures are accessible at the LHC?



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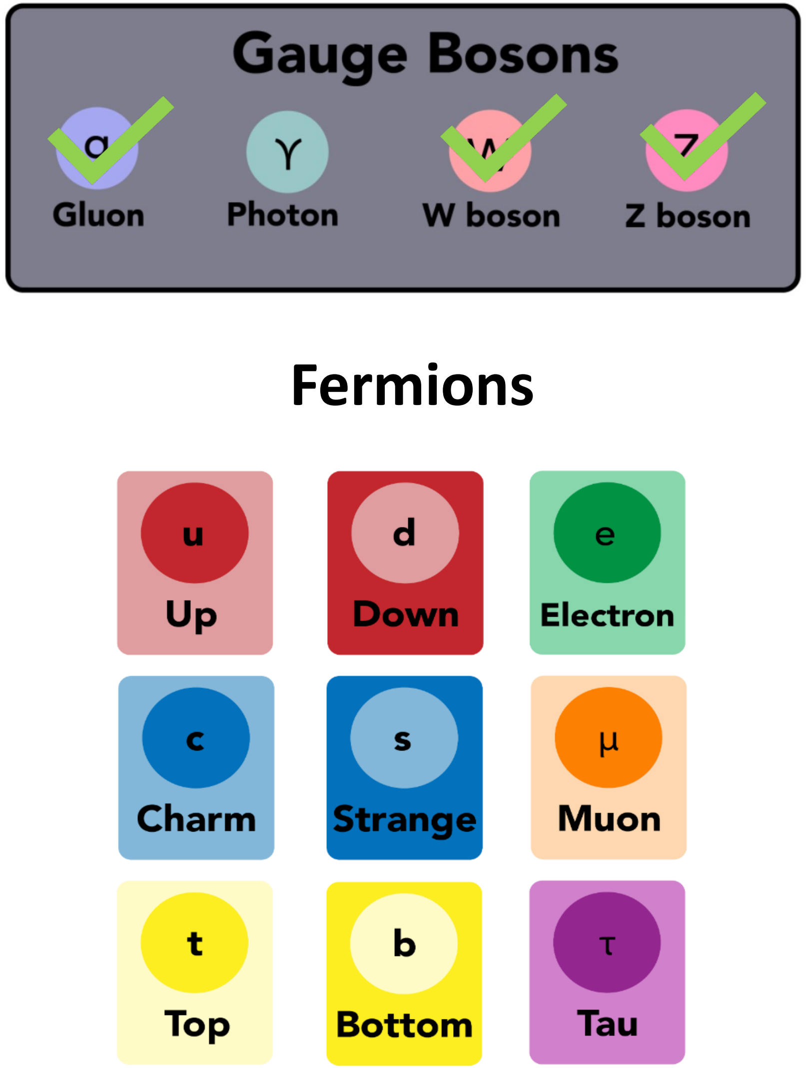

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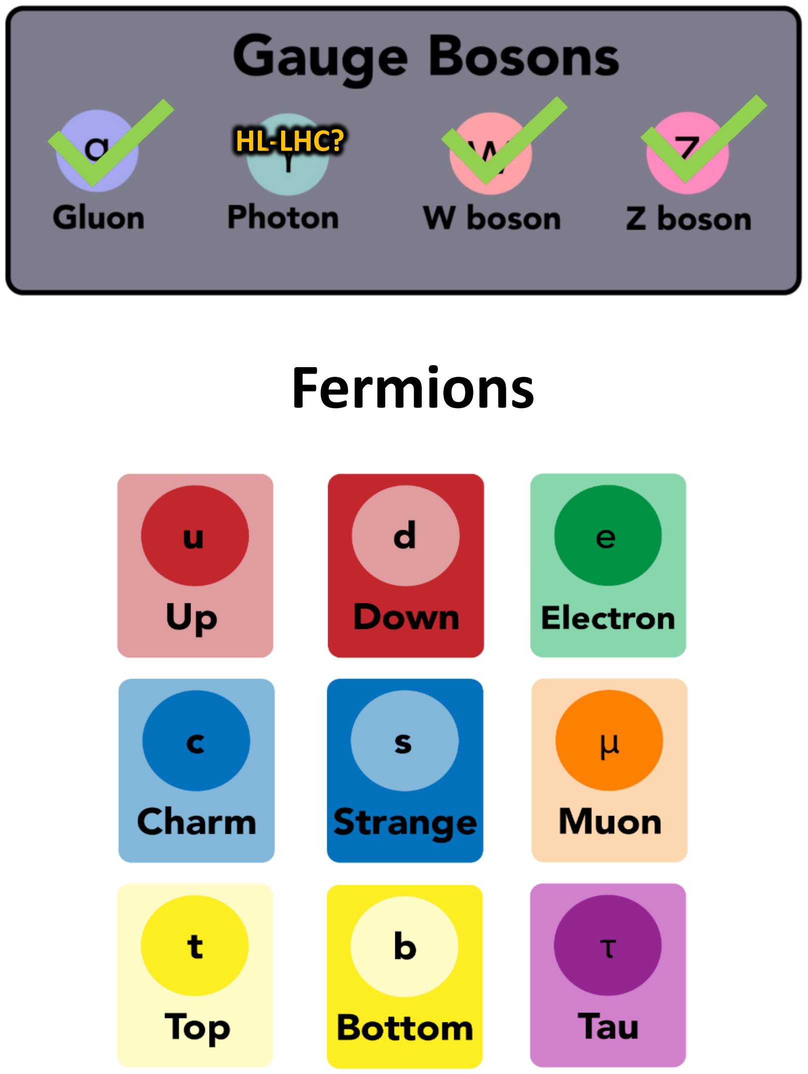

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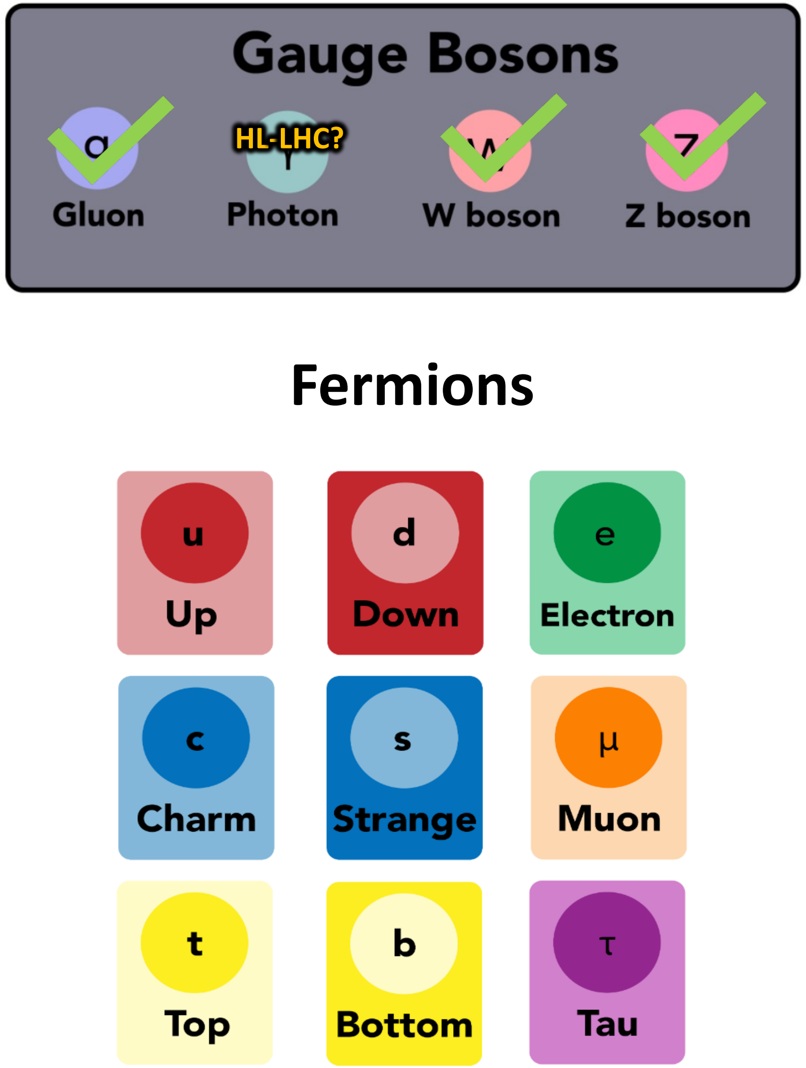

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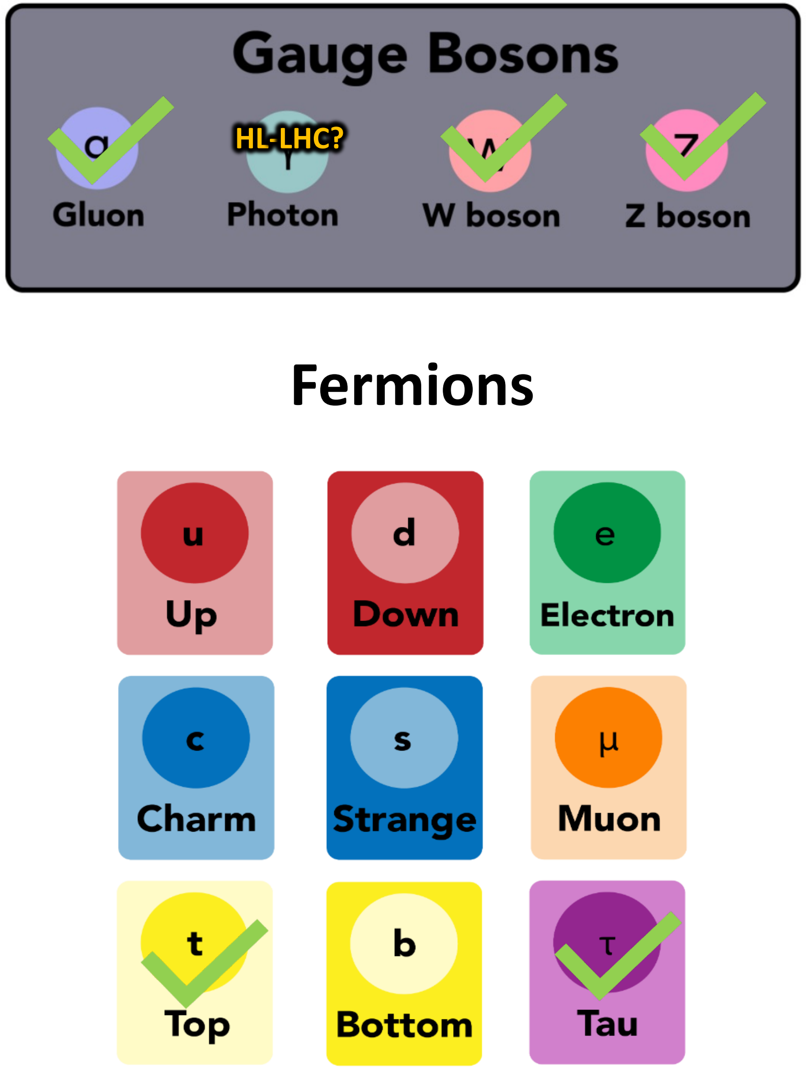

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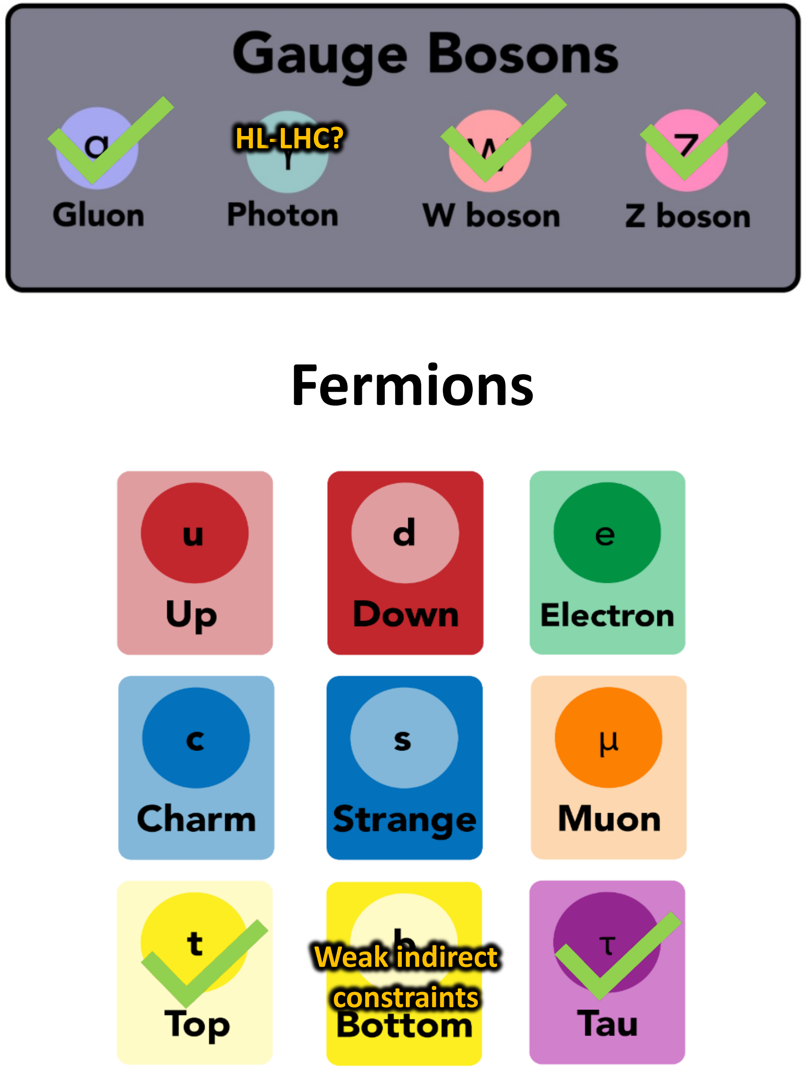

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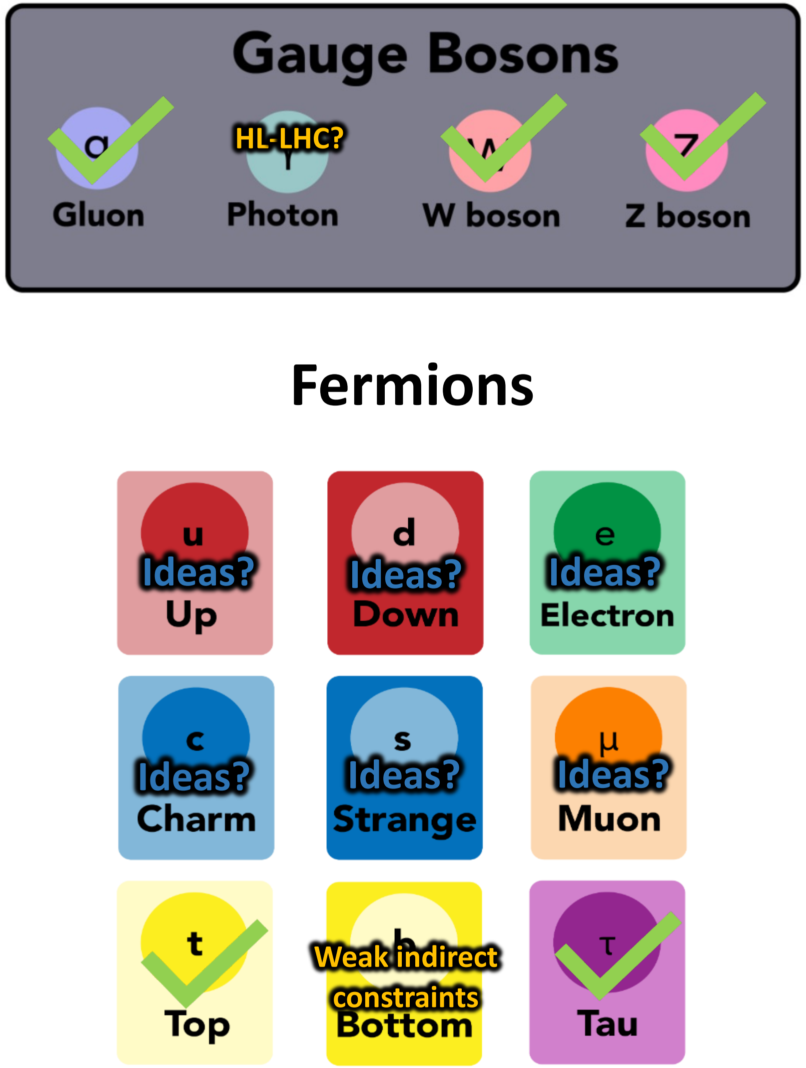

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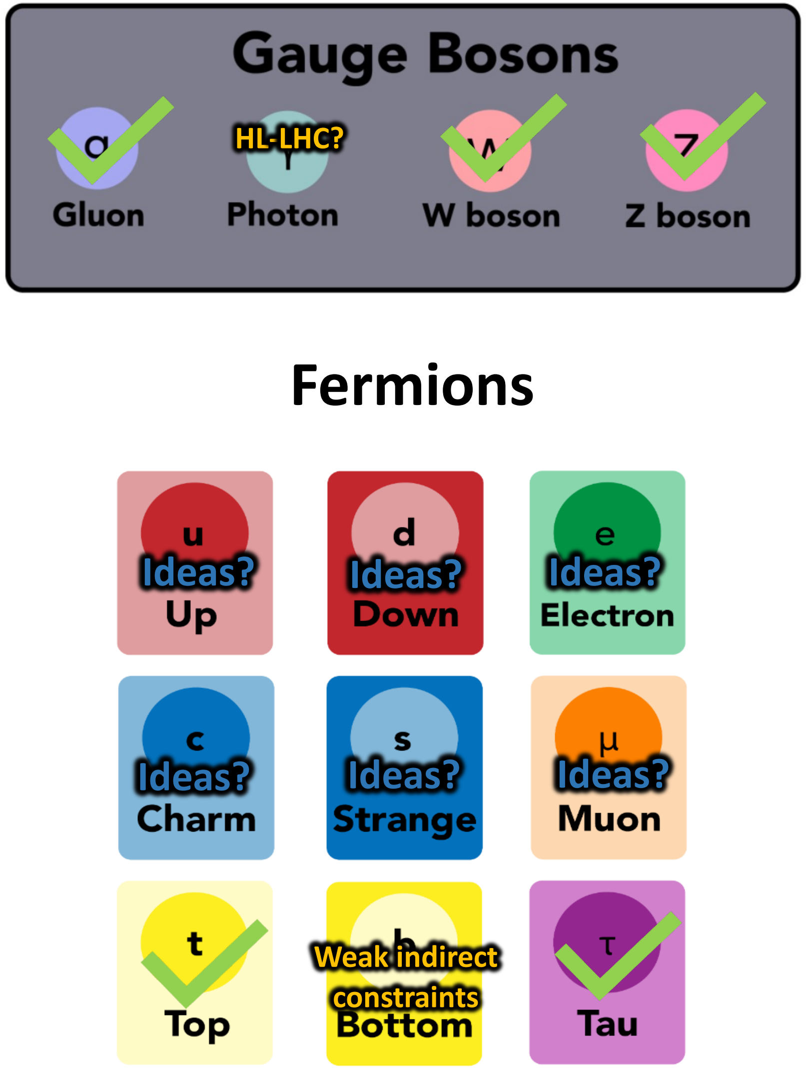

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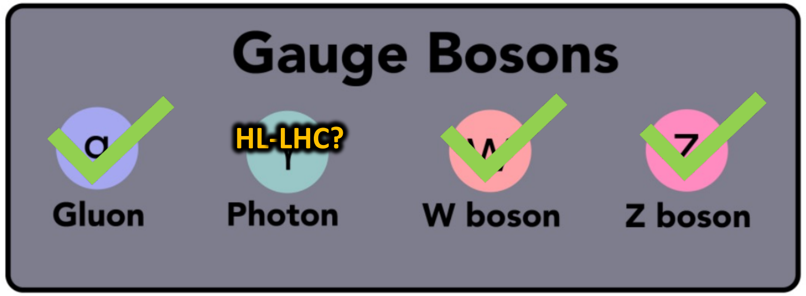

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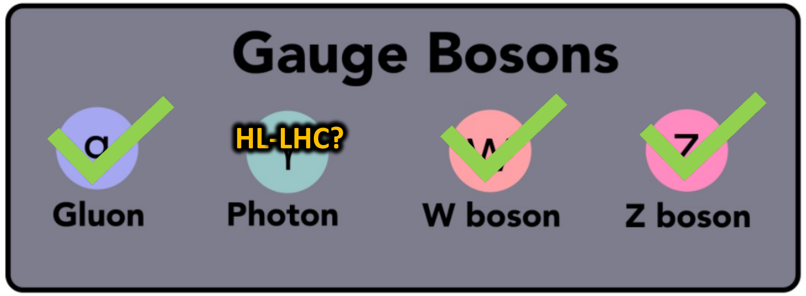
- Most BSM theories predict largest CP violation in $Hf\bar{f}, H\gamma\gamma, Hgg$ couplings.

Which CP structures are accessible at the LHC?



Fermions

- CP structure of HWW, HZZ interactions is comparably well-constrained. [ATLAS,CMS:..,2002.05315, 2104.12152,2109.13808,2202.06923,2205.05120]
- The CP structure of the $Hf\bar{f}, H\gamma\gamma, Hgg$ interactions is far less known.
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New ideas/techniques are needed to make the most of current and future data!

Constraining CP violation

CP violation in the Higgs sector can be constrained using:

- **Pure CP-odd observables**:
  - Unambiguous markers for CP violation: e.g.
    - EDM measurements,
    - decay angle in $H \to \tau^+\tau^-$.
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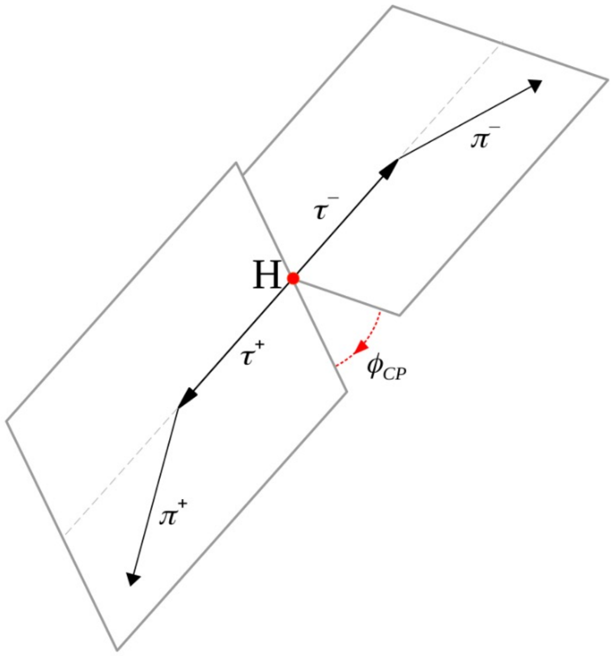

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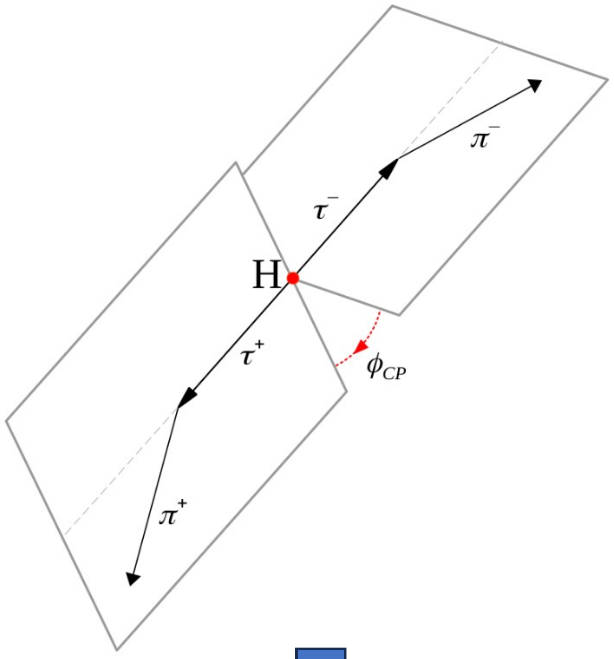

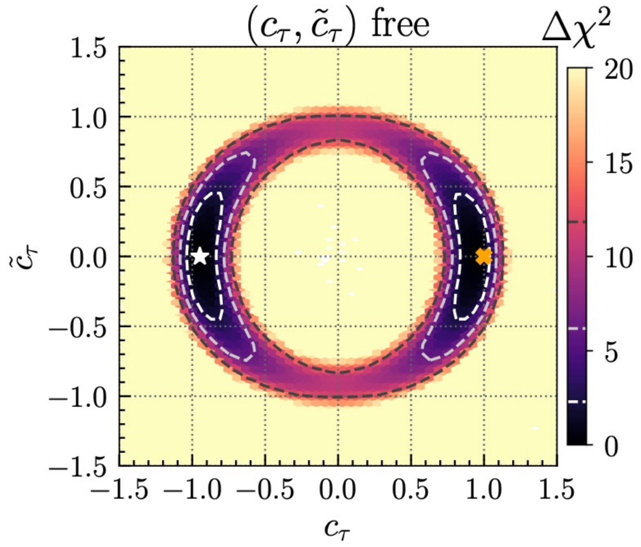

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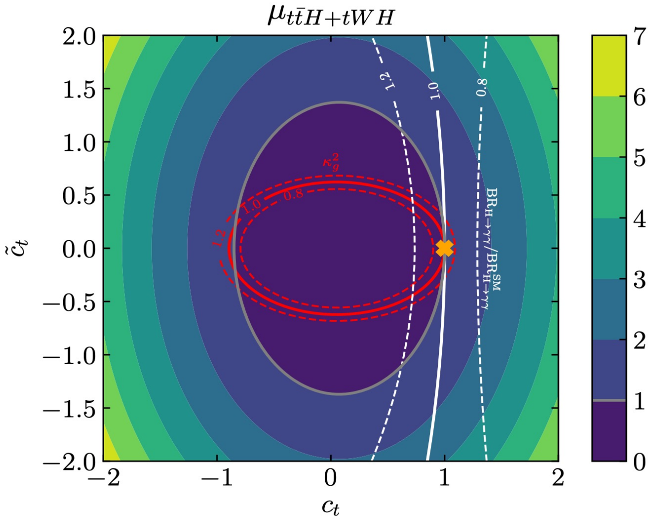

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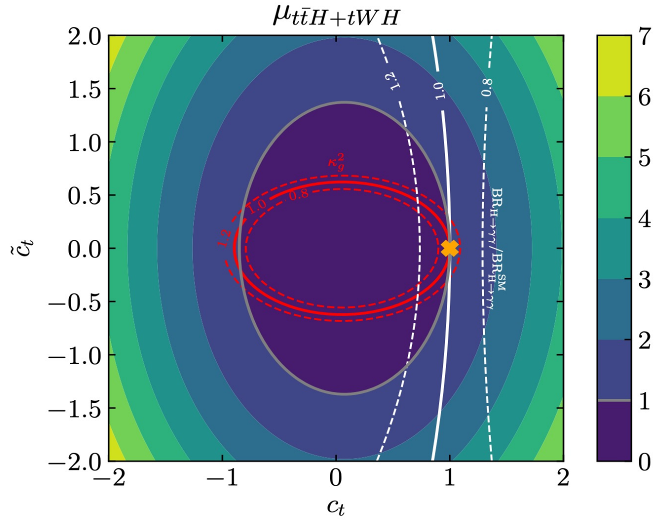

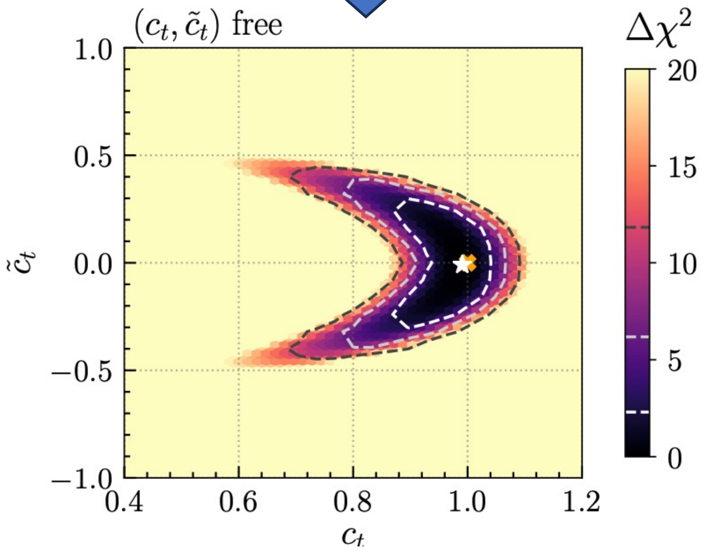

[HB et al., 2007.08542]

Constraining CP violation

- **Multivariate analyses:**
  - Exploit full kinematic information using machine learning.
  - Often mixes CP-even and CP-odd observables.
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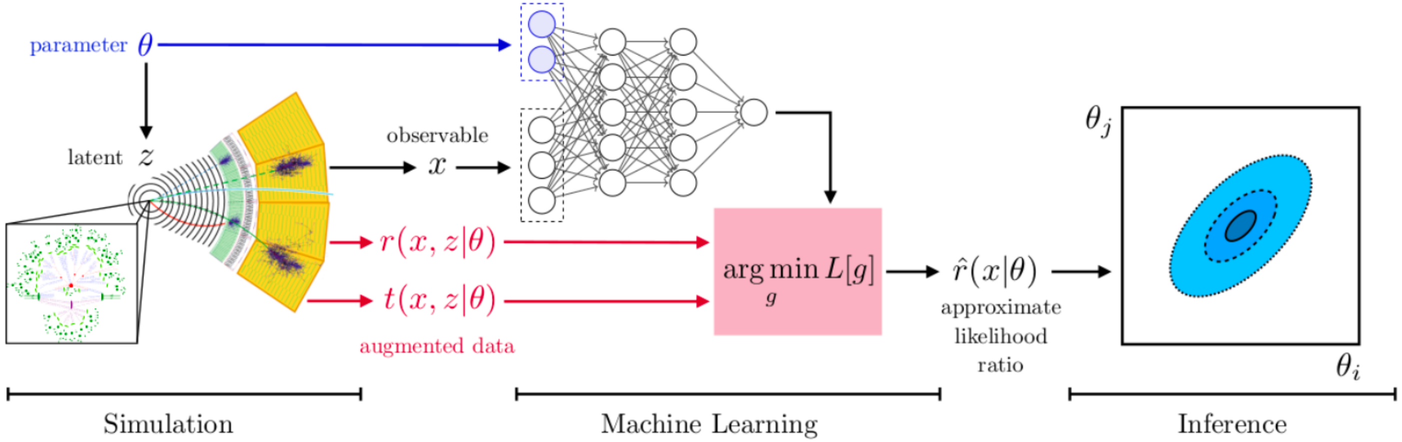

[e.g. simulation-based inference, Brehmer et al.,1805.00013, …]

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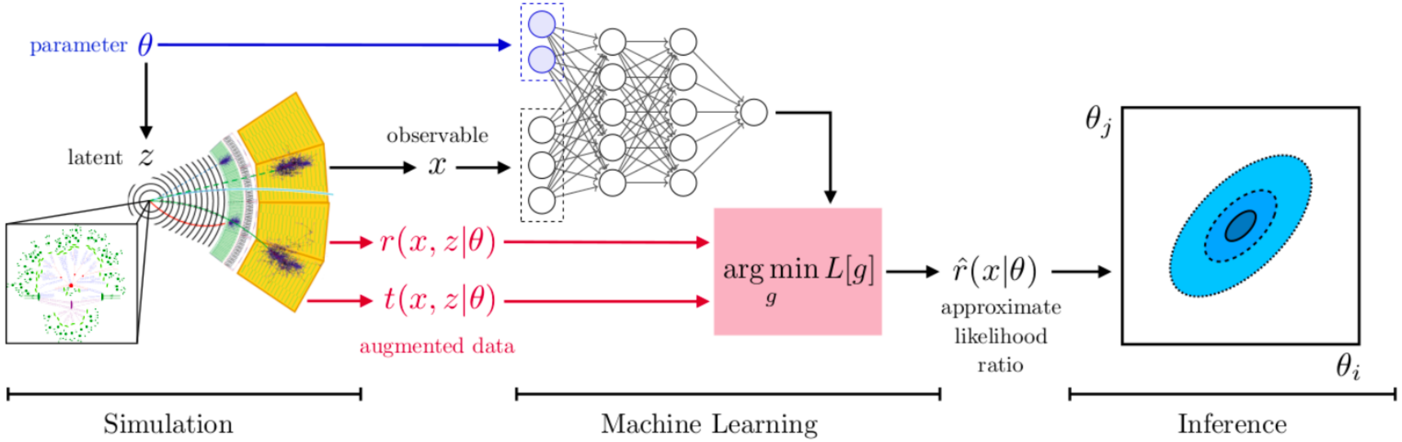

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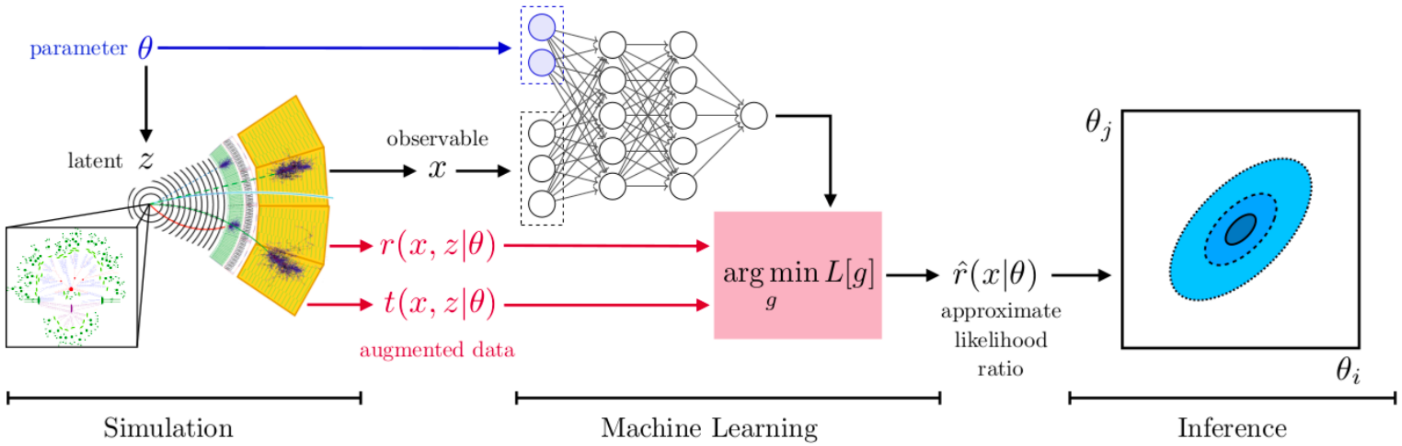

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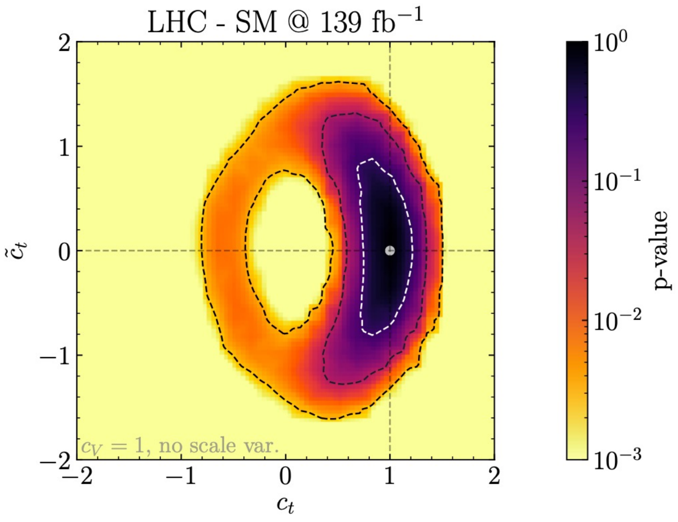

[HB&Brass,2110.10177]

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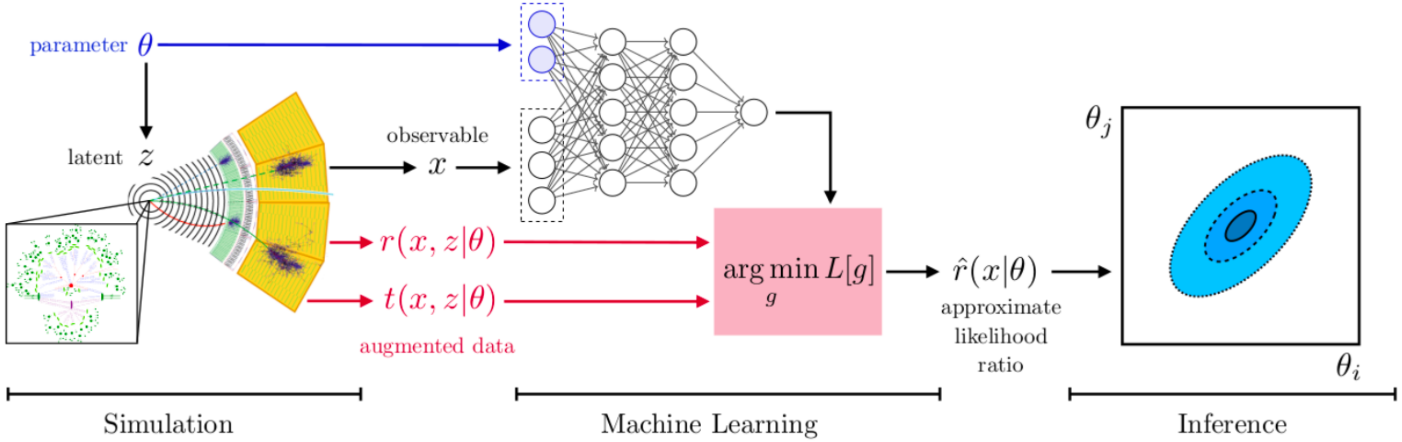
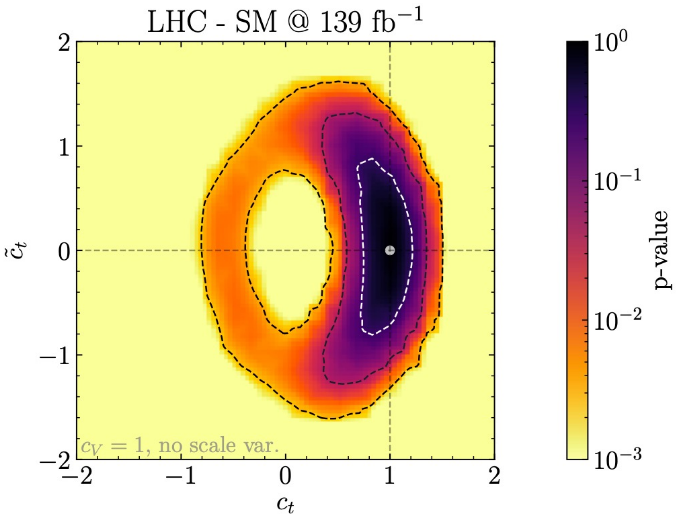


[e.g. simulation-based inference, Brehmer et al.,1805.00013, …]

Exploit and combine all three complementary approaches to learn as much as possible!

$t\bar{t}H, H \to \gamma\gamma$



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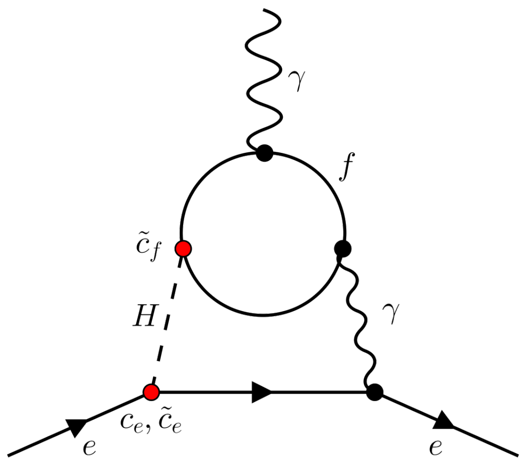
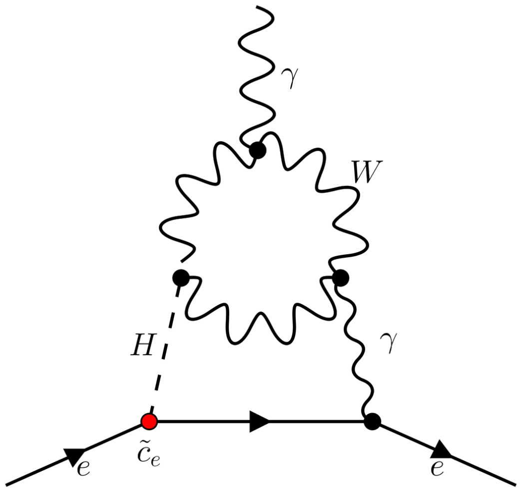
Complementarity with EDM constraints

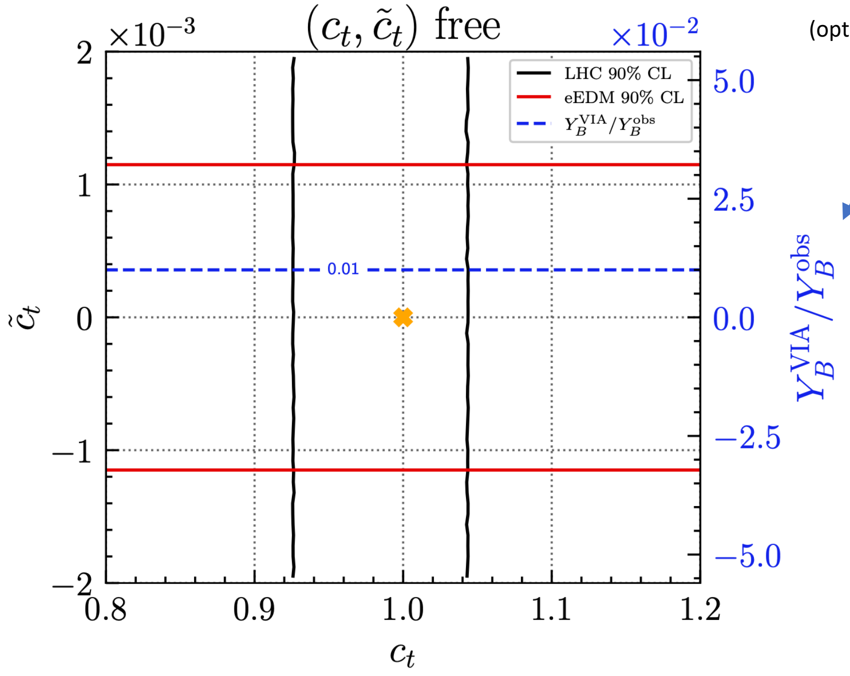




- Several EDMs are sensitive to CP violation in the Higgs sector.
- Consider here only constraints from theoretically cleanest EDM: the electron EDM.
- Limit by ACME collaboration: $d_e^{\text{ACME}} = 1.1 \cdot 10^{-29} e$ cm at 90% CL.

Complementarity with EDM constraints: t and τ

[HB et al., 2202.11753]



Ratio of baryon asymmetry
to observation
(optimistic upper bound)

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

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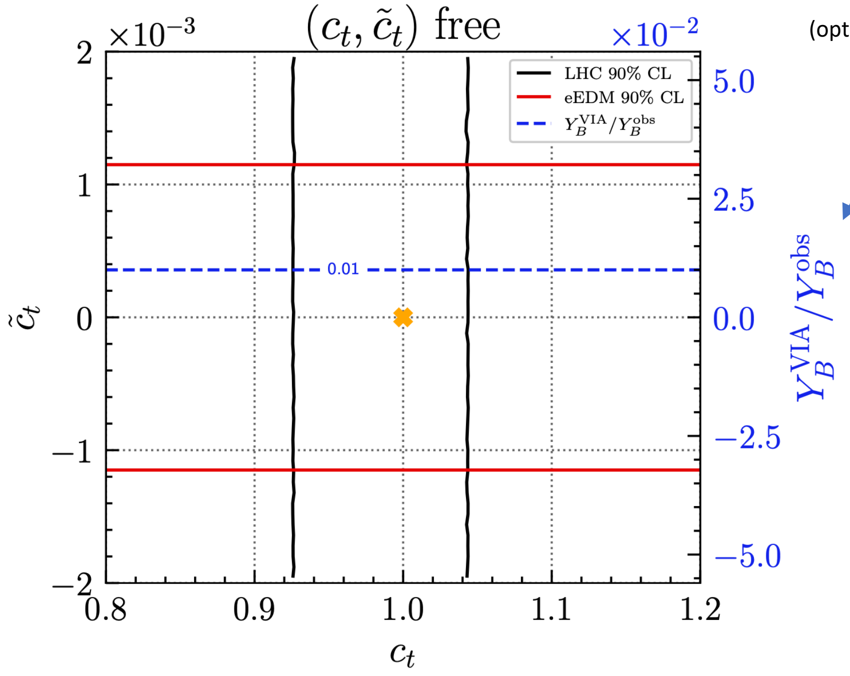

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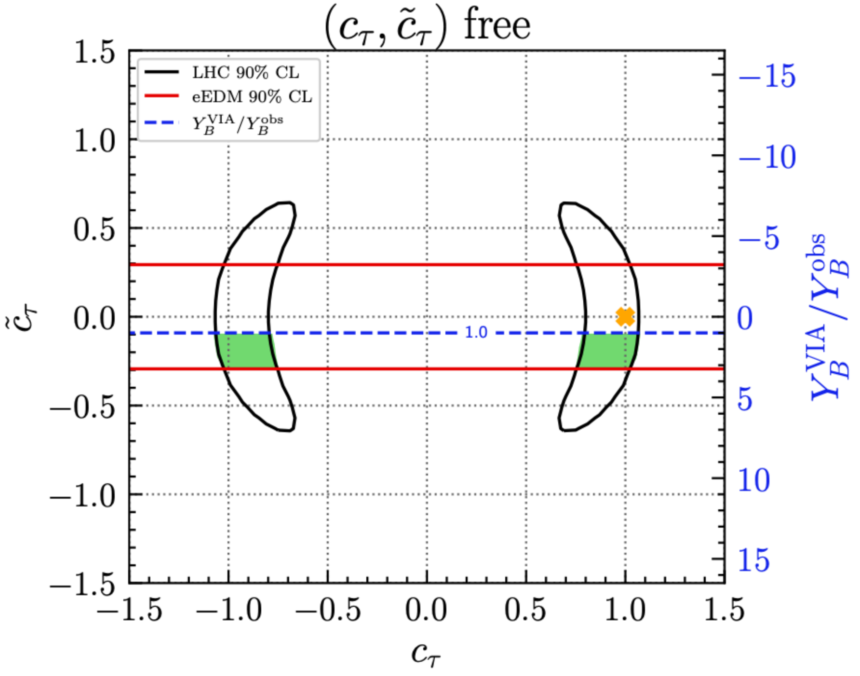

CP-odd τ coupling can contribute significantly to baryon asymmetry.

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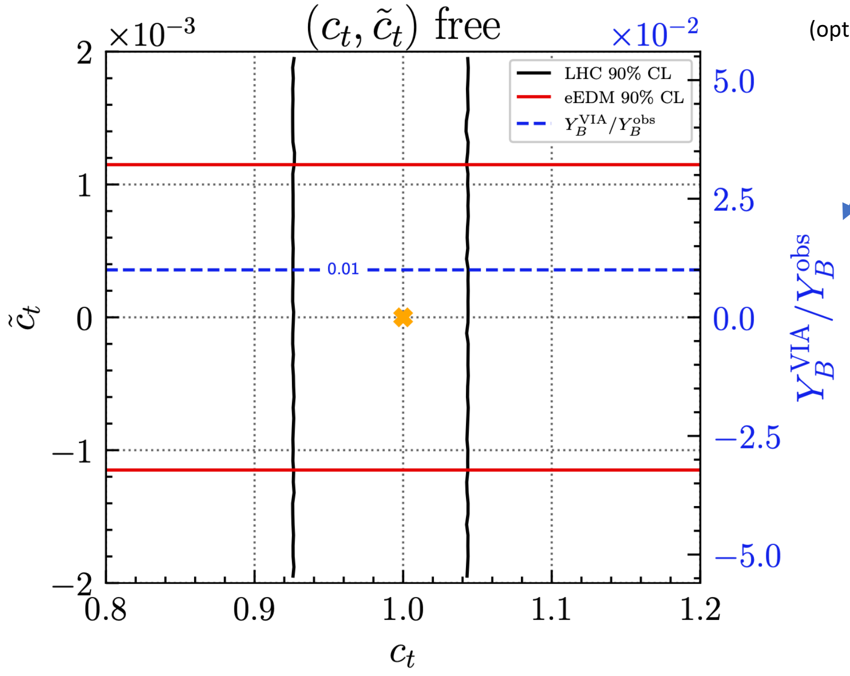

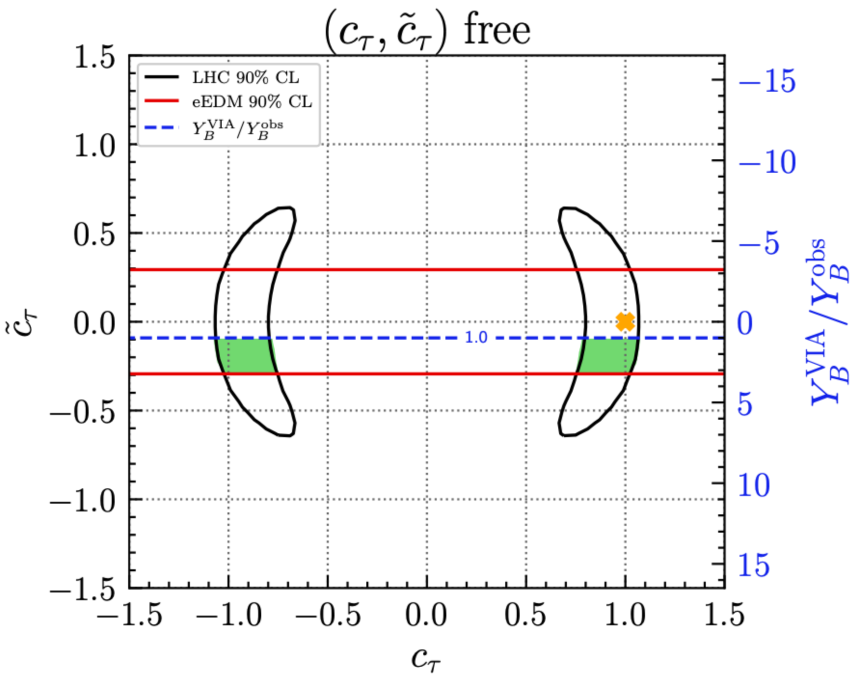

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→ updated EDM measurement almost completely excludes green area
[Roussy et al., 2212.11841]

EDM > LHC?

[see also Fuchs et al.,1911.08495]

EDM > LHC? **No.**

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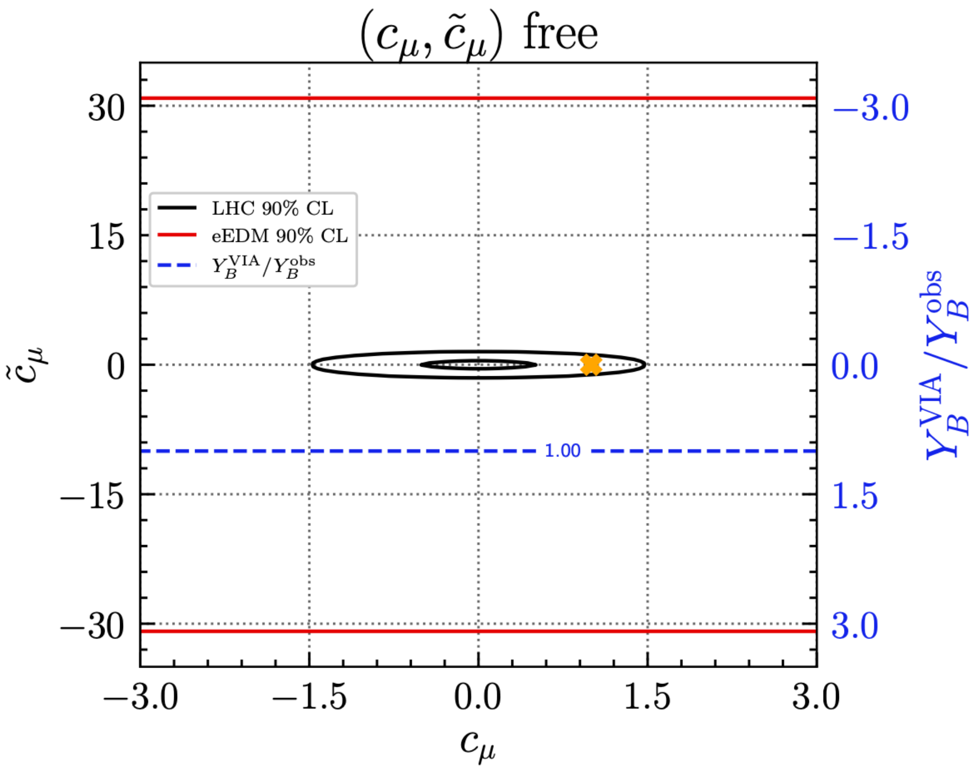
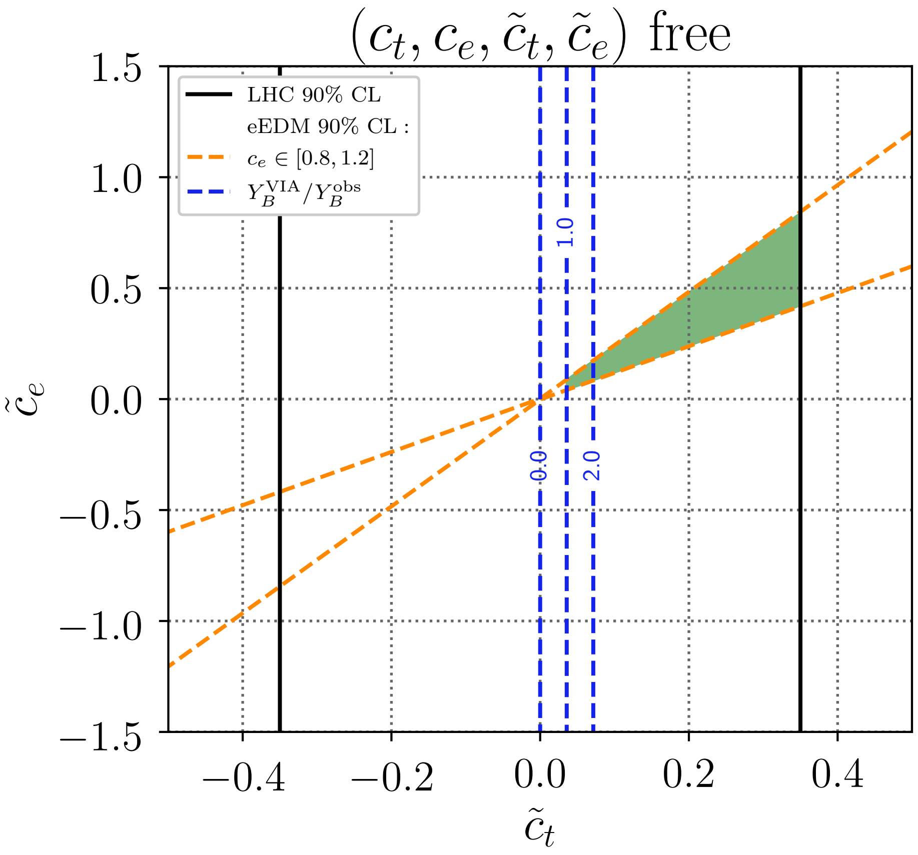


$\Gamma_{H\to\mu^+\mu^-} \propto c_\mu^2 + \tilde{c}_\mu^2$

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

Dependence on electron-Yukawa coupling



- 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 $d_e < d_e^{\mathrm{ACME}}$.
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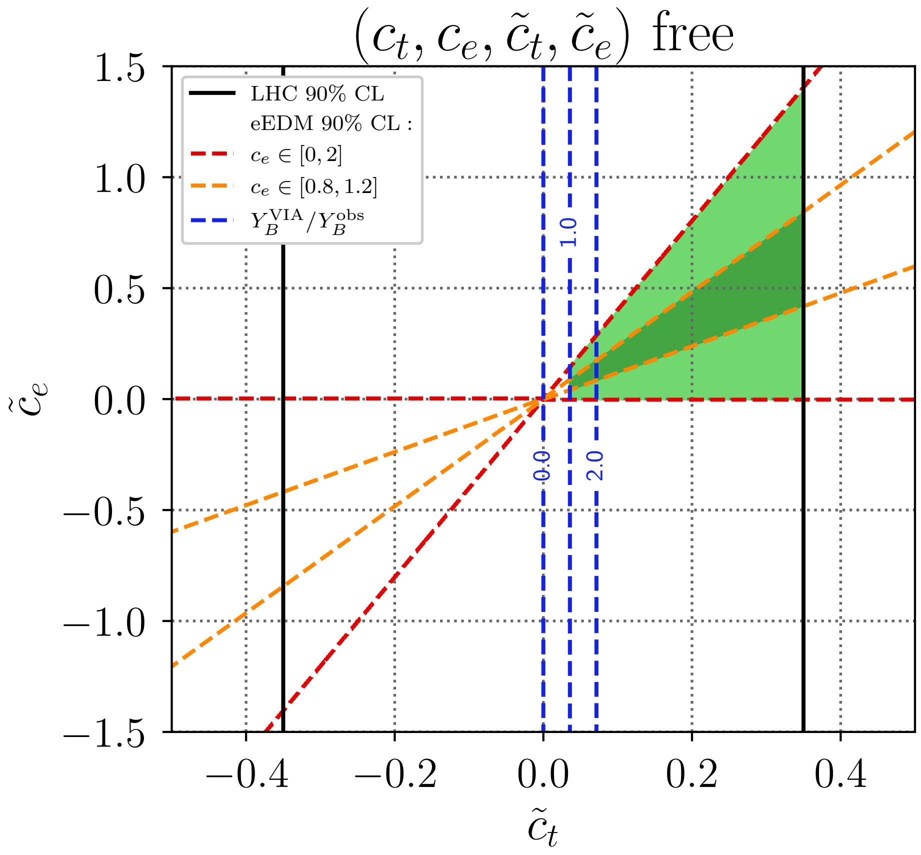

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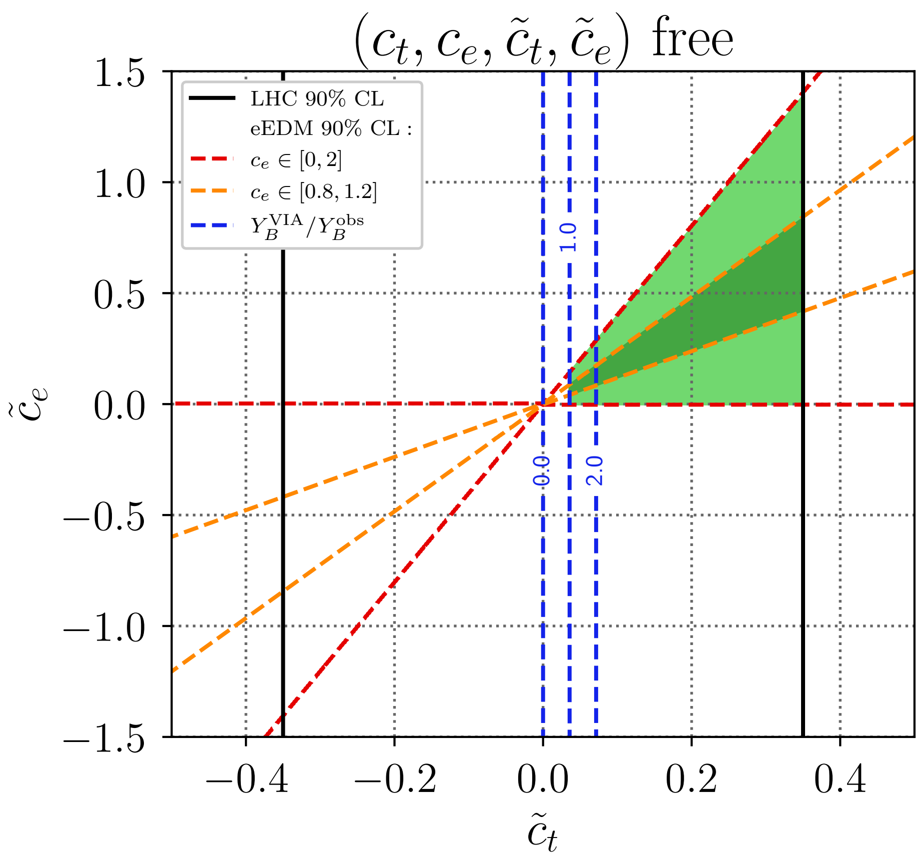

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LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

Conclusions

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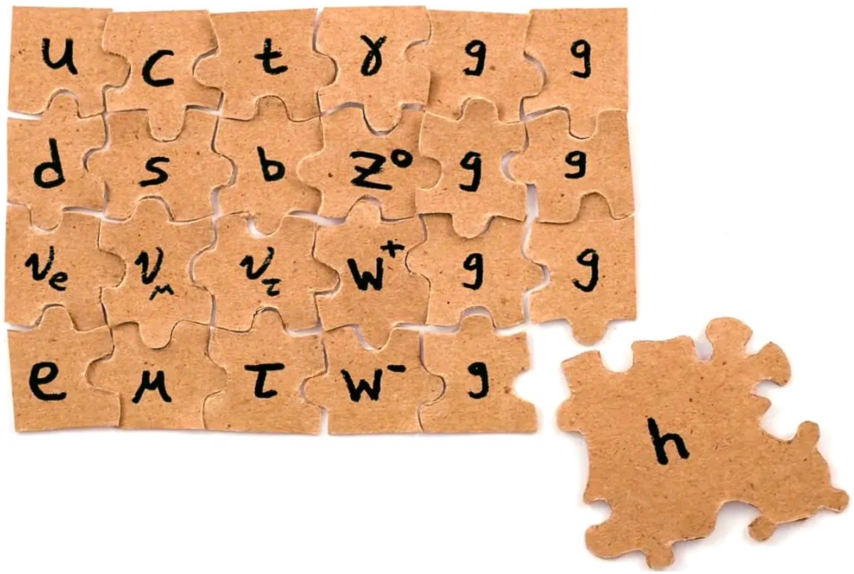
- Higgs precision measurements and precision predictions are crucial to understand electroweak symmetry breaking.

- 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,
  - …



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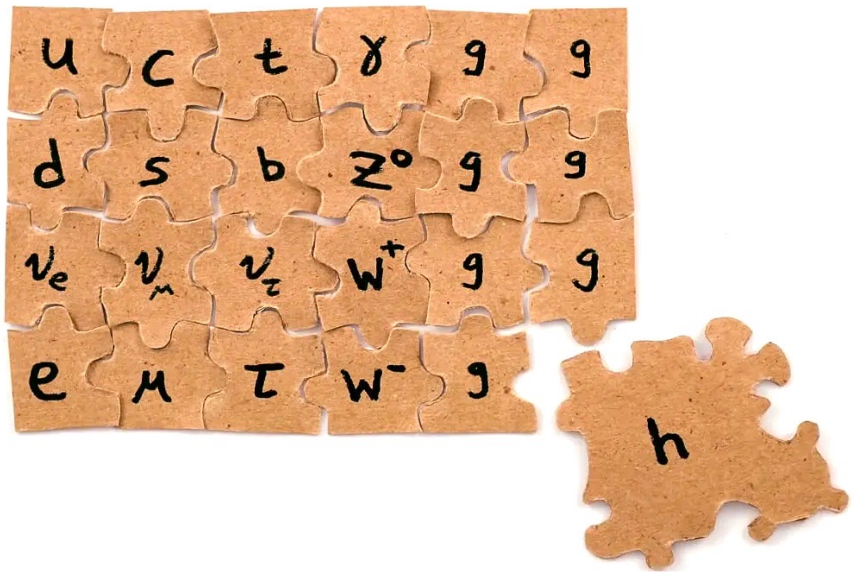

The Higgs will keep us busy for many decades to come!

Appendix

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

$$c(h_1VV) \propto \sin(\beta - \alpha)$$
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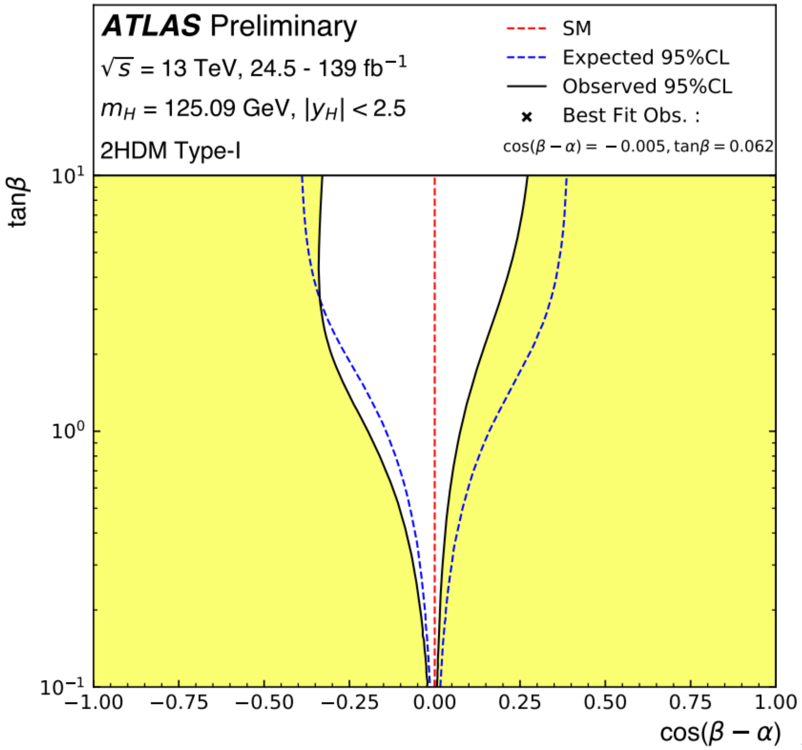
→ Measurements enforce approximate alignment of the SM-like Higgs with the electroweak vacuum.



[ATLAS-CONF-2020-027]

assumes that h_1 is h_{125}

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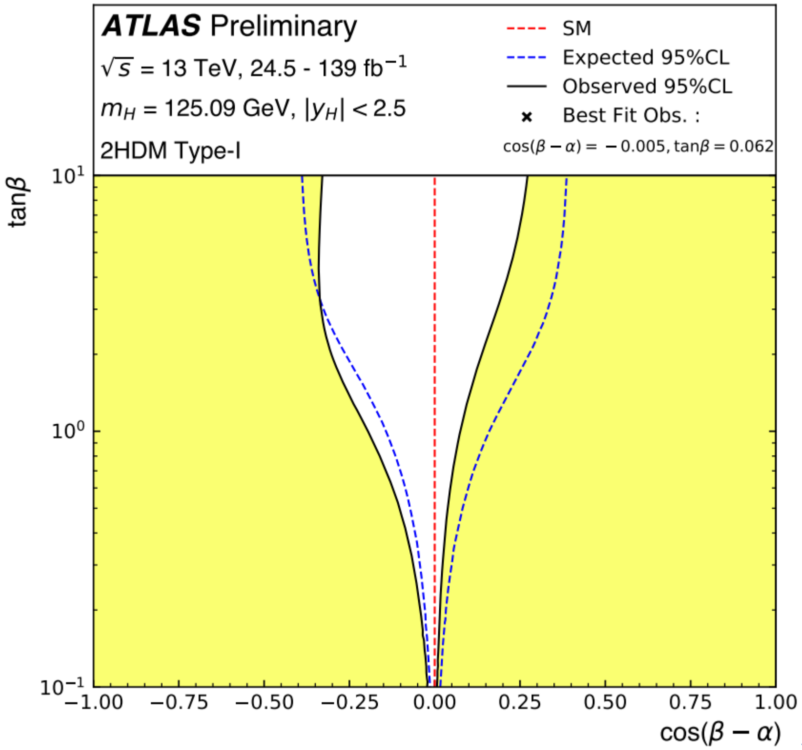

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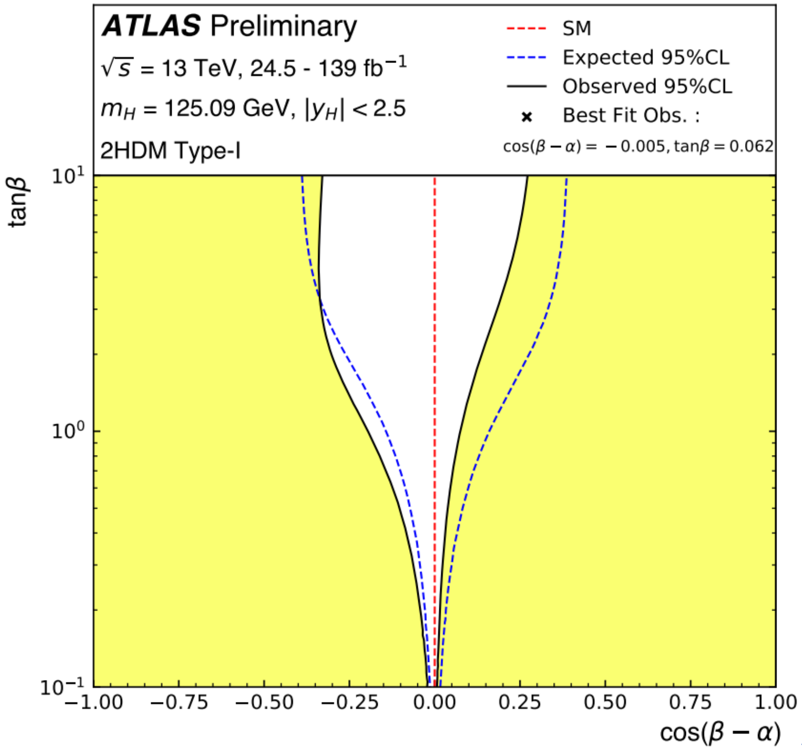
How can we distinguish the two cases?



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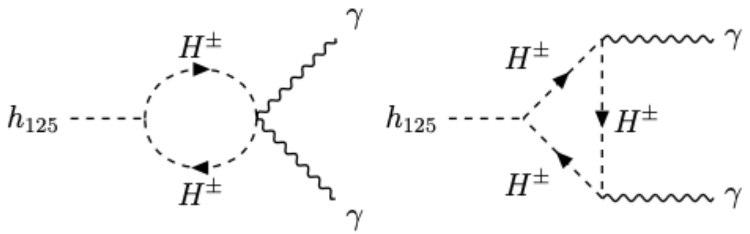
Interplay with $H\gamma\gamma$ coupling

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

- Charged Higgs yields sizeable contribution:



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

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

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

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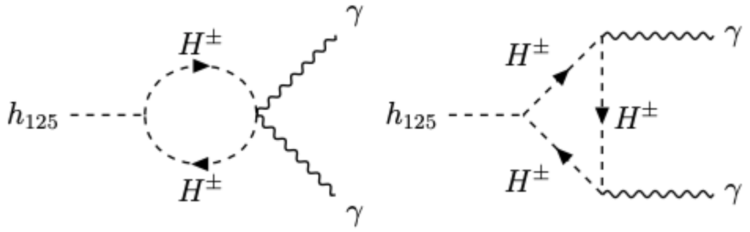

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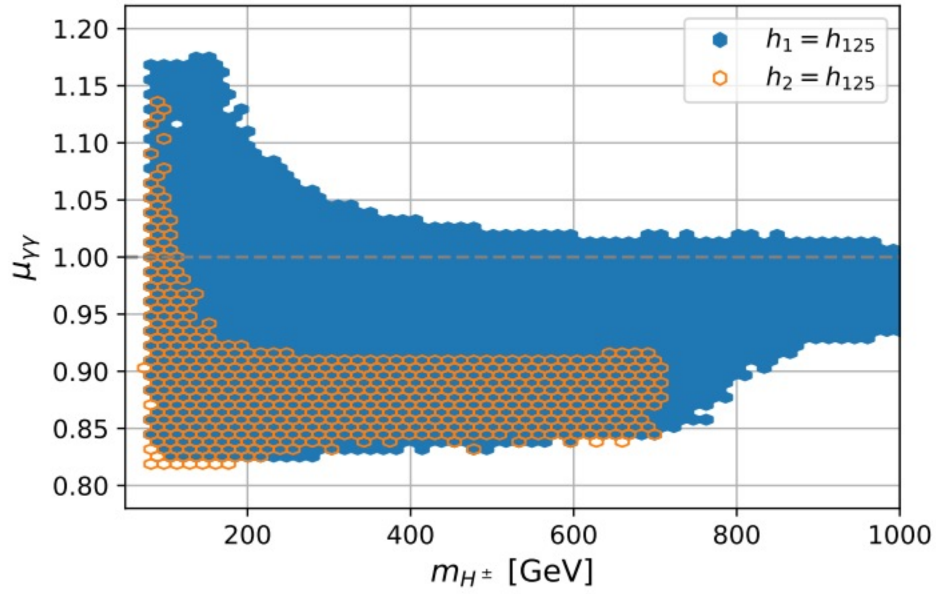
2HDM type-I



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

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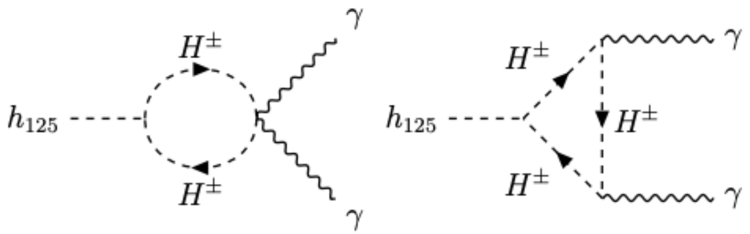

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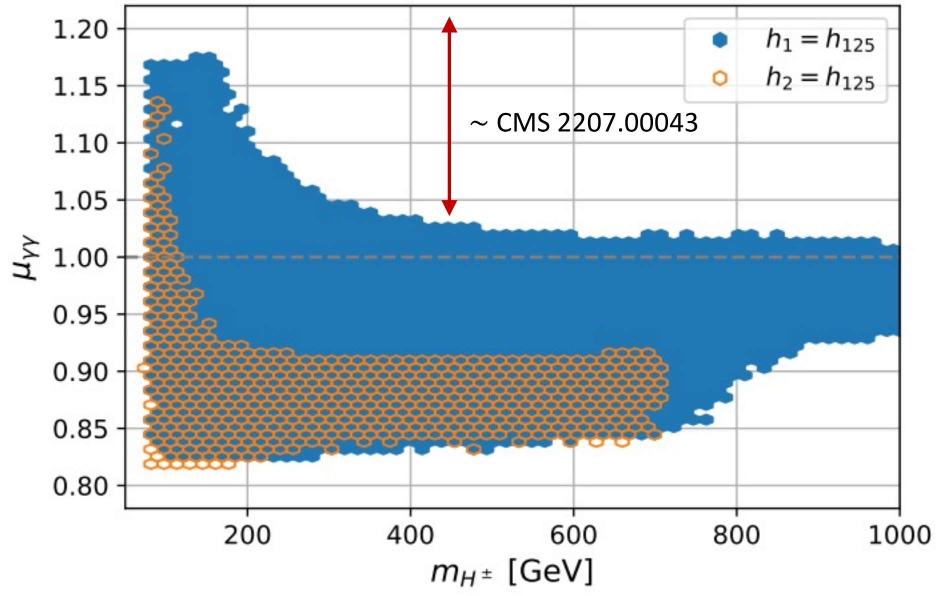

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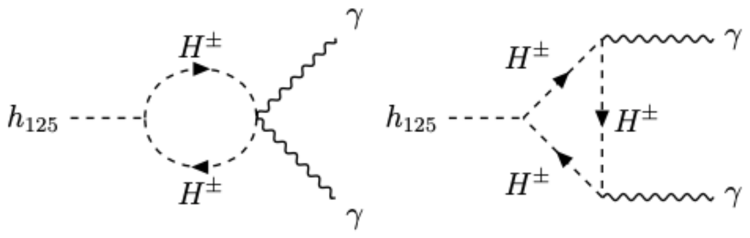

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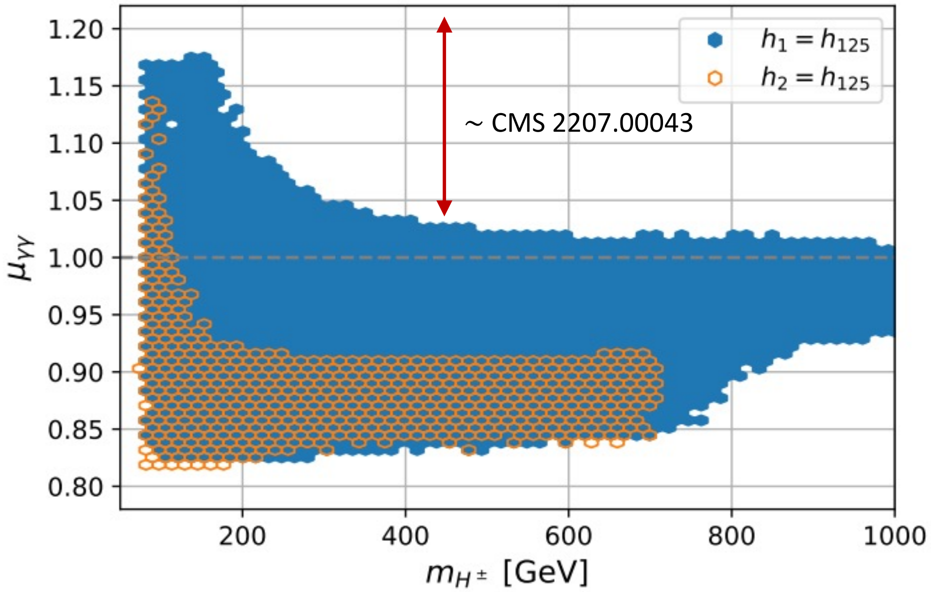

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Important interplay between different Higgs couplings!

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

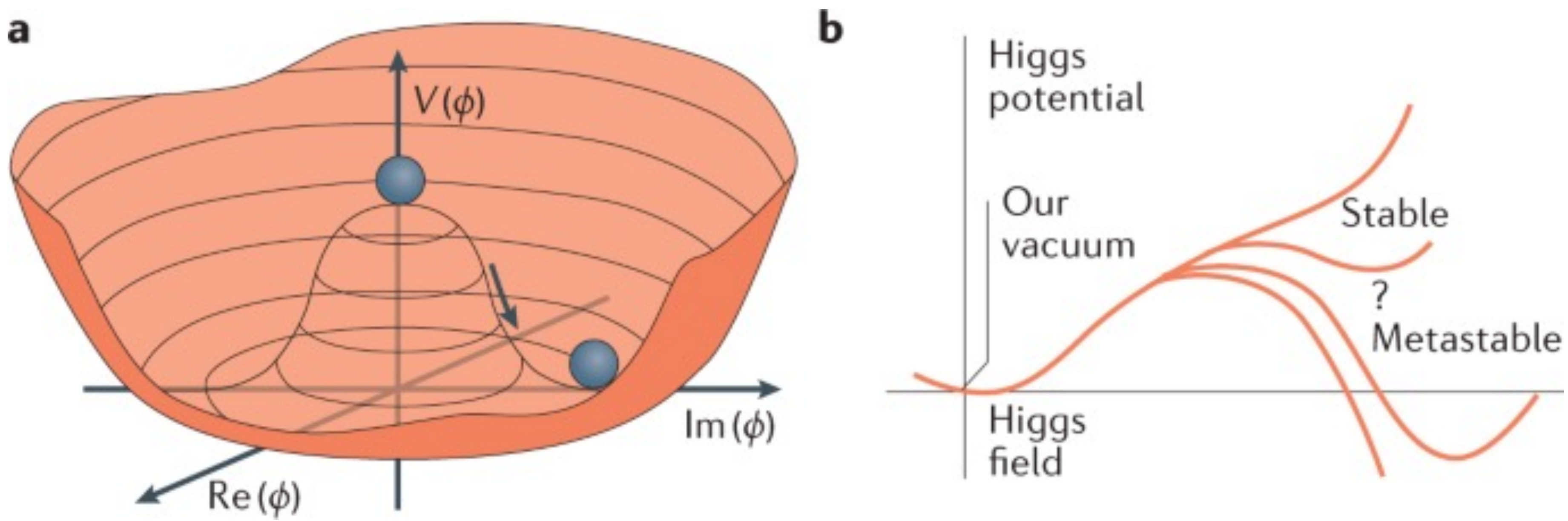
current status: 258 limits

HiggsSignals-3

current status: 131 measurements

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

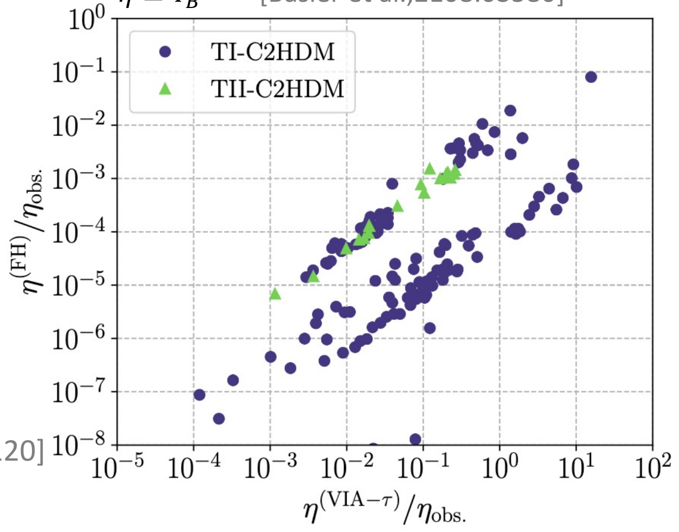
The stability of the Universe



But could we see a BSM effects first in the Higgs potential?

Baryon asymmetry of the Universe

$\eta \equiv Y_B$ [Basler et al.,2108.03580]



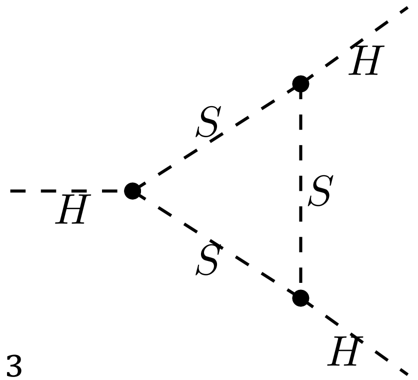
- Different techniques used in the literature to calculate BAU Y_B:
  - Vev-insertion approach (VIA),
    [Huet&Nelson,9504427,9506477;Carena et al., 9603420;Riotto, 9712221;Lee et al.,0412354;Postma et al.,2206.01120]
  - WKB (or FH) approximation.
    [Joecy et al.,9410282;Kainulainen et al.,0105295, 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

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

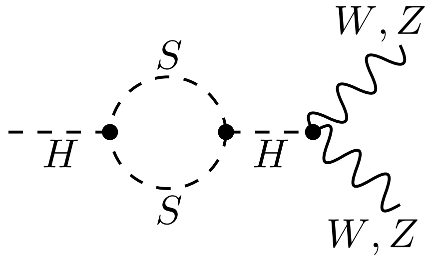


If S does not get a vev, $\lambda_{HHH} = \lambda_{HHH}^{\text{SM}}$ at the tree-level ($m_S^2 = \mu_S^2 + \lambda_{S\Phi} v^2$).

The 1L correction to λ_{HHH} scales like

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

whereas the dominant correction to other Higgs couplings scale like

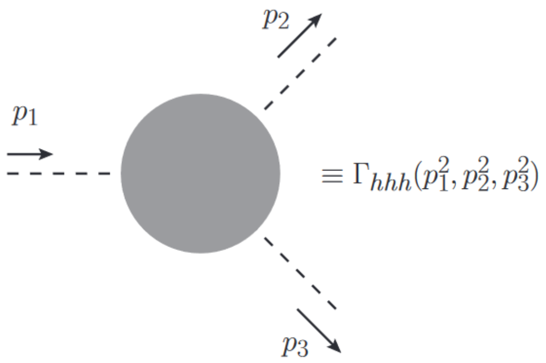


$$g^{1L} \propto \frac{g_{HSS}^2}{(4\pi)^2} B_0'(\dots) \cdot g_{\text{tree}} \propto \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2 \Rightarrow \kappa_g \equiv \frac{g}{g^{\text{SM}}} = 1 + \frac{1}{(4\pi)^2}\frac{m_S^2}{v^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^2$$

➡ 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!

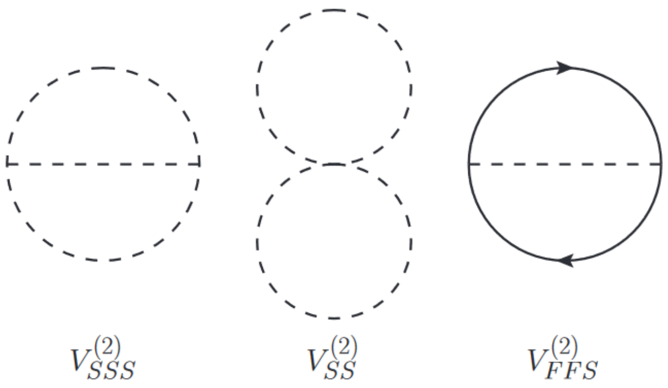
Calculating BSM corrections to κ_λ

- Need to calculate Higgs three-point function:



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

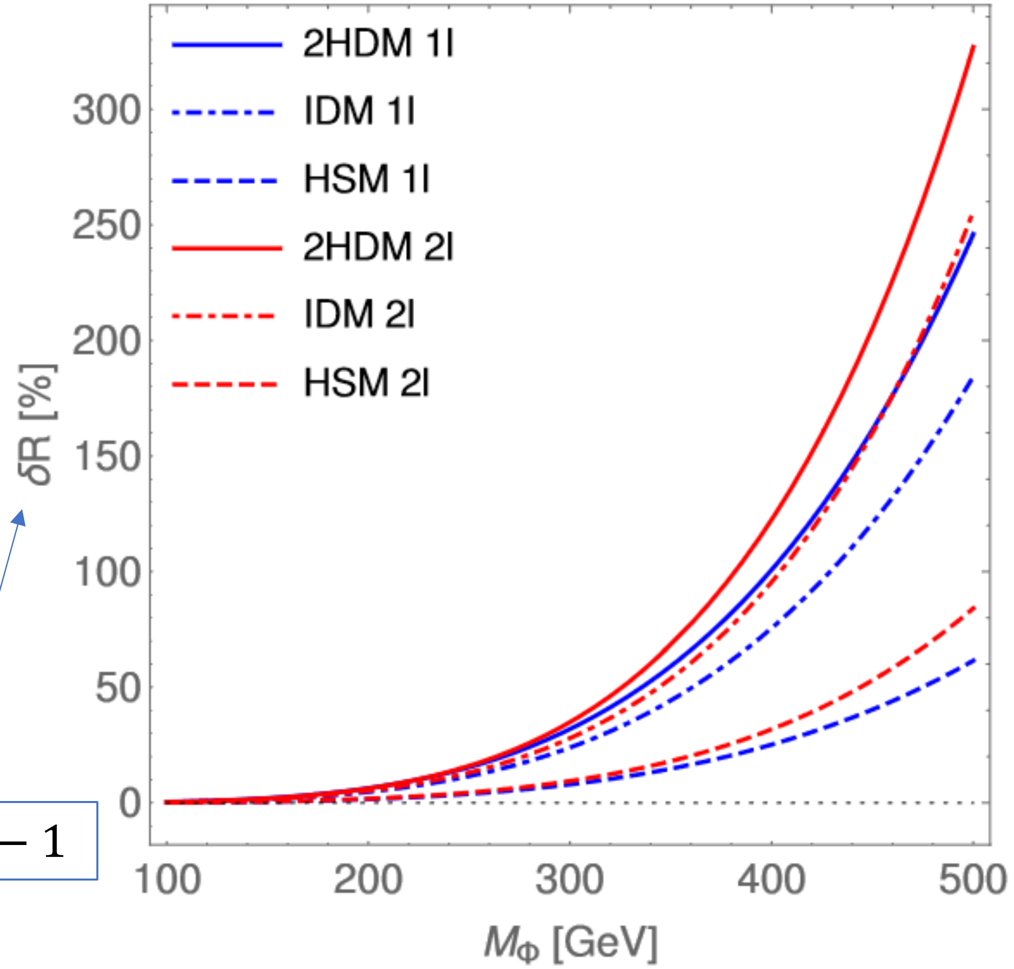
$$\lambda_{hhh} \equiv \left.\frac{\partial^3 V_{\text{eff}}}{\partial h^3}\right|_{\text{min}} \equiv \lambda_{hhh}^{(0)} + \kappa\delta^{(1)}\lambda_{hhh} + \kappa^2\delta^{(2)}\lambda_{hhh}$$



- 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:

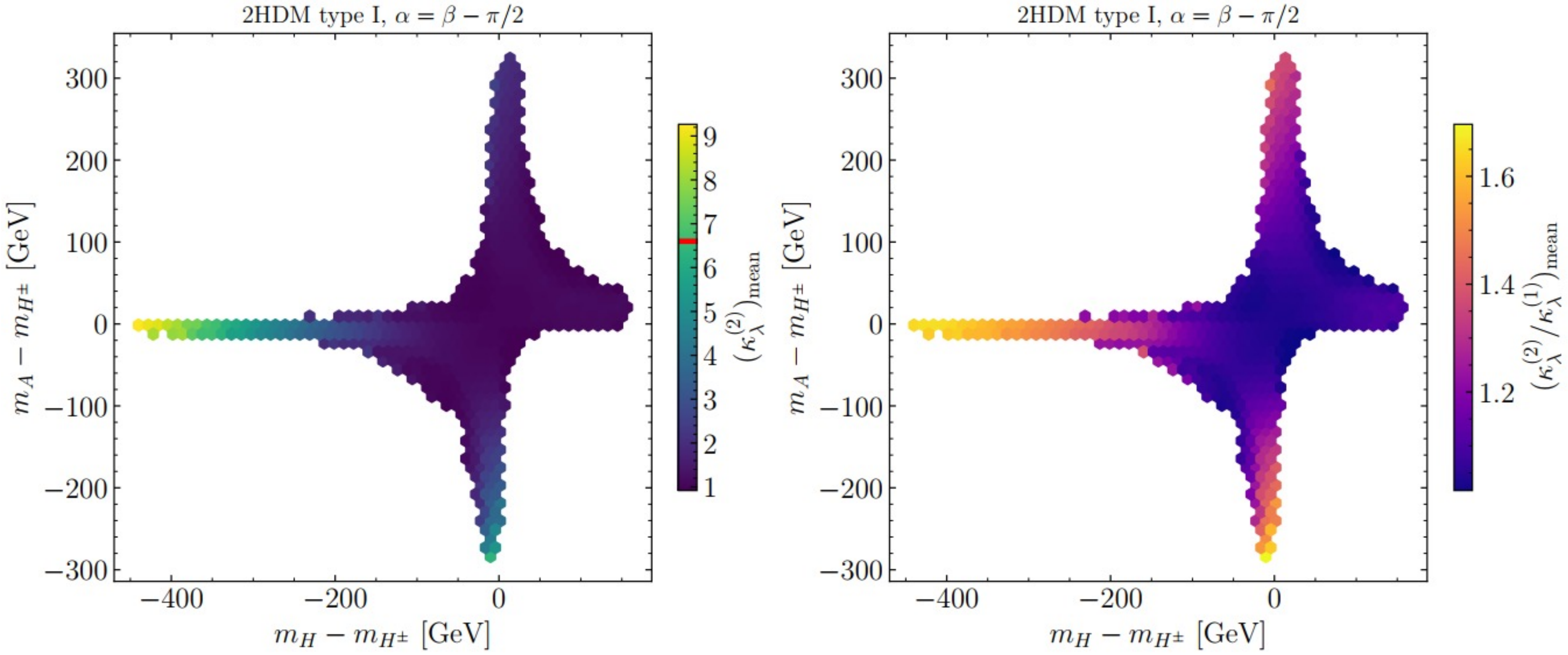
Can we constrain these models based on the large corrections to κ_λ?

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)

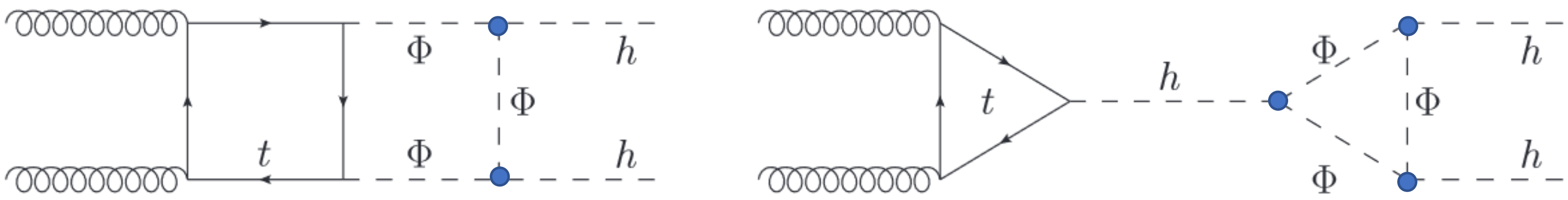


- Largest corrections for $m_A \simeq m_{H^\pm}$, $m_H < m_{H^\pm}$ and $m_H \simeq m_{H^\pm}$, $m_A < m_{H^\pm}$ (κ_λ of up to 9).
- 2L corrections have sizeable impact (up to 70%).

Can we apply the experimental constraints on κ_λ?

Assumptions of experimental bound:

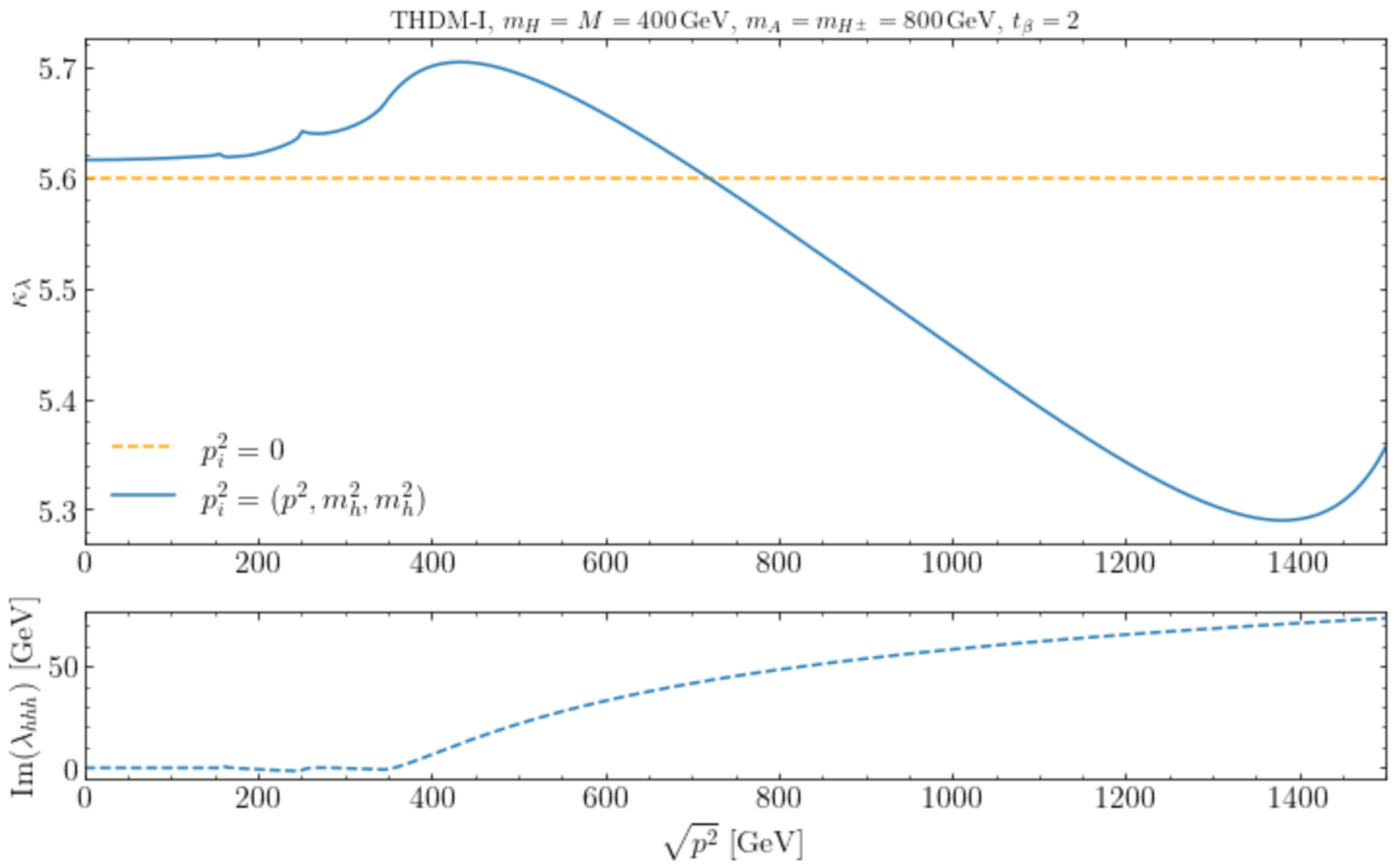
- All other Higgs couplings are SM-like.
  - ➢ 2HDM in the alignment limit with heavy BSM masses.
- Higgs-boson pair production only deviates from the SM via a modified trilinear Higgs coupling.
  - ➢ No resonant contribution because Hhh coupling is zero in alignment limit.
  - ➢ Other BSM contributions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

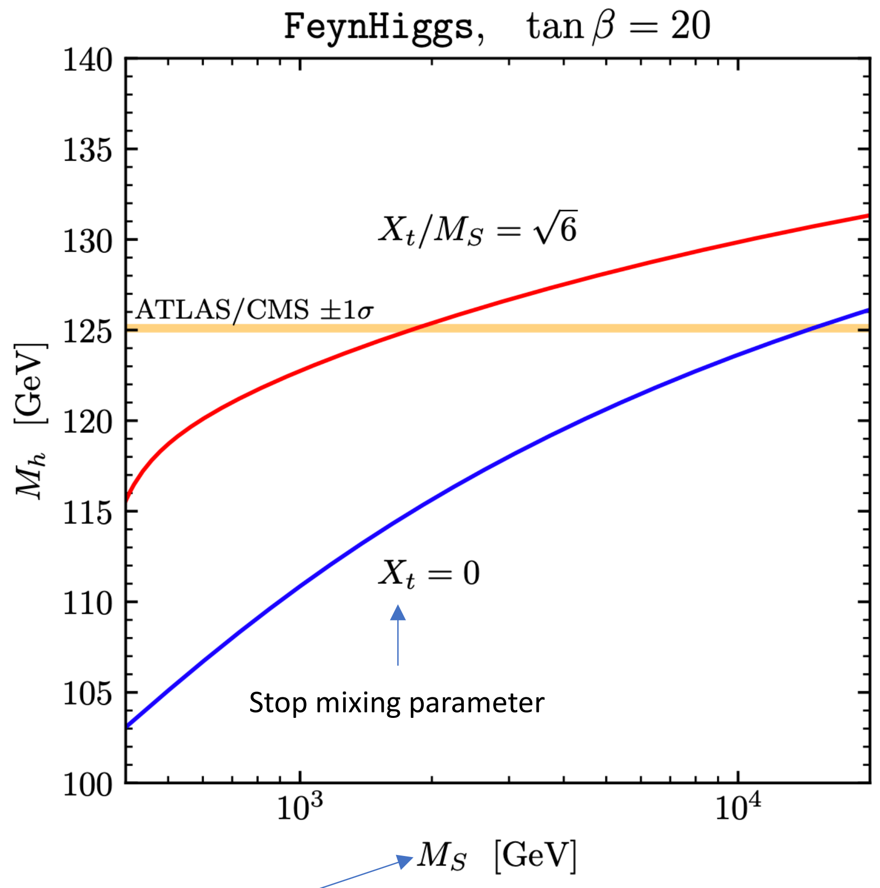
  - ➢ We include the all corrections leading in the large coupling $g_{hh\Phi\Phi}$ at the NLO and NNLO level.

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 $X_t/M_S = \sqrt{6}$)



Stop mass scale

[Slavich, HB et al., 2012.15629]