CP violation in the Higgs couplings and beyond

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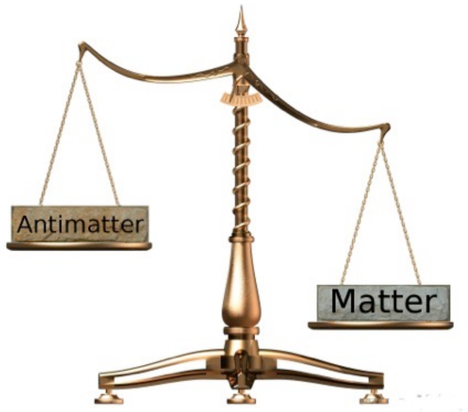
The 20th Workshop of the LHC Higgs WG, CERN, 13.11.23

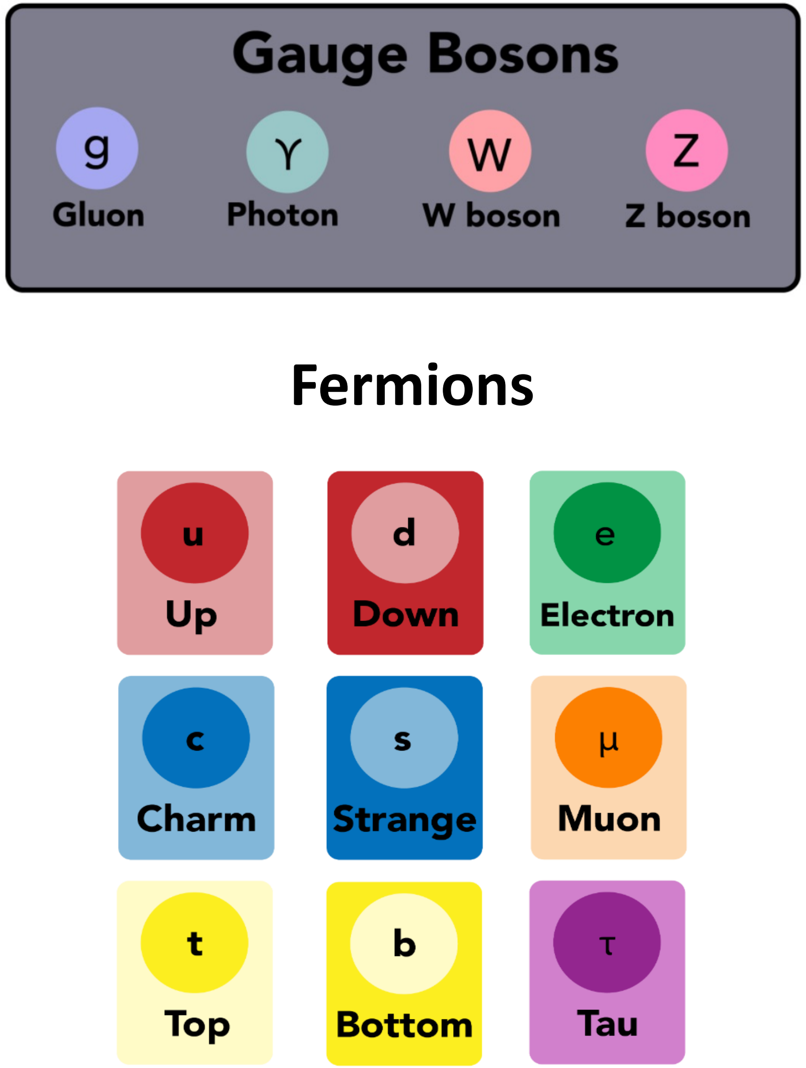
CP violation in the Higgs sector

- New sources of CP violation are necessary to explain the baryon asymmetry of the Universe.
- One possibility: CP violation in the Higgs sector.



Is the SM-like Higgs boson a CP-admixed state?

CP structure of Higgs couplings



- How can we constrain CP-violating couplings at the LHC?
  - Direct constraints: CP-odd observables.
  - Indirect constraints: CP-even observables.
  - Multivariate analyses: potentially mixing CP-odd and CP-even observables.

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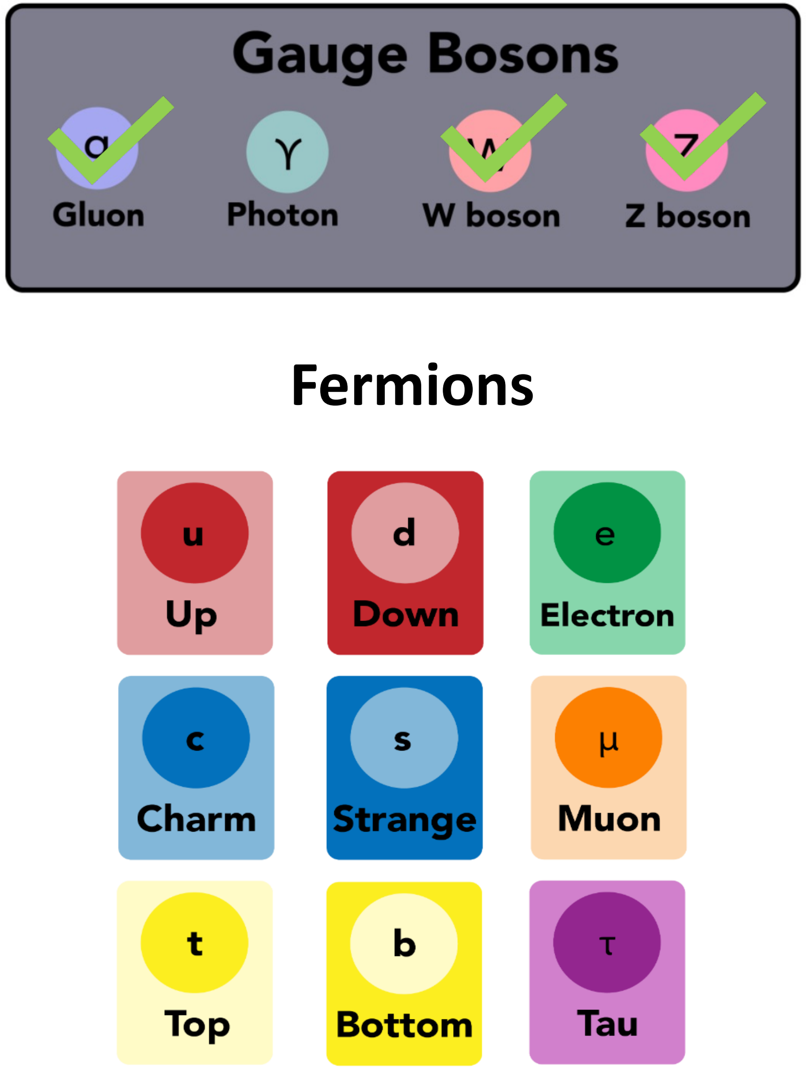

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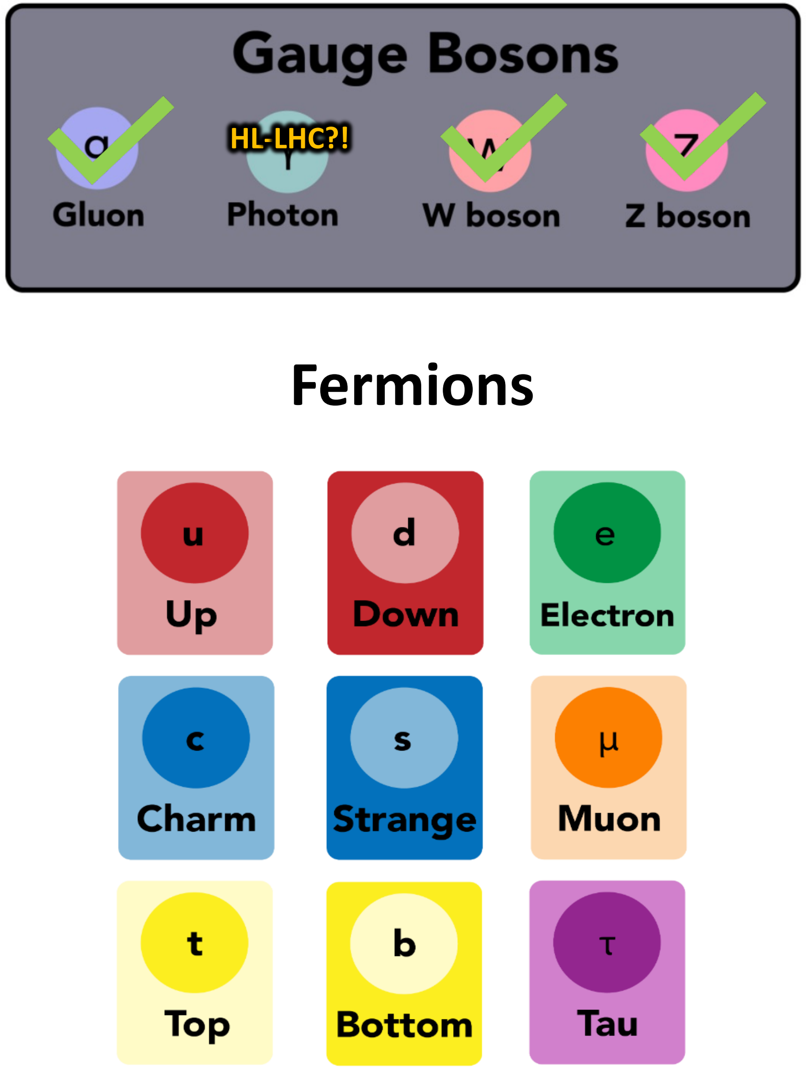

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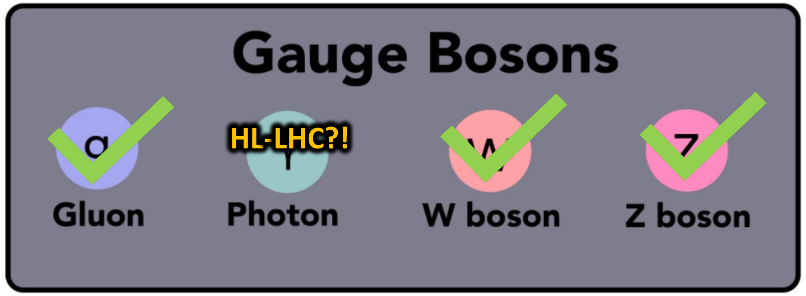

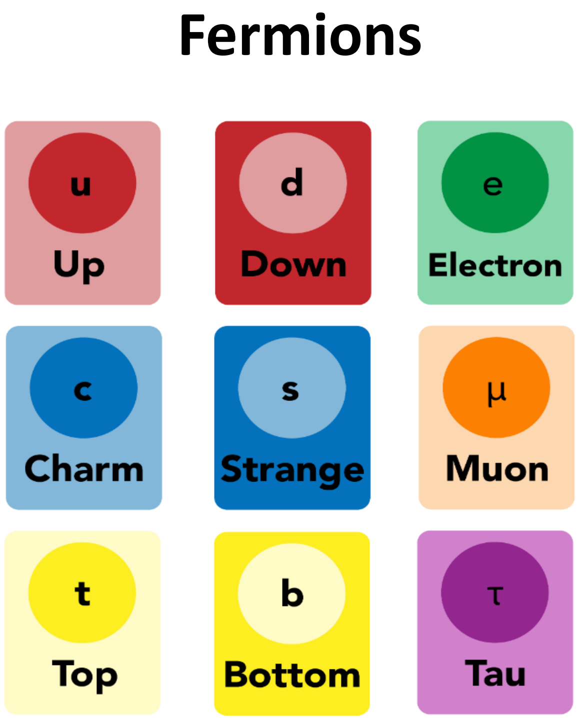

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$$\mathcal{L}_{\text{yuk}} = -\sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f}\left(c_f + i\gamma_5 \tilde{c}_f\right) f H,$$

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

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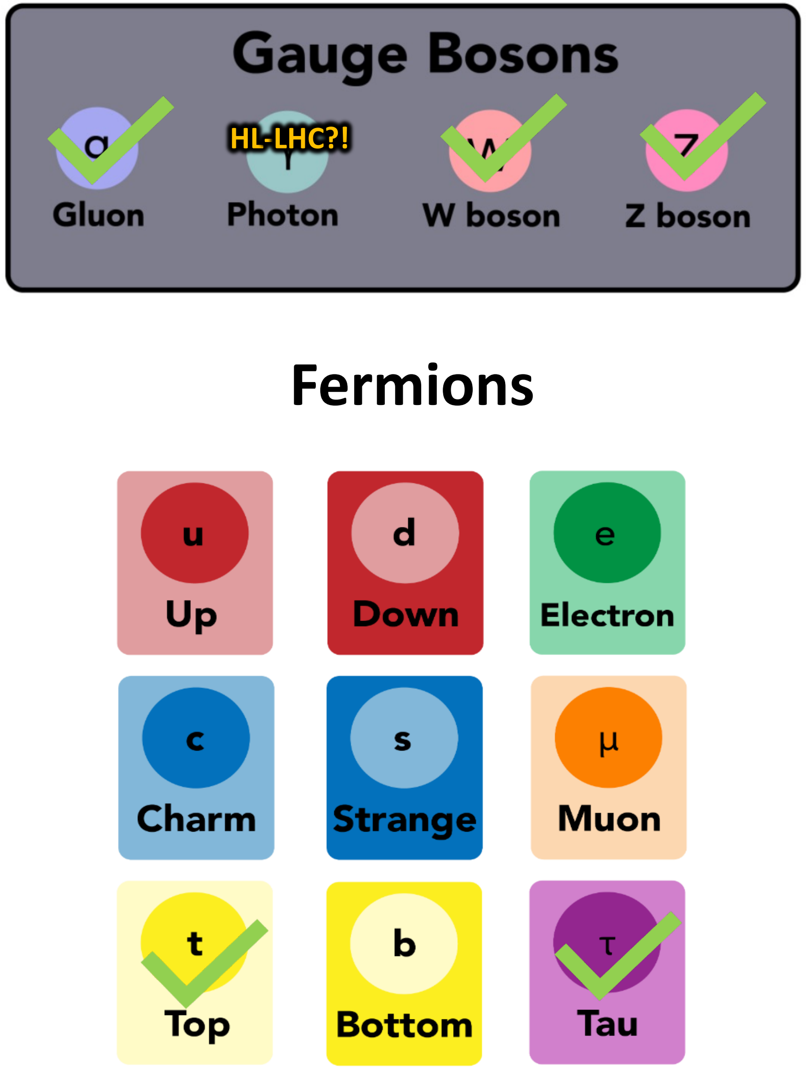

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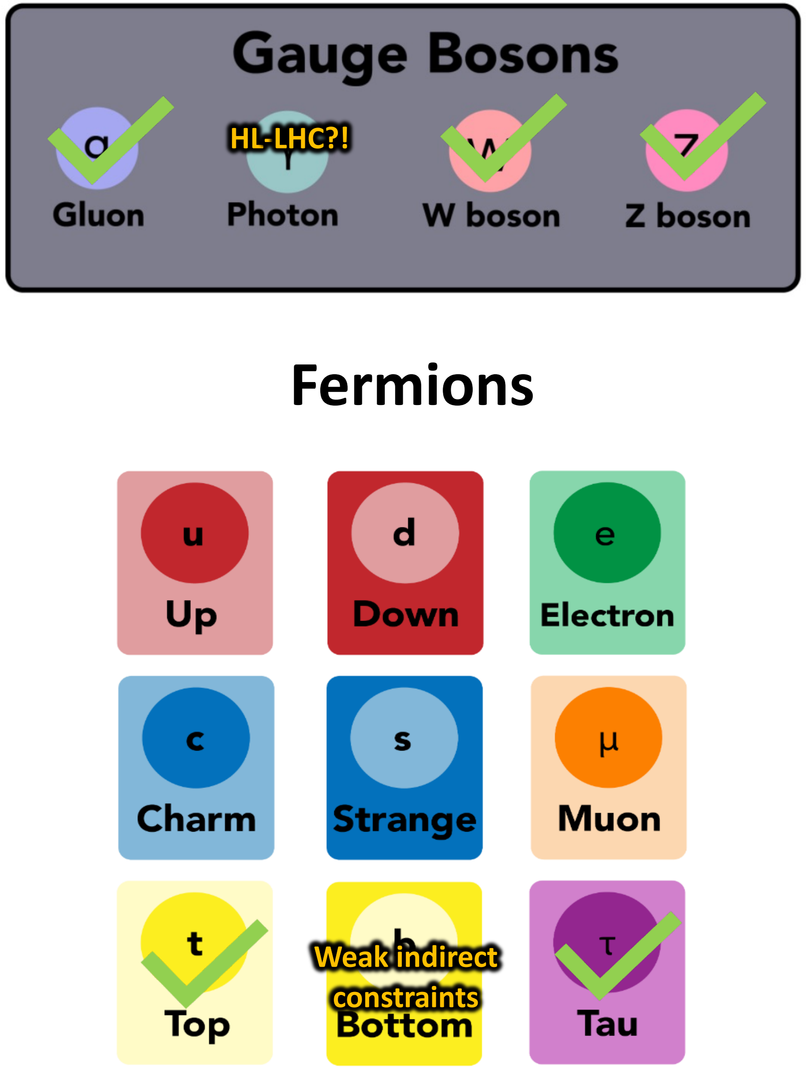

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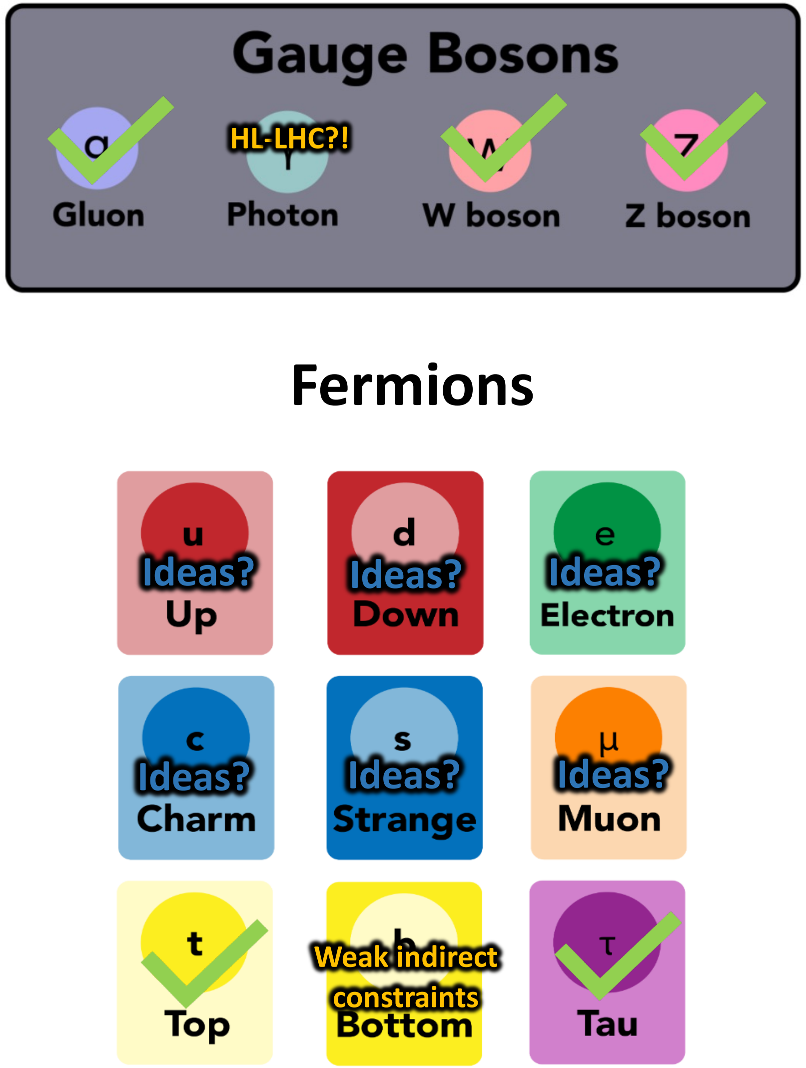

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Current status and future outlook

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~1	✓	–	–	–	~1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

Limits set on: $f_{CP}^{HX} \equiv \frac{\Gamma_{H\to X}^{CP\,\mathrm{odd}}}{\Gamma_{H\to X}^{CP\,\mathrm{odd}} + \Gamma_{H\to X}^{CP\,\mathrm{even}}}$

On-going activities

Higgs CP

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New observables/STXS extension
(→ Wednesday talk)

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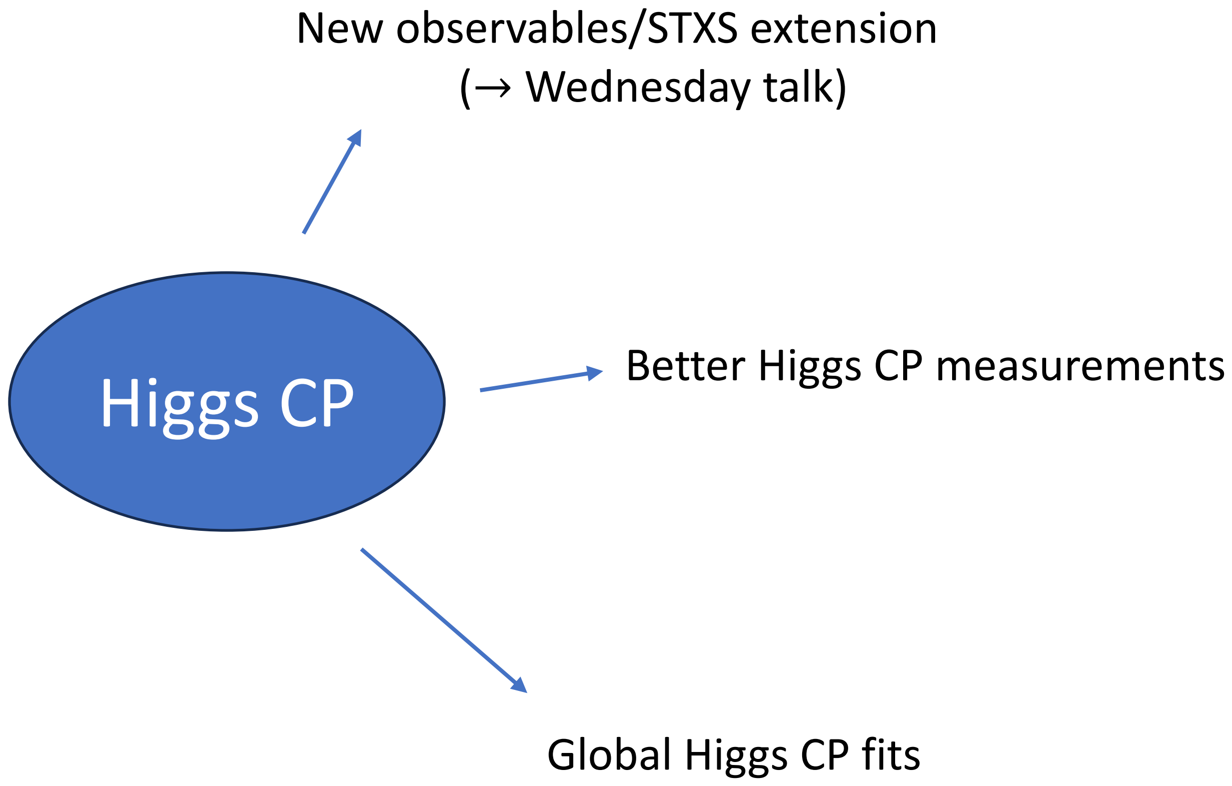
Higgs CP

Better Higgs CP measurements

On-going activities



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Better Higgs CP measurements

Global Higgs CP fits

Interplay with EDM measurements

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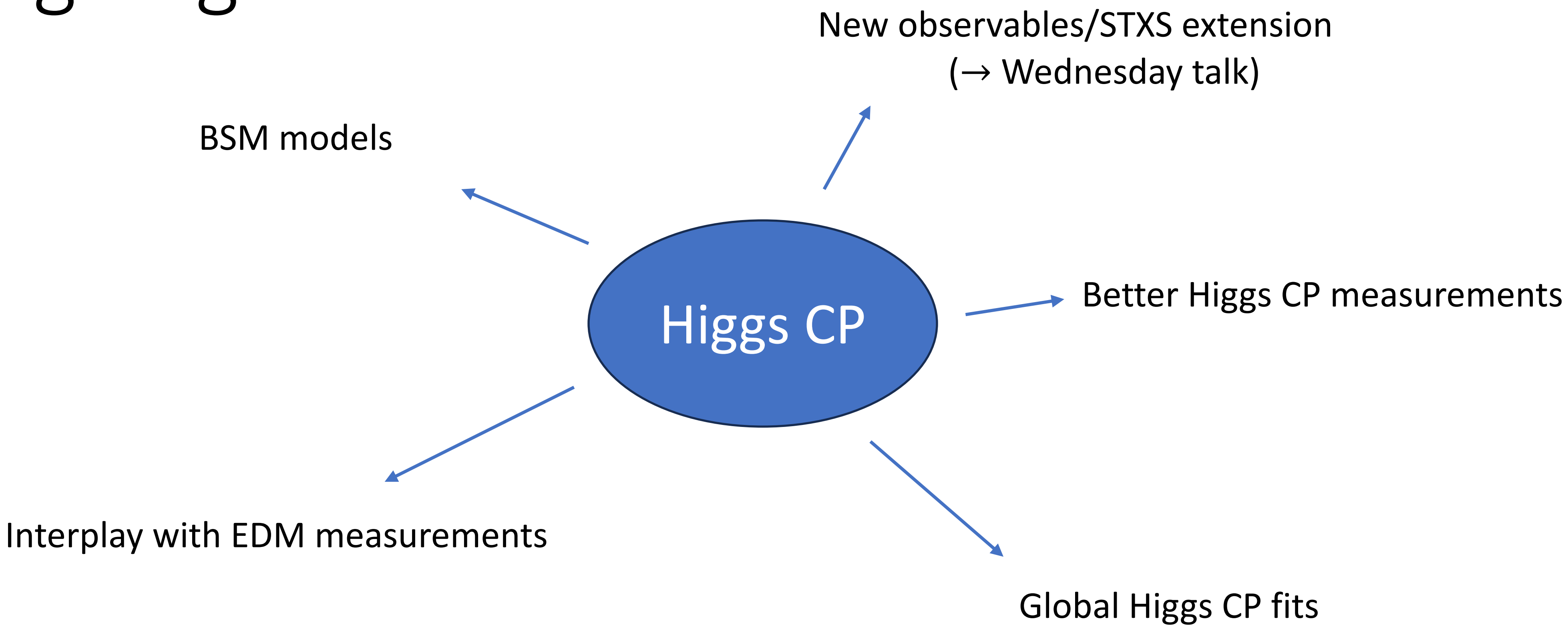

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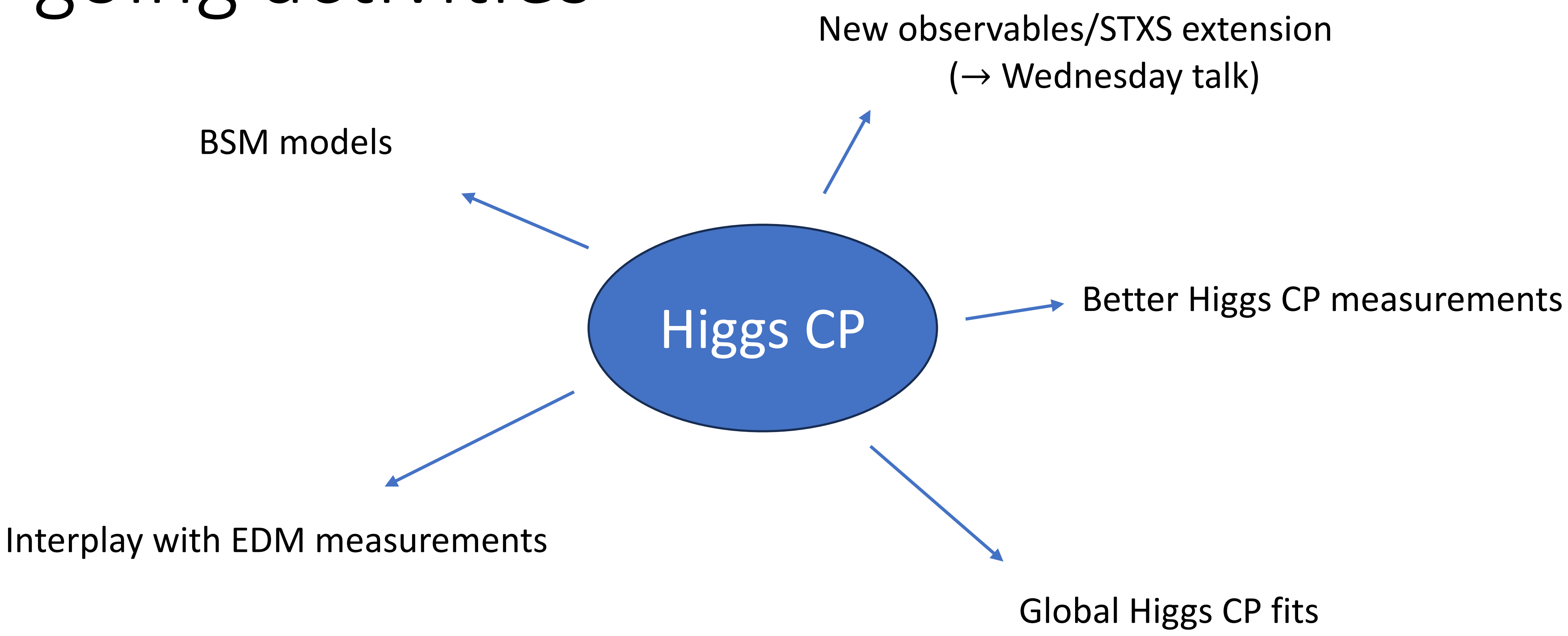

- 11.1.23: WG2+WG3 joint meeting on CPV in Higgs sector
- 21.4.23: WG2 ttH CPV meeting
- 26.9.23: WG2+WG3 joint meeting on CPV in Higgs sector
- 27.9.23: WG2 ttH CPV meeting

Better Higgs CP measurements

Exploiting the full kinematic information

Improving Higgs CP measurements

General amplitude structure for CP measurements:

$$|\mathcal{M}|^2 = c_{\text{even}}^2 \left|\mathcal{M}^{\text{CP-even}}\right|^2 + \underbrace{2c_{\text{even}}c_{\text{odd}}\text{Re}[\mathcal{M}^{\text{CP-even}}\mathcal{M}^{\text{CP-odd}^*}]}_{\text{interference}} + c_{\text{odd}}^2 \left|\mathcal{M}^{\text{CP-odd}}\right|^2$$

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CP can be tested either by:

- Distinguishing $\left|\mathcal{M}^{\text{CP-even}}\right|^2$ from $\left|\mathcal{M}^{\text{CP-odd}}\right|^2$ → CP-even observables.
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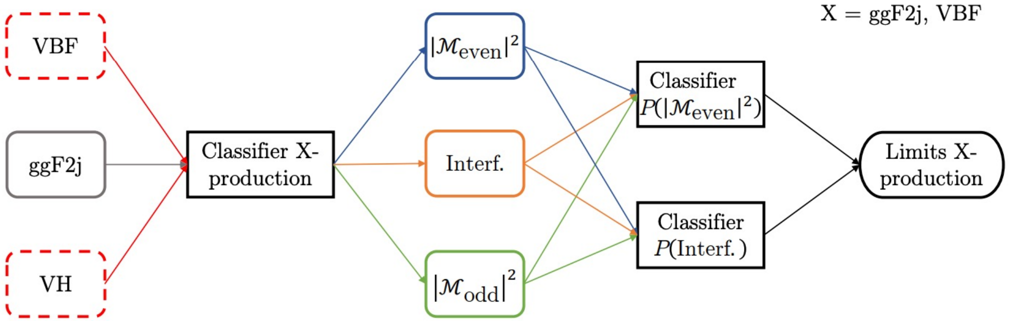
➡ Higgs CP has become a testing ground for new analysis ideas/methods!

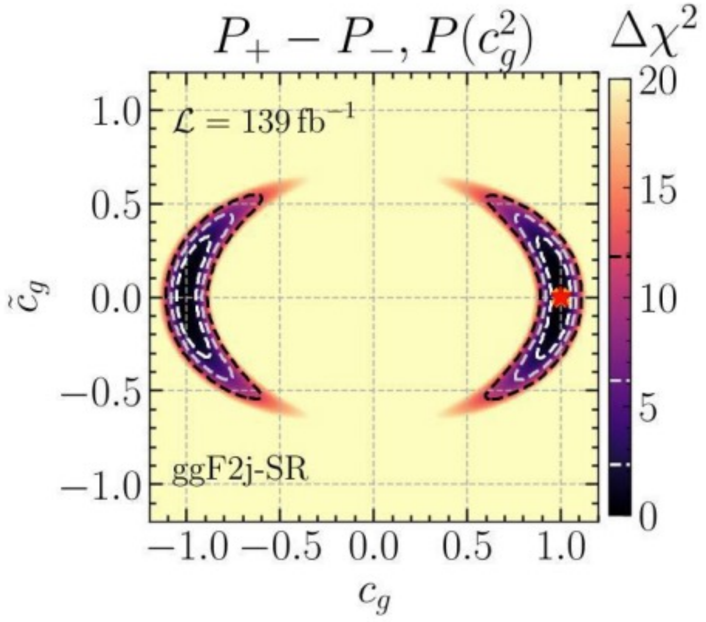
Classifying the CP properties of the ggH coupling in H+2j production

[HB,Fuchs,Hannig,Menen,2309.03146]



Train two classifiers to define optimal CP-even and CP-odd observables

[see also Gritsan et al. 1606.03107, Bhardwaj et al., 2112.05052]



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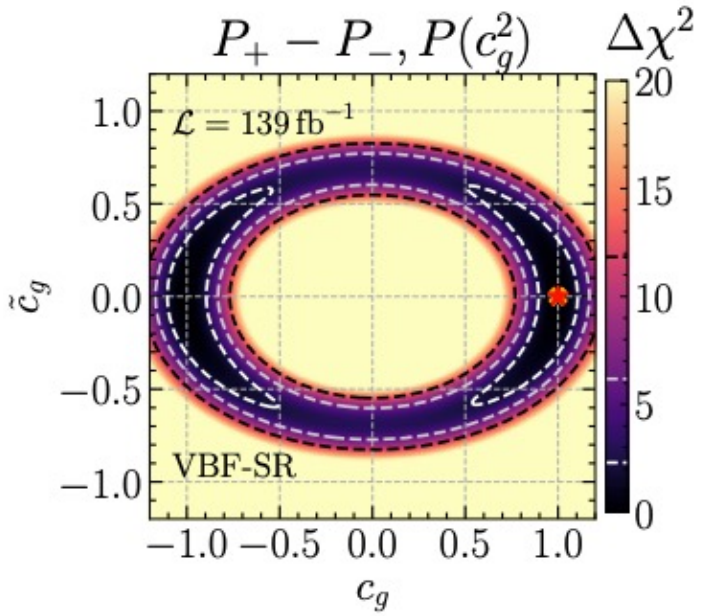

Dedicated ggF2j signal region could help to strengthen limits on CPV in ggH coupling!

Simulation-based inference

[Brehmer et al.,1906.01578,1805.12244,1805.00013,1805.00020,1808.00973,1907.10621]

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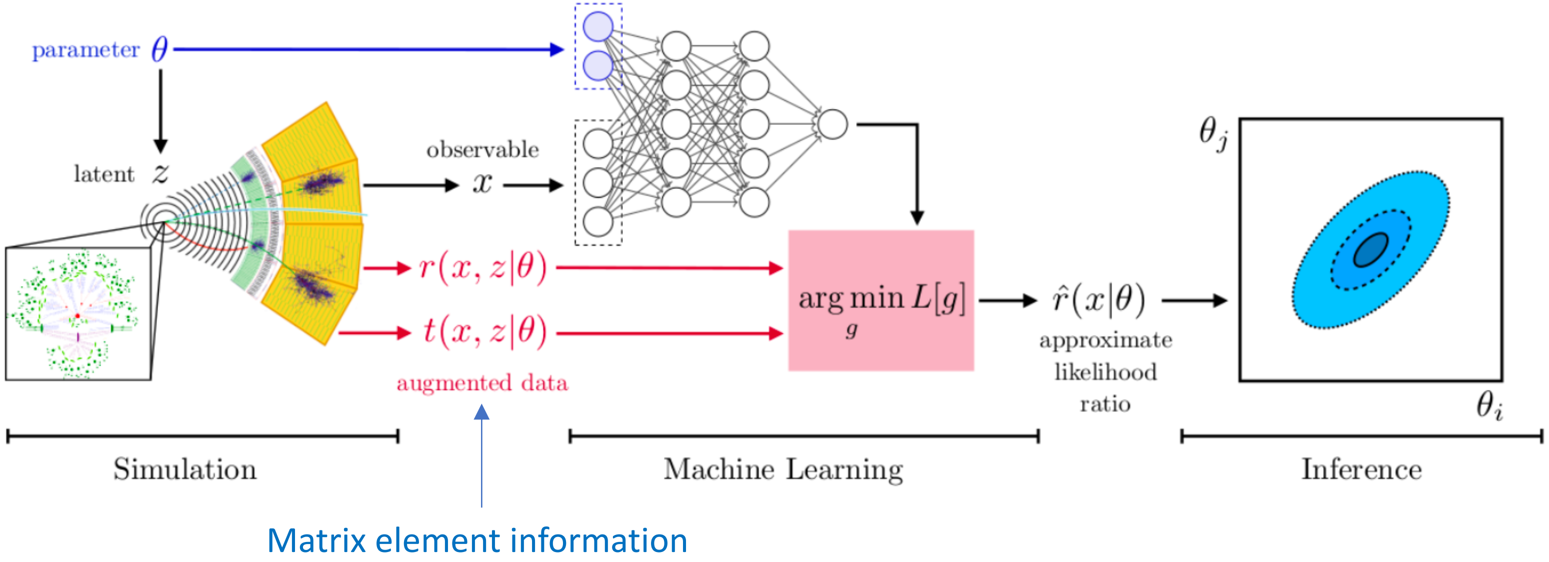

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- No information loss due to binning (as for BDT analysis).
- No approximation of shower and detector effects

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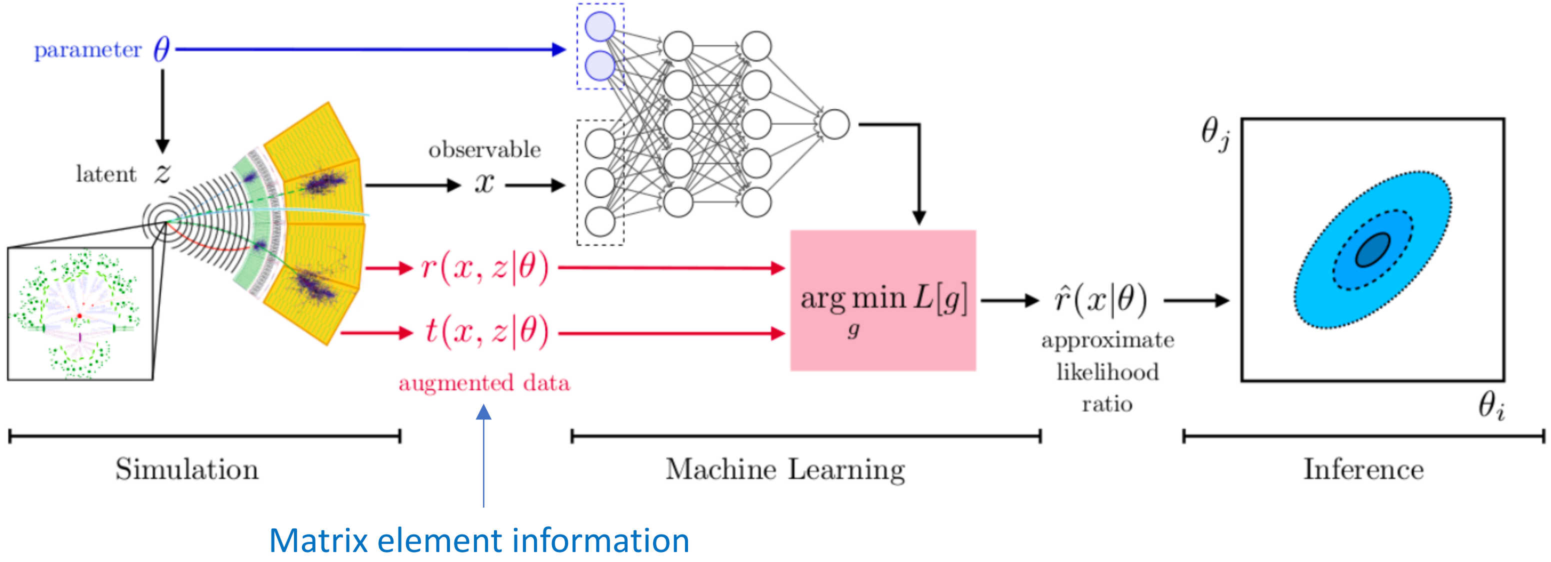

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Example applications:

- $t\bar{t}H \rightarrow \sim$ 35% better limits on CP phase than from 2D histogram.
  [Barman et al.,2110.07635;HB & Brass 2110.10177]
- $WH \rightarrow$ ~25% better limits on $c_{\tilde{H}W}$ than from 2D histogram [Barrue et al., 2308.02882]

Global Higgs CP fits

Interplay between different couplings

“Global” ttH CPV fit

Most studies so-far concentrate on fitting CP character of a single Higgs coupling, e.g.

$$\mathcal{L}_{\text{top-Yuk}} = -\frac{y_t^{\text{SM}}}{\sqrt{2}}\bar{t}(c_t + i\gamma_5\tilde{c}_t)tH$$

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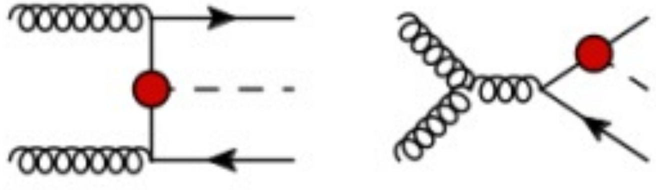
[Maltoni,Vryonidou,Zhang,1607.05330]



In SMEFT, this coupling can be generated by rewriting:

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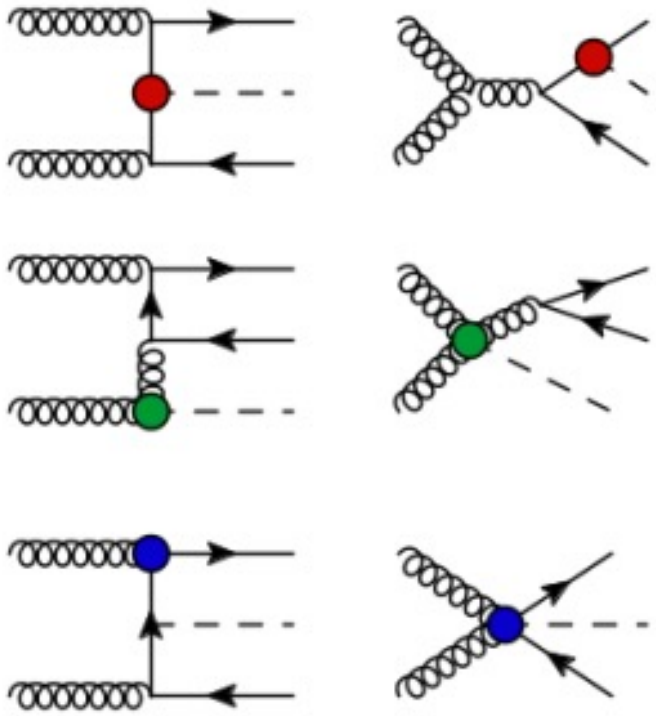

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There are, however, further “Higgs” operators which contribute to e.g. $t\bar{t}H$:

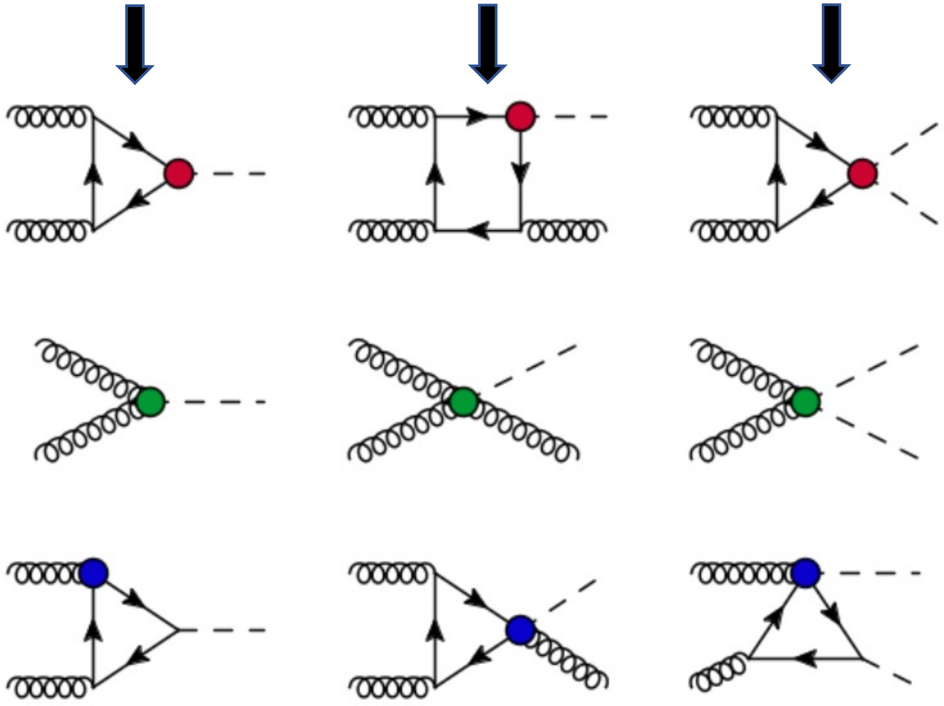
- $O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$,

- $O_{\phi G} = (\phi^\dagger\phi)\left(G^A_{\mu\nu}G^{A\mu\nu}\right)$,
  $O_{\phi\tilde{G}} = (\phi^\dagger\phi)\left(G^A_{\mu\nu}\tilde{G}^{A\mu\nu}\right)$.

Interplay of the different operators not well understood if CPV is present.

Correlation with other Higgs channels

$gg \to H$ $\quad$ $gg \to Hj(+Hjj)$ $\quad$ $gg \to HH$



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(+ interplay with bottom Yukawa etc.)

[see e.g. HB et al.,]

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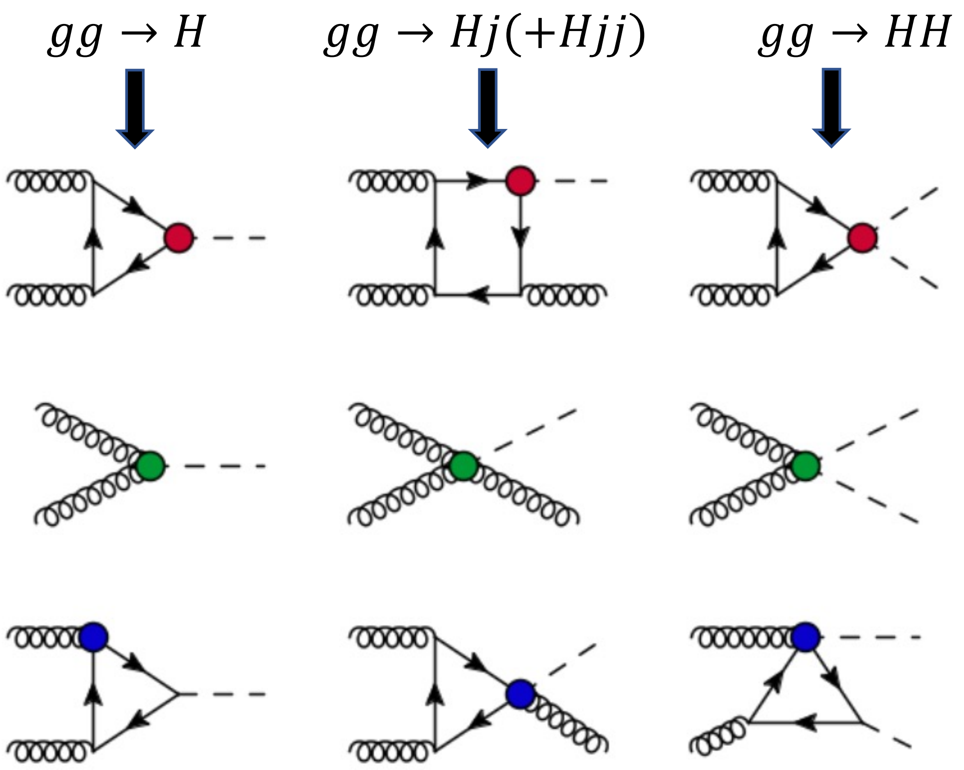

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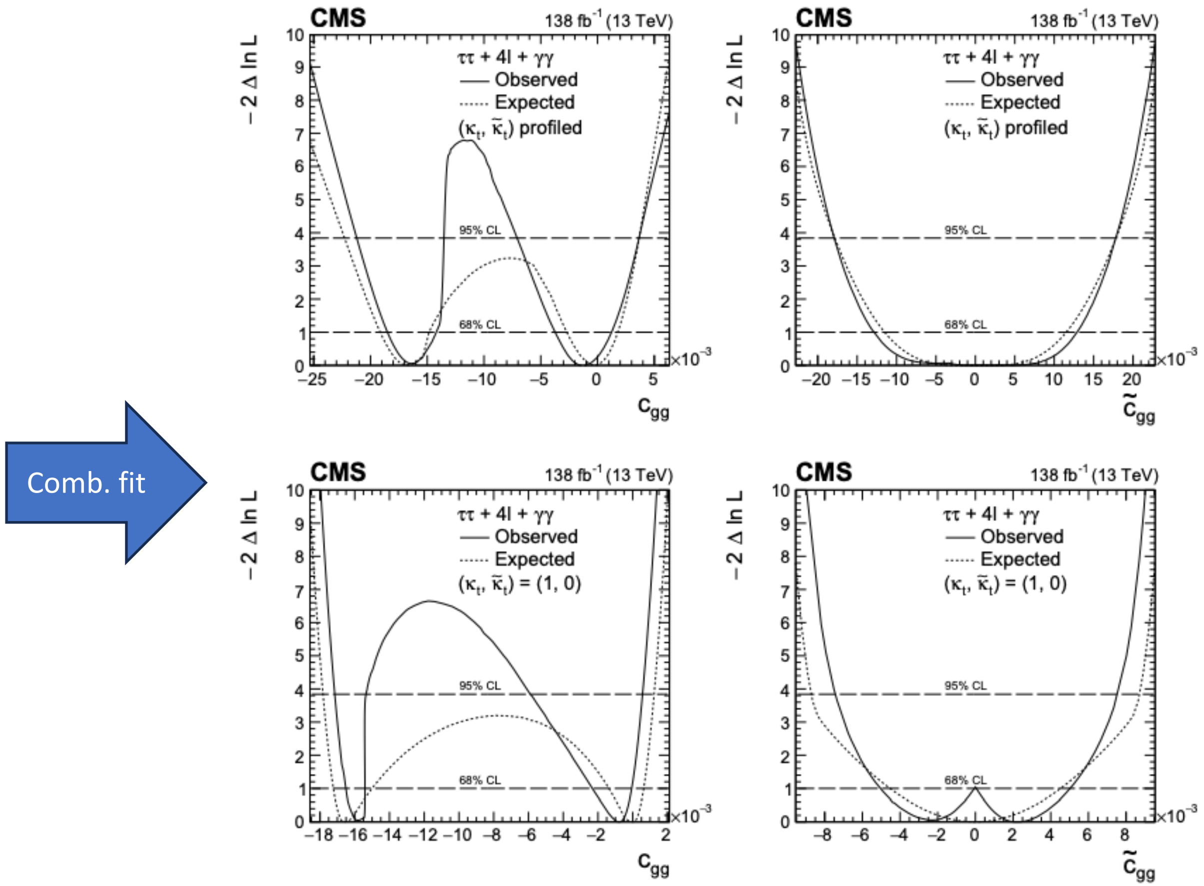

[CMS, 2205.05120]

→ Would be great to get full likelihood information!

CP dependence via EW NLO corrections

- With increased precision, electroweak NLO corrections become important.
- EW NLO corrections often depend on Higgs CP nature.

→ ”Background” processes become CP sensitive.

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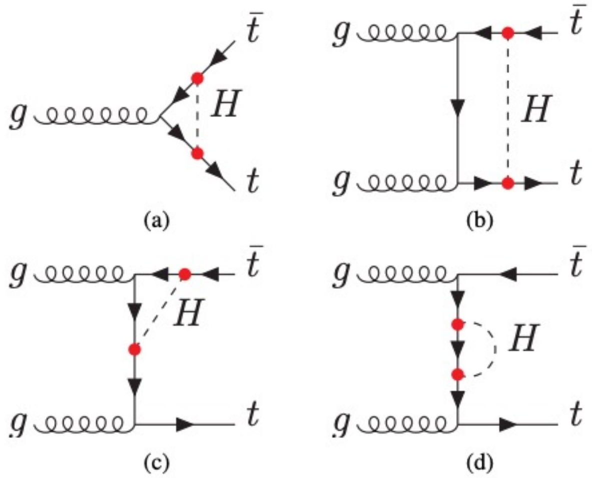

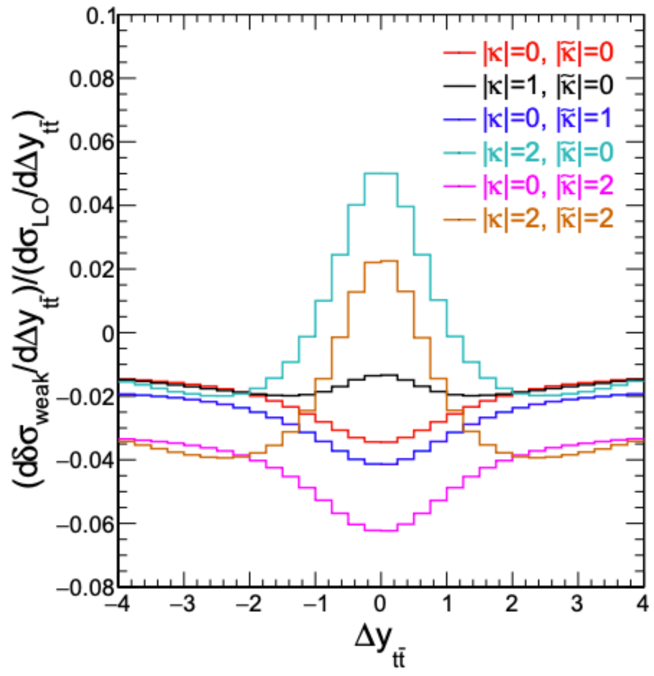

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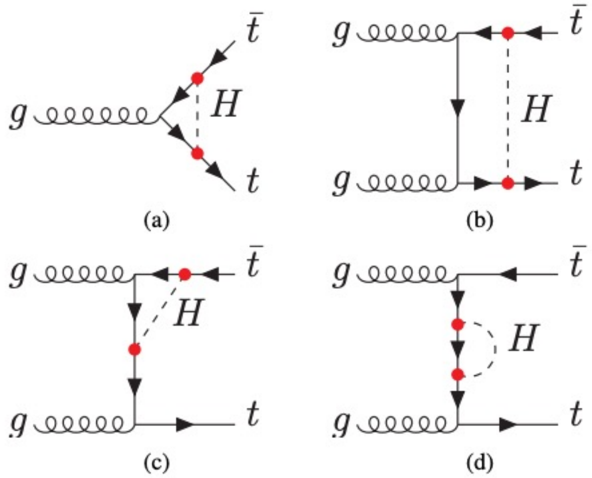
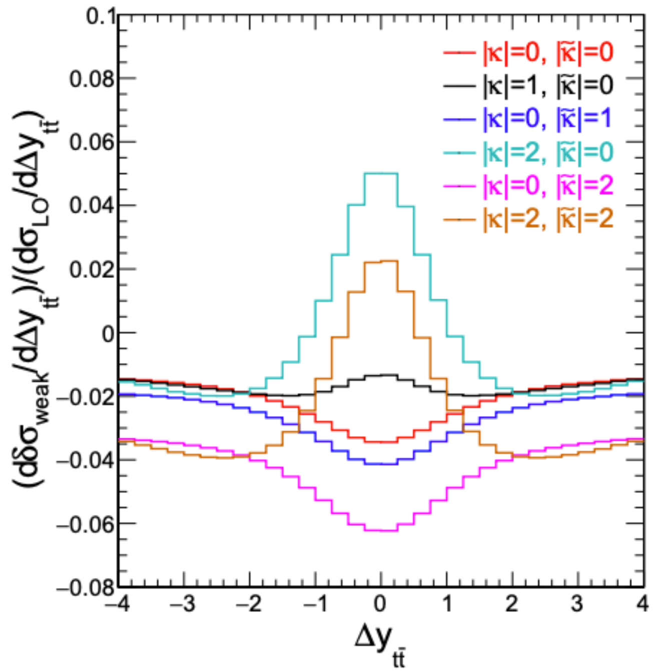
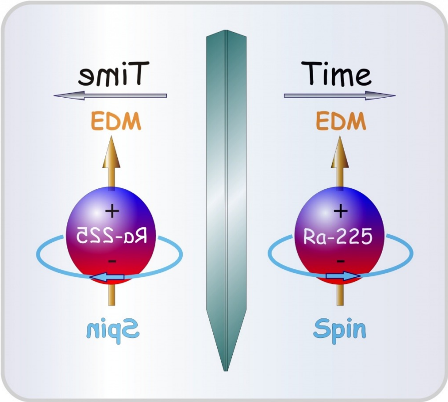




Could become a significant complication of future studies.



EDM constraints

and the importance of the LHC

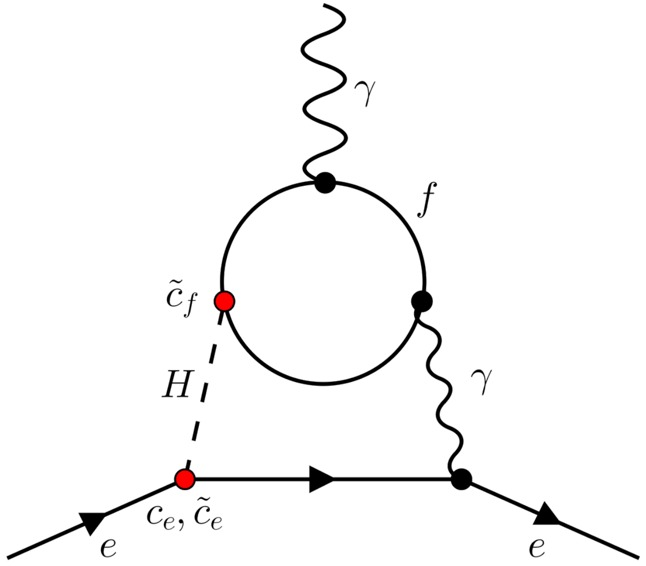
Complementarity with EDM constraints

- Several EDMs are sensitive to CP violation in the Higgs sector via 2L Bar-Zee diagrams.

- Bounds strongly depend on assumptions about
  - first-generation Yukawa coupling,
  - absence of other CP-violating BSM physics.

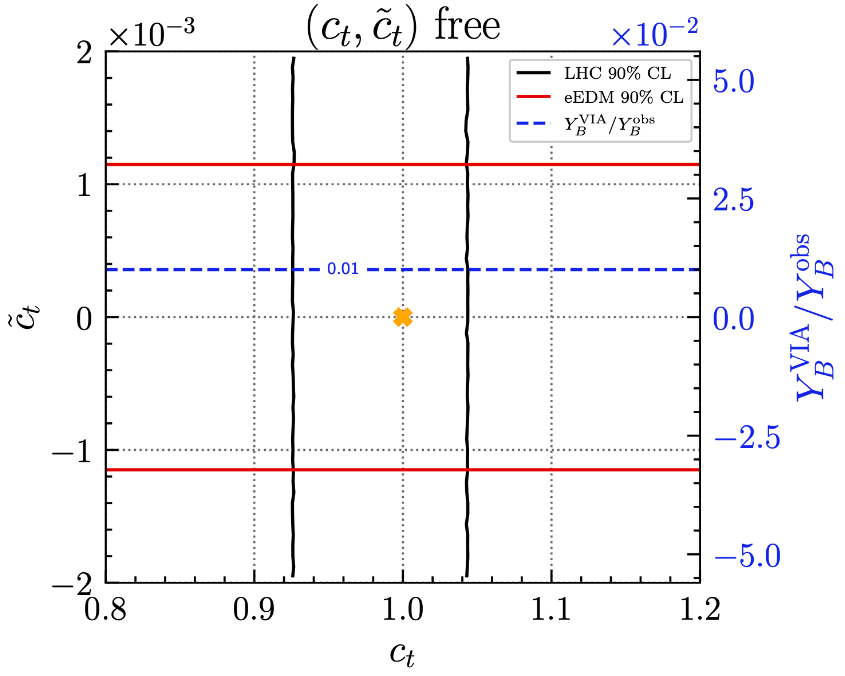
- Significant increase in precision expected within the next years! (see e.g. [Snowmass report, 2203.08103])

- Evaluation of NLO corrections will become necessary. (see e.g. [Brod et al., 2306.12478])



t and τ Yukawas: EDM and LHC complementarity

[HB et al., 2202.11753; see also Brod et al., 2203.03736]



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

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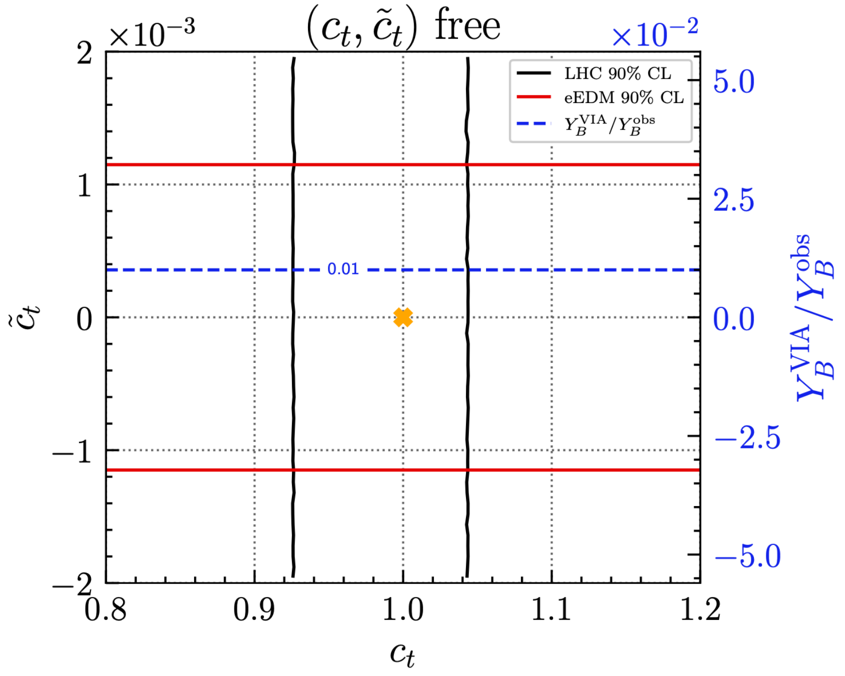

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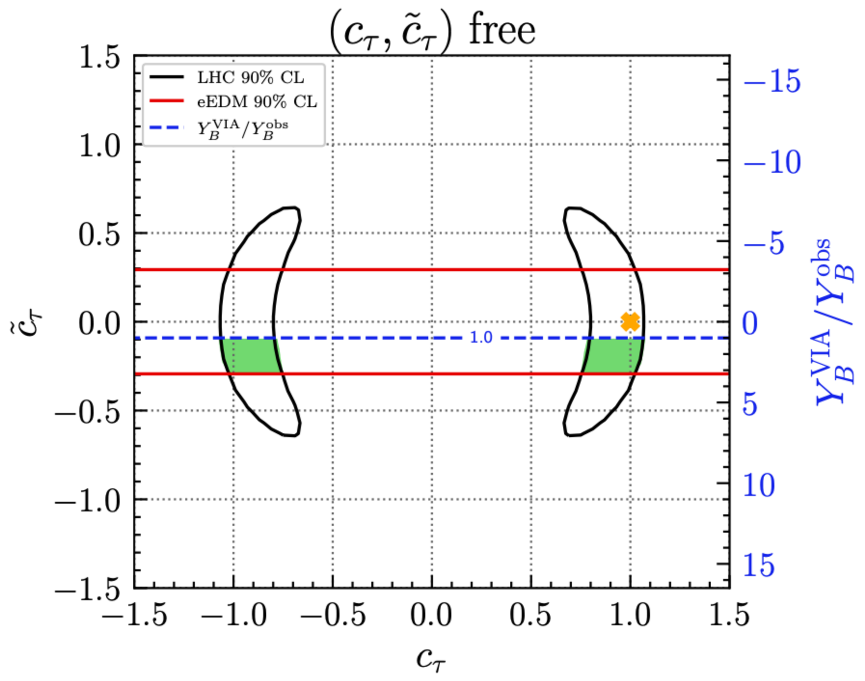

CP-odd τ coupling can potentially give sizeable contribution to baryon asymmetry.

EDM > LHC?

[Fuchs et al.,1911.08495;HB et al., 2202.11753]

EDM > LHC? **No.**

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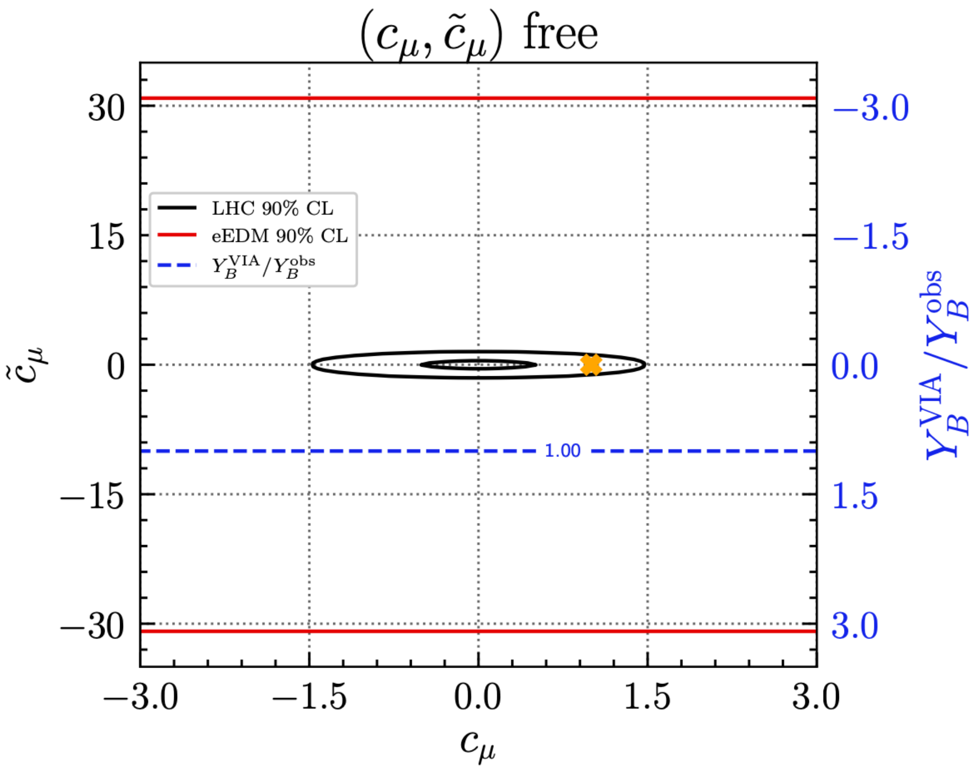
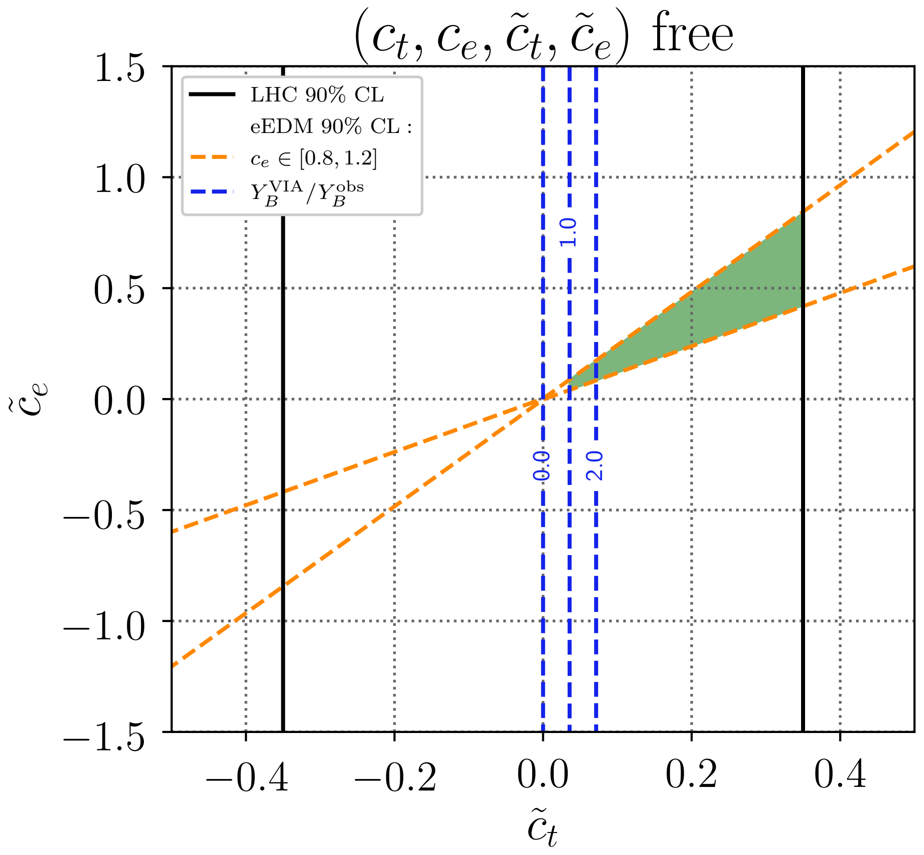


CP-insensitive $H \to \mu^+\mu^-$ rate measurement outperforms EDM constraint.

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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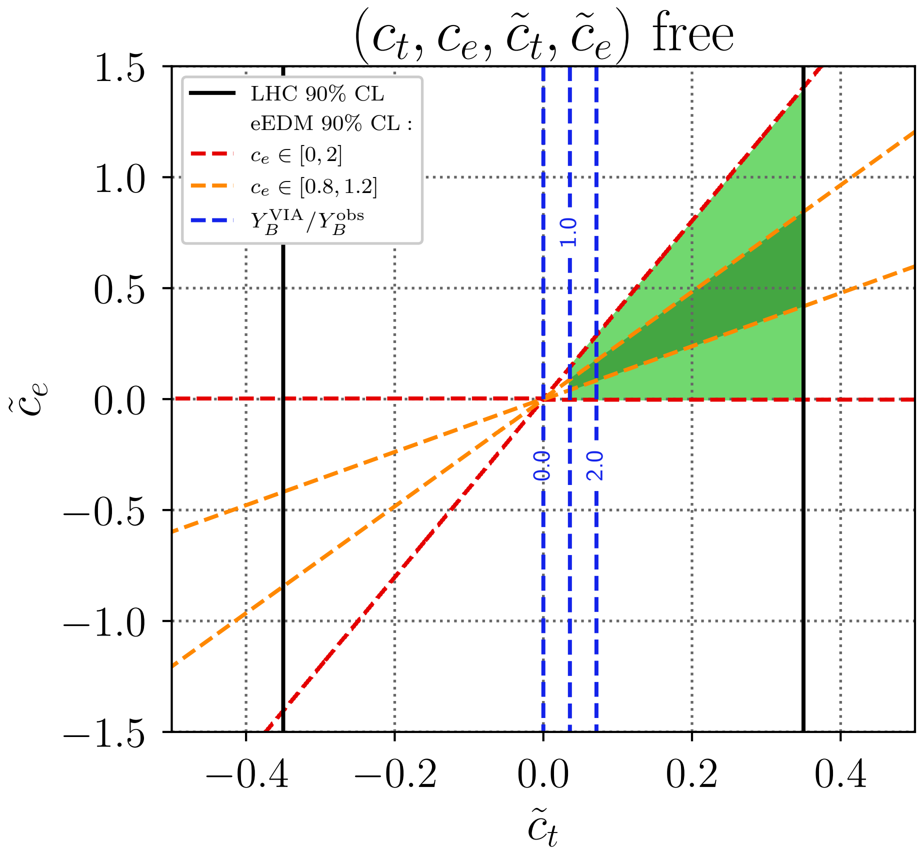
[HB et al.,2202.11753]



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- If c_e smaller, eEDM significantly weakened.
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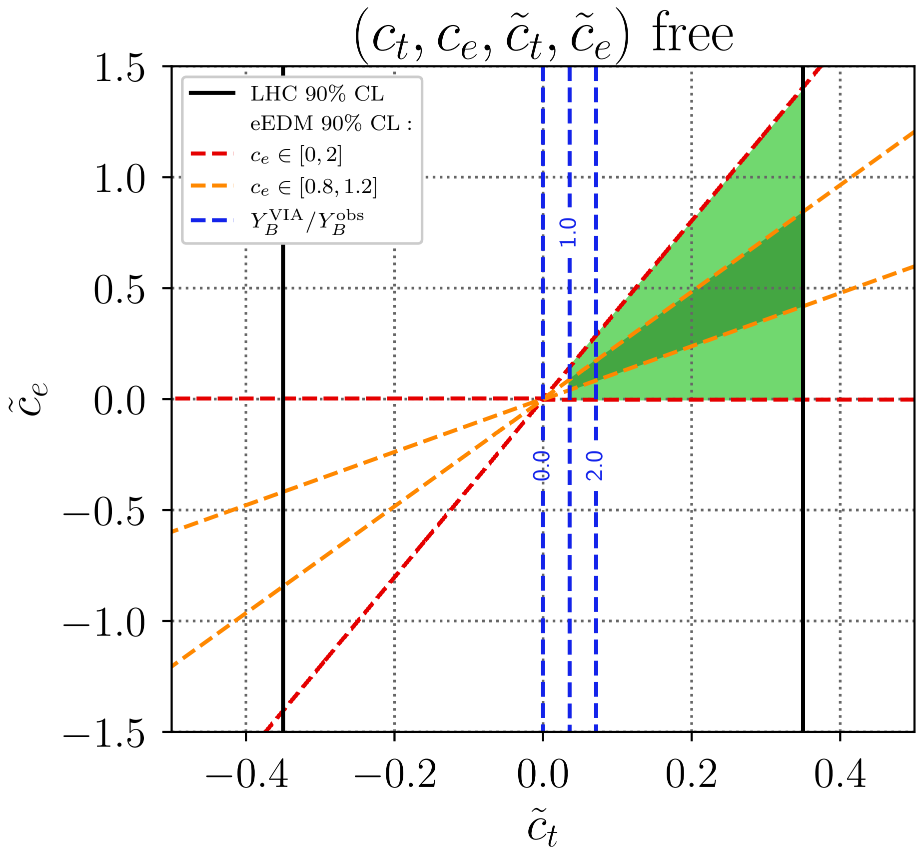
- Neutron EDM has similar dependence on first-generation quark-Yukawa couplings.

Dependence on electron-Yukawa coupling

[HB et al.,2202.11753]



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

BSM models

BSM scenarios for Higgs CP violation

- $\mathcal{O}(1)$ CP-odd Yukawa couplings require new physics to show up at $\mathcal{O}(\text{few } 100)$ GeV.
- Most studied model: **complex 2HDM** with mixing between two CP-even and one CP-odd Higgs boson.

$$\frac{\mathcal{M}^2}{v^2} = \begin{pmatrix} Z_1 & \mathrm{Re}(Z_6) & \boxed{-\mathrm{Im}(Z_6)} \\ & Y_2/v^2 + \frac{1}{2}Z_{345}^+ & -\frac{1}{2}\mathrm{Im}(Z_5) \\ & & Y_2/v^2 + \frac{1}{2}Z_{345}^- \end{pmatrix}$$

CP-odd h_{125} couplings $\Rightarrow$ also CP-even h_{125} couplings deviate from SM.

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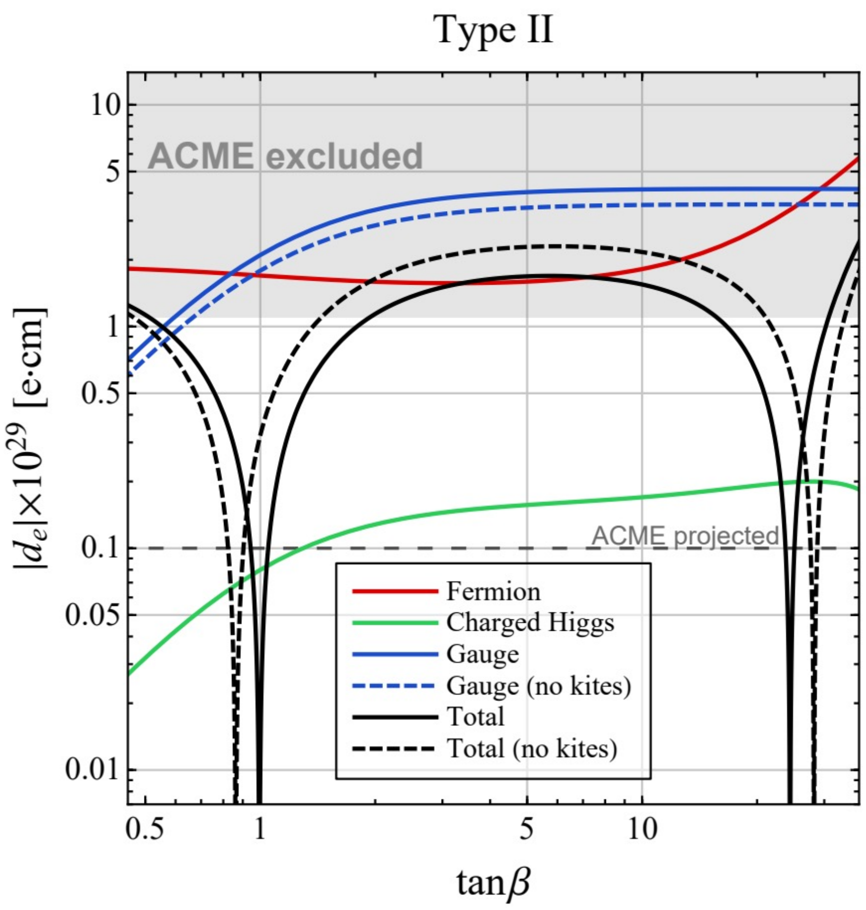
- Intricate interplay between h_{125} measurements, direct searches, flavor constraints, EWPOs, EDM measurements, …
  (see e.g. recent [de Giorgi et al.,2304.10560])

Electron EDM in the complex 2HDM

[Altmannshofer et al., 2009.01258]

- Not only the SM-like Higgs has CP-violating couplings, but also the BSM Higgs bosons.
- Cancellations between different contributions become possible.

- Combine multiple EDMs.
- Exploit complementarity with direct searches.



Conclusions

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- Characterizing the CP nature of the Higgs boson is an important goal for the (HL-)LHC .
- Key points to remember:
  - Novel analysis methods promise significant precision improvements,
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    $\rightarrow$ need more global analyses,
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  - LHC allows to constrain specific couplings while EDM measurements are sensitive to all kind of CP-violating physics,
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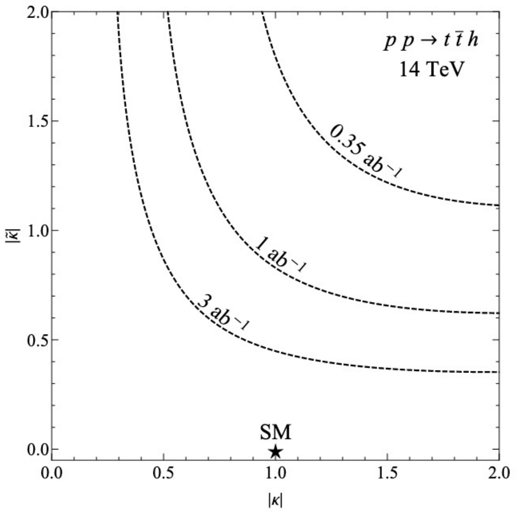
Thanks for your attention!

Appendix

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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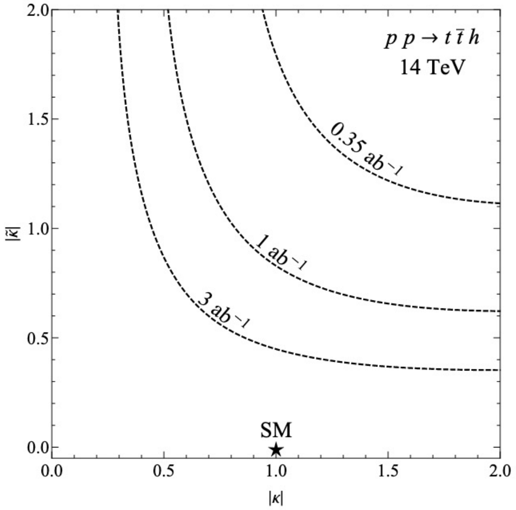

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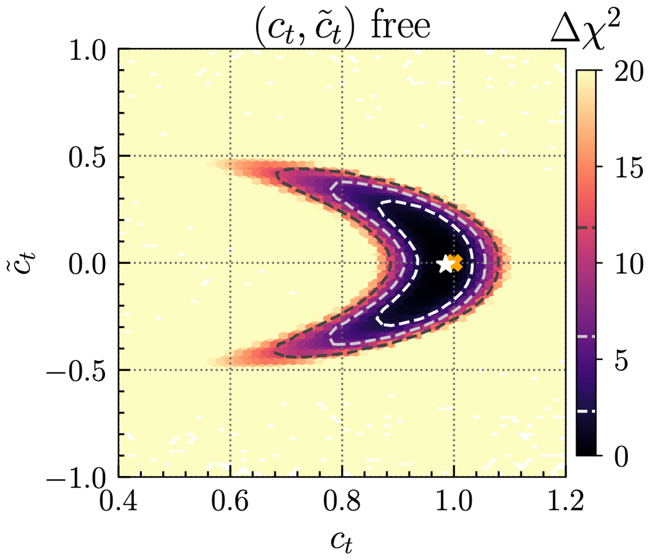
Indirect constraints:
- Strong constraints from ggH and $H\gamma\gamma$ rate measurements.
- Constraints very model-dependent.



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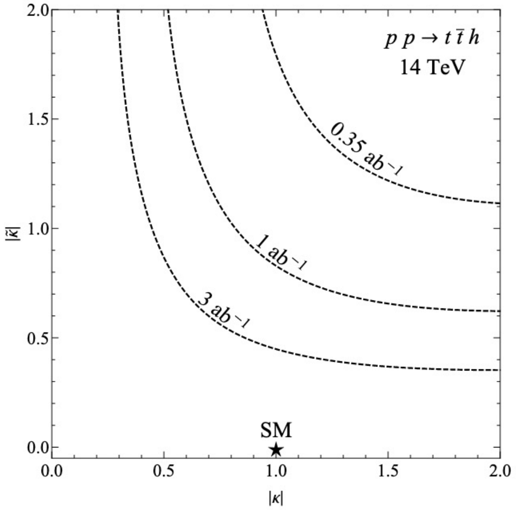

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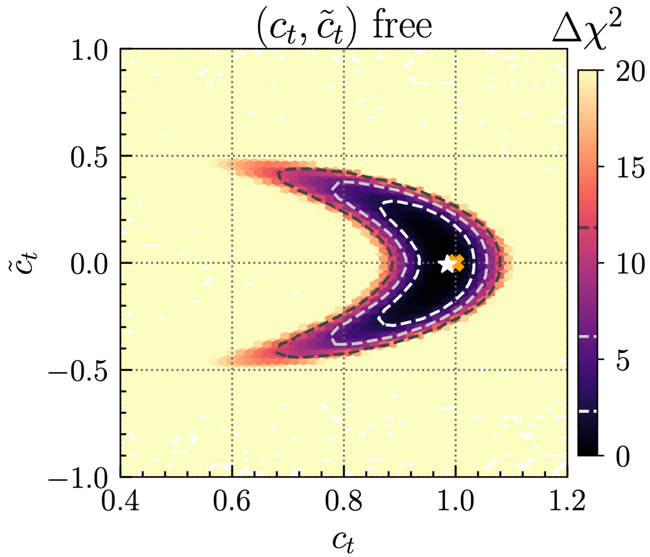

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Kinematic information:
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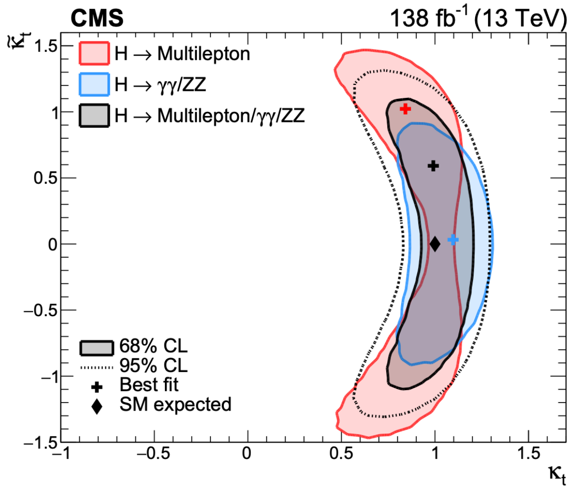
- Combination of different decay channels and across experiments difficult.



[CMS, 2208.02686]

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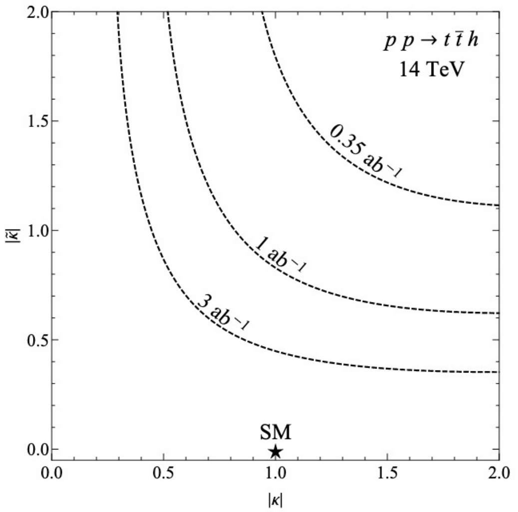

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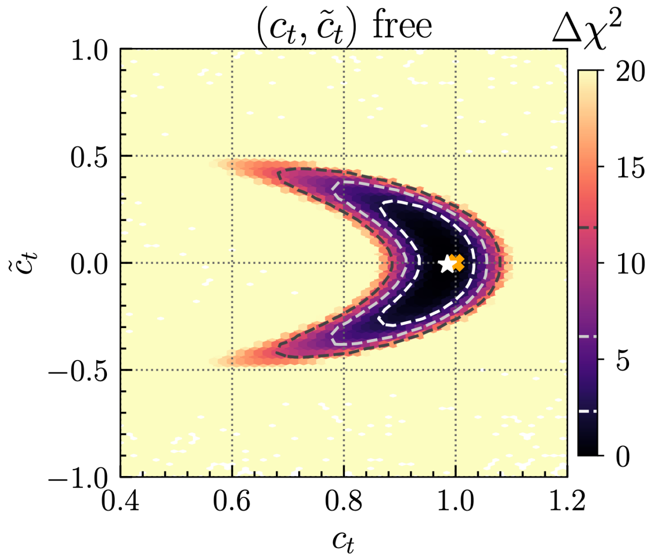

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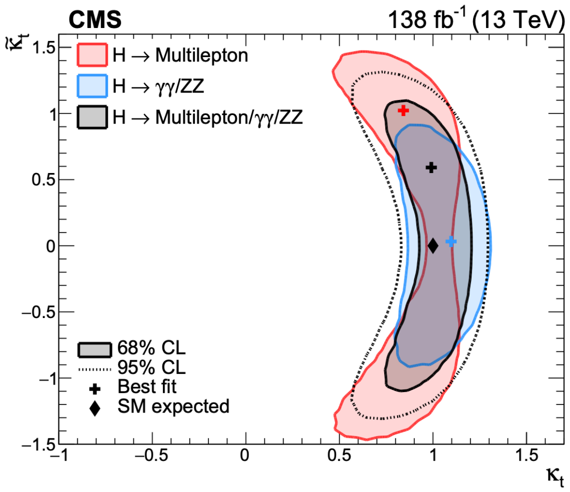


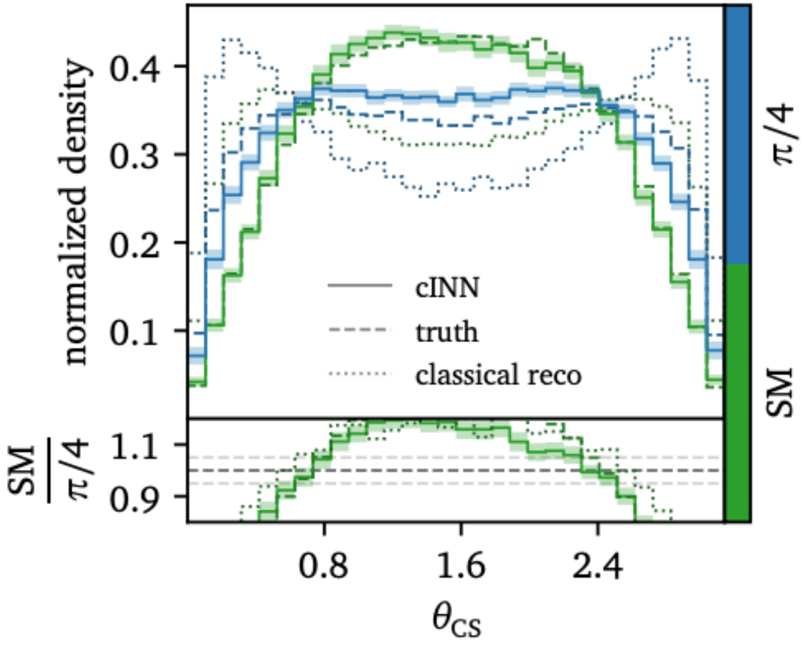
[CMS, 2208.02686]

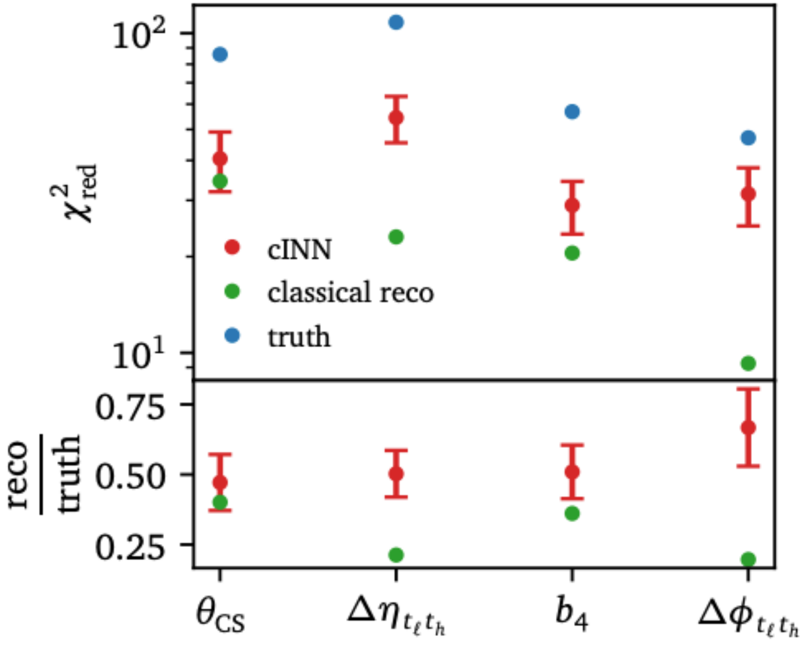
Exploit complementarity of different approaches!

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

Generative unfolding for $t\bar{t}H$

[Ackerschott et al.,2308.00027]

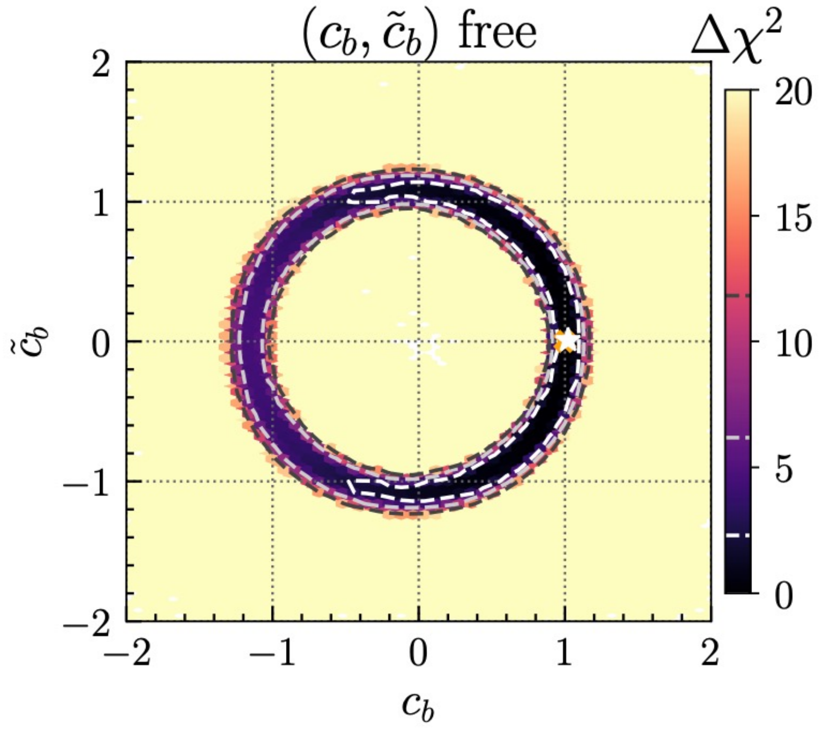




- Perform unfolding using conditional invertible neural network (cINN).
- Construct parton-level CP-sensitive observables.

1 flavor fits: b

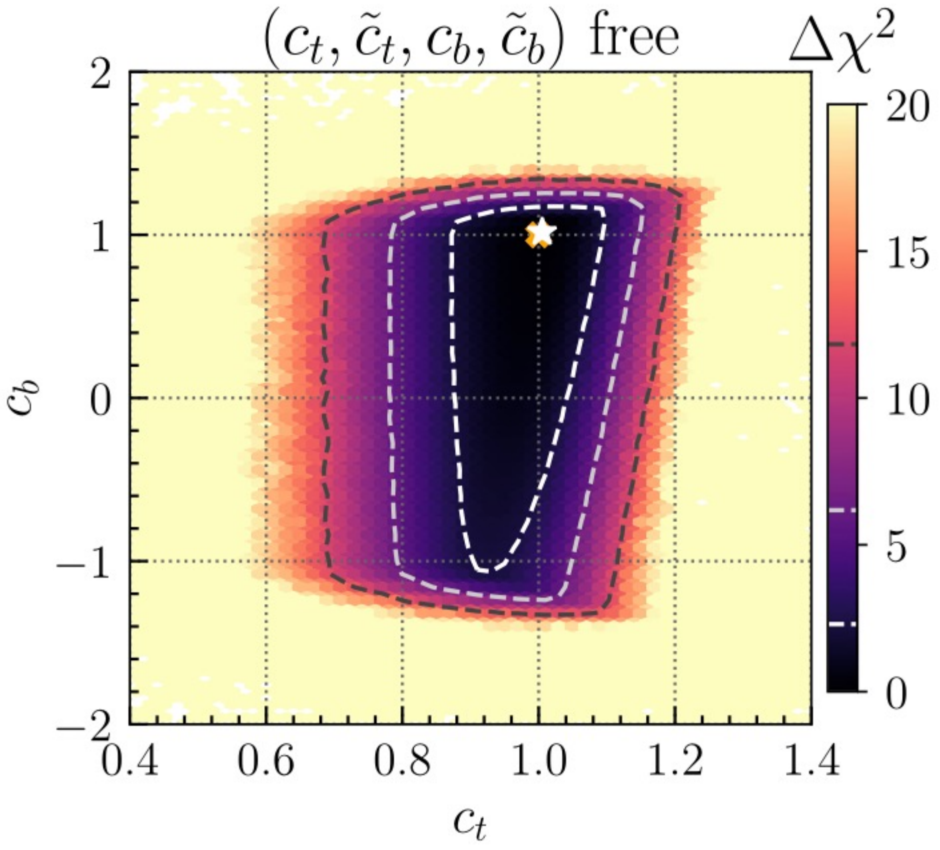
[HB et al.,2202.11753]

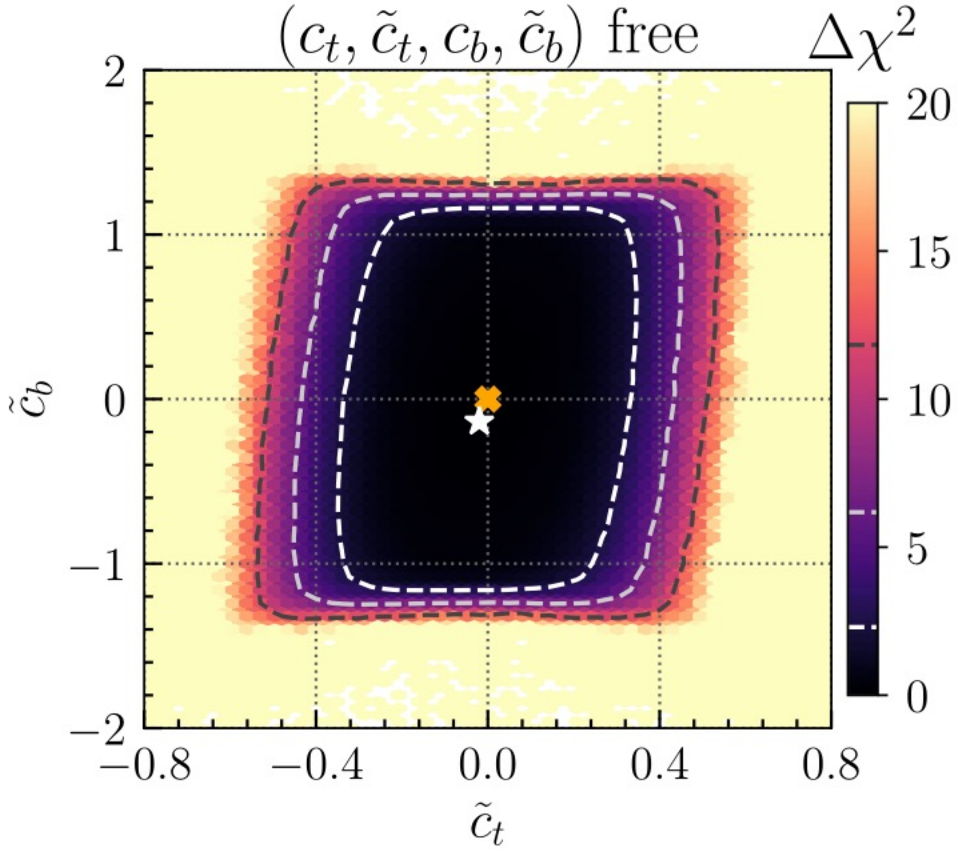


- Ring-like structure since $\Gamma_{H\to bb} \propto c_b^2 + \tilde{c}_b^2$.
- Bottom-Yukawa coupling, however, also affects ggH rate:
  - $\frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\rm SM}} \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 \boxed{- 0.1c_t c_b} + \cdots.$
- Negative c_b values disfavored since ggH rate is enhanced by $\sim 20\%$.
- Direct bottom CP measurements very difficult.

➡ Indirect CP constraints will remain important for the bottom-Yukawa coupling.

Interplay of bottom and top Yukawas



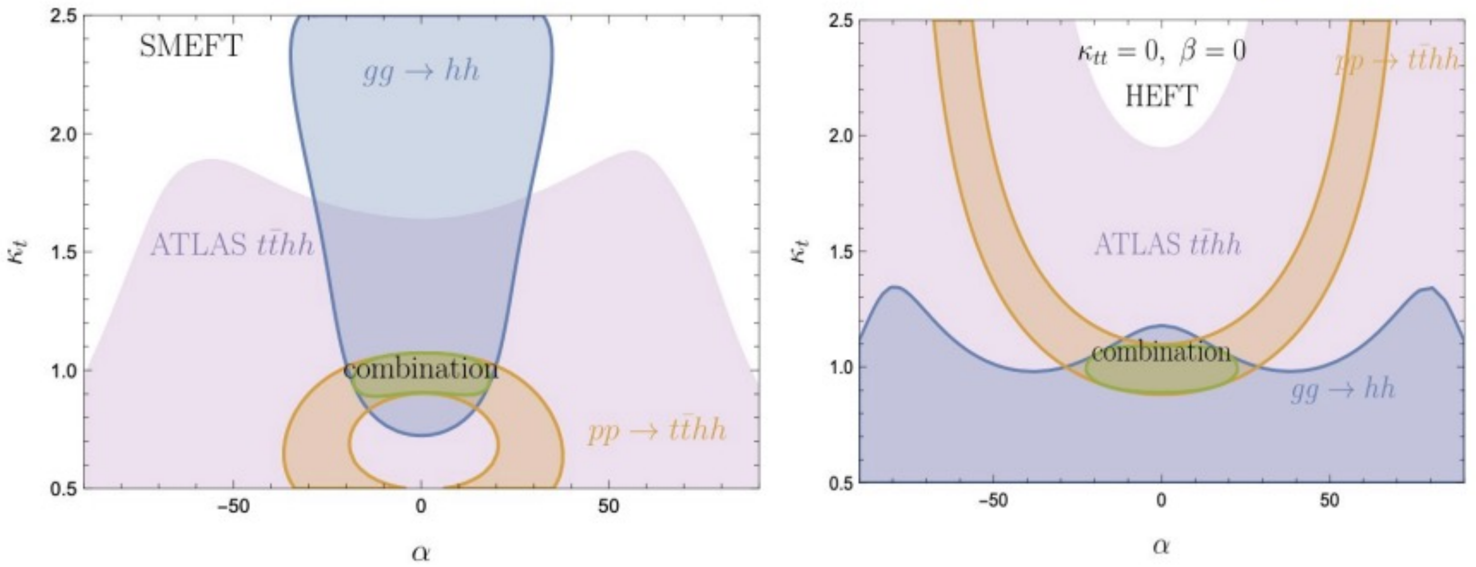


Non-linear top-Higgs CP violation

[Bhardwaj,Englert,Goncalves,Navarro, 2308.11722]

$$\mathcal{L}_{\text{HEFT}} \supset -\frac{m_t}{v}\,\kappa_t\,\bar{t}(\cos\alpha + i\gamma^5\sin\alpha)\,t\,h - \frac{m_t}{2v^2}\,\kappa_{tt}\,\bar{t}(\cos\beta + i\gamma^5\sin\beta)\,t\,h^2$$

Probe correlations between tth and $tthh$ couplings using di-Higgs production modes at HL-LHC.



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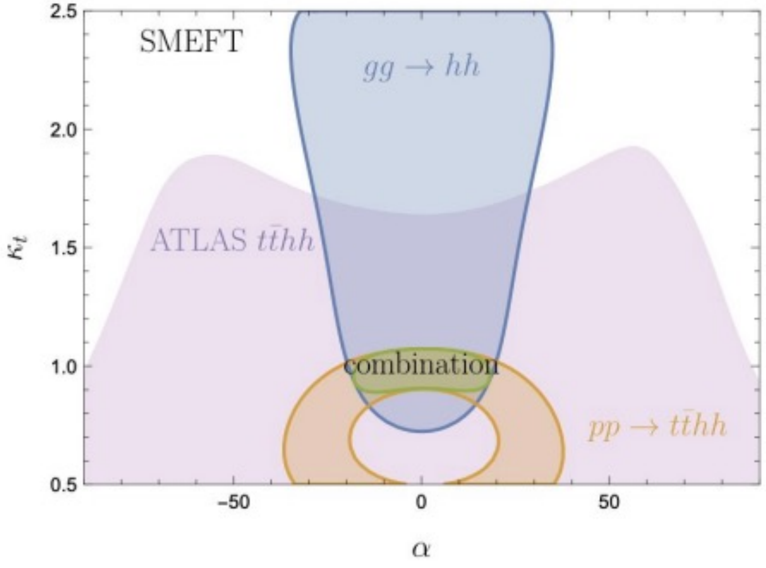
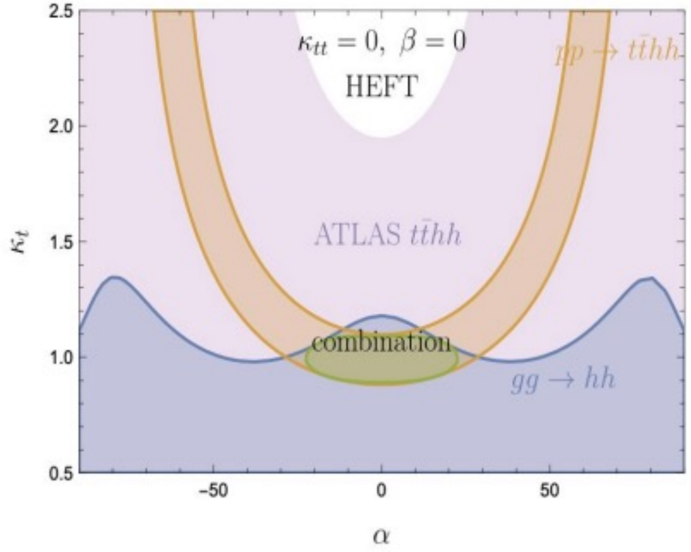
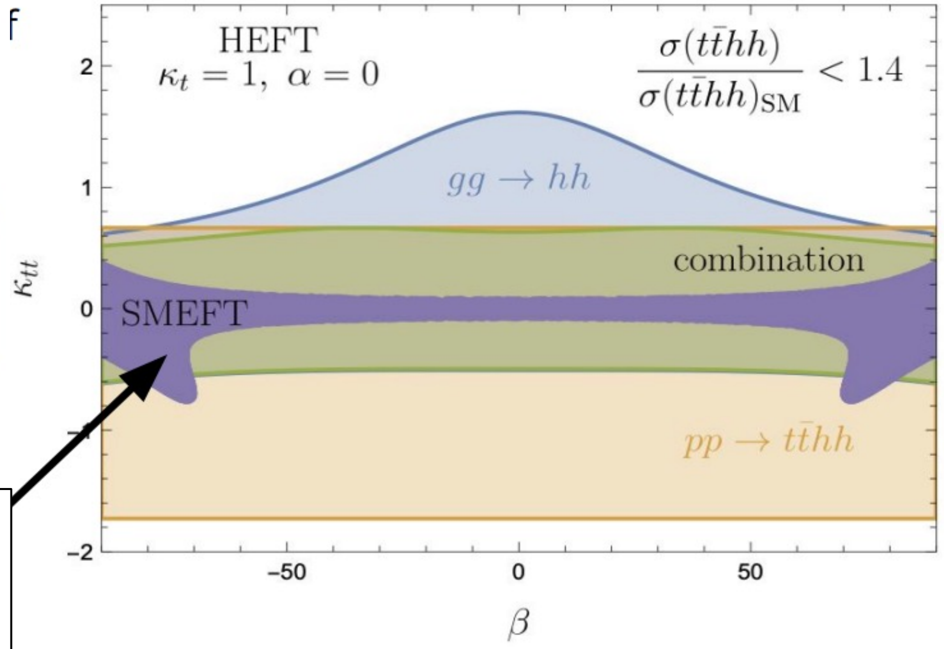






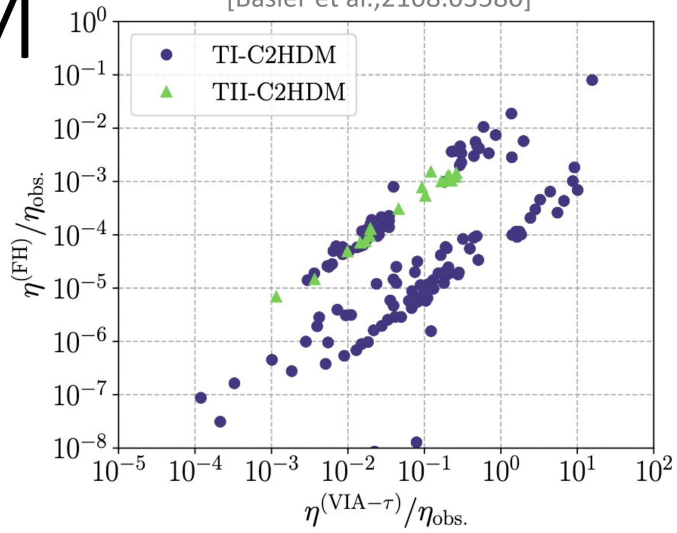
$$\kappa_{tt}^2 = 9(1 - 2\kappa_t\cos\alpha + \kappa_t^2)$$
$$\tan\beta = \frac{\kappa_t\sin\alpha}{\kappa_t\cos\alpha - 1}$$

Baryogenesis in the complex 2HDM

- Complex 2HDM provides all ingredients for electroweak baryogenesis:
  - Additional sources of CP violation.
  - Modifications of the Higgs potential to trigger strong first-order phase transition.

- Calculation of baryon asymmetry suffers from large theoretical uncertainty:
  - thermal resummation,
  - VIA vs WKB/FH approximation,
  - description of bubble wall,
  - …

[Basler et al.,2108.03580]



[Goncalves et al., 2307.03224]