Probing CP violation in the Higgs sector

Henning Bahl

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

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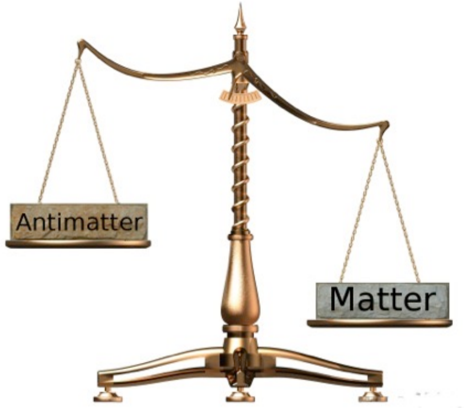
CP violation in the Higgs sector

- new sources of CP violation are necessary to explain the baryon asymmetry of the Universe
- one possibility: CP violation in the Higgs sector.
- SM prediction: Higgs is (almost) CP-even



How can we probe CP violation in the Higgs sector?

Higgs CP measurements

general amplitude structure for CP measurements:

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

CP can be tested either

- directly by constraining interference term → CP-odd observables
- indirectly by distinguishing $\left|\mathcal{M}^{\text{CP-even}}\right|^2$ from $\left|\mathcal{M}^{\text{CP-odd}}\right|^2$ → CP-even observables
- multivariate analyses mixing CP-odd and CP-even observables

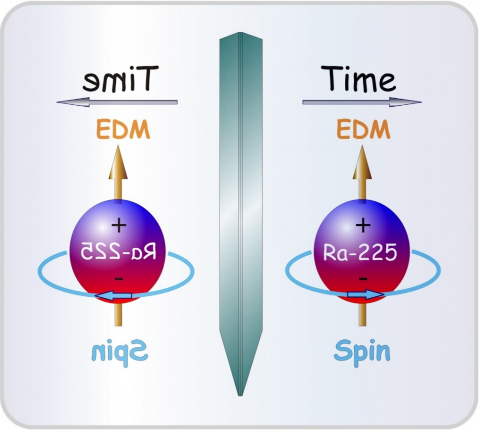
CP-odd observables

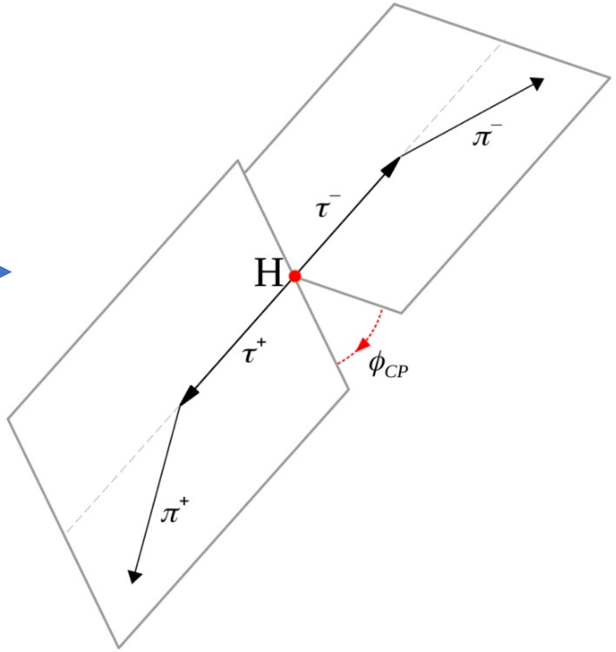
- unambiguous markers for CP violation

- examples:
  - EDM measurements,
  - decay angle in $H \to \tau^+\tau^-$

- need at least four independent four vectors (e.g. momenta or polarization vectors)

- can be difficult experimentally



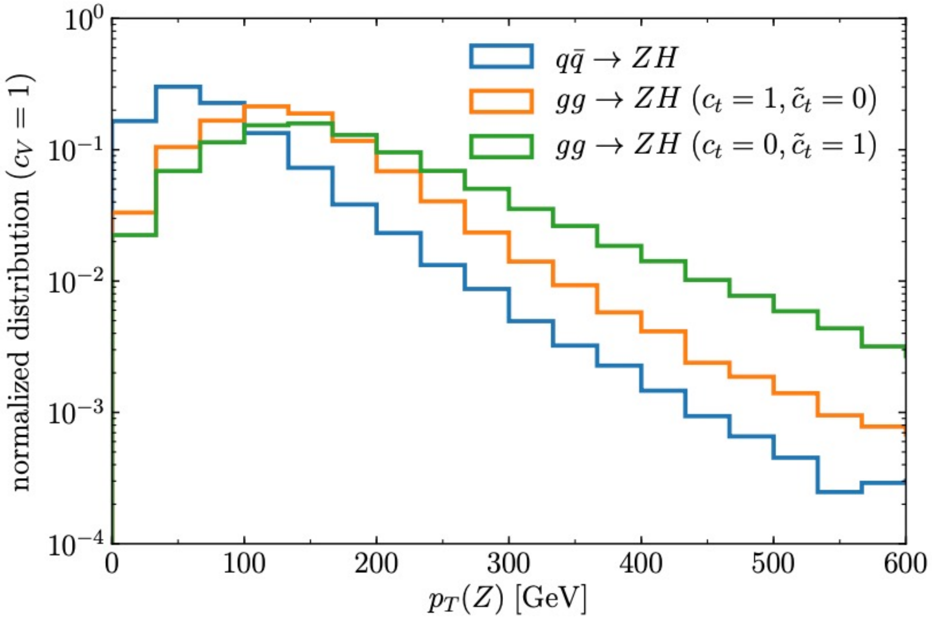


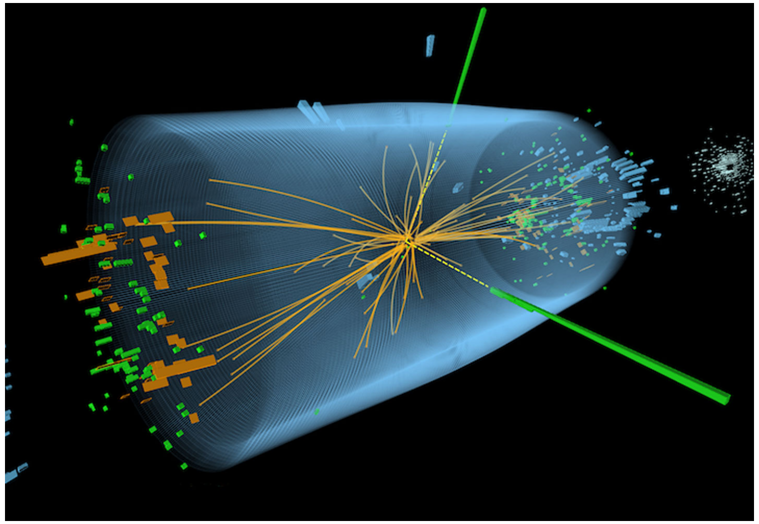
CP-even observables

- many rate and kinematic measurements are indirectly sensitive

- examples:
  - gluon fusion rate,
  - $gg \to ZH\ p_T^Z$ shape

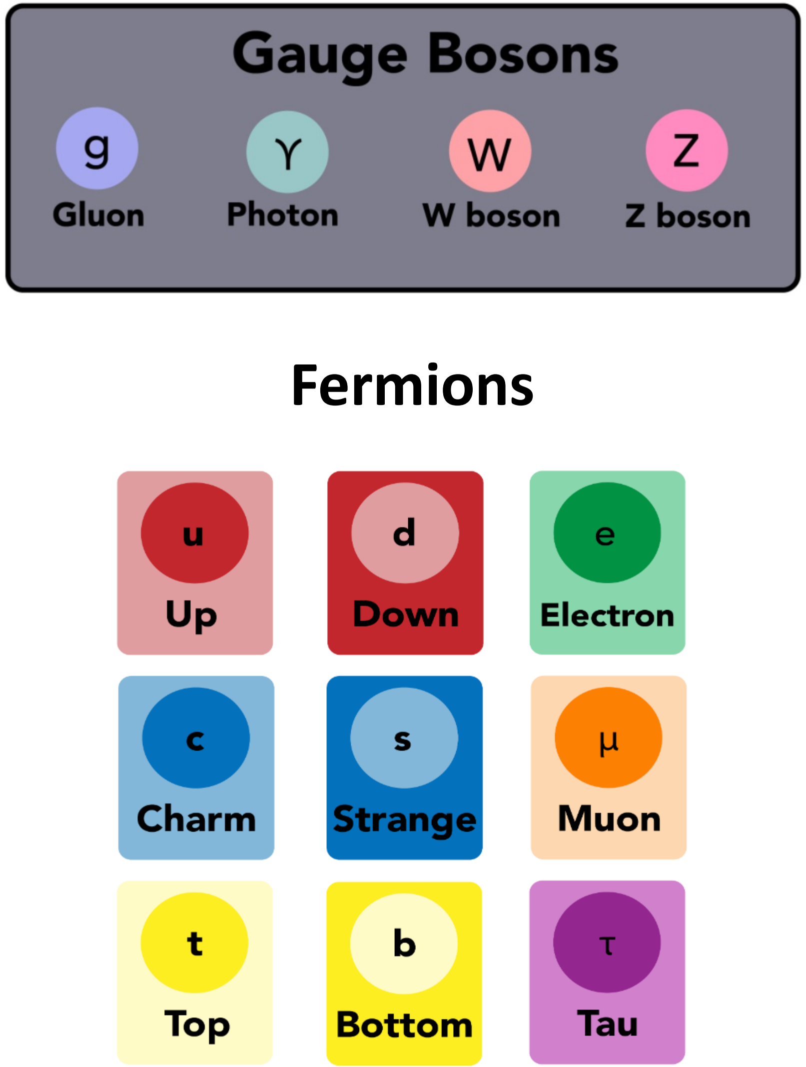
- deviations from SM need not be due to CP violation





Probing Higgs CPV at the LHC

CPV Higgs couplings at the LHC



Gauge Bosons

g Gluon

γ Photon

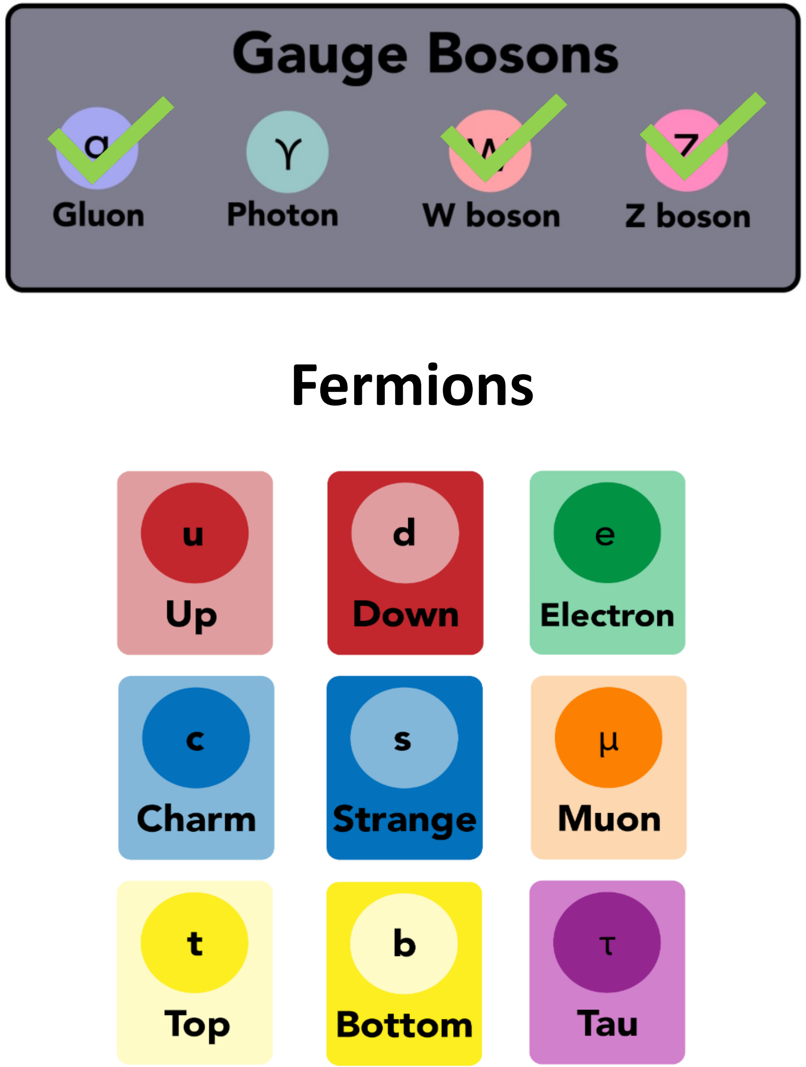
W W boson

Z Z boson

Fermions

u Up	d Down	e Electron
c Charm	s Strange	μ Muon
t Top	b Bottom	τ Tau

CPV Higgs couplings at the LHC



- CP structure of HVV interactions is comparably well-constrained

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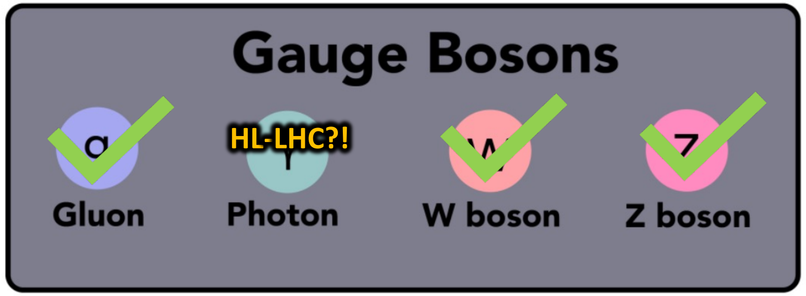
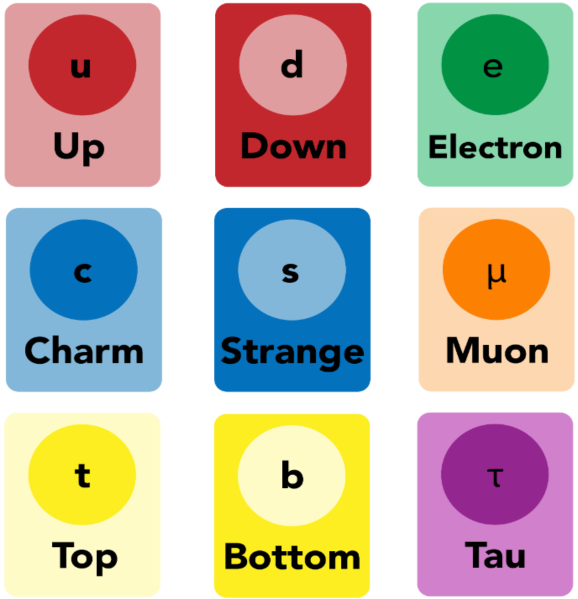


Fermions



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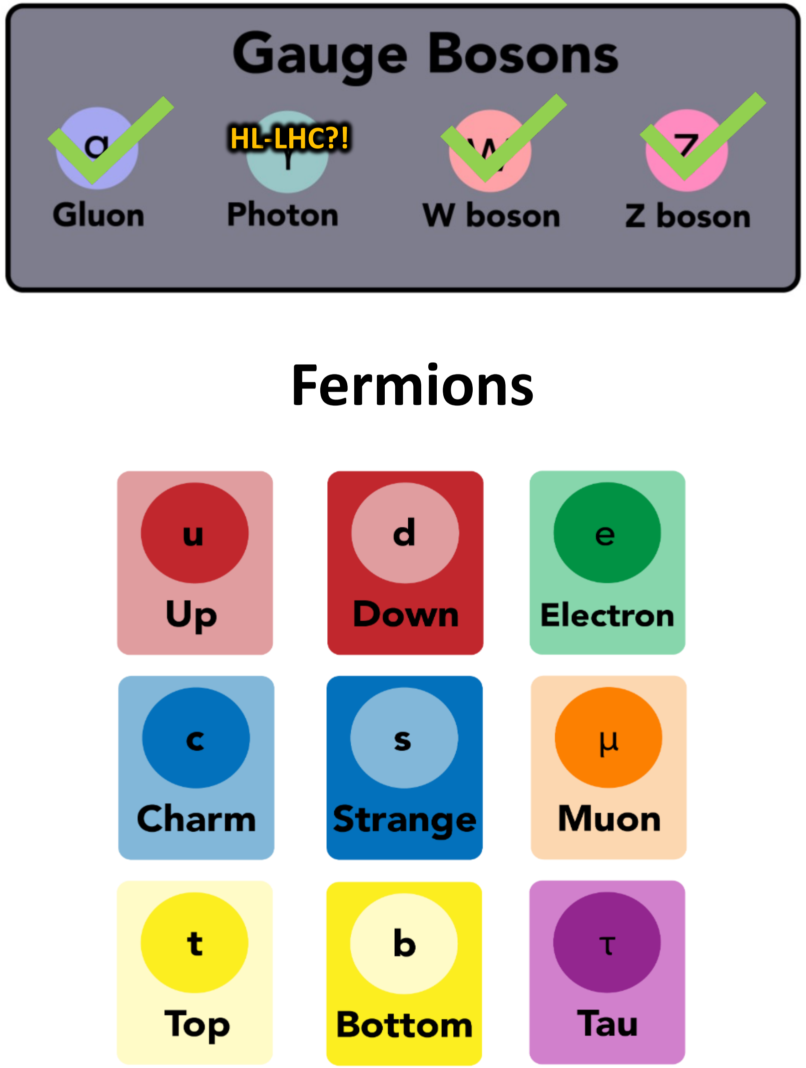

- CP structure of HVV interactions is comparably well-constrained
- the CP structure of the $Hf\bar{f}$ interactions is far less known
- most BSM theories predict largest CP violation in $Hf\bar{f}$ couplings

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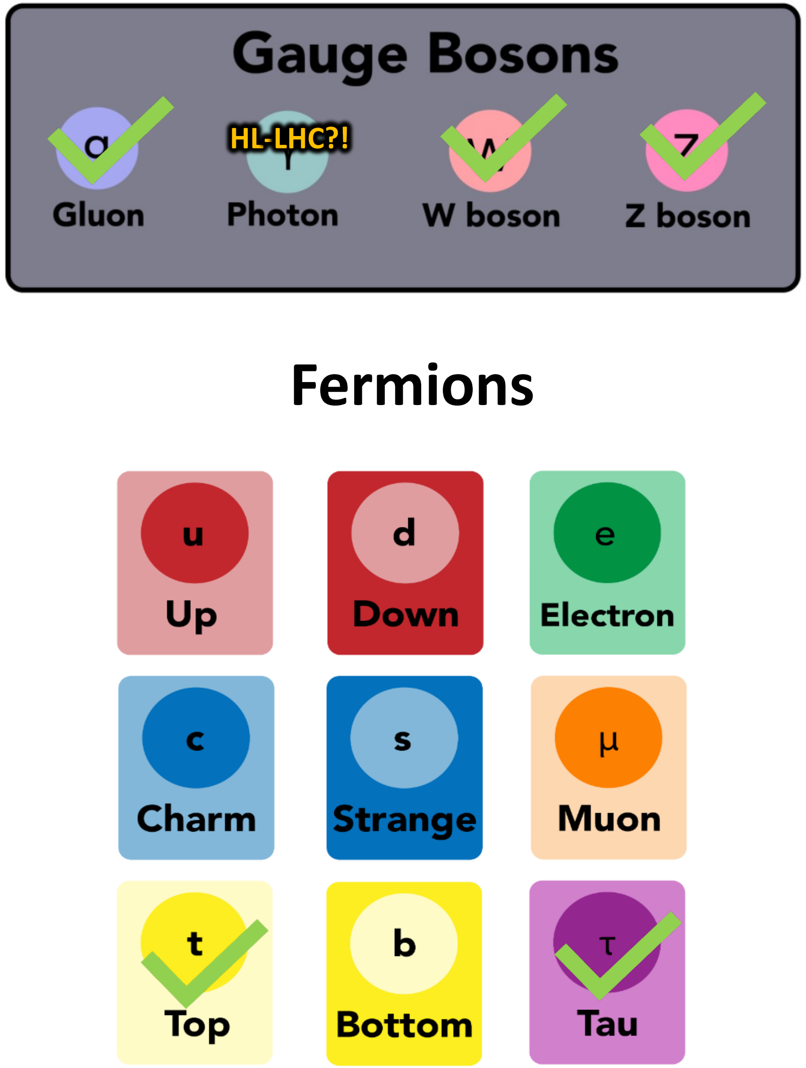

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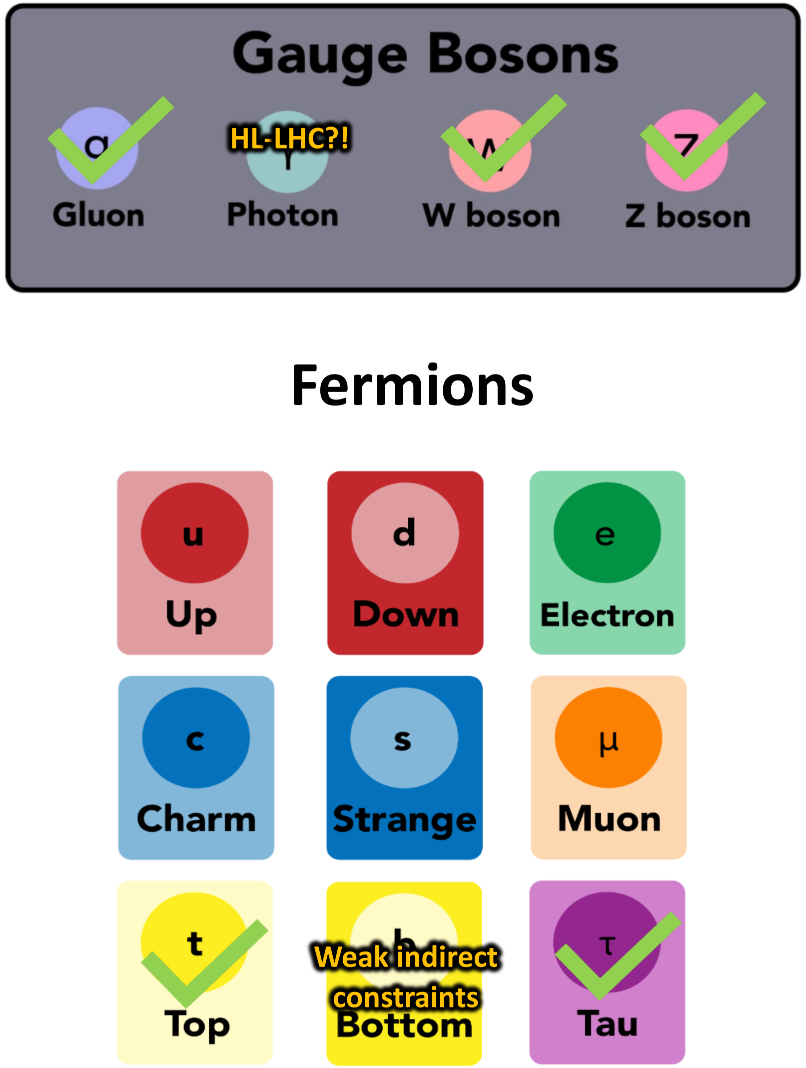

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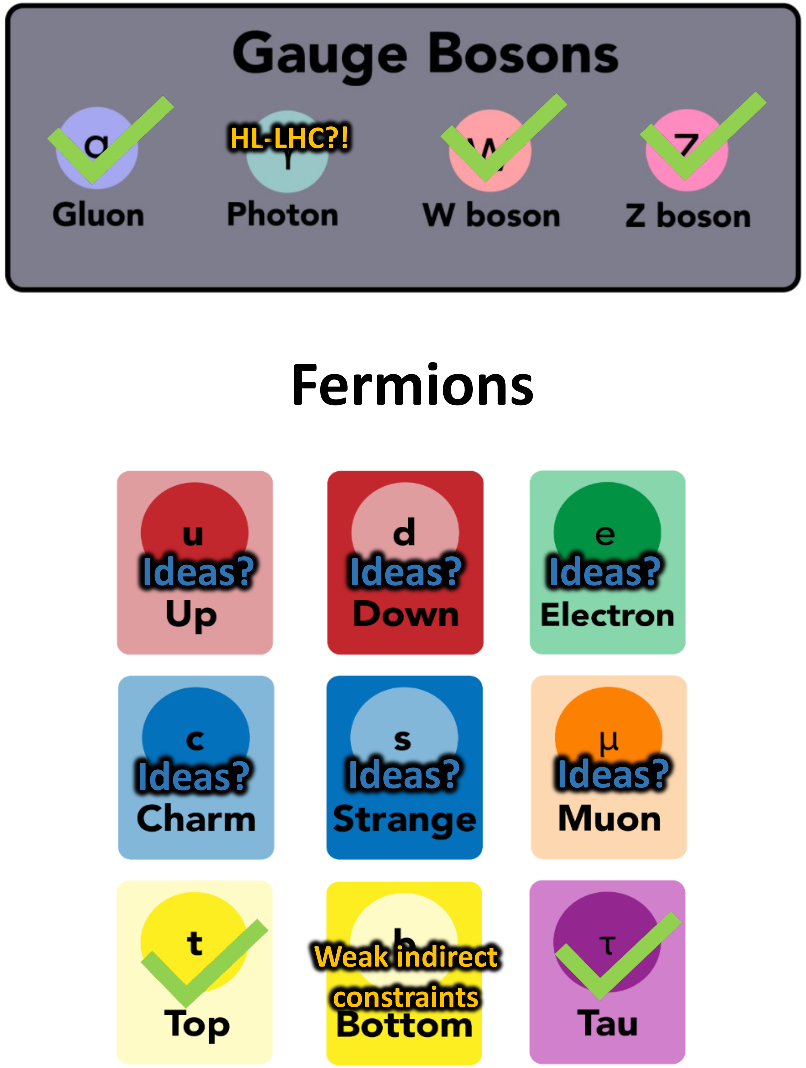

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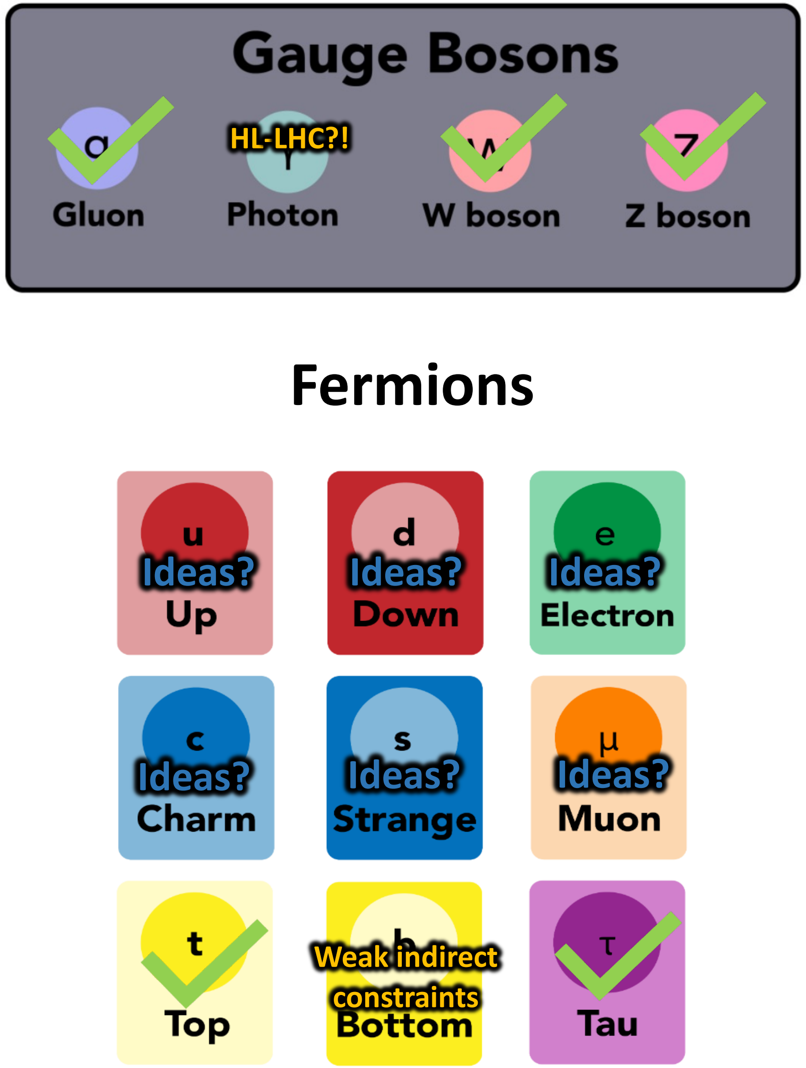

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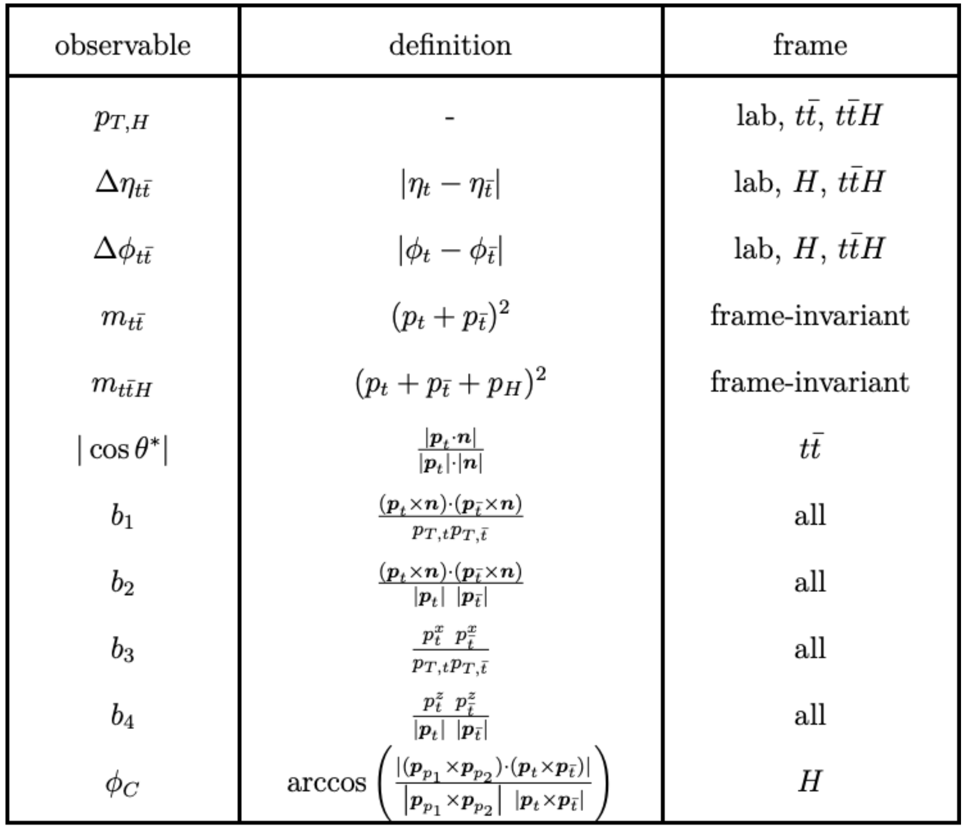
exploit kinematic constraints, rate measurements, and CP-odd observables to tighten constraints

$t\bar{t}H$ — kinematic constraints [HB et al., 2406.03950]

→ See Marco's talk for more details!

- CP-odd observables experimentally very challenging

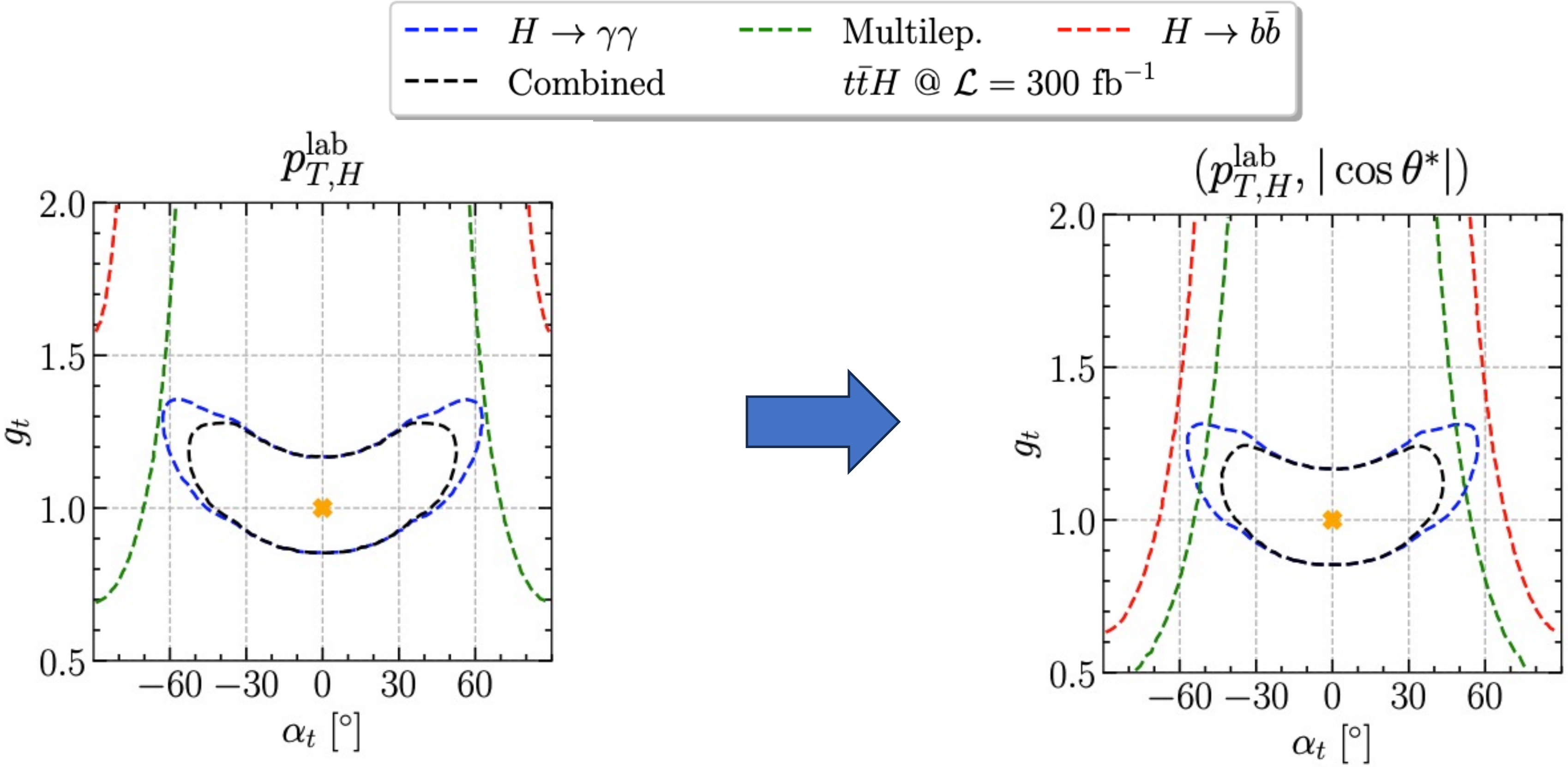
- exploit kinematics
- combine decay channels/experiments via CP-sensitive STXS extension (so far binning in $p_{T,H}$)
- check 2D combinations of 11 CP-sensitive observables
- best combinations: $p_{T,H}$ + b_2^{lab}, $\Delta\eta_{t\bar{t}}$, $|\cos\theta^\star|$



observable	definition	frame
$p_{T,H}$	-	lab, $t\bar{t}$, $t\bar{t}H$
$\Delta\eta_{t\bar{t}}$	$\lvert\eta_t - \eta_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$\Delta\phi_{t\bar{t}}$	$\lvert\phi_t - \phi_{\bar{t}}\rvert$	lab, H, $t\bar{t}H$
$m_{t\bar{t}}$	$(p_t + p_{\bar{t}})^2$	frame-invariant
$m_{t\bar{t}H}$	$(p_t + p_{\bar{t}} + p_H)^2$	frame-invariant
$\lvert\cos\theta^*\rvert$	$\frac{\lvert\boldsymbol{p}_t \cdot \boldsymbol{n}\rvert}{\lvert\boldsymbol{p}_t\rvert \cdot \lvert\boldsymbol{n}\rvert}$	$t\bar{t}$
b_1	$\frac{(\boldsymbol{p}_t \times \boldsymbol{n}) \cdot (\boldsymbol{p}_{\bar{t}} \times \boldsymbol{n})}{p_{T,t} p_{T,\bar{t}}}$	all
b_2	$\frac{(\boldsymbol{p}_t \times \boldsymbol{n}) \cdot (\boldsymbol{p}_{\bar{t}} \times \boldsymbol{n})}{\lvert\boldsymbol{p}_t\rvert \; \lvert\boldsymbol{p}_{\bar{t}}\rvert}$	all
b_3	$\frac{p_t^x \; p_{\bar{t}}^x}{p_{T,t} p_{T,\bar{t}}}$	all
b_4	$\frac{p_t^z \; p_{\bar{t}}^z}{\lvert\boldsymbol{p}_t\rvert \; \lvert\boldsymbol{p}_{\bar{t}}\rvert}$	all
ϕ_C	$\arccos\left(\frac{\lvert(\boldsymbol{p}_{p_1} \times \boldsymbol{p}_{p_2}) \cdot (\boldsymbol{p}_t \times \boldsymbol{p}_{\bar{t}})\rvert}{\lvert\boldsymbol{p}_{p_1} \times \boldsymbol{p}_{p_2}\rvert \; \lvert\boldsymbol{p}_t \times \boldsymbol{p}_{\bar{t}}\rvert}\right)$	H

CP-sensitive STXS for $t\bar{t}H$

$$\mathcal{L}_{t\text{-Yuk}} = \frac{g_t y_t^{\mathrm{SM}}}{\sqrt{2}} \bar{t}\,(\cos\alpha_t + i\gamma_5 \sin\alpha_t)\, tH$$



→ 2nd dimension provides important information, performance close to BDT

"Global" ttH CPV fit

Most studies concentrate on CP character of a single Higgs coupling, e.g.

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

in SMEFT, this coupling is generated by rewriting:

🔴 $O_{t\phi} = (\phi^\dagger\phi)(\bar{Q}t\tilde{\phi})$

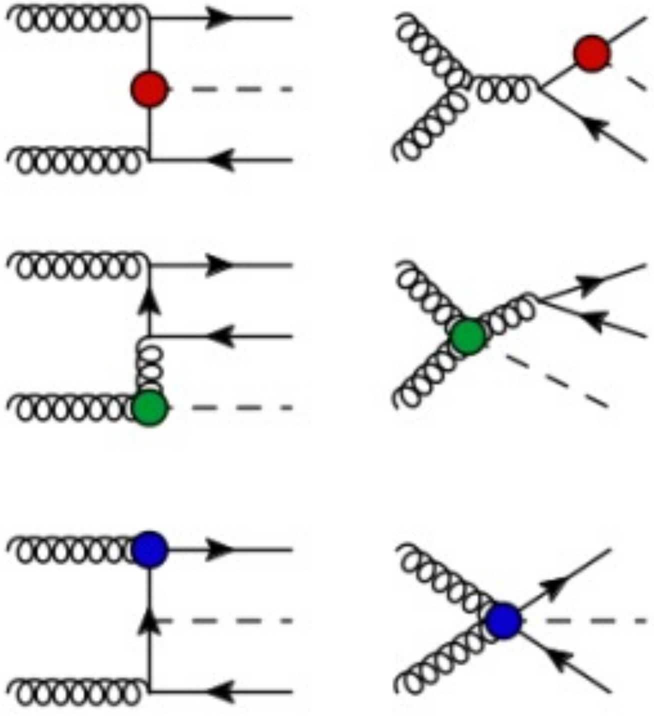
further "Higgs" operators which contribute to e.g. $t\bar{t}H$:

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

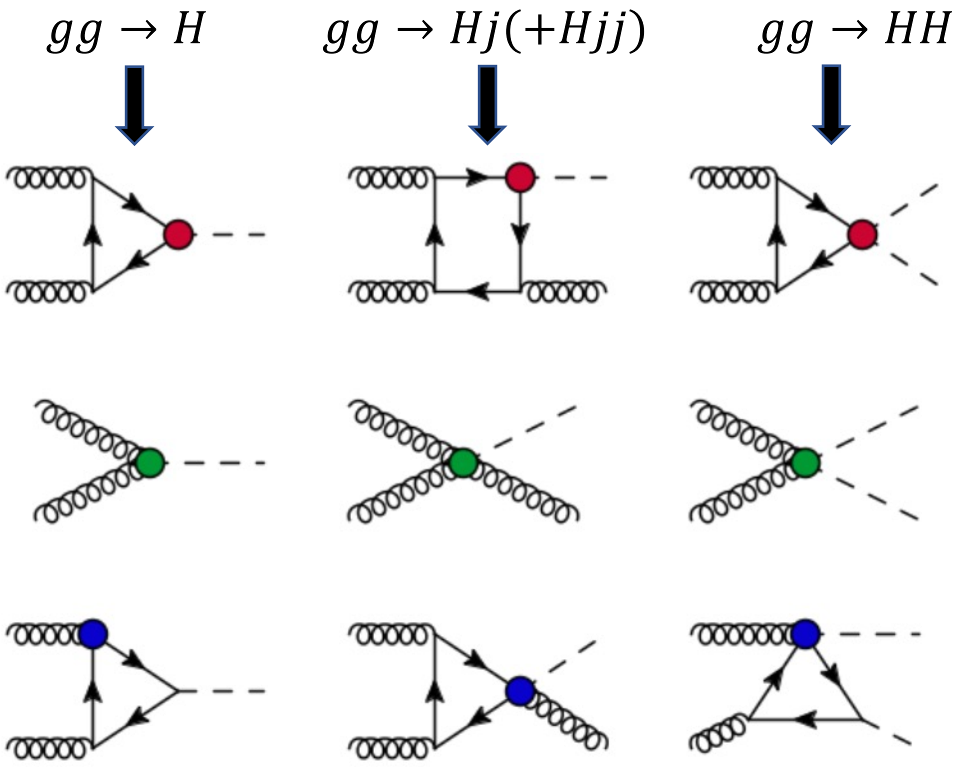
🟢 $O_{\phi G} = (\phi^\dagger\phi)\left(G^A_{\mu\nu}G^{A\mu\nu}\right)$
$O_{\phi\tilde{G}} = (\phi^\dagger\phi)\left(G^A_{\mu\nu}\tilde{G}^{A\mu\nu}\right)$

→ interplay of the different CPV operators across different channels

[Maltoni,Vryonidou,Zhang,1607.05330]



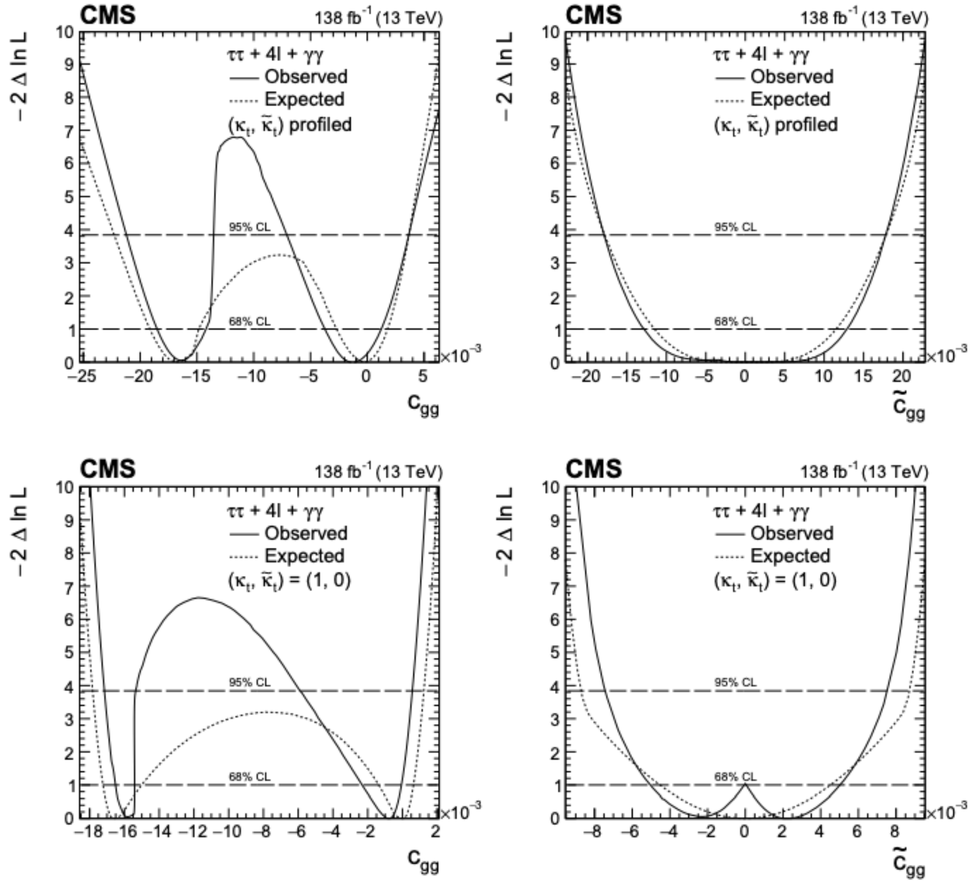
$t\bar{t}H$: correlation with other Higgs channels



[Maltoni,Vryonidou,Zhang,1607.05330]

(+ interplay with bottom Yukawa etc.)

Comb. fit



[CMS, 2205.05120]

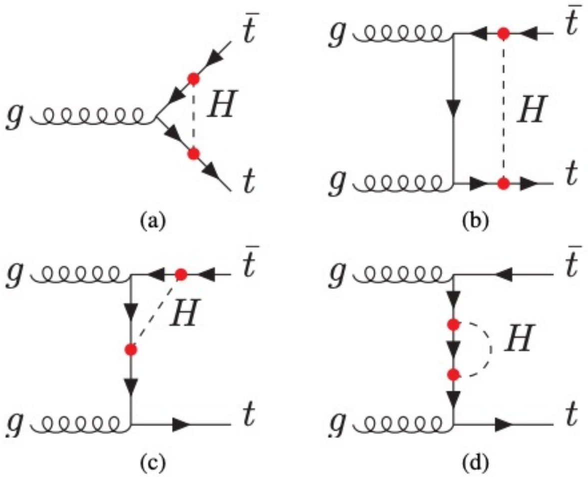
→ combined analysis increasingly important

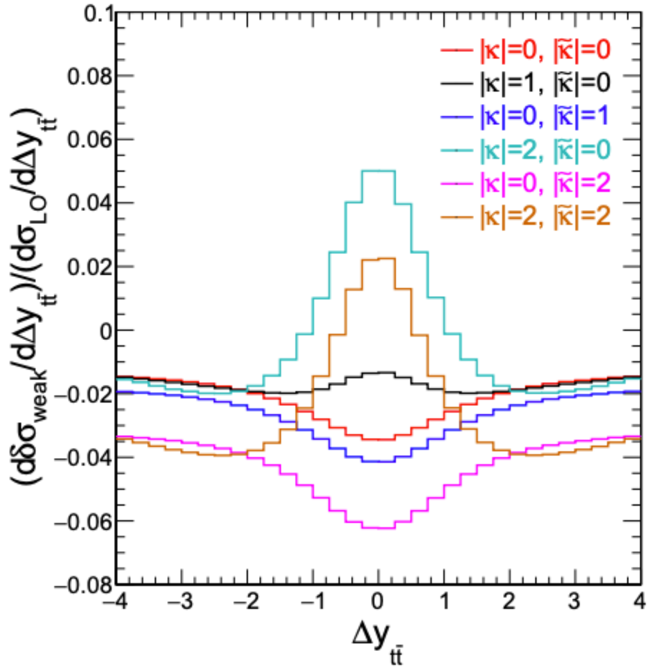
Future: CP-dependent EW NLO corrections

- with increased precision, electroweak NLO corrections become important
- EW NLO corrections can depend on Higgs CP nature

→ ”background” processes become CP sensitive

Example: $t\bar{t}$ production [Martini et al.,2104.04277]

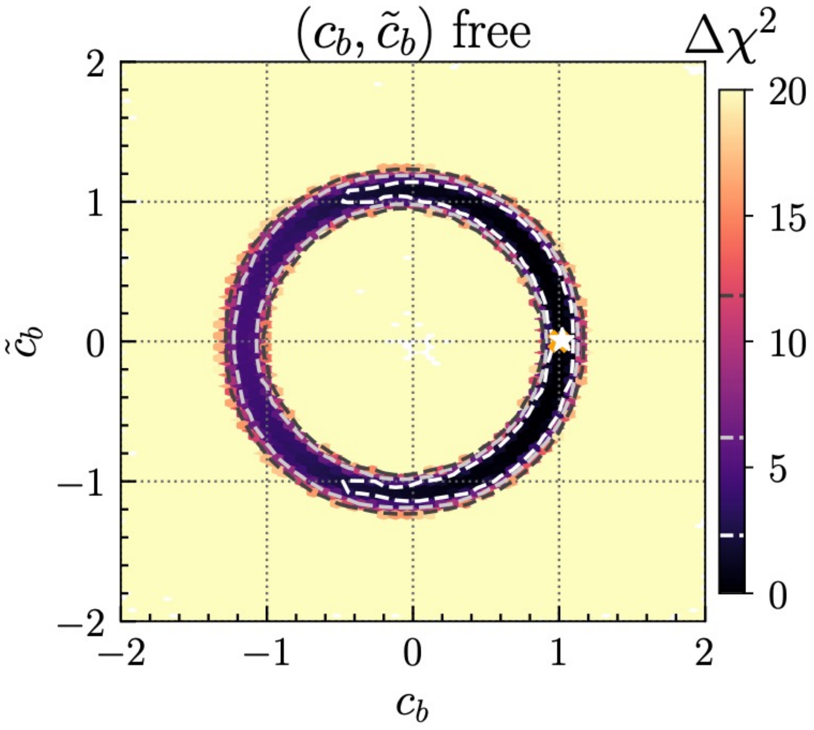




➡ could become a significant complication for future studies

Bottom Yukawa — rate constraints

[HB et al.,2202.11753]



$$\mathcal{L}_{b\text{-Yuk}} = \frac{y_b^{\mathrm{SM}}}{\sqrt{2}} \bar{b} \left(c_b + i\gamma_5 \tilde{c}_b\right) bH$$

- ring-like structure since $\Gamma_{H\to bb} \propto c_b^2 + \tilde{c}_b^2$.
- negative c_b values disfavored since ggH rate is enhanced by $\sim 20\%$.
- direct bottom CP measurements basically impossible

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

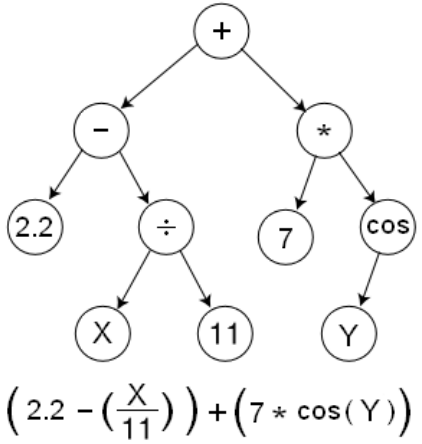
Symbolic regression for CP-odd observables

[HB,Fuchs,Menen,Plehn,in preparation]

- modify VBF by dim-6 operator

$$\frac{c_{H\widetilde{W}}}{\Lambda^2}\Phi^\dagger\Phi\widetilde{W}^a_{\mu\nu}W^{a\mu\nu}$$

- construct optimal CP-odd observable by training pos. $c_{H\widetilde{W}}$ sample against neg. $c_{H\widetilde{W}}$ sample
- use symbolic regression to obtain analytic equation
- allows to confirm that learned observable is indeed CP-odd



$$\left(2.2-\left(\frac{X}{11}\right)\right)+\left(7*\cos(Y)\right)$$

Symbolic regression for CP-odd observables

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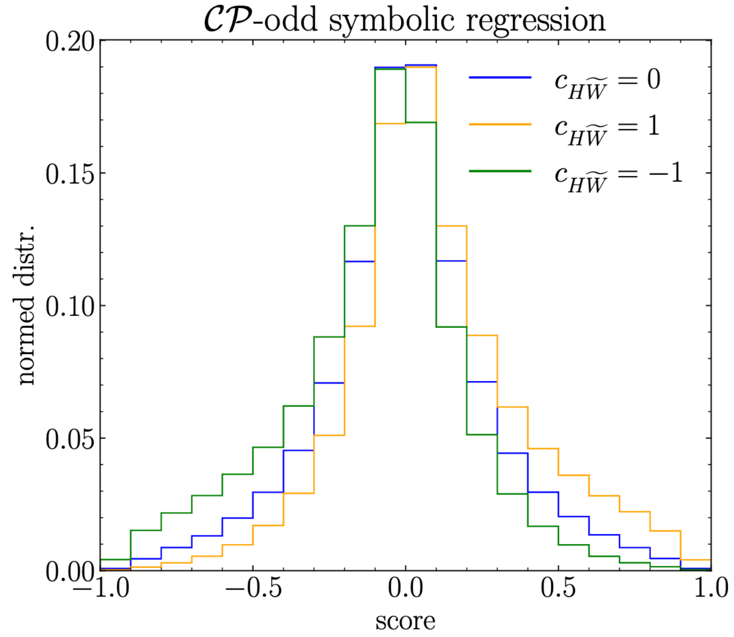
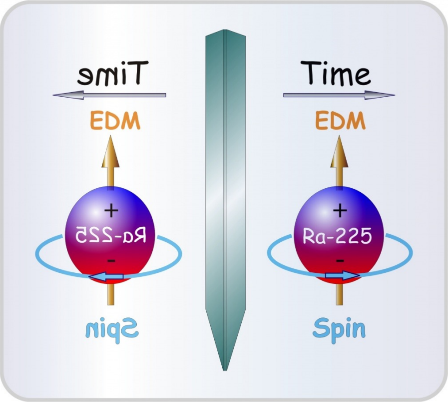
- construct optimal CP-odd observable by training pos. $c_{H\widetilde{W}}$ sample against neg. $c_{H\widetilde{W}}$ sample
- use symbolic regression to obtain analytic equation
- allows to confirm that learned observable is indeed CP-odd
- similar performance as normal classifier, 50% better than $\Delta\phi_{jj}$



$$\text{score} = 2\cdot\text{sigmoid}\left\{\frac{\sin(\Delta\phi_{jj})\eta_{jj}}{\cosh\left(\eta_{jj} - \log\left(\frac{m_{jj}}{m_h}\right) - 0.743\log\left(\frac{p_T^h}{m_h}\right)\right)}\right\} - 1$$



Probing Higgs CPV via EDMs

and the role of the LHC

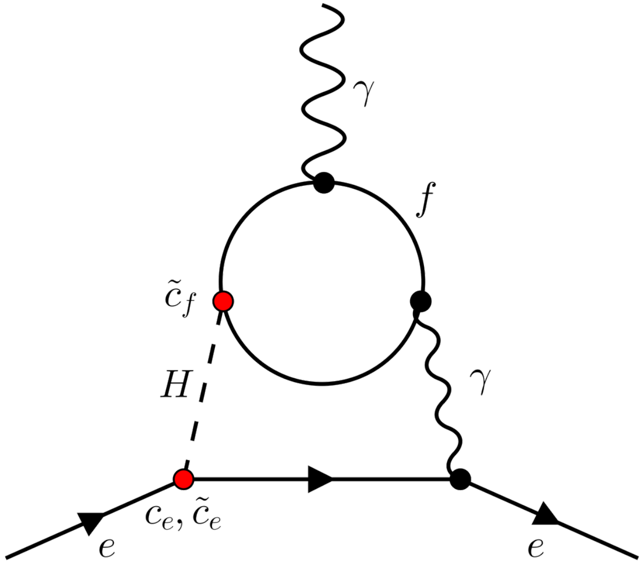
EDM constraints

- EDMs sensitive to CPV Higgs couplings via 2L Bar-Zee diagrams

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

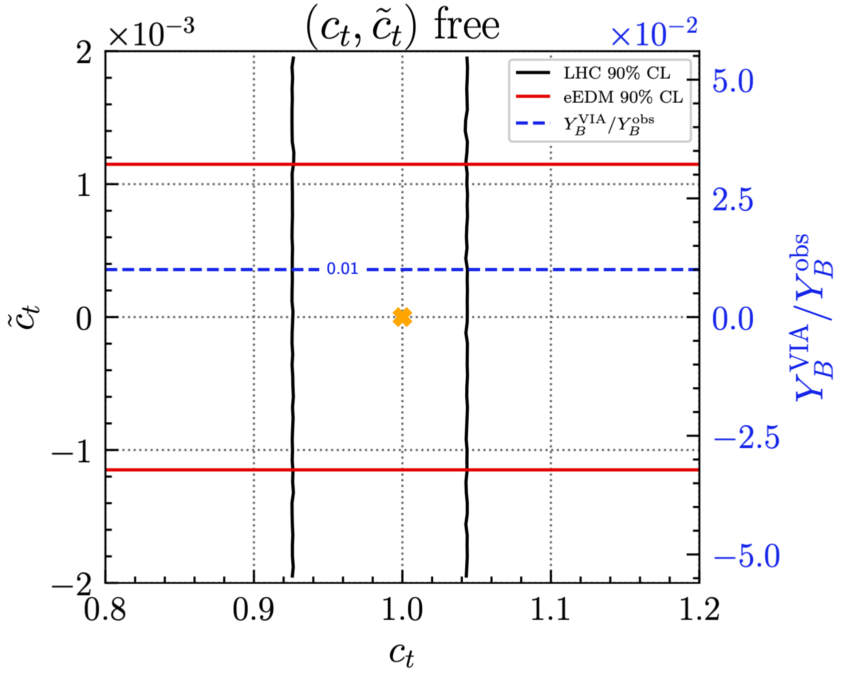
- significant increase in precision expected within the next years (see e.g. [Snowmass report, 2203.08103])

- 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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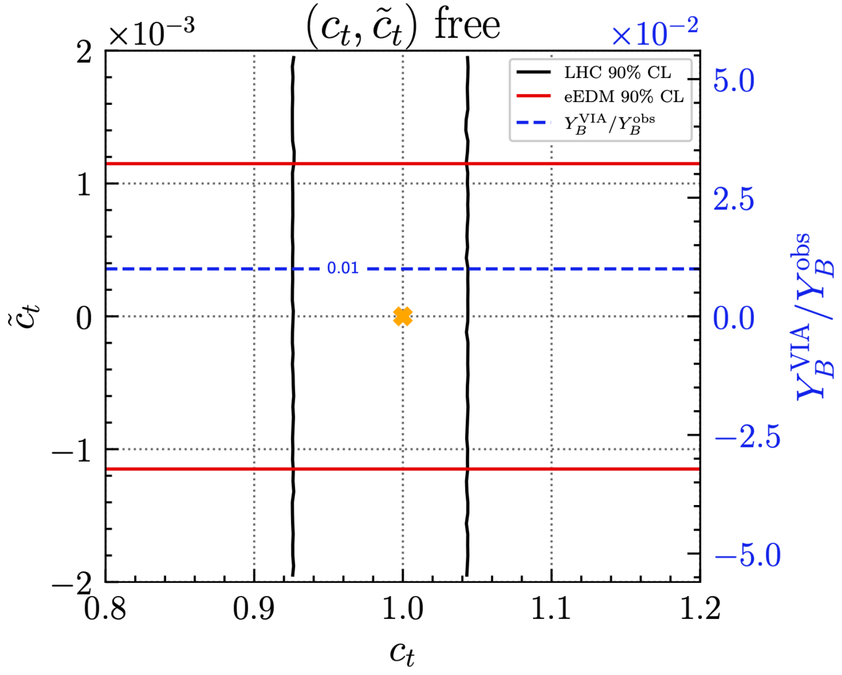

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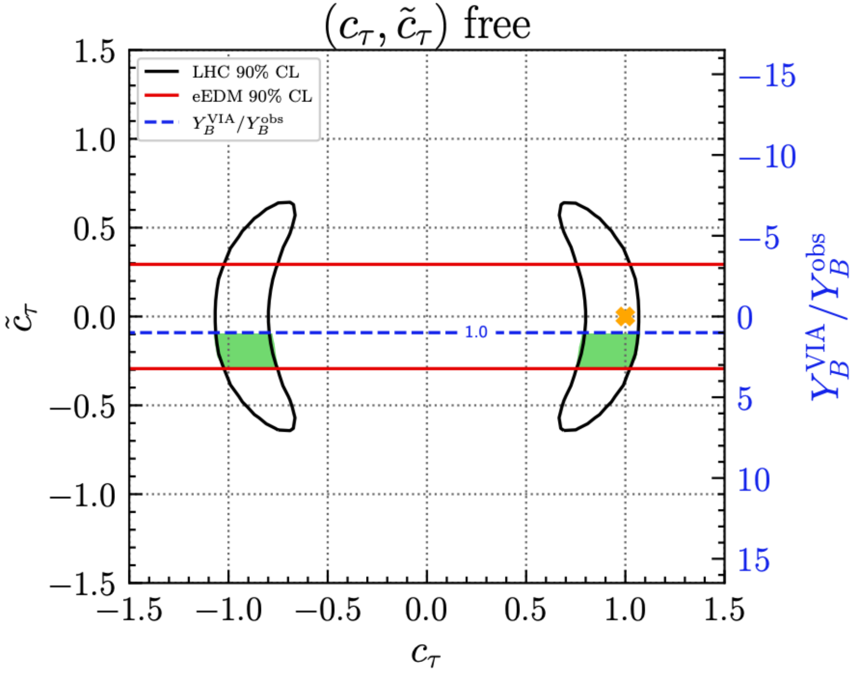

CP-odd τ coupling can potentially give sizeable contribution to baryon asymmetry

EDM > LHC?

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

EDM > LHC? **No.**

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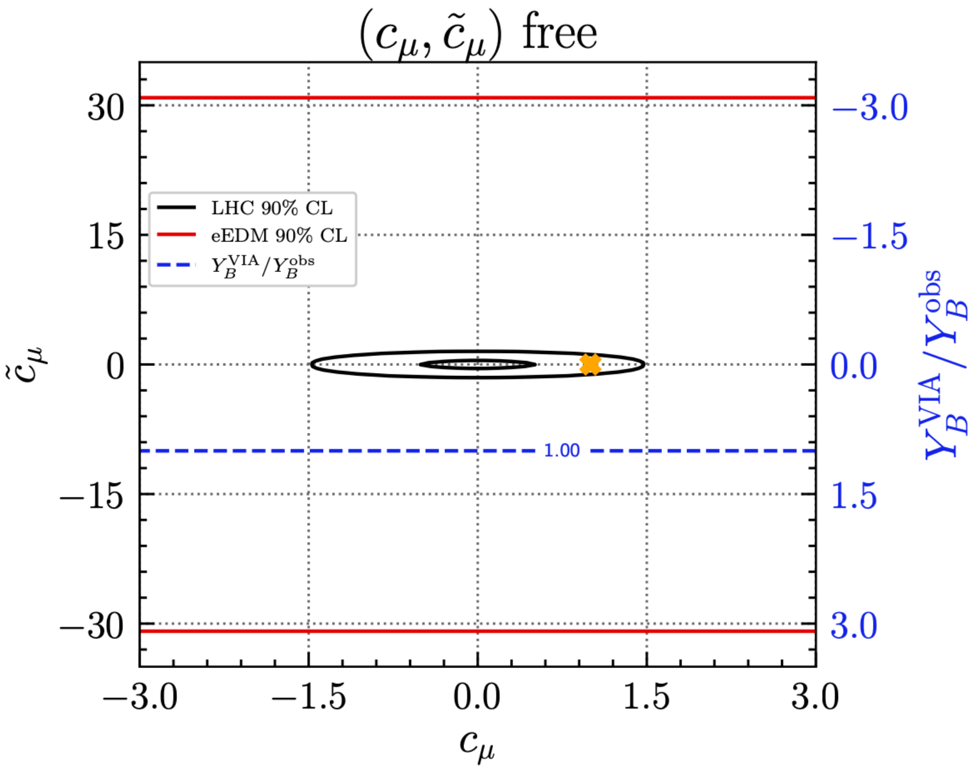
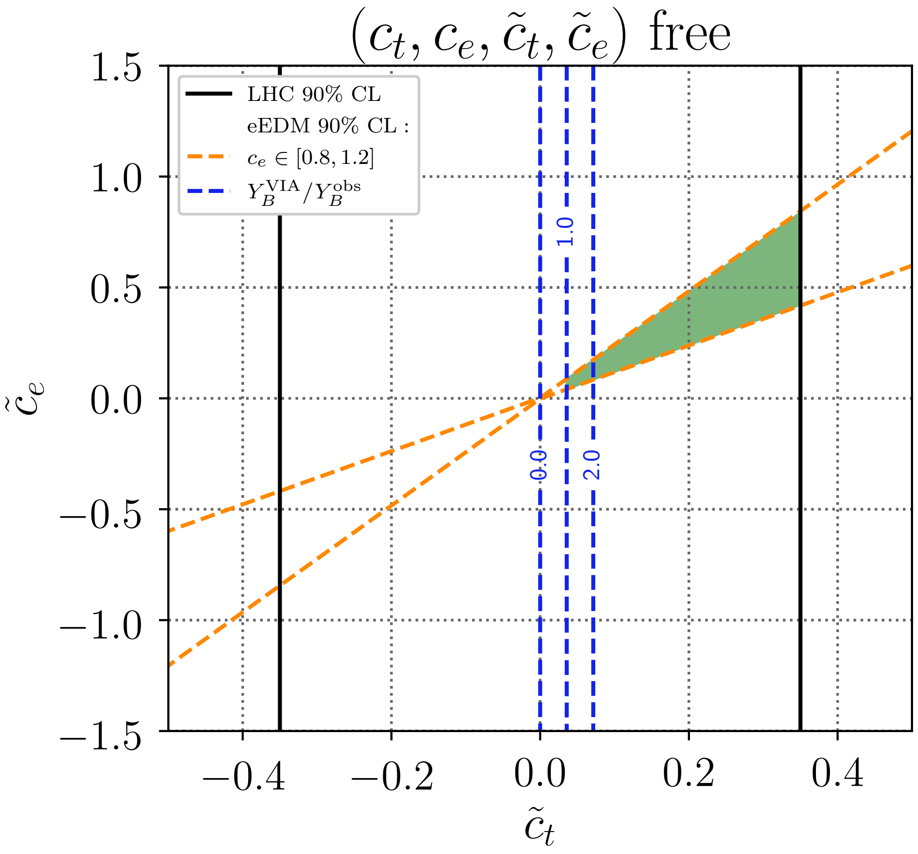


CP-insensitive $H \rightarrow \mu^+\mu^-$ rate measurement outperforms EDM

Dependence on electron-Yukawa coupling

[HB et al.,2202.11753]



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

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

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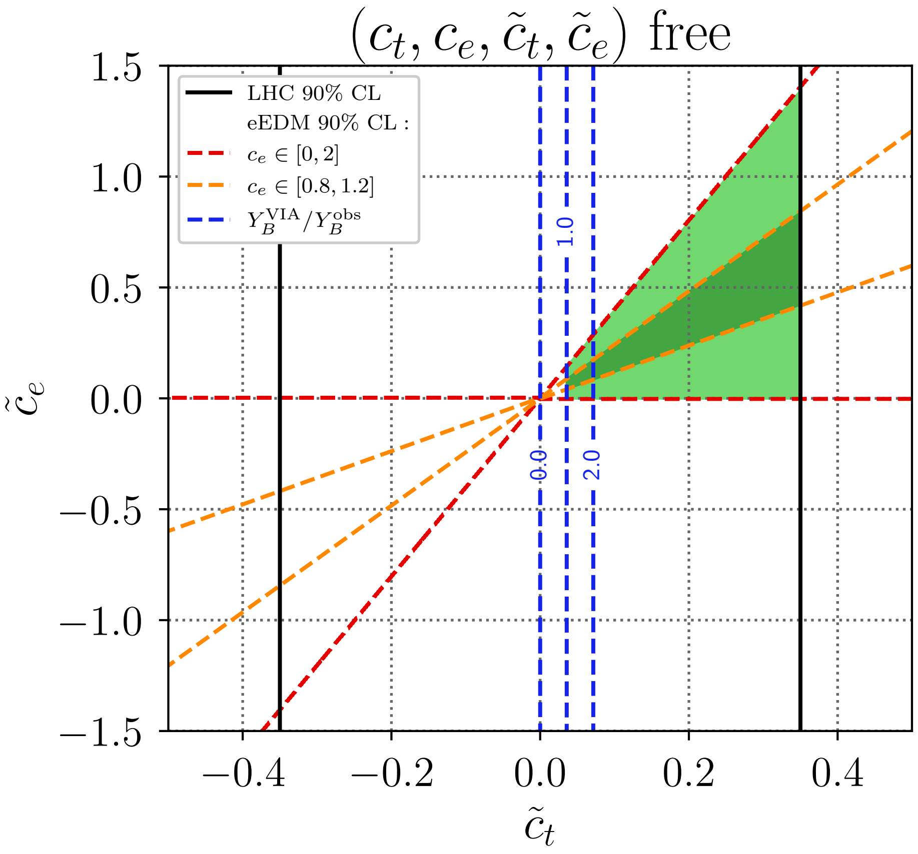

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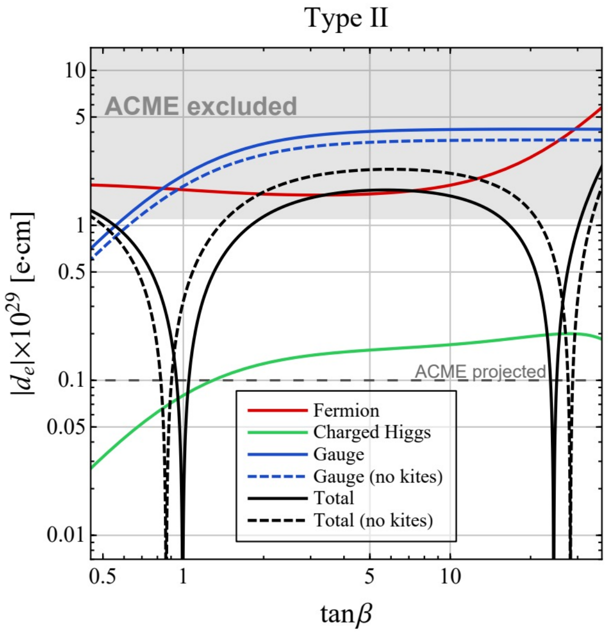
BSM contributions to EDMs

- also BSM particles can have CP-violating coupling
- cancellations between different contributions

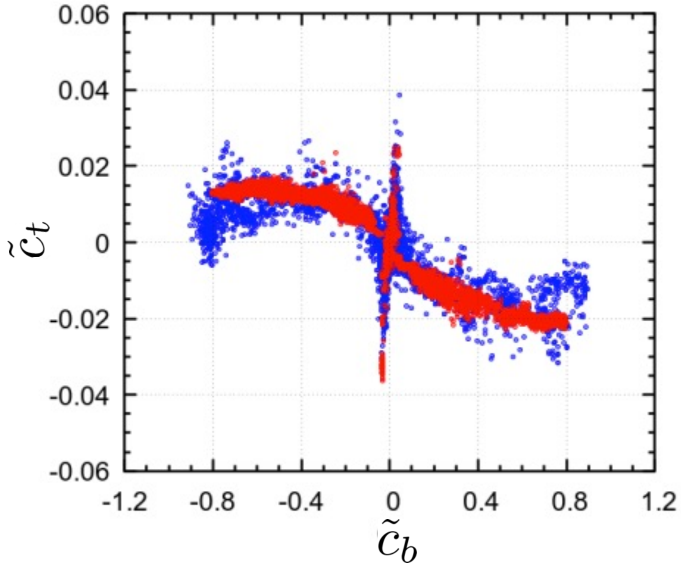
- combine multiple EDMs
- complementarity with direct searches

complex 2HDM



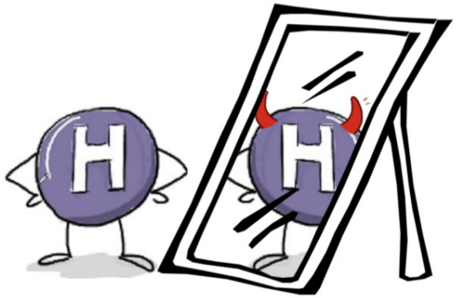
[Altmannshofer et al., 2009.01258]

complex 3HDM



[Boto et al.,2407.19856]

Conclusions



Conclusions

Initial question: how can we probe CP violation in the Higgs sector?

- LHC probes:
  - CP-sensitive but CP-even kinematic distributions → CP sensitive $t\bar{t}H$ STXS extension
  - rate constraints → CP character of bottom-Yukawa
  - CP-odd observables → optimal CP-odd observables using symbolic regression

- EDM constraints:
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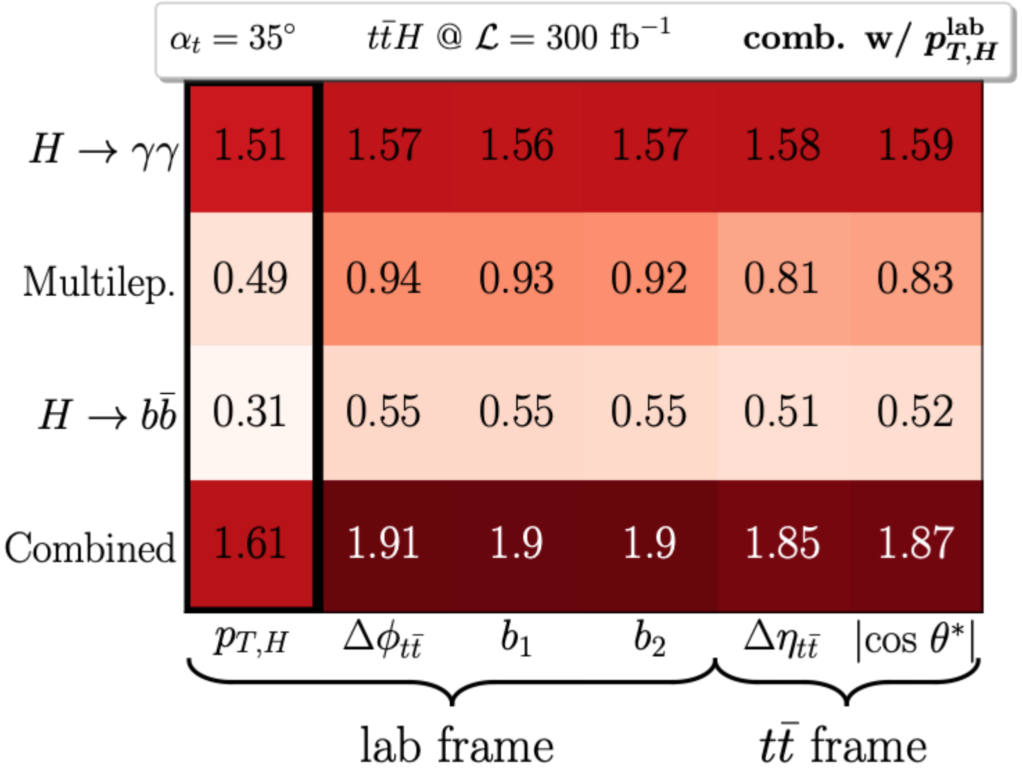
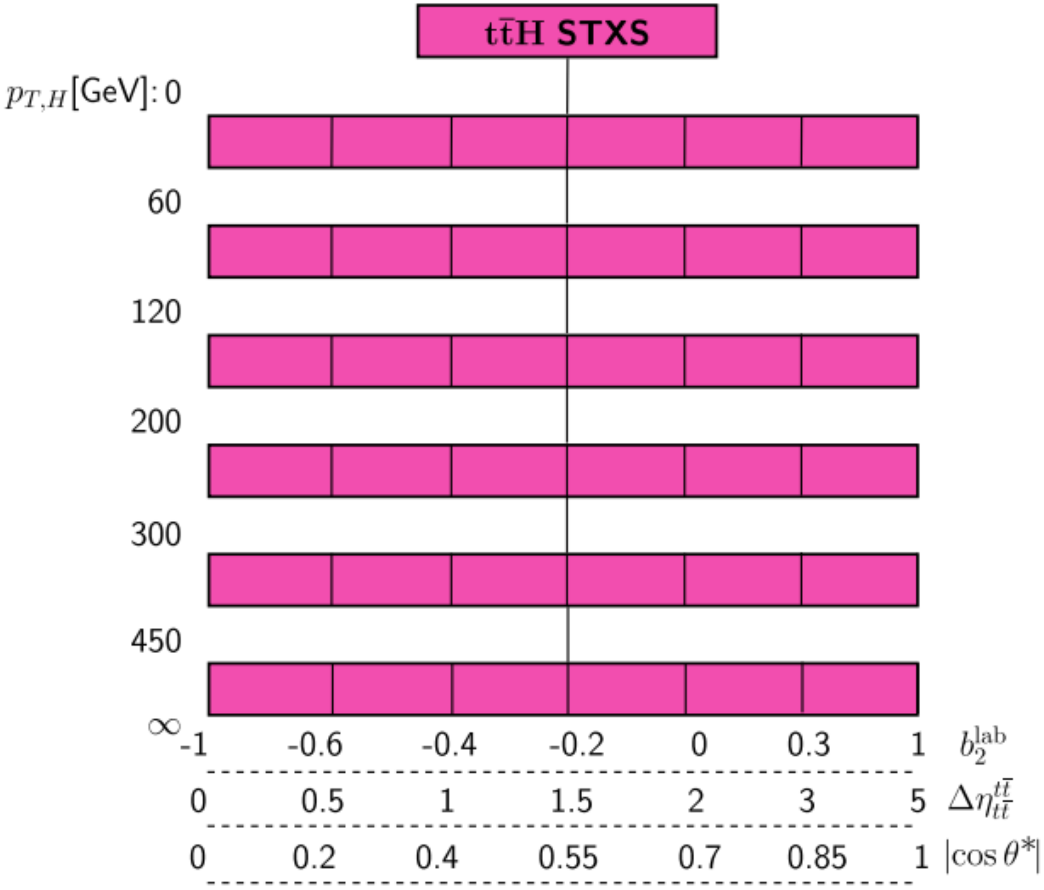
Thanks for your attention!

Appendix



$\alpha_t = 35^\circ$ $t\bar{t}H$ @ $\mathcal{L} = 300\ \text{fb}^{-1}$ **comb. w/ $p_{T,H}^{\text{lab}}$**

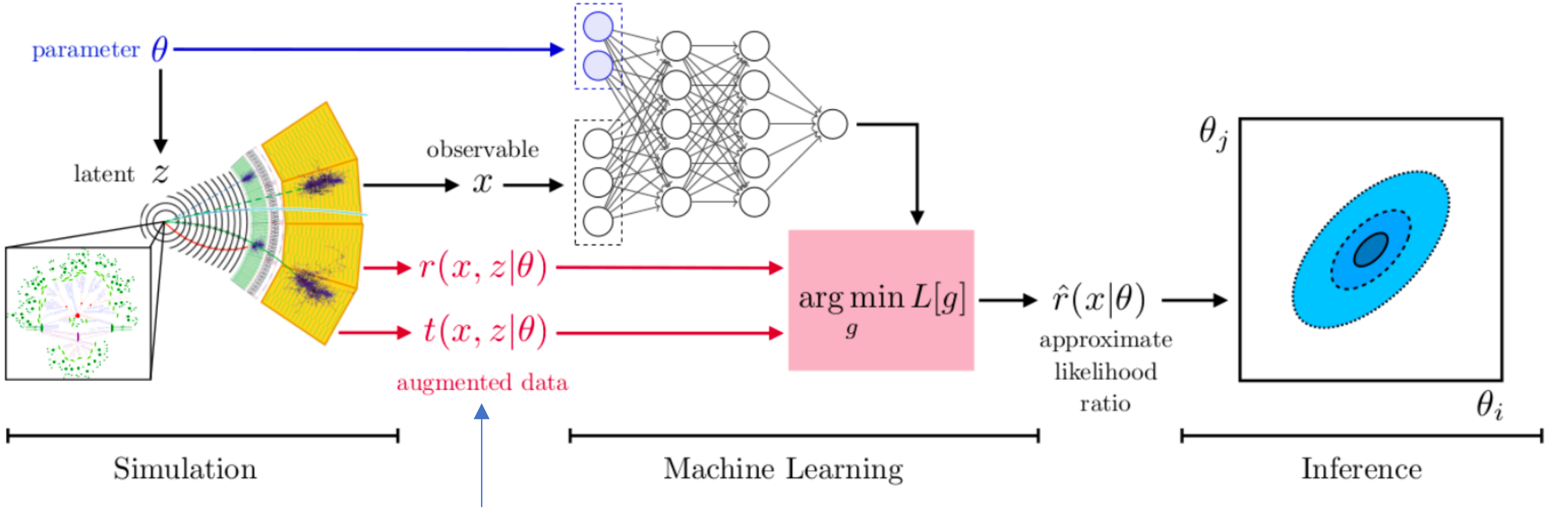
	$p_{T,H}$	$\Delta\phi_{t\bar{t}}$	b_1	b_2	$\Delta\eta_{t\bar{t}}$	$\lvert\cos\theta^*\rvert$
$H \to \gamma\gamma$	1.51	1.57	1.56	1.57	1.58	1.59
Multilep.	0.49	0.94	0.93	0.92	0.81	0.83
$H \to b\bar{b}$	0.31	0.55	0.55	0.55	0.51	0.52
Combined	1.61	1.91	1.9	1.9	1.85	1.87



Simulation-based inference

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

[Brehmer et al.,1805.00013]



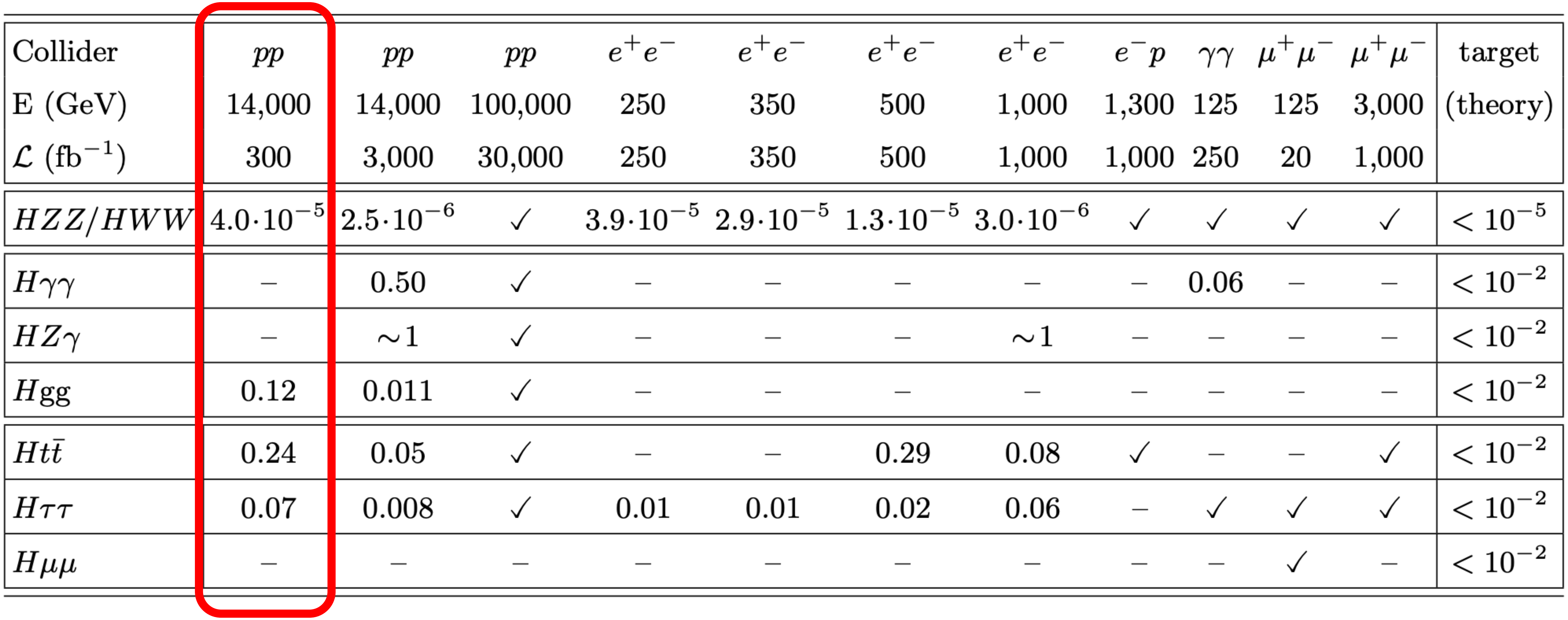
Matrix element information

- Allows to extract the full available information (maximal sensitivity).
- No information loss due to binning (as for BDT analysis).
- No approximation of shower and detector effects

Example applications:

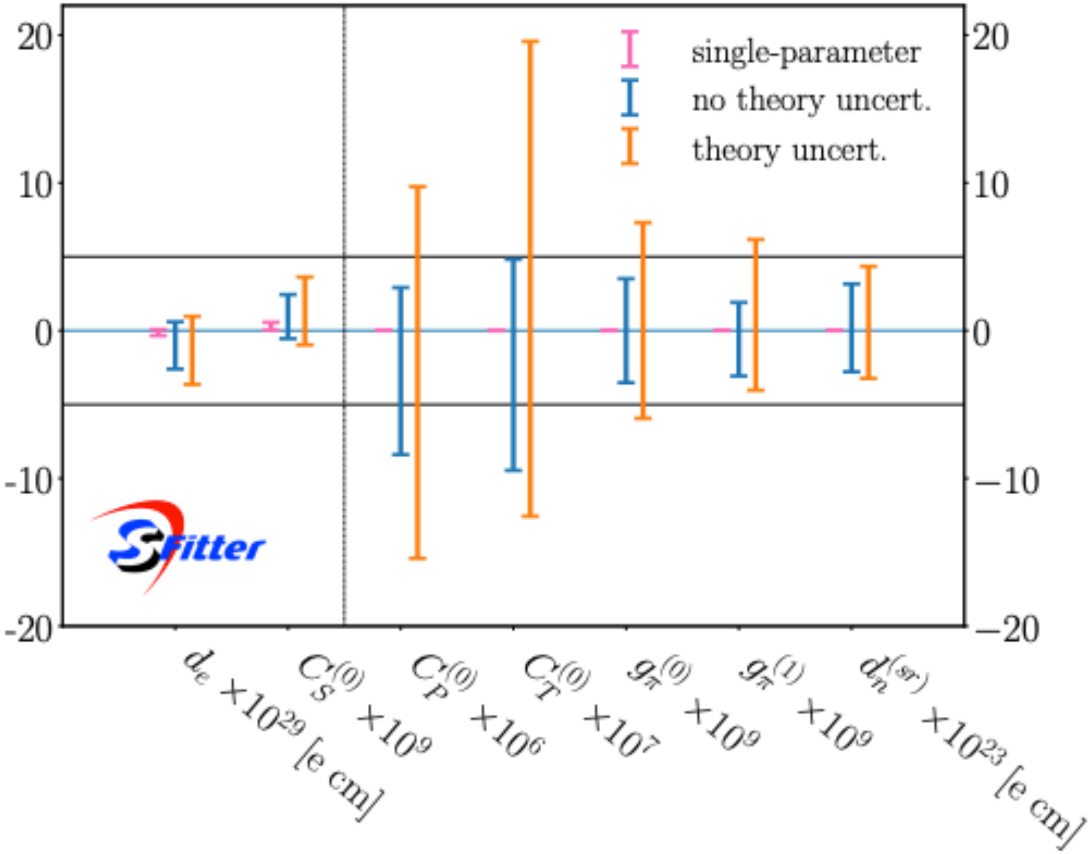
- $t\bar{t}H \rightarrow \sim$ 35% better limits on CP phase than from 2D histogram. [Barman et al.,2110.07635;HB & Brass 2110.10177]
- $WH \rightarrow$ ~25% better limits on $c_{\tilde{H}W}$ than from 2D histogram [Barrue et al., 2308.02882]

Current status and future outlook



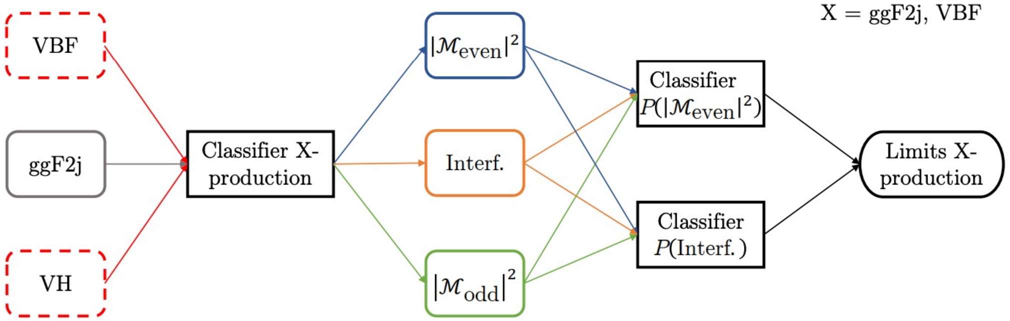
Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	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: $f_{CP}^{HX} \equiv \dfrac{\Gamma_{H\to X}^{CP\,\mathrm{odd}}}{\Gamma_{H\to X}^{CP\,\mathrm{odd}} + \Gamma_{H\to X}^{CP\,\mathrm{even}}}$


20
10
0
-10
-20
20
10
0
−10
−20
single-parameter
no theory uncert.
theory uncert.
SFitter
$d_e \times 10^{29}$ [e cm]
$C_S^{(0)} \times 10^9$
$C_P^{(0)} \times 10^6$
$C_T^{(0)} \times 10^7$
$g_\pi^{(0)} \times 10^9$
$g_\pi^{(1)} \times 10^9$
$d_n^{(sr)} \times 10^{23}$ [e cm]

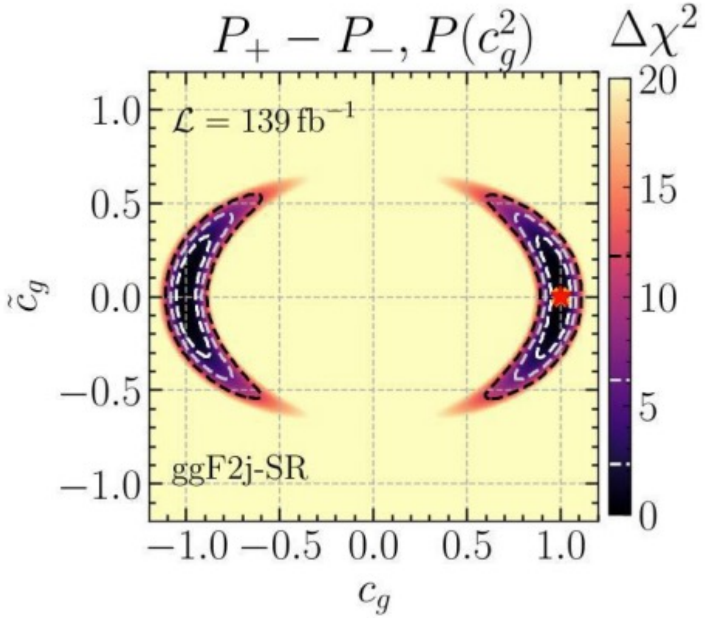
Classifying the CP properties of the ggH coupling in H+2j production

[HB,Fuchs,Hannig,Menen,2309.03146]

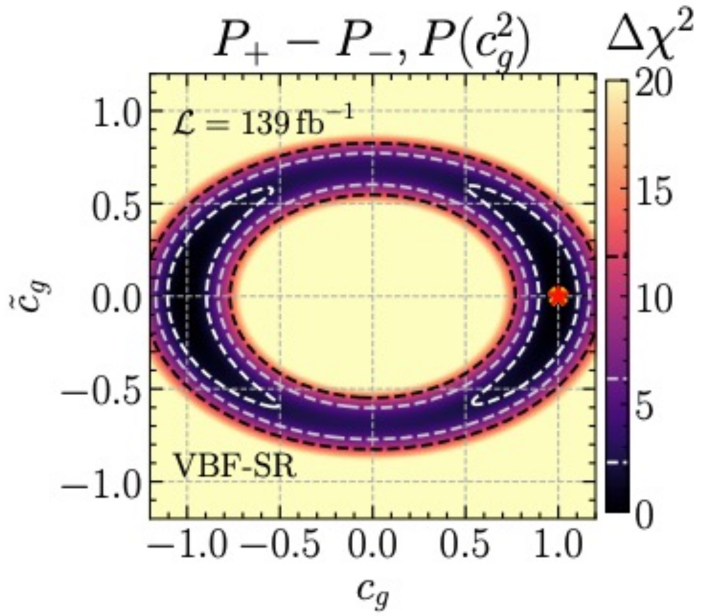


Train two classifiers to define optimal CP-even and CP-odd observables

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

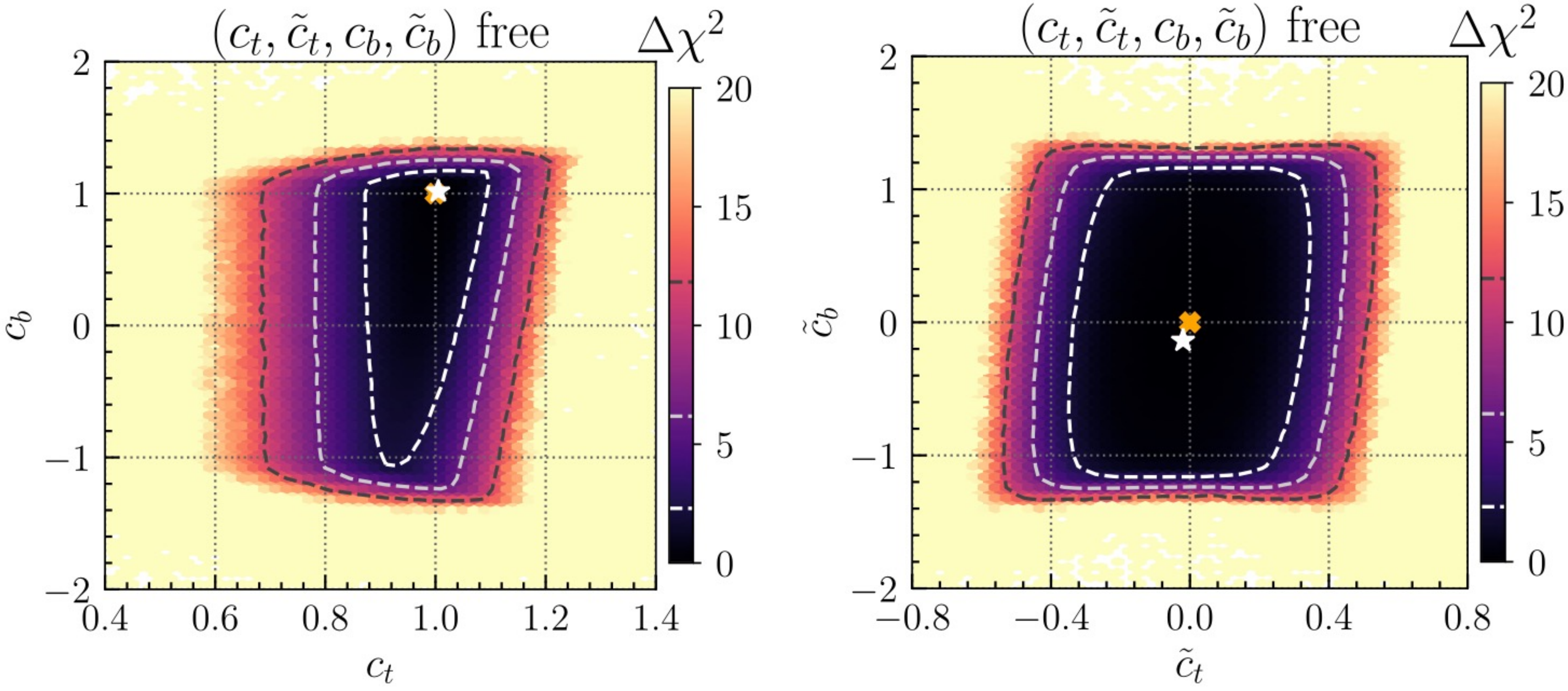


vs.



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

Interplay of bottom and top Yukawas

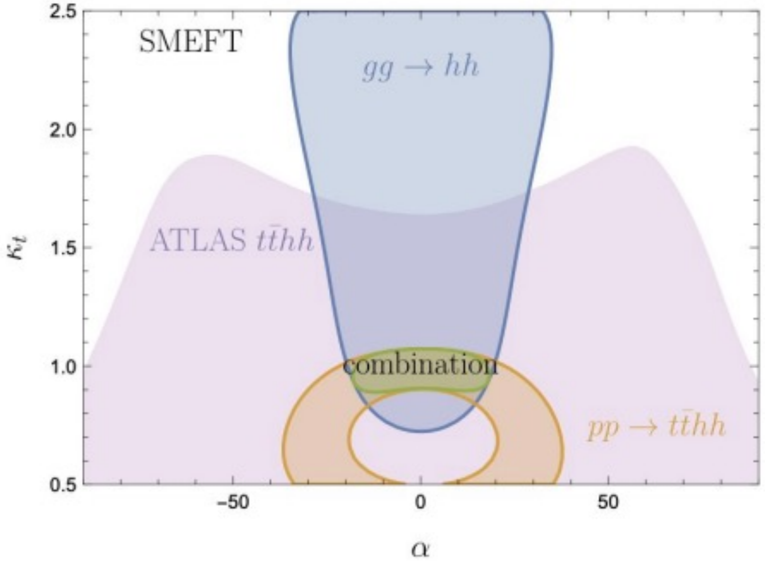


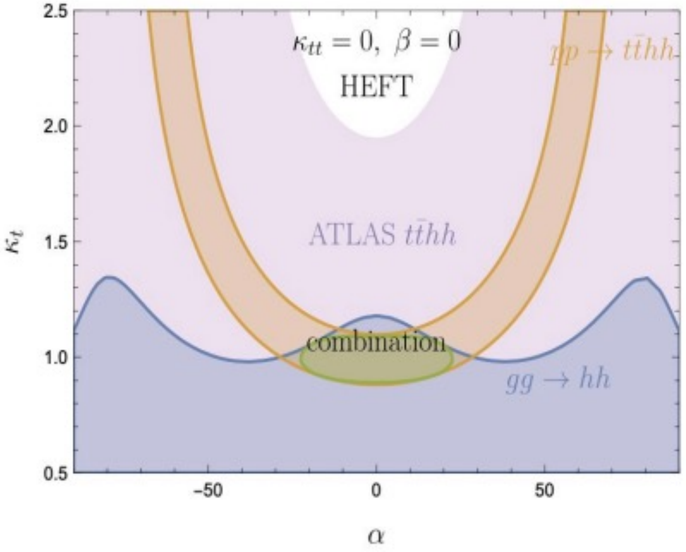
Non-linear top-Higgs CP violation

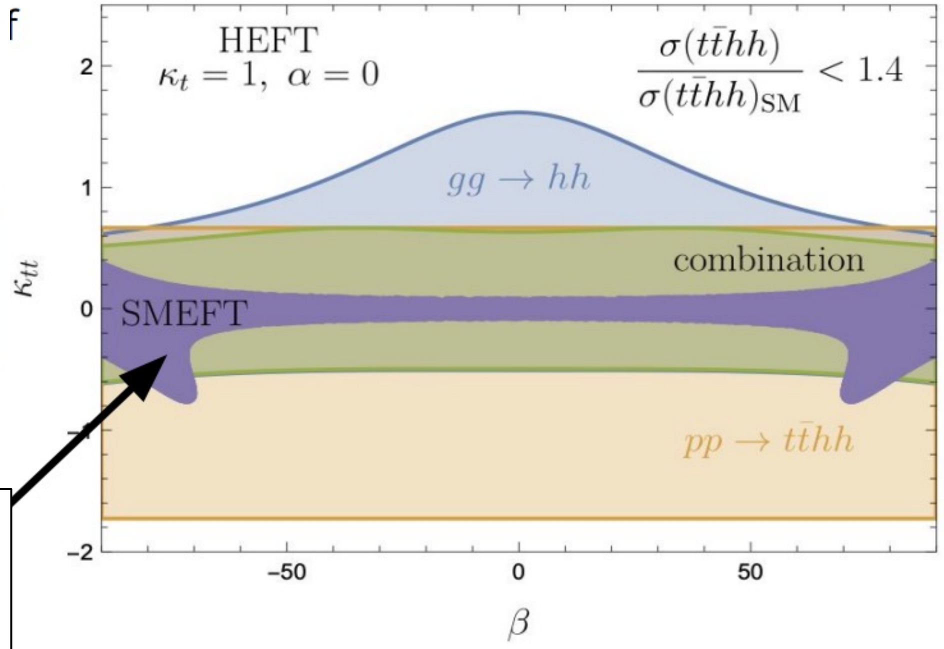
[Bhardwaj,Englert,Goncalves,Navarro, 2308.11722]

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

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







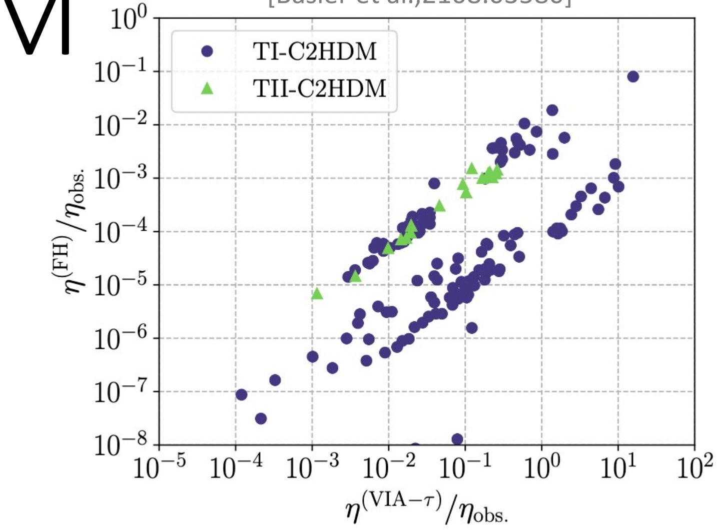
$$\kappa_{tt}^2 = 9(1 - 2\kappa_t\cos\alpha + \kappa_t^2)$$
$$\tan\beta = \frac{\kappa_t\sin\alpha}{\kappa_t\cos\alpha - 1}$$

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]