Deciphering the CP nature of the Higgs boson

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The Higgs discovery

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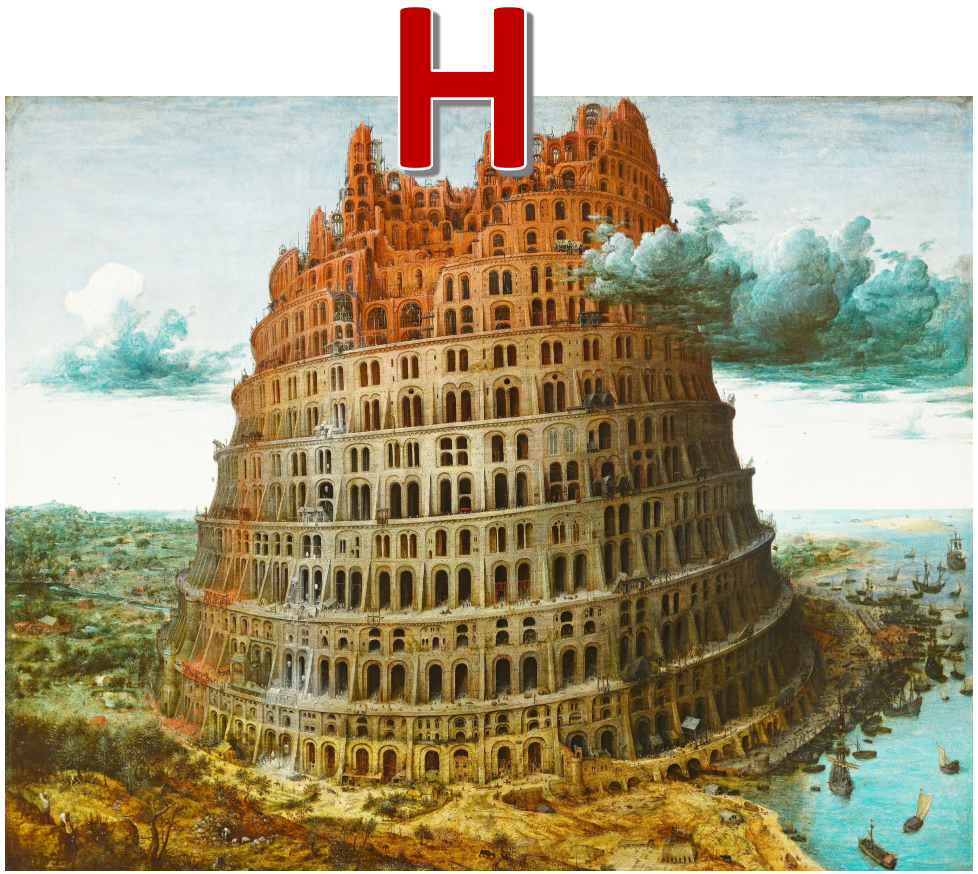

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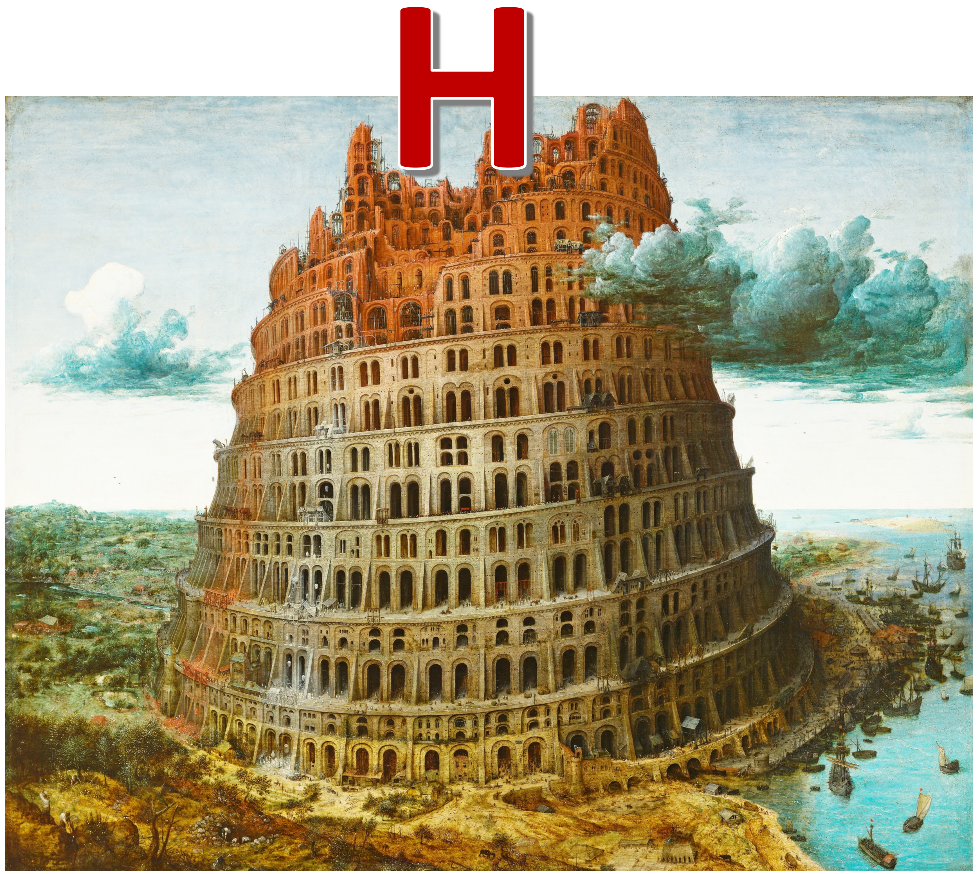

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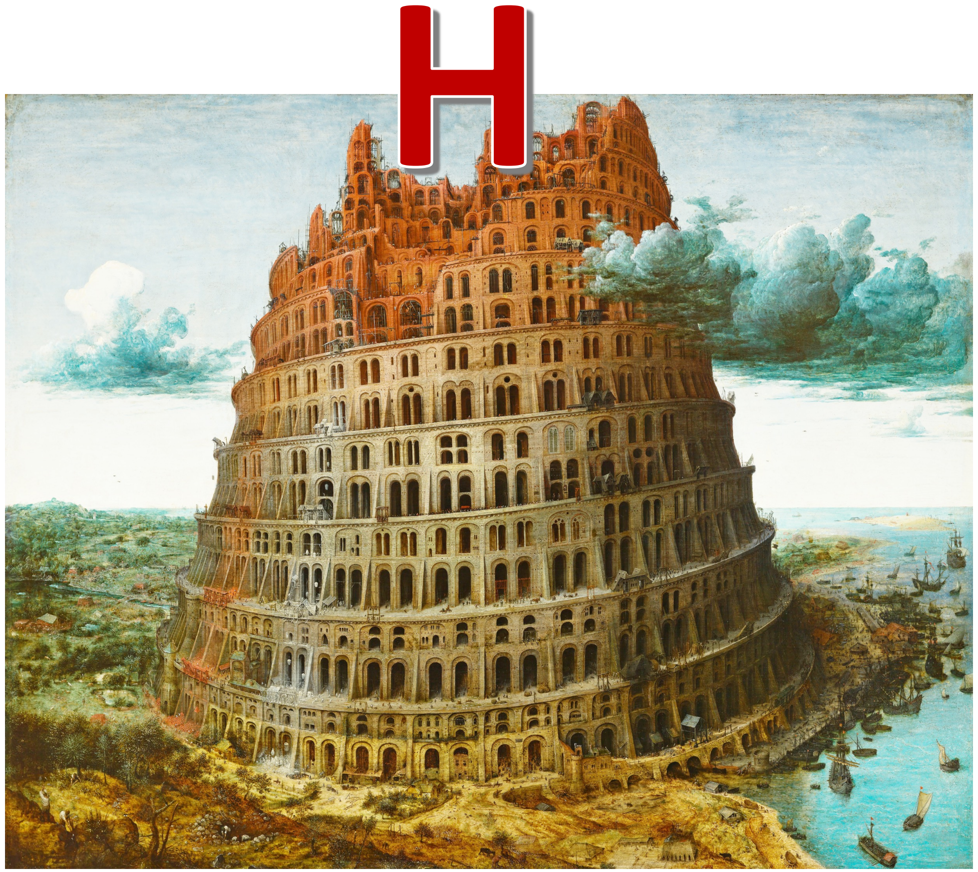

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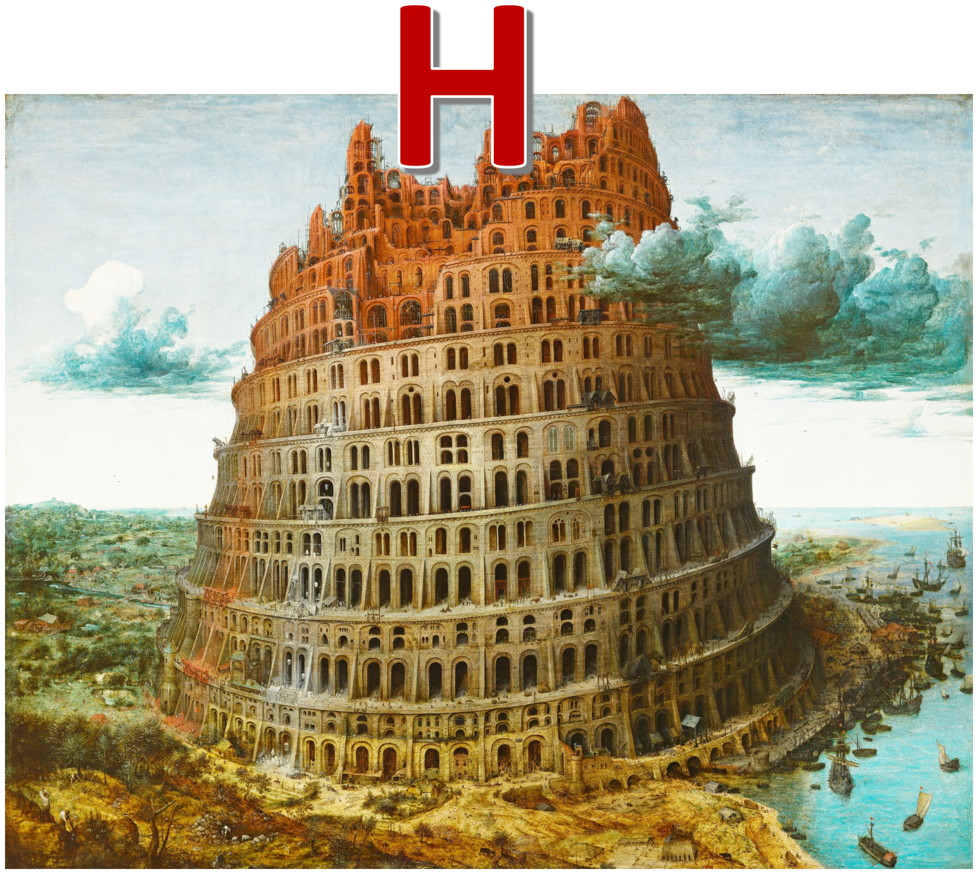
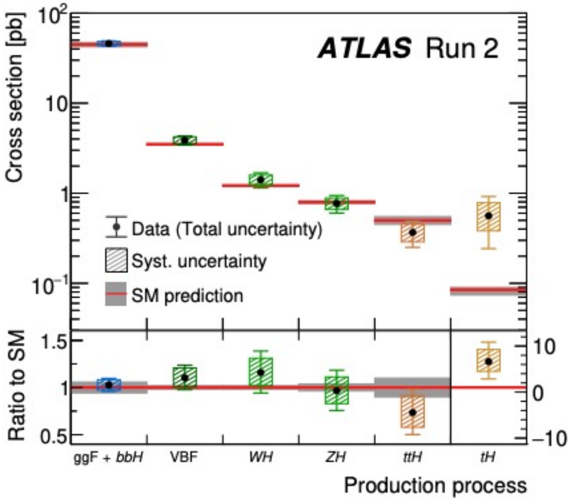
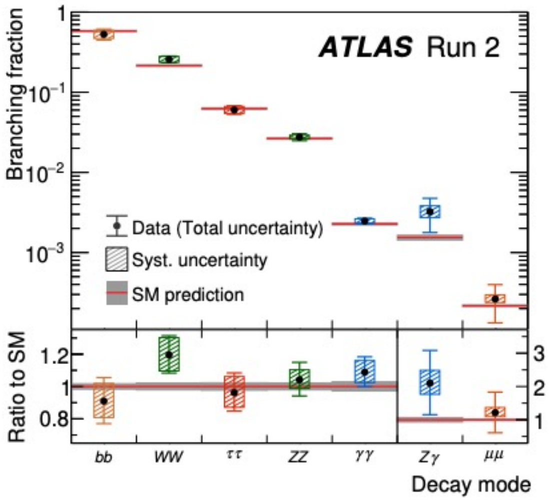
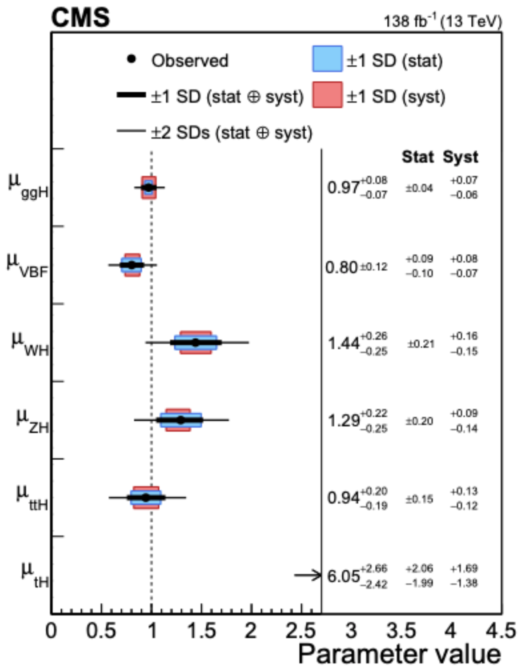


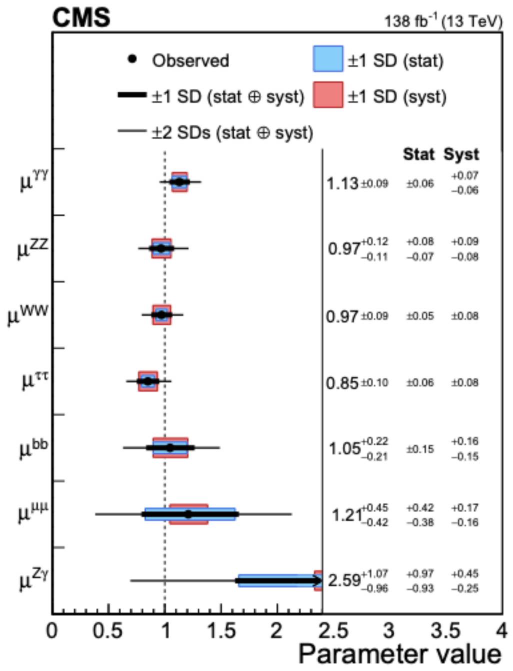
The Higgs 10 years later

[ATLAS 2207.00092, CMS 2207.00043]









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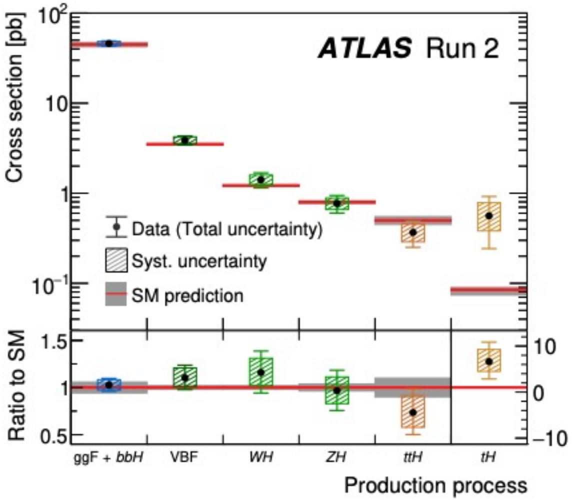

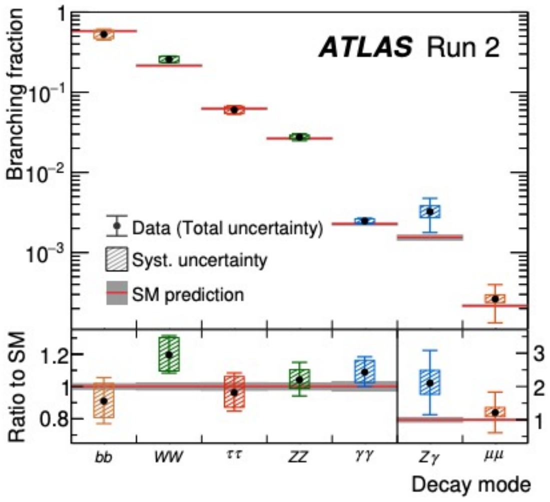

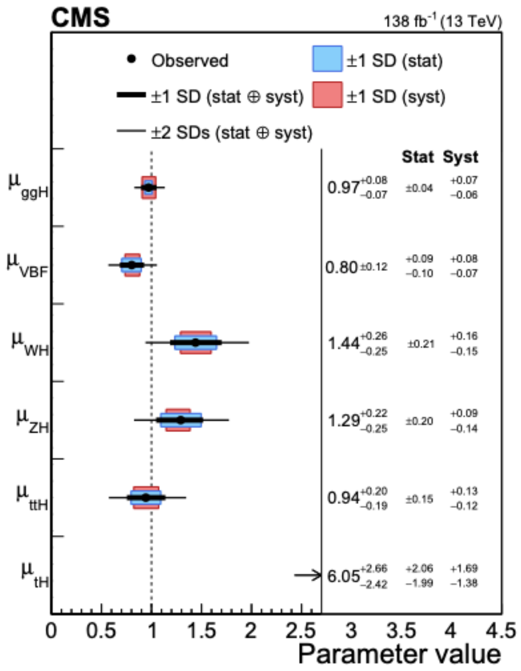

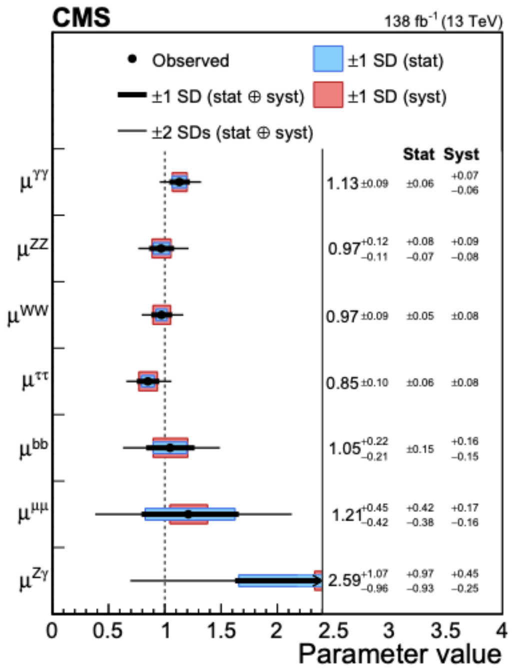

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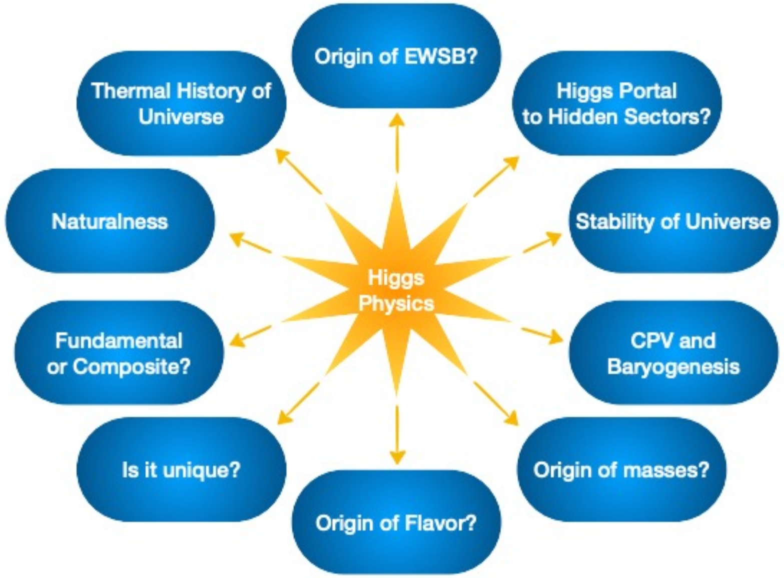

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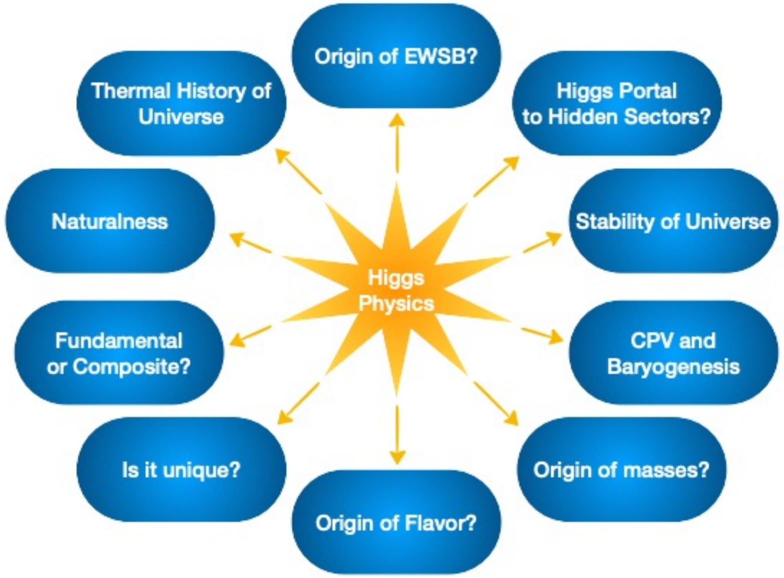

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$\Rightarrow$ Strong motivation for on-going and future Higgs precision programs.

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Have we found the SM Higgs?

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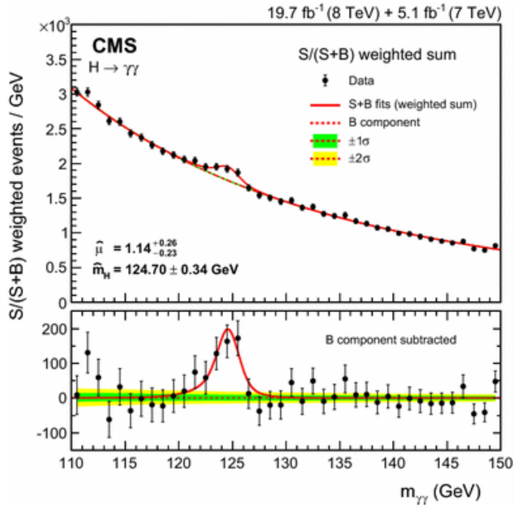

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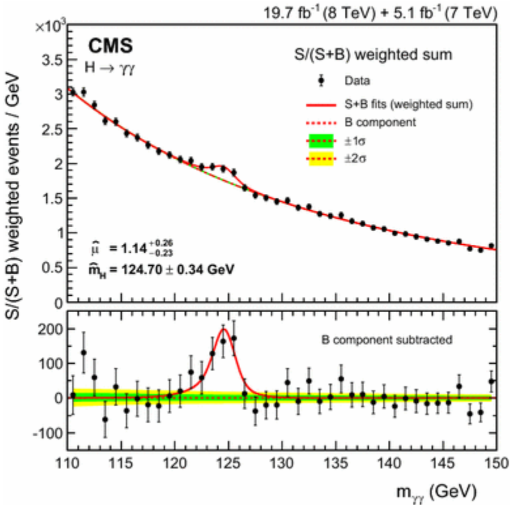

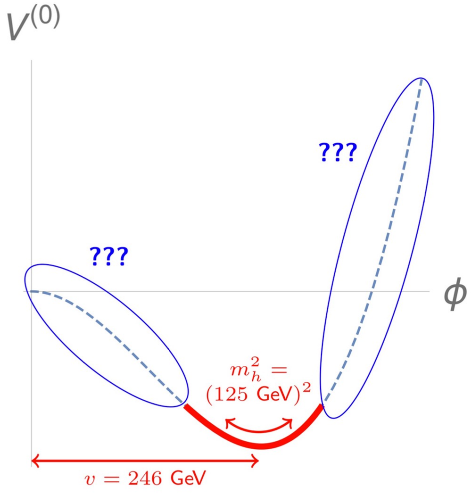

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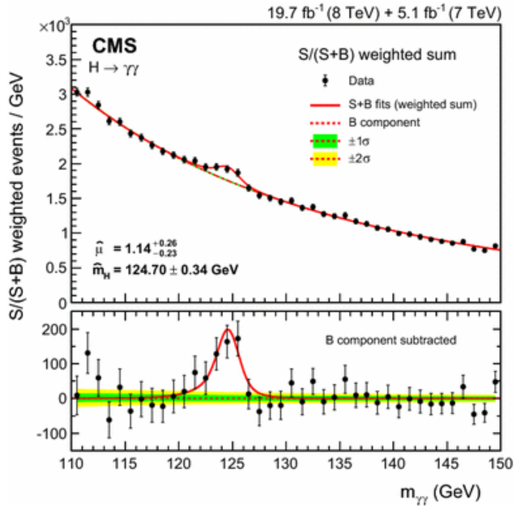

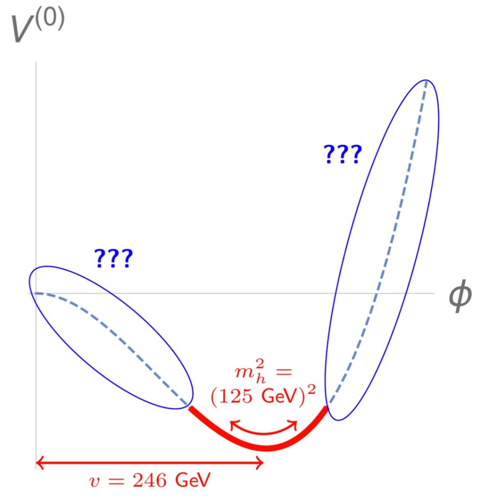

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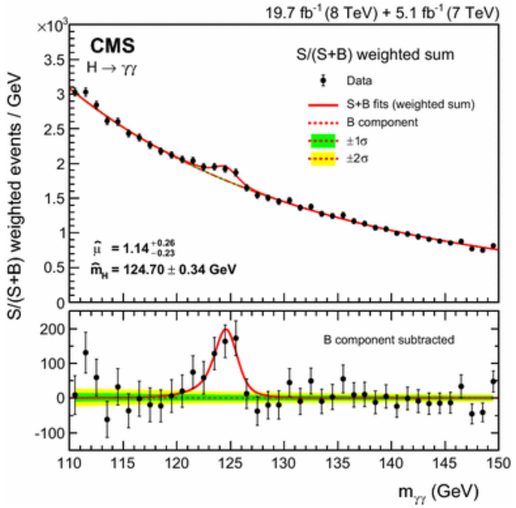

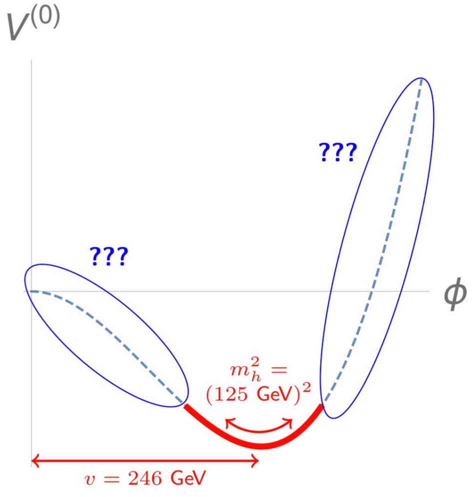

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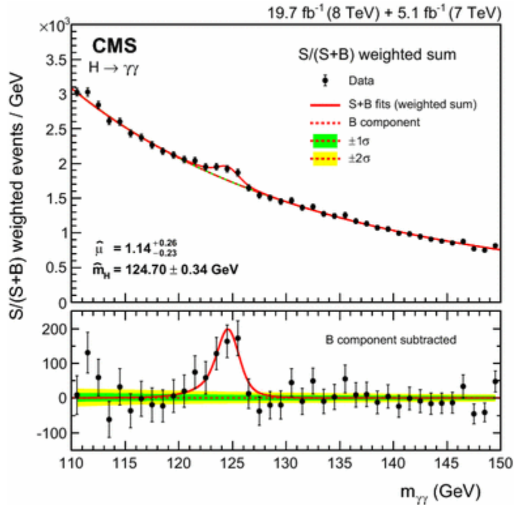

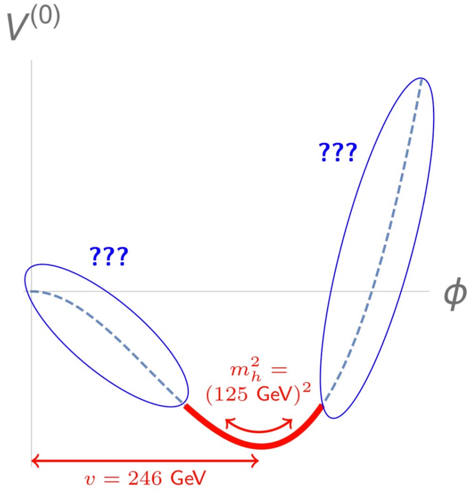

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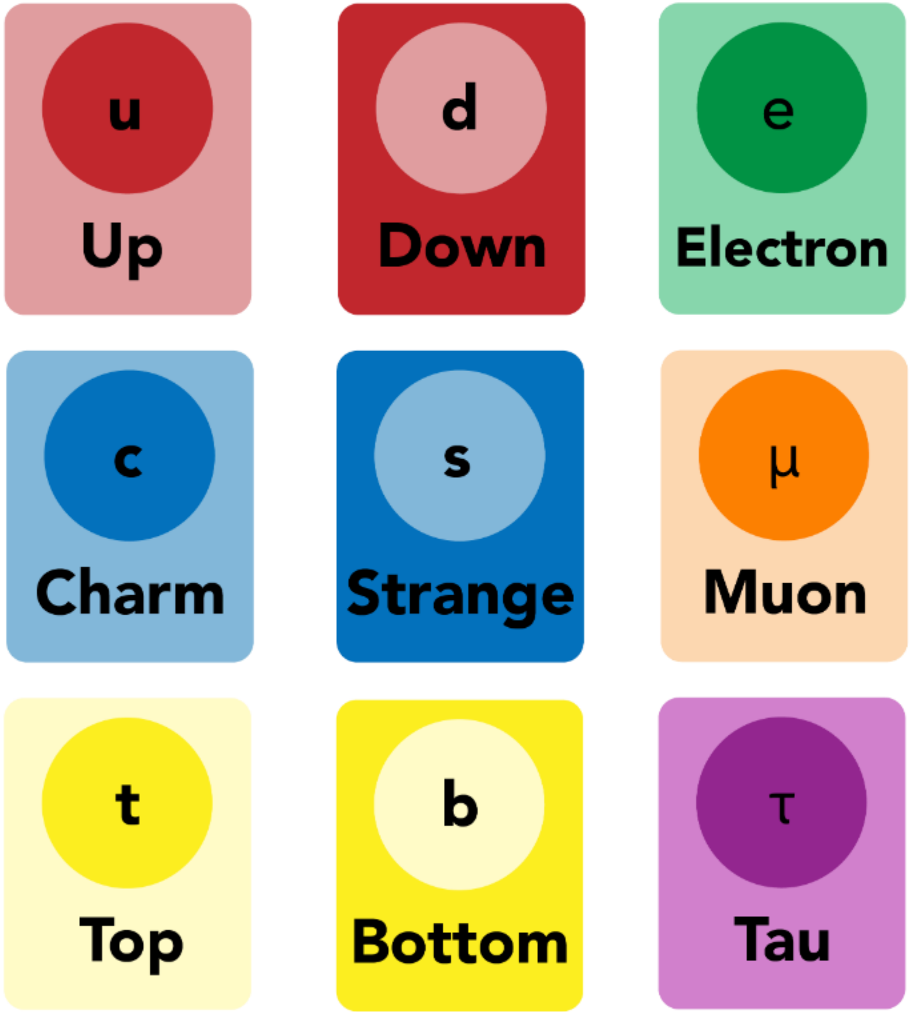

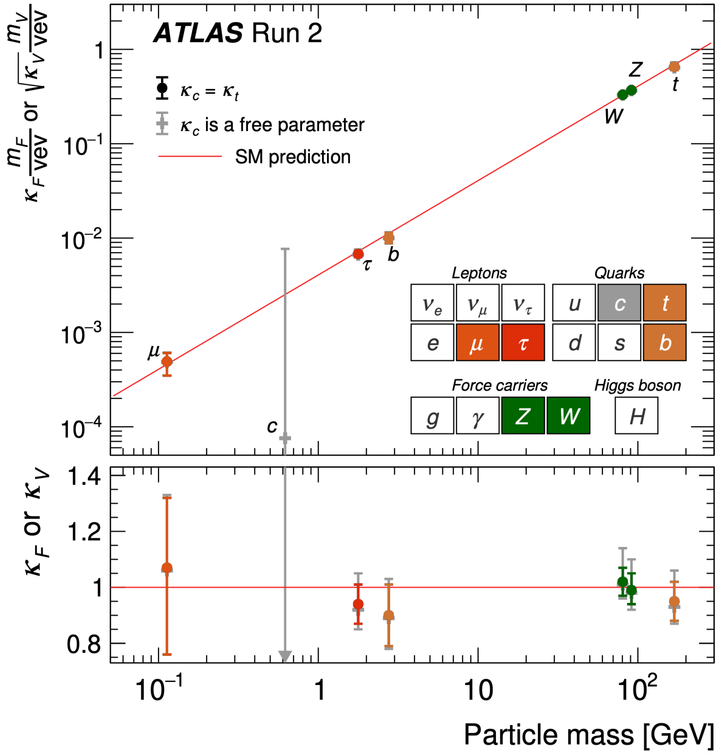

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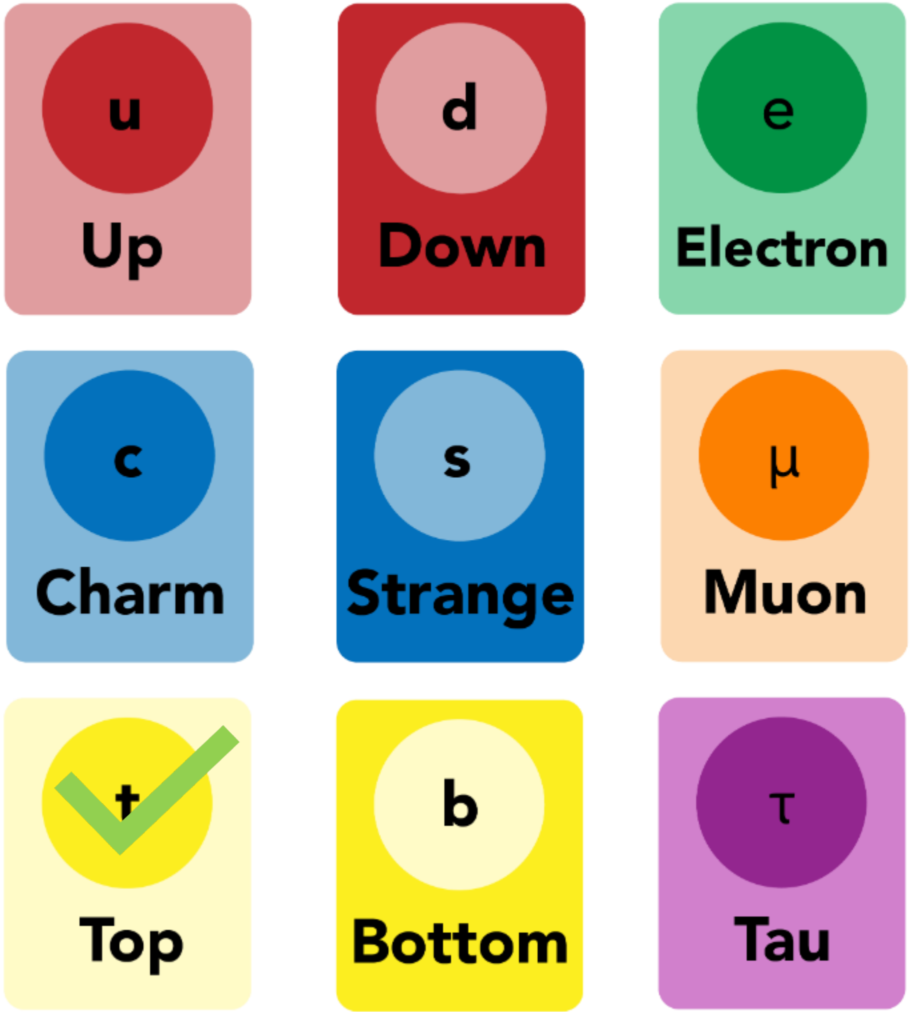

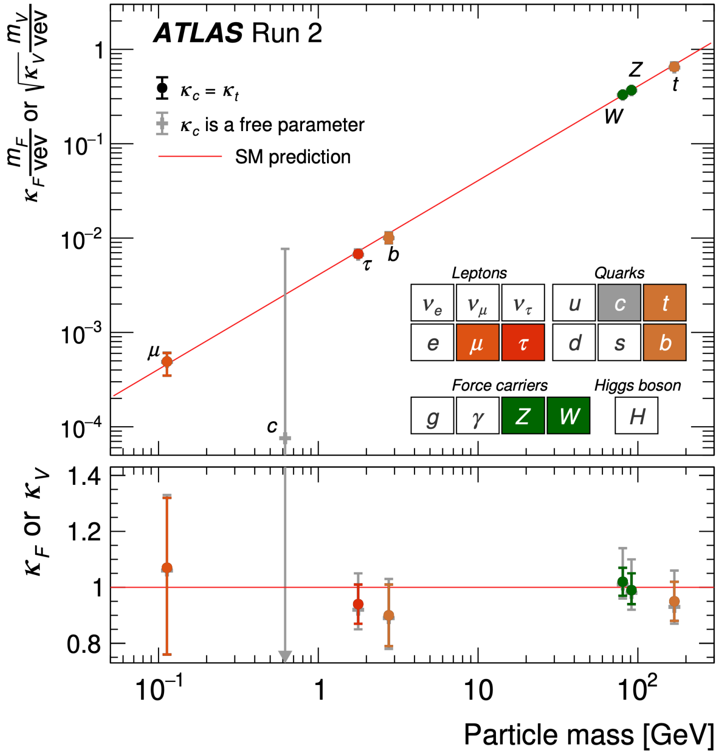

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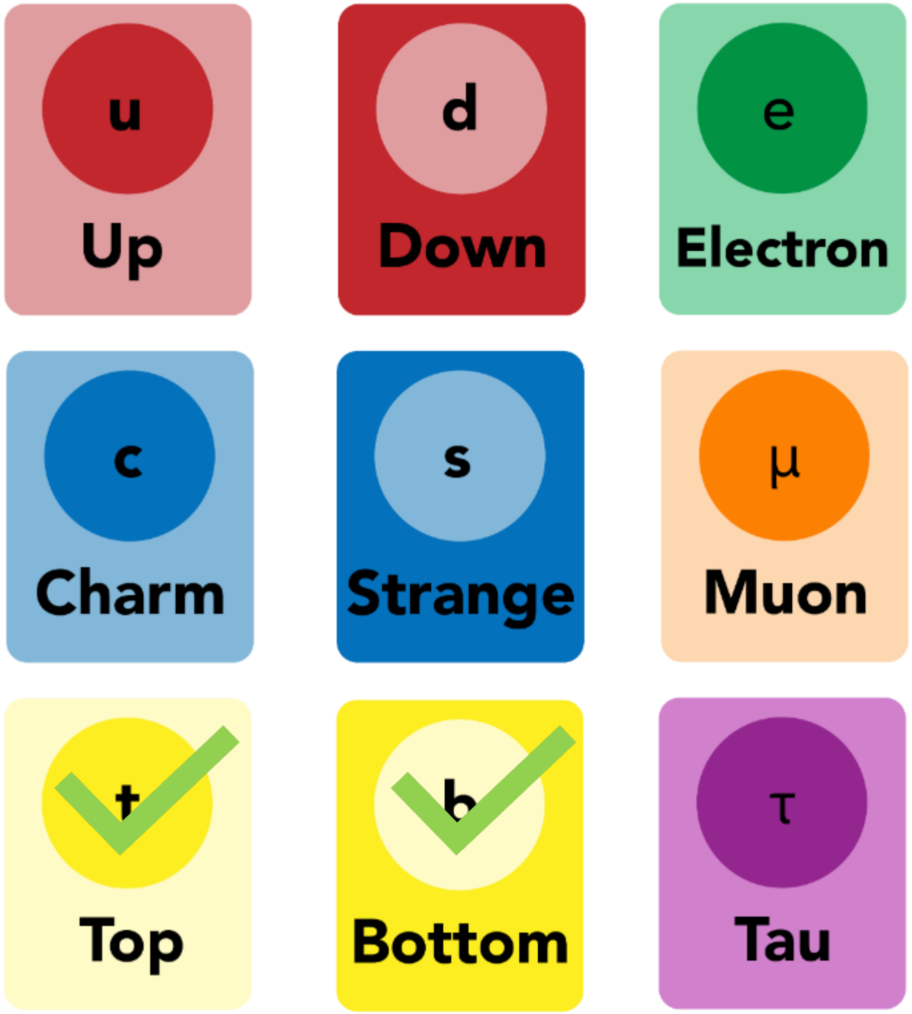

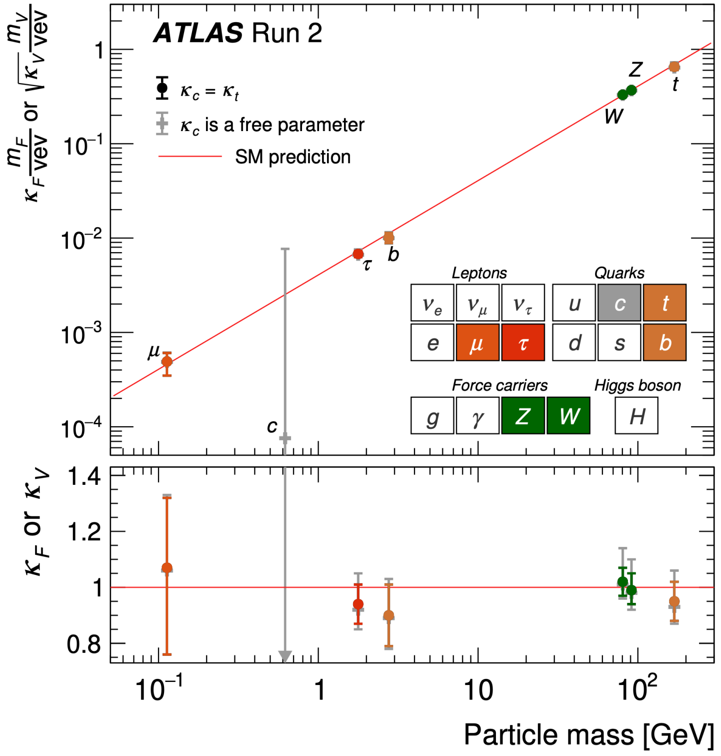

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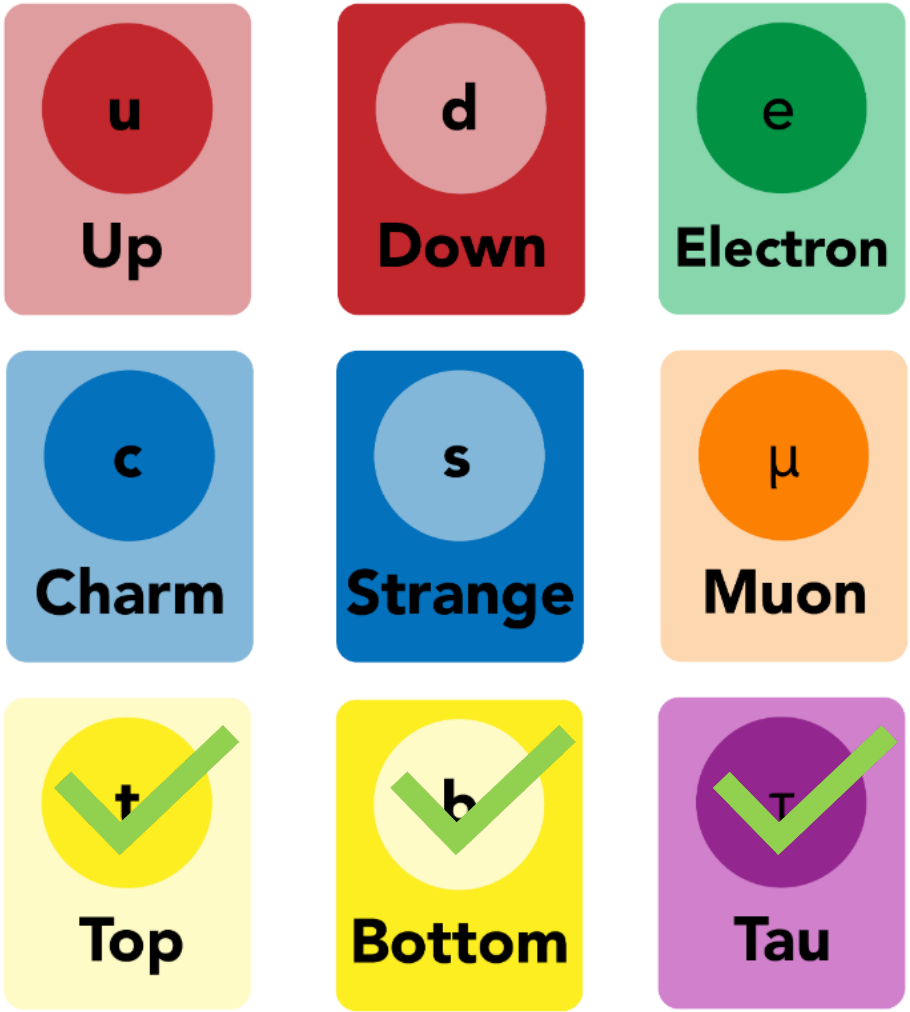

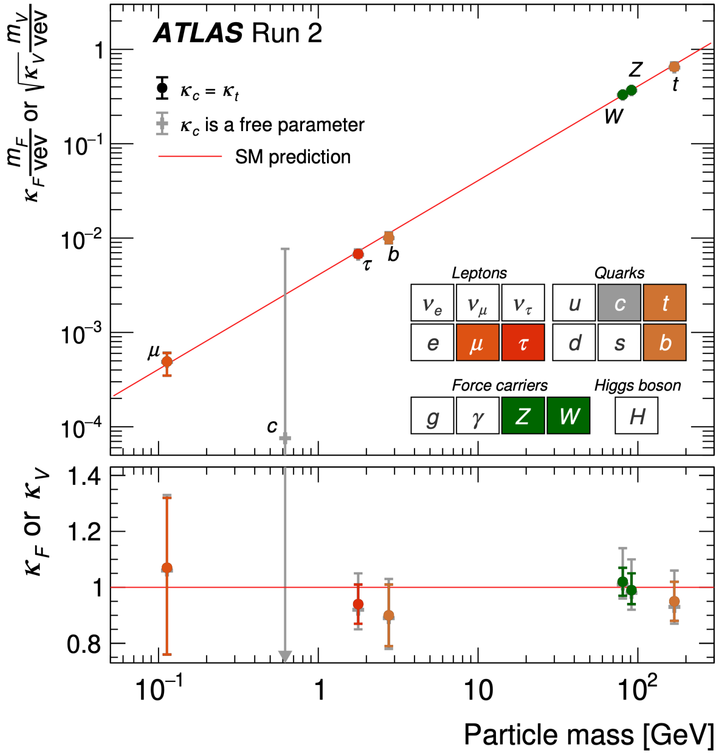

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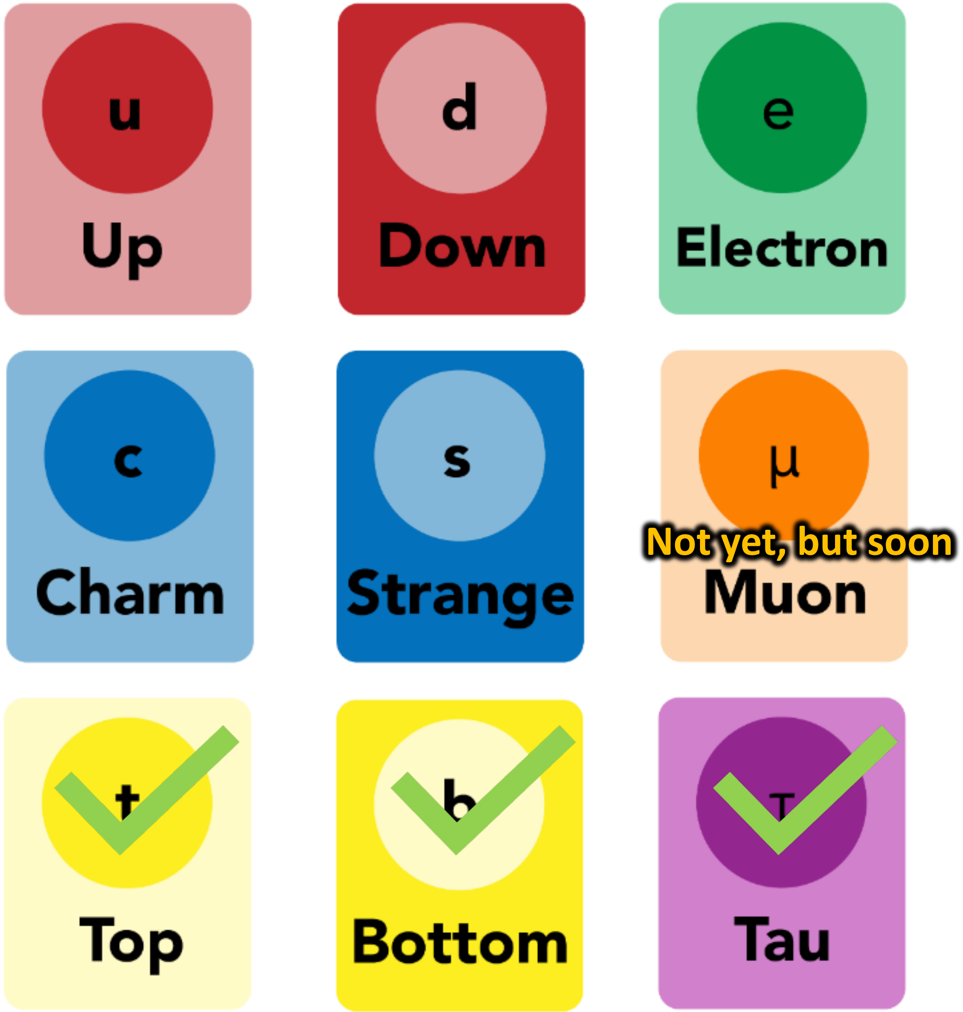

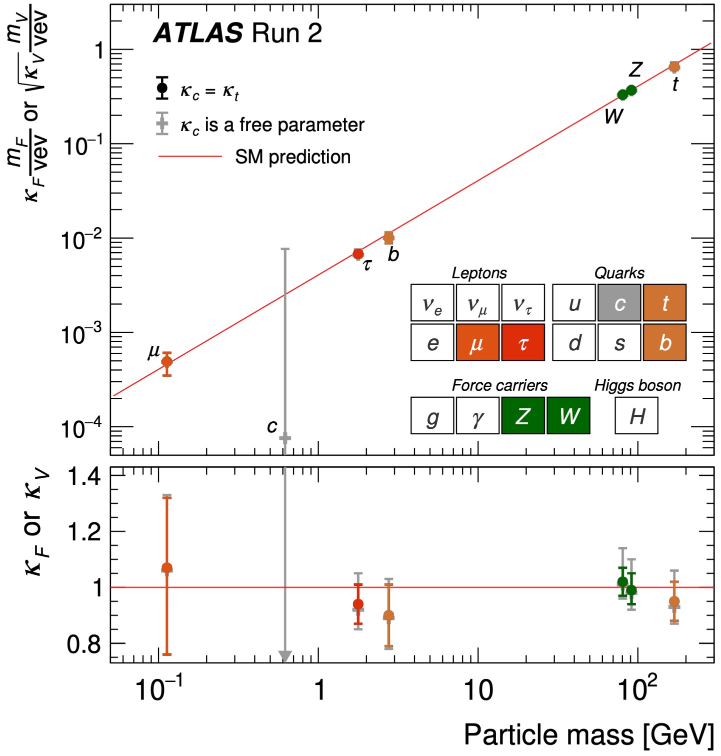

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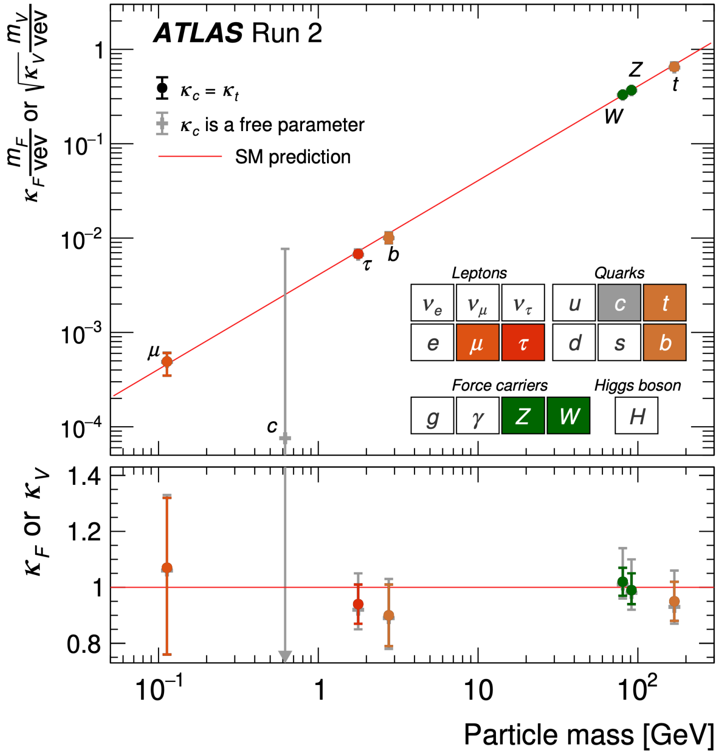

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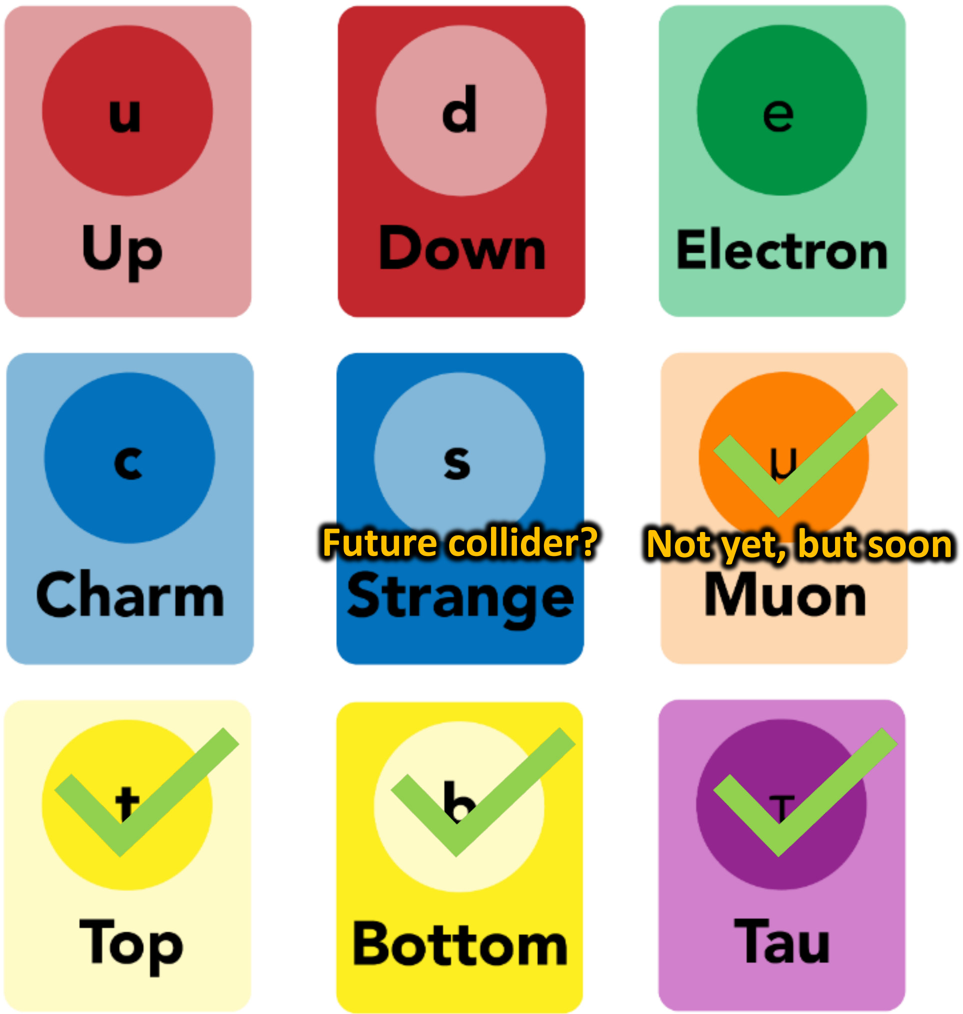

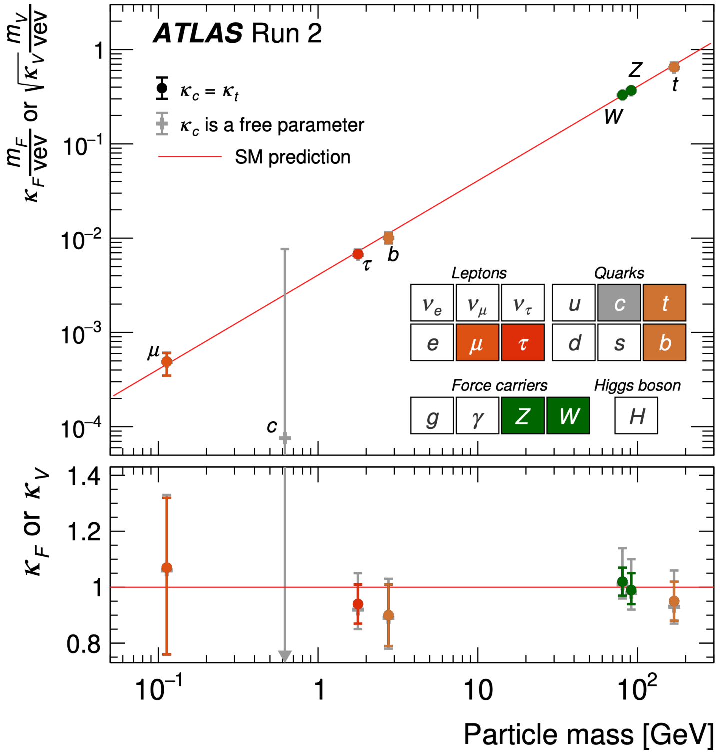

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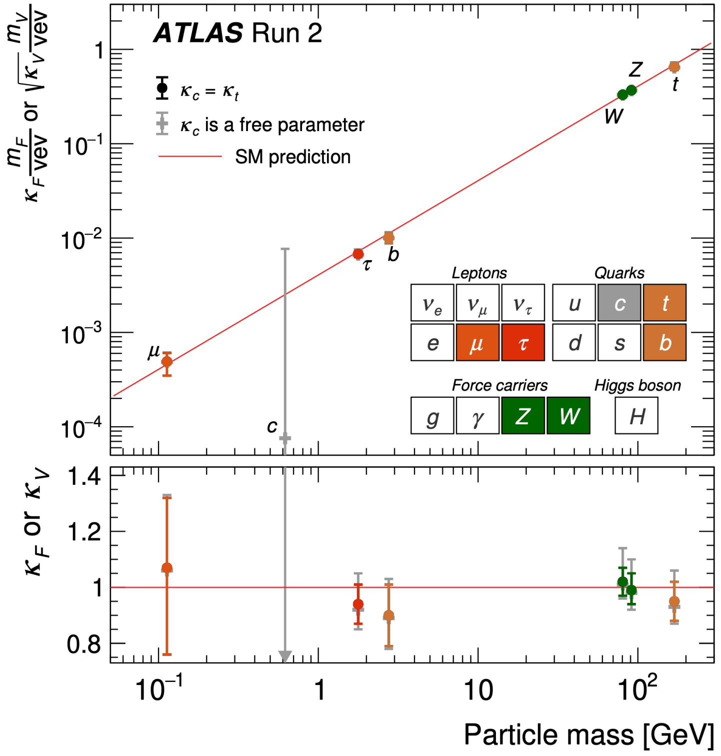

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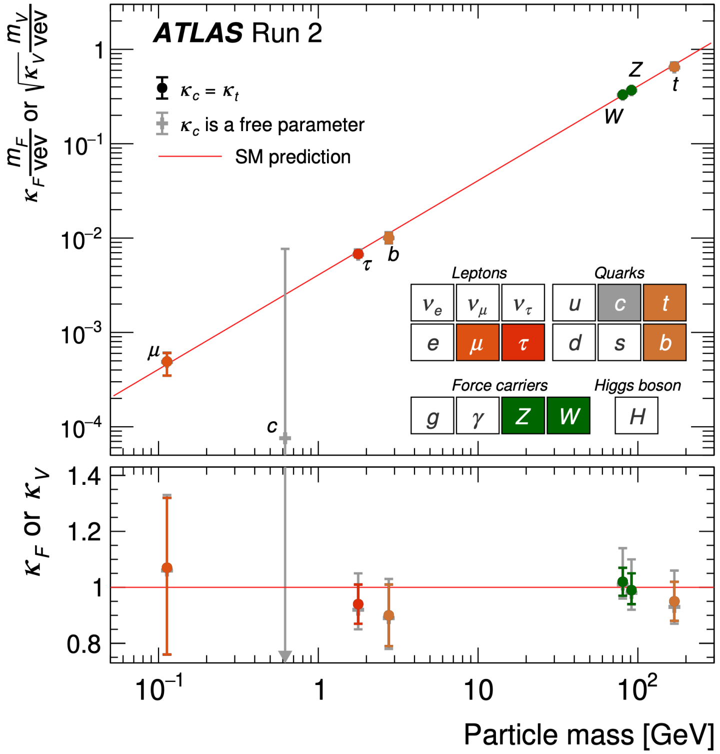

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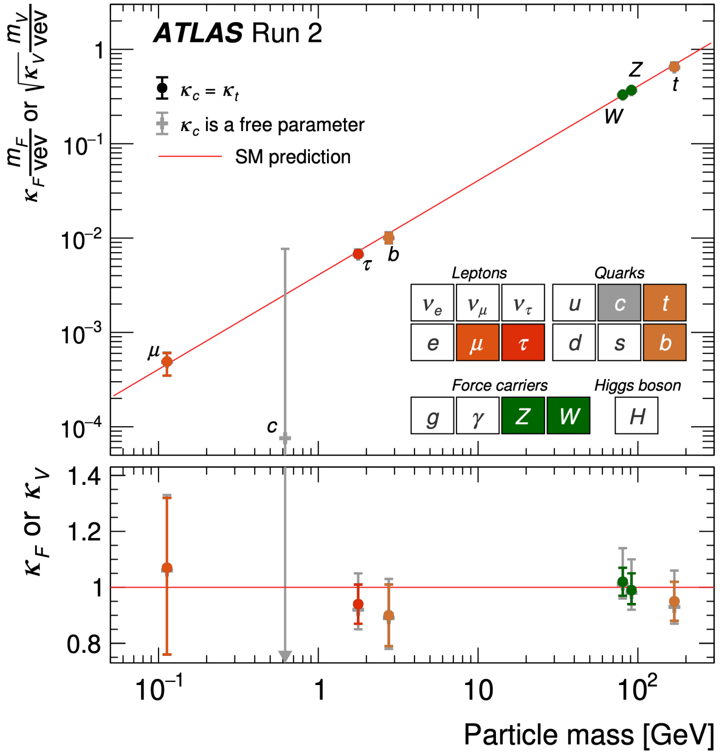

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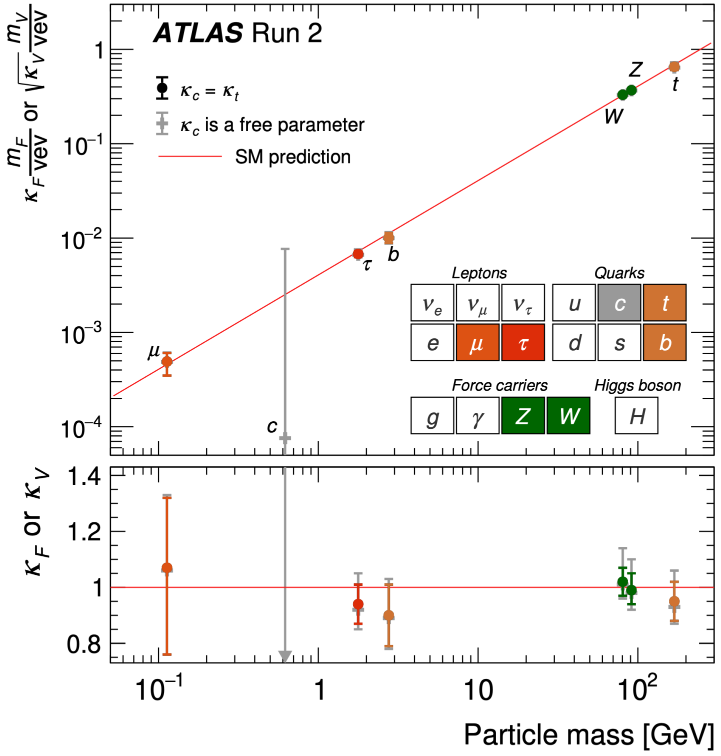

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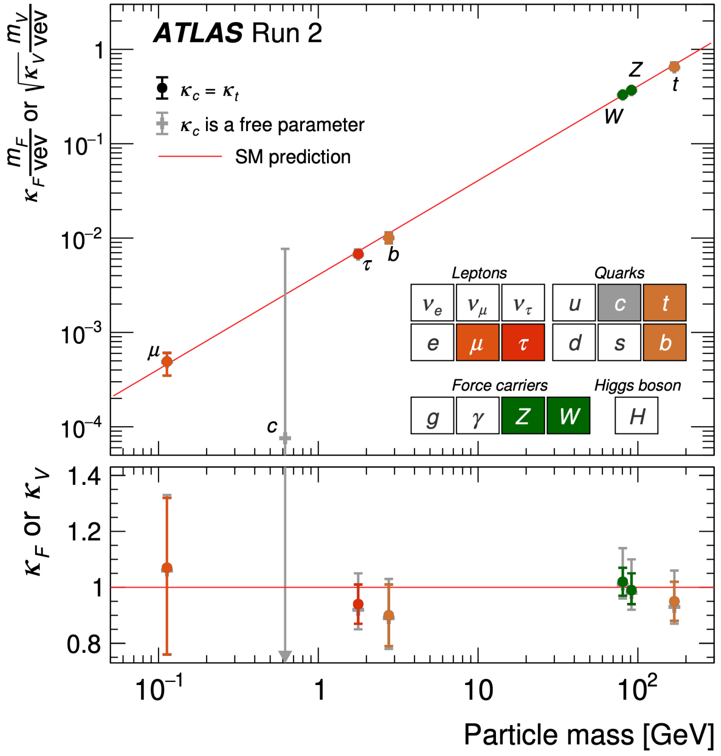

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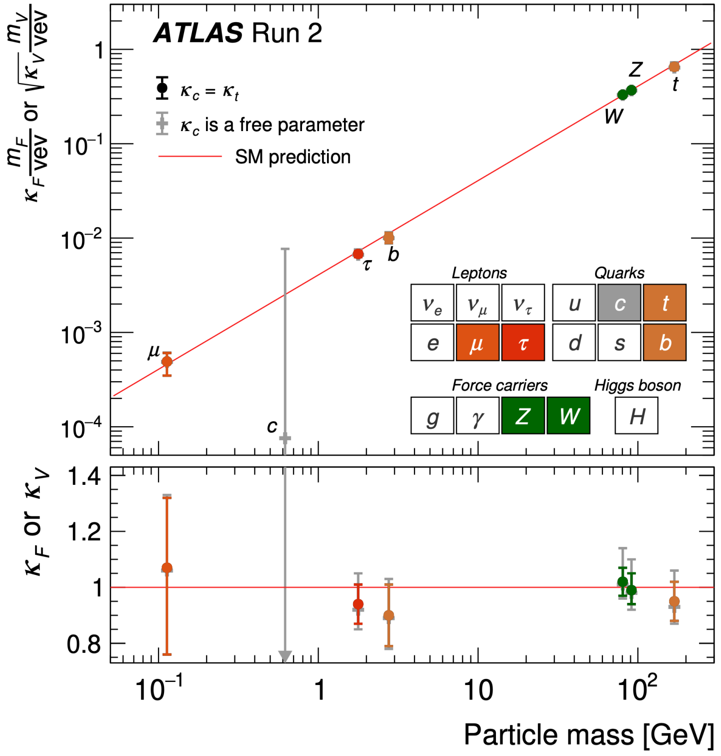

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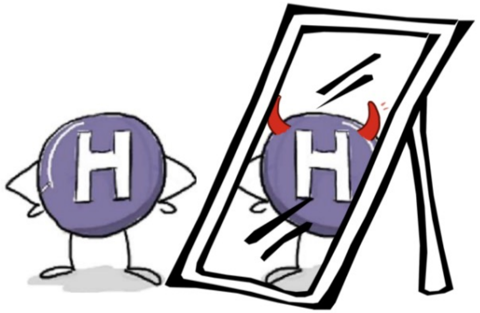
→ What do we know about their CP structure?



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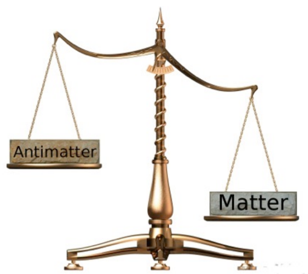

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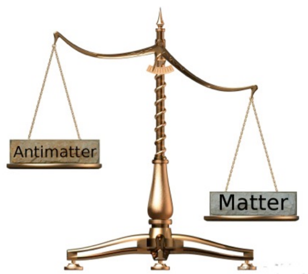

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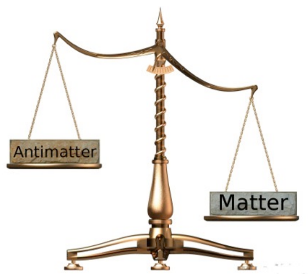

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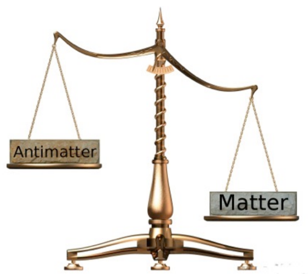

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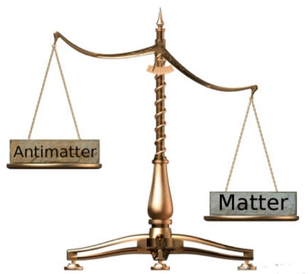

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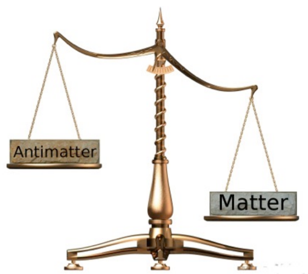

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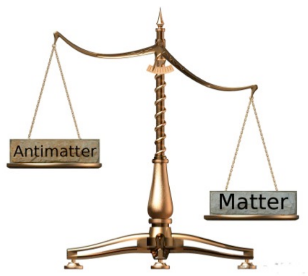

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Rewrite: $$\mathcal{L}_{\text{yuk}} = -\sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\text{SM}}}{\sqrt{2}} \bar{f}\left(c_f + i\gamma_5\tilde{c}_f\right) f H,$$

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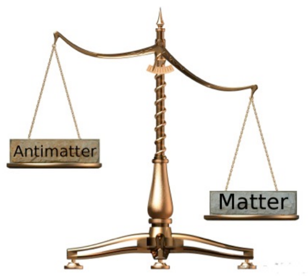

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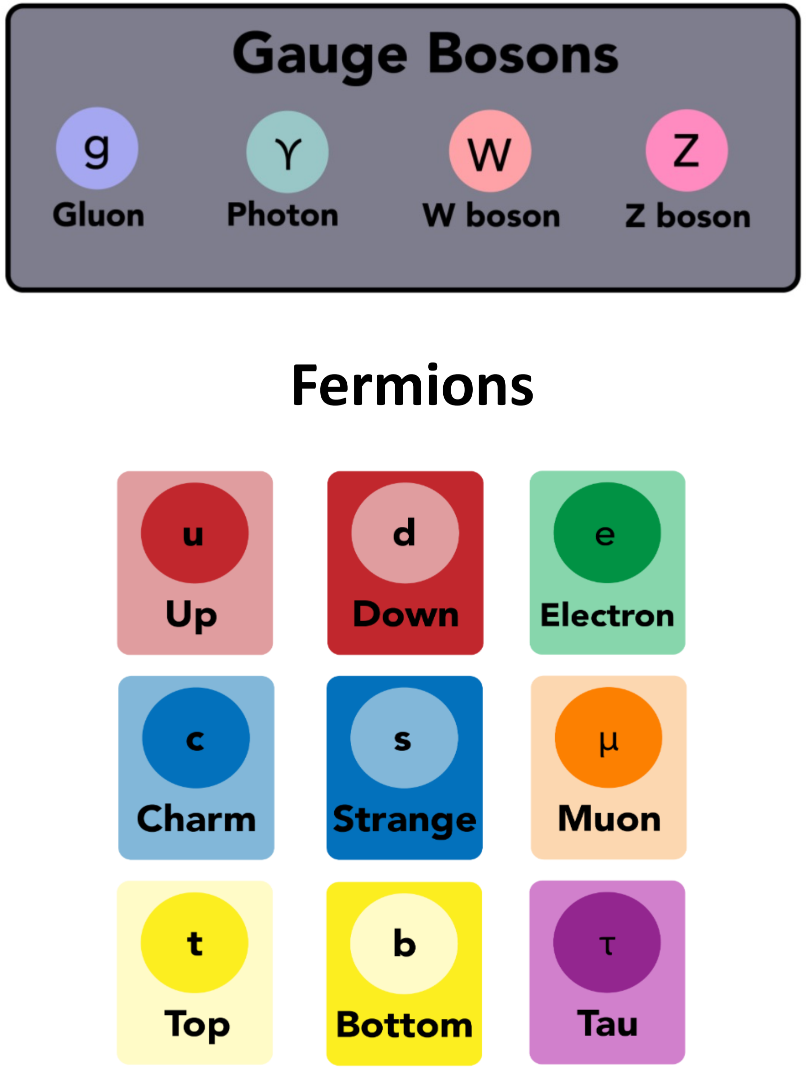
    - Fermion interactions: $\Phi^\dagger\Phi\left(Qu\widetilde{\Phi}\right), \Phi^\dagger\Phi(Qd\Phi), \Phi^\dagger\Phi(Qe\Phi)$ with complex Wilson coefficients

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

What is the current status?

Which CP structures are accessible at the LHC?



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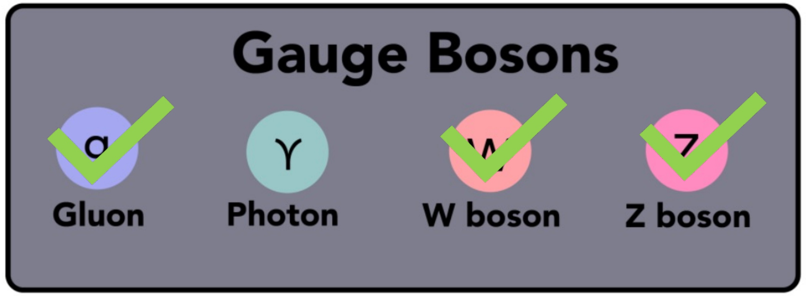

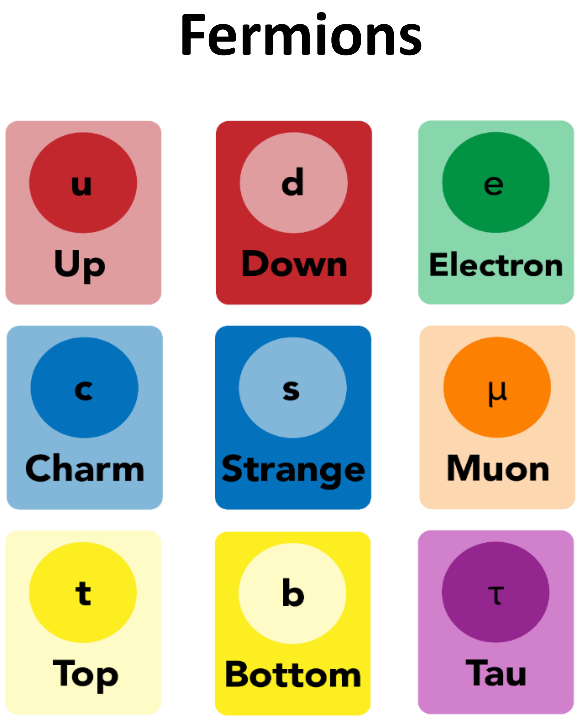

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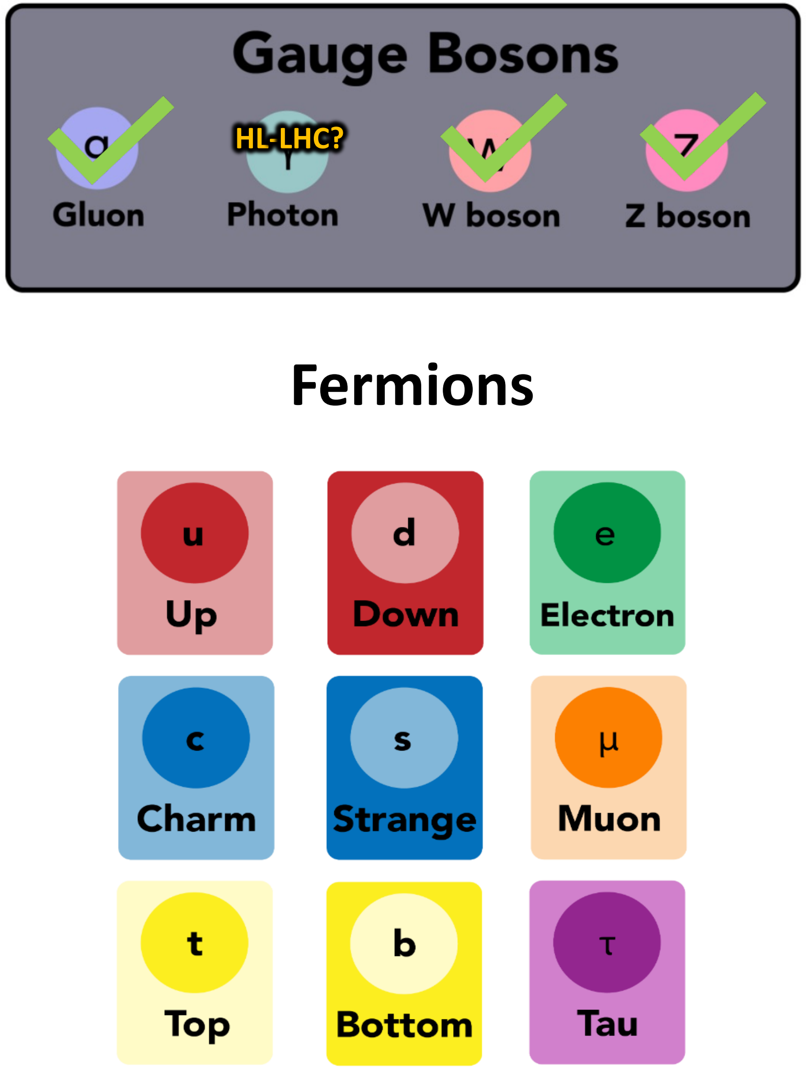

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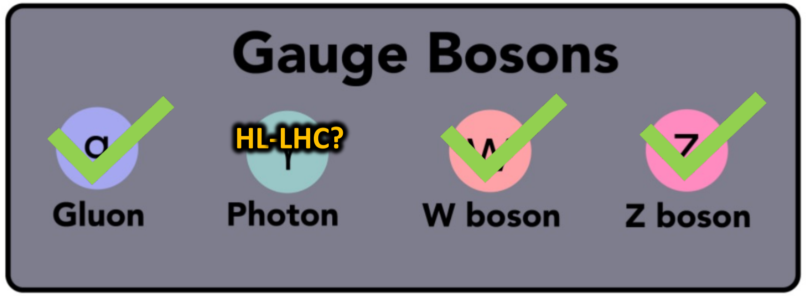

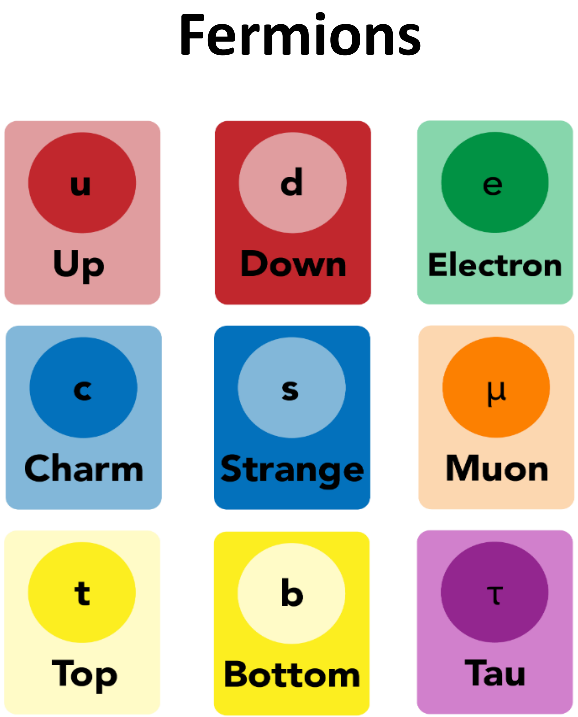

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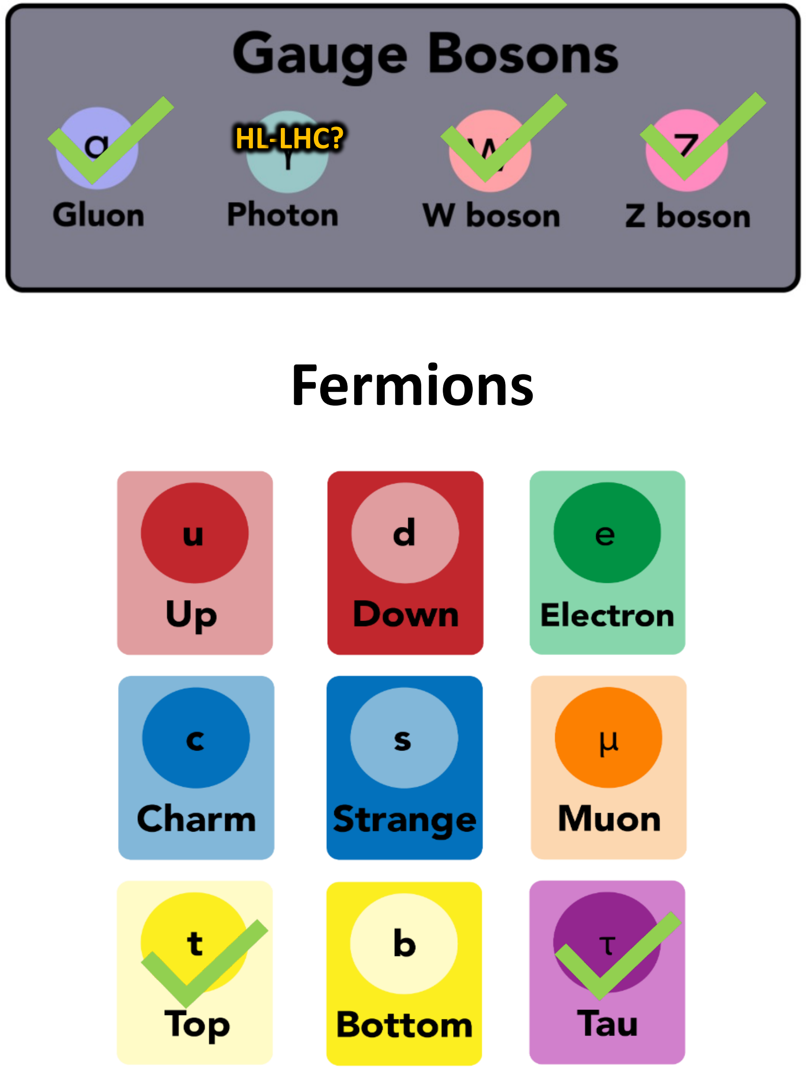

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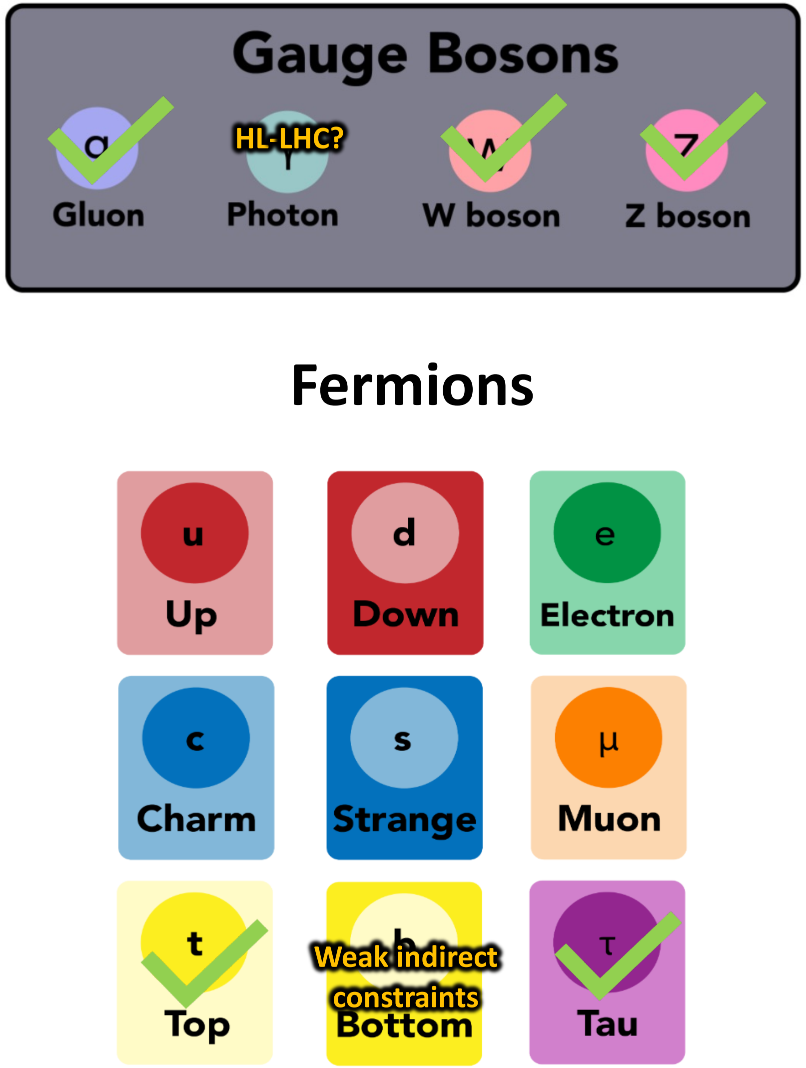

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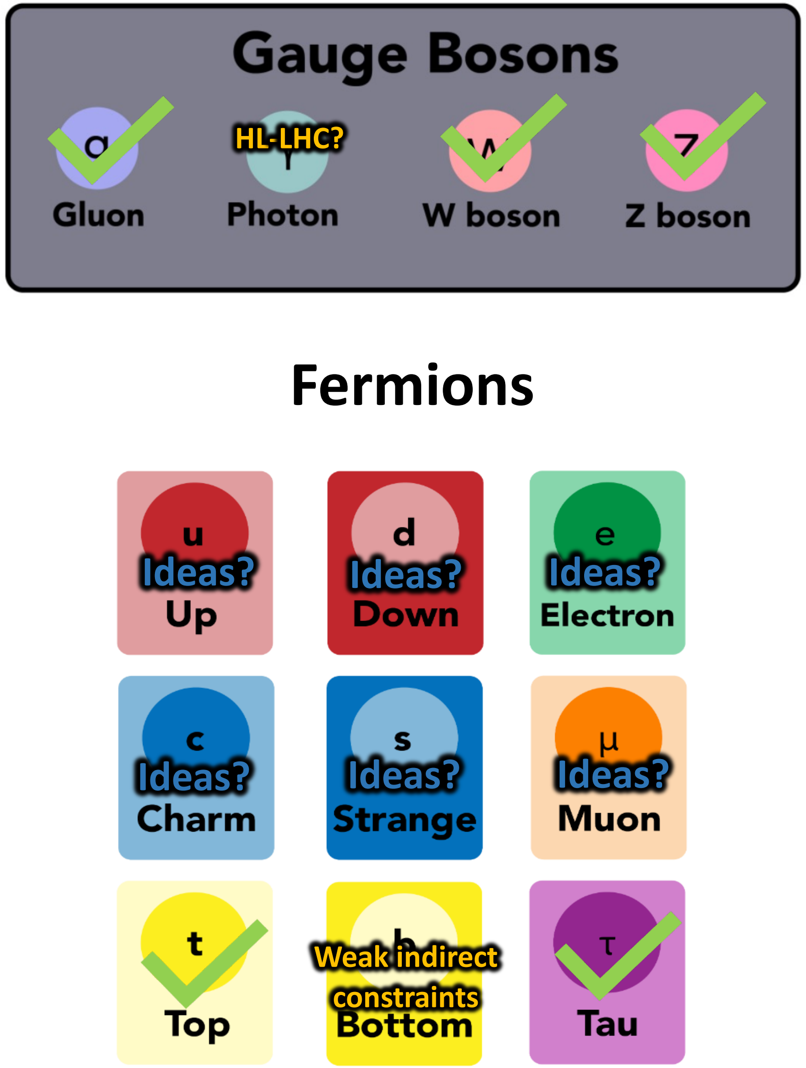

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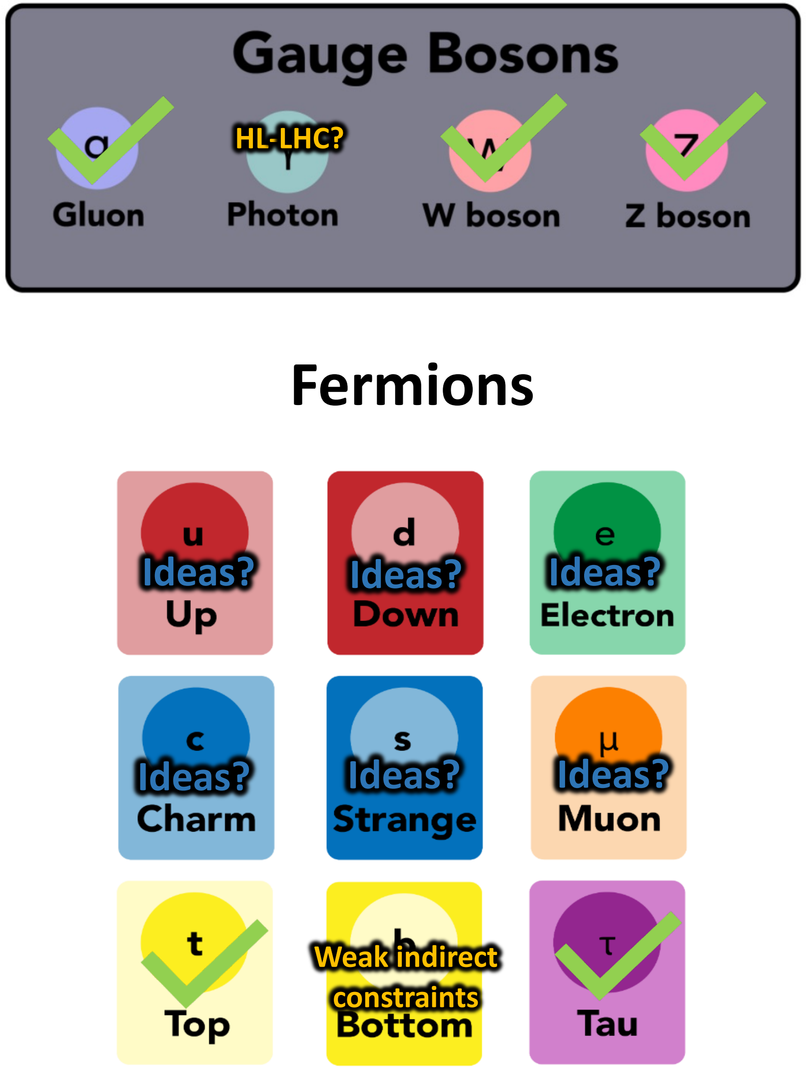

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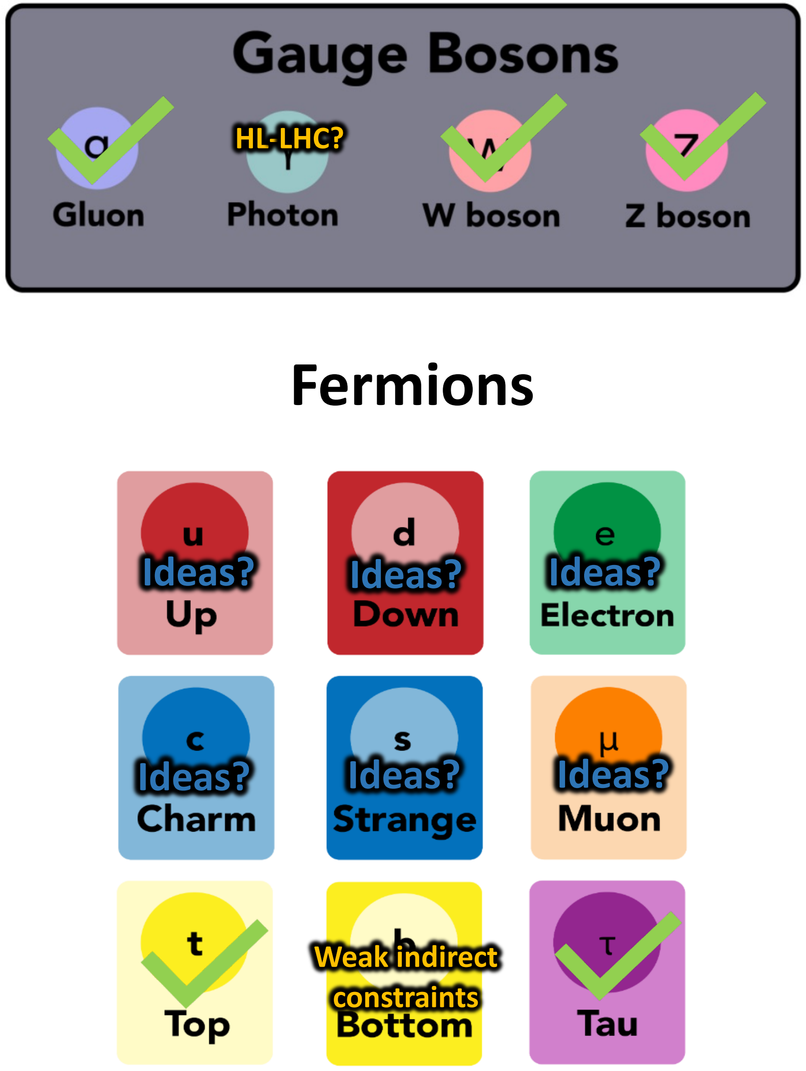

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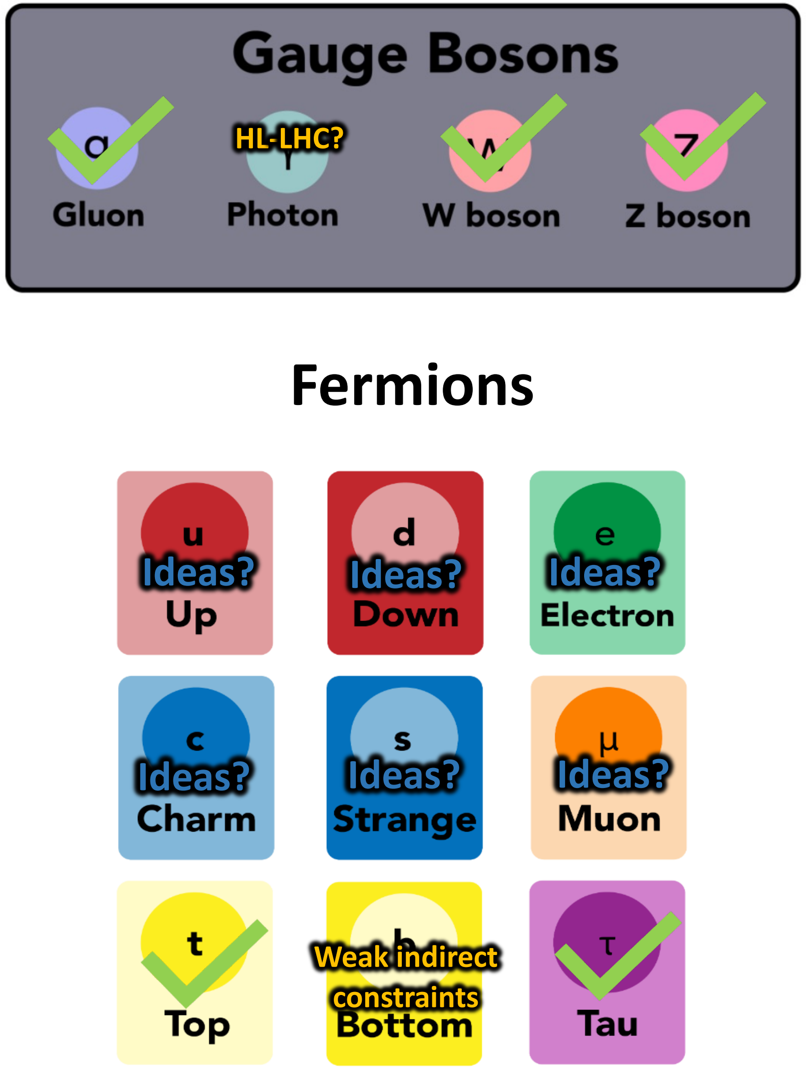

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➡ What about future colliders?

Future collider outlook

[Snowmass Higgs CP report, 2205.07715]

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

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	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

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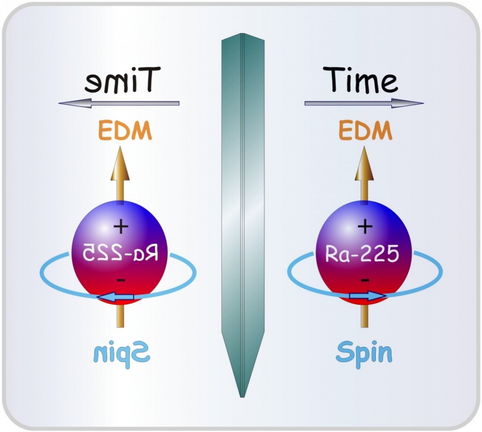
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

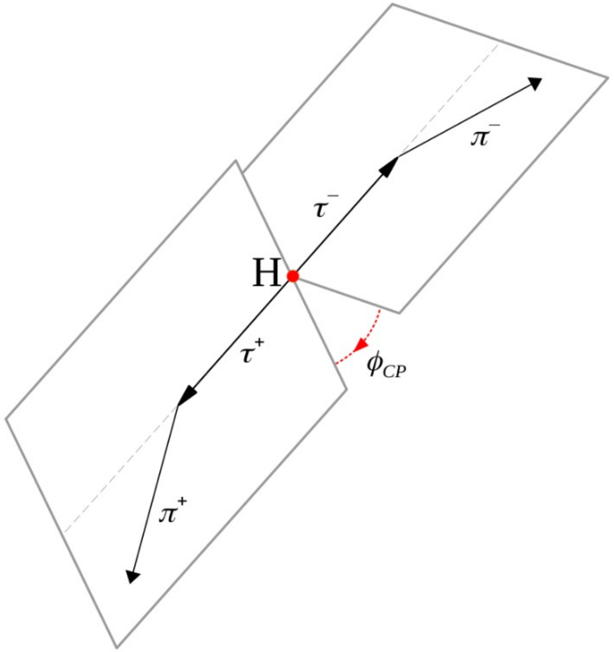
➡ New ideas/techniques are needed to make the most of current and future data!

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 $H \to \tau^+\tau^-$.
  - Typically requires to access polarization of particles coupling to the Higgs.
  - Experimentally difficult for many LHC processes (i.e., top-associated Higgs production).
  - Almost impossible for $H \to b\bar{b}$ or $H \to \mu^+\mu^-$

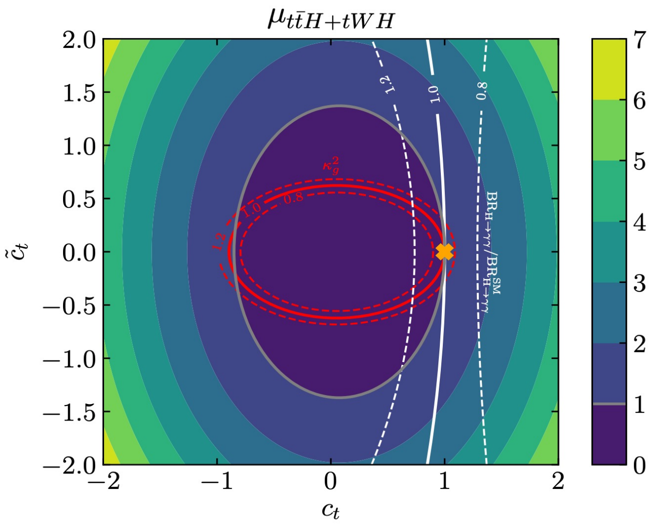




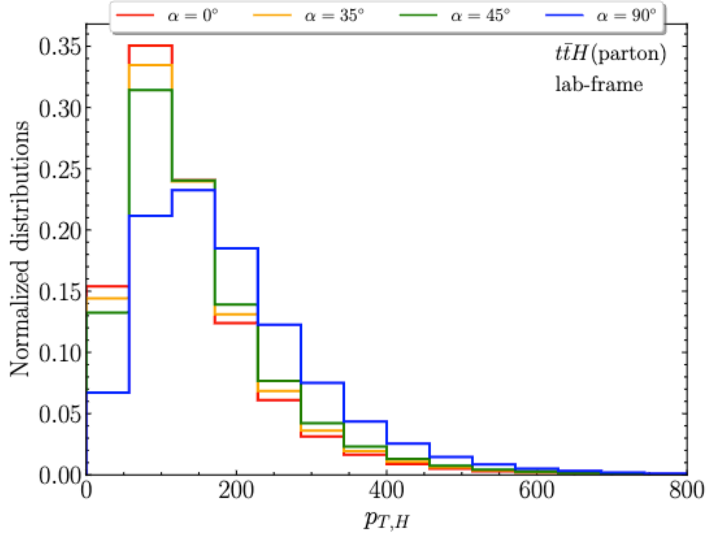
Constraining CP violation

CP violation in the Higgs sector can be constrained using:

- **Pure CP-even observables**:
  - Many rate measurements are indirectly sensitive: e.g. ggH.
  - Subtle effects in kinematic distributions of CP-even observables (e.g. $p_{T,H}$ in $t\bar{t}H$).
  - Deviations from SM need not be due to CP violation → degeneracies with non-CPV BSM effects.



[HB et al., 2007.08542]

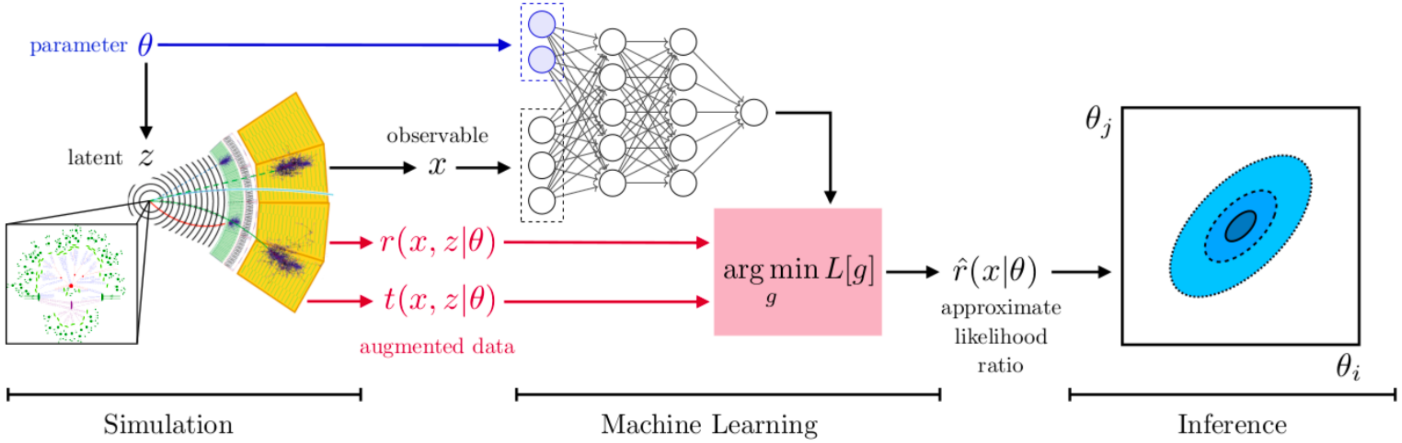


[HB et al., to appear]

Constraining CP violation

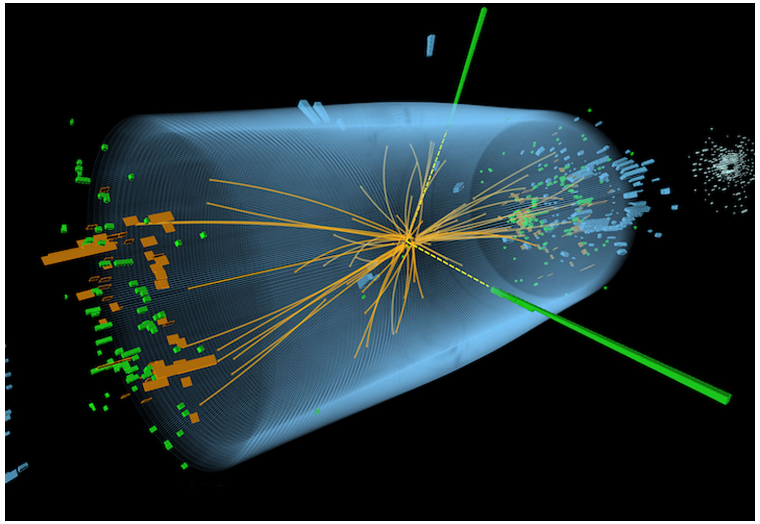
CP violation in the Higgs sector can be constrained using:

- **Multivariate analyses:**
  - Exploit full kinematic information using machine learning.
  - Often mixes CP-even and CP-odd observables.
  - High sensitivity.
  - Can be difficult to reinterpret.



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

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

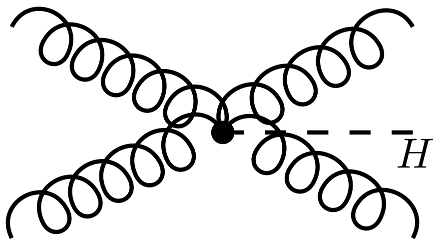


Improving LHC CP measurements

Higgs + 2 jet production as an exemplary process

[HB et al., 2309.03146]

Higgs + 2jet production (ggF2j)



Why is ggF2j production interesting for Higgs CP tests? [Hankele, Klamke, Zeppenfeld `06,`07, …]

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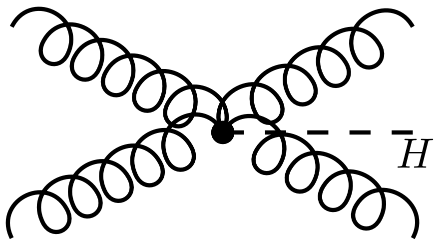

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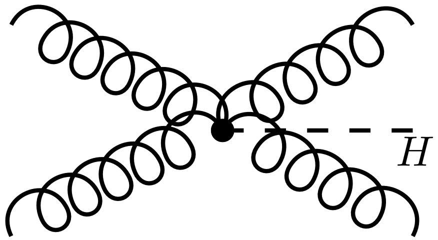

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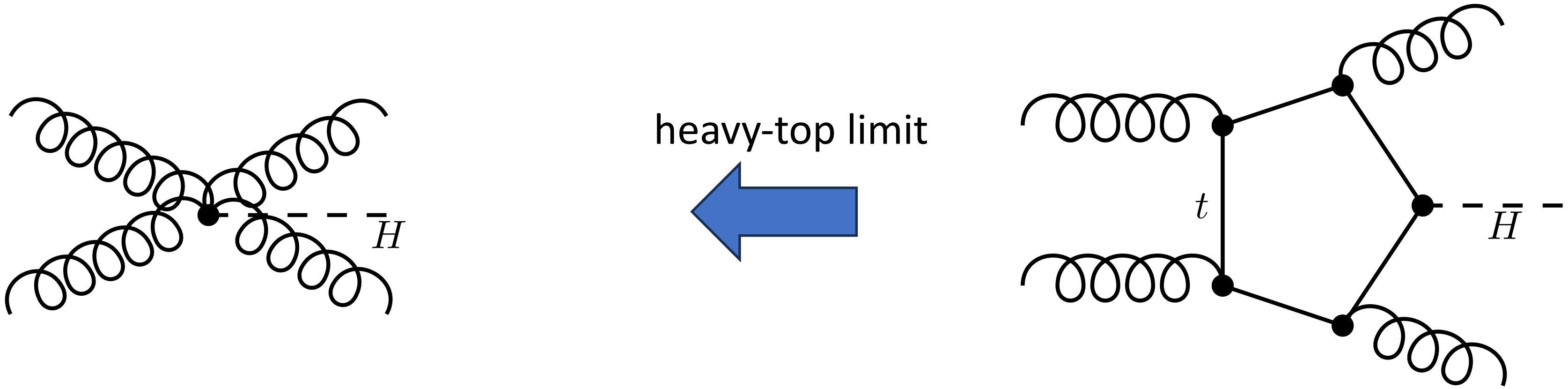

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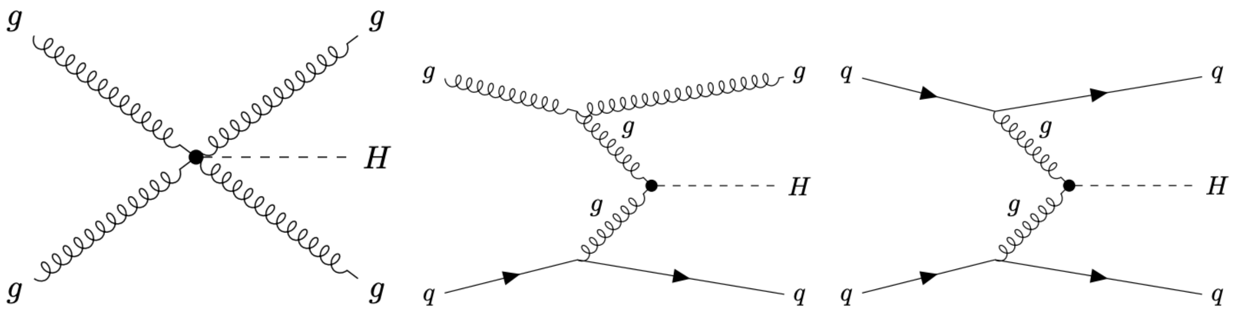
  → direct CP test.
- Allows for indirect constraint of CP character of top-Yukawa interaction.

ggF2j— amplitude structure



(a) gg-initiated (b) gq-initiated (c) qq-initiated

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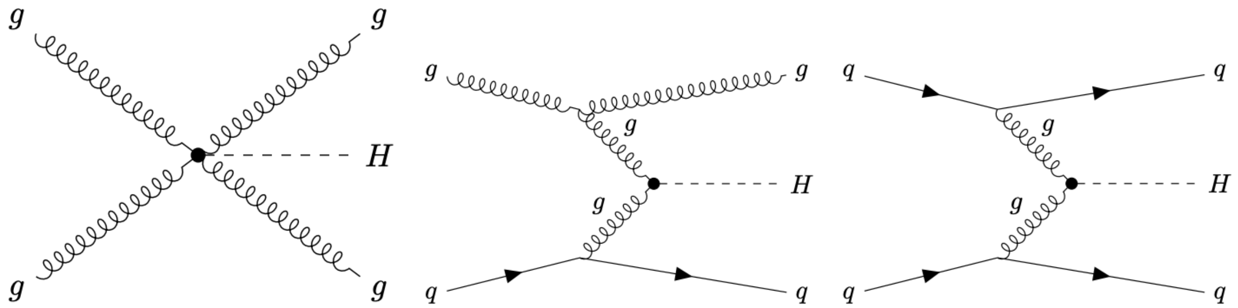

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- Effective Lagrangian (after integrating out the top quark, SM: $c_g = 1$, $\tilde{c}_g = 0$):

$$\mathcal{L}_{Hgg} = -\frac{1}{4v} H \left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{a,\mu\nu} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \right)$$

(heavy top limit enforced by p_T cut)

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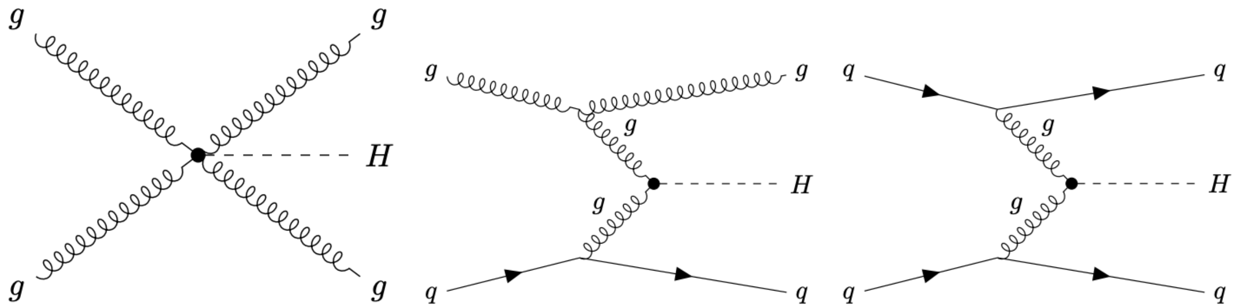

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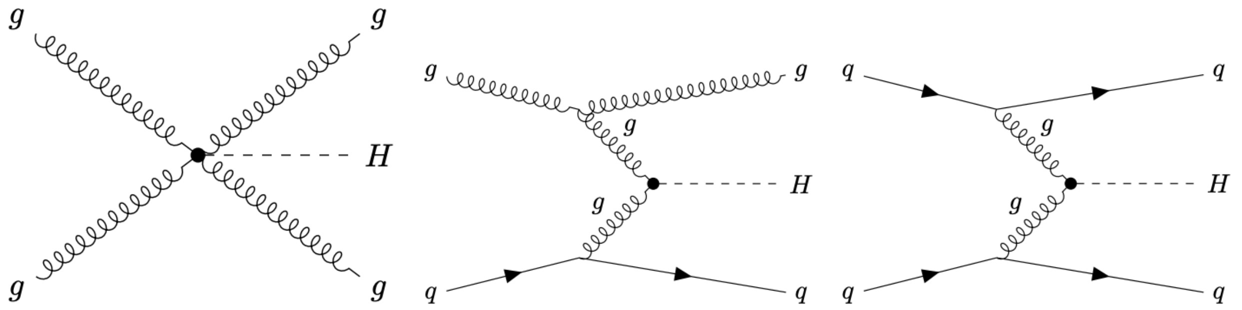
(heavy top limit enforced by p_T cut)

- Amplitude splits up into three pieces:

$$\left|\mathcal{M}_{\mathrm{ggF2j}}\right|^2 = c_g^2 |\mathcal{M}_{\mathrm{even}}|^2 + \underbrace{2 c_g \tilde{c}_g Re[\mathcal{M}_{\mathrm{even}} \mathcal{M}_{\mathrm{odd}}{}^*]}_{\text{interference}} + \tilde{c}_g^2 |\mathcal{M}_{\mathrm{odd}}|^2$$

ggF2j— amplitude structure



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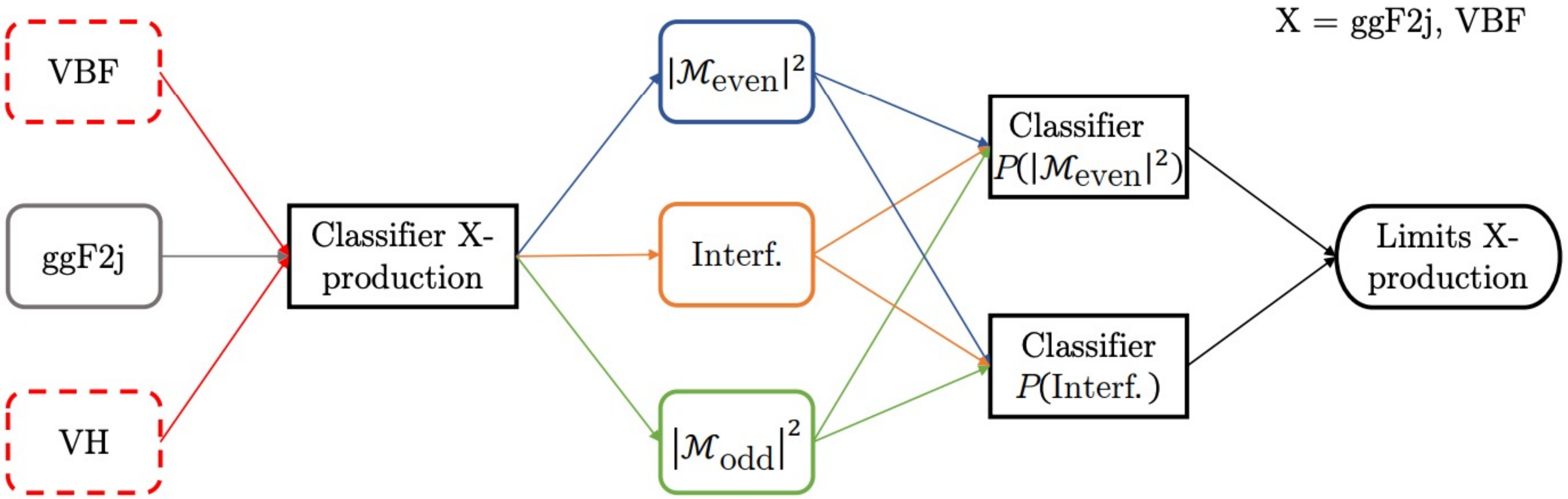
- Existing measurements focus on CP-odd $\Delta\phi_{jj}$ observable to constrain interference term.

Analysis flow



- Focus on $H \to \gamma\gamma$ decay channel.

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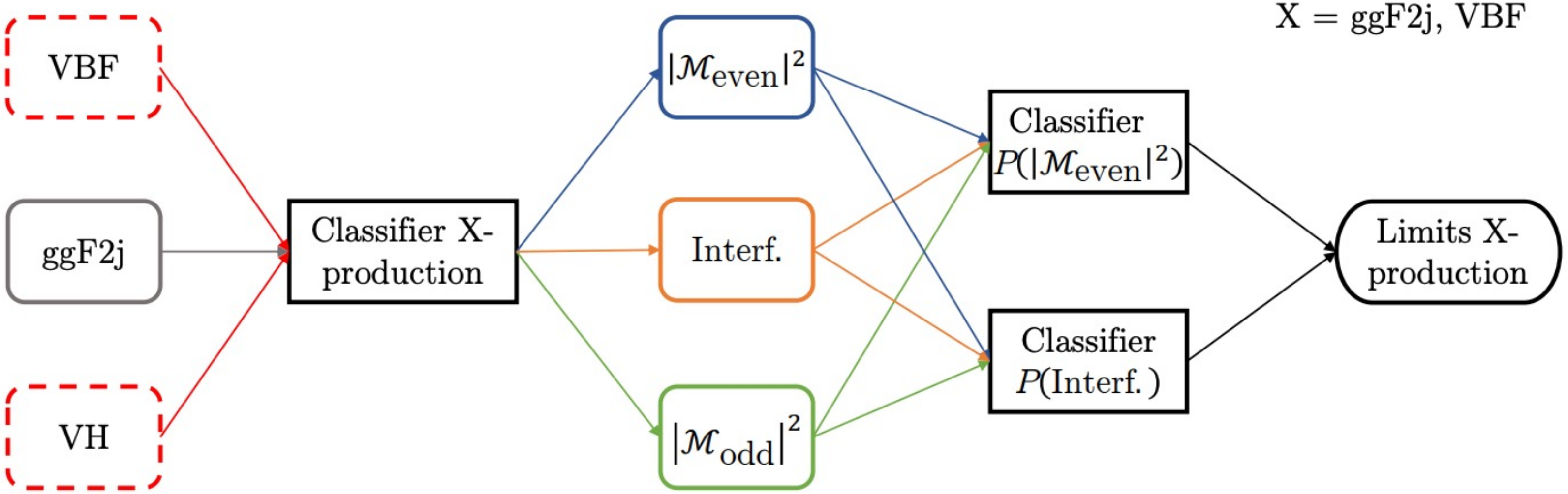

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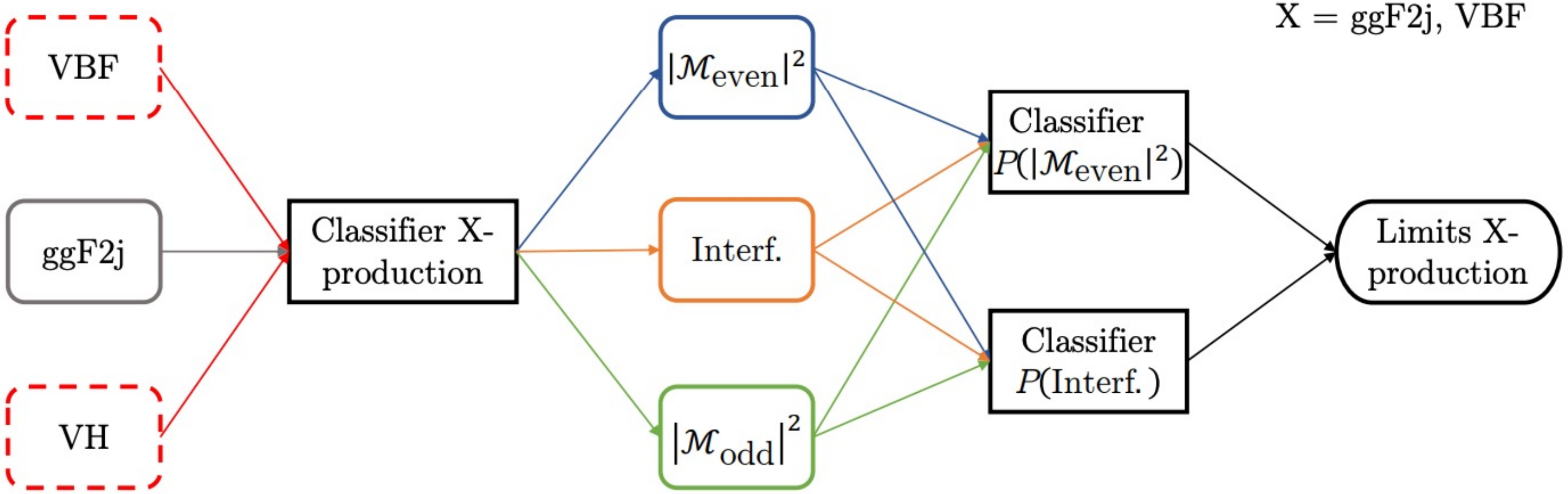

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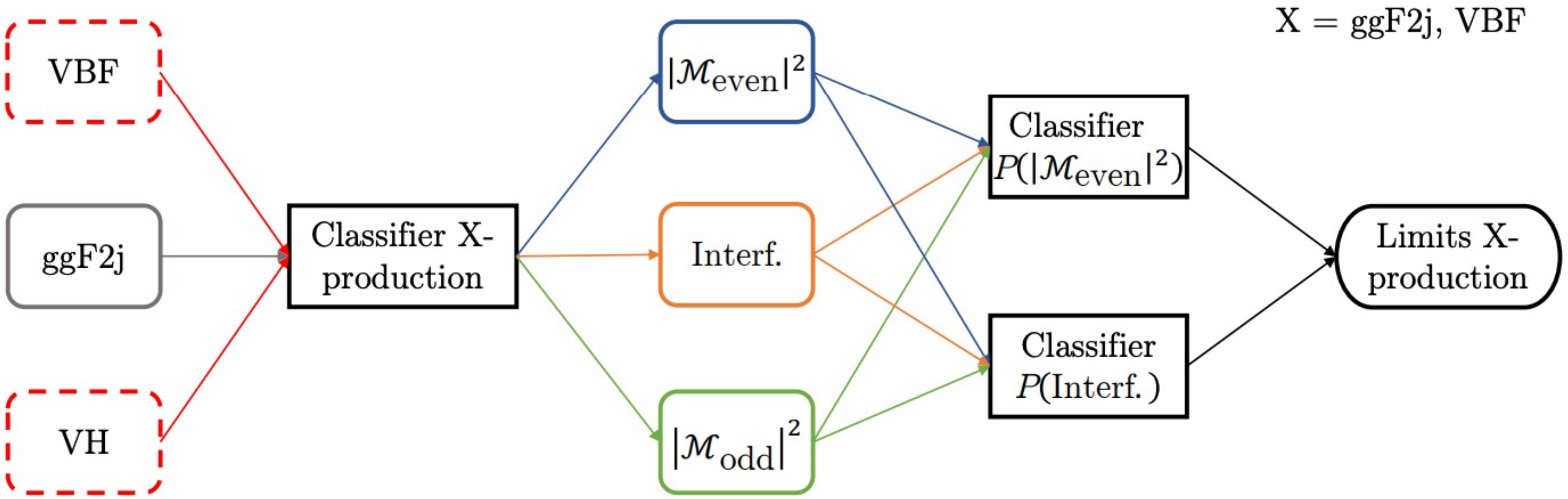

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  - $|\mathcal{M}_{\text{even}}|^2$ vs. $|\mathcal{M}_{\text{odd}}|^2 \to P(|\mathcal{M}^2_{\text{even}}|)$, and
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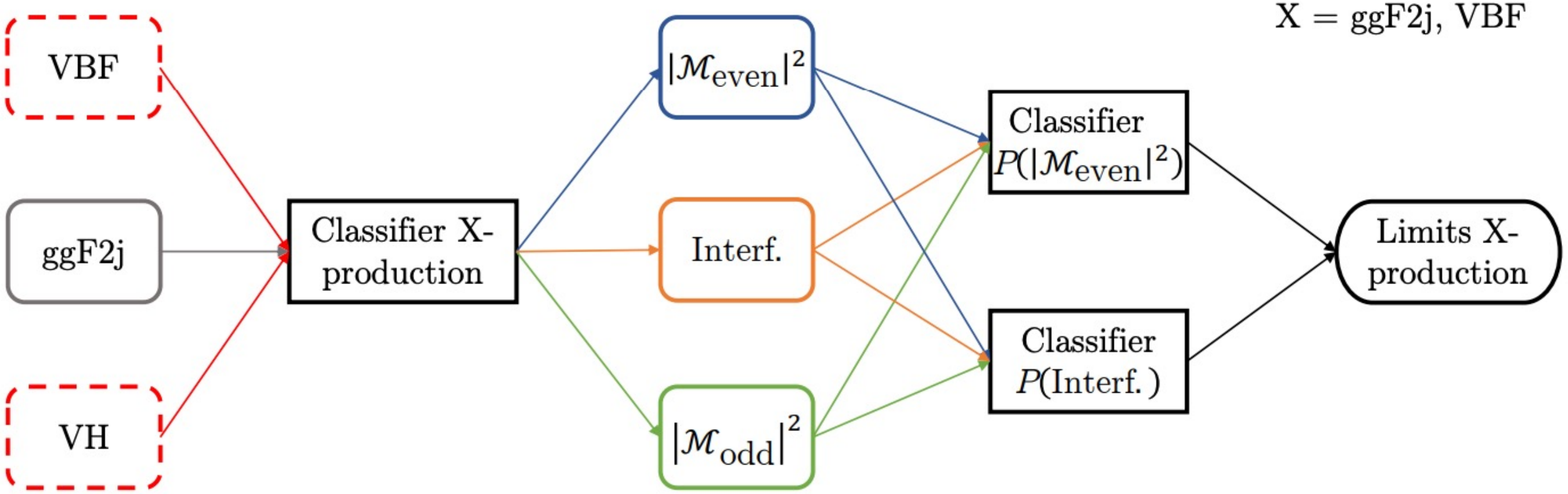

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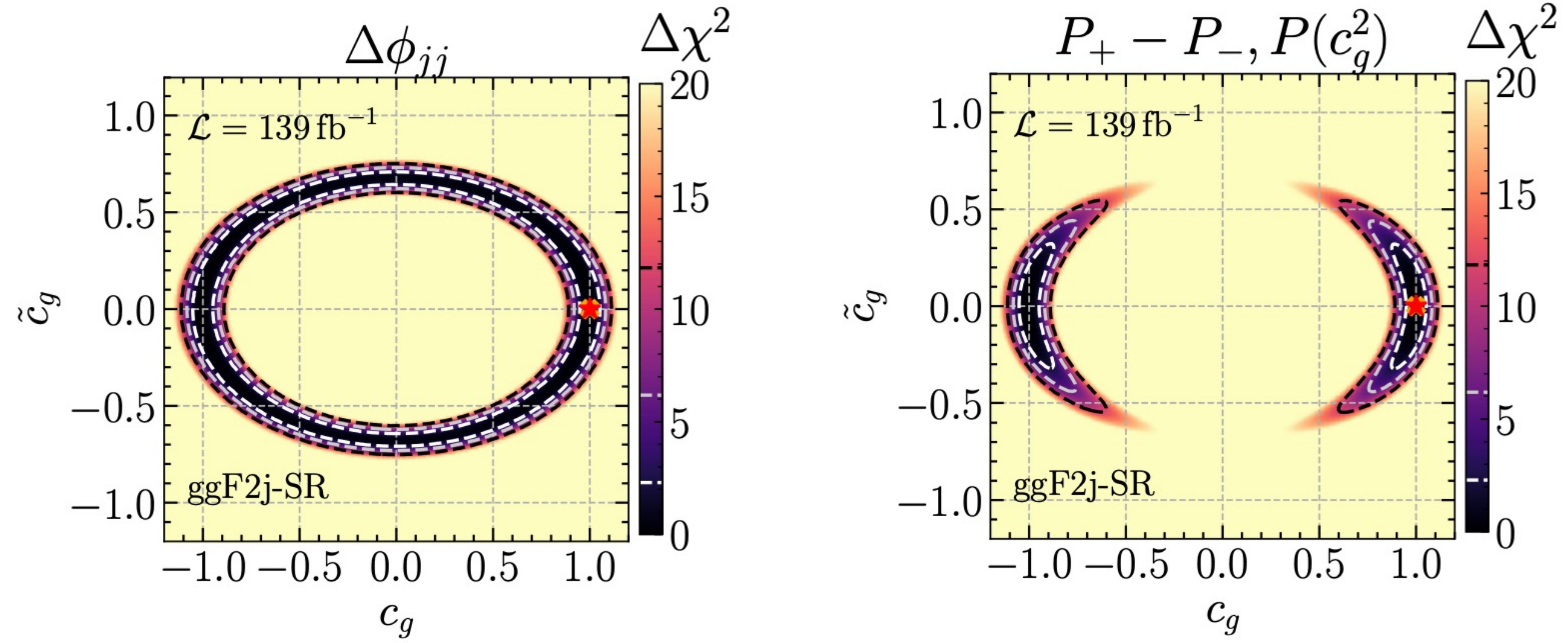
- Build two observables: CP-even $P(c_g^2)$ and CP-odd $P_+ - P_-$.

ggF2j signal region



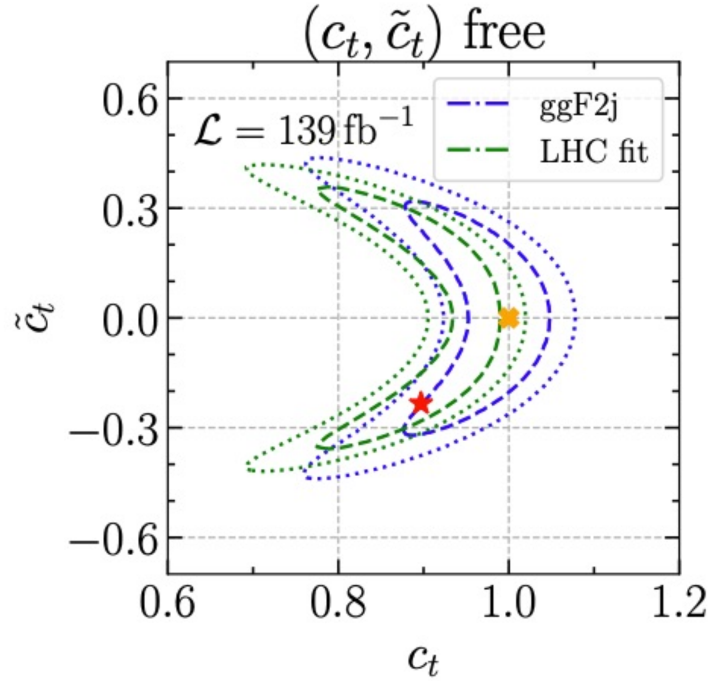
- ggF2j signal region outperforms VBF signal region (not shown),
- $\Delta\phi_{jj}$ limit is significantly worse.

Interpretation in terms of top-Yukawa coupling

- Effective Lagrangian (SM: $c_t = 1, \tilde{c}_t = 0$)

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

- If no colored BSM particles at low energies: $c_g \simeq c_t, \tilde{c}_g \simeq \tilde{c}_t$



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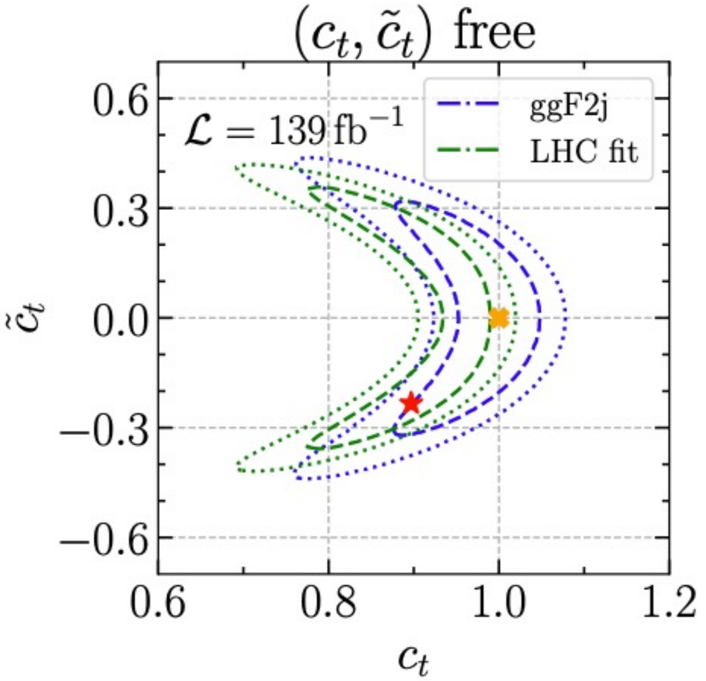
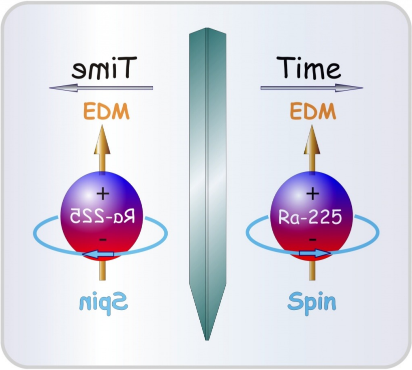


- Competitive with global LHC fit (which is dominated by ggH XS and $H \to \gamma\gamma$ BR constraints).
- Less model-dependent than global fit to mainly XS measurements.

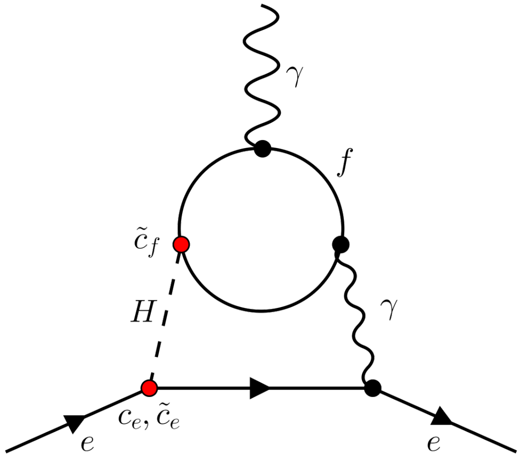


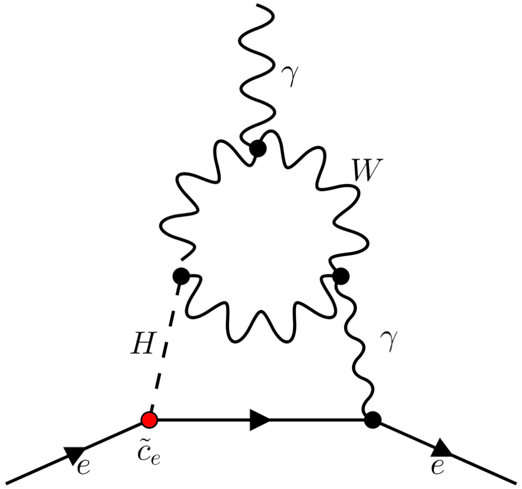
Complementarity with EDM measurements

What do EDM measurements tell us about the Higgs CP nature?

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

Complementarity with EDM constraints





- Several EDMs are sensitive to CP violation in the Higgs sector.
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  [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: $d_e^{\mathrm{ACME}} = 1.1 \cdot 10^{-29} e\ \mathrm{cm}$ at 90% CL. [ACME, *Nature* 562 (2018) 7727, 355-360]

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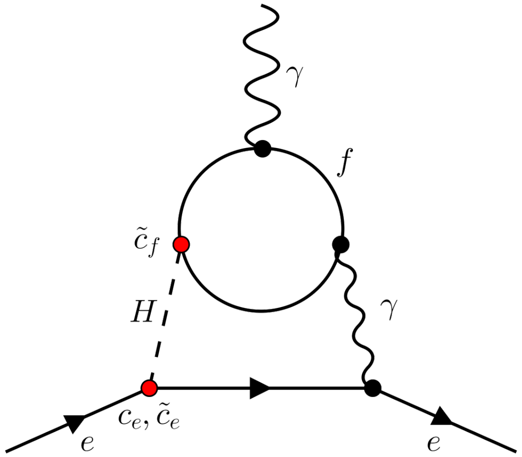

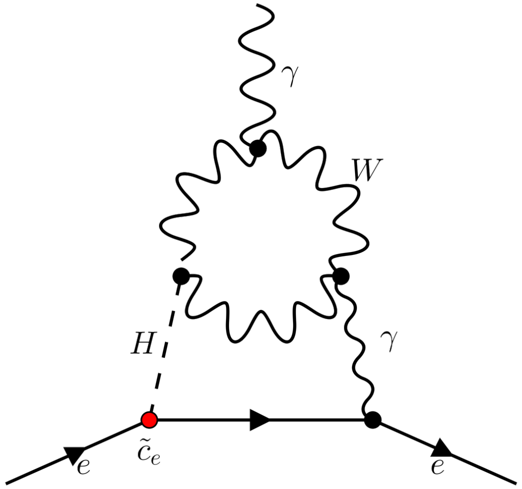

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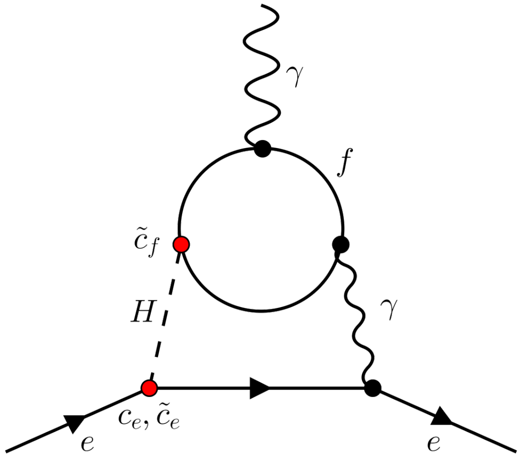

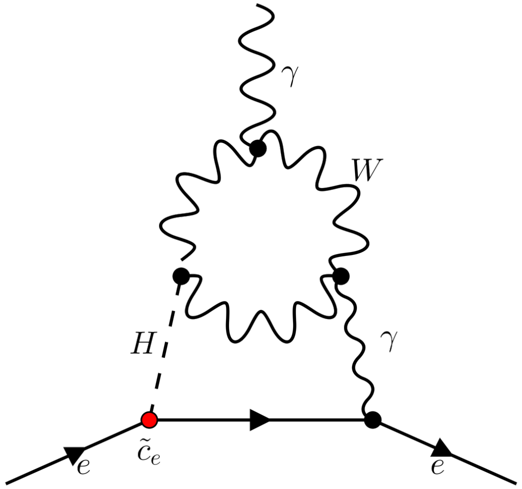

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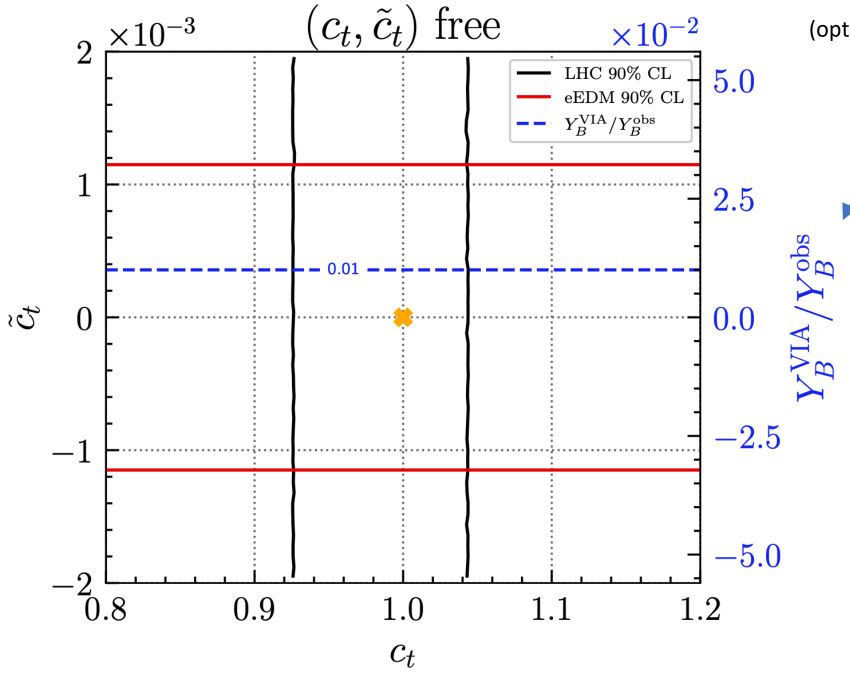
- Bounds strongly depend on assumptions about electron-Yukawa coupling.

Complementarity with EDM constraints: t and τ



Ratio of baryon asymmetry
to observation
(optimistic upper bound)

Very strong constraints on CP-odd
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Complementarity with EDM constraints: t and τ

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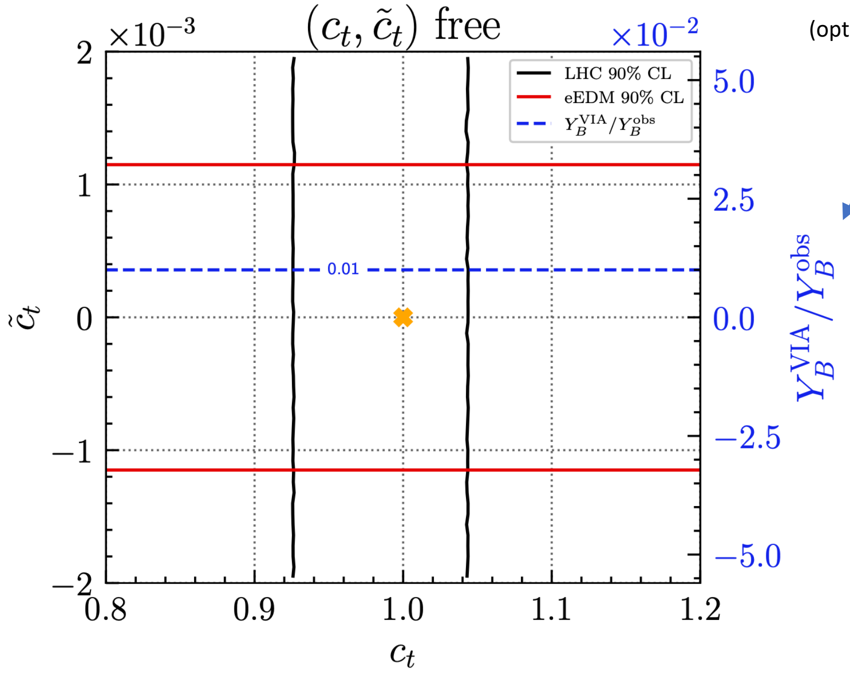

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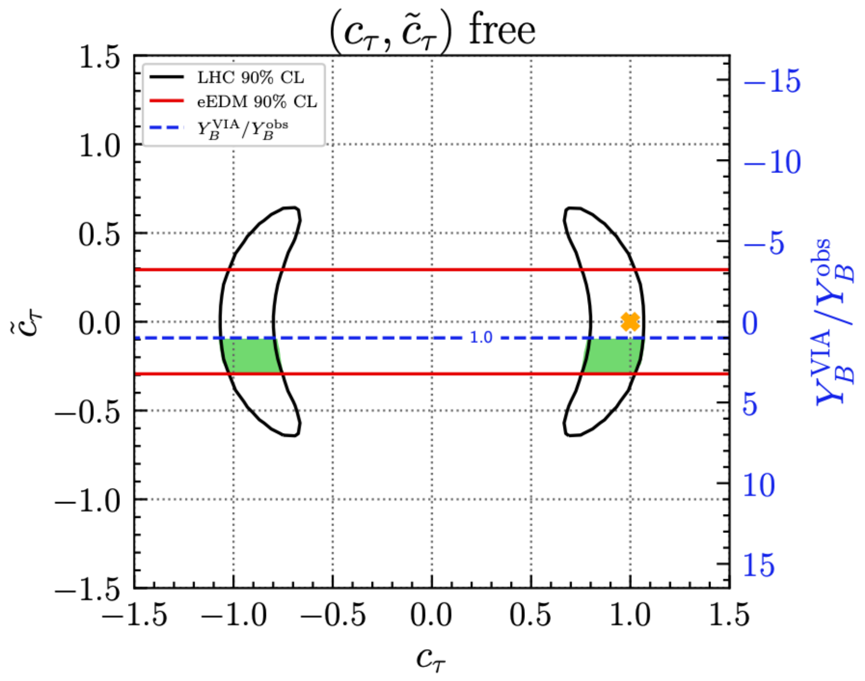

CP-odd τ coupling can contribute significantly to baryon asymmetry.

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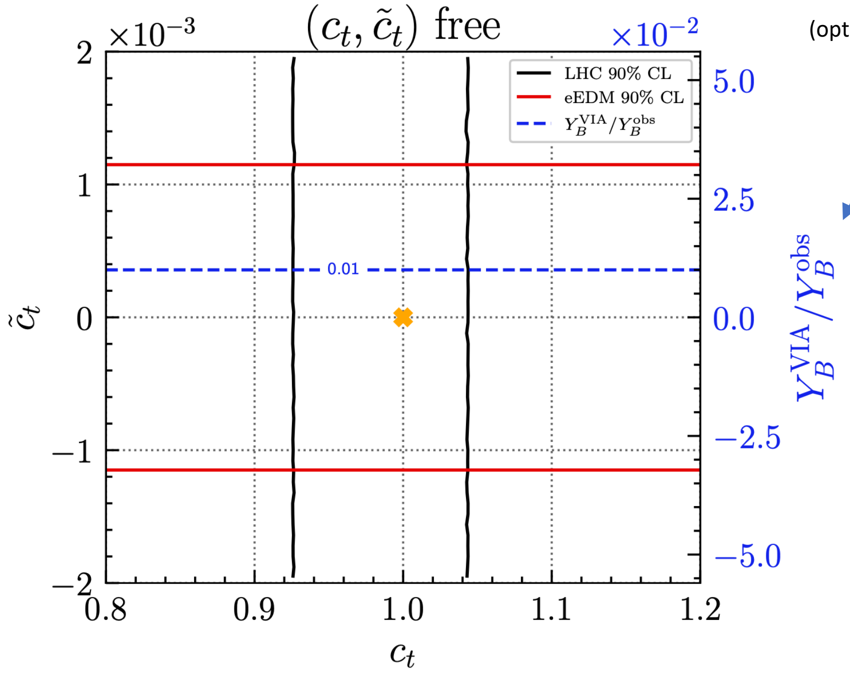

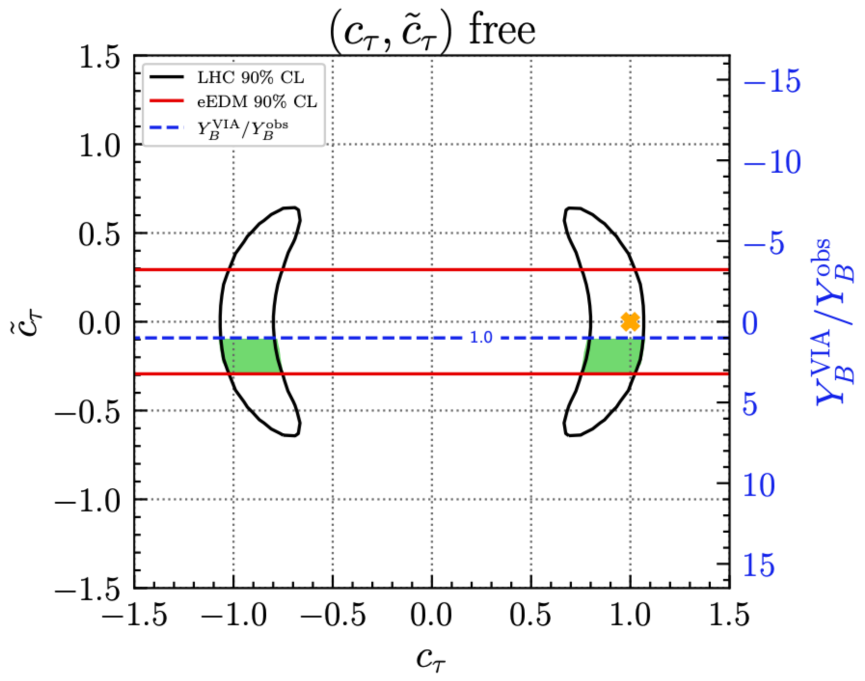

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CP-odd τ coupling can contribute significantly to baryon asymmetry.

→ 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.**

[see also Fuchs et al.,1911.08495]

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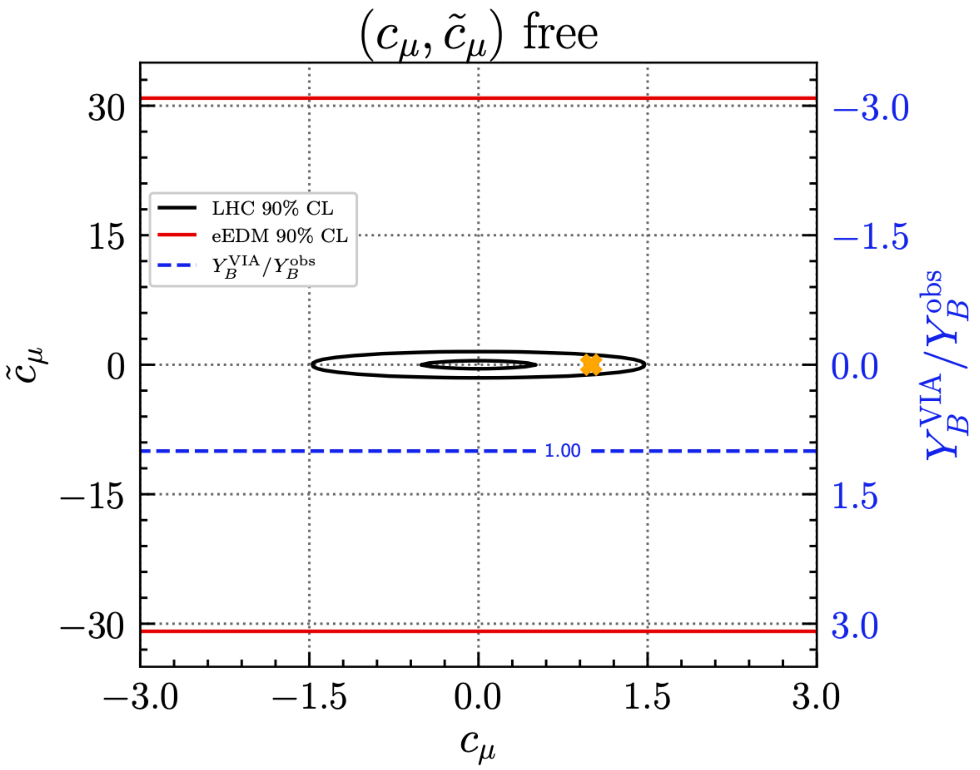
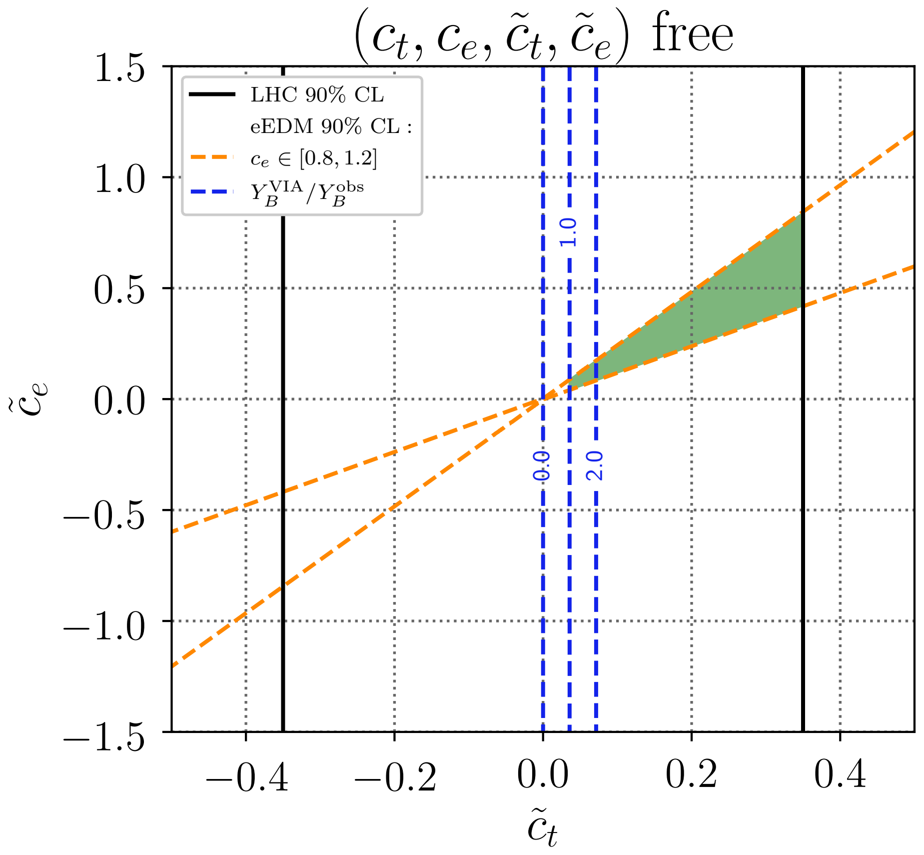


CP-insensitive $H \to \mu^+\mu^-$ rate measurement outperforms EDM constraint.

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 $d_e < d_e^{\rm ACME}$.
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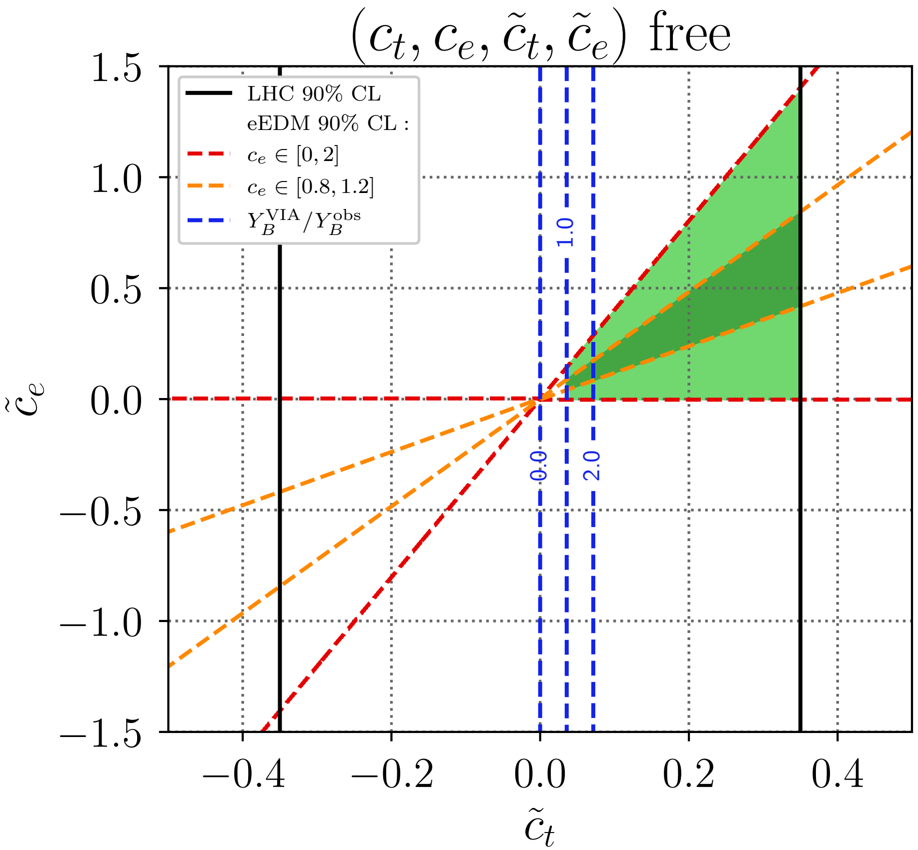

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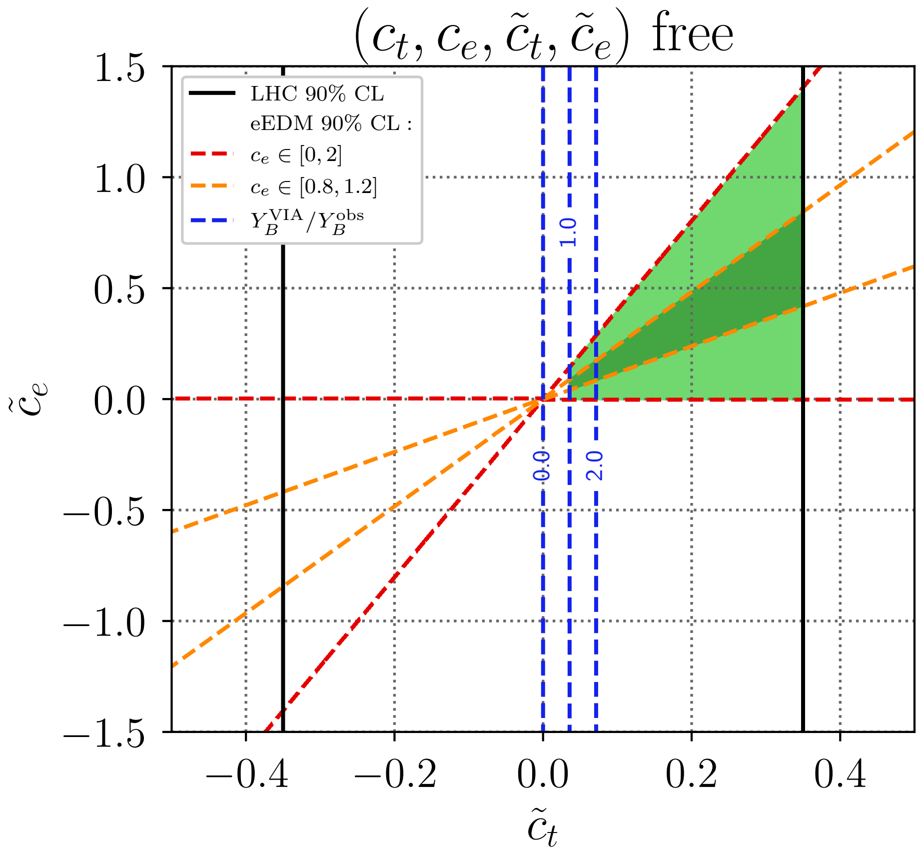

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→ LHC bounds important since they do not depend on 1st gen. Yukawa couplings.

Conclusions

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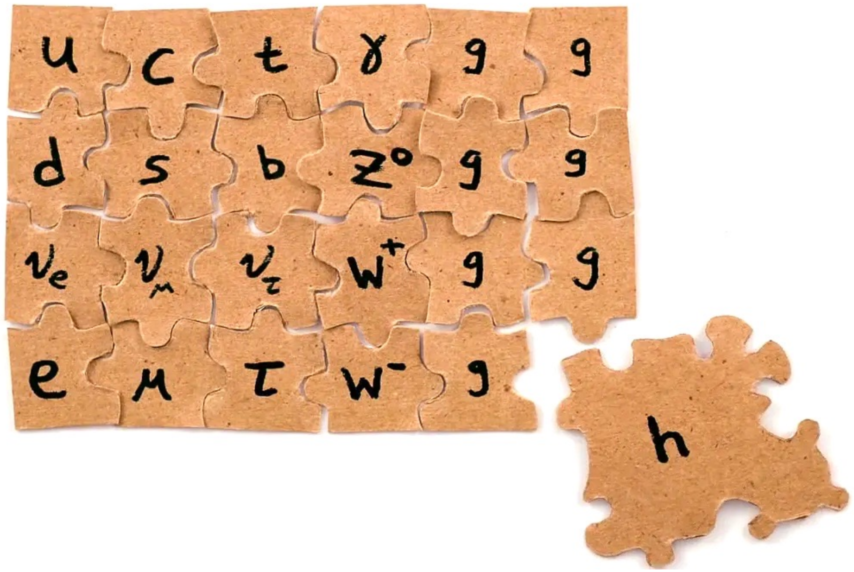
- The Higgs is not the last missing puzzle piece of the SM but could be the link to many BSM scenarios.



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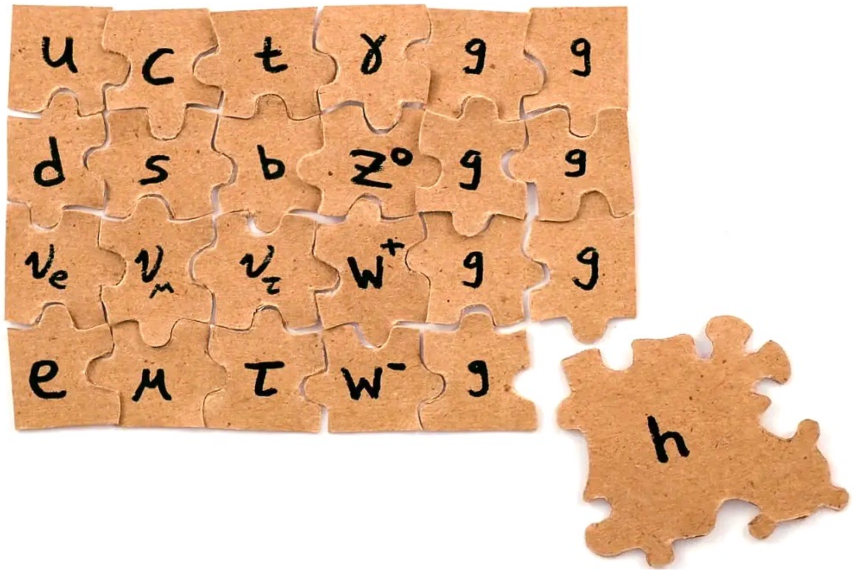
  - Higgs width,
  - …



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  - Novel analysis methods promise significant improvements.
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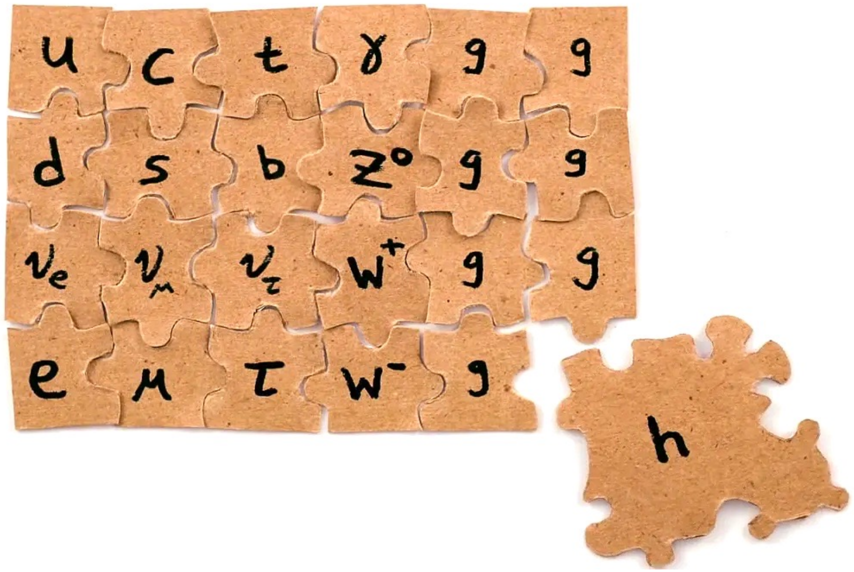

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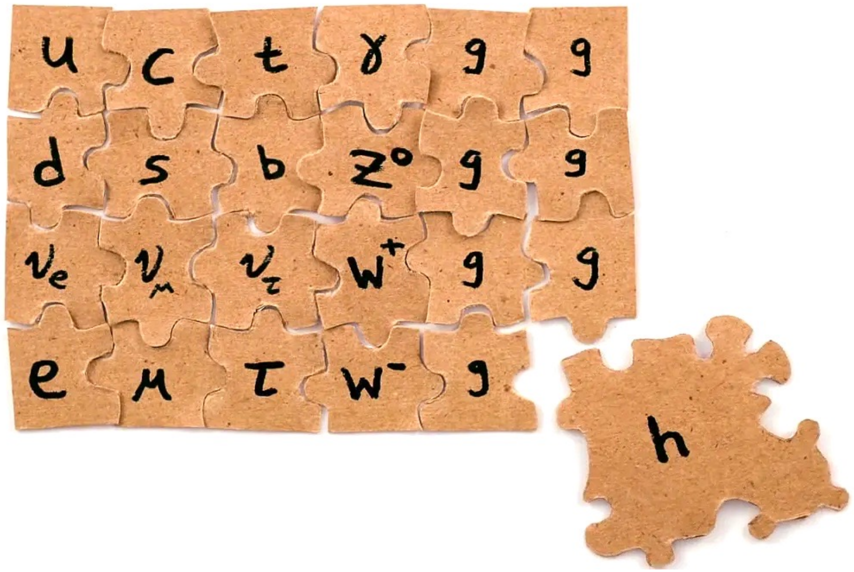
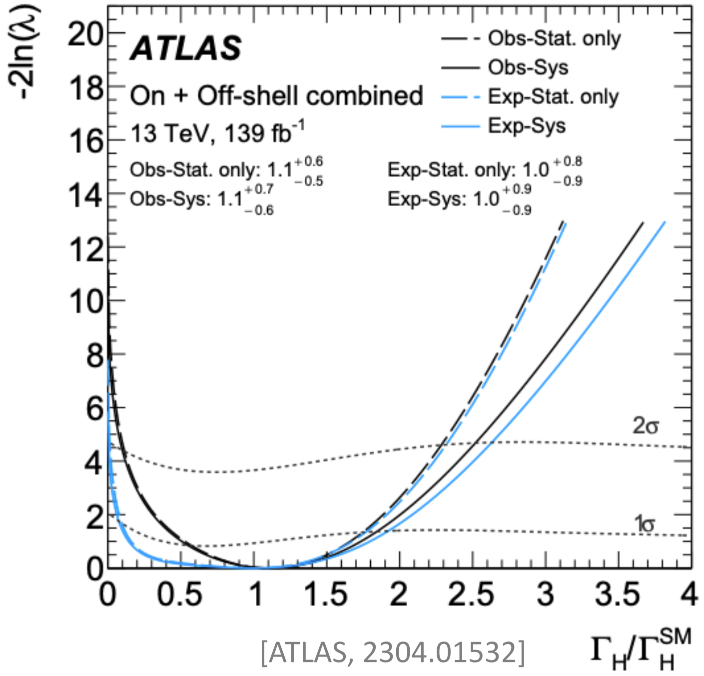


The Higgs will keep us busy for many decades to come!

Appendix

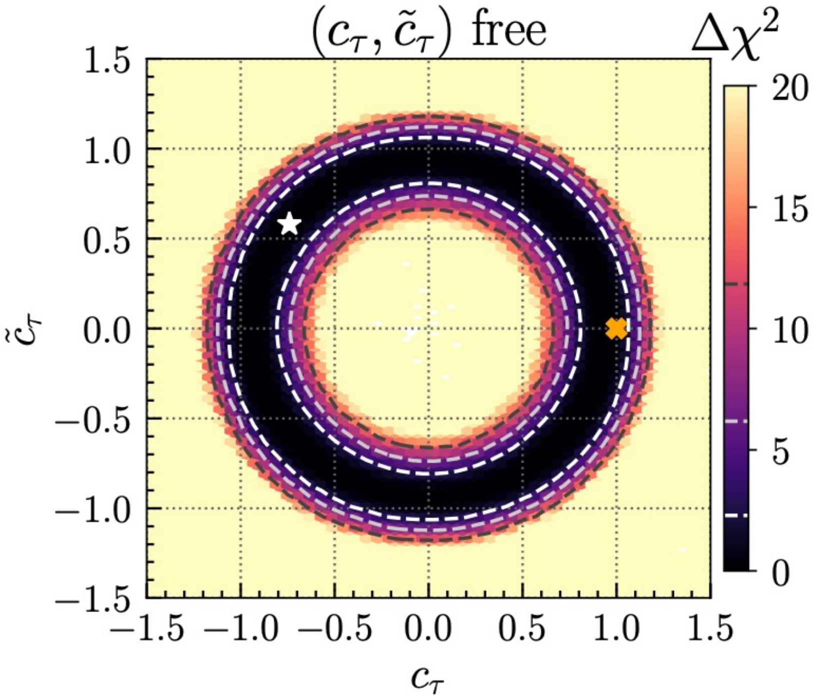
Higgs width constraints



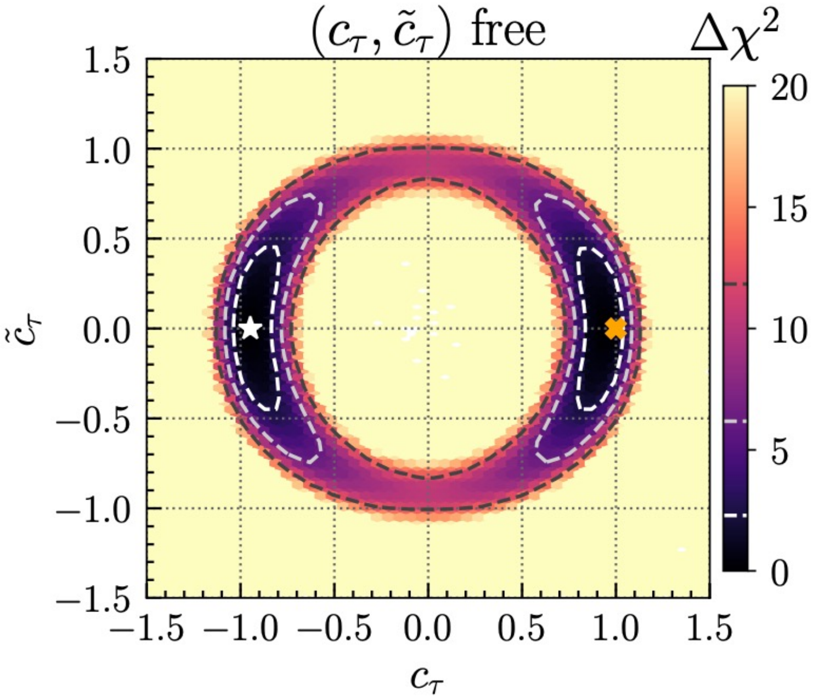
[ATLAS, 2304.01532]

Starting point — 1 flavor fits: τ

[HB et al.,2202.11753]



Without CMS $H \to \tau\tau$ CP analysis.

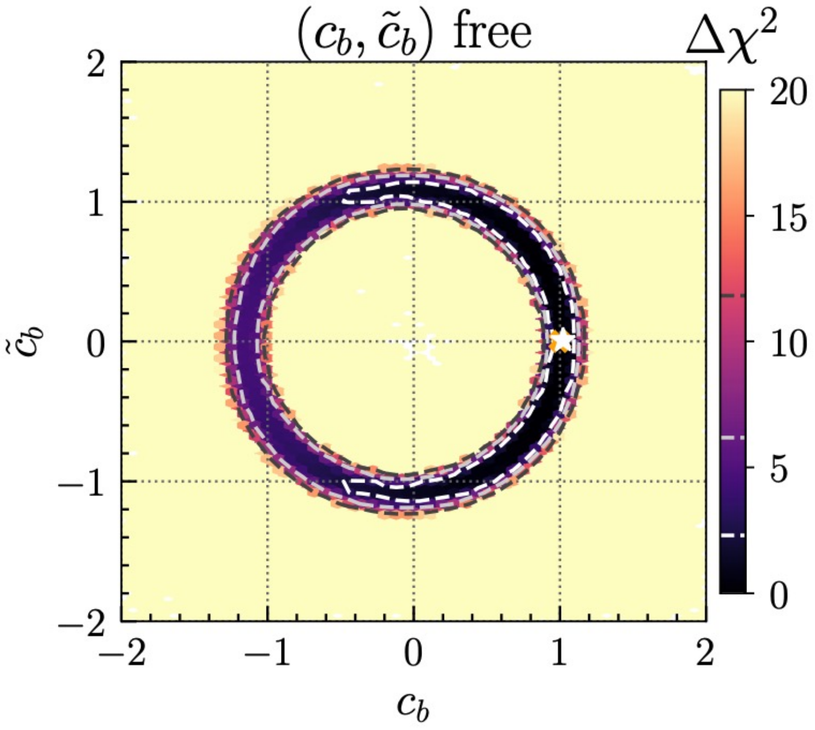


With CMS $H \to \tau\tau$ CP analysis.

- Without CMS $H \to \tau\tau$ CP analysis ring-like structure since $\Gamma_{H\to\tau\tau} \propto c_\tau^2 + \tilde{c}_\tau^2$ (similar for muon-Yukawa coupling).
- With CMS $H \to \tau\tau$ CP analysis, we can differentiate between CP-even and CP-odd tau-Yukawa coupling.

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:
  - $\frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\text{SM}}} \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 - 0.1c_t c_b + \cdots$.
- 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.

Top-Yukawa coupling

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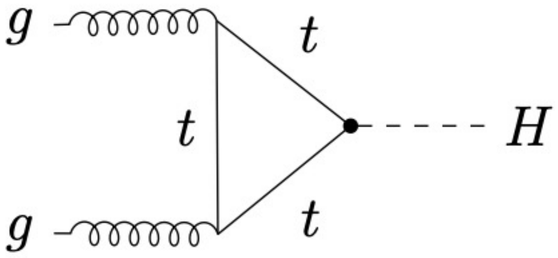

- $\kappa_g^2 \equiv \frac{\sigma_{gg\to H}}{\sigma_{gg\to H}^{\text{SM}}} \simeq 1.1 c_t^2 + 2.6 \tilde{c}_t^2 - 0.1 c_t c_b - 0.2 \tilde{c}_t \tilde{c}_b + \cdots$, disfavors large $\tilde{c}_t$.

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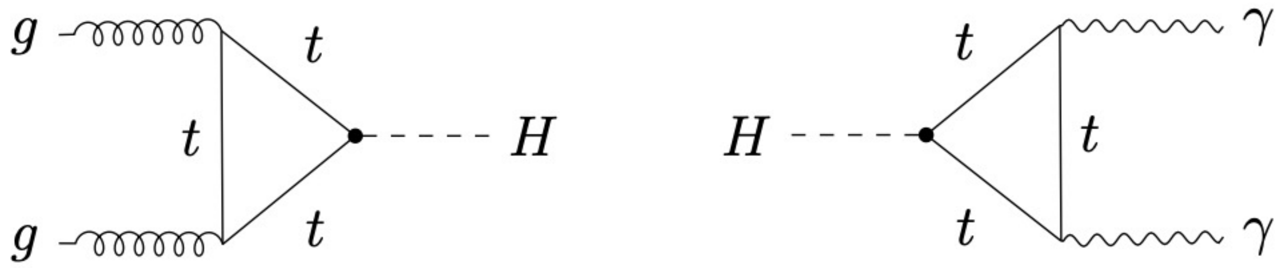

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- $\kappa_\gamma^2 \equiv \frac{\Gamma_{H\to\gamma\gamma}}{\Gamma_{H\to\gamma\gamma}^{\text{SM}}} \simeq 1.6c_V^2 - 0.7c_V c_t + 0.1c_t^2 + 0.2\tilde{c}_t^2 + \cdots$, disfavors negative/small c_t.

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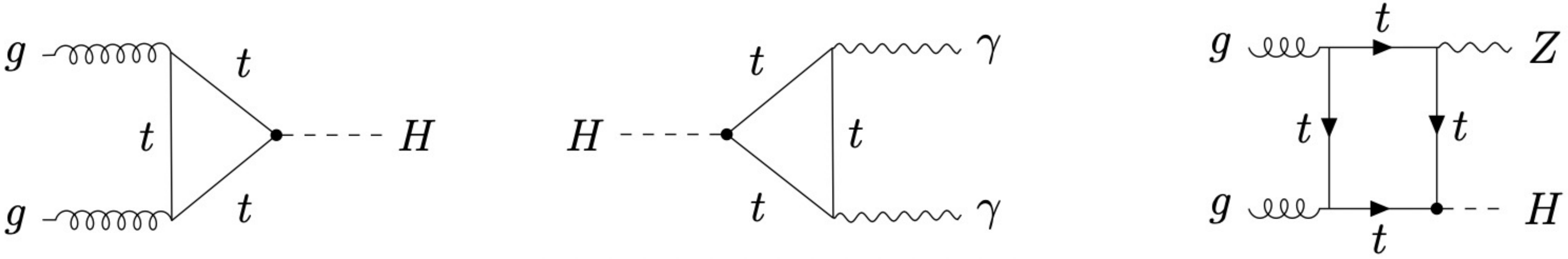

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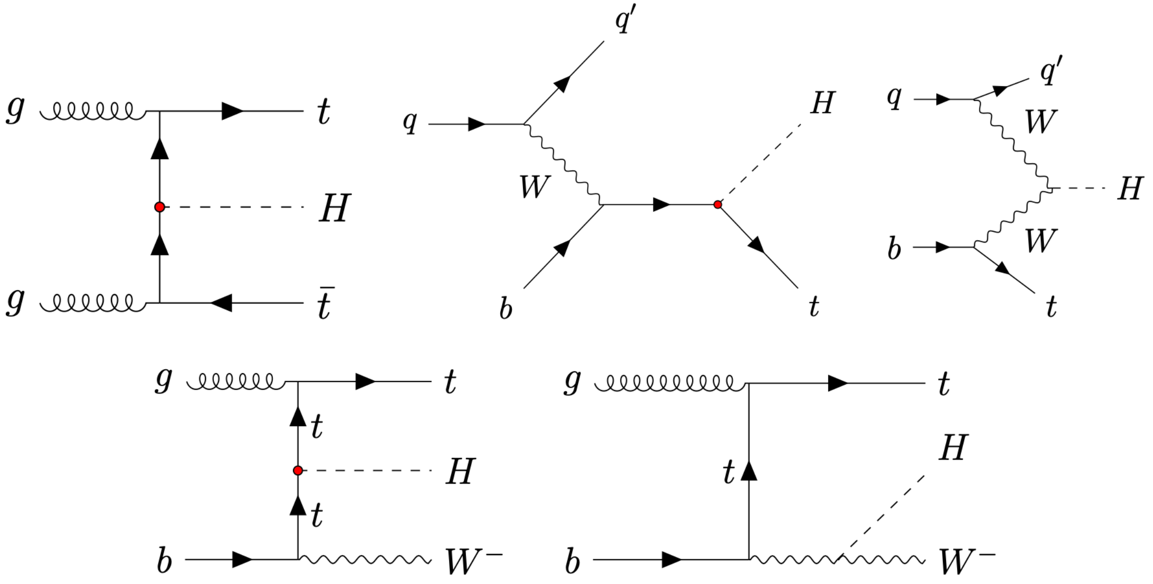
- $\frac{\sigma_{gg\to ZH}}{\sigma_{gg\to ZH}^{\rm SM}} \simeq 0.5c_t^2 + 0.5\tilde{c}_t^2 + 2.4c_V^2 - 1.9c_V c_t$..., disfavors negative c_t.

Top-Yukawa coupling

- Probe top-Yukawa coupling at the tree-level via top-associated Higgs production:
  - Three subchannels: $t\bar{t}H$, tH, tWH.
  - Difficult to disentangle experimentally.
  - Consider combined signal strength

$$\mu_{tH+t\bar{t}H+tWH} = \frac{\sigma(tH+t\bar{t}H+tWH)}{\sigma^{SM}(tH+t\bar{t}H+tWH)}.$$



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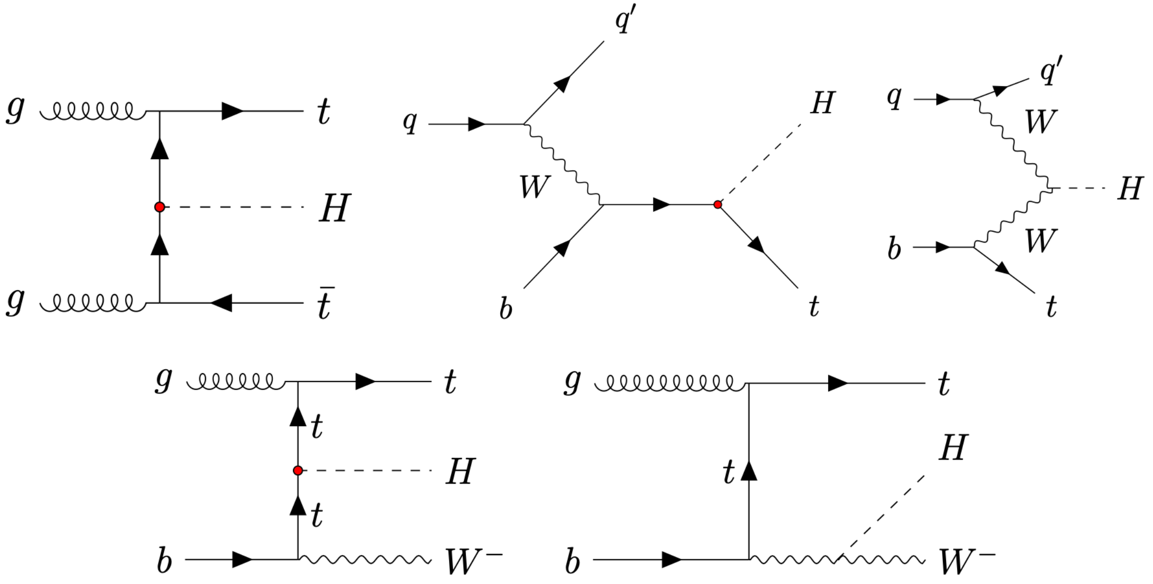
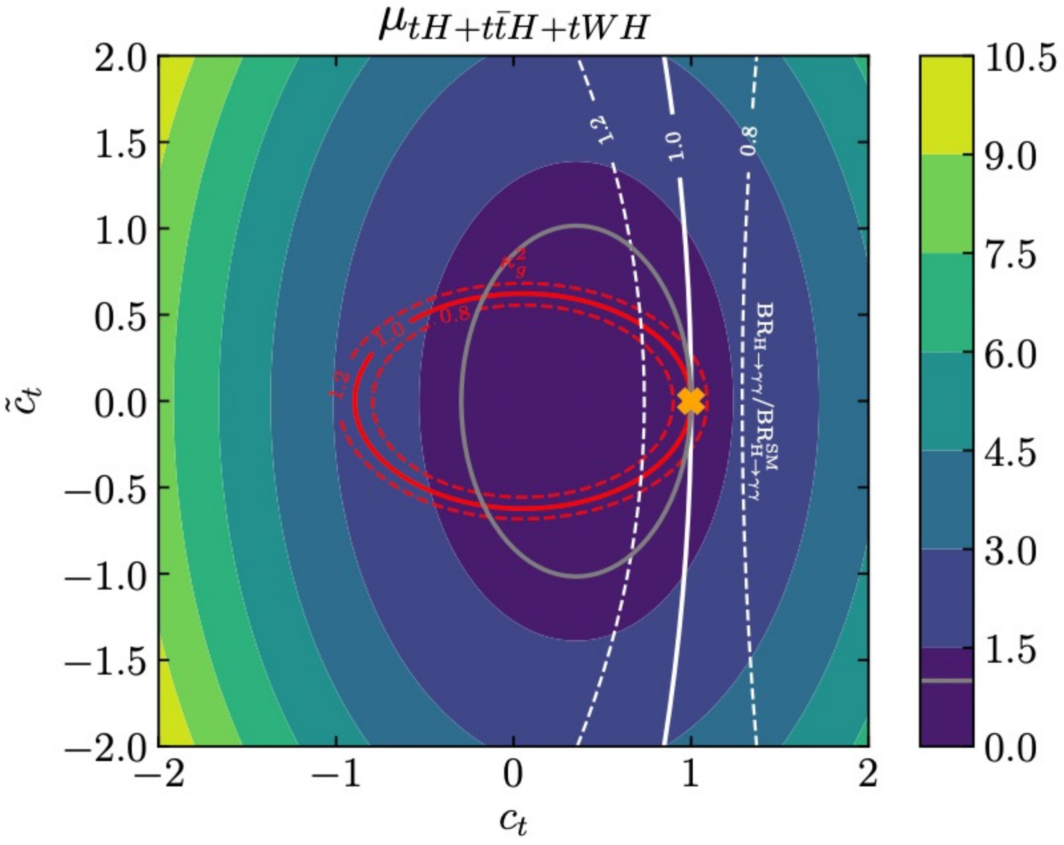
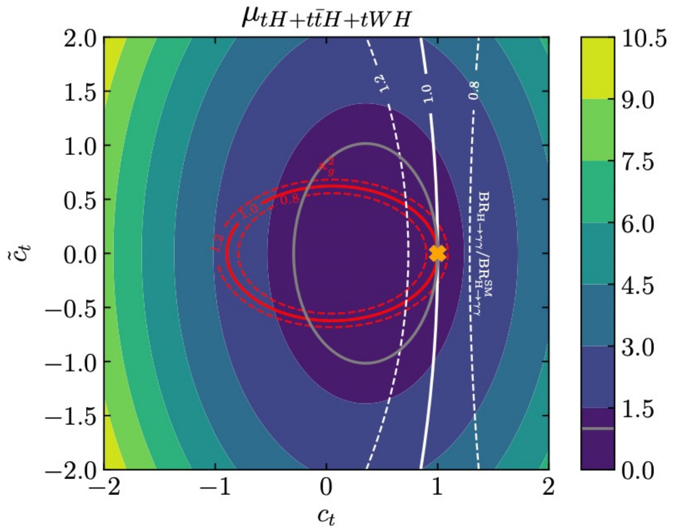
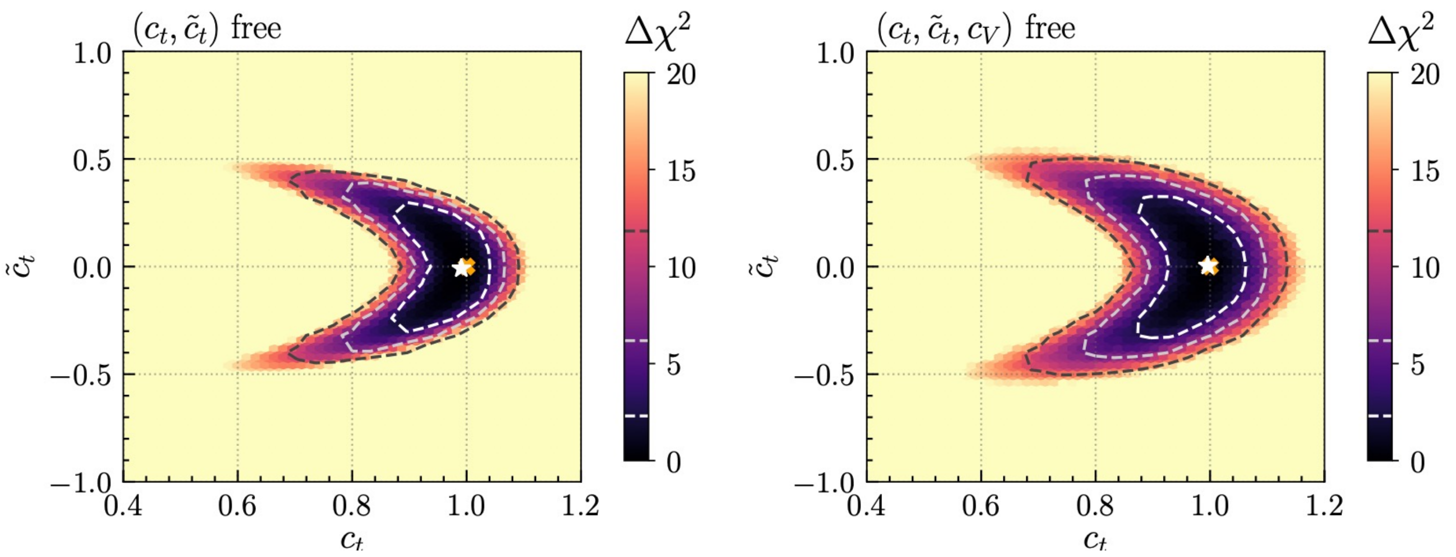




1 flavor fits: t

[HB et al.,2007.08542]

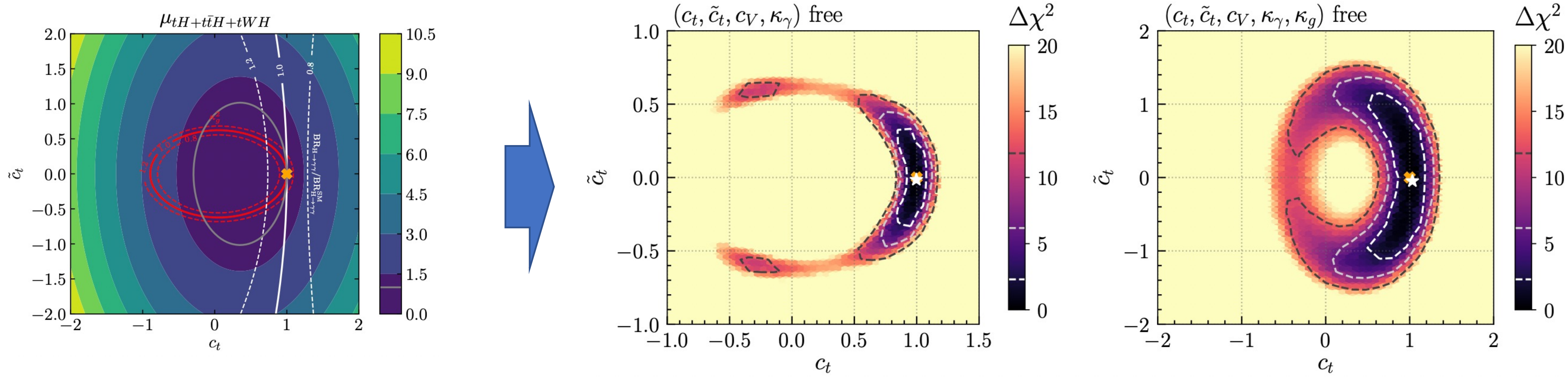




- ggH and $H \to \gamma\gamma$ total rates strongly constraint CP violation in top-Yukawa coupling.
- Relies on assumption that no other BSM physics affect ggH and $H \to \gamma\gamma$.
- What happens if we allow κ_γ and κ_g to float freely?

1 flavor fits: t — free κ_γ, κ_g

[HB et al.,2007.08542]

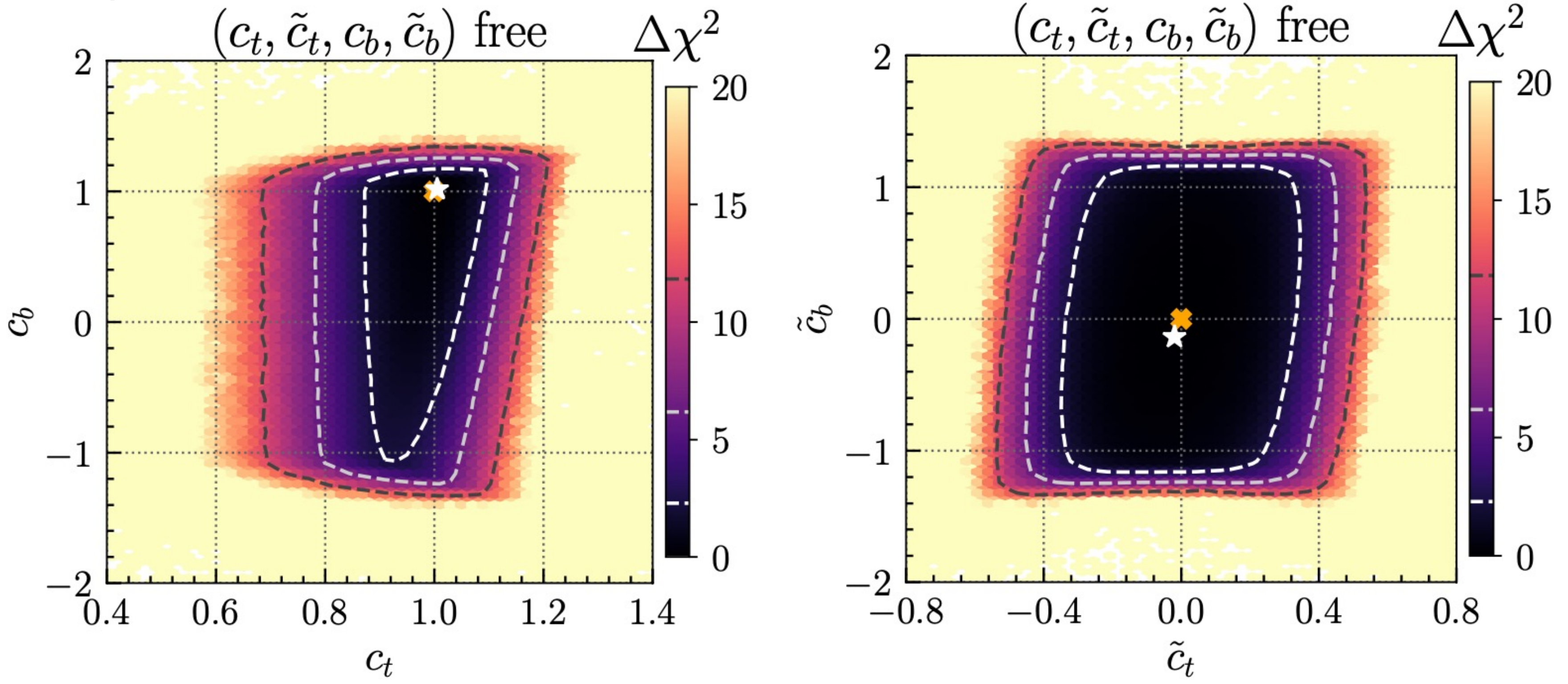


- Colored and charged BSM particles can cancel the effect of a modified top-Yukawa coupling.
- Top-associated Higgs production is a more model-independent but weaker probe.

≥ 2 flavor fits ⇒ only weak correlations between different Yukawa couplings.

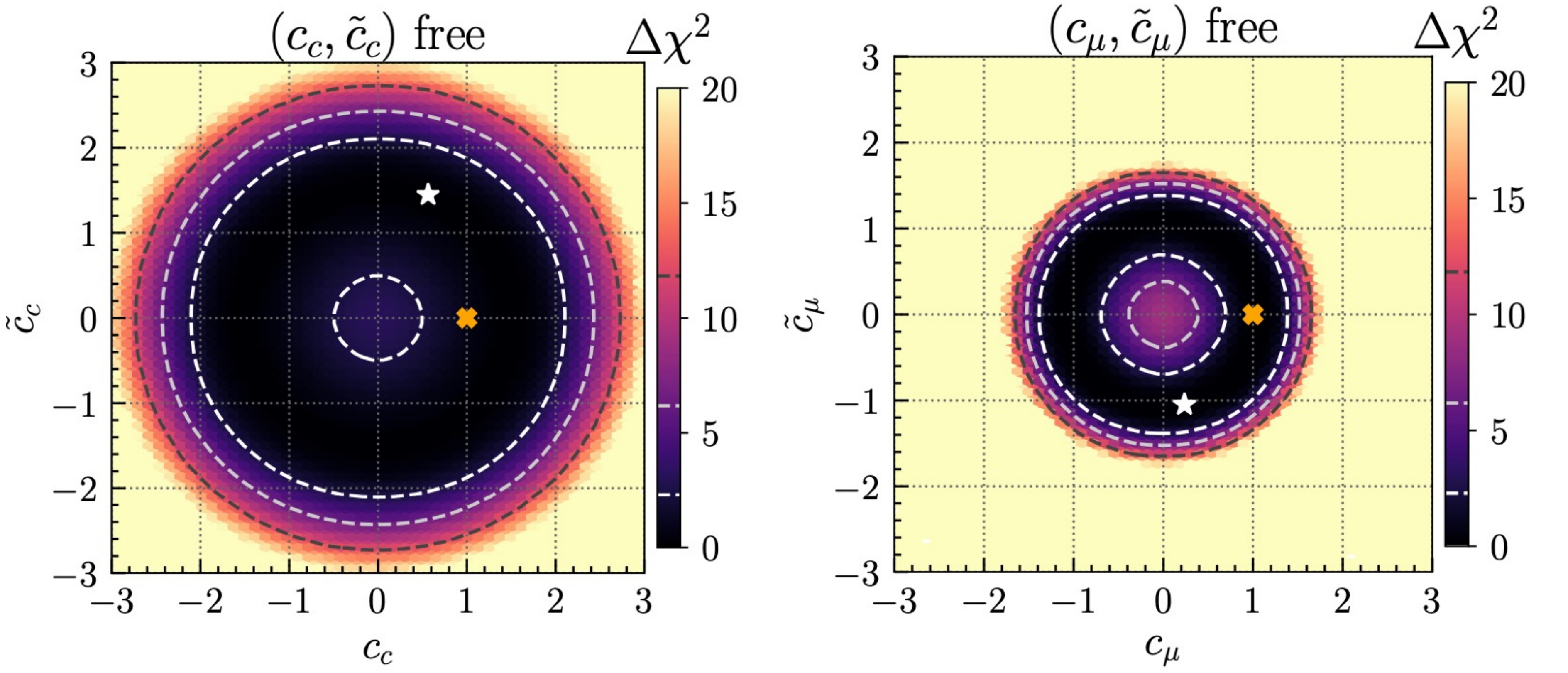
2 flavor fits: t and b

[HB et al.,2202.11753]

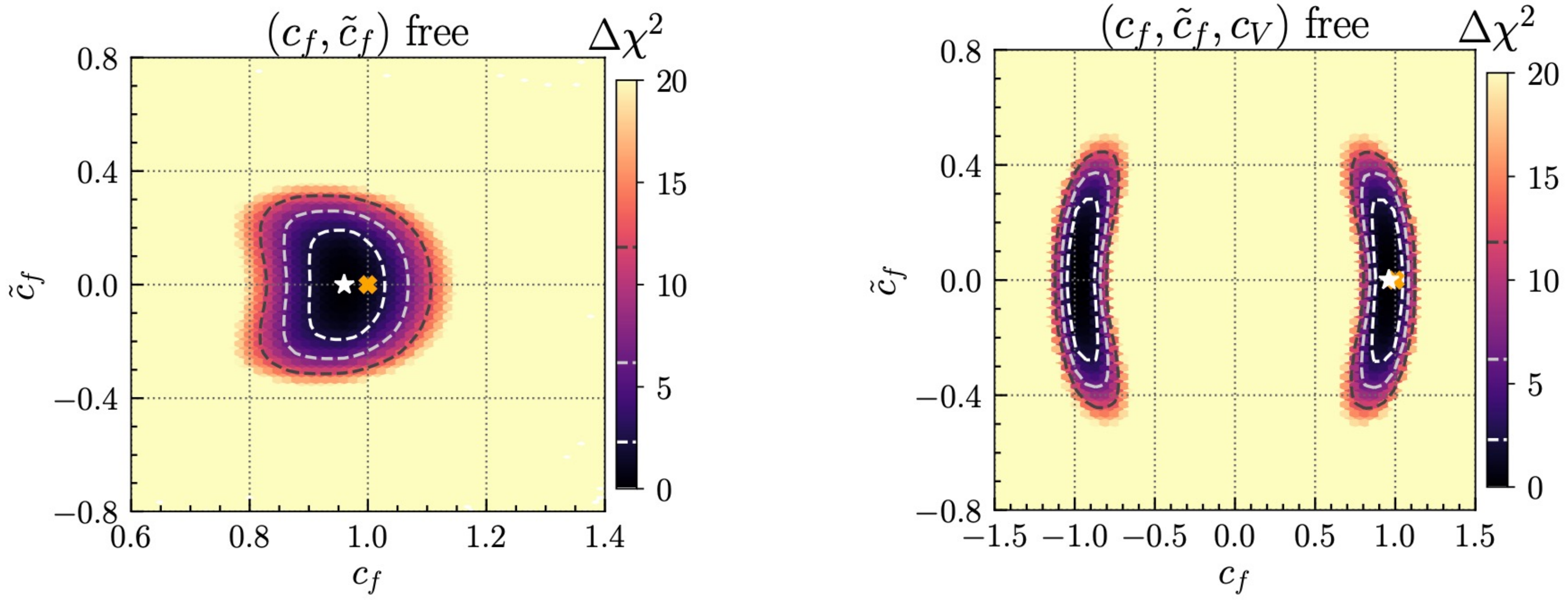


- ggH rate correlates top and bottom Yukawa couplings: $\kappa_g^2 \simeq 1.1c_t^2 + 2.6\tilde{c}_t^2 - 0.1c_tc_b - 0.2\tilde{c}_t\tilde{c}_b$.
- Correlation of CP-odd coupling modifiers weaker since bounds on $\tilde{c}_t$ are stronger.

Charm- and muon-Yukawa couplings



Global modification fits



- Universal fermion coupling modifiers: $c_f = c_t = c_b = \cdots = c_\tau$, $\tilde{c}_f = \tilde{c}_t = \tilde{c}_b = \cdots = \tilde{c}_\tau$.
- Dominated by constraints on top-Yukawa coupling.
- Additional varying c_V reopens negative c_f range.

"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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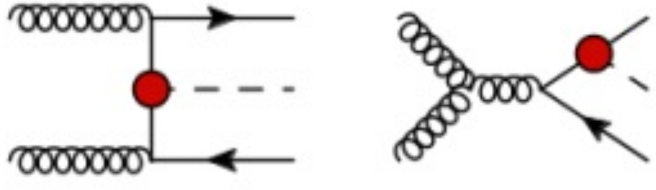
[Maltoni,Vryonidou,Zhang,1607.05330]



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

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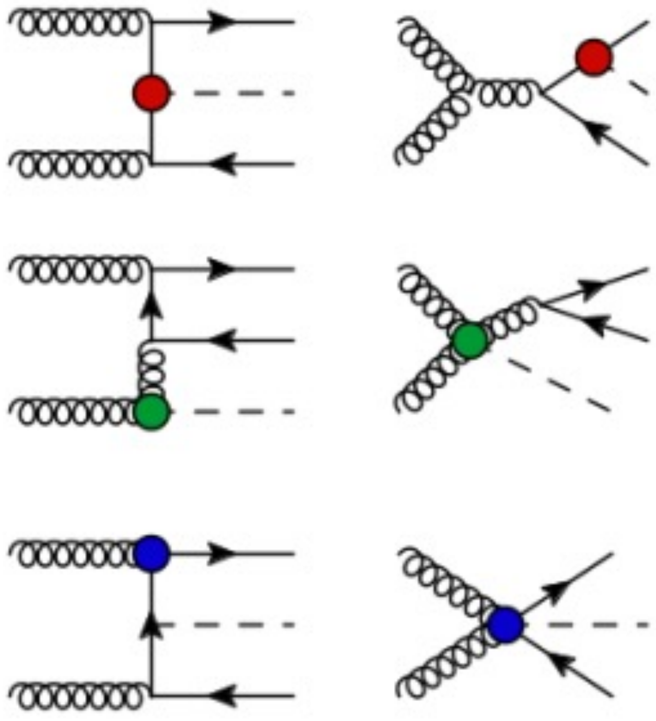

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There are, however, further "Higgs" operators which contribute to e.g. $t\bar{t}H$:

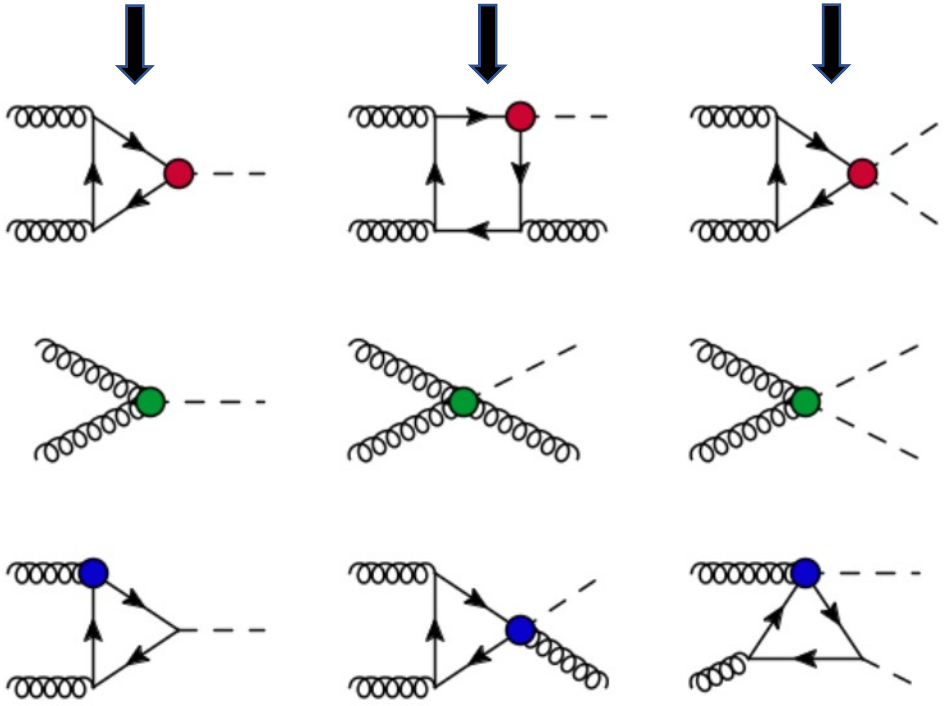
- $O_{tG} = (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$,

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

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

Correlation with other Higgs channels

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



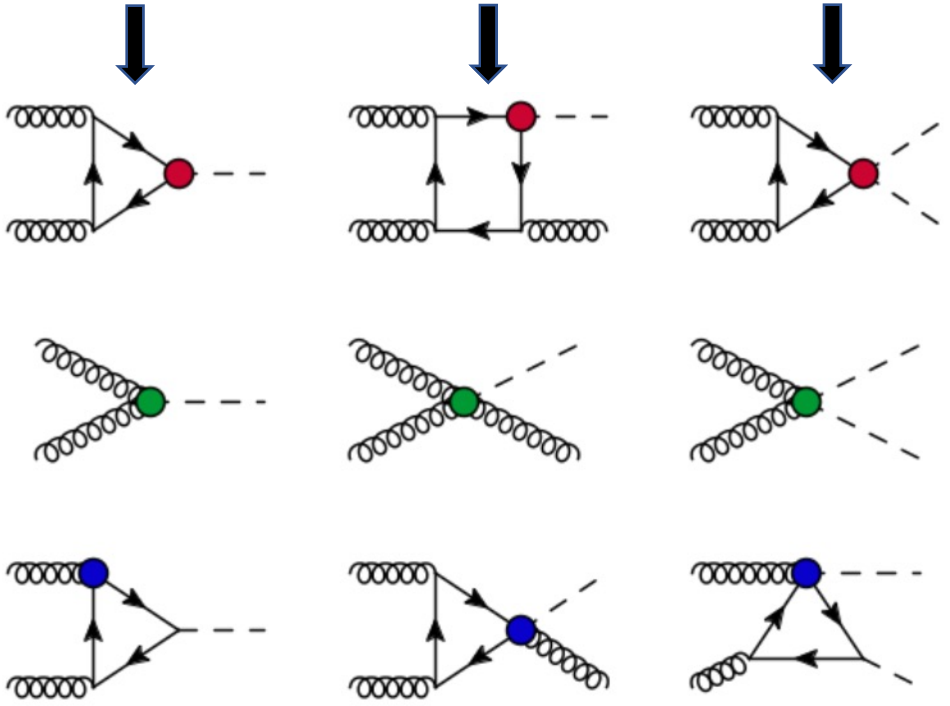
[Maltoni,Vryonidou,Zhang,1607.05330]

(+ interplay with bottom Yukawa etc.)

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

Correlation with other Higgs channels

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

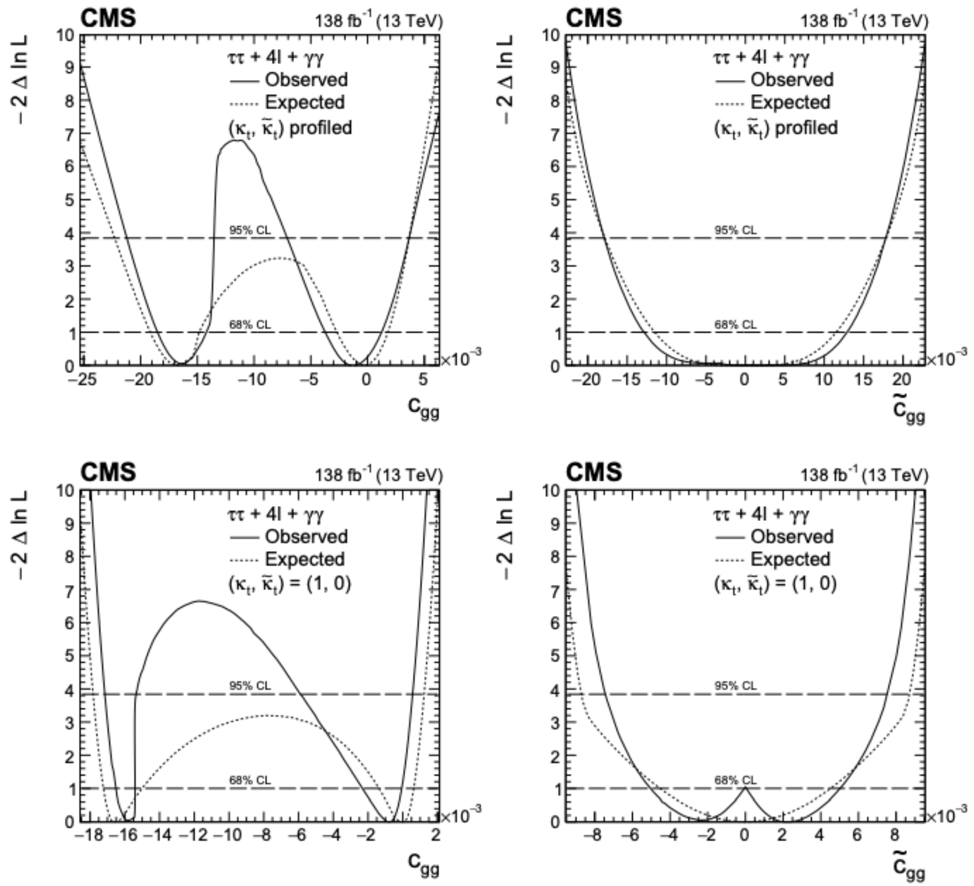


[Maltoni,Vryonidou,Zhang,1607.05330]

(+ interplay with bottom Yukawa etc.)

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

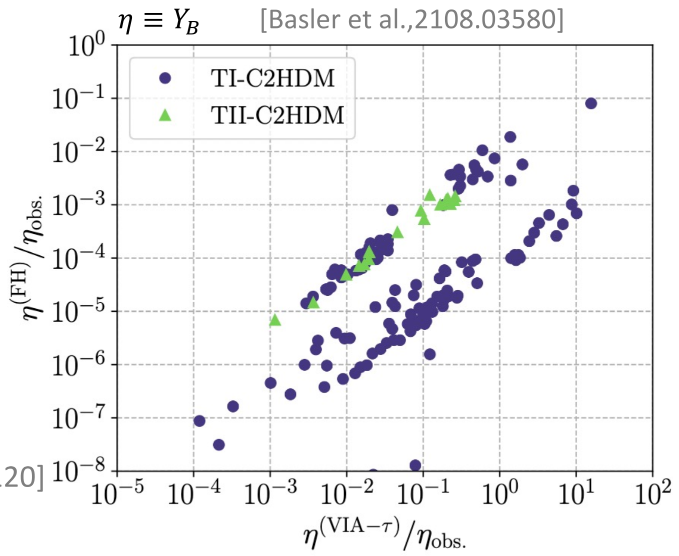
Comb. fit



[CMS, 2205.05120]

→ Would be great to get full likelihood information!

Baryon asymmetry of the Universe



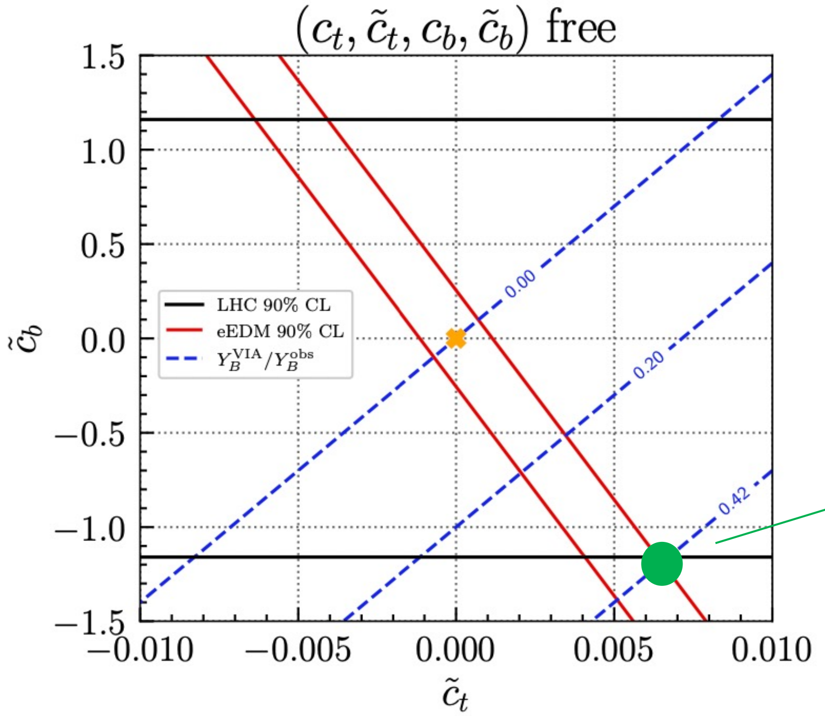
- Different techniques used in the literature to calculate BAU Y_B:
  - Vev-insertion approach (VIA),
    [Huet&Nelson,9504427,9506477;Carena et al., 9603420;Riotto, 9712221;Lee et al.,0412354;Postma et al.,2206.01120]
  - WKB (or FH) approximation.
    [Joecy et al.,9410282;Kainulainen et al.,0105295,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

2 flavor results: t and b

[HB et al.,2202.11753]



Maximal $Y_B/Y_B^{\rm obs}$ within LHC and eEDM constraints:

	t	b	c	τ	μ
t	0.03				
b	**0.42**	0.05			
c	0.37	0.19	0.01		
τ	6.9	6.9	6.9	3.2	
μ	0.18	0.19	0.16	3.2	0.16

- Presence of more than one CP-violating coupling allows for cancellation in eEDM.

  → Larger values for $Y_B/Y_B^{\rm obs}$ can be reached.