Global Constraints on CP Violation in the SM Higgs Sector

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Based on Joachim Brod, JC, Dimitrios Skodras, and Emmanuel Stamou, JHEP 08 (2022) 294, arXiv:2203.03736

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Baryogenesis requires more CP violation than the SM provides...

Could it be due to the interactions of the Higgs?

This possibility has largely been considered in the coupling of the SM Higgs to the **third** generation of quarks and leptons, with the CP violation parameterized by the "**κ**-framework":

$$\mathcal{L}_{\mathrm{Yukawa},\kappa} = -\sum_{f=b,t,\tau} \kappa_f \frac{y_f^{\mathrm{SM}}}{\sqrt{2}} h\bar{f}(\cos\phi_f + i\gamma_5 \sin\phi_f)f$$

However, the non-observation of electric-dipole moments in multiple systems (the electron, neutron, and mercury) constrain $\boldsymbol{\kappa_f}$ and $\boldsymbol{\phi_f}$ substantially.

Brod, Haisch, Zupan (2013) and others

Limitations of this approach

1. Allowing for CP-violation in the coupling of the Higgs to **lighter** fermions leads to interesting phenomenology (e.g. cancellations in EDM calculations).

2. The "**κ**-framework" is not a consistent field theory and leads to a possibly incorrect result when calculating EDMs.

Altmannshofer, et al. (2020)

EFT Approach

$$\mathscr{L}_{\text{Yukawa}} = -\bar{Q}_L \tilde{H} Y_u u_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{Q}_L \tilde{H} C'_{uH} u_R$$

Λ = 1 TeV

$$-\bar{Q}_L H Y_d d_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{Q}_L H C'_{dH} d_R$$

$$-\bar{L}_L H Y_\ell \ell_R + \frac{1}{\Lambda^2}(H^\dagger H)\bar{L}_L H C'_{\ell H} \ell_R + \text{h.c.}\,.$$

In the EW broken phase, after rotating into the mass-eigenstate basis and setting off diagonal terms in the Yukawa matrices to zero:

$$\mathscr{L}_{\text{Yukawa}} = \sum_f \left[\left(-m_f - m_f \frac{h}{v} + \frac{v^3}{2\sqrt{2}\Lambda^2} C_{fH+} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \right) \bar{f} f \right.$$

$$\left. + \frac{v^3}{2\sqrt{2}\Lambda^2} C_{fH-} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \bar{f} i\gamma_5 f \right]$$

SM fermion masses and Higgs Couplings

CP conserving couplings between Higgs and fermions

$$\mathscr{L}_{\text{Yukawa}} = \sum_f \left[\left(-m_f - m_f \frac{h}{v} + \frac{v^3}{2\sqrt{2}\Lambda^2} C_{fH+} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \right) \bar{f}f \right.$$

CP violating couplings between Higgs and fermions

$$\left. + \frac{v^3}{2\sqrt{2}\Lambda^2} C_{fH-} \left(2\frac{h}{v} + 3\frac{h^2}{v^2} + \frac{h^3}{v^3} \right) \bar{f} i\gamma_5 f \right]$$

19 Parameter Model: $f = u, d, c, s, t, b, e, \mu, \tau$

C_{Hf+} 9 CP Conserving Higgs Coupling Modifiers

C_{Hf-} 9 CP Violating Higgs Coupling Modifiers

Our Question: How constrained are these 18 parameters in light of relevant constraints (LHC and EDMs)?

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, S Bloor, LL Braseth, T Bringmann, A Buckley, J Butterworth, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, M Lecroq, P Jackson, D Jacob, C Lin, FN Mahmoudi, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, JJ Renk, R Ruiz, A Scaffidi, P Scott, N Serra, P Stöcker, W. Su, J Van den Abeele, A Vincent, C Weniger, A Woodcock, M White, Y Zhang ++

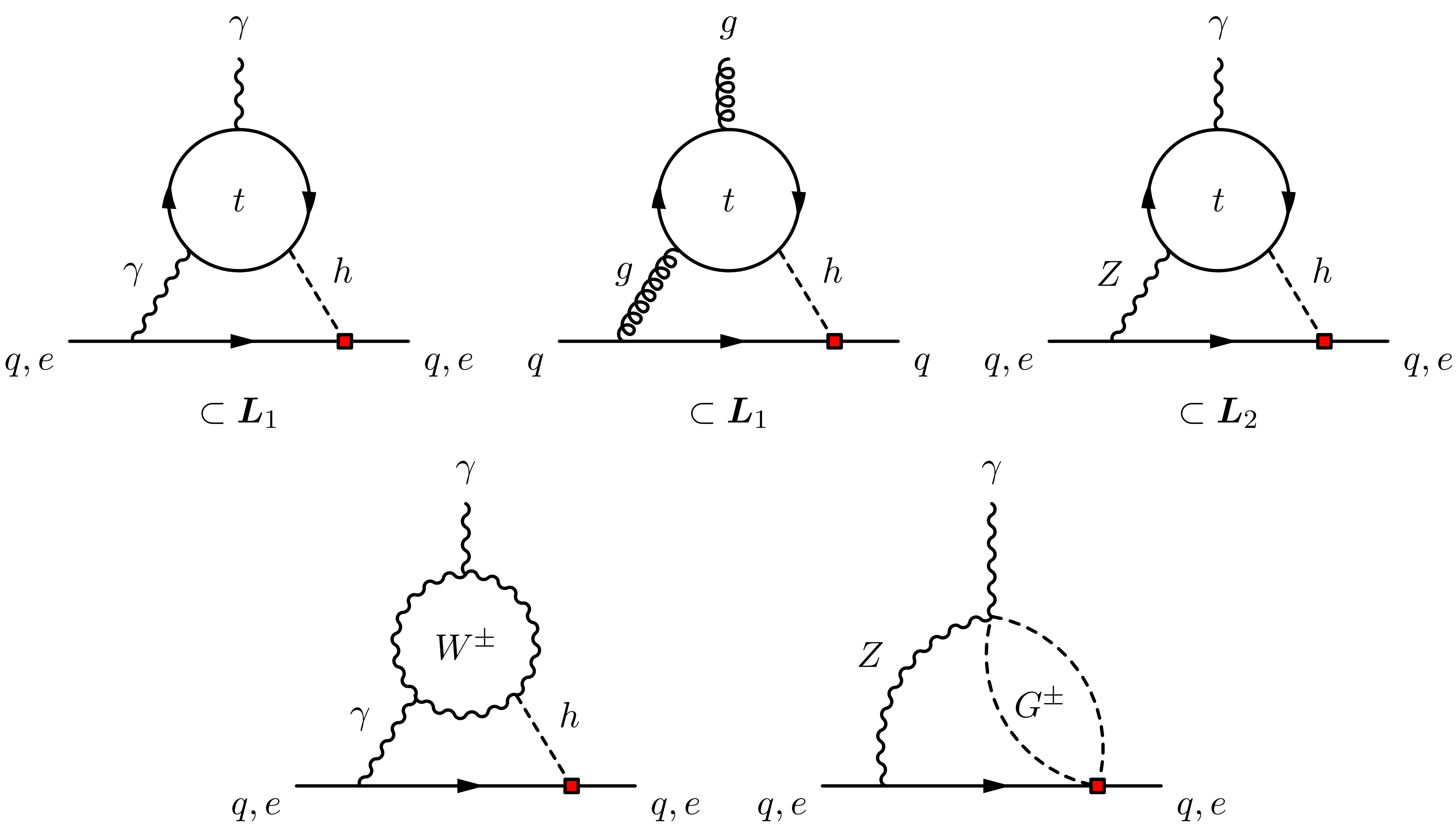
80+ participants in many experiments and numerous major theory codes

Additional GAMBIT talks at this conference by Tomas Gonzalo:

Monday – A global analysis of decaying cosmological ALPs

Tuesday, 17:00 (B100/1001) – LHC constraints on SUSY with a light gravitino.

(Chromo) Electric Dipole Moment



Interactions such as those diagrammed above are used to determine the (C)EDMs of the light quarks and electron, which are subsequently used to calculate the EDMs of the neutron and mercury.

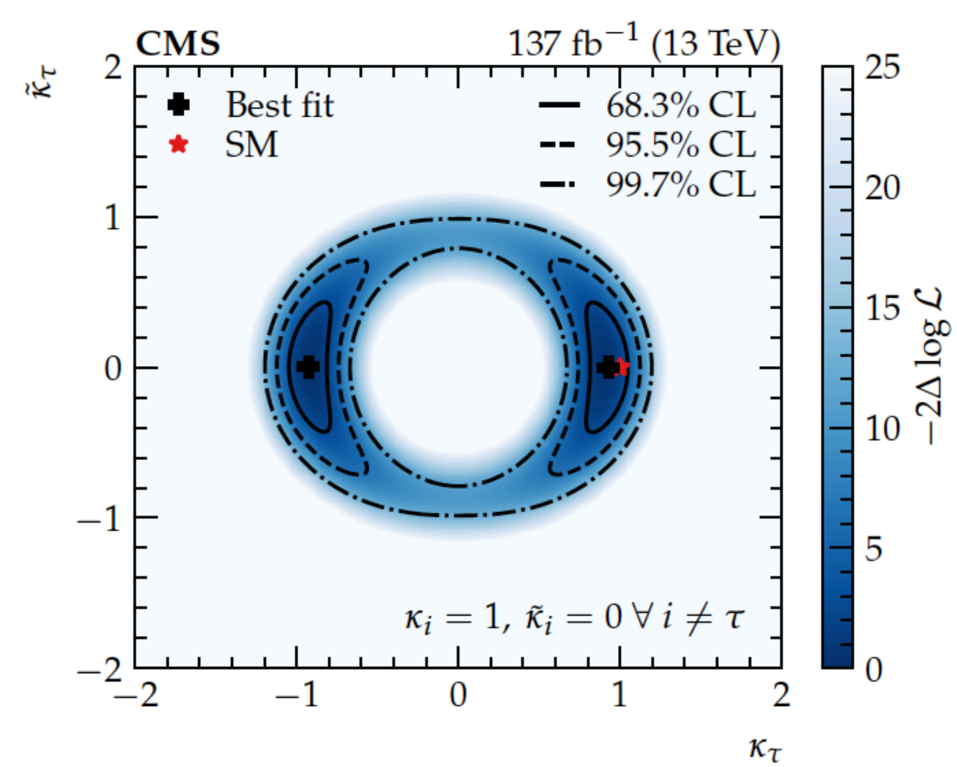
LHC Higgs Studies

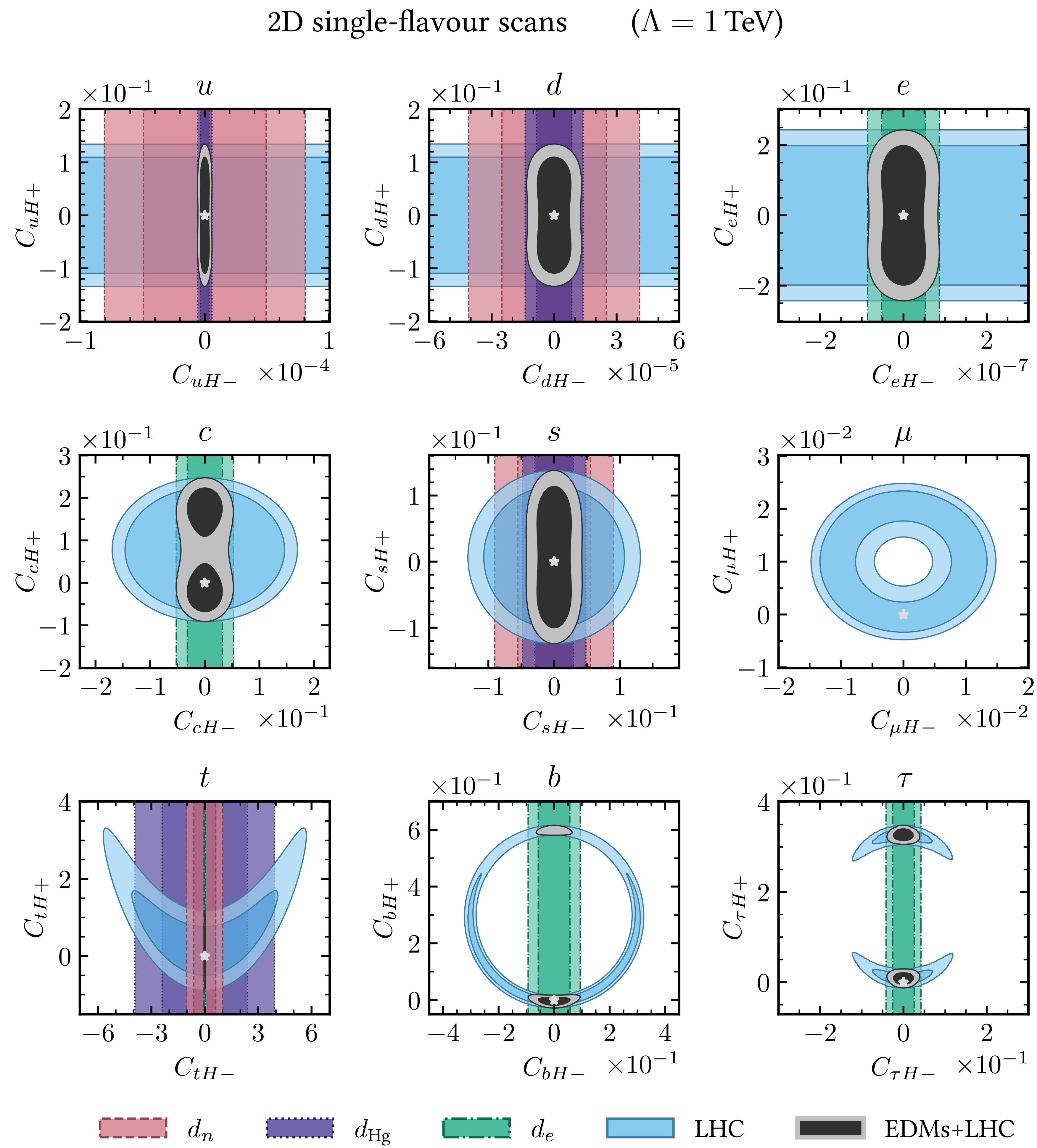
We calculate corrections to the following rates:

- $gg \to h$
- $h \to \gamma\gamma$
- $h \to \bar{b}b$
- $h \to \bar{c}c$
- $h \to \tau^+\tau^-$
- $h \to \mu^+\mu^-$

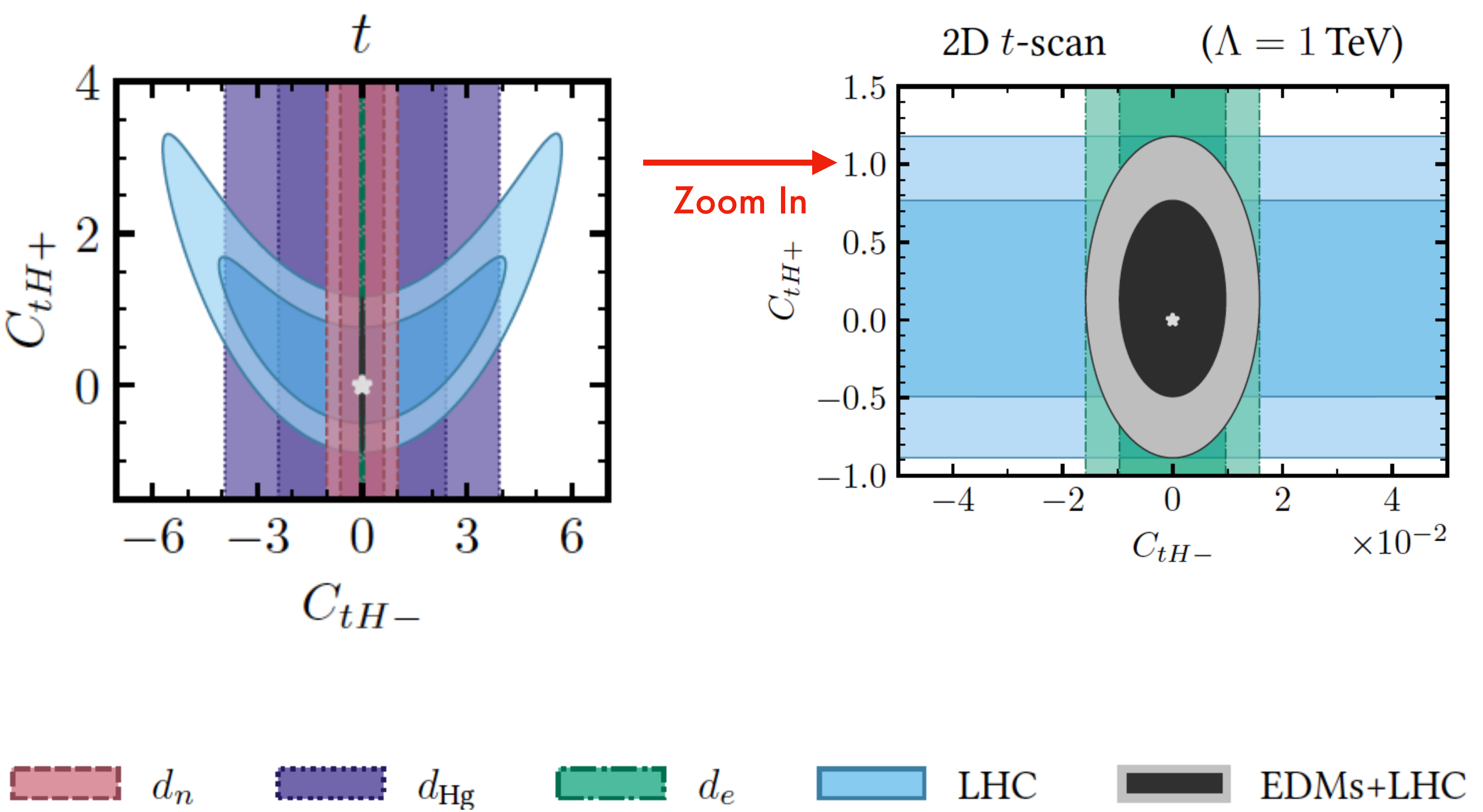
As well as the total width of the Higgs. Constraints are taken from `HiggsBounds` and `HiggsSignals`. Bechtle, et al. 2020

In addition, we make use of a $h \to \tau^+\tau^-$ angular analysis to directly constrain CP violation in the Higgs-tau coupling. CMS 2021



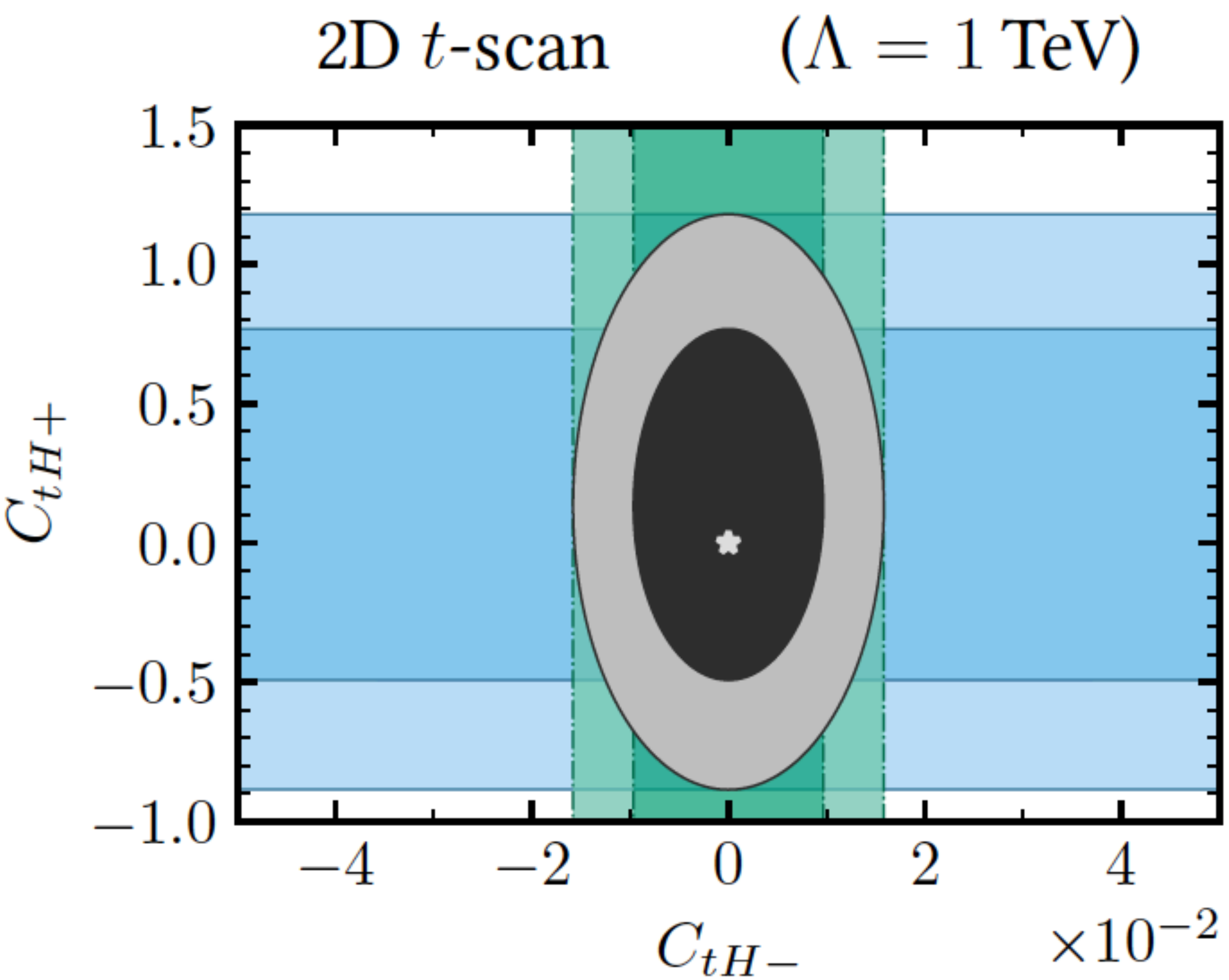

2D single-flavour scans (Λ = 1 TeV)
u
d
e
c
s
μ
t
b
τ
C_{uH+}
C_{uH−}
C_{dH+}
C_{dH−}
C_{eH+}
C_{eH−}
C_{cH+}
C_{cH−}
C_{sH+}
C_{sH−}
C_{μH+}
C_{μH−}
C_{tH+}
C_{tH−}
C_{bH+}
C_{bH−}
C_{τH+}
C_{τH−}
×10^{−1}
×10^{−4}
×10^{−5}
×10^{−7}
×10^{−2}
d_n
d_Hg
d_e
LHC
EDMs+LHC

Single flavour scans

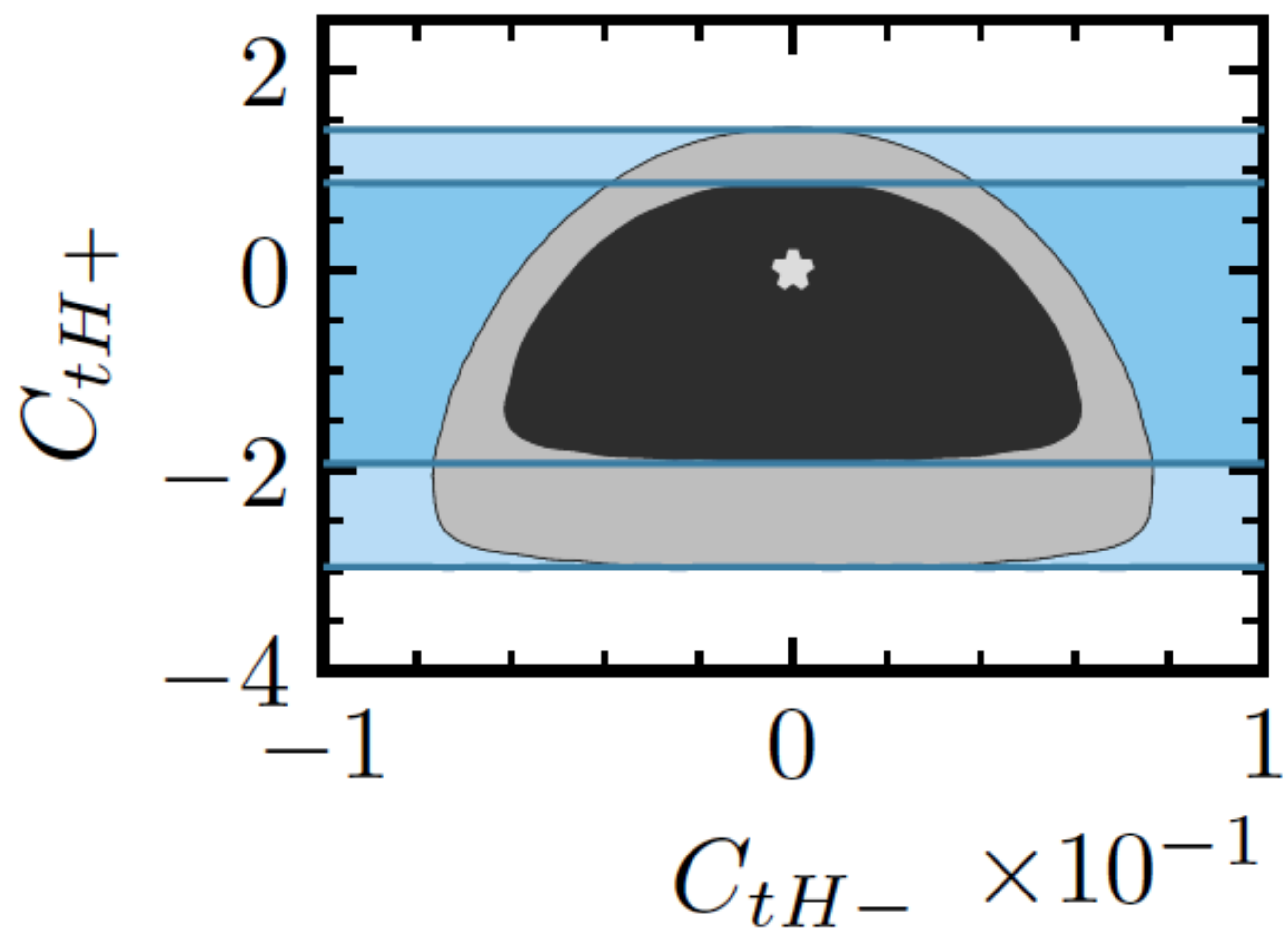


A 4D Scan

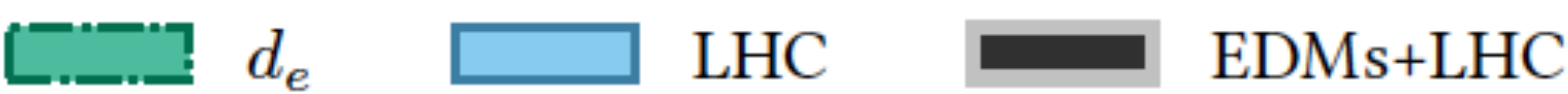
2 Parameters: C_{tH+}, C_{tH-}



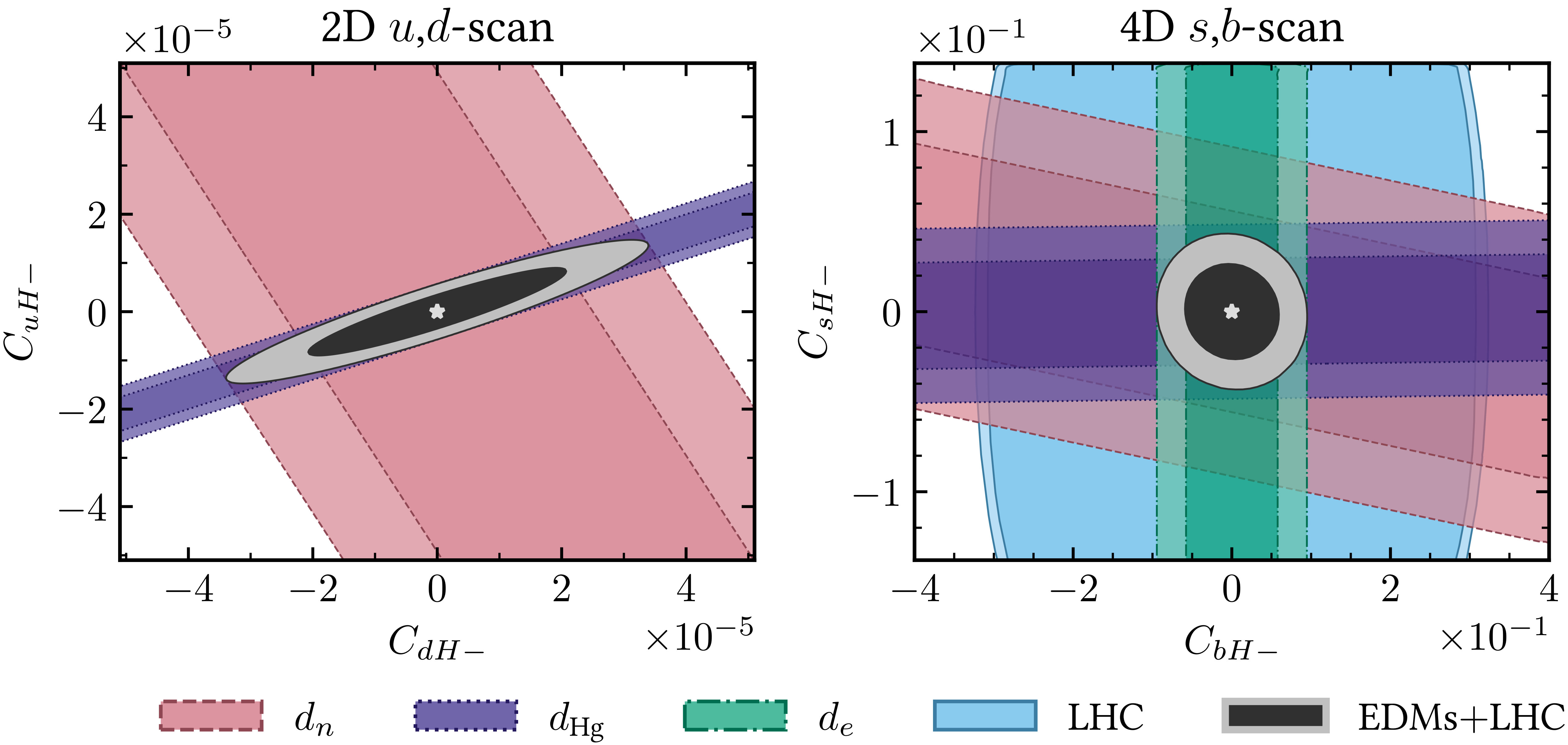
4 Parameters:
C_{tH+}, C_{tH-}, C_{sH+}, C_{sH-}



EDM constraints weakened!



All EDM Measurements Are Not the Same



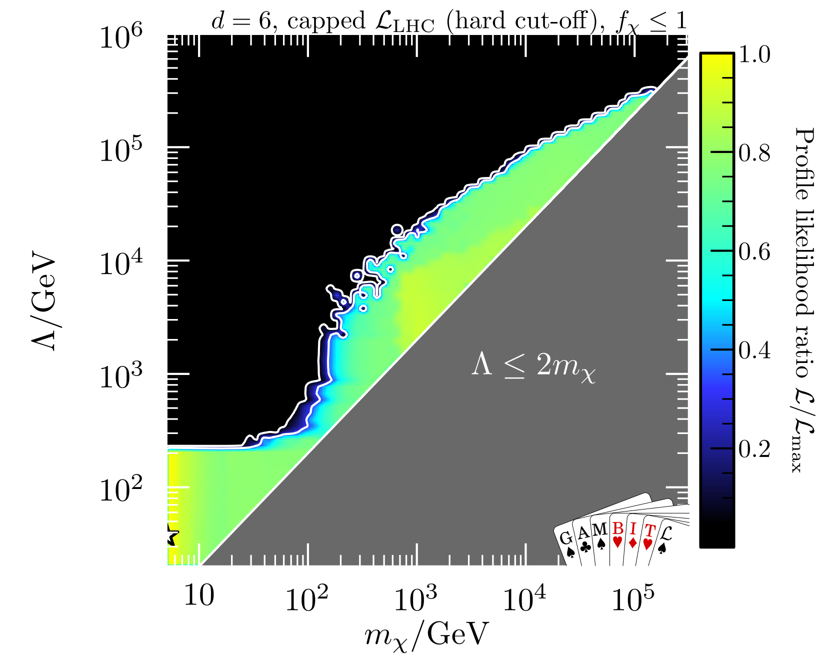
Summary

- EDMs are often the most constraining observable for CP violating interactions.
- We have added EDM constraints to the GAMBIT global fitting framework and used them to constrain CP violating Higgs couplings to fermions.
- We find that constraints on these couplings are substantially relaxed by allowing for CP violating in the interactions of the Higgs with *multiple* fermions, as would be expected in more realistic UV models.

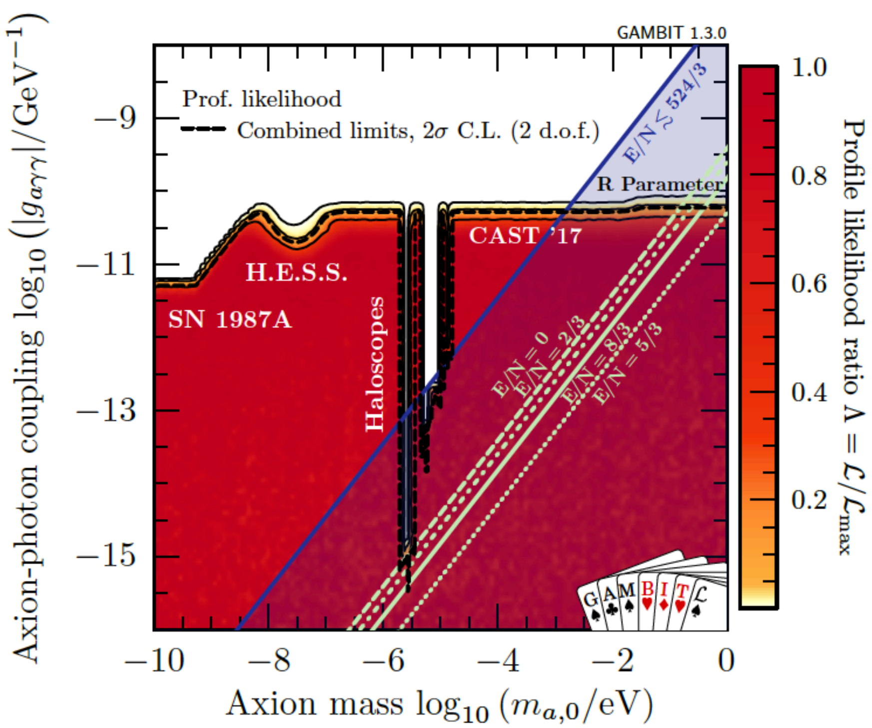
Backups

Other GAMBIT Results

Dark Matter EFT (arXiv:2106.02056)

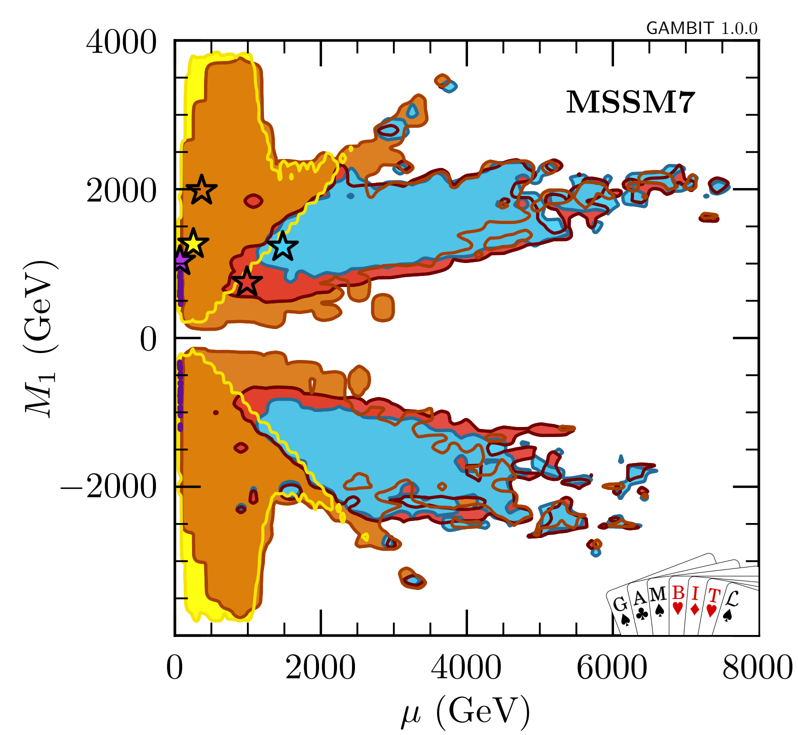


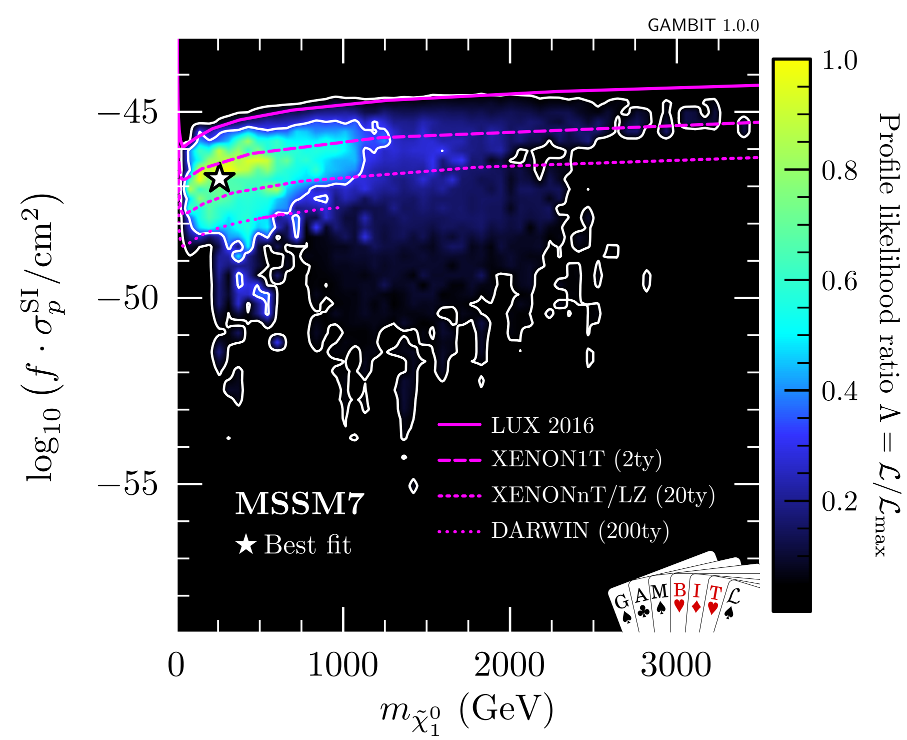
Axions (arXiv:1810.07192)



Weak Scale SUSY (arXiv:1705.07917)

- $\tilde{t}_1$ co-annihilation
- A/H funnel
- $\tilde{\chi}_1^\pm$ co-annihilation
- $\tilde{b}_1$ co-annihilation
- h/Z funnel





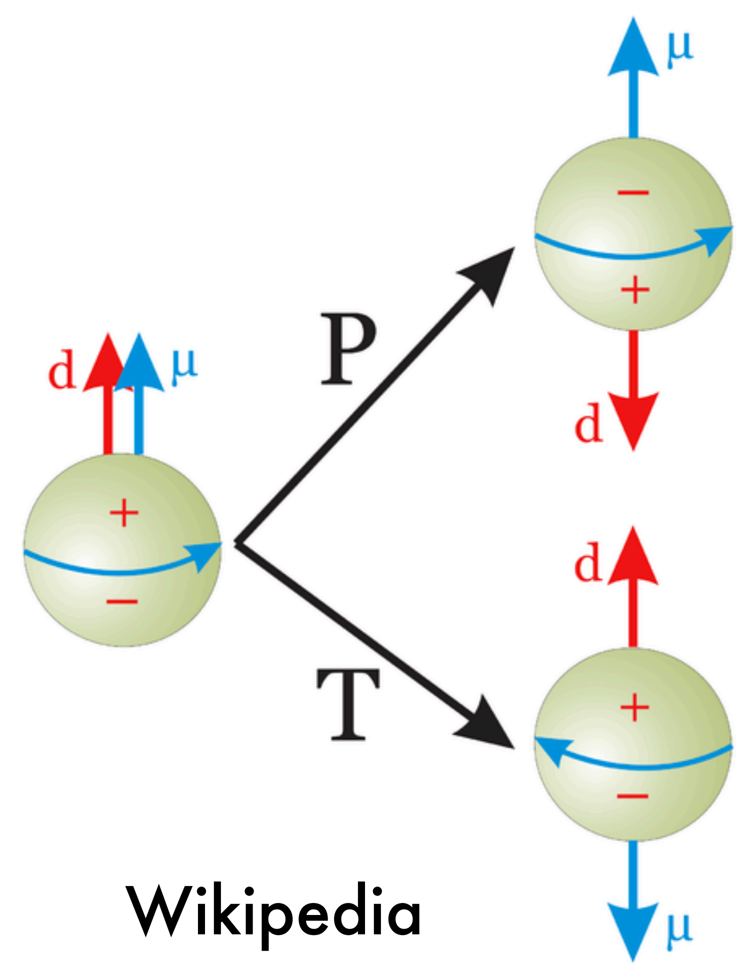
Experimental Constraints

Direct: The Large Hadron Collider

Measurements of Higgs width, decay rates to fermion final states, production rates, and $\tau\bar{\tau}$ angular analysis (only observable that directly probes CP violation).

Indirect: Electric dipole moments (of electron, neutron, and mercury)

Usually much more constraining for CP violating couplings!



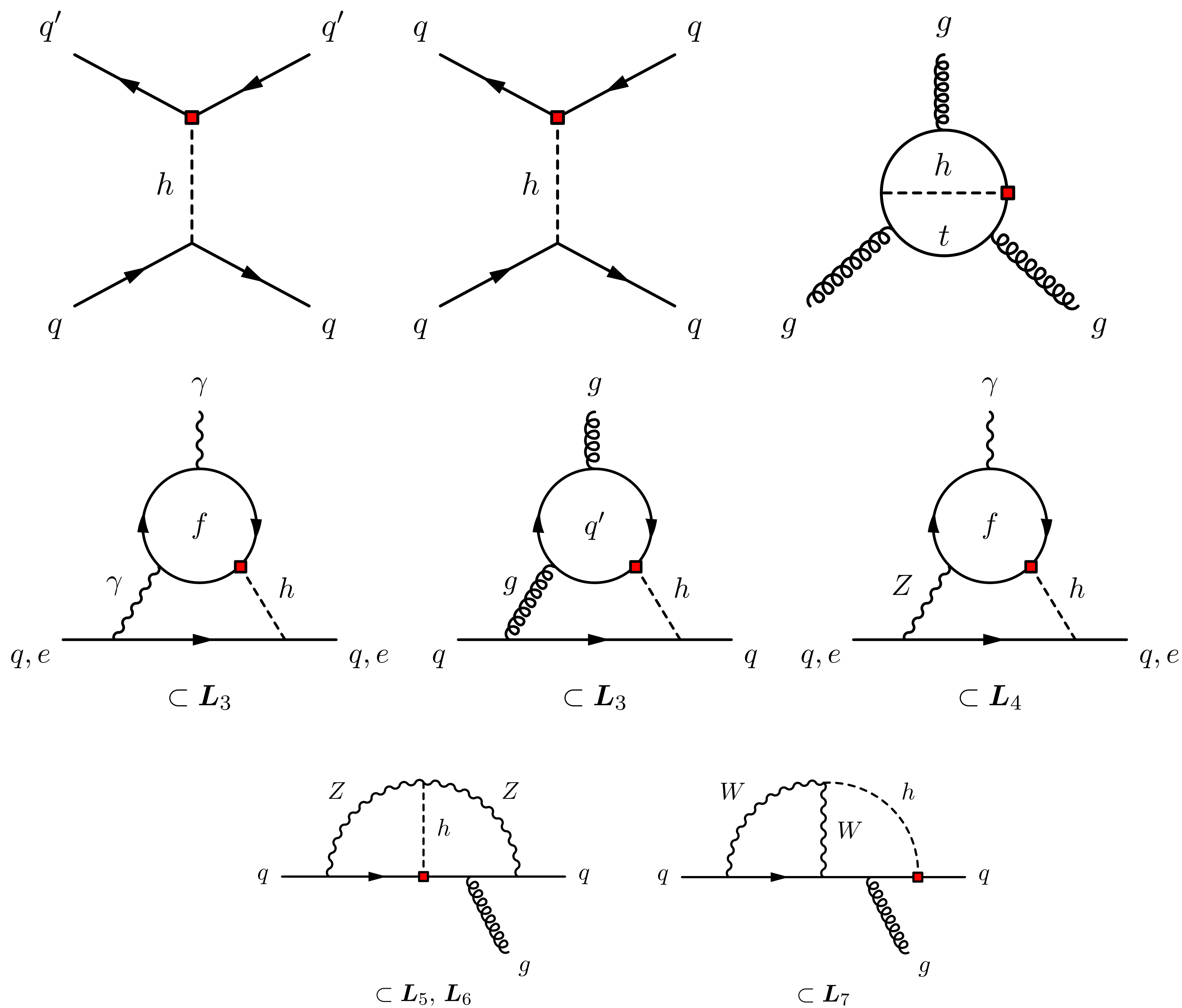
Wikipedia

Relation Between κ-Framework and Our Parameters

$$\kappa_f \cos\phi_f \stackrel{\circ}{=} 1 - \frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH+}$$

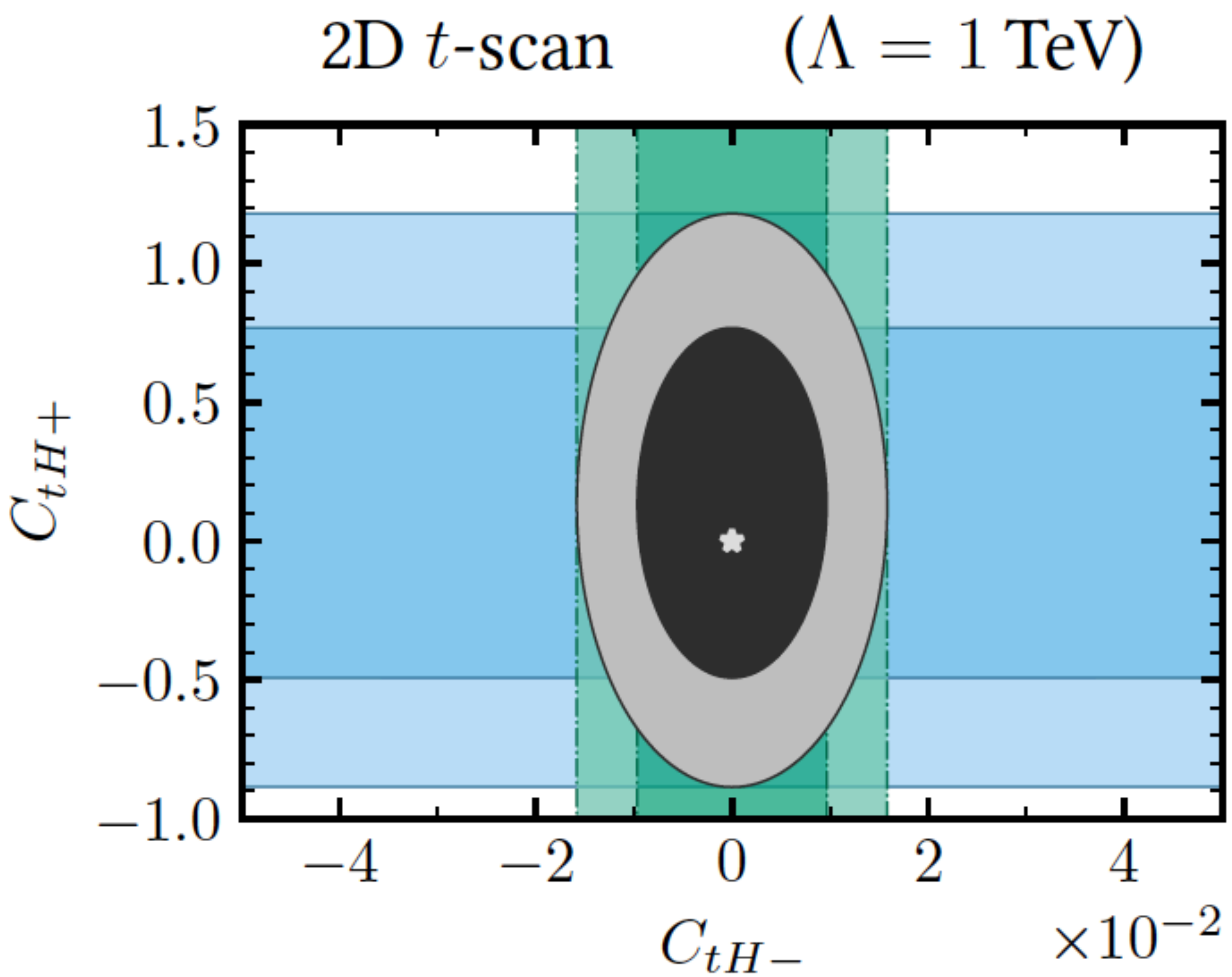
$$\kappa_f \sin\phi_f \stackrel{\circ}{=} - \frac{v}{\sqrt{2}m_f}\frac{v^2}{\Lambda^2}C_{fH-}$$

More Relevant Feynman Diagrams



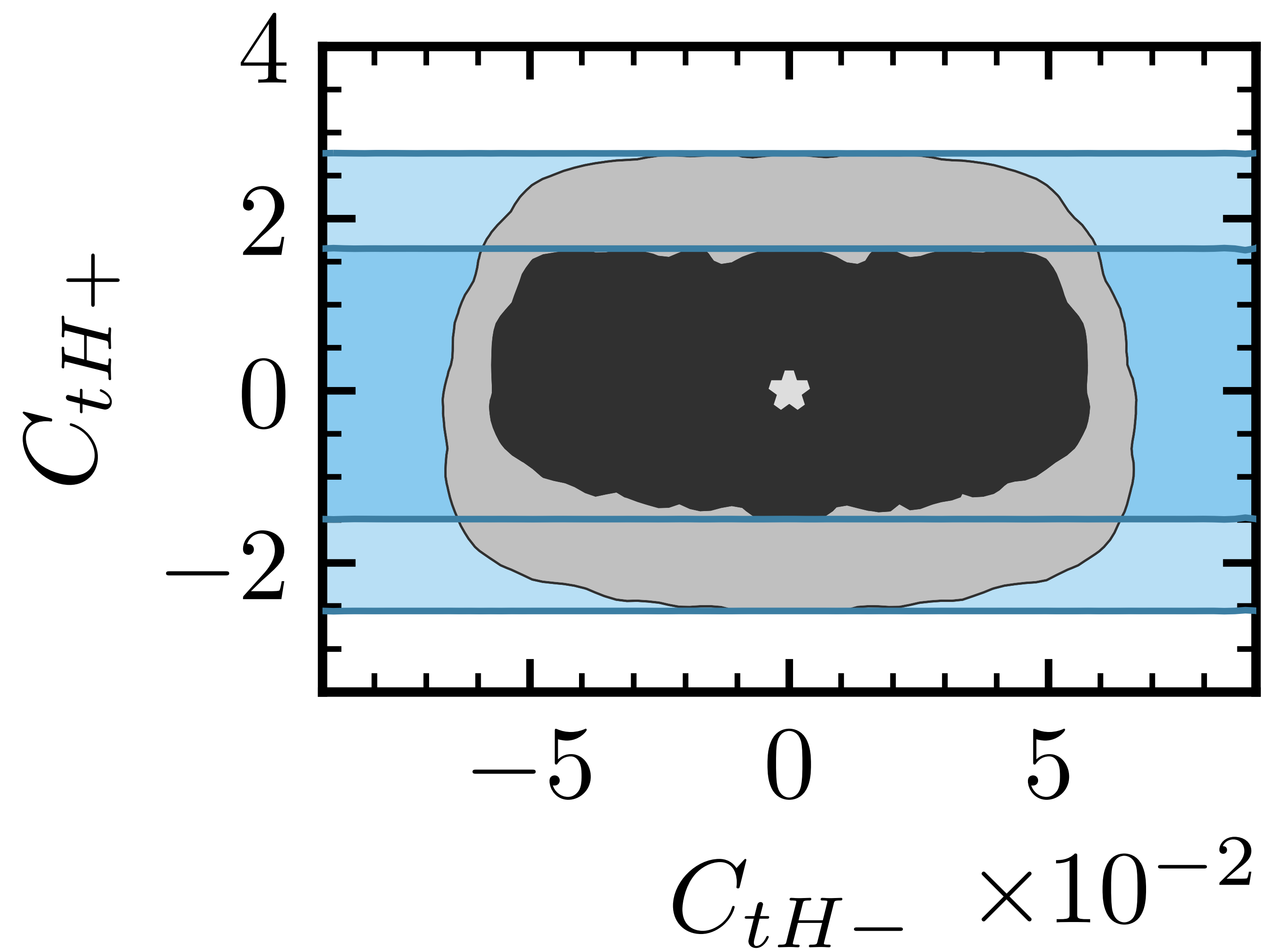
A 4D Scan

2 Parameters: C_{tH+}, C_{tH-}



4 Parameters:

C_{tH+}, C_{tH-}, C_{bH+}, C_{bH-}

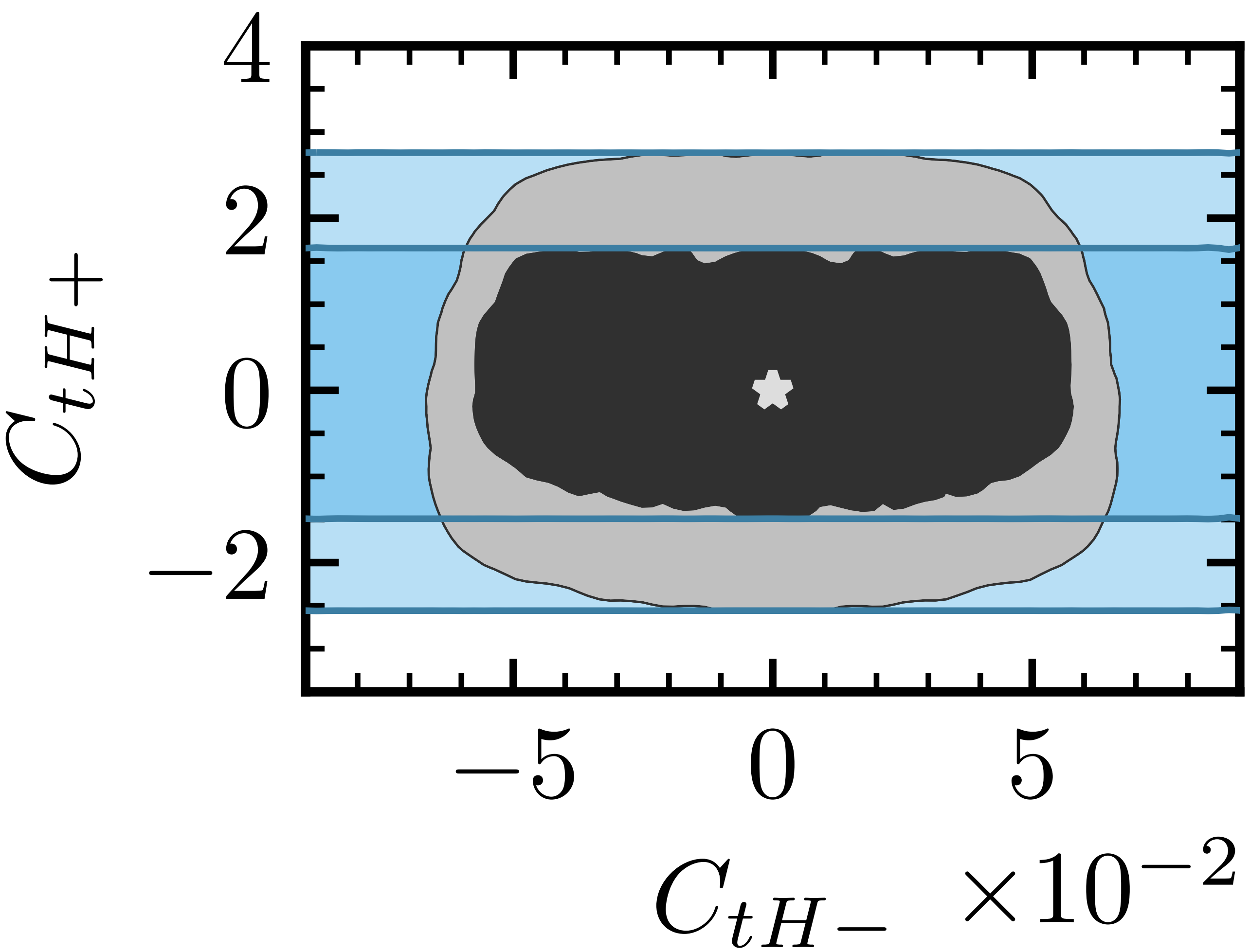


EDM and LHC constraints weakened!

A 6D Scan

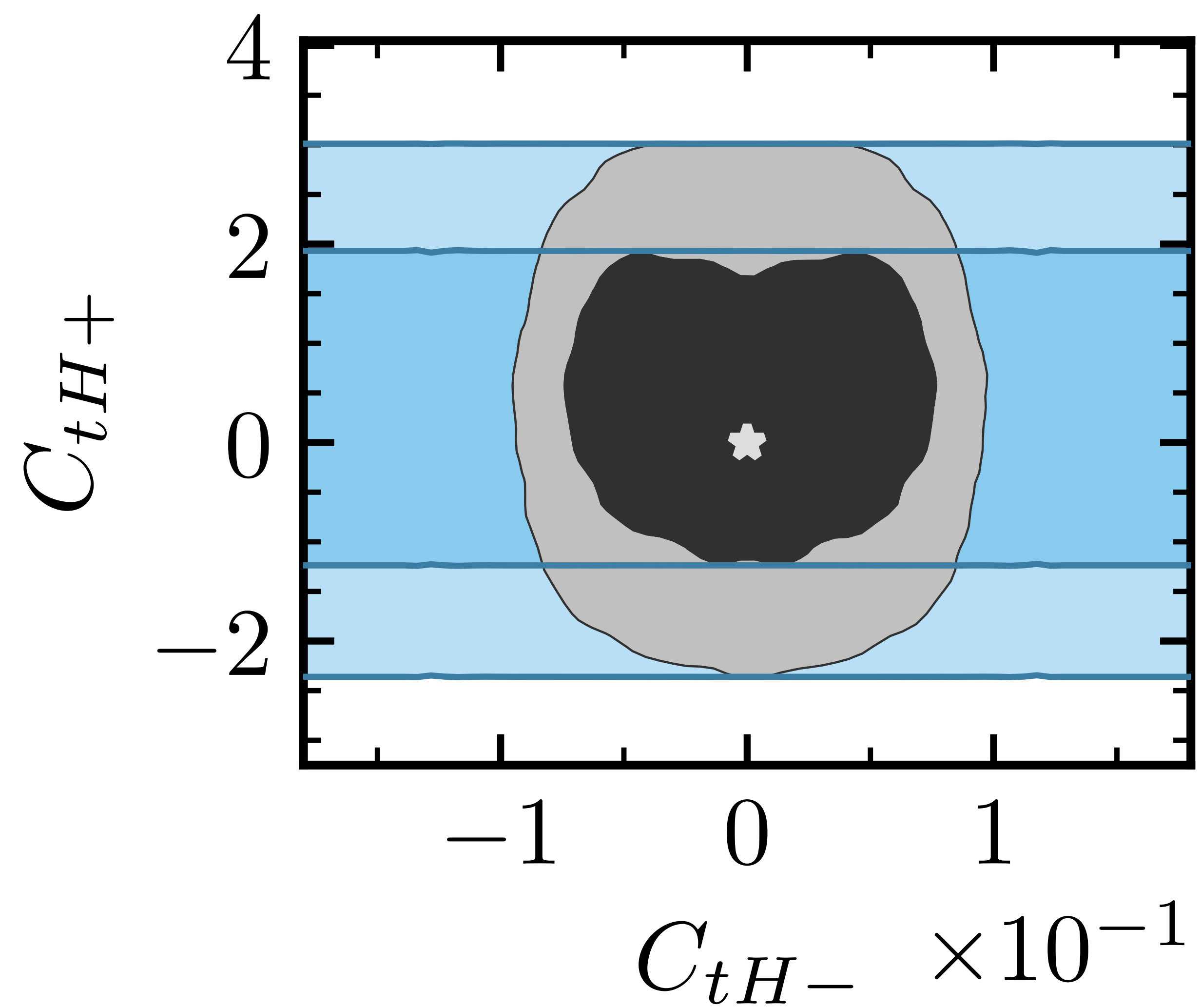
4 Parameters:

C_{tH+}, C_{tH-}, C_{bH+}, C_{bH-}

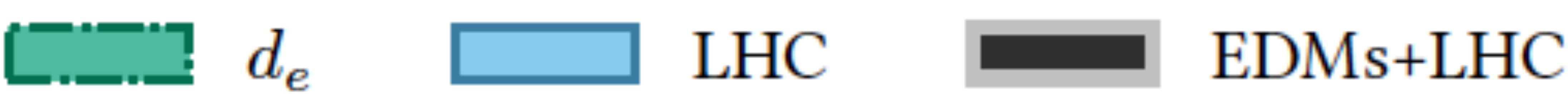


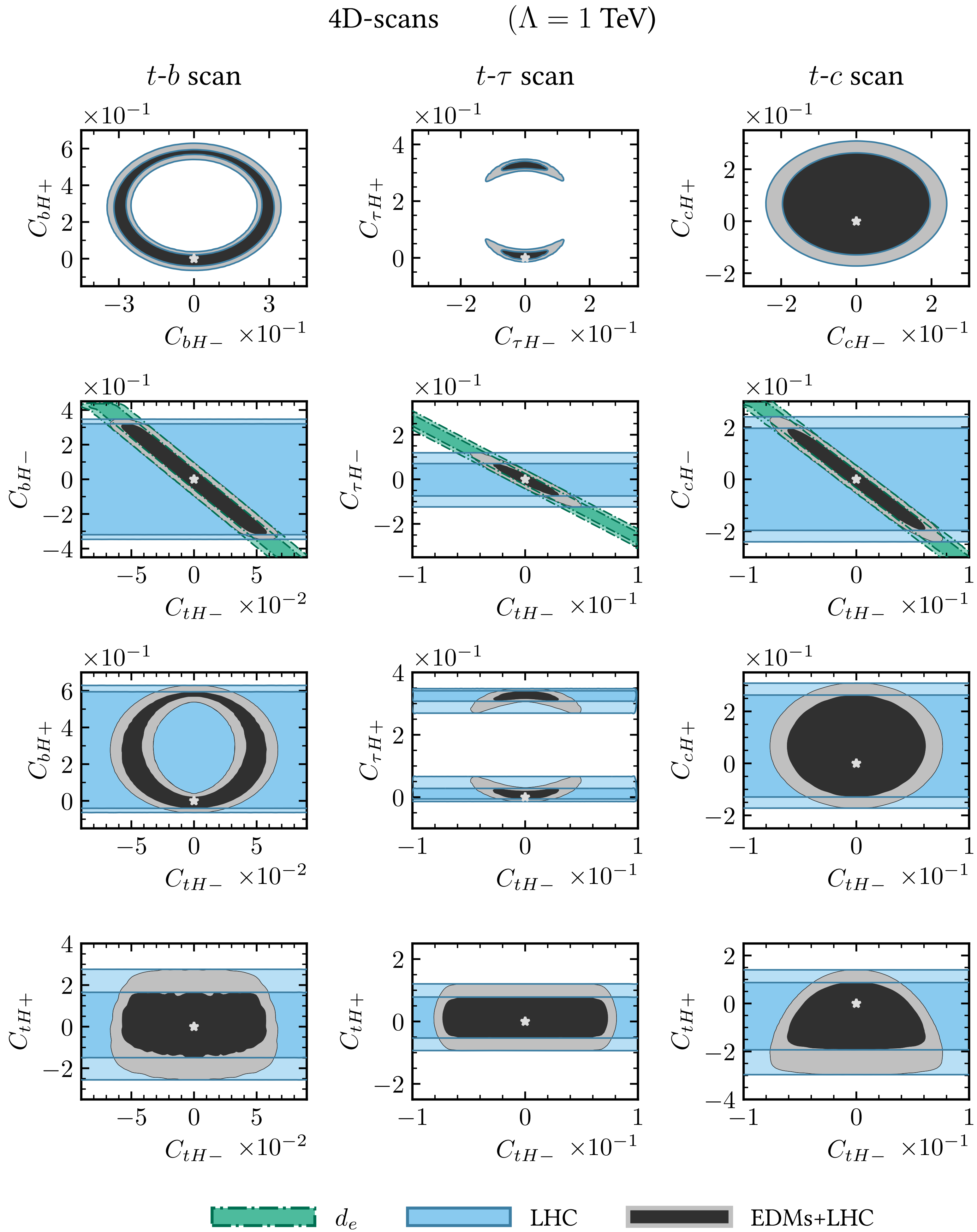
6 Parameters:

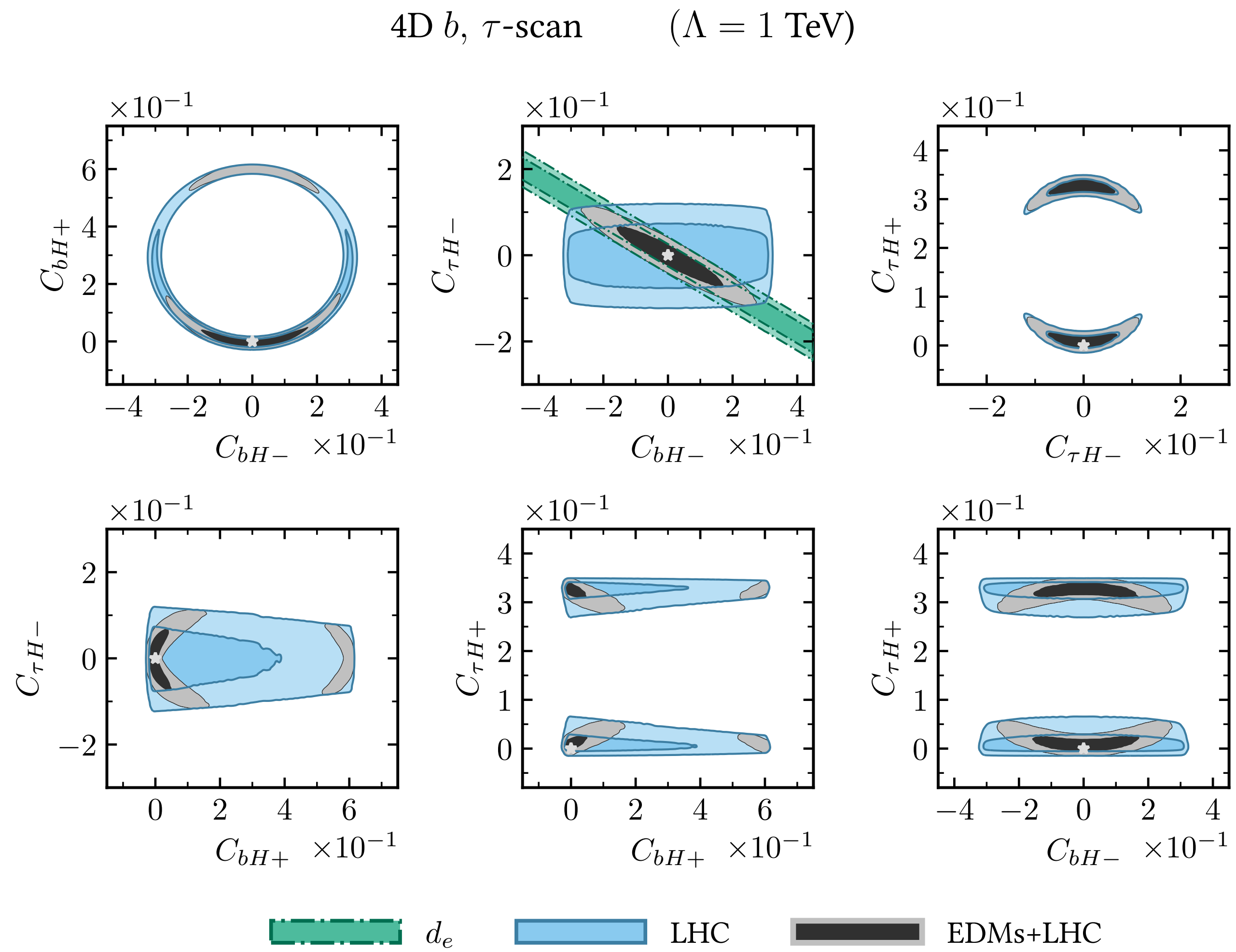
C_{tH+}, C_{tH-}, C_{bH+}, C_{bH-}, $C_{\tau H+}$, $C_{\tau H-}$

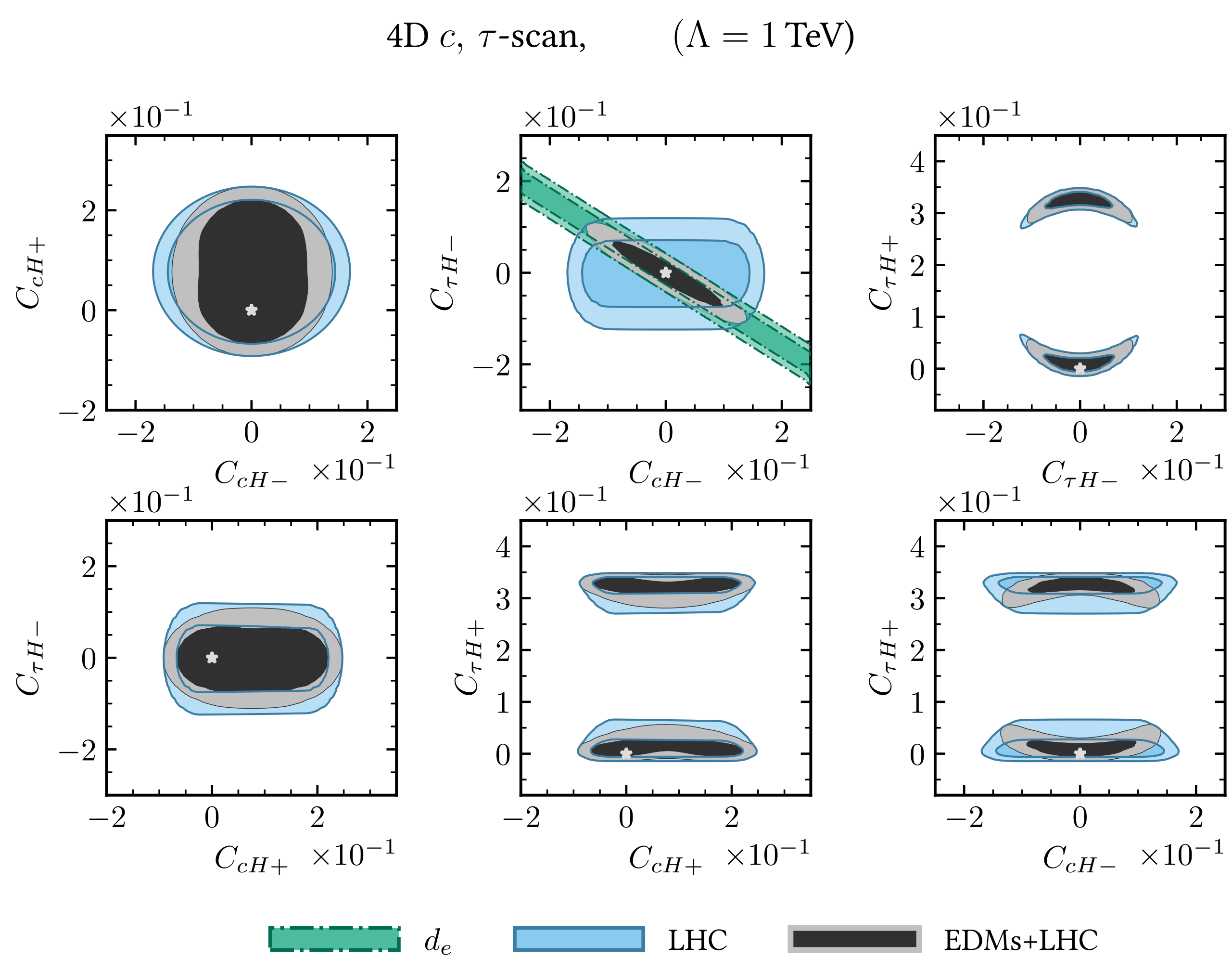


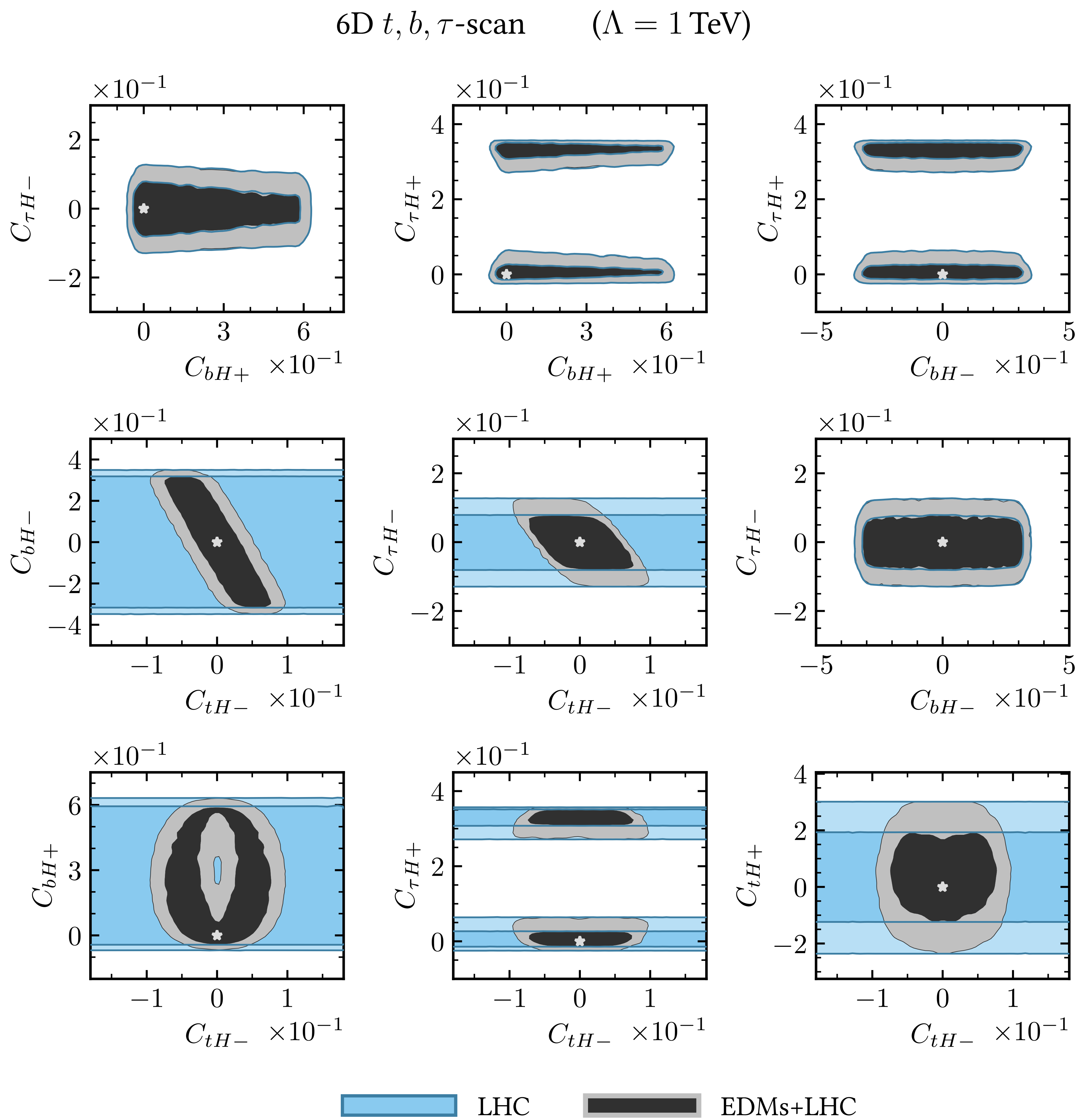
Even weaker constraints!




4D-scans (Λ = 1 TeV)
t-b scan
t-τ scan
t-c scan
C_{bH+}
C_{bH-}
$C_{\tau H+}$
$C_{\tau H-}$
C_{cH+}
C_{cH-}
C_{tH+}
C_{tH-}
×10^-1
×10^-2
d_e
LHC
EDMs+LHC


4D b, τ-scan ($\Lambda = 1$ TeV)
C_{bH+}
C_{bH-}
$C_{\tau H-}$
$C_{\tau H+}$
$\times10^{-1}$
d_e
LHC
EDMs+LHC


4D c, τ-scan, ($\Lambda = 1$ TeV)
C_{cH+}
C_{cH-}
$C_{\tau H-}$
$C_{\tau H+}$
$\times10^{-1}$
d_e
LHC
EDMs+LHC



6D t, b, τ-scan $(\Lambda = 1$ TeV$)$
$C_{\tau H-}$
C_{bH+}
$C_{\tau H+}$
C_{bH-}
C_{tH-}
C_{tH+}
$\times 10^{-1}$
LHC
EDMs+LHC