Flavor-violating Higgs decays and stellar cooling hints in axion models

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based on:
arXiv:2107.09708, MB, G. Grilli di Cortona, M. Tabet, R. Ziegler

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Outline

- Motivation
- QCD axion and stellar cooling hints
- DFSZ-like models with generation-dependent PQ charges
- Flavor-violating Higgs decays
- Interplay of axion and Higgs phenomenology

Motivation

Legacy of the LHC so far

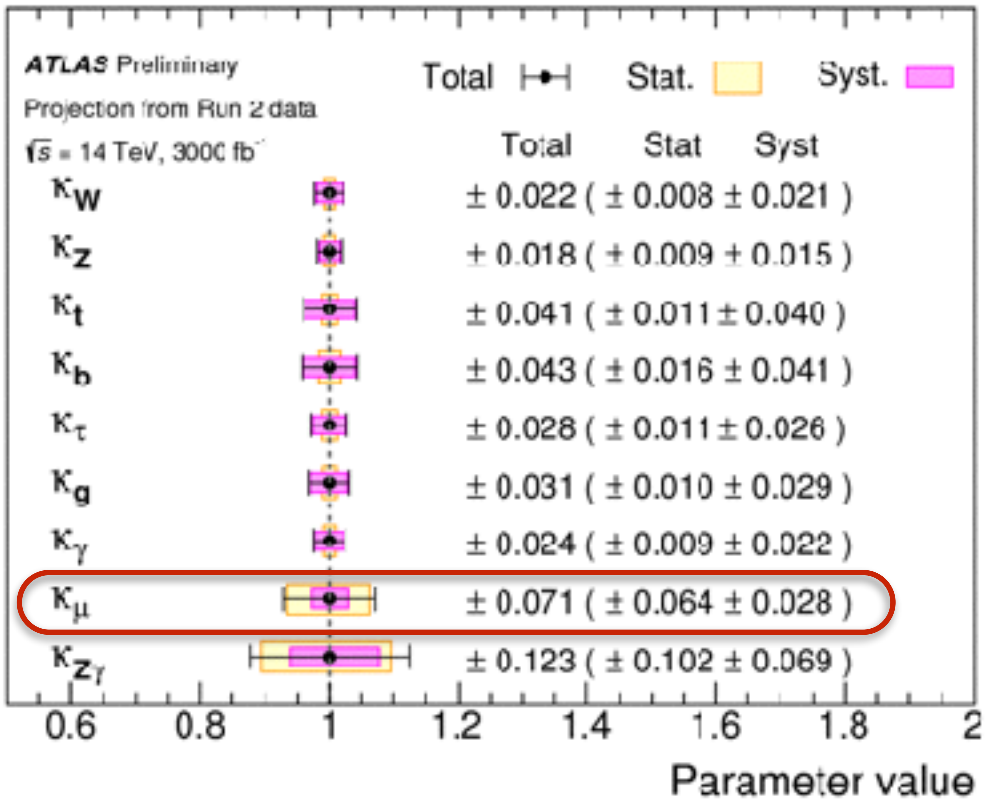
- 125 GeV Higgs discovered with SM-like couplings to 3rd generation of fermions
- No BSM particles found

Where can we expect to find BSM physics at the LHC run 3 and HL-LHC?

The biggest gain in luminosity so (my) best bet is:

Higgs precision measurements and rare Higgs decays

Motivation



ATL-PHYS-PUB-2018-054

- Higgs muon coupling will be precisely measured at HL-LHC
- $\mathrm{BR}(h \to \tau e)$ and $\mathrm{BR}(h \to \tau\mu)$ will be tested down to 10^{-4}

Motivation

It is well-known that large deviations in $h \to \mu\mu$ and $h \to \tau e$ (or $h \to \tau\mu$) can be obtained in several ad-hoc BSM models e.g. general 2HDM

see e.g. Harnik, Kopp, Zupan '12

In this talk:

Study rare Higgs decays in a well-motivated framework solving strong CP problem, explaining dark matter puzzle and hints from stellar cooling anomalies:

DFSZ-type models for the QCD axion with *light* second Higgs doublet

QCD axion

QCD axion - one of the best candidates for New Physics

- predicted by Peccei-Quinn (PQ) mechanism solving the strong CP problem
- constitutes a good dark matter candidate

Axion Models

Need anomalous breaking of PQ (fermion sector)
and spontaneous PQ breaking (scalar sector)

$$U(1)_{\text{PQ}} \times SU(3)_c^2$$

SM fermions | BSM fermions

2Higgs | 2Higgs+Singlet | Higgs+Singlet

PQWW

[Peccei, Quinn, Wilczek, Weinberg '78]

excluded

$J/\psi \to \gamma a$

DFSZ

[Dine, Fischler, Srednicki, Zhitnitsky '80]

KSVZ

[Kim, Shifman, Vainshtein, Zakharov '80]

$\langle\text{Singlet}\rangle \gg v$: "Invisible" axion models

slide borrowed from R. Ziegler

Axion effective Lagrangian

- UV models can be described by effective Lagrangian well below the PQ scale

$$\mathcal{L} = \frac{a}{f_a}\frac{\alpha_s}{8\pi} G\tilde{G} + \frac{E}{N}\frac{a}{f_a}\frac{\alpha_{\rm em}}{8\pi} F\tilde{F} + \frac{\partial_\mu a}{2 f_a}\bar{f}_i \gamma^\mu \left(C^V_{ij} + C^A_{ij}\gamma_5\right) f_j$$

solves strong CP problem
and generates axion mass:

$$m_a \approx 6 \text{ meV} \left(\frac{10^9 \text{ GeV}}{f_a}\right)$$

axion photon couplings
allowing to search for
axions in helioscopes
e.g. IAXO

axion fermion couplings
(in general flavor-violating)

DFSZ Models

SM fermions + 2Higgs + Singlet $\begin{cases} \langle H_1 \rangle = c_\beta v \qquad \langle H_2 \rangle = s_\beta v \\ \langle \Phi \rangle = v_{\rm PQ} \gg v \end{cases}$

Construct 2HDM Lagrangian invariant under single U(1)

$$\mathcal{L}_{\rm yuk} = y^u_{ij} \overline{Q}_i U_j \begin{cases} H_1 \\ H_2 \end{cases} \xrightarrow[\text{U(1) charges}]{\text{flavor-universal}} \begin{array}{l} \overline{Q}_i U_j \, H_1 \\ \overline{Q}_i D_j \, \tilde{H}_2 \\ \overline{L}_i E_j \, \tilde{H}_{1 \text{ or } 2} \end{array}$$

Break residual U(1) by H-Singlet couplings $\mathcal{L} \sim H_1^\dagger H_2 \Phi$

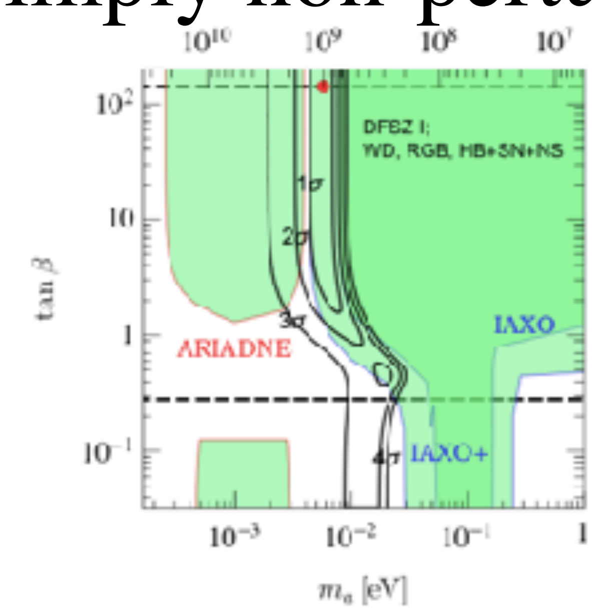
Axion fermion couplings fixed by $\tan\beta$

Stellar cooling hints

- Excessive energy losses have been observed in several stellar environments e.g. anomalous cooling of White Dwarfs
- This can be explained by emission of axions with a sizeable coupling to electrons [Giannotti, Irastorza, Redondo, Ringwald '16]

Constraints from SN1987A and neutron star cooling

- Light axions efficiently cool SN and neutron stars via axion bremstrasslung off nucleons $N + N \to N + N + a$
- SN1987A and neutron star cooling set lower bound on $f_a \gtrsim \mathcal{O}(10^9)$ GeV in standard axion models
- In standard DFSZ models best-fit to cooling anomalies imply non-perturbative Yukawa couplings:



[Giannotti, Irastorza, Redondo, Ringwald, Saikawa '17]

Nucleophobic axion models

[Di Luzio, Mescia, Nardi, Panci, Ziegler '17]

- SN1987A and NS bounds can be relaxed if axion nucleon coupling is suppressed which happens for

$$C_u + C_d = 1 \qquad\qquad C_u \approx 2/3$$

- Nucleophobia realised in DFSZ-like models with non-universal PQ charges

Nucleophobia ⇒ flavor-violating axion couplings!

Non-universal DFSZ models

Generalized DFSZ-type models:
PQ charges universal only for two generations

Have non-trivial transition to mass basis

$$X_f = \mathrm{diag}(X_1, X_1, X_3) \to V_f^\dagger X_f V_f = X_1 \delta_{ij} + (X_3 - X_1)\xi_{ij}^f$$

$$\xi_{ij}^f \equiv (V_f)^*_{i3}(V_f)_{j3} \qquad\qquad f = u_L, u_R, d_L, d_R, e_L, e_R$$

Depend on 2 misalignment parameters in each sector

$$0 \leq \xi_{ii}^f \leq 1 \qquad\qquad \sum_i \xi_{ii}^f = 1 \qquad |\xi_{ij}^f| = \sqrt{\xi_{ii}^f \xi_{jj}^f}$$

$$C_{ii}^f = X_1 + (X_3 - X_1)\xi_{ii}^f \qquad\qquad |C_{i\neq j}^f| = |X_3 - X_1| \left|\xi_{ij}^f\right|$$

Non-universal DFSZ models

There are 4 nucleophobic charge assignments in the quark sector: non-universal in q **or** u/d sector

e.g. $$\mathcal{L} \sim \begin{matrix} \overline{f}_{L3} f_{R3} \\ \overline{f}_{L3} f_{Ra} \end{matrix} \begin{cases} h_1 & u \\ \tilde{h}_2 & d \end{cases} + \begin{matrix} \overline{f}_{La} f_{Rb} \\ \overline{f}_{La} f_{R3} \end{matrix} \begin{cases} h_2 & u \\ \tilde{h}_1 & d \end{cases}$$

Each model in the quark sector can be combined with 4 models in the charged lepton sector

16 nucleophobic models in total

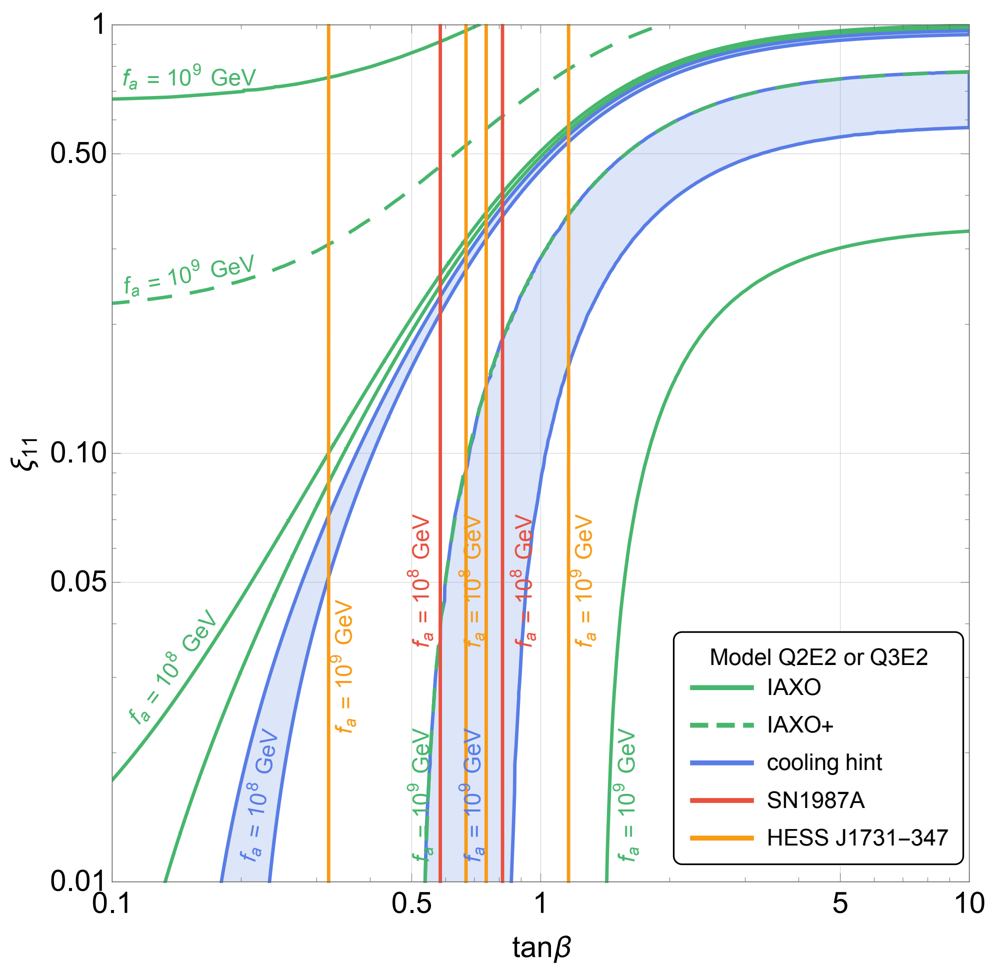
Model	E_Q/N	$C^A_{u_iu_i}$	$C^A_{d_id_i}$	$C^{V,A}_{u_i\neq u_j}$	$C^{V,A}_{d_i\neq d_j}$
Q1	$2/3+6c^2_\beta$	c^2_β	$\xi^{d_R}_{ii}-c^2_\beta$	0	$\xi^{d_R}_{ij}$
Q2	$-4/3+6c^2_\beta$	$c^2_\beta-\xi^{u_L}_{ii}$	$-\xi^{d_L}_{ii}+s^2_\beta$	$\pm\xi^{u_L}_{ij}$	$\pm\xi^{d_L}_{ij}$
Q3	$-4/3+6c^2_\beta$	$c^2_\beta-\xi^{u_R}_{ii}$	$-\xi^{d_R}_{ii}+s^2_\beta$	$-\xi^{u_R}_{ij}$	$-\xi^{d_R}_{ij}$
Q4	$-10/3+6c^2_\beta$	$-s^2_\beta+\xi^{u_R}_{ii}$	s^2_β	$\xi^{u_R}_{ij}$	0

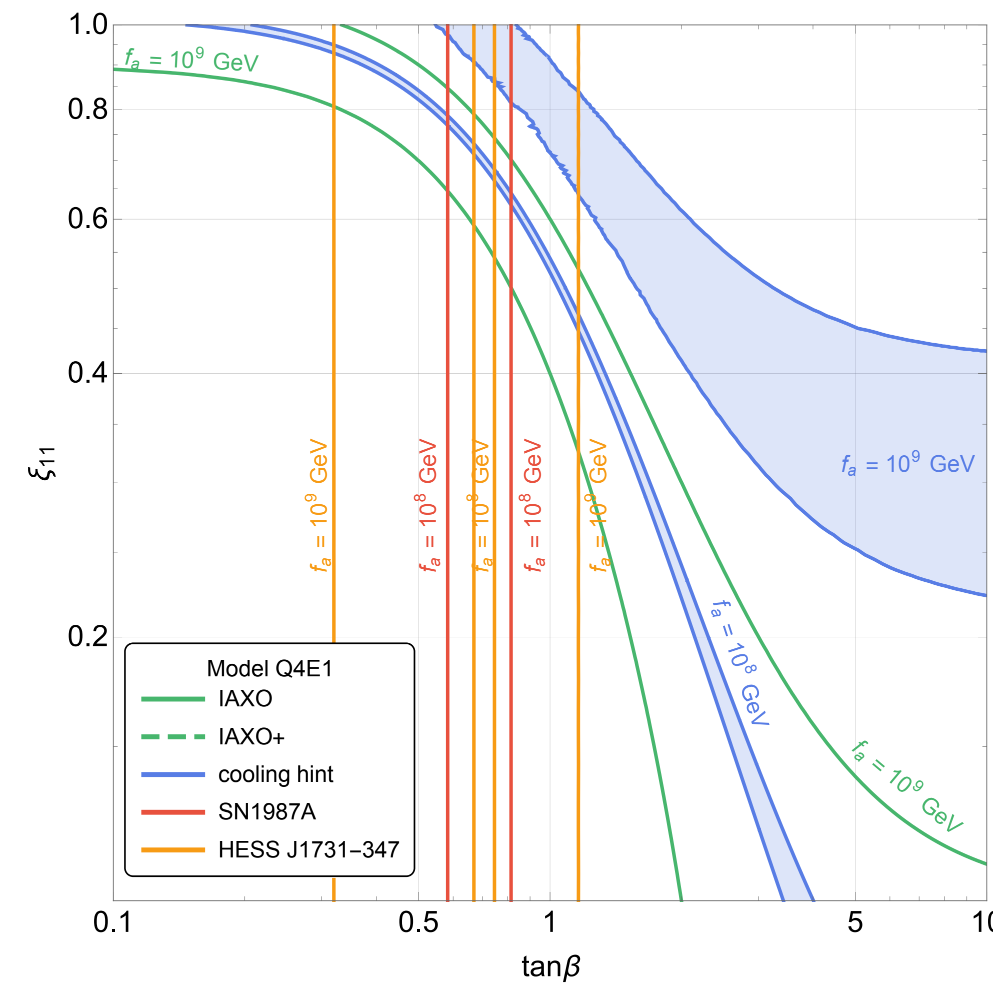
Model	E_L/N	$C^A_{e_ie_i}$	$C^{V,A}_{e_i\neq e_j}$
E1L	$2-6c^2_\beta$	$-c^2_\beta+\xi^{e_L}_{ii}$	$\mp\xi^{e_L}_{ij}$
E1R	$2-6c^2_\beta$	$-c^2_\beta+\xi^{e_R}_{ii}$	$\xi^{e_R}_{ij}$
E2L	$4-6c^2_\beta$	$s^2_\beta-\xi^{e_L}_{ii}$	$\pm\xi^{e_L}_{ij}$
E2R	$4-6c^2_\beta$	$s^2_\beta-\xi^{e_R}_{ii}$	$-\xi^{e_R}_{ij}$

Axion phenomenology

- Quark flavor violation does not impact stellar cooling anomalies so we neglect it (by setting only one non-zero ξ^q_{ii})
- Nucleophobia realised for $\tan\beta \approx 1/\sqrt{2}$
- $\xi^e_{22} \approx 0$ to avoid $\mu \to e\gamma$ and $\mu \to ea$ decays
- Axion phenomenology determined by $\xi^e_{11} \equiv \xi_{11}$ (controlling coupling to electrons) and $\tan\beta$

Axion phenomenology





- Cooling hints explained for large range of $\tan\beta$ and ξ_{11}
- For $f_a = 10^8$ GeV bounds from SN1987A enforce flavor violation $(\xi_{11} \neq 0)$
- IAXO will probe the entire region explaining cooling anomalies even up to $f_a = 10^9$ GeV

Flavor-violating Higgs decays

- Stellar cooling hints → flavor-violating axion couplings → flavor-violating Higgs decays

$$\Gamma(h \to \tau e) \propto \frac{c_{\alpha-\beta}^2}{c_\beta^2 s_\beta^2} \xi_{11}(1-\xi_{11})$$

- Decay width grows with $\cos(\beta-\alpha) \propto v^2/m_H^2$

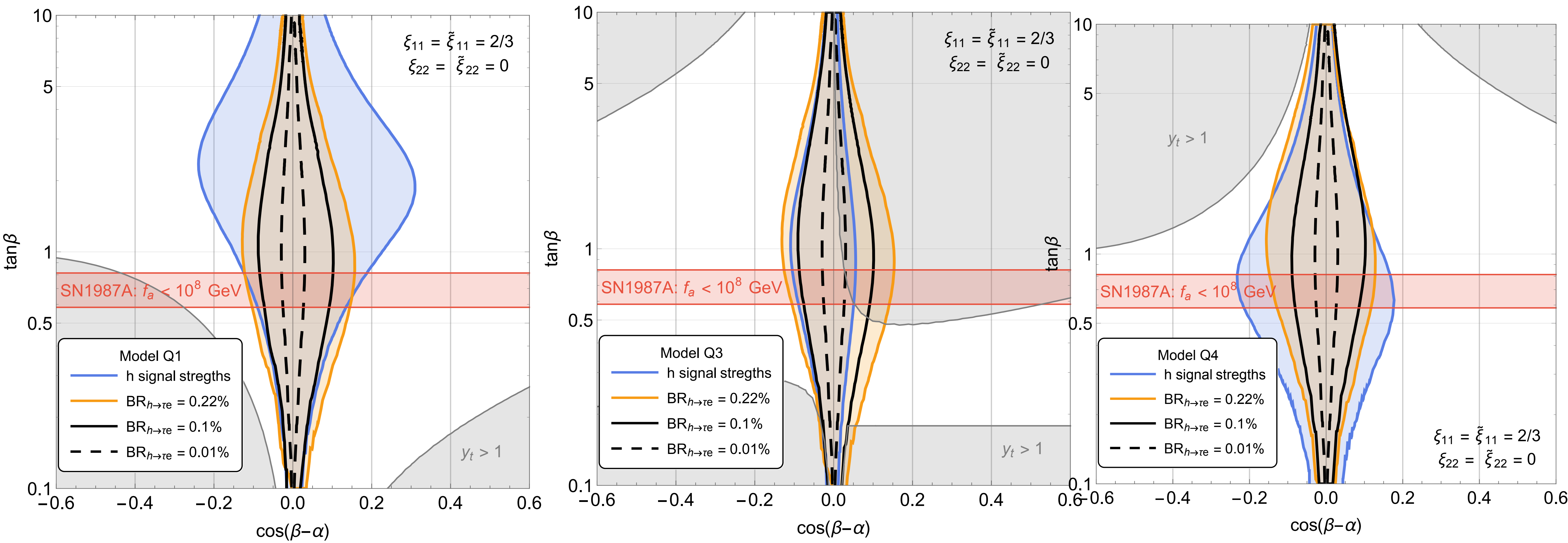
Higgs quark couplings

Approximate Higgs quark couplings (normalized to SM)

	Q1	Q2	Q3	Q4
κ_t	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$
κ_c	c_α/s_β	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$
κ_b	c_α/s_β	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$
κ_s	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$

In Q1/Q4 models modifications to top and bottom couplings are correlated which allows for larger $\cos(\beta - \alpha)$ consistent with the Higgs coupling measurements

LHC constraints from Higgs coupling measurements



In Q1 and Q4 models $\mathrm{BR}(h \to \tau e)$ can be as large as the current upper bound from the LHC of 0.22%

Higgs decays to muons

- Higgs couplings to muons are modified too

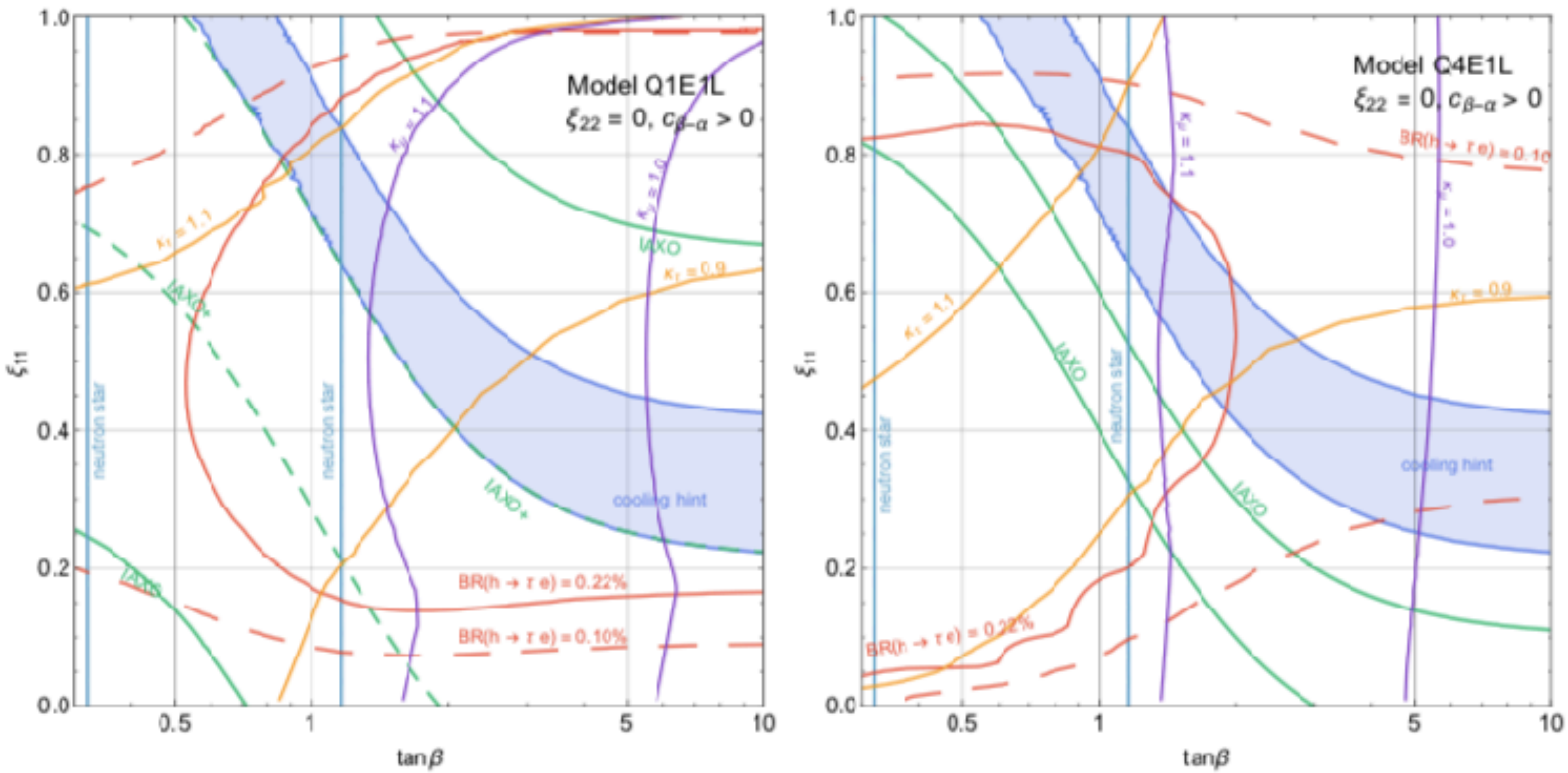
$$\kappa_\mu = s_{\beta-\alpha} - t_\beta c_{\beta-\alpha} + \frac{v}{m_\mu}\frac{c_{\beta-\alpha}}{c_\beta}\epsilon^e_{22}$$

$$(\epsilon^e_{E1})_{ij} = \frac{m_{e_i}\delta_{ij}}{s_\beta v} - \frac{m_\tau}{s_\beta v}\sqrt{\xi^{e_L}_{ii}\xi^{e_R}_{jj}}\,, \qquad (\epsilon^e_{E2})_{ij} = \frac{m_\tau}{s_\beta v}\sqrt{\xi^{e_L}_{ii}\xi^{e_R}_{jj}}$$

- Higgs decays to muons can be substantially different from the SM!

Higgs-axion interplay

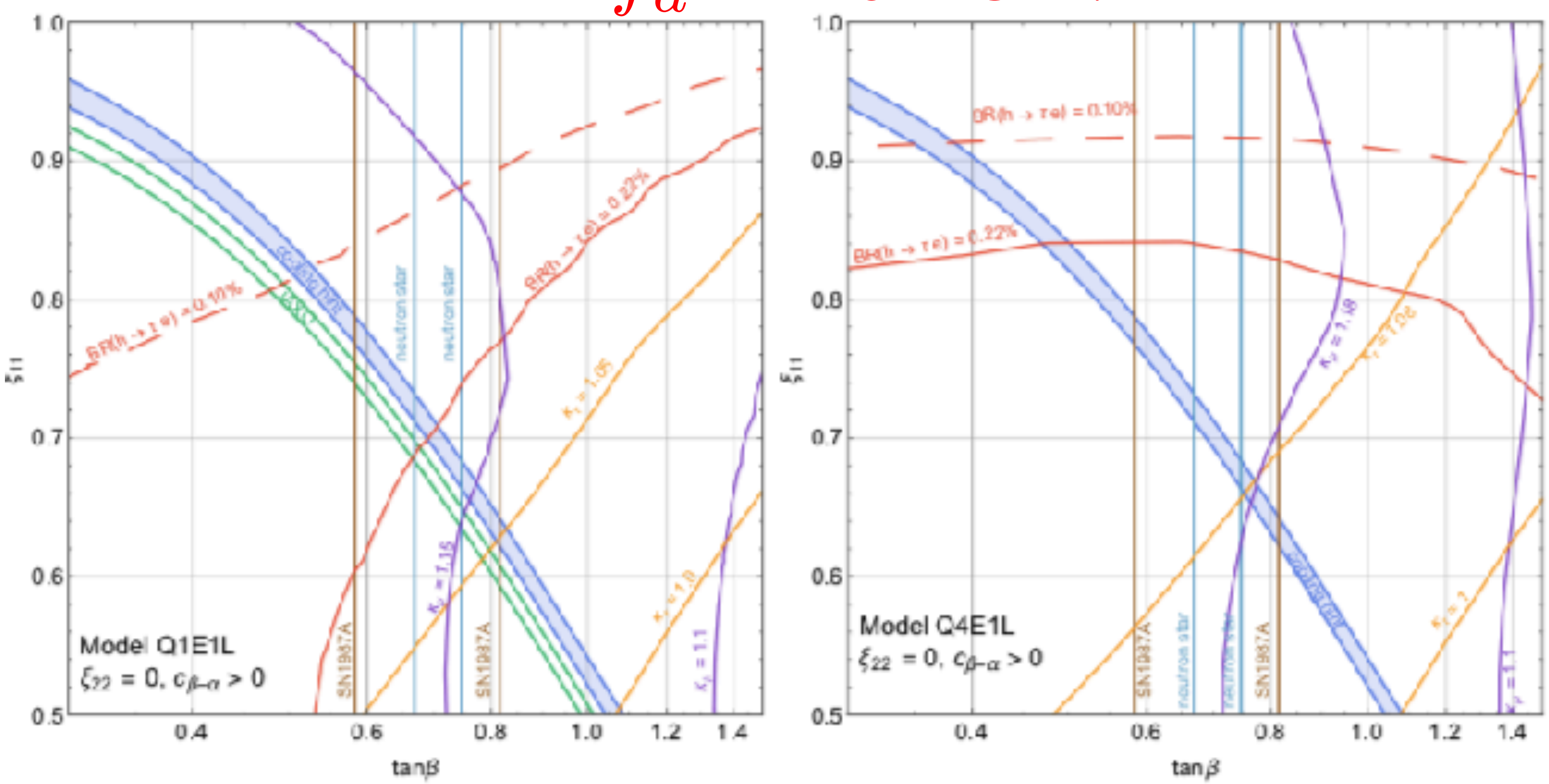
$f_a = 10^9$ GeV



LHC bound on $\mathrm{BR}(h \to \tau e)$ saturated in large parts of parameter space explaining the cooling anomalies

Higgs-axion interplay

$f_a = 10^8$ GeV



- SN1987A and NS constraints shrink parameter space but still $\mathrm{BR}(h \to \tau e) \sim \mathcal{O}(0.1)\%$
- Higgs muon coupling larger than in the SM by up to 20%
- In Q4E1 model $\mathrm{BR}(h \to \mu\mu) \gtrsim 1.6\mathrm{BR}(h \to \mu\mu)_{SM}$
  (due to enhanced κ_μ and suppressed κ_b)

Summary

- Non-universal DFSZ models easily accommodate stellar cooling anomalies
- $\mathrm{BR}(h \to \tau e)$ can be as large as allowed by the LHC
- $\mathrm{BR}(h \to \mu\mu)$ larger than in the SM by up to 60%
- The stellar cooling hint region will be complementarily tested by IAXO and Higgs searches at the HL-LHC