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The Anomalous Case of Axion EFTs and Massive Chiral Gauge Fields

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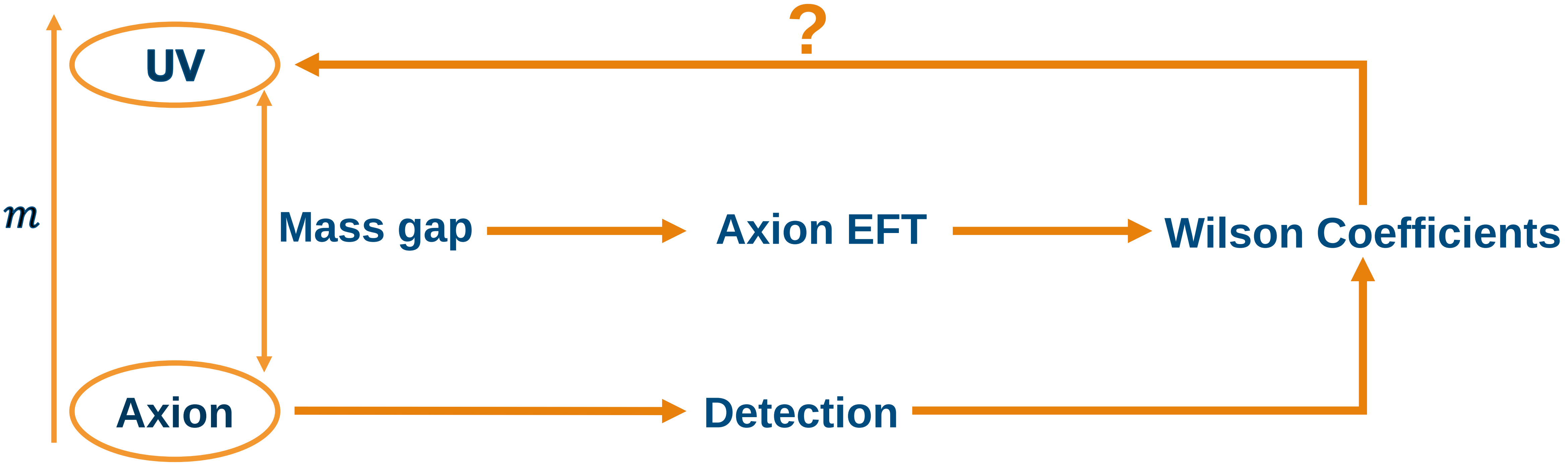
Axions, axions everywhere

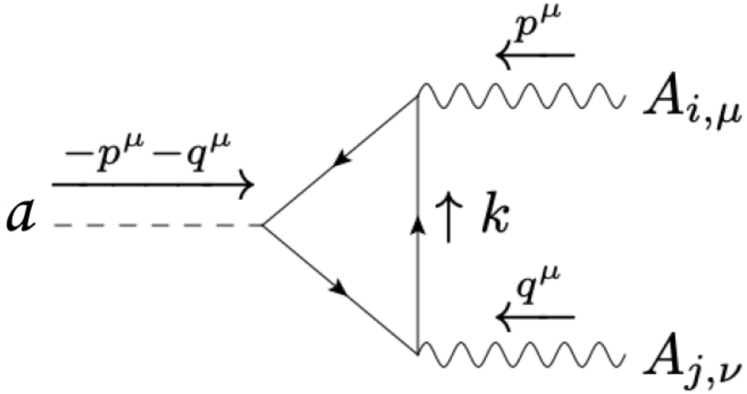
- **ALPs (axions) are very appealing BSM candidates.**
- **There is an intense experimental program.**



What does an IR measurement say about the UV?

Axion phenomenology

Effective axion-gauge boson couplings play the main role.



$$\mathcal{A}\left(a \to AA\right) \propto \mathcal{C}$$

Axion

Photons and gluons ⟷ **Anomalies** $\quad \delta_{PQ}\left(\mathcal{L}_{\mathrm{EFT}}\right) \propto D^{\mathrm{PQ}AA}$

$\mathcal{C} = D^{\mathrm{PQAA}}$

$$D^{\mathrm{PQ}AA} = \sum_{LH\,\psi} q_\psi^{\mathrm{PQ}} \left(q_\psi^A\right)^2 - \sum_{RH\,\psi} q_\psi^{\mathrm{PQ}} \left(q_\psi^A\right)^2$$

W*$^\pm$*, Z ⟷ **?** ⟷ **Anomalies**

This relation is not so clear…

E.g. it is violated in DFSZ [Q&S, 1903.12559]

Axion EFT with a massive abelian gauge field

Non-anomalous coupling linked to longitudinal degrees of freedom.

$$\mathcal{L} \supset -g^2 \frac{D^{\mathrm{PQ}AA}}{16\pi^2 f} \underbrace{a F_{\mu\nu} \tilde{F}^{\mu\nu}}_{\text{(1): anomalous}} - g \frac{\mathcal{C} - D^{\mathrm{PQ}AA}}{8\pi^2 f} \underbrace{\partial_\mu a \left(\frac{\partial_\nu \theta_A}{m_A} - g A_\nu \right) \tilde{F}^{\mu\nu}}_{\text{(2): non-anomalous}}$$

(1): anomalous

$$\delta_{PQ} \left(\mathcal{L}_{\mathrm{EFT}} \right) \propto D^{\mathrm{PQ}AA}$$

(2): non-anomalous

$$\mathcal{A} \left(a \to AA \right) \propto \mathcal{C}$$

When does this happen?

Massive chiral → $\mathcal{C} \neq D^{\mathrm{PQ}AA}$ → **(2) Non- zero**

Non-abelian: EFT terms for the SM

Anomalous

$$-\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a$$

$$-\frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B}$$

Non-anomalous

$$\partial_\mu a\,\mathrm{Tr}(TV_\nu)\,\tilde{B}^{\mu\nu}$$

$$\partial_\mu a\,\mathrm{Tr}(V_\nu\,\tilde{W}^{\mu\nu})$$

$$\partial_\mu a\,\mathrm{Tr}(TV_\nu)\mathrm{Tr}(T\tilde{W}^{\mu\nu})$$

$$U = e^{i\frac{\pi^a}{v}\sigma^a}\,, \quad D_\mu U = \partial_\mu U - igW_\mu U + ig'B_\mu U\frac{\sigma_3}{2} \quad V_\mu = D_\mu U U^\dagger\,, \quad T = U\sigma_3 U^\dagger$$

Non-linear EW is a consequence of chiral matter in the UV.

[Cohen et al, 2008.08597]

Sum rules for the axion EFT

Sum rules from anomalous-only operators

$$C_{\gamma\gamma} + s_W^{-2}(1 - t_W^2)C_{Z\gamma} - \frac{1}{s_W^2 c_W^2} C_{ZZ} = 0\ , \quad C_{\gamma\gamma} + s_W^{-2} C_{Z\gamma} - (1 + t_W^{-2}) C_{WW} = 0$$

In the mass basis: $-\frac{16\pi^2}{e^2}\mathcal{L} \supset C_{\gamma\gamma}\frac{a}{f}F\tilde{F} + 2\frac{C_{Z\gamma}}{c_W s_W}\frac{a}{f}F\tilde{Z} + \frac{C_{ZZ}}{c_W^2 s_W^2}\frac{a}{f}Z\tilde{Z} + \frac{2C_{WW}}{s_W^2}W^+\tilde{W}^-$

Sum-rules violation by non-anomalous effects

$$C_{\gamma\gamma}+s_W^{-2}(1-t_W^2)C_{Z\gamma}-\frac{1}{s_W^2 c_W^2}C_{ZZ} = \frac{c_1 - c_2 - c_3}{2c_W^2 s_W^2}\ , \quad C_{\gamma\gamma}+s_W^{-2}C_{Z\gamma}-(1+t_W^{-2})C_{WW} = \frac{c_1 - c_2 + c_3}{2s_W^2}$$

$$i\frac{c_1 g'}{8\pi^2 f}\partial_\mu a \mathrm{Tr}\left(TV_\nu\right)\tilde{B}^{\mu\nu} + i\frac{c_2 g}{4\pi^2 f}\partial_\mu a \mathrm{Tr}\left(V_\nu \tilde{W}^{\mu\nu}\right) + i\frac{c_3 g}{4\pi^2 f}\partial_\mu a \mathrm{Tr}\left(TV_\nu\right)\mathrm{Tr}\left(T\tilde{W}^{\mu\nu}\right)$$

… which only appear after integrating out chiral matter

The violation of these sum rules is the hallmark of chiral matter!

A minimal model with axions and chiral matter

DFSZ-like extended scalar sector

$(SU(3)_c,\, SU(2)_L,\, U(1)_Y)_{U(1)_{PQ}}$

$$H_{1,2} \backsim \left(1, 2, \pm\tfrac{1}{2}\right)_{X_{1,2}}$$

$$\Phi \backsim (1, 1, 0)_1$$

$$a = \frac{1}{f}\left(V_\Phi a_\Phi + X_1 v_1 a_1 + X_2 v_2 a_2\right), \qquad f^2 = V_\Phi^2 + X_1^2 v_1^2 + X_2^2 v_2^2$$

$$H_1 \supset \frac{v_1}{\sqrt{2}} e^{i\frac{a_1}{v_1}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \qquad H_2 \supset \frac{v_2}{\sqrt{2}} e^{i\frac{a_2}{v_2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \Phi \supset \frac{V_\Phi}{\sqrt{2}} e^{i\frac{a_\Phi}{V_\Phi}}$$

New heavy fermions

Left Handed:

$$L_1 \sim (1, 2, +Y)_{X_{L_1}}$$
$$L_2 \sim (1, 2, -Y)_{X_{L_2}}$$

Right Handed:

$$E_1 \sim \left(1, 1, +Y - \tfrac{1}{2}\right)_{X_{L_1} - X_1} \qquad N_1 \sim \left(1, 1, +Y + \tfrac{1}{2}\right)_{X_{L_1} + X_2}$$
$$E_2 \sim \left(1, 1, -Y + \tfrac{1}{2}\right)_{X_{L_2} + X_2} \qquad N_2 \sim \left(1, 1, -Y - \tfrac{1}{2}\right)_{X_{L_2} - X_1}$$

$$-\mathcal{L}_Y = y_{E_1} \bar{L}_1 E_1 H_1 + y_{E_2} \bar{L}_2 E_2 \tilde{H}_2 + y_{N_1} \bar{L}_1 N_1 \tilde{H}_2 + y_{N_2} \bar{L}_2 N_2 H_1 + \text{h.c.}$$

Vector-like UV charges, but chiral spectrum

Axion-gauge bosons EFTs and sum rules

$$-g'^2 \frac{(1+12Y^2)(X_1-X_2)}{96\pi^2}\frac{a}{f}B\tilde{B} - g^2\frac{X_1-X_2}{96\pi^2}\frac{a}{f}W^a\tilde{W}^a\Big|_{\text{lin.}} - gg'\frac{X_1-X_2}{96\pi^2}\frac{a}{f}B\tilde{W}^3\Big|_{\text{lin.}}$$

Non-anomalous

Broken
Sum rules

$$C_{\gamma\gamma} + s_W^{-2}(1-t_W^2)C_{Z\gamma} - \frac{1}{s_W^2 c_W^2}C_{ZZ} = \frac{X_1-X_2}{12c_W^2 s_W^2} \qquad C_{\gamma\gamma} + s_W^{-2}C_{Z\gamma} - (1+t_W^{-2})C_{WW} = \frac{X_2-X_1}{12s_W^2}$$

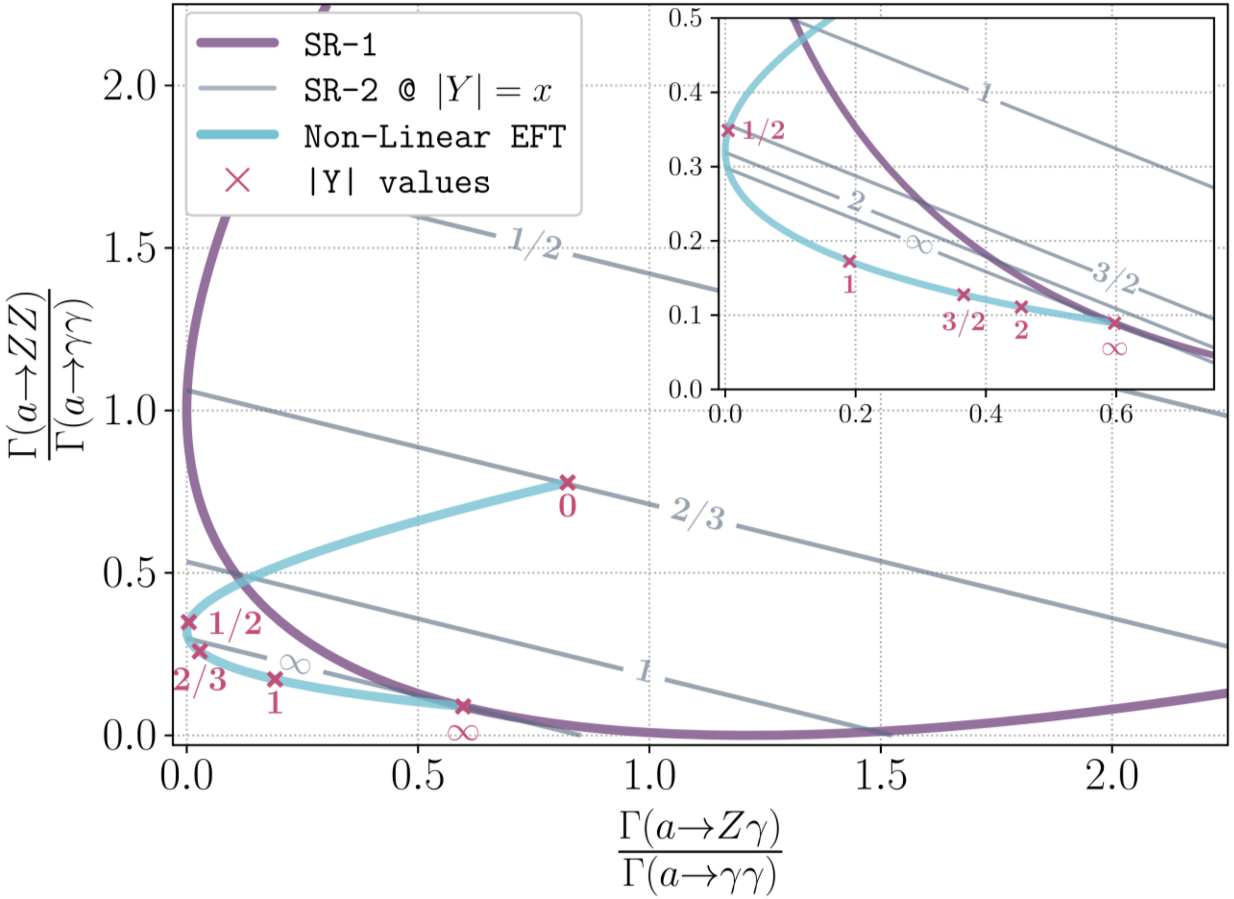
The sum rules can be written with observables

$$m_a > 2m_Z$$

$$\text{SR-1:} \quad \left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{(t_W^2-1)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2(t_W^2-1)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} = 0$$

$$\text{SR-2:} \quad \Gamma(a\to\gamma\gamma) + \frac{1}{2}(t_W^{-2}-1)\Gamma(a\to WW) - t_W^{-2}\Gamma(a\to ZZ) + \frac{1}{2}(1-t_W^{-2})\Gamma(a\to Z\gamma) = 0$$

Sum rules for partial widths, graphically

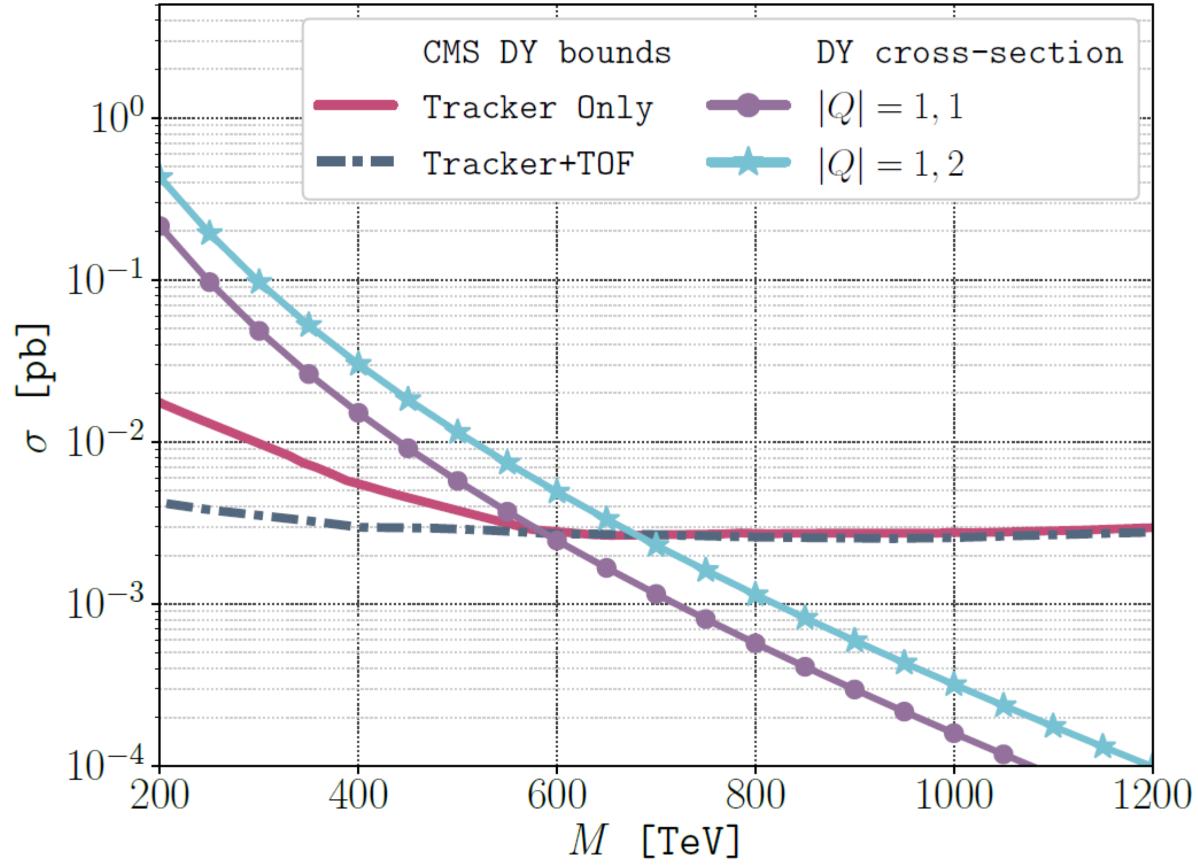


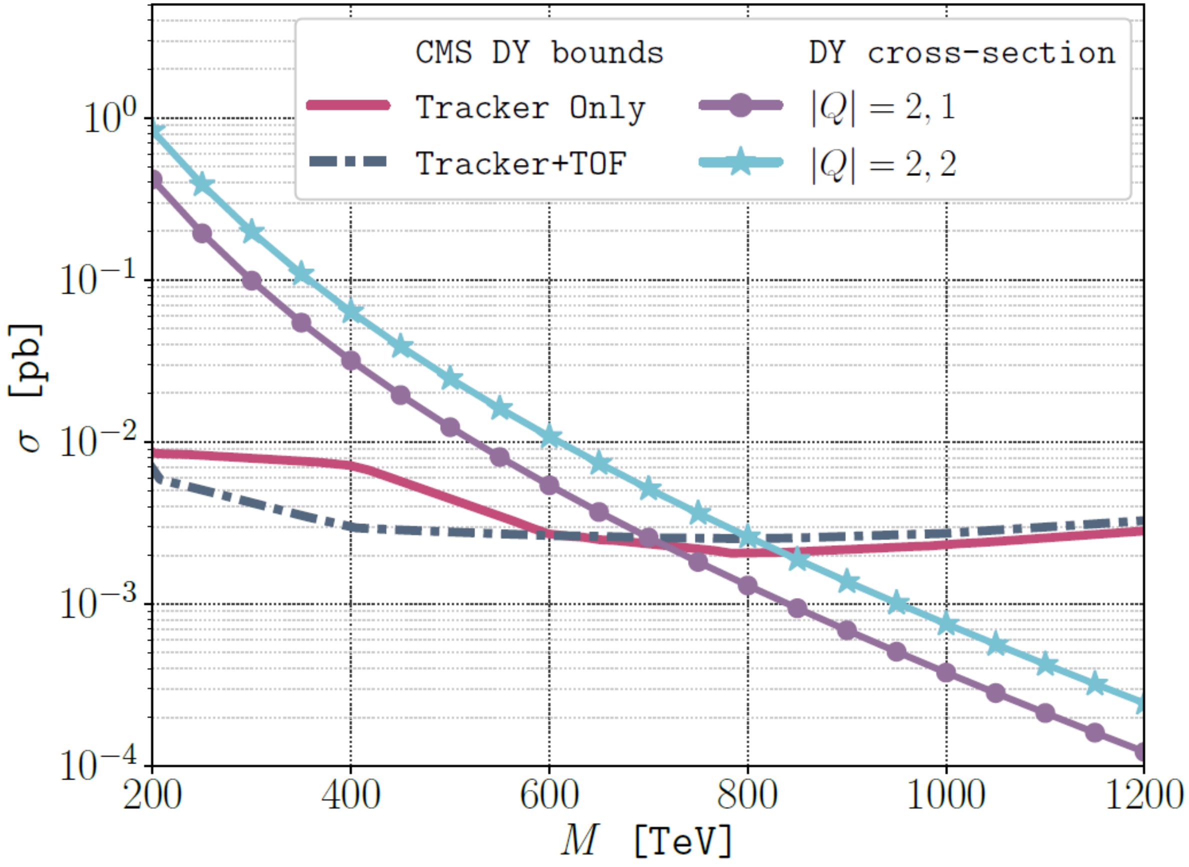
$$\text{SR-1:}\quad \left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} = 0$$

$$\text{SR-2:}\quad \Gamma(a\to\gamma\gamma) + \frac{1}{2}\left(t_W^{-2}-1\right)\Gamma(a\to WW) - t_W^{-2}\Gamma(a\to ZZ) + \frac{1}{2}\left(1-t_W^{-2}\right)\Gamma(a\to Z\gamma) = 0$$

Chiral extensions: heavy fermions direct searches

$$Y = 3/2$$





Custodial limit → $M \gtrsim 720$ GeV

Fully degenerate → $M \gtrsim 840$ GeV

Conclusions

- **The longitudinal component of massive gauge fields allows us to write non-anomalous axion-gauge field operators.**
- **They break the correlation between couplings and anomalies.**
- **Integrated-out chiral matter generates those operators.**
- **In the non-abelian case, sum rules distinguish between couplings fully related or not to anomalies.**
- **This is relevant for axion couplings to EW gauge bosons.**
- **It links axions with chiral extensions of the SM.**
- **We provided an explicit chiral extension of the SM that showcases this phenomenon and is still allowed by experiments.**

Thank you for your attention

Contact

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Appendix

UV and IR chirality

Vector-like gauge charges can yield a *chiral* mass spectrum.

Charge under	ψ_L	ψ'_L	ψ_R	ψ'_R
U(1)	+1	0	0	+1

$$\mathcal{L} \supset -y\overline{\psi_L}\psi_R\phi - y'\overline{\psi'_L}\psi'_R\phi^\dagger + h.c. \supset -m\overline{\psi}\psi - m'\overline{\psi'}\psi'$$

$$\psi = \begin{pmatrix}\psi_L \\ \psi_R\end{pmatrix} \qquad \psi' = \begin{pmatrix}\psi'_L \\ \psi'_R\end{pmatrix}$$

$$\overline{\psi_L}\psi'_R + h.c.$$

$$\overline{\psi'_L}\psi_R + h.c.$$

? → **Can be forbidden by symmetries**

Axion EFT in the abelian case

Consider a pseudoscalar axion, a, and abelian gauge field A_μ

Lowest dim. CP-inv. Operator with those fields

$$\mathcal{L}_{\rm EFT} \supset -g^2 \frac{\mathcal{C}}{16\pi^2 f} a\, F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$\delta_{\rm PQ} a = \epsilon_{\rm PQ} f$ → $\delta_{PQ}\left(\cdot\right) \propto \mathcal{C}$

$\mathcal{A}\left(a \to AA\right) \propto \mathcal{C}$

Sum and subtract $D^{{\rm PQ}AA}$ and integrate by parts

$$-g^2 \frac{D^{{\rm PQ}AA}}{16\pi^2 f} a F_{\mu\nu}\, \tilde{F}^{\mu\nu} + g^2 \frac{\mathcal{C} - D^{{\rm PQ}AA}}{8\pi^2 f} \partial_\mu a\, A_\nu\, \tilde{F}^{\mu\nu}$$

→ $\delta_{PQ}\left(\cdot\right) \propto D^{\rm PQAA}$

Anomalies may not capture all of the axion-gauge bosons couplings

EFT with a fake PQ-gauge symmetry

Couple your theory to an auxiliary gauge field A_μ^{PQ}

And consider "local" PQ transformations $\partial_\mu \epsilon_{\mathrm{PQ}} \neq 0$

Anomaly matching <u>must</u> hold for consistency of the fake gauge theory

$D^{\mathrm{PQ}AA}$ **is the same for global and local PQ transformations**

$$\delta_{PQ}\left(\mathcal{L}_{\mathrm{EFT}}\right) = -g^2 \epsilon_{\mathrm{PQ}} \frac{D^{\mathrm{PQ}AA}}{16\pi^2 f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

But:

$$\delta_{PQ}\left(-g^2 \frac{D^{\mathrm{PQ}AA}}{16\pi^2 f} a\, F_{\mu\nu} \tilde{F}^{\mu\nu} + g^2 \frac{\mathcal{C} - D^{\mathrm{PQ}AA}}{8\pi^2 f} \partial_\mu a\, A_\nu\, \tilde{F}^{\mu\nu}\right) = -g^2 \epsilon_{\mathrm{PQ}} \frac{\mathcal{C}}{16\pi^2 f} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$\mathcal{C} \neq D^{\mathrm{PQ}AA}$

We'd like this term to not contribute to the anomaly

Introducing the GCS term

$$\frac{\partial_\mu a}{f} A_\nu \tilde{F}^{\mu\nu}$$

Non PQ invariant
Gauge invariant

$$\left(\frac{\partial_\mu a}{f} - g_{\rm PQ} A_\mu^{\rm PQ}\right) A_\nu \tilde{F}^{\mu\nu}$$

Generalized Chern-Simons (GCS) term

PQ invariant **Non gauge invariant**

If A_ν^{PQ} is massive

$$A_\mu \to A_\mu - \frac{\partial_\mu \theta_A}{g\, m_A}$$

$$-\frac{1}{g}\left(\frac{\partial_\mu a}{f} - g_{\rm PQ} A_\mu^{\rm PQ}\right)\left(\frac{\partial_\nu \theta_A}{m_A} - g A_\nu\right)\tilde{F}^{\mu\nu}$$

At the end, set $A_\nu^{PQ} = 0$

A4.

Minimal chiral axion model: Yukawa sector

$$-\mathcal{L}_Y = y_{E_1}\bar{L}_1 E_1 H_1 + y_{E_2}\bar{L}_2 E_2 \tilde{H}_2 + y_{N_1}\bar{L}_1 N_1 \tilde{H}_2 + y_{N_2}\bar{L}_2 N_2 H_1 + \text{h.c.}$$

$$\begin{pmatrix} L_1 = (N_{L_1}, E_{L_1})^T \\ L_2 = (E_{L_2}, N_{L_2})^T \end{pmatrix}$$

Axion couplings

$$-\mathcal{L}_Y \supset m_{E_1}\left(e^{iX_1\frac{a}{f}}\right)\bar{E}_{L_1}E_1 + m_{E_2}\left(e^{-iX_2\frac{a}{f}}\right)\bar{E}_{L_2}E_2$$
$$+ m_{N_1}\left(e^{-iX_2\frac{a}{f}}\right)\bar{N}_{L_1}N_1 + m_{N_2}\left(e^{iX_1\frac{a}{f}}\right)\bar{N}_{L_2}N_2 + \text{h.c.}$$

Mass eigenstates:

$$N_i = N_i + N_{L_i}$$
$$E_i = E_i + E_{L_i}$$

Custodial limit

$$m_{N_i} = m_{E_i}$$

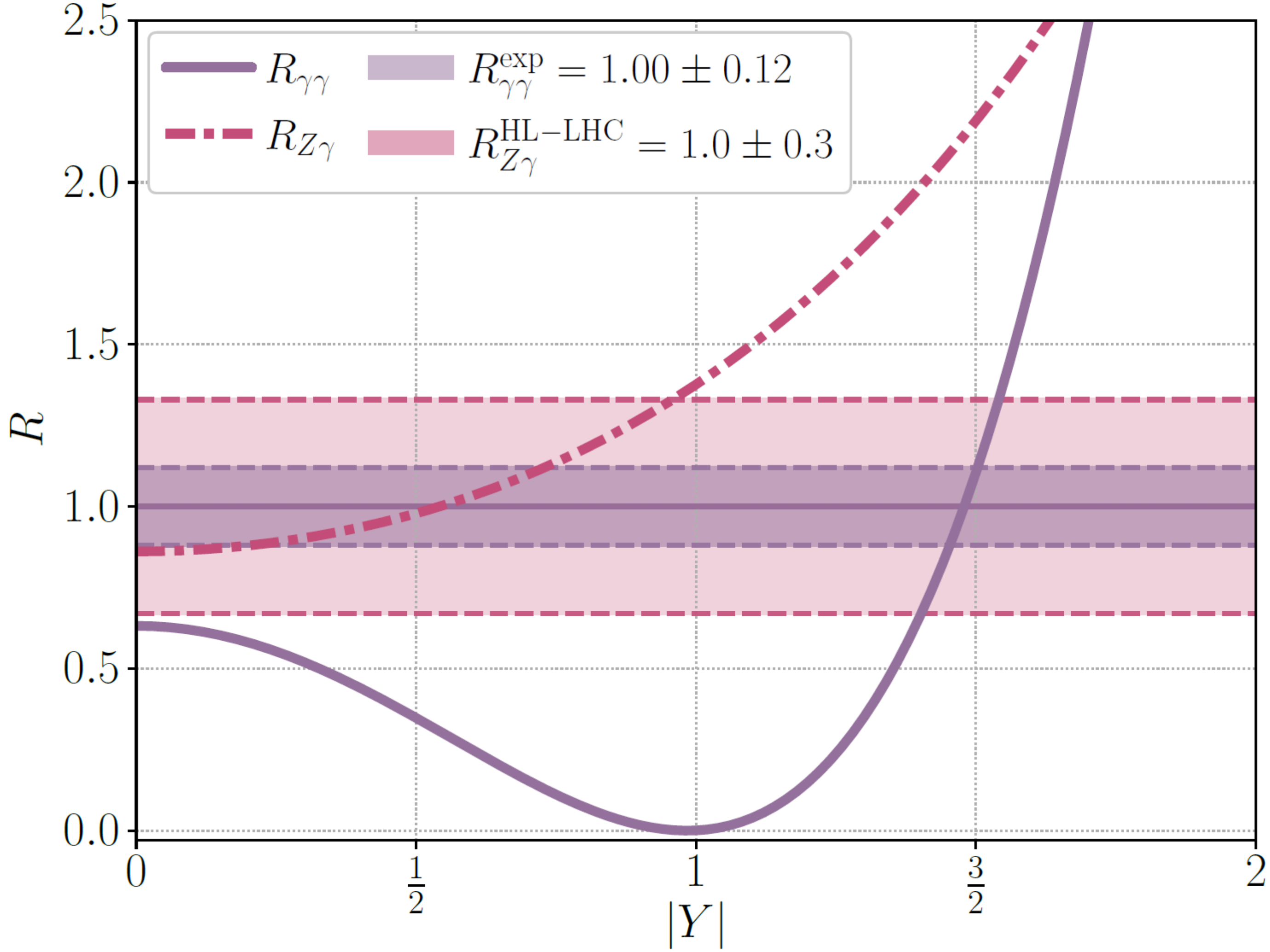
A5.

Chiral extensions + 2HDM: Higgs couplings

Alignment limit

$\beta - \alpha = \pi/2$

$$R_{(Z,\gamma)\gamma} = \frac{\left|\mathcal{A}^{\rm SM}_{(Z,\gamma)\gamma} + \mathcal{A}^{\rm new}_{(Z,\gamma)\gamma}\right|^2}{\left|\mathcal{A}^{\rm SM}_{(Z,\gamma)\gamma}\right|^2}$$



Custodial limit $m_{N_i} = m_{E_i}$ → **Constraints on S and T are satisfied**