Axion couplings to EW gauge bosons

Work in preparation

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The axion solution

Strong CP problem: Why is it so small?

$$\mathcal{L} \supset \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$\bar{\theta} \lesssim 10^{-10}$$

➔ If $\bar{\theta}$ were a scalar field, its vev would be zero

$$\bar{\theta}\,\frac{\alpha_s}{8\pi}G\tilde{G} \quad \longrightarrow \quad \left(\bar{\theta} - \frac{a}{f_a}\right)\frac{\alpha_s}{8\pi}G\tilde{G}$$

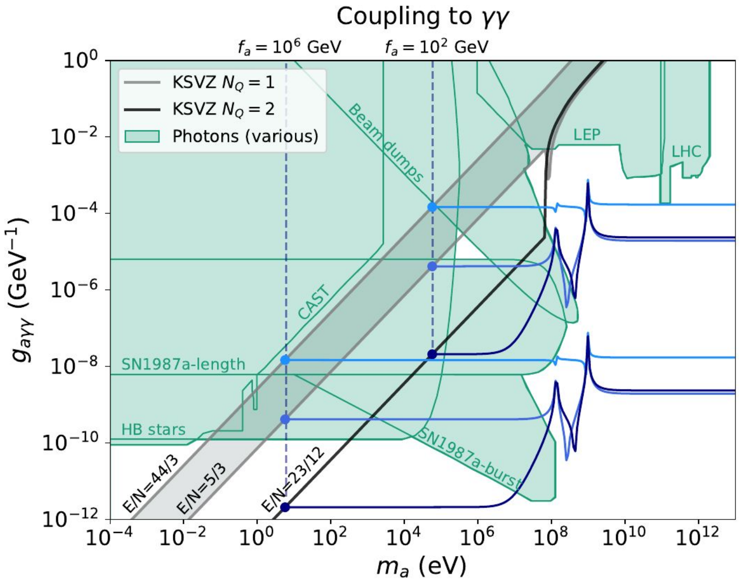
[Peccei+Quinn 77]

[Weinberg 78]

[Wilczek 78]

Axion phenomenology: photons

The most studied phenomenology of the axion: coupling to photons



$$\mathcal{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

$$g_{a\gamma\gamma} \propto \frac{1}{f_a} \quad \Longrightarrow \quad g_{a\gamma\gamma} \propto m_a$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a} \alpha_{\rm em} \left(\frac{E}{N} - 1.92(4) \right)$$

Motivation

Can axion couplings to W and Z-bosons help covering the axion parameter space?

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Are couplings to photons enough?

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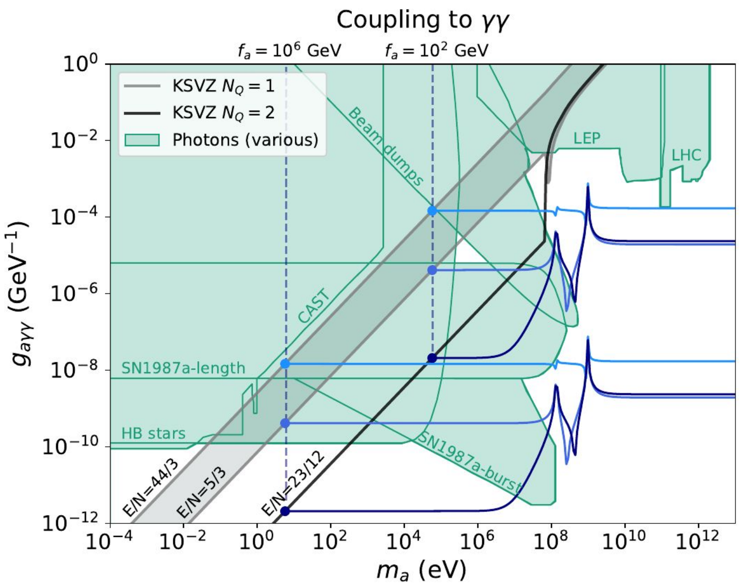

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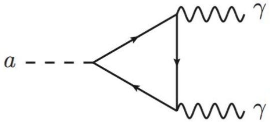
Model dependent

Model independent



Where does it come from?

Pablo Quílez

The axion mass matrix

There are two pseudoscalars that couple to the anomaly: the axion and the η:

$$\frac{\alpha}{8\pi}\left(2\frac{\eta_0}{f_\pi}-\frac{a}{f_a}\right)\tilde{G}G \longrightarrow \frac{1}{2}\Lambda^4_{QCD}\left(2\frac{\eta_0}{f_\pi}+\frac{a}{f_a}\right)^2$$

$$M^2_{\{\pi_3,\eta_0,a\}} = 4\begin{pmatrix} B_0\left(m_u+m_d\right) & B_0\left(m_u-m_d\right) & 0 \\ B_0\left(m_u-m_d\right) & 4K/f_\pi + B_0(m_u+m_d) & 2K/(f_\pi f_a) \\ 0 & 2K/(f_\pi f_a) & K/f_a^2 \end{pmatrix}$$

The physical axion is a (model-independent) combination of the pion and the eta:

$$a_{phys} \simeq \hat{a} - \frac{f_\pi}{2f_a}\frac{m_d-m_u}{m_u+m_d}\pi_3 - \frac{f_\pi}{2f_a}\eta_0$$

Axion couplings bellow confinement

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{\hat{a}}{f_a} G\tilde{G} + \frac{1}{4} g^0_{aWW}\,\hat{a}\,W\tilde{W} + \frac{1}{4} g^0_{aZZ}\,\hat{a}\,Z\tilde{Z} + \frac{1}{4} g^0_{a\gamma\gamma}\,\hat{a}\,F\tilde{F} + \frac{1}{4} g^0_{a\gamma Z}\,\hat{a}\,F\tilde{Z}$$

$$\boxed{g_{aXX} = g^0_{aXX} + \theta_{a\pi}\, g_{\pi XX} + \theta_{a\eta'}\, g_{\eta' XX}}$$

$$\frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d} \sim 1.92$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right),$$

$$g_{aWW} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2}\left(\frac{L}{N} - \frac{3}{4}\right),$$

$$g_{aZZ} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2 c_w^2}\left(\frac{Z}{N} - \frac{11 s_w^4 + 9 c_w^4}{12} - \frac{s_w^2(s_w^2 - c_w^2)}{2}\frac{m_d - m_u}{m_u + m_d}\right),$$

$$g_{a\gamma Z} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w c_w}\left(\frac{2K}{N} - \frac{9c_w^2 - 11 s_w^2}{6} - \frac{1}{2}(c_w^2 - 3 s_w^2)\frac{m_d - m_u}{m_u + m_d}\right).$$

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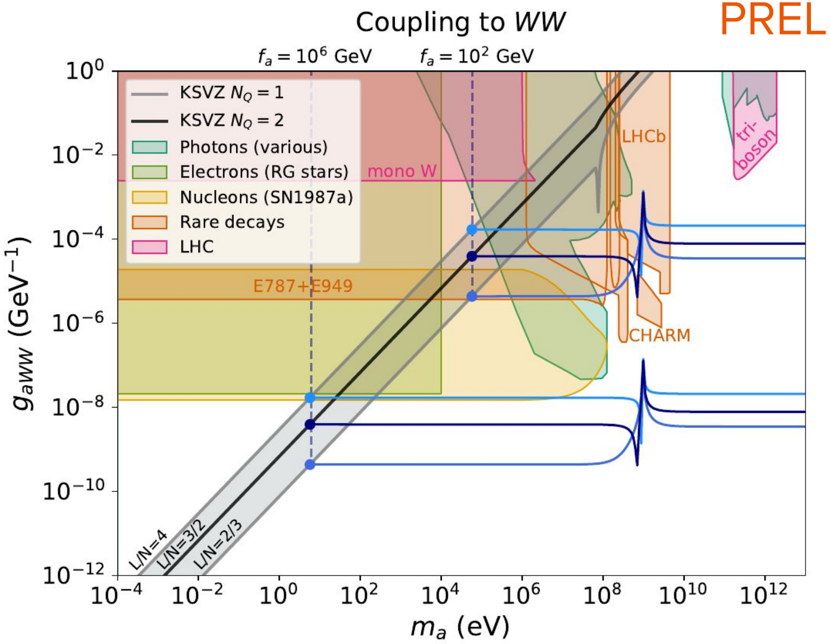
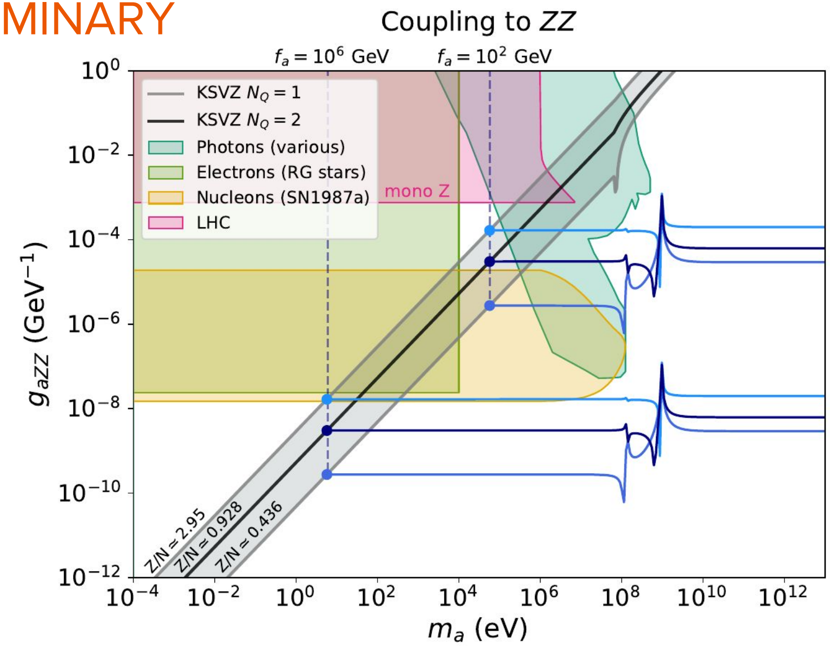
Model independent (present for $m_a < \Lambda_{QCD}$)

Model dependent

Axion phenomenology: g_{aWW}, g_{aZZ} and $g_{a\gamma Z}$

PRELIMINARY





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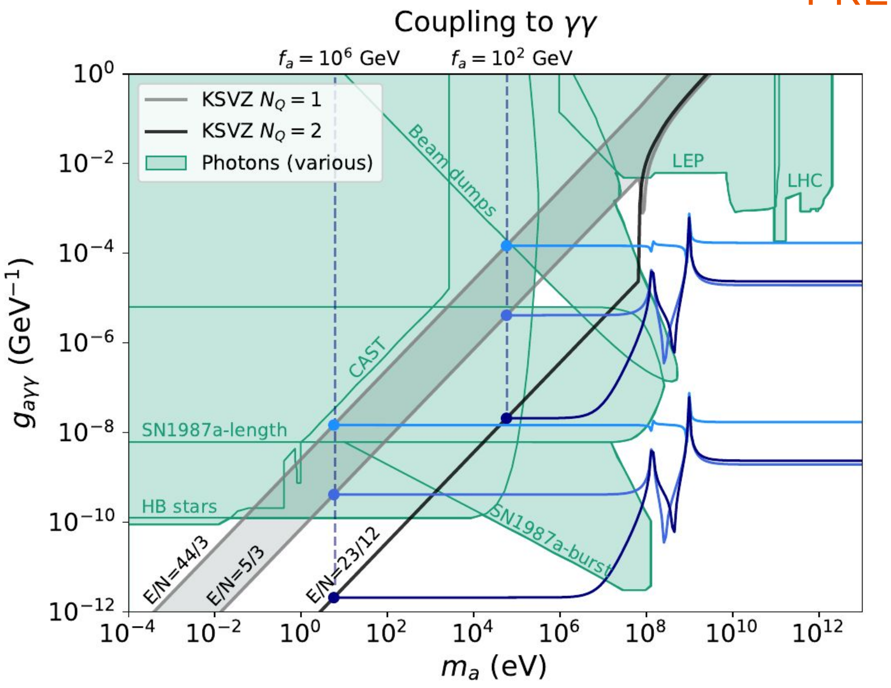
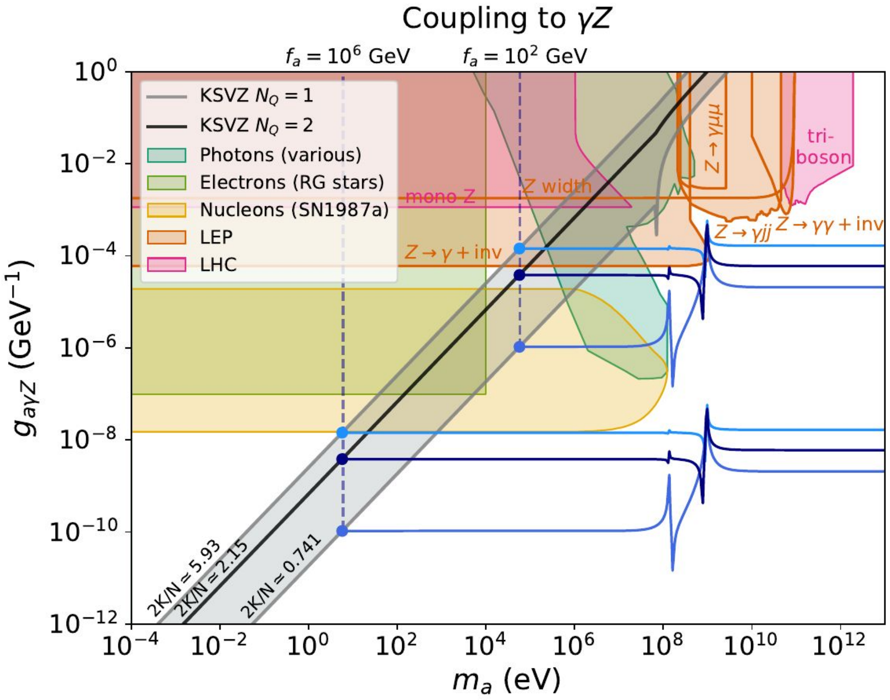
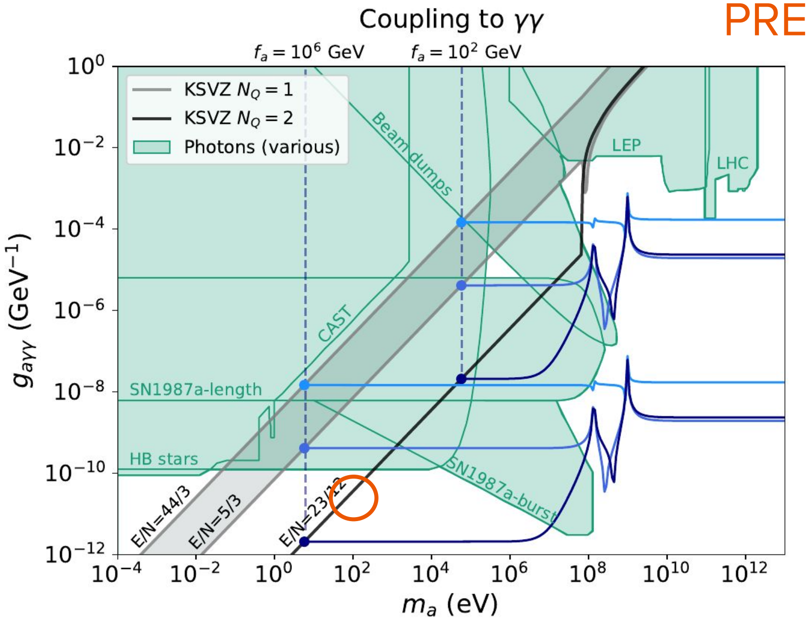
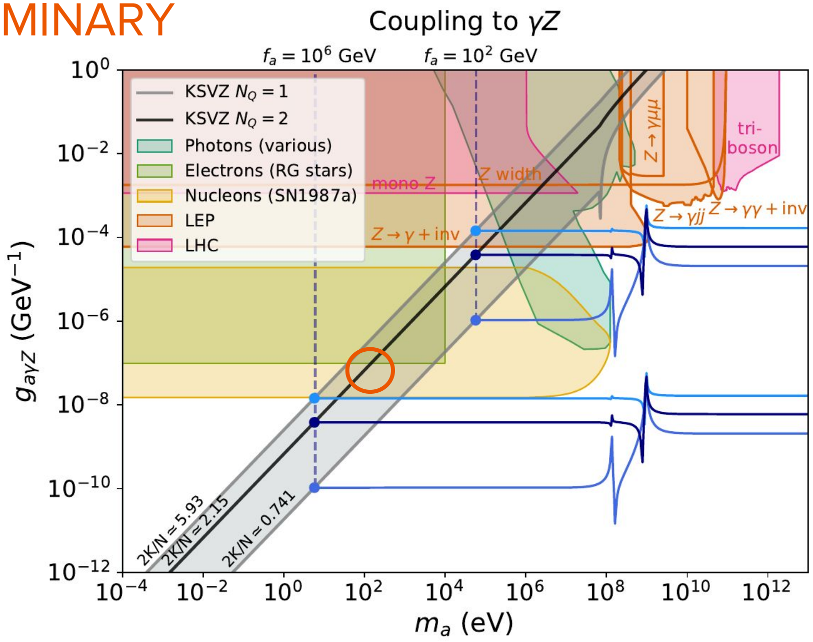




Applications: photophobic axion

PRELIMINARY





$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left(\frac{E}{N} - \frac{2}{3}\frac{m_u + 4m_d}{m_u + m_d}\right)$$

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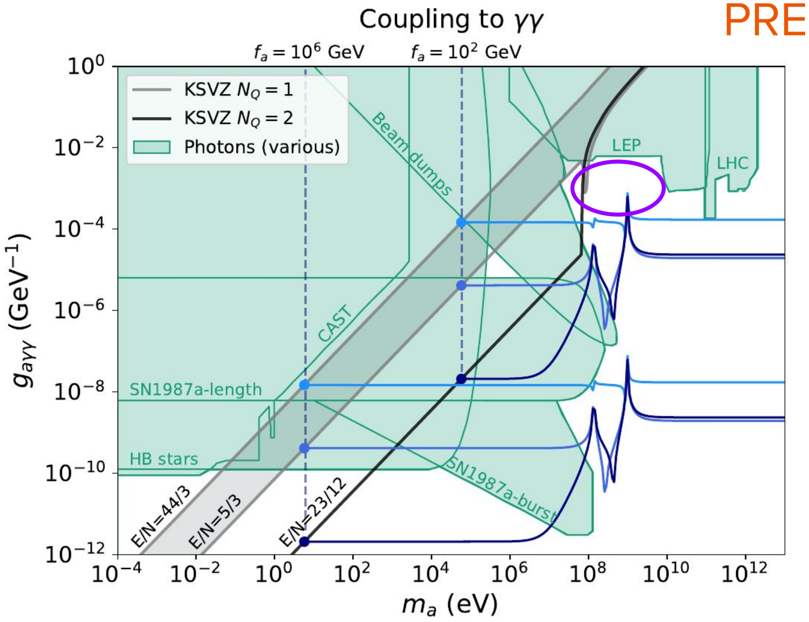
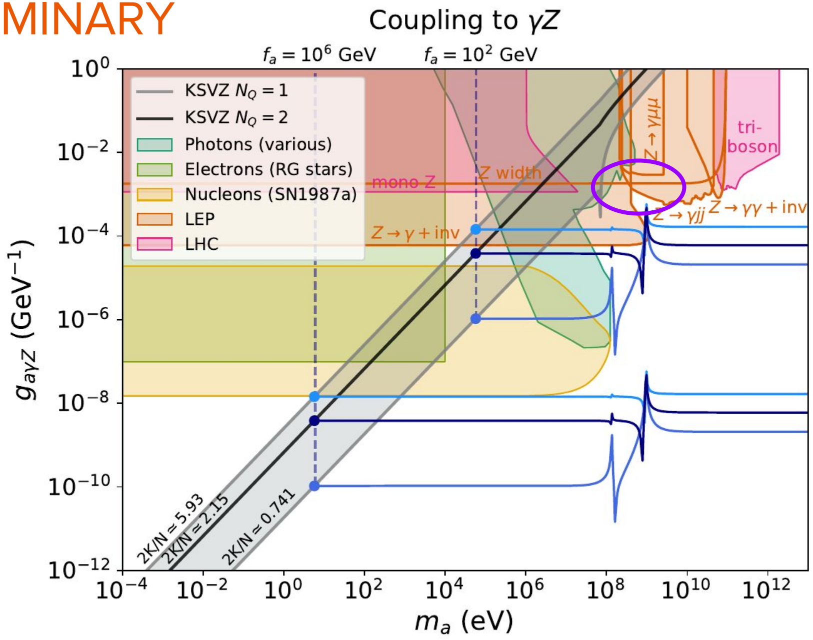
Applications: heavy axion with LEP

PRELIMINARY





Conclusions

- ➔ We have computed the model-independent contribution of the axion couplings to the heavy EW bosons for both, the standard and heavy axion.
- ➔ We have explored the phenomenology associated to these couplings.

Photophobic and heavy axion (m_a~0.1-100 GeV) can be better probed through their EW boson couplings.

Thank you!

Back up I: heavy axion

$$\delta\mathcal{L}_a = \frac{1}{2} M^2 \hat{a}^2$$

$$\theta_{a\pi} \simeq -\frac{f_\pi}{2f_a}\frac{m_d - m_u}{m_u + m_d}\frac{1}{1-\frac{M^2}{m_\pi^2}}\frac{1}{1-\frac{M^2}{m_{\eta'}^2}}\,, \qquad \theta_{A\eta'} \simeq -\frac{f_\pi}{2f_a}\frac{1}{1-\frac{M^2}{m_{\eta'}^2}}$$

$$g_{aWW} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2}\left(\frac{L}{N} - \frac{3}{4}\frac{1}{1-\left(\frac{M}{m_{\eta'}}\right)^2}\right),$$

$$g_{a\gamma\gamma} = -\frac{1}{2\pi f_a}\alpha_{\rm em}\left[\frac{E}{N} - \frac{1}{1-\left(\frac{M}{m_{\eta'}}\right)^2}\left(\frac{5}{3} + \frac{m_d - m_u}{m_u + m_d}\frac{1}{1-\left(\frac{M}{m_\pi}\right)^2}\right)\right],$$

$$g_{aZZ} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w^2 c_w^2}\left[\frac{Z}{N} - \frac{1}{1-\left(\frac{M}{m_{\eta'}}\right)^2}\left(\frac{11 s_w^4 + 9 c_w^4}{12} - \frac{s_w^2(s_w^2 - c_w^2)}{2}\frac{m_d - m_u}{m_u + m_d}\frac{1}{1-\left(\frac{M}{m_\pi}\right)^2}\right)\right],$$

$$g_{a\gamma Z} = -\frac{1}{2\pi f_a}\frac{\alpha_{\rm em}}{s_w c_w}\left[\frac{2K}{N} - \frac{1}{1-\left(\frac{M}{m_{\eta'}}\right)^2}\left(\frac{9c_w^2 - 11 s_w^2}{6} - \frac{1}{2}(c_w^2 - 3s_w^2)\frac{m_d - m_u}{m_u + m_d}\frac{1}{1-\left(\frac{M}{m_\pi}\right)^2}\right)\right]$$

Back up I: RGE in the phenomenology

Effective couplings to fermions appear at one loop. Following [63], we get

$$
\begin{aligned}
\frac{c_f^{\mathrm{eff}}}{f_a} &= \frac{c_f(\Lambda)}{f_a} - \frac{3}{4}\left(\frac{\alpha_L}{4\pi}\frac{3}{4}g_{aWW} + \frac{\alpha_Y}{4\pi}\left(Y_{f_L}^2 + Y_{f_R}^2\right) g_{aBB}\right)\log\frac{\Lambda^2}{m_W^2} - \frac{3}{2}Q_f^2\frac{\alpha_{\mathrm{em}}}{4\pi}g_{a\gamma\gamma}\log\frac{m_W^2}{m_f^2} \\
&= \frac{c_f(\Lambda)}{f_a} - \frac{3}{2}\frac{\alpha_{\mathrm{em}}}{4\pi}Q_f^2 g_{a\gamma\gamma}\log\frac{\Lambda^2}{m_f^2} - \frac{9}{16}\frac{\alpha_L}{4\pi}g_{aWW}\log\frac{\Lambda^2}{m_W^2} \\
&\quad - \frac{3}{4}\frac{\alpha_Z}{4\pi}\left(\frac{3}{4}c_W^4 + \left(Y_{f_L}^2 + Y_{f_R}^2\right)s_W^4\right) g_{aZZ}\log\frac{\Lambda^2}{m_W^2} \\
&\quad - \frac{3}{4}\frac{\alpha_{\gamma Z}}{4\pi}\left(\frac{3}{4}c_W^2 - \left(Y_{f_L}^2 + Y_{f_R}^2\right)s_W^2\right) g_{a\gamma Z}\log\frac{\Lambda^2}{m_W^2}.
\end{aligned}
$$

The photon coupling also receives 1-loop corrections in the presence of fermion or gauge boson couplings. The contribution can be expressed as

$$
g_{a\gamma\gamma}^{\mathrm{eff}} = g_{a\gamma\gamma}(\Lambda) + \sum_f N_C^f Q_f^2 \frac{\alpha_e m}{\pi}\frac{2c_f}{f_a}B_1\tau_f + 2\frac{\alpha_e m}{\pi}g_{aWW}B_2(\tau_W), \tag{3.12}
$$