CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Probing chiral SM extensions :
sum-rules on axion couplings

Quentin Bonnefoy
(DESY Hamburg)

HPNP2021 - Osaka U.
26/03/2021

Based on 2011.10025 [hep-ph]
with L. Di Luzio, C. Grojean, A. Paul, A. Rossia

Let’s assume we detected an **axion-like particle** (ALP)

Let's assume we detected an **axion-like particle** (ALP)

$$\mathcal{L} \supset -\frac{1}{2}(\partial a)^2 - \frac{g^2 \mathcal{A}}{16\pi^2 f_a} a F\tilde{F} - \frac{\mathcal{C}_L^i}{f_a} \partial_\mu a \overline{\psi_L^i} \gamma^\mu \psi_L^i$$

Effective couplings to the SM : **UV origin ? Heavy sector ?**

Let's assume we detected an **axion-like particle** (ALP)

$$\mathcal{L} \supset -\frac{1}{2}(\partial a)^2 - \frac{g^2 \mathcal{A}}{16\pi^2 f_a} a F\tilde{F} - \frac{\mathcal{C}_L^i}{f_a} \partial_\mu a \overline{\psi_L^i} \gamma^\mu \psi_L^i$$

Effective couplings to the SM : **UV origin ? Heavy sector ?**

UV information via **non-decoupling effects**

Let's assume we detected an **axion-like particle** (ALP)

$$\mathcal{L} \supset -\frac{1}{2}(\partial a)^2 - \frac{g^2 \mathcal{A}}{16\pi^2 f_a} a F\tilde{F} - \frac{\mathcal{C}_L^i}{f_a}\partial_\mu a \overline{\psi_L^i}\gamma^\mu \psi_L^i$$

Effective couplings to the SM : **UV origin ? Heavy sector ?**

UV information via **non-decoupling effects**

Typical example : **anomalies**

[Wess/Zumino '71, 't Hooft, '80, Witten '83, Agrawal, Hook, Huang '19]

Let's assume we detected an **axion-like particle** (ALP)

$$\mathcal{L} \supset -\frac{1}{2}(\partial a)^2 - \frac{g^2 \mathcal{A}}{16\pi^2 f_a} aF\tilde{F} - \frac{\mathcal{C}_L^i}{f_a}\partial_\mu a \overline{\psi_L^i}\gamma^\mu \psi_L^i$$

Effective couplings to the SM : **UV origin ? Heavy sector ?**

$$\mathcal{A} = \sum_{\psi_L^i} q_{\mathrm{PQ}} q^2$$

UV information via **non-decoupling effects**

Typical example : **anomalies**

[Wess/Zumino '71, 't Hooft, '80, Witten '83, Agrawal, Hook, Huang '19]

Let's assume we detected an **axion-like particle** (ALP)

$$\mathcal{L} \supset -\frac{1}{2}(\partial a)^2 - \frac{g^2 \mathcal{A}}{16\pi^2 f_a} a F\tilde{F} - \frac{\mathcal{C}_L^i}{f_a}\partial_\mu a \overline{\psi_L^i}\gamma^\mu \psi_L^i$$

Effective couplings to the SM : **UV origin ? Heavy sector ?**

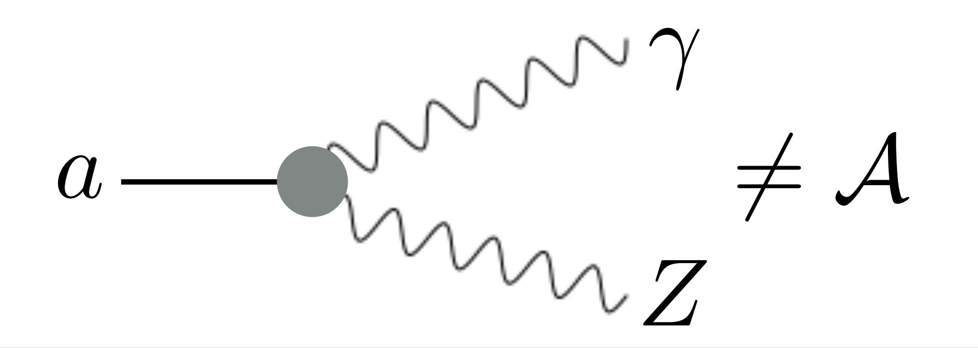
$$\mathcal{A} = \sum_{\psi_L^i} q_{\mathrm{PQ}} q^2$$

UV information via **non-decoupling effects**

Typical example : **anomalies**

[Wess/Zumino '71, 't Hooft, '80, Witten '83, Agrawal, Hook, Huang '19]

Not so clear for **massive gauge fields** : ex. in DFSZ model



[Quevillon, Smith '19]

Linked to the presence of **longitudinal components** :

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2 \mathcal{A}}{16\pi^2 f_a} a F \tilde{F}$$

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2 \mathcal{A}}{16\pi^2 f_a} aF\tilde{F} \\ -\frac{1}{2}\left(\partial_\mu \theta_A - m_A A_\mu\right)^2$$

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2\mathcal{A}}{16\pi^2 f_a} aF\tilde{F} - \frac{g^2\mathcal{E}}{16\pi^2 f_a}\partial_\mu a\left(\partial_\nu\theta_A - m_A A_\nu\right)\tilde{F}^{\mu\nu}$$
$$-\frac{1}{2}\left(\partial_\mu\theta_A - m_A A_\mu\right)^2$$

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2\mathcal{A}}{16\pi^2 f_a} aF\tilde{F} - \frac{g^2\mathcal{E}}{16\pi^2 f_a}\partial_\mu a\left(\partial_\nu\theta_A - m_A A_\nu\right)\tilde{F}^{\mu\nu}$$

Dim-5

$$-\frac{1}{2}\left(\partial_\mu\theta_A - m_A A_\mu\right)^2$$

For the electroweak sector : use a **non-linear EW symmetry**

[Callan, Coleman, Wess, Zumino '69, Feruglio '93]

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2\mathcal{A}}{16\pi^2 f_a} aF\tilde{F} - \frac{g^2\mathcal{E}}{16\pi^2 f_a}\partial_\mu a\left(\partial_\nu\theta_A - m_A A_\nu\right)\tilde{F}^{\mu\nu}$$
$$-\frac{1}{2}\left(\partial_\mu\theta_A - m_A A_\mu\right)^2$$

For the electroweak sector : use a **non-linear EW symmetry**

$$\partial_\mu\theta_A - m_A A_\mu = e^{-i\theta_A} D_\mu e^{i\theta_A}$$

[Callan, Coleman, Wess, Zumino '69, Feruglio '93]

Linked to the presence of **longitudinal components** :

$$\mathcal{L} \supset -\frac{g^2\mathcal{A}}{16\pi^2 f_a} aF\tilde{F} - \frac{g^2\mathcal{E}}{16\pi^2 f_a}\partial_\mu a \left(\partial_\nu \theta_A - m_A A_\nu\right)\tilde{F}^{\mu\nu}$$
$$-\frac{1}{2}\left(\partial_\mu \theta_A - m_A A_\mu\right)^2$$

For the electroweak sector : use a **non-linear EW symmetry**

$$\partial_\mu \theta_A - m_A A_\mu = e^{-i\theta_A} D_\mu e^{i\theta_A}$$

[Callan, Coleman, Wess, Zumino '69, Feruglio '93]

generalizes to →

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

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} + \frac{i}{8\pi^2}\frac{\partial_\mu a}{f}\left(\frac{g' c_1}{2}\mathrm{Tr}(TV_\nu)\tilde{B}^{\mu\nu} + g c_2 \mathrm{Tr}(V_\nu \tilde{W}^{\mu\nu}) + g c_3 \mathrm{Tr}(TV_\nu)\mathrm{Tr}(T\tilde{W}^{\mu\nu})\right)$$

[Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17]

For the electroweak sector : use a **non-linear EW symmetry**

[Callan, Coleman, Wess, Zumino '69, Feruglio '93]

$$U = e^{i\frac{\pi^a}{v}\sigma^a} \;, \quad D_\mu U = \partial_\mu U - igW_\mu U + ig' B_\mu U \frac{\sigma_3}{2}$$

$$V_\mu = D_\mu U U^\dagger \;, \quad T = U\sigma_3 U^\dagger$$

$$
\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f} W^a \tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f} B\tilde{B}
+ \frac{i}{8\pi^2}\frac{\partial_\mu a}{f}\left(\frac{g' c_1}{2}\mathrm{Tr}(TV_\nu)\tilde{B}^{\mu\nu} + g c_2 \mathrm{Tr}(V_\nu \tilde{W}^{\mu\nu}) + g c_3 \mathrm{Tr}(TV_\nu)\mathrm{Tr}(T\tilde{W}^{\mu\nu})\right)
$$

[Brivio, Gavela, Merlo, Mimasu, No, del Rey, Sanz '17]

For the electroweak sector : use a **non-linear EW symmetry**

[Callan, Coleman, Wess, Zumino '69, Feruglio '93]

modify

$a\gamma Z,\ aZZ$

aWW

$$
U = e^{i\frac{\pi^a}{v}\sigma^a}\ , \quad D_\mu U = \partial_\mu U - igW_\mu U + ig' B_\mu U \frac{\sigma_3}{2}
$$

$$
V_\mu = D_\mu U U^\dagger\ , \quad T = U\sigma_3 U^\dagger
$$

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} - \frac{c_1 g'}{16\pi^2 f}a(gW^3 - g'B)\tilde{B}$$
$$-\frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3$$

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} - \frac{c_1 g'}{16\pi^2 f}a(gW^3 - g'B)\tilde{B}$$
$$- \frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3$$

beyond SU(2) anomalies

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f} W^a \tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f} B\tilde{B} - \frac{c_1 g'}{16\pi^2 f} a(gW^3 - g'B)\tilde{B}$$
$$-\frac{c_2 g}{16\pi^2 f} a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f} a(gW^3 - g'B)\tilde{W}^3$$

beyond SU(2) anomalies

Pheno impact : **breakdown of sum rules**

$a\gamma\gamma,\ a\gamma Z$

$aZZ,\ aWW$

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} - \frac{c_1 g'}{16\pi^2 f}a(gW^3 - g'B)\tilde{B}$$

$$-\frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3$$

beyond SU(2) anomalies

Pheno impact : **breakdown of sum rules**

$a\gamma\gamma,\ a\gamma Z$
$aZZ,\ aWW$

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

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} - \frac{c_1 g'}{16\pi^2 f}a(gW^3 - g'B)\tilde{B}$$
$$-\frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3$$

beyond SU(2) anomalies

Pheno impact : **breakdown of sum rules**

$a\gamma\gamma,\ a\gamma Z$

$aZZ,\ aWW$

$$\left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} \neq 0$$

New structures in **axion couplings** :

$$\mathcal{L} \supset -\frac{g^2 C_{WW}}{16\pi^2}\frac{a}{f}W^a\tilde{W}^a - \frac{g'^2 C_{BB}}{16\pi^2}\frac{a}{f}B\tilde{B} - \frac{c_1 g'}{16\pi^2 f}a(gW^3 - g'B)\tilde{B}$$
$$-\frac{c_2 g}{16\pi^2 f}a(gW^a\tilde{W}^a - g'B\tilde{W}^3) - \frac{c_3 g}{16\pi^2 f}a(gW^3 - g'B)\tilde{W}^3$$

beyond SU(2) anomalies

Pheno impact : **breakdown of sum rules** $a\gamma\gamma,\ a\gamma Z$ $aZZ,\ aWW$

$$\left[\frac{\Gamma(a\to ZZ)}{\Gamma(a\to\gamma\gamma)} - 1 - \frac{\left(t_W^2-1\right)^2}{2t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)}\right]^2 - \frac{2\left(t_W^2-1\right)^2}{t_W^2}\frac{\Gamma(a\to Z\gamma)}{\Gamma(a\to\gamma\gamma)} \neq 0$$

When does this happen ?

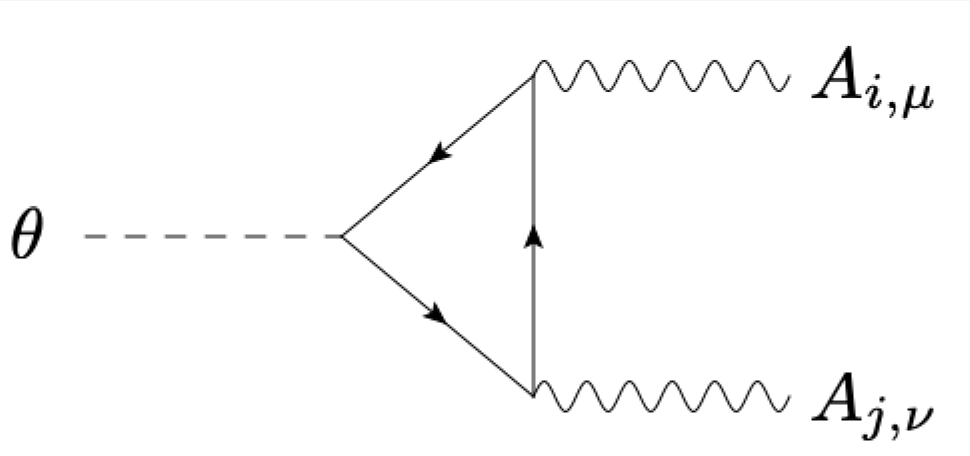
Non-linear EW symmetry needed when **heavy fields acquire a mass from EWSB**

[Alonso, Jenkins, Manohar '16, Falkowski, Rattazzi '19, Cohen, Craig, Lu, Sutherland '20]

Non-linear EW symmetry needed when **heavy fields acquire a mass from EWSB**

[Alonso, Jenkins, Manohar '16, Falkowski, Rattazzi '19, Cohen, Craig, Lu, Sutherland '20]

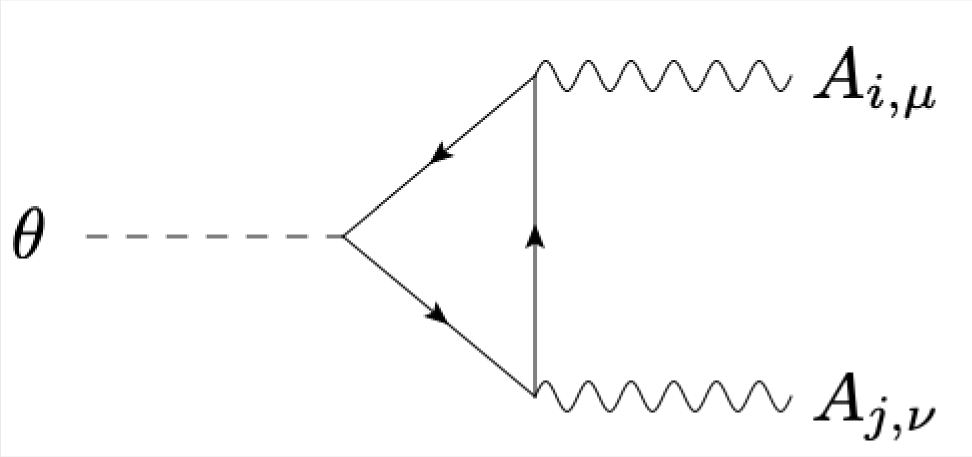
Here : heavy fermions coupled to gauge fields and the light (pseudoscalar) ALP



Non-linear EW symmetry needed when **heavy fields acquire a mass from EWSB**

[Alonso, Jenkins, Manohar ’16, Falkowski, Rattazzi ’19, Cohen, Craig, Lu, Sutherland ’20]

Here : heavy fermions coupled to gauge fields and the light (pseudoscalar) ALP



Importantly : such fields are **chiral**

$$\mathcal{L} \supset -\overline{\psi}(\partial_\mu - ig(\alpha + \beta\gamma_5)A_\mu + m)\psi$$

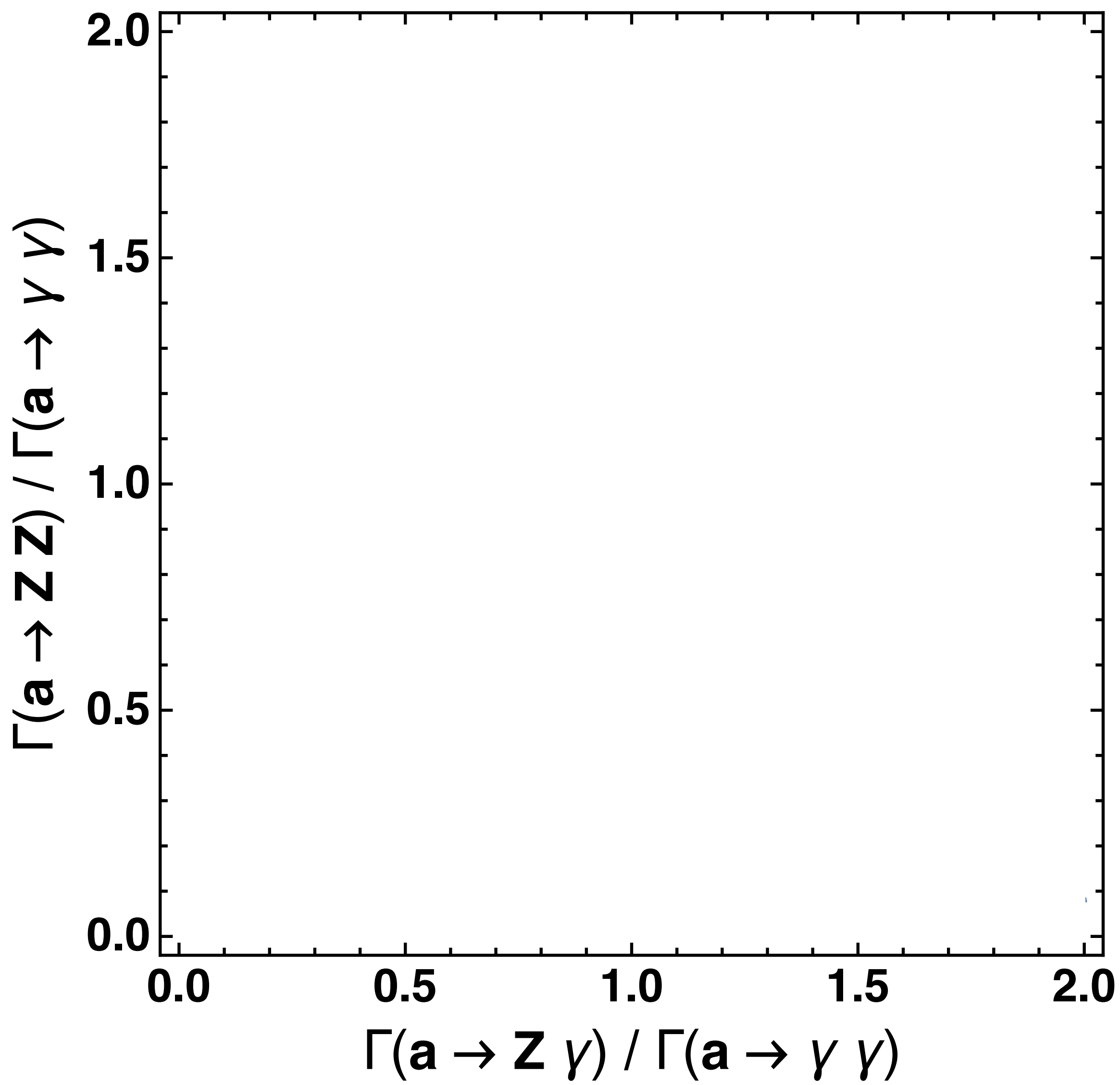
	$SU(3)$	$SU(2)$	$U(1)$
L_1	1	2	Y
E_1	1	1	$Y - \frac{1}{2}$
N_1	1	1	$Y + \frac{1}{2}$
L_2	1	2	$-Y$
E_2	1	1	$-Y + \frac{1}{2}$
N_2	1	1	$-Y - \frac{1}{2}$

$$\mathcal{L} \supset \bar{L}_1 N_1 H\,, \quad \bar{L}_1 E_1 \tilde{H}\,,$$

$$\bar{L}_2 E_2 H\,, \quad \bar{L}_2 N_2 \tilde{H}$$

	$SU(3)$	$SU(2)$	$U(1)$
L_1	1	2	Y
E_1	1	1	$Y-\frac{1}{2}$
N_1	1	1	$Y+\frac{1}{2}$
L_2	1	2	$-Y$
E_2	1	1	$-Y+\frac{1}{2}$
N_2	1	1	$-Y-\frac{1}{2}$

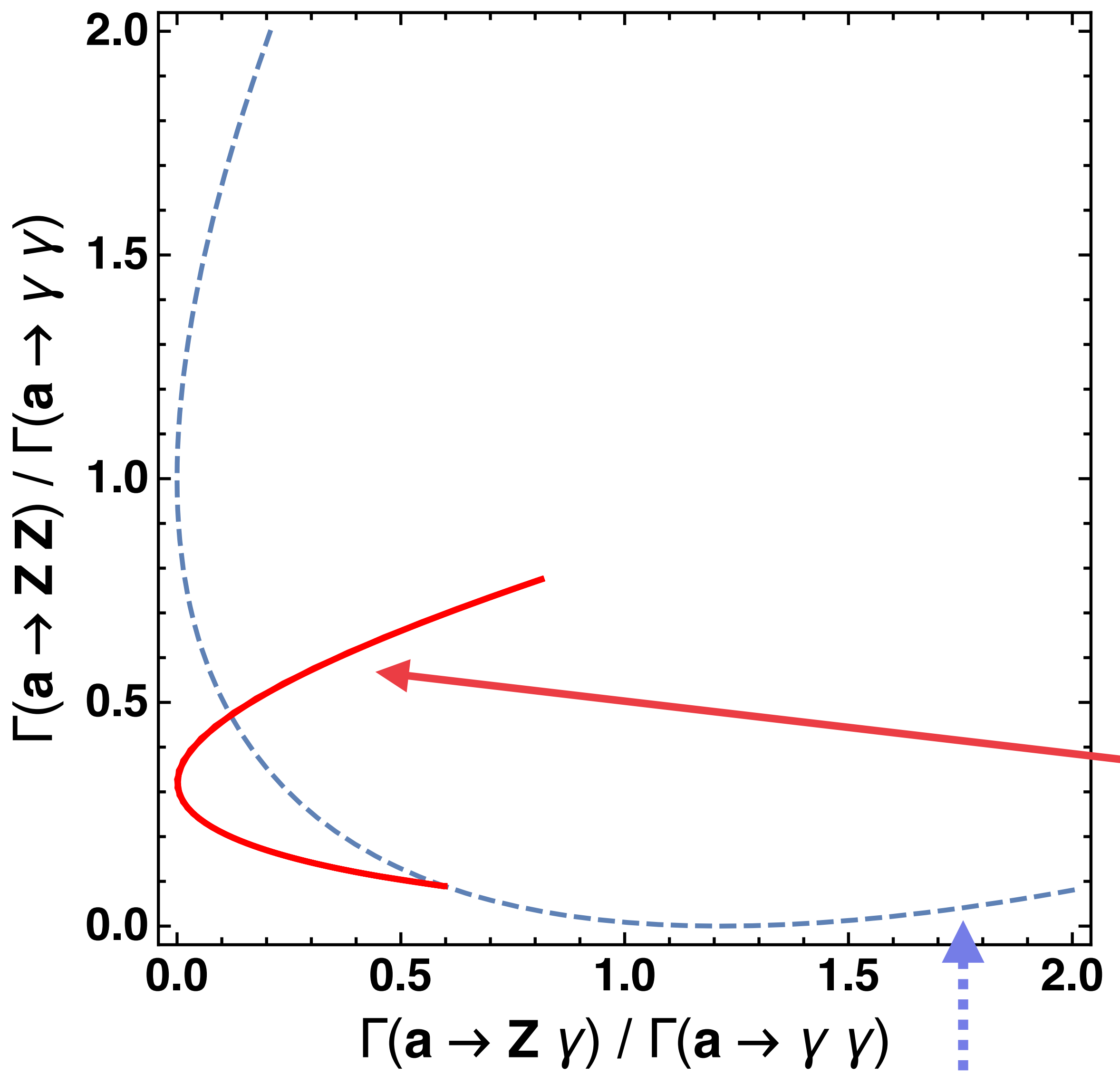
$$\begin{aligned}\mathcal{L}_Y = &- y_{E_1}\bar{L}_1 E_1 H_1 \\ &- y_{E_2}\bar{L}_2 E_2 \tilde{H}_2 \\ &- y_{N_1}\bar{L}_1 N_1 \tilde{H}_2 \\ &- y_{N_2}\bar{L}_2 N_2 H_1 + \text{h.c.}\end{aligned}$$



	$SU(3)$	$SU(2)$	$U(1)$
L_1	1	2	Y
E_1	1	1	$Y-\frac{1}{2}$
N_1	1	1	$Y+\frac{1}{2}$
L_2	1	2	$-Y$
E_2	1	1	$-Y+\frac{1}{2}$
N_2	1	1	$-Y-\frac{1}{2}$

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

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

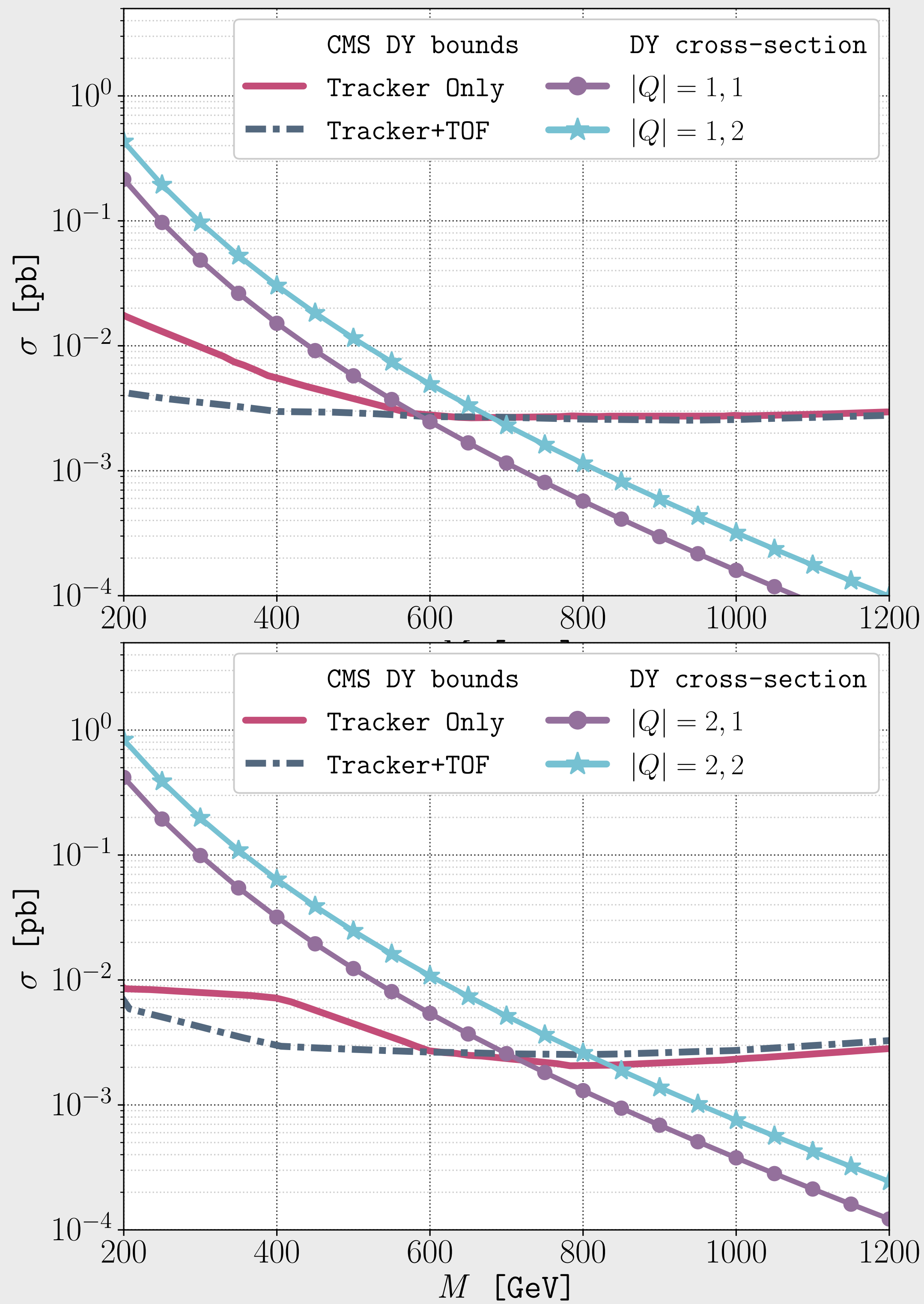


	$SU(3)$	$SU(2)$	$U(1)$
L_1	1	2	Y
E_1	1	1	$Y-\frac{1}{2}$
N_1	1	1	$Y+\frac{1}{2}$
L_2	1	2	$-Y$
E_2	1	1	$-Y+\frac{1}{2}$
N_2	1	1	$-Y-\frac{1}{2}$

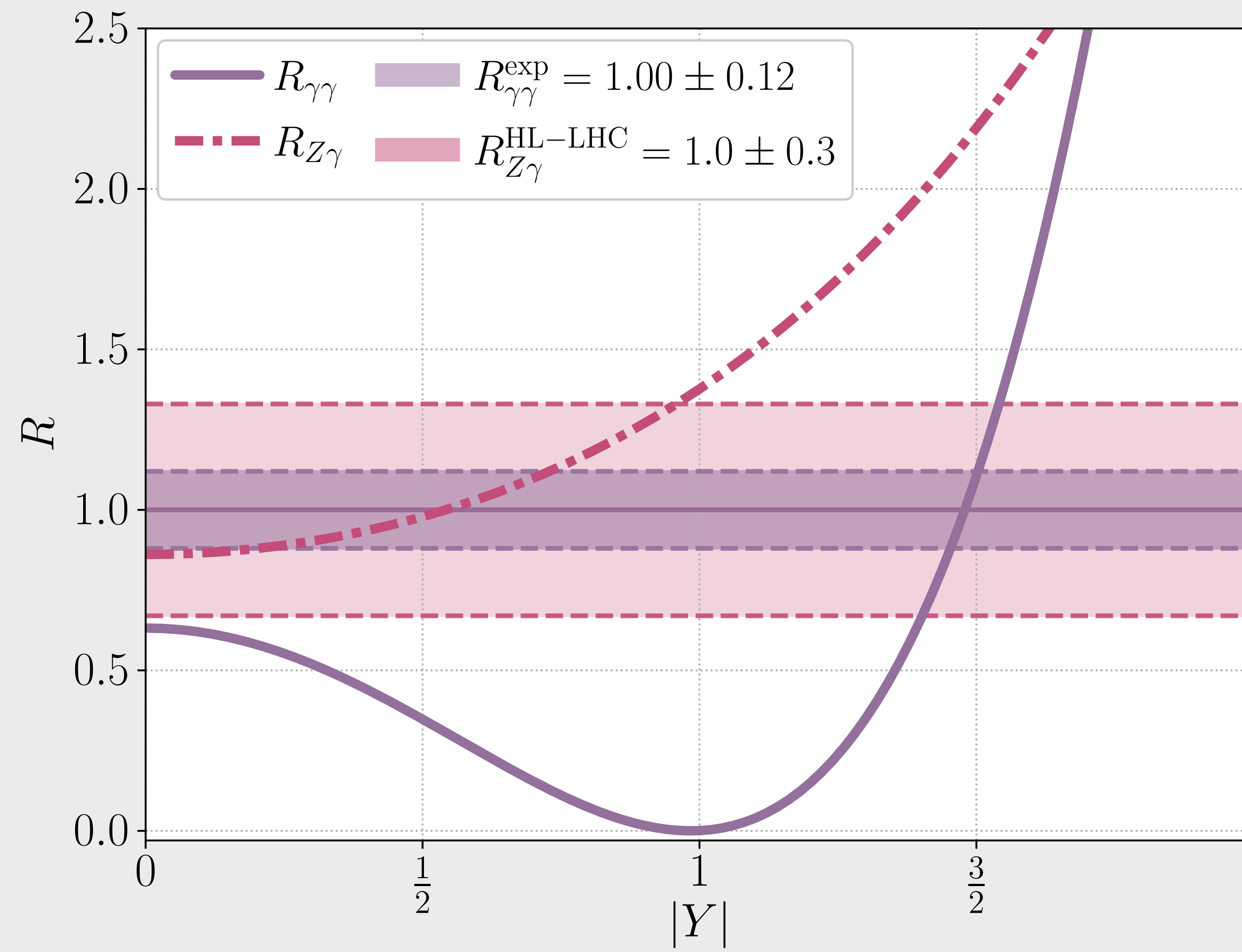
$$\begin{aligned}\mathcal{L}_Y = &- y_{E_1}\bar{L}_1 E_1 H_1 \\ &- y_{E_2}\bar{L}_2 E_2 \tilde{H}_2 \\ &- y_{N_1}\bar{L}_1 N_1 \tilde{H}_2 \\ &- y_{N_2}\bar{L}_2 N_2 H_1 + \text{h.c.}\end{aligned}$$

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

- **electroweak precision tests** : satisfied in the custodial limit
- **direct searches** for stable charged particles :



- **Higgs couplings** (in the alignment limit) :



Take away

Axion couplings to electroweak gauge fields allow to proble a **non-linear EW symmetry** above the Higgs vev

Take away

Axion couplings to electroweak gauge fields allow to proble a **non-linear EW symmetry** above the Higgs vev

A **violation of sum rules** signals the presence of **heavy chiral matter**

Take away

Axion couplings to electroweak gauge fields allow to proble a **non-linear EW symmetry** above the Higgs vev

A **violation of sum rules** signals the presence of **heavy chiral matter**

The simplest model which realizes this **is not yet excluded**

Thank you !