Axions in some anomalous extensions of the Standard Model

Roberta Armillis

Department of Physics, Università del Salento
and INFN, Lecce, Italy

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Outline

We present an extension of the Standard Model containing an extra anomalous U(1) in the Stueckelberg phase and corrected by dimension-5 operators to ensure anomaly cancellation.

The effective action that we study appears in several contexts, such as strings/branes scenarios but also in partial decoupling of heavy chiral fermions.

The presence of a generalized Peccei axion (axion-like field) and of new neutral currents renders the model interesting both in cosmology and in collider physics.

Part of this talk is based on *C.Corianò, M.Guzzi, R.A. - arXiv:0709.2111*

The “traditional” PQ axion

Peccei and Quinn → $U(1)_{PQ}$ symmetry

Weinberg and Wilczek → the axion as a pseudo Goldstone boson

The mass and the coupling of the axion to photons depend on the SAME scale f_a

$$\boxed{m_a = \frac{v_F}{f_a}\bar{m}_a \simeq 6.3[\frac{10^6\mathrm{GeV}}{f_a}]\ \mathrm{eV}}$$

$$\boxed{g \approx \frac{1}{f_a}}$$

$$\boxed{f_a \geq 10^{10}\,GeV}$$

Astrophysical constraint
linked to the stellar evolution

$$\boxed{f_a \leq 10^{12}\,GeV}$$

Cosmological constraint

$$\boxed{10^{-6}\,eV \leq m_a \leq 10^{-3}\,eV}$$

Axion-like particles (ALP)

We investigate a class of field theories which are common to several constructions/extensions of the Standard Model all of them having as a specific signature:

the presence of an axion in the physical spectrum.

This axion, differently from a traditional Peccei-Quinn axion, appears in an effective action with

1) anomalous gauge interactions
2) new neutral currents
3) generalized Chern-Simons terms.

C. Corianò, N. Irges, S. Morelli – *JHEP* 0707:008, 2007
C. Corianò, N. Irges, S. Morelli – Nucl.Phys. B, in press
C.Corianò, N. Irges - Phys.Lett. B651: 298-305, 2007

Properties of this new axion

The axion

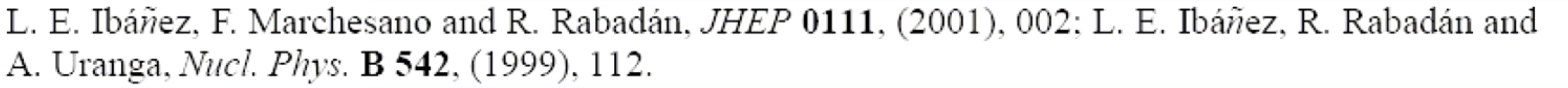
- is the result of gauging a global U(1) symmetry
- is linked to the Higgs sector of the SM and its extension (for instance in 2-Higgs doublet models)
- can be rendered in SUSY (supersymmetric generalization of the Stueckelberg construction)

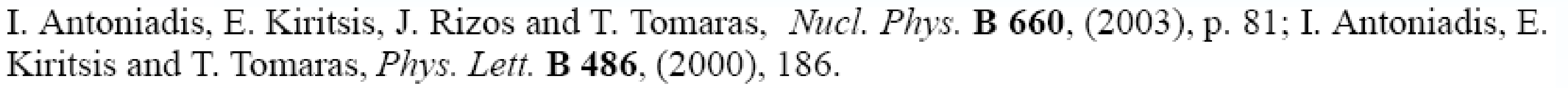
The mass and the coupling of the gauged axion
to the gauge fields are independent

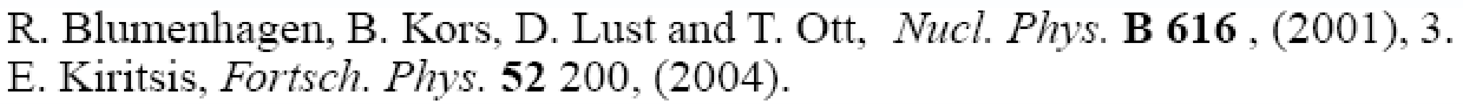
The origin of ALP (1) – String origin

This particle appears naturally in some extensions of the Standard Model inspired by string theory and is involved in the anomaly cancellation mechanism

- String models based on intersecting branes can generate abelian anomalous gauge interactions and axions (orientifold construction)
- Low energy manifestations of the Green-Schwarz mechanism of string theory


L. E. Ibáñez, F. Marchesano and R. Rabadán, *JHEP* **0111**, (2001), 002; L. E. Ibáñez, R. Rabadán and A. Uranga, *Nucl. Phys.* **B 542**, (1999), 112.


I. Antoniadis, E. Kiritsis, J. Rizos and T. Tomaras, *Nucl. Phys.* **B 660**, (2003), p. 81; I. Antoniadis, E. Kiritsis and T. Tomaras, *Phys. Lett.* **B 486**, (2000), 186.


R. Blumenhagen, B. Kors, D. Lust and T. Ott, *Nucl. Phys.* **B 616** , (2001), 3.
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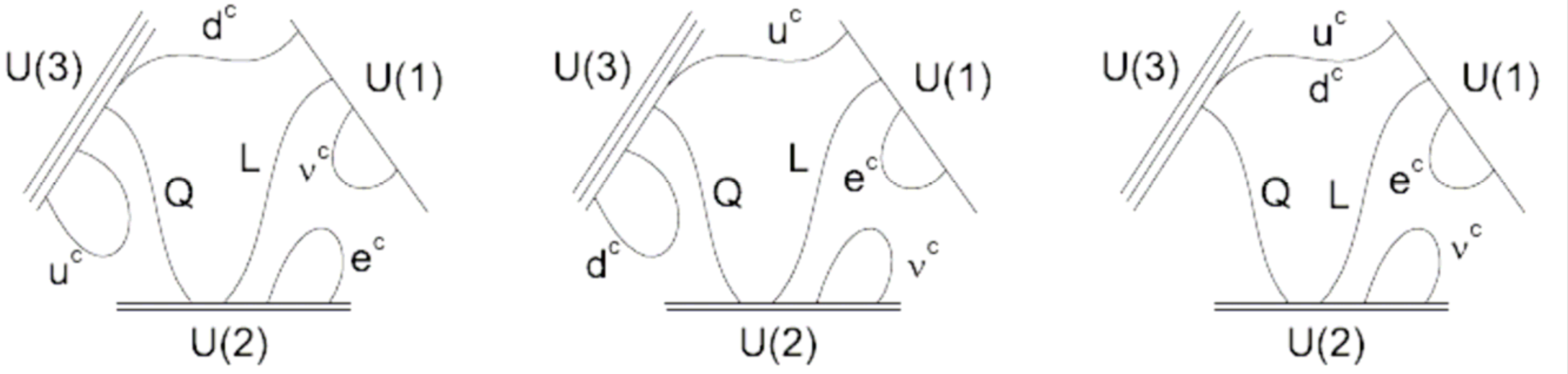
Intersecting brane models



	Q	d^c	u^c	L	e^c
a_1:	$(3,2;1,\epsilon_1,0)$	$(\bar{3},1;-1,0,\epsilon_2)$	$(\bar{3},1;2\epsilon_3,0,0)$	$(1,2;0,\epsilon_4,\epsilon_5)$	$(1,1;0,2\epsilon_6,0)$
b_1:	$(3,2;1,\epsilon_1,0)$	$(\bar{3},1;2\epsilon_2,0,0)$	$(\bar{3},1;-1,0,\epsilon_3)$	$(1,2;0,\epsilon_4,\epsilon_5)$	$(1,1;0,0,2\epsilon_6)$
c_1:	$(3,2;1,\epsilon_1,0)$	$(\bar{3},1;-1,0,\epsilon_2)$	$(\bar{3},1;-1,0,\epsilon_3)$	$(1,2;0,\epsilon_4,\epsilon_5)$	$(1,1;0,0,2\epsilon_6)$

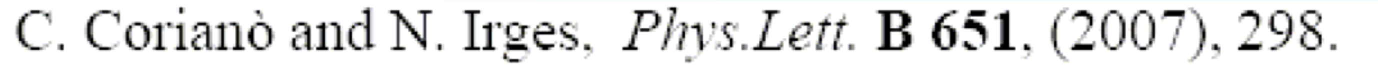
$$U(n) \sim SU(n) \times U(1)$$

$$SU(3) \times SU(2) \times U(1)^{N+2}$$

Gioutsos, Leontaris, Psallidas, Phys. Rev. D74 (2006)

The origin of ALP (2) – Partial decoupling

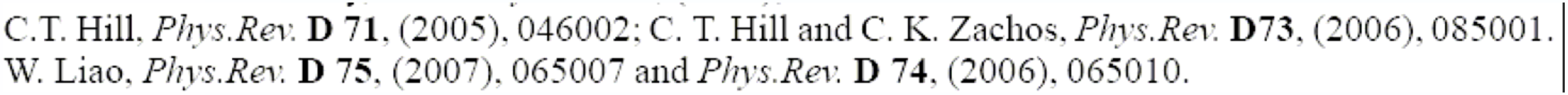
The partial decoupling of a heavy chiral fermion can generate an axion as the (massless) phase of an additional Higgs



C. Corianò and N. Irges, *Phys.Lett.* **B 651**, (2007), 298.

The origin of ALP (3) – Anomaly inflow with chiral delocalization

Extra dimensional models with anomalies on the branes and additional interactions in the bulk (for instance 5D Chern-Simons) can have Stueckelberg fields and CS interactions coming from the KK expansion of the extra components of the abelian gauge fields



C.T. Hill, *Phys.Rev.* **D 71**, (2005), 046002; C. T. Hill and C. K. Zachos, *Phys.Rev.* **D73**, (2006), 085001.
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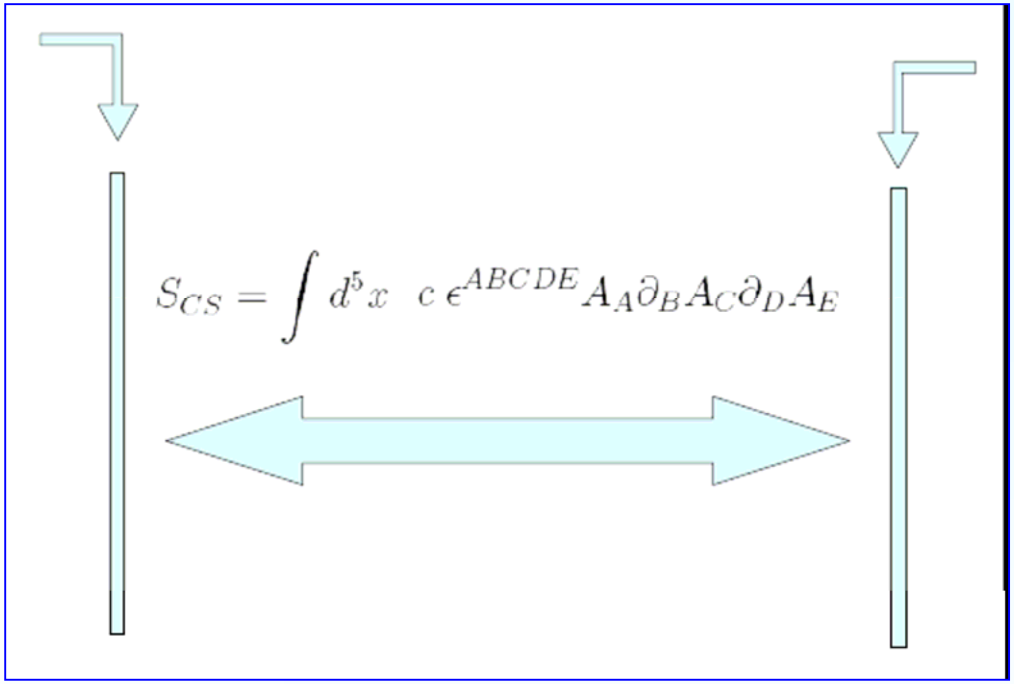
Anomaly inflow on branes

$$\int_I d^4x \, \overline{\psi}_L i \not{D}_L \psi_L$$



$$S_{CS} = \int d^5x \;\; c \, \epsilon^{ABCDE} A_A \partial_B A_C \partial_D A_E$$

$$\int_{II} d^4x \, \overline{\psi}_R i \not{D}_R \psi_R$$

Hill, Phys. Rev. D74 (2006)

$$A_A(x_\mu, y) \to A_A(x_\mu, y) + \partial_A \theta(x_\mu, y)$$

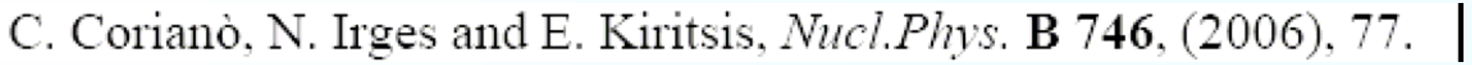
$$S_{CS} \;\to\; S_{CS} + \frac{c}{4} \int_{II} d^4x \, \theta(R) \, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}(R) - \frac{c}{4} \int_I d^4x \, \theta(0) \, \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}(0)$$

Resulting effective field theory

In all cases the resulting effective energy at low energy is the same

Particular vacua of string theory predict a low energy structure of the form

$$SU(3)\times SU(2)\times U(1)\times\ldots\times U(1)$$



C. Corianò, N. Irges and E. Kiritsis, *Nucl.Phys.* **B 746**, (2006), 77.

Where

- we have two different broken phases in the presence of a Stueckelberg term;
- the extra U(1)s are anomalous and broken;
- a linear combination of them is anomaly-free → hypercharge;
- number of anomalous U(1)s = number of axions = number of anomalous gauge bosons; the physical axion (axi-Higgs) is only ONE

This gauge structure extends the one of the SM

The Stueckelberg mechanism

It gives mass to an abelian gauge boson preserving the gauge invariance of the lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}M_1^2(B_\mu)^2 + \frac{1}{2}(\partial_\mu b)^2 - M_1 B_\mu \partial^\mu b$$

shift

Stueckelberg mass

$$\begin{aligned} b &\rightarrow b' = b - M\theta \\ B_\mu &\rightarrow B'_\mu = B_\mu + \frac{1}{M_1}\partial_\mu \theta. \end{aligned}$$

the axion is a Goldstone boson

The Stueckelberg shifts like the phase of a Higgs field

The two broken phases

These effective models have 2 broken phases

1) A Stueckelberg phase (the axion b is a Goldstone boson)
2) A Higgs-Stueckelberg phase (there is a Higgs-axion mixing if the Higgs is charged under the anomalous U(1))

Higgs field

$$\phi = \frac{1}{\sqrt{2}}\left(v + \phi_1 + i\phi_2\right),$$

Stueckelberg field

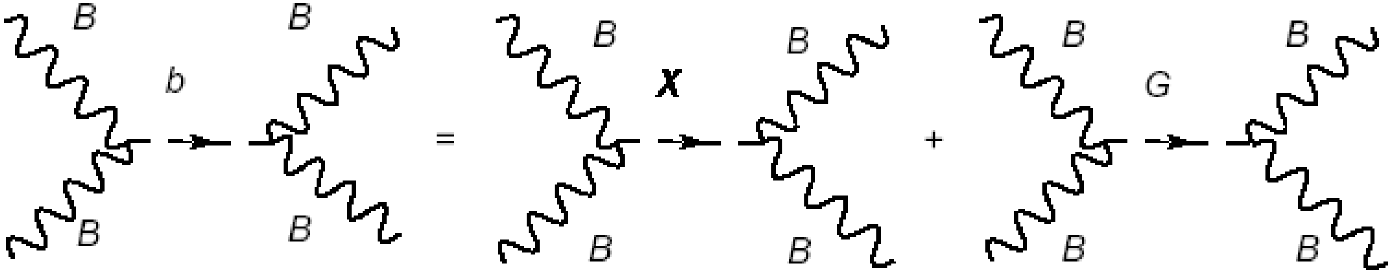
$$b = \alpha_1 \chi_B + \alpha_2 G_B = \frac{q_B g_B v}{M_B}\chi_B + \frac{M_1}{M_B}G_B,$$

Goldstone boson

Physical axion

Gauge boson mass

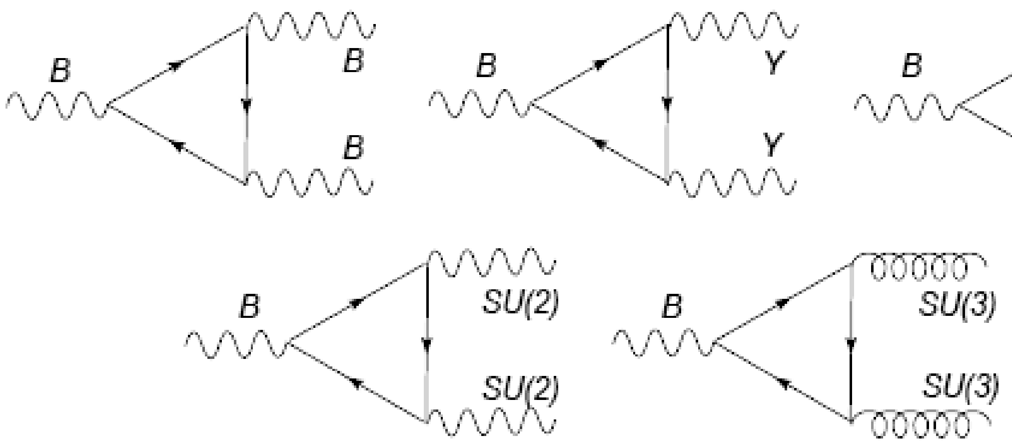
$$M_B = \sqrt{M_1^2 + (q_B g_B v)^2}.$$



Diagrams from the Green-Schwarz coupling after symmetry breaking.

Extension of the SM

- The gauge structure of our model is $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_B$
- ordinary anomaly cancellation for triangle diagrams also present in the SM
- Green-Schwarz mechanism for diagrams involving the anomalous $U(1)_B$
- Chern-Simons interactions to redistribute the total anomaly



Anomalous triangle diagrams in the non-abelian $U(1)_Y \times U(1)_B$.

The $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_B$ model

$$
\begin{aligned}
\mathcal{L} = & - \frac{1}{2}Tr\,[F^G_{\mu\nu}F^{G\mu\nu}] - \frac{1}{2}Tr[\,F^W_{\mu\nu}F^{W\,\mu\nu}] - \frac{1}{4}F^B_{\mu\nu}F^{B\mu\nu} - \frac{1}{4}F^Y_{\mu\nu}F^{Y\,\mu\nu} \\
& + \left|(\partial_\mu + ig_2\frac{\tau^j}{2}W^j_\mu + ig_Y q^Y_u A^Y_\mu + ig_B\frac{q^B_u}{2}B_\mu)H_u\right|^2 \\
& + \left|(\partial_\mu + ig_2\frac{\tau^j}{2}W^j_\mu + ig_Y q^Y_d A^Y_\mu + ig_B\frac{q^B_d}{2}B_\mu)H_d\right|^2 \\
& + \overline{Q}_{Li}\,i\gamma^\mu\left(\partial_\mu + ig_3\frac{\lambda^a}{2}G^a_\mu + ig_2\frac{\tau^j}{2}W^j_\mu + ig_Y q^{(Q_L)}_Y A^Y_\mu + ig_B q^{(Q_L)}_B B_\mu\right)Q_{Li} \\
& + \overline{u}_{Ri}\,i\gamma^\mu\left(\partial_\mu + ig_Y q^{(u_R)}_Y A^Y_\mu + ig_B q^{(u_R)}_B B_\mu\right)u_{Ri} + \overline{d}_{Ri}\,i\gamma^\mu\left(\partial_\mu + ig_Y q^{(d_R)}_Y A^Y_\mu + ig_B q^{(d_R)}_B B_\mu\right)d_{Ri} \\
& + \overline{L}_i\,i\gamma^\mu\left(\partial_\mu + ig_2\frac{\tau^j}{2}W^j_\mu + ig_Y q^{(L)}_Y A^Y_\mu + ig_B q^{(L)}_B B_\mu\right)L_i \\
& + \overline{e}_{Ri}\,i\gamma^\mu\left(\partial_\mu + ig_Y q^{(e_R)}_Y A^Y_\mu + ig_B q^{(e_R)}_B B_\mu\right)e_{Ri} + \overline{\nu}_{Ri}\,i\gamma^\mu\left(\partial_\mu + ig_Y q^{(\nu_R)}_Y A^Y_\mu + ig_B q^{(\nu_R)}_B B_\mu\right)\nu_{Ri} \\
& - \Gamma^d\,\overline{Q}_L H_d d_R - \Gamma^u\,\overline{Q}_L(i\sigma_2 H^*_u)u_R + c.c. \\
& - \Gamma^e\,\overline{L}H_d e_R - \Gamma^\nu\,\overline{L}(i\sigma_2 H^*_u)\nu_R + c.c. \\
& + \frac{1}{2}(\partial_\mu b + M_1 B_\mu)^2 \\
& + \frac{C_{BB}}{M}bF_B \wedge F_B + \frac{C_{YY}}{M}bF_Y \wedge F_Y + \frac{C_{YB}}{M}bF_Y \wedge F_B \\
& + \frac{F}{M}bTr[F^W \wedge F^W] + \frac{D}{M}bTr[F^G \wedge F^G] \\
& + d_1 BY \wedge F_Y + d_2 YB \wedge F_B + c_1\epsilon^{\mu\nu\rho\sigma}B_\mu C^{SU(2)}_{\nu\rho\sigma} + c_2\epsilon^{\mu\nu\rho\sigma}B_\mu C^{SU(3)}_{\nu\rho\sigma} \\
& + V(H_u, H_d, b), \qquad (1)
\end{aligned}
$$

SM

The potential $V(H_u, H_d, b)$

$$V(H_u, H_d, b) = V_{PQ} + V_{\not{P}\,\not{Q}}$$

$$\begin{aligned} V_{PQ} &= \sum_{a=u,d} \left[\mu_a^2 H_a^\dagger H_a + \lambda_{aa} (H_a^\dagger H_a)^2 \right] \\ &- 2\lambda_{ud} (H_u^\dagger H_u)(H_d^\dagger H_d) + 2\lambda'_{ud} |H_u^T \tau_2 H_d|^2 \end{aligned}$$

$$\begin{aligned} V_{\not{P}\,\not{Q}} &= b_1 \left(H_u^\dagger H_d \, e^{-i(q_u^B - q_d^B)\frac{b}{M_1}} \right) + \lambda_1 \left(H_u^\dagger H_d \, e^{-i(q_u^B - q_d^B)\frac{b}{M_1}} \right)^2 \\ &+ \lambda_2 (H_u^\dagger H_u) \left(H_u^\dagger H_d \, e^{-i(q_u^B - q_d^B)\frac{b}{M_1}} \right) \\ &+ \lambda_3 \left(H_d^\dagger H_d \right) \left(H_u^\dagger H_d \, e^{-i(q_u^B - q_d^B)\frac{b}{M_1}} \right) + c.c.. \end{aligned}$$

mass squared dimension

dimensionless

After electroweak spontaneous symmetry breaking

Rotation matrix from the interaction basis to the mass basis for the CP-odd neutral sector

$$\begin{pmatrix} \mathrm{Im} H_u^0 \\ \mathrm{Im} H_d^0 \\ b \end{pmatrix} = O^{\chi} \begin{pmatrix} \chi \\ G_1^0 \\ G_2^0 \end{pmatrix}$$

$$\begin{aligned} m_\chi^2 &= -\frac{1}{2} c_\chi \, v^2 \left[1 + \left(\frac{q_u^B - q_d^B}{M_1} \frac{v \sin 2\beta}{2} \right)^2 \right] \\ &= -\frac{1}{2} c_\chi \, v^2 \left[1 + \frac{(q_u^B - q_d^B)^2}{M_1^2} \frac{v_u^2 v_d^2}{v^2} \right], \end{aligned}$$

$$\tan\beta = \frac{\sin\beta}{\cos\beta} = \frac{v_u}{v_d}$$

$$c_\chi = 4 \left(4\lambda_1 + \lambda_3 \cot\beta + \frac{b_1}{v^2} \frac{2}{\sin 2\beta} + \lambda_2 \tan\beta \right)$$

The physical axi-Higgs can be massless or massive whether it is part of the scalar potential or not. In the second case its mass is related to the parameters of the PQ symmetry breaking potential.

After electroweak spontaneous symmetry breaking

$$\begin{pmatrix} A_\gamma \\ Z \\ Z' \end{pmatrix} = O^A \begin{pmatrix} W_3 \\ A^Y \\ B \end{pmatrix}$$

$$O^A \simeq \begin{pmatrix} \frac{g_Y}{g} & \frac{g_2}{g} & 0 \\ \frac{g_2}{g} + O(\epsilon_I^2) & -\frac{g_Y}{g} + O(\epsilon_I^2) & \frac{g}{2}\epsilon_I \\ -\frac{g_2}{2}\epsilon_I & \frac{g_Y}{2}\epsilon_I & 1 + O(\epsilon_I^2) \end{pmatrix}.$$

SM-like

$$\begin{aligned} m_Z^2 &= \frac{1}{8}\left(2M_I^2 + g^2v^2 + N_{BB} - \sqrt{\left(2M_I^2 - g^2v^2 + N_{BB}\right)^2 + 4g^2x_B^2}\right) \\ &\simeq \frac{g^2v^2}{4} - \frac{1}{M_I^2}\frac{g^2x_B^2}{8} + \frac{1}{M_I^4}\frac{g^2x_B^2}{16}(N_{BB} - g^2v^2), \end{aligned}$$

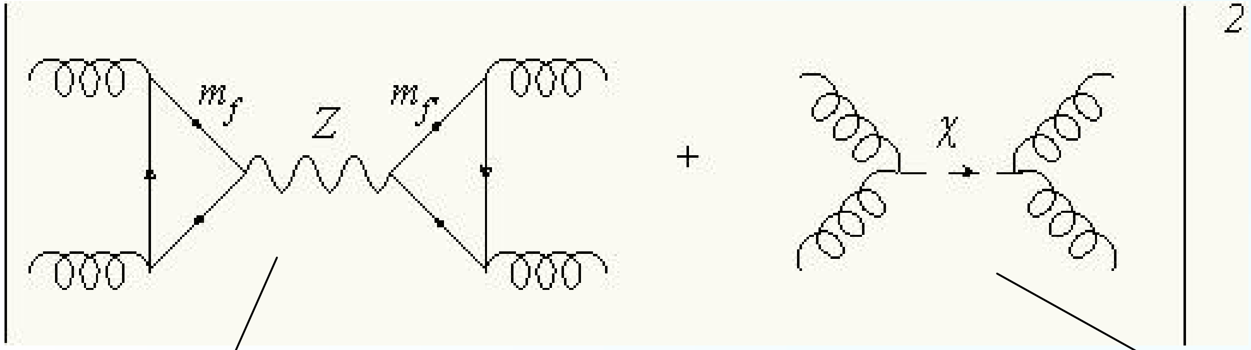
1/M

$$\begin{aligned} m_{Z'}^2 &= \frac{1}{8}\left(2M_I^2 + g^2v^2 + N_{BB} + \sqrt{\left(2M_I^2 - g^2v^2 + N_{BB}\right)^2 + 4g^2x_B^2}\right) \\ &\simeq \frac{1}{2}M_I^2 + \frac{1}{4}N_{BB}. \end{aligned}$$

O(M)

Unitarity bounds on the model

We consider this process with $m_f = m_{f'} = 0$



$$\sigma_1(s) \propto \frac{s^2}{M_Z^4}$$

$$\sigma_2(s) \propto \frac{s^2}{M_Z^2 M_I^2}$$

Interference term

$$\sigma_3(s) \propto \frac{s^2}{M_I^4}$$

The Froissart bound is a consequence of the unitarity of the S-matrix and states that total cross sections cannot grow faster than $\ln^2 s$ as $s \to \infty$.

By imposing it we obtain a constraint for the gauge couplings of the model.

Conclusions

- this class of models show an important connection between cosmology and particle physics;
- in these models the axion is fundamental in the cancellation of the gauge-dependence and of anomalies;
- the extra neutral currents could be seen at LHC;

Extra slides

Gauge sector

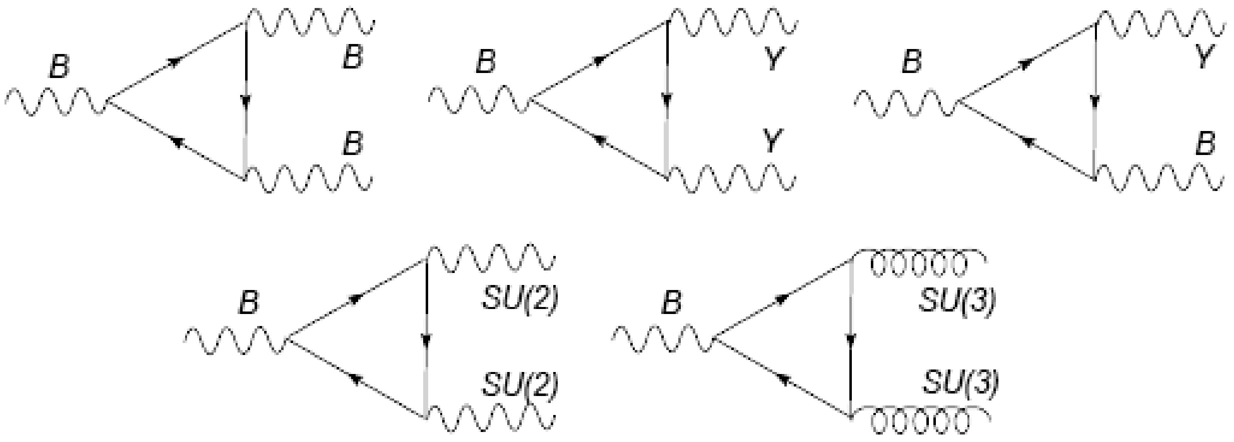
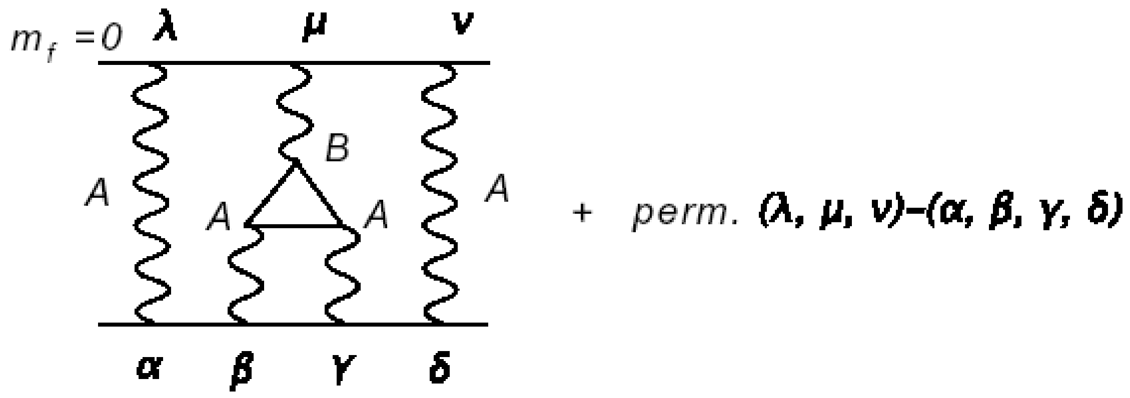


Figure 22: Anomalous triangle diagrams in the non-abelian $U(1)_Y \times U(1)_B$.

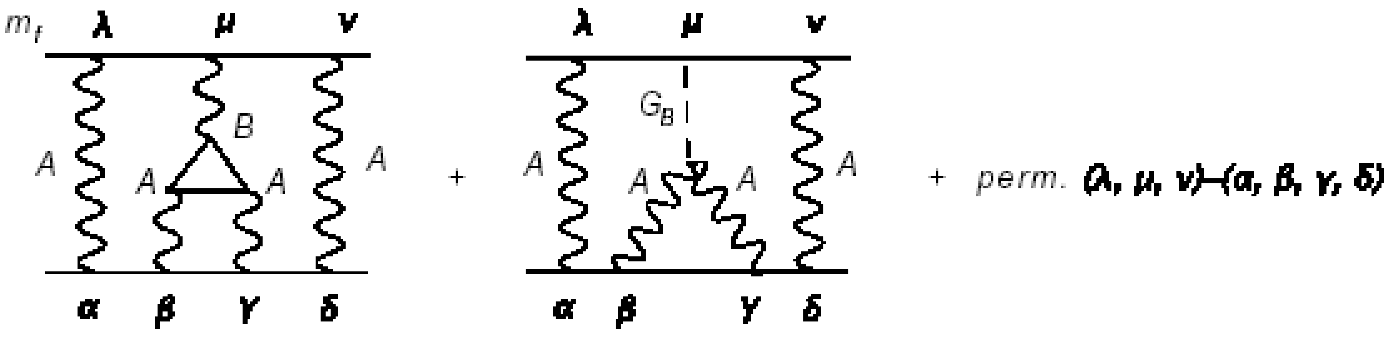
$$
\begin{aligned}
\mathcal{S}_{eff} &= \mathcal{S}_{ab} + \mathcal{S}_{non-ab} \\
&= \int dxdydz \Bigg(\frac{1}{2!} T^{\lambda\mu\nu}_{BSU(2)SU(2)}(z,x,y) B^{\lambda}(z) W^{\mu}(x) W^{\nu}(y) \\
&\quad + \frac{1}{2!} T^{\lambda\mu\nu}_{BSU(3)SU(3)}(z,x,y) B^{\lambda}(z) G^{\mu}(x) G^{\nu}(y) + \frac{1}{3!} T^{\lambda\mu\nu}_{BBB}(z,x,y) B^{\lambda}(z) B^{\mu}(x) B^{\nu}(y) \\
&\quad \frac{1}{2!} T^{\lambda\mu\nu}_{BYY}(z,x,y) B^{\lambda}(z) Y^{\mu}(x) Y^{\nu}(y) + \frac{1}{2!} T^{\lambda\mu\nu}_{YBB}(z,x,y) Y^{\lambda}(z) B^{\mu}(x) B^{\nu}(y) \Bigg) \qquad (308)
\end{aligned}
$$

Checks in the fermionic sector

These are the typical classes of diagrams one needs to worry about



Anomaly in the t-channel



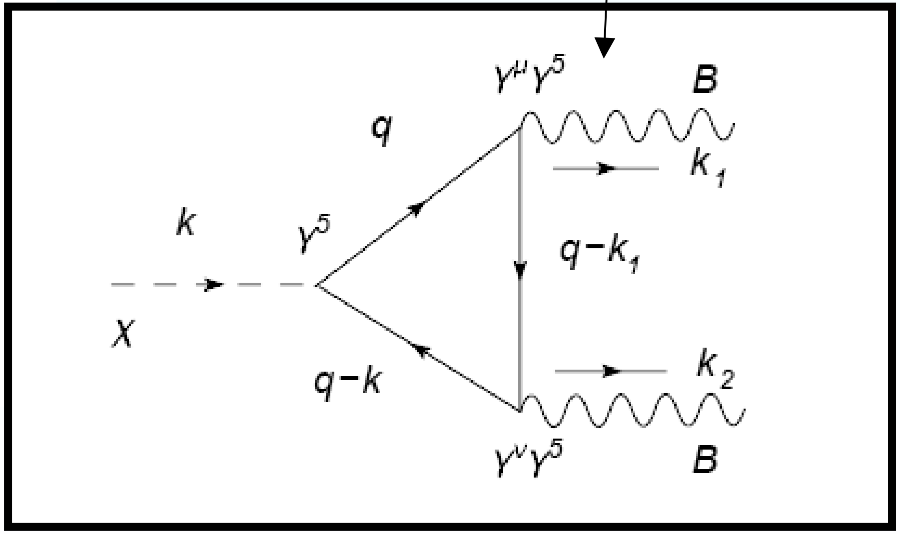
(A) (B)

Some properties of the axi-Higgs: Yukawa couplings

$$
\begin{aligned}
H_u &= \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} H_u^+ \\ v_u + \frac{H^0_{uR}+iH^0_{uI}}{\sqrt{2}} \end{pmatrix} \\
&= \begin{pmatrix} \frac{G^+ \sin\beta - H^+ \cos\beta}{\sqrt{2}} \\ v_u + \frac{(h^0 \sin\alpha - H^0 \cos\alpha) + i(O^\chi_{11}\chi + O^\chi_{12}G^0_1 + O^\chi_{13}G^0_2)}{\sqrt{2}} \end{pmatrix},
\end{aligned}
$$

$$
\begin{aligned}
-\mathcal{L}^{unit.}_{\mathrm{Yuk}} &= m_d \overline{d} d + \left[\Gamma^d \overline{d}_L d_R \left(i\frac{N \sin\beta}{\sqrt{2}}\chi\right) + c.c. \right] \\
&+ m_u \overline{u} u + \left[\Gamma^u \overline{u}_L u_R \left(i\frac{N \cos\beta}{\sqrt{2}}\chi\right) + c.c. \right] \\
&+ m_e \overline{e} e + \left[\Gamma^e \overline{e}_L e_R \left(i\frac{N \sin\beta}{\sqrt{2}}\chi\right) + c.c. \right] \\
&+ m_\nu \overline{\nu} \nu + \left[\Gamma^\nu \overline{\nu}_L \nu_R \left(i\frac{N \cos\beta}{\sqrt{2}}\chi\right) + c.c. \right]
\end{aligned}
$$

Induces the decay of the Axi-Higgs, similar to Higgs decay



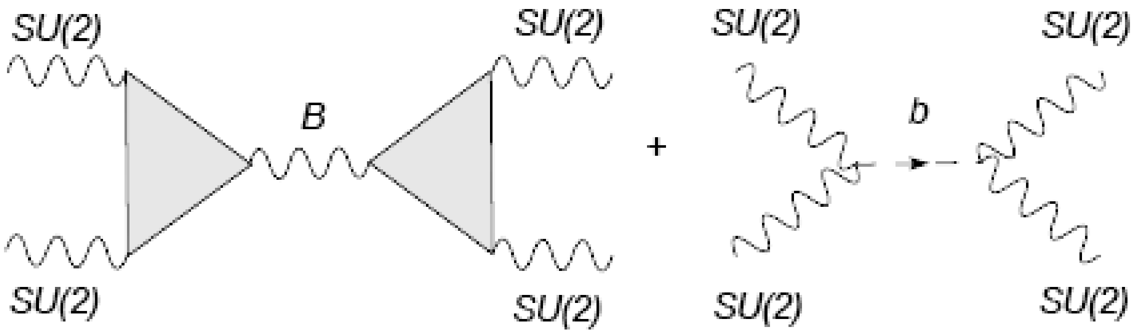


Figure 23: Unitarity check in SU(2) sector for the MLSOM.

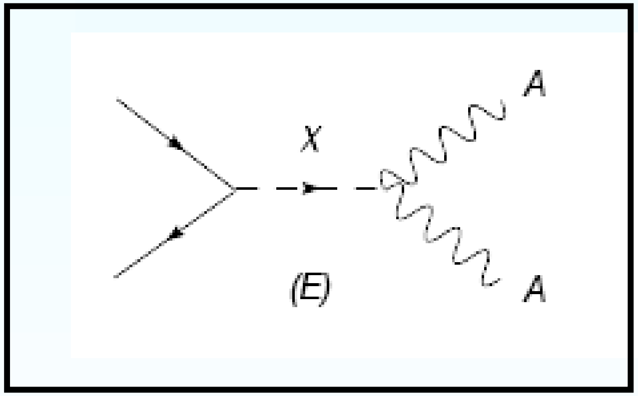
Moving to the broken phase, the axion has to be rotated into its physical component, the Axi-Higgs and the Goldstones

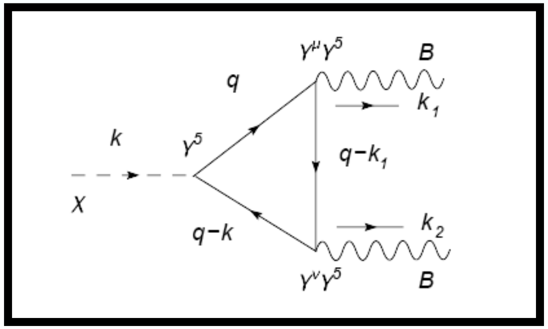
$$
\begin{aligned}
b &= \boldsymbol{\Theta}\,\chi + \sum_{i=1}^{2} c_i G_i^0 = \boldsymbol{\Theta}\,\chi + c_1 G_1^0 + c_2 G_2^0 \\
&= O^{\chi}_{31}\chi + O^{\chi}_{32} G_1^0 + O^{\chi}_{33} G_2^0
\end{aligned}
$$

$$
\boldsymbol{\Theta} = O^{\chi}_{31} = -\frac{q_u^B - q_d^B}{2}\frac{v}{M_1} N \sin 2\beta = -(q_u^B - q_d^B)\frac{v}{M_1} N \sin\beta\cos\beta
$$

$$
\begin{aligned}
& \left[\Gamma^{d}\overline{d}_L d_R\left(i\frac{N\sin\beta}{\sqrt{2}}\chi\right)+\Gamma^{u}\overline{u}_L u_R\left(i\frac{N\cos\beta}{\sqrt{2}}\chi\right)+\Gamma^{e}\overline{e}_L e_R\left(i\frac{N\sin\beta}{\sqrt{2}}\chi\right)\right.\\
+ \quad & \left.\Gamma^{\nu}\overline{\nu}_L \nu_R\left(i\frac{N\cos\beta}{\sqrt{2}}\chi\right)+c.c.\right]\\
+ \quad & \partial_\mu\chi\,\partial^\mu\chi+g^{\chi gg}\,\chi\,tr\,\{G\wedge G\}+g^{\chi+-}\,\chi\,tr\,\{W^{+}\wedge W^{-}\}+g^{\chi}_{\overline{p}\overline{q}}\,\chi\,F^{\overline{p}}\wedge F^{\overline{q}}.
\end{aligned}
$$

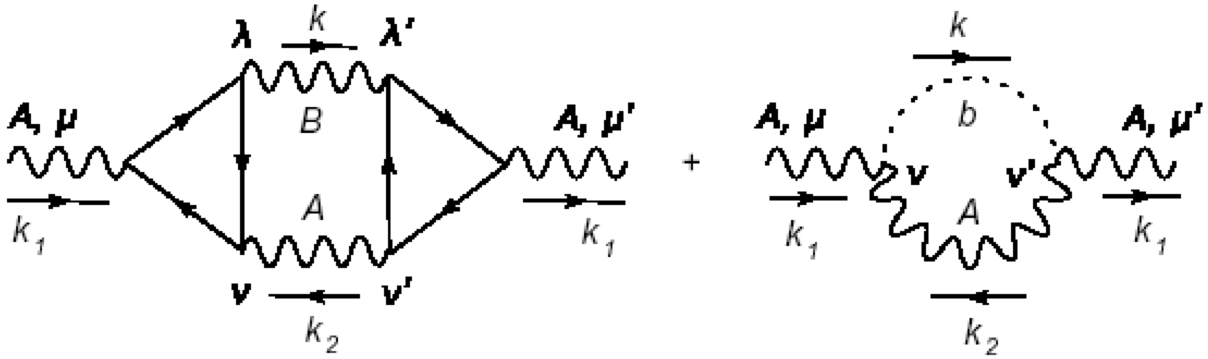
Direct coupling to gauge fields





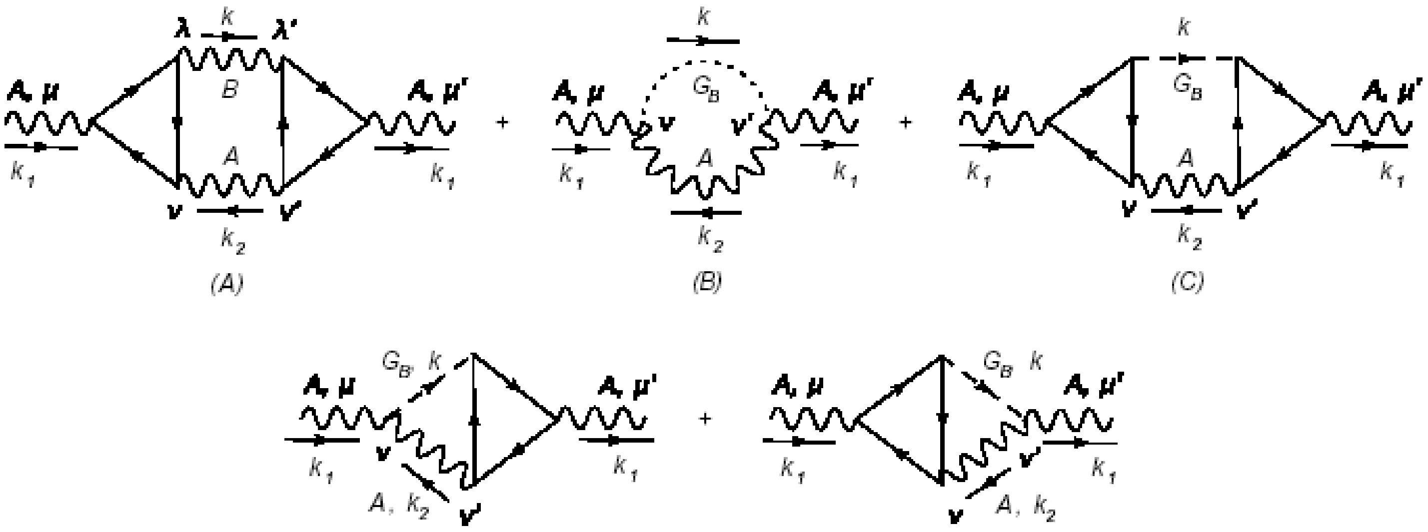
Check of gauge independence in the two phases(3 loop)

In the Stueckelberg phase: cured by the axion b



(A) (B)

In the HS phase: cured by the Goldstone G_B



(A) (B) (C)

(D) (E)

Simple example: $U(1)_A \times U(1)_B \times U(1)_C$

anomalous

Higgs field $$\phi = \frac{1}{\sqrt{2}}\left(v + \phi_1 + i\phi_2\right).$$

$$\begin{aligned}\mathcal{L}_q &= \frac{1}{2}\left(\partial_\mu\phi_1\right)^2 + \frac{1}{2}\left(\partial_\mu\phi_2\right)^2 + \frac{1}{2}\left(\partial_\mu b\right)^2 + \frac{1}{2}\left(\partial_\mu c\right)^2 + \frac{1}{2}\left(M_1^2 + (2v)^2\right)B_\mu^2 \\ &+\frac{1}{2}M_C^2 C_\mu^2 + B_\mu\partial_\mu\left(M_1 b + 2v\phi_2\right) + M_C C^\mu \partial_\mu c - \frac{1}{2}m_h^2\phi_1^2\end{aligned}$$

b, c are Stueckelberg axions

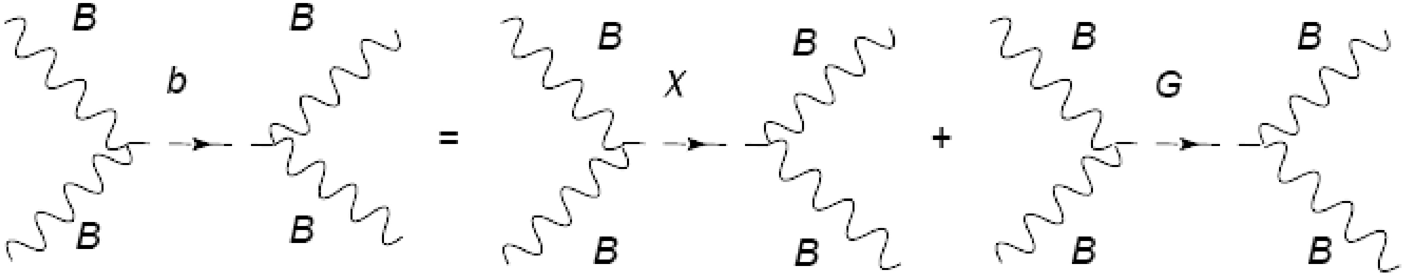
from which, after diagonalization of the mass terms we obtain

$$\begin{aligned}\mathcal{L}_q &= \frac{1}{2}\left(\partial_\mu\chi\right)^2 + \frac{1}{2}\left(\partial_\mu G\right)^2 + \frac{1}{2}\left(\partial_\mu h\right)^2 + \frac{1}{2}\left(\partial_\mu c\right)^2 + \frac{1}{2}M_B^2 B_\mu^2 \\ &+\frac{1}{2}M_C^2 C_\mu^2 + M_B B^\mu \partial_\mu G + M_C C^\mu \partial_\mu c - \frac{1}{2}m_h^2 h^2\end{aligned}$$

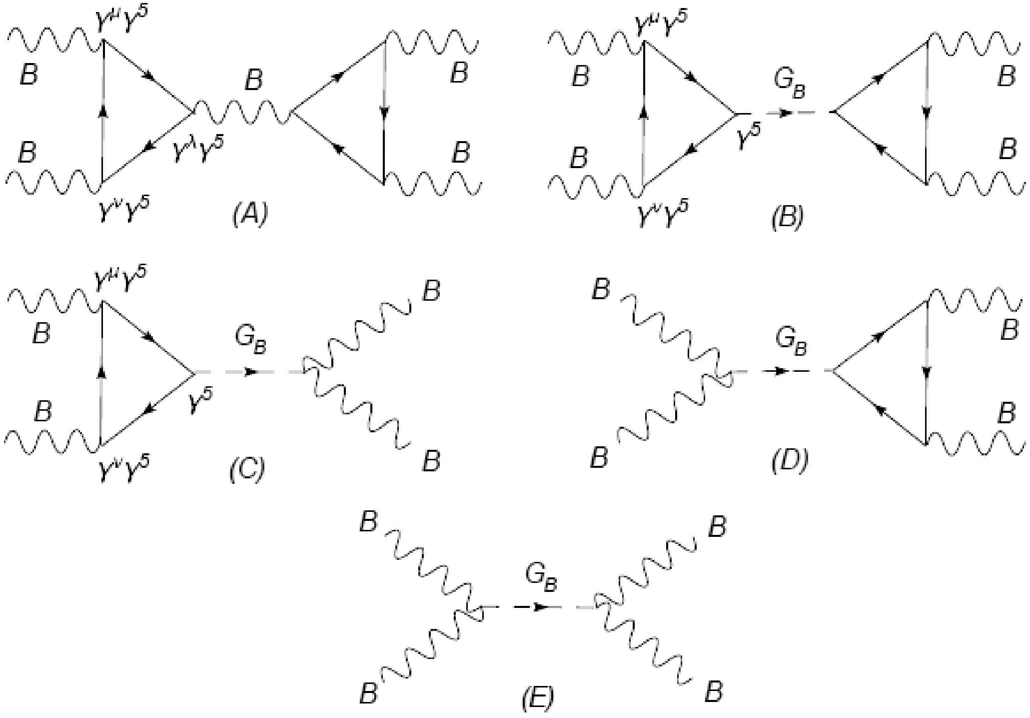
where we have redefined $\phi_1(x) = h(x)$ and $m_h = \sqrt{2\lambda}v$ for the Higgs field and its mass and we have identified the two linear combinations

physical axion → $$\chi = \frac{1}{M_B}\left(-M_1\phi_2 + 2vb\right)$$

Goldstone boson → $$G = \frac{1}{M_B}\left(2v\phi_2 + M_1 b\right)$$



$$
\begin{aligned}
k_{1\mu}\Delta^{\lambda\mu\nu}(\beta',k_1,k_2) &= a_1(\beta)\varepsilon^{\lambda\nu\alpha\beta}k_1^\alpha k_2^\beta + 2m_f\Delta^{\lambda\nu},\\
k_{2\nu}\Delta^{\lambda\mu\nu}(\beta',k_1,k_2) &= a_1(\beta)\varepsilon^{\lambda\mu\alpha\beta}k_2^\alpha k_1^\beta + 2m_f\Delta^{\lambda\mu},\\
k_{\lambda}\Delta^{\lambda\mu\nu}(\beta',k_1,k_2) &= a_3(\beta)\varepsilon^{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta + 2m_f\Delta^{\mu\nu},
\end{aligned}
$$



The coefficients of the counterterms

$$C_{BB} = \frac{M}{M_1}\frac{i g_B^3}{3!} a_n D_{BBB},$$

$$C_{YY} = \frac{M}{M_1} i g_B g_Y^2 \frac{a_n}{2} D_{BYY},$$

$$C_{YB} = \frac{M}{M_1} i g_Y g_B^2 \frac{a_n}{2} D_{YBB}.$$

$$F = \frac{M}{M_1} i g_B g_2^2 \frac{a_n}{2} D_B^{(L)}, \qquad D = \frac{M}{M_1} i g_B g_3^2 \frac{a_n}{2} D_B^{(L)}.$$

$$c_1 = -i g_B g_2^2 \frac{2}{3} a_n D_B^{(L)}, \qquad c_2 = -i g_B g_3^2 \frac{2}{3} a_n D_B^{(L)}.$$

$$d_1 = -i g_B g_Y^2 \frac{2}{3} a_n D_{BYY}, \qquad d_2 = i g_Y g_B^2 \frac{a_n}{3} D_{YBB}.$$

Momentum shifts in the loop generate linear terms in the independent momenta

$$\Delta^{\lambda\mu\nu}(\beta', k_1, k_2) = \Delta^{\lambda\mu\nu}(\beta, k_1, k_2) + \frac{i\beta'}{4\pi^2}\varepsilon^{\lambda\mu\nu\sigma}(k_1 - k_2)_\sigma$$

$$\begin{aligned}
k_{1\mu}\Delta^{\lambda\mu\nu}(\beta', k_1, k_2) &= (a_1 + \frac{i\beta'}{4\pi^2})\varepsilon^{\lambda\nu\alpha\beta}k_1^\alpha k_2^\beta, \\
k_{2\nu}\Delta^{\lambda\mu\nu}(\beta', k_1, k_2) &= (a_2 + \frac{i\beta'}{4\pi^2})\varepsilon^{\lambda\mu\alpha\beta}k_2^\alpha k_1^\beta, \\
k_\lambda\Delta^{\lambda\mu\nu}(\beta', k_1, k_2) &= (a_3 - \frac{i\beta'}{2\pi^2})\varepsilon^{\mu\nu\alpha\beta}k_1^\alpha k_2^\beta.
\end{aligned}$$

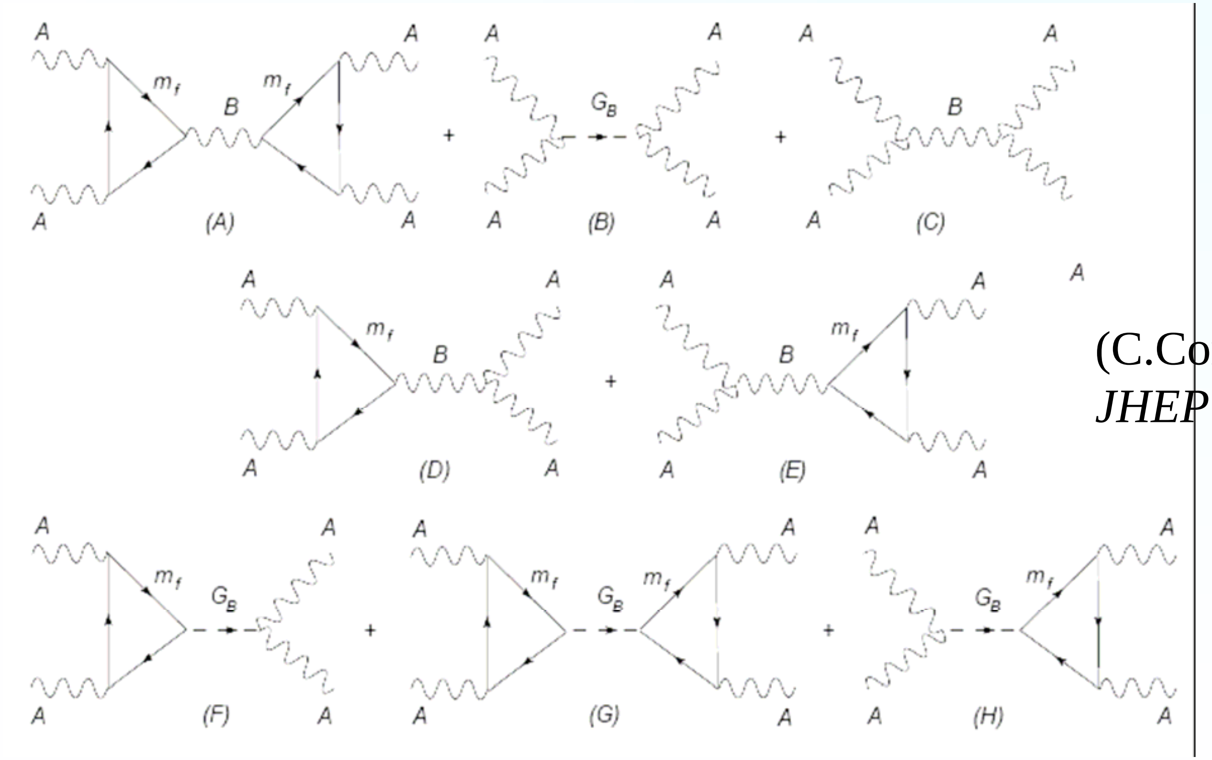
redistribute
the anomaly.
Their sum is fixed

$$\begin{aligned}
\Delta_{\underline{\lambda}\mu\nu} + \Delta_{\underline{\lambda}\nu\mu} &= (\hat{a}_1 - \hat{a}_2)\epsilon[k_1, \mu, \nu, \lambda] + (a_2 - a_1)\epsilon[k_2, \mu, \nu, \lambda] \\
&\quad + (\hat{a}_3 - \hat{a}_6)\epsilon[k_1, k_2, \mu, \lambda]k_1{}^\nu + (\hat{a}_4 - \hat{a}_5)\epsilon[k_1, k_2, \mu, \lambda]k_2^\nu \\
&\quad + (\hat{a}_5 - \hat{a}_4)\epsilon[k_1, k_2, \nu, \lambda]k_1^\mu + (\hat{a}_6 - \hat{a}_3)\epsilon[k_1, k_2, \nu, \lambda]k_2^\mu \\
&= \underline{a}_1\epsilon[k_1, \mu, \nu, \lambda] + \underline{a}_2\epsilon[k_2, \mu, \nu, \lambda] + \underline{a}_3\epsilon[k_1, k_2, \mu, \lambda]k_1{}^\nu \\
&\quad + \underline{a}_4\epsilon[k_1, k_2, \mu, \lambda]k_2{}^\nu + \underline{a}_5\epsilon[k_1, k_2, \nu, \lambda]k_1^\mu + \underline{a}_6\epsilon[k_1, k_2, \nu, \lambda]k_2^\mu
\end{aligned}$$

These two invariant amplitudes correspond to CS interactions and can be defined by external Ward Identities. In the Standard Model one chooses VC, but this is not necessary because of traceless conditions on the anomalies

Anomaly cancellation and renormalizability

- SM is anomaly-free by charge assignment
- the Green-Schwarz mechanism in string theory invokes an axion
- the presence of the 5D operator $\frac{1}{M}\phi F\tilde{F}$ renders the theory non-renormalizable, but for the rest unitary



(C.Corianò, N.Irges, S.Morelli, *JHEP* 0707:008, 2007)

Conclusioni e sviluppi futuri

- la presenza di campi assionici in teorie effettive è indicazione di un diverso meccanismo di cancellazione delle anomalie di gauge;
- la determinazione dei coefficienti dei controtermini introdotti può essere effettuata mediante opportune identità di Slavnov-Taylor;
- nell’estensione del Modello Standard analizzata compare un bosone extra aggiuntivo e accoppiamenti anomali;
- il calcolo delle sezioni d’urto per particolari processi testabili presso LHC è tuttora in corso.

The axion in the Green-Schwarz terms (AB model case) 2

The gauge variations are

$$
\begin{aligned}
\delta_B \mathcal{L}_{an} &= \frac{i g_B g_A^2}{2!} a_3(\beta) \frac{1}{4} F_A \wedge F_A \theta_B + \frac{i g_B^3}{3!} \frac{a_n}{3} \frac{3}{4} F_B \wedge F_B \theta_B \\
\delta_A \mathcal{L}_{an} &= \frac{i g_B g_A^2}{2!} a_1(\beta) \frac{2}{4} F_B \wedge F_A \theta_A
\end{aligned}
$$

The axion b in the Green-Schwarz terms

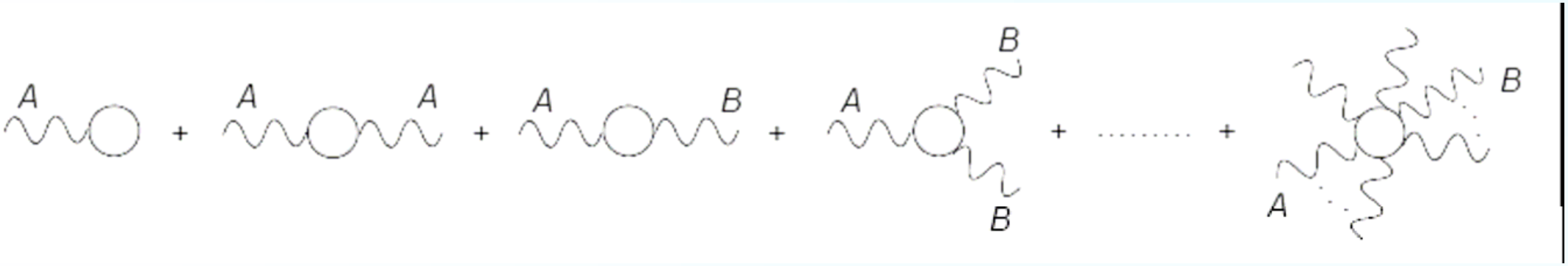
$$\mathcal{L}_b = \frac{C_{AA}}{M} b\, F_A \wedge F_A + \frac{C_{BB}}{M} b\, F_B \wedge F_B \Big|$$

Anomaly cancellation if and only if $\delta_A \mathcal{L}_{an} = 0$ and $\delta_B \left(\mathcal{L}_b + \mathcal{L}_{an} \right) = 0$

$$C_{AA} = \frac{i\, g_B g_A^2}{2!} \frac{1}{4} a_3(\beta_0) \left. \frac{M}{M_1} \right| \qquad C_{BB} = \frac{i g_B^3}{3!} \frac{1}{4} a_n \left. \frac{M}{M_1} \right|$$

The axion in the Green-Schwarz terms (AB model case) 1

AB model → $\boxed{U(1)_A \times U(1)_B}$



Anomalous effective action for the AB model $\mathcal{S}_{an} = \mathcal{S}_1 + \mathcal{S}_3$

$$\mathcal{S}_1 = \int dx\, dy\, dz \left(\frac{g_B\, g_A^2}{2!} T^{\lambda\mu\nu}_{\mathbf{AVV}}(x,y,z) B_\lambda(z) A_\mu(x) A_\nu(y) \right)$$

$$\mathcal{S}_3 = \int dx\, dy\, dz \left(\frac{g_B^3}{3!} T^{\lambda\mu\nu}_{\mathbf{AAA}}(x,y,z) B_\lambda(z) B_\mu(x) B_\nu(y) \right)$$

1) Intersecting Brane Models (orientifold construction)

2) I. Antoniadis

2) Extra dimensional models with anomalies on the branes and additional interactions in the bulk

(for instance 5D Chern-Simons)

3)Partial Decoupling of a chiral fermion

A brief discussion of these points is in
C. Corianò, M. Guzzi, R.A. arXiv 0709.2111…
More references
C.C