Enhanced Axion-Photon Coupling in GUT with Hidden Photon

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Fuminobu Takahashi, Masaki Yamada, N.Y. arXiv:1604.07145, PLB
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Motivations to go beyond the SM

- Dark matter
- Strong CP problem

\{ \text{Solved by QCD axion} \}

Unification of SM gauge couplings and charge quantization

The figure shows the RG running of the SM gauge couplings

In SM, the unification fails
Motivations to go beyond the SM

- Dark matter
- Strong CP problem

\{ \text{Solved by QCD axion} \}

Unification of SM gauge couplings and charge quantization

Moreover, it predicts too rapid proton decay

\[
\text{For } M_x = 10^{15}\text{GeV} \\
\approx 5 \times 10^{31} \text{ years (p } \rightarrow \pi^0 \text{ e}^+) \\
\text{exp: } > 1.7 \times 10^{34} \text{ years}
\]

[Takhistov, 2016]
Possible ways for unification

- Adding incomplete SU(5) multiplets

\begin{itemize}
  \item Supersymmetry
  \item Unbroken hidden U(1)_H symmetry, which mixies with U(1)_Y
\end{itemize}

[Redondo, 2008; Takahashi, Yamada, Yokozaki, 2016; Daido, Takahashi, Yokozaki, 2016, 2018]
A model with a hidden photon ($U(1)_H$ gauge boson)
Consider $U(1)_Y \times U(1)_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4} F'_Y^{\mu\nu} F'_Y{}_{\mu\nu} - \frac{1}{4} F'_H^{\mu\nu} F'_H{}_{\mu\nu} - \frac{\chi}{2} F'_Y^{\mu\nu} F'_H{}_{\mu\nu}$$

$$F'_i^{\mu\nu} \equiv \partial^\mu A'_i{}^\nu - \partial^\nu A'_i{}^\mu \ (i = Y, H)$$

[Holdom, 1986]
Consider $\text{U}(1)_Y \times \text{U}(1)_H$ model with a kinetic mixing

$$
\mathcal{L} = -\frac{1}{4} F'_Y F'_{Y \mu \nu} - \frac{1}{4} F'_H F'_{H \mu \nu} - \frac{\chi}{2} F'_Y F'_{H \mu \nu}
$$

$$
F'_{i \mu \nu} \equiv \partial^\mu A'_{i \nu} - \partial^\nu A'_{i \mu} \quad (i = Y, H)
$$

By the field redefinitions, we can go to the canonical basis

$$
A'_{Y \mu} = \frac{A'_{Y \mu}}{\sqrt{1 - \chi^2}}
$$

$$
A'_{H \mu} = A'_{H \mu} - \frac{\chi}{\sqrt{1 - \chi^2}} A'_{Y \mu}
$$

$$
\mathcal{L} = -\frac{1}{4} F^\mu \nu F_Y^\mu \nu - \frac{1}{4} F^\mu \nu F_H^\mu \nu
$$
Consider $U(1)_Y \times U(1)_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4} F'_{Y \mu \nu} F'_Y - \frac{1}{4} F'_{H \mu \nu} F'_H - \frac{\chi}{2} F'_{Y \mu \nu} F'_{H \mu \nu}$$

$$F'_{i \mu \nu} \equiv \partial^\mu A'_{i \nu} - \partial^\nu A'_{i \mu} \quad (i = Y, H)$$

Let's consider a matter field charged only under $U(1)_H$

$$\bar{\Psi}_i \gamma_\mu (g'_H q_{H i} A'_{H \mu}) \Psi_i$$

$$= \bar{\Psi}_i \gamma_\mu \left( -\frac{q_{H i} g_H \chi}{\sqrt{1 - \chi^2}} A^\mu_Y + g_H q_{H i} A^\mu_H \right) \Psi_i$$

The hidden matter obtains fractional $U(1)_Y$ charge in the canonical basis
Consider $\text{U}(1)_Y \times \text{U}(1)_H$ model with a kinetic mixing

$$\mathcal{L} = -\frac{1}{4} F'_{\mu \nu} F'_{\mu \nu} - \frac{1}{4} F'_{\mu \nu} F'_{\mu \nu} - \frac{\chi}{2} F'_{\mu \nu} F'_{\mu \nu}$$

$$F'_{i \mu \nu} \equiv \partial^\mu A'_i^\nu - \partial^\nu A'_i^\mu \ (i = Y, H)$$

Let's consider a matter field charged only under $\text{U}(1)_Y$

$$\bar{\Psi}_i \gamma_\mu (g'_Y Q_i A'_Y^\mu) \Psi_i$$

$$= \bar{\Psi}_i \gamma_\mu \left( \frac{g'_Y}{\sqrt{1 - \chi^2}} Q_i A_Y^\mu \right) \Psi_i$$

$$= \bar{\Psi}_i \gamma_\mu (g_Y Q_i A_Y^\mu) \Psi_i$$

The visible matter does not couple to $\text{U}(1)_H$

The normalization of $\text{U}(1)_Y$ coupling changes
Consider $\text{U}(1)_Y \times \text{U}(1)_H$ model with a kinetic mixing

\[ \mathcal{L} = -\frac{1}{4} F_Y^{'\mu\nu} F_Y^{\mu\nu} - \frac{1}{4} F_H^{'\mu\nu} F_H^{\mu\nu} - \frac{\chi}{2} F_Y^{'\mu\nu} F_H^{\mu\nu} \]

\[ F_i^{'\mu\nu} \equiv \partial^\mu A_i^{'\nu} - \partial^\nu A_i^{'\mu} \quad (i = Y, H) \]

The gauge couplings in the two bases are related as

<table>
<thead>
<tr>
<th>$g_Y$</th>
<th>$g_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_Y$</td>
<td>$g_H$</td>
</tr>
</tbody>
</table>

\[ = \frac{g_Y'}{\sqrt{1 - \chi^2}} = g_H' \]

observed
value

couplings in the canonical basis
Grand unification with $U(1)_H$
Without matter fields

\[ \alpha_1'^{-1}(\chi=0) \]

\[ \alpha_1'^{-1}(\chi=0.4) @ m_Z \]

\[ \alpha_2^{-1} \]

\[ \alpha_3^{-1} \]

\[ Q [\text{GeV}] \]

With one-loop RGEs

\[ \alpha_1'^{-1} = \left( \frac{\alpha_1}{1 - \chi^2} \right)^{-1}_\text{canonical} \]

[J. Redondo, 2008]
Case with a hidden matter which is a singlet of SU(5)

\[ \mathcal{L} = -\frac{1}{4} F'_\mu \nu F'^{\mu \nu} - \frac{1}{4} F'_{H \mu \nu} F'_{H \mu \nu} - \frac{\chi}{2} F'_{H \mu \nu} F'^{\mu \nu} \]

\[ -M_0 \bar{\Psi}_0 \Psi_0 \]

1 TeV \quad q_H(\Psi_0) = 1

one-loop RGEs are

\[ \frac{d g_Y'}{dt} = \frac{1}{16\pi^2} \left( \frac{41}{6} \right) g_Y'^3, \]

\[ \frac{d g_2}{dt} = \frac{1}{16\pi^2} \left( -\frac{19}{6} \right) g_2^3, \]

\[ \frac{d g_3}{dt} = \frac{1}{16\pi^2} \left( -7 \right) g_3^3 \]

\[ \frac{d g_H}{dt} = \frac{1}{16\pi^2} \left( \frac{4}{3} \right) g_H^3 \]
Running of the gauge couplings

\[ \alpha_1'^{-1} = \left( 1 - \chi^2 \right) \frac{5 g_Y^2}{3} \frac{1}{4\pi} \]

\[ g_H = 1.1, \chi = 0.365 \]

green dashed: one-loop
black solid: two-loop
Running of the gauge couplings

$$\alpha_1^{-1} = \left[ (1 - \chi^2) \frac{5 g_Y^2}{3} \frac{3}{4\pi} \right]^{-1}$$

Unification is insensitive to $g_H$
(we check it by changing $g_H=10^{-4}$ to 1.0)

It depends only on $\chi$ (mZ)

green dashed: one-loop
black solid: two-loop
With SU(5) multiplets charged under U(1)$_H$

\[ \mathcal{L} = -M_V \sum_{i=1}^{N_b} \left( \bar{\Psi}_{L,i} \Psi_{L,i} + \bar{\Psi}_{D,i} \Psi_{D,i} \right), \]

\( \Psi_{L,i} (\Psi_{D,i}) \) is 2 of SU(2)$_L$ (3 of SU(3)$_C$);

\((Q_{L,i}, q_{H_{L,i}}) = (-1/2, 1)\) and \((Q_{D,i}, q_{H_{D,i}}) = (1/3, 1)\).

one-loop RGEs are

\[ \frac{dg'_Y}{dt} = \frac{1}{16\pi^2} \left( \frac{41}{6} + \frac{10}{9} N_b \right) g_Y^3, \quad \frac{dg_H}{dt} = \frac{1}{16\pi^2} \left( \frac{20}{3} N_b \right) g_H^3 \]

\[ \frac{dg_2}{dt} = \frac{1}{16\pi^2} \left( -\frac{19}{6} + \frac{2}{3} N_b \right) g_2^3, \]

\[ \frac{dg_3}{dt} = \frac{1}{16\pi^2} \left( 7 + \frac{2}{3} N_b \right) g_3^3, \]

and two-loop corrections...
\( M_V = 1 \text{ TeV} \)

\( M_V = 10^{10} \text{ GeV} \)

(Again, the unification depends only on \( \chi (m_Z) \))
A GUT axion model

Setup

\[ \mathcal{L} = - \left[ \sqrt{2} \phi ( \bar{\psi}_{5L} \psi_{5R} + \bar{\psi}_{HL} \psi_{HR}) + h.c. \right] \]

- PQ breaking field including axion
- SU(5) complete multiplet
- Hidden matter with charge of \( q_H \)

\[ \phi = \frac{v_{PQ} + \rho(x)}{\sqrt{2}} \exp \left( \frac{i a(x)}{v_{PQ}} \right) \quad f_a = \frac{v_{PQ}}{N_{DW}} = v_{PQ} \]

\( \phi \) contains the axion in its phase component
A GUT axion model

Setup

\[ \mathcal{L} \supset - \sqrt{2} \phi (\bar{\psi}_5^L \psi_5^R + \bar{\psi}_H^L \psi_H^R) + h.c. \]

- PQ breaking field including axion
- SU(5) complete multiplet
- Hidden matter with charge of \( q_H \)

In the canonical basis, hidden matter gets an effective electric charge:

\[ q_{\text{eff}} = -q_H \frac{\chi}{\sqrt{1 - \chi^2}} \frac{g_H}{g_Y} \]
Then, axion-photon coupling gets an additional contribution from the hidden matter field through the electromagnetic anomaly

\[ \mathcal{L} = \frac{g_{a \gamma \gamma}}{4} a F_{\mu \nu} \tilde{F}^{\mu \nu} \]

\[ g_{a \gamma \gamma} \approx \frac{\alpha_{\text{EM}}}{2\pi f_a} \left( \frac{8}{3} + \frac{2q_H^2 g_H^2}{g_Y^2} \frac{\chi^2}{1 - \chi^2} - 1.92 \right) \]

from SU(5) complete multiplet

For large \( g_H \) and \( \chi \), the enhancement is significant.

**Large \( \chi \) and \( g_H \) are required for consistency with GUT**

Gauge coupling unification

\[ \chi(m_Z) \approx 0.37 \]

large \( \chi \) of O(0.1) \( \rightarrow \) large \( g_H \)
Generation of large $\chi$

Around the GUT scale

$U(1)_Y$ \[\Psi_{L_i}, \Psi_{D_i}\] \[g_{\text{GUT}}\] \[g_H\] $U(1)_H$

With the GUT breaking mass induced by $\Sigma_{24}$:

$$\chi(M_{\text{GUT}}) \approx 0.12 N_f \left(\frac{g_{\text{GUT}}}{0.53}\right) \times \left[\frac{g_H(M_{\text{GUT}})}{4\pi}\right] \left[\frac{\ln(M_{D'}/M_{L'})}{\ln 4}\right]$$

large $g_H$ is required
Enhanced Axion-Photon Coupling

We take the possibly large $g_H$ avoiding the Landau Pole

The kinetic mixing is taken as $\chi(m_Z) = 0.365$
required for GUT

Case (i) : $\mathcal{L} \supset - \left[ \sqrt{2} \phi (\bar{\psi}_5 L \psi_5 R + \bar{\psi}_{HL} \psi_{HR}) + h.c. \right]$, 

Case (ii) : $\mathcal{L} \supset - \left[ \sqrt{2} \phi \psi_5^b L \psi_5^b R + h.c. \right]$, 

$U(1)_H$ charges are

$q_H(\psi_H) = 1 \quad q_H(\psi_5) = 0 \quad q_H(\psi_5^b) = -1$
$g_{\alpha \gamma}$ (GeV$^{-1}$)

$10^{-11}$

$10^{-13}$

$10^{-15}$

$10^{-17}$

$10^{-19}$

$m_\alpha$ [eV]

$10^{-8}$

$10^{-6}$

$10^{-4}$

$10^{-2}$

$E/N = 0$

$E/N = 8/3$

(no hidden charged matters)

$\text{bi-charged}$

CAST

IAXO

MADMAX

ADMX

CULTASK

ABRACADABRA (Broad)

ABRACADABRA (Res)

$\text{blue: case (i)}$

$\text{red: case (ii)}$

$f_\alpha = 10^{16}$ GeV

$m_\alpha = 5.70 \mu$eV \left( \frac{10^{12} \text{ GeV}}{f_\alpha} \right)$
Axion-photon coupling is enhanced by about a factor 10-100 for \( f_a = 10^{10}\text{GeV}-10^{16}\text{GeV} \) compared to the case without \( U(1)_H \)
\[ \chi(m_Z) = 0.365 \]
\[ f_a = 10^{12} \text{ GeV} \]

Of course, the gauge coupling unification is maintained.
Summary

- Massless hidden photon can achieve the gauge coupling unification
- The unification is rather robust, allowing the existence of matter fields charged under \( SU(5)/U(1)_H \)
- No rapid proton decay problem
- If the QCD axion is accommodated, axion-photon coupling is significantly enhanced (by about a factor 10-100).
- With the enhancement, the QCD axion is more easily tested in future experiments
Thank you for your attention!
Once we have the hidden charged field

\[
\bar{\Psi} \gamma_\mu (g_Y ' Q_Y A'_Y + g_H q_H A'_H) \Psi = \bar{\Psi} \gamma_\mu (g_Y (Q_Y + \delta Q_Y) A'^{\mu}_Y + g_H q_H A'^{\mu}_H) \Psi
\]

(original basis)

\[
\begin{pmatrix}
2 & 2 & 2 \\
2 & 2 & -3 \\
2 & -3 & -3 \\
\end{pmatrix}
\]

(canonical basis)

This basis is not ready to be embedded into SU(5)

(There is a fractional charge)

\[
\delta Q_Y = -\frac{g_H q_H}{g_Y} \frac{\chi}{\sqrt{1 - \chi^2}}
\]

The basis of the unification becomes manifest

Does the hidden charged field affect the unification?
However, without a hidden charged field, unification basis is not fixed

\[ \bar{\Psi} \gamma_\mu (g'_Y Q_Y A'^\mu_Y) \Psi = \bar{\Psi} \gamma_\mu (g_Y Q_Y A^\mu_Y) \Psi \]

(original basis)

( canonical basis )

\[
A'^\mu_Y = \frac{A^\mu_Y}{\sqrt{1 - \chi^2}}
\]

\[
A'^\mu_H = A^\mu_H - \frac{\chi}{\sqrt{1 - \chi^2}} A^\mu_Y
\]

\[
g_Y = \frac{g'_Y}{\sqrt{1 - \chi^2}},
\]

\[
\frac{1}{2\sqrt{15}} \left( \begin{array}{ccc}
2 & 2 & 2 \\
2 & 2 & -3 \\
-3 & -3 & -3
\end{array} \right)
\]

A generator of SU(5)