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Gauge see-saw: A mechanism for a light gauge boson

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ABSTRACT

There has been rapidly growing interest in the past decade in a new gauge boson which is considerably lighter than the standard model Z boson. A well-known example of this kind is the so-called dark photon, and it is actively searched for in various experiments nowadays. It would be puzzling to have a new gauge boson which is neither massless nor electroweak scale, but possesses a rather small yet nonzero mass. We present a mechanism that can provide a light gauge boson as a result of a mass matrix diagonalization.

1. Introduction

It is amusing to observe that a square matrix of the equal size of entities

$$M = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \tag{1}$$

results in the eigenvalues $\lambda = 0$ and 2. When the matrix is slightly tilted or misaligned from the original matrix, there will be a nonzero but tiny eigenvalue $\lambda \ll 1$. There are even more general cases than the one presented in Eq. (1). In this letter, we will use this mechanism to rationalize a very light gauge boson.

A light gauge boson, sometimes called dark gauge boson (typically, MeV–GeV scale, but it can be even lighter) has been a popular subject to study after it was shown it could potentially address many puzzling observations such as the positron excess, the small scale problems around the galaxy, and the muon $g-2$ anomaly [1]. If its lifetime is sufficiently long, the dark gauge boson itself can be a dark matter candidate [2–4].

For such a light particle to survive all the experimental constraints, it should have a very small coupling. A popular model is called the dark photon, because it couples only to the electromagnetic current like the photon when it is substantially lighter than the Z boson of the standard model (SM) [5]. A dark $U(1)$ can mix with the hypercharge $U(1)_Y$ of the SM through a gauge kinetic mixing term $\frac{\varepsilon}{2\cos\theta_W} Z'_{\mu\nu} B^{\mu\nu}$, and couples to the SM particles through this mixing, which can be suppressed by the loops of some heavy fermions that have charges under both the dark $U(1)$ and the $U(1)_Y$ [6].

The smallness of the mass may be explained by taking the vacuum expectation value (vev) of a scalar, which is responsible for the dark $U(1)$ symmetry breaking, is also of very small scale. Yet, it would be desirable to find a possible mechanism to obtain a very light gauge boson from the high scale (electroweak or UV scale) physics without introducing a new scale. Some models that can address this using the supersymmetry framework can be found in Refs. [7–9].

In this letter, we will employ two massive gauge bosons of the same heavy mass scale and their large mixing to realize a similar mass matrix texture as Eq. (1) or even a more general form. The mass matrix of this form can be realized with, for instance, Higgs mechanism or Stückelberg mechanism. We shall call our mechanism *Gauge see-saw* as they rely on the mass matrix diagonalization like the neutrino see-saw to obtain a small mass for one particle while its partner remains in the heavy scale, although the mass matrix texture is very different from the typical (type-I) neutrino see-saw [10,11].

There are some relations between the properties of the two gauge bosons in our mechanism, and a discovery of one particle can help in searching for the other particle. We will discuss some implications of the gauge see-saw later in this letter.

2. Gauge see-saw

For a 2×2 gauge boson mass-squared matrix

$$M = \begin{pmatrix} a & b \\ b & d \end{pmatrix}, \tag{2}$$

the eigenvalues (physical mass-squared values) are given by

$$\lambda = \frac{1}{2}\left(\mathrm{tr}[M] \pm \sqrt{\mathrm{tr}[M]^2 - 4\det[M]}\right) \tag{3}$$

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where

$$\det[M] = ad - b^2\,, \tag{4}$$

$$\mathrm{tr}[M] = a + d\,. \tag{5}$$

The diagonal mass-squared terms (a, d) are always positive-definite. While the off-diagonal mixing term (b) can be negative, it appears only in squared (b^2) in Eq. (4). Thus, $\det[M]$ always contains a destructive sum, possibly resulting in a significant suppression from the original scales, while $\mathrm{tr}[M]$ always has a constructive sum. When all elements (a, b, d) are at the same scale, $\mathrm{tr}[M]$ should remain at the original scale, while the $\det[M]$ can be orders of magnitude smaller in principle.

We define a mass alignment parameter r as

$$r \equiv \frac{\det[M]}{\mathrm{tr}[M]^2}\,. \tag{6}$$

The gauge see-saw can be achieved for $r \ll 1$, under which the physical masses of two gauge bosons (Z_L, Z_H) can be well approximated as

$$m^2_{Z_L} \simeq \frac{\det[M]}{\mathrm{tr}[M]}\,, \quad m^2_{Z_H} \simeq \mathrm{tr}[M]\,, \tag{7}$$

and the mass alignment parameter itself clearly shows the disparate mass scales as

$$r \simeq \frac{m^2_{Z_L}}{m^2_{Z_H}} \ll 1\,. \tag{8}$$

A GeV–TeV level mass hierarchy would require $r \approx 10^{-6}$. In the perfect mass alignment case ($r = 0$), Z_L becomes massless.[1]

Since r parametrizes how much the gauge symmetry of Z_L is spontaneously broken, quantum radiative corrections to $m^2_{Z_L}$ would vanish in the $r \to 0$ limit to enhance the gauge symmetry. In this sense, a small $m^2_{Z_L}$ is technically natural [13]. While any spin objects (scalar, fermion, vector, etc.) with the same mass texture should give the same results,[2] it is a superior part of the vector gauge boson case that its gauge symmetry will automatically protect the small mass from the loop corrections.

The gauge see-saw mechanism relies on the large mixing among the interaction eigenstates. In the perfect mass alignment case (with a zero eigenvalue), the mixing angle is given by

$$\sin\theta = \sqrt{\frac{a}{a+d}}\,, \quad \cos\theta = \sqrt{\frac{d}{a+d}}\,. \tag{9}$$

The texture in Eq. (1) would give the maximal mixing ($\theta = \pi/4$) of this case.

3. Illustrations

The gauge see-saw can work for any model that gives the masses to two $U(1)$s simultaneously. It can be extended to a larger number of the $U(1)$s in a straightforward way. We illustrate the realization of the gauge see-saw in the mass matrix using the Higgs mechanism and the Stückelberg mechanism.

We take two Abelian gauge groups: $U(1)'$ with a gauge boson $\hat{Z}'$ and a gauge coupling constant g', and $U(1)''$ with $\hat{Z}''$ and g''.

[1] In this limit, there are similar aspects with Ref. [12], in which a certain kind of mass matrix was exploited to realize the massless gauge bosons.

[2] See Ref. [14] for the natural inflation with multi-axion, where specific alignment of couplings of axions to non-Abelian instantons allows a flat direction, along which an effective axion decay constant can be enhanced.

(i) Using Higgs mechanism:
In this realization, we first assume the couplings of the $\hat{Z}'$, $\hat{Z}''$ to the SM fermions are vectorial. Otherwise, the SM Higgs contribution to the mass matrix should be considered, which is beyond the scope of our simple illustration.

We consider two SM singlet complex scalars to break the two gauge symmetries spontaneously: Φ_1 with a $U(1)'$ charge q'_1, a $U(1)''$ charge q''_1, a vev v_1, and Φ_2 with q'_2, q''_2, v_2. The relevant Lagrangian is given by

$$\mathcal{L} \sim \sum_{i=1,2} \left| \left(\partial_\mu + i g' q'_i \hat{Z}'_\mu + i g'' q''_i \hat{Z}''_\mu\right)\Phi_i \right|^2. \tag{10}$$

The mass-squared matrix for the gauge bosons in the $(\hat{Z}', \hat{Z}'')$ basis is given by

$$M = \begin{pmatrix} g'^2(q'^2_1 v_1^2 + q'^2_2 v_2^2) & g'g''(q'_1 q''_1 v_1^2 + q'_2 q''_2 v_2^2) \\ g'g''(q'_1 q''_1 v_1^2 + q'_2 q''_2 v_2^2) & g''^2(q''^2_1 v_1^2 + q''^2_2 v_2^2) \end{pmatrix}. \tag{11}$$

Then $\det[M] = g'^2 g''^2 (q'_1 q''_2 - q''_1 q'_2)^2 v_1^2 v_2^2$, which tells the perfect mass alignment case is achieved for $q'_1 q''_2 - q''_1 q'_2 = 0$.

For $(q'_1 q''_2 - q''_1 q'_2)^2 \ll 1$, the gauge see-saw mechanism works ($r \ll 1$), and the physical masses are approximated by

$$m^2_{Z_L} \approx \frac{g'^2 g''^2 (q'_1 q''_2 - q''_1 q'_2)^2 v_1^2 v_2^2}{(g'^2 + g''^2 (q''^2_2/q'^2_2))(q'^2_1 v_1^2 + q'^2_2 v_2^2)}, \tag{12}$$

$$m^2_{Z_H} \approx (g'^2 + g''^2 (q''^2_2/q'^2_2))(q'^2_1 v_1^2 + q'^2_2 v_2^2). \tag{13}$$

In the case of $g' \sim g''$, $v_1 \sim v_2$, $q'_1 \sim q''_1 \sim q''_2 \sim q'_2 \sim \mathcal{O}(1)$, we get

$$m^2_{Z_L} \sim \mathcal{O}(1)\, g'^2 v_1^2 (q'_1 q''_2 - q''_1 q'_2)^2, \tag{14}$$

$$m^2_{Z_H} \sim \mathcal{O}(1)\, g'^2 v_1^2, \tag{15}$$

which clearly shows that m_{Z_H} stays at the original scale while m_{Z_L} is suppressed by the small mass differences (or charge differences) in Eq. (11), giving $r \sim \mathcal{O}(1)\,(q'_1 q''_2 - q''_1 q'_2)^2$.

If the two $U(1)$s are re-defined to have only diagonal masses ($m^2_{Z_L}$, $m^2_{Z_H}$), then the two Higgs scalars become linear combinations of each other with mixed $U(1)$ charges and vevs. One can see the gauge see-saw mechanism works only when one of these combinations has small mixed $U(1)$ charges and vevs.

(ii) Using Stückelberg mechanism:
In the Stückelberg mechanism [15–17], we do not need real scalars, but need at least two pseudoscalars (a_1, a_2) transforming non-linearly under the two $U(1)$s.

Under the $U(1)'$, they transform as

$$a_1 \to a_1 - c'_1 \lambda'(x), \quad a_2 \to a_2 - c'_2 \lambda'(x), \tag{16}$$

$$\text{while } \hat{Z}'_\mu \to \hat{Z}'_\mu + \partial_\mu \lambda'(x), \tag{17}$$

and similarly for the $U(1)''$.

With two gauge invariant combinations $\partial_\mu a_1 + c'_1 \hat{Z}'_\mu + c''_1 \hat{Z}''_\mu$ and $\partial_\mu a_2 + c'_2 \hat{Z}'_\mu + c''_2 \hat{Z}''_\mu$, the mass terms are given by

$$\mathcal{L} \sim \sum_{i=1,2} \frac{1}{2} \rho_i^2 \left(\partial_\mu a_i + c'_i \hat{Z}'_\mu + c''_i \hat{Z}''_\mu\right)^2, \tag{18}$$

with some mass parameters ρ_1 and ρ_2, giving the mass-squared matrix

$$M = \begin{pmatrix} c'^2_1 \rho_1^2 + c'^2_2 \rho_2^2 & c'_1 c''_1 \rho_1^2 + c'_2 c''_2 \rho_2^2 \\ c'_1 c''_1 \rho_1^2 + c'_2 c''_2 \rho_2^2 & c''^2_1 \rho_1^2 + c''^2_2 \rho_2^2 \end{pmatrix}. \tag{19}$$