Diphoton Excess as a Hidden Monopole

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We provide a theory with a monopole of a strongly-interacting hidden U(1) gauge symmetry that can explain the 750-GeV diphoton excess reported by ATLAS and CMS. The excess results from the resonance of monopole, which is produced via gluon fusion and decays into two photons. In the low energy, there are only mesons and a monopole in our model because any baryons cannot be gauge invariant in terms of strongly interacting Abelian symmetry. This is advantageous of our model because there is no unwanted relics around the BBN epoch.

I. INTRODUCTION

The concepts of confinement and chiral symmetry breaking are long standing mystery in particle physics, which is not completely understood yet. It may seem to be natural that a non-abelian gauge theory is confined and develops quark condensation in low energy because its gauge coupling constant can be asymptotically free and may blow up at low energy. One might think that confinement does not occur in Abelian gauge theory, where the beta function of gauge coupling constant is positive in the presence of any charges of electrons. However, to understand the quark confinement fact, as Nambu showed, confinement can occur in an Abelian gauge theory where a scalar monopole as well as electrons and positrons are introduced \cite{2}. Once the scalar monopole develops a condensation, each electron and positron pair is attached by a physical string and is confined by its tension.

In this paper we consider a phenomenological model of a U(1)\textsubscript{H} gauge theory with hidden electrons (quarks) and a monopole. In fact, there really exist concrete models with the same qualitative features. First of all, there exist conformal field theories (CFTs) which can be interpreted as U(1) gauge theories with electrons and monopoles \cite{3,4}. Given such abstract CFTs, we can deform the theory by introducing relevant operators whose scaling dimensions are less than 4. In particular, in those U(1) theories, there exist a relevant operator which can be interpreted as the electron masses [corresponding to our Eq. (8)], and it was also discussed \cite{5} (see also \cite{6–8}) that there exists a relevant operator which cause monopole condensation [corresponding to our Eq. (9)], leading to confinement and mesons.

In this paper, we provide a hidden Abelian gauge theory with a hidden monopole that explains diphoton excess at the energy scale of 750 GeV reported by the ATLAS and CMS collaborators \cite{9,10}.

\footnote{1 See Ref. \cite{11} for another phenomenological application of monopole condensation.}

\footnote{2 When the baryon is neutral under the SM gauge interactions, it can be DM \cite{13}.}
is the absence of colored baryons, which are disastrous in cosmology if they are long lived or stable.

Then, in Sec. III, we explain our model with a scalar monopole, where hidden quarks are confined by an Abelian gauge interaction due to a monopole condensation. As a result, there are a monopole and mesons in low energy and the former is responsible to the resonance at the LHC. Then we discuss cosmology and explain that the mesons are unstable and there is no unwanted relics around the BBN epoch. Finally, we conclude in Sec. IV.

## II. MODEL WITH SU(N)$_H$

Let us consider a SU(N)$_H$ gauge theory with a singlet scalar field $\Phi$ and Weyl fermions $U$ and $\bar{U}$. The fields $U$ and $\bar{U}$ are charged under SU(N)$_H$ as well as the SM gauge symmetries as shown in Table I. We call them as extra quarks because they are charged under the SU(3)$_c$. We introduce a Yukawa interaction such as

$$\mathcal{L} = y\Phi U\bar{U} + h.c.,$$

and assume that $\Phi$ develops condensation such as $\langle \Phi \rangle \equiv v/\sqrt{2}$, which gives extra quarks an effective mass of $m_U \equiv yv/\sqrt{2}$.

Below the energy scale of quark mass $m_U$, we obtain the effective interaction of the phase direction of $\Phi$ such as

$$\mathcal{L} = \frac{N\alpha_3 a}{8\pi} \frac{1}{v} \bar{G}_{\mu\nu}G^{\mu\nu} + \frac{3Ng^2}{4\pi} \frac{1}{v} B_{\mu\nu}B^{\mu\nu}$$

where we decompose the scalar field as $\Phi = (v + \varphi)e^{i\eta/v}/\sqrt{2}$. Thus, the decay rates of $a$ into SM gauge bosons are given as

$$\Gamma(a \to gg) \simeq \frac{N^2\alpha_3^2}{32\pi^3v^2} m_a^3$$

$$\text{Br}_{a\to\gamma\gamma} = \frac{9g_Y^4\alpha_3^2}{2\alpha_Y^2} \simeq 3.5 \times 10^{-2} \times g_Y^4,$$

where we assume $\text{Br}_{a\to gg} \simeq 1$ and use $\alpha_3 \simeq 0.09$ and $\alpha \simeq 1/126.5$ at the energy scale of 750 GeV. The mass of $a$, denoted as $m_a$, is independent of $m_U$ and assumed to be 750 GeV. The cross section of the process $\sigma(pp \to a \to \gamma\gamma)$ at the center-of-mass energy $\sqrt{s} = 13$ TeV can be written as

$$\sigma(pp \to a \to \gamma\gamma) \simeq C_{gg}^2 \frac{\Gamma(a \to gg)}{m_a^8} \text{Br}_{a\to\gamma\gamma} \simeq 3.5 \text{ fb} \ g_Y^4 y^2 \left( \frac{N}{3} \right)^2 \left( \frac{m_U}{1 \text{ TeV}} \right)^{-2}$$

where $C_{gg} = (\pi^2/8) \int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1 x_2 - m_a^2/s) g(x_1) g(x_2)$ and $g(x)$ is the gluon parton distribution function. We use $C_{gg} \simeq 2.1 \times 10^3$ from MSTW2008 NLO set at the scale of $m_a = 750$ GeV [14]. Here a large value of $y$ is crucial to make the quarks heavier than of order 1 TeV.

A large Yukawa coupling can be realized via the renormalization group running when the gauge coupling of SU(N)$_H$ is large. The RG equation is given by

$$(16\pi^2) \frac{dy}{d\log \mu} = (3 + 3N)g_Y^3 - \left( \frac{3N^2 - 1}{N} g_H^2 + 8g_Y^2 + 6g_Y^2 g_Y^2 \right) y,$$

so that the Yukawa coupling can be as large as $g_H$. Thus when the gauge coupling constant $g_H$ is large at the energy scale of order $m_a$, the Yukawa coupling can also be large and extra quark masses can be as large as of order 1 TeV.

In this model, however, there is a stable baryon that is charged under the SU(3)$_c$, whose abundance is severely constrained in cosmology. In the next subsection, we provide a theory that predicts no baryon and is safe cosmologically.

## III. MODEL WITH U(1)$_H$ AND A MONOPOLE

### A. Model

Now, we consider a hidden Abelian gauge theory with a scalar monopole $\phi$ and extra quarks $Q$, $\bar{Q}$, $U$, and $\bar{U}$. The charge assignment for the extra quarks are shown in Table II. We denote the fine-structure constant for extra quarks and SM particles [12].

| SU(3)$_c$ | SU(2)$_L$ | U(1)$_Y$ | SU(N)$_H$ |
|-----------|-----------|-----------|-----------|
| $U$       | $\square$ | $1$       | $qv$      |
| $\bar{U}$ | $\square$ | $1$       | $-qv$     |

TABLE I. Charge assignment for extra matter fields in the model without monopole.

The model might be safe if we could introduce a higher dimensional interaction between the extra quarks and SM particles [12].
order unity at the UV fixed point [3, 4]. Once we add mass terms for extra quarks such as
\[ - \mathcal{L} = m_Q Q \bar{Q} + m_U U \bar{U}, \] (8)
then the hidden electrically charged particles are decoupled below these mass scale. The $U(1)_H$ theory contains only a scalar monopole after the extra quarks decouple, which means that the low energy theory is equivalent to a scalar QED due to the electromagnetic duality of $U(1)_H$. When we write the potential of scalar monopole such as
\[ V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4, \] (9)
the renormalization group (RG) equations can be written as
\[ (16\pi^2) \frac{d m_m}{d \ln \mu} = \frac{g_m^3}{3} \] (10)
\[ (16\pi^2) \frac{d \lambda}{d \ln \mu} = 20\lambda^2 - 12g_m^2 \lambda + 6g_m^4, \] (11)
within one-loop order. The RG group flow is shown in Fig. 1, where we assume $g_m = g_e = \lambda^{1/2} = (4\pi)^{1/2}$ at the UV fixed point. Note that the couplings are larger than unity, so that the above perturbative calculation cannot be trusted and the figure should be regarded as a schematic plot. The theory is at the UV fixed point in the energy scale higher than $m_{Q,U}$ and the coupling constants run below that scale. The magnetic coupling becomes smaller in lower energy scale while the electric coupling becomes larger due to the Dirac’s quantization condition. Note that in this theory there are only two free parameters: quark mass scale $m_{Q,U}$ and monopole mass parameter $\mu$. The other parameters, such as electric and magnetic couplings and monopole quartic coupling, can be determined in principle by the RG running from the UV fixed point. However, we do not know the values of these parameters at the UV fixed point, so that we just expect that these couplings at the UV fixed point are of order unity. The couplings at the energy scale of 750 GeV should be determined by solving renormalization group equations between the quark mass scale and 750 GeV. The RG equations of Eq. (11) imply that the quartic coupling of monopole $\lambda$ may be smaller than the hidden magnetic coupling $g_m$ in low energy (see Fig. 1).

At the minimum of the potential, the monopole develops a condensation such as $\sqrt{2} \langle |\phi| \rangle = \mu/\sqrt{\lambda}$ ($\equiv v$) and the mass of its radial component, which we denote as $\varphi$ ($\equiv \sqrt{2} |\phi|$), is given by $m_\varphi = \sqrt{2}\mu$. The hidden $U(1)_H$ gauge boson acquires a mass of $m_\varphi = g_m v$, which we assume to be larger than $m_\varphi$. After the monopole acquires the VEV, extra quarks are attached by strings via the Meisner effect and are confined by the tension of the string [2]. Its tension $\mu_s$ determines the dynamical scale and is given as
\[ \mu_s = 2\pi \alpha_{H,e} \alpha_{H,m} v^2 \log \left( \frac{m_\varphi^2}{m_v^2} + 1 \right), \] (12)
which is almost independent of $\alpha_{H,e}$ and $\alpha_{H,m}$ due to the Dirac quantization condition. We assume that the extra quark masses $m_{Q,U}$ are larger than the confinement scale, so that there is only the radial component of monopole below the confinement scale. We identify the monopole as a particle with a mass of 750 GeV that is responsible for the diphoton resonance.

**B. Collider signals**

The monopole and SM gauge fields are coupled via the heavy quarks. Therefore the couplings is inversely proportional to the typical mass scale of $Q$ and $U$. In the naive dimensional analysis [15], the couplings between

| $Q$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_H$ |
|-----|------------|----------|----------|
| $Q$ | 1          | $q_v$    | 1        |
| $U$ | 1          | $-q_v$   | 1        |
| $\bar{Q}$ | 1        | $-\bar{q}_v$ | -1      |
| $\bar{U}$ | 1         | $-(q_v - 1/2)$ | -1      |

**TABLE II.** Charge assignment for extra matter fields in the model with monopole.
the monopole and SM gauge fields are given by

\[
\mathcal{L} = c_1 \frac{g_1^2}{16\pi^2} (4\pi)^2 \frac{\alpha^2}{m_{Q,U}^2} G_{\mu\nu} G^{\mu\nu} + c_2 \frac{g_2^2}{16\pi^2} (4\pi)^2 \frac{\alpha^2}{m_{Q,U}^2} W_{\mu\nu} W^{\mu\nu} + c_3 \frac{g_3^2}{16\pi^2} (4\pi)^2 \frac{\alpha^2}{m_{Q,U}^2} B_{\mu\nu} B^{\mu\nu},
\]

(13)

where \( c_i \) (\( i = 1, 2, 3 \)) are unknown \( O(1) \) constants and \( m_{Q,U} \) is a typical mass parameter of order \( m_Q \) and \( m_U \). Then, using \( |\alpha|^2 = v^2/2 + v\phi + \ldots \), we obtain the decay rates of \( \phi \) into SM gauge bosons such as

\[
\Gamma(\phi \to gg) \approx \frac{8\sqrt{2} \alpha^2 (4\pi v)^2}{4\pi m_{Q,U}^2} m_{V},
\]

(14)

\[
\Gamma(\phi \to \gamma\gamma) \approx \frac{c_1^2 e^4}{8c_3^2 v_{\phi}^2},
\]

(15)

\[
\Gamma(\phi \to W^+W^-) \approx \frac{(c_2 t_W^2 + c_3 t_W^2)^2 e^4}{4c_3^2 v_{\phi}^2},
\]

(16)

\[
\Gamma(\phi \to ZZ) \approx \frac{c_2 t_W^2 c_3 t_W^2 e^4}{4c_3^2 v_{\phi}^2},
\]

(17)

\[
\Gamma(\phi \to Z\gamma) \approx \frac{(c_1 t_W^2 - c_2 t_W^2)^2 e^4}{4c_3^2 v_{\phi}^2},
\]

(18)

where we assume \( Br_{\phi \to gg} \approx 1 \) and define \( s_W \equiv \sin \theta_W \) and \( v_{\phi} \equiv \tan \theta_{\phi} \). The cross section of the process \( \Gamma(pp \to \phi \to \gamma\gamma) \) can be written as

\[
\sigma(pp \to \phi \to \gamma\gamma) \approx C_{gg} \frac{\Gamma(\phi \to gg)}{m_{\phi}} Br_{\phi \to \gamma\gamma} \times 3.8 \text{ fb}(c_1 + c_2)^2 \left( \frac{\lambda}{10} \right)^{-1} \left( \frac{m_{Q,U}}{2 \text{ TeV}} \right)^{-4},
\]

(19)

where we use \( C_{gg} \approx 2.1 \times 10^3 \), \( m_{\phi} = 750 \text{ GeV} \), and \( \alpha_c \approx 0.09 \) for \( \sqrt{s} = 13 \text{ TeV} \). We find that the masses of extra quarks can be larger than \( O(1) \) TeV for \( \lambda = O(10) \).

The hidden vector boson mass \( m_v \) is related to the value of \( \lambda \) such as \( m_v = g_m v = g_m m_{\phi} / \sqrt{2 \lambda} \). Assuming that \( g_m \approx \sqrt{4\pi} \) and \( \lambda \approx 3 - 10 \), which is expected from the RG running (see Fig. 1), we estimate \( m_v \approx 0.6 - 1.1 \text{ TeV} \). Note that the hidden gauge boson acquires an effective mass by the monopole condensation, so that the hidden gauge coupling does not mix with the electroweak coupling. Thus the hidden gauge boson, which we denote by \( Z' \), can be produced by collider experiments only via loop effects. A model that predicts similar signals has been investigated in Ref. [16]. They focused on \( gg \to Z'g \) associated with \( Z' \to gg' \to gtU \), where \( g \) and \( g' \) represent on-shell and off-shell gluons, respectively. Since the scattering cross section is suppressed by the masses of extra quarks, which is of order \( 2 - 4 \text{ TeV} \), the signal is much below background signals. A process \( pp \to Z' + \text{jets} \) is also predicted in our model. However, its background signal cross section is as large as \( 10^{4-5} \text{ pb} \) [17], so that we cannot obtain any signals from this process.

Here we comment on a consequence from sequestering property of conformal field theory [3, 4]. One may naively expect that the decay rate into diphoton is roughly proportional to \( q_1^4 \) for \( q_1 \gg 1 \) because its process is mediated by extra quarks with \( U(1)_{Y} \) charge of order \( q_Y \). However, this may not be the case in the conformal Abelian gauge theory. First, note that the hypercharge of \( Q, Q^\dagger, U, \) and \( U^\dagger \) can be shifted by \( -q_Y \) by redefinition of \( U(1)_H \) gauge field and be rewritten by a kinetic mixing term between \( U(1)_Y \) and \( U(1)_H \) (\( \propto q_Y \mathcal{B}_{\mu\nu} F^{\mu\nu} \), where \( F_{\mu\nu} \) is the field strength of \( U(1)_H \)). When the \( U(1)_H \) gauge theory is conformal, its gauge field strength \( F_{\mu\nu} \) has an anomalous dimension larger than 2. This implies that the kinetic mixing term \( \mathcal{B}_{\mu\nu} F^{\mu\nu} \) is an irrelevant operator and is suppressed at low energy. As a result, if the hypercharges of \( Q, Q^\dagger, U, \) and \( U^\dagger \) are identical, their hypercharge would be suppressed in the low energy effective theory. This is the reason why we do not expect that the decay rate of monopole into diphoton is proportional to \( q_1^4 \). Since their hypercharges are not identical in our model, we expect nonzero decay rate of monopole into diphoton. Note that if the kinetic mixing term is not suppressed at low energy, we do not need to introduce \( Q \) and \( \bar{Q} \) to explain the diphoton signal.

### C. Mesons and cosmology

In the low energy effective theory, there are mesons as well as monopoles. Their SM gauge charges are listed in Table III. As we discussed in the previous section, the mass of the mesons are as heavy as \( 2m_{Q,U} \approx 4 \text{ TeV} \), so that we may not be able to produce them at the LHC. In any case, we should check that they do not affect the standard cosmological scenario, such as the BBN theory.

In the low energy, we can write the following operators

| SU(3)_c | SU(2)_L | U(1)_Y |
|---------|---------|---------|
| \psi_Q  | Adj     | Adj     | 0       |
| \phi_Q  | Adj     | 1       | 0       |
| \phi^\dagger_Q | 1 | Adj | 0 |
| \pi^\pm | Adj     | ±1/2    |         |
| \eta, \eta' | 1     | 1       | 0       |
Since it acquires an effective mass by the monopole condensation at an intermediate scale. The decay into diphoton. We predict mesons with the masses diphoton excess results from the resonance production of a monopole condensation at an intermediate scale. The other mesons because the dynamical scale \( v \) is much smaller than the typical mass scale of extra quarks \( m_Q \) and \( m_\psi \). In order to make the other mesons (\( \pi^\pm \) and \( \pi^{\pm\prime} \)) decay, we introduce interactions of

\[
\mathcal{L}_{\text{int}} = y Q \bar{U} H + h.c.,
\]

where \( y \) is a Yukawa constant. This interaction allows \( \pi^\pm \) and \( \pi^{\pm\prime} \) to decay into SM particles so fast that we can avoid the BBN constraint.

IV. DISCUSSION AND CONCLUSIONS

We have provided a simple model that explains the diphoton excess reported by ATLAS and CMS and predicts no unwanted relics in the Universe. First we explain a model with non-Abelian gauge symmetry to illustrate our mechanism, where extra quarks can be as heavy as \( O(1) \) TeV. Then we discuss our model based on a confinement in Abelian gauge theory, which can be realized by a monopole condensation at an intermediate scale. The diphoton excess results from the resonance production of 750-GeV monopole by gluon fusion and its subsequent decay into diphoton. We predict mesons with the masses of order 5 TeV, which decay fast and do not spoil the success of the BBN theory in cosmology. We also predict a massive hidden gauge boson with mass about 1 TeV. Since it acquires an effective mass by the monopole condensation, its production process is different from the ordinary \( Z' \). It may be challenging to search its signals in LHC.

Finally, we comment on another interesting possibility for application of monopole condensation in cosmology and phenomenology. As discussed in the final paragraph in Sec. III B, the kinetic mixing between \( U(1)_Y \) and hidden \( U(1)_H \) is suppressed in low energy when the hidden \( U(1)_H \) is conformal due to the presence of monopole as well as electrons. The suppression depends on the (unknown) anomalous dimension of field strength of \( U(1)_H \), so that the kinetic mixing may be a nonzero small value. This provides a simple mechanism to suppress the kinetic mixing of Abelian gauge theories, which is severely constrained by many experiments.

In the literature, strongly interacting massive particles (SIMPs) are well motivated as DM in light of a solution to a tension between the cold DM model and astrophysical observations (see e.g., Refs. [18–20]). In Ref. [21], they considered strongly-interacting hidden SU(N) gauge theory and identified pions in low energy effective theory as SIMPs. Their relic abundance is determined by 3 \( \to 2 \) scattering and can explain the observed one around a parameter space consistent with astrophysical observations [22]. However, we need interactions between the pions and SM sector so that the energy of pions can be reduced in order not to be hot DM. In Ref. [23], they introduced an additional \( U(1)_H \) gauge symmetry and assume a kinetic mixing between the \( U(1)_H \) and \( U(1)_Y \). Here, we can consider a simpler model where the above hidden SU(N) is replaced by our hidden \( U(1)_H \). The hidden electrons are confined by the monopole condensation, leading the electron and anti-electron chiral condensation. The kinetic mixing between \( U(1)_H \) and \( U(1)_Y \) can be naturally small as discussed above and allows pions to reduce its energy without affecting their relic abundance. In addition, there is no unwanted baryon in this theory as discussed in the main part of this paper. A detailed study will be presented elsewhere [24].

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