Footprints of New Strong Dynamics via Anomaly and the 750 GeV Diphoton

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The chiral anomaly provides a smoking-gun evidence of a new confining gauge theory. Motivated by a reported event excess in a diphoton invariant mass distribution at the LHC, we discuss a scenario that a pseudo-Nambu-Goldstone (pNG) boson of a new QCD-like theory is produced by gluon fusion and decays into a pair of the standard model gauge bosons. Despite the strong dynamics, the production cross section and the decay widths are determined by anomaly matching condition. The excess can be explained by the pNG boson with mass of around 750 GeV. The model also predicts exotic hadrons such as a color octet scalar and baryons. Some of them are within the reach of the LHC experiment.

I. INTRODUCTION

A new confining gauge theory is ubiquitous in physics beyond the standard model (SM). Most models to solve the hierarchy problem, such as technicolor \cite{1}, (the holographic picture of) Randall-Sundrum scenarios \cite{2} and a class of little Higgs models \cite{3}, involve new strong dynamics. Even in supersymmetry \cite{4}, the breaking scale is often assumed to be given by dimensional transmutation of a new gauge theory \cite{5}. In addition, the dark matter can be like a new pion originating from strong dynamics \cite{6}. Furthermore, string theory seems to prefer non-minimal models with extra gauge groups. Therefore, from the viewpoint of such prevailing nature of strong dynamics, even if we do not intend to solve the hierarchy problem, it is well motivated to pursue a possibility of a new asymptotically free gauge theory to be explored at the LHC \cite{7}.

Recently, the ATLAS and CMS collaborations have reported an excess in diphoton invariant mass distribution around $m_{\gamma\gamma} \simeq 750$ GeV \cite{11}. If this peak comes from a new scalar boson $\phi$ with mass of around 750 GeV, the reported event number can be fitted with a relatively large production cross section times branching ratio $\sigma(pp \to \phi) Br(\phi \to \gamma\gamma) = 1.4-18$ fb (see the discussion in Section III). Then, the scalar $\phi$ must be efficiently produced, which is achieved by gluon fusion. The relevant interaction terms of $\phi$ are parametrized as

$$L_{\text{eff}} = \frac{\alpha}{4\pi} \frac{k_\gamma}{\Lambda_\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{\alpha_s}{4\pi} \frac{k_g}{\Lambda_g} G_\mu^a G_a^{\mu\nu} \tilde{G}^{\mu\nu},$$

where $F$ denotes the field strength of the photon, $\tilde{F}^{\mu\nu} = \frac{i}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$, and $G$ indicates the gluon field strength. $k_\gamma$ and $k_g$ are dimensionless constants and $\Lambda_\gamma$, $\Lambda_g$ are mass parameters. From the effective interactions of Eq. (1), the widths of $\phi$ decays into $gg$ and $\gamma\gamma$ are calculated as \cite{12}

$$\Gamma(\phi \to gg) = \frac{\alpha^2}{8\pi^3} \frac{k_g^2 m_\phi^3}{\Lambda_g^2}, \quad \Gamma(\phi \to \gamma\gamma) = \frac{\alpha^2}{64\pi^3} \frac{k_\gamma^2 m_\phi^3}{\Lambda_\gamma^2},$$

where $m_\phi$ is the mass of $\phi$. With a natural assumption $k_\gamma/\Lambda_\gamma \sim k_g/\Lambda_g$, the scalar boson $\phi$ dominantly decays into two gluons, and the total decay width is approximately given by $\Gamma_\phi \simeq \Gamma(\phi \to gg)$. We can also take the branching ratio of diphoton as $Br(\phi \to \gamma\gamma) \simeq \Gamma(\phi \to \gamma\gamma)/\Gamma(\phi \to gg)$. By using the narrow width approximation \cite{13,14}, the production cross section times branching ratio is then estimated as

$$\sigma(pp \to \phi + X) Br(\phi \to \gamma\gamma) \simeq \frac{\pi^2}{8m_\phi s} \Gamma(\phi \to \gamma\gamma) \times \int_0^1 dx_1 \int_0^1 dx_2 \left[ \delta(x_1 x_2 - m_\phi^2/s) g(x_1) g(x_2) \right],$$

where $s$ is the square of center-of-mass energy and $g(x_\alpha) (\alpha = 1, 2)$ is the parton distribution function (PDF) of the gluon. We evaluate it numerically by using the MSTW PDF \cite{15}. For $m_\phi = 750$ GeV, the quantity of Eq. (3) is given by

$$\sigma(pp \to \phi + X) Br(\phi \to \gamma\gamma) \simeq \left( \frac{\Lambda_\gamma/k_\gamma}{100 \text{ GeV}} \right)^{-2} \times \begin{cases} 1.8 \text{ fb (8 TeV)} \quad (4) \\ 8.6 \text{ fb (13 TeV)} \end{cases},$$

where we have presented both cases of $\sqrt{s} = 8$ and 13 TeV.

If the effective interactions of Eq. (1) come from loops of some heavy particles as in Fig. 1, $\Lambda_\gamma, \Lambda_g (\gtrsim m_\phi)$ are given by typical mass scales of the heavy particles. For fitting the reported event number, Eq. (4) indicates that

\footnotetext{1}{As a scenario with the similar motivation, vector-like confinement was studied in Ref. \cite{7}. For a different confinement scale, there is Hidden Valley scenario \cite{8} (see also, Refs \cite{9,10}).}
the combination of the parameters $\Lambda_\gamma/k_\gamma$ must be around 100 GeV. Since the scalar mass is $m_\phi \simeq 750$ GeV, it is suggested that the dimensionless constant $k_\gamma$ is much larger than one. That is, we need some strong dynamics to explain the reported diphoton excess. Alternatively, we can consider a scenario in which $\phi$ is produced by quark anti-quark fusion via e.g., $(1/\Lambda) q_L q_R^c H \phi$. However, basically the discussion is parallel and we need a large effective coupling $k_\gamma/\Lambda_\gamma \sim (100 \text{ GeV})^{-1}$.

In this paper, motivated by the reported event excess, we explore a possibility of a new QCD-like theory to appear at the TeV scale. The effective theory after confinement contains pseudo-Nambu-Goldstone (pNG) bosons of an approximate chiral symmetry. We discuss LHC phenomenology of these pNG bosons. The lightest pNG boson is produced by gluon fusion and decays into a pair of the SM gauge bosons as in Fig. 1 which explains the reported excess. Importantly, despite the strong dynamics, the production cross section and the decay widths are determined by the ’t Hooft’s anomaly matching condition like $\pi^0 \rightarrow \gamma\gamma$ in the ordinary QCD. The excess can be explained by the pNG boson with mass of around 750 GeV. Unlike most cases, the lightest pNG boson produced by gluons has a photon-enriched signal as the second dominant decay. As discussed in the technicolor models [16, 17], the model also predicts exotic hadrons such as color octet and triplet scalars and baryons some of which are within the reach of the LHC experiment.

The rest of the paper is organized as follows. In section 2, we present a model with a new confining gauge interaction. The masses of the pNG bosons and their effective interactions with the SM gauge bosons after confinement are analyzed. In section 3, we discuss collider phenomenology of the lightest pNG boson and explain the reported event excess. In section 4, phenomenology of exotic hadrons such as color octet and triplet scalars and baryons is described. We make some concluding remarks in section 5.

II. A NEW QCD

Let us consider an asymptotically free $SU(N)$ gauge theory with new Weyl fermions, $\psi, \bar{\psi}$ (color triplets) and $\chi, \bar{\chi}$ (color singlets), which are (anti-)fundamental under the $SU(N)$. Their charge assignments are summarized in Table I. The new fermions have vector-like masses,

$$\mathcal{L} \supset -M_\psi \psi \bar{\psi} - M_\chi \chi \bar{\chi},$$

where $M_\psi$ and $M_\chi$ are mass scales of around 100 GeV. When we neglect the $SU(3)_C$ and $U(1)_Y$ gauge couplings and the mass scales $M_\psi, M_\chi$, the theory has a global $SU(4)_L \times SU(4)_R \times U(1)_B \times U(1)_A$ symmetry where $U(1)_B$ is the baryon number symmetry and $U(1)_A$ is anomalous under the $SU(N)$ gauge interaction.

The considered $SU(N)$ gauge theory is asymptotic free and confines at low energies. As in the case of the ordinary QCD, the new fermions condense,

$$\langle \psi \bar{\psi} \rangle \sim \frac{4\pi}{\sqrt{N}} f_S^3 1, \quad \langle \chi \bar{\chi} \rangle \sim \frac{4\pi}{\sqrt{N}} f_S^3,$$

where $f_S$ is the decay constant and we have used naive dimensional analysis (NDA) for counting the factors of $4\pi$ and $N$ (see e.g., Ref. [18, 19]). Then, the approximate $SU(4)_L \times SU(4)_R$ global symmetry is broken down to the diagonal subgroup $SU(4)_V$, in which the SM $SU(3)_C$ and $U(1)_Y$ gauge groups are embedded. Associated with the chiral symmetry breaking, there are 15 pNG bosons as light degrees of freedom and they behave under the $SU(3)_C$ as $15 \rightarrow 8 + 3 + \bar{3} + 1$. In the following discussion, we denote the $SU(3)_C$ octet, triplet and singlet pNG bosons as $\phi_8, \phi_3$ and $\phi$ respectively.

A. The masses of the pNG bosons

We now estimate the masses of the pNG bosons by using chiral perturbation theory (for a review, see [23]). The dependence on the mass parameters $M_\psi, M_\chi$ is determined by group theory, while the squared masses of the pNG bosons are also proportional to an undetermined mass scale of order one in the unit of the dynamical scale $\Lambda_S$. Then, we estimate the squared mass of the singlet pNG boson by scaling up the formula for the QCD pion

2 If we took $M_\psi = M_\chi = 0$ and the hypercharges of the new fermions as zero, the Lagrangian would be the same as that of the Kim’s composite axion model [20]. The authors of Refs. [21, 22] considered similar models where matter fermions have different representations of the SM gauge groups. In their models, the decays of the pNG bosons lead to $WW, ZZ$ rich signals.
mass $m_\pi$. The result is given by

$$m_\phi^2 \simeq \frac{3}{N} \frac{M_\psi/4 + 3M_\chi/4}{f_\pi} m_\pi^2 \frac{f_\phi}{\sqrt{N}},$$

where we have used $\Lambda_S \sim 4\pi f_\phi/\sqrt{N}$ from NDA and the QCD pion decay constant is $f_\pi \approx 93$ MeV.

Once we fix the mass of the singlet pNG boson $m_\phi$, the masses of the colored pNG bosons are determined by chiral perturbation theory and radiative corrections from the ordinary QCD. The squared masses of the triplet and octet pNG bosons are estimated as

$$m_{\phi_3}^2 = \frac{M_\psi}{M_\psi/4 + 3M_\chi/4} m_\phi^2 \approx \frac{25}{3} \mathrm{GeV},$$

$$m_{\phi_8}^2 = \frac{M_\psi}{M_\psi/4 + 3M_\chi/4} m_\phi^2 \approx 3.5 \mathrm{MeV}.$$

Radiative corrections from QCD [24,25] are

$$\delta m_3^2 \simeq \frac{4}{3} \Delta \simeq (650 \mathrm{GeV})^2 \frac{f_\phi}{\sqrt{N} \times 400 \mathrm{GeV}},$$

$$\delta m_8^2 \simeq 3 \Delta \simeq (970 \mathrm{GeV})^2 \frac{f_\phi}{\sqrt{N} \times 400 \mathrm{GeV}}.$$

$$\Delta = \frac{\alpha_s(\Lambda_S)}{\alpha(\Lambda_{QCD})} \Lambda_{QCD}^2 (m_{\phi_3}^2 - m_{\phi_8}^2),$$

where the gauge couplings are evaluated at their respective dynamical scales, $m_{\phi_8}$ and $m_{\phi_3}$ are the neutral and charged pion masses and we have used $\Lambda_S/\Lambda_{QCD} \sim \sqrt{3/N} f_\phi/2$ from NDA. Because of the QCD radiative correction, the colored pNG bosons obtain large masses compared to the singlet pNG boson. Furthermore, when the color triplet fermion $\psi$ is heavier than the singlet $\chi$, $M_\psi \gtrsim M_\chi$, the colored pNG bosons obtain large masses from the explicit chiral symmetry breaking. Hereafter, we focus on a situation where the lightest new hadron is the singlet pNG boson $\phi$.

**B. The effective interactions**

To discuss LHC phenomenology of the pNG bosons, we here present their effective interactions with the SM gauge bosons. It is important that the coefficients of these interactions are determined by the 't Hooft's anomaly matching condition like $\pi^0 \rightarrow \gamma\gamma$ in the ordinary QCD (see e.g. Ref. [26]). We now write the pNG bosons collectively as $\pi_i = (\phi_3^a T_3^a + \phi_3^i T_3^i)^1 + \phi_1^i$, where $a = 1, \ldots, 8$ and $i = 1, \ldots, 3$ are the indices of the adjoint and fundamental representations of the $SU(3)_C$ gauge group. The generators of the $SU(4)$ are given by

$$T_{ij}^a = \frac{1}{6} \left( \begin{array}{cc} \lambda^a & 0 \cr 0 & \lambda^a \end{array} \right), \quad T_1 = \frac{1}{2\sqrt{6}} \left( \begin{array}{cc} \lambda^a & 0 \cr 0 & -3 \end{array} \right),$$

$$(T_3^8)_{ij} = \delta_{ij} / \sqrt{2}.$$

Here, $\lambda^a_j (a = 1, \ldots, 8)$ are the Gell-Mann matrices of the $SU(3)_C$ and $I, J = 1, \ldots, 4$. Then, the chiral anomaly leads to the effective Lagrangian of the pNG bosons $\pi_i$ interacting with the SM gauge bosons without precise knowledge of particles inside the loops, known as Wess-Zumino-Witten anomaly [27,29]. The result is given by

$$\mathcal{L}_{\text{eff}} = - \frac{N}{8\pi^2 f_\phi} \text{tr}[\pi_i F_{\mu\nu} \tilde{F}^{\mu\nu}],$$

where the field strength $\tilde{F}$ is defined as $F_{\mu\nu} \equiv g_s G_{\mu\nu} T_8 + g_Y B_{\mu\nu} Q_Y$. Here $G$ and $B$ are the field strengths of the $SU(3)_C$ and $U(1)_Y$ gauge groups, $g_Y$ is the $U(1)_Y$ gauge coupling and $Q_Y \equiv \text{diag}(-1/3, -1/3, -1/3, 1)$. With the effective interaction Eq. (11), we can discuss LHC phenomenology of the pNG bosons as we will see next.

**III. THE LIGHTEST PNG BOSON**

We now consider LHC phenomenology of the singlet pNG boson and show that the reported excess can be explained by this boson $\phi$ with mass of 750 GeV. We can extract the interactions of $\phi$ with the SM gauge bosons from Eq. (11) as

$$\mathcal{L}_{\phi, F_\phi} = - \frac{N}{\sqrt{6}} \frac{g_s^2}{f_{\phi}} \frac{1}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{16N}{3\sqrt{6}} \frac{e^2}{f_{\phi}} \frac{1}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{32N}{3\sqrt{6}} \frac{e^2}{f_{\phi}} \frac{1}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{16N}{3\sqrt{6}} \frac{e^2}{f_{\phi}} \frac{1}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{16N}{3\sqrt{6}} \frac{e^2}{f_{\phi}} \frac{1}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu},$$

where $Z_{\mu\nu}$ is the field strength of the $Z$ boson, $e$ is the electric charge and we have defined $t_W \equiv \tan \theta_W$ for simplicity. Then, we can compare these effective interactions with the Lagrangian of Eq. (11), which leads to $k_\gamma/\Lambda_\gamma = 8N/(3\sqrt{6} f_{\phi})$ and $k_\phi/\Lambda_\phi = -N/(2\sqrt{6} f_{\phi})$. Note that we can take $(k_\gamma/\Lambda_\gamma)^{-1}$ to be around 100 GeV by choosing $f_\phi$. This is consistent with $m_\phi \approx 750$ GeV for appropriate values of $M_\psi$, $M_\chi$ by virtue of new strong dynamics.

Given the effective interactions, the lightest pNG boson is efficiently produced with gluon fusion and decays into a pair of the SM gauge bosons at the LHC. The
decay widths of $\phi$ are calculated as

$$
\Gamma(\phi \rightarrow gg) = \frac{N^2 \alpha_s^2 m_\phi^3}{192\pi^3 f_S^2}, \quad \Gamma(\phi \rightarrow \gamma\gamma) = \frac{N^2 \alpha_s^2 m_\phi^3}{54\pi^3 f_S^2},
$$

$$
\Gamma(\phi \rightarrow \gamma Z) = \frac{N^2 \alpha_s^2 t_W m_\phi^3}{27\pi^3 f_S^2} \left(1 - \frac{m_Z^2}{m_\phi^2}\right)^3,
$$

$$
\Gamma(\phi \rightarrow ZZ) = \frac{N^2 \alpha_s^4 t_W^2 m_\phi^4}{54\pi^3 f_S^2} \left(1 - \frac{m_Z^2}{m_\phi^2}\right)^{3/2},
$$

where $m_Z$ is the Z boson mass. Although these widths depend on $f_S$, their ratios are independent. When we fix the mass of $\phi$ as $m_\phi = 750$ GeV, the ratios are numerically given by

$$
\Gamma(gg) : \Gamma(\gamma\gamma) : \Gamma(\gamma Z) : \Gamma(ZZ) \\
\simeq 0.965 : 0.021 : 0.012 : 0.002.
$$

We can see that the decay to two gluons is dominant and the decay to diphoton is next. By using the MSTW PDF [15], we obtain the production cross section times branching ratio for the decays to two gluons and photons (up to NLO uncertainty which is beyond the scope of the present paper),

$$
\sigma(pp \rightarrow \phi + X) Br(\phi \rightarrow gg) \\
\simeq \left(\frac{N}{3}\right)^2 \left(\frac{f_S}{400 \text{ GeV}}\right)^{-2} \times \left\{ \begin{array}{l}
56 \text{ fb} \ (8 \text{ TeV}) \\
220 \text{ fb} \ (13 \text{ TeV})
\end{array} \right.,
$$

$$
\sigma(pp \rightarrow \phi + X) Br(\phi \rightarrow \gamma\gamma) \\
\simeq \left(\frac{N}{3}\right)^2 \left(\frac{f_S}{400 \text{ GeV}}\right)^{-2} \times \left\{ \begin{array}{l}
1.2 \text{ fb} \ (8 \text{ TeV}) \\
5.8 \text{ fb} \ (13 \text{ TeV})
\end{array} \right..\tag{15}
$$

We have shown the cases of $\sqrt{s} = 8$ and 13 TeV for each decay.

In Fig. 2, we show the lightest pNG boson signal expected at the LHC run of $\sqrt{s} = 13$ TeV. The lines are $\sigma$-Br of $\phi \rightarrow gg, \gamma\gamma, Z\gamma, ZZ$ from a gluon fusion production with $m_\phi = 750$ GeV. The PDF uncertainty is given by a band along with each line. Upper bounds (95% C.L.) from resonance searches at $\sqrt{s} = 8$ TeV in $\gamma\gamma$ [30], $ZZ$ [31] and $Z(\rightarrow l\ell)\gamma$ [32] final states are rescaled by a ratio of cross section, $\sigma_{\text{ATLAS}}^{\text{ggF}}/\sigma_{\text{CMS}}^{\text{ggF}}$, and plotted as dashed lines. For $\sqrt{s} = 13$ TeV results, the orange shaded region is consistent with an excess of $\gamma\gamma$ resonance reported by ATLAS [33] while CMS places an upper bound in the similar analysis (red dashed line) [34].

The results of ATLAS and CMS are consistent, and the excess can be explained by $f_S/N(3)^{-1} = 250–800$ GeV. Other upper bounds are obtained by relevant resonance searches at $\sqrt{s} = 8$ TeV in $\gamma\gamma$ [30], $ZZ$ [31], and $Z(\rightarrow l\ell)\gamma$ [32], which are rescaled by a ratio of $\sigma_{\text{ATLAS}}^{\text{ggF}}/\sigma_{\text{CMS}}^{\text{ggF}} \approx 4.7$ in Fig. 2. For the $Z(\rightarrow l\ell)\gamma$ bound [32], the signal efficiency within the fiducial volume is assumed to be 80%.

If the diphoton signal will be established, the next evidence is expected in $Z\gamma$ resonance. Based on the current sensitivity [32], the prospect at $\sqrt{s} = 14$ TeV estimated by rescaling the gluon parton luminosity is that the interesting parameter space of $f_S/N(3)^{-1} \lesssim 800$ GeV can be proven with 300 fb$^{-1}$ at 95% C.L.

IV. EXOTIC HADRONS

In addition to the singlet pNG boson $\phi$, there are the color octet ($\phi_8$) and triplet ($\phi_3$) pNG bosons. The model also has baryonic states whose masses are around a TeV. Some of them are within the reach of the LHC experiment. In this section, we discuss the phenomenology...
of the color octet scalar and also comment on the other bound states.

A. The octet pNG boson

We here consider the color octet pNG boson \( \phi_8 \). As in the case with the lightest pNG boson, the octet \( \phi_8 \) has the interaction terms with the SM gauge bosons from the chiral anomaly, which can be read from Eq. (11) as

\[
\mathcal{L}_{\phi_8} = - \frac{N g_s^2}{32 \pi^2} \phi_8^a G^{b \mu \nu} d_{ab}^{\mu \nu} - \frac{N g_\gamma e}{24 \pi} \phi_8^a G^{\mu \nu} F^{\mu \nu} + \frac{N g_\gamma e t_W}{24 \pi} \phi_8^a G^{\mu \nu} \tilde{Z}^{\mu \nu}. \tag{17}
\]

Here, we have used \( \{ \lambda^i, \lambda^j \} = (4/3) \delta_{ij} + 2 d_{abc} \lambda^a \) and \( \text{tr}[\lambda^i \lambda^j] = 2 \delta^{ij} \). The decay widths of \( \phi_8 \) into two SM gauge bosons are then calculated as

\[
\Gamma(\phi_8 \to gg) = \frac{5 m_{\phi_8}^3}{4 m_{\phi_8}^2} \Gamma(\phi \to gg),
\]

\[
\Gamma(\phi_8 \to g\gamma) = \frac{2}{3} \alpha_s \frac{m_{\phi_8}^2}{m_{\phi_8}} \Gamma(\phi \to gg), \tag{18}
\]

\[
\Gamma(\phi_8 \to gZ) = \frac{2}{3} \alpha_s \frac{m_{\phi_8}^2}{m_{\phi_8}} \left( 1 - \frac{m_Z^2}{m_{\phi_8}^2} \right)^3 \Gamma(\phi \to gg),
\]

where \( \sum_{abc} d_{abc} d_{bcd} = (5/3) \delta_{ad} \) has been used. When we take \( m_{\phi_8} = 750 \text{ GeV} \) and \( m_{\phi_8} = 1300 \text{ GeV} \), the ratios of the decay modes are numerically given by \( \Gamma(\phi gg) : \Gamma(\phi g\gamma) : \Gamma(\phi gZ) \approx 0.943 : 0.044 : 0.013 \). We can see that the decay to two gluons is dominant and the decay to a gluon and a photon is next.

In addition to the decay modes to the SM gauge bosons, the octet scalar can decay into \( \phi \) because \( \phi_8 \) is heavier than the singlet \( \phi \). While \( \phi_8 \to \phi g \) is prohibited by angular momentum conservation \( \frac{m_\phi}{4 m_{\phi_8}} \) suppressed by the following term in chiral perturbation (see the \( L_{\phi \phi} \) term in Ref. [23]),

\[
( g_\gamma^2 / 16 \pi^2 f_\pi^2 ) \phi \phi \xi G^{b \mu \nu} G^{\mu \nu} d_{abc}. \]

However, this three body decay receives phase space suppression compared to the decays to the SM gauge bosons such as \( \phi_8 \to gg \) and can be neglected.

For a future prospect, rescaling the current sensitivity of the jet+\( \gamma \) resonance search for \( m_{\phi_8} = 1.5 \text{ TeV} \) to that of \( \sqrt{s} = 14 \text{ TeV} \) with 3000 fb\(^{-1} \), the octet scalar with \( f_S(N/3)^{-1} \lesssim 500 \text{ GeV} \) can be probed at the LHC.

B. The triplet pNG boson

We next consider the triplet scalar \( \phi_3 \) briefly. Since \( \phi_3 \) has the hypercharge \(-4/3\), it cannot decay into the SM gauge bosons. Then, the triplet decays into the SM fermions via the following dimension 6 operator, \( \Delta \mathcal{L}_{\phi_3} \sim (\lambda^i_j / \Lambda^2) (\bar{\psi} \chi) d_{R,i} e_{R,j} \), where \( \lambda^i_j \) are coupling constants, \( \Lambda' \) is some mass scale, and the indices \( i, j \) here denote three generations of the SM fermions. If we take a sufficiently small \( \Lambda' \), the triplet \( \phi_3 \) decays promptly in the LHC experiment. The constraint on \( \phi_3 \) depends on the detailed flavor structure of the \( \lambda^i_j \) couplings. When \( \phi_3 \) mainly decays into an electron or a muon and a light quark, the present upper bound on the mass \( m_{\phi_3} \) is around 1 TeV \( [37] \). If \( \phi_3 \) mainly decays into a tau lepton and a bottom quark, the bound becomes slightly weaker and is around 750 GeV \( [38] \).

C. The baryons

Finally, we look at the baryons in the present model. The mass of the light baryons can be estimated by the scaling-up argument as \( [39] \)

\[
m_B \simeq m_p f_S \sqrt{N/3} \simeq 4 \text{ TeV} \times \sqrt{N/3} \left( \frac{f_S}{400 \text{ GeV}} \right), \tag{19}
\]

where \( m_p \) is the proton mass. The mass parameters of \( M_{\phi_8} \) and \( \Lambda \) generate mass splitting between the light baryons and the lightest baryon is \( \chi^N \) for \( M_{\phi_8} > \Lambda \). The decay of this baryon is induced by the following higher dimensional operator,

\[
\Delta \mathcal{L}_B \sim (\lambda^i_{1 i \cdots i_N} / \Lambda^m N!) \chi^N e_{R,1} \cdots e_{R,N}, \]

where \( \lambda^i_{1 i \cdots i_N} \) are coupling constants, and \( \Lambda' \) is some mass scale. If we take a sufficiently small \( \Lambda' \), the lightest baryon \( \chi^N \) decays before the era of the Big Bang Nucleosynthesis. The detailed analyses are left for future investigations.

V. CONCLUSION

In this paper, from the viewpoint of the prevailing nature of new strong dynamics, we have pursued a possibility of a new asymptotically free gauge theory to be explored at the LHC. Motivated by the reported event excess in diphoton invariant mass distribution, we have discussed a scenario that the lightest color-singlet pNG boson of a new QCD-like theory is produced by gluon fusion and decays into a pair of the SM gauge bosons. Despite the strong dynamics, the production cross section and the decay widths are calculated by the chiral anomaly. The excess can be explained by the pNG boson with mass of around 750 GeV. The pNG boson will yield \( Z \gamma \) resonance. The model also predicts exotic hadrons such as color octet and triplet scalars and baryons some of which are within the reach of the LHC experiment.

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[1] C. T. Hill and E. H. Simmons, “Strong dynamics and electroweak symmetry breaking,” *Phys. Rept.* **381** (2003) 235–402 [arXiv:hep-ph/0203079 [hep-ph]] [Erratum: *Phys. Rept.* **390**, 553(2004)].

[2] L. Randall and R. Sundrum, “A Large mass hierarchy from a small extra dimension,” *Phys. Rev. Lett.* **83** (1999) 3370–3373 [arXiv:hep-ph/9905221 [hep-ph]].

[3] E. Katz, J.-y. Lee, A. E. Nelson, and D. G. E. Walker, “A Composite little Higgs model,” *JHEP* **10** (2005) 088 [arXiv:hep-ph/0312287 [hep-ph]].

[4] S. P. Martin, “A Supersymmetry primer,” [arXiv:hep-ph/9709356 [hep-ph]] [Adv. Ser. Direct. High Energy Phys.**18**,1 (1998)].

[5] E. Witten, “Dynamical Breaking of Supersymmetry,” *Nucl. Phys.* **B188** (1981) 513.

[6] Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, and J. G. Wacker, “Model for Thermal Relic Dark Matter of Strongly Interacting Massive Particles,” *Phys. Rev. Lett.* **115** no. 2, (2015) 021301 [arXiv:1411.3727 [hep-ph]].

[7] C. Kilic, T. Okui, and R. Sundrum, “Vectorlike Confinement at the LHC,” *JHEP* **02** (2010) 018 [arXiv:0906.5077 [hep-ph]].

[8] M. J. Strassler and K. M. Zurek, “Echoes of a hidden valley at hadron colliders,” *Phys. Lett.* **B651** (2007) 374–379 [arXiv:hep-ph/0604261 [hep-ph]].

[9] M. J. Strassler, “Possible effects of a hidden valley on supersymmetric phenomenology,” [arXiv:hep-ph/0607160 [hep-ph]].

[10] Y. Nakai, M. Reece, and R. Sato, “SUSY Higgs Mass and Collider Signals with a Hidden Valley,” [arXiv:1511.00691 [hep-ph]].

[11] “ATLAS and CMS physics results from Run 2.” https://indico.cern.ch/event/442432/

[12] G. G. Raffelt, “Astrophysical axion bounds,” *Lect. Notes Phys.* **741** (2008) 51–71 [arXiv:hep-ph/0611350 [hep-ph]] [51(2006)].

[13] H. M. Georgi, S. L. Glashow, M. E. Machacek, and D. V. Nanopoulos, “Higgs Bosons from Two Gluon Annihilation in Proton Proton Collisions,” *Phys. Rev. Lett.* **40** (1978) 692.

[14] R. N. Cahn and S. Dawson, “Production of Very Massive Higgs Bosons,” *Phys. Lett.* **B136** (1984) 196 [Erratum: *Phys. Lett.*B138,464(1984)].

[15] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Parton distributions for the LHC,” *Eur. Phys. J.* **C63** (2009) 189–285 [arXiv:0901.0002 [hep-ph]].

[16] S. Dimopoulos, “Technicolored Signatures,” *Nucl. Phys.* **B168** (1980) 69–92.

[17] S. Dimopoulos, S. Raby, and G. L. Kane, “Experimental Predictions from Technicolor Theories,” *Nucl. Phys.* **B182** (1981) 77–103.

[18] M. A. Luty, “Naive dimensional analysis and supersymmetry,” *Phys. Rev.* **D57** (1998) 1531–1538 [arXiv:hep-ph/9706235 [hep-ph]].

[19] E. Ponton, “TASI 2011: Four Lectures on TeV Scale Extra Dimensions,” in *The Dark Secrets of the Terascale*, pp. 283–374. 2013. [arXiv:1207.3827 [hep-ph]].

[20] J. E. Kim, “A COMPOSITE INVISIBLE AXION,” *Phys. Rev.* **D31** (1985) 1733.

[21] G. Cacciapaglia, A. Deandrea, and M. Hashimoto, “Scalar Hint from the Diboson Excess?,” *Phys. Rev. Lett.* **115** no. 17, (2015) 171802 [arXiv:1507.03098 [hep-ph]].

[22] H. Cai, T. Flacke, and M. Lepsina, “A composite scalar hint from di-boson resonances?,” [arXiv:1512.04508 [hep-ph]].

[23] J. Gaspar and H. Leutwyler, “Chiral Perturbation Theory: Expansions in the Mass of the Strange Quark,” *Nucl. Phys.* **B250** (1985) 465.

[24] E. Farhi and L. Susskind, “Technicolor,” *Phys. Rept.* **74** (1981) 277.

[25] B. A. Dobrescu, “The Strong CP problem versus Planck scale physics,” *Phys. Rev.* **D55** (1997) 5826–5833 [arXiv:hep-ph/9609221 [hep-ph]].

[26] S. Weinberg, “The quantum theory of fields. Vol. 2: Modern applications.” Cambridge University Press, 2013.

[27] J. Wess and B. Zumino, “Consequences of anomalous Ward identities,” *Phys. Lett.* **B37** (1971) 95.

[28] E. Witten, “Global Aspects of Current Algebra,” *Nucl. Phys.* **B223** (1983) 422–432.

[29] E. Witten, “Current Algebra, Baryons, and Quark Confinement,” *Nucl. Phys.* **B223** (1983) 433–444.

[30] CMS Collaboration, V. Khachatryan et al., “Search for diphoton resonances in the mass range from 150 to 850 GeV in pp collisions at $\sqrt{s} = 8$ TeV,” *Phys. Lett.* B750 (2015) 494–519. [arXiv:1506.02301 [hep-ex]].

[31] ATLAS Collaboration, G. Aad et al., “Search for an additional, heavy Higgs boson in the $H \rightarrow ZZ$ decay channel at $\sqrt{s} = 8$ TeV in pp collision data with the ATLAS detector,” [arXiv:1507.05930 [hep-ex]].

[32] ATLAS Collaboration, G. Aad et al., “Search for new resonances in W+Z and Z+Z final states in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *Phys. Lett.* B738 (2014) 428–447. [arXiv:1407.8150 [hep-ex]].

[33] ATLAS Collaboration, “Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” Tech. Rep. ATLAS-CONF-2015-081, CERN, Geneva, Dec, 2015. https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-081/

[34] CMS Collaboration, “Search for new physics in high mass diphoton events in proton-proton collisions at 13 TeV,” Tech. Rep. CMS-PAS-EXO-15-004, CERN, Geneva, Dec, 2015. http://cds.cern.ch/record/2114808.

[35] J. J. Sakurai, *Invariance Principles and Elementary Particles*. Princeton University Press, 1964.

[36] ATLAS Collaboration, G. Aad et al., “Search for new phenomena with photon+jet events in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector,” [arXiv:1512.05910 [hep-ex]].
[37] ATLAS Collaboration, G. Aad et al., “Searches for scalar leptoquarks in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” arXiv:1508.04735 [hep-ex].

[38] CMS Collaboration, V. Khachatryan et al., “Search for pair production of third-generation scalar leptoquarks and top squarks in protonproton collisions at $\sqrt{s} = 8$ TeV,” Phys. Lett. B739 (2014) 229–249, arXiv:1408.0806 [hep-ex].

[39] R. S. Chivukula and T. P. Walker, “TECHNICOLOR COSMOLOGY,” Nucl. Phys. B329 (1990) 445.