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

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The chiral anomaly provides 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 an 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.

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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 [1] (the holographic picture of) Randall-Sundrum scenarios [2] and a class of little Higgs models [3], involve new strong dynamics. Even in supersymmetry [4], the breaking scale is often assumed to be given by dimensional transmutation of a new gauge theory [5]. In addition, the dark matter can be like a new pion originating from strong dynamics [6]. Furthermore, string theory seems to prefer nonminimal 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. [As a scenario with similar motivation, vectorlike confinement was studied in Ref. [7]. For a different confinement scale, there is the hidden valley scenario [8] (see, also, Refs. [9,10])].

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

$$\mathcal{L}_{\mathrm{eff}} = \frac{\alpha}{4\pi}\frac{k_\gamma}{\Lambda_\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_s}{4\pi}\frac{k_g}{\Lambda_g}\phi G^a_{\mu\nu}\tilde{G}^{a\mu\nu}, \tag{1}$$

where F denotes the field strength of the photon, $\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$, and G indicates the gluon field strength. k_γ and k_g are dimensionless constants and Λ_γ, Λ_g are mass parameters. From the effective interactions of Eq. (1), the widths of ϕ decays into gg and $\gamma\gamma$ are calculated as [12]

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

where m_ϕ is the mass of ϕ. With a natural assumption $k_\gamma/\Lambda_\gamma \sim k_g/\Lambda_g$, the scalar boson ϕ 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 the diphoton as $\mathrm{Br}(\phi \to \gamma\gamma) \simeq \Gamma(\phi \to \gamma\gamma)/\Gamma(\phi \to gg)$. By using the narrow width approximation [13,14], the production cross section times branching ratio is then estimated as

$$\sigma(pp \to \phi + X)\mathrm{Br}(\phi \to \gamma\gamma) \simeq \frac{\pi^2}{8 m_\phi s}\Gamma(\phi \to \gamma\gamma) \times \int_0^1 dx_1 \int_0^1 dx_2 [\delta(x_1 x_2 - m_\phi^2/s) g(x_1) g(x_2)], \tag{3}$$

where s is the square of the 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 Martin-Stirling-Thorne-Watt (MSTW) [15] PDF. For $m_\phi = 750$ GeV, the quantity of Eq. (3) is given by

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

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, Λ_γ, Λ_g ($\gtrsim m_\phi$) are given by typical mass scales of the heavy particles. For fitting the reported event number, Eq. (4) indicates that the combination of the parameters Λ_γ/k_γ must be around 100 GeV. Since the scalar mass is $m_\phi \simeq 750$ GeV, it is suggested that the dimensionless constant k_γ is much larger than 1. That is, we need some strong dynamics to explain the reported diphoton excess. Alternatively, we can consider a scenario in which ϕ is

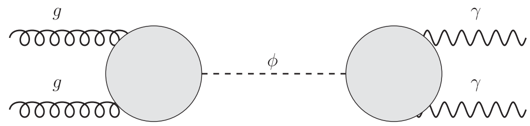

FIG. 1. A new scalar ϕ is produced by gluon fusion and decays into two photons. In our model, the effective interactions are from the chiral anomaly.

produced by quark antiquark 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 $k_\gamma/\Lambda_\gamma \sim (100\ \mathrm{GeV})^{-1}$.

In this Letter, 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 't Hooft's anomaly matching condition like $\pi^0 \to \gamma\gamma$ 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 Letter is organized as follows. In the next section, 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. After that, we discuss the collider phenomenology of the lightest PNG boson and explain the reported event excess. Next, the phenomenology of exotic hadrons such as color-octet and -triplet scalars and baryons is described. We make some concluding remarks in the last section.

A new QCD.—Let us consider an asymptotically free $SU(N)$ gauge theory with new Weyl fermions, ψ, $\bar{\psi}$ (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 vectorlike masses,

$$\mathcal{L} \supset -M_\psi \psi\bar{\psi} - M_\chi \chi\bar{\chi}, \tag{5}$$

where M_ψ and M_χ 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_ψ, M_χ, 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,

TABLE I. The charge assignments of the new fermions.

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(N)$
ψ	$\mathbf{3}$	$\mathbf{1}$	$-1/3$	$\mathbf{N}$
χ	$\mathbf{1}$	$\mathbf{1}$	1	$\mathbf{N}$
$\bar{\psi}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$\bar{\mathbf{N}}$
$\bar{\chi}$	$\mathbf{1}$	$\mathbf{1}$	-1	$\bar{\mathbf{N}}$

$$\langle\psi\bar{\psi}\rangle \sim \frac{4\pi}{\sqrt{N}} f_S^3 \mathbf{1}, \qquad \langle\chi\bar{\chi}\rangle \sim \frac{4\pi}{\sqrt{N}} f_S^3, \tag{6}$$

where f_S is the decay constant, and we have used naive dimensional analysis (NDA) for counting the factors of 4π and N (see, e.g., Refs. [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. (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 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.) 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 $\mathbf{15} \to \mathbf{8} + \mathbf{3} + \bar{\mathbf{3}} + \mathbf{1}$. In the following discussion, we denote the $SU(3)_C$ octet, triplet, and singlet PNG bosons as ϕ_8, ϕ_3, and ϕ, respectively.

The masses of the PNG bosons: We now estimate the masses of the PNG bosons by using chiral perturbation theory (for a review, see Ref. [23]). The dependence on the mass parameters M_ψ, M_χ 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 Λ_S. Then, we estimate the squared mass of the singlet PNG boson by scaling up the formula for the QCD pion mass m_π. The result is given by

$$\begin{aligned} m_\phi^2 &\simeq \sqrt{\frac{3}{N}} \frac{M_\psi/4 + 3M_\chi/4}{(m_u + m_d)/2} \frac{f_S}{f_\pi} m_\pi^2 \\ &\simeq (750\ \mathrm{GeV})^2 \times \sqrt{\frac{3}{N}} \left(\frac{M_\psi/4 + 3M_\chi/4}{25\ \mathrm{GeV}}\right) \\ &\quad \times \left(\frac{f_S}{400\ \mathrm{GeV}}\right) \left(\frac{(m_u + m_d)/2}{3.5\ \mathrm{MeV}}\right), \end{aligned} \tag{7}$$

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

Once we fix the mass of the singlet PNG boson m_ϕ, 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

$$\begin{aligned} m_{\phi_3}^2 &= \frac{M_\psi/2 + M_\chi/2}{M_\psi/4 + 3M_\chi/4} m_\phi^2 + \delta m_3^2, \\ m_{\phi_8}^2 &= \frac{M_\psi}{M_\psi/4 + 3M_\chi/4} m_\phi^2 + \delta m_8^2. \end{aligned} \tag{8}$$

Radiative corrections from QCD [24,25] are

$$\delta m_3^2 \simeq \frac{4}{3}\Delta \simeq (650\ \mathrm{GeV})^2 \times \frac{3}{N}\left(\frac{f_S}{400\ \mathrm{GeV}}\right)^2,$$
$$\delta m_8^2 \simeq 3\Delta \simeq (970\ \mathrm{GeV})^2 \times \frac{3}{N}\left(\frac{f_S}{400\ \mathrm{GeV}}\right)^2,$$
$$\Delta \equiv \frac{\alpha_s(\Lambda_S)}{\alpha(\Lambda_{\mathrm{QCD}})}\frac{\Lambda_S^2}{\Lambda_{\mathrm{QCD}}^2}(m_{\pi^\pm}^2 - m_{\pi^0}^2), \qquad (9)$$

where the gauge couplings are evaluated at their respective dynamical scales, m_{π^0} and $m_{\pi^\pm}$ are the neutral and charged pion masses, and we have used $\Lambda_S/\Lambda_{\mathrm{QCD}} \sim \sqrt{3/N} f_S/f_\pi$ 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 ψ is heavier than the singlet χ, $M_\psi \gtrsim M_\chi$, 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 ϕ.

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 't Hooft's anomaly matching condition like $\pi^0 \to \gamma\gamma$ in the ordinary QCD (see, e.g., Ref. [26]). We now write the PNG bosons collectively as $\pi_s \equiv \phi_8^a T_8^a + \phi_3^i T_3^i + (\phi_3^i T_3^i)^\dagger + \phi T_1$, where $a = 1, \ldots, 8$ and $i = 1, \ldots, 3$ are the indices of the adjoint and fundamental representations of the $\mathrm{SU}(3)_C$ gauge group. The generators of the SU(4) are given by

$$T_8^a = \frac{1}{2}\begin{pmatrix} \lambda^a & 0_{1\times 3} \\ 0_{3\times 1} & 0 \end{pmatrix}, \quad T_1 = \frac{1}{2\sqrt{6}}\begin{pmatrix} 1_{3\times 3} & 0_{1\times 3} \\ 0_{3\times 1} & -3 \end{pmatrix},$$
$$(T_3^k)_{IJ} = \delta_{4I}\delta_{Jk}/\sqrt{2}. \qquad (10)$$

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

$$\mathcal{L}_{\mathrm{eff}} = -\frac{N}{8\pi^2 f_S}\mathrm{tr}[\pi_s \mathcal{F}_{\mu\nu}\tilde{\mathcal{F}}^{\mu\nu}], \qquad (11)$$

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

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 ϕ with mass of 750 GeV. We can extract the interactions of ϕ with the SM gauge bosons from Eq. (11) as

$$\mathcal{L}_{\phi\mathcal{F}\tilde{\mathcal{F}}} = -\frac{N}{\sqrt{6}}\frac{\phi}{f_S}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{16N}{3\sqrt{6}}\frac{\phi}{f_S}\frac{e^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$-\frac{32N}{3\sqrt{6}}\frac{\phi}{f_S}\frac{e^2 t_W}{32\pi^2}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{16N}{3\sqrt{6}}\frac{\phi}{f_S}\frac{e^2 t_W^2}{32\pi^2}Z_{\mu\nu}\tilde{Z}^{\mu\nu}, \qquad (12)$$

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. (1), which leads to $k_\gamma/\Lambda_\gamma = 8N/(3\sqrt{6}f_S)$ and $k_g/\Lambda_g = -N/(2\sqrt{6}f_S)$. Note that we can take $(k_\gamma/\Lambda_\gamma)^{-1}$ to be around 100 GeV by choosing f_S. This is consistent with $m_\phi \simeq 750$ GeV for appropriate values of M_ψ, M_χ 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 ϕ are calculated as

$$\Gamma(\phi \to gg) = \frac{N^2\alpha_s^2 m_\phi^3}{192\pi^3 f_S^2},$$
$$\Gamma(\phi \to \gamma\gamma) = \frac{N^2\alpha^2 m_\phi^3}{54\pi^3 f_S^2},$$
$$\Gamma(\phi \to \gamma Z) = \frac{N^2\alpha^2 t_W^2 m_\phi^3}{27\pi^3 f_S^2}\left(1 - \frac{m_Z^2}{m_\phi^2}\right)^3,$$
$$\Gamma(\phi \to ZZ) = \frac{N^2\alpha^2 t_W^4 m_\phi^3}{54\pi^3 f_S^2}\left(1 - \frac{4m_Z^2}{m_\phi^2}\right)^{3/2}, \qquad (13)$$

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 ϕ as $m_\phi = 750$ GeV, the ratios are numerically given by

$$\Gamma(gg):\Gamma(\gamma\gamma):\Gamma(\gamma Z):\Gamma(ZZ)$$
$$\simeq 0.965:0.021:0.012:0.002. \qquad (14)$$

We can see that the decay to two gluons is dominant, and the decay to the 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 next-to-leading-order uncertainty, which is beyond the scope of the present Letter),

$$\sigma(pp \to \phi + X)\mathrm{Br}(\phi \to gg)$$
$$\simeq \left(\frac{N}{3}\right)^2\left(\frac{f_S}{400\ \mathrm{GeV}}\right)^{-2} \times \begin{cases} 56\ \mathrm{fb} & (8\ \mathrm{TeV}) \\ 220\ \mathrm{fb} & (13\ \mathrm{TeV}), \end{cases}$$
$$\sigma(pp \to \phi + X)\mathrm{Br}(\phi \to \gamma\gamma)$$
$$\simeq \left(\frac{N}{3}\right)^2\left(\frac{f_S}{400\ \mathrm{GeV}}\right)^{-2} \times \begin{cases} 1.2\ \mathrm{fb} & (8\ \mathrm{TeV}) \\ 5.8\ \mathrm{fb} & (13\ \mathrm{TeV}). \end{cases} \qquad (15)$$

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 σBr of $\phi \to gg, \gamma\gamma, Z\gamma, ZZ$ from a gluon fusion production with $m_\phi = 750$ GeV. The PDF uncertainty is given by a band along with each line. The CMS diphoton resonance search with integrated luminosity $\mathcal{L} = 2.6\ \text{fb}^{-1}$ places an upper bound, $\sigma\text{Br}_{\gamma\gamma} \lesssim 15$ fb [30]. Based on an excess in the corresponding search of ATLAS with $\mathcal{L} = 3.2\ \text{fb}^{-1}$ [31], we estimate the allowed region in the following way. We take the two bins nearest to 750 GeV (Fig. 1 in Ref. [31]), which have 23 numbers of events and 10.5 expected background. Using a log-likelihood ratio constructed from the Poisson probability distribution function, we find the allowed number of signals S is from 4.3 to 23 events at 95% C.L. Systematic uncertainties are assumed to be subdominant since the statistical error is large. When it is rescaled to σBr, we vary the acceptance times efficiency $\mathcal{A}\epsilon = 40\%–100\%$, and, therefore, we obtain

$$1.4\ \text{fb} \lesssim \sigma\text{Br}_{\gamma\gamma} = \frac{S}{\mathcal{L}(\mathcal{A}\epsilon)} \lesssim 18\ \text{fb}\,(95\%\text{C.L.}). \quad (16)$$

These 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 $\gamma\gamma$ [32], ZZ [33], and $Z(\to ll)\gamma$ [34], which are rescaled by a ratio of $\sigma^{ggF}_{13\ \text{TeV}}/\sigma^{ggF}_{8\ \text{TeV}} \approx 4.7$ in Fig. 2. For the $Z(\to ll)\gamma$ bound [34], 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 the $Z\gamma$ resonance. Based on the current sensitivity [34], 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.

Exotic hadrons.—In addition to the singlet PNG boson ϕ, there are the color-octet (ϕ_8) and -triplet (ϕ_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.

The octet PNG boson: We here consider the color-octet PNG boson ϕ_8. As in the case with the lightest PNG boson, the octet ϕ_8 has the interaction terms with the SM gauge bosons from chiral anomaly, which can be read from Eq. (11) as

$$\mathcal{L}_{\phi_8\mathcal{F}\tilde{\mathcal{F}}} = -\frac{Ng_s^2}{32\pi^2 f_S}\phi_8^a G^b_{\mu\nu}\tilde{G}^{c\mu\nu}d_{abc} - \frac{Ng_s e}{24\pi^2 f_S}\phi_8^a G^a_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{Ng_s e t_W}{24\pi^2 f_S}\phi_8^a G^a_{\mu\nu}\tilde{Z}^{\mu\nu}. \quad (17)$$

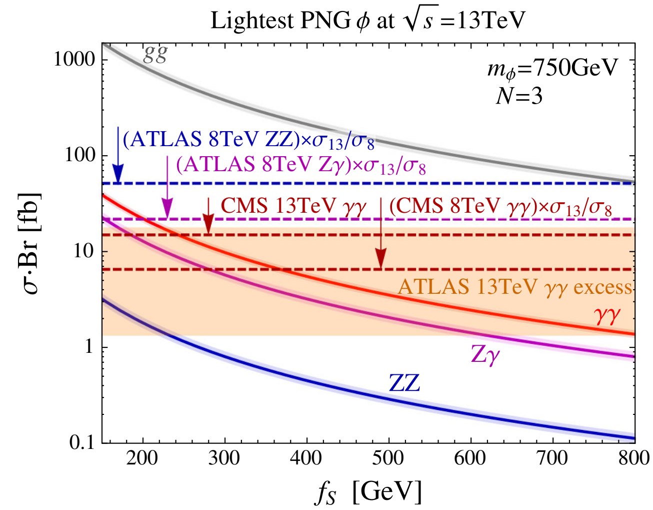

FIG. 2. The lightest PNG boson signal expected at the LHC run of $\sqrt{s} = 13$ TeV. The lines are σBr of $\phi \to gg, \gamma\gamma, Z\gamma, ZZ$ from a gluon fusion production with $m_\phi = 750$ GeV. Here, SU(3) new strong dynamics is adopted. The PDF uncertainty is given by a band along with each line. Upper bounds (95% C.L.) from resonance searches at $\sqrt{s} = 8$ TeV in $\gamma\gamma$ [32], ZZ [33], and $Z(\to ll)\gamma$ [34] final states are rescaled by a ratio of cross section, $\sigma^{ggF}_{13\ \text{TeV}}/\sigma^{ggF}_{8\ \text{TeV}}$ and plotted as dashed lines. For the $\sqrt{s} = 13$ TeV results, the orange shaded region is consistent with an excess of $\gamma\gamma$ resonance reported by ATLAS [31] while CMS [30] places an upper bound in the similar analysis (red dashed line).

Here, we have used $\{\lambda^b, \lambda^c\} = (4/3)\delta_{bc} + 2d_{abc}\lambda^a$ and $\text{tr}[\lambda^a\lambda^b] = 2\delta^{ab}$. The decay widths of ϕ_8 into two SM gauge bosons are then calculated as

$$\Gamma(\phi_8 \to gg) = \frac{5}{4}\frac{m^3_{\phi_8}}{m^3_\phi}\Gamma(\phi \to gg),$$

$$\Gamma(\phi_8 \to g\gamma) = \frac{2}{3}\frac{\alpha}{\alpha_s}\frac{m^3_{\phi_8}}{m^3_\phi}\Gamma(\phi \to gg),$$

$$\Gamma(\phi_8 \to gZ) = \frac{2}{3}\frac{\alpha t_W^2}{\alpha_s}\frac{m^3_{\phi_8}}{m^3_\phi}\left(1 - \frac{m_Z^2}{m^2_{\phi_8}}\right)^3\Gamma(\phi \to gg), \quad (18)$$

where $\sum_{b,c} d_{abc}d_{bcd} = (5/3)\delta_{ad}$ has been used. When we take $m_\phi = 750$ GeV and $m_{\phi_8} = 1300$ GeV, the ratios of the decay modes are numerically given by $\Gamma(gg){:}\Gamma(g\gamma){:}\Gamma(gZ) \simeq 0.943{:}0.044{:}0.013$. 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 ϕ because ϕ_8 is heavier than the singlet ϕ. While $\phi_8 \to \phi g$ is prohibited by angular momentum conservation [35], the decay mode $\phi_8 \to \phi gg$ is induced by the following term in chiral perturbation (see the L_{10} term in Ref. [23]) $(g_s^2/16\pi^2 f_S^2)\phi\phi_8^a G^b_{\mu\nu}G^{c\mu\nu}d_{abc}$. 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 $m_{\phi_8} = 1.5$ TeV [36] to that of $\sqrt{s} = 14$ TeV with 3000 fb^{-1}, the octet scalar with $f_S(N/3)^{-1} \lesssim 500$ GeV can be proven at the LHC.

The triplet PNG boson: We next consider the triplet scalar ϕ_3 briefly. Since ϕ_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-six operator, $\Delta\mathcal{L}_{\phi_3} \sim (\kappa'_{ij}/\Lambda'^2)(\bar{\psi}\chi)d^c_{R,i}e^c_{R,j}$, where κ'_{ij} are coupling constants, Λ' is some mass scale, and the indices i, j here denote three generations of the SM fermions. If we take a sufficiently small Λ', the triplet ϕ_3 decays promptly in the LHC experiment. The constraint on ϕ_3 depends on the detailed flavor structure of the κ'_{ij} couplings. When ϕ_3 mainly decays into an electron or a muon and a light quark, the present upper bound on the mass m_{ϕ_3} is around 1 TeV [37]. If ϕ_3 mainly decays into a tau lepton and a bottom quark, the bound becomes slightly weaker and is around 750 GeV [38].

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]

$$m_B \simeq m_p \frac{f_S}{f_\pi}\sqrt{\frac{N}{3}} \simeq 4\ \text{TeV} \times \sqrt{\frac{N}{3}}\left(\frac{f_S}{400\ \text{GeV}}\right), \qquad (19)$$

where m_p is the proton mass. The mass parameters of M_ψ and M_χ generate mass splitting between the light baryons, and the lightest baryon is χ^N for $M_\psi > M_\chi$. The decay of this baryon is induced by the following higher-dimensional operator, $\Delta\mathcal{L}_B \sim (\kappa''_{i_1\cdots i_N}/\Lambda''^{3N-4})\bar{\chi}^N e^c_{R,i_1}\cdots e^c_{R,i_N}$, where $\kappa''_{i_1\cdots i_N}$ are coupling constants, and Λ'' is some mass scale. If we take a sufficiently small Λ'', the lightest baryon χ^N decays before the era of the big bang nucleosynthesis. The detailed analyses are left for future investigations.

Conclusion.—In this Letter, 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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Note added.—Recently, the analysis of the diphoton excess was updated by both ATLAS and CMS using $\sqrt{s} = 13$ TeV data [40]. Now, CMS reports an excess rather than only the upper bound, and ATLAS increases the significance of the excess. The mass and size of the signal are consistent within both experiments. The lightest PNGB still explains the results well, although there is small tension with the 8 TeV diphoton result by CMS [32]. Numerous studies appeared after the excess was reported, and see e.g., Refs. [41–43].

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