750 GeV dark pion: Cousin of a dark G-parity odd WIMP

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Phys. Rev. D **93**, 076009 — Published 21 April 2016

DOI: 10.1103/PhysRevD.93.076009

A 750 GeV Dark Pion: Cousin of a Dark G-parity-odd WIMP

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Abstract

We point out a potential common origin of the recently observed 750 GeV diphoton resonance and a Weakly Interacting Massive Particle (WIMP) candidate. In a dark QCD sector with an unbroken dark G-parity, the diphoton resonance could be a dark G-even pion, while the WIMP could be the lightest dark G-odd pion. Both particles are Standard Model gauge singlets and have the same decay constant. For the dark pion decay constant of around 500 GeV, both the diphoton excess at the LHC and the dark matter thermal abundance can be accommodated in our model. Our model predicts additional dark G-even and dark G-odd color-octet pions within reach of the 13 TeV LHC runs. For the $5 + \bar{5}$ model, compatible with the Grand Unified Theories, the WIMP mass is predicted to be within $(613, 750)$ GeV.

1 Introduction

Strongly coupled composite sectors are a generic prediction of asymptotically free gauge theories. As such, they have long played a role in particle physics models, not the least of which is determining the phenomenology of hadrons. In the context of physics beyond the Standard Model (BSM), they can also provide interesting and unique signals at the Large Hadron Collider (LHC) [1] and can alleviate the hierarchy problem [2]. The bound states that arise in strongly coupled sectors can have accidental discrete symmetries that suppress or eliminate their decays. For example, if the constituent "quarks" are vector-like, transform under representations of a $SU(2)$ flavor symmetry and otherwise fall into real representations of any non-Abelian gauge groups, they can be protected by a new G-parity [3], which is a generalization of charge conjugation symmetry. An approximate version of such a symmetry protects light hadrons from decaying in QCD, but is broken by electroweak interactions. A new strongly coupled composite sector could also exhibit its own G-parity. If the symmetry is exact, then the lightest G-odd particle is stable and is a candidate for dark matter. We will call the sector with new strong dynamics similar to QCD the dark QCD sector.

Recent results [4,5] from Run 2 at the LHC have hinted at a new diphoton resonance with a mass of 750 GeV. If the data are really displaying the first signs of BSM physics at the LHC, then they point to a relatively large $\sigma \times \mathrm{Br} \sim 5-10$ fb for the new resonance into diphoton. The large couplings of the neutral resonance to gluons and photons hint at a new strongly coupled sector, of which the 750 GeV particle could be a pion. Such a scenario has been considered independently in Refs. [6–14], but in this work we extend such models to a case where the new strongly coupled sector (dark QCD) has an exact dark G-parity and demonstrate that this model has a viable dark matter candidate as the lightest G-odd pion. Other potential explanations of the LHC diphoton excess have been presented in Refs. [15–22].

The dark G-odd pion, as a cousin of the 750 GeV diphoton resonance, can annihilate into photons and gluons, so that it can be a thermal relic dark matter. Its couplings to photons and gluons are related to the 750 GeV diphoton resonance couplings, because both particles arise from the same strongly coupled sector. We demonstrate below that these interactions could lead to the stable dark pion making up either a significant fraction or all of the observed dark matter. The same interactions generate potential signals for dark matter direct and indirect detection, as well as mono-X type signals at the LHC.

In addition, the relative couplings of the G-even dark pion corresponding to the 750 GeV diphoton resonance to other gauge bosons are predicted within the model with no free parameters. In particular, we provide concrete predictions for $Z\gamma$, ZZ, WW and gg observations of this unstable dark pion. The remaining dark pions in this model couple directly to QCD or electroweak gauge bosons and could lead to spectacular dijet or multi-particle signals.

The rest of this paper is structured as follows. In Section 2, we present the $5+\bar{5}$ dark QCD model and determine its basic properties in Section 2.1, compatibility with the LHC diphoton excesses in Section 2.2, and dark matter potential in Section 2.3. We briefly discuss the other $8+1+1$ model in Section 2.5 and conclude in Section 3.

2 Dark QCD Models with a Dark G-parity

As noted in Ref. [3], one could have an unbroken G parity in the dark QCD sector under the assumption that the dark quarks have real representations under the SM gauge interactions. For irreducible representations under the SM gauge group, no G-even dark pions can explain the 750 GeV diphoton resonance, at least for models in Ref. [3]. Beyond the simplest models, one could choose dark quark representations to have both a G-odd dark pion for dark matter and a G-even dark pion for the diphoton resonance. In this section, we present one representative model to discuss the correlation between the dark matter phenomenology and the diphoton-related signals.

2.1 The $5+\bar{5}$ Model

To be compatible with the Grand Unified Theories, it is natural to consider the $SU(5)_{\rm GUT}$ representations. Furthermore, to conserve the G-parity, we need to have a "real" representation of $SU(5)_{\rm GUT}$, so we introduce $5+\bar{5}$ as the first example. [1] The particle content in terms of dark quarks is listed in Table 1.

	$SU(N_d)_{\rm dQCD}$	$SU(5)_{\rm GUT}$
$\psi_{1\,L,R}$	N_d	5
$\psi_{2\,L,R}$	N_d	$\overline{5}$

Table 1: Field content of a model with a confining dark QCD gauge group $SU(N_d)_{\rm dQCD}$.

[1] We also note the possibility of combining $5+\bar{5}$ into a real representation, 10, of $SO(10)$. A common Dirac mass for ψ_1 and ψ_2 can be explained.

The basic Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}(\hat{F}^a_{\mu\nu})^2 + \bar{\psi}_1 \left(i \partial\!\!\!/ + \hat{g}\, \hat{A\!\!\!/}^b\, \hat{t}^b + g_5\, A\!\!\!/^a\, t^a \right) \psi_1 + \bar{\psi}_2 \left(i \partial\!\!\!/ + \hat{g}\, \hat{A\!\!\!/}^b\, \hat{t}^b - g_5\, A\!\!\!/^a\, t^{a*} \right) \psi_2$$
$$- (\bar{\psi}_1\, \mathcal{M}_\psi\, \psi_1 + \bar{\psi}_2\, \mathcal{M}_\psi\, \psi_2)\,. \tag{1}$$

Here, the dark QCD gauge field is denoted by $\hat{A}_\mu$ with the generator as $\hat{t}^b$; the GUT $SU(5)$ gauge field is denoted by A^a_μ with the generator as t^a with $\mathrm{Tr}[t^a t^b] = \frac{1}{2}\delta^{ab}$. We also introduce a mass matrix, $\mathcal{M}_\psi$, for both ψ_1 and ψ_2. At the scale around 1 TeV, in order to conserve the SM gauge symmetry, there are two parameters for this mass matrix

$$\mathcal{M}_\psi = \mathrm{diag}(m_1\, \mathbb{I}_3, m_2\, \mathbb{I}_2)\,, \tag{2}$$

with $m_1, m_2 \geq 0$ in our convention.

The above Lagrangian is invariant under the "dark G-parity", under which the dark quarks, dark gauge fields and the GUT gauge fields transform as

$$\begin{aligned} \psi_1 &\xrightarrow{G} \psi_2^{\mathcal{C}} = i\,\gamma^2\,\psi_2^*\,, & \psi_2 &\xrightarrow{G} \psi_1^{\mathcal{C}} = i\,\gamma^2\,\psi_1^*\,, \\ \hat{A}^b\,\hat{t}^b &\xrightarrow{G} (\hat{A}^b)^{\mathcal{C}}\,\hat{t}^b = \hat{A}^b\,(-\hat{t}^{b*})\,, & A^a_\mu &\xrightarrow{G} A^a_\mu\,. \end{aligned} \tag{3}$$

with $\mathcal{C}$ denoting charge conjugation. Note in particular that A^a_μ, as well as all remaining SM fields are invariant. It is readily verified that the Lagrangian in Eq. (1) is invariant under the G-parity transformation in Eq. (3). Hence dark G-parity is a good quantum number of the theory, and all SM particles are G-even.

In order to keep asymptotic freedom for both $SU(N_d)_{\rm dQCD}$ and SM QCD gauge couplings, we further require $2 \leq N_d \leq 5$. The $SU(N_d)_{\rm dQCD}$ gauge coupling becomes strong in the infrared and the confinement and chiral symmetry breaking happen at a scale $\Lambda_d \approx 4\pi f_\Pi$, with f_Π as the dark pion decay constant. For $m_1, m_2 \lesssim \Lambda_d$ and in the low energy theory below Λ_d, we have totally 99 PNGB's, dark pions. Decomposing them into $SU(5)$ representations, we have

$$\mathbf{10} \times \mathbf{10} - \mathbf{1} = \mathbf{24}^+ + \mathbf{24}^- + \mathbf{1}^- + \mathbf{10}^+ + \mathbf{15}^+ + \overline{\mathbf{10}}^+ + \overline{\mathbf{15}}^+\,. \tag{4}$$

Here, the superscript "$+(-)$" denotes G-parity even(odd) states. [2] We can further decompose these pions into SM gauge group representations. For instance, using the notation of $(SU(2)_W, SU(3)_{\rm QCD})_{U(1)_Y}$ one has

$$\begin{aligned} \mathbf{24}^+ &= (\mathbf{1},\mathbf{1})^+_{\mathbf{0}} + (\mathbf{3},\mathbf{1})^+_{\mathbf{0}} + (\mathbf{2},\mathbf{3})^+_{-\mathbf{5/6}} + (\mathbf{2},\overline{\mathbf{3}})^+_{\mathbf{5/6}} + (\mathbf{1},\mathbf{8})^+_{\mathbf{0}}\,, \\ \mathbf{24}^- &= (\mathbf{1},\mathbf{1})^-_{\mathbf{0}} + (\mathbf{3},\mathbf{1})^-_{\mathbf{0}} + (\mathbf{2},\mathbf{3})^-_{-\mathbf{5/6}} + (\mathbf{2},\overline{\mathbf{3}})^-_{\mathbf{5/6}} + (\mathbf{1},\mathbf{8})^-_{\mathbf{0}}\,. \end{aligned} \tag{5}$$

[2] For the model based on 10 of $SO(10)$, the decomposition of 99 dark pions under $SO(10)$ is $\mathbf{10}\times\mathbf{10}-\mathbf{1} = \mathbf{45}^- + \mathbf{54}^+$.

There are totally three SM gauge singlets with one G-parity even and two G-parity odd. We will denote $(\mathbf{1},\mathbf{1})^+_{\mathbf{0}}$ simply as $\mathbf{1}^+$ and $(\mathbf{1},\mathbf{1})^-_{\mathbf{0}}$ simply as $\mathbf{1}^-_A$, while the singlet in Eq. (4) as $\mathbf{1}^-_B$. Their generators are

$$\begin{aligned} T^{\mathbf{1}^+} &= \frac{1}{2\sqrt{30}}\,\mathrm{diag}(2\,\mathbb{I}_3, -3\,\mathbb{I}_2, 2\,\mathbb{I}_3, -3\,\mathbb{I}_2)\,, \\ T^{\mathbf{1}^-_A} &= \frac{1}{2\sqrt{30}}\,\mathrm{diag}(2\,\mathbb{I}_3, -3\,\mathbb{I}_2, -2\,\mathbb{I}_3, 3\,\mathbb{I}_2)\,, \\ T^{\mathbf{1}^-_B} &= \frac{1}{\sqrt{20}}\,\mathrm{diag}(\mathbb{I}_5, -\mathbb{I}_5)\,, \end{aligned} \tag{6}$$

which have canonical normalization with $\mathrm{Tr}(T^{\mathbf{1}^+}T^{\mathbf{1}^+}) = 1/2$as for the other pion generators. To calculate couplings of dark pions with SM gauge bosons, we will use the 10×10 matrix representation of the $SU(5)$ generators as $T^a = \mathrm{diag}(t^a, -t^{a*})$ with $\mathrm{Tr}(T^aT^a) = \delta^{ab}$. To complete the decomposition into SM gauge group representation, we also have $\mathbf{10} = (\mathbf{1},\mathbf{1})_{\mathbf{1}} + (\mathbf{1},\overline{\mathbf{3}})_{-\mathbf{2/3}} + (\mathbf{2},\mathbf{3})_{\mathbf{1/6}}$ and $\mathbf{15} = (\mathbf{3},\mathbf{1})_{\mathbf{1}} + (\mathbf{2},\mathbf{3})_{\mathbf{1/6}} + (\mathbf{1},\mathbf{6})_{-\mathbf{2/3}}$.

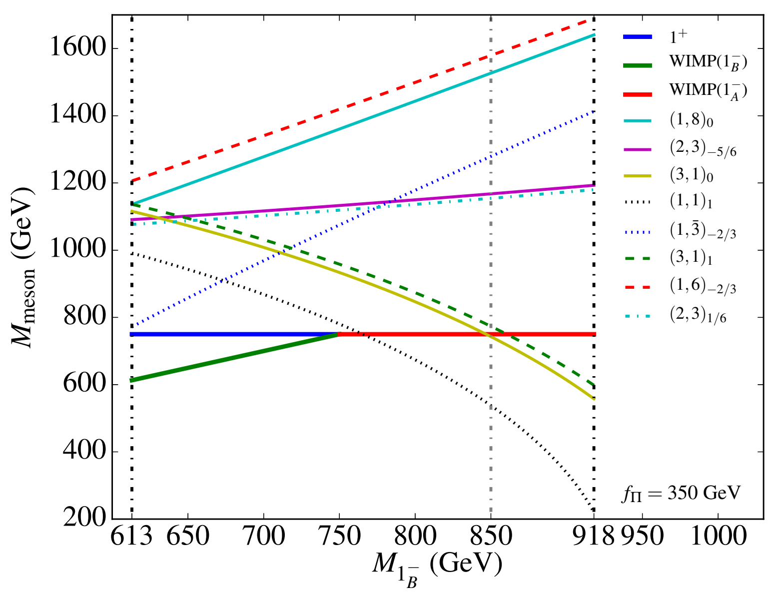

Figure 1: Dark pion masses as a function of the $\mathbf{1}^-_B$ mass after fixing the lightest G-even dark pion, $\mathbf{1}^+$, to be 750 GeV and $f_\Pi = 350$ GeV. The QCD gauge couplings is chosen to have $\alpha_s(1\ \mathrm{TeV}) \approx 0.09$. We do not show the masses of additional dark pions related to the ones in this plot by complex conjugation.

Since the SM gauge interactions can provide masses for charged pions, we anticipate that the three SM-singlet pions are lighter than others. The bare dark quark masses contribute to the dark pions via the general formula

$$M_{AB}^2 = \frac{1}{f_\Pi^2}\,\langle \overline{Q}\,\{T^A, \{T^B, M_Q\}\}\,Q\rangle_0\,. \tag{7}$$

with $A, B = 1, \cdots, 10$ and $M_Q = \mathrm{diag}(\mathcal{M}_\psi, \mathcal{M}_\psi)$. The dark quark condensation can be used to define the dark QCD chiral symmetry breaking scale via $\langle \overline{Q}Q\rangle = \Lambda_d^3/(16\pi^2)\,\mathbb{I}_{10}$. Applying the general formula Eq. (7) to our model, we have

$$M^2_{\mathbf{1}^+} = M^2_{\mathbf{1}^-_A} = \left(\frac{4}{5}m_1 + \frac{6}{5}m_2\right)\frac{\langle \overline{Q}Q\rangle}{f_\Pi^2}\,, \qquad M^2_{\mathbf{1}^-_B} = \left(\frac{6}{5}m_1 + \frac{4}{5}m_2\right)\frac{\langle \overline{Q}Q\rangle}{f_\Pi^2}\,. \tag{8}$$

The contributions to other SM charged dark pion masses are proportional to $2m_1$, $2m_2$, or $m_1 + m_2$, depending on their charges. For SM charged dark pions, the contributions from SM gauge boson loops are quadratically divergent and are

$$\Delta M^2[(d_2, d_3)_Y] \approx \frac{3}{16\pi^2}\Lambda_d^2\left[g_s^2 C_2(d_3) + g_2^2 C_2(d_2) + g_Y^2 Y^2\right]\,. \tag{9}$$

For a benchmark point of $f_\Pi = 350$ GeV and fixing $M_{\mathbf{1}^+} = 750$ GeV, we show various dark pion masses as a function of $M_{\mathbf{1}^-_B}$ in Fig. 1. For $0 \le m_1 < m_2$, the lightest G-odd particle is $\mathbf{1}^-_B$, while for $0 \le m_2 < m_1$ the lightest G-odd particles is $\mathbf{1}^-_A$. As a result and after fixing $M_{\mathbf{1}^+} = 750$ GeV, our model predicts a range for the potential WIMP mass as

$$\mathbf{613\ GeV} \le \mathbf{M_{WIMP}} \le \mathbf{750\ GeV}\,. \tag{10}$$

We also note that there is an upper mass $M_{\mathbf{1}^-_B} \le 918$ GeV, saturated by choosing $m_2 = 0$. Furthermore, for $M_{\mathbf{1}^-_B} \ge 850$ GeV (denoted by the vertical dot-dashed line in Fig. 1), the lightest G-odd pion is the electric neutral component of $(\mathbf{3}, \mathbf{1})^-_{\mathbf{0}}$, which would be a dark matter candidate. As with the pure wino lightest superpartner case in the Minimal Supersymmetric Standard Model (MSSM), its annihilation cross section is too large to have a relic abundance that accounts for the entire dark matter energy density, so we restrict ourselves in the parameter region with $M_{\mathbf{1}^-_B} \le 850$ GeV and consider $\mathbf{1}^-_{A,B}$ as the WIMP candidate.

2.2 Properties of $\mathbf{1}^+$: 750 GeV diphoton resonance

For the G-even dark pion, the triangular anomalies mediate its interactions with two gluons and two photons. The general form for the anomaly-mediated interactions are

$$\mathcal{L}_{\rm anomaly} = -\frac{g_B g_C\,\Pi_A}{16\pi^2\,f_\Pi}\epsilon_{\mu\nu\rho\sigma}F_B^{\mu\nu}F_C^{\rho\sigma}\,\mathrm{Tr}\{T^A T^B T^C\} + \cdots\,. \tag{11}$$

Applying this general form to $\mathbf{1}^+$ in our model, we have

$$\mathcal{L}_{\rm anomaly} = -\frac{N_d}{\sqrt{30}}\frac{g_s^2}{16\pi^2 f_\Pi}\Pi_{\mathbf{1}^+}\,\epsilon_{\mu\nu\rho\sigma}G^{\mu\nu\,a}G^{\rho\sigma\,a} + \frac{3\,N_d}{2\sqrt{30}}\frac{g_2^2}{16\pi^2 f_\Pi}\Pi_{\mathbf{1}^+}\,\epsilon_{\mu\nu\rho\sigma}W^{\mu\nu\,i}W^{\rho\sigma\,i} + \frac{N_d}{2\sqrt{30}}\frac{\left(\sqrt{\frac{5}{3}}g_Y\right)^2}{16\pi^2 f_\Pi}\Pi_{\mathbf{1}^+}\,\epsilon_{\mu\nu\rho\sigma}B^{\mu\nu}B^{\rho\sigma}\,. \tag{12}$$

For this model, we have several decay channels for $\mathbf{1}^+$. We show the branching fractions and the total widths in Table 2. We note that neglecting the phase space factors, the ratio of the branchings of $\gamma\gamma$,

Mode	gg	$\gamma\gamma$	$Z\gamma$	ZZ	WW
Branching ratio	0.90	0.0046	0.0083	0.021	0.065
$\Gamma_{\rm tot}$	$0.13~{\rm GeV}\left(\frac{N_d}{4}\right)^2\left(\frac{500~{\rm GeV}}{f_\Pi}\right)^2$				

Table 2: The decay branching ratios of $\mathbf{1}^+$ and its total width for the $5+\bar{5}$ model with a mass of 750 GeV.

$Z\gamma$ and ZZ is

$$\text{Br}(\gamma\gamma):\text{Br}(Z\gamma):\text{Br}(ZZ) = 1 : \frac{(9\cos^2\theta_W - 5\sin^2\theta_W)^2}{98\,\cos^2\theta_W\,\sin^2\theta_W} : \frac{(9\cos^4\theta_W + 5\sin^4\theta_W)^2}{196\,\cos^4\theta_W\,\sin^4\theta_W}\,, \tag{13}$$

with θ_W as the weak mixing angle and $\sin^2\theta_W \approx 0.23$.

Using the MSTW 2008 PDFs [23] and the narrow-width approximation, we calculate the production cross section times diphoton branching ratio in Fig. 2 as a function of f_Π. For the diphoton excess, we estimate a range for the allowed values of the cross-section by combining the CMS and ATLAS 13 TeV results. We consider the number of observed and expected background predicted in the respective analysis papers by summing over the two bins nearest to 750 GeV. Using the signal acceptances determined by simulations in the experimental papers, we determine that the maximum likelihood cross section for the combined CMS and ATLAS excesses is 7.1 fb, with 1σ ranges of $[3.6, 11.2]$ fb and 2σ ranges of $[1.7, 14.2]$ fb. The maximum likelihood cross-section is indicated by a black line and the 1σ and 2σ lines by green and yellow bands respectively in Fig. 2. One can see that for N_d from 3 to 5 and f_Π from 300 GeV to 1 TeV, the 750 GeV diphoton excess can be explained in our model.

A prior search using data from Run 1 constrained the production of a $Z\gamma$ resonance with a mass of 750 GeV. They obtained a limit at this mass of

$$\sigma(pp \to \mathbf{1}^+)\,\text{Br}\left[\mathbf{1}^+ \to (Z \to \ell\ell)\gamma\right] < 0.27~\text{fb}\,, \qquad (8~\text{TeV})\,, \tag{14}$$

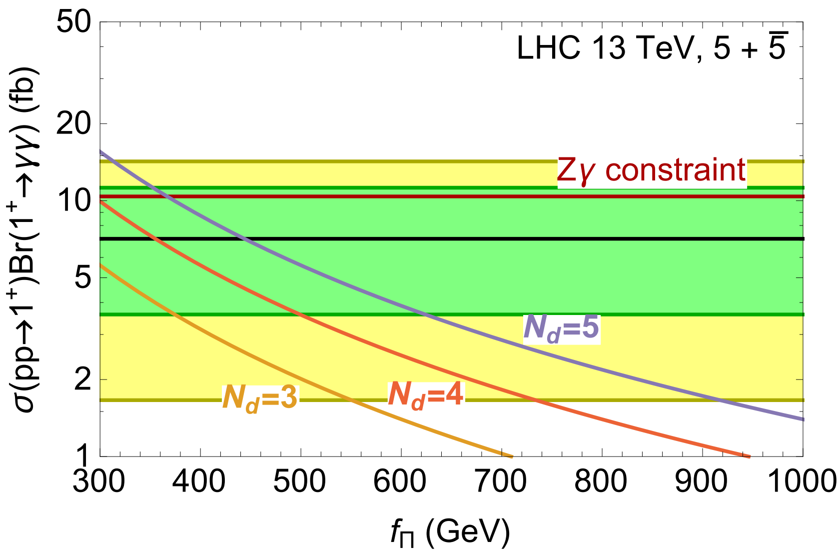

Figure 2: The production cross section times branching ratio for $pp \to \mathbf{1}^+ \to \gamma\gamma$ at the 13 TeV LHC, with $M_{\mathbf{1}^+} = 750$ GeV. The $\sigma \times \mathrm{Br}$ for the 750 GeV diphoton excess is shown in the black line with 1σ (green) and 2σ (yellow) bands. We also show the rescaled $Z\gamma$ constraint from the 8 TeV results [24].

from Ref. [24]. Using the well-known leptonic branching fraction of the Z to leptons, $\mathrm{Br}(Z \to \ell^+\ell^-) = 0.0673$, the gg parton luminosity ratio at 750 GeV from 13 TeV to 8 TeV of 4.7, and the branching fraction ratios determined from Eq. (13), we can relate this to a constraint on 13 TeV production of $\gamma\gamma$ via the $\mathbf{1}^+$ resonance. We find

$$\sigma(pp \to \mathbf{1}^+)\,\mathrm{Br}(\mathbf{1}^+ \to \gamma\gamma) < 9.6~\mathrm{fb}\,, \qquad (13~\mathrm{TeV})\,. \tag{15}$$

We show this constraint line in Fig. 2. The majority of the parameter space that offers an explanation of the diphoton excess remains allowed after imposing this constraint.

2.3 Properties of a $\mathbf{1}^-$ WIMP

As discussed above, the lightest G-odd particle, $\mathbf{1}^-_A$ or $\mathbf{1}^-_B$, could serve as a candidate for WIMP dark matter. If $\mathbf{1}^-_B$ is lighter than $\mathbf{1}^-_A$, the WIMP mass could be from 613 GeV to 750 GeV. If $\mathbf{1}^-_A$ is lighter, the WIMP mass is fixed to be 750 GeV, the same as the 750 GeV diphoton resonance. Here we don't consider the multi-component dark matter case with a degenerate mass for $\mathbf{1}^-_A$ and $\mathbf{1}^-_B$. For both cases, the WIMP is a SM singlet and does not have renormalizable interactions with SM particles. On the other hand, because of the composite nature of $\mathbf{1}^-_{A,B}$, it has higher-dimensional operator interactions with SM gauge fields. Specifically, we have three relevant operators for both cases

$$c_G \frac{g_s^2\, N_d}{16\pi^2 f_\Pi^2}\, \Pi_{\mathbf{1}^-}\Pi_{\mathbf{1}^-}\, G^{\mu\nu\, a} G^a_{\mu\nu} \,+\, c_W \frac{g_2^2\, N_d}{16\pi^2 f_\Pi^2}\, \Pi_{\mathbf{1}^-}\Pi_{\mathbf{1}^-}\, W^{\mu\nu\, i} W^i_{\mu\nu}$$
$$+\, c_B \frac{\left(\sqrt{\frac{5}{3}} g_Y\right)^2\, N_d}{16\pi^2 f_\Pi^2}\, \Pi_{\mathbf{1}^-}\Pi_{\mathbf{1}^-}\, B^{\mu\nu} B_{\mu\nu}\,. \tag{16}$$

The first operator is the dark matter chromo-Rayleigh interaction [25, 26] and the second and third operators are related to the electromagnetic polarizability of dark matter [27, 28]. Up to an order-of-unity number, η, from non-perturbative physics, we have

$$\mathbf{1}^- = \mathbf{1}^-_B: \quad 613 \text{ GeV} \le M_{\mathbf{1}^-} < 750 \text{ GeV}, \qquad c_G = c_W = c_B = \frac{1}{20}\eta\,, \tag{17}$$

$$\mathbf{1}^- = \mathbf{1}^-_A: \quad M_{\mathbf{1}^-} = 750 \text{ GeV}, \qquad c_G = \frac{1}{30}\eta\,, c_W = \frac{3}{40}\eta\,, c_B = \frac{7}{120}\eta\,. \tag{18}$$

The WIMP candidate, $\mathbf{1}^-$, mainly annihilates to two gluons with the annihilation rate

$$\langle \sigma v\rangle(\mathbf{1}^-\mathbf{1}^- \to GG) = \frac{4\, c_G^2\, N_d^2\, \alpha_s^2}{\pi^3}\, \frac{M_{\mathbf{1}^-}^2}{f_\Pi^4} + \mathcal{O}(v^2) \,\approx\, 1.0 \text{ pb}\cdot\text{c}\,, \tag{19}$$

for $c_G = \eta/20$ with $\eta = 1.3$, $N_d = 4$, $M_{\mathbf{1}^-} = 650$ GeV and $f_\Pi = 350$ GeV. This has an annihilation rate that can consistently provide a thermal WIMP dark matter abundance.

For direct detection experiments, following a standard calculation like in Ref. [26], we obtain a spin-independent scattering cross section

$$\sigma^{\rm SI}_{\mathbf{1}^- N} \,=\, \frac{\kappa^2\, c_G^2\, N_d^2\, m_N^4}{4\pi f_\Pi^4 (m_N + M_{\mathbf{1}^-})^2} \,=\, 1.4\times 10^{-47}\ \text{cm}^2\,, \tag{20}$$

for $c_G = \eta/20$ with $\eta = 1.3$, $N_d = 4$, $M_{\mathbf{1}^-} = 650$ GeV and $f_\Pi = 350$ GeV. Here, m_N is the nucleon mass and $\kappa \approx -0.20$ and is related to the matrix element of gluon operators inside a nucleon. We note that the predicted scattering cross section in our model is below the current bound from LUX [30] and could be probed by future direct detection experiments. Furthermore, taking the ratio of Eq. (19) and Eq. (20), one can see that only the dark matter mass $M_{\mathbf{1}^-}$ becomes the relevant parameter for the direct detection predictions in our model. In Fig. 3, we show our model predictions for WIMP spin-independent scattering cross sections together with the LUX limits. The predicted cross sections for our $5 + \bar{5}$ model are around two orders of magnitude below the current constraints.

Searches for dark matter at colliders could also probe our model. One sensitive channel is mono-jet. Using the results at the 8 TeV LHC with 19.7 fb^{-1} from the CMS collaboration [31], we have found that the constraint on our model parameters is less stringent than the one from LUX. Another way

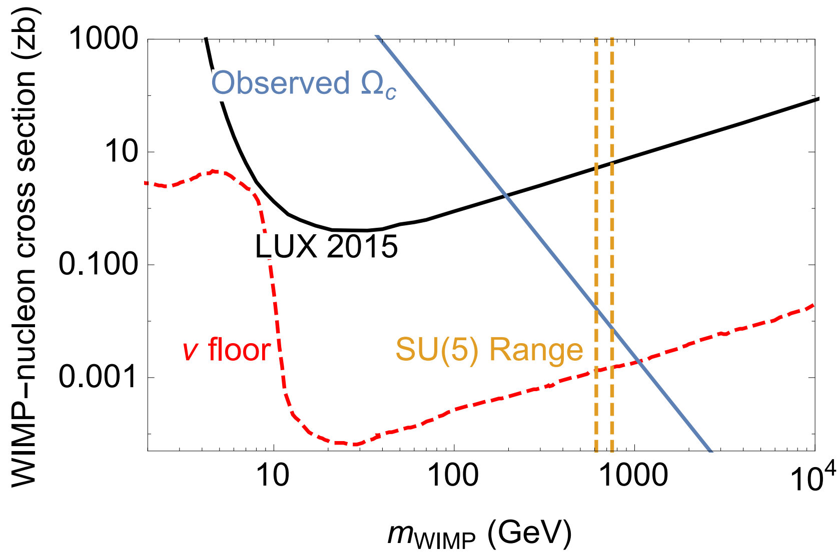

Figure 3: The blue line is our model predictions of the spin-independent scattering cross sections after satisfying the dark matter thermal relic abundance Ω_c. For the $5+\bar{5}$ model, the WIMP mass is predicted to be within $(613, 750)$ GeV. The dashed and red line is the "neutrino floor" cross section [29].

to search for particle properties of dark matter is indirect detection of the annihialtion of dark matter into SM particles. For our model, the main constraint of this sort comes from the anti-proton flux. Using the AMS-02 anti-proton fraction result [32], the current constraint on the WIMP mass with a thermal annihilation rate into hadrons is between 100 to 200 GeV [33], which does not constrain the parameter space of our model.

2.4 Other Pions and Baryons

In the model we have presented, there are 99 pions which are naturally divided into G-odd and G-even states as in Eq. (4). For the two G-even states, $(\mathbf{3},\mathbf{1})^+_{\mathbf{0}}$ and $(\mathbf{1},\mathbf{8})^+_{\mathbf{0}}$, the triangle-anomaly can generate interactions of the form $\Pi^i_{(\mathbf{3},\mathbf{1})^+_{\mathbf{0}}}\widetilde{W}^i_{\mu\nu}B^{\mu\nu}$, $d_{abc}\,\Pi^a_{(\mathbf{1},\mathbf{8})^+_{\mathbf{0}}}\widetilde{G}^b_{\mu\nu}G^{\mu\nu\,c}$ and $\Pi^a_{(\mathbf{1},\mathbf{8})^+_{\mathbf{0}}}\widetilde{G}^a_{\mu\nu}B^{\mu\nu}$. As a result, the electric-neutral part of the weak triplet can decay into $2\gamma(Z)$ and $\gamma+Z$, while the color-octet state can decay into $2g$ or $g+\gamma(Z)$. After they are produced in pairs at the LHC, one could search for a pair of resonances with an equal mass. For the two G-odd states, $(\mathbf{3},\mathbf{1})^-_{\mathbf{0}}$ and $(\mathbf{1},\mathbf{8})^-_{\mathbf{0}}$, higher-dimensional operators generated by the strong dynamics having the form $\Pi^i_{(\mathbf{3},\mathbf{1})^-_{\mathbf{0}}}\Pi_{\mathbf{1}^-_{A,B}}W^i_{\mu\nu}B^{\mu\nu}$ and $\Pi^a_{(\mathbf{1},\mathbf{8})^-_{\mathbf{0}}}\Pi_{\mathbf{1}^-_{A,B}}G^a_{\mu\nu}B^{\mu\nu}$, mediate the decays of the weak-triplet and color-octet pions into the WIMP plus two SM gauge bosons. At the LHC, one has an interesting signature of $2j+2\gamma(Z)+$ MET for the color-octet pion.

Additional global symmetries forbid the decays of the color triplet pions $(\mathbf{2},\mathbf{3})^{\pm}_{\mathbf{-5/6}}$, $(\mathbf{1},\bar{\mathbf{3}})^{\pm}_{\mathbf{-2/3}}$, and $(\mathbf{2},\mathbf{3})^{\pm}_{\mathbf{1/6}}$ at the level considered so far. Since they are not viable dark matter candidates because of their QCD interactions, there must be additional interactions which mediate their decays. The simplest possibility is to add four-fermi interactions of pairs of dark quarks to pairs of SM fermions in the UV theory. These interactions should conserve G-parity in order that for them to not allow dark matter decays. Operators for which the pair of dark quarks transforms as a pseudo-scalar or pseudo-vector will yield interactions for G-even pion decay into pairs of SM fermions in the IR. On the other hand, operators for which the pair of dark quarks transforms as a scalar or vector yield interactions for G-odd pions to decay to lighter G-odd pions along with a pair of SM fermions. For example, the following operator can give G-even color-triplet pions a leptoquark-like decay:

$$(\bar{\psi}_1\gamma^\mu\gamma^5 T^A\psi_1 + \bar{\psi}^c{}_2\gamma^\mu\gamma^5 T^A\psi_2^c)\bar{5}\gamma^\mu P_R T^A 5, \tag{21}$$

where 5 denotes the (right-handed) SM fermion that transforms as a 5 of $SU(5)_{\rm GUT}$. The same operator without a vector rather than pseudo-vector,

$$(\bar{\psi}_1\gamma^\mu T^A\psi_1 + \bar{\psi}^c{}_2\gamma^\mu T^A\psi_2^c)\bar{5}\gamma^\mu P_R T^A 5, \tag{22}$$

gives G-odd pions a decay into lighter G-odd pions and SM fermions. [3] Other dimension 6 operators could have the same effect. The scale of the operators is a priori arbitrary, but at the very least all of the pions other than the lightest G-odd pion should not be cosmologically stable. They could, however, be long lived, which would yield striking signatures with displaced vertices or R-hadrons [34] which will be well covered by searches at Run 2 of the LHC. To summarize, the G-odd pions should be pair produced and will yield leptons + jets + MET signals from potential cascade decays and with possibly long lived states. The G-even QCD triplets must also be pair produced, but will yield equal mass pair produced leptoquark or diquark resonances.

Our model also predicts additonal baryon-like states. Their masses are anticipated to be relatively large based on the QCD scaling relation $M_{B_d} \sim \sqrt{N_d/3}(f_\Pi/f_\pi)m_p \sim 10\sqrt{N_d/3}f_\Pi$. Similar to proton and anti-proton annihilations in the SM, they mainly annihilation into multi pions. Using the unitary bound for the annihilation cross section $\langle\sigma v\rangle \sim \pi/(M_{B_d}^2\, v)$ with $v \sim 0.3\, c$, its relic abundance is at most a few percent of the total dark matter relic abundance and does not change our thermal relic calculation for the G-odd pion.

[3] This operator also generates decays for G-even pions into ligther G-even pions and SM fermions, but this decay is higher operator than those previously mentioned and is therefore subdominant.

2.5 The $8+1+1$ Model

Before we finish this section, we briefly mention other possible models with no obvious compatibility with a GUT theory. For instance, we could have a "$8+1+1$" model with one QCD octet dark quarks plus two dark quarks with opposite hypercharges. Their charges under the SM gauge group is listed in Table 3. We note that for $N_d \geq 2$, SM QCD is not asymptotic free above the dark confinement scale and has a Landau-pole scale depending on N_d. The resulting SM QCD Landau pole scale can be above the Planck scale only for $N_d = 2$.

	$SU(N_d)_{\rm dQCD}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\psi_{L,R}$	N_d	8	1	0
$\chi_{1\,L,R}$	N_d	1	1	x
$\chi_{2\,L,R}$	N_d	1	1	$-x$

Table 3: Field content of the $8+1+1$ model.

The basic Lagrangian is

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} - \frac{1}{4}(\hat{F}^a_{\mu\nu})^2 + \bar{\psi}\left(i\,\partial\!\!\!/ \;+\; \hat{g}\,\hat{A\!\!\!/}^{\,b}\,\hat{t}^b \;+\; g_s\,G\!\!\!\!/^{\,a}\,t^a\right)\psi \\ &\quad + \bar{\chi}_1\left(i\,\partial\!\!\!/ \;+\; \hat{g}\,\hat{A\!\!\!/}^{\,b}\,\hat{t}^b \;+\; x\,g_Y\,B\!\!\!\!/\right)\chi_1 \;+\; \bar{\chi}_2\left(i\,\partial\!\!\!/ \;+\; \hat{g}\,\hat{A\!\!\!/}^{\,b}\,\hat{t}^b \;-\; x\,g_Y\,B\!\!\!\!/\right)\chi_2 \\ &\quad - m_1\,\bar{\psi}\psi \;-\; m_2\,(\bar{\chi}_1\chi_1 + \bar{\chi}_2\chi_2)\,. \end{aligned} \tag{23}$$

Here, the SM QCD gauge field is denoted by G^a_μ with the generator as t^a with ${\rm Tr}[t^a t^b] = C(8)\,\delta^{ab} = 3\,\delta^{ab}$. The dark G-parity is defined as

$$\begin{aligned}\psi &\stackrel{G}{\rightarrow} \psi^{\mathcal{C}} = i\,\gamma^2\,\psi^*\,, \qquad \chi_1 \stackrel{G}{\rightarrow} \chi_2^{\mathcal{C}} = i\,\gamma^2\,\chi_2^*\,, \qquad \chi_2 \stackrel{G}{\rightarrow} \chi_1^{\mathcal{C}} = i\,\gamma^2\,\chi_1^* \\ \hat{A}^b\,\hat{t}^b &\stackrel{G}{\rightarrow} (\hat{A}^b)^{\mathcal{C}}\,\hat{t}^b = \hat{A}^b\,(-\hat{t}^{b*})\,, \qquad G^a_\mu \stackrel{G}{\rightarrow} G^a_\mu\,, \qquad B_\mu \stackrel{G}{\rightarrow} B_\mu\,. \end{aligned} \tag{24}$$

In the low energy theory below Λ_d, we have totally 99 PNGB's, which are

$$\begin{aligned}\mathbf{10}\times\mathbf{10}-\mathbf{1} &= \mathbf{8}^-_{\rm A} + \mathbf{10}^- + \overline{\mathbf{10}}^- + \mathbf{8}^+_{\rm S} + \mathbf{27}^+ + \mathbf{8}_x + \mathbf{8}_{-x} + \mathbf{8}_x + \mathbf{8}_{-x} \\ &\quad + \mathbf{1}_{2x} + \mathbf{1}_{-2x} + \mathbf{1}^+ + \mathbf{1}^-\,. \end{aligned} \tag{25}$$

Here, the subscript denotes the electric charge of dark pions; "A" and "S" mean anti-symmetric and the symmetric combinations. Applying the general formula in Eq. (7) to our model, we have

$$M^2_{\mathbf{1}^+} = \left(\frac{2}{5}m_1 + \frac{8}{5}m_2\right)\frac{\langle\overline{Q}Q\rangle}{f^2_\Pi}\,, \qquad M^2_{\mathbf{1}^-} = 2\,m_2\,\frac{\langle\overline{Q}Q\rangle}{f^2_\Pi}\,. \tag{26}$$

In this model, $\mathbf{1}^-$ is the lightest G-odd dark pion in the spectrum. In the latter study, we just treat $M_{\mathbf{1}^+}$ and $M_{\mathbf{1}^-}$ as two free parameters.

The $\mathbf{1}^+$ dark pion can serve as the 750 GeV diphoton resonance. Its anomalous couplings to gauge bosons are

$$\mathcal{L}_{\text{anomaly}} = -\frac{3\,N_d}{4\sqrt{5}}\,\frac{g_s^2}{16\pi^2\,f_\Pi}\,\Pi_{\mathbf{1}^+}\,\epsilon_{\mu\nu\rho\sigma}G^{\mu\nu\,a}G^{\rho\sigma\,a} + \frac{x^2\,N_d}{\sqrt{5}}\,\frac{g_Y^2}{16\pi^2\,f_\Pi}\,\Pi_{\mathbf{1}^+}\,\epsilon_{\mu\nu\rho\sigma}B^{\mu\nu}B^{\rho\sigma}\,. \tag{27}$$

It has the ratios of the branchings of $\gamma\gamma$, $Z\gamma$ and ZZ as

$$\text{Br}(\gamma\gamma) : \text{Br}(Z\gamma) : \text{Br}(ZZ) = 1 : \frac{2\sin^2\theta_W}{\cos^2\theta_W} : \frac{\sin^4\theta_W}{\cos^4\theta_W}\,. \tag{28}$$

In Fig. 4, we show the production cross section times diphoton branching ratio as a function of f_Π for the benchmark model point $x = 1$. One can see that for N_d from 2 to 5 and f_Π from 400 GeV to 1 TeV, the 750 GeV diphoton excess can be explained in this model. The derived constraint from the 8 TeV $Z\gamma$ resonance searches is less than 32 fb and much weaker than that for the $5 + \bar{5}$ model.

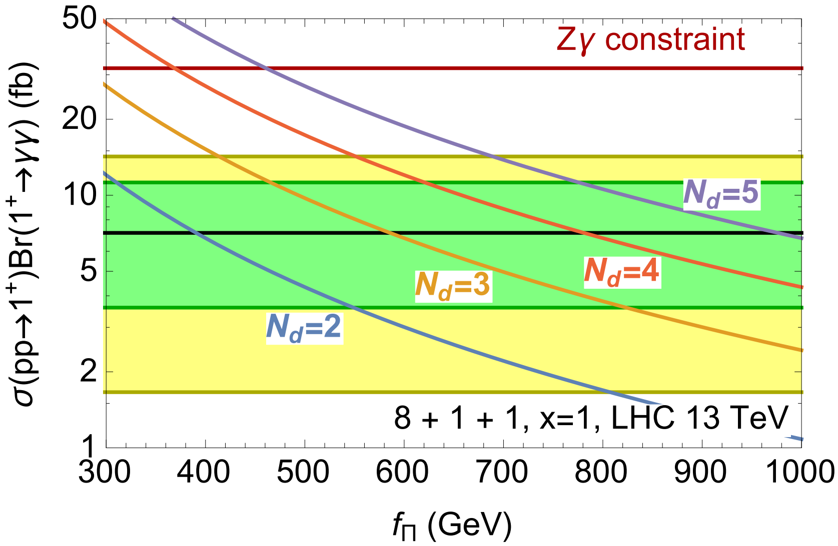

Figure 4: The same as Fig. 2 but for the $8 + 1 + 1$ model with $x = 1$.

The G-odd dark pion $\mathbf{1}^-$ is a stable particle and could be a WIMP candidate. The calculation is very similar to the $5 + \bar{5}$ model except with different coefficients in Eq. (16). For this $8 + 1 + 1$ model, one has $c_G = \frac{3}{2}\eta$, $c_W = 0$ and $c_B = \frac{x^2}{2}\eta$. After satisfying the WIMP thermal relic abundance, the predicted direct detection cross sections for different WIMP masses are also as shown in Fig. 3. The LUX experiments have already imposed a bound on the dark matter mass to be above ~ 160 GeV.

3 Discussion and Conclusions

The model described in this work has additional pions that could be observed at the LHC. For the $5+\bar{5}$, many QCD-charged pions have a mass around 1 TeV. Pair productions of them at the LHC will lead to interesting signatures with or without missing energy. For instance, the G-even color-octet, $(\mathbf{1},\mathbf{8})^+_{\mathbf{0}}$ or $\mathbf{8}^+_S$, appears as high mass pair-produced dijet resonances at $m > 750$ GeV. For the $8+1+1$ model, the **10** and **27** receive large color factor enhancements and give spectacular signals. In addition, there are hypercharged octets, which may require large multiplicity final states in order to decay depending on their hypercharges. We defer a detailed discussion of their phenomenology.

Since the WIMP candidate, $\mathbf{1}^-$, can annihilate into a pair of gluons, which will eventually hadronize, and produce secondary particles including photons, positrons, antiprotons and neutrinos. Those particles can give dark matter indirect detection signals. On the other hand, if we require the WIMP thermal relic abundance match to the observed dark matter energy density, the annihilation cross section is too small to be constrained by the current dark matter indirect searches. Besides the dominate gluon annihilation channel, our WIMP candidate can also annihilate into a pair of photons, generating a monochromatic gamma ray signal. This signal is suppressed by $\alpha_s^2/\alpha_Y^2 \sim \mathcal{O}(100)$, so the current experiments are not sensitive to it. It is still an interesting signal for future indirect dark matter search experiments.

In summary, we have constructed a dark QCD model with an unbroken dark G-parity. The 750 GeV diphoton resonance could be explained by the dark G-even and SM gauge singlet pion. In the same model, the lightest dark G-odd pion provides a good WIMP candidate.

Acknowledgments

This work is supported by the U. S. Department of Energy under the contract DE-FG-02-95ER40896.

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