A 750 GeV dark matter messenger at the Galactic Center

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Abstract

The first data from the LHC Run-2 have shown a possible excess in the events containing two photons with invariant mass around 750 GeV, suggesting the existence of a new resonance $\phi$ which decays dominantly into new undetected particles, such as the dark matter (DM) particles. In a simple model where $\phi$ is a pseudo-scalar and couples to a scalar DM particle, we show that the 750 GeV two-photon excess reported by the LHC is consistent with another photon excess, the GeV excess in the cosmic gamma-rays towards the Galactic Center observed by the Fermi-LAT collaboration. Both excesses can be explained by a DM particle with mass around 60 GeV and annihilates dominantly into gluons with a typical thermal annihilation cross section. The predicted cross section for the gamma-ray line in this model can be confirmed or ruled out by the Ferm-LAT and future experiments.

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1 Introduction

Recently, the ATLAS and CMS collaborations have reported the first data based on the integrated luminosity of $3 \text{ fb}^{-1}$ from the LHC Run-2 at the center-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ [1]. Both collaborations have shown a possible excess in the events with two photons, which suggests the existence of a new resonance particle $\phi$ generated from gluon fusion. Based on the integrated luminosity of $3.2 \text{ fb}^{-1}$, the ATLAS collaboration has shown that the excess is at the two photon invariant mass $\sim 750 \text{ GeV}$ with a local (global) significant of $3.9\sigma$ ($2.3\sigma$). The distribution of the observed 14 two-photon events (with selection efficiency 0.4) suggests that the width of the resonance is $\Gamma/M \approx 0.06$, and the corresponding production cross section for $pp \rightarrow \phi \rightarrow \gamma\gamma$ is $10 \pm 3 \text{ fb}$. The CMS collaboration has reported 10 events with a mild peak at $\sim 760 \text{ GeV}$ with a local (global) significance of $2.6\sigma$ ($1.2\sigma$), and the data prefer a narrow width. If $\Gamma/M \approx 0.06$ is assumed, the corresponding cross section is $6 \pm 3 \text{ fb}$. A fit to the excess from the observed number of events gives $\sigma = 5.6 \pm 2.4 \text{ fb}$ ($6.2^{+2.4}_{-2.0} \text{ fb}$) for ATLAS (CMS) [2].

While the reported excess events could be simply due to statistic fluctuations, it is useful to consider its implications for new physics beyond the standard model (SM). The $2\gamma$ final states as the decay products indicates that the spin of the resonance is 0 or 2. The large production cross section suggests that it is likely to couple strongly to gluons, as the luminosity of gluons increases rapidly with the center-of-mass energy. Since the couplings to the SM particles $W^\pm$, $Z^0$, charged leptons and light quarks are severely constrained by the data of LHC at $\sqrt{s} = 8 \text{ TeV}$, a large decay width of around 45 GeV implies that the resonance particle may decay into new undetected particles. A plausible candidate of such a particle is the dark matter (DM) particle [3, 4, 5, 6, 7, 8, 9, 10, 11, 36]. The leading DM candidates are weakly interacting massive particles (WIMPs) which are responsible for $\sim 26.8\%$ of the energy budget of the Universe, and can naturally obtain the observed relic abundance through thermal freeze out. It is highly expected that WIMPs can be detected by the current and future DM detection experiments.

If the resonance $\phi$ couples to the DM particles, the DM particles couple to gluons and photons as well, which implies that the DM particles in the Galactic halo can be probed by cosmic-ray particles and gamma-rays from its annihilation into gluons, or gamma-ray lines from its annihilation into photons. The Galactic Center (GC) is expected to harbour high densities of DM, which makes it a promising place to look for signals of DM annihilation. Recently, a number of groups have analysed the data from the Fermi-LAT and found statistically strong evidence of an extended emission of gamma rays in either the inner few degrees around the GC [12, 13, 4, 5, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24], or the larger inner Galaxy region extending to a few tens of degrees away from the GC [21, 22, 23, 24]. Similar results are obtained by the Fermi-LAT collaboration [25]. The spatial distribution of this Galactic...
Center excess (GCE) emission is consistent with a spherical emission profile which scales with \( r \), the distance to GC, as \( r^{-\Gamma} \) with \( \Gamma = 2.2 - 2.4 \) \cite{17, 18, 21, 23}. The determined energy spectrum of the excess emission, although suffers from the uncertainties in the diffuse gamma-ray backgrounds, is in general compatible with a 30 – 50 GeV DM particle self annihilating into \( b\bar{b} \) final states with a cross section \( \langle \sigma v \rangle \approx (1 - 2) \times 10^{-26} \text{cm}^3\text{s}^{-1} \) compatible with the typical thermal cross section responsible for the observed DM relic density \cite{21, 23}.

In this work, we consider a simple model where the resonance \( \phi \) is a pseudo-scalar, and the DM particle is a scalar particle. We show that the possible two-photon excess reported by the LHC is consistent with the GCE in gamma-rays observed by Fermi-LAT experiment. The DM particle mass is found to be around 60 GeV, and annihilates into gluons with a typical thermal annihilation cross section. The predicted cross section for the gamma-ray line is close to the current limit from Fermi-LAT gamma-ray line search.

\section{Effective interactions}

In this work, we consider the scenario where the 750 GeV resonance \( \phi \) is a pseudo-scalar. A pseudo-scalar does not mix with the SM Higgs boson, and is less constrained by the measured properties of the Higgs boson. The particle \( \phi \) couples to the SM gauge fields through one-loop processes with heavier charged particles in the loop (see e.g. Refs. \cite{26, 27, 29, 30, 31, 32, 33, 34}). Since \( \phi \) is much heavier than the electroweak scale, we begin with the dimension-five \( SU(2)_L \otimes SU(1)_Y \otimes SU(3)_C \) gauge-invariant interactions

\[
\mathcal{L} = \frac{g_1}{\Lambda} \phi B_{\mu\nu} \tilde{B}^{\mu\nu} + \frac{g_2}{\Lambda} \phi W^a_{\mu\nu} \tilde{W}^{a\mu\nu} + \frac{g_3}{\Lambda} \phi G^a_{\mu\nu} \tilde{G}^{a\mu\nu},
\]

where \( F_{\mu\nu} = \partial_{\mu} F_{\nu} - \partial_{\nu} F_{\mu}, \tilde{F}_{\mu\nu} = \frac{i}{2} \epsilon_{\mu\nu\alpha\beta} F^{\alpha\beta} (F = B, W \text{ and } G), g_{1,2,3} \) are the dimensionless effective coupling strength, and \( \Lambda \) is the energy scale involved in the one-loop processes, which is fixed at 1 TeV. After the electroweak symmetry breaking the gauge fields mix together. In the mass basis, the effective interaction can be rewritten as

\[
\mathcal{L} = \frac{g_A}{\Lambda} \phi A_{\mu\nu} \tilde{A}^{\mu\nu} + \frac{g_Z}{\Lambda} \phi Z_{\mu\nu} \tilde{Z}^{a\mu\nu} + \frac{g_{AZ}}{\Lambda} \phi A^a_{\mu\nu} \tilde{Z}^{a\mu\nu} + \frac{g_2}{\Lambda} \phi G^a_{\mu\nu} \tilde{G}^{a\mu\nu},
\]

where the couplings \( g_{A,Z} \) are related to the gauge couplings as \( g_A = g_1 c_W^2 + g_2 s_W^2, g_Z = g_1 s_W^2 + g_2 c_W^2, \) and \( g_{AZ} = 2s_W c_W (g_2 - g_1) \), where \( s_W^2 = \sin^2 \theta_W \approx 0.23 \) with \( \theta_W \) the electroweak mixing angle. In order to suppress the \( ZZ \) and \( Z\gamma \) productions which are severely constrained by the LHC 8 TeV data \( \sigma(pp \to ZZ) \lesssim 12 \text{ fb} \) \cite{35}, \( \sigma(pp \to Z\gamma) \lesssim 4.0 \text{ fb} \) \cite{36}, we assume \( g_2 \approx 0 \), which leads to \( g_Z^2 / g_A^2 = \tan^4 \theta_W \approx 0.08 \) and \( g_{AZ}^2 / g_A^2 = 2 \tan^2 \theta_W \approx 0.6 \).
The DM particle $\chi$ with mass $m_\chi$ is assumed to be a scalar particle. The effective interaction related to $\phi$ and $\chi$ is given by

$$L = \frac{1}{2} g_\chi \phi \chi^2 + \frac{1}{2} M^2 \phi^2 + \frac{1}{2} m_\chi^2 \chi^2,$$

where $g_\chi$ is the dimensionful coupling strength. Since $\phi$ is a pseudo-scalar, the DM-nucleus scattering matrix element $\langle N | G^a_{\mu\nu} \tilde{G}^{a\mu\nu} | N \rangle$ is vanishing as $G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$ is CP-odd, which makes the DM particle evades the stringent upper limits from DM direct detection experiments such as LUX. The two-photon events are assumed to be generated from gluon fusion through s-channel resonance $\phi$. Other non-resonance mechanisms are considered in Refs. 37, 38, 39, 40, 41. The partial decay widths for the decays $\phi \to \gamma\gamma$, $gg$ and $\chi\chi$ are given by

$$\Gamma_{\gamma\gamma} = \frac{g_A^2}{4\pi} \left( \frac{M}{\Lambda} \right)^2, \quad \Gamma_{gg} = \frac{2g_g^2}{\pi} \left( \frac{M}{\Lambda} \right)^2, \quad \text{and} \quad \Gamma_{\chi\chi} = \frac{g_\chi^2 \beta_\chi}{32\pi M^2},$$

respectively, where $\beta_\chi = \sqrt{1 - 4m_\chi^2/M^2}$ is the velocity of the DM particle in the $\phi$ rest frame.

### 3 LHC di-photon excess

The production cross section for $pp \to \gamma\gamma$ through an s-wave resonance by gluon fusion and quark annihilation at the LHC is given by

$$\sigma(pp \to \phi \to \gamma\gamma) = \frac{2J + 1}{M \Gamma_s} \left[ C_{gg} \Gamma_{gg} + \sum_q C_{qq} \Gamma_{qq} \right] \Gamma_{\gamma\gamma},$$

where $J$ is the spin of the resonance, the coefficients $C_{gg}$ and $C_{qq}$ incorporate the integration over the parton distribution functions of the proton. At $\sqrt{s} = 13$ (8) TeV, $C_{gg} \approx 2137$ (174) and $C_{bb} \approx 15.3$ (1.07) [42]. The high order QCD corrections can be taken into account by the $K$-factors with $K_{gg (qq)} \approx 1.48$ (1.20). In this work, we shall focus on the case where the resonance is produced dominantly by gluons, as the luminosity of gluons grow fast with increasing energy. This leads to a simple relation between $\Gamma_{gg}$ and $\Gamma_{\gamma\gamma}$

$$\frac{\Gamma_{gg}}{M} \cdot \frac{\Gamma_{\gamma\gamma}}{M} = 6.6 \times 10^{-8} \left( \frac{\sigma}{8 \text{ fb}} \right) \left( \frac{\Gamma/M}{0.06} \right).$$

If the resonance particle can decay into the DM particles, the total width is $\Gamma = \Gamma_{gg} + \Gamma_{\gamma\gamma} + \Gamma_{\chi\chi}$. The DM partial width $\Gamma_{\chi\chi}/M$ is related to the width of the two-gluon channel as

$$\frac{\Gamma_{\chi\chi}}{M} = \frac{\Gamma}{M} \left[ 1 - 1.1 \times 10^{-6} \left( \frac{\sigma}{8 \text{ fb}} \right) \frac{M}{\Gamma_{gg}} \right] - \frac{\Gamma_{gg}}{M}.$$
FIG. 1: Left) Allowed regions in the \((\Gamma_{gg}/M, \Gamma_{\gamma\gamma}/M)\) plane. The light green band corresponds to the constraints \(2 \text{ fb} \lesssim \sigma \lesssim 14 \text{ fb}\) and \(0.03 \lesssim \Gamma/M \lesssim 0.12\). Three solid lines correspond to \(\Gamma/M = 0.03, 0.07,\) and 0.12 with \(\sigma\) fixed at 8 fb. The dark green region is the allowed region including the constraints from the GCE data \([24]\). The dashed curve represents the region excluded by \(pp \rightarrow jj\) at LHC 8 TeV \([43]\). Right) Allowed regions in the \((\Gamma_{gg}/M, \Gamma_{\chi\chi}/M)\) plane. The dark green band correspond to the region allowed by the GCE data alone at 95% C.L. Three solid curves correspond to \(\Gamma/M = 0.03, 0.07,\) and 0.12 as that in the left.

We scan the two-photon production cross section and the total width of \(\phi\) in the following ranges

\[
2 \text{ fb} \lesssim \sigma \lesssim 14 \text{ fb}, \quad \text{and} \quad 0.03 \lesssim \left( \frac{\Gamma}{M} \right) \lesssim 0.12, \tag{8}
\]

and show the allowed regions of the partial widths in the \((\Gamma_{gg}/M, \Gamma_{\gamma\gamma}/M)\) plane and \((\Gamma_{gg}/M, \Gamma_{\chi\chi}/M)\) plane in the left and right panel of Fig. 1 respectively. Three lines for typical values of \(\Gamma/M = 0.03, 0.07\) and 0.12 with \(\sigma = 8\) fb are also shown. The figure shows that a significant portion of parameter space is constrained by the limits on \(pp \rightarrow jj\) from the LHC 8 TeV data, \(\sigma(pp \rightarrow jj) \lesssim 2.5\) pb \([43]\). The allowed partial width to gluons is constrained to be \(\Gamma_{gg}/M \lesssim 1.6 \times 10^{-3}\). Although \(\Gamma_{gg}\) and \(\Gamma_{\gamma\gamma}\) can vary in a large range. The large cross section \(\sigma\) and \(\Gamma/M\) cannot be explained by the sum of all the SM final states, as the related channels are stringently constrained by the data from LHC 8 TeV \([42, 44]\).
4 Halo DM annihilation and the GCE

One of the direct consequences of the sizable DM couplings to gluons and photons is that the DM particle in the Galactic halo can annihilate into these particles and contribute to two types of extra cosmic gamma rays. The annihilation into two gluons generates diffuse gamma rays with a broad energy spectrum due to the hadronization process, while the annihilation into two photons generates a line-shape spectrum centered at the DM particle mass. Both signatures are under active search by the current DM indirect detection experiments, such as the Fermi-LAT and HESS experiments. The gamma-ray flux generated from DM particle annihilation and averaged over a solid angle $\Delta \Omega$ is given by

$$\frac{d\Phi}{dE} = \frac{1}{4\pi} \frac{dN_\gamma}{dE} \int \frac{d\Omega}{\Delta \Omega} \int_{\text{l.o.s.}} \frac{\langle \sigma v \rangle}{2\eta m_\chi^2} \rho^2(r) ds,$$

where $dN_\gamma/dE$ is the photon energy spectrum per DM annihilation, and $\langle \sigma v \rangle$ is the velocity averaged product of the annihilation cross section and the relative velocity $v$ of the annihilating DM particles. The value of $\eta = 1(2)$ for the case where the DM particle is (not) its own antiparticle. $\rho(r)$ is the spatial distribution of halo DM energy density, which is generally assumed to be spherically symmetric and depend only on $r$. The integration is to be performed over the distance $s$ along the light-of-sight which is related to $r$ through the relation $r^2 = r_\odot^2 + s^2 - 2sr_\odot \cos \psi$, where $\psi$ is the angle of direction away from the GC and $r_\odot = 8.5$ kpc is the distance of the Sun to the GC. N-body simulations suggest an universal DM profile of the form

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^\gamma \left[1 + \left(\frac{r}{r_s}\right)^\alpha\right]^\frac{\alpha-\gamma}{\alpha}}$$

which is characterized by three parameters $\alpha$, $\beta$, $\gamma$, and a reference scale $r_s \simeq 20$ kpc. For the standard NFW profile, $\alpha = \gamma = 1$ and $\beta = 3$. The value of $\rho_s$ is determined by the local DM density $\rho_0 = 0.4$ GeV/cm$^3$.

The DM annihilation cross section can be written as $\sigma v = a + bv^2$, where the coefficient $a$ (b) corresponds to the s(p)-wave annihilation process. Since in the Galactic halo $v$ is very small $v^2/c^2 \sim O(10^{-6})$, it is a good approximation to neglect the p-wave contribution. In the model under consideration, the cross section for DM annihilation into two gluons is given by

$$\langle \sigma v \rangle_{gg} \approx \frac{256\pi m_\chi^2 \left(\frac{\Gamma_{gg}}{M}\right) \left(\frac{\Gamma_{\chi\chi}}{M}\right)}{\left[(M^2 - 4m_\chi^2)^2 + M^2\Gamma^2\right] \beta_\chi}.$$

We perform a $\chi^2$-fit to the GCE data derived in Ref. [24]. The correlations in the data are taken into account. We consider a square region of interest (ROI) $20^\circ \times 20^\circ$ in the sky.
with latitude $|b| < 2^\circ$ masked out. The injection spectrum $dN_\gamma/dE$ for DM annihilating into two gluons are generated by Pythia 8.201 [46]. For the DM density profile, we use a modified NFW profile with inner slope $\gamma = 1.26$, as suggested by the observed morphology of the gamma-ray emission [17, 18, 21, 24]. The diffuse gamma-ray flux is calculated using Eq. (9). We find the best-fit DM particle mass and annihilation cross section as follows

$$m_\chi = 62.0^{+6.6}_{-6.3} \text{ GeV}, \quad \langle \sigma v \rangle_{gg} = (1.96^{+0.26}_{-0.24}) \times 10^{-26} \text{ cm}^3\text{s}^{-1}. \quad (12)$$

This result is in agreement with that from the analysis in Ref. [47]. The correspond gamma-ray spectrum for the best-fit parameters are shown in Fig. 2, together with the Fermi-LAT data. Although the predicted flux looks slightly lower than the data in the energy range $\sim 0.5-10 \text{ GeV}$ from the figure, the obtained $\chi^2_{\text{min}}/\text{d.o.f} = 24.6/22$ indicates a good agreement with the data, which is due to the the inclusion of the correlations among the data. The allowed regions for the parameters $(m_\chi, \langle \sigma v \rangle)$ at 68% C.L. and 95% C.L., corresponding to $\Delta \chi^2 = 2.3$ and 6.0, respectively, for two parameters are shown in Fig. 2.

![Image](image_url)

**FIG. 2:** Left) parameter regions allowed by the GCE data (in a region of interest of $20^\circ \times 20^\circ$ with latitude $|b| \leq 2^\circ$ excluded) in the $(m_\chi, \langle \sigma v \rangle)$ plane, at 68% C.L. and 95% C.L., respectively. The cross symbol indicates the best-fit values in Eq. (12). Right) Energy spectrum of the gamma-ray flux from the best-fit DM mass and annihilation cross section, together with the GCE data derived in Ref. [24].

As can be seen in Eq. (11), the GCE data can impose an independent constraint on the product $\Gamma_{\chi\chi} \Gamma_{gg}$. From the regions of parameters $m_\chi$ and $\langle \sigma v \rangle$ allowed by the GCE data within 95% C.L. in Fig. 2, we map the allowed region in $(\Gamma_{\chi\chi}, \Gamma_{gg})$ plane in the right panel of Fig. 1. Combined with the range of $\Gamma/M$ and the limits from $pp \rightarrow jj$, the allowed values of $\Gamma_{\chi\chi}$ is $0.05 \lesssim \Gamma_{\chi\chi} \lesssim 0.12$. The allowed region in $(\Gamma_{gg}, \Gamma_{\gamma\gamma})$ plane is shown in the left panel of Fig. 1. As it can be seen from the figure, combining the GCE data and the limit from $pp \rightarrow jj$ leads to a lower limit on $\Gamma_{\gamma\gamma}/M$, which indicates that there exists
a lower bound on the cross section for the annihilation \(\chi\chi \rightarrow \gamma\gamma\) which can generate a gamma-ray line.

![Graph](image)

**FIG. 3:** Prediction for \(\langle \sigma v \rangle_{\gamma\gamma}\) from a scan in parameters \{\(\Gamma_{\chi\chi}, \Gamma_{gg}, \Gamma_{\gamma\gamma}\)\} which are consistent with the GCE data at 95\% C.L., \(2 \text{ fb} \lesssim \sigma \lesssim 14 \text{ fb}, 0.03 \lesssim \Gamma/M \lesssim 0.12\) and the limits from \(\sigma(pp \rightarrow jj)\) at LHC 8 TeV. The blue dashed contour and the filled region describe the allowed region before and after considering the limits from \(\sigma(pp \rightarrow jj)\), for a fixed \(\Gamma/M = 0.07\) and \(\sigma = 3 \text{ fb}\). The exclusion limits from Fermi-LAT [48] are also shown.

## 5 Limits from Fermi-LAT gamma-ray line search

Combining the constraints from \(\Gamma\) and \(\sigma\), we show in Fig. 3 the predicted cross section for the DM annihilation \(\chi\chi \rightarrow \gamma\gamma\) which can generate a gamma-ray line with energy equal to the DM particle mass. The current limit at 95\% C.L. from the Fermi-LAT gamma line search based on 3.7 year data [48] is also shown in Fig. 3. As can be seen from the figure, the predicted cross section is \((10^{-28} - 10^{-26}) \text{ cm}^3\text{s}^{-1}\). The existence of the lower bounds on \(\langle \sigma v \rangle_{\gamma\gamma}\) is due to the constraints from \(pp \rightarrow jj\). For an illustration, we show the regions allowed by the GCE data for fixed values of \(\Gamma/M = 0.07\) and \(\sigma = 3 \text{ fb}\), before and after the inclusion of the limits from \(pp \rightarrow jj\). As can be clearly seen in the figure, the \(pp \rightarrow jj\) process play an very important role in determine the allowed cross
section $\langle \sigma v \rangle_{\gamma\gamma}$. The future results from 13 TeV LHC on the $pp \rightarrow jj$ will be crucial. The constraints from Fermi-LAT is typically a few $\times 10^{-28}$ cm$^3$s$^{-1}$. There is a portion of parameter space excluded by the Fermi-LAT data. The Fermi-LAT experiment is able to confirm or rule out the rest of the parameter space in a near future with larger statistics.

6 Conclusions

In summary, the first data from the LHC Run-2 have shown the possibility of an excess in the events containing two photons with invariant mass around 750 GeV, suggesting the existence of a new resonance $\phi$ which may decay dominantly into DM particles. We have show that the two-photon excess reported by the LHC is consistent with the GeV excess in the cosmic gamma-rays towards the Galactic Center, in a simple model where $\phi$ is a pseudo-scalar and couples to a scalar DM particle, Both excesses can be explained by a DM particle with mass around 60 GeV and annihilates dominantly into gluons with a typical thermal annihilation cross section. We have found that the predicted cross section for the line-shape gamma-ray spectrum can be constrained by the Ferm-LAT and future experiments.

7 Acknowledgements

This work is supported in part by the National Nature Science Foundation of China (NSFC) under Grants No. 10905084, No. 11335012 and No. 11475237.

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