SUSY explanation of the Fermi Galactic Center Excess and its test at LHC Run-II

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We explore the explanation of the Fermi Galactic Center Excess (GCE) in the Next-to-Minimal Supersymmetric Standard Model. We systematically impose various experimental constraints and perform a fit to the updated Higgs data. For each surviving sample we further generate its gamma-ray spectrum from dark matter (DM) annihilation and compare it directly with the Fermi data. We find that the GCE can be explained by the annihilation $\chi \chi \rightarrow a^* \rightarrow b \bar{b}$ only when the CP-odd scalar satisfies $m_a \simeq 2m_\chi$, and in order to obtain the measured DM relic density, a sizable $Z$-mediated contribution to DM annihilation must intervene in the early universe. As a result, the higgsino mass $\mu$ is upper bounded by about 350 GeV. Detailed Monte Carlo simulations on the $3\ell + E_T^{miss}$ signal from neutralino/chargino associated production at 14-TeV LHC indicate that the explanation can be mostly (completely) excluded at 95% C.L. with an integrated luminosity of 100(200) fb\textsuperscript{-1}.

I. INTRODUCTION

As a building block of the universe, Dark Matter (DM) is a focus of current particle physics. The existence of a Weakly Interacting Massive Particle (WIMP) as a DM candidate has been indicated by some direct detection experiments like DAMA/LIBRA \textsuperscript{1} and CDMS \textsuperscript{2}, although these experimental results are not consistent with each other very well and not supported by other experiments such as Xenon \textsuperscript{3} and LUX \textsuperscript{4}. On the other hand, indirect DM searches, which look for the products of DM annihilation or decay in the Galactic halo/center and nearby dwarf galaxies or inside the sun, also reported some anomalies. Recent data analyses of Fermi Gamma Ray Space Telescope have shown an excess around $1 \sim 4$ GeV in the energy spectrum of secondary photons coming from the Galactic Center \textsuperscript{5,6}. It has been pointed out that this gamma-ray excess can be well explained by a $\sim 35$ GeV DM annihilating 100\% into $b \bar{b}$ with a thermal averaged cross section of about $2 \times 10^{-26}$ cm\textsuperscript{3}/s, which is remarkably close to the value required by the measured thermal relic density $\Omega h^2$ \textsuperscript{7,8}. So far several works have been devoted to interpret such a Galactic Center Excess (GCE) in supersymmetry (SUSY) \textsuperscript{9,10}. It was found that, after considering the constraints from the relic density, the most promising DM annihilation channel is $\chi \chi \rightarrow a^* \rightarrow b \bar{b}$, where $a$ is a CP-odd Higgs boson with mass below about 100 GeV. In the Minimal Supersymmetric Standard Model (MSSM), due to the mass correlation between the pseudoscalar and the charged/heavy CP-even scalar, the pseudoscalar is generally heavier than about 300 GeV and thus cannot give an explanation for the GCE. In the Next-to-Minimal Supersymmetric Standard Model (NMSSM), an extra singlet superfield $\hat{S}$ is introduced and consequently it predicts three CP-even Higgs bosons $h_{1\sim 3}$, two CP-odd Higgs bosons $a_{1,2}$ and five neutralinos $\chi_{1\sim 5}^0$ (here an ascending mass order is assumed for the same type of particles, so $\chi_1^0$ acts as DM, which is denoted by $\chi$ hereafter) \textsuperscript{11}. Since the CP-odd Higgs boson $a_1$ may be singlet-like and rather light, light DM pair can annihilate mainly through the $s$-channel mediation of $a_1$ in both the early universe and today, and thus provide a possible explanation for the GCE. In fact, as pointed out in \textsuperscript{12}, in NMSSM a bino-like DM can explain both the GCE and the measured $\Omega h^2$ through an off-shell $a_1$, while a singlino-like DM requires a tuned resonance $2m_\chi \simeq m_{a_1}$ to achieve the same goal.

We note that previous analyses usually assumed a wide range of today’s DM annihilation rate $\langle \sigma v \rangle_{v \rightarrow 0} = (0.5 \sim 4.0) \times 10^{-26} \text{cm}^3/\text{s}$, which allows the height of the photon spectrum to vary greatly, i.e. $E^2 dN/dE = (1.0 \sim 7.0) \times 10^{-6} \text{GeV}/(\text{cm}^2 \cdot \text{s} \cdot \text{sr})$ for $m_\chi \simeq 35 \text{GeV}$ and $E = 2 \text{ GeV}$ (see Fig.\textsuperscript{12} below). Consequently, the parameter regions favored by GCE are easy to coincide with those favored by the measured $\Omega h^2$. Moreover, previous analyses usually missed some experimental constraints pertinent to the GCE explanation, such as the LEP search for light Higgs bosons and recently updated LHC Higgs data. So it is necessary to give a comprehensive study and further examine its implication at the LHC Run-II.

In this work we scan the NMSSM parameter space by considering various experimental constraints. Then for each surviving sample, we generate the photon spectrum so that we can compare it directly with the Fermi data presented in \textsuperscript{12} (we define an appropriate $\chi_2^2$ for such a comparison). Due to these improvements, we obtain different observations from those in \textsuperscript{12}. For example, we find that a singlino-like DM instead of a bino-like DM is easier to explain both the GCE and the measured $\Omega h^2$. More importantly, we observe that the annihilation process $\chi \chi \rightarrow a_1^* \rightarrow b \bar{b}$ can not be alone responsible for both the GCE and the measured $\Omega h^2$, and in order to get the correct $\Omega h^2$, a sizable $s$-channel $Z$ contribution to the DM annihilation in the early universe is usually necessary. As a result, the higgsino mass $\mu$ is upper bounded by about...
350 GeV, which will be readily tested at the LHC Run-II through the trilepton singal of neutralino/chargino associated production. We emphasize that since only some specific corners of the NMSSM parameter space can accommodate the GCE and the measured $\Omega h^2$ simultaneously, it is hard to get our observations by traditional random scan method, which is usually adopted in previous analyses.

The paper is organized as follows. In Section II we briefly describe our scan of the NMSSM parameter space, calculation of the gamma-ray spectrum and the Monte Carlo simulation for the trilepton signal at the LHC. In Section III we present our results and discussions. Finally we draw our conclusion in Section IV.

II. CALCULATIONS

The superpotential and Higgs potential of the NMSSM are given by [13]

$$W^{\text{NMSSM}} = W_F + \lambda \tilde{H}_u \cdot \tilde{H}_d \tilde{S} + \frac{1}{3} \kappa \tilde{S}^3,$$

$$V^{\text{NMSSM}} = m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + m_s^2 |S|^2 + (\lambda A_A S H_u \cdot H_d + \frac{1}{3} \kappa A_S \tilde{S}^3 + h.c.),$$

where $W_F$ is the superpotential of the MSSM without the $\mu$-term, $H_u$ and $H_d$ are MSSM Higgs superfields, $\lambda$ and $\kappa$ are coupling coefficients for Higgs superfields, and $m_{u,d,s}^2$, $A_\lambda$ and $A_\kappa$ are all soft breaking parameters. With such a framework, the CP-even (odd) Higgs mass eigenstates are obtained from the mixture of the real (imaginary) parts of the singlet scalar $S$ and the CP-even (odd) MSSM doublet Higgs fields, and similarly the neutralino mass eigenstates are the mixture of bino ($\tilde{B}$), wino ($\tilde{W}^0$), higgsinos ($\tilde{H}_u^0$, $\tilde{H}_d^0$) and singlino ($\tilde{S}$). In practice, the parameters $m_{u,d,s}^2$ are traded for $m_Z$, $\tan \beta \equiv v_u/v_d$ and $\mu \equiv \lambda v_t$ (by the minimization conditions of the Higgs potential) as theoretical inputs.

In our analysis, we fix all soft masses and soft trilinear parameters in squark (slepton) sector at 2 (0.3) TeV except that we allow $A_t = A_b$ to vary to obtain a 125 GeV CP-even Higgs. In order to get a light bino-like DM, we abandon the GUT relation among gaugino masses and set wino mass $M_2 = 1$ TeV and gluino mass $M_3 = 2$ TeV. Thus the free parameters are $\tan \beta$, $\mu$, $\lambda$, $\kappa$, $A_\lambda$, $A_\kappa$ in the Higgs sector, bino mass $M_1$ and the soft trilinear coupling $A_t$, which are all defined at 2 TeV. We adopt the Markov Chain Monte Carlo method to scan the following parameter space with NMSSMTools-4.3.0 [12]:

$$1 < \tan \beta < 40, \ 0 < \lambda < 0.7, \ 0 < \kappa < 0.7, \ 0 < |A_\kappa| < 2 \text{ TeV}, \ 0 < A_\lambda < 5 \text{ TeV}, \ |A_t| < 5 \text{ TeV},$$

$$0 < |M_1| < 0.6 \text{ TeV}, \ 0.1 \text{ TeV} < \mu < 0.6 \text{ TeV}. \quad (1)$$

We select the samples by the following steps:

1) We impose all constraints encoded in the NMSSMTools, including the relic density at 3σ level (corresponding to $0.107 \leq \Omega h^2 \leq 0.131$), LUX exclusion limit at 90% C.L., various B-physics measurements and muon anomalous magnetic moment etc, with criteria described in detail in [13]. Then we use HiggsBounds-4.1.2 [14] to systematically impose the collider constraints from Higgs searches at LEP, Tevatron and LHC.

2) For each sample, we perform a fit to the Higgs data updated in the summer of 2014 with details described in [15]. Subsequently we generate the gamma-ray spectrum with micrOMEGAs-3.6.9.2 [16] with the inner slope $\gamma$ of the generalized NFW DM halo profile [17] chosen to be 1.26 according to the best fit result of [6]. We first checked our gamma-ray spectrum by reproducing Fig.5 of [5]. Then we choose the first 13 experimental data points between 0.3 GeV $< E_{\gamma} < 6.0$ GeV, assuming they are not correlated with each other, to build a $\chi^2$ for each sample: $\chi^2 = \sum_{i=1}^{13} (y_{i_{\text{th}}} - y_{i_{\text{exp}}})^2 / (\sigma_{\text{exp}})^2$, where $y_{i_{\text{th}}}$ denotes theoretical prediction of $E^2dN/dE|_{E=E_i}$ (see Fig.2). We keep samples satisfying $\chi^2 < 32.0/10$, where the degree of freedom (d.o.f) is counted naively by $d.o.f = n_{\text{data}} - n_{\text{para}}$ with $n_{\text{data}} = 13$ and $n_{\text{para}} = 3$ standing for the three parameters of the inner slope $\gamma$, $m_\chi$ and $\langle s_{\gamma \nu} \rangle_{|v=0}$. With such a treatment, the surviving samples are consistent with the GCE data at 99.96% C.L..

We find that the surviving samples are characterized by $10 < \tan \beta < 28$, 170 GeV $< \mu < 340$ GeV, 30 GeV $< m_\chi < 42$ GeV and $m_0 > 500$ GeV. In the following analysis we classify them into four scenarios according to the dominant component of DM and which Higgs scalar corresponds to the SM-like one $h_{\text{SM}}$, i.e. for scenario I-S (I-B), $h_1$ corresponds to $h_{\text{SM}}$ and DM is singlino-like (bino-like), while for scenario II-S (II-B), $h_2$ acts as $h_{\text{SM}}$ with DM being singlino-like (bino-like).

Furthermore, since the higgsino mass $\mu$ of the surviving samples is not very large, they should be testable at 14-TeV LHC through the channel $pp \rightarrow \tilde{\chi}_{\pm1}^0 \tilde{\nu} \rightarrow 2\chi_{1}^0 W Z \rightarrow 3\ell + E_{\gamma}\text{miss}$ [18]. For each sample we perform a MC simulation, in which we use MadGraph5 [19] and Pythia [20] to generate relevant events and apply the parton shower
TABLE II. Best Benchmark points for scenario II-S, II-B and I-B, respectively. Quantities with mass dimension are in unit of GeV and the GCE annihilation cross section is in unit of cm²/s.

| mχ | mα | mβ | mγ | mχ± | Aχ | Aγ | μ |
|----|----|----|----|----|----|----|---|
| (II-S) 35.8 | 70.8 | 61 | 125 | 3900 | 2250 | -168 |
| (II-B) 40.32 | 80.62 | 49 | 126 | 4480 | 2770 | 43.5 |
| (I-B) 40.43 | 80.78 | 126 | 287 | 5080 | 4350 | 43.5 |

| (σv)kk|v→0 | λ | κ | tan β | Aχ | Aγ | μ |
|-------|-----|----|----|-------|----|----|---|
| 1.7 × 10⁻²⁶ | 0.45 | 0.03 | 15.5 | 3940 | -100 | 248 |
| 1.9 × 10⁻²⁶ | 0.11 | 0.015 | 19.2 | 4380 | -67 | 237 |
| 1.9 × 10⁻²⁶ | 0.41 | 0.23 | 22.2 | 4630 | -13 | 252 |

| σv² (pb) | O(κ²) | [yα,XX] | [yα, bb] | Brhαχχ,inv | Γχχ,inv | λχ² |
|-----------|-------|--------|---------|------------|---------|-------|
| 2.1 × 10⁻¹⁰ | 0.12 | 0.042 | 0.008 | 0.3% | 3 × 10⁻⁴ | 11.2 |
| 3.3 × 10⁻¹⁰ | 0.12 | 0.001 | 0.002 | 14% | 2 × 10⁻⁴ | 19.2 |
| 3.3 × 10⁻¹⁰ | 0.13 | 0.005 | 0.007 | 14% | 1 × 10⁻⁴ | 27.3 |

for the signals and the dominant SM backgrounds. Using the well tuned fast detection simulation Delphes II encoded in CheckMATE-1.16 [22], we obtain the cut efficiencies for the six signal regions (SRs) of [18]. Then with the cross section of $\chi^±\chi^0$ associated production calculated by Prospino2 [23] at next-to-leading order (NLO), we evaluate the significance $S_i = s_i / \sqrt{b_i + (10%b_i)}$, in which $s_i$ and $b_i$ correspond to the number of signal and background events after cuts and 10% is the systematical uncertainty of the backgrounds we assume. Moreover, in order to prove the moderately large $\mu$ region more efficiently, besides the six SRs in [18] we add one more SR named SRZd, which has the same cuts as SRZe in [18] except that it requires $E_{T}^{miss} > 165$ GeV. In Table II we list our backgrounds after cuts in different SRs. We also performed similar analysis of the trilepton signal at 8-TeV LHC and found that it has no limitation on the samples.

III. RESULTS AND DISCUSSION

A. Scan results: Among the four scenarios to explain both the GCE and the relic density in the experimentally allowed parameter space, we found that II-S is most favored, and II-B and I-B are marginally okay by tuning the relevant parameters (we get only a few benchmark points after a long time scan), while I-S can not provide any viable sample. In Fig.4 we show the range (shaded cyan band) of the gamma-ray spectrum predicted by the II-S surviving samples along with the Fermi data taken from Fig.5 of [18]. We checked that the shaded region has $\langle σv ⟩_{kk|v→0} ≃ 0.9 × \langle σv ⟩_{v→0} = (1.3 \sim 2.1) \times 10^{-26}$ cm²/s as a result of the requirement $λχ^2 ≤ 32.0$. Note that such a range is much narrower than those assumed in previous analyses. We also present the best benchmark points of the three scenarios, and show their details in Fig.1 and Table II.

To understand why scenario II-S is most favored by the GCE, we start with an effective Lagrangian

$$- L_{int} = iy_{α,XX}a_{1}χγ^5χ + iy_{α, bb}a_{1}bγ^5b,$$ (2)

where $y_{α,XX}$ and $y_{α, bb}$ are Yukawa couplings. The cross section for the annihilation $α_{1} → b b$ is given by

$$\langle σv ⟩_{bb|v→0} ≃ \frac{g_{α}^2}{(4m_{α}^2 - m_{α}^2)^2 + m_{α}^2Γ_{α}^2},$$ (3)

This formula indicates that in order to predict a relatively large $\langle σv ⟩_{bb|v→0}$, either $y_{α,XX}a_{1}$ takes a sufficiently large value or $m_{α_{1}}$ approaches to $2m_{χ}$. As far as NMSSM is concerned, the experimental bounds we considered have limited $m_{α_{1}} ≃ 70$ GeV to be highly singlet-like (so $Γ_{α_{1}}$ is very small), and $m_{α_{2}} ≥ 500$ GeV. Consequently the coupling $y_{α,XX}$ in scenario II-S mainly gives contribution from the superpotential term $κS^3$, so it is approximated by $v^2κ$. In contrast, since DM is bino-like in scenarios II-B and I-B, the leading contribution to $y_{α,XX}$ is suppressed by a factor $λm_{χ}^2 sin^2θ_{W} sin 2β/μ^2$ with $θ_{W}$ being the weak mixing angle (see Eq.(III.40) in [5]). Since $y_{α,XX}$ in scenario II-S can be much larger than in scenarios II-B and I-B, $m_{α_{1}}$ in this scenario may slightly deviate from $2m_{χ}$, in explaining the GCE so that the theory is less tuned (see Table II for the three best benchmark points). We emphasize that all these three scenarios require a low $μ$: in scenario II-S, a low $μ$ is needed to predict $m_{χ_{2}} ≃ 125$ GeV [24], while in scenarios II-B and I-B, a low $μ$ is necessary to keep $y_{α,XX}$ moderately large.

Finally we discuss scenario I-S, which is featured by $2κv_{α} ≃ 35$ GeV to get the desired DM mass and the CP-even singlet Higgs mass $|M_{S,33}| ≃ 125$ GeV to ensure
All have 2

B. DM annihilation in the early universe: From Table II one can learn that the three benchmark points all have $2m_\chi/m_{a_1} > 1$, which means that $\langle \sigma v \rangle$ today $\langle \sigma v \rangle_{|v=0}$ is usually larger than that at freezing out $\langle \sigma v \rangle_0$. It is due to the thermal broadening, if DM annihilates only through the intermediate $a_1$. On the other hand, in order to predict the measured \(\Omega h^2\), $\langle \sigma v \rangle_0$ should be generally larger than about $3 \times 10^{-26}$ cm$^3$/s, which implies that the process $\chi\chi \rightarrow Z^* \rightarrow bb$ must also contribute sizably to the DM annihilation in the early universe. To illustrate this point, we concentrate on the samples of scenario II-S. In the upper and lower panels of Fig.2 we show the variations of $y_{a_1\chi\chi}$ and $y_{a_1bb}$ as a function of $2m_\chi/m_{a_1}$ and the correlation between $\langle \sigma v \rangle_{|blook at v=0}$ and $Z$ boson invisible decay width $\Gamma_{Z,inv}$, respectively. The upper panel indicates that as $2m_\chi/m_{a_1}$ increases, $y_{a_1\chi\chi}$ and $y_{a_1bb}$ must also increase to maintain an appropriate $\langle \sigma v \rangle_{|v=0}$ to explain the GCE. This panel also shows that a larger $\langle \sigma v \rangle_{|v=0}$ generally corresponds to a $2m_\chi/m_{a_1}$ closer to 1 since the cross section in Eq.3 is very sensitive to the resonance. The lower panel indicates that near the resonance region where $\langle \sigma v \rangle_{|v=0}$ is large, $\Gamma_{Z,inv}$ is small corresponding to a minor $Z$ contribution to $\langle \sigma v \rangle_0$. While as $2m_\chi/m_{a_1}$ departs from the resonance, we usually have an increased $\Gamma_{Z,inv}$ and decreased $\langle \sigma v \rangle_{|v=0}$. This can be understood as follows. In the resonance region, the correlation between the $a_1$ contribution to $\langle \sigma v \rangle_0$ and $\langle \sigma v \rangle_{|v=0}$ is relatively weak \(25\) and both can be quite large, in which case the $Z$ contribution to $\langle \sigma v \rangle_0$ can be small. While if $a_1$ is off-shell, the $a_1$ contribution to $\langle \sigma v \rangle_0$ is less than $\langle \sigma v \rangle_{|v=0}$, which means that a sizable $Z$ contribution must be present to push up $\langle \sigma v \rangle_0$ to reach $3 \times 10^{-26}$ cm$^3$/s.

Note that in order to obtain a sizable $Z$ contribution which requires a moderately large coupling $g_{ZXX}$, $\mu$ can not be too large since $g_{ZXX} \propto \lambda^2 v^2/\mu^2$ for singlino-like DM and $g_{ZXX} \propto m_Z^2 s_v^2/\mu^2$ for bino-like DM \(8\). As shown in Fig.2 a sizable $Z$ contribution can allow $2m_\chi/m_{a_1}$ to deviate slightly from unity, which makes the theory less tuned. Interestingly, we recall that a low $\mu$ is also favored to stabilize the weak scale.

C. Test the explanation at 14-TeV LHC: Now we discuss the ability of 14-TeV LHC to test the GCE-
favored NMSSM parameter space. In Fig. 3 we show the needed integrated luminosity to exclude the II-S samples at 95% C.L. as a function of the lightest chargino mass $m_{\tilde{\chi}^\pm_1}$. For each sample, we choose its most sensitive SR, which is usually SRZc for $m_{\tilde{\chi}^\pm_1} \leq 220$ GeV and SRZd for $m_{\tilde{\chi}^\pm_1} \geq 280$ GeV, and require the corresponding $S_\ell$ to be 1.96 to get the exclusion luminosity. Fig. 3 indicates that with an integrated luminosity of 100 fb$^{-1}$ (200 fb$^{-1}$) which can be reached at the initial stage of LHC Run-II, most (all) of the II-S surviving samples will be excluded. In Fig. 3 we also use squares (red) and bullets (dark green) to indicate samples that may be discovered at 14-TeV LHC with 1000 fb$^{-1}$ and 3000 fb$^{-1}$ luminosities, respectively.

As for the benchmark point of scenario II-B (I-B), we find that it will be excluded with an integrated luminosity of 25.3 fb$^{-1}$ (21.2 fb$^{-1}$), or be discovered with 700 fb$^{-1}$ (400 fb$^{-1}$) luminosity. Note that, if the trilepton signal is combined with the 2-lepton+jets signal of the $\tilde{\chi}^\pm_1 \chi^0_1$ associated production processes as done in [20], the significance for a given sample may be further improved.

IV. CONCLUSION

We scanned the NMSSM parameter space by considering various experimental constraints to explain both the GCE and the measured DM relic density. Unlike previous analyses where a wide range of $\langle |v\tilde{\nu}|^2 \rangle_{\nu\rightarrow 0}$ was usually assumed, we generate the gamma-ray spectrum and compare it directly with the Fermi data. We have three main observations: a) The GCE can be explained by the DM annihilation $\chi \chi \rightarrow a_1^\pm \rightarrow bb$ only when $m_{\tilde{a}_1} \approx 2m_\chi$, and a singlino-like DM is more favored than a bino-like DM; b) In order to produce the measured relic density, a sizable $Z$ boson contribution to the DM annihilation in the early universe must be present, resulting in the higgsino mass $\mu$ upper bounded by about 350 GeV; c) Detailed MC simulations on the $3\ell + E_T^{miss}$ signal from neutralino/chargino associated production at 14-TeV LHC indicate that the surviving samples can be mostly (completely) excluded at 95% C.L. with an integrated luminosity of 100(200) fb$^{-1}$, and a large portion of them may also be discovered with an integrated luminosity of 3000 fb$^{-1}$.

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Note added: While we prepare this manuscript, a similar work [27] appeared in the arXiv. Like previous studies, [27] also assumed a wide range of $\langle |v\tilde{\nu}|^2 \rangle_{\nu\rightarrow 0}$ and did not systematically consider the LHC Higgs data. As a result, we have different conclusions.

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