Inert Higgs Dark Matter for New CDF $W$-boson Mass and Detection Prospects

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The $W$-boson mass, which was recently measured at FermiLab, suggests the presence of new multiplets beyond the Standard Model (SM). One of the minimal extensions of the SM is to introduce an additional scalar doublet, in which the non-SM scalars can enhance $W$-boson mass via the loop corrections. On the other hand, with a proper discrete symmetry, the lightest new scalar in the doublet can be stable and play the role of dark matter particle. We show that the inert two Higgs doublet model can naturally handle the new $W$-boson mass without violating other constraints, and the preferred dark matter mass is between 54 and 74 GeV. We identify three feasible parameter regions for the thermal relic density: the SA co-annihilation, the Higgs resonance, and the $SS \rightarrow WW^*$ annihilation. We find that the first region can be fully tested by the HL-LHC, the second region will be tightly constrained by direct detection experiments, and the third region could yield detectable GeV gamma-ray and antiproton signals in the Galaxy that may have been observed by Fermi-LAT and AMS-02.

I. INTRODUCTION

The origin of mass is one of the most fundamental problems in modern physics. The central idea of generating masses of the electroweak gauge bosons in the SM is the spontaneous symmetry breaking (SSB). Therefore, the precision measurement of the gauge boson masses is of great importance in testing the SSB mechanism. With the full dataset, the CDF collaboration has recently reported their newly measured $W$-boson mass $m_{W,\text{CDF}} = 80.4335 \pm 0.0094$ GeV [1], which deviates from the SM prediction $m_{W,\text{SM}} = 80.357 \pm 0.006$ GeV [2] about 7σ. Since the estimated higher order corrections are small, such a large discrepancy strongly indicates the presence of new physics related with the SSB, such as models with extended Higgs sectors.

On the other hand, the existence of dark matter (DM) has been favored by various astrophysical and cosmological observations. For decades, Weakly Interacting Massive Particles (WIMPs) are considered as the strongest candidate for DM. One of the minimal scalar WIMP dark matter models is the inert two Higgs doublet model (2i2HDM) [3–6], where one doublet $H_1$ is the SM Higgs doublet and the other doublet $H_2$ is hidden in the dark sector are given by,

\[ H_1 = \left( \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix} \right), \quad H_2 = \left( \frac{1}{\sqrt{2}} \begin{pmatrix} H^+ \\ S + iA \end{pmatrix} \right). \]

Here $G^\pm$ and $G^0$ are the charged and neutral Goldstone bosons, and $v \approx 246$ GeV is the vacuum expectation value (VEV) of the SM Higgs field. The discrete $\mathbb{Z}_2$ symmetry ($H_1 \rightarrow H_1$ and $H_2 \rightarrow -H_2$) is introduced to ensure the lightest scalar stable and cannot be spontaneously broken, i.e., $\langle H_2 \rangle = 0$. After the SSB, there will be five physical mass eigenstates, including two CP-even Higgs bosons $h$ and $S$, one CP-odd Higgs boson $A$, and a pair of charged Higgs $H^\pm$. The $\mathbb{Z}_2$-even scalar $h$ is identified as the SM Higgs boson, and $\mathbb{Z}_2$-odd scalar $S$ or $A$ can be the DM particle.

In general, the corrections of non-SM scalars to the squared $W$-boson mass can be expressed in term of the oblique parameters $S$, $T$, and $U$ [7, 8], i.e.,

\[ \Delta m_W^2 = \frac{\alpha c_W m_Z^2}{c_W^2 - s_W^2} \left[ \frac{S}{2} + c_W^2 T + \frac{c_W^2 - s_W^2}{4s_W^2} U \right], \]

where $c_W$ and $s_W$ are cosine and sine of Weinberg angle. The fine structure constant and $Z$ boson mass are denoted as $\alpha$ and $m_Z$. In Eq. [1] the dominant contribution to the $W$-boson mass arises from $T$ parameter, which is sensitive to the mass splitting of new particles running in the loop of gauge boson self-energy. Meanwhile, when the charged Higgs boson is lighter than the neutral Higgs bosons, they produce a positive $S$ and thus reduce the corrections to $W$-boson mass. Therefore, enhancing $W$-boson mass prefers the scenario with a heavy $H^\pm$ and light $S$ and $A$. Due to the symmetry of exchanging $S$ and $A$, the result in our study is the same for either $S$ or $A$ being DM [9–19]. We will show that the 2i2HDM can account for the $W$-boson mass anomaly naturally and offer a successful thermal WIMP paradigm without violating other constraints. Future collider and DM experiments will be able to test the favored regions.

II. METHODOLOGY

The scalar potential of 2i2HDM can be written as

\[ V = \mu_1^2 |H_1|^2 + \mu_2^2 |H_2|^2 + \lambda_1 |H_1|^4 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1^\dagger H_2|^2 + \lambda_5 \left( |H_1^\dagger H_2|^2 + \text{h.c.} \right). \]
In order to present the allowed parameter space, we use “Profile Likelihood” method [27] to get rid of nuisance parameters while showing the two dimensional contours. In Table II we list the above experimental constraints incorporated in our likelihood functions. The total $\chi^2_{\text{tot}}$ is to sum over the individual $\chi^2$ of these constraints. We use Gaussian likelihood with

$$\chi^2 = \left( \frac{\mu - \mu_{\exp}}{\sigma} \right)^2 \quad \text{and} \quad \sigma = \sqrt{\sigma^2_{\text{theo}} + \sigma^2_{\text{exp}}},$$

where $\mu$ is the theoretical prediction and $\mu_{\exp}$ is the experimental central value. The uncertainty $\sigma$ includes both theoretical and experimental errors. For those Half-Gaussian functions, we can set $\mu_{\exp} = 0$ based on the null signal. We use the hard cuts for the theoretical bounds, LEP-II, and OPAL limits.

To examine the impact of the new CDF $m_W$ measurement, we perform two sets of numerical scans by taking two different likelihoods for electroweak precision data. Please bear in mind that these two scans share the same constraints in Table I except for electroweak precision likelihood. The first likelihood, which is denoted as PDG2020 and does not take into account the latest CDF $m_W$ data, includes the previous complete electroweak precision measurements which are parameterized by three oblique parameters $S = -0.01 \pm 0.1$, $T = 0.03 \pm 0.12$ and $U = 0.02 \pm 0.11$ (all intervals are for 68% confidence level). The correlation coefficients of $(S, T)$, $(S, U)$ and $(T, U)$ are $0.92$, $-0.8$, and $-0.93$, respectively [2]. We refer the readers to Ref. [14] for the implementation of the covariance matrix with oblique parameters. For the second, we utilize the CDF $W$-boson mass measurement $m_{W,\text{CDF}} = 80.4335 \pm 0.009$ GeV as the electroweak precision test likelihood function.

On the other hand, since the DM indirect detection constraints likely suffer from some systematic uncertainties, we will not include them in the likelihood but compare our allowed parameter space with the limits set by the Fermi-LAT observations of dwarf Spheroidal galaxies [25] as well as the signal regions of the Fermi-LAT galactic center gamma-ray excess [26-29], and AMS-02 anti-proton excess [30].

We adopt the MCMC scans by using the code *emcee* [37]. To reach a good coverage of the parameter space, we perform several scans and finally collect $\mathcal{O}(4.5 \times 10^6)$ data points. The confidence intervals are calculated from the tabulated values of $\Delta \chi^2 \equiv -2 \ln(\mathcal{L}/\mathcal{L}_{\text{max}})$. For a two dimensional plot, the 95% confidence (2$\sigma$) region is defined by $\Delta \chi^2 \leq 5.99$ under the assumption of approximate Gaussian likelihood.

### III. NUMERICAL RESULTS AND DISCUSSIONS

As mentioned above, we present two sets of results based on the likelihoods summarized in Table II. One is in gray (see Fig.1 and Fig.2), which is obtained from the

<table>
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<td>Half-Gaussian</td>
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<td>Gaussian</td>
<td>$R_{\gamma \gamma}$ [26]</td>
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**TABLE I.** Likelihood distributions and constraints used in our analysis.
global fit with PDG2020 EWPT [2]. While the other, marked in green, blue and red, takes into account the new CDF $m_W$ data in the fit [1].

In Fig. 1 we display the 95% allowed regions on the planes of $m_S/m_{H^\pm}$ versus $m_W$ as well as $m_A/m_{H^\pm}$ versus $m_W$ with and without constraint of the latest CDF $m_W$ measurement. We find that the loop correction to $m_W$ is dominated by the oblique parameter $T$ so that a large mass splitting between the charged Higgs bosons and neutral Higgs bosons can enhance $W$-boson mass sizably. Besides, we note that the mass ratios of $m_S/m_{H^\pm}$ and $m_A/m_{H^\pm}$ have to be less than one, i.e., $m_S/m_{H^\pm} < 0.5$ and $0.35 < m_A/m_{H^\pm} < 1$, since they can produce a negative oblique parameter $S$ to further increase the $W$-boson mass. There is a clear gap at $m_W \sim 80.4$ GeV between gray and other three color in both $(m_S/m_{H^\pm}, m_W)$ and $(m_A/m_{H^\pm}, m_W)$ planes, owing to the fact that the central value of $m_W$ from PDG2020 differs with the recent CDF measurement by 7σ. Hence, they do not overlap in $m_W$-axis at the 95% significance level.

In Fig. 2 we present the allowed 95% regions for above two cases on the planes of $m_S$ versus $m_A$ as well as $m_S$ versus $m_{H^\pm}$. It can be seen that the DM mass $m_S$ is bounded within the range of $54 - 74$ GeV. The previous higher mass region of $m_S > 500$ GeV for $S - A - H^\pm$ co-annihilation is excluded. To account for the new CDF $W$-boson mass, the mass differences between the charged Higgs bosons and neutral Higgs bosons should be enhanced, hence the mass degeneracy needed by the $S - A - H^\pm$ co-annihilation is broken. The explicit correlations between the oblique parameters and new mass spectra can be found in Appendix V.

Therefore, only three different favored parameter space for the DM relic density remains: $SA$ co-annihilation with $m_S \approx m_A$ (green region), the Higgs resonance with $m_S \approx m_h/2$ (blue region), and the off-shell annihilation of $SS \rightarrow WW^*$ (red region). The first two mechanisms are in general with small couplings but the four-point interaction $\lambda_{33} = 2(m_{H^\pm}^2 - m_h^2)/v^2$ can efficiently govern DM annihilation for $m_S > 60$ GeV even though one of $W$-bosons is off-shell. One can see that a kink of the co-annihilation region, induced by the four-point interaction, appears at $m_S \sim 60$ GeV in Fig. 2.

In Fig. 3 we show the prospects of testing the above three favored scenarios in future collider and dark matter experiments. In the case of the Higgs resonance, we find that the DM-Higgs coupling is within the range of $|\lambda_{33}| < 0.003$. The survived region covers the range of $4 \times 10^{-50}$ cm$^2 \leq \sigma v \lesssim 5 \times 10^{-47}$ cm$^2$, which has been tightly constrained by the latest PandaX-4T limit. Most of the rest parameter space will be probed by the DM direct detection experiments in the near future. On the contrary, a large portion of the survived parameter space of $SA$ co-annihilation and $SS \rightarrow WW^*$ regions is below the so-called neutrino floor and hence beyond the scope of the conventional DM direct detection experiments. Fortunately, these two scenarios can be probed in future collider and DM indirect detection experiments. To be specific, due to a small mass splitting between $S$ and $A$ (see middle panel), we recast the current exclusion limit from the LHC search for the compressed SUSY [10], and also show the expected bound for the integrated luminosity 750 fb$^{-1}$. We can see that the $SA$ co-annihilation region can be fully covered at the future LHC. In addition, we note that the DM annihilation cross-section can be around the thermal cross-section $\langle \sigma v \rangle \sim 10^{-20}$ cm$^3$s$^{-1}$ in $SA$ co-annihilation, Higgs resonance and $SS \rightarrow WW^*$ interaction.
IV. CONCLUSION

The CDF collaboration has just reported their latest measurement of $m_W$ with unprecedented accuracy and the mass is above the standard model prediction at a significance level of $7\sigma$. Such a W-boson mass anomaly likely points toward the presence of new particles that can be related to the dark matter. The simplest dark matter model to account for the anomaly is the i2HDM. After addressing current theoretical and experimental/astrophysical constraints, we obtain viable regions of $m_S/m_{H^\pm} < 0.5$ and $0.35 < m_A/m_{H^\pm} < 1$, for which the mass degeneracy of co-annihilation at $m_S > 500$ GeV has been broken. This is remarkably different from the pre-2022 data. As a result, the heavy dark matter mass region has been thoroughly excluded and the charged Higgs must be heavier than $S$ and $A$. The DM mass is inferred to be between 54 GeV and 74 GeV and the thermal relic density was governed by the process of either the Higgs resonance, or $SA$ co-annihilation, or $SS \rightarrow WW^*$ annihilation. The $m_{W,CDF}$ favored dark matter mass range is well consistent with being a weakly-interacting massive particle (WIMP; which is the most extensively discussed dark matter candidate). Encouragingly, the GeV gamma-ray excess in the Galactic center and the possible GeV antiproton excess do consistently suggest a dark matter particle within the same mass range. Further dedicated efforts are highly needed to explore whether these two astrophysical signals and the $m_{W,CDF}$ indeed have the common origin.

ACKNOWLEDGMENTS

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APPENDIX

V. ADDITIONAL INFORMATION ON THE DISTRIBUTION OF THE PHYSICAL PARAMETERS

Here we present more complete information on the distribution of the physical parameters constrained by current experimental/astrophysical constraints.

In Fig. 1 we show the DM-Higgs coupling as a function of $m_S$. The PLANCK relic density constraint results in a small favored region because other regions are corresponding to DM relic abundance $\Omega h^2$ overproduced. Because of the correlation $\Omega h^2 \propto 1/(\sigma v)$, a tiny coupling requires specific mechanisms, such as the SA co-annihilation (green), the Higgs resonance (blue) and $SS \rightarrow WW^*$ annihilation via four points interaction (red), to boost the annihilation cross section. The PDG2020 data has already imposed stringent constraints on $\lambda_S$ and the inclusion of $m_{W,CDF}$ has just narrowed down the viable region slightly.

Since $\Delta m_W^2$ is proportional to $-S$, $T$ and $U$ [see Eq. (1)], the sizeable $W$-boson mass anomaly thus calls for a negative $S$ or almost zero if positive and a relative large $T$. Note that in 12HDM usually the absolute value of $U$ is smaller than that of $T$ by one or two orders. In particular, a positive $S$, which is only allowed in the SA co-annihilation scenario, would favor a high $T$. The correlations between oblique parameters and mass spectra are displayed in Fig. 2. As anticipated, $m_{W,CDF}$ sets stringent constraints on the ranges of $S$ and $T$ and we have $S \leq 0.025$ and $T \geq 0.07$.

In Fig. 6(a) and Fig. 6(b) we present the $\Delta^0$ and $\Delta^\pm$ as a function of $m_S$ in a wide range of $40 \text{ GeV} < m_S < 4 \text{ TeV}$.

In the absence of the CDF $W$-boson mass measurement data, $m_S > 500 \text{ GeV}$ is allowed under the co-annihilation condition $m_S \approx m_A \approx m_{H^\pm}$, as found in the literature [11, 15]. Such a massive DM region, however, has been convincingly excluded by $m_{W,CDF}$. For the SA co-annihilation scenario, we have a $\Delta^0$ clustering in the range of $7.5-8.8 \text{ GeV}$. The mass splitting $\Delta^0 \sim 30-520 \text{ GeV}$ is needed for the other two scenarios. The CDF $m_W$
FIG. 5. The correlations between oblique parameters and mass spectra. The CDF $W-$boson mass measurement plays a key role in shaping the viable ranges of $S$, $T$ and $U$. To reproduce the data, $S$ should be negative or almost zero if positive, while $T$ is relatively high.

anomaly also requires a $60 \text{ GeV} < \Delta^+ < 530 \text{ GeV}$.

[8] D. Eriksson, J. Rathsman and O. Stal, Com-
FIG. 6. The favored 95% regions of $\Delta^0$ [panel (a)] and $\Delta^\pm$ [panel (b)] as a function of the dark matter mass (i.e., $m_S$). Different colors represent different physical processes governing the thermal relic density, as labeled in the plots. The regions of $m_S > 500$ GeV are also presented but they have been excluded by the latest CDF $m_W$ measurement.


