Physics Letters B 775 (2017) 196–205

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# The semi-Hooperon: Gamma-ray and anti-proton excesses in the Galactic Center

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ARTICLE INFO

*Article history:*
Received 14 June 2017
Received in revised form 2 October 2017
Accepted 27 October 2017
Available online 31 October 2017
Editor: A. Ringwald

ABSTRACT

A puzzling excess in gamma-rays at GeV energies has been observed in the center of our galaxy using Fermi-LAT data. Its origin is still unknown, but it is well fitted by Weakly Interacting Massive Particles (WIMPs) annihilations into quarks with a cross section around $10^{-26}$ cm$^3$ s$^{-1}$ with masses of 20–50 GeV, scenario which is promptly revisited. An excess favoring similar WIMP properties has also been seen in anti-protons with AMS-02 data potentially coming from the Galactic Center as well. In this work, we explore the possibility of fitting these excesses in terms of semi-annihilating dark matter, dubbed as semi-Hooperon, with the process WIMP WIMP $\to$ WIMP X being responsible for the gamma-ray excess, where $X = h, Z$. An interesting feature of semi-annihilations is the change in the relic density prediction compared to the standard case, and the possibility to alleviate stringent limits stemming from direct detection searches. Moreover, we discuss which models might give rise to a successful semi-Hooperon setup in the context of $\mathcal{Z}_3$,$\mathcal{Z}_4$ and extra "dark" gauge symmetries.



## 1. Introduction

Dark matter is one of the pillars of the Standard Cosmological Model, but its nature is unknown, despite the compelling evidence at different time scales of the universe evolution and distance scales of the universe today. Since the Standard Model of particle physics has no particle able to account for the presence of dark matter in our universe, theories beyond the Standard Model are needed. Therefore, the nature of dark matter is one of the most important open problems in modern cosmology and particle physics, as can be seen by the enormous theoretical and experimental effort being put forth toward its identification.

One of the most compelling candidates are the Weakly Interacting Massive Particles (WIMPs) [1–4]. A signal in indirect dark matter detection represents a major step towards unveiling the nature of dark matter, and from this perspective, gamma-rays play a key role. WIMPs are, indeed, expected to shine in gamma-rays and these enable us to trace back the source, serving as a good handle for background discrimination [5].

Albeit, it is quite challenging to disentangle a potential DM signal from the large astrophysical foreground and backgrounds that dominate the measured gamma-ray flux. Thus, two searches for a DM signal stand out: signal maximization or background reduction. In the former, targets such as the Galactic Center (GC) are used, whereas in the latter Dwarf Spheroidal Galaxies (dphs) become ideal hosts [6–13].

In particular, the GC is expected to be the brightest source in gamma-rays [14,15], but our current knowledge of the astrophysical foreground and background is subject to large uncertainties. For this reason is not surprising to spot gamma-ray excesses towards the inner region of our galaxy. Anyways, several groups reported the observation of a residual gamma-ray emission using the publicly available gamma-ray data from the Fermi-LAT satellite [16–26]. The excess is peaked around 1–3 GeV, and has spectral and morphological features similar to those expected from DM annihilations.

Excitingly, the excess has been confirmed by the Fermi-LAT collaboration [27] to enliven the signal, and its seems to be extended up to higher latitudes as expected from dark matter annihilation [24,28]. Past studies have been done to determine the best-fit region for the gamma-ray excess in terms of dark matter annihilations [29–31], motivating model building endeavors in terms of WIMP annihilations.

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https://doi.org/10.1016/j.physletb.2017.10.065

Moreover, more recently an excess in anti-protons has been observed in the AMS-02 data [32,33]. The source of this excess is unknown but it is quite plausible to come from the GC. This excess seems similar to one firstly observed in the PAMELA data [34]. Anyways, in [32] the authors went beyond the usual benchmark propagation models MIN/MED/MAD scenarios that are motivated by the Boron over Carbon ratio [35], and performed a global fit to the AMS-02 anti-proton data to claim an over $4\sigma$ signal from dark matter annihilation. As described in [36], the WIMPs properties favored by this signal are similar to those from the GeV excess in gamma-rays. Therefore, in what follows, we will assume that the processes capable of explaining the GeV gamma-ray excess are also providing a good fit to the anti-proton excess. For this reason, whenever we refer to the GeV excess in gamma-rays bear in mind that there is also a similar excess in anti-protons.

However recent null results from direct dark matter detection experiments and colliders have shrunk quite a bit the number of models capable of accounting for the gamma-ray excess [37–70] in agreement with existing bounds. Therefore, it is worthwhile to investigate different setups.

That said, after briefly reviewing the status of dark matter annihilations as an explanation to the GC excess, we discuss the possibility of explaining the gamma-ray excess in the GC via semi-annihilations [71–80]. By semi-annihilations one typically refers to processes of the type $DM\,DM \to DM\,X$ involving three DM particles, two in the initial state and one in the final state, and a state $X$ which can be either an SM state or an additional (unstable) exotic state. It can be noted that semi-annihilations occur in scenarios where the DM is made stable via symmetries larger than $\mathcal{Z}_2$, as for example $\mathcal{Z}_3$.

In most of the WIMP scenarios, direct and indirect detection observables are tightly connected. This feature is particularly evident in the so-called simplified models [43,81–96], where DM annihilations and the WIMP-nucleon scattering cross section are governed by the same mediator and couplings. Semi-annihilation that can have a strong impact on the DM relic density, on the other hand, are not necessarily connected to the WIMP-nucleon scattering rate. Therefore, sizeable semi-annihilations without conflicting direct detection limits are feasible. For this reason, semi-annihilations represent a plausible mechanism to explain the GeV gamma-ray excess in agreement with existing data.

As we shall see further, indirect detection limits are still strong as in the case of annihilating dark matter, since a good fit to the GeV excess through semi-annihilation requires a relatively large semi-annihilation cross-section which can be probed with indirect detection experiments. We emphasize that the crucial aspect of models with dominant semi-annihilations is the possibility to weaken the restrictive limits from direct detection experiments which typically force the existing models to live in regions of parameter space where resonance effects are dominant.

In summary, in this work we will assess the capability of two specific semi-annihilation processes, $DMDM \to DMZ$ and $DMDM \to DMh$, with $Z$ and $h$ being the SM $Z$ and $h$ bosons, of yielding a good fit of the GeV excess. Pursuing a model-independent approach we will express our results in terms of best-fit DM mass and semi-annihilation cross-section, in the considered final states, without referring to any specific Particle Physics construction. In the second part of the paper, we will provide a brief overview of some possible models, involving scalar, fermionic and vectorial DM, potentially capable of reproducing the GeV excess through semi-annihilations and featuring, at the same time, viable DM relic density compatible with observational limits.

## 2. The gamma-ray excess

Interestingly, since the first observation [16], independent analyses of the Fermi-LAT data toward the Galactic Center have spotted an excess in gamma-rays peaked around 3 GeV [5,14,15,17,18,20–25], which is also known as the GeV excess. Though the excess is statistically significant, it relies on a diffuse background model which provides a reasonable fit to the diffuse emission over the whole sky, but it is not clear that it is appropriate for the GC. This systematic uncertainty on the background dominates the statistical one and is difficult to quantify. A first attempt at accounting for systematics was made in [31] through the study of a large number of galactic diffuse emission models, where the excess persisted. Subsequent studies performed by Fermi-LAT collaboration reached the same conclusion [27]. In particular, in [97] it has been concluded that is most likely comprised of two components, where one of them is from dark matter. Therefore, we will assume the signal is robust and due to dark matter annihilations, commonly known as Hooperons [38].

## 3. The anti-proton excess

Several studies have been conducted regarding the anti-proton flux originated from dark matter annihilation [98–104]. Throughout the years no excess has been observed except in [34] where an excess has been spotted using PAMELA data. Analysis favored a dark matter annihilation cross section which has now been ruled by the non-observation of gamma-rays in dphs by Fermi-LAT collaboration [105]. Recently, however, two independent studies, using up-to-date data from AMS-02 claimed the observation of a significant excess of anti-proton production over the background expectations [32,33].

This excess regardless its origins clearly shows the importance of data taking and further extending AMS-02 lifetime. The main differences between these two studies and previous ones where no excess was observed are the use of new data and a global likelihood analysis, where both background and signal are simultaneously fitted, without assuming a fixed propagation model. Keep in mind that this signal is subject to several systematic uncertainties and rely on the non-existence of secondary production of cosmic-rays, which could significantly abate the signal [106–110].

The recent analysis presented in [36] clearly shows that the excess in anti-proton observed in the AMS-02 data strongly overlaps with the one seen by Fermi-LAT in the Galactic Center. Therefore, instead of doing data fitting for independent data sets and repeat what has been done in [36], we will concentrate on one of them (gamma-ray data), and assume throughout that the best-fit regions derived for the annihilation and semi-annihilation cases coincide with those from anti-proton.

Moreover, we emphasize as suggested in the title that this source of anti-proton should be local with a large J-factor, otherwise the best-fit region in the plane *annihilation cross section vs. dark matter mass* would be moved upwards being in direct conflict with the non-observation of gamma-rays in the direction of dwarf galaxies as seen by Fermi-LAT.

## 4. Fitting the data

In order to find the goodness of fit to the GeV excess, we need to compute the differential photon flux in the direction of the GC which is written as,

$$\frac{d\Phi^{\gamma}}{dE^{\gamma}} = \sum_{f} \frac{1}{8\pi} \frac{\langle \sigma v_f \rangle}{M_{DM}^2} \frac{dN_f^{\gamma}}{dE^{\gamma}} \times \bar{J}(\Delta\Omega), \qquad (1)$$