Decaying fermionic dark matter search with CALET

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Abstract. The ISS-based CALET (CALorimetric Electron Telescope) detector can play an important role in indirect search for Dark Matter (DM), measuring the electron+positron flux in the TeV region for the first time directly. With its fine energy resolution of approximately 2% and good proton rejection ratio (1 : 10^5) it has the potential to search for fine structures in the Cosmic Ray (CR) electron spectrum. In this context we discuss the ability of CALET to discern between signals originating from astrophysical sources and DM decay. We fit a parametrization of the local interstellar electron and positron spectra to current measurements, with either a pulsar or 3-body decay of fermionic DM as the extra source causing the positron excess. The expected CALET data for scenarios in which DM decay explains the excess are calculated and analyzed. The signal from this particular 3-body DM decay which can explain the recent measurements from the AMS–02 experiment is shown to be distinguishable from a single pulsar source causing the positron excess by 5 years of observation with CALET, based on the shape of the spectrum. We also study the constraints from diffuse γ-ray data on this DM-only explanation of the positron excess and show that especially for the possibly remaining parameter space a clearly identifiable signature in the CR electron spectrum exists.

Keywords: cosmic rays detectors, dark matter detectors, dark matter simulations

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1 Introduction

While the existence and cosmological properties of Dark Matter (DM) are well established, nature and particle properties of DM are largely unknown. Many theoretical models predict that a TeV scale Cold DM (CDM) can decay or annihilate into Standard Model (SM) particles. As a result, CDM could be detected indirectly by observing an excess in cosmic ray (CR) spectra relative to the astrophysical background [1]. Recent results from space based CR detectors such as AMS-02 [2] and PAMELA [3] show an increase of the positron fraction above 10 GeV up to 300 GeV which is not expected from the secondary production of positrons in the Interstellar Medium (ISM). This excess may be explained by an extra source emitting electron-positron pairs, such as emission from pulsars or decay and annihilation of DM [4]. To explain the positron excess with DM annihilation would require a large boost factor because the cross section of DM annihilation from relic density measurements [5] yields a positron flux which is too low to produce the excess observed in the measurements [6, 7]. The DM decay scenario can naturally explain the positron excess if the lifetime of the DM is less than $\sim 10^{25}$ s [1, 8]. Among different DM decay scenarios, a 3-body leptonic decay is favorable to explain the recent positron excess, because the 3-body decay produces a softer spectrum compared to 2-body decay. Moreover, since the decay products are only leptonic, the absence of a hadronic component allows for compatibility with the recent anti-proton measurements [9].

In this paper, we will present the prospects of discerning such a signal from decaying DM with 1–2 TeV mass from a single pulsar source in the $(e^{+} + e^{-})$ spectrum by the measurement taken with the CALorimetric Electron Telescope (CALET). CALET, in operation on the ISS since October 2015, is designed to search for signatures from nearby CR sources and DM in this spectrum with fine energy resolution of approximately 2% and high proton rejection power ($1 : 10^5$) [10, 11].

We study a DM candidate undergoing 3-body decay into two charged leptons and a neutrino, as a possible extra source which can explain the excess of the positron fraction observed by AMS-02 [12].

The AMS-02 collaboration proposed an extra source emitting electron-positron pairs with an exponentially cut-off power-law spectrum [13] as an empirical model to the positron...
excess. This spectrum corresponds well to that of a single young pulsar [14], making it a generic scenario against which we test the DM model explaining the positron excess. This parametrization for the positron fraction is extended to the \((e^+ + e^-)\) flux and into the TeV region, including effects of propagation in the galaxy. The free parameters of this local CR parametrization with DM or pulsar as extra source are determined from the best fit to AMS-02 positron flux and \((e^+ + e^-)\) measurements [2, 15]. Using this parametrization, we calculate the expected \((e^+ + e^-)\) spectrum for 5 years of observation with CALET for DM with a mass in the range of 1–2 TeV, and investigate the possibility of discerning this particular DM decay from a generic single pulsar source.

The recent diffuse \(\gamma\)-ray data measured by the Fermi-LAT experiment [16] gives a strong constraint on DM annihilation or decay in the galactic halo. We compare the \(\gamma\)-ray emission predicted by this DM model with the \(\gamma\)-ray measurement and show that \(\gamma\)-ray production can be reduced significantly, when the charged primary decay products from the DM are only electron and muon, excluding tau leptons. The ability of CALET to discern the DM signal from a single pulsar depends on the shape of the \((e^+ + e^-)\) spectrum based on the DM decay products, and we show the scenario with low \(\gamma\)-ray yield would have an especially well distinguishable signature.

2 Positron and electron spectra from 3-body decay of dark matter

To explain the positron excess, various particle physics models with a 3-body decay of DM are proposed [17–19]. In this context, we investigate a scenario where a TeV scale DM decays to leptons (DM \(\rightarrow l^- l^+ \nu\)), namely a charged standard model lepton+anti-lepton pair and a neutrino. In a recently proposed theoretical model, this type of DM decay is predicted by extending the SM with 3 fermionic singlets \(N_L, \psi_R, S_R\) and two Higgs doublets \(\eta, \chi\) [12]. The DM candidate is the lightest fermion \(N_L\), which decays by breaking the lepton number by two units due to the interaction between \(\eta, \chi\) \((h\eta^\dagger N_l + f\chi^\dagger l\nu)\), contributing to the CR lepton spectra.

Focusing on this model has two important implications for our study. The branching ratios of the outgoing leptons are proportional to the inverse of the decay time \(\left(\frac{1}{\tau_e}, \frac{1}{\tau_\mu}, \frac{1}{\tau_\tau}\right)\) of the DM for the individual decay channels \((e\nu\nu, \mu\mu\nu, \tau\tau\nu)\) which depends on the coupling constants \((h, f)\) at both vertices of the decay process. These coupling constants \((h, f)\) are completely independent of the lepton mass hierarchy [12], making \(\frac{1}{\tau_e}, \frac{1}{\tau_\mu}, \frac{1}{\tau_\tau}\) completely free parameters in our study. Also, the decay of the DM is mediated by heavy scalar \(\eta, \chi(\sim 10^3\) TeV), so the lifetime can be assumed to be negligible, making 4-point scalar interaction a good approximation for the DM decay process. We use this assumption to calculate the energy distribution of the charged leptons \((e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-)\) which is given by eq. (2.1).

\[
\frac{1}{\Gamma} \frac{d\Gamma}{dx} = 2x^2(3 - 2x) \tag{2.1}
\]

where \(x = E/E_{\text{max}}\) and \(E_{\text{max}} = 0.5\) \(M_{\text{DM}}\) and \(\Gamma, M_{\text{DM}}\) are the decay rate and mass of the DM respectively.

From this initial energy distribution, the \(e^+\) and \(e^-\) spectrum \(\frac{dN}{dx}\) produced per decay is calculated using the event generator PYTHIA (Version 8.2) [20]. The spectra for \(e^+\) and \(e^-\) are identical and the \(e^+\) spectrum is propagated in GALPROP [21, 22]. The propagation parameters in GALPROP, which is modified to include the spiral arm nature of the galaxy, are determined from comparing the background CR propagation calculation (Proton spectrum
and B/C ratio) with AMS-02 measurements, which is discussed in appendix A. We assume a Navarro-Frenk-White (NFW) profile \[23\] for the DM distribution in our galaxy.

\[
\rho = \frac{\delta_c \rho_c (r/r_s)}{(1 + r/r_s)^2}
\]  \hspace{1cm} (2.2)

\(\delta_c\) is defined as

\[
\delta_c = \frac{200}{3} \frac{c_v^3}{\ln(1 + c_v) + (c_v/(1 + c_v))}
\]  \hspace{1cm} (2.3)

where \(c_v\) is defined as the ratio of virial radius \(r_v\) and scale radius \(r_s\), and we assume \(c_v = 10\) \[24\]. \(\rho_c\) is determined from the mass of the halo as

\[
\rho_c = \frac{4}{3} \pi r_v^3 M_v
\]  \hspace{1cm} (2.4)

where \(r_v, M_v\) are taken as 200 kpc and 1.5 \(\times\) \(10^{12}\) M\(_\odot\) \[25\]. With these assumptions, we calculate the injected particles per volume and time in the decaying DM scenario using the equation

\[
Q = \Gamma \frac{\rho}{M_{DM}} \frac{dN}{dE}
\]  \hspace{1cm} (2.5)

### 3 Parametrization of local \(e^+\) and \(e^-\) flux and fit to current data

The locally observed \(e^+\) and \(e^-\) spectra are parametrized to reflect the variability from the free parameters of injection and propagation. Using this parametrization we determine multiple scenarios for DM as the extra source explaining the positron excess from the minimum \(\chi^2\) in comparison with the \((e^+ + e^-)\) and positron flux measurements from AMS-02 \[2, 15\]. Later we investigate the possibility of discerning signals of the decay of fermionic DM from a generic single pulsar source using CALET simulated data. For the propagated \(e^+, e^-\) spectra in the parametrization we consider

- Distant supernova remnants (SNR) giving a power law spectrum for primary electrons. For the unknown \((e^+ + e^-)\) spectrum in the TeV region, we consider an electron-only contribution flux from the Vela SNR. The radiative energy loss processes experienced by the electrons are modeled as an exponential cut-off term.

- A secondary component from primary nuclei interactions with the ISM is added to the primary flux. Radiative energy loss processes are assumed to be negligible for the secondary particles due to less propagation length compared to primaries.

- To this astrophysical background, DM and pulsar sources are added as extra sources emitting electron-positron pairs, in order to explain the positron excess.

- The flux from the 3-body decay of fermionic DM is scaled by the inverse of the decay time \(\left(\frac{1}{\tau_e} , \frac{1}{\tau_\mu} , \frac{1}{\tau_\tau}\right)\) of the individual lepton channels \((e\nu, \mu\nu, \tau\nu)\).

- For the pulsar source scenario, the flux (common for both electron and positron) is parametrized by a normalization factor, a power law index and a cut-off energy.
With the parameters listed in table 1, the total flux (primary + secondary) and positron flux can be written as

\[ \phi_T = C_p E^\gamma_p \left( 2 C_s \frac{E^\gamma_s}{E^\gamma_p} + e \left( \frac{E}{E_d} \right) \right) + 2 \phi_{\text{extra}} \]

\[ \phi_{e^+} = C_s E^\gamma_s + \phi_{\text{extra}} \quad \text{(3.1)} \]

where \( \phi_{\text{extra}} \) is the flux from the extra sources emitting electron-positron pairs.

The extra source flux from the decay of the DM is given by

\[ \phi_{\text{DM}} = \frac{1}{\tau_e} \phi_e + \frac{1}{\tau_\mu} \phi_\mu + \frac{1}{\tau_\tau} \phi_\tau \quad \text{(3.2)} \]

with \( \phi_e, \phi_\mu, \phi_\tau \) being the \((e^+ + e^-)\) decay spectra for \( ee\nu, \mu\mu\nu, \tau\tau\nu \) channel respectively, propagated with GALPROP with the propagation parameters discussed in appendix A.

The parametrization of the extra source in the pulsar scenario is given by

\[ \phi_{pn} = C_{pn} E^\gamma_{pn} e^{-\left( \frac{E}{E_{pn}} \right)} \quad \text{(3.3)} \]

The free parameters of this parametrization with DM or pulsar as extra source are determined from the best fit to current \((e^+ + e^-)\) and positron flux measurements. Using the predicted flux from these fits, CALET expected data with DM as extra source is calculated, and the possibility of discerning pulsar and DM model is investigated as discussed in section 5.

The range of data points used for the fitting is from 15 GeV–1 TeV, to determine values of the free parameters, which are given in table 1 along with the parameters that are kept fixed. The CR spectra below 15 GeV are influenced by solar modulation, diffusive reacceleration and possibly a change in the injection index, and this variability in the spectra is difficult to represent by a simple parametrization. However, a charge independent solar modulation above 15 GeV [26] is applied to the parametrization by assuming force field approximation with a fixed value of 500 MeV for the common \((e^+ + e^-)\) modulation potential.

The upper bound of the fit range is 1 TeV as there are no high resolution data points above 1 TeV from AMS-02 measurements. \( E_d \), which has influence only in the TeV region, cannot be determined from the experimental data and several values (1 TeV, 2 TeV, 5 TeV, 10 TeV) are studied. Electron-only flux from Vela SNR, which is the most influential nearby source with distance around 1 kpc and age less than \( 10^5 \) years [27], is calculated with GALPROP for the propagation parameters as described in appendix A to estimate the unknown TeV region \((e^+ + e^-)\) spectrum. In the parametrization, different values of \( E_d \) reflect the variability of the contribution from Vela due to gradual or delayed electron release and also the influence of spiral arm thickness on the \((e^+ + e^-)\) spectrum (see appendix A).

For the fit of the parametrization with DM as extra source to the AMS-02 \((e^+ + e^-)\) and positron flux, we show an example in figure 1. The fit converges at branching ratios of 0.77 for \( \tau\tau\nu \) channel and 0.23 for \( ee\nu \) channel, with no contribution from \( \mu\mu\nu \) channel for a 2 TeV fermionic DM, assuming \( E_d = 2 \) TeV. This type of DM decay spectrum is characterized by a drop in the \((e^+ + e^-)\) and positron flux almost at the half of the mass of the DM as depicted in figure 1. This spectral feature is significantly different from a relatively smooth spectrum as shown in figure 2, where the parametrization with single pulsar as only extra source is fitted to AMS-02 measurements. \( E_{pn} \) is kept fixed at 1 TeV, however this choice has no influence in the study, as the expected CALET data is calculated with DM as extra
Figure 1. 2 TeV fermionic DM decay spectra on top of the background (dotted line) are fitted to the AMS-02 $(e^+ + e^-)$ flux (left) and positron flux (right), resulting in a branching fraction of 0.77 for $\tau\nu$ channel and 0.23 for $ee\nu$ channel (solid line). $E_d$ is 2 TeV.

Figure 2. The parametrization of the background and a single pulsar as extra source (solid line) is fitted to the AMS-02 $(e^+ + e^-)$ flux (left) and positron flux (right), assuming $E_{pn} = 1$ TeV and $E_d = 2$ TeV.

source. $E_{pn}$ is taken as a free parameter when CALET’s capability of discerning DM and pulsar is calculated.

It is shown in a recent work [28] that there are several candidates among pulsars within a distance of $< 0.5$ kpc from the solar system and with an age of $4 \times 10^4 - 4.5 \times 10^5$ years which could provide a single source explanation of the positron excess. So the single young pulsar is taken as a generic case against which we compare the DM decay model.

4 Diffuse $\gamma$-ray constraints and low $\gamma$-ray flux scenario

The decay or the annihilation of DM directly produces $\gamma$-rays in the form of Final State Radiation (FSR) and also secondary $\gamma$-rays from Inverse Compton and Bremsstrahlung processes during propagation of charged decay or annihilation products. Through these processes it is expected that the decay of the investigated DM into charged leptons ($e^\pm, \mu^\pm, \tau^\pm$) in the galactic DM-halo would produce a diffuse $\gamma$-ray flux. For DM decay which can explain the positron excess, this predicted $\gamma$-ray flux has to be compared with the Fermi-LAT [16] diffuse $\gamma$-ray measurement taken at high latitudes. Looking away from the galactic plane ($|b| > 20^\circ$) strongly reduces the background from galactic astrophysical sources and thus comparison
| Parameter | Definition | Comment |
|-----------|------------|---------|
| $C_p$     | Absolute normalization of primary $e^-$ flux | Free parameter |
| $C_s/C_p$ | Ratio of absolute normalization of secondary to primary flux | Free parameter, always $< 1$ |
| $\gamma_p$ | Primary $e^-$ index | Free parameter |
| $E_d$     | Background cut-off energy | In AMS-02 fit 1,2,5,10 TeV fixed values are studied |
| $\gamma_p - \gamma_s$ | Difference between primary and secondary electron indices | $\gamma_p - \gamma_s \approx \delta = 0.4$, fixed from the propagation model in appendix A |
| $1/\tau_e, 1/\tau_\mu, 1/\tau_\tau$ | Inverse of the decay time of the lepton channels $(ee\nu, \mu\mu\nu, \tau\tau\nu)$ | Free parameters |
| $C_{pn}/C_p$ | Ratio of absolute normalization of pulsar to primary flux | Free parameter, always $< 1$ |
| $\gamma_p - \gamma_{pn}$ | Difference between pulsar and primary electron indices | Free parameter |
| $E_{pm}$ | Cut-off energy for pulsar parametrization | $E_{pm} = 1$ TeV, fixed parameter in AMS-02 fit |

| DM       | $1/\tau_e, 1/\tau_\mu, 1/\tau_\tau$ | Free parameters |
| Pulsar    | $C_{pn}/C_p$ | Free parameter, always $< 1$ |

Table 1. List of parameters used in the parametrization of the local ($e^+ + e^-$) and $e^+$ spectra.

of $\gamma$-ray flux from DM with the measurement in this region gives the strongest constraint. The remaining contribution from astrophysical sources depends on the different modelings of $\gamma$-ray emission [29, 30], but the total measured flux can be considered a conservative upper bound. While the diffuse $\gamma$-ray spectrum in the relevant sky region and energy range is currently only available from Fermi-Lat, it is going to be reaffirmed by the currently operating detectors with calorimeters capable of absorbing the full shower energy up to the TeV region, such as CALET [31] and also DAMPE [32].

The $\gamma$-ray flux from DM decay depends on both the mass of the decaying DM and the decay products. As the $\tau\tau\nu$ channel produces more $\gamma$-rays compared to $ee\nu$ and $\mu\mu\nu$ channel, to study the possibility of a DM-only explanation of the positron excess compatible with the current $\gamma$-ray measurements, we reduce the $\tau\tau\nu$ component from the decay products of the DM and this is possible in the chosen DM model, as described in section 2. Adapting all other free parameters in each step and starting with the parameters obtained from the initial fit, we reduce the $\tau\tau\nu$ component in steps until either the $\chi^2$ of positron flux or ($e^+ + e^-$) flux exceeds 95% CL, or the scale factor for $\tau\tau\nu$ channel reaches zero. The branching ratios for the initial fit and the fit with the reduced tau contribution are given in table 2 for different values of DM mass and cut-off energy $E_d$. It is shown that a good fit with completely removed $\tau\tau\nu$ channel is possible for DM with mass 1.5 TeV and 1 TeV, and $E_d$ equal to or larger than 2 TeV and 10 TeV respectively. However, no good fit even including $\tau\tau\nu$ channel is possible for 1 TeV DM and $E_d$ equal to or smaller than 2 TeV.
Figure 3. Predicted \( \gamma \)-ray flux from DM decay compared to Fermi-LAT diffuse \( \gamma \)-ray measurement. In the left panel we show the \( \gamma \)-ray flux from 1 TeV DM (60% \( \mu\mu \nu \), 40% \( ee\nu \)) of the primary (Black dashed line) and secondary production (black dotted line). On the right panel the combined \( \gamma \)-ray flux from primary and secondary production are shown for 2 TeV DM (77% \( \tau\tau\nu \), 23% \( ee\nu \)) with black dotted line, 1.5 TeV DM (73% \( \mu\mu\nu \), 27% \( ee\nu \)) with black dashed line, 1 TeV DM with black solid line.

The \( \gamma \)-ray fluxes from the FSR and decay of the primary decay products have been calculated with PYTHIA assuming NFW profile, and three different cases are plotted in figure 3 including contribution from secondary \( \gamma \)-rays. The charged particles from the decay of DM and their interaction with the interstellar radiation field (ISRF) produce secondary \( \gamma \)-rays. This isotropic diffuse \( \gamma \)-ray flux is calculated in GALPROP at latitudes \( |b| > 20^\circ \), for different DM models using the default ISRF [33] provided by GALPROP. As shown in the left panel of figure 3, \( \gamma \)-rays from secondary production have lower energy than the primary component. For a DM of mass 2 TeV decaying to \( \tau\tau\nu \) (73%) and \( ee\nu \) (27%) channel, the predicted \( \gamma \)-ray flux exceeds the Fermi-LAT data significantly. However with 1.5 TeV and 1 TeV DM decaying only to \( \mu\mu\nu \) and \( ee\nu \) channel, the \( \gamma \)-ray fluxes from the decay are closer to the experimental data as shown in the right panel of figure 3.

The \( \gamma \)-ray flux from the 1 TeV DM decay scenario, as shown in figure 3, is least in conflict with the experimental data. Models with these characteristics (low DM mass, and no decay to \( \tau\tau\nu \) channel) may be a unique possibility to explain the positron excess by DM, without violating the constraints from \( \gamma \)-ray measurements, making this model of special interest to study. For 1 TeV DM decaying only to \( \mu\mu\nu \) and \( ee\nu \) channel, the fit converges at branching ratios of 0.60 for \( \mu\mu\nu \) channel and 0.40 for \( ee\nu \) channel with \( E_d = 10\,\text{TeV} \) as shown in figure 4b. Similarly, for a 1.5 TeV DM decaying only to \( \mu\mu\nu \) and \( ee\nu \) channel the best fit converges at branching ratios of 0.73 for \( \mu\mu\nu \) channel and 0.27 for \( ee\nu \) channel with \( E_d = 2\,\text{TeV} \), shown in figure 4a. This 1.5 TeV fermionic DM matches best the new AMS-02 positron flux recently presented at CERN [34], making this another case to be studied. Although the predicted \( \gamma \)-ray flux from the 1 TeV DM is somewhat higher than the Fermi-LAT measurement, there should be an uncertainty in the lifetime of the DM, and thus the \( \gamma \)-ray flux, from the choice of propagation conditions used for the positrons of the DM decay. Also the shape of the DM halo may influence the charged CRs (\( e^+, e^- \)) and \( \gamma \)-ray flux. The \( \gamma \)-ray flux measured at higher latitudes may be reduced and the charged CR flux enhanced if the DM accumulates close to galactic plane, as in the ”Dark-Disc” model [35] for partly self-interacting DM.
Figure 4. (a) 1.5 TeV DM (without $\tau\tau\nu$ channel) decay spectra on top of the background (dotted line) are fitted to the $(e^+ + e^-)$ and positron flux from AMS-02 with $E_d$ set to 2 TeV. This decaying DM matches well the new 5-year AMS-02 positron flux data (shown with cyan dots) which was not used in the fit. (b) As figure 4a but for a 1 TeV DM with $E_d = 10$ TeV.

Table 2. Branching ratios (in the order: $ee\nu/\mu\nu/\tau\tau\nu$) from the fit to AMS-02 $(e^+ + e^-)$ and positron flux for all the studied values of $M_{DM}$ and $E_d$. Upper line of each cell: branching ratios of the best fit including all the leptonic components, lower line: branching ratios of the best fit with $\tau\tau\nu$ component reduced in the decay products. Colored boxes correspond to the examples shown in figure 1, figure 4a and figure 4b respectively.
Fit of the single pulsar source to one of the simulated 10000 statistical samples of 5-year CALET data for \((e^+ + e^-)\) flux (left panel) for the 2 TeV DM (green line) and positron flux (right panel) from AMS-02 data is shown here with the black dashed lines, assuming \(E_d = 2\) TeV. Background CR spectra are shown as dotted lines (green and black) for the two different extra source scenarios (DM and pulsar respectively).

To estimate CALET’s capability to distinguish a DM signal from a single pulsar source, we perform these following steps:

1. From the fits of the parametrization with DM as extra source to the current experimental results as described in section 3, the expected CALET data was calculated.

2. To simulate the statistical fluctuations in the event rates, 10000 event samples were generated, representing different outcomes of the \((e^+ + e^-)\) flux measurement in each of the DM decay scenarios.

3. The single pulsar source parametrization was then fitted to the simulated \((e^+ + e^-)\) CALET data for the DM and the positron flux measured by AMS-02, giving a \(\chi^2\) distribution.

4. From re-fitting the DM model to these same data points we obtain a \(\chi^2\) distribution for DM model.

5. These two distributions are compared with each other to find CALET’s capability to discern between the fermionic DM decay and the pulsar model.

To calculate CALET expected data we assume, a detector aperture of 1200 cm\(^2\) sr [36], and 5 years of data-taking with 90% reconstruction efficiency. In figure 5, we show an example of the single pulsar parametrization fit to one of the 10000 simulated samples of 2 TeV DM. The equivalent fits of the single pulsar parametrization to a DM case sample for 1.5 TeV and 1 TeV DM decaying only to \(\mu\mu\nu\) and \(ee\nu\) are shown in figure 6a and figure 6b respectively.

The \(\chi^2\) distribution obtained from this two different scenarios is shown in the left panel of figure 7. Since the DM and the single pulsar source model are independent of each other (non-nested), a quantitative separation strength between them such as a likelihood-ratio test statistic cannot be determined. However we can assess the quality of DM and single pulsar
model relative to each other by a qualitative measure, such as Akaike’s Information Criterion (AIC) \[37\], to select one model over another. The AIC value of a particular model is given by

\[ \text{AIC} = -2L_m + m \]  

(5.1)

where \(L_m\) is the maximum value of the log-likelihood function and \(m\) is the number of free parameters in the model. Given a set of models, the model with lowest AIC value is most favorable for representing data under the condition that the likelihood for both models follows a normal distribution. Both the pulsar model and DM model show a normal distribution which can be concluded from the \(\chi^2\) distribution plots (e.g. left panel of figure 7). From table 1, in the pulsar source parametrization, including \(E_{\text{pn}}\) as a free parameter for the single pulsar fit to CALET simulated data, the pulsar model has three free parameters. In the DM model three free parameters are the scale factors for the three decay modes. Both the models share four free parameters for the CR background spectra (see table 1). Since both

\[ \text{Figure 6. (a) As figure 5 but for 1.5\,\text{TeV} \text{ DM without} \tau\tau\nu \text{ channel, assuming} \ E_d = 2\,\text{TeV}. (b) As figure 6a for 1\,\text{TeV} \text{ DM without} \tau\tau\nu \text{ channel, assuming} \ E_d = 10\,\text{TeV}.} \]
Figure 7. $\chi^2$ distribution for the fit of the single pulsar source to the simulated CALET data for 10000 DM samples + AMS-02 positron flux data (green) and re-fit of DM samples using the same data points (red). On the right panel the difference between the $\chi^2$ for pulsar and DM ($\chi^2_{\text{pulsar}} - \chi^2_{\text{DM}}$) is shown (blue).

| $M_{\text{DM}}$ (TeV) | $E_d$ (TeV) | 1 | 2   | 5  | 10        |
|-----------------------|------------|---|-----|----|-----------|
| 2 TeV                 | 10000/13   | 211.15/61.16 | 150.61/58.90 | 123.87/58.31 | 116.19/58.29 |
|                       |            | 9958/31     | 8932/6       | 7771/1       |            |
| 1.5 TeV               | -          | -            | 142.37/75.54 | 132.98/76.06 | 131.46/76.59 |
|                       |            | 9943/138    | 9632/97     | 10000/49     |            |
| 1 TeV                 | -          | -            | -            | 269.85/72.87 | 10000/49   |

Table 3. Upper line of each cell: average $\chi^2$ obtained from the fits of the single pulsar source to the 10000 samples of simulated CALET data + positron flux from AMS-02 and the re-fit of the DM model to the same data points as a function of $M_{\text{DM}}$ and $E_d$, in the order Pulsar fit/DM fit. Lower line: number of excluded samples ($\chi^2 > 95\%$CL) for each case. Average Number Degree of Freedom (NDF) is 80. Colored boxes are the examples shown in figure 7, figure 8a, figure 8b respectively.

models have the same number of free parameters and the $\chi^2$ distribution for each model resembles a normal distribution, comparison of $\chi^2$ is equivalent to a comparison of the AIC value. As shown in the right panel of figure 7, the $\chi^2$ difference ($\chi^2_{\text{pulsar}} - \chi^2_{\text{DM}}$) between single pulsar source fit and the DM re-fit is always positive except for very few samples, indicating that the simulated DM model is favored over the wrongly assumed pulsar model. A clear discernibility can be claimed for those cases where the DM model is allowed at 95% CL, while the pulsar model is excluded. The re-fit of the DM model yields $\chi^2 < 95\%$ CL for all but a negligible fraction of samples as shown in table 3. Therefore, the exclusion of the pulsar case is sufficient for the separation.

For the 2 TeV DM model including decay to $\tau\tau\nu$, the average $\chi^2$ of the pulsar fit decreases with increasing $E_d$. However, still a majority of samples could be excluded even at $E_d = 10$ TeV, with exact numbers given in table 3. The 1.5 TeV and 1 TeV DM mass cases where no decay to $\tau\tau\nu$ takes place, can be well separated from the pulsar case, independent of $E_d$. 


Figure 8. (a) As figure 7, but for the model of the 1.5 TeV DM decay without $\tau\tau\nu$ channel with $E_d$ set to 2 TeV. (b) As figure 8a, but for the low $\gamma$-ray model of the 1 TeV DM decay without $\tau\tau\nu$ channel and $E_d = 10$ TeV.

The 1 TeV DM features the largest difference between the two $\chi^2$ distributions as shown in figure 8b, demonstrating that this model of DM decay is best distinguishable from a single pulsar by the CALET ($e^++e^-$) flux measurement. In the low $\gamma$-ray scenario with 1 TeV DM the branching fraction obtained from the fit to the experimental results (see figure 4b) is 40% for the $ee\nu$ channel. This causes a sharp drop in the ($e^++e^-$) flux and positron flux at half the mass of the DM (see figure 6b) which is a well detectable signature. This model has the lowest predicted $\gamma$-ray flux of all the studied cases, showing a complementarity between the sensitivity of CALET and $\gamma$-ray measurements.

6 Conclusion

CALET will measure the ($e^++e^-$) spectrum from 10 GeV to 20 TeV for the first time directly with fine energy resolution. DM decaying to three leptons may still be a candidate for a DM-only explanation of the positron excess, despite strong constraints from anti-proton and diffuse $\gamma$-ray measurements. We studied CALET’s ability to discern the signature of such a DM from a single pulsar source by precise measurement of the ($e^++e^-$) spectrum. We found that a separation between these two possible explanation of the positron excess will be
possible with high probability, especially for DM models which show low $\gamma$-ray emission and are potentially compatible with Fermi-LAT data. These models are characterized by DM mass around 1 TeV and the absence of the $\tau\tau\nu$ channel in the decay. The decay through $e\nu e\nu$ and $\mu\nu\nu$ channels creates a hard drop in the $(e^+ + e^-)$ spectrum, which can be well identified by CALET.

### A Numerical calculation of cosmic ray propagation

The publicly available code GALPROP [21] is used to determine the propagation parameters for charged CR in the galaxy, which was used for the propagation of DM decay products. GALPROP solves the CR propagation according to eq. (A.1) on a grid in space and momentum numerically, which involves diffusion, diffusive reacceleration and momentum loss during propagation.

$$\frac{\partial \psi}{\partial t} = Q(x, p) + \nabla \cdot (D_{xx} \nabla \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{\psi} - \frac{\partial}{\partial p} \dot{\psi}$$  

(A.1)

Here $\psi$ is the density of CR particles per unit momentum, $Q$ is the source term, $D_{xx}$ is the spatial diffusion coefficient and $D_{pp}$ is the diffusion coefficient in momentum space, which describes the reacceleration process. The spatial diffusion coefficient is described as

$$D_{xx} = \beta D_0 \left( \frac{R}{R_0} \right)^{\delta}$$  

(A.2)

where $D_0$ is the normalization constant, $\beta = \frac{v}{c}$ is the ratio of speed of CR particles with respect to the speed of light, $R = \frac{p}{Ze}$ is the rigidity of the particle and $\delta$ is the power law index of the spatial diffusion coefficient [38] as a function of rigidity. The diffusion coefficient in momentum space $D_{pp}$ is related to the spatial diffusion coefficient as

$$D_{pp} D_{xx} = \frac{4 p^2 v_A^2}{3 \delta (4 - \delta^2)(4 - \delta)}$$  

(A.3)

where $v_A$ is the Alfven Speed.

A wide range of values for the GALPROP propagation parameters were tested against the recent results of proton spectrum and B/C ratio by AMS-02 [39, 40] and we concluded on the values given in table 4. Assuming force field approximation for the solar modulation [41], we choose the value of 500 MeV for the potential [26]. We introduce a low energy spectral break of primary particles where the break is set at a rigidity of 7 GV [42]. As shown in the left panel of figure 9, we compare the proton flux from GALPROP with the AMS-02 measurement. The focus range for comparison is 5–100 GeV, since the spectrum above 100 GV progressively hardens as reported by AMS-02 [39]. On the right panel of figure 9, using the same propagation parameters and solar modulation potential, we also show the B/C ratio which provides information about two CR propagation parameters. The slope of the B/C ratio gives us an estimation of $\delta$, the diffusion coefficient index and for a chosen diffusion zone height ($Z = 6$ kpc), B/C ratio determines the diffusion coefficient normalization ($D$). Since we don’t consider changes in $\delta$ as a function of rigidity in our propagation model, it doesn’t reflect the structures in the B/C ratio recently reported by AMS-02 [40]. The best match with the measurement over the whole energy range is obtained with $\delta = 0.4$. The propagation parameters as listed in table 4 are used for the propagation of electron, positron and also the decay products of the DM.
| Parameter          | Value       | Unit      |
|--------------------|-------------|-----------|
| $Z_{\text{max}}/\Delta Z$ | 6/0.25      | kpc       |
| $X_{\text{max}}/\Delta X$ | 16/0.25     | kpc       |
| $Y_{\text{max}}/\Delta Y$ | 16/0.25     | kpc       |
| $E_{\text{min}}$    | 10          | MeV       |
| $E_{\text{max}}$    | 100         | TeV       |
| $D_0$ (Diff. coeff.) | $2.90 \times 10^{28}$ | cm$^2$ s$^{-1}$ |
| $R_0$ (ref. rigidity for diff. coeff.) | 4           | GV        |
| $\gamma_1/\gamma_2$ (injection index) | 1.70/2.45 |           |
| $R_\gamma$ (Break in injection Index) | 7           | GV        |
| $\delta$ (Diff. coeff. index) | 0.40        |           |
| $v_A$ (Alfven Velocity) | 12.0        | km s$^{-1}$ |
| start-timestep      | $6.4 \times 10^7$ | years    |
| end-timestep        | 10          | years     |
| timestep-factor     | 0.90        |           |
| timestep-repeat     | 20          |           |

**Table 4.** GALDEF file parameters used for CR propagation in GALPROP.

**Figure 9.** Proton spectrum and B/C ratio calculated with GALPROP (green line) for the propagation parameters given in table 4 are compared with the experimental measurements by AMS-02 (magenta dots).

It is shown in figure 10, that using the same propagation parameters and spectral indices for nuclei and electrons, the electron spectrum obtained from GALPROP is too hard to match the AMS-02 observation at all, even without the addition of an extra source needed for explanation of the positron excess. The GALPROP source distribution is modeled after the SNR distribution derived from the EGRET $\gamma$-ray observation [43]. The spatial distribution of the source function in GALPROP [22] is defined as

\[
q = q_0 \left( \frac{d}{d_0} \right)^\eta \exp \left( -\zeta \frac{d - d_0}{d_0} - \frac{|Z|}{0.2} \right) \tag{A.4}
\]
Figure 10. In the left panel we show the modified source function (in green thick line) with $\sigma = 0.6$ kpc (see eq. (A.5)) compared with the original GALPROP source function (black thin line). Position of the solar system is shown with the blue dot. Dependence of the $(e^+ + e^-)$ spectrum on $\sigma$ is shown in the right panel.

where $q_0$ is the normalization constant, and $\eta, \zeta$ are taken as 0.5 and 1 respectively. In 3D propagation $d$ is taken as $\sqrt{X^2 + Y^2}$ and $d_0$ is the distance of the solar system from the center of the galaxy, set to 8.5 kpc. However to represent the spiral arm structure of our galaxy [44–47], the source distribution is modeled as 4 concentric rings with a Gaussian density profile assuming a half-width ($\sigma$) in the range 0.5–0.7 kpc. This new spatial distribution of the source function is given by

$$q_N = q \times \left( \sum_{i=1}^{4} e^{-\frac{(d-r_i)^2}{2\sigma^2}} \right)$$

(A.5)

here $r_i$ are the distances of the ring profile centers from the center of the galaxy. Compared to the original GALPROP source distribution, this spiral arm structure causes the primary cosmic rays to propagate on average a larger distance and experience more energy loss, which makes the CR electron spectra softer. A comparison between the new source distribution and the GALPROP source distribution is shown in the left panel of figure 10. The effect of the thickness of the spiral arms, which is represented by the $\sigma$ parameter in eq. (A.5), on the electron spectrum is shown in the right panel of figure 10.

Since all the CR species (nuclei, electrons and positrons) are propagated in GALPROP with the modified spiral arm source distribution in one run, we used a high value for the timestep-factor (0.90) and 10 years for the end-timestep to obtain a properly converged solution of the CR propagation equation [38].

To link the fitted values of the parameters of the parametrization described in section 3, with a specific model of CR propagation, parametrized flux is compared with the GALPROP propagation calculations and the results are shown in figure 11. In the lower panel of figure 11, we show the deviation between GALPROP calculation and parametrization and in the relevant energy range the difference is on the order of 70% at most. As shown in figure 11a, the GALPROP calculation with $\sigma = 0.6$ kpc, corresponds to a value of 2 TeV for $(E_d)$ in the parametrization. Variation of $(E_d)$ in the parametrization represents different values of the $\sigma$ parameter in the numerical calculation which represents the ring thickness in this new GALPROP source distribution.
Figure 11. (a) CR spectra calculated with GALPROP (red dotted line) with $\sigma = 0.6$ kpc are compared with the parametrization (green line) with DM as extra source and $E_d = 2$ TeV. In the lower panel the fractional difference between the GALPROP results and parametrization are shown. (b) Same as figure 11a but now with $\sigma = 0.5$ kpc for the GALPROP calculation and $E_d = 10$ TeV in the parametrization to which Vela SNR (magenta dots) is added.

Electron-only flux from Vela SNR is calculated in GALPROP assuming propagation parameters as listed in table 4, except that the time progression is taken as 1200 steps of 10 years and the spatial grid distance is 0.1 kpc in a cube of 12 kpc calculated on the solar system. This flux added to the GALPROP calculated spectrum from distant SNR with $\sigma = 0.5$ kpc corresponds best to the parametrization with a value of 10 TeV for $E_d$ as is shown in figure 11b. Emission of CRs from the Vela SNR is assumed to be instantaneous and the total energy emitted as electron above 1 GeV normalized to $10^{48}$ erg [48]. It should also be noted that a harder injection spectrum [48] and/or a specific energy-dependent release [49] of the electrons from Vela could create a distinct signature in the TeV region. If such a signature is found by CALET, the background model for DM search would have to be adapted.

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