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Dark Matter "Transporting" Mechanism Explaining Positron Excesses

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We propose a *novel* mechanism to explain the positron excesses, which are observed by satellite-based telescopes including PAMELA and AMS-02, in dark matter (DM) scenarios. The *novelty* behind the proposal is that it makes direct use of DM *around the Galactic Center* where DM populates most densely, allowing us to avoid tensions from cosmological and astrophysical measurements. The key ingredients of this mechanism include DM annihilation into *un*stable states with a very long laboratory-frame life time and their "retarded" decay near the Earth to electron-positron pair(s) possibly with other (in)visible particles. We argue that this sort of explanation is *not* in conflict with relevant constraints from big bang nucleosynthesis and cosmic microwave background. Regarding the resultant positron spectrum, we provide a generalized source term in the associated diffusion equation, which can be readily applicable to any type of two-"stage" DM scenarios wherein production of Standard Model particles occurs at completely different places from those of DM annihilation. We then conduct a data analysis with the recent AMS-02 data to validate our proposal.

Introduction. Very recently, the AMS-02 Collaboration has released new results from a set of data accumulated for past five years [1]. The reported positron flux and fraction clearly exhibit not only a rise from ~ 10 GeV above the rate expected from cosmic-ray collisions, which is consistent with previous results by PAMELA [2, 3], Fermi-LAT [4], and AMS-02 [5, 6], but also a sharp drop-like behavior at several hundreds of GeV. As the latter spectral feature is a characteristic signature of dark matter (DM) with mass of $\mathcal{O}$(TeV), the observed positron excess may be in more favor of DM scenarios, upon the future confirmation, rather than an alternative speculation from other astrophysical sources such as pulsars [7] or supernova remnants [8].

The positron flux Φ from annihilating DM is essentially determined by the DM density ρ and the velocity-averaged annihilation cross section $\langle\sigma v\rangle$:

$$\Phi \propto \rho^2 \langle\sigma v\rangle\,. \tag{1}$$

We remark that the positrons produced within $\sim$1 kpc from the Earth dominantly contribute to the flux. The local density and the typical annihilation cross section of the thermal relic DM, however, predict a much smaller flux than the observed. Therefore, it has been a major challenge to identify an adequate DM source to supply the measured positron flux.

Several ideas have been proposed to resolve this issue. The first set of attempts is to secure enough flux by enhancing the annihilation cross section today, i.e., the second component in Eq. (1), compared to what is required by the standard thermal production, with the current relic abundance being the same. Example mechanisms include Sommerfeld enhancement [9, 10] and relaxation of the thermal relic relation via late decays of DM partners [11]. However, since any moving charged particles radiate photons, the gamma-ray data from Milky Way satellite galaxies [12–14] sets quite stringent limits on the allowed DM annihilation cross section. The second set of attempts is to increase the local DM density itself, i.e., the first component in Eq. (1), by a clumpy DM distribution. ΛCDM N-body simulation studies, however, suggest that the flux enhancement by the local clumpy DM distribution may not suffice to satisfy the observed data [15]. Due to these difficulties in explaining the large positron excess by annihilating DM, the other class of attempts utilizes decaying DM with a long life time of $\sim 10^{26}$ seconds [16]. However, typical decaying DM models favored by the positron excesses are also excluded by or in tension with Fermi-LAT gamma-ray observations, depending on decay channels and modeling of astrophysical foregrounds and backgrounds [17–19]. Given the drawbacks of previous trials, in this letter, we propose a *novel*, alternative mechanism to invoke a sufficient positron flux by taking *annihilating/decaying DM around the Galactic Center* (GC), where DM densely populates, in the context of non-minimal dark-sector scenarios.

Mechanism. Our mechanism is predicated upon a non-conventional situation, wherein DM particles annihilate or decay *not* promptly to leptonic final states *but* to *un*stable particles around the GC. We assume that this unstable particle has a sufficiently long life time to propagate a large enough distance from the GC and decay to electron-positron pair(s) potentially with other particles near the Earth. FIG. 1 delineates our benchmark scenario for the positron excesses: a pair of (heavier) DM particles χ_h annihilate to a pair of unstable (possibly dark-sector) states ϕ each of which subsequently disintegrates to an electron, a positron, and a (lighter) DM particle χ_l, in the vicinity of the Earth, via a three-body decay process. We emphasize that the scenario under consideration is similar to what arises in typical boosted DM scenarios [20–23] based on the assisted freeze-out [24] (modulo the heavier dark-sector state like in Ref. [25]), in which χ_h is the dominant relic component while χ_l typically comprises of $< 1\%$.

The survival rate by which a ϕ arrives near the Earth without breaking apart and its subsequent decay are dictated by the decay width Γ_ϕ and the Lorentz boost factor

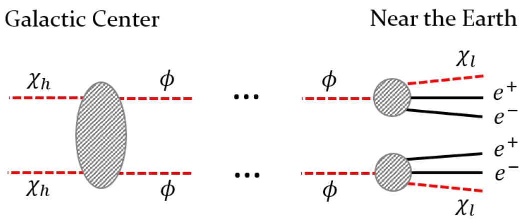

FIG. 1: A benchmark scenario for the positron excesses.

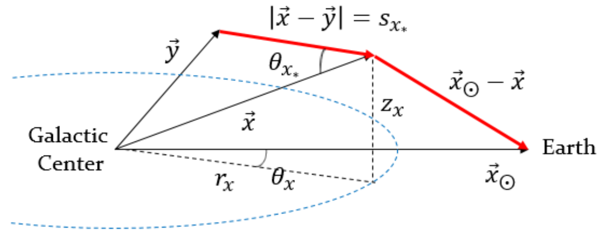

FIG. 2: Schematic situation from production and decay of ϕ at $\vec{y}$ and $\vec{x}$ to propagation of $e^{\pm}$. All position vectors are defined with respect to the GC as the origin. s_{x_*} and θ_{x_*} are measured with respect to $\vec{x}$.

γ_ϕ of ϕ. We remark that the Earth is quite distant from the GC, implying that typical sizes of the dilated life time $\tau_\phi\gamma_\phi$ should be as large as $\sim 8\times 10^{11}$ seconds to travel about 8 kpc. Assuming that the heavier DM species χ_h is non-relativistic, we see that the ϕ mass m_ϕ has a simple relation with the χ_h mass m_{χ_h} as $m_{\chi_h}=\gamma_\phi m_\phi$. Stringent constraints [26, 27] on the long-lived particle ϕ, which stem from big bang nucleosynthesis (BBN) and cosmic microwave background (CMB), enforces us to consider the scenario with a large boost factor γ_ϕ. Thus, we are able to treat both ϕ and χ_l effectively massless compared to m_{χ_h}.

Obviously, under this mass hierarchy, m_{χ_h} governs the overall scale of the positron energy spectrum. Adopting the nominal positron spectrum by AMS-02 [1] which drops at high energies, we expect m_{χ_h} to be in the range of $\sim$ 1 TeV. On the other hand, m_ϕ should be greater than the sum of positron and electron masses, i.e., $\sim$1 MeV. We then find that the value of γ_ϕ reaches at most a few 10^6, implying that its minimum life time should be greater than a few 10^5 seconds in order for ϕ produced around the GC to travel close to the Earth. As mentioned above, due to this long life time of ϕ, some cosmological constraints come into play. Above all, since ϕ decays to charged particles after BBN, they would affect the evolution of nuclei fractions in the history of the Universe. The constraints from BBN and CMB depend on the energy density of ϕ at the early Universe (ρ_ϕ) times the fraction of decay energy going to stable photon and $e^{\pm}$, as displayed in Figure 5 of Ref. [27]. For $\rho_\phi\sim 10^{-2}-10^{-5}$ relative to the DM relic $\rho_{\rm DM}$ (mostly χ_h here), the life time of ϕ is limited as $\tau_\phi\lesssim 10^6-10^8$ seconds by BBN constraints, under the assumption that 100% of the decay energy is deposited to stable photon and $e^{\pm}$. If ρ_ϕ is in-between 10^{-5} and 10^{-11} of $\rho_{\rm DM}$, the existence of ϕ is constrained not by BBN but by CMB, requiring $\tau_\phi\lesssim 10^{12}$ seconds. For $\rho_\phi\lesssim 10^{-11}\cdot\rho_{\rm DM}$, there are no constraints even from the CMB observation.

Another important issue in realizing our mechanism is to secure an enough ϕ flux near the Earth for explaining the positron bump reported by AMS-02. In other words, a sufficient amount of DM should be guaranteed near the GC. While ordinary DM halo profiles in the market yields an $\mathcal{O}(1)$ enhancement in the positron flux, we remind that the DM density near the galactic core still comes with a huge uncertainty irrespective of the choice of DM profiles [28, 29]. Reflecting this uncertainness, we shall treat the core size and the DM density inside the core as free parameters in our data analysis.

Propagation. Once electron-positron pairs are created by the ϕ decay, they should propagate to the Earth according to the following diffusion equation:

$$\frac{\partial}{\partial t}f(\vec{x},E)-\vec{\nabla}\cdot\left[K(\vec{x},E)\vec{\nabla}f(\vec{x},E)\right] \\ -\frac{\partial}{\partial E}\left[b(\vec{x},E)f(\vec{x},E)\right]=Q(\vec{x},E)\,. \quad (2)$$

Here $f(\vec{x},E)$ denotes the electron and positron differential number density with energy E at $\vec{x}$, from which the differential flux of $e^{\pm}$ is evaluated as

$$\frac{d}{dE}\Phi(\vec{x},E)=\frac{v}{4\pi}f(\vec{x},E)\,, \quad (3)$$

where v, the velocity of $e^{\pm}$, is essentially the same as the speed of light. $K(\vec{x},E)$ and $b(\vec{x},E)$ describe the diffusion and energy-loss rates by external electromagnetic activities during propagation, respectively. We point out that in the standard DM scenario the source term $Q(\vec{x},E)$ is associated with the DM density at the same position because DM promptly annihilates to electrons and positrons in the final state. However, in our setup, ϕ is ultra-relativistic and propagates very far without decaying to an electron-positron pair, motivating us to modify $Q(\vec{x},E)$ by carefully incorporating non-conventional aspects.

FIG. 2 schematically shows the situation at hand: the production and the decay of ϕ take place at $\vec{y}$ and $\vec{x}$, respectively, and $e^{\pm}$ from the ϕ decay transports to the solar system $\vec{x}_\odot$. The source at $\vec{x}$ can be described by the ϕ decay:

$$Q(\vec{x},E)=n_\phi(\vec{x})\,\Gamma_\phi^{\rm lab}\,\frac{dN}{dE}\,, \quad (4)$$

where dN/dE represents the electron or positron (injection) energy spectrum at $\vec{x}$ measured in the laboratory frame. The laboratory-frame ϕ decay rate $\Gamma_\phi^{\rm lab}$ is given by the ratio of the rest-frame decay rate Γ_ϕ $(=1/\tau_\phi)$ to the ϕ boost factor γ_ϕ. As usual, the ϕ flux $\Phi_\phi(\vec{x})$ relates the ϕ density $n_\phi(\vec{x})$ and its speed v_ϕ as

$$\Phi_\phi=n_\phi\cdot v_\phi\,, \quad (5)$$

where v_ϕ is simply given by the speed of light c for relativistic ϕ. Given the assumption that ϕ is non-diffusive, we formulate Φ_ϕ in an analogous manner to the case of the DM annihilation to a photon pair as follows:

$$\frac{d\Phi_\phi(\vec{x})}{d\Omega_{x_*}dE_\phi} = \left(\frac{1}{2}\right)\cdot\frac{1}{4\pi}\int_{\text{l.o.s}} ds_{x_*}\frac{n^2_{\chi_h}(\vec{y})}{2}\langle\sigma v\rangle_{\chi_h\chi_h\to\phi\phi} \times e^{-\frac{|\vec{x}-\vec{y}|}{c}\Gamma_\phi^{\text{lab}}}\frac{dN_\phi}{dE_\phi}\,, \tag{6}$$

where the additional factor of two in the parentheses is available when χ_h and $\bar{\chi}_h$ are distinguishable. Here l.o.s implies a line-of-sight integral along the $(\vec{x}-\vec{y})$ direction with the coordinates ds_{x_*} and $d\Omega_{x_*}$ defined relative to $\vec{x}$, and therefore we find

$$|\vec{x}-\vec{y}| = s_{x_*}\,. \tag{7}$$

The exponential factor in the second line describes the survival rate of ϕ from $\vec{y}$ to $\vec{x}$ without disintegrating into e^+e^-. dN_ϕ/dE_ϕ represents the (injection) energy spectrum of ϕ, which is simply given by

$$\frac{dN_\phi}{dE_\phi} = 2\cdot\delta(E_\phi - m_{\chi_h})\,, \tag{8}$$

since we assume χ_h non-relativistic.[38]

A couple of comments are in order. First, as we shall see shortly, the χ_h number density depends only on $y \equiv |\vec{y}|$. We then express y in terms of s_{x_*} and $\cos\theta_{x_*}$ as follows:

$$y^2 = r_x^2 + z_x^2 + s_{x_*}^2 - 2\sqrt{r_x^2+z_x^2}\,s_{x_*}\cos\theta_{x_*}\,, \tag{9}$$

where $x^2 = r_x^2 + z_x^2$ in the cylindrical coordinate relative to the GC (see also FIG. 2). Second, one may argue that the expected positron spectrum in the DM scenarios of interest would come with a significant anisotropy since particle ϕ, the immediate source of $e^\pm$ is highly relativistic and its decay is substantially delayed. However, the fact that the source point fairly far away is not resolvable in the point-like source interpretation (e.g., pulsars) for the positron excess [1] suggests that the positron flux will come into detectors almost isotropically in our case.

Data analysis. Equipped with the formalism developed thus far, we are now in the position to conduct a data analysis with the AMS-02 data in order to test the validity of our proposed mechanism. We basically vary the mass parameters for particles χ_h, ϕ, and χ_l in order to find out the best set of parameter values.

As mentioned earlier, we implement the uncertainness of the DM density around the GC, employing a χ_h profile wherein n_{χ_h} is enhanced nearby the GC compared to usual cuspy profiles. A simple example is given as

$$\rho_{\chi_h}(y) = \begin{cases} \rho_0\,\frac{(y/y_s)^{-1}}{(1+y/y_s)^2} \equiv \rho_{\text{NFW}}(y) & \text{for} \quad y \geq y_C \\ \mathcal{N}\times\rho_{\text{NFW}}(y_C) & \text{for} \quad y < y_C \end{cases}\,, \tag{10}$$

where y_C and $\mathcal{N}$ are fit parameters responsible for the core size and the density scale factor, respectively. A scale radius y_s is set to be 20 kpc, while ρ_0 is chosen in such a way that the local DM density at $r_\odot \simeq 8.33$ kpc is $\rho_\odot \simeq 0.4$ GeV/cm^3. Our toy profile implies that the χ_h density outside y_C simply follows the Navarro-Frenk-White (NFW) halo profile [30, 31], while there exists a large amount of χ_h inside y_C with a flat and central profile. As we will see shortly, an excellent fit to the AMS-02 data arises with $\mathcal{N} = 277\,(5900)$ for $y_C = 0.5\,(10^{-3})$ kpc (see the left panel in FIG. 3). We emphasize that the total amount of DM within 60 kpc around the GC remains almost the same as the NFW profile case due to the small volume defined by the core radius.

In order to obtain the injection spectrum dN/dE, we take a three-body decay of ϕ by phase space. The decay may involve a non-trivial matrix element, potentially distorting the overall shape. However, it has been shown that such an effect upon the three-body decay is indeed subleading in well-motivated new physics scenarios [32]. In addition, given the typical size of γ_ϕ, phase-space decay can be a good approximation. In the massless limit of the electron/positron, the unit-normalized injection spectrum has a form of

$$\frac{dN}{dE} = \frac{1}{2\gamma_\phi\beta_\phi}\left[\frac{m_\phi^4 - m_{\chi_l}^2}{8m_\phi} + \frac{m_{\chi_l}^2 m_\phi}{2}\log\left(\frac{m_{\chi_l}}{m_\phi}\right)\right]^{-1} \times \left[m_\phi(E^+ - E^-) + \frac{m_{\chi_l}^2}{2}\log\left(\frac{m_\phi - 2E^+}{m_\phi - 2E^-}\right)\right]\,, \tag{11}$$

where $E^\pm$ are defined as follows:

$$E^+ = \min\left[\frac{E}{\gamma_\phi(1-\beta_\phi)}, \frac{m_\phi^2 - m_{\chi_l}^2}{2m_\phi}\right]\,, \tag{12}$$

$$E^- = \frac{E}{\gamma_\phi(1+\beta_\phi)}\,. \tag{13}$$

Note that E spans 0 to $\gamma_\phi(1+\beta_\phi)(m_\phi^2 - m_{\chi_l}^2)/(2m_\phi)$.

Although in our actual data analysis we use the full form in Eq. (11), it is instructive to examine the injection spectrum in a phenomenologically well-motivated mass hierarchy, i.e., $m_{\chi_h} \gg m_\phi \gg m_{\chi_l}$, in order to check its effective dependence over the mass parameters. We find that a simple algebra can further simplify the expression in Eq. (11) to

$$\frac{dN}{dE} \sim \frac{m_{\chi_h} - E}{m_{\chi_h}} + R^2\log\left[R^2\left(\frac{m_{\chi_h} - E}{m_{\chi_h}}\right)^{-1}\right]\,, \tag{14}$$

with R defined as m_{χ_l}/m_ϕ. In this limit, the positron spectrum becomes sensitive only to m_{χ_h} and R out of three masses.

For obtaining the actual positron spectrum, we simply apply the results in PPPC4DM [28] rather than directly solve the diffusion equation, Eq. (2). In general, the (induced) density profile of ϕ differs from all of the DM halo profiles implemented in the PPPC4DM package. However, for explaining positron excesses, the relevant features of halo functions are restricted mostly near

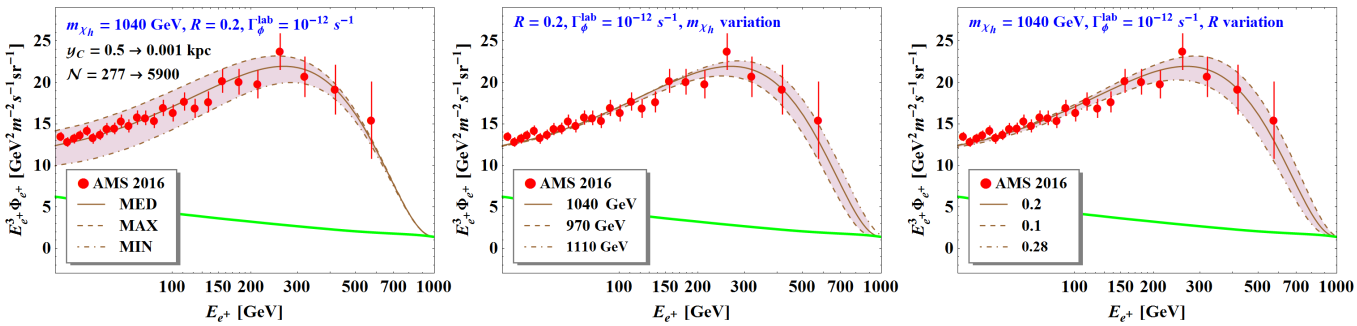

FIG. 3: The fit results of the scenario in FIG. 1 into the positron spectrum reported by the AMS-02 Collaboration [1]. The fits are performed with 26 data points within 35 – 600 GeV. Left panel: the best-fit with the variations of y_C, $\mathcal{N}$, and the galactic cylinder model. Middle and right panels: the fit sensitivities to m_{χ_h} (middle) and R (right).

the Earth where the halo profiles barely show variation. Thus, we can use any conventional profiles implemented in the package with an appropriate normalization. To reduce the number of fit parameters, we fix $\langle\sigma v\rangle_{\chi_h\chi_h\to\phi\phi}$ and $\Gamma_\phi^{\rm lab}$ to be 3×10^{-26} cm^{3}s^{-1} and 10^{-12} s^{-1}, respectively, and take the third magnetic field model in PPPC4DM throughout our data analysis.[39] Also, we assume that χ_h is self-conjugate and ϕ exclusively decays into the electron-positron pair along with χ_l for the sake of simplicity.

We now demonstrate the best-fit spectrum for the nominal positron excess announced by AMS-02 in the left panel of FIG. 3 where the dependence on the propagation parameters appears as a shaded band for the well-established MIN, MED, and MAX models [33]. We also dial y_C and $\mathcal{N}$ as well and observe that the required value of $\mathcal{N}$ (relatively) mildly increases as y_C decreases. To develop our intuition on the mass spectrum dependence of the fit, we vary m_{χ_h} and R with the other parameters fixed to those in the best fit. The middle panel of FIG. 3 shows the former variation. As m_{χ_h} determines the maximum positron energy, we clearly see the corresponding shift in three curves. The right panel of FIG. 3, on the other hand, shows the latter variation. We note that a larger (smaller) value of R implies that a smaller (larger) fraction of the ϕ decay energy is carried away by the positron. So, the resulting spectrum becomes softer (harder) as R increases (decreases), which is apparently respected in our fit results. We have also explicitly checked that $\sim50\%$ variation in the best-fit $\Gamma_\phi^{\rm lab}$ still keeps $\sim90\%$ of the flux.

Finally, let us discuss the choice of m_{χ_l} and m_ϕ, although only the ratio R between them enters in determining the shape of the positron spectrum. One can avoid the constraints from BBN [27] up to $\tau_\phi\simeq10^{12}$ seconds when the CMB bounds come into play, as far as the following relation holds:

$$\frac{2}{3}\cdot\frac{\rho_\phi}{\rho_{\rm DM}}=\frac{2}{3}\cdot\frac{m_\phi n_\phi}{m_{\rm DM}n_{\rm DM}}\lesssim2\times10^{-5}\,. \tag{15}$$

In the scenarios where the number densities of χ_h and ϕ are similar at the early Universe ($n_{\chi_h}\simeq n_\phi$), we can simply read off $m_\phi/m_{\chi_h}=\gamma_\phi^{-1}\lesssim3\times10^{-5}$ by assuming that χ_h is the dominant DM relic. Given that $\Gamma_\phi^{\rm lab}\sim10^{-12}\,{\rm s}^{-1}$ and $m_{\chi_h}\sim1$ TeV, therefore, $m_\phi\lesssim30$ MeV can be a proper parameter choice realizing our novel mechanism for positron excesses. On the other hand, other scenarios of $n_{\chi_h}\gg n_\phi$ are allowed, given that the ϕ number density can be reduced by its pair annihilation, e.g., $\phi\phi\to\chi_l\chi_l$. The exact number densities of χ_h, ϕ, and χ_l can be obtained by solving the coupled Boltzmann equations similarly done in some scenarios [24, 34–36]. While we leave the detailed calculation for future [37], our (rough) assessment finds that $\rho_\phi/\rho_{\rm DM}\lesssim10^{-5}$ for $m_{\chi_h}=1$ TeV, $m_\phi=0.5$ GeV, and $m_{\chi_l}=0.1$ GeV in a dark U(1)$_X$ scenario. Note again that this parameter choice provides the best fit as displayed in the left panel of FIG. 3.

Conclusions. In this letter, we provided a *new* mechanism which can possibly explain the current and future positron excesses in terms of *annihilation/decay* of thermal DM. A prominent feature of this proposal is that the existence of a very long-lived dark sector particle ϕ allows us to make use of the huge DM (χ_h) number density *near* the GC to accommodate the data, instead of that in the region close to the Earth where much less DM exists. A χ_h pair basically annihilates to a ϕ pair near the GC, while the ϕ decay (to positron) occurs mostly in the region close to the Earth. The produced positrons thereby propagate a much shorter distance than 8.33 kpc (between the GC and the Earth) so that a large amount of positron flux can be observed. This mechanism is in a sharp contrast to other proposals fitting the observed positron spectrum by boosting up the DM annihilation cross section or introducing *ad hoc* local DM clumps. We also argued that quite a broad range of mass spectra are allowed without any severe conflicts with various cosmological and astrophysical observations. In conclusion, we encourage people to revisit existing DM models or construct new DM models to explain the positron excesses in conjunction with the mechanism suggested here.

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[38] Note that the ϕ flux in Eq. (6) straightforwardly applies to decaying DM models by replacing $n_{\chi_h}(\vec{y})^2/2$ and $\langle\sigma v\rangle_{\chi_h\chi_h\to\phi\phi}$ by $n_{\chi_h}(\vec{y})$ and $\Gamma_{\chi_h\to\phi\phi}$, respectively.

[39] We have tried the other magnetic field models, but observed no significant differences.