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Charge Asymmetric Cosmic Rays
as a probe of
Flavor Violating Asymmetric Dark Matter

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The recently introduced cosmic sum rules combine the data from PAMELA and Fermi-LAT cosmic ray experiments in a way that permits to neatly investigate whether the experimentally observed lepton excesses violate charge symmetry. One can in a simple way determine universal properties of the unknown component of the cosmic rays. Here we attribute a potential charge asymmetry to the dark sector. In particular we provide models of asymmetric dark matter able to produce charge asymmetric cosmic rays. We consider spin zero, spin one and spin one-half decaying dark matter candidates. We show that lepton flavor violation and asymmetric dark matter are both required to have a charge asymmetry in the cosmic ray lepton excesses. Therefore, an experimental evidence of charge asymmetry in the cosmic ray lepton excesses implies that dark matter is asymmetric.

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I. CHARGE ASYMMETRY IN COSMIC RAYS

Shedding light on astrophysical and particle physics origins of cosmic rays can lead to breakthroughs in our understanding of the fundamental laws ruling the universe. In [1] we introduced a new model independent approach for efficiently combine observations from different cosmic rays experiments. These *cosmic sum rules* showed how to investigate the possible charge asymmetries in the *unknown* components of high energy cosmic rays. We found that at present even large deviations from charge symmetry are experimentally viable. Interestingly, future experimental observations could better constrain the tolerated amount of asymmetry. We now review the sum rule method proposed in [1].

The data recently collected by PAMELA [2] indicate that there is a positron excess in the cosmic ray energy spectrum above 10 GeV. The rising behavior observed by PAMELA does not fit previous estimates of the cosmic ray formation and propagation implying the possible existence of a direct excess of cosmic ray positrons of unknown origins. Interestingly PAMELA's data show a clear feature of such a positron excess but no excess in the anti-protons [3]. While ATIC [4] and PPB-BETS [5] reported unexpected structure in the all-electron spectrum in the range 100 GeV-1 TeV, the picture has changed with the higher-statistics measurements by Fermi-LAT [6] and HESS [7], leading to a possible slight additional unknown component in the CR $e^{\pm}$ flux over and above the standard astrophysical model predictions, like for instance the specific Moskalenko and Strong [8, 9] one. These interesting features have drawn much attention, and many explanations have been proposed: For example, these excesses could be due to an inadequate account of the cosmic ray astrophysical background in previous modeling; They could be due to the presence of new astrophysical sources; They could also originate from annihilations and/or decays of dark matter. We refer to [10] for a recent review.

Whatever the origin of these excesses might be, the observed flux of electrons and positrons can be written as the sum of two contributions: A background component, $\phi^B_{\pm}$, describing all known

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astrophysical sources (which, at least for the electrons, are considered to be quite well known), and an unknown component, $\phi^U_\pm$. Explicitly:

$$\phi_\pm = \phi^U_\pm + \phi^B_\pm \ . \tag{1}$$

The component $\phi^U_\pm$ is the one needed to explain the features in the spectra observed by PAMELA and Fermi-LAT. These experiments measure respectively the positron fraction and the total electron and positron fluxes as a function of the energy E of the detected $e^\pm$, i.e.:

$$P(E) = \frac{\phi_+(E)}{\phi_+(E) + \phi_-(E)} \ , \qquad F(E) = \phi_+(E) + \phi_-(E) \ . \tag{2}$$

The left-hand side of the equations above refer to the experimental measures.

Our aim is to investigate the unknown contribution leading to the lepton excesses in cosmic rays. Clearly, this can be done only assuming a definite astrophysical background model. In particular we want to investigate the fundamental properties of the unknown contribution, like its charge asymmetry. This step is necessary to better understand its origin. The contribution from the unknown source can be written as:

$$\begin{aligned} \phi^U_+(E) &= P(E)\ F(E) - \phi^B_+(E) \ , & (3)\\ \phi^U_-(E) &= F(E)\ (1 - P(E)) - \phi^B_-(E) \ . & (4) \end{aligned}$$

We model the background spectrum using

$$\phi^B_\pm(E) = N_B B^\pm(E) \quad , \tag{5}$$

where N_B is a normalization coefficient and $B^\pm(E)$ are provided using specific astrophysical models. In this paper we adopt the popular Moskalenko and Strong model [8, 9], for which $B^\pm(E)$ are given, for example, in [1]. We checked that our results remain unchanged when using instead the astrophysical background model adopted by the Fermi-LAT Collaboration (model zero) [11, 12].

In terms of their sum:

$$\phi^U_+(E) + \phi^U_-(E) = F(E) - (\phi^B_-(E) + \phi^B_+(E)) \ . \tag{6}$$

The latter equation implies $F(E)/(B^-(E) + B^+(E)) \geq N_B$.

The ratio of the unknown fluxes is thus a direct measure of the charge asymmetry of the source of the high energy cosmic rays [1]:

$$r_U(E) \equiv \frac{\phi^U_-(E)}{\phi^U_+(E)} = \frac{F(E)\ (1 - P(E)) - \phi^B_-(E)}{P(E)\ F(E) - \phi^B_+(E)} \quad . \tag{7}$$

This equation can be rewritten as

$$R(E) \equiv \frac{F(E)}{B^-(E)}\ \frac{1 - (1 + r_U(E))P(E)}{1 - r_U(E)\frac{\phi^B_+(E)}{\phi^B_-(E)}} = N_B \ . \tag{8}$$

Although the sum rule $R(E)$ seems to depend on the energy it should, in fact, be a constant as is clear from the right hand side of the previous equation. This leads to a nontrivial constraint linking together in an explicit form the experimental results, the model of the backgrounds and the dependence on the energy of the unknown component charge asymmetry. Since we use simultaneously the results of Fermi-LAT and PAMELA we consider the common energy range, i.e. from about 20 to 100 GeV.

In order to test whether current data could support charge asymmetric cosmic rays in [1] we considered the oversimplifying assumption that r_U is nearly constant as function of the energy, in

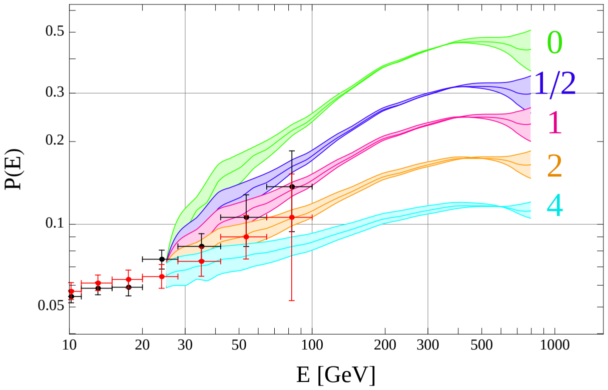

FIG. 1: Positron fraction $P(E)$ as a function of the energy E of electrons and positrons for different values of $r_U = 0, 1/2, 1, 2, 4$, from top to bottom. Secondaries are estimated according to the expressions in [8, 9]. The shaded regions reflect the one sigma errors of Fermi-LAT and PAMELA when determining the allowed values of N_B deduced from the sum rule (8). We display the 2010 (lower red) and 2008 (upper black) PAMELA data, with 1σ error bars.

the energy region common to PAMELA and Fermi-LAT. We then extrapolated the prediction for the positron fraction and compared it with the PAMELA results [1]. We summarize our results in Fig. 1. It is clear that the resulting picture shows that the current data allow for a substantial charge asymmetry corresponding to $r_U \neq 1$.

The special case $r_U = 1$ is an automatic prediction of a great deal of models for dark matter which assume that charge symmetry holds both in the production and propagation of the unknown component of the cosmic rays. Symmetric dark matter always implies $r_U = 1$, as we will prove in the following.

II. FLAVOR VIOLATING ASYMMETRIC DARK MATTER MODELS

In this work we attribute the experimental cosmic rays excesses to the existence of a dark matter component of asymmetric type. This type of candidates appeared first in [13] in the form of technibaryons, and in [14] as Goldstone bosons. Since then, asymmetric dark matter candidates of all types have appeared in the literature [14–22]. We should note that the possibility of mixed dark matter with a thermally produced symmetric component and an asymmetric component [22]. Having reviewed the constrains coming from the cosmic sum rules on the cosmic rays charge asymmetry [1] we now construct models able to naturally account for such an asymmetry. This will also allow us to determine the explicit energy dependence of $r_U(E)$.

Furthermore we will show that violation of the flavor symmetry in the dark sector is essential to have phenomenologically viable charge asymmetries. Flavor violating operators from the dark sector were discovered in [23].

We will consider here three distinct types of dark matter. A complex scalar T, a spin-one state T_μ and a fermionic one N similar to the fourth generation neutrinos. We assume that dark matter is of asymmetric type and therefore only half of the decays allowed at the Lagrangian level are dominant, i.e. the ones deriving from the surviving component. In this investigation we assume dark matter to couple only to leptons.

1. *Scalar Asymmetric Dark Matter*

The scalar interactions we consider are therefore:

$$c_{\ell\ell'}\, T\overline{\ell}\ell' + \text{h.c.}\ . \tag{9}$$

Here $\ell = e, \mu$ or τ and we assume summation over the standard model leptonic flavor indices. A generic $c_{\ell\ell'}$ leads to violations of the lepton numbers. As explained above we assume that, during the evolution of the universe, an asymmetry in the relic densities of T and T^* arises. We further consider the case in which T^* has disappeared and that we are left today only with T. The latter decays via the first interaction term given in (9). Explicitly, this leads to

$$T \to \ell^-_L \ell'^+_L + \ell^-_R \ell'^+_R \ , \tag{10}$$

where the notation means that leptons in the pair are produced with the same helicity and that there is equal probability for both chiralities. Parity is thus conserved. If $\ell \neq \ell'$ then asymmetric dark matter implies charge-conjugation violation in the decay. Clearly, if ℓ (ℓ') is not directly the flavour e, electrons (positrons) are produced in its decay chain. If we were to have symmetric type dark matter then, as it is clear from (10), we would have an equal energy spectrum of electron and positrons since they would be produced via T and T^*.

2. *Vector Asymmetric Dark Matter coupling to a L or R lepton current.*

Similarly we consider the following left and right handed leptonic currents involving the complex T_μ spin one massive dark matter field

$$d_{\ell\ell'}\, T_\mu \overline{\ell}\gamma^\mu \frac{1 \pm \gamma_5}{2}\ell' + \text{h.c.}\ . \tag{11}$$

Assuming again asymmetric spin one dark matter component made by the T_μ states we find that the decay products are

$$T_\mu \to \ell^-_L \ell'^+_R \ , \ \ \text{L} - \text{current}\ , \qquad \text{and} \qquad T_\mu \to \ell^-_R \ell'^+_L \ , \ \ \text{R} - \text{current}\ . \tag{12}$$

By construction this model violates parity maximally. Furthermore if we have no asymmetry in the dark matter relic density there will be no charge asymmetry in the cosmic rays and, last but not the least, flavor violation is needed to achieve this charge asymmetry.

3. *Fermionic Dark Matter with the quantum numbers of a fourth active neutrino.*

We also consider semileptonic decays from a fourth generation like heavy neutrino [24] stemming from interactions of the type:

$$p_{N\ell}\, W^+_\mu \overline{N}\gamma^\mu \frac{1 - \gamma_5}{2}\ell + \text{h.c.}\ , \tag{13}$$

with $p_{N\ell}$ the coupling strength. The heavy Dirac neutrino N carries a new lepton number which differentiates it from its conjugate $\bar{N}$. An asymmetry would imply that either N or $\bar{N}$ are left today to be a fraction of dark matter. Accordingly, only one among these decays take place:

$$N \to \ell^-_L W^+_L \ , \qquad \bar{N} \to \ell^+_R W^-_L\ . \tag{14}$$

The labels stress the fact that in both cases the W boson is longitudinally polarized. A symmetric-type dark matter would still produce charge symmetric cosmic rays despite the evident flavor violation. The Majorana heavy neutrino, as a corollary of the previous statement, would lead to charge symmetric cosmic rays [24]. Recently other models have been explored providing also charge asymmetric cosmic rays [25].

III. CHARGE ASYMMETRIC COSMIC RAYS

We now discuss the energy spectra of the high energy electrons and positrons coming from the decays of the different types of asymmetric dark matter envisioned above. It is possible to investigate the different types of dark matter by simply patching together the spectra coming from the dark matter direct products. We now consider in turn the different decay products. For definiteness, we adopt here the same propagation model discussed in detail in our previous work [24]. This is a propagation model commonly used when investigating dark matter as primary source of cosmic ray excesses.

When the flavor of ℓ is the electron one the resulting electrons or positrons spectra are monochromatic with an energy $E_e = M_{DM}/2$, for the scalar and spin-one dark matter. There is a tiny kinematic correction to this value for the semileptonic one [24]. After propagation they display therefore a hard spectrum depicted in fig. 2 for $M_{DM} = 1, 3$ and 10 TeV.

For $\ell = \mu$, the initial muon has energy $M_{DM}/2$ and the resulting electrons (positrons) produced in the decay of μ_L^- (μ_R^+), turn out to have a slightly harder spectrum than those produced in the decay of μ_R^- (μ_L^+). The associated spectral functions after propagation are displayed in fig. 2. Clearly, for an unpolarized $\mu^\pm$, as it is the case of a scalar dark matter, the energy spectrum of $e^\pm$ is given by the mean of the solid and dotted curves. A similar result applies to the case of $\ell = \tau$ and the associated spectral curves are displayed in fig. 2. Finally, in the same figure we show also the spectrum of $e^\pm$ coming from the decay of a longitudinally polarized $W^\pm$. For the specific details of the propagation model, intermediate computations and explicit formulae we refer to [24].

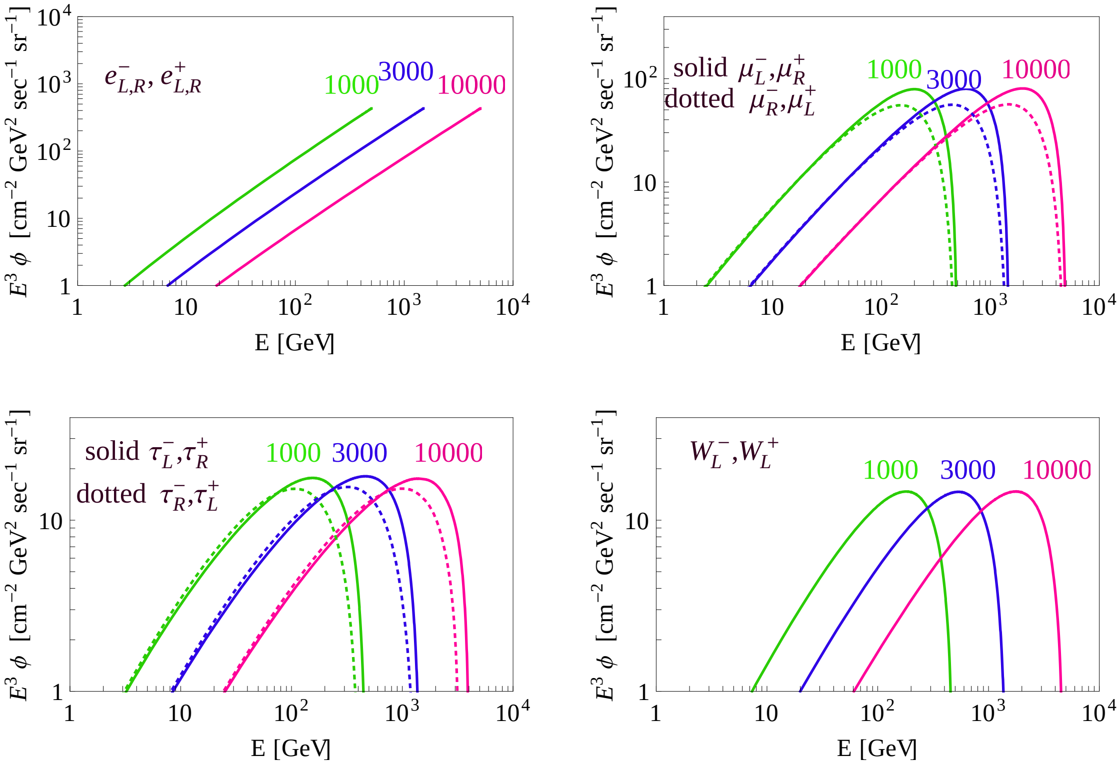

FIG. 2: Different spectra for the cosmic rays electrons and positrons coming from the primary particles shown in the different panels. We assumed M_{DM} to be respectively 1000, 3000 and 10000 GeV. The lifetimes, fixing the size of the couplings, are chosen to be 10^{22} s for the plots.

We are now ready to investigate our predictions for charge asymmetric cosmic rays by computing $r_U(E)$ defined in (7) as the ratio of the electron to positron fluxes of the unknown component, here assumed to come from asymmetric dark matter, measured at Earth.

4. Scalar and Vector Asymmetric Dark Matter prediction for Charge Asymmetric Cosmic Rays

Let us first consider the decay of the scalar and vector dark matter. If the decay is flavour conserving, namely $\ell = \ell'$, the electrons and positrons have the same energy spectrum and consequently $r_U = 1$ over the entire energy range.

As we explained above a necessary condition for charge asymmetric cosmic rays is the presence of a lepton flavor violation. This will lead to a specific energy dependent $r_U(E)$ different from unity. For a decaying scalar or vector dark matter there are six possibilities to combine two different flavours. Each of these different combinations lead to a specific $r_U(E)$. We report the results for $r_U(E)$ in fig. 3 for a 3 TeV decaying dark matter. The decays of a scalar dark matter is represented as the inner solid line, the vector coupling to a L(R)-current is the (dot) dashed curve. The two panels have been constructed to better elucidate the results but carry the same information given that one is the inverse of the other. The (right) left panel represents values of $r_U(E)$ mostly (smaller) greater than one.

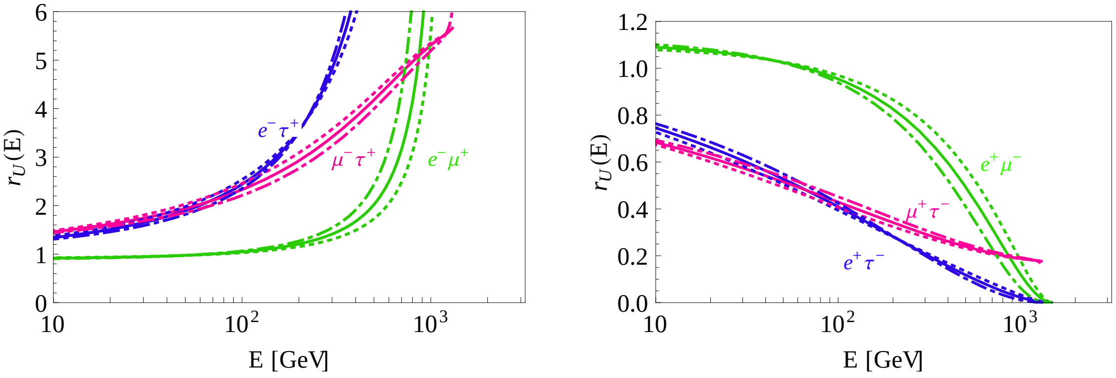

FIG. 3: We plot $r_U(E)$ for a 3 TeV decaying dark matter of either scalar or vector type. The scalar dark matter is represented as the inner solid line, the vector dark matter with coupling to a L(R)-current is the (dot) dashed curve.

The ratio $r_U(E)$ varies by a factor of two in the energy range for primary $\mu\tau$ leptons. The reader will also notice that there is little difference between the scalar and the vector dark matter. It is clear that a vector dark matter coupling to the leptons vectorially, i.e. of left plus right type current, would be indistinguishable from scalar dark matter.

5. Fermionic Asymmetric Dark Matter prediction for Charge Asymmetric Cosmic Rays

In the case of a decaying heavy neutrino the two processes are either $N \to W^+\ell^-$ or $\bar{N} \to W^-\ell^+$. If the heavy neutrino is of Majorana type, clearly $r_U = 1$. As it is the case for the bosonic asymmetric dark matter we find that lepton flavour must be violated to have a r_U which is not unity over the all range of energy. The resulting ratio $r_U(E)$ is displayed in fig. 4.

We find that in these decays the ratio $r_U(E)$ is nearly constant or linear in the energy for primary μ and τ leptons.

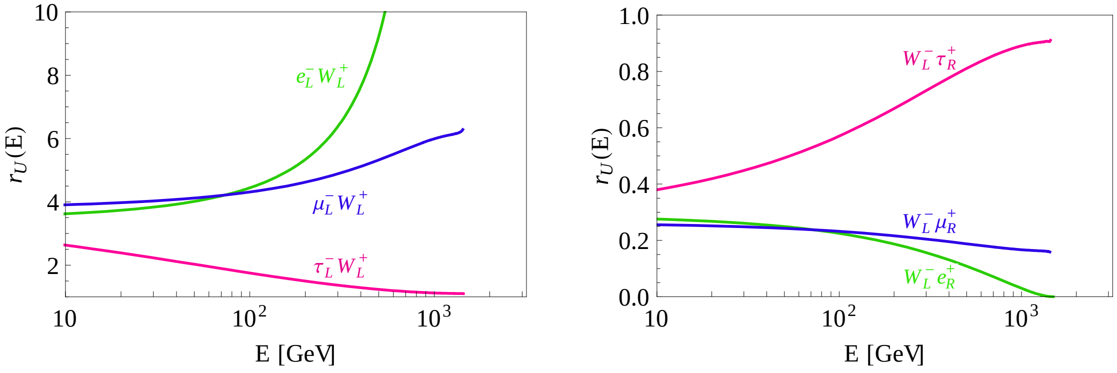

FIG. 4: We plot $r_U(E)$ for a 3 TeV decaying dark matter of Dirac type. The left (right) panel corresponds to $N \to W^+\ell^-$ ($\bar{N} \to W^-\ell^+$).

IV. COMPARISON WITH FERMI-LAT AND PAMELA

To connect to previous studies we start by considering the flavour preserving dark matter decays, i.e. $\ell = \ell'$ for the scalar and vector dark matter. The results are presented in fig. 5. It is known that $\ell = e$ cannot fit the Fermi-LAT data. The case of the muon pair is instead compatible with both Fermi-LAT and PAMELA while the tau pair yields an even better fit. The dashed (upper) and dot-dashed (lower) curves, corresponding to a specific primary decay mode, represent respectively the vector dark matter coupling with the left and right current. Interestingly the difference between the scalar and left or right vector dark matter is within reach of the experimental errors. This implies that experiments can determine, in the near future, whether the dark side violates parity maximally as it is the case for the bright side.

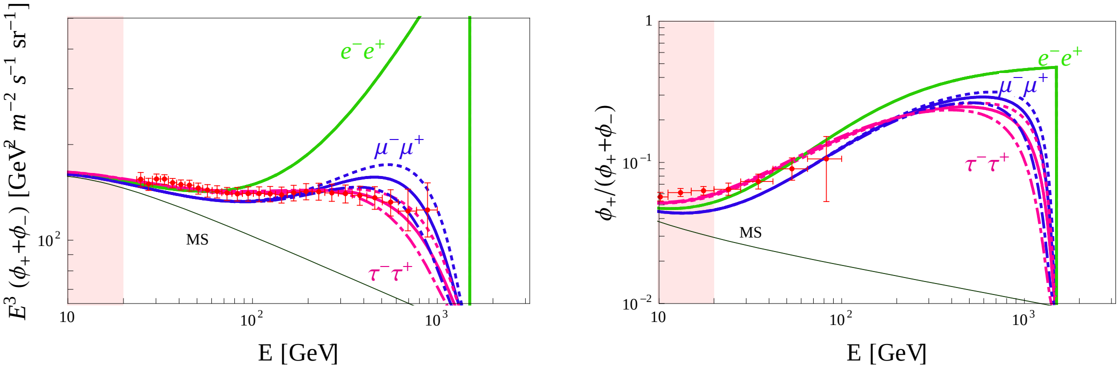

FIG. 5: Comparison of flavour preserving dark matter decays for Fermi-LAT (left panel) and PAMELA (right panel). The solid lines correspond to scalar decays while the dashed (upper) and dot-dashed (lower) curves, corresponding to a specific primary decay mode, represent respectively the vector dark matter coupling with the left and right current. The MS stands for the Moskalenko and Strong background. We have chosen the decay time for the decaying in e^+e^- to be 10^{26} s, for $\mu^+\mu^-$ we have taken 1.5×10^{26} s, and for $\tau^+\tau^-$ we have taken 0.5×10^{26} s. These values correspond to the best fit to the Fermi-LAT data. We have also chosen the parameter $N_B = 0.64$.

We now study the flavour violating case in which $\ell \neq \ell'$ for the bosonic and fermionc asymmetric dark matter case starting from the bosonic case presented in fig. 6. The comparison with Fermi-LAT is shown in the upper panel while the comparison with PAMELA is shown in the two figures of the lower panel. Fermi-LAT results dictates that the most promising processes must not involve electron/positron primaries from the decays. When comparing the three pictures there is a preference for the $\mu\tau$ primary lepton pair. Furthermore PAMELA type experiment is sensitive to charge asymmetric cosmic rays. In particular by reducing the experimental errors and increasing the higher end of the energy range one will be able to determine whether the cosmic rays are asymmetric and which kind of asymmetry produces them. Interestingly a charge asymmetry stemming solely from $\mu^-\tau^+$ primaries is currently disfavored while the $\mu^+\tau^-$ is favored for both PAMELA and Fermi-LAT.

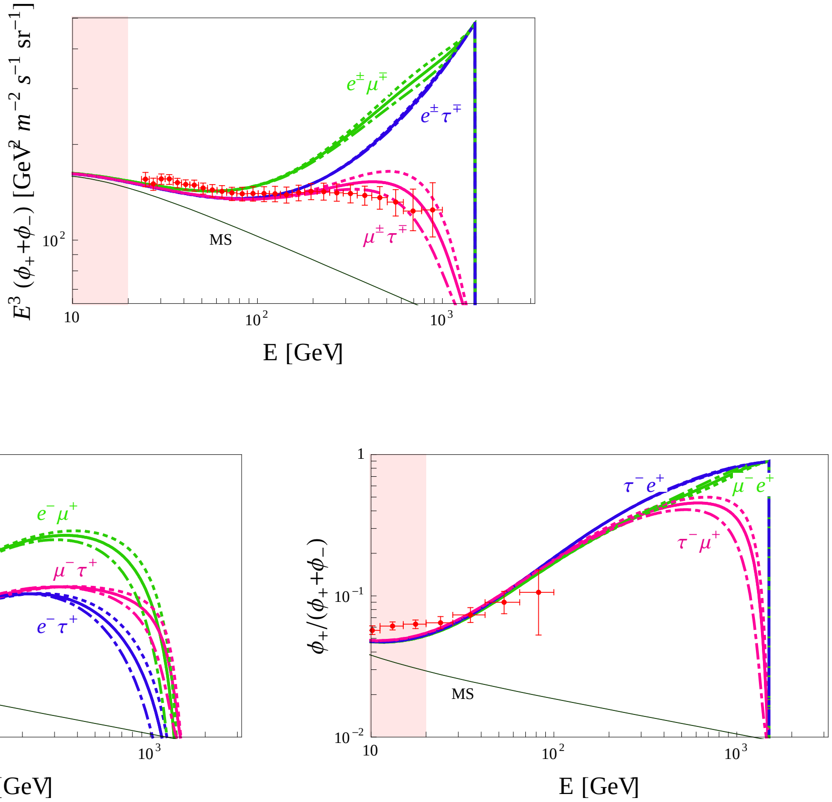

FIG. 6: Comparison of flavour violating dark matter decays for Fermi-LAT (upper panel) and PAMELA (lower panels). The solid lines correspond to scalar decays while the dashed (upper) and dot-dashed (lower) curves, corresponding to a specific primary decay mode, represent respectively the vector dark matter coupling with the left and right current. The MS stands for the Moskalenko and Strong background. We have chosen the lifetime to be 10^{26} s for all the primary decays and $N_B = 0.64$.

We have performed a similar comparison for the fermion case. The results are shown in fig. 7. It is evident, by inspection, that the best fit occurs for the decay of $\bar{N}$ in W and a right-handed anti-muon or anti-tau. Comparing these processes with the right panel of fig. 4 we find that for the anti-muon case there is a stronger, but nearly constant, charge asymmetric component in the cosmic ray while the anti-tau process leads to a smaller smaller asymmetry raising towards unity at high energies. The investigation for the Majorana case has been performed recently in [24] and corresponds to $r_U = 1$. Our results apply also to the case in which the asymmetric dark matter constitutes only a fraction of the dark matter relic density by opportunely modifying the lifetimes.

Very recent data of the PAMELA collaboration [26] on the negative electron flux have been released which, however, given the large uncertainties for energies higher than 100 GeV do not affect our results.

For the scalar and vector dark matter there are no constraints coming from the antiproton to

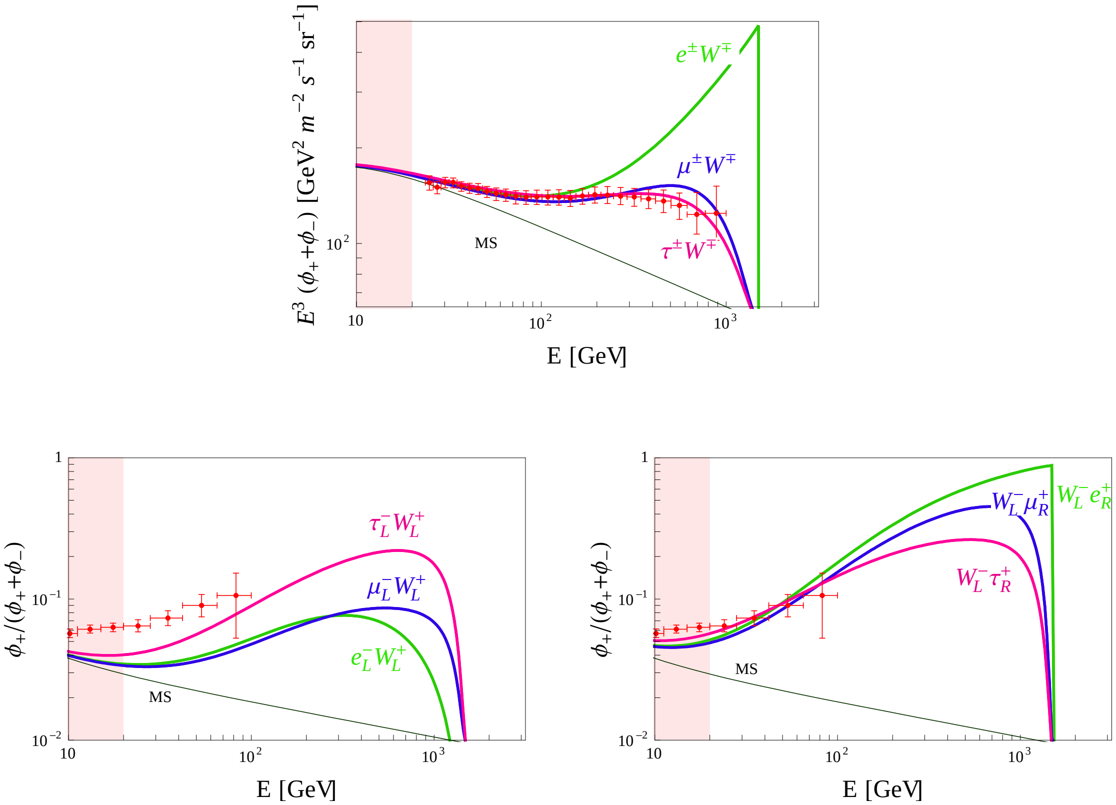

FIG. 7: Comparison of flavour violating dark matter decays for Fermi-LAT (upper panel) and PAMELA (lower panels) for Dirac type asymmetric dark matter. The different solid lines correspond to indicated primary decay modes. We have chosen the lifetime for decaying in eW to be 10^{26} s, for μW we have taken 1.2×10^{26} s, and for $W\tau^-$ we have taken 0.5×10^{26} s. We have also chosen the parameter $N_B = 0.7$.

proton ratio [3]. For the heavy neutrino dark matter there is an excess of antiprotons which we will compute in the next section. While the interpretation in terms of dark matter annihilations often leads to an unobserved excess of gamma and radio photons, the interpretation in terms of dark matter decays is compatible with photon observations [27, 28], even though some channels now start to show some tension [29–32]. A discrimination strategy was proposed in [33, 34]. However, the gamma photons analysis, like the one presented in [25, 35] for models similar to ours, show that our results are compatible with the experimental constraints [36, 37]. The AMS-02 space station experiment will hopefully provide additional relevant informations [38].

V. COSMIC RAY ANTIPROTONS FOR THE HEAVY NEUTRINO DECAY

In this section we give an estimate for the cosmic ray antiproton flux resulting from the heavy neutrino decay and compare it with current data.

Protons and antiprotons are generated via the hadronic decay of the primary W boson, with BR of about 67%. Their energy spectrum is determined by the fragmentation and hadronization processes. In this case an analytic approach is not suitable and we rather adopt the numerical recipies provided in ref. [35]. In particular, the antiproton (proton) flux obtained from a 1.5 TeV dark matter annihilating into W^+W^- is twice the antiproton (proton) flux in our model.

The propagation for antiprotons through the galaxy is described by a diffusion equation whose

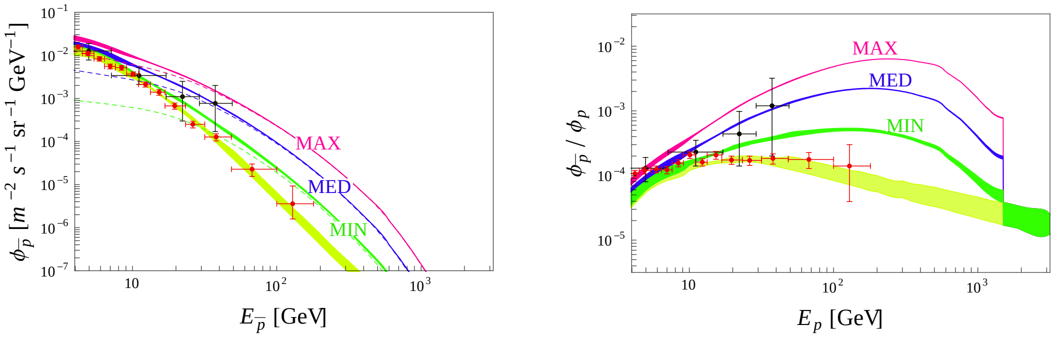

FIG. 8: Antiproton flux (left) and antiproton/proton ratio (right) for the MAX, MED, MIN propagation models, $M_{N_1} = 3$ TeV and life time 1.9×10^{26} s. The dashed curves in the left panel show the primary antiprotons for MAX, MED, MIN models. The lower shaded region represents the secondary antiprotons only, according to ref. [39]. The upper three curves correspond to the sum of the primary and secondary antiprotons. The (lower) PAMELA data [3] have smaller error bars with respect to the (upper) CAPRICE data [40].

solution can be cast in a factorized form as discussed *e.g.* in [35]. In this case the astrophysical uncertainties associated to the dark matter profile and to the propagation parameters are large, about one order of magnitude. We display the antiproton flux in the left panel of fig. 8 for the MAX, MED, MIN propagation models and for $M_{N_1} = 3$ TeV and life time 1.9×10^{26} s. The dashed curves show these primary antiprotons for MAX, MED, MIN models; the lower shaded region represents the flux of the secondary antiprotons according to ref. [39]; the upper three curves correspond to the sum of the primary and secondary antiprotons. The (lower) PAMELA data [3] have smaller error bars with respect to the (upper) CAPRICE data [40]. It turns out that only the MIN propagation parameter set is compatible with the data, the MED one is barely compatible, while the MAX seems disfavored.

The antiproton/proton ratio is studied in the right panel of fig. 8. For the proton flux, we consistently adopt the parameterization of ref. [39] with spectral index equal to -2.72. This parameterization is valid for energies higher than about 10 GeV. Again, the (lower) PAMELA data points [3] are more precise than the (upper) CAPRICE ones [40]. The plot shows that the heavy neutrino model displays tension with the PAMELA data and therefore we expect the scalar model to be favored. Future measurements confirming the PAMELA results could be able to rule out the heavy decaying neutrino model presented here.

VI. CONCLUSIONS

Concluding, in [1] we asked whether cosmic rays could feature a charge asymmetry. We demonstrated, by combining the data from PAMELA and Fermi-LAT via sum rules, that such a a charge asymmetry is experimentally viable and can be tested. In [1] we did not make any assumption on the specific model which could lead to such an asymmetry in the cosmic rays. Here we attributed the cosmic rays potential charge asymmetry to the dark sector and provided relevant examples of asymmetric, flavor violating, decaying dark matter made of a complex scalar, vector or a Dirac fermion. We determined the associated energy dependent charge asymmetry $r_U(E)$ for these models. We then compared our predictions for the charge asymmetric cosmic rays with the data coming from PAMELA and Fermi-LAT.

We discovered that dark matter must both be of asymmetric type and violate lepton flavour to generate charge asymmetric cosmic rays excesses. Therefore a model independent way to directly demonstrate that dark matter is of asymmetric type is to observe a charge asymmetry in the cosmic rays.

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