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New positron spectral features from supersymmetric dark matter: A way to explain the PAMELA data?

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The space-borne antimatter experiment PAMELA has recently reported a surprising rise in the positron to electron ratio at high energies. It has also recently been found that electromagnetic radiative corrections in some cases may boost the gamma-ray yield from supersymmetric dark-matter annihilations in the galactic halo by up to 3 or 4 orders of magnitude, providing distinct spectral signatures for indirect dark matter searches to look for. Here, we investigate whether the same type of corrections can also lead to sizeable enhancements in the positron yield. We find that this is indeed the case, albeit for a smaller region of parameter space than for gamma rays; selecting models with a small mass difference between the neutralino and sleptons, like in the stau-coannihilation region in mSUGRA, the effect becomes more pronounced. The resulting, rather hard positron spectrum with a relatively sharp cutoff may potentially fit the rising positron ratio measured by the PAMELA satellite. To do so, however, very large ''boost factors'' have to be invoked that are not expected in current models of halo structure. If the predicted cutoff would also be confirmed by later PAMELA data or upcoming experiments, one could either assume nonthermal production in the early universe or nonstandard halo formation to explain such a spectral feature as an effect of dark-matter annihilation. At the end of the paper, we briefly comment on the impact of radiative corrections on other annihilation channels, in particular, antiprotons and neutrinos.

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The existence of a sizeable dark-matter contribution to the total cosmological energy density seems by now to be established beyond any reasonable doubt, the most recent estimates [1] giving the fraction of cold dark matter to the critical density as $\Omega_{\mathrm{CDM}} \sim 0.233 \pm 0.013$. Against this background, searches for experimental signatures that may determine the so far still elusive nature of the cosmological dark matter are becoming ever more important.

On the theoretical side, maybe the best motivated, and certainly most extensively studied, dark-matter candidate is the supersymmetric neutralino (for reviews, see [2]). The methods of detection for this type of particle dark matter can be grouped into *accelerator* searches, trying to directly produce dark matter or related new particles (the signature of the former usually being missing energy), the *direct detection* of dark-matter particles scattering off the nuclei of a terrestrial detector, or *indirect detection* of particles generated by the annihilation of dark-matter particles in the Galactic halo or (for neutrinos) in the Sun or Earth. With the LHC soon operating and new detectors of liquid noble gases being developed for direct detection, aiming to further improve the already impressive recent upper limits [3], the near future promises very interesting times for the field.

As far as indirect detection is concerned, the antimatter detection satellite PAMELA has just announced its first set of data for cosmic ray antiprotons [4] and has very recently done so also for positrons [5]. Although the antiproton data seems to agree with conventional secondary production by cosmic rays, the positron data shows an unexpected rise in the differential ratio $e^+/(e^- + e^+)$ above some 7–10 GeV. This interesting situation may be further investigated by the PEBS balloon experiment [6] and, in particular, the AMS-02 experiment, if installed on the international space station [7]. These experiments could further improve these data, both concerning statistics and energy range, and, in particular, investigate whether a return to a ''normal'' ratio at some energy exists—something that is predicted by models of dark-matter annihilation due to the kinematic limit that appears at an energy equal to the dark-matter particle mass. Of course, it will also be important to rule out positron misidentification through proton contamination in this high-energy range.

Further information may possibly be obtained from the huge IceCUBE [8] detector which will soon start to look for cosmic neutrinos at the South Pole. For gamma rays, the recently launched GLAST satellite [9] opens up a new window to the high-energy universe, for energies from below a GeV to about 300 GeV. The sensitivity to gamma rays of even higher energies is, furthermore, expected to improve considerably with next generation Air Cherenkov Telescopes like the CTA or AGIS [10,11].

Most likely, in fact, a signal from more than one type of experiment will be needed to confirm a dark-matter interpretation of the observed signal and, in the best case, to fully identify the particle making up the dark matter; it is thus important to realize the complementary nature of the methods described above. This is even more true since, in all of these cases, the signal searched for may be quite

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weak and dominated by a much larger background. In this context, one should also keep in mind (see, e.g., [12]) that it may be possible to explain a signal like the one recently reported by PAMELA in a more conventional way, without having to invoke unreasonably strong astrophysical sources; for example, a supernova remnant of age 10^5 years some 100 pc distance from the Sun/Earth would both have the appropriate energetics and the right energy spectrum to account for the PAMELA results.

A first assessment of the situation (see, e.g., [13]) concerning dark-matter candidates after the surprising PAMELA results seems to indicate that the otherwise favored supersymmetric neutralino cannot explain the data. This is because it is a Majorana particle and therefore does not give hard positrons directly, due to the helicity suppression of light fermions in the annihilation process. The resulting positron spectrum is thus expected to be rather soft, in disagreement with the PAMELA data, and therefore a Dirac particle, or a spin-1 particle like Kaluza-Klein dark matter [14] would fit better (another proposal put forward in connection with the PAMELA data has been minimal dark matter, where the combination of a very high dark-matter particle mass (~ 10 TeV) and a very efficient enhancement mechanism for the annihilation into charged gauge bosons would result in the required hard spectrum at low energies [15]).

However, this simple intuition may prove wrong when computing radiative corrections. Gamma rays, for instance, have a sharp cutoff [16,17] at an energy equal to the dark-matter particle's mass, $E_\gamma = m_\chi$, and, in some cases, even prominent line signals from the direct annihilation into photons [18–20]. While the origin of the first feature is associated with photons directly radiated from charged final legs ("final state radiation"), it was recently pointed out that even photons radiated from charged virtual particles ("virtual" internal bremsstrahlung (IB), or direct emission) can have a significant impact on the resulting gamma-ray spectrum, leading not only to an even more pronounced cutoff, but also to clearly observable bumplike features at slightly lower energies [21]. In fact, these effects generically dominate the total spectrum at high photon energies, including even the line signals, and may lead to an enhancement of the annihilation rate by several orders of magnitude. Such a large radiative "correction" can appear since the annihilation of neutralinos into lepton pairs is strongly helicity suppressed, while for the three-body final state containing an additional photon this suppression is circumvented [22].

With these recent results in mind, the question thus naturally arises whether the same effects also have a significant impact on, e.g., the yield in positrons—especially since the largest enhancement factors appear for neutralino annihilations into leptons [21]. Let us first consider the *direct annihilation* into positrons. As e^+e^- two-body final states are strongly suppressed, the dominant contribution comes always from the process $\chi\chi \to e^+e^-\gamma$, in particular, from those diagrams where the photon is radiated from a t-channel selectron. Setting $m_e \to 0$, we find for the differential annihilation rate into positrons:

$$\frac{d}{dx}(v\sigma)^{\chi\chi\to e^+e^-\gamma}_{v\to 0} = \frac{\alpha_{\rm em}|\tilde{g}_R|^4}{256\pi^2 m_\chi^2}\frac{1}{(\mu_R - 1 + 2x)^2} \times \Big\{[4(1-x)^2 - 4x(1+\mu_R) + 3(1+\mu_R)^2]\log\frac{1+\mu_R}{1+\mu_R-2x} - [4(1-x)^2 - x(1+\mu_R) + 3(1+\mu_R)^2]\frac{2x}{1+\mu_R}\Big\} + (R \leftrightarrow L), \tag{1}$$

where $x = E_{e^+}/m_\chi$, $\mu_{R,L} \equiv m^2_{\tilde{e}_{R,L}}/m_\chi^2$ and $\tilde{g}_R P_L$ $(\tilde{g}_L P_R)$ is the coupling between neutralino, electron and right-handed (left-handed) selectron. In the corresponding limit, this reproduces the result found in [22] for photino annihilation. Integrating Eq. (1) gives

$$(v\sigma)^{\chi\chi\to e^+e^-\gamma}_{v\to 0} = \frac{\alpha_{\rm em}|\tilde{g}_R|^4}{64\pi^2 m_\chi^2}\Big\{\frac{3+4\mu_R}{1+\mu_R} + \frac{4{\mu_R}^2 - 3\mu_R - 1}{2\mu_R} \times \log\frac{\mu_R - 1}{\mu_R + 1} - (1+\mu_R) \times \Big[\frac{\pi^2}{6} - \Big(\log\frac{\mu_R+1}{2\mu_R}\Big)^2 - 2{\rm Li}_2\Big(\frac{\mu_R+1}{2\mu_R}\Big)\Big]\Big\} + (R \leftrightarrow L), \tag{2}$$

where ${\rm Li}_2(z) = \sum_{k=1}^\infty z^k/k^2$ is the dilogarithm. The direct annihilation of neutralinos (with small galactic velocities v) into positrons is thus only suppressed by a factor of (α/π) and not, as often quoted, by the much smaller factor of (m_e^2/m_χ^2) that is connected with two-body final states. In the above expression, the highest annihilation rate is obtained in the limit $\mu_{R,L} \to 1$ where the selectrons are degenerate in mass with the neutralino:

$$(v\sigma)^{\chi\chi\to e^+e^-\gamma}_{v\to 0} \le \frac{\alpha_{\rm em}}{\pi}\frac{|\tilde{g}_R|^4 + |\tilde{g}_L|^4}{\pi m_\chi^2}\frac{21 - 2\pi^2}{384}. \tag{3}$$

Positrons may also be produced in the decay of other annihilation products. The number $dN^f_{e^+}/dx$ of such *secondary* positrons per annihilation into the corresponding final state f can be simulated with Monte Carlo event generators like `PYTHIA` [23]. For two-body final states $X\bar{X}$, we use the tabulated values contained in `DarkSUSY` [24] that were obtained through a large number of `PYTHIA` runs. For three-body final states containing a photon, the positron yield is approximately given by

$$\frac{dN_{e^+}^{X\bar{X}\gamma}}{dx} \approx \int dE_X \frac{dN_X^{X\bar{X}\gamma}}{dE_X}\frac{d\tilde{N}_{e^+}^{X\bar{X}}}{dx}, \tag{4}$$

where $d\tilde{N}_{e^+}^{X\bar{X}}/dx$ is the (two-body final state) positron multiplicity $dN_{e^+}^{X\bar{X}}/dx$ that results from the annihilation of two dark-matter particles with mass E_X. The analytically obtained expressions for $dN_X^{X\bar{X}\gamma}/dE_X$ are too lengthy to reproduce here but have been fully implemented in the current public release of `DarkSUSY` [24] (for light fermions, of course, the same functional form as in Eq. (1) is recovered). When compared to gamma rays from the corresponding channel, the positron contribution (4) to the total spectrum is considerably less pronounced at the observationally most relevant energies near the cutoff since part of the energy is taken away by the photon; the fact that positrons are not the only decay products induces a further kinematical suppression at high energies. On general grounds, we therefore cannot expect large radiative corrections to the yield in secondary positrons—even in situations where large gamma-ray contributions are found (as, e.g., for heavy neutralino annihilation into W^+W^- [25]). An exception to this conclusion could only occur in a situation where the annihilation rate into the three-body final state is many times larger than for the two-body final state. As pointed out in [21], this is indeed possible for lepton final states in the stau-coannihilation region of mSUGRA. However, as also the annihilation into $e^+e^-\gamma$ is usually greatly enhanced in this region, it is, rather, the latter contribution that dominates in this case.

For illustration, we show in Fig. 1 the effect of radiative corrections on the positron yield for a typical model in the mSUGRA coannihilation region (introduced as benchmark point BM3 in [21]), which is characterized by small mass differences between neutralino and sleptons. A spectacular boost in the positron yield can be observed, leading to an extremely pronounced cutoff at $E_{e^+} = m_\chi$. As anticipated, this is mainly due to primary positrons, following the distribution (1), but at smaller energies the effect of radiative corrections becomes also visible for other decay channels (mainly $\mu^+\mu^-$).

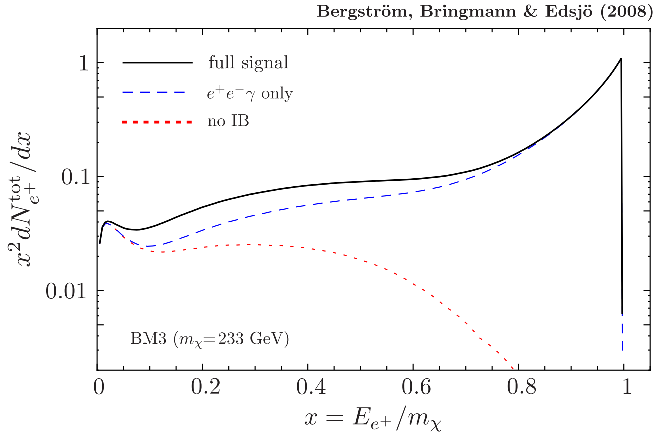

FIG. 1 (color online). The solid line gives the total number of positrons per neutralino pair annihilation and positron energy for the benchmark model BM3 of [21] ($m_\chi = 233$ GeV, $m_{\tilde{e}} = 240$ GeV). Shown separately is the same quantity without radiative corrections (dotted line) and, on top of this, only the $e^+e^-\gamma$ final states (dashed line).

The propagation of charged particles is influenced by magnetic fields residing in the Milky Way which, in contrast to the case of photons, tend to erase clearly pronounced spectral features. To be able to compare our results with the cosmic ray positron spectrum as measured at the top of the atmosphere (TOA) or, in the case of the recent PAMELA data, in space, we adopt the standard assumption of randomly distributed magnetic fields, in which case the determination of the positron flux at a given galactic position boils down to solving a diffusion equation (for more details on the procedure we follow, see [26]). We assume an NFW profile [27] for the dark-matter distribution in the galactic halo, but allow for an additional "boost factor" to account for the effect of dark-matter substructure.

Let us now quantify our general expectations outlined above and try to assess the general importance of IB effects on the positron yield. For that purpose, we consider a scan (based on the work in [28]) over the mSUGRA parameter space, keeping only models that feature the right relic density and pass all current collider bounds. In this setup, as mentioned before, the stau-coannihilation region is characterized by light leptons; since, at the same time, the total annihilation cross section (today, i.e. for $v \to 0$) is very small, we expect rather large enhancements in the positron yield in this case. In the upper panel of Fig. 2, indeed, we clearly observe the expected strong correlation between the $m_{\tilde{e}}$-m_χ mass splitting and the resulting enhancement in the positron flux due to radiative corrections; outside the coannihilation region, no sizeable flux enhancements are encountered.

In mSUGRA, however, in the presence of light selectrons, also the other sleptons have to be light. Hence, to investigate the situation in more general terms, we have set up a low-energy phenomenological scan with 9 free parameters. We start with the usual parameters of minimal supersymmetric standard model (MSSM)-7: the Higgsino mass parameter μ, the gaugino mass parameter M_2, a common sfermion mass scale m_0, the ratio of the Higgs vacuum expectation values $\tan\beta$, the trilinear couplings in the third generation A_t and A_b, and the mass of the CP-odd Higgs boson, m_A. In addition to these, we add a selectron mass parameter that goes into the selectron entries in the mass parameters of the soft SUSY-breaking Lagrangian; furthermore, we relax the grand unified theory condition on M_1 and M_2 by allowing M_1 to be varied freely. We then generate models by varying these 9 parameters of our MSSM-9 model between generous bounds, focusing on

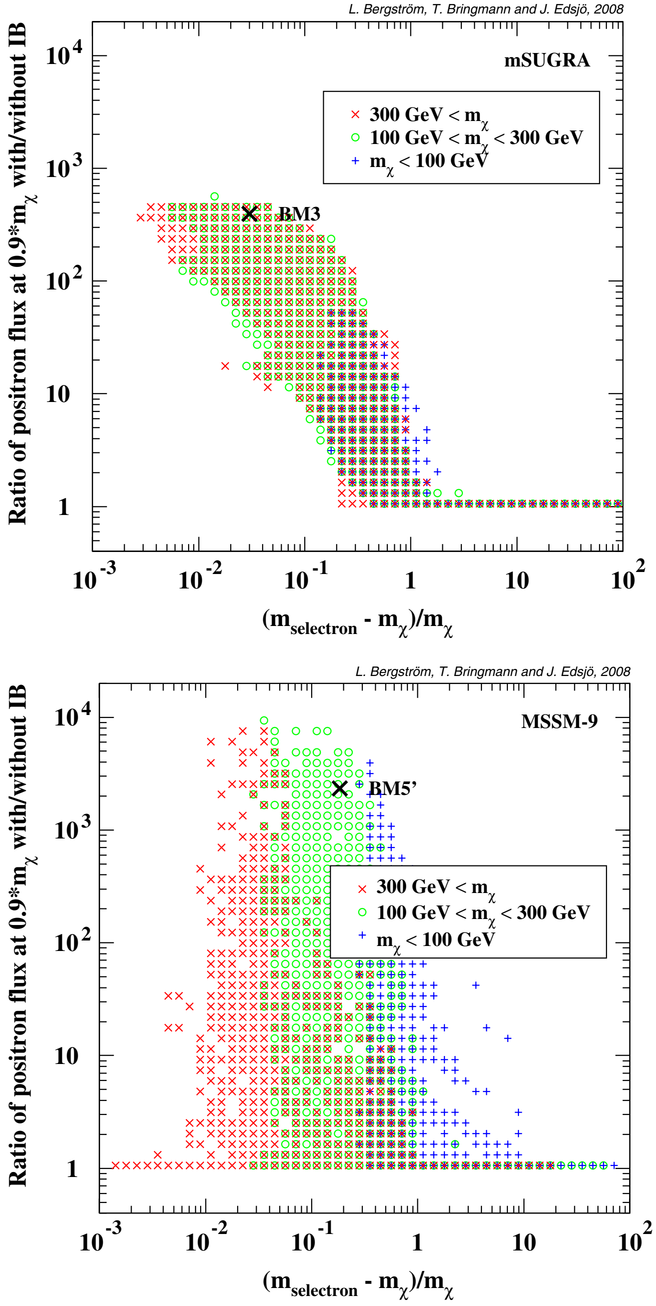

FIG. 2 (color online). Scan over mSUGRA (upper) and MSSM-9 (lower) models that shows the enhancement in the positron flux (at $E_{e^+} = 0.9 m\chi$) due to radiative corrections vs the mass splitting between the lightest selectron and the neutralino, $\delta \equiv (m_{\tilde{e}} - m_\chi)/m_\chi$. Also indicated in this figure are the benchmark model BM3 from [21] and a further benchmark model BM5' as introduced in the text.

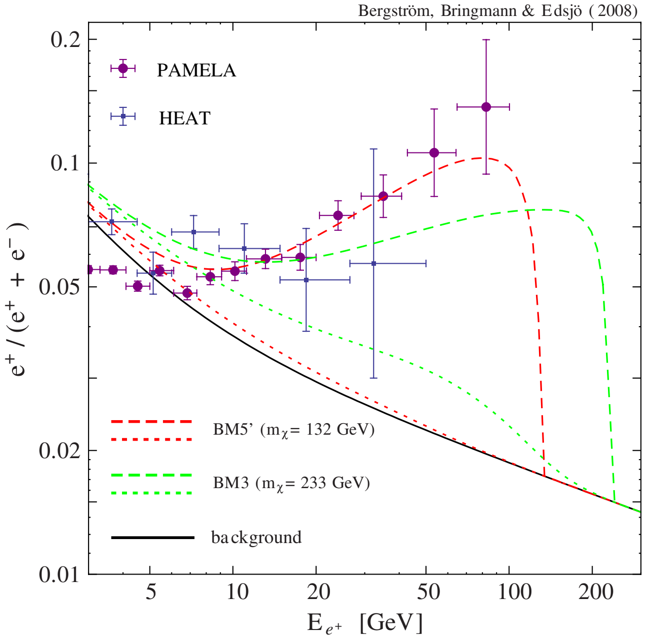

FIG. 3 (color online). The solid line is the expected flux ratio $e^+/(e^+ + e^-)$ as calculated following [29]. The data points are the combined HEAT [38] and PAMELA data [5]. Furthermore, the expected flux ratio for our benchmark models is shown without (dotted lines) and after taking into account radiative corrections (dashed lines). See text for further details.

models with light selectrons and, again, keeping only models that feature the right relic density and pass all current collider bounds. In the lower panel of Fig. 2, we plot the enhancements from IB for these models; the effect of introducing more free parameters as compared to mSUGRA is mainly that the total annihilation cross section is not anymore closely linked to the $m_{\tilde{e}}$-m_χ mass splitting by the relic density requirement. As a result, the enhancements in the total positron flux can be both considerably larger and smaller than in the mSUGRA case, depending on the total annihilation rate to lowest order; the main contribution to the flux enhancement, however, is in any case found from the $e^+e^-\gamma$ channel.

In Fig. 3, we plot the resulting flux ratio $e^+/(e^+ + e^-)$ from neutralino annihilations for both BM3 and a point BM5' in the MSSM-9 parameter space (with $m_\chi = 132$ GeV, $m_{\tilde{e}} = 157$ GeV; both models are marked in Fig. 2) and compare it to the PAMELA data. For comparison, we also show the expected background flux [29]. Propagation effects thus considerably smear the spectrum shown in Fig. 1, but the clearly pronounced cutoff at $E_{e^+} = m_\chi$ still remains as a prominent feature. It is interesting to note that this type of pronounced spectral signature so far has only been associated to Kaluza-Klein dark matter [30]. Even though the cutoff in this latter case appears, due to the large branching ratio into e^+e^-, to be even more pronounced, it would be observationally very challenging to see this difference with an energy resolution of the about 5% expected for PAMELA. The apparent discrepancy between the background expectation and the new data at small energies is most likely due to a change in the solar potential which has not been taken into account so far [5]; this effect, however, is expected to be negligible at positron energies above around 10 GeV and we will therefore not discuss it further here.

Unfortunately, the need for large boost factors is generic for all models that show a high positron yield enhancement in the way reported here (in Fig. 3, we used boost factors of 3×10^4); the reason being that models in the coannihilation region have very small annihilation rates to start with. While such large boost factors are difficult to achieve in standard scenarios [31], they are easily encountered if, e.g., the Milky Way hosts a typical population of intermediate mass black holes [32]; other possibilities include a nonthermal neutralino production in the early universe (see, e.g., [33]), a nonstandard pre-big bang nucleosynthesis expansion rate [34], or a very nearby dark-matter ‘‘clump’’ (which, however, is quite unlikely according to present models of structure formation).

One should also keep in mind that boost factors of at least 50–100 are needed in most cases, anyway [35], to see the effect of supersymmetric dark-matter annihilation in the positron spectrum—but even for very large boosts, the resulting positron spectra are too soft to explain the observed steep rise in the $e^+/(e^+ + e^-)$ ratio. As becomes apparent from Fig. 3, this is actually also true for the already quite hard spectra reported here in case of masses higher than $m_\chi \gtrsim 100$ GeV. In order to really fit the PAMELA data through primary positrons from neutralino annihilations would thus require rather small neutralino masses. A generic prediction of this model is therefore that a sharp cutoff in the spectrum has to be observed already at energies only slightly higher than so far accessible. Such a well-pronounced, steplike feature would be a spectacular discovery in the next release of PAMELA data, or in future experiments like AMS-02.

In concluding, let us briefly address the consequences of this type of radiative corrections for possible dark matter induced contributions in other cosmic ray species. For *neutrinos*, for the same reasons as discussed for secondary positrons, the only chance for large effects appears in situations with great enhancements of the annihilation into leptons, i.e. the channels $\mu^+\mu^-\gamma$ and $\tau^+\tau^-\gamma$. Still, just as in the case of positrons, these channels are unlikely to have a large impact on the *total* neutrino yield. A potentially interesting source for *antiprotons*, on the other hand, are gluons from the annihilation into $t\bar{t}g$ final states—which, in the stop coannihilation region, is considerably enhanced compared to the lowest order result in exactly the same way as the $t\bar{t}\gamma$ channel discussed in [21]. However, since the lowest order annihilation rate is extremely small in the region of interest, the resulting absolute yield is still too small to be of great significance. This general expectation is in agreement with earlier studies [36].

To summarize, we have shown that radiative corrections may significantly enhance the dark-matter induced positron yield and result in a pronounced spectral signature, a rising positron to electron ratio and a sharp cutoff in the positron spectrum at the neutralino mass m_χ. To obtain such a spectral feature, similar to that observed by PAMELA [5], very large boost factors are needed. On the other hand, *if* such a feature is observed, a strong enhancement can also be expected in the gamma-ray flux at photon energies close to m_χ [21] (while the impact on, e.g., the expected antiproton spectrum would be negligible); such a cross-correlation would of course provide even stronger evidence for the dark-matter nature of the signal. An unambiguous, testable prediction of this class of models is that the positron excess will be cut off at an energy not too far from the maximal energy presently reported by the PAMELA collaboration, as larger masses do not reproduce the slope of the rising positron ratio (for a very similar situation for another class of dark-matter particles, see [37]).

Finally, let us mention that the radiative corrections to the positron yield from neutralino annihilations that have been reported here have been implemented in the current, publicly available version 5.0.1 of `DarkSUSY` [24].

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