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A novel prediction for secondary positrons and electrons in the Galaxy

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The Galactic flux of cosmic-ray (CR) positrons in the GeV to TeV energy range is very likely due to different Galactic components. One of these is the inelastic scattering of CR nuclei with the atoms of the interstellar medium. The precise amount of this component determines the eventual contribution from other sources. We present here a new estimation of the secondary CR positron flux by incorporating the latest results for the production cross sections of $e^{\pm}$ from hadronic scatterings calibrated on collider data. All the reactions for CR nuclei up to silicon scattering on both hydrogen and helium are included. The propagation models are derived consistently by fits on primary and secondary CR nuclei data. Models with a small halo size ($L \leq 2$ kpc) are disfavored by the nuclei data although the current uncertainties on the beryllium nuclear cross sections may impact this result. The resulting positron flux shows a strong dependence on the Galactic halo size, increasing up to factor 1.5 moving L from 8 to 2 kpc. Within the most reliable propagation models, the positron flux matches the data for energies below 1 GeV. We verify that secondary positrons contribute less than 70% of the data above a few GeV, corroborating that an excess of positrons is already present at very low energies. At larger energies, our predictions are below the data with, the discrepancy becoming more and more pronounced. Our results are provided together with uncertainties due to propagation and hadronic cross sections. The former uncertainties are below 5% at fixed L, while the latter are about 7% almost independently of the propagation scheme. In addition to the predictions of positrons, we provide new predictions also for the secondary CR electron flux.

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1. Introduction

A guaranteed component of cosmic rays (CRs) is due to the so-called secondary production, originating from spallation reactions of CR nuclei against the atoms of the interstellar medium (ISM). Most of the secondary contribution is produced by the collision of CR protons or alpha particles interacting with hydrogen and helium ISM atoms. The secondary component plays an undisputed role in explaining the data collected by different space-based and ground-based experiments. This is particularly true for the fluxes of cosmic antiprotons and positrons (e^+), which have been measured with high accuracy and in a wide energy range . Indeed, the antiproton flux is explained at a large extent to be of secondary origin [1, 2]. On the other side, the measured e^+ flux and e^+ fraction, defined as the ratio between the flux of e^+ and the sum of e^+ and electrons (e^-), clearly indicate that a secondary component alone cannot explain the data [3–6]. In fact, secondary e^+ contribute mostly at energies below tens of GeV while at higher energies this process contributes to the data very likely less than a few tens of %. This is even more pronounced in the e^- flux data, which are mainly explained by the cumulative flux of e^- accelerated by Galactic supernova remnants [7–10]. We provide here a new evaluation of the CR flux of secondary e^+ and e^- at Earth by implementing the new results on the production cross sections [11]. In order to estimate the uncertainties coming from the propagation model, we perform a new fit to the 7 years fluxes of primary and secondary CRs measured by AMS-02 [12], by using different assumptions for the physical processes that characterize the propagation of particles in the Galaxy and the diffusive halo size L. In particular, we estimate the uncertainties in the secondary flux which is due to various propagation parameters, devoting a specific discussion to the effect of the value of L, and to the $e^\pm$ production cross sections. Our e^+ and e^- secondary fluxes are predicted from the implementation of the innovative results from both sectors, production cross sections and Galactic propagation.

2. Cosmic-ray production and propagation

The charged particles injected in the ISM by their sources encounter several processes due to interaction with the Galactic magnetic fields, atoms or photons in the ISM, or Galactic winds. All these processes can be modeled in a chain of coupled propagation equations for the densities ψ_i of the CR species i. We refer to [13] and references therein for a complete discussion on the propagation modeling. We only remind here that a piece of novelty is the description of the diffusion coefficient by a double broken power law in rigidity, R, with the functional form

$$D_{xx}(R) \propto \beta R^{\delta_l} \cdot \left(1 + \left(\frac{R}{R_{D,0}}\right)^{\frac{1}{s_{D,0}}}\right)^{s_{D,0}\,(\delta-\delta_l)} \cdot \left(1 + \left(\frac{R}{R_{D,1}}\right)^{\frac{1}{s_{D,1}}}\right)^{s_{D,1}\,(\delta_h-\delta)} . \quad (1)$$

Here β is the CR velocity in units of speed of light, $R_{D,0}$ and $R_{D,1}$ are the rigidities of the two breaks, δ_l, δ, and δ_h are the power-law index below, between, and above the breaks, respectively. We also allow a smoothing of the breaks through the parameters $s_{D,0}$ and $s_{D,1}$. The diffusion coefficient is normalized to a value D_0 at a reference rigidity of 4 GV so that $D_{xx}(R = 4\,\mathrm{GV}) = \mathrm{D}_0$. The first break, if included in the model, is typically in the range of 1–10 GV while the second break, whose existence is suggested by the flux data for secondary CRs, is at about 200-400 GV.

Secondary CRs such as $e^{\pm}$ are produced in the interaction and fragmentation of primary CRs with the atoms of the ISM. The source term of secondary CRs is generically given by the convolution of the primary fluxes, the ISM components and the fragmentation cross-sections. The calculation of the secondary $e^{\pm}$ follows from the $e^{\pm}$ production cross sections recently published in Ref. [11], which include all the possible channels due to pions, kaons and hyperons, and take into account nuclei contribution both in the ISM and in the incoming CR fluxes. The implementation of these new cross sections is the main novelty of this paper. They have been obtained with a very small uncertainty bands.

The propagation model is derived on the most recent sets of nuclei data. We fit the latest data measured by the AMS-02 experiment after 7 years of data taking, from 2011 to 2018, [12]. In particular we fit the absolute fluxes of protons, He, C, O, N, B/C, Be/C and Li/C. The ratio of secondaries over primaries (B/C, Be/C and Li/C) are particularly relevant for fixing the propagation parameters, while the one of He, C, O, N to derive the injection spectra. Since all the AMS-02 measurements considered have been measured for the same data-taking period, we adopt one unique Fisk potential for the all the species. The AMS-02 data for the fluxes available for $R > 1$ GV are complemented with the proton and helium data from Voyager [14] above 0.1 GeV/nuc. For all the details of the calculation, the choice of the free parameters and the results of the fits we remind to [13].

3. Results

We report here the main results for the prediction of secondary electrons and positrons, primary and secondary nuclei fluxes. For the propagation parameters and for details on any of the topics we refer to [13]. The predictions for the secondary e^+ and e^- is computed once the propagation parameters best-fit and uncertainties have been found by fitting CR data as explained above.

In Fig. 1 we display the predictions for the secondary positron flux obtained with all the different models introduced [13] for L fixed to 4 kpc. We show the best-fit and 1σ uncertainty band found in the Bayesian framework. The models `Conv` $v_{0,c}$, $\texttt{Reacc}_0$ and $\texttt{Reacc}_{10}$ predict a similar flux in the entire energy range. In particular, at the lowest measured energies the secondary fluxes are comparable to the e^+ data, while they are increasingly smaller with respect to the AMS-02 measurements at larger energies. At 5 GeV the secondary positrons can account for about 50-70% of the data while at the highest energy they are about 20-30% of the measured e^+ flux.

In Fig. 2 we show the e^+ flux predicted for different values of the diffusive halo size between 0.5 and 8 kpc within the `Conv` $v_{0,c}$ model. Above about 5 GeV, the secondary e^+ $E^3\,\Phi$ flux decreases systematically with L. This can be understood from the well-known degeneracy between L and the normalization of the diffusion coefficient [15]. For small L, CR nuclei spend on average more time in the Galactic disc, which increases the secondary nuclei production. The latter has then to be compensated by a smaller diffusion coefficient (i.e. faster diffusion). Therefore, to a first approximation, CR nuclei data only constrain the ratio D_0/L. Indeed, as we confirm in [13], there is a linear correlation between L and D_0. In contrast, e^+ (and also e^-) suffer from stronger energy losses which restrict them more locally than nuclei, such that they do not perceive the same effect of the boundary at L as nuclei. For them the degeneracy between L and D_0 is broken and they only sense the effect of decreasing D_0, which increases the secondary flux. For $L = 0.5$ kpc the e^+ flux

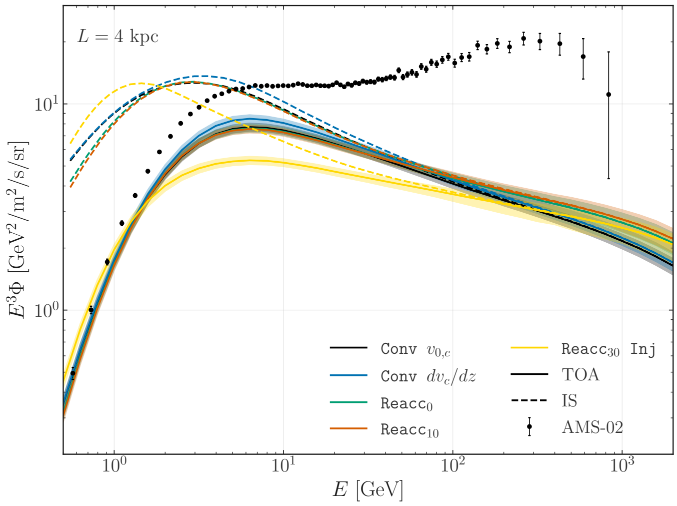

Figure 1: Prediction for the secondary positron flux at Earth as obtained for all the propagation model tested in [13] when fixing $L = 4$ kpc. For each case, we show the interstellar (IS, dashed lines) and modulated top of atmosphere flux (TOA, solid lines). We display the best-fit and 1σ Bayesian uncertainty band. AMS-02 data are included for comparison.

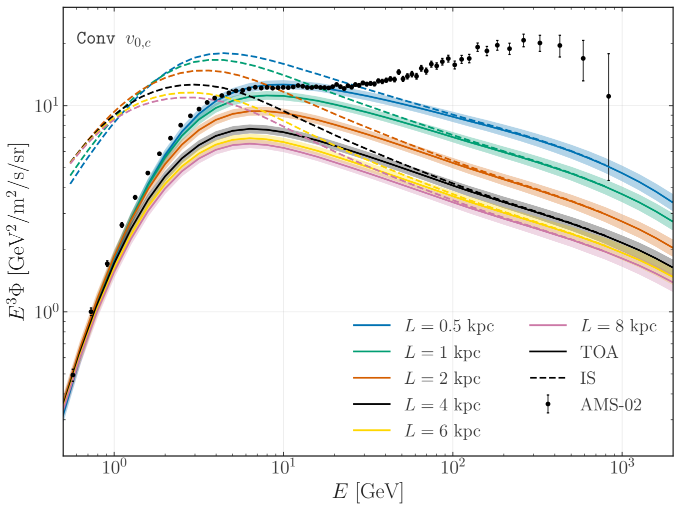

Figure 2: Prediction for the positron flux at Earth within the model `Conv` $v_{0,c}$ when varying the size of diffusive halo from $L = 0.5$ to 8 kpc. Line styles and data as in Fig. 1.

is at the level of the data between 0.5 to 20 GeV, while the flux for $L = 2$ kpc (4 kpc) decreases by of 20% (40%) at 5 GeV. For 8 kpc, the predicted secondary flux is about 50% of the data at 5 GeV. The predictions obtained with different L converge to very similar values below 2 GeV because energy losses become less important at small positron energies. The contribution of secondary positrons to the highest AMS-02 energy at $E \sim$ TeV spans from few percent to 50% of the data, mostly depending on the value of L.

In Fig. 3 we show the flux for secondary electrons and positrons compared to $e^{\pm}$ AMS-02 data. As expected, secondary electrons have a smaller flux with respect to positrons, reflecting the

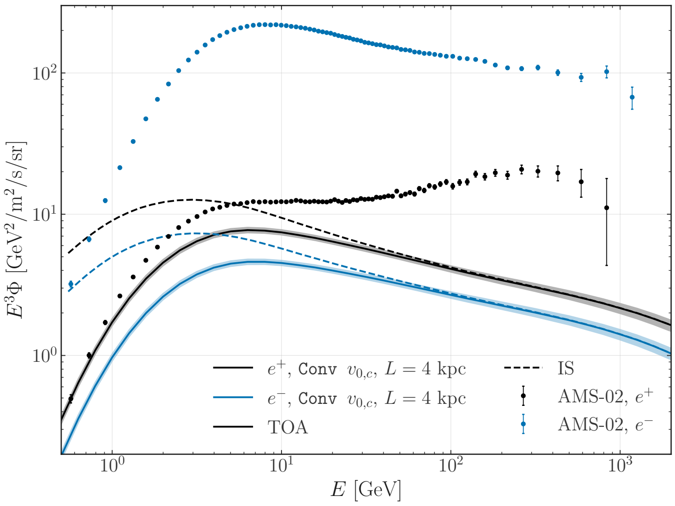

Figure 3: Flux of positrons (black line and band) and electrons (blue line and band) obtained for the model `Conv` $v_{0,c}$ with $L = 4$ kpc. We show the AMS-02 data for positrons (black data) and electrons (blue data).

charge asymmetry in the colliding CR and ISM particles, mostly positively charged. We verified that the variation of the secondary electrons with the size of the diffusive halo and propagation model follows the e^+ trends, as shown in Fig. 1 and Fig. 2.

Our results indicate that, within the propagation model explored here, an excess of positrons is present at energies larger than a few GeV, where the secondary flux starts to be less than 50% than the data. While this is consistent with a number of previous works [16–18], we [13] prove that for fixed values of $L \sim 4$ kpc, positron cross sections uncertainties are too small to explain the mismatch at low energies. However, we should notice that a larger secondary production is still not firmly excluded for smaller values of L, even if they correspond to worse fits to current nuclei CR data. From a study of the nuclear fragmentation cross section, we can conclude that measurements for the nuclear cross sections involving the production of beryllium and its isotopes are needed with a precision below 5% in order to estimate the size of the diffusive halo with a precision better than 50%.

Fig. 4 summarizes the results of the fit for `Conv` $v_{0,c}$ along with the AMS-02 data for primaries and secondaries species as a function of rigidity. In the left panel we report the results for the primary p, He, O and C nuclei, and the half-primary N flux. On the left panel we show the secondary-to-primary flux ratios for B/C, Li/C and Be/C. In [13] we report the best-fit values for the propagation parameters and the residual plots for different cases.

4. Conclusions

We have provided a new prediction for the secondary e^+ flux in the Galaxy. We implement new e^+ production cross sections for pp and p-nuclei collisions that became available recently [11]. In order to improve the Galactic propagation as well, we have performed new fits to CR nuclei data by computing the CR fluxes using Galprop, and have obtained new state-of-the-art propagation

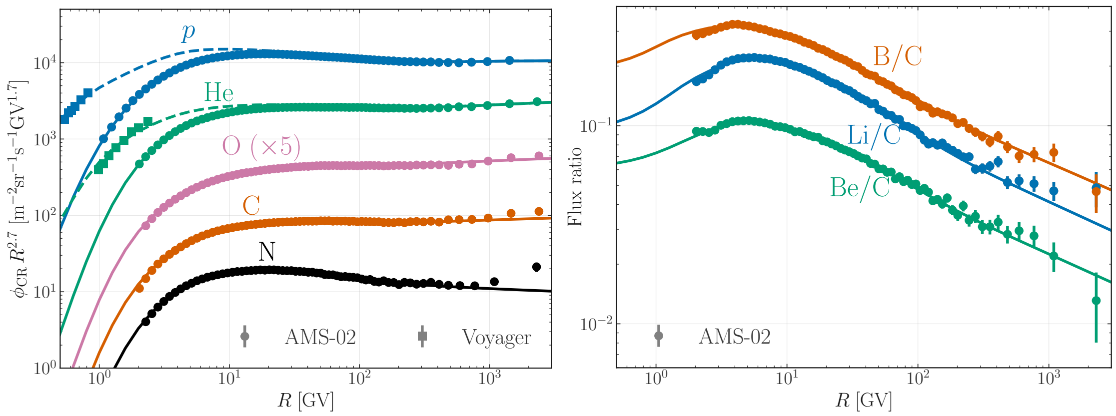

Figure 4: Left: Fluxes of p, He, O, C and N nuclei as predicted by the parameters fitted on the data by AMS-02 and Voyager (for p and He). Right: secondary-to-primary flux ration for B/C, Li/C and Be/C along with AMS-02 data.

models. We test different propagation scenarios, characterized by specific choices on the diffusion coefficient, the convective wind, and reacceleration amount.

The results on the e^+ flux show that for all the propagation models selected by nuclei CR data, the e^+ flux never exceeds AMS-02 data. The excess of the data with respect to secondary e^+ production is significant from energies greater than few GeV. The e^+ flux at Earth depends in a significant amount on the size L of the diffusive halo. Models with $L \gtrsim 2$ kpc can only explain the few AMS-02 data for positron energy $E < 1$ GeV. We also assess the uncertainties on the e^+ flux due by propagation modeling and by production cross sections. The former are limited to 2-5%, at fixed L and depending on E, and are driven by the precision of AMS-02 nuclei data. A variation of L from 8 to 2 (0.5) kpc implies a maximum rise of 50% (250%) in the propagated flux. Uncertainties in the flux due to cross sections amount to 5-7%, reflecting directly the results on the hadronic cross sections. This results reduces significantly this class of uncertainties with respect to the state of the art, and is a major finding of our work.

Contextually, we have computed the flux of secondary e^- at Earth, following the same strategy as for e^+. As for e^+, the e^- flux is determined with a high accuracy on the whole energy spectrum, thanks to the improvement in the determination of the hadronic cross sections, and the constraints on the propagation models. At $E < 1$ GeV, the e^- secondary fluxes is about 10% of AMS-02 data, while for energies above few GeV the gap is about two orders of magnitude. This commonly known result is now reached with an unprecedented precision well below 10% on the whole energy spectrum, depending on the extension of the diffusive halo.

Summarizing, our results can be considered new in a number of points: i) the uncertainties on the positron flux due inelastic hadronic cross sections have been firmly reduced to a few %, and shown to be almost independent of propagation parameters. This result builds on previous consolidated fits on a wealth of collider data; ii) the most updated theoretical propagation model has been fitted to a wide number of AMS data on CR primary and primary/secondary nuclei, and the free parameters have been newly derived with their uncertainty bands; iii) the propagation uncertainties on the positron flux have been firmly quantified. We have computed positron and electron fluxes at Earth within the selected propagation models, quantifying the uncertainties both at fixed L and varying L, in particular between 2 and 8 kpc. Smaller values of L are found disfavoured by our analysis of nuclei data; iv) we provide parallel new predictions for the propagated secondary electron flux.

The results presented in this paper clearly indicate that a further better determination of e^+ flux - not necessarily due to secondary origin - is only possible after a more precise determination of the size of the region in which CRs are confined. An improvement in this direction could come, *i.e.* from precise data of radioactive isotopes such as the ^{10}Be/^{9}Be ratio on a wide range of energies extending preferably above 20 GeV/n. CR positron measurements by the planned missions such as AMS-100 [19] and Aladino [20] would permit to explore the secondary positron emission up to ~ 5 TeV with percent statistical uncertainties. An increased statistics in the measurement of positrons in the multi-TeV range could also help to break the degeneracy between the model's propagation parameters.

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