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New determination of the production cross section for secondary positrons and electrons in the Galaxy

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Abstract

The cosmic-ray fluxes of electrons and positrons ($e^{\pm}$) are measured with high precision by the space-borne particle spectrometer AMS-02. To infer a precise interpretation of the production processes for $e^{\pm}$ in our Galaxy, it is necessary to have an accurate description of the secondary component, produced by the interaction of cosmic-ray proton and helium with the interstellar medium atoms. We determine new analytical functions of the Lorentz invariant cross section for the production of $e^{\pm}$ by fitting data from collider experiments. The total differential cross section $d\sigma/dT_{e^{\pm}}(p+p \to e^{\pm}+X)$ is predicted with an uncertainty of about 5-7% in the energies relevant for AMS-02 positron flux. For further information about this work refer to [1].

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1 Introduction

The text of this proceeding is reformulated from [1], to which we refer for further details, under the copyright licence number RNP/22/AUG/056699. During the last decades, the space-based experiments PAMELA, AMS-02, DAMPE and CALET have performed precise measurements of the cosmic-ray(CR) $e^{\pm}$ fluxes, that have inspired numerous analyses on the lepton production from astrophysical sources like pulsars [2] and supernova remnants. CR $e^{\pm}$ are first of all generated by secondary production, that is the production coming from the interaction of CRs with the interstellar medium (ISM). To infer precise conclusions on the possible contribution of primary sources, it is necessary an accurate description of the secondary flux. The dominant production of secondary leptons comes from the proton-proton ($p+p$) channel, that is CR protons interacting on ISM hydrogen atoms. Other relevant contributions are CR projectile or ISM target atoms given by helium. Channels including heavier CR species can contribute at the few percent level. There are two different strategies to describe the $e^{\pm}$ production cross sections that are present in the secondary source term. The first one is to find an analytic description of the double differential and Lorentz invariant cross section for the production of $\pi^{\pm}$, $K^{\pm}$ and other subdominant channels, trough a fit to cross section data. The other option is to use predictions from Monte Carlo event generators. As reported in Ref. [6], the adoption of different cross section models produces a variation in the normalization of the secondary $e^{\pm}$ flux up to a factor of 2. Thanks to the availability of new recent experimental datasets [7, 10, 11], a reevaluation of the $e^{\pm}$ production cross sections is mandatory.

2 From cross sections to the source term

The source term of the secondary $e^{\pm}$ is computed as the sum of all the combination between the primary CR fluxes species i (ϕ_i), the density components j of the ISM ($n_{\mathrm{ISM},j}$) and the energy-differential cross section ($d\sigma/dT_{e^{\pm}}$) for the reaction $i+j \to e^{\pm}+X$:

$$q(T_{e^{\pm}}) \quad = \quad \sum_{i,j} 4\pi\, n_{\mathrm{ISM},j} \int dT_i\, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{e^{\pm}}}(T_i, T_{e^{\pm}}), \tag{1}$$

where $T_{e^{\pm}}$ is the $e^{\pm}$ kinetic energy. Secondary $e^{\pm}$ are not produced directly in the $i+j$ collisions, but by the decay of intermediate mesons and hadrons. The $e^{\pm}$ production cross section is calculated from the $\pi^{\pm}$ production cross section combining the $d\sigma_{ij}/dT_{\pi^{\pm}}$ with the probability $P(T_{\pi^{\pm}}, T_{e^{\pm}})$ of decay of $\pi^{\pm}$ into a $e^{\pm}$. In the computation of P for the first time in literature we considered also the next-to-leading-order corrections of the muon decay. Experiments provide measurements of the fully differential production cross section usually described by $\sigma_{\mathrm{inv}}^{(ij)} = E_{\pi^{\pm}} d^3\sigma_{ij}/dp^3_{\pi^{\pm}}$. Here $E_{\pi^{\pm}}$ is the total $\pi^{\pm}$ energy and $p_{\pi^{\pm}}$ its momentum. $\sigma_{\mathrm{inv}}^{(ij)}$ depends on three kinematic variables, chosen to be the center of mass(CM) energy $\sqrt{s}$, the transverse momentum of the $\pi^{\pm}$ p_T and the quantity $x_R = E^{*}_{\pi^{\pm}}/E^{\max *}_{\pi^{\pm}}$, (asterisk denotes the CM reference frame). A similar approach is applied to the other channels. In this paper we will focus on e^{+}.

3 Positrons from $p+p \to \pi^{+}+X$ collisions

The measurement of π^{+} production in the interesting energy range for secondary e^{+} and with the largest coverage of the kinetic parameter space is provided by the NA49 experiment [7] at $\sqrt{s} = 17.3$ GeV. We decided to tune our modeling of the π^{+} invariant cross section on NA49. σ_{inv} is scaling invariant to good approximation, but two ingredients are violating this rough invariance: the rise of the inelastic cross section for $p+p$ collisions and the softening of the p_T shape at large CM energies. Our strategy is: in the first step, we fix the kinematic behaviour of the π^{+} cross section using only the NA49 data. Then we combine measurements of the multiplicity at different $\sqrt{s}$ down to 3 GeV [13, 14] and of the σ_{inv} by CMS [10] and ALICE [11] to calibrate our model over a huge range of energies. We developed a new parametrization of σ_{inv} that can fit a large number of datasets of the inclusive production of π^{+} in $p+p$ collisions, with $\sqrt{s}$ spanning from few GeV up to LHC energies. As reported in Ref. [7], the π^{+} are produced by a combination of prompt emission, coming from the hadronization chains, and the decay of hadronic resonances, so σ_{inv} is composed by two terms, called F_p and F_r, which should roughly describe the prompt and resonance components. The σ_{inv} is given by:

$$\sigma_{\mathrm{inv}} = \sigma_0(s)\, c_1 \Big[F_p(s, p_T, x_R) + F_r(p_T, x_R) \Big] A(s), \tag{2}$$

where $\sigma_0(s)$ is the total inelastic $p+p$ cross section. Finally, we include an additional scaling $A(s)$ with $\sqrt{s}$, which is required to obtain the correct π^+ multiplicity at different $\sqrt{s}$. We perform a χ^2-fit using MULTINEST [12], considering statistical and systematic uncertainties combined in quadrature. Finally, we obtain the uncertainties on our cross section, that result to be about 5% at the 1 σ level. Then we focus on the scaling of the cross section at different $\sqrt{s}$, with all the other parameters fixed to the values of the fit to the NA49 data. Overall, our model provides a good fit to all the datasets considered.

4 Contribution from other channels

About 10% of the e^+ produced in $p+p$ collisions come from the decays of charged kaons. We follow the two-step procedure previously explained for π^+, fixing first the x_R–p_T shape with NA49 data [15] and then modelling the $\sqrt{s}$ behavior with the multiplicity measurements from Antinucci, NA61/SHINE, ALICE and CMS. Our formula provides a very good description of the data.

K_S^0 decays into neutral or charged pions contributing to the $e^\pm$ cross sections. The NA61/SHINE experiment recently measured the production cross section of K_S^0 from $p+p$ collisions at $\sqrt{s} = 17.3$ GeV [16]. With a similar strategy as for π^+, at first we fix the p_T and x_F dependence of the cross section through a fit to the data of NA61/SHINE at $\sqrt{s} = 17.3$ GeV, while the $\sqrt{s}$ behaviour is obtained by a second fit to the multiplicities at different $\sqrt{s}$. For the K_L^0 meson, the lack of experimental data does not allow to determine an independent model of the production cross section. Employing the Pythia event generator [18] we find that the p_T and x_F behaviour for the production of e^+ is very similar for the K_L^0 and K_S^0 particles with a just difference in the normalization (K_L^0 produces about a factor of 1.16 more e^+ than K_S^0). We then assume that the contribution from K_L^0 is obtained from K_S^0 by rescaling with a factor 1.16.

The Λ hyperon contributes to the e^- through the decay of the π^-. However, the Λ production cross section helps to tune some of the other subdominant channels (S. C.) for e^+ production. The NA61/SHINE experiment recently measured the production cross section of Λ from $p+p$ collisions with at $\sqrt{s} = 17.3$ GeV [17]. With a similar strategy as for K_S^0, we fix the p_T and x_F dependence of the cross section through a fit to the data of NA61/SHINE at $\sqrt{s} = 17.3$ GeV, while the $\sqrt{s}$ behaviour is obtained by a second fit to the multiplicities at different $\sqrt{s}$.

Other channels contribute with a subdominant amount to the e^+ and e^- yield, for example the $\bar{\Lambda}$, the charged Σ and Ξ. No data are available at the energies of interest for the secondary $e^\pm$ and we decide thus to estimate the contribution of these particles assuming that their input to e^+ cross sections is equal to the Λ one to the e^- cross sections rescaled by a normalization calculated with the Pythia code. We proceed in this way because for Λ we have a parametrization for the invariant cross section and its mass is similar or equal to these particles, so we expect the dependence of the cross section on the kinematic parameters to be similar. In particular we calculate the multiplicities of these hyperons, n_i and the ratio n_i/n_Λ, both derived with Pythia. Then, we use the ratio n_i/n_Λ to add these S. C. to the total yield of $e^\pm$, rescaling the Λ cross sections into e^- and taking into account of the branching ratio B_r for the decay of the hyperons into $\pi^\pm$. In the end we also add the contribution from π^0 to the $e^\pm$ production multiplying the $\pi^\pm$ cross sections by a factor $(1 + n_{\pi^0} \cdot B_r^{\pi^0}/n_{\pi^\pm})$, where $B_r^{\pi^0} = 0.017$.

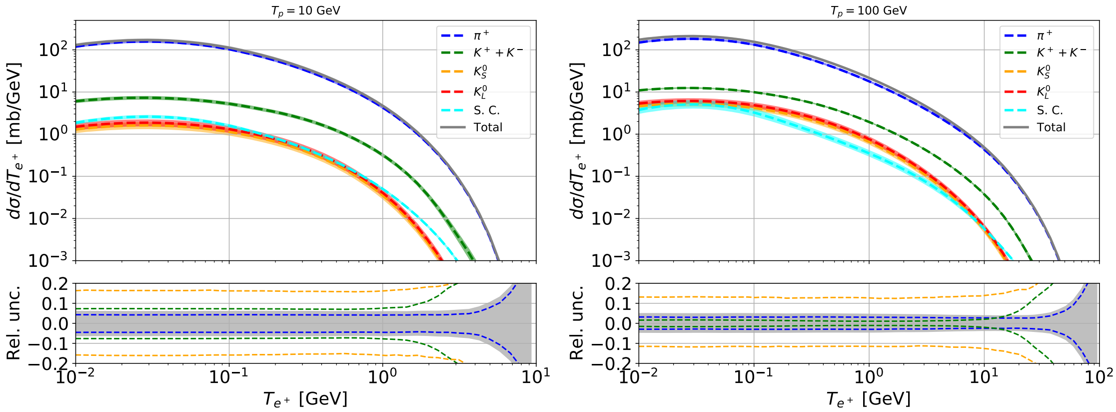

Figure 1: Differential cross section for the inclusive production of e^+ in $p + p$ collisions, derived from fits to the data as described in Sec. 3 and 4. We plot separate production channels and their sum. The curves are displayed with their 1σ error band. Figures taken from [1] under the copyright licence number RNP/22/AUG/056699.

5 Contribution from nuclei collisions

In the Galaxy, nuclei collisions ($p + A$, $A + p$, and $A + A$) give an important contribution to the production of secondary $e^{\pm}$. To compute the values of these cross sections we use the data of NA49 for the production of π^+ in p+C interactions at $p_p = 158$ GeV [19]. To perform the fit we assume that the $\sigma_{\rm inv}$ for a $p + A$ is equal to the one of $p + p$ interactions, multiplied by a rescaling factor connected to the mass number of the nuclei of the interaction and modified in the shape to take into account of possible asymmetries between forward and backward production.

6 Results on the e^+ production cross section and source spectrum

Now we can compute the total differential cross section $d\sigma/dT_{e^+}$ for the inclusive production of e^+ in $p + p$ collisions, summing all the contributions. In Fig. 1 we plot $d\sigma/dT_{e^+}$ for the different production channels and their sum, along with the relevant 1σ uncertainty band. The π^+ channel dominates the total cross section, being about 10 times higher than the K^+ and K^- channels. e^+ productions from K_0^S, K_0^L and S. C. contribute at a few % level. The main comment to these results is the smallness of the uncertainty at which $d\sigma/dT_{e^+}$i is determined, that at 1σ is 4% to 7% at all T_p energies. We conclude that the e^+ production cross section from $p+p$ collisions is obtained with very high precision. In Fig. 2, we report the computation of the source spectrum of e^+ in the Galaxy as a function of T_{e^+}, using Eq. (1). We fix $n_{\rm H} = 0.9\,{\rm cm}^{-3}$ and $n_{\rm He} = 0.1\,{\rm cm}^{-3}$. The CR fluxes ϕ_i for a nucleus i are taken from [20]. We plot separate results for the different type of interactions, with their uncertainties of the production cross sections computed in this paper. The $q(E)$ is predicted with a remarkably small uncertainty, spanning from 5% to 8% depending on the energy. We find similar results for the e^-.

7 Discussion and conclusions

In this paper, we determine the differential cross section $d\sigma/dT_{e^{\pm}}(p + p \to \pi^{\pm} + X)$ that enters in the computation of the $e^{\pm}$ source term, including all the production and decay channels,

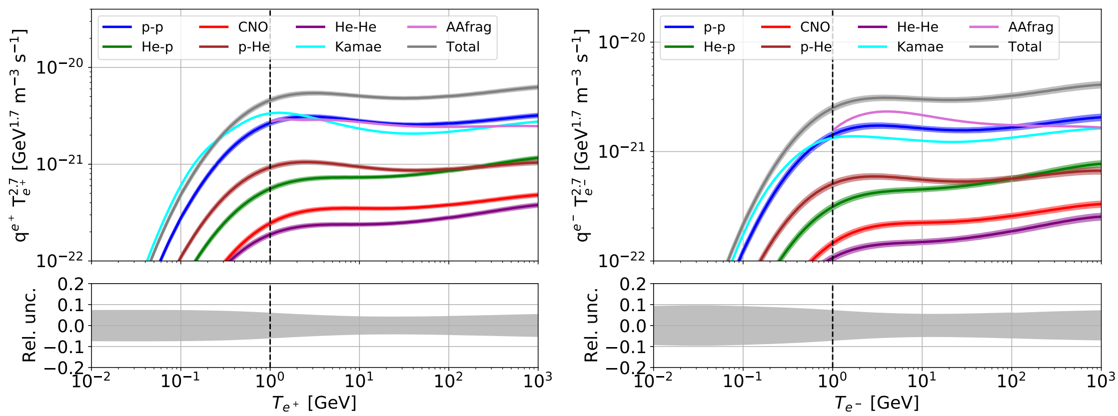

Figure 2: Source terms of CR e^+ (left panel) and e^- (right panel). Next to the total source term we show the separate CR-ISM contributions. In the bottom panels, we display the relative uncertainty of the total source term. Figures taken from [1] under the copyright licence number RNP/22/AUG/056699.

from 10 MeV up to tens of TeV of $e^{\pm}$ energy, obtaining an uncertainty of about 4-7%. We provide a prediction for the Galactic $e^{\pm}$ source spectrum that is obtained from a convolution of the differential production cross section with the incident CR flux and the ISM density. Our major result is the precision with which this source term is predicted, which ranges between 5% and 8% for e^+ and 7% and 10% for e^-, and so is heavily decreased with respect to the state of the art. We provide numerical tables for the energy-differential cross sections $d\sigma/dT_{e^{\pm}}$ as a function of the $e^{\pm}$ and nuclei energies and a script to read them. The material is available at https://github.com/lucaorusa/positron_electron_cross_section. For further information about this work refer to [1].

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