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New cross section determination for secondary cosmic ray electrons and positrons in the light of new data from collider experiments

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The cosmic-ray fluxes of electrons and positrons ($e^{\pm}$) are measured with high precision by the space-borne particle spectrometers AMS-02. To infer a precise interpretation of the dominant production process for $e^{\pm}$ in our Galaxy, it is necessary to have a correct description of the secondary component, produced by the interaction of cosmic-ray proton and helium with the interstellar medium. We update the parametrization of the $e^{\pm}$ cross sections in order to obtain a new estimate of the lepton secondary component flux of the cosmic radiation. In the light of new cross section measurements performed at collider experiments of p+p→ $\pi^{\pm}$+X, we update the parametrization of the cross sections for these processes and then compute the $e^{\pm}$ ones from $\pi^{\pm}$ decay. We use for the first time in this field the $e^{\pm}$ spectrum obtained from the muon decay computed till the next to leading order. The peculiarity of this work is the experiment based approach, that we adopt in order to obtain a better shape determination and a significant reduction of uncertainty of the current secondary cosmic ray $e^{\pm}$ flux predictions.

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1. Introduction

During the last decades, the space-based spectrometers PAMELA, AMS-02, DAMPE and CALET have performed unprecedented precise measurements of the cosmic ray (CR) fluxes with uncertainties at the percent level in an energy range from 1 GeV to a few TeV, making the physics of charged CRs a precision discipline. They have measured the CR nuclear [1–7] and leptonic (positron and electron, $e^{\pm}$) [8–12] components, as well as CR antiprotons [13, 14]. The most recent positron flux measurement by AMS-02 extends from 1 to 1000 GeV with an uncertainty $< 5\%$ for almost the whole energy range. The new precise flux data have stimulated numerous analyses on Galactic CR propagation, lepton production in astrophysical environments like pulsars and supernova remnants and particle dark matter annihilation into antimatter (see, e.g., [15–17]). It is generally established that a large part of $e^{\pm}$ in our Galaxy is produced by the interaction of CRs with the interstellar medium (ISM) [18], conventionally called secondary production. Therefore, to infer correct conclusions on any modeling and interpretation of other possible primary sources, an accurate description of this contribution is necessary. The dominant production of secondary flux comes from the proton-proton (pp) channel, namely CR proton on ISM hydrogen, and from the cases with the CR projectile or the ISM target replaced by helium (Hep, pHe, and HeHe). Heavier channels can contribute at the few percent level. The energy-differential cross sections of $e^{\pm}$, that are mainly generated from the decay of pions ($\pi^{\pm}$) and kaons($K^{\pm}$) produced in these collisions, enter in the secondary source term calculation.

There are two different strategies to parametrize these cross sections. The first possibility is to find an analytic description of the fully-differential and Lorentz invariant cross section of production of $\pi^{\pm}$ and $K^{\pm}$, performing a fit to cross section data. Then, a Lorentz transformation, an angular integration and the convolution with the $e^{\pm}$ spectrum from $\pi^{\pm}$ and $K^{\pm}$ decays are applied to find the $e^{\pm}$ energy-differential cross section. This strategy was first pursued by [19]. The other option is to use Monte Carlo predictions to extract the required cross section as in [20], strategy that may be easily affected by uncertainties. As outlined in [18], the adoption of the predictions from different models produces a variation in the normalization of the secondary $e^{\pm}$ flux up to a factor of 2.

Concerning the first approach, the Tan and Ng parameterizations [19] of the production cross-section of $\pi^{\pm}$ and $K^{\pm}$ are still largely used, despite being mostly 40 years old. The reason is that, until recently, the available dataset was limited to data only collected in the sixties and seventies. In the last decades, however, new experimental datasets have become available, for example the NA61/SHINE Collaboration results collected at the CERN Super Proton Synchrotron (SPS) [21], which provided important information for the energies of interest for AMS-02. Given the importance of these nuclear data for new measurements in astroparticle physics, it is necessary a re-evaluation of the leptonic production cross sections in pp, Hep, pHe, and HeHe collisions in light of this new available information. In this paper we engage ourselves in this task, in order to provide the community with an updated parametrization for the inclusive $e^{\pm}$ production cross section.

1.1 Spallation cross-section for p + p → $e^{\pm}$

We first shortly review the basic equations and procedure to calculate the cosmic secondary $e^{\pm}$ source term. The source term $q_{ij}(E_{e^{\pm}})$ originating from the interaction of the CR component i on the ISM component j is given by a convolution integral of the energy-differential $e^{\pm}$ production cross section $d\sigma_{ij}/dE_{e^\pm}$ with the incoming CR flux ϕ_i and the ISM target density $n_{ISM,j}$ over the CR energy per nucleon E_i:

$$q_{ij}(E_{e^\pm}, \vec{x}) = 4\pi n_{ISM,j}(\vec{x}) \int \phi_i(E_i) \frac{d\sigma_{ij}}{E_{e^\pm}}(E_i, E_{e^\pm}) dE_i \tag{1}$$

Here the factor 4π corresponds to the angular integration of an isotropic CR flux. In order to compute the expected flux of secondary $e^\pm$, the energetic of the projectiles, the composition of the targets and their spatial properties are needed. The interstellar medium gas density of a species j is in general a function of the position in the Galaxy $n_{ISM,j}(\vec{x})$. However, an average local value of $n_{ISM,j}$ is used when dealing with $e^\pm$, since the radiative losses limit their propagation scale to few kpc. As for the projectiles, the primary flux of cosmic p (and He) are typically considered in terms of parametrizations or fits to observed fluxes at the Earth [22]. We now focus on the differential cross–section for the production of $e^\pm$, which occurs through a nuclear reaction between two colliding nuclei, generating mainly charged pions and other mesons. $e^\pm$ are one of the final products of the decay chain. For the sake of clarity, we present only the formulae for the proton-proton collisions. $e^\pm$ are mainly produced as the final output of the decay of charged pions and subsequent muons coming from the excitation of a Δ resonance:

$$\mathrm{p} + \mathrm{H} \rightarrow X + \Delta \tag{2}$$

that can decay into different combinations of pions, proton and neutron. Instead, at higher energies the direct production of charged pions and kaons dominates, following the reaction:

$$\mathrm{p} + \mathrm{H} \rightarrow X + \pi^\pm \qquad \mathrm{p} + \mathrm{H} \rightarrow X + K^\pm \tag{3}$$

and kaons decay into muons (63.56%), pions (28.01%) and pions and leptons(8.42%) together, which then decay into $e^\pm$ as final products of their decay chain. The production processes of e^+ and e^- are very similar, thought different inclusive cross sections have to be considered. In fact, since both the target and the projectiles involved in the production process are positively charged particles, charge conservation implies that more positrons with respect to electrons are produced in the final states (see [20]). To compute the differential cross section for the $e^\pm$ production processes from pions for example, we need the probability of spallation of a proton of kinetic energy E_p to produce a pion with energy $E_{\pi^\pm}$ and the probability $P(E_{\pi^\pm} \rightarrow E_{e^\pm})$ of such a pion to eventually decay into a $e^\pm$ of energy $E_{e^\pm}$. This second quantity can be computed thanks to quantum electrodynamics.

$$\frac{d\sigma}{dE_{e^\pm}}(E_p \rightarrow E_{e^\pm}) = \int \frac{d\sigma}{dE_{\pi^\pm}}(E_p \rightarrow E_{\pi^\pm}) \times P(E_{\pi^\pm} \rightarrow E_{e^\pm}) \times dE_{\pi^\pm} \tag{4}$$

The cross section for the process involving kaons can be computed in a similar way to the calculation of pion production. However, experiments do not directly measure the energy-differential cross section but the fully-differential cross section, usually expressed in a Lorentz invariant form.

$$\sigma_{\mathrm{inv}} = E_{\pi^\pm} \frac{d^3\sigma}{dp^3}(\sqrt{s}, x_R, p_T) \tag{5}$$

where $E_{\pi^\pm}$ is the total $\pi^\pm$ energy and p its momentum. It is typically a function of the kinematic variables $\sqrt{s}$, $x_R = E^*_{\pi^\pm}/E^{max*}_{\pi^\pm}$, p_T , which are the center of mass (CM) energy, the $\pi^\pm$ energy divided by the maximal $\pi^{\pm}$ energy in the CM frame, and the transverse $\pi^{\pm}$ momentum, respectively. To obtain the energy-differential cross section in Eq. 4, the variables are transferred into the LAB frame, the frame where the target particle is at rest, using a Lorentz transformation. Convenient variables in the LAB frame are the energies of the CR E_i and of the pion $E_{\pi^{\pm}}$ and the angle θ of the produced pion with respect to the incident CR. Finally, the integral over the solid angle Ω lead to the energy-differential cross sections:

$$\frac{d\sigma_{ij}}{dE_{\pi^{\pm}}}(E_i, E_{\pi^{\pm}}) = p_{\pi^{\pm}} \int d\Omega\, \sigma_{\text{inv}}^{(ij)}(E_i, E_{\pi^{\pm}}, \theta) \tag{6}$$

2. $e^{\pm}$ spectrum from pion decay

In this Section we review the principal steps in the computing of the $e^{\pm}$ spectrum from pion decay. For the first time in this field we consider the polarized muon decay in the muon rest frame, computed till the next to leading order term(NLO) in [23], adopting the Fermi theory. Cosmic ray muons origin from pion decay and are then polarized. The $e^{\pm}$ spectrum in the muon rest frame is described by:

$$F(\epsilon'_{e^{\pm}}, \cos\theta') = C[f(\epsilon'_{e^{\pm}}) \pm g(\epsilon'_{e^{\pm}})\cos\theta'] \tag{7}$$

where $g(\epsilon'_{e^{\pm}})$ is the term generated by the muon polarization, $\epsilon'_{e^{\pm}}$ is the energy of the $e^{\pm}$ and θ' is the angle between the direction of polarization of the muon and the direction of motion of the $e^{\pm}$. For the unpolarized muon decay, only $f(\epsilon'_{e^{\pm}})$ enters in Eq. 7. As in [24], we perform two Lorentz transformations from the muon rest frame to the pion rest frame and from the pion rest frame to the LAB/Galaxy frame (we indicate the $e^{\pm}$ energy in the LAB frame as $\epsilon_{e^{\pm}}$). In the numerical code GALPROP [25] the $e^{\pm}$ spectrum from pion decay is currently implemented using the Eqs. 36,37,38,39 reported in [26]. In this work we upgrade their results thanks to the NLO term of the muon decay and without adopting the approximation of $m_e = 0$. In Fig. 1 we report $\epsilon_{\pi} F(\epsilon_{e^{\pm}}, \epsilon_{\pi})$ obtained for different pion energies in the LAB frame.

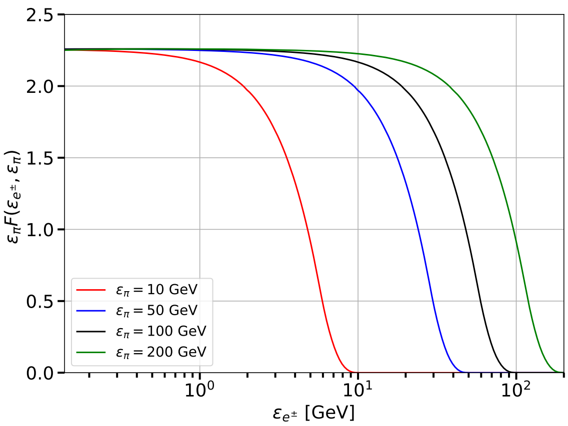

Figure 1: $\epsilon_{\pi} F(\epsilon_{e^{\pm}}, \epsilon_{\pi})$ obtained from the pion and subsequent muon decays for 4 pion different energies.

2.1 Fit to the NA61 data

In this section we report some preliminary results concerning the fit to cross section data. We start our analysis from the measures provided by NA61/SHINE Collaboration [21] and collected at the CERN Super Proton Synchrotron (SPS), that performed recently precise measurements of $\pi^{\pm}$ and $K^{\pm}$ inclusive cross sections from p + p interaction, for different $\sqrt{s}$ values. The experiment kinematic setup is based on the collision between an incident beam and a fixed target, which is exactly the scenario that takes place in the Galaxy. We begin the analysis from the $\pi^{\pm}$ data, testing different possible parametrizations. In [27] a similar procedure, without performing a fit, was realized using the NA49 measurements [28], outlining how the currently available parametrizations for the inclusive pion cross-section do not provide an adequate description of the data. At the moment we are searching for a new satisfying model able to take into account of the Δ resonance and of the direct production of $\pi^{\pm}$. In Fig. 2 we report some preliminary results, obtained from the fit to the NA61/SHINE π^{+} data [21] at $\sqrt{s}$ = 17.3, grouped in different p_T values, using a tester parametrization. For clarity, the data and the theoretical curves at each p_T have been multiplied by a factor of $0.6^{n_{p_T}}$, where n_{p_T} is the integer(starting from 0) counting the p_T, from lower to higher (i.e. for p_T = 0.25 GeV/c^2 the rescaling is 0.6^2).

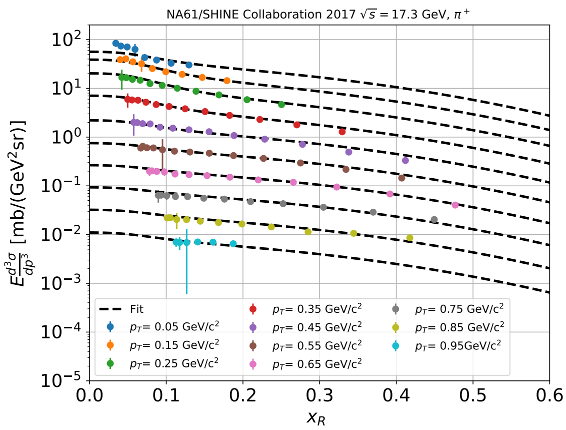

Figure 2: Comparison between NA61 π^{+} data, grouped in different p_T values, with a tester fitting function. For clarity, the data and the theoretical curves at each p_T have been multiplied by a factor of $0.6^{n_{p_T}}$, where n_{p_T} is the integer counting the p_T, from lower to higher (i.e. for p_T = 0.25 GeV/c^2 the rescaling is 0.6^2).

3. Conclusions

We discussed a novel approach in the determination of the $e^{\pm}$ cross section from pp collisions. Our preliminary results show that the method can provide useful information in the computing of the secondary positron production. The next step of our analysis will be the combination between different datasets, considering also measurements from NA49 [28], ALICE [29] and CMS [30]. The procedure will be repeated also for $K^{\pm}$ and for the other possible reactions (pHe, Hep, HeHe). Once obtained the parametrizations, we will perform the convolution with the decay spectrum of $e^{\pm}$ from pions and kaons in order to obtain the inclusive $e^{\pm}$ cross section in nuclear reactions that enters in the source term of the secondary flux.

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