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

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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 $d\sigma/dT_{e^{\pm}}(p+p \rightarrow e^{\pm}+X)$ 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].

**** 27th European Cosmic Ray Symposium - ECRS ****
**** 25-29 July 2022 ****
**** Nijmegen, the Netherlands ****

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PoS(ECRS)125

1. Introduction

The text of this proceeding is reformulated from [1], to which I refer for further details, under the copyright licence number RNP/22/NOV/060230. 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. [3], 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 [4–6], 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 $i + j \to e^{\pm} + X$:

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

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 I 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 [4] at

$\sqrt{s}$ = 17.3 GeV. We decided to tune our modeling of the π^+ invariant cross section on NA49. $\sigma_{\rm inv}$ 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 [7, 8] and of the $\sigma_{\rm inv}$ by CMS [6] and ALICE [5] to calibrate our model over a huge range of energies. We developed a new parametrization of $\sigma_{\rm inv}$ 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. [4], the π^+ are produced by a combination of prompt emission, coming from the hadronization chains, and the decay of hadronic resonances, so $\sigma_{\rm inv}$ is composed by two terms, called F_p and F_r, which should roughly describe the prompt and resonance components. The $\sigma_{\rm inv}$ is given by:

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

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 sS. We perform a χ^2-fit using Multinest [9], considering statistical and systematic uncertainties combined in quadrature. Our results are summarized in Fig. 1, where we plot the invariant cross section for the inclusive π^+ production in $p+p$ collisions as a function of x_R (left) and p_T (right). The data are displayed along with our best fit results and the 1σ uncertainty for a few representative values at fixed p_T and x_F, respectively. The residuals of the data and the width of the theoretical uncertainty band are displayed in the bottom panels. The data are well described at all p_T and x_F values. The structures in the low p_T data are very well followed by our parametric formulae. 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 [10] 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^0_S 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^0_S from $p+p$ collisions at $\sqrt{s}$ = 17.3 GeV [11]. 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^0_L meson, the lack of experimental data does not allow to determine an independent model of the production cross section. Employing the Pythia event generator [12] we find that the p_T and x_F behaviour for the production of e^+ is very similar for the K^0_L and K^0_S particles with a just difference in the normalization (K^0_L produces about a factor of 1.16 more e^+ than K^0_S). We then assume that the contribution from K^0_L is obtained from K^0_S by rescaling with a factor 1.16.

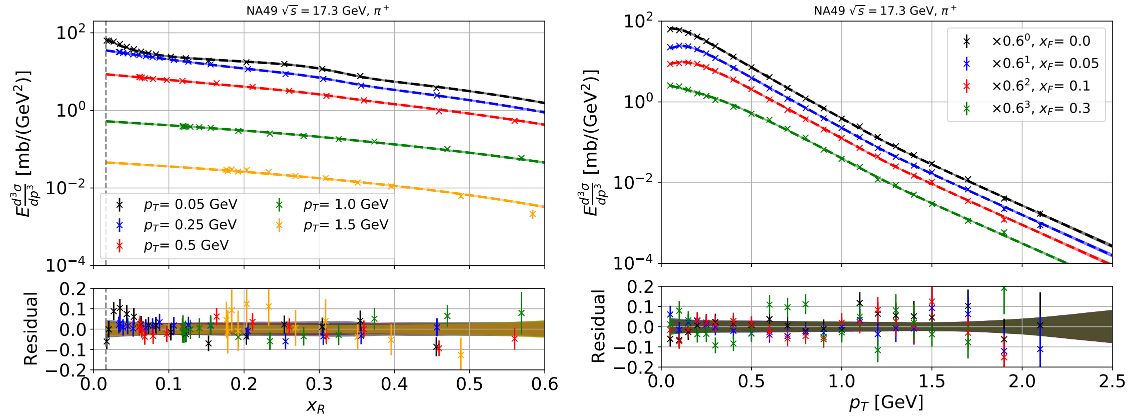

Figure 1: Results of the fit on the NA49 data [4] invariant cross section for the inclusive π^+ production in $p + p$ collisions. The left (right) panel shows the NA49 data along with our fit results for representative p_T (x_F) values, as a function of x_R (p_T). Each curve is plotted along with its 1σ uncertainty band. In the bottom part of each panel we plot the residuals, which are defined as (data-model)/model, and the width of the 1σ uncertainty band on the model.

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 [13]. With a similar strategy as for K^0_S, 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 comparable. 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 π^{pm}. In the end neutral pions are expected to be produced in $p + p$ collisions with a similar rate as charged pions. However, π^0s decay with a branching ratio of 98.82% into two photons and only with 1.17% into $e^+e^-\gamma$. Therefore, the contribution of the π^0 to the $e^\pm$ production is expected to be at the 1% level. We also add the contribution from π^0 to the $e^\pm$ production multiplying the π^{pm} cross sections by a factor $(1 + n_{\pi^0} \cdot B_r^{\pi^0}/n_{\pi^\pm})$, where $B_r^{\pi^0} = 0.017$.

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

PoS(ECRS)125

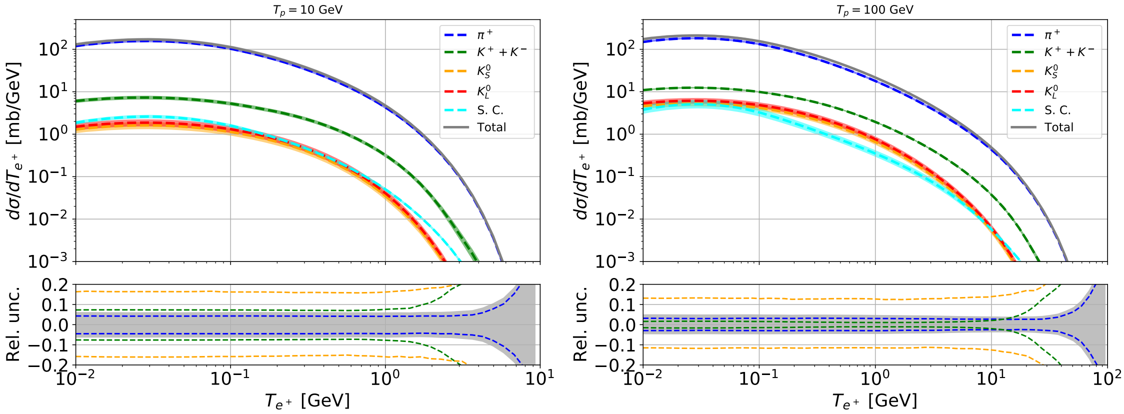

Figure 2: Differential cross section for the inclusive production of e^+ in $p + p$ collisions, derived from fits to the data as described in Sec. 3 and 4. We plot separate production channels and their sum. The curves are displayed with their 1σ error band. Figures taken from [1] under the copyright licence number RNP/22/NOV/060230.

for the production of π^+ in p+C interactions at $p_p = 158$ GeV [14]. While pion production in $p + p$ collisions is by definition symmetric under a reflection along the beam axis in the CM frame, this is not necessarily the case in $p + A$ collisions (in the nucleon-nucleon CM frame). Actually, the NA49 p+C data reveals an asymmetry in the cross section between forward and backward production [15], which is plausible, because the carbon target contains not only protons but also neutrons and the binding of the nucleons could play a role. 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. 2 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. 3, 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 [16]. We plot separate results for the collision of $p + p$, p+He, He+p, He-He and C, N and O CR scattering off H, with their uncertainty due 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^-.

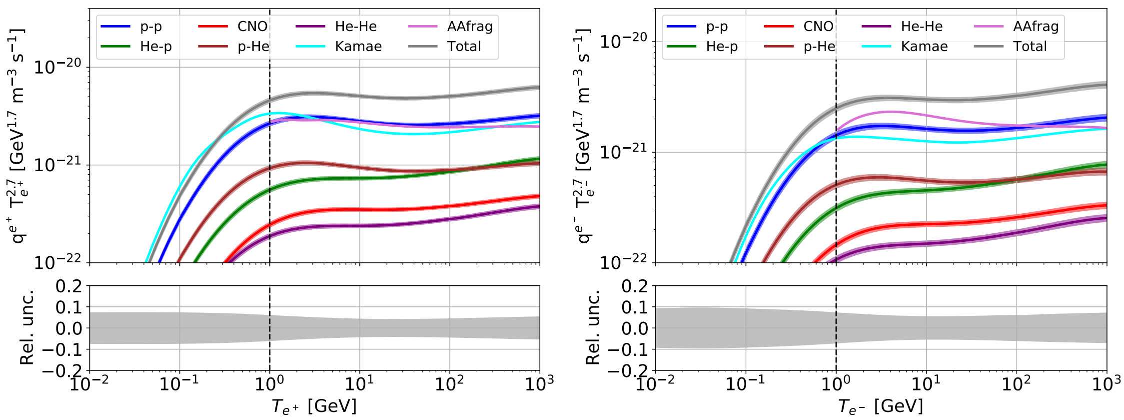

Figure 3: Source terms of CR e^+ (left panel) and e^- (right panel). Next to the total source term we show the separate CR-ISM contributions. In the bottom panels, we display the relative uncertainty of the total source term. Figures taken from [1] under the copyright licence number RNP/22/NOV/060230.

7. Discussion and conclusions

The secondary production of $e^\pm$ in our Galaxy presents a significant contribution to the $e^\pm$ fluxes measured at Earth. In particular, the e^+ flux is dominated by secondaries below 10 GeV. At higher energies, several primary contributions are discussed in the literature, the most popular being pulsars and dark matter annihilation or decay. The correct interpretation of those primary contributions depends on the accurate description of the secondary production.

Most of the secondary $e^\pm$ are produced in $p + p$ collisions, nonetheless, the contributions from collisions involving helium, both as a target and as a projectile, are relevant. The main production channels of the secondary $e^\pm$ involve the intermediate production and decay of $\pi^\pm$ and $K^\pm$, while some additional channels can contribute to the source term at the percent level each.

In the last years, new experimental data have become available covering large portions of the kinematic phase space. In this paper, we determine an analytical description of the Lorentz invariant cross section for the production of $\pi^\pm$ and $K^\pm$, especially focusing on $p+p$ collisions. Then, we also evaluate, either by exploiting further data or by referring to Monte Carlo generators, the inclusive cross section into K_0^S, K_0^L, Λ, $\bar{\Lambda}$, π^0, Σ and Ξ. For all these particles, we implement the relevant 2 and 3 body decay channels, which finally contribute to $e^\pm$. The most important decay of polarized $\mu^\pm$ is computed including NLO corrections.

The most relevant data are provided by the NA49 experiment which measured $\pi^\pm$ and $K^\pm$ production in $p+p$ fixed-target collisions at proton momenta of 158 GeV. These data are intrinsically precise at a level of a few percent (maximum 10%). Our analytical expressions for the invariant cross section fit this data very well. For the important $\pi^\pm$ channels the invariant cross section is determined with an uncertainty of about 5% in the relevant kinematic parameter space. Further data at lower and higher $\sqrt{s}$ are also described well by our parametrizations. The differential cross section $d\sigma/dT_{e^\pm}(p + p \rightarrow \pi^\pm + X)$, which enters in the computation of the $e^\pm$ source term, is determined with about 5% precision. Including all the production and decay channels, the total $d\sigma/dT_{e^\pm}(p + p \rightarrow e^\pm + X)$ is predicted from 10 MeV up to tens of TeV of $e^\pm$ energy, with an uncertainty of about 5-7%.

The cross section for scattering of nuclei heavier than protons is obtained by fitting the NA49 data for the production of $\pi^\pm$ on p+C collisions. The statistical uncertainties are very small, however, we cannot exclude systematic effects, for example, due to the rescaling from the p+C. Future measurements of pion production in the p+He could help to remove this ambiguity.

Finally, we provide a prediction for the Galactic $e^\pm$ source spectrum, which is obtained from a convolution of the differential production cross section with the incident CR flux and the ISM density. We include CR nuclei up to O and p and He ISM targets. Our major result resides in the precision with which this source term is predicted, which ranges between 5% and 8% for e^+ and 7% and 10% for e^-. The uncertainty in the secondary e^+ and e^- production is therefore dramatically decreased with respect to the state of the art, where different descriptions of the cross section vary by a factor of about two, posing a large systematic uncertainty due to spallation reactions. We note, however, that for $T_{e^+} \lesssim 1$ GeV the source term is not constrained by cross section data but rather an extrapolation of our parametrization which could possibly be affected by systematics. Our results, especially in the e^+ sector, finally open the door to interpretations of CR data, especially from the AMS-02 experiment, in which the second component is no longer a limiting factor in pinpointing primary components.

We provide numerical tables for the energy-differential cross sections $d\sigma/dT_{e^\pm}$ as a function of the $e^\pm$ and proton 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].

References

[1] L. Orusa, M. D. Mauro, F. Donato, and M. Korsmeier, *New determination of the production cross section for secondary positrons and electrons in the galaxy*, *Physical Review D* **105** (jun, 2022).

[2] L. Orusa, S. Manconi, F. Donato, and M. Di Mauro, *Constraining positron emission from pulsar populations with ams-02 data*, *Journal of Cosmology and Astroparticle Physics* **2021** (Dec, 2021) 014.

[3] T. Delahaye, R. Lineros, F. Donato, N. Fornengo, J. Lavalle, P. Salati, and R. Taillet, *Galactic secondary positron flux at the earth*, *Astronomy & Astrophysics* **501** (May, 2009) 821–833.

[4] **NA49** Collaboration, C. Alt et al., *Inclusive production of charged pions in p+p collisions at 158 gev/c beam momentum*, *Eur. Phys. J. C* **45** (Dec, 2005) 343–381.

[5] K. e. a. Aamodt, *Production of pions, kaons and protons in pp collisions at $\sqrt{s} = 900$ GeV with alice at the lhc*, *The European Physical Journal C* **71** (Jun, 2011).

[6] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, and et al., *Study of the inclusive production of charged pions, kaons, and protons in pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV*, *The European Physical Journal C* **72** (Oct, 2012).

PoS(ECRS)125

[7] **NA61/SHINE** Collaboration, A. Aduszkiewicz et al., *Measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS*, *Eur. Phys. J. C* **77** (2017), no. 10 671, [arXiv:1705.0246].

[8] M. Antinucci, A. Bertin, and P. Capiluppi, *Multiplicities of charged particles up to isr energies.*, *Lett. Nuovo Cim. 6: No. 4, 121-128(27 Jan 1973).* (1, 1973).

[9] F. Feroz, M. P. Hobson, and M. Bridges, *Multinest: an efficient and robust bayesian inference tool for cosmology and particle physics*, *Monthly Notices of the Royal Astronomical Society* **398** (Oct, 2009) 1601–1614.

[10] T. Anticic, B. Baatar, J. Bartke, et al., *Inclusive production of charged kaons in p+p collisions at 158 gev/c beam momentum and a new evaluation of the energy dependence of kaon production up to collider energies*, *The European Physical Journal C* **68** (Jun, 2010) 1–73.

[11] **NA61/SHINE** Collaboration, A. Acharya et al., *K^0_S meson production in inelastic p+p interactions at 158 GeV /c beam momentum measured by NA61/SHINE at the CERN SPS*, *Eur. Phys. J. C* **82** (2022), no. 1 96, [arXiv:2106.0753].

[12] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159–177, [arXiv:1410.3012].

[13] **NA61/SHINE** Collaboration, A. Aduszkiewicz et al., *Production of Λ -hyperons in inelastic p+p interactions at 158* GeV/*c*, *Eur. Phys. J. C* **76** (2016), no. 4 198, [arXiv:1510.0372].

[14] C. Alt and et al., *Inclusive production of charged pions in p + c collisions at 158 gev/c beam momentum*, *The European Physical Journal C* **49** (Feb, 2007) 897–917.

[15] G. Barr, O. Chvala, H. Fischer, M. Kreps, M. Makariev, C. Pattison, A. Rybicki, D. Varga, and S. Wenig, *Charged pion production in p+c collisions at 158gev/c beam momentum: Discussion*, *The European Physical Journal C* **49** (Jan, 2007) 919–945.

[16] M. Korsmeier and A. Cuoco, *Testing the universality of cosmic-ray nuclei from protons to oxygen with AMS-02*, arXiv:2112.0838.