“Discrepant hardenings” in cosmic ray spectra: a first estimate of the effects on secondary antiproton and diffuse gamma-ray yields.

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Recent data from CREAM seem to confirm early suggestions that primary cosmic ray spectra at few TeV/nucleon are harder than in the 10-100 GeV range. Also, helium and heavier nuclei spectra appear systematically harder than the proton fluxes at corresponding energies. We note here that if the measurements reflect intrinsic features in the interstellar fluxes, appreciable modifications are expected in the sub-TeV range for the secondary yields, such as antiprotons and diffuse gamma-rays. Presently, this effect represents a systematic error in the extraction of astrophysical parameters as well as for background estimates for indirect dark matter searches. We find that the spectral modifications are appreciable above 100 GeV, and can be responsible for ∼30% effects for antiprotons at energies close to 1 TeV or for gamma's at energies close to 300 GeV, compared to currently considered predictions based on simple extrapolation of input fluxes from low energy data.

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I. INTRODUCTION

A more accurate determination of primary cosmic ray spectra at the top of the atmosphere has obvious implications for the understanding of the acceleration and propagation of Galactic cosmic rays. It is also crucial for other fields of investigations in astroparticle physics, two notable examples being atmospheric neutrino studies and indirect dark matter searches. Especially at energy $T \gg 1\,\text{TeV/nucleon}$, the scarce statistics and experimental difficulties make challenging to infer accurate spectra. Even when the issue of uncertainties in secondary yields is of concern, the usual practice is to fit primary data to some parameterization and extrapolate to high energies (see e.g. [1, 2] for the case of atmospheric neutrino and Galactic antiprotons, respectively). While this is a reasonable prescription for most applications given the present level of understanding, here we note that this approach might hide a systematic error when searching for signatures showing peculiar energy features. For example, for antiprotons this is the case involving dark matter annihilation signals [3] or production at the sources [4].

The reason is that the standard prescriptions do not usually account for the possibility that a *systematic* departure (rather than statistical scattering) is present in the *spectral shape* of the fitting formula, which is mostly “calibrated” thanks to low energy data. Recent data from the CREAM balloon-borne experiment [5] seem to confirm earlier suggestions (see e.g. [6]) that cosmic ray spectra at few TeV/nucleon are harder than in the 10-100 GeV range, and that helium (He) and heavier nuclei fluxes are harder than the proton (p) flux at corresponding energies. Preliminary data from PAMELA also suggest a hardening in p and He spectra at a rigidity of about 250 GV, with a He spectrum having an index ~ 0.1 lower than the proton one over all energies above a few GeV [7].

We refrain from discussing the robustness of the present determination of this effect, nor we discuss possible astrophysical interpretations, see for example [8]. In this article, instead, we limit ourselves to note that if the measurements reflect intrinsic features in the interstellar spectra, appreciable modifications (i.e. above $\sim 10\%$) are expected for the secondary yields in the 0.1 to 1 TeV range, which is directly accessible (with growing precision) to present and forthcoming experiments like PAMELA, FERMI, and AMS-02.

The structure of this article is the following: in Sec. II we discuss the input fluxes and parameterization used to provide a first estimate of the effect. In Sec. III we present the results for antiprotons and gamma-rays, finally in Sec. IV we discuss some implications of our findings, and conclude.

II. INPUT FLUXES

In the present exploratory study, we refrain from the ambitious goal of analyzing the whole body of cosmic ray flux data in the $10 - 10^4\,\text{GeV/n}$ range. Rather we limit ourselves to provide a first assessment of the systematic effect potentially introduced by deviations from the power law behaviour at high energy, in general with different spectral indexes for different species. To this purpose, we explore the effects of combining the fits of “low-energy” (namely in the range about 10-100 GeV/n) proton ($i = 1$) and helium ($i = 2$) flux data, ϕ_i^L, taken from AMS-01 [9] (in turn, to large extent consistent with what reported by other experiments), with the “high-energy” (above about 1 TeV/n) fluxes ϕ_i^H inferred by

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CREAM [5]. We adopt broken power-laws to connect the two sets, using the following flux parameterizations (differential fluxes with respect to kinetic energy per nucleon T):

$$\phi_1(T) = \phi_1^L(T)\Theta(B_1 - T) + \phi_1^H(T)\Theta(T - B_1)\,, \quad (1)$$
$$\phi_2(T) = \phi_2^L(T)\Theta(B_2 - T) + \phi_2^H(T)\Theta(T - B_2)\,. \quad (2)$$

The fluxes "L" are the best fit values taken from AMS-01 [9], rewritten in terms of kinetic energy T per nucleon (in GeV/n) instead of rigidity and asymptotically decreasing as $\sim T^{-2.78}$ for p and $T^{-2.74}$ for He. The high energy fluxes "H" are taken from CREAM with the following criteria: i) power-laws in T are assumed, with the spectral indexes fixed to the best-fit values reported in [5], i.e. 2.66 for p and 2.58 for He; ii) the proton spectrum normalization is taken from the first CREAM point in Fig. 3 of [5]; iii) the Helium spectrum normalization follows from imposing that at $T = 9$ TeV/nucleon the proton to helium flux ratio is equal to 8.9 [5]. The crossover energies B_1, B_2 for the broken power-laws are simply obtained by continuity, and are approximately $B_p = 1000\,\text{GeV}$, $B_{\text{He}} = 30\,\text{GeV/n}$ for the parameters above[1]. A comparison with the predictions following from the extrapolation of the AMS-01 fits (i.e. the ϕ_i^L) to arbitrarily high energy will be presented to provide an estimate of the impact of high-energy spectral uncertainty on the secondary yield flux.

III. RESULTS

Discrepant hardenings of primary cosmic ray fluxes would affect in principle all secondary fluxes: from μ's and ν's induced in the Earth atmosphere to the yields of e^+, $\bar{p}$ and γ secondaries produced by collisions in the interstellar medium (ISM). Concerning the latter process, here we do not discuss charged leptons simply because the primary flux effects do not provide the major uncertainty in the flux shape (even fixing the average propagation parameters): very likely recent data [10–12] indicate that additional sources of "primary" positrons exist for which the above mentioned effects are expected to be subleading (see e.g. [13]). Additionally, energy losses make the range shorter and the computation of the actual flux at the Earth non-trivial, so it would be more difficult to disentangle the effects due to the break in primary spectra from a complicated interplay of effects involving the discreteness of local sources, inhomogeneities in the radiation field, etc. as illustrated for instance in [14]. The effect of the primary CR hardening should be appreciable in the predicted shape of the antiproton or diffuse gamma-ray signal. Here we report a careful computation of the effect on the antiproton spectrum, where the impact is expected to be the largest in view of future high-statistics results from AMS-02, and an estimate of the effect on the hadronic gamma-ray diffuse background, of some interest for the interpretation of FERMI data.

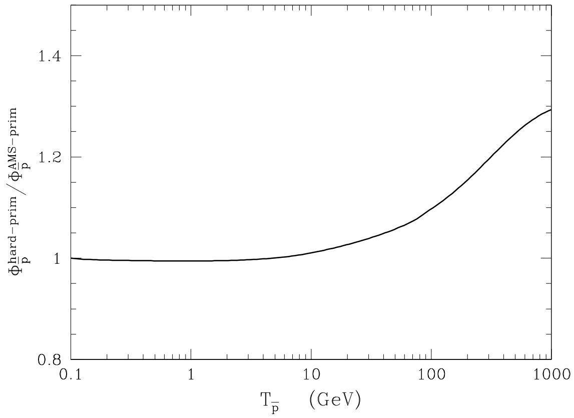

FIG. 1: Ratio of antiproton fluxes from hard sources (Eqs.(1, 2)) to the same flux obtained with p and He extrapolated from AMS data to all energies (see text for details).

A. Effects on $\bar{p}/p$

The computation of the secondary $\bar{p}$ flux has been performed as described in Refs. [2, 3], to which we refer for all the details. The only component which we will modify in the present calculation is the input p and He spectra. We briefly remind that secondary $\bar{p}$ are yielded by the spallation of cosmic ray proton and helium nuclei over the H and He nuclei in the ISM, the contribution of heavier nuclei being negligible. The framework used to calculate the antiproton flux is a two–zone diffusion model with convection and reacceleration, as well as spallations on the ISM, electromagnetic energy losses and the so–called tertiary component, corresponding to non–annihilating inelastic scatterings on the ISM. The relevant transport parameters are constrained from the boron-to-carbon (B/C) analysis [15] and correspond to: i) the half thickness of the diffusive halo of the Galaxy L; ii) the normalization of the diffusion coefficient K_0 and its slope δ ($K(E) = K_0 \beta R^\delta$); iii) the velocity of the constant wind directed perpendicular to the galactic disk $\vec{V_c} = \pm V_c \vec{e_z}$; and iv) the reacceleration intensity parameterized by the the Alfvénic speed V_a. The above parameters show significant degeneracies when confronted to B/C data [15]. Nevertheless, the impact on the secondary $\bar{p}$ flux is marginal [2]. The fluxes presented below have been obtained for the B/C best fit propagation parameters, i.e. L = 4 kpc, $K_0 = 0.0112$ kpc^{2}Myr^{-1}, $\delta = 0.7$, $V_c = 12.$ km s^{-1} and $V_a = 52.9$ km s^{-1} [15].

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[1] Assuming a *relative* uncertainty in the flux normalization of the two experiments of $\lesssim 20\%$—certainly consistent with published values—would suffice to bring these crossover values in consistency with the rigidity ~ 250 GV hinted to by PAMELA, ref. [7]

We are interested in the effect of primary p and He hardening at high energies on the $\bar{p}$ flux and therefore concentrate on the relative shape effect through the $\bar{p}/p$ flux ratios. Our results are reported in Fig. 1, where we plot the $\bar{p}/p$ ratio of obtained with two different primary spectra. The flux at the numerator has been obtained with the spectra in Eqs.(1, 2), while in the denominator we employ the fit to AMS data arbitrarily extrapolated to the highest energies. The modification of the antiproton flux clearly reflects in its shape. The effect of the hardening of primary spectra at hundreds of GeV/n starts to be visible on the antiproton flux at around 100 GeV. It is near 15% at 200 GeV and reaches 30% at 1 TeV. Given the weak dependence of the secondary antiproton flux on the B/C selected transport parameters, our results can be considered nearly independent of the propagation model. If the hardening of primary nuclei will be confirmed at high energies, a spectral distortion of the secondary antiproton flux has to be expected. This effect could be potentially observable by a future high precision space-based mission, such as AMS-02.

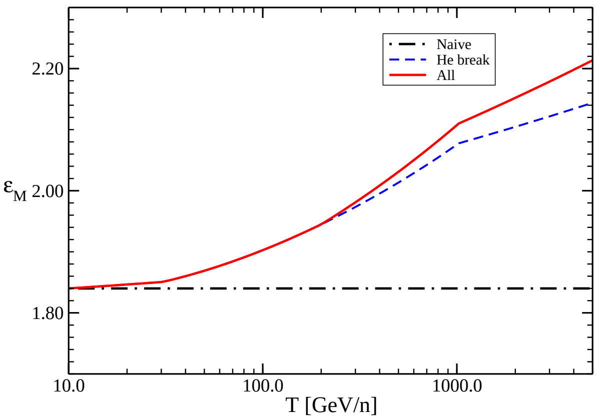

FIG. 2: Enhancement factor, see Eqs. (3,4), for the three representative cases described in Sec. III B.

B. Effects on "hadronic" diffuse gamma-rays.

The cosmic gamma ray flux observed in our Galaxy is expected to be mainly due to the inelastic scattering of incoming CRs on the nuclei of the ISM. The involved hadronic reactions produce gamma rays mostly via π^0 decays. In addition to this "hadronic" component, other contributions are expected - at different levels depending on the specific model - to Inverse Compton and bremsstrahlung radiation. The basic models for the production of gamma rays from π^0 decays – considered e.g. by the Fermi-LAT Collaboration [16] – do not introduce high-energy spectral breaks in the proton spectrum ϕ_1, and account for nuclear effects (both in CR spectra and in target composition) in the π^0 yield simply by rescaling the *pp* production via a *constant* "nuclear enhancement factor", taken from the value at the reference energy $T_* \equiv 10$ GeV/n reported in [17]. This enhancement encodes the relative yield of gamma-rays from nucleus-p and nucleus-Helium collisions compared with that from p-p collisions via appropriate factors $m_{ip}\,, m_{i\alpha}$, basically constant at $T > 10\,\mathrm{GeV/n}$ (the effects discussed in this paper are only relevant at high energy, so it's enough to focus on quantities at $T > 10\,\mathrm{GeV/n}$). This enhancement is defined as

$$\epsilon_{\mathrm{M}}(T) = \sum_i m_{i1}\frac{\phi_i(T)}{\phi_1(T)} + \sum_i m_{i2}\frac{\phi_i(T)}{\phi_1(T)} \times \frac{r}{1-r}\,, \quad (3)$$

where the index i runs over all CR species (including protons, $i = 1$), $r \simeq 0.096$ is the He/H fraction in the ISM and ϕ_i being the CR spectrum of the species i. If all the nuclei have roughly identical $T-$*dependence* of their spectra, as suggested in [5], one can write

$$\epsilon_{\mathrm{M}}(T) = 1 + \frac{m_{12}\,r}{1-r} + \left(m_{21} + \frac{m_{22}\,r}{1-r}\right)\frac{\phi_2}{\phi_1} + k_N\,\frac{\phi_N}{\phi_1}\,, \quad (4)$$

where $\phi_N(T)$ is any nuclear-like CR flux, and k_N is a normalization factor. In Fig. 2 we show $\epsilon_{\mathrm{M}}(T)$ for three cases: i) the constant value $\epsilon_{\mathrm{M}} = 1.84$, adopted for example in [16] (long-dashed, black); ii) the fluxes of p and He are set to the broken power-law functions described above, while the last term $k_N\,\phi_N/\phi_1$ is taken constant in energy and fixed so that $\epsilon_{\mathrm{M}}(T_*) = 1.84$ (short-dashed, blue). iii) As in ii) for p and He, but assuming for nuclei heavier than He a constant contribution to ϵ below $200\,\mathrm{GeV/n}$ (so that $\epsilon_{\mathrm{M}}(T_*) = 1.84$), then rising as $T^{0.1}$, as suggested by CREAM data (solid, red).

In Fig. 3, we show the result of computing the diffuse gamma ray spectrum (via the kernel provided in [18][2]) using the AMS-01 spectral fits ϕ_i^L, extrapolated to arbitrarily high energy (long-dashed, black curve). The flux has been multiplied by $E_\gamma^{2.78}$ to underline the departure from identical power-law behaviour between photons and parent CR due to production cross section/multiplicity effects. Instead, if one keeps $\epsilon_{\mathrm{M}} = 1.84$, but introduces the broken power-law spectrum for the protons *only* as from Eq. (1), around 300 GeV one would obtain $\sim 10\%$ higher gamma fluxes, as shown by the long-dashed, purple curve in Fig. 3. This case is introduced in order to gauge visually the effect of the break of $2.78 - 2.66 \simeq 0.12$

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[2] Note that we are only interested in the effects that different high-energy CR spectra have on the gamma-ray spectrum at $E_\gamma \gg 1\,\mathrm{GeV}$, so the simplified formalism presented in [18] and valid in the high-energy regime is sufficient for our purposes.

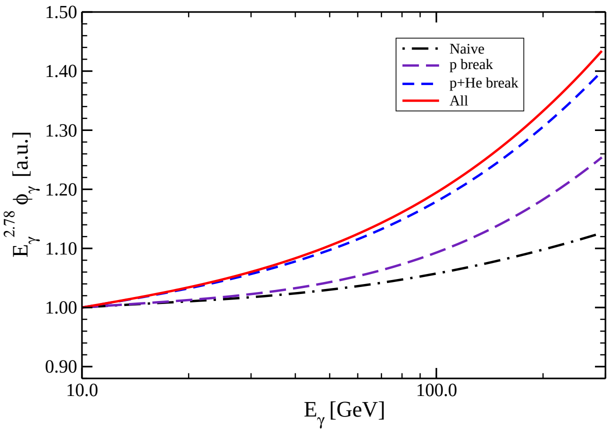

FIG. 3: γ-ray spectrum: the standard departure from equality of power-law with parent flux (dot-dashed, black), of adding the hardening in the p spectrum at TeV scale as suggested by CREAM (long-dashed, purple), of assuming the CREAM hardening for *both* p and He (short-dashed, blue), and of including the small effect of other nuclei as well (solid, red).

in the spectral index, between AMS and CREAM determination of proton spectra (to be compared with the $\sim$ 0.01 and 0.02 fit errors, respectively reported by the experiments). The solid, red curve shows the effect of "discrepant hardenings" of the spectra, namely the $T-$dependence of $\epsilon_{\rm M}$. This constitutes the major distortion and is mostly due to He (as shown by the short-dashed, blue curve); overall, the spectrum around 300 GeV is 30% higher with respect to naive expectations.

The effect discussed here is already "an estimate of error": assessing the error on this quantity goes beyond our purpose. However, we can safely conclude that our results are not significantly affected by the *statistical errors* with which the fluxes are known. We have checked this explicitly as follows: while keeping the Helium fluxes at low and high energies at the values described above, we have varied the normalization of the p fluxes at low/high energy in such a way that the p to He ration varies within ± 1 (i.e. twice the statistical error) of 18.8 at 100 GeV/nucleon [9], and within ± 0.6 of 8.9 at 9 TeV/nucleon [5]. The resulting variations in *the shape* of secondary radiation are negligible (i.e. at most at a few percent level). This is due to the fact that the (relatively small) effect of p flux renormalization and the change in $\epsilon_{\rm M}$anti-correlate, and tend to cancel each other. On the other hand, the exact value of the spectral hardening is more important: Fig. 3 shows that more than 1/3 of the hardening is due to the assumed "best fit" spectral index difference of ± 0.12 between low and high energy. This should be compared with the *statistical* errors of about $\sim \pm 0.01$ and ± 0.02 quoted by the AMS and CREAM collaborations, respectively.

IV. DISCUSSION AND CONCLUSIONS

In this article we have argued that departure at high energy from a simple and universal power-law for all cosmic ray spectra, as suggested by recent data, can cause a spectral distortion in the spectra of secondary cosmic ray yields (like diffuse photons and antiprotons) compared to the predictions obtained extrapolating the best fits to low-energy data sets. We have illustrated this effect using the best fit results of AMS-01 data at low energies and the CREAM data at high-energy, finding effects exceeding 10% above $\sim$100 GeV, and reaching about 30% for photons around 300 GeV and for $\bar{p}/p$ close to TeV energy; this figure is somewhat sensitive to the systematic error on the spectral index at high energy as well as other eventual systematics which do not cancel out in ratios of species (like p/He).

One might wonder how relevant is a high-energy effect of a few tens of percent in a field where data are usually plagued by larger errors. We think that, at present, this level of accuracy is becoming crucial for at least a couple of reasons: First, space experiments like FERMI or the future AMS-02 [23] are introducing us to a new era of large exposures, which can reveal more subtle features than previous cosmic ray or gamma-ray experiments. Fermi data errors at $E_\gamma \simeq 100\,$GeV are already $\sim \pm 20\%$ [19], and forecasts that have been presented suggest that AMS-02 (if performing close to specifications) will be certainly sensitive to effects of this magnitude, see for example [20]. Second, both diffuse gamma-rays [21] and the combination of hadronic data [22] are consistent, at least at leading order, with a "standard" scenario for the production and propagation of cosmic rays in the Galaxy. It is very likely that any departure from baseline models, if detectable, is going to be present at such a sub-leading level. Modelling thus the astrophysical background for indirect DM searches as a simple power law, as often done in the literature, might lead to wrong conclusions about the evidence of a signal, or to a bias in the inferred values of the parameters describing the new phenomena, should they be detected.

Even in a conservative scenario, the detection of such spectral signatures in secondary channels would provide a way to check the *interstellar* nature of the spectral features in the cosmic ray flux at the Earth suggested by the present experiments. We believe that secondaries provide an important handle for an *empirical* cross-check. One should also consider the partial degeneracy of such effects with the extraction of propagation parameters, in order to fully exploit the statistical power of forthcoming data sets. Knowing better the primary flux shapes would allow one to set strategies to minimize these effects.

While we are entering a much higher precision era in cosmic ray studies, it is important to keep in mind a couple of points: i) that multi-messenger and multichannel analyses are mandatory, if one is to gain some deeper knowledge of cosmic ray astrophysics. ii) That any hope for the detection of new physics (not to speak of extracting new physics parameters) requires a more robust understanding of the possible range of astrophysical yields. In that respect, a natural development of this initial investigation would be to (re)assess how the errors on primary flux knowledge map into the predictions for secondaries (including their normalization), as much as possible in a parameterization-independent way.

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