On the flux saturation of SOHO/ERNE proton events

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Abstract. This study lists the main procedures completed on the analysis of solar proton events using data from the SOHO/ERNE high energy detector in the period 1996−2017. The highest possible temporal resolution of 1 minute is used here. The proton fluxes from the two analyzed energy channels, at ∼25 and ∼50 MeV, are compared with the respective fluxes observed with a similar energy coverage from another proton instrument, Wind/EPACT. The proton events with flux saturation effects are identified and a correction procedure is proposed. Pearson correlation analysis with solar flare class and linear speed of the coronal mass ejections is completed, both with the observed and corrected proton fluxes. The outcomes are presented and discussed.

Key words: solar energetic protons - saturation effects - statistical correlations

Introduction

The solar energetic particles (SEPs), observed in situ, continue to be of prime academic and engineering interest to date (Schwenn, 2006; Klein and Dalla, 2017). Electrons, protons and heavy ions are the topic of investigation with various instrumental suites on past, operating and scheduled solar dedicated missions. The reason behind the continuing efforts towards the physical understanding of the particle acceleration, escape, transport and interactions is undoubtedly the ground-based and space-borne technological risks they carry (Pulkkinen, 2007; Jiggens et al. 2014). Moreover, future manned missions outside the terrestrial magnetosphere are impeded by the dangerous levels of proton radiation exposure, estimated to be received in the interplanetary space by the crew (Schwadron et al. 2017).

Thus, together with developing new technological solutions for radiation protection, one could schedule future flights in periods of low SEP activity. This is why the forecasting of SEP occurrence and the maximum reached flux or its integrated value (fluence) is receiving much attention from the scientific community. Various prediction schemes are still being proposed and compared, see e.g. `https://ccmc.gsfc.nasa.gov/challenges/sep.php`.

With the availability of in situ SEP data, detected with the same instruments over nearly two solar cycles, several proton event catalogs have been organized and published. Here we focus only on those that are based on the instruments under consideration of this work: SOHO/ERNE (Torsti et al. 1995) and Wind/EPACT (von Rosenvinge et al. 1995). Some of the proton event lists, known to us, are freely available online: SOHO/ERNE major proton events (1996−1999): `https://srl.utu.fi/erne_data/events/`

`proton/HED/eventlist.html`; SOHO/ERNE particle events (1996−2007): `https://srl.utu.fi/SEPCatalog/index.php`; SEPserver event catalogs (1997−2012/2015): `http://server.sepserver.eu/`; Wind/EPACT proton events (1996−2018): `http://newserver.stil.bas.bg/SEPcatalog/`.

Alternatively, proton catalogs can be found in recently published papers, e.g., Miteva et al. (2013): GOES, Wind/EPACT, ACE/EPAM (1996-2006); Paassilta et al. (2017): SOHO/ERNE (1997−2016); Miteva et al. (2018a): Wind/EPACT (1996−2016).

In addition to the proton events, the research studies and catalogs contain information on the solar origin of these protons. The parent activity of the accelerated particles at the Sun are solar flares and coronal mass ejections (CMEs), Bazilevskaya (2017). Either eruptive phenomenon have been shown, both observationally and theoretically, to be able to energize particles even to relativistic energies (Klein and Dalla, 2017). The degree of the flare vs. CME contribution to a given SEP event, however, is still unknown and could well vary from case to case. In our work we offer impartial investigation and regard flares and CME as independent sites for simultaneous or/and subsequent SEP acceleration. This is in line with the recently accepted assumption in the SEP community that both solar activities contribute to a SEP event.

The focus of this study is the proton data detected with the SOHO/ERNE instrument. The ERNE instrument consists of two detectors, low energy detector (LED) from 1.6 to 13 MeV, and high energy detector (HED) from 14 to 131 MeV, each of them detecting protons in 10 separate energy ranges.

The second HED-2 channel, 17−22 (19.5) MeV, is selected as a reference channel. However, the explicit results will be reported elsewhere. The energy is close to the traditional energy band used in the literature to define a solar proton event, at ∼25 MeV. We started the cataloguing by performing a visual identification of the ∼20 MeV proton enhancements and specifying their duration for the follow-up quantitative analysis. Note that the events in a lower or a higher energy channel are the proton signatures detected in these already specified time ranges.

Observing the same solar activity with multiple instruments is justified since each spacecraft is subject to instrument degradation, saturation and data gaps. Data by detectors with similar energy ranges provides not only confirmation of the phenomena under investigation but also a way to recover missing or uncertain information. Thus, a cross-check is recommendable, whenever possible. In our case, proton data from two detectors with similar energy coverage, namely SOHO/ERNE 21−28 and 40−51 MeV, and Wind/EPACT 19−28 and 28−72 MeV, are used to perform a cross-calibration. Despite the similar periods of observations of the two satellites, SOHO/ERNE provides a much wider energy coverage for the protons, split into 20 channels, compared to the Wind/EPACT two, rather broad energy channels. Namely, SOHO/ERNE allows for investigations as a function of the proton energy, thus discriminating trends valid predominantly for the lower or for the higher energy protons, respectively.

The availability of SEP catalogs facilitates the comprehensive statistical studies available in the recent years, exploring the linear link between some selected SEP properties (amplitude, fluence, etc.) and characteristics of the SEP solar origin (solar flare class, fluence, location and CME speed, angular width, etc.). The availability of analysed and organized SEP results facilitates also the validation of the different forecasting schemes and provides the observational requirements for the model improvement.

1. Proton event identification

In our earlier works, the proton analysis was done using a 5-min data smoothing. The results are reported in Miteva (2017); Miteva and Danov (2018); Miteva (2019); Miteva and Tsvetkov (2019).

In order to take advantage of the best available temporal resolution for the onset and peak proton intensity identification (1 minute), we reanalysed the amplitudes of all proton events in two specifically chosen for this study energy channels: HED-3 21−28 (24.5) MeV and HED-6 40−51 (45.5) MeV. They will be referred to as low and high energy channels respectively, and denoted as ∼25 MeV and ∼50 MeV, for simplicity. For the event identification, as noted above, we used the visual cross-check of the times as specified by the reference HED-2 17−22 MeV energy channel of SOHO/ERNE.

For the SOHO/ERNE events we utilize a proven procedure for proton event analysis as described in Miteva et al. (2018a) for the Wind/EPACT data. Onset time is defined as three standard deviations above the pre-event average background level. The range for pre-event background is selected individually for each event after visual inspection by an observer. The value for the flux intensity of the background is also provided by the routine as the averaged flux value in the so-chosen range. The peak time is calculated at the maximum of the proton intensity before any local shock signatures, if any. Finally, for the correlation analysis we use the proton amplitude, e.g., the peak proton intensity value after subtraction of the background level. The intensity for the proton events from both instruments is measured in $(\mathrm{cm}^2\ \mathrm{s\ sr\ MeV})^{-1}$, and will be denoted as differential proton flux units, or DPFU.

After completing the analysis over nearly two solar cycles (SCs), 1996−2017, we obtain 639 proton events in ∼25 MeV energy channel and 428 proton events in ∼50 MeV energy channel.

2. Solar origin association

The issue of solar origin association has been the topic of different works, see e.g., Bazilevskaya (2017) and the references therein. The procedure for the association of in situ observed particle event and the remotely observed solar flare and CME is based on temporal, intensity and profile requirements as described in Miteva et al. (2018a). Nevertheless, subjectivity cannot be completely avoided. Occasionally, alternative solar flares/CMEs can be proposed to the same proton event by different authors as investigated in Miteva (2019). The differences can reach up to 15% and are shown to change the obtained statistical correlations, which in turn will modify the interpretations of the physical nature of the SEP events. Thus, despite care taken when identifying the solar flares and CMEs, the correlations investigated in this study rely on the identified and proposed by us solar origin association for the proton events.

Information about the solar flare class is used from the available flare catalog: `https://hesperia.gsfc.nasa.gov/goes/goeseventlistings/`. The number of proton-associated flares for the low energy protons with identified flux is 410, which constitutes about 64% association rate. We obtain 306 flare identifications related to the high energy protons, or 71% association rate.

The linear speed of the CMEs is adopted from SOHO/LASCO CDAW catalog: `https://cdaw.gsfc.nasa.gov/CME_list/`. The number of CME associations is 491 (359), which is larger compared to solar flare identification number in relationship with the number of low (high) energy proton events. The corresponding association rate is 77% (84%, respectively). As expected the association rate for the high energy protons is higher, since in general they constitute of larger activity phenomena that are better determined.

The finalized proton catalog in all SOHO/ERNE HED energy channels together with the solar flare association is planned to be released online and to be publicly available. A dedicated web-site is organized and can be found here: `https://catalogs.astro.bas.bg/`

3. Proton flux correlation: SOHO/ERNE vs. Wind/EPACT

The SOHO/ERNE HED instrument has been known to suffer from saturation when the proton intensity is high (Miteva, 2017). Devoting some efforts to the development of various correction procedures is advisable. One simple procedure is to relate the value for peak proton flux (and/or profile) considering the outcomes from two independent instruments for the same particle event. In this study, we will estimate the SOHO/ERNE flux level by means of their linear correlation with the Wind/EPACT flux response.

Correlation between the proton fluxes from different instruments was already investigated in details in Miteva et al. (2018b) over SC23. A high correlation between the fluxes of the same proton events when observed with two different instruments was obtained there and is also expected here for data covering two SCs. The fluxes of the Wind/EPACT proton events are adopted from the catalog presented by Miteva et al. (2018a).

We perform $\log_{10}-\log_{10}$ Pearson linear correlation between the peak proton intensities observed by SOHO/ERNE (denoted in the text below as $J_{\rm ERNE}$) and Wind/EPACT (as $J_{\rm EPACT}$) for a given event. The total number of pairs is 365 for the low energy and 312 for the high energy. Both, the low and high energy channel show flattening at some value for the SOHO/ERNE detected intensity for the SEP events. As expected, the saturation effect is prominent for the high intensity proton events.

The scatter plots for the low energy channel are shown in Fig. 1. The events are plotted with empty circles. With different colors are highlighted (over-plotted) three sub-samples with a different upper limit for the peak intensity. Namely, green color is used for all data points with $J_{\rm ERNE} \leq 0.05$, blue for $J_{\rm ERNE} \leq 0.1$ and red for $J_{\rm ERNE} \leq 1$ DPFU. The regression line is calculated for the respective sub-sample and is shown in each plot in black

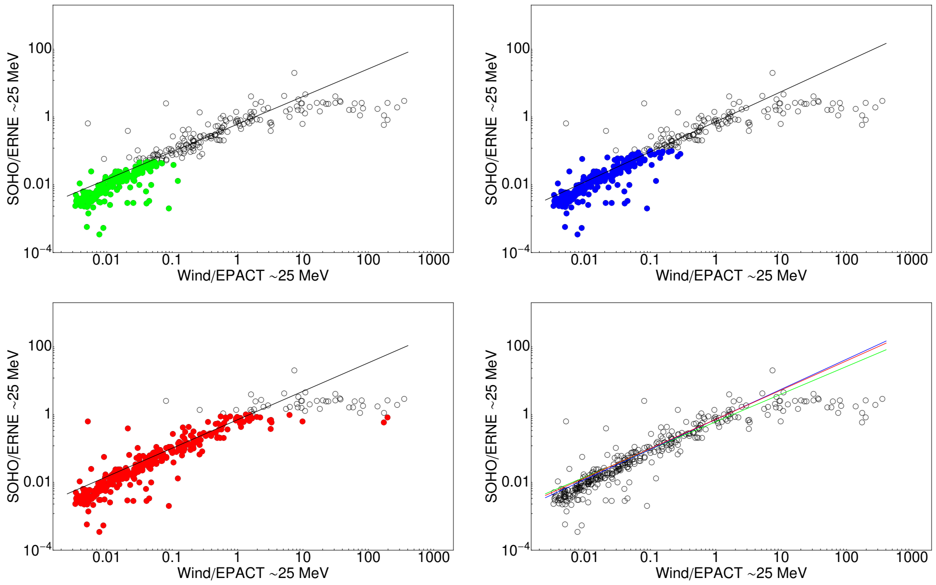

Fig. 1. Correlation plots between the ~25 MeV peak proton intensities from SOHO/ERNE and Wind/WPACT instruments. See text for explanations and the color used.

color to be easily discernible. In the last plot (lower row, right), the three regression lines are plotted together with the respective color of their subsample. The three regression lines give very close results, compared to the spread of the data points. In the background all data points with empty circles are given for comparison.

The high energy channel is plotted in a similar way and shown in Fig. 2. In this case, the linear regression is based on sub-samples with $J_{\mathrm{ERNE}} \leq$ 0.01, 0.05, 0.1 DPFU, denoted in green, blue and red color, correspondingly. Again, the respective regression lines are very similar.

4. SOHO/ERNE proton flux correction

The effect of proton intensity saturation is shown in Fig. 3 for the example event on 20011104 (YYYYMMDD), both for the low and high energy channel under consideration. The SOHO/ERNE saturation is evidenced only on the declining slope of the curve as a much lower sampling and showing peculiar irregularities and dropouts. The adopted correction procedure for a given proton event relates the SOHO/ERNE peak flux to the Wind/EPACT level by means of a simple linear correlation.

The data points in Figs. 1 and 2 show a flattening branch, with a slightly longer arm for the low energy protons, although a large scatter is also present. For the ~25 MeV proton events the flattening effect becomes evident at J_{ERNE} of about 1 DPFU for the SOHO/ERNE events, and about

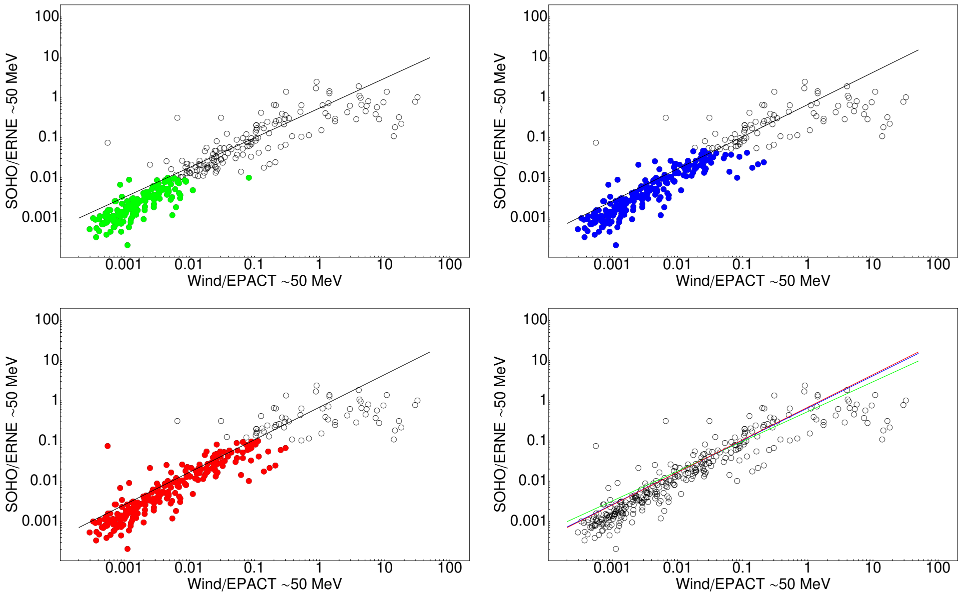

Fig. 2. Correlation plots between the ~50 MeV peak proton intensities from SOHO/ERNE and Wind/WPACT instruments. See text for explanations and the color used.

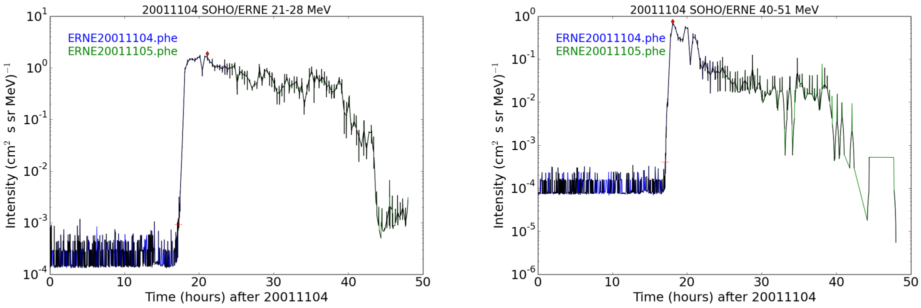

Fig. 3. Example plots for ~25 MeV (left) and ~50 MeV (right plot) SOHO/ERNE proton event for 2001-11-04, each plotted over a period of two days.

10 DPFU for the Wind/EPACT. For the ~50 MeV energy range, these values are at around 1 and 2−4 DPFU, correspondingly.

The aim of the proposed here procedure is to offer a simplified but straightforward flux correction method for the proton events affected by SOHO/ERNE saturation. However, we will correct only the upper right sector of the entire event sample in order to minimize the number of corrected events. This is done in order not to over-correct the events just next to the horizontal branch, i.e. for which any correction procedure could introduce artificial effects. We finally decide to proceed by visual splitting

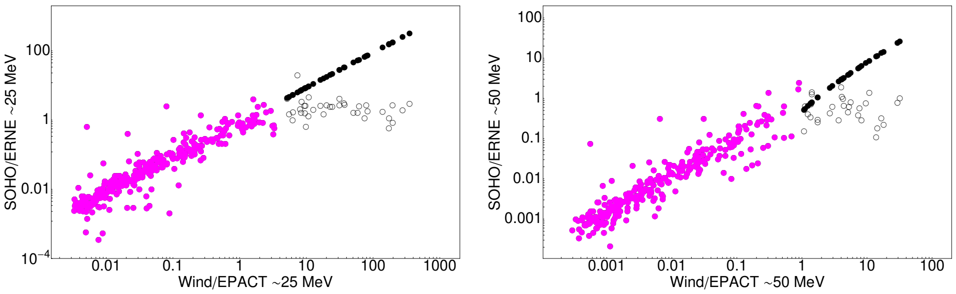

Fig. 4. Corrected peak intensity of the saturated SOHO/ERNE proton events for $\sim$25 MeV (left) and $\sim$50 MeV (right plot) energy channels, denoted in filled black dots.

of the event sample. In Fig. 4 we plot again the data with empty circles, whereas with magenta color we highlight the sample of events that will not be modified by the correction.

We use just a simple visual selection of the data points on the horizontal branch for which to apply the correction. For the low energy events, Fig. 4, left plot, we select all data points for which Wind/EPACT flux $J_{\mathrm{EPACT,l}} > 4$ (plotted with empty circles). The subscript 'l' denotes the low energy channel. The corresponding SOHO/ERNE flux from the pair will be corrected using a linear regression relationship. The number of corrected events in this case is 37. For the quantitative evaluation of the correction, we use the top regression line in the range of high intensity events, in order to obtain an upper limit for the corrected SOHO/ERNE flux. In this case this is the blue regression line (from Fig. 1), namely $J_{\mathrm{ERNE,corr}} = -0.32 + 0.89 J_{\mathrm{EPACT,l}}$, for the corrected SOHO/ERNE flux. The results are shown in Fig. 4, left plot, with filled black circles.

The corrected flux for the lower energy protons increases from just a few to over 300 DPFU, depending on the event. For the example case plotted in Fig. 3 the correction gives an increase from the observed value of just 2 to 246 DPFU.

The amplitude reached by the particles in the higher energy channels is generally lower compared to the respective fluxes in the low energy channels. Thus, for the high energy protons, Fig. 4, right plot, we use the condition for the selection to be $J_{\mathrm{EPACT,h}} > 1$. The subscript 'h' denotes the high energy channel. The number of events subject to correction in this case is 30. Here we use the red regression line (from Fig. 2): $J_{\mathrm{ERNE,corr}} = -0.37 + 0.81 J_{\mathrm{EPACT,h}}$. The corrected data is shown in Fig. 4, right plot, again in filled black circles. Fewer data points are corrected here, although one can argue for a larger data spread of the horizontal branch.

In either energy range, the correction is the largest for the largest (i.e., plotted right-most) in amplitude SOHO/ERNE events, although there is a slight drop in the horizontal branches before reaching that limit. For example, the data point subject to a maximum flux increase for the low energy case is 312 DPFU and up to 26 DPFU for the high energy SOHO/ERNE protons.

Table 1. Table of the $\log_{10}-\log_{10}$ Pearson correlation coefficients between the peak proton fluxes with solar flare class and CME linear speed. The number of the events in each sample is given in brackets.

Pearson	SOHO/ERNE $\sim$25 MeV		SOHO/ERNE $\sim$50 MeV	
correlations	observed	corrected	observed	corrected
	Solar cycle 23: 1996−2008			
flare class	0.52±0.05 (287)	0.49±0.06 (182)	0.48±0.06 (213)	0.52±0.06 (168)
CME speed	0.52±0.04 (328)	0.50±0.05 (203)	0.47±0.05 (241)	0.48±0.05 (185)
	Solar cycle 24: 2009−2017			
flare class	0.41±0.08 (123)	0.42±0.08 (80)	0.44±0.08 (93)	0.45±0.07 (70)
CME speed	0.51±0.05 (163)	0.45±0.07 (107)	0.46±0.06 (118)	0.41±0.08 (92)
	Solar cycles 23+24: 1996−2017			
flare class	0.49±0.04 (410)	0.47±0.05 (262)	0.47±0.05 (306)	0.50±0.05 (238)
CME speed	0.52±0.03 (491)	0.49±0.04 (310)	0.46±0.04 (359)	0.47±0.04 (277)

5. Results and Discussion

When developing a mechanism for proton flux correction, in either energy channel, we did not attempt to introduce artificial data spread around the regression line. This is because, the aim of this study is to estimate the effect of the saturated flux when performing statistical correlation using the entire data sample. Thus, the proposed above procedure is more suitable for filtering some averaged properties compared to a single event analyses. We are interested in the amount of correlation between the proton events and the properties of the solar origin, solar flare class and CME speed. The standard procedure in this field of research is to calculate Pearson correlation coefficients between the $\log_{10}$ value of the proton amplitude (as provided by the instrument, with saturation effects or after the correction) and the $\log_{10}$ of the flare class or linear speed of the CME. For estimating the statistical uncertainty, the bootstrapping method is used as utilized for the first time in Miteva et al. (2013).

Table 1 summarizes the results for the observed and corrected proton fluxes for both energy ranges. In addition, the calculations are done for three time periods, SC23 (1996−2008), SC24 (2009−2017) and SCs 23+24 (1996−2017).

For the $\sim$25 MeV protons, the correlations, when using the corrected proton flux, are slightly lower in value compared to the uncorrected one, for the majority of the cases, whereas for the $\sim$50 MeV protons, the correlation coefficients are slightly larger in general. However, within the uncertainty, none of the differences are statistically significant.

Similar results are obtained when we compare the outcomes about the solar origin of the protons. For the lower energy proton channel, the correlations when done with CME speed are in general slightly larger, compared to the coefficients obtained with the flare class, both for the observed and corrected SOHO/ERNE data. The opposite is noticed for the higher energy proton channel, namely correlations with flare class are slightly larger. Again, the differences are within the uncertainty ranges.

The values of the obtained correlation coefficients are consistent with the reported ones from previous studies using the same instrument (Paassilta et al. 2017; Miteva, 2019).

6. Conclusion

We analysed the peak proton intensities from two channels of SOHO/ERNE instrument, 21−28 and 40−51 MeV, over the period 1996−2017. The study marks the compilation of a new proton event catalog using the highest available time resolution over nearly two solar cycles, that is planned to be released via the platform: `https://catalogs.astro.bas.bg/`.

Large intensity proton events from SOHO/ERNE have been shown to be a subject to saturation effects. In this study we propose a straightforward way for estimating the amount of correction. This is done by a linear comparison between the saturated SOHO/ERNE flux and the flux for the same proton event observed by Wind/EPACT. The latter is assumed to provide a representative value. The study provides the regression equations in order to recover the corrected for saturation proton fluxes. Information on the finalized SOHO/ERNE proton catalog, e.g., observed and corrected proton flux, onset and peak times, solar origin associations as well as quick-look plots, is planned to be freely available online at the dedicated web-site: `https://catalogs.astro.bas.bg/`

The results from our analysis show that the saturation effects on the large proton intensity events do not compromise the validity of the correlation coefficient analysis done over the entire event sample. The differences are very small and within the statistical uncertainty. This validates our previous results using uncorrected SOHO/ERNE proton data (Miteva, 2017; Miteva and Danov, 2018; Miteva, 2019; Miteva and Tsvetkov, 2019). When a single event analysis is considered, however, differences of over 300 DPFU in $\sim$25 MeV SOHO/ERNE peak proton intensity are to be expected, based on the assumption for linear correlation with the observed proton flux from a different instrument, Wind/EPACT. Note that the proposed procedure offers a flux correction in just two out of all ten SOHO/ERNE HED energy channels. Development of alternative procedures for flux corrections, also as a function of the proton energy, and inter-comparison of the obtained results is recommended.

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