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# GeV Proton Detection in the 8 November 2000 Solar Event

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**Abstract:** In this study, we analyze the L3 precision muon spectrometer data from November 2000. The results showed that a 4.7σ muon excess appeared at a time coincident with the solar flare of 8 November 2000. This muon excess corresponded to primary protons above 40 GeV, coming from a sky cell of solid angle 0.048 sr. The probability of being a background fluctuation was estimated to be about 0.1%. It is interesting and noteworthy that an M-class solar flare may also accelerate solar protons to such high energies.

**Keywords:** solar flares; solar energetic protons; ground level enhancement (GLE); muon enhancements; muon drift chamber; neutron monitor (NM)

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## 1. Introduction

It is known that solar energetic particles are accelerated during intense solar high energy processes which are usually accompanied by solar flares and/or coronal mass ejections (CMEs). When the flux of solar protons with energies above 10 MeV exceeds 10 pfu (1 pfu = 1 proton $(\mathrm{cm}^2\ \mathrm{s\ sr})^{-1}$), the event is referred to as a solar proton event (SPE). From 1976 to the present day, more than 360 SPEs have been observed by spacecraft-based detectors [1]. If solar energetic particles with energies above several hundred MeV in some SPEs produce particle cascades at the top of the atmosphere and give rise to an available flux, increasing the cosmic rays on the surface of the Earth, these SPEs are also called cosmic ray ground level enhancements (GLEs). Currently, 73 GLEs have been recorded—mainly by the worldwide network of neutron monitors (NMs) [2]—since the first GLE observation in 1942 [3].

The worldwide NMs detect the fluxes of secondary neutrons produced by incident protons at ground level and show the energy threshold of incident protons with the local geomagnetic rigidities. Compared to NMs, some directional detectors (such as muon telescopes) operating at higher energies are better suited for detecting higher energy solar proton beams in big solar flares [4]. Since energy thresholds are typically fixed by the instrument design and their atmospheric or underground depth, these instruments can register events, in principle, with energies up to or beyond 100 GeV. Unfortunately, for a long period of time, very few muon detectors have been in operation.

In recent years, the technique of particle trajectory tracing [5] of a GLE has been modelled from different NMs' data with an advanced model of the magnetospheric magnetic field [6,7]. The solar proton beam approaching the Earth can be described in simulations. Many such studies have shown that the arrival direction of relative solar protons in big flares is often anisotropic, sometimes quite anisotropic, and that these protons often follow a steep spectrum [8–10].

Lots of investigations of SPEs and GLEs have been reported in many typical papers, such as these works [11–20]. Measurements of these GLEs have indicated that the Sun could accelerate protons up to tens of GeV in energy [21–26]. In contrast, the information

on the solar relativistic protons produced in those SPEs without GLEs is still scarce. It would be very interesting to identify whether there are still high-energy solar proton beams, and how far the energies these solar protons can be accelerated in large SPEs without GLE. In 1971, a positive correlation was obtained between a significant muon intensity increase and a specific solar flare by a narrow-angle telescope located at an underground mine in Colorado [27], although there were no responses of NMs to this event. This is the first piece of experimental evidence for solar particle production in the above ~75 GeV energy region in an M8 solar flare. After that, we have not seen any other significant reports on this subject.

The L3 + C experiment could measure the momentum and direction of cosmic ray muons [28] with the precision muon chamber of the L3 spectrometer [29]. Its typical superiorities should be high directional resolution, high momentum resolution, low momentum threshold, and a large sensitive volume. Its running periods (1999–2000) cover the peak years of the solar cycle 23. These factors offer a great opportunity for us to search for high-energy solar protons in SPEs and to try to answer the questions discussed above.

Using L3 precision muon spectrometry, a muon excess correlated with the GLE of 14 July 2000 was obtained from a small sky cell of a solid angle of 0.046 sr [24,25], corresponding to primary solar protons from 40 GeV to 100 GeV. Except for the GLE of 14 July, the biggest SPE happened on 8 November of the same year. Adopting the same analysis technique for the GLE of 14 July 2000, we also analyzed the data of 8–9 November 2000 and found a new muon excess. In this paper, we will present the data analysis and the results for this event. After a brief introduction of this event and our experiment in the next two sections, we will mainly explain the data analysis technique and the results in Section 4, followed by some discussion and a conclusion in the last two sections.

## 2. The Solar Proton Event of 8 November 2000

The SPE of 8 November 2000 was associated with an M7.4/3F solar flare produced in the optical coordinates N10W77. Several small flares in the regions NOAA9212, NOAA9213, and NOAA9218 gave rise to this strong flare at 23:28 UT and triggered a strong solar storm of high-energy particles [30–32]. The X-ray flare, lasting from 22:42 UT to 00:05 UT of 9 November with a peak at 23:28 UT, was accompanied by a fast partial halo CME at 23:06 UT [31–33]. The CME speed was about 1738 km/s. It was the second largest SPE in 2000. A type IV radio burst happened at 23:45 UT [34], designating the start of the high-energy phenomena in the flare; this was thought to be close to the time of relativistic proton acceleration [11]. Soon after that, a strong solar storm of high-energy particles was triggered. The satellite-borne detectors, such as ACE and GOES, observed a rapid increase in proton fluxes, as shown in Figure 1 [35]. The flux of protons with energy up to 500 MeV peaked at about three orders high at about 00:10 UT on the 9th. The solar wind exceeded about 900 km/s about two days later on the solar-terrestrial activity chart. However, no NMs had a significant response to this event, so the event became an exception to the large SPE events of solar cycles 23 and 24 [36].

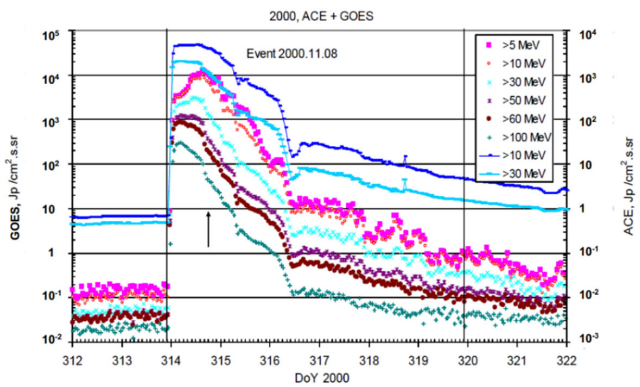


**Figure 1.** Time profiles of the proton fluxes for the event of 8 November 2000 [35].

## 3. The L3 + C Experiment

The L3 + Cosmics (L3 + C) detector [28] combines the high-precision muon drift chambers of the L3 spectrometer with an air shower array on the surface. As shown in Figure 2, only the muon detectors, the magnet, and the scintillator tiles of the L3 spectrometer were used to measure cosmic rays. The muon drift chamber, installed in a 1000 $m^3$ magnetic field of 0.5 T, shows an octant shape in the plane perpendicular to the beam (11 m in width and 11 m in height) and a square shape in the plane along the beam (11 m in length). The maximum geometrical acceptance is ~200 $m^2$ sr, covering a zenith angle range from 0° to ~ 60°.

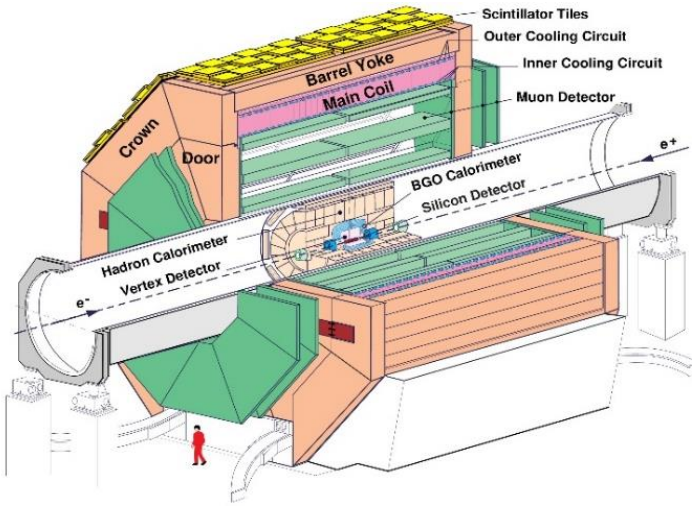


**Figure 2.** The L3 spectrometer. Only the muon detectors, the magnet, and the scintillator tiles were used in this experiment.

The detector is located shallow underground near Geneva (6.02° E, 46.25° N) at an altitude of 450 m above sea level, where the vertical geomagnetic rigidity cutoff is ~5 GV. The approximately 30 m overburden above the detector provides a 15 GeV cutoff for the muon energy, corresponding to primary proton energies above 40 GeV. In order to independently observe cosmic ray events, a timing detector composed of 202 $m^2$ of plastic scintillators was installed on top of the magnet, and a separate trigger and DAQ system were used for the data taking of the cosmic ray events.

Although an independent data-taking system was set up for the cosmic ray event register, much high background still existed when the LEP positron–electron collider was operating. Fortunately, the collision experiment was stopped after the end of October 2000. So, the subsequent muon data taken by the muon drift chambers had very low background, which is crucial for the analysis of the SPE of 8 November 2000.

## 4. Data Analysis and Results

This analysis was undertaken to search for possible muon excess signals from our reconstructed muon data set during the period of the SPE of 8 November 2000 to identify if there were high-energy protons of tens of GeV. In view of the features of solar high-energy protons mentioned in Sections 1 and 2, and based on our analysis experience for the GLE of 14 July 2000, we were able to make the following judgments: (1) the GeV high-energy protons, if they existed, possibly came from a narrow sky cell; and (2) their onset time to arrive on the Earth should have been a little earlier than a hundred MeV protons. Observations from GOES-8 showed that the fluxes of protons with energies up to 500 MeV peaked at about 00:10 UT on the 9th of November. Thus, the search for a possible muon excess should mainly focus on each sky cell and the short time period around the peak time of the increase seen by GOES, starting at 24:00 UT on the 8th. This is to find whether there was any time-coincident muon excess with GOES-8 data.

A data set of muons with surface energies over 20 GeV within the full acceptance of the L3 + C detector was used for this analysis. In order to ensure real muon events, exact event selections are necessary for reconstructed muons. In the next subsections, we introduce the event selection criteria and analysis techniques which were adopted in a previous study on the GLE of 14 July 2000 [24,25].

### *4.1. Event Selection*

As stated above, the LEP positron–electron collider stopped after the end of October 2000. However, the muon drift chambers of the L3 spectrometer were still running normally. A clean muon data set was obtained. So, in this analysis, we did not need to use the cut of variable T0 which was applied in previous analysis. Other previous selection criteria were still adopted:

1. Only a single muon track was present in the muon chamber;
2. The track was composed of at least three segments of hits in P-chambers (wires parallel to the magnetic field) and two segments of hits in Z-chambers (wires perpendicular to the magnetic field), ensuring that it was a good muon track;
3. The back-tracking of the track from the muon chambers to the surface was successful in order to ensure good pointing.

### *4.2. Time Binning and Sky Mapping*

All selected events were binned in time according to live-time, and in space according to the muon arrival direction on the ground. The L3 + C data-taking system set 0.839 s as a minimal time bin. We also used this minimal time bin as a live-time interval. In our analysis, we combined 100 live-time intervals to form an 83.9 s live-time bin as the basic time unit.

In space division, the direction cosines $l = \sin\theta\cos\phi$ and $m = \sin\theta\sin\phi$ were used as measurables of the muon directions, where $\theta$ and $\phi$ are the zenith and azimuth angles of the muon direction at the surface. The squared area of the variables L and m was divided into a $10 \times 10$ ($l$,m) grid. Ignoring those cells with poor statistics within the detector acceptance, 59 sky cells containing at least 50 events remained for the analysis. The contour lines for directions with an equal event rate are shown in Figure 3 for the data of 8 November 2000.

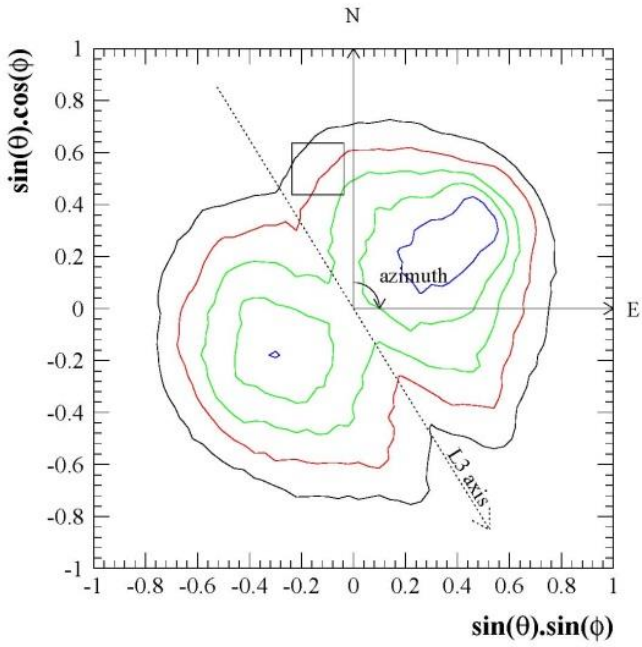


**Figure 3.** The distribution of the arrival directions of muons observed by the L3 + C detector. The contour lines indicate directions having an equal event rate. The square represents the sky cell No. 48.

### 4.3. Background

The Sun was relatively inactive on 6 and 7 November, and proton fluxes showed in Figure 1 were low and stable. So, we chose 12 h data before 21:00 UT on the 8th as a background measurement. The same event selection criteria with the same time binning and direction binning were applied to the background analysis.

### 4.4. Results

To find possible excesses we compared the data with the background for each sky cell within the peak time of GOES-8. As a result, a count excess in a bin containing 634 events was found (seeing Figure 4a) in the sky cell No. 48, defined as $0.4375 \leq l \leq 0.6375$, $-0.2375 \leq m \leq -0.0375$ (with a solid angle of 0.048 sr). It was within an 8.39 min live-time window (with the real time from 00:07 UT to 00:16 UT on the 9th). This excess was obtained after a first search for an 83.9 s live-time bin (resulting from the online live-time counting), starting from 24:00 UT and having an anomalously large number of events followed by another two 83.9 s live-time bins, which also had a higher number of events. The bin at 00:07 UT that met these requirements was taken as the starting bin for a possible excess. The following five live-time bins were combined with it to form the 8.39 min live-time window.

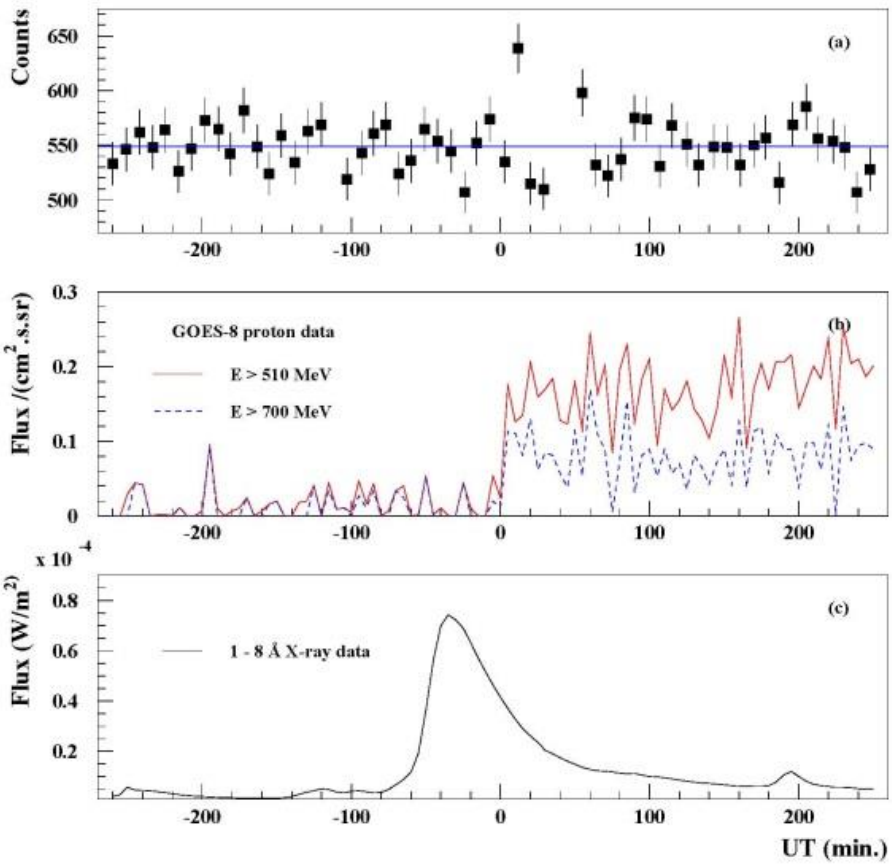


**Figure 4.** (**a**) Number of events versus time in minutes for 6 h (around the zero of the horizontal axis at 24:00 UT on 8 November 2000) in sky cell No. 48. The live-time bin width is 8.39 min. The blue solid line shows the mean value of the background. (**b**) Time profiles of proton fluxes registered by GOES-8. The red solid line corresponds to proton energies higher than 510 MeV and the blue–dashed line to energies above 700 MeV. (**c**) Time profile of 1–8 Å soft X-ray registered by GOES-8.

We can see from Figure 4b that the excess appeared at a time just coincident with the peak increase in lower energy solar protons. With the 8.39 min live-time bins, we investigated the background of 12 h before 21:00 UT for the same sky cell. The background

distribution is shown in Figure 5 and is fitted by a Gaussian. Using the fitted mean of 535 and the standard deviation equal to 20.9, the excess of 99 events gives rise to a 4.7 σ effect.

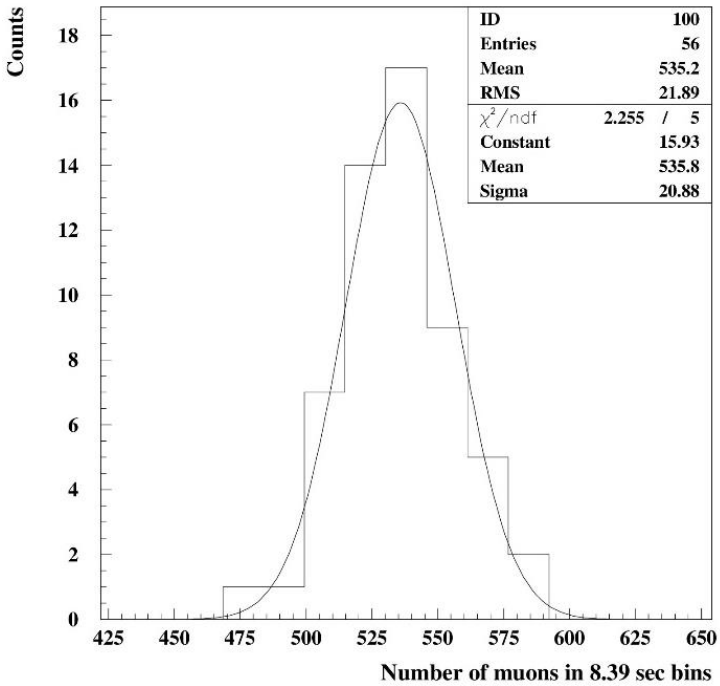


**Figure 5.** The distribution of background events in the sky cell No. 48 obtained from the 12 hours' data before 21:00 UT on 8 November 2000.

There were 373 muons plus and 261 muons minus out of the 634 muons in sky cell No. 48 and in the 8.39 min live-time bin at 00:07 UT on 9th November 2000. The charge ratio of muons was about 1.43 and the distribution of their momenta up to 100 GeV/c is shown in Figure 6.

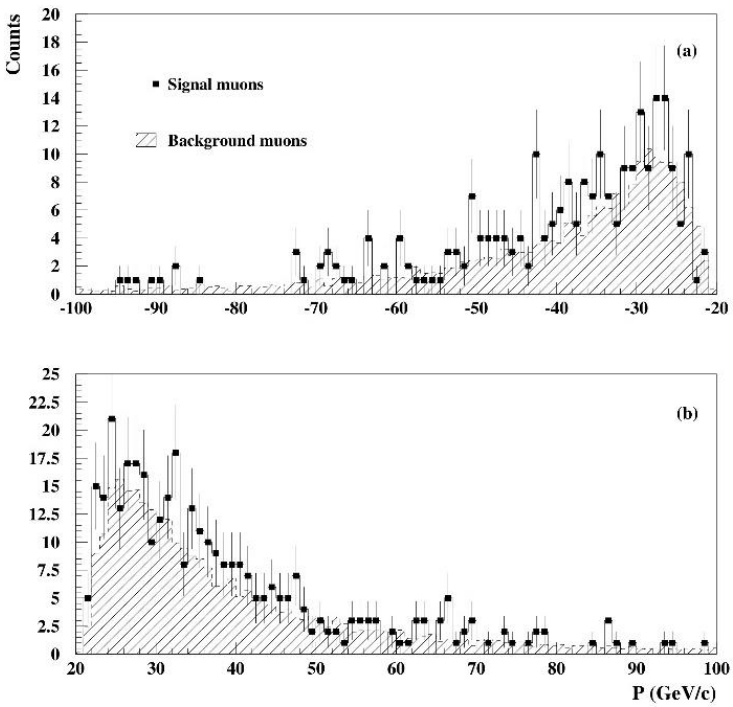


**Figure 6.** Momenta distribution of muons in the cell No. 48 and in the 8.39 min live-time bin at 00:07 UT on 9 November 2000. (**a**) Muon minus momenta and (**b**) muon plus momenta.

The sigma distribution of 59 sky cells in the 8.39 min live-time bin at 00:07 UT on 9 November 2000 is shown in Figure 7. It is obvious that the most significant cell appeared in the sky cell No. 48.

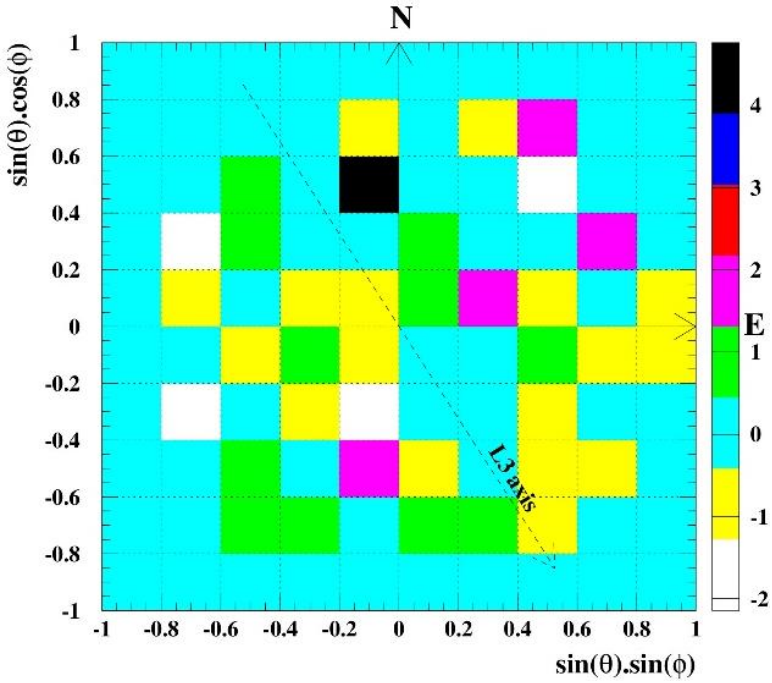


**Figure 7.** The sigma distribution of 59 sky cells in the 8.39 min live-time bin at 00:07 UT on 9 November 2000.

## 5. Discussion

We found an excess of 4.7σ in 1 of the 59 sky cells with the selected live-time binning of 8.39 min. The total number of trials was equal to the number of cells timing the number of time window selections. In this searching process, the total number of trials was estimated as 59 × (9 + 5) = 826. Here, the 9 corresponds to the number of trials to find the start bin within 00:00–00:10 UT—which had a large number of events over the mean and should be followed by the other two 83.9 s live-time bins, which also had a higher number of events than the mean—and the 5 corresponds to the 5 time period combinations to obtain the 8.39 min live-time bin. Based on the total number of trials, we could estimate that the probability for such an excess being due to a background fluctuation was about 0.1%. Using the same event selection criteria, and the same time binning and direction binning, five days' data (5, 6, 7, 10, 11 November) were independently analyzed with the 'running mean' method. The result confirmed that no significant excesses other than 4.7σ were found, except for 8 November.

Using the air shower simulation code CORSIKA [37], a Monte Carlo simulation was carried out in order to estimate the primary energies of the solar protons which could have been at the origin of the observed excess. The simulation considerations were as follows: primary protons were assumed to be incident along the directions that made the produced muons appear in the direction of sky cell No. 48. Supposing this major SPE also had a soft solar proton spectrum such as the GLE of 14 July 2000, the index of the primary power law was also set to −6 above 20 GeV. The simulation result showed that about 90% of the recorded muons were produced by primary proton energies ranging from 40 GeV to 200 GeV, with a most probable energy of ~74 GeV. The highest energy of the protons was up to about 1000 GeV.

An upper limit of primary proton flux was also estimated for this excess. Sampling a proton flux with a power index −6 and penetrating into the atmosphere from directions around the sky cell No. 48, muons were produced and traced as reaching the surface by the Monte Carlo program. A centered area around the muon chambers was marked off on the

surface. This area needed to be large enough to contain the air shower cores in order to ensure a very small loss of muons (less than 1%). Each muon in this area was traced through the overburden and the muon chambers and reconstructed using the same program as for the data. For the background, the same simulation procedure was performed except for changing a power law index from −6 to −2.7 for a primary cosmic ray spectrum. Since the primary proton flux was known, we could calculate an upper limit of primary solar protons by comparing the observed data with the simulated data. The flux upper limit of the solar proton beam entering the upper atmosphere around the direction of the sky cell No. 48 may have been I ($E_p \geq 40$ GeV) $\leq 9.2 \times 10^{-3}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (90% c.l.). This value is same order as the one estimated for the 14 July 2000 event [24,25], and is consistent with the valuations in other studies [38]. It should be noted that the flux upper limit estimated here with the hypothesis of the energy spectrum of power law indices −6 and −2.7 is in a certain direction, not in full space.

There were no abnormalities in the experimental environment during November 2000. The L3 muon spectrometer was still running stably. Furthermore, the background from the collision events completely disappeared because the LEP positron–electron collider stopped running after the end of October 2000. It was because of this background that about 2/3 muon data were cut off in the event of 14 July 2000 [24,25]. So, the amount of muon data for the 8 November event increased by about three times from the 14 July event. Until that day, for this muon excess, any other related sources had not been found except for the solar flare of 8 November 2000.

The event of 8 November 2000 is the largest SPE we have identified, except for 16 GLEs in solar cycle 23. It should still possess the following features, like most GLEs: a related flare located in the Western Hemisphere of the Sun; a shock driven by a fast wide CME for particle acceleration; and an accompanied radio-type II/IV burst [13,36]. A location map of 00:07 UT on 9th November 2000 is drawn in Figure 8. In this drawing, the curved–dashed thick line represents shocks driven by large-tagged eruptions, expressed as a dashed thin line, and the curved solid lines connecting the Sun to the Earth are the Parker spiral field lines whose tangent parallel lines near the earth are at a 45° angle with the Sun–Earth line.

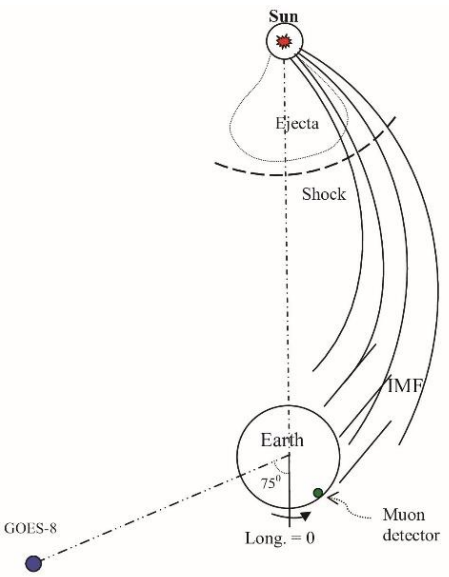


**Figure 8.** Schematic configuration of the relative positions of the Sun, Earth, satellite GOES-8 and L3 + C muon detector at 00:07 UT on 9th November 2000. The curved–dashed lines indicate the ejections and ejection-driven shocks. The Parker spiral field line connects the Sun to the Earth and its tangent near the Earth along a roughly 45-degree angle with the Sun–Earth line, which indicates the interplanetary magnetic field (IMF) direction. The prime meridian at Greenwich (longitude = 0) is just at the reverse direction of the Sun–Earth line.

It has been reported that anti-sunward detectors may still see high-energy solar protons in some extreme events. For example, the earliest arriving particles were detected by stations observing the Sun during the GLE of 28 October 2003 [39]. In the case of the 8 November event, it is understood that the L3 muon detector had a count excess because it was located slightly close to the sun, but not entirely near the sun.

Why did NMs not respond to this event? There are a wide variety of explanations. A typical method is to compare this event with other GLEs, e.g., GLE63 [36]. Both of them are similar in characteristics, except for the latter being a GLE and the former not. The main inferences drawn from the comparison are solar proton energies being only slightly above 700 MeV, CME-shock formation at a great height, anisotropic solar protons, and other source factors.

Our possible explanations are as follows. Due to being quite anisotropic, the relativistic solar protons usually arrive at the Earth in a narrow spatial direction, that is, forming a solar proton beam. Ground-based NMs as integrating detectors are usually not sensitive to these particle beams if their flux is not enough large. Even if detected, there may be a hidden registration GLE or a small GLE [40,41]. However, for those muon detectors with directional resolution, it is still possible to register these particle beams if their flux in some direction is large enough. In fact, no excess was observed during the 8 November event after the full-space overall (without space division) search was first performed. This means this small excess from the sky cell No. 48 was not able to be detected by NMs. It is difficult to simulate the particle trajectories of this event because of the lack of NM data and the limited data of the satellite-borne detectors.

## 6. Conclusions

In the solar proton event of 8 November 2000, an excess of 99 muons with $E_\mu \geq 20$ GeV over a background of 535 was observed in a particular sky region, lasting from 0:07 to 0:16 UT on the 9th. The chance probability for such an excess to be a background fluctuation was about 0.1% in this search. It was time-coincident with the peak increase observed by the satellite-borne detector GOES-8 during the impulsive phase of the solar flare. If the excess was really induced by solar protons, the observation indicates that solar protons with energies greater than 40 GeV were required to produce the excess. If so, this may be the second evidence of solar protons above tens of GeV in major SPEs without GLEs since 1971.

This study shows that a high directional resolution muon spectrometer at a shallow depth may detect high-energy solar proton beams which are not able to be recorded by NMs. This seems to show that a major SPE without a GLE may also produce GeV solar protons.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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