A Proposed Observation to Study the 'Knee' Composition from Underground Multimuon Events

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Abstract

An approach to increase the sensitivity in the study of the chemical composition in the 'knee' energy region of cosmic rays by setting up a detector array in a shallow depth underground to observe multimuon events is proposed.

1 Introduction

It is commonly thought that the appearance of the 'knee' in the cosmic ray all-particle spectrum might mainly be related with the origin, acceleration and propagation of galactic cosmic rays. In these aspects the different models are known to predict different chemical compositions of cosmic rays at the 'knee' energies, and should be verified by the experimemtal evidence of the composition. This topic has been discussed for decades as one of fundamental problems of cosmic ray physics. In recent years, in addition to many old observations done by extensive air shower (EAS) arrays and mountain emulsion chambers, some new experimental efforts have been devoted to this topic. Examples are the multiparameter measurement of EASs [1], the direct measurement of shower maxima by Cherenkov radiation [2] and underground multimuon measurements [3].

In an EAS muons are decay products of hadrons produced in hadronic and nuclear interactions that are originally induced by a cosmic ray nucleus incident on the atmosphere. For incidences of different nuclei with the same energy, as commonly recognised, the number of muons, the lateral distributions and their energy spectra are statistically different. In this work we will propose an approach aiming to utilise this information as much as possible to increase the observational sensitivity of the composition in the 'knee' region from the underground multimuon events.

2 Basic Considerations

Figure 1 shows two randomly chosen events produced by a proton and an iron nucleus from our Monte Carlo simulation (for details, see Section 4). They are examples of multimuon events with an energy of 5 000 TeV, just at the 'knee'. In the simulation E_{min} is taken to be 50 GeV. It is seen that, compared with the proton event, muons in the iron event have the following features: larger total number, less concentrated in the core, and a smaller number density gradient in the lateral distribution. These features result naturally from the larger cross-section for the iron event (and the higher height of the first interaction in the atmosphere), the lower average energy of mesons (and larger number as well as larger angular spread of muons). In the nucleus incidence case, its fragmentation also contributes a further lateral spread. Besides, a smaller energy density gradient in the lateral distribution for iron events than for proton events is expected.

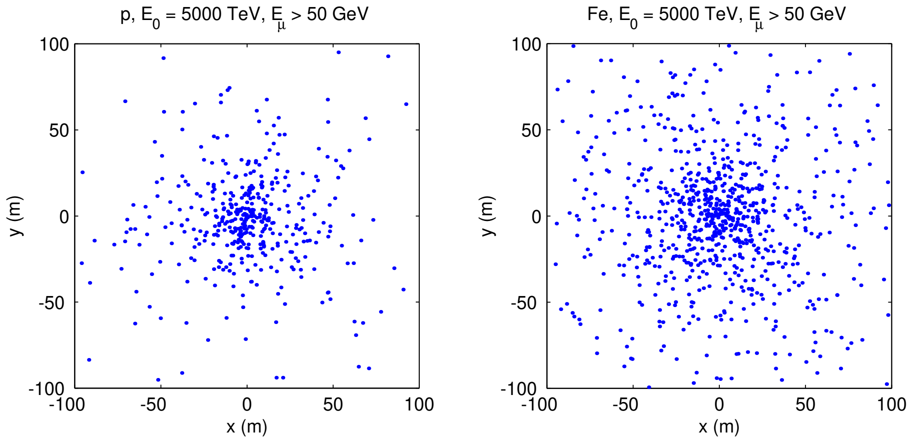

Figure 1: Examples of multimuon events with energy 5000 TeV, showing how muons (with energy higher than 50 GeV) distribute laterally for cases of proton and iron incidence.

These features can be further seen in Figure 2 which are from a sample of Monte Carlo events obtained in the energy region $10^{15} - 10^{16}$ eV. We are interested in the differences both in the absolute values and in the slopes of proton and iron distributions.

In order to observe these differences experimentally it is important to utilise this information in the design of the experiment. Our basic demands to the proposed observation are:

- having a larger detector area and setting up the detector at a shallower depth undergound to record more muons;

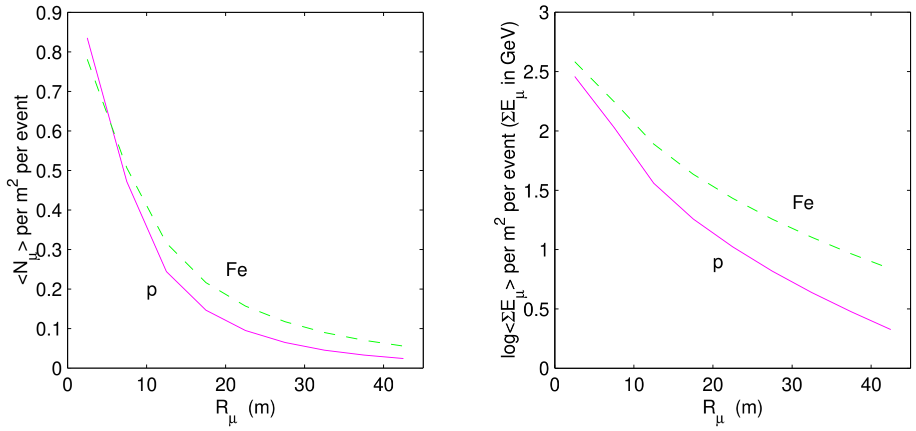

Figure 2: The differences in the radial gradients of theaveraged number density (left) and averaged energy density (right) of muons from samples induced by protons and iron nuclei in the energy region of 10^{15} eV -10^{16} eV, respectively.

- having a good position resolution and multi-track reconstruction efficiency to obtain a more precise number of hitting muons;
- being able to choose events with the shower core hitting an area inside or very close to a detector and to measure the gradient with its closest neighbouring detectors;
- being able to measure energies of high energy muons with some resolution.

Besides these, minimising the cost is always a point to be considered.

3 Detector Design Considerations

Based on the above requirements, the whole facility is proposed to consist of 7 identical detectors, corresponding electronics and data acquisition systems, and is planned to be set up at a depth of about 50 m underground, arranged as a hexagonal array with one detector located in the centre and other six in the six vertices with a mutual distance of about 35 m (Figure 3-1).

Each detector has an area of 100 m^2 (10 m$\times$10 m), and is composed of 12 layers. The first and the last layers are RPCs (Resistive Plate Chambers), and ten layers in between are TRDs (Transition Radiation Detectors composed of transition radiation radiators and proportional counters). The total thickness of a detector is about 3 m (Figure 3-2).

The RPC provides a good position resolution (depending on how narrow a readout strip is used), and at the first stage a 5 cm position resolution, or about 1 degree angular resolution, is required. Our simulation shows that on the average only 0.1% of muon pairs in an EAS event in the energy region $10^{15} - 10^{16}$ eV will have a mutual distance shorter than 5 cm. The RPCs also provide timing information of particle hitting, which is used as event trigger.

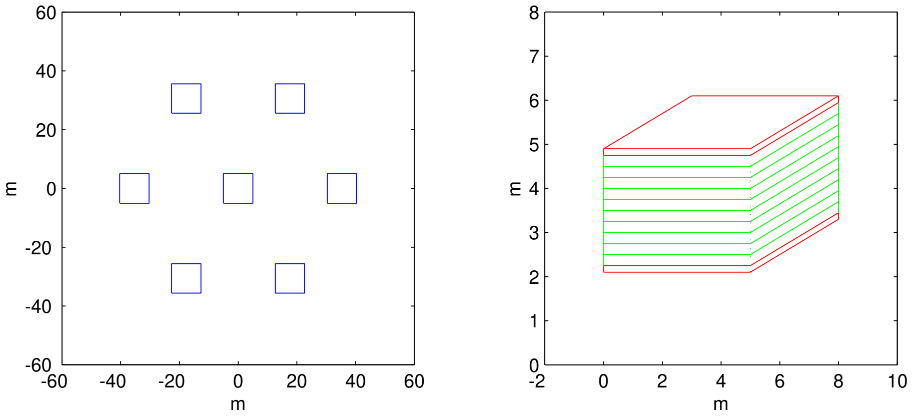

Figure 3: A schematic display of the detector array configuration (3-1, left) and of a quarter of a detector (3-2, right). The first and the last layers are RPCs, while the ten middle layers are TRDs.

Each TRD has a rectangular cross-section of 10 cm×25 cm. On its uppermost part (10 cm×15 cm) a radiator is positioned. When a charged particle with high energy passes through the radiator, the radiated X-rays are measured by the same TRD in the lower part, i.e., a proportional counter (10 cm×10 cm), to avoid absorption. When the energy of a muon is higher than about 100 GeV, its Lorentz factor is determined by the amount of X-rays it emits. Using the cluster-counting method [4] to determine the Lorentz factor, the relative error of the energy determination for 100 GeV muons is estimated to be about 100%. This error is not low enough, but it will nevertheless provide important energy information.

4 Brief Description of the Monte Carlo

We use the Monte Carlo code [5] developed in Beijing - Hong Kong for the EAS simulation. For the hadron-hadron collision the minijet model is used, well adjusted to reproduce the existing hadron collider data. A superposition model is adopted for the nucleus-nucleus interactions. For hadron-air nucleus inelastic interactions an $E^{0.05}$ cross section law is taken to fit other cosmic ray data.

All muons with energies higher than 50 GeV are traced until they reach the sea level. When they penetrate underground an average energy loss including the ionisation, bramsstrahlung, pair production and photonuclear interactions is taken into account [6]. The multiple scattering is also evaluated [6]. The fluctuation of muon energy loss in the rock is temporarily ignored, as well as single large angle scattering.

At this stage the detector efficiency is set to 100%. We assume that the multimuon events can be well reconstructed and the number of muons can be counted correctly. In the event statistics concerning the energy only those muons with $E_\mu > 100$ GeV are included, meaning that we only consider those muons whose energy could be measured by TRD. However the energy error is not displayed in the following figures. The readers are reminded that a relative error about 100% exists.

5 Event Selection

First we define the 'central' detector and the 'outer' detectors. Any one detector in the seven can be the 'central'. If the detector in the centre of the array is the 'central' one, the six surrounding ones are 'outer'. If any one of the other six is the 'central' one, its three nearest neighbours are 'outer'.

The event selection criteria are:

(1) There is at least one muon hitting in every 'outer' detector;

(2) The number of muons hitting the 'central' detector is equal to or larger than w times the number of muons hitting any one of the 'outer' detectors.

For w=1, 2, 3, 4, and 5, the efficiency versus the core position to the centre of the 'central' detector is seen in Figure 4 obtained from a sample of proton incidence in the energy region $10^{15} - 10^{16}$ eV. In the following analyses we will use w=5. This selects those events with cores more close to the 'central' detector, but gives a smaller trigger efficiency.

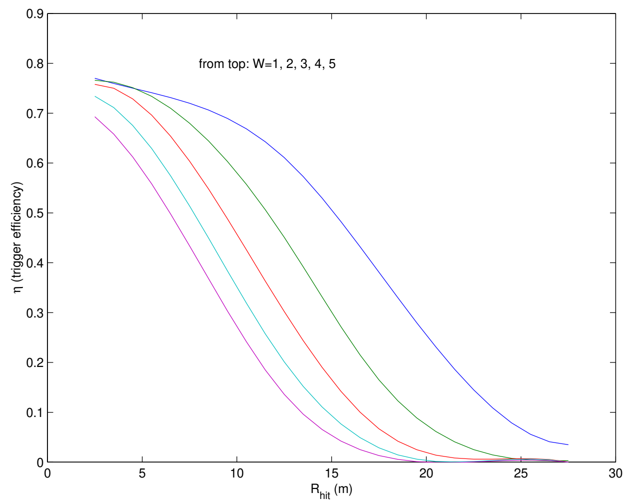

Figure 4: The efficiency with different w (for definition, see the text) versus the core position to the centre of the 'central' detector obtained from a proton sample at the energy region of $10^{15} - 10^{16}$ eV.

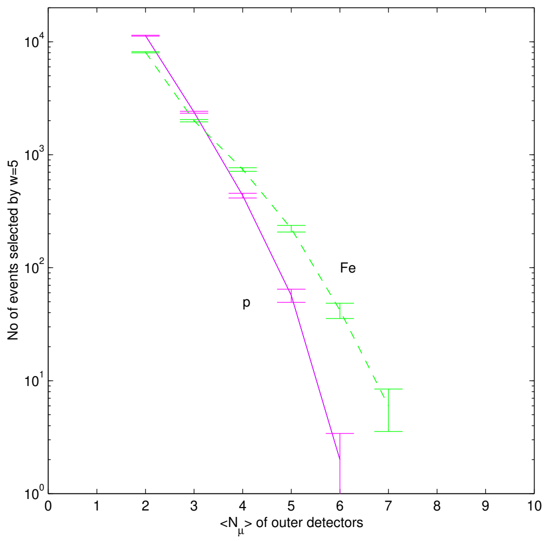

Figure 5: Taking w=5, the distributions of the average number of muons in the 'outer' detectors for cases of proton and iron incidence with energy $10^{14} - 10^{15}$ eV.

In order to concentrate more on the detection of the 'knee' region events, the contamination of those multimuon events that satisfy the selection criteria (1) and (2) but come from lower energy region (say, from $10^{14} - 10^{15}$ eV) must be ruled out. Fortunately, when using w=5 in this energy region, the distributions of the average number of muons in the 'outer' detectors for both proton and iron cases decrease rapidly as shown in Figure 5. So these events could be cut by adding a new criterion:

(3) The $< N_\mu^{outer} >$ must be equal to or larger than 7.

6 Result Expectation

In both proton and iron incidence cases we dropped 240 000 simulation events with energy from 10^{15} eV to 10^{16} eV in a circle with a radius of 55 m from the centre of the detector array. In these event samples the zenith angles were taken from 0 to 20 degrees only. This sample is equivalent to a data set of 500 days of operation, not including those events having larger zenith angles, which are also useful for the composition study.

In Figure 6 the primary energy spectrum sampled and the primary energy spectra for events selected by $w = 5$ are plotted together.

More iron events than protons are seen to be selected. This is because more proton events than iron events are cut by the criterion (3). For the selected events the core position distribution is seen in Figure 7 where R is the distance

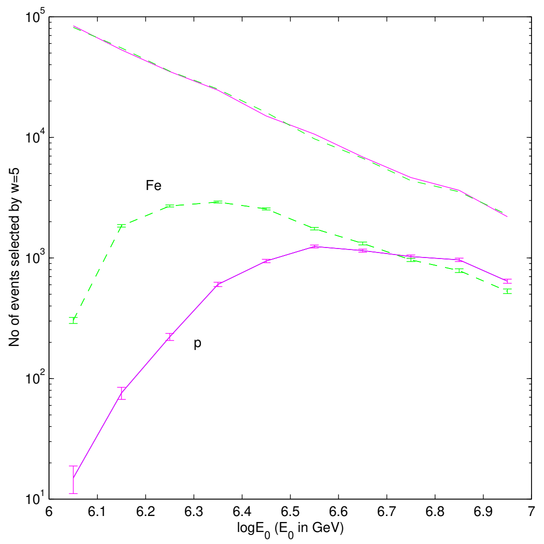

Figure 6: The primary energy spectrum sampled and the primary energy spectra for events selected by $w = 5$ for both proton and iron cases.

from the array centre.

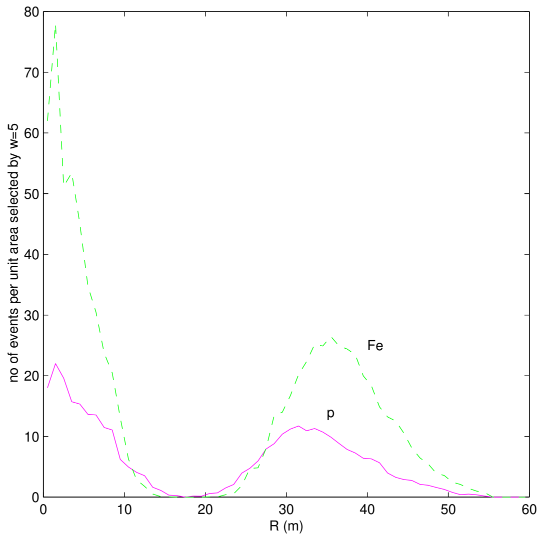

Figure 7: The core position distribution for the events selected by w=5, where R is the distance counted from the array centre.

The 2-dimensional distributions of the core positions are shown in Figure 8 providing evidence that using w=5 could select events with core position inside or very close to the 'central' detector. Therefore, the composition sensitivity existing in the core region and in the lateral gradients could be kept in the selected event samples.

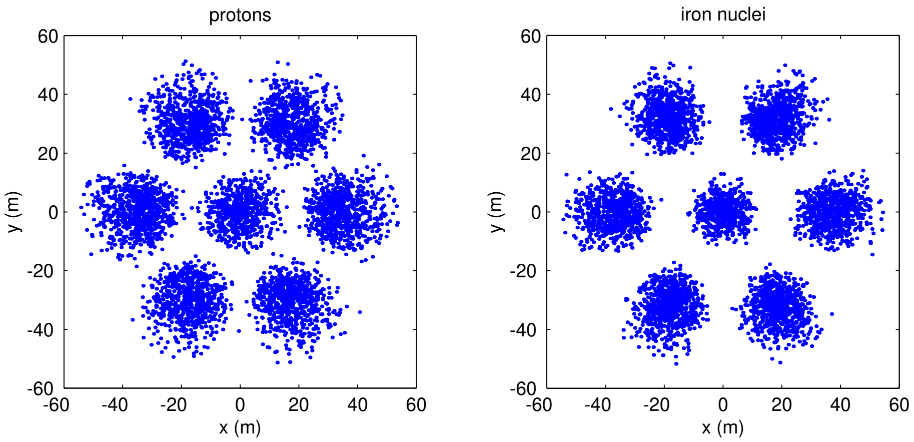

Figure 8: The 2-dimensional distributions of the core positions of events selected by w=5 in the proton and iron cases.

The results are seen in Figs. 9, 10 and 11. First, the distributions of the ratios of the 'central' detector over the average of 'outer' detectors for the number of muons and the total energy (only the part being measured by TRD as mentioned) of muons are shown in Figures 9-1 and 9-2, respectively. The slopes of p events and Fe events are seen to be significantly different.

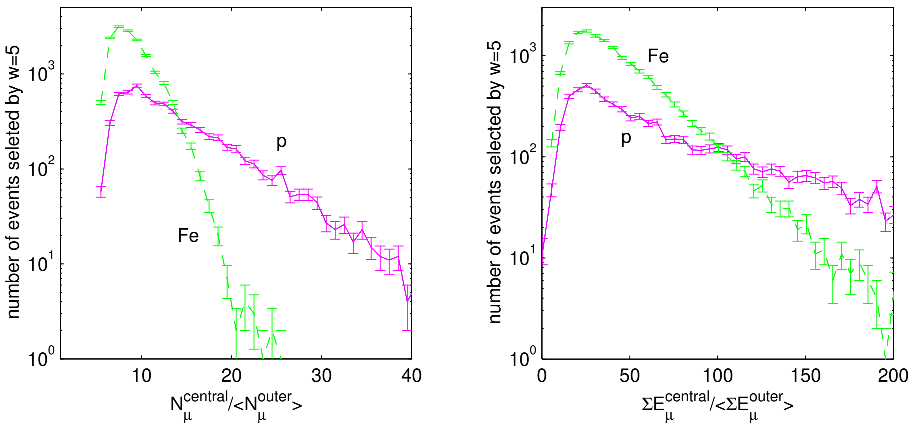

Figure 9: The distributions resulting from the selection w=5 of $N_\mu^{central}/<N_\mu^{outer}>$ (Figure 9-1, left) and of $\Sigma E_\mu^{central}/<\Sigma E_\mu^{outer}>$ (Figure 9-2, right). The energy region is $10^{15} - 10^{16}$ eV and the zenith angles within $0° - 20°$.

Figure 10 shows distributions of the muon number and of the total muon energy in 'central' detectors, respectively. Considering the lower energy resolution of the TRD, Figure 10-2 may not be able to provide much information on the composition.

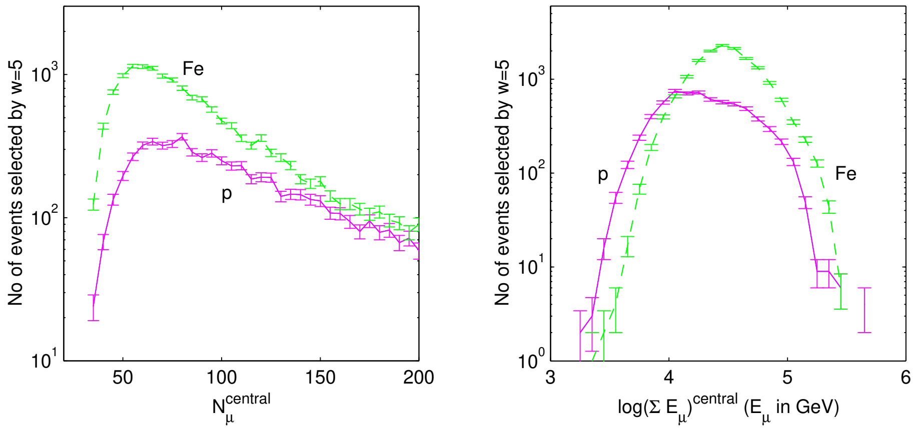

Figure 10: Same as in Figure 9, but for $N_\mu^{central}$ (10-1, left) and $\Sigma E_\mu^{central}$ (10-2, right)

Figure 11 shows the same distributions as in Figure 10 but for 'outer' detectors. It is seen that from the comparison between Figure 10 and Figure 11 that the 'outer' detectors may provide more composition information than the 'central' detectors.

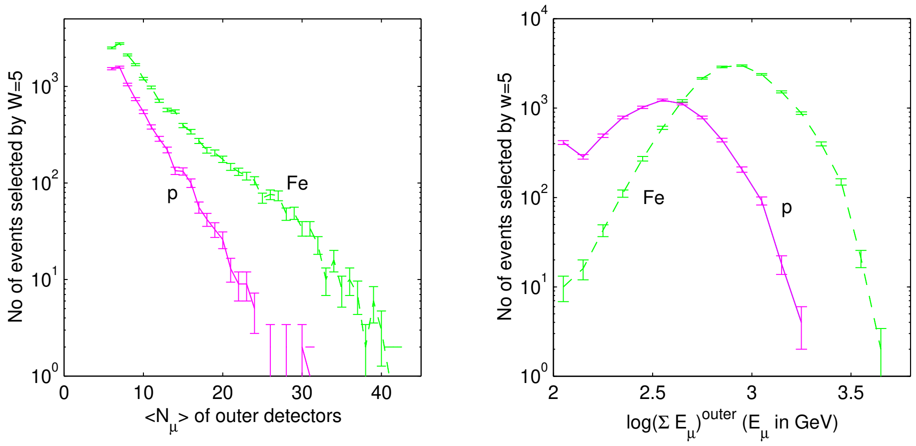

Figure 11: Same as in Figure 9, but for N_μ^{outer} (11-1, left) and ΣE_μ^{outer} (11-2, right).

7 Discussion

(1) We have removed the contamination coming from the lower energy region ($10^{14} - 10^{15}$ eV). The contamination from higher energy region ($10^{16} - 5 \times 10^{16}$ eV) is also analysed. It cannot be removed in a straightforword way. But due to the much lower event flux in higher energy region the distributions of Figures 9, 10, and 11 are shown not to be essentially influenced by it.

(2) The results of the simulation for zenith angles from 20 to 40 degrees also show a sensitivity similar to Figures 9, 10, and 11. Due to the larger acceptance 240 000 incident events corresponds to an exposure of 200 days in this case.

(3) If the energy resolution of the TRD cannot be improved or in a real case is even worse than the value mentioned in Section 4, the composition sensitivity shown in Figures 9-2, 10-2 and 11-2 will be very much limited. It appears to us that the stress point of this proposal will be the number counting of arriving muons and the reconstruction of multimuon events. From Figure 9-1, an event containing 200 (or more) muons that hit the 'central' detector is requested to be reconstructed. For this aim, the number of layers as well as the number of readout strips of RPC might be required to increase. This will be determined after a detector R&D and a detailed detector simulation.

(4) The 50 m depth, the 100 m^2 single detector area, the 35 m distance between individual detectors and the value$w = 5$ are all chosen on the basis of simplified quantitative considerations. More analyses are needed to achieve optimal values.

(5) We have to consider the model dependence of the results since all results were obtained by a special Monte Carlo code that uses the minijet model. The analysis of the differences existing in the features of proton events and iron events as discussed in Section 2 should be qualitatively correct for any interaction model. Some model dependence may exist. It may change the slope and the intensity of Figures 9, 10 and 11 somewhat, and thus needs to be checked. Importing more models and doing the same types of simulations and analyses will be the next step. As a better way for the self-calibration of a model used it is suggested to test, after taking all detection efficiencies into account in the Monte Carlo data, whether the experimental data really cross at the crossing point of proton and iron curves as shown in Fig 9-1 (and possibly in Figure 10-2 and Figure 11-2).

8 Summary

We propose an approach to observe the core of multimuon events in the 'knee' region at a shallow depth underground. For the event selection criterion w=5, the distributions of the number of muons and its lateral gradients have a higher composition sensitivity, and the distributions of the total energy of muons (with E_μ >100 GeV) and its lateral gradients also have a rather high sensitivity.

However, considering the lower energy resolution by using TRDs to measure energies, the former method is clearly preferable.

This is only a preliminary concept design of an underground multimuon experiment. A more detailed design relies on the detector R&D, putting the detector efficiency into the Monte Carlo, evaluating the errors of the muon number counting and the energy measurement, and studying how to reach a high reconstruction efficiency of multimuon events.

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