

# Detecting Ultra High Energy Muons in Iron Calorimeter Detectors

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The origin of the knee in the energy spectrum of cosmic rays is still an unresolved problem. It arises because of the change in the slope of cosmic ray energy spectrum at the energy  $(4 - 7) \times 10^{15} eV$ . Existing detectors are insensitive to energies of secondary muons, allowing for the possibility that there which there may be missing energy carried away by the undetected particles produced at the knee. We model the cosmic ray muon flux above the knee by invoking new physics without relying on any specific model. With a large mass iron calorimeter(ICAL) detector one would be able to measure the energies of these muons using the pair meter technique. We estimate the event rates of muons in such a detector which would signal new physics, the number of interactions and their energy distribution, taking into account the effect of surrounding rock.

## 1. Introduction

Cosmic rays are observed in a wide range of energies. Energy of the cosmic rays ranges from  $eV$  to  $10^{20} eV$ . The energy spectrum of cosmic rays obeys a power law over a many order of magnitude. This power law behaviour breaks at the knee which occurs at energy  $\simeq 4 \times 10^{15} eV$  and again at the ankle which occurs at energy  $\simeq 5 \times 10^{18} eV$ . Let's consider the differential flux  $dN/dE \sim E^{-\alpha}$ .  $\alpha$  takes value 2.7 until knee. After the knee  $\alpha$  changes to 3.1. This change in the slope of the cosmic ray spectrum at the knee is not clearly understood so far because above the knee energy, energy resolution of the ground array experiments is very poor.

Interaction of high energetic primary cosmic rays with the air nuclei in the atmosphere develops extensive air shower with electromagnetic, hadronic and deeply penetrating muon component. Basically energy of primary particles is distributed among these components. In most of the ground array experiments we measure number of secondary particle produced such as electrons, muons etc but not the energy. The knee problem can be solved in two ways. First way is to consider a change in the composition of the primary cosmic ray flux near knee energy. Second way may be the creation of new heavy particles at knee energy. For a review of several models, we refer the reader to [1]. Here we will concentrate on the second case. For the measurement of energy of muon we use pair meter technique. This technique is useful only when we have large-scale iron calorimeter detector. Future Indian neutrino observatory(INO) experiments will be able to measure energy of muons more accurately.

## 2. Interaction of Muons With Matter

A better understanding of muon energy loss in any medium at high energies is required for the energy measurement. Muon loses its energy through ionization, bremsstrahlung, pair production and photonuclear scattering at high energies. The direct production of electron-positron pairs dominate other processes at low energy transfers and complete screening [2, 3]. In the approximation,  $\frac{\epsilon}{E} \ll \frac{2m_e}{m_\mu}$  and  $\epsilon \gg 2m_e 189\sqrt{\epsilon} Z^{-1/3} \simeq 0.3Z^{-1/3} GeV$ , integral cross section for pair production is given by

$$\sigma_i(E, \epsilon) \simeq \frac{7\alpha}{9\pi t_0} \left( \ln^2 \left( \frac{\kappa m_e E}{\epsilon_0 m_\mu} \right) + C \right), \quad (1)$$

where  $C \simeq 1.4$ ,  $\epsilon$  is the energy transfer,  $E$  is the muon energy,  $m_e$  is the mass of electron,  $m_\mu$  is the mass of muon,  $\alpha = 1/137$ ,  $\kappa \simeq 1.8$  and  $t_0$  is the radiation length (r.l) which is

$$t_0 = \left( \frac{4Z(Z+1)}{A} \alpha r_0^2 N_0 \ln(189Z^{-1/3}) \right)^{-1}, \quad (2)$$

where  $A$  is the atomic weight,  $r_0$  is the classical radius,  $N_0$  is the Avagadro number and  $Z$  is the atomic number.

### 3. Flux Model

Here we describe three flux models.

As a model 1 we consider differential conventional muon fluxes from the decay of pion and muon decays[4] which is given by,

$$\frac{dN}{dE} = \frac{N_0 E^{-\gamma-1}}{1 + AE} \quad (3)$$

for  $E < E_0$ .

$$\frac{dN}{dE} = \frac{N'_0 E^{-\gamma'-1}}{1 + AE} \quad (4)$$

for  $E > E_0$ . For conventional flux  $N_0 = 0.2$ ,  $N'_0 = 0.2$ ,  $\gamma = 1.74$ ,  $\gamma' = 2.1$ ,  $E_0 = 5.3 \times 10^5$ ,  $A = 0.007$ .

As we explained in the Introduction of this paper that we would be looking at a option for the explanation of cosmic ray knee in which new processes dominates the dynamics at the knee energy. In this option we assume that some new particle of mass  $\approx TeV$  are produced at knee because center of mass energy of the interaction of primary cosmic rays with the air nuclei at knee is of the order of TeV. This might be responsible for the change of the cosmic ray spectrum slope at knee.

We can calculate the missing energy by comparing the following two fluxes at knee energy  $E_0$ . Assumed two energy spectra with different exponent, we write

$$N_1 = N \left( \frac{E_0}{E_1} \right)^{\gamma_1} \quad (5)$$

and

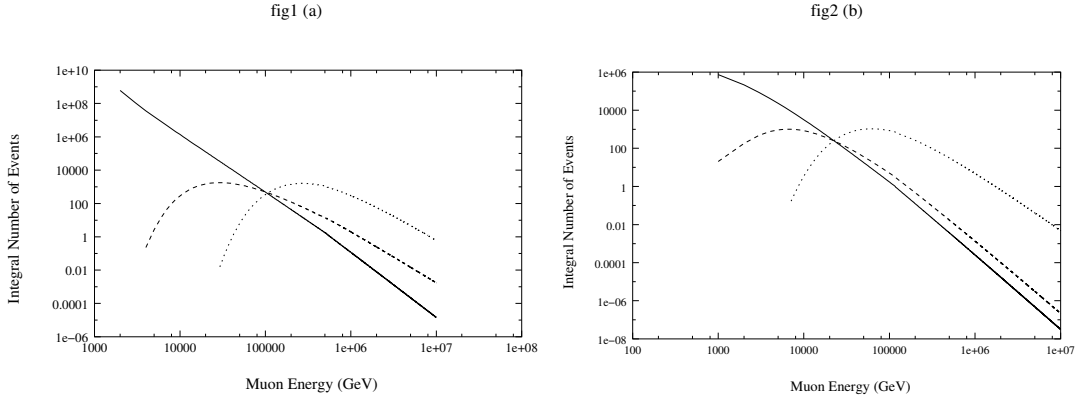
$$N_2 = N \left( \frac{E_0}{E_2} \right)^{\gamma_2}, \quad (6)$$

where  $N$  is the particle density at knee energy. By comparing the Eq. 5 and Eq. 6, we get missing energy  $\delta E$  as

$$\delta E = E_1 \left( 1 - \left( \frac{E_0}{E_1} \right)^{\delta\gamma/\gamma_2} \right) \quad (7)$$

where  $\delta E = E_1 - E_2$  and  $\delta\gamma = \gamma_2 - \gamma_1$ . For  $E_0 = (4-7) \times 10^{15} eV = (4-7) PeV$ ,  $\gamma_2 = 2.1$  and  $\delta\gamma = 0.4$ .

In order to explain the knee puzzle, this extra energy must be taken away by unobserved particles as we don't measure the energy in ground array experiments. In the framework of Standard Model(SM) the unobserved particles can be three neutrinos and muons. Among these particles muons can be detected with higher probability. To estimate the event rate of muons in Iron Calorimeter detectors we need to know the muon flux after including new processes at the knee. Here one searches for models beyond SM where one can accomodate



**Figure 1.** Fig.1(a) represents the number of events vs. muon energy for 100 KTon ICAL detectors in 3 years of exposure time for flux model 1(solid line), model 2(dotted line) and model 3(dashed line) without degradation of muon energy due to surrounding rock. Fig.1(b) represents the number of events vs. muon energy for 100 KTon ICAL detectors in 3 years of exposure time for flux model 1(solid line), model 2(dotted line) and model 3(dashed line). with taking into account surrounding rock effect. Width of rock is taken to be  $4 \times 10^5 g/cm^2$ .

such a scenario. Without knowing the details of the model here we calculate energy spectrum of muons by considering two limiting cases[5]. Then any model lies in between these two limiting cases could be a reasonable model to solve the knee puzzle.

In first limiting case we construct our muon flux where three neutrinos and only one muon produced in the process. Then energy carried away by the muon is  $\delta E/4$ . We call this as model 2. In second limiting case we consider apart from three neutrinos, ten muons are produced in the process. In this case energy carried away by the muon is  $\delta E/40$ . We construct muon flux for this case and call this as model 3.

#### 4. Event Rate

Number of integral events in ICAL detectors can be expressed as

$$Eventrate = \int_{E_i, h}^{\infty} \sigma_i(E, \epsilon_0) \frac{dN}{dE_\mu} \times \rho \times A \times T \times t, \quad (8)$$

where  $\rho$  is the density of the material, A is the area of the detector, T is the thickness of the detector and t is the exposure time. For INO ICAL detectors, we have taken  $A = 13.5 \times 10^6 cm^2$ ,  $T = 1310cm$  and  $\rho = 7.87g/cm^2$  for steel. This all amounts to 100 Kton ICAL detector.

#### 5. Discussion

Results of the event rate calculations for all three models are given in Fig. 1(a) and Fig. 1(b). We can observe clearly at muon energies of 100 TeV order of thousand events for model 2 and order of hundred events for model 3 in three years of exposure time of the 100 Kton ICAL detectors. With the conventional flux (model 1) one can observe at muon energies of 100 TeV few hundred events in 3 years of exposure time of the 100 Kton ICAL detectors.

**References**

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