Probing Very High Energy Prompt Muon and Neutrino fluxes and the Cosmic Ray Knee via Underground Muons

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Abstract

We estimate event rates and demonstrate the observational feasibility of very high energy muons (1 TeV-1000 TeV) in a large mass underground detector operating as a pair-meter. Such measurements will improve our understanding of the prompt contribution to ν_e, ν_μ and μ fluxes in present and future ultra-high energy neutrino detectors and observed 'knee' in the cosmic ray spectrum.

1 The Cosmic Ray Spectrum and Uncertainities in Muon and Neutrino fluxes

Cosmic ray studies, with the spectrum extending over ten decades in energy, have proved to be fertile terrain for furthering our knowledge of both astrophysics and particle physics (reviews may be found in [1]). The cosmic ray spectrum, characterised by a steeply falling power-law behaviour over its entire range, exhibits two transition regions where the slope changes noticeably:

- A steepening of the spectrum occurs around $E \approx 5 \times 10^6$ GeV, *i.e.* the index γ describing the power-law behaviour of the differential flux, $dN/dE \sim E^\gamma$, changes from $\gamma \approx -2.7$ to $\gamma \approx -3.1$; leading to the feature called the 'knee'.
- A flattening of the spectrum occurs around $E \approx 5 \times 10^9$ GeV, *i.e* at the "ankle"; with the index γ changing back to $\sim 2.4 - 2.7$. Beyond the ankle, in the realm of ultra high energy cosmic rays, data is sparse and conflicting, not free from ambiguities.

The physical reason for the existence of the knee is at present an unresolved problem of great significance to understanding the origin of galactic cosmic rays. Its worthwhile to mention here is that any new physics effect to explain the knee would be overshadowed by the uncertainties (in the knee region) in the CR composition and prompt muon and neutrino fluxes.

When present data culled and correlated, appear to favour one or more astrophysical reasons for the existence of the knee. These include it being a rigidity-dependant effect related to the

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(different) maximum acceleration energies for different nuclei either in the cosmic ray source itself or during the propagation process. Data from surface air-showers and optical detectors indicate, without being conclusive, that the average mass of the cosmic ray spectrum nuclei differs before and after the steepening at the knee. In particular, there appears to be some evidence[3, 4] that the composition is heavier above the knee region. If this is true, then, as discussed in [5], significant suppression of the very high energy ($\geq 10^5$ GeV) muon and neutrino fluxes resulting from CR interactions in the atmosphere and in the interstellar medium can occur.

A second major factor in determining the enhancement (or lack thereof) of muon and neutrino fluxes above several TeV are the uncertain magnitudes of the prompt (*i.e.* those resulting from prompt decays of charmed hadrons. At low energies, pion and kaon decays contribute to the muon and neutrino fluxes called conventional fluxes. But we approach $\sim$ TeV energies, the production of heavy short lived hadrons takes place. While upper bounds on the flux of muons and neutrinos have been provided by several experiments *e.g* LVD [6], AKENO [7] and AMANDA [8], they still allow for a very large possible range of prompt flux magnitudes.

Having emphasized the importance of muon energy measurements in the several TeV to several hundred TeV range, we proceed in the next section to study the potential of the *pair meter* method [9, 10, 11] as applied to such measurements made in a *large iron calorimeter* (50 kT)[12]. Since individual muon energies will become measurable using this technique, it will be possible to augment the sparse existing data on cosmic ray muons in the important range where they have *surface* energies of $\approx 5-5000$ TeV. We mention here that this range in *muon surface energy* roughly corresponds to a range of $50 - 5 \times 10^4$ TeV in *primary cosmic ray energy*, which is crucial to an enhanced understanding of the origin of the knee.

In this draft, we first provide a discussion of the pair-meter technique. We then calculate anticipated event rates for a 50 kT detector and demonstrate that even after accounting for energy losses in the surrounding rock, event rates can be appreciably large for the $1 - 1000$ TeV range, corresponding to *surface* muon energies in the range of several TeV to several PeV.

2 The Pair Meter Technique

The pair meter technique[9, 10, 11] skirts some of the disadvantages of traditional muon detectors by relying on a somewhat indirect method, *i.e.* the measurements of the energy and frequency of electron-positron pair cascades produced by the passage of a high energy muon in dense matter.

It is important to mention here that the capability and effectiveness of the pair meter method for high energy muons has been tested and demonstrated by the NuTEV/CCFR collaboration, as described in [13]. The calculations which follow are performed for a 50 kT iron calorimeter. Our prototype is based on the suggested design for INO; see [12] for details.

It is also relevant to remark here that the relative energy measurement error, $\delta E_\mu/E_\mu$ in the pair meter is given by

$$\delta E_\mu/E_\mu = \sqrt{\frac{9\pi}{28\alpha T}} \simeq \sqrt{\frac{137}{T}}\ . \tag{1}$$

For $v = (10^{-3} - 10^{-2})$, which is the range we focus on here, this allows a liberal tolerance for error in the measurements of individual cacade energies. We note also that the errors do not worsen with increasing muon energy, which is an important advantage of the pair-meter technique.

	Number of muons per solid angle entering the detector in 5 years					
$E_\mu(TeV)$	conv+TIG	conv	TIG	PRS1	PRS2	PRS3
1	1.035×10^7	1.03×10^7	37461	55482	95489	136871
10	52486	51282	1204	2952	5341	10443
50	770	696	74	236	431	1104
100	127	106	21	73	134	387
200	22	16	6	22	40	129
300	8	5	3	11	19	66
400	4	2	2	6	11	41
500	2	1	1	4	7	28
600	1.5	1	.5	3	5	20
700	1	.5	.5	4	7.5	31
800	.8	.35	.5	1.5	3	12
900	.65	.25	.37	1.25	2.5	10
1000	.5	.2	.3	1	2	4
10000	.0025	.0003	.0022	.007	.013	.08

Table 1: Number of muons per solid angle entering the detector over 5 years for various energies of the entering muon, E_μ.

		Number of cascades per muon for different thresholds E_0 in GeV								
E_μ	E_μ^s	5	10	20	50	100	300	500	1000	5000
1	6.1	3.08	2.56	3.78						
10	40.26	17.28	10.99	6.43	3.08	2.56				
20	83.16	25.3	17.28	10.99	5.34	3.08				
50	205	38.58	28.26	19.67	10.99	6.43	2.78	2.56		
100	407.58	50.63	38.58	28.26	17.28	10.99	4.58	3.08	2.56	
200	813	64.43	50.63	38.58	25.30	17.28	8.11	5.34	3.08	
300	1218	73.3	58.49	45.42	30.8	21.76	10.99	7.46	4.19	
400	1624	79.96	64.43	50.63	35.06	25.3	13.39	9.33	5.34	
500	2029	85.33	69.24	54.89	38.58	28.26	15.45	10.99	6.43	2.56
600	2435	89.85	73.3	58.49	41.58	30.8	17.28	12.47	7.46	2.58
700	2841	93.76	76.83	61.64	44.21	33.05	18.91	13.82	8.43	2.6
800	3246	97.23	79.96	64.43	46.56	35.06	20.4	15.06	9.33	2.72
900	3652	100.33	82.77	66.95	48.69	36.9	21.76	16.21	10.18	2.89
1000	4057	103.16	85.33	69.24	50.63	38.58	23.02	17.28	10.99	3.08
10000	40554	174.84	151.24	129.38	103.16	85.33	60.63	50.63	38.58	17.28

Table 2: Number of cacades above thresholds $E_0 = 5, 10, 20, 50, 100, 300, 500, 1000, 5000$ GeV per muon. Here E_μ is the energy of the muon in TeV entering the detector, and E_μ^s is its corresponding energy in TeV at the surface of the earth, assuming it traversed a depth of rock corresponding to $3.5 \times 10^5 gm/cm^2$.

3 Muon Fluxes

For our representative calculations of muon event rates, we have used the relatively conservative predictions for charm induced fluxes given in [14, 15]. The large variation in muon rates possible due to flux uncertainties even when these fluxes are used is amply reflected in our results, most noticeably in Table 2. One would expect much larger variations if the full range of prompt flux models available is used to calculate event rates.

The second set of representative prompt muon fluxes we use are calculated in [15] (henceforth referred to as the PRS1,PRS2 and PRS3 fluxes). The differences in the three fluxes originate in different choices of parton distribution functions(PDF) and factorisation ($\tilde{M}$) and renormalisation scales($\tilde{\mu}$) of the theory. Uncertainties in the conventional flux, unlike the prompt case, are not major. accomplish this.

4 Results and Discussion

We are now in a position to calculate the expected cascade events for a 50 kT detector in the energy range of interest discussed above. n_μ, the number of muons above a given threshold entering the detector per ster-radian for an exposure of t years,

$$n_\mu = \int_{E_{th}}^{\infty} dE_\mu \frac{dN}{dE_\mu} A \times t \ , \tag{2}$$

where A is the exposed area of a 50 kT iron detector. This is shown in Table 1. We note that while the number of entering muons for the lowest energy in Table 1, *i.e.* 1 TeV is very large, one also obtains an observable number, *i.e.* 1-3 events after integrating over solid angle (considering that there is no "back-ground" as such for such events) over the 5 year period even for $E_\mu = 1000$ TeV for the most conservative flux choice (TIG). These energies delineate the muon energy range accesible. The number of entering muons for all choices of PRS fluxes will be substantially higher, as shown. Even for the most conservative (TIG) flux choice, one expects good observational capability upto several hundred TeV.

The *total* number of cascade events per ster-radian $N_c(E_0)$ (above a given threshold E_0 and for a 50 kT $\times$ 5 yr exposure) is given by

$$N_c(E_0) = M(E_\mu, E_0) n_\mu \ , \tag{3}$$

where $M(E_\mu, E_0)$ is the cascade number calculated given in Table 1. From Table 1 and Table 2, we observe that this number is considerable for most thresholds, promising rich observational capabilities. For example, for the (most conservative) conventional+TIG flux model which we use as our benchmark, one finds that at even at muon energies of 1000 TeV,one can produce 51 events per solid angle for a threshold of 5 GeV and $\sim$1 event per solid angle for a threshold of 5000 GeV. Expectedly, the PRS models predict significantly more events compared to these estimates.

We have used the TIG flux as a benchmark to establish observability, since it leads to the most conservative event rate predictions. All other flux parametrisations lead to higher predictions. We note that even though TIG and PRS are not vastly different from each other in a qualitative sense since both are based on perturbative QCD inputs, their event rates in a large mass pair meter differ significantly. Indeed, the variations amongst fluxes in the same family(PRS1, PRS2, PRS3) are also large. Thus, the muon event rate can act as a soft (*i.e* not definitive, given the large uncertainties in the QCD predictions) discriminator between various prompt flux models and provide pointers to the physics input that should guide their development. Similarly, this rate provides a tool to better understand the present spectral uncertainities in the cosmic ray knee origin.

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