29th International Cosmic Ray Conference Pune (2005) **9**, 9–12

Precise simulation of secondary particle production and propagation in the atmosphere

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Precise simulation of secondary particle production and propagation in the atmosphere is a very important issue for the atmospheric neutrino oscillation studies. To this purpose a full 3-Dimensions Monte-Carlo simulation of particle transport in the atmosphere is used to compute the flux of protons, muons and neutrinos. Recent balloon borne experiments performed a set of accurate measurement of different particle flux at different altitudes in the atmosphere. This set of data can be used to test and improve the calculations for the atmospheric neutrino production. The simulation results will be reported and compared with the latest flux measurements. In the oral presentation and in the updated version of the proceedings it will be shown that the level of precision reached by these experiments could be used to constrain the nuclear models used in the simulation. The implication of these results for the atmospheric neutrino flux calculation will also be presented and discussed.

1. Introduction

With the rapidly increasing amount and statistical significance of the data collected by underground neutrino detectors [1], the precise calculation of the atmospheric neutrino flux is highly desirable. To this purpose, a 3 dimensional simulation describing the CR induced cascade in the atmosphere, particle propagation in the geomagnetic field, and interactions with the medium, is used. This code was successfully used previously to reproduce the proton, electron-positron and helium 3 [2] flux data measured by AMS and their relevant dependence on the geomagnetic coordinates.

The calculation proceeds by means of a full 3D-simulation program. Incident Cosmic Rays are generated on a virtual sphere chosen at a 2000 km altitude. The geomagnetic cut-off is applied by back-tracing the particle trajectory in the geomagnetic field, and keeping in the sample only those particles reaching a backtracing distance of 10 Earth radii.

For the primary flux, the calculation uses the 1998 AMS measurement of CR proton and helium flux [3] and the fit from [4] for heavier elements. The kinetic energy range of incident CRs covered in the simulation is $[0.2, 10000]$ GeV.

Each particle is propagated in the geomagnetic field and interacts with nuclei of the local atmospheric density. Every secondary particles are processed the same way as their parent particle, leading to the generation of atmospheric cascades. Nucleons, pions and kaons are produced with their respective cross sections.

The cross section used to produce secondary particles (p, n, $\pi^{\pm}$, $K^{\pm}$) is a very important input and is the main source of uncertainty in the atmospheric flux estimation. This work reports on an effort to reduce and to evaluate this uncertainty. In our approach the particle production cross section are fitted over a wide set of experimental data [5]. One advantage of this method is that together with the best fit parameter set for each interaction type, one can estimate the errors on the parameters. These errors can be used to compute the uncertainty on the atmospheric flux and a confidence interval.

In the simulation, for the decay of muons, the spectra of the produced $(\nu, \bar{\nu}, e^{\pm})$ are generated according to the Fermi theory, and the muon polarization is taken into account.

2. Proton flux in the atmosphere

To probe the proton production in the atmosphere, the simulated flux are compared with recent p flux measurements by the CAPRICE experiment between sea level and high altitude ($\sim$ 40 km) [6], and by BESS at mountain altitude (2.77 km) [7]. Figure 1 shows a comparison of the measured flux measured by the BESS experiment at mountain altitude 2770 m above sea level, and the calculated flux from the simulation. The large width of the confidence interval in this estimation is due to the large number (approximatively 8 on the average) of collisions between the primary particle and the detected proton at low altitude. Any uncertainty in the proton production cross section is then amplified by a large factor. It also shows that precise proton flux measurement [6, 7] at low altitude can be used to constrain the parametrization of the secondary particle production more precisely than the available nuclear data.

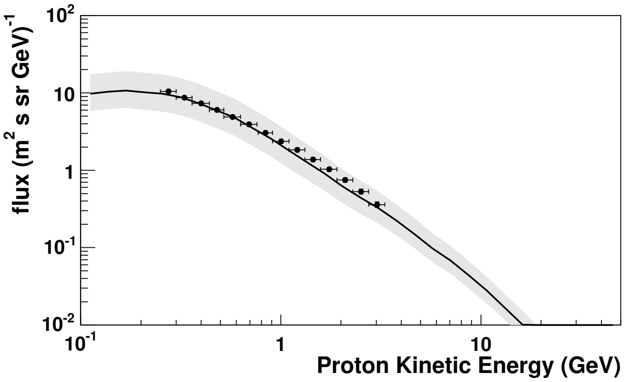

Figure 1. Proton Flux measured by the BESS experiment at mountain altitude 2770 m above sea level. The solid line is the estimated flux from the simulation and the light gray area correspond to the 95 % confidence interval.

3. Muon flux in the atmosphere

Atmospheric muons are produced in the same reaction chain as neutrino and is then an essential probe to support the reliability of the neutrino flux calculated in the same framework. Several experiments CAPRICE, HEAT, BESS [8] have made precise flux measurement at various altitude in the atmosphere. Figure 2 shows a comparison of the flux measured by the BESS experiment at mountain altitude 2770 m above sea level [9], and the calculated flux from the simulation. The 95 % confidence interval include only the uncertainty coming from the parametrization of secondary the particle production, see [5].

4. Neutrino flux at SuperKamiokande Location

The calculated energy distributions of the atmospheric neutrino flux around the SuperK detector have been computed with the same simulation program. A virtual detector center on (36^oN,137^oE) was used with a size of 4^o in latitude and 9^o in longitude ($\sim$450$\times$1000 km^2). The virtual detector size has been chosen so as not to change the estimated flux more than 1 %.

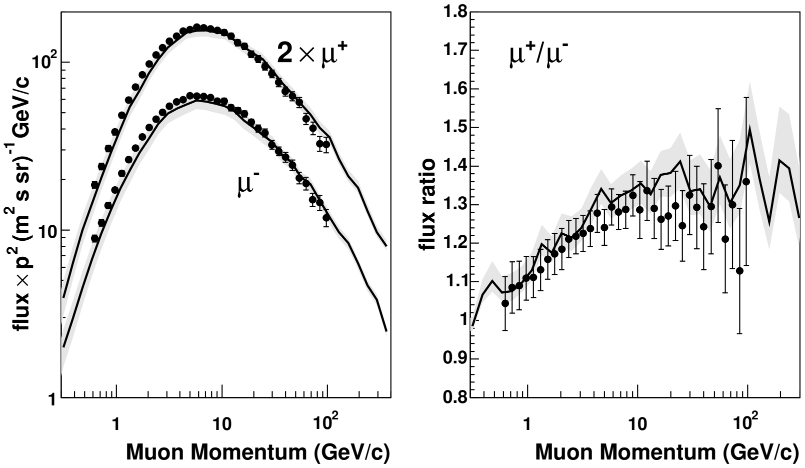

Figure 2. Muon Flux and flux ratio at mountain altitude. The solid line is the estimated flux from the simulation and the gray area corresponds to the 95 % confidence interval.

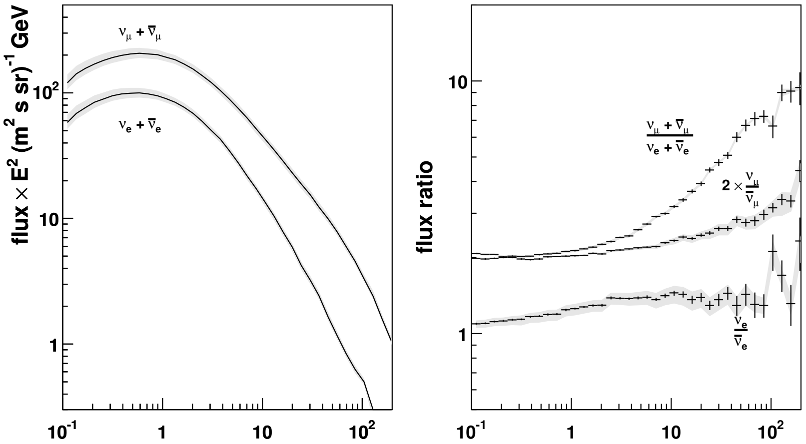

Figure 3. Neutrino flux and Neutrino flux ratio at the SK location average over 4π, the gray area correspond to the 95 % confidence interval.

Figure 3 shows the 4π average flux for $\nu_\mu + \bar{\nu}_\mu$ and $\nu_e + \bar{\nu}_e$ (left) and the flux ratio $\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}$, $\frac{\nu_\mu}{\bar{\nu}_\mu}$ and $\frac{\nu_e}{\bar{\nu}_e}$ (right). The gray area represent the 95% confidence level corresponding to the particle production uncertainty. The uncertainty for the absolute neutrino flux is of the order of 10% and, as expected, these error contributions are largely reduced for the ratio of flux $\frac{\nu_e}{\bar{\nu}_e}$ (insensitive to proton/neutron production cross sections) and for $\frac{\nu_\mu}{\bar{\nu}_\mu}$ (insensitive to proton/neutron production cross sections but also to pion production cross sections for low energy) and vanished for the $\frac{\nu_\mu+\bar{\nu}_\mu}{\nu_e+\bar{\nu}_e}$ ratio flux (insensitive to proton/neutron and pion production cross sections).

5. Conclusion

A full 3D simulation have been used to compute secondary particle production in the atmosphere. In our approach the dominant error comes from the uncertainty in the particle production cross section which are fitted to the available set of experimental data. In this is paper we have studied quantitatively this uncertainty by computing the interval of confidence relative to the flux estimation. In the updated version of the proceedings the use of atmospheric proton and muon measurements to constrain neutrino flux estimation will be reported and discussed.

References

[1] Super-Kamiokande Collaboration, Y. Fukuda, et al., Phys. Rev. Lett. 81, 1562(1998), B433, 9(1998), B436, 33(1998). The Soudan 2 Collaboration, W. W. M. Allison, et al., Phys. Lett. B449, 137(1999). W. W. M. Allison, et al., Phys. Lett. B391, 491(1997).
[2] L. Derome et al., Phys. Lett. B489, 1(2000). L. Derome, M. Buénerd, and Yong Liu, Phys. Lett. B515, 1(2001). L. Derome, and M. Buénerd, Phys. Lett. B521, 139(2001).
[3] The AMS collaboration, J. Alcaraz et al., Phys. Lett. B472, 215(2000), Phys. Lett. B490, 27(2000), Phys. Lett. B494, 19(2000).
[4] B. Wiebel-Sooth et al., Astronomy and Astrophysics 330, 389(1998)
[5] L. Derome and M. Buenerd, Proc. 29th ICRC, Pune, HE.2.1 (2005).
[6] E. Mocchiutti, PhD thesis, Royal Institute of Technology, Stockholm, 2003
[7] T. Sanuki et al., Phys. Lett. B577, 10(2003).
[8] CAPRICE Collaboration, J. Kremer, et al., Phys. Rev. Lett. 83, 4241(1999). M. Boezio, et al., Phys. Rev. Lett. 82, 4757(1999). HEAT Collaboration, S. Coutu, et al., Phys. Rev. D62, 032001(2000). BESS Collaboration, T. Sanuki et al., Phys. Lett. B541, 234(2002).
[9] T. Sanuki et al., Phys. Lett. B541, 234 (2002).