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# Measurement of the atmospheric muon spectrum from 20 to 2000 GeV

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## Abstract

The absolute muon spectrum between 20 and 2000 GeV was measured with the L3 magnetic muon spectrometer for zenith angles ranging from 0 to 58 degrees. Due to the large data set and the good detector resolution, a precision of 2.6% at 100 GeV was achieved for the absolute normalization of the vertical muon flux. The momentum dependence of the ratio of positive to negative muons was studied between 20 and 600 GeV.

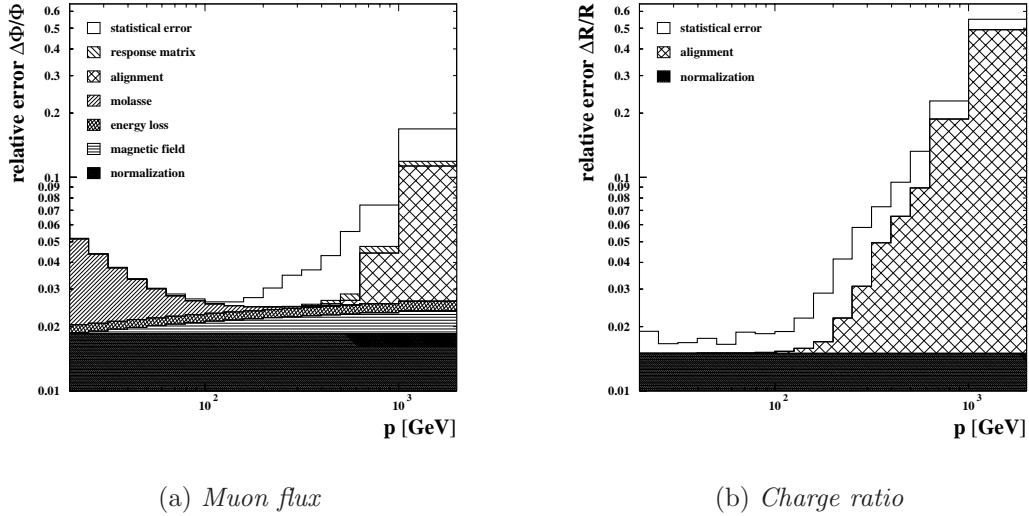
## 1. Introduction

Atmospheric muons are amongst of the final products of primary cosmic ray induced air shower cascades. A precise measurement of the ground level muon flux can therefore be used to test the understanding of the primary cosmic ray flux and the hadronic interactions involved in the production of the muons' parent mesons. Moreover, it provides a crucial test for theoretical neutrino flux calculations, because each muon is produced with an accompanying muon neutrino. The ground level muon flux has been measured many times with different experimental techniques, see [3] and references therein. However, the reported results show discrepancies much larger than the quoted errors indicating the presence of systematic effects not accounted for.

Here a new measurement of the atmospheric muon flux is presented using the precise muon spectrometer of the L3 detector [1] located at the LEP accelerator at CERN, Geneva. During the analysis special attention was given to the precise determination of all relevant detector and environmental parameters needed to convert the raw data distributions to an absolute surface level flux. Due to the large amount of available statistics, extensive studies of the residual systematic uncertainties were possible.

## 2. Experimental Setup

The momentum distribution of atmospheric muons is measured with the upgraded L3 setup known as L3+C, which is described in detail in [2]. It is located 450 m above sea level and shielded from the hadronic and electromagnetic air



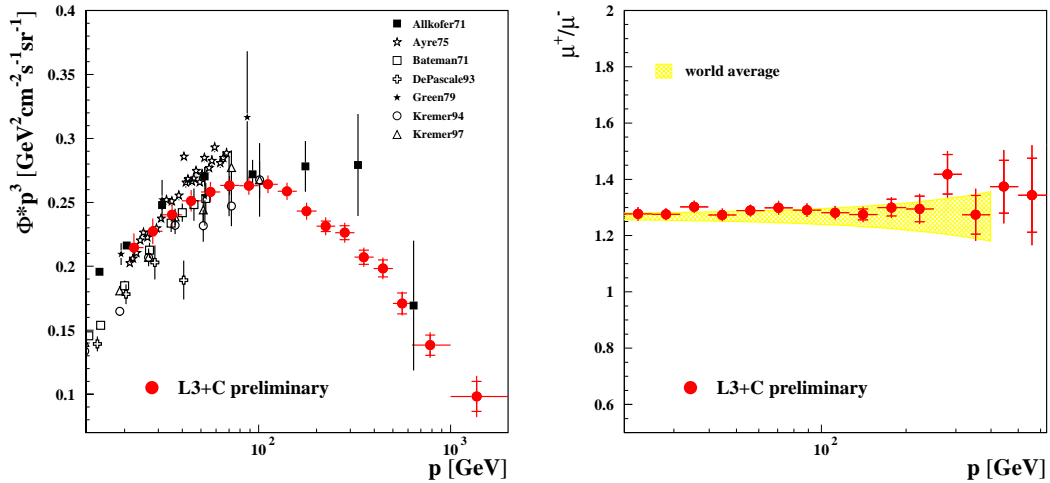
**Fig. 1.** Systematic uncertainties of the muon flux and charge ratio measurement for the vertical zenith angle bin

shower components by a 30 m thick molasse overburden. The muon momentum is measured with the L3 muon spectrometer, which is situated inside a large magnetic volume of  $1000 \text{ m}^3$  with a field of 0.5 T. A  $202 \text{ m}^2$  scintillator array was installed on top of the detector to record the arrival time of the muons.

With this arrangement a relative momentum resolution ranging from 2.2% at 20 GeV to 52% at 2000 GeV was achieved. Being equipped with a trigger and data acquisition system independent of the normal L3 data taking, L3+C recorded  $1.2 \cdot 10^{10}$  atmospheric muon triggers during its operation in the years 1999 and 2000.

### 3. Analysis

To achieve the momentum resolution mentioned above, a stringent quality selection is applied to the data after which  $2 \cdot 10^7$  events remain for the muon spectrum analysis. The geometrical acceptance of the detector as well as the energy loss in the molasse overburden is calculated with a GEANT [4] simulation of the L3+C setup and its surroundings. The detector efficiencies are determined from the data itself as a function of time, charge, momentum and zenith angle. The raw event distributions at the detector level are deconvoluted taking into account the detector resolution and the stochastic energy loss in the molasse.

(a) *Muon flux and data from [5-10]*(b) *Charge ratio and world average from [3]*

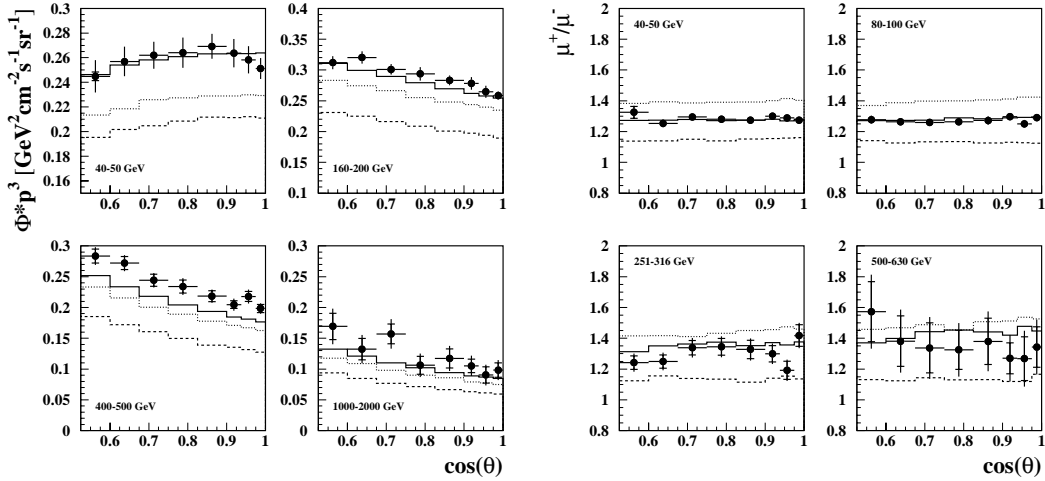
**Fig. 2.** The L3+C muon vertical flux and charge ratio. The inner error bar denotes the statistical error, the full error bar is the total error.

#### 4. Systematic uncertainties

The systematic uncertainties of the muon flux as well as the ratio of positive to negative muons are displayed in figure 1. As can be seen, the dominant contribution at high energies is the uncertainty on the detector alignment. At low energies, the muon flux measurement is limited by the uncertainty on the molasse overburden. The minimal total error on the vertical flux measurement is 2.6% at 100 GeV.

#### 5. Results

The L3+C vertical muon spectrum is shown in figure 2a along with previous measurements providing an independent absolute normalization. The measured vertical charge ratio is compared to an average of previous measurements in figure 2b. As there are no previous experiments covering the same wide zenith angle range up to highest energies, the angular flux and charge ratio dependence is compared to a MC simulation with the TARGET2.1 transport code [11] using the TARGET2.1, SIBYLL2.1 [12] and QGSJET01 [13] interaction models and the primary flux parameterization from [14]. As can be seen in figures 3a and 3b, the simulations nicely reproduce the measured relative angular dependence of the muon flux and charge ratio, whereas the combination of the interaction models

(a) *Muon flux*(b) *Charge ratio*

**Fig. 3.** The zenith angle dependence of the muon flux and charge ratio at four different momenta. The inner error bar denotes the statistical error, the full error bar is the total error. The histograms show the simulation with the TARGET2.1 (solid), QGSJET01 (dashed) and SIBYLL2.1 (dotted) interaction model.

[12] and [13] with the primary flux model [14] are incompatible with our measured absolute values.

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