Measurement of the Atmospheric Muon Spectrum from 20 to 3000 GeV

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on behalf of the

L3 Collaboration

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Atmospheric muons

Current uncertainty

primary spectrum $\Phi = \Phi_0 . E_p^{-\gamma}$

10 - 25 %

(from 10 GeV to 10 TeV)

$\Phi_p \times \sigma_{p+A} \rightarrow \pi, K + X$

~ 10 % (π) 30 %(K)

hadronic interactions

(theoretical and experimental)

$\Phi_{\pi,K}$

decay

0 %

(kinematics)

μ and ν spectrum $\Phi_\mu \quad \Phi_\nu$ $\approx$

15 % (μ , **exp.),**

20 – 30 % (ν , **theo.)**

Use the measured flux of muons to constrain hadronic interactions and atmospheric neutrino flux

L3+C

Ref. [1-2]

Device to measure the
momentum
charge *and*
angle *of*
muons *created in air showhers*

Location: 6.02^0 E, 46.25^0 N

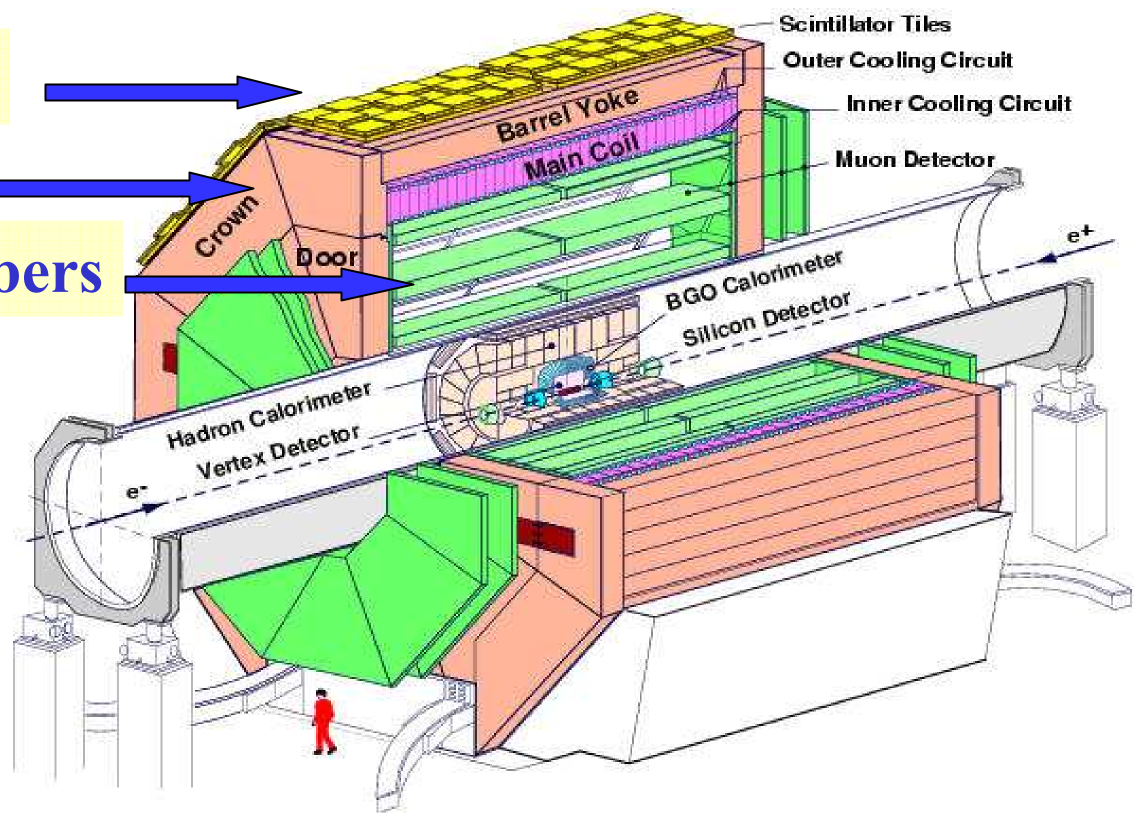
Altitude: 450 m, 30 m underground

Detector:

t_0- detector (202 m^2 scint.)

Magnet (0.5 T, 1000 m^3)

High precision drift chambers



Trigger and DAQ :
independent of L3

GPS timing :
(event time up to 1 μsec)

Schematic view of the experimental setup

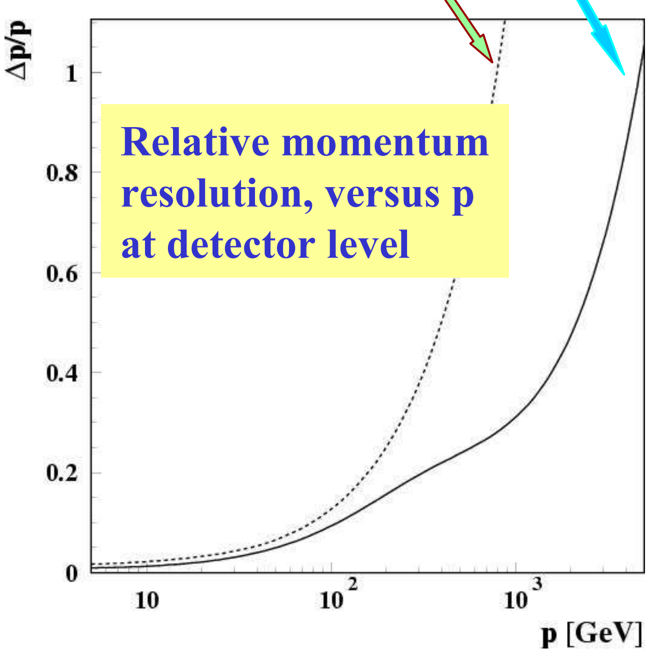
From good quality tracks on opposite octants:

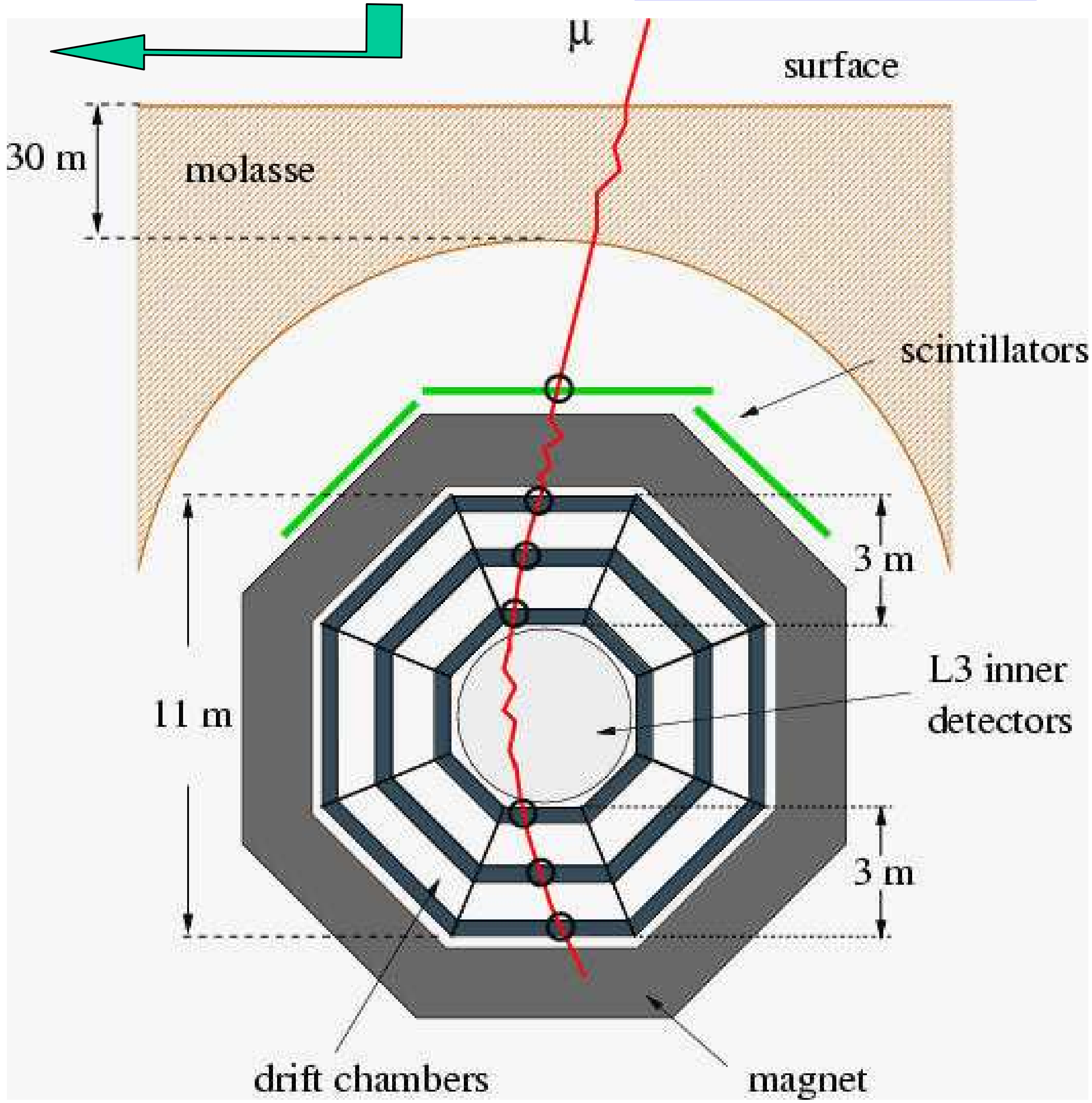
One 3-plet at least
1 Scintillator hit
Good running conditions

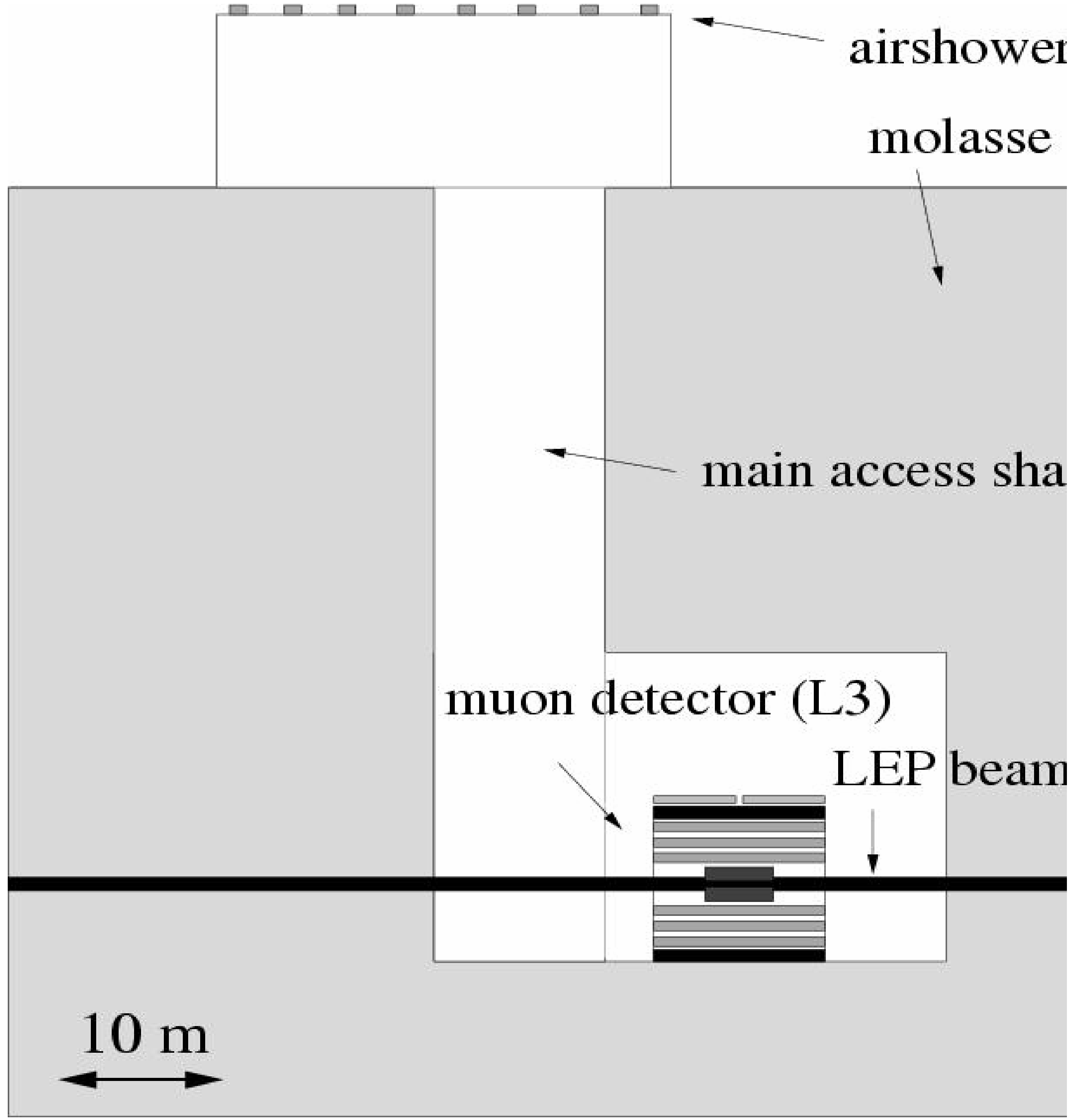
-momentum resolution
-max. detectable momentum
-scintillator efficiencies
-track selection efficiency

Double octant fit

Single octant fit



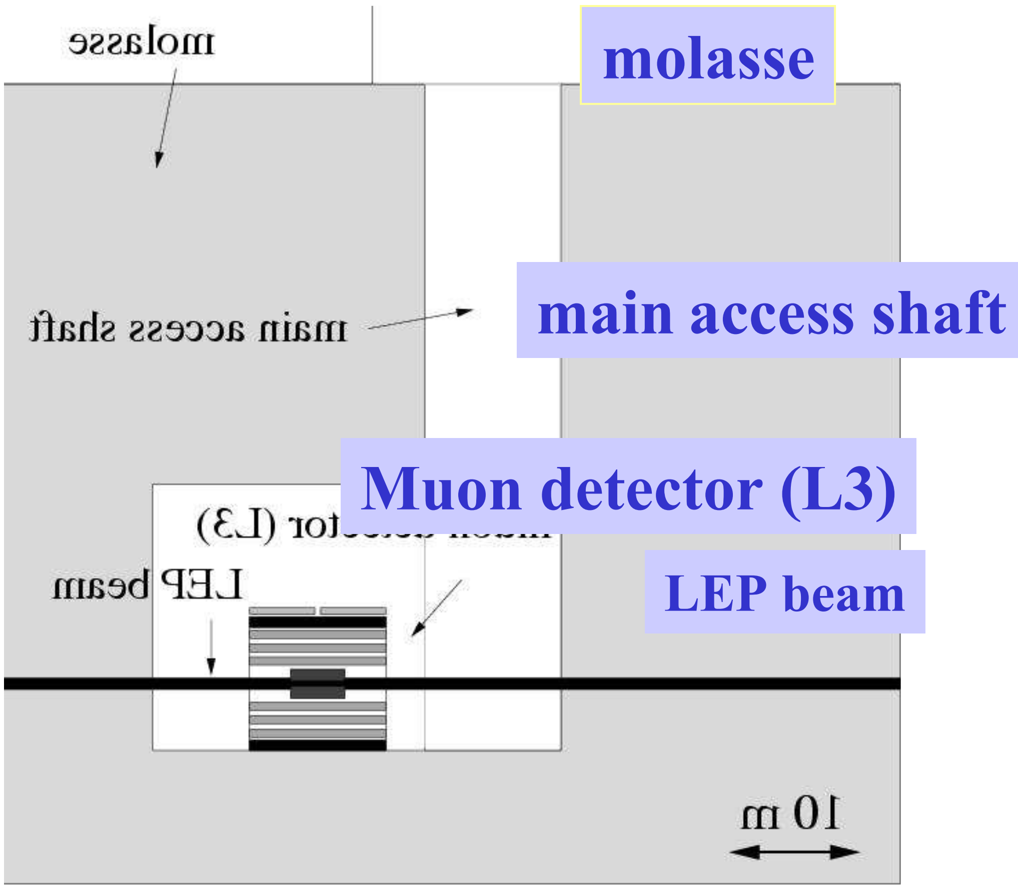


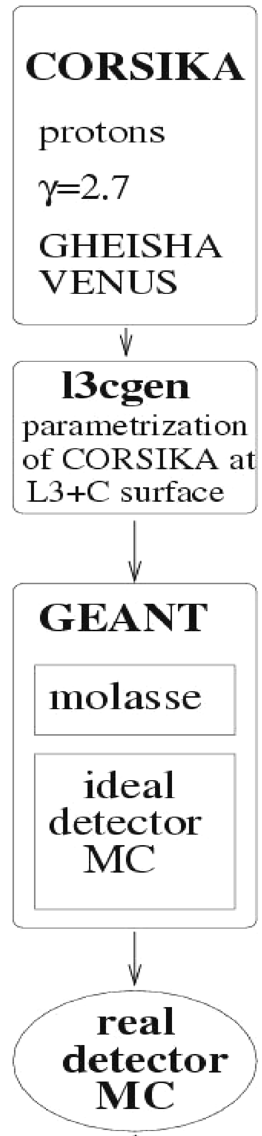

airshowe
molasse
main access sha
muon detector (L3)
LEP beam
10 m

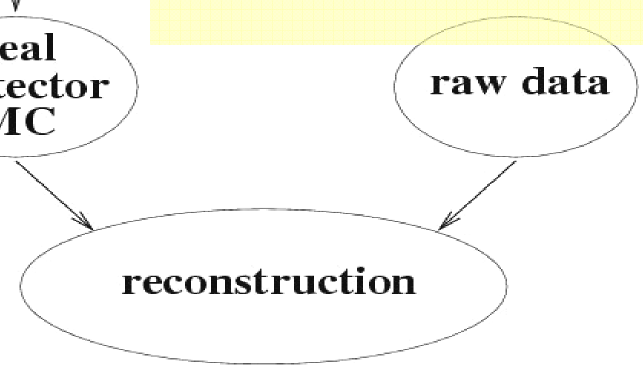
Detector and molasse simulation

Due to the energy loss in the molasse and in the magnet, the μ threshold :

$E_\mu > 15$ GeV (> 7 GeV) (upon μ direction)

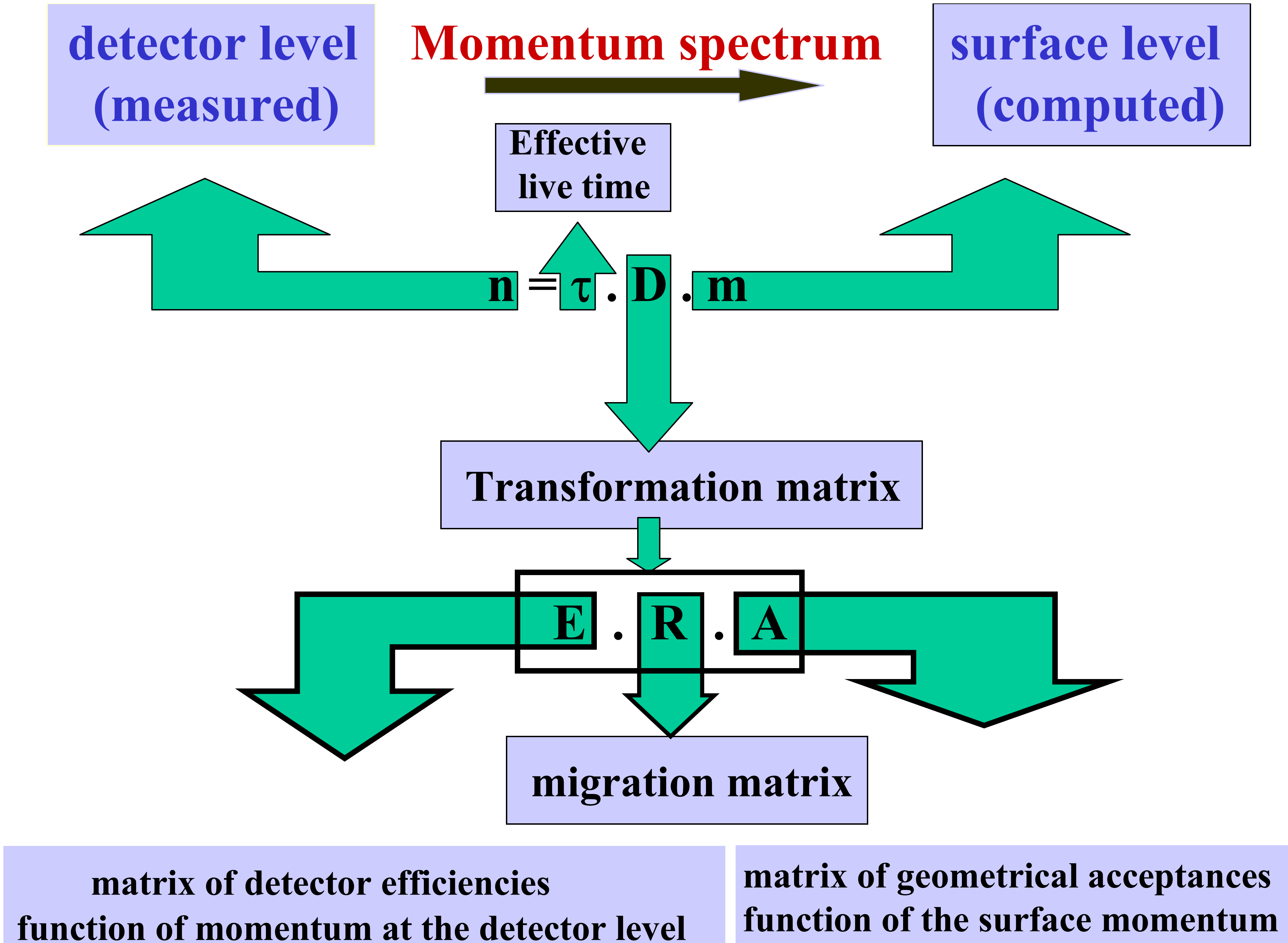






The muon input flux at surface, the L3+C environment and the detector response are simulated.

The resulting muons are reconstructed by the same program used for the data (1.7×10^9 reconstructed Monte Carlo events and 2×10^7 data events after quality cuts for this analysis)

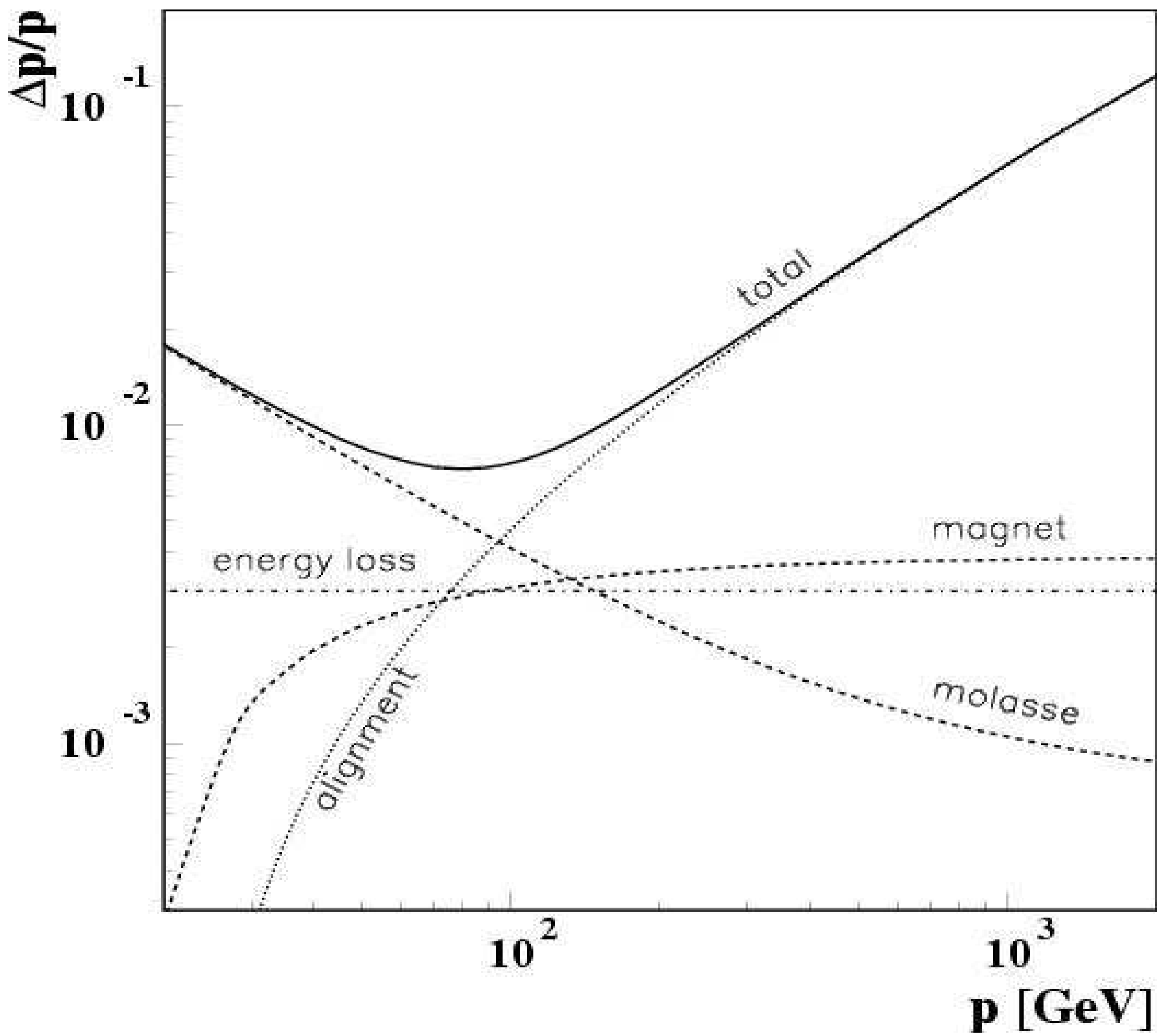

detector level
(measured)
Momentum spectrum
surface level
(computed)
Effective
live time
n = τ . D . m
Transformation matrix
E . R . A
migration matrix
matrix of detector efficiencies
function of momentum at the detector level
matrix of geometrical acceptances
function of the surface momentum

Statistical and systematic uncertainties

(momentum scale)

Relative uncertainties of the vertical zenith angle bin measurements

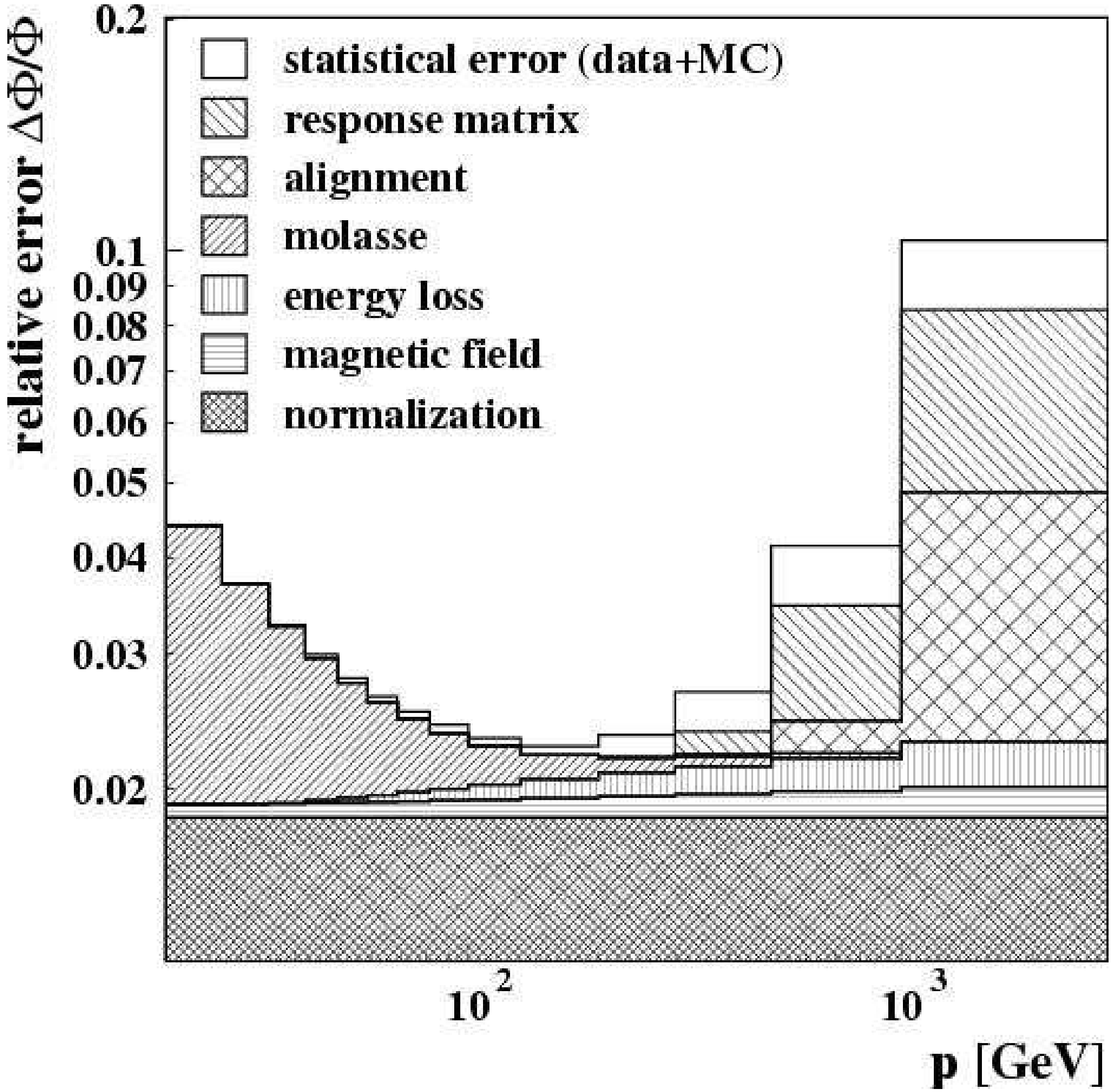
The individual contributions are added in quadrature.



Statistical and systematic uncertainties (μ flux)

Relative uncertainties of the vertical zenith angle bin measurements

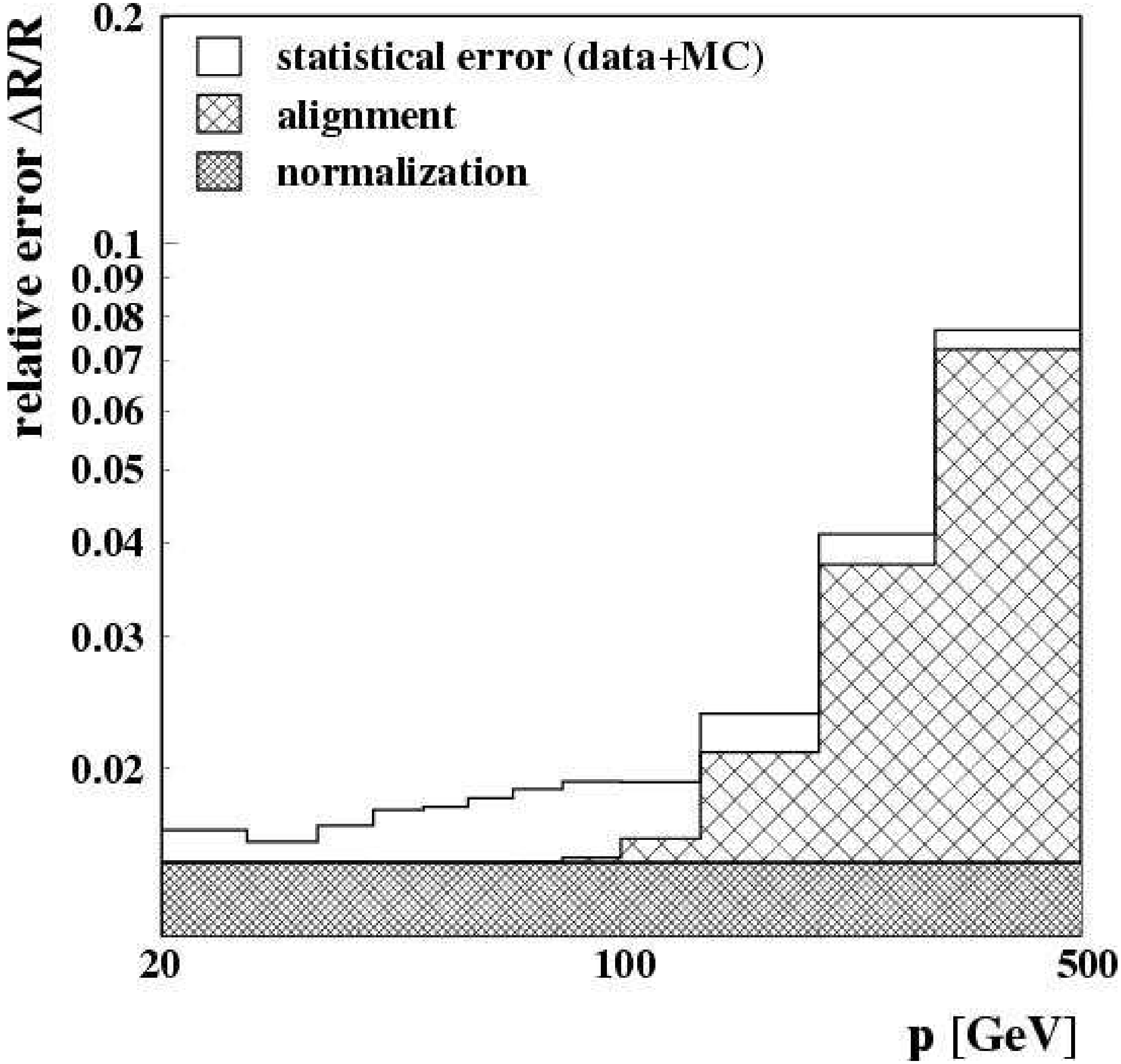
The individual contributions are added in quadrature.



Statistical and systematic uncertainties (ch. ratio)

Relative uncertainties of the vertical zenith angle bin measurements

The individual contributions are added in quadrature.



Total uncertainty:

Obtained by adding the different sources in quadrature.

Muon flux uncertainty:
dominated by :

***The uncertainty of molasse overburden at low momenta.**
***The alignment and resolution uncertainty at high momenta.**
Minimum is 2.3 % at 150 GeV in the vertical direction.

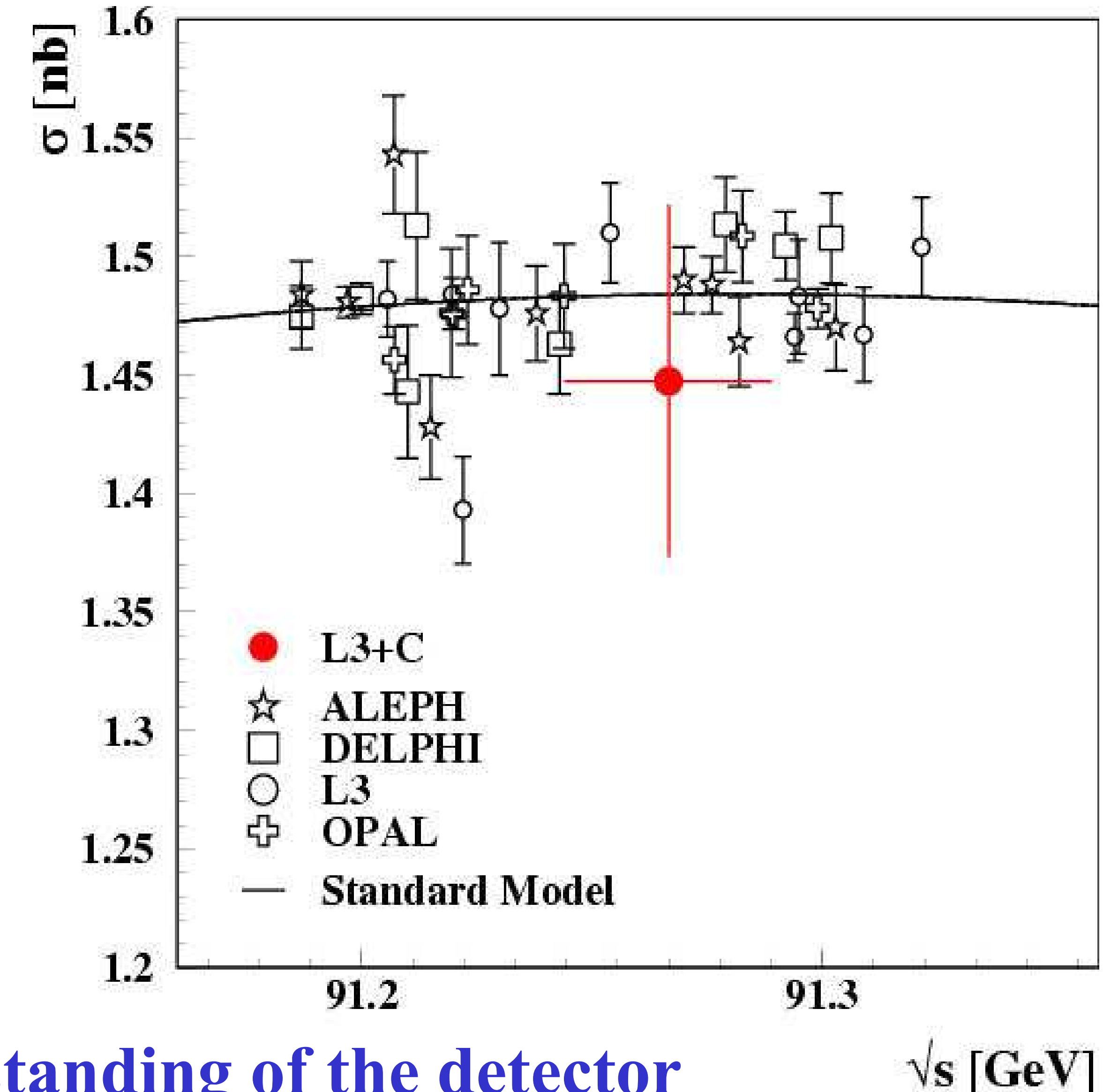
Vertical charge ratio uncertainty:

Below 2 % up to 100 GeV
Above 100 GeV, rises rapidily with the alignment uncertainties.

Analize the LEP events : $e^+ e^- \to Z \to \mu^+ \mu^-$

* c.m. energy : 91.27 GeV
* μ track close to collision point
* event-time in coincidence with the LEP beam crossing time
* p_μ>27.4 GeV

Absolute cross-section in excellent agreement with LEP precision measurements

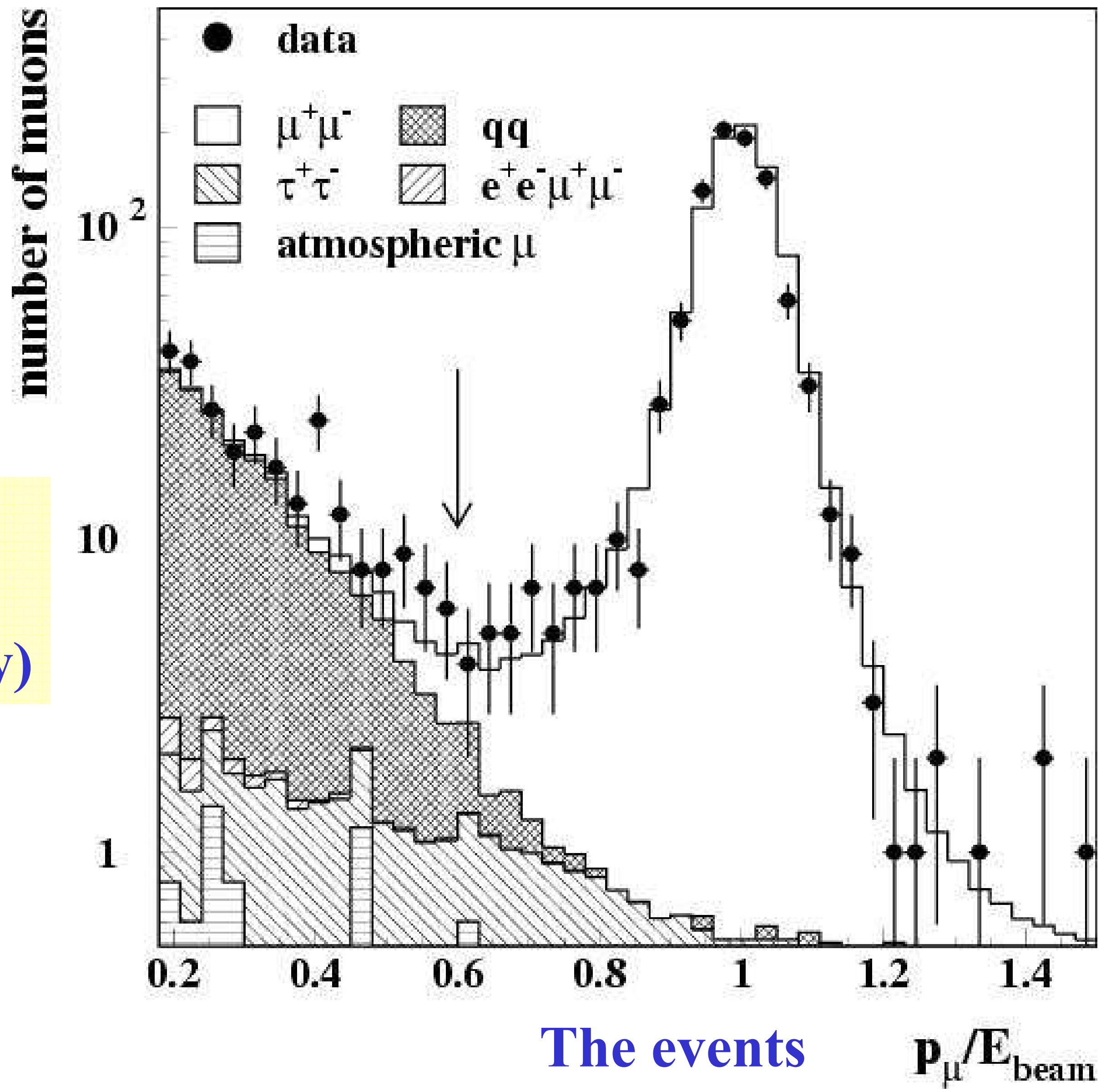


Validates our understanding of the detector

Momentum distribution of the events $e^+ e^- \to Z \to \mu^+ \mu^-$ + background

The Monte Carlo events are normalized to the LEP luminosity

The arrow indicates the low-momentum cut (60% of the beam energy)



The events

The fluxes are neither corrected for the altitude of L3+C nor for the atmospheric profile to avoid additional theoretical uncertainties.

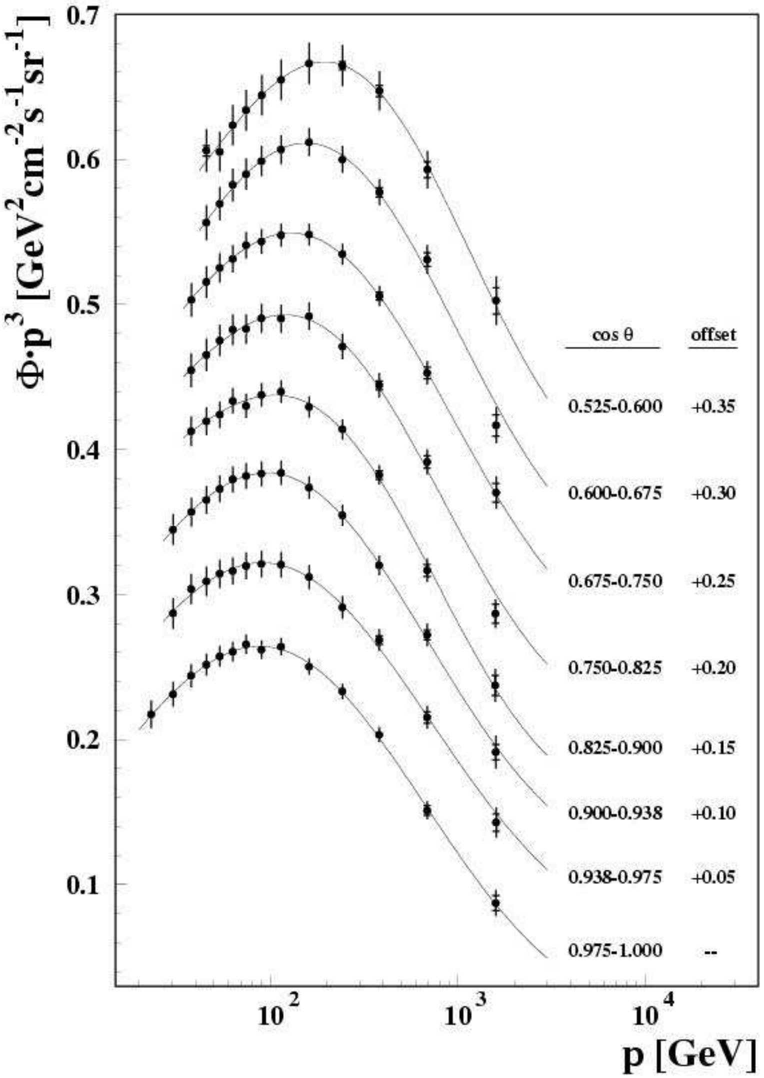
Instead, we quote the average atmospheric mass overburden X above L3+C, which was continously measured with balloon flights from close to the experiment to altitudes of over 30 Km, and parametrized as :

$$X(h) = \begin{cases} A(h_b - h)^{(\alpha-1)}, & h<11 \text{ Km} \\ B\, e^{(-h/h_0)}, & h>11 \text{ Km} \end{cases}$$

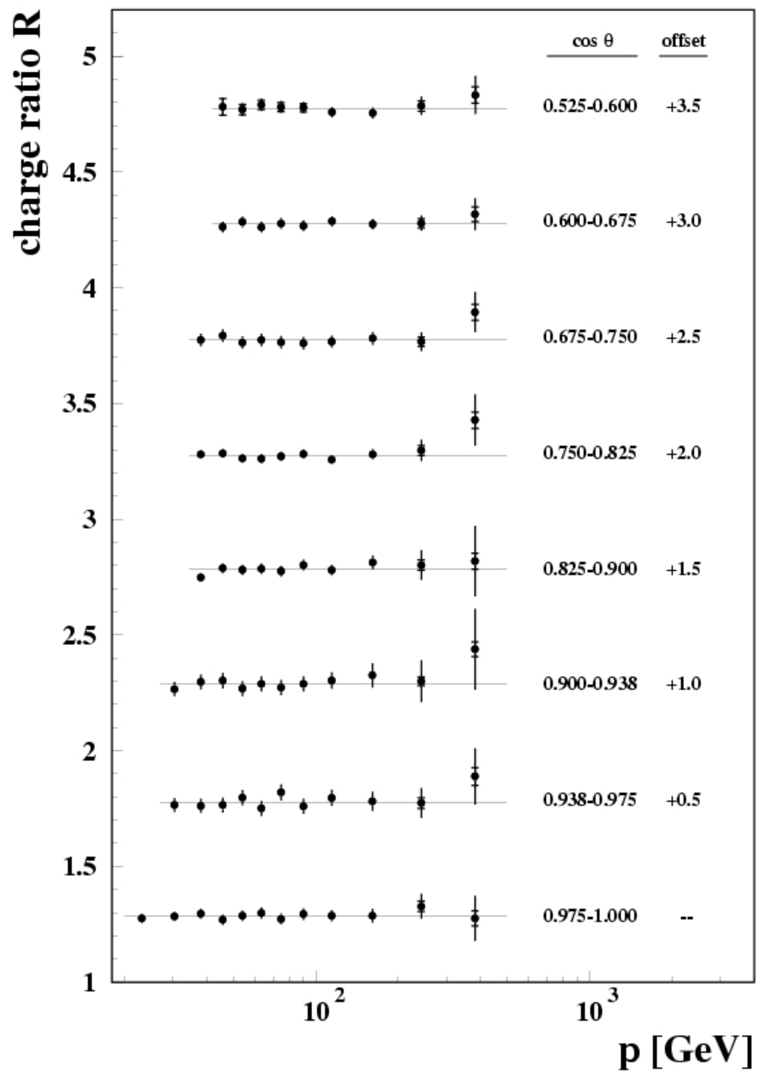
Fit to the data yields:

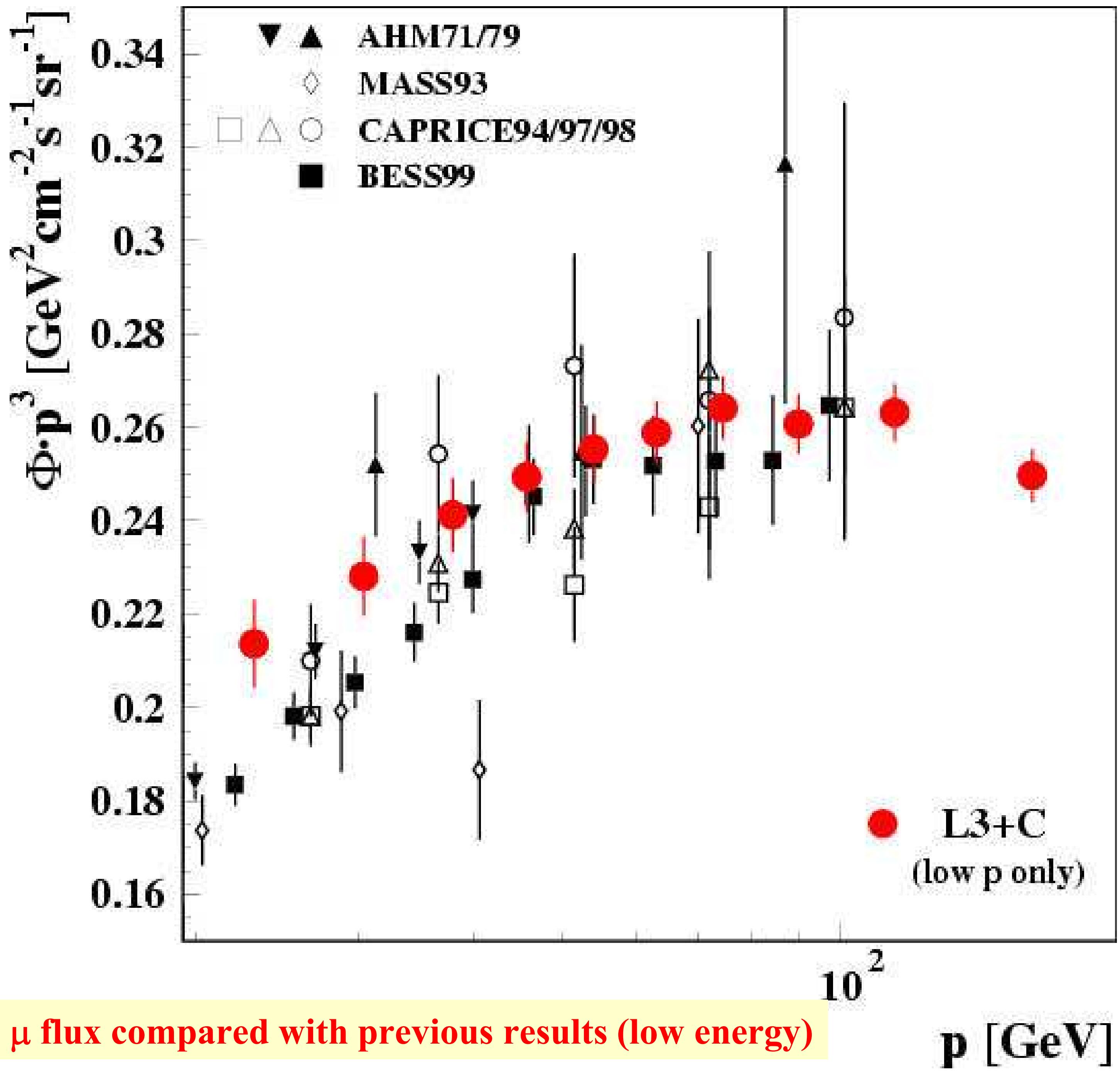
$A = 8.078 \times 10^{-5}$
$B = 1332$
$h_b = 39.17$
$h_0 = 6.370$
$\alpha = 3.461$

Measured μ flux for zenith angles from 0 ⁰ (bottom) to 58 ⁰ (top)

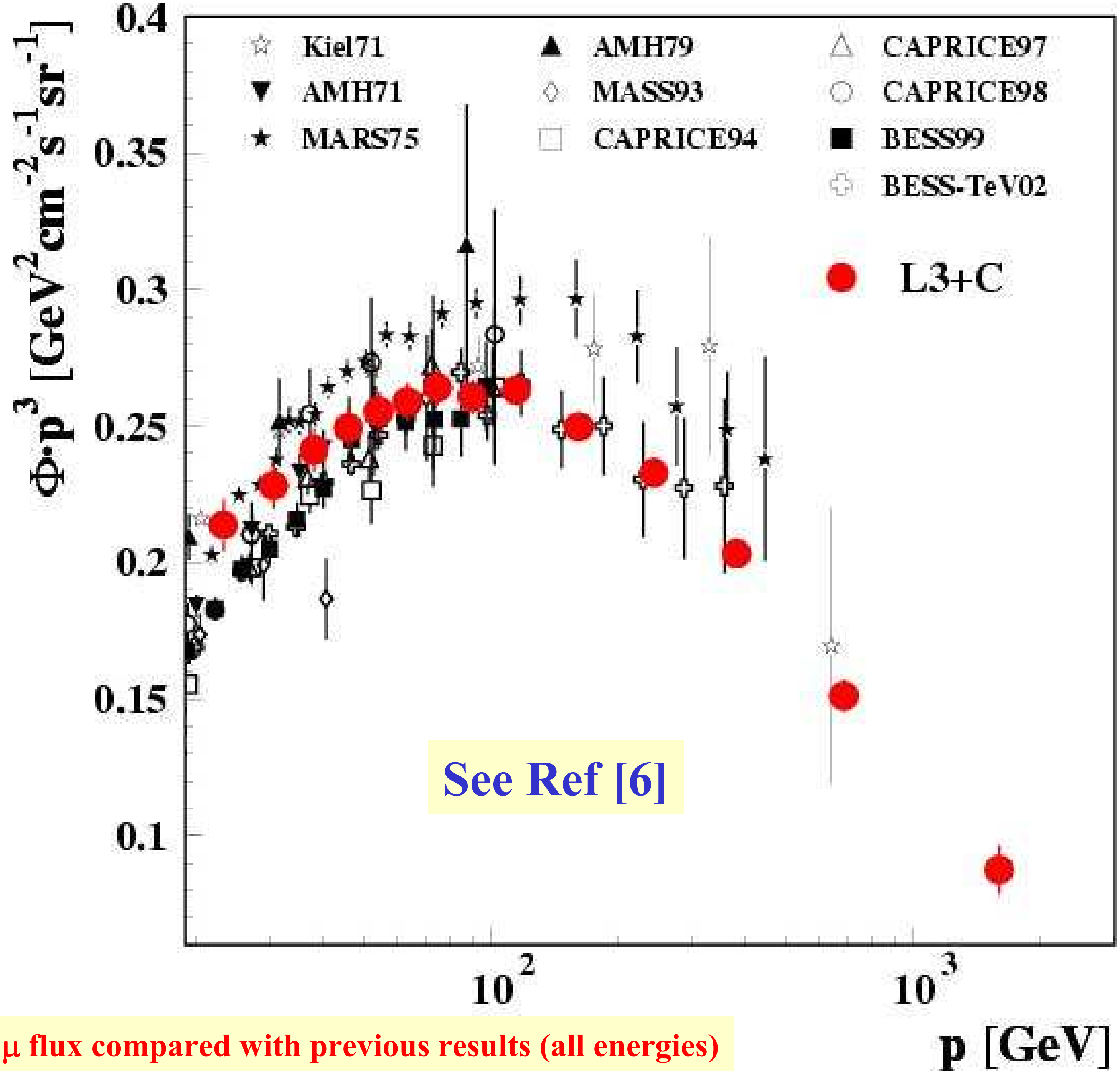


Measured μ^+/μ^- charge ratio for zenith angles from 0^0 (bottom) to 58^0 (top)





Vertical μ flux compared with previous results (low energy)



Vertical μ flux compared with previous results (all energies)

Vertical μ flux:

* Comparison with low energy experiments gives good overall agreement above 40-50 GeV

* At lower momenta a systematic slope difference seems to be present. Probably due to the systematic molasse uncertainty

μ+/μ– ratio:

*The limit is 500 GeV due to the alignment uncertainties.

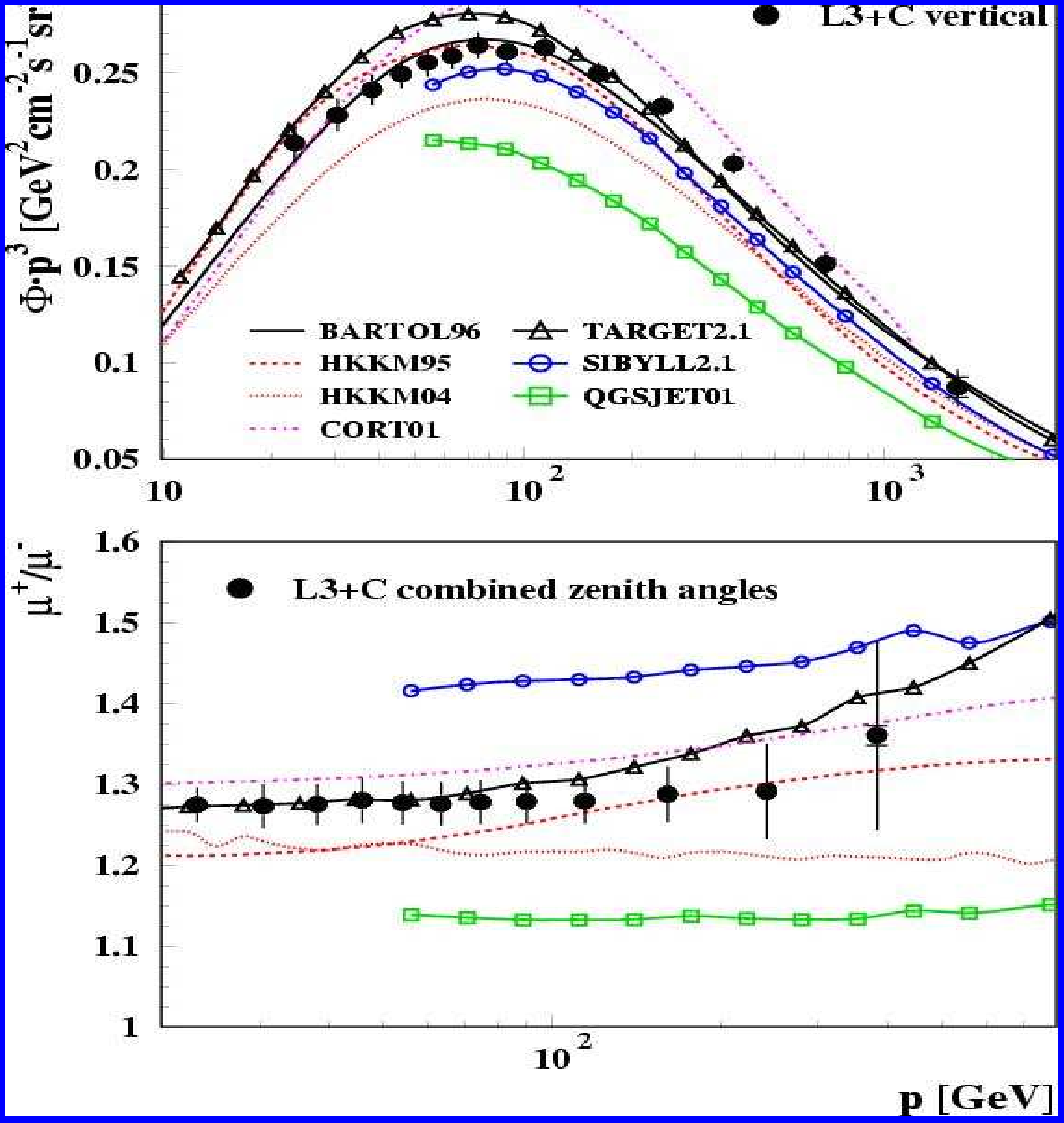
*In the considered range and within the experimental uncertainties,
it is independent of momentum.

*Mean value in vertical direction:
1.285 + - 0.003(stat.) + - 0.019 (syst.) (chi2/ndf=9.5/11.) to be compared with
1.270 + - 0.003(stat.) + - 0.015 (syst.) (average of all previous measurements) (Ref [3])

Worth noting that the precision of the data of a single L3+C zenith angle bin is comparable to the combined uncertainty of all data collected in the past.

Comparison with recent MC muon flux predictions

See Ref [7]



The conection of the atmospheric muon flux and neutrino flux.

* μ flux is a good calibration source of the atmospheric ν flux

* Honda (Ref [4]) has presented to the 29th ICRC,(Pune,2005) the comparison of the last measured fluxes from BESS TeV (99) BESS (2002) and L3+C with the HKKM04 model.

* The ratio between measured fluxes and model show:
  - Agreement of < 5% in the 1-30 GeV region.
  - Larger disagreement out of this interval.

* Honda et al. modified the DPMJET-III interaction model (differential cross sections of secondary mesons production) (only BESS data used under 50 GeV and all data for >50 GeV)

  * Better agreement in 1-300 GeV range obtained for μ fluxes

  * ν fluxes more reliable than that of HKKM04 in wider range.

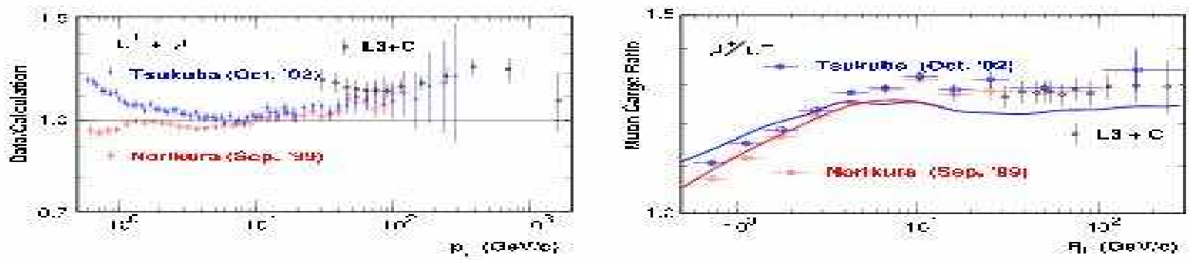


Figure 2. The comparison between calculated muon flux with DPMJET-III and observed data. The total flux is compared in left panel taking the ratio, and the charge ratio in right panel.

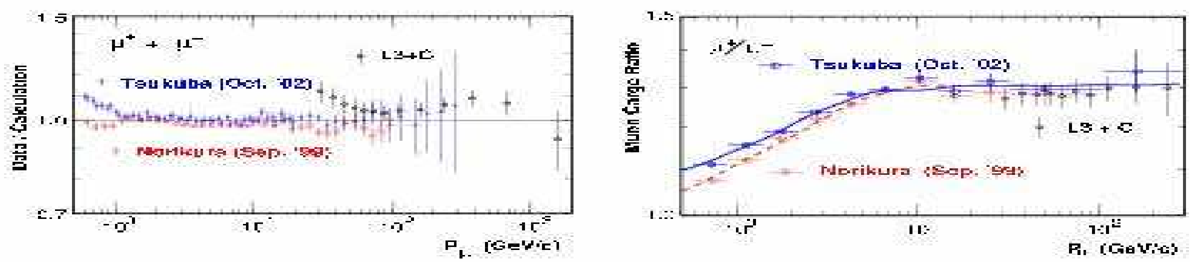


Figure 3. The comparison between calculated muon flux with the modified interaction model and observed data. The total flux is compared in left panel taking the ratio, and the charge ratio in right panel.

muon flux observed by L3+C in $\gtrsim$ 30 GeV is higher than that by BESS. We used the BESS data in this energy region, since they are not suffered from the overlaying material.

In Fig. 3, the muon fluxes calculated with the modified interaction model are compared with the observed data, showing a better agreements in 300 GeV/c. Note, we have used the air density structure measured by the meteorological office in the calculation with the modified interaction model for Tsukuba and Norikura. Then the calculated muon fluxes are much closer to the observed data consistently in GeV region.

4. Summary

We have studied the muon flux with the calculation code used in HKKM04, and find that the uncertainties of the atmospheric neutrino fluxes are around 10 % for the absolute values in 1 − 10 GeV/c. Some modifications are necessary for DPMJET-III, since the model fails to reproduce the observed muon flux at higher energies. Applying a modification to DPMJET-III, the agreement of calculation and data for the muon flux becomes

Conclusions

Using the L3+Cosmics μ detector (6.02^0 E, 46.25^0 N) we have determined:

1-the atmospheric μ spectrum from 20 GeV to 3 TeV
as a funtion of 8 zenith angles ranging from 0^0 to 60^0
with good overall agreement with previous data above 40-50 GeV
for the vertical flux .

2- the ratio $\mu+/\mu-$ from 20 GeV to 500 GeV for the same
zenith angles as above.
The mean value in the vertical direction is in perfect
agreement with the average of all the previous data.

3- L3+Cosmics has extended the knowledge of the μ momentum spectrum
by a factor ~10 in the momentum range.

4- The precision of the data of a single L3+C zenith angle
bin is comparable to the combined uncertainty of all data
collected in the past.

5- The interest of L3+C data to constrain the MC π,K p-A production
models and the atmospheric ν flux calculations as a consequence,
is pointed out.

Outlook

ALICE, the heavy ions collisions dedicated detector in LHC (located in the same cavern and magnet than L3+C) will implement a t0 detector based on plastic scintillators for the trigger and will use the TPC,TOF and TRD detectors to detect the atmospheric muons. (ACORDE)

The L3+C pioneer work will then be continued with better statistics for several years.

References

[1] L3+C Collaboration. Adriani et al.,Nucl. Instrum. Methods A488 (2002) 209.
[2] Measurement of the atmospheric spectrum from 20 to 3000 GeV. Phys. Letters B598 (2004) 15-32
[3] T.Hebbeker,C. Timmermans., Astropart. Phys. 18 (2002) 107.
[4] T. Sanuki et al., Atmospheric neutrino and muon fluxes. 29 ICRC, Pune (2005) 00,101-104.
[5] ACORDE, A Cosmic Ray Detector for ALICE. J. Arteaga et al., 29 ICRC, Pune (2005) 00,101-104

[6] Experiments providing an absolute normalization:

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MARS75 : C.A. Ayre et al., J. Phys. G 1 (1975) 584.
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BESS-TeV02 : S. Haino et al., astro-ph/0403704
MASS93 : M.P. De Pascuale et al., J. Geophys. Res. 98 (1993) 3501.

[7] MonteCarlo models:

SIBYLL2.1 : R.S. Fletcher et al., Phys. Rev. D50 (1994) 5710.
BARTOL96 : Phys. Rev. D53 (1996) 1314.
QGSJET01 : R. Engel et al., Proc. 26th ICRC(1999) 415.
TARGET2.1 : R. Engel et al., Proc. 27th ICRC(2001) 1381.
DPMJET-III : S. Roesler et al., Proc. 27th ICRC, Hamburg, 1, 439 (2001); Phys. Rev. D 57, 2889 (1998)
CORT : G. Fiorentini et al., Phys. Lett. B 510 (2001) 173;hep-ph/0103322 v2 27/April/2001
HKKM04 : M. Honda et al., Phys. Rev. D70: 043008 (2004)

End of presentation

Thank you !!

Extra transparencies

The transformation matrix D = E.R.A

R: migration matrix :The conditional probability of measuring a momentum $q\,p_i$ given a surface momentum $q\,p_j$

A: diagonal matrix of geometrical acceptance as a funcion of the surface momentum.

E: diagonal matrix of detector efficiencies as a function of momentum at detector level.

$$D_{ij} = \varepsilon_i\, r_i\, S_{MC}(n^{sel}_{ij} / N^{gen}_j)_{MC}\, \Delta\Omega$$

S_{MC} : Surface area used in the MonteCarlo generator.

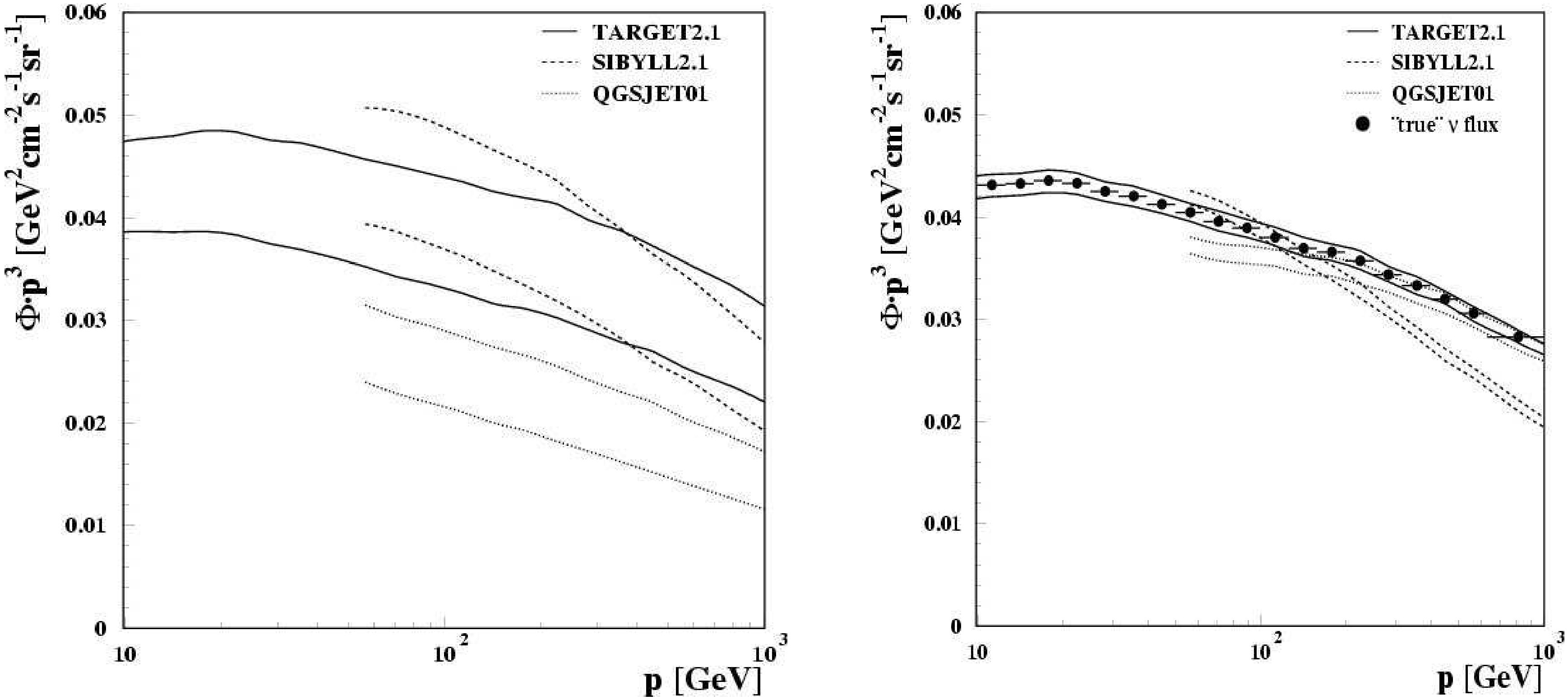
$\Delta\Omega$: Solid angle of the zenith bin under study.

ε_i : Includes the scintillator and trigger efficiency.

r_i : Selection efficiency correction.

n^{sel}_{ij} : The number of selected MonteCarlo events found within a detector-level momentum bin i, wich were generated within the momentum bin j at the surface.

N^{gen}_j : Total number of MonteCarlo events generated within this surface momentum bin.



MC study on the neutrino flux constraint. For each interaction model two different primary fluxes are used, as indicated by the two curves per model.

(From Michael Unger PhD thesis , Humboldt-University, Berlin, 9/February/2004)

Some characteristics of the different referenced experiments

Kiel : Solid iron magnet with spark chambers and scintillator counters.
Location: Kiel (Germany) 54^0 N, 10^0 E
Altitude : 10 m. asl

MARS : Solid iron magnet + scintillators + flash tubes.
Location: Durham (Great Britain) 54^0 N, 1^0 W
Altitude : 70 m. asl

AMH : 2 solid iron magnets + spark chambers +scintillators.
Location: Huston (USA) 29^0 N, 95^0 W
Altitude : 10 m. asl

CAPRICE 94 : 4T superconducting magnet spectrometer (balloon) with proportional and drift chambers, particle identification achieved via silicon-tungsten calorimeter, RICH and scintillator TOF system.
Location: Lynn Lake (Canada) 56.5^0 N, 101.0^0 W
Altitude : 360 m. asl (1000 g/cm^2)
Data: July 19-20, 1994.

CAPRICE 97 : Location: Fort Sumner (USA) 34.3^0 N, 104.1^0 W
Altitude : 1270 m. asl (887 g/cm2) (balloon)
Data : April 26- May 2, 1997

MASS : Superconducting magnet spectrometer (balloon)
Location: Prince Albert (Canada) 530 N, 1060 W
Altitude: 600 m. asl

BESS : Balloon Borne Experiment with a Superconducting Spectrometer
Altitude: 1030 g/cm^2 (1995) , 5-30 g/cm^2 (2001)

Interaction models

TARGET2.1 : Phenomenological model, based on the parametrization of accelerator data which are extrapolated to the full phase space, energies and target nuclei needed in atmospheric air showers. Calculations of the neutrino flux based on this model are extensively used to interpret the data of atmospheric neutrino detectors.

QGSJET01 and SIBYLL2.1 are microscopic models, which predict the hadronic interactions from first principles and consequently have a much smaller number of free parameters as TARGET.

* For large momentum transfers between the projectile and target nucleus, the well tested perturbative QCD theory is applicable.

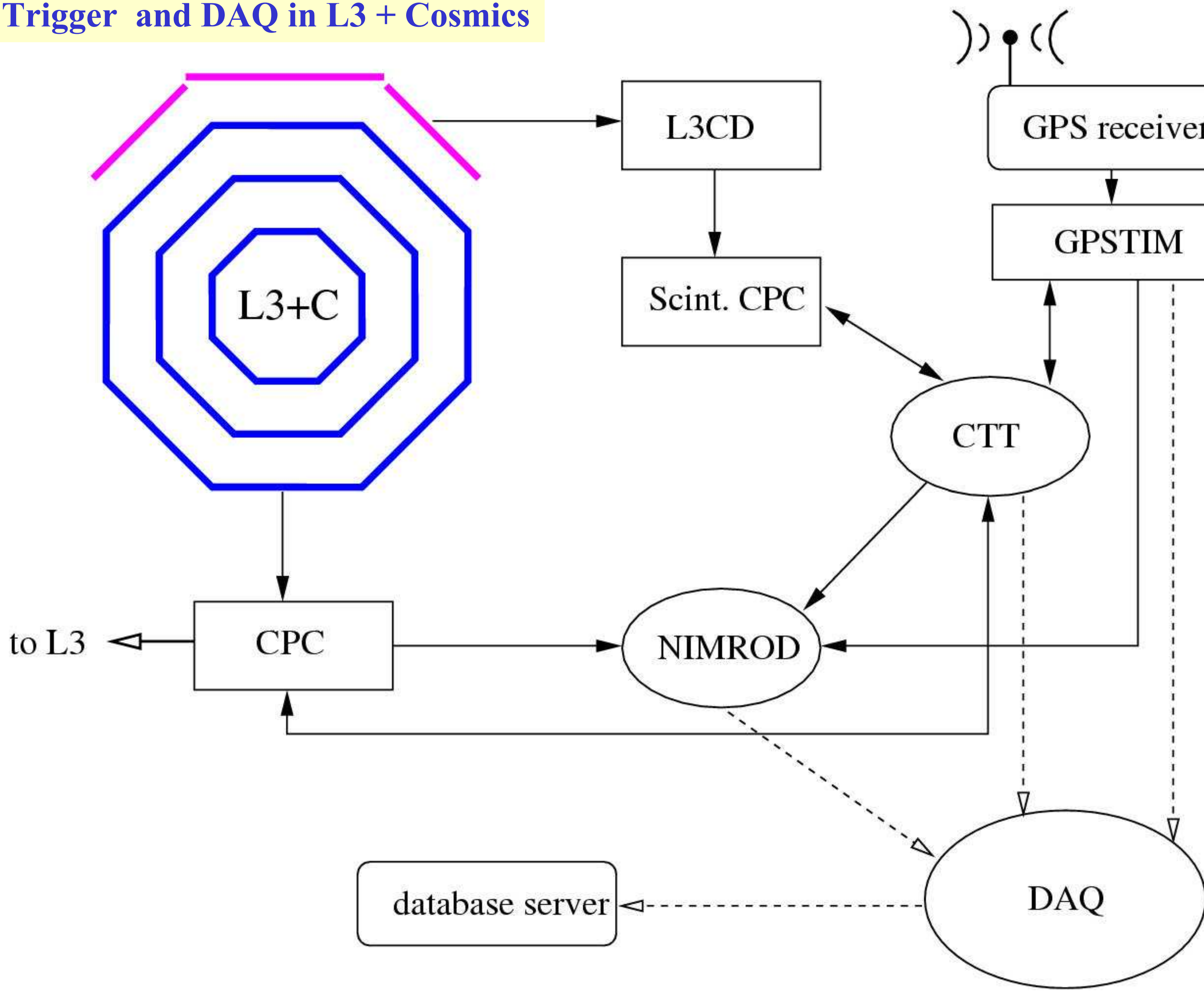
* For momentum transfers below a few GeV,

-the hadronic interactions are modeled based on the Grivob-Regge theory in case of QGSJET01

-whereas they are described by the production of colored strings in SIBYLL2.1

As no low energy model other than TARGET is implemented in the current version of the transport code all interactions below a laboratory energy of 100 GeV are handled by this model.

Trigger and DAQ in L3 + Cosmics



Efficiencies

Scintillator efficiencies:

In 50 % of the cases,the muon arrival time is also deduced from the muon chambers. These tracks are used to determine the scintillator efficiencies (95.6 % -> 94.5 %)

Drift cell efficiency:

The possibility of reconstructing a muon within a single octant is used to scan the drift-layer performance of the facing octant. (10% of drift cells with efficiency < 80%)

Total effective running time:

Live-time counter and external trigger signals agreed within 0.02 %

Selection efficiency :

Efficiencies $\varepsilon 1$, $\varepsilon 2$ in two opposite hemisferes , are computed for data and MC and compared by means of

$$r = (\varepsilon 1 \times \varepsilon 2)^{data} / (\varepsilon 1 \times \varepsilon 2)^{MC}$$ **(funcion of charge,momentum and zenith)**

8 % inefficiency for the full track selection.

Systematic uncertainties

Normalization uncertainties:

Live-time + trigger + scintillator

Uncertainties on the efficiencies of the above give rise to a normalization uncertainty of 0.7 %

Detector acceptance

Uncertainty on detector acceptance is assesed by means of 3 methods:

Comparison of the independent data from 1999 and 2000

Muon flux and charge ratio measured as a function of the azimuthal angle, at large momentum.

Stability of the measured flux and charge ratio with respect to the variation of the selection criteria.

Absolute flux addicional normalization uncertainty :1.7 % -> 3.7 % (depending on the zenith angle)

Charge ratio addicional normalization uncertainty : 1.0 % -> 2.3 %

Momentum scale uncertainties:

Magnetic field strenght : momentum scale bias < 0.4 %

Uncertainties on the detector alignment : may induce a constant offset (relative alignment of the muon chamber octants determined with precision 0.075 -> 0.152 TeV^{-1}

Molasse overburden: Uncertainty on the average rock density of 2 % ->
energy loss uncertainty of 0.4 GeV (in vertical direction)

Detector matrix uncertainty:

Mainly due to statistical uncertainty (MC and data)

Total uncertainty:

Obtained by adding the different sources in quadrature.

Muon flux uncertainty:
dominated by :

***The uncertainty of molasse overburden at low momenta.**
***The alignment and resolution uncertainty at high momenta.**
Minimum is 2.3 % at 150 GeV in the vertical direction.

Vertical charge ratio uncertainty:

Below 2 % up to 100 GeV
Above 100 GeV, rises rapidily with the alignment uncertainties.

L3+C

Location: 6.02^0 E, 46.25^0 N

Altitude: 450 m, 30 m underground

Device to measure the

momentum

charge *and*

angle *of*

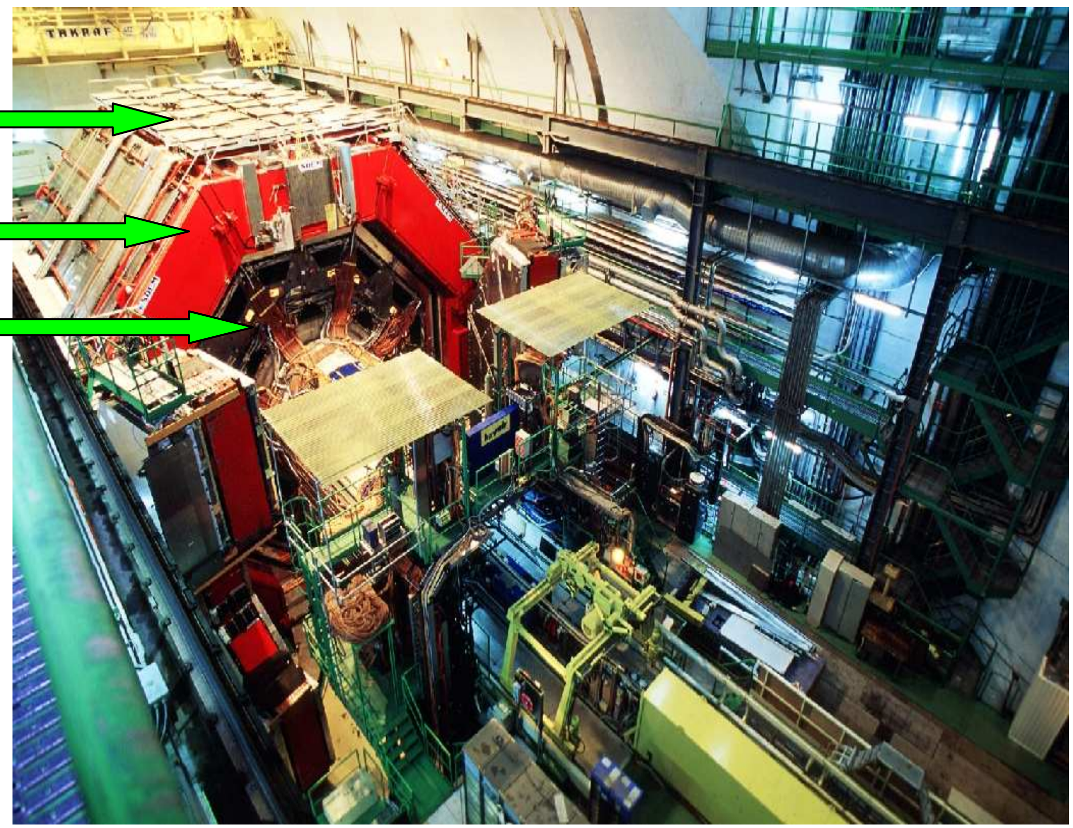
muons *created in air showhers*

Detector:

t_0- detector (202 m^2 scint.)

Magnet (0.5 T, 1000 m^3)

High precision drift chambers



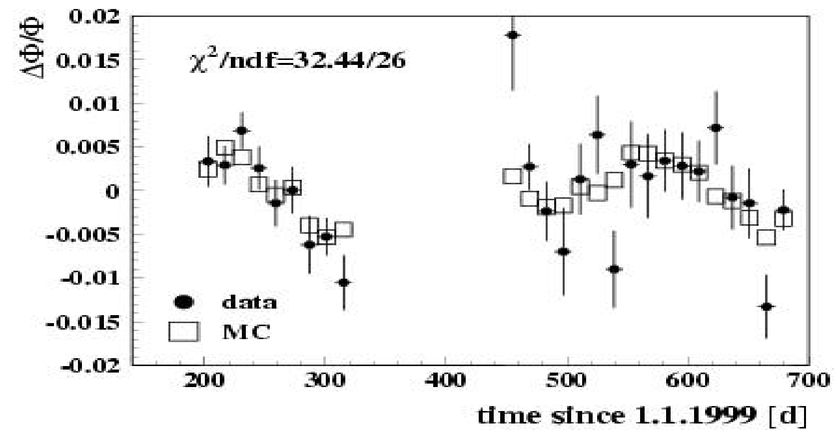


Figure 4: Relative rate change with time for muon momenta between 50 and 62 GeV, compared to a prediction of the atmospheric effect obtained with the TARGET air-shower simulation. The value of a χ^2 comparison of data and Monte Carlo is also shown.