Measurement of the atmospheric muon spectrum from 20 to 2000 GeV

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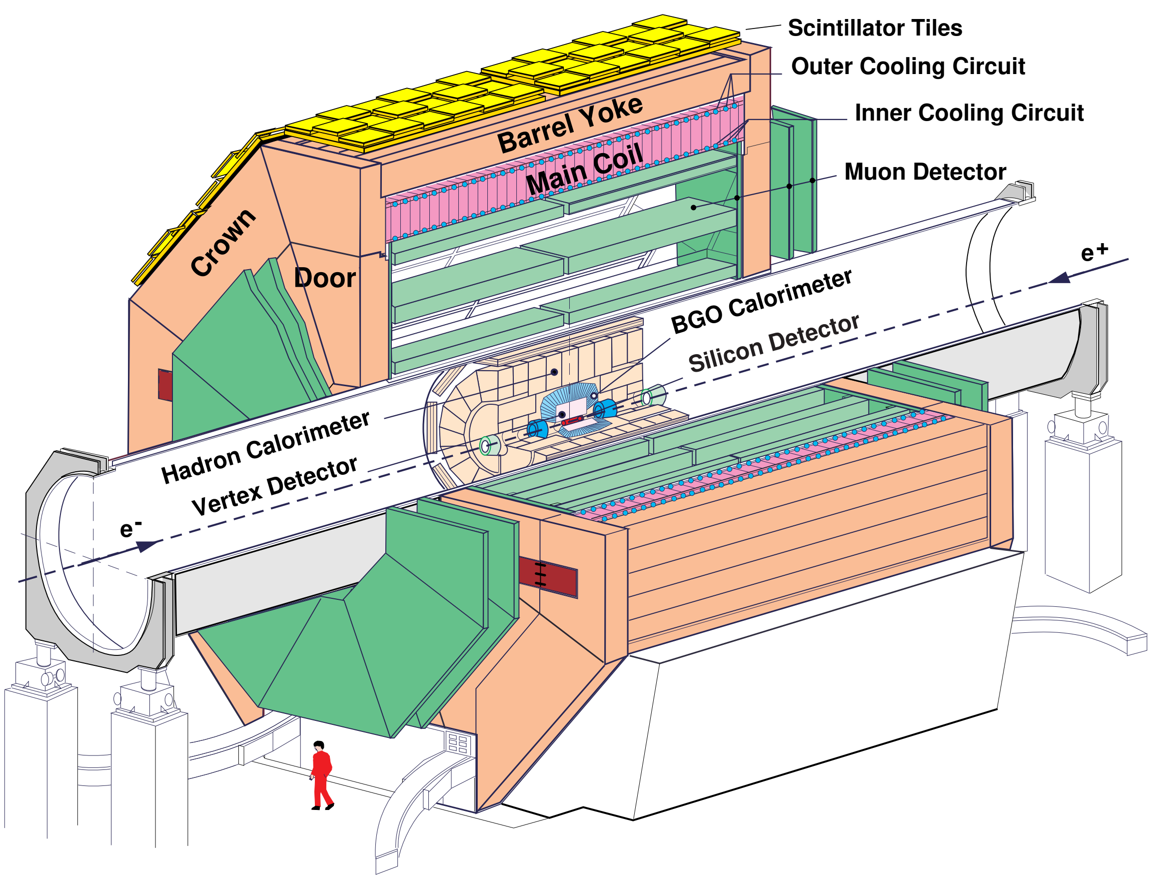
on behalf the L3 Collaboration

- The L3+C experiment
- Data analysis
- Results
  - absolute muon flux
  - muon charge ratio
  - zenith angle dependence
- Conclusions

The L3+C Experiment



- 30 m below surface
- drift chambers in 1000 m^3 magnetic volume ($\mathbf{0.5}\mathrm{T}$)
- 202 m^2 scintillator area
- additional readout hardware
  $\longrightarrow$ DAQ independent from L3
- air shower array at surface
  (50 scint. (0.5 m^2) on 1800 m^2)
- data taking 1999 and 2000
- 12 billion muon triggers collected

Momentum measurement

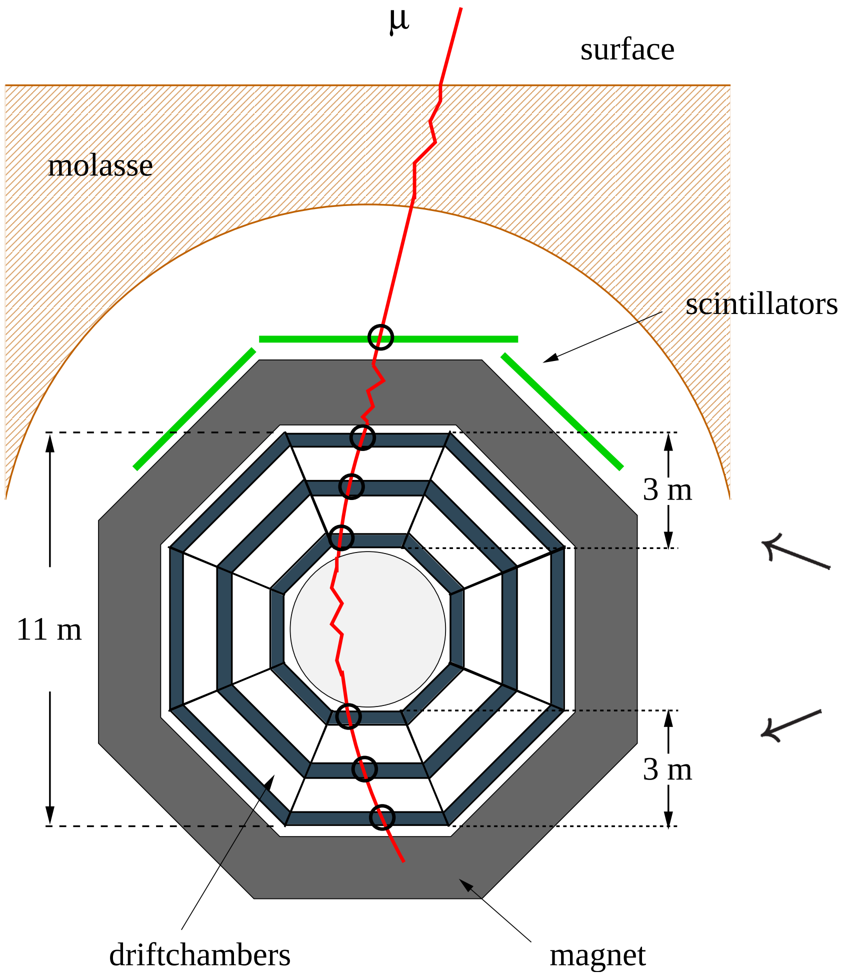
measurement of track coordinates up to six times in bending plane with $\langle \boldsymbol{\sigma_x} \rangle = \mathbf{60}$ μm

stochastic energy loss in molasse and magnet

$\langle \boldsymbol{\Delta E} \rangle = \mathbf{19}\,\mathrm{GeV}$

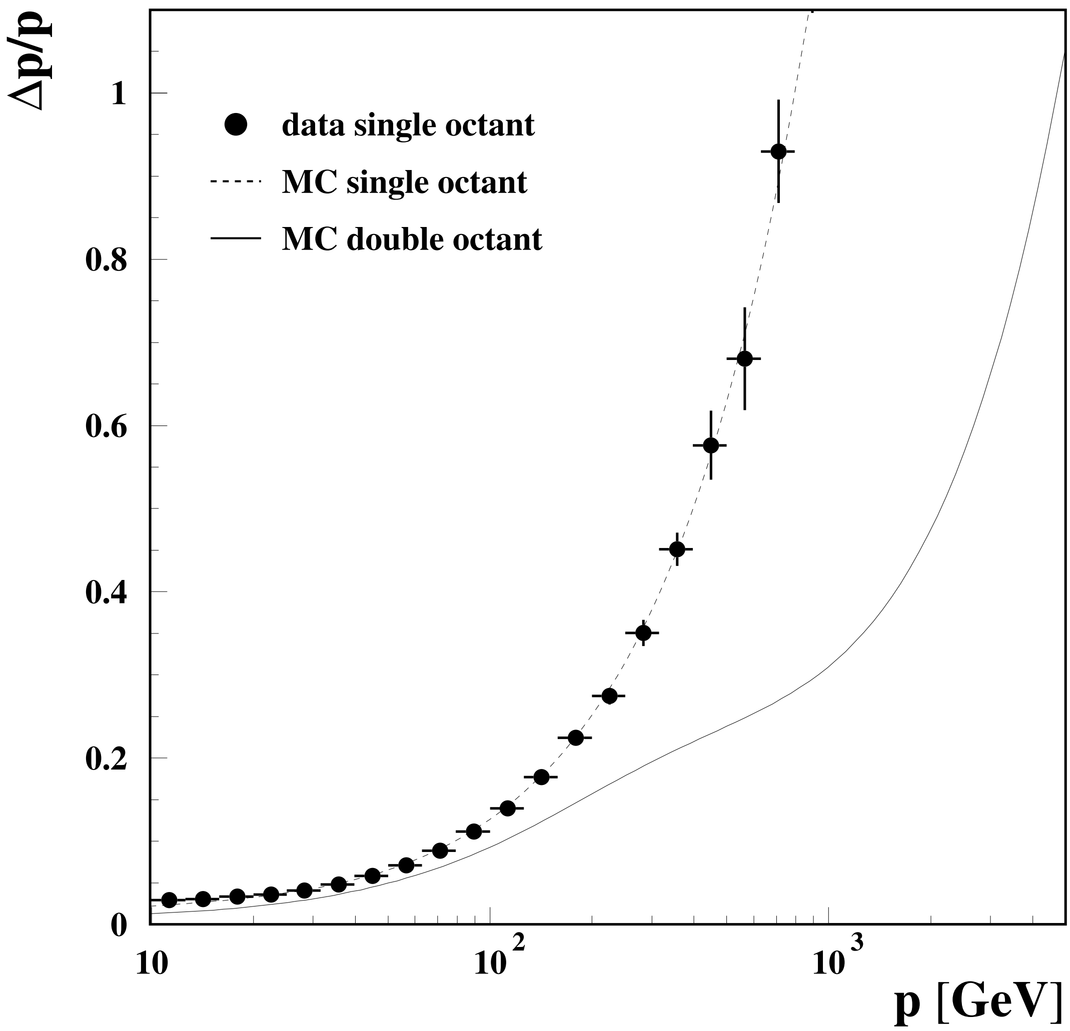
(vertical direction)

momentum fit over full detector length ('double octant')



two independent measurements of muon ('single octant')

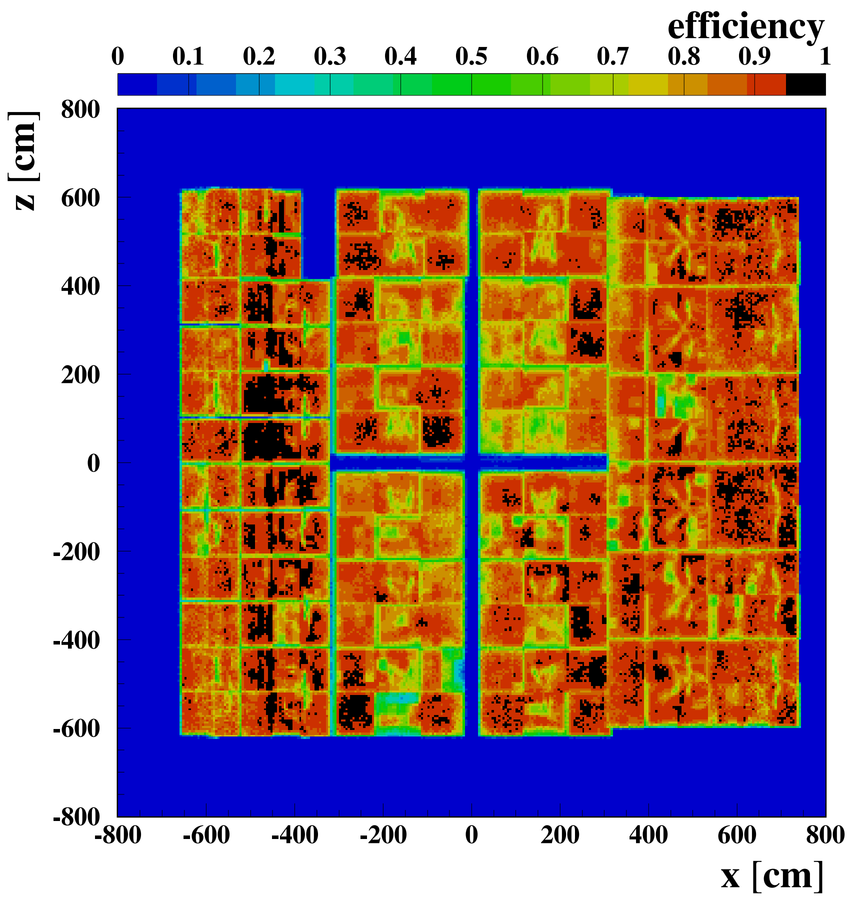
Momentum resolution



maximum detectable momentum at 4.7±0.4 TeV

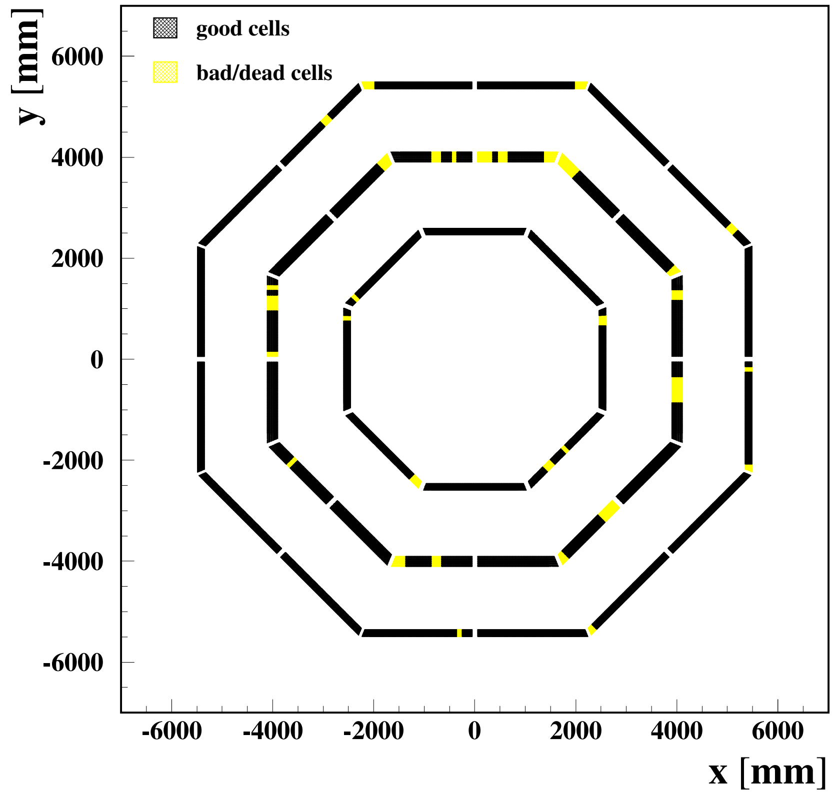
Detector efficiencies

scintillator efficiency



(average efficiency 1999/2000)

muon chamber efficiency



(end 2000 efficiency of 'master' detector half)

Acceptance

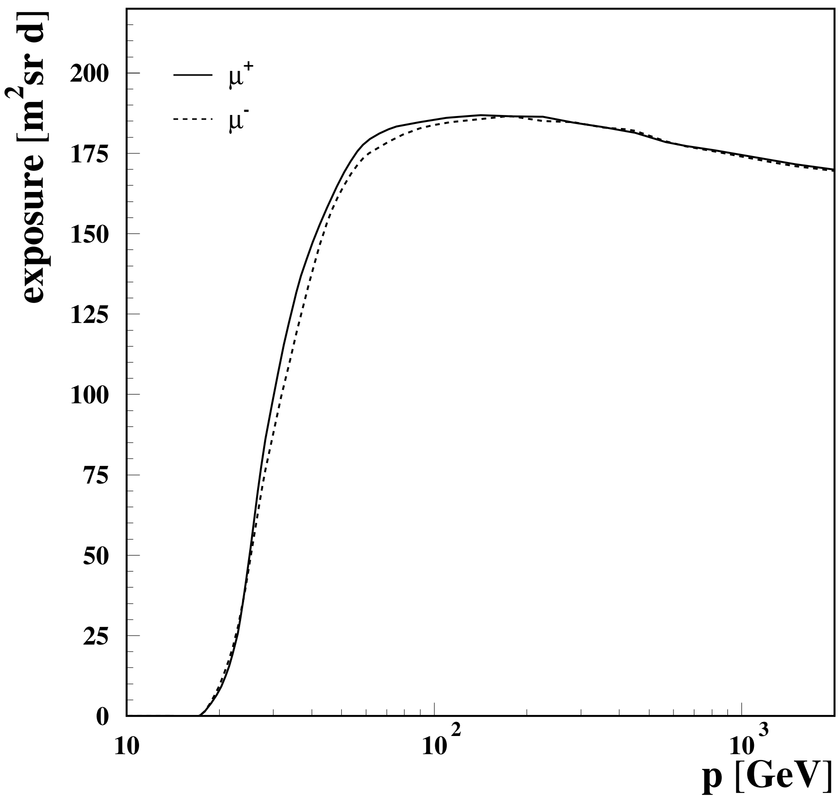
- data quality selection
  $\longrightarrow$ 2.0$\cdot$ 10^7 events for spectrum analysis
  (3.8$\cdot$ 10^{6} in vertical direction)

- GEANT simulation of detector response and L3+C surroundings

- subsequent reconstruction of simulated hits with same reconstruction algorithm used for data

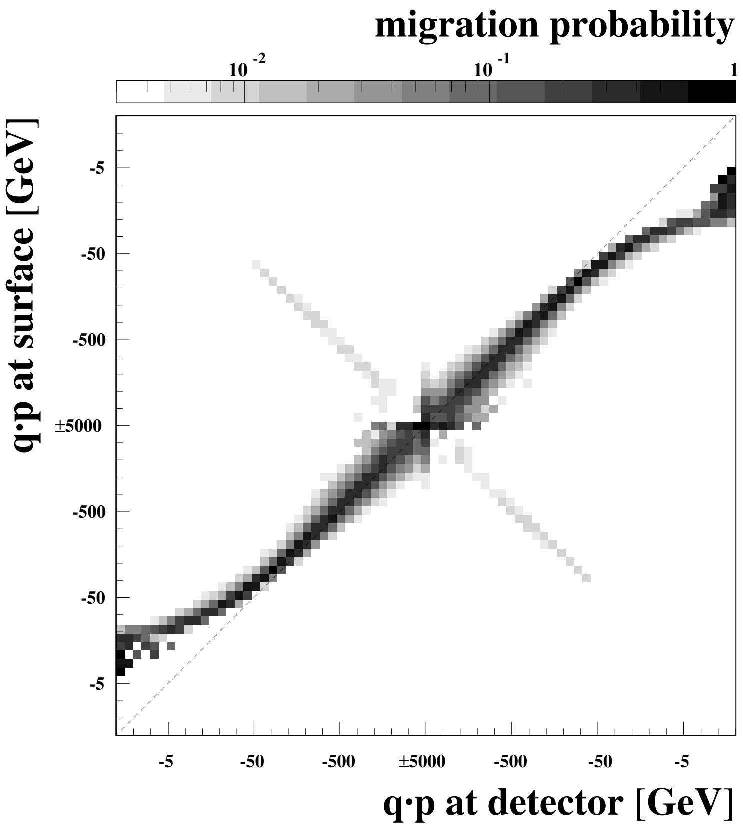
- correction of residual differences between data and MC by measuring single octant efficiencies $\boldsymbol{\varepsilon_i}$:

$$\mathrm{corr} = \frac{(\boldsymbol{\varepsilon_1} \cdot \boldsymbol{\varepsilon_2})^{\mathrm{data}}}{(\boldsymbol{\varepsilon_1} \cdot \boldsymbol{\varepsilon_2})^{\mathrm{MC}}}$$



exposure = acceptance $\cdot$ live-time

Calculation of surface spectrum



visualization of vertical migration matrix

Deconvolution of measured momentum distribution at detector level taking into account

- stochastic energy loss in molasse
- momentum resolution
- momentum dependent efficiencies

True positive and negative muon spectra are supposed to follow

$$\Phi(p) = \Phi_0 \; p^{\gamma}$$

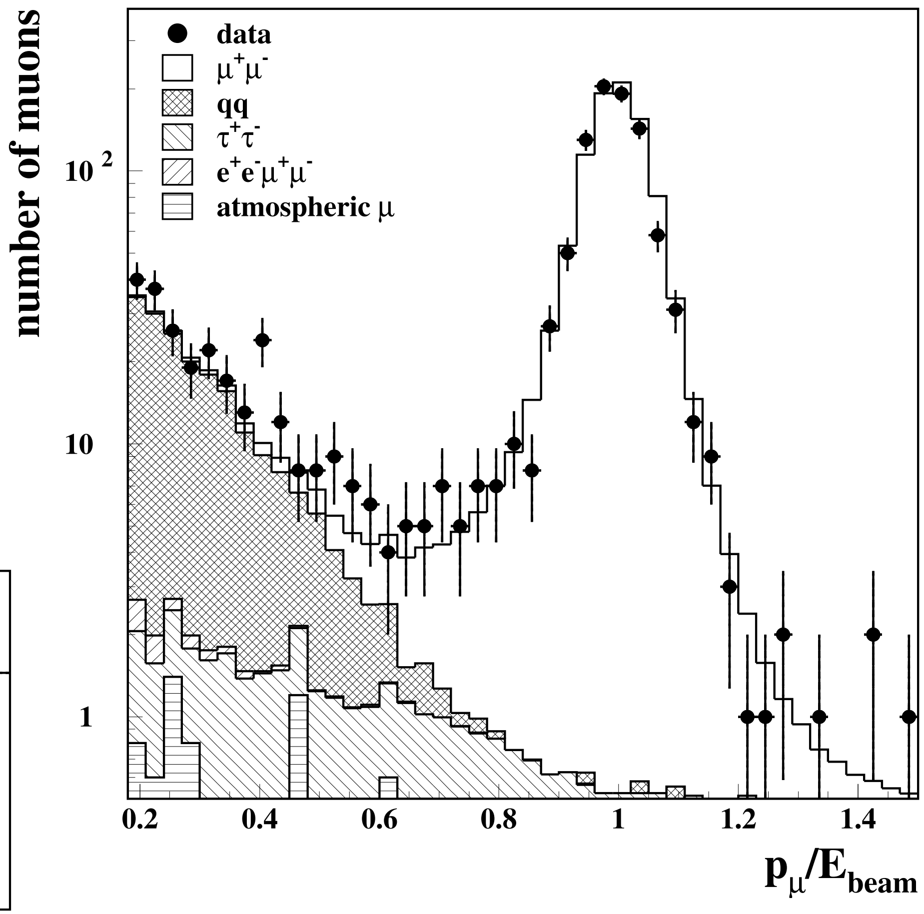
with a variable spectral index

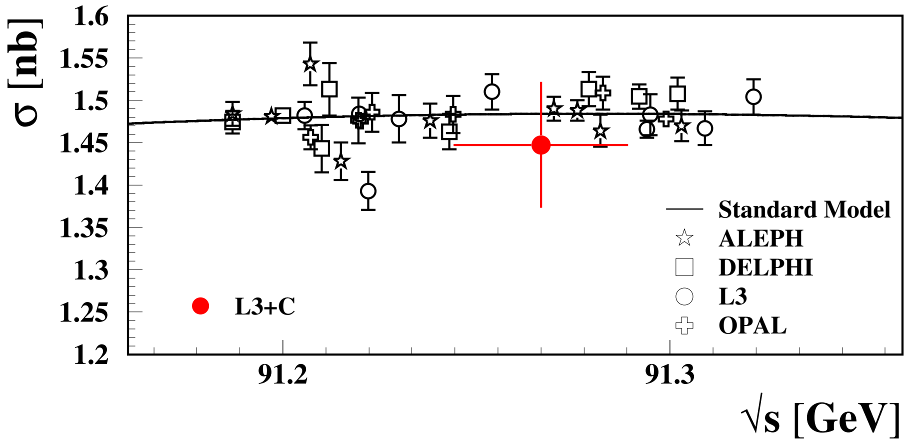
$$\gamma = a + b \cdot \log(p) + c \cdot \log(p)^2$$

to regularize solution of unfolding problem

$Z^0 \rightarrow \mu^+\mu^-$ events

- LEP calibration runs
- 634 events selected out of $7{\cdot}10^7$ cosmic triggers selected
- check of detector understanding
- determined cross section compatible with precise LEP1 measurements





Estimation of systematic uncertainties

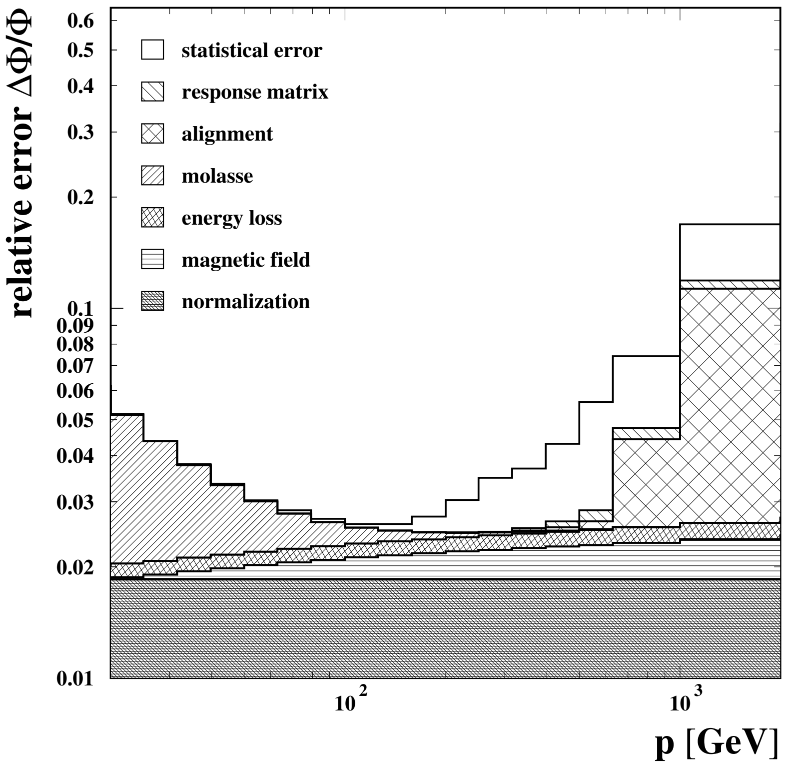
- calibration and efficiency uncertainties
- variation of selection cuts
- variation of results wrt. azimuth angle
- data subsamples

$\longrightarrow$ vertical muon flux uncertainty of

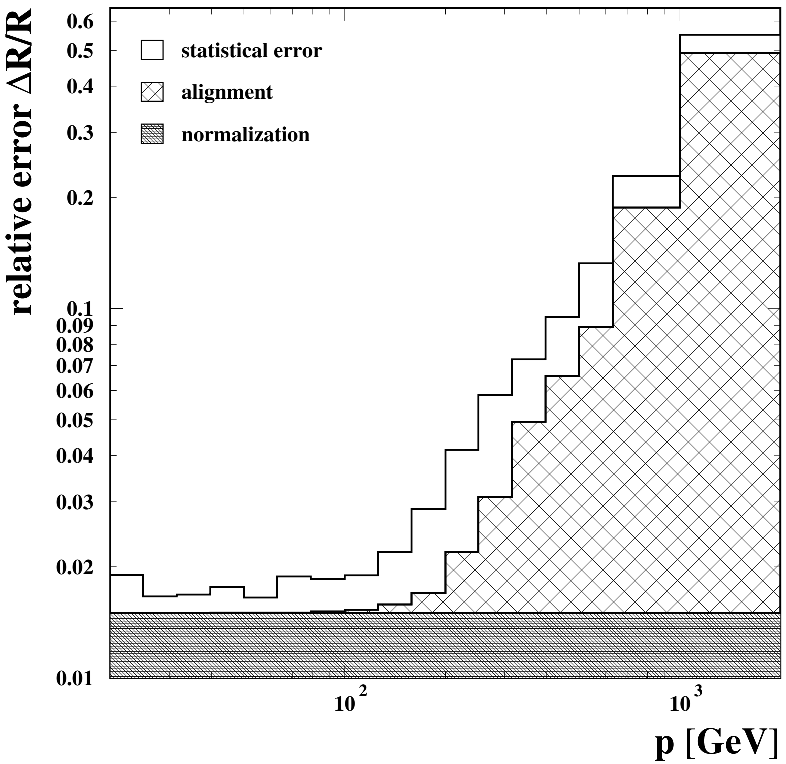
2.6% at 100 GeV

(3.5% averaged over all zenith angles)

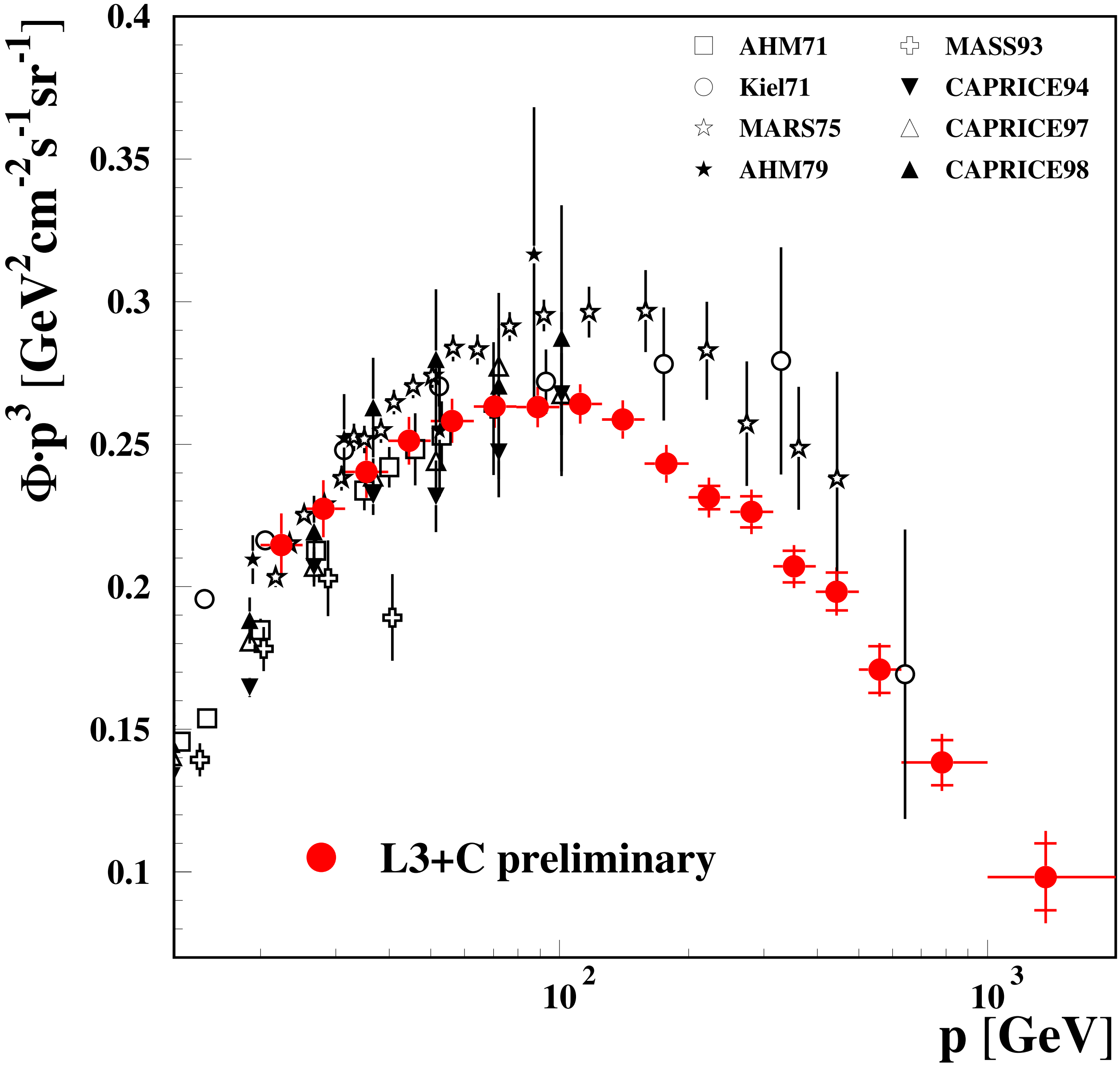
vertical muon flux



vertical charge ratio



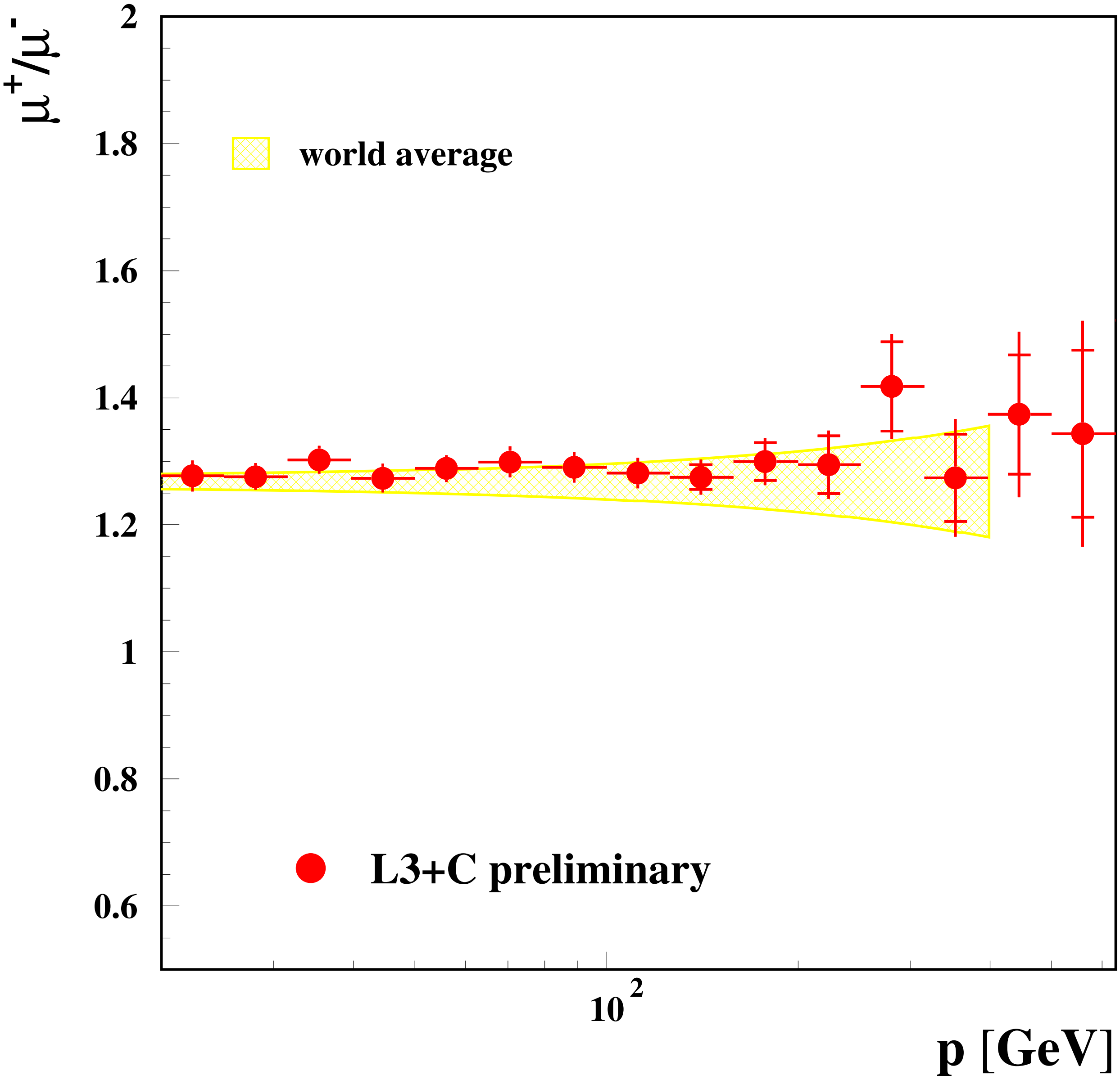
Vertical muon spectrum
$(\cos(\theta) > 0.975)$



inner error bar: statistical error
full error bar: total error

Vertical muon charge ratio

$(\cos(\theta) > 0.975)$

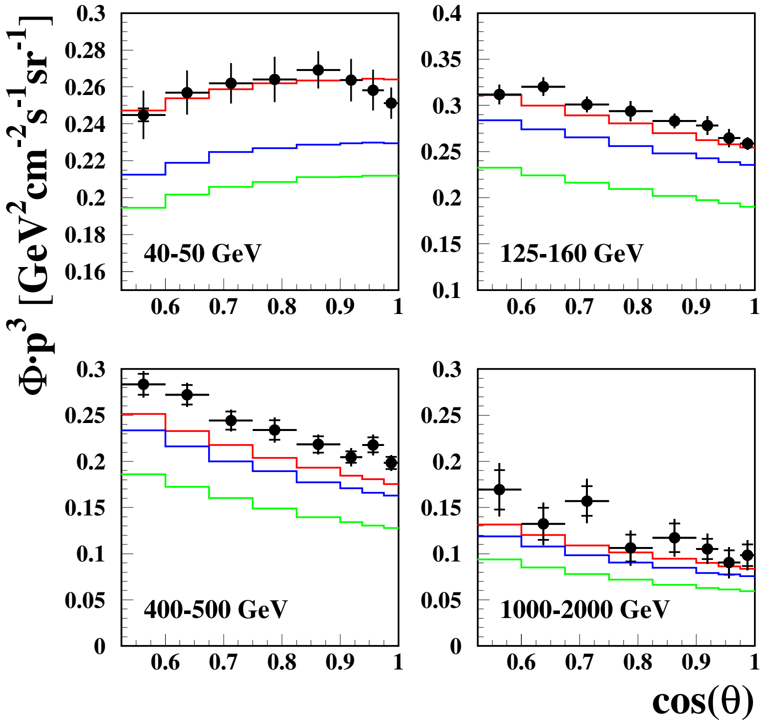


inner error bar: statistical error
full error bar: total error

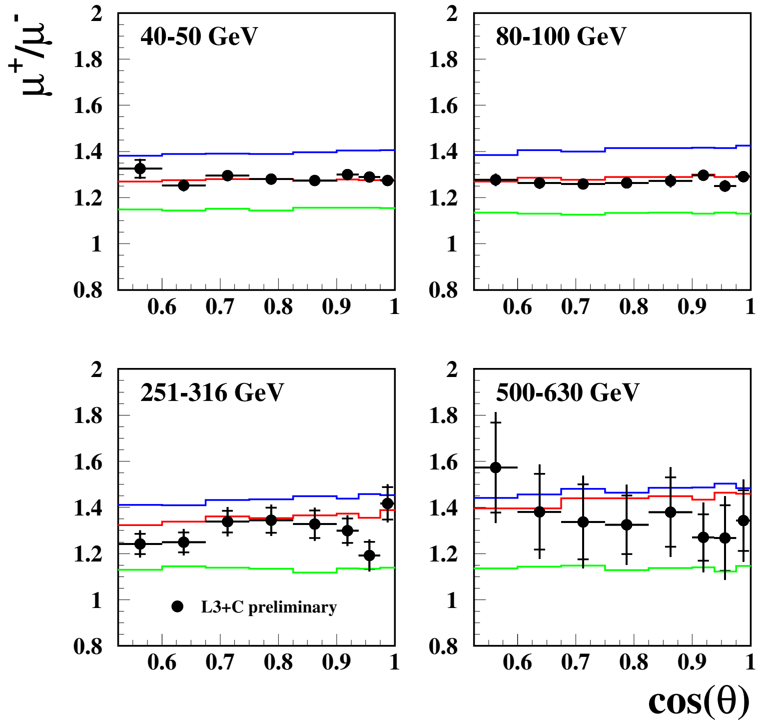
average of previous experiments from Astropart. Phys. **18** (2002), 107

Zenith angle dependence

muon flux



charge ratio



- air shower simulations with transport code `TARGET2.1` (one dimensional)
- high energy interaction models: `TARGET2.1`
  `QGSJET01`
  `SIBYLL2.1`
- primary flux: Ann. Rev. of Nucl. Part. Sci. **52** (2002), 153

Summary

- L3+C measured
  - vertical muon flux 20-2000 GeV
  - charge ratio 20-600 GeV
  - zenith angle dependencies up to 58^o
- large exposure factor of about 180 m^2 sr d
- maximum detectable momentum at 4.7$\pm$0.4 TeV
- Minimum systematic error of vertical muon flux is 2.6%

Presented results are close to final and will be published soon