Cosmic Ray Results from CosmoALEPH
.... What can one learn from a hole in the ground?

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Siegen University, September 2015

Outline

- Introduction
- Experimental Setup
- Decoherence curve
- Muon multiplicities
- Muon Spectrum
- Muon Charge Ratio
- Muon Tridents
- Outlook

Introduction: Objectives of CosmoALEPH

Measurement of underground cosmic ray muons for:

- chemical composion of primary cosmic rays
- interactions of high energy primaries in the atmosphere
- precision measurement of the muon momentum spectrum
- precision measurement of the muon charge ratio
- study of local interactions of muons, in particular
- muon tridents

Comparison with results of:

- MC simulations based on different hadronic interaction models
- other experimental results

Experimental Setup

ALEPH detector:

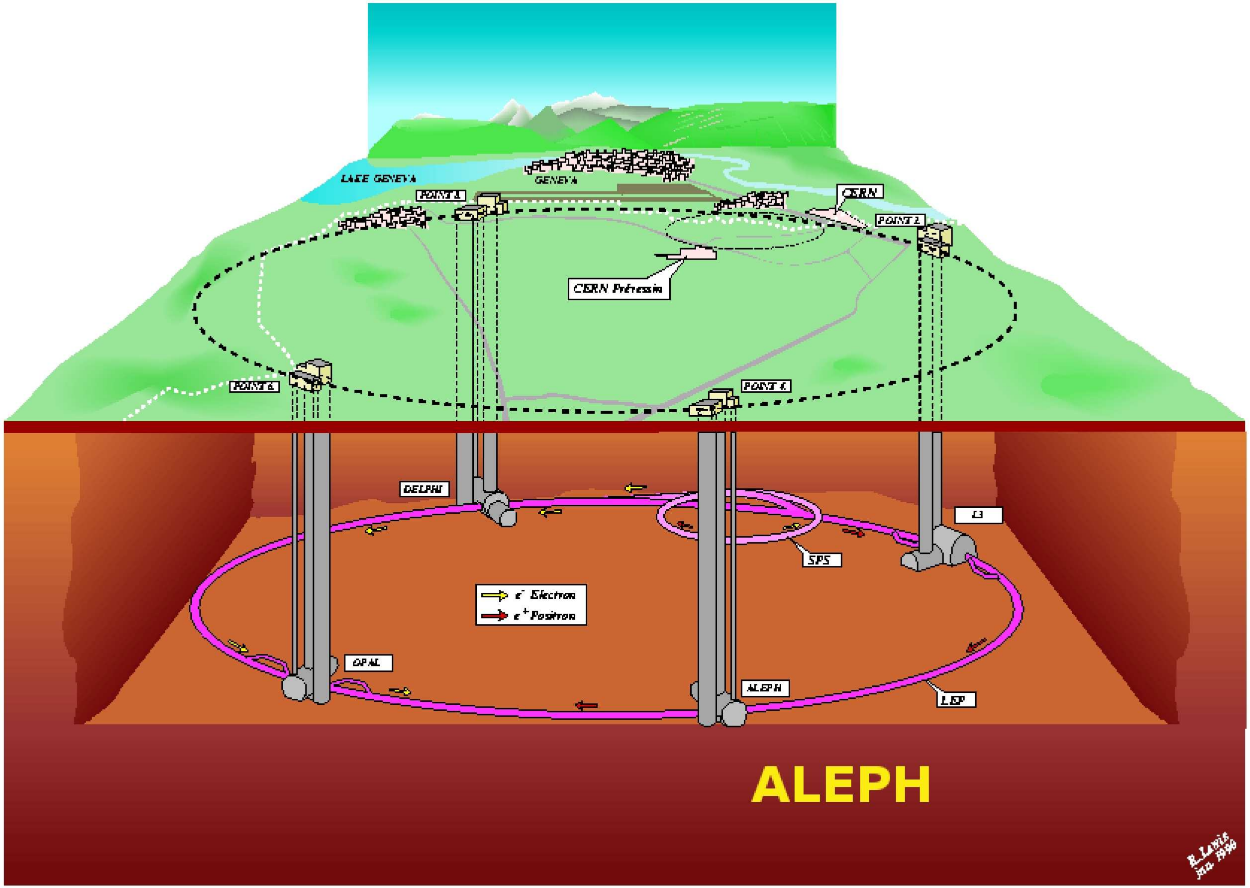
Location: overburden 125 m of molasse and rock
(75 GeV cutoff for vertical incidence)

- TPC (Time Projection Chamber) Spatial resolution $= 160\ \mu$m
  Momentum resolution $\Delta p/p \approx 2.5\%$ at 50 GeV/c
  $\approx 60\%$ at 1.5 TeV/c Maximum detectable momentum ≈ 3 TeV
  Angular resolution < 2 mrad
- HCAL (Hadron Calorimeter)

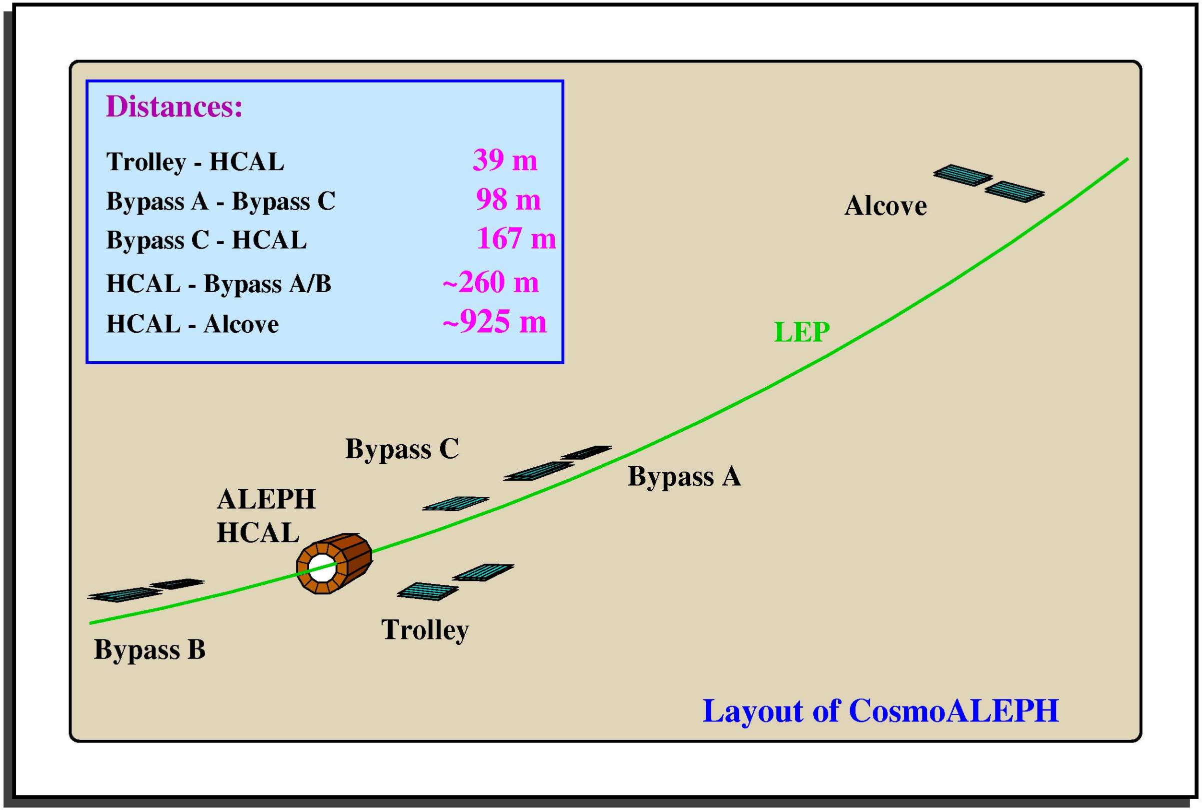
The four LEP experiments at the LEP collider

ALEPH detector:

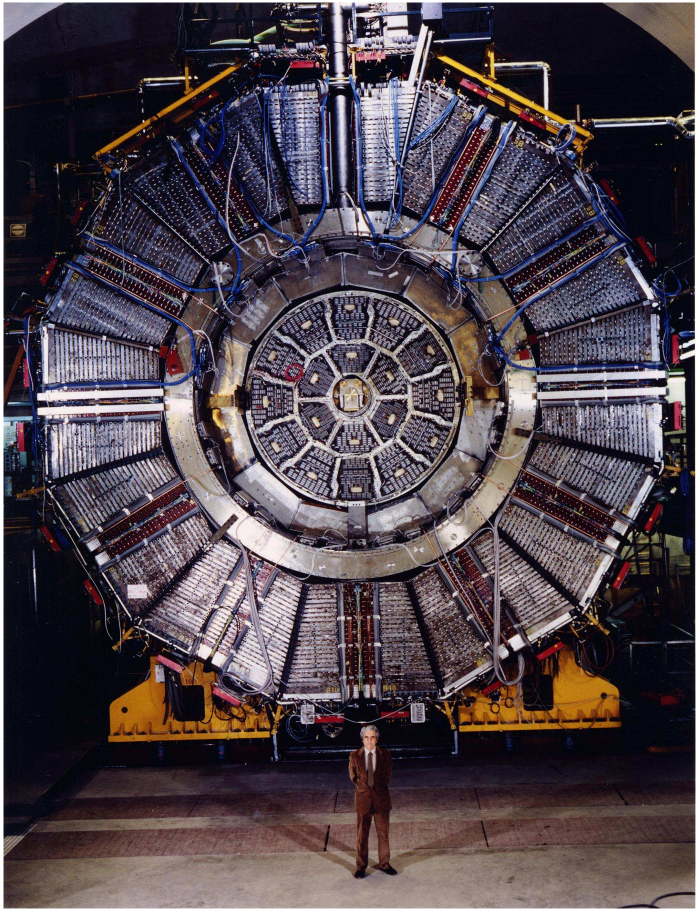
LEP at CERN (Geneva) , CosmoALEPH -320 m.w.e.



The CosmoALEPH Experiment at LEP



The ALEPH Detector



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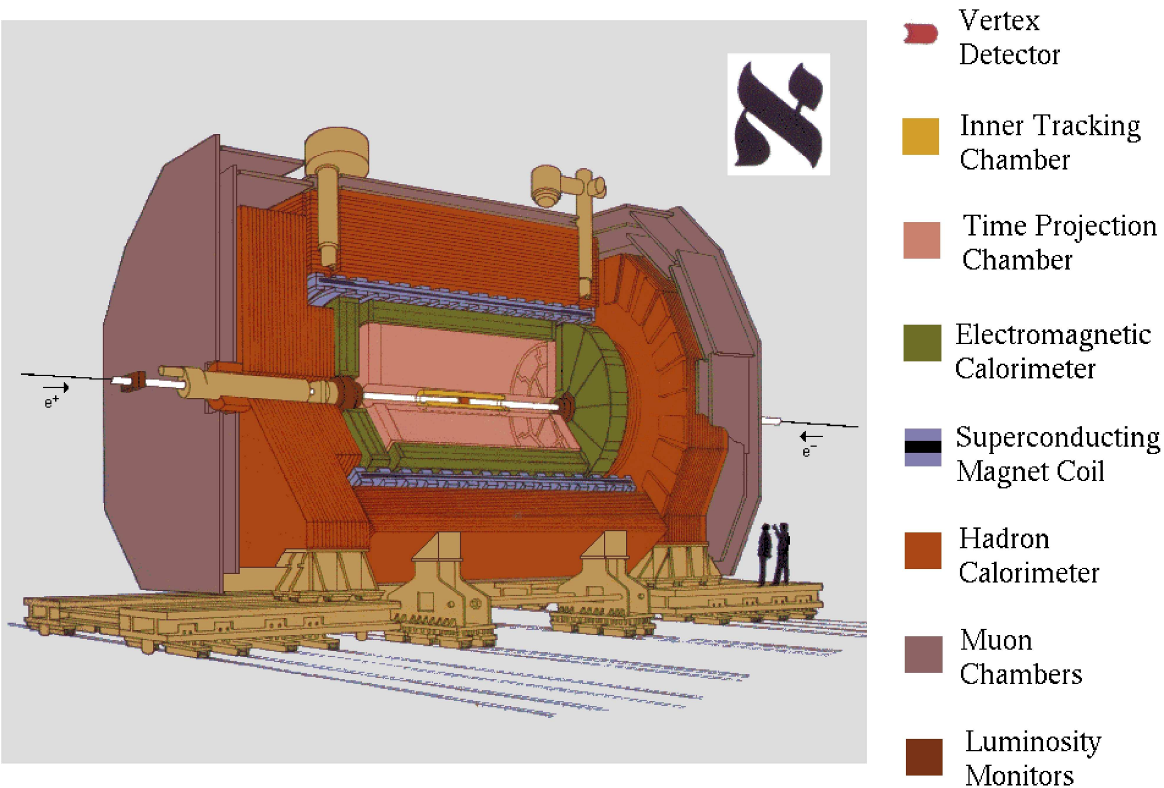
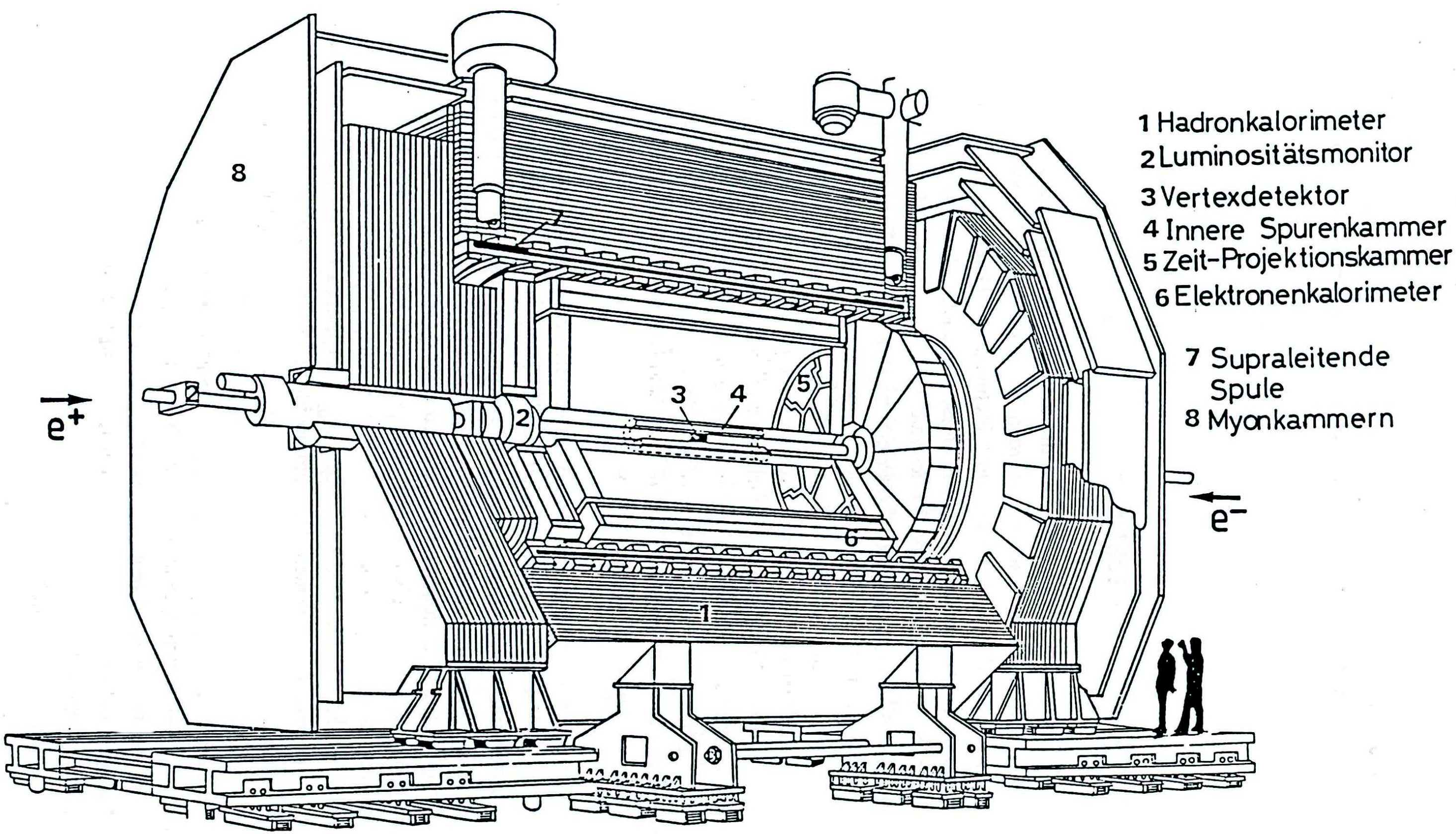
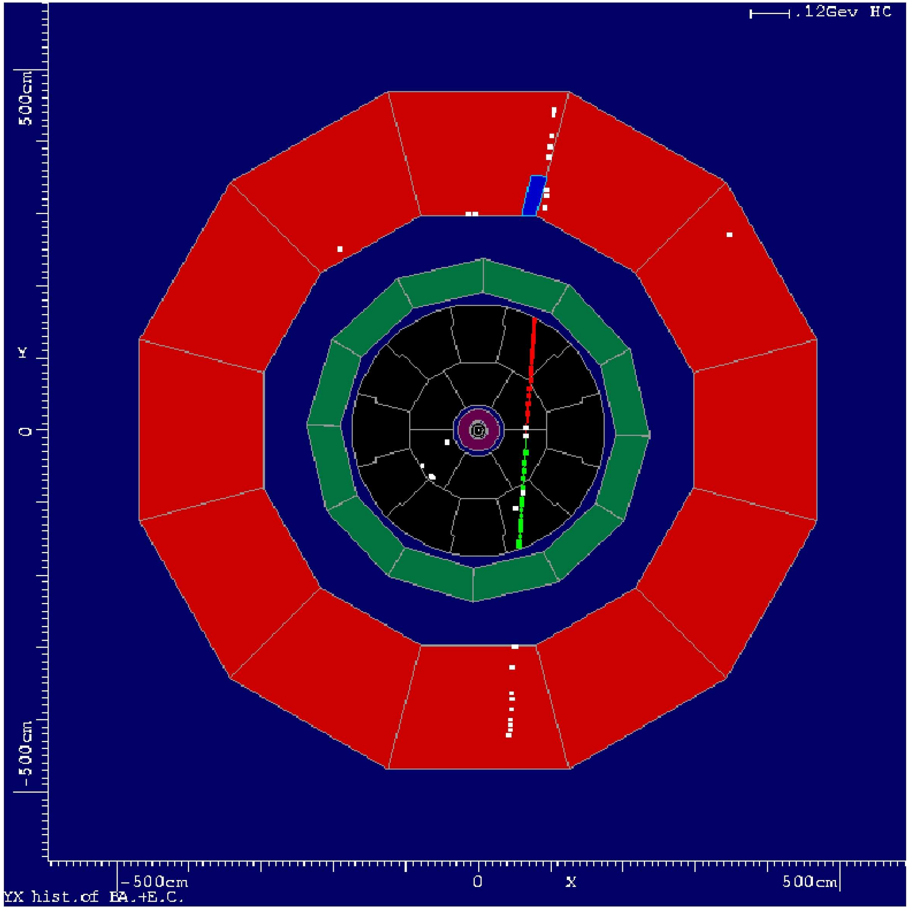


- CosmoALEPH dedicated runs: only HCAL and TPC used, no e+ e- beam.

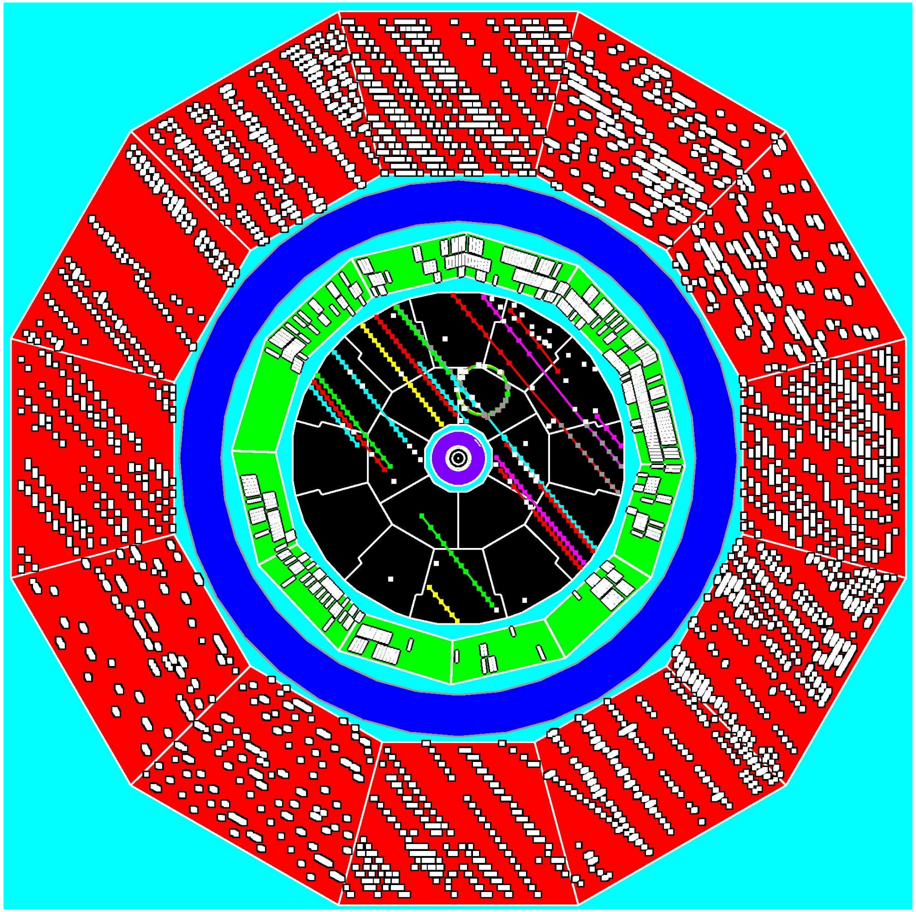
Details of the ALEPH Detector



A Single Cosmic Ray Muon Event in ALEPH



A Cosmic Ray Muon Shower in ALEPH



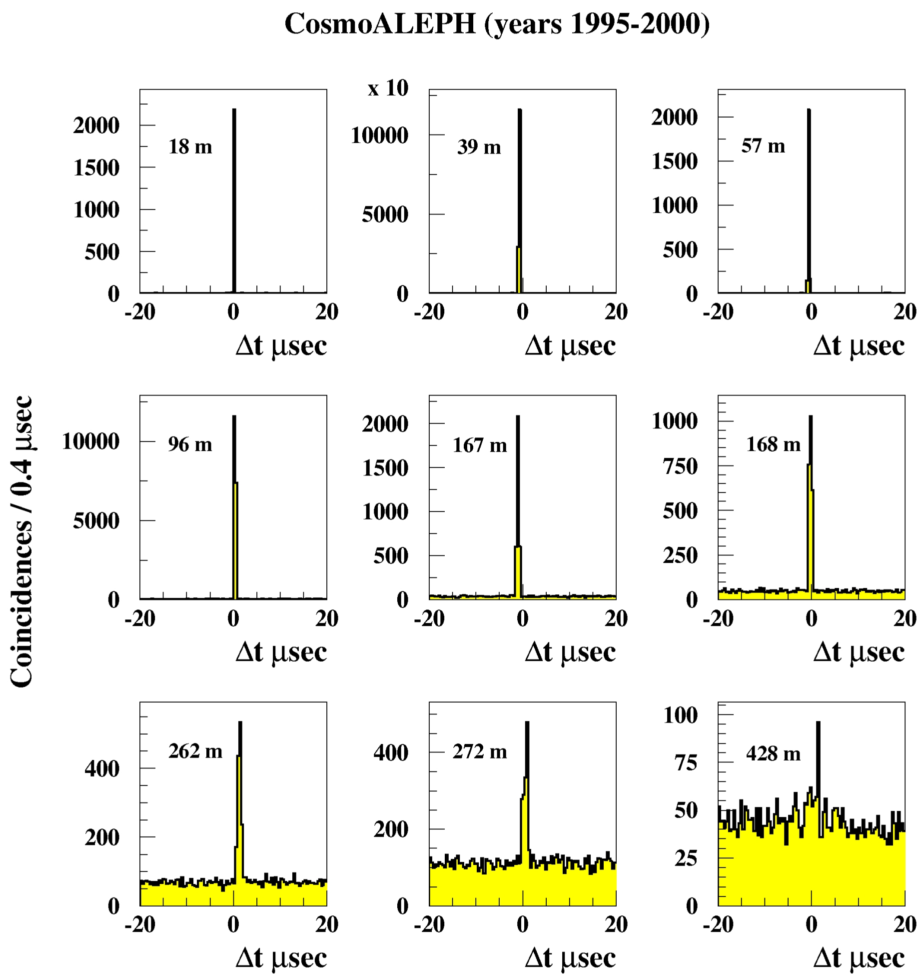
Coincidence rates between different detector stations (ALEPH and telescopes in the pit and the LEP tunnel)

Requirements

- clear muon tracks in ALEPH and muon hits in the telescopes

total number of events $\approx 9 \cdot 10^8$
for the years 1995 - 2000
$1.1 \cdot 10^6$ events from runs with a
dedicated cosmic ray trigger in ALEPH

Coincidence rates between different detector stations



Definition of the Decoherence Distribution

The decoherence distribution is defined as coincidence rate per unit of time divided by the product of the areas of two detectors and corrected for detector acceptance, trigger efficiency and for the difference in the thickness of the overburden on top of each detector:

$$\text{Rate}\ (m^{-4} day^{-1}) = \frac{N_{coin}}{\epsilon_i \epsilon_j\ a_i a_j\ S_i S_j\ \epsilon_{ov_i} \epsilon_{ov_j}\ T}$$

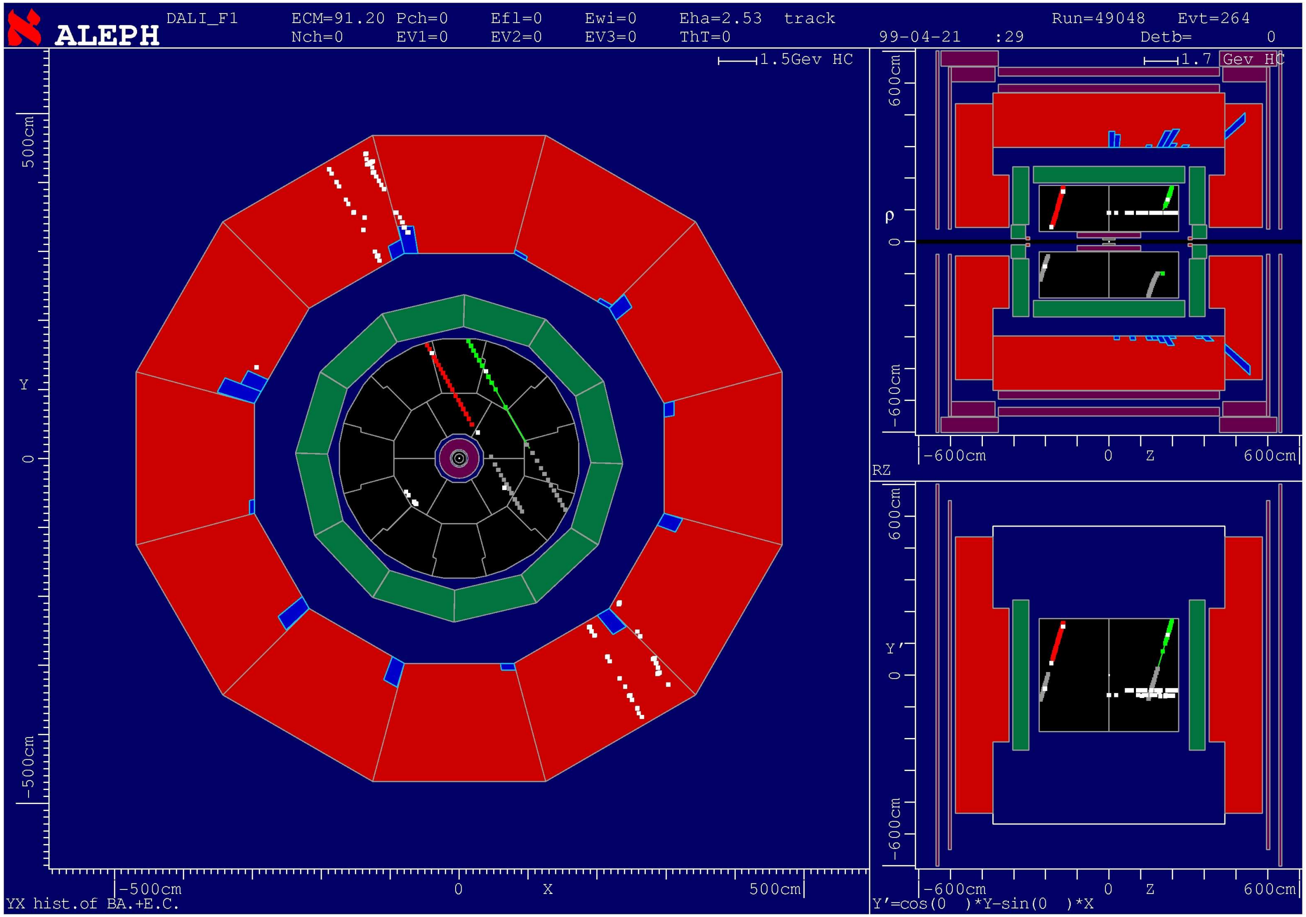
- N_{coin} is the background-subtracted coincidence rate
- $\epsilon_{i,j}$ are the efficiencies of stations
- $a_{i,j}$ correction factors for geometrical acceptances
- $\epsilon_{ov_{i,j}}$ overburden correction factors
- $S_{i,j}$ the areas of detectors in m^2
- T is the total effective up-time of stations in days

Details of the detector stations

[htb]

Station	Gallery	ByC	Trolley	ByA	ByB	HCAL	Alcove
Area (m^2)	4.4	4.6	4.5	5.3	6.7	9.4	7.0
Stacks	5	5	5	6	4	*	8
Total events (10^7)	0.17	6.7	16.0	17.9	13.8	10.3	21.9
Total uptime (days)	10.8	534.8	849.4	868.7	775.8	470.8	750.5
Rate (Hz)	1.8	1.5	2.2	2.4	2.1	2.5	3.4
Correction for accep.	0.95	0.90	0.95	0.97	0.96	0.87	0.95
Efficiency	0.66	0.73	0.68	0.90	0.80	0.99	0.79
Correction for overb.	1.0	0.84	1.0	0.84	0.84	0.83	0.84

Short distance correlations



CORSIKA Simulations

Models: QGSJET, VENUS, SIBYLL and NEXUS

- About 10^8 air showers of protons, He, and Fe nuclei primaries were generated
- Primary zenith angle θ range from 0° to 89°
- Primary energy in the range from 170 GeV to 10 PeV
- Two mass compositon models: Constant mass composition **(CMC)** with identical spectral slopes $\gamma = 2.7$ for all primary elements and energies and the Maryland composition model **(MCM)** with varying energy dependent spectral indices.
- **Energy cut-off for muons:** $E_\mu = 0.55 \cdot (e^{\frac{0.4 \cdot 0.32}{\cos\theta}} - 1)$ **[TeV]**

Parameters for the Maryland Composition

MCM for protons, helium and iron

Composition model	Elements	γ	E_c (GeV)	γ ($E > E_c$)
MCM	proton	2.75	$3.0 \cdot 10^5$	3.35
	helium	2.77	$6.0 \cdot 10^5$	3.37
	iron	2.50	$8.4 \cdot 10^6$	3.10

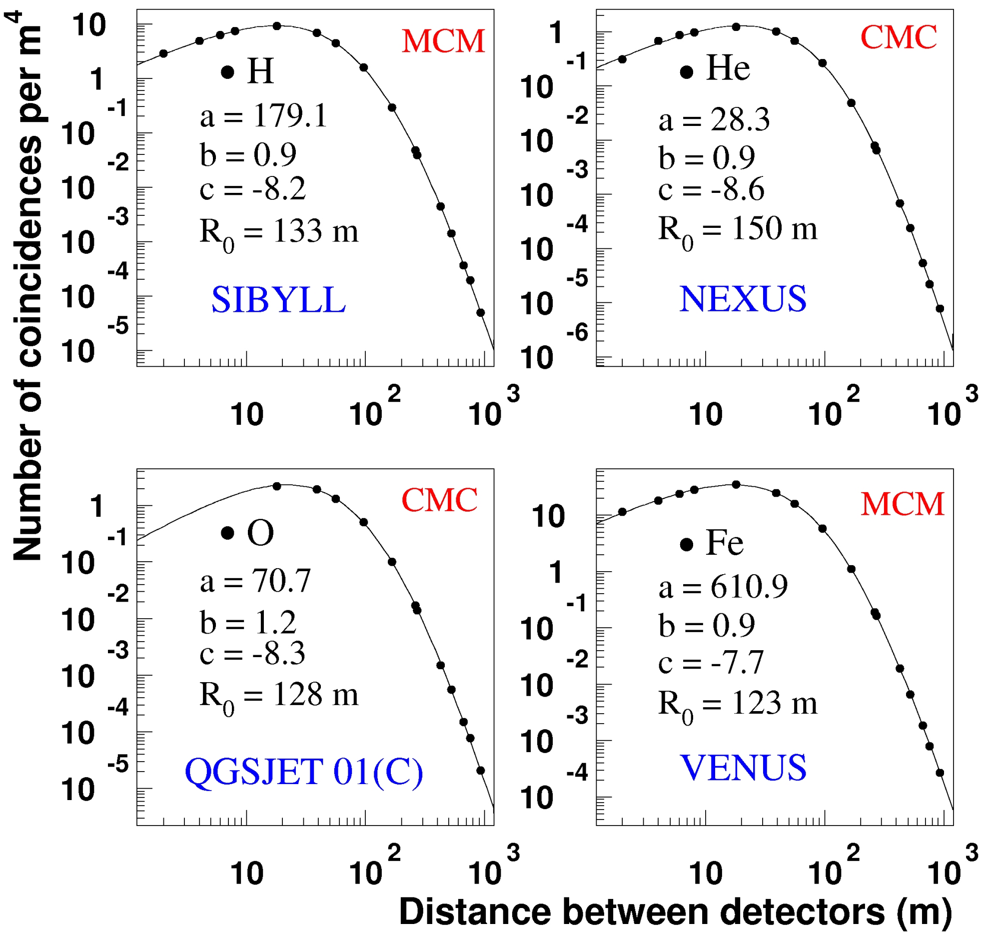
Monte Carlo Coincidence Rates

For each shower with ≥ 2 muons underground at the CosmoALEPH experiment level the distance and time difference between all possible pairs of two muons (for all showers) were computed.
The obtained coincidence rates of muons for each simulated primary element for different hadronic models and composition approaches are best fit with the Nishimura-Kamata-Greisen (NKG) formula:

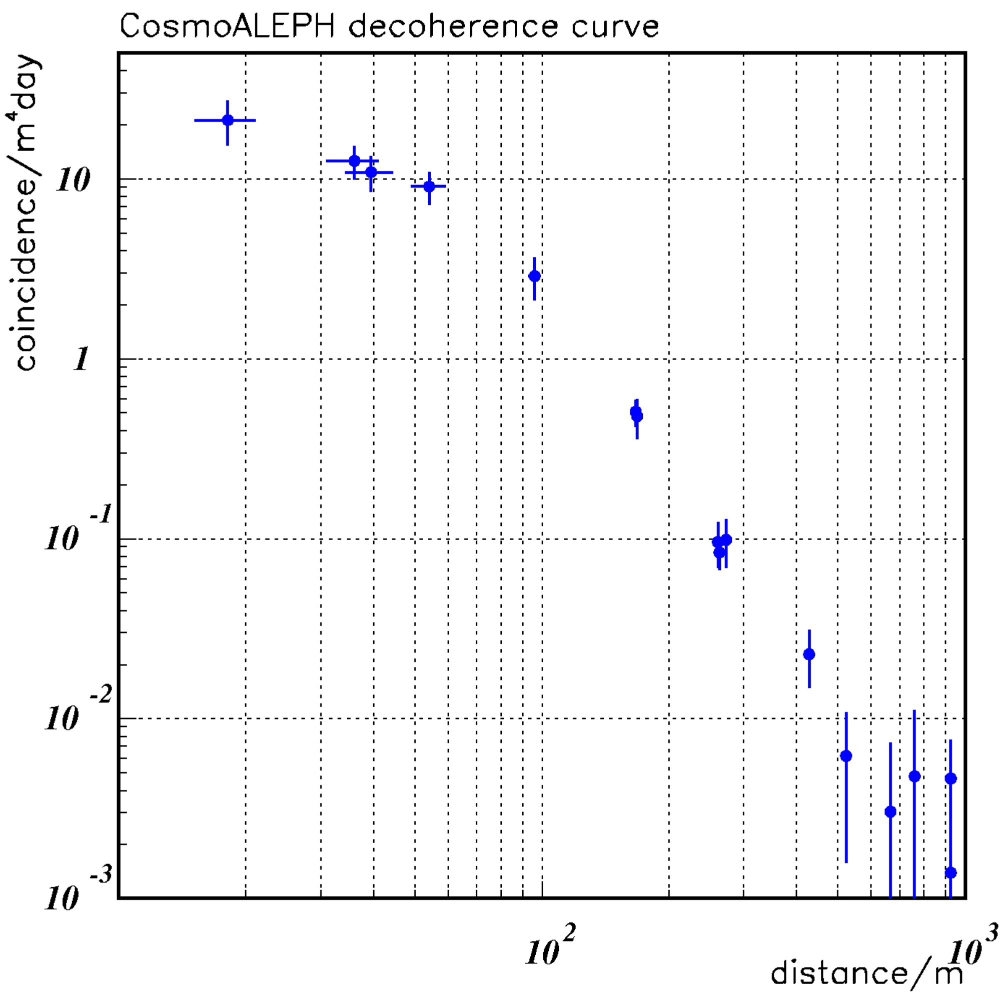
$$\rho_\mu = a \cdot \left(\frac{R}{R_0}\right)^b \left(1 + \frac{R}{R_0}\right)^c \quad (1)$$

The constrained fit of the CosmoALEPH data is performed with the sum of obtained functions for protons, He and Fe and the contribution of each element is estimated.

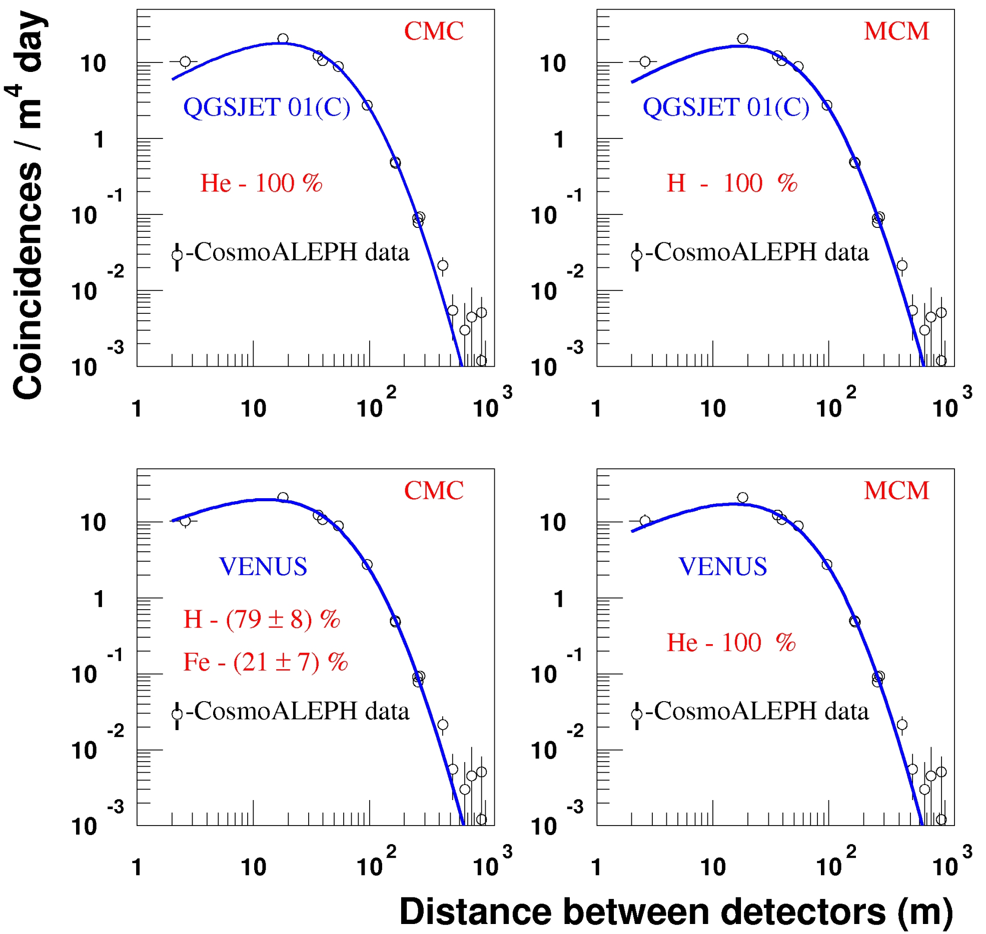
Monte Carlo lateral distributions



Experimentally observed lateral distributions



Results compared to Monte Carlo distributions



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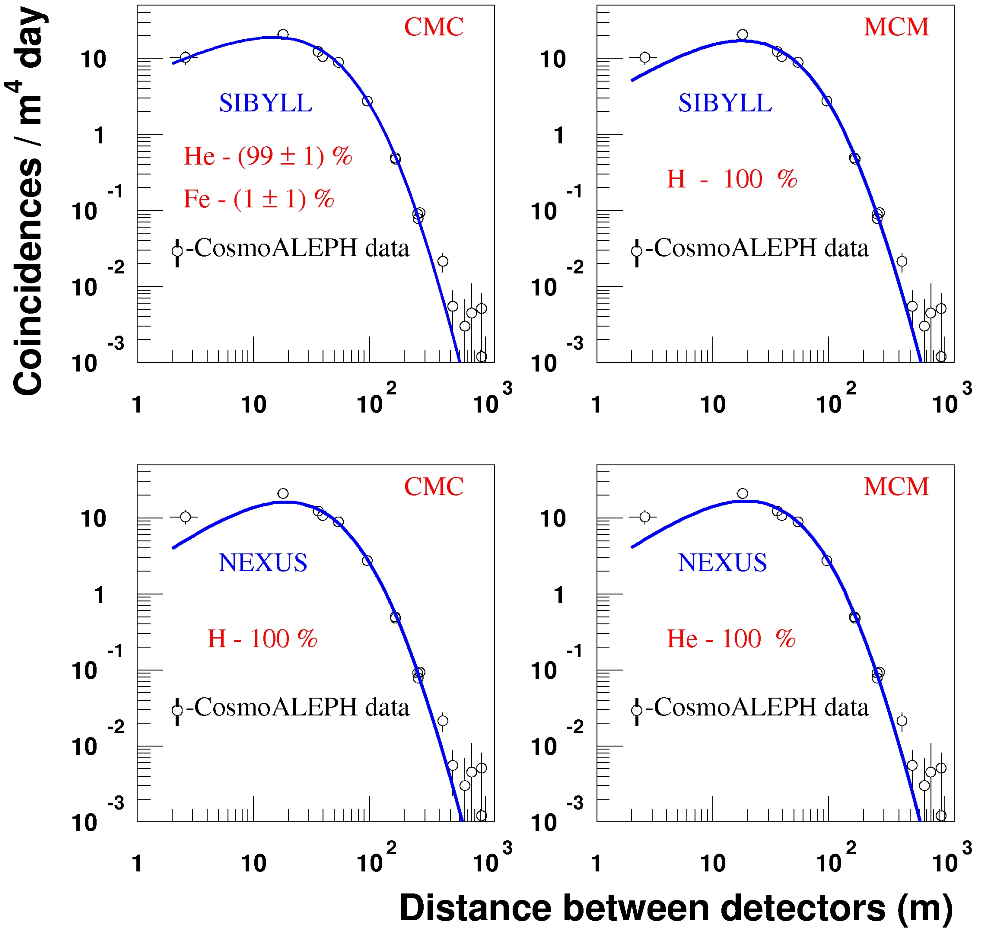


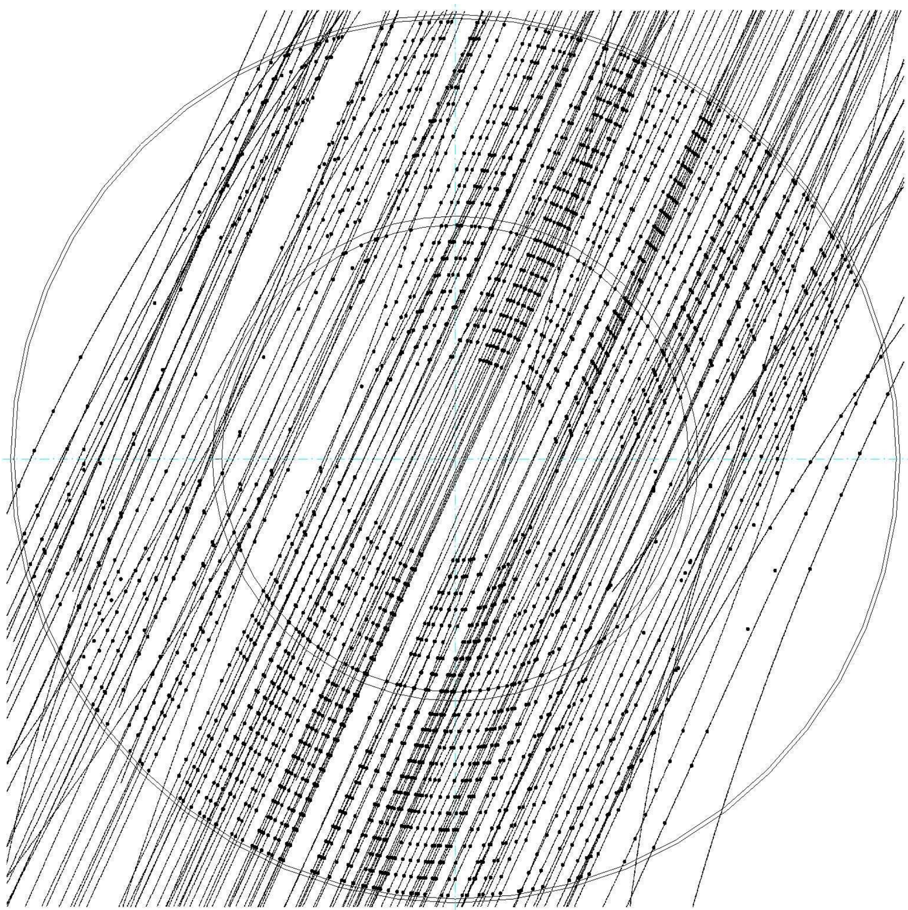
Preliminary conclusions on the lateral distributions

- **It is very difficult to arrive at firm conclusions for the chemical composition of primary cosmic rays.**
- **The comparison of the measured CosmoALEPH decoherence distribution with the predictions from the CORSIKA models in the energy region $10^2 - 10^7$ GeV favours a light composition for most hadronic models.**
- **An exception is the VENUS model for the CMC spectra where a substantial amount of iron is found.**
- **The helium dominance for some models (e.g. QGSJET) is a surprise; but it is also found in KASCADE.**

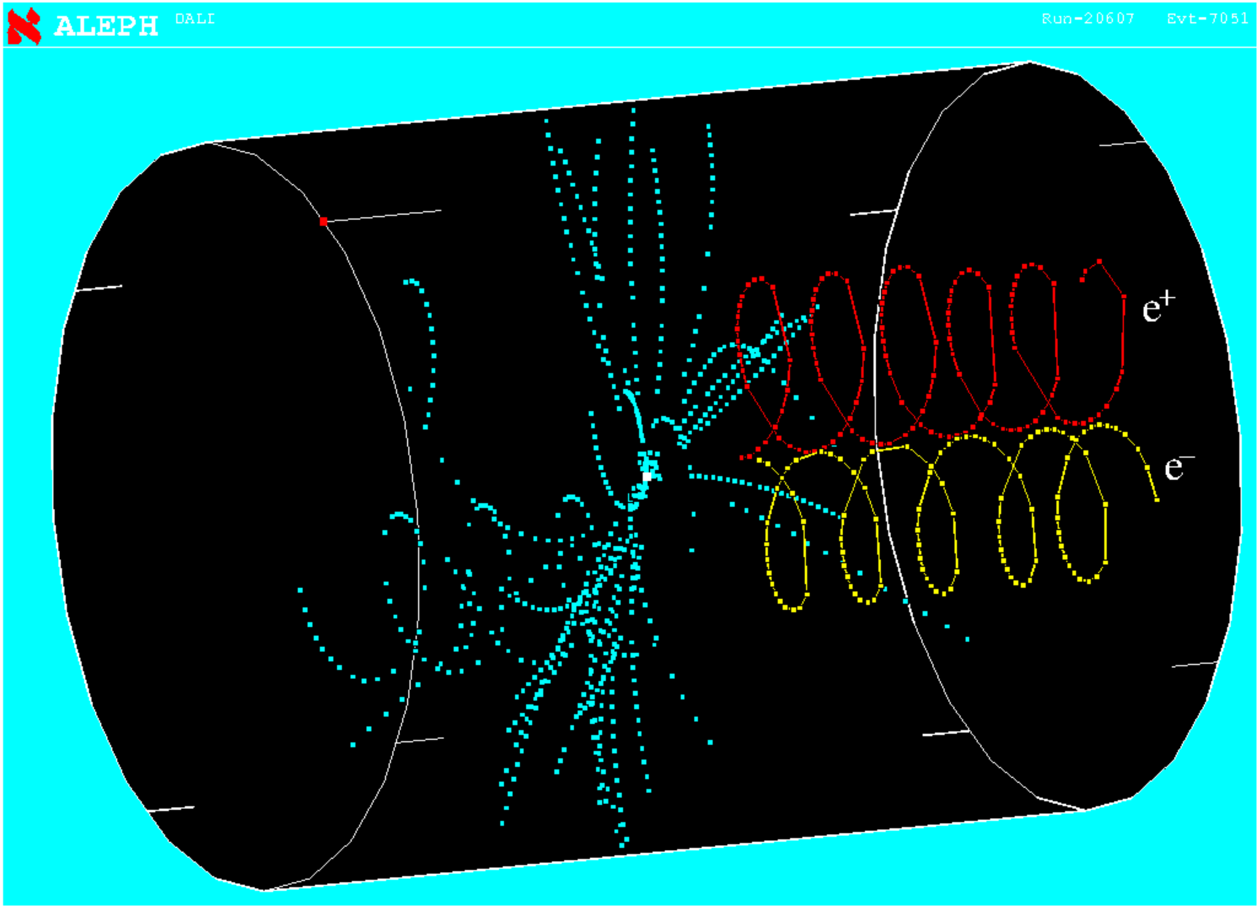
Multiplicity distributions from parasitic runs

- Cosmic ray events taken during data runs of electron-positron interactions
- select events with clear muon tracks in HCAL and the TPC
- compare with QGSJET CORSIKA simulation for proton and iron primaries
- benefit from the very high spatial resolution of the TPC

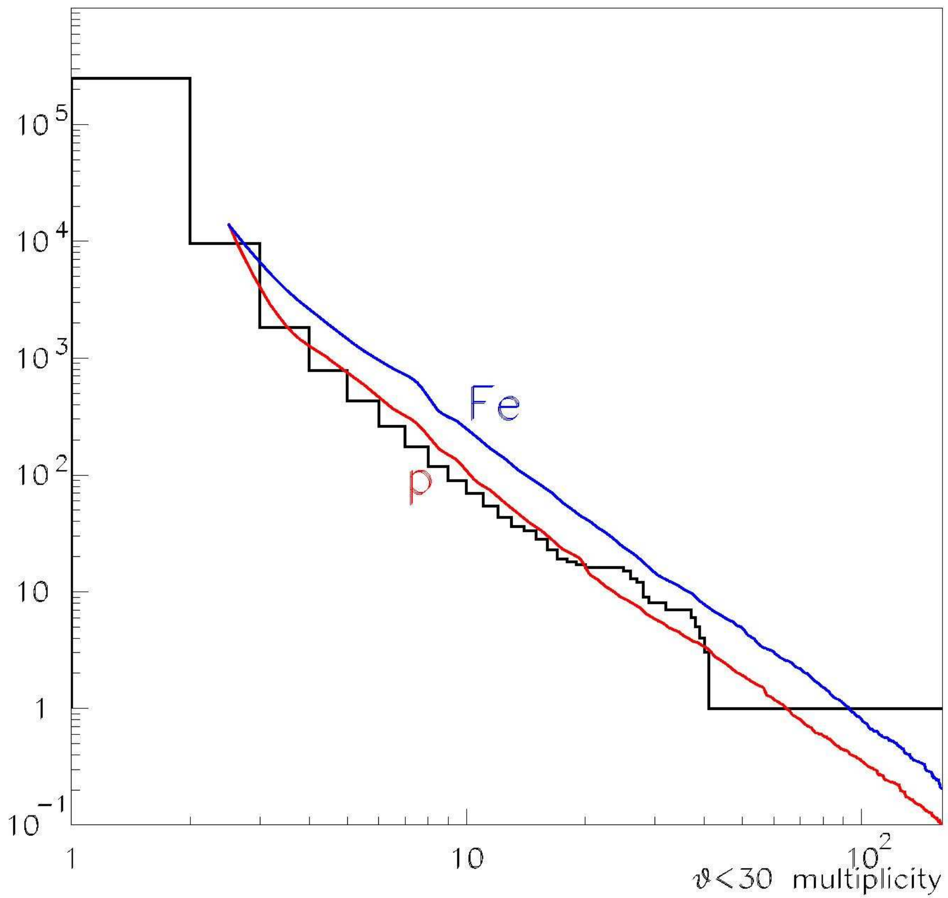
Multi muon tracks in the TPC



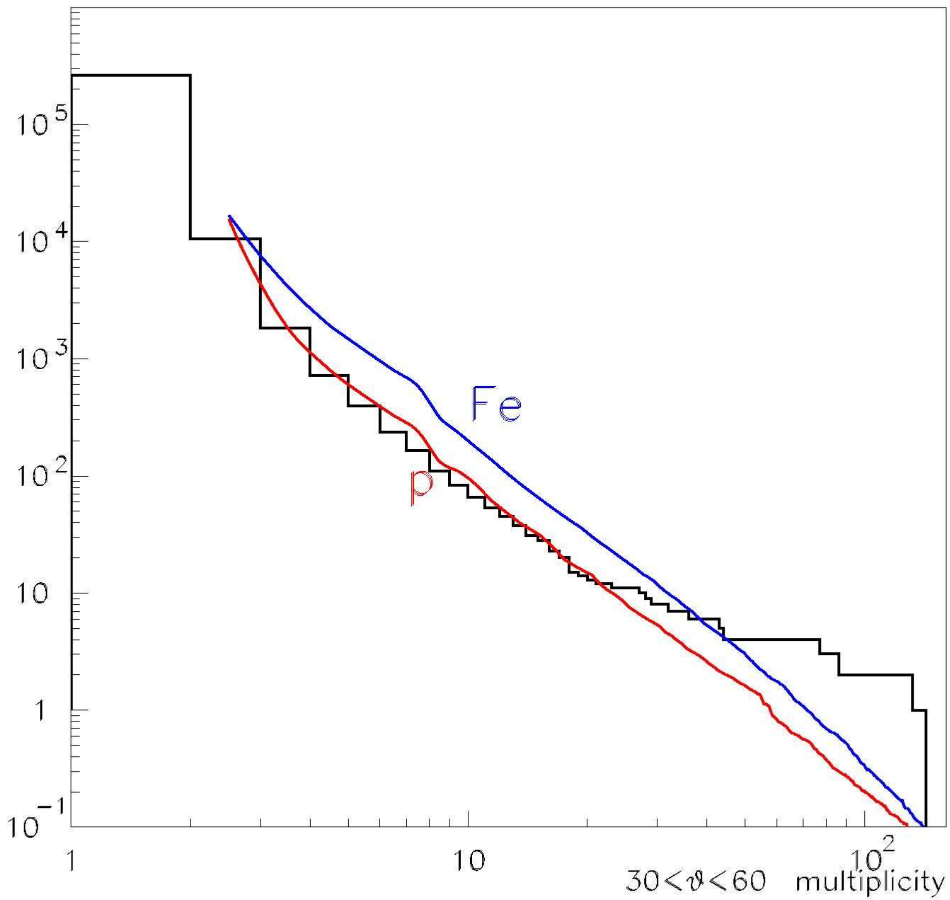
Electron-Positron pair in the TPC



Muon multiplicity distribution for zenith angles $\leq 30^\circ$



Muon multiplicity distribution for zenith angles between 30 and 60°



Muon multiplicity distribution

not easily interpreted

- for multiplicities below 20 a light composition is favoured
- higher multiplicities favour iron
- there is even an excess over iron for very high multiplicites at larger zenith angles

Determination of the vertical momentum spectrum

Data Selection:

- muons with $E_\mu > 5$ GeV
- vertically incident muons up to 10°

$$N_\mu \approx 66\,000 \text{ are preselected}$$

Extrapolated energy at the surface (from $\frac{dE}{dx} = a + b \cdot E$)

$$E_\mu(GeV) = \frac{a}{b}\left(e^{bR/\cos\theta} - 1\right) + E_\aleph(GeV) \cdot e^{bR/\cos\theta}$$

$E_\aleph$ is the measured muon energy in ALEPH at depth $R = 320$ mwe ,

$a = 2.2\,\mathrm{MeV} \cdot \mathrm{cm}^2/g$, $b = 4 \cdot 10^{-6}\,\mathrm{cm}^2/g$ - describe the energy losses.

Calculation of the Muon flux

Calculation of the Muon Flux:

$$\Phi_\mu = \frac{N_\mu(p, p + \Delta p)}{\varepsilon \cdot \tau \cdot S_{\text{eff}} \cdot \Omega \cdot \Delta p}$$

$N_\mu(p, p + \Delta p)$ is the number of muons with momentum within $(p, p + \Delta p)$ at the surface.
ε is the efficiency of HCAL $\approx (85.6 \pm 0.6)\%$
τ is the effective run time (≈ 1 week)
S_{eff} is the effective detector area ($16\,\mathrm{m}^2$)
Ω is the solid angle

Unfolding Experimental Data: Basics

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Experimental observations Y_i can be expressed as:

$$Y_i = \sum R_{i,j} X_j$$

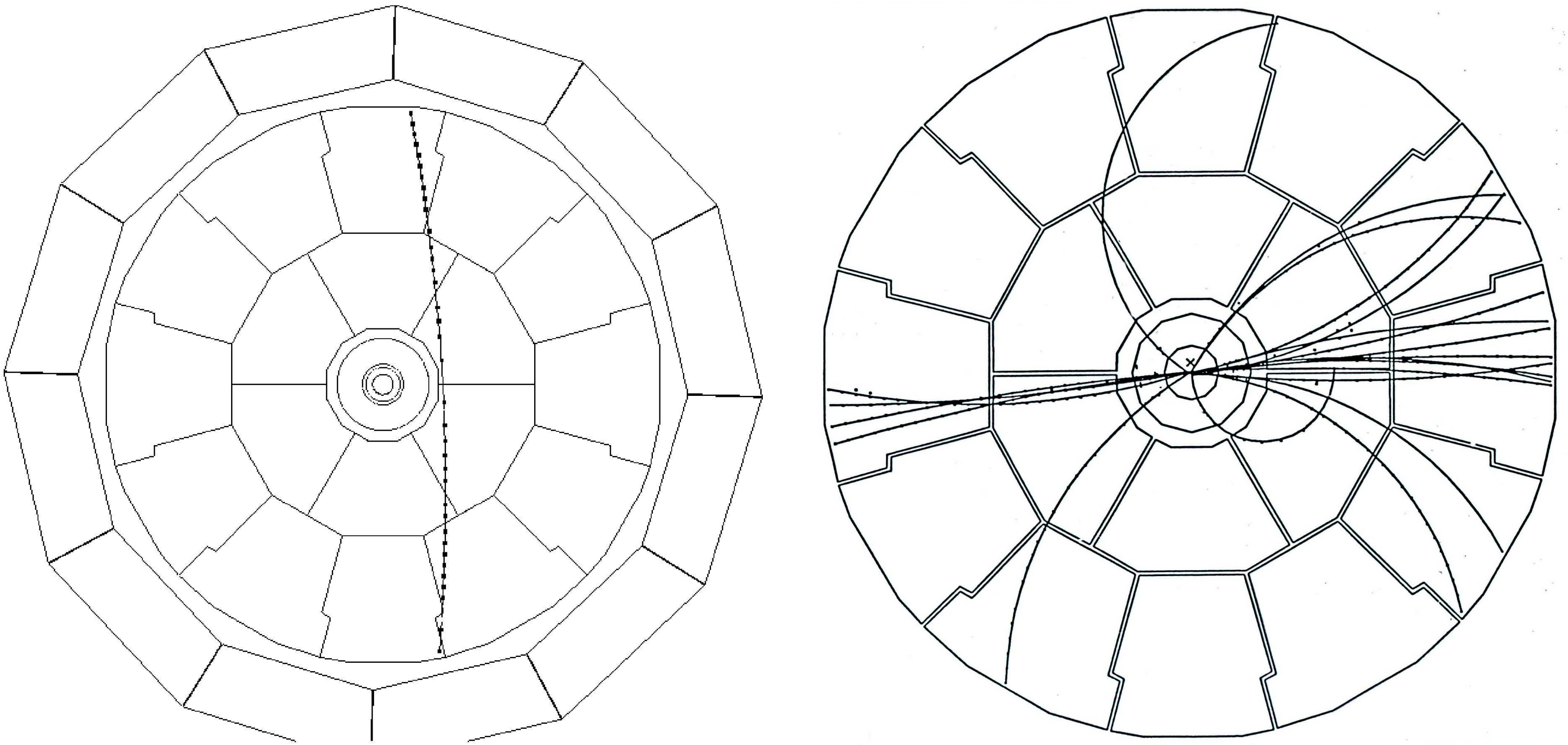
the above relation can be inverted to obtain the true values X_j

$$X_j = \sum (R_{i,j})^{-1} Y_i$$

$R_{i,j}$ is the response matrix, which depends on the measurement apparatus and can be effectively determined by:

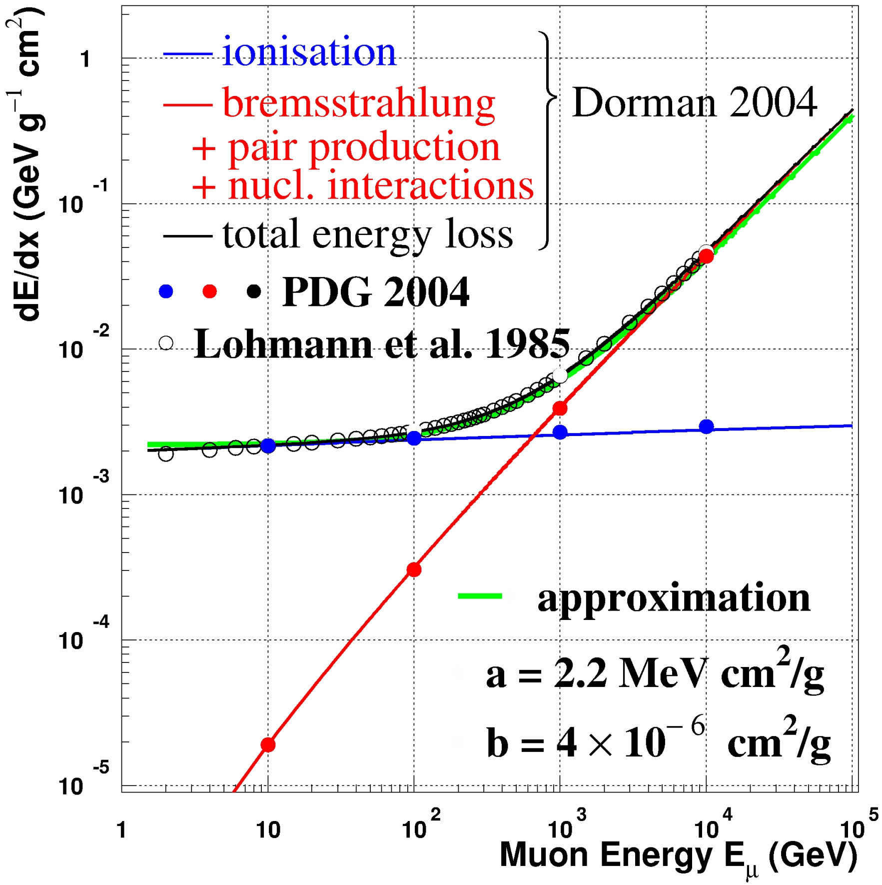
- calibration experiments, true values known a priori
- MC simulation based on physical processes in the detector

Reconstruction of Cosmic Ray Muon Tracks in ALEPH

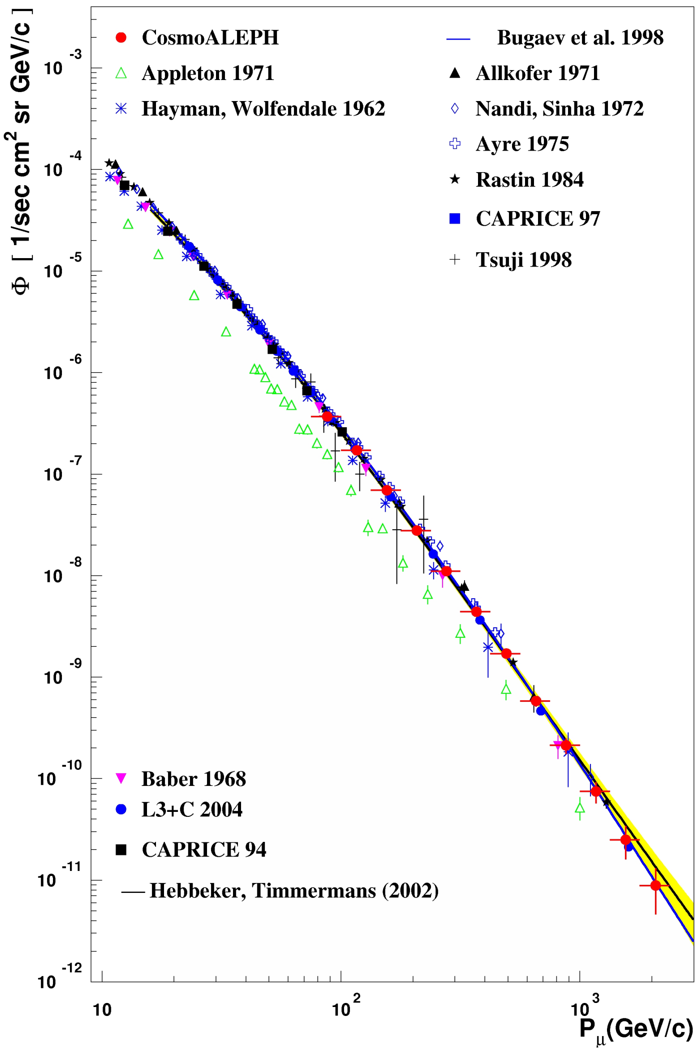


- MC Simulations are used to calculate the track reconstruction efficiency.

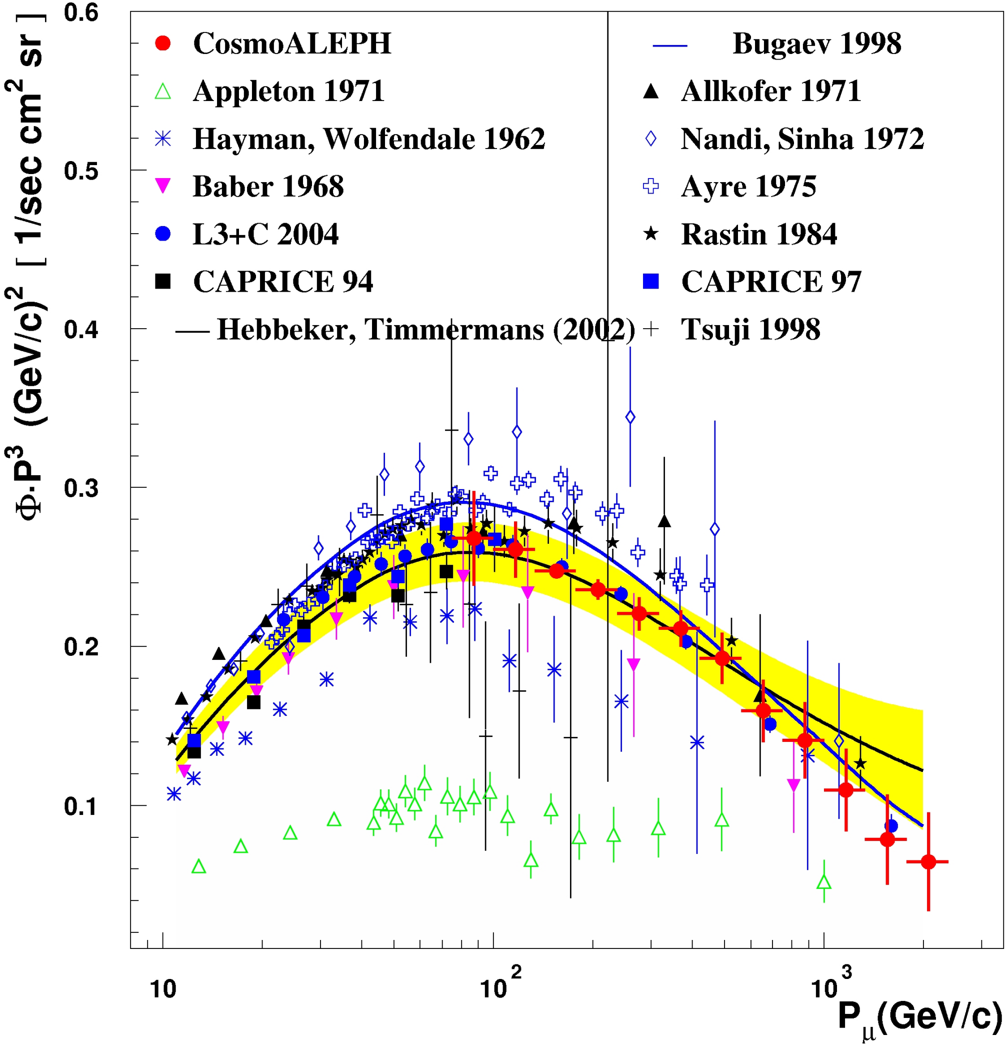
Energy Loss Distribution



Vertical muon spectrum



Vertical muon spectrum



Final muon spectrum

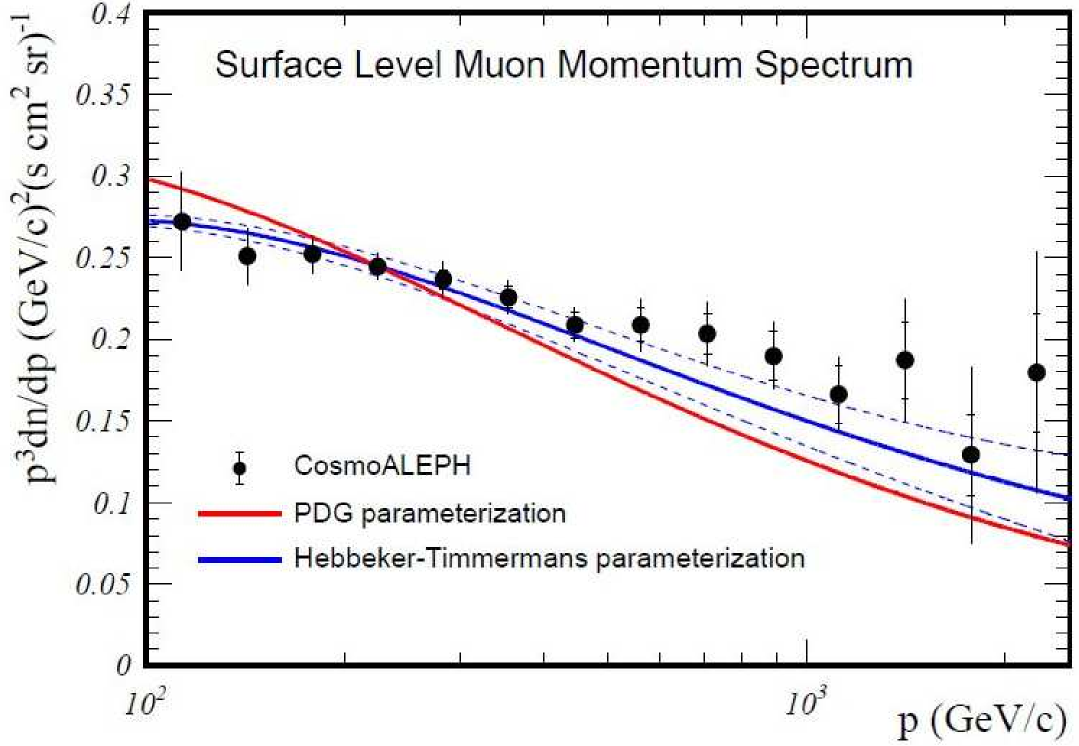
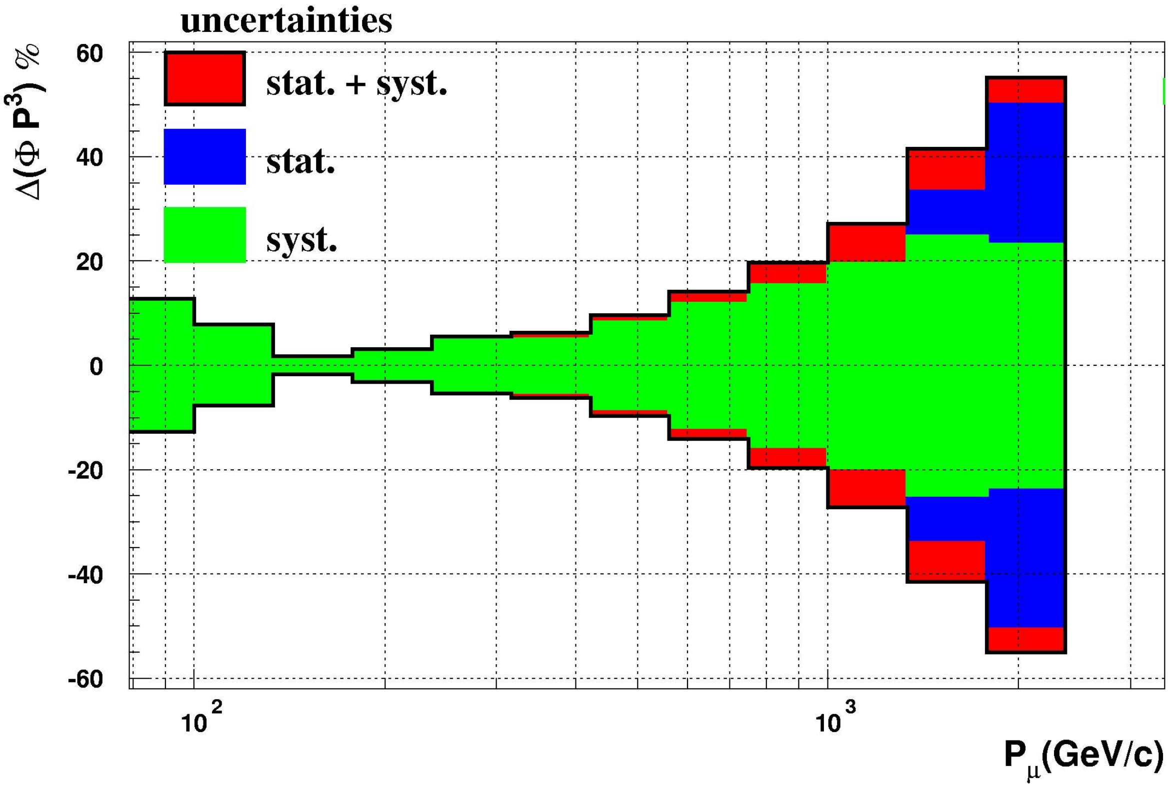
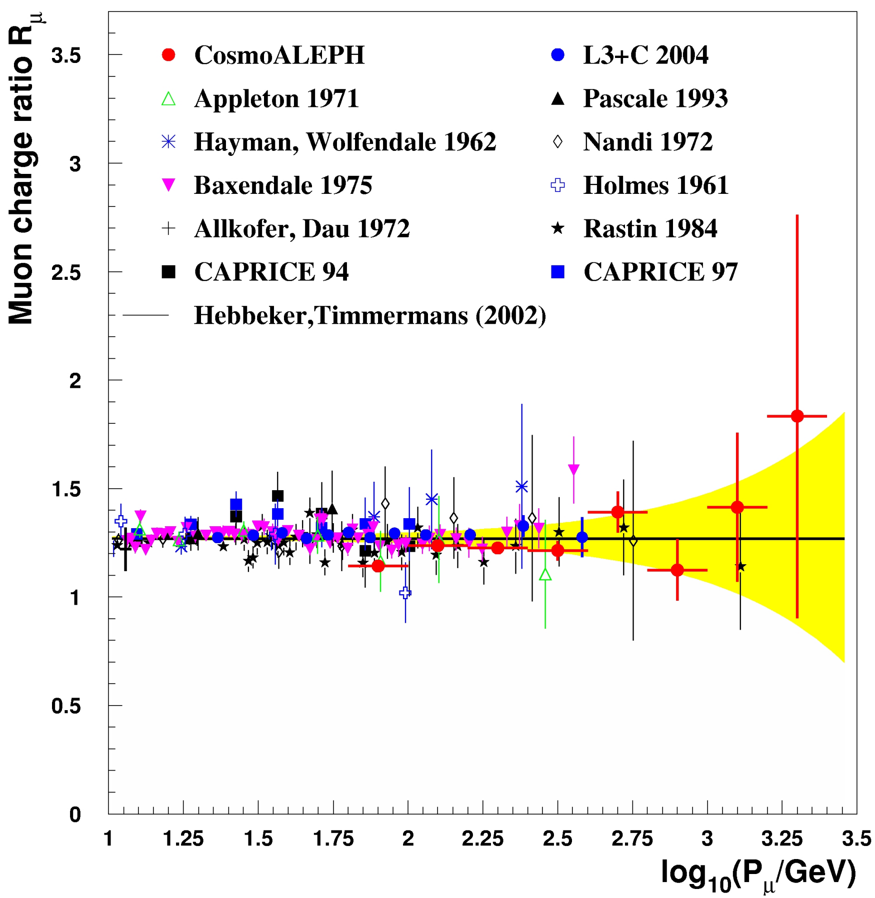


FIG. 2: Measured surface level momentum spectrum of cosmic ray muons compared to the parameterizations given in reference [1] and by the Particle Data Group [15]. For better visibility the momentum spectrum has been multiplied by p^3.

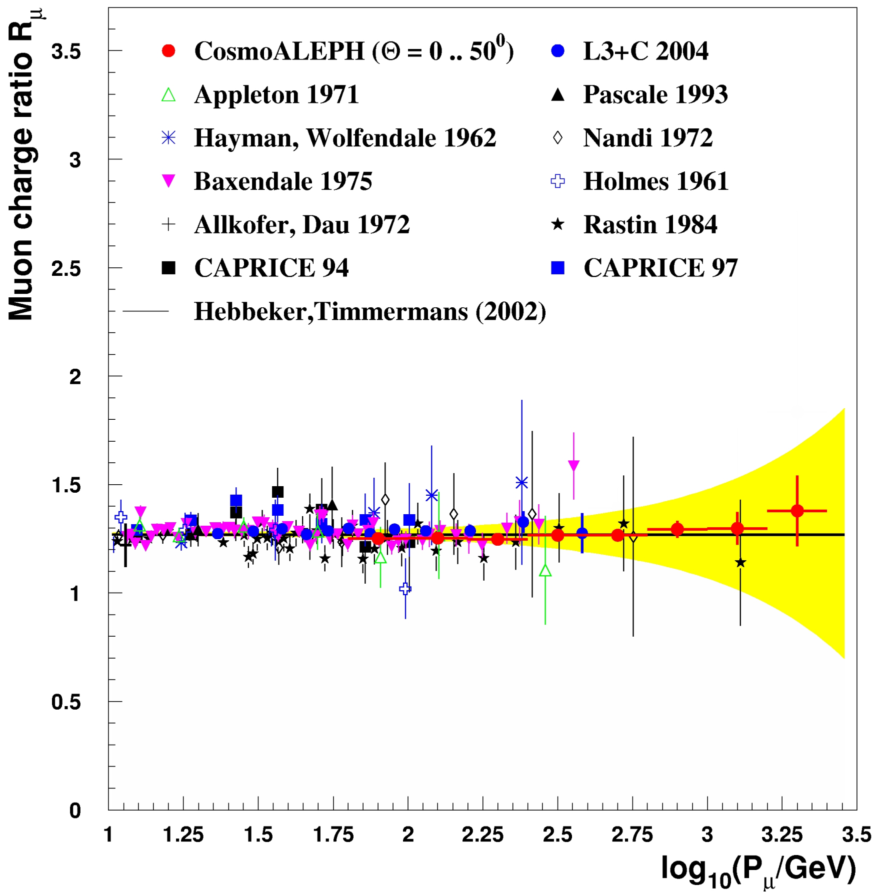
Errors of the muon spectrum



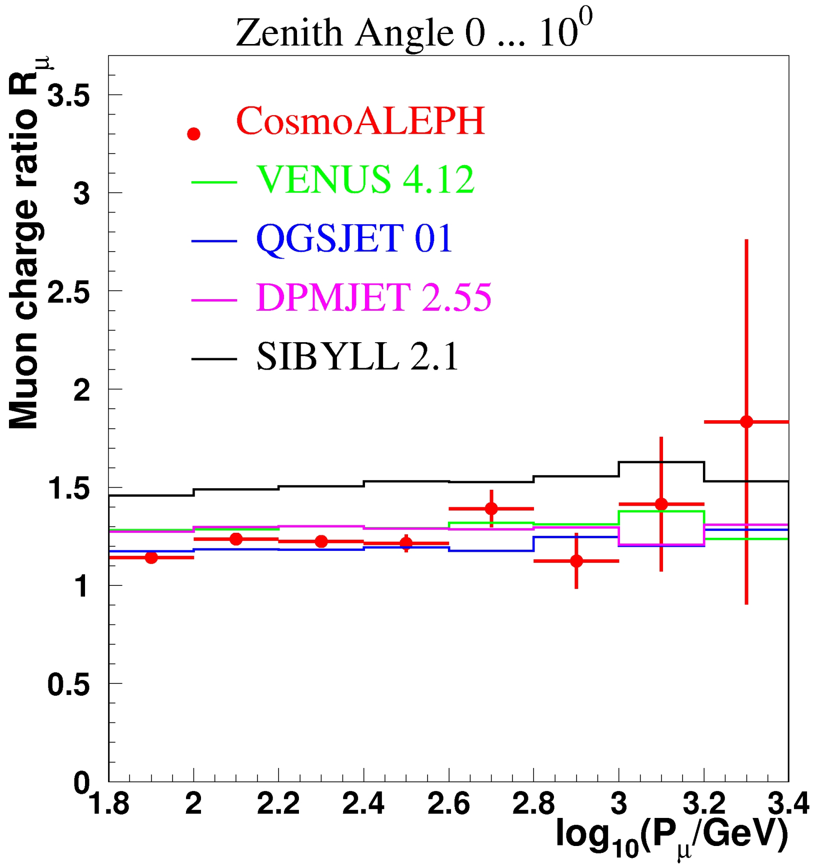
Charge ratio for vertical muons



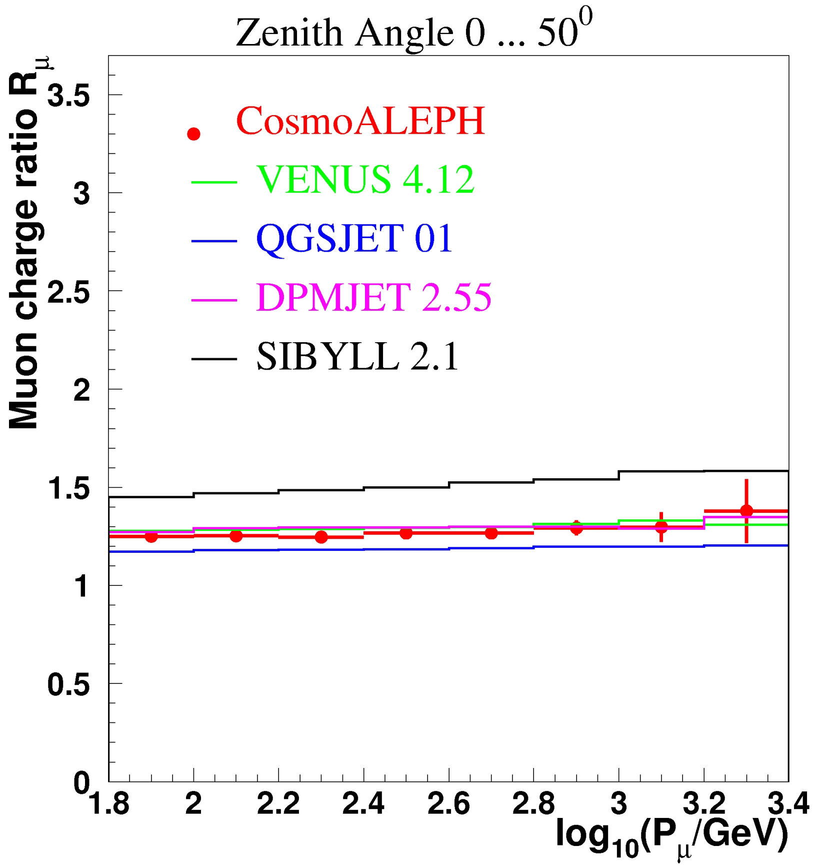
Charge ratio for muons up to 50 degrees



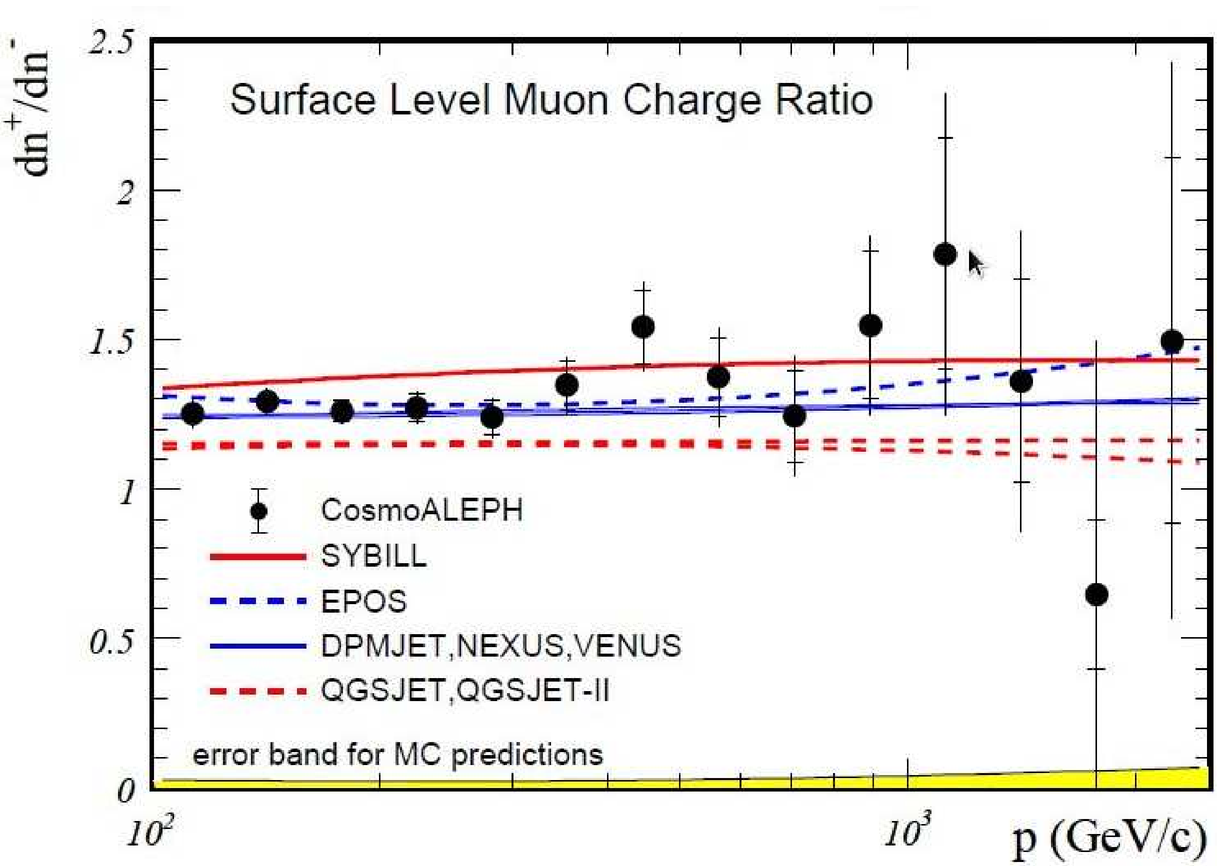
Charge ratio for vertical muons, MC



Charge ratio for muons up to 50 degrees



Final charge ratio for near vertical muons



The Charge Ratio

The Charge Ratio

Our average value in the momentum range 80 to 2500 GeV is

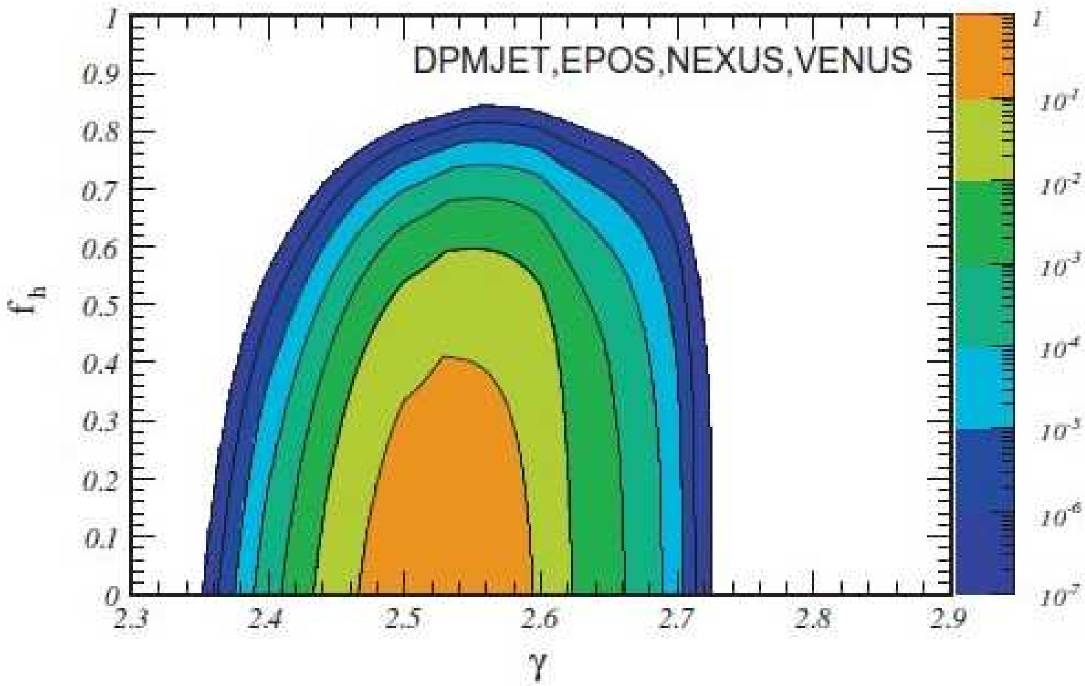
$$R_\mu(CosmoALEPH) = 1.278 \pm 0.011$$

with only statistical errors is comparable to the world average value compiled by Hebbeker and Timmermans (2002),

$$R_\mu = \frac{N_\mu^+}{N_\mu^-} = 1.268 \pm [0.008 + 0.0002 \cdot p/\mathrm{GeV}]$$

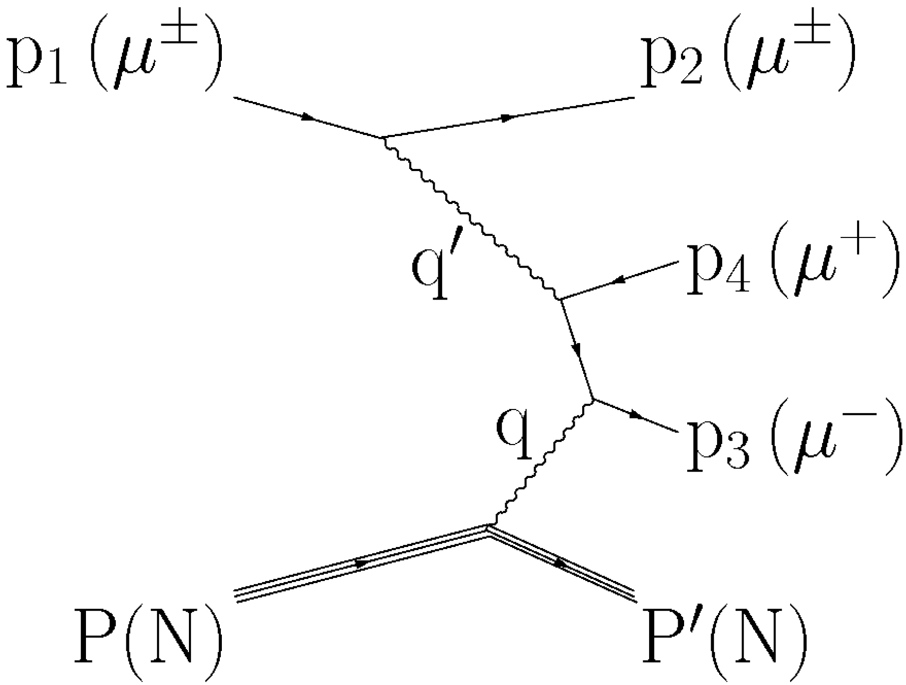
which favours a momentum independent ratio.

Idea on the chemical composition of primaries



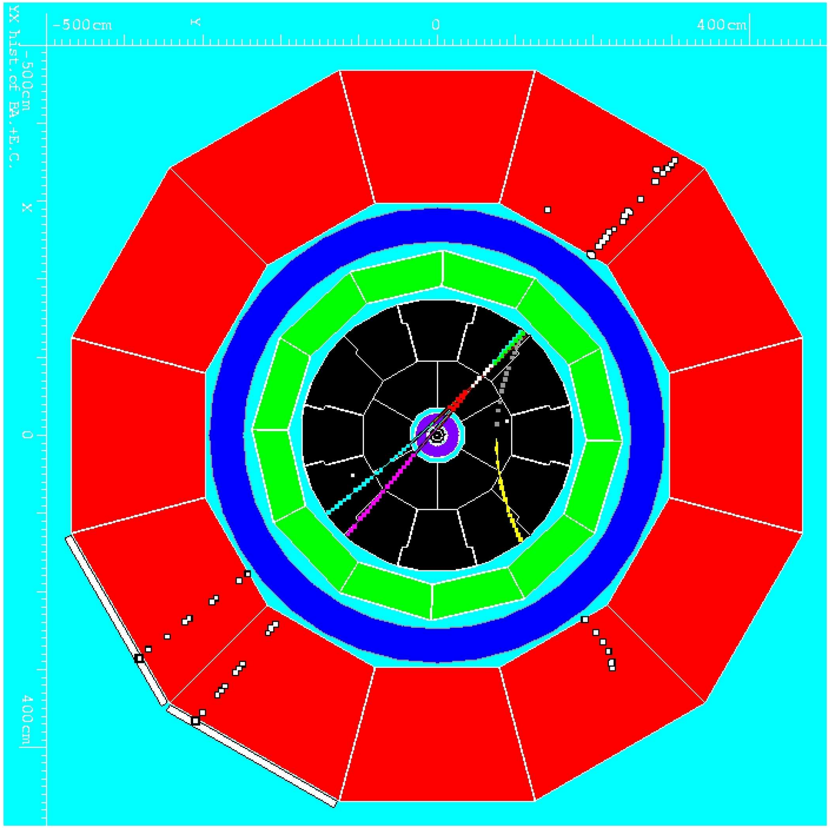
- exponent of the primary spectrum versus fraction of heavy primaries (0.3 He; 0.2 N; 0.3 Mg; 0.2 Fe)

Feynman Diagram for Muon Tridents



- there are also three other similar diagrams which contribute

A Trident Event in ALEPH



- $\mu + \textit{nucleus} \rightarrow \mu + \textit{nucleus} + \mu^+ + \mu^-$

Conclusion and Outlook

chemical composition of primary cosmic rays

- The results on the chemical composition of primary cosmic rays from the lateral distributions at ground level and underground are very sensitive to the interaction model used.
- Most models favour a light composition, although there are exceptions.
- The important message from these measurements is that we urgently need a better and consistent understanding of the interactions of high energy particles (in the atmosphere)

muon momentum spectrum and tridents

muon momentum spectrum and tridents

- The absolute momentum spectrum and charge ratio for vertical muons compare well with data from a recent compilation and from other experiments.
- SIBYLL fails to describe the charge ratio

- Clear muon trident events have been recorded.
- The theoretical description requires a nuclear form factor.

Further work on muon spectra:

- chemical composition of primary cosmic rays

CosmoALEPH Collaboration

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