Cosmic Rays from a Hole in the Ground – Results from CosmoALEPH

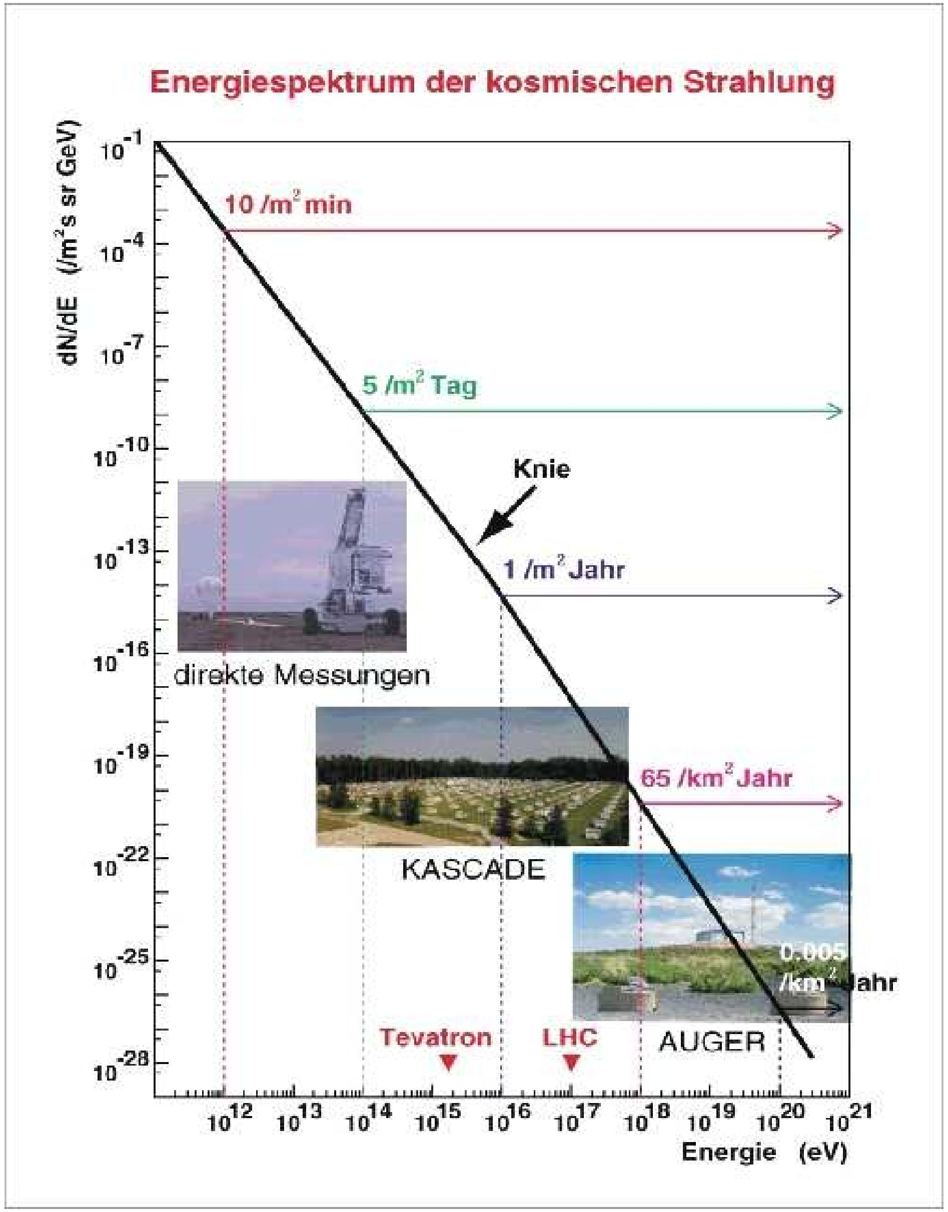
Claus Grupen

Universität Siegen

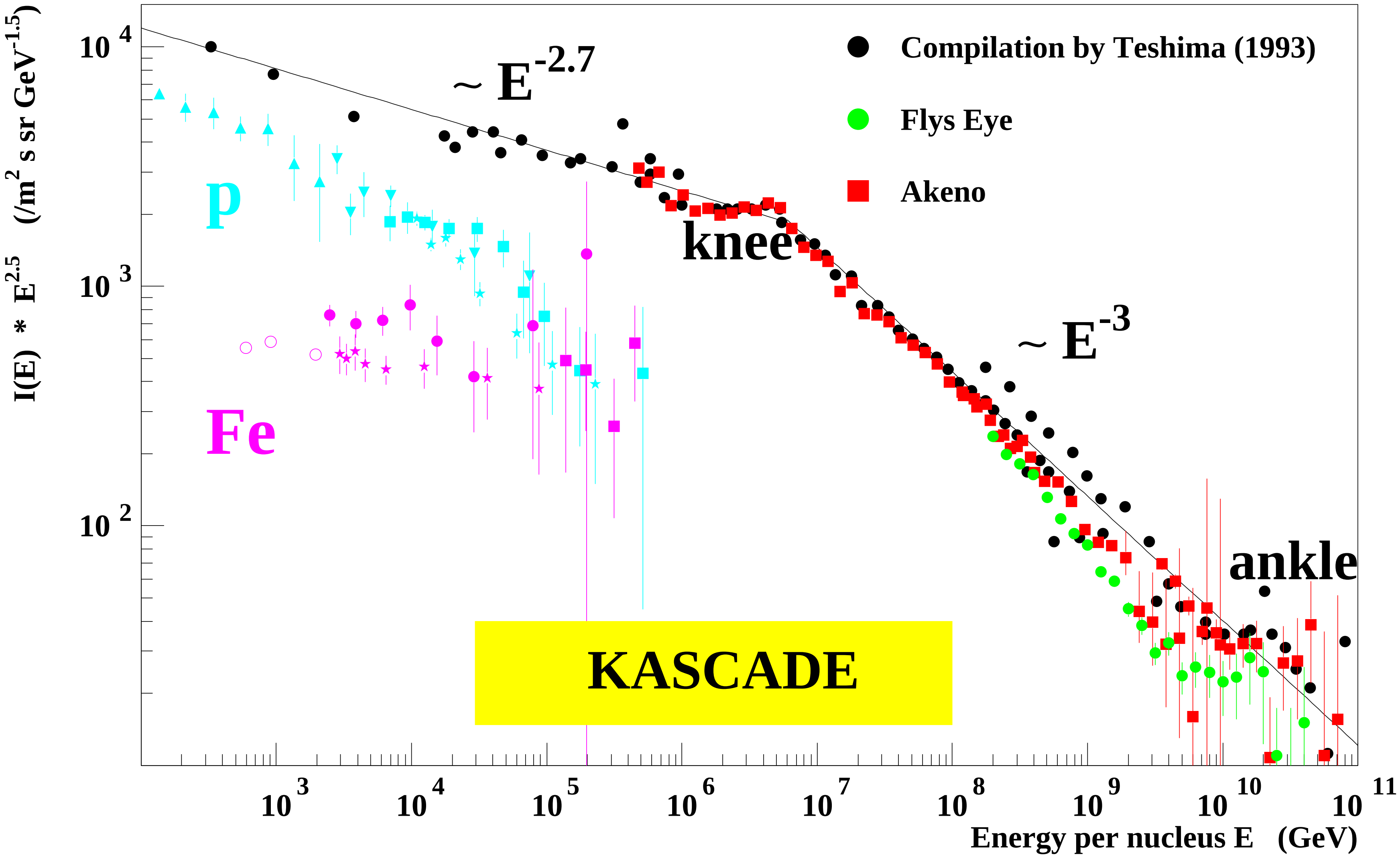
Overview

- Introduction
- Primary and Secondary Cosmic Rays
- CosmoALEPH
- Data Set
- Decoherence curve
- Muon multiplicities
- Muon Spectrum
- Muon Charge Ratio
- Muon Tridents
- Outlook

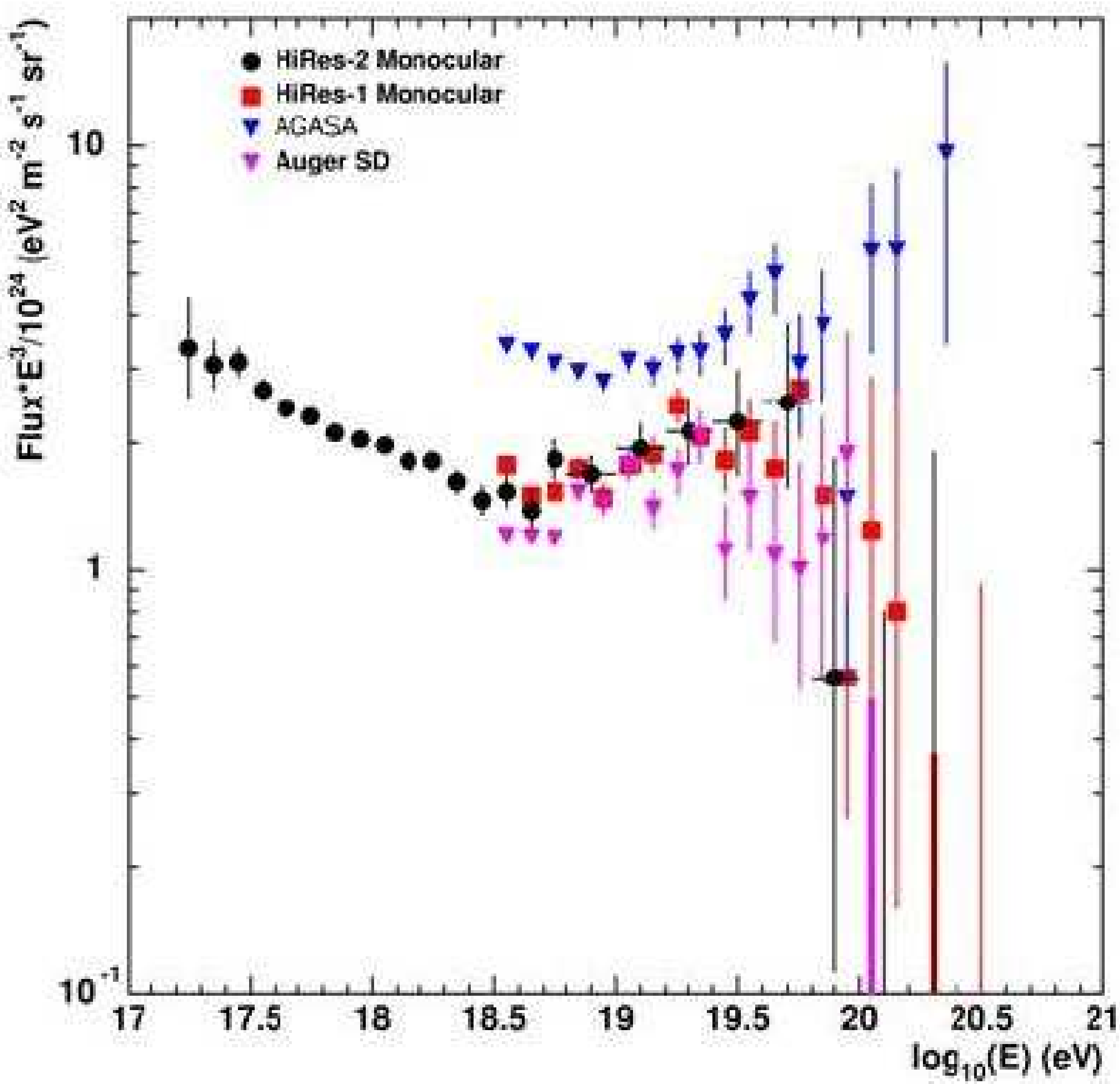
Primary Cosmic Rays



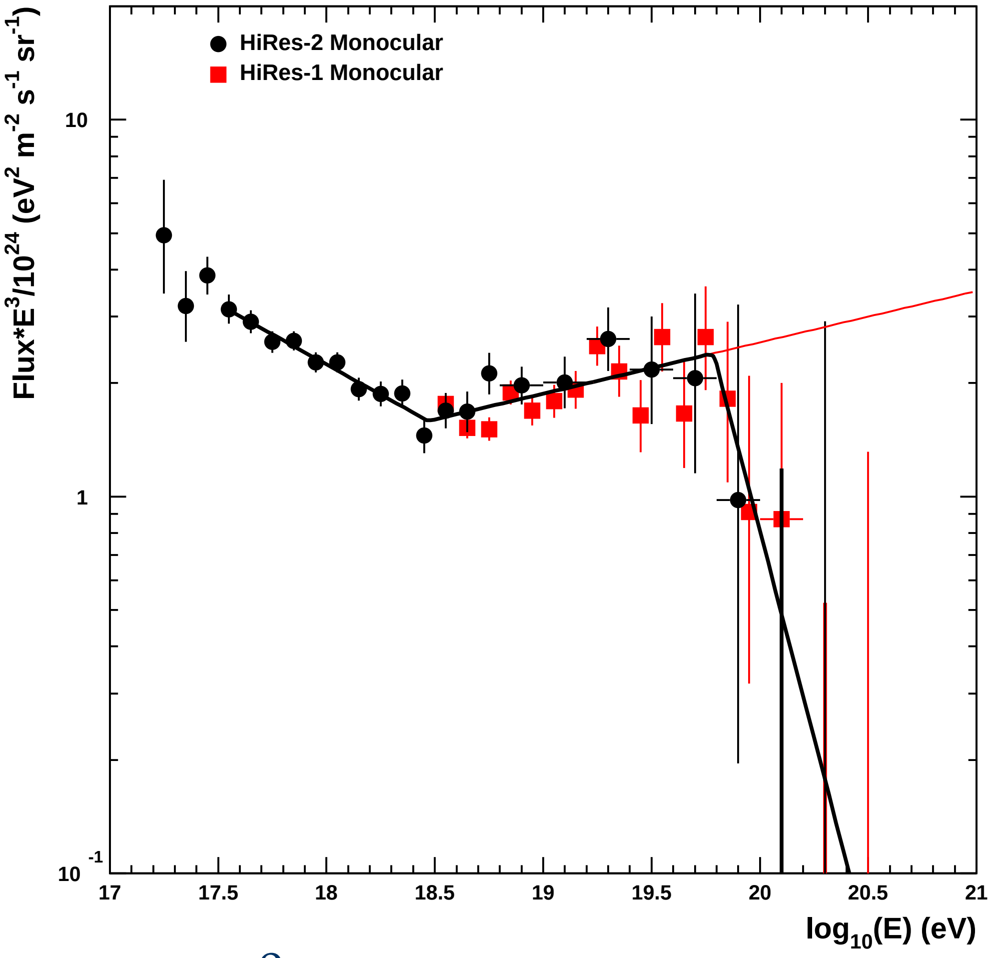
Primary Cosmic Rays



Primary Cosmic Rays



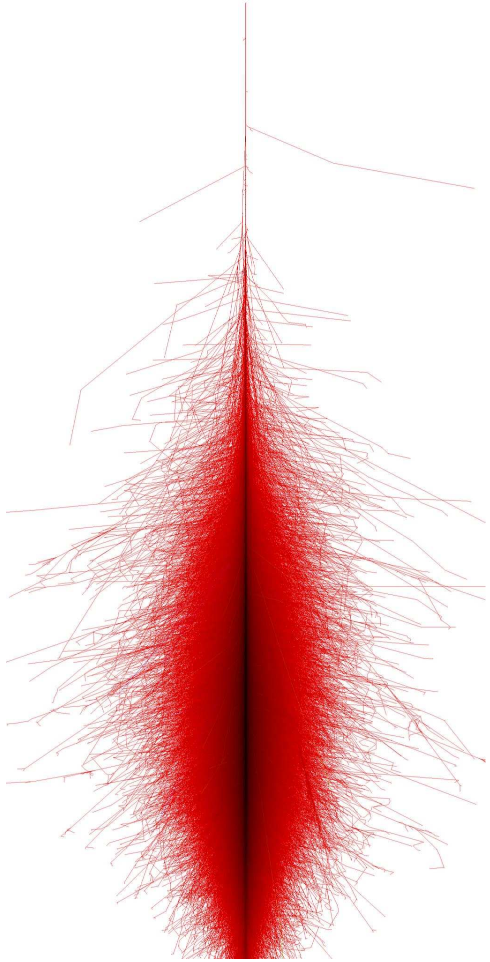
Primary Cosmic Rays



$$\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$$

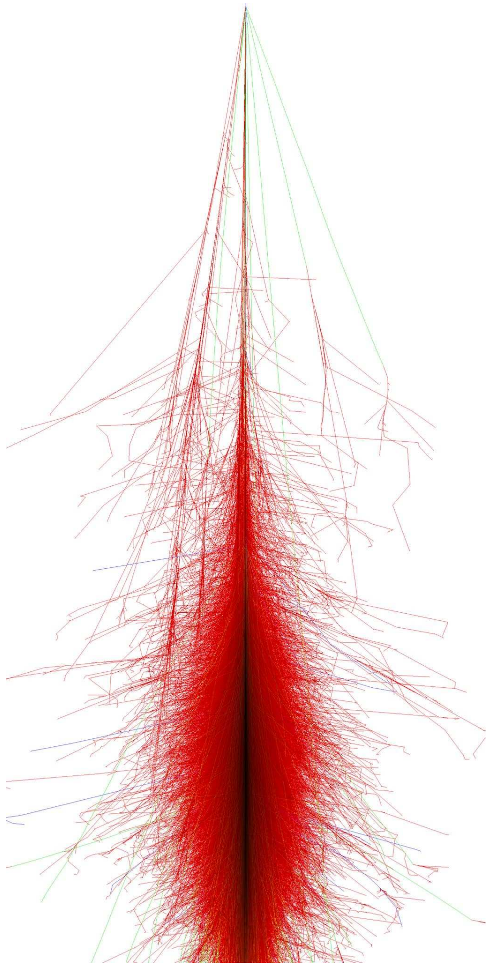
Cosmic Rays in the Atmosphere

Cosmic Rays in the Atmosphere



10 TeV photon shower in the atmosphere (J. Knapp)

Cosmic Rays in the Atmosphere



10 TeV proton shower in the atmosphere (J. Knapp)

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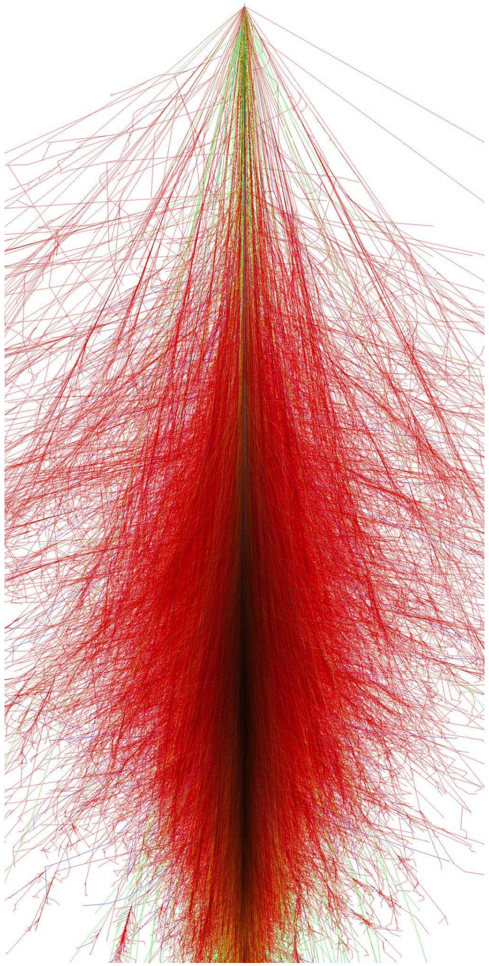
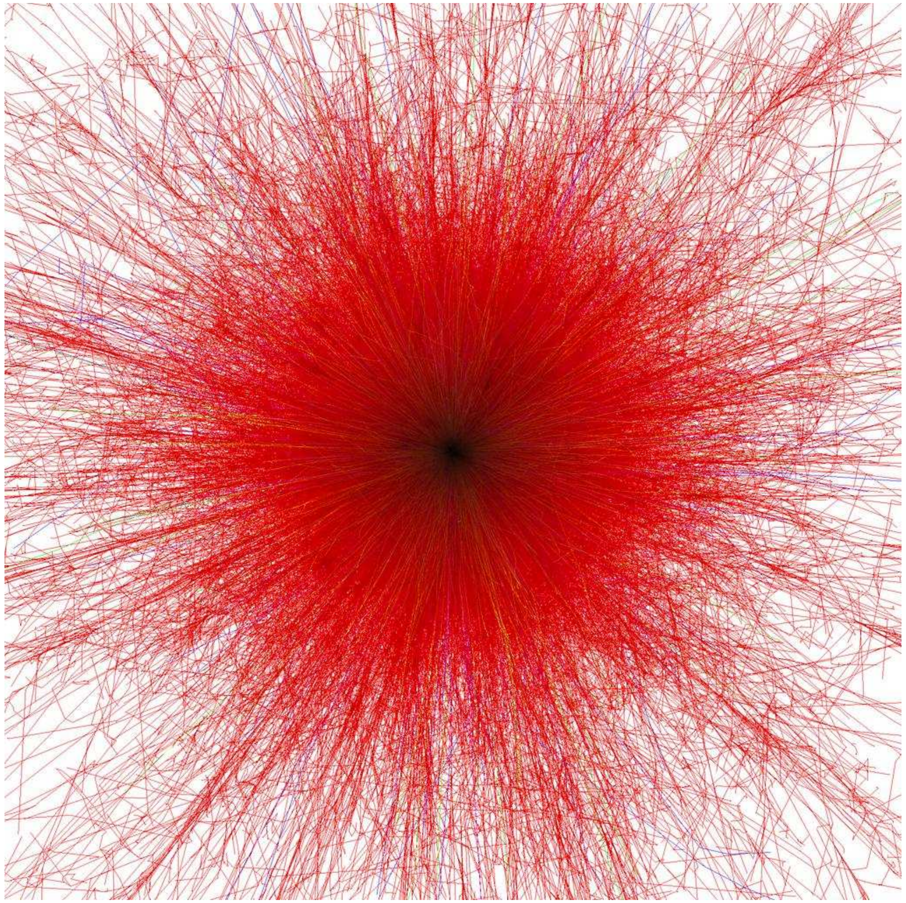


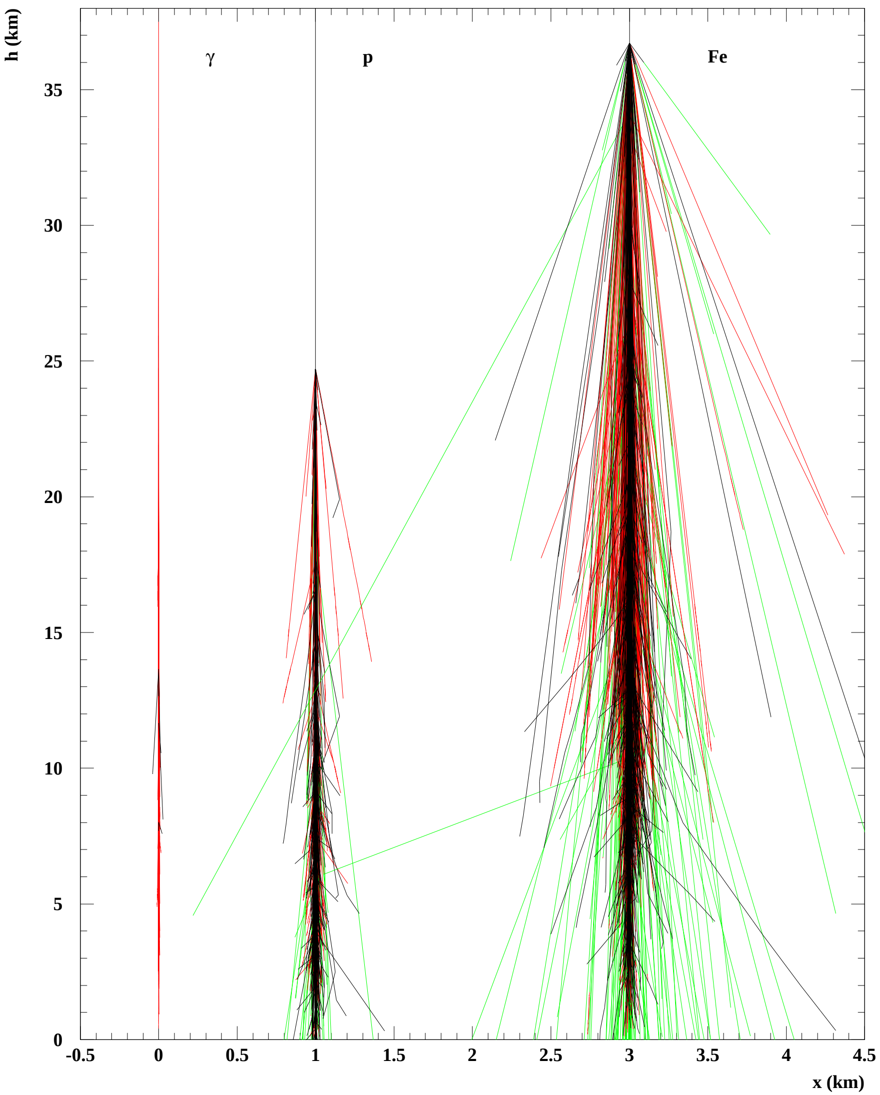
10 TeV iron shower in the atmosphere (J. Knapp)

Cosmic Rays in the Atmosphere



10 TeV iron shower in the atmosphere (J. Knapp)

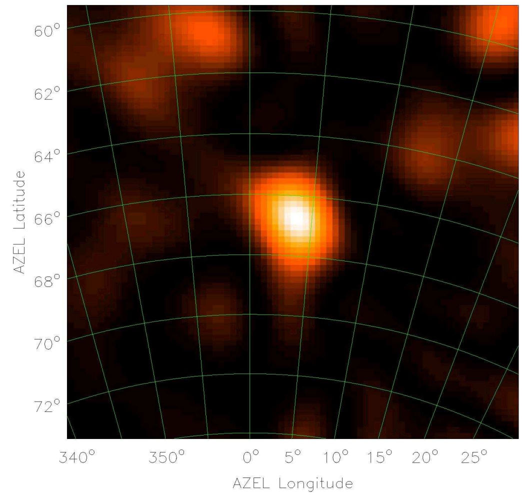
Cosmic Rays in the Atmosphere



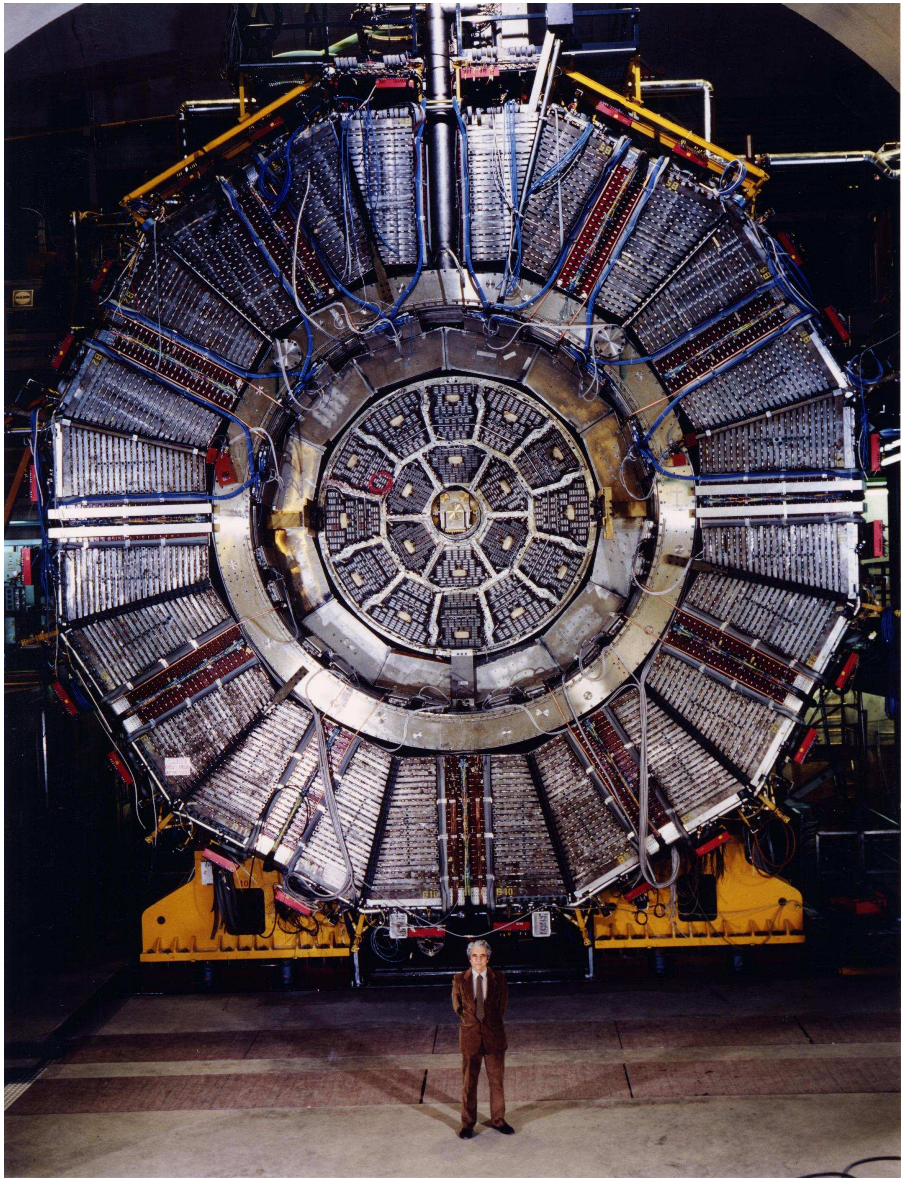
100 TeV showers, high threshold for secondaries (J. Knapp)

Measurement techniques

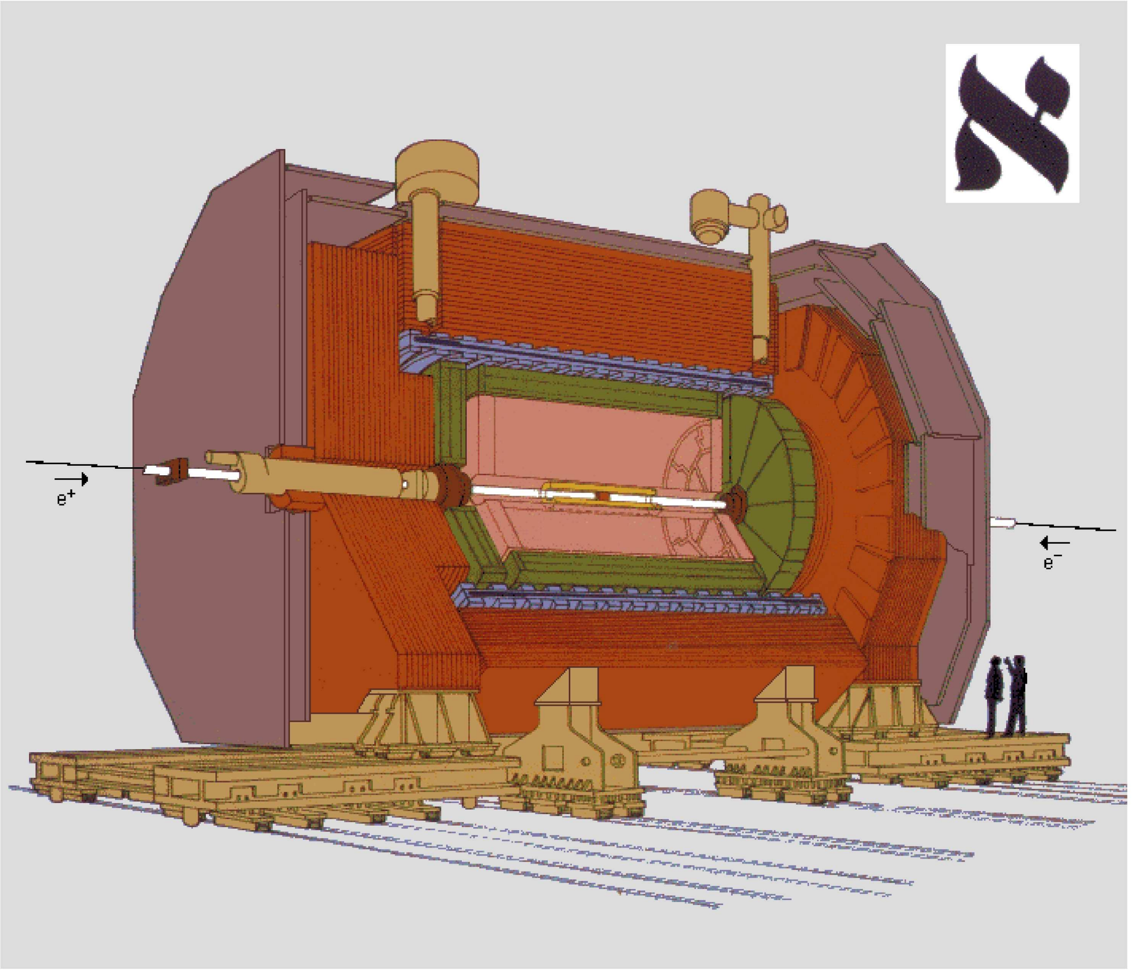
- the classical system: ground array of particle detectors (e.g. AGASA, Auger)
- air fluorescence (e.g. HiRes, Auger)
- measurement of the Cherenkov light (HESS, MAGIC)
- radio technique (LOPES, LOFAR)
- acoustic detection ?



Cosmic Rays Underground



Cosmic Rays Underground



Vertex Detector

Inner Tracking Chamber

Time Projection Chamber

Electromagnetic Calorimeter

Superconducting Magnet Coil

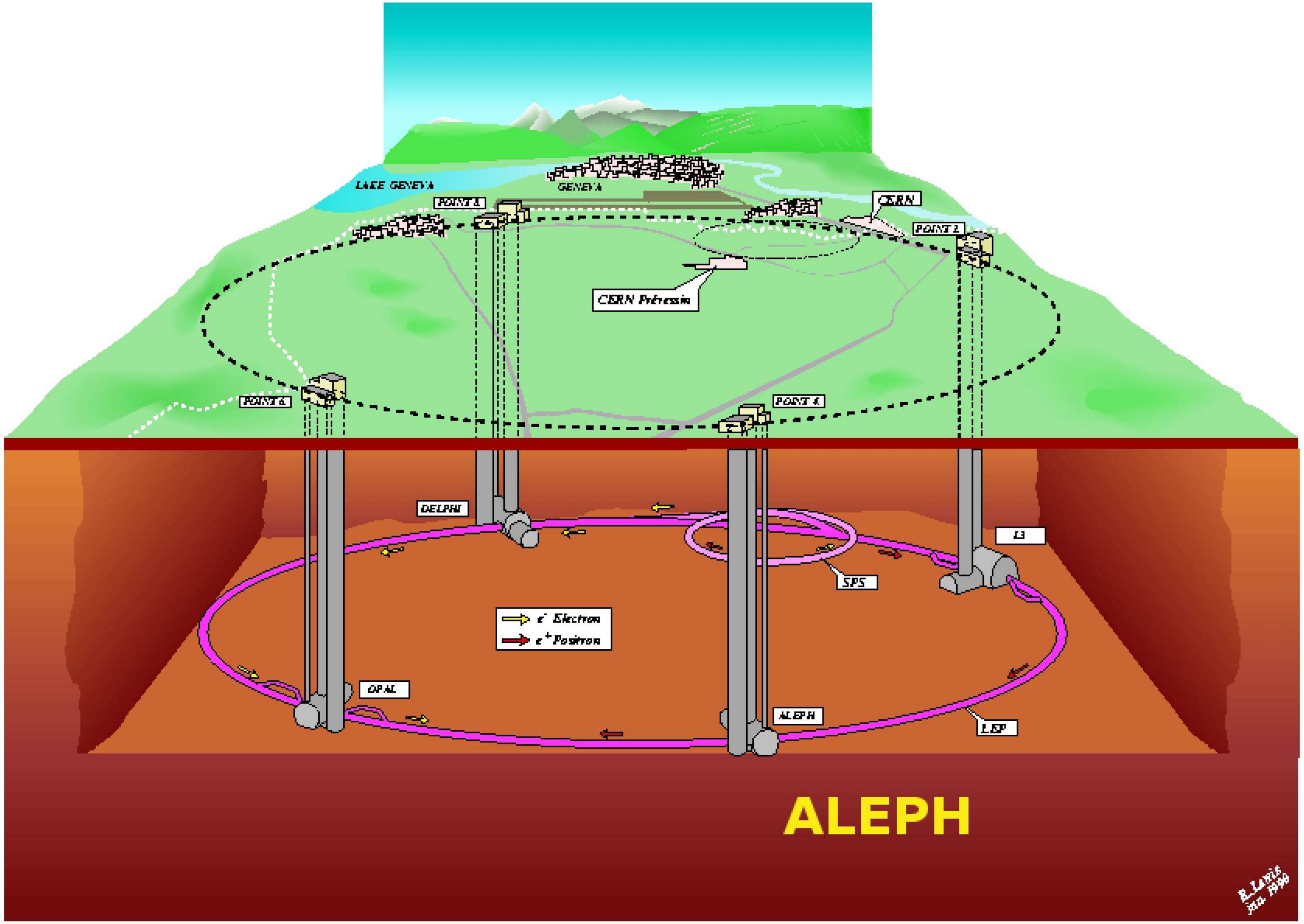
Hadron Calorimeter

Muon Chambers

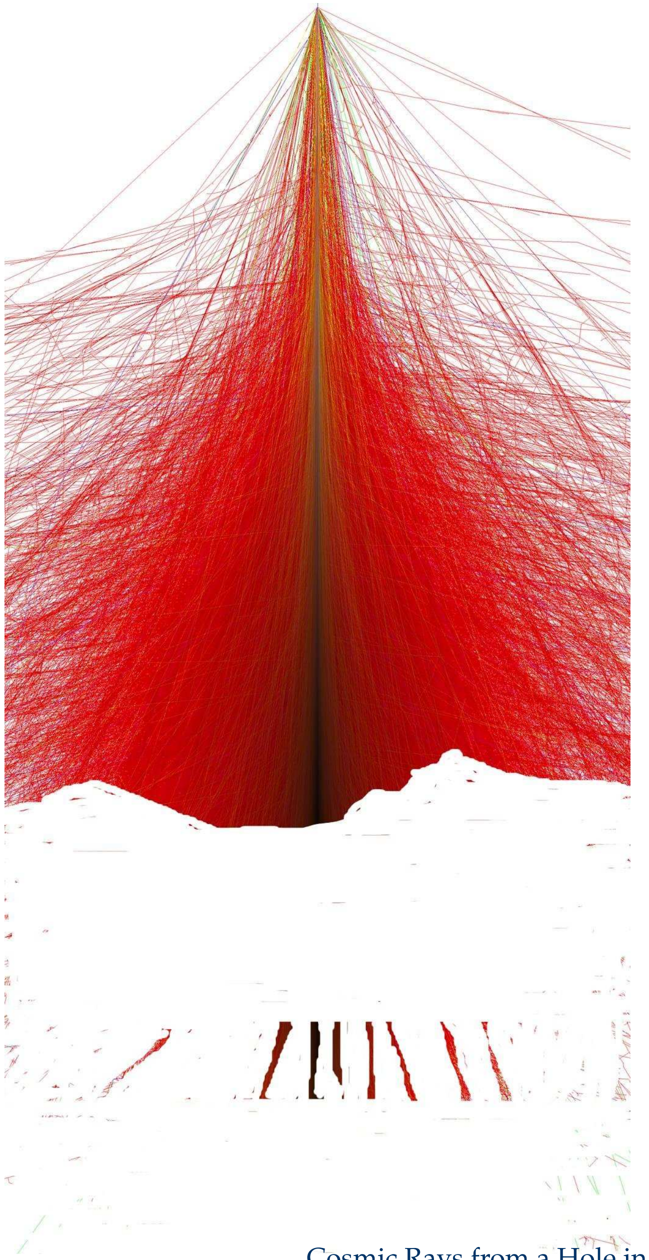
Luminosity Monitors

Cosmic Rays Underground

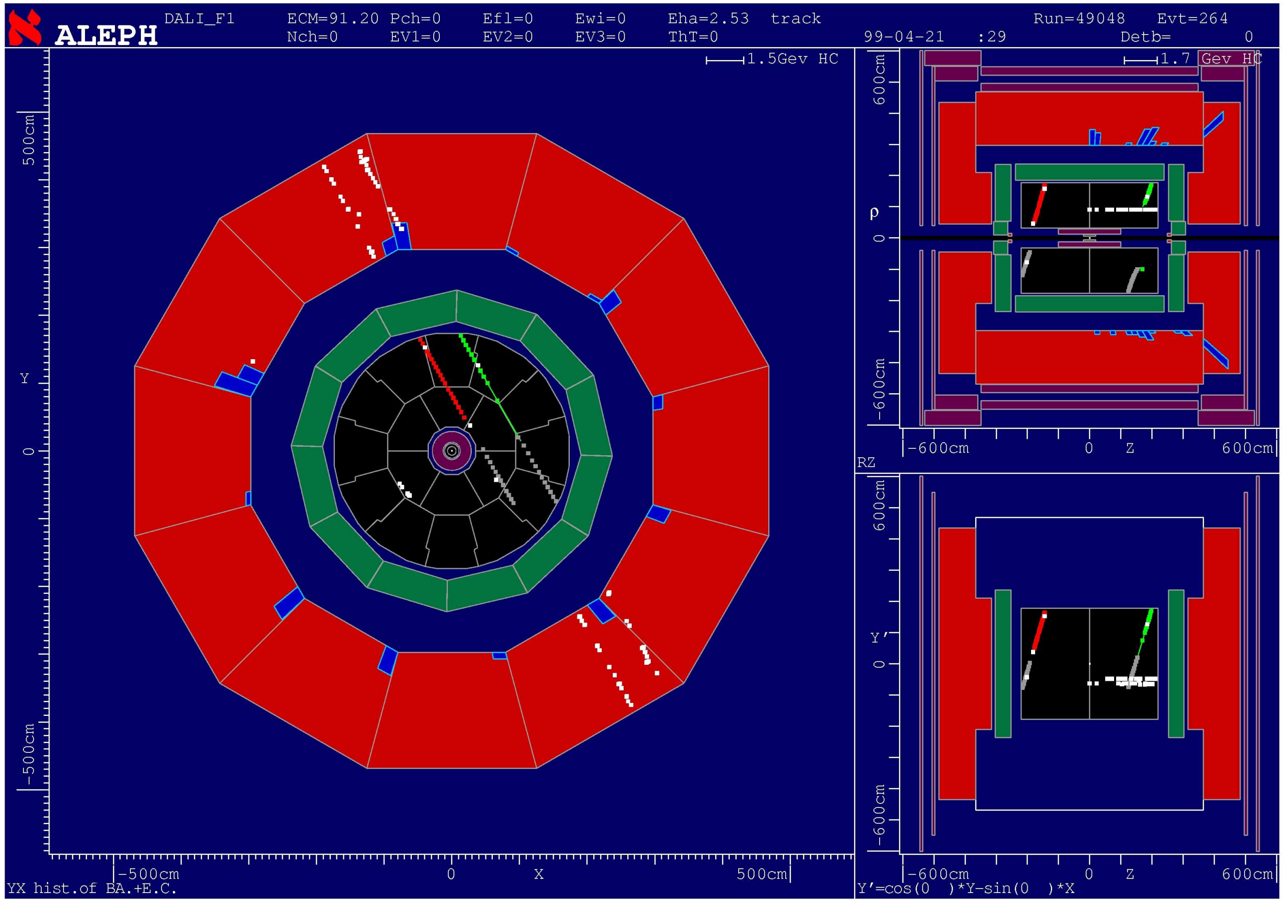
LEP at CERN (Geneva) , CosmoALEPH -320 m.w.e.



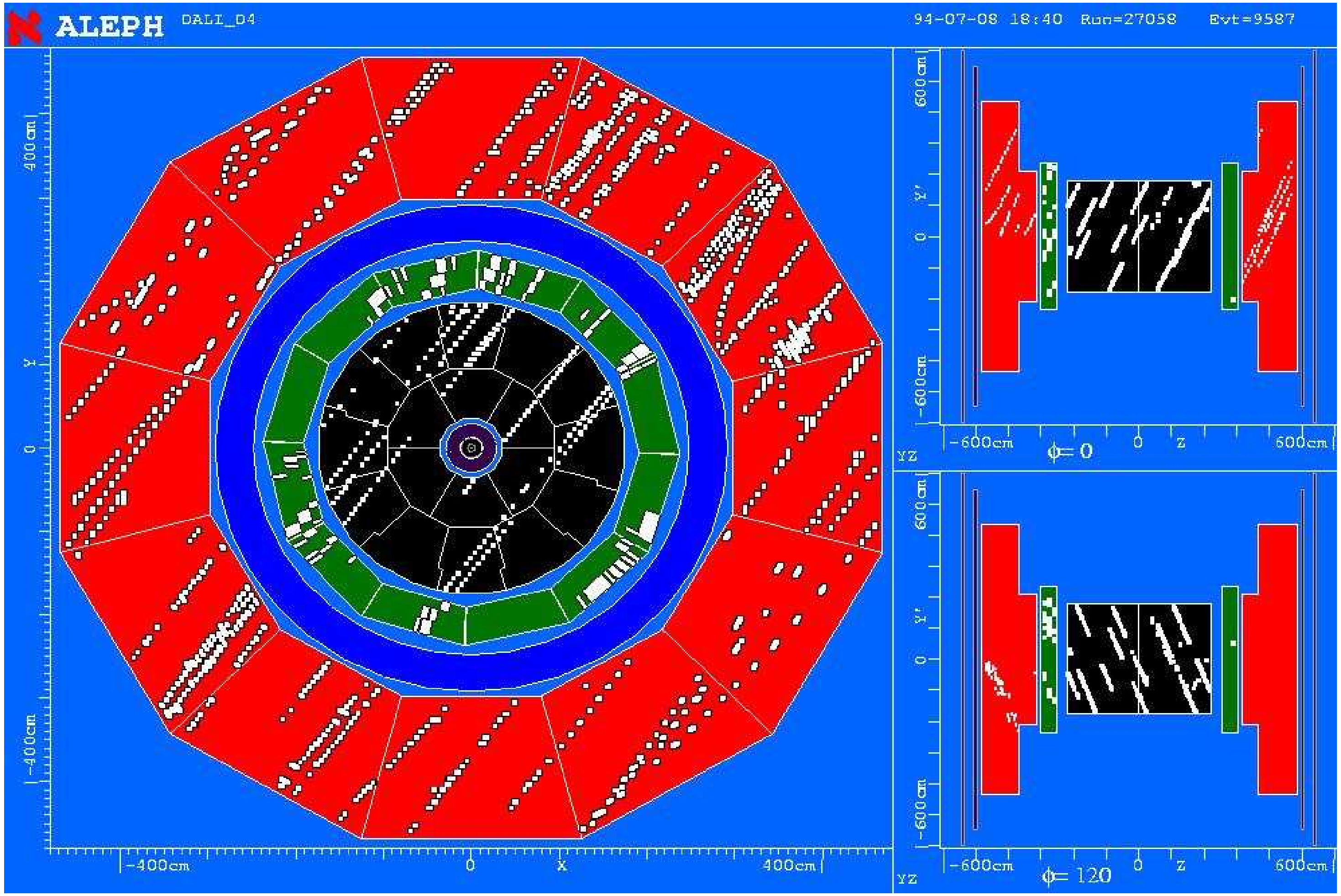
What is measured underground



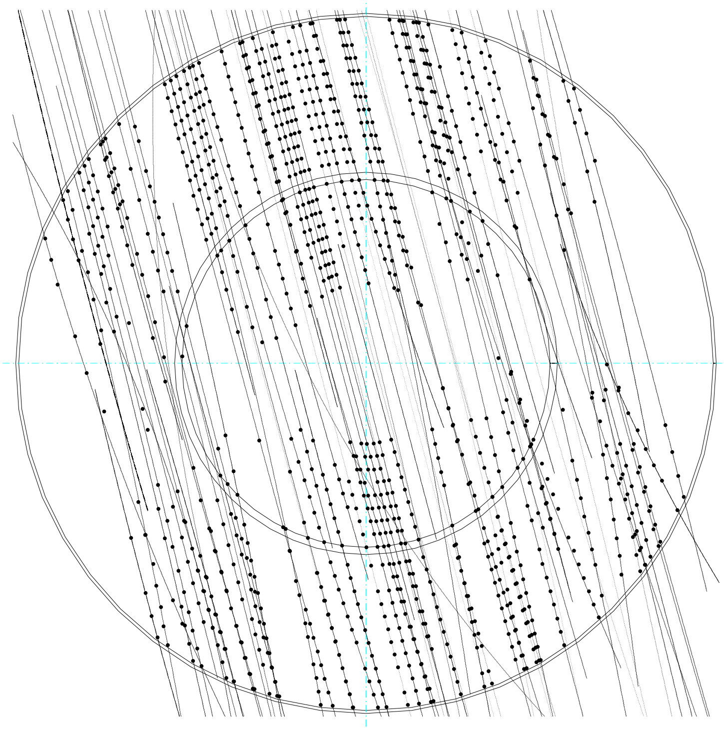
Some events


ALEPH
DALI_F1
ECM=91.20 Pch=0
Nch=0
EV1=0
Efl=0
EV2=0
Ewi=0
EV3=0
Eha=2.53 track
ThT=0
99-04-21 :29
Run=49048 Evt=264
Detb= 0
1.5Gev HC
1.7 Gev HC
500cm
Y
0
-500cm
-500cm
X
500cm
YX hist.of BA.+E.C.
600cm
ρ
-600cm
-600cm
Z
600cm
RZ
Y'
Y'=cos(0)*Y-sin(0)*X

Some events


ALEPH
DALI_D4
94-07-08 18:40 Run=27058 Evt=9587
400cm
-400cm
0
Y
X
-400cm
400cm
600cm
-600cm
Y'
Z
YZ
ϕ= 0
ϕ= 120

Some events



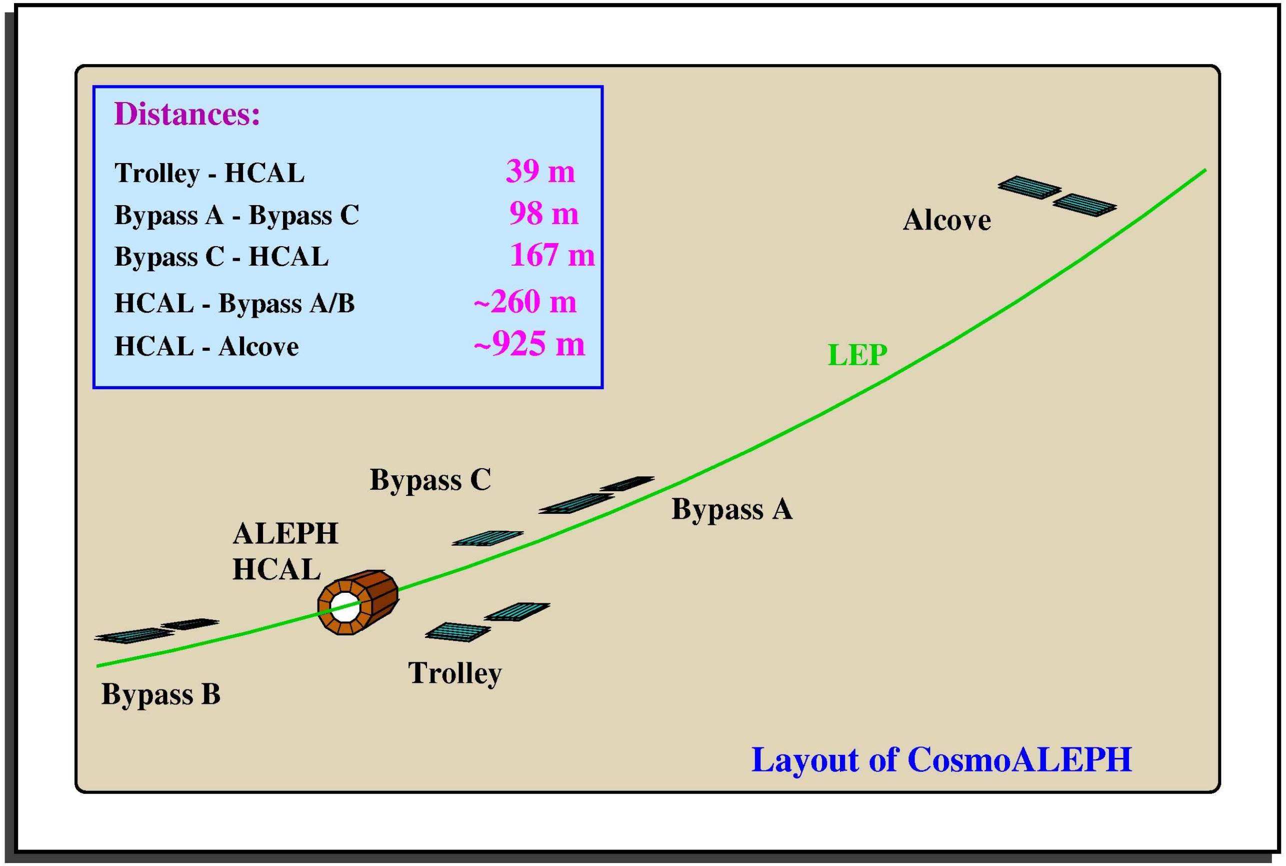
muon bundle in the TPC with ≈ 150 muons

Experimental Setup

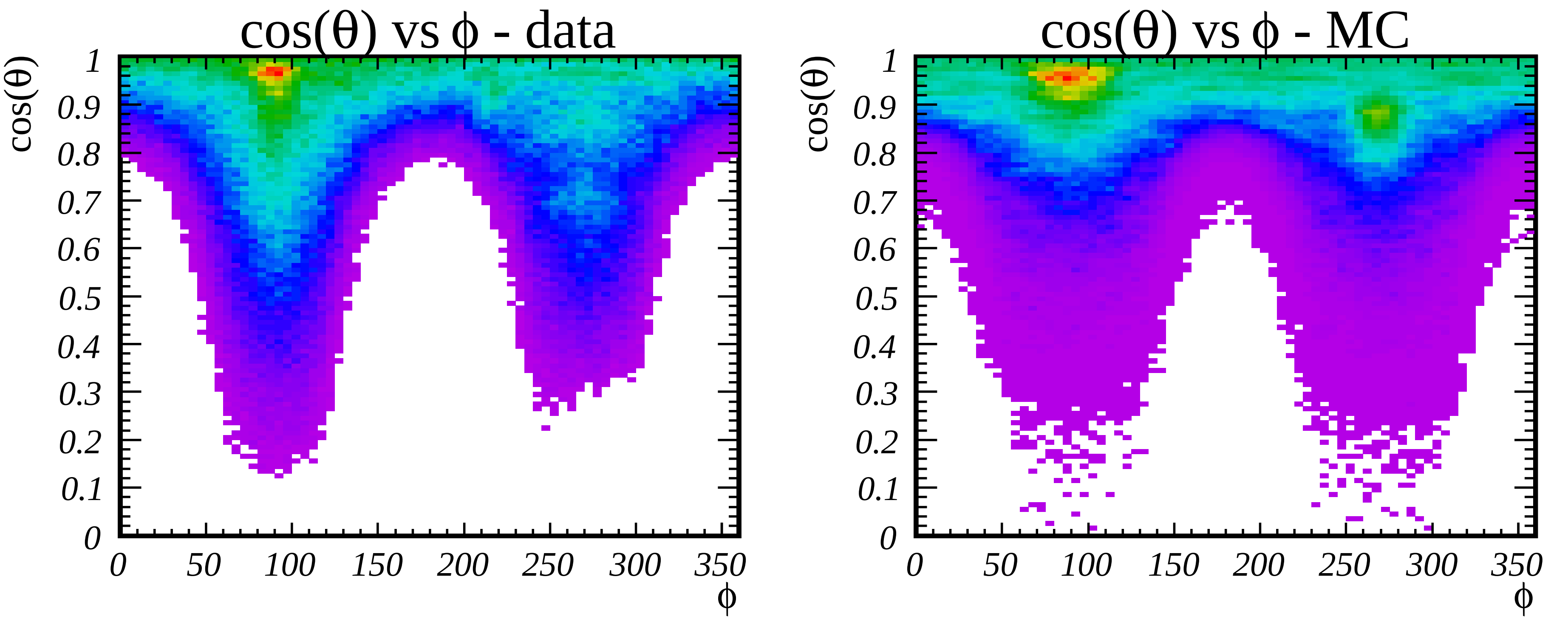
Location: overburden 125 m of molasse and rock
(75 GeV cutoff for vertical incidence)

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

Layout of CosmoALEPH



Angular Distribution



originates from the barrel shape of ALEPH, and the trigger;

large angles are cut off by the Jura;

access shaft visible

Data Set

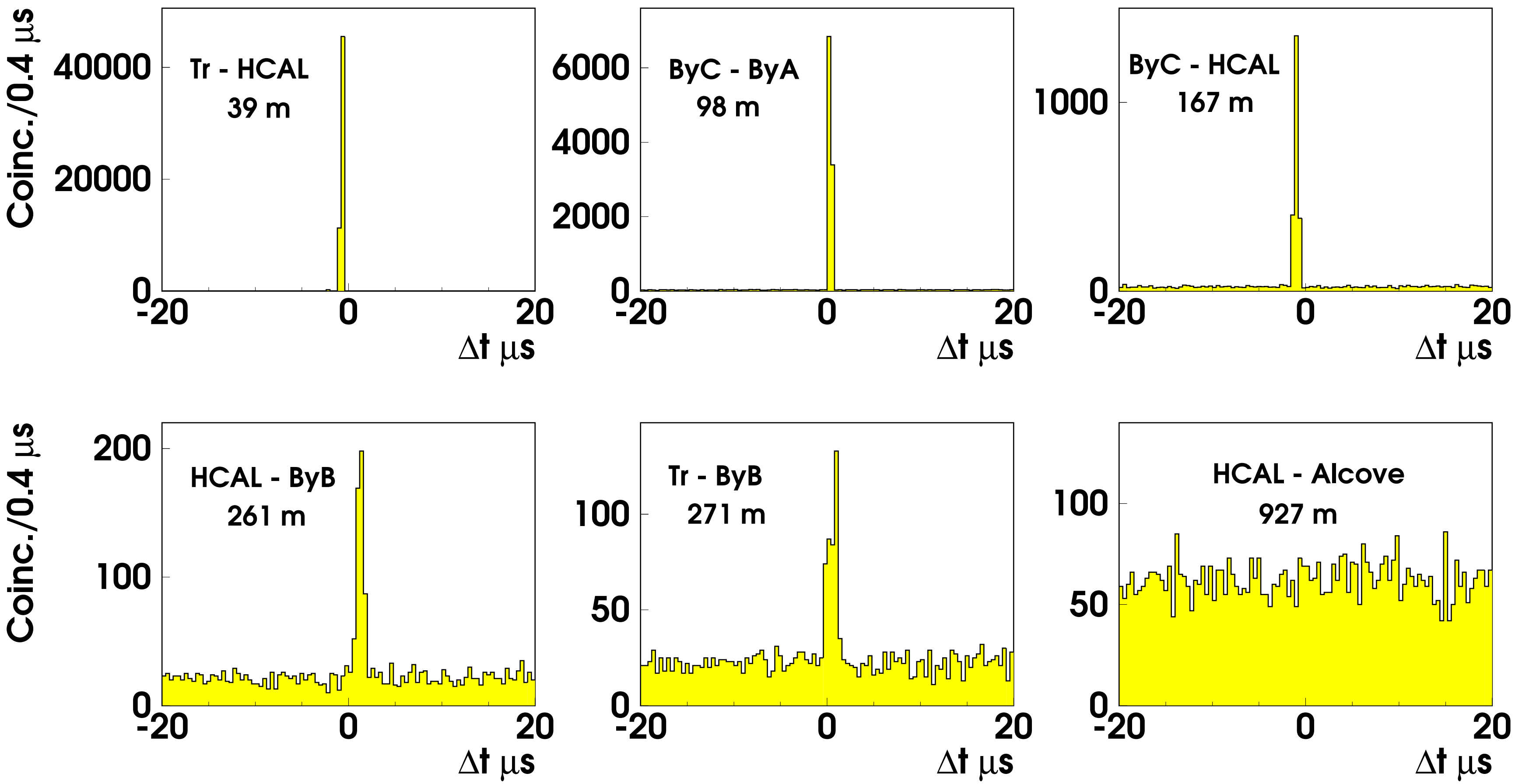
Coincidence rates between different detector stations (ALEPH and telescopes in the pit and the LEP tunnel)

Requirements:

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

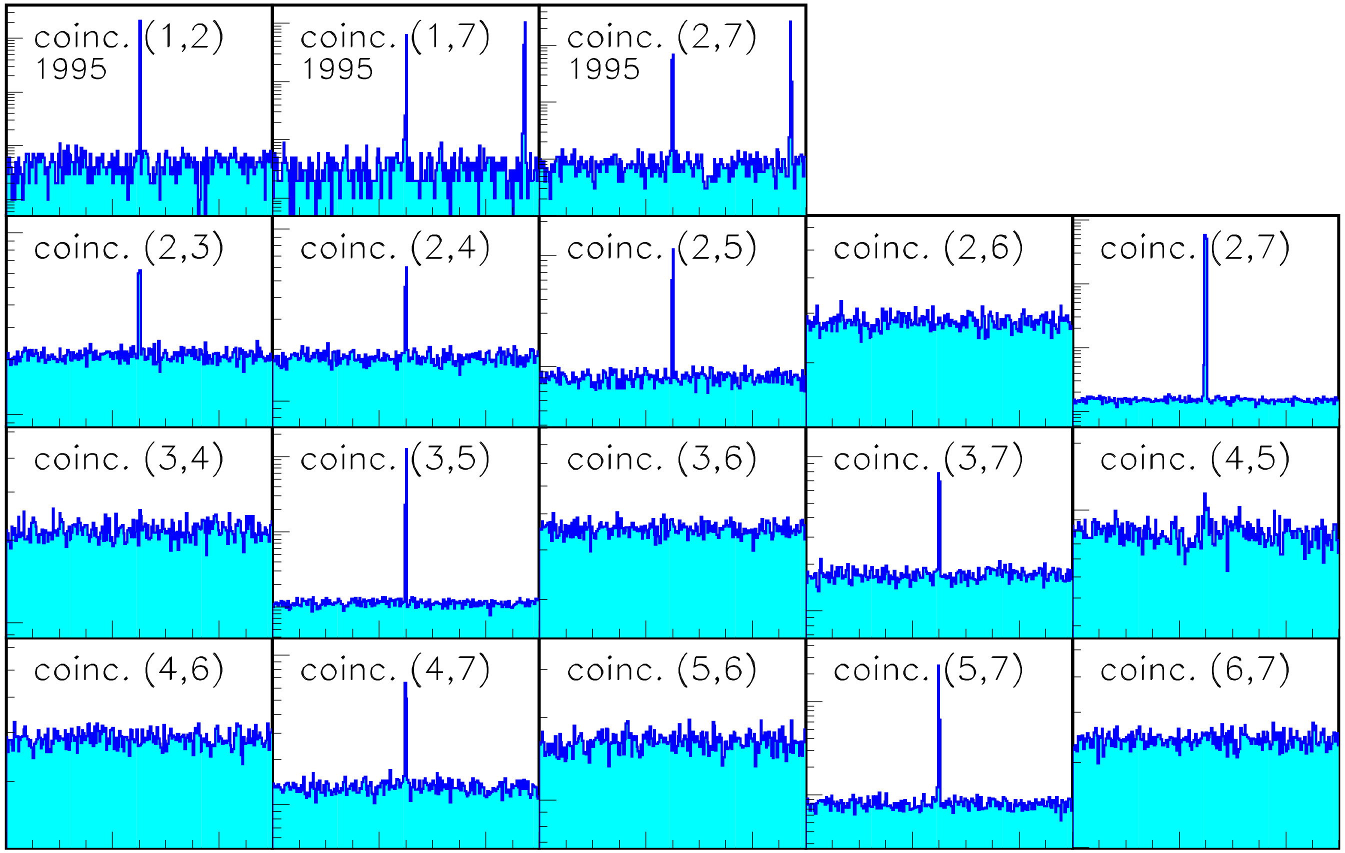
total number of events $\approx 9 \cdot 10^8$
for the years 1995 - 2000
$1.1 \cdot 10^6$ events from runs with a
dedicated cosmic ray trigger in ALEPH
(trigger rate $2.5 Hz$)

Measured coincidence rates



Arif Mailov

Measured coincidence rates



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Analysis: Decoherence Distribution

The decoherence distribution is defined as coincidence rate per unit of time divided by the product of the areas of two detectors corrected for detector effects.

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

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

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

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:**

$$E_\mu = 0.55 \cdot (e^{\frac{0.4 \cdot 0.32}{\cos\theta}} - 1) \qquad [\boldsymbol{TeV}]$$

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

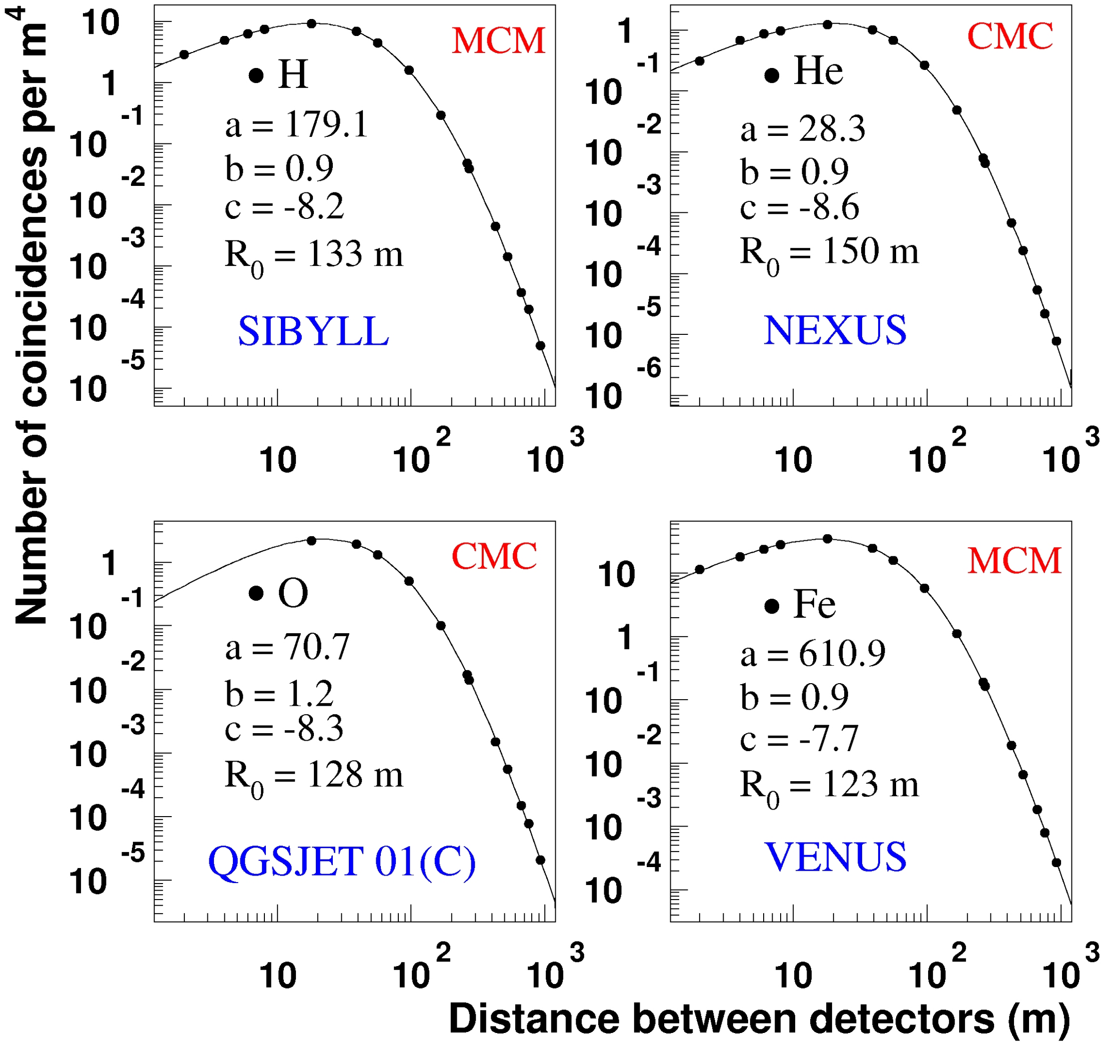
Monte Carlo Coincidence Rates

Coincidence rates of muons for each simulated primary element for different hadronic models and compositions: best fit with the Nishimura-Kamata-Greisen (NKG) formula:

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

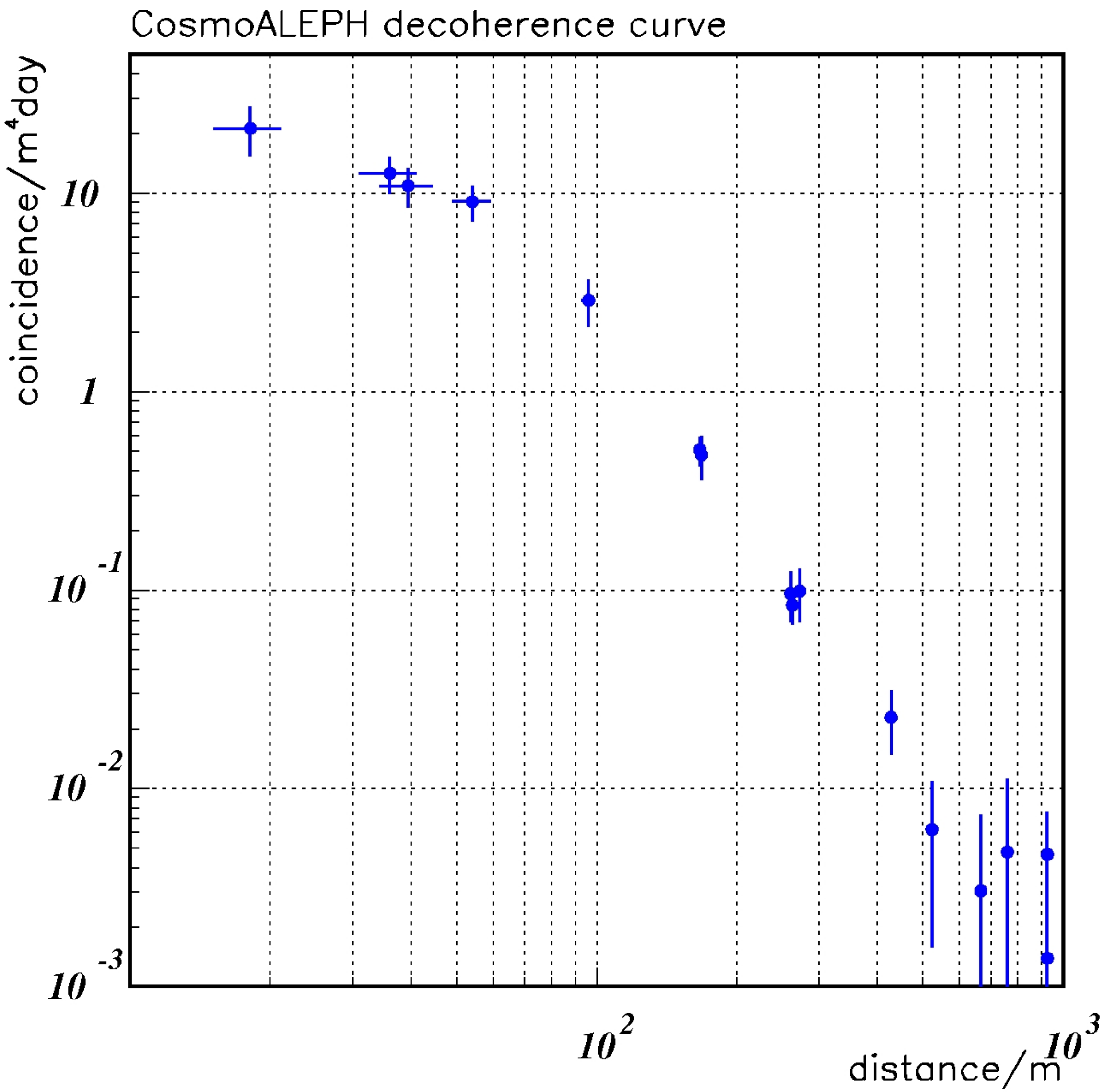
The constrained fit of the CosmoALEPH data is performed with the sum of obtained functions for protons, He and Fe and the contribution of each element is estimated.

Monte Carlo lateral distributions



Rodica Tcaciuc

Experimental distributions



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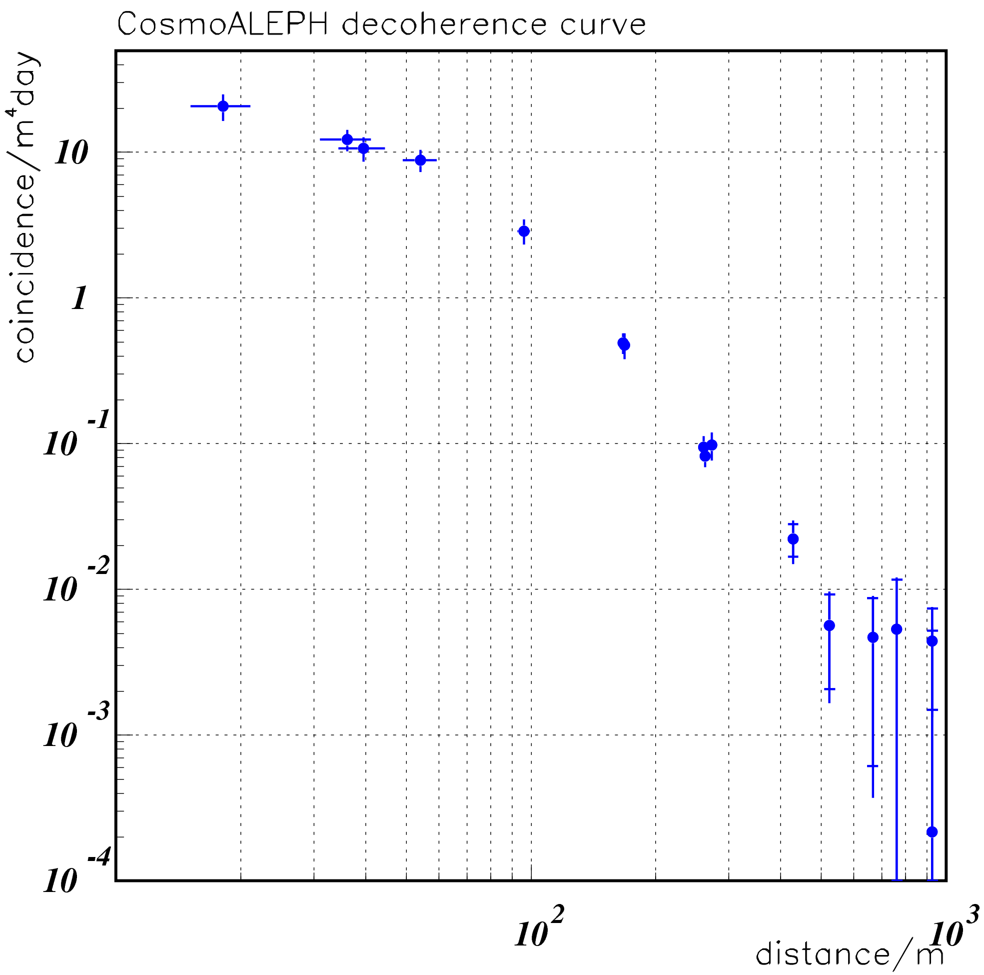
Experimental distributions



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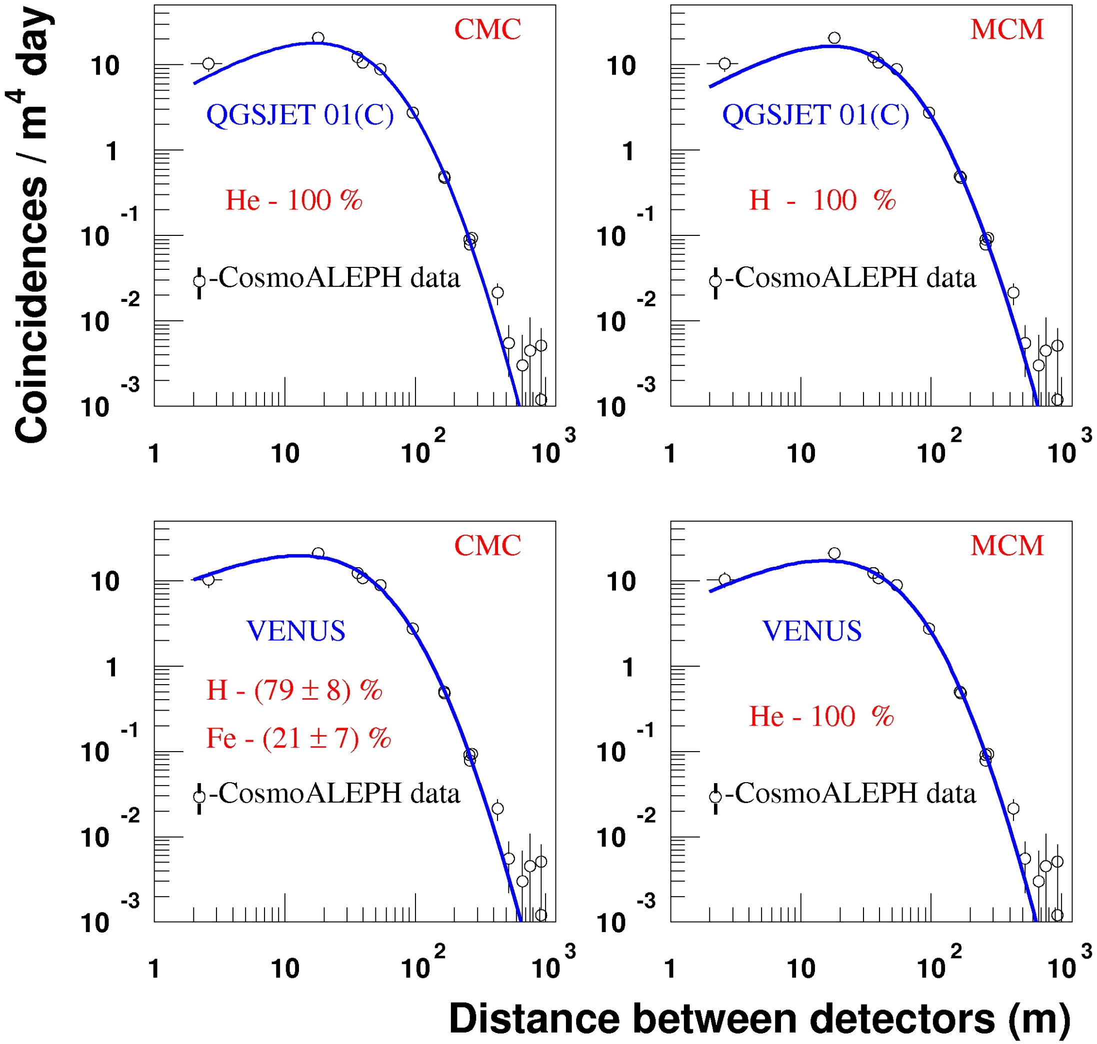
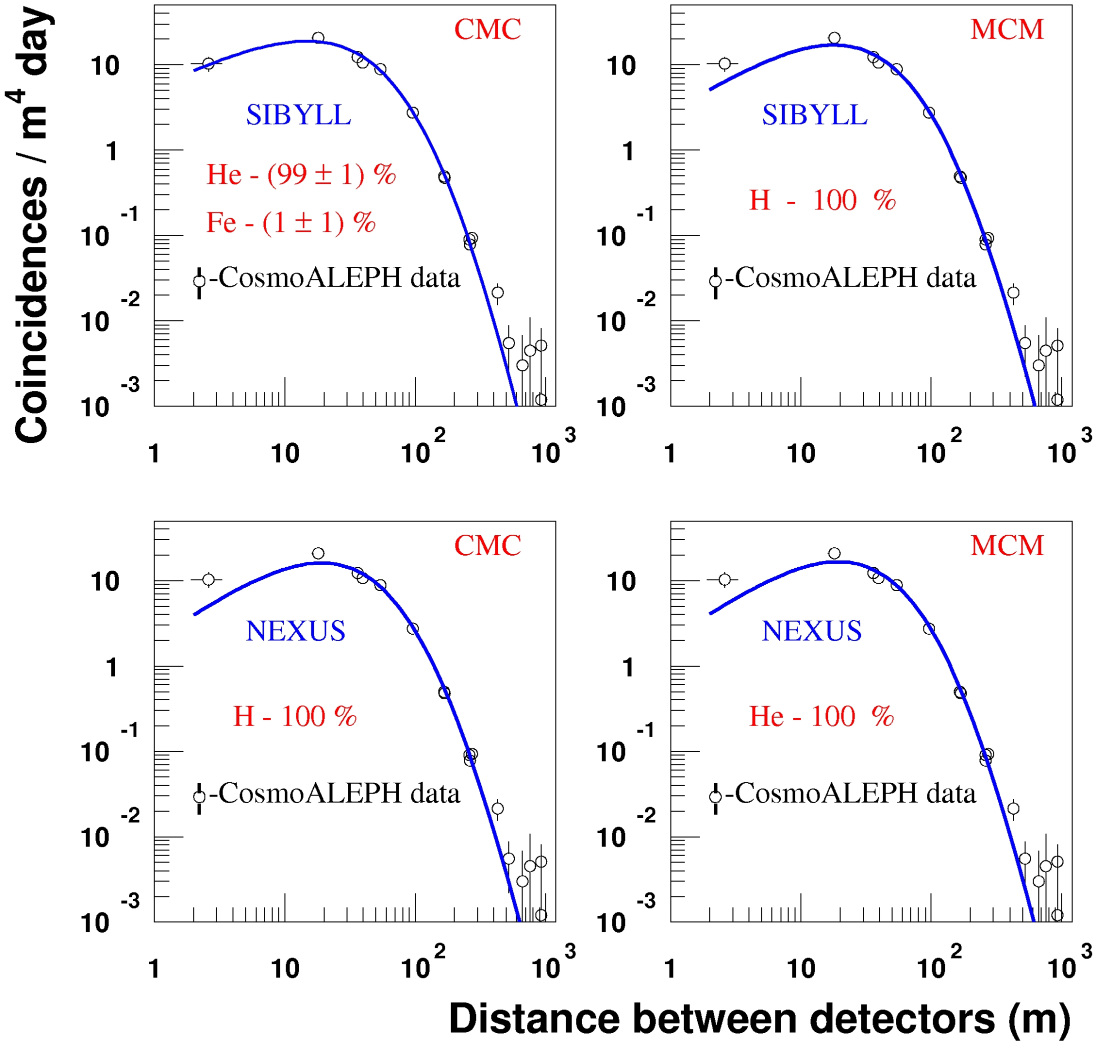
Comparison



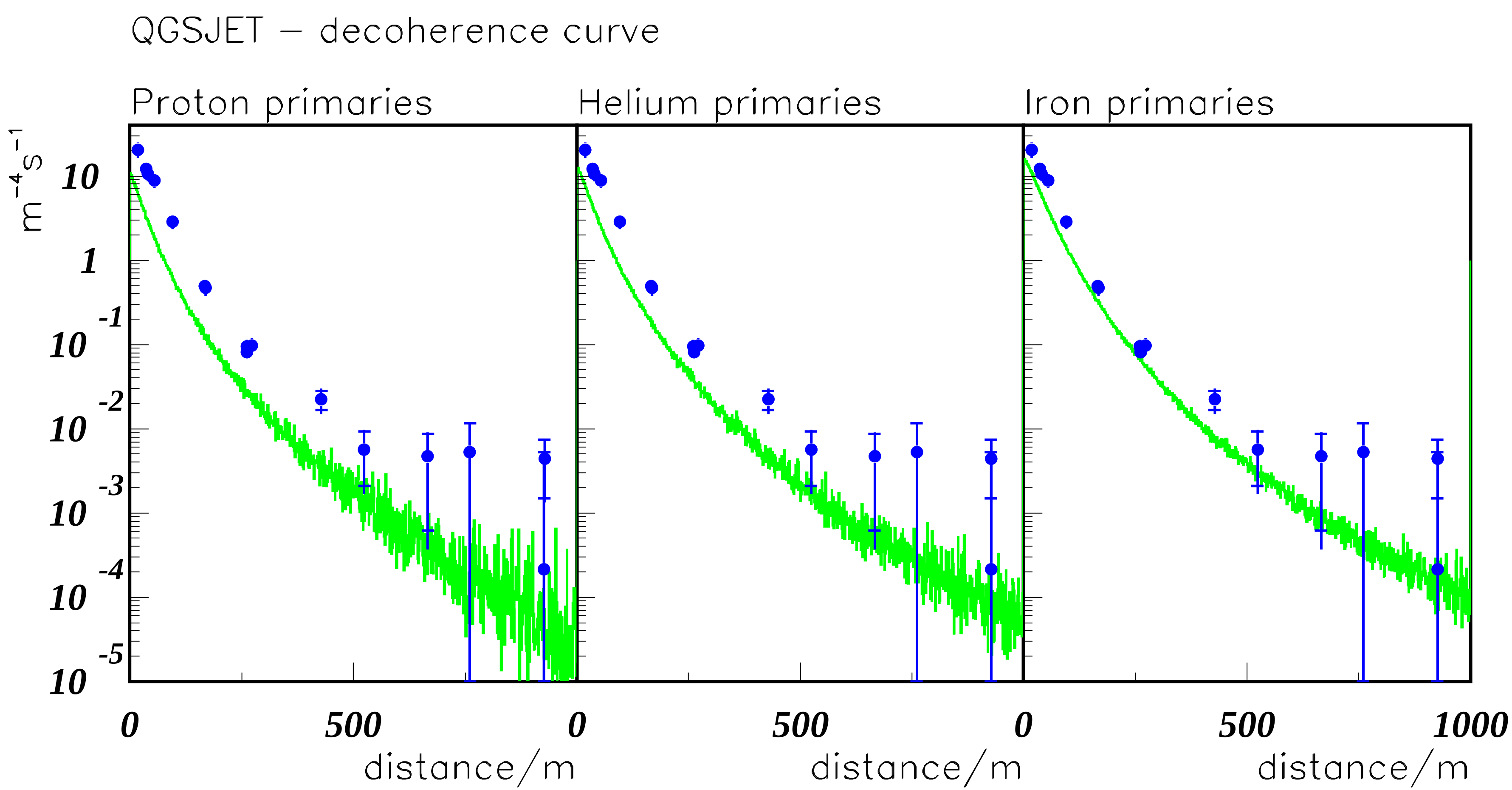
Coincidences / m^4 day
CMC
QGSJET 01(C)
He - 100 %
-CosmoALEPH data
MCM
QGSJET 01(C)
H - 100 %
-CosmoALEPH data
CMC
VENUS
H - (79 ± 8) %
Fe - (21 ± 7) %
-CosmoALEPH data
MCM
VENUS
He - 100 %
-CosmoALEPH data
10
1
10^{-1}
10^{-2}
10^{-3}
1
10
10^2
10^3
Distance between detectors (m)

Comparison



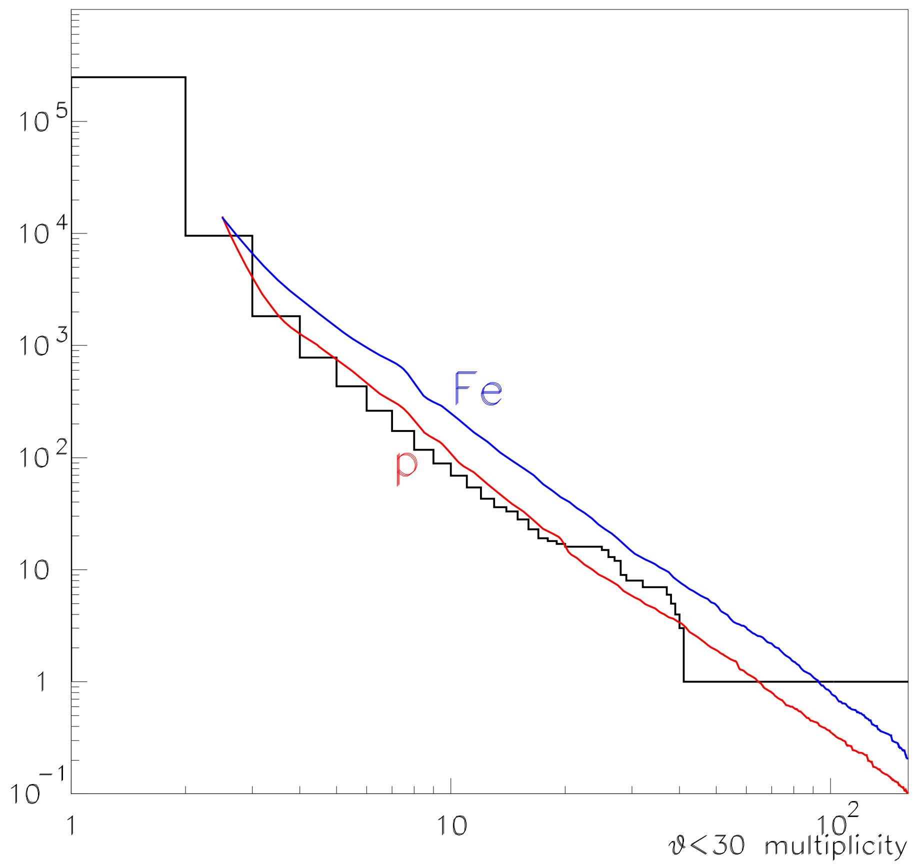
Coincidences / m^4 day
CMC
SIBYLL
He - (99 ± 1) %
Fe - (1 ± 1) %
-CosmoALEPH data
MCM
SIBYLL
H - 100 %
-CosmoALEPH data
CMC
NEXUS
H - 100 %
-CosmoALEPH data
MCM
NEXUS
He - 100 %
-CosmoALEPH data
Distance between detectors (m)

Comparison



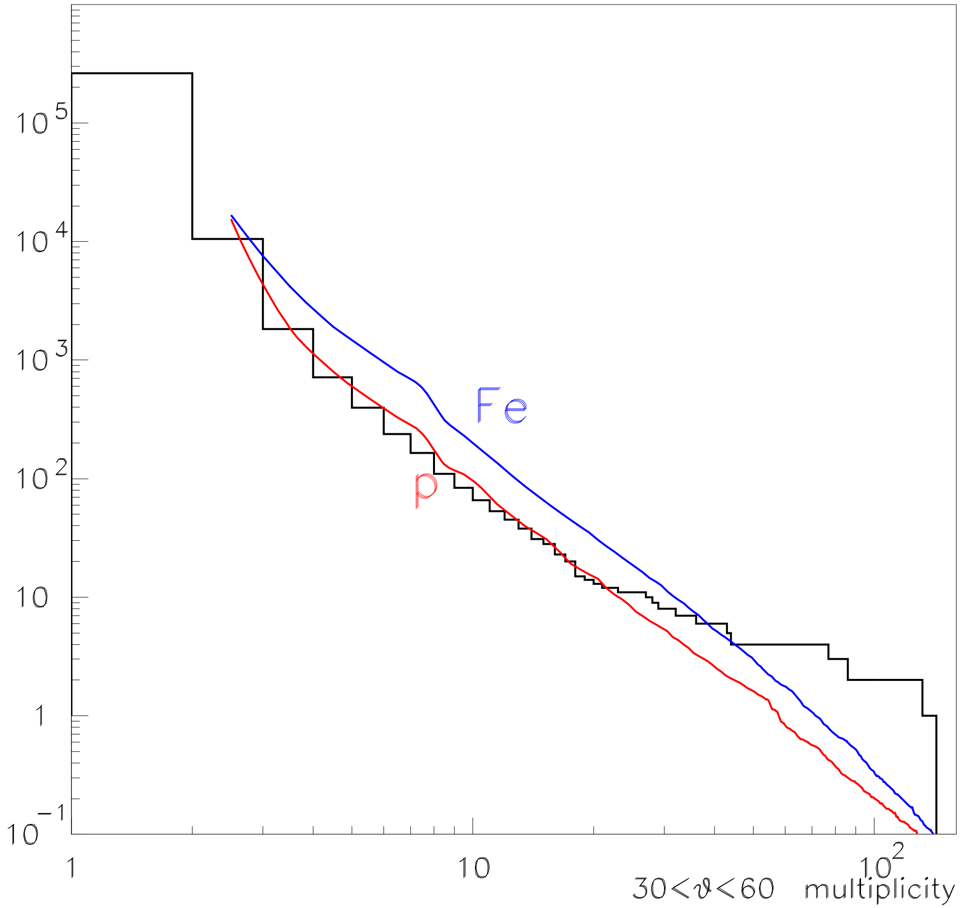
coincidences are sensitive to higher mass primaries

Multiplicities in the ALEPH TPC



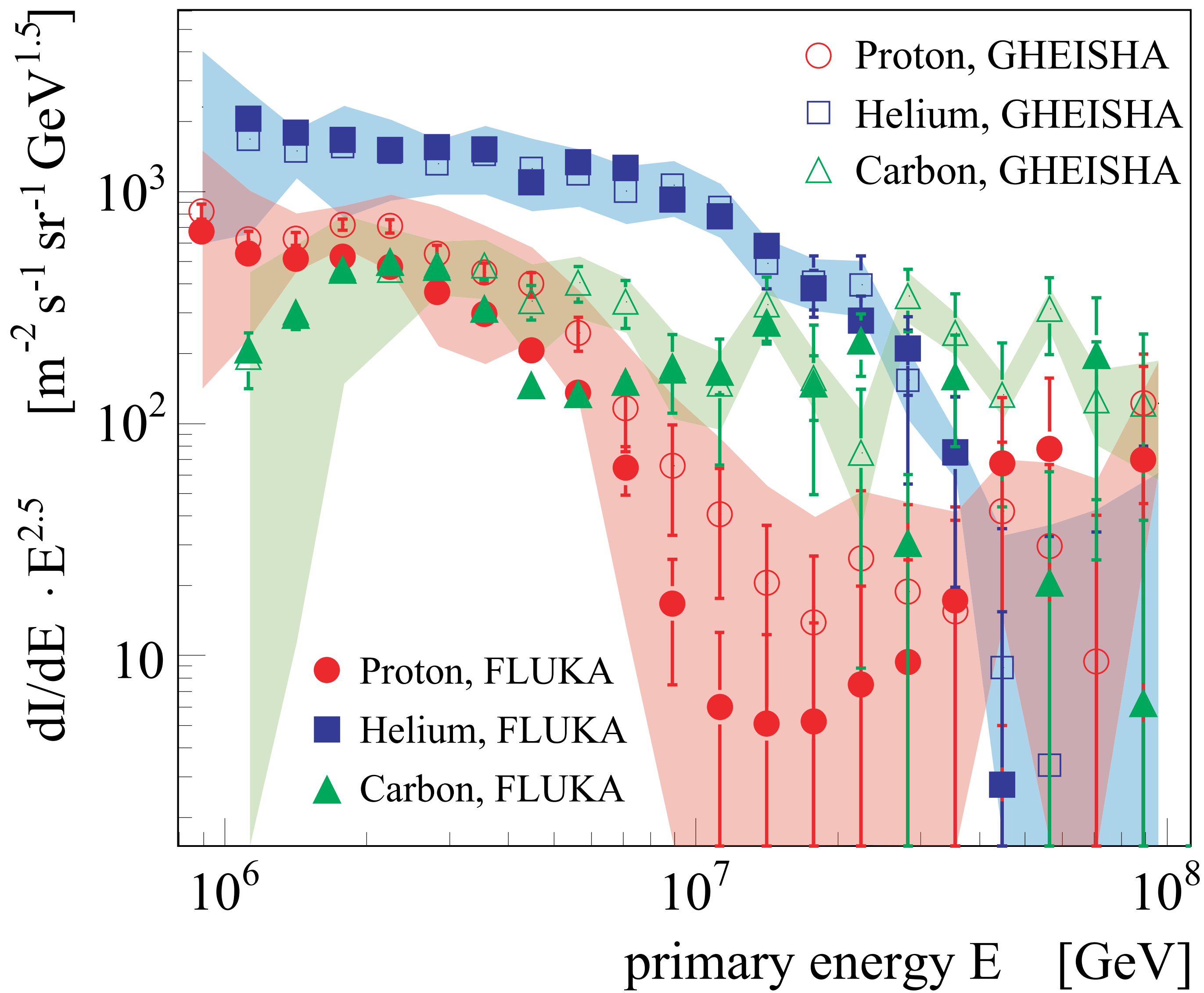
V. Avati et al., Astropart. Phys. **19** (2003) 513

Multiplicities in the ALEPH TPC



V. Avati et al., Astropart. Phys. **19** (2003) 513

KASCADE results

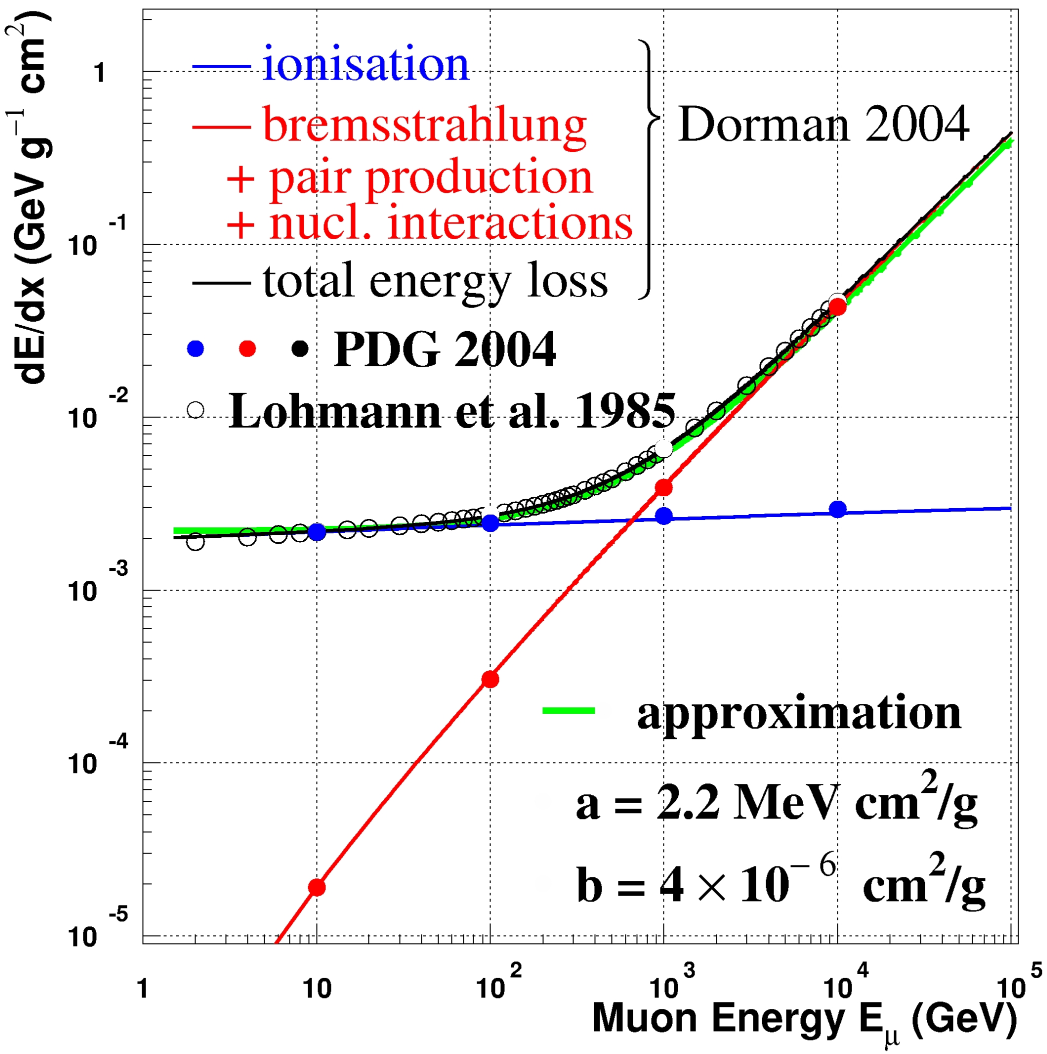


KASCADE air shower experiment unfolding Karlsruhe 2008

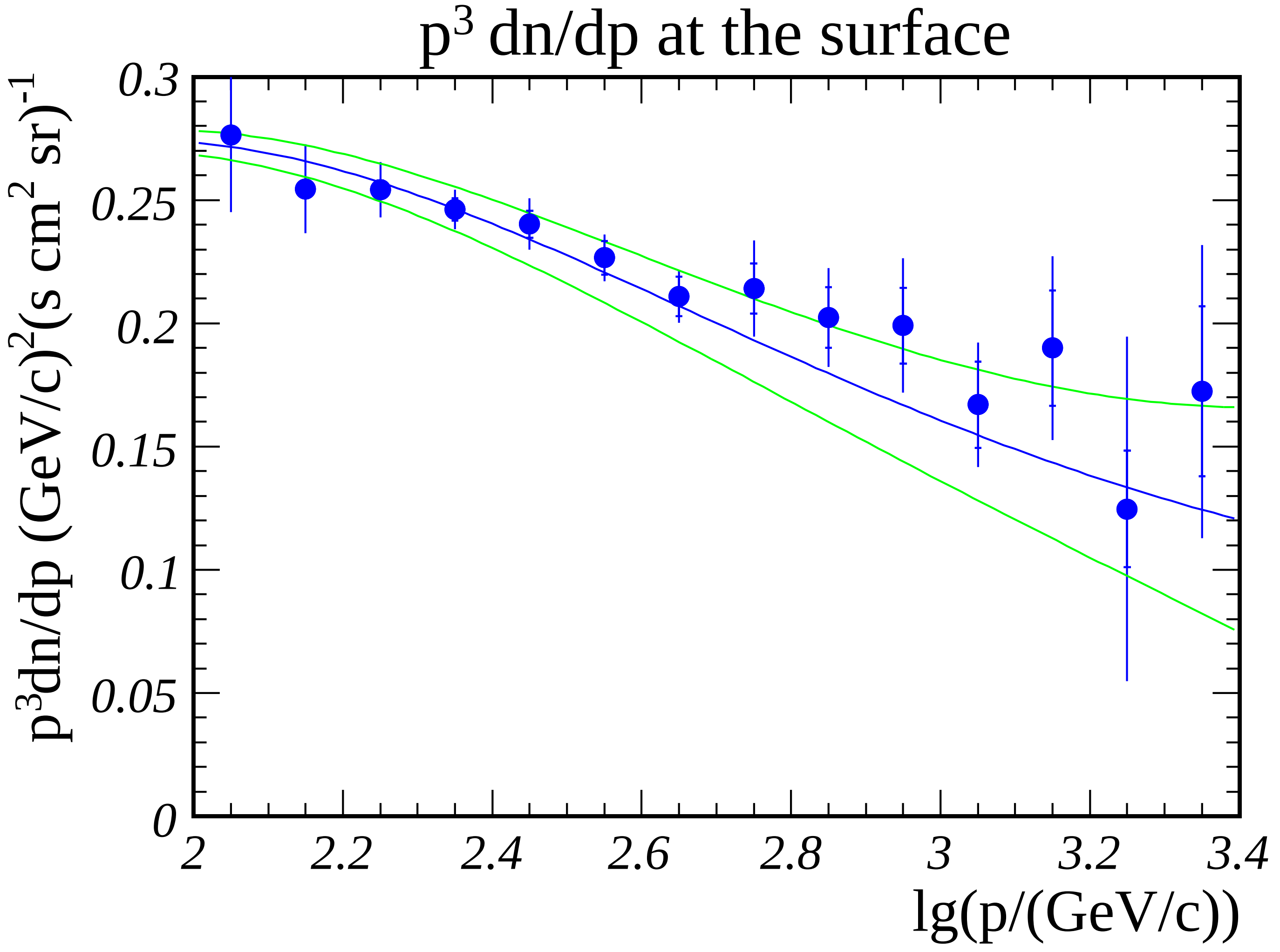
Results: chemical composition

- 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.

Muon Energy Loss



Muon Spectrum



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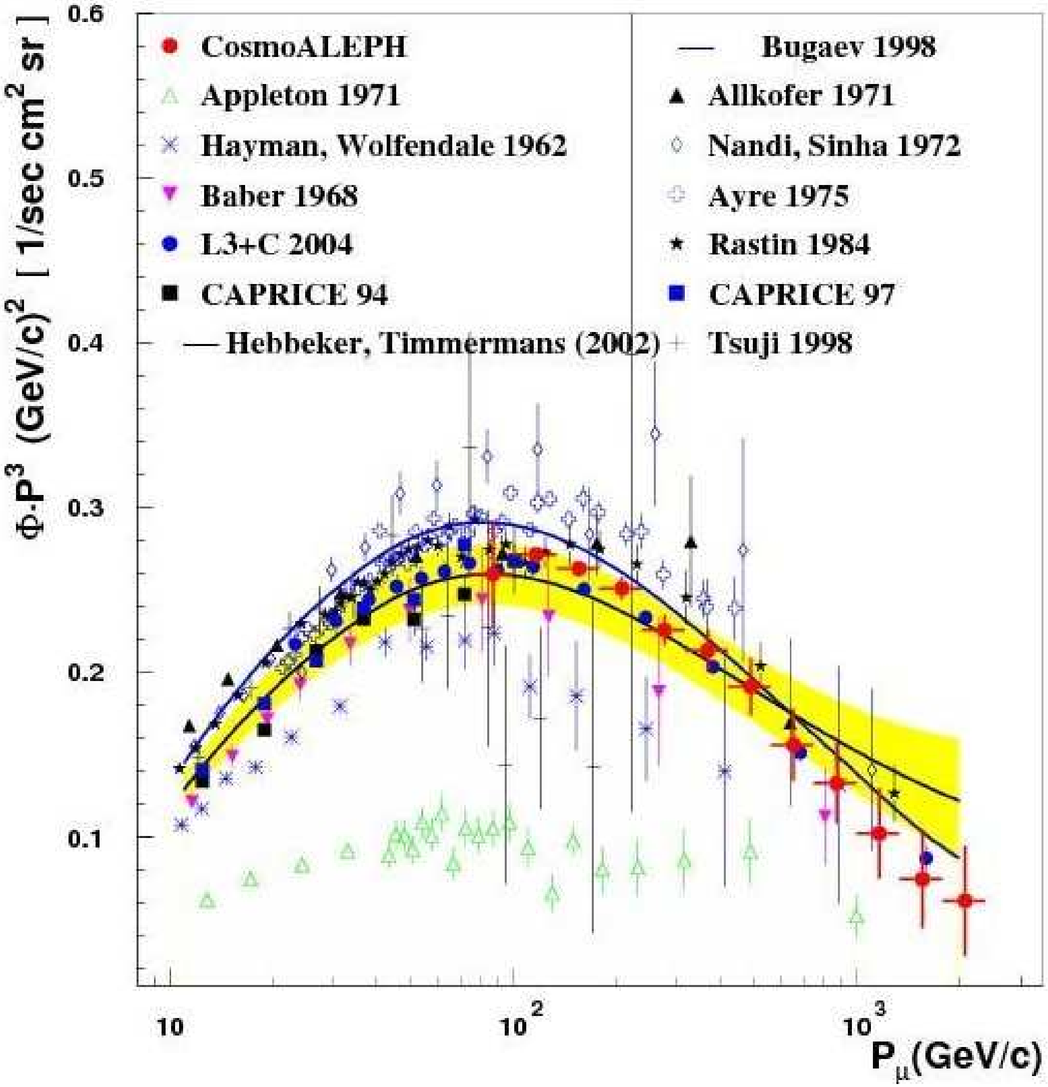
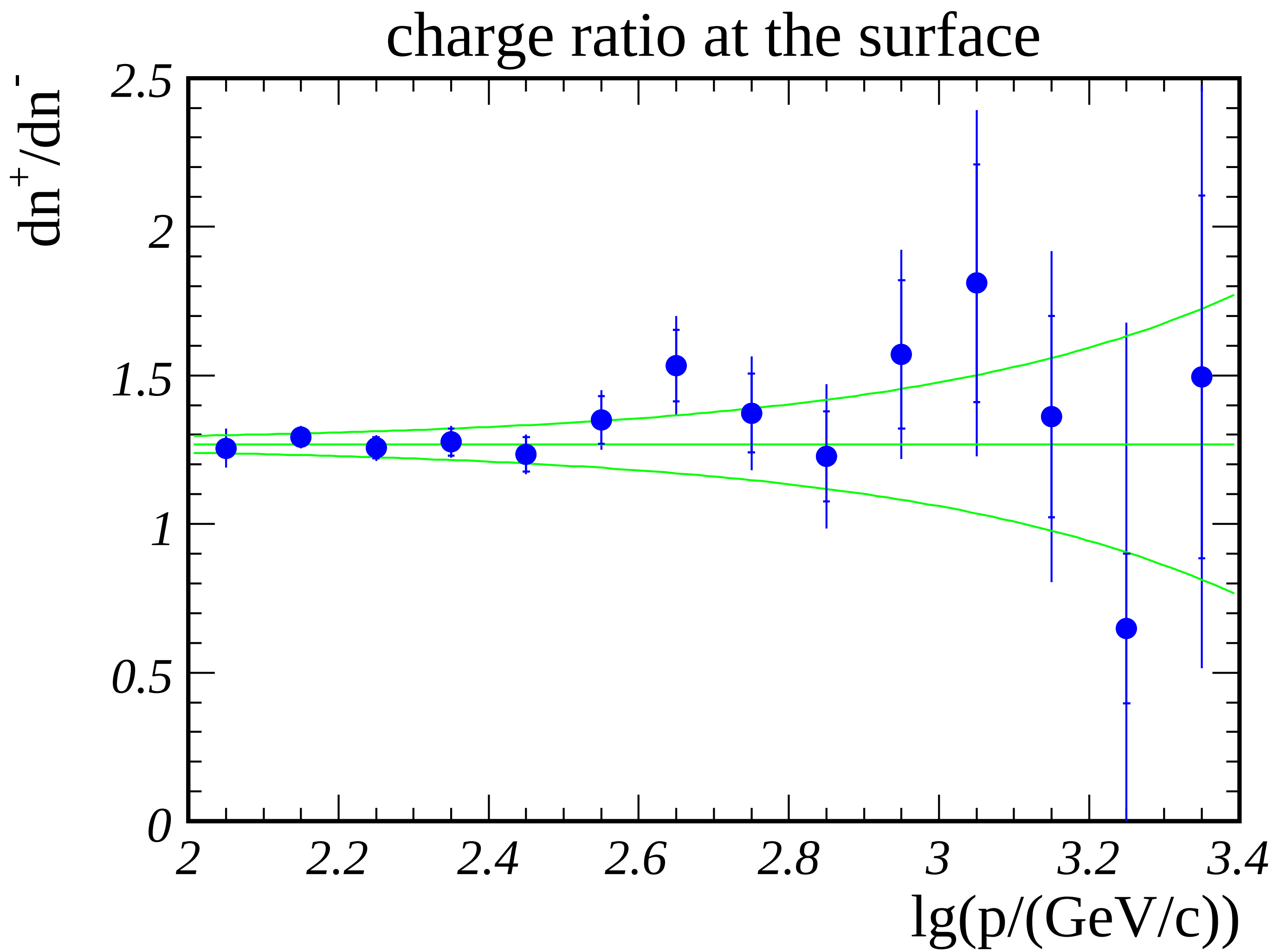
Muon Spectrum



Nadir Omar Hashim

Muon Charge Ratio



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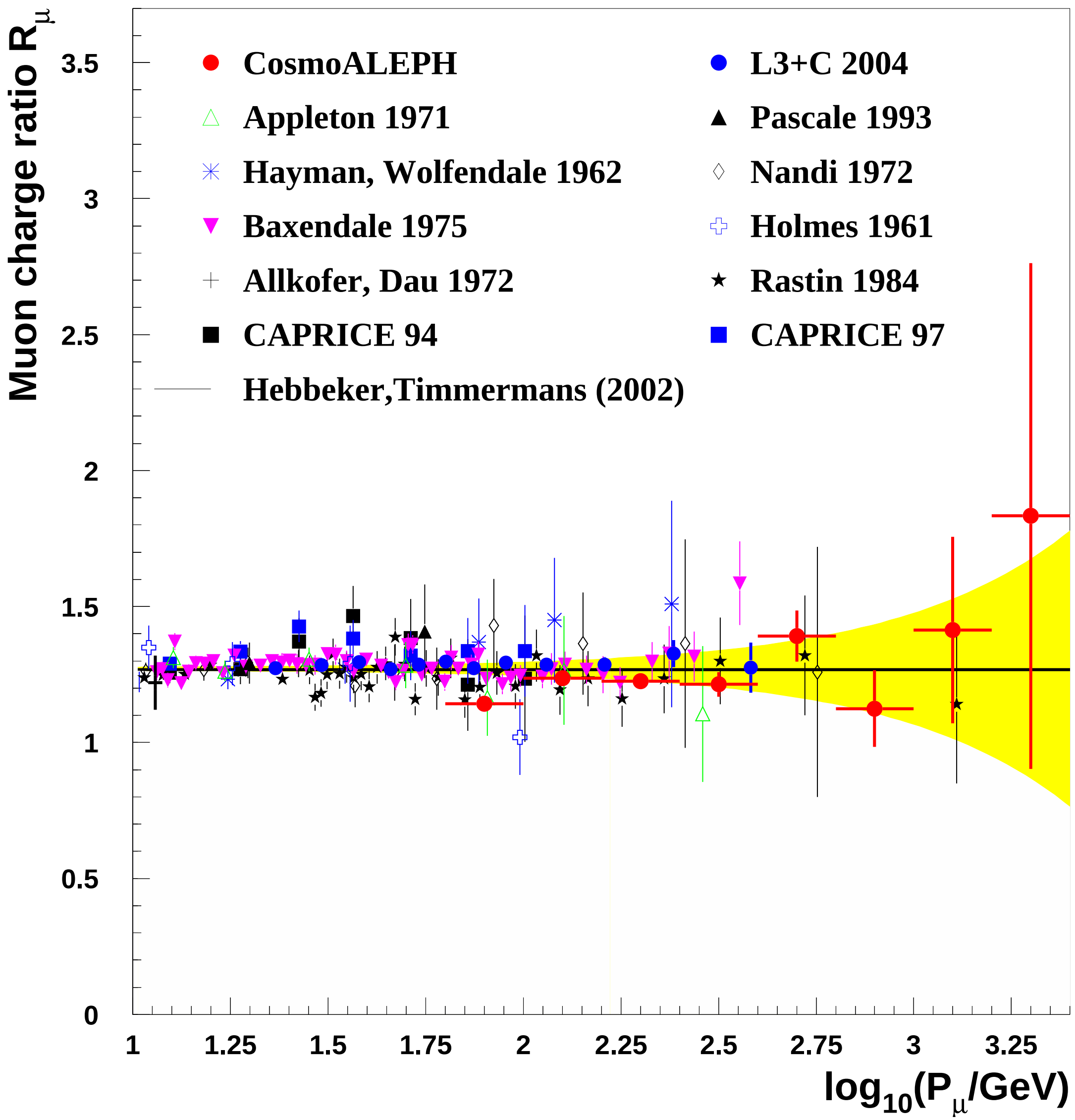
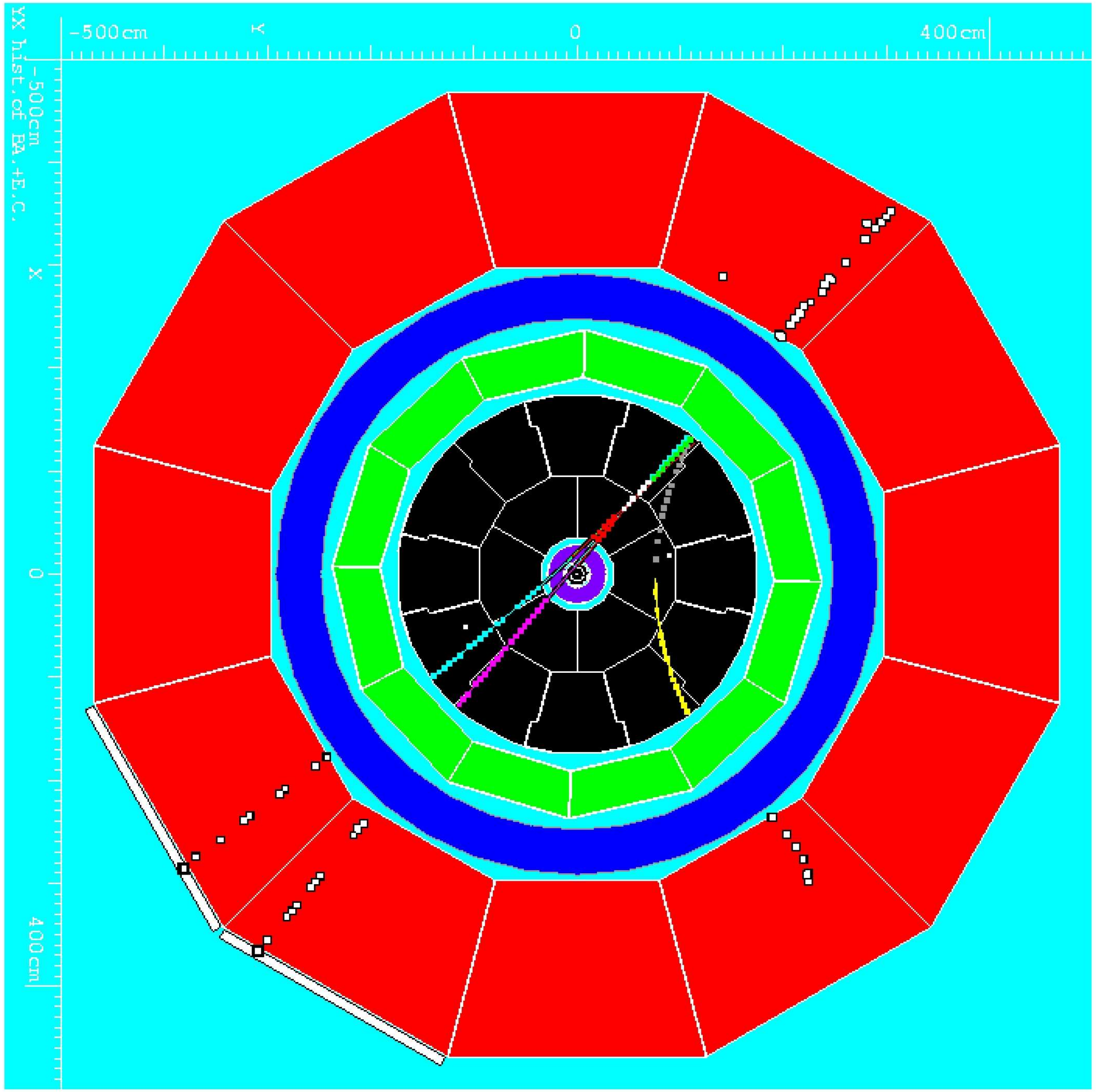
Muon Charge Ratio



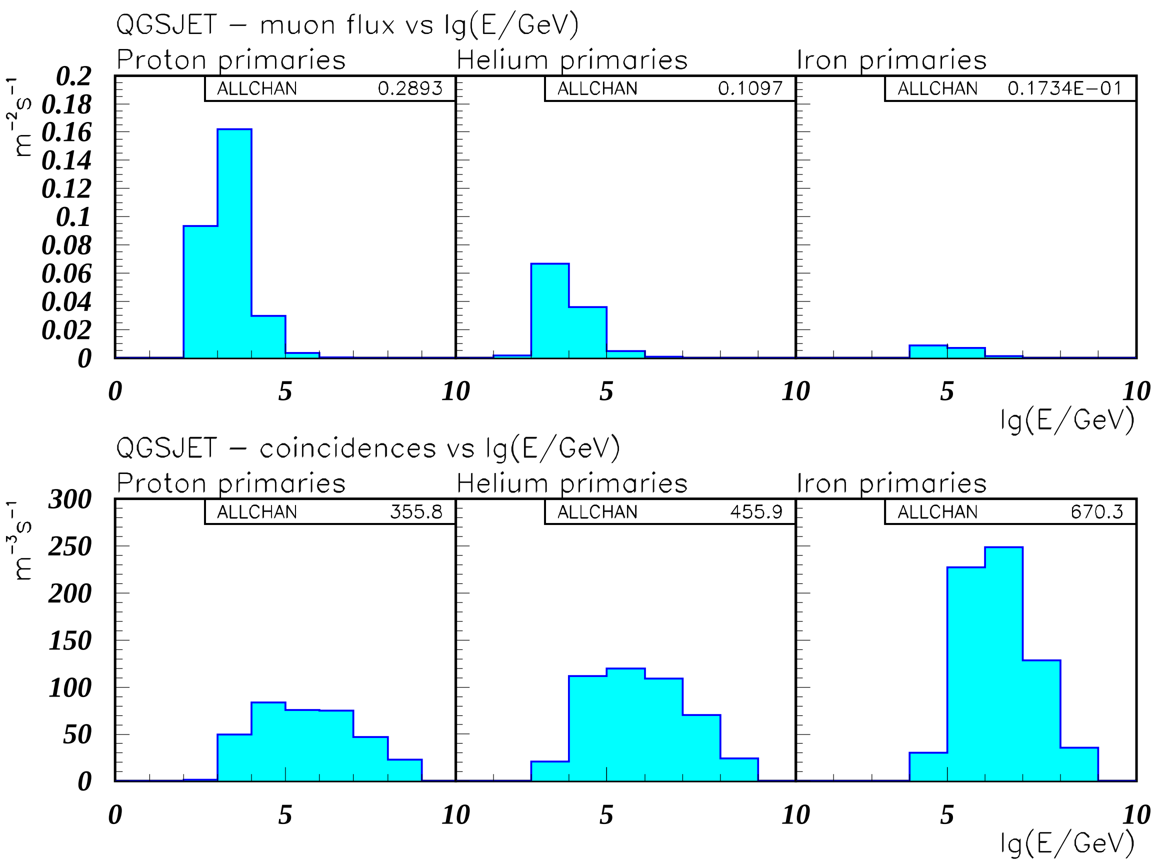
Nadir Omar Hashim

Muon Tridents



Florin Maciuc

Comparison



muon spectrum dominated by low primary energies

decoherence more sensitive to heavy primaries

heavy primaries become more important at high energies

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Conclusions/Outlook

- the determination of the chemical composition involves many open questions at the same time, like
- hadronic cross sections at energies beyond accelerator energies
- uncertain Monte Carlo simulations for propagating the primaries through the atmosphere
- conversion of the experimental quantities into energies
- below the knee most of the particles are protons
- at higher energies heavier elements start to dominate
- at very high energies not much is known

The CosmoALEPH Collaboration

A. Mailov; Technical University of Baku, Azerbaijan

B. Jost, S. Schmeling, H. Wachsmuth; CERN, Geneve

K. Zuber; TU Dresden

B. Rensch; erphi electronics GmbH, Holzkirchen

F. Maciuc, M. Schmelling; Max-Planck-Institut für Kernphysik, Heidelberg

A. Putzer; Universität Heidelberg

Th. Ziegler; Hewlett-Packard, Geneve

A.-S. Müller; Forschungszentrum Karlsruhe

N.-O. Hashim; Kenyatta University, Nairobi, Kenia

H.-G. Sander; Universität Mainz

C. Grupen; R. Tcaciuc; Universität Siegen

S. Luitz; SLAC, USA