CERN/2001-003

SPSC/P321

CORAL

A Cosmic Ray experiment in and above the LHC tunnel

- Principle of CORAL and Observables
- Physics motivations
  - Astroparticle Physics
  - Particle interactions
- The experimental set-up (at Point 4)
- Test experiment in BA4
- Performance simulations
- Schedule and Budget

Presented to the SPSC by Karsten Eggert, 23.1.2001

CORAL proposes to measure:

- Cosmic ray air showers in the energy interval $10^{15} \leq E \leq 10^{17}$ eV

  "knee" in the energy spectrum
  energy of TEV + LHC colliders

- Astroparticle Physics

  particle spectrum, chemical composition

  point-like sources

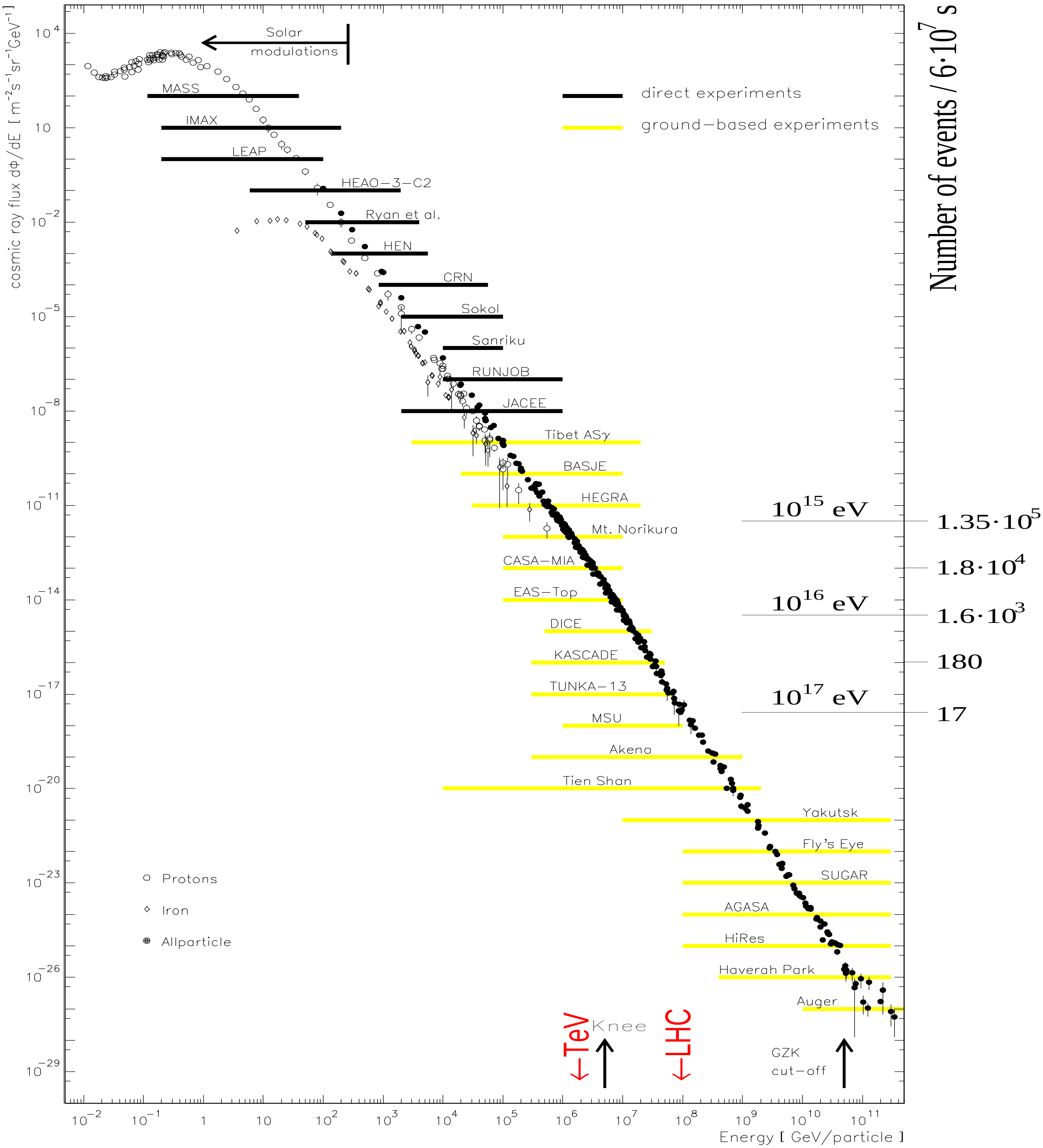
- Particle Interaction Physics

  characteristic of forward particle production

  search for new phenomena: Centauro, DCC, QGP, heavy flavour production....

  detailed studies of high multiplicity muon bundles

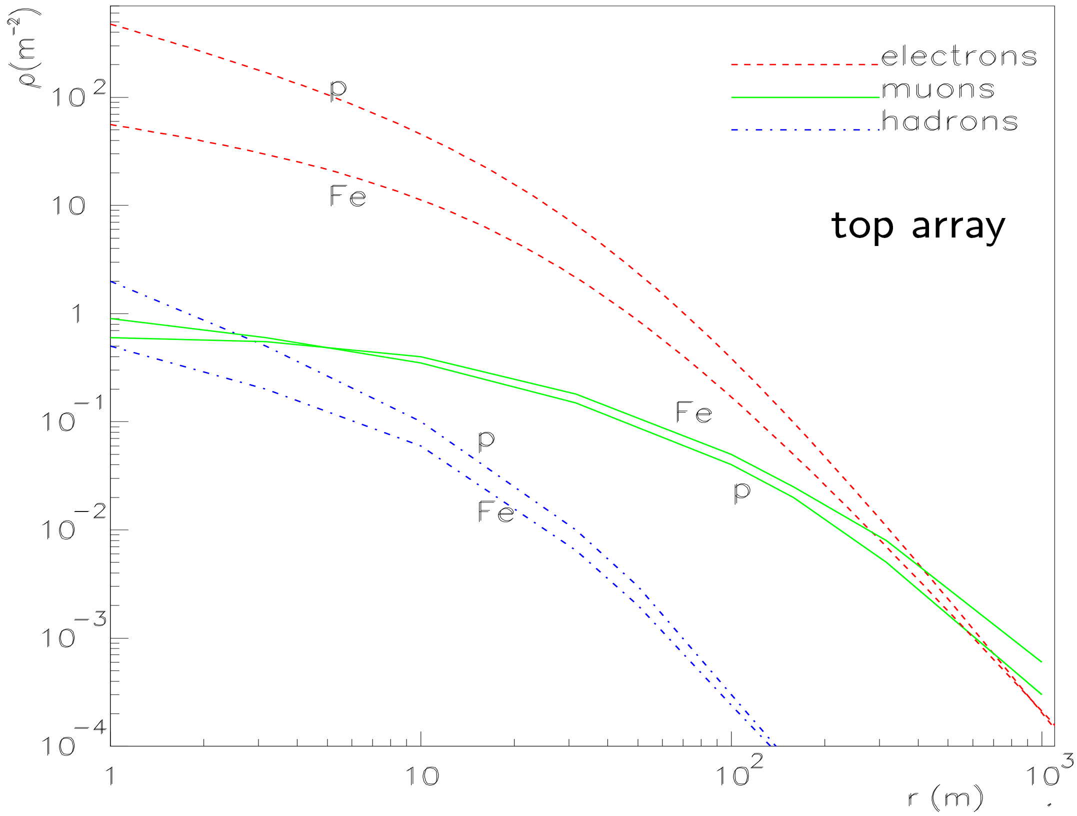
Energy spectrum of primary cosmic rays

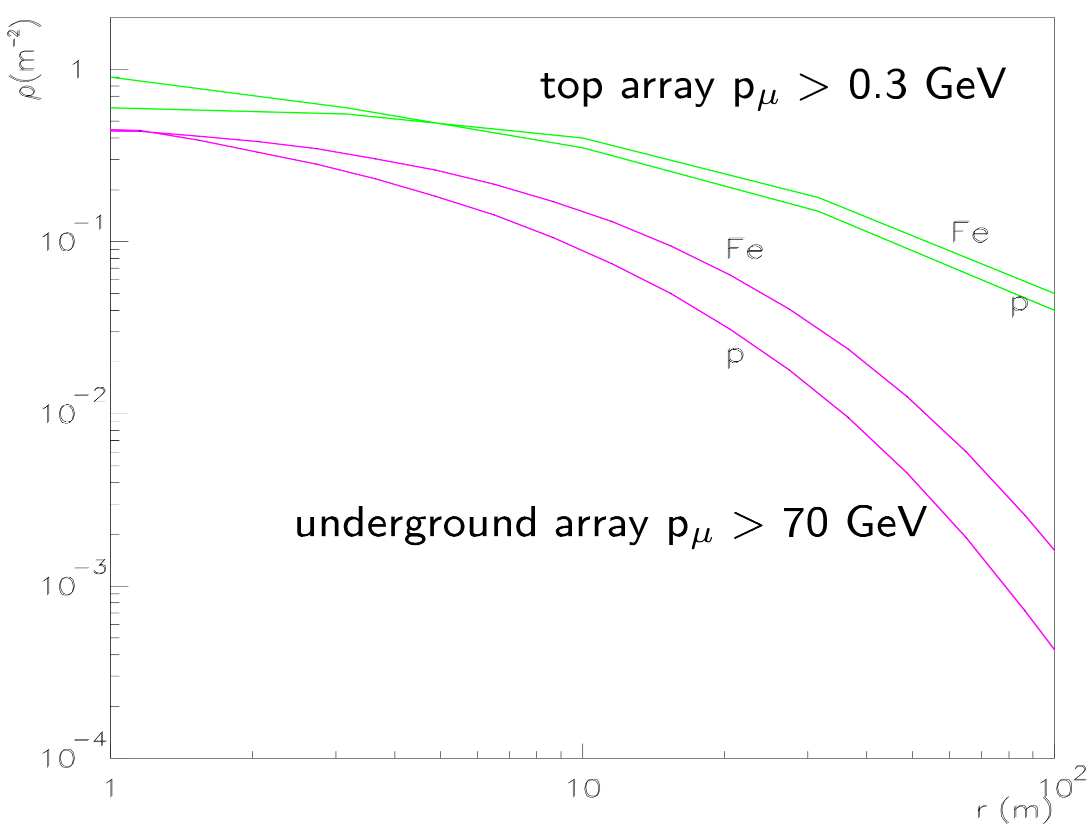


(from B. Wiebel-Sooth, Dissertation, University. of Wuppertal, WUB-DIS-98-9, Sept. 1998)

Observables

Lateral distributions for E=10^{15} eV





CORAL

Probe with muons

Muons transport the information about the first interactions through the atmosphere

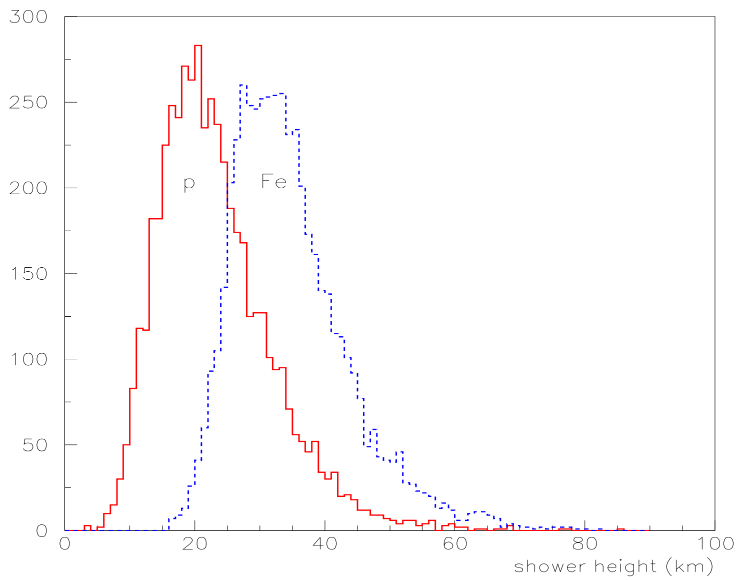
Muons of different momenta trace details of the cosmic ray cascades at different heights

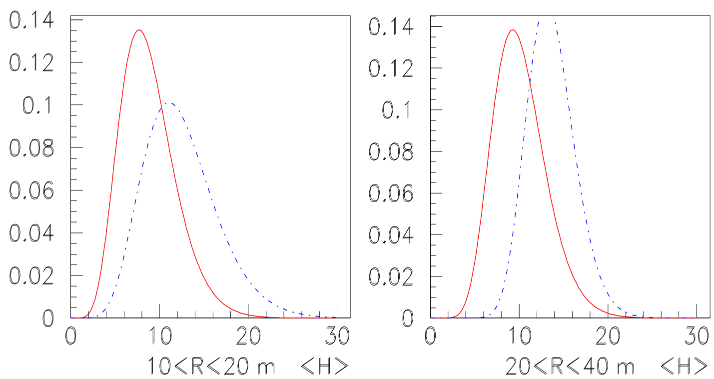
Surface:	$E_\mu \sim$ few GeV probes the end of the air shower cascade
Underground:	$E_\mu \sim$ 70 GeV interaction and decay probabilities of pions are similar at a height of $\sim$ 15 Km probes the early interactions
Deep: underground:	$E_\mu \sim$ 1 TeV probes early interactions, but with very low statistics

$$N_\mu(p_\mu > 1TeV)/N_\mu(p_\mu > 70GeV) \sim 1.5\%$$

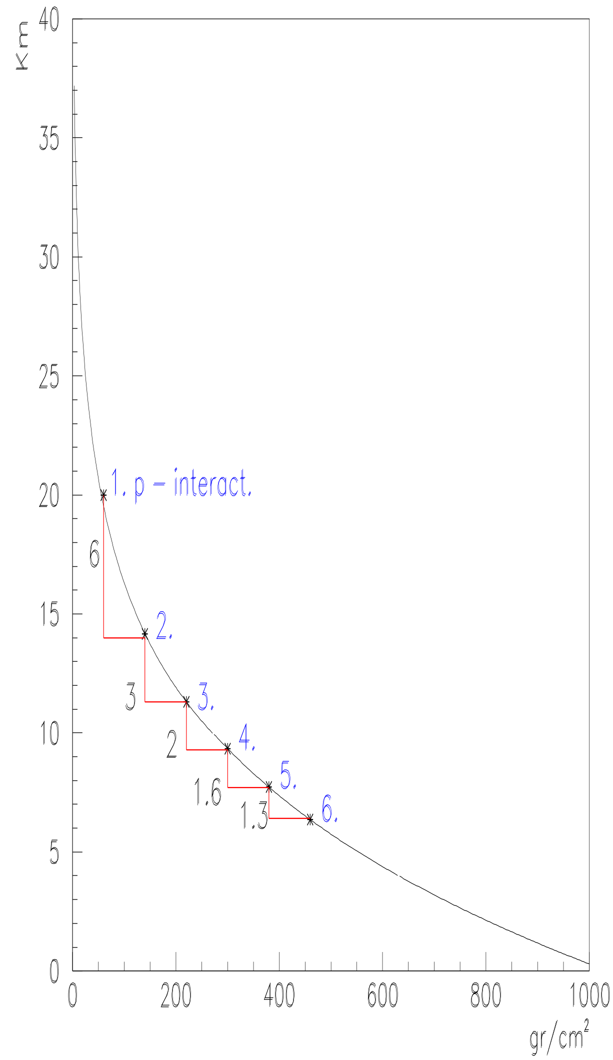
CORAL (p$_\mu$ $>$ 70 GeV) is at the right depth

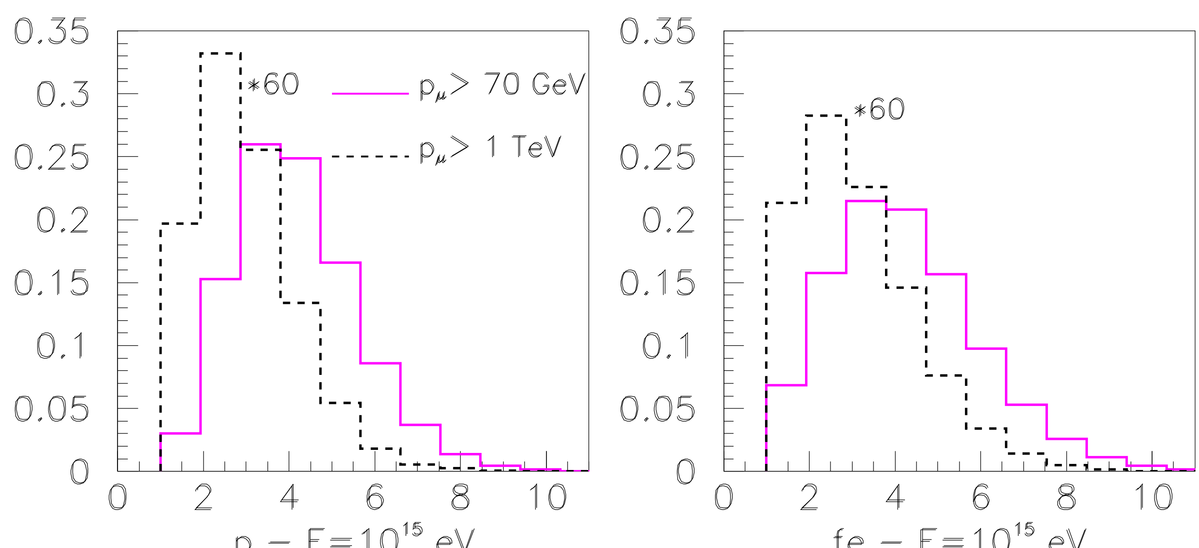
Muons in air showers





Reconstructed height





Generation

$$N_\mu(p_\mu > 1TeV)/N_\mu(p_\mu > 70GeV) \sim 1.5\%$$

CORAL principal set-up

Astroparticle Physics

- particle spectrum + composition
- point like sources ???

Particle Interaction Physics

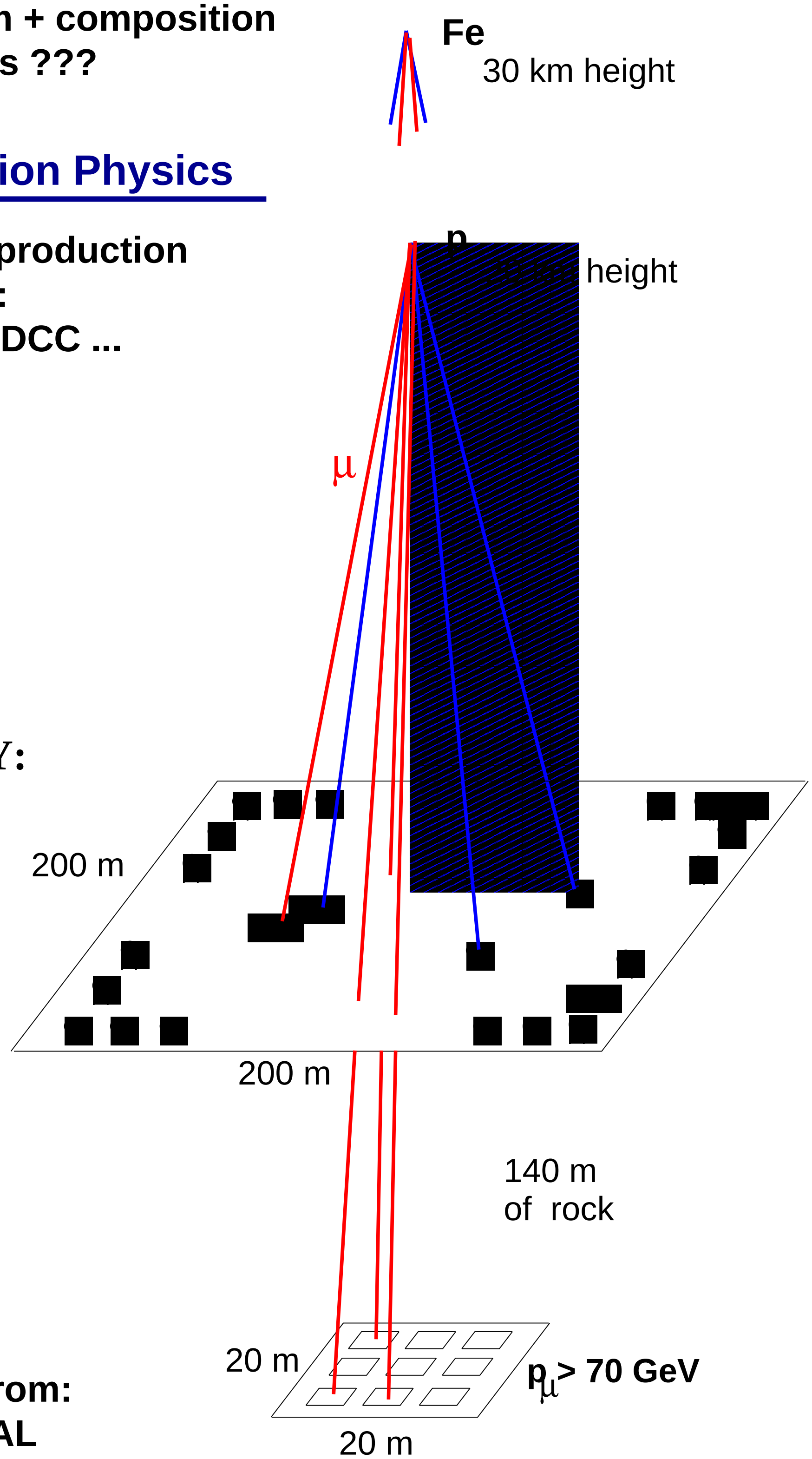
- forward particle production
- new phenomena:
  Centauro, QGP, DCC ...

SURFACE ARRAY:

HEGRA counters
Indian counters

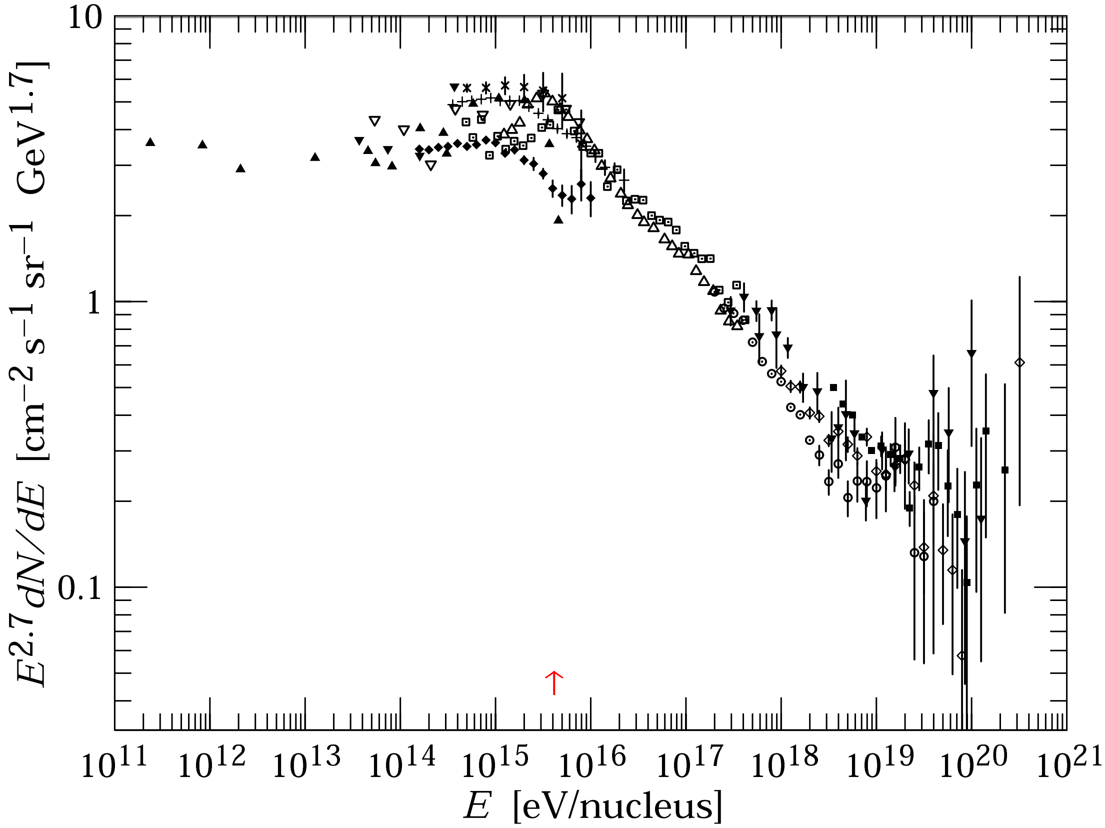
UNDERGROUND ARRAY:

muon chambers +
trigger counters from:
UA1, DELPHI, OPAL



not in scale

The "knee"



acceleration in our galaxy ↔ extra-galactic

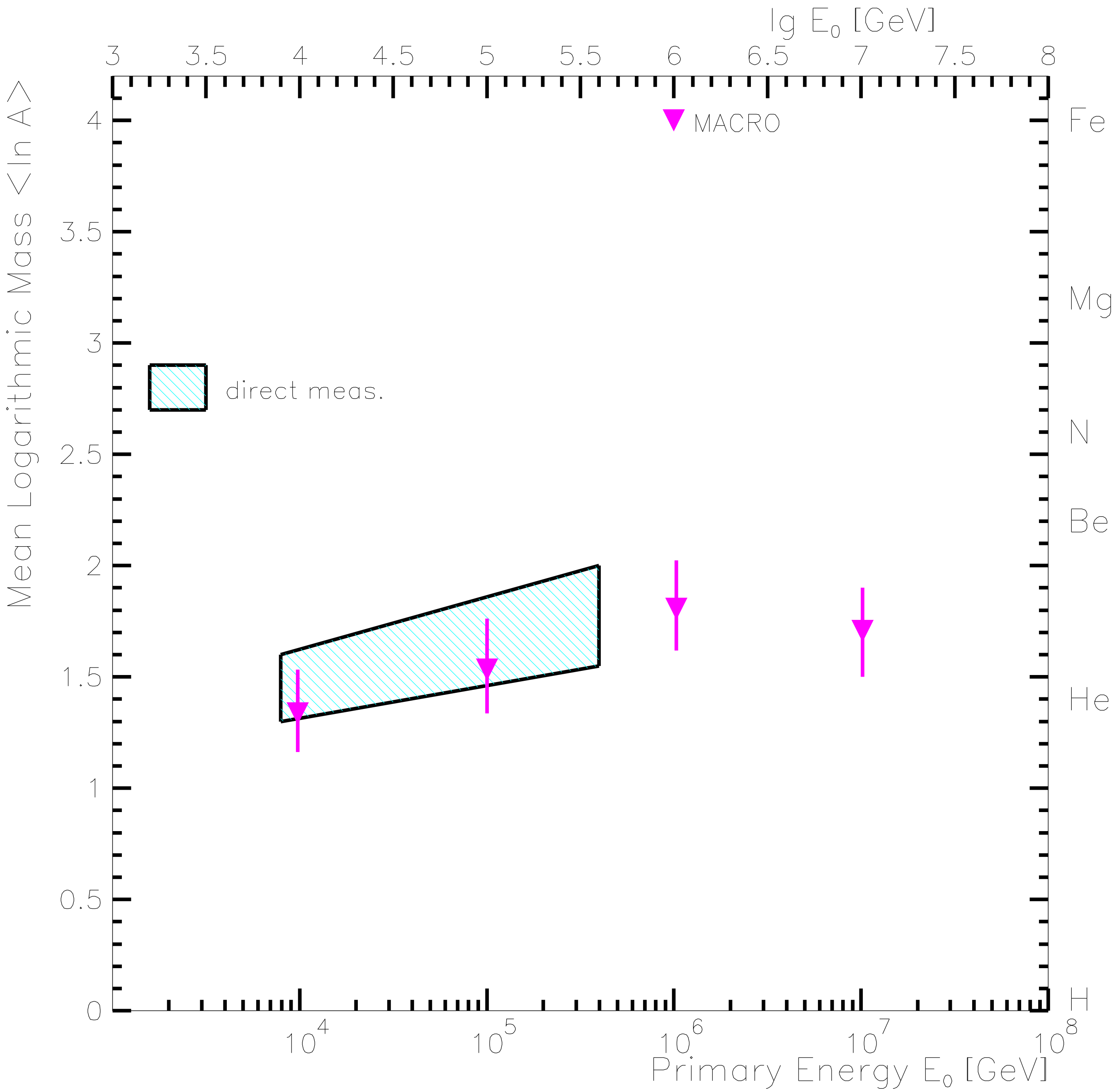
expectation: trend to heavier elements above the "knee"

speculation: physics change at the "knee"

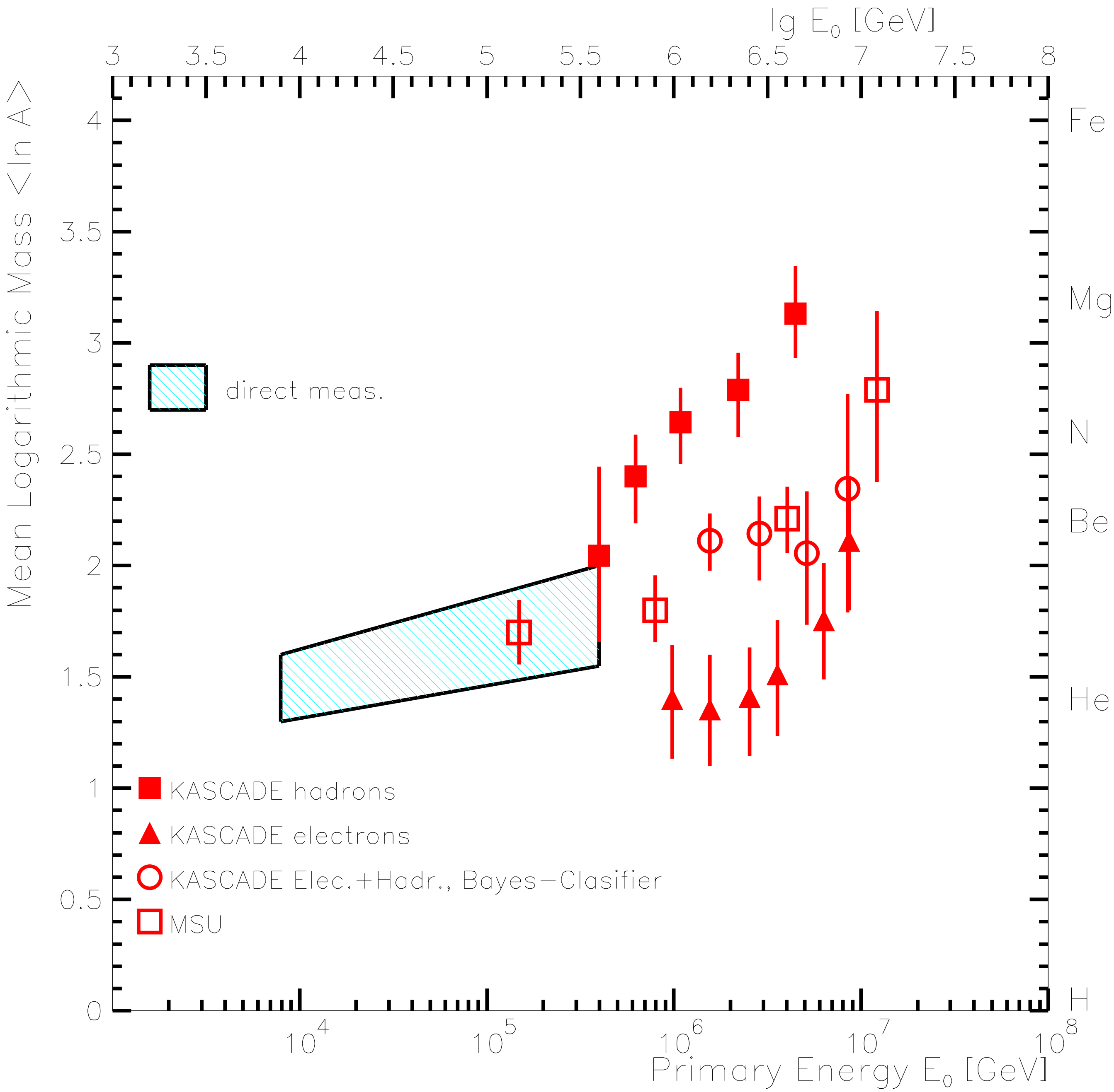
Composition for $E < 10^{14}$ eV is measured directly.
For $E \sim 10^{13}$-10^{14} eV:

p	He	O	Si	Fe
24%	31%	21%	12%	12%

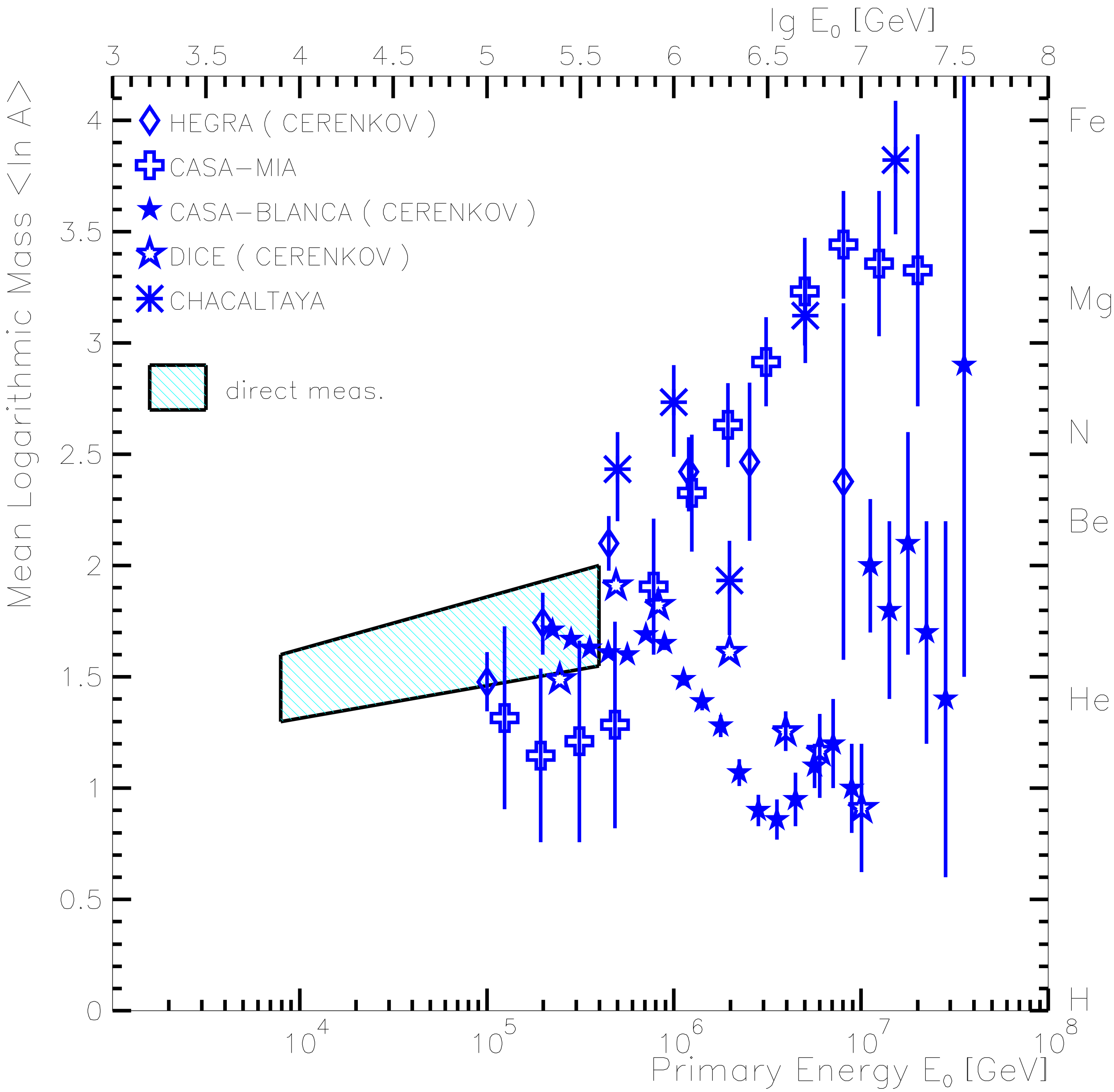
Particle Composition



Particle Composition



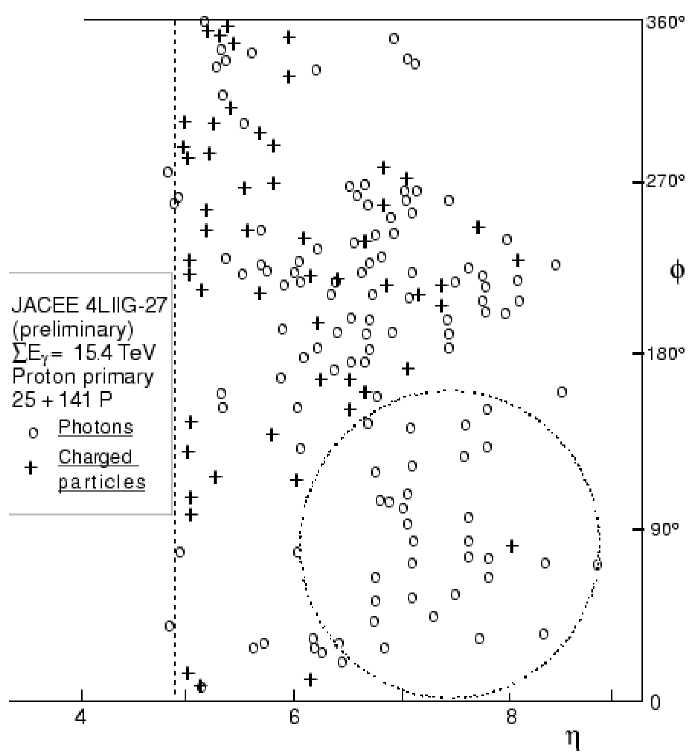
Particle Composition



Particle interactions

- Forward particle production in nucleon-nucleus and nucleus-nucleus at $\sqrt{s} \sim$ 2 - 20 TeV almost unknown
  Model dependence $\rightarrow$ chemical composition
- Anomalies have been frequently reported
  - Centauros and Anticentauros
  - coherent pion production : Disoriented Chiral Condensate (DCC)
  - abundant heavy flavour production
  - QGP

Important:
correlation between EM component (π^0)
and
muonic component ($\pi^{\pm}$)

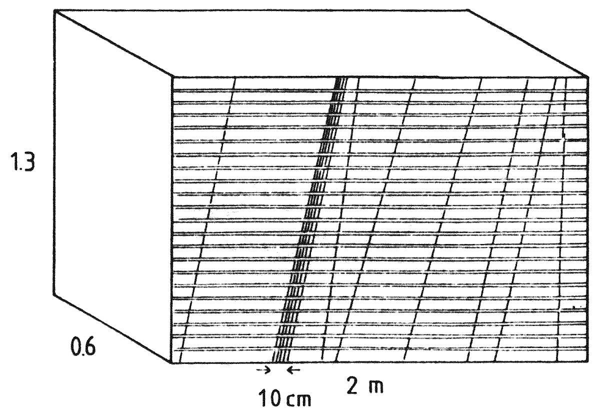


$$\eta = -\ln \tan \theta/2$$

Multi-muon bundles in cosmic rays

- Mt. Norikura (2770 m a.s.l.)
  5 muons within 10 cm with $E_\mu \gtrsim 50$ GeV (from "parallelness")

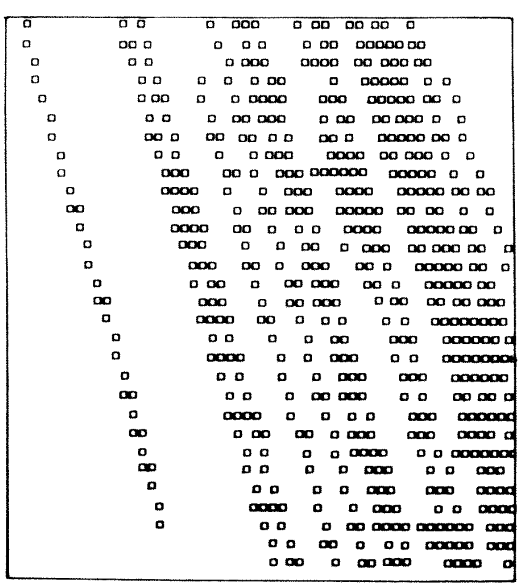
  (S. Miyake et al., J. Phys. Soc. Jpn., 18(1963)464)



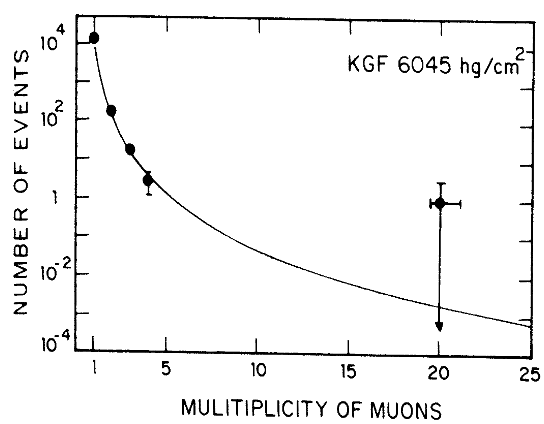
- Kolar Gold Field (6045 hg/cm^2)
  20 muons with $E_\mu \sim 10$ TeV

  (H. Adarkar et al., Phys. Lett. B, 267(1991)138)

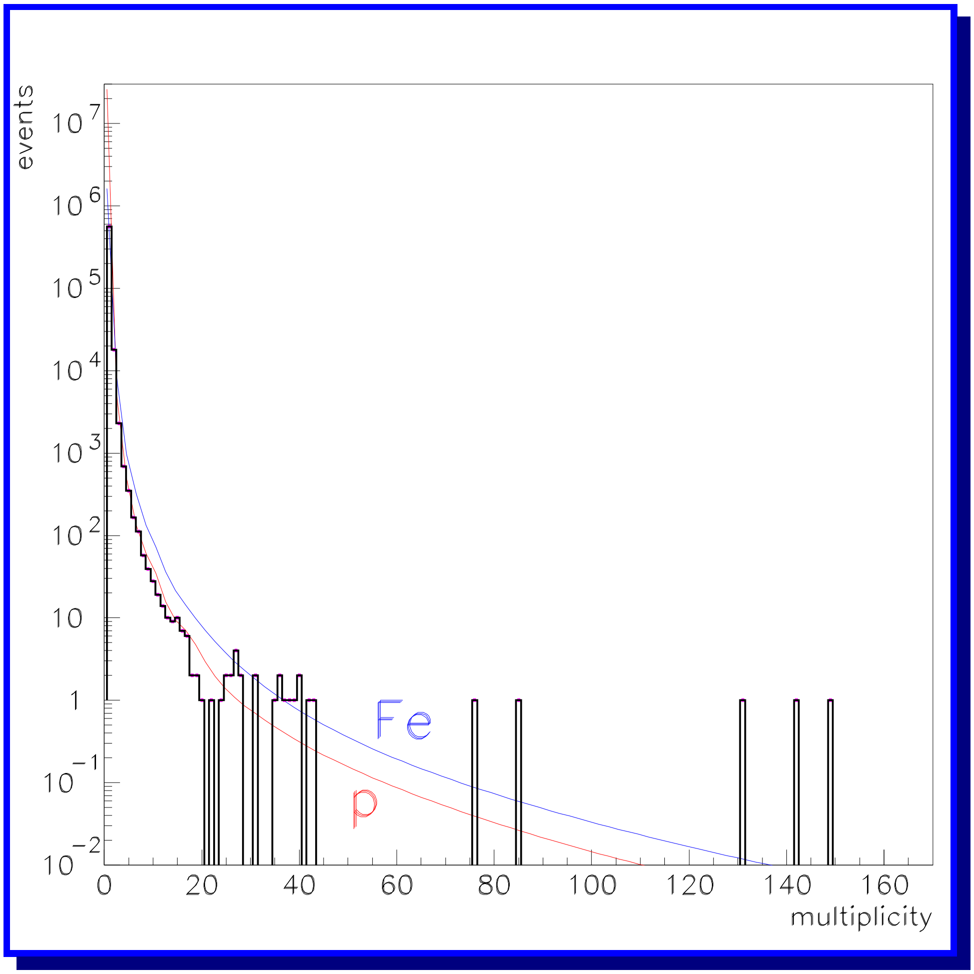
6.5 m



6 m



Muon multiplicity distribution (TPC)



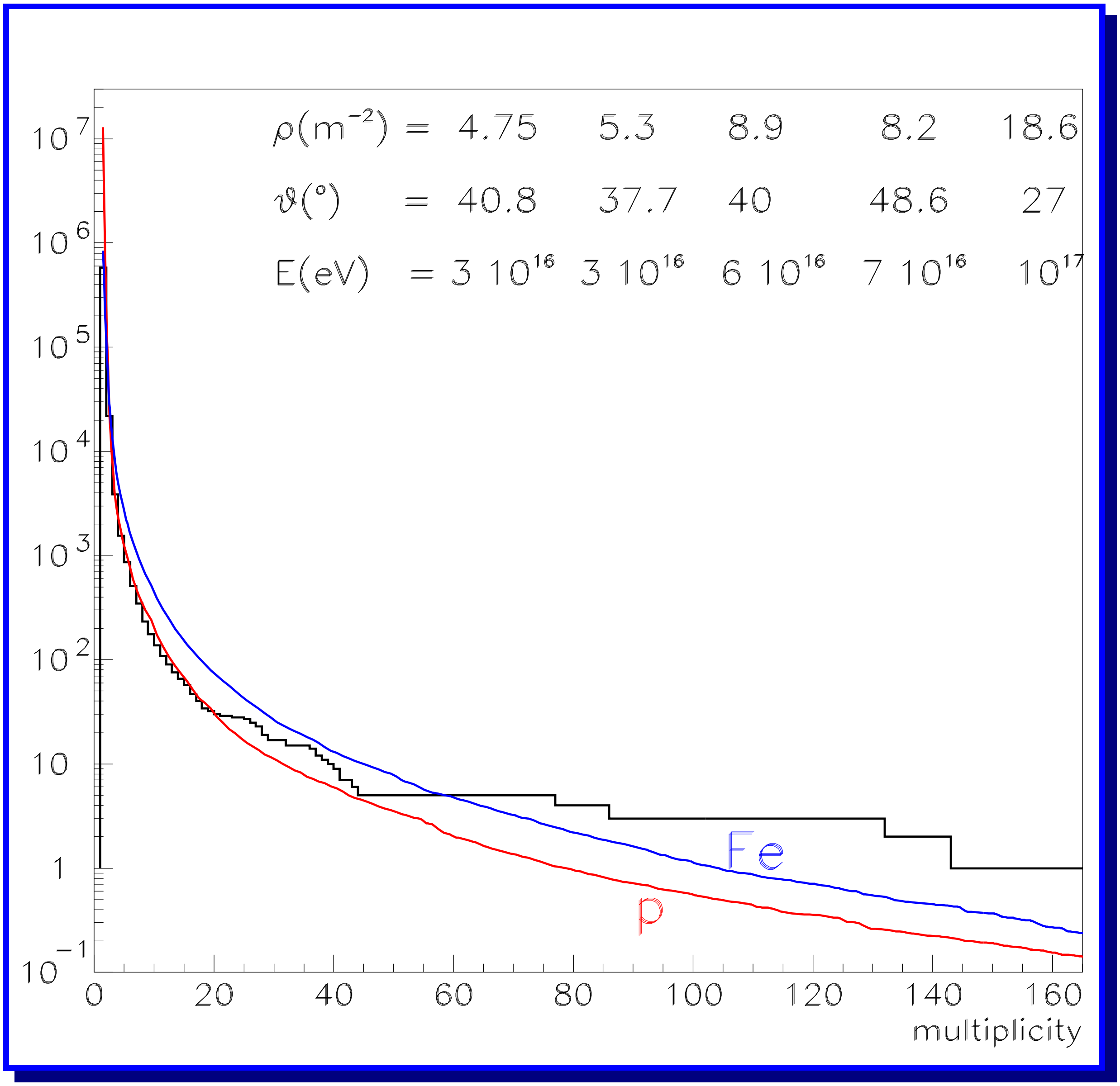
$$\int dt = 1.7 \cdot 10^6 \text{ sec}$$

Area TPC $=$ 16 m^2

almost independent of zenith angle

event	muon density (m^{-2})	zenith angle (^{o})	primary energy (eV)
97-a	4.75	40.8	$3 \cdot 10^{16}$
97-b	5.3	37.7	$3 \cdot 10^{16}$
97-c	8.9	40	$6 \cdot 10^{16}$
98-a	8.2	48.6	$7 \cdot 10^{16}$
98-b	18.6	27	10^{17}

Integral muon multiplicity distribution (TPC)



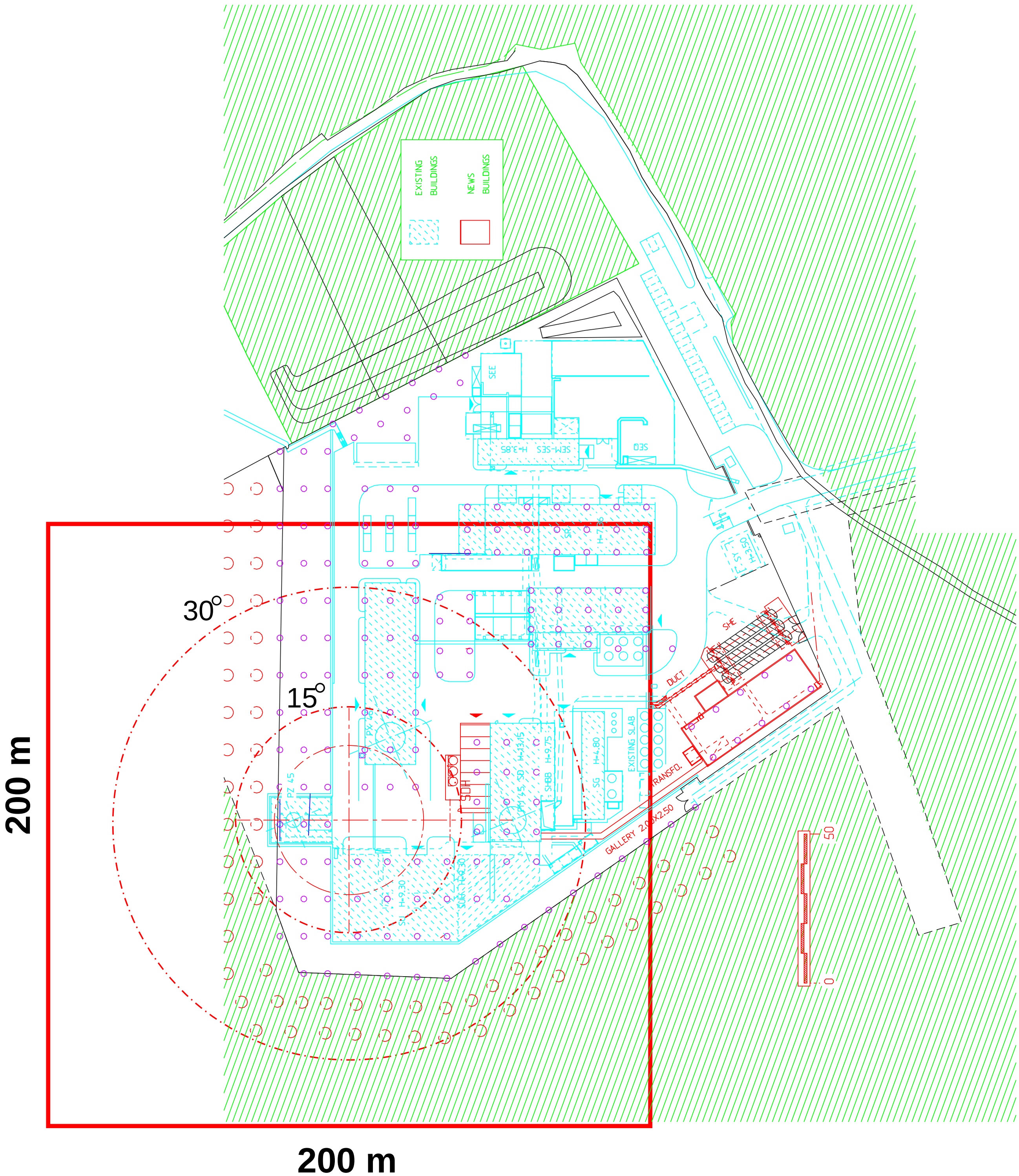
Data from the 1997/98/99 LEP runs

$\int dt = 1.7 \cdot 10^6 sec$

p,Fe curves form CORSIKA Monte Carlo.

The energy of the highest multiplicity events has been calculated assuming the shower center close to the TPC

Surface Array at PA4



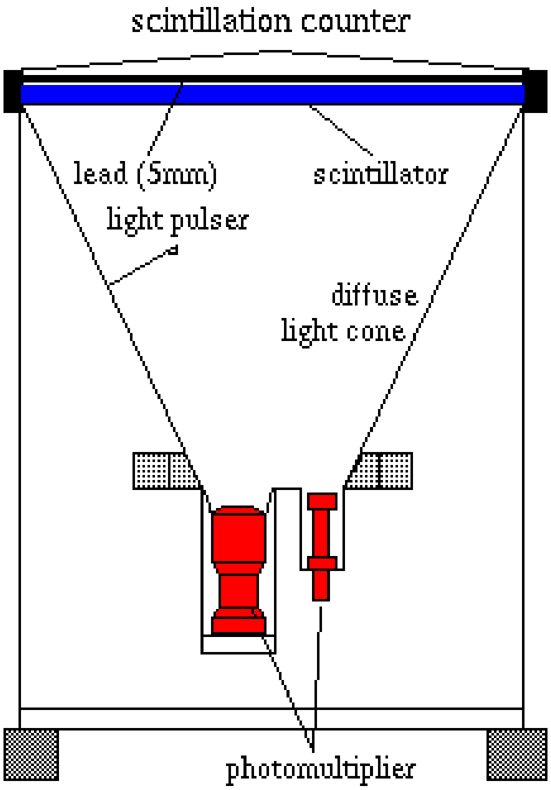
CERN AREA: 186 counters

EXTENDED ARRAY: 251 counters

Negotiations with farmers are positive

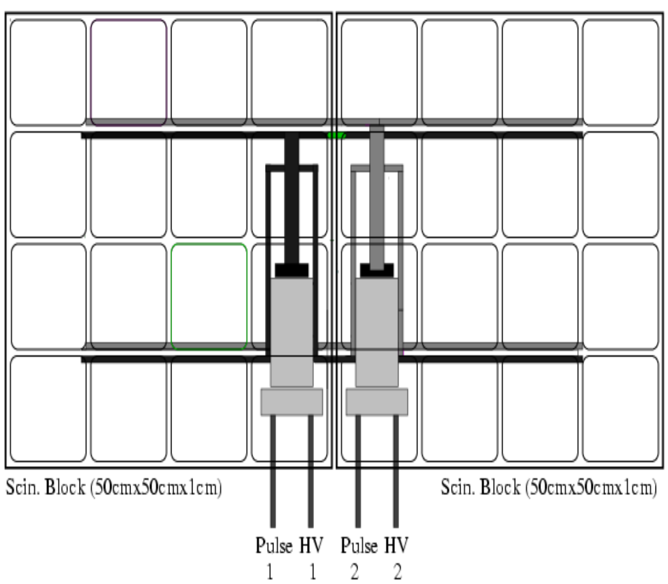
(ref.: Buhler - Broglin, Troendle)

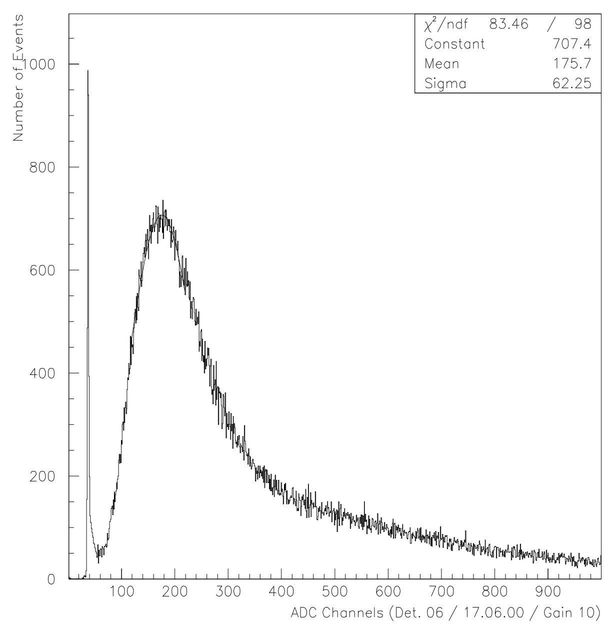
Surface array counters



- dynamical range: 10^4
  $\rightarrow$ 2 photomultipliers
- isotropic response
- excellent timing
  ($<$ 1 nsec)
- size : 0.5 - 1 m^2

HEGRA detectors

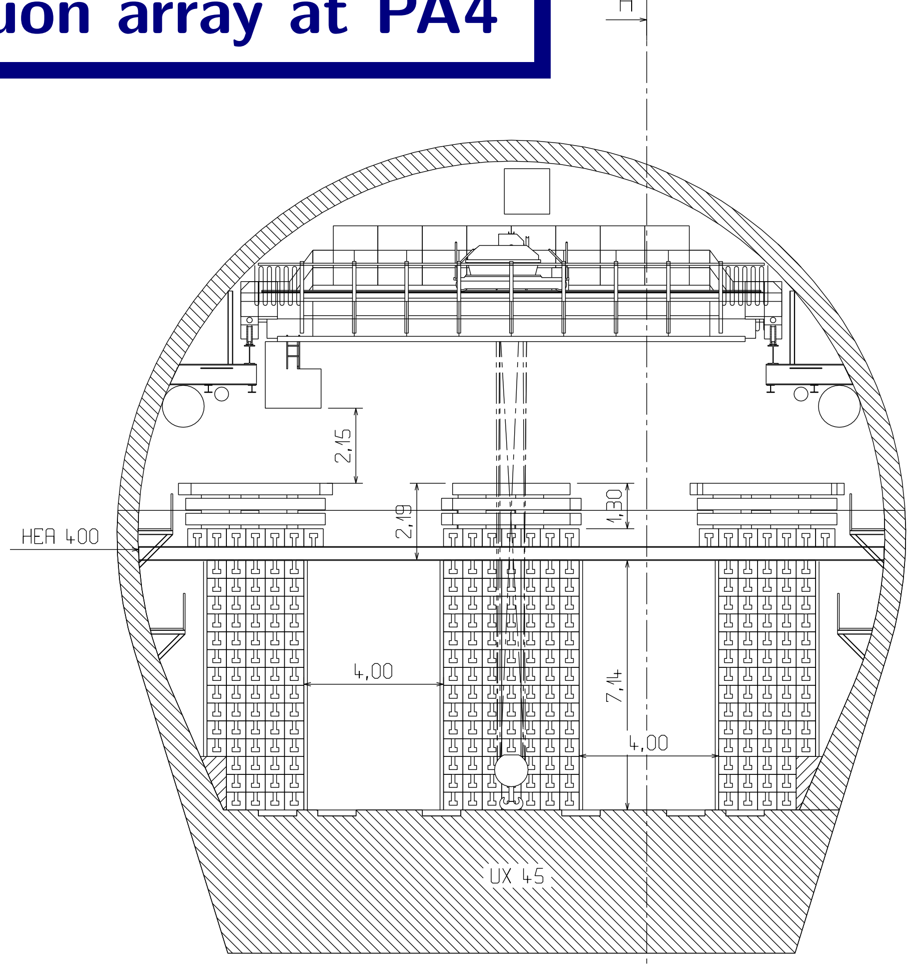


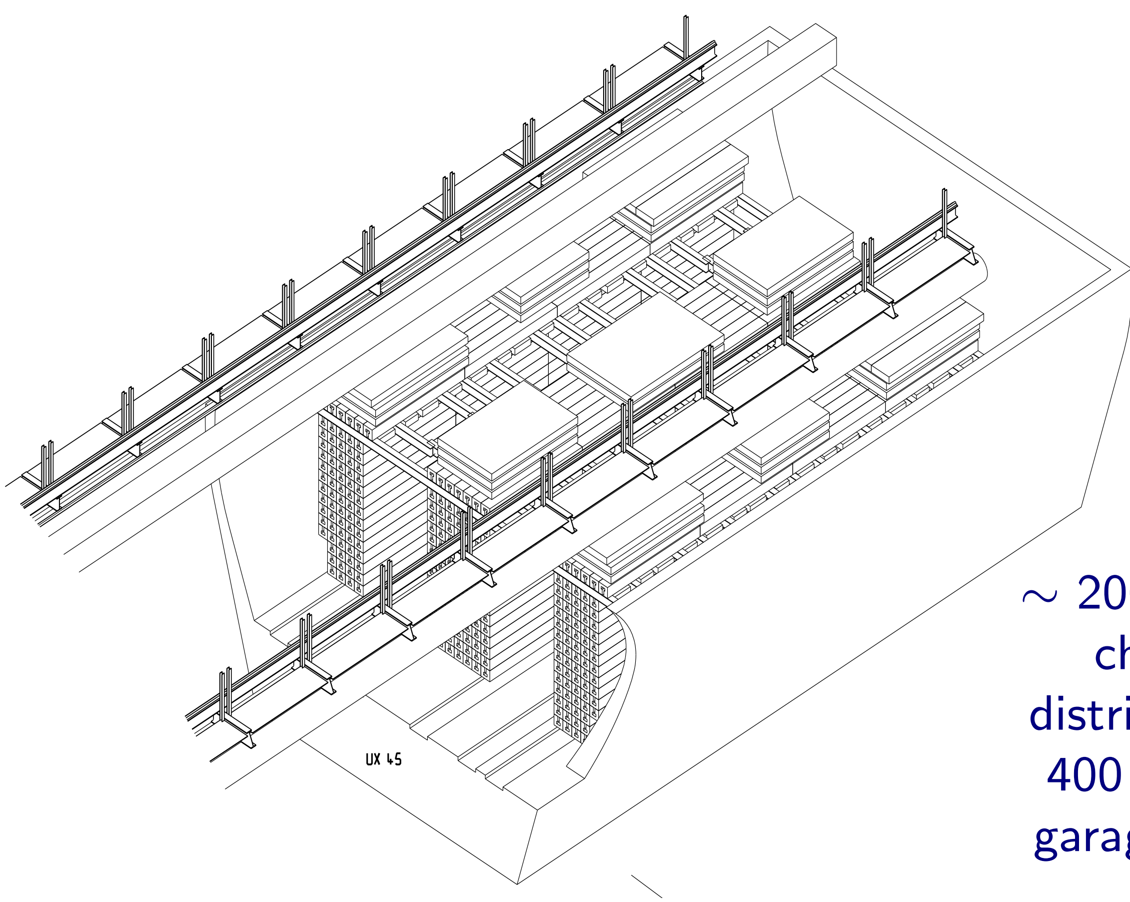


Indian counters

Underground muon array at PA4

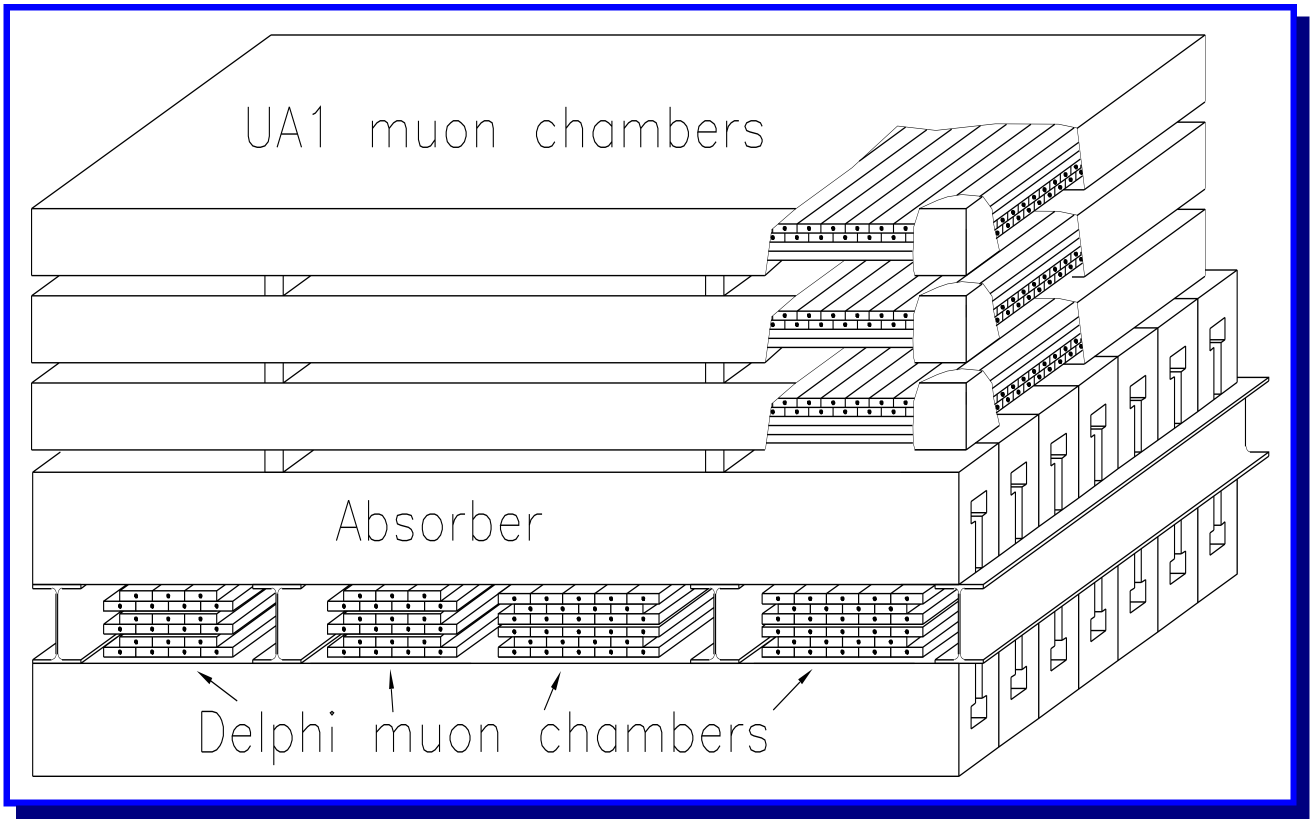
Platform 7 m height
(constructed from LEP
magnets)
leaving access
for LHC installations





$\sim$ 200 m^2 muon
chambers
distributed over
400 m^2 in the
garage position

Muon chamber module

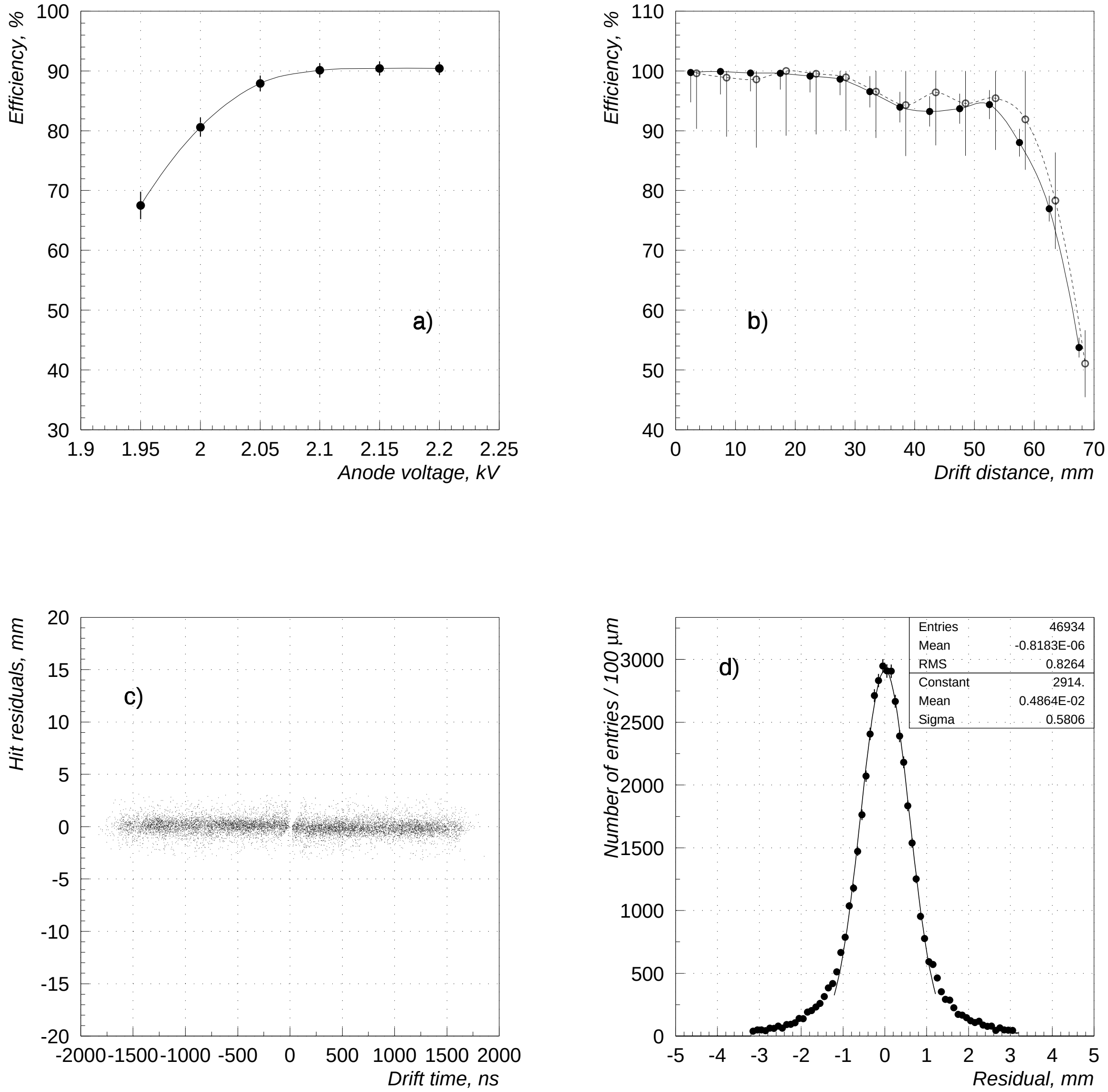


- 3 UA1 chambers with two planes/projection
- 3 DELPHI chambers with two planes in one projection
- Absorber (LEP magnets) with 200 g/cm^2
- $\sim$20% of the area is covered with trigger counters
- Trigger: n-fold coincidence

Test set-up in the UA2 underground area

- Operation of the chambers with a non-flammable gas
  90% Ar / 5% CO_2 / 5% CH_4
  good efficiencies and resolutions
- Reconstruction of multi-muon bundles
  max. reconstructed muon density
  $100\mu/$ 20 m^2
- Effect of an absorber between the chambers
  improved reconstruction efficiency

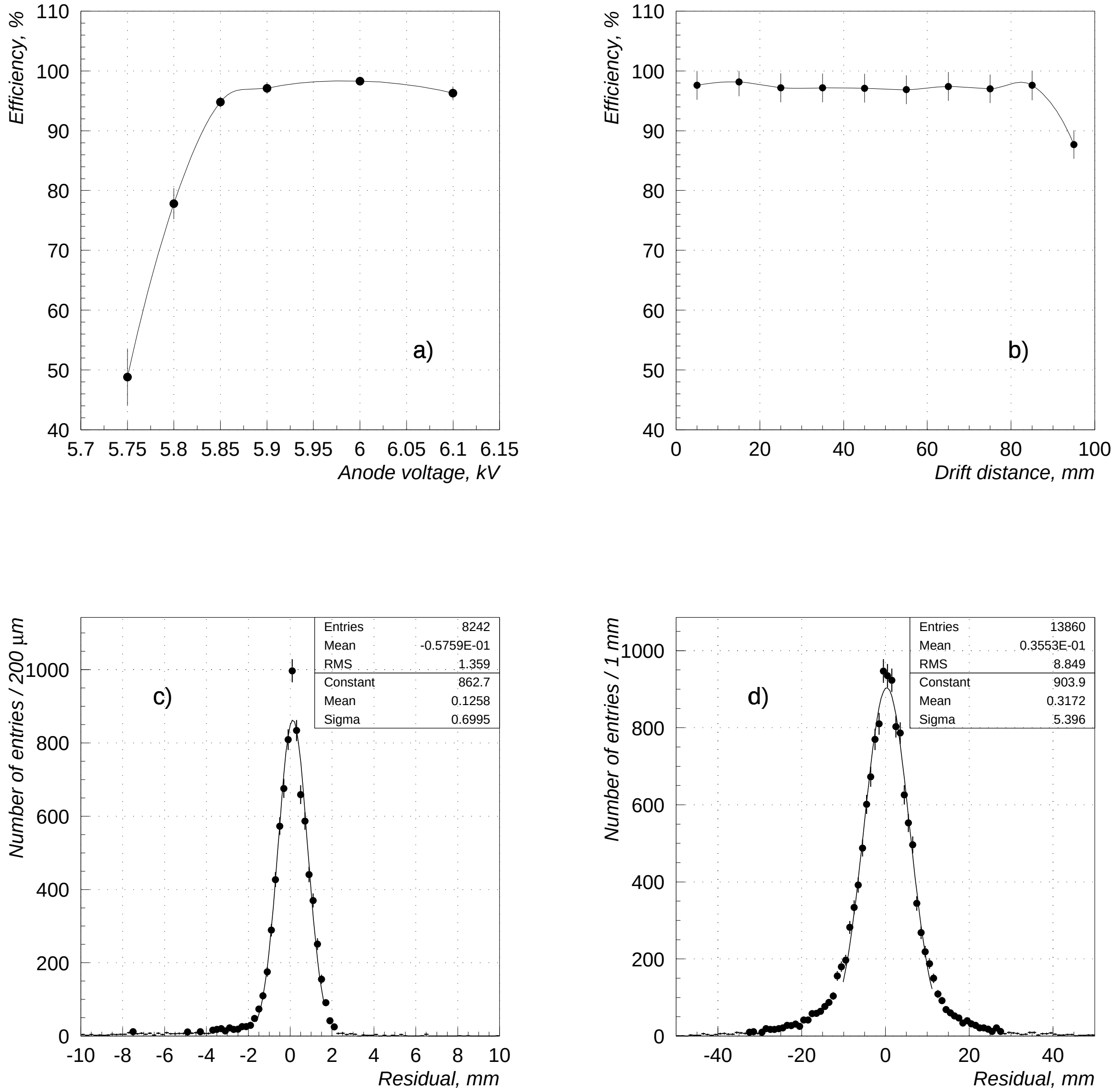
Calibration of UA1 muon chambers



resolution: $\sigma = 0.6$ mm

efficiency: 90% (including dead space)

Calibration of DELPHI muon chambers

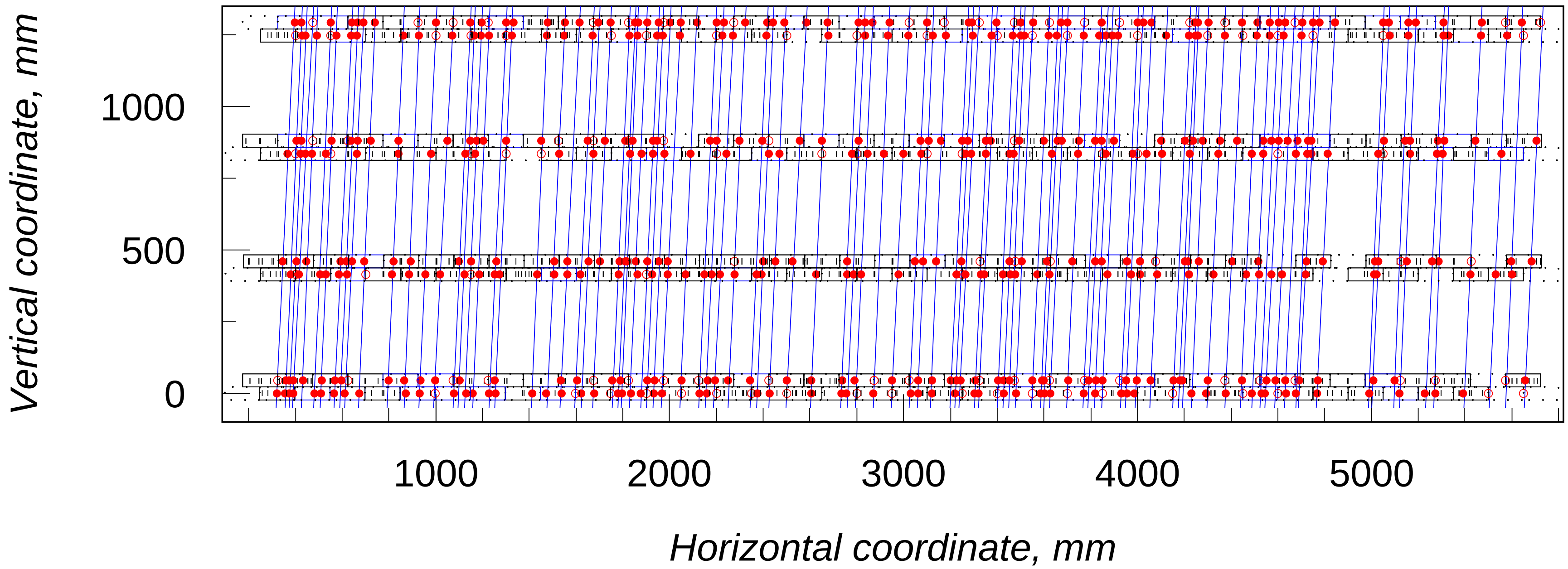


resolution: $\sigma = 0.7$ mm

$\sigma = 5.4$ mm (along the wire)

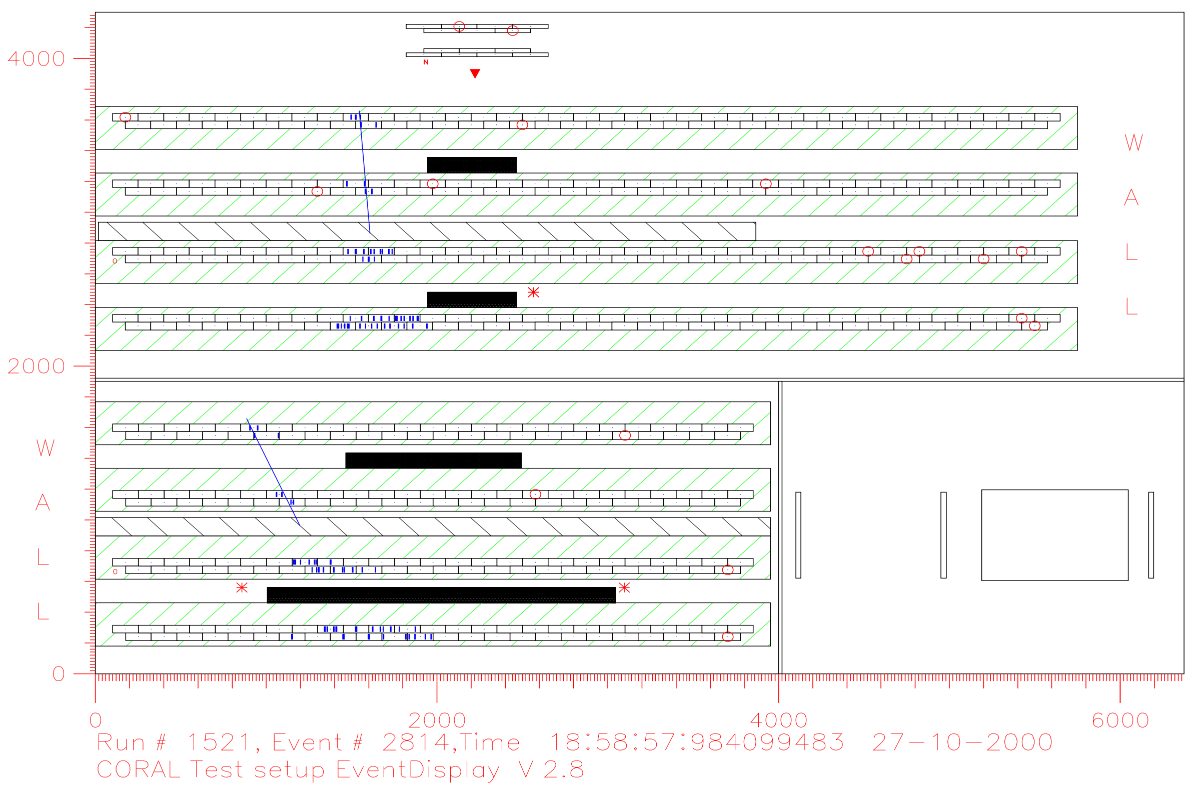
efficiency: 98%

100 reconstructed muon tracks out of 805 hits



Shower from the rock of the overburden

Shower in the absorber

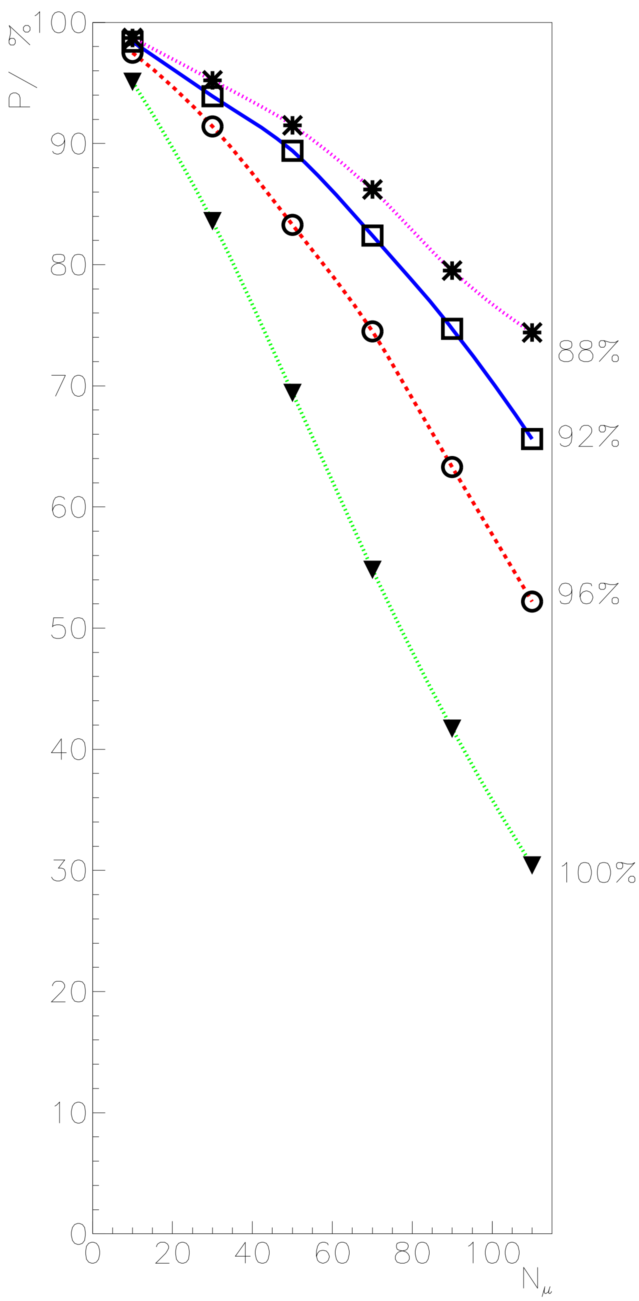


Reconstruction

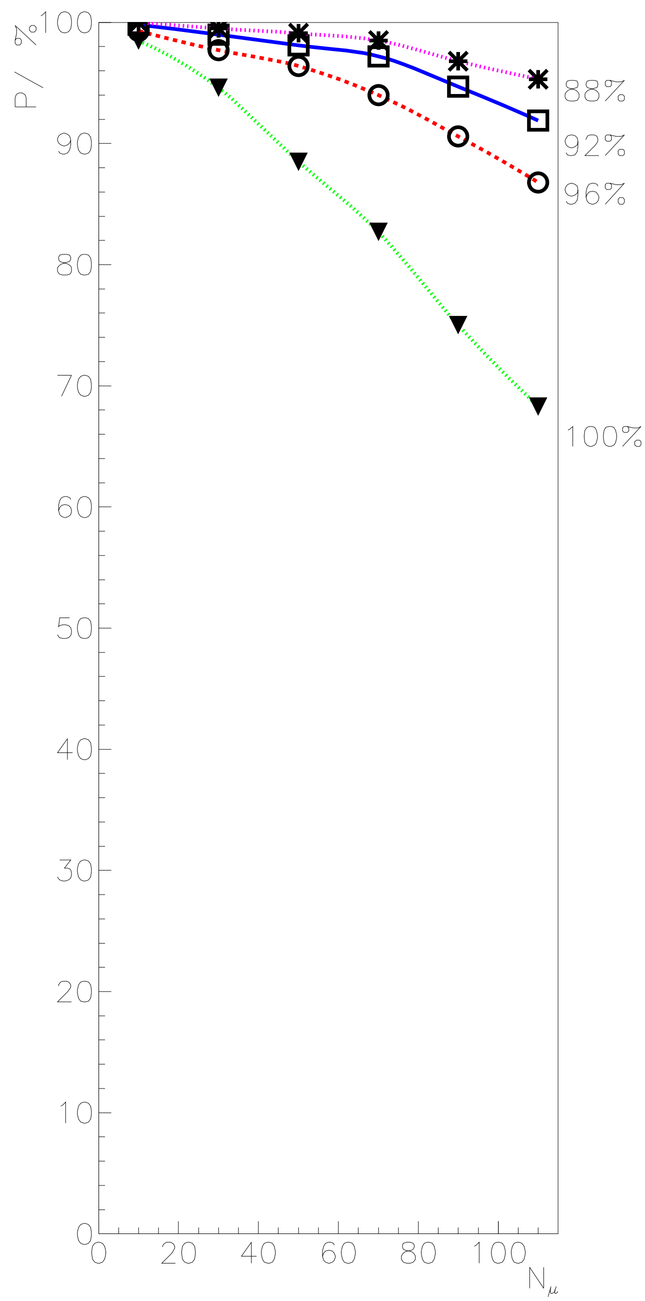
Probability for events with an effective area not obscured by muon interactions:

N_μ - number of muons in $24\,m^2$ module
absorber - $50\ cm$ of concrete - $\rho = 4\ g\,cm^{-3}$

without absorber:



with absorber:



Trigger

Underground : double layer of 0.2 x 4 m^2 counters
coverage : 20 - 40 % of chambers
Surface : all counters in the top array

Independent trigger for surface and underground:

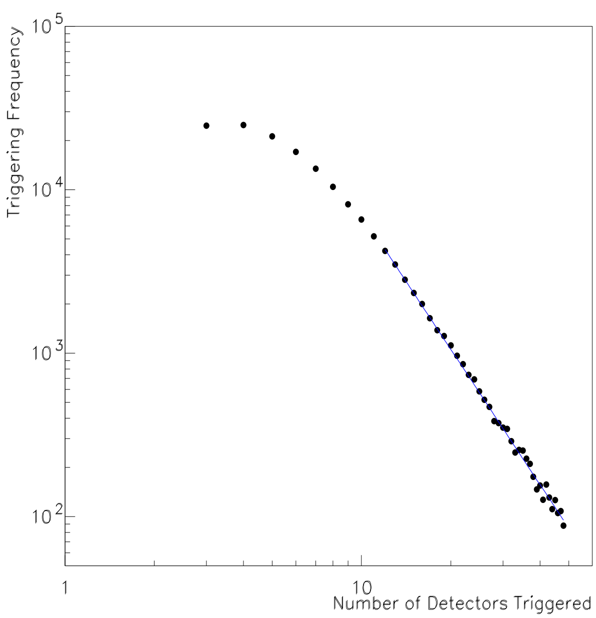
$\geq$ 4 counters (top)	**.OR.**	**$\geq$ 3 counters (under.)**
$\geq 10^{14}$ eV		**$\geq 5 \cdot 10^{14}$ eV**

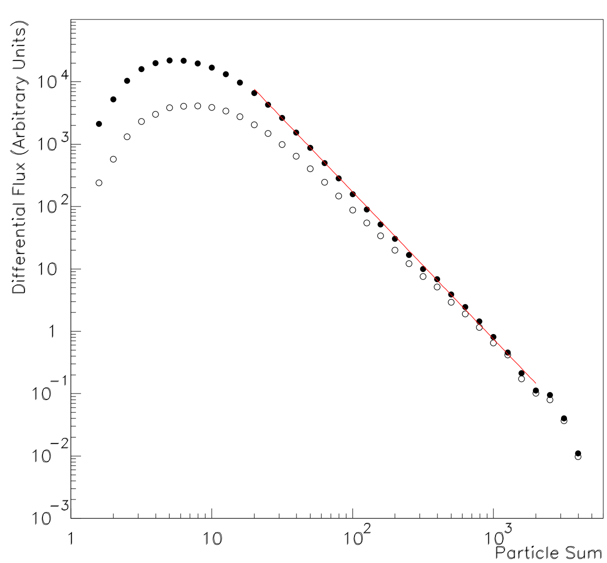
Rate $<$ 10 Hz

Minimum bias trigger sensitive to unforeseen topologies

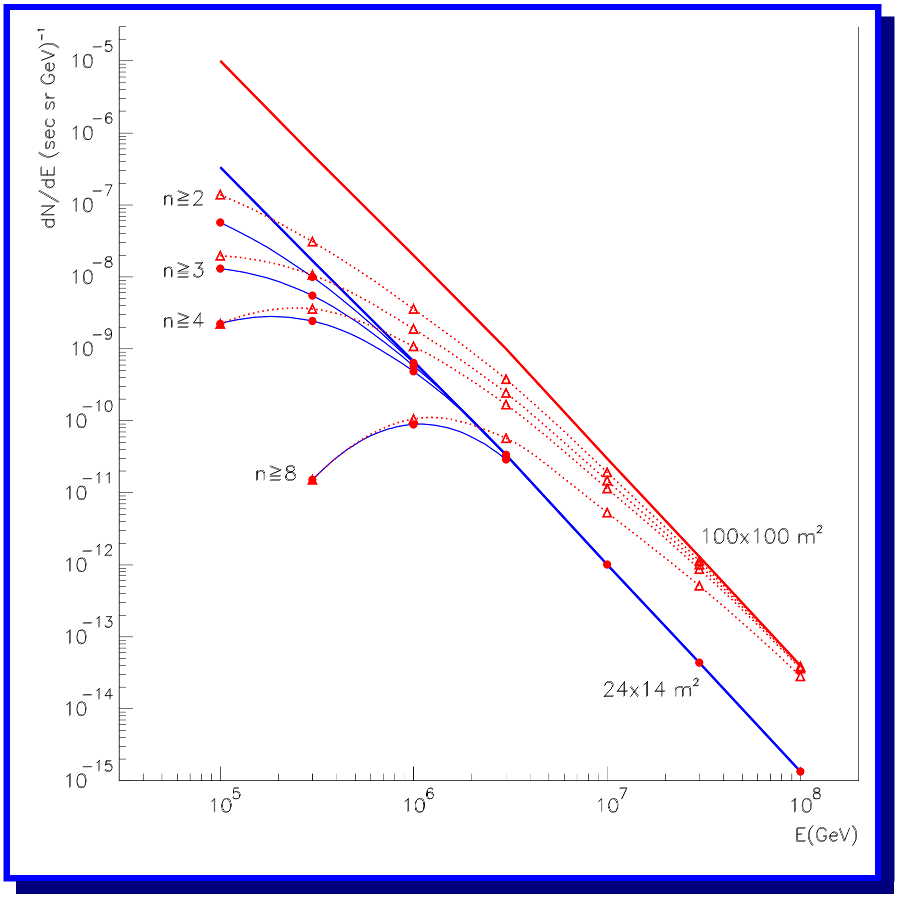
- EM shower + no muons
- muon bundles + no EM shower

Experience from L3C surface array:

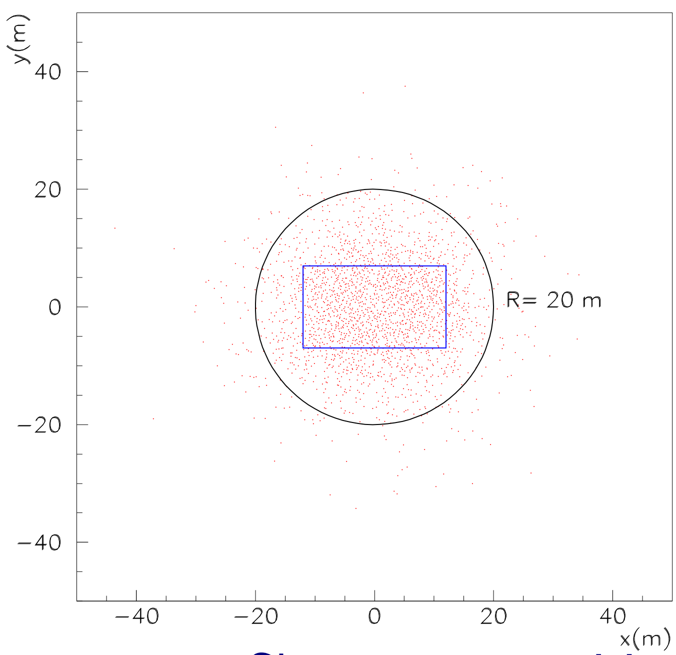




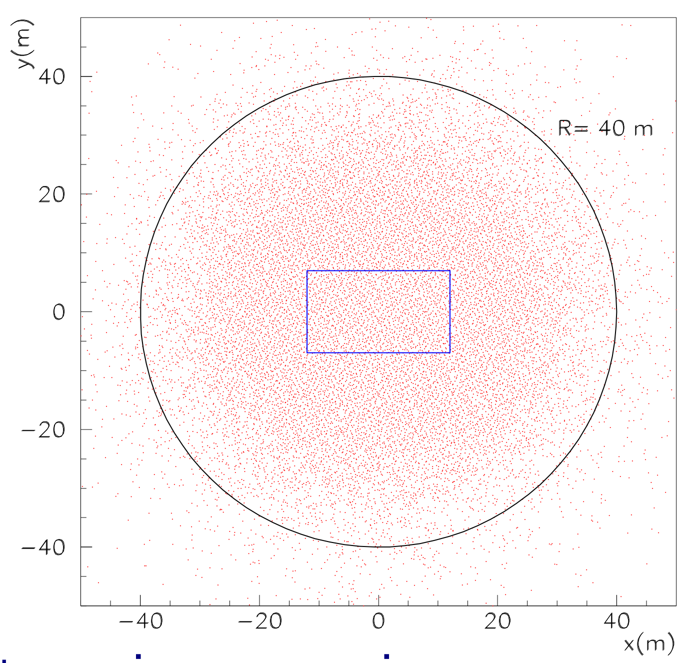
Effect of the n-fold coincidence trigger on the primary spectrum (protons) for two areas



E= 10^6 GeV



E= 10^7 GeV



Shower core positions for two primary energies

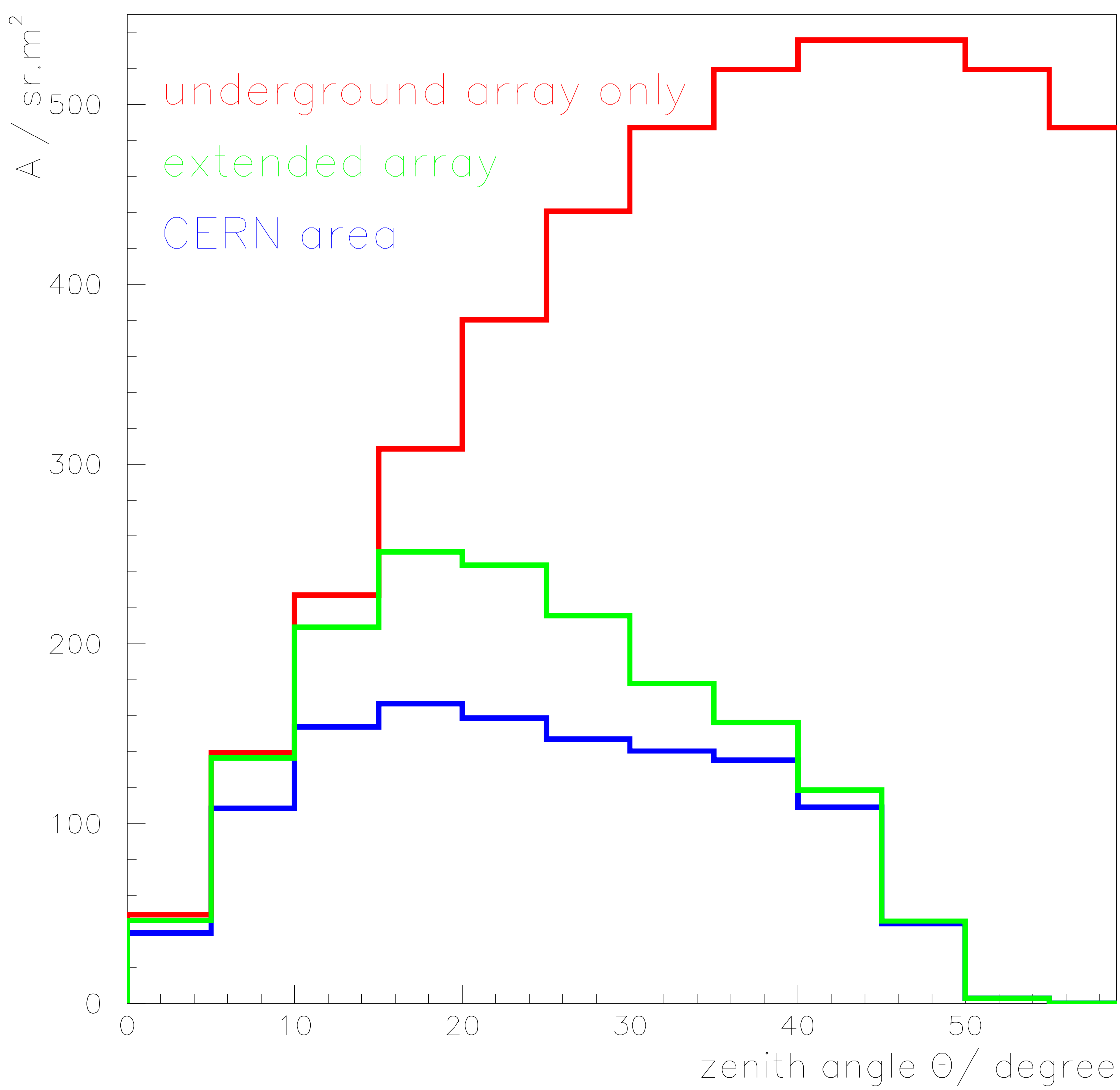
A 4-fold coincidence was required as a trigger

Geometrical Acceptance

A_μ: underground array alone

$A_{e,\mu}$: coincidence of surface and underground arrays

array:		extended	CERN
Θ	$A_\mu/sr\,m^2$	$A_{e,\mu}/sr\,m^2$	$A_{e,\mu}/sr\,m^2$
$0^o - 15^o$	413.2	391.7	301.2
$15^o - 30^o$	1129.0	710.5	472.3
$30^o - 45^o$	1542.2	452.5	384.8

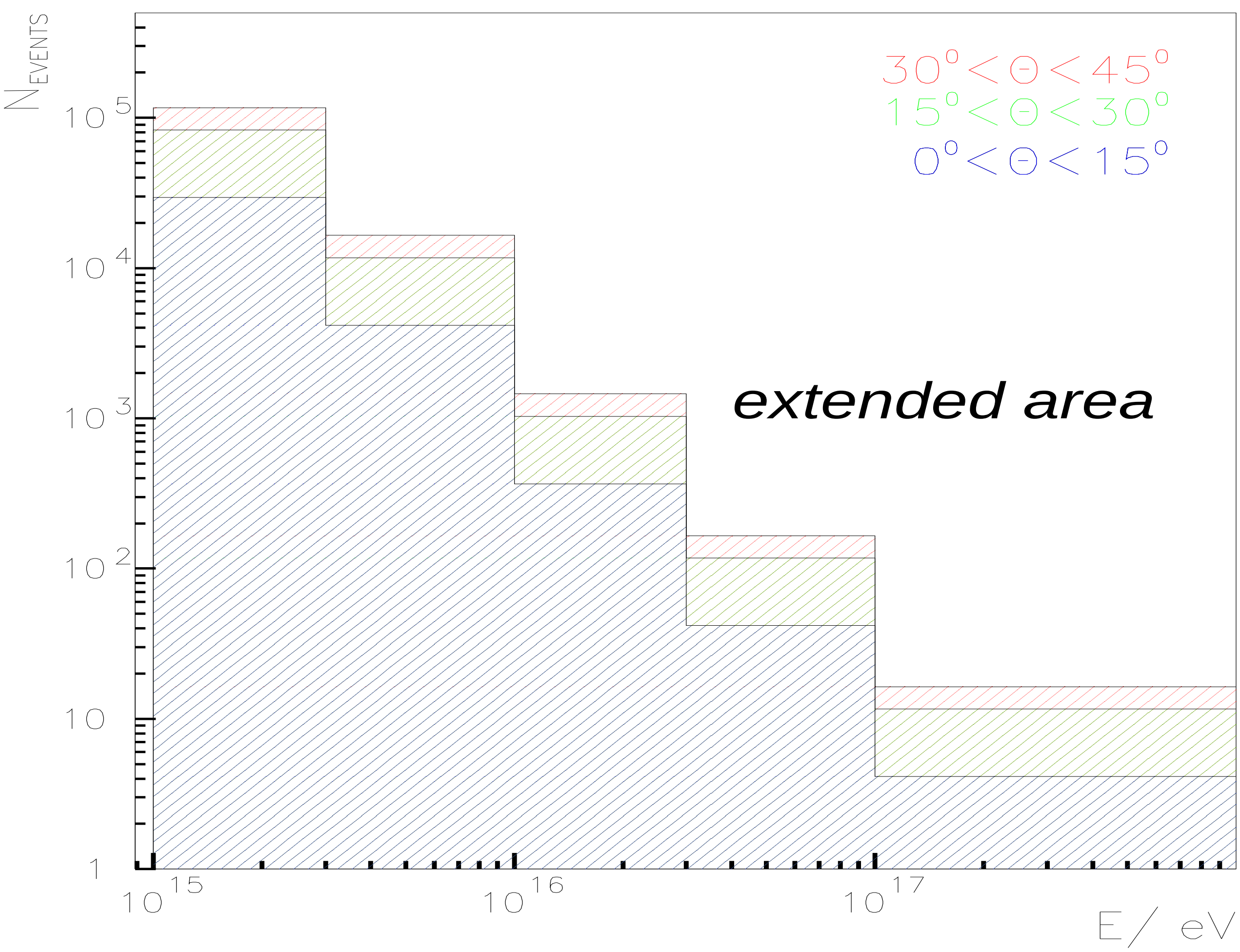


Expected Statistic

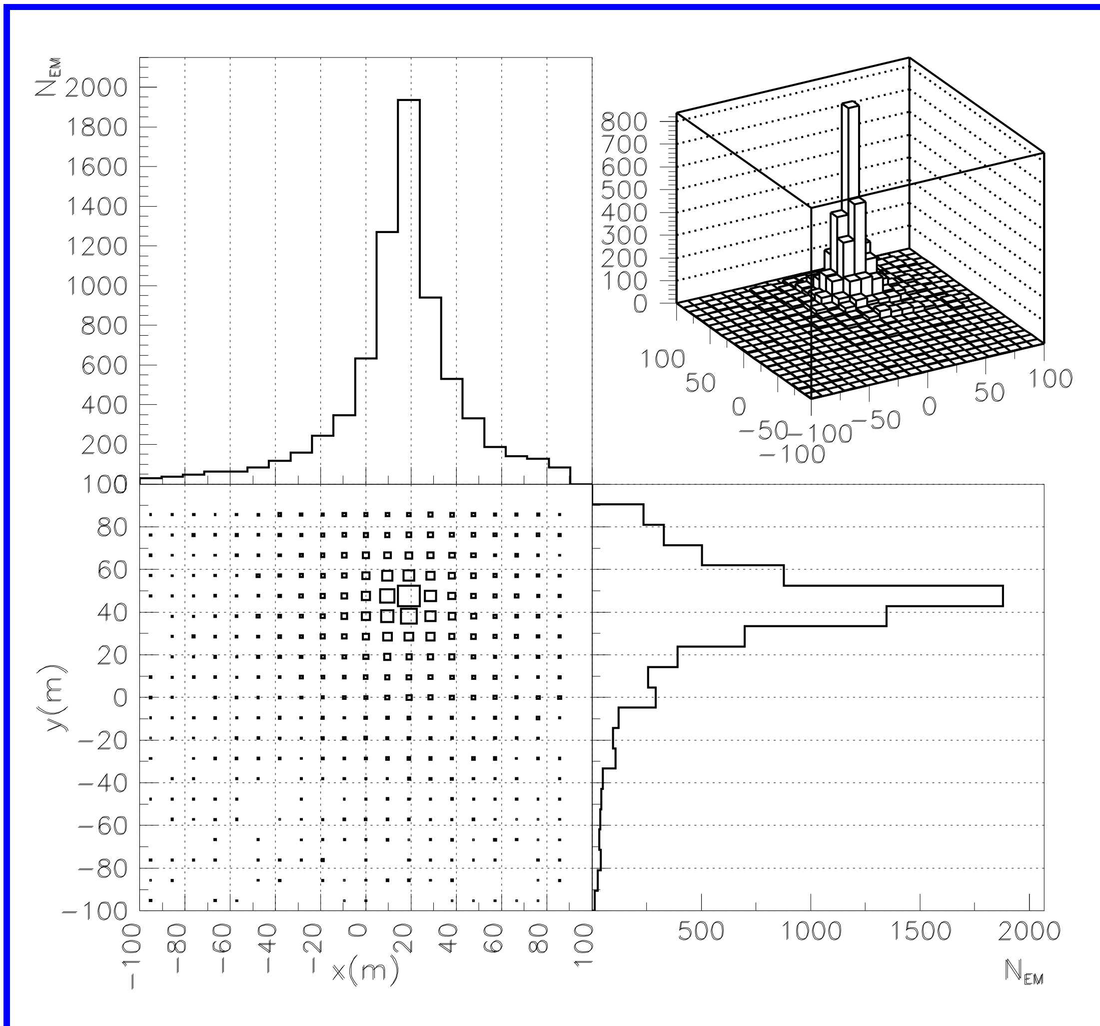
in $6 \cdot 10^7\ sec$ ($\sim$ 3 years of running)

coincidence of surface and underground arrays

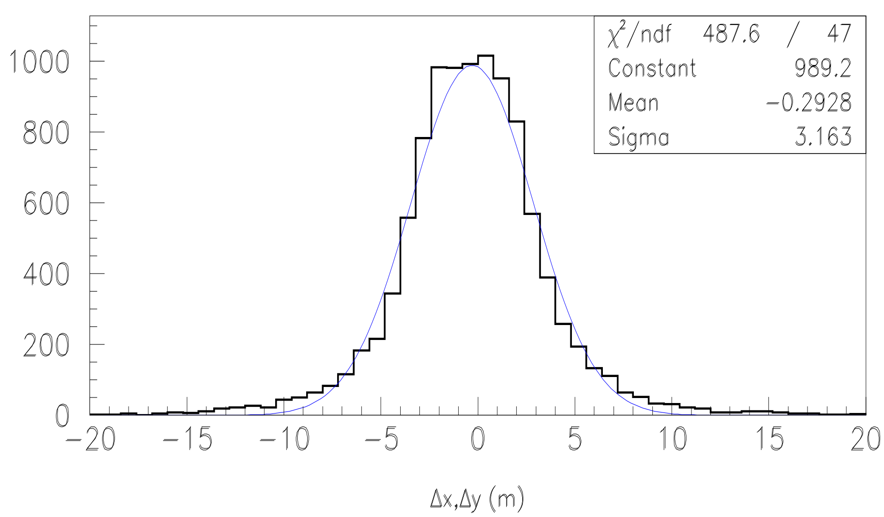
$E[eV] \downarrow / \Theta \rightarrow$	$0^o - 15^o$	$15^o - 30^o$	$30^o - 45^o$
$> 1 \cdot 10^{15}$	34100	61800	39400
$> 3 \cdot 10^{15}$	4580	8310	5290
$> 1 \cdot 10^{16}$	410	750	480
$> 3 \cdot 10^{16}$	46	84	53
$> 1 \cdot 10^{17}$	4	8	5



Location of the shower core in the top array



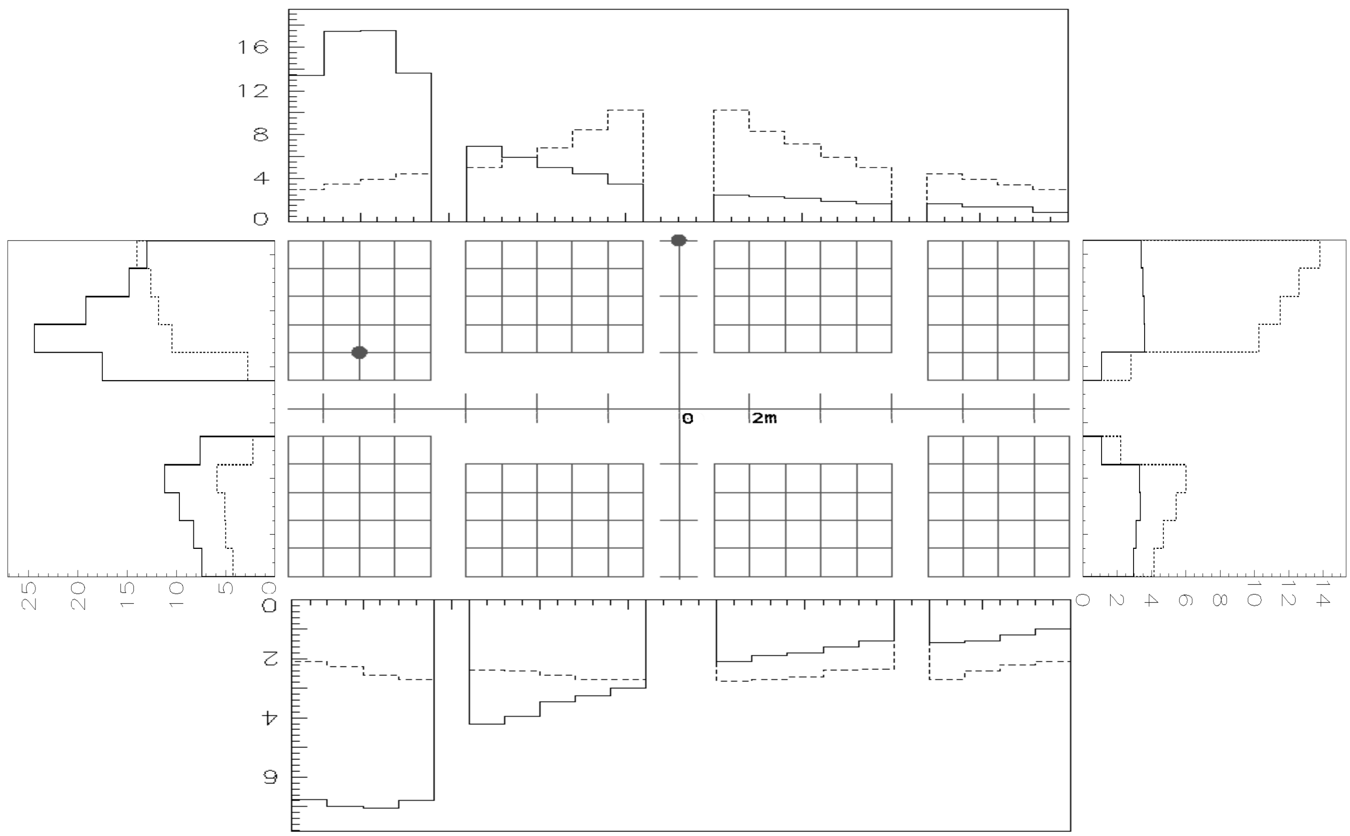
$\sigma \sim 3m$



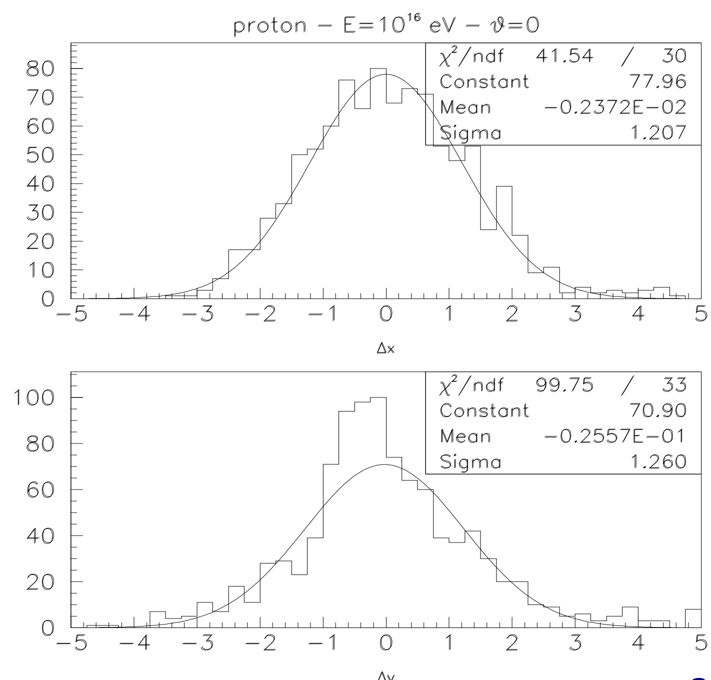
Reconstruction of muon bundle core

Muon shower profile for two core positions

(protons, E=10^{16} eV)

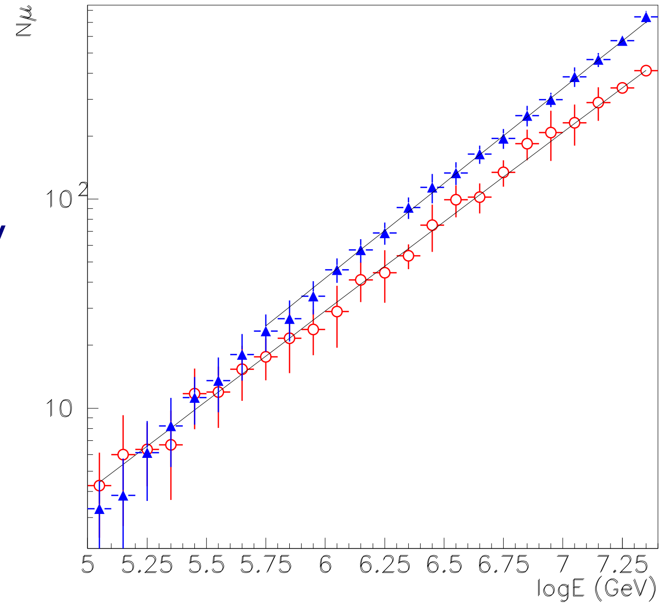


$\sigma_{core} \sim 1.2$ m
(E=10^{16} eV)

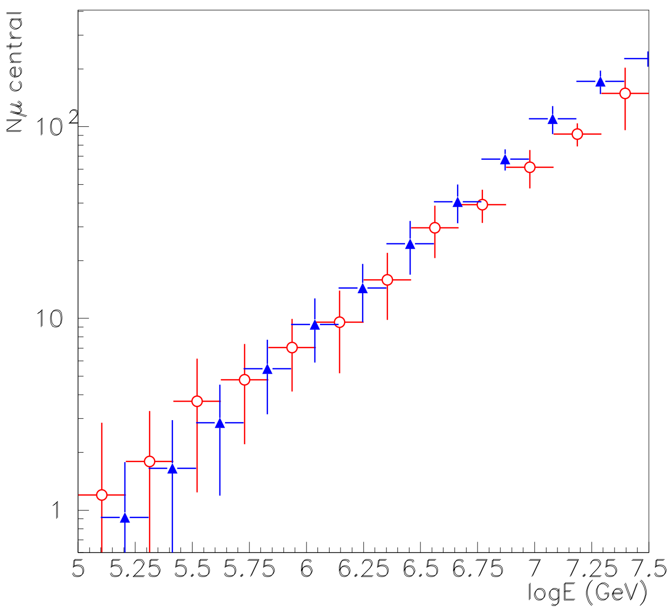


Energy determination

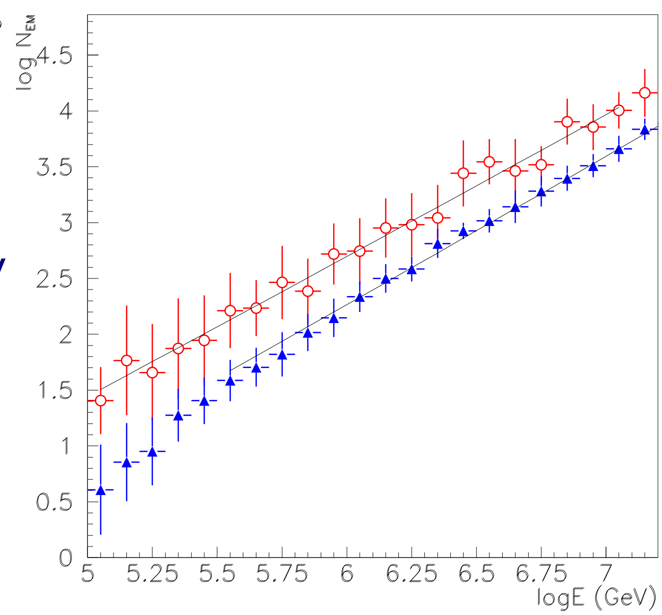
$\theta < 15^\circ$ ○ p △ Fe



Muon number in the total array
$\sigma(E)/E$ (p) $\sim$ 30% at 10^{15} eV
$\sigma(E)/E$ (Fe) $\sim$ 20%



Muon number in the core (central chamber)
Calibration almost independent of primary particle



Electron number for R$<$ 50 m

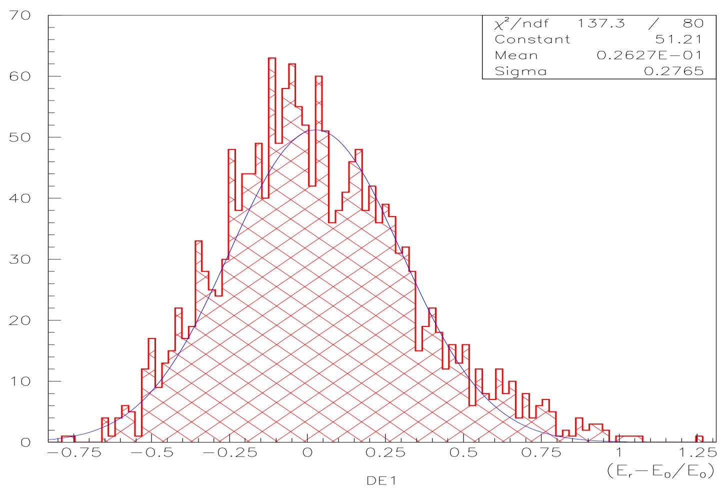
$\sigma(E)/E$ (p) $\sim$ 40% at 10^{15} eV
$\sigma(E)/E$ (Fe) $\sim$ 30%

Strong dependence on primary particle

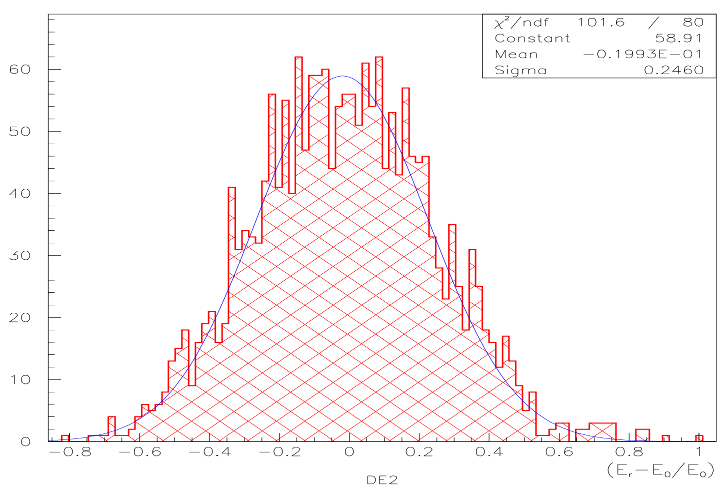
Energy determination is best via muons
Primary particle determination via e-μ combination

Energy resolution from muons

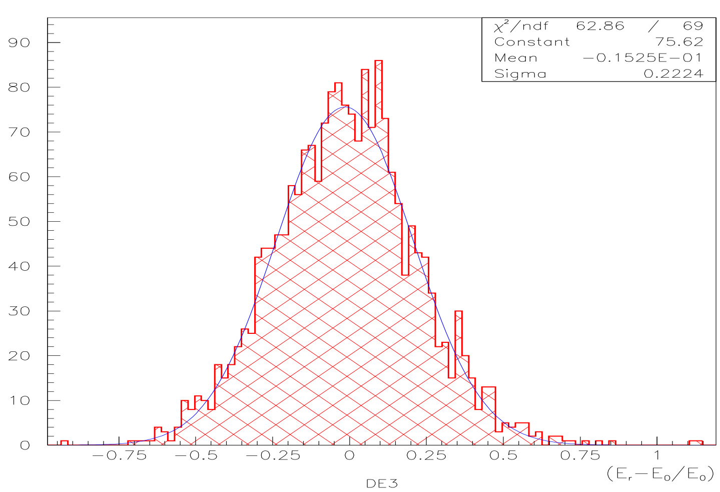
$10^{15} < E < 3 \cdot 10^{15}$ eV



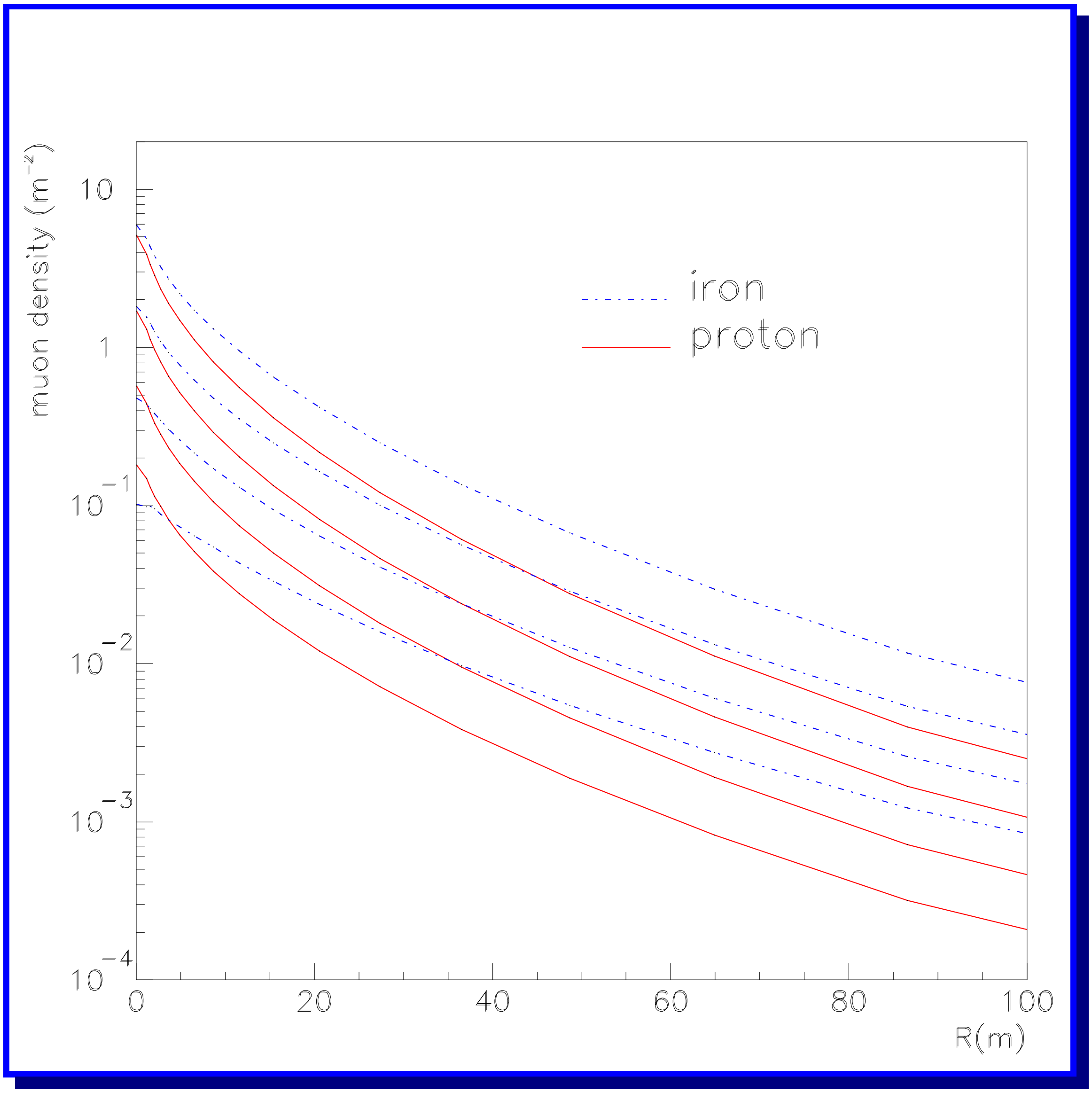
$3 \cdot 10^{15} < E < 10^{16}$ eV



$10^{16} < E < 3 \cdot 10^{16}$ eV



Muon lateral distribution



E$=3 \cdot 10^{14}, 10^{15}, 3 \cdot 10^{15}, 10^{16}$ eV

The distribution is flatter for Fe-induced muon bundles with almost the same density in the center.

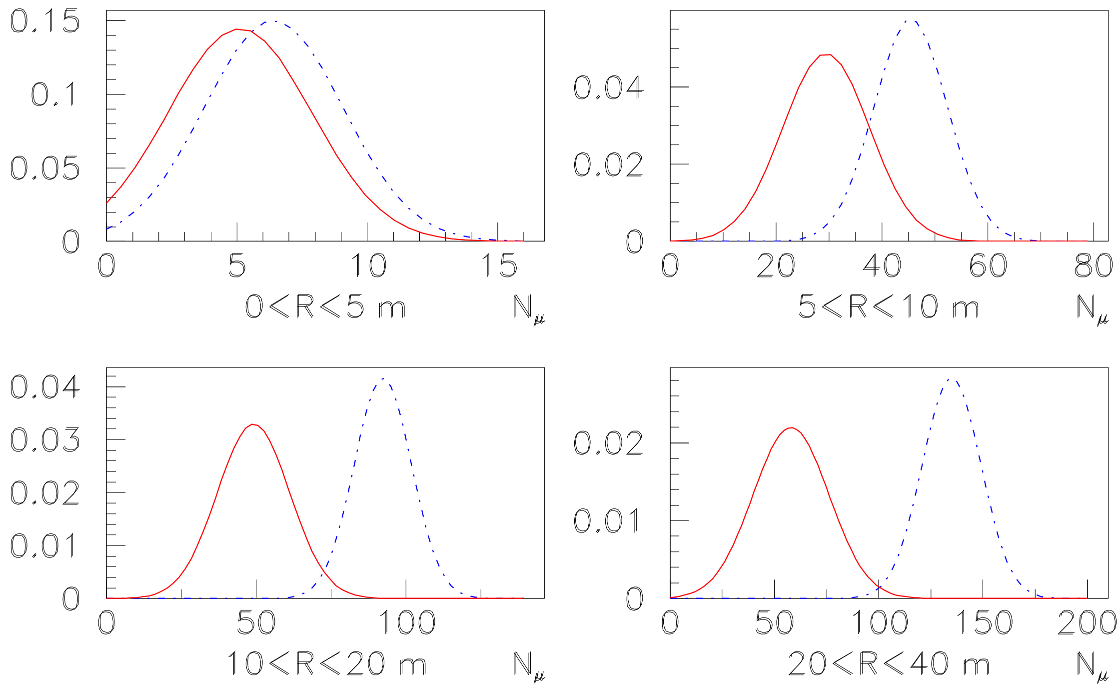
key: to separate p from Fe

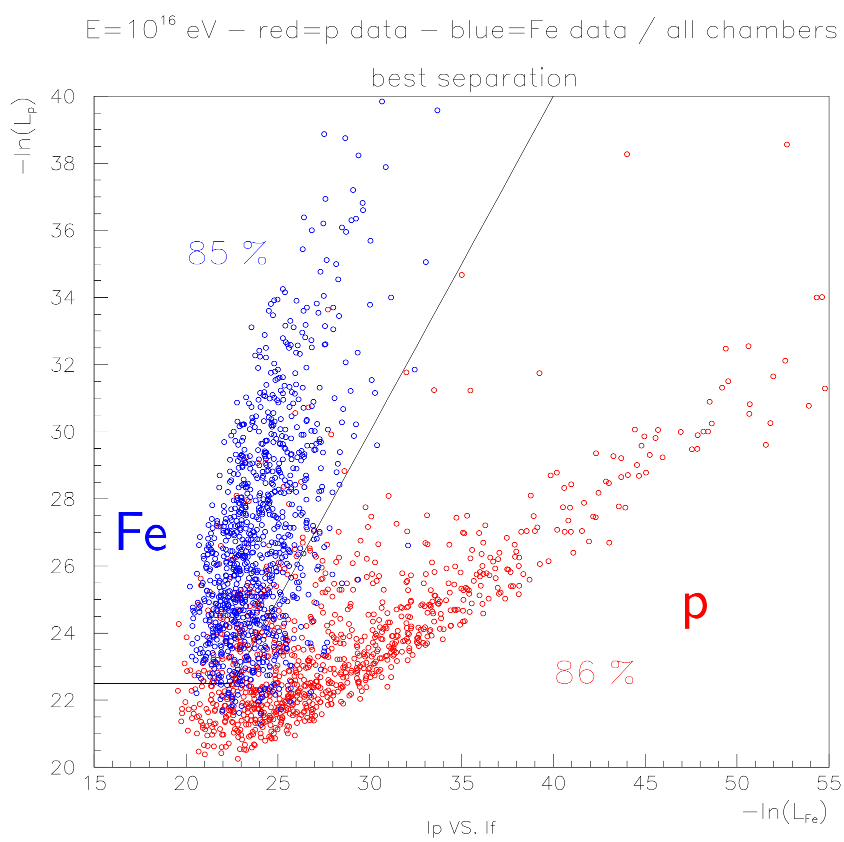
p - Fe separation with muons alone

—— p

- - - Fe

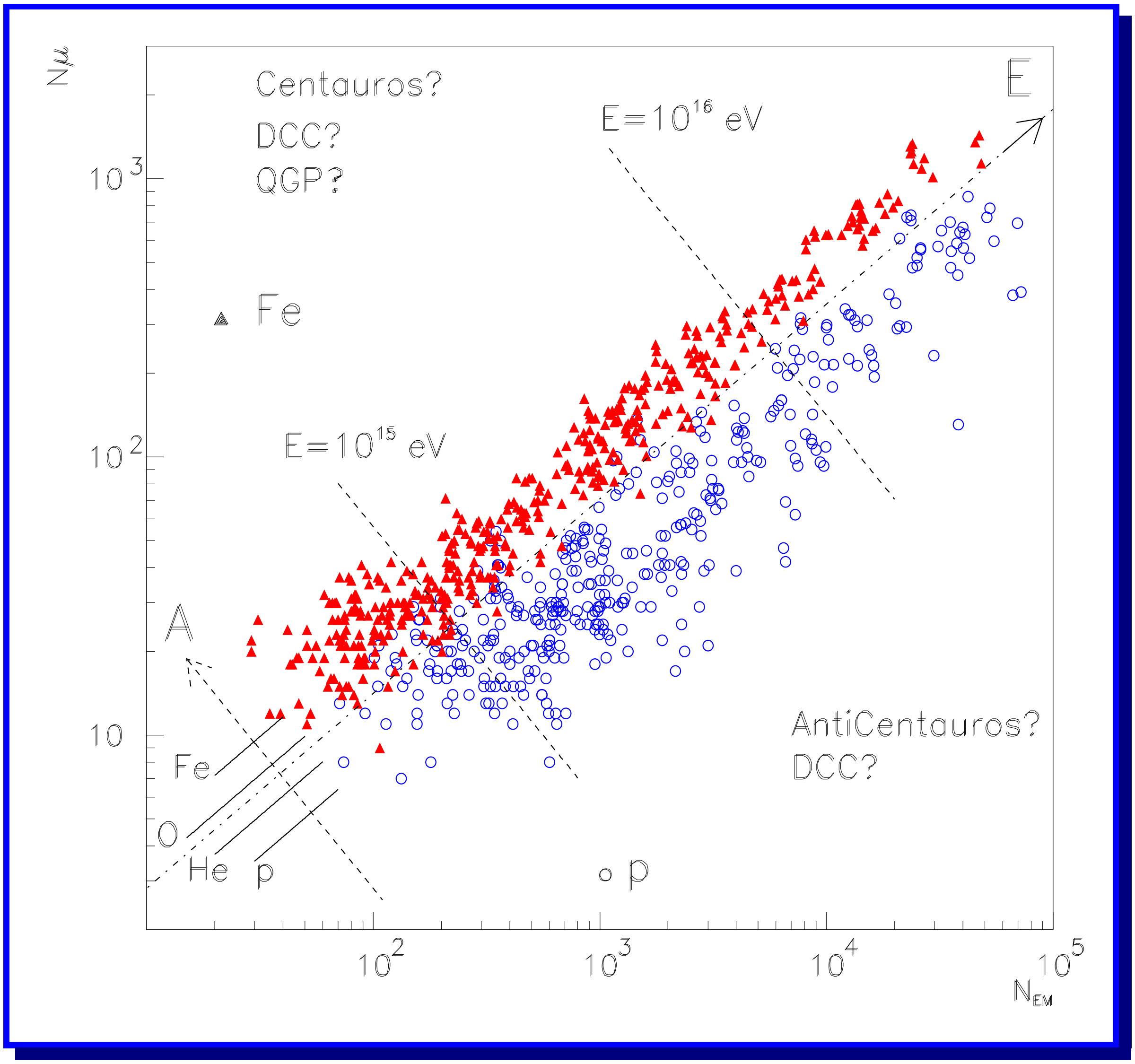
Normalized muon distributions





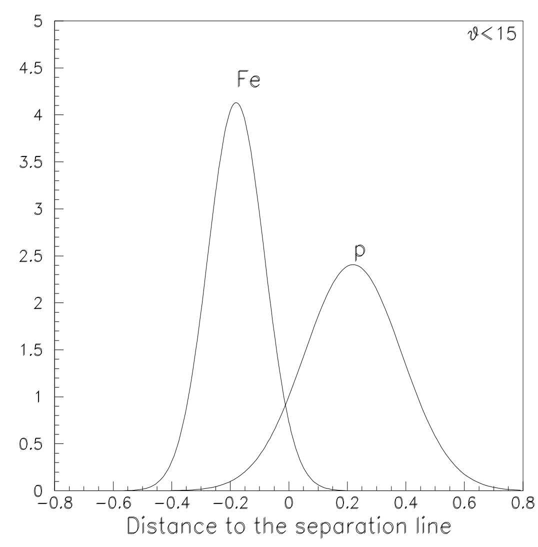
CORAL

Electron - muon correlation



$\theta < 15^o$
N$_e$ in R$<$ 50 m
N$_\mu$ in array (20x20 m^2),
p$_\mu$ $>$ 70 GeV
Shower core in the
muon array

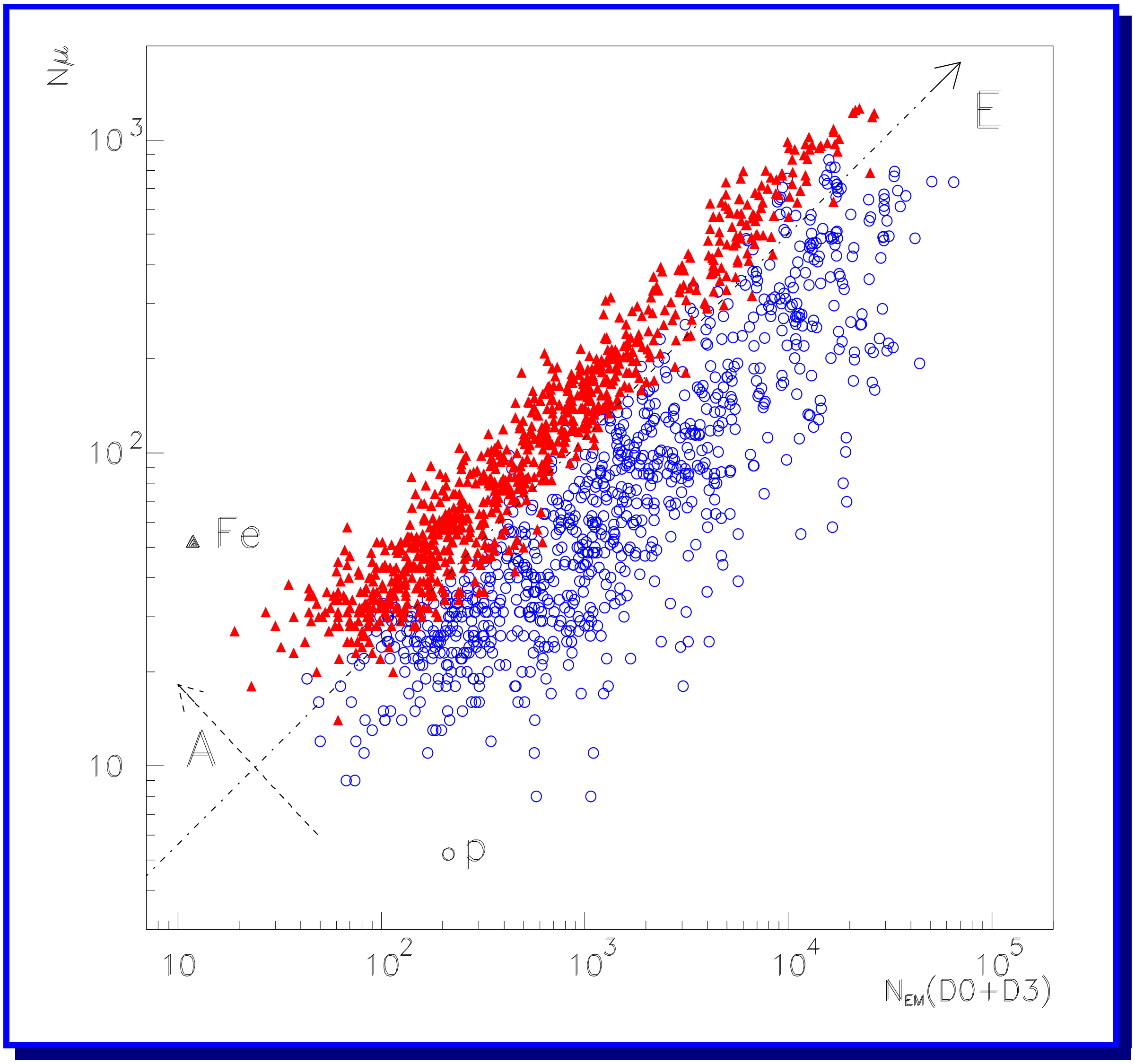
$5 \cdot 10^{14} <$ E $< 5 \cdot 10^{16}$ eV



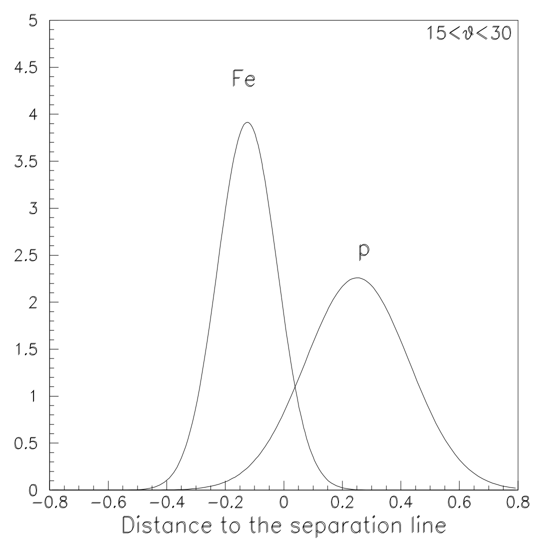
Particle composition

Search for exotic events

Electron - muon correlation

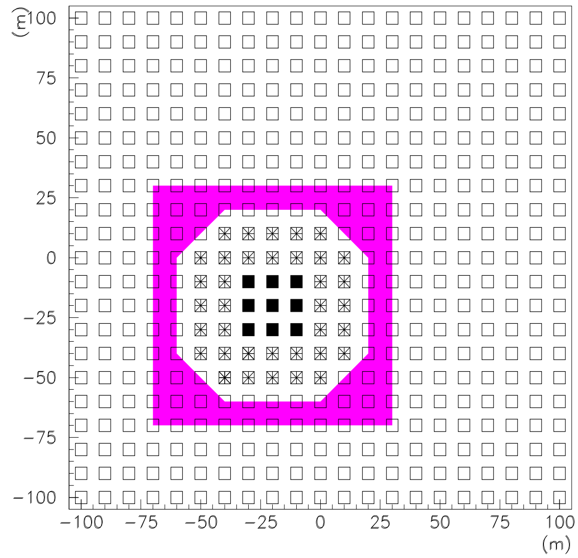


$15^o < \theta < 30^o$
N_e in R< 30 m
N_μ in array (20x20 m^2),
$p_\mu > 70$ GeV
Shower core in the
muon array
$1 \cdot 10^{15} < E < 5 \cdot 10^{16}$ eV

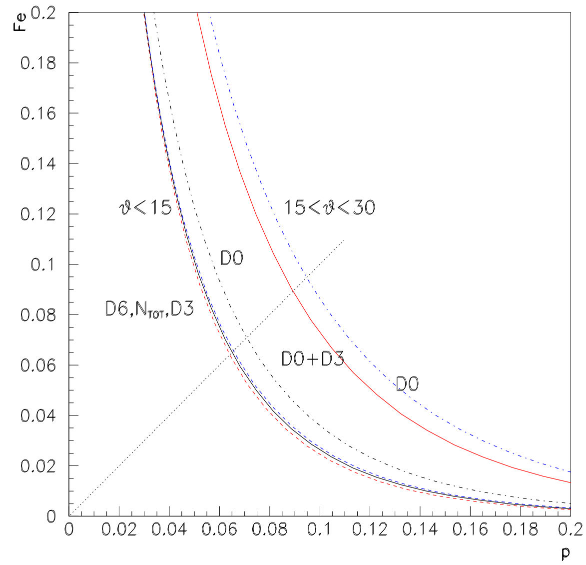


p - Fe separation

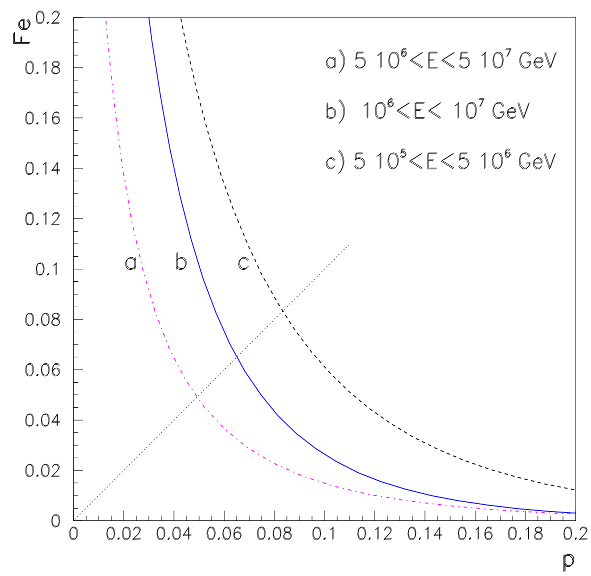
Definition of EM arrays:
D0 ■
D3 ⊠
D6 ■



$\theta < 15^o$
$15^o < \theta < 30^o$
Different EM arrays
$10^{15} <$ E $< 10^{16}$ eV



energy dependence



Summary

- All detectors are available from HEGRA, UA1, DELPHI and OPAL.

- PA4 is an ideal location for CORAL

  easy installation of a surface array

  superb experimental hall and infrastructure for the underground muon detector

  depth of 140 m corresponds to a particularly useful muon momentum cut-off (p$_\mu > 70$ GeV/c)

$$\frac{N_\mu(p_\mu > 70\, GeV/c)}{N_\mu(p_\mu > 1\, TeV)} \sim 60$$

- Schedule fits well with the LHC installation

$\Rightarrow$ Economic experiment

Summary

- Study of the structure of multi-muon events with precise multi-layer muon detectors over an area of 400 m^2

- Simultaneous and complementary measurement of the electromagnetic structure of the air shower

$$\Downarrow$$

- Search for new effects in the forward particle production (Centauro, DCC, heavy flavour, QGP.....)

- Significant extension of the study of the high-multiplicity excess, previously observed with the ALEPH detector.
  Increase of the statistics by a factor 1000.

- Determination of the composition of cosmic ray primaries in the energy range $5{\cdot}10^{14}$ - $5{\cdot}10^{16}$ eV.

Budget

Years:	2001	2002	Total
Underground muon array			
Infrastructures at I4,experimental platform...	-	120	120 KFS
Installation of all (UA1+DELPHI) muon chambers, gas system and safety cables and connectors, repairs	80	150	230 KFS
Trigger counters underground (cables, connectors, infrastructure, repairs)	30	30	60 KFS
Trigger logic, GPS	15	80	95 KFS
DAQ, Data storage	30	60	90 KFS
Surface detector array			
Construction and repair of $\sim$200 counters	50	60	110 KFS
Cables, controls....	40	40	80 KFS
Trigger logic,DAQ, GPS	40	50	90 KFS
Maintenance	20	20	40 KFS
Total	305	610	915 KFS
Consumption:			
Rental fee for electronics	50	80	130 KFS
Gas consumption	20	40	60 KFS

Investments and maintenance
for the years $\geq$ 2003

	2003	$\geq$ 2004
Upgrades	60	- KFS
Maintenance	60	60 KFS
Rental fee for electronics	80	80 KFS
Gas consumption	40	40 KFS

CORAL Schedule

Constrained by:

- removal of the ALEPH detector
- installation of the LHC

2001

- Construction of surface array counters
- Design of the electronics (HV supplies, DAQ, trigger, GPS)
- Coincidence between a small array at PA4 and the L3C top array
- Tests of muon chambers and trigger counters
- Design of the gas system

2002

- Finalize the surface array
- Construction of the platform
- Installation of the muon chambers
- Test of surface + underground trigger and DAQ

End 2002

- Start data taking

2003-2005

- Data taking $\rightarrow \int dt \sim 6 \cdot 10^7$ sec

Collaboration

Armenia:	Yerevan Physics Institute
Austria:	Institute for High Energy Physics
Bulgaria:	Institute for Nuclear Research and Nuclear Institute
	Central Laboratory of Mechatronics and Instrumentation, Bulgarian Academy of Sciences
Czech Republic:	FzU, Institute of Physics of the AS CR
	Institute of Particle and Nuclear Physics, Charles University
Finland:	Helsinki Institute of Physics
	Rovaniemi Polytechnic
	University of Oulu and Sodankylä Geophysical Observatory
Germany:	University of Siegen
India:	Tata Institute of Fundamental Research
Italy:	Laboratori Nazionali del Gran Sasso and INFN
Japan:	Osaka City University
Mexico:	Cinvestsav-IPN
	Universidad Autonoma de Puebla
Poland:	Warsaw University of Technology
Russia:	IHEP, Institute for High Energy Physics
Switzerland:	CERN
USA:	Case Western Reserve University
	University of Michigan

20 Institutes from 14 countries