Timo Enqvist
University of Oulu
Oulu Southern institute

lecture cource on

Astroparticle physics

15.09.2009 – 15.12.2009

A. General things

The lecture cource

- 6 credit units,
  suitable for advanced studies and Ph.D. studies
- Lectures 39 h (= 13 × 3h) every tuesday at 14 – 17,
  first 15.09. and last 15.12.
- Lecturer: Timo Enqvist (timo.enqvist@oulu.fi)
- Excercises 12 h (= 6 × 2h), date & time to be fixed
  (proposition: tuesday 10 – 12, starting 06.10.)
- Examination methods and dates to be fixed
  - normal way (exam)
  - (comprehensive) literature work
  - data analysis, simulations, ...
- Lecture notes available at http://cupp.oulu.fi/timo

- Is introductory lecture on particle and nuclear physics, on particle interactions and cross sections and on detection methods needed/ wanted ?

A. General things

Astroparticle physics

- Definition for astroparticle physics (at the present lecture cource)
  - research of particle and nuclear physics without accelerators
  - natural (astronomical) sources and phenomena studied by means of particle and nuclear physics
  - in most cases studied deep underground

B. Lecture Contents

Astroparticle physics: topics and tentative schedule

- high-energy cosmic rays (15.09. and 22.09.) ☞
- past, current and future experiments (06.10.)
- Sun (stars) and solar neutrinos (13.10.)
- supernovae, supernova and relic supernova neutrinos (20.10.)
- atmospheric and geoneutrinos (27.10.)
- double beta-decay (03.11.)
- dark matter (10.11.)
- proton decay (17.11.)
- background in underground measurements (24.11.)
- cosmic microwave background, Big Bang nucleosynthesis (01.12.)
- gravitational waves (08.12.)
- (15.12.)

C. Literature & Articles

Astroparticle physics

- Thomas G. Gaisser: Cosmic Rays and Particle Physics, Cambridge University Press, 1990
- Pierre Sokolsky: Introduction to Ultrahigh Energy Cosmic Rays Physics, Westview Press, 2004
- Claus Grupen: Astroparticle Physics, Springer, 2005
- John N. Bahcall: Neutrino Astrophysics, Cambridge University Press, 1989
- Donald Perkins: Particle Astrophysics, Oxford University Press, 2003
- Claus E. Rolfs and William S. Rodney: Cauldrons in the Cosmos, The University of Chicago Press, 1988
- Donald H. Perkins: Introduction to High Energy Physics, Cambridge University Press, 2000
- Kai Zuber: Neutrino Physics, IOP Publishing Ltd, 2004

1 High-energy cosmic rays

Content

1.1 Cosmic rays

General

- Cosmic rays at high energies are particles hitting on earth, most probably atomic nuclei (hydrogen – iron), but the exact composition is not known and depends on the energy
- High-energy cosmic rays studied already for several decades by many various arrays (deep underground, at the surface, at the mountins)
  - cosmic-ray experiment started at the beginning of the century
  - the knee was introduced at the end of 1950's
- In the present lecture, high-energy cosmic ray means that $E_{\mathrm{cr}} > 10^{14}$ eV ($=$ 100 TeV)
  - flux so low that currently direct measurements are not possible
- Research still very active at high energies (knee and above) – tens of different experiments
  - at the knee–ankle region: KASCADE-Grande
  - at the highest energies: Pierre Auger Observatory
- General aim of cosmic-ray research: find out sources and origin, acceleration and propagation mechanisms, etc.

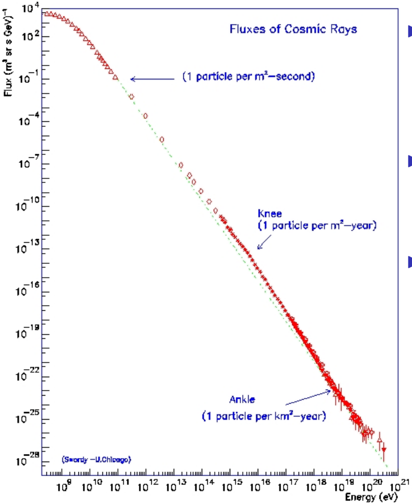
1.1 Cosmic rays

General

- Due to low flux and bending (diffusion) in galactic magnetic field, sources can not be observed, located or studied directly
  ☞ analysis of cosmic-ray origin, sources and acceleration mechanisms is based on the measurement of cosmic-ray composition
  - at high energies also indirect measurement of composition
    ☞ **Extended Air Showers (EAS)**
- Results very model dependent
  - interactions at these high energies not known accurately enough
    ☞ no accelerator data
  - LHC at CERN may help
- Large fluctuations, like the depth (height) of the first interaction, can also exist
- No firm conclusions yet for the cosmic-ray composition above the knee region

1.2 Cosmic-ray energy spectrum

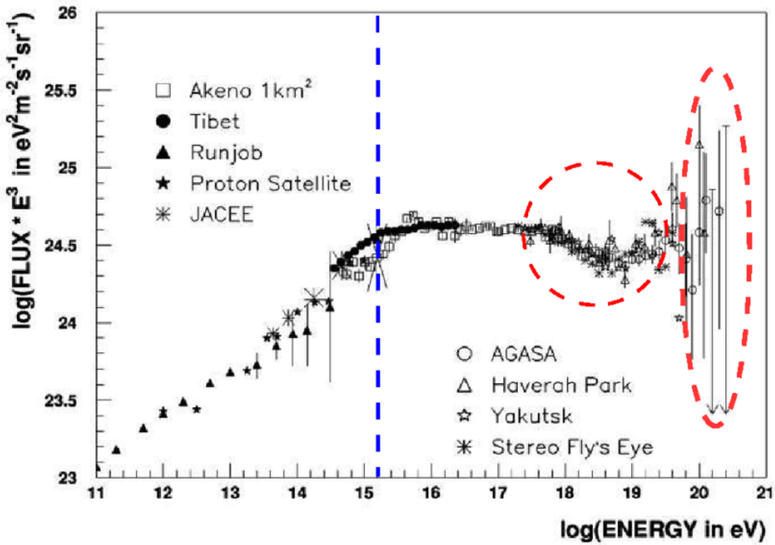
Energy vs. flux



- Energy spectrum (flux vs. energy) is quite reliably known
  - the slope is very deep: $dN/dE \propto E^{-(\gamma+1)}$, $\gamma \sim 1.7$
- The composition is poorly known due to conflicting experimental results
  - composition : light/heavy -ratio
- Three features in the spectrum
  - knee at $E \sim 10^{15} - 10^{16}$ eV
    ☞ different production or acceleration mechanism
  - ankle at $E \sim 10^{18} - 10^{19}$ eV
    ☞ transition from galactic sources to extra-galactic
  - GZK-cutoff at $E \sim 6 \times 10^{20}$ eV
    ☞ collision with CMB

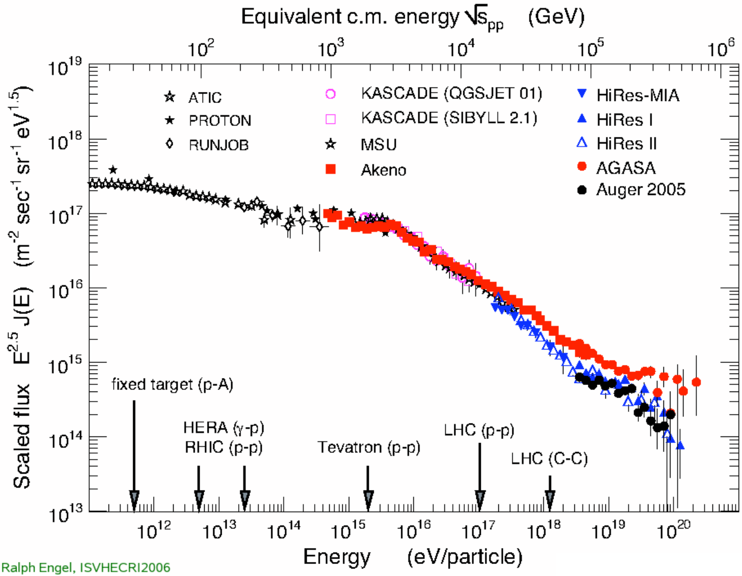
1.2 Cosmic-ray energy spectrum

Spectrum features: knee, ankle and GZK



1.2 Cosmic-ray energy spectrum

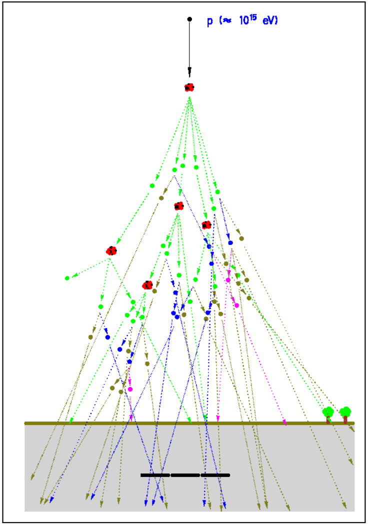
Comparison with accelerator energies



Ralph Engel, ISVHECRI2006

1.3 Extensive Air Shower

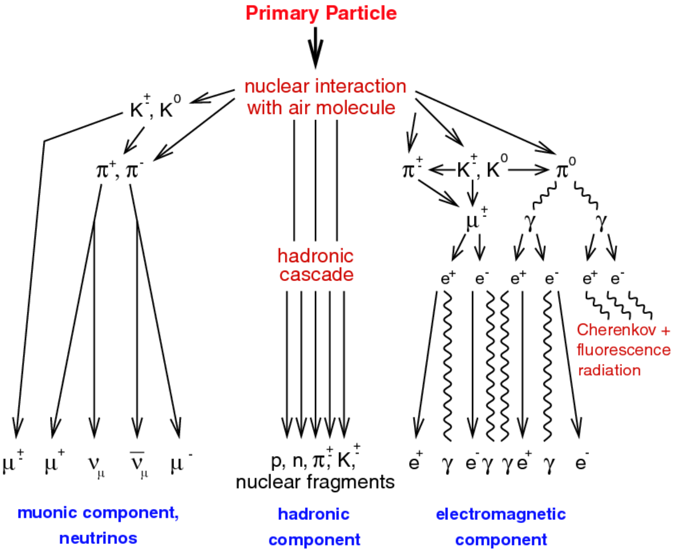
EAS



- Particle cascades developing in the atmosphere
  - approximately all known particles produced
- Initiated by energetic primary cosmic particles at high altitude
  - tens (hundreds) of pions (π^0, $\pi^{\pm}$) created
- Contains electromagnetic, muonic, hadronic and neutrino components
  - see next page
- For the identification of the primary particle and its energy, all physics (interactions) of the EAS should be known

1.3 Extensive Air Shower

EAS components



1.3 Extensive Air Shower

pions and kaons

- The thickness of the atmosphere H$\sim$1000 g/cm^2
  - increases for inclined showers as $1/\cos(\theta)$
  - at 35–40 km, h$\sim$10 g/cm^2 (balloon flights)
  - at 15–20 km, h$\sim$100 g/cm^2 (first interaction)
  - nuclear physics (Coulomb barrier), t$\sim$0.5 mg/cm^2
  - (1 GeV/nucleon), t$\sim$100 mg/cm^2
- Characteristic interaction lengths
  - radiation length for photons and electrons in air
    $X_0 \approx 37$ g/cm^2 (H$\sim$25X_0)
  - interaction length for hadrons (protons, ...) in air
    $\lambda \approx 90$ g/cm^2 (H$\sim$10X_0)
- First interaction $\Rightarrow$ pions (π^0, $\pi^\pm$) and kaons (K^0, $K^\pm$)
  - kaons/pions $\sim$ 0.1
  - $m(\pi^\pm) = 140$ MeV (0.15 m_p), $\tau(\pi^\pm) = 26$ ns
    $\pi^+ \longrightarrow \mu^+ + \nu_\mu, \quad \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$
  - $m(K^\pm) = 494$ MeV, $\tau(K^\pm) = 12$ ns
    $K^+ \longrightarrow \mu^+ + \nu_\mu, \quad K^- \longrightarrow \mu^- + \bar{\nu}_\mu$ (63 %)

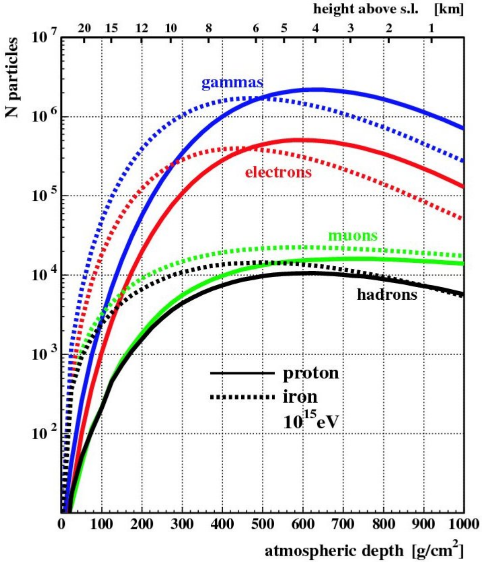
1.3 Extensive Air Shower

muons and electrons

- Electrons produced by π^0, $K^0 \longrightarrow \gamma$'s $\longrightarrow e^\pm$ and by muon decay
- Muons produced by decays of pions and kaons
  - $m(\mu^\pm) = 106$ MeV, $\tau(\mu^\pm) = 2.2\ \mu$s
    $\mu^+ \longrightarrow e^- + \bar{\nu}_e + \nu_\mu, \quad \mu^- \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- Competition between decay and interaction
  - function of energy at 1 TeV, $\lambda(\pi) \sim 10$ %
    $\lambda(K) \sim 30$ %
  - interaction (with air) produces more particles (more pions and kaons) than decay
- Muons loss only approximately 2 GeV of their energy in the atmosphere
  - penetrating component
- Shower development in the atmosphere ☞
  - longitudinal development (X_{max})
  - lateral distribution

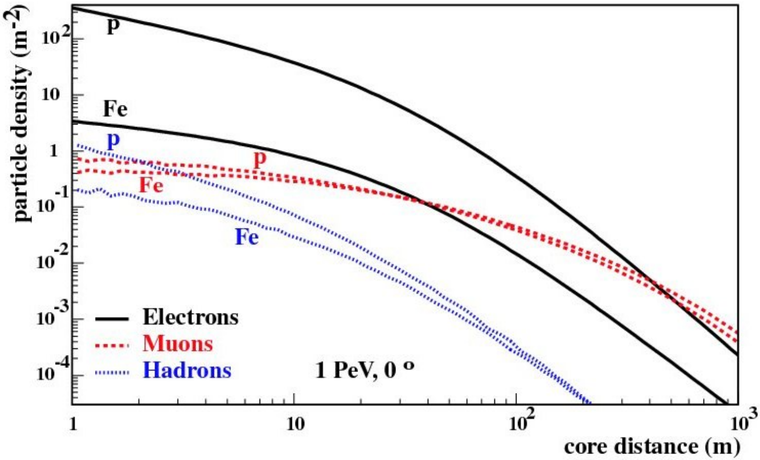
1.3 Extensive Air Shower

EAS longitudinal development



1.3 Extensive Air Shower

EAS lateral distribution



1.3 Extensive Air Shower

EAS longitudinal development parametrisations

- Number of particles at the shower maximum (X_{max}) can be expressed as

$$N_{max} = (1.1 - 1.6) \cdot E_0[\text{GeV}]$$

where E_0 is the primary-particle energy
(at the knee $N_{max} \sim 10^6$, at the ankle $N_{max} \sim 10^9$)

- The longitudinal development of number of electrons in proton-initiated shower, the electron size, can be expressed as

$$N_e(X) = N_{max} \cdot \left(\frac{X - X_0}{X_{max} - X_0}\right)^{(X_{max} - X_0)/\lambda} \cdot \exp\left(\frac{X_{max} - X}{\lambda}\right)$$

X is the depth of the observation and X_0 the initial interaction as g/cm^2 and $\lambda = 70$ g/cm^2

- $X_{max} \propto E_0/A \Longrightarrow \Delta X_{max} \propto \ln A \Longrightarrow X_{max}(p) - X_{max}(Fe) \approx 100$ g/cm^2

1.3 Extensive Air Shower

EAS lateral distribution parametrisations

- For electrons:
  Nishimura – Kamata – Greisen (NKG) parametrisation

$$\rho_{ch}(r) = \frac{N_{ch}}{2\pi r_0^2} \cdot C \cdot \left(\frac{r}{r_0}\right)^{s-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s-4.5}$$

  N_{ch} is the total number of charged particles ($e^{\pm}$, $\mu^{\pm}$), s is the age paramerer, r_0 is the Moliére radius ($\approx$ 79 m at sea level), C is constant:

$$C = \frac{\Gamma(4.5 - s)}{\Gamma(s) \cdot \Gamma(4.5 - 2s)}$$

  Based on theoretical description of purely electromagnetic shower, but approximatively correct also for muons (with effective age of 1.25)

1.3 Extensive Air Shower

EAS lateral distribution parametrisations

For muons

- Greisen parametrisation

$$\rho_\mu(r) = 18 \cdot r^{-0.75} \cdot \left(1 + \frac{r}{320}\right)^{-2.5} \cdot \left(\frac{N_e}{10^6}\right)^{0.75} \quad \text{muons}/\text{m}^2$$

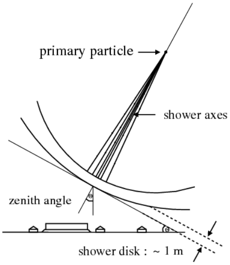
- Tien-Shan experiment parametrisation

$$\rho_\mu(r) = 5.95 \times 10^{-4} \cdot r^{-0.7} \cdot \exp\left(-\frac{r}{80 \text{ m}}\right)$$

1.3 Extensive Air Shower

EAS analysis scheme

EAS-Experiment



Data Acquisition

Monte-Carlo Simulation

Primary Energy **E**
Primary Particle **A**

EAS simulations

including hadronic interaction models

Detector-Response

Reconstruction of EAS-Observables

e.g. N_e, N_h, N_μ, X_{max}, Lateral Distributions, ...

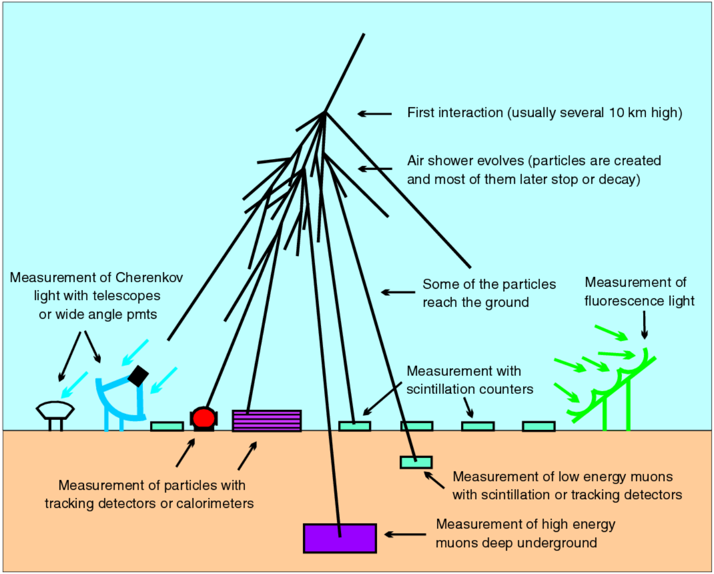
Comparison of Distributions; Bayes Classifier, Neural Nets, Unfolding ...

E_{est} , A_{est}
Energy Spectra
Chemical Composition

Tests of High-Energy Interaction Models

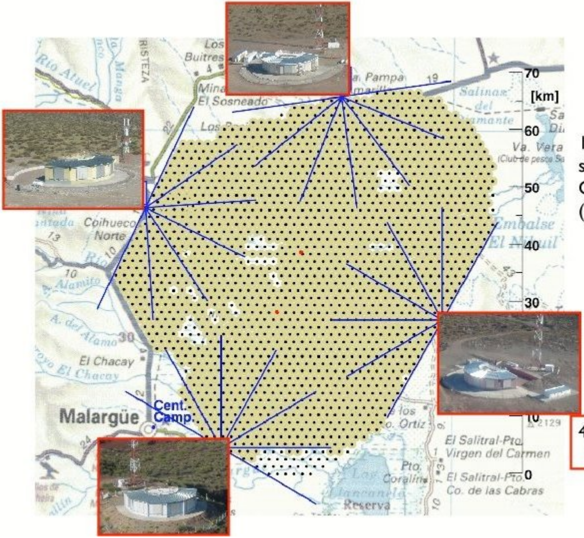
1.3 Extensive Air Shower

EAS detection possibilities & methods



1.4 EAS detection

The Pierre Auger Observatory: Auger South



1600 surface detector stations: water-Cherenkov tanks (triangular grid of 1.5 km)

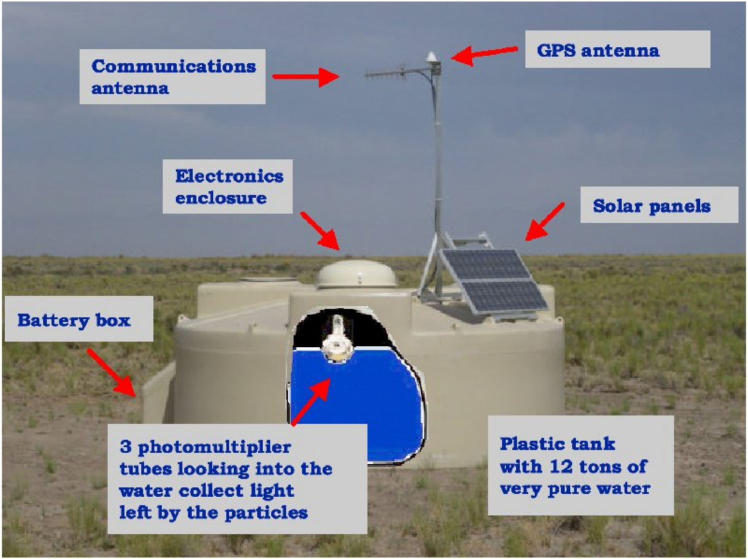
4 fluorescence detectors (24 telescopes in total)

1.4 The Pierre Auger Observatory

Water Cherenkov surface detectors

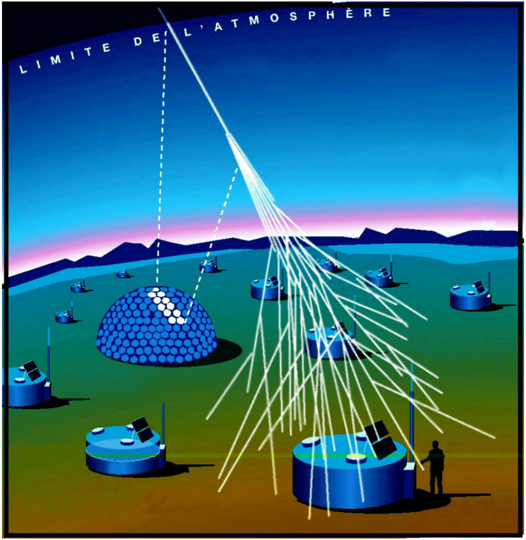
1.4 The Pierre Auger Observatory

Water Cherenkov surface detector



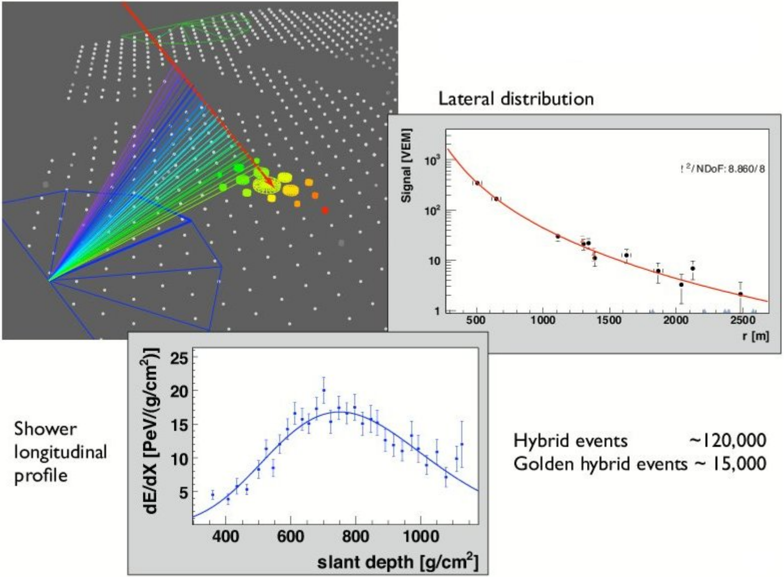
1.4 The Pierre Auger Observatory

Hydrid Measurement: Water Cherenkov's & Fluorescense detector



1.4 The Pierre Auger Observatory

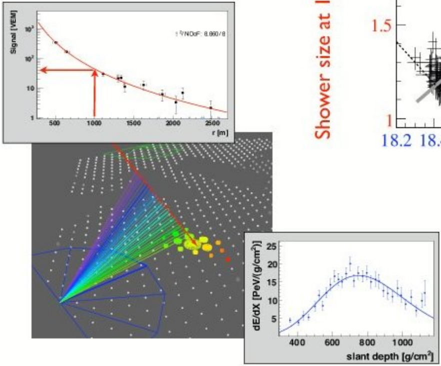
A detected high-energy cosmic particle



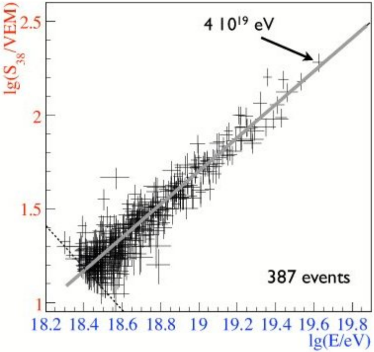
Hybrid events ~120,000
Golden hybrid events ~ 15,000

1.4 The Pierre Auger Observatory

Energy of the primary particle



Shower size at 1000m and θ=38°



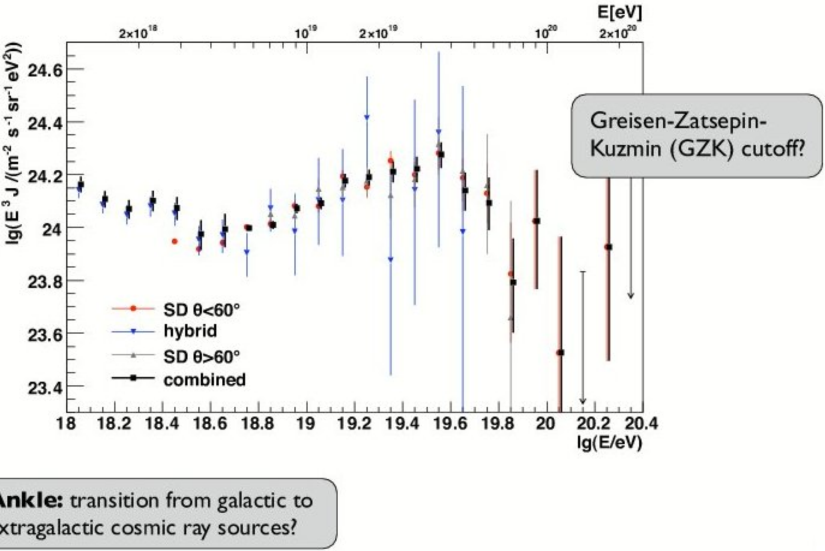
Fluorescence detector energy

$$E_{\mathrm{prim}} = f_{\mathrm{corr}} \cdot \int \frac{\mathrm{d}E_{\mathrm{ion}}}{\mathrm{dX}}\,\mathrm{dX}$$

(Fluorescence yield uncertainty)

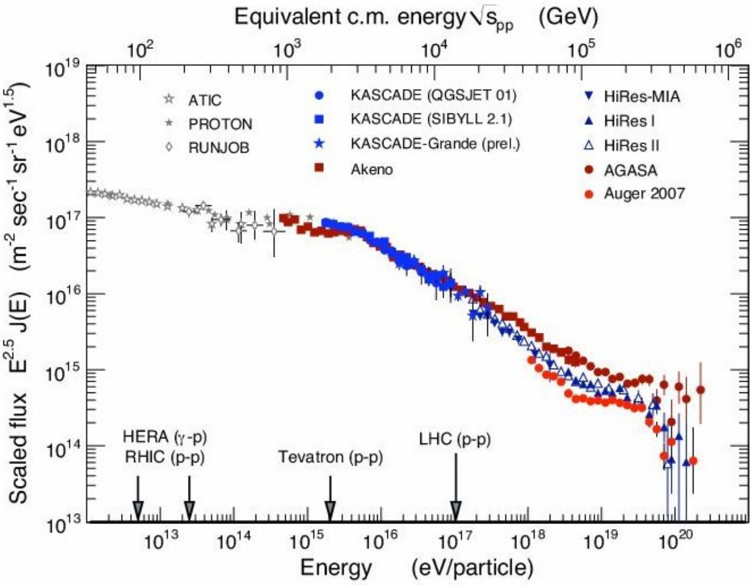
1.4 The Pierre Auger Observatory

Cosmic-ray flux at highest energies



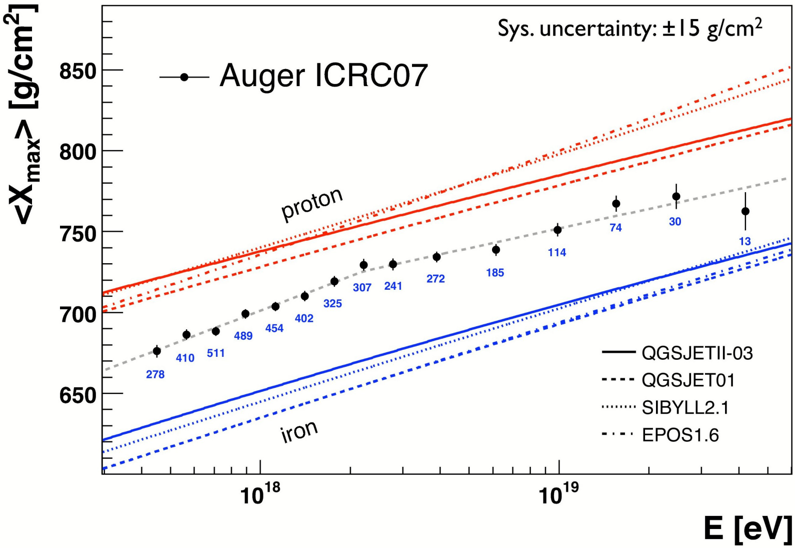
1.4 Cosmic-ray flux at the GZK-cutoff

Combined measurements



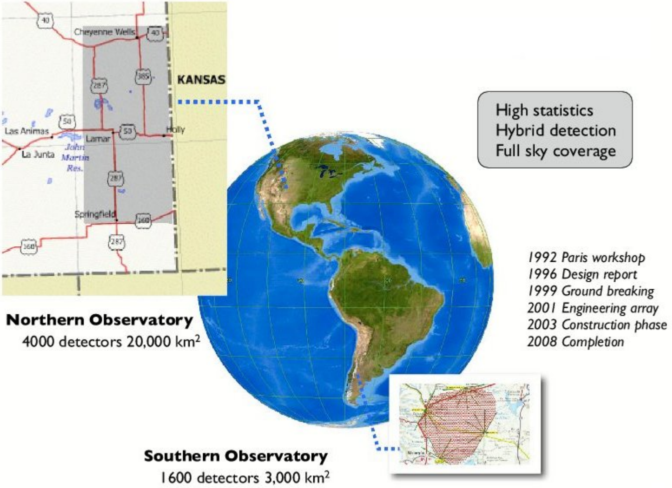
1.4 The Pierre Auger Observatory

Composition (mean depth of shower maximum)



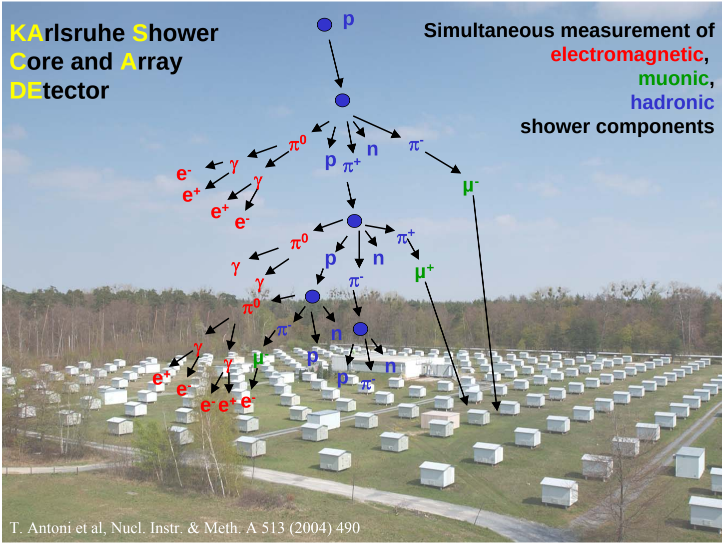
1.4 EAS detection

The Pierre Auger Project: Auger South & Auger North



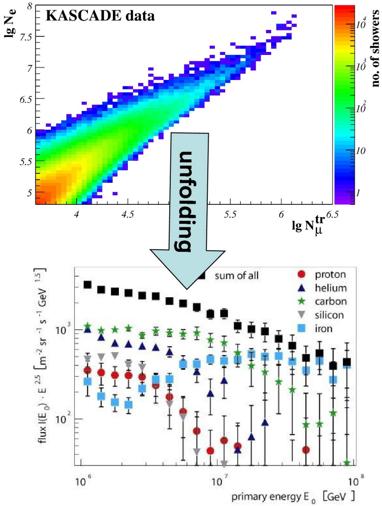
1.4 KASCADE–Grande

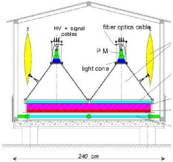
Leading experiment at knee – ankle region



1.4 KASCADE–Grande

Analysis prodecure





Measurement:

KASCADE array data
900 days;
0-18° zenith angle
0-91m core distance
$\lg N_e > 4.8$;
$\lg N_\mu^{tr} > 3.6$
➔ 685868 events

Searched:

E and A of the Cosmic Ray Particles

Given:

N_e and N_μ for each single event

➔ **solve the inverse problem**

$$g(y) = \int K(y, x) p(x) dx$$

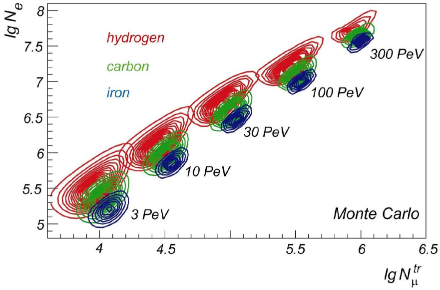
with $y = (N_e, N_\mu^{tr})$ and $x = (E, A)$

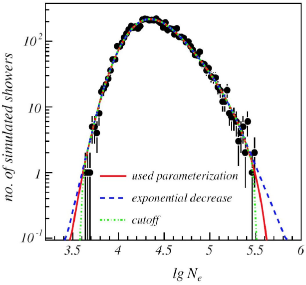
1.4 KASCADE–Grande

Analysis prodecure: unfolding

$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \; p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \; d\lg E$$

- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution

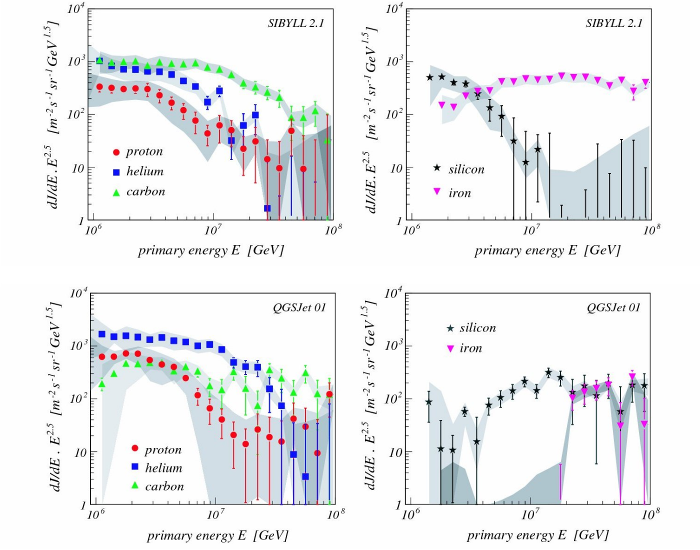




1.4 KASCADE–Grande

Element group analysis

T. Antoni et al. / Astroparticle Physics 24 (2005) 1–25



1.4 EAS Experiments

Page 1 (Table from A. Haungs et al., Rep. Prog. Phys. **66** (2003) 1145–1206)

Table 1. EAS experiments.

Experiment	Location	Detector	Observables	References
CASA (nlo)	Dugway, Utah, US	Scint. array	N_e	[20]
MIA (nlo)	870 $\mathrm{g\,cm^{-2}}$	μ-underground	N_μ	[21]
BLANCA (nlo)	W 112.8 N 40.2	Č-light	X_{max}	[22]
DICE (nlo)		2 imag. Č-telesc.	X_{max}	[23]
HEGRA (nlo)	La Palma (Canary Isl.)	Scint. array	N_e	[24]
AIROBICC	790 $\mathrm{g\,cm^{-2}}$	Č-light	X_{max}	[25]
	W 17.9 N 28.8	CRT	Part. tracking	[26]
MSU (nlo)	Moscow, Russia	Scint. array	N_e	[27]
	1000 $\mathrm{g\,cm^{-2}}$	μ-underground	μ	[28]
EAS-TOP (nlo)	Gran Sasso, Italy	Scint. array	N_e	[29]
	810 $\mathrm{g\,cm^{-2}}$	h-μ-calorimeter	N_μ, h	
MACRO (nlo)	Undergr. 3100 m w.e.	μ-Tracking	Multi-μ	[30]
	E 13.6 N 42.4	($E_\mu > 13$ TeV)		
AKENO (nlo)	Akeno, Japan	Scint. array	N_e	[31]
	920 $\mathrm{g\,cm^{-2}}$	μ-counter	N_μ	[32]
	E 138.5 N 35.8	Č-counter	X_{max}	
KASCADE	Karlsruhe, Germany	Scint. array	N_e, N_μ	[11]
	1020 $\mathrm{g\,cm^{-2}}$	LST-tunnel	μ-Tracking	[33]
	E 8.4 N 49.0	Calorimeter	N_h, E_h	[34]
		MWPC, LST,	N_μ, ρ_μ	[35]
		Scint.	μ-Arrival times	

1.4 EAS Experiments

Page 2 (Table from A. Haungs et al., Rep. Prog. Phys. **66** (2003) 1145–1206)

KASCADE-Grande		Scint. array	N_{ch}	[36]
MAKET-ANI	Mt Aragats, Armenia	Scint. array	N_e	[37]
GAMMA	700 g cm^{-2} E 45.2 N 41.2	Scint. array	N_e	[38]
TIBET ASγ	Yanbajing, China	Scint. array	N_e	[39]
ARGO	606 g cm^{-2} E 90.5 N 30.1	RPC-carpet	N_{ch} μ-Multiplicity	[40]
Haverah Park (nlo)	Yorkshire, UK 1020 g cm^{-2}	Water Č-array	N_e, rise times	[41]
Grex/ cover-plastex	W 1.6 N 56.0	RPC stack	Arrival times	[42]
AGASA	Akeno, Japan 920 g cm^{-2} E 138.5 N 35.8	Scint. array	N_{ch}	[7]
Yakutsk	Russia 1020 g cm^{-2} E 129.4 N 61.7	Scint. array Č-light μ-underground	N_e,N_μ X_{max}	[43]
Fly's Eye (nlo)	Dugway, Utah, US 870 g cm^{-2} W 112.8 N 40.2	FD-telescope	Fluor. light	[44]
HiRes Fly's Eye	Dugway, Utah, US 870 g cm^{-2} W 112.8 N 40.2	FD-telescopes	Fluor. light	[45]
AUGER	Argentina 875 g cm^{-2} W 69.3 S 35.5	Water Č-array FD-telescopes	N_e, N_μ Fluor. light	[12]

1.4 EAS Experiments

Page 3 (Table from A. Haungs et al., Rep. Prog. Phys. **66** (2003) 1145–1206)

1154 A Haungs *et al*

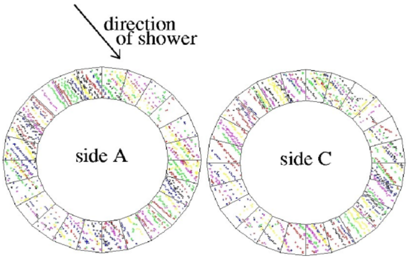
Table 1. EAS experiments.

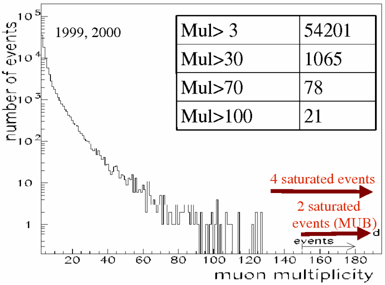
Experiment	Location	Detector	Observables	References
NORIKURA (nlo)	Japan, 740 $\mathrm{g\,cm^{-2}}$ E 137.3 N 36.1	Scint. array	N_e	[46]
GRAPES III	Ooty, India 600 $\mathrm{g\,cm^{-2}}$	Scint. array Prop. counters	N_e N_μ	[47]
SPASE VULCAN (nlo)	Southpole 650 $\mathrm{g\,cm^{-2}}$	Scint. array Č-light	N_e X_{max}	[48]
Tien-Shan	Kyrgyzstan 690 $\mathrm{g\,cm^{-2}}$	Scint. array Č-light	N_e X_{max}	[49]
L3+C (nlo)	CERN, Switzerland 1000 $\mathrm{g\,cm^{-2}}$ E 6.01 N 46.15	Scint. array μ-tracking ($E_\mu > 15$ GeV)	N_e μ-Multip., E_μ	[50]
Tunka 13	Russia, 950 $\mathrm{g\,cm^{-2}}$ E 103 N 51.5	Č-light	X_{max}	[51]
BAKSAN BUST	Russia, 833 $\mathrm{g\,cm^{-2}}$ E 42.7 N 43.4	Scint. array Undergr. array	N_e Muons	[52] [53]
Mt Chacaltaya BASJE	Bolivia, 540 $\mathrm{g\,cm^{-2}}$ W 68.2 S 16.4	Emulsion Ch. Scint. array	$h+\gamma$ N_e	[54]
PAMIR	Tadjikistan 600 $\mathrm{g\,cm^{-2}}$	Emulsion Ch.	TeV $h+e/\gamma$	[55]
Mt Kanbala	Japan 520 $\mathrm{g\,cm^{-2}}$	Emulsion Ch.	TeV $h+e/\gamma$	[56]
Mt Fuji	Japan 650 $\mathrm{g\,cm^{-2}}$	Emulsion Ch.	TeV $h+e/\gamma$	[57]

1.4 EAS Detection

Special Topic: High muon multiplicities

- Events with high muon multiplicities were observed by DELPHI, ALEPH and L3+C detectors of LEP
- Effective running time only about a month
- Origin is not clear: cosmic-ray models are not able to explain observed multiplicities
  - would require heavier that Fe for highest multiplicities
- Tentatively observed also at LHC
- EMMA can also measure high-multiplicity events



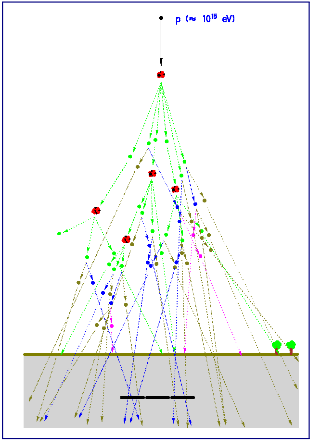


DELPHI Collab., APP 28 (2007) 273–296, Study of multi-muon bundles in cosmic ray showers detected with the DELPHI detector at LEP

1.4 EMMA – Experiment with MultiMuon Array

Cosmic-ray experiments in Pyhäsalmi

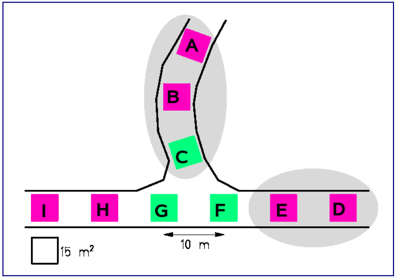
- New type of cosmic-ray experiment
  ☞ at the depth of 75 metres in Pyhäsalmi mine
- Studying high-energy cosmic rays
  ☞ composition at the knee region
- Idea: the rock overburden filters out low-energy muons (cutoff $\sim$50 GeV)
  High-energy muons more sensitive on the primary particle than low-energy muons
- New type of experiment: measuring muon multiplicity and their lateral spread at the shallow depth
- Also the arrival direction of the shower is measured by tracking



1.4 EMMA

Experiment with MultiMuon Array

- The design started 2005, construction 2006 and will be ready 2010
  - ☞ measurements can be started already this year
  - ☞ duration: 5–10 years
- Consists of nine detector units (cottages) each of 15 m^2
- Detector area 130 m^2 (in one level), alltogether 250 m^2



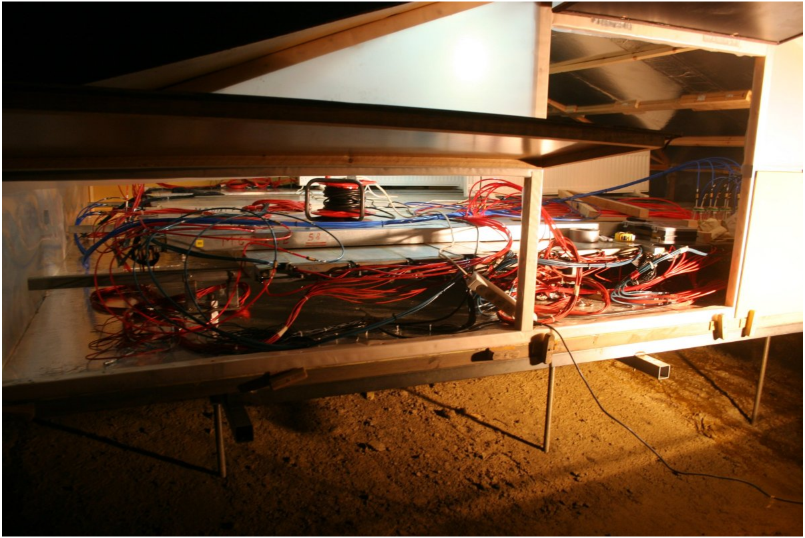
- Detectors are drift chambers otained from CERN (DELPHI-experiment at LEP collider) and new-design small-size plastic scintillation detectors (especially designed for EMMA)

1.4 EMMA

The cottages – outside view

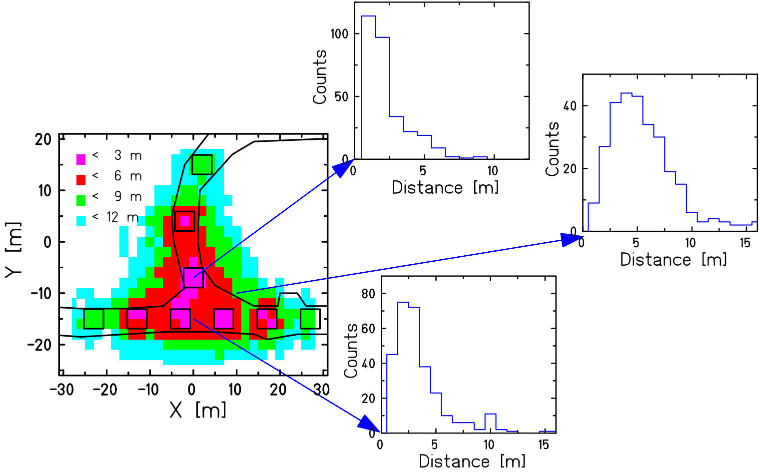
1.4 EMMA

The cottages – inside view



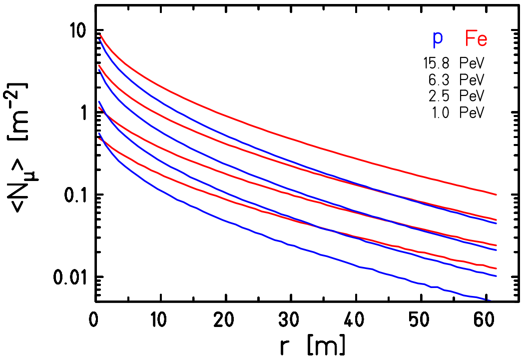
1.4 EMMA

Shower axis determination for 4-Pev proton-induced showers



1.4 EMMA

Muon lateral distribution functions



LDF parametrisation

$$\rho(\mathrm{r}) = \frac{\mathrm{N}_\mu}{2\pi \cdot 0.11 \cdot \mathrm{R}_0^2} \cdot \left(\frac{\mathrm{r}}{\mathrm{R}_0}\right)^{-0.4} \cdot \left(1 + \frac{\mathrm{r}}{\mathrm{R}_0}\right)^{-5}$$

r is the distance from the shower core,
N_μ is the total number of muons,
R_0 is related to the gradient of the LDF

EMMA-koe

Kollaboraatio & Kiitokset

T. Enqvist, J. Joutsenvaara, P. Kuusiniemi, L. Olanterä, T. Räihä, J. Sarkamo, T. Jämsén, I. Usoskin University of Oulu, Finland
E. Heikkilä, P. Jones, T. Kalliokoski, K. Kolos, W.H. Trzaska University of Jyväskylä, Finland
L. Bezrukov, L. Inzhechik, B. Lubsandorzhiev, V. Petkov RAS/INR, Moscow, Russia
H. Fynbo
University of Århus, Denmark

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