4. Cosmic-ray Experiments Underground

General

- There are no dedicated underground cosmic-ray experiment performed or running at the shallow depth (besides EMMA)
- Cosmic-ray experiments and studies have been performed deep underground, but cosmic rays have not been the main topic
  - except (perhaps) MACRO in Gran Sasso

Deep underground

- measurement of the highest-energy muons $\implies$ sensitivity very close to the primary collisions
- low number of muons, in quite small area

Shallow depth

- measurement of the high-energy muons $\implies$ sensitivity close to the primary collisions
- higher number of muons, lateral density distribution can be used
4. Cosmic-ray Experiments Underground
Homestake, USA

- Measurement time 534 days (effective) from Jan 1, 1985 to May 6, 1987
- Homestake mine, South Dakota, depth 4100 mwe, $E_\mu \geq 2.6$ TeV
- The composition: $(83 \pm 13)$% of p and 17% of Fe in the energy interval from $3 \times 10^{13}$ to $3 \times 10^{15}$ eV

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<th>Number of $\mu$ ($i$)</th>
<th>Number of Events $D_i$</th>
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<tr>
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<td>6</td>
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</table>

$^a$ Detector on time is 533.9 days.
4. Cosmic-ray Experiments Underground

MACRO & EAS–TOP, Gran Sasso, Italy

- **EAS-TOP**
  - 35 SCI modules of 10 m² each, 80 m separation
  - fully effective for \( N_e > 10^5 \)

- **MACRO**
  - Monopole, Astrophysics, and Cosmic Ray Observatory
  - Large size (\( A \approx 900 \text{ m}^2 \)):
    - 76 m \times 12 m \times 9 m
  - tracking capability
4. Cosmic-ray Experiments Underground

MACRO – Example event

\begin{verbatim}
R  =  6665  E    =  9258  14-OCT-93  00:50:33  HT    =  FFFF-C209-FFF-F208  ST    =  0  M    =  0
\end{verbatim}
4. Cosmic-ray Experiments Underground

MACRO – Muon multiplicities

- Muon energy $E_\mu > 1.3$ TeV
- Effective measurement time 5850 h (244 days)
Decoherence curve is, according to air-shower simulations, sensitive to the primary cosmic-ray composition.

It is based on the distances between muon pairs.

Location of the core position is not needed.
4. Cosmic-ray Experiments Underground

MACRO & EAS–TOP – Energy determination

- Energy determination by electron size ($\log_{10}(N_e)$)
  - normal method in surface detectors
  - six energies around the knee
- $N_\mu$ is muon multiplicity underground
4. Cosmic-ray Experiments Underground

MACRO & EAS–TOP – Composition

- Composition coming heavier around the knee
- Fe
- Si
- O
- He
5. Cosmic-ray Experiment EMMA

Introduction of the experiment

- The main scientific purposes are
  - to study the composition of cosmic rays at the knee region
  - to study the high muon multiplicities (muon bundles)

- The idea of EMMA is to detect high-energy muons formed in the upper part of an air shower, by filtering out low-energy muons with the rock overburden
  - to be carried out at the depth of 75 metres in the Pyhäsalmi mine
    ⇒ the cut-off is approximately 50 GeV

- The array is able to determine the
  - muon multiplicity proportional to energy
  - muon lateral distribution proportional to mass
  - arrival direction of the air shower

- Existing caverns are used ⇒ low-cost experiment

- Continuous data taking started in summer 2012 with a partial array
  - stations added on the DAQ one-by-one, currently 4 stations measuring
  - 7 stations constructed, 2 under construction, 3 to be done (in 2013)
  - Large experiment
5. Cosmic-ray Experiment EMMA

Cosmic-ray energy spectrum – High energies

![Energy spectrum graph](image)

- **Knee**
- **GZK**
- **Ankle**

**Equivalence c.m. energy** $E_{equ} = s_{pp}$ (GeV)

**Scaled flux** $E^{2.5} J(E)$ (m$^2$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

**Energy** (eV/particle)

**Data Sources:**
- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande (prelim)
- Akeno
- HiRes-MIA
- HiRes I
- HiRes II
- AGASA
- Auger 2007

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APP 2013 – UOulu – 5.2 –
5. Cosmic-ray Experiment EMMA

Cosmic-ray energy spectrum – the knee region

![Graph showing the cosmic-ray energy spectrum with labeled points and energy intervals for EMMA.]
3. High-energy Cosmic Rays

The knee region

- Energy spectrum changes at $3 \times 10^{15}$ eV ($E^{-2.7} \rightarrow E^{-3.1}$)
  - WHY?
  - there are no clear explanation for the change
- The change is expected to come from astrophysical origin, not from particle physics interactions
  - no more power in the galactic sources for higher energies
  - high-energy cosmic rays escape from the galaxy
- Observed at 1958 (Kulikov & Khristicsen)
- Several experiments running, among others
  - GRAPES (India), Tibet and ARGU-YBJ (China), KASCADE-Grande (Germany), CARPET and Tunka (Russia), IceTop/IceCube (South Pole)
  - EMMA – a new approach to study cosmic ray composition
- The way to study: Measuring composition (ratio of light and heavy cosmic rays) and its changes in the knee region
  - sources and acceleration mechanisms
- Composition measurement: air shower
At high energies (above $\sim 10^{14}$ eV) cosmic-ray composition cannot be determined in direct measurements due to too small flux.

Indirect method is applied at high energies: the air-shower technique

- large-area arrays at the ground measuring electrons and muons
- interactions at the atmosphere: fluorescence light, radio waves

The knee region is difficult

- at ankle and GZK-regions fluorescence (and other) methods can be used to evaluate the composition ($X_{\text{max}}$)
- at the knee the composition can be evaluated from high-energy muons (gradient of lateral distribution)

$\Rightarrow$ EMMA is the first
5. Cosmic-ray Experiment EMMA
Ankle to GZK region experiments – PAO – A detected high-energy cosmic particle

Shower longitudinal profile

Lateral distribution

Hybrid events \( \sim 120,000 \)
Golden hybrid events \( \sim 15,000 \)
Composition seems to get consistently heavier at the knee, but differences of various experiments are significant.
5. Cosmic-ray Experiment EMMA

Muon lateral distribution – measured at the ground
5. Cosmic-ray Experiment EMMA

Muon lateral distribution – cut-off energy 50 GeV (75 m of rock)
5. Cosmic-ray Experiment EMMA

Muon lateral distribution – cut-off energy 50 GeV (75 m of rock)

- CORSIKA + QGSJET 01
- CORSIKA + EPOS 1.99

Muon density [m^-2] vs. Distance from the core [m]

- Fe (dashed line)
- p (solid line)

Energy dependence: $\propto$ Energy

CORSIKA + QGSJET 01
CORSIKA + EPOS 1.99
5. Cosmic-ray Experiment EMMA

Muon lateral distribution – cut-off energy 50 GeV (75 m of rock)

\[ \propto \text{Energy} \]
\[ \propto \text{Composition} \]
5. Cosmic-ray Experiment EMMA

Detector geometry (by the end of 2013)
5. Cosmic-ray Experiment EMMA

Detector geometry (by the end of 2013)

Total detector area = 250 m$^2$ + 24 m$^2$ + 180 m$^2$ = 450 m$^2$
5. Cosmic-ray Experiment EMMA

Detectors

- Three types of detectors: drift chambers, small-size plastic scintillation detectors, and Limited Streamer Tube detectors
  - accurate location of muon hit positions in large area
  - measurement of large muon multiplicities
  - determination of shower arrival angle

- Drift chambers
  - in total 7 × 84 chambers, approximately 250 m²
  - obtained from CERN by the expense of the delivery

- Plastic scintillation detectors (SC16)
  - new product, especially designed for EMMA
  - 16 × 96 pixels of 12 × 12 cm² (total area 24 m²)
  - paid by the Dept Conversion Programme (nominal price 1 MUSD)

- Limited Streamer Tube detectors
  - muon detectors of KASCADE–Grande experiment
  - 60 modules, 180 m², with the price of ∼30 kEUR
5. Cosmic-ray Experiment EMMA

Detectors – Drift chambers arrival (November, 2005)
5. Cosmic-ray Experiment EMMA

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5. Cosmic-ray Experiment EMMA

Detectors – Drift chambers (in the old surface laboratory)
5. Cosmic-ray Experiment EMMA

Detectors – Drift chambers

- Former muon detectors from the DELPHI experiment at LEP (at CERN)
  - a plank – 7 individual chambers
  - mass 120 kg per plank
  - chamber: 365 cm × 20 cm
  - 3 signals per chamber
- In total 84 planks (∼250 m²)
  - form the basis of the array
- Position resolution is good: ∼1 cm²
  - needed by tracking
- Ar (92%) : CO₂ (8%) at 1 bar
  - min ∼0.25 bar·ℓ/min /4 planks
5. Cosmic-ray Experiment EMMA
Detectors – Plastic scintillation detectors

- SC16 detector
  - $50 \times 50$ cm$^2$, $H = 13$ cm
  - mass $\sim 20$ kg per SC16
  - 16 individual pixels of $12 \times 12$ cm$^2 \times 3$ cm pixels
  - APD light collection
  - time resolution good: $\sim 2$ ns
  - In total 96 SC16-detectors (24 m$^2$), 1536 individual pixels

- Designed especially for
  - large muon multiplicities
  - fast trigger
  - initial guest for the arrival angle

- Made by Russian Academy of Sciences
  - Oulu and Jyväskylä Universities involved in the design
5. Cosmic-ray Experiment EMMA

Detectors – Limited Streamer Tubes arrival (May, 2012)
5. Cosmic-ray Experiment EMMA

Detectors – Limited Streamer Tubes arrival (May, 2012)
5. Cosmic-ray Experiment EMMA

Detectors – Limited Streamer Tubes arrival (May, 2012)
5. Cosmic-ray Experiment EMMA

Detectors – Limited Streamer Tubes (in the new surface laborartory)
5. Cosmic-ray Experiment EMMA

Detectors – Limited Streamer Tube (LST) detectors

- Muon detectors of KASCADE–Grande experiment (Karlsruhe)
- To be used as the second detector layer at the edge of the array and at 45-level
- Arrived in Pyhäsalmi at the end of May, 2012, to be done
  - read-out electronics and software
  - HV power supplied
- 60 LST modules
  - \( \sim 180 \text{ m}^2 \)
- Properties
  - \( 2.9 \text{ m} \times 1.0 \text{ m} \)
  - pixel size (PAD):
    - \( 2 \text{ cm} \times 8 \text{ cm} \)
  - gas: CO\(_2\) at 1 bar
5. Cosmic-ray Experiment EMMA

Drift chamber position calibration – Cosmic muons

Planks P15, P39, P18, and P17 were calibrated with radioactive $^{22}$Na $\beta$-source, ...

... and the rest of the planks with cosmic muons

Resolution ($\sigma$) $\approx$ 1 cm (delay line)

In total, the calibration process took approximately 4 years (for 84 planks, or 588 chambers), and 20 different calibration setups.
The time offset was adjusted and the time resolution determined using cosmic muons. The time difference can be used to estimate the arrival angle (initial guess for the tracking).

It took two weeks to collect the statistics and a week to built the setup for nine SC16 detectors. In total nearly a year.

The time resolution ($\sigma$) was determined to be $\sim 2$ ns. Accuracy of $\sim 10$ deg for the initial guess of the arrival angle.
Two drill holes for cables and pipes, \(~50\) m each
5. Cosmic-ray Experiment EMMA

Infrastructure – Gas system from surface to 75 m

Total flux $\sim 7 \ell / \text{min (Ar:CO}_2 \ 92:8)$, $\sim 15000$ euros per year
5. Cosmic-ray Experiment EMMA

Infrastructure – Gas system from surface to 75 m
5. Cosmic-ray Experiment EMMA

Infrastructure – Gas system from surface to 94 m

Ar (92%) from 600 ℓ dewar (LAr)

CO₂ (8%) from 30 kg bottle

94 m drill hole
5. Cosmic-ray Experiment EMMA

Infrastructure – Underground detector stations

Cavern conditions
pH \approx 3 \text{ (water)}
Rel.
Humidity \approx 100 \%
T \approx 10 \degree C

Inside the stations
Rel.
Hum. \approx 40–60 \%
T \approx 15-20 \degree C

\textbf{Good conditions}
5. Cosmic-ray experiment EMMA

Infrastructure – Underground detector stations
5. Cosmic-ray Experiment EMMA

An example of measured shower (2010)

Number of Tracks = 16
5. Cosmic-ray experiment EMMA

An example of measured shower (Feb. 2013)
5. Cosmic-ray experiment EMMA

Statistics

- Single muon rate at EMMA
  \[ \approx 1 \mu \text{ m}^{-2} \text{ s}^{-1} \]
  - good for detector monitoring
5. Cosmic-ray experiment EMMA

Statistics

- Single muon rate at EMMA
  \[ \approx 1 \, \mu \text{m}^{-2} \text{s}^{-1} \]
  - good for detector monitoring

- Single muon rate per station (C,F,G) \(\approx 5 \, \mu \text{s}^{-1}\)

- Shower rates
  - Stations CF, CG, or FG: \(1\text{–}1.5 \text{ min}^{-1}\)
  - Stations CFG: \(\sim 15 \text{ h}^{-1}\)

- At the knee or above (\(\geq 10 \, \mu\) per station in CFG)
  - some events per day

- Data rate currently \(\sim 30 \text{ MB per hour}\)
  - with the whole array \(\sim 200 \text{ MB per hour and } \sim 5 \text{ GB per day}\) (possible to save on hard disks)
5. Cosmic-ray experiment EMMA

Multiplicity with Stations C & F – 62 days (2012)

Track multiplicity

Counts

$10^3$

$10^2$

$10$

$1$  $10^{-1}$

4 PeV p  10 PeV p

Black histogram: Simulation
+ Corsika+QGSJET
+ 100% proton composition
+ normalized to $N_{\text{tracks}}(\text{C})=6$

$T_{\text{eff}} = 62$ days

- Station C
- Station F

PRELIMINARY
5. Cosmic-ray experiment EMMA

Trigger rate in Stations C & F & G

‘μ-Trigger’ Rates, Runs R148, ..., R150 (partial)
5. Cosmic-ray Experiment EMMA

Core Location Accuracy

![Diagram showing cosmic-ray location accuracy with histograms and a color-coded heat map.](image-url)
5. Cosmic-ray experiment EMMA

Near-future plans

- Currently four stations connected on the DAQ
  - stations C, E, F, G
- Station D connected to a test-DAQ
  - HV applied for a month
  - will be connected on the DAQ still in April
- Station A will be connected on the DAQ in May (or early June)
- In May/June the installation of plastic scintillation detectors underground starts

- Construction works
  - stations X and Y will be finished before the summer
  - after summer stations H, I, and Z are constructed
  - constructions finished by the end of 2013
5. Cosmic-ray Experiment EMMA
Muon bundles at CERN

- Events with high muon multiplicities (muon bundles) were observed by DELPHI, ALEPH and L3+C detectors of LEP at shallow depth.
  - origin of the bundles is not clear
  - current cosmic-ray or particle physics models can not explain

- Such bundles have also been observed at ALICE detector (LHC)

- Measured with short running times
  - colliding-beam experiments had the priority
  - not rare

- EMMA is also able to measure high-multiplicity events, especially with high-granularity scintillation detectors
  - composition analysis
  - can be studied for several years
5. Cosmic-ray Experiment EMMA

Muon bundles at CERN – ALICE at LHC
5. Cosmic-ray Experiment EMMA

Muon bundles at CERN – DELPHI (LEP)

$T_{\text{eff}} \approx 18$ days
DELPHI Hadron Calorimeter
$A_{\text{HCAL}} = 75 \text{ m}^2$
$E_\mu > 52 \text{ GeV}$

| $\text{Mul} > 3$ | 54201 |
| $\text{Mul} > 30$ | 1065 |
| $\text{Mul} > 70$ | 78 |
| $\text{Mul} > 100$ | 21 |

4 saturated events
2 saturated events (MUB)
5. Cosmic-ray Experiment EMMA
Muon bundles at CERN – ALICE (LHC)

∼180 muon tracks
(∼12 µ/m²)

E_µ > 15 GeV
Atmospheric $\mu$ multiplicity distribution for 2010 and 2011 data
Data of effectively $\sim$11 days in 2010 and 2011
5. Cosmic-ray Experiment EMMA

EMMA Collaboration (in summer 2010)

T. Enqvist, J. Joutsenvaara, J. Karjalainen, P. Kuusiniemi, T. Monto, T. Räihä, J. Sarkamo Univ. of Oulu, Finland
T. Kalliokoski, K. Loo, M. Slupecki, W.H. Trzaska, A. Virkajärvi University of Jyväskylä, Finland

L. Bezrukov, L. Inzhechik, B. Lüsandsorzhiev, V. Petkov RAS/INR, Moscow, Russia
H. Fynbo University of Aarhus, Denmark
6. Cosmic-ray Sources

Sources, acceleration mechanisms, propagation, ...

- The origin of cosmic rays is one of the major unsolved astrophysical problem
- In principle, separation between the particle sources and acceleration mechanisms
  - generally assumed that cosmic-ray particles are also accelerated near or in the source
- Candidate (or possible) sites for cosmic-ray production and/or acceleration
  - supernova explosion shock fronts
  - magnetized, rapidly rotating neutron stars (pulsars)
  - accreting black holes (or other binary systems)
  - centres of active galactic nuclei (AGN)
  - "external acceleration" in the interstellar or intergalactic medium (extensive magnetic gas clouds)
  - decay of relics of Big Bang (topological defects, domain walls or cosmic strings) [top-down models]
6. Cosmic-ray Sources

Sources, acceleration mechanisms, propagation, ...

- Large number of models for cosmic-ray acceleration have been developed
  - actual acceleration mechanisms are not completely understood and identified
  - it is also possible that various mechanisms together produce cosmic rays of different energies

- According to most popular models, the bulk of cosmic-ray particles is accelerated by shock fronts of supernova remnants (Fermi acceleration)
  - particle gain energy each time it traverses from unshocked region to shocked region and back
    \[\Rightarrow\] power-low energy spectrum
6. Cosmic-ray Sources

Supernova shock fronts

- Supernova explosion produces elements up to iron (Z=26)
  - can also include $^{27}$Co and $^{28}$Ni
  - end of the fusion process
- The maximum energy of cosmic rays by supernova explosion shock fronts can be estimated as (Greisen, chapter 11)

$$E_{\text{max}} \leq \frac{3}{20} \cdot \frac{u}{c} \cdot Ze \cdot B \cdot (uT_A)$$

For $10 \, \text{M}_{\odot}$ ejected at $5 \times 10^8 \, \text{cm/s}$ into the nominal ISM with 1 proton per cm$^3$, and assuming $T_A \sim 1000$ years and $B_{\text{ISM}} \sim 3 \, \mu\text{G}$

$$E_{\text{max}} \leq Z \cdot 3 \times 10^4 \, \text{GeV} \quad (\ast)$$

$Z = 1$ (p) : $E_{\text{max}} \approx 30 \, \text{TeV}$
$Z = 26$ (Fe) : $E_{\text{max}} \approx 1000 \, \text{TeV} = 1 \, \text{PeV}$
6. Cosmic-ray Sources

Supernova shock fronts

- The equation (*) "holds" for an average SN explosion, but includes large uncertainties and oversimplifications
  - both in supernova and acceleration mechanisms

- Some other models or estimations suggest slightly higher maximum energies, but the efficiency of the acceleration process may be too strong
  - A good round number to be used as the maximum energy for cosmic-ray acceleration by supernova explosions shock waves is
    \[ E_{\text{max}} \sim 100 \text{ TeV} \quad (= 10^{14} \text{ eV}) \]

- Conclusion: The equation (*), particle acceleration at supernova shock waves, would account for the origin of the bulk of cosmic rays
- Then, how to accelerate energies greater than \(~100 \text{ TeV}\) (i.e. above the knee region)?
6. Cosmic-ray Sources

Acceleration to 100 TeV and higher

- The equation
  \[ E_{\text{max}} \leq \frac{3}{20} \cdot \frac{u}{c} \cdot Z \cdot e \cdot B \cdot (uT_A) \]

  does not explain origin of cosmic rays with energies greater than
  \(~100\ \text{TeV} \ (\approx 10^{14}\ \text{eV})\)

- Higher energies can be reached (still in SN explosion shock fronts)
  by the same equation
  - by increasing the magnetic field (strength and/or orientation)
  - by increasing the time-scale of the acceleration

- Some other acceleration mechanisms (than SN shock fronts) may
  also be active in the galaxy
  - below \(10^{18} - 10^{19}\ \text{eV}\) : galactic origin
  - above \(10^{18} - 10^{19}\ \text{eV}\) : extragalactic origin
6. Cosmic-ray Sources

Supernova shock fronts – Higher energies

- Supernova explosion shock wave mechanism may itself accelerate particles at higher energies
  - Not always average explosion or interstellar medium
    - magnetic field strength and orientation
    - environment

- Magnetic field orientation
  - by having B perpendicular instead of parallel (to the direction of propagation of the shock front)
    - increase the B (and $E_{\text{max}}$) by a factor of 10 or more

- Environment
  - SN1987A: exploded into an "enriched" environment (riched by its progenitor)
    - $E_{\text{max}}$ could be higher by 1–2 order of magnitudes

- In total: $E_{\text{max}} \sim 10$ PeV
6. Cosmic-ray Sources

Pulsars

- Pulsars and binary systems in young supernovae have one advantage over the supernova shock waves
  - magnetic field much higher around the collapsed object than in the interstellar medium

- Acceleration powered by the rotational energy

\[ E_{\text{max}} \approx \frac{e \cdot B \cdot R^3 \cdot \Omega^2}{\sqrt{3} \cdot c^2} \]

where \( B \) is the magnetic field strength, \( R \) the radius and \( \Omega \) the angular frequency of the neutron star

- Typical 10-ms pulsar with a \( 10^{12} \) G surface magnetic field (\( R \approx 10 \) km and \( \Omega \approx 100 \) s\(^{-1}\))

\[ E_{\text{max}} \approx 10^5 \text{ TeV} = 100 \text{ PeV} \quad (10^{17} \text{ eV}) \]
Magnetars

- Neutron stars having exceptionally large magnetic field, $B \sim 10^{15}$ G
  - in normal neutron stars, $B \sim 10^{12}$ G
  - magnetic field of Magnetars decreases quite rapidly (in 10000 years)
  - a dozen known Magnetars

- A Magnetar model for the acceleration of cosmic-ray particles proposes
  \[ E_{\text{max}} \approx 3 \times 10^{22} \cdot Z \cdot B_{15} \cdot \Omega_4^2 \text{ eV} \]
  where $B_{15}$ is the magnetic field strength in $10^{15}$ G and $\Omega_4$ the angular frequency of the neutron star in s$^{-1}$.
  - this can lead to very high energies