The Extreme Energy Events
HECR array
status and perspectives

Extreme Energy Events
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Istituto Nazionale di Fisica Nucleare (To/Al/Bs)
University of Bari, Pisa, Siena, Torino, Cagliari
Bologna, Roma Tor Vergata, Salerno
CNAF (Bologna)
ICSC World Laboratory (Geneva)
CERN (Geneva)
JINR (Dubna)

European Cosmic Ray Symposium, 2016, September 5-9, Turin (Italy)
The Experiment
The Extreme Energy Events is a project started in 2004 for studying Low and High ECR and related phenomena by measuring muons and electrons in showers with a broad and sparse telescope array. Keeping also educational and outreach parallel mission.
The Experiment

EEE Scientific program - short/long baseline correlations

Telescopes are arranged in clusters with typical distances 100 m to 6 km. Each cluster size shows different energy thresholds:

i.e. 3 station - 1 km clusters $E_{th} \sim 10^{17}$ eV.
Clusters are 30 - 1000 km far away.

+ solar activity survey, effects on climate etc.
The Telescopes
The Multigap Resistive Plate Chambers

EEE chamber is an extended version of ALICE TimeOfFlight modules

- **6 gas gaps**: 2 glass plates with their external surfaces painted with resistive paint; 5 floating glass plates (spaced by 300 µm)
- **C₂H₂F₄ (98%)** and **SF₆ (2%)** continuously fluxed by (3l/h)
The Fishing line is used as a simple spacer (300 $\mu$m) between glasses.
The telescope

The avalanche detection and pitch

- 24 readout copper strips mounted on both sides of the stack of glass plates (i.e. cathode and anode read-out strips) ⇒ a differential signal is obtained by reading out both anode and cathode
- Strip pitch of 3.2 cm
- HV up to 20 kV (avalanche mode) supplied by 2 DC/DC converters
The Telescope

- Each telescope: 3 MRPC modules, 160 x 80 cm
- 6 Fast amplifier/discriminator NINO ASIC
- GPS
- VME-based data acquisition
  - 2 Multi-hit TDCs
  - (100 ps resolution)
- Weather Station
The telescope equipment
The Station Performances
Chamber Efficiencies and Dark Count

Test beam @ CERN PS

@ schools with CRs

CH 40 Efficiency - Dark Rate

CH 41 Efficiency - Dark Rate

CH 42 Efficiency - Dark Rate
Spatial resolution along strip direction

$$\Delta X = \frac{X_{BOT} + X_{TOP}}{2} - X_{MID} \Rightarrow \sigma_X = \sqrt{\frac{2}{3}} \sigma \sim 2.1 \text{ cm}$$

Several factors affect X resolution:
- Chambers alignment
- Multiple scattering
- Strip calibration
- Propagation of signal along strips
- TDC resolution
Station performances

Spatial resolution across strip direction
\[ \Delta Y = \frac{Y_{BOT} + Y_{TOP}}{2} - Y_{MID} \Rightarrow \sigma_Y = \sqrt{\frac{2}{3}}\sigma \sim 1 \text{ cm} \]

which is compatible with expected resolution
\[ \sigma_Y = \frac{3.2}{\sqrt{12}} \sim 0.9 \text{ cm} \]
Station performances

Time Resolution

σ_X ~ 141 ps

\[ \frac{2}{3} \sigma_X \sim 210 \text{ ps} \]
The Data Taking, Concentration, Reconstruction Philosophy
Data Taking and Coordinated Runs

![Graph showing total number of candidate tracks vs months of data acquisition. The x-axis represents months of data acquisition from 01 Oct 2014 to 01 Jul 2016, while the y-axis represents the number of tracks in log scale. The graph includes data from different dates and is color-coded to indicate different runs.](image-url)
Data Transfer and automatic reconstruction @ CNAF

- Data are stored at the INFN-CNAF computer centre of Bologna
- A complex software architecture has been set-up to reconstruct the data and provide quasi-online (few hours) Data Quality checks on the web for monitoring purposes.
Data Quality Monitor

Rate Monitor

Daily and Run by Run based trending fluxes are provided in a few hours and published online.

Environment

Pressure, Temperature and Humidity Data are also collected and made available for corrections and analysis.
Analysis and first results

Coincidences and showers
Available Clusters during RUN-2
The Path corrections and coincidences

Tracks Angular correction

Tracks time are corrected by path differences

30 m double coincidences

The EEE closest telescope pair at CERN
The Coincidences with increasing cluster size

205 m double coincidences

520 m double coincidences
The Coincidences with increasing cluster size

1.075 km double coincidences at TURIN

MC vs data comparison

Preliminary corrected coincidences rates agree with MC expectations (COSMOS and CORSIKA)
Analysis and first results

Anisotropies at subTeV scale
⇒ (single station analysis)
Near Universe CR Anisotropies

In the near Universe, anisotropies at $10^{-3} - 10^{-5}$ scales for TeV scale CR were measured. They were expected because of local non-uniformity of intergalactic magnetic fields (Compton getting effect due to e.g. Earth rotation around the Sun).
Shuffling corrections and first Aitoff maps

RAW DATA

Corrected Map

equatorial dots are border effects

SHUFFLE CORRECTIONS

Shuffling statistical approach was used to correct for time exposure and acceptance. No anisotropies observed at the level of $5 \cdot 10^{-3} - 10^{-2}$ scale.
Analysis and first results

*Upward particle flux*

... understanding the feasibility of a measurement *upward going* $\nu$
Analysis and first results

CR flux modulation
Forbush decreases and sun-related phenomena

Forbush decreases are prompt CR flux decrease correlated to CME and Flares on Sun.

Flares are prompt e.m. flashes at $\sim 10^{25}$ J ($P_{\text{sun}} \sim 10^{26}$ W).

Coronal Mass Ejections are proton burst at $\sim 10^{23-24}$ J with speed 20-2000 km/s.

A complete understanding of both Flares, CME and Forbush is not yet available.
Forbush 2015-11
very good correlations with Neutron Monitors

GCRD 2015-11-07

% flux variation

2h bins

EEE: BOLO-03 + BOLO-04 + LAQU-01 + SAVO-02 + TORI-03

OUNLU neutron mon.

preliminary
Forbush 2015-12

low correlations with Neutron Monitors and **two-step recovery mechanisms**

GCRD 2015-12-31: EEE-OULU fluxs

2h bins

EEE: ALTA-01 + BOLO-03 +
+ CATZ-01 + TORI-04

OULU neutron mon.

preliminary
Pressure, Temperature corrections have to be deeply studied in order to perform a robust correction to the non-CR related modulation effects.

Latitude and Longitude dependance studies are possible also with the EEE detectors (10 degrees in lat and long coverage).

crossing the data with NM net is on the way

... 

after stabilizing the telescopes, long term studies on solar cycle survey are feasible.
Summary and Conclusions
Telescopes are built at CERN by students and teachers installed in high schools monitored by students > 500 students involved ...growing

- Masterclasses
- Lectures
- Trainings on detectors
- Analysis
- Schools
- Events
Conclusions

- EEE is a wide tracking telescope array
  - 52 telescope already working
  - > 25 in construction
- high time resolution
- tracking capabilities
- 10 degrees in latitude and longitude coverage
- suitable both for studies at energies below and above the knee
- multipurpose array
  - HECR
  - CR flux modulation
  - local anisotropies (with coincidences also higher energies available)
  - studying the feasibility of upward flux identification
- Environmental Studies
- + educational purposes
2015 Articles

- EEE coll.: Looking at the sub-TeV sky by cosmic muons detected in the EEE MRPC telescopes"
  - EPJ-Plus (2015), 130:187
- EEE coll.: A study on upward going particles with the Extreme Energy Events telescopes
- ... and preparing
- ”The EEE Telescope performances”
- ”An extended study of subTeV anisotropies with the EEE array”
- ”A study of multistation coincidences at the km scale with the EEE array”
- ”A Forbush decrease survey with the EEE telescopes”
Backup
EEE Scientific program - single station

- Anisotropies (subTeV)
- Upward particle flux (mainly background)
- Rare events
  - high multiplicity
  - non random events
- long term solar activity correlation
- prompt solar events
- effects on atmosphere and climate
EEE Scientific program - long baseline correlations

Search for rare correlations due to:

- primaries photodisintegration nearby the Sun
- GZK-like effect
- interaction with interstellar medium
- ....
- possible astronomy? to be investigated

⇒ ≥ 2 high energy correlated secondaries
EEE Telescope distributions

The array is regularly extended:

- Since 2004 Pilot Phase with 7 telescopes in Lecce, Bologna, Cagliari, Catania, Frascati, L’Aquila, Torino
- At present 52 telescopes arranged both in clusters and single station, installed in High Schools (47), at CERN (2) and inside INFN sections (3)
- ... growing
The **Requirements** and the solutions to address these topics

- Extended array ($>10^5$ km$^2$)
- Telescope clusters with variable geometry
- Long term operation (survey physics)
- High efficiency (rare events)
- High time resolution (Upward-Downward)
- Tracking capabilities on secondaries
- Reasonable costs

$\Rightarrow$ Multigap Resistive Plate Chambers
Stations are far away, thus remote control is fundamental

- HV-LV systems
- DAQ
- Weather station
- Data Transfer
- Gas system
Each module provides a two-dimensional position information with efficiency close to 100% and a good spatial resolution.

- **x coordinate**: difference of signal arrival times at the strip ends measured by TDCs
- **y coordinate**: number of fired strip or weighted average of strip cluster
Chamber Signal/Background and Station efficiency

**S/B**

At plateau the S/B is $\sim 5$ orders of magnitude

**Telescope Cluster Efficiency**

High efficiency is fundamental for clusters total efficiency if looking to $\sim$ few events/years
Angular and speed resolution

1/\beta distribution

Slow muons and electrons tails can be tagged with $\chi^2$ (next slides)

Tracks Angular residuals

Geometrical simulation: evaluation of the relative angle between a simulated track and the track reconstructed with the telescope.
The main challenge in coordinated Data Taking is related to the **sparse** and far away geometry of the array (up to **1000 km** of distance).

- **Pilot-run**: first simultaneous acquisition of half (23) of the EEE telescopes.
  - Nearly 1 billion events i.e. muon tracks collected in the period 27 October-14 November 2014.
- **Run-1**: 35 EEE telescopes took part in the data taking.
  - More than 5 billion events i.e. muon tracks collected in about three months (2 February-30 April 2015).
- **Run-2**: ~40 EEE telescopes in acquisition from the end of October 2015 till mid May 2016.
  - More than 15 billion events i.e. muon tracks collected.
Data Quality Monitor
Data Quality Monitor

<table>
<thead>
<tr>
<th>PLOT</th>
<th>ALARM</th>
<th>STATUS</th>
<th>OUTPUT</th>
<th>LIMITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RateHitEvents</td>
<td>y_values</td>
<td>Clean</td>
<td>52.34 +/- 0.94</td>
<td>[4/8 – 80/100]</td>
</tr>
<tr>
<td>DeltaTime</td>
<td>exp_fit_lambda</td>
<td>Clean</td>
<td>50.05 +/- 0.23</td>
<td>[4/8 – 80/100]</td>
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<tr>
<td>HitMultTop</td>
<td>x_average</td>
<td>Clean</td>
<td>1.0928 +/- 0.0021</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
</tr>
<tr>
<td>HitMultMid</td>
<td>x_average</td>
<td>Clean</td>
<td>1.1306 +/- 0.0026</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
</tr>
<tr>
<td>HitMultBot</td>
<td>x_average</td>
<td>Clean</td>
<td>1.1043 +/- 0.0022</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
</tr>
<tr>
<td>HitMultTotal</td>
<td>x_average</td>
<td>Clean</td>
<td>3.3150 +/- 0.0059</td>
<td>[1.50 / 2.50 – 6 / 9]</td>
</tr>
<tr>
<td>ClusterMultTop</td>
<td>x_average</td>
<td>Clean</td>
<td>1.0933 +/- 0.0021</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
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<tr>
<td>ClusterMultMid</td>
<td>x_average</td>
<td>Clean</td>
<td>1.1307 +/- 0.0026</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
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<tr>
<td>ClusterMultBot</td>
<td>x_average</td>
<td>Clean</td>
<td>1.1048 +/- 0.0023</td>
<td>[0.500 / 0.750 – 2 / 3]</td>
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<tr>
<td>ClusterMultTotal</td>
<td>x_average</td>
<td>Clean</td>
<td>3.3289 +/- 0.0059</td>
<td>[1.50 / 2.50 – 6 / 9]</td>
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<tr>
<td>ChiSquare</td>
<td>x_average</td>
<td>Clean</td>
<td>2.958 +/- 0.021</td>
<td>[1 / 2 – 6 / 10]</td>
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<tr>
<td>RateTrackEvents</td>
<td>y_values</td>
<td>Clean</td>
<td>49.83 +/- 0.92</td>
<td>[4/8 – 80/100]</td>
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<tr>
<td>FractionTrackEvents</td>
<td>y_values</td>
<td>Clean</td>
<td>0.9631 +/- 0.0036</td>
<td>[0.400 / 0.800 – 1 / 1]</td>
</tr>
<tr>
<td>Phi</td>
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</tr>
<tr>
<td>Theta</td>
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<tr>
<td>TimeOfFlight</td>
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<tr>
<td>TrackLength</td>
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</tbody>
</table>

A set of monitoring parameters and distributions are automatically evaluated and **alarms** are generated.
This study is for understanding the feasibility of a measurement upward going $\nu$, both atmospheric and extraterrestrial.

The total upward/downward flux ratio is $2 \cdot 10^{-3}$.

This means we have $S/B \sim 10^{-7}$ to be resolved ($S/B \sim 10^{-10}$ expected for atm. $\nu$).

A component with $\sim 2 \mu s$ TDP is clearly evident.

The population at TDP$\sim 23$ ms is related with uncorrelated time-adiacent events.
Events at TDP\(-23\) ms are related to parent slow muons

\textbf{TDP vs parent muon }\beta

\textbf{Exponential fit - particle Lifetime}

\(\mu\) decay population with \(\tau \sim 2.2\mu s\)
First step done, now increasing statistics for deeper studies

Only 6% of the upward flux is identified as electrons from $\mu$ decay.

The upward flux apparently uncorrelated to previous muons contains electrons and backscattered muons with untriggered parent muons.

These components are now the ones to be investigated, since they mimic genuine upward muon flux.
The EEE TOF measurements allows to tag upward flying particles.

The study of Upward flux is of interest for understanding the feasibility of a measurement of upward going neutrinos converting in the Earth crust, both atmospheric and extraterrestrial. The expected down/upward ratio for EEE telescopes is $<10^{-10}$ just for atmospheric components.
Shuffling corrections and first Aitoff maps

RAW DATA

Corrected Map

equatorial dots are border effects

SHUFFLE CORRECTIONS

Shuffling statistical approach was used to correct for time exposure and acceptance. Each real event correspond to 20 false events randomized over 24 h.

**TRIN-01 corrected**

Trinitapoli telescope Aitoff Map corrected using the shuffling method.

**4 Stations Average**

Weighted average of the corrected maps for the TRIN-01, CAGL-01, SAVO-01, CATA-01 telescopes. No anisotropies observed at the level of $5 \cdot 10^{-3} - 10^{-2}$ scale.
The most reliable scenario is a two step mechanism which involves:

- The magnetic line disruption via plasma thermal pressure, with a proton burst emission.
- Magnetic line reconnection and reheating with a flare emission.
Interplanetary magnetic field and low energy CR are
- first swept and compressed by the shock wave
- then again disturbed by the proton burst
Flare 2014-11: X Class
few days waiting for the effects on Earth...
Forbush 2014-11

good correlations with Neutron Monitors

but muon amplitude a factor $\sim 2$ higher
Forbush 2015-06

good correlations with Neutron Monitors

but muon amplitude a factor $\sim 2$ lower
Forbush 2015-11
very good correlations with Neutron Monitors
Forbush 2015-12
low correlations with Neutron Monitors and two-step recovery mechanisms

GCRD 2015-12-31: EEE-OULU fluxs

preliminary

2h bins
EEE: ALTA-01 + BOLO-03 + CATZ-01 + TORI-04

OULU neutron mon.
the different CR Forbush effects on muon and neutron component is not understood (and not confirmed)

Pressure, Temperature corrections have to be deeply studied in order to perform a robust correction to the non-CR related modulation effects

Latitude and Longitude dependance studies are possible also with the EEE detectors (10 degrees in lat and long coverage)

crossing the data with NM net is on the way

... 

after stabilizing the telescopes, long term studies on solar cycle survey are feasible.
2015 Conferences

- Frontier detectors for Frontier Physics (13th Pisa Meeting on advance detectors)
  ⇒ Nucl. Instr. & Meth. A
  - M. P. Panetta: The EEE Project: an extended network of muon telescopes for the study of cosmic rays
  - F. Noferini: The computing and data infrastructure to interconnect EEE stations

- International School of Subnuclear Physics Erice 2015
  - L. Cifarelli: The EEE Project of the Enrico Fermi Centre

- 34th International Cosmics Rays Conference ICRC 2015 (The Hague)
  ⇒ Proceedings of Science
  - I. Gnesi: Results from the observations of Forbush decreases by the Extreme Energy Events experiment
  - F. Pilo: First results from Run-1 of the Extreme Energy Experiment
2015 Conferences

- Cosmic Ray Internation Seminars 2015
  ⇒ Nuclear and Particle Physics Proceedings
  - De Gruttola: First results from coordinated data taking by the Extreme Energy Events experiment

- Topics in Astroparticle and Underground Physics 2015
  - L. Perasso: EEE Extreme Energy Events: an astroparticle experiment in italian high schools

- Congresso SIF 2015
  - M. Abbrescia: Run-1 of the Extreme Energy Events experiment
  - E. Bossini: Test and characterization of Multigap Resistive Plate Chambers for the EEE Project.
  - M. P. Panetta: Distribuzioni angolari di muoni cosmici osservati dai Telescopi del Progetto EEE.
2016 Conferences

- 14th Vienna Conference on Instrumentation 2016
  - P. La Rocca: "Operation and performance of the EEE network array for the detection of cosmic rays"
- The XIII workshop on Resistive Plate Chambers and related detectors
  - M. P. Panetta: "Recent results and performance of the EEE Project MRPCs network"
- + 4 more within the end of the year