CERN Colloquium

MEASURING COSMIC RAY SHOWERS UP TO THE NORTH POLE

L. Cifarelli
University & INFN, Bologna (IT)
Centro Fermi, Rome (IT)
Italian Physical Society

Geneva, 26 September 2018
A. ZICHICHI, Progetto "La Scienza nelle Scuole"
EEE – Extreme Energy Events
Società Italiana di Fisica (SIF), Bologna
1st Ed. 2004; 2nd Ed. 2005
5th Ed. 2017

Collaboration project
Centro Fermi
CERN
INFN
MIUR
SIF

Launch event on 3 May 2004 at CERN

R. Aymar – CERN DG
L. Moratti – Minister of Science & Education
A. Zichichi – Centro Fermi President
Physics goal of EEE Project

Detect atmospheric showers of very high or extreme energy by detecting secondary muons on ground coming from very high energy primary cosmic rays
Cosmic ray shower

Muon flux at sea level ≈ 1 muon / cm² mn

Most of the (secondary) cosmic rays are muons
Atmospheric shower of very high or extreme energy coming from a very high energy primary cosmic ray producing a large number of muons on ground

Primary cosmic proton of $10^{17}$ eV interacting at 15 km altitude $\rightarrow$ shower with $10^6$ muons on the city of Bologna
How to achieve the goal to detect high energy cosmic ray showers?

By equipping a large number of Italian High Schools each with a large EEE telescope:

a very sophisticated particle tracking detector with outstanding timing capabilities

→ The EEE Project has a dual role:

• Education instrument for students together with their tutors & teachers

• Scientific instrument for physicists which involves students in a forefront research experiment

It is indeed a physics experiment!
51 telescopes in High Schools

+ 2 telescopes at CERN
+ 6 telescopes in INFN Units
  [Bologna (2), Catania, Genova, Lecce, Pisa]

Total: **59 telescopes**

 Mostly distributed in clusters over the whole Italian territory (+ Geneva)

… 54 Italian High Schools participating without telescopes
The EEE Project

Largest surface covered by a detector of cosmic muons on ground so far

\[ \approx 0.5 \times 10^6 \text{ km}^2 \approx 10^\circ \text{ of latitude/longitude} \]

moreover with both tracking and timing capabilities \( \rightarrow \) pointing capabilities

Largest area of MRPC (Multigap Resistive Plate Chamber) detectors built and operating so far

\[ \approx 200 \text{ m}^2 \]

moreover not in Research Labs but in High Schools
THE EEE COLLABORATION

Centro Fermi — CERN
INFN Bari, Bologna, Catania, Genova, Pisa, Torino — INFN CNAF, LNGS, LNF

Order of 500-1000 students & teachers / yr involved !!!!
Largest world Laboratories for Cosmic Ray studies

Pierre Auger Observatory

Extreme Energy Events EEE Project

70 km

with “Telescope”

without
EEE telescope with 3 MRPCs and relative system

Freon 98% / SF₆ 2%

INFN CNAF

Gas mixer

FE Right

-LV

Internet

USB Connected

DAQ

VME CRATE

GPS Receiver

HV/LV Controller

+LV

FE Left
MRPC chambers are built by High School students at CERN (starting from 2004) and maintained by them under the supervision of EEE researchers.

ALICE-TOF @ CERN LHC
Multigap Resistive Plate Chamber (MRPC)
Main features of EEE MRPC

- The MRPCs developed for the EEE Project are characterized by 6 gas gaps each, 300 µm thick, obtained by separating glass plates, 1.1 mm thick, 80 x 160 cm² in dimensions, by means of commercial nylon fishing lines used as spacers.

- The outer glass plates are coated with resistive paint, and act as high voltage electrodes, while the inner ones are left electrically floating.

- The gas mixture is $\text{C}_2\text{H}_2\text{F}_4$ (tetrafluoroethane, Freon) / $\text{SF}_6$ (hexafluoride) mixed in 98 / 2 % proportions, flowing at a typical rate of 2–3 l/h.
Main features of EEE MRPC

- Standard operating voltage ranges around 18-20 kV, so that the chambers operate in avalanche saturated mode

- Signals are induced on 24 copper strips (per chamber) glued on the two vetronite plates placed on top and bottom of the glass outer layers

- Signals are sent to Front End electronics based on NINO-ASIC chips (as for the CERN ALICE experiment), amplified, discriminated and subsequently acquired by means of multi hit TDCs
Main features of EEE MRPC

- Since readout strips (180 cm along x, 2.5 cm with 0.7 cm pitch along y) lie longitudinally on the chambers, one coordinate (x) of the muon impact point is given by the difference of the signal arrival times at the two strip extremities, while the other (y) is directly obtained from the position of the fired strip.
EEE Project
MRPC construction
Construction at CERN during 2017-2018

2017
- 20-27 February → Lampedusa
- 12-18 March → Genova
- 23-29 April → Siena
- 7-13 May → Torino + Moscow
- 21-27 May → Lodi
- 10-14 July → Lodi + Korçë (spare MRPCs)
- 25-29 September → Cagliari

2018
- 11-16 February → Altamura (BA)
- 23 Feb – 3 March → Carcare (SV)
- 18-23 March → Roma
- 21-25 May → PolarQuEEEst

Mixed team of teachers/students from Majorana Lyceum in Lampedusa: the southermost point of Italy
Main features of EEE MRPC

Since EEE stations operate in High Schools, particular attention has been put on safety issues.

- The gas mixture does not contain any flammable component (no isobutane, which is routinely used with this kind of chambers).

- High voltage is provided by small DC/DC converters of the EMCO-Q series, providing an output voltage up to 10 kV when powered with 0-5 V, packed in small boxes and connected directly to the electrodes of the detector.
Main features of EEE system

- The DAQ system makes use of VME standards and the DAQ program is LabView based and runs on a PC connected to the VME crate by means of a CAEN USB-VME bridge.

- Each event acquired must be provided with the relative time stamp; this is given by a Global Positioning System (GPS) VME module integrated in the system and readout by the DAQ program.

- New card integrating trigger card, GPS and GPS interface.

- Pressure and temperature sensors recorded by DAQ.

- Independent gas control system.
The EEE telescope

MRPC Chambers are built by High School students at CERN (starting from 2004) and maintained by them under the supervision of EEE researchers.

1 MRPC = 24 strips

Acceptance
$\Omega = 1.6 \text{ sr}$

3 MRPC planes with 24 strips each read at both ends $\rightarrow$ 144 readout channels

- The trigger requires a hit signal on each end of the 3 MRPCs within a $\pm 500 \text{ ns}$ window
- Cosmic muons are tracked & reconstructed
Muon rate depends on local conditions in high schools:

- material budget above telescope
- altitude of the telescope
- MRPC settings etc.

$\rightarrow 20 \approx 60 \text{ Hz}$
EEE telescopes installed inside High Schools
... and real life / real time installation
The Extreme Energy Event (EEE) experiment is devoted to the search of high-energy cosmic rays through a network of telescopes installed in over 50 High Schools + Labs distributed throughout the Italian territory.

One of the main goals of the project is to involve young students in a high-level scientific enterprise.

Therefore the experiment is very peculiar and requires new solutions for the data management.

Data are collected (all Schools → CNAF) and automatically reconstructed.
The EEE Project Runs

2014 Pilot run
2015 Run-1
2016 Run-2
2017 Run-3
2018 Run-4

EEE monitor – DQM
with information in real time
http://eee.centrofermi.it/monitor
Almost all telescopes (49) connected to INFN CNAF and transferring data using bittorrent sync

A CNAF front-end is dedicated to receive all the data with a required bandwidth of 300 kB/s

A btsync client is installed in each School (Win OS)

5-10 TB per year are expected

Overall statistics until now including 5 data taking runs: more than 70 billion cosmic rays

*Pilot run from 27-10-2014 to 14-11-2014
Run-1 from 02-03-2015 to 30-04-2015
Run-2 from 06-11-2015 to 20-05-2016
Run-3 from 01-11-2016 to 30-06-2017
Run-4 from 02-10-2017 to 30-05-2018
Run-5 from 15-10-2018 to 31-05-2019
FULL monitor of EEE telescopes
Run-2

EACH DAY

RED if n. tracks = 0
GREEN if n. tracks ≥ 432000
(≥5 Hz for 24 h)
YELLOW else
EEE Telescopes: Performance


Statistics from the four coordinated runs. The number of active telescopes in Pilot Run, Run 1, Run 2 and Run 3, is respectively 15, 28, 38 and 46. The purity is calculated as candidate tracks/triggers.

<table>
<thead>
<tr>
<th></th>
<th>Pilot Run</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>starting date</td>
<td>27/10/2014</td>
<td>27/02/2015</td>
<td>07/11/2015</td>
<td>01/11/2016</td>
</tr>
<tr>
<td>ending date</td>
<td>14/11/2014</td>
<td>30/04/2015</td>
<td>20/05/2016</td>
<td>31/05/2017</td>
</tr>
<tr>
<td>number of days</td>
<td>19</td>
<td>63</td>
<td>196</td>
<td>212</td>
</tr>
<tr>
<td>tracks/day (M)</td>
<td>(\sim 27)</td>
<td>(\sim 53)</td>
<td>(\sim 69)</td>
<td>(\sim 85)</td>
</tr>
<tr>
<td>purity (%)</td>
<td>75</td>
<td>84</td>
<td>83</td>
<td>80</td>
</tr>
</tbody>
</table>

(purity defined with \(\chi^2 < 5\) reconstructed tracks)

Performance study with a sample of 8 billion tracks over 31 billion tracks collected in Run-2 and Run-3
TOF resolution

$\Delta t$ distribution is obtained by using top & bottom MRPCs as reference and comparing expected and measured hits on the middle MRPC

$\Delta t$ distribution for one of the EEE telescopes (TREV-01), showing the gaussian fit and the time resolution $\sigma_t = 184 \text{ ps}$ (after Time Slewing correction)

Time resolution measured with data taken in Run 3, for 33 telescopes: the average time resolution is given by the gaussian fit and is $\sigma_t = 238 \pm 40 \text{ ps}$
Reconstructed track multiplicity in a typical EEE telescope

$(\chi^2 < 5$ for reconstructed tracks$)$
Longitudinal & transverse spatial resolution with 39(44) EEE telescopes in Run 2(3)

\( \Delta t \) distribution is obtained by using top & bottom MRPCs as reference and comparing expected and measured hits on the middle MRPC

(0.84 cm on test beam)
Efficiency in the middle MRPC with 31 EEE telescopes

- Example of HV scan with 9 telescopes
- Corrected for pressure and temperature effects

Efficiency obtained at the plateau of the middle MRPC for 31 EEE telescopes

An efficiency better than 90% is reached by 77% of the telescopes
Cosmic rays flux and EEE

EEE telescopes collect secondary muons coming from primary cosmic rays of over $10^{11}$ eV.

Coincidences between telescopes allow to select primary energies above $10^{15}$ eV (thousands of TeV).

Single telescope sensitivity

Multi-telescope analyses
Galactic Cosmic Ray Decrease (GCRD)

Among the non-periodic intensity variations, **rapid decreases of the galactic cosmic-ray (GCR) flux due to solar activity** (the so-called Forbush decreases) are the most common and the most interesting.

GCRD events consist of an impressive transient change in the cosmic-ray intensity. They are characterized by a **rapid** (a few hours) intensity reduction, followed by a **slow** recovery in a few days time range.

GCRD events are complex phenomena. Such strong variations of cosmic-ray intensity are related to **solar flares** and the associated **geomagnetic disturbances** caused by the external field of the magnetic storm.
Solar flares & cosmic rays

It was a solar flare of category X2 followed by an important Coronary Mass Emission (CME)

This kind of flares are constantly monitored since they can have relevant consequences on Earth
Galactic Cosmic Ray Decrease (GCRD)

The 2011 Valentine’s Day solar flare observed as GCRD event by 2 EEE telescopes (Altamura, Catania)

First High Schools ever to observe a cosmic-ray flux decrease associated with a solar flare !!!

- Observed in the muon channel (rather rare)
- First in the world published !!!
- Data quality comparable to that of professional observatories such as the Oulou (Finland) detector of the Neutron Monitor Network
In March 2012 a GCRD event observed by the Oulou (Finland) and Rome detectors of the Neutron Monitor Network was also observed for the first time by 5 EEE telescopes: Altamura, Bologna (3), Catania.
Flare of class M3.7 by the Solar Dynamics Observatory (SDO)

Flare of class M1.8 by the Solar Dynamics Observatory (SDO)
Flare of class M3.7

Flare of class M1.8

GCRD 2015-11-07: EEE-NULL fluxes

2h bins
EEE: BOLO-03 + BOLO-04 + LAQU-01 + SAVO-02 + TORI-03

OULU neutron mon.

GCRD 2015-12-31: EEE-OULU fluxes

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

OULU neutron mon.


\[
\frac{\sigma_{XY}}{\sigma_X \sigma_Y} = 0.83
\]

GCRD 2015-12-31: EEE-OULU corr.

\[
\frac{\sigma_{XY}}{\sigma_X \sigma_Y} = 0.44
\]
New results on recent GCRD of 16/7/2017

Very intense (7% decrease) as seen by Oulu neutron monitor

Try observation with single EEE telescopes and with coincidences of nearby EEE telescopes to look at two different energy ranges

WORK IN PROGRESS
High energy events

Dense of secondaries at sea level

- $E = 10^{11}$ eV
- $E = 10^{12}$ eV
- $E = 10^{13}$ eV
- $E = 10^{14}$ eV
- $E = 10^{15}$ eV

Measure **coincidences between distant telescopes**

- Increasing the distance between telescopes, the energy of the shower and of the primary observed increases as well.

- The flux of muons on ground depends not only on the energy but also on the lateral profile of the shower.

  - many days/months of operation needed for very large distances between (2) telescopes

Corsika MC simulations

5 events/day

20 events/day
As from 2014

– with more statistics via coordinated data taking Runs
– taking advantage of the tracking capability of the telescopes to select different impact angles and to apply angular & time corrections

➔ the search for coincidence events from near and distant telescopes is successfully ongoing
2-telescope coincidences

Single-track coincidences between 2 telescopes were well reconstructed for several distances between telescopes.

The relative angle between 2 tracks was required to be $< 30^\circ$ ($\approx 10\text{-}15^\circ$ on average).

The width of the reconstructed peak is usually of the order of $200\text{-}250\text{ ns}$ (CERN and Bologna cases differ because of particular GPS setups).
The width of the reconstructed peak is usually of the order of 200-250 ns (CERN and Bologna cases differ because of particular GPS setups)

The correction event by event of the time delay between two telescopes (because of the propagation of the wave front of the shower) significantly improves the S/B ratio
For the first time coincidences were observed between two telescopes installed in High Schools at a distance greater than 1 km (significance $S/\sqrt{S+B} = 5.1$)

**2-telescope coincidence results from Run-2 and Run-3 (2016-2017)**

**Coincidences at Torino**
- Telescopes distance = 1076 m
- Days analyzed = 138
- Preliminary Run-2

**Coincidences at Savona**
- Telescopes distance = 1180 m
- Days analyzed = 339
- Preliminary Run-0 + Run-1 + Run-2

**Coincidences at Bologna**
- Telescopes distance = 1500 m
- 2 INFN tel. vs Liceo Galvani
- Preliminary Run-2 + Run-3

Counts (at 400 ns)

Delta t (ns)
Multi-track events

Preliminary simulation of Corsika MC showers using EEE telescope geometry

Average energy (Corsika, 220 days)

Single telescope

$\langle E \rangle$ (GeV)

$N_{\text{tracks}}$

$10^5$ GeV $< E_{\text{primary}} < 10^7$ GeV

$(10^{14}$ eV $< E_{\text{primary}} < 10^{16}$ eV)
An ambitious goal is to use the EEE experiment to search for cosmic ray correlations at large distances (from 10 km up to thousand km) taking advantage of the EEE configuration to provide maximum detection sensitivity.

The observation of such large-distance correlations between detectors separated by distances much larger than the extension of the highest energy atmospheric shower is a powerful tool to search for “anomalies” ...

Nuclear fragmentation via photodisintegration (Gerasimova-Zatsepin effect) is one possibility … but not only.

EEE typical distances between 2 telescopes

With 50 telescopes > 1200 combinations
Long distance shower correlations

Extensive Air Showers (EAS) reconstructed via cluster signals i.e. telescope-pair coincidences

Search for coincidences of 2 EAS i.e. of 2 clusters = 2 telescope-pair coincidences
Showers reconstructed via cluster signals (cluster = telescope-pair coincidence)

10 EEE clusters active in Run-1 & Run-2 → 45 possible cluster pairs

Single cluster signal:
• telescope-pair coincidence within 1 µs (average telescope time as cluster time)
• $\theta_{\text{rel}} < 40^\circ$ for the two tracks

Single cluster rate:
$10^{-3} – 10^{-2}$ Hz i.e. 10 – 100/day

→ Consider 2-cluster coincidences within a certain time window

→ Distances from 86 km to 1200 km

→ 15 billion tracks

→ 96 observed events against 77.8 of estimated background
Long distance shower correlations


Number of coincidence events vs. decreasing time window

| Event | EEE pairs      | Distance (km) | $|t_1 - t_2|$ (μs) | $\vartheta_{rel}$ (deg) | Expected events | p-value | UTC time                  |
|-------|----------------|---------------|------------------|------------------------|-----------------|---------|---------------------------|
| (A)   | BOLO-CAGL      | 614           | 86               | 27.1                   | 0.0069 ± 0.0002 | 0.007   | 26.11.2015 19 h 07' 16'' |
| (B)   | BOLO-LAQU      | 290           | 740              | 9.1                    | 0.014 ± 0.001  | 0.014   | 25.03.2016 18 h 31' 05'' |
| (C)   | CATA-TORI      | 1040          | 88               | 9.2                    | 0.0265 ± 0.0005| 0.026   | 09.01.2016 06 h 42' 15'' |
| (D)   | GROS-TORI      | 377           | 297              | 14.4                   | 0.032 ± 0.001  | 0.031   | 04.06.2016 02 h 31' 08'' |
| (E)   | CERN-CATA      | 1200          | 248              | 9.3                    | 0.049 ± 0.001  | 0.048   | 15.02.2016 01 h 28' 29'' |
| (F)   | CAGL-CERN      | 817           | 690              | 8.7                    | 0.073 ± 0.002  | 0.070   | 26.02.2016 09 h 21' 58'' |
| (G)   | CERN-SAVO      | 285           | 99               | 6.1                    | 0.108 ± 0.001  | 0.102   | 24.11.2015 12 h 35' 47'' |
| (H)   | CAGL-SAVO      | 566           | 99               | 19.9                   | 0.115 ± 0.001  | 0.109   | 08.04.2015 00 h 02' 50'' |
| (I)   | BOLO-CERN      | 450           | 73               | 19.4                   | 0.1194 ± 0.0001 | 0.112 | 03.05.2016 06 h 46' 35'' |
| (L)   | LAQU-SAVO      | 453           | 760              | 10.9                   | 0.142 ± 0.003  | 0.132   | 13.12.2015 21 h 43' 00'' |

5 candidate events with a p-value < 0.05
NEW APPROACH

Also include coincidences between

- multi-track telescope with $N_{\text{track}} \geq 3$
- telescope-pair cluster with a $(N_{\text{track}})^{\text{total}} \geq 3$
Long distance shower correlations

Analysis performed with:

- 39 telescopes + 5 clusters
- 50 million telescopes or clusters with $N_{\text{track}} \geq 3$
- data taking period: 01/01/2016 → 26/03/2018 (Run-2 up to Run-4 → ≈ 50 billion tracks)
- distance telescope-telescope or telescope-cluster > 5 km
- $N_{\text{track}} \geq 5$ in each telescope or cluster

→ 11 coincidence events observed in a narrow time window $\sim 10^{-5} – 10^{-4}$ s (with an expected background $\sim 5$ events) corresponding to a p-value $\sim 4 \times 10^{-3}$
## Long distance shower correlations

Correlations between multi-track events in both telescopes

<table>
<thead>
<tr>
<th>Tel 1 (ID)</th>
<th>Tel 2 (ID)</th>
<th>$N_{\text{track}}$ 1</th>
<th>$N_{\text{track}}$ 2</th>
<th>Date</th>
<th>Rel. angle (deg)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>115 CERN</td>
<td>7 Bologna</td>
<td>7</td>
<td>5</td>
<td>09/01/2016</td>
<td>21</td>
<td>456</td>
</tr>
<tr>
<td>122 L’Aquila</td>
<td>7 Bologna</td>
<td>6</td>
<td>5</td>
<td>27/04/2016</td>
<td>41</td>
<td>290</td>
</tr>
<tr>
<td>115 CERN</td>
<td>14 Catanzaro</td>
<td>7</td>
<td>5</td>
<td>12/05/2016</td>
<td>18</td>
<td>1194</td>
</tr>
<tr>
<td>22 L’Aquila</td>
<td>41 Torino</td>
<td>5</td>
<td>5</td>
<td>21/05/2016</td>
<td>23</td>
<td>551</td>
</tr>
<tr>
<td>27 Lodi</td>
<td>35 Savona</td>
<td>5</td>
<td>5</td>
<td>21/01/2016</td>
<td>24</td>
<td>137</td>
</tr>
<tr>
<td>19 Frascati</td>
<td>31 Reggio E.</td>
<td>5</td>
<td>5</td>
<td></td>
<td>71</td>
<td>361</td>
</tr>
<tr>
<td>10 Cagliari</td>
<td>27 Lodi</td>
<td>6</td>
<td>5</td>
<td>27/01/2017</td>
<td>71</td>
<td>675</td>
</tr>
<tr>
<td>15 CERN</td>
<td>30 Paternò</td>
<td>5</td>
<td>5</td>
<td>19/03/2017</td>
<td>1208</td>
<td></td>
</tr>
<tr>
<td>7 Bologna</td>
<td>14 Catanzaro</td>
<td>6</td>
<td>5</td>
<td>31/03/2017</td>
<td>36</td>
<td>767</td>
</tr>
<tr>
<td>23 L’Aquila</td>
<td>24 Lecce</td>
<td>6</td>
<td>5</td>
<td>02/06/2017</td>
<td>64</td>
<td>456</td>
</tr>
<tr>
<td>5 Bologna</td>
<td>36 Savona</td>
<td>5</td>
<td>5</td>
<td>08/10/2017</td>
<td>24</td>
<td>229</td>
</tr>
</tbody>
</table>

**WORK IN PROGRESS**
Search for multi-messenger events with EEE telescopes

- Six GW events detected so far by interferometers
- Recent searches for other probes synchronized with GW events
  - 1 Gamma Ray Burst event (detected by INTEGRAL and FERMI)
  - High energy neutrinos by Auger, IceCube and ANTARES within +/- 500 s → No evidence found

- Possible activities from EEE
  - Continuous data taking
  - Several analysis strategies (single track, multi-tracks, showers)

GW170814
### Search for multi-messenger events with EEE telescopes

<table>
<thead>
<tr>
<th>GW event</th>
<th>Date</th>
<th>Notes</th>
<th>N. EEE ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>14/09/2015</td>
<td>First GW detection; first BH merger observed; largest progenitor masses to date</td>
<td>3</td>
</tr>
<tr>
<td>GW151226</td>
<td>26/12/2015</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>GW170104</td>
<td>04/01/2017</td>
<td>Farthest confirmed BH event to date</td>
<td>26</td>
</tr>
<tr>
<td>GW170608</td>
<td>08/06/2017</td>
<td>Smallest BH progenitor masses to date</td>
<td>32</td>
</tr>
<tr>
<td>GW170814</td>
<td>14/08/2017</td>
<td>First BH detection by three observatories; first measurement of GW polarization</td>
<td>6</td>
</tr>
<tr>
<td><strong>GW170817</strong></td>
<td><strong>17/08/2017</strong></td>
<td>First NS merger observed in GW; first detection of EM counterpart; nearest event to date</td>
<td><strong>6</strong></td>
</tr>
</tbody>
</table>
Search for multi-messenger events with EEE telescopes

<table>
<thead>
<tr>
<th>GW event</th>
<th>Date</th>
<th>Operative EEE telescopes</th>
<th>N. EEE ON</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW150914</td>
<td>14/09/2015</td>
<td>BARI-01, BOLO-01, BOLO-04</td>
<td>3</td>
</tr>
<tr>
<td>GW151226</td>
<td>26/12/2015</td>
<td>ALTA-01, AREZ-01, BARI-01, BOLO-01, BOLO-03, BOLO-04, CAGL-01, CAGL-02, CAGL-03, CATA-01, CATA-02, CATZ-01, COSE-01, FRAS-02, FRAS-03, GROS-01, LAQU-02, PARM-01, PISA-01, REGG-01, SAVO-02, SAVO-03, TERA-01, TORI-02, TORI-03, TORI-04,</td>
<td>26</td>
</tr>
<tr>
<td>GW170104</td>
<td>04/01/2017</td>
<td>AREZ-01, BARI-01, BOLO-01, BOLO-02, BOLO-03, BOLO-04, CAGL-02, CAGL-03, CATA-01, CATA-02, CATZ-01, COSE-01, GROS-01, GROS-02, LAQU-01, LODI-01, PARM-01, PATE-01, REGG-01, SALE-01, SAVO-01, SAVO-02, TORI-01, TORI-03, TORI-04, TRAP-01,</td>
<td>26</td>
</tr>
<tr>
<td>GW170608</td>
<td>08/06/2017</td>
<td>ALTA-01, AREZ-01, BOLO-01, BOLO-02, BOLO-03, BOLO-04, CAGL-01, CAGL-02, CATA-01, CATA-02, CATZ-01, CERN-01, CERN-02, COSE-01, GROS-01, GROS-02, LAQU-01, LAQU-02, LODI-01, LODI-02, PARM-01, PATE-01, PISA-01, SALE-01, SALE-02, SIEN-01, TORI-01, TORI-03, TORI-04, TRAP-01, TREV-01</td>
<td>32</td>
</tr>
<tr>
<td>GW170814</td>
<td>14/08/2017</td>
<td>AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-04, TRAP-01</td>
<td>6</td>
</tr>
<tr>
<td>GW170817</td>
<td>17/08/2017</td>
<td>AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-03, TORI-04</td>
<td>6</td>
</tr>
</tbody>
</table>
Search for multi-messenger events with EEE telescopes

VERY PRELIMINARY analysis of GW events observed in August 2017

- GW170814: First measurement of GW polarization
- GW170817: First detection of EM counterpart of GW

Analysis strategy: search for multi-track events

- Rate of multi-track events: 10-60 events in 1000 s
- First analysis carried out in +/- 500 s around the GW event of interest with $N_{\text{track}} \geq 3$

CERN-02 telescope

No observation of any specific anomaly but the analysis is still ongoing
Search for multi-messenger events with EEE telescopes

VERY PRELIMINARY analysis of GW events observed in August 2017

- GW170814: First measurement of GW polarization
- GW170817: First detection of EM counterpart of GW

Analysis strategy: search for multi-track events

- Rate of multi-track events: 10-60 events in 1000 s
- First analysis carried out in +/- 500 s around the GW event of interest with $N_{\text{track}} \geq 3$

GW170817

No observation of any specific anomaly but the analysis is still ongoing
The EEE project sails to North Pole!

Airship Italia – 1928
Umberto Nobile

Polar QuEEEst 1928 – 2018
Measure Cosmic Rays flux with three detectors
45° in latitude span
5000 km distance

http://www.polarquest2018.org/
EXTREME ADVENTURE
Complete circumnavigation, aboard a sailing boat, of the Svalbard Archipelago, in the Arctic Ocean, above the Polar Arctic circle (from 74° to 81° North latitude).

EXTREME SCIENCE
An international team of arctic researchers, today’s explorers of the unknown, looking for answers to some of the great enigmas of science, from climate change to measuring the impact of human pollution at extreme latitudes, from the study of paleoclimate to the origin of high energy cosmic rays.

EXTREME EXPLORATION
A quest for the wreck of the Italia airship on the 90th anniversary of the crash which made the history of polar exploration.

A MESSAGE FOR THE PLANET
A voyage to the last untouched wilderneses on earth, to convey the importance of the Arctic for our sustainable future.
The EEE project sails to North Pole!

ExPeDitiOn Timeline

21 July 2018 → 1 August 2018 → 4 – 24 August 2018 → 4 September 2018

Departure of Nanuq from Isafjordur, Iceland (66° 04’ N, 23° 07’ W)

Arrival Longyearbyen, Svalbard (78° 13’ N, 15° 39’ E), Ny Alesund, Svalbard (78° 55’ N, 11° 55’ E)

Nobile Expedition GEOHACK Location Nordaustlandet, Svalbard (81° 14’ N, 28° 14’ E)

Tromsø, Norway (69°40’58”N 18°56’34”E)
The EEE project sails to North Pole!

- 8 scintillator tiles + 16 SiPMs in two planes
- Full TDC custom readout (< 10 W)
- GPS time stamp

22 - 25 May 2018

18 High School students from Norway, Switzerland and Italy at CERN to build the detectors

PolarQuEEEst detector
The PolarQuEEEst detector electronics

Centero Fermi, INFN (Bari, Bologna), Politecnico di Torino
The PolarQuEEEst detector electronics

(overall power consumption: 12-13 W)

- Power box
- Readout board
  FPGA Altera Cyclone 5
  For Trigger and TDC readout
- HPTDC piggy-back
  for TDC readout
- Data stored on SDD memory or transmitted via internet

Centro Fermi, INFN (Bari, Bologna), Politecnico di Torino
≥ 3 SiPMs coincidence required → Single POLA rate ≈ 30 Hz

- POLA-01
- POLA-02
- POLA-03

~351 coinc/h
~30 coinc/h
~40 coinc/h
~120 coinc/h
The trip

The PolarQuEEEst expedition started on the 22 July (data from 21 July) from Isafjordur and ended in Tromso on 3 September.

During this period one PolarQuEEEst detector (POLA-01) was hosted on Nanuq and sailed towards the North Pole.

Two other identical detectors were installed in two high schools: one in Norway (POLA-02) and one in Italy (POLA-03).

Data monitor accessible at eee.centrofermi.it/monitor
The PolarQuEEEst detector

- 2 scintillator planes
- Distance between planes: 15 cm
- 4 tiles per plane
  - 30 cm x 20 cm
- Each tile 2 SiPMs
- Efficiency (overall) > 96%

Detector construction @CERN

POLA-01 installation on Nanuq’s bow
You have to be smart ...
Nanuq leaving Isafjordur (Iceland)
Nanuq en route to the Svalbard Islands
Nanuq at the Svalbard Islands
Sailboat roll and temperature

Accelerometer

Roll of Nanuq

Gyroscope

Temperature effect
Orientation of the detector (zenithal)

The acceptance depends on the zenithal orientation of the detector.

When sailing this orientation may change but it can be measured using the accelerometer on board and looking at the direction of the gravity acceleration in the local system \( \cos \theta = \frac{g_z}{g} \)

The max acceptance is expected to be at \( \cos \theta = 1 \) (\( \theta = 0 \)) since the flux of secondaries has a maximum in the vertical direction.
Corrections

1. Rates have to be corrected for the barometric effect since the absorption of secondaries (muons) increases with the amount of matter in the atmosphere, to which the pressure is proportional. 
   \[ \text{corrections obtained by fitting the rate dependence on the pressure for each detector separately during the full period} \]

2. For POLA-01 also correction due to the detector orientation which may change when sailing (less relevant than pressure correction).
   \[ \text{corrections obtained by correlating the rate with the azimuthal angle using the accelerometer installed in the station (z-projection of the acceleration, i.e. gravity)} \]

\[
p = 0.705 \pm 0.017 \\
\text{Slope} = -0.002183 \pm 0.000016
\]

\[
p^0 = 33.2 \pm 0.0 \\
p^1 = 1.341 \pm 0.020
\]

\[ \text{rate} = p^0 \left(1 - p^1 \left(1 - \frac{g_z}{|g|}\right)\right) \]
On 30 July a problem occurred for Nanuq (during low tide) …

Data were nevertheless collected before reaching this “exotic” position.

This special event allowed to verify the proper calibration of the orientation correction!!
Rate (corrected)

Preliminary
Rate vs. latitude

POLA-02 (in Oslo @ 59° N) used as reference since closer in latitude than POLA-03 (in Turin @ 45° N)

No significant effect observed → possible variation < 1%

82° N (max) – North of Svalbard
POLA-01 on Nanuq
66° N (min) - Iceland
Previous cosmic ray measurements underwater at the North Pole with EEE Project

A. Chilingarov and A. Zichichi – 2007
Measurements done at the North Pole in a submersible for few hours down to more than 4000 m depth
→ «No rate anomaly»
Previous cosmic ray measurements underwater at the North Pole

ETTORE MAJORANA – ERICE – SCIENCE FOR PEACE
PRIZE 2007 TO ARTHUR NIKOLAIEVICH CHILINGAROV

«In charge of Arctic and Antarctic research, including International Polar Year activities, Arthur Nikolaievich Chilingarov has established scientific observatories, organised and conducted several research expeditions in the Arctic and Antarctic regions, including the 2007 sub-marine exploration of the sea-bed under the North Pole, a scientific and technological achievement which has been compared to the walking of the man on the moon.»

December 2008
Pontifical Academy of Sciences
Previous cosmic ray measurements at sea level

A.H. Compton
Phys. Rev. 43 (1933) 387

Soya Ship Route, 1960

... vs. latitude

Fig. 8. Intensity vs. geographic latitude.

Polar Ship Survey, 1999

... on boat

Soya Ship Route, 1960
Ions/cc s in standard air

Fig. 8. Intensity vs. geographic latitude.

PolarQuEEEst latitude coverage

EEE latitude coverage (36°N – 46°N)
The arrival in Longyearbyen after Svalbard circumnavigation
Thanks to those to whom I have borrowed/stolen slides

and thank you all for the attention