"Ettore Majorana" Foundation and Centre for Scientific Culture
56th Course – From Gravitational waves to QED, QFD and QCD
INTERNATIONAL SCHOOL OF SUBNUCLEAR PHYSICS

The EEE – Extreme Energy Events Project

Extreme
Energy
Events
Science inside Schools

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

Erice, 21 June 2018

A. ZICHICHI, *Progetto "La Scienza nelle Scuole"*
EEE – Extreme Energy Events
Società Italiana di Fisica (SIF), Bologna
1st Ed. 2004; 2nd Ed. 2005
3rd Ed. 2012; 4th Ed. 2014
5th Ed. 2017

Collaboration project

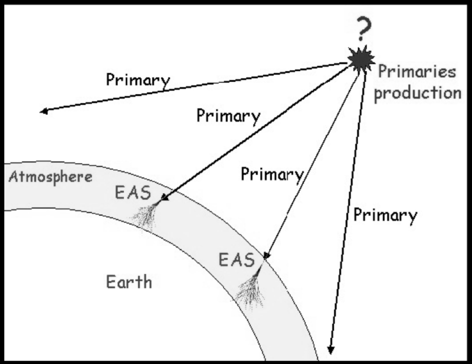
Centro Fermi
CERN
INFN
MIUR
SIF

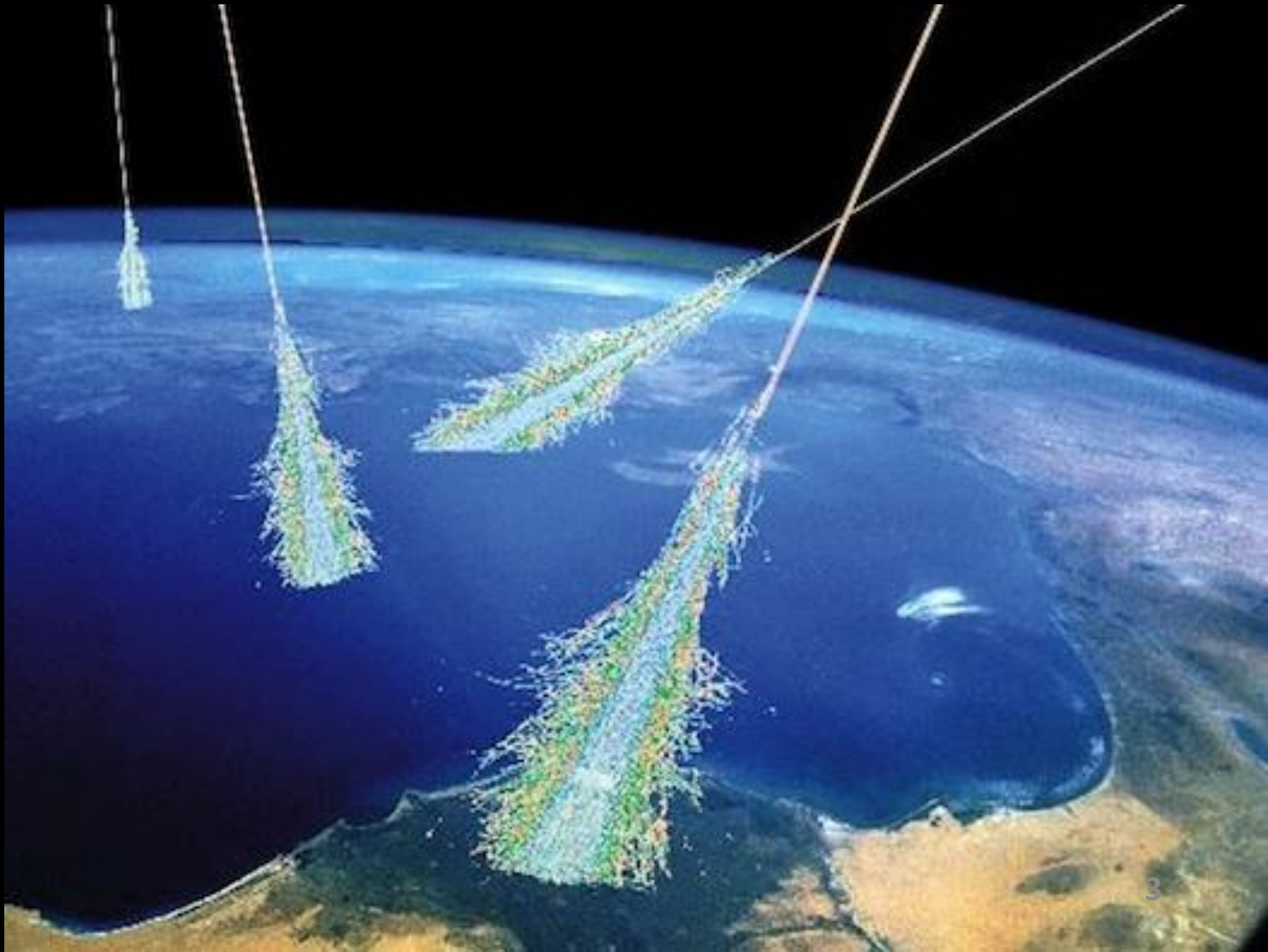
Launch event on 3 May 2004 at CERN

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

Physics goal of EEE Project

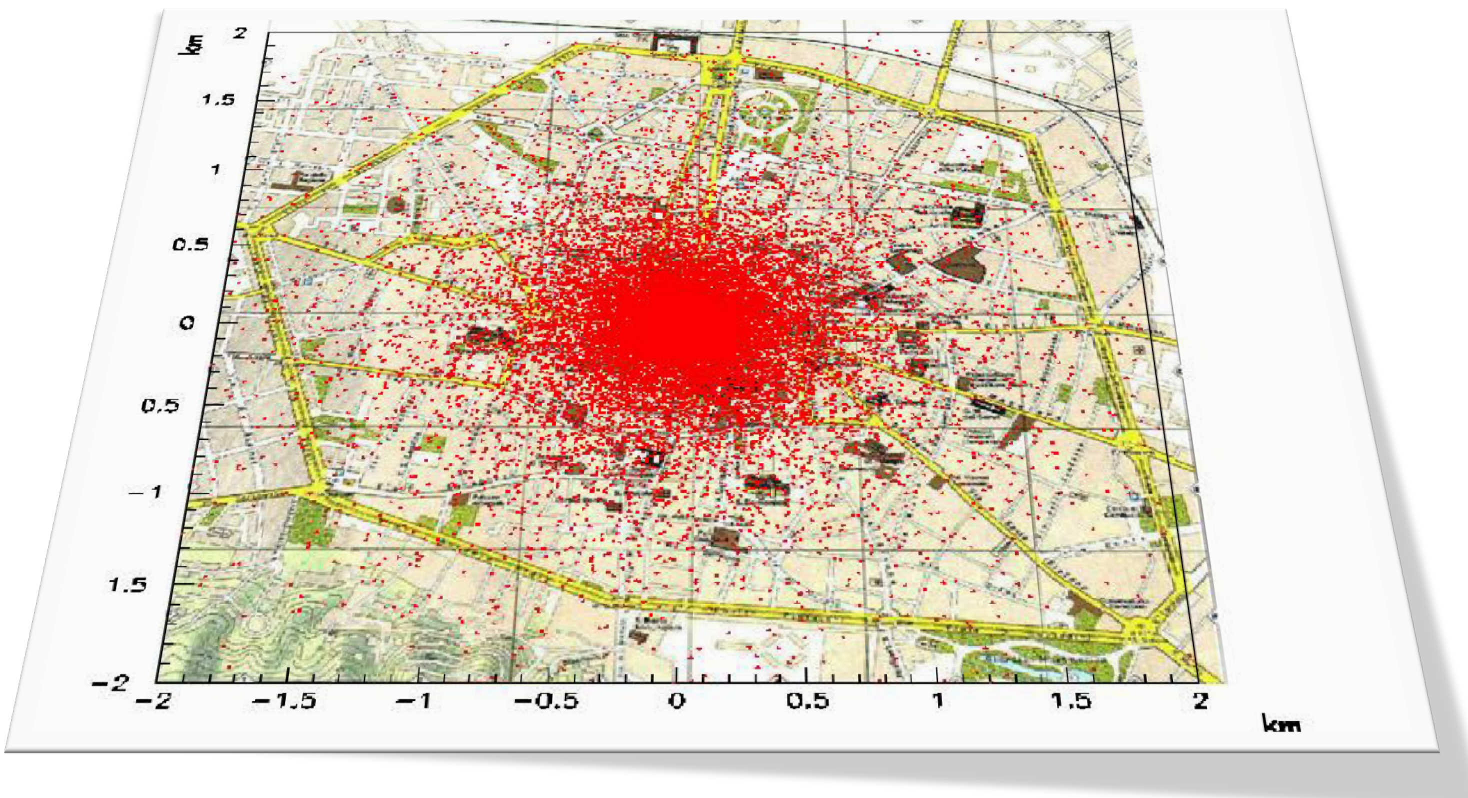
Detect atmospheric showers of very high or extreme energy by detecting secondary muons on ground coming from very high energy primary cosmic rays





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 → shower with 10^{6} muons on the city of Bologna



How to achieve this goal?

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

a very sophisticated particle <u>tracking</u> detector
with outstanding <u>timing</u> 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 !

The EEE Project

Since 2004 …

Pilot project with 7 EEE telescopes in High Schools (Bari, Bologna, Cagliari, Catania, Frascati, L'Aquila, Torino)

→ In 2018: 59 EEE telescopes
51 in High Schools
+ 8 in Research Labs

across an overall area of $\gtrsim 0.5 \times 10^6$ km^2

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

- *Telescopes in operation in High Schools*
- *Telescopes in operation in Research Labs*
- *High Schools without telescopes*

The EEE Project

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

$\approx 0.5 \times 10^6$ km^2 $\approx 10°$ of latitude/longitude

moreover with both tracking and timing capabilities

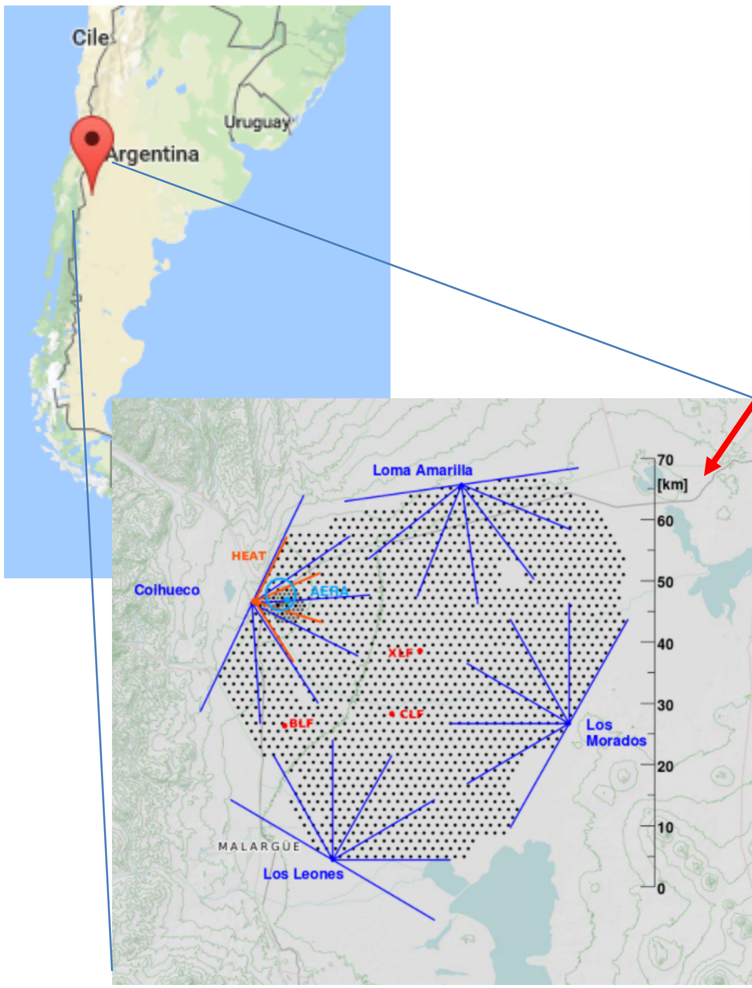
Largest area of MRPC (Multigap Resistive Plate Chamber) detectors built and operating so far

≈ 200 m^2

moreover not in Research Labs but in High Schools

Largest world Laboratories for Cosmic Ray studies

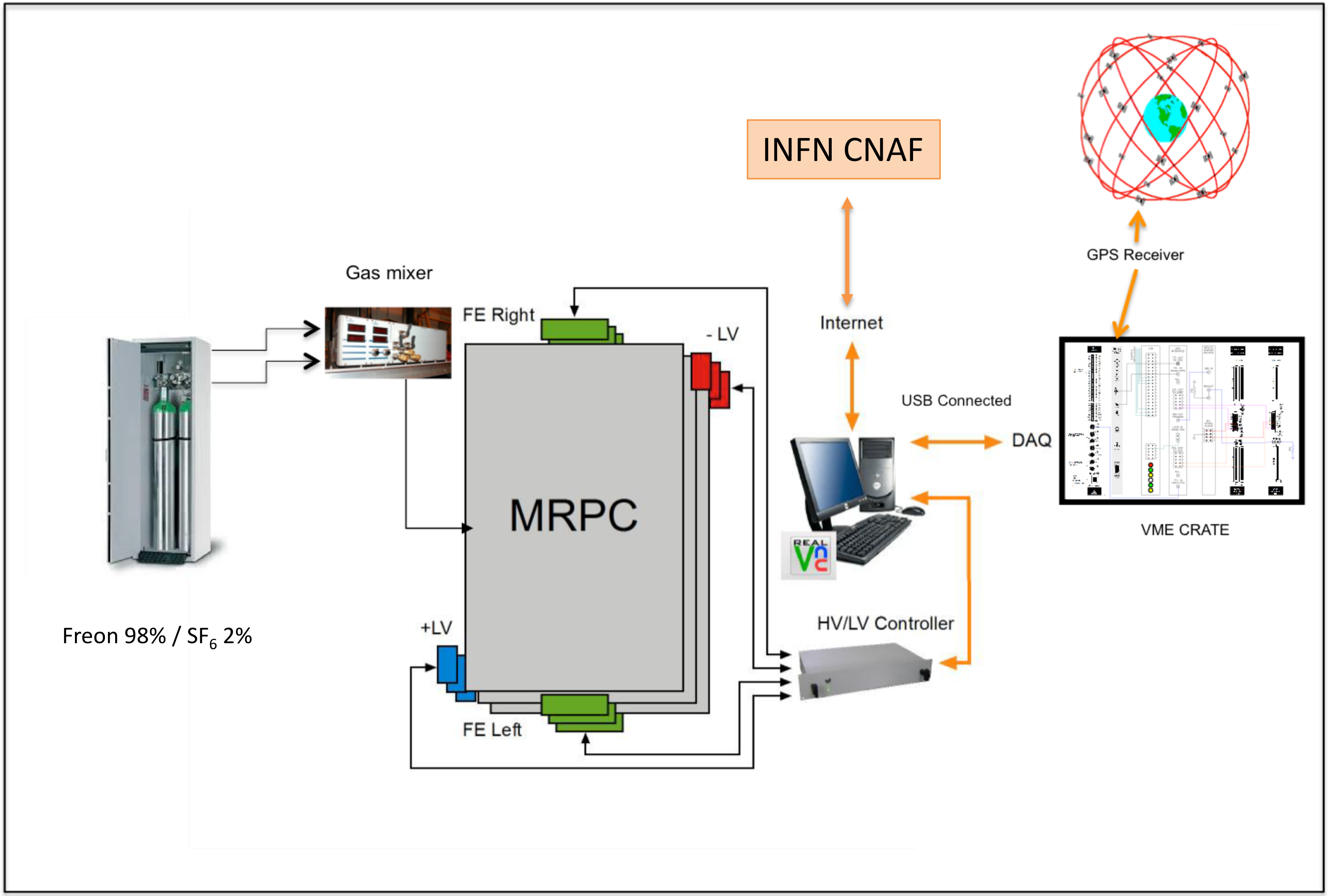
Pierre Auger Observatory



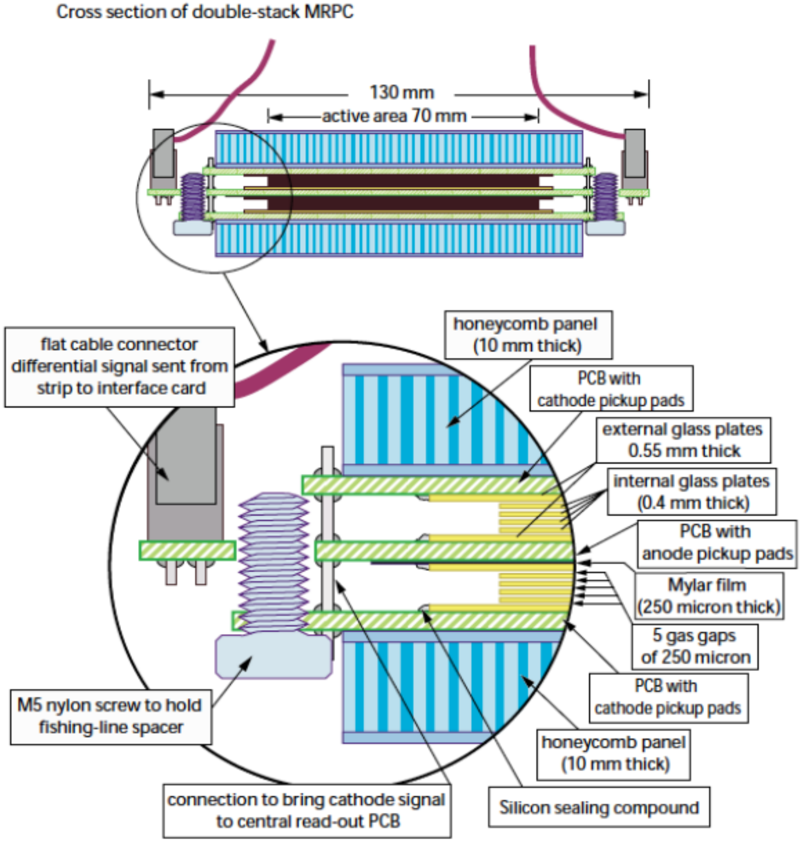
70 km

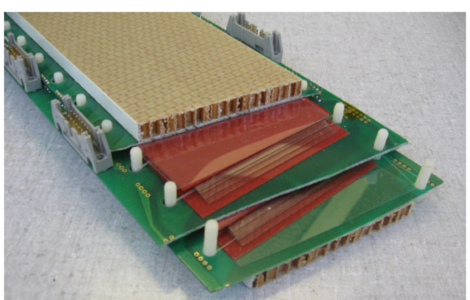
Extreme Energy Events
EEE Project

EEE telescope with 3 MRPCs and relative system

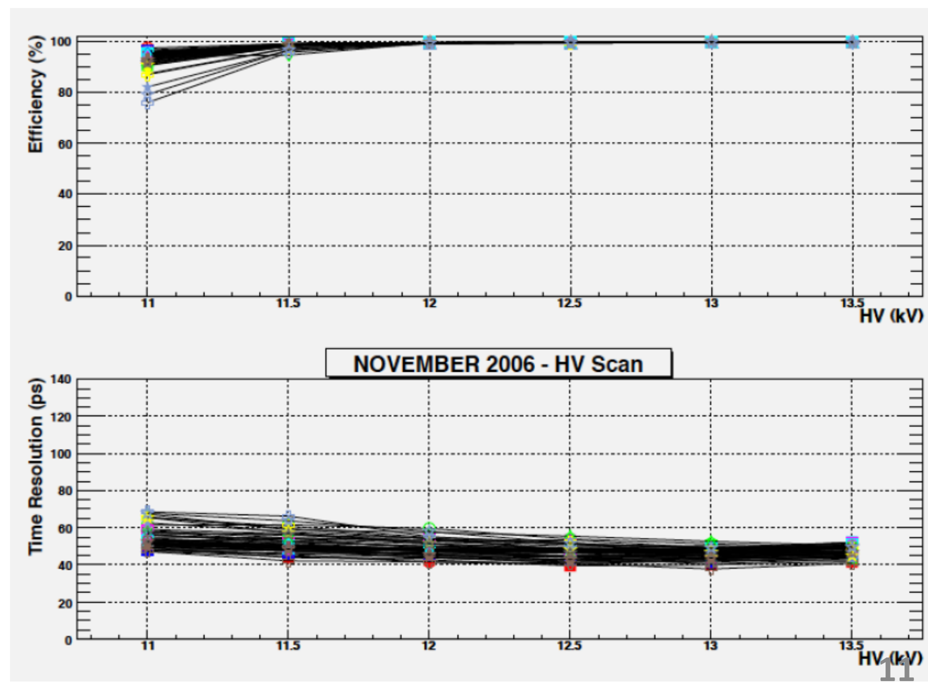


ALICE-TOF @ CERN LHC
Multigap Resistive Plate Chamber (MRPC)

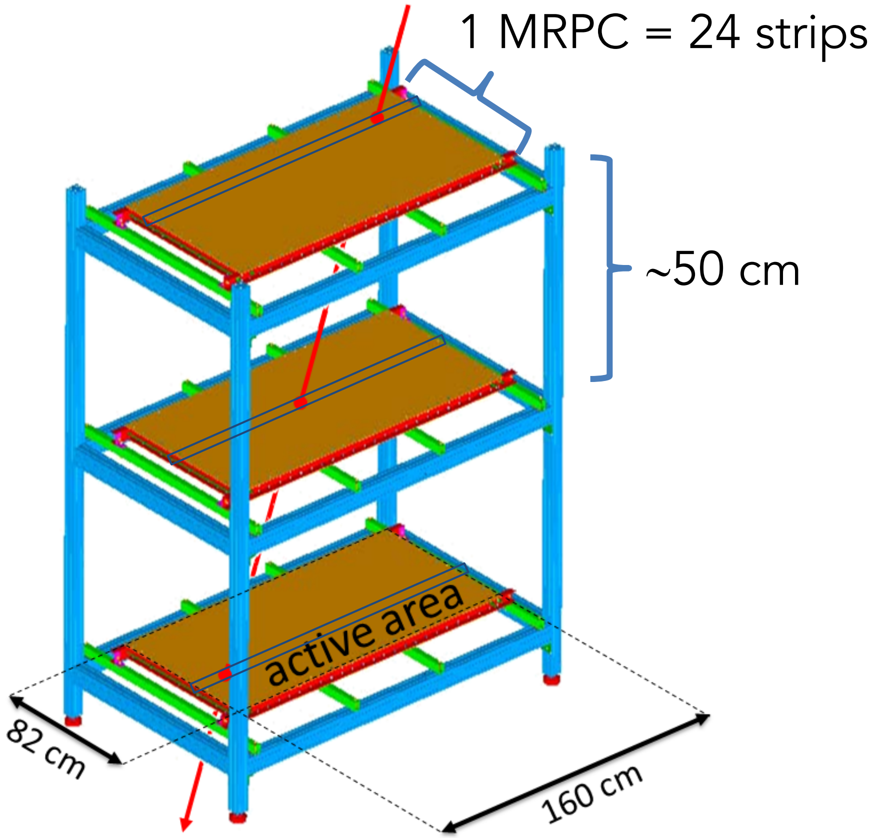




$C_2H_2F_4$ 93% / SF_6 7%



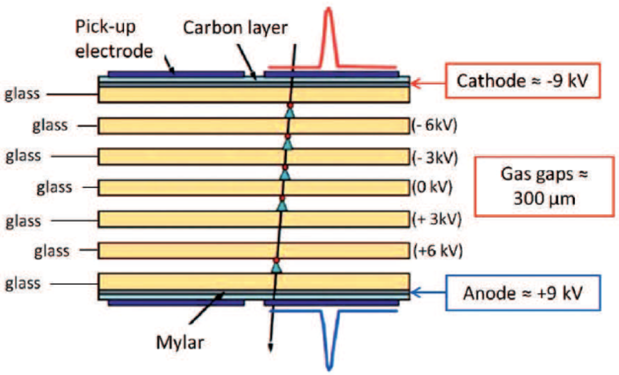
The EEE telescope



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

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 cm^2 in dimensions, by means of commercial nylon fishing lines used as spacers

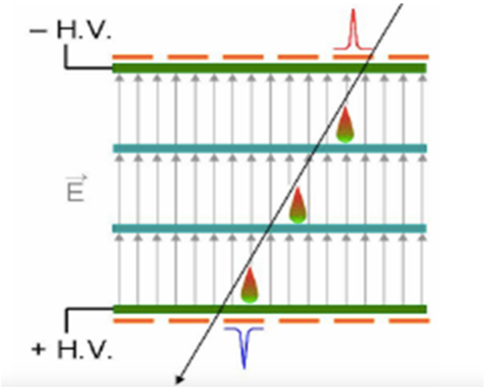


- The outer glass plates are coated with resistive paint, and act as <u>high voltage electrodes</u>, while the inner ones are left <u>electrically floating</u>

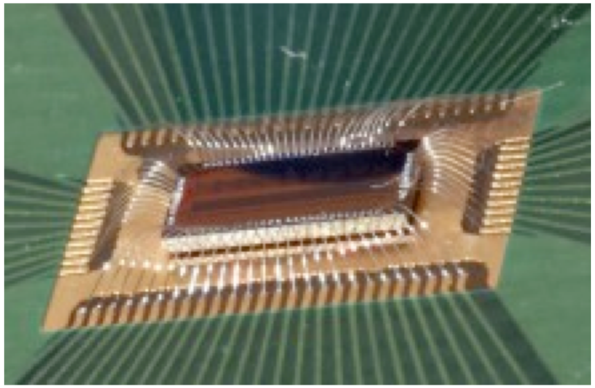
- The gas mixture is $C_2H_2F_4$ (tetrafluoroethane, Freon) / SF_6 (hexafluoride) mixed in 98 / 2 % proportions, flowing at a typical rate of 2–3 l/h

Main features of EEE MRPC

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

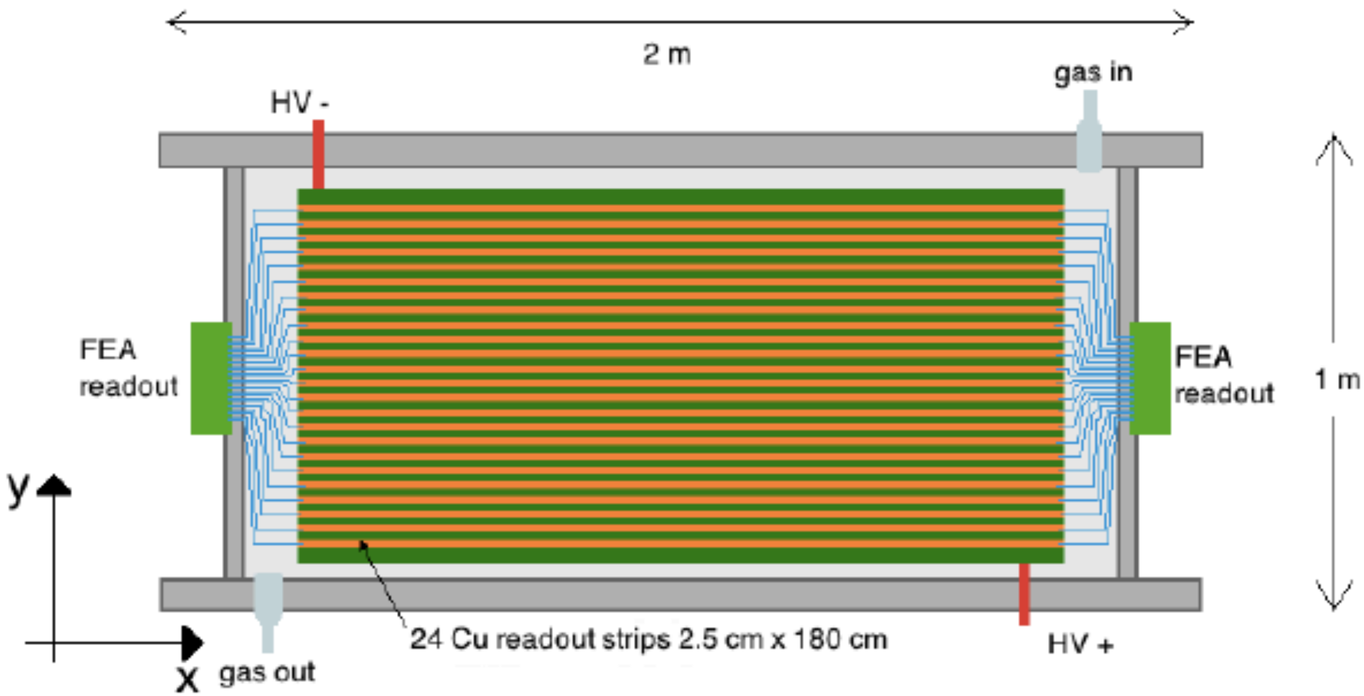


- Signals are induced on 24 copper strips (per chamber) glued on the two vetronite plates placed on top and bottom of the glass outer layers



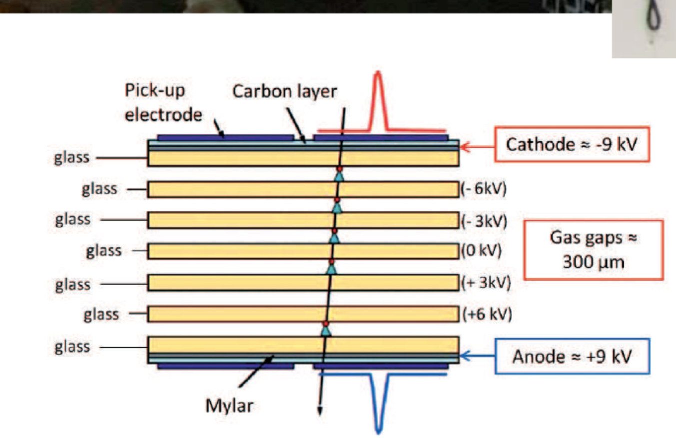
- Signals are sent to Front End electronics based on NINO-ASIC chips (as for the CERN ALICE experiment), amplified, discriminated and subsequently acquired by means of multi hit TDCs

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 <u>difference of the signal arrival times</u> at the two strip extremities, while the other (y) is directly obtained from the position of the <u>fired strip</u>

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

Eco-friendly gas mixture for gaseous detectors: why?

Greenhouse effect potential (GWP) of as gas measured with respect to to CO_2
(GWP of $CO_2 = 1$)

- Gas mixtures with GWP > 150 have been banned by EU

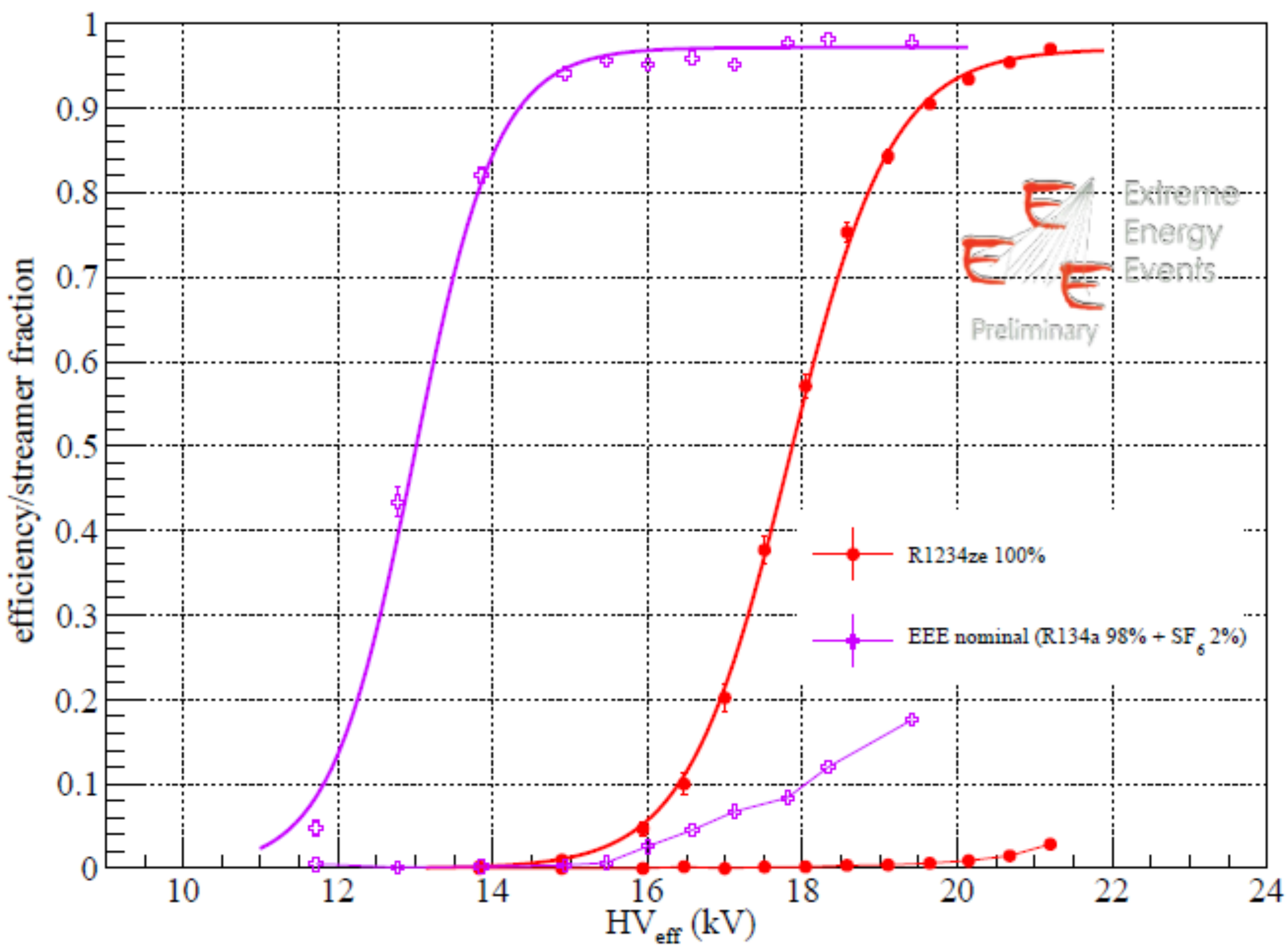
- Present RPCs adopt mixtures with high GWP

EEE MRPCs use:

$$98\%\ C_2H_2F_4 + 2\%\ SF_6 \Rightarrow \text{GWP} = 1889$$

R1234ze tetrafluoropropane ($C_3H_2F_4$) is the most promising candidate to replace tetrafluoroethante ($C_2H_2F_4$)

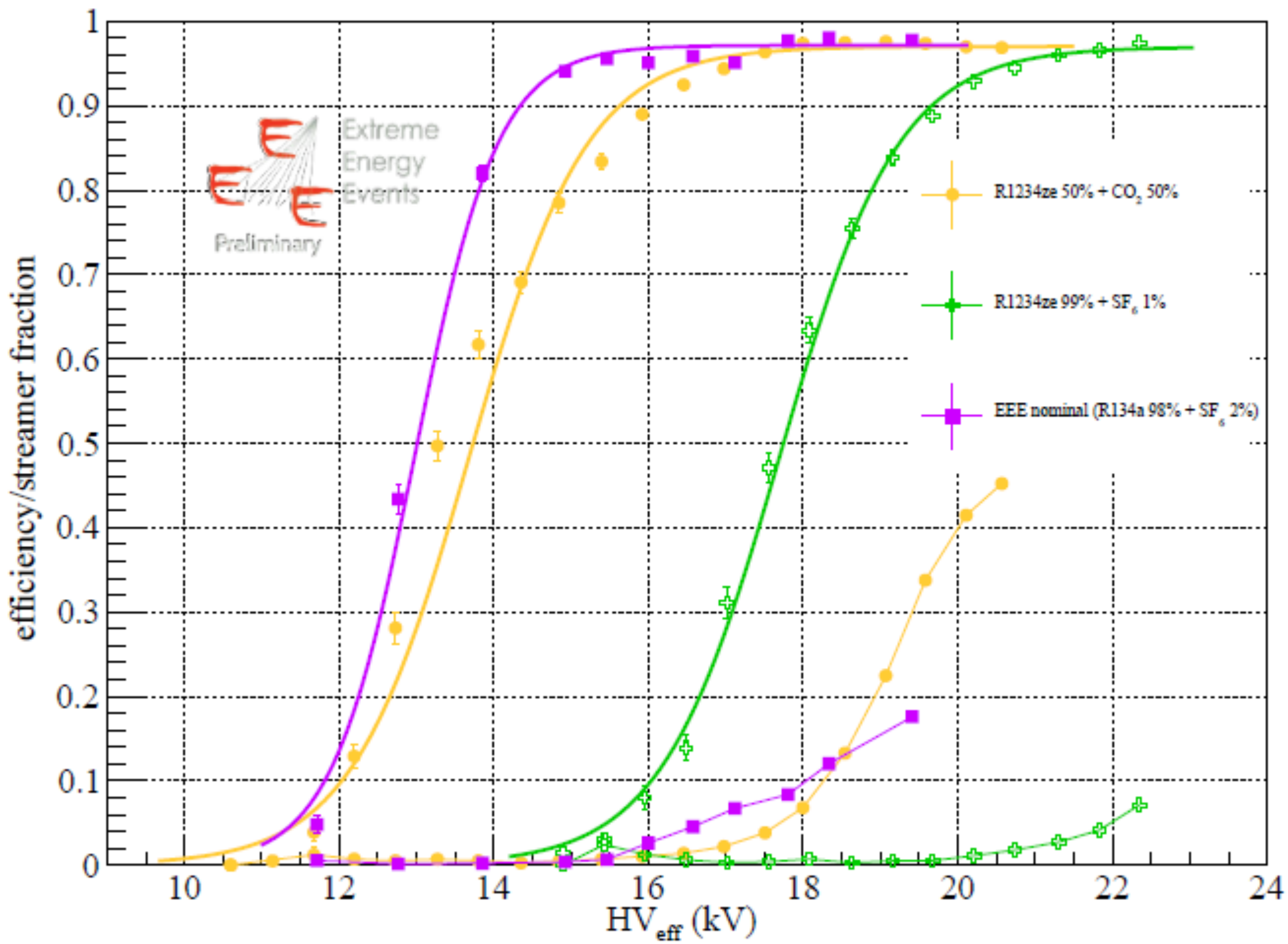
but the corresponding operating voltage is too high > 20 kV



EEE has tested alternative promising mixtures

- R1234ze + CO_2
- R1234ze + SF_6

→ high efficiency, low streamer probability



Main features of EEE system

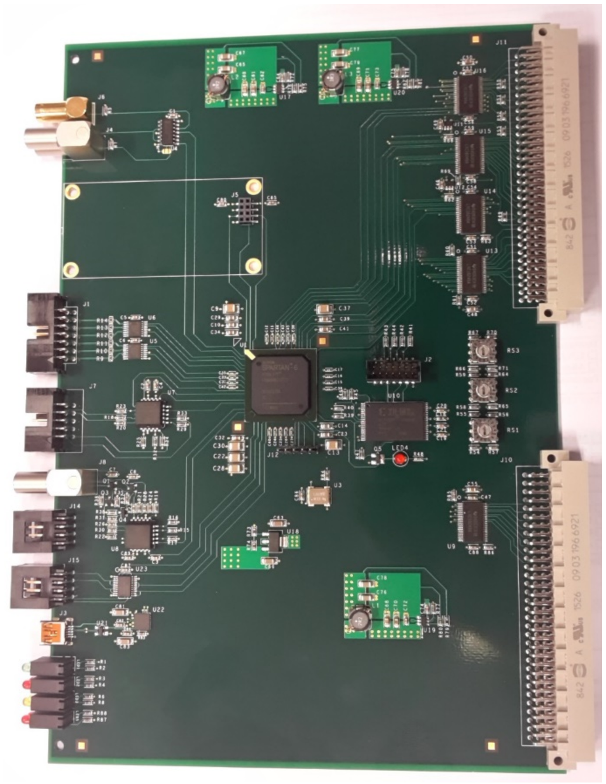
- The DAQ system makes use of VME standards and the DAQ program is LabView based and runs on a PC connected to the VME crate by means of a CAEN USB-VME bridge

- 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

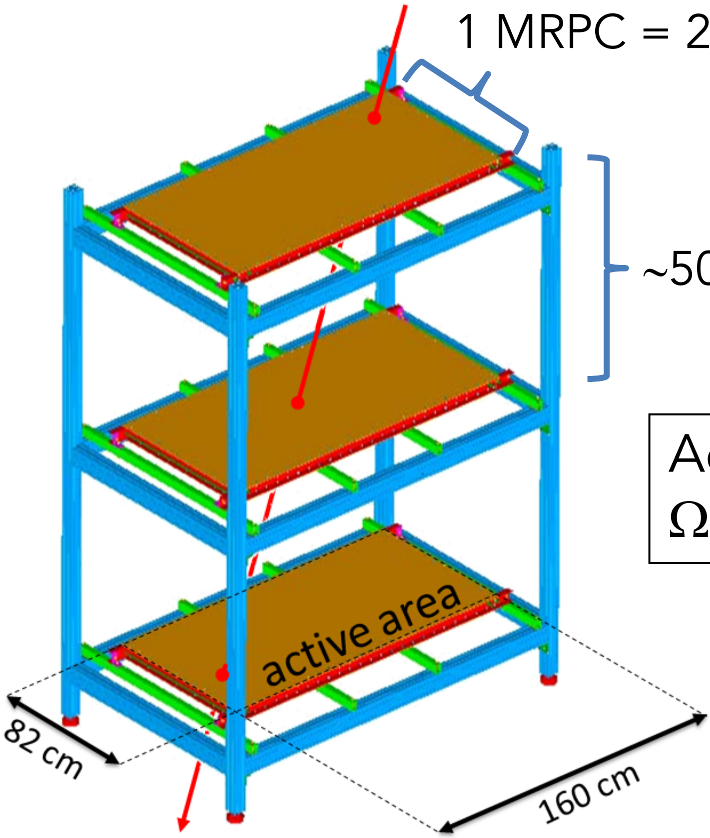
- New card integrating trigger card, GPS and GPS interface

- Pressure and temperature sensors recorded by DAQ

- Independent gas control system

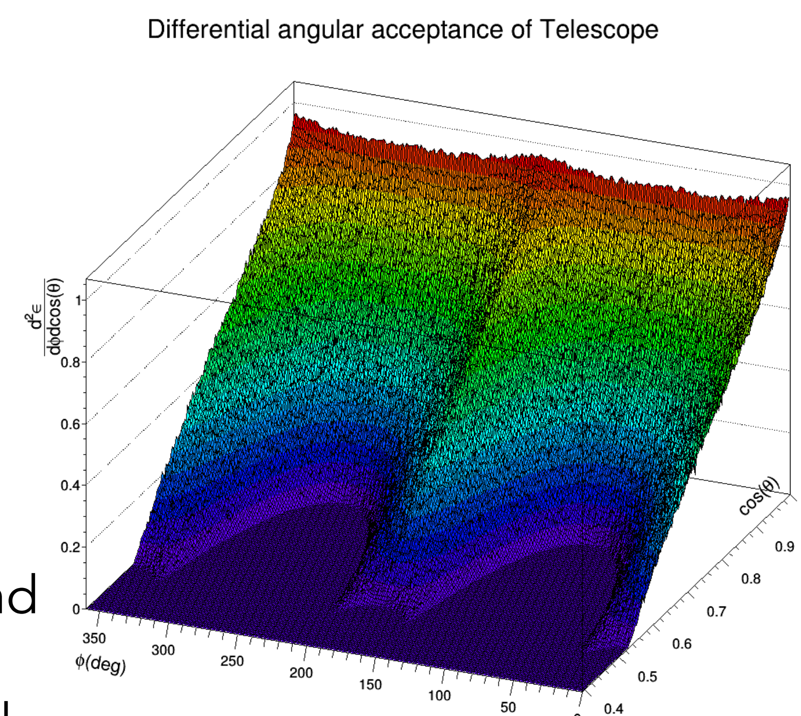


The EEE telescope



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

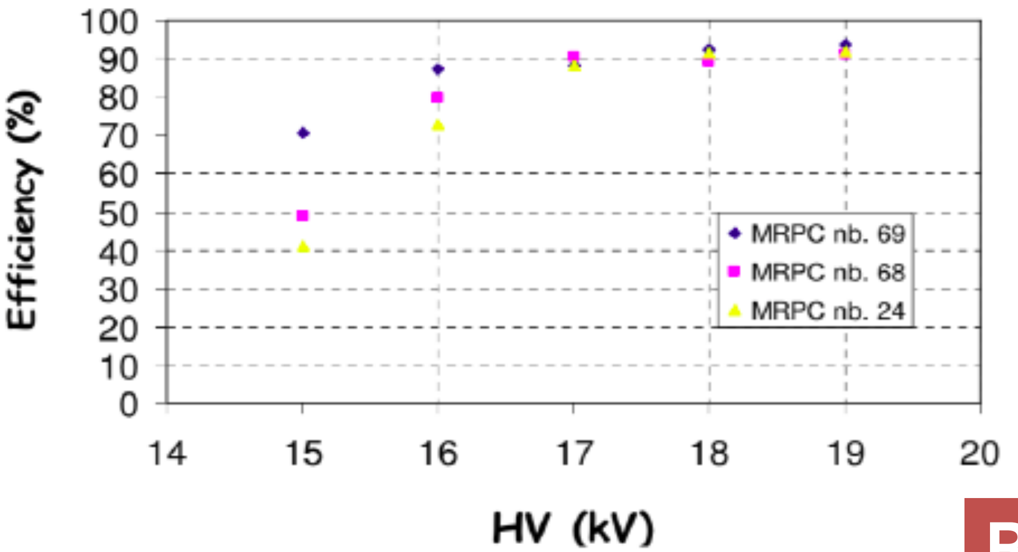
Acceptance
$\Omega = 1.6$ sr

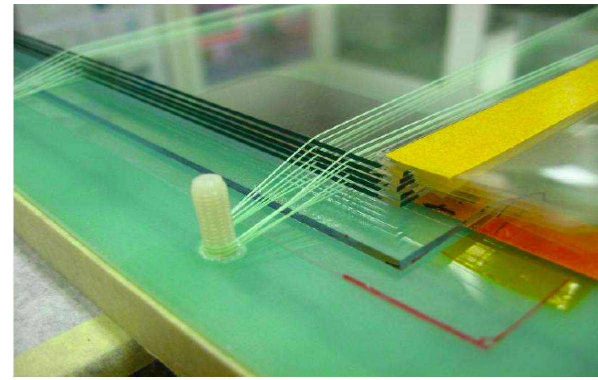


3 MRPC planes with 24 strips each read at both ends → 144 readout channels

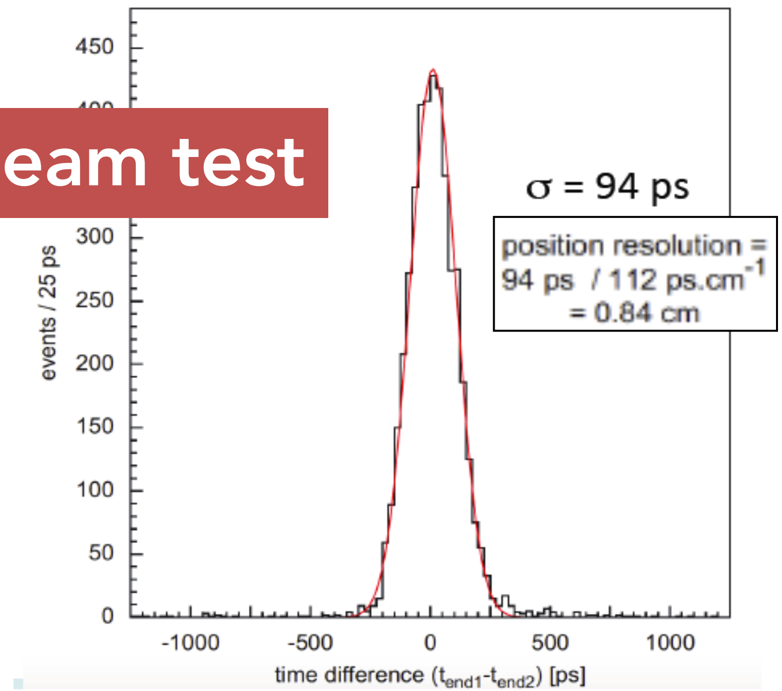
- The trigger requires a hit signal on each end of the 3 MRPCs within a ±500 ns window
- Cosmic muons are tracked & reconstructed

The EEE MRPC resolution





Beam test



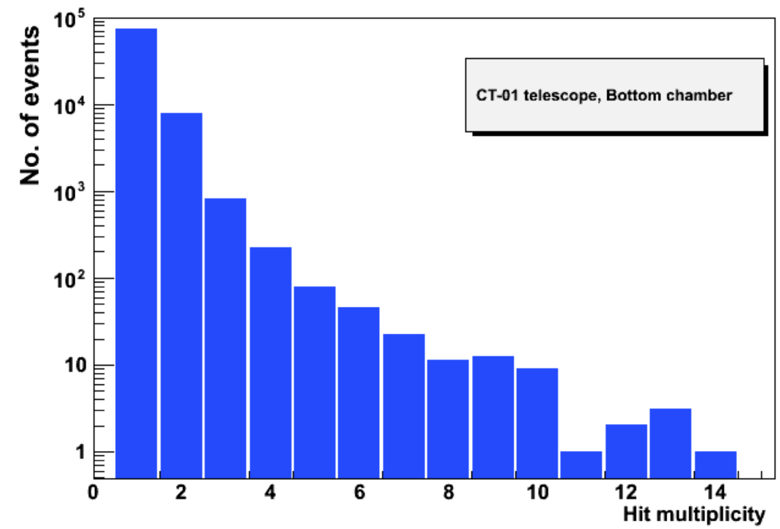
The time resolution of the MRPC is better than 100 ps, allowing to reconstruct the position x along the strip with a precision of 0.84 cm

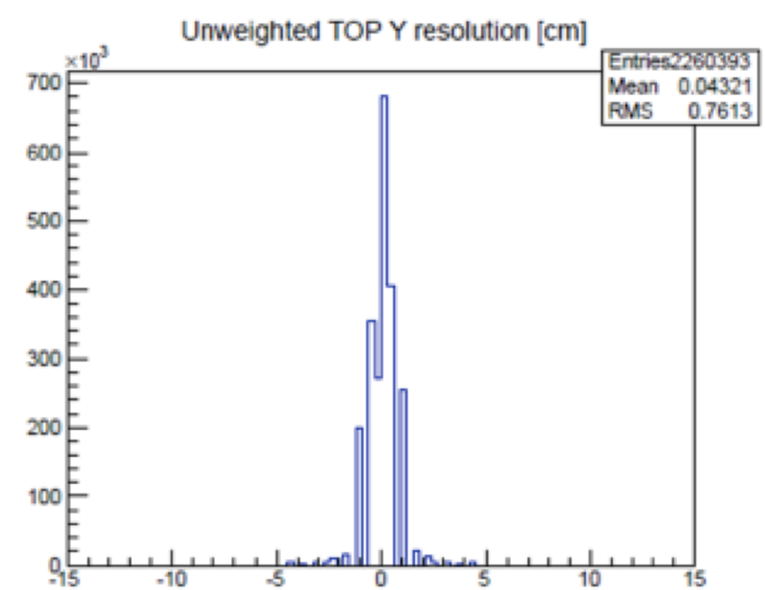
The EEE MRPC resolution

- Strip width 2.5 cm
  with 0.7 cm gap
  → 3.2 cm pitch

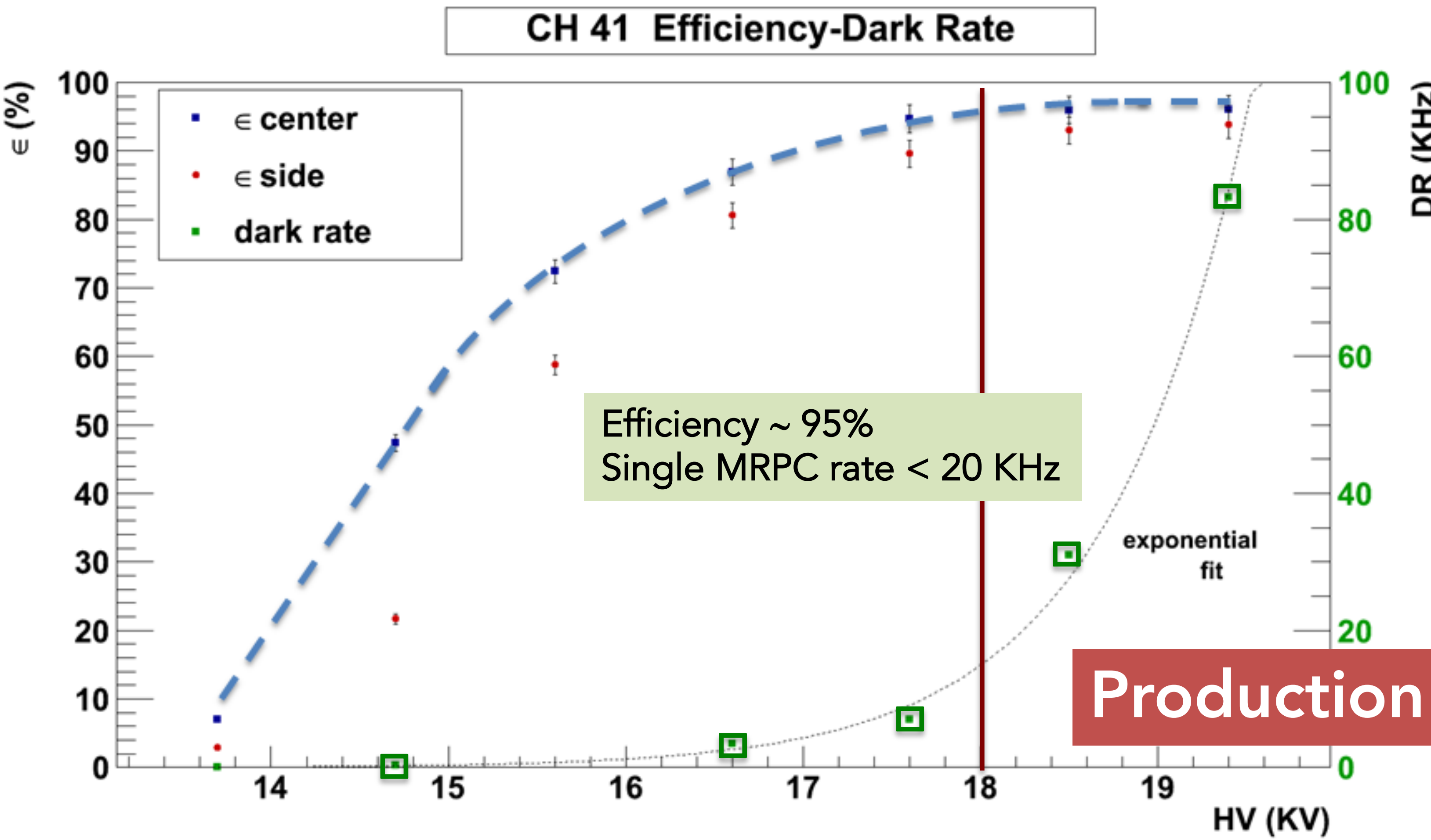
- For each MRPC plane
  average hit multiplicity
  $\langle N_{hit} \rangle \sim 1.1$

- Space resolution
  for y coordinate
  $\sigma = 3.2 / \sqrt{12} \sim 0.92$ cm
  typical for <u>segmented</u>
  detector readout





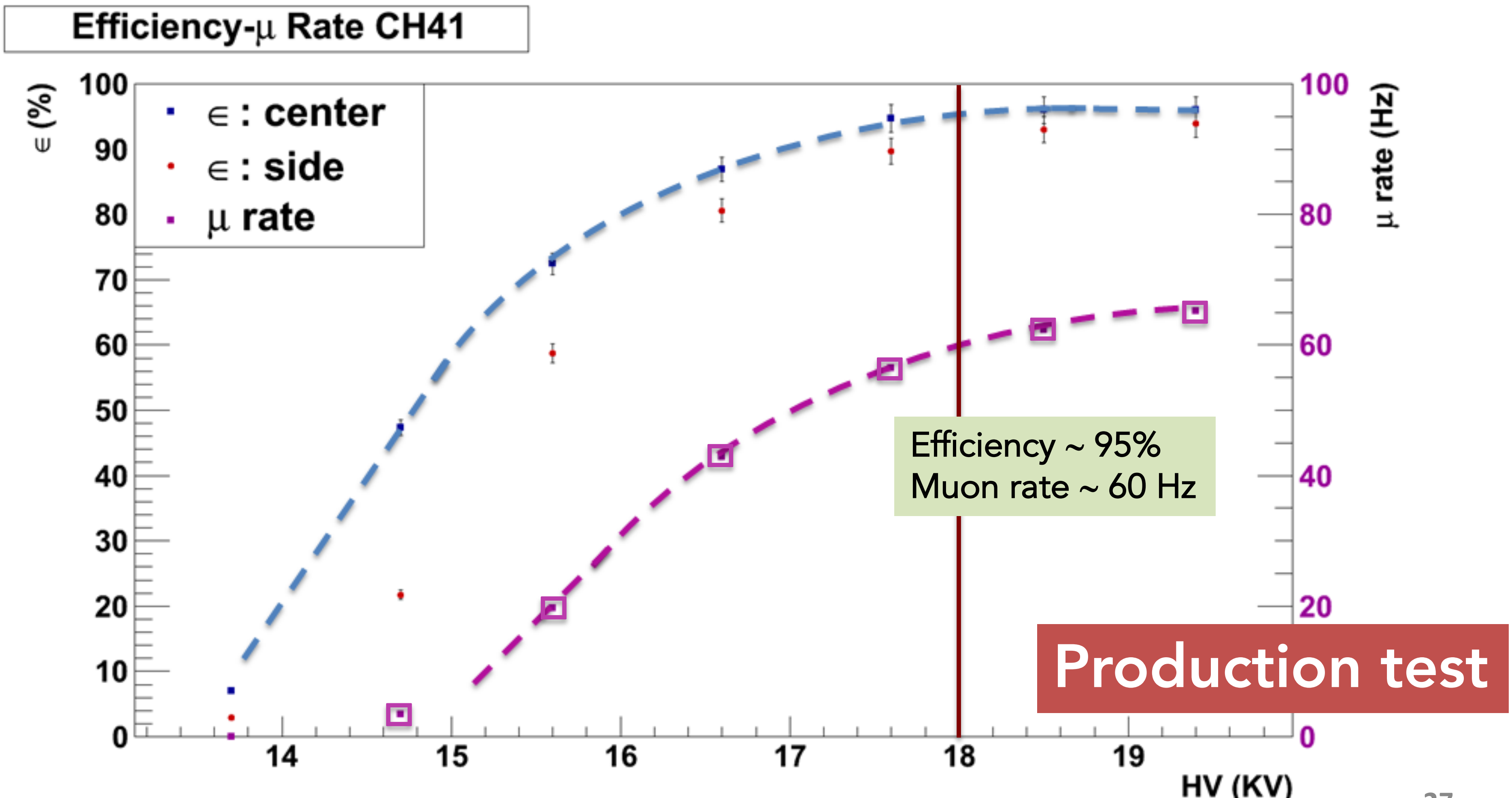
Efficiency vs. noise

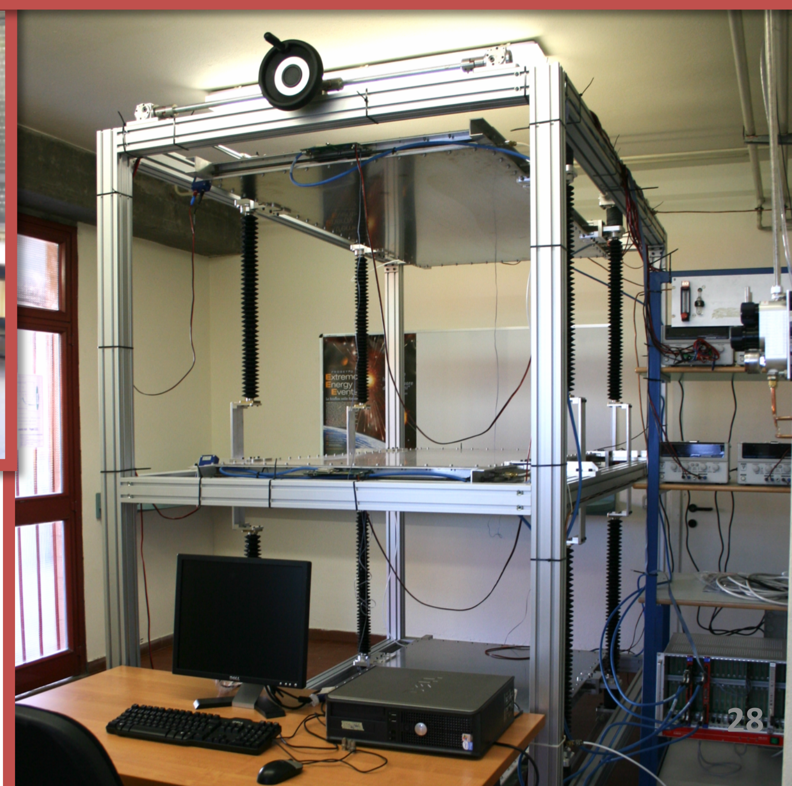


Efficiency ~ 95%
Single MRPC rate < 20 KHz

Production test

Efficiency vs. muon rate (3-MRPC coincidence rate)

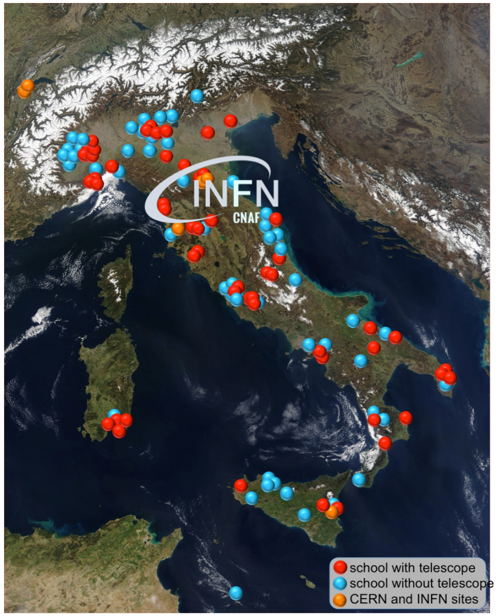


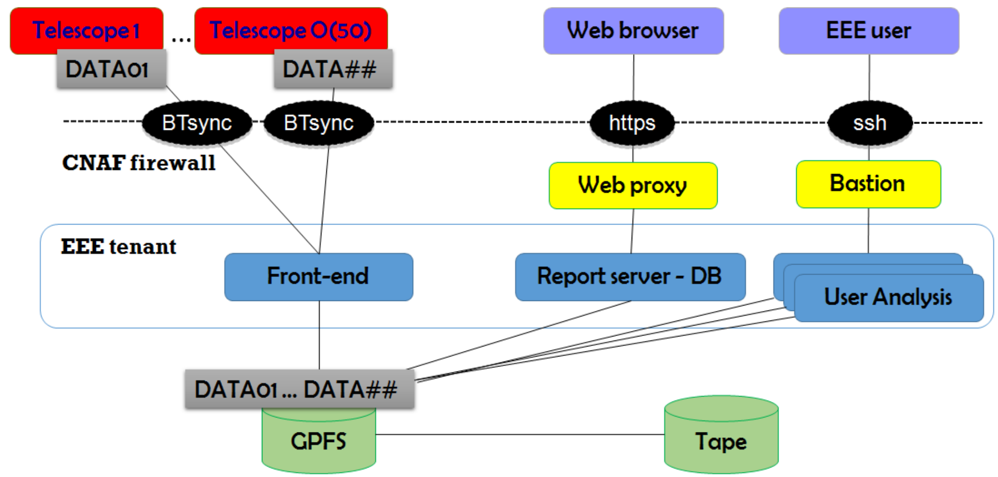


EEE telescopes installed inside High Schools

… and real life / real time installation

The computing and data infrastructure to interconnect EEE telescopes





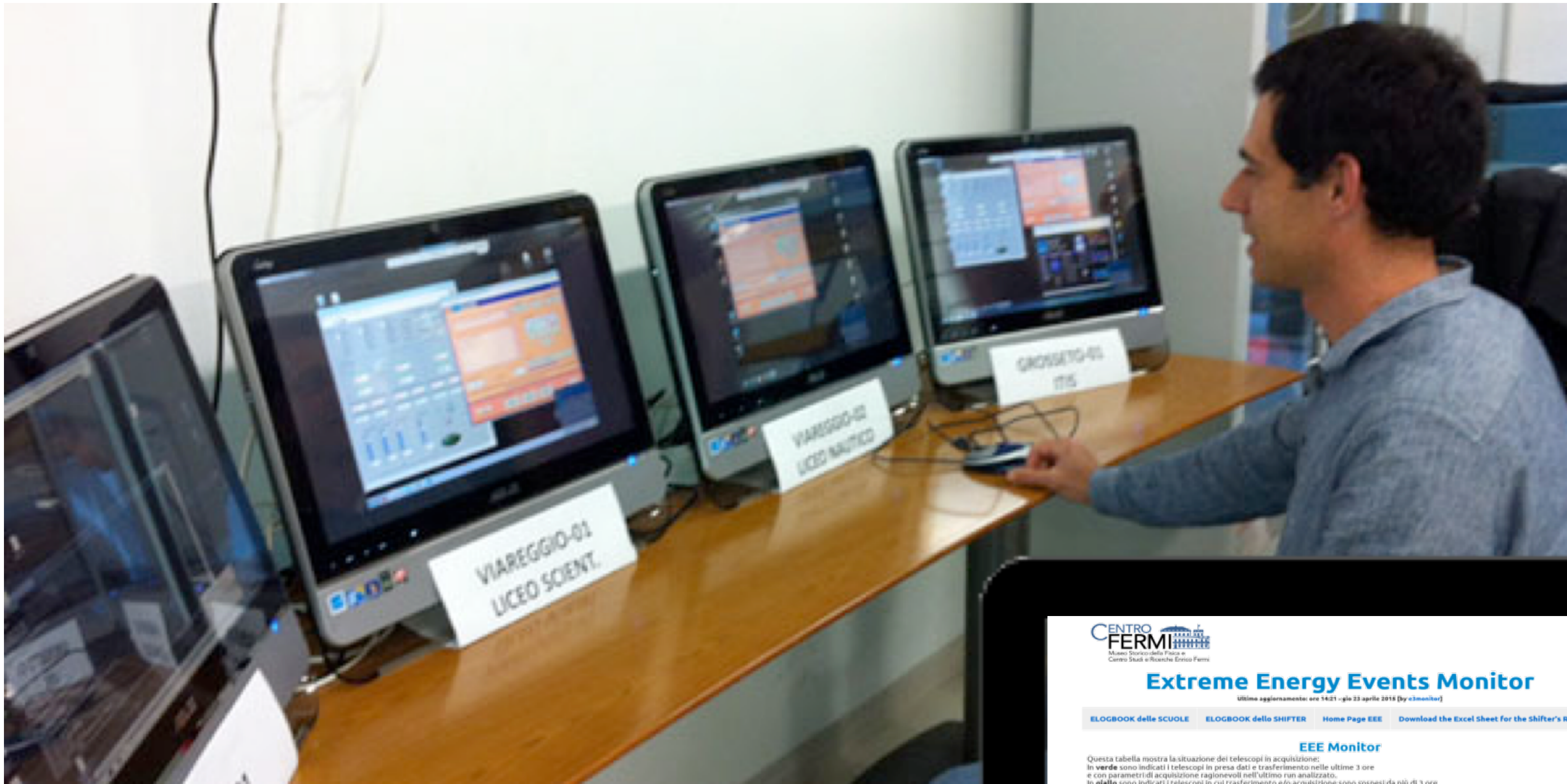
The Extreme Energy Event (EEE) experiment is devoted to the search of high-energy cosmic rays through a network of telescopes installed in over 50 High Schools + Labs distributed throughout the Italian territory.

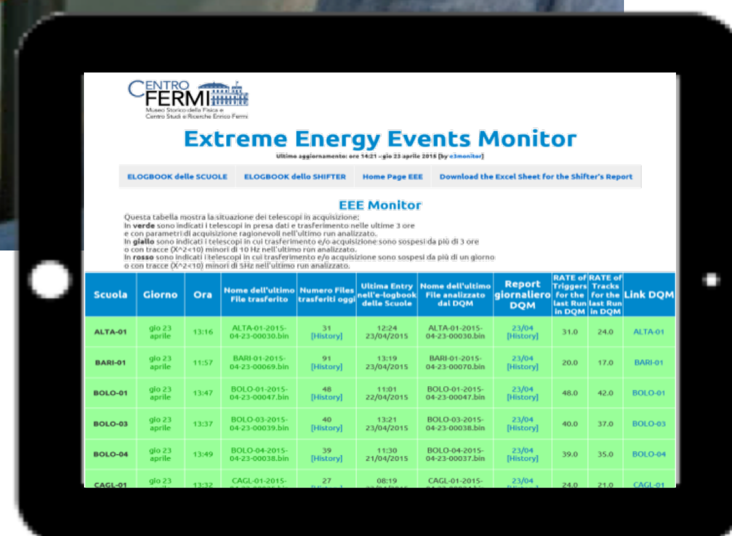
One of the main goals of the project is to involve young students in a high-level scientific enterprise.

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





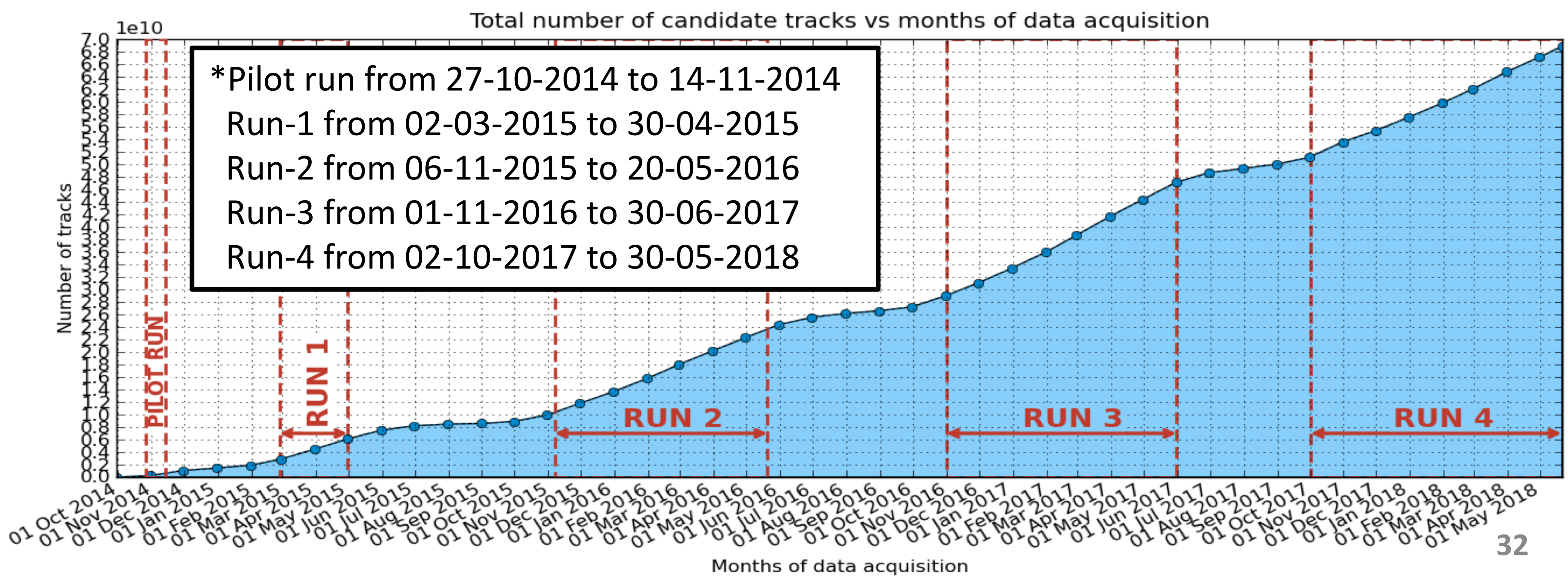
2014 Pilot run
2015 Run-1
2016 Run-2
2017 Run-3
2018 Run-4 just ended

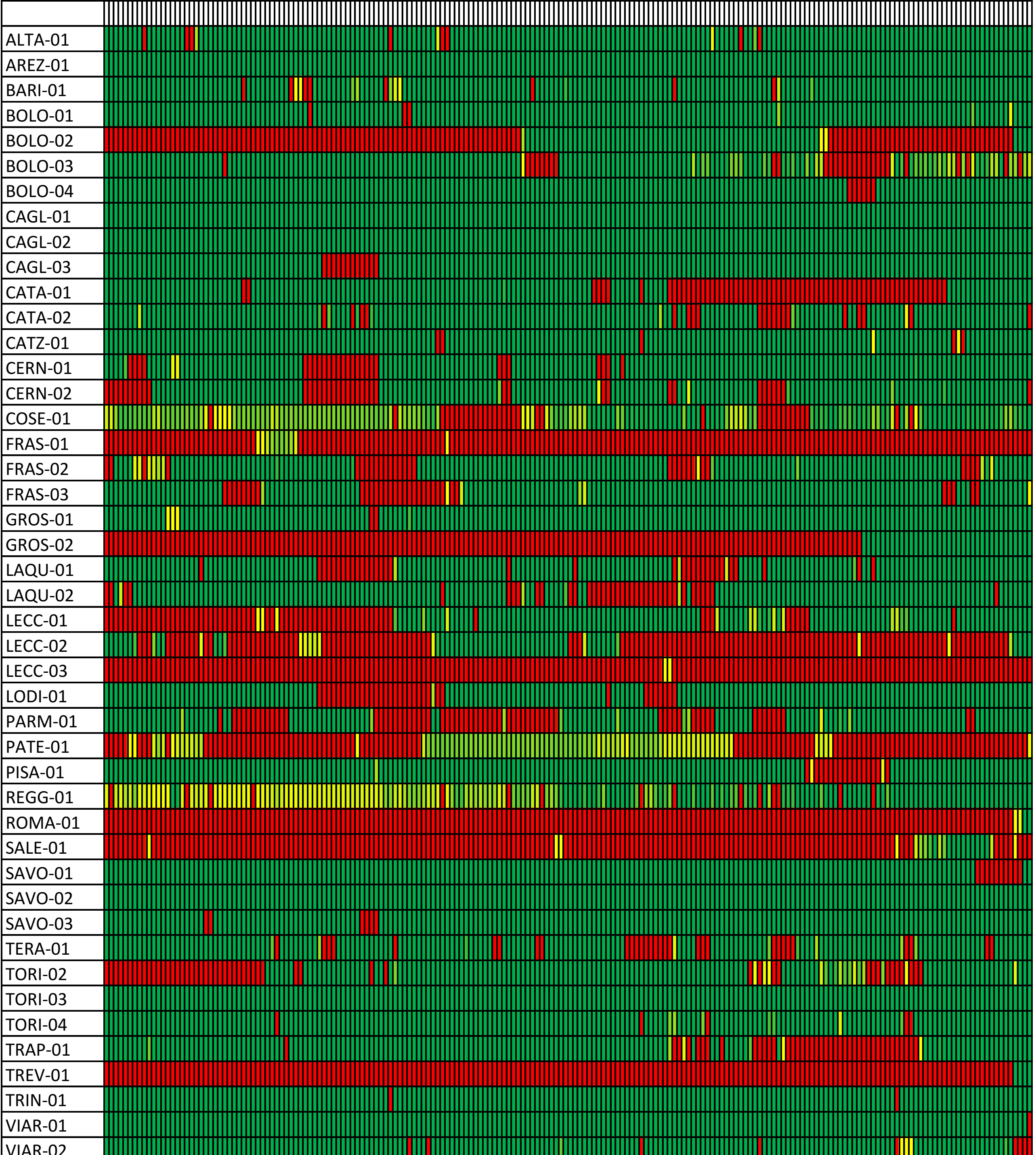
EEE monitor with information in real time
http://eee.centrofermi.it/monitor/

Data transfers & all runs statistics

- **Almost all telescopes (49) connected to INFN CNAF** and transferring data using *bittorent 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: **almost 70 billion cosmic rays**





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

Quasi online monitor

Extreme Energy Events Monitor

Ultimo aggiornamento: ore 09:42 - dom 28 giugno 2015 [by e3monitor]

ELOGBOOK delle SCUOLE | ELOGBOOK dello SHIFTER | Home Page EEE | Download the Excel Sheet for the Shifter's Report

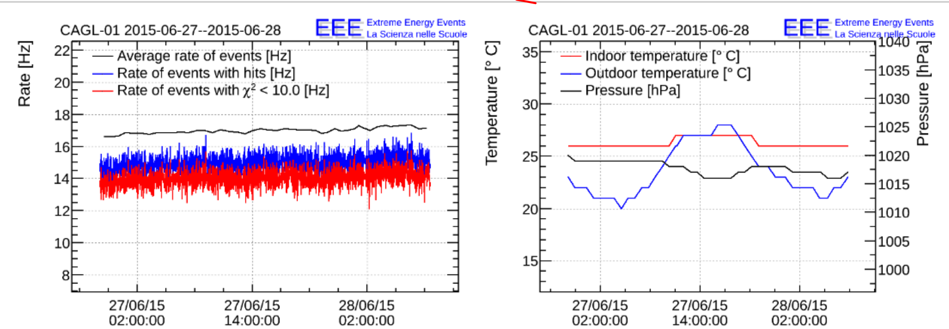
EEE Monitor

Scuola	Giorno	Ora	Nome dell'ultimo File trasferito	Numero Files trasferiti oggi	Ultima Entry nell'e-logbook delle Scuole	Nome dell'ultimo File analizzato dal DQM	Report giornaliero DQM	RATE of Triggers for the last Run in DQM	RATE of Tracks for the last Run in DQM	Link DQM
ALTA-01	lun 11 maggio	14:31	ALTA-01-2015-05-07-00029.bin	0 [History]	11:25 27/04/2015	ALTA-01-2015-05-07-00028.bin	08/05 [History]	31.0	23.0	ALTA-01
BARI-01	sab 13 giugno	11:45	BARI-01-2015-06-13-00016.bin	0 [History]	14:00 22/05/2015	BARI-01-2015-06-13-00015.bin	14/06 [History]	20.0	17.0	BARI-01
BOLO-01	dom 28 giugno	09:17	BOLO-01-2015-06-28-00026.bin	27 [History]	09:24 05/05/2015	BOLO-01-2015-06-28-00025.bin	28/06 [History]	38.0	28.0	BOLO-01
BOLO-03	lun 22 giugno	17:14	BOLO-03-2015-06-22-00003.bin	0 [History]	10:14 26/05/2015	BOLO-03-2015-05-26-00034.bin	27/05 [History]	36.0	32.0	BOLO-03
BOLO-04	dom 28 giugno	09:33	BOLO-04-2015-06-28-00025.bin	26 [History]	12:31 04/05/2015	BOLO-04-2015-06-28-00023.bin	28/06 [History]	37.0	34.0	BOLO-04
CAGL-01	dom 28 giugno	08:58	CAGL-01-2015-06-28-00013.bin	14 [History]	11:16 26/06/2015	CAGL-01-2015-06-28-00012.bin	28/06 [History]	17.0	14.0	CAGL-01

Daily summary (trending infos available for analyses)

Run by run (50000 events) quality monitor (real time)

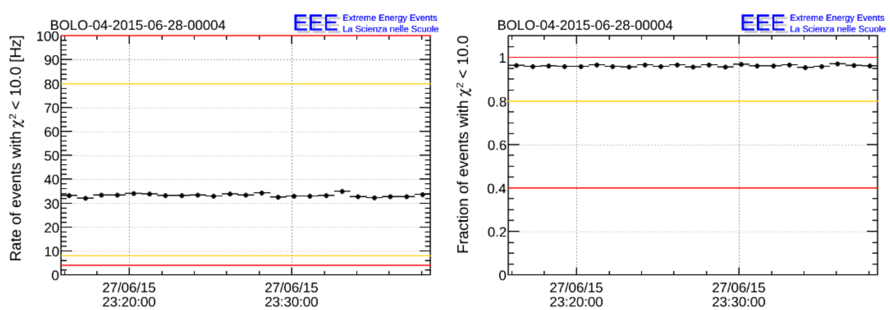
EEE DQM summary report



SUMMARY

- Station: CAGL-01
- Time period: 2015-06-27--2015-06-28
- Number of runs processed: 46
- Total number of events: 2099422

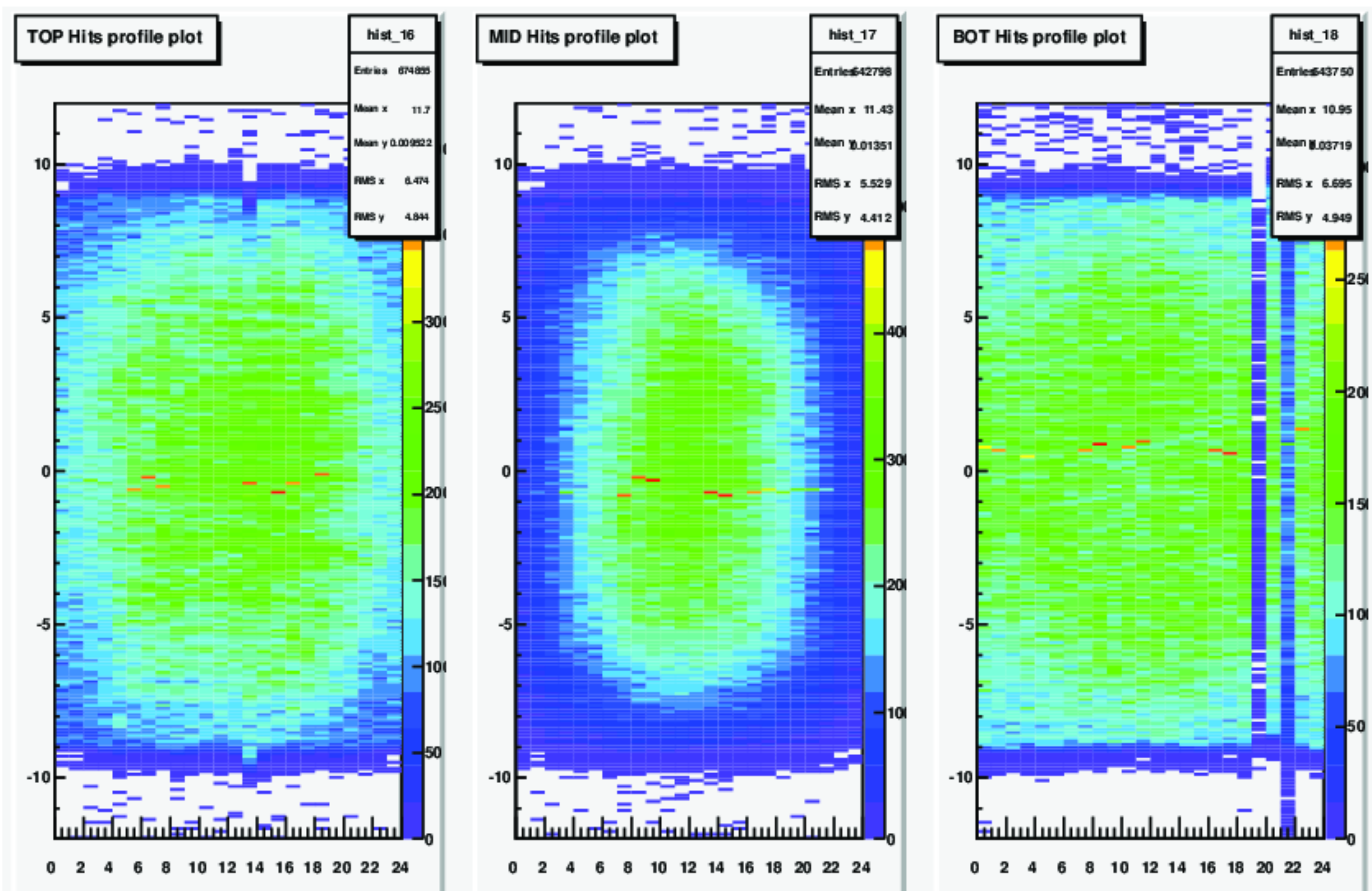
EEE DQM run report



RUN SUMMARY

- DST file path: /home/analisi/eeetmp/BOLO-04-2015-06-28-00004_dst.root
- Unique run identifier: 8310000004
- Smallest event timestamp: 267837347.038 s UTC
- Largest event timestamp: 267838712.109 s UTC

MRPC hits


TOP Hits profile plot
hist_16
MID Hits profile plot
hist_17
Entries 642798
Mean x 11.43
RMS x 5.529
RMS y 4.412
BOT Hits profile plot
hist_18
Mean x 10.95
RMS x 6.695
RMS y 4.949

EEE Telescopes: Performance

"The Extreme Energy Events experiment: an overview of the telescopes performance", EEE Collaboration, submitteted to JINST, arXiv:1805.04177v1 [physics.ins-det] 10 May 2018

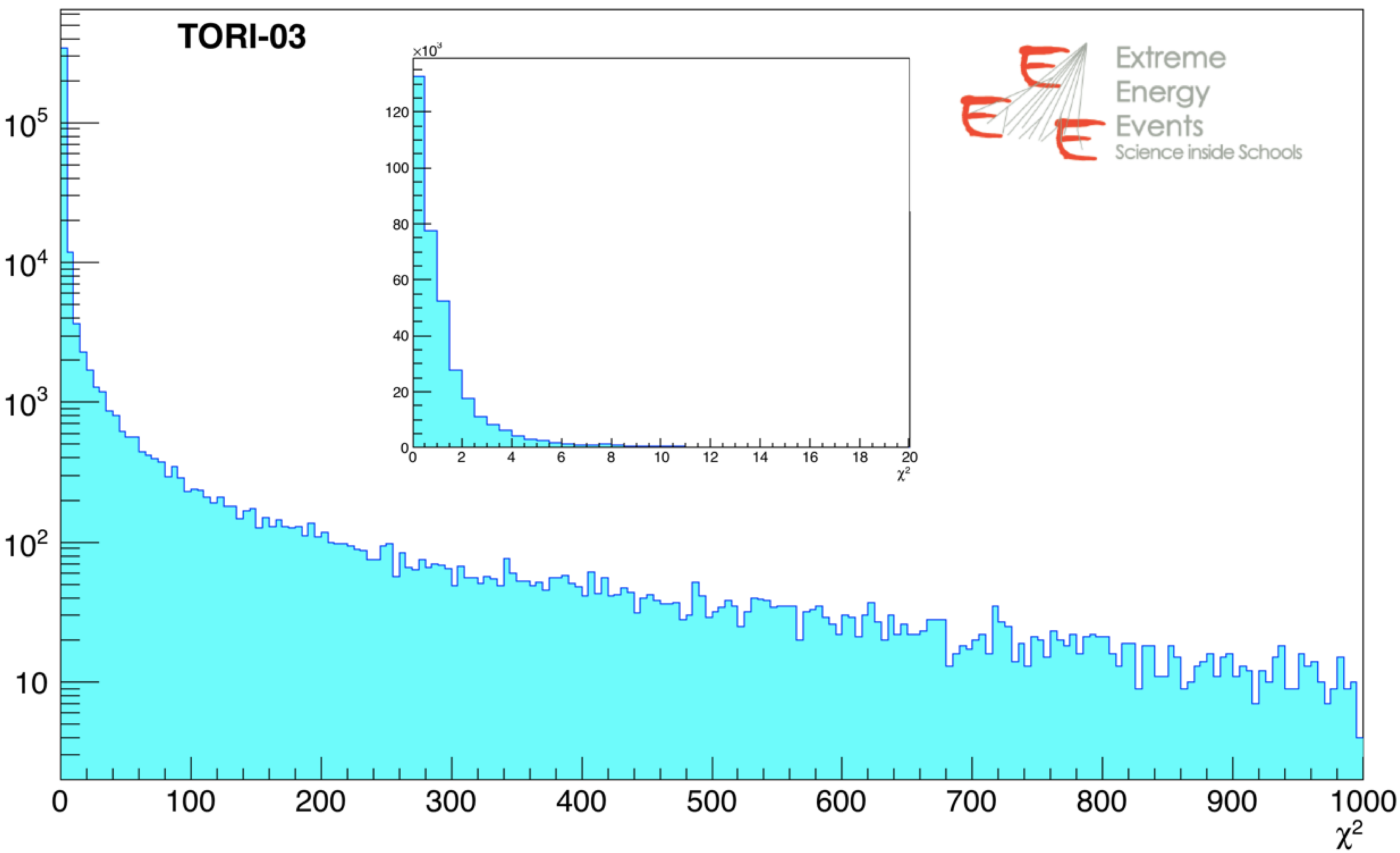
Statistics from the four coordinated runs. The number of active telescopes in Pilot Run, Run 1, Run 2 and Run 3, is respectively 15, 28, 38 and 46. The purity is calculated as candidate tracks/triggers.

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

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

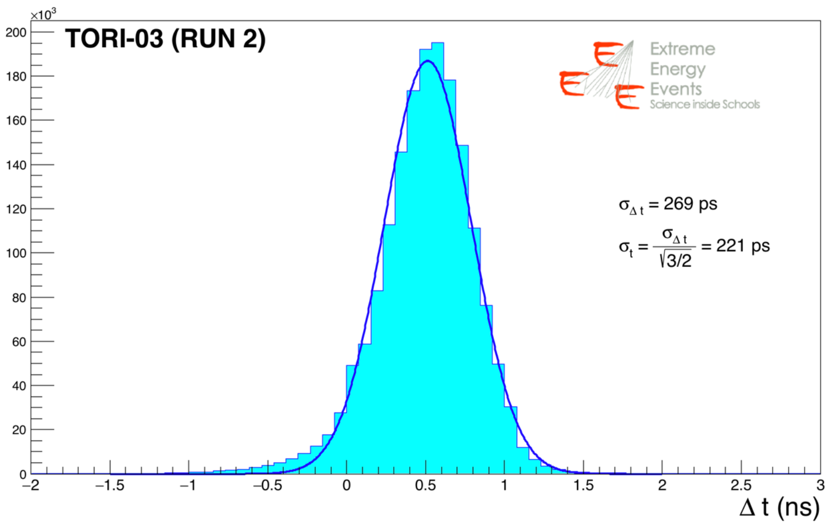
Performance study with a sample of 8 billion tracks over 31 billion tracks collected in Run-2 and Run-3

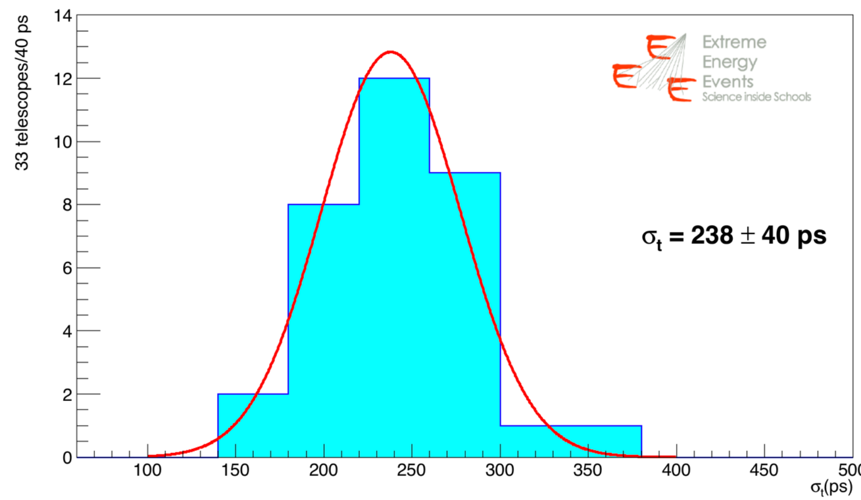
χ^2 distribution for track reconstruction in a typical EEE telescope



TOF resolution

Production performance

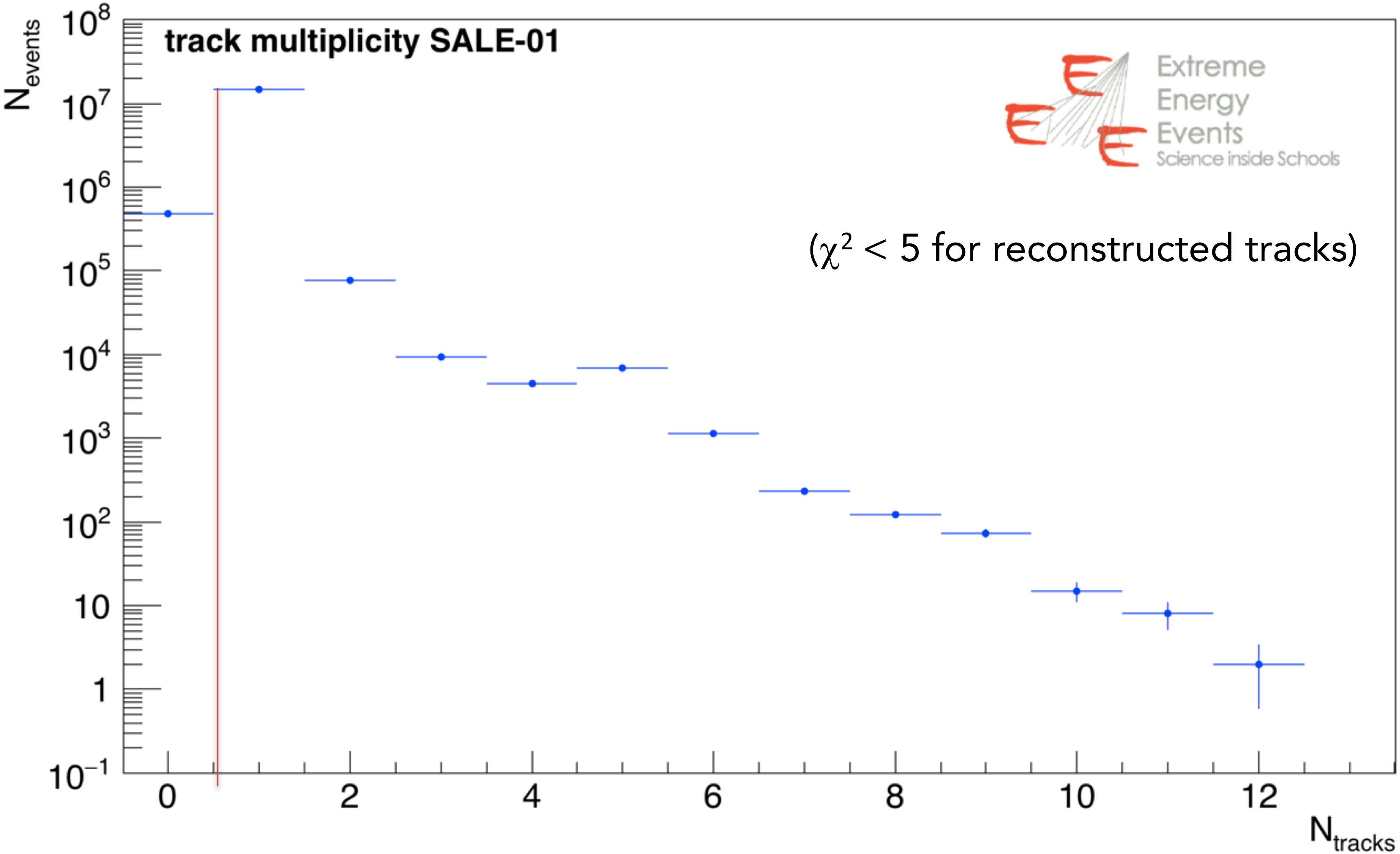




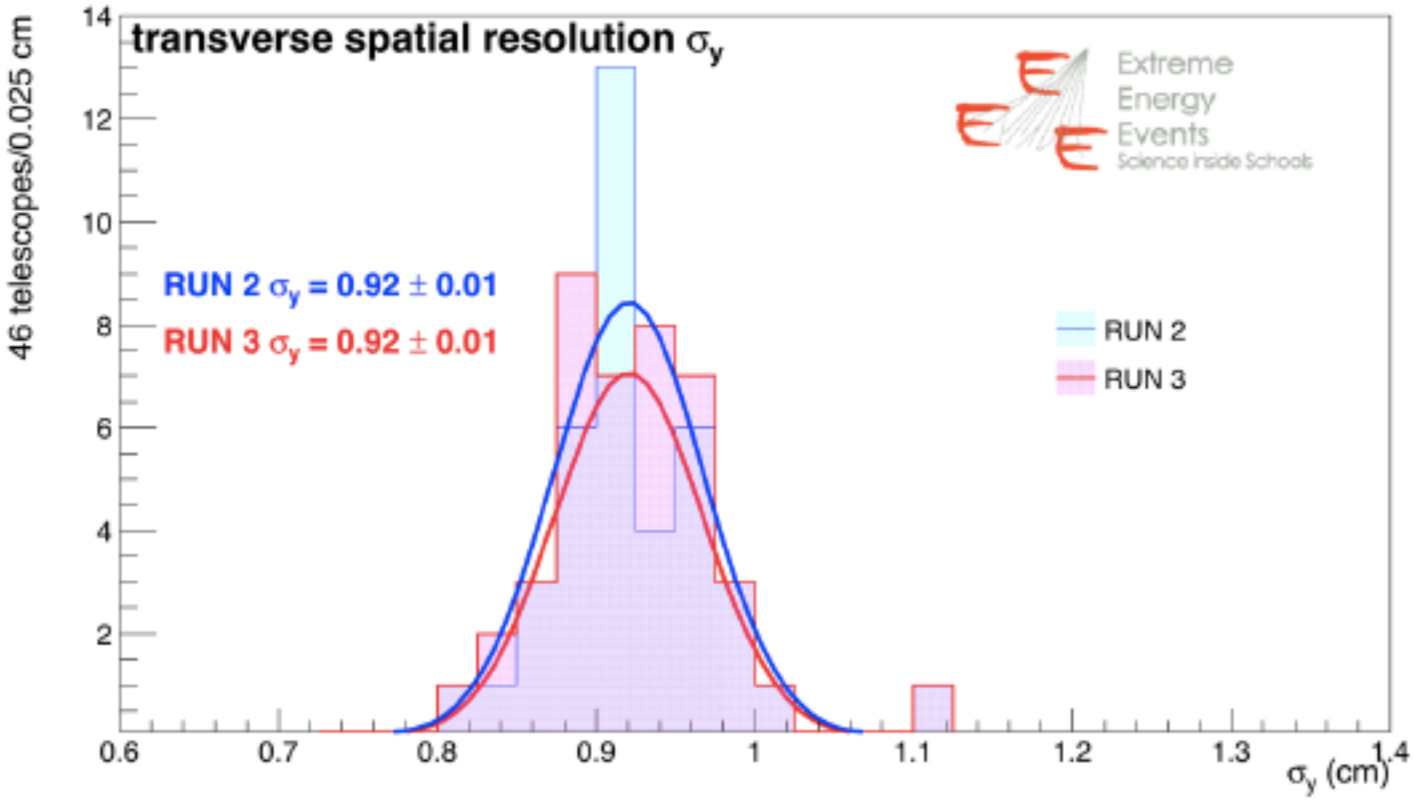
Δt distribution for one of the EEE telescopes (TORI-03), showing the gaussian fit and the time resolution σ_t = 221 ps

Time resolution measured with data taken in Run 3, for 33 telescopes: the average time resolution is given by the gaussian fit and is σ_t = 238 ps

Reconstructed track multiplicity in a typical EEE telescope

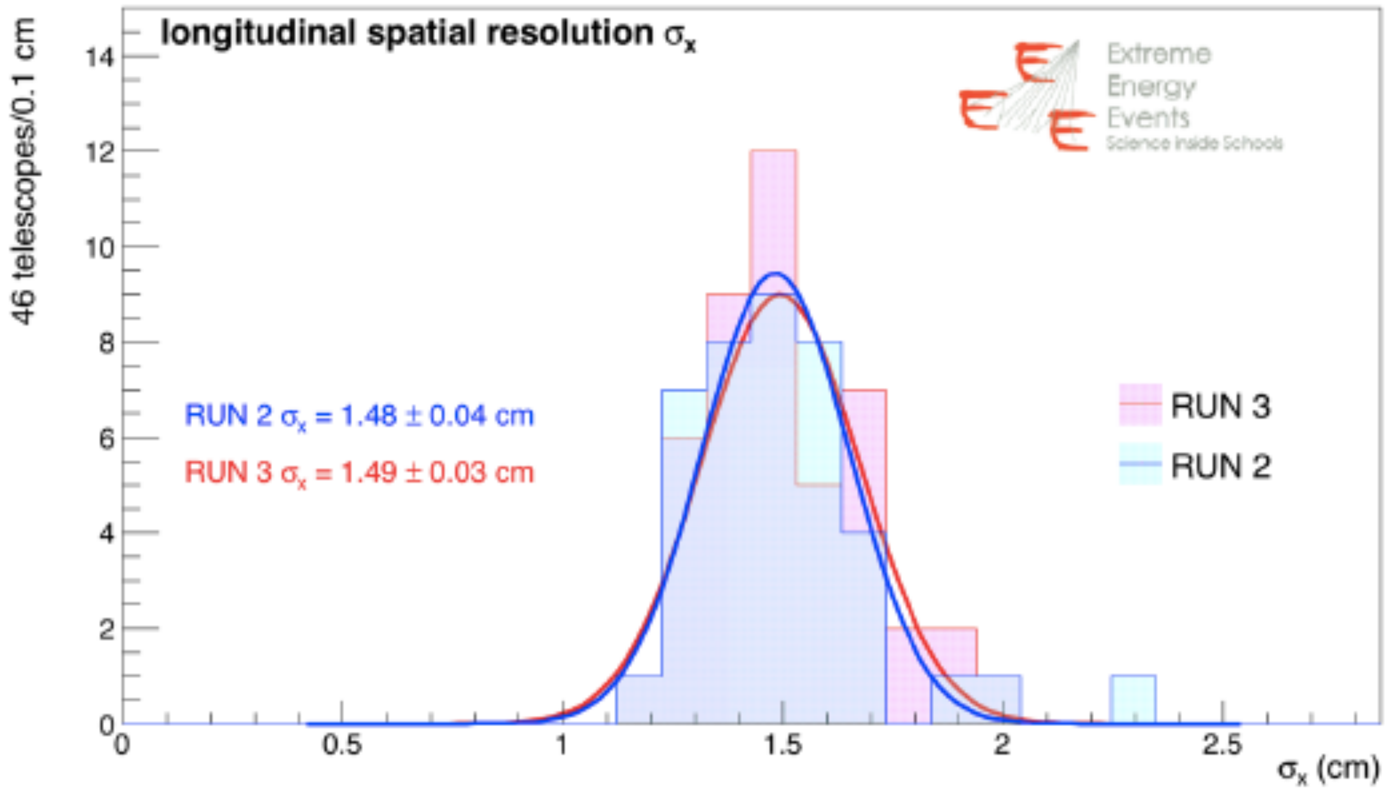


Spatial resolution with 46 EEE telescopes



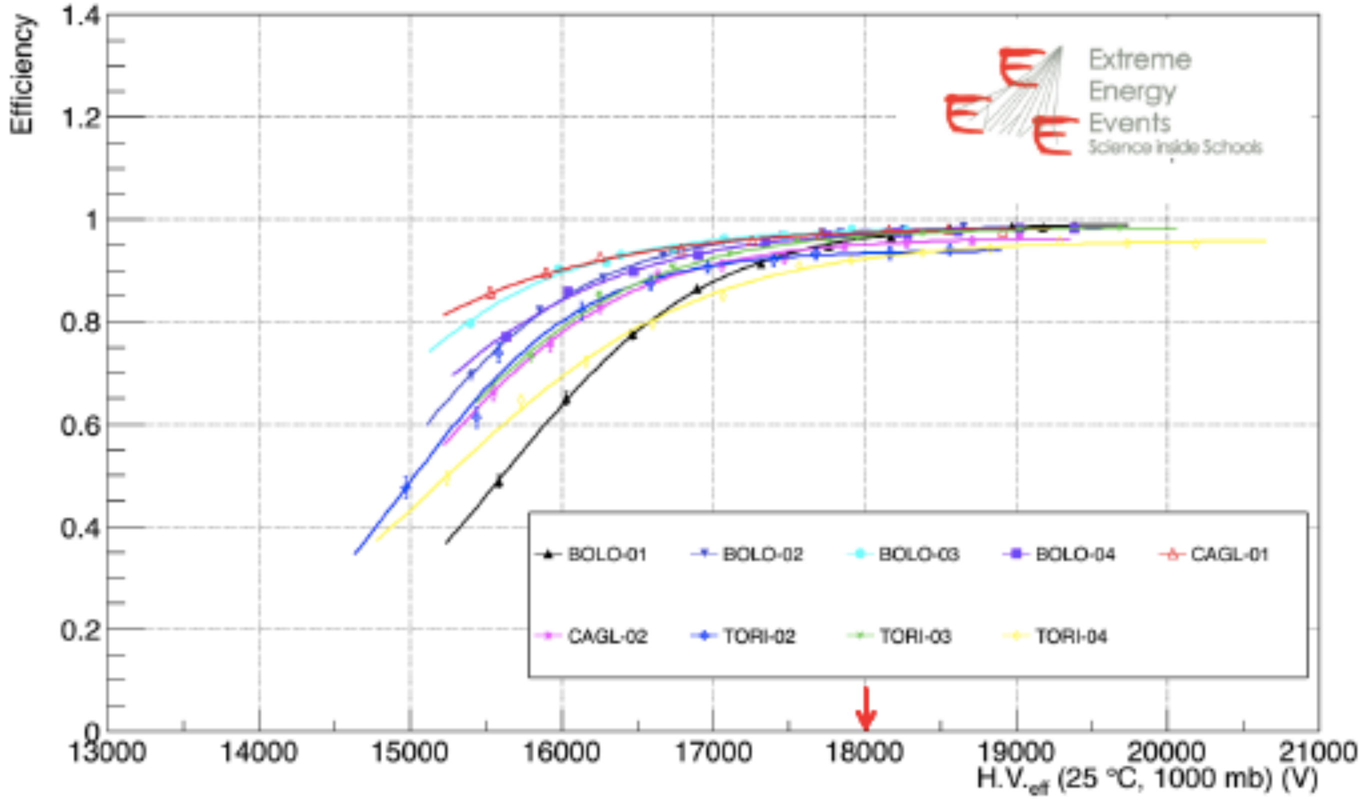
(0.92 cm expected)

Spatial resolution with 46 EEE telescopes



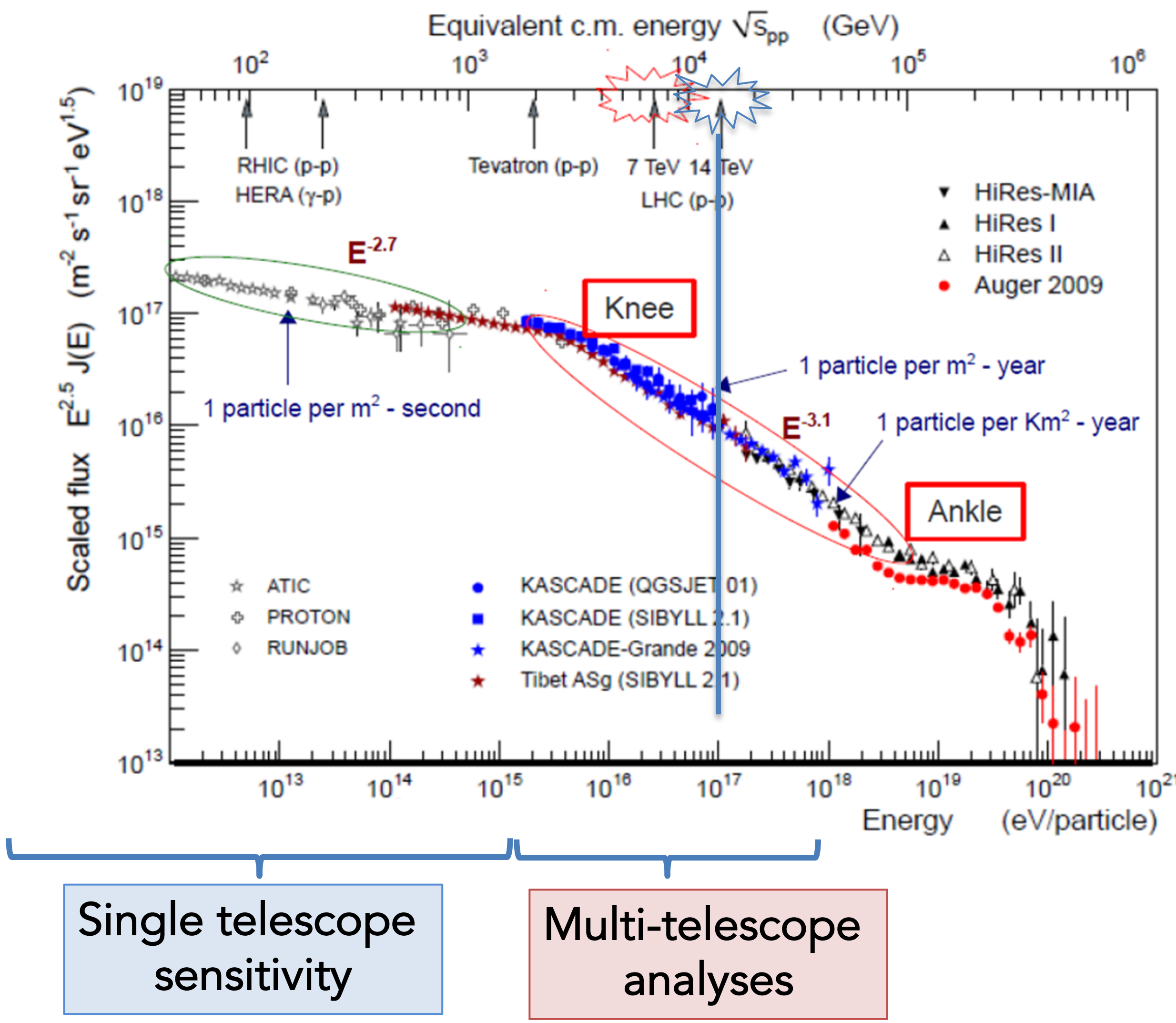
(0.84 cm on test beam)

Efficiency in the middle MRPC with 9 EEE telescopes



(corrected for p and T effects)

Cosmic rays flux and EEE



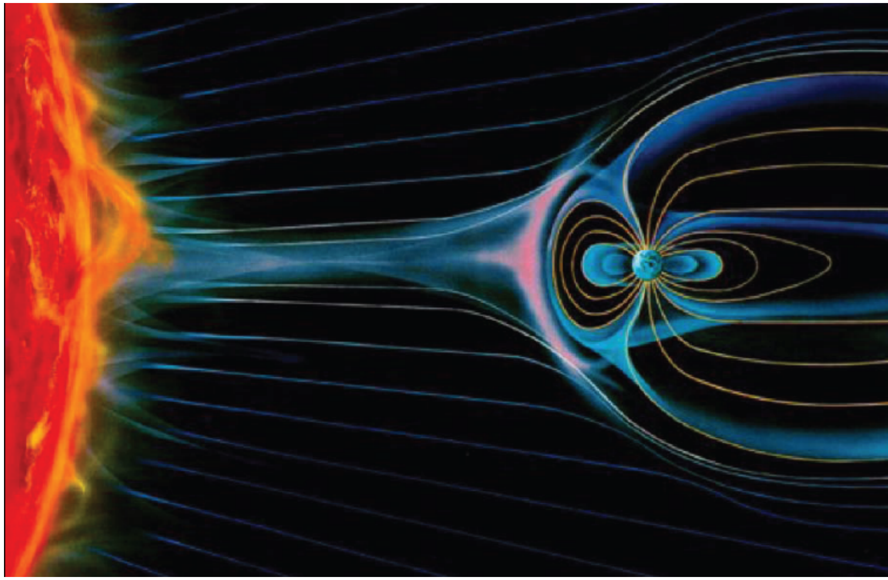
EEE telescopes collect secondary muons coming from primary cosmic rays of **over 10^{11} eV**

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

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

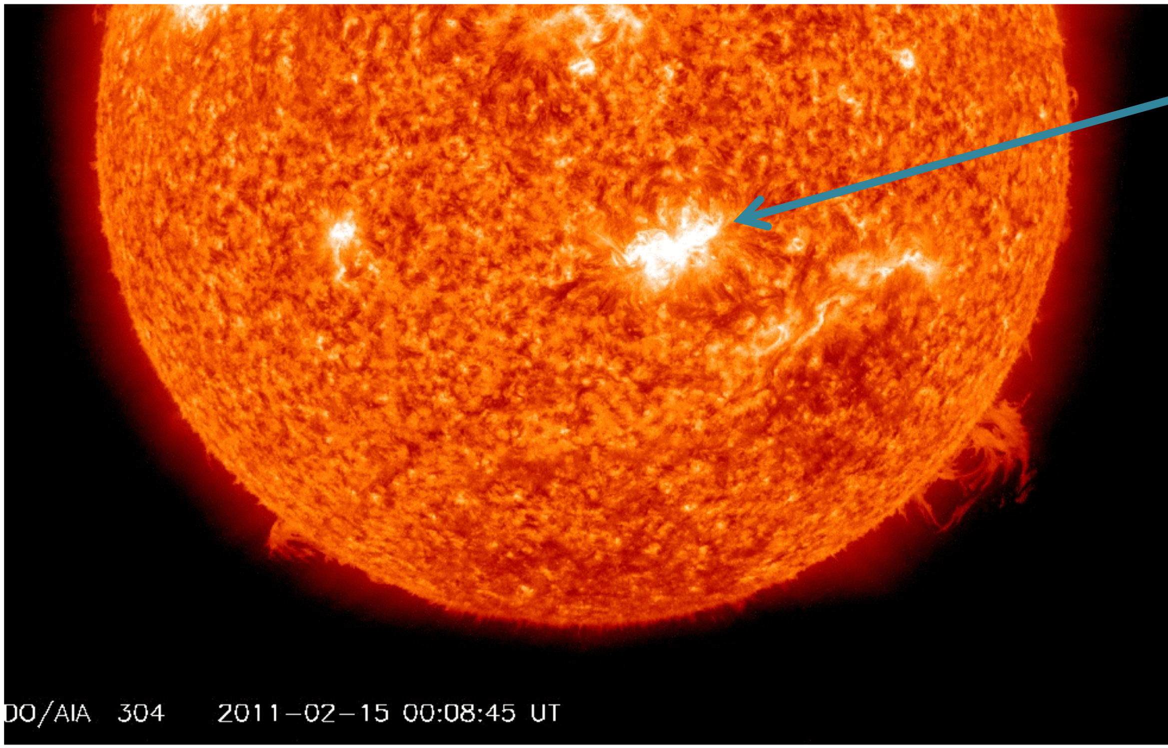
GCRD events consist of <u>an impressive transient change</u> in the cosmic-ray intensity



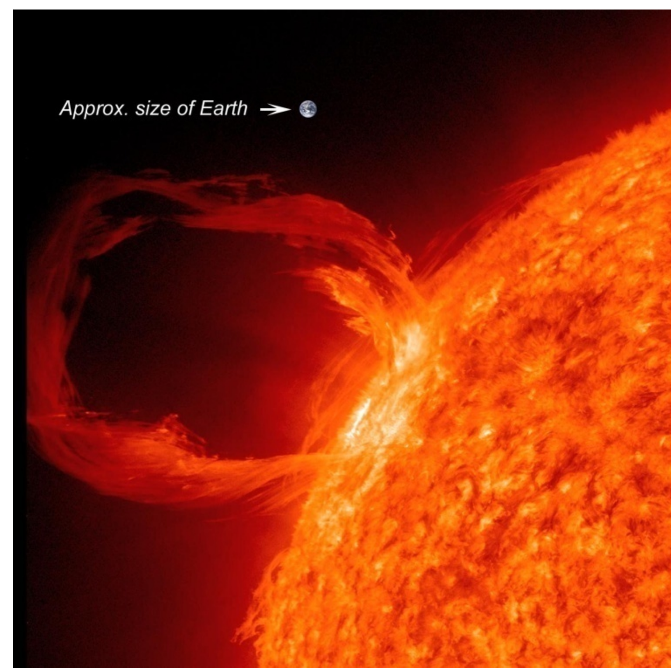
They are characterized by a <u>rapid</u> (a few hours) intensity reduction, followed by a <u>slow</u> recovery in a few days time range

Such strong variations are probably related to **solar flares** and the associated **geomagnetic disturbances**

Solar flares & cosmic rays



Flare recorded by the Solar Dynamics Observatory (SDO) on the night of 14-15 February 2011 (Valentine's day)

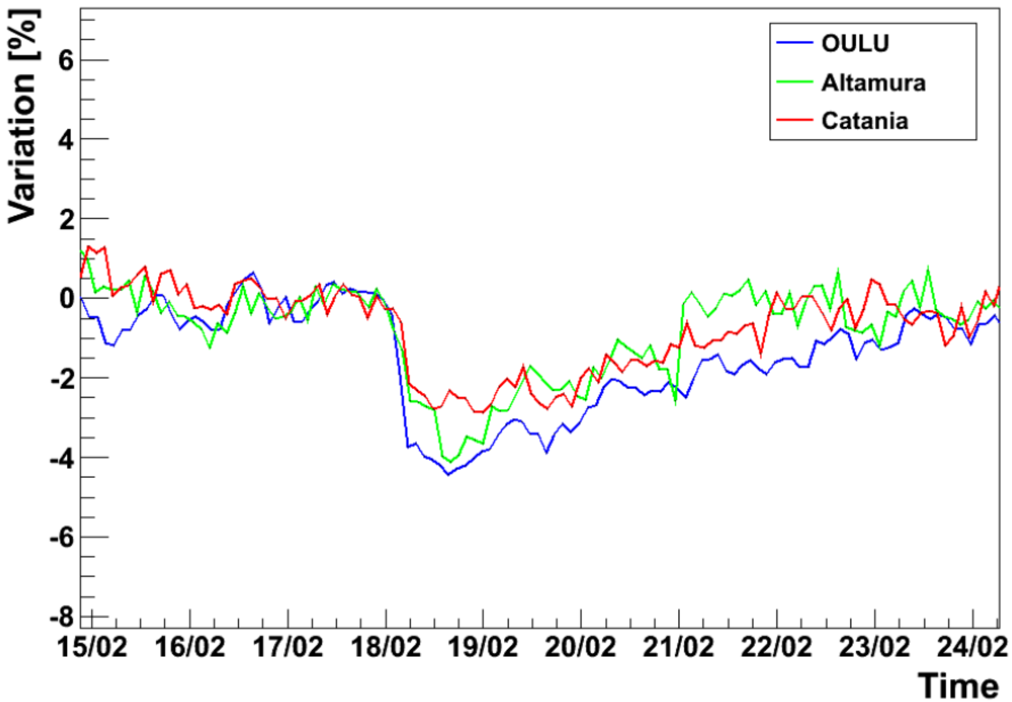


It was a solar flare of category X2 followed by an important Coronary Mass Emission (CME)

This kind of flares are constantly monitored since they can have relevant consequences on Eartth

Galactic Cosmic Ray Decrease (GCRD)

Eur. Phys. J. Plus (2011) **126**: 61
Observation of the February 2011 Forbush decrease by the EEE telescopes



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

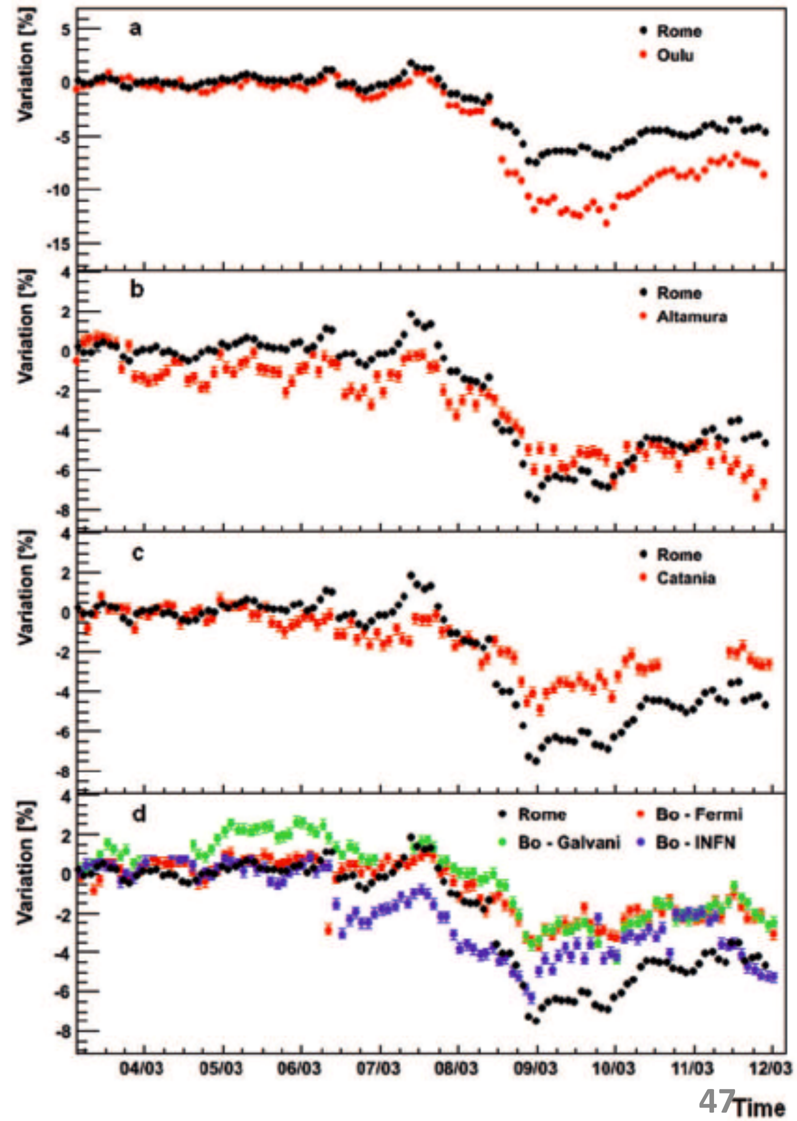
First High Schools ever to observe a cosmic-ray flux decrease associated with a solar flare !!!

- 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

Galactic Cosmic Ray Decrease (GCRD)

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

Eur. Phys. J. Plus (2013) **128**: 62
The EEE experiment project: status and first physics results



Galactic Cosmic Ray (GCR) flux variation due to solar activity

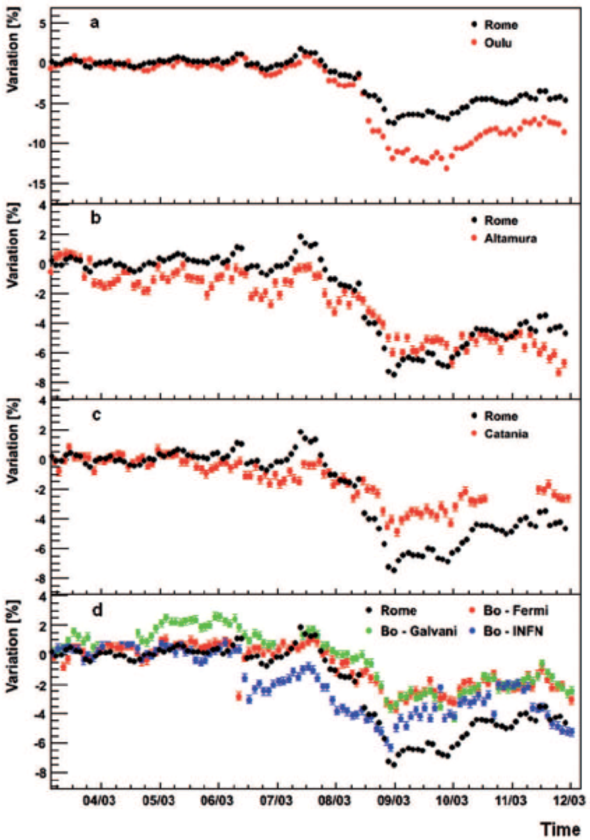
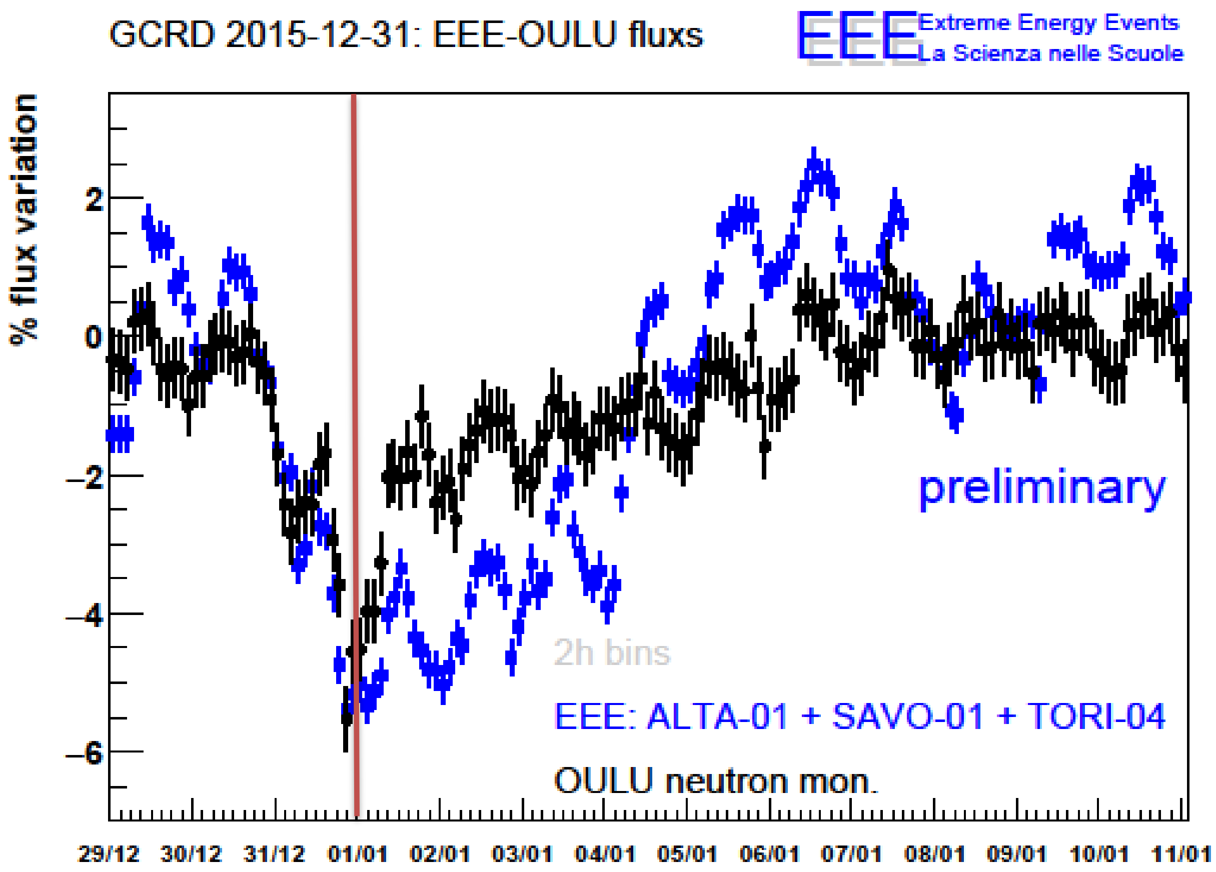


Fig. 5. The March 2012 GCR decrease, as observed by (a) the Oulu and Rome detectors of the Neutron Monitor Network and by (b) the Altamura, (c) Catania, and (d) Bologna EEE telescopes. For an easier comparison, the EEE measurements are superimposed to the Rome data.

Unprecedented with muons in High Schools !!!

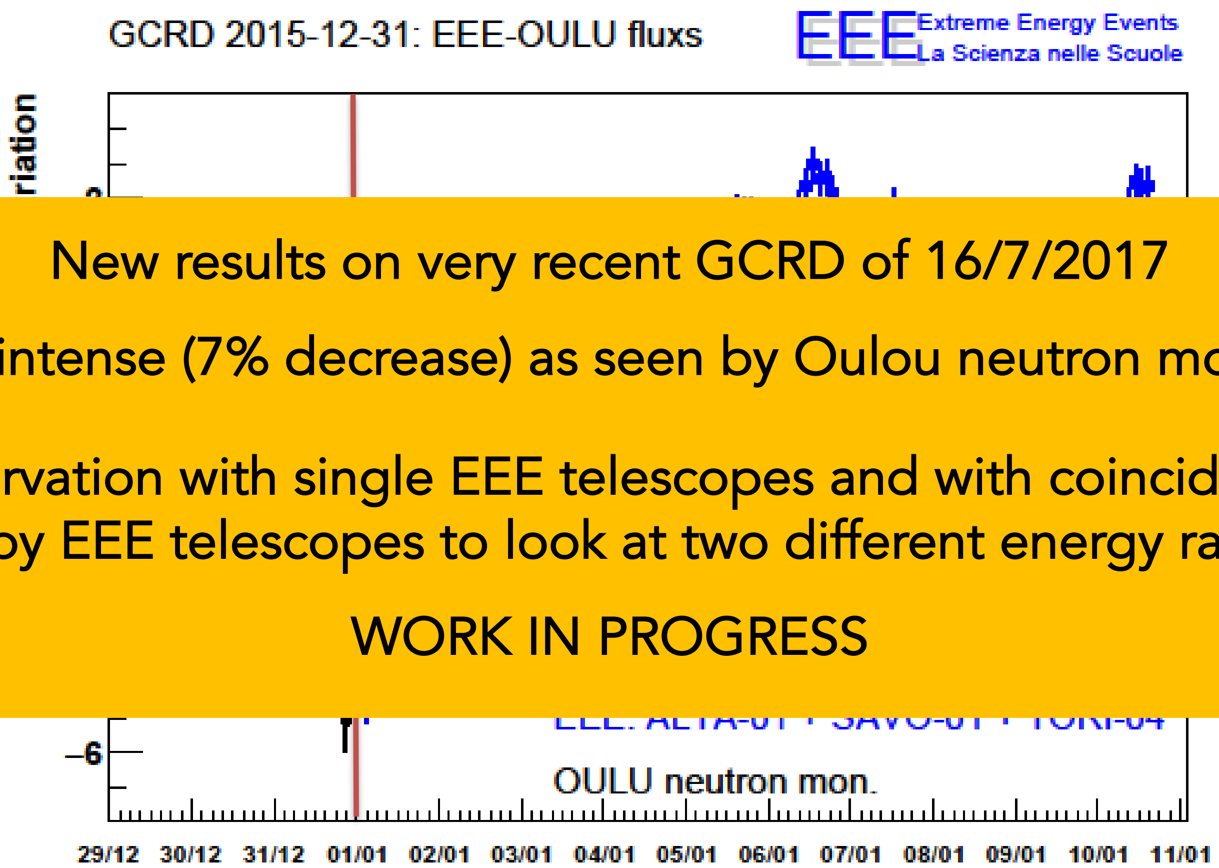
Being up h24

The 2016 new year GCRD: at 24.00 of 31/12/2015 the EEE telescopes – **inside Schools** – were up and running!



Being up h24

The 2016 new year GCRD: at 24.00 of 31/12/2015 the EEE telescopes – **inside Schools** – were up and running!



New results on very recent GCRD of 16/7/2017

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

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

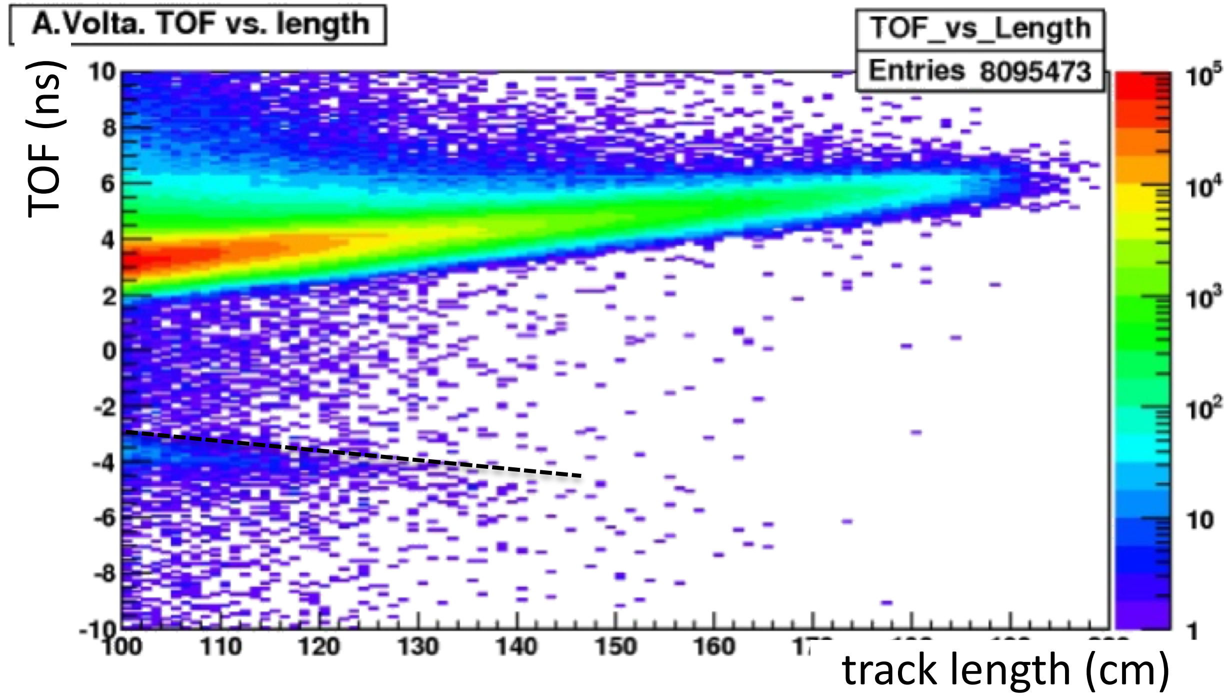
WORK IN PROGRESS

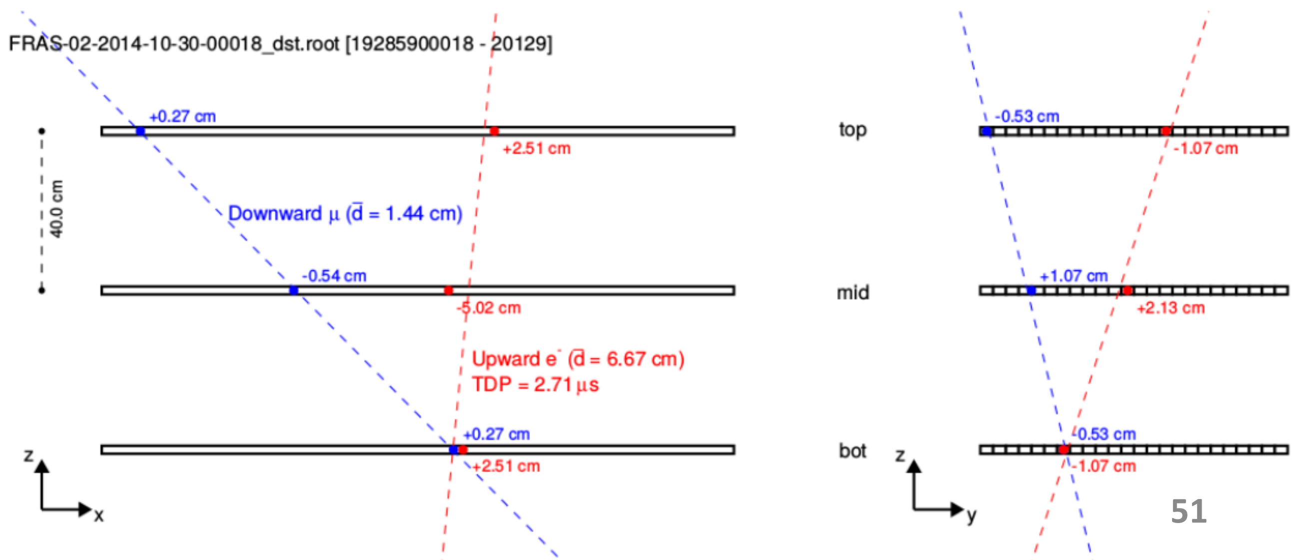
Upgoing events

Few upgoing events are observed (1/2000) in EEE telescopes

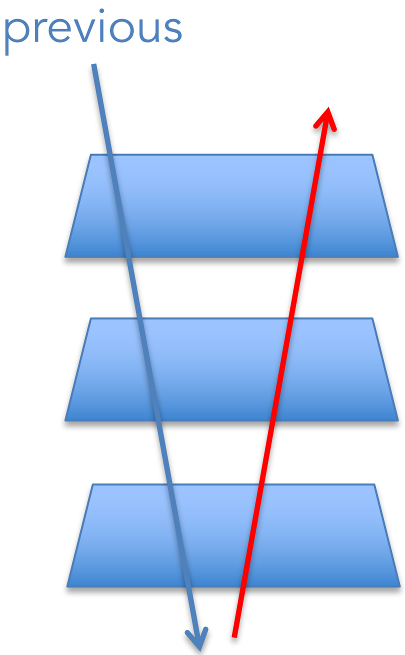
The nature of such events is under investigation

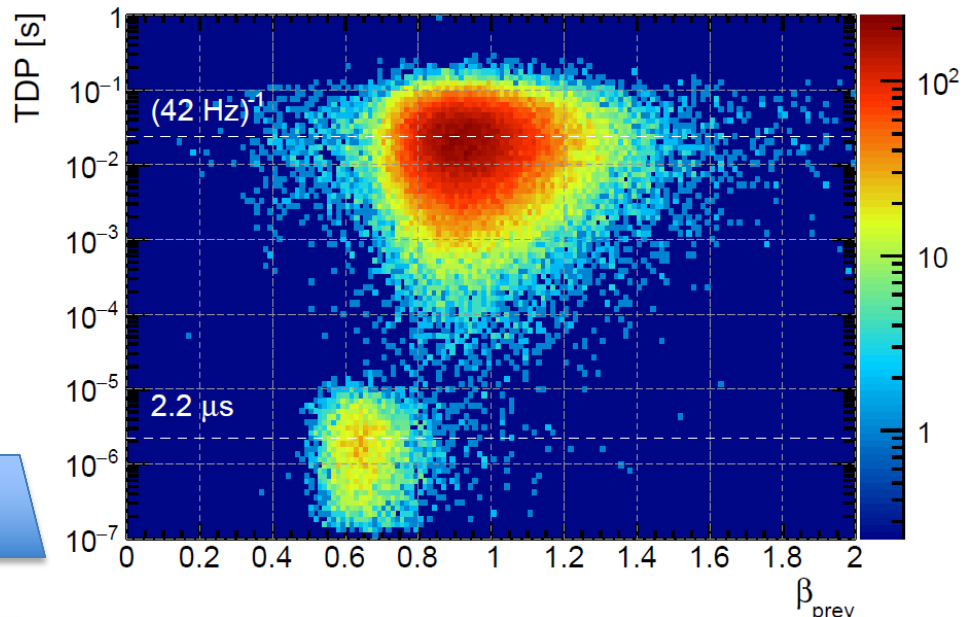
A fraction of them can be clearly identified as electrons coming from muon decays (in the floor under the telescope), looking at their time correlation with previous events (~ 2 μs)

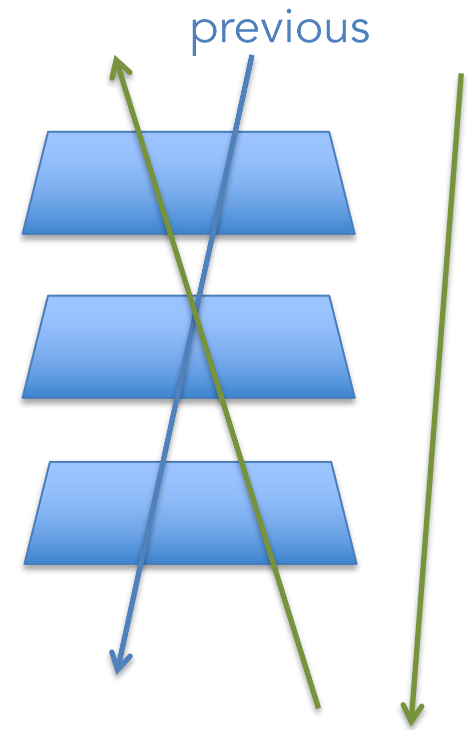




Muon decay in EEE telescopes







Distribution of the delay (TDP) between upward track and previous downward (parent) track vs. β of previous track

Telescope rate: 42 Hz

Muon backscattering

Muon decay

$$\mu^{\pm} \to e^{\pm} + \nu_{e/\mu} + \bar{\nu}_{\mu/e}.$$

High energy events

Density of secondaries at sea level

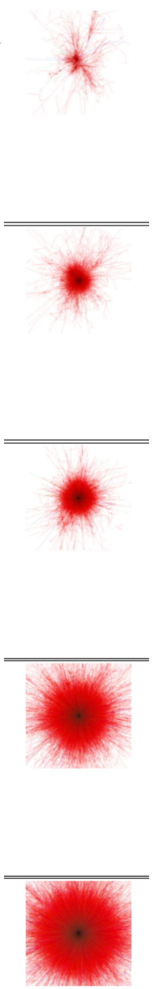
E = 10^{11} eV

E = 10^{12} eV

E = 10^{13} eV

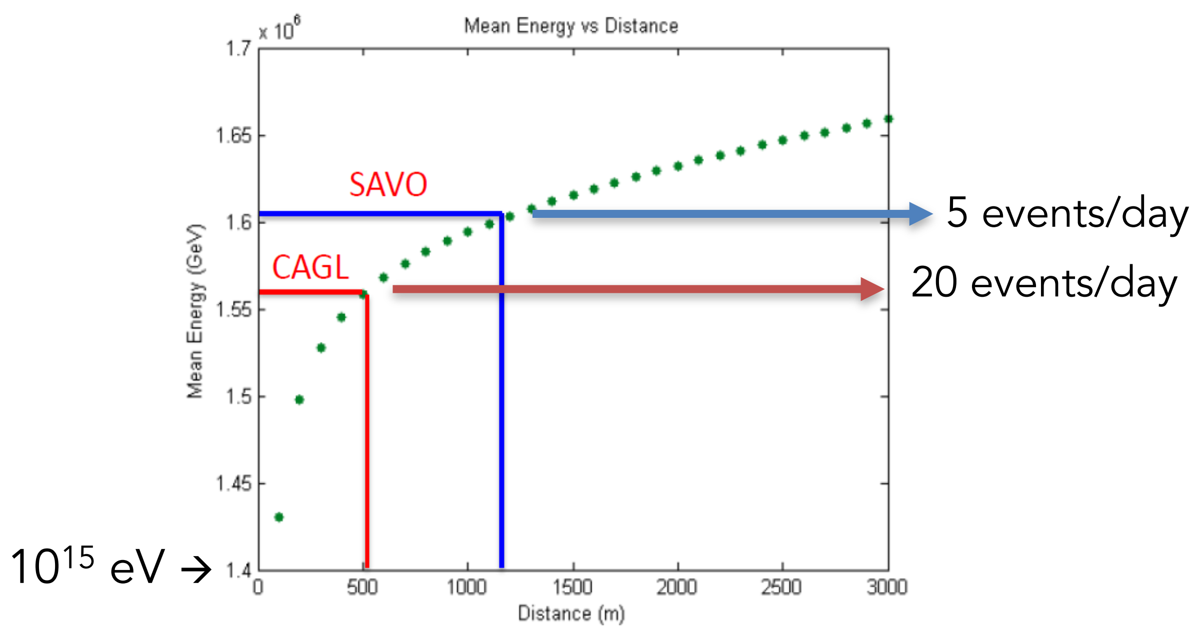
E = 10^{14} eV

E = 10^{15} eV



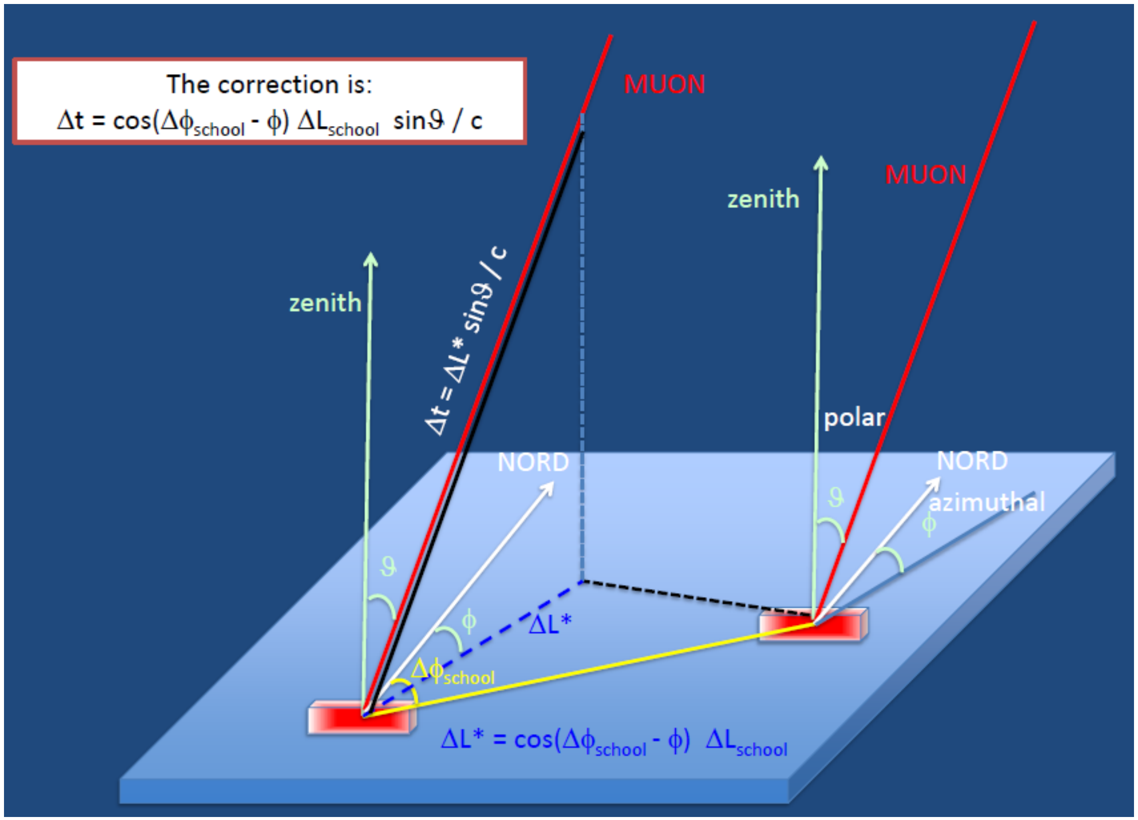
Measure coincidences between distant telescopes

- 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

Reconstruction of the primary cosmic ray direction



EEE telescopes allow to reconstruct the direction of the shower secondaries, i.e. of the shower axis

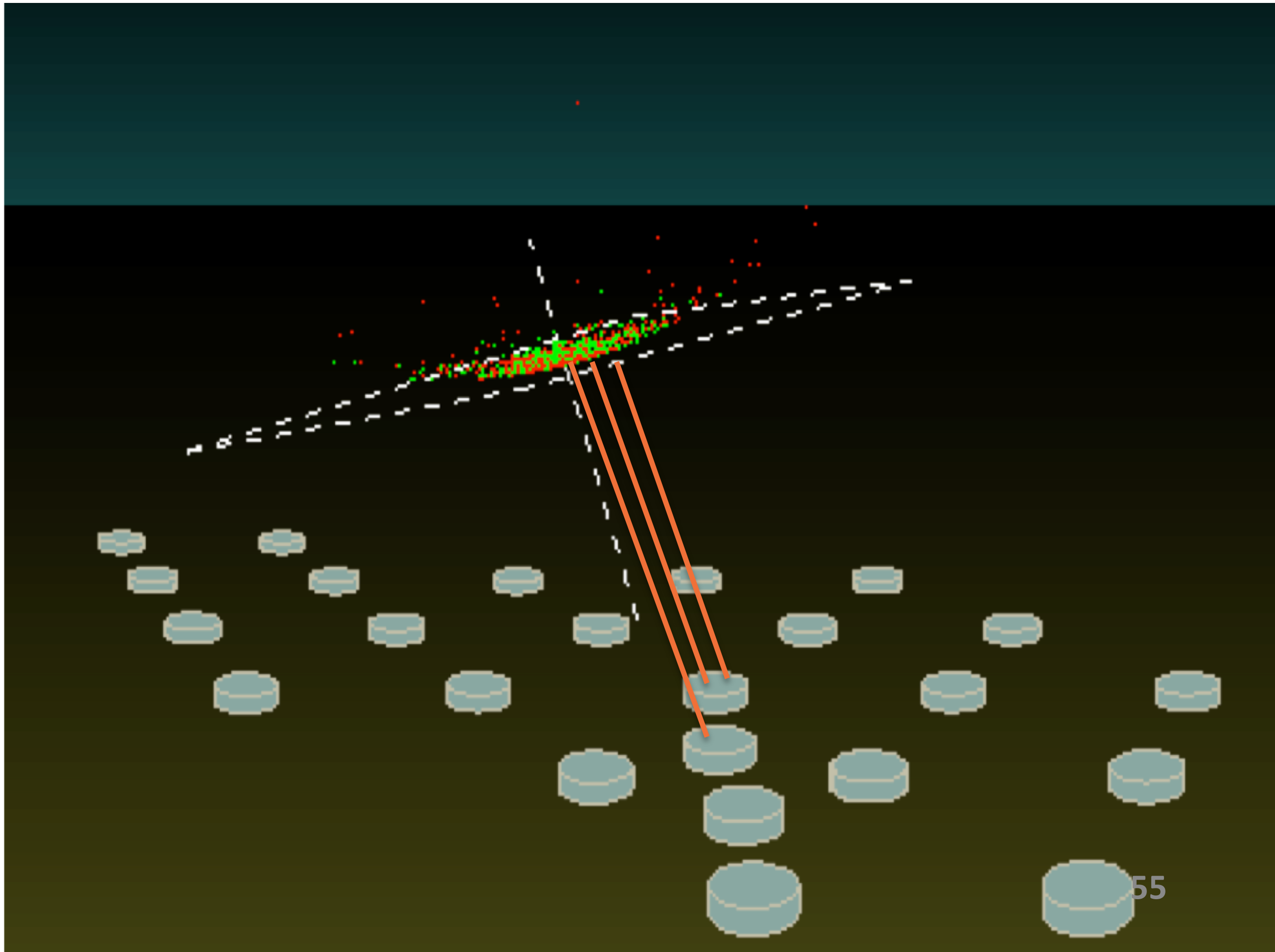
Such a feature allows to correct, event by event, the time delay between two telescopes because of the propagation of the wave front of the shower

This is very important when looking at coincidences at very large distances since above 1 km the time delay may be of the order of few microseconds

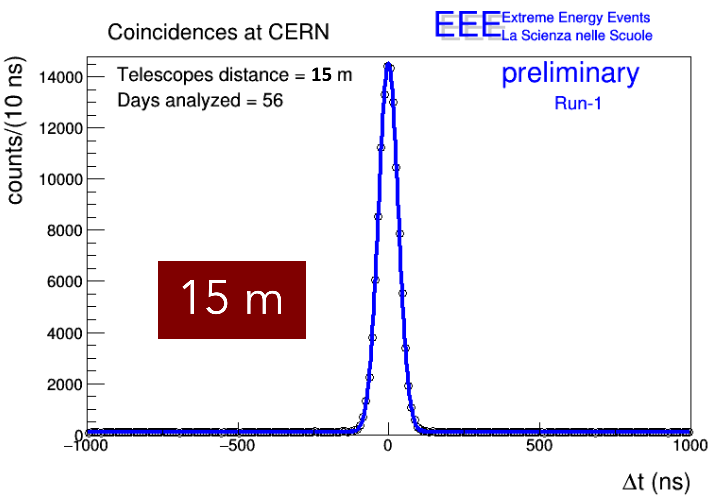
As from 2014

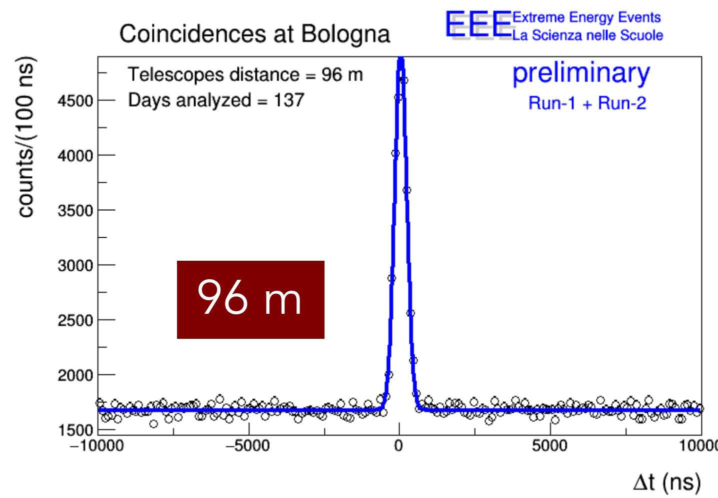
– with more statistics via coordinated data taking Runs
– taking advantage of the **tracking capablity of the telescopes to select different impact angles and to apply angular & time corrections**

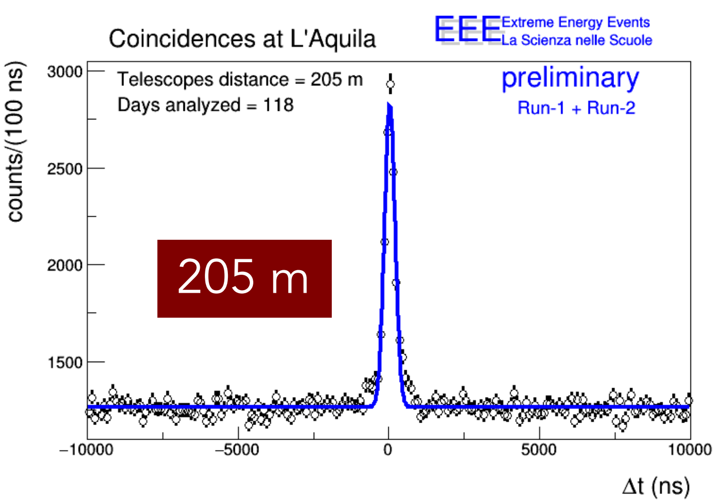
→ the search for **coincidence events** from near and distant telescopes is **successfully ongoing**



2-telescope coincidences





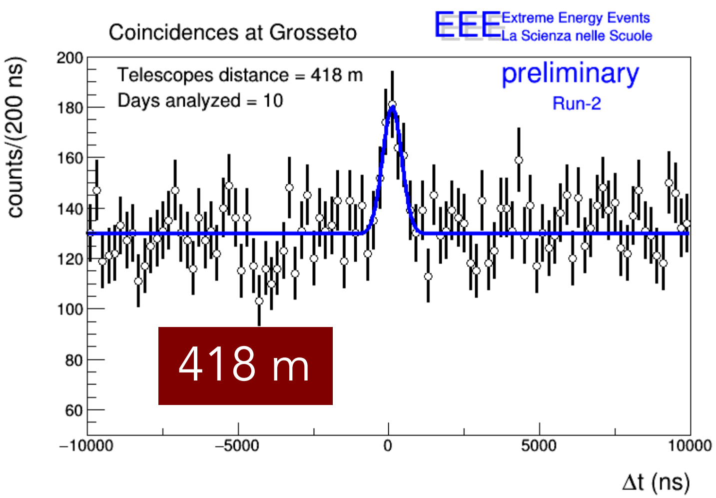


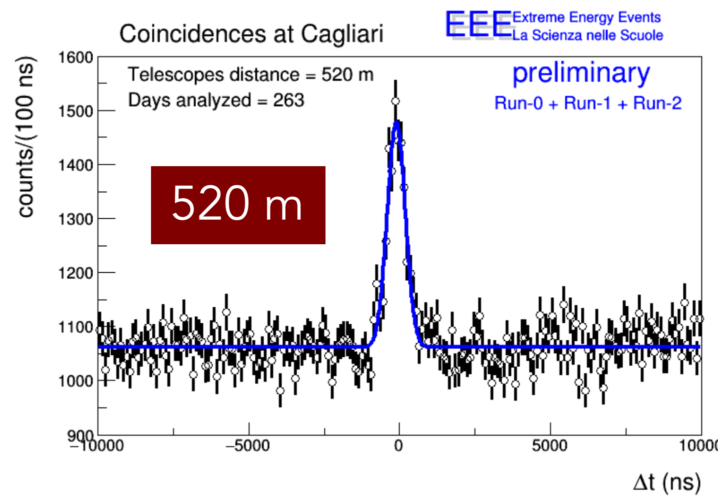
Single-track coincidences between 2 telescopes were well reconstructed for several distances between telescopes

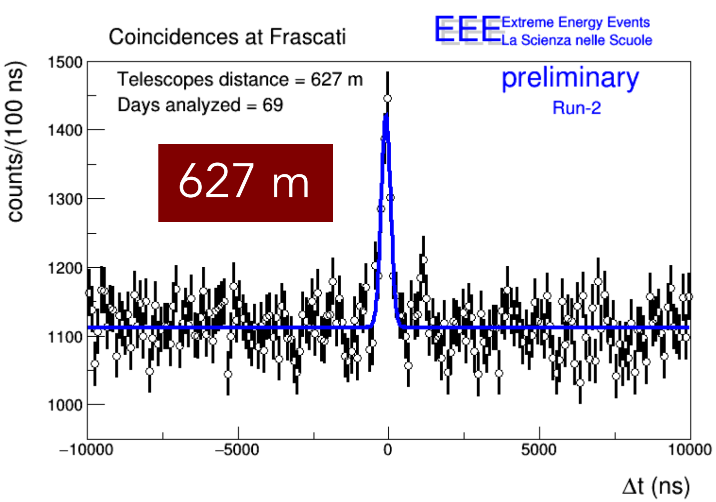
The relative angle between 2 tracks was required to be < 30° (≈ 10-15° on average)

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)

2-telescope coincidences



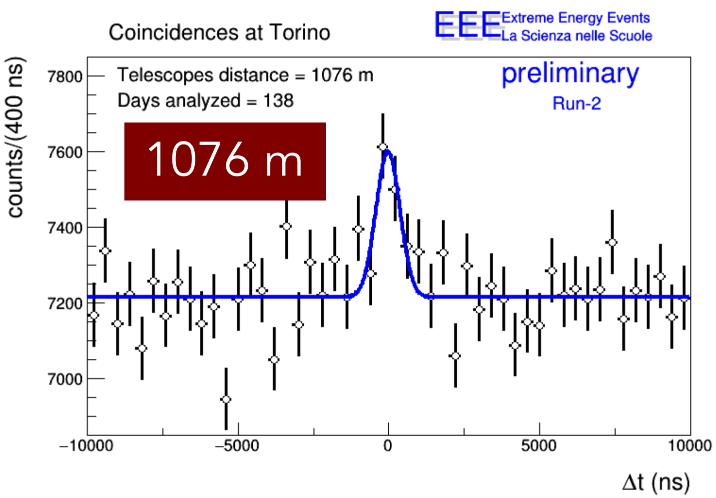


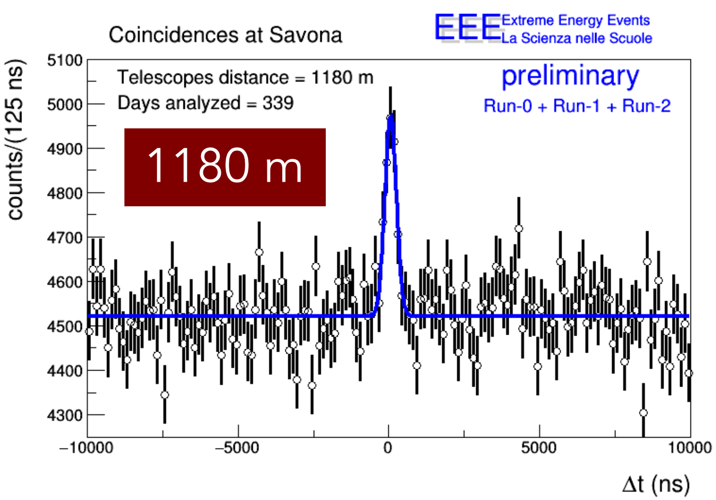


The width of the reconstructed peak is usually of the order of **200-250 ns** (CERN and Bologna cases differ because of particular GPS setups)

The correction **event by event** of the <u>time delay</u> between two telescopes (because of the propagation of the <u>wave front</u> of the shower) significantly improves the S/B ratio

2-telescope coincidences



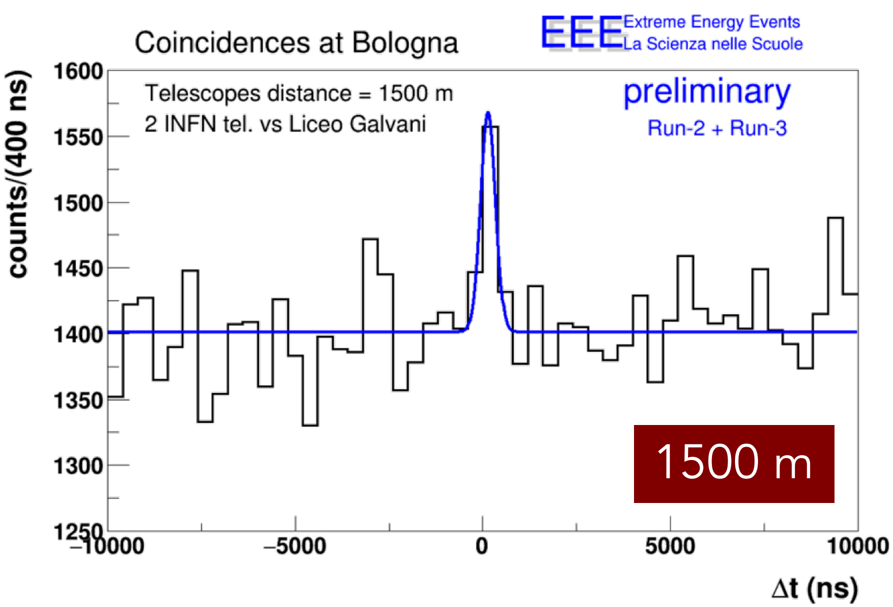


For the **first time** coincidences were observed between two telescopes installed in <u>High Schools</u> at a **distance greater than 1 km**
(significance $S/\sqrt{(S+B)} = 5.1$)

The statistics used here includes also the data acquired in the Pilot run of 2014

2-telescope coincidences

Preliminary results from Run-2 and Run-3 (2016-2017)

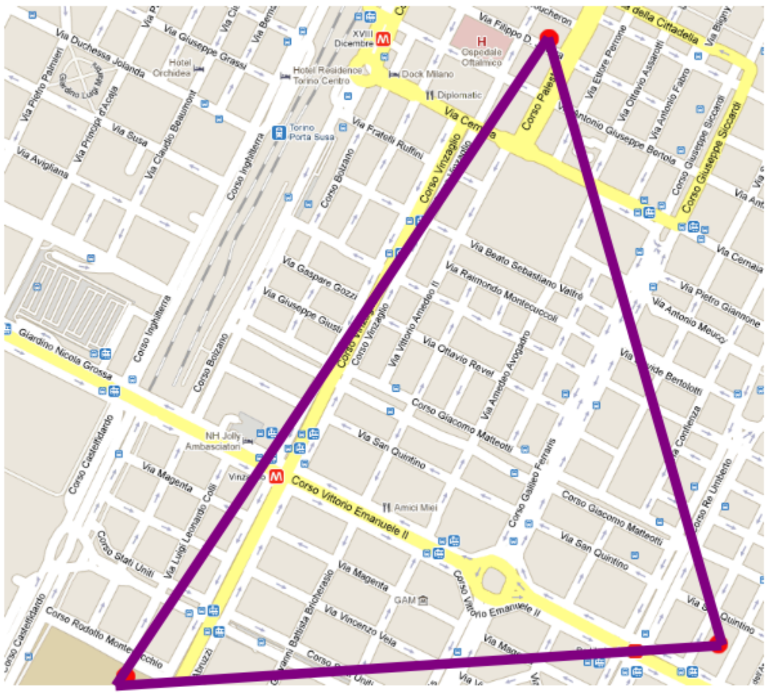


→ One of the goals for the near future is to extend such measurements to <u>larger distances</u> (up to 2 or more km) and to extend the study to telescopes located in <u>different cities</u> to look for exotic ("unexpected") high energy events

3-telescope coincidences

Liceo Scientifico “A. Volta”

1350 m



1080 m

Liceo Scientifico “G. Ferraris”

1045 m

Liceo Classico “M. D'Azeglio”

Coincidence studies will be extended also to the case of **3 telescopes**

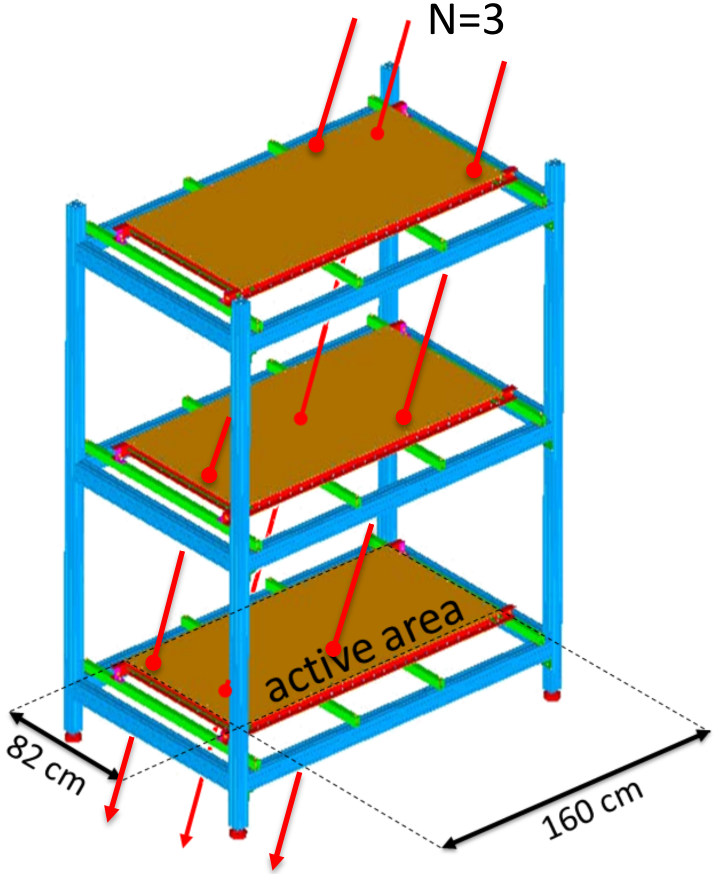
<u>Advantages</u>

- The energy of the primary is expected to be higher
- Background from accidental combinations is strongly suppressed

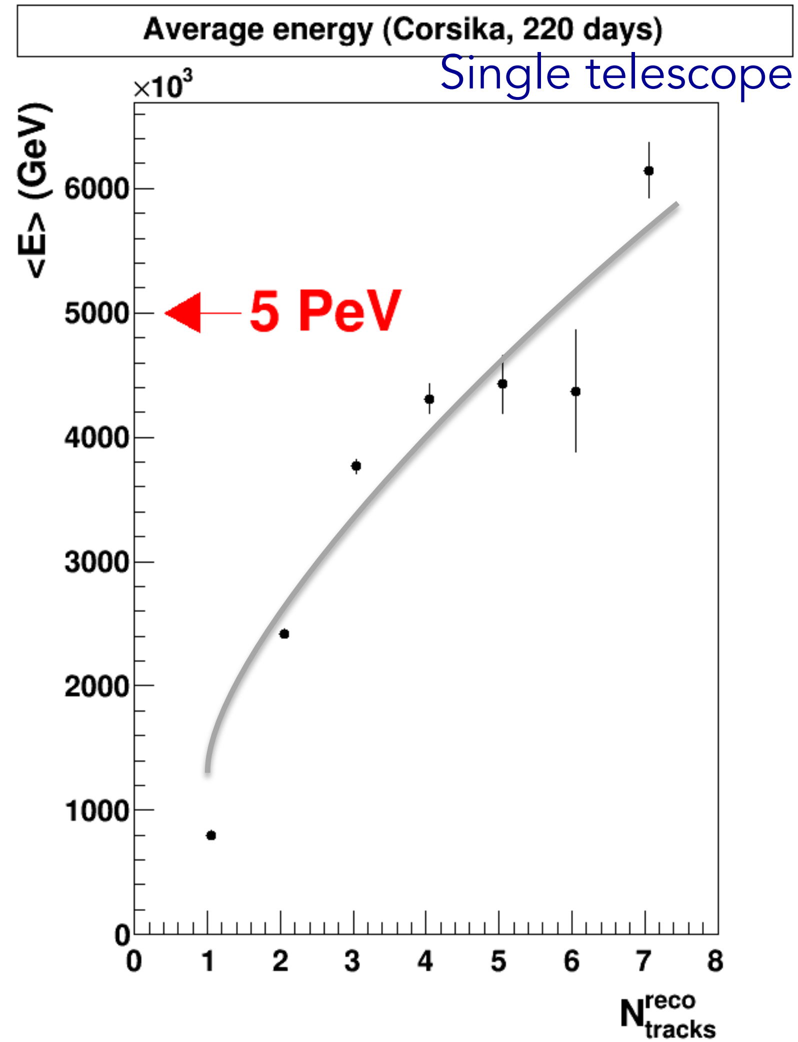
<u>Disadvantages</u>

- The rate expected is much lower than in the 2-telescope case → more data taking needed

Multi-track events



Preliminary simulation of Corsika MC showers using EEE telescope geometry

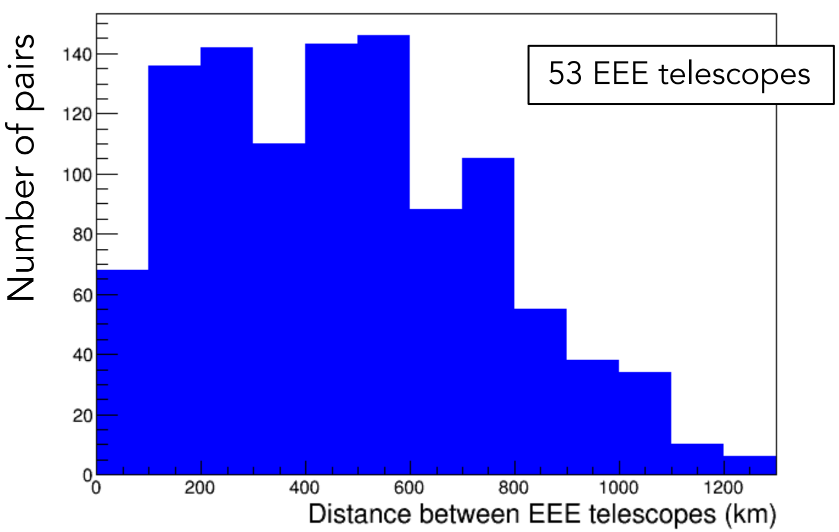


10^5 GeV $< E_{primary} <$ 10^7 GeV
(10^{14} eV $< E_{primary} <$ 10^{16} eV)

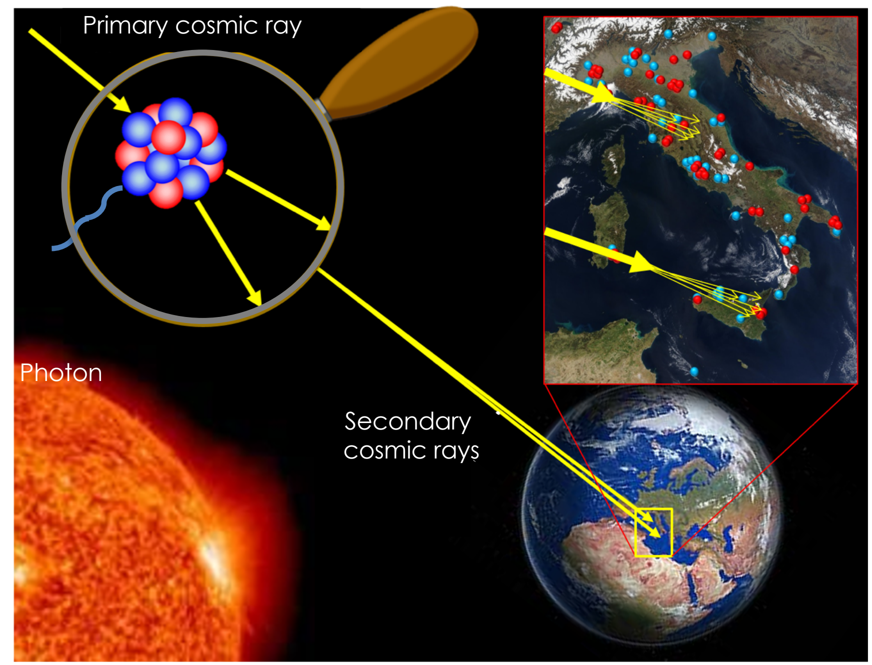
Long distance shower correlations

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" …



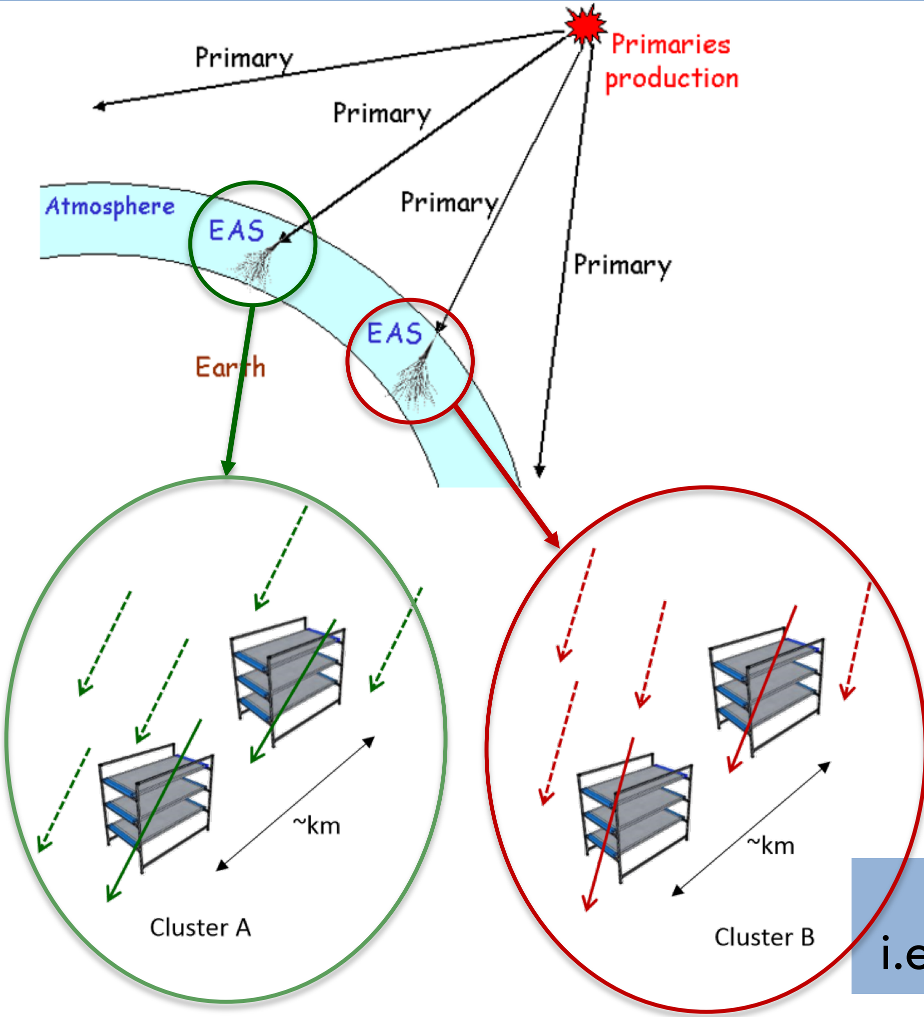
EEE typical distances between 2 telescopes



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

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

Long distance shower correlations

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)
- $\theta_{rel} < 40°$ for the two tracks

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

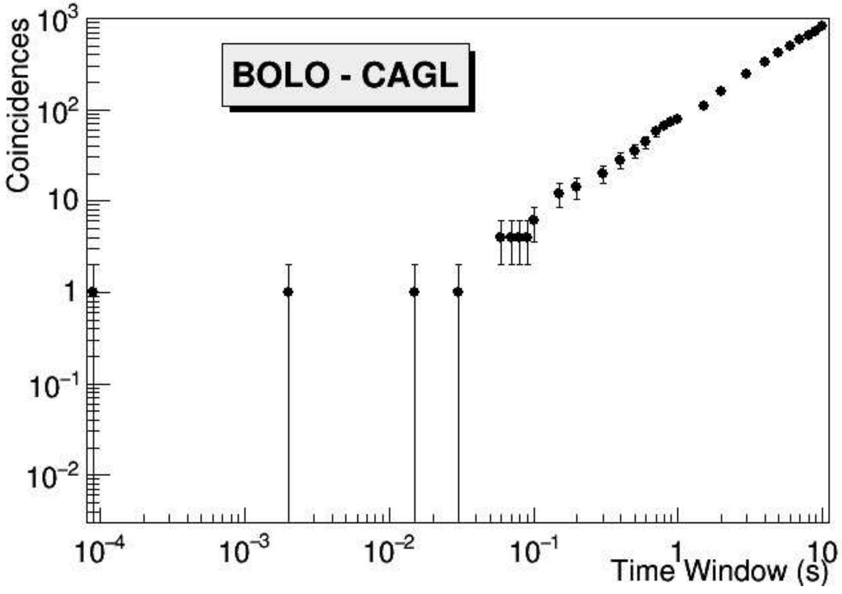
→ Consider 2-cluster coincidences
within a certain time window

→ Distances from 86 km to 1200 km

→ 15 billion tracks

→ 96 observed events
against 77.8 of estimated background

Long distance shower correlations



"Search for long distance correlations between extensive air showers detected by the EEE network", EEE Collaboration, Eur. Phys. J. Plus (2018) 133: 3

Number of coincidence events vs. decreasing time window

Event	EEE pairs	Distance (km)	$\|t_1 - t_2\|$ (μs)	ϑ_{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″

The most significant candidate events observed within a time window compatible with the distance between the sites

5 candidate events with a p-value < 0.05

Long distance shower correlations

FOR RARE EVENTS → NEGLIGIBLE BACKGROUND NEEDED

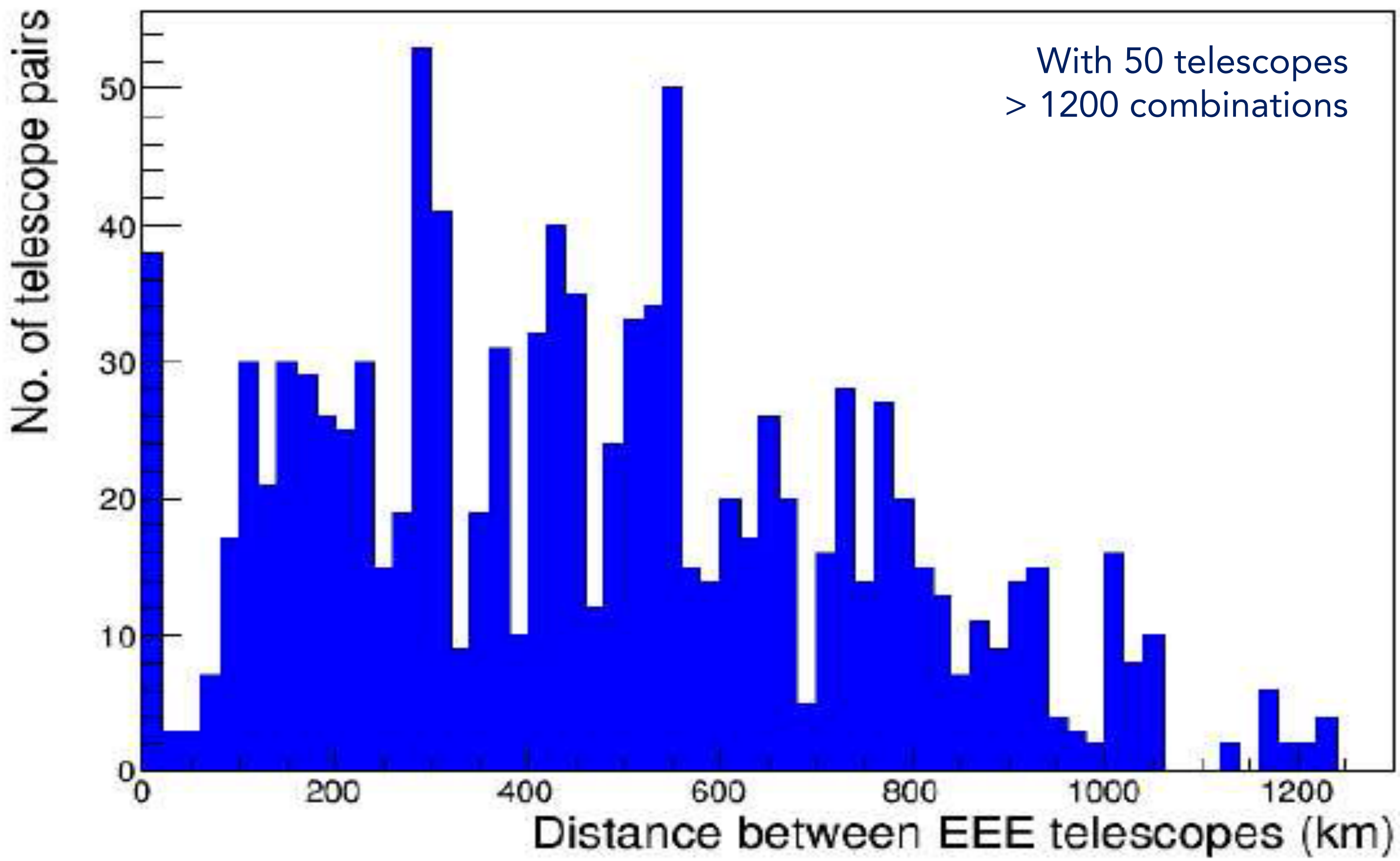
Possible analysis strategies:

- **Correlations between pairs of telescope <u>clusters</u>**
  - ✓ Low spurious coincidence rate between clusters ($\sim 10^{-7}$ Hz)
  - ✘ Few sites with a cluster of telescopes (only 10)

- **Correlations between pairs of <u>multi-track</u> (single) telescopes**
  - ✓ High number of telescopes combinations (higher statistics)
  - ✓ More different distances covered
  - ✘ Higher spurious coincidence rate between telescopes ($\sim 10^{-6}$ Hz)

Long distance shower correlations

Correlations between pairs of multi-track telescopes

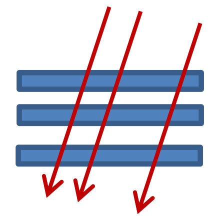


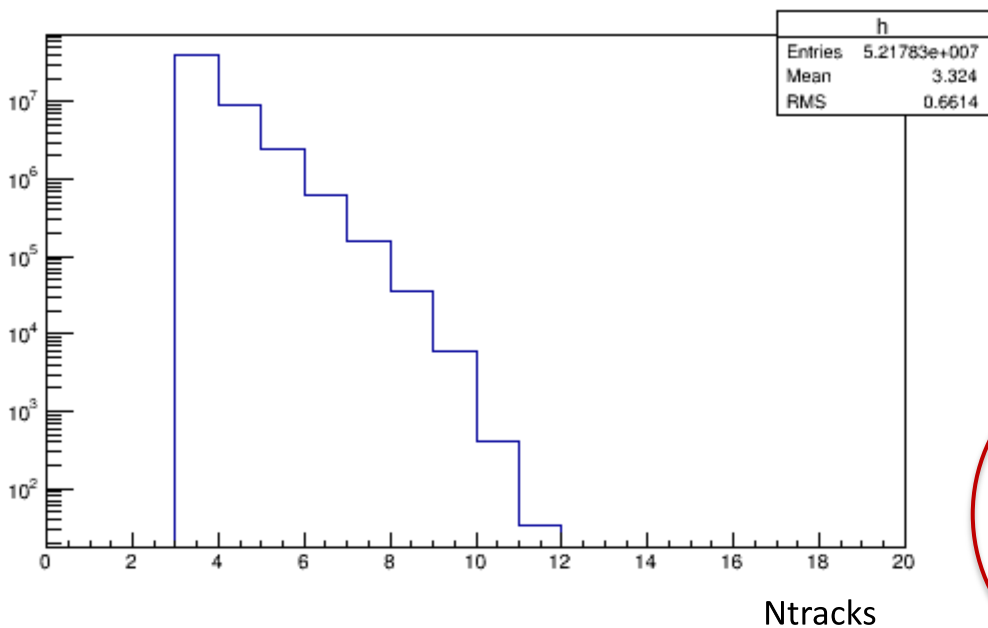
Long distance shower correlations

Correlations between multi-track telescopes

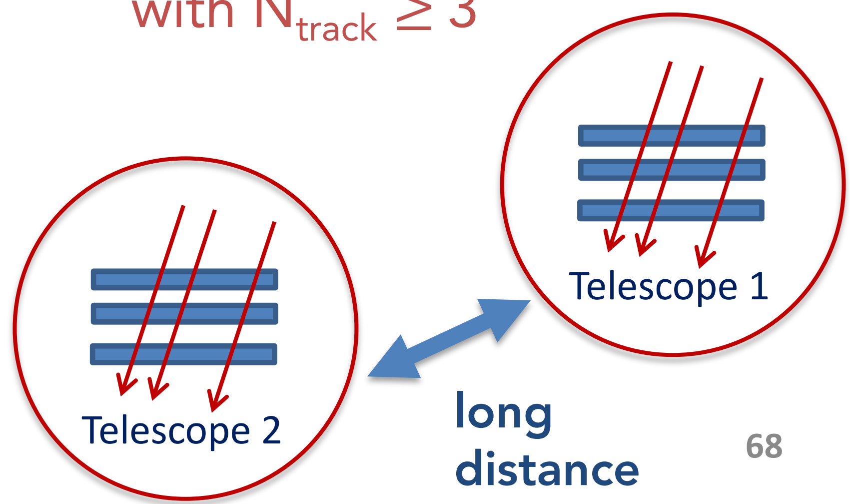
Selection of multi-track telescope:

- $\chi^2 < 50$ for track reconstruction
- parallelism constrain
  → scalar product with the seed track (i.e. track with best χ^2) > 0.8 in the same telescope





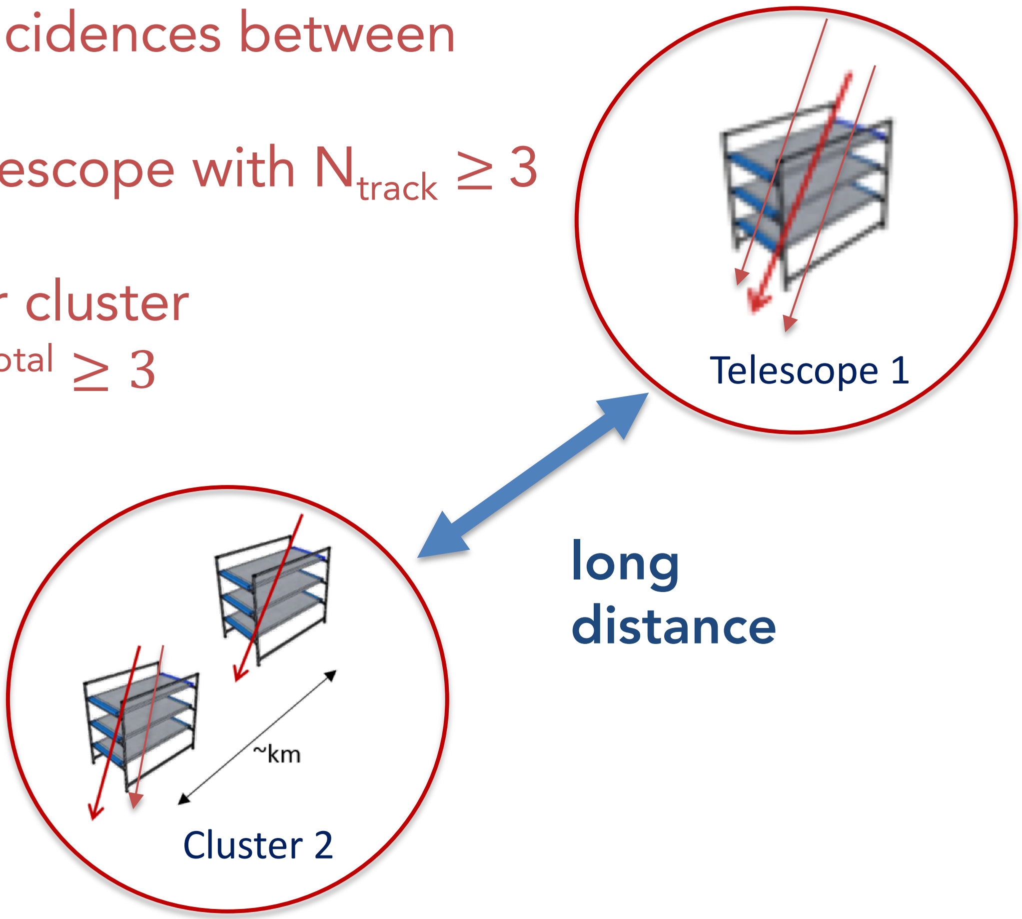
Require coincidences between two multi-track telescopes with $N_{track} \geq 3$



Long distance shower correlations

Also include coincidences between

- multi-track telescope with $N_{track} \geq 3$
- telescope-pair cluster with a $(N_{track})^{total} \geq 3$



Long distance shower correlations

Analysis performed with:

- 39 telescopes + 5 clusters
- **50 million telescopes or clusters with $N_{track} \geq 3$**
- data taking period: 01/01/2016 $\rightarrow$ 26/03/2018
  (Run-2 up to Run-4 → ≈ 50 billion tracks)

- distance telescope-telescope or telescope-cluster **> 5 km**
- **$N_{track} \geq 5$** in each telescope or cluster

$\rightarrow$ **11 coincidence events observed**
in a narrow time window ~ 10^{-5} – 10^{-4} s
(with an expected background ~ 5 events)
corresponding to a p-value ~ 4 x 10^{-3}

Long distance shower correlations

Correlations between multi-track events in both telescopes

Tel 1 (ID)	Tel 2 (ID)	N_{track} 1	N_{track} 2	Date	Rel. angle (deg)	Distance (km)
115 CERN	7 Bologna	7	5	09/01/2016	21	456
122 L'Aquila	7 Bologna	7	6	27/04/2016	41	290
115 CERN	14 Catanzaro	5	7	12/05/2016	18	1194
22 L'Aquila	41 Torino	5	5	21/05/2016	23	551
27 Lodi	35 Savona	5	5	08/10/2016	24	137
19 Frascati	31 Reggio E.	5	5	21/12/2016	71	361
10 Cagliari	27 Lodi	6	5	27/01/2017	50	675
15 CERN	30 Paternò	5	5	19/03/2017	41	1208
7 Bologna	14 Catanzaro	6	5	31/03/2017	36	767
23 L'Aquila	24 Lecce	6	5	02/06/2017	64	456
5 Bologna	36 Savona	5	5	08/10/2017	24	229

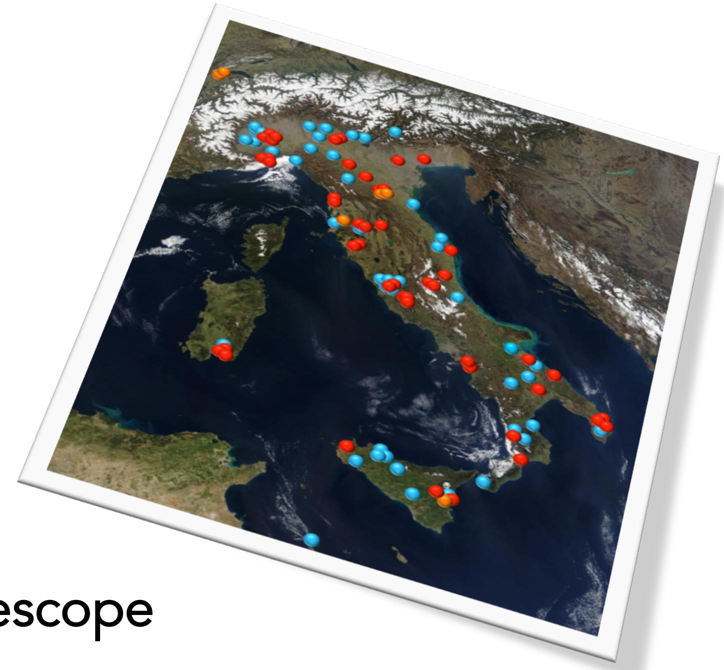
Long distance shower correlations

Correlations between multi-track events in both telescopes

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

WORK IN PROGRESS

What next

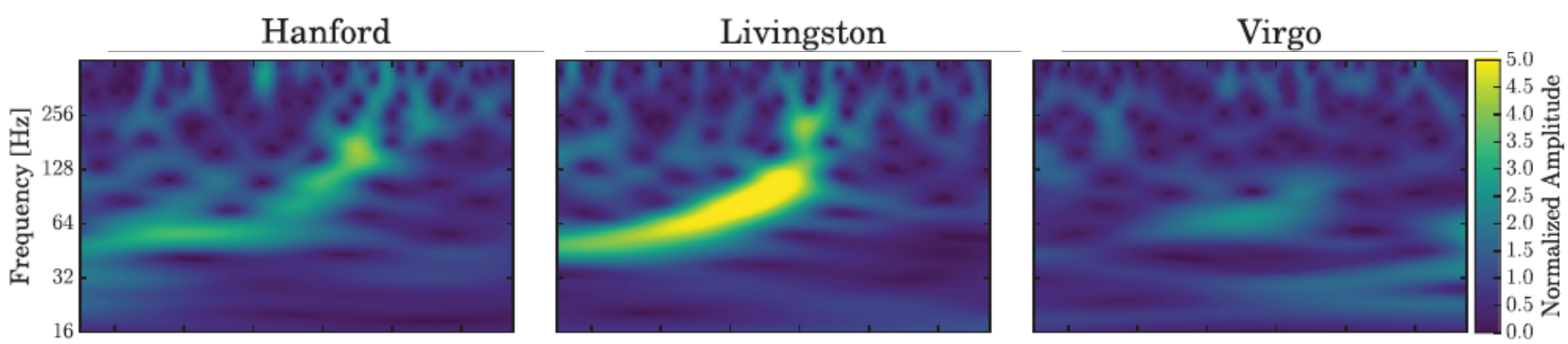


- Increase the number of EEE telescopes from 53+6 to 100 High Schools (original project!)
- Increase the statistics of two-telescope coincidences and search for three-telescope coincidences within the same city
- Increase the statistics for multi-track telescope analysis in the search
- Test the pointing capabilities of telescopes
- Increase the statistics for coincidences of clusters of telescopes between different cities
- Search for upgoing events in single telescopes and in two-telescope coincidences

→ SEARCH FOR THE UNEXPECTED …

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

GW event	Date	Notes	N. EEE ON
GW150914	14/09/2015	First GW detection; first BH merger observed; largest progenitor masses to date	3
GW151226	26/12/2015		26
GW170104	04/01/2017	Farthest confirmed BH event to date	26
GW170608	08/06/2017	Smallest BH progenitor masses to date	32
GW170814	14/08/2017	First BH detection by three observatories; first measurement of GW polarization	6
GW170817	17/08/2017	First NS merger observed in GW; first detection of EM counterpart; nearest event to date	6

Search for multi-messenger events with EEE telescopes

GW event	Date	Operative EEE telescopes	N. EEE ON
GW150914	14/09/2015	BARI-01, BOLO-01, BOLO-04	3
GW151226	26/12/2015	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, SAV0-02, SAVO-03, TERA-01, TORI-02, TORI-03, TORI-04,	26
GW170104	04/01/2017	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,	26
GW170608	08/06/2017	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	32
GW170814	14/08/2017	AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-04, TRAP-01	6
GW170817	17/08/2017	AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-03, TORI-04	6

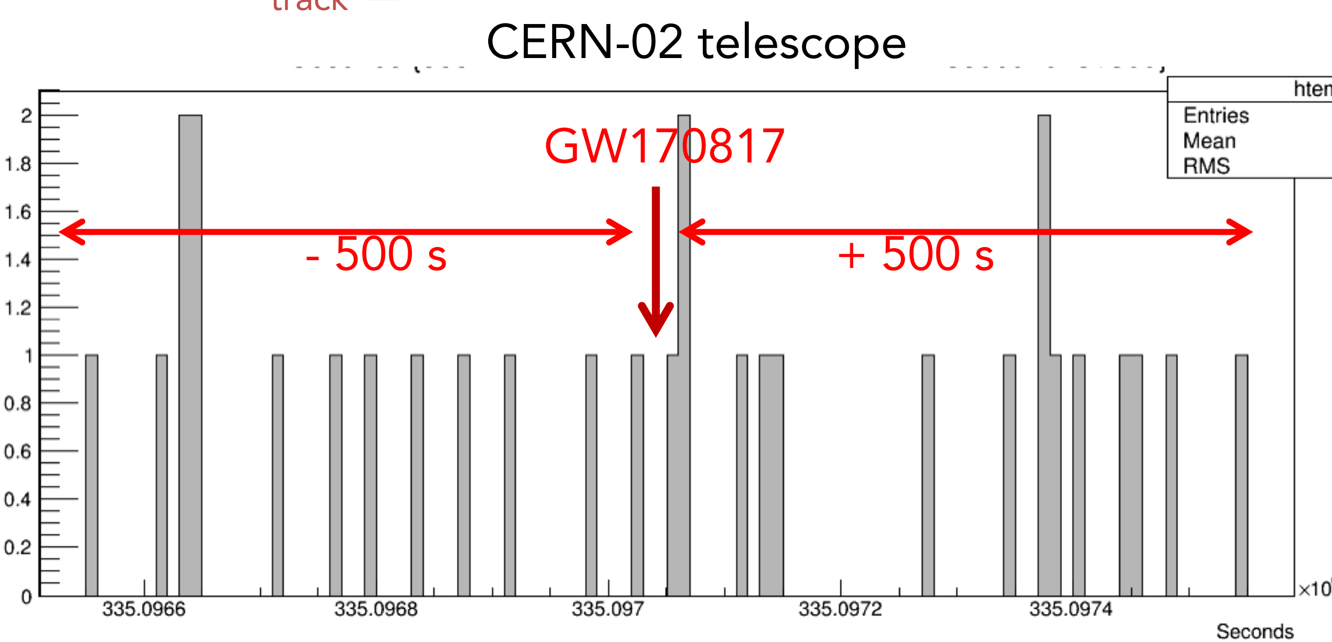
Search for multi-messenger events with EEE telescopes

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 $N_{track} \geq 3$



No observation of any specific anomaly
but the analysis is still ongoing

Search for multi-messenger events with EEE telescopes

GW event	Date	Operative EEE telescopes	N. EEE ON
GW150914	14/09/2015	BARI-01, BOLO-01, BOLO-04	3
GW151226	26/12/[illegible]	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, SAV0-02, SAVO-03, TERA-01, TORI-02, TORI-03, TORI-04,	26
GW170104	04/01/2017	[illegible] ARI-01, BOLO-01, BOLO-02, BOLO-03, BOLO-04, CAGL-[illegible] ATA-01, CATA-02, CATZ-01, COSE-01, GROS-01, [illegible] DI-01, PARM-01, PATE-01, REGG-01, SALE-[illegible] RI-01, TORI-03, TORI-04, TRAP-01,	26
GW170608	08/06/2017	ALTA-01, [illegible] O-02, BOLO-03, BOLO-04, CAGL-01, CAGL-0[illegible] TZ-01, CERN-01, CERN-02, COSE-01, GROS-01, [illegible] U-02, LODI-01, LODI-02, PARM-01, PATE-01, [illegible] 2, SIEN-01, TORI-01, TORI-03, TORI-[illegible]	32
GW170814	14/08/2017	AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-04, TR[illegible]	6
GW170817	17/08/2017	AREZ-01, BOLO-04, CERN-01, CERN-02, TORI-03, TORI-04	6

WORK IN PROGRESS

External collaborations

- EGO-VIRGO collaboration interested in having one (or more) EEE telescopes hosted at their lab in Cascina as a veto for cosmic ray showers in coincidence with possible signals coming from gravitational waves (there is a similar device at LIGO)

EGO - Virgo

- University of Santiago de Compostela (Spain) interested in anaylizing EEE data looking for correlations between cosmic ray flux and temperature and pressure conditions in the throposphere

- High Schools abroad in:

Albania (Korçë)
Cina (Beijing)
Mexico (Mexico City)
Russia (Dubna, Novosibirsk)
South Africa (Cape Town)
Taiwan (Taipei)
Norway (Bergen, Oslo)
Israel

The EEE Open Data Project

1) Remote & continuous monitor of EEE telescopes and access to data **even for Schools without telescopes**

2) The EEE Open Data Project

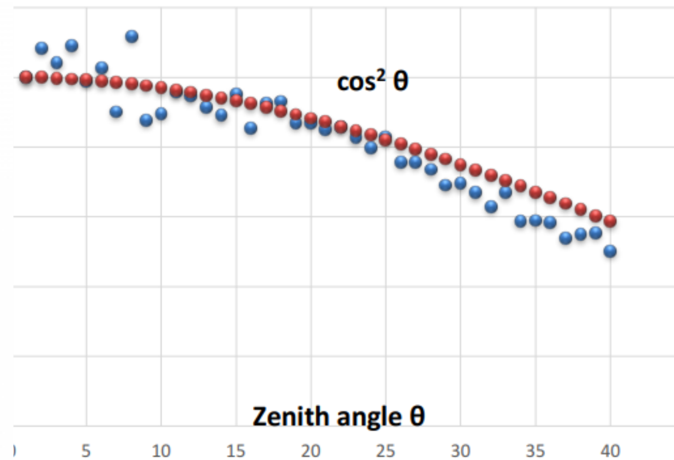
3) In collaboration with **IPPOG (International Particle Physics Outreach Group)** the EEE Project – Italy is participating in the newborn

GLOBAL HIGH SCHOOL COSMIC RAYS PROJECT

involving similar projects in Czech Republic, Denmark, France, Germany, Greece, The Netherlands, UK, USA, Canada …

CENTRO FERMI

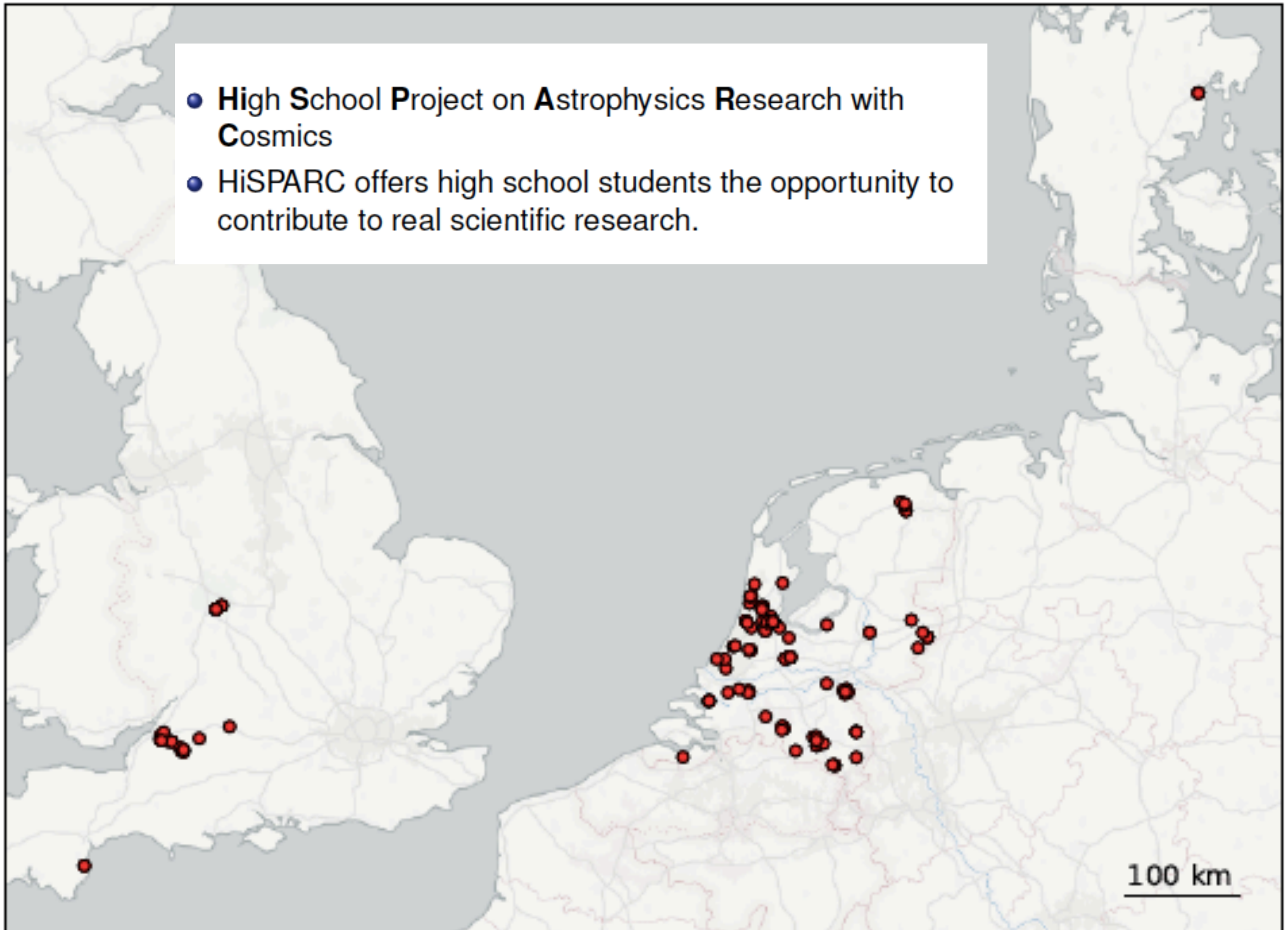
EEE at IPPOG-ICD 2017
47 Schools 550 students



Liceo Galvani (BO):
data from their telescope

Schools involved in the measurement of muon velocity during ICD

- **H**igh **S**chool **P**roject on **A**strophysics **R**esearch with **C**osmics
- HiSPARC offers high school students the opportunity to contribute to real scientific research.



$\sim$140 stations

HiSPARC

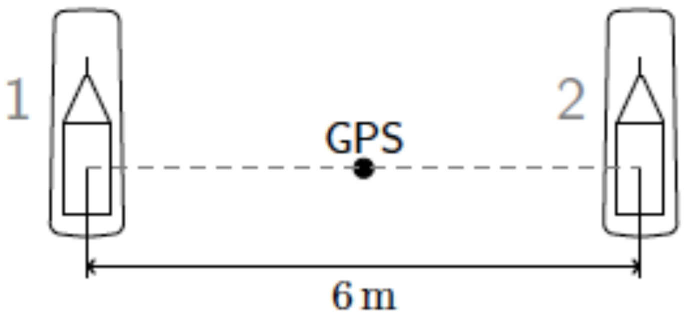
HiSPARC Station

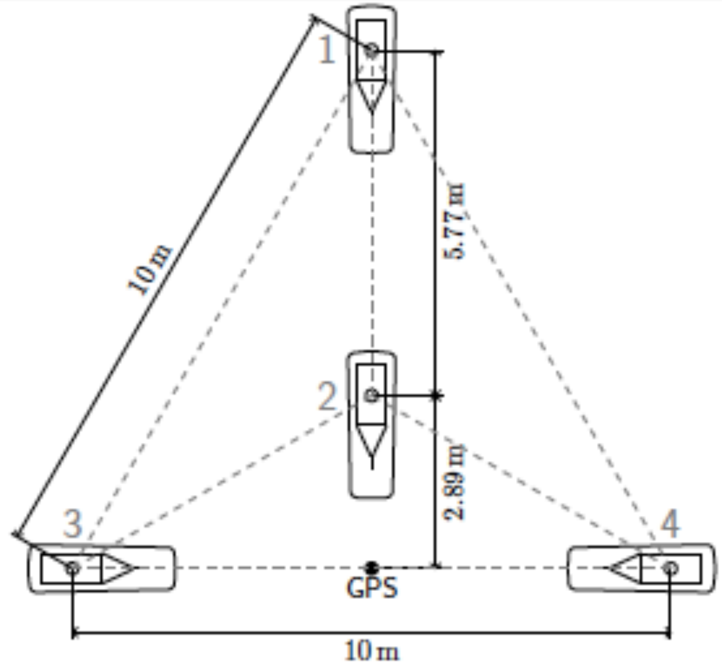
Principle:

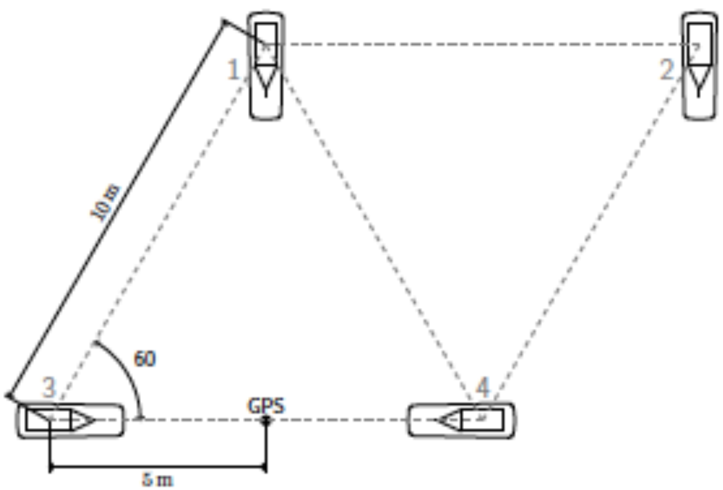
- If multiple detectors are hit within a narrow time window, these hits are deemed to be caused by particles from the same shower.
- We store coincidences and single rates.

HiSPARC

HiSPARC Station

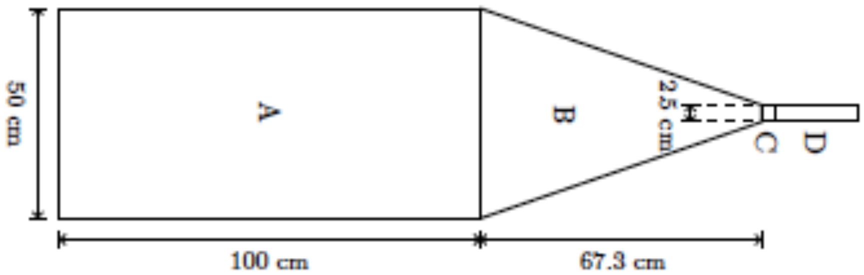






- Otherwise if no roof space available

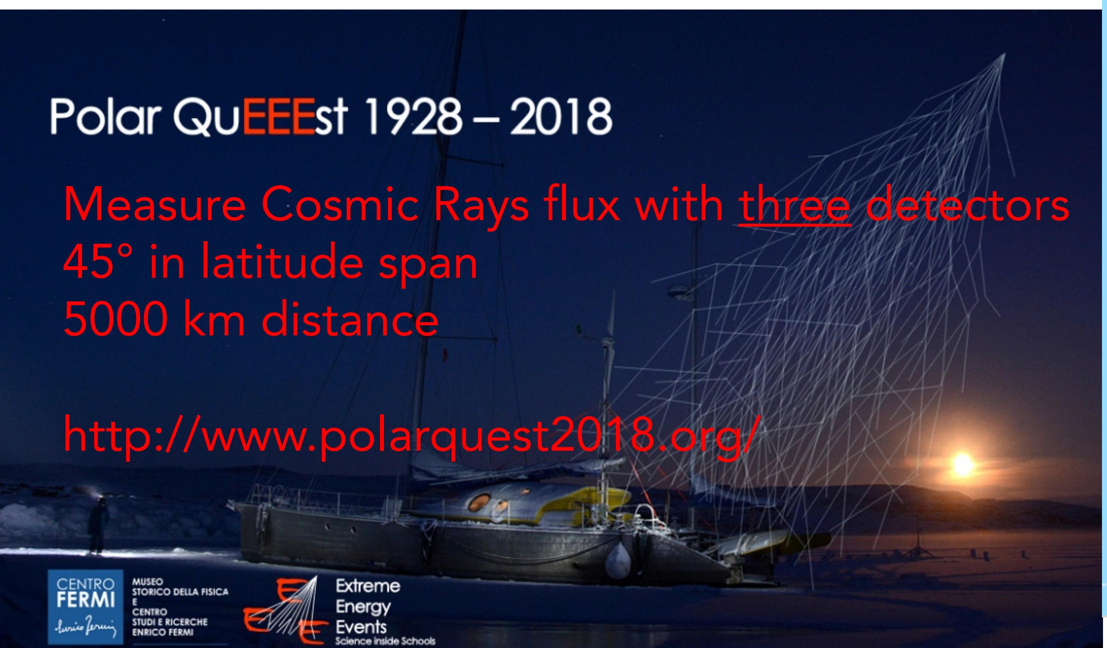
HiSPARC Detector



- A = Scintilator
- B = Lightguide
- C = Adaptor piece
- D = PMT

HiSPARC

The EEE project sails to North Pole !



POLAR QUEST 1928 2018

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 wildernesses on earth, to convey the importance of the Arctic for our sustainable future.

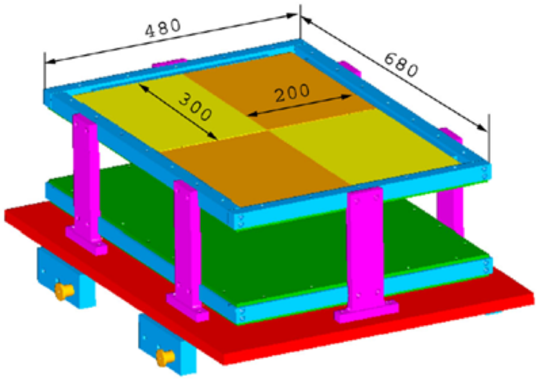
Nanuq – The passive Igloo project

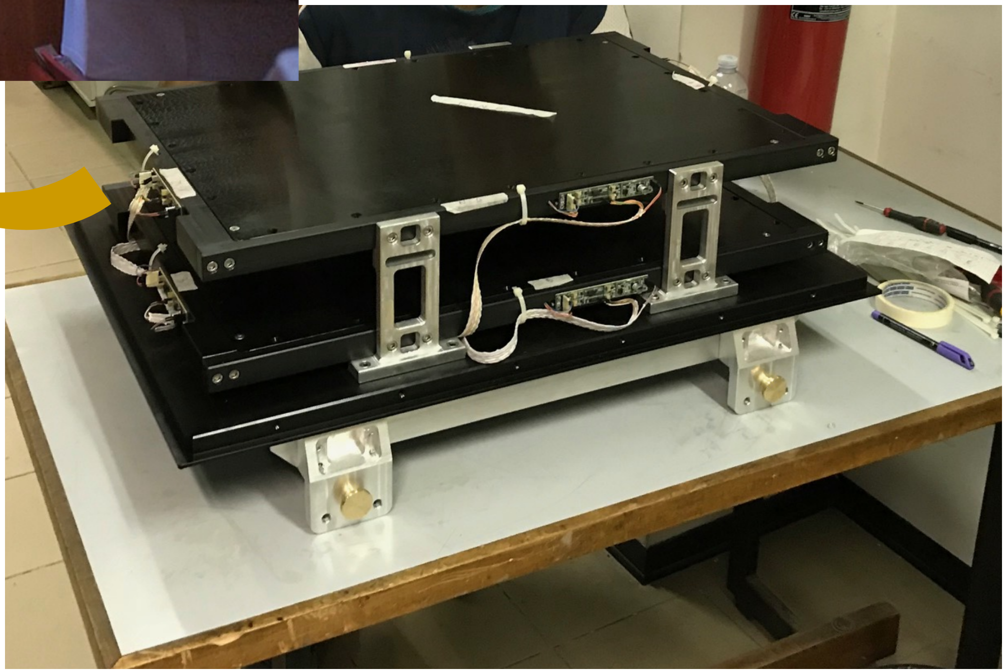
In the harbour … with Northern Lights


nuq North Sea
06-2015 The Passive Igloo Project

The EEE project sails to North Pole !

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



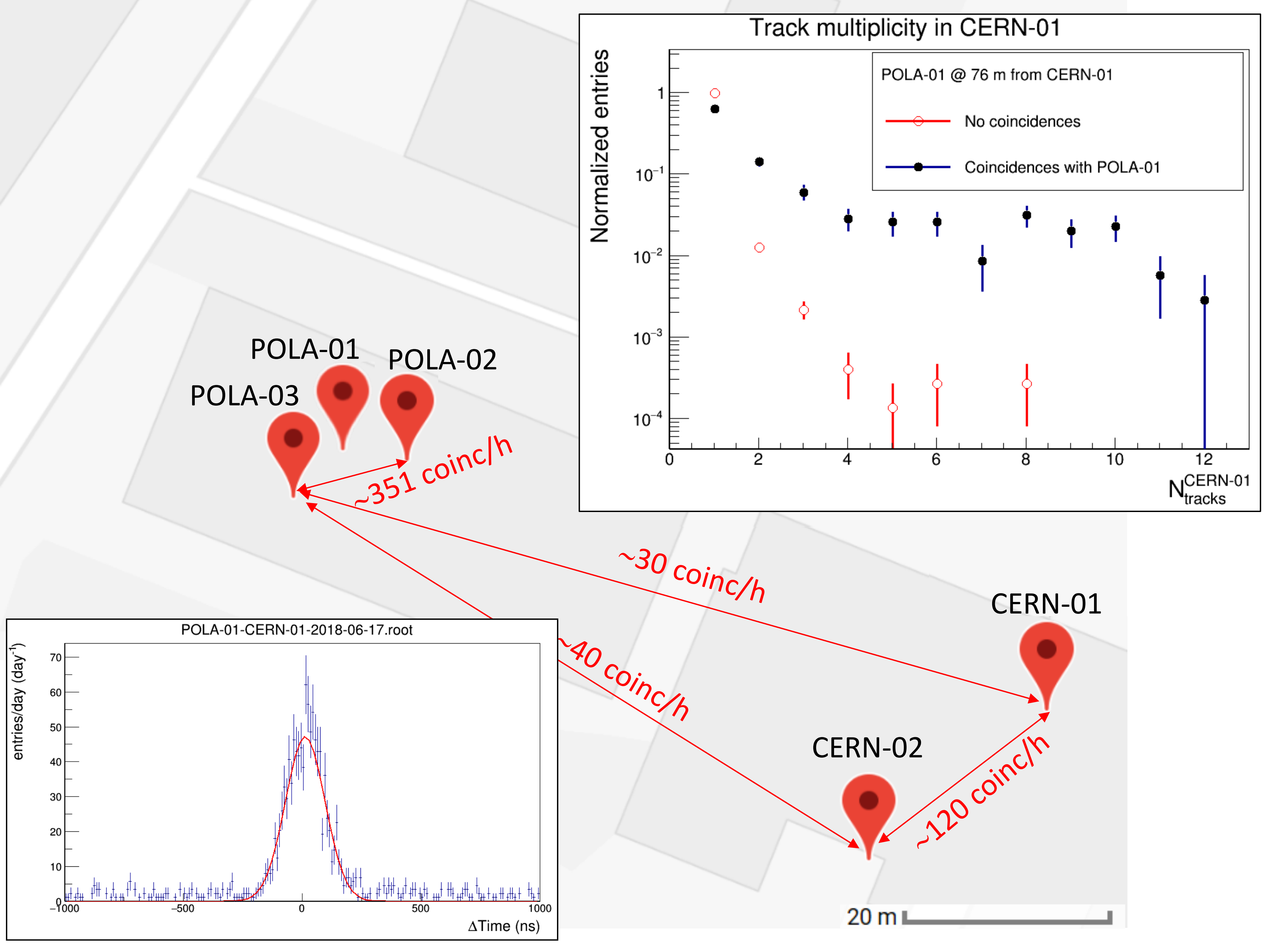


May 22nd - May 25th

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

CERN
24 May 2018

with
Antonino
Zichichi



Track multiplicity in CERN-01
Normalized entries
POLA-01 @ 76 m from CERN-01
No coincidences
Coincidences with POLA-01
$N^{CERN-01}_{tracks}$
POLA-01
POLA-02
POLA-03
~351 coinc/h
~30 coinc/h
~40 coinc/h
~120 coinc/h
CERN-01
CERN-02
POLA-01-CERN-01-2018-06-17.root
entries/day (day^{-1})
ΔTime (ns)
20 m

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)		Tromsö, Norway (69°40′58″N 18°56′34″E)

EEE meeting in Erice
physicists & students & teachers

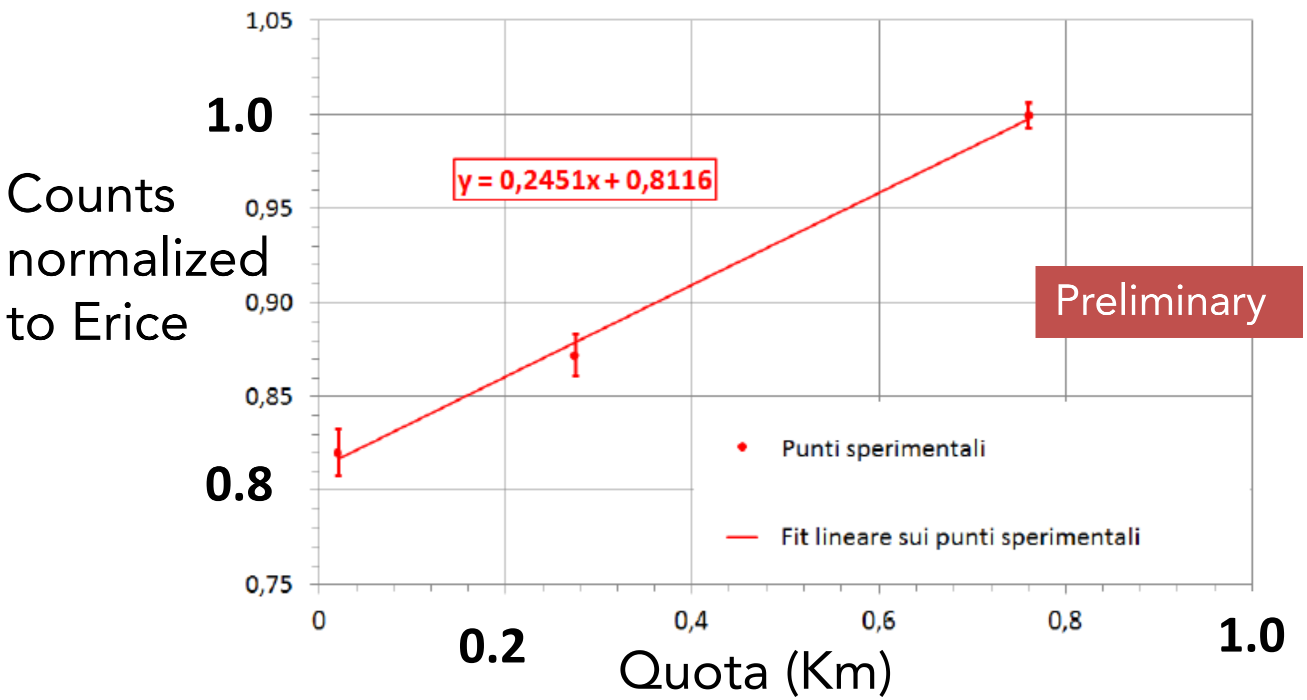
Erice — December 2014

SCIENCE IN THE HEART OF THE YOUNG

EEE in Erice 2017

MASTERCLAAS: Measurement of Cosmic Ray flux at different altitudes

To appear in **Giornale di Fisica** with students' signatures



EEE meeting in Erice
physicists & students & teachers

Erice — May 2017

IT'S A LOT OF FUN !!!

Extreme
Energy
Events
Science inside Schools

Thanks to those to whom
I have borrowed/stolen slides

and thank you all for the attention

EEE Physics Publications until 2017

- \- Abbrescia M. et al. (EEE Collaboration), *Search for long distance correlations between extensive air showers detected by the EEE experiment,* in preparation (2017)
- \- Abbrescia M. et al. (EEE Collaboration), *Looking at the sub-TeV sky with cosmic muons detected in the EEE MRPC telescopes*, Eur. Phys. J. Plus 130 (2015) 187
- \- Abbrescia M. et al. (EEE Collaboration), *A study of upward going particles with the Extreme Energy Events telescopes*, Nuclear Instruments and Methods in Physics Research A 816 (2016) 142–148.
- \- Abbrescia M. et al. (EEE Collaboration), *Cosmic rays Monte Carlo simulations for the Extreme Energy Events Project*, Eur. Phys. J Plus 129 (2014) 166
- \- Abbrescia M. et al. (EEE Collaboration), *Time correlation measurements from extensive air showers detected by the EEE telescopes,* Eur. Phys. J Plus 128 (2013) 148
- \- Abbrescia M. et al. (EEE Collaboration), *The EEE experiment project: status and first physics results,* Eur. Phys. J Plus 128 (2013) 62
- \- Abbrescia M. et al. (EEE Collaboration), *The EEE Project: cosmic rays, multigap resistive plate chambers and high school students*, JINST, 7 (2012) P11011
- \- Abbrescia M. et al. (EEE Collaboration), *The EEE experiment: cosmic rays, multigapresistive plate chambers and high school students*, XI Workshop on Resistive Plate Chambers and Related Detectors, PoS (RPC2012) 012
- \- Abbrescia M. et al. (EEE Collaboration), *Observation of the February 2011 Forbush decrease by the EEE telescopes*, Eur. Phys. J. Plus 126 (2011) 61
- \- Abbrescia M. et al. (EEE Collaboration), *First detection of extensive air showers with the EEE experiment*, Il Nuovo Cimento B-Basic Topics in Physics 125 (2010) 243-254
- \- Abbrescia M. et al. (EEE Collaboration), *Towards the installation and use of an extended array for cosmic ray detection: The EEE Project*, Nuclear Physics B (Proc. Suppl.) 190 (2009) 38-43
- \- Abbrescia M. et al. (EEE Collaboration), *Performance of a six gap MRPC built for large area coverage,* Nuclear Instruments and Methods in Physics Research A, 593 (2008) 263-268
- \- Abbrescia M. et al. (EEE Collaboration), *Extreme Energy Events Project: Construction of the detectors and installation in Italian High Schools*, Nuclear Instruments and Methods in Physics Research A, 588 (2008) 211-214
- \- Abbrescia M. et al. (EEE Collaboration), *Multigap Resistive Plate Chambers for EAS study in the EEE Project*, Proceedings of the 30th International Cosmic Ray Conference, Vol. 5, HE part 2 (2008) 1565–1568
- \- An S. et al. (EEE Collaboration), *Multigap resistive plate chambers for EAS study in the EEE Project*, Nuclear Instruments and Methods in Physics Research A, 581 (2007) 209-212
- \- Antolini R. et al. (EEE Collaboration), *The EEE Project: status and perspectives*, Nuclear Physics B (Proc. Suppl.), 165 (2007) 333-340

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THE EEE COLLABORATION

NALTA Network

Other projects involving Schools

Most of the major groups in Canada and USA have formed a loose collaboration (North American Large-area Time Coincidence Arrays) with more than 100 detector stations spread across North America.

The detector systems are plastic scintillators which are read by custom made electronics and which use GPS for precise coincident timing with others nodes.

European projects

The European groups are also developing a similar collaboration called Eurocosmics.

It is clear that the natural next step is to combine North America and European networks into a worldwide network to comprehend the Extreme Energy Universe

The "event time" measurement

Each telescope is equipped with a GPS to measure the UTC time with very high precision (GPS resolution $\leq$100 ns)

The GPS cannot provide directly a time when a telescope trigger signal is obtained

→ The GPS provides a signal **once per second** and it resets a TDC counter which is devoted to count time (TDC bin ~ 25 ns) in between two GPS signals

→ The TDC counts are **read & associated to the event** when the telescope trigger signal is obtained

The GPS time is crucial to study coincidences between near and far telescopes → extensive air showers → **extreme energy events**

Long distance shower correlations

- LAAS (Japan) network of plastic scintillators – coincidences < 1000 km
- CELTZA (Czech Republic) – ALTA (Canada) networks of plastic scintillators – coincidences 200 km to few 1000 km (when Europe-Canada coincidences)
- Telescope Array Project (United States, Japan, Korea, Russia, and Belgium) network of surface detectors (plastic scintillators and fluorescence telescopes) – coincidences 50-60 km
- AUGER (Argentina) network of Cerenkov detectors – coincidences 50-60 km

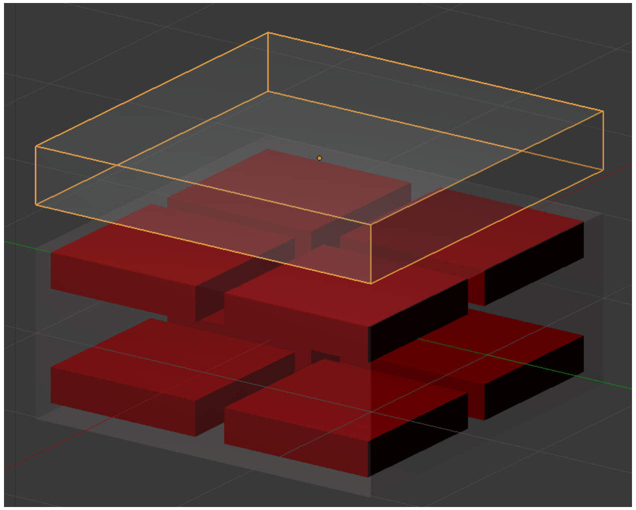
The PolarQuEEEst Detector

The electronics case

will contain

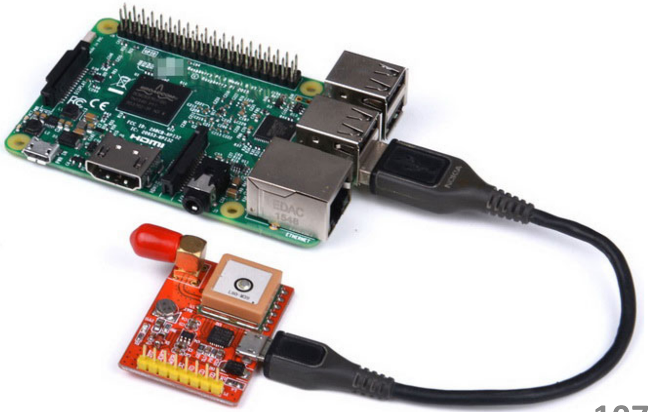
- Discriminators-digitalization
- Coincidence Unit
- P/T/U analog signal processing
- GPS engine
- SSD disk for data storage

Could be powered by a dedicated photovoltaic panel cabling

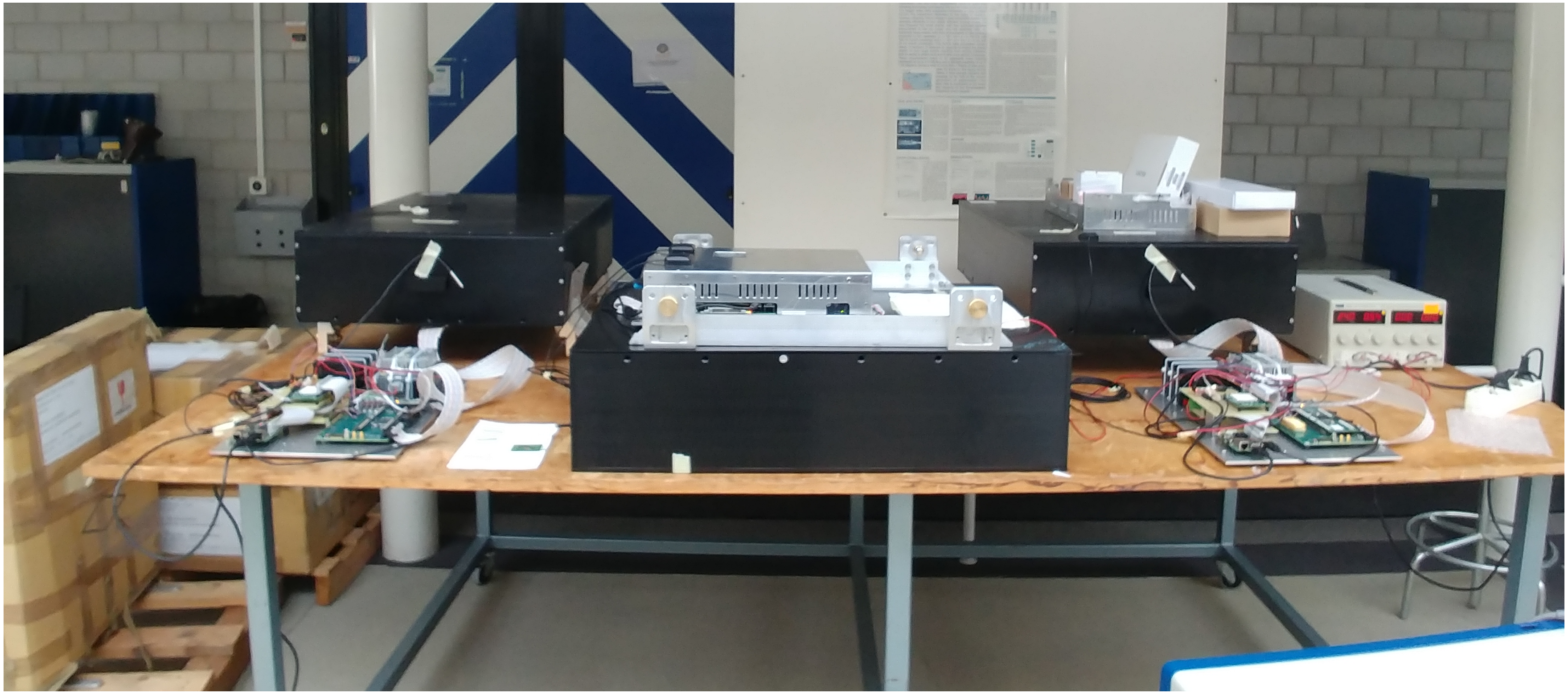


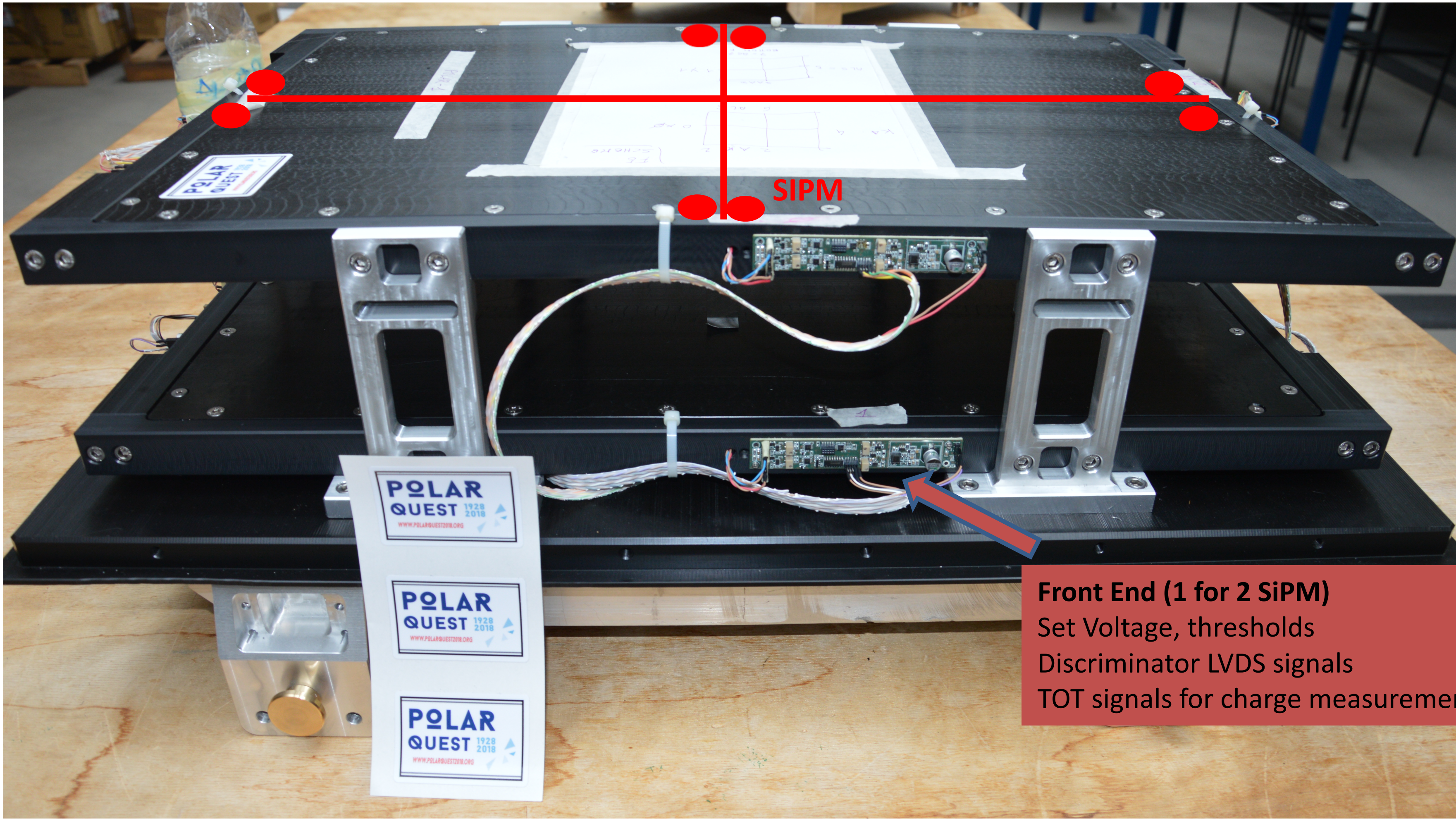
Prototype based on Raspberry Pi + GPS unit

+ weather station (onboard or dedicated)



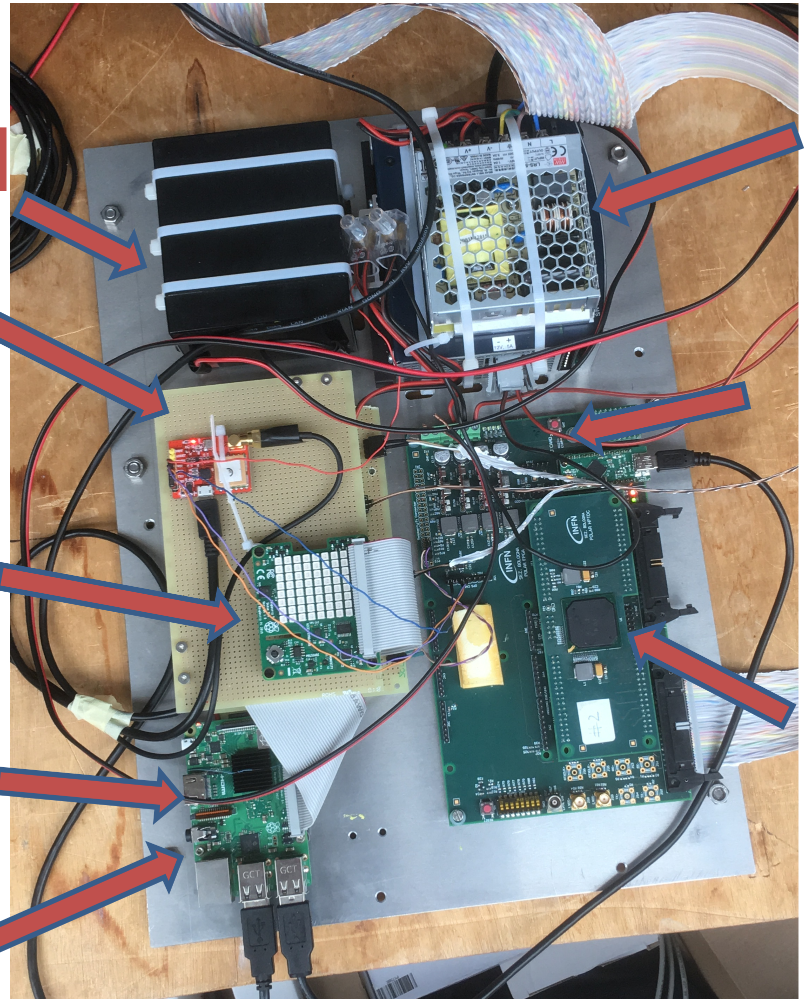
PolarQuEEEst detectors : Polar-01 , Polar-02 , Polar-03





Front End (1 for 2 SiPM)
Set Voltage, thresholds
Discriminator LVDS signals
TOT signals for charge measurement

The PolarQuEEEst Detector Electronics



Back-up Battery

Power box

GPS
GNSS-Ublox

Readout board
FPGA Altera Cyclone 5
For Trigger and TDC readout

Sense Hat
Gyroscope
Accelerometer
Magnetometer
Temperature
Barometric pressure
Humidity

HPTDC piggy-back
for TDC readout

Raspberry PI
Control readout

GPS
GNSS-Ublox

MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE
ENRICO FERMI
HISTORICAL MUSEUM OF PHYSICS AND RESEARCH & STUDY CENTRE

ROME - ITALY

CENTRO FERMI

MUSEO
STORICO DELLA FISICA
E
CENTRO
STUDI E RICERCHE

Centro Fermi

CENTRO FERMI is a research institution established in 2001 and devoted to interdisciplinary studies

Its institutional premises are in the old Institute of Physics in Via Panisperna in Rome

It aims to integrate the knowledge generated in different fields, and to promote discussion among top scientists with different areas of expertise, in order to create what **Enrico Fermi** would have liked to establish in the Institute where he worked and that now bears his name:

a centre dedicated to frontier research in physics and to its wide interdisciplinary applications for the benefit of humankind

How and where it all began …
at the Physics Institute of Via Panisperna in Rome

PHOTOGRAPH OF THE FIRST INTERNATIONAL CONGRESS OF NUCLEAR PHYSICS PHYSICS INSTITUTE, ROME, 1931

CENTRO FERMI

NOW

Activities of Centro Fermi

CENTRO FERMI is characterized by:

1. Grants for "New Talents" and Junior/Senior researchers to study original and interdisciplinary research topics

2. Research Projects, including those defined as Strategic Projects, for the realization and promotion of interdisciplinary original research

3. Activities for the Dissemination of Scientific Culture and Historic Memory through the **restoration** of the "Monumental Complex" of Via Panisperna, the old Institute of Physics which has an extraordinary historical value, to be used in part for the Museum

http://www.mostrafermi.it/

Enrico Fermi's Exhibition in 2015-2016
with over 30 000 visitors in 6 months → future MUSEO FERMI

Mostra Enrico Fermi

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ENRICO FERMI

A dual genius between theories and experiments
Una duplice genialità tra teorie ed esperimenti

Why the Exhibition| **Perchè la mostra**

The exhibition highlights the extaordinary figure of Enrico Fermi, the great Italian physicist who, paradoxically, is better known abroad than in

Who is it for | **A chi si rivolge**

The scientific achievements, integrated into the various stages of the scientist's life, are presented in a new light suitable for the general public, including the very young, combining objects and traditional panels with video and audio

A stop in Bologna | **Uno stop a Bologna**

After the success of its debut at the "Festival delle Scienza di Genova" of 2015 (about 15.000 visits), the exhibition arrives in the Emilian city, thanks to

CENTRO FERMI's PROJECTS

1. Extreme Energy Events (EEE) – Science inside Schools → Astrophysics & Education
2. Advanced Techniques for Fundamental Physics
3. Advanced Techniques for Biomedical Applications
4. Energy
5. Environment and Cultural Heritage
6. History of Physics
7. Science Museum

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   Schools → Astrophysics & Educatio

Leading Project

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