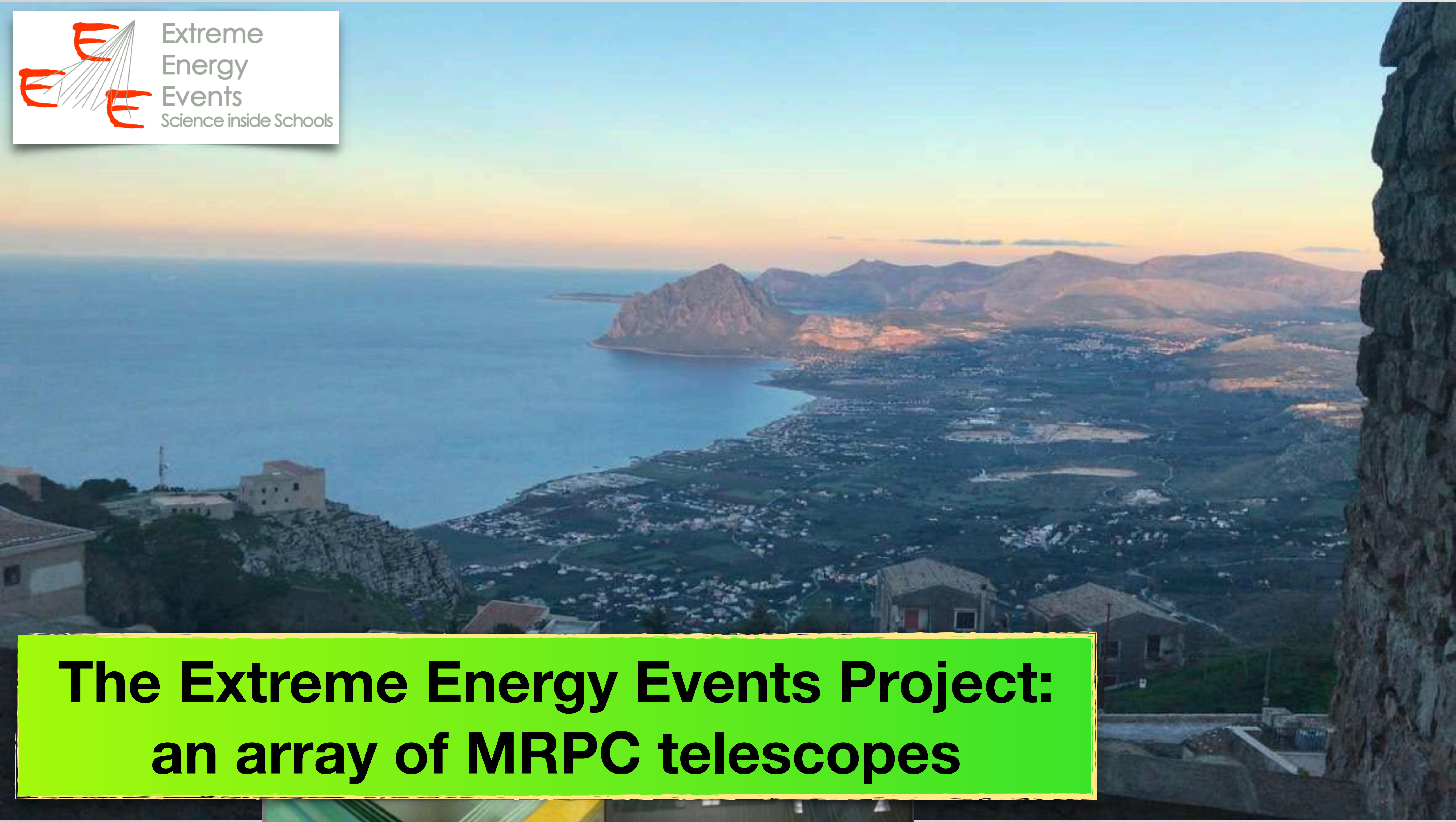
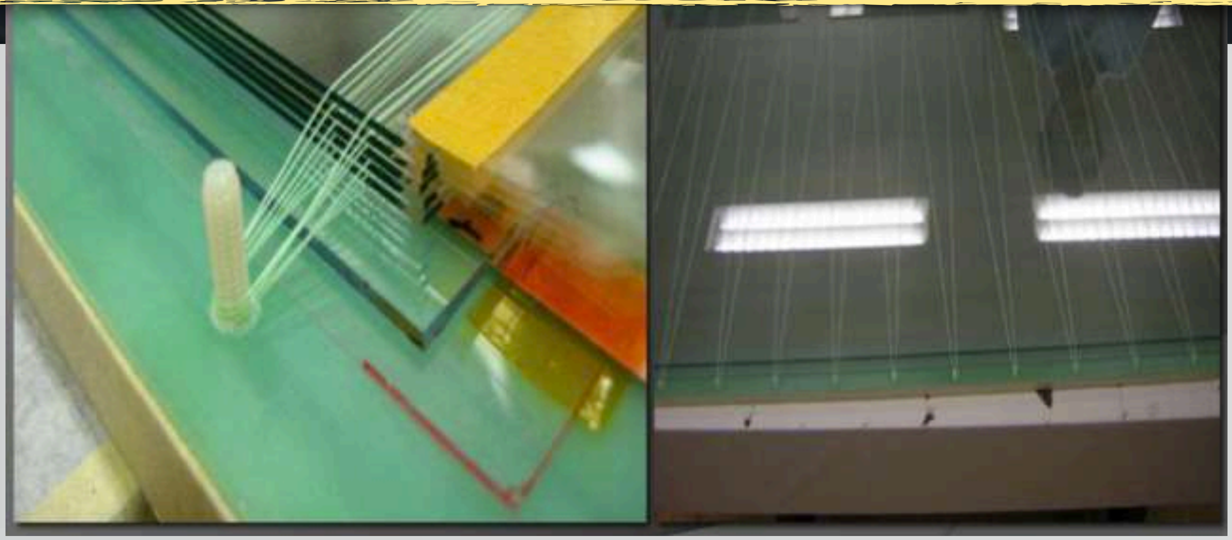
Extreme Energy Events
Science inside Schools



The Extreme Energy Events Project: an array of MRPC telescopes



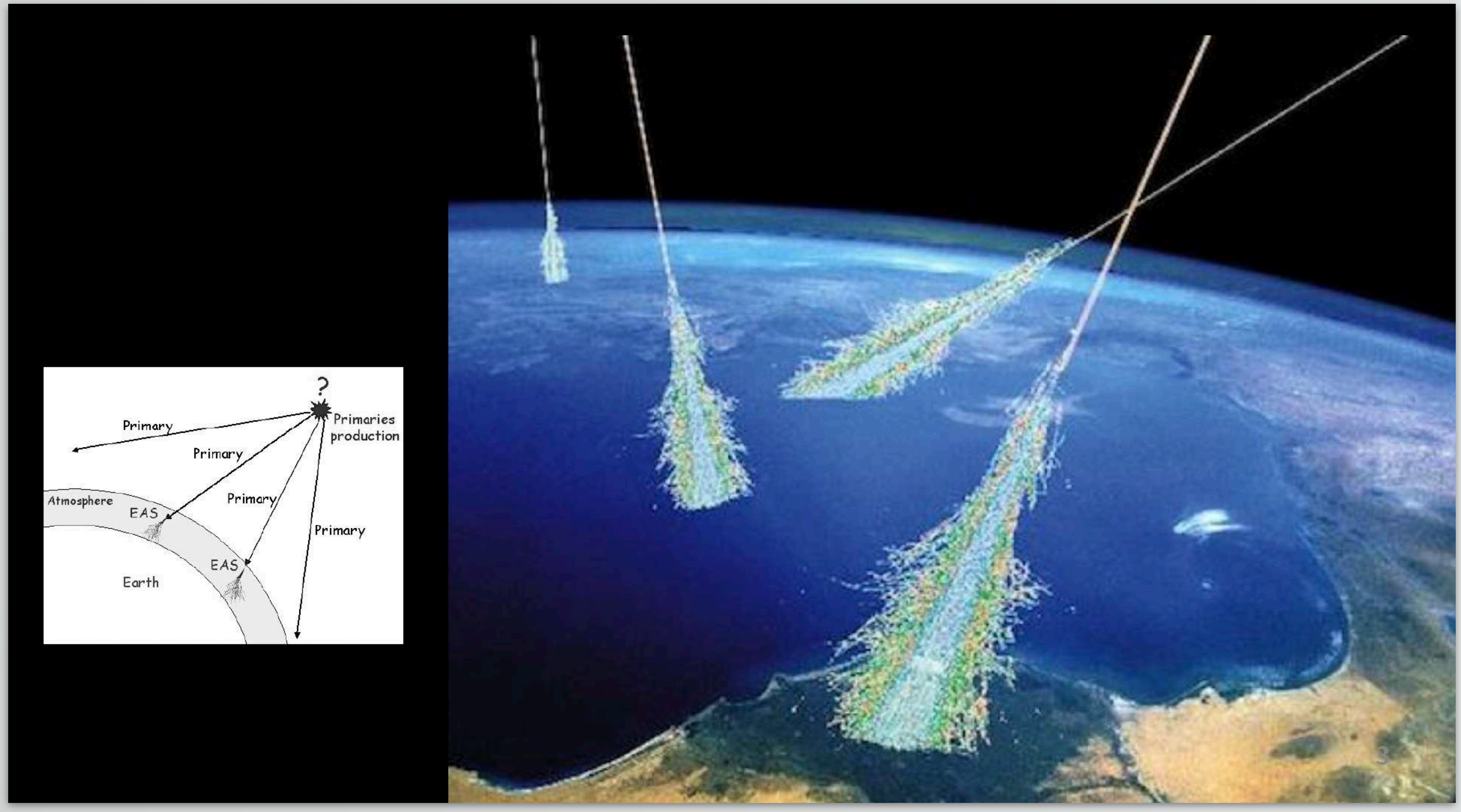
D. De Gruttola

University and INFN Salerno

INFN Istituto Nazionale di Fisica Nucleare

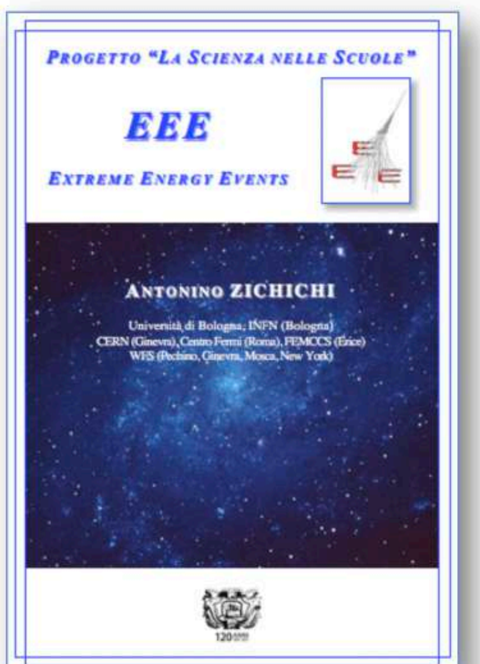
Physics goal of the experiment

- Detect **Extensive Air Showers** by detecting secondary muons on ground coming from primary cosmic rays
- The muon detection is performed by means of **MRPC telescopes** installed across an overall area of $\approx 0.5 \times 10^6 km^2$



Dual role of the Project

- Research
  - EEE telescopes - array of muon telescopes covering a **very large area**
  - High performance **tracking** and **timing** system
- Education
  - Equip **High School** buildings with detectors
  - Actively **involve teachers and students** in construction, assembling, maintenance, data taking, analysis



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

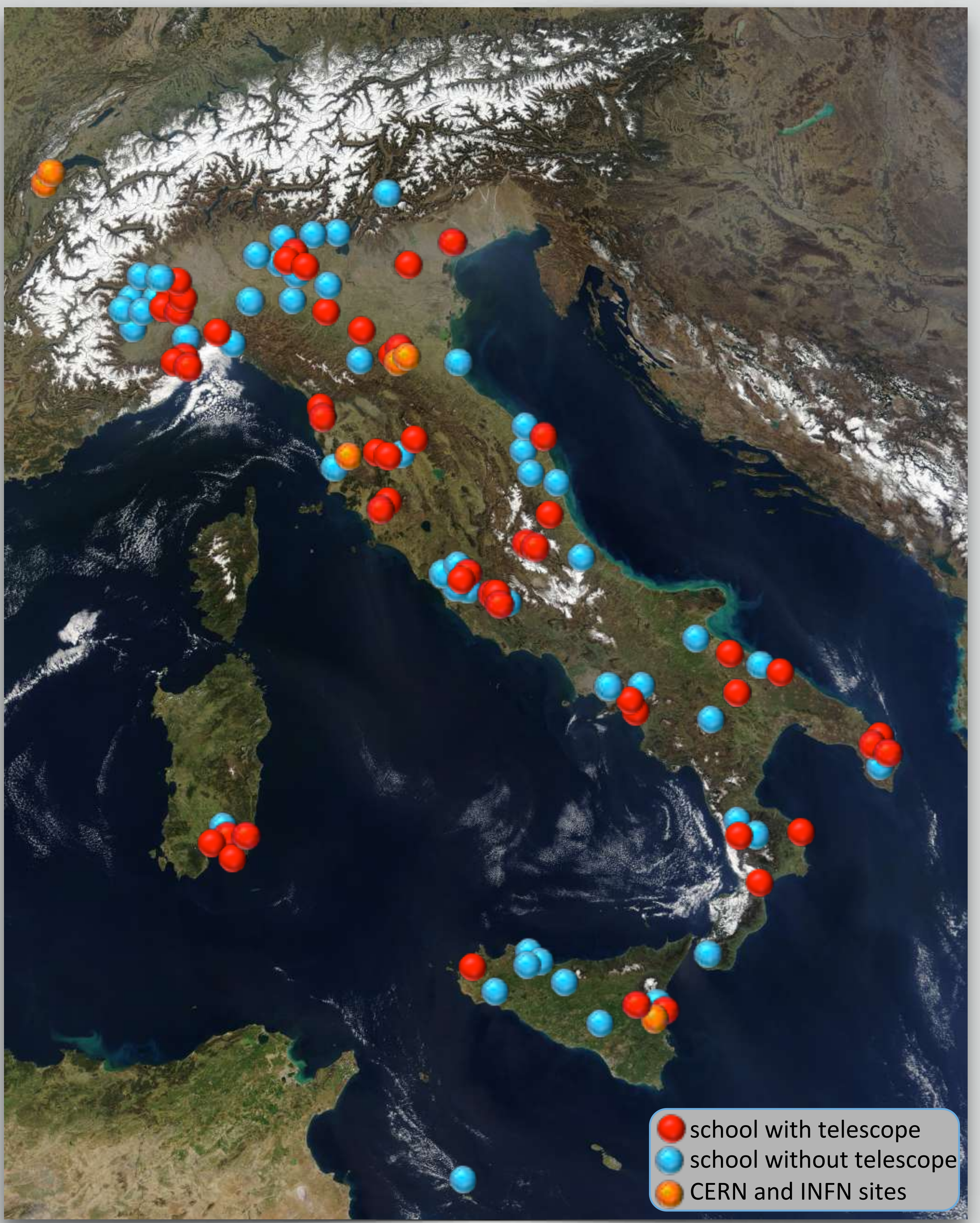
Centro Fermi
CERN
INFN
MIUR
SIF

Launch event on 3 May 2004 at CERN

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

- Since 2004 …
- Pilot project with 7 EEE telescopes in High Schools (Bari, Bologna, Cagliari, Catania, Frascati, L'Aquila, Torino)
- In 2022: 59 EEE telescopes
  - 53 in High Schools
  - 6 in Research Labs (4 @INFN and 2 @CERN)
- Mostly distributed in clusters over the whole Italian territory (+ Geneva)

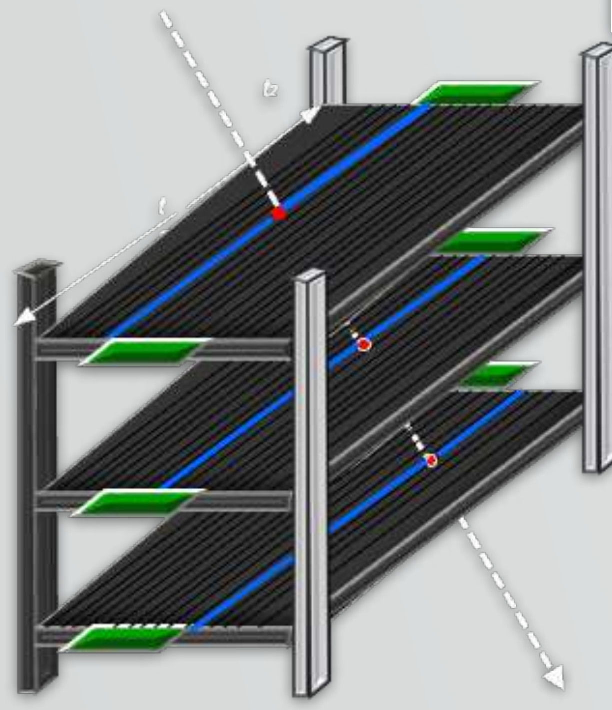
The EEE Project



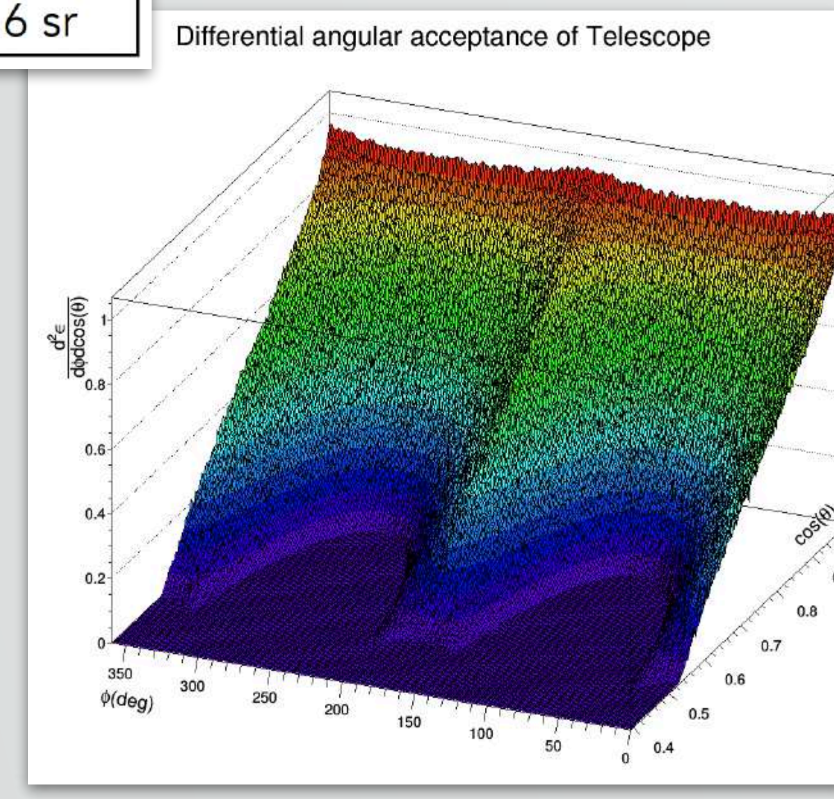
- **Largest surface** covered by a detector of cosmic muons on ground, with both tracking and timing capabilities
  - $\approx 0.5 \times 10^6 km^2 \approx 10^\circ$ of latitude/longitude
- **Largest area of MRPC** detectors built and operating, in unconventional working sites
  - $\approx 200 m^2$
  - mainly school buildings
  - non-professional electrical lines
  - non-controlled environmental parameters
  - heterogeneous maintenance conditions

  Challenge
- **Long-living** MRPC-based system (18 years)

The EEE station



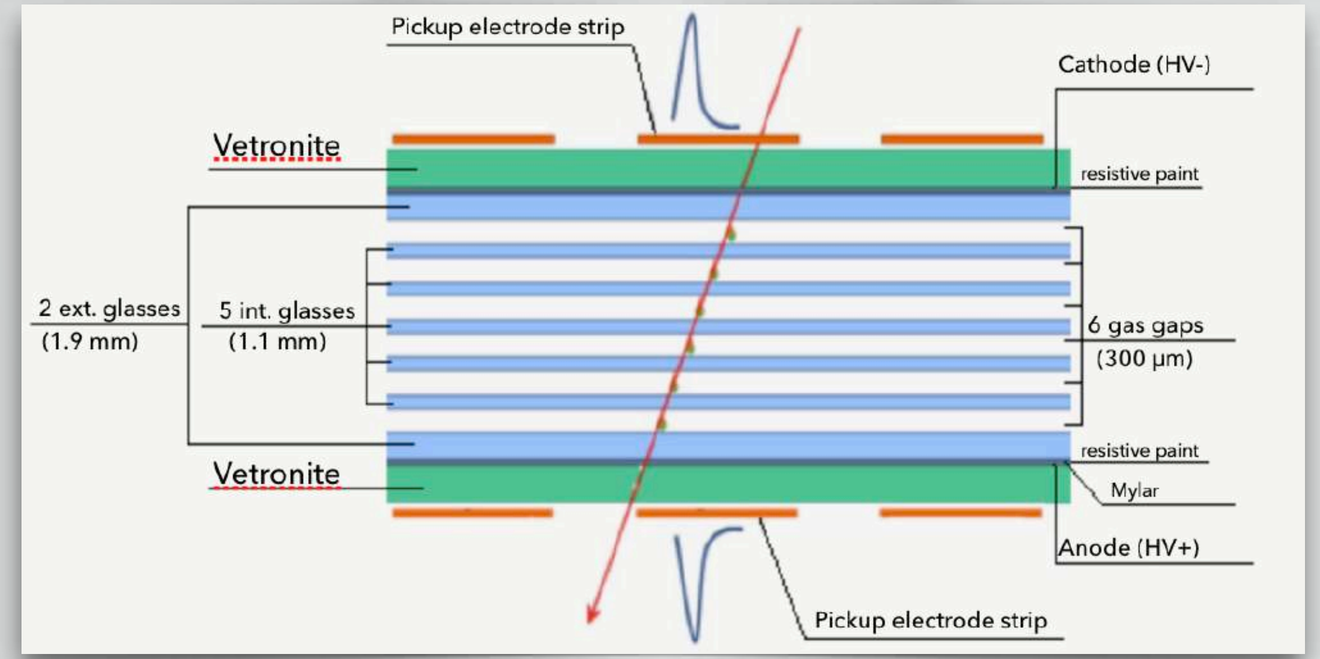
Acceptance
$\Omega = 1.6$ sr



- **Telescope**
  - Each telescope is made by **3 MRPCs** ($\sim 80 \times 160 m^2$ each)
  - *Chambers built by students and teachers at CERN*
  - *Reasonable cost*
  - **Long term** operation required
  - Reconstruction of **muon orientation**
  - **TOF** measurement

- **MRPC**
  - Time Resolution $\sim 240ps$
  - Longitudinal Spatial Resolution $\sim 1.5cm$
  - TransverseSpatialResolution $\sim 1cm$
  - Efficiency $> 90\,\%$
  - Synchronization guaranteed by a GPS unit (precision $\sim 40ns$)

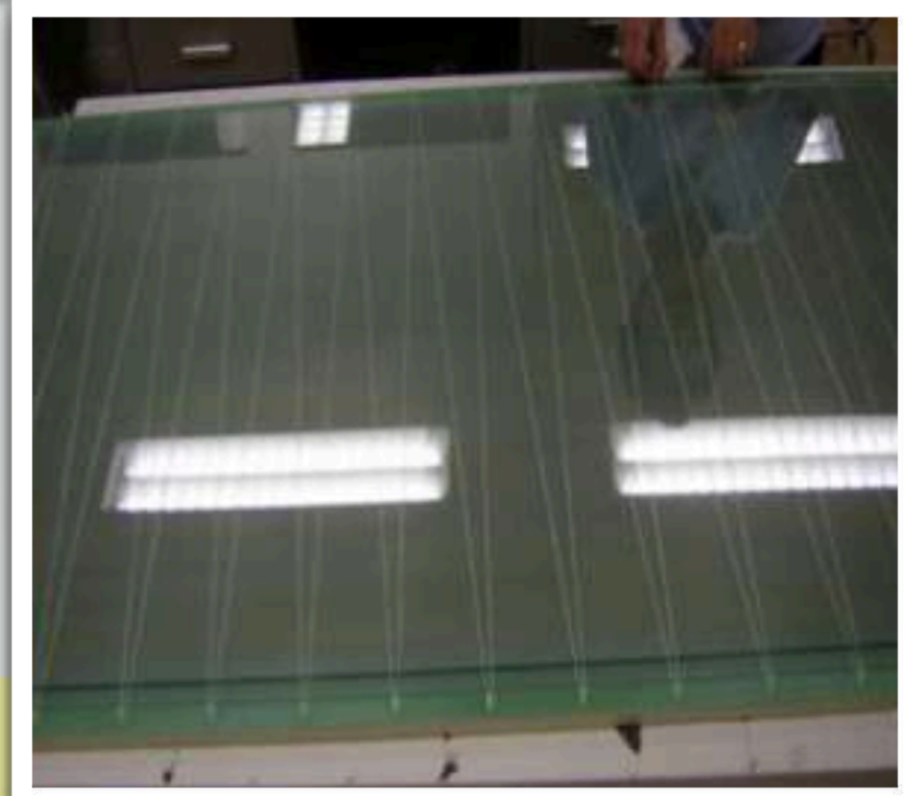
The EEE MRPC



- **6 gas gaps** $300\mu m$ ($250\mu m$ after the upgrade)
- **2 external glass sheets** (anode and cathode) - $160cm \times 85cm$, $1.9mm$ thick (**resistive paint** $5 - 20M\Omega/\square$)
- **5 intermediate glass sheets** - $158cm \times 82cm$, $1.1mm$ thick
- Signal induced on **24 copper strips** (anode and cathode) - $158cm \times 25cm$, spaced by $7mm$
- Honeycomb panels to ensure mechanical stability - $182cm \times 90cm$
- Gas-tight aluminum box - $200cm \times 100cm$
- **Standard gas mixture** $98\,\%\ C_2F_4H_2$-$2\,\%\ SF_6$ (*see C. Ripoli's talk about new gas mixtures*)
- HV up to $20kV$ (**avalanche mode**) supplied by 2 DC/DC converters

The EEE MRPC

- Glasses
- $300\mu m$ ($250\mu m$) fishing line as spacer to create gas gaps
- Vetrinate panel



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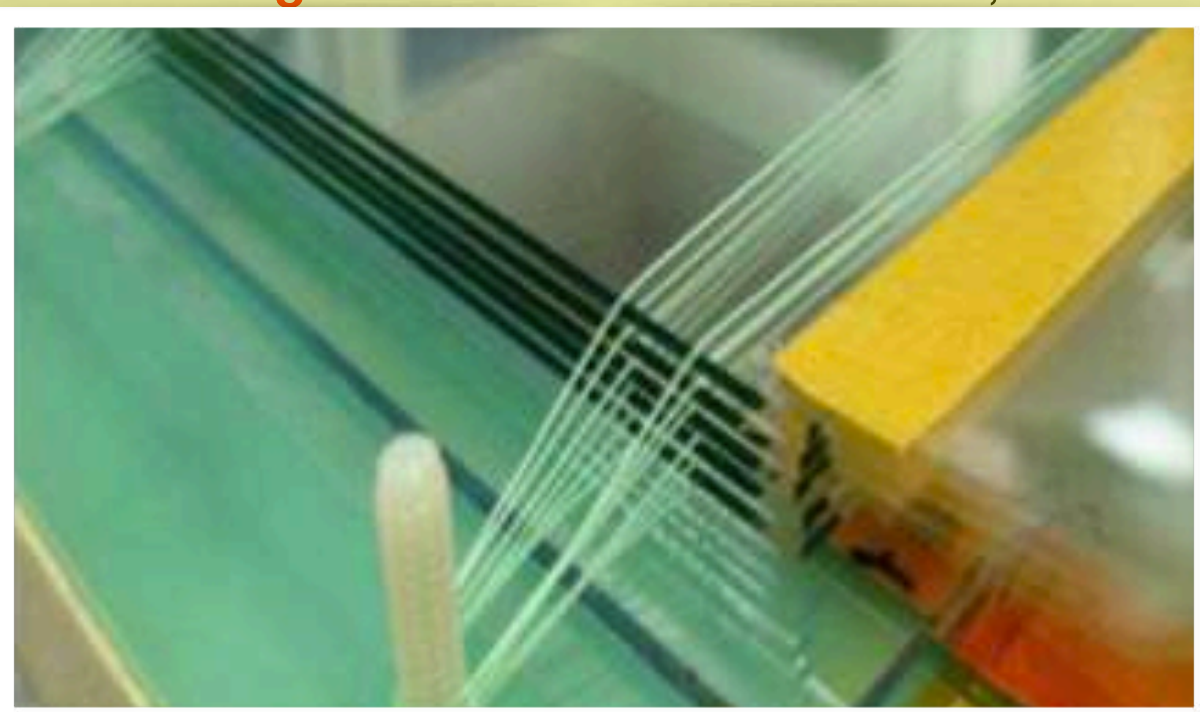
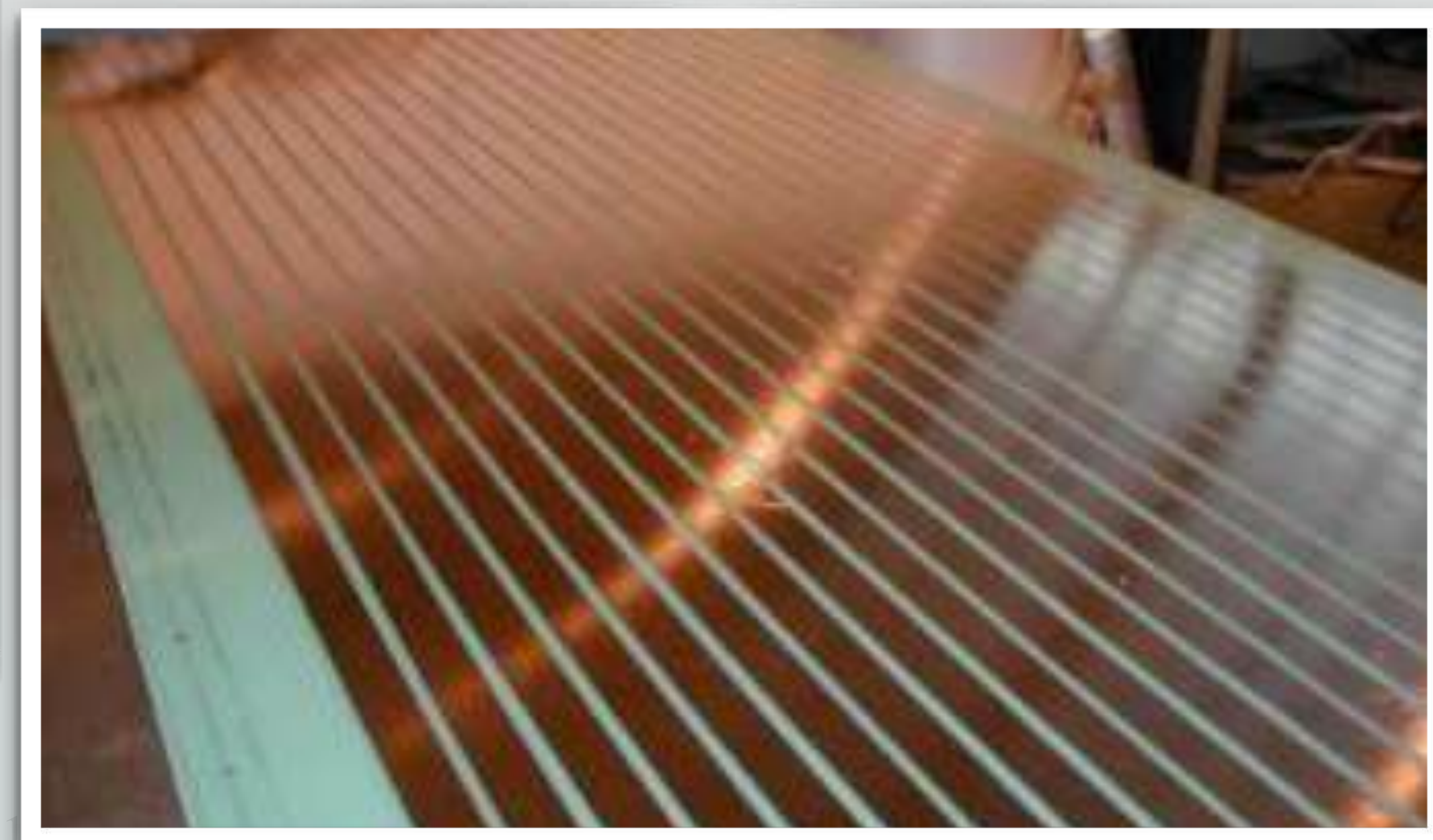


The EEE MRPC



- **2 external glass sheets** (anode and cathode) -
- **5 intermediate glass sheets** - $158cm \times 82cm$,
- **24 copper strips** (anode and cathode) to collect the signal - $158cm \times 25cm$, spaced by $7mm$
- Honeycomb panels to ensure mechanical stability - $182cm \times 90cm$
- Gas-tight aluminum box - $200cm$

> - 24 copper strips to pickup the signal
> - Pitch $3.2cm$

- **Gas mixture** $98\,\%\ C_2F_4H_2$-$2\,\%\ SF_6$ *(see C. Ripoli's talk about new gas mixtures)*
- HV up to $20kV$ (avalanche mode) supplied by 2 DC/DC converters

The EEE MRPC

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The EEE MRPC

160$cm \times 85cm$, 1.9mm thick (**resistive paint** $5-20M\Omega/\square$)

.1mm thick

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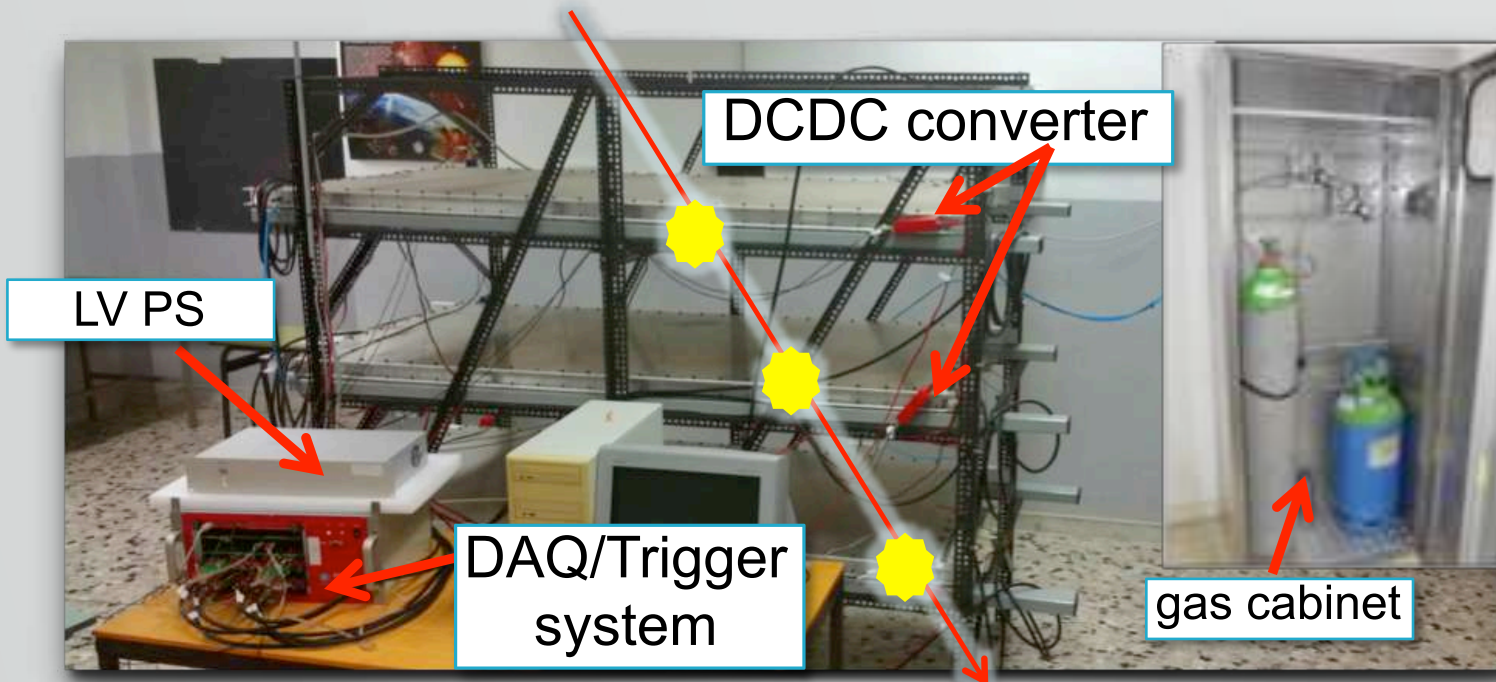
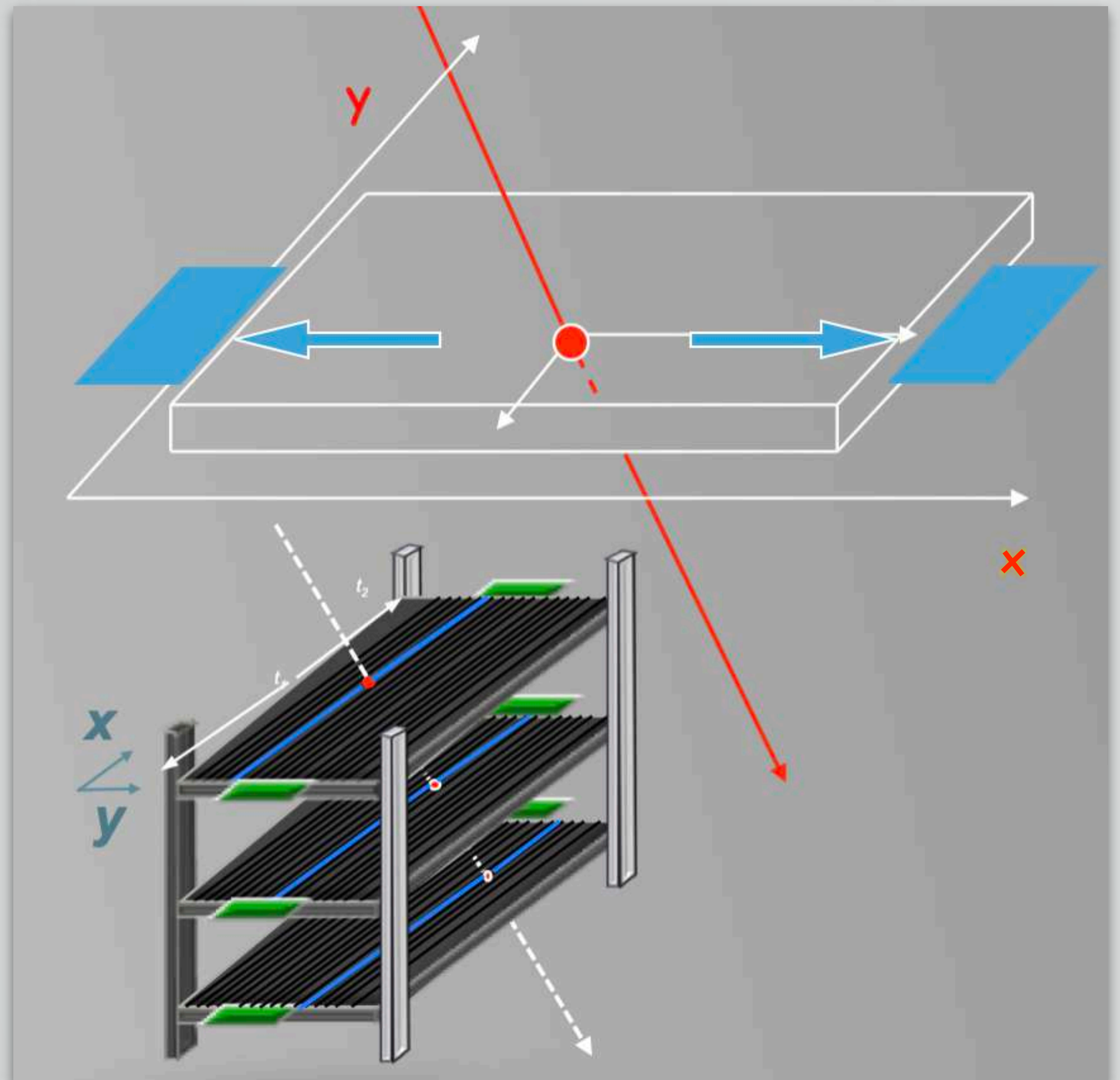
Telescope and electronics

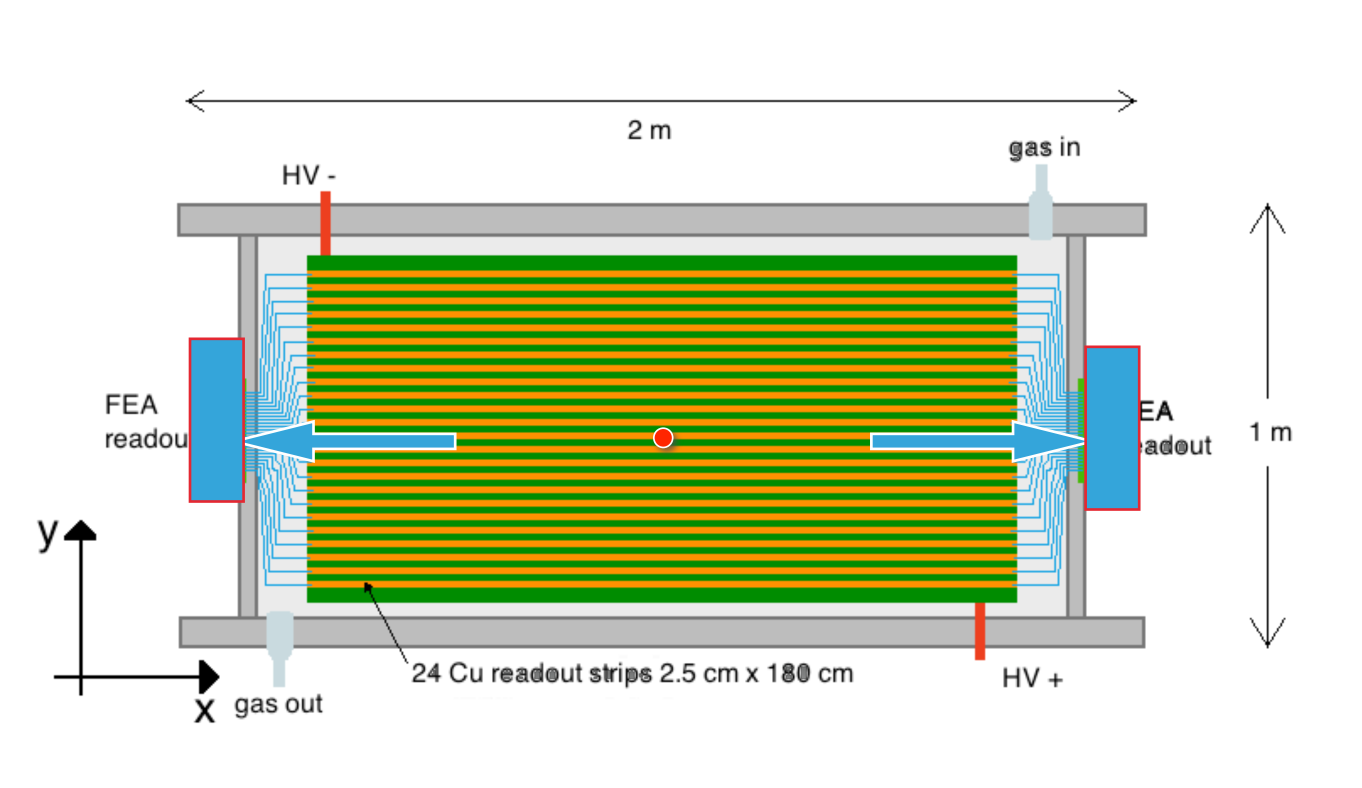


- **6 Front-End boards** (FEAs) with 24 channels (pre-amplification + discrimination)
- **2 Multi-hits Time to Digital Converters** (TDCs 128 + 64 channels)
- **1 Trigger Card**
  - OR signal of 24 channels from each FEA
  - a **six-fold coincidence** of both FEAs of the three MRPCs generates the trigger signal
- **GPS** unit provides the event time stamp (UTC time) to record and synchronize information
- Weather station to monitor the **temperature** and the **pressure** inside and outside the telescopes building

Telescope and electronics

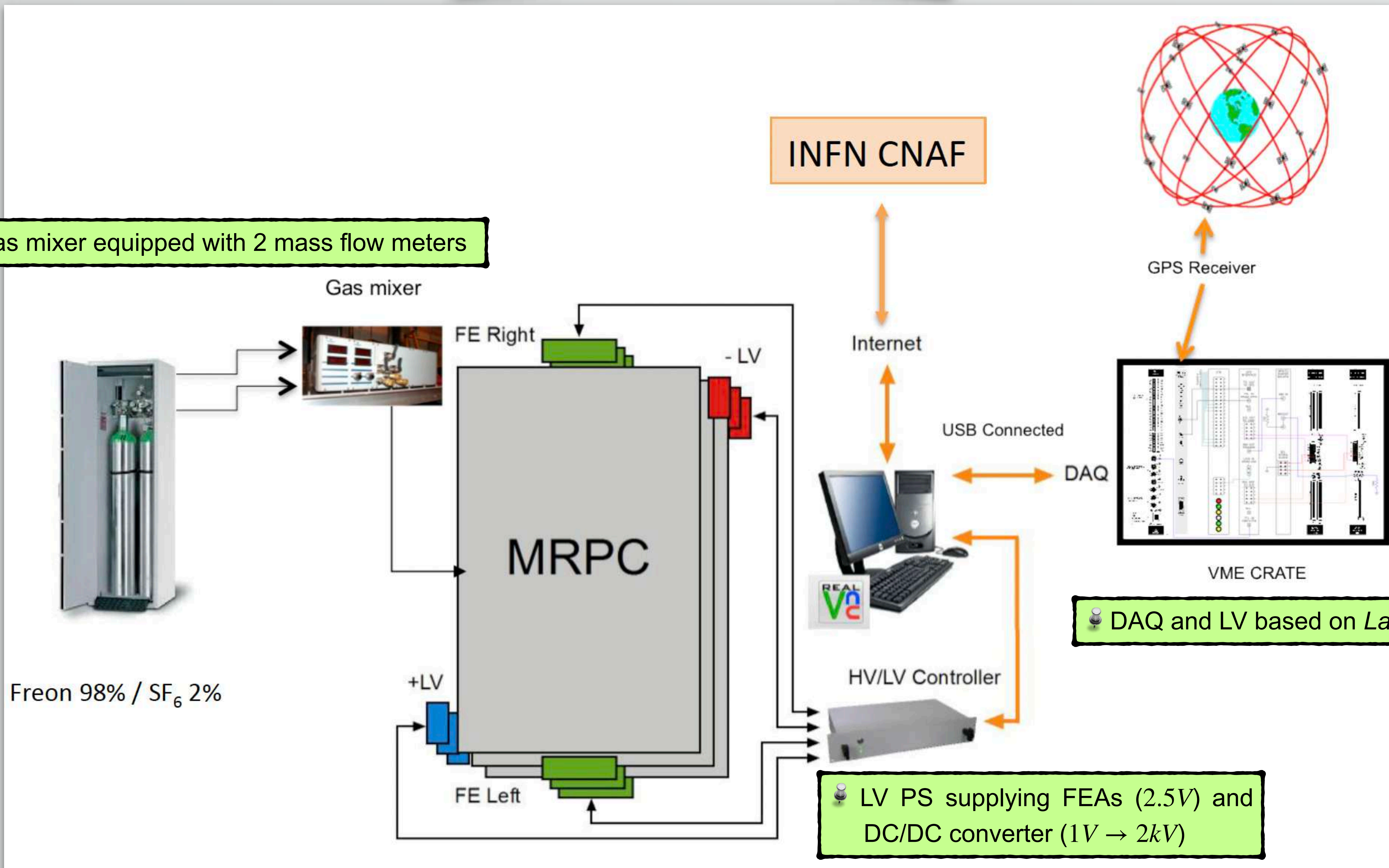


Particle impact point reconstructed by
- fired strip in one direction y
- difference of signal arrival times at the strip ends measured by TDCs in the other direction x



- $100 ps$ time resolution of the TDC bin
- $\sim 1 cm$ spatial resolution along both coordinate
- $95\ \%$ MRPC efficiency at the operating voltage 18-19kV
- few tens ns GPS time resolution

Telescope and electronics

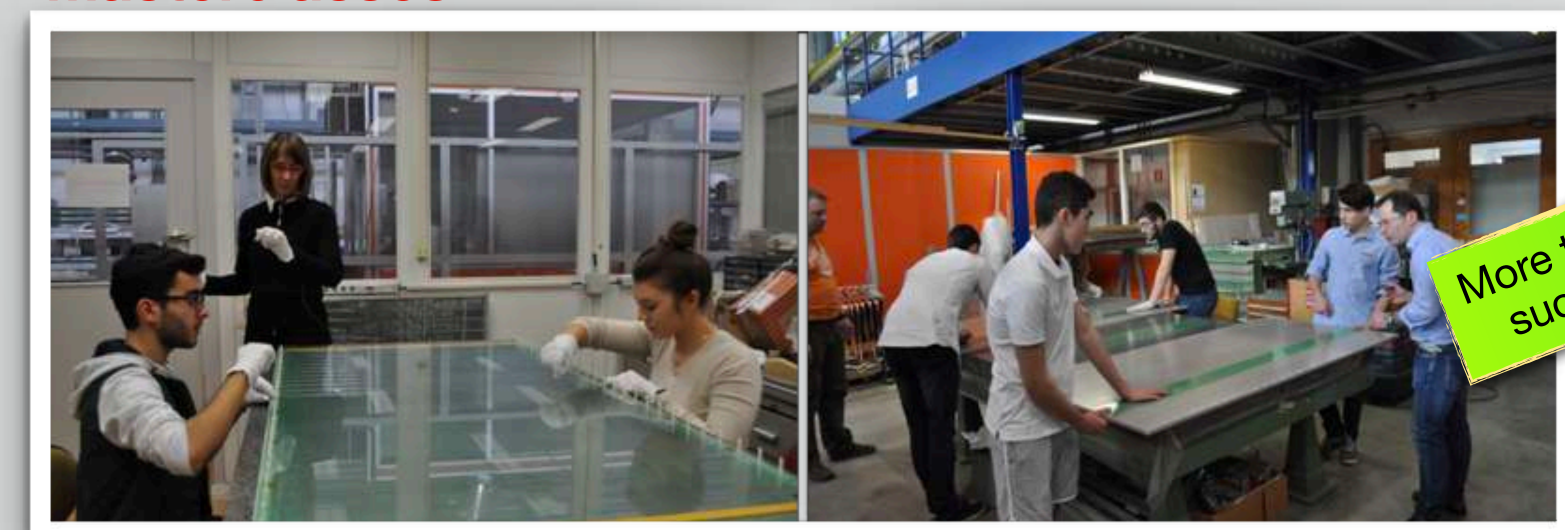


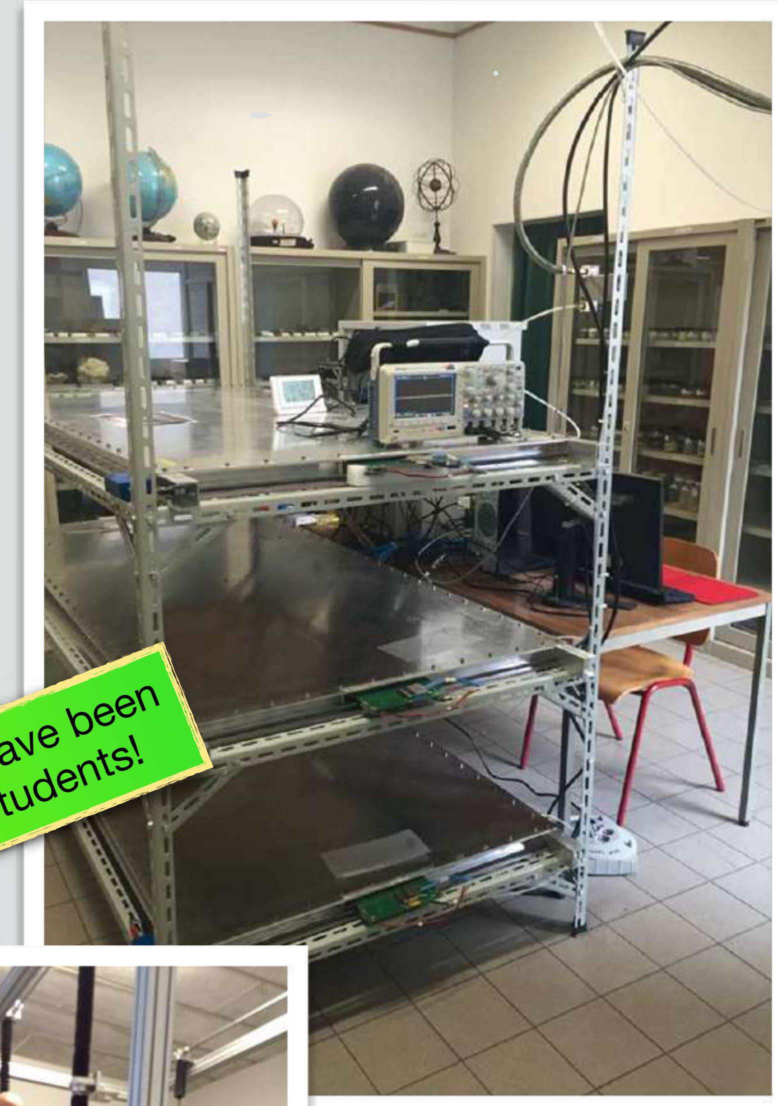
- Gas mixer equipped with 2 mass flow meters
- DAQ and LV based on *Labview*
- LV PS supplying FEAs ($2.5V$) and DC/DC converter ($1V \rightarrow 2kV$)

- Muons are detected and reconstructed with $\sim cm^2$ spatial resolution and hundreds of ps time resolution
- The telescopes are **GPS synchronized** for offline analysis on time correlated events
- Data from each station are sent to Bologna INFN **CNAF** for the **track reconstruction** and **storage**

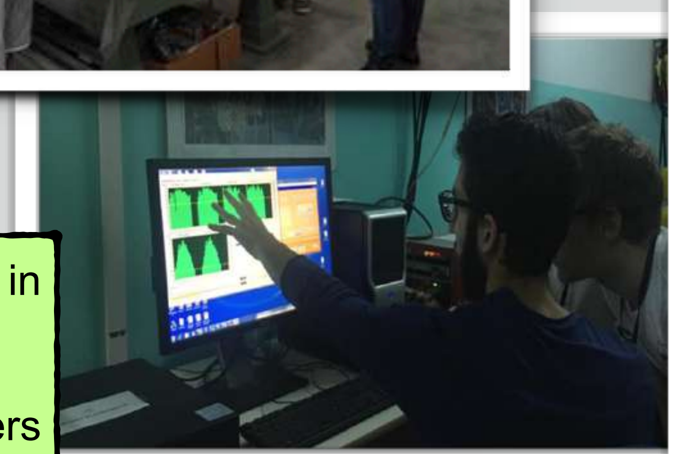
Students involvement

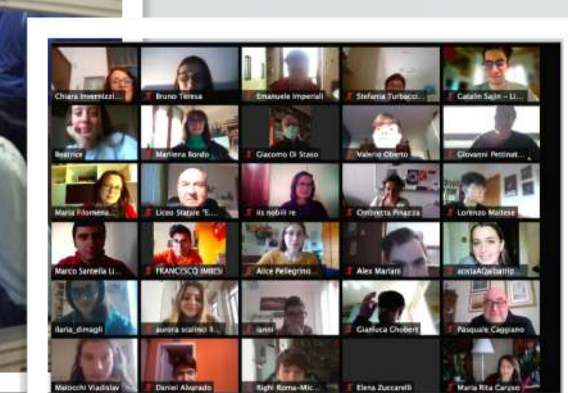
- Young students and teachers are involved in each phase of the experiment
- They **build chambers** at CERN
- They are involved in the **installation at school**, in the **operation** and (daily) **monitoring** of the telescopes
- They participate to monthly online and in presence (bi-annual pre COVID) **meetings** presenting their **analysis** or attending **masterclasses**





More than 180 MRPCs have been successfully built by students!

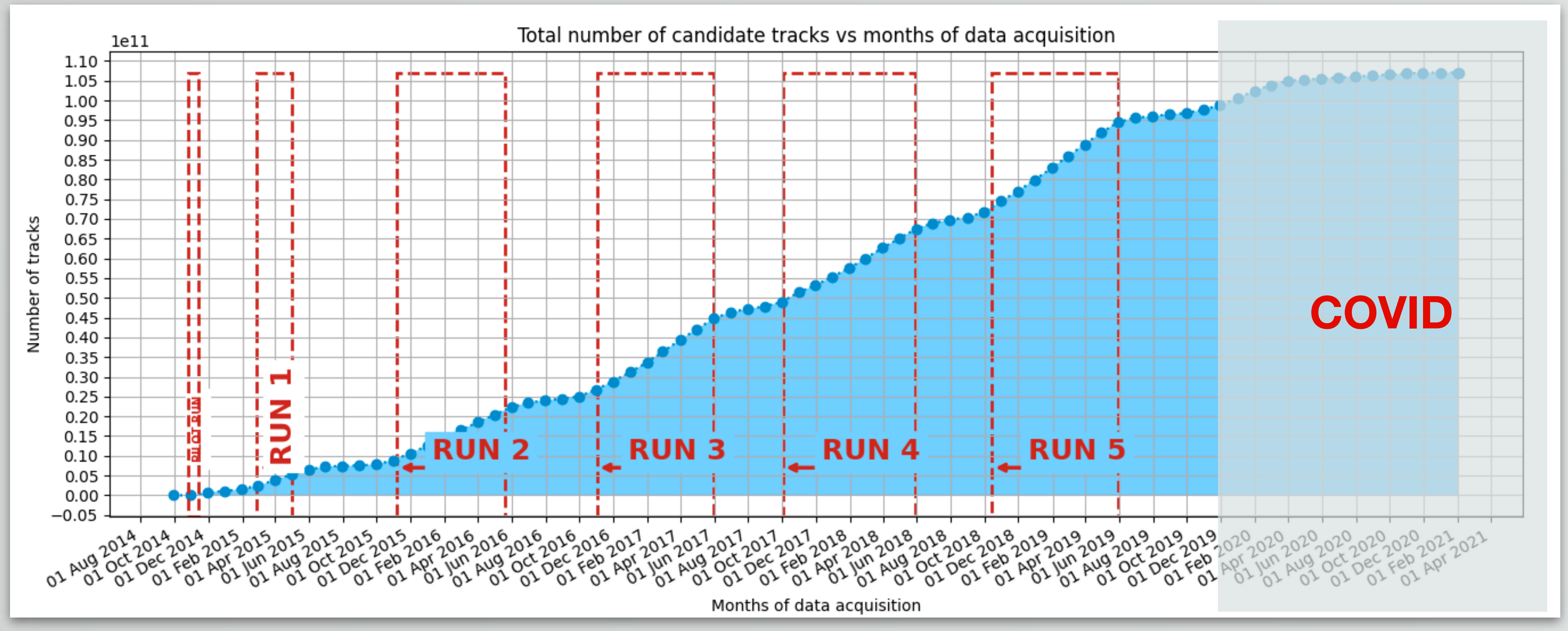




- ~ 10 students + 1/2 teachers per school involved in the chamber construction at CERN
- thousands of students and hundreds of teachers participating to the project

Data taking strategy

- Coordinated **RUNs** starting from 2014
- *~ 2 billion events per month*
- Tests, efficiency measurements, maintenance in between RUNs (still a good amount of muon tracks collected)
- More than **100 billion tracks** currently collected

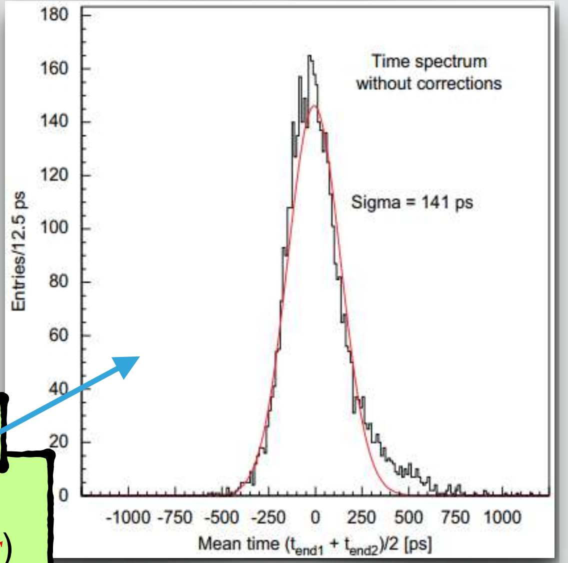


- *More than 180 MRPCs have been successfully built by students*
- Many results published (see next slides)
- Forced pause due to pandemic situation - ***we profited to perform tests on eco gas mixtures***

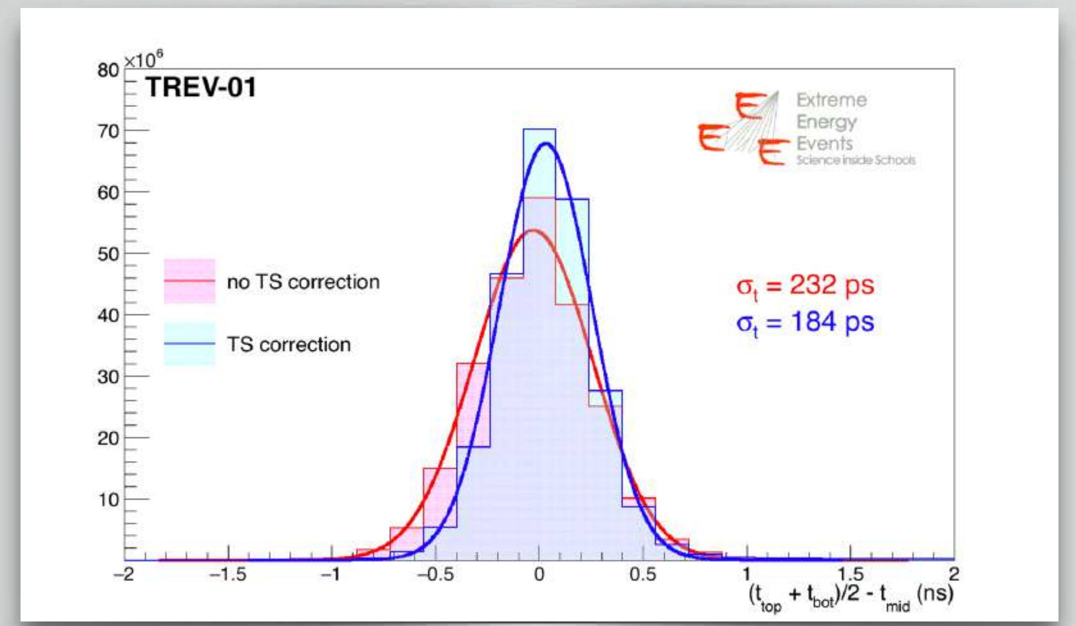
Performance

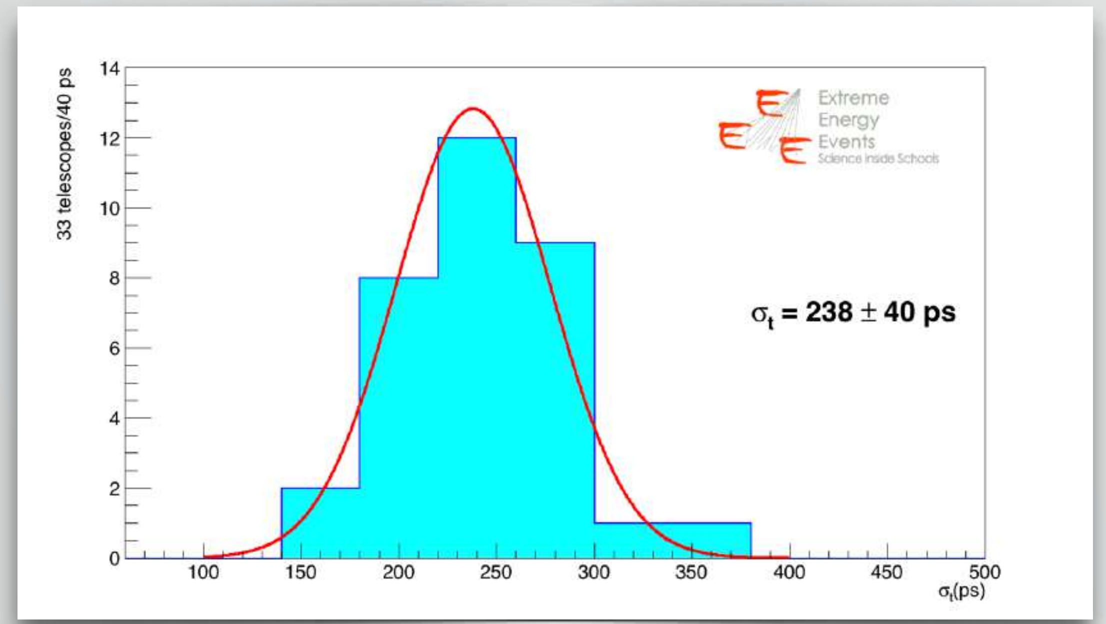
Time resolution

- Cut on reconstructed tracks $\chi^2 < 10$
- Time Slewing correction improves the resolution of $\sim 20\,\%$
- Results published in *JINST (2018) 13 P08026*



- Beam tests @CERN
- $\sim 100ps$ in the center of the strip
- TDC $25ps$ bins, trigger by scintillators (time resolution $30ps$)





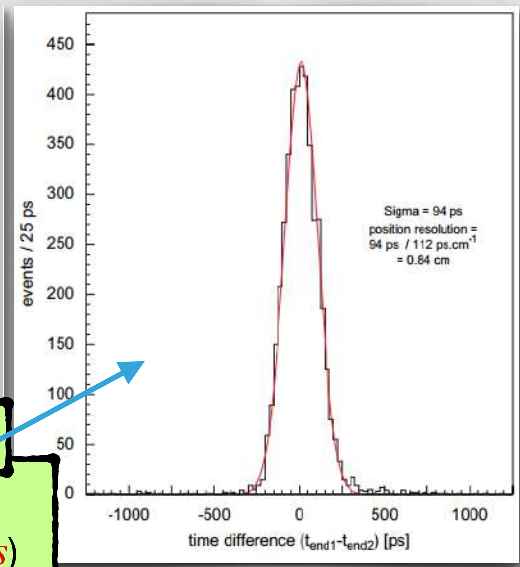
Time resolution estimated by measuring the time information on the upper and lower chambers and using these values to determine the expected time on the middle chamber (to be compared with the hit time measured on the middle chamber)

$$\Delta t_{hit} = \frac{t_{bot} + t_{top}}{2} - t_{mid} \qquad \sigma_t = \frac{\sigma_t}{\sqrt{3/2}} \sim 240ps$$

- Average time resolution $\sim 240ps$
- Resolution within expectations (order of $10^2 ps$) and compatible with requirements

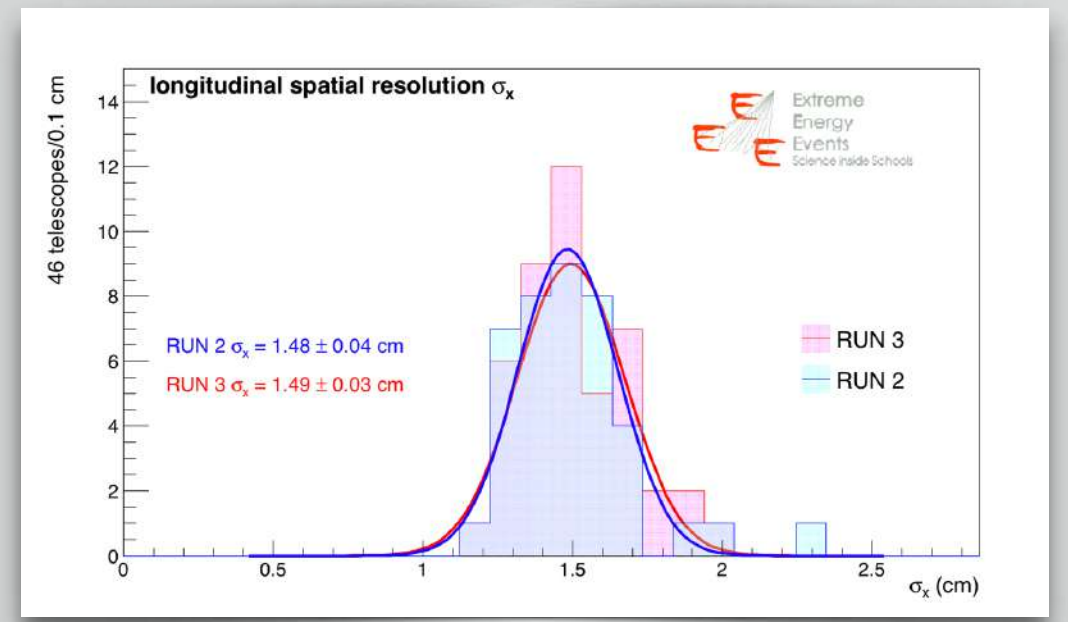
Space resolution

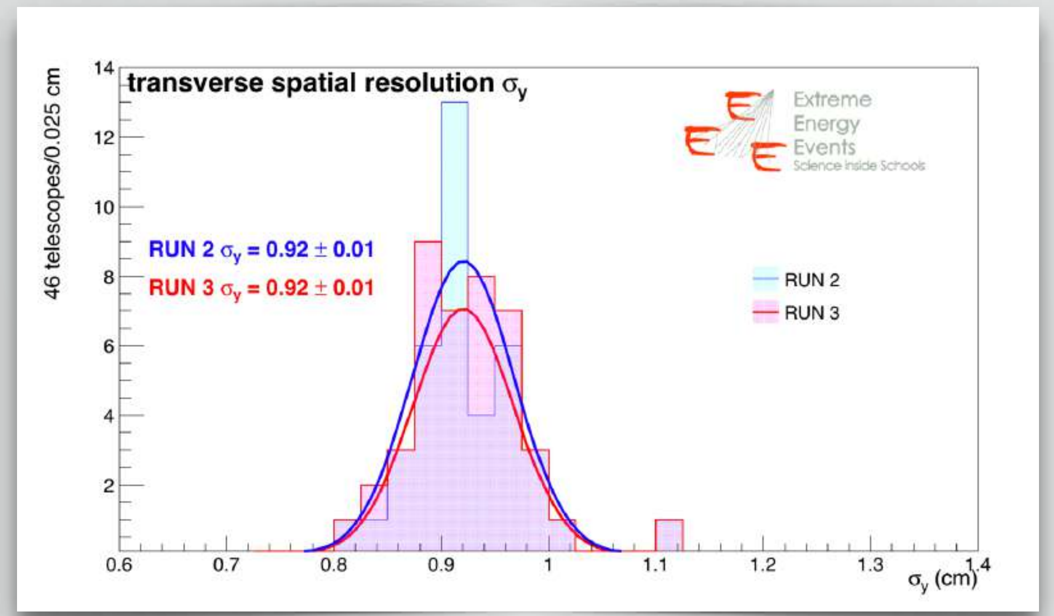
- Same strategy to estimate the spatial resolution
- Results published in *JINST (2018) 13 P08026*



- Beam tests @CERN

- Spatial resolution along the strip $0.8cm$
- TDC $25ps$ bins, trigger by scintillators (time resolution $30ps$)

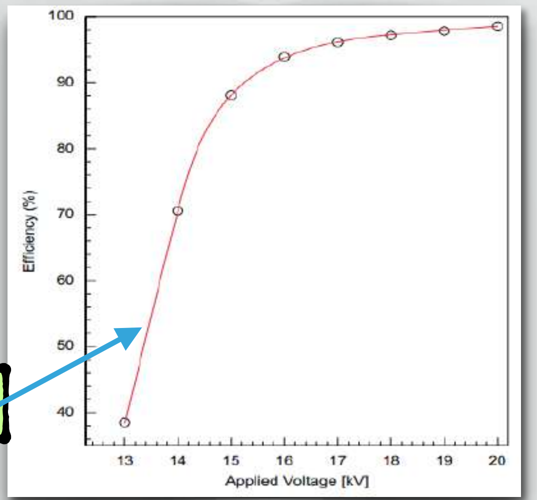




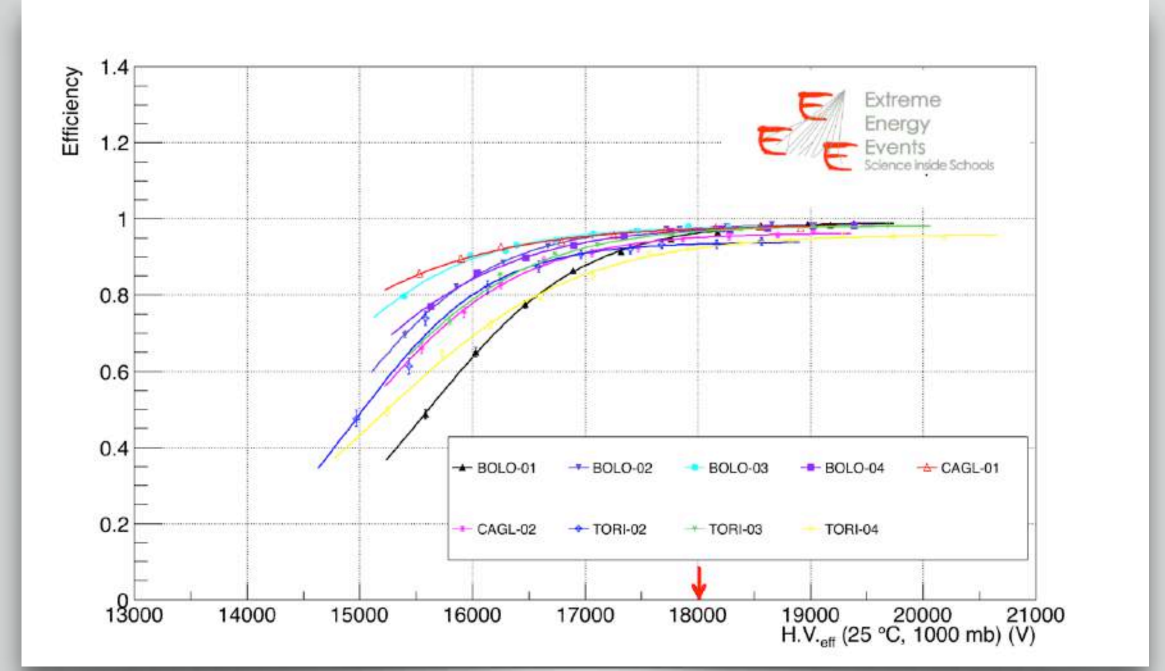
- Average transverse resolution $1.49cm$
- Average longitudinal resolution $0.92cm$
- Resolution compatible with requirements

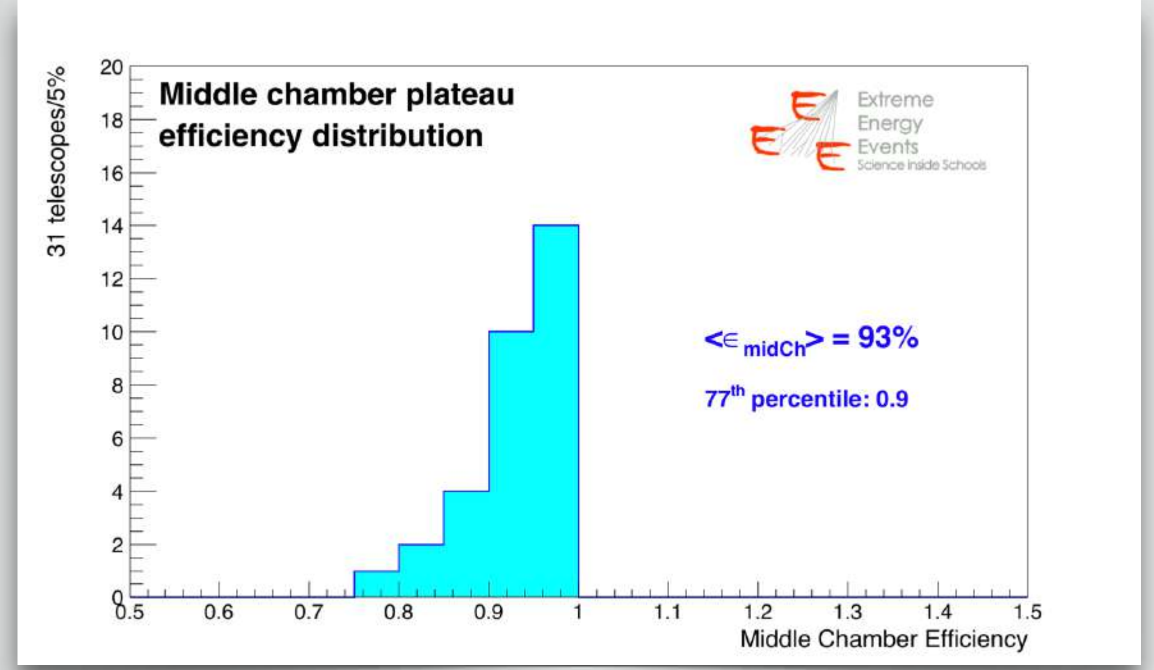
Efficiency

- External chambers used as **trigger**
- Efficiency of the **middle chamber** measured on all telescopes
- _Students involved in the measurement_
- Results published in *JINST (2018) 13 P08026*



- Beam tests @CERN
- Efficiency vs HV for a single MRPC chamber
- Trigger by scintillators

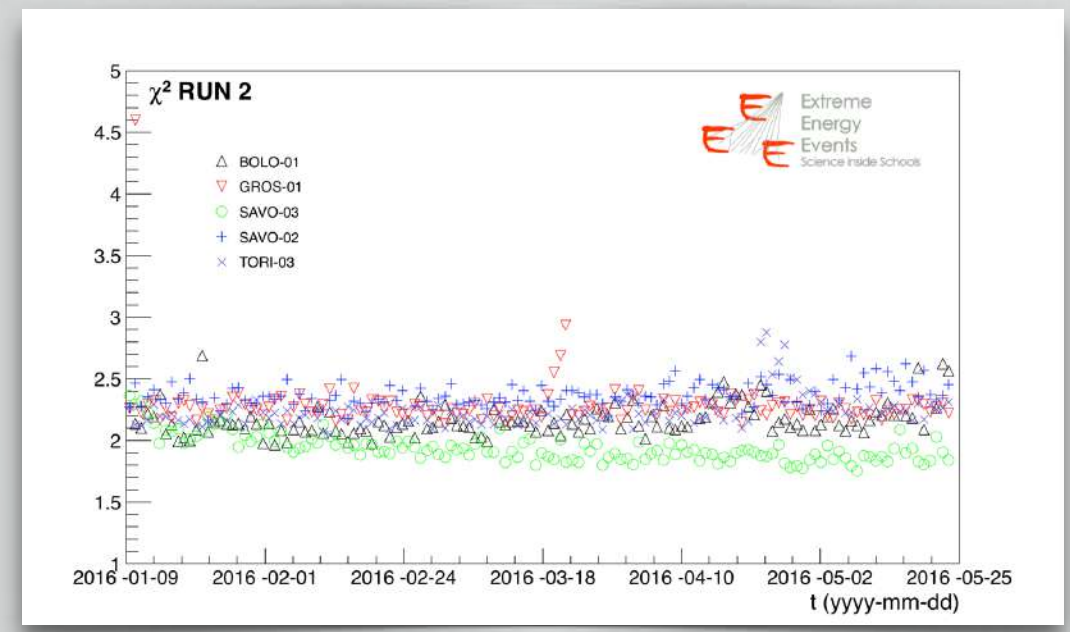


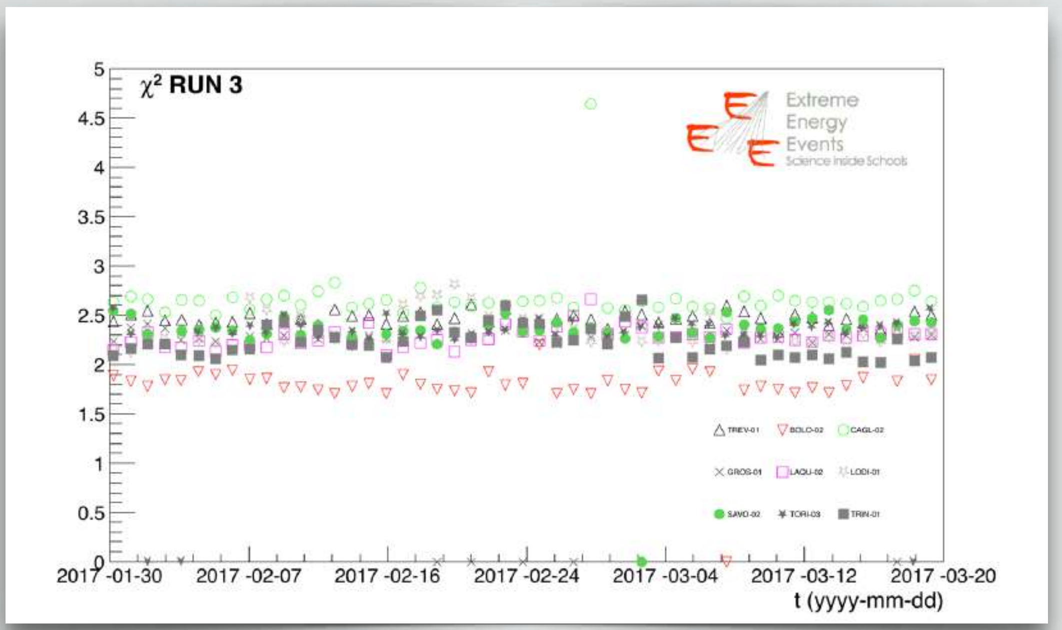


- Average efficiency of the telescope network ~ 93 %
- Compatible within expectations and with the results from beam-tests performed at CERN
- Efficiency better than 93 % is reached by 77 % of the network

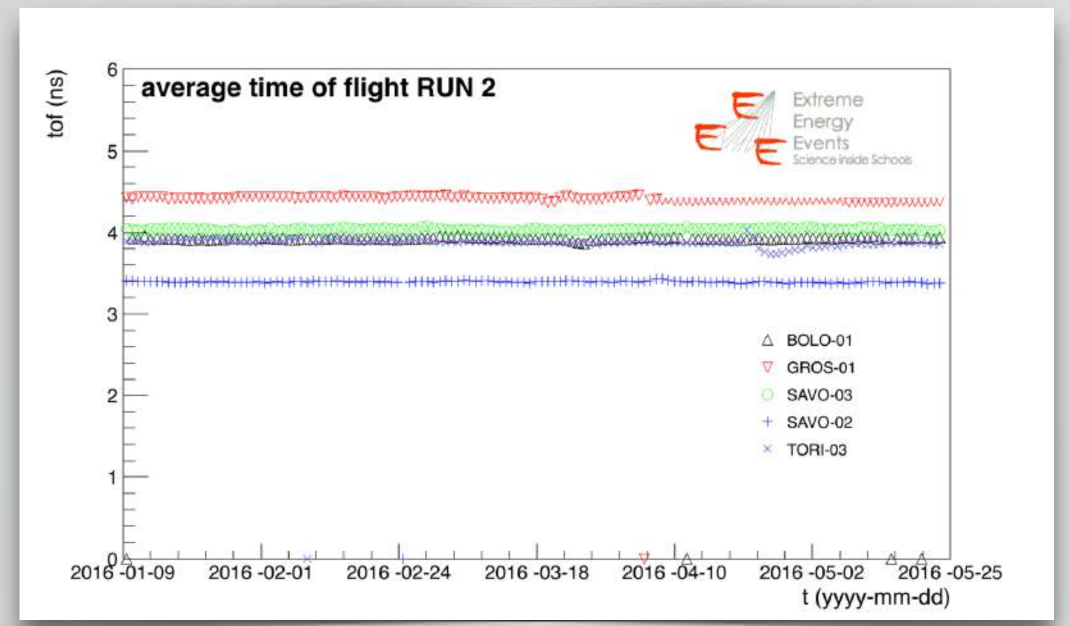
Long term stability

- **Average track χ^2** - computed as the best track in the event if at least one hit on each chamber is recorded





- **Time Of Flight** - average track TOF between top and bottom chambers



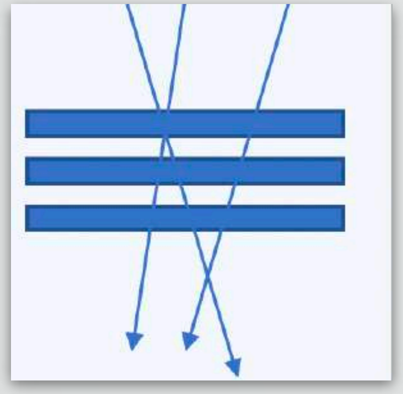
- More details and results in *JINST (2018) 13 P08026*

Physics

Analysis strategy

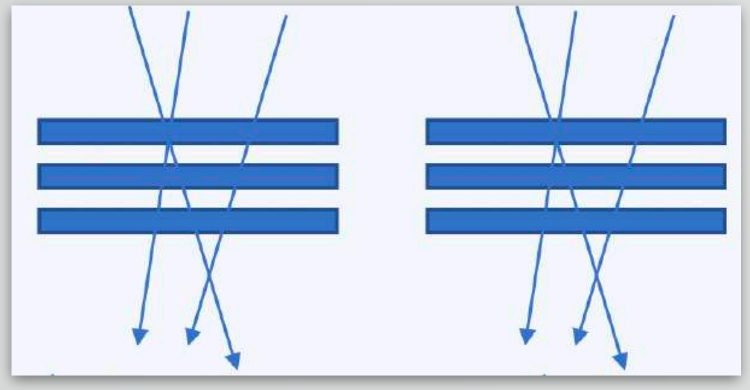
Single telescopes

- Local **cosmic ray flux** and **weather-correlated** features
- Local **cosmic ray flux** and phenomena related with **Solar activity**
- **Anisotropies** in the muon angular distribution
- Phenomena related with **upward-going particles**



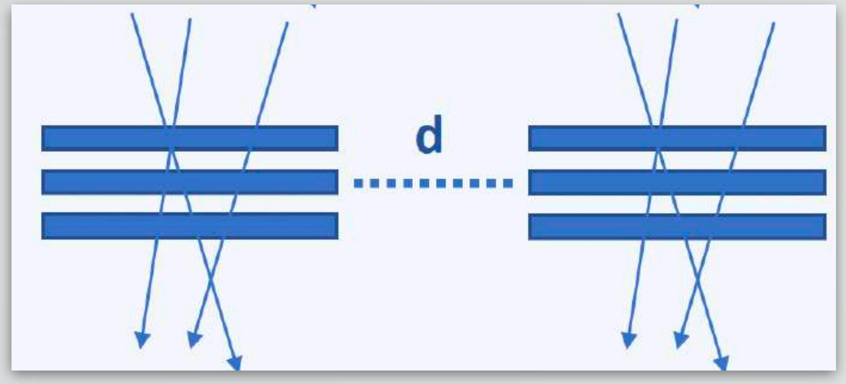
2 or more telescopes in the same metropolitan area

- **Exstensive Air Showers**



Telescopes at distance $d >$ EAS extension

- **Coincidence** events involving **many telescopes**
- **Long-range** time correlation between far telescopes



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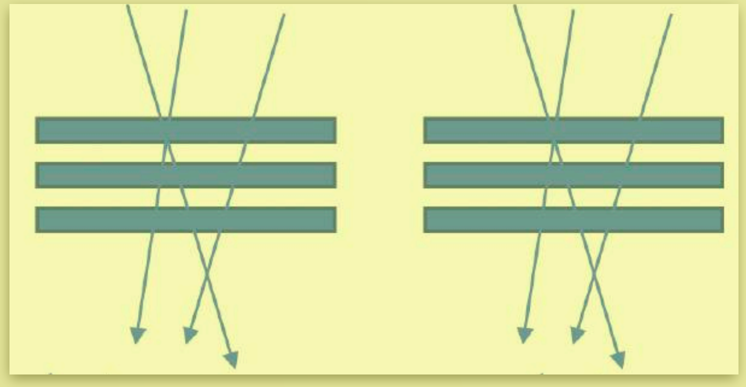

Telescopes at distance d > EAS extension

- Coincidence events involving many telescopes
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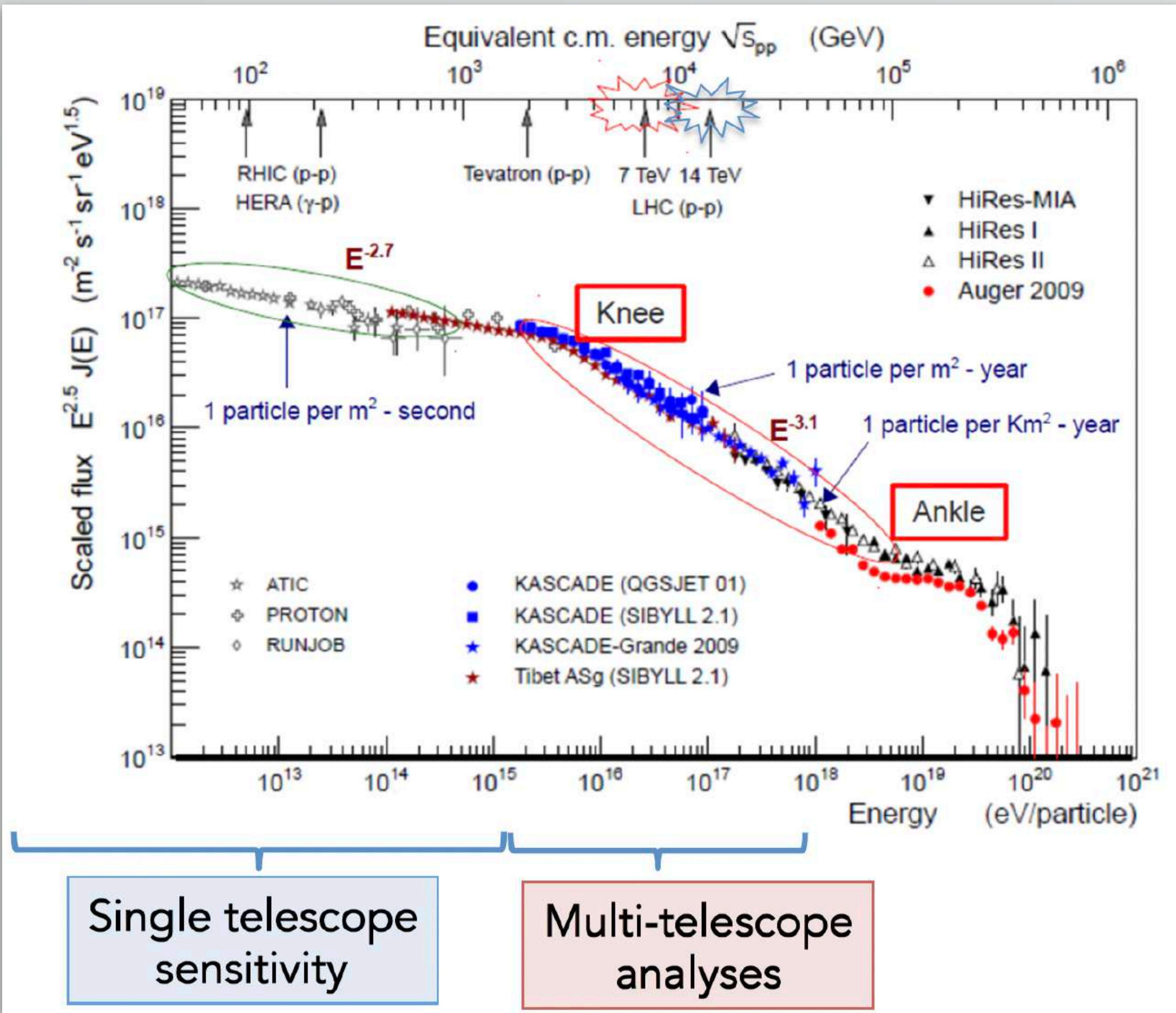
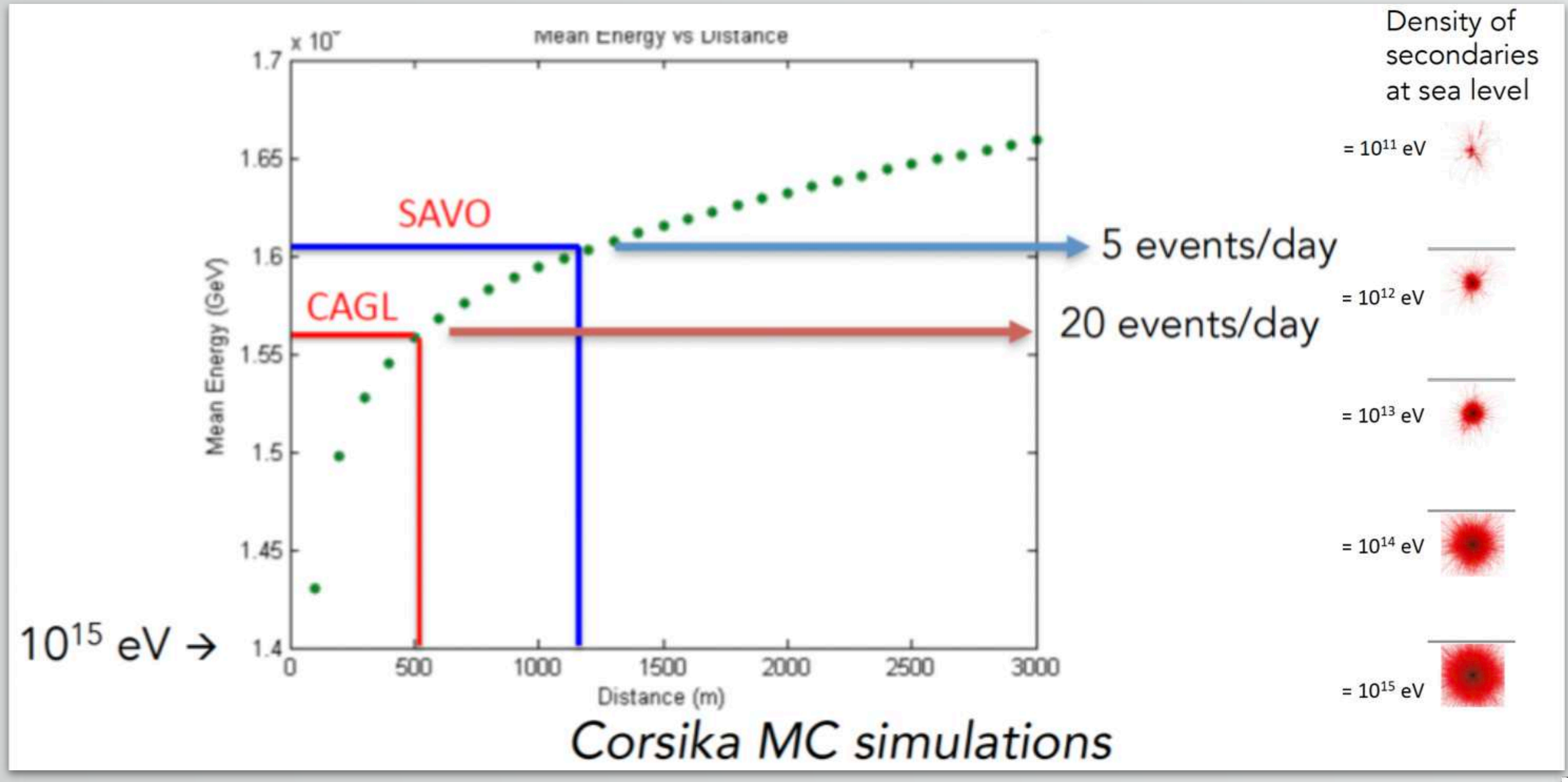
Cosmic ray flux and EEE



- EEE array allows several Physics studies (described in the next slides)
- A peculiar Physics case involves coincidences at large distances

High energy events

- **Coincidences** between telescopes
- The larger the distance the higher the energy of the primary (and the shower dimension)
- High statistics needed for very large distances (months of data taking)

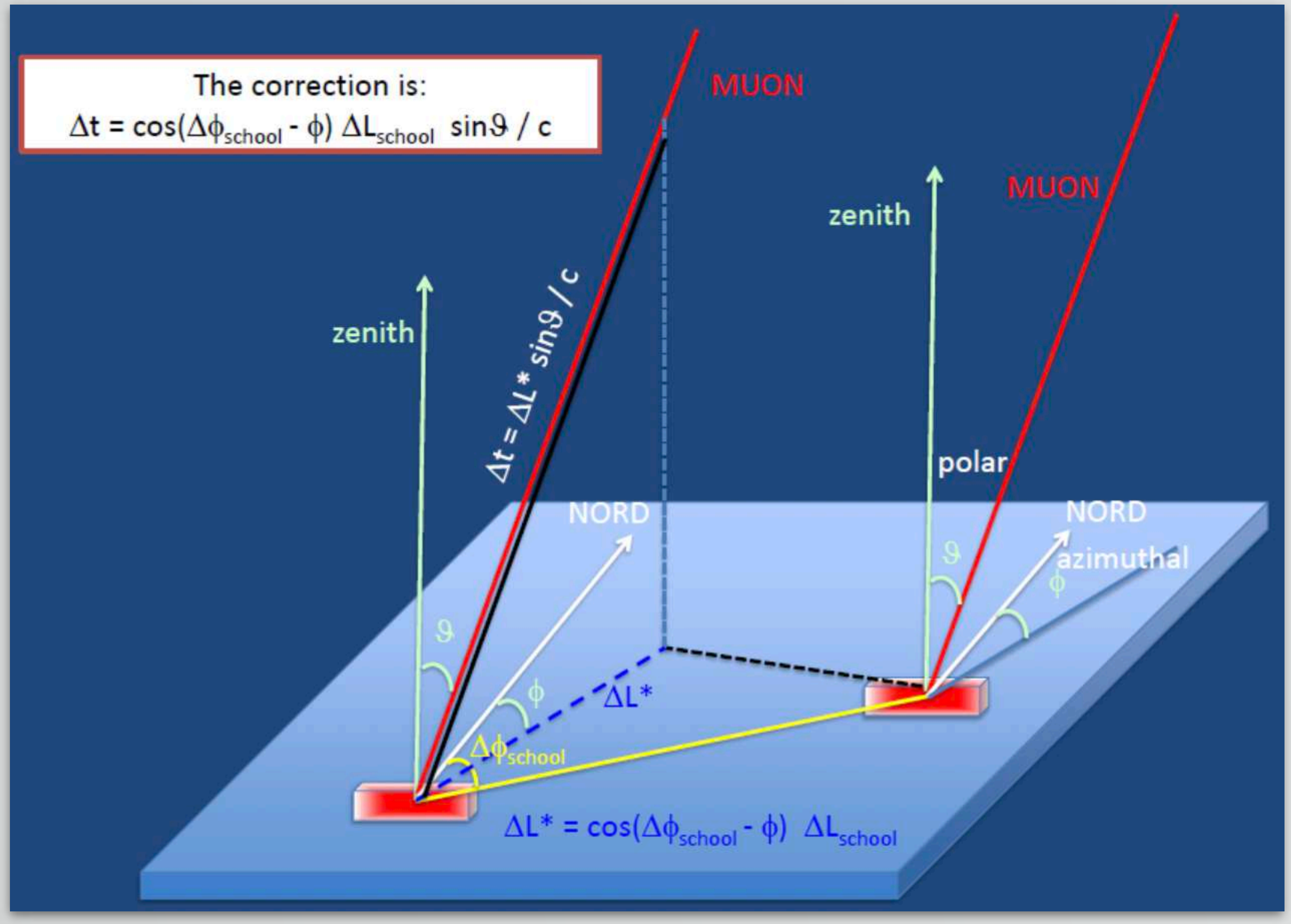


Direction reconstruction

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

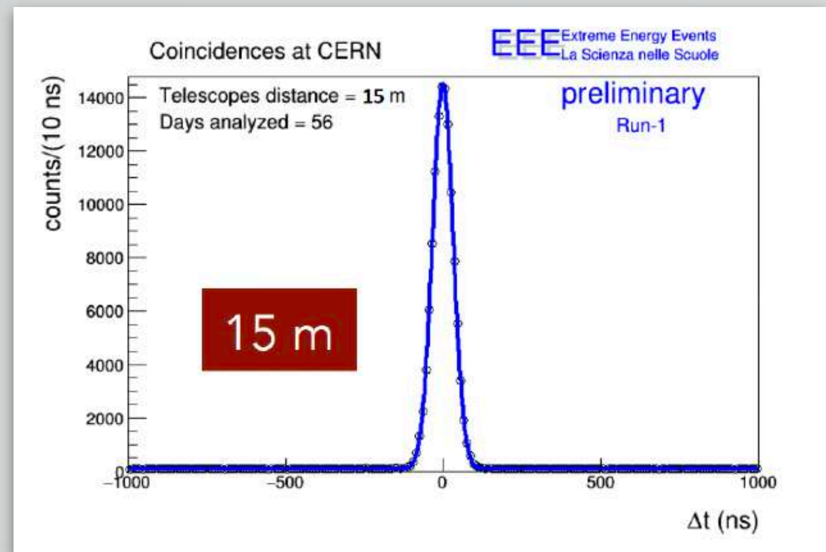
- ⇒ **Correction** event by event of the **time delay** due to the propagation of the **wave front** of the shower

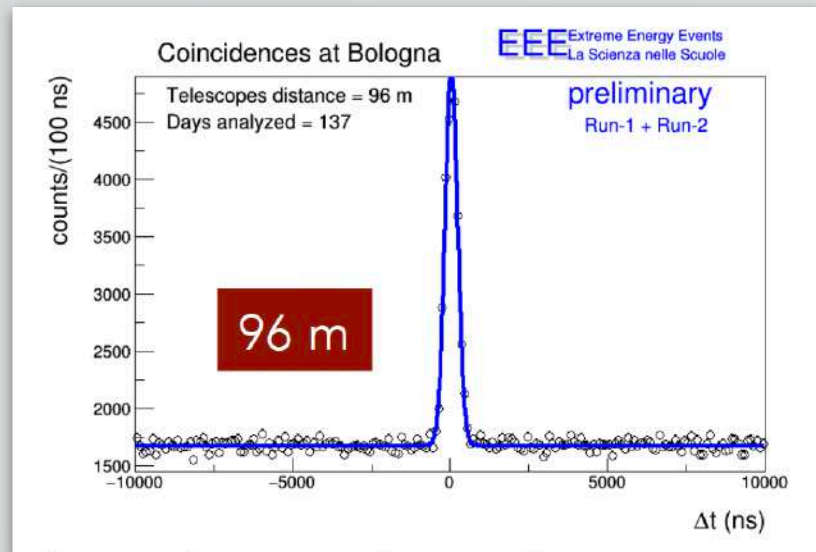
- Crucial for very large distances (**above $1km$** the delay can be of the order of **few microseconds**)

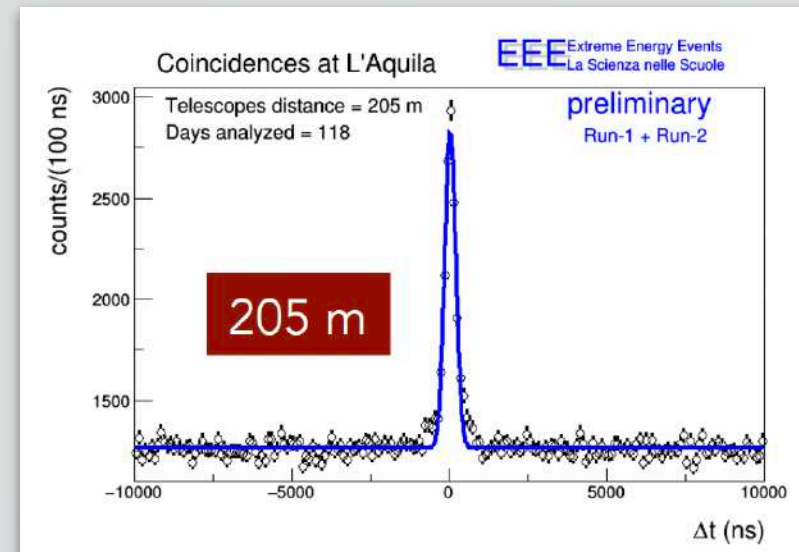


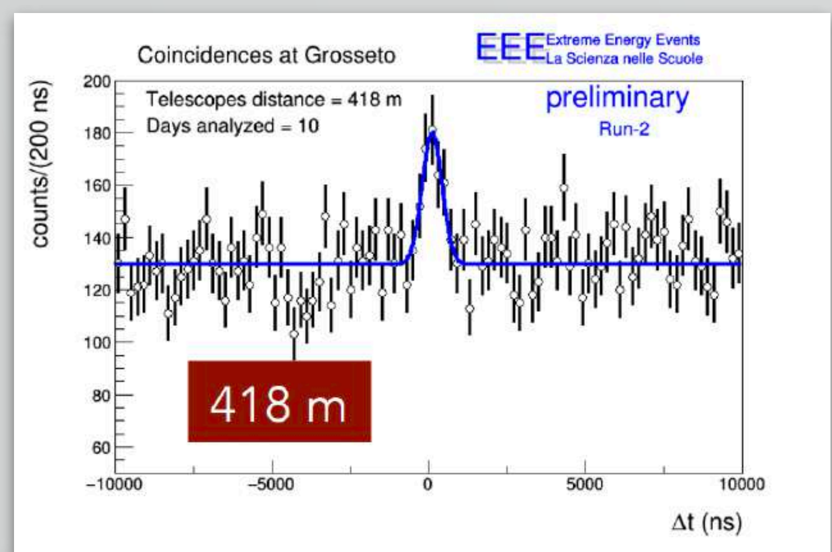
2-telescope coincidences

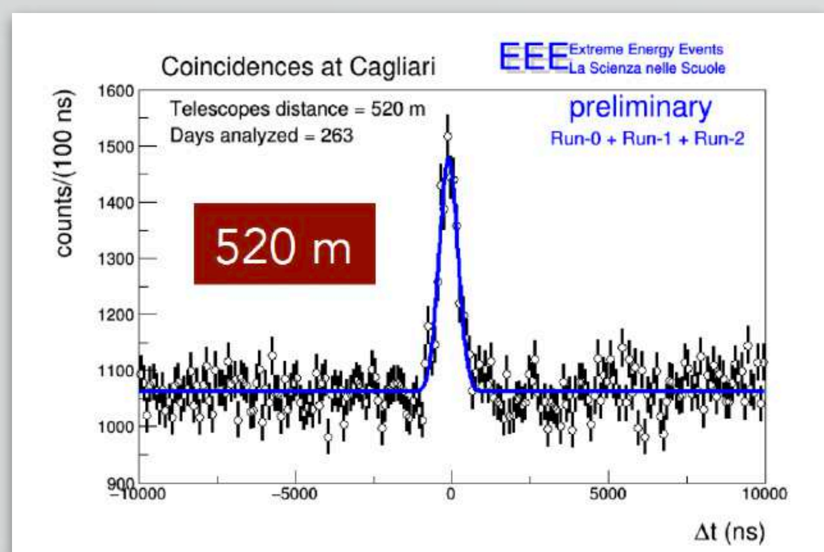
- **Single track coincidences** between 2 telescopes
- Coincidences well reconstructed for several distances between sites
- Relative angle between 2 tracks required to be $< 30°$ (≈ 10-$15°$ on average)

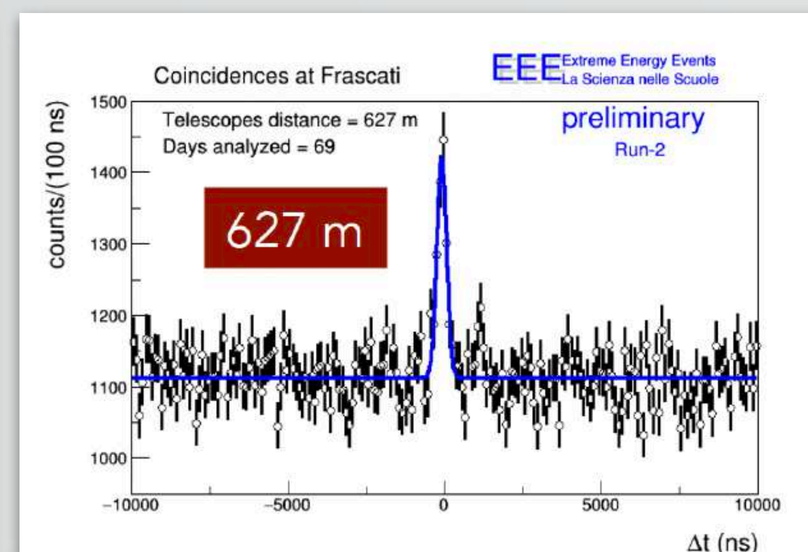






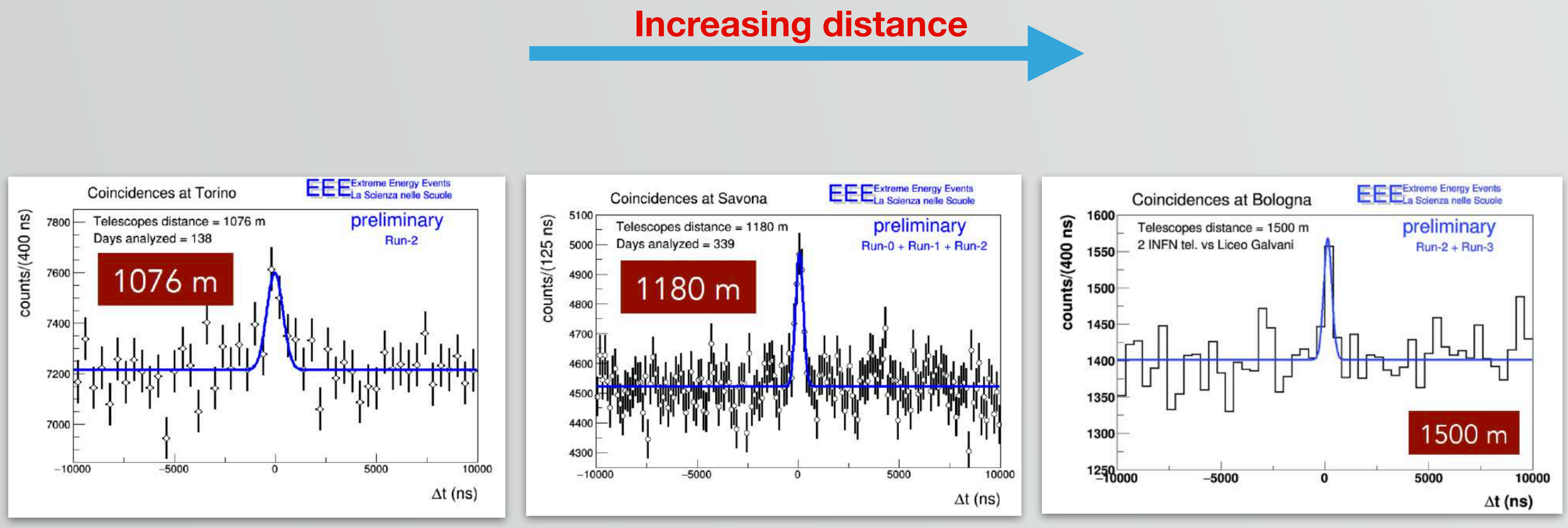






Increasing distance

2-telescope coincidences



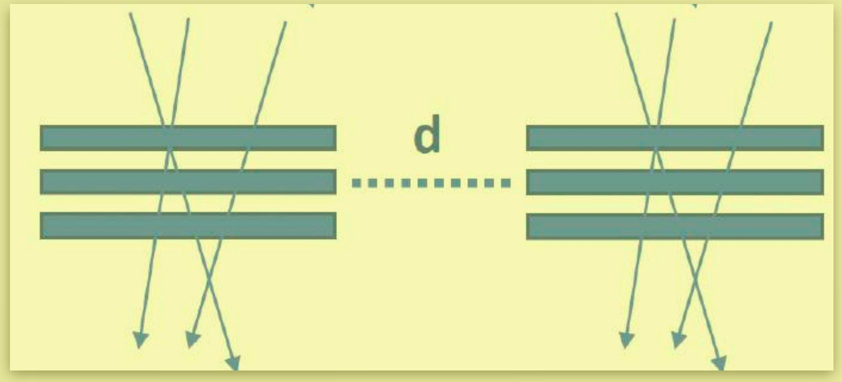
The correction event by event of the time delay between two telescopes (propagation of the wave front of the shower) significantly improves the S/B ratio

Analysis strategy

- **Single telescopes**
  - Local **cosmic ray flux** and **weather-correlated** features
  - Local **cosmic ray flux** and phenomena related with **Solar activity**
  - **Anisotropies** in the muon angular distribution
  - Phenomena related with **upward-going particles**

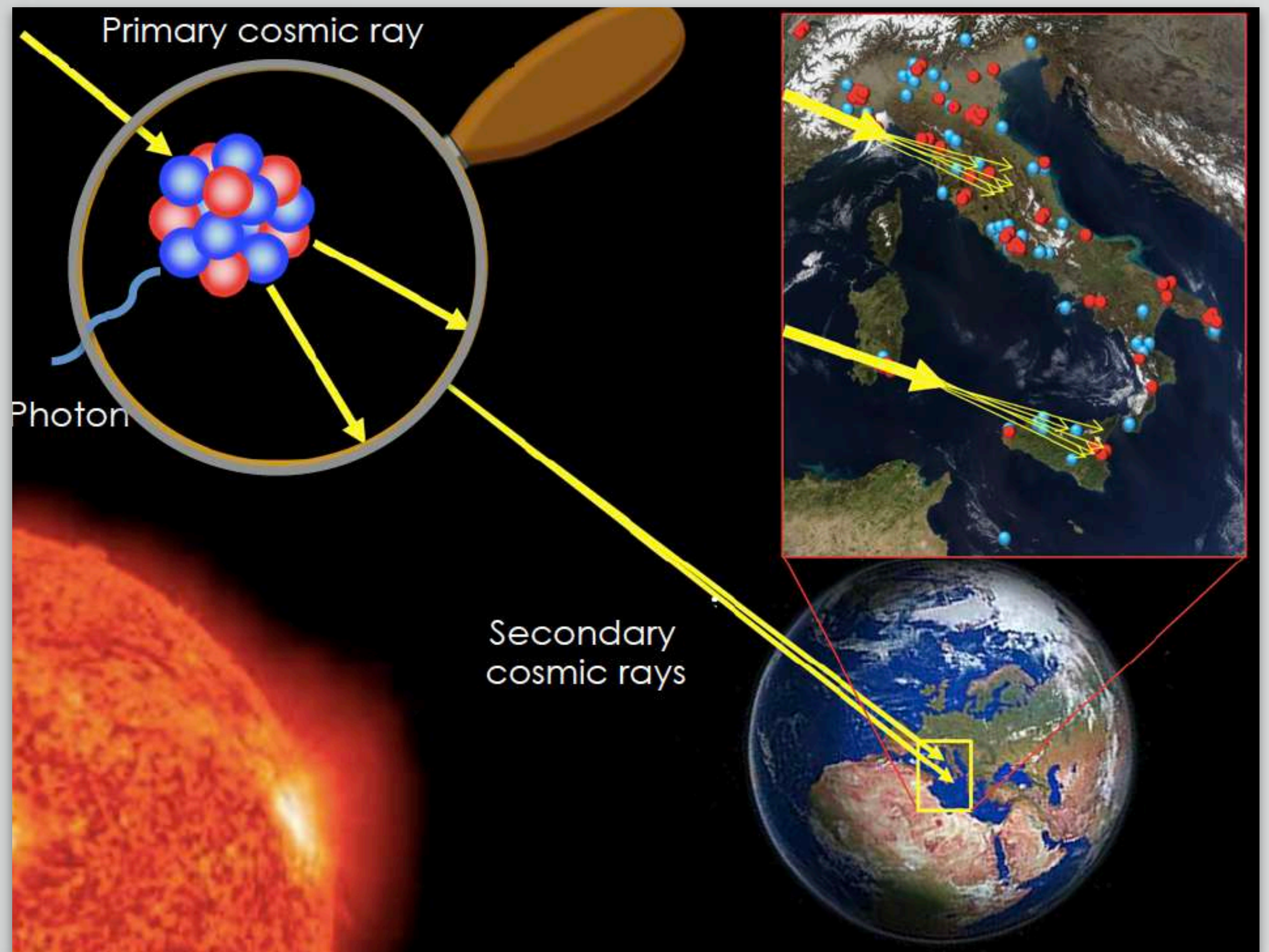
- **2 or more telescopes in the same metropolitan area**
  - **Exstensive Air Showers**

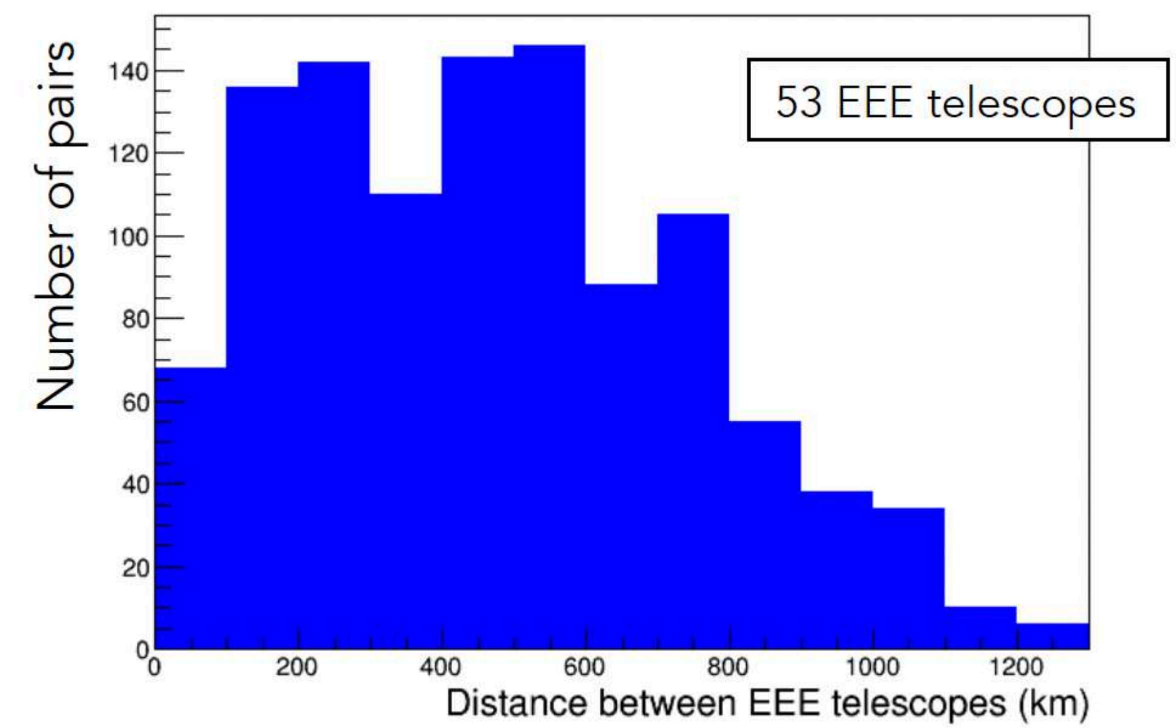
- **Telescopes at distance $d >$ EAS extension**
  - **Coincidence** events involving **many telescopes**
  - **Long-range** time correlation between far telescopes



Long distance correlation between EAS

- Correlation between EASs at large distances
  - **Two primary cosmic rays** originating from the **same source** (limited by the presence of magnetic fields)
  - Interaction of primary cosmic rays with photon radiation in the Universe (CMB radiation) or **nuclear fragmentation** via photo-disintegration in our Solar system (**Gerasimova-Zatsepin, GZ effect**)



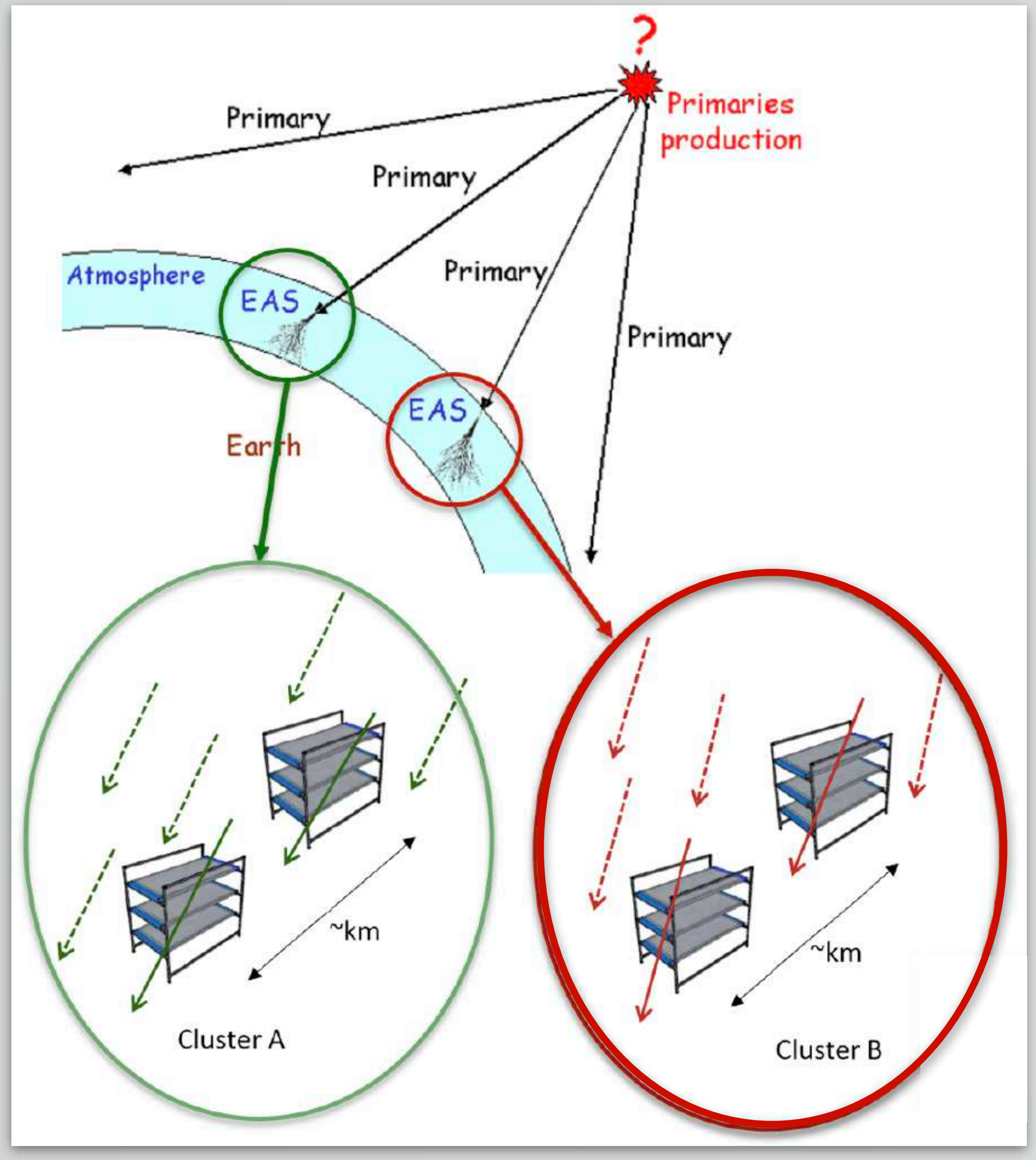


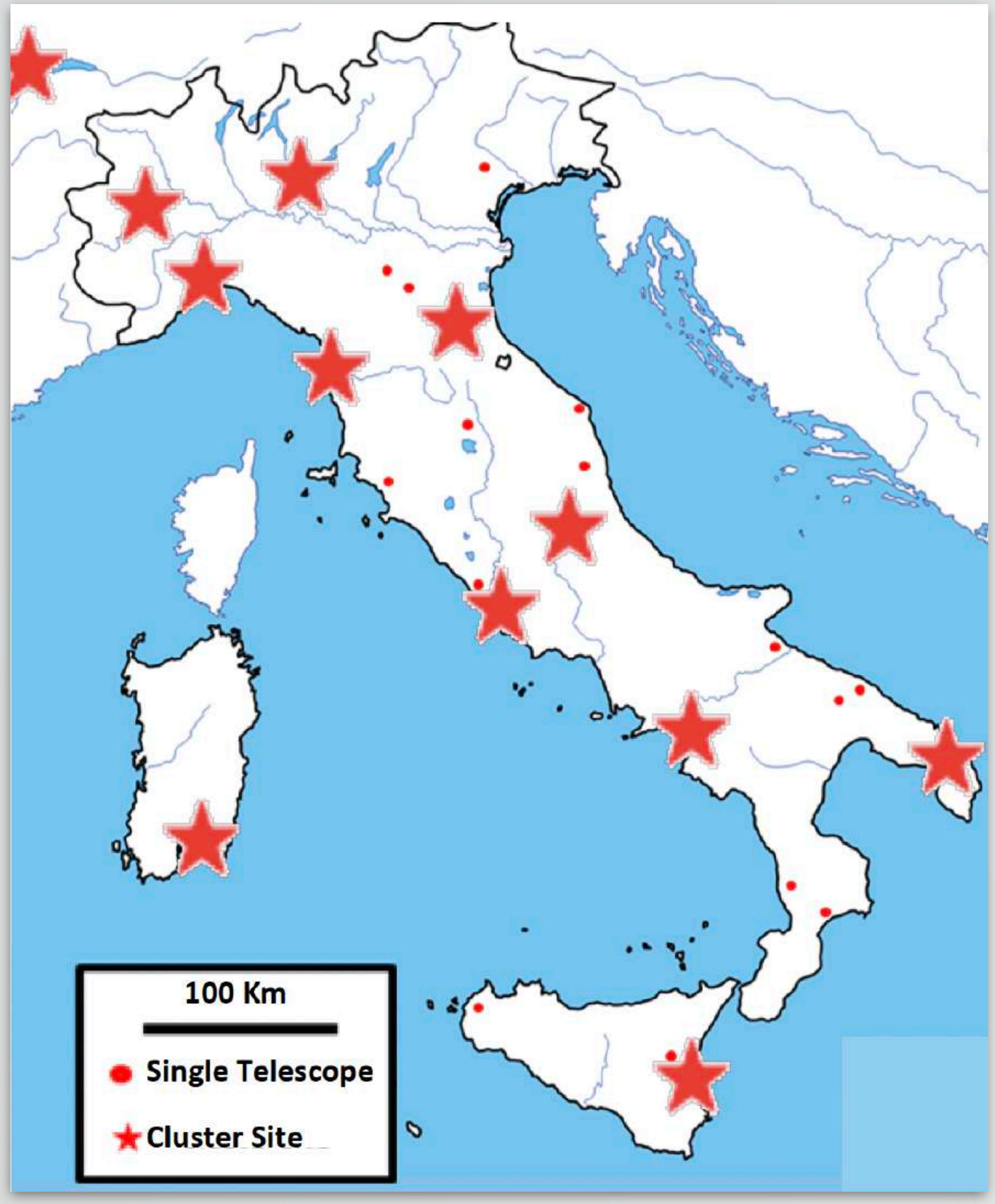
EEE typical distances between 2 telescopes

- Results published in *Eur. Phys. J. Plus (2018) 133: 34*

Long distance correlation between EAS

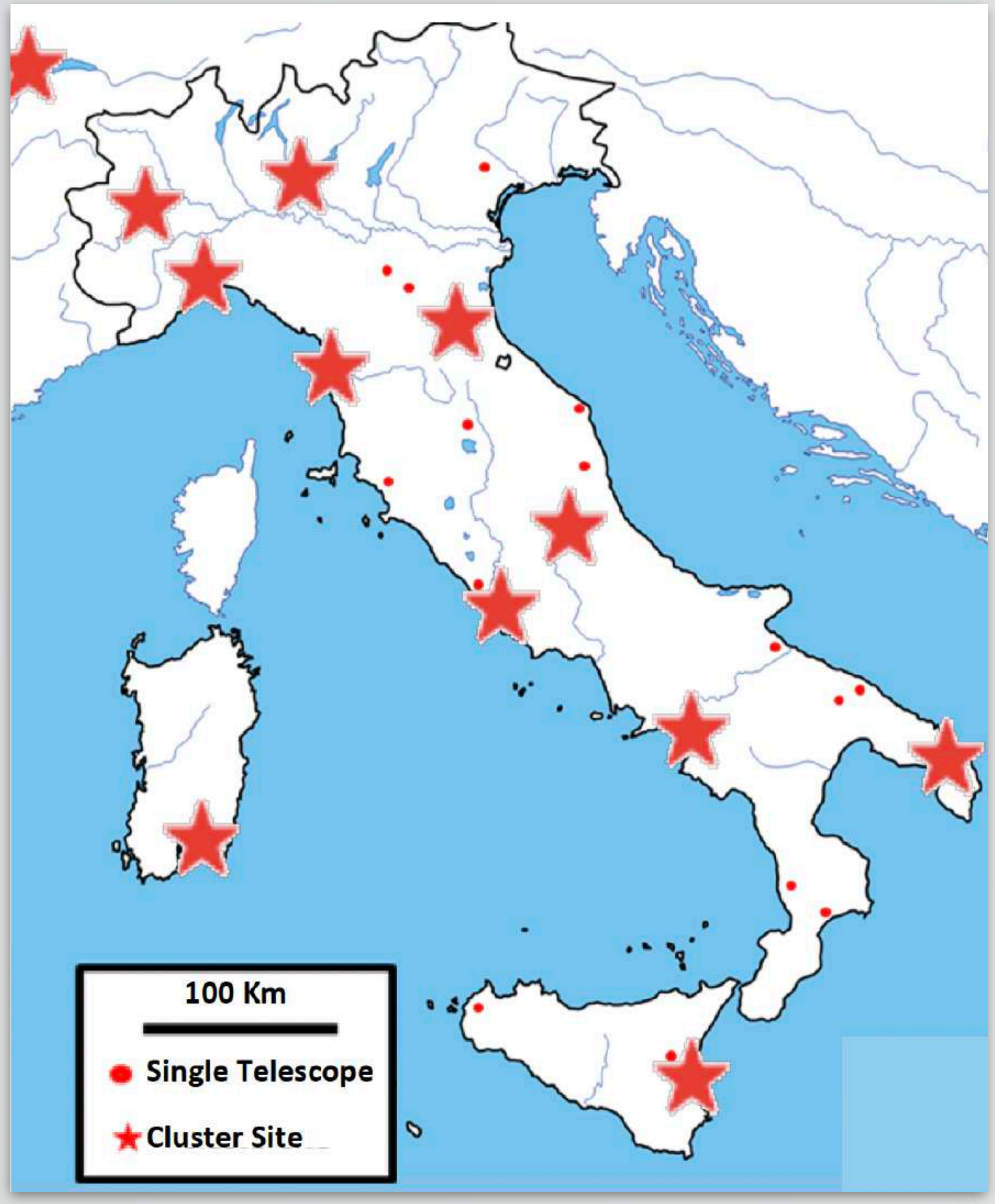
- Correlation between EASs at **large distances**
- EAS reconstructed via clusters (2-telescope coincidences)
- Search for **coincidences of 2 showers** (2 clusters = 2 x (2-telescope coincidences)





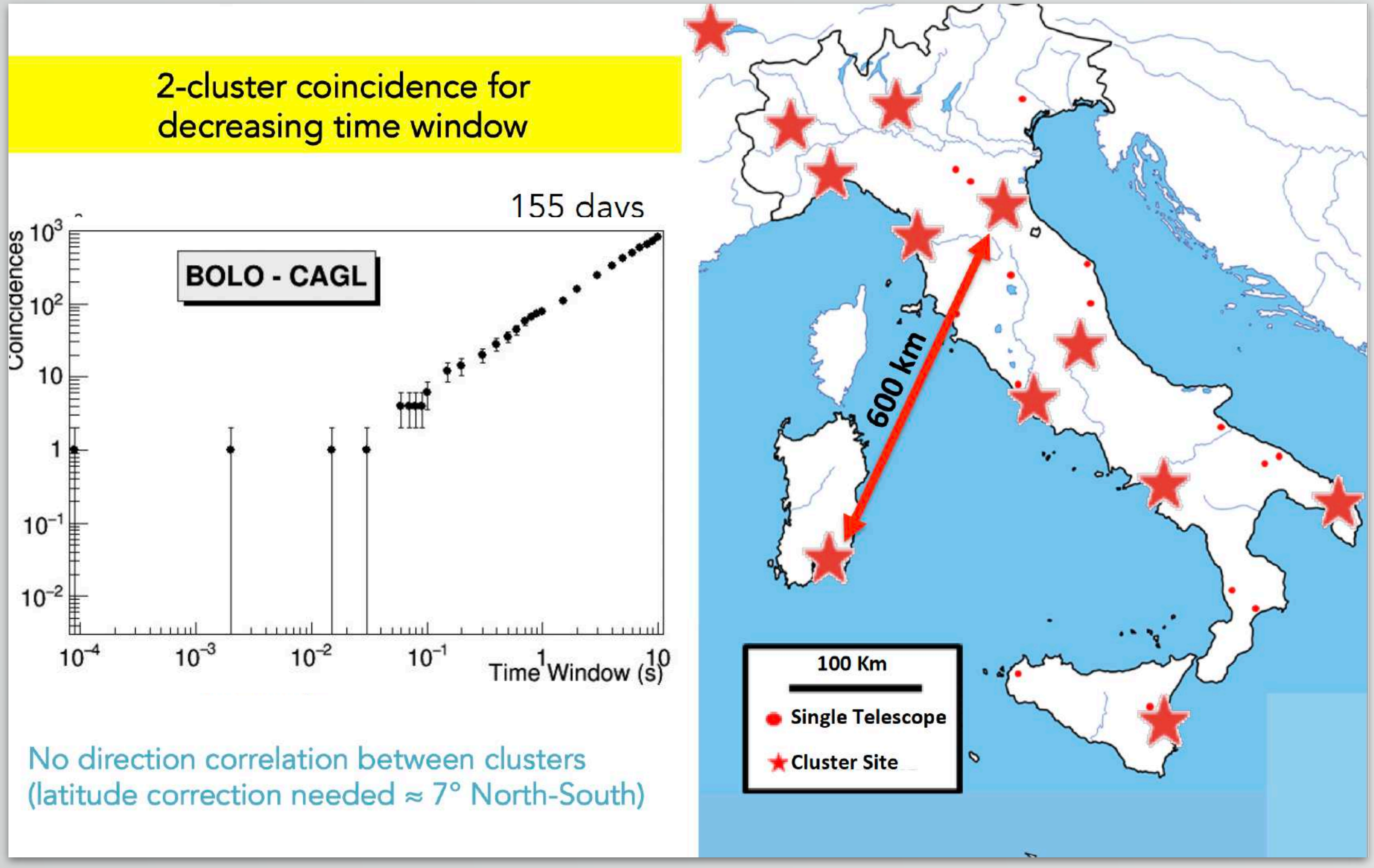
Long distance correlation between EAS

- Correlation between EASs at **large distances**
- Showers reconstructed via clusters (2-telescope coincidences)
- 10 EEE clusters in RUN 1 and RUN 2 → **45 cluster pairs**
- Single cluster signal → 2-telescope coincidence within $1\mu s$
- Single cluster signal → average telescope time as cluster time
- Single cluster rate → 10^{-3}-$10^{-2}Hz$ (10-$100/day$)
- Consider 2-cluster coincidences within a certain time window



Long distance correlation between EAS

- Correlation between EASs at large distances



- Results published in *Eur. Phys. J. Plus (2018) 133: 34*

Long distance correlation between EAS

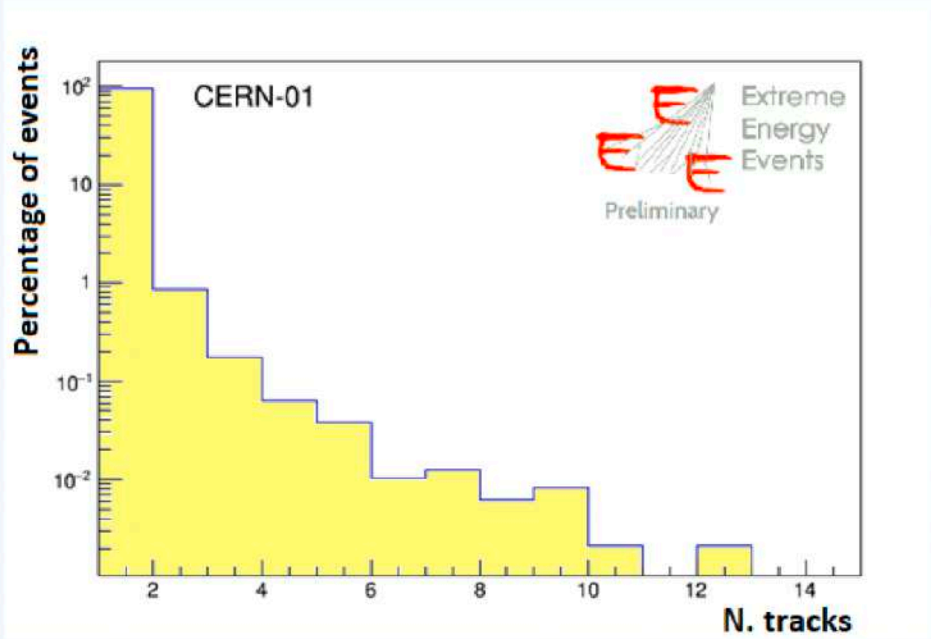
- Improve the analysis
  - Increase the number of EEE telescopes
  - Increase the statistics of two-telescope coincidences and search for **three-telescope coincidences** within the same city
  - Include **multi-track** telescope analysis in the search

Spurious coincidences between 2 telescopes (each detecting 2 tracks) in 1 ms:

$R_{spurious}$ = 2 x 0.02 x 0.02 x 10^{-3} = **8 x 10^{-7} Hz** (typical values)

Strategy: Correlations between multi-track events in far telescopes

Multi-track events correspond to a few percent of collected events



Long distance correlation between EAS

Data set

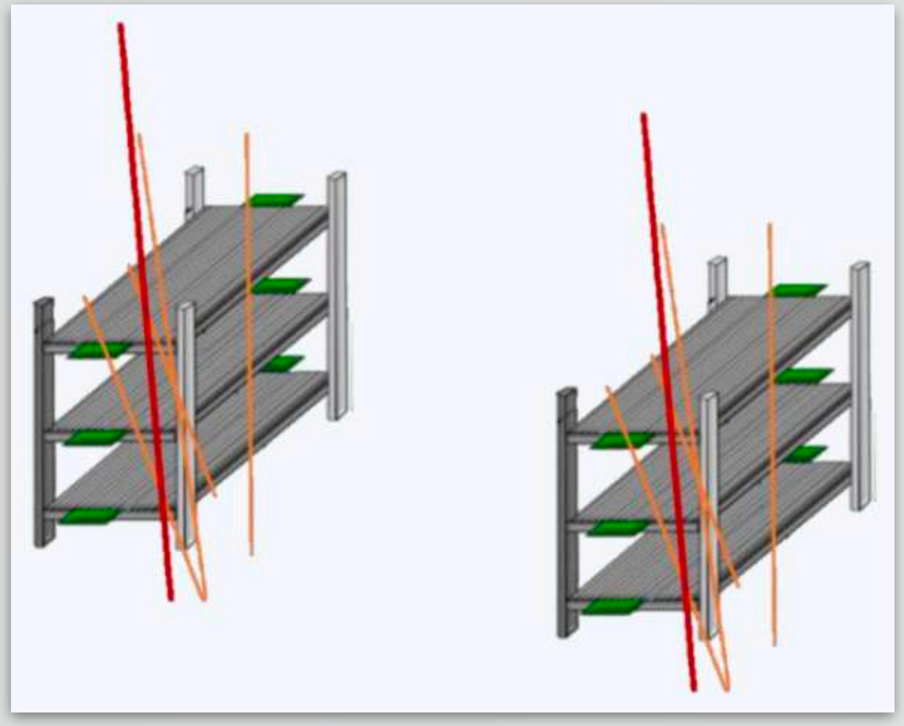
- *Full available statistics* (2015-2020)
- Number of preselected events - *25 millions of coincidence events* (in $\pm 2s$ window)

Pre-selection of multi-track events

- $\chi^2 < 10$
- *Rough alignment* between tracks in the same telescope

Analysis cuts

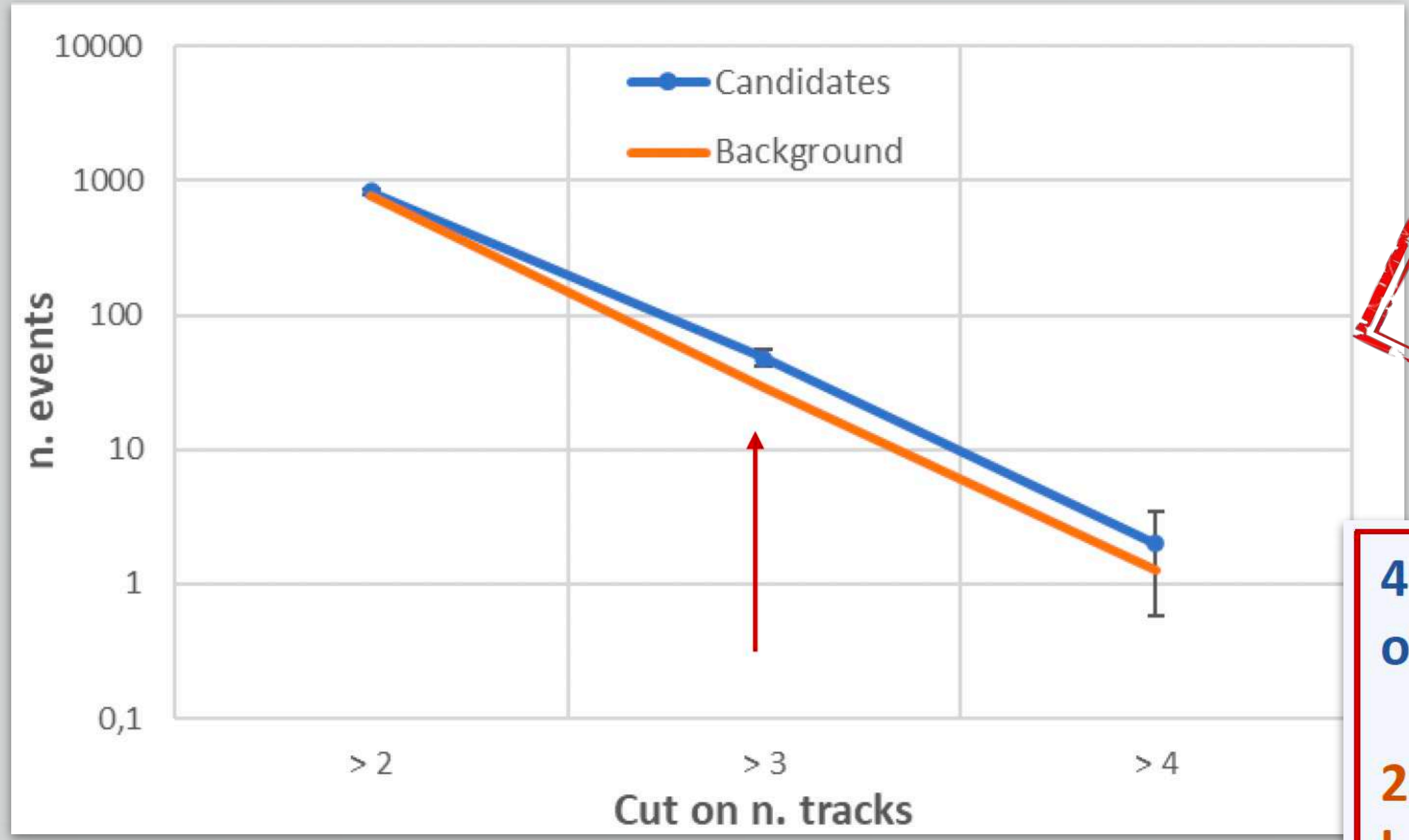
- *Parallelism of tracks* in each telescope
- $N_{tracks} > 3$ on both telescopes
- Distance between telescopes $> 5km$
- Coincidence time windows variation (from $\pm 1s$ to $\pm 10^{-5}s$)



Long distance correlation between EAS

Preliminary results

- **Events excess observed** for $\Delta t \sim 10^{-5}$-$10^{-4}s$ - $N_{tracks} > 3$ - site distance $> 5km$
- Number of preselected events - *25 millions of coincidence events* (in $\pm 2s$ window)



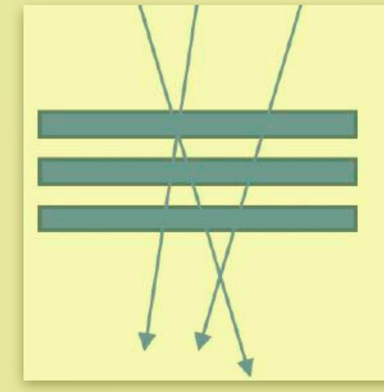
48 coincident events observed

29 events of expected background

Analysis strategy

Single telescopes

- Local **cosmic ray flux** and **weather-correlated** features
- Local **cosmic ray flux** and phenomena related with **Solar activity**
- **Anisotropies** in the muon angular distribution
- Phenomena related with **upward-going particles**



2 or more telescopes in the same metropolitan area

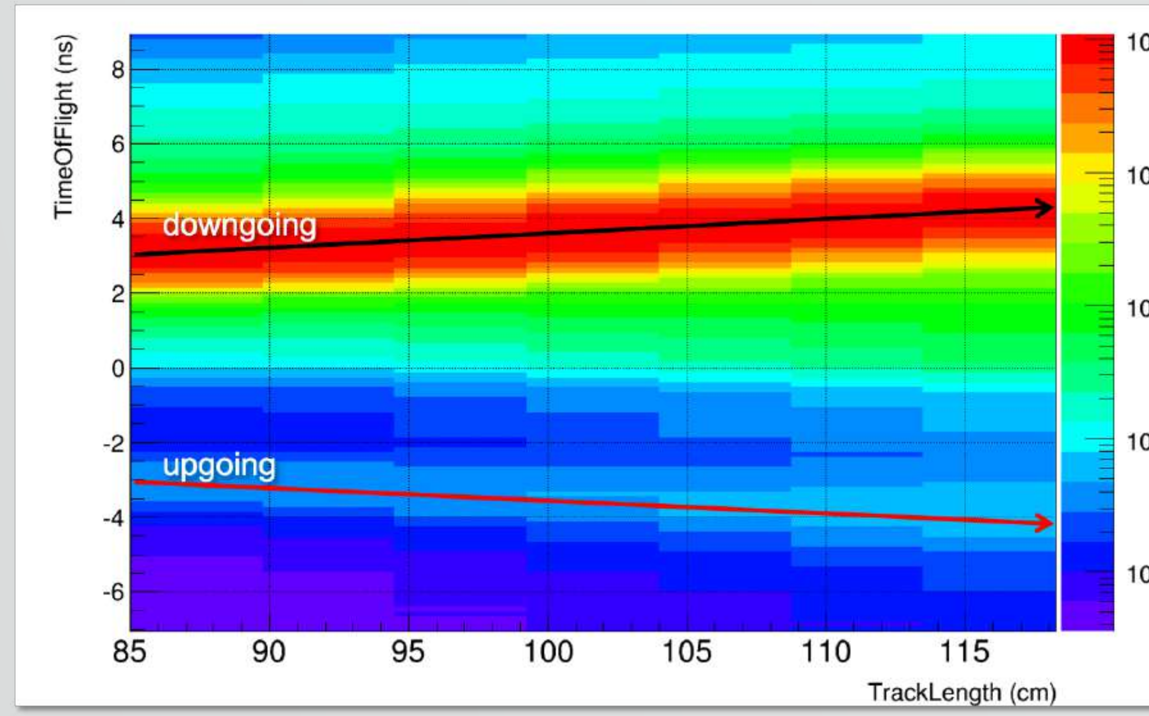
- **Exstensive Air Showers**

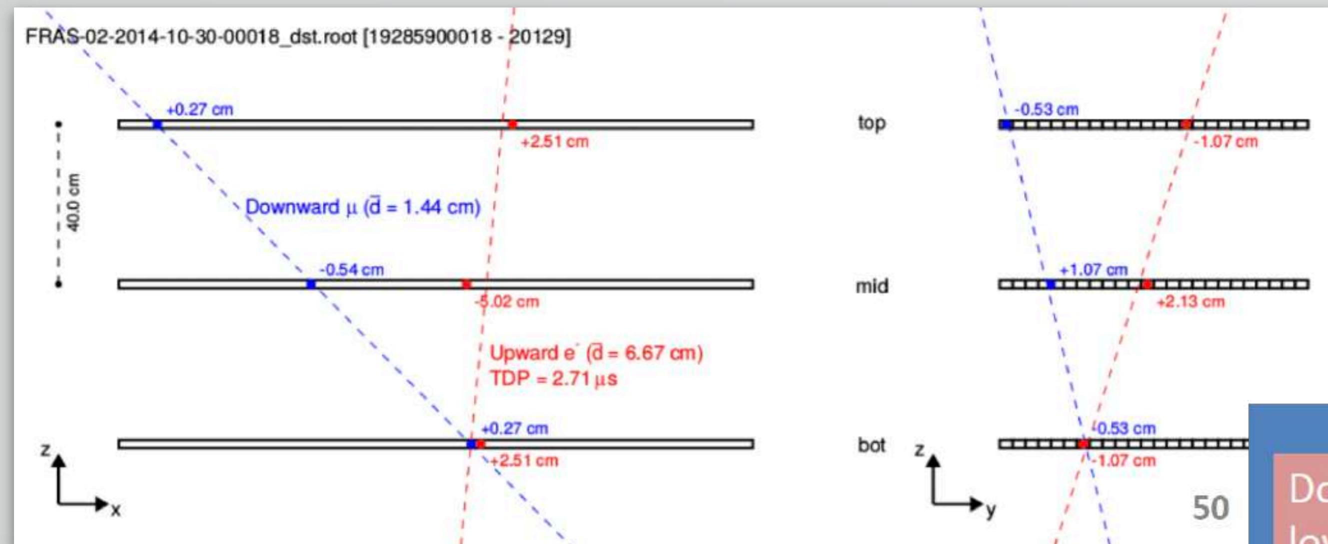
Telescopes at distance $d >$ EAS extension

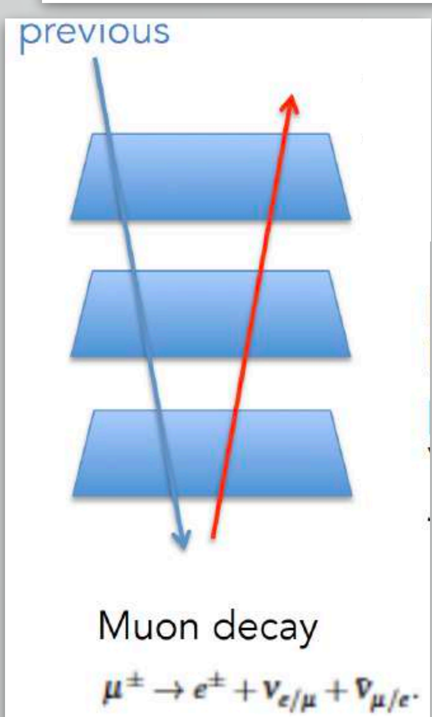
- **Coincidence** events involving **many telescopes**
- **Long-range** time correlation between far telescopes

Upgoing tracks

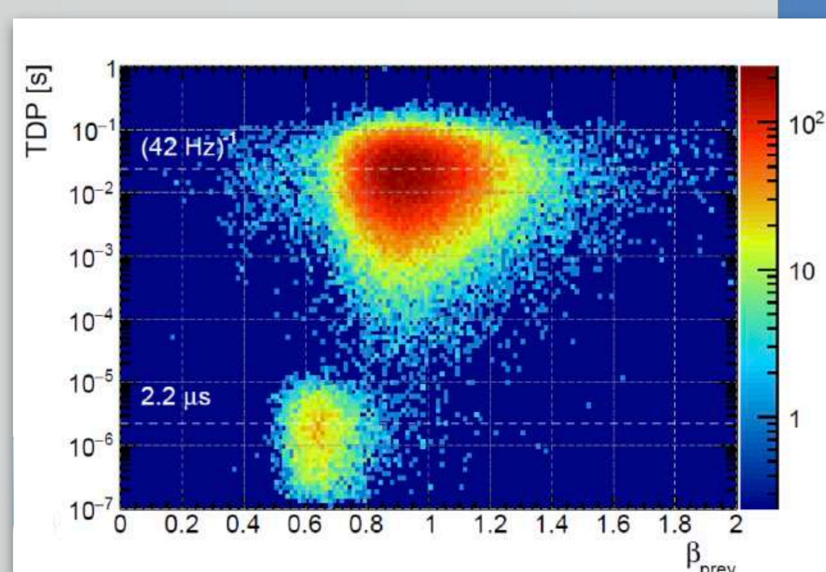
- Few **upgoing particle** events observed (1/2000) in EEE telescopes
- A fraction can be clearly identified as electrons coming from **muon decay** (in the floor under the telescope)

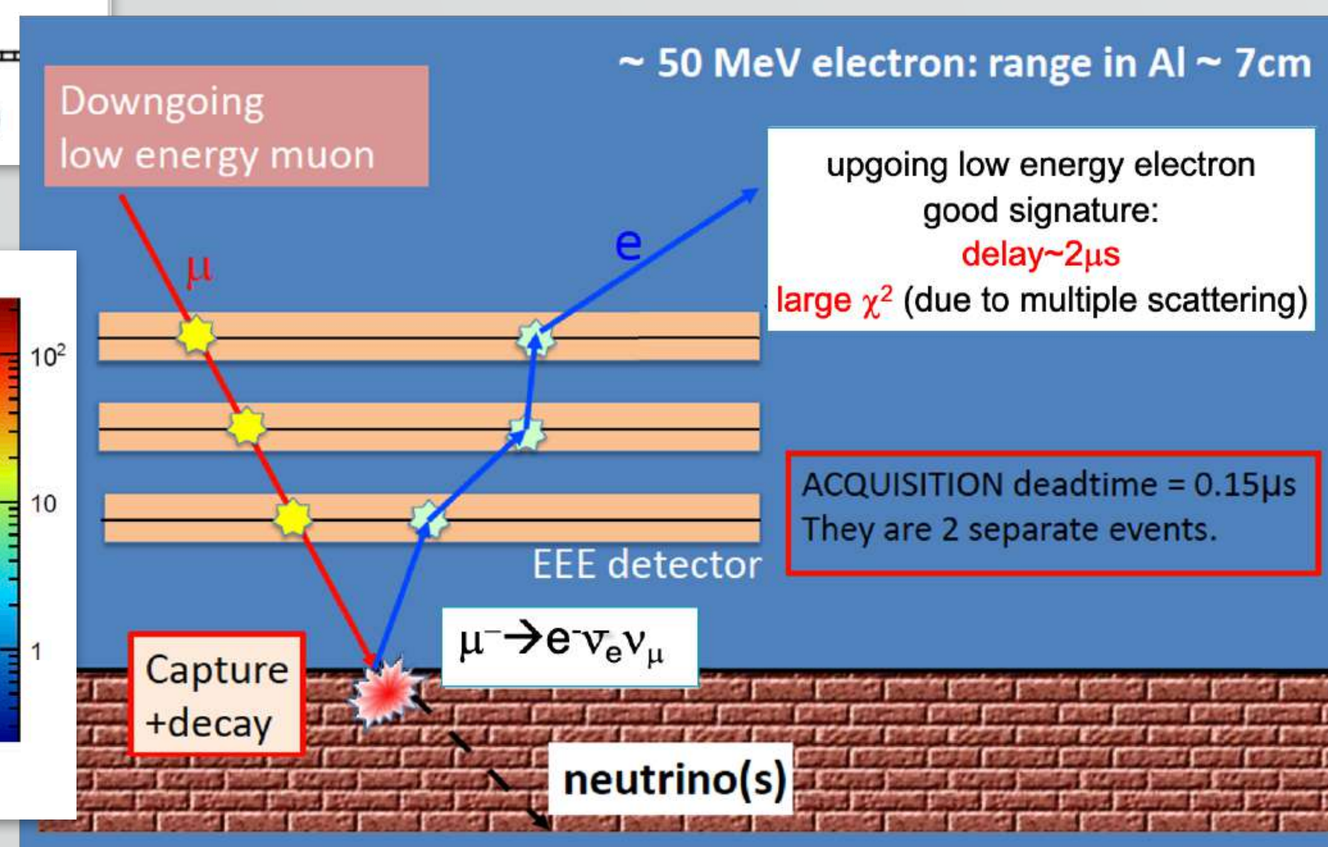






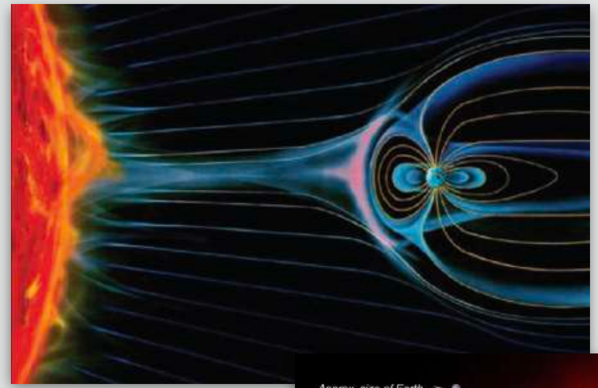
$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e/\mu} + \bar{\nu}_{\mu/e}$

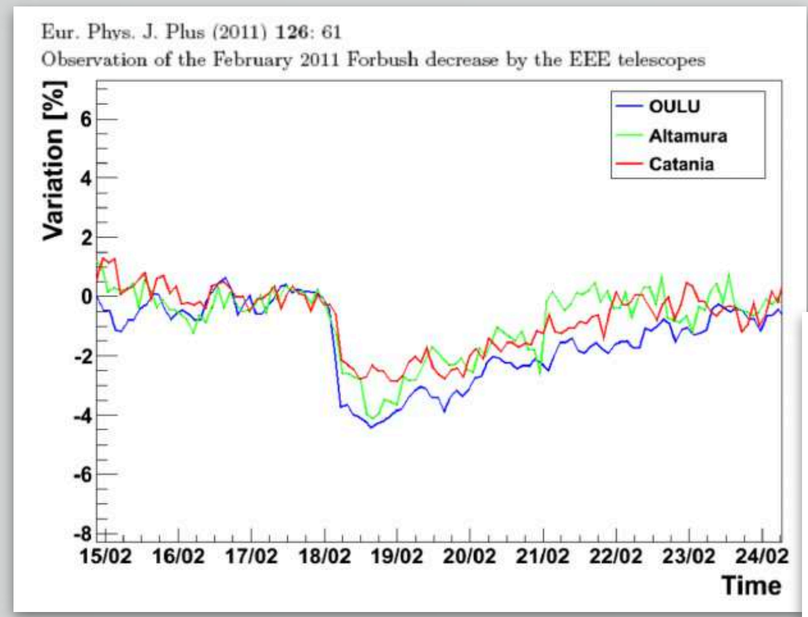


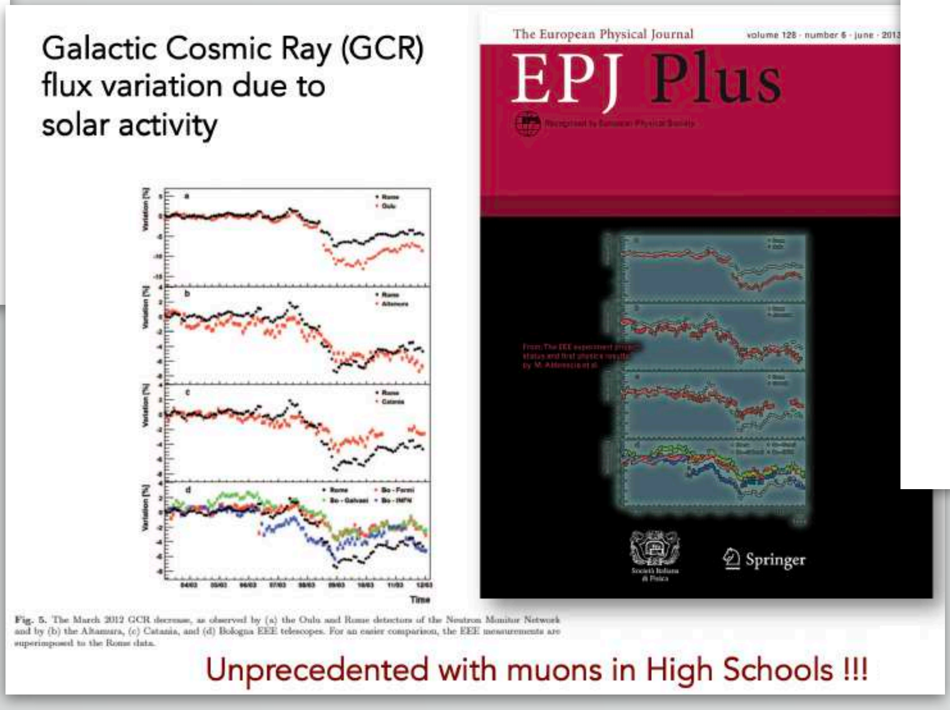


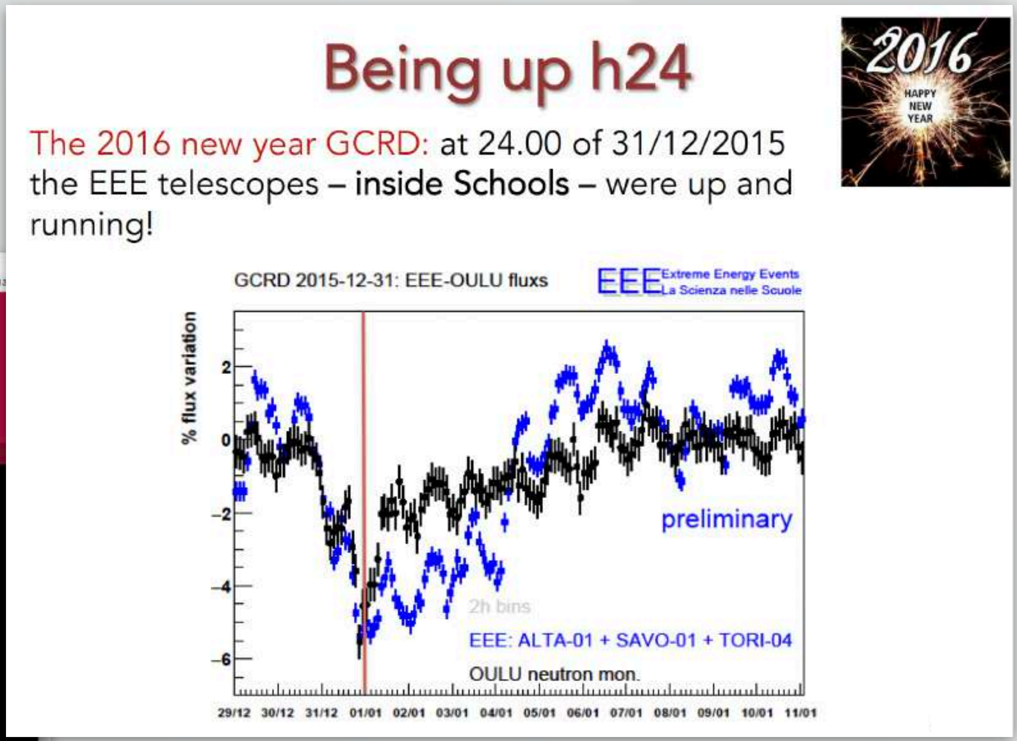
Forbush decrease

- Rapid decrease (a few hours) of galactic comic ray flux due to solar activity - **Forbush decrease**
- **Solar flares** (constantly monitored) and geomagnetic disturbance
- Slow recovery in a few days time range
- ***<u>First ever observed in the muon channel (and first in a school)</u>***
- Data quality comparable to professional observatories (Neutron Monitor Network)







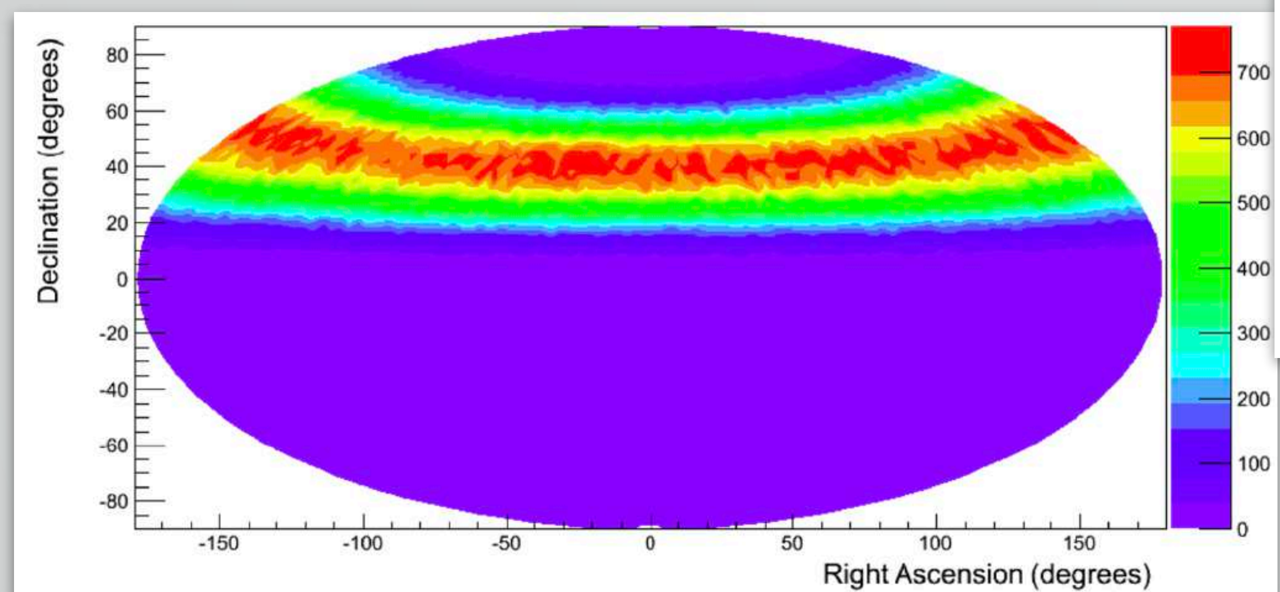


Cosmic ray anisotropy

- Cosmic ray **anisotropies** in the TeV range due to non uniformity of solar/galactic magnetic field

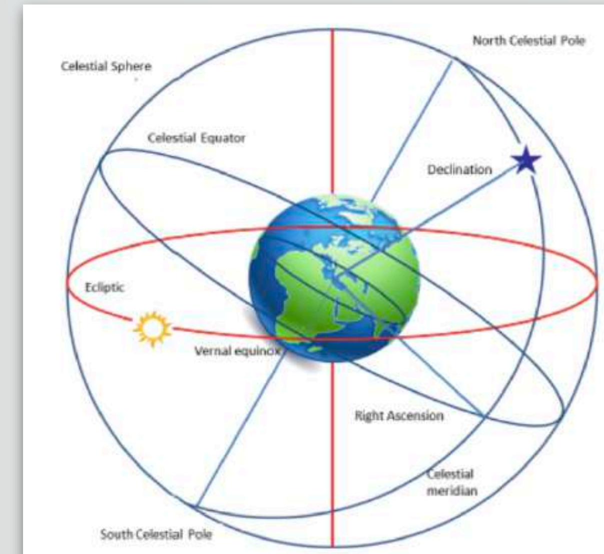
- Its magnitude already observed to be 10^{-5}-10^{-3} by other experiments at higher energies ($20TeV$-$1PeV$)

- ***No anisotropies have been observed at the level of*** 10^{-2}

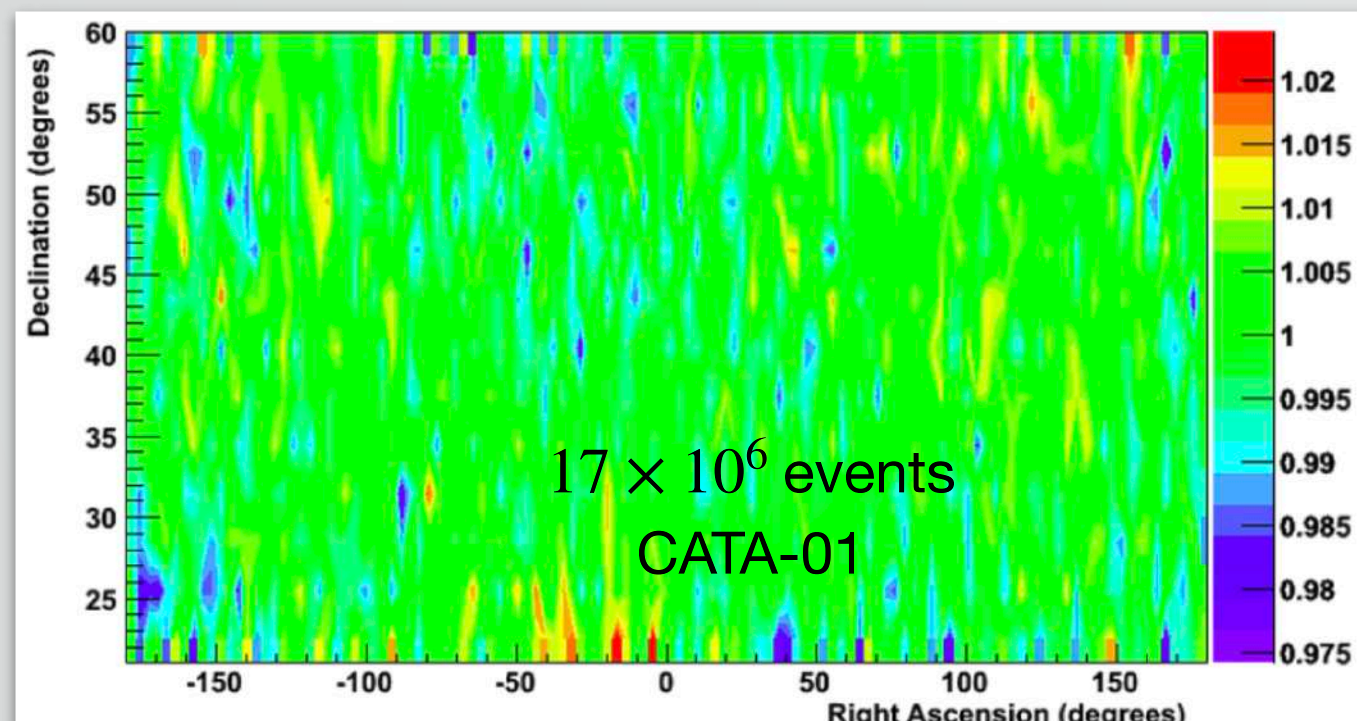


EEE acceptance: sky map for one of the EEE telescopes (CATA-01), located around 37° Lat. North, 15° Long. East

1 day data taking, 20 Hz
1.5 x 10^6 events



Equatorial Coordinate System



...and many more (not listed here)

PolarquEEEst

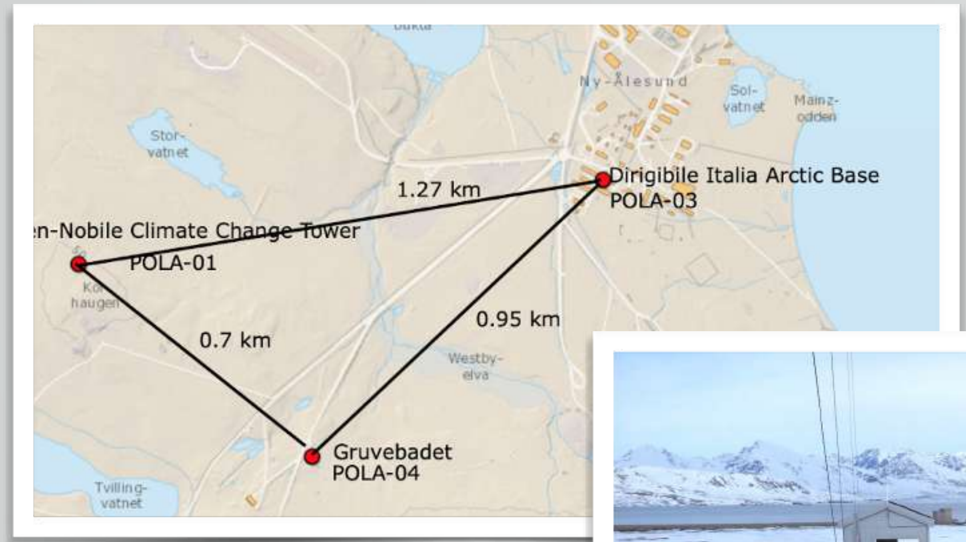
- The **Polar Quest 2018 mission** was a scientific multidisciplinary exploration of Svalbard archipelago
- The EEE Project and INFN contribute to the mission with a cosmic ray detector, **POLA**, to observe **Cosmic Rays at very high latitude**
- 3 POLA detectors were **assembled at CERN by high school students**
    - POLA-01 - installed on **Nanuq sailboat**
    - POLA-02 - installed in a **Italian High School (Bra)**
    - POLA-03 - installed in a **Norwegian High School (Nesodden)**

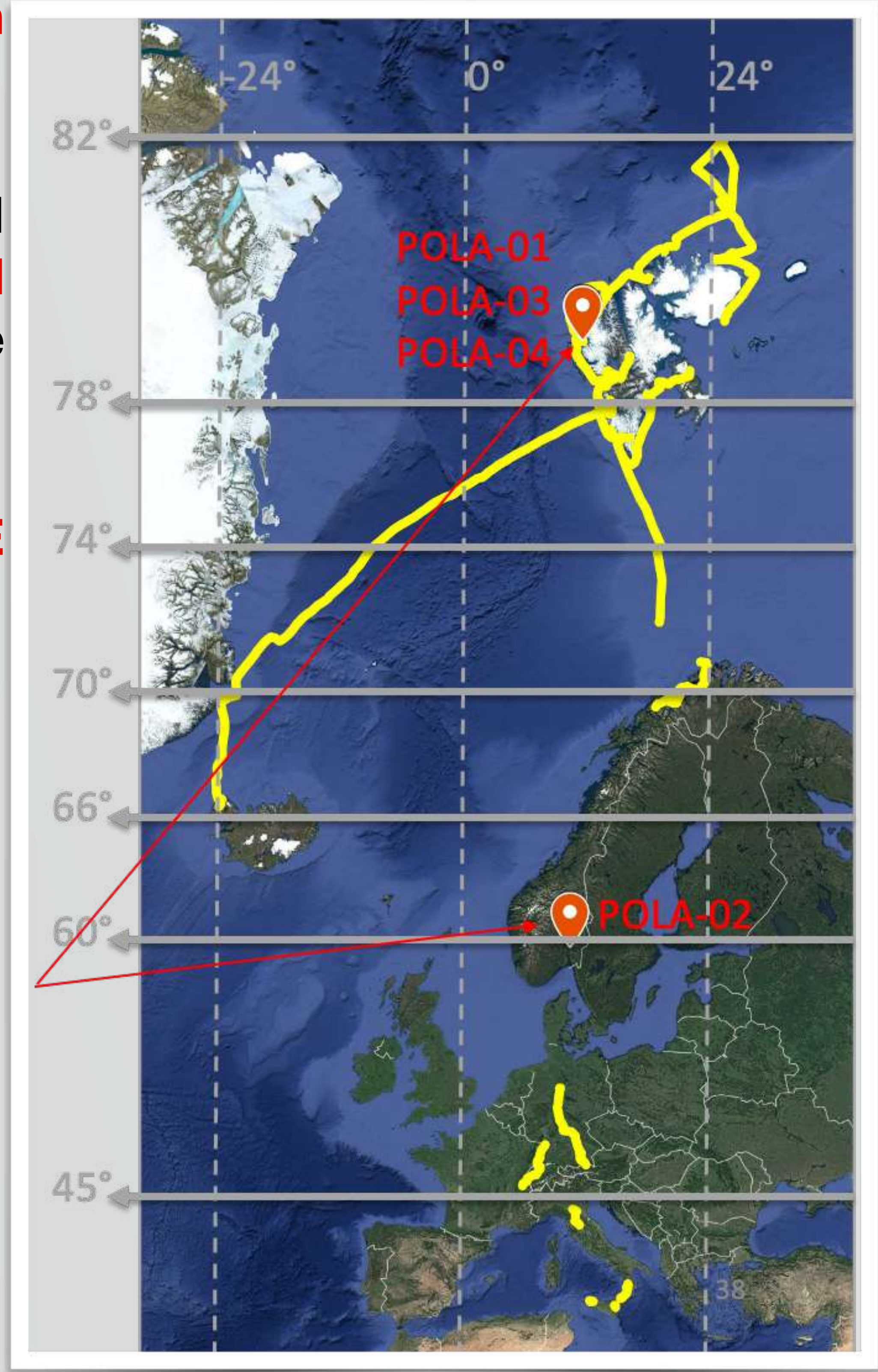
PolarquEEEst

- The data collected during the **Polar Quest 2018 mission** have been used to study the cosmic rays flux vs latitude

- Thanks to the collaboration with CNR in 2019 we installed three detectors in the **CNR arctic base at Ny.Alesund (Svalbard)** to study extended air showers at the extreme latitudes

- Data from the PolarquEEEst mission are used in **EEE masterclasses**





(Non-comprehensive) publication list

❑ Construction and performance

- Performance of a six gap MRPC built for large area coverage, NIM A593(2008)263
- Extreme Energy Events project: construction of the detectors and installation in italian high schools, NIM A588(2008)211
- The EEE Project: cosmic rays, multigap resistive plate chambers and high school students, JINST (2012) 7 P11011
- Recent results and performance of the multi-gap resistive plate chambers network for the EEE Project, JINST, 11 (2016) C11005
- The Extreme Energy Events experiment: an overview of the telescopes performance, JINST (2018) 13 P08026
- The cosmic muon and detector simulation framework of the extreme energy events (EEE) experiment, Eur. Phys. J. C (2021) 81:464

❑ Physics results

- Observation of the February 2011 Forbush decrease by the EEE telescopes, Eur. Phys. J. Plus (2011) 126, 61
- Time Correlation measurements from extensive air showers detected by the EEE telescopes, Eur. Phys. J. Plus (2013) 128, 148
- The EEE experiment project: status and first physics results, Eur. Phys. J. Plus (2013) 128, 62
- Looking at the sub-TeV sky with cosmic muons detected in the EEE MRPC telescopes, Eur. Phys. J. Plus 130 (2015) 187
- Results from the observation of Forbush decreases by the Extreme Energy Events experiment, PoS (ICRC 2015) 097
- A study of upward going particles with the Extreme Energy Events telescopes, NIM A 816 (2016) 142–148
- The EEE MRPC telescopes as traking tools to monitor building stability, JInst 14 (2019) C05022
- New high precision measurements of the cosmic charged particle rate beyond the Arctic Circle with the PolarquEEEst experiment, EPJ C (2020) 80:665

❑ Upgrade

- The new trigger/GPS module for the EEE project, NIM A936 (2019) 376
- Test of new eco-gas mixtures for the multigap resistive plate chambers of the EEE project, NIM A936(2019)493
- New eco-gas mixtures for the Extreme Energy Events MRPCs: results and plans, JInst 14 (2019) C08008
- First results from the upgrade of the Extreme Energy Events experiment, JInst 14 (2019) C08005

A few papers signed by students too

❑ Outreach

- EEE Project - Students from all parts of peninsula collaborate to study cosmic rays, PoS Volume 314, (EPS-HEP2017) 823
- How does cosmic ray flux vary with altitude? Let's ask it to EEE project students, Giornale di Fisica, VOL. LIX, N. 3, Lug – Sett 2018
- Gli studenti del progetto EEE sulle orme di Eratostene per la misura del raggio della Terra, Giornale di Fisica 60 (2019) 107

see more @ https://eee.centrofermi.it/research/pubblicazioni

Conclusions

- MRPC technology used to build a muon telescope array on an overall area of $\approx 0.5 \times 10^6 km^2$
- **Very good performance** in terms of **efficiency** and time and spatial **resolution**
- Dual role of the project: *research and education*
- *Young students actively involved in the project (a few of them in our groups now!)*
- Possibility to study different (..and possible unexpected) Physics cases
- Spread laboratory available for new ideas too..

Challenge is successful…
and to be continued…with new gas mixtures

Thank you for the attention!