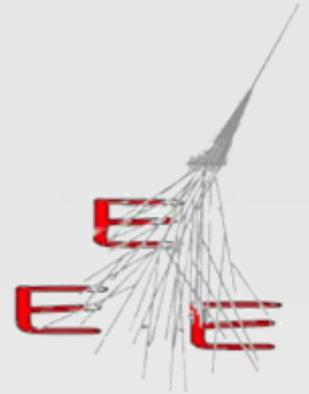


Operation and performance of the EEE network array for the detection of cosmic rays



P. La Rocca* for the EEE Collaboration

*Centro Fermi and University of Catania

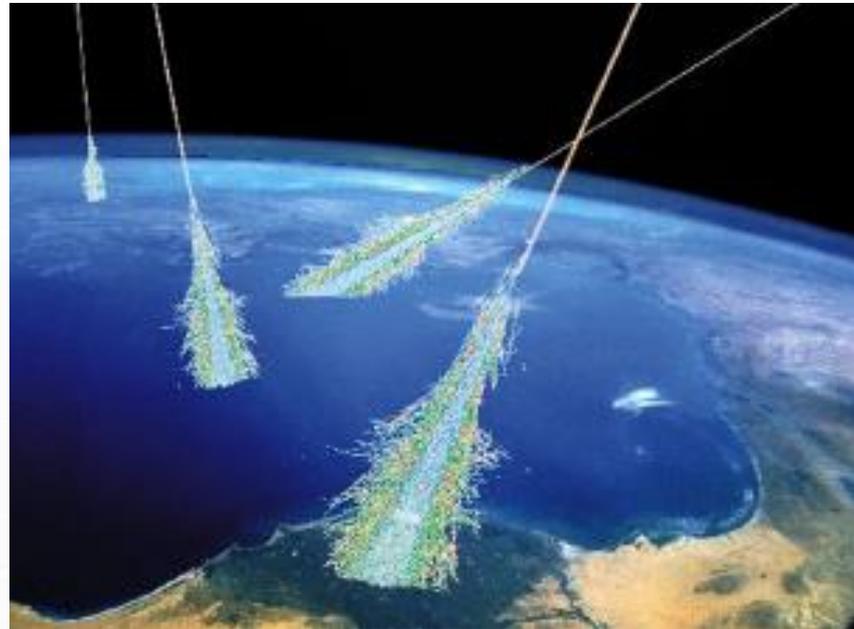
Overview

- The EEE experiment
- The EEE telescope
- Telescope performance
- Data taking
- Some results of data analyses

The Project

- The **EEE** (**E**xtrême **E**nergy **E**vents) Project was conceived in 2004
- Collaboration of Centro Fermi, INFN, CERN, MIUR

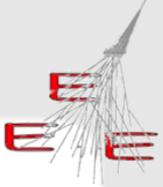
It aims at the detection of cosmic ray muons by means of a sparse array of telescopes, distributed over all the Italian territory





Requirements and solutions

- Need for an extended array (over a large area)
- Large number of telescopes (in the order of 100)
- Reasonable cost
- Long term operation required
- Efficiency close to 100 %
- Reconstruction of muon orientation -> at least 3 planes (position sensitive) with good granularity
- Good time resolution (TOF measurements)



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- Good time resolution (TOF measurements)

CHOICE:
Telescope based on Multigap
Resistive Plate Chambers



Scientific goals

1. Local measurements, with a single telescope, may give information on:
 - Atmospheric effects (press, temp)
 - Daily and long term variations (time series analysis)
 - Correlation to solar events
 - Search for non-random events
 - Anisotropy
 - Upgoing tracks
 - Multiple tracks events

Scientific goals

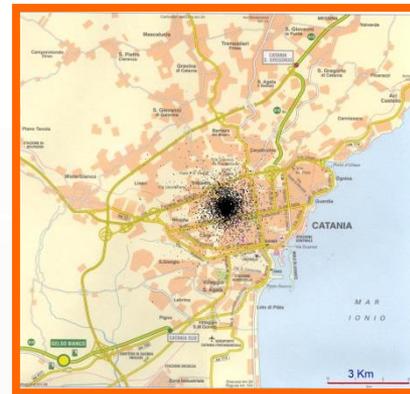
2. Detection of extensive air showers by telescopes located in the same metropolitan area



10^{13} eV



10^{14} eV



10^{15} eV

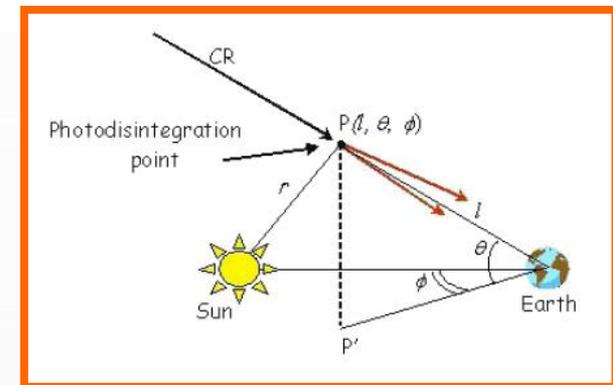


10^{16} eV

Scientific goals

3. Search for long-baseline correlations due to:

- existence of two primary cosmics, originating from the same source, and producing independent showers in the Earth's atmosphere
- single primary interacting with the interstellar medium and/or the radiation field, thus producing two intermediate products (GZ-effect)



Educational aspects

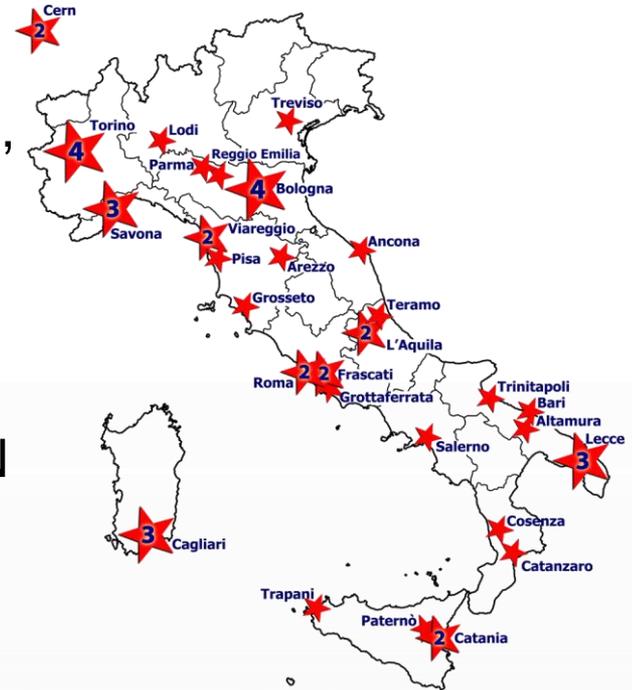
- The EEE telescopes are installed in Italian High Schools
- High school students and teachers have built their own telescope at CERN and take care of the data taking
- Introducing high-school students and teachers to high energy physics
- >100 teachers, ~500 students directly involved in the last 3 years





status of the experiment

- Pilot phase with telescopes in 7 High Schools in 2004 (Lecce, Bologna, Cagliari, Catania, Frascati, L'Aquila, Torino)
- At present **52 EEE directional telescopes** mostly distributed in clusters in the whole Italian territory (47 at schools + 2 at CERN + 3 in INFN Units)

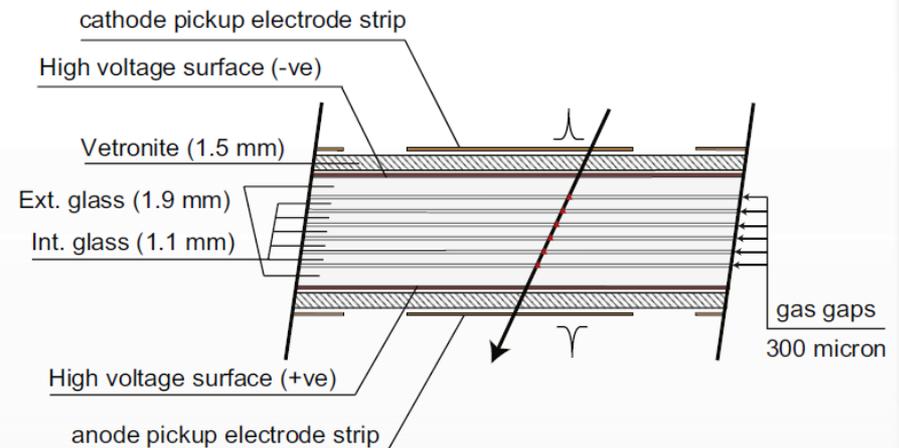




Multi-gap Resistive Plate Chambers

It is a larger ($\sim 2 \text{ m}^2$) and simpler version of the Multi gap RPC developed for the ALICE TOF.

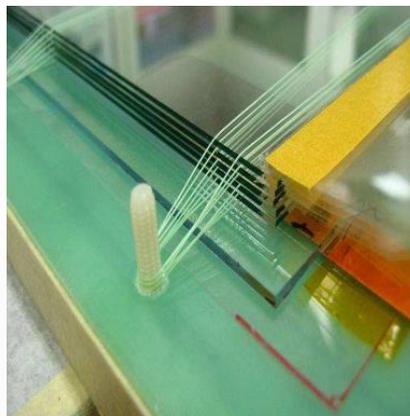
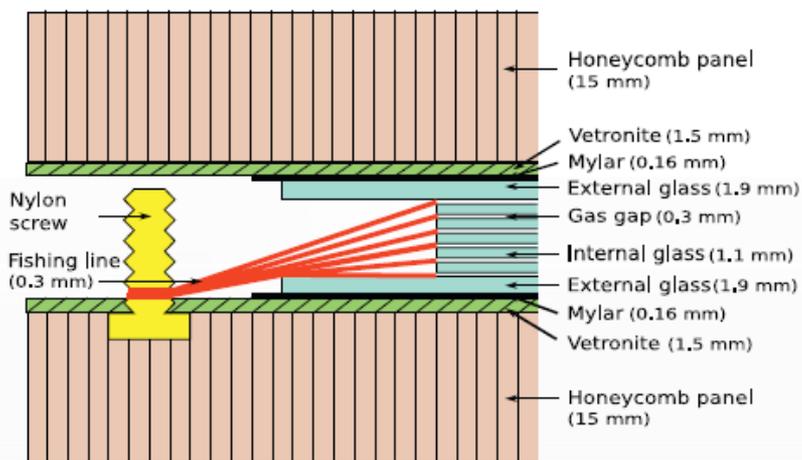
- 6 gas gaps: 2 glass plates with their external surfaces painted with resistive paint; 5 floating glass plates (spaced by $300 \mu\text{m}$)
- $\text{C}_2\text{H}_2\text{F}_4$ (98%) and SF_6 (2%) continuously fluxed (3l/h)





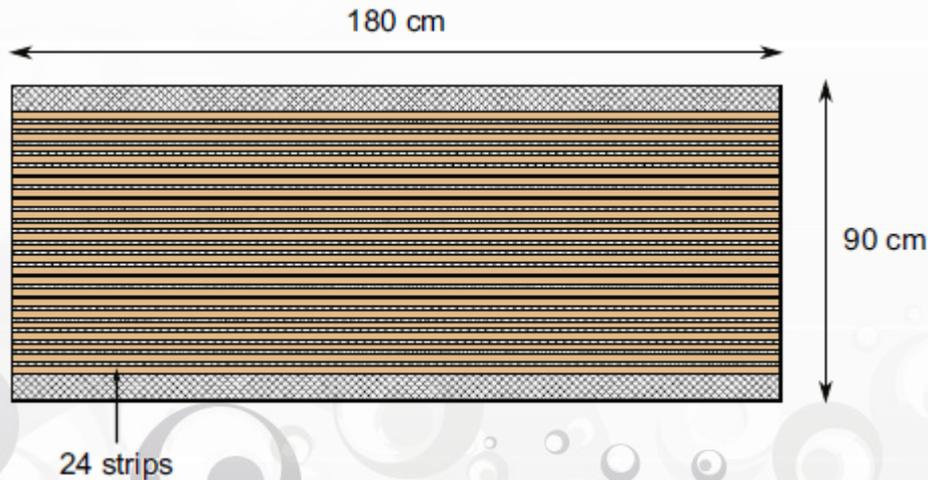
Multi-gap Resistive Plate Chambers

Fishing line is used to create uniform small gaps (300 microns) between glasses



Multi-gap Resistive Plate Chambers

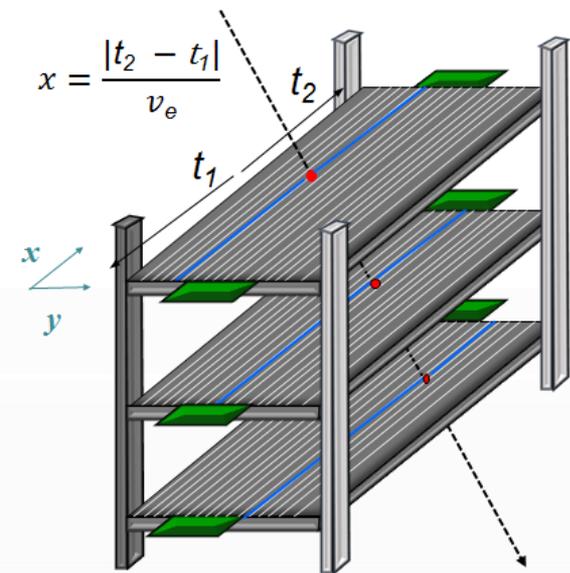
- 24 readout copper strips mounted on both sides of the stack of glass plates (i.e. cathode and anode read-out strips) → a differential signal is obtained by reading out both anode and cathode
- Strip pitch of 3.2 cm
- HV up to 20 kV (avalanche mode) supplied by 2 DC/DC converters



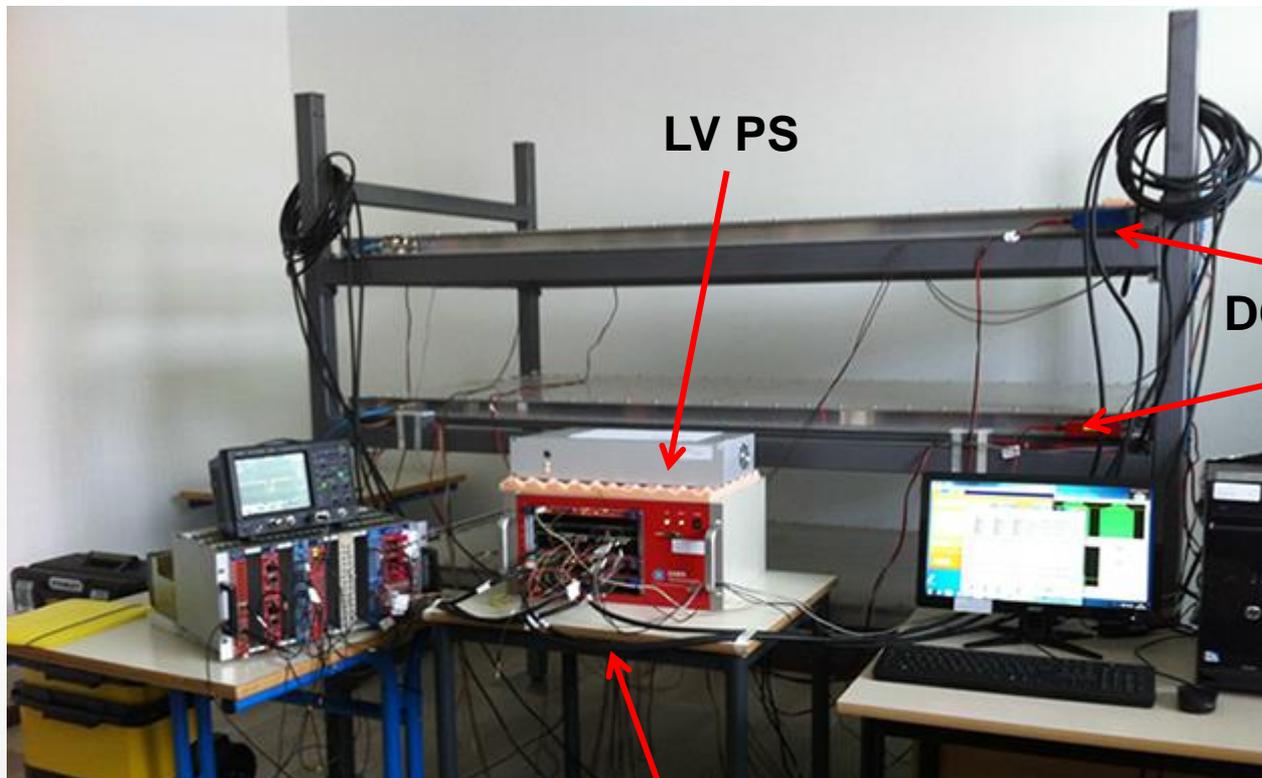


The MRPC telescope

- Each telescope is made of 3 MRPC modules, approx. 160 cm x 80 cm
- 6 FE cards with 24 channels each for readout and trigger
- DC/DC converters for HV (± 10 kV) to chambers
- GPS time-stamp of the collected events to synchronize stations at different locations
- VME-based data acquisition
 - 1 Multi-trigger card (six-fold coincidence of the 6 FEA cards)
 - 2 Multi-hit TDCs (128 + 64 channels)
- Weather Station



The MRPC telescope



LV PS

DC/DC converter

DAQ/Trigger system

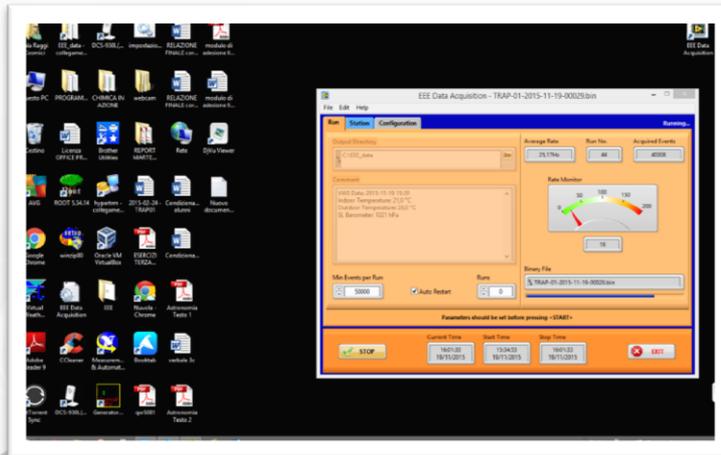


Monitor and control



Stations are sometimes located several km apart from the closest INFN section: remote control is essential

- HV-LV system
- DAQ & online analysis
- Gas system
- Data transfer

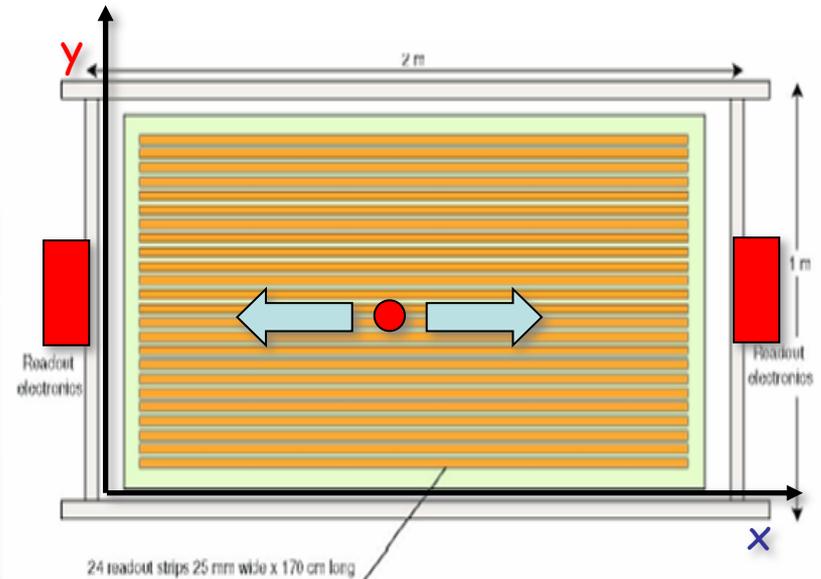




The MRPC performance

Each module provides a two-dimensional position information with efficiency close to 100% and a good spatial resolution.

- x coordinate: difference of signal arrival times at the strip ends measured by TDCs
- y coordinate: fired strip

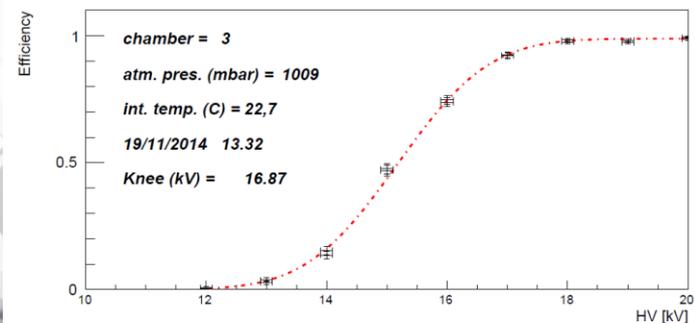
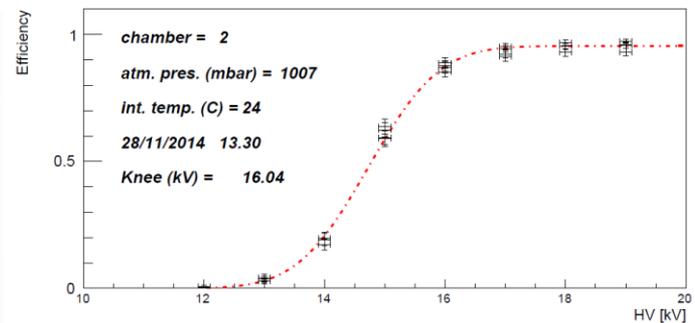
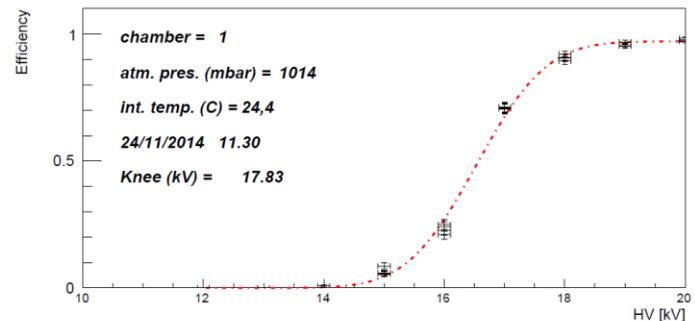
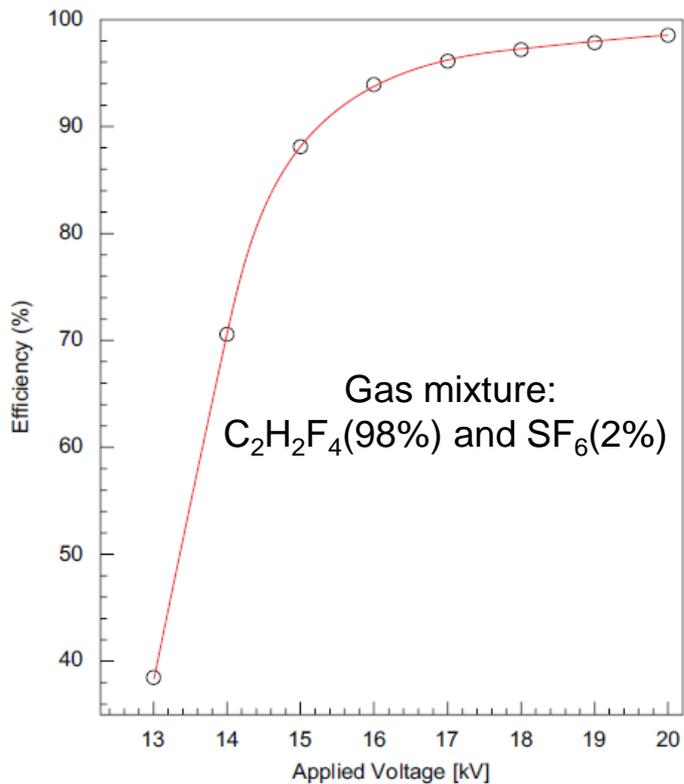




Efficiency

Efficiency measured @ school with cosmics

Test beam results @CERN
Proton Synchrotron facility

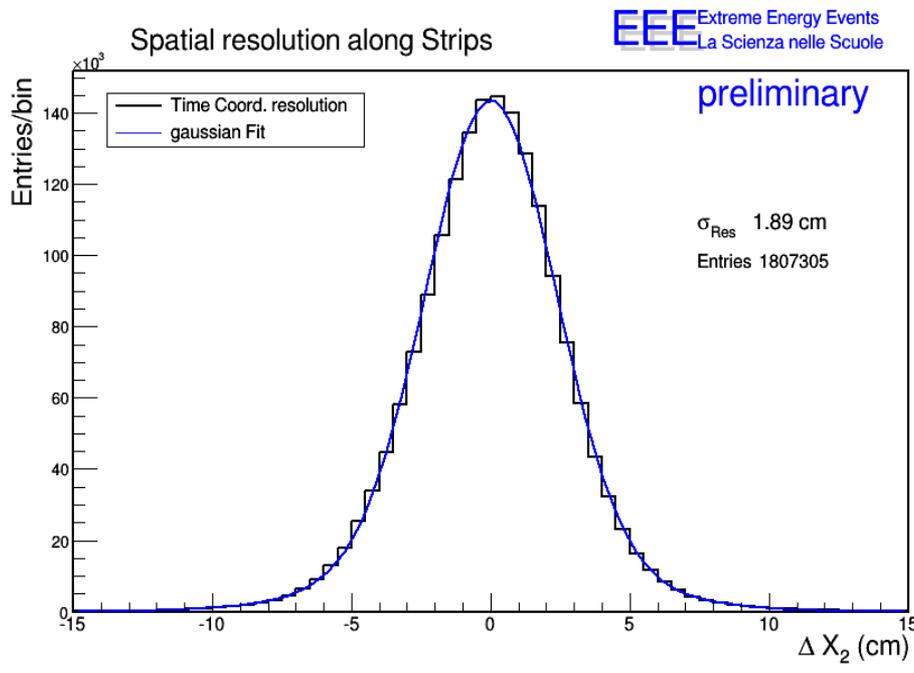


Spatial Resolution along X dir

Spatial resolution measured @ school with cosmics

$$\Delta X = \frac{X_{\text{BOT}} + X_{\text{TOP}}}{2} - X_{\text{MID}}$$

$$\sigma_X = \sqrt{\frac{2}{3}} \sigma = \mathbf{1.9 \text{ cm}}$$



Factors that can affect the spatial resolution along X dir:

- Chambers alignment
- Multiple scattering
- Strip calibration
- Propagation of the signal along the strips
- TDC resolution

Spatial Resolution along γ dir

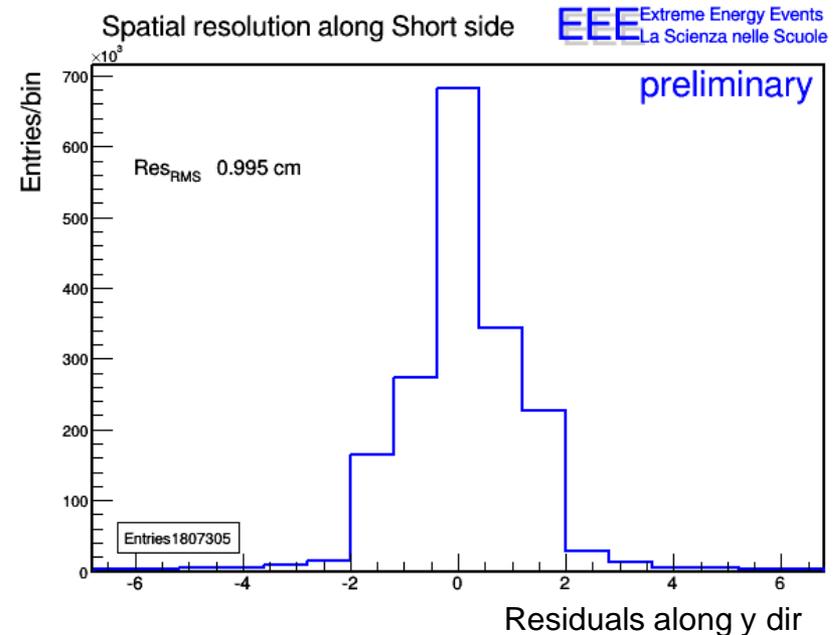
Spatial resolution measured @ school with cosmics

$$\Delta Y = \frac{Y_{\text{BOT}} + Y_{\text{TOP}}}{2} - Y_{\text{MID}}$$

$$\sigma_Y = \sqrt{\frac{2}{3}} \sigma = \mathbf{1.0 \text{ cm}}$$

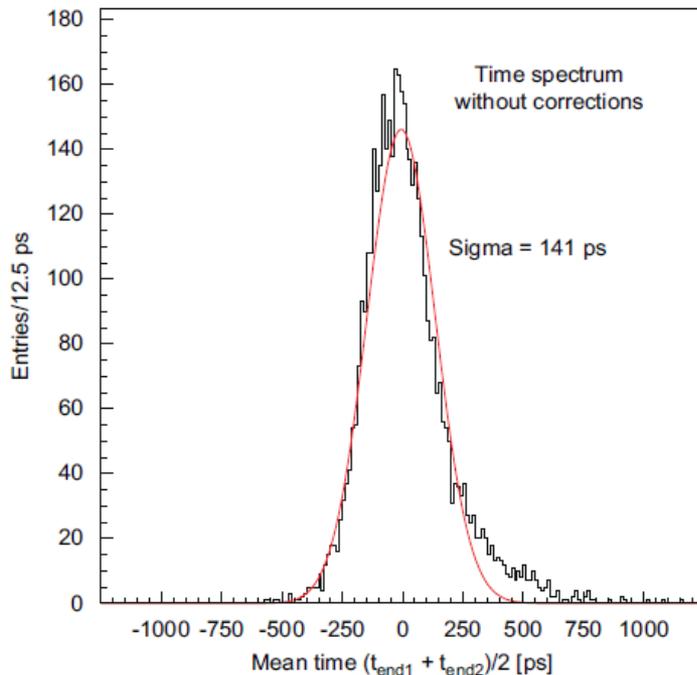
Expected spatial resolution

$$\sim 3.2 \text{ cm} / \sqrt{12} = \mathbf{0.9 \text{ cm}}$$



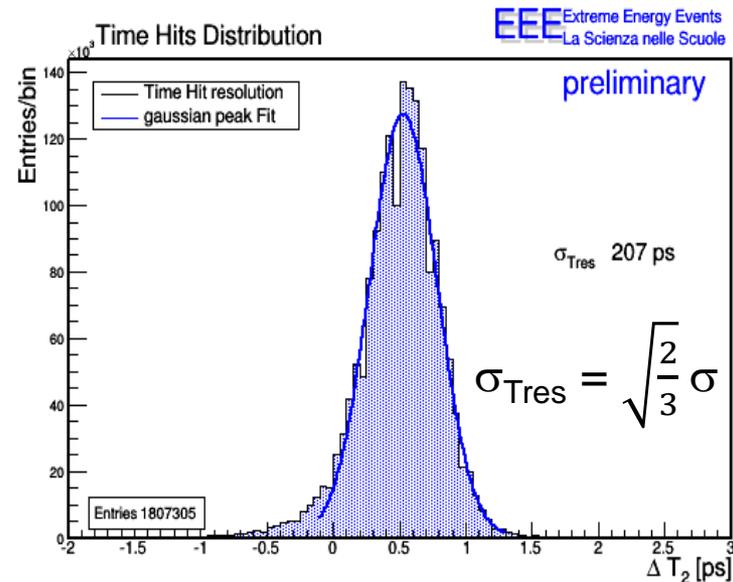
Time Resolution

Test beam results @CERN
Proton Synchrotron facility



TDCs in 25 ps/bin mode

Time resolution measured @
school with cosmics



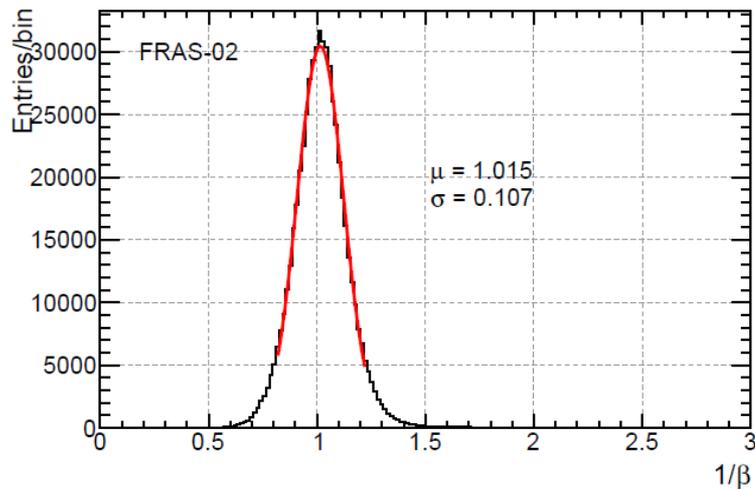
$$\Delta T = \frac{T_{BOT} + T_{TOP}}{2} - T_{MID}$$

TDCs in 100 ps/bin mode



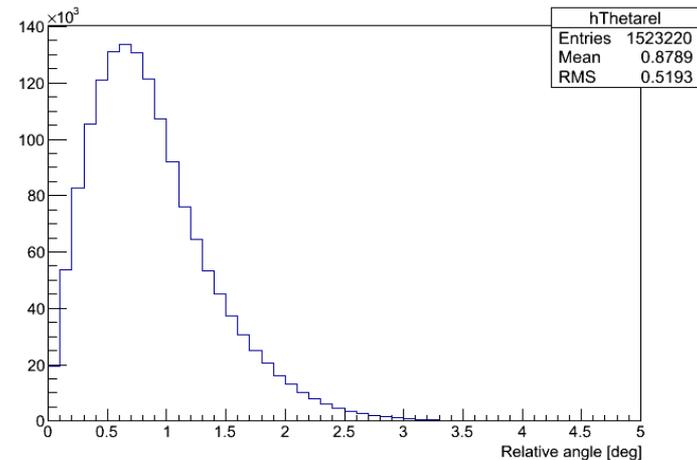
Angular and velocity resolution

$$\beta = \frac{L_{track}}{TOF c}$$



Significant component of relatively slow muons ($\beta \sim 0.95$).
Resolution on $1/\beta$ measurement $\sim 10\%$

The direction of cosmic particles passing through the telescope is reconstructed with a precision that depends on the MRPC spatial resolution.



Geometrical simulation: evaluation of the relative angle between a simulated track and the track reconstructed with the telescope.

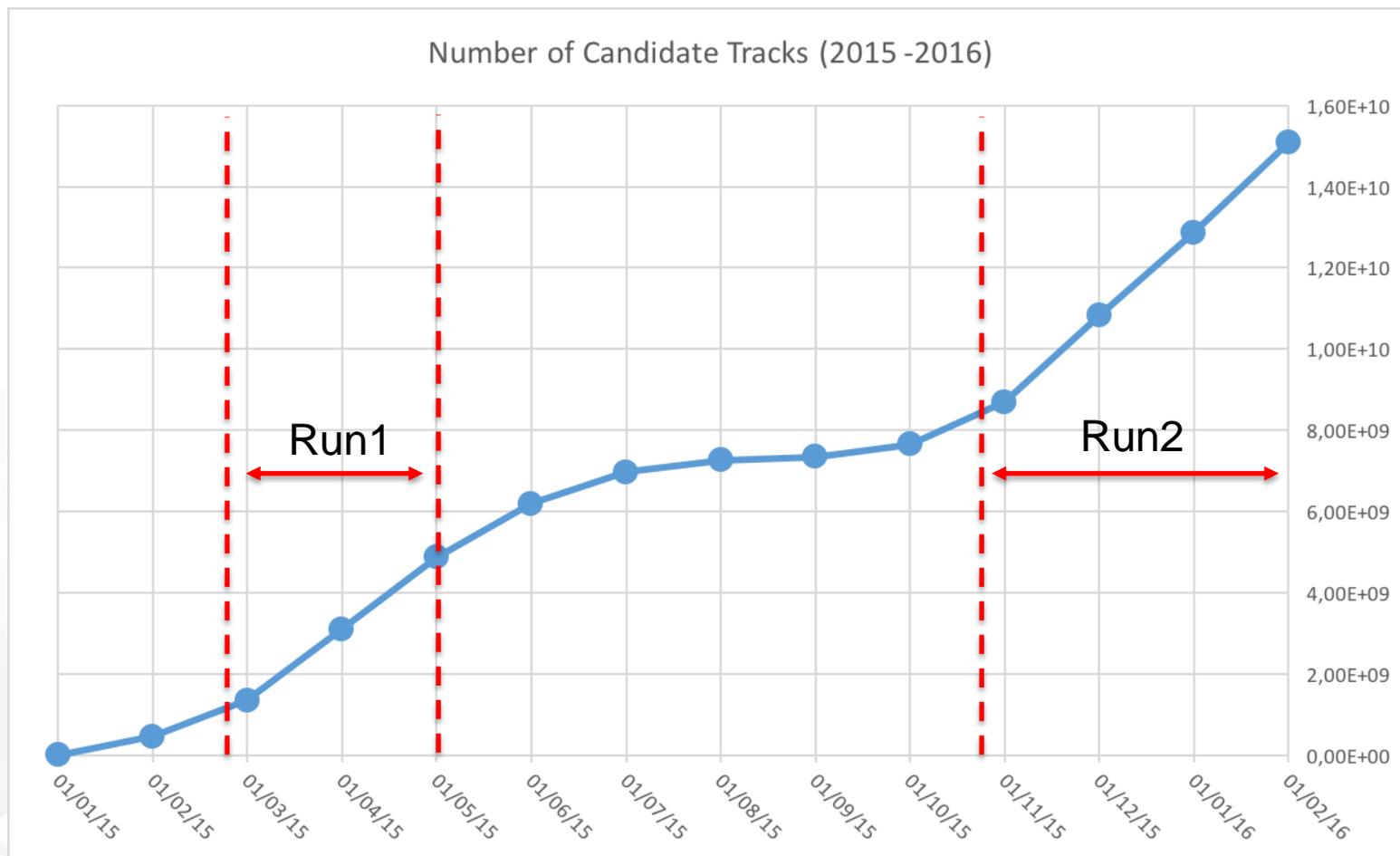


Data Taking

- **Pilot-run:** first simultaneous acquisition of half (23) of the EEE telescopes.
 - ✓ Nearly 1 billion events i.e. muon tracks collected in the period 27 October-14 November 2014
- **Run-1:** 35 EEE telescopes took part in the data taking.
 - ✓ More than 5 billion events i.e. muon tracks collected in about three months (2 February-30 April 2015)
- **Run-2:** ~40 EEE telescopes in acquisition from the end of October 2015 (till mid May 2016). The goal is to achieve 15 billion tracks in 7 months.
 - ✓ Nearly 7 billion events i.e. muon tracks collected in about three months



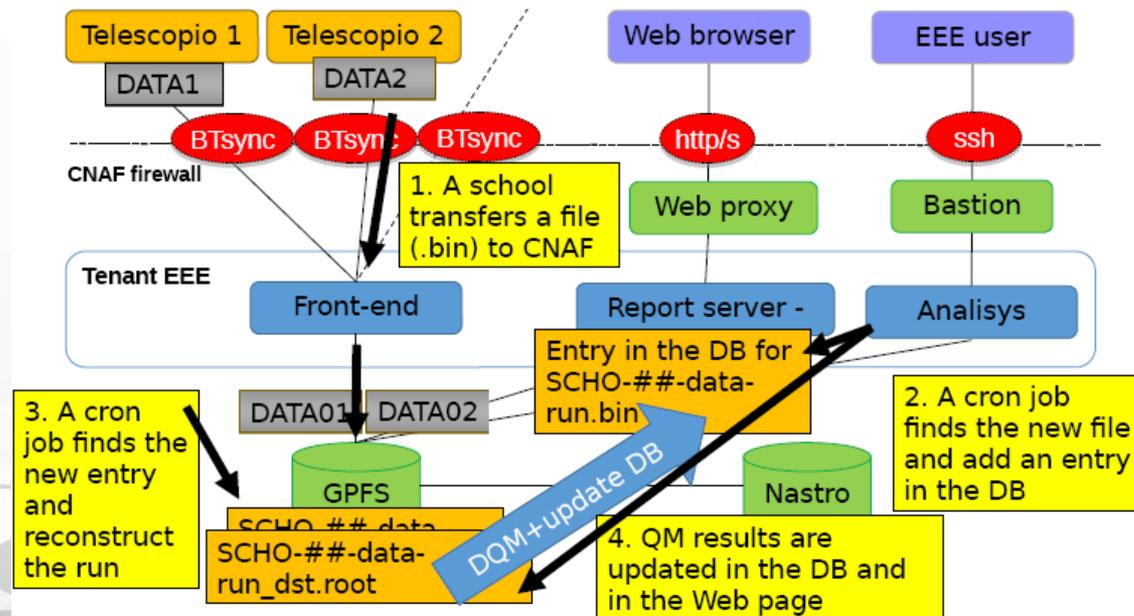
Data Taking



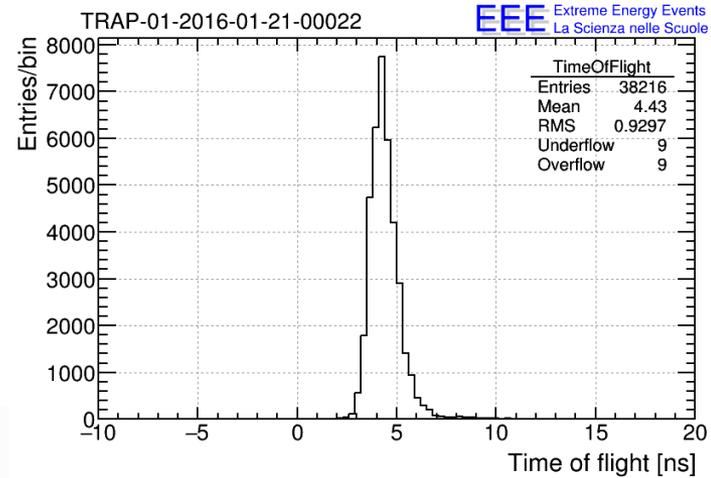
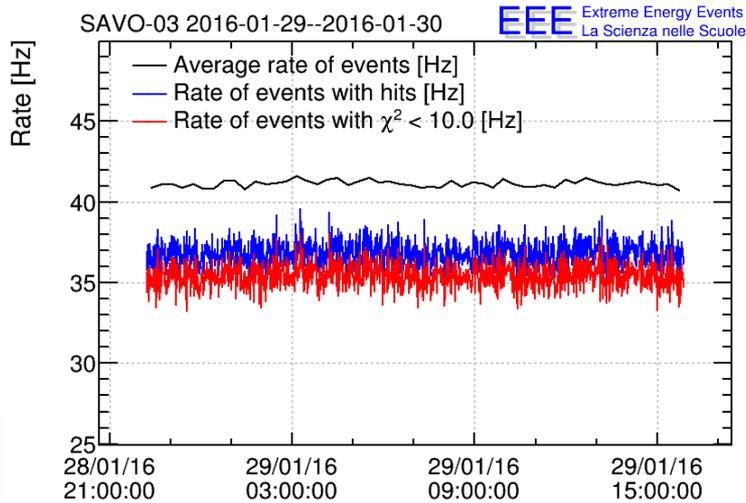


Data transfer and analysis @ CNAF

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



Data quality monitor

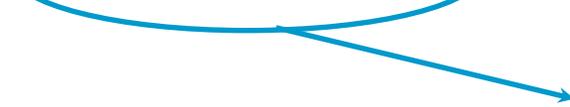


PLOT	ALARM	STATUS	OUTPUT	LIMITS
RateHitEvents	y_values	Clean	8.44 +- 0.37	[4 / 8 - 80 / 100]
DeltaTime	exp_fit_lambda	Clean	9.523 +- 0.052	[4 / 8 - 80 / 100]
HitMultTop	x_average	Clean	1.2163 +- 0.0026	[0.500 / 0.750 - 2 / 3]
HitMultMid	x_average	Clean	1.1373 +- 0.0028	[0.500 / 0.750 - 2 / 3]
HitMultBot	x_average	Clean	1.0687 +- 0.0017	[0.500 / 0.750 - 2 / 3]
HitMultTotal	x_average	Clean	3.4215 +- 0.0053	[1.50 / 2.50 - 6 / 9]
ClusterMultTop	x_average	Clean	1.2163 +- 0.0026	[0.500 / 0.750 - 2 / 3]
ClusterMultMid	x_average	Clean	1.1373 +- 0.0028	[0.500 / 0.750 - 2 / 3]
ClusterMultBot	x_average	Clean	1.0687 +- 0.0017	[0.500 / 0.750 - 2 / 3]
ClusterMultTotal	x_average	Clean	3.4223 +- 0.0053	[1.50 / 2.50 - 6 / 9]
ChiSquare	x_average	Error	18.452 +- 0.062	[1 / 2 - 6 / 10]
RateTrackEvents	y_values	Error	2.28 +- 0.19	[4 / 8 - 80 / 100]
FractionTrackEvents	y_values	Error	0.235 +- 0.017	[0.400 / 0.800 - 1 / 1]
Phi				
Theta				
TimeOfFlight				
TrackLength				

Some Physics results

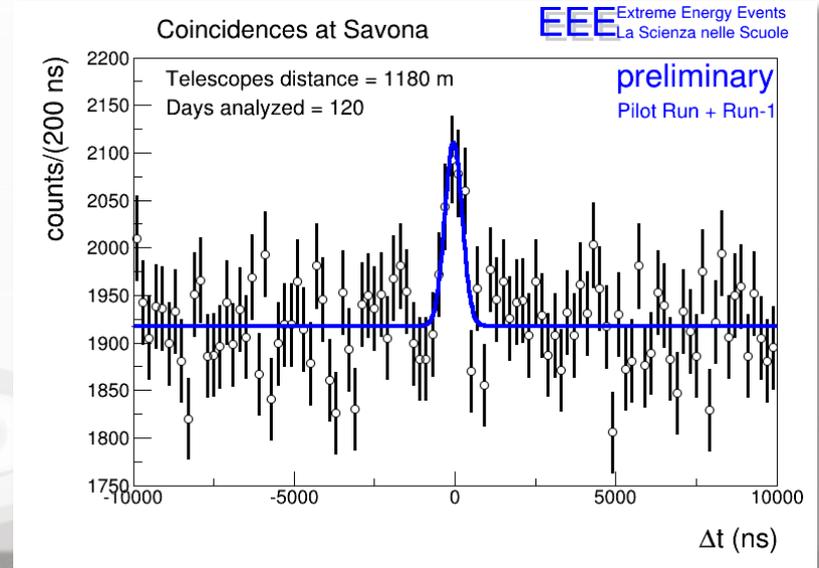
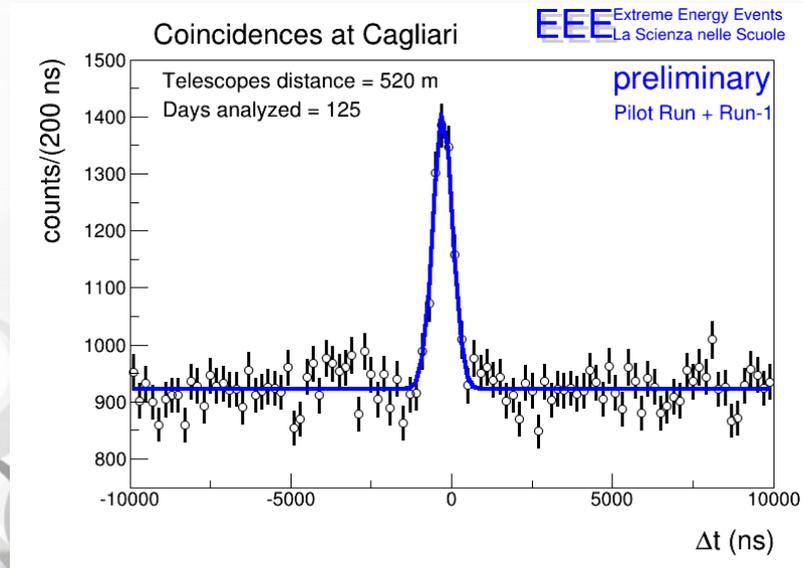
Search for coincidences

- Relative distance between the telescopes of the EEE array goes from few meters to more than 1000 km
- Time coincidence and angular parallelism of the tracks is required



Angular resolution

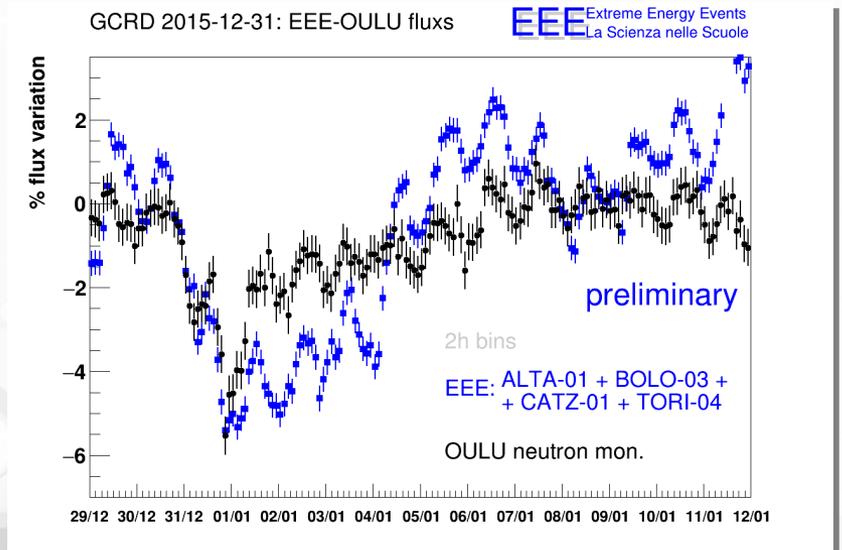
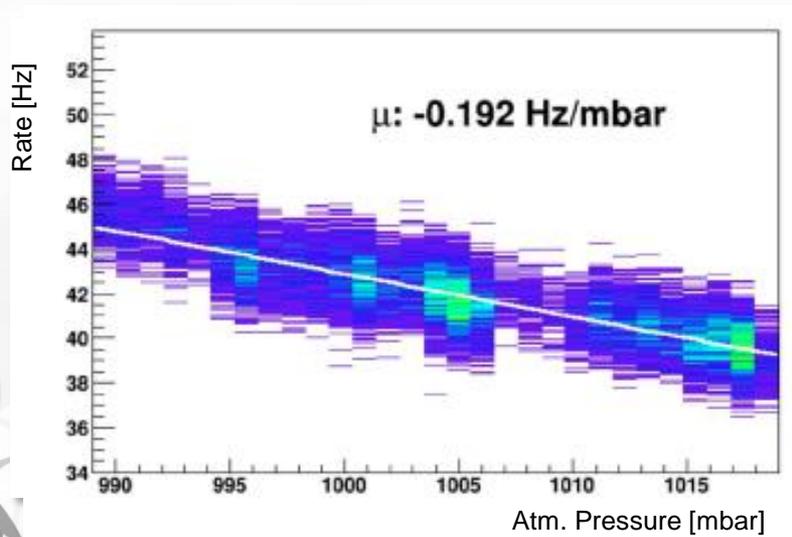
Timing precision
(GPS resolution ~ 50 ns)



Some Physics results

Study of local cosmic flux variation

- With an average rate of 30 Hz from each station, the EEE detector can detect flux variation of few % in 5 minutes
- Sensitivity to:
 - day/night variation
 - pressure and temperature variation
 - solar flare perturbations

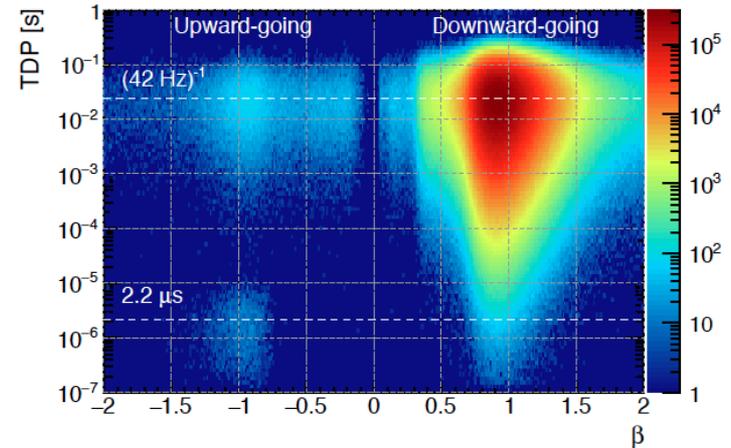
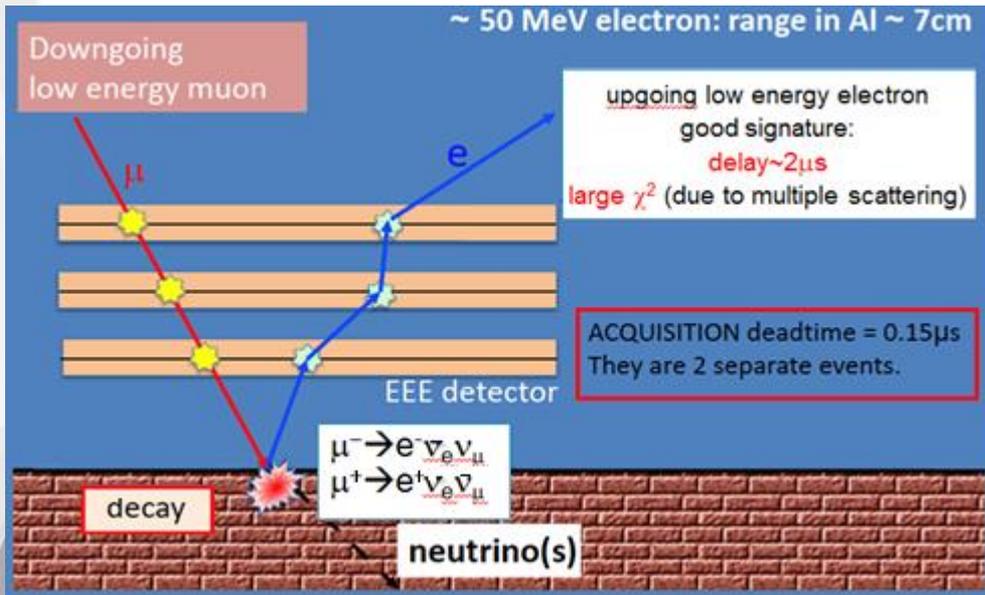




Some Physics results

Up-going tracks

Thanks to the tracking and timing capability of the MRPC telescope it is possible to discriminate between downgoing and upgoing tracks, and between high and low β particles.

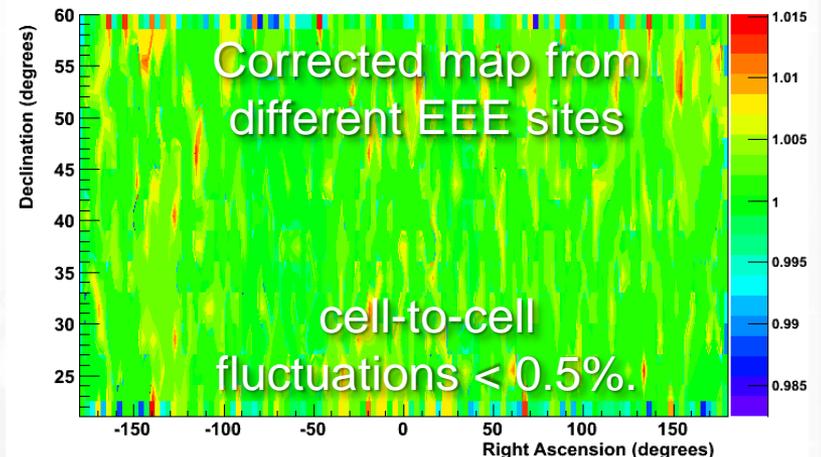
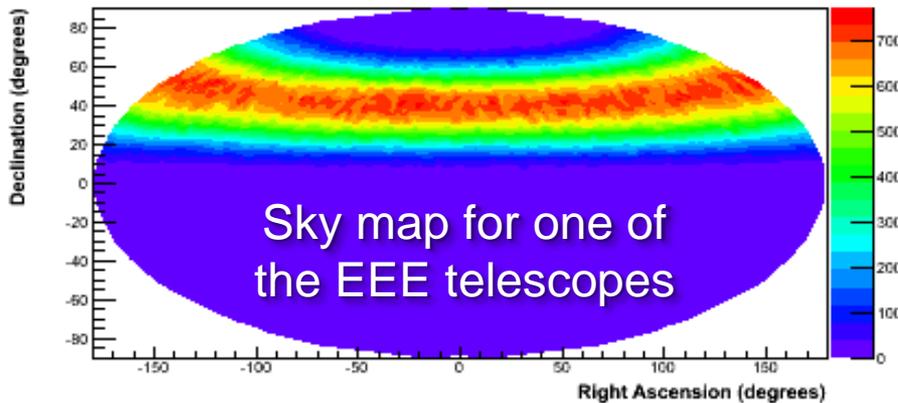


“A study on upward going particles with the Extreme Energy Events telescopes”
accepted on NIMA (in press)

Some Physics results

Local anisotropies

- Small but measurable anisotropies in the arrival distribution of cosmics may be evidenced (due to large scale as well as local magnetic field features)
- The array of EEE telescopes, with their tracking capability, allows to look for small anisotropies in a wide portion of the equatorial sky



" Looking at the sub-TeV sky by cosmic muons detected in the EEE MRPC telescopes"

Eur. Phys. J. Plus **130** (2015) 187



Conclusions

- Large number of detection stations already installed and acquiring data almost continuously
- Very good performance of the EEE array
- Several analysis tools developed and available to the users
- Many physics results already published
- New analyses expected with Run 2 data (large statistics)
- New schools (and new telescopes) will join the Project
- Strong involvement of high school students and teachers (powerful impact on education)

EEE Website

<http://eee.centrofermi.it/>



**CENTRO
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Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

Progetto Extreme Energy Events (EEE) La Scienza nelle Scuole



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 [Area Riservata Scuole](#)



Extreme Energy Events (EEE) - La Scienza nelle Scuole

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Il Progetto EEE - La Scienza nelle Scuole consiste in una speciale attività di ricerca, in collaborazione con il CERN, l'INFN e il MIUR, sull'origine dei raggi cosmici, condotta con il contributo determinante di studenti e docenti degli Istituti Scolastici Superiori.

In ciascuna delle scuole aderenti al Progetto viene costruito un "telescopio" fatto con i più moderni e avanzati rivelatori di particelle (Multigap Resistive Plate Chambers, MRPC), da mettere in coincidenza tramite strumentazione GPS con i telescopi di altre scuole allo scopo di rivelare i muoni cosmici e gli sciami estesi, grandi anche quanto intere cittadine o più, prodotti dai raggi cosmici primari di più alta energia.

Ai ragazzi viene dato, inoltre, l'importantissimo compito della costruzione degli stessi rivelatori a partire da elementi di base, affinché si rendano conto di come si possa passare da materiali poveri a strumenti di altissima precisione.

EEE News

- Giornate di Studio EEE - Istituti Scolastici delle Regioni del Nord Italia Bologna, 6-7 Novembre 2015
- Giornata di studio del Progetto EEE



- Riunione del 5 marzo 2015 (Biblioteca del Ministero dell'Interno)



- Conferenza Nazionale del Progetto EEE Extreme Energy Events - La Scienza nelle Scuole (15-16/12/2014)
[Leggi tutto...](#)



List of 2015 papers/talks

Frontier detectors for Frontier Physics (13th Pisa Meeting on advance detectors)

- ✓ M. P. Panetta: “The EEE Project: an extended network of muon telescopes for the study of cosmic rays.”
- ✓ F. Noferini: “The computing and data infrastructure to interconnect EEE stations.”
(with proceedings published on Nucl. Instr. & Meth. (2015), doi:10.1016/j.nima.2015.10.069)

International School of Subnuclear Physics – Erice 2015

- ✓ L. Cifarelli: “The EEE Project of the Enrico Fermi Centre.”

34th International Cosmics Rays Conference ICRC 2015 (The Hague)

- ✓ I. Gnesi: “Results from the observations of Forbush decreases by the Extreme Energy Events experiment.”
- ✓ F. Pilo: “First results from Run-1 of the Extreme Energy Experiment.”
(with proceedings published on Proceedings of Science)

Cosmic Ray Internation Seminars 2015

- ✓ De Gruttola: “First results from coordinated data taking by the Extreme Energy Events experiment.”
(with proceedings published on Nuclear and Particle Physics Proceedings)

Topics in Astroparticle and Underground Physics 2015

- ✓ L. Perasso: “EEE – Extreme Energy Events: an astroparticle experiment in italian high schools.”

Congresso SIF 2015

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

And, in addition two papers ready and more in preparation

- ✓ EEE collaboration: “Looking at the sub-TeV sky by cosmic muons detected in the EEE MRPC telescopes.”,
Eur. Phys. J. Plus **130** (2015) 187
- ✓ EEE collaboration: “A study on upward going particles with the Extreme Energy Events telescopes.”, in
press on NIMA

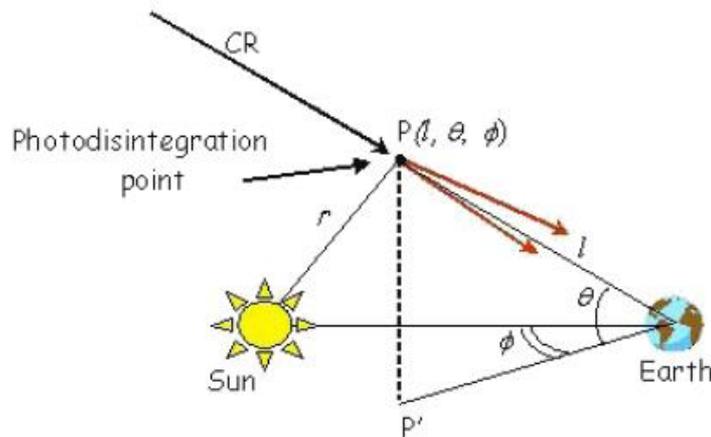


Back-up slides

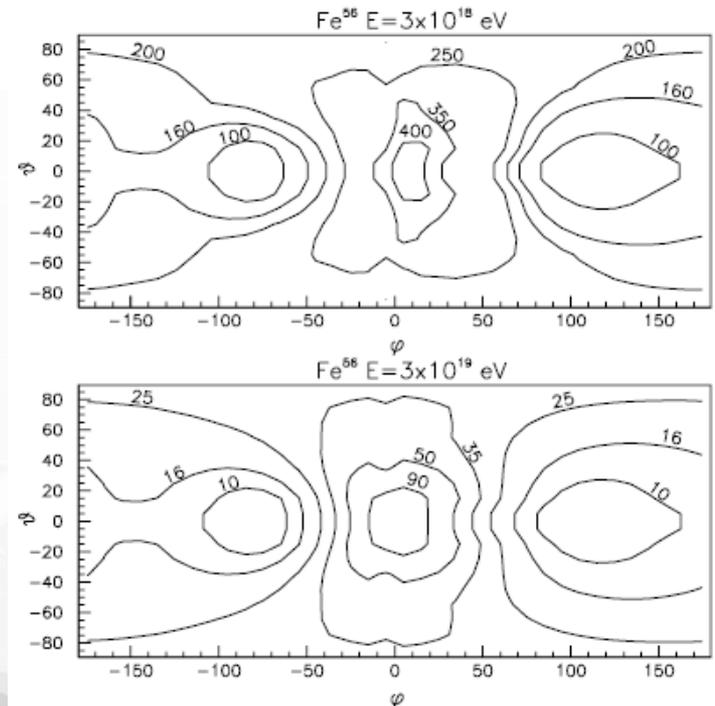
116/111

GZ-effect

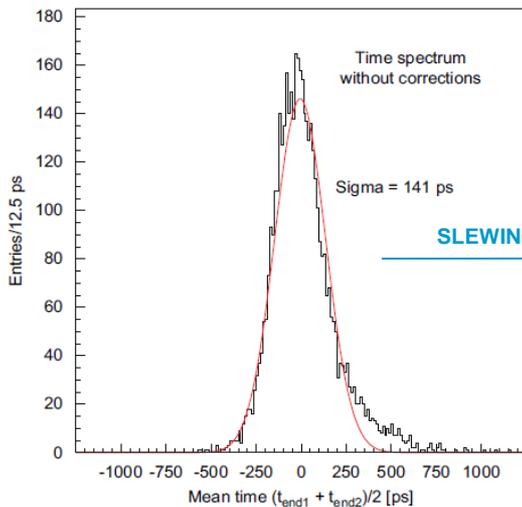
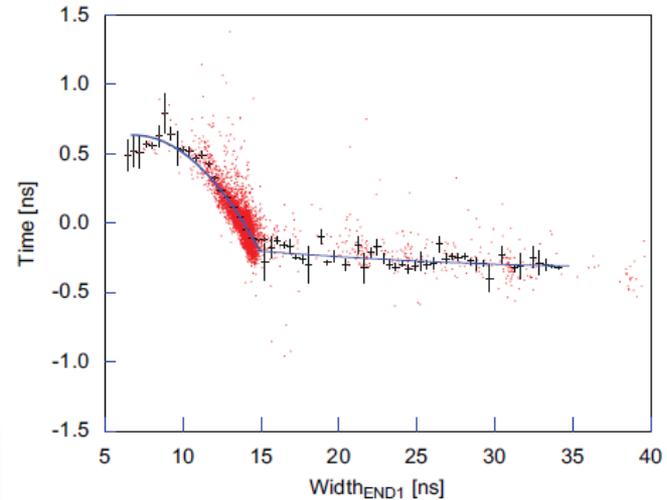
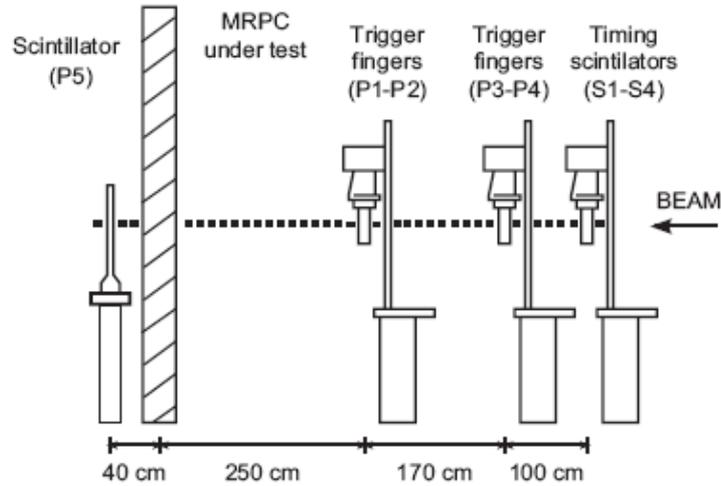
- ✓ The GZ-effect (photodisintegration of heavy nuclei in the solar field), early discussed by Gerasimova and Zatsepin (1960), and revisited by other authors, is one of the possible mechanisms responsible for long range correlations of individual showers
- ✓ Knowledge of solar flux, photodisintegration cross-sections, and interplanetary magnetic field required
- ✓ Specific calculations carried out in our case for several primary nuclei and energies



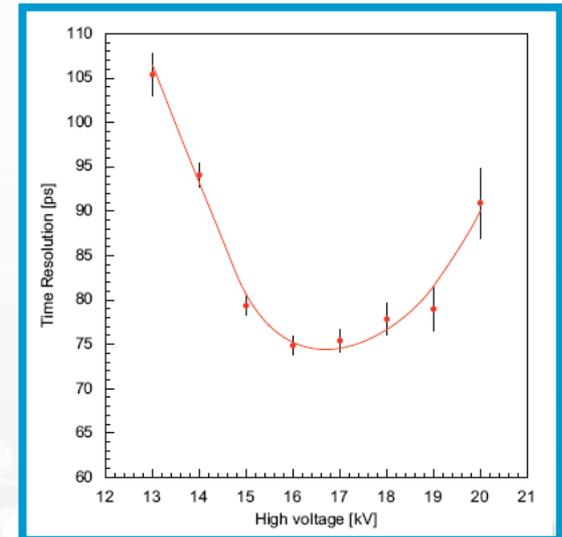
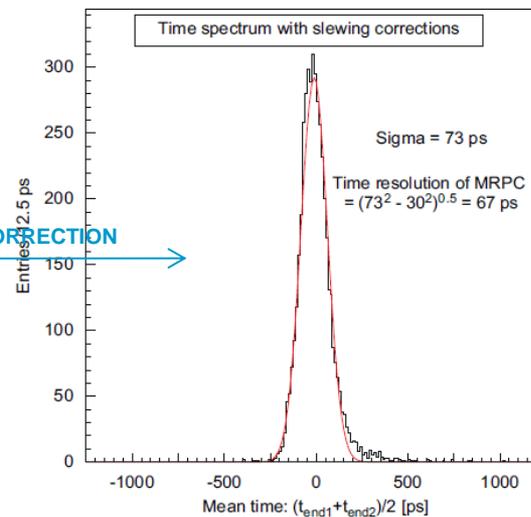
Average expected distance between the 2 fragments in the GZ phenomenology



Test beam @ CERN

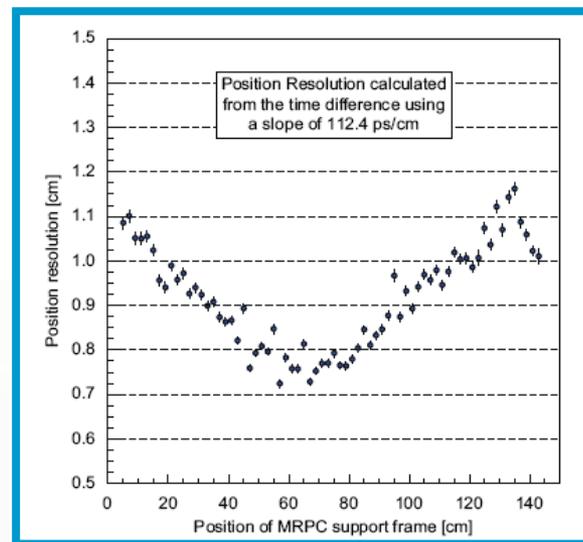
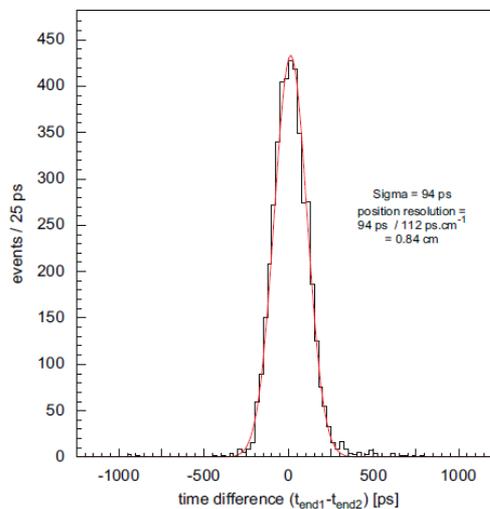
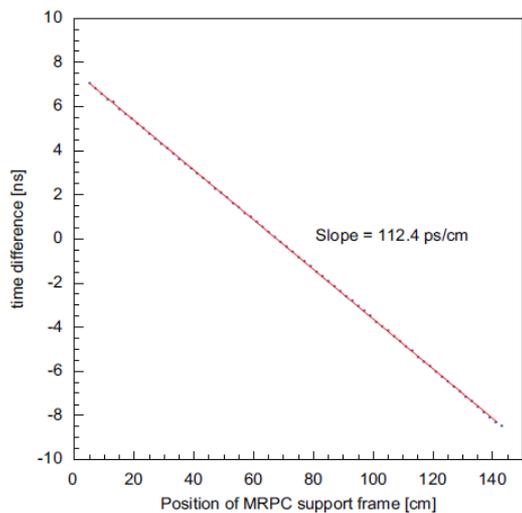


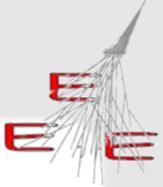
SLEWING CORRECTION





Test beam @ CERN





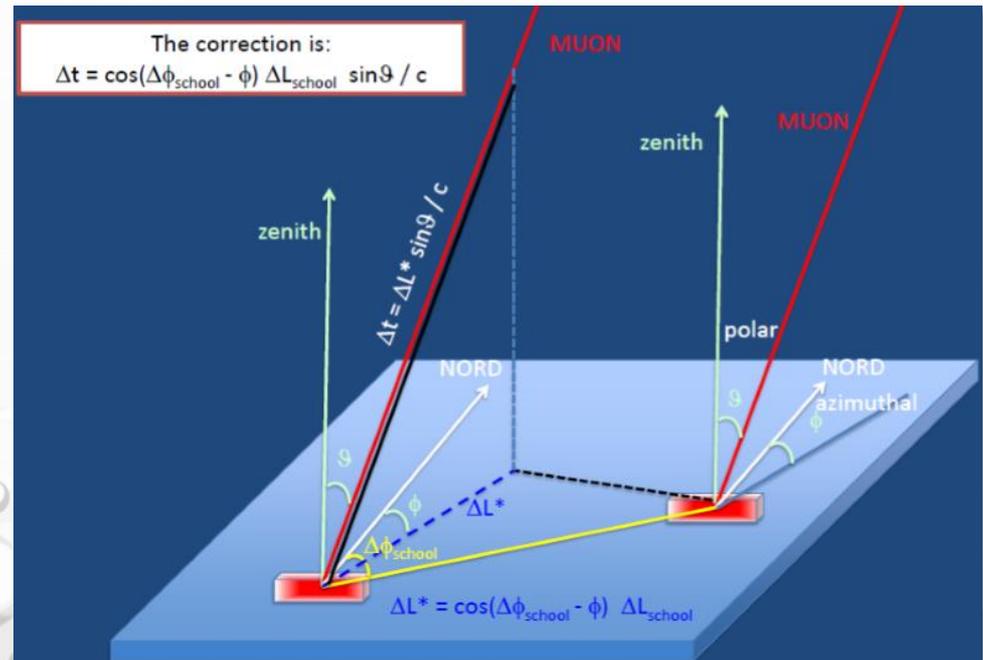
Search for coincidences

- ✓ the telescopes' relative distance ranges from a few hundred meters for clusters of 2, 3 and 4 telescopes in the same city, to more than 1000 km for the farthest stations.
- ✓ muons from the same Extensive Air Shower (EAS) are detected by different stations
- ✓ arrival time difference of particles in the same EAS depends on their own angular position from the axis shower and on the axis shower direction



time intervals for checking out muon coincidences are correlated to the distance between the different stations

- ✧ $\Delta L_{\text{station}}$ = relative distance between telescopes
- ✧ θ = polar angle of the EAS axis
- ✧ ϕ = relative azimuth angle between telescopes and the North
- ✧ $\Delta\phi_{\text{station}}$ = relative azimuth angle between stations



Search for coincidences

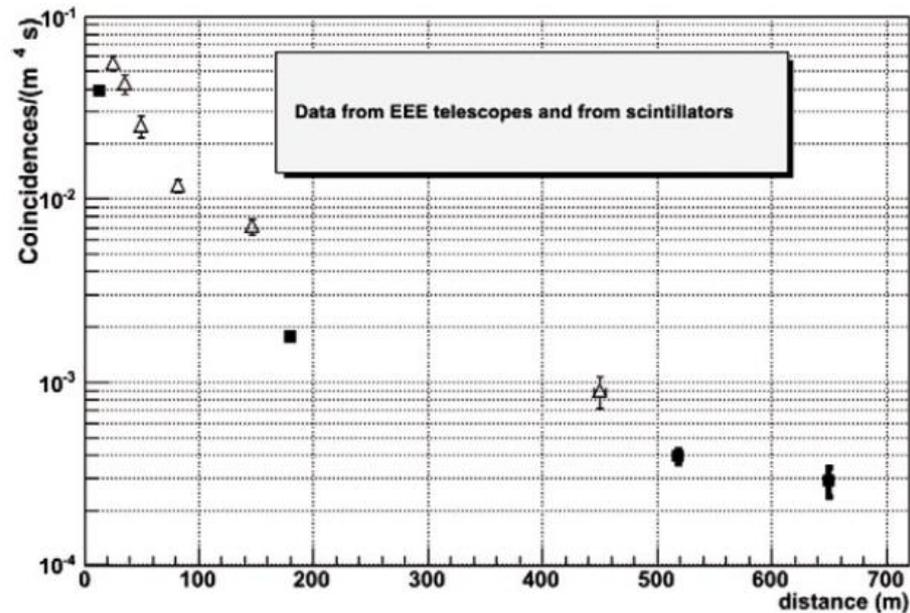
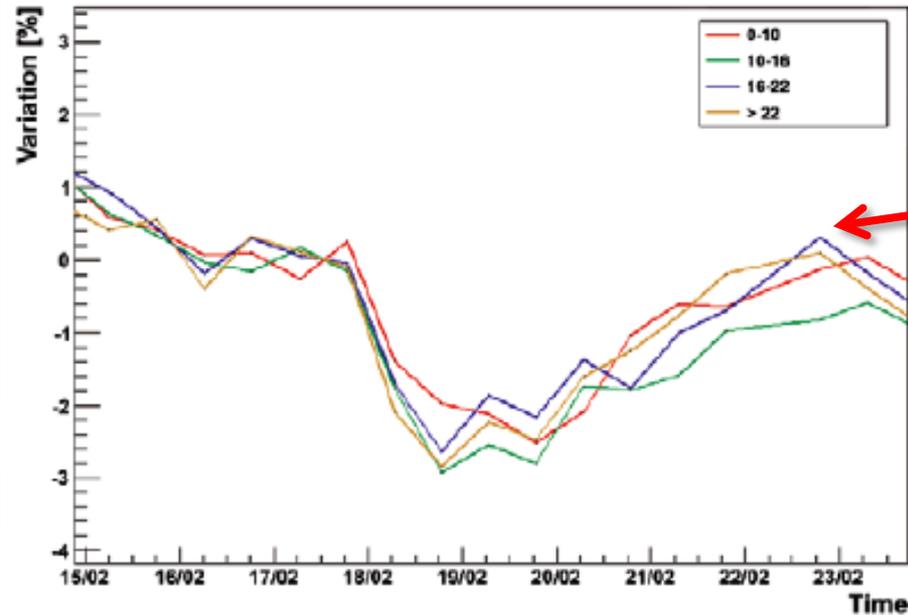


Fig. 6. Corrected number of coincidences, normalized to the sensitive areas of the two apparatus, as a function of their relative distance. Full squares are the results from the EEE telescope pairs located at CERN (15 m), in L'Aquila (180 m), in Cagliari (520 m) and in Frascati (650 m). Open triangles show the results from the correlation between one EEE telescope and the small scintillators. The point at 50 m was measured in the Cagliari site, while data measured at 25, 36, 82, 148 and 450 m refer to the Catania site.

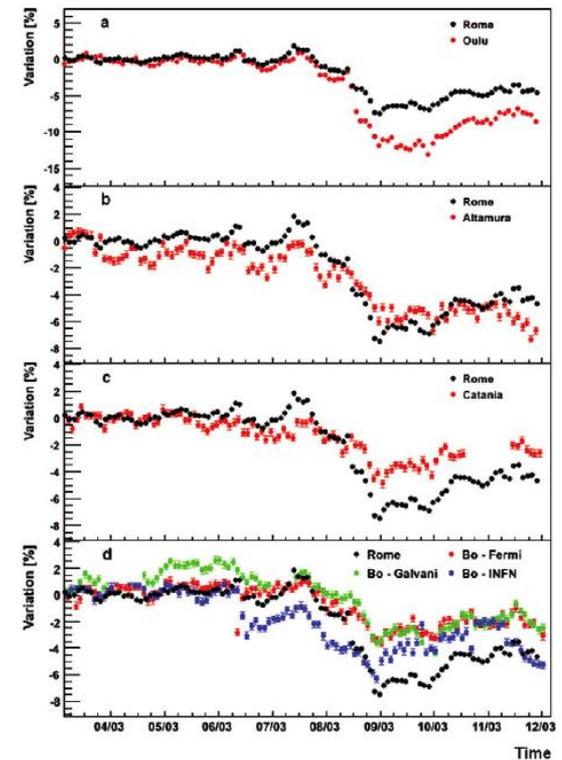


Forbush decreases



February 2015 flux

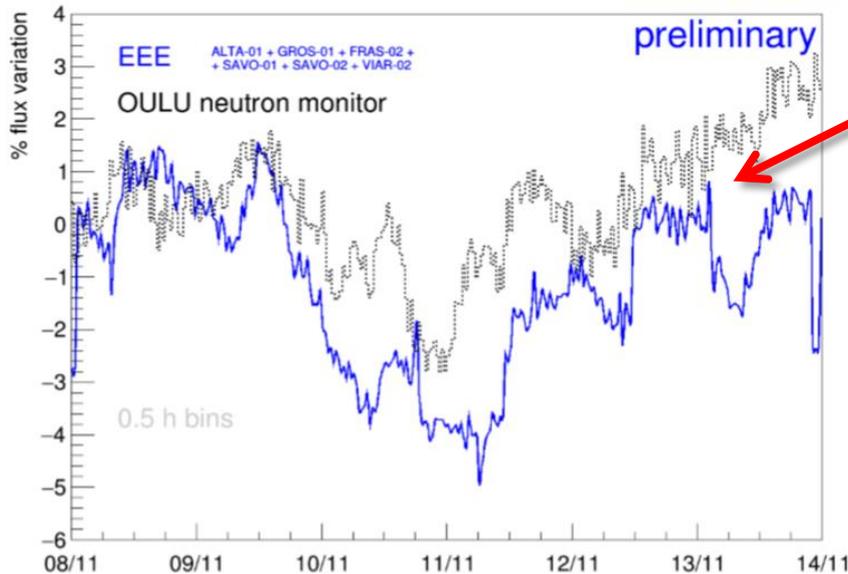
March 2012 flux decrease





Forbush decreases

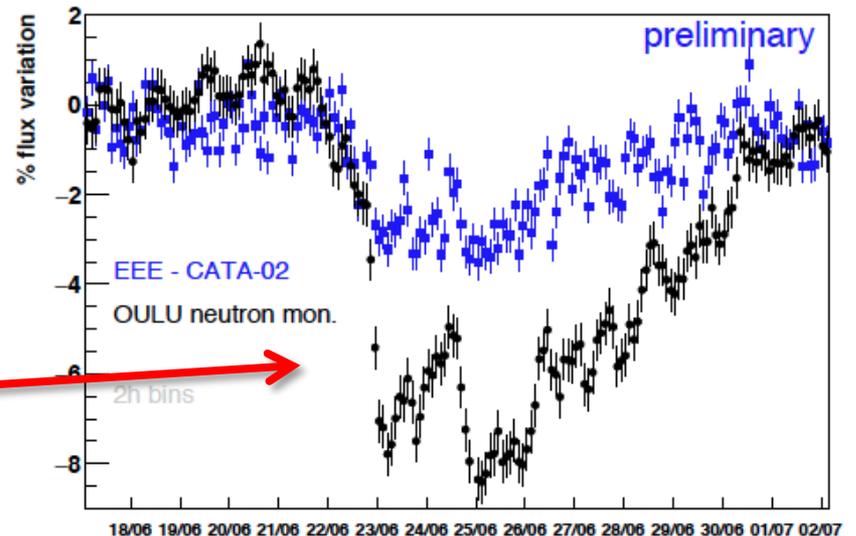
GCRD 2014-11-10: 6 stations average **EEE** Extreme Energy Events
La Scienza nelle Scuole



November 2014 flux decrease as observed by 6 stations
(adding up data set from different stations allows to reduce the *signal/noise* value)

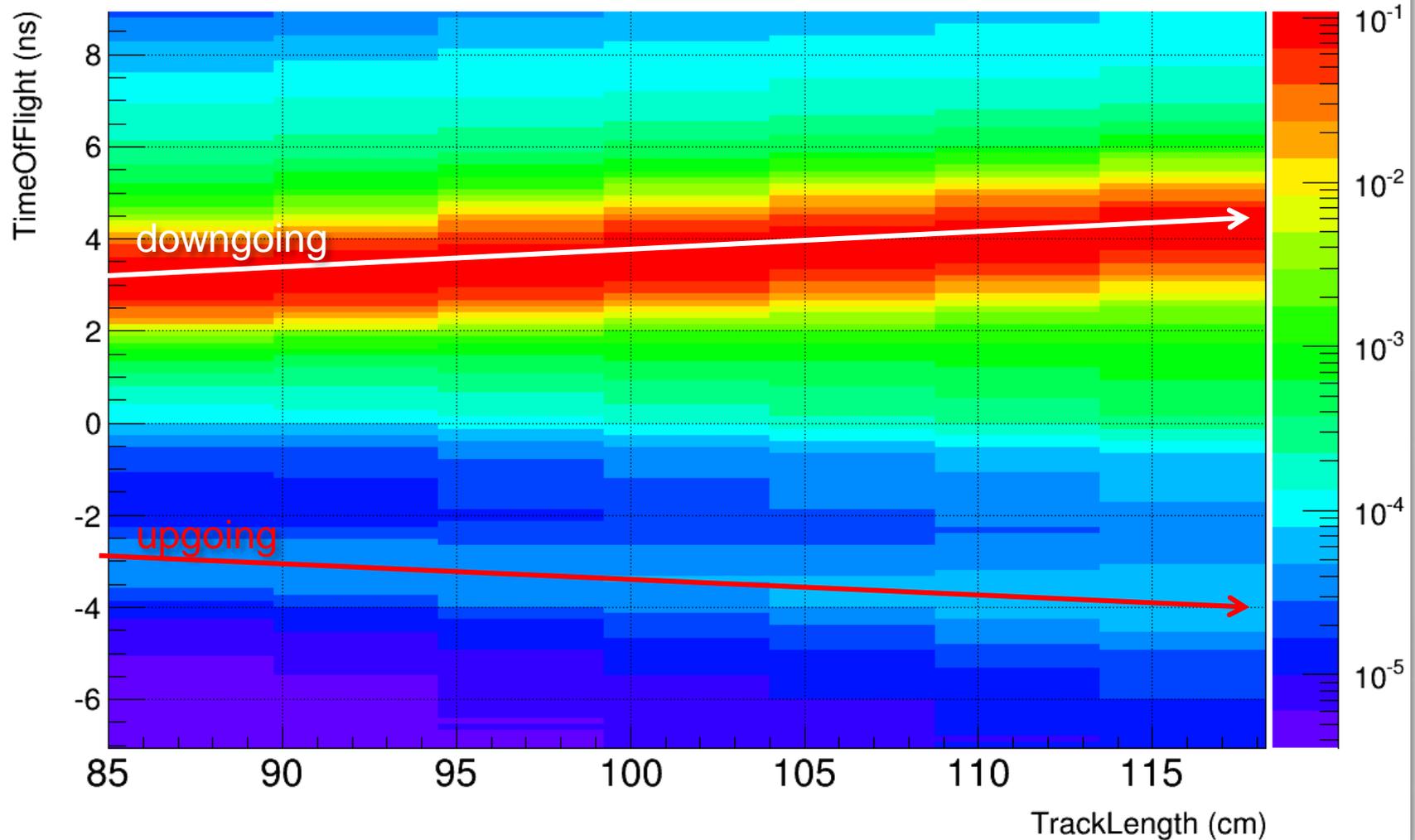
June 2015 flux decrease as observed by the CATA-02 station

GCRD 2015-06-23: CATA-02 station **EEE** Extreme Energy Events
La Scienza nelle Scuole



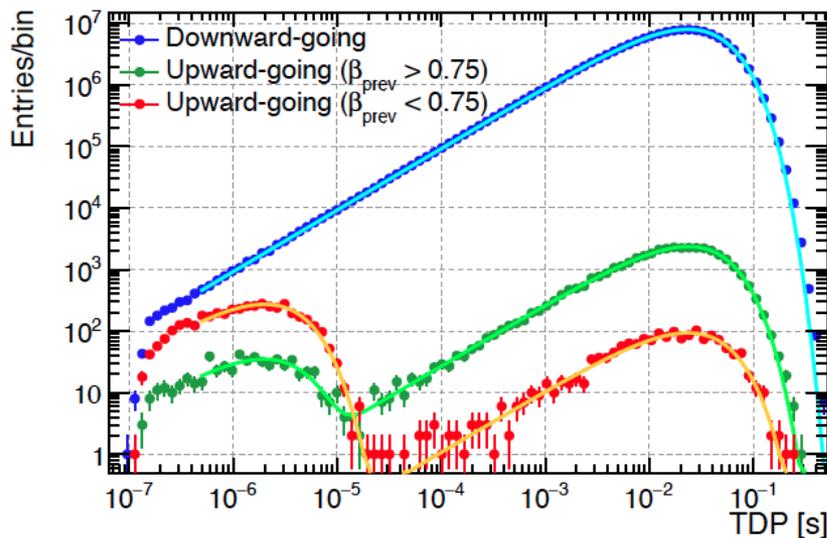


Muon decay



Muon decay

- ✓ upgoing electron delay of $\sim 2\mu\text{s}$ with respect to parent muon
- ✓ β of parent muon has to be small (low energy muon)
- ✓ χ^2 of upgoing electron has to be much larger with respect to downgoing muons (because of multiple scattering)
- ✓ χ^2 of parent muon has to be slightly larger with respect to high energy muons (because of multiple scattering)



- ✓ from the fit we obtain $2.04 \pm 0.04 \mu\text{s}$ is $\sim 10\%$ smaller than the lifetime of the muon at rest
- ✓ this is related to the matter effects for stopping muons



Search for anisotropies

- ✓ observation of cosmic rays at energies sensibly smaller than 10^{15} eV (1-10 TeV) is a useful tool to inspect the magnetic field structure in the interstellar environment close to our Solar System
- ✓ in this energy range small anisotropies may be induced by large scale as well as local magnetic field features, which may cause deviations from the isotropic diffusion model
- ✓ over the last few years, detection of low energy primary cosmics (several tens GeV to PeV) from various experiments has demonstrated that small but measurable anisotropies in the arrival distribution of cosmics may be evidenced
- ✓ observed anisotropies are very small, at the level of 10^{-5} - 10^{-3} , hence they have required a huge amount of data collected for several years

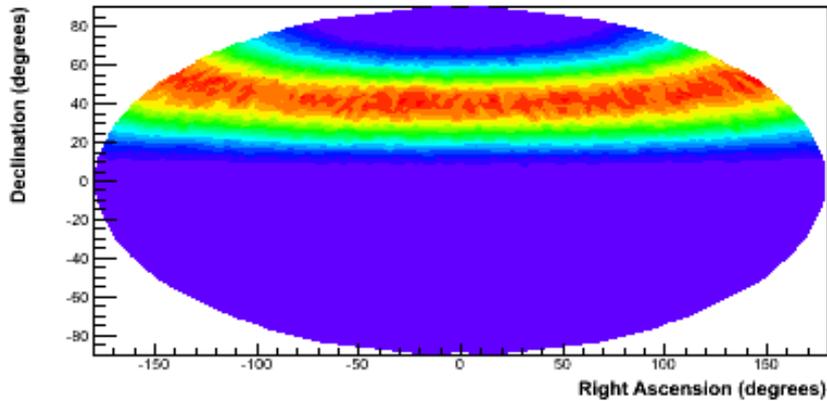


Search for anisotropies

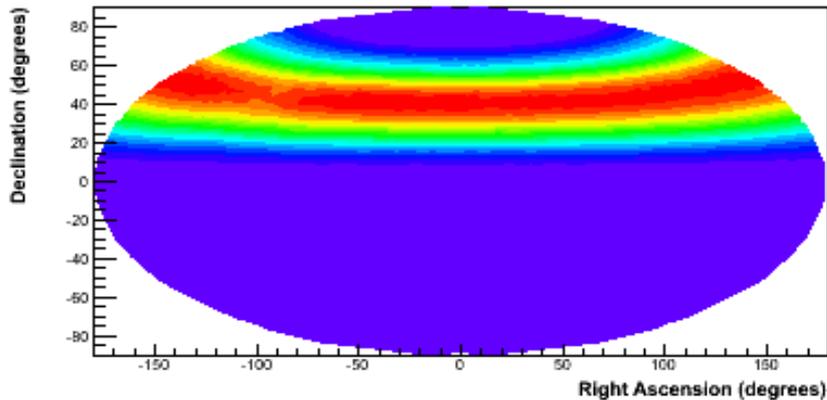
- ✓ Monte Carlo technique through the **scrambling** procedure is used to correct by possible dead times in data taking
- ✓ it considers two (RA, Dec) maps:
 - ✧ a **data map** is obtained from real events transforming θ , ϕ and t of the event into RA and Dec variables
 - ✧ a **reference map** is obtained by considering the same muon orientation, associated to the time t_R of a random event (chosen within a period where the running conditions are believed to be stable)
- ✓ 24 hours period was assumed, for an analysis on a daily basis
- ✓ a **corrected map** is then obtained by the ratio between the previous two maps (unity corresponds to isotropy)
- ✓ to reduce the statistical error on the reference map, 20 fake events were generated for each real event, with a proper normalization



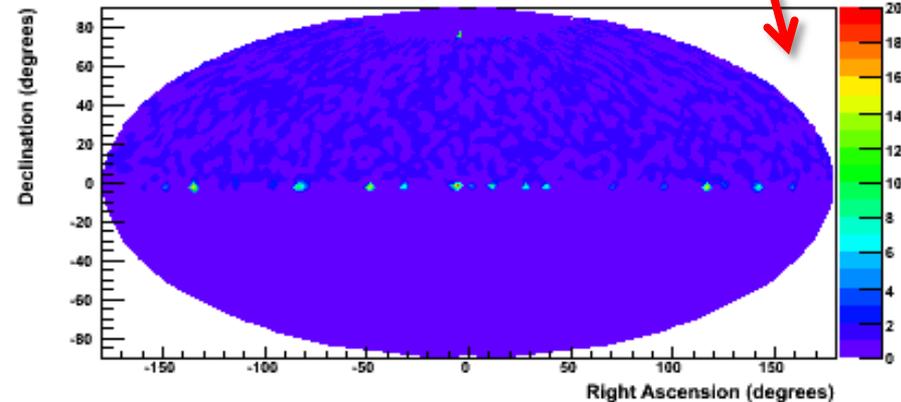
Search for anisotropies



data map



reference map



corrected map

Search for anisotropies

- ✓ results obtained from each day in a single telescope station were summed together, with a weight proportional to the number of collected events in each day
- ✓ due to the geometrical acceptance of the telescopes, the range between 20° and 60° was considered, to avoid border effects where statistics is low
- ✓ apart from a few cells, mostly located close to the border regions, the majority of the cells exhibit variations within 2-3%, compatible with the isotropy hypothesis

