CRIS Cosmic Ray International Seminar

Gallipoli, Castello Angioino, September 14-16, 2015

The status and the future of the UHE Cosmic Ray Physics in the post LHC era

First results from coordinated data taking by the Extreme Energy Events experiment

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EEE Collaboration
*Centro Fermi Roma
and
Salerno University and INFN - Italy

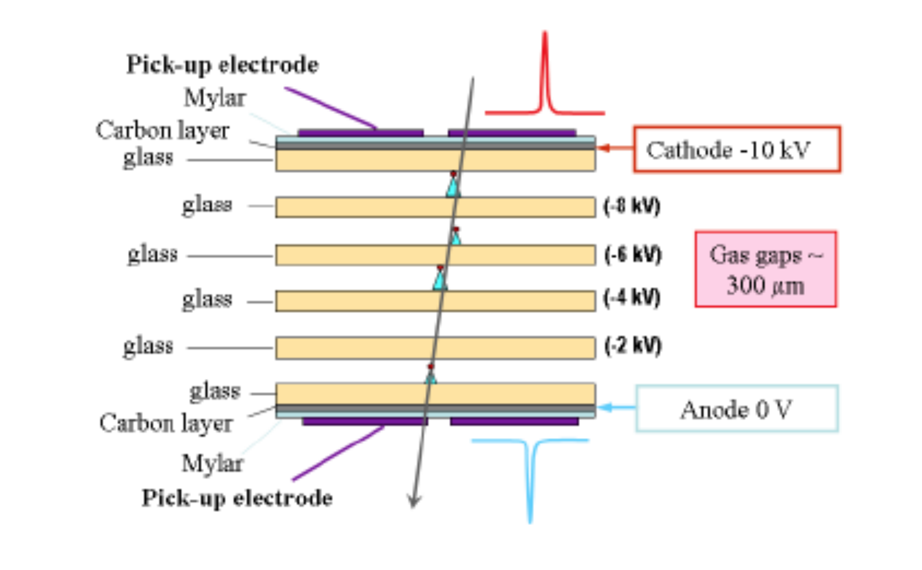
Overview

- ✓ Multigap Resistive Plate Chamber (MRPC) for a large array of muon telescopes
- ✓ EEE telescope
- ✓ coincidences between telescopes
- ✓ observatoin of Forbush decrease
- ✓ muon decay
- ✓ local anisotropies at the sub-TeV scale

Experimental setup

EEE MRPCs

- ✓ 6 gas gaps: 2 glass plates with their external surfaces painted with resistive paint; 5 floating glass plates (spaced by 300 μm)
- ✓ volume resistivity of the glass $\sim 10^{13}\Omega cm$
- ✓ $C_2H_2F_4$(98%) and SF_6(2%) continuously fluxed by (3l/h)
- ✓ 24 readout copper strips as electrodes (pitch 3.2 cm)
- ✓ HV up to 20 kV (avalanche mode) supplied by 2 DC/DC converters



- ✓ Townsend avalanche process
- ✓ the glass plates terminate the avalanche development in each gap
- ✓ the induced signals, sum of the signals due to all avalanches in all gaps, are picked up by the copper strips on both vetronite panels

EEE MRPCs

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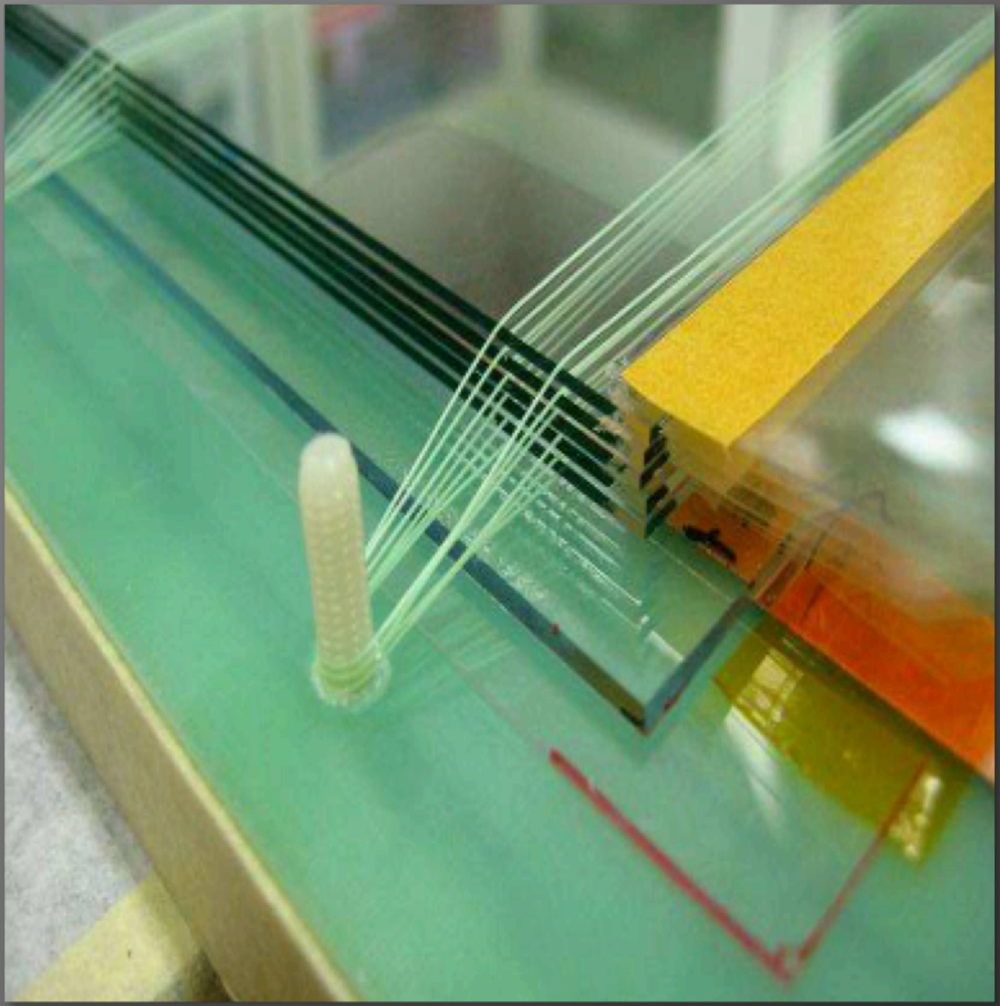
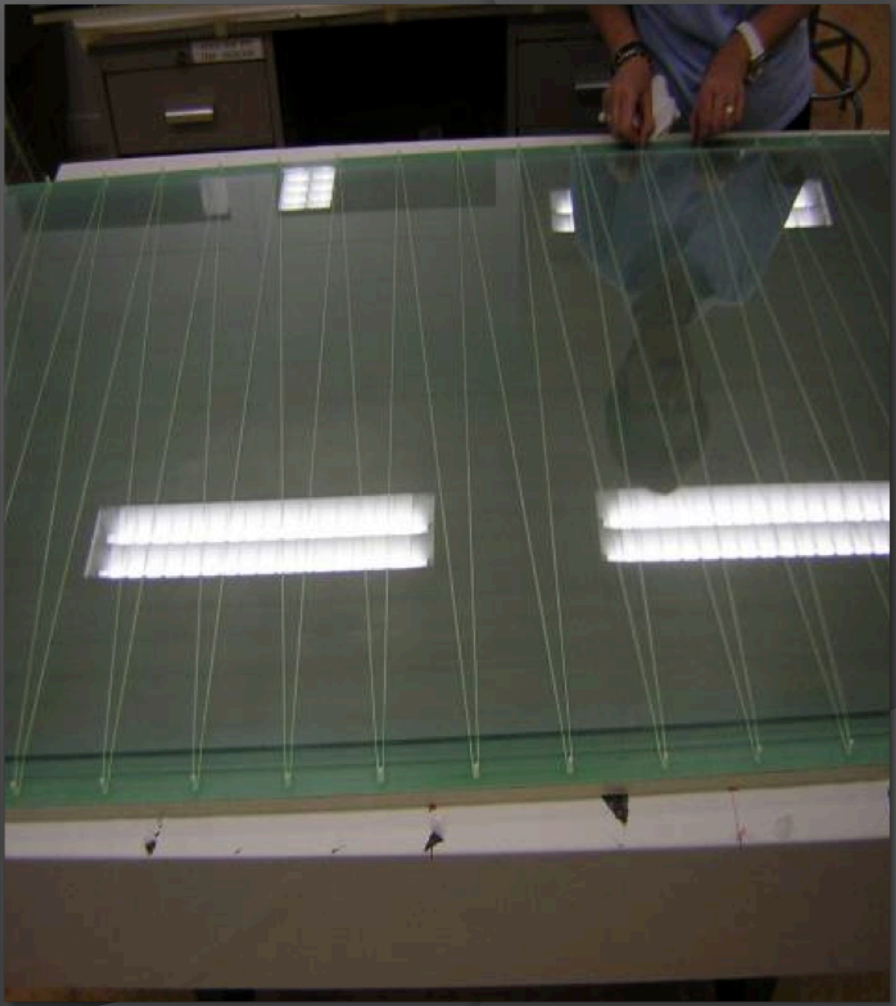
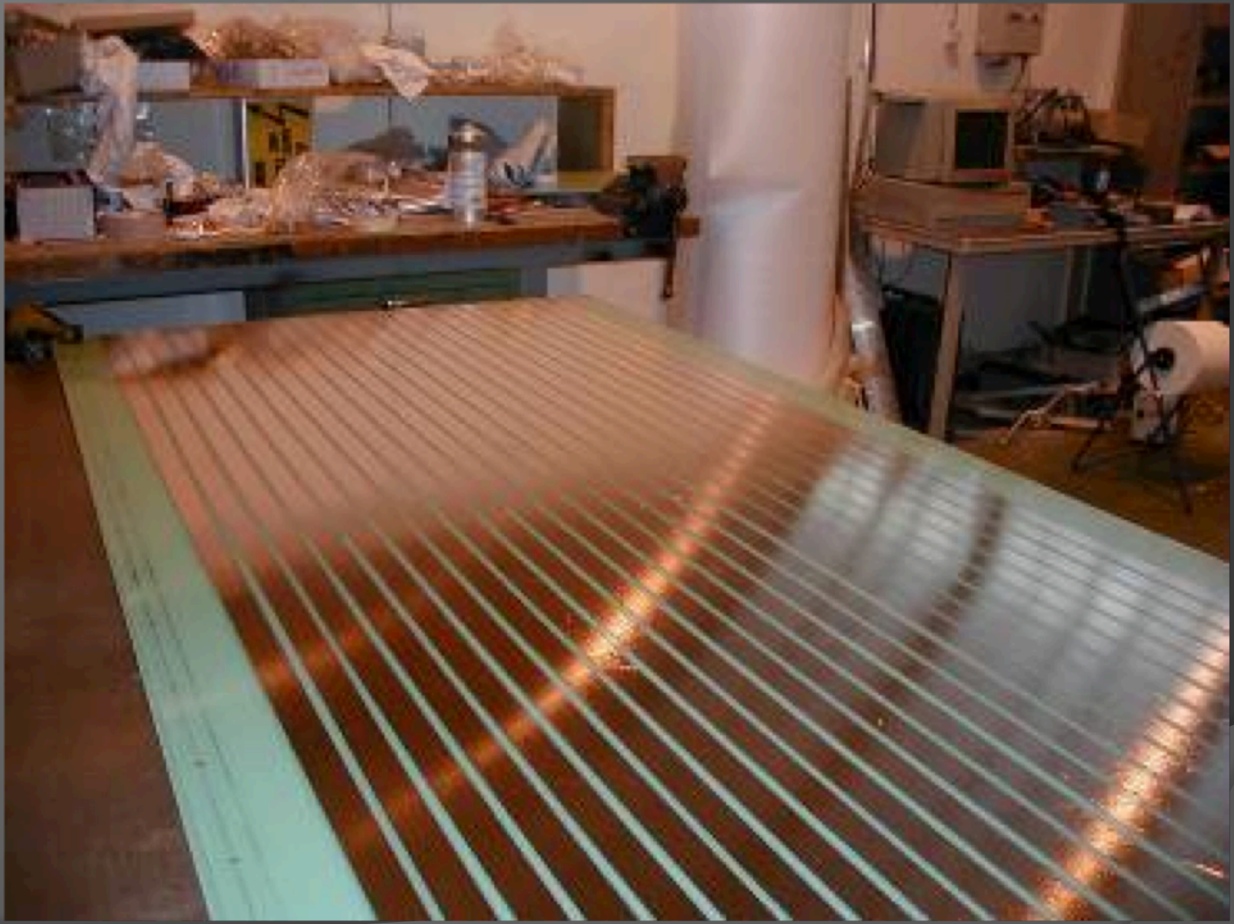




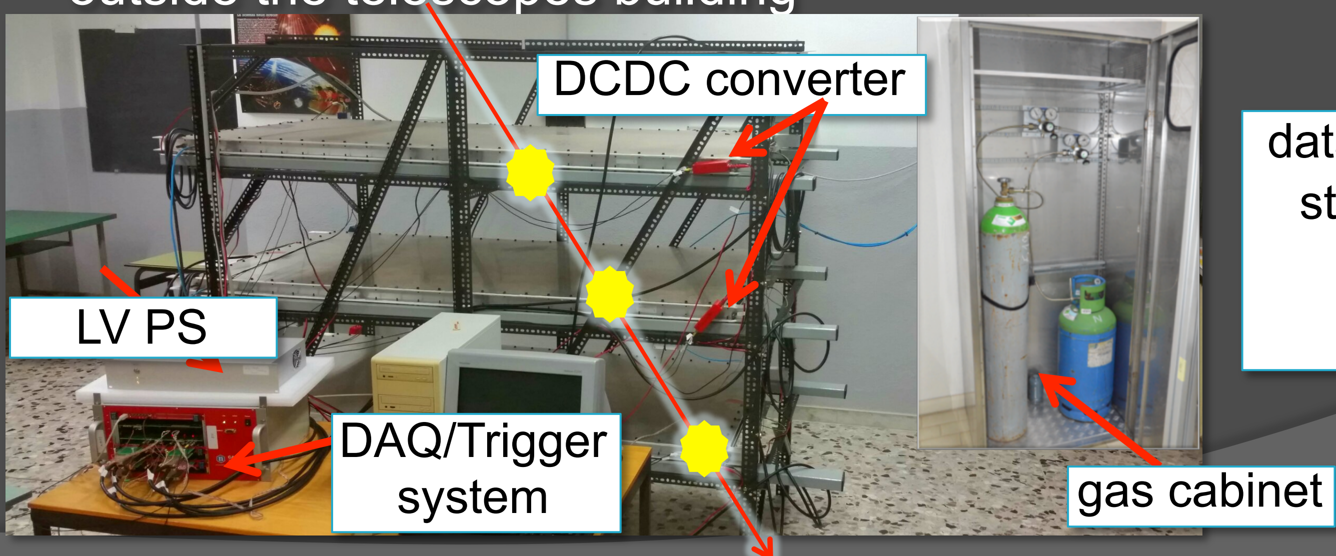
EEE MRPCs

✓ 24 readout copper strips as electrodes (pitch 3.2 cm)



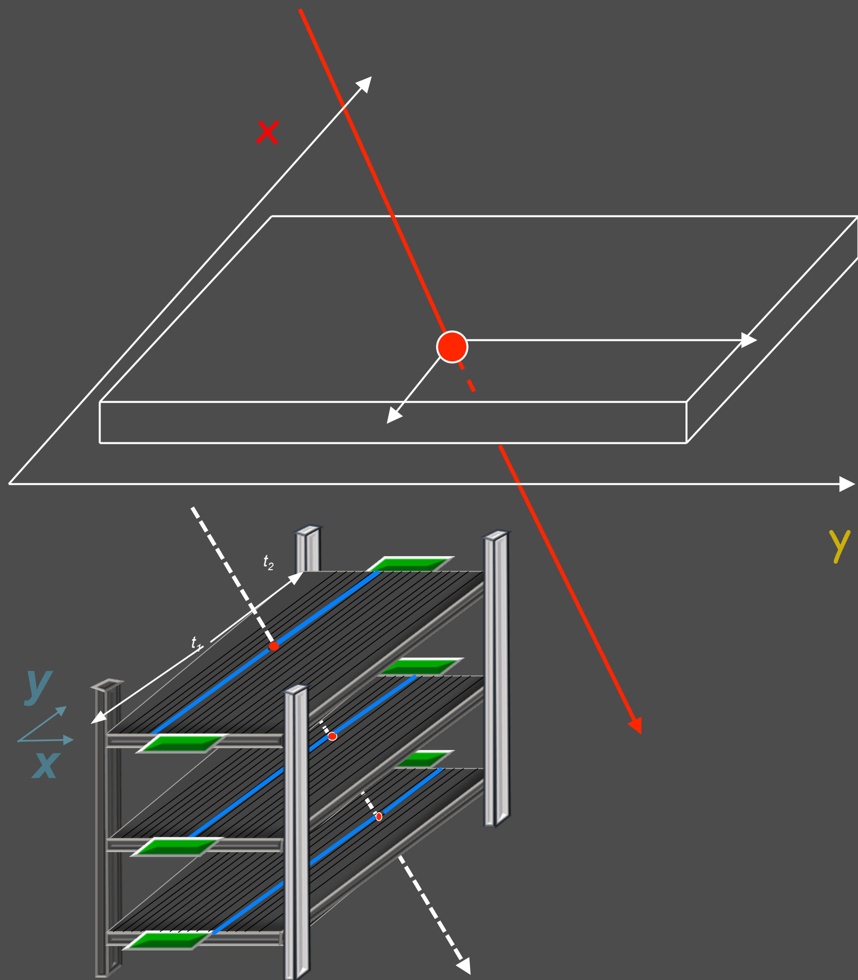
EEE telescope

- ✓ 6 FRONT-END boards (FEAs) with 24 channels to process readout signal (pre-amplification + discrimination)
- ✓ 2 MULTI-HITS TIME TO DIGITAL CONVERTERS (TDCs 128 + 64 channels) to reconstruct the particle impact point
- ✓ 1 MULTI-TRIGGER CARD: a six-fold coincidence of both FEAs of the three MRPCs generates the Data AcQuisition (DAQ) trigger
- ✓ GPS UNIT provides the event time stamp (UTC time) to record and synchronize informations
- ✓ HIGH VOLTAGE provided by DC/DC converters
- ✓ WEATHER STATION to monitor the temperature and the pressure inside and outside the telescopes building

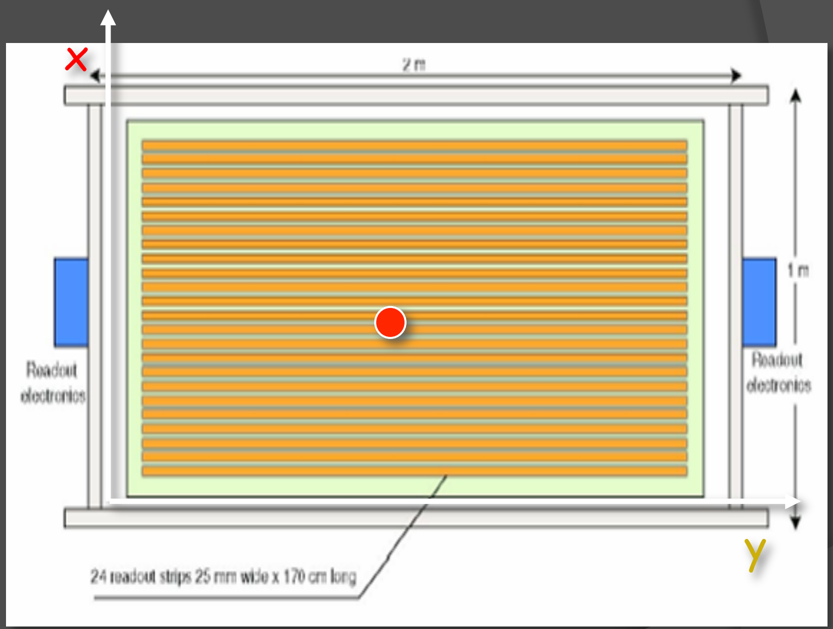


data sent to CNAF to be stored, reconstructed and analysed

Coordinates and performance

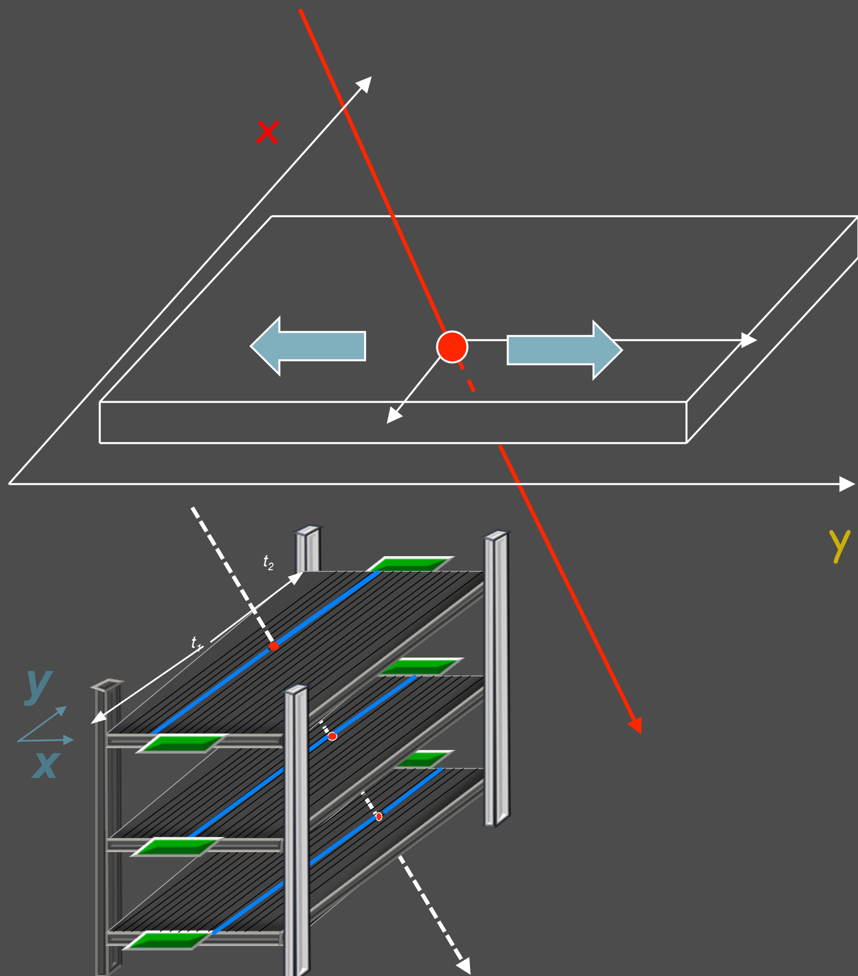


particle impact point reconstructed by:
- ✓ fired strip (x) in one direction
- ✓ difference of signal arrival times at the strip ends (y) measured by TDCs in the other direction



- ✓ 100 ps time resolution of the TDC bin
- ✓ ~7 mm spatial resolution along both coordinate
- ✓ > 95% MRPC efficiency at the operating voltage of 18 kV
- ✓ few tens ns GPS time resolution

Coordinates and performance



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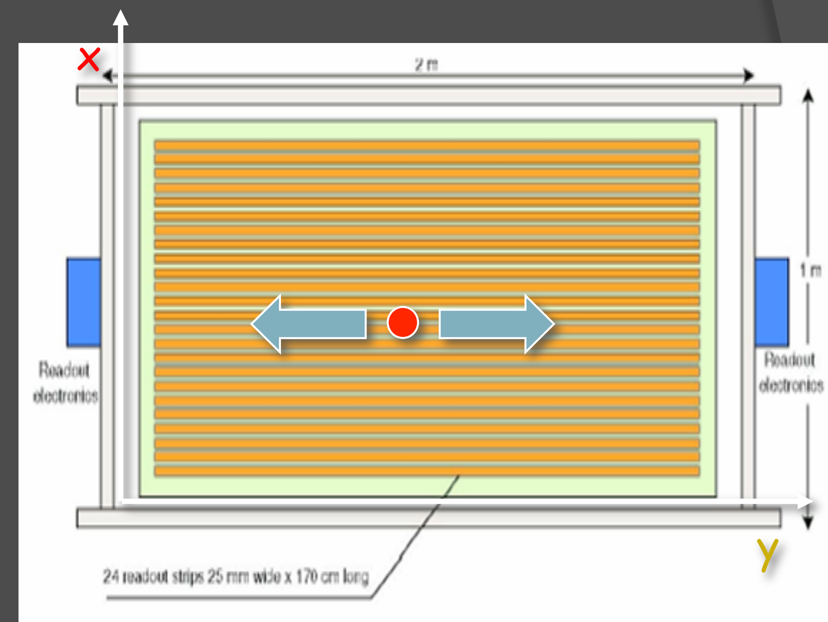

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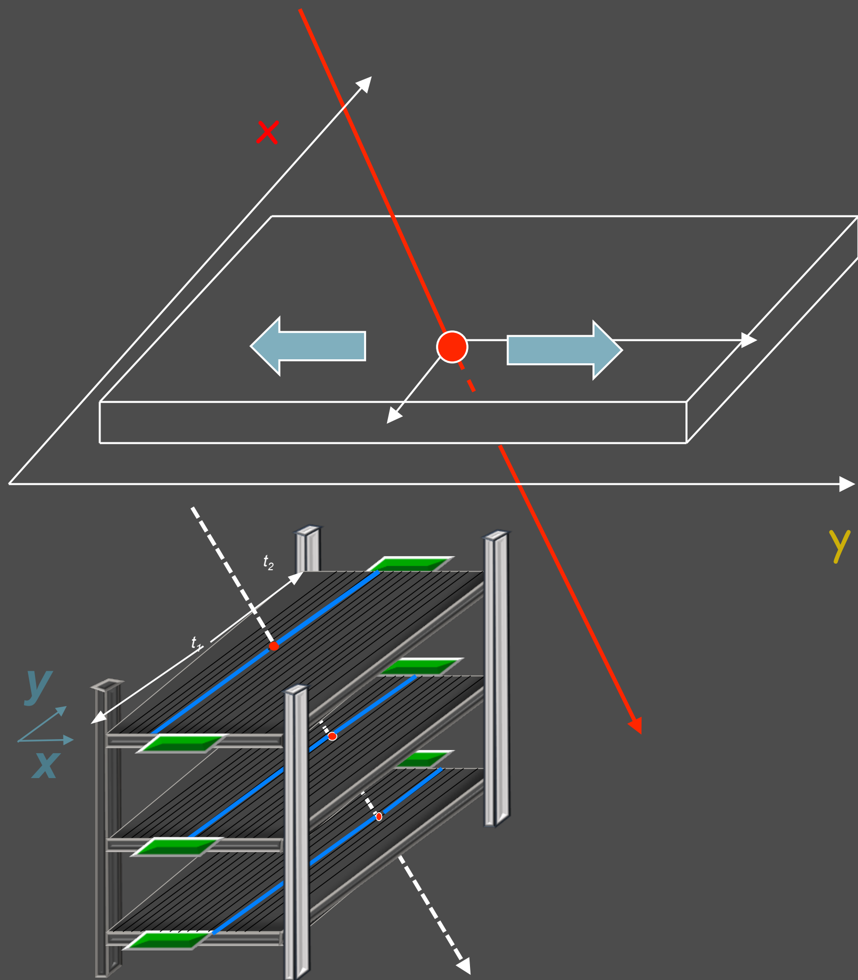

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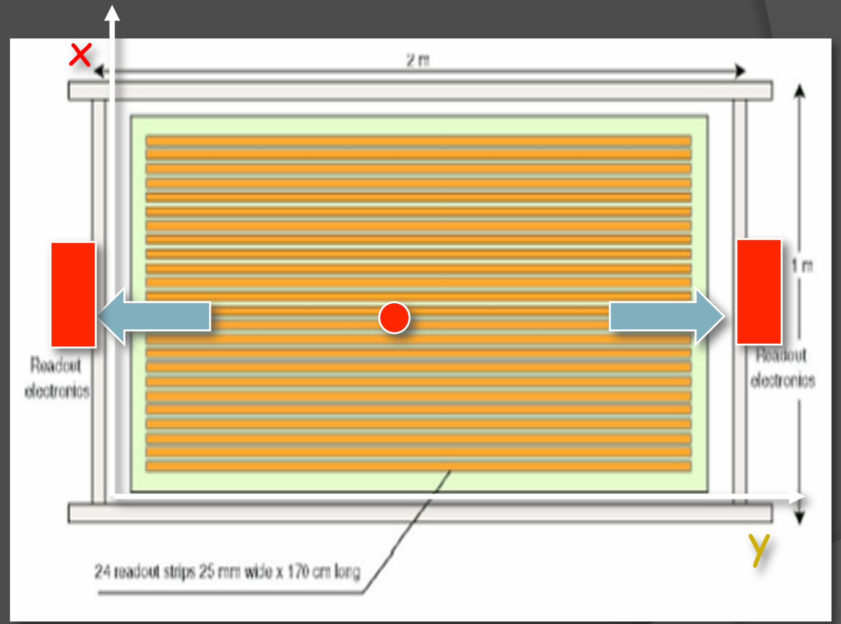

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EEE array

- ✓ a *pilot phase* with telescopes in 7 High Schools started in 2004 (Bari, Bologna, Cagliari, Catania, Frascati, L'Aquila, Torino)

- ✓ in *2015*:
an *experiment* with 47 EEE directional telescopes for cosmic ray muons detection (52 in 2016)
  - ✧ 42 in Italian High Schools (+ 5 in preparation) + 2 at CERN + 3 at INFN units

- ✓ overall area 3×10^5 km^2

in addition:

- ✓ powerful impact on education
- ✓ introducing high-school students and teachers to particle physics
- ✓ direct involvement in the construction, operation and data analysis
- ✓ >100 teachers, ~500 students directly involved in the last 3 years

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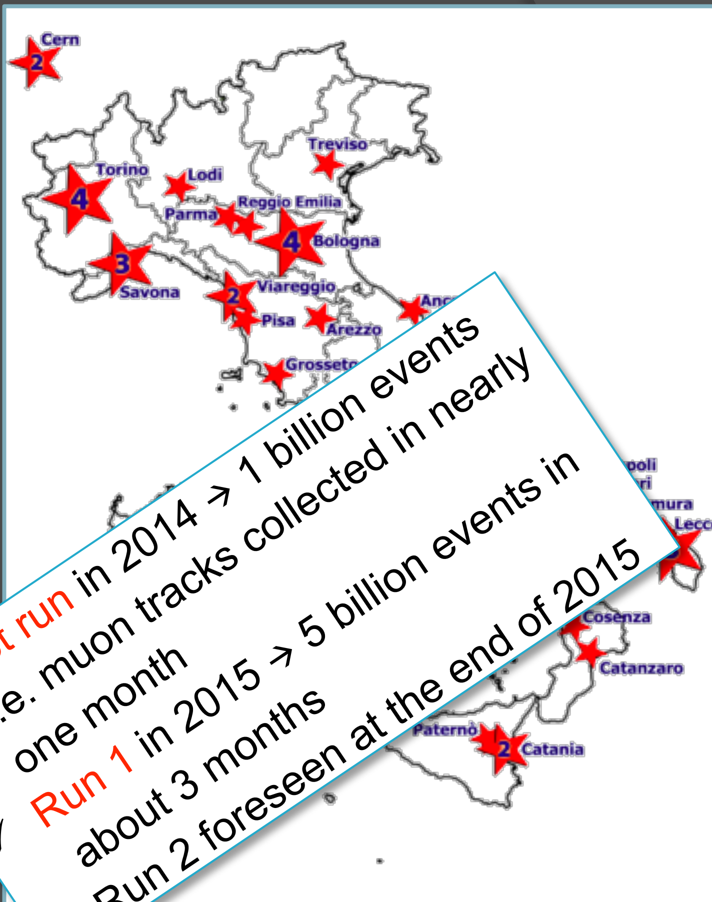

- ✓ pilot run in 2014 → 1 billion events i.e. muon tracks collected in nearly one month
- ✓ Run 1 in 2015 → 5 billion events in about 3 months
- ✓ Run 2 foreseen at the end of 2015

in addition:
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- ✓ direct involvement in the construction, operation and data analysis
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Students involvement

- ✓ one week to build 3 chambers (activity at CERN)
- ✓ secondary school students work under researchers' supervision (activity at CERN)
- ✓ all chambers are correctly working in each single telescope (daily monitor)
- ✓ setup of the telescope (activity at school)
- ✓ chamber efficiency measurements (activity at school)

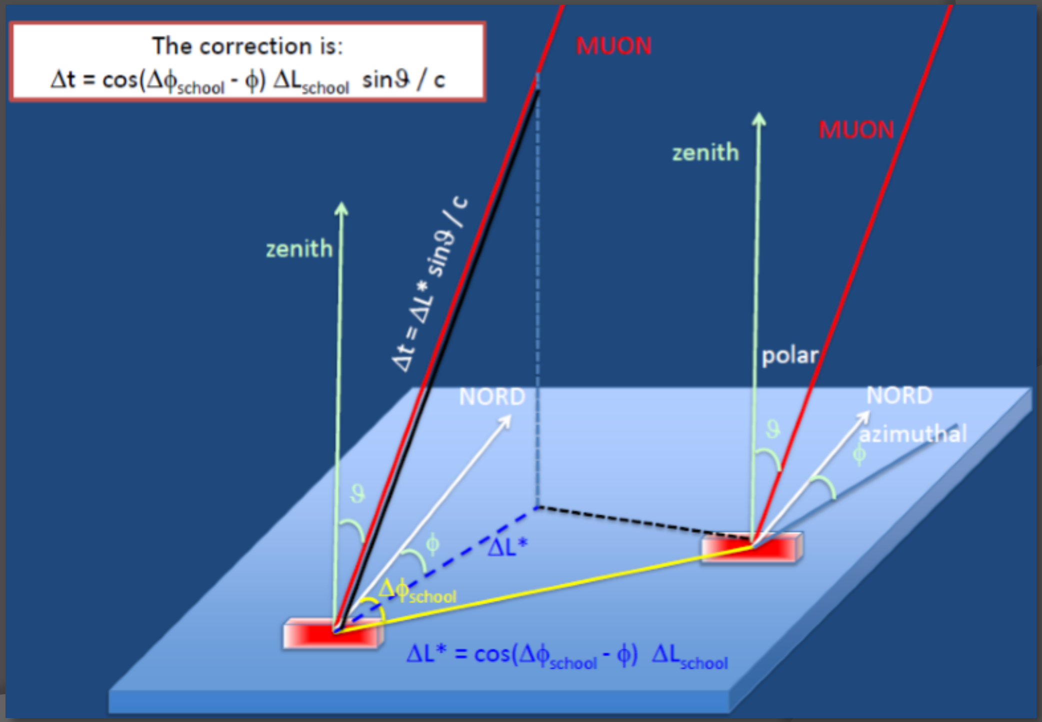
- ✓ students coming at CERN for the detector assembly in 2004-2015
- ✓ 46 schools
- ✓ 5-7 students + 2-3 teachers per school
- ✓ ~300 students and ~80 teachers in total

Search for coincidences

Search for coincidences

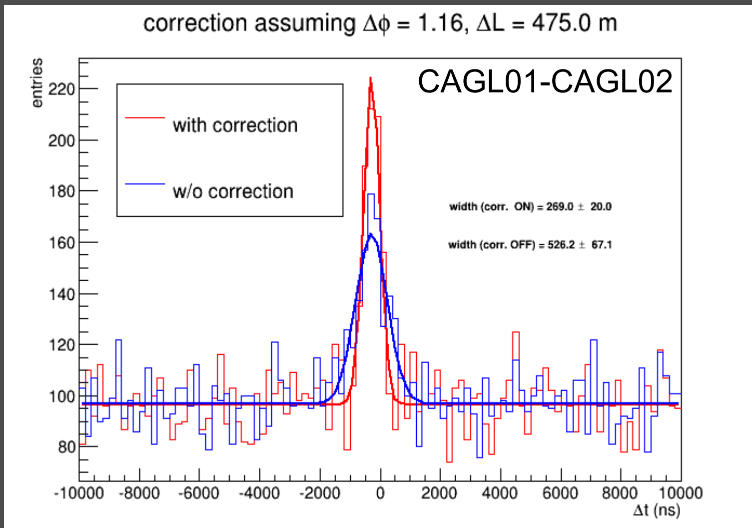
- ✓ the telescopes' relative distance ranges from a few hundred meters for clusters of 2, 3 and 4 telescopes in the same city, to more than 1000 km for the farthest stations.
- ✓ muons from the same Extensive Air Shower (EAS) are detected by different stations
- ✓ arrival time difference of particles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



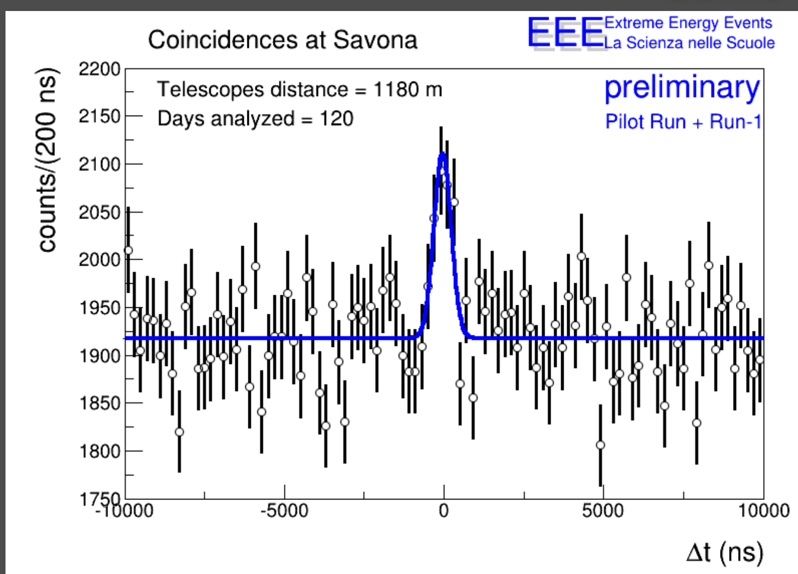
- ✧ $\Delta L_{station}$ = relative distance between telescopes
- ✧ θ = polar angle of the EAS axis
- ✧ ϕ = relative azimuth angle between telescopes and the North
- ✧ $\Delta\phi_{station}$ = relative azimuth angle between stations

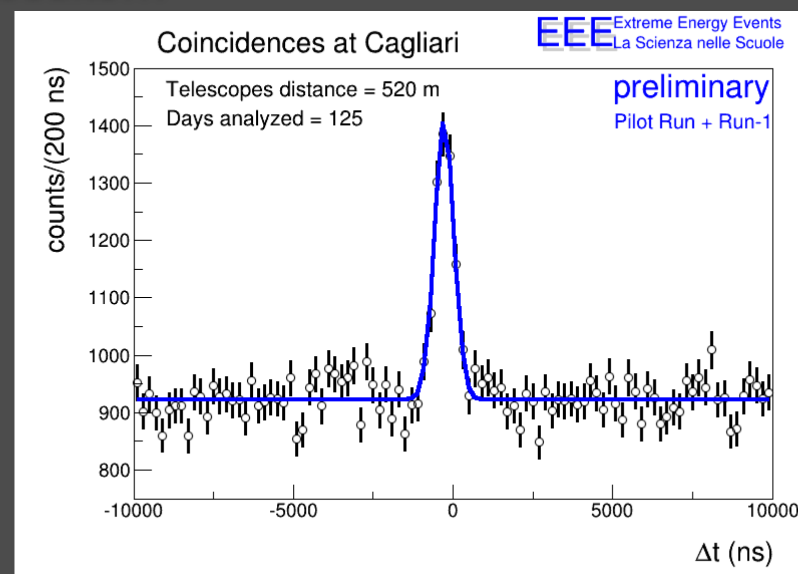
Search for coincidences



- ✓ distance correction reduces background due to accidental coincidences (S/N and σ)
- ✓ these corrections are important for High Energy EAS research among far away telescopes (>2km) since coincidences peak width is proportional to ΔL

some results…





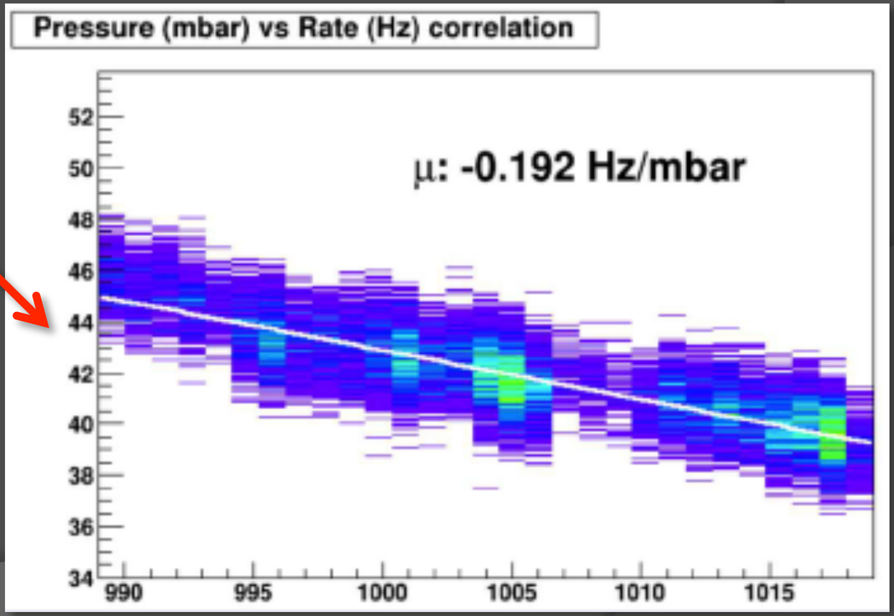
..among many others

Forbush decreases

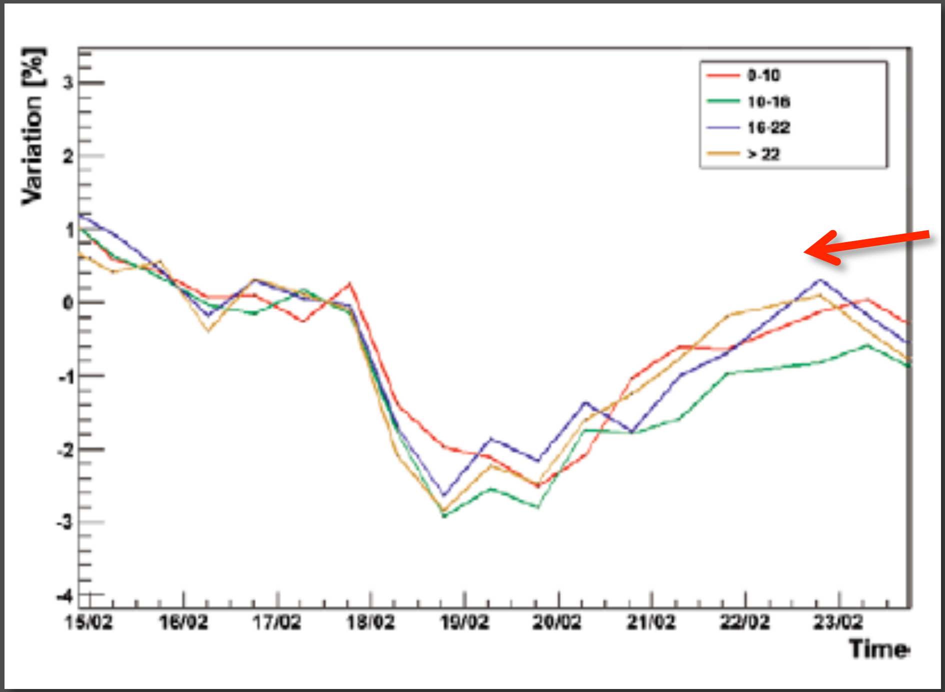
Forbush decrease

- ✓ rapid variations of the cosmic rays flux over the course of a few hours
- ✓ associated to solar phenomena as CME and solar flares
- ✓ they have been already observed by single EEE telescopes and also by different telescopes simultaneously
- ✓ comparison with Oulu neutron monitor station
- ✓ needed corrections in order to cancel out systematics which may mask the effect:
  - ✧ EAS development to the ground affected by absorption phenomena in atmosphere
  - ✧ $I = I_0 exp\,[-\mu(P - P_0)]$, at the first order correction $\Delta I = -\mu\Delta P$

- ➢ example of rate vs pressure correlation for the site SAVO-02
- ➢ baromteric factor assigned to each telescope

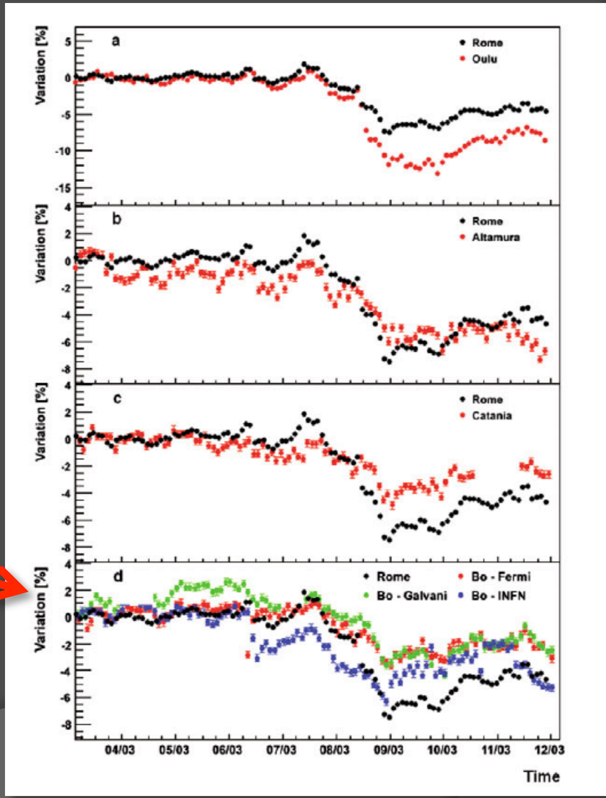


Forbush decrease



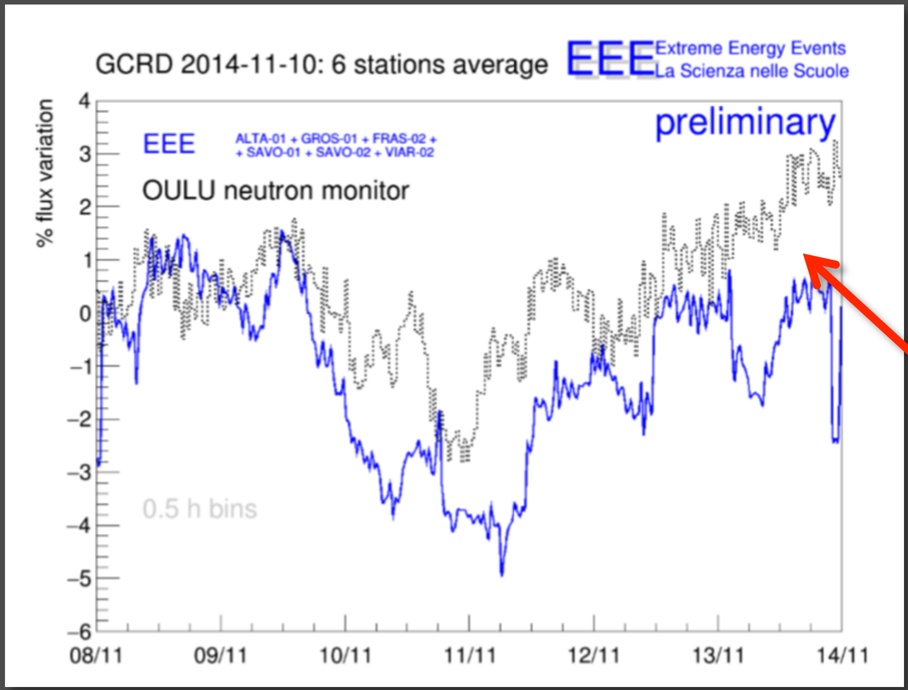
February 2015 flux

March 2012 flux decrease



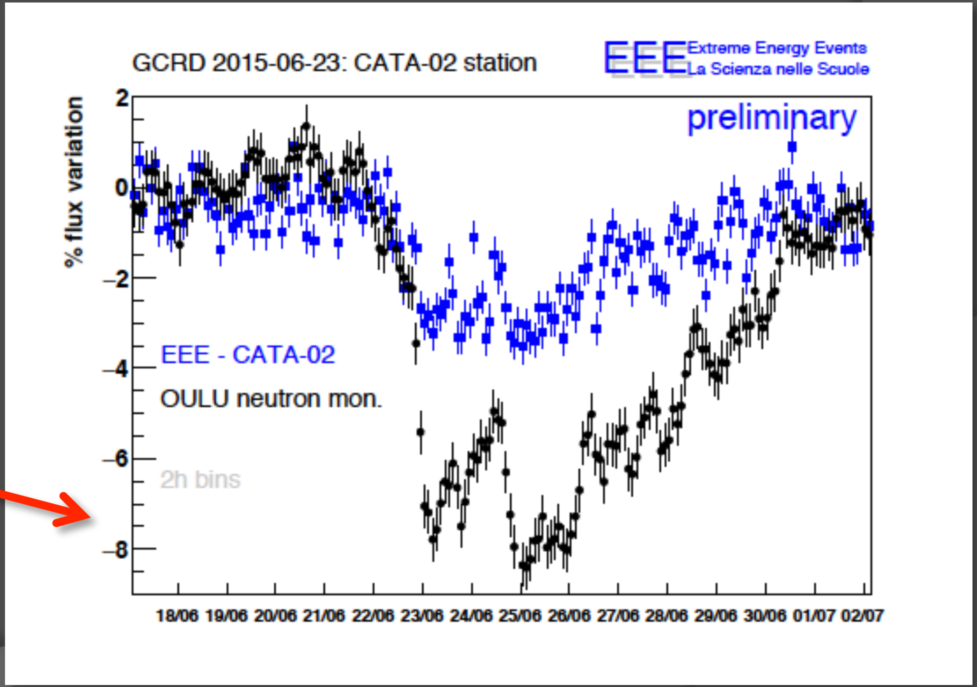
- ✓ comparison with Oulu neutron monitor station

Forbush decrease



November 2014 flux decrease as observed by 6 stations

(adding up data set from different stations allows to reduce the *signal/noise* value)

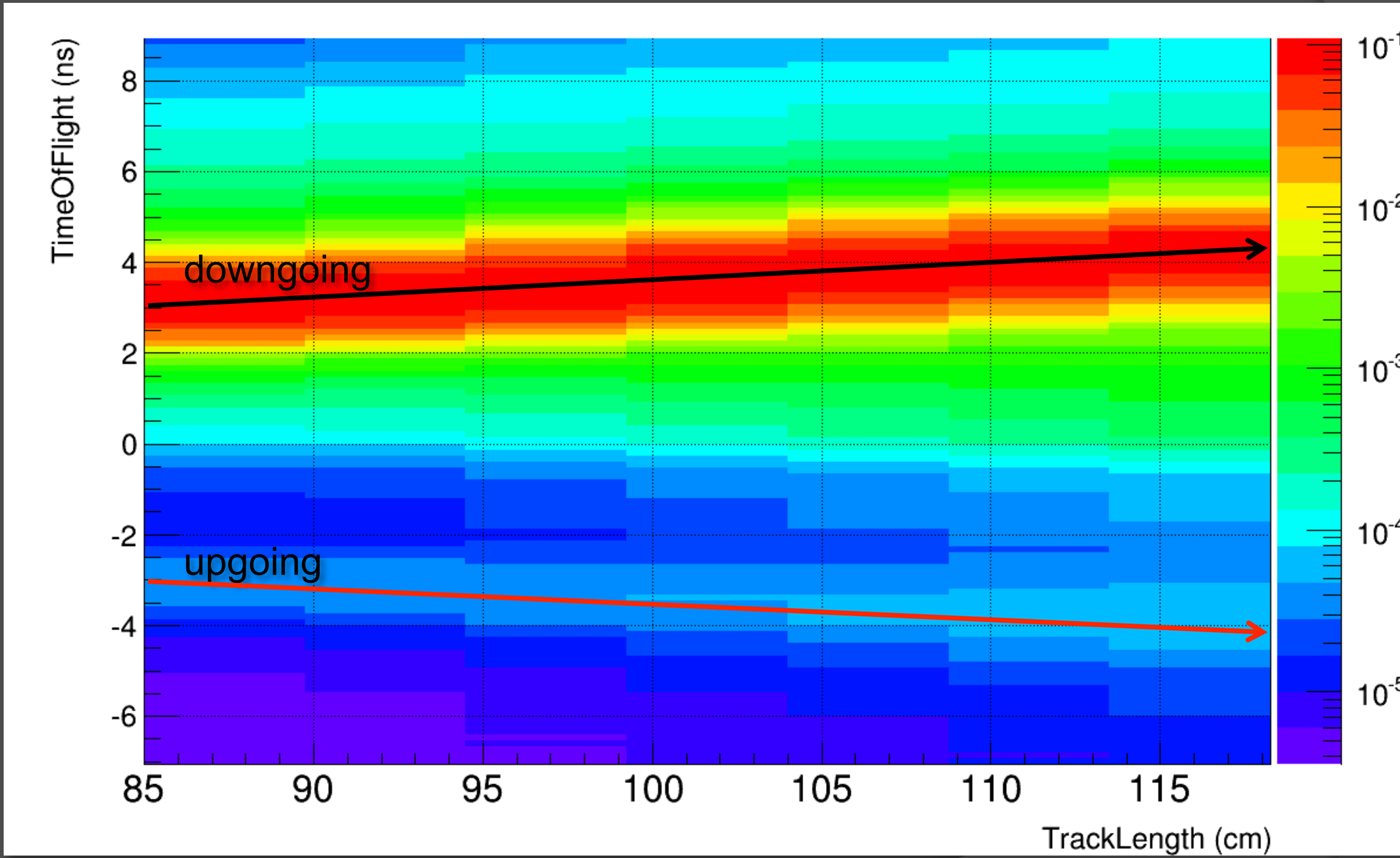


June 2015 flux decrease as observed by the CATA-02 station

- ✓ comparison with Oulu neutron monitor station

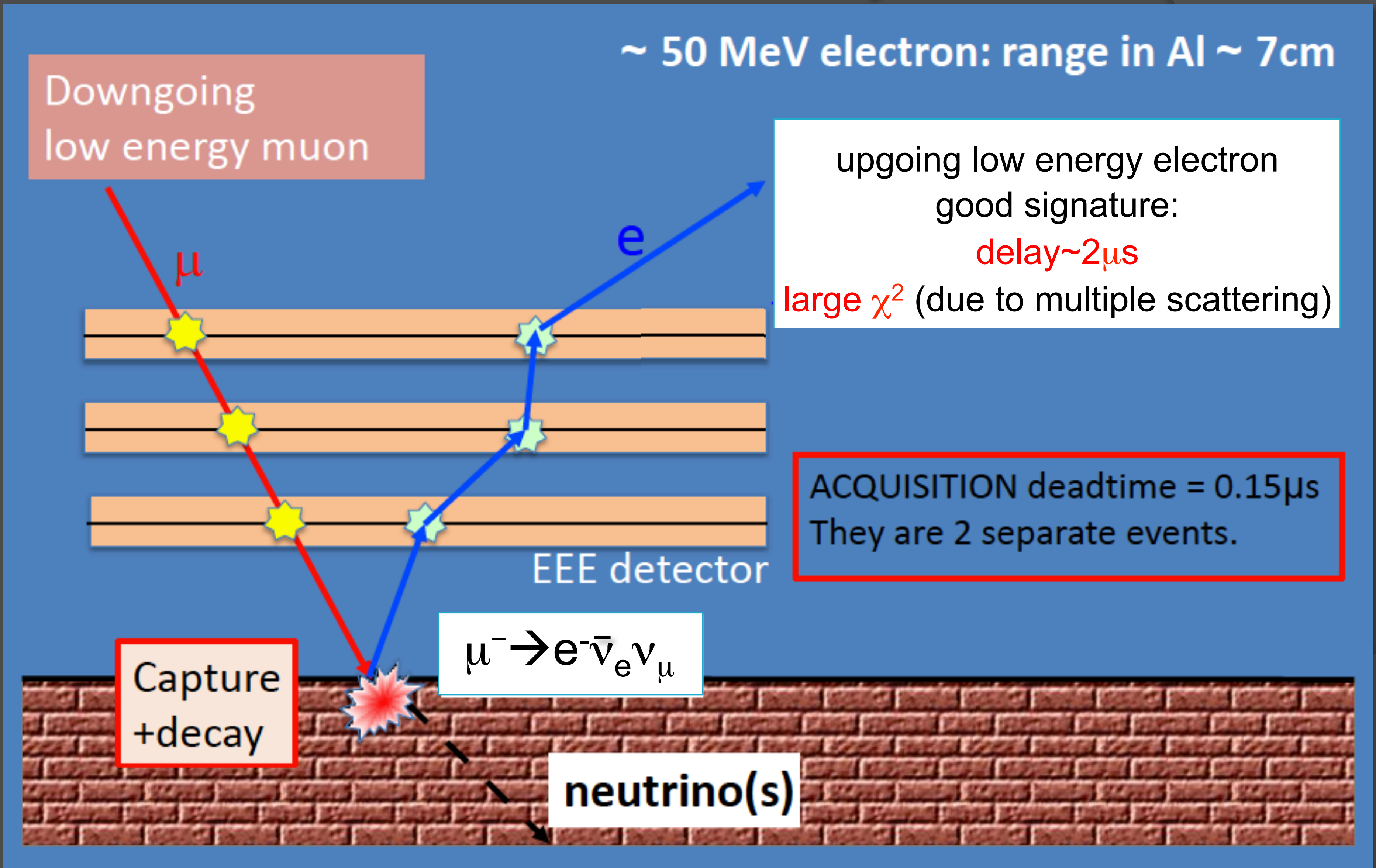
Upgoing particles and muon decay

Muon decay



few upgoing particles ~1/200

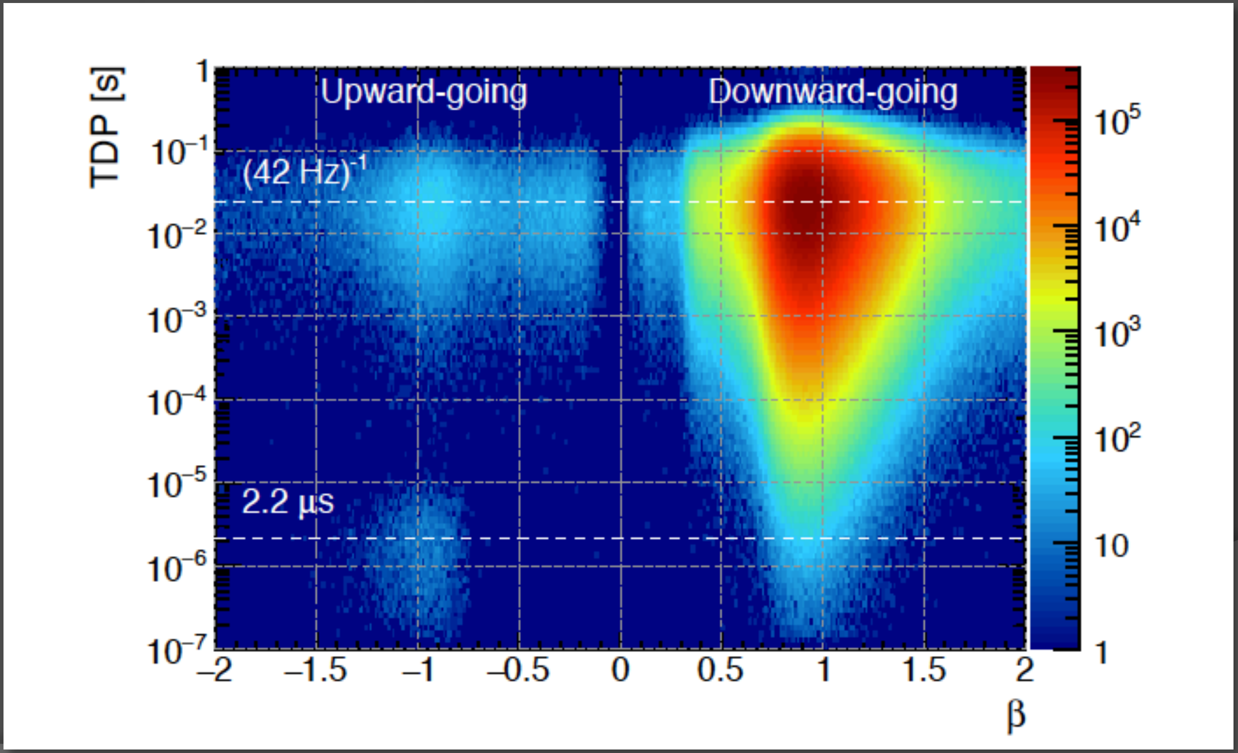
Muon decay



low energy electrons from muon decay are a robust explanation for upgoing particles

Muon decay

- ✓ upgoing electron delay of ~ 2μs 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)



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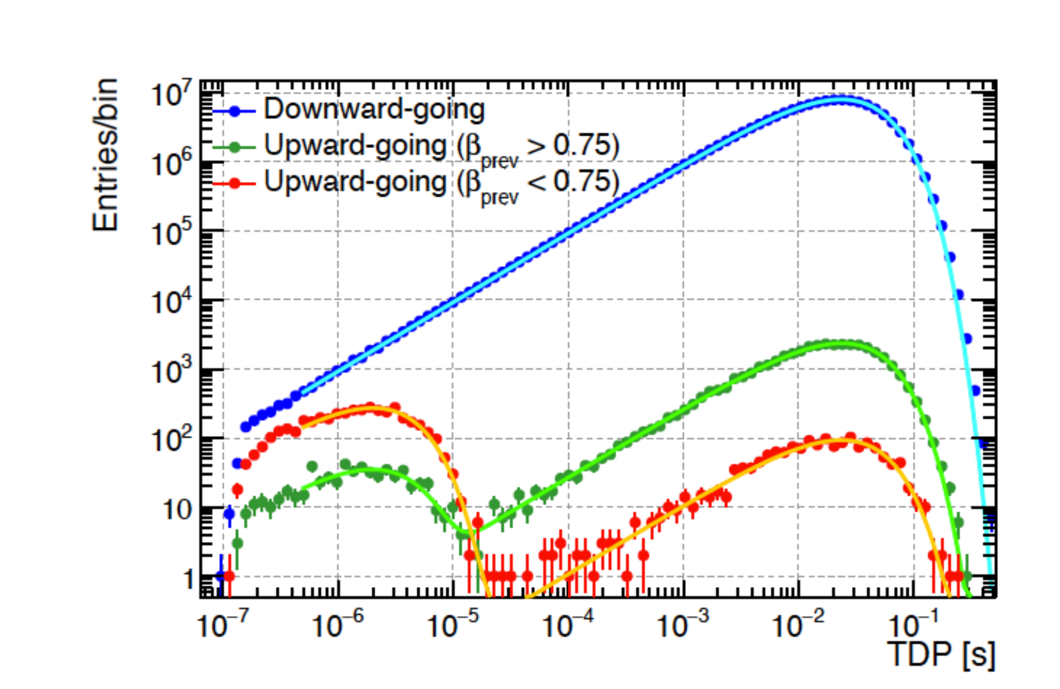


- ✓ from the fit we obtain 2.04±0.04 μs is ~10% smaller than the lifetime of the muon at rest
- ✓ this is related to the matter effects for stopping muons*,**

* B. Rossi, High Energy Particles, Prentice Hall, 1952.
** A. Grossheim et al., Decay of negative muons bound in Al^{27}, Phys. Rev. D 80 052012 (2009)

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

M.Abbrescia[2], R.Antolini[13], C.Avanzini[9], L.Baldini[9], R.Baldini Ferroli[14], G.Batignani[9], G.Bencivenni[14], E.Bossini[9], E.Bressan[3], A.Chiavassa[12], C. Cicalo[4], L. Cifarelli[2], E.Coccia[13], A.Corvaglia[8], D.De Gruttola[11], S. De Pasquale[11], A.Di Giovanni[13], M.D'Incecco[13], M.Dreucci[14], F.L.Fabbri[14], E.Fattibene[18], A.Ferraro[18], R.Forster[17], V.Frolov[12], P.Galeotti[12], M.Garbini[3], G.Gemme[7], I.Gnesi[12], S.Grazzi[7], C.Gustavino[13], D.Hatzifotiadou[3,17], P.La Rocca[5], S.Li[17], A.Maggiora[12], G.Maron[15], M.Mazziotta[2], S.Miozzi[14], M.Panareo[8], M.P.Panetta[8], R.Paoletti[9], L.Perasso[7], F.Pilo[9], G.Piragino[12],, F.Riggi[5], G.C.Righini[1], A.R.Rodriguez[17], G.Sartorelli[3], E.Scapparone[3], M.Schioppa[6], A.Scribano[9], M.Selvi[3], S.Serci[4], E.Siddi[4], S.Squarcia[7], M.Taiuti[7], G.Terreni[9], F.Tosello[12], M.C.Vistoli[18], L.Votano[13], M.C.S.Williams[3,17], S.Zani[18], A.Zichichi[1,3,17], and R.Zuyeuski[17]

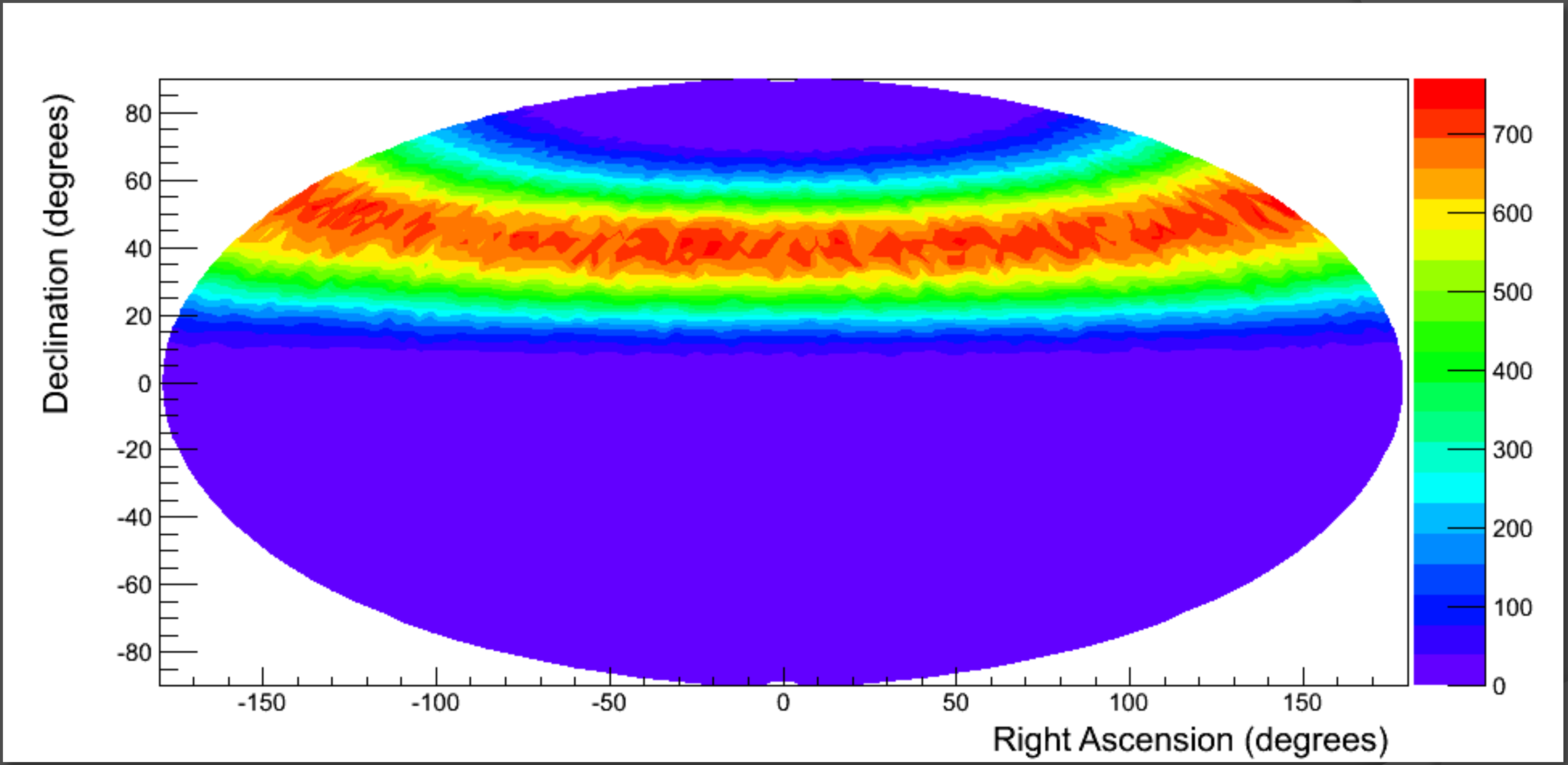
accepted by EPJ

Search for anisotropies

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

Aitoff map

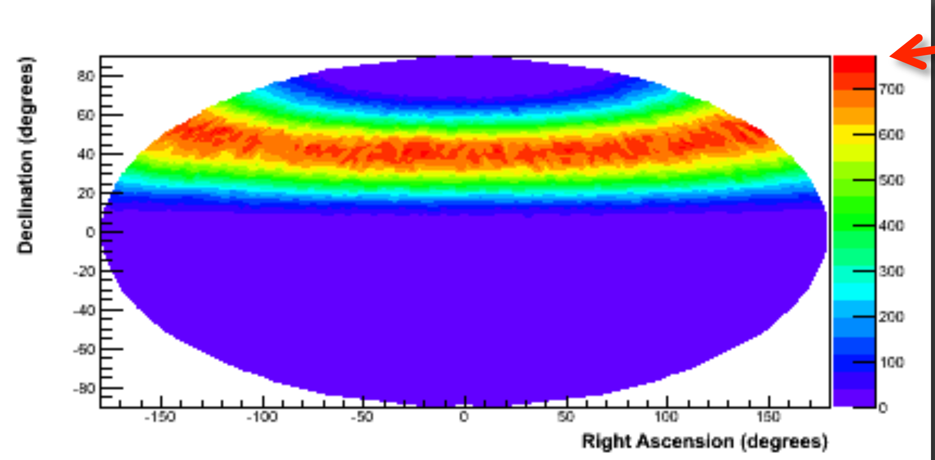


- ✓ Aitoff projection of the sky map for one of the EEE telescopes (CATA-01), located around 37° Lat. North, 15° Long. East
- ✓ transformation to equatorial coordinates (back up)

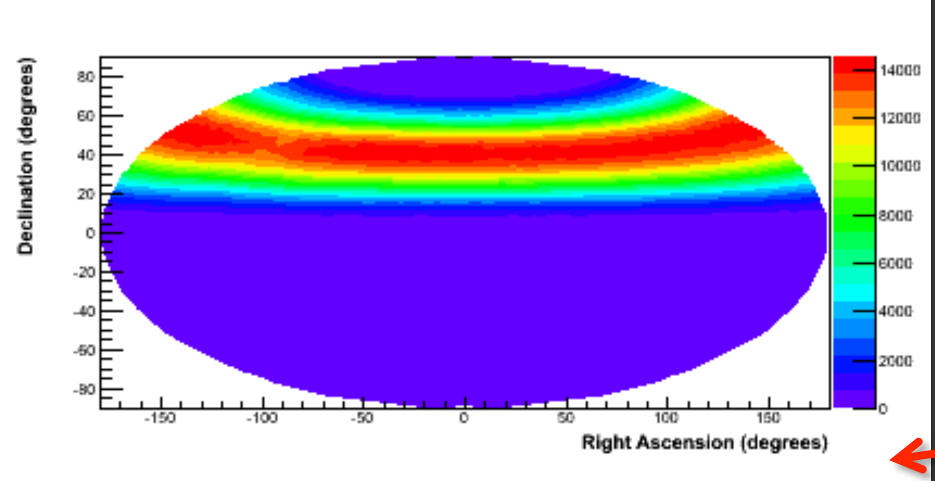
Corrected map

- ✓ 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

Corrected map

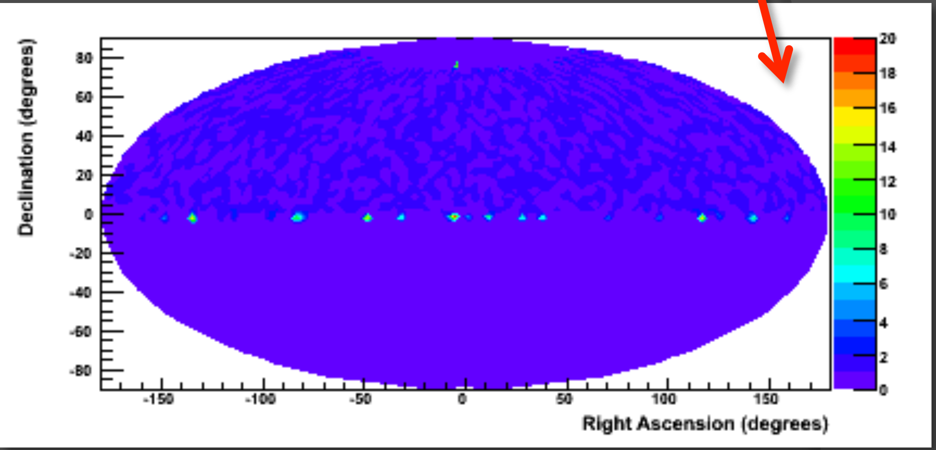


data map



reference map

corrected map

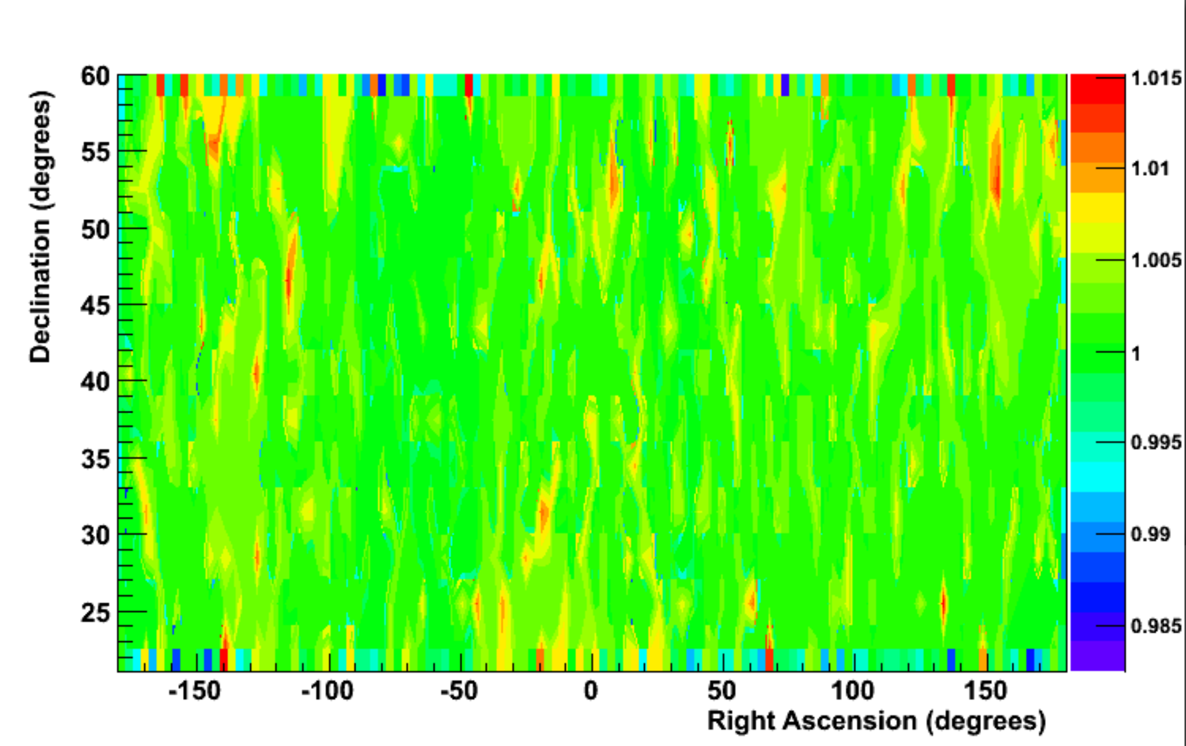


Results

✓ 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



Summary

- ✓ Multigap Resistive Plate Chamber (MRPC) technology used to create an array of muon telescopes for an overall area of $3x10^5$ km^2
- ✓ very good performance in terms of time resolution and efficiency
- ✓ good amount of results and teaching activity carried out
- ✓ new physics results with Run 2 data (large statistics expected)
- ✓ *young students involved in the project*
- ✓ new schools will join the project

Back up

Equatorial coordinates

- ✓ about 100 M events, collected by different EEE telescopes, were used to produce sky maps in equatorial coordinates
- ✓ the orientation of a muon track is defined by the values of the azimuthal angle ϕ (referred to the magnetic North direction) and by the polar angle θ (measured starting from the vertical direction), or by the altitude $a = (90° - \theta)$
- ✓ the use of the horizontal reference system implies that the coordinates of a sky object change with time (two muon tracks, seen as vertical by the same telescope but at different times, clearly originate from a different region of the sky)
- ✓ unambiguous position needed → the equatorial coordinate system makes use of the plane of Earth's equator, extending such plane to cut the celestial sphere
- ✓ the two coordinates in such a system are called Right Ascension (RA) and Declination (Dec)
- ✓ Dec is measured in degrees, positive north of the equator, negative south of it
- ✓ RA may be measured in hours (0 to 24) or in degrees (0° to 360°, or -180° to +180°), and the origin is usually related to a fixed direction in the sky

Equatorial coordinates

✓ given the orientation of a muon track its Dec and hour angle H are

$$sin\delta = sina\ sin\varphi + cosa\ cos\varphi_L\ cos\varphi$$

$$cosH = \frac{sina - sin\varphi_L\ sin\delta}{cos\varphi_L\ cos\delta}$$

where ϕ_L is the observer's geographical latitude

✓ the hour angle H and RA are related by the formula H = LST - RA
where LST is the local sidereal time, which depends in turn on the GPS time associated to the detected event

✓ since all the telescopes of the EEE network are presently located in Italy (along geographical latitudes between 37° and 46° North), they mostly cover the part of the sky between the equator and about 70° in Dec

✓ the coverage in Dec also depends on the largest polar angle with respect to the vertical visible by the telescope, that for most of the telescopes is around 40°