Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TOR VERGATA

RPCs to extend the sensitivity of particle sampling arrays to low gamma-ray energies

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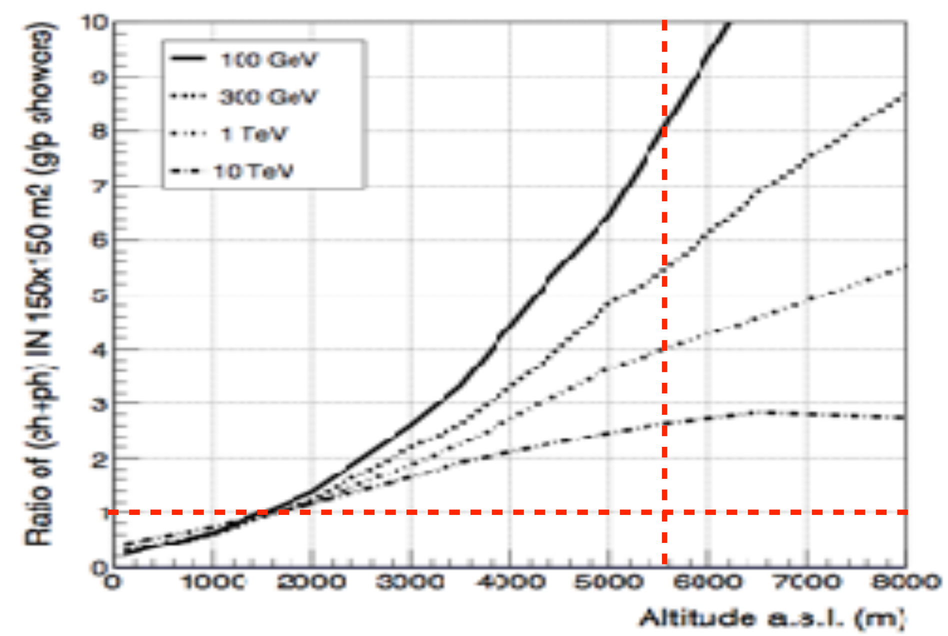
The key parameters in γ-ray astronomy

Sensitivity of a ground-based array in 1 year

$$S \propto \frac{\Phi_\gamma}{\sqrt{\Phi_{CR}}} \cdot \sqrt{\frac{A^\gamma_{eff}}{A^{CR}_{eff}}} \cdot \sqrt{A^\gamma_{eff}} \cdot \frac{1}{\sigma_\theta} \cdot Q_f \sim E_{thr}^{-2/3} \cdot R \cdot \sqrt{A^\gamma_{eff}} \cdot \frac{1}{\sigma_\theta} \cdot Q_f$$

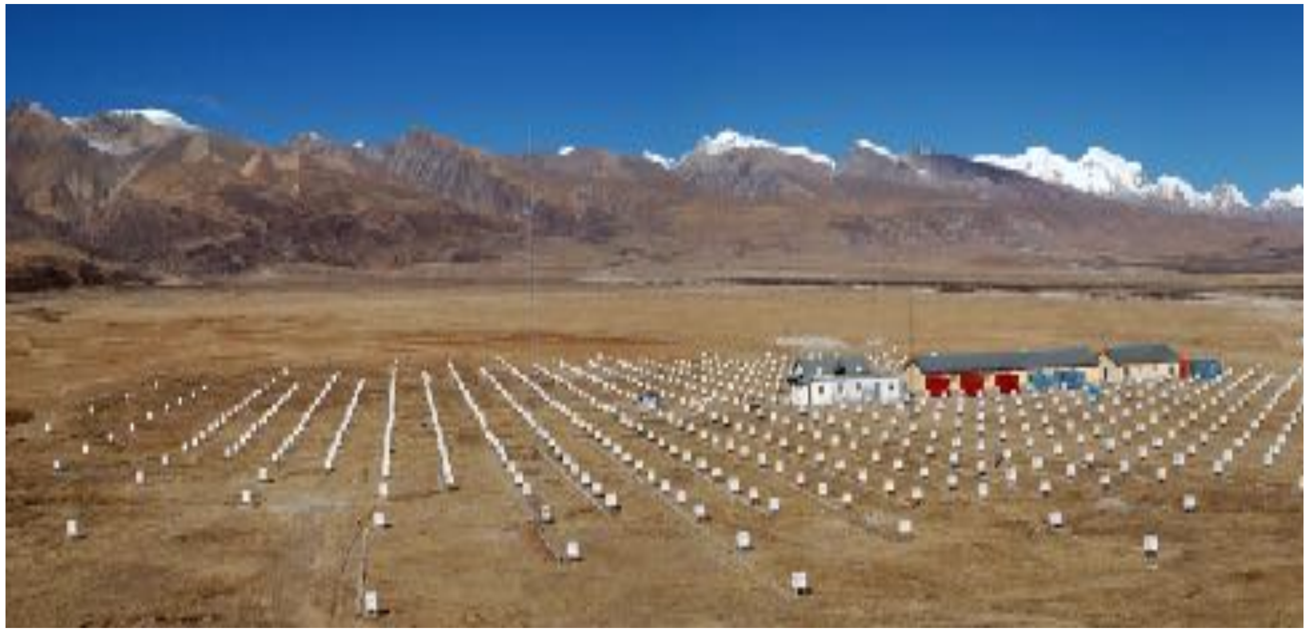
The key parameters to improve the sensitivity are

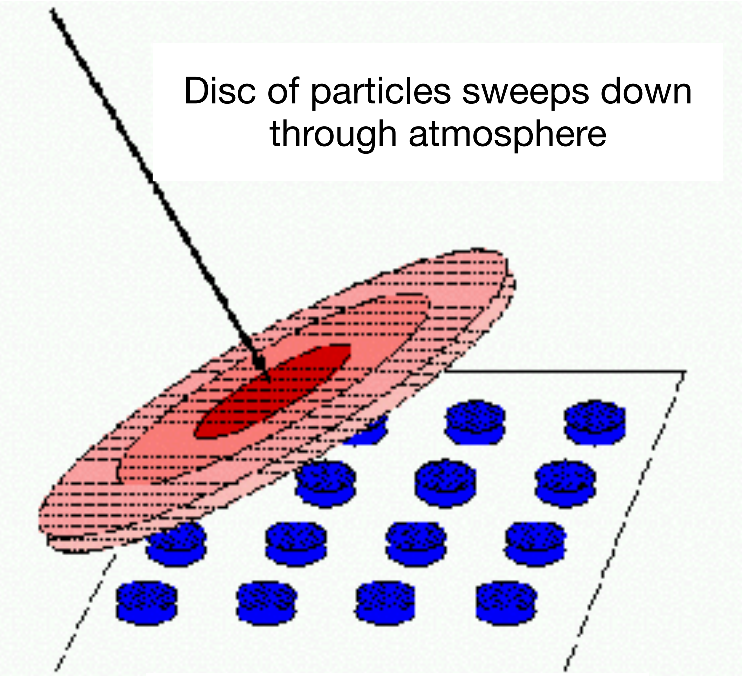
- The energy threshold E_{thr}
- R, the signal/background relative trigger efficiency (depends mainly on the altitude)
- The effective area A^γ_{eff} (not crucial for low energies)
- The angular resolution σ_θ
- Q-factor, the background rejection capability (with arrays mainly provided by muons)



A classical Air Shower Array

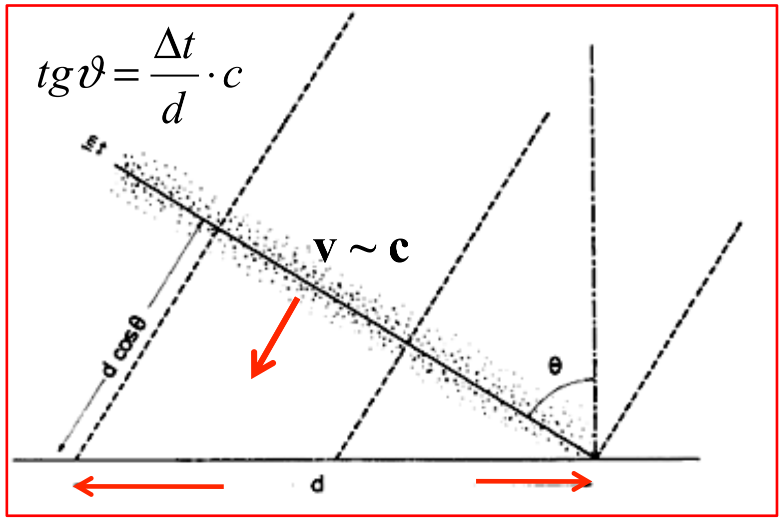
Large number of particle detectors
spread over an area of order 10^5 m^2





Detectors fire in sequence as shower front hits

scintillators, RPCs, water tanks (Cherenkov light in water), hadron calorimeters, muon detectors, emulsions, etc.



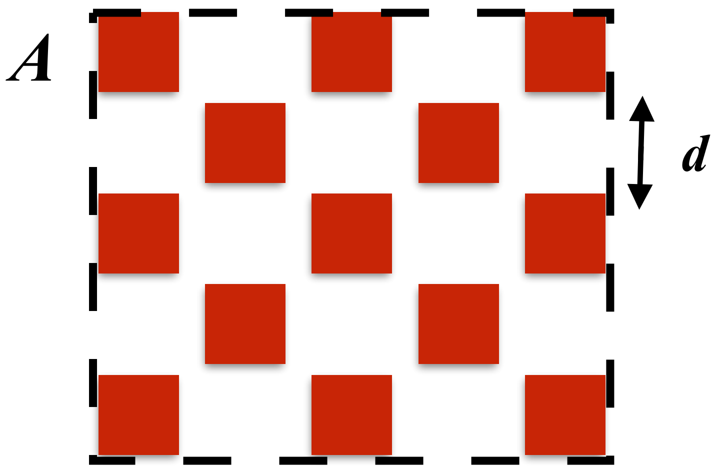
coverage factor (sensitive area / instrumented area) ***≈10^{-4} - 10^{-2}***

➜ *only a small sub-set of secondary particles are recorded*

100% duty cycle, relatively easy to operate
aperture = area of array (independent of energy)
energy resolution $\sigma(E)/E \approx 30\%$
Wide field of view instrument

Particle sampling with arrays

Sample lateral distribution with an array of detectors



A: *area of the array* (= instrumented area)

determines the rate of *high energy* events recorded
(i.e. the maximum energy via limited statistics)

d: *grid distance*

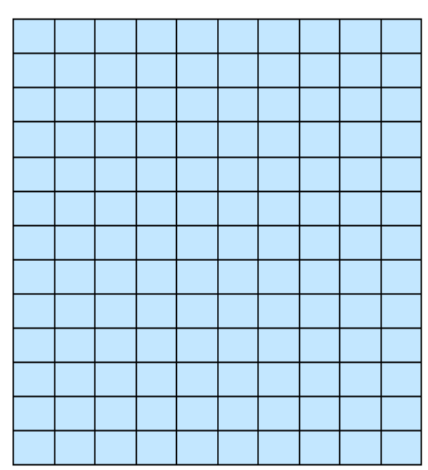
determines the *low energy* threshold
(small showers are lost in the gaps between detectors)
and the quality of sampling of the shower

C_d: *cost per detector*

determines quality, size, efficiency, resolution,…
i.e. detail of measurement

For best physics:

A large, d small, C_d high
But *cost* rises with $C_d A/d^2$



Always compromise needed.
How good is "good enough"?

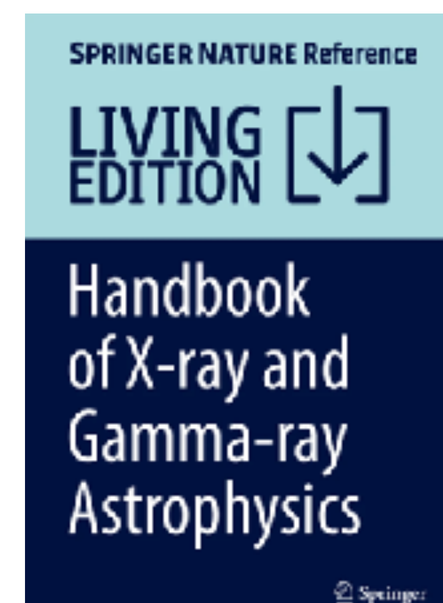
Detection of showers with arrays

From an experimental point of view, the sampling of secondary particles at ground can be realized with ***two different approaches***

(1) ***Particle Counting***. A measurement is carried out with thin (≪ 1 radiation length) counters providing *a signal proportional to the number of charged particles* (as an example, plastic scintillators or RPCs). The typical detection threshold is in the keV energy range.

(2) ***Calorimetry***. *A signal proportional to the total incident energy of electromagnetic particles* is collected by a thick (many radiation lengths) detector. An example is a detector constituted by many radiation lengths of water to exploit the Cherenkov emission of secondary shower particles. The Cherenkov threshold for electrons in water is 0.8 MeV and the light yield ≈320 photons/cm or ≈160 photons/MeV emitted at 41°.

The critical parameters of a detector are the *time* and the *amplitude resolutions*.



"Detecting gamma-rays with moderate resolution and large field of view: Particle detector arrays and water Cherenkov technique"
Michael A. DuVernois, Giuseppe Di Sciascio
Chapter for "Handbook of X-ray and Gamma-ray Astrophysics" (Eds. C. Bambi and A. Santangelo, Springer Singapore) arXiv:2211.04932

Milagro vs ARGO-YBJ

2 different approaches in the last 2 decades for TeV ground-based survey instruments

(1) Calorimetry: MILAGRO

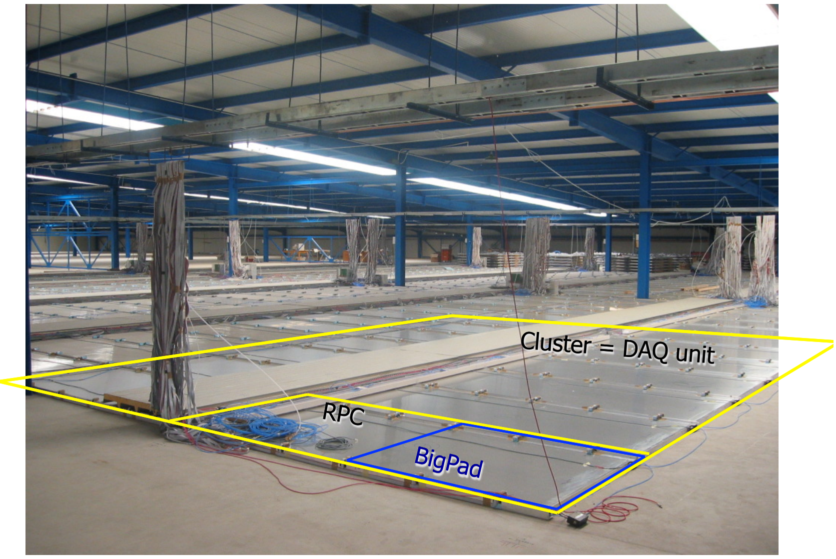
Water Cherenkov Technology

- operated from 2000 to 2008
- *2600 m* above sea level
- angular resolution ≈0.5°
- 1700 Hz trigger rate
- *Median Energy at the threshold: ≈ 2 TeV*
- *Energy range: 2 - 40 TeV*
- poor background rejection (with outrigger)
- conversion of secondary photons in water

Widely used technology in cosmic ray physics

(2) Particle Counting: ARGO-YBJ

Resistive Plate Chamber Technology

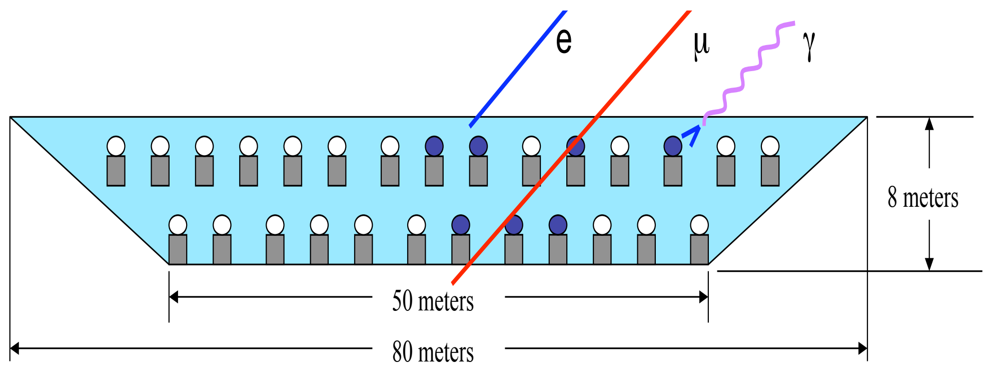


- operated from 2007 to 2012 (final configuration)
- *4300 m* above sea level
- *angular resolution ≈0.5° at 1 TeV*
- 3500 Hz trigger rate
- high granularity of the readout
- *Median Energy at the threshold: ≈340 GeV*
- *Energy Range: 340 GeV - 10 PeV*
- NO background rejection (no outrigger)
- NO conversion of secondary photons (no lead)

Widely used technology in particle physics

Milagro vs ARGO-YBJ

Milagro
Water Cherenkov Technology



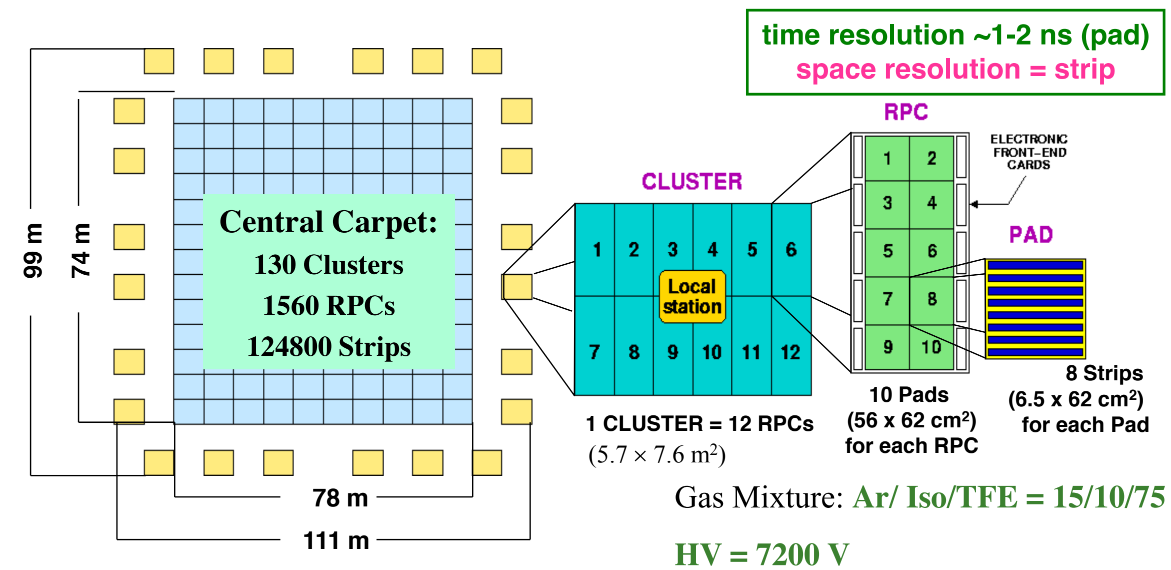
Central 80 m x 60 m x 8 m water reservoir, containing two layers of PMTs

- 450 PMTs at 1.4 m below the surface (top layer)
- 273 PMTs at 6 m below the surface (bottom layer)

Outrigger Array, consisting of 175 tanks filled with water and containing one PMT, distributed on an area of 200 m x 200 m around the central water reservoir.

→ ***HAWC*** and ***LHAASO***

ARGO-YBJ
Resistive Plate Chamber Technology



Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m²)
+ sampling guard ring (6700 m² in total)

Space pixels: *146,880 strips* (7×62 cm²)
Time pixels: *18,360 pads* (56×62 cm²)

2 read-outs:

$\rho_{max-strip} \approx 20$ *particles/m²*

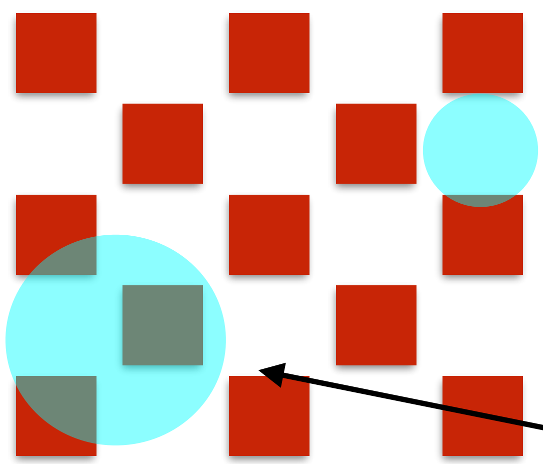
$\rho_{max-analog} \approx 10^4$ *particles/m²*

→ ***MATHUSLA*** proposal, CR and hadronic physics at CERN (RPC carpets above CMS/ATLAS)

Main limits of a classical array

(1) Higher energy threshold

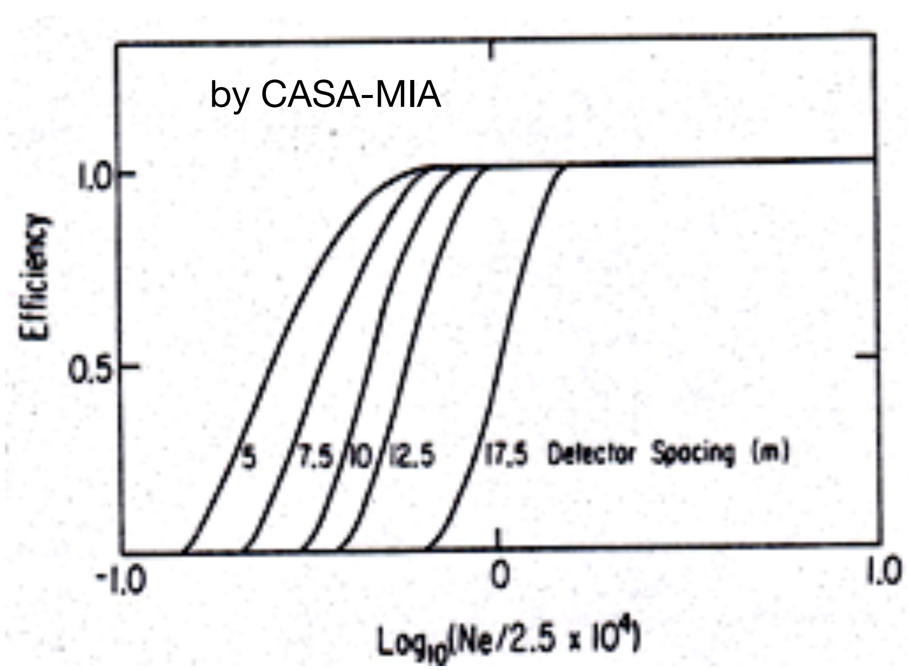
sparse array



low energy shower = small shower
➔ NO trigger

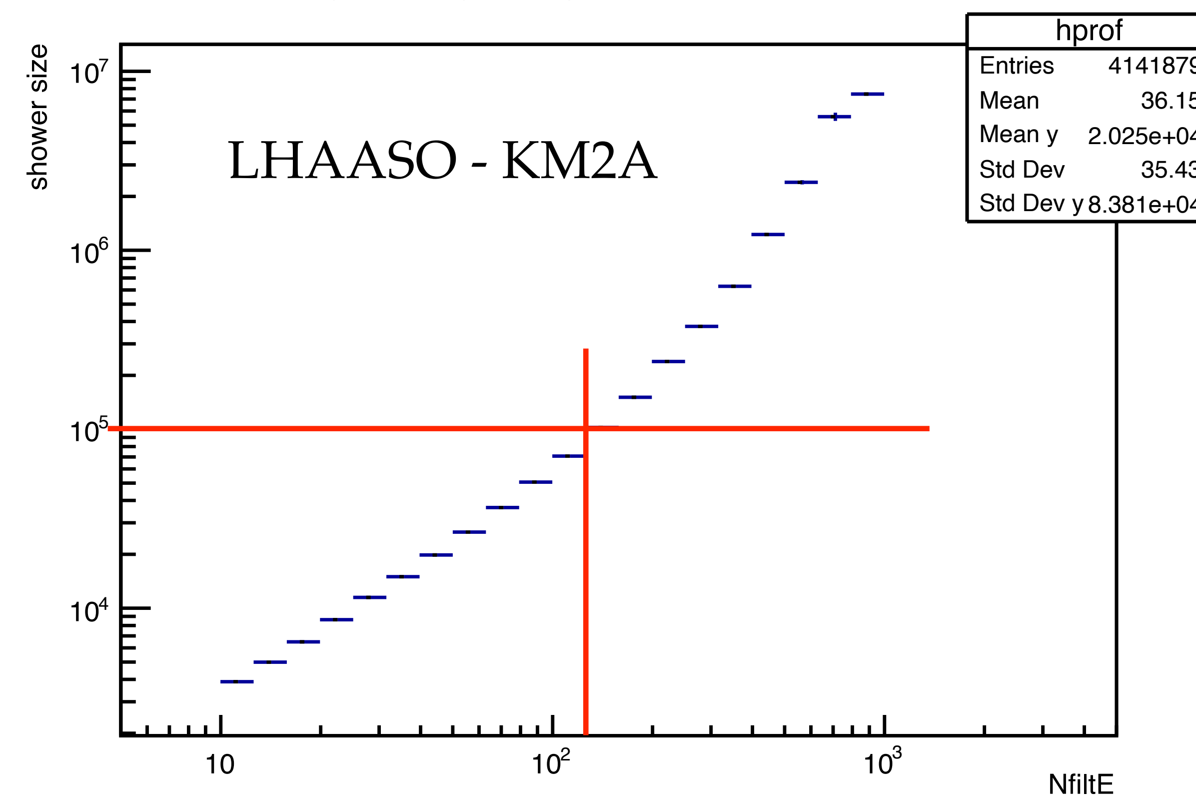
high energy shower = big shower
➔ OK trigger

coverage factor ≈ 10^{-3} - 10^{-2}



(2) Poor sampling → large fluctuations

shower size v.s. number of fired ED

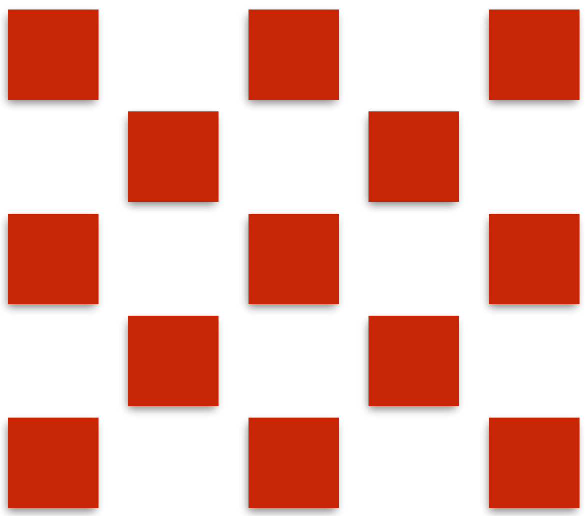


Reducing detector spacing → Lower the energy threshold

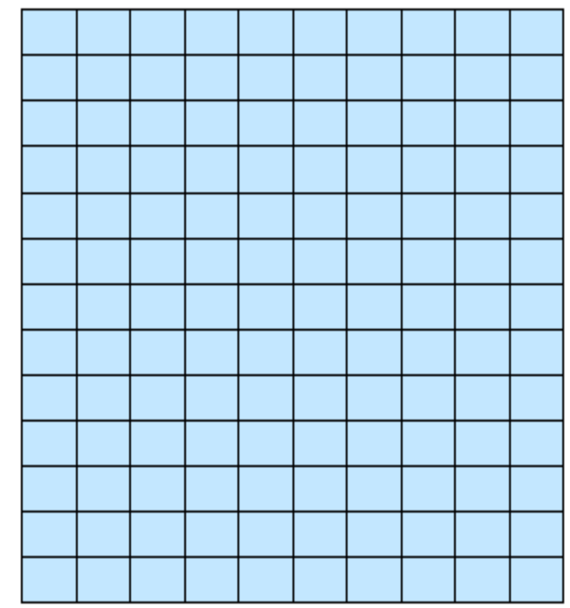
Full coverage approach

The "full coverage" approach

sparse array



coverage factor ≈ 10^{-3} - 10^{-2}

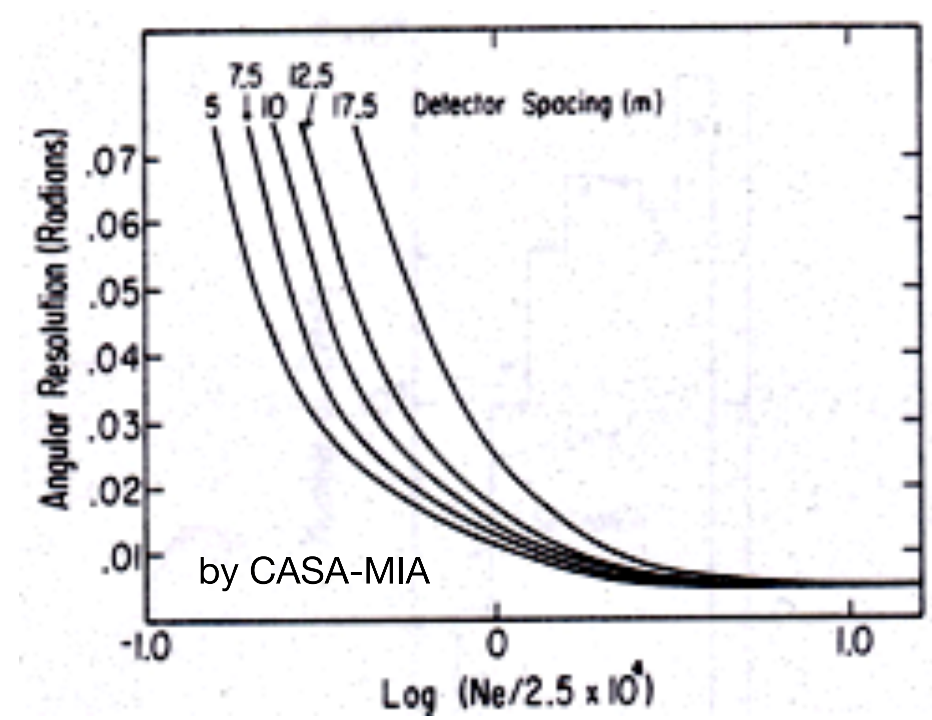


a continuous "carpet" of detectors

coverage factor >90%

Increasing the sampling (~1% ➜100%)

- Lowers energy threshold
- Reduces the sampling fluctuations
- Improves angular resolution



Angular resolution and time resolution

Angular resolution

$$\sigma_\theta \propto \frac{\sigma_t(N)}{\sqrt{N}}\sqrt{\sec\theta}$$

Shower multiplicity

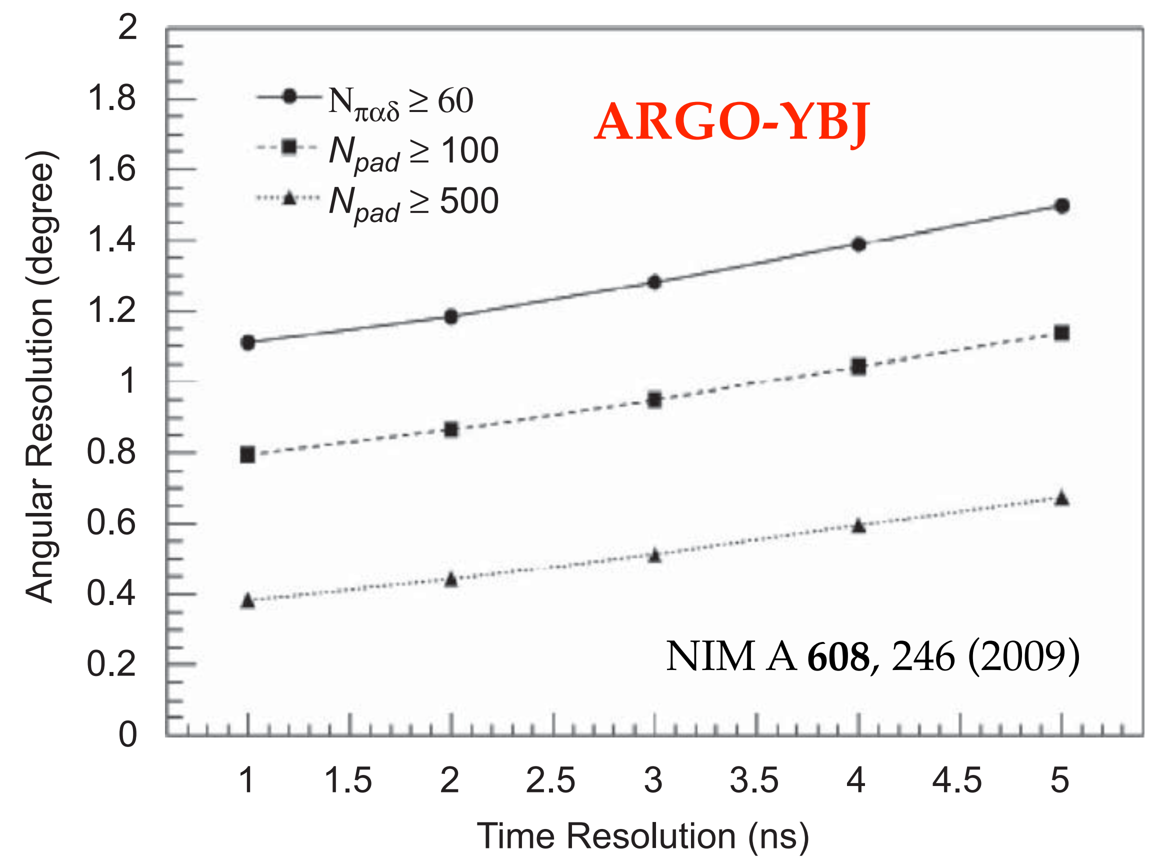
→ Large number of time pixels improves the time resolution → ***Full coverage***

The *time resolution* can affect the *angular resolution* of the apparatus if it is not comparable with the rising edge of the shower front (~ns).

→ **Detector with time resolution $\approx ns$ mandatory!**

Full coverage reduces this effect

Angular resolution limited to 0.1˚ - 0.15˚ mainly due to the description of the temporal profile

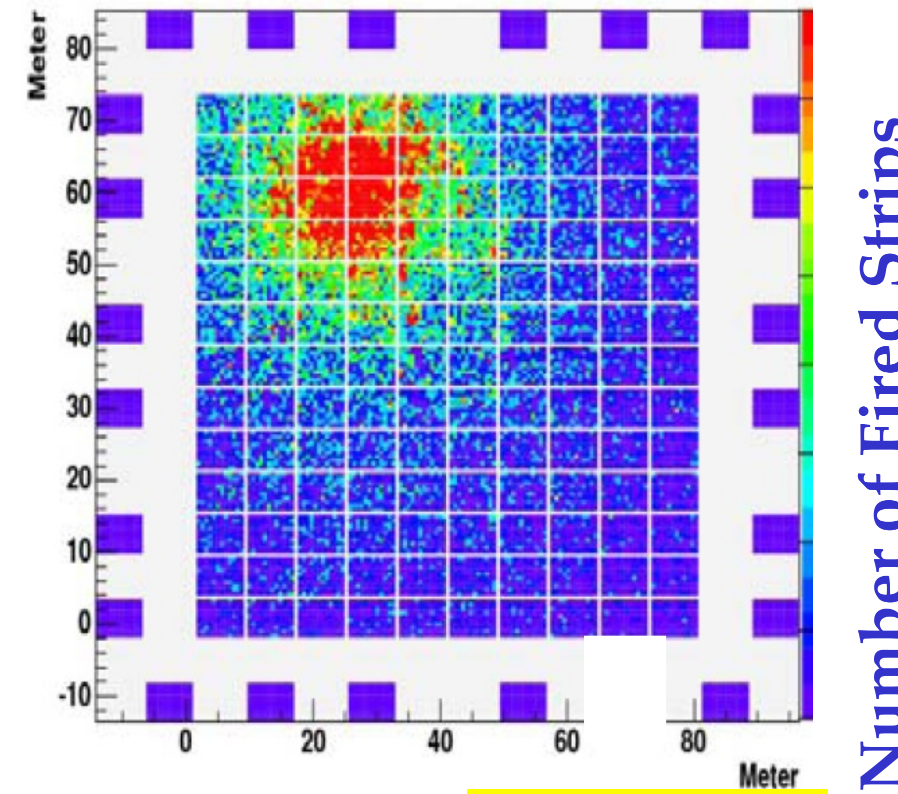


“Full coverage” with high segmentation of the readout

A “full-coverage” detector allows to exploit a *high segmentation of the read-out*

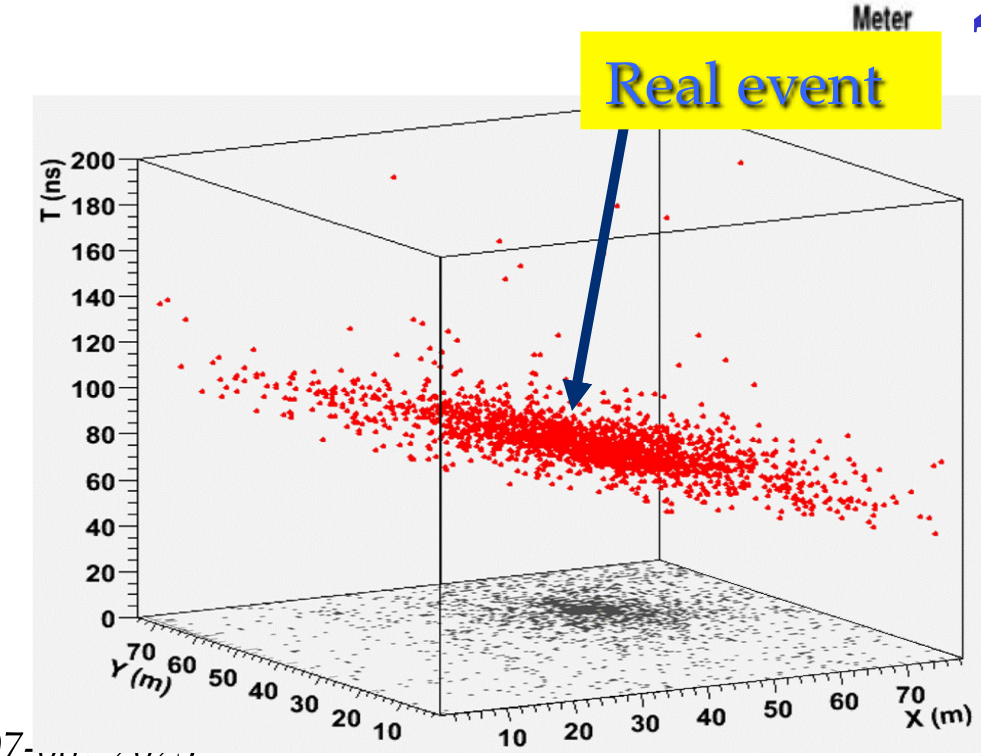
- To further improve the quality of the sampling
- To further lower the energy threshold

→ *Small space - time pixels*



ARGO-YBJ strip/pad readout

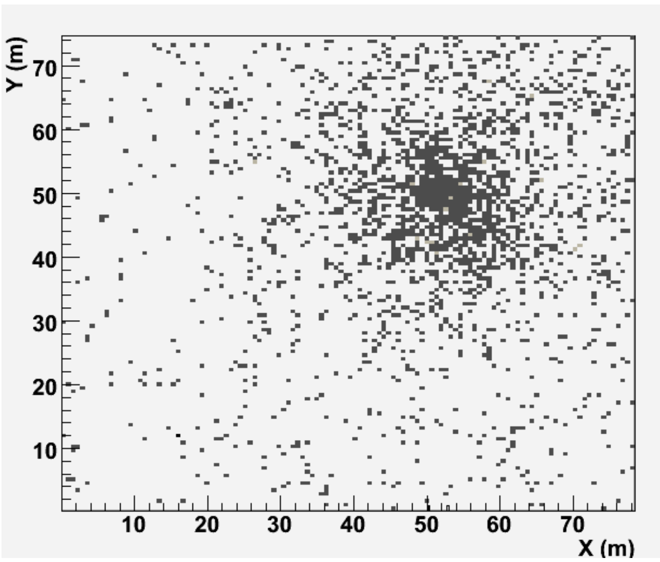
Space pixels: 146,880 strips (7×62 cm²)
Time pixels: 18,360 pads (56×62 cm²)



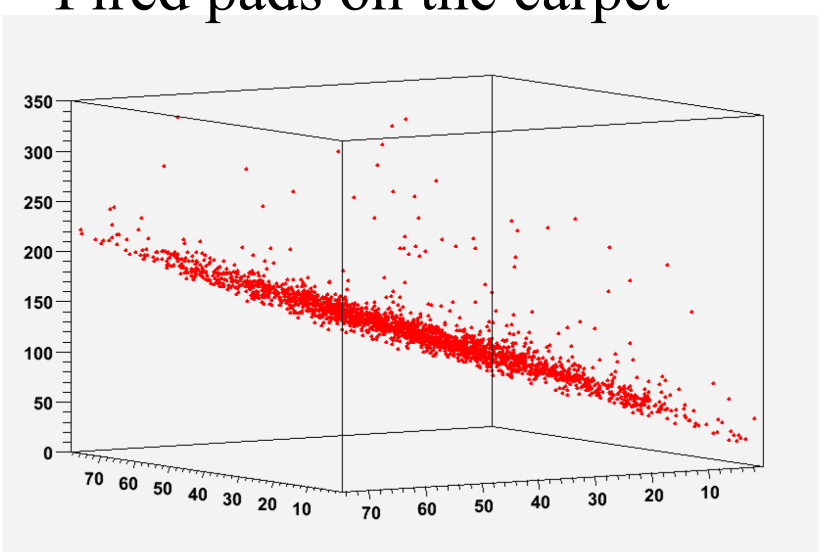
The granularity of the read-out is made possible by the particular detector utilised: the ***Resistive Plate Chamber***

Shower detection with small space-time pixels

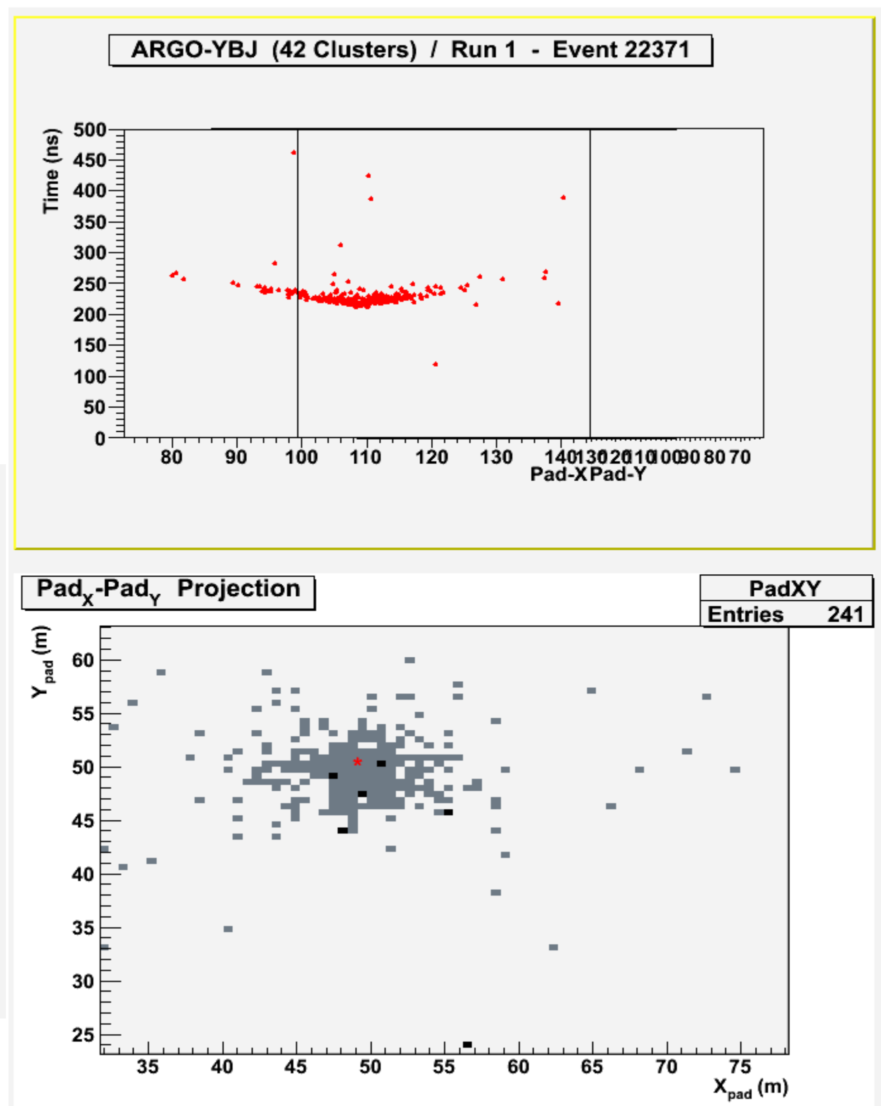
Small and compact events

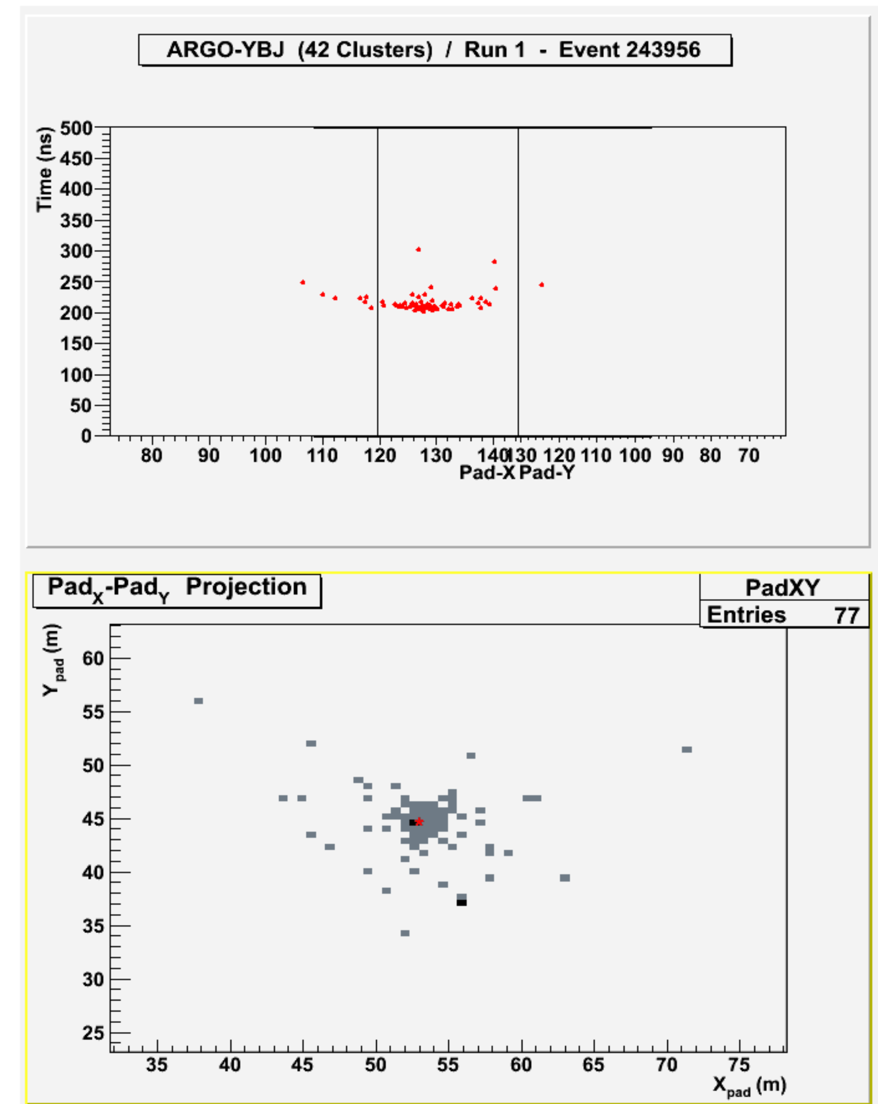


Fired pads on the carpet



Arrival time vs position

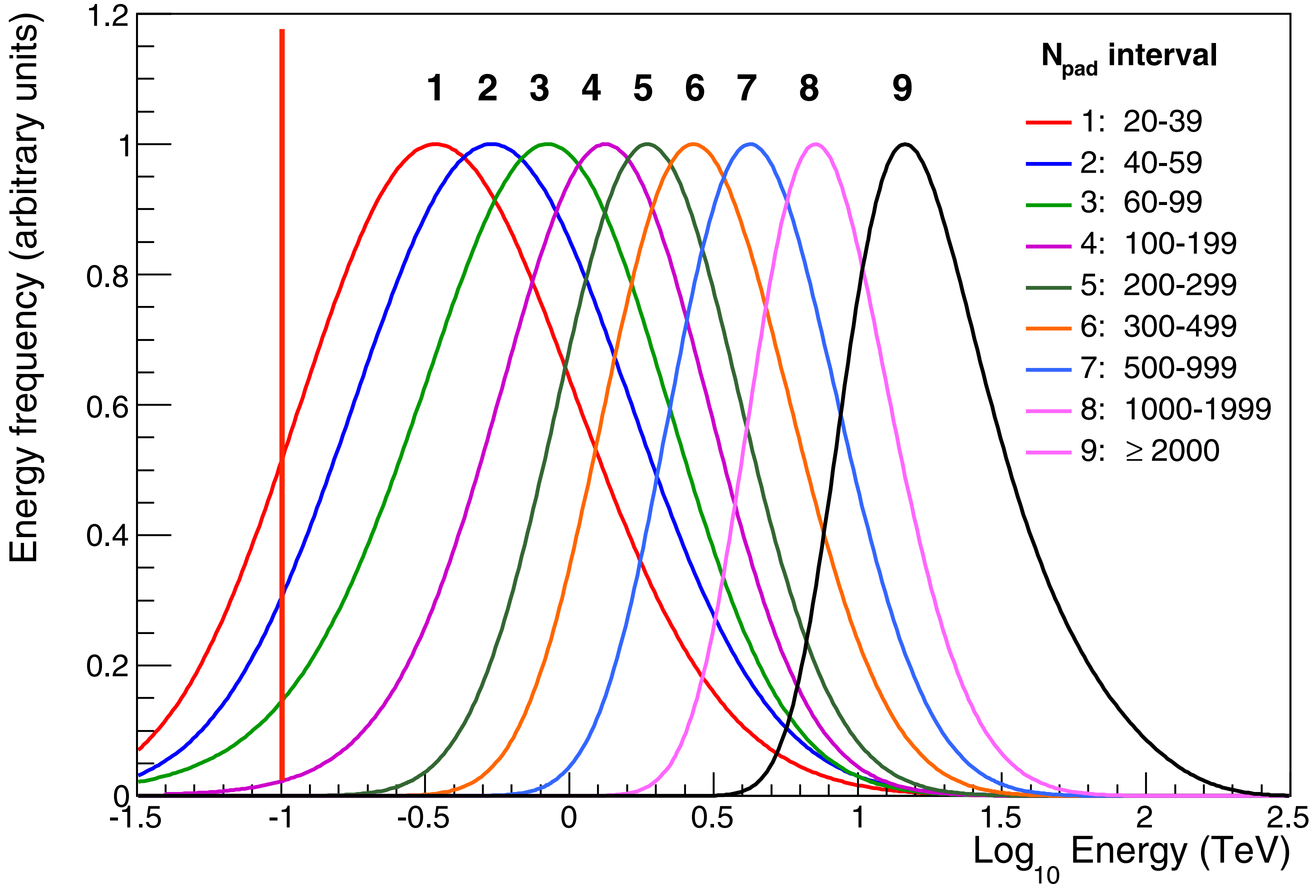




Space pixels: *146,880 strips* (7 × 62 cm^2)
Time pixels: *18,360 pads* (56 × 62 cm^2)

ARGO-YBJ energy threshold

ARGO-YBJ (ALL triggered events, not internal)



ApJ 842 (2017) 31

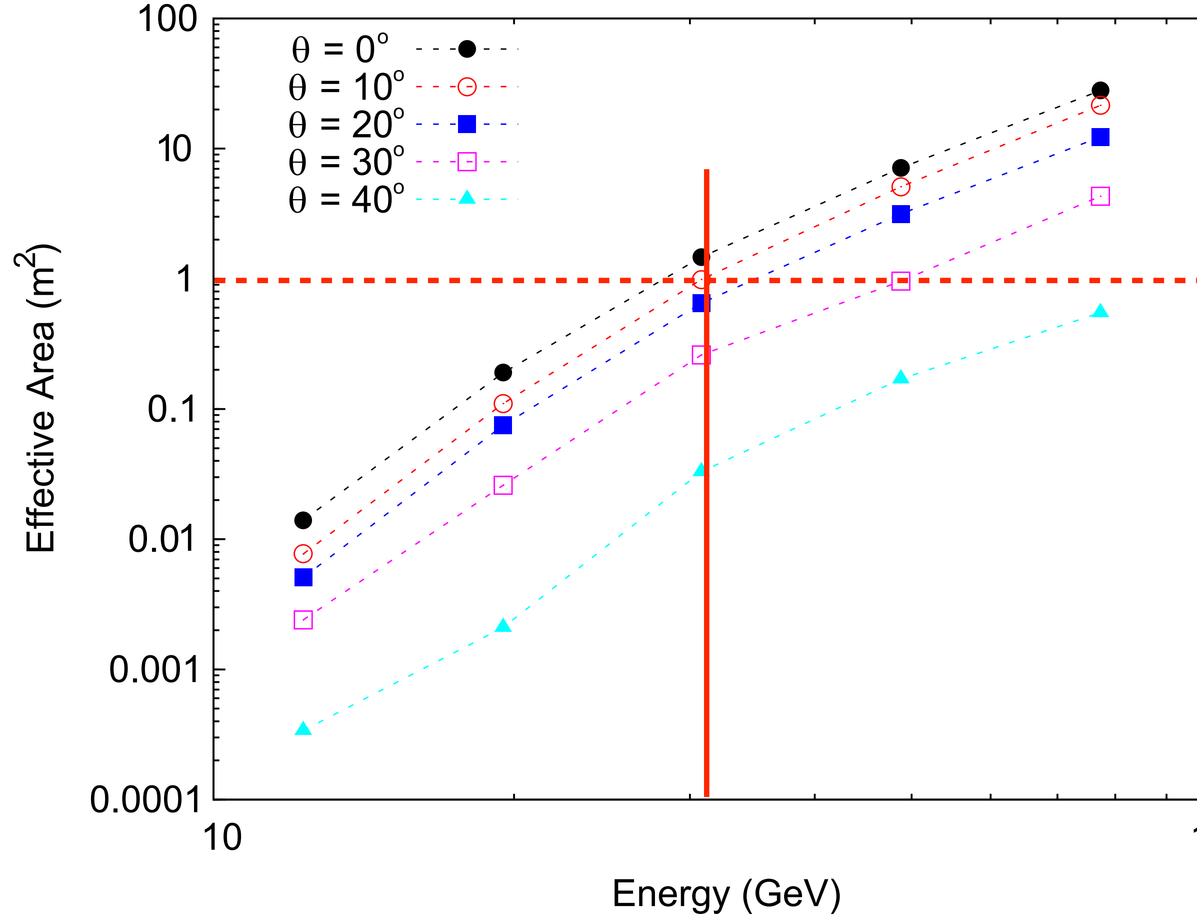


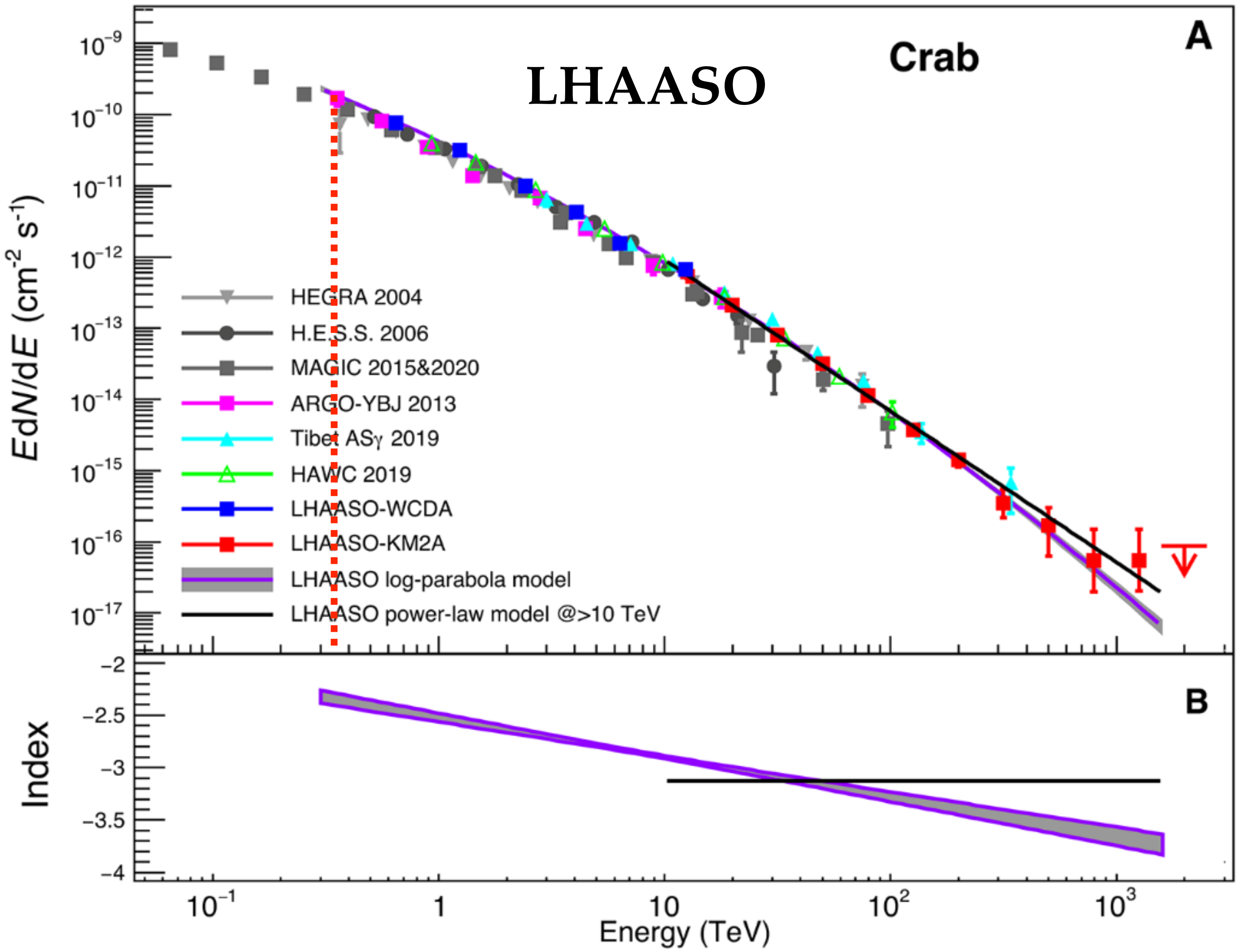
Figure 2. Effective area of ARGO-YBJ for events with $N_{pad} = 20–60$ and different zenith angles, as a function of the primary energy.

Inclusive trigger by a majority of 20 pads out 15,600 pads *accidental free!*

Noise: 380 Hz/pad

1 m² at ≈30 GeV!

The 100 GeV challenge (ARGO-YBJ)



median energy of first mult. bin: ***340 GeV***, with ε_γ ***(100 GeV) = 73%*** at 4300 m asl

ARGO-YBJ: the only array who measured the Crab spectrum starting from ≈300 GeV !

Waiting for LHAASO-WCDA

RPCs are the only detection technique that demonstrated the capability to detect showers in the 100 GeV range

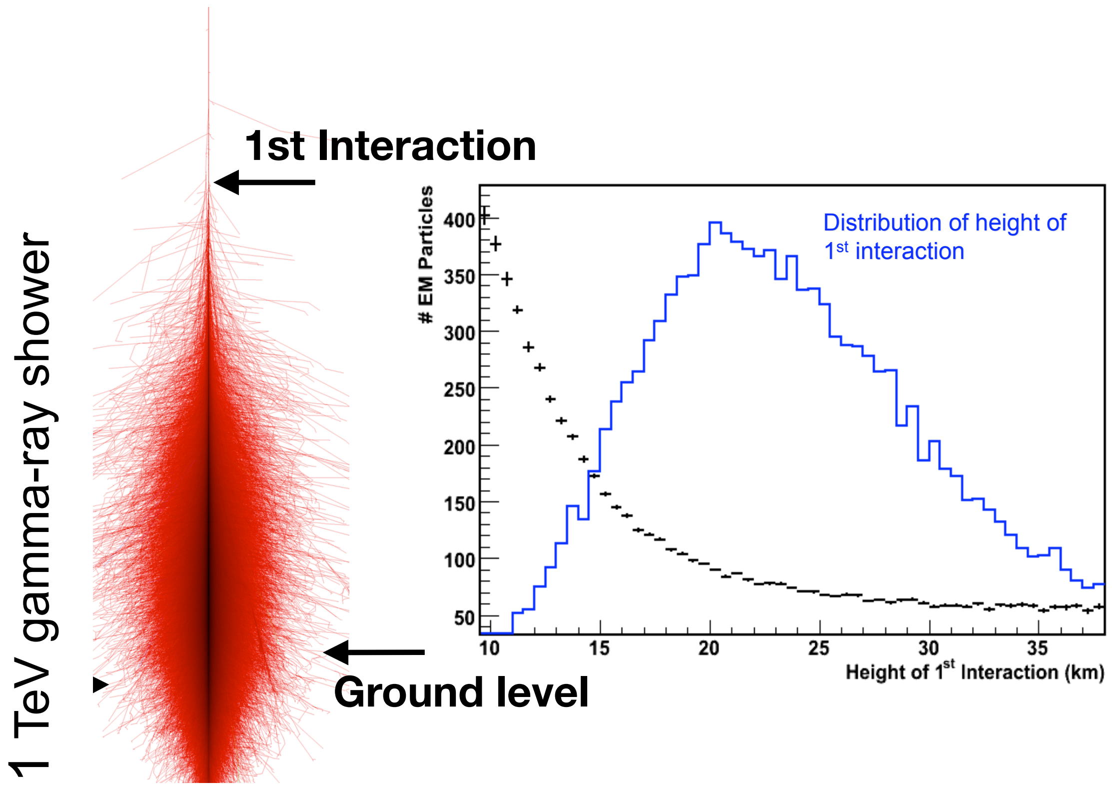
Very silent detector (380 Hz/pad, a half from soil radioactivity) and a particle multiplicity built up correlating at different time scales increasing portions of the carpet (cluster, supercluster,…. full detector) made it possible to achieve this performance.

Energy resolution

The energy resolution is given by the folding of

Shower fluctuations
Fluctuations in the depth of the first interaction point

Sampling fluctuations
Fluctuations in the measured number of secondary particles



Shower fluctuations dominate energy resolution of EAS arrays.

Can be reduced with high coverage and high granularity of the read-out
➜ all particles are measured !

HAWC: 40% - 55% at 1 TeV (gamma internal)
HAWC: 23% - 30% at 50 TeV (gamma internal)

ARGO: 10% at 10 TeV (protons internal)
ARGO: 5% at 100 TeV (protons internal)

IACT: 8% - 15% at 1 TeV
IACT: 15% - 35% at 50 TeV

The PeV challenge (ARGO-YBJ)

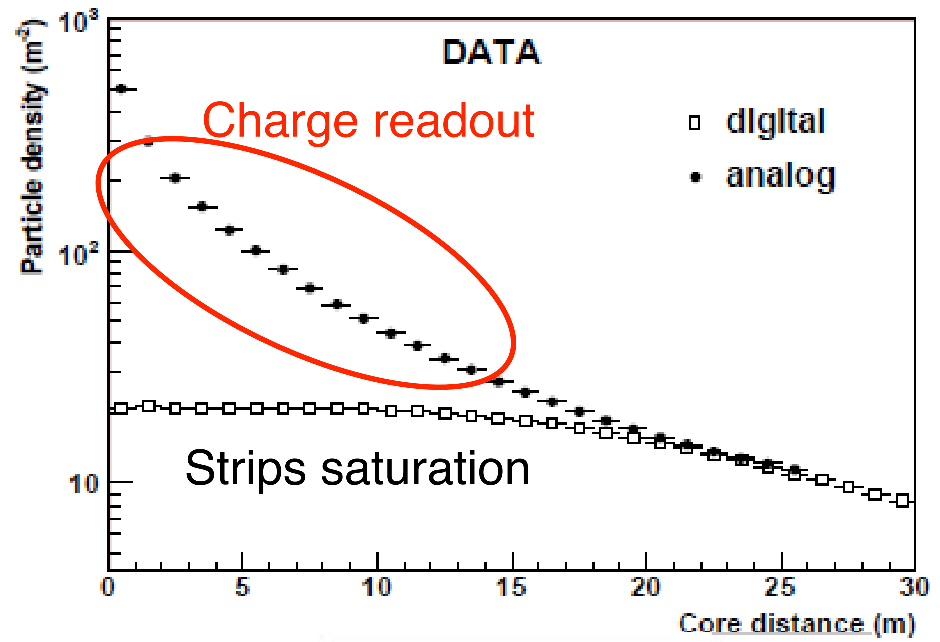
These RPCs have been also equipped with 2 large Big Pads to *collect the total charge* and measure the number of particle hitting the detector.

Indeed the operation in *streamer mode* assures a *high uniformity of the charge delivered by each particle.*

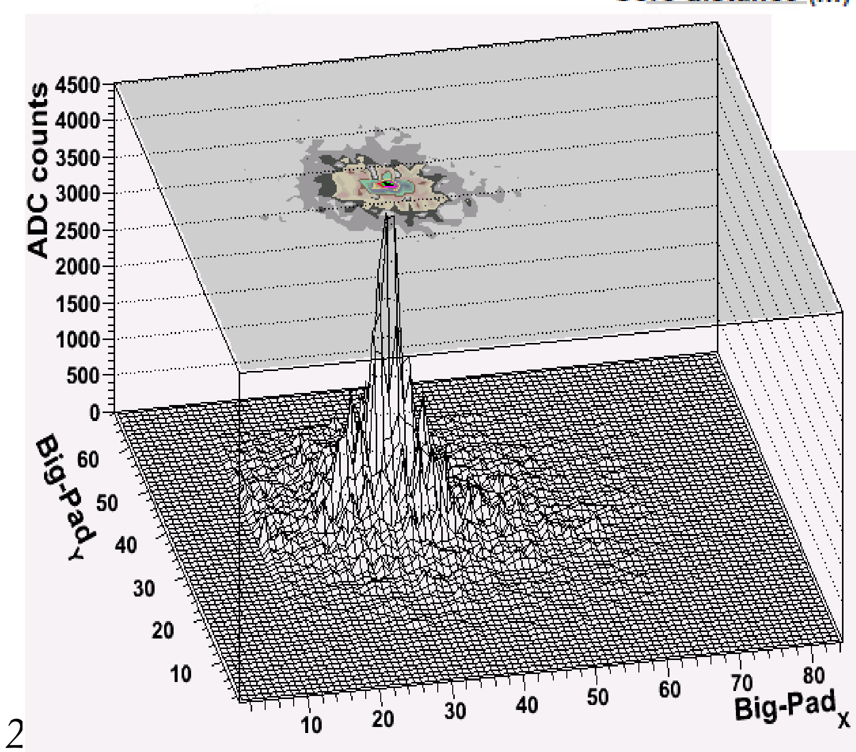
Particle number used as energy proxy

time resolution about 1.5 ns (including electronics)

- up to 20/m^2 by digital read-out ➜ *200 TeV*
- up to 8 x 10^4/m^2 at least by charge read-out, resolution = 20% /$\sqrt{N}$ + 4.4% ➜ *10 PeV*



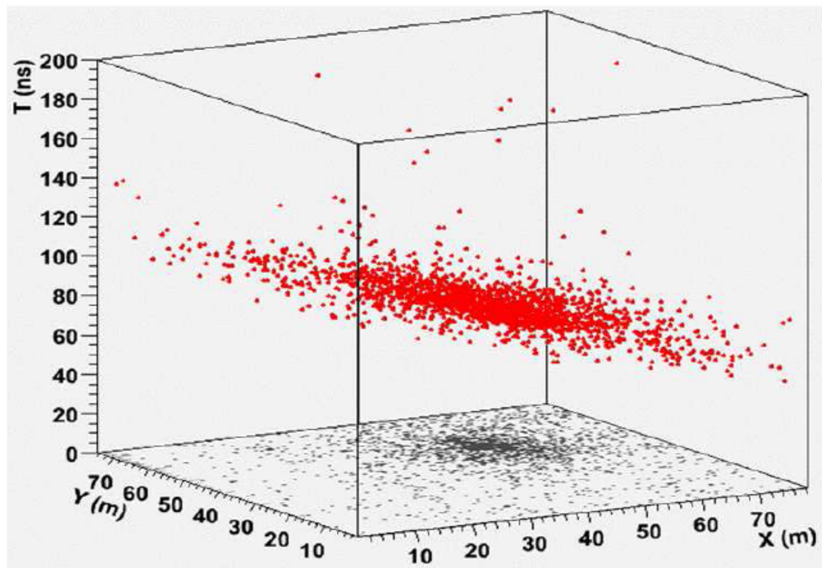
High stability (efficiency ≈ 97%, T = 8° ÷ 22° C)

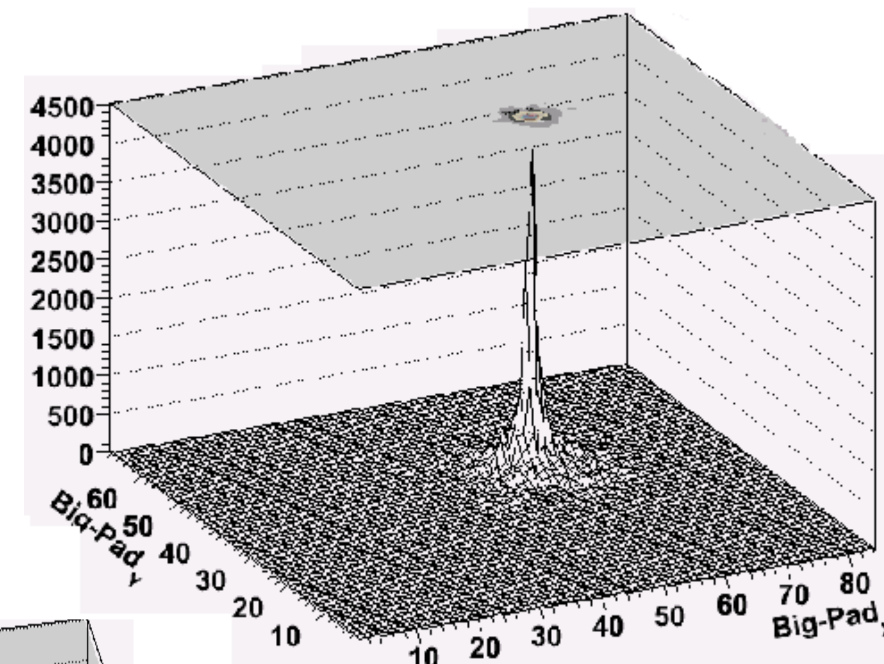


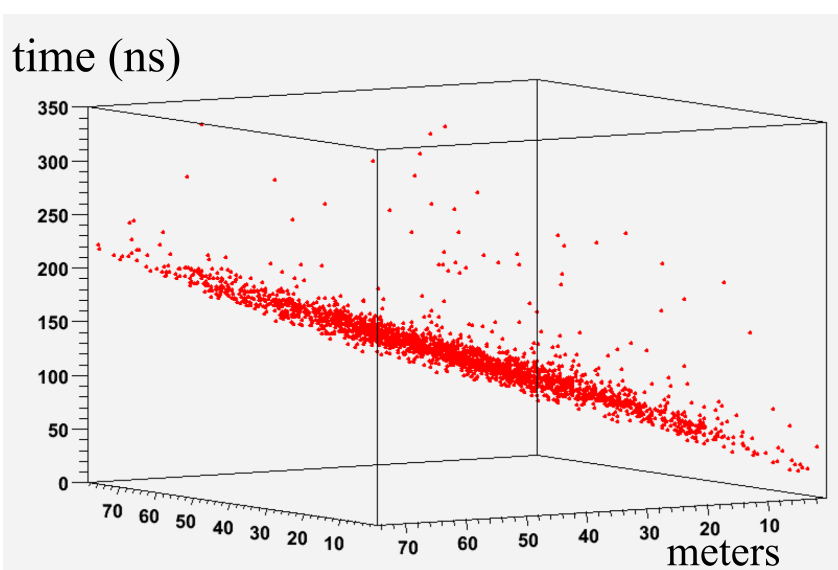
- the *main drawback*: the need of a high gas flow, about 4 volume changes /day
- for a large-scale use a gas recirculation/purification system is needed to operate these RPCs in closed loop

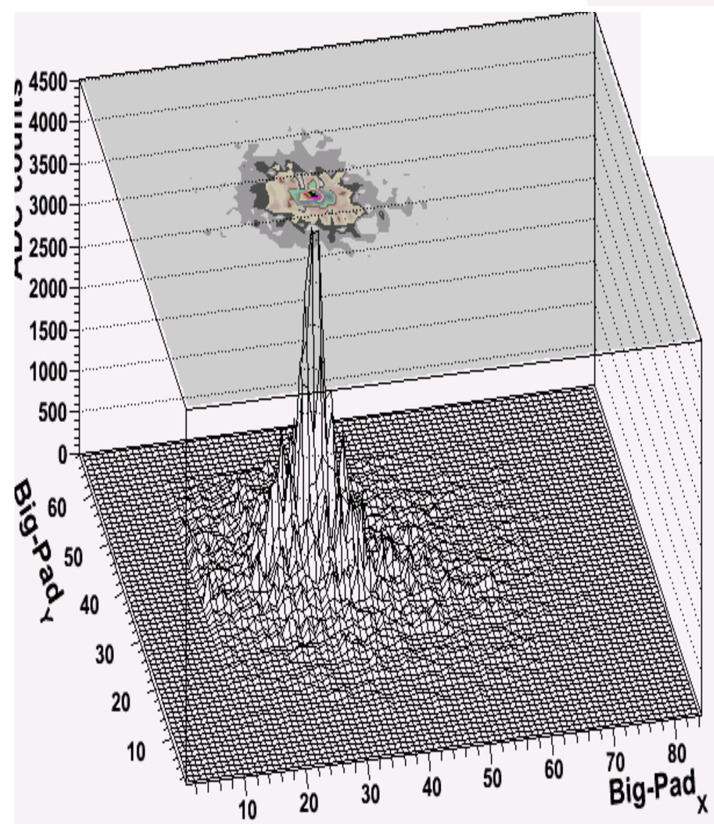
The imaging capability of RPCs ARGO-style

The same shower as seen by the digital readout (left) and by the charge readout (right)









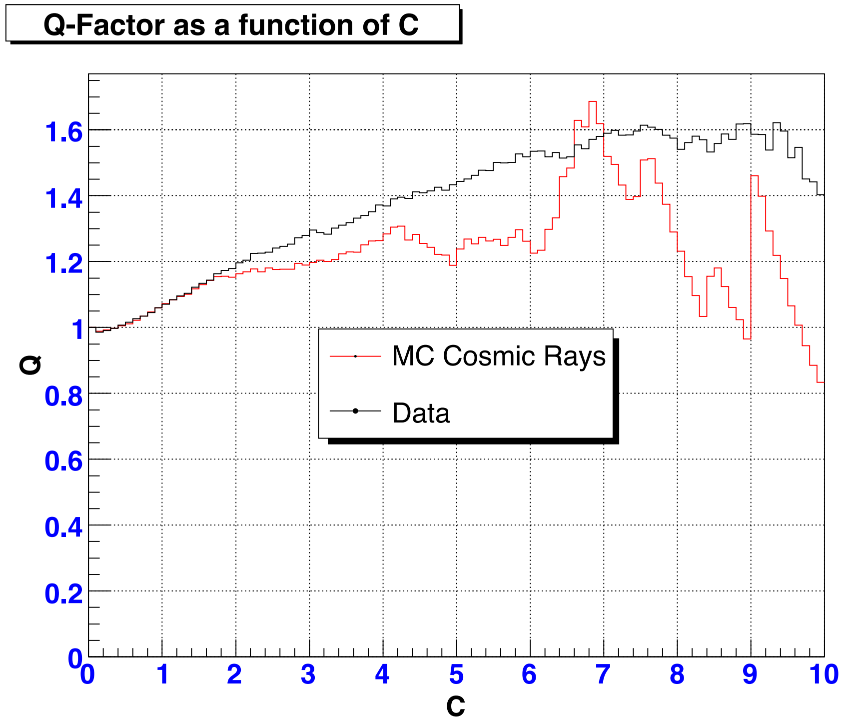
Unprecedented details in the core region useful to study hadronic interactions

Background rejection: Milagro

compactness parameter

$$C = \frac{N_{bot \geq 2PEs}}{PE_{maxB}}$$

where $N_{bot \geq 2PEs}$ is the number of PMTs in the bottom layer with more than 2 PEs, and PE_{maxB} is the number of PEs in the bottom layer tube with the maximum number of PEs.



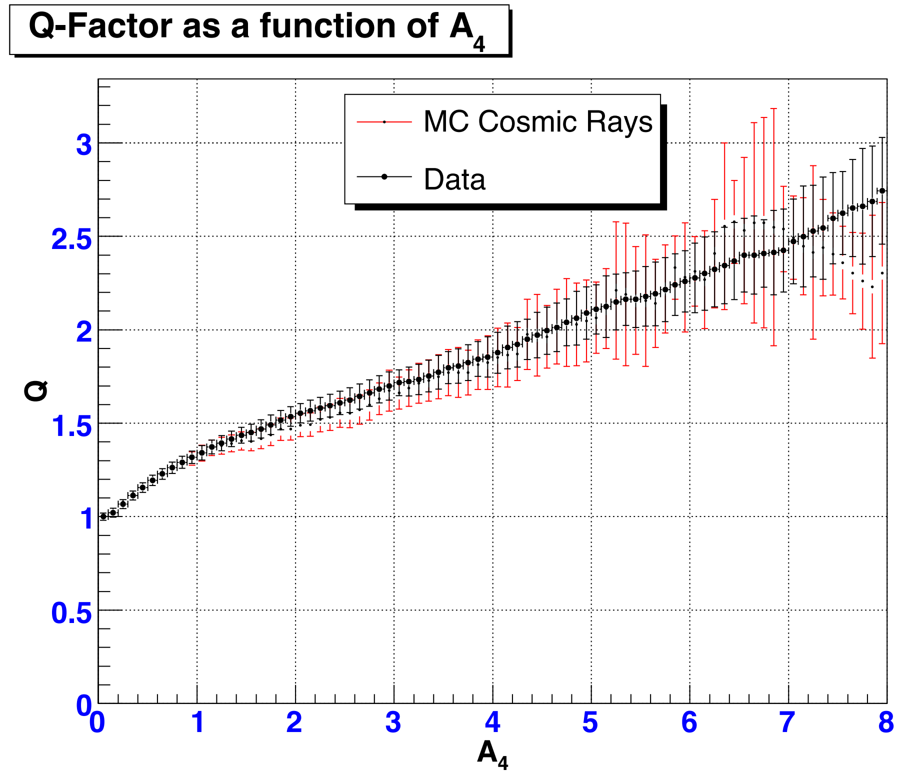
Consistent with ARGO findings after cuts on χ^2 of the temporal fit

$$A_4 = \frac{(f_{top} + f_{out}) \times N_{fit}}{PE_{maxB}}$$

- f_{top} is the fraction of the air shower layer PMTs hit in an event.
- f_{out} is the fraction of the outriggers hit in an event.
- N_{fit} is the number of PMTs that entered in the angle fit.

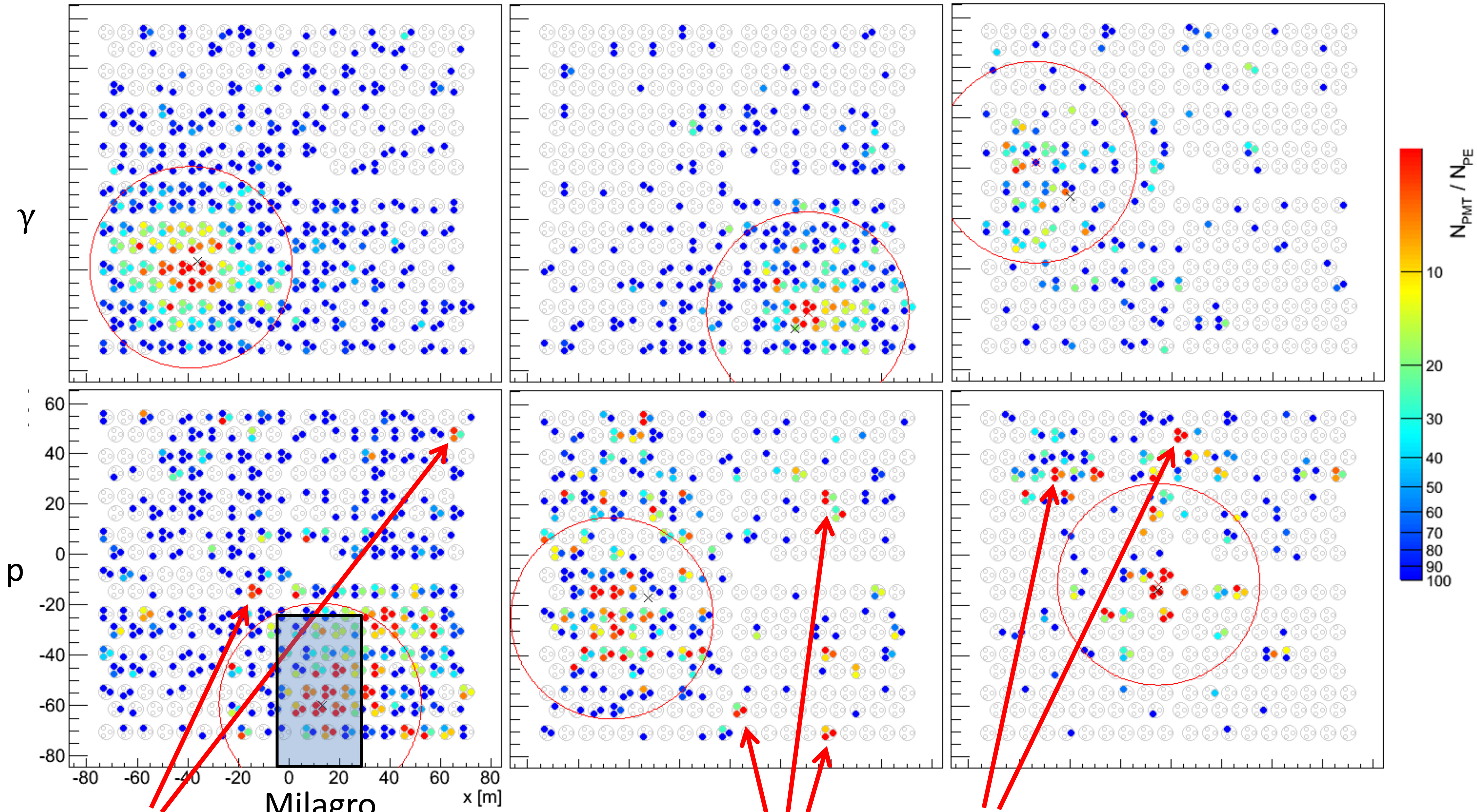
$(f_{top} + f_{out})$ = info on the size of the shower

N_{fit} carries information about how well the shower was reconstructed. PE_{maxB} carries information about the *clumpiness in the muon layer* that is due to the penetrating muons and hadrons which are mostly presented in hadronic air showers.



Abdo, PhD thesis

Dimensions are important…



- Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location

Well known! In fact, 30 years ago we proposed to INFN a 120×120 m² full coverage carpet…
With a possible muon detector below!

What's next? γ-ray astronomy in the South

LHAASO observed a lot of sources above 100 TeV with a maximum emission up to 1.4 PeV in the North

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26_{-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71_{-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

Nature 594: 33-36 (2021)

We expect to observe dozens of γ sources above 100 TeV in the South, probably up to 10 PeV range ("SuperPeVatrons")!

→ We need a new array with a wide dynamical range: 50 GeV → 10 PeV!

An idea from scratch for a new wide FoV array

A "core" detector made by a 150 x 150 m² RPC carpet above a muon detector

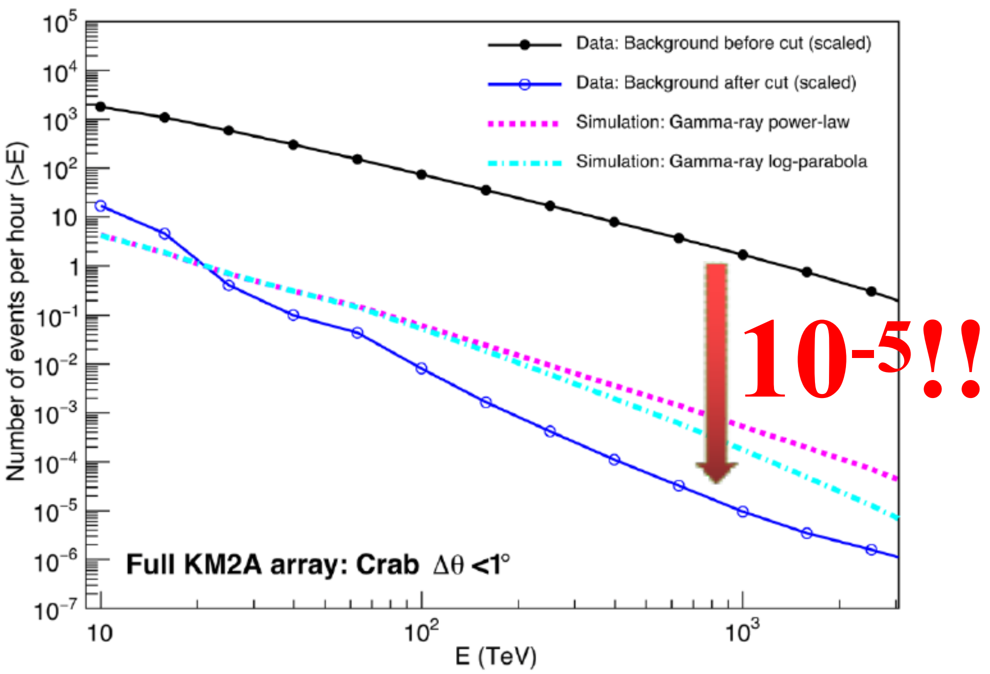
+ an array >0.5 km² to improve statistics above 100 TeV

Detection of muons is the key to reject background of charged CRs

BUT, to detect PeVatrons in a bkg-free regime
a bkg rejection at 10^{-5} level is mandatory!

Determination of muon number is far from trivial.

Although muons represent ≈10% of all charged particles in a typical EAS at ground level *their density is very low* owing to their wide lateral distribution which results from their large production height.

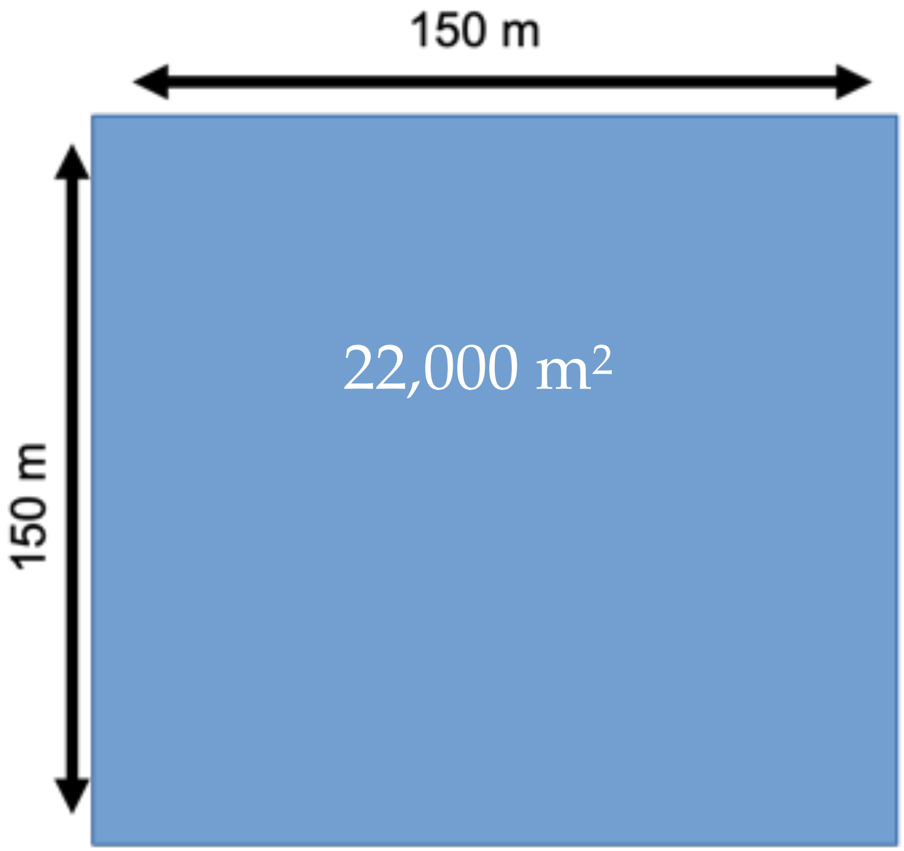


Example: *a 10^{15} eV proton shower contains about 10^4 muons above 300 MeV at sea level (≈10 μ/TeV).*
Density in the shower core ≈1 m^{-2} ➜ a 100 m² detector will register at most ≈1% of all μ in the EAS!
In typical arrays there is only 1 μ-detector
Small number of measured muons ➜ large sampling fluctuations

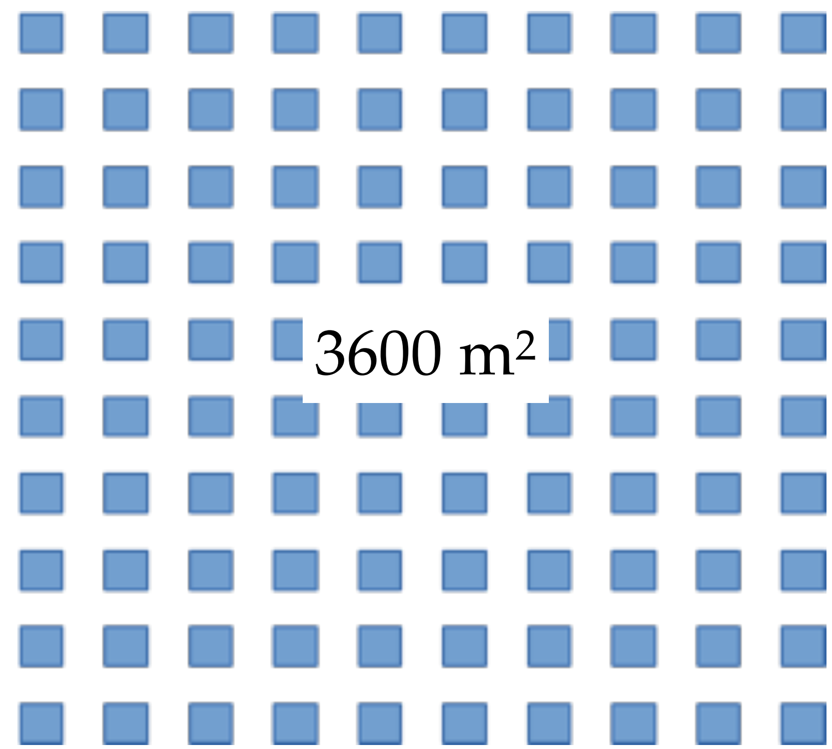
To improve the number of measured muon in the TeV range ➜ ***Full Coverage Muon detector !***

Muon detector layouts below the RPC carpet

A water Cherenkov pond



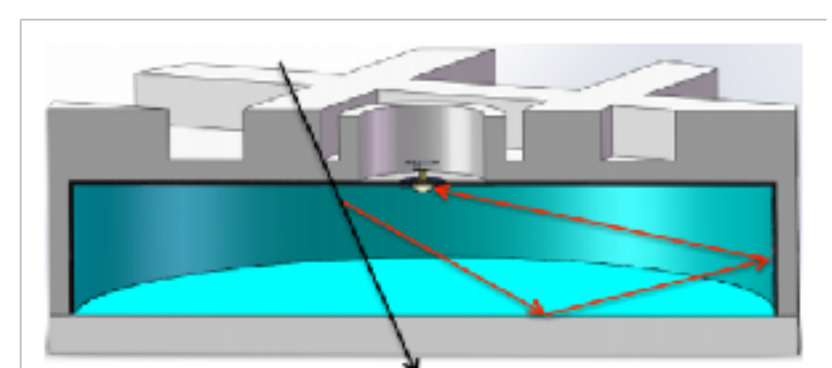
A water Cherenkov array (tanks) below RPC carpet



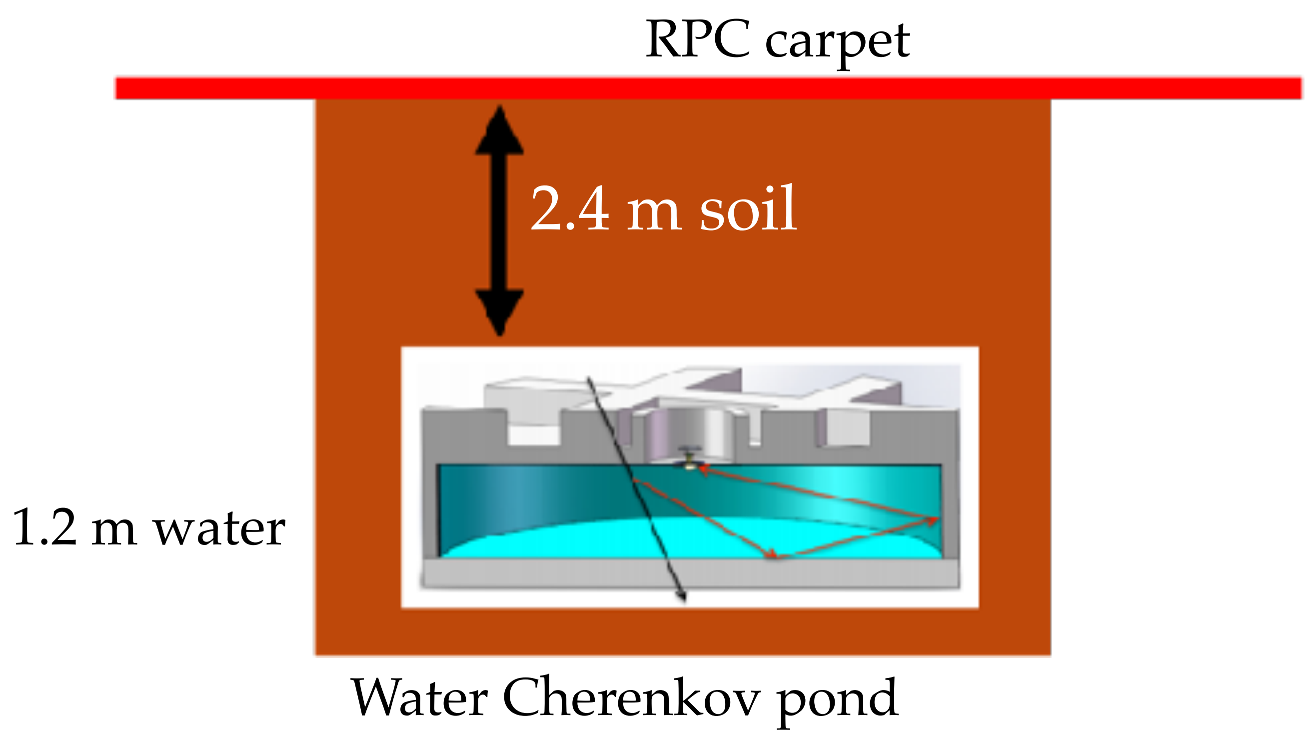
10 x 10 muon detectors 6x6 m² each separated by 10 m

Few muons at low energy.
bkg rejection increases with the number of muons
→ full coverage pond to increase the bkg rejection capability at lower energies.

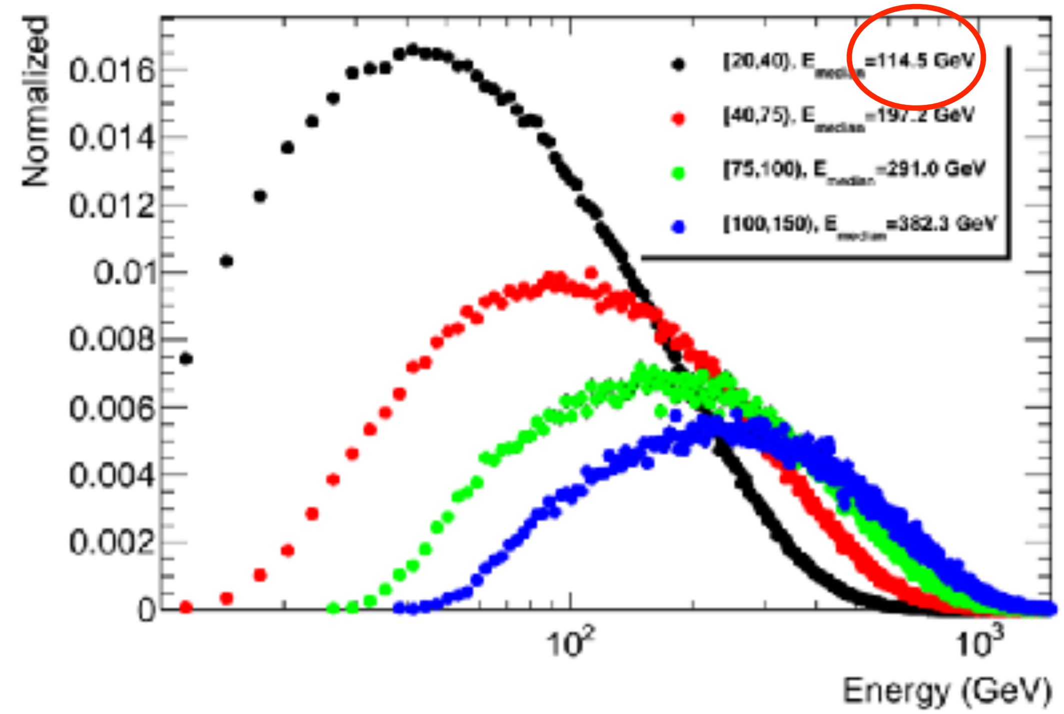
water Cherenkov detector LHAASO-like
1.2 m of water + 8″ PMT downward

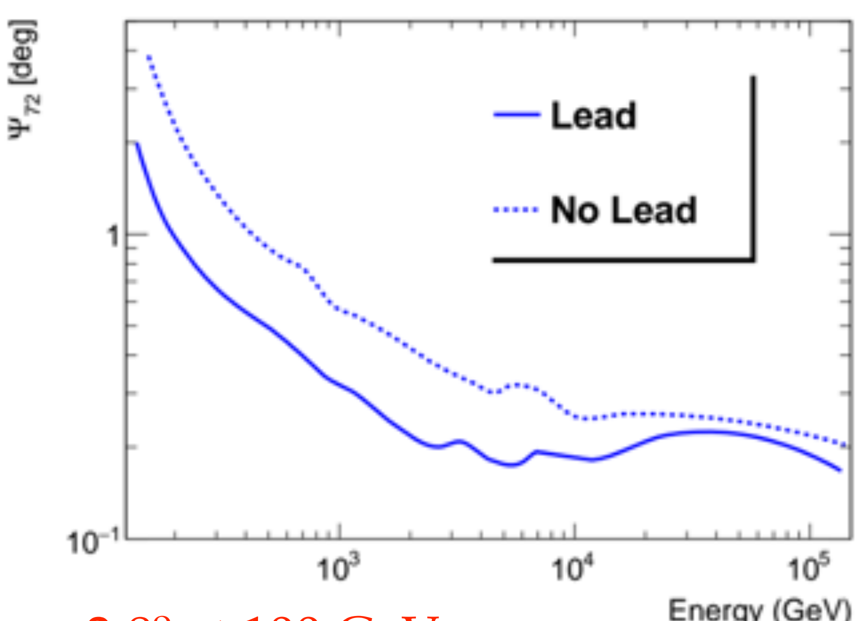


STACEX proposal: very preliminary calculations

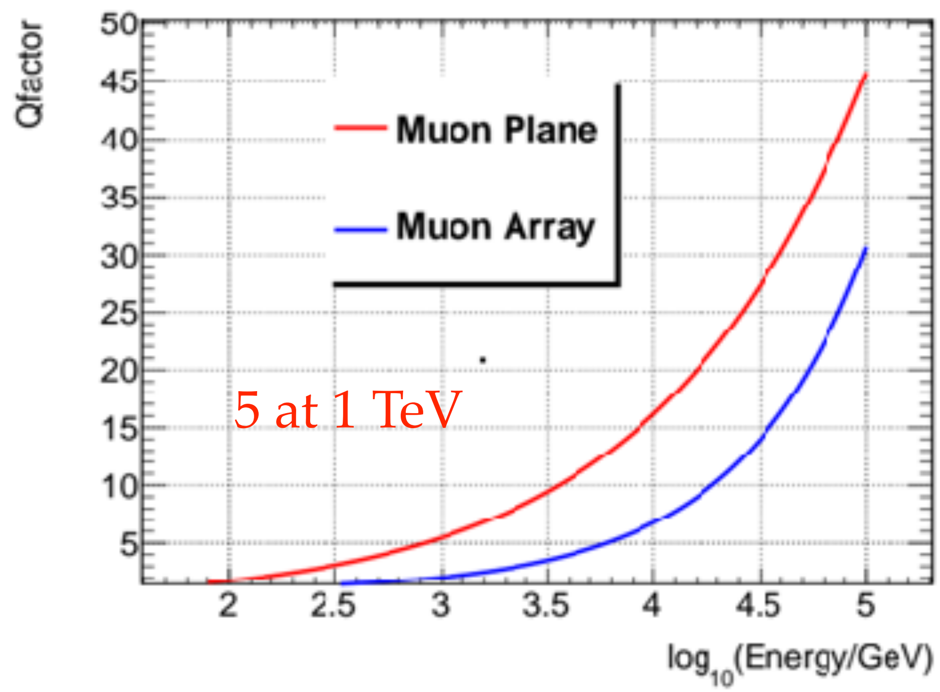


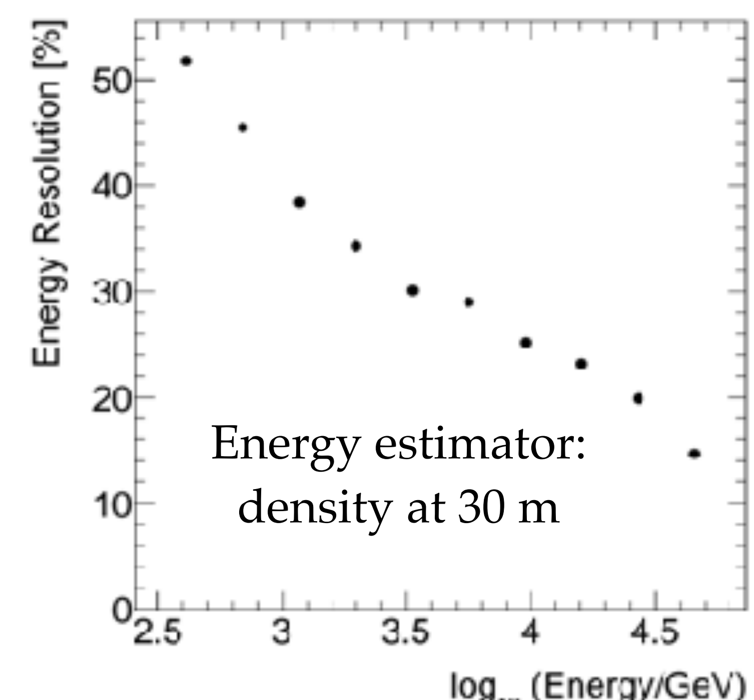
At 5000 m asl



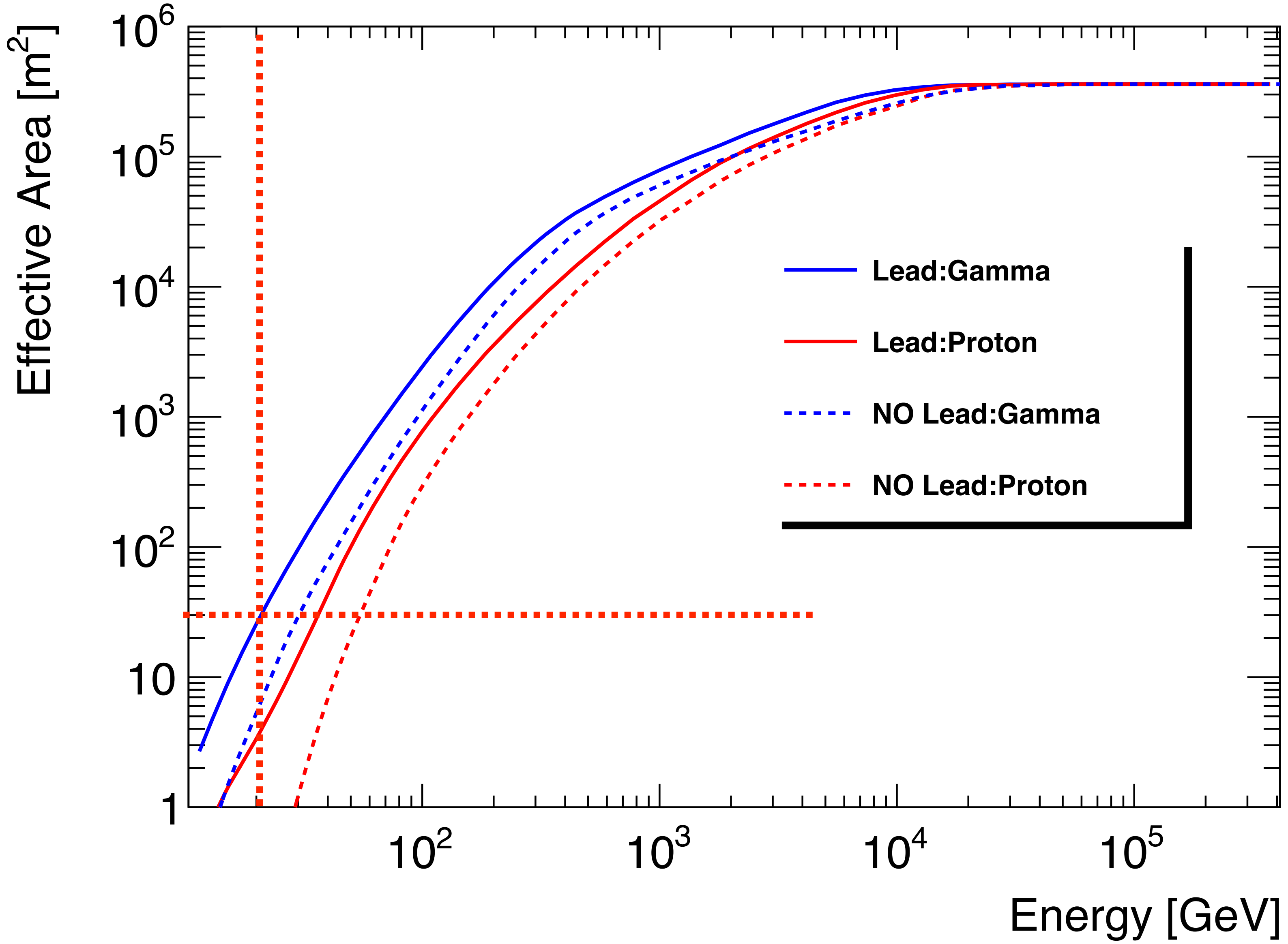


2.8° at 100 GeV
0.30° at 1 TeV



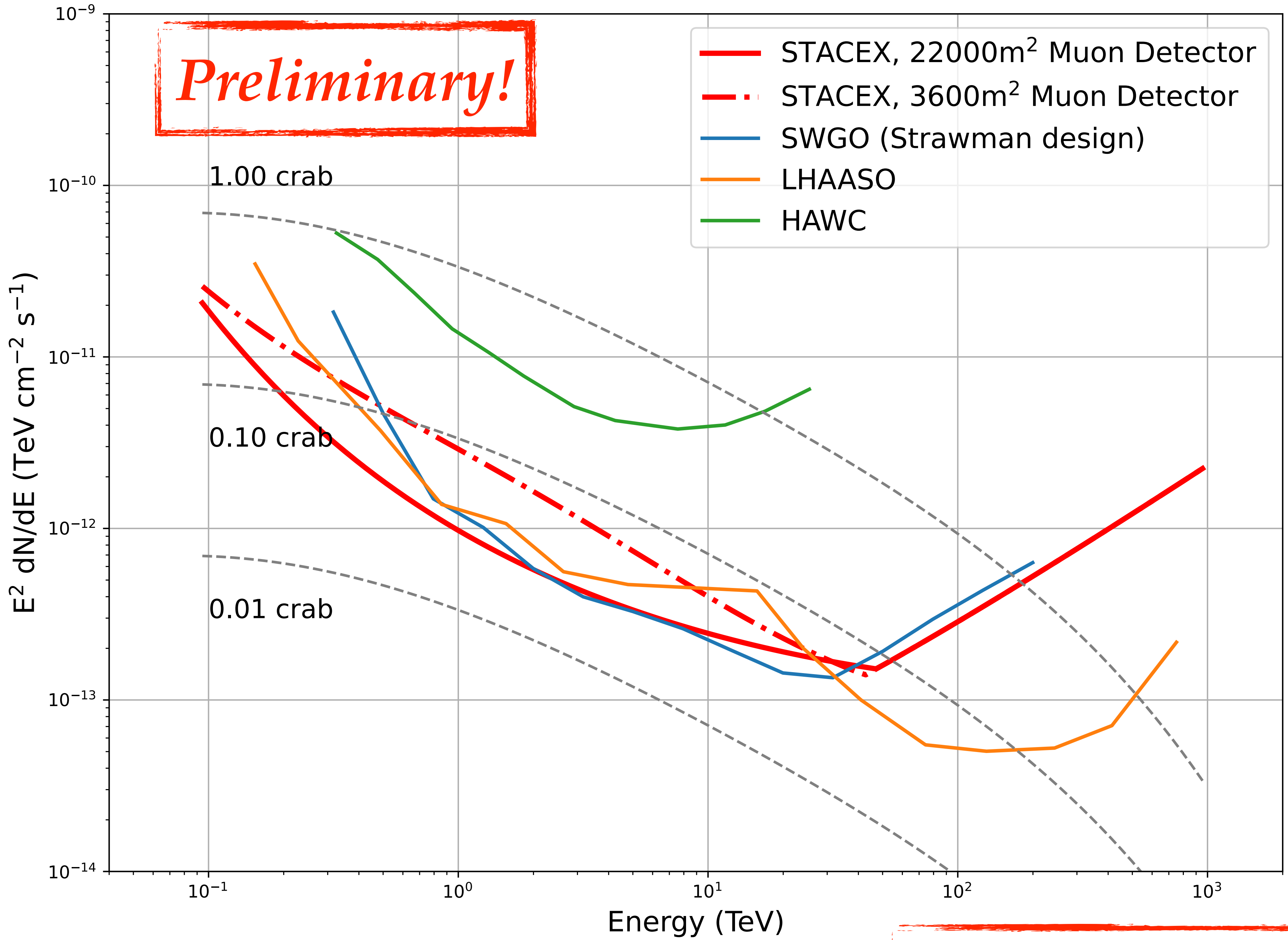


STACEX Effective Area



30 m² at ≈20 GeV!

Sensitivity of the "core" detector



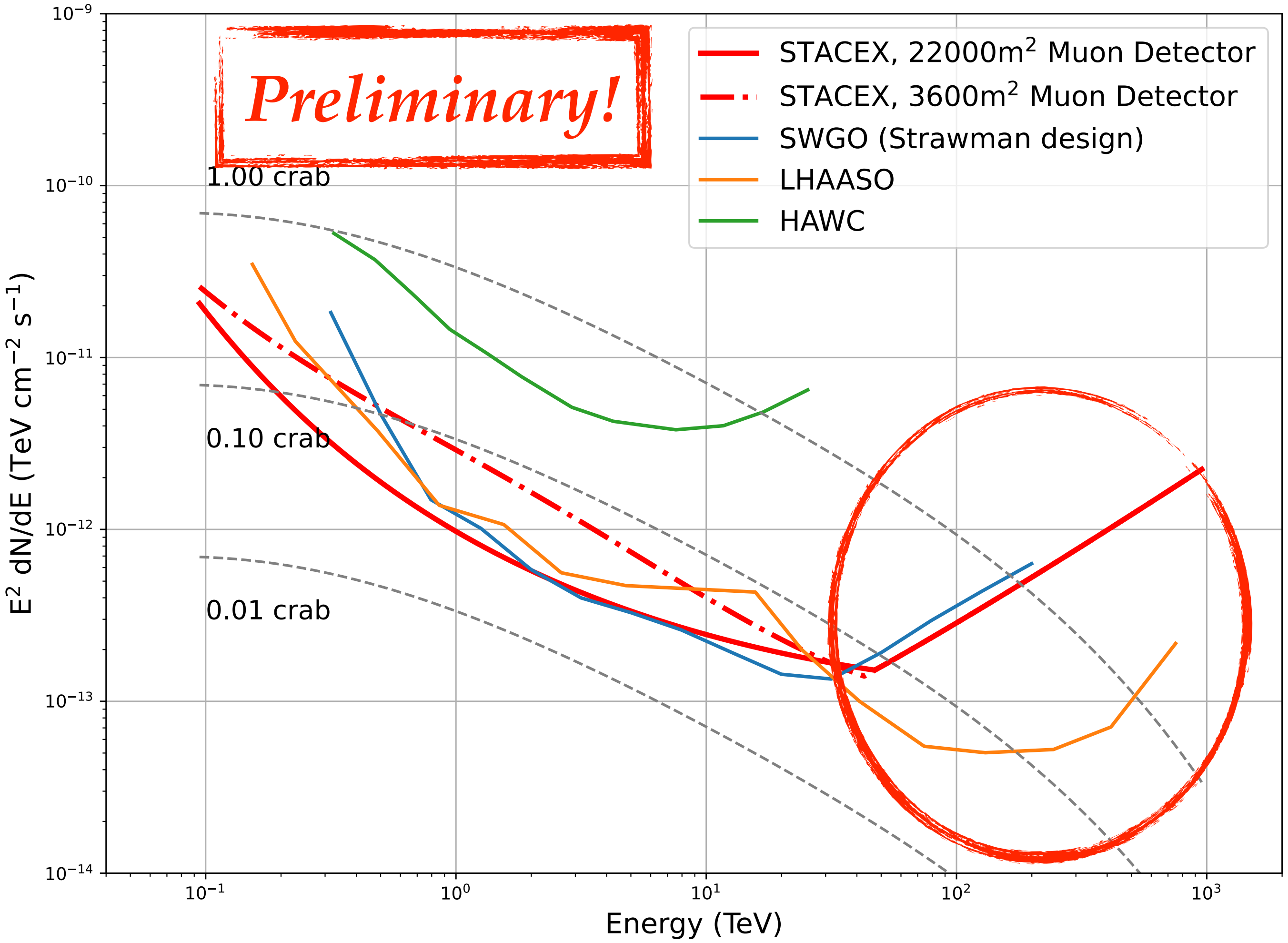
Bkg-free regime starts at ≈50 TeV

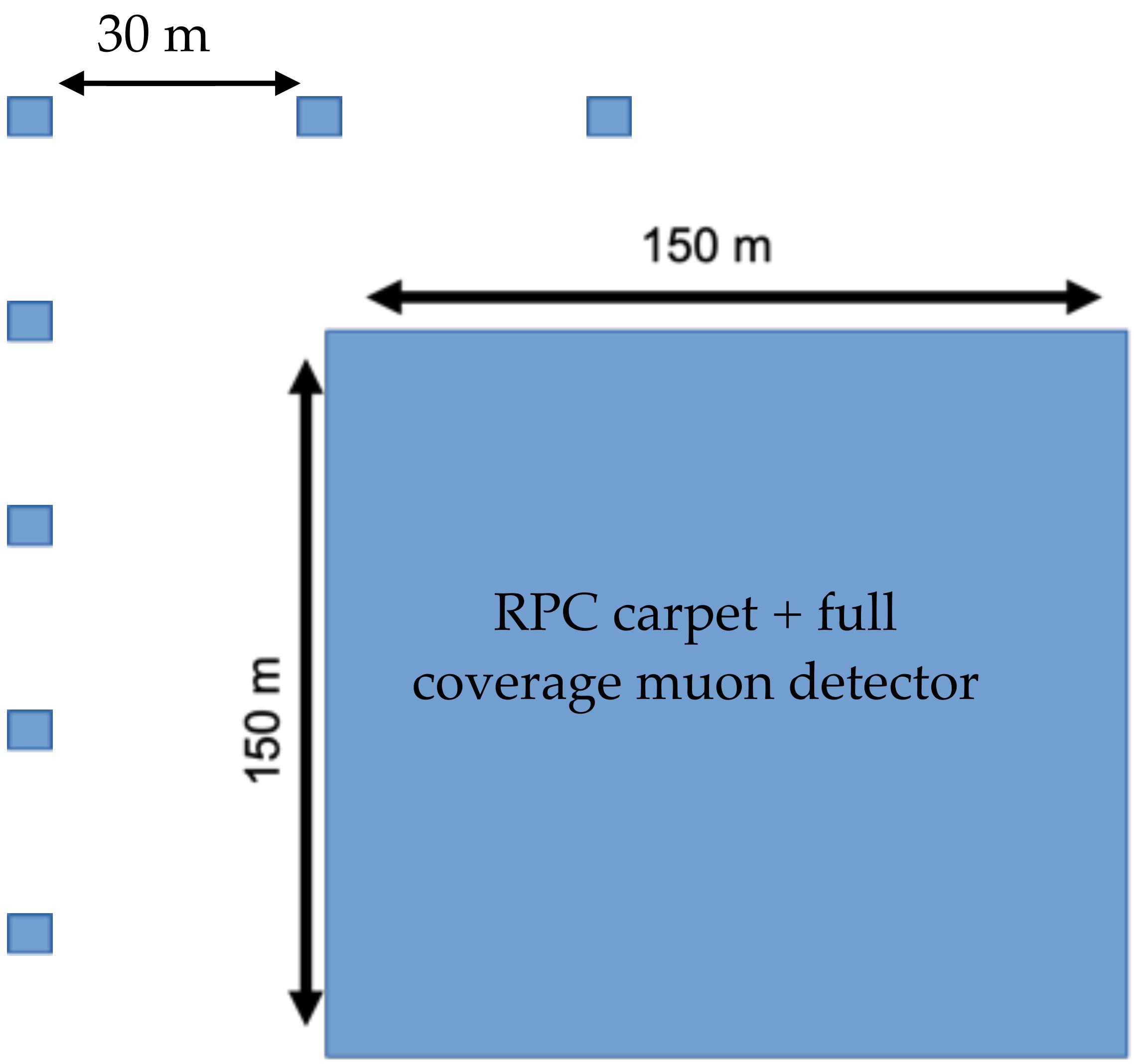
An additional array >0.5 km²

An additional array to collect statistics up to the 10 PeV range is under study

In bkg-free regime only e.m. modules in the array are enough → no additional muon detector array

The full coverage 22,000 m² muon detector seems ok to have bkg discrimination capability better than 10^{-4}

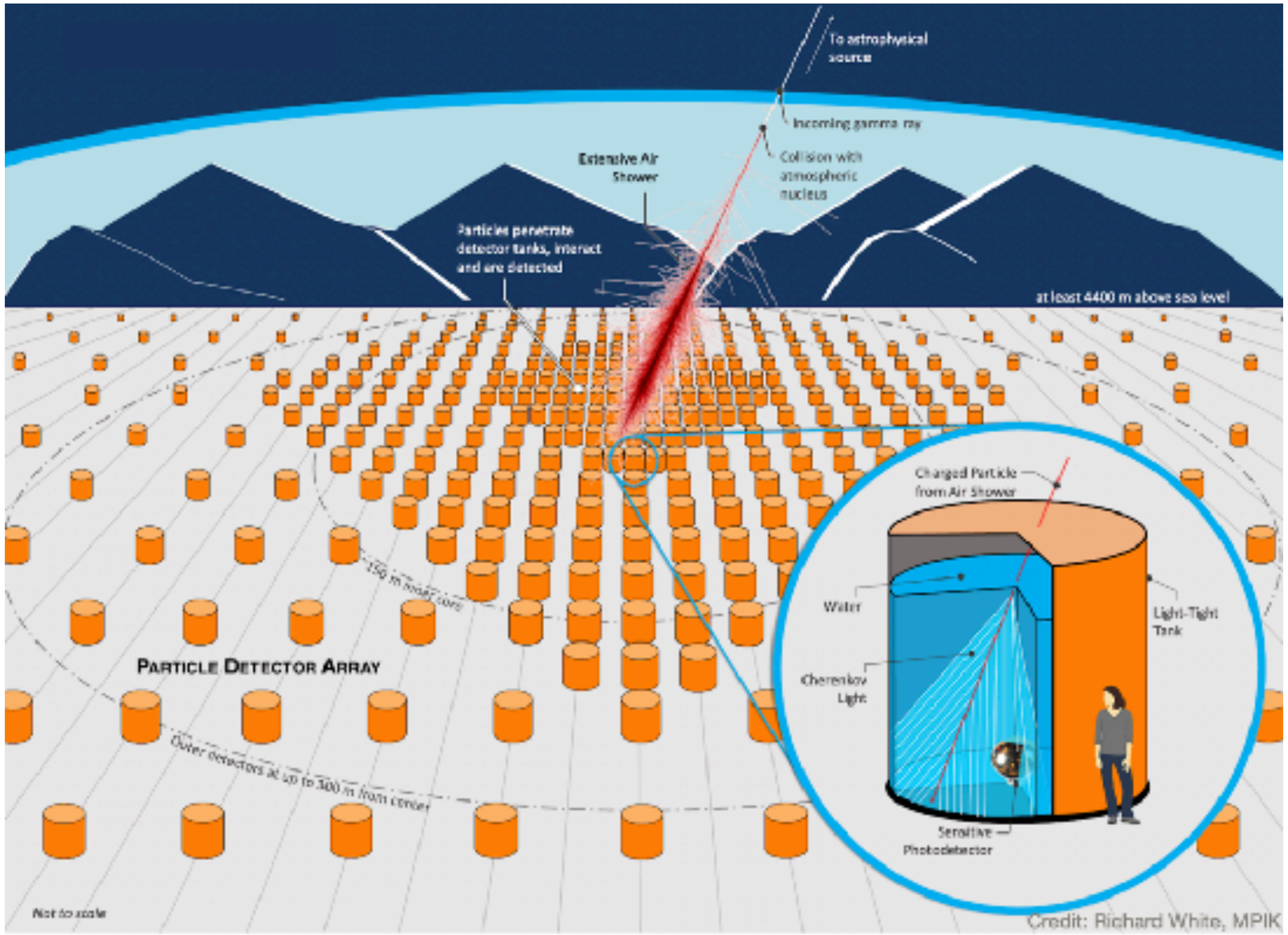


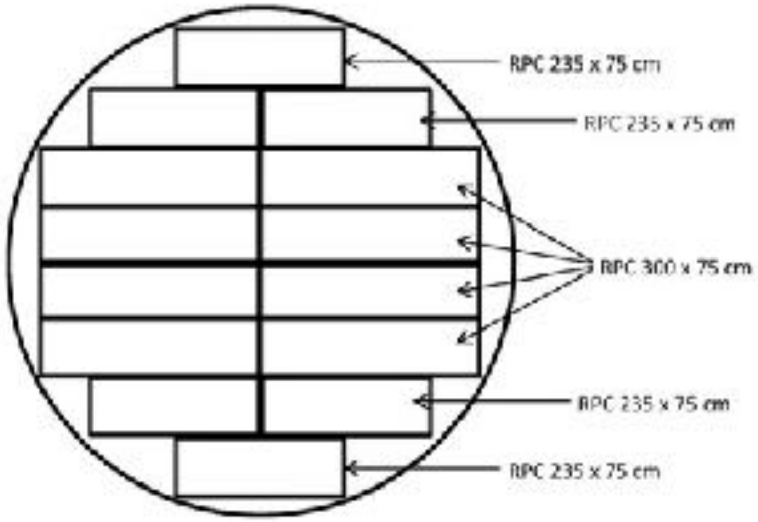


SWGO + RPC?

SWGO proposal: array of HAWC-like water Cherenkov tanks with different coverage

Water Cherenkov is a detector easier to operate with respect to RPCs but energetic range much smaller





A test of a hybrid detector is planned in the framework of PNRR CTA+

Can covering tanks with RPCs improve sensitivity?
As well as reduce threshold energy.

Conclusions

- Extragalactic flaring/transient detection (GRBs, AGNs,…) requires ***low threshold, ≈50-100 GeV***.
- LHAASO demonstrated GP is full of PeVatrons and possibly of ***10 PeV SuperPeVatrons!***
- We need a **new array with a wide dynamical range: 50 GeV → 10 PeV** in the South!
- A full coverage carpet of RPCs is a detector able to cover the 50 GeV - 10 PeV energy range
- Background rejection with arrays is mainly based on muons → full coverage μ-detector to increase the bkg rejection capability at TeV energies.

- ***Take home message:*** Preliminary calculations show that the sensitivity of a *"small" (150×150 m^2)* carpet above a ***full coverage muon detector*** could be similar to much bigger arrays (LHAASO, SWGO).

- A test of a **hybrid detector with RPCs above water Cherenkov** (tanks, pond) will be organized in the framework of CTA+ (with HAWC, LHAASO ?)

EAS arrays

Experiment	g/cm^2	Detector	ΔE (eV)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
ARGO-YBJ	606	RPC/hybrid	$3 \cdot 10^{11} - 10^{16}$	6700	11,000	0.93 (central carpet)
BASJE-MAS	550	scint./muon	$6 \cdot 10^{12} - 3.5 \cdot 10^{16}$		10^4	
TIBET ASγ	606	scint./burst det.	$5 \cdot 10^{13} - 10^{17}$	380	3.7×10^4	10^{-2}
CASA-MIA	860	scint./muon	$10^{14} - 3.5 \cdot 10^{16}$	1.6×10^3	2.3×10^5	7×10^{-3}
KASCADE	1020	scint./mu/had	$2 - 90 \cdot 10^{15}$	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	1020	scint./mu/had	$10^{16} - 10^{18}$	370	5×10^5	7×10^{-4}
Tunka	900	open Cher. det.	$3\cdot10^{15} - 3 \cdot 10^{18}$	-	10^6	-
IceTop	680	ice Cher. det.	$10^{16} - 10^{18}$	4.2×10^2	10^6	4×10^{-4}
LHAASO	600	Water C scintill/muon/hadron Wide FoV Cher. Tel.	$10^{12} - 10^{17}$	5.2×10^3	1.3×10^6	4×10^{-3}

		μ Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO	4410	4.2×10^4	10^6	4.4×10^{-2}
TIBET ASγ	4300	4.5×10^3	3.7×10^4	1.2×10^{-1}
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
CASA-MIA	1450	2.5×10^3	2.3×10^5	1.1×10^{-2}