Istituto Nazionale di Fisica Nucleare
SEZIONE DI ROMA TOR VERGATA

STACEX: RPC-based detector for a multi-messenger observatory in the Southern Hemisphere

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Beyond HAWC/LHAASO

In the next decade CTA-North and LHAASO are expected to be the most sensitive instruments to study γ-ray astronomy in the *Northern Hemisphere from ≈20 GeV up to PeV.*

➡ *Southern Hemisphere*

- *An all-sky detector in the Southern Hemisphere should be a high priority* to face a broad range of topics and to complement CTA-South.

Science case for survey instruments is clear

- Galactic/Extragalactic *unbiased survey*: detection of *unexpected sources.*
- Discovering rare transient events requires full sky coverage and very low energy threshold (100 GeV range): *transient factory*
- *GRB finder* for LIGO/VIRGO
- AGN flares & GRBs as distant probes of high energy physics (e.g. Lorentz invariance and axions)
- Survey of the *Inner Galaxy* and *Galactic Center* ➜ *quest for PeVatrons*
- TeV Source *finder for CTA South*

The SWGO project

*The **S**outhern **W**ide field-of-view **G**amma-ray **O**bservatory* is a collaboration aimed to support the proposal of a new survey instrument in the South.

The shared concept for the future observatory is, currently, as follows

- A gamma-ray observatory based on ground-level particle detection, with close to 100% duty cycle and order steradian field of view.
- Located in South America at a latitude between 10 and 30 degrees south.
- At an altitude of 4.4 km or higher.
- Covering an energy range from 100s of GeV to 100s of TeV.
- *Based primarily on water Cherenkov detector units* but *final layout still under study*
- With a high fill-factor core detector with area considerably larger than HAWC and significantly better sensitivity, and a low density outer array.

The first version of the *science case* is on the ArXiv, *arXiv:1902.08429*

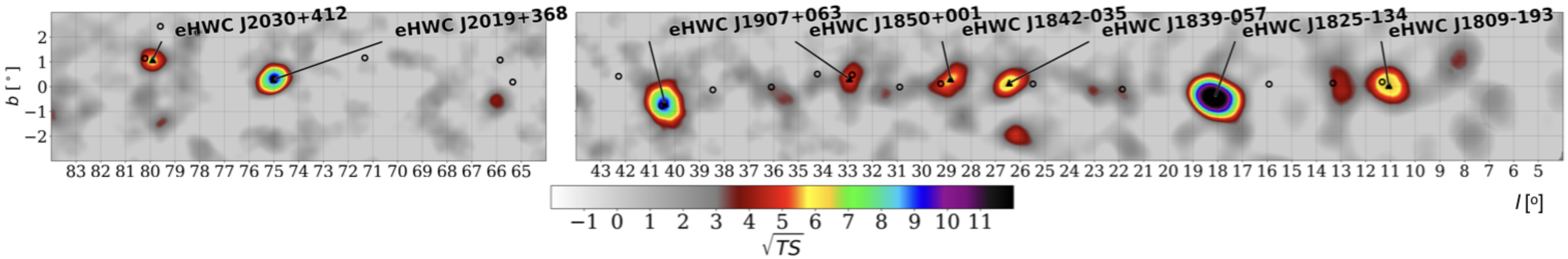
https://www.swgo.org

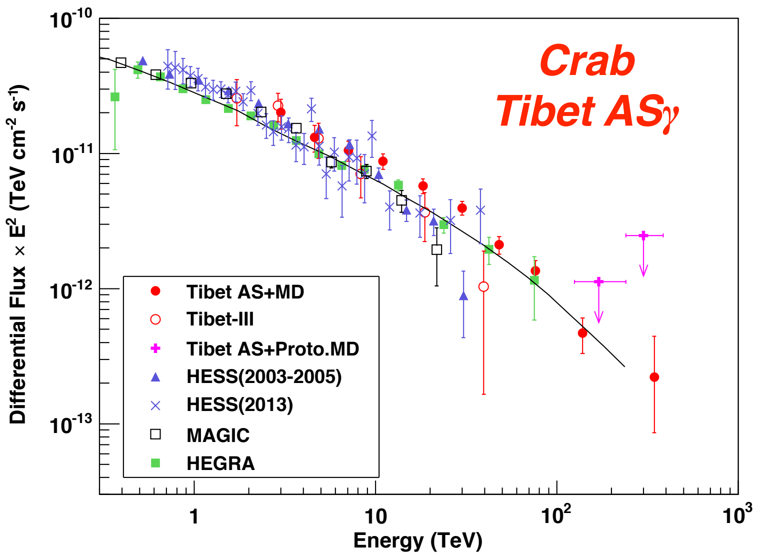
Next talk by Samridha Kunwar

The Ideal Observatory for PeVatrons

HAWC High Energy Survey

E>56 TeV

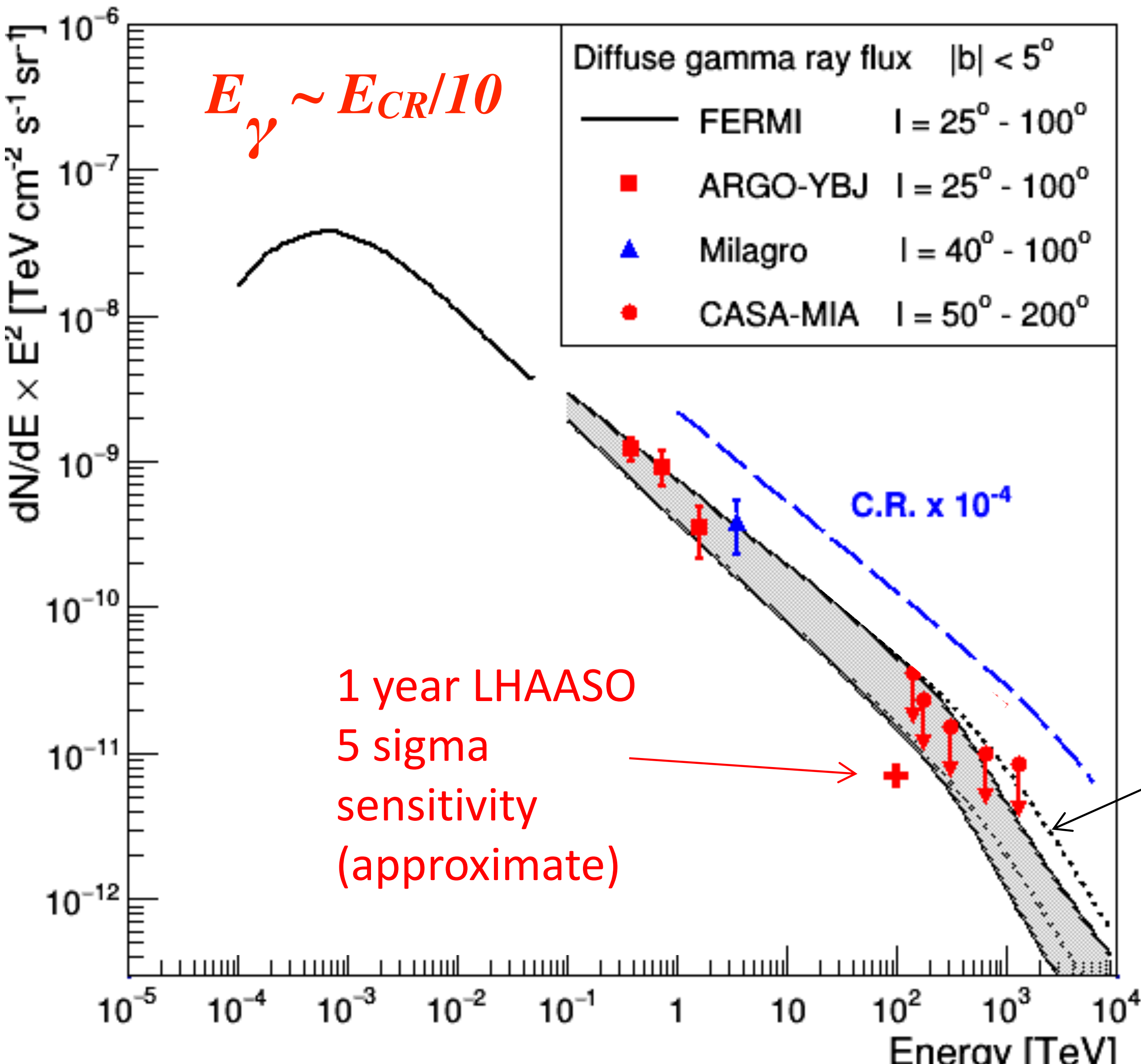




- Search for sources of cosmic rays close to PeV energies: proton cut-off at ≈1 PeV imply gamma cut-off at ≈30 TeV
  ➡ *High sensitivity at about 30-40 TeV*
- Test spectral break and cutoffs at several TeV
  ➡ *Good energy resolution at several TeVs*
- Search for different and possibly unexpected classes of sources ➡ *Unbiased survey*
- Resolve sources which might be hidden in the tails of bright sources and compare and correlate with gas surveys
  ➡ *Good angular resolution at several TeV*

Expected knee in the diffuse γ-ray flux

Is the knee a source property, in which case we should see a corresponding spectral feature in the gamma-ray spectra of CR sources, or the result of propagation, so we should observe *a knee that is potentially dependent on location*, because the propagation properties depend on position in the Galaxy ?



S. Vernetto & P. Lipari: ICRC 2017

Observing a location dependence of the knee energy (or of the spectral index !) would provide important clues on the nature of the knee.

Grey band: expected γ-ray flux in the region |lat|<5°, long=25°-100°

Extrapolation of the Fermi spectrum $E^{-2.65\pm0.05}$ with a steepening due to CR knee

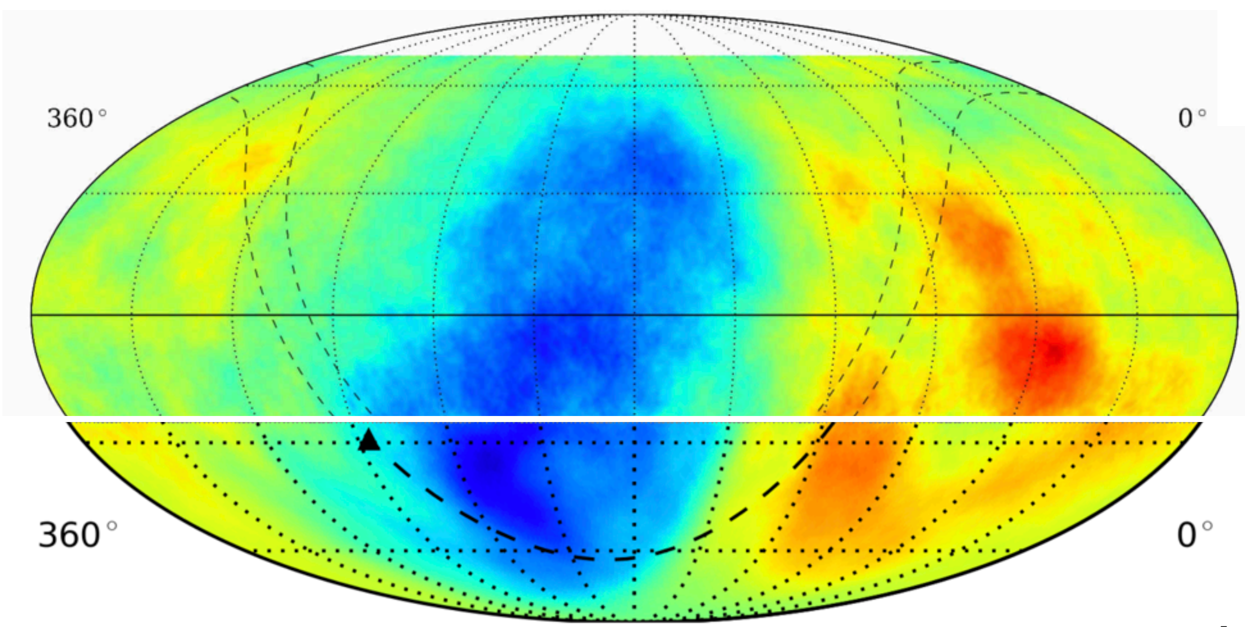
$$S_{ext} = S_{point} \cdot \frac{\theta_{PSF}}{\theta_{ext}}$$

Detectors with a 'poor' angular resolution are favoured in the extended source studies.

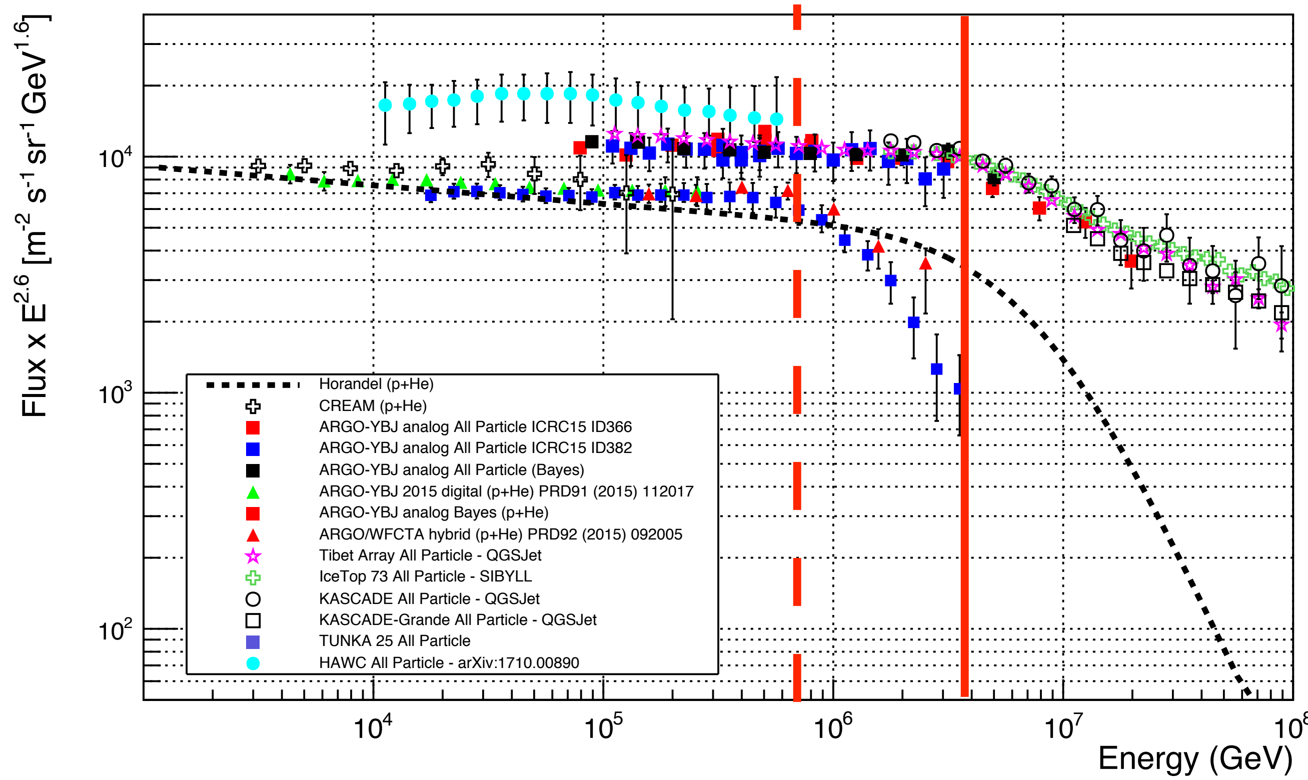
Cosmic Rays

- *Origin of the knee*: data conflicting
  ➜ still an open problem!
- Galactic / x-galactic energy transition
- *Anisotropy* vs particle rigidity

HAWC



IceCube



The *proton knee* is connected to the maximum energy of accelerated particles in CR sources!

➜ *Elemental composition!*

Muon tagging?

At extreme altitude the sensitivity of the N_e/N_μ technique in selecting primary masses is reduced
➜ new observables
➜ suitable detector/readout !

Scientific requirements

A future Wide FoV Observatory *to be useful (to CTA)* needs:

- *Low energy threshold* (≈ 100 GeV) to detect extragalactic transients (AGN, GRBs).
- *Angular resolution <1°* at the threshold for survey of Inner Galaxy (source confusion).
- *<10% Crab sensitivity below TeV* to have *high exposure for flaring activity.*
- Good energy resolution above 10 TeV to detect spectral cut-offs
- Background discrimination capability at level of *10^{-5} (!!!) in the 100 TeV range* to observe *the knee in the energy spectrum of the γ diffuse emission* in different regions of the GP.
- Capability to *select different primary masses across the knee* to investigate the origin of the knee *(proton knee)* and *for anisotropy observations vs CR particle rigidity !*

★ *Is this possible ?*

Physical limits mainly due to the detection technique !

Milagro vs ARGO-YBJ

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

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

ARGO-YBJ
Resistive Plate Chamber Technology

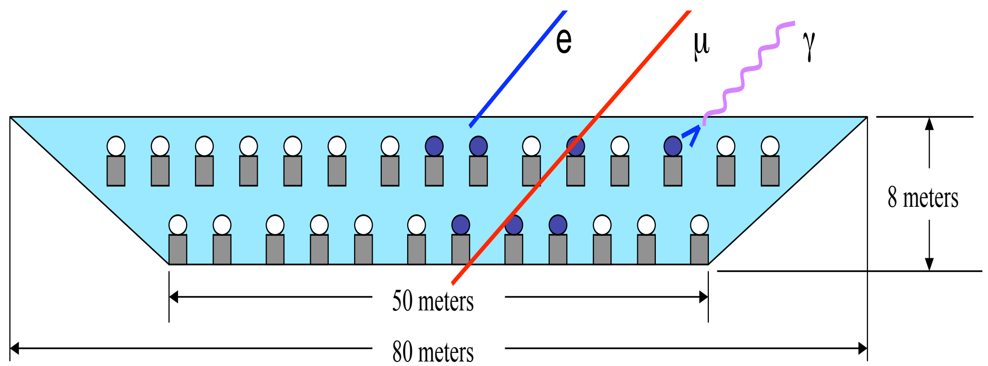
- operated from 2007 to 2012 (final configuration)
- *4300 m* above sea level
- *angular resolution ≈0.5° at 1 TeV*
- 3500 Hz trigger rate
- high granularity of the readout
- *Median Energy at the threshold: ≈340 GeV*
- *Energy Range: 340 GeV - 10 PeV*
- NO background rejection (no outrigger)
- NO conversion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

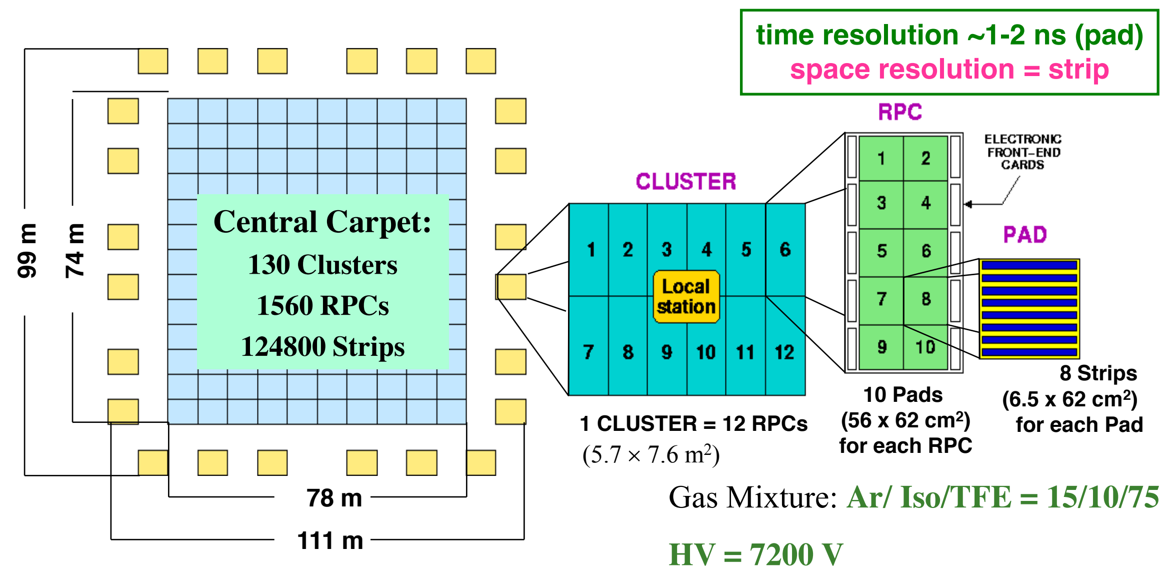
- 450 PMTs at 1.4 m below the surface (top layer)
- 273 PMTs at 6 m below the surface (bottom layer)

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:

$\rho_{max-strip} \approx 20\ particles/m^2$

$\rho_{max-analog} \approx 10^4\ particles/m^2$

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

STACEX: γ-ray astronomy in the South

***S**outhern sub-**T**eV **A**strophysics and **C**osmic rays **EX**periment*

STACEX proposal combines in a hybrid detector both approaches so far used in survey instruments

- Water Cherenkov technique (LHAASO-style)
- RPC technique (ARGO-style)

Two experimental techniques operated for many years at high altitude

Benefit of RPCs:

✦ Full coverage and high granularity of the read-out (*very low energy threshold*)

✦ *Good energy resolution*, in particular above 10 TeV (10% at 50 TeV)

✦ *Wide energy range* (100 GeV → 10 PeV)

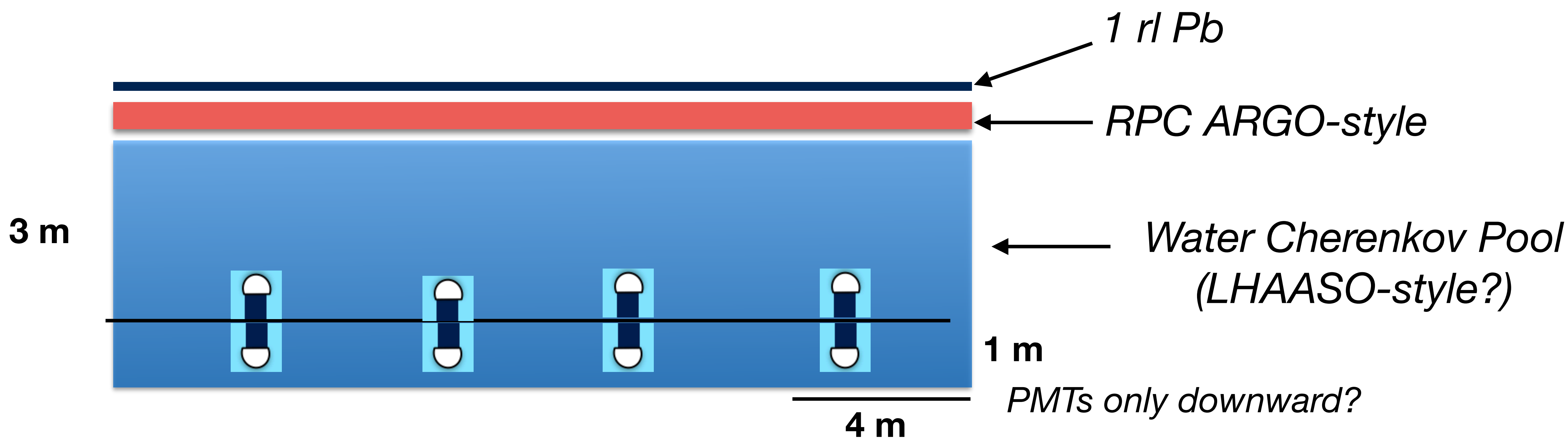
✦ *Elemental composition* up to ≈10 PeV (with charge readout)

Benefit of Water Cherenkov:

✦ Gamma/Hadron discrimination above TeV at distances > 40 m from the core

STACEX: γ-ray astronomy in the South

A 150 × 150 m^2 water pool covered by a RPC carpet with a lead layer on top with array around up to 200 × 200 m^2 operated at 5000 m asl.



1 rl Pb ➜ mainly to improve the angular resolution

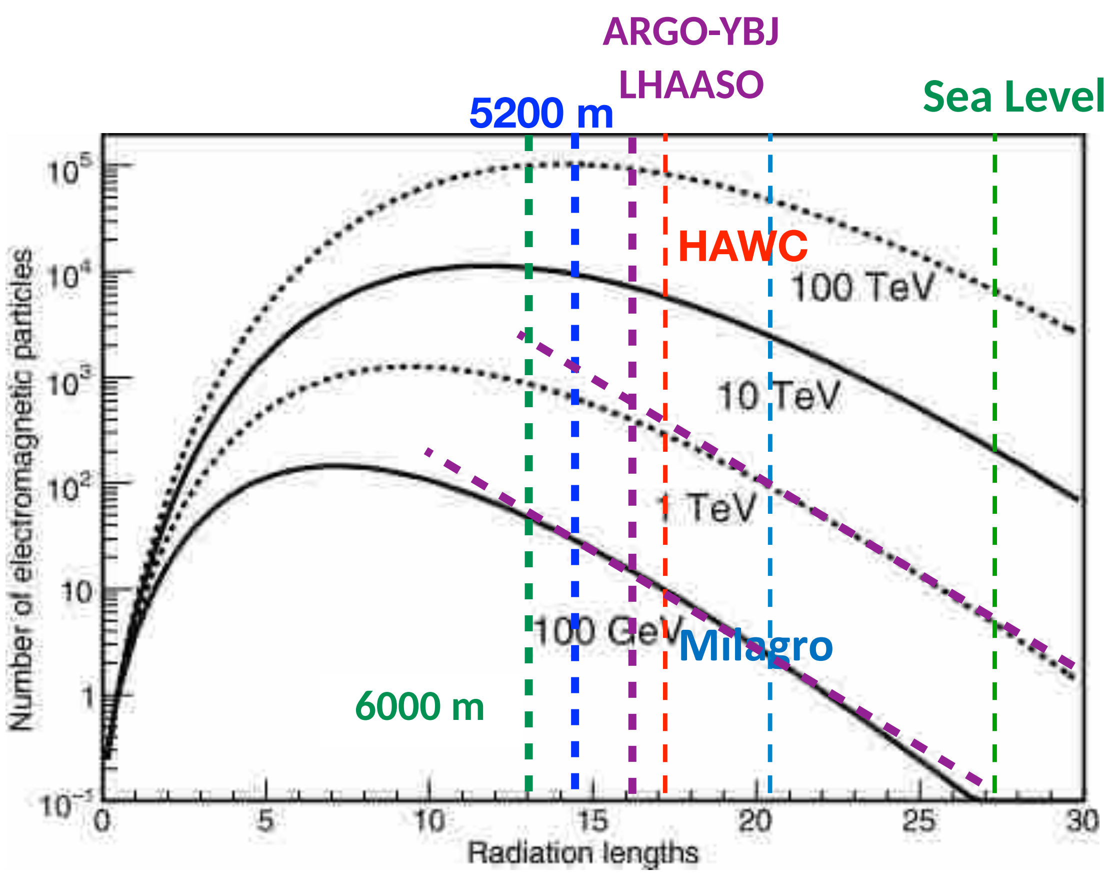
RPC ➜ space-time pattern starting from the 100 GeV range

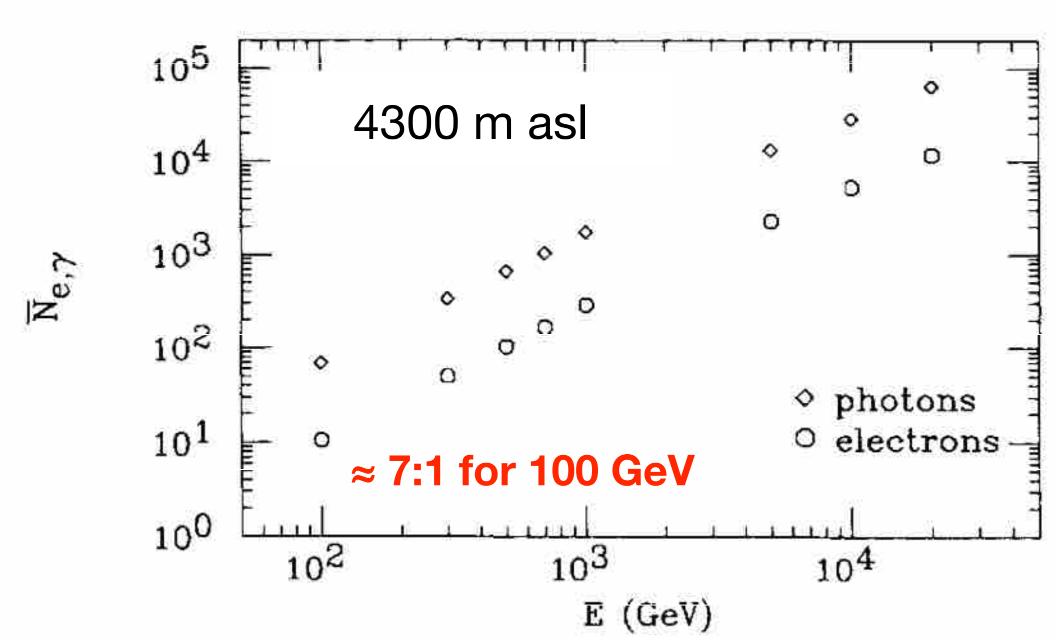
Water Cherenkov Detector ➜ mainly for γ/h discrimination (only muon tagging?)

A water pool inside a building can be more easily insulated even to favour RPC operations

With only muon tagging reduced water depth? Easier water supplying!

Main Goal: 100 GeV energy threshold





The key: extreme altitude

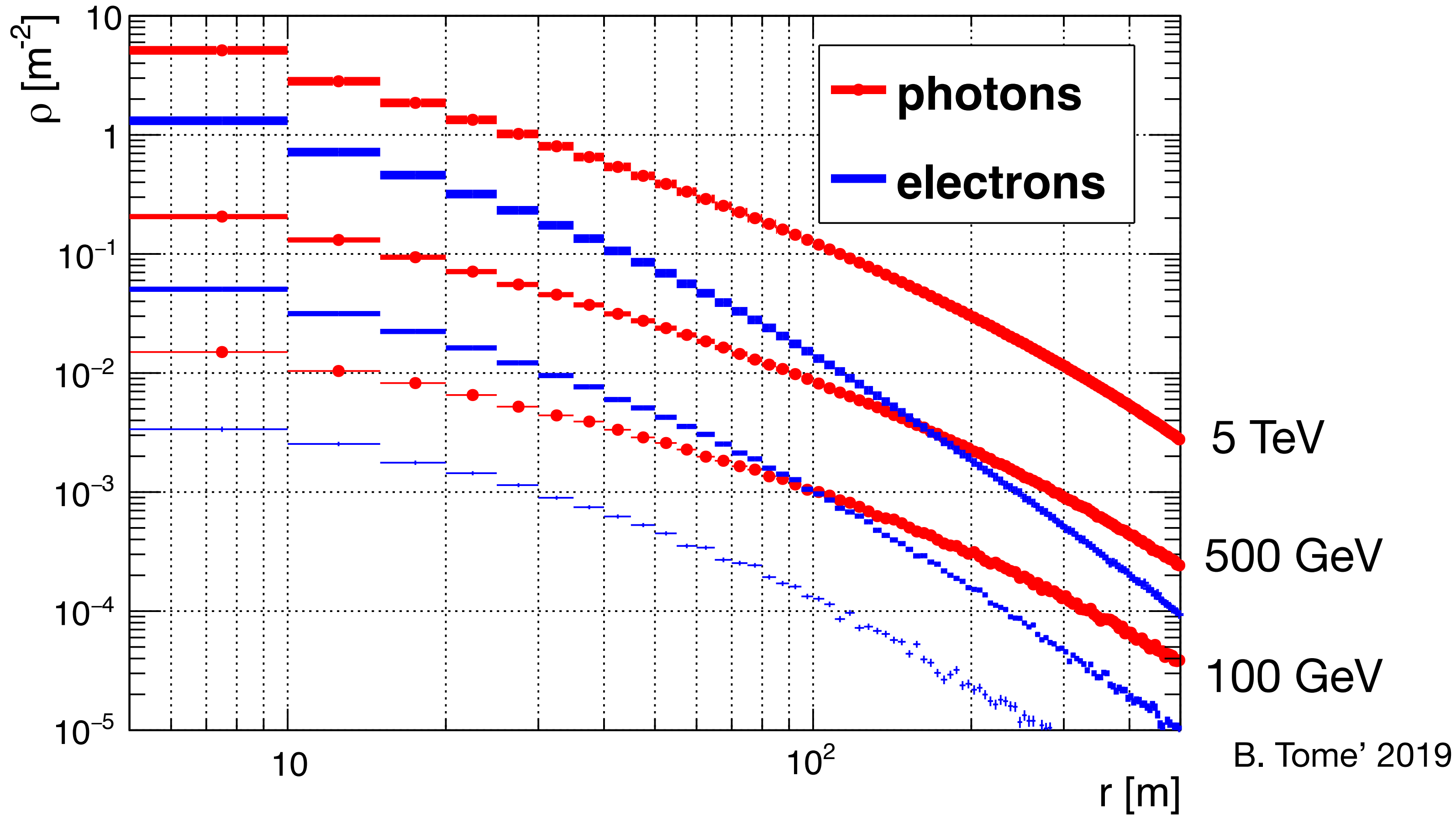
Showers of all energies have the same slope after shower max: ≈1.65x decrease per r.l. .
So, for all energies, if a detector is located 1 r.l. higher in atmosphere, the result will be a ≈1.65x decrease in the energy observable.

E = 100 GeV ➜ ~100 e.m. particles at 5200 m asl

Lowering the energy threshold:

- *Extreme altitude (≈5000 m asl)*
- *Detector and layout*
- *Coverage and granularity of the read-out*
- *Trigger logic*
- *Detection of secondary photons*

Mean LDF at 5200 m asl

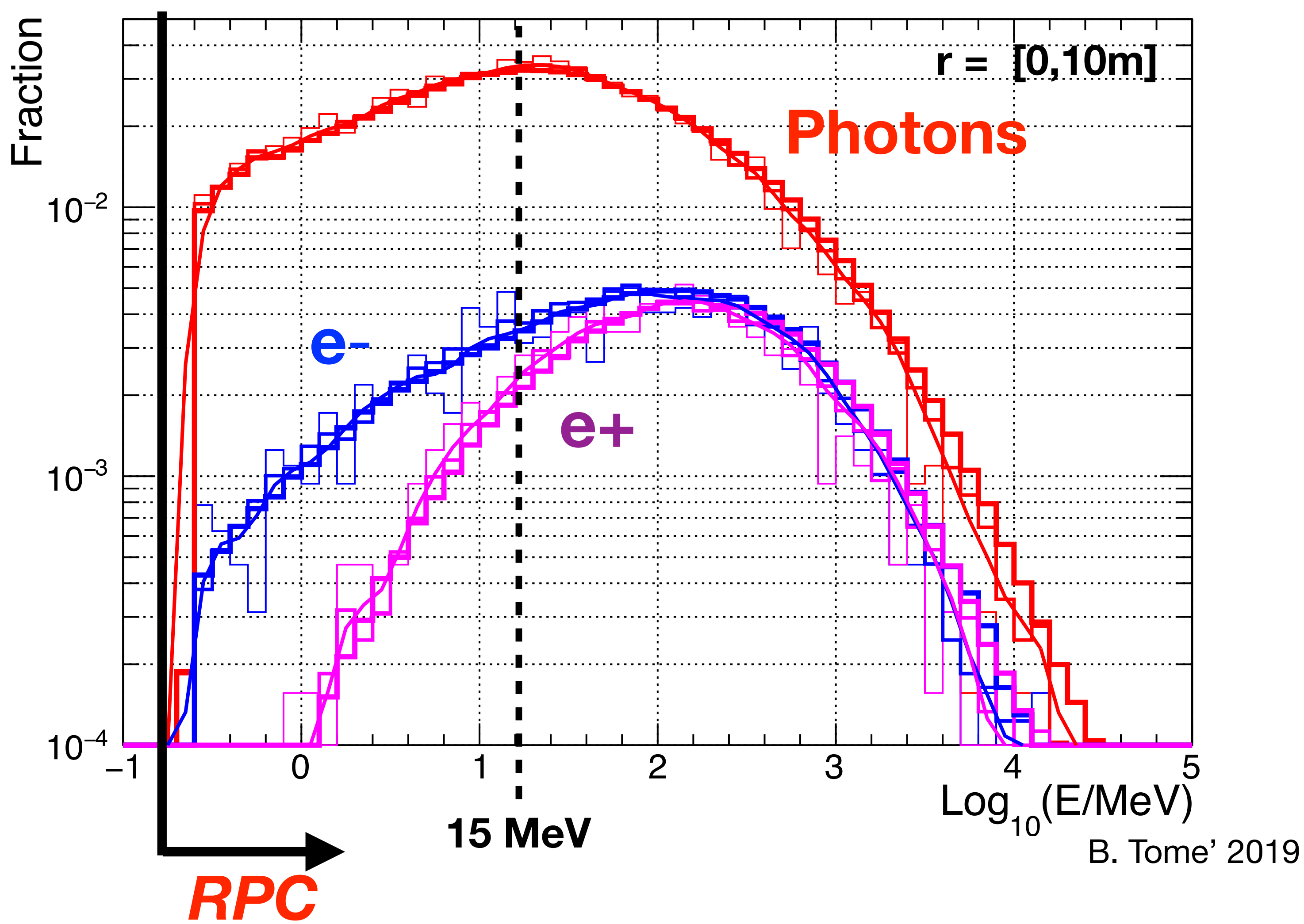


At 100 GeV

- R = 100 m ➜ <ρ> ≈ 0.0001 electrons/m², 0.001 photons/m²
- R = 10 m ➜ <ρ> ≈ 0.003 electrons/m², 0.015 photons/m²

➜ *Full coverage approach !*
with high granularity of the read-out

Secondary particle spectra at 5200 m asl



WCD sensitivity to single ~ 10 MeV - 15 MeV photons is a challenge !

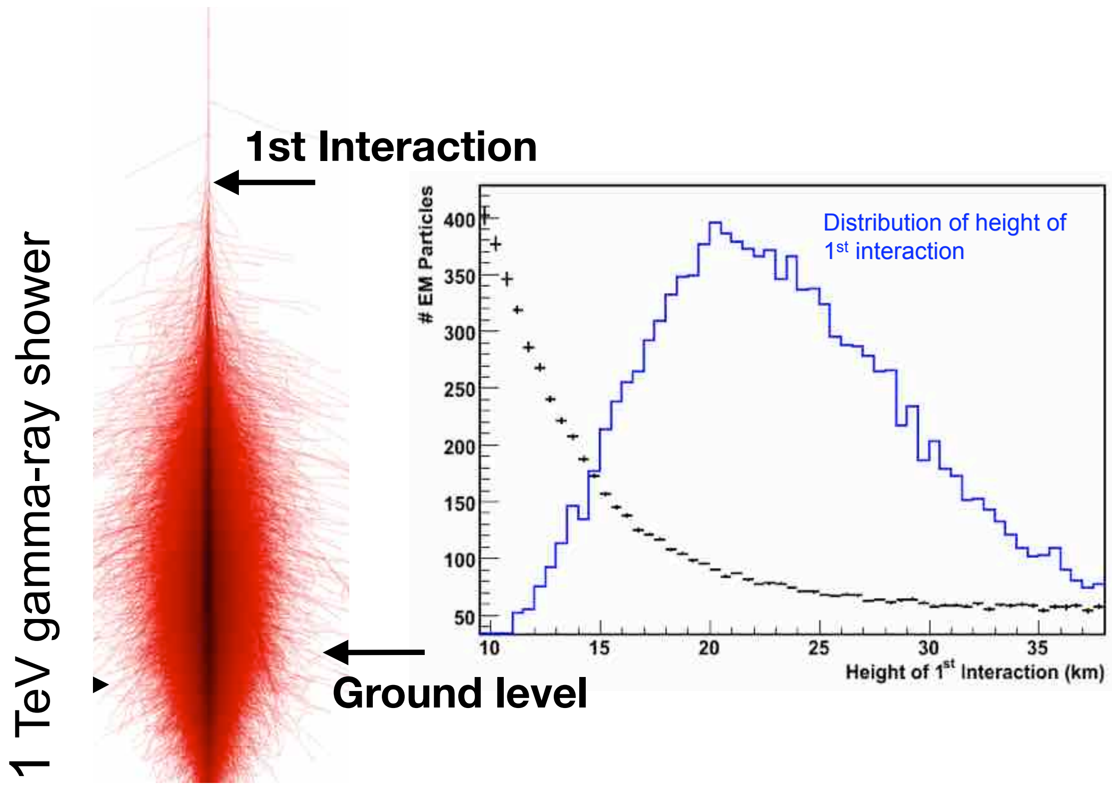
RPCs detect all particles starting from KeV !

➜ Crucial for energy resolution !

Energy resolution

The energy resolution is given by the folding of

Shower fluctuations	⊗	**Sampling fluctuations**
Fluctuations in the depth of the first interaction point		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)

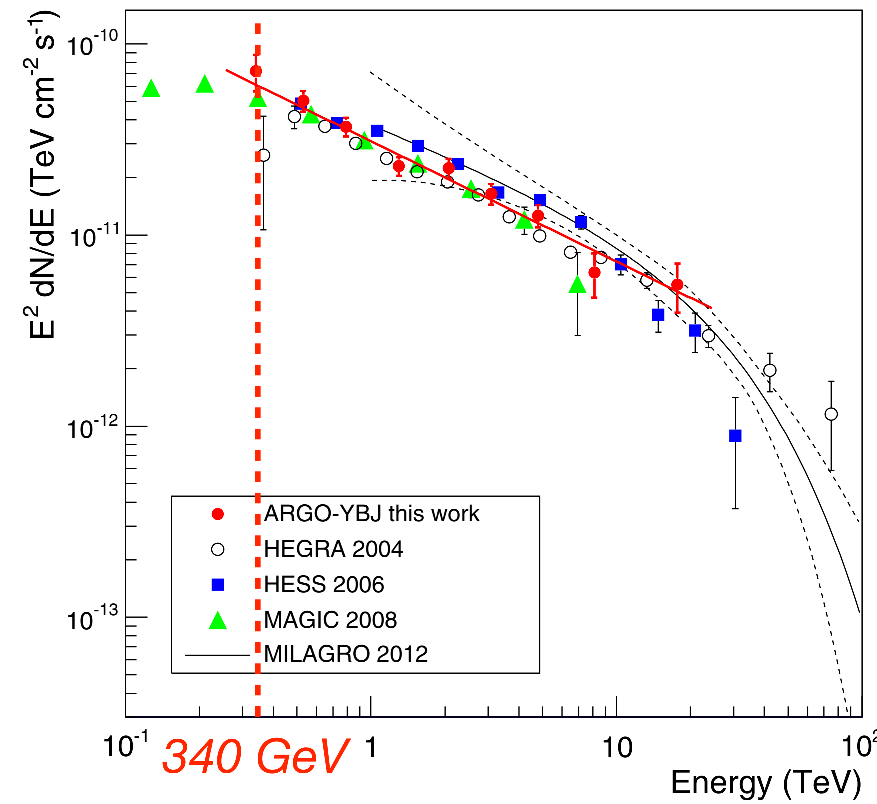
ARGO: 10% at 10 TeV (protons internal)
ARGO: 5% at 100 TeV (protons internal)

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

The 100 GeV challenge (ARGO-YBJ)

Why ARGO-style RPC carpet a crucial component of a new experiment ?

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



The combination of high-altitude site (4300 m. a.s.l.), high fill-factor (92% active area), low RPC noise, high segmentation of the read-out and a *dedicated trigger* allowed this achievement.

High read-out segmentation:

- pads 56 x 62 cm^2 for timing and trigger
- strips 7 x 62 cm^2 to count the particle number

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

median energy of first mult. bin: ***340 GeV***,

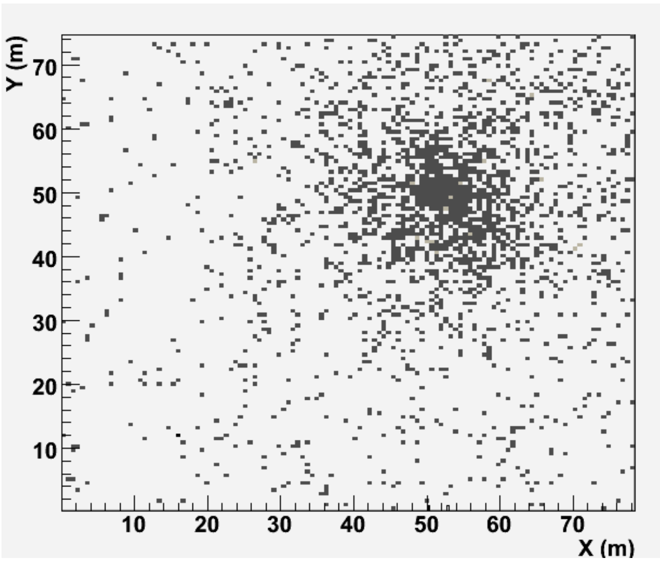
with ε_γ *(100 GeV)* = ***73%*** at 4300 m asl

Very silent pads (380 Hz, 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.

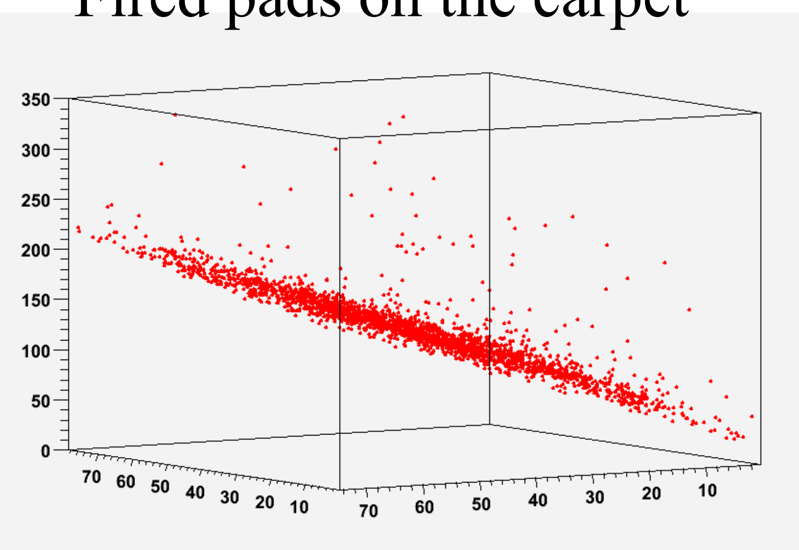
RPCs are the only detection technique who demonstrated the capability to detect showers in the 100 GeV range

Imaging capability of a RPC carpet

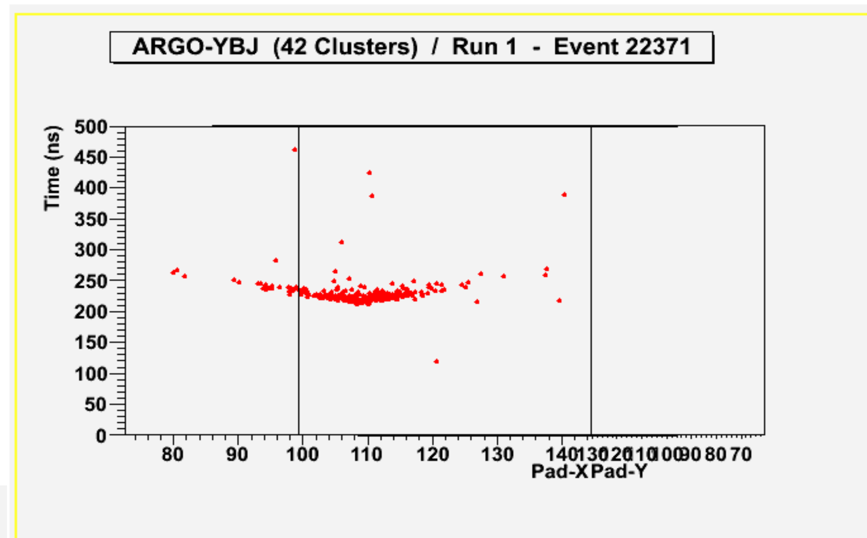
Small and compact low energy events

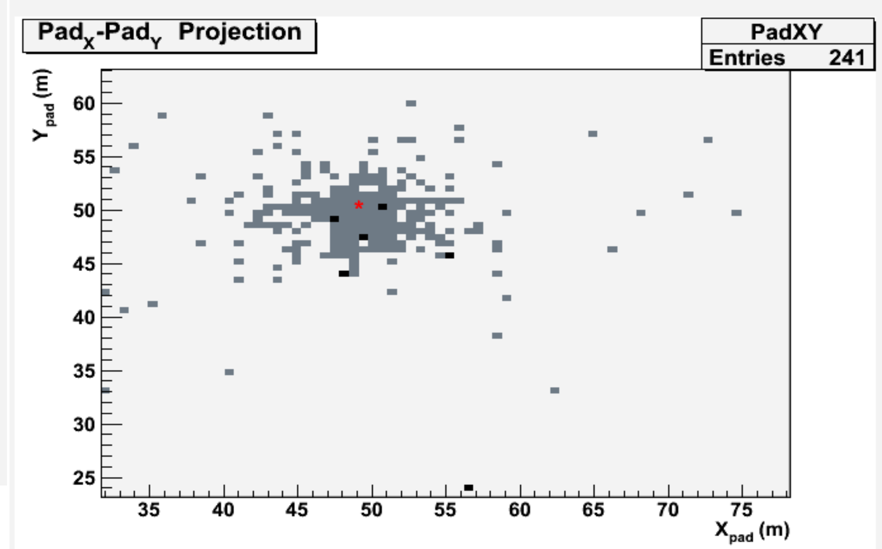


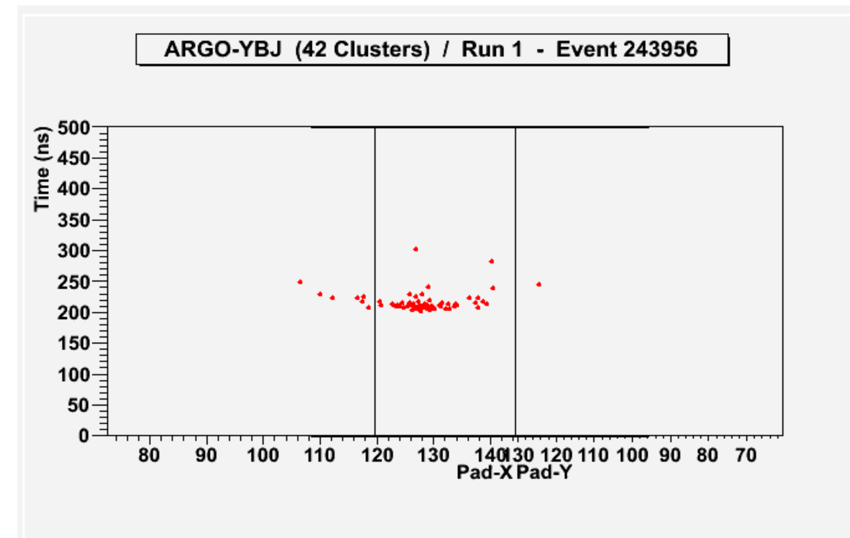
Fired pads on the carpet

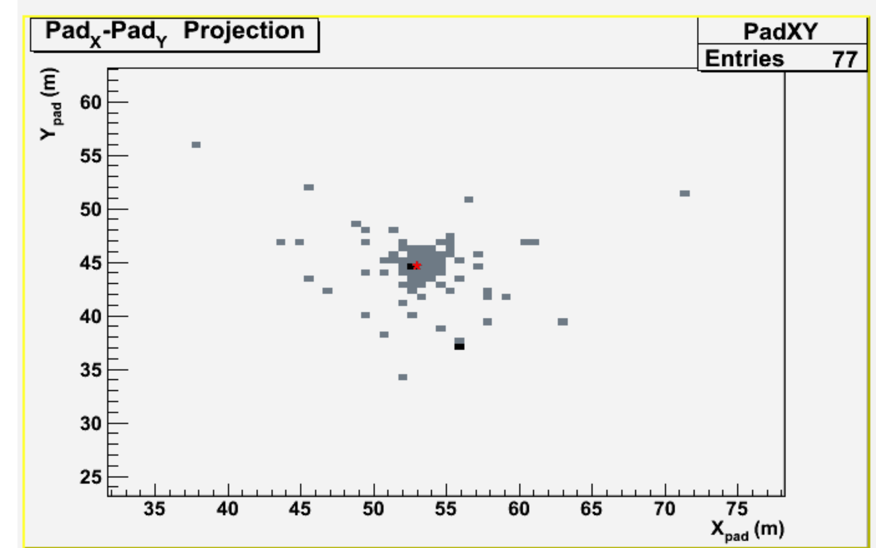


Arrival time vs position









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

The PeV challenge (ARGO-YBJ)

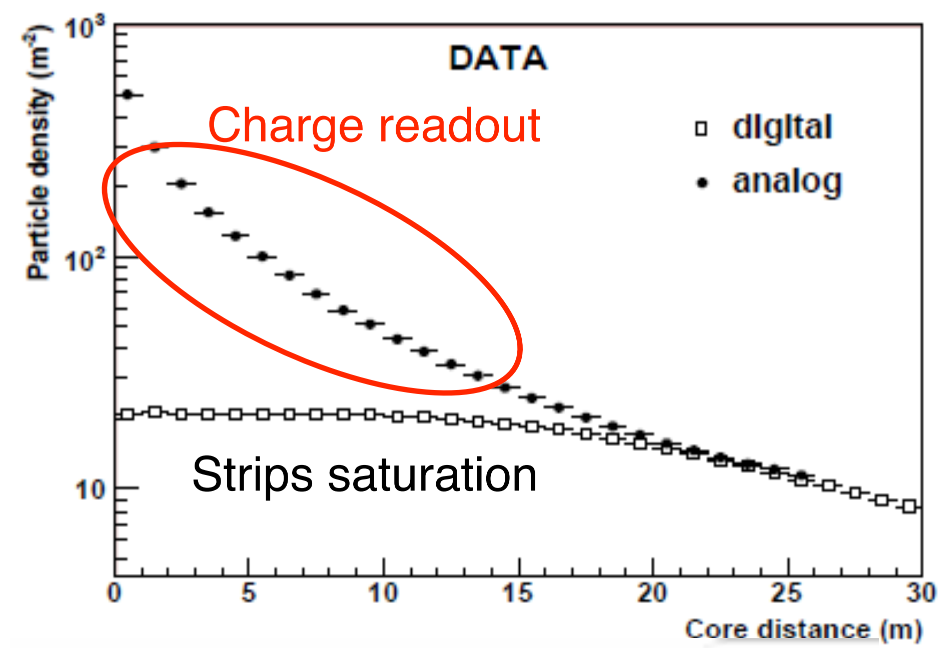
These RPCs have been also equipped with 2 large Big Pads to *collect the total charge* and measure the number of particle hitting the detector.

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

Particle number used as energy proxy

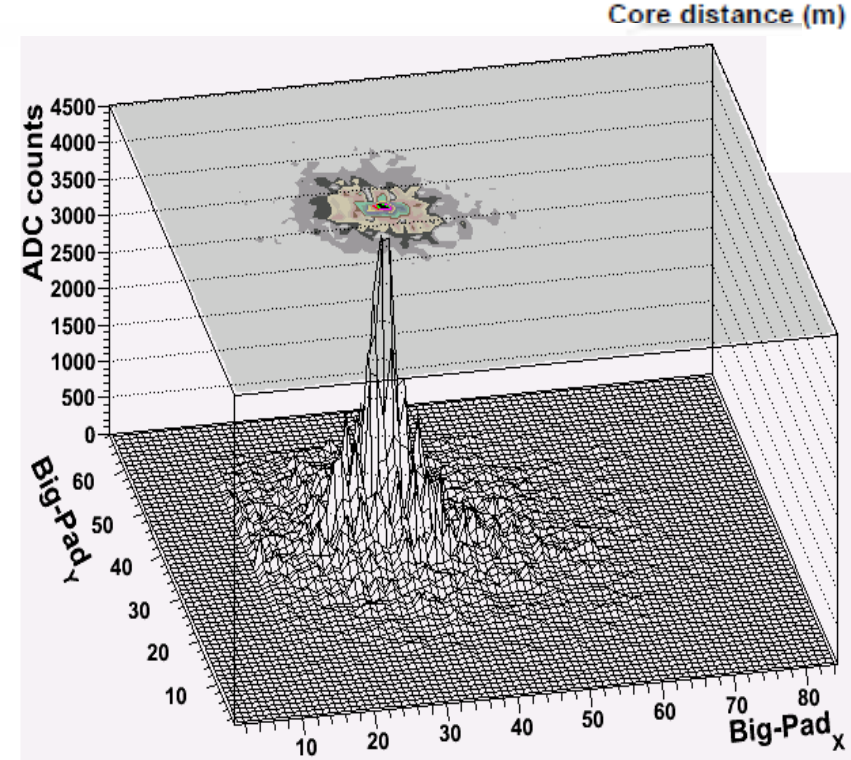
time resolution about 1.5 ns (including electronics)

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



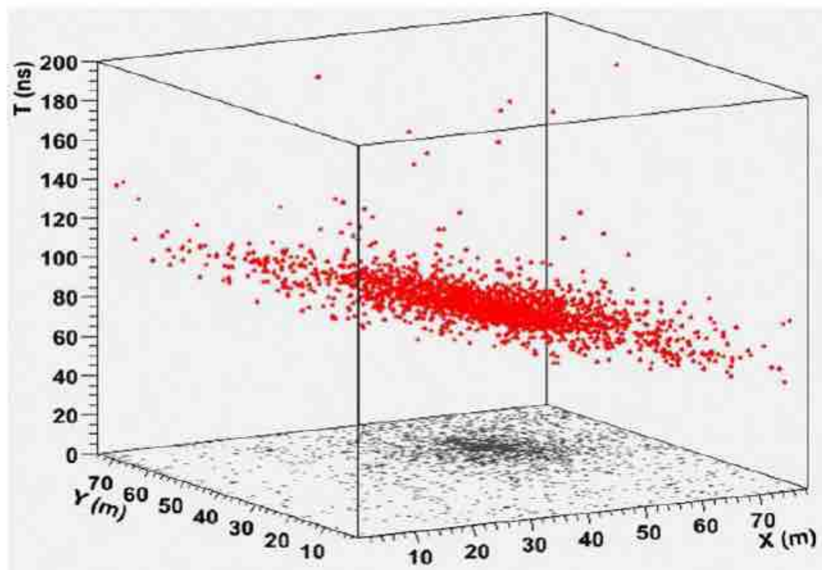
High stability (efficiency ≈ 97%, T = 8° ÷ 22° C)

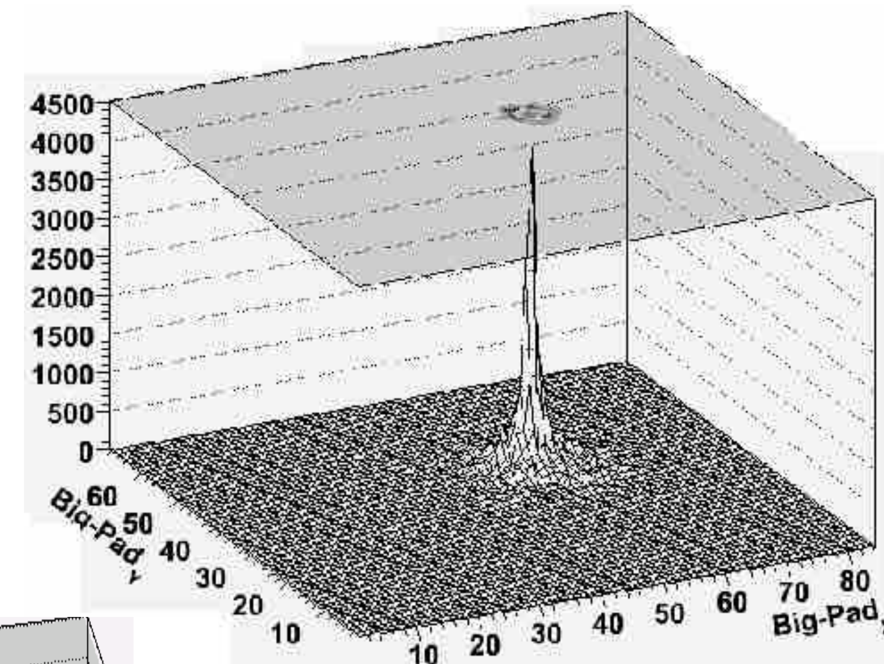
- the *main drawback* : the need of a high gas flow, about 4 volume changes /day
- for a large-scale use a gas recirculation/purification system is needed to operate these RPCs in closed loop

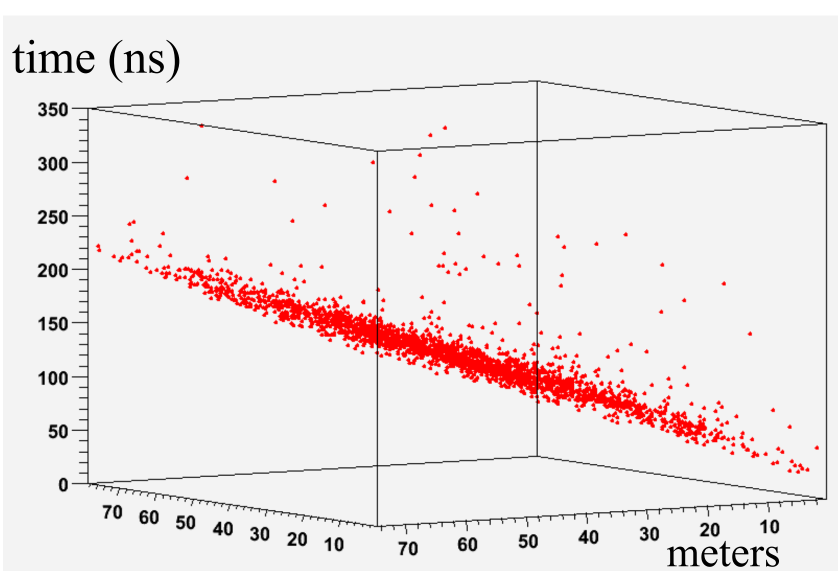


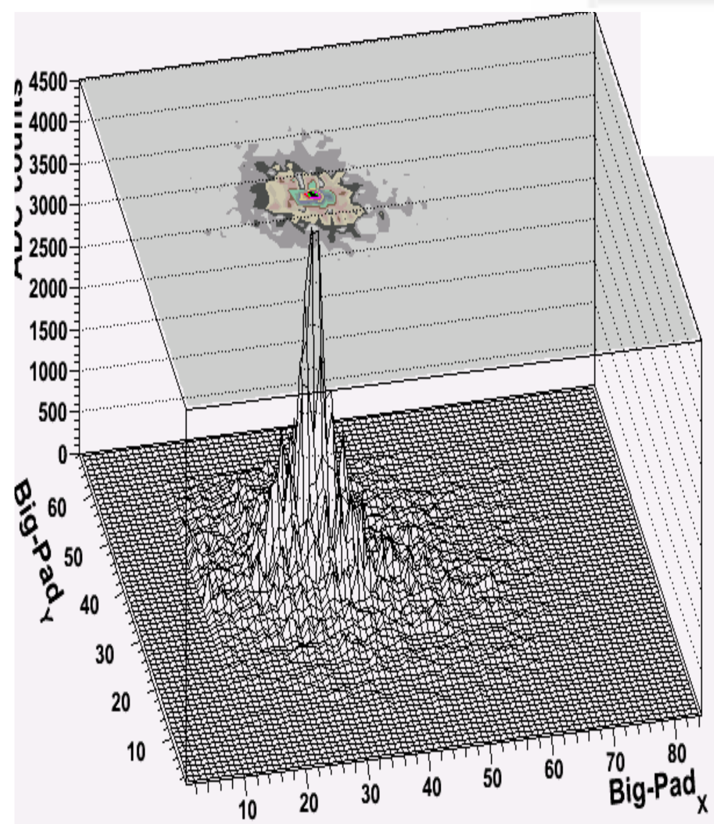
The imaging capability of RPCs ARGO-style

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









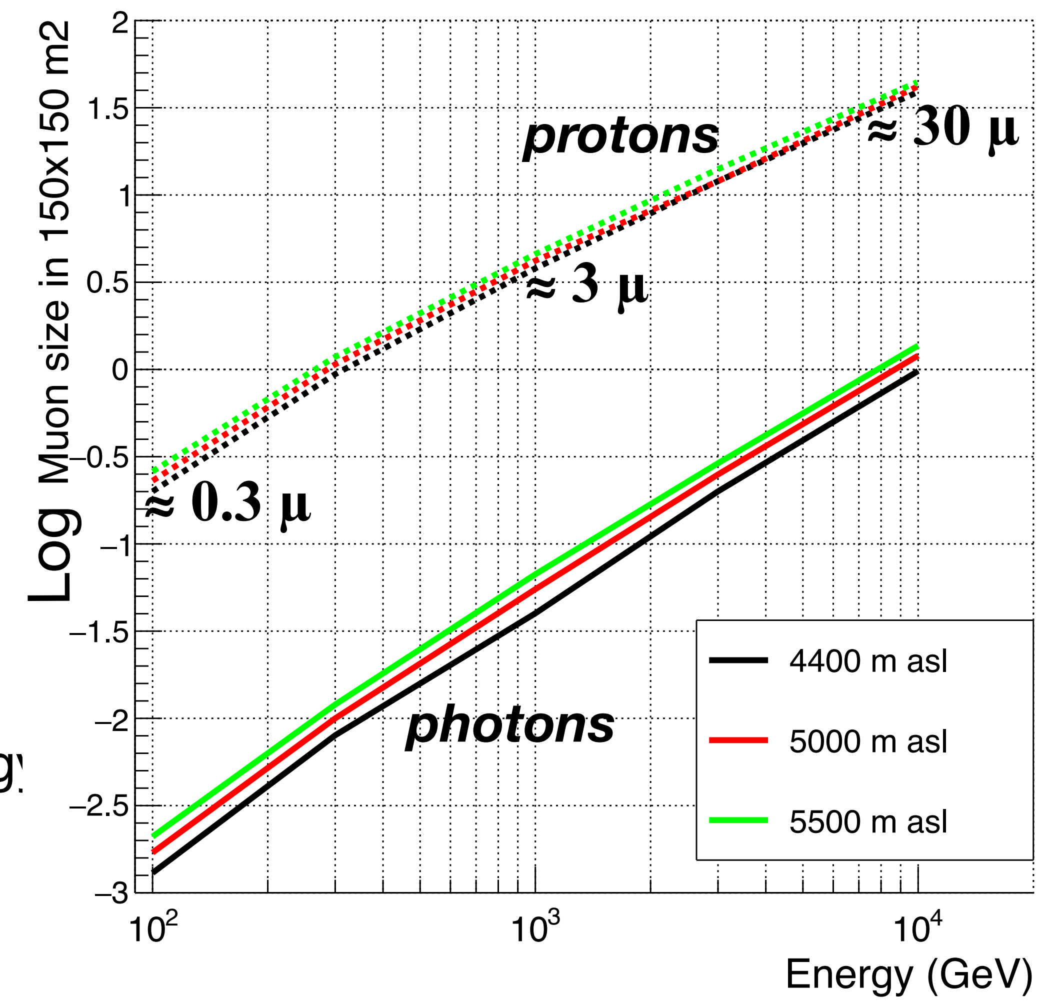
Unprecedented details in the core region

Gamma/Hadron discrimination with arrays

Classical technique:
measurement of the *muon content* event by event

But, muon size very small: ≈ 3 μ per TeV (protons)

➡ *Only at high energies* muon counting is a powerful gamma/hadron discriminator (> 5 - 10 TeV) !



HAWC/LHAASO approach requires large area:
discrimination based on topological cut in the pattern of energy deposition far from the core (>40 m).

But topology requires sufficient number of triggered channels (>70 - 100) ➜ minimum energy required: E > 0.7 - 1 TeV ?

*Background discrimination < TeV is **OPEN PROBLEM** !*

Very small number of particles ➜ topology can be hardly applied

New ideas < TeV ?

- *Combined measurement of space-time pattern ➜ RPCs*

Conclusions

- Extragalactic transient detection requires *low threshold, ≈100 GeV*.
- *Extreme altitude* (≈5000 m asl), *full coverage* and *high granularity of the read-out* are key.
- *Background rejection below TeV challenging ➜ space + time ?*
- *Selection of primary masses* up to 10 PeV crucial ➜ *RPCs with charge readout*
- Capability of Water Cherenkov facilities in selecting primary masses must be investigated.

STACEX final layout still under investigation (only 150×150 m^2 carpet, preliminary!):

- Energy threshold: 100 GeV with ARGO-style RPCs not an issue
- Angular resolution: ≈ 0.7° at 100 GeV
- Energy resolution: ≈10% at 10 TeV
- Effective area: ≈6000 m^2 at 100 GeV

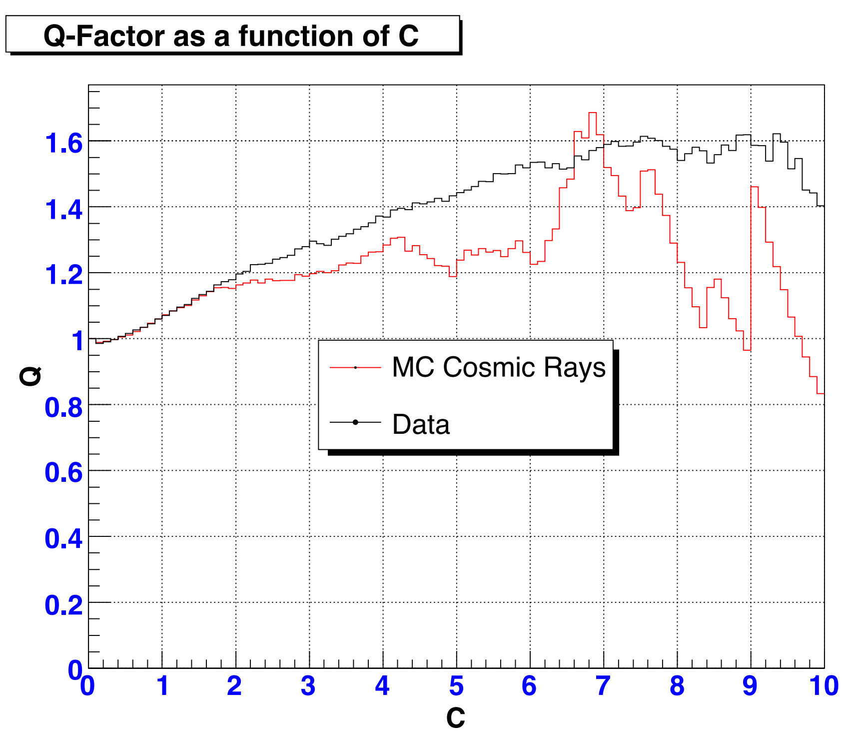
STACEX Sensitivity ≈10% Crab at 100 GeV

Background rejection in 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.



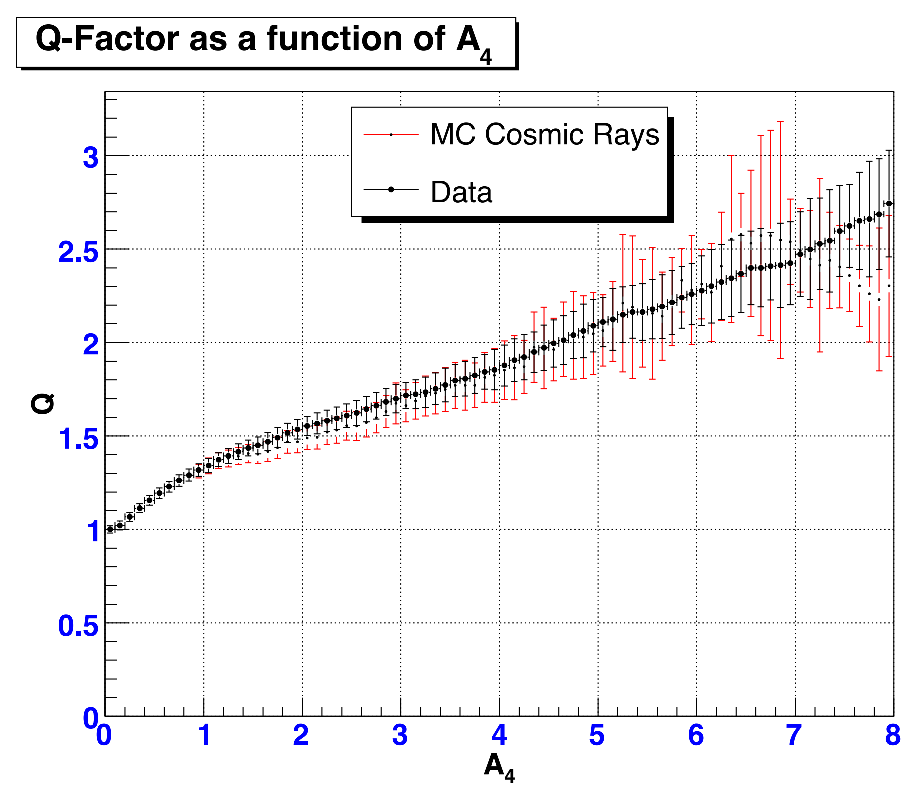
Consistent with ARGO findings after cuts on χ^2 of the temporal fit

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

- 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.

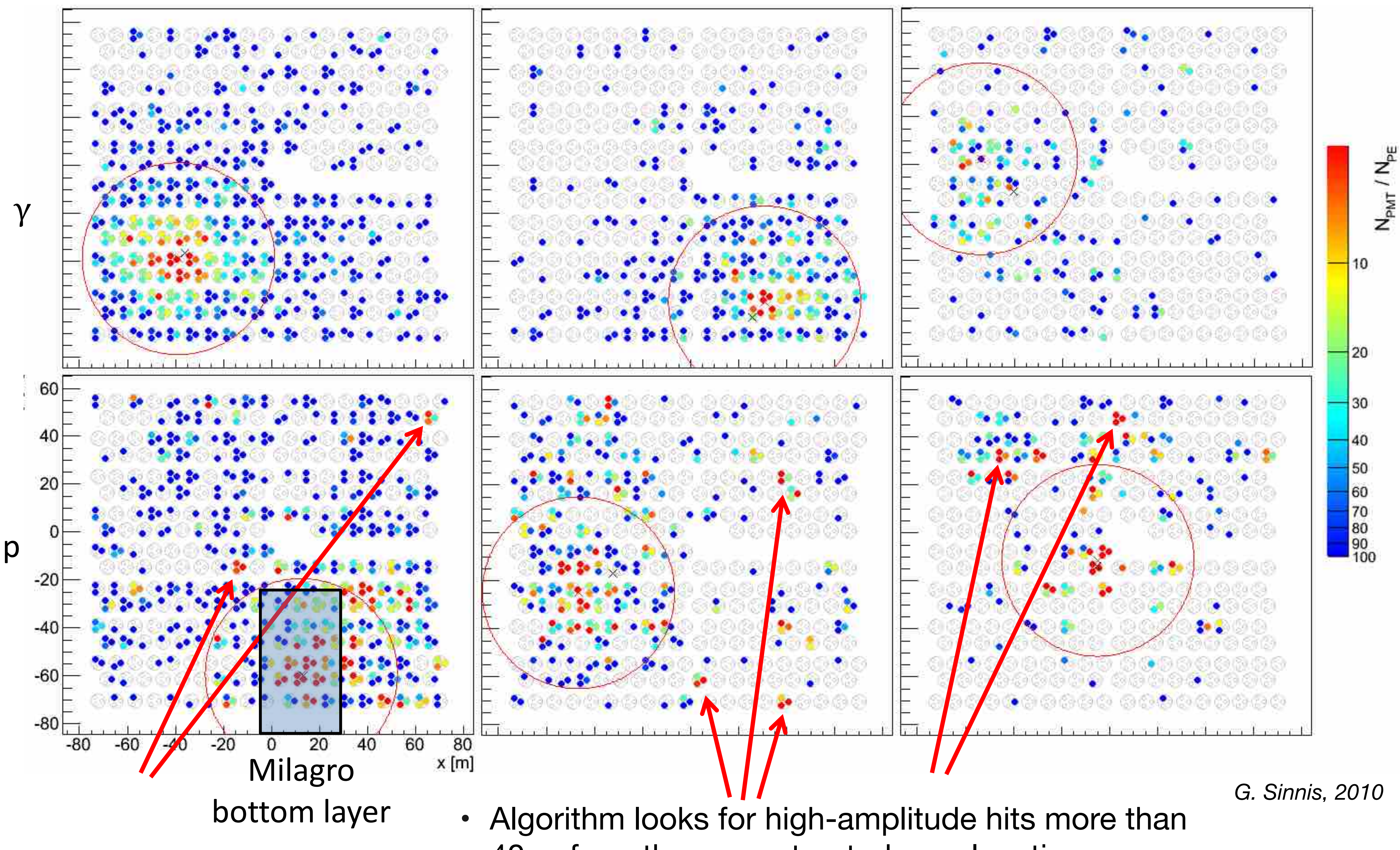
$(f_{top} + f_{out})$ = info on the size of the shower

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…

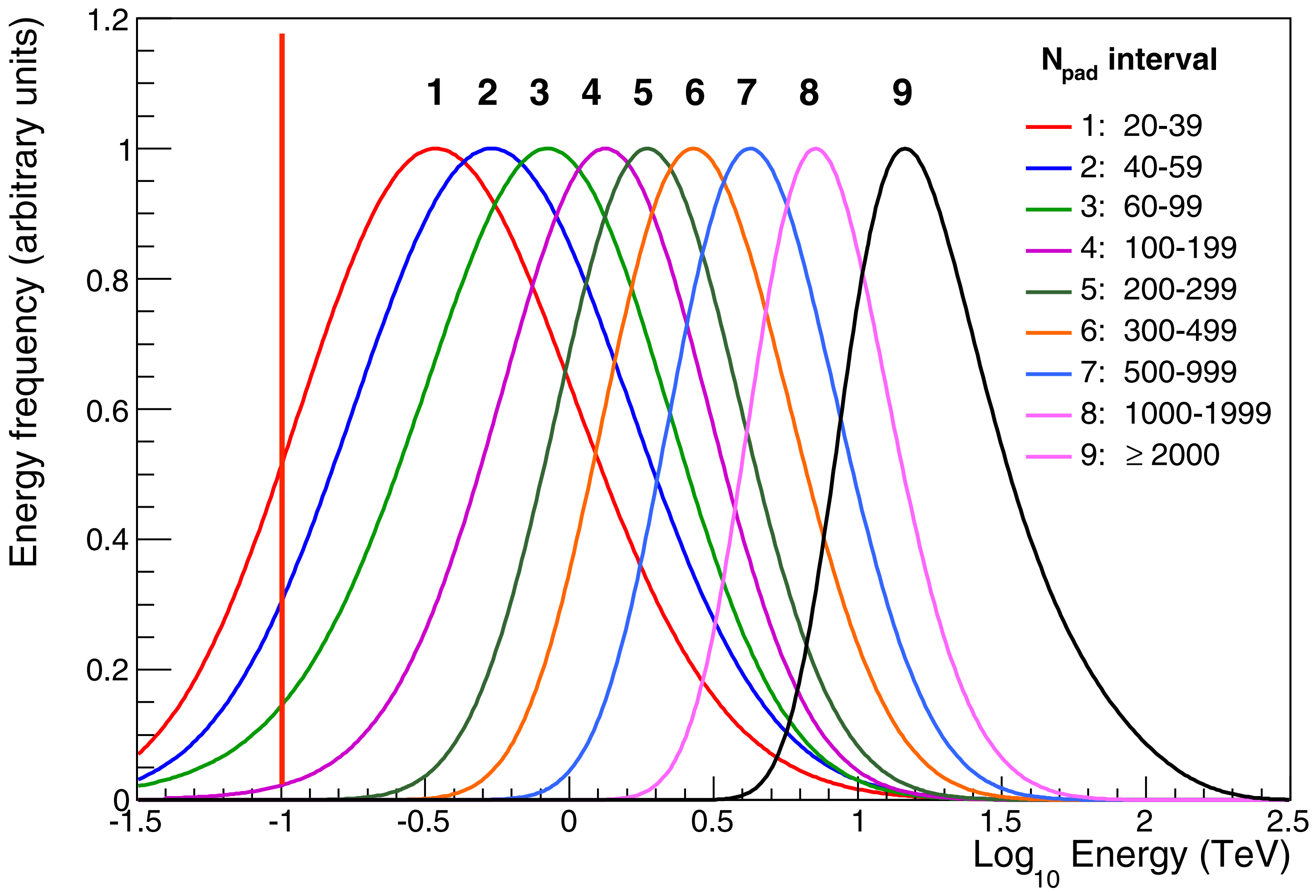


- Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location

G. Sinnis, 2010

Energy threshold and resolution

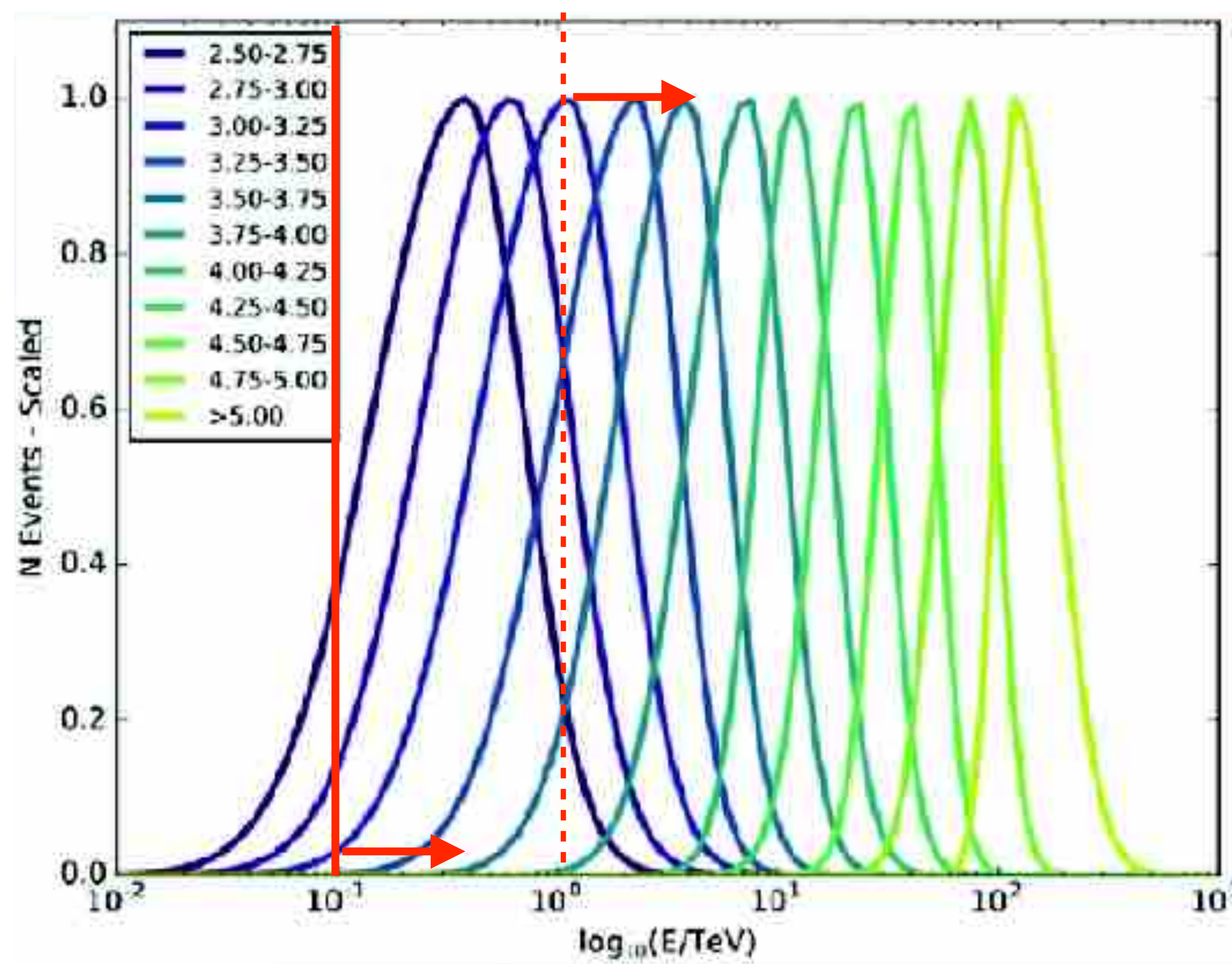
ARGO-YBJ (all triggered events)



full coverage RPC carpet operated at 4300 m asl

coverage ≈ 92%
high granularity (cm level)
Topological-based Trigger logic;
>20 pads out of 15,000 bkg free !
Noise: 380 Hz/pad

HAWC (2019) internal events only

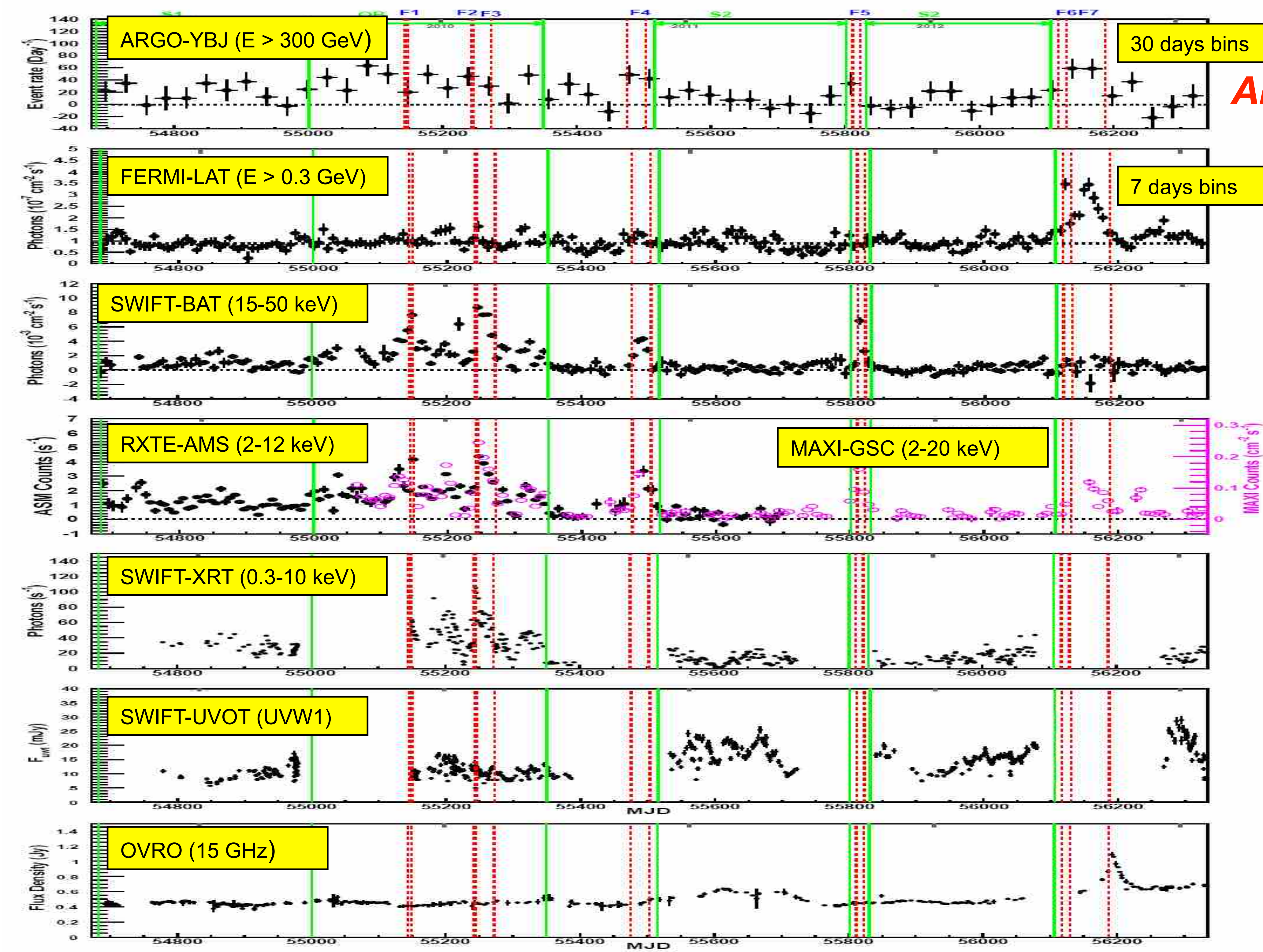


array of water tanks operated at 4100 m asl

coverage ≈ 60%
poor granularity (m level)
Trigger rate: 24 kHz
Noise: 20-30 kHz/8" PMT (40-50 kHz/10"PMT)

The flaring γ-ray sky: Mrk421

ApJ Supplement, 222 (2016) 6

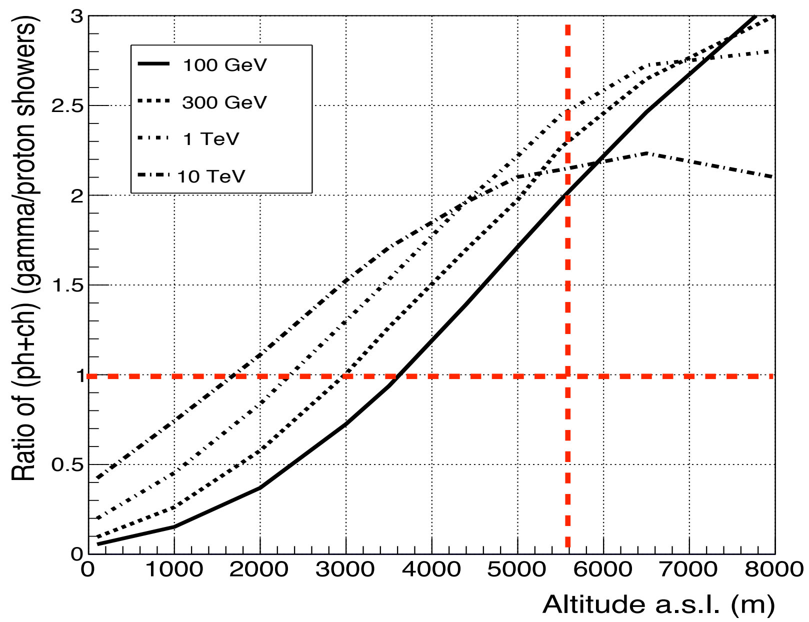


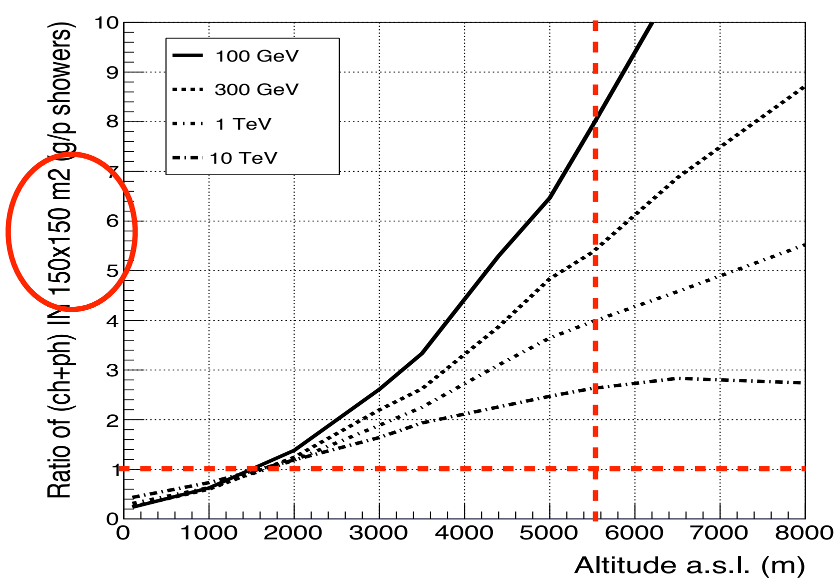
ARGO-YBJ 5 years

γ/p detection efficiency

Increasing the *γ/hadron relative trigger efficiency*

$$R = \sqrt{\frac{A^{\gamma}_{eff}(E)}{A^{B}_{eff}(E)}}$$

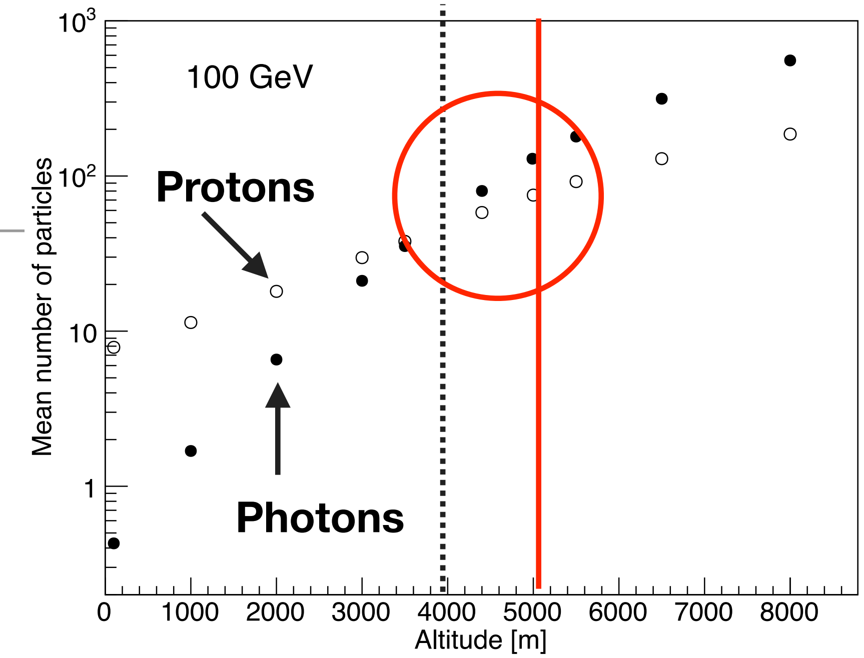


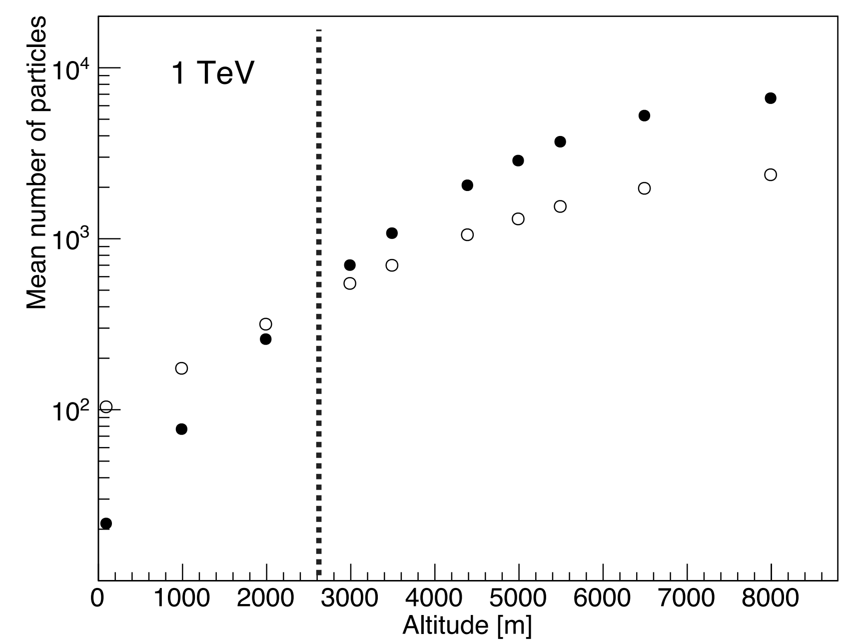


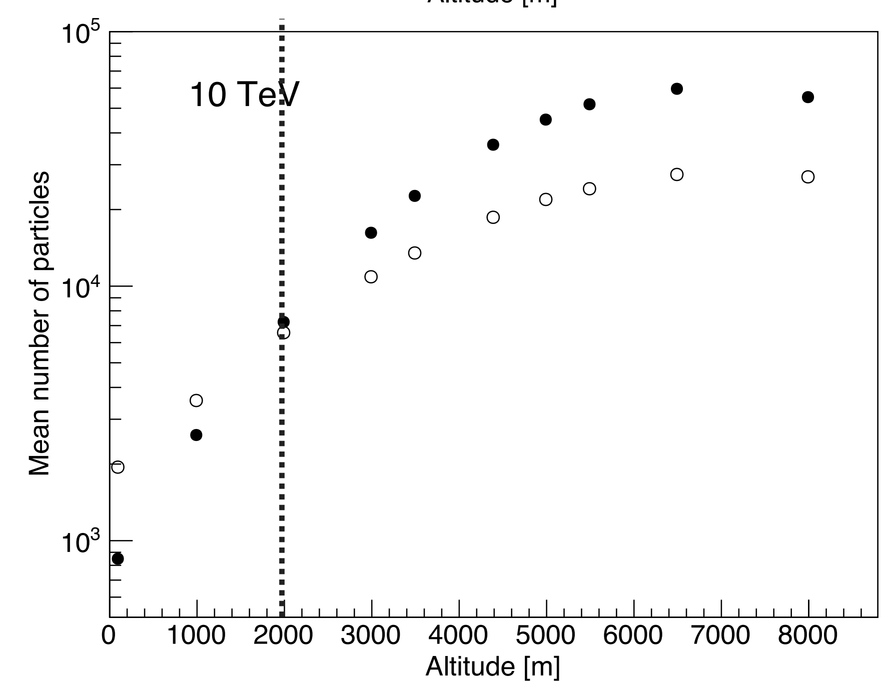
The number of particles in γ-showers exceeds the number of particles in p-showers at extreme altitude.

Trigger probability of a detector larger for γ-showers than for p-showers at extreme altitude.

Better close to the core







The energy threshold 'suggests' the appropriate altitude