STACEX: RPC-based detector for a multi-messenger observatory

G. Di Sciascio *with M. Tavani and R. Santonico*
INFN - Roma Tor Vergata
disciascio@roma2.infn.it

SGSO Meeting

Heidelberg, October 08-09, 2018

The STACEX proposal

Southern TeV Astrophysics and Cosmic rays Experiment

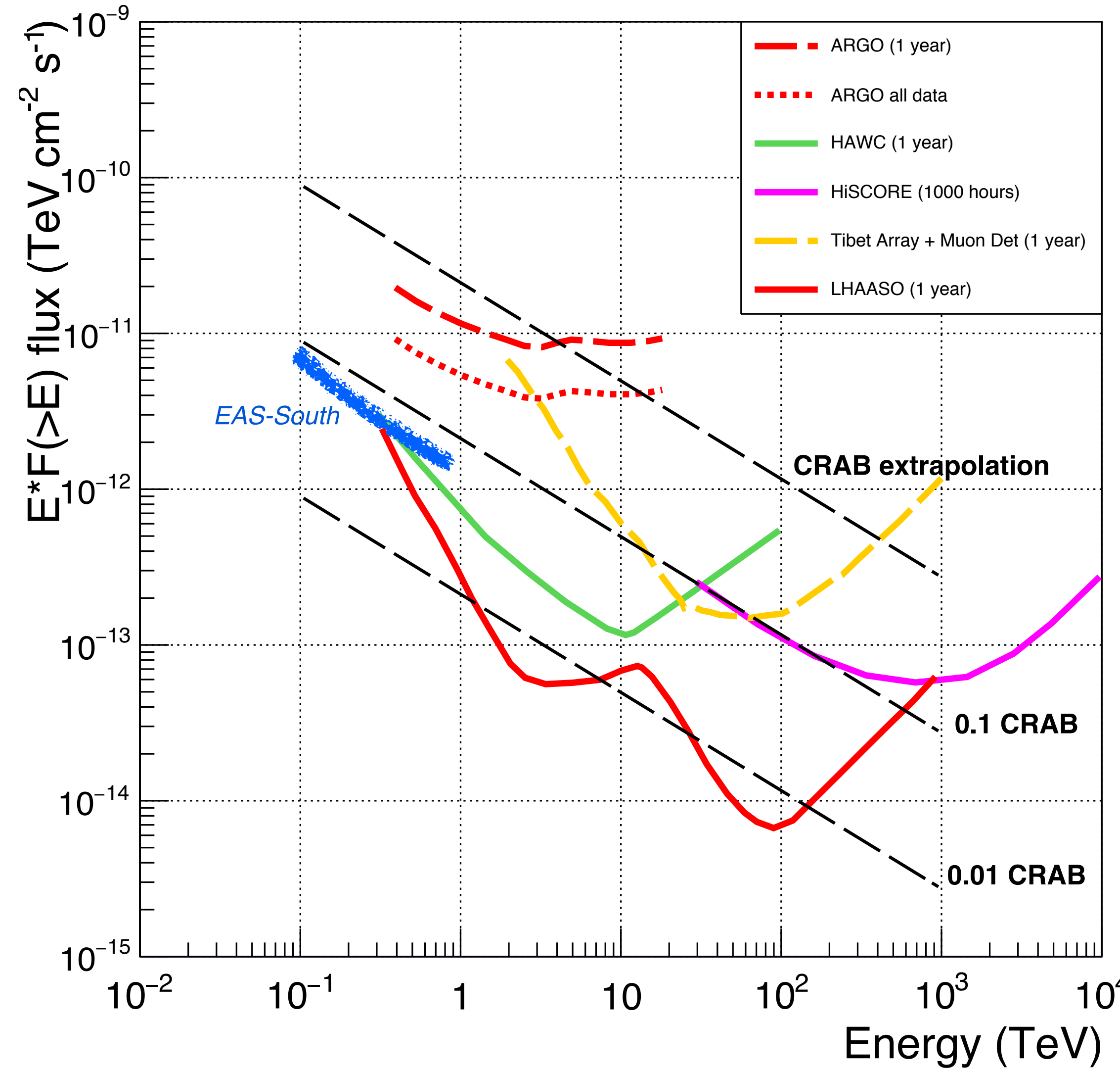
A Wide FoV Detector for Gamma-Ray Astrophysics in the Range 100 GeV - 10 TeV in the Southern Hemisphere

G. Di Sciascio, R. Santonico, M. Tavani

March 9, 2015

Abstract

We present the concept of a new wide-FoV high-altitude detector in the Southern hemisphere dedicated to gamma-ray astronomy in the range 100 GeV - 10 TeV. The new instrument is based on large-area particle detectors (Resistive Plate Chambers, RPCs) already tested and implemented in the ARGO shower array experiment. The new experiment will have a sensitivity better than 10% Crab Nebula flux per year at 100 GeV with a very good angular resolution. It will be unique and complementary to CTA-South and other TeV detectors planned to be active during the next decade. We consider here a possible site in Argentina at the 4800 m asl of the Alto Chorrillos region, currently hosting also the Long Latin American Millimeter Array (LLAMA).



unpublished note

updated ARGO carpet operated at 5000 m asl
Instrumented area 150 x 150 m^2
hypothesis: $Q_f = 2$ below TeV

Very preliminary calculation made with ARGO simulation and reconstruction codes and with ARGO trigger logic

The motivation

EAS arrays are *multi-messenger* instruments by definition

Operation at extreme altitude very difficult

➡ A *"small"* array (≈150 × 150 m^2) with high performance and sensitivity to investigate the '*cosmic ray connection*' through a combined study of *cosmic rays* and *gamma-rays* in the energy range *10^{11} -- 10^{16} eV*.

We believe the ARGO-like RPCs should be an important element of a future experiment

STACEX Workshop 2016

WORKSHOP

"TOWARDS A LARGE FIELD-OF-VIEW TEV EXPERIMENT IN THE SOUTH"

JANUARY 14-15, 2016

UNIVERSITY OF TOR VERGATA, ROME, ITALY

DEPARTMENT OF PHYSICS, "GRASSANO CONFERENCE ROOM"

http://www.iaps.inaf.it/stacex/index.html

Scientific Program

WORKSHOP

"TOWARDS A LARGE FIELD-OF-VIEW TEV EXPERIMENT IN THE SOUTH"

January 14-15, 2016, University of Tor Vergata, Rome

Thursday, January 14

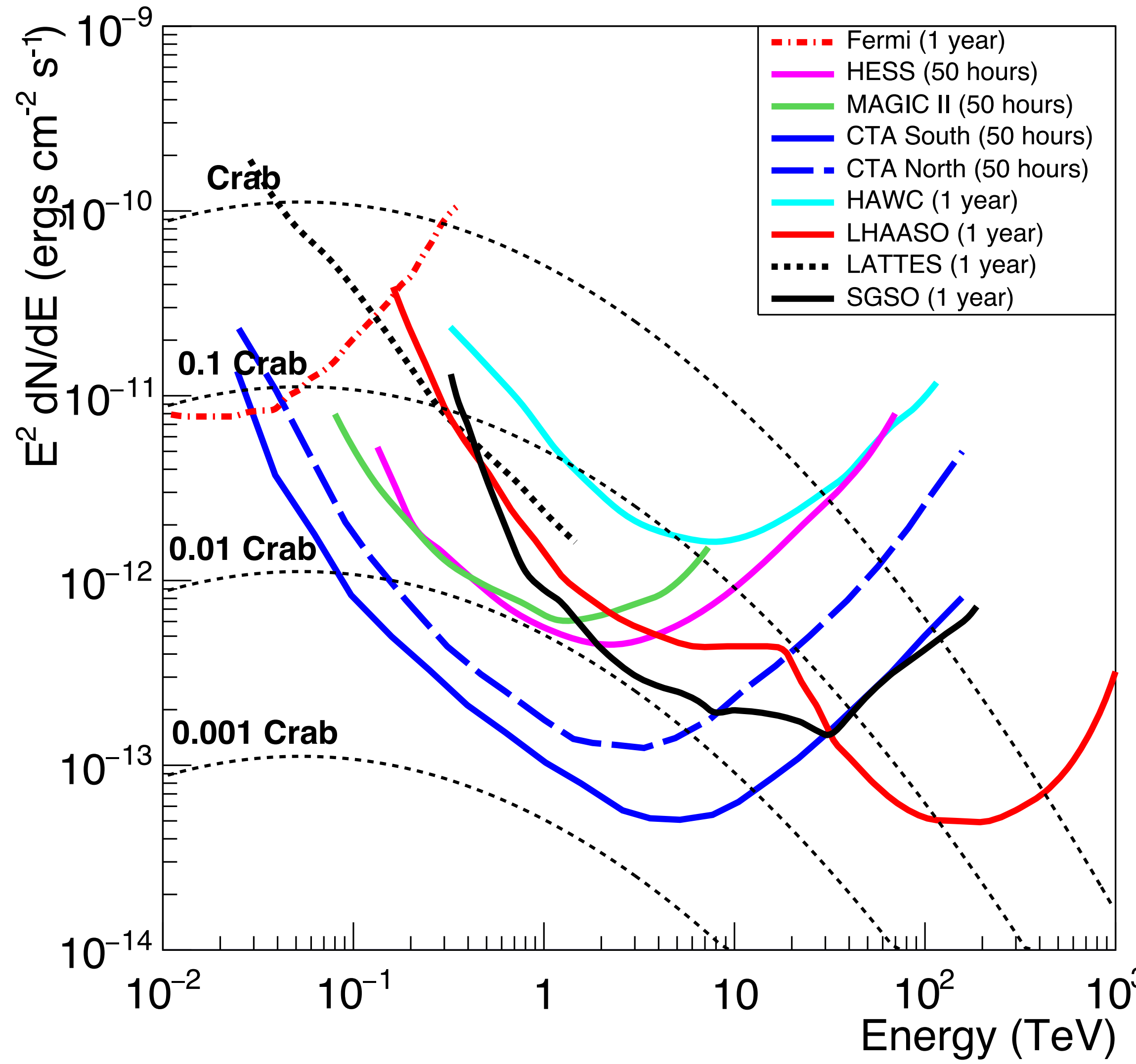
14:00 - 14:15	*Welcome/Introduction*	M. Tavani/R. Santonico	PDF
14:15 - 14:35	*Status of Current Wide FoV Experiments/Projects*	G. Di Sciascio	PDF
14:35 - 15:00	*HAWC and Ideas for a Southern HAWC*	M. Du Vernois	PDF
15:00 - 15:20	*CTA*	G. Pareschi	PDF
15:20 - 15:40	*LATTES*	G. Matthiae	PDF
15:40 - 16:10	*Marta RPCS*	P. Fonte	PDF
16:10 - 16:30	*Studies on LATTES Performance at Low Energies*	R. Conceição	PDF
16:30 - 16:50	Coffee Break		
16:50 - 17:15	*Simulation Framework for LATTES*	B. Tomé	PDF
17:15 - 17:35	*ARGO-YBJ Legacy to Next Generation Wide FoV Experiments*	R. Iuppa	PDF
17:35 - 18:00	*Electronics for LATTES Prototypes*	P. Assis	
18:00 - 18:20	*New Electronics for RPCs (TBC)*	R. Cardarelli	PDF
18:20	*End*		
	Social Dinner		

Friday, January 15

09:30 - 10:00	*Evidence for a Presence of a Powerful PeVatron in the Galactic Center: is it Sgr A*?*	F. Aharonian	
10:00 - 10:30	*Galactic Gamma-Ray Emission at Very High Energy*	P. Lipari	PDF
10:30 - 10:50	*Galactic Cosmic Rays*	A. Chiavassa	PDF
10:50 - 11:10	*CR Spectrum, Composition and Arrival Direction Distribution at the South Pole*	P. Desiati	
11:10 - 11:30	Coffee Break		
11:30 - 11:50	*ASTRI*	S. Vercellone	PDF
11:50 - 12:10	*Neutrino Telescopes in a Multimessanger Context*	G. De Bonis	PDF
12:10 - 12:30	*Fermi and VHE Sources*	P. Giommi	PDF
12:30 - 12:50	*Observing the High Energy Fermi Sources with the Air Shower Arrays: the Case for LHAASO and LATTES*	B. D'Ettore Piazzoli	PDF
13:00 - 15:00	*Lunch*		
15:00 - 17:00	Round table chaired by Tavani/Santonico		PDF PDF Violini
17:00	*End*		

Why a new Wide FoV detector in the CTA era ?

- Galactic/Extragalactic *unbiased survey*: detection of *unexpected sources*
- High exposure for *flaring activity* (AGN, GRBs, solar flares): *transient factory*
- “Finder” telescope for CTA: provides *targets for in-depth observations*
- *Extended objects* (PWN, diffuse gamma-ray emission)
- *Fundamental physics*
- “Classical” *Cosmic Ray Physics* (energy spectrum, *elemental composition*, anisotropy, hadronic interactions in the PeV domain)



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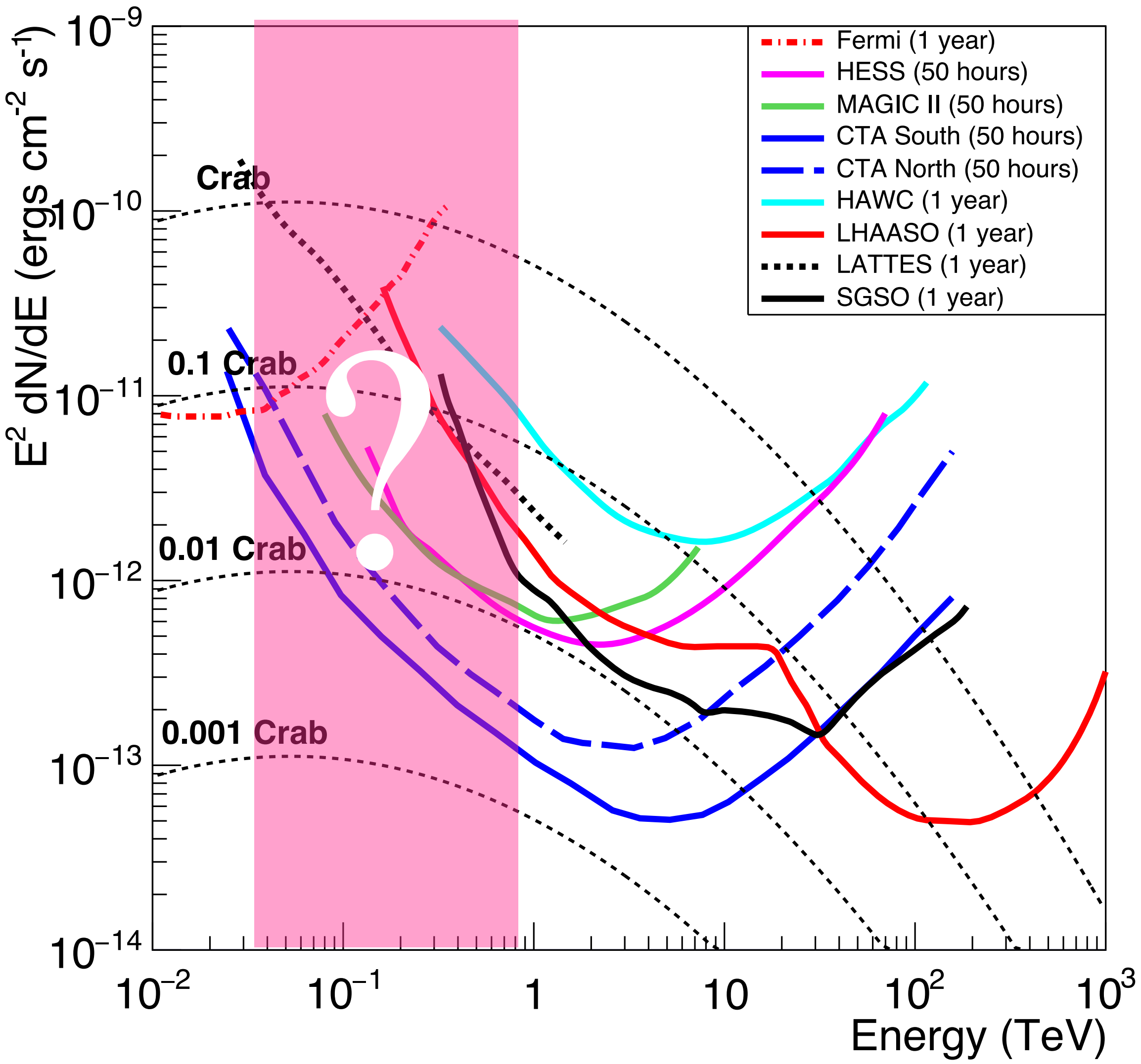


No Wide FoV experiment to:

- *Explore the 100 GeV energy region*
- *Survey the Inner Galaxy and the Galactic Center*
- *Explore the 100 TeV range*

Scientific requirements

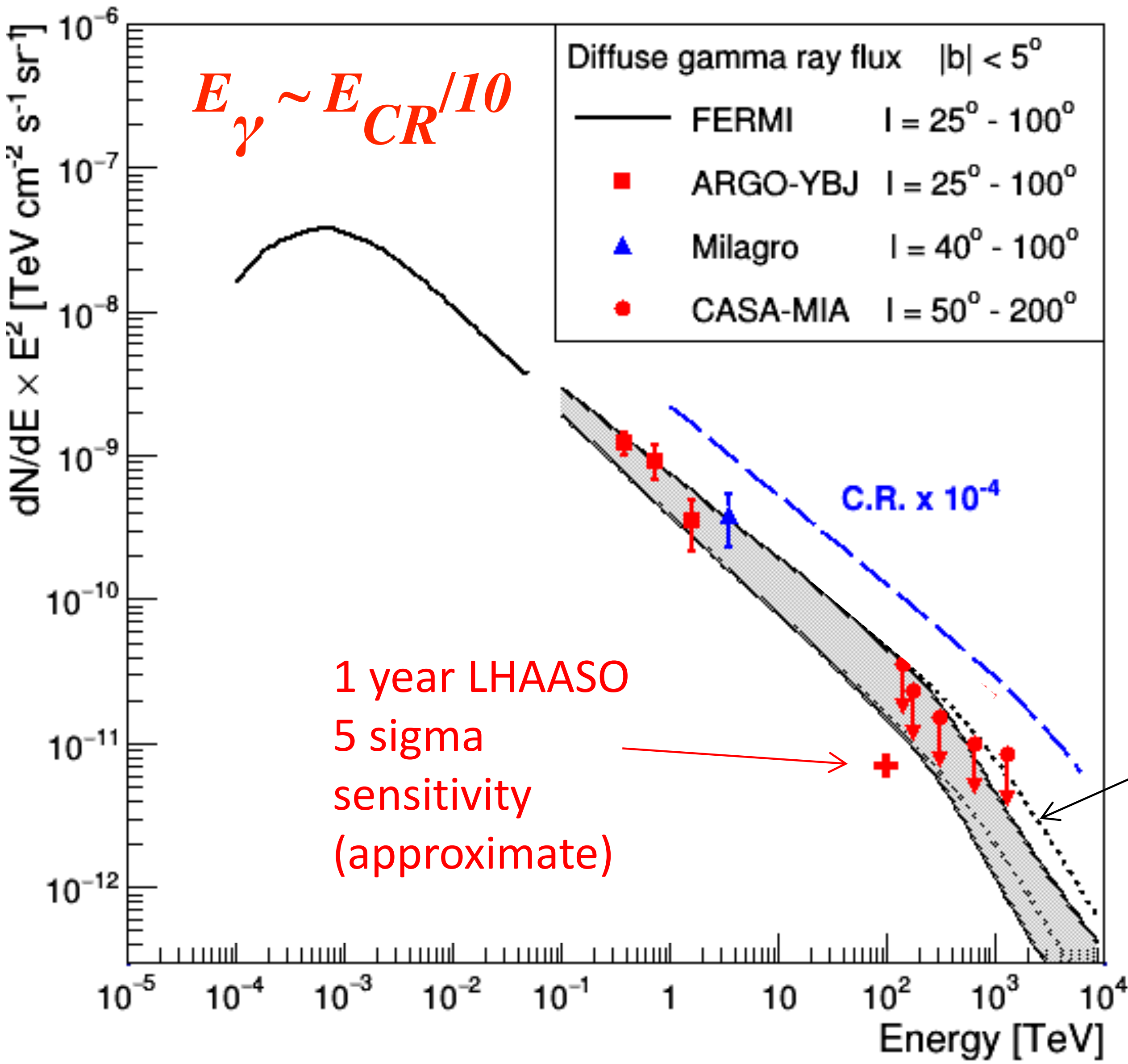
A future Wide FoV Observatory *to be useful (to CTA)* needs:

- *Low energy threshold* (≈ 100 GeV) to detect extragalactic transient (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.*
- Capability to measure the *proton knee* in different regions of the Galactic Plane to investigate the maximum energy of accelerated particles in CR sources and for understanding the observed gamma-ray spectra.
- Capability to *select different primary masses across the knee* to investigate the origin of the knee and *for anisotropy observations vs CR particle rigidity !*
- Background discrimination capability at level of *10^{-5} (!!!) in the 100 TeV range* to observe *the knee in the energy spectrum of the diffuse emission* in different regions of the GP.

★ Is this possible ?

Expected Galactic 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 ?



by 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°

Unabsorbed flux

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

The key parameters

$$S \propto \frac{\Phi_\gamma}{\sqrt{\Phi_{bkg}}} \cdot R \cdot \sqrt{A^{\gamma}_{eff}} \cdot \frac{1}{\sigma_\theta} \cdot Q$$

Φ_B = background flux

ψ_{70} = opening angle

$A^{\gamma,p}_{eff}(E)$ = effective area

$$\Phi_\gamma \sim E_{thr}^{-\gamma}$$

$$\Phi_{bkg} \sim E_{thr}^{-\gamma_{bkg}}$$

$$Q_f = \frac{\text{fraction of surviving photons}}{\sqrt{\text{fraction of surviving hadrons}}}$$

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

The *key parameters* to improve the sensitivity are

- The energy threshold
- R, the signal/background relative trigger efficiency
- The angular resolution
- Q-factor, the background rejection capability

Milagro vs ARGO-YBJ

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

Milagro

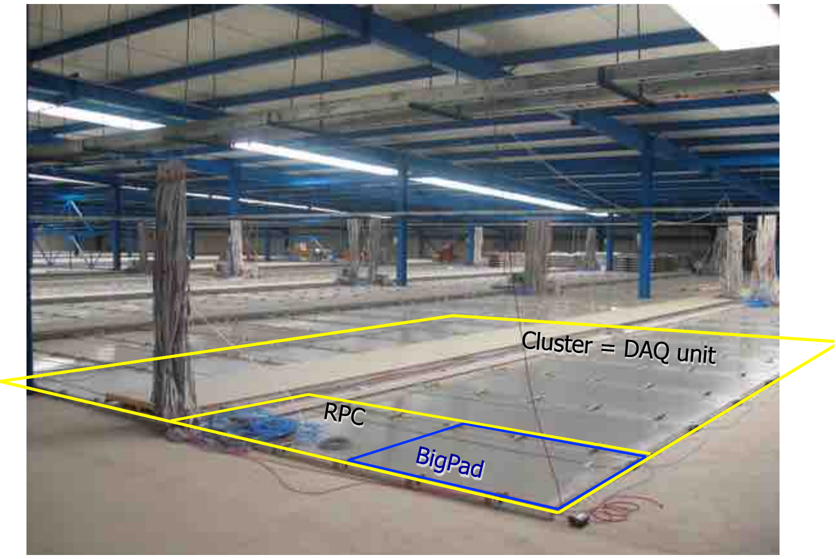
Water Cherenkov Technology

- 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

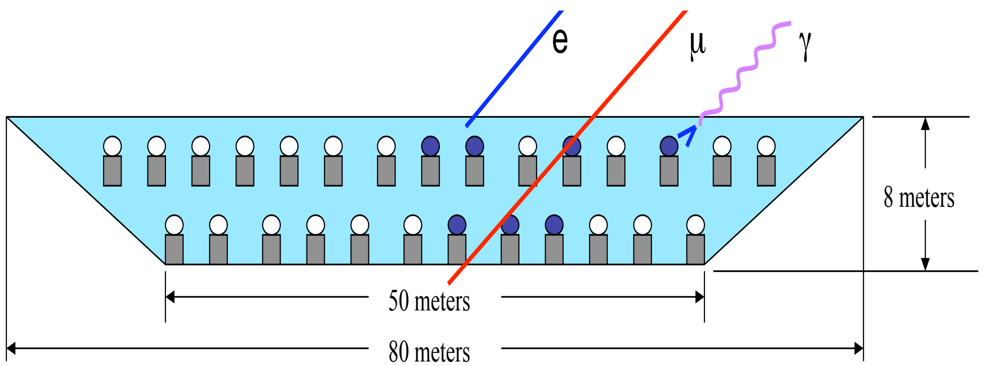


- operated from 2007 to 2012 (final configuration)
- *4300 m* above sea level
- *angular resolution ≈0.5° at 1 TeV*
- 3500 Hz trigger rate
- high granularity of the readout
- *Median Energy at the threshold: ≈340 GeV*
- *Energy Range: 340 GeV - 10 PeV*
- NO background rejection (no outrigger)
- NO conversion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

Widely used technology in particle physics

Milagro vs ARGO-YBJ

Milagro
Water Cherenkov Technology



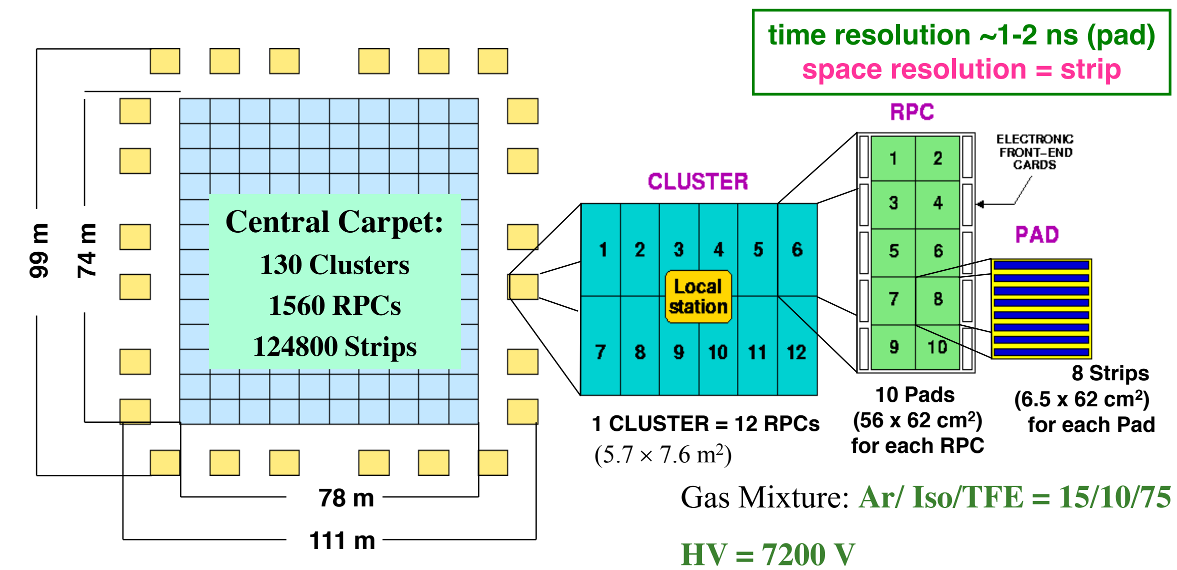
Central 80 m x 60 m x 8 m water reservoir, containing two layers of PMTs

- 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 m^2) + sampling guard ring (6700 m^2 in total)

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

2 read-outs:

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

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

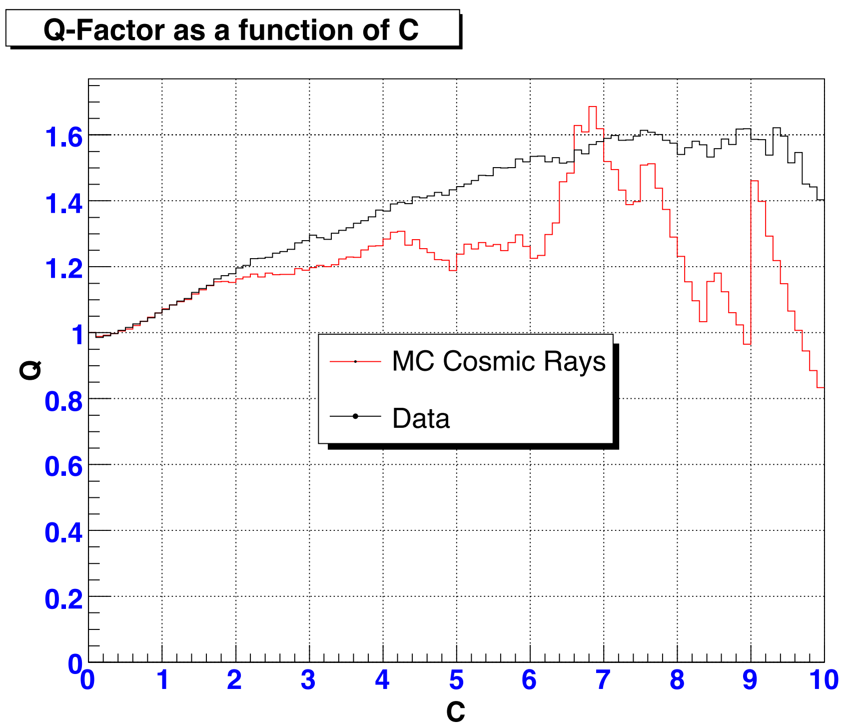
→ ***MATHUSLA*** proposal, CR and hadronic physics at CERN (RPC carpets above ATLAS)

Background rejection in Milgaro

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.



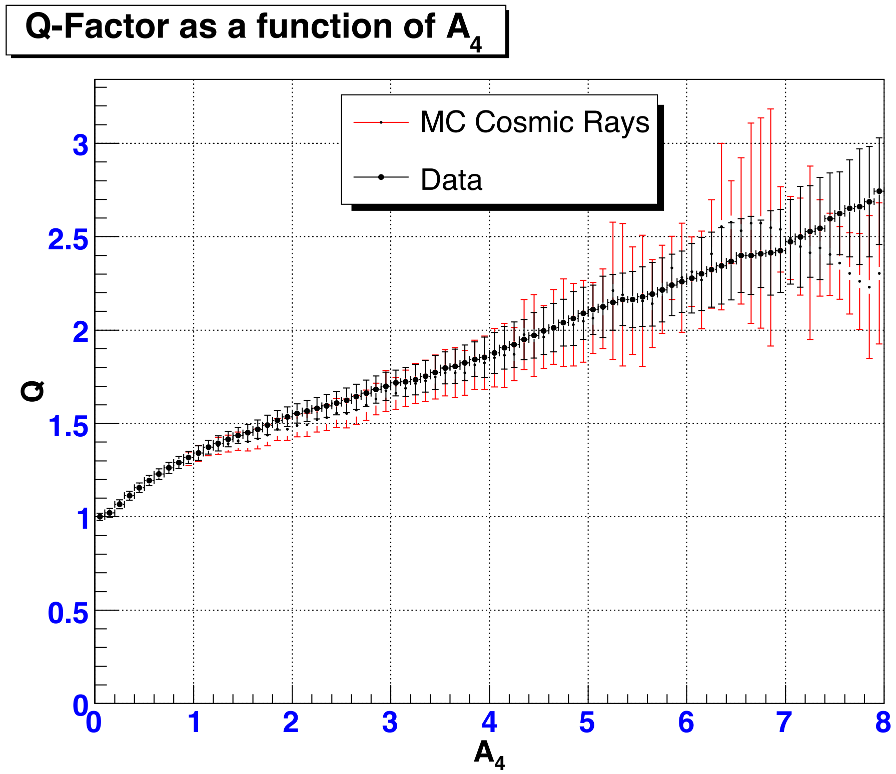
Consistent with ARGO findings after cuts on χ^2 of the temporal fit

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

- 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.

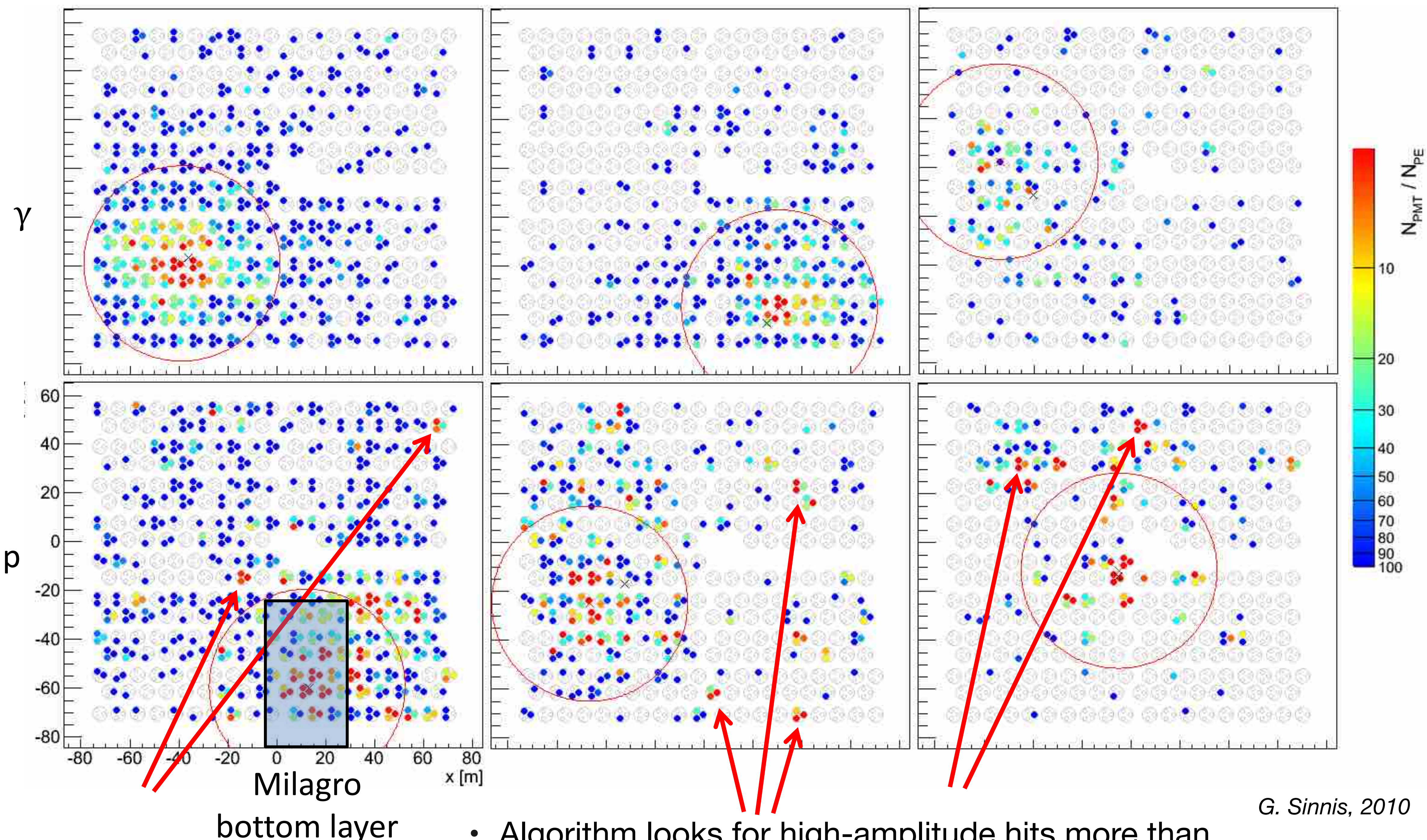
$(f_{top} + f_{out})$ = info on the size of the shower

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…



G. Sinnis, 2010

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

Scientific results

Milagro

Water Cherenkov Technology

- Gamma-ray Astronomy
- CR anisotropy
- *No results on selection of different primary masses and spectra of different elements*

HAWC

Water Cherenkov Technology

- Gamma-ray Astronomy
- CR anisotropy
- All-particle energy spectrum
- *Still no results on the selection of different primary masses*

ARGO-YBJ

Resistive Plate Chamber Technology

- Gamma-ray Astronomy
- CR anisotropy
- All-particle energy spectrum up to the knee range
- Study of the shower core region
- Selection of light component (p+He) and *observation of the proton knee*

With ARGO-YBJ we demonstrated that RPCs can be safely operated at extreme altitude for many years.

Benefits of RPCs in ARGO-YBJ:

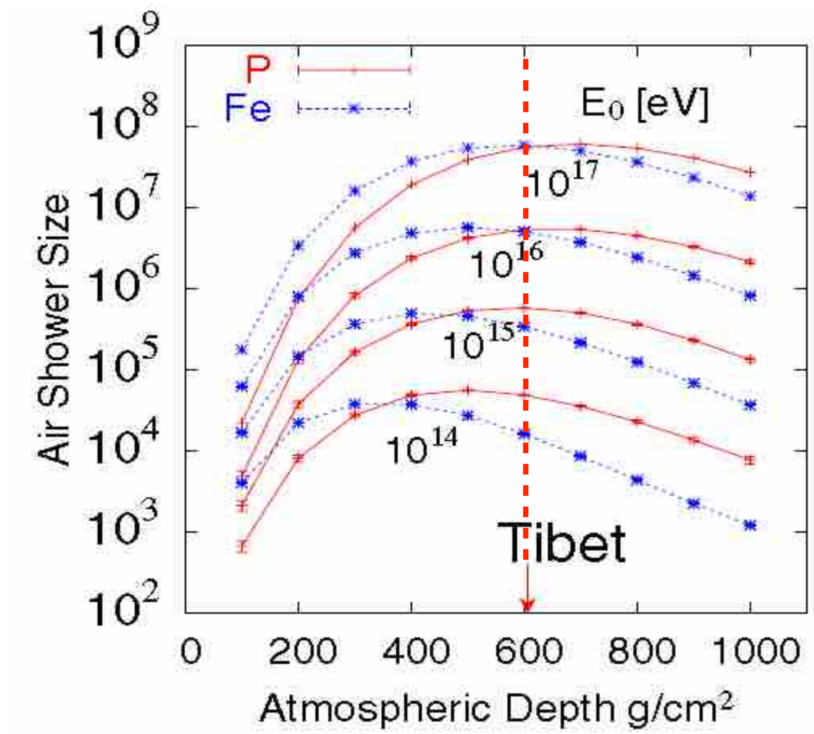
- dense sampling → low energy threshold (≈ 300 GeV)
- wide energy range: ≈300 GeV → 10 PeV
- high granularity of the read-out → good angular resolution and unprecedented details in the core region

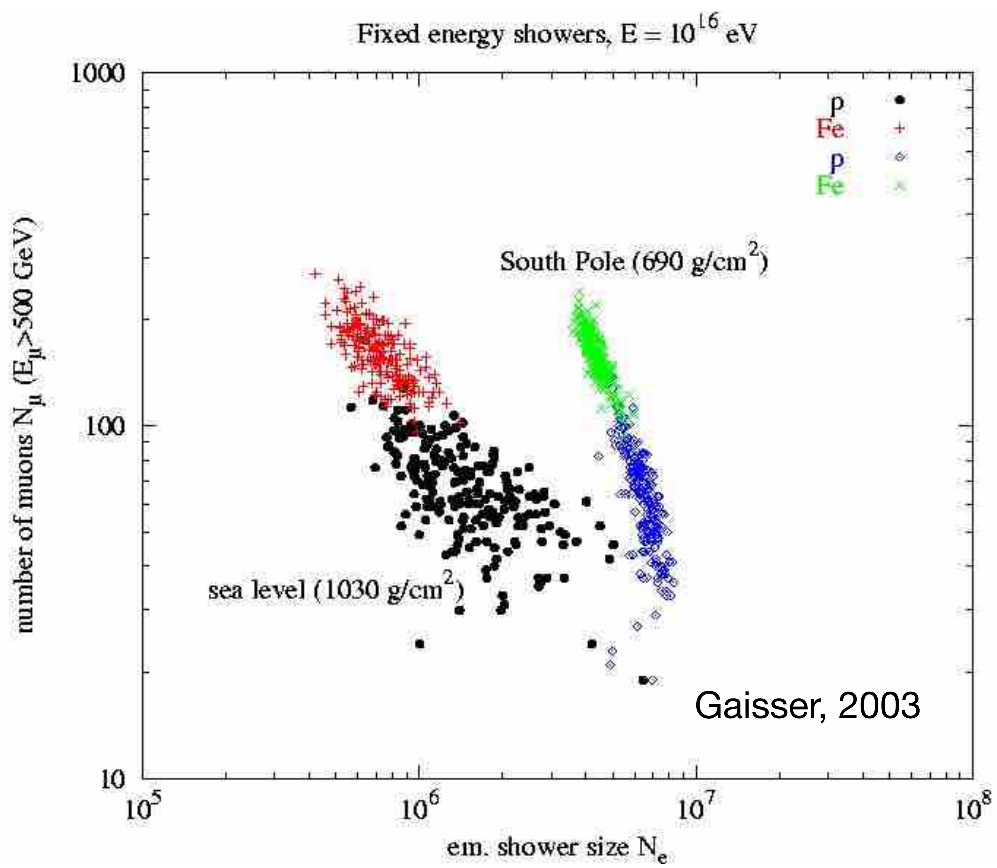
→ *The capability of Water Cherenkov facilities in extending the energy range to PeV and in selecting primary masses must be investigated*

Extreme Altitude

1. *All nuclei produce showers with similar size* $N^A_{e,max} \approx N^p_{e,max}$
2. *Unbiased trigger threshold* for all nuclei
3. Primary *energy reconstruction mass-independent* $Ne(E_0, A) = \alpha(A) \bullet E^{\beta(A)}$
4. *Small fluctuations:* shower maximum
5. *Low energy threshold:* absolute energy scale calibration with the Moon

   Shadow technique and overposition with direct measurements
6. Trigger probability larger for γ-showers than for p-showers





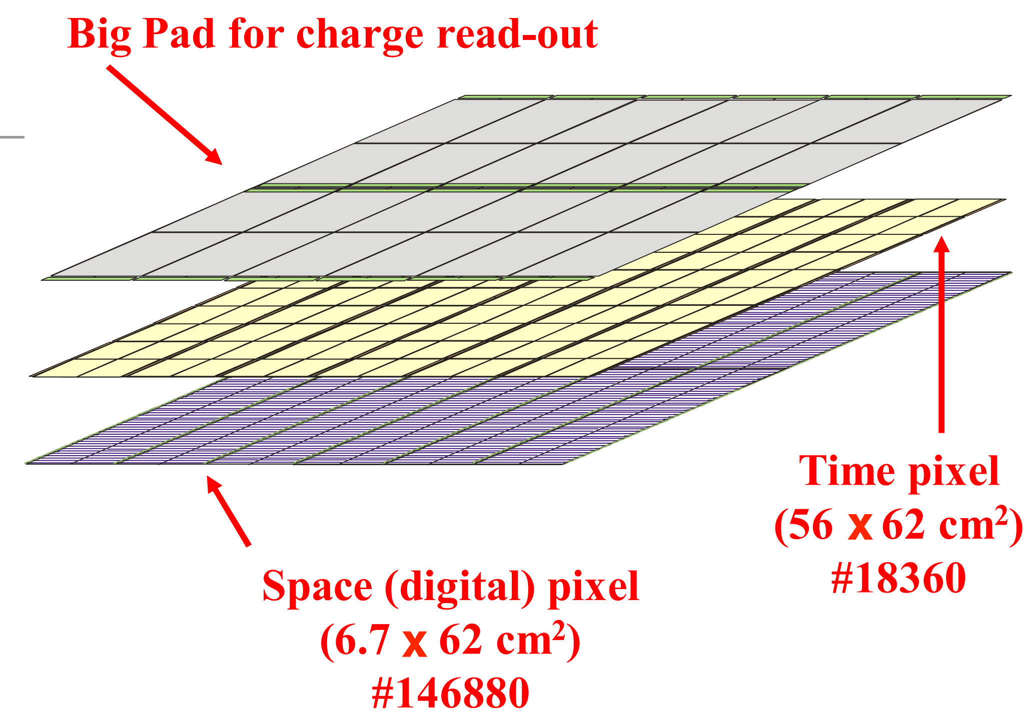
Fluctuations smaller but *reduced sensitivity of the N_e/N_μ technique in selecting primary masses*

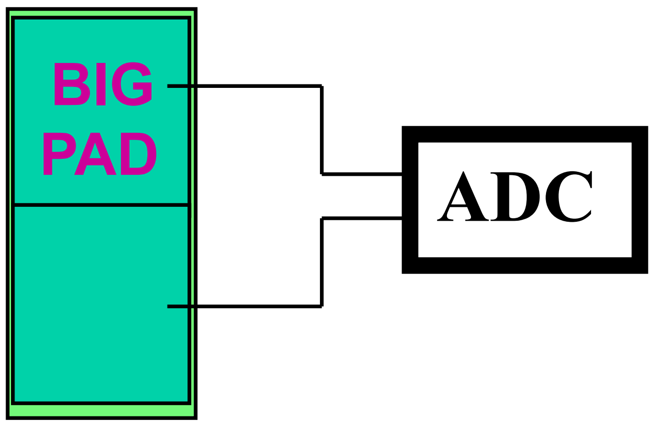
➜ Different technique to select primary masses: ARGO-YBJ, Tibet ASγ, BASJE-MAS exploited *characteristics of the shower core region.*

No muons ? ➜ results nearly independent on hadronic interaction models !

The RPC charge readout

…extending the dynamical range up to 10 PeV

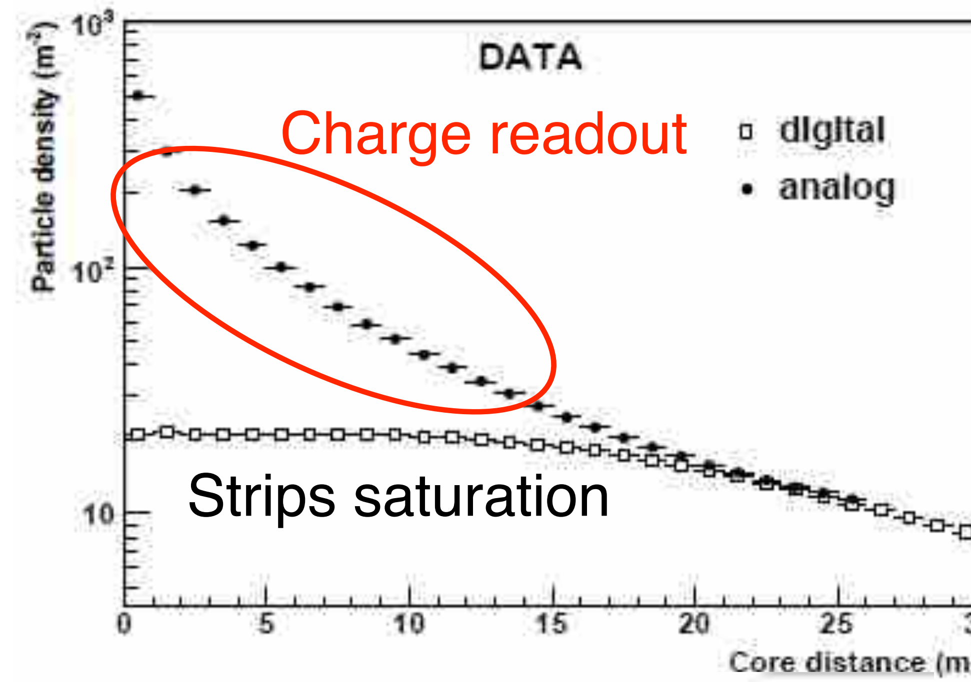


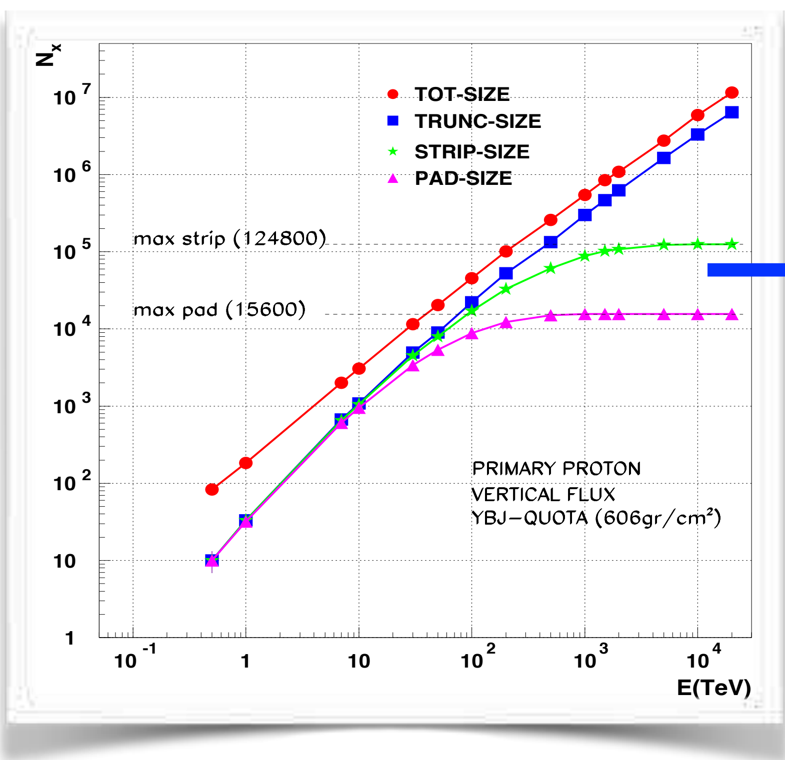


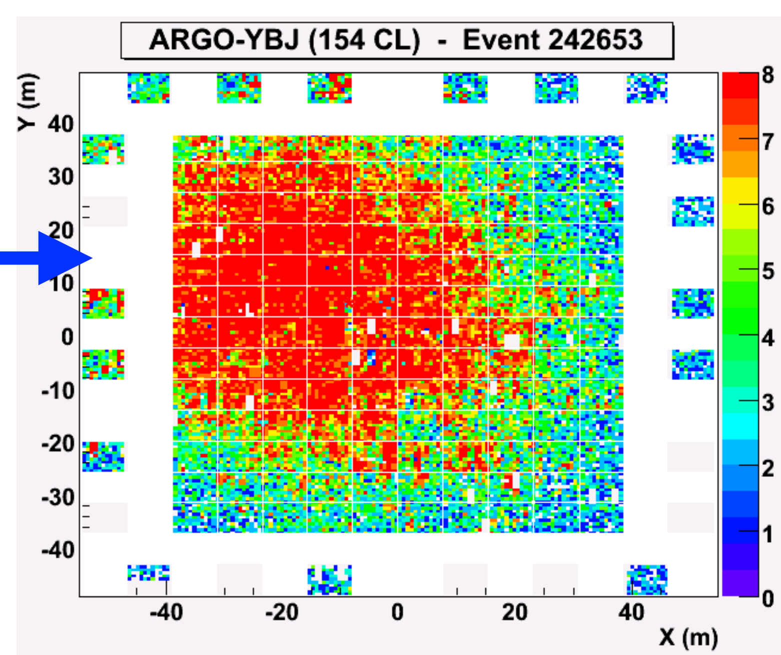
4 different gain scales used to cover a wide range in particle density:

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

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

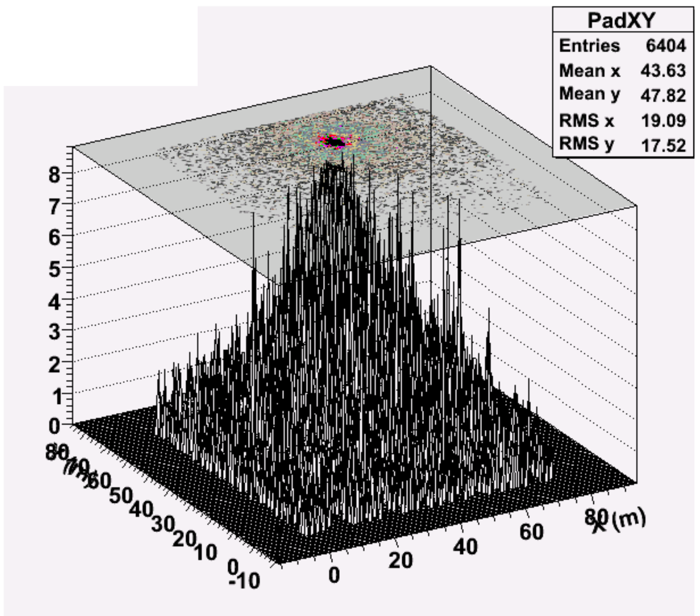






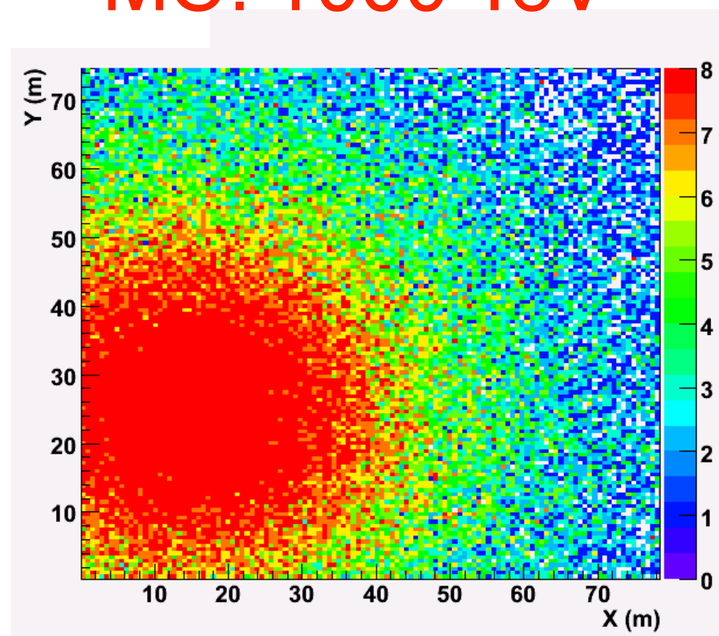
The RPC charge readout: the core region

MC: 100 TeV



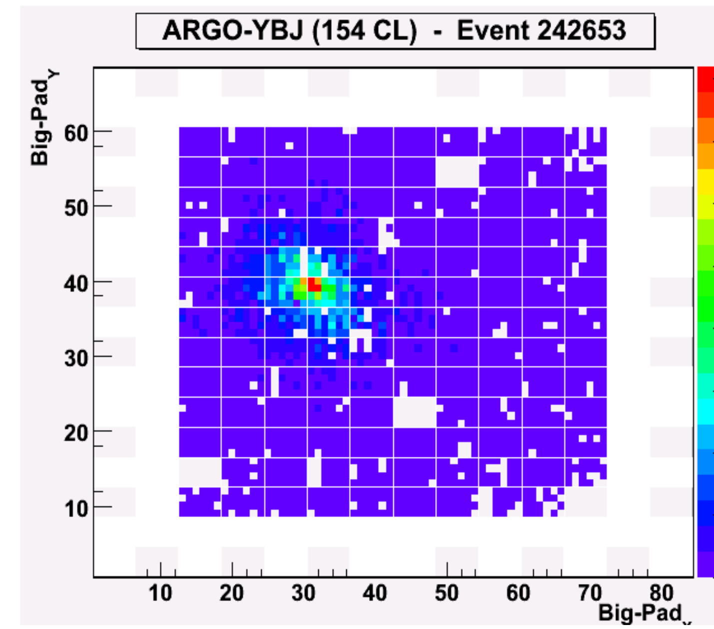
Strip read-out

MC: 1000 TeV

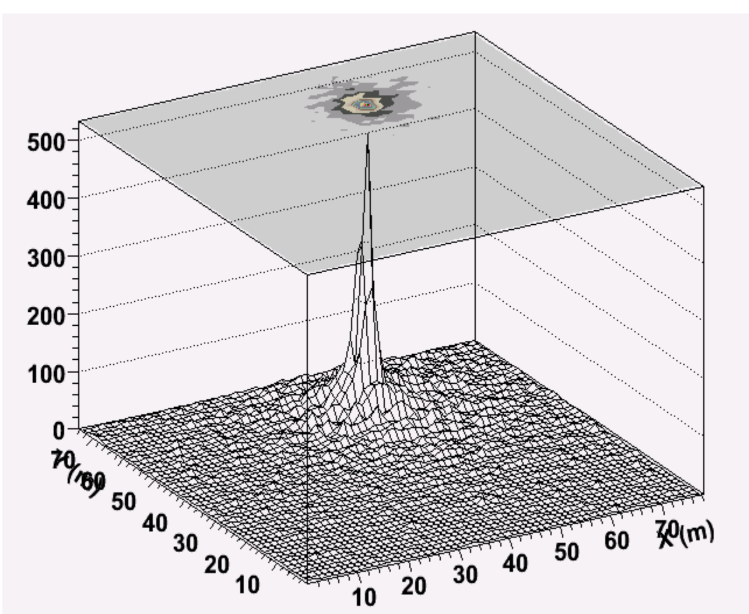


Strip read-out

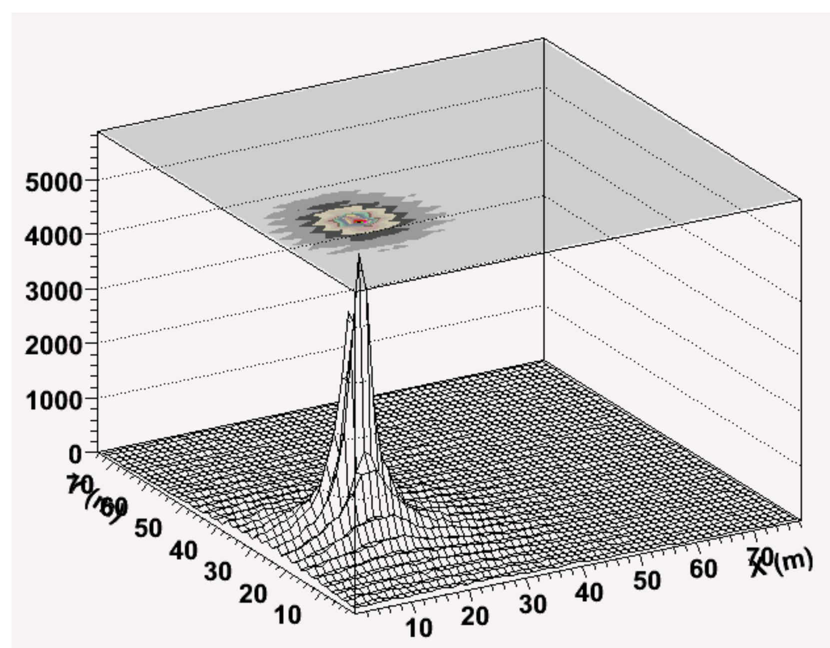
Data



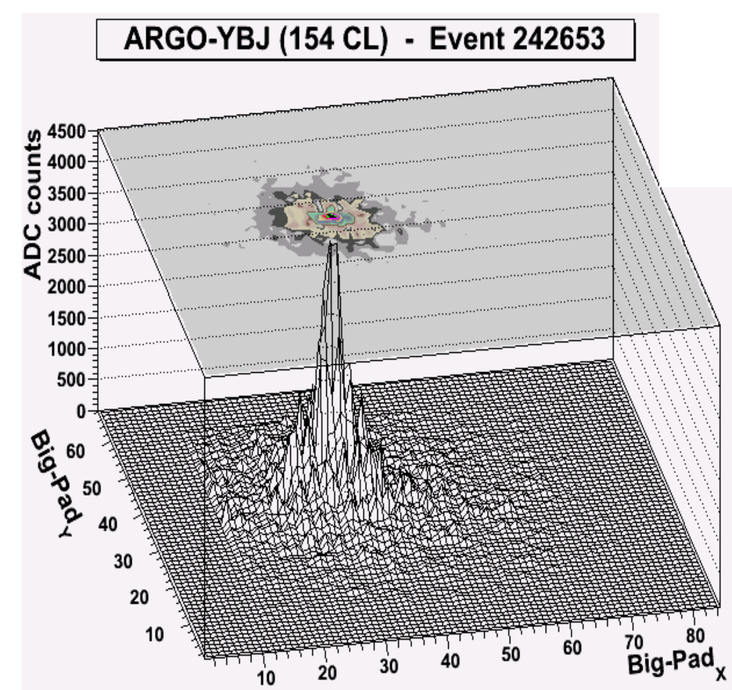
Strip read-out



Charge read-out



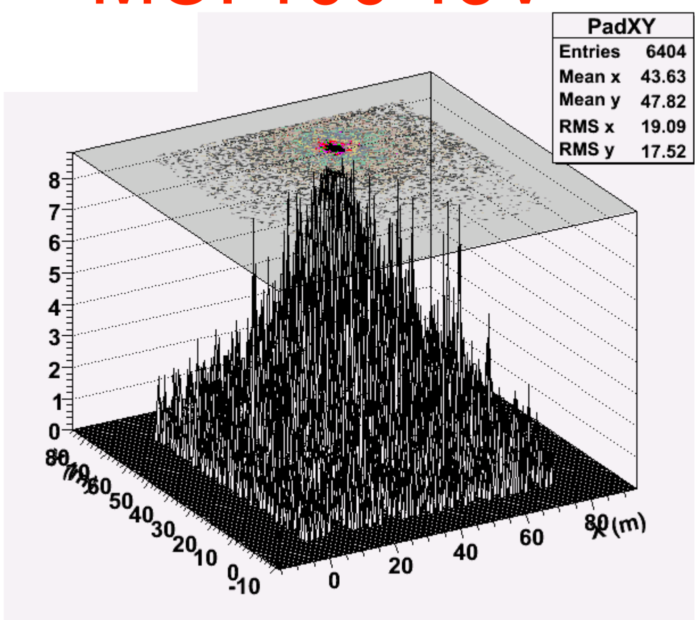
Charge read-out



Charge read-out

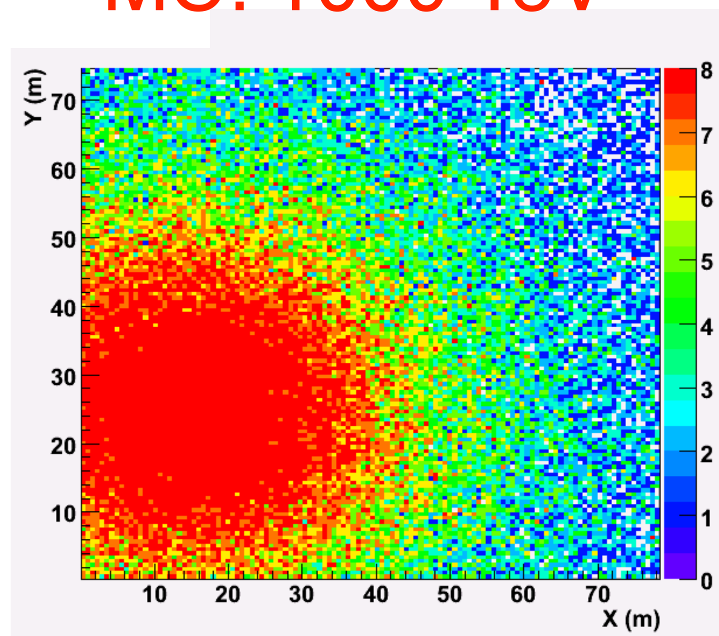
The RPC charge readout: the core region

MC: 100 TeV



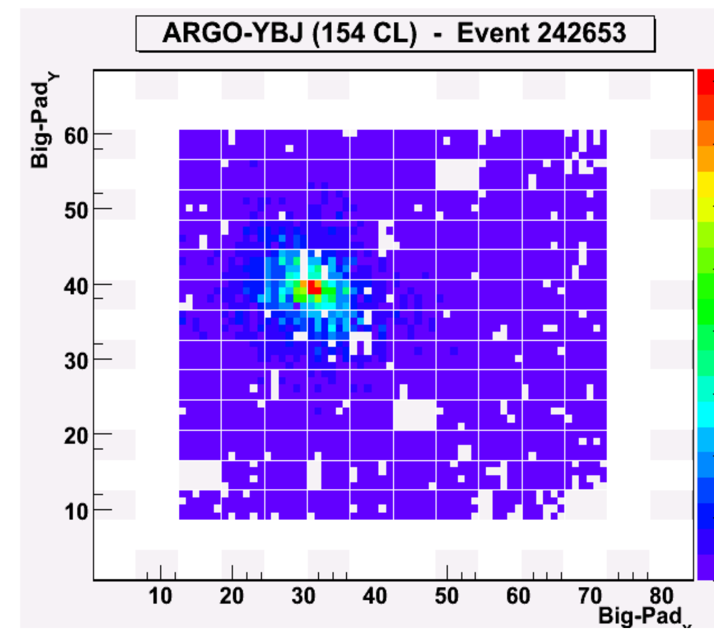
Strip rea

MC: 1000 TeV



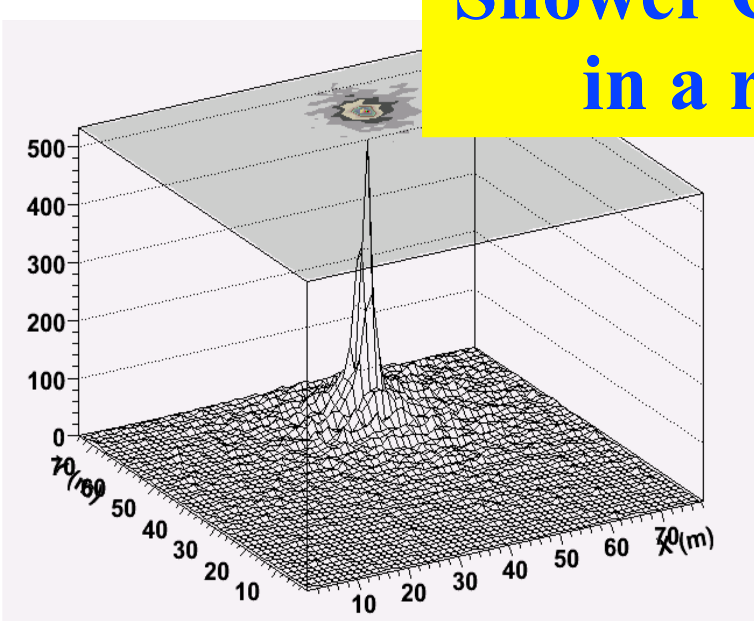
Strip read-out

Data

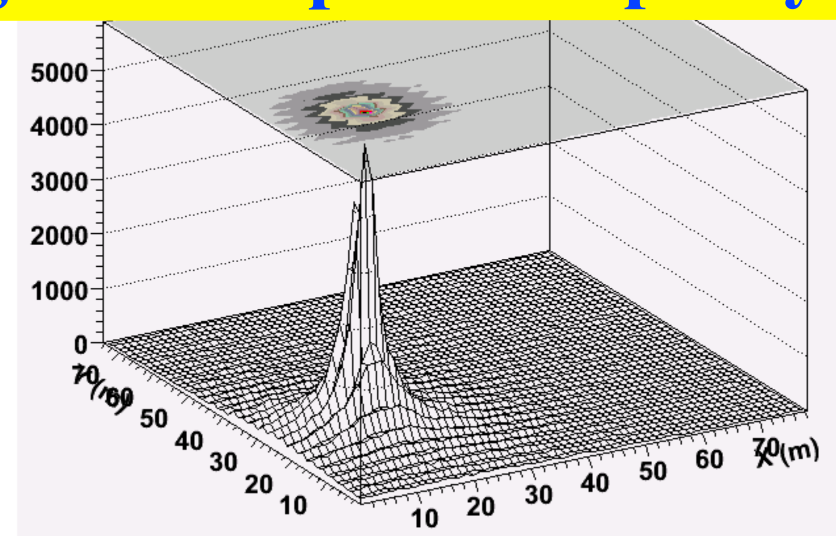


Strip read-out

Shower Core = study of hadronic interactions in a region with pseudorapidity > 8 !!!



Charge read-out



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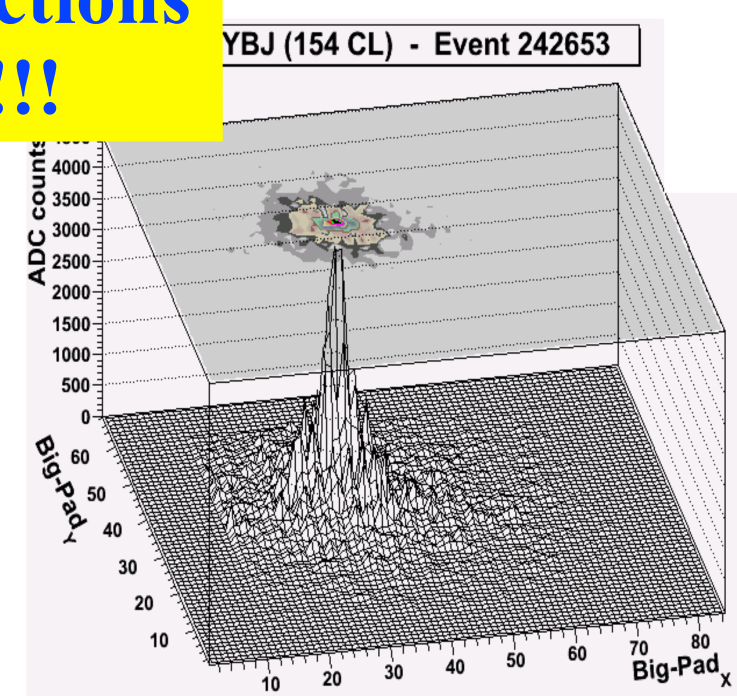
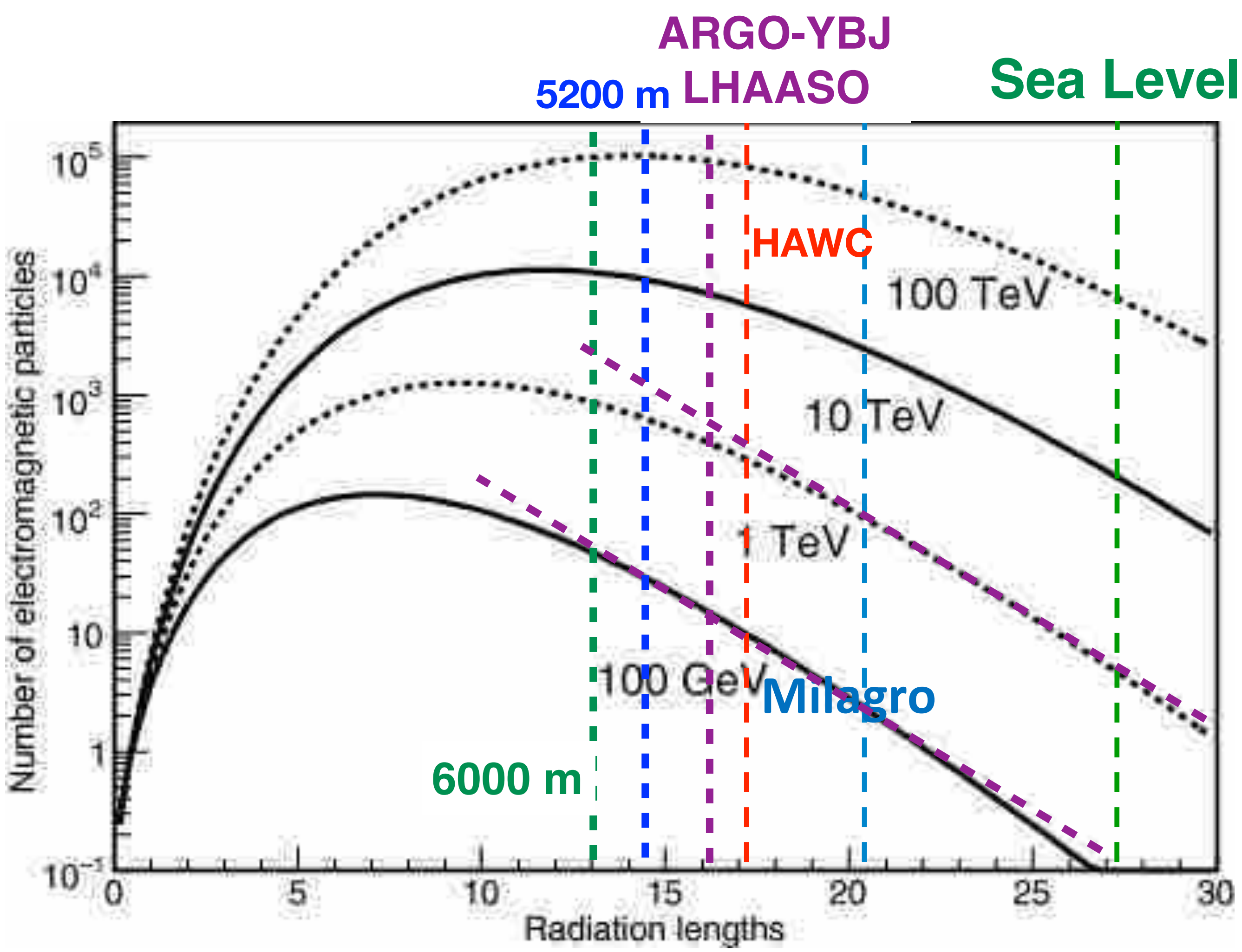


Charge read-out

Lowering the energy threshold: extreme altitude



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

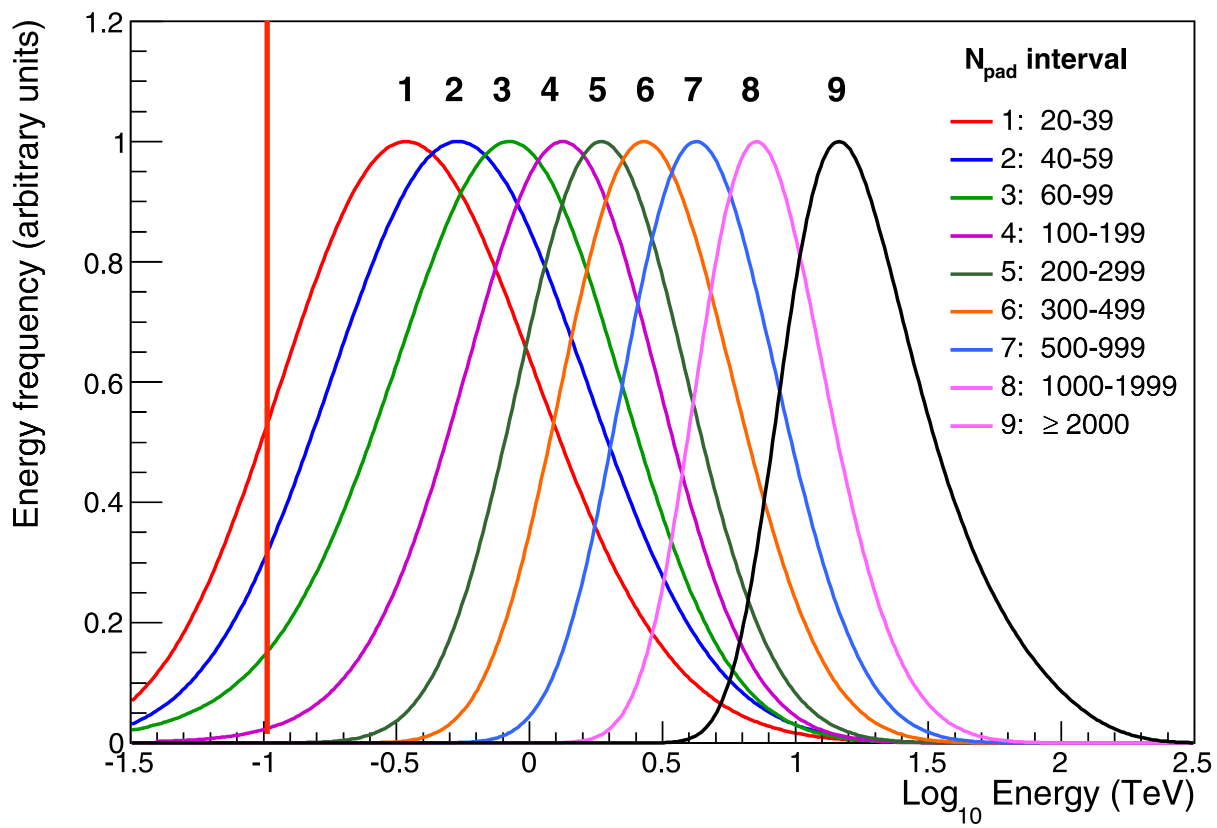
This imply that the effective areas of EAS detectors increases at low energies.

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*

Energy threshold

ARGO-YBJ



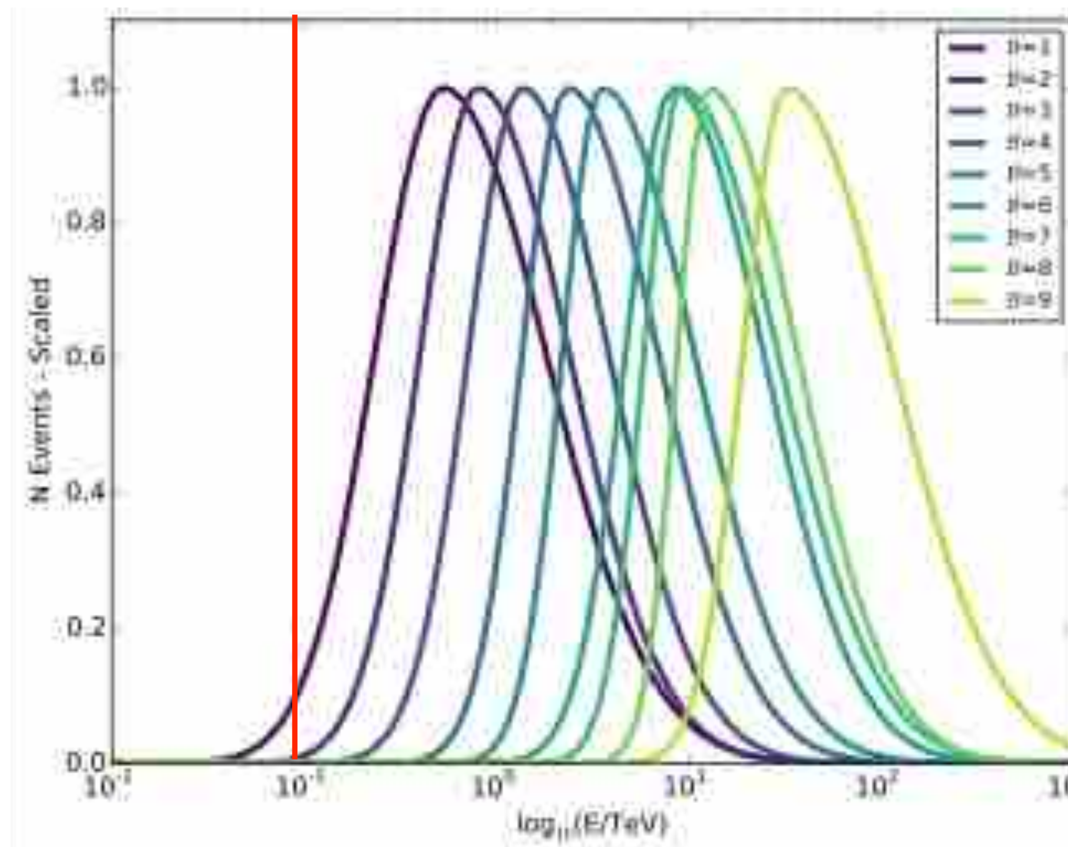
full coverage RPC carpet operated at 4300 m asl

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

Topology ➔ well structured showers
➔ γ-showers !

Median energy first bin = 340 GeV

HAWC (2017)

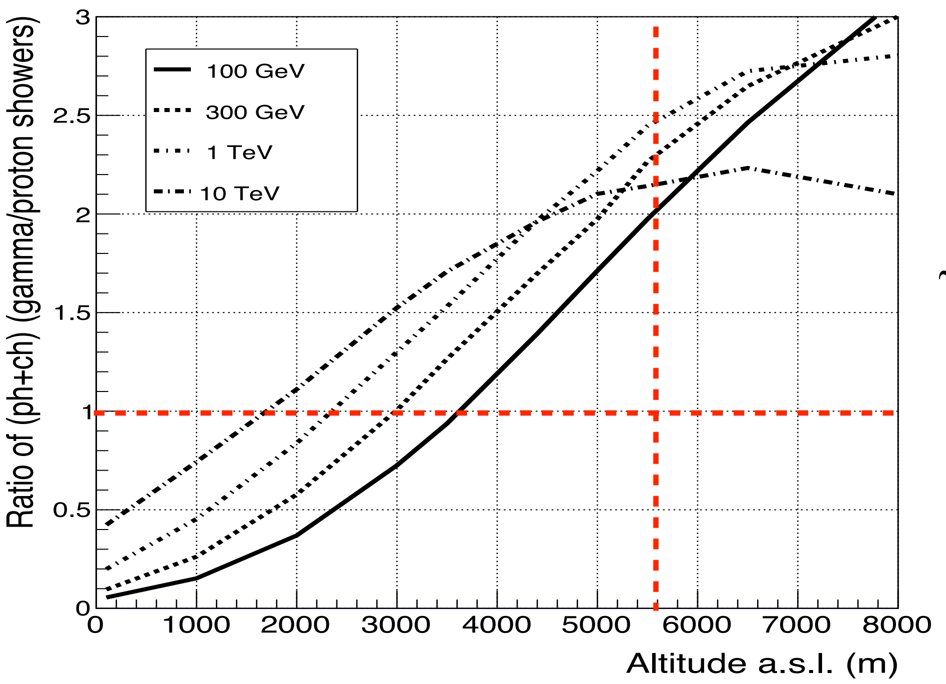


array of water tanks operated at 4100 m asl
coverage ≈ 60%
poor granularity (m level)

Median energy first bin = 700 GeV

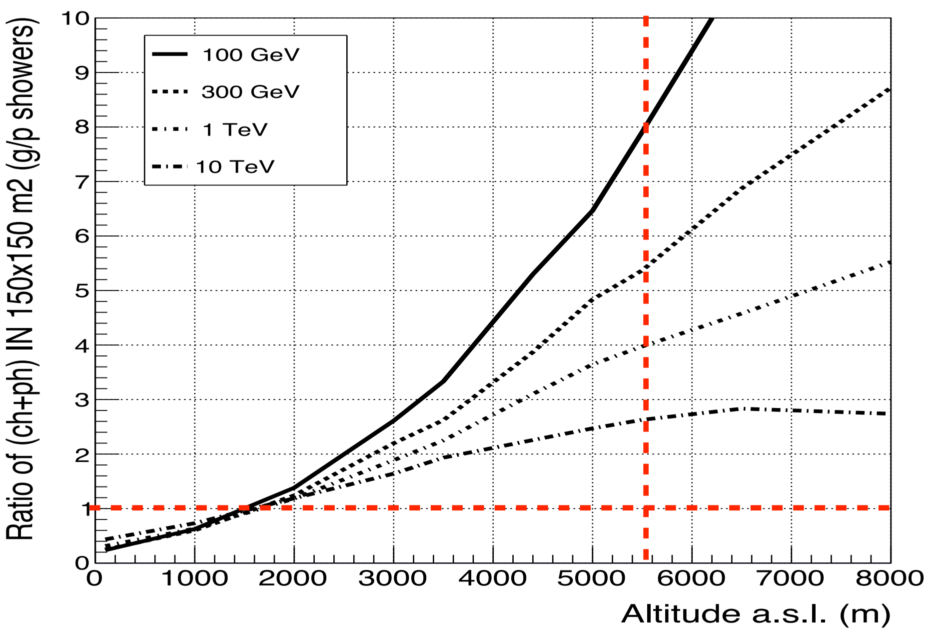
γ/p detection efficiency

High altitude → rejection of the background ‘for free’ !



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

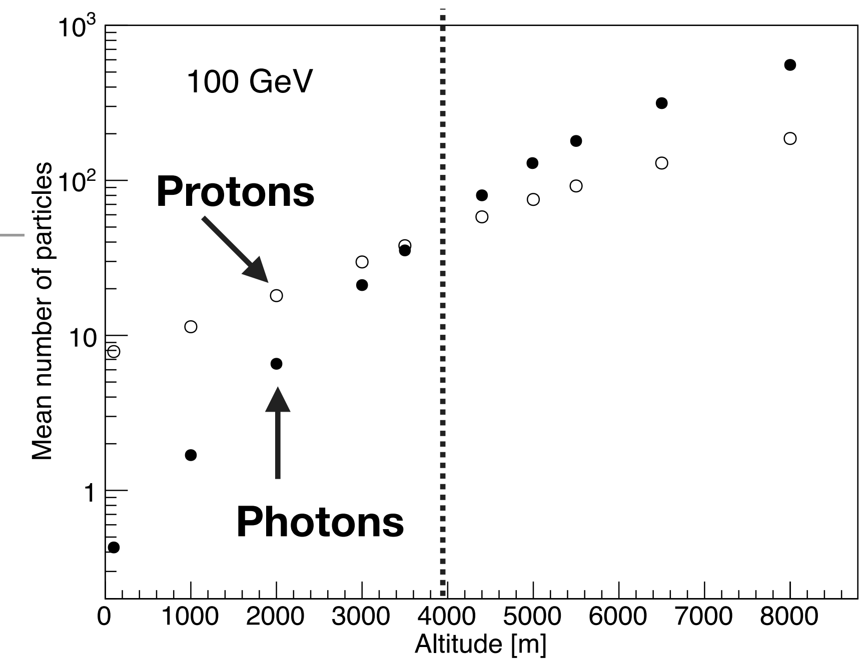
γ/hadron relative trigger efficiency

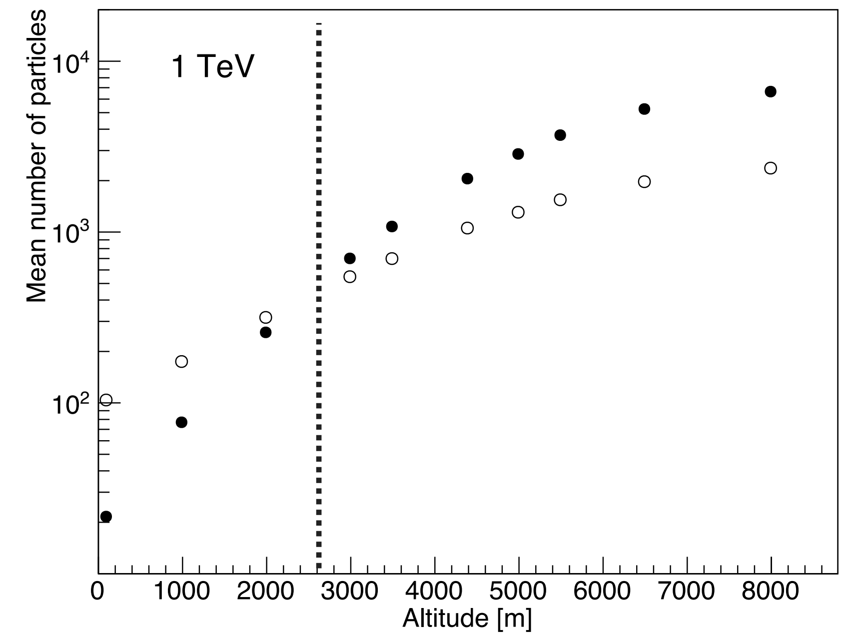


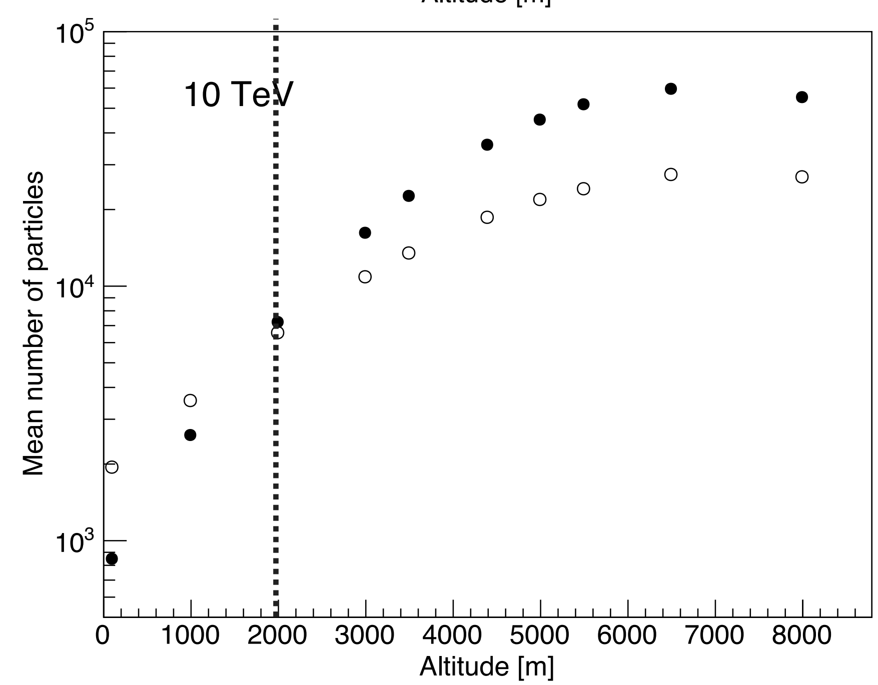
The number of particles in γ-showers exceeds the number of particles in p-showers at extreme altitude.

↓

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

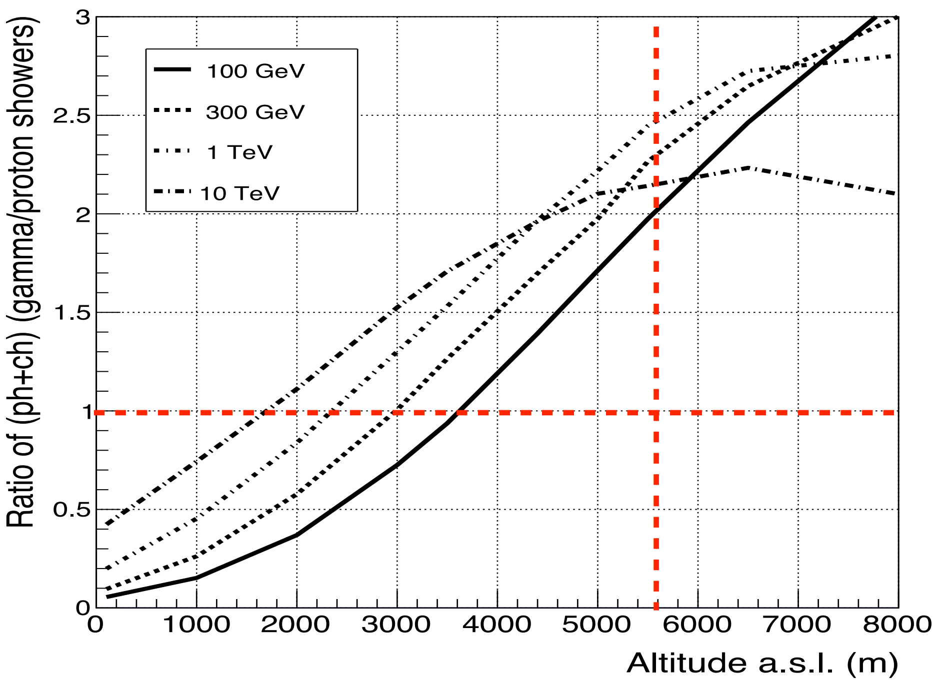






γ/p detection efficiency

High altitude → rejection of the background ‘for free’ !



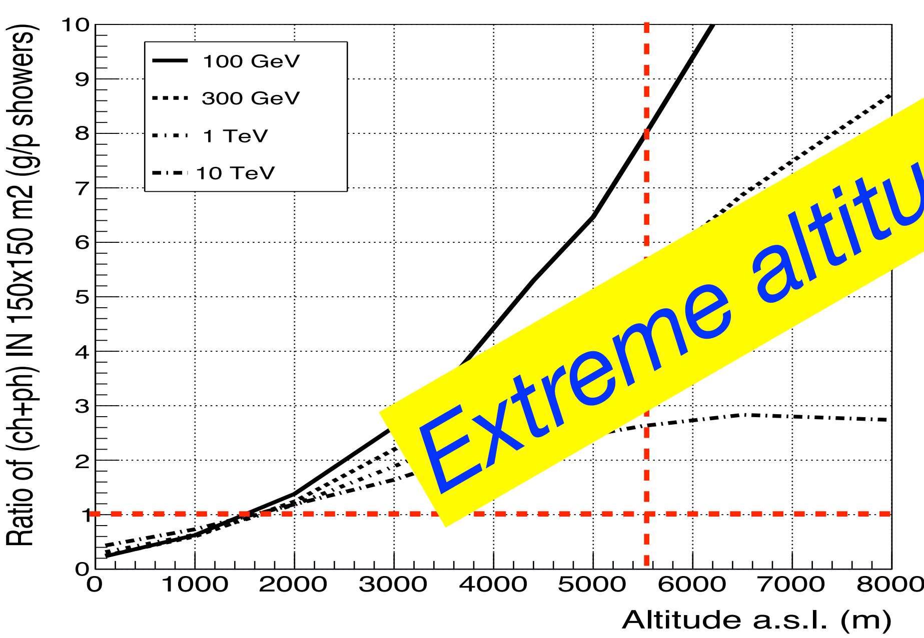
$$R = \sqrt{\frac{A^{\gamma}_{eff}(E)}{A^{B}_{eff}(E)}}$$

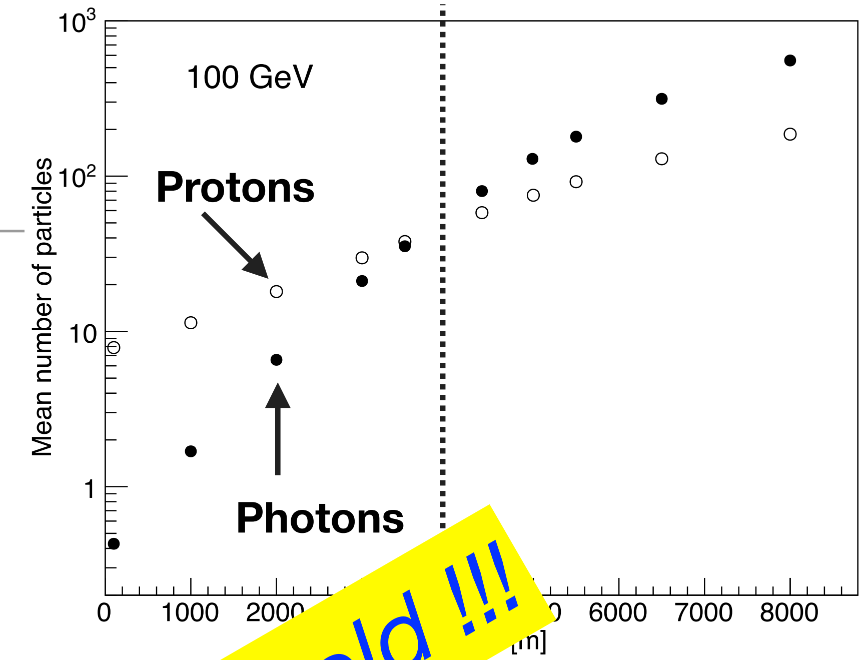
γ/hadron relative trigger efficiency

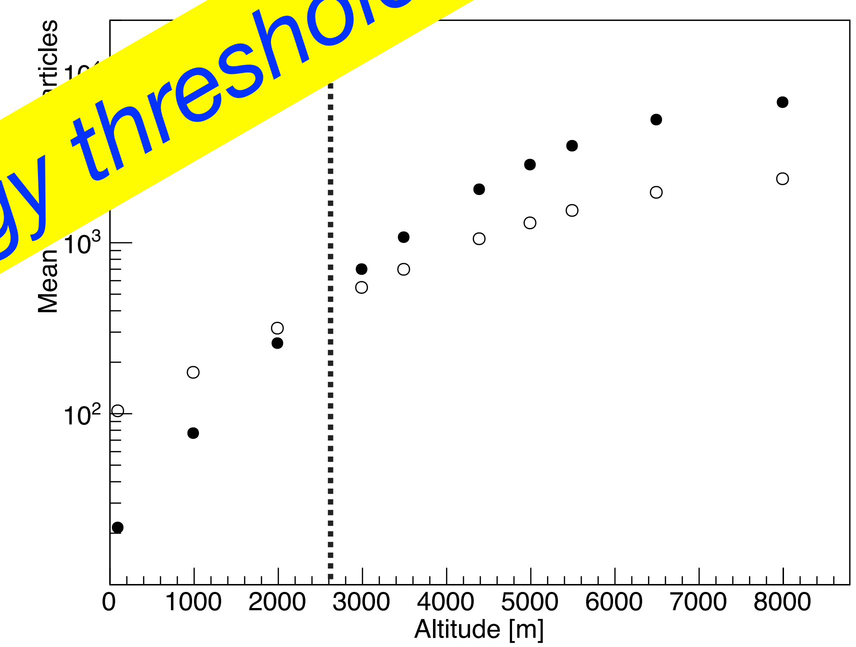
The number of [...] γ-showers exceeds t[...] of particles in p-s[...] extreme altitude.

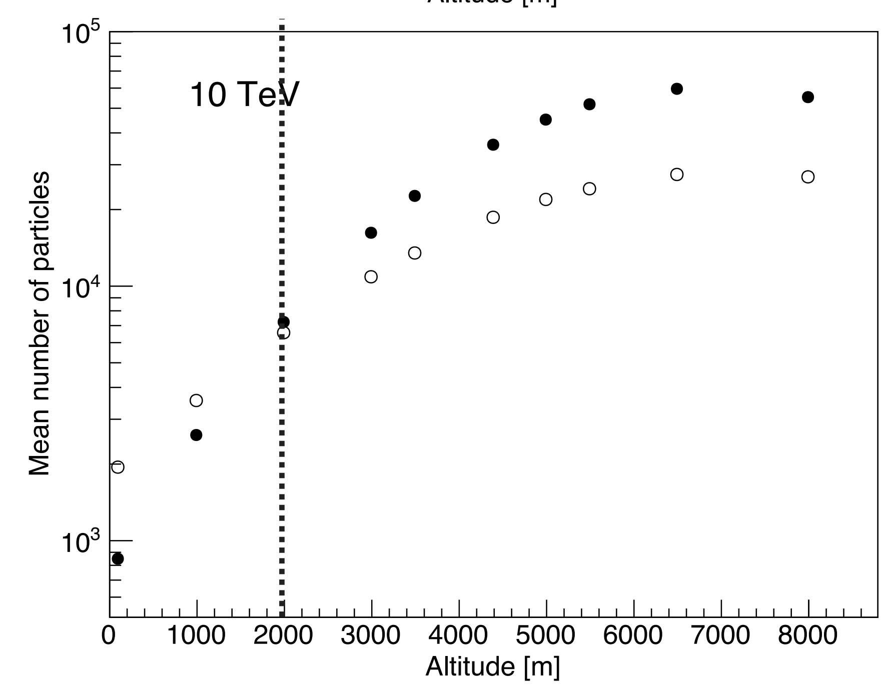
Trigger probability of a detector larger for γ-showers than for p-showers at extreme altitude.

Extreme altitude: not only low energy threshold !!!



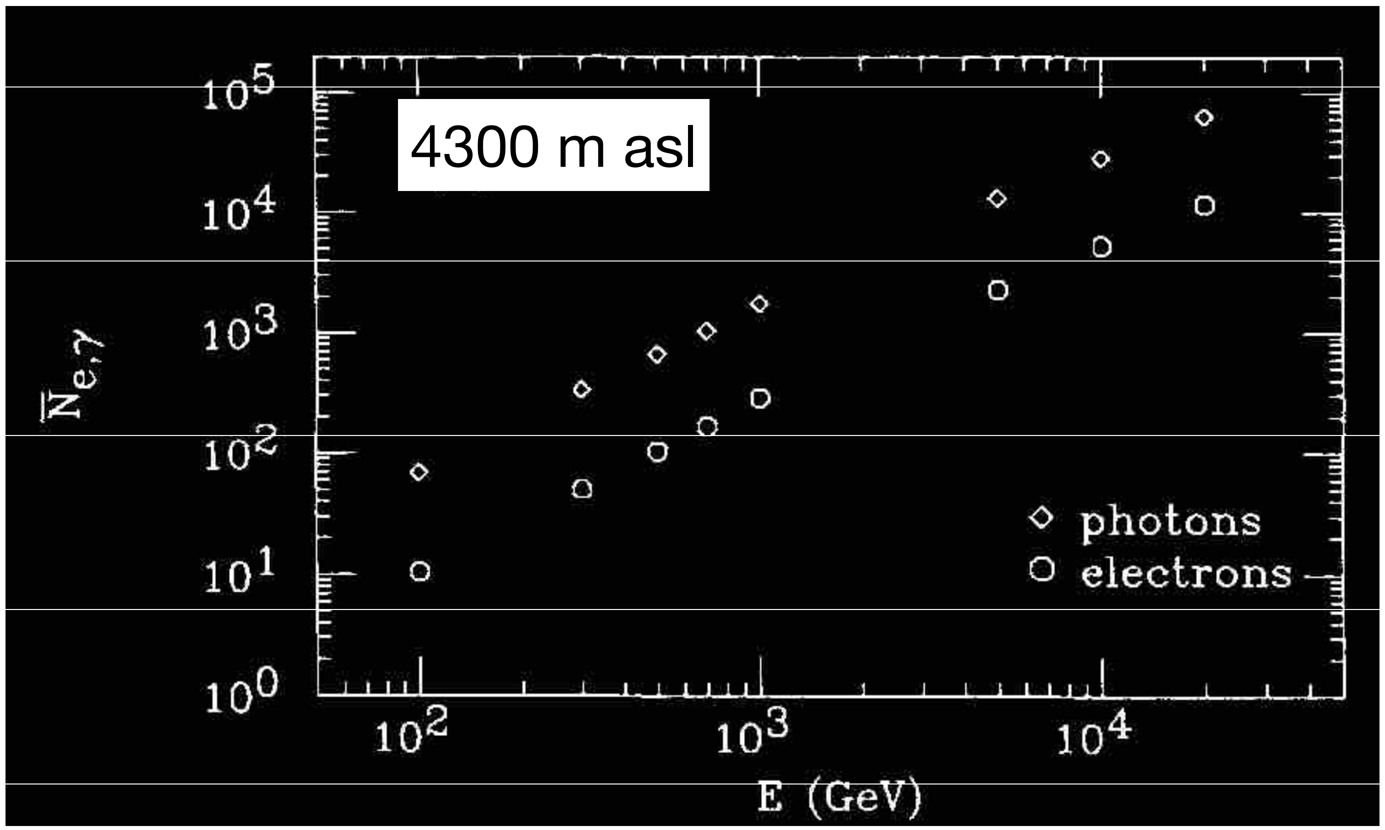


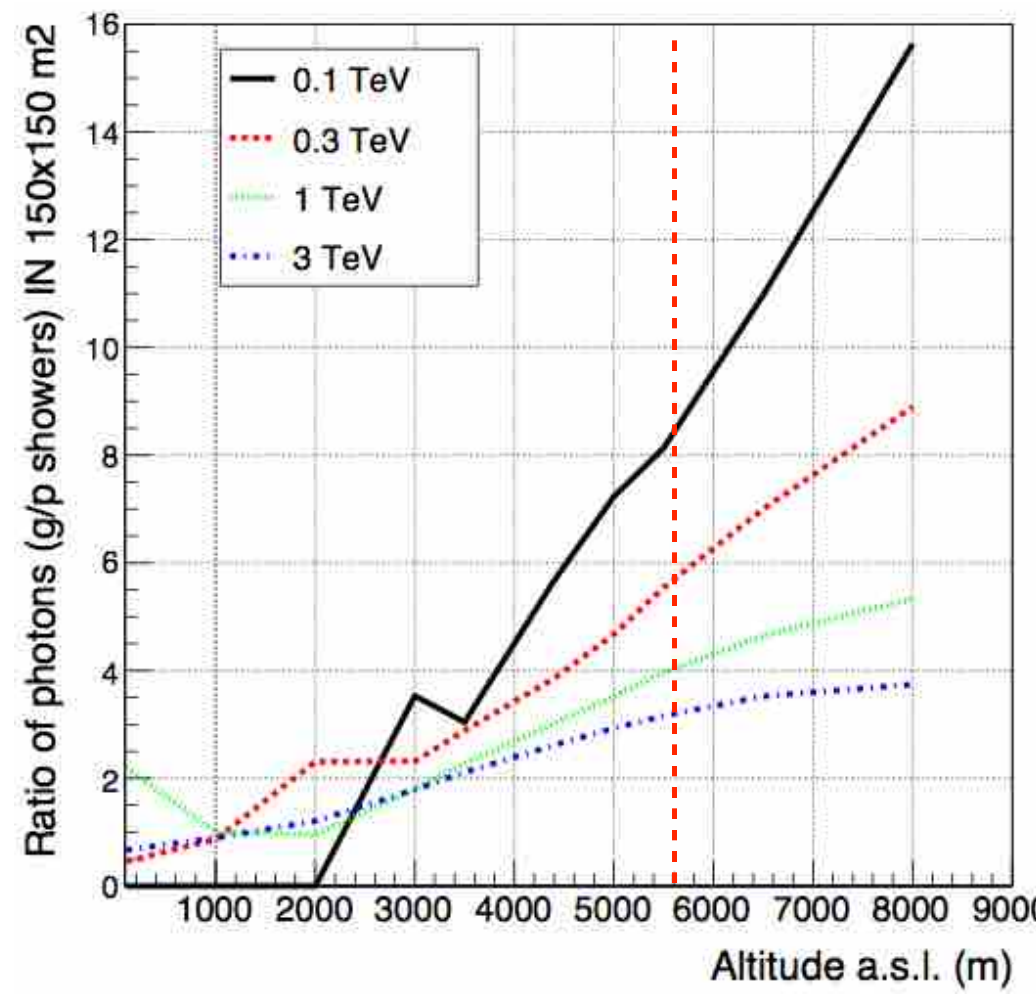




Secondary photons

gamma rays dominate the particles on ground (≈7:1 for 100 GeV γ-showers at 4300 m asl)





In γ-showers the ratio Nγ/Nch decreases if the comparison is restricted to a small area around the shower core. For instance, we get Nγ/Nch ≈3.5 at a distance *r* < 50 m from the core for 100 GeV showers.

The number of secondary photons in γ-showers exceeds the number of gammas in p-showers with increasing altitude.

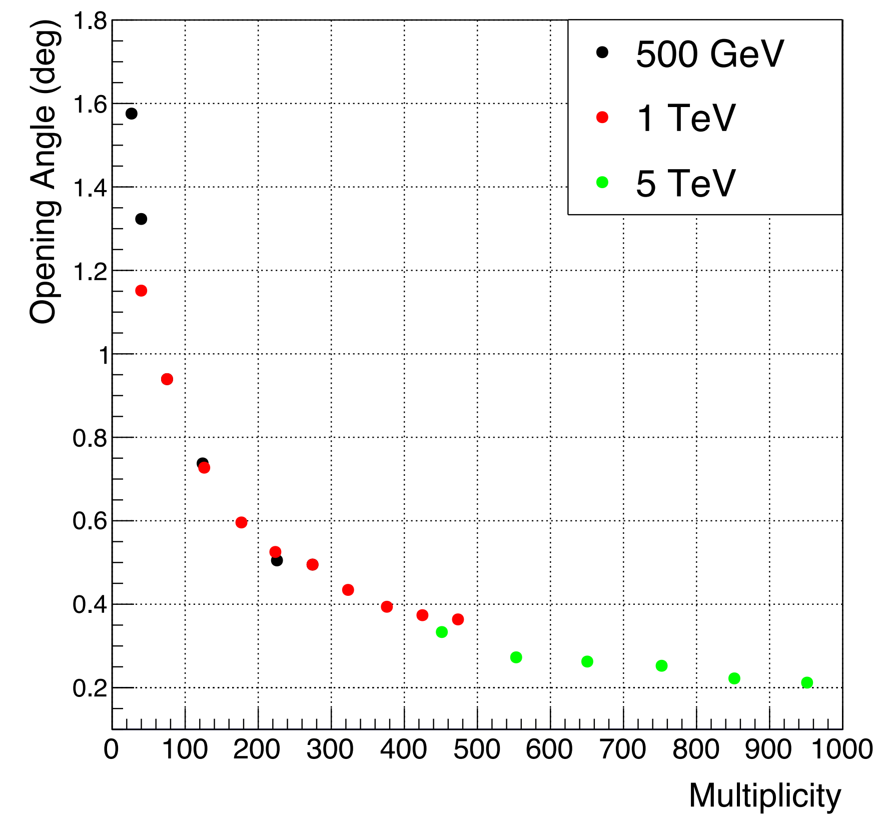
Detection of secondary photons very important to lower the energy threshold and to improve the angular resolution

Angular Resolution

The angular resolution is a function of multiplicity and zenith angle

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

$\sigma_t(m)$ is the average time fluctuation for events with m hits.
The factor $(\sec\,\theta)^{1/2}$ accounts for the geometrical effect related to the reduction with increasing θ of the effective distance between detectors.



ARGO-YBJ

bin 20 - 40 pads: photons
$E_{50} \approx 360$ GeV (≈ 1 TeV for protons)
$\sigma_\theta \approx 1.66^o$ (2D Gaussian PSF)
$\varepsilon_\gamma = 73\%$
no converter (no lead)

Preliminary Calculations

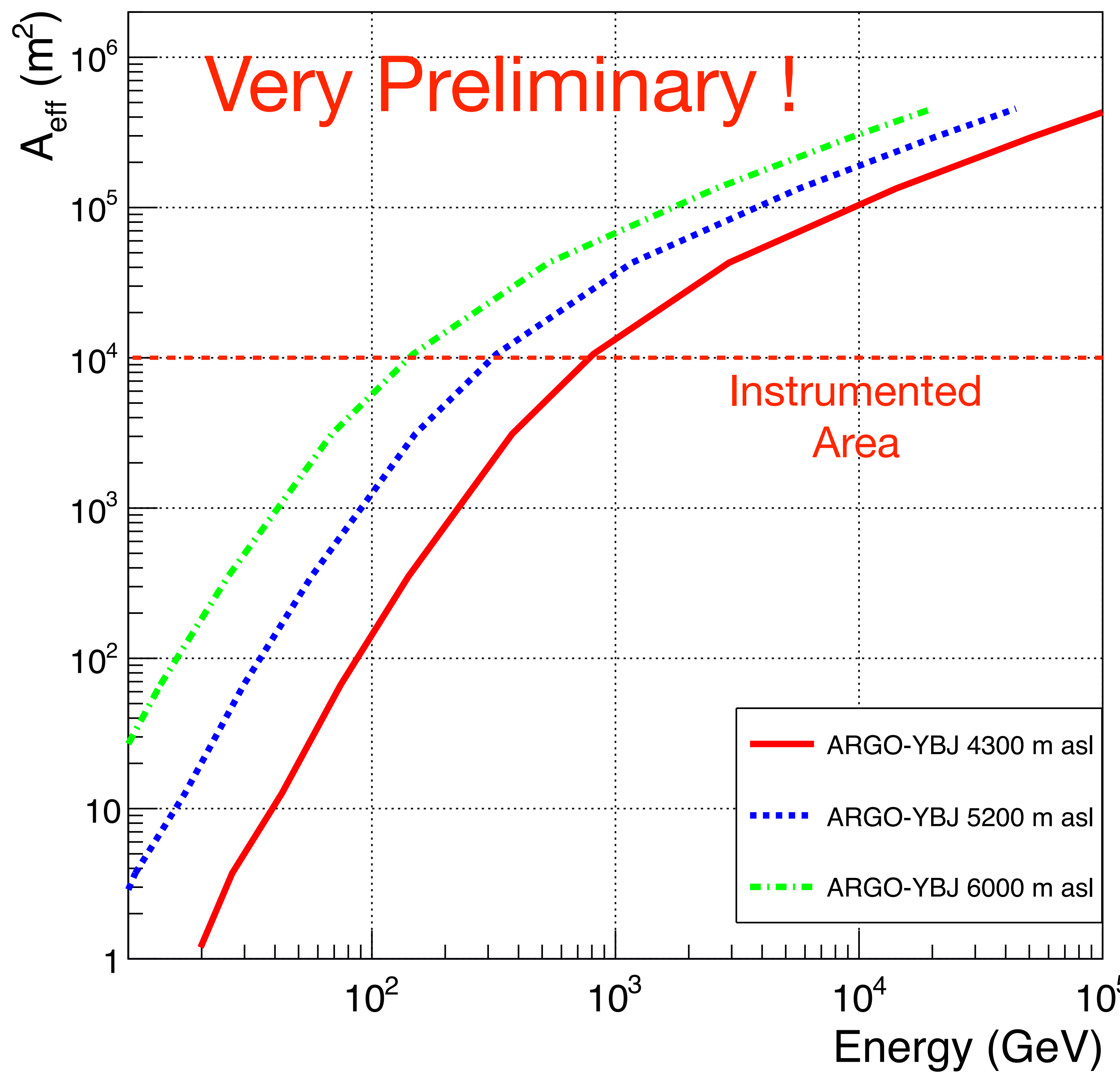
ARGO-like 150 x 150 m^2 carpet operated at 5200 m asl
➔ $\sigma_\theta \approx 0.7^o$ at ≈100 GeV

Consistent with expectations
at 5200 m: ≈2x increase in size, ≈3x energy thr.
larger carpet: ang. res. improves with the lever arm ➔ from ARGO to 150 x 150 m^2: ≈1.8x
0.5 mm lead: ≈1.5x at the threshold
➔ we expect ≈ 2.7x improvement

Effective Area

The Effective Area is function of

- Number of charged particles
- Dimension and coverage of the detector
- Trigger Logic



Effective Areas at 100 GeV:
≈ 1000 m² at 5200 m asl
≈ 5000 m² at 6000 m asl

Effective Areas at 300 GeV:
≈ 10,000 m² at 5200 m asl
≈ 20,000 m² at 6000 m asl

Caveat: In this calculation we simply moved ARGO carpet at different altitudes
➔ larger carpet with new trigger logic for different layout and shower topology at different altitude required !

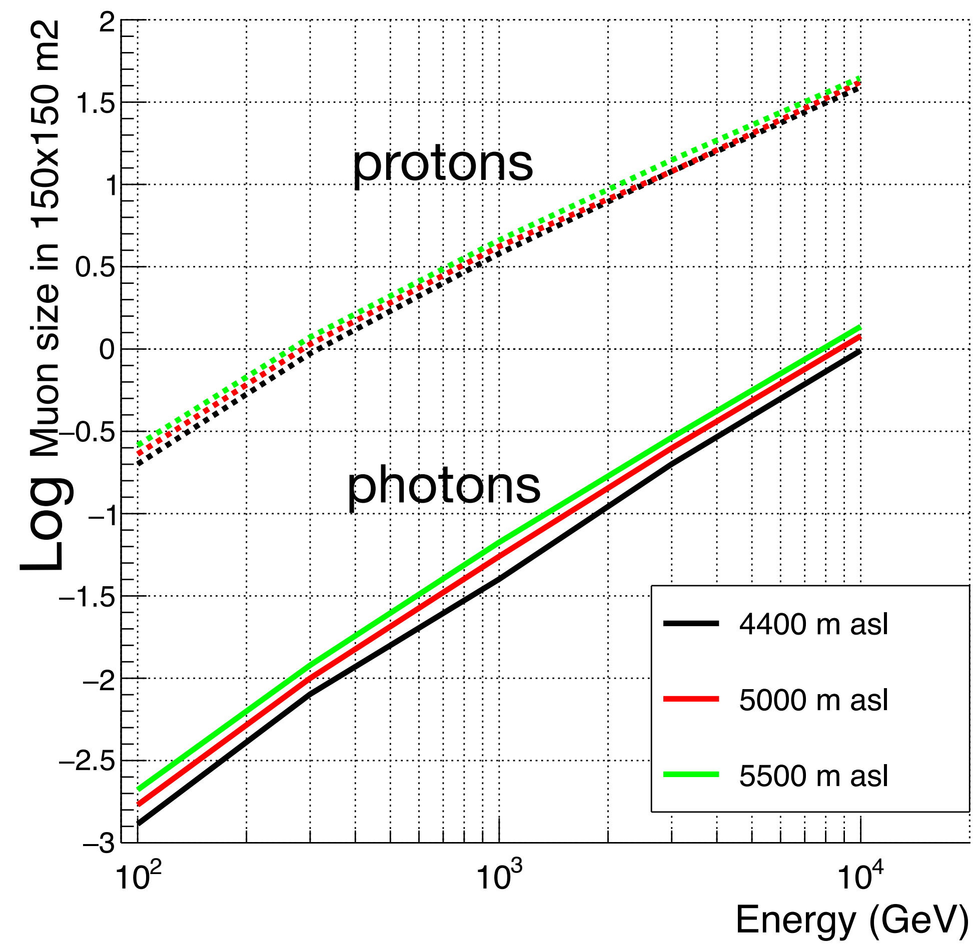
Gamma/Hadron discrimination

Very difficult at low energy (< 1 TeV)

Muon size very small

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

Requires sufficient number of triggered channels (>70 - 100)
→ minimum energy required: E>0.5 - 1 TeV ?



New ideas ?

- *Suitable trigger logic to reject not 'symmetric' showers*
- *Calorimetry with multi-layer RPCs*
- *Calorimetry with RPCs + water Cherenkov tanks ?*

Avalanche mode not streamer

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Technical Note

Test for YBJ-ARGO RPC working in avalanche mode

Q. Gou*

Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Division 3, P.O. Box 918-3, Beijing 100049, People's Republic of China

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Abstract

The measurement of YBJ-ARGO Resistive Plate Chamber (RPC), working in avalanche mode was performed. With different component of i-C_4H_{10} in $C_2H_2F_4$-based gas mixtures $C_2H_2F_4$/i-C_4H_{10}/SF_6, the behavior of the detector with respect to the high voltage was studied. The experiment confirms that it is possible to operate YBJ-ARGO RPC in avalanche mode. The results show that with the gas mixtures containing 10% of i-C_4H_{10} the detector achieves its optimum performance.

PACS: 29.40.Cs; 95.55.Vj; 95.55.Ka

Keywords: Avalanche; i-C_4H_{10}; YBJ-ARGO; RPCs

Conclusions

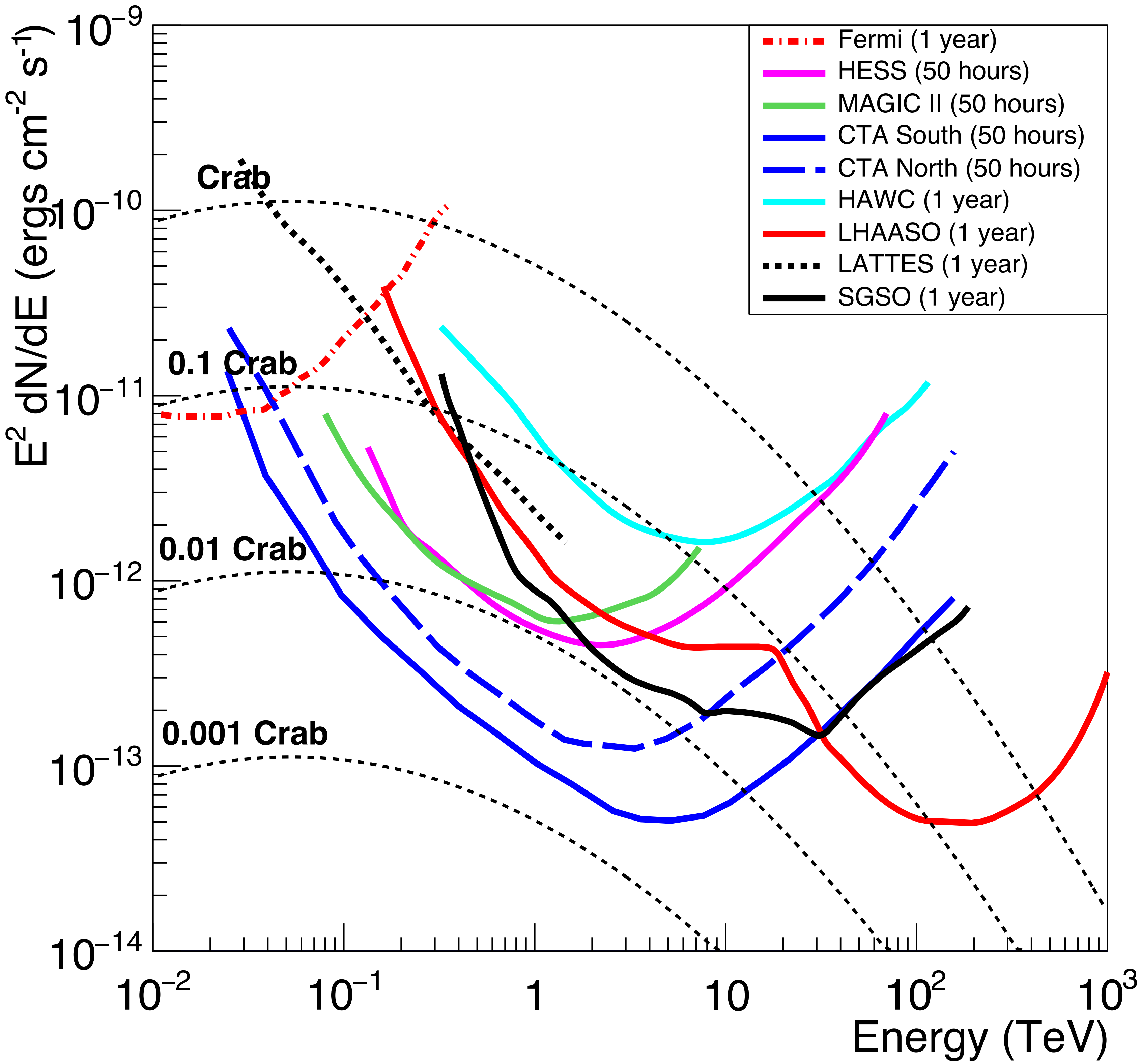
In the next decade CTA-North and LHAASO are expected to be the most sensitive instruments to study γ-ray astronomy in the Northern hemisphere from ≈20 GeV up to PeV.

- *An all-sky detector in the Southern Hemisphere should be a high priority* to face a broad range of topics.
- Extragalactic transient detection requires *low threshold, ≈100 GeV*.
- *Extreme altitude* (≈5000 m asl), *high coverage* and *high granularity of the read-out* are key.
- *Background rejection below TeV challenging* ➜ *multi-layer RPCs, RPCs + Water Cherenkov ?*
- *Selection of primary masses* crucial ➜ *RPCs with charge readout ?*
- Capability of Water Cherenkov Facilities in selecting primary masses must be investigated.
- High energy gamma-ray astronomy (≈100 TeV) and CR physics covered by ALPACA ?

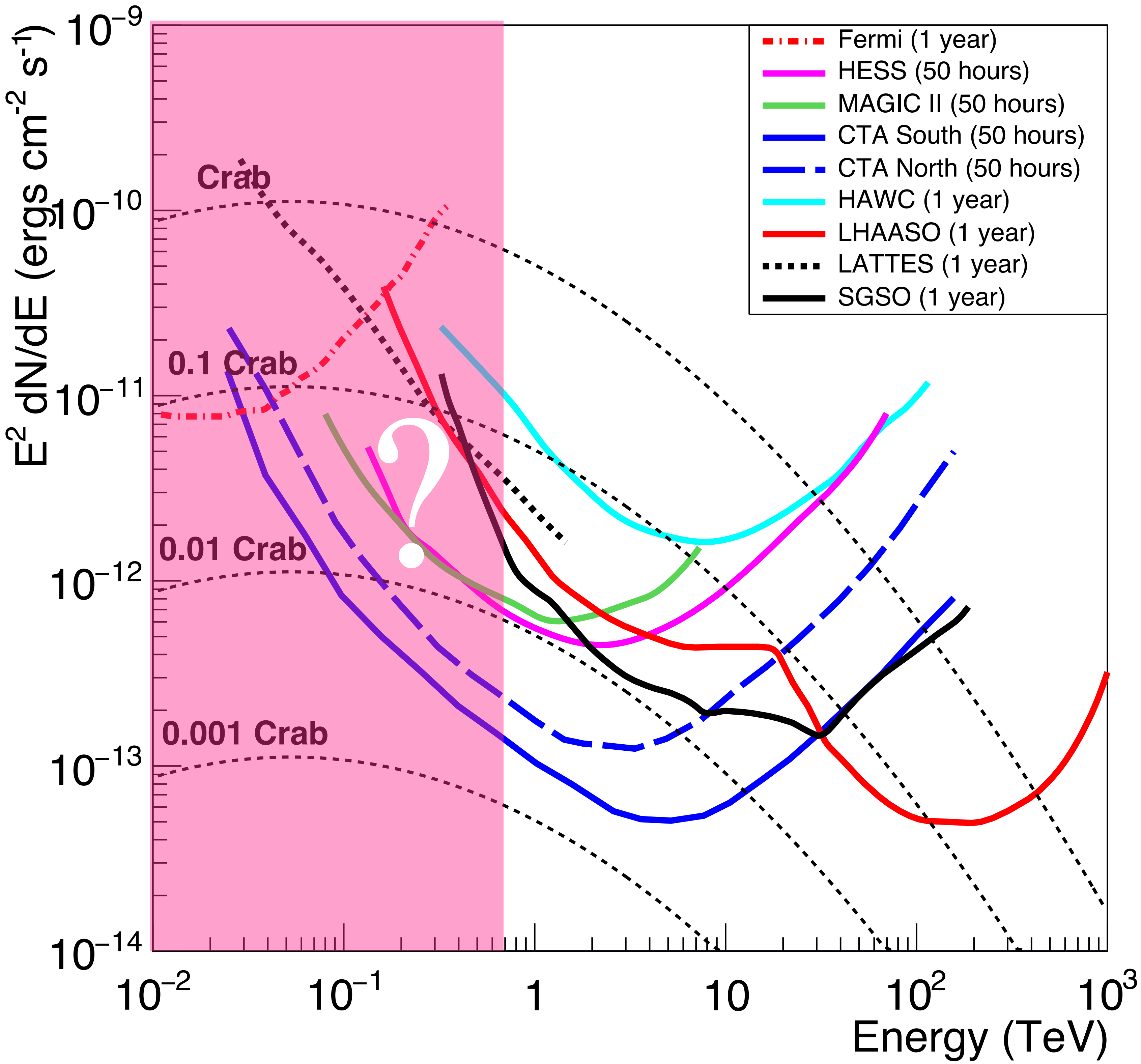
Benefits of ARGO-like RPCs:

- dense sampling → low energy threshold (≈ 300 GeV)
- wide energy range: ≈300 GeV → 10 PeV
- high granularity of the read-out → good angular resolution and unprecedented details in the core region

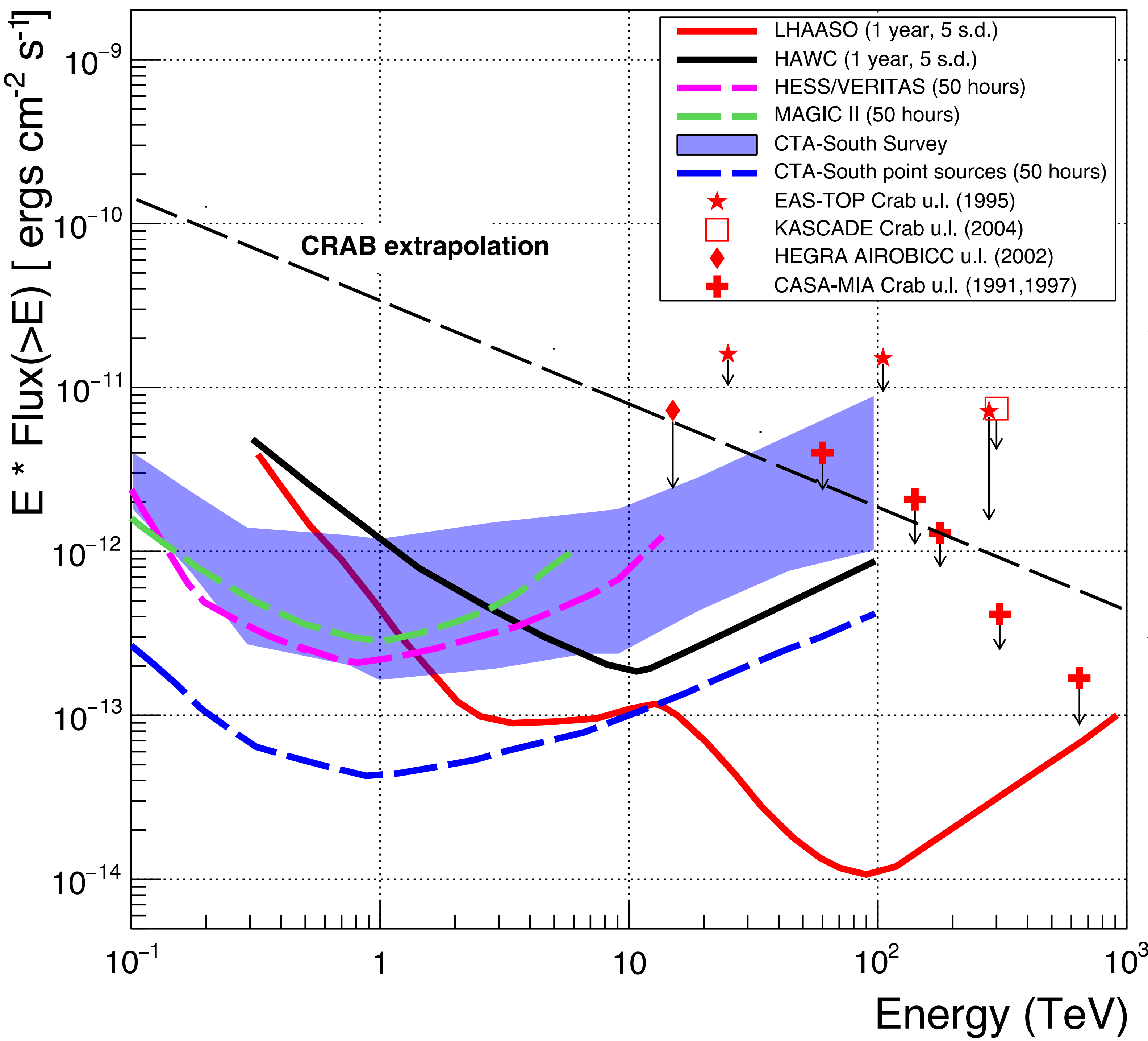
Point source sensitivity



Point source sensitivity



Sensitivity



EAS-array: 5 s.d. in 1 year

Cherenkov: 5 s.d. in 50 h *on source*

★ 1 year for EAS arrays means:

(5 h × 365 d) ~1500 - 2200 of observation hours for each source (about 4-6 hours per day).

★ For Cherenkov:

(5 h × 365 d) × d.c. (≈ 15%) ≈ 270 h/y for each source.

Effect of a lead converter above a detector

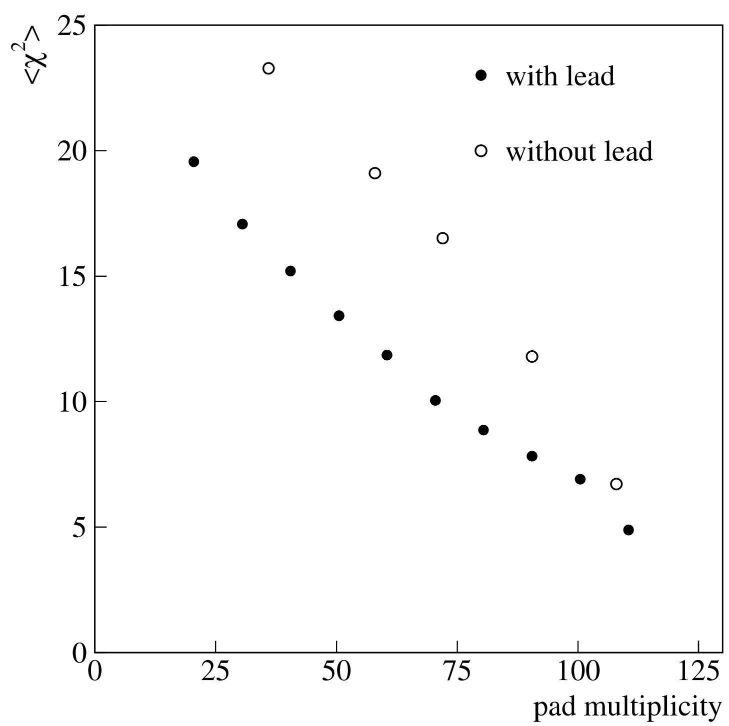
The consequences of placing a thin sheet of dense, high-Z material, above detectors are, qualitatively:

(1) low-energy electrons are absorbed and no longer contribute to the signal (low-energy photons are also absorbed),

(2) high-energy electrons produce an enhanced signal size through multiplication,

(3) high-energy photons materialise, producing additional signal contributions similar in size to those produced by (2).

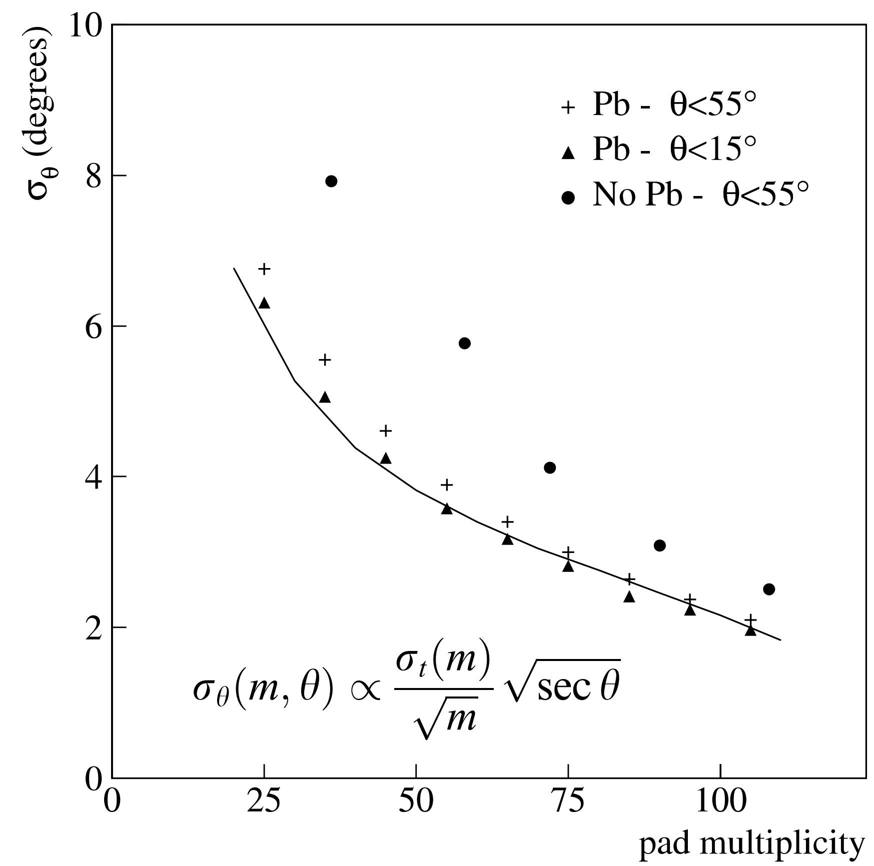
The number of particles gained from processes (2) and (3) exceeds that lost through (1) and hence the *Rossi transition effect* is observed.



$(\chi^2)^{1/2}$ represents (approximately) the average time spread

The enhanced signal alone, arising from this, will reduce the timing fluctuations.

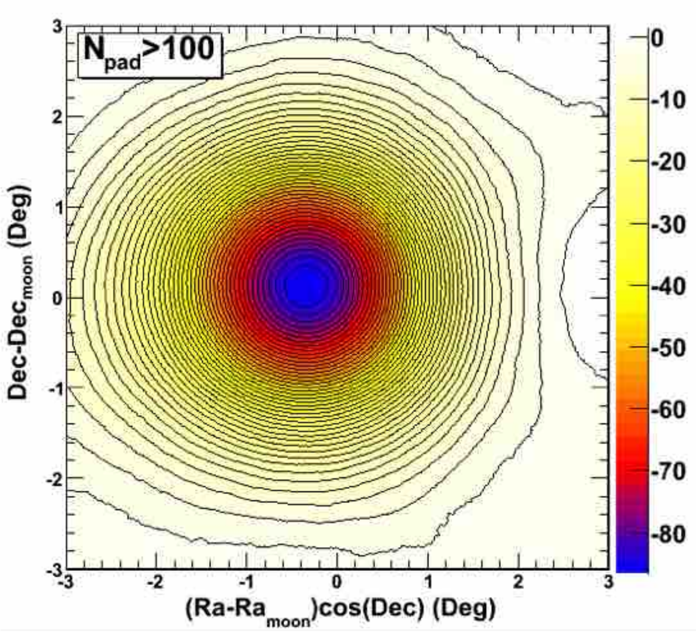
In addition, the contributions gained are concentrated near the ideal time because the higher energy electrons and photons travel near the front of the particle swarm (they suffer from smaller time delays) while those lost tend to lag far behind.

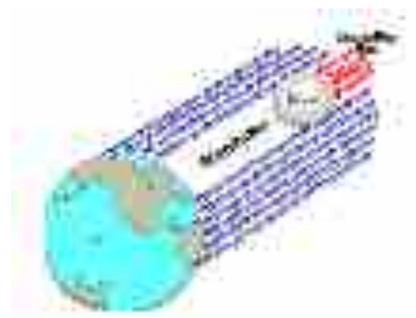


Measurement with ARGO at YBJ

Calibration of the energy scale

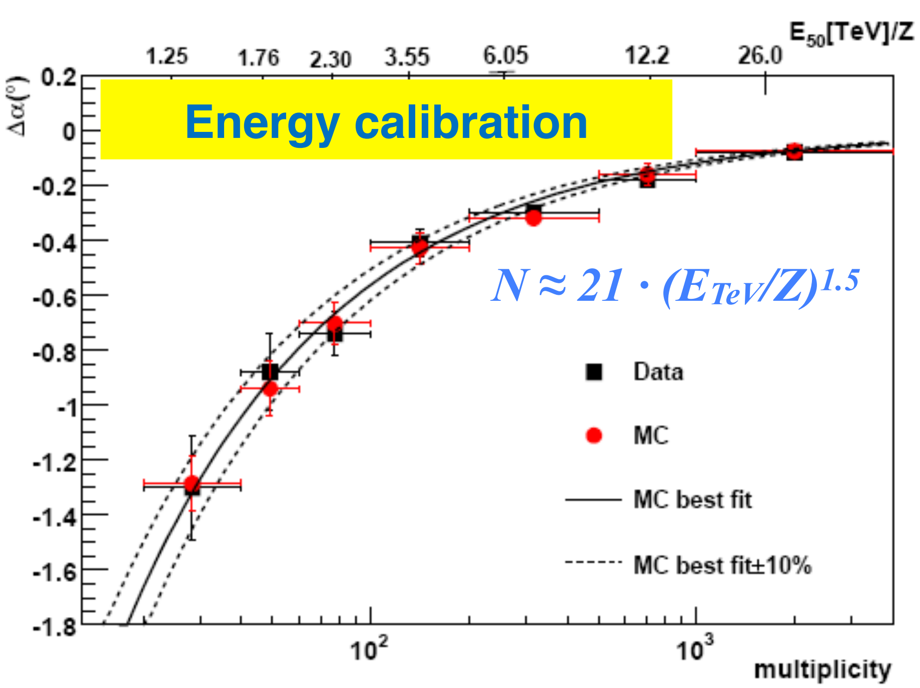
ARGO-YBJ: *Moon shadow* tool



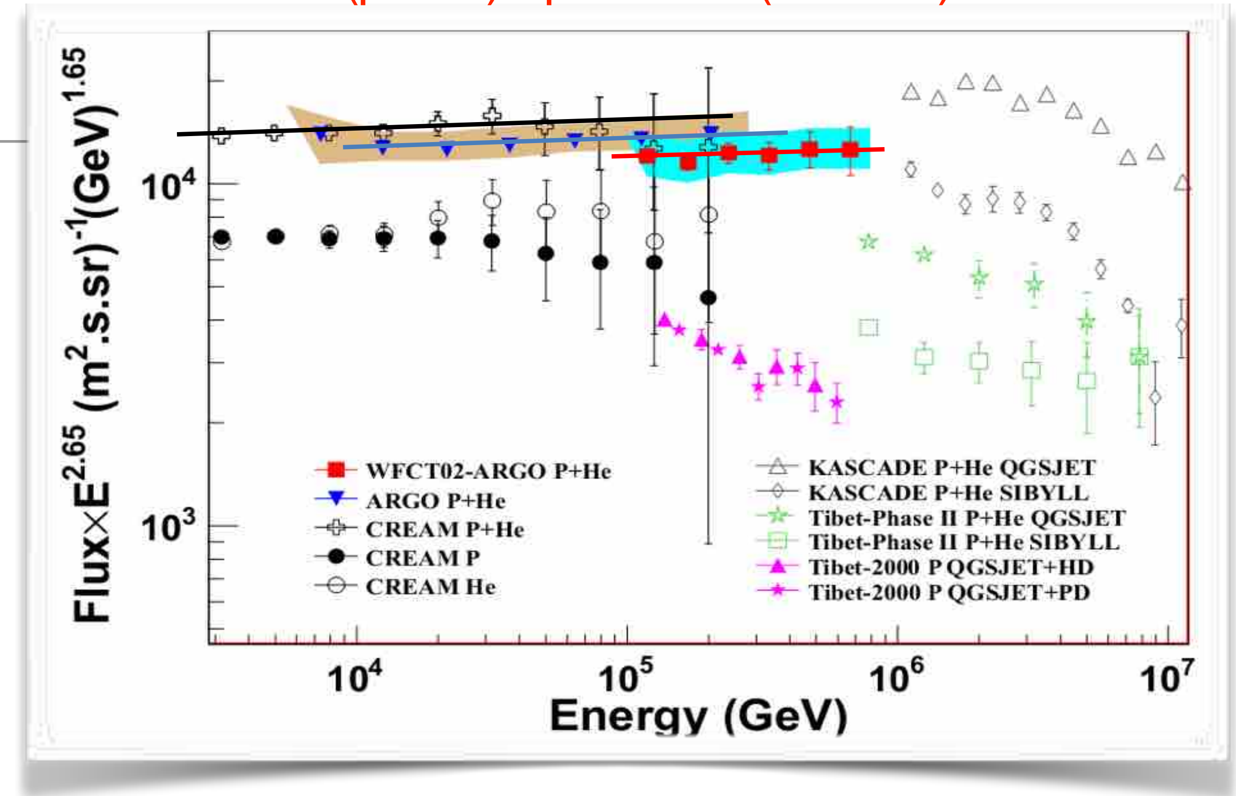


PRD 84 (2011) 022003

The energy scale uncertainty is estimated at 10% level in the energy range 1 – 30 (TeV/Z).



(p+He) spectrum (2 - 700) TeV



Chin. Phys. C 38, 045001 (2014)

- CREAM: 1.09 × 1.95 × 10^{-11} (E/400 TeV)$^{-2.62}$
- ARGO-YBJ: 1.95 × 10^{-11} (E/400 TeV)$^{-2.61}$
- Hybrid: 0.92 × 1.95 × 10^{-11} (E/400 TeV)$^{-2.63}$

Single power-law: 2.62 ± 0.01

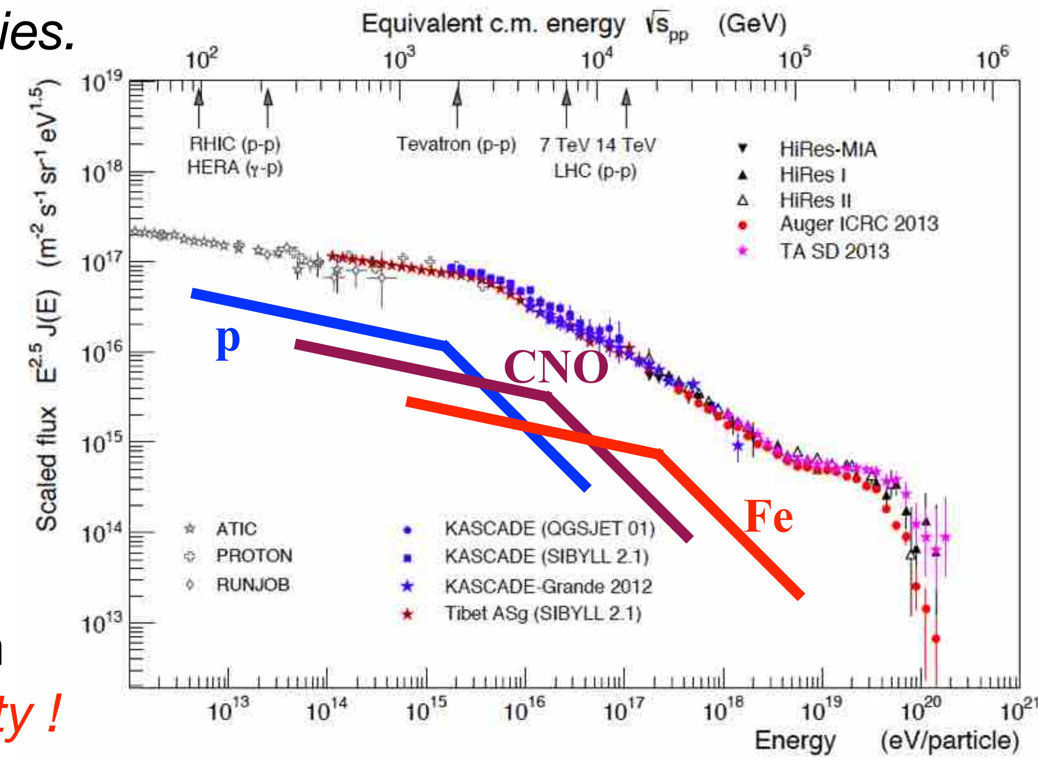
Flux at 400 TeV:

1.95 × 10^{-11} ± 9% (GeV^{-1} m^{-2} sr^{-1} s^{-1})

The 9% difference in flux corresponds to a difference of ± 4% in energy scale between different experiments.

Knee as end of Galactic population ?

Understanding the origin of the "knee" is the key for a comprehensive theory of the origin of CRs up to the highest observed energies.



In fact, the knee is connected with the issue of the end of the Galactic CR spectrum and the transition from Galactic to extra-galactic CRs.

★ *Rigidity* models can be *rigidity-acceleration* models or *rigidity-confinement* models

- *Accelerator feature*: maximum energy of acceleration
  ➜ implies that all accelerators are similar: *source property !*

- *Structure generated by propagation:* ➜ we should observe a *knee that is potentially dependent on location*, because the propagation properties depend on position in the Galaxy
  ➜ the (main) Galactic CR accelerators must be capable to accelerate to much higher energy
  ➜ the Galaxy contains *"super-PeVatrons" !* ➜ *Gamma-Ray Astronomy above 100 TeV*

If the mass of the knee is *light* according to the standard model
➜ Galactic CR spectrum is expected to end around 10^{17} eV

If the composition at the knee is *heavier* due to CNO / MgSi
➜ we have a problem !

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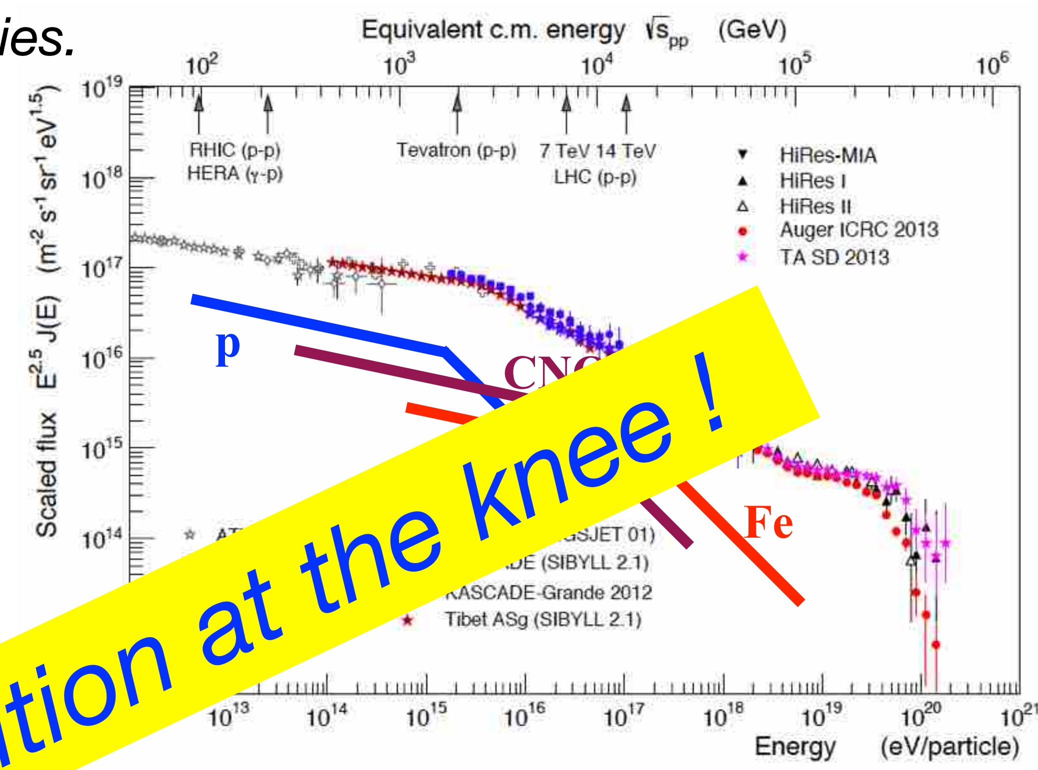

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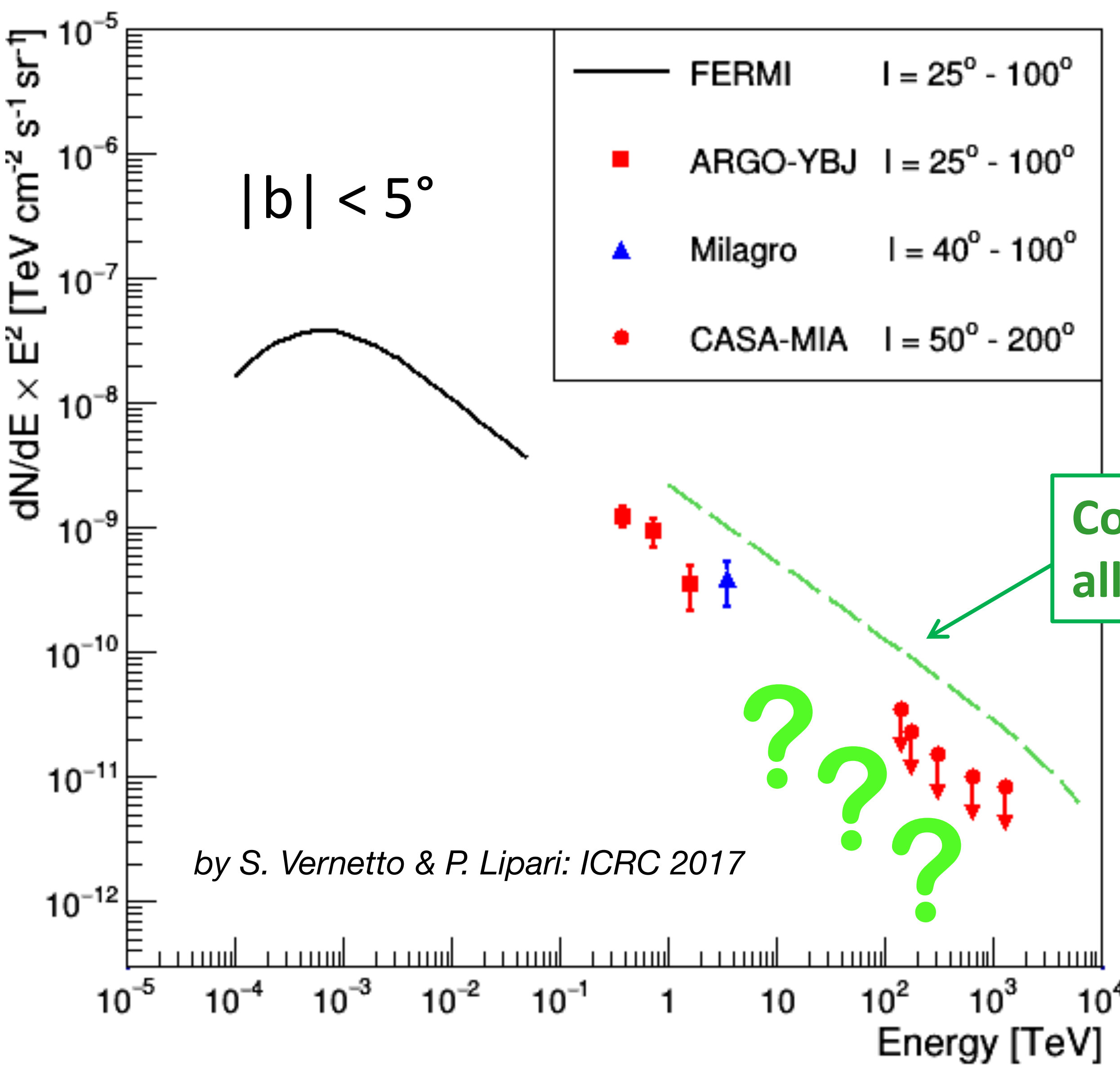
Strong Message: composition at the knee !

s of the knee is *light* according to the standard model
Galactic CR spectrum is expected to end around 10^{17} eV

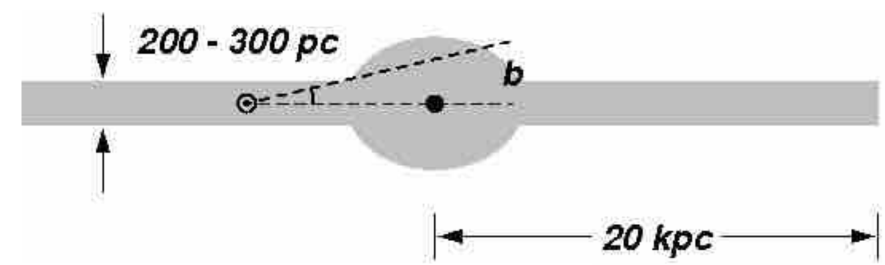
If the composition at the knee is *heavier* due to CNO / MgSi
➜ we have a problem !

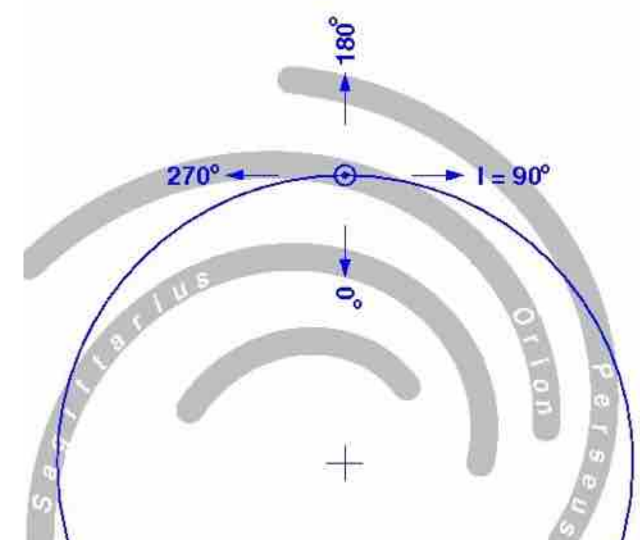
Diffuse γ-rays from the Galactic Plane

Diffuse γ-rays are produced by relativistic electrons by bremsstrahlung or inverse Compton scattering on bkg radiation fields, or by protons and nuclei via the decay of π^o produced in *hadronic interactions* with interstellar gas.



The space distribution of this emission can trace the location of the CR sources and the distribution of interstellar gas.





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

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

Diffuse Gamma Emission

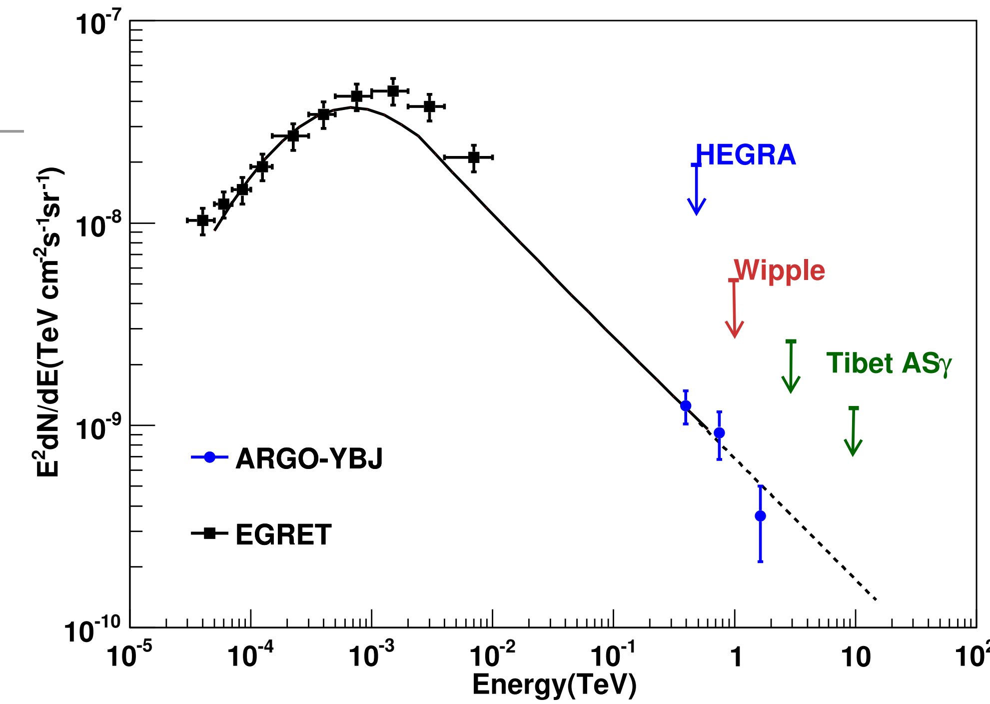
Diffuse gamma-ray emission from the Galactic plane for |b| < 5°

l Intervals	Significance	Spectral index	Energy (GeV)	Flux[a]
$25° < l < 100°$	6.9 s.d.	-2.80 ± 0.26	390	8.06 ± 1.49
			750	1.64 ± 0.43
			1640	0.13 ± 0.05
			1000[b]	0.60 ± 0.13
$40° < l < 100°$	6.1 s.d.	-2.90 ± 0.31	350	10.94 ± 2.23
			680	2.00 ± 0.60
			1470	0.14 ± 0.08
			1000[b]	0.52 ± 0.15
$65° < l < 85°$	4.1 s.d.	-2.65 ± 0.44	440	5.38 ± 1.70
			780	1.13 ± 0.60
			1730	0.15 ± 0.07
			1000[b]	0.62 ± 0.18
$25° < l < 65°$ & $85° < l < 100°$	5.6 s.d.	-2.89 ± 0.33	380	9.57 ± 2.18
			730	1.96 ± 0.59
			1600	0.12 ± 0.07
			1000[b]	0.60 ± 0.17
$130° < l < 200°$	-0.5 s.d.	–	–	< 5.7[c]

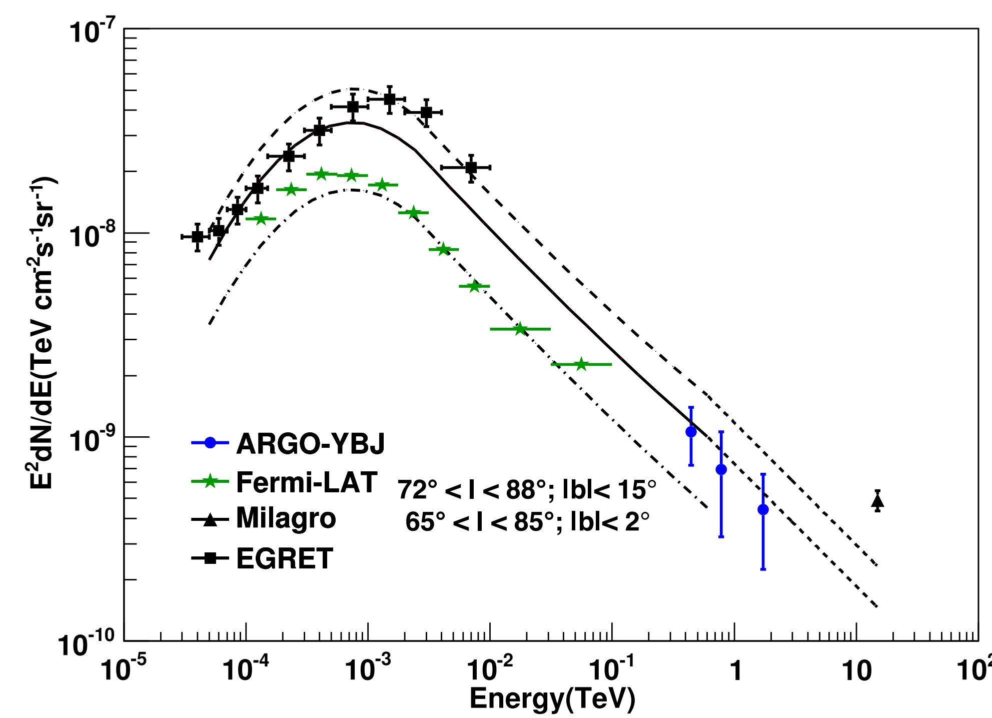
[a] In units of 10^{-9} TeV^{-1} cm^{-2} s^{-1} sr^{-1}.

ApJ 806 (2015) 20

25° < l < 100°; lbl< 5°



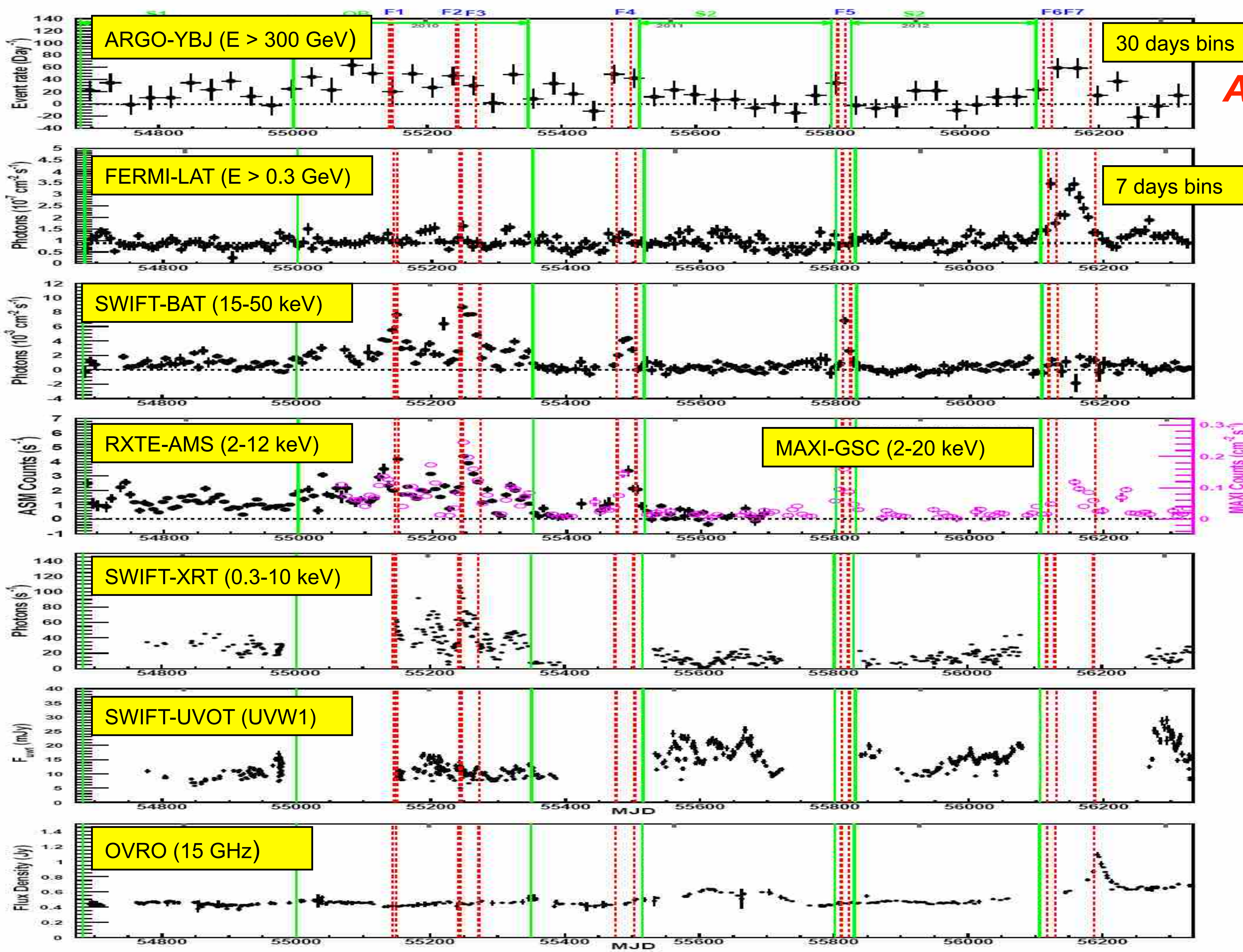
Cygnus region: 65° < l < 85°; lbl< 5°



Interestingly, *the energy spectrum of the light component (p+He) up to 700 TeV measured by ARGO-YBJ follows the same spectral shape as that found in the Cygnus region.*

A precise comparison of the spectrum of young CRs, as those supposed in the Cygnus region, with the spectrum of old CRs resident in other places of the Galactic plane, could help to determine the *distribution of the sources of CRs*.

The flaring γ-ray sky: Mrk421



ARGO-YBJ
5 years

One-zone Synchrotron Self-Compton model

Consider a population of relativistic electrons in a magnetized region. They will produce *synchrotron radiation*, and therefore they will fill the region with photons. These synchrotron photons will have some probability to interact again with the electrons, by the *Inverse Compton* process.

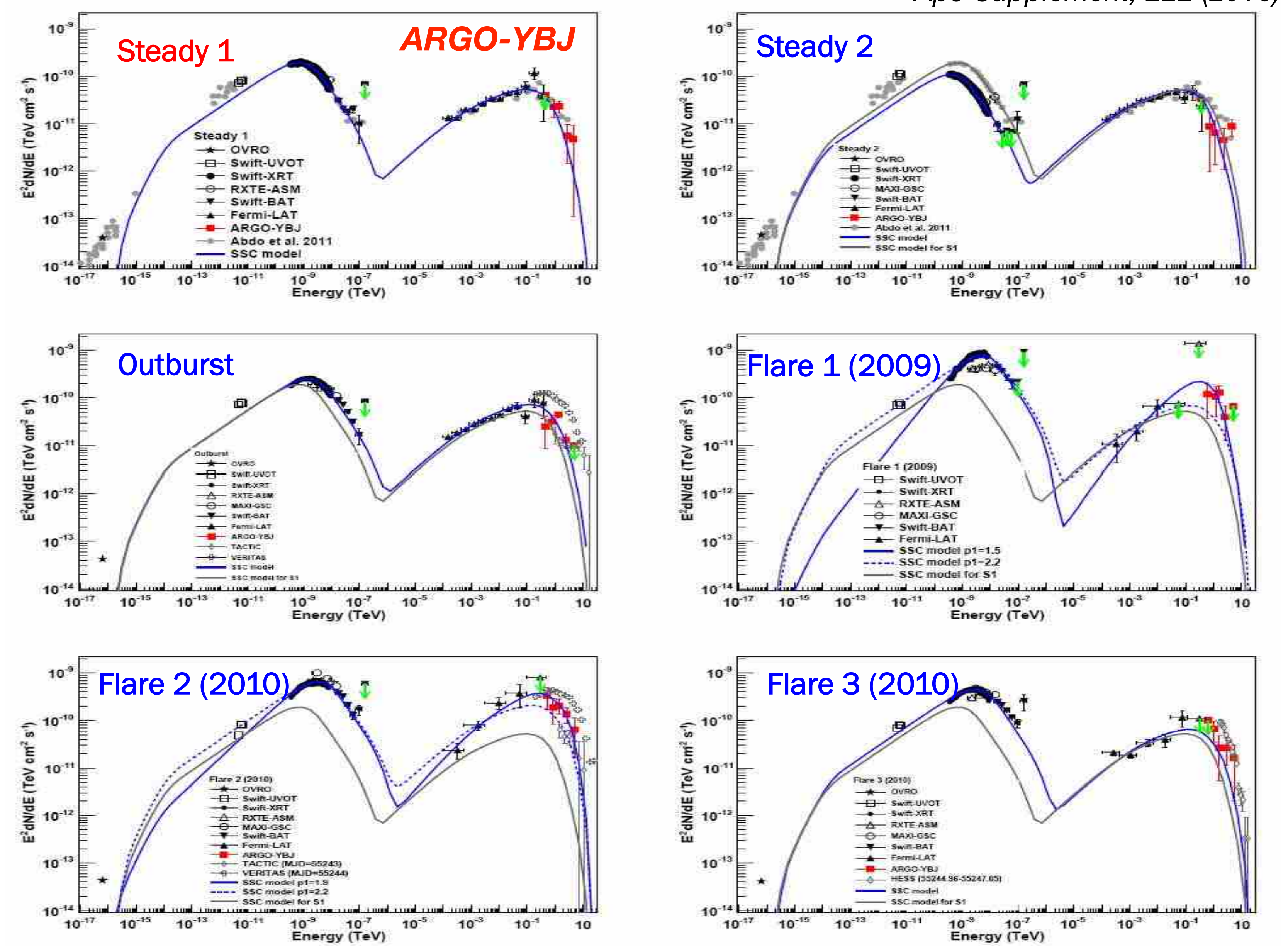
Since the *electron "work twice"* (first making synchrotron radiation, then scattering it at higher energies) this particular kind of process is called *synchrotron self–Compton*, or *SSC* for short.

ApJ Supplement, 222 (2016) 6

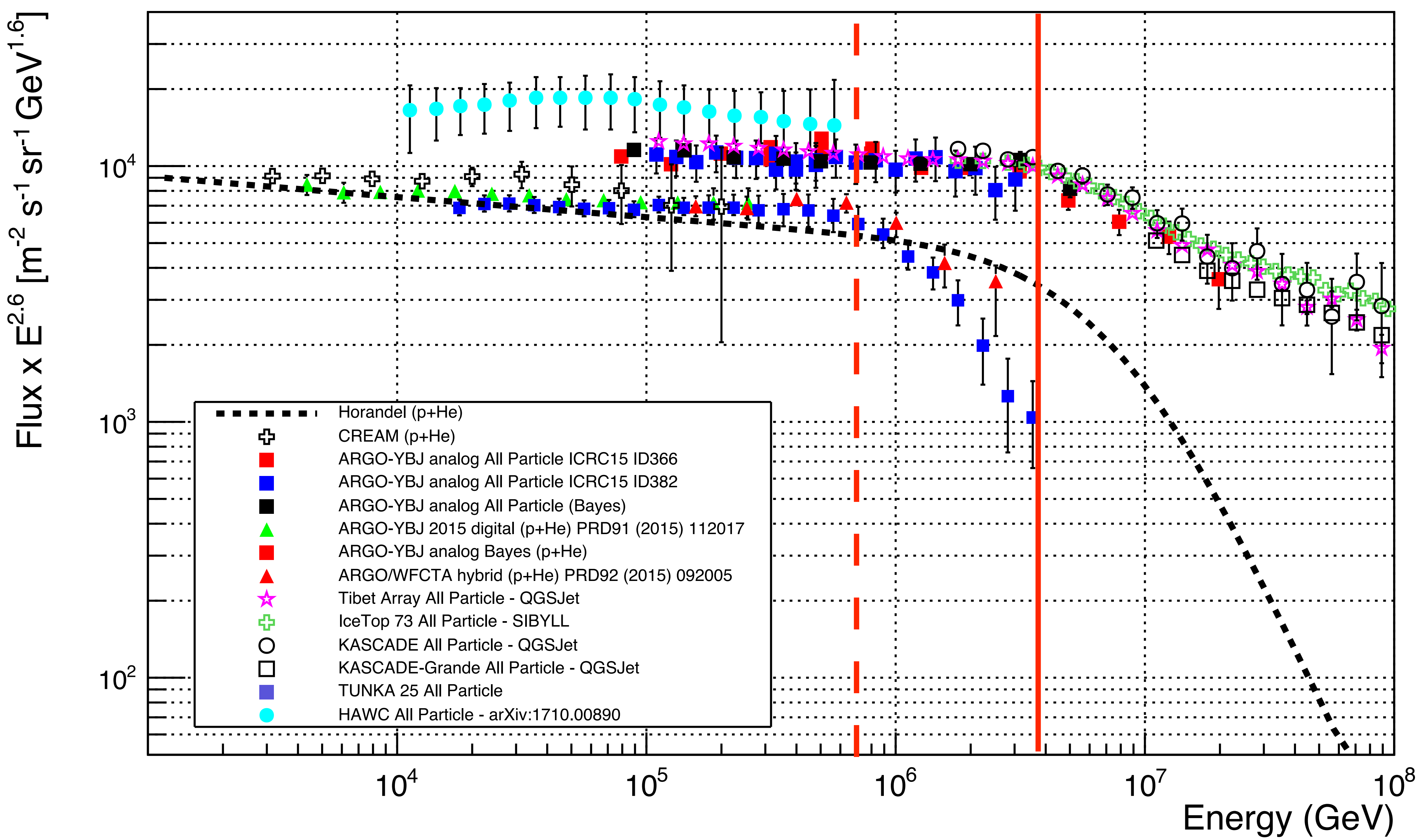
The *one-zone model* assumes that non-thermal radiations are produced in a single, homogeneous and spherical region in the jet.

The emission region moves relativistically toward us, and consequently the intrinsic radiation is strongly amplified due to the Doppler boosting.

Three parameters are needed to characterise the emission region: the comoving magnetic field, the Doppler factor and the comoving radius of the emission region.



CR energy spectrum: the overall picture



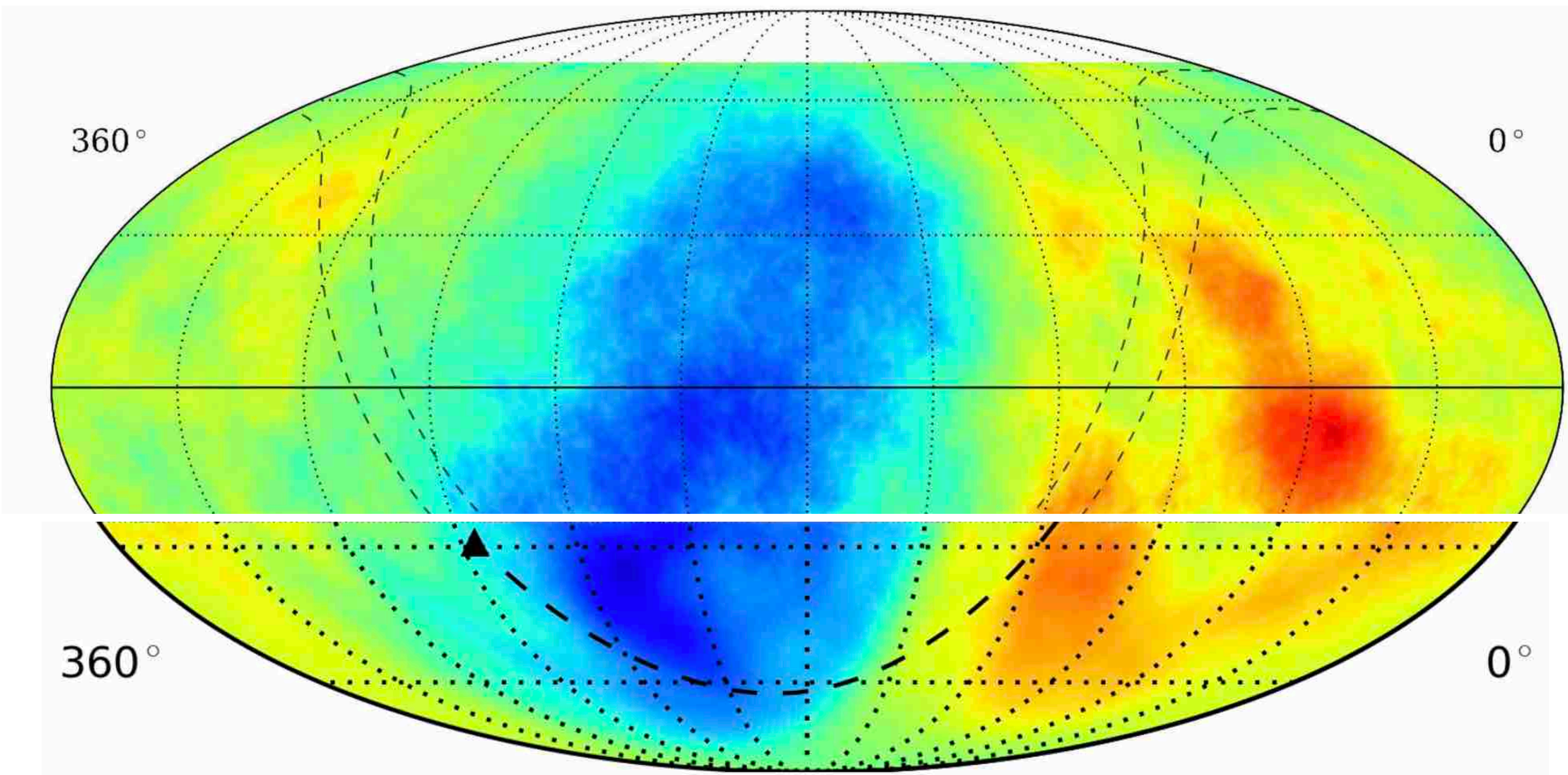
Experimental results in the knee region still conflicting:

ARGO-YBJ reports evidence for a *proton knee starting at about 700 TeV*

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

Full-Sky Cosmic Ray Anisotropy

HAWC



Credit: P. Desiati & J.C. Diaz Velez

IceCube

Cosmic Ray mass dependency ?

Energy dependency (< knee)

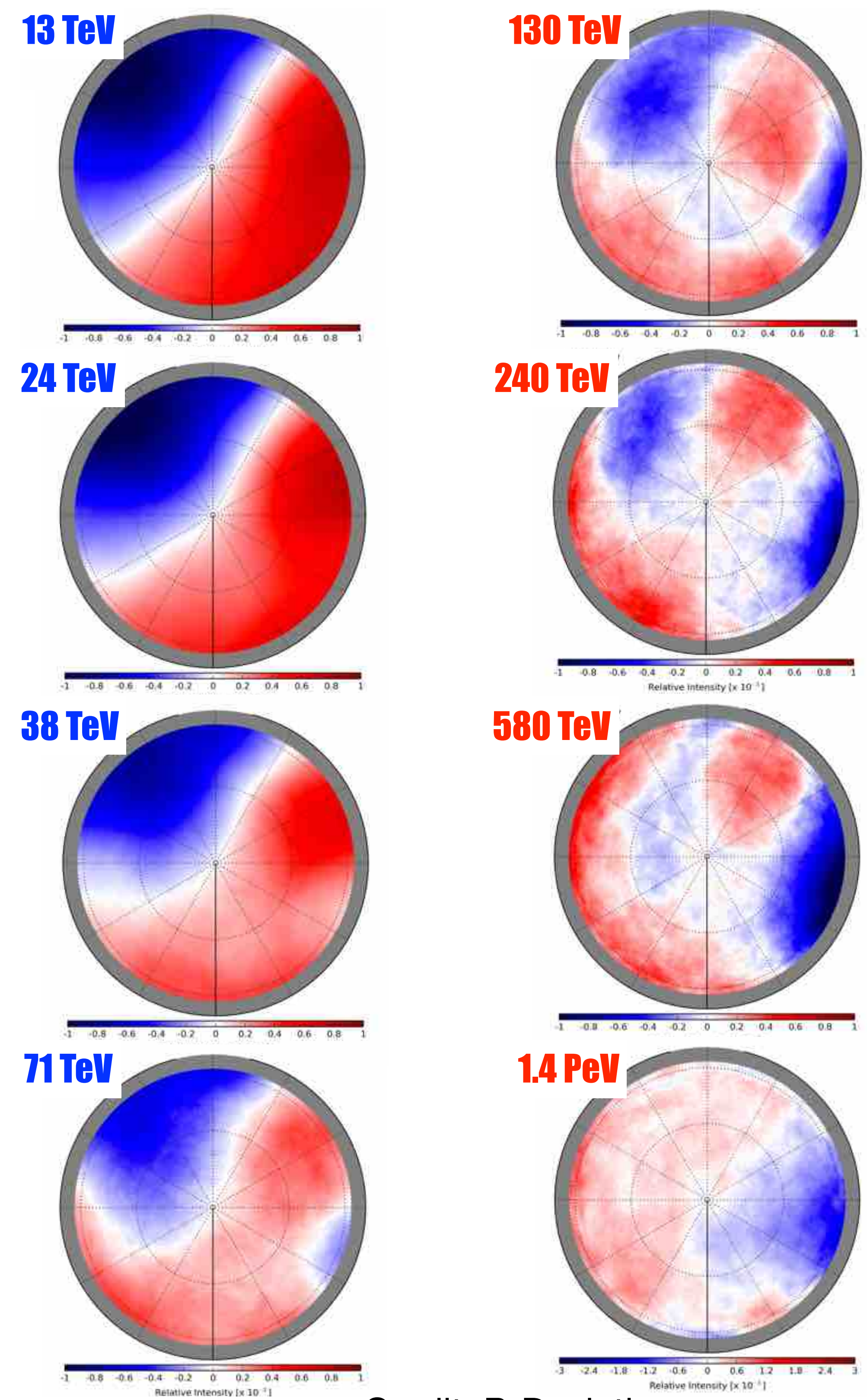
Anisotropy depends on primary energy

CR composition changes as well with energy

After IceCube/IceTop observations we know very well the anisotropy in the Southern Hemisphere at different angular scales but…

…we need anisotropy observations vs CR particle rigidity !

A *combined measurement* of CR energy spectrum, mass composition and anisotropy inevitably probes the properties and spatial distribution of their sources as well as of the long propagation journey through the magnetized medium.

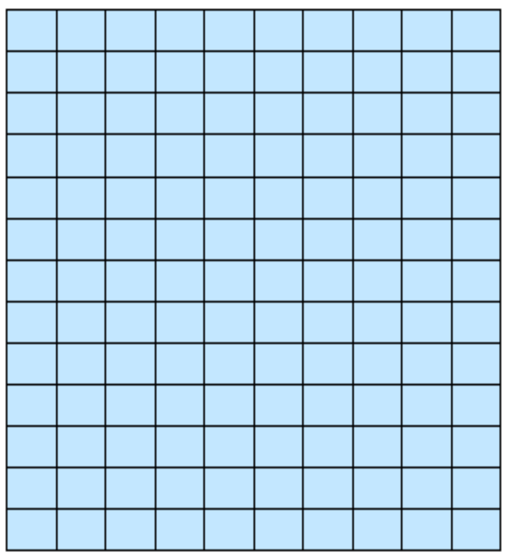


Credit: P. Desiati

The full coverage approach

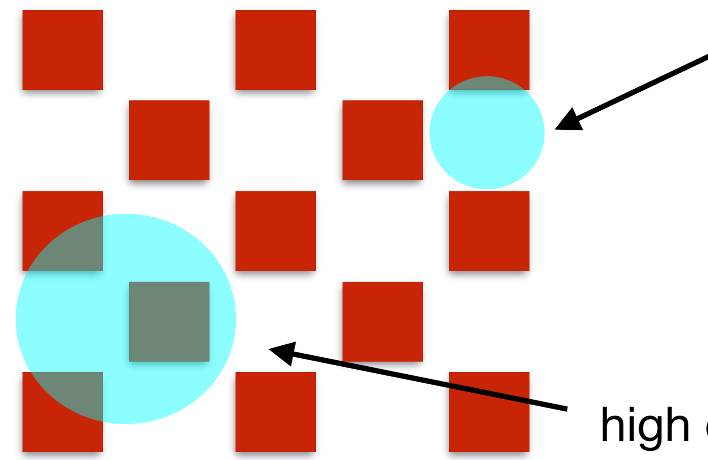
ARGO-YBJ is a high altitude full coverage EAS-array
optimized for the detection of small size air showers.

ARGO-YBJ central carpet



a continuous carpet of detectors
coverage factor ≈ 0.92

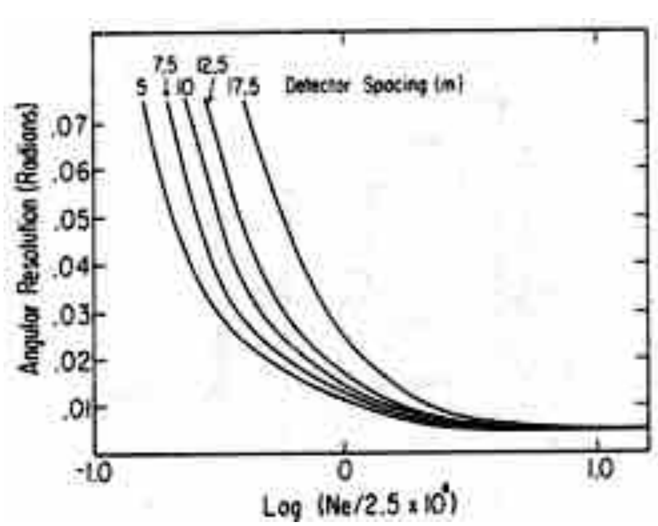
sparse array

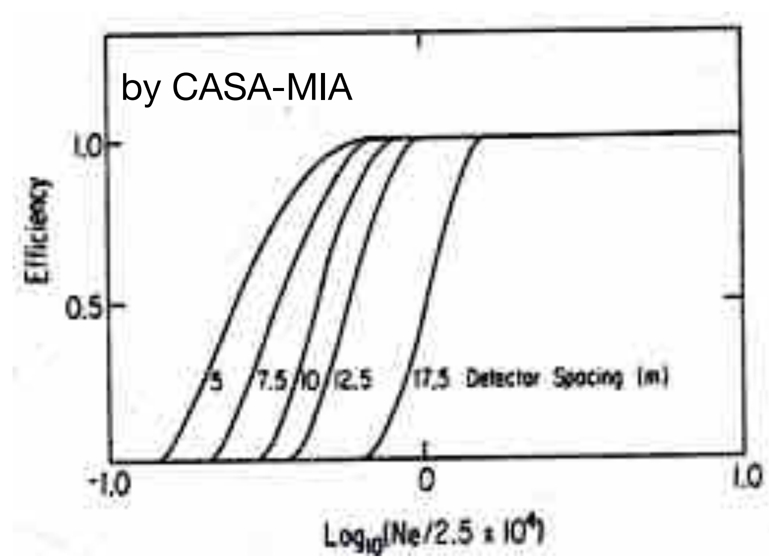


low energy shower = small shower
➔ NO trigger

high energy shower = big shower
➔ trigger

coverage factor ≈ 10^{-3} - 10^{-2}





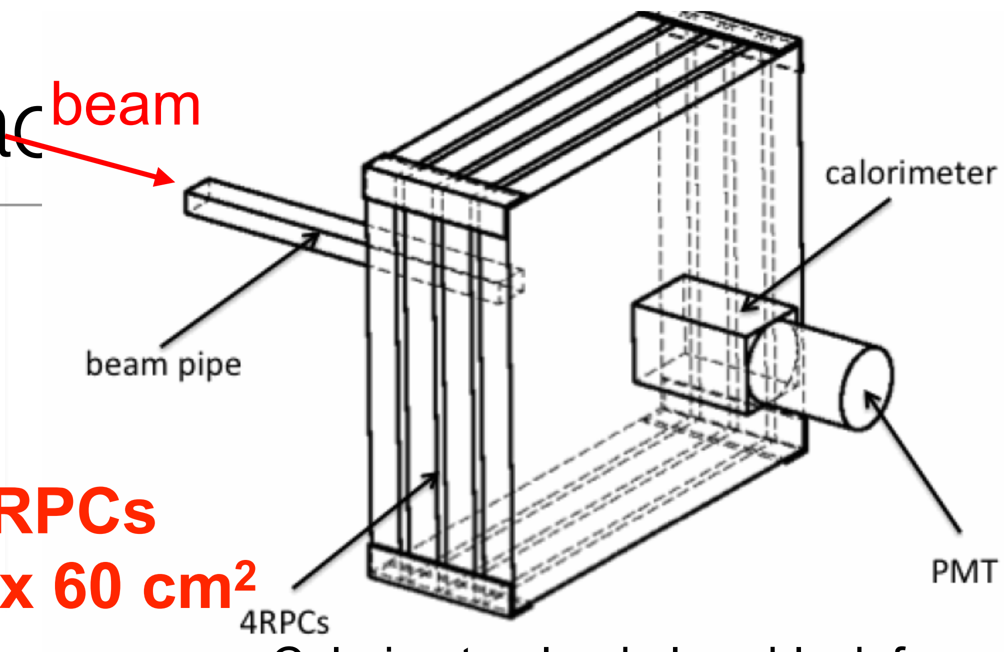
Increasing the sampling (~1% ➔100%)

- Improves angular resolution
- Lowers energy threshold

Intrinsic linearity: test at the BTF facility

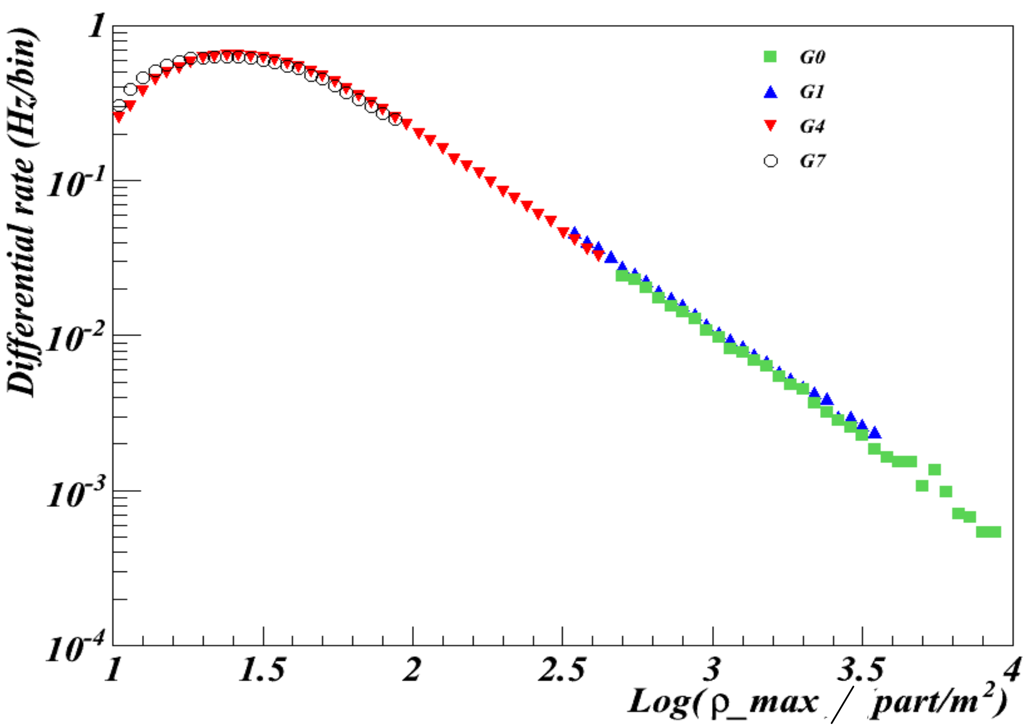
Linearity of the RPC @ BTF in INFN Frascati Lab:

- *electrons (or positrons)*
- *E = 25-750 MeV (0.5% resolution)*
- *<N>=1÷10^8particles/pulse*
- *10 ns pulses, 1-49 Hz*
- *beam spot uniform on 3×5 cm*

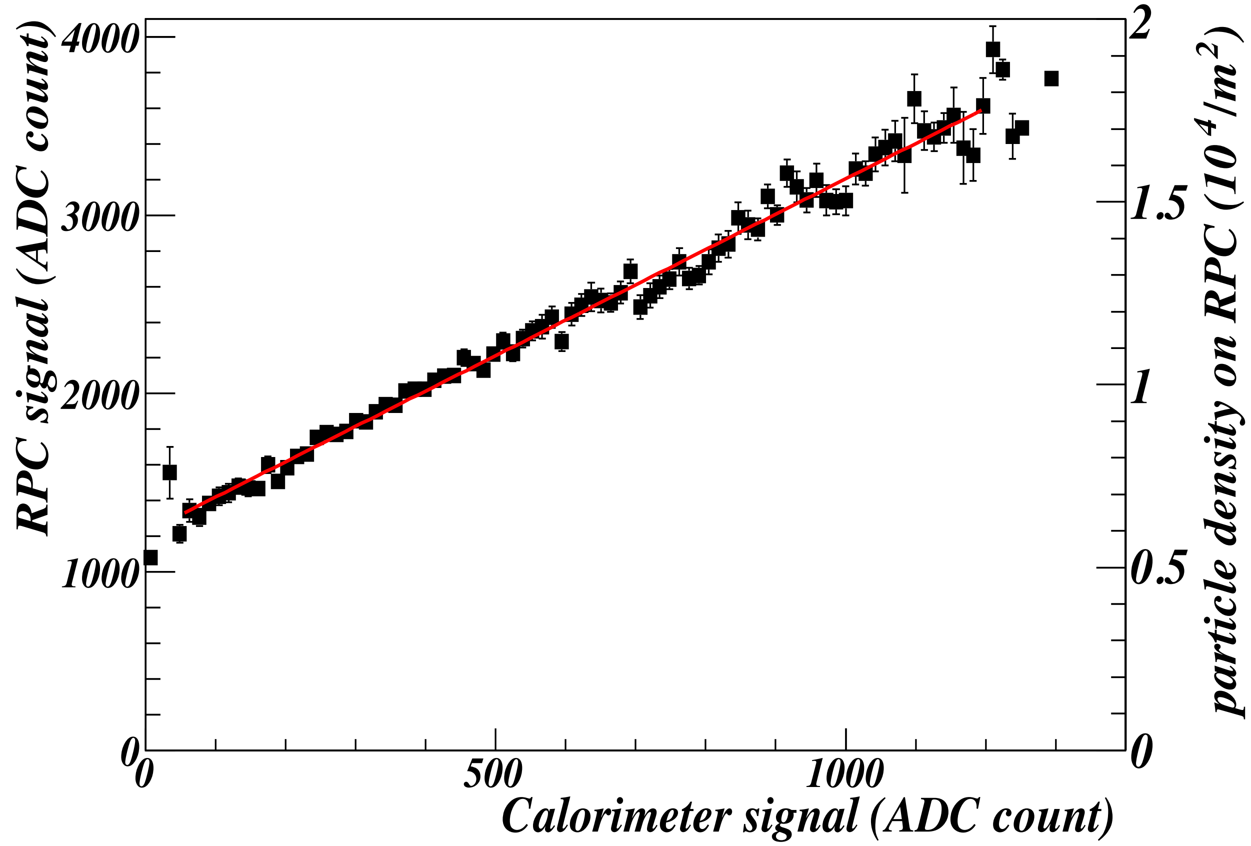


Calorimeter: lead glass block from OPAL, PMT a Hamamatsu R2238.

Good overlap between 4 scales with the maximum density of the showers spanning over three decades



The RPC signal vs the calorimeter signal



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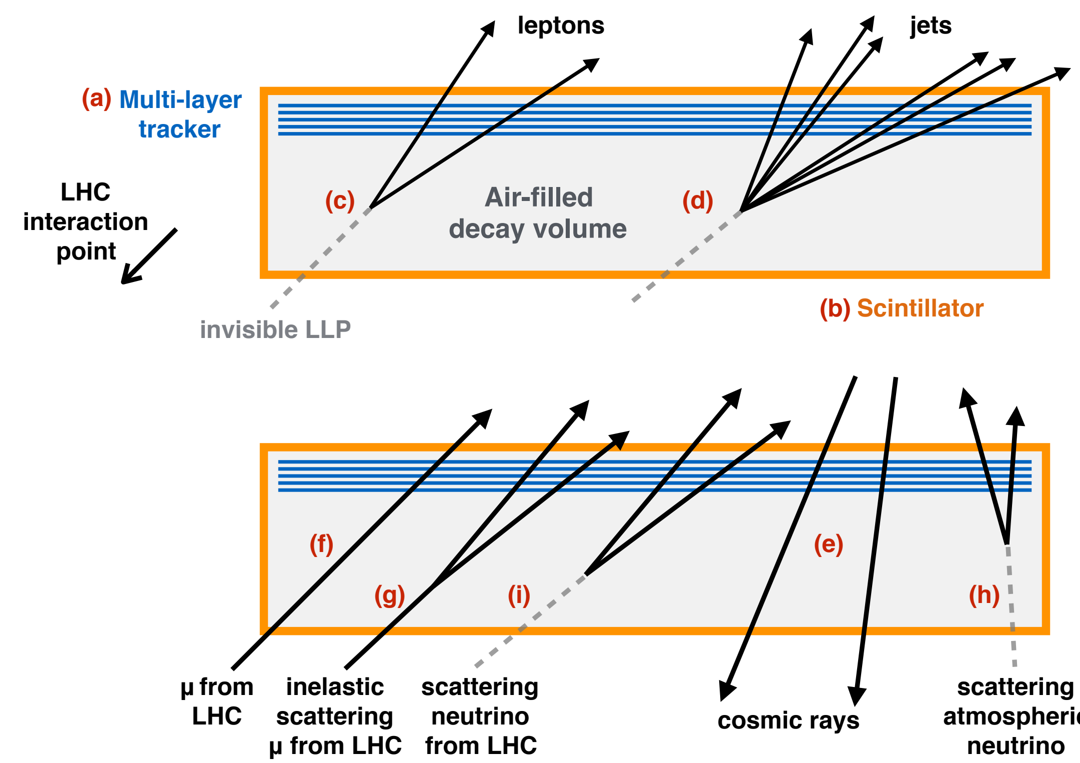
➔ Linearity up to ≈ 2 · 10^4 particle/m^2

MATHUSLA proposal

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball, [o] Liron Barak, [c] James Beacham, [ah] Yan Benhammo, [c] Tingting Cao, [c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi, [c] David Morrissey,[p] Meny Raviv Moshe, [c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver, [c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita,[w,ac]



Under review at the LHCC committee