

# ARGO-YBJ Legacy to next generation of Wide Field of View experiments

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# Outline

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## ★ The ARGO-YBJ experiment

### ★ Gamma-Ray Astronomy

- Study of the Cygnus region: the Cygnus Cocoon
- Diffuse  $\gamma$ -ray emission
- Flaring TeV  $\gamma$ -ray sky

### ★ Cosmic Ray Physics

- All-particle and (p + He) energy spectra
- Observation of the proton “knee”
- Anisotropies

## ★ New Wide FoV experiments: the LHAASO project

## ★ Future Wide FoV experiments: What's Next ?

# ARGO-YBJ: a multi-purpose experiment

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A multi-purpose experiment **capable of acting simultaneously as a Cosmic Ray detector and a Gamma Ray Telescope** to face the open problems in Galactic CR Physics

- Sky survey  $-10\% \leq \delta \leq 70\%$  ( $\gamma$ -sources, diffuse emission)
- High exposure for flaring activity ( $\gamma$ -sources, GRBs, solar flares)
- CR 1 TeV  $\rightarrow$   $10^4$  TeV 

{	p + He energy spectrum
	Proton “ <i>knee</i> ”
	Composition at the <i>knee</i>
	Anisotropies
- Antip/p at TeV energies
- Solar and heliospheric physics
- Hadronic interactions, cross sections

“Main physics results of the ARGO-YBJ experiment”, Int. J. of Mod. Phys. D23 (2014) 1430019

# ARGO-YBJ: a full coverage detector

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

# ARGO-YBJ: a full coverage detector

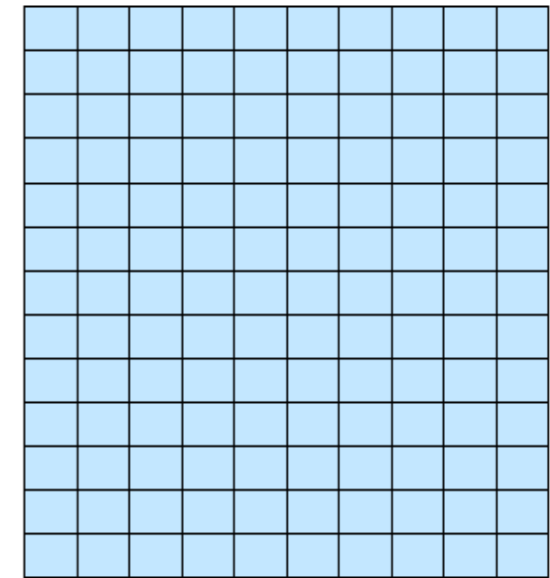
ARGO-YBJ is a high altitude **full coverage** EAS-array optimized for the detection of small size air showers.



large number of detectors spread over an area of  $\approx 10^5 \text{ m}^2$

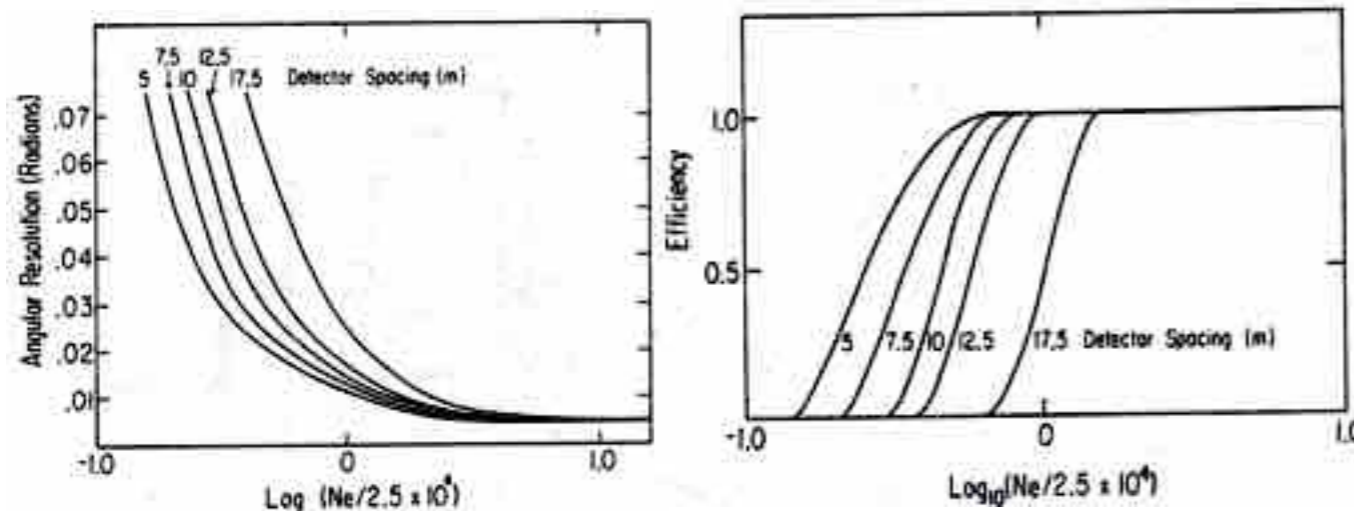
**coverage factor** (sensitive area/instrumented area)  $\approx 10^{-3} - 10^{-2}$

ARGO-YBJ central carpet



a continuous carpet of detectors

**coverage factor**  $\approx 0.92$



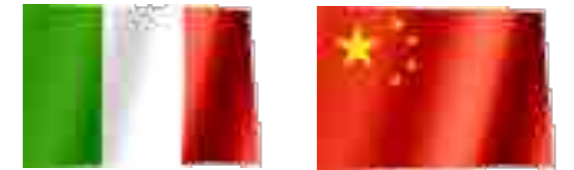
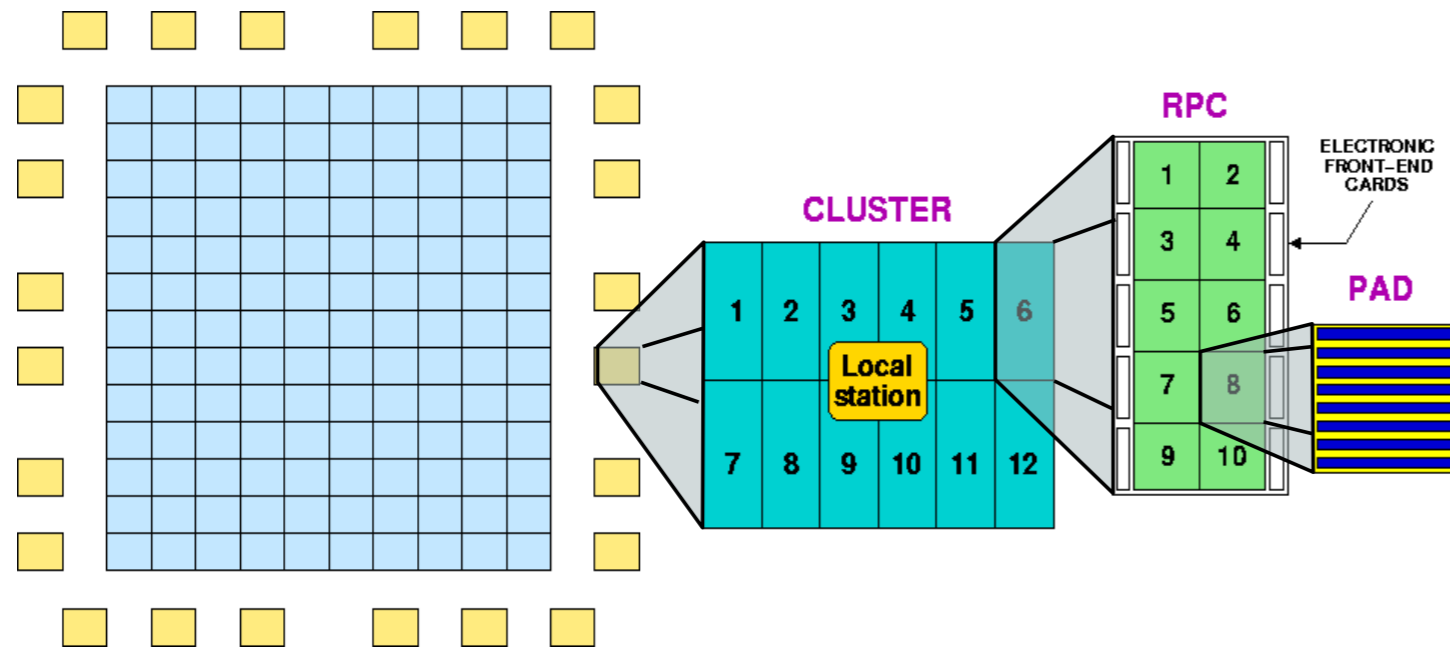
Increasing the sampling ( $\sim 1\% \rightarrow 100\%$ )



- Improves angular resolution
- Lowers energy threshold

# The ARGO-YBJ experiment

*ARGO-YBJ is a telescope optimized for the detection of small size air showers*



INFN IHEP/CAS

Longitude: 90° 31' 50" East  
Latitude: 30° 06' 38" North

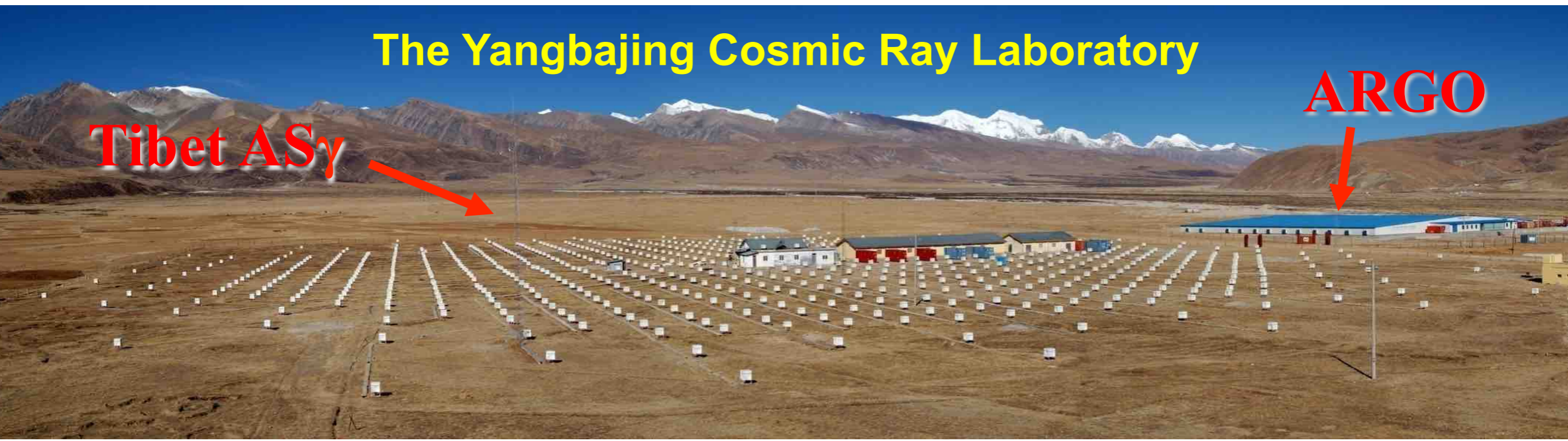
90 km North from Lhasa (Tibet)

4300 m above sea level  
~ 600 g/cm<sup>2</sup>

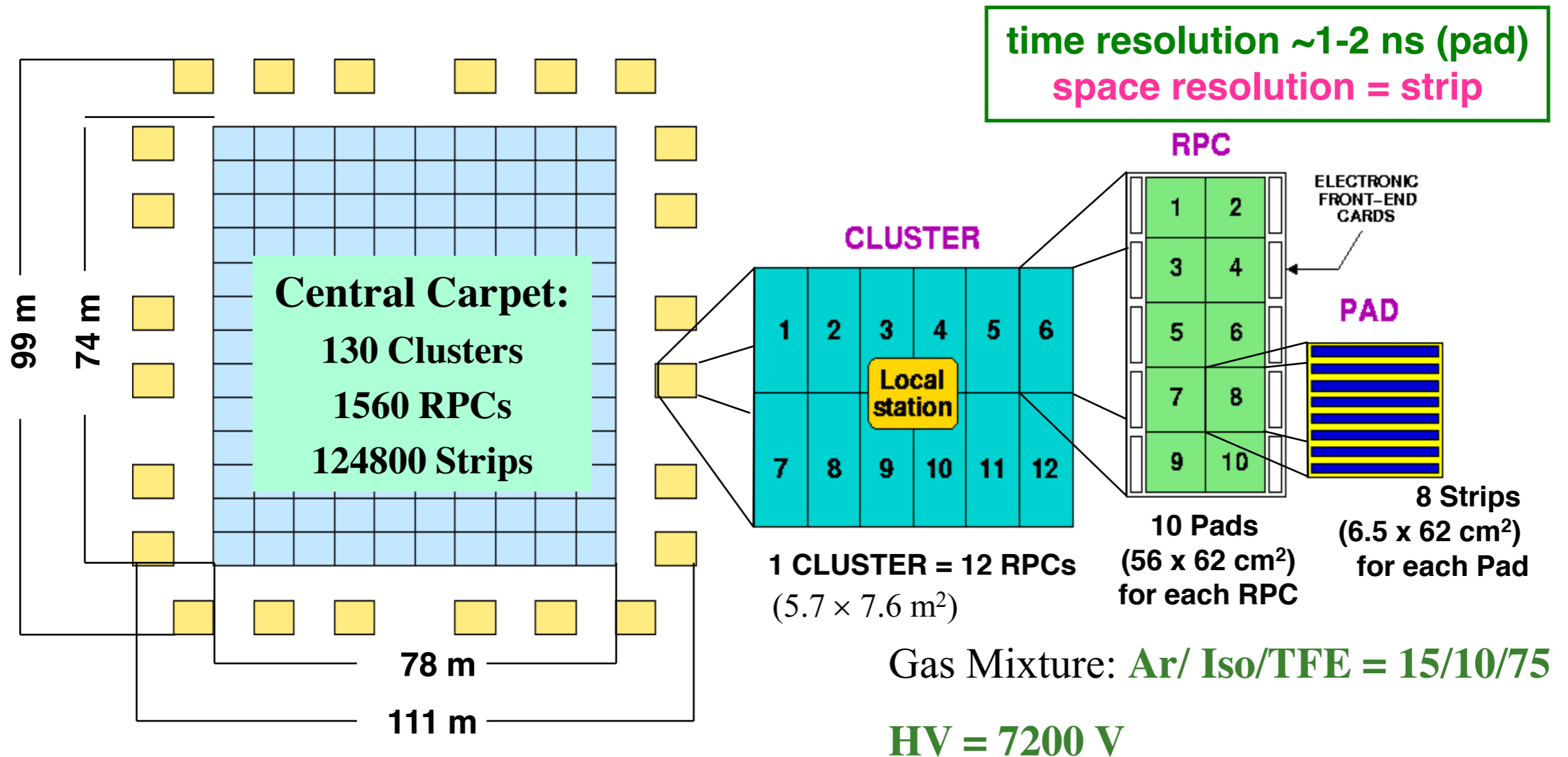
## The Yangbajing Cosmic Ray Laboratory

Tibet ASy

ARGO

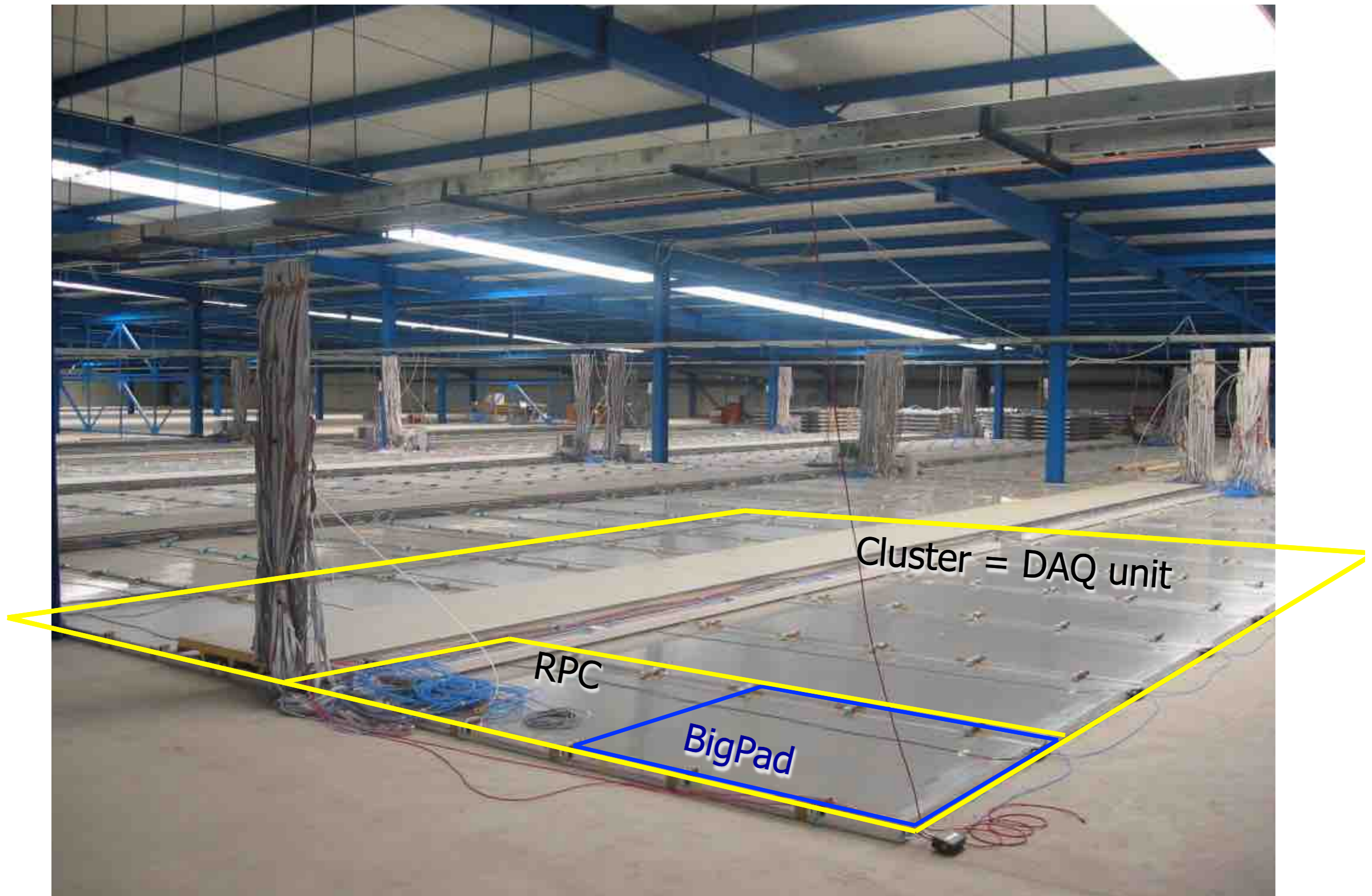


# The ARGO-YBJ layout



**Single layer of Resistive Plate Chambers (RPCs)  
 with a full coverage (92% active surface) of a large area (5600 m<sup>2</sup>)  
 + sampling guard ring (6700 m<sup>2</sup> in total)**

# The experimental hall



# The basic concepts

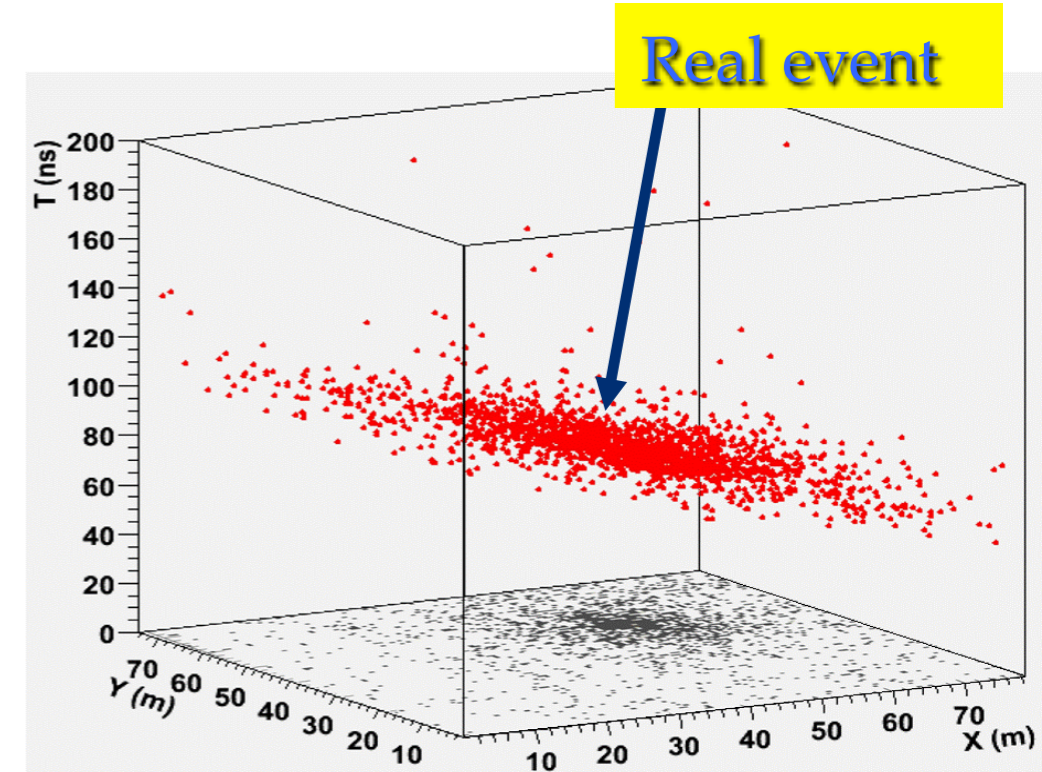
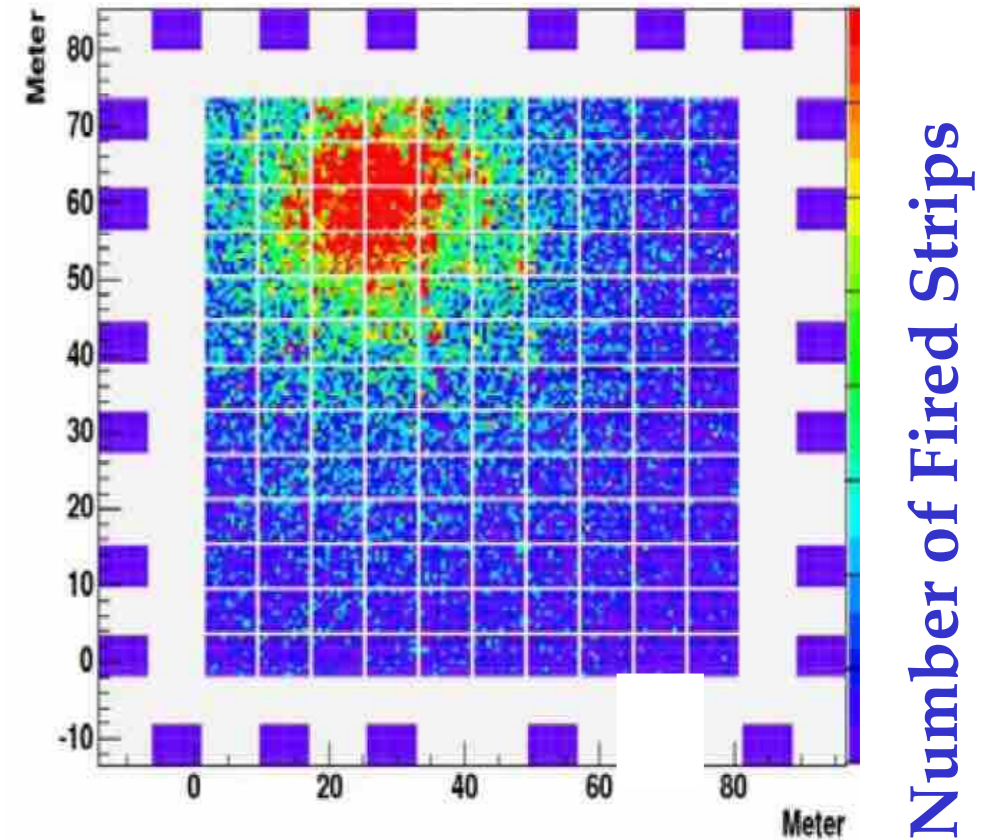
...for an unconventional air shower detector

- ❖ **HIGH ALTITUDE SITE**  
(YBJ - Tibet 4300 m asl - 600 g/cm<sup>2</sup>)
- ❖ **FULL COVERAGE**  
(RPC technology, 92% covering factor)
- ❖ **HIGH SEGMENTATION OF THE READOUT**  
(small space-time pixels)

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

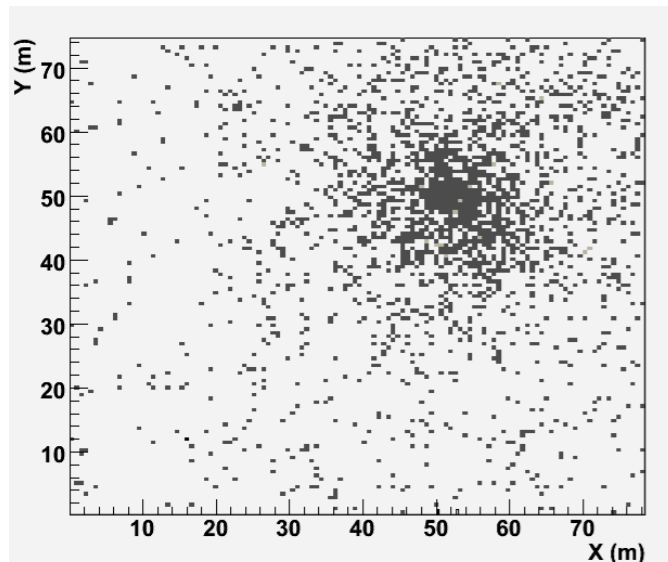
... in order to

- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV

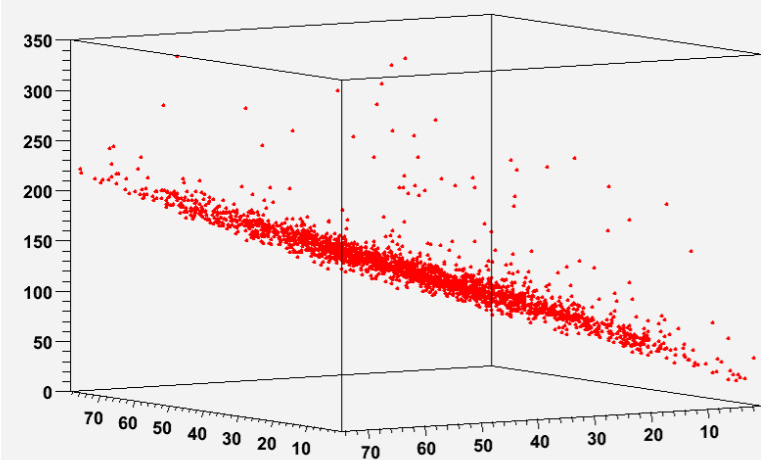


# Shower detection

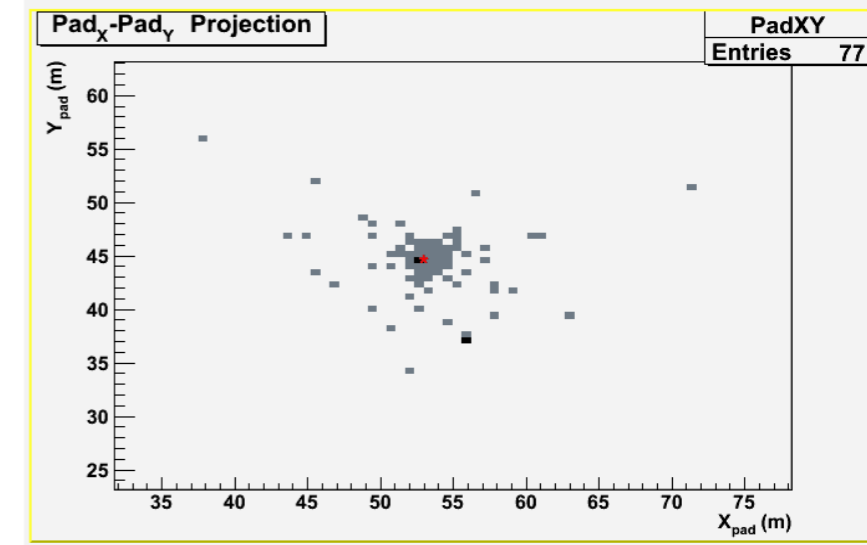
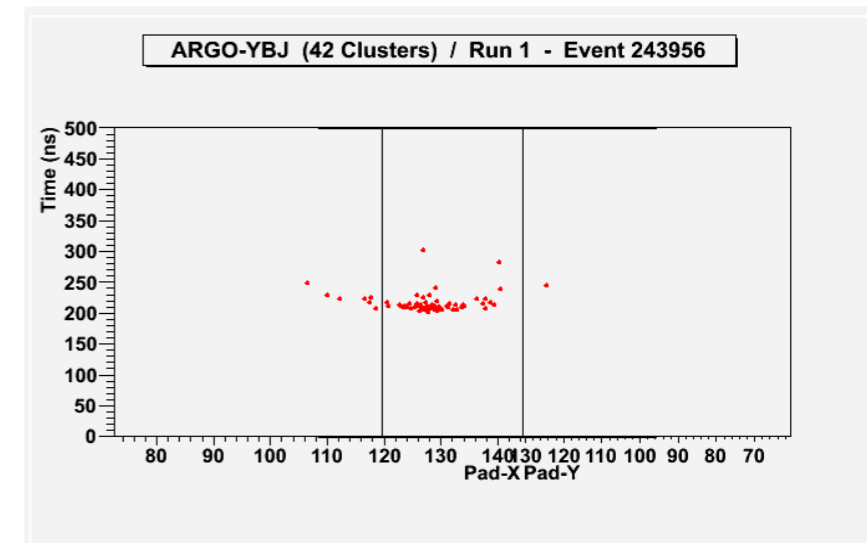
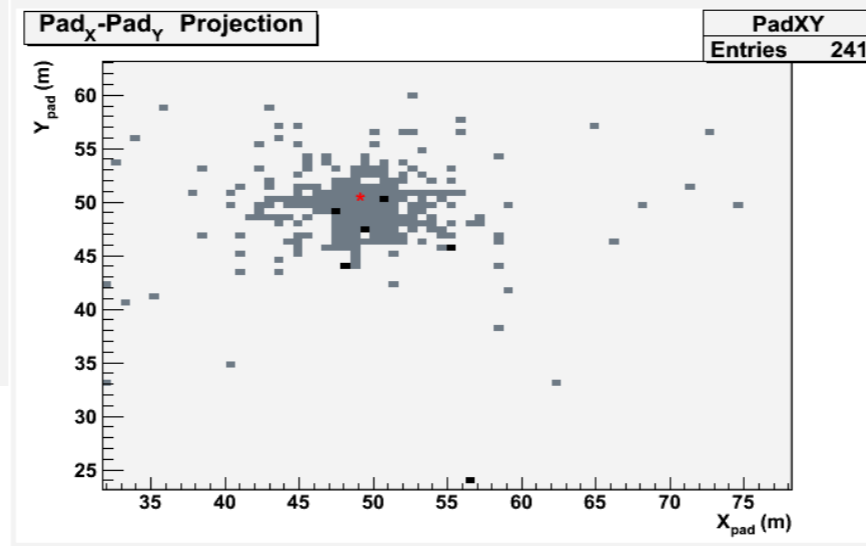
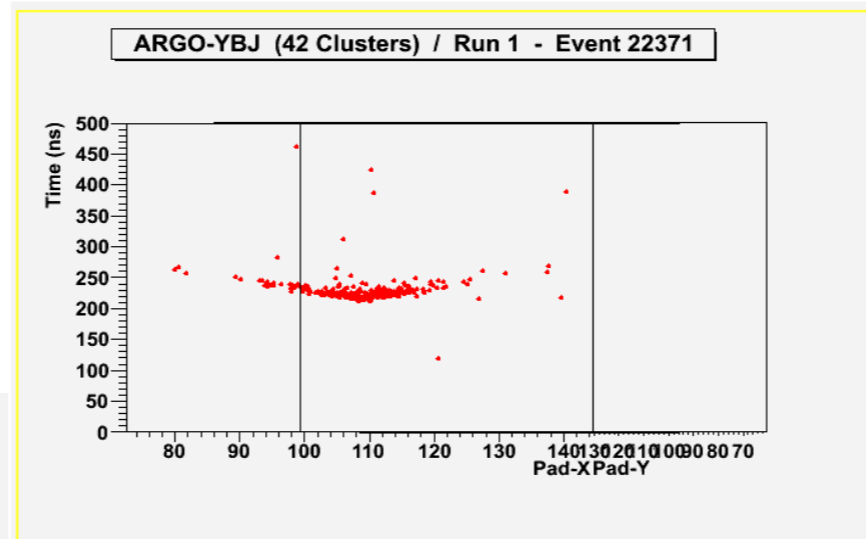
## Small and compact events



Fired pads on the carpet

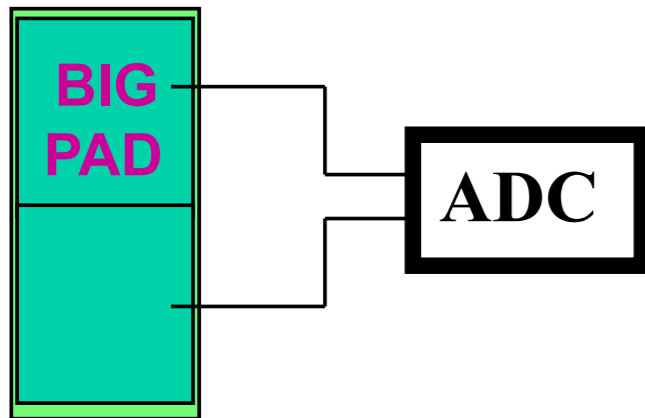


Arrival time vs position



# The RPC charge readout

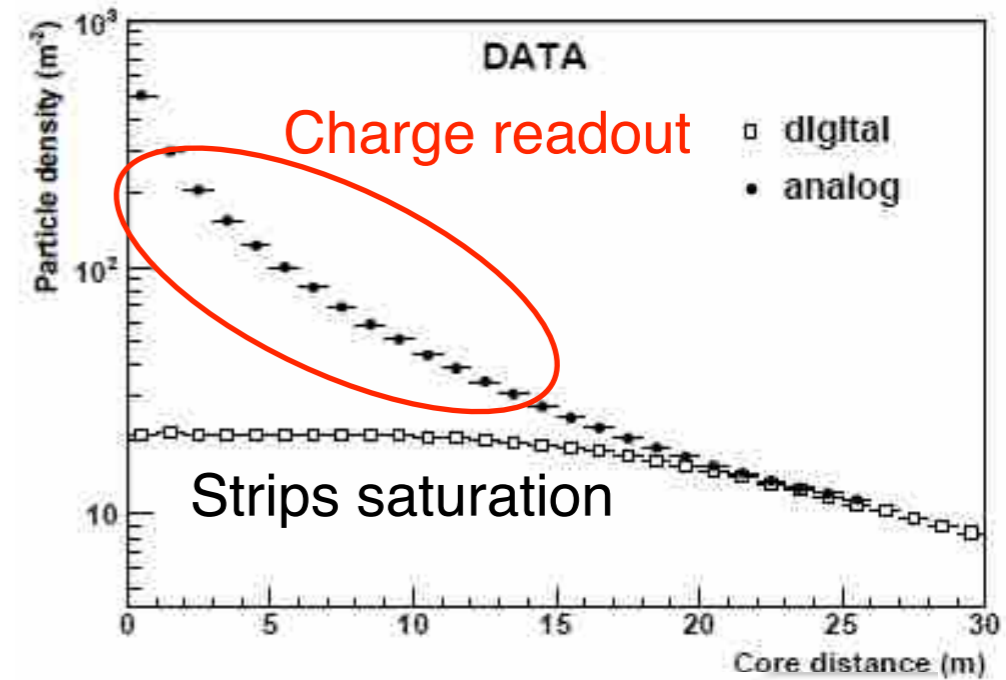
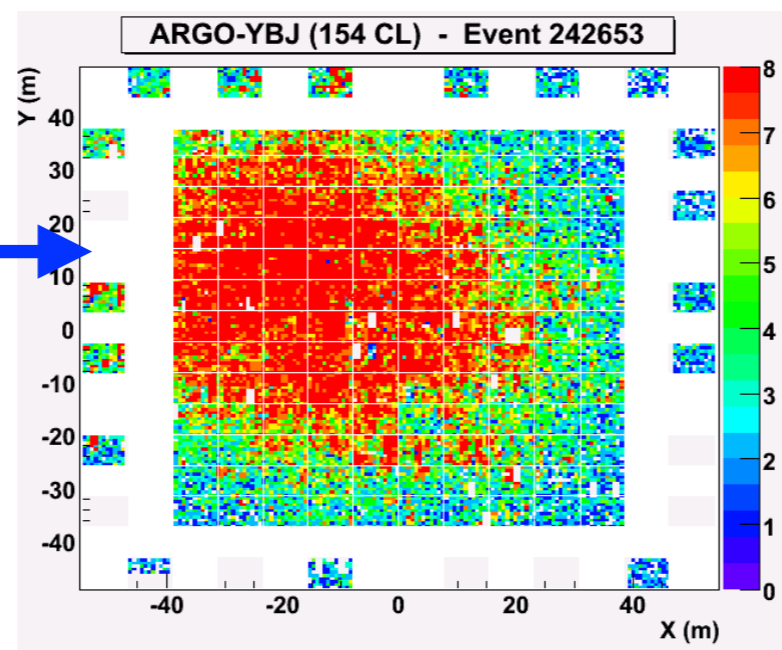
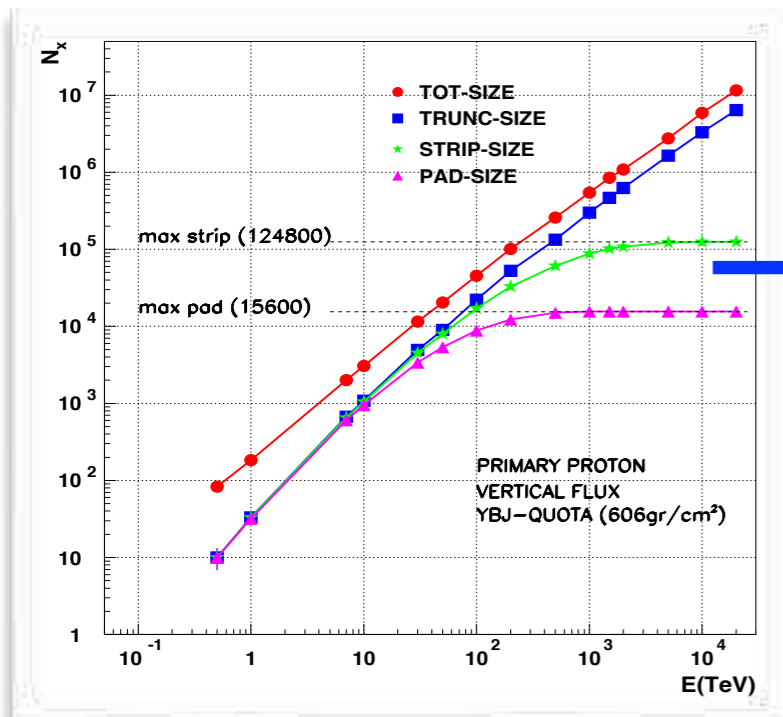
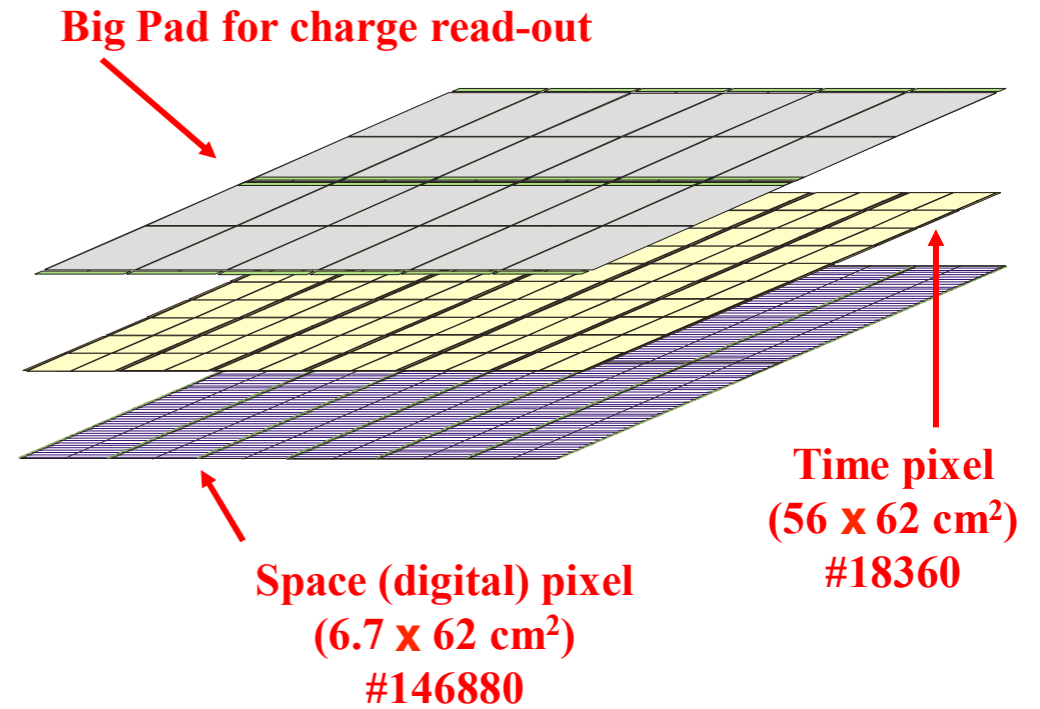
...extending the dynamical range up to 10 PeV



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

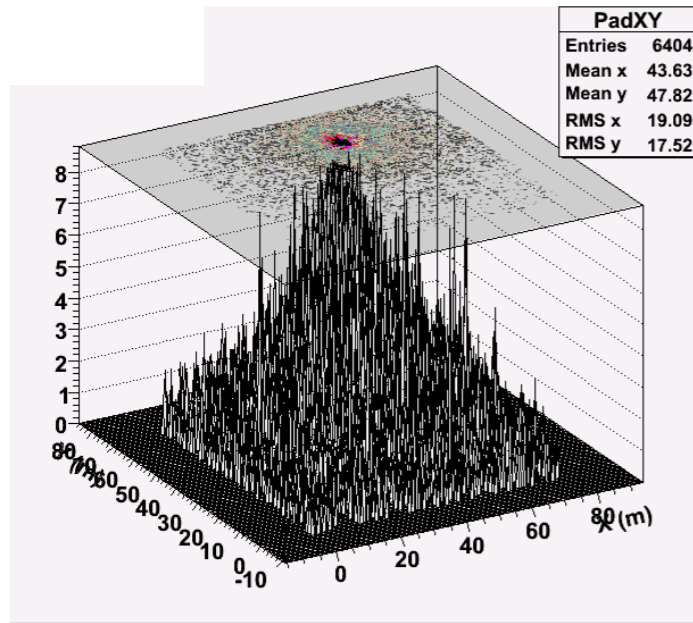
$$\rho_{\text{max-strip}} \approx 20 \text{ particles/m}^2$$

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



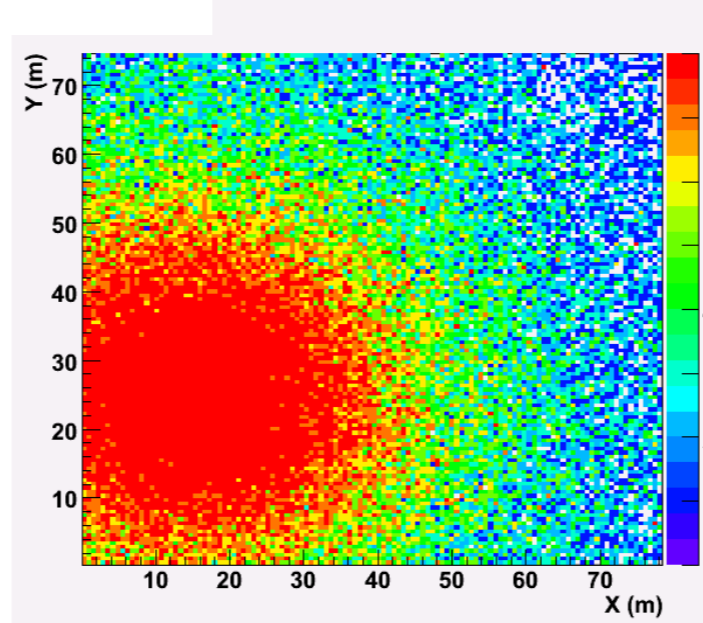
# The RPC charge readout: the core region

MC: 100 TeV



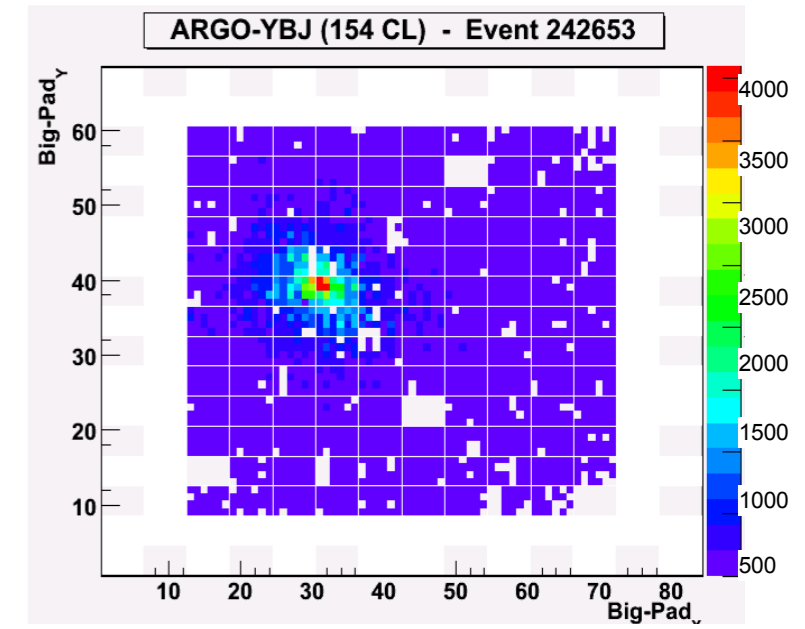
Strip read-out

MC: 1000 TeV

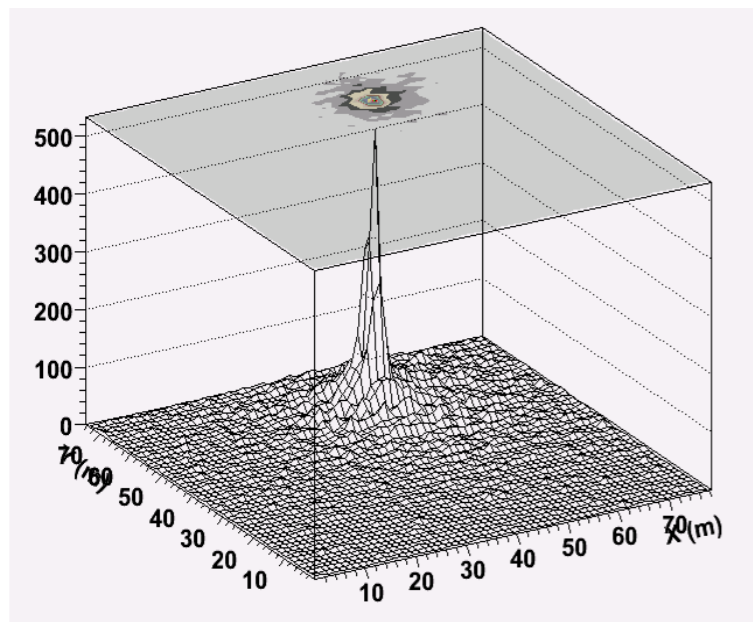


Strip read-out

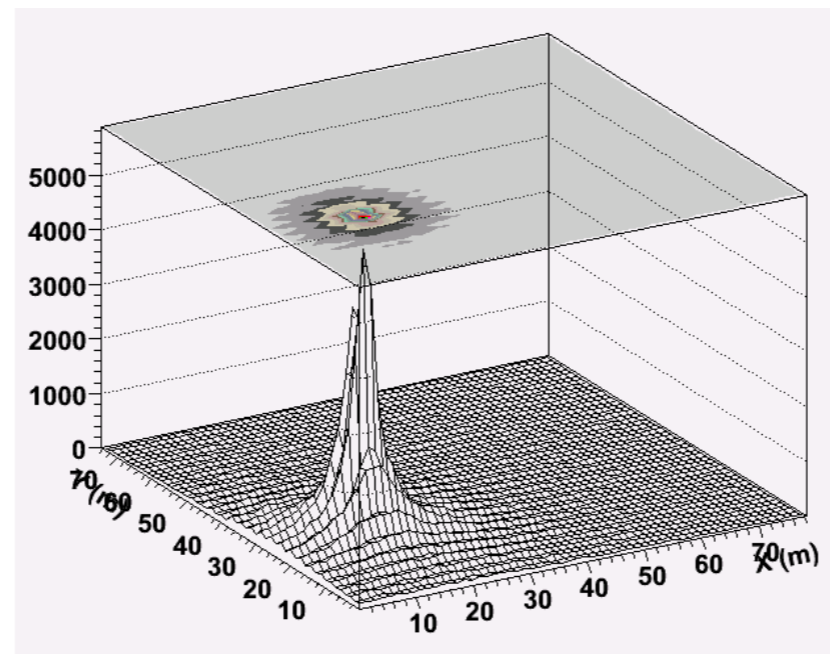
Data



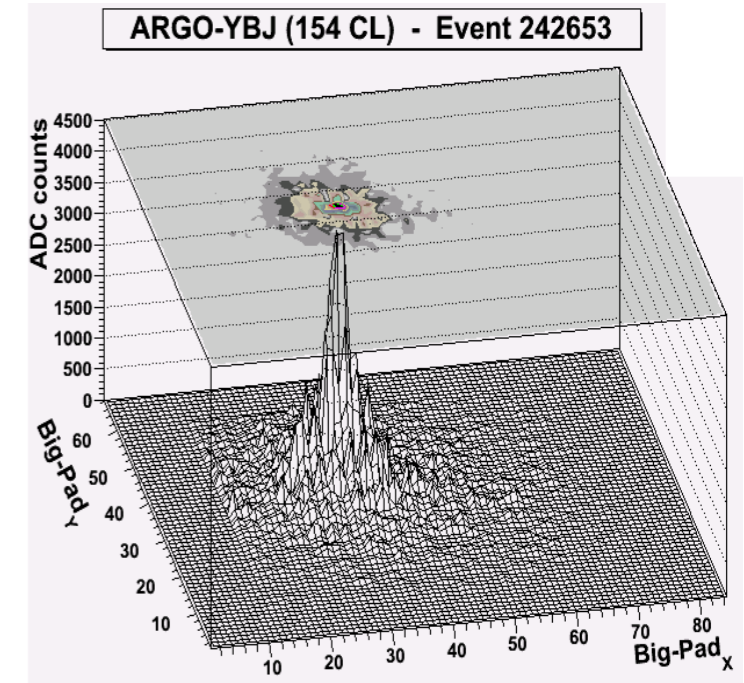
Strip read-out



Charge read-out



Charge read-out

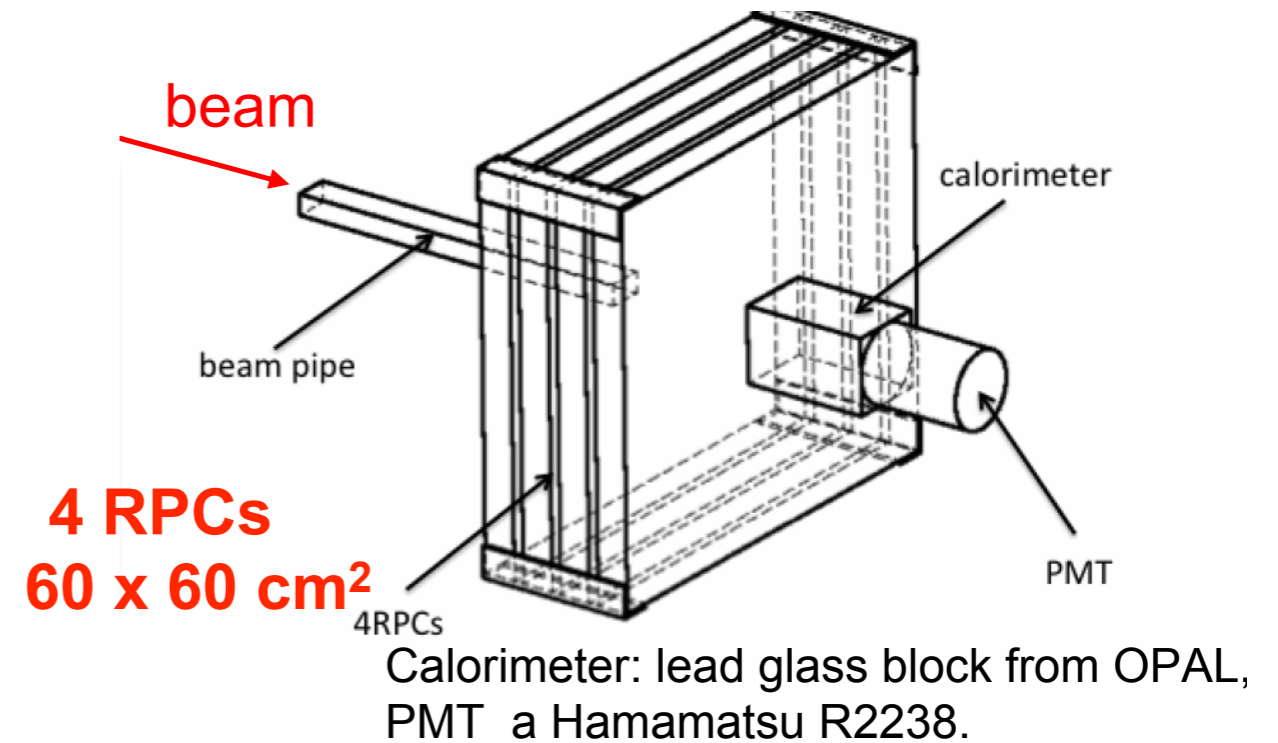


Charge read-out

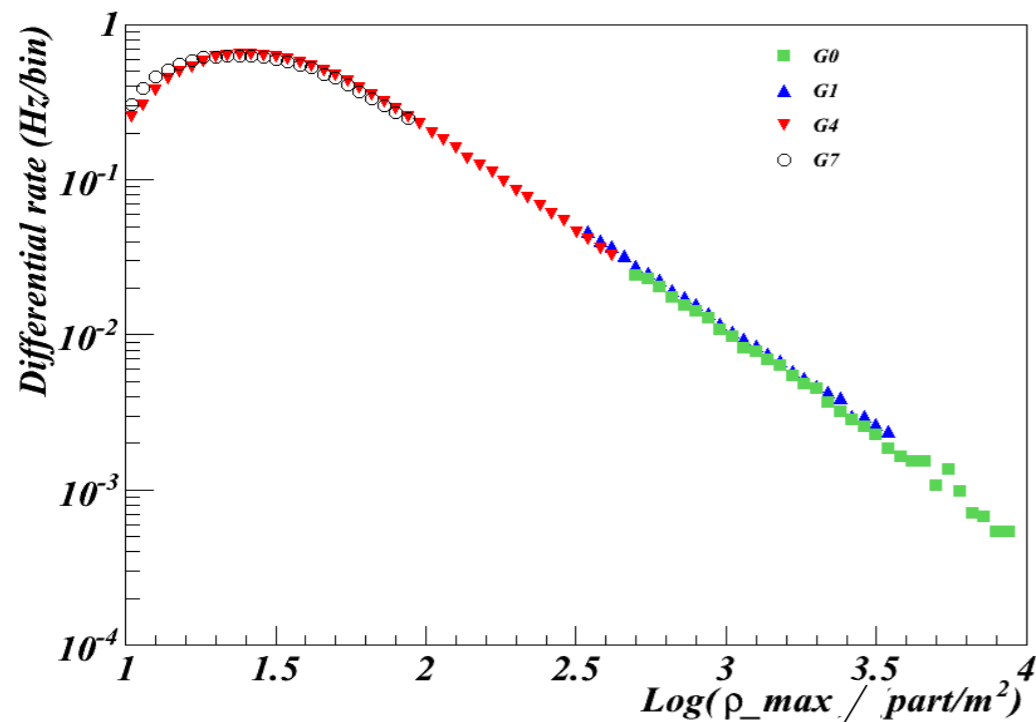
# Intrinsic linearity: test at the BTF facility

## Linearity of the RPC @ BTF in INFN Frascati Lab:

- electrons (or positrons)
- $E = 25\text{-}750\text{ MeV}$  (0.5% resolution)
- $\langle N \rangle = 1 \div 10^8$  particles/pulse
- 10 ns pulses, 1-49 Hz
- beam spot uniform on  $3 \times 5\text{ cm}$

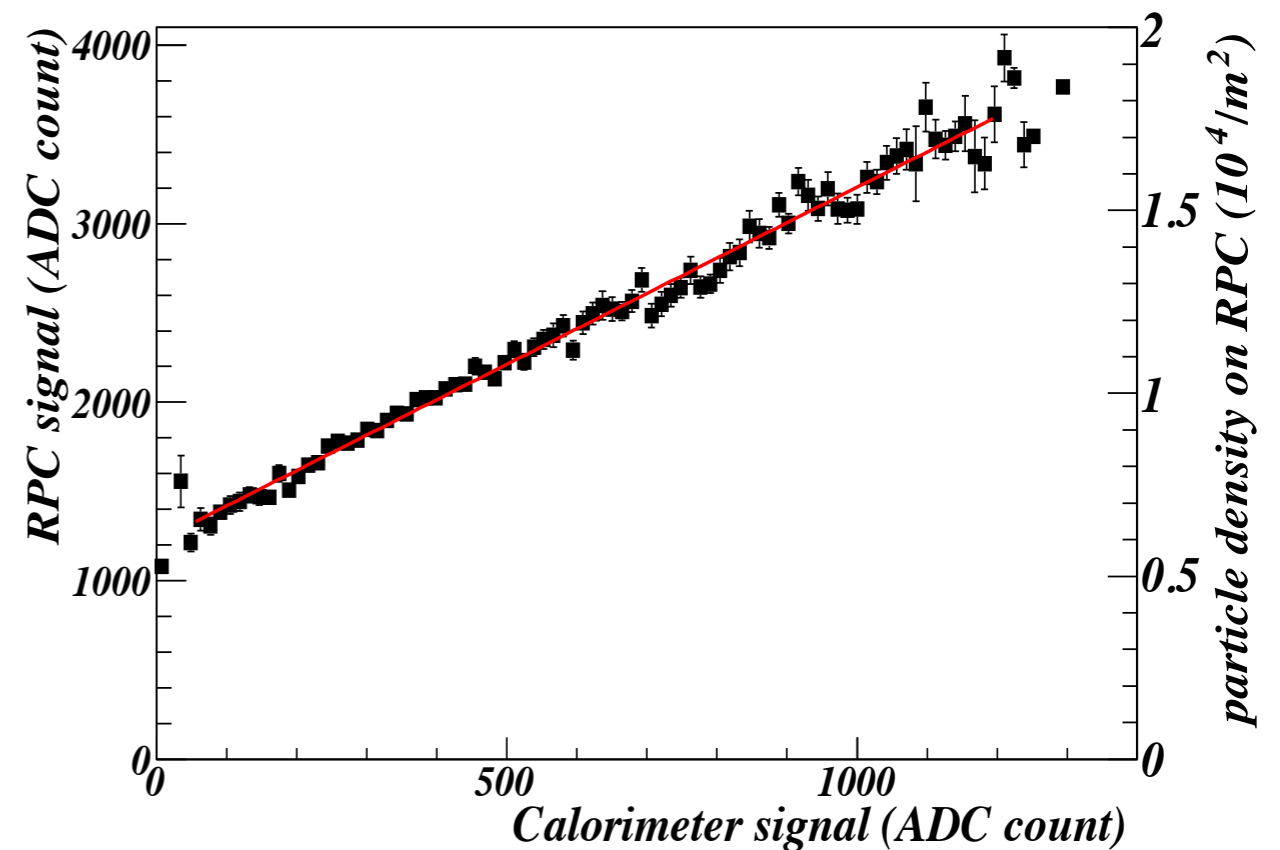


Good overlap between 4 scales with the maximum density of the showers spanning over three decades



Astrop. Phys. 67 (2015) 47

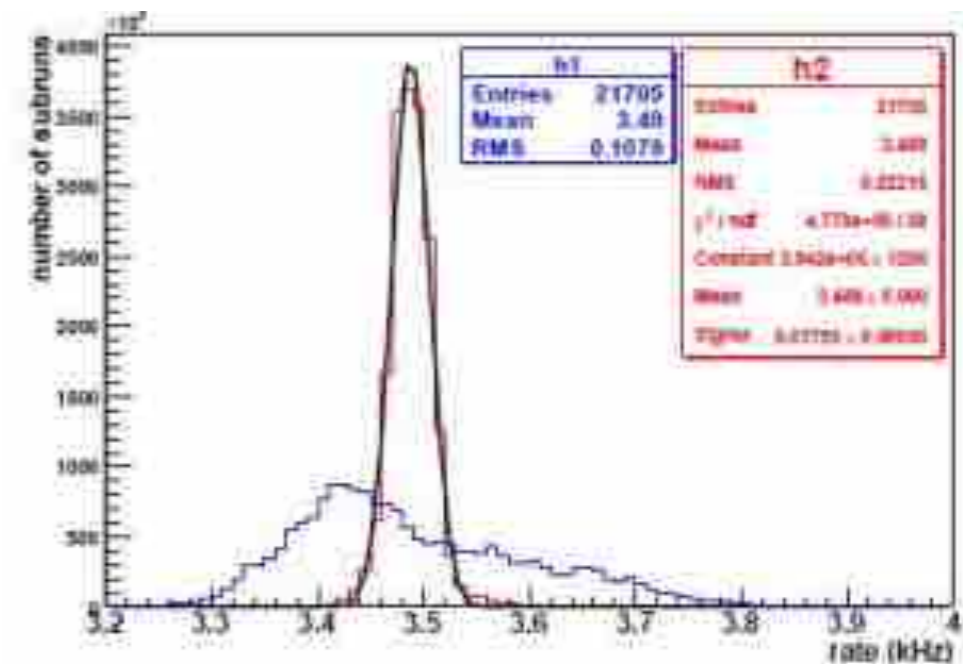
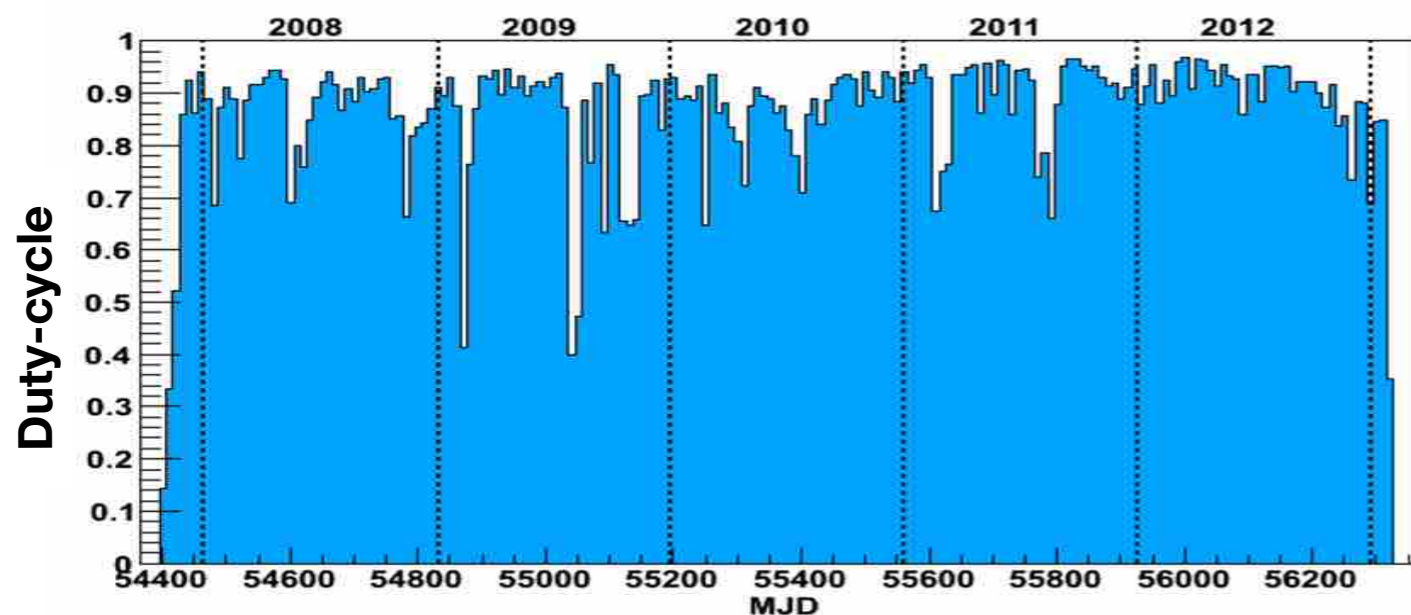
The RPC signal vs the calorimeter signal



→ Linearity up to  $\approx 2 \cdot 10^4$  particle/m<sup>2</sup>

# ARGO-YBJ milestones

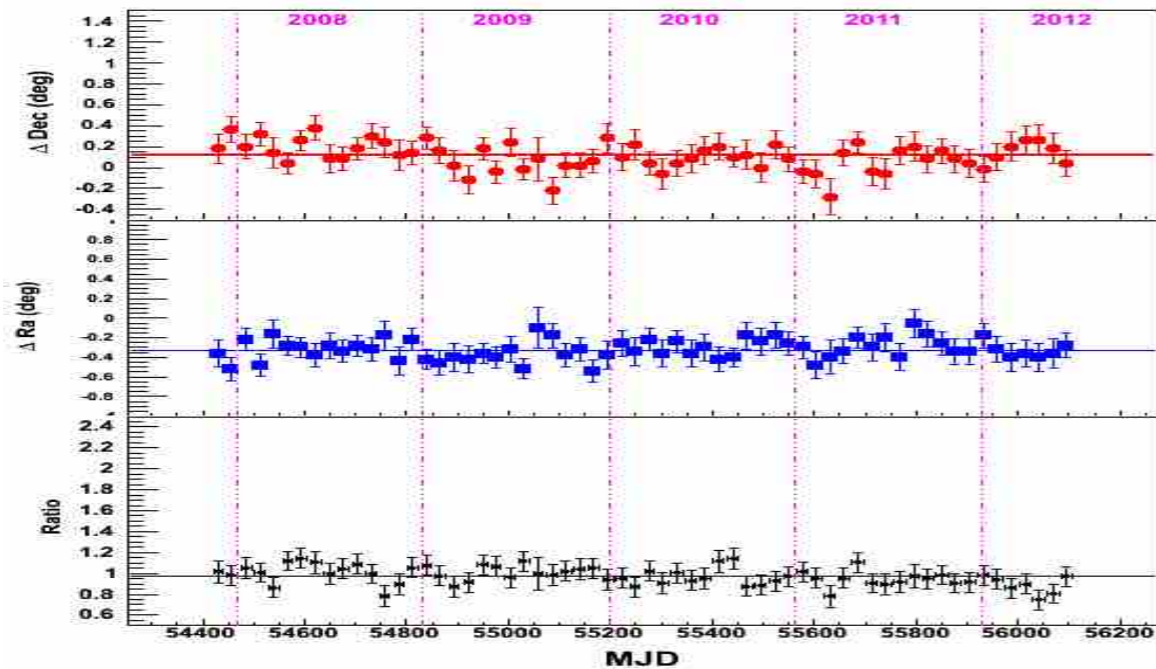
- In data taking since **July 2004** (with increasing portions of the detector)
  - Commissioning of the central carpet in **June 2006**
  - Stable data taking full apparatus since **November 2007**
  - End/Stop data taking: **February 2013**
- 
- **Average duty cycle ~87%**
  - **Trigger rate ~3.5 kHz @ 20 pad threshold**
  - **N. recorded events:  $\approx 5 \cdot 10^{11}$  from 100 GeV to 10 PeV**
  - **100 TB/year data**



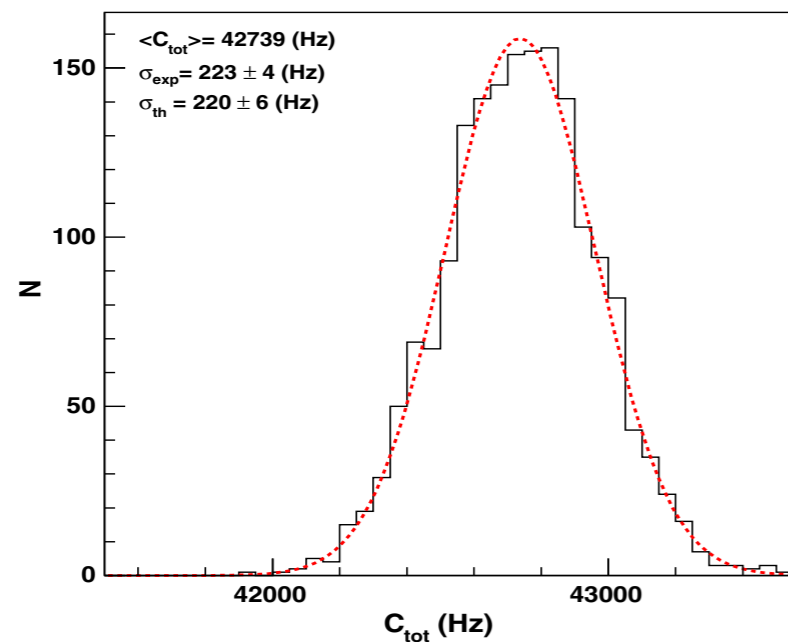
**Intrinsic Trigger Rate stability 0.5%**  
(after corrections for T/p effects)

# Detector stability at different energies

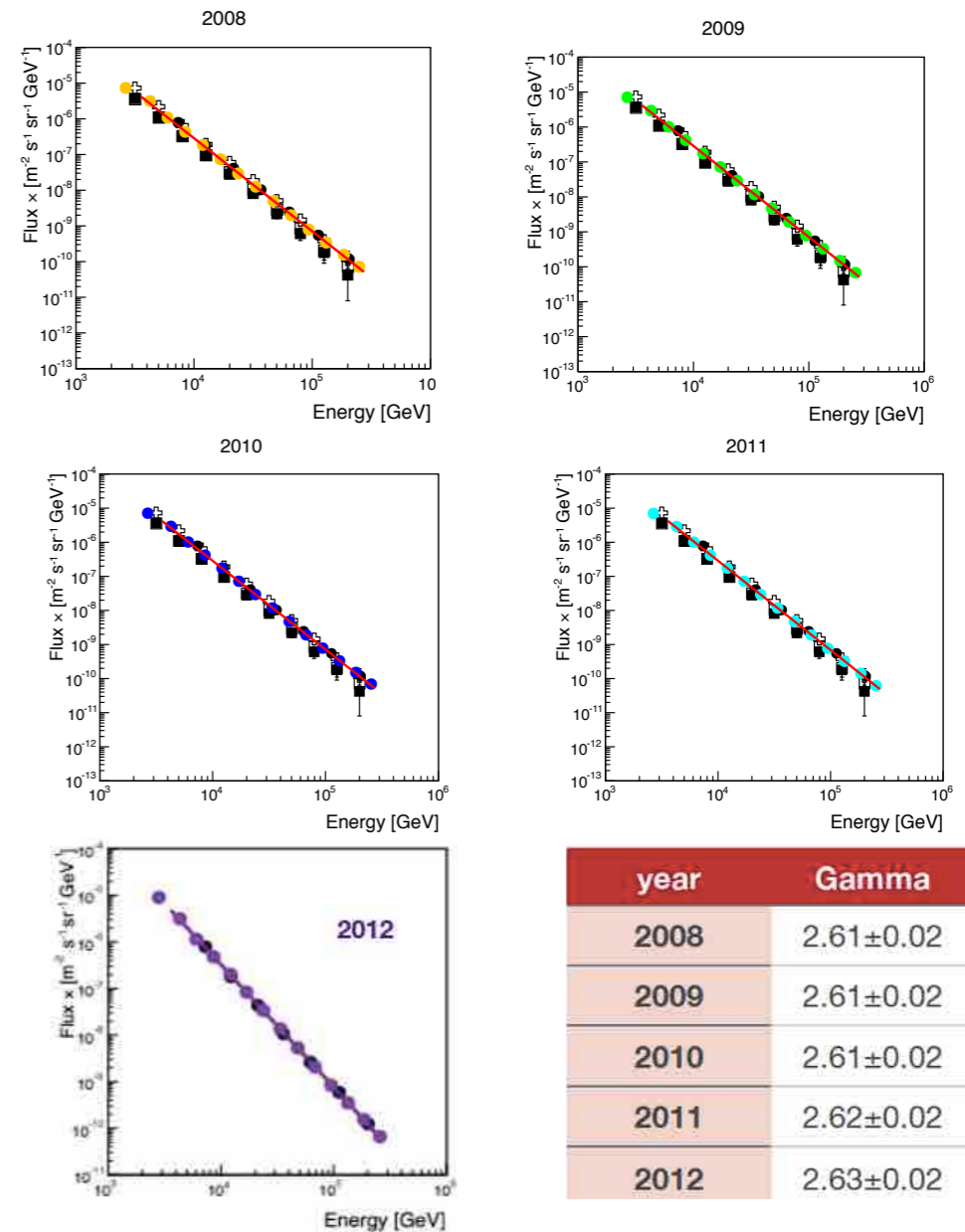
Stability of angular resolution and pointing accuracy (TeV)



Distribution of particles hitting a cluster (GeV)



Stability of CR flux measurement p+He spectrum (3 - 300 TeV)



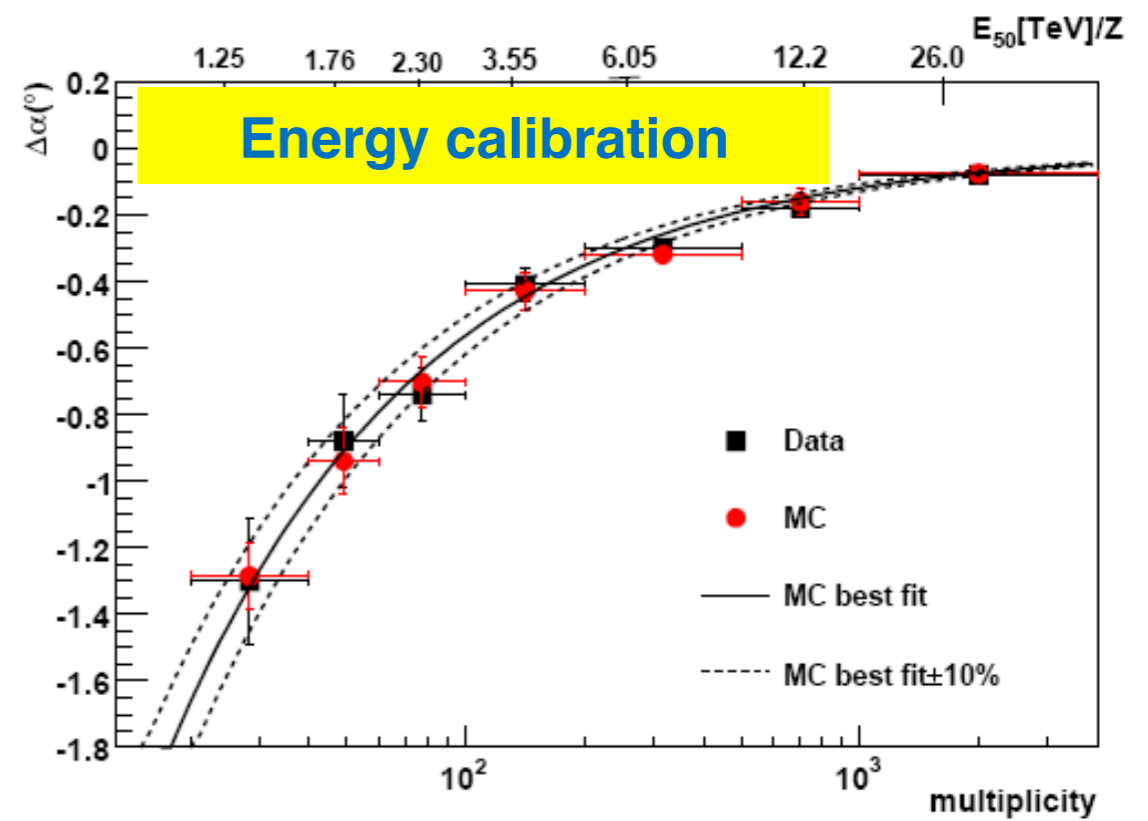
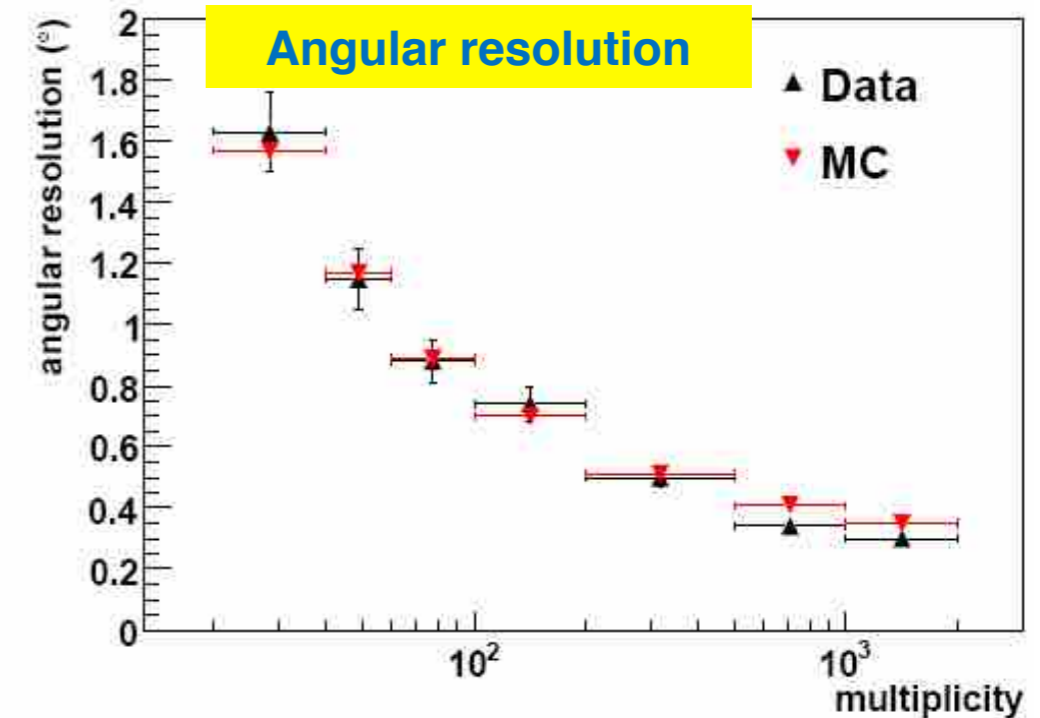
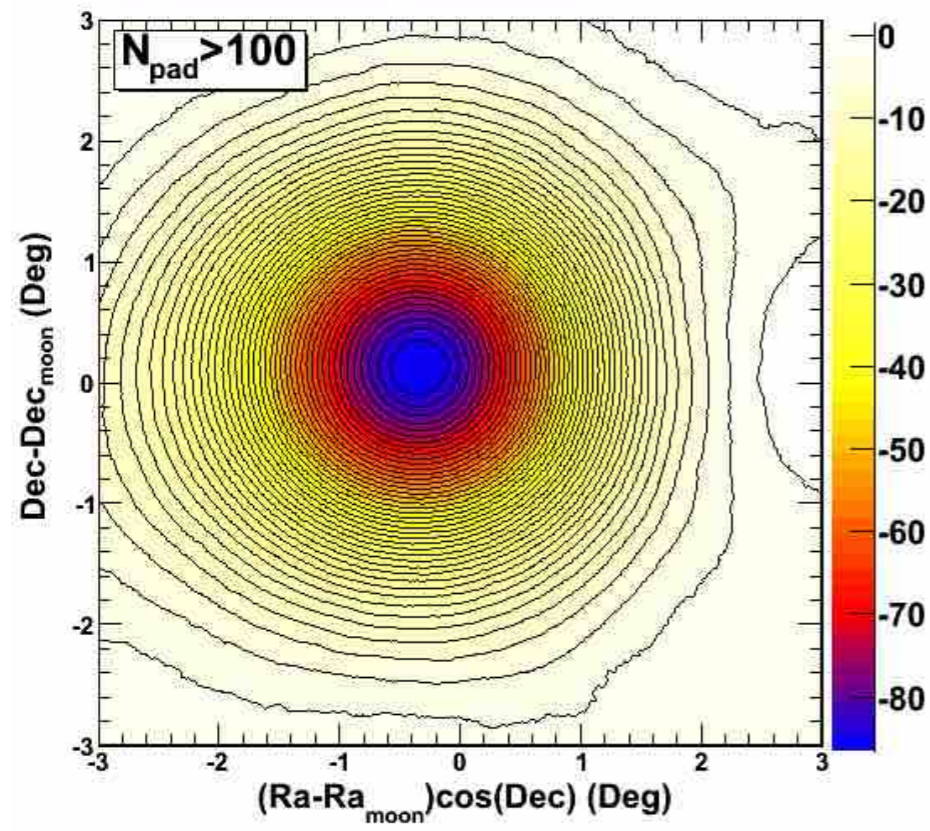
year	Gamma
2008	2.61±0.02
2009	2.61±0.02
2010	2.61±0.02
2011	2.62±0.02
2012	2.63±0.02

flux difference at 5% level

# The *Moon shadow* analysis

★ A tool to evaluate the detector performance

- Pointing accuracy
- Angular resolution
- Absolute energy calibration

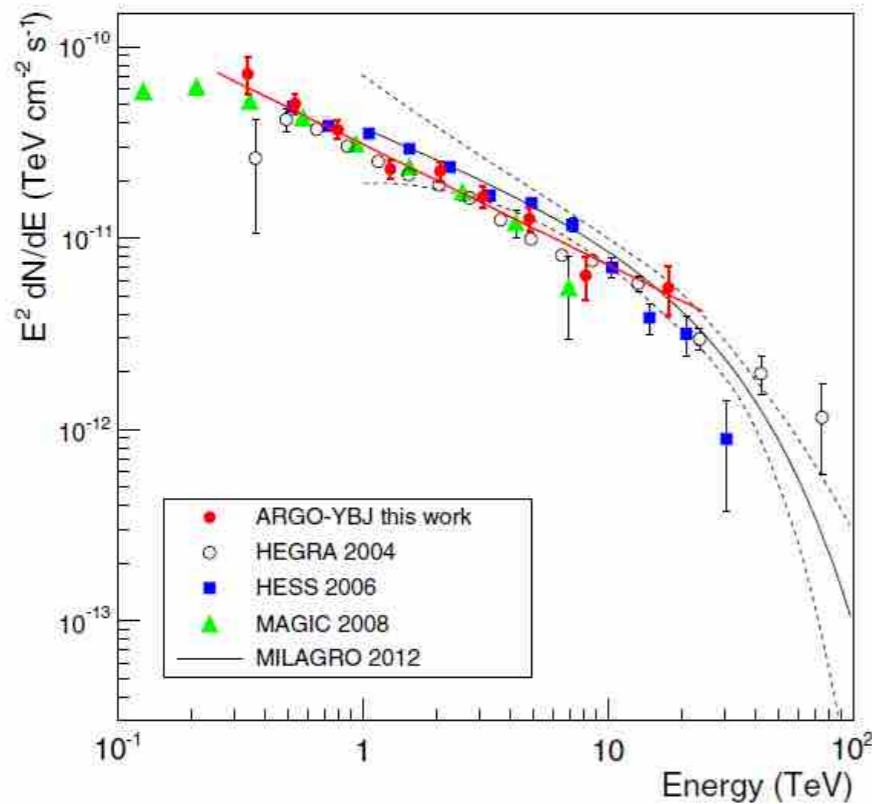


PRD 84 (2011) 022003  
PRD 85 (2012) 022002

The energy scale uncertainty is estimated to be smaller than 13% in the energy range 1 – 30 (TeV/Z).

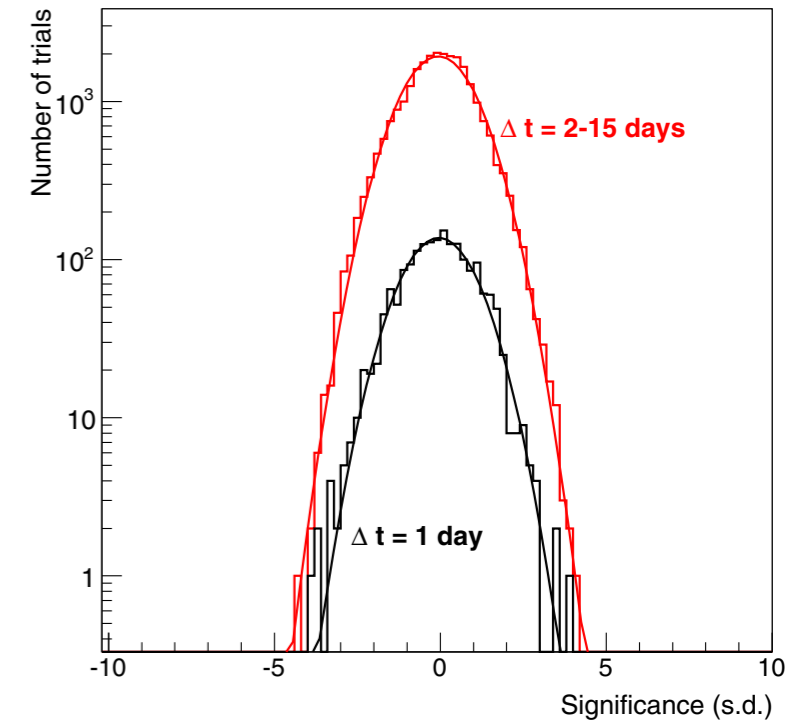
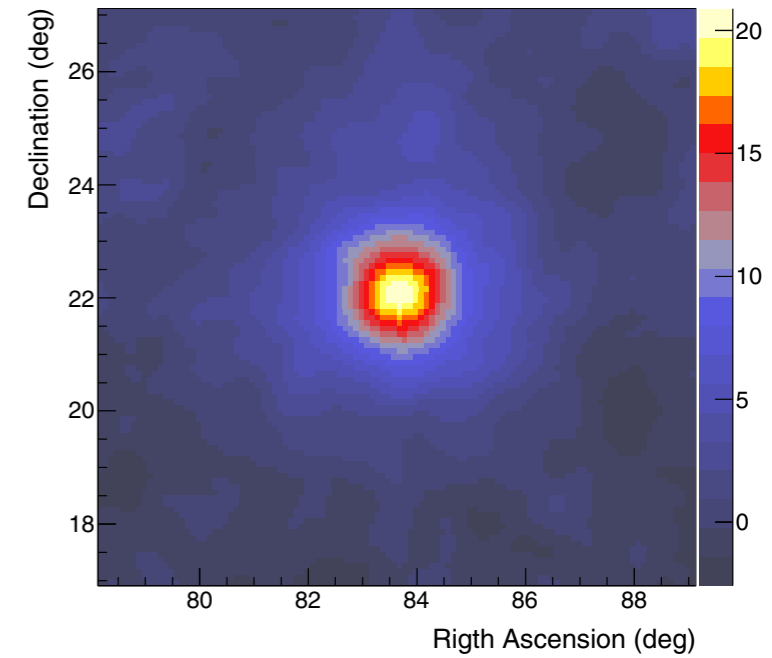
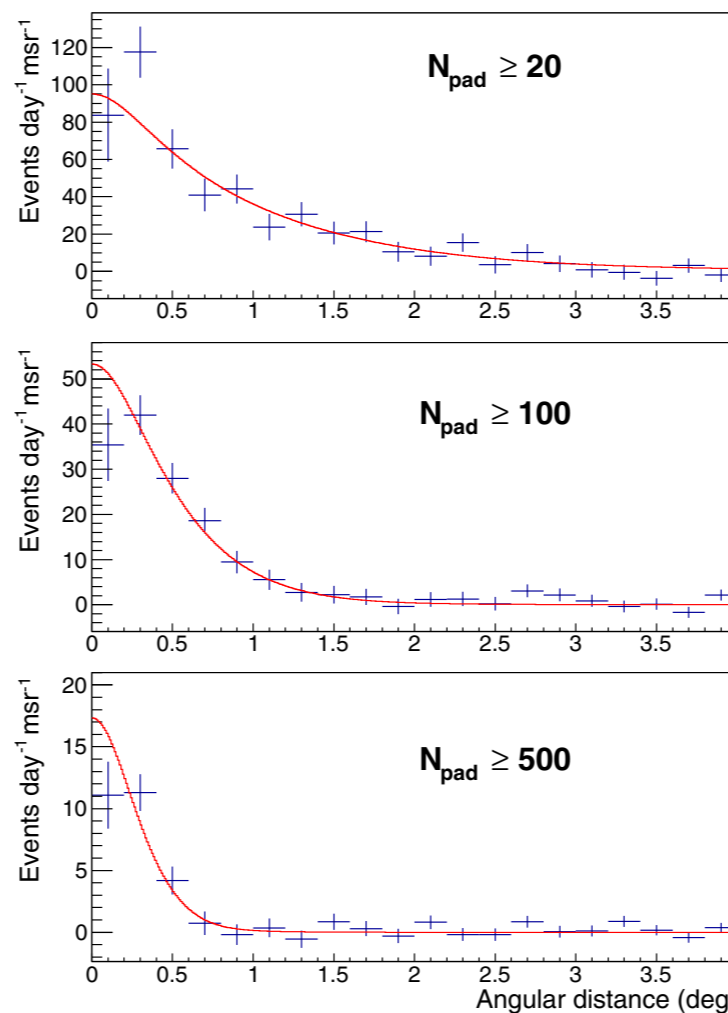
# The Crab Nebula

$$dN/dE = (5.2 \pm 0.2) \cdot 10^{-12} \cdot (E/2 \text{ TeV})^{-(2.63 \pm 0.05)} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$$



- Energy spectrum in 0.3–20 TeV in agreement with other experiments
- Light curve over five years compatible with a steady emission

PSF: data vs MC simulation



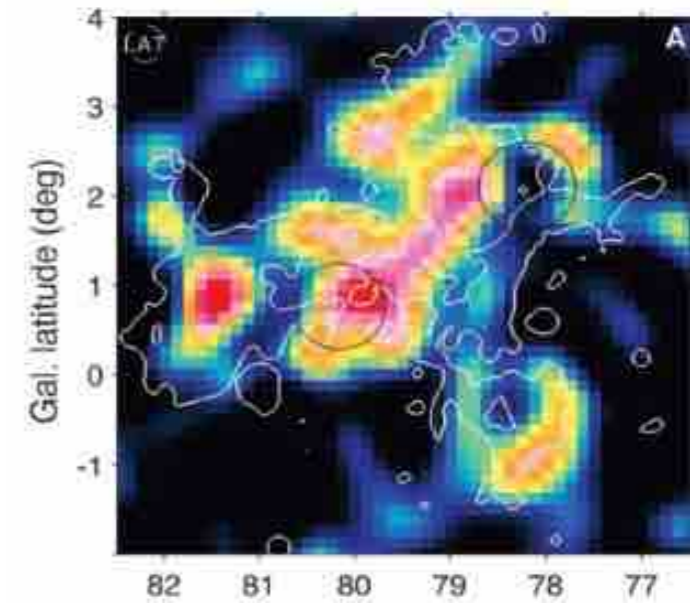
Search for flares: distribution of the excesses from the Crab around the average value, in units of s.d., for different flare durations  $\Delta t$ .

ApJ 798 (2015) 119

# ARGO J2031+4157 as the Cygnus Cocoon

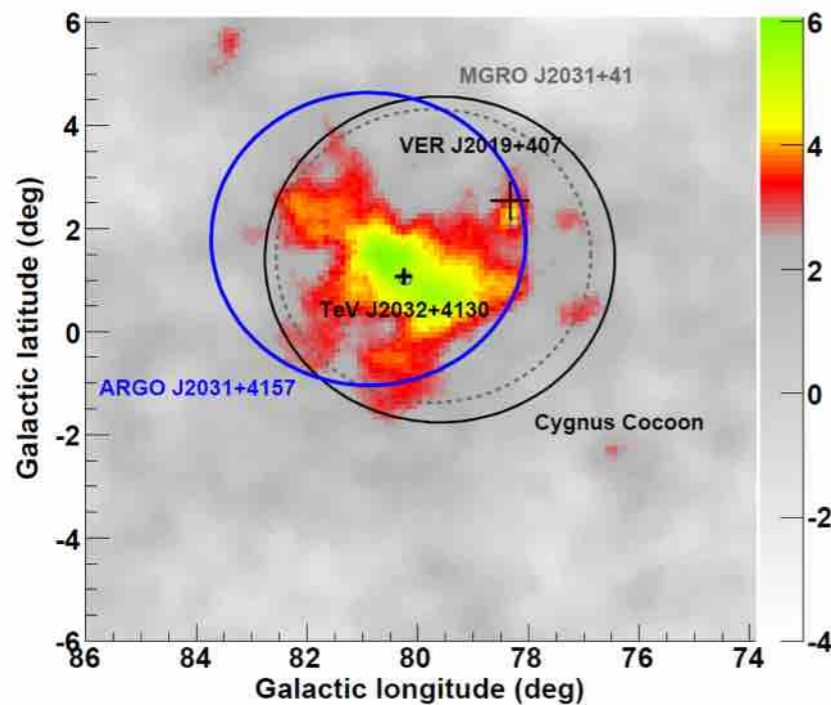
The emission of ARGO J2031+4157 can be identified as the counterpart of Cygnus Cocoon at TeV energies.

The Fermi/LAT view  
in the 10-100 GeV band



Science 334 (2011) 1103

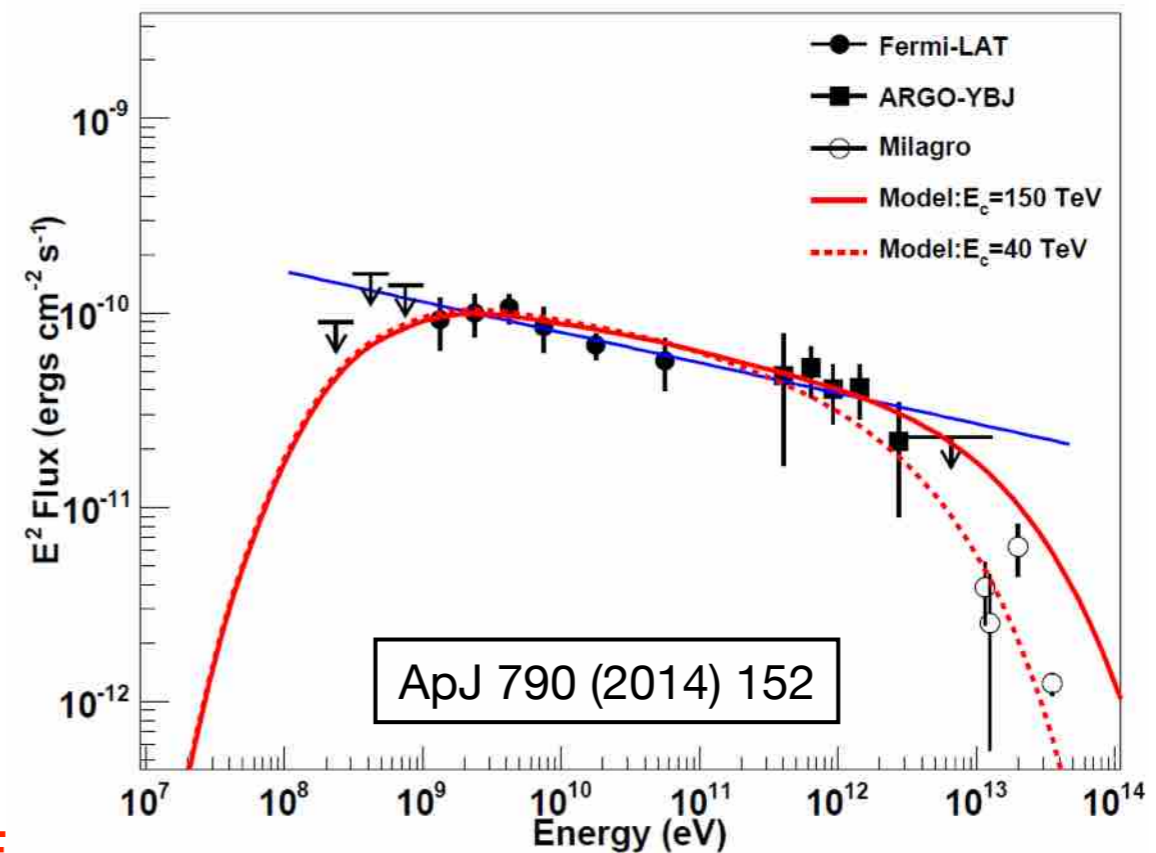
The ARGO-YBJ view at TeV energies  
after reanalysis with the full data



$S_{\max} = 6.1$  s.d.  
 $\sigma_{\text{ext}} = 1.8^{\circ} \pm 0.5^{\circ}$

A cocoon of freshly accelerated cosmic rays

A pure hadronic model was assumed  
with a power law and a cutoff energy  $E_c$



Spectrum of ARGO J2031+4157:  $dN/dE \propto E^{-2.62 \pm 0.27}$

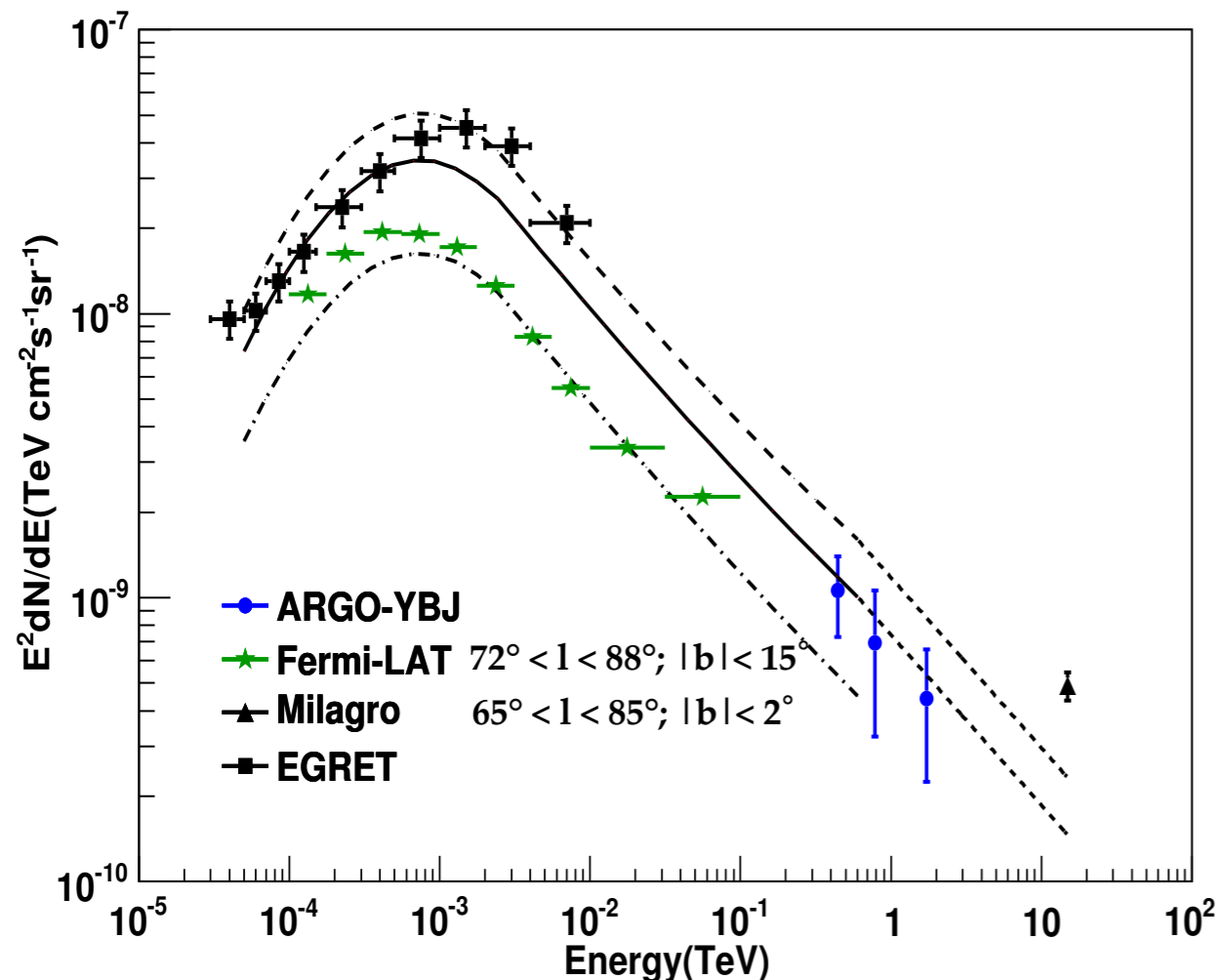
Combined LAT&ARGO spectrum:  $dN/dE \propto E^{-2.16 \pm 0.04}$

# Diffuse $\gamma$ -rays from the Galactic Plane

Diffuse  $\gamma$ -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  $\pi^0$  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.

Cygnus region:  $65^\circ < l < 85^\circ$ ;  $|b| < 5^\circ$



This result is obtained after masking all the sources detected in the region (in particular the TeV counterpart of the Cygnus Cocoon) and removing the residual contamination.

The TeV diffuse flux in the Cygnus region does not show a strong excess like that reported by Milagro at 15 TeV.

The difference may be due to the Cygnus Cocoon, not yet discovered at the time of the Milagro measurement.

The different lines indicate the energy spectra expected from the Fermi/LAT template (with spectral index -2.6) in the different sky regions investigated by the detectors.

ApJ 806 (2015) 20

# Diffuse $\gamma$ Emission

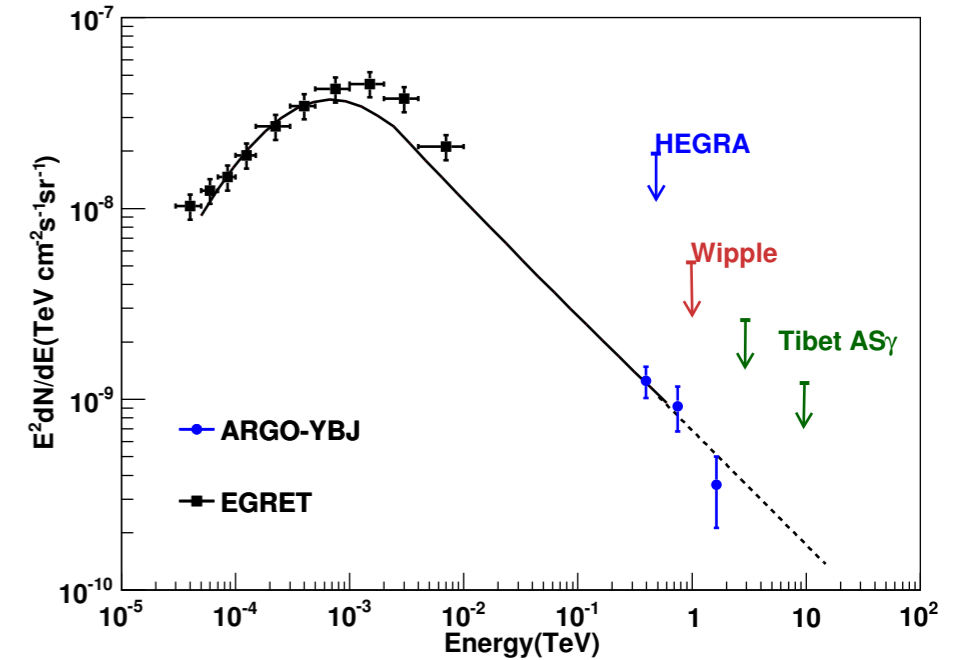
Diffuse gamma-ray emission from the Galactic plane for  $|b| < 5^\circ$

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

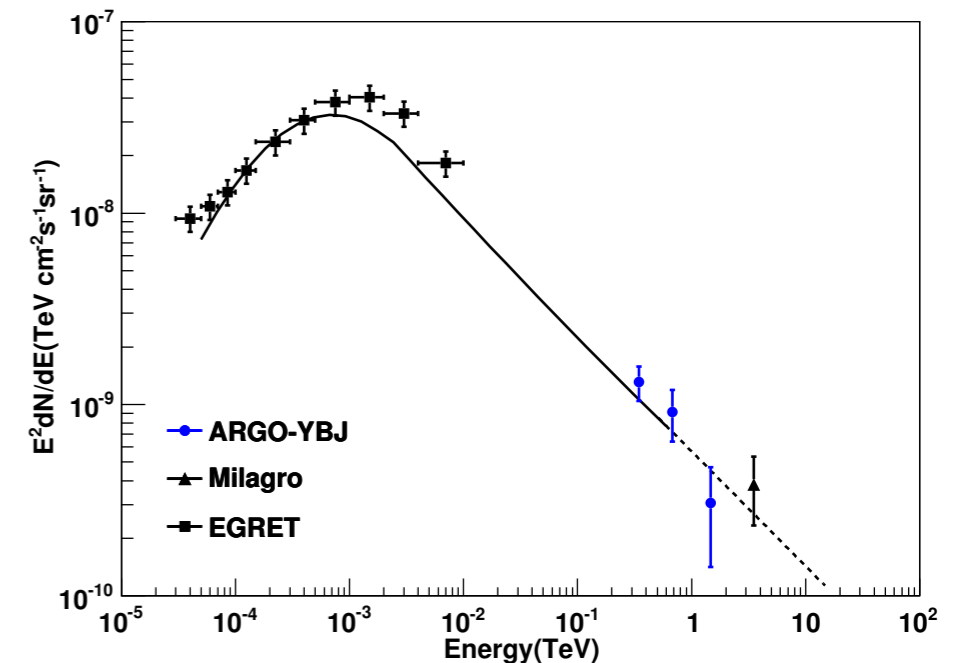
<sup>a</sup>In units of  $10^{-9} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ .

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.

$25^\circ < l < 100^\circ; |b| < 5^\circ$



$40^\circ < l < 100^\circ; |b| < 5^\circ$



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.

ApJ 806 (2015) 20

# Study of the flaring sky: Mrk421

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During 4.5 years (August 2008 – Feb 2013), Mrk 421 was continuously monitored by ARGO-YBJ and Fermi-LAT, covering the energy range from 0.1 GeV to 10 TeV without any gap.

Using the data of many different detectors, the MWL SEDs (from radio to TeV gamma rays) have been studied during 7 flares, one outburst phase and 2 quiescent periods

- **ARGO-YBJ ( $E > 300$  GeV)**
- **FERMI-LAT ( $E > 0.3$  GeV)**
- **SWIFT-BAT ( $E = 15-50$  keV)**
- **RXTE-AMS ( $E = 2-12$  keV)**
- **MAXI-GSC ( $E = 2-20$  keV)**
- **SWIFT-XRT ( $E = 0.3-10$  keV)**
- **SWIFT-UVOT (UVW1)**
- **OVRO (radio 15 GHz)**

By analysing the public data, we have evaluated:

- Light curves
- SEDs

for 4.5 years

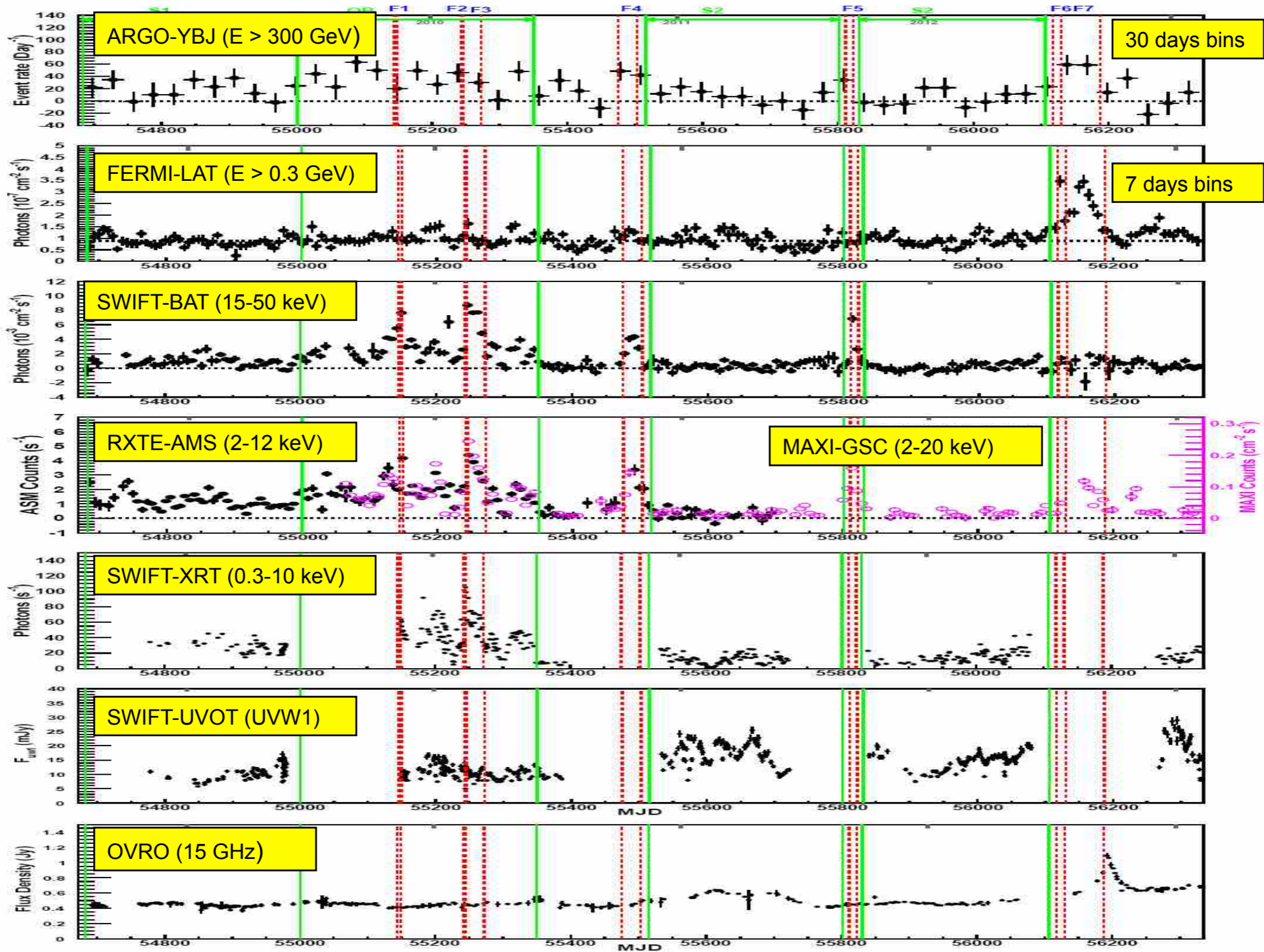
ApJ Supplement, 222 (2016) 6

Cherenkov data exist for limited periods

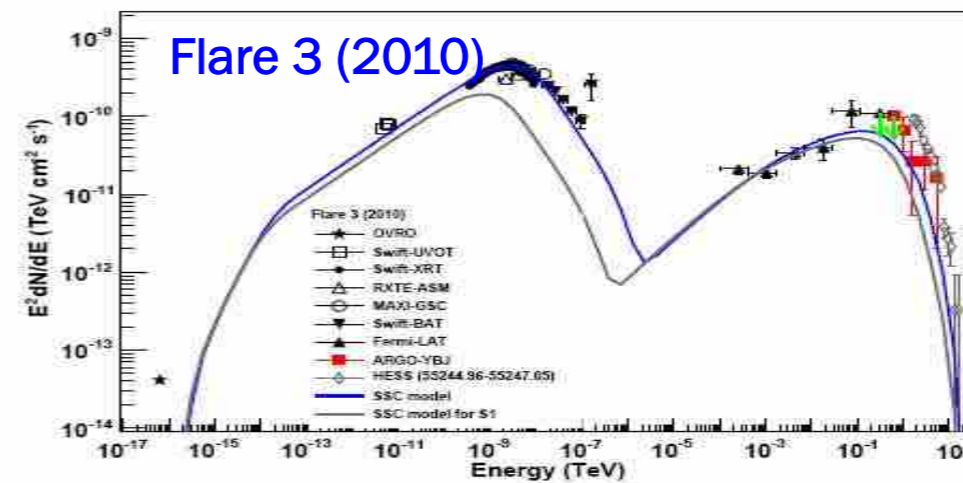
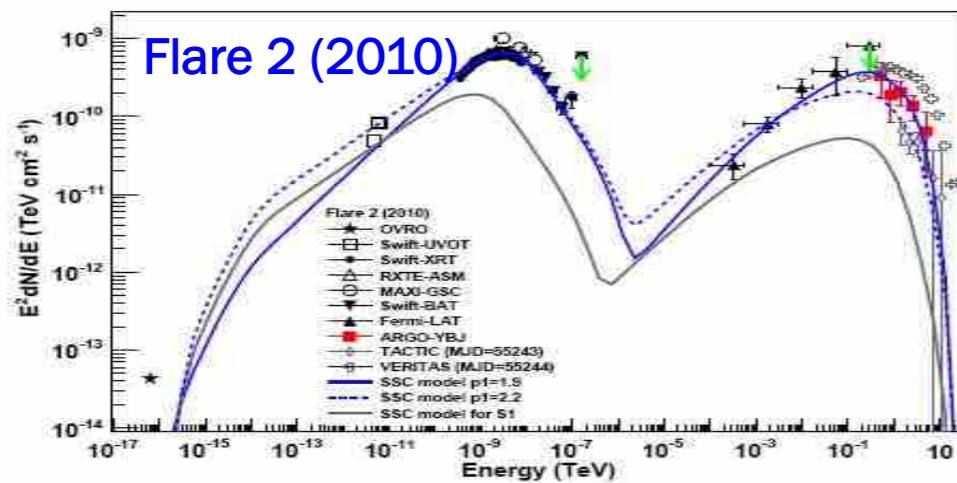
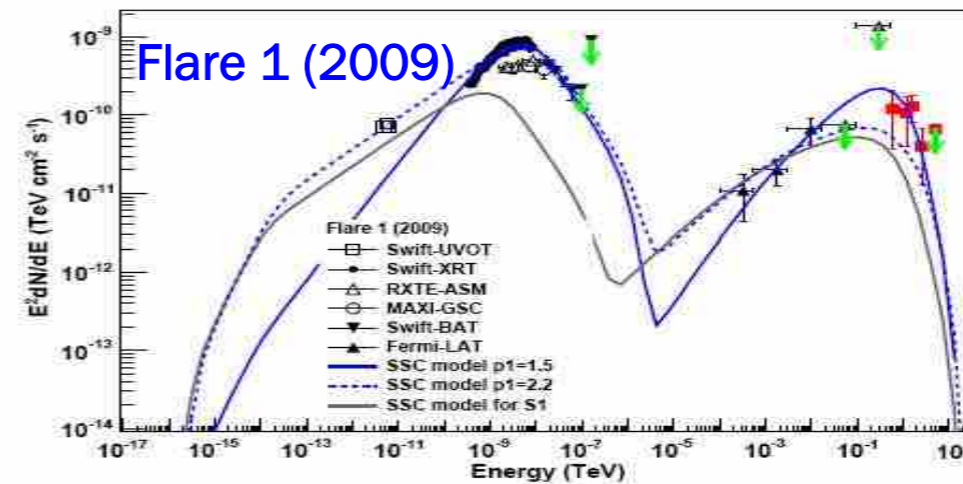
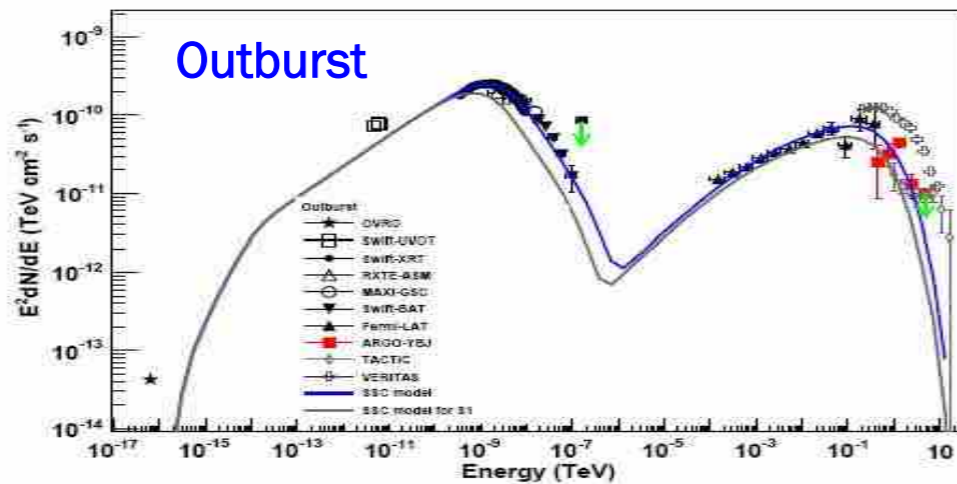
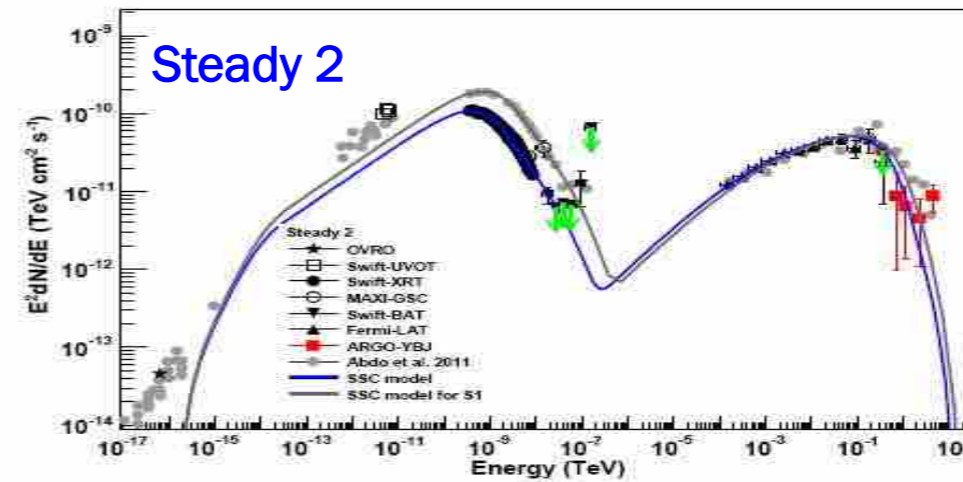
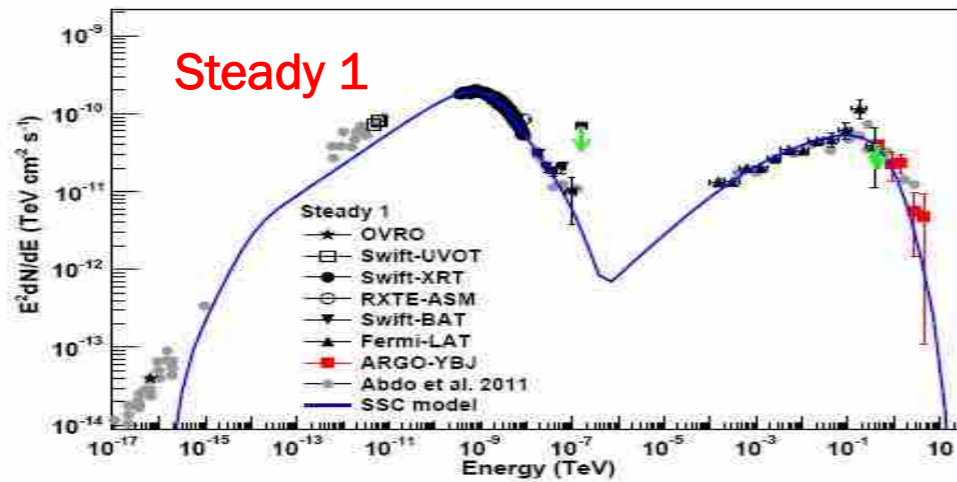
All these data provide a **unique chance** to investigate the multi-wavelength SED evolution during different states of activity of Mrk421.

The multi wavelength emission can be reasonably described by the **one-zone SSC model**, however different models cannot be excluded by these data.

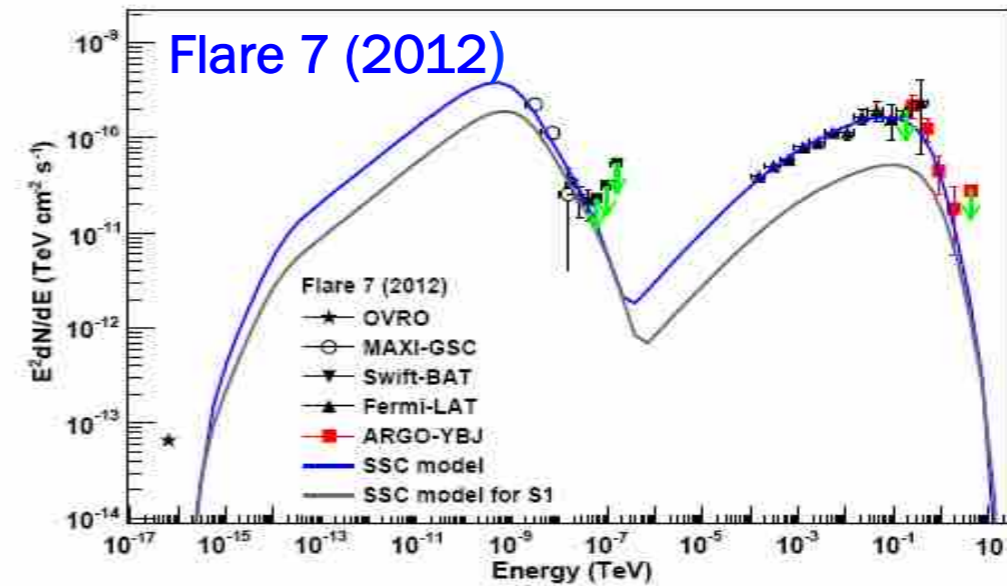
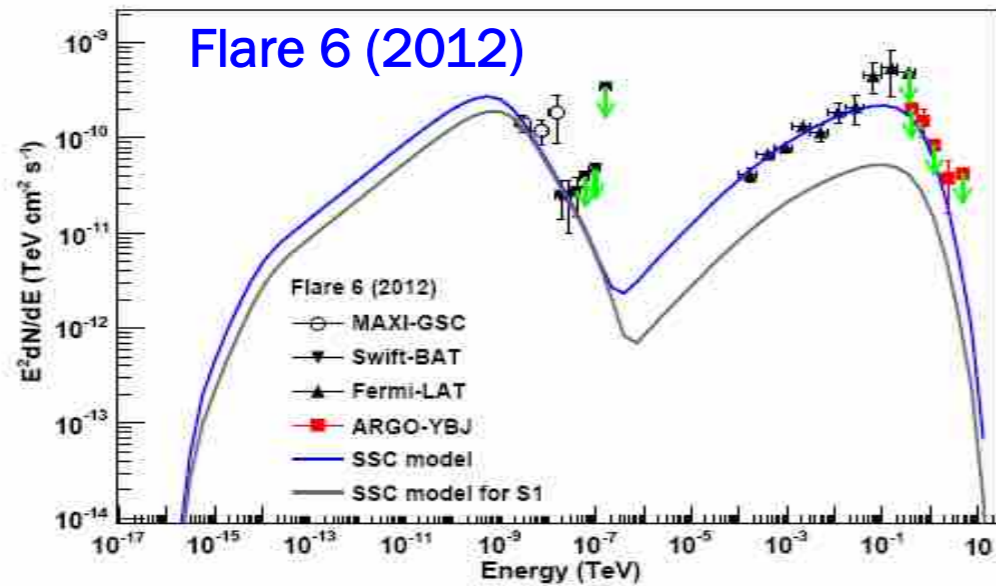
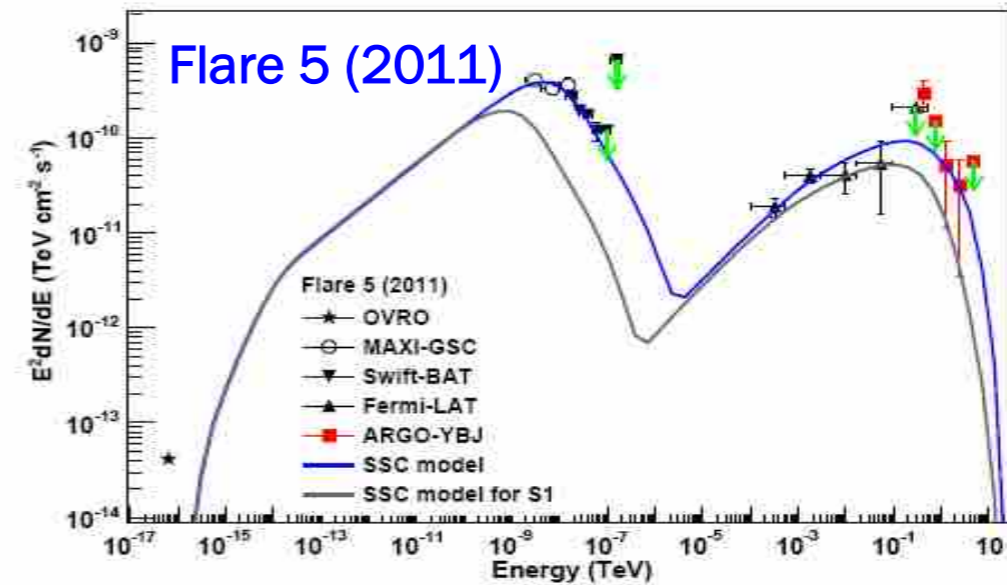
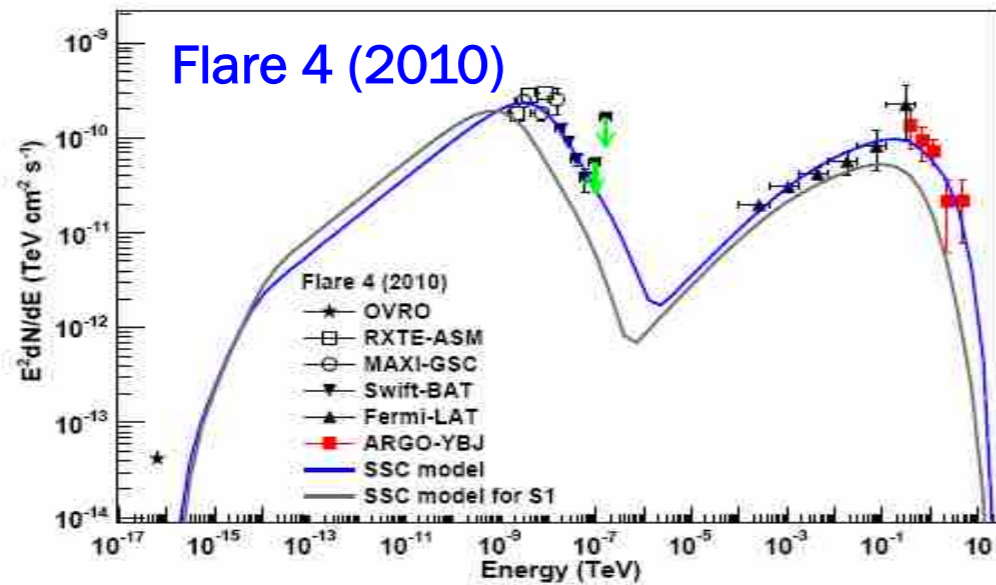
# Mrk421 emission



# One-zone Synchrotron Self-Compton model



# One-zone Synchrotron Self-Compton model



The one-zone SSC model reasonably describes all the measured SEDs

# Take Home Message - 1

---

- Maps of the gamma-ray sky not unbiased.
- PeVatrons '*smoking gun*' signature still missing.
- Measurement of diffuse  $\gamma$ -ray emission at 100 TeV crucial.
- Monitoring of flaring emissions (GRBs, AGNs, etc) very important.

## Homework

- ✓ All-sky survey instrument for an unbiased map of the sky at % Crab flux level
- ✓ Observation of gamma-ray sky in the 100 - 1000 TeV range !
- ✓ Wide-angle instrument for **very extended sources** and **diffuse emission**.

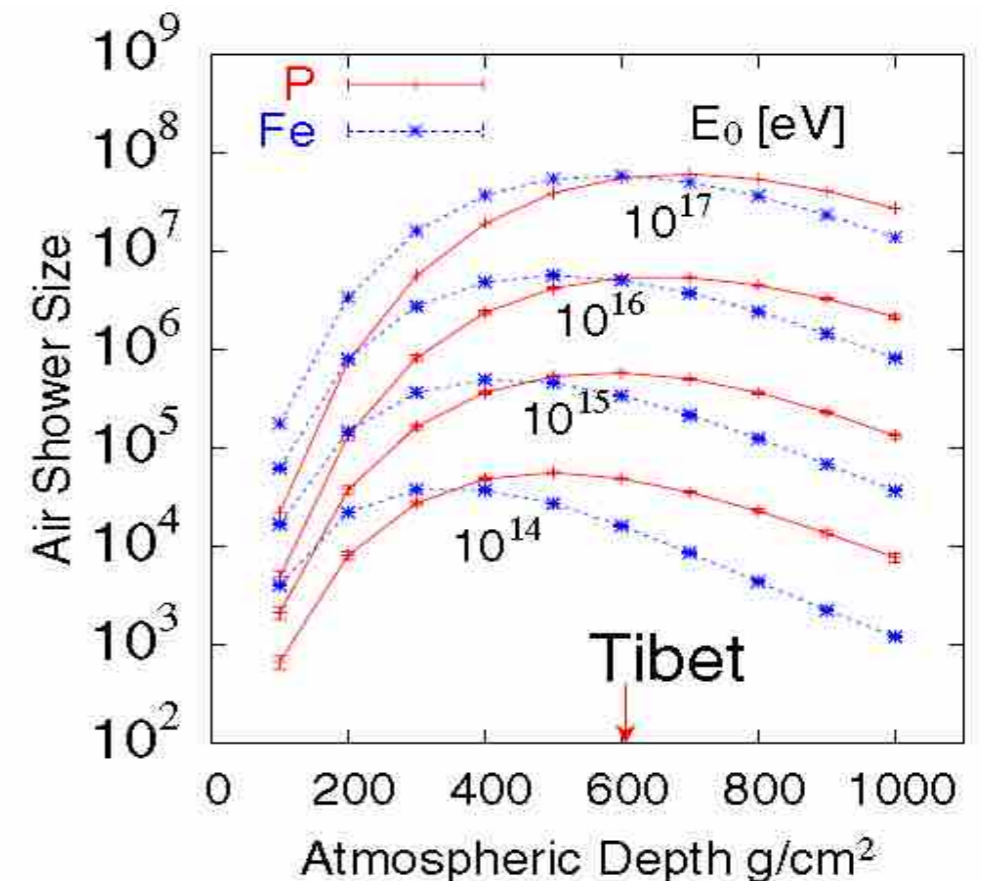
# Measurement of CR energy spectrum with ARGO-YBJ

- Measurement of the CR energy spectrum (all-particle and light component) in the energy range **TeV - 20 PeV** by ARGO-YBJ with *different 'eyes'*
  - ▶ *'Digital readout'* (based on *strip multiplicity*) below 300 TeV
  - ▶ *'Analog readout'* (based on the *shower core density*) up to 20 PeV
  - ▶ *'Hybrid'* measurement with a Wide Field of view Cherenkov Telescope 200 TeV - few PeV

- Working at high altitude (4300 m asl):

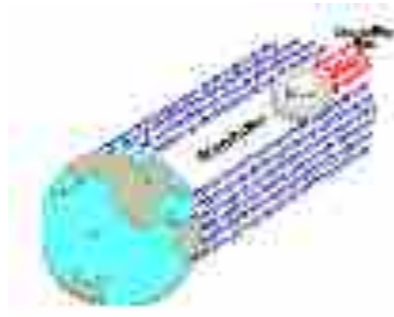
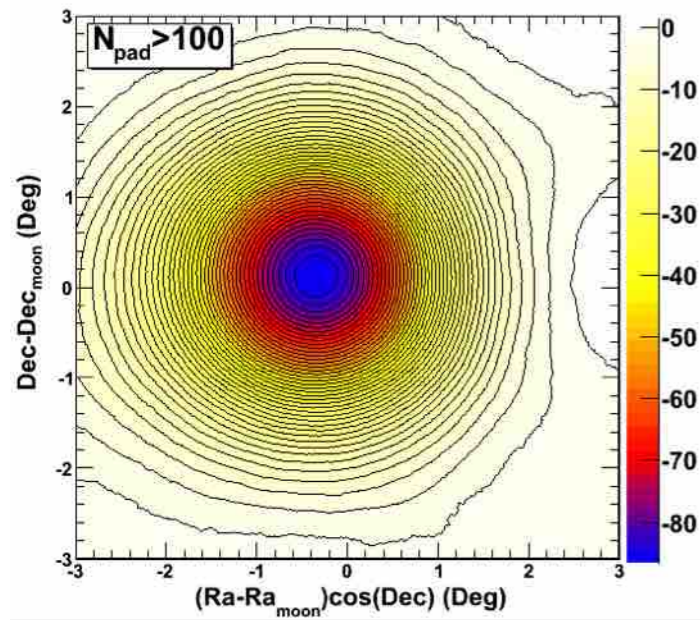
1. **p and Fe produce showers with similar size**
2. **Small fluctuations:** shower maximum
3. **Low energy threshold:** absolute energy scale

calibration with the Moon Shadow technique and overposition with direct measurements



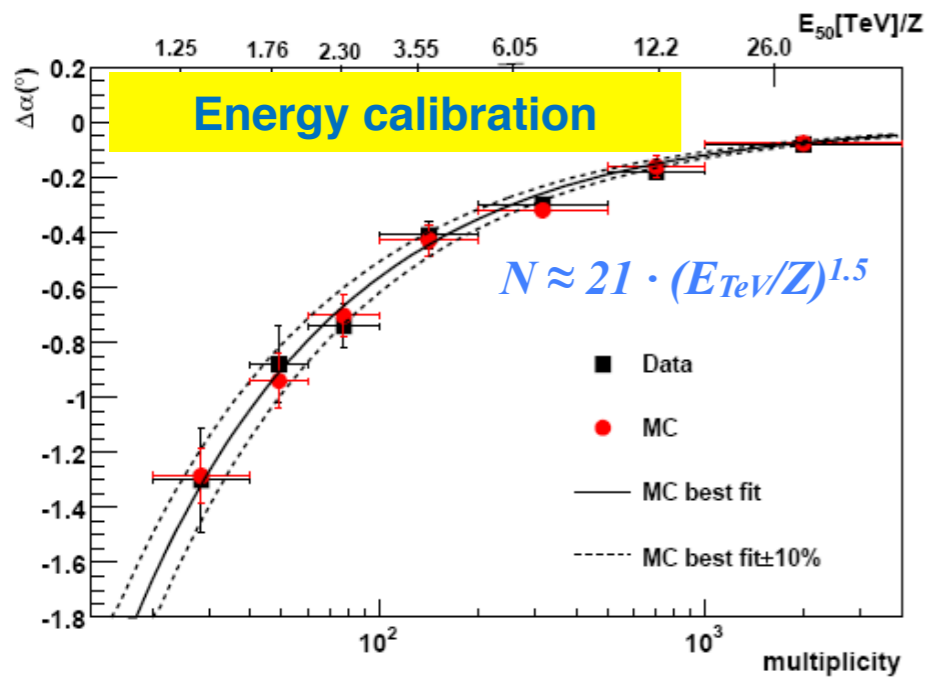
# Calibration of the energy scale

ARGO-YBJ: Moon shadow tool

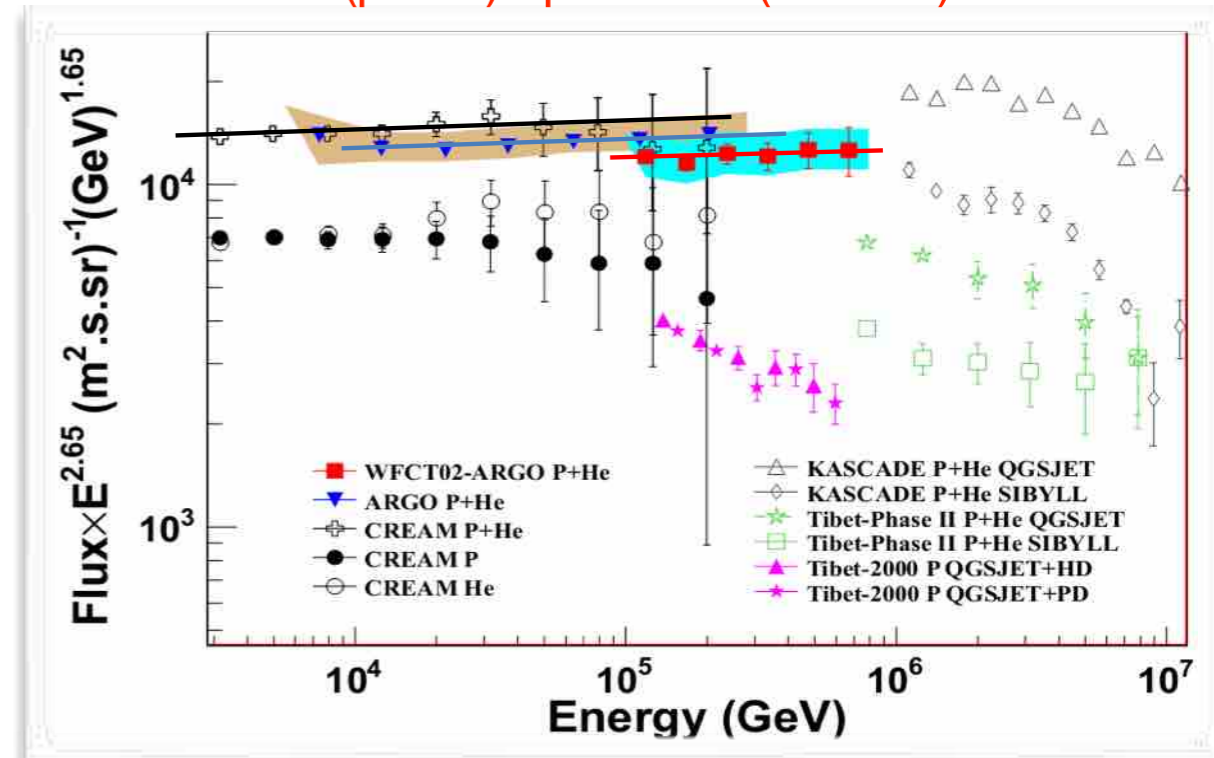


PRD 84 (2011) 022003

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

Single power-law:  $2.62 \pm 0.01$

Flux at 400 TeV:

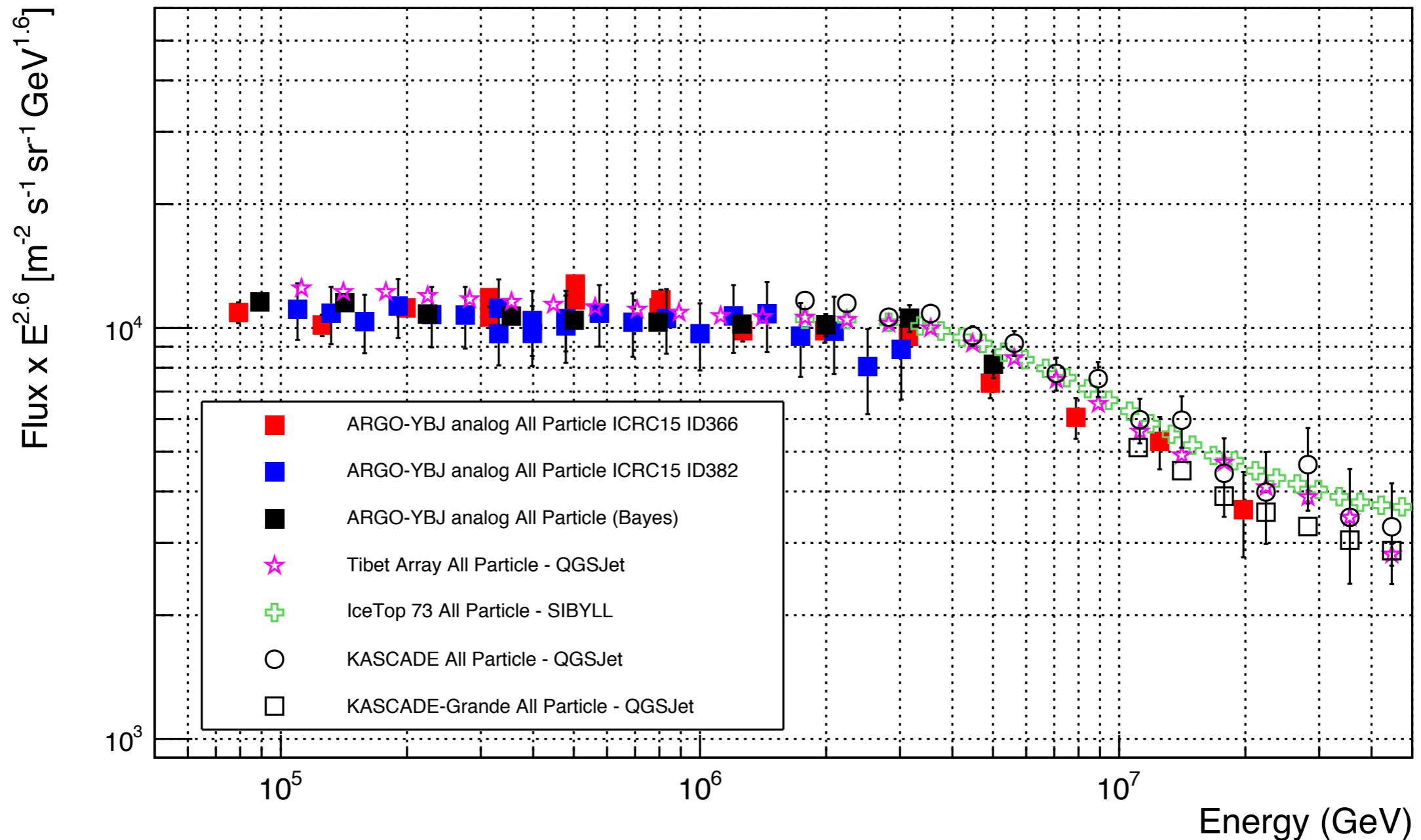
$1.95 \times 10^{-11} \pm 9\% (\text{GeV}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1})$

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

# All-particle energy spectrum by ARGO-YBJ

ARGO-YBJ reports evidence for the **all-particle knee** at the expected energy

## All-particle energy spectrum by ARGO-YBJ

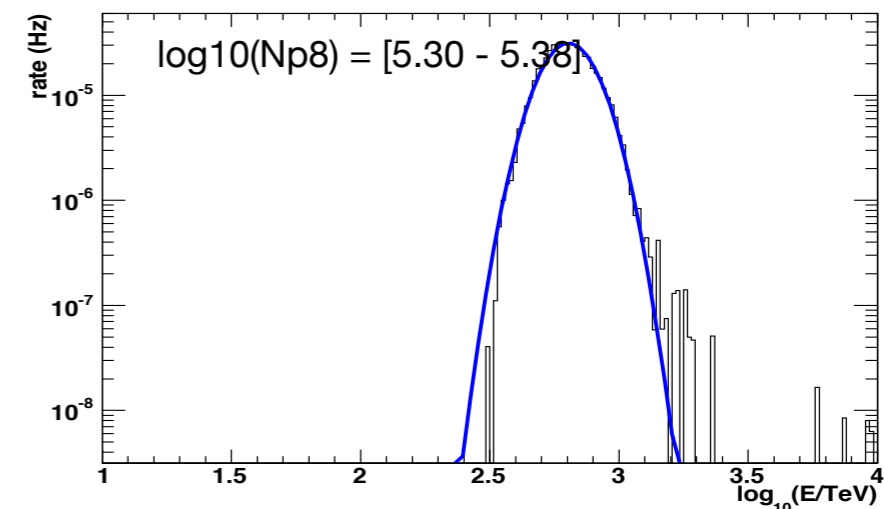
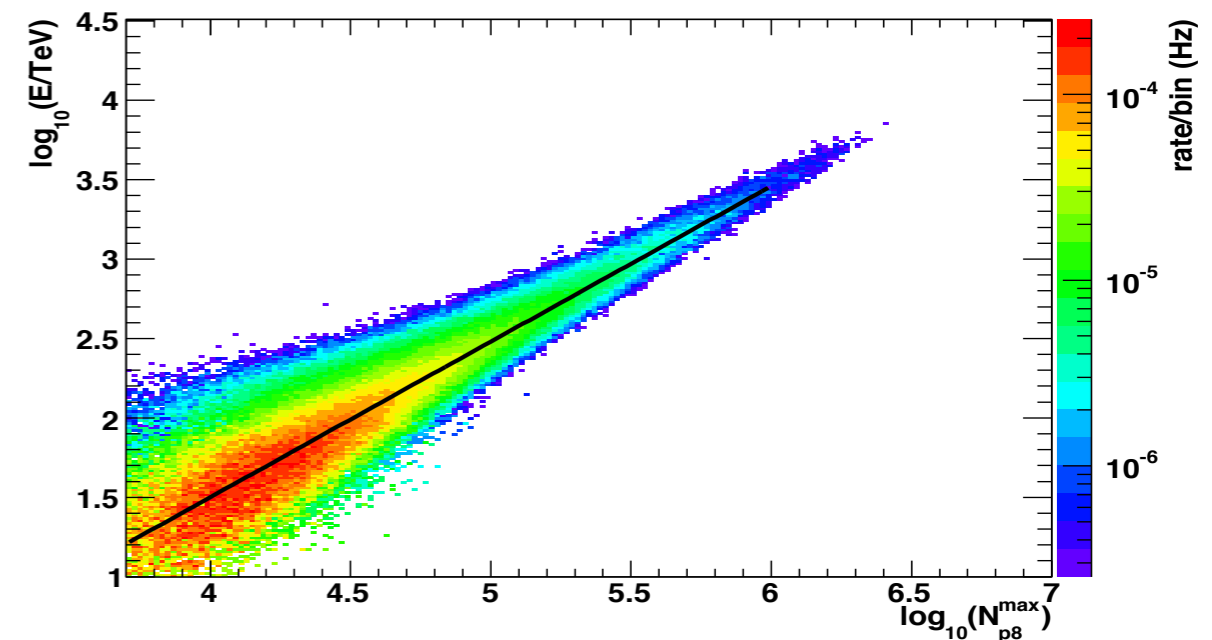
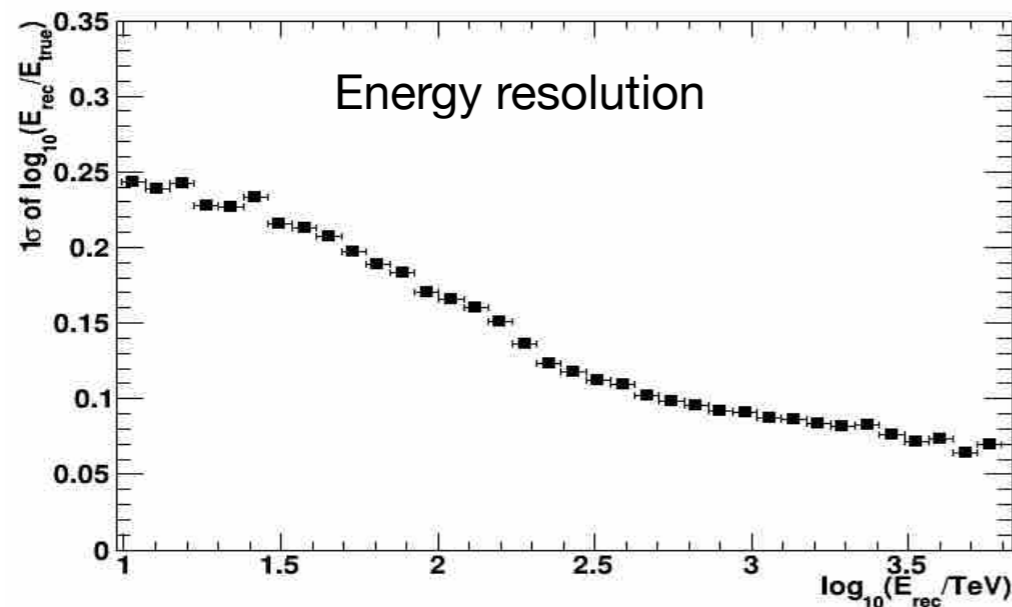


# Selection of light (p+He) component

- Selection of (p+He)-induced showers: **NOT** by means of an unfolding procedure after the measurement of electronic and muonic sizes, but **on an event-by-event basis exploiting showers topology**, i.e. the lateral distribution of charged secondary particles.
- Energy reconstruction is based on the  $N_p^{8m}$  parameter: the number of particle within 8 m from the shower core position.

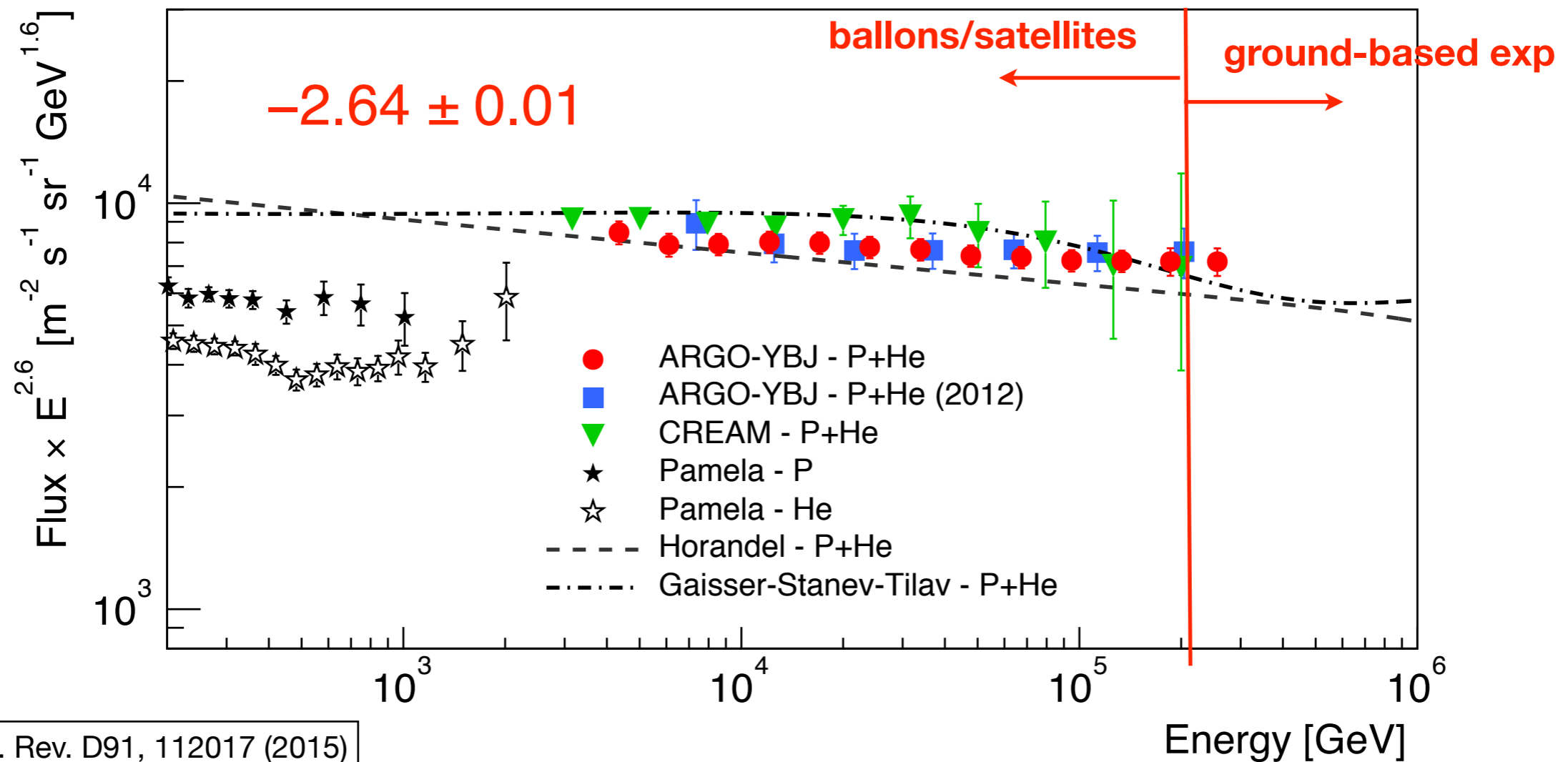
This truncated size is

- well correlated with primary energy
- not biased by finite detector effects
- weakly affected by shower fluctuations



# The light-component spectrum (2.5 - 300 TeV)

Measurement of the **light-component (p+He)** CR spectrum in the energy region **(2.5 - 300) TeV** via a Bayesian unfolding procedure



Phys. Rev. D91, 112017 (2015)

*Direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.*

# Hadronic Interaction Models

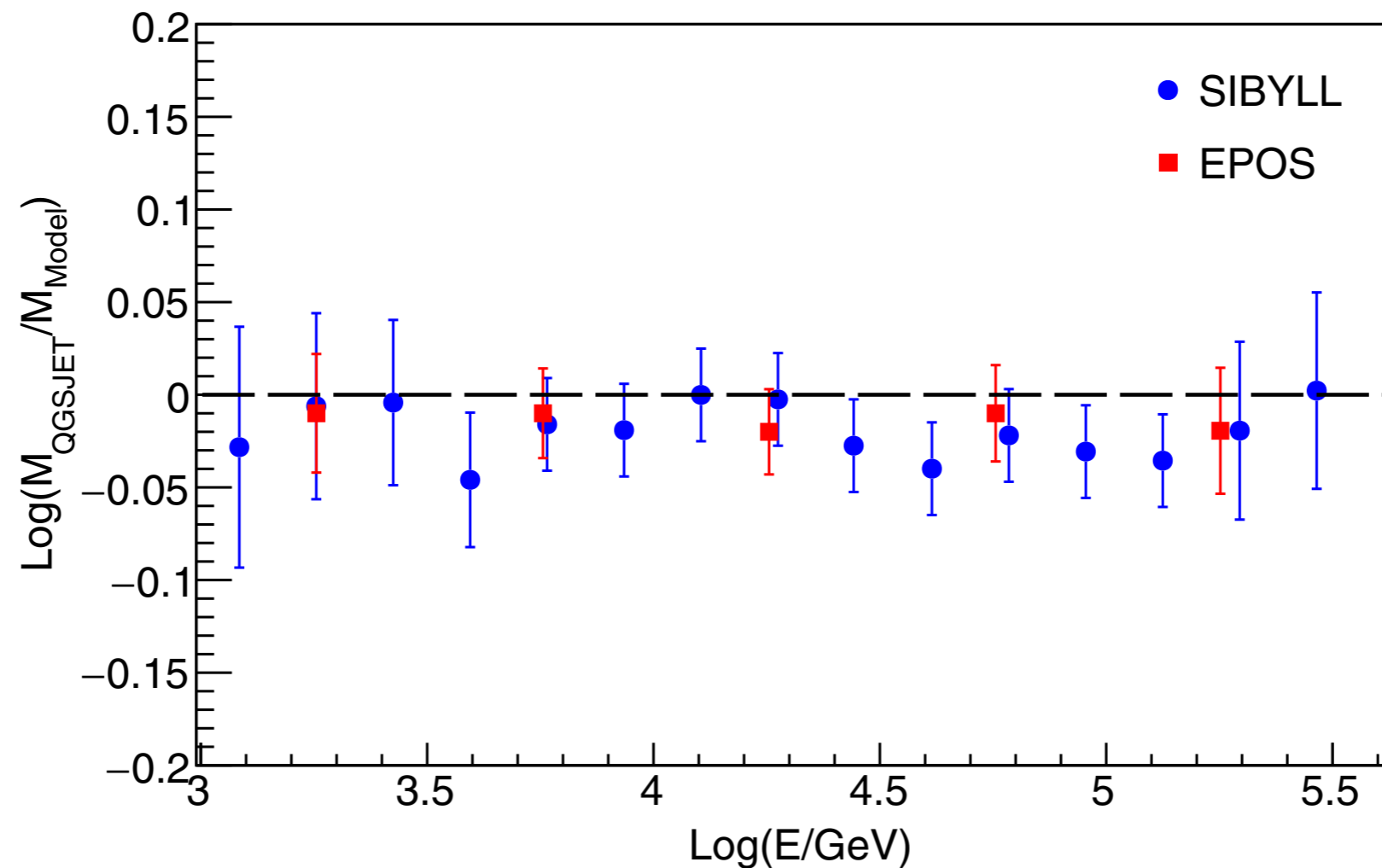
Corsika v 6980 + Fluka + EGS4

- QGSJET II.03
- SIBYLL 2.1
- EPOS 1.99

Phys. Rev. D91, 112017 (2015)

Not muons but lateral distribution → topology

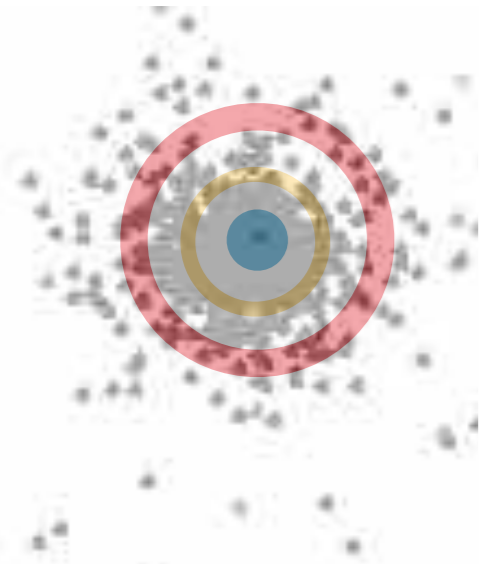
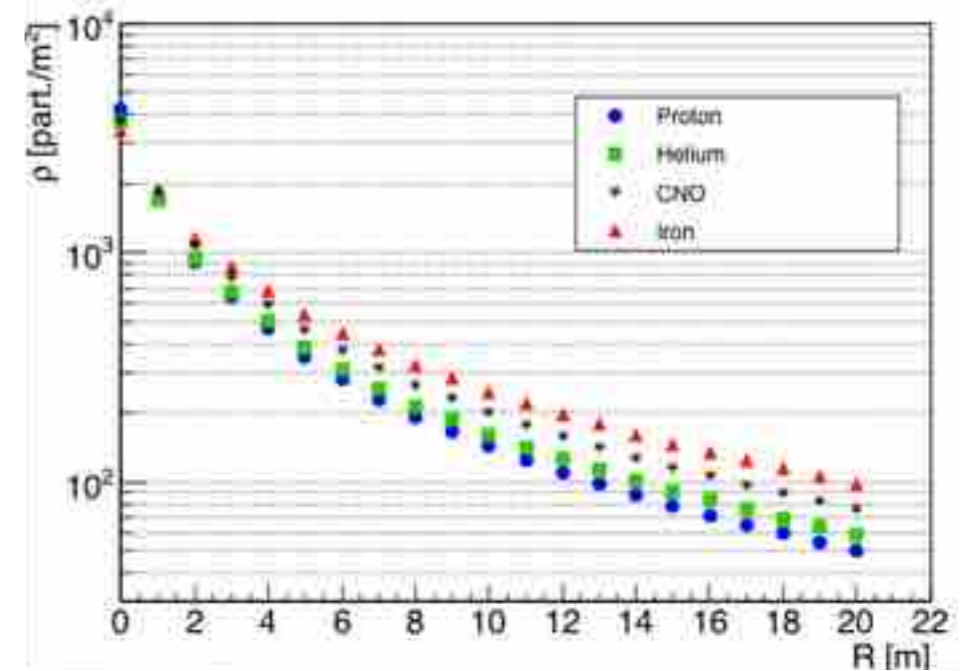
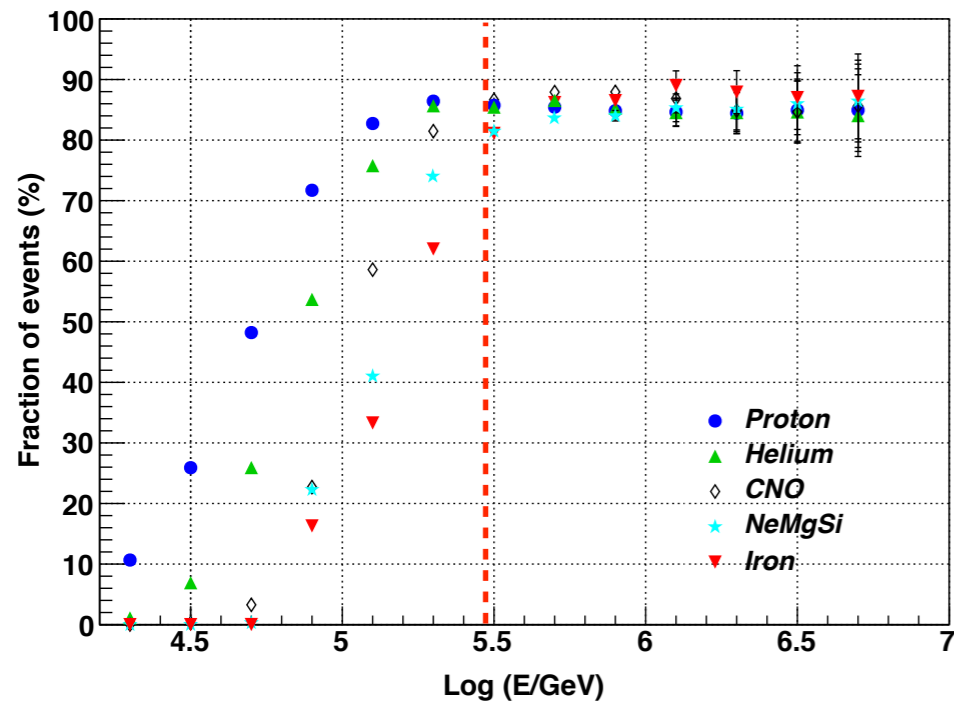
Ratio between multiplicity distributions obtained with different models



# The light-component spectrum (0.3 - 5 PeV)

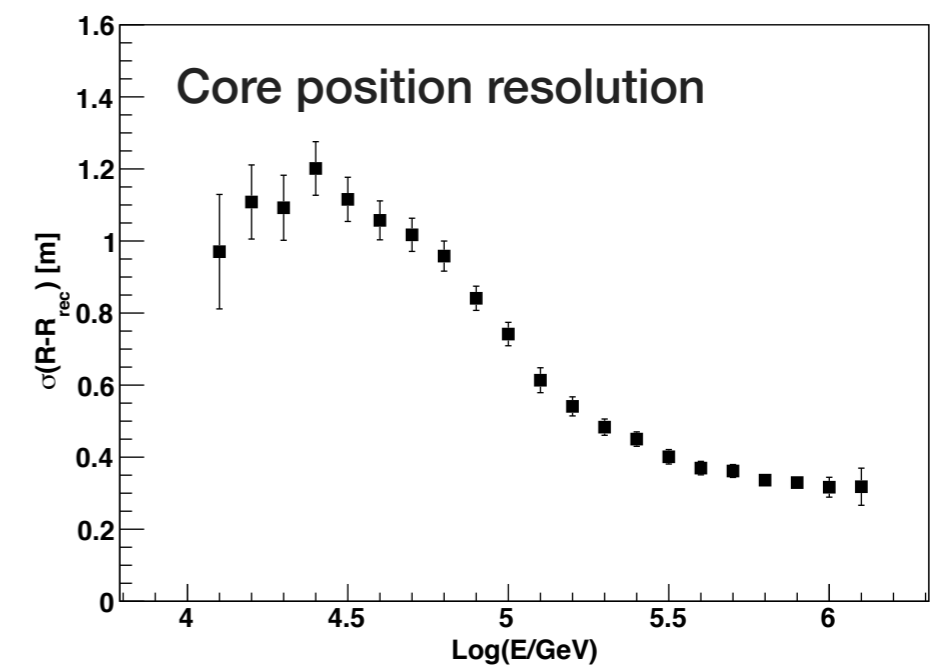
The high segmentation of the read-out allows to access the LDF down to the shower core.

Discrimination Light/Heavy based on the **measurement of the LDF at different distances from the core**

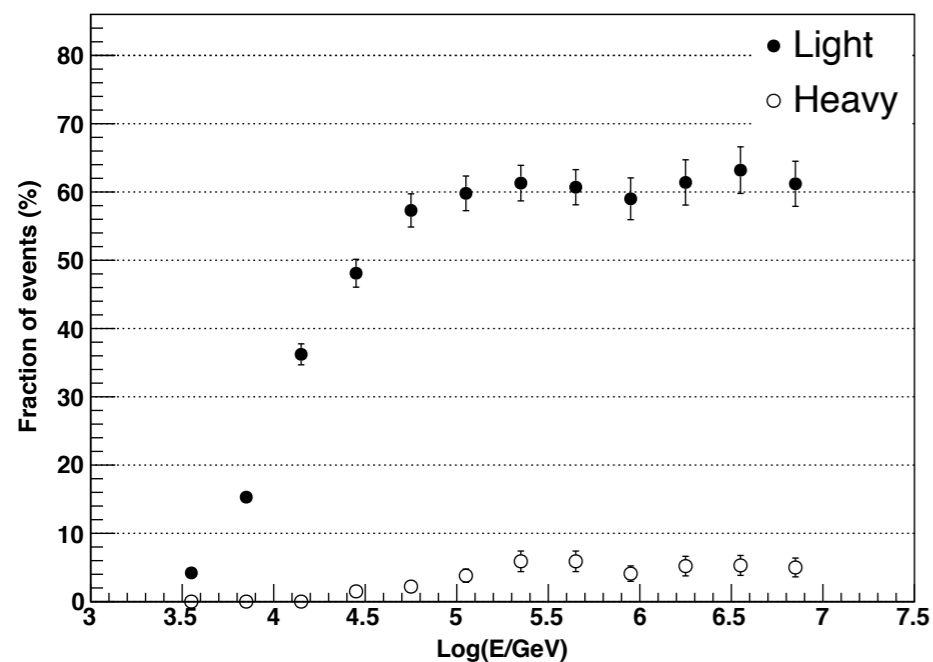
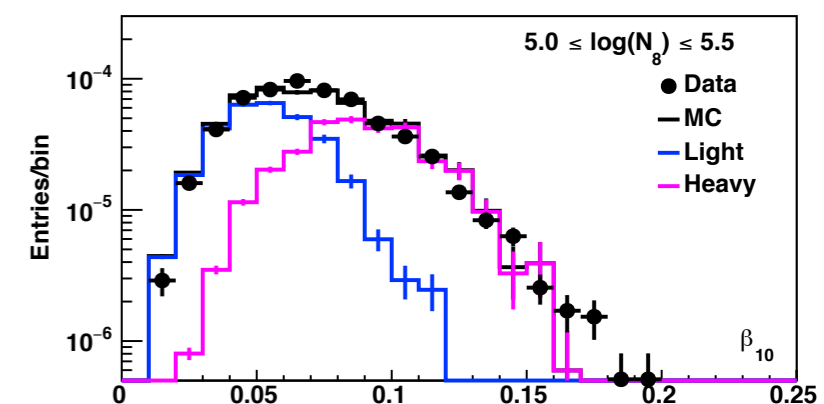
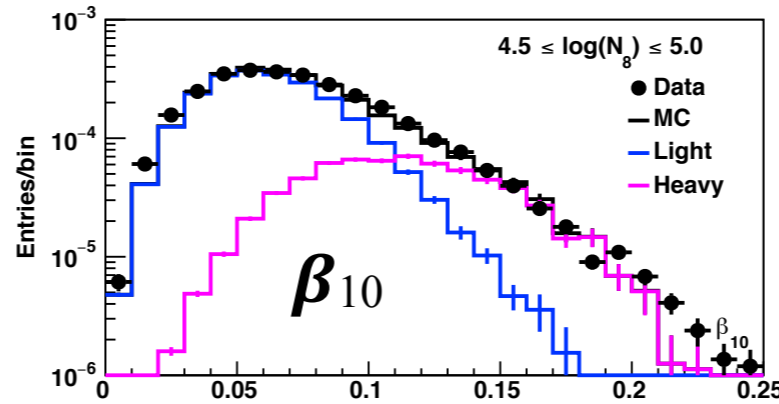
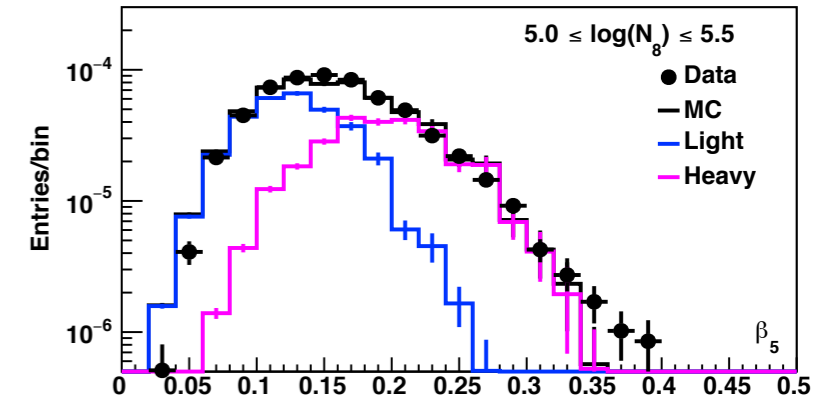
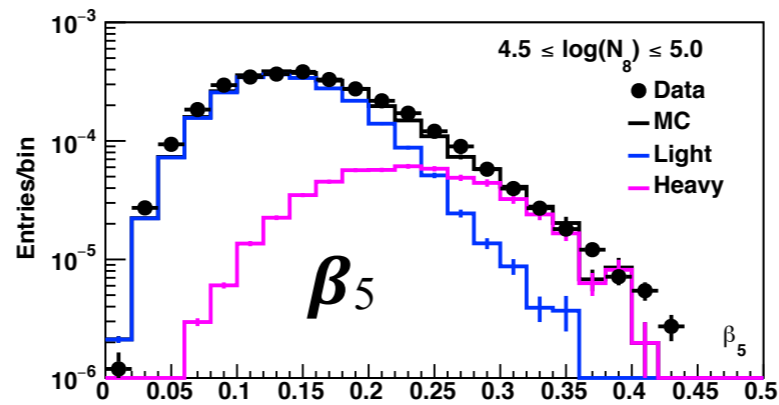
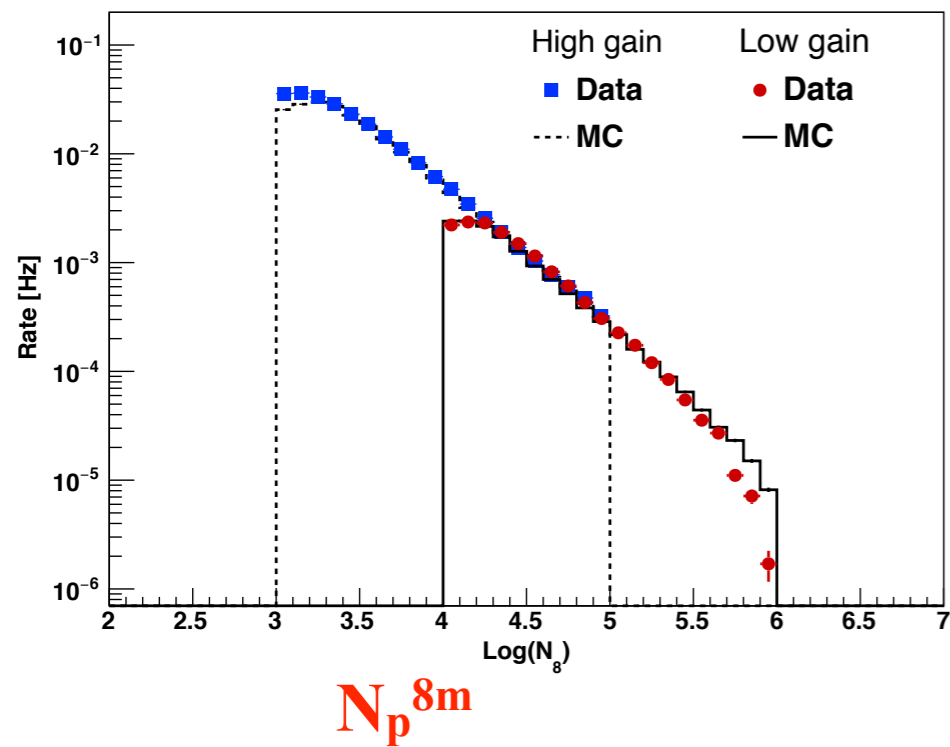


$$\beta_5 = \rho_5 / \rho_0$$

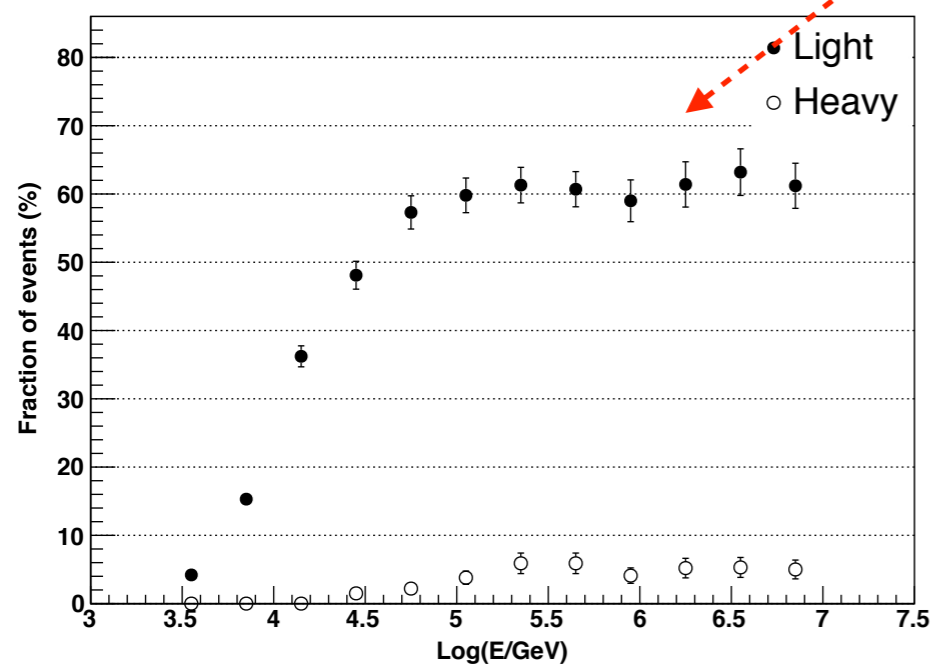
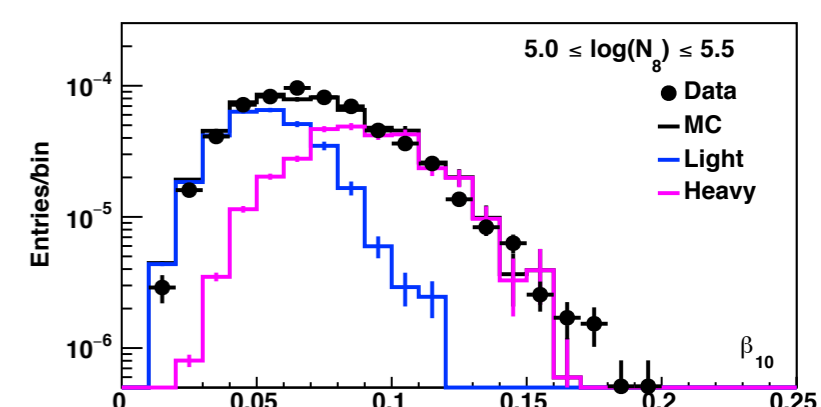
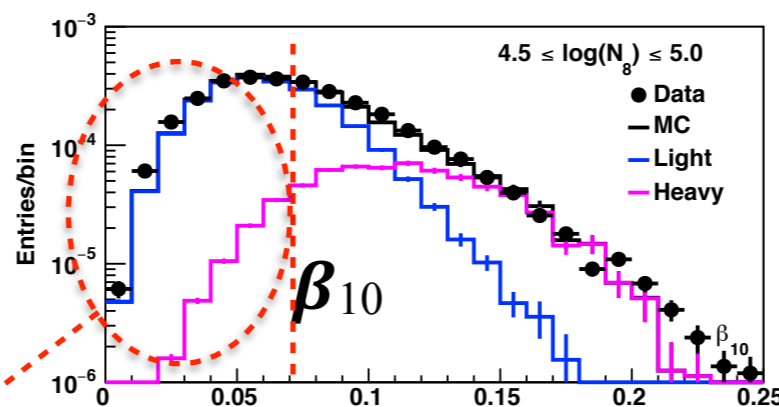
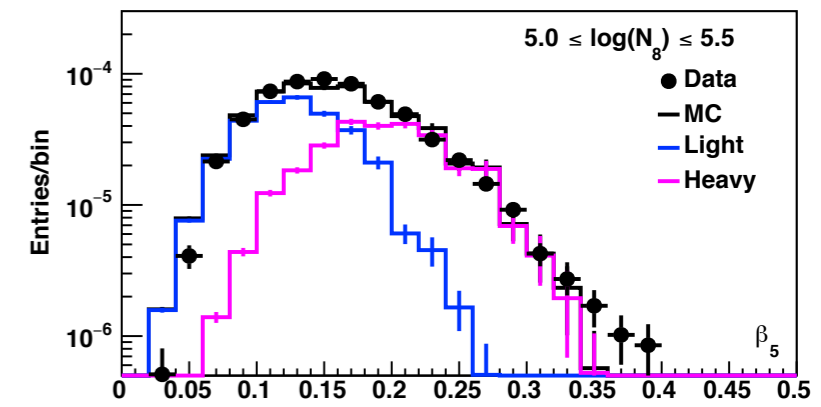
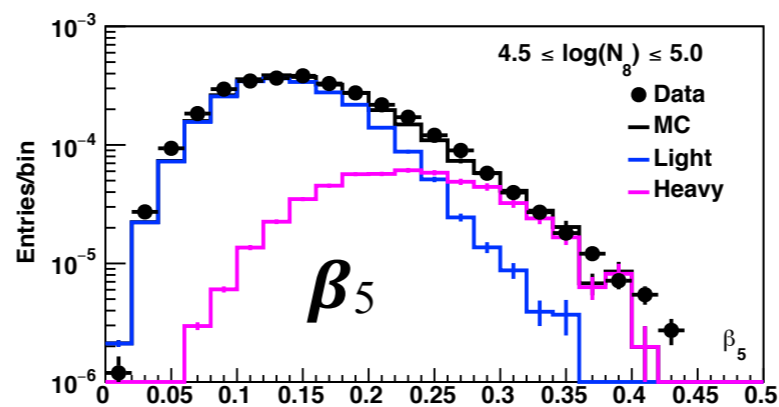
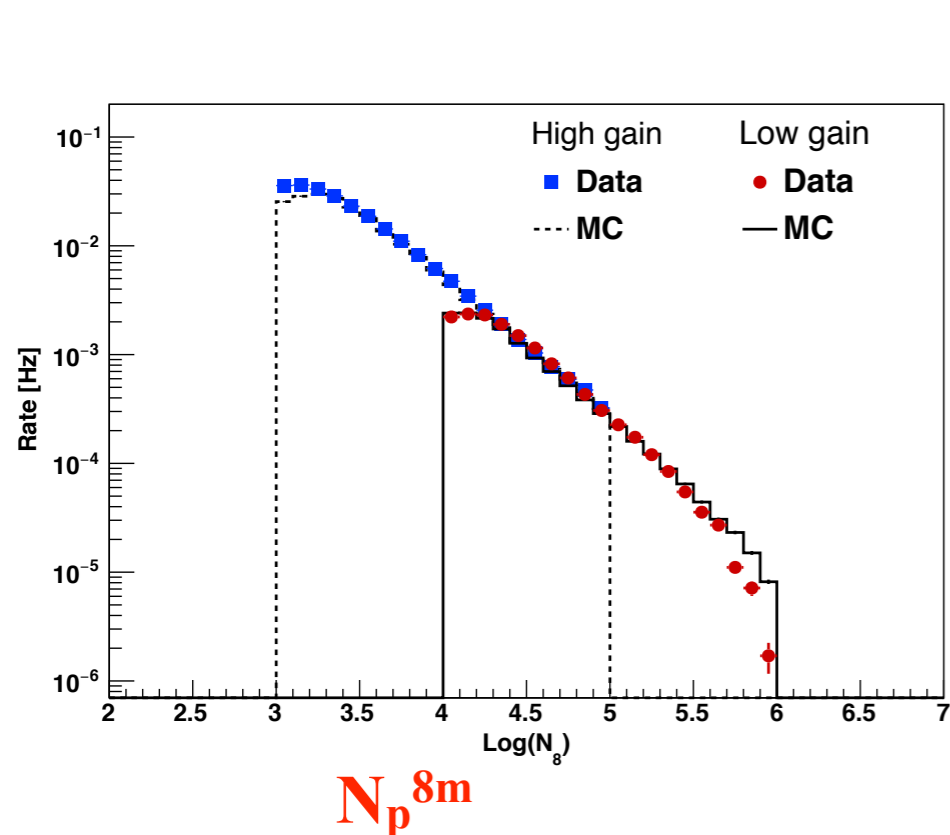
$$\beta_{10} = \rho_{10} / \rho_0$$



# Light/Heavy discrimination



# Light/Heavy discrimination

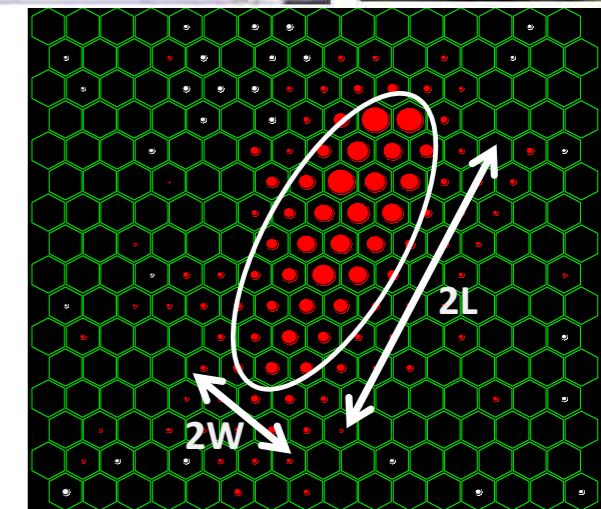


Fraction of events in the Light-selected sample only:  
 above  $\approx 100$  TeV  $\approx 60\%$  of all Light and  $\approx 5\%$  of all Heavy are selected

# ARGO-YBJ + WFCTA

A prototype of the future LHAASO telescopes has been operated in combination with ARGO-YBJ

- ▶ 4.7 m<sup>2</sup> spherical mirror composed of 20 hexagon-shaped segments
- ▶ 256 PMTs (16 × 16 array)
- ▶ 40 mm Photonis hexagonal PMTs (XP3062/FL)
- ▶ pixel size 1°
- ▶ FOV: 14° × 14°
- ▶ Elevation angle: 60°



❖ *ARGO-YBJ*: core reconstruction & lateral distribution in the core region

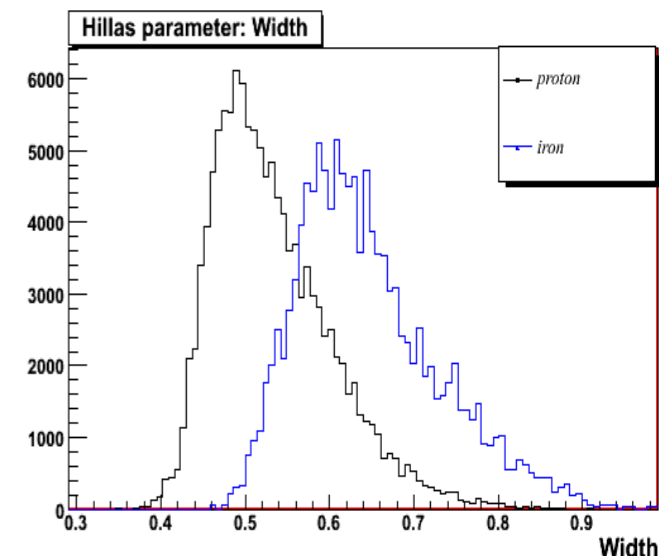
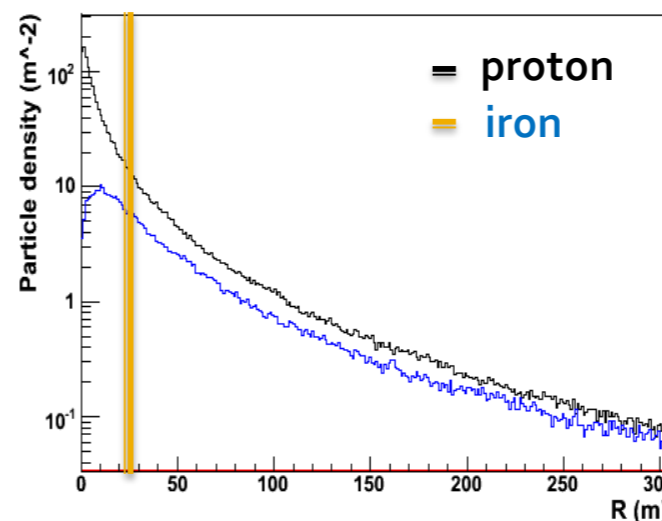
→ mass sensitive

❖ *Cherenkov telescope*: longitudinal information

Hillas parameters → mass sensitive

- angular resolution: 0.2°
- shower core position resolution: 2 m

*Phys. Rev. D 92, 092005 (2015)*



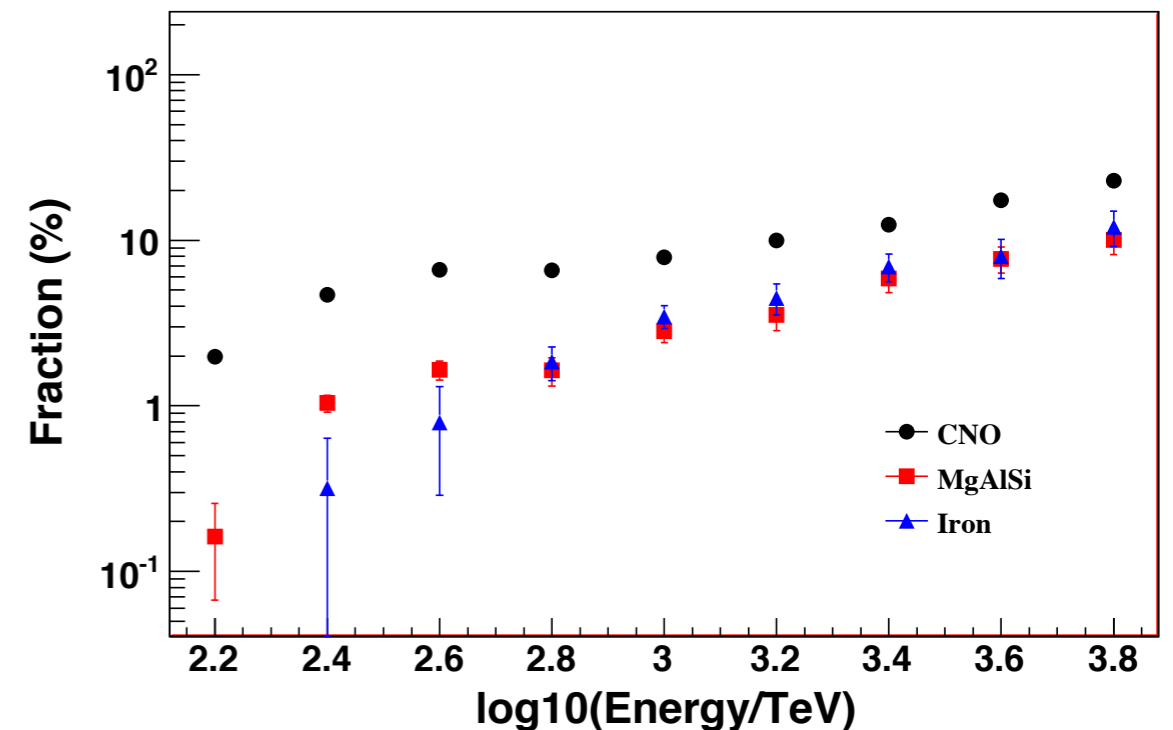
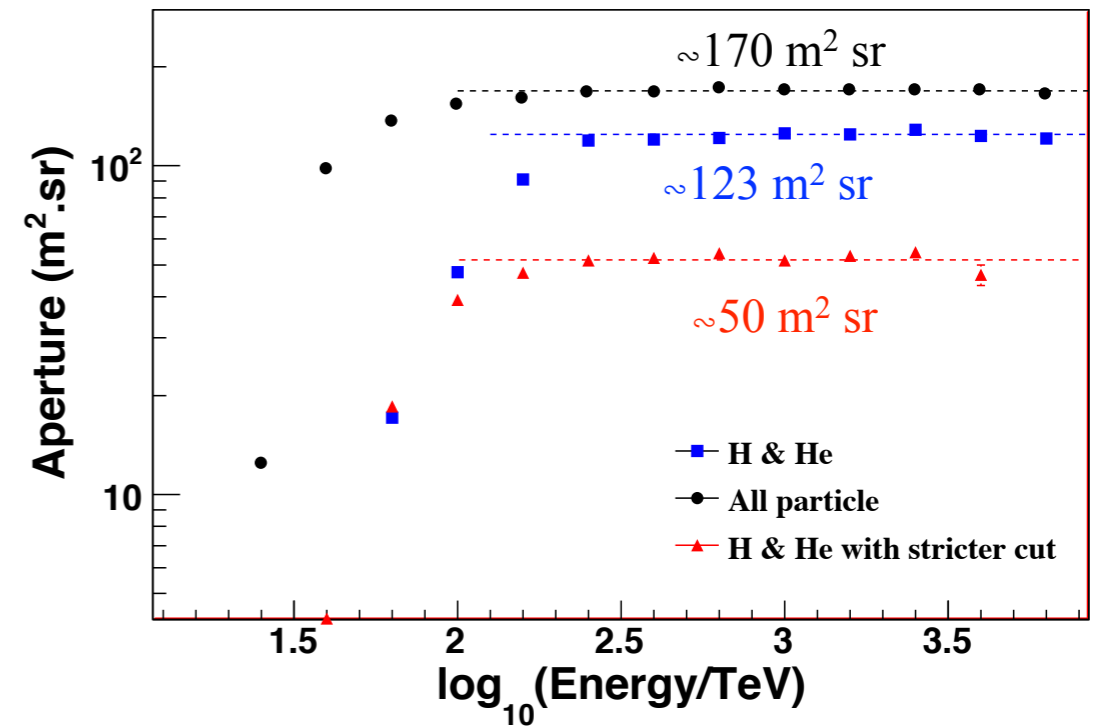
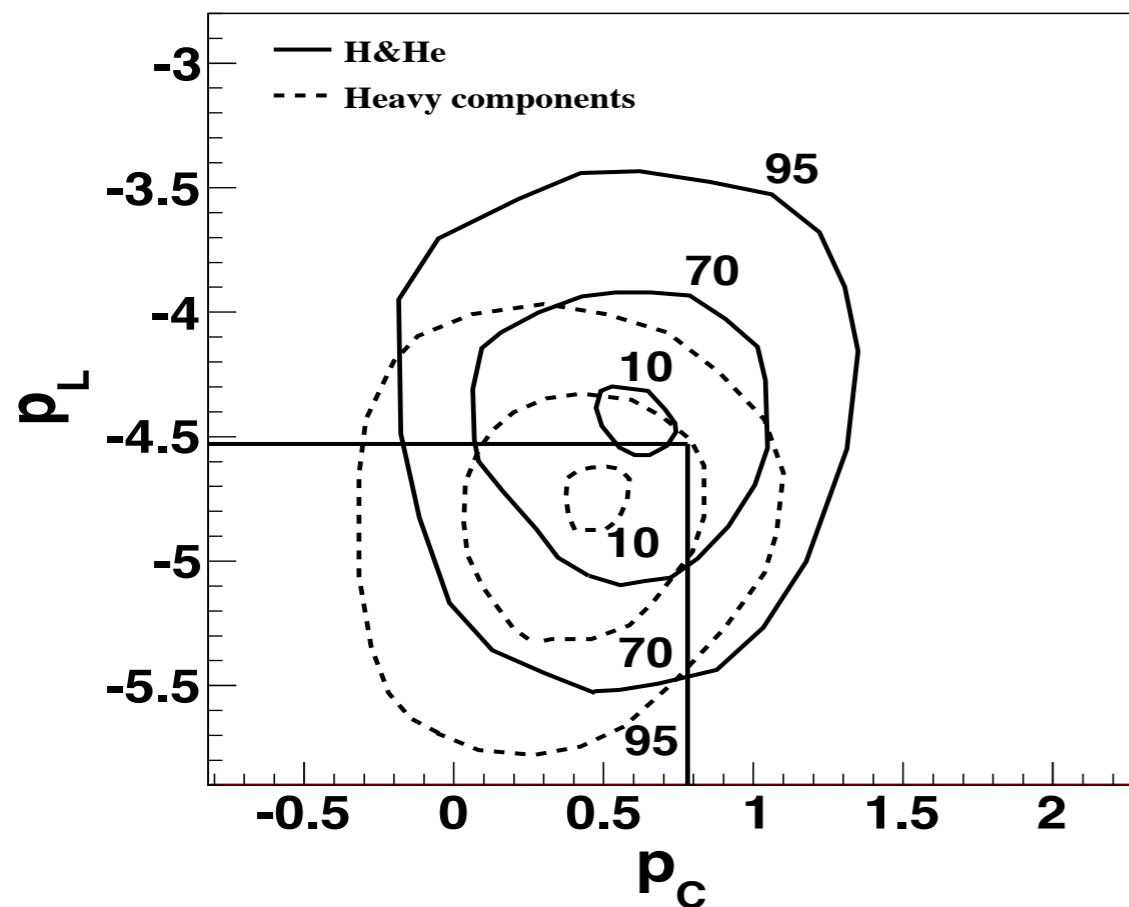
# Light component (p + He) selection

- **Contamination** of heavier component  $\approx 10\%$
- **Energy resolution**:  $\sim 25\%$  constant with energy
- **Uncertainty** :  $\sim 25\%$  on flux

$$p_L = \log_{10}(N_{max}) - 1.44 \cdot \log_{10}(E_{rec}/TeV)$$

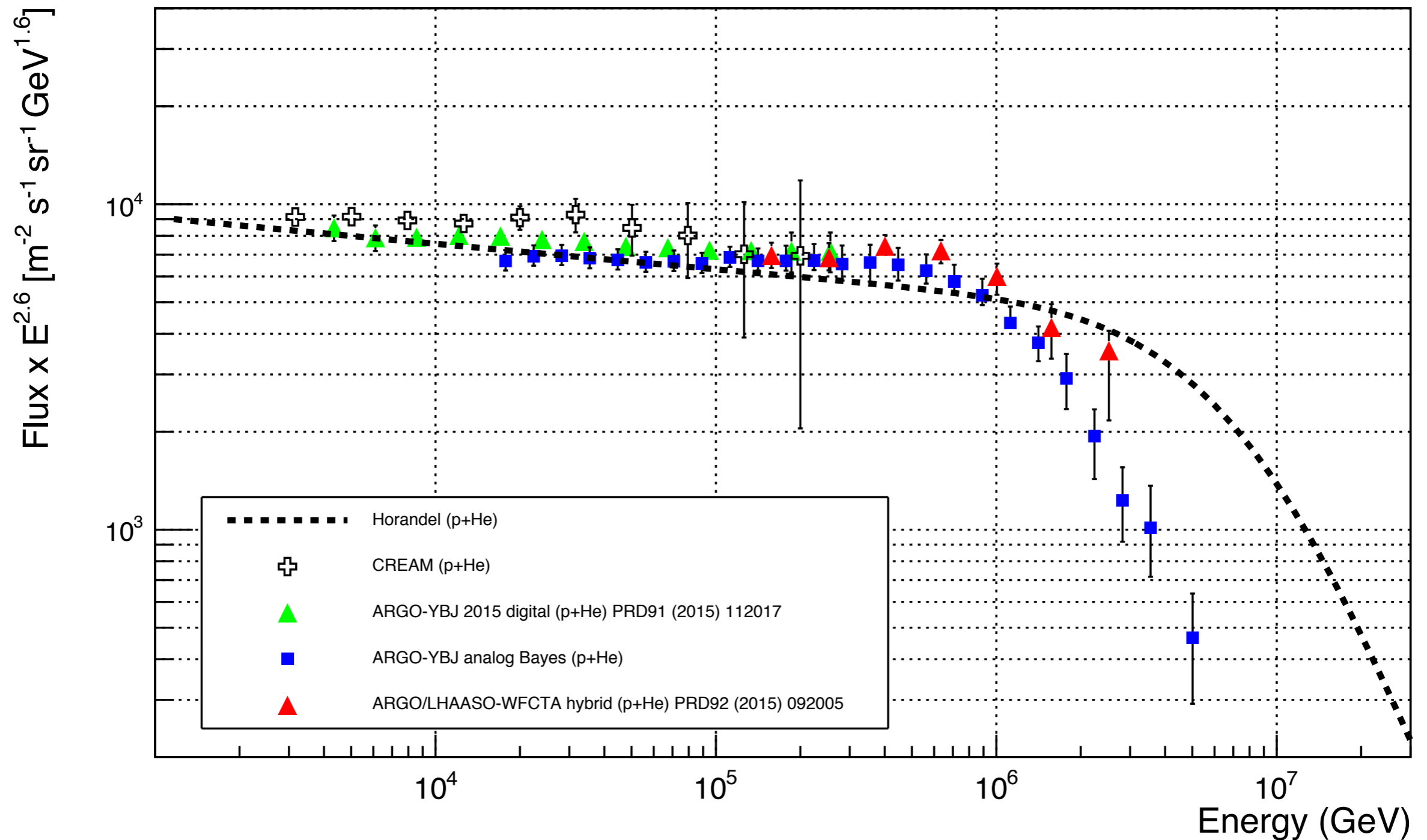
$$p_C = L/W - 0.0091(R_p/1m) - 0.14 \cdot \log_{10}(E_{rec}/TeV)$$

Events for which  $p_L \leq -4.53$  and  $p_C \leq 0.78$  are rejected

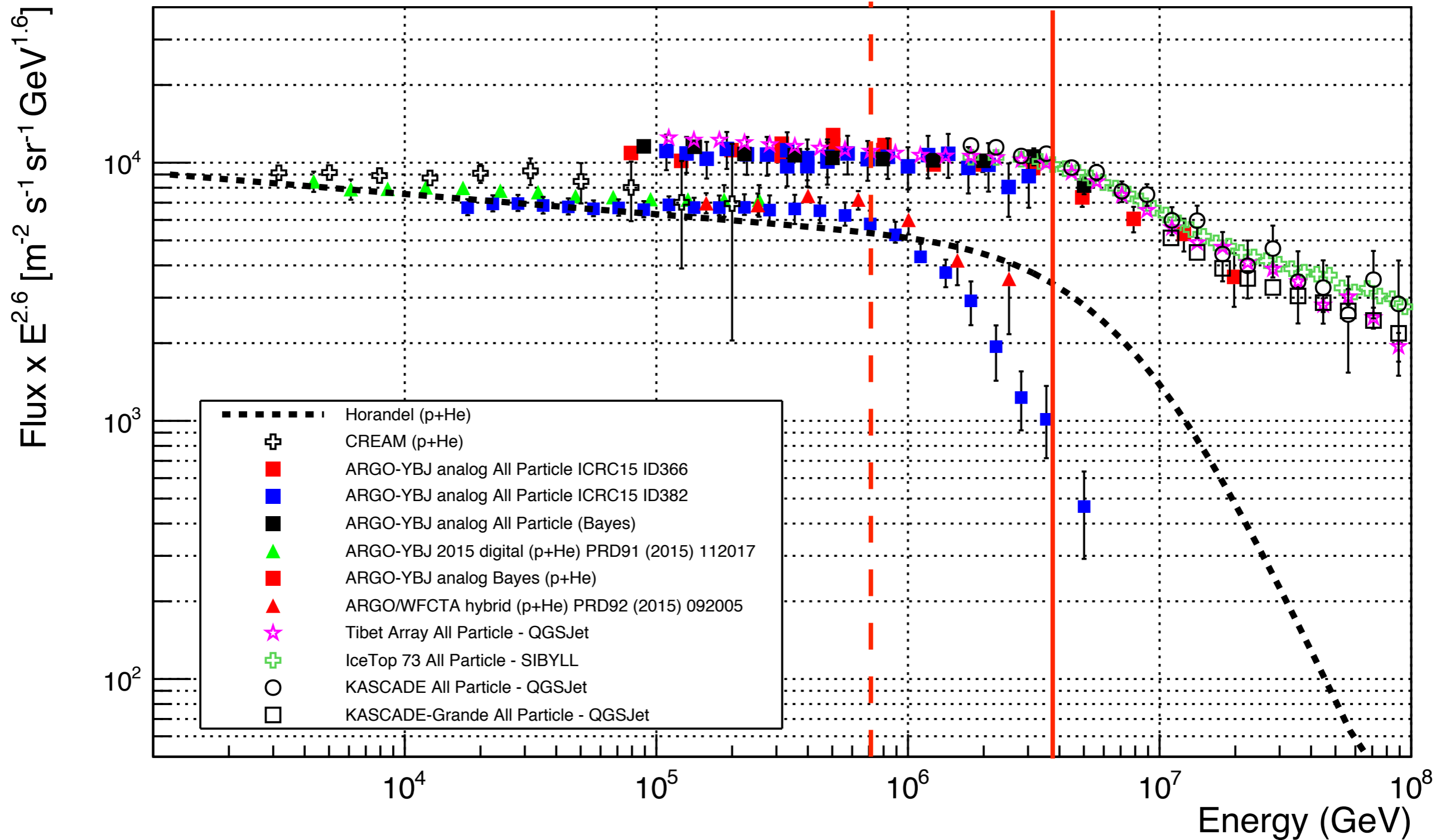


# Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

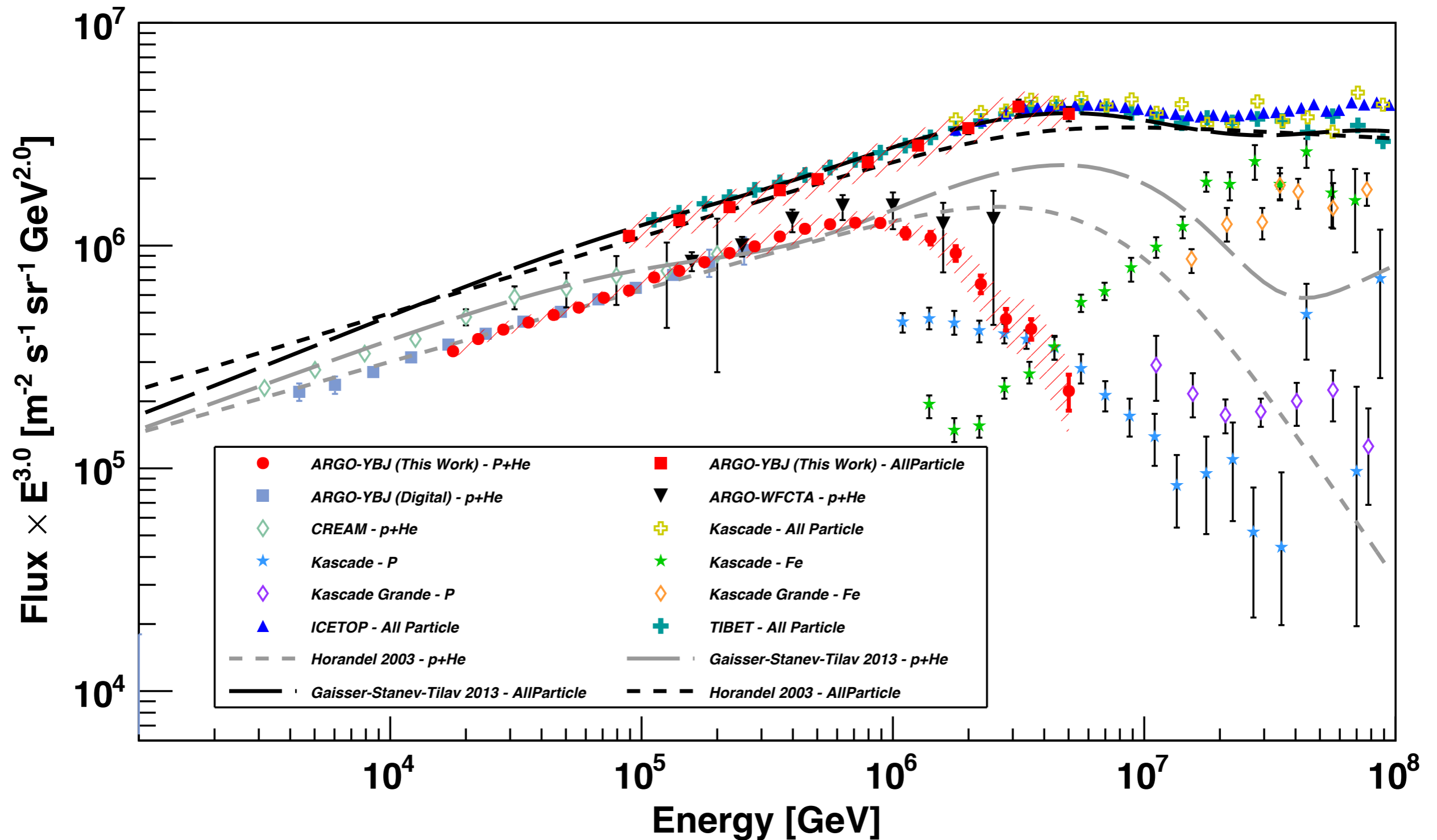
ARGO-YBJ reports evidence for a **proton knee starting at about 700 TeV**



# The overall picture



# Comparison with other experiments



# Medium/Small Scale Anisotropy

Data: November 8, 2007 - May 20, 2012  
 $\approx 3.70 \times 10^{11}$  events

dec. region  $\delta \sim -20^\circ \div 80^\circ$

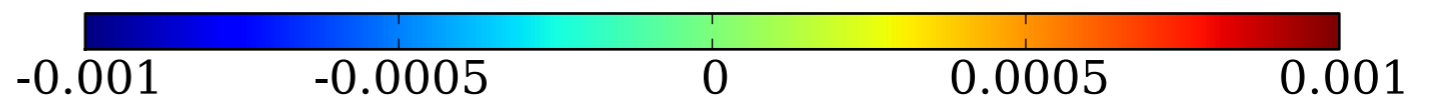
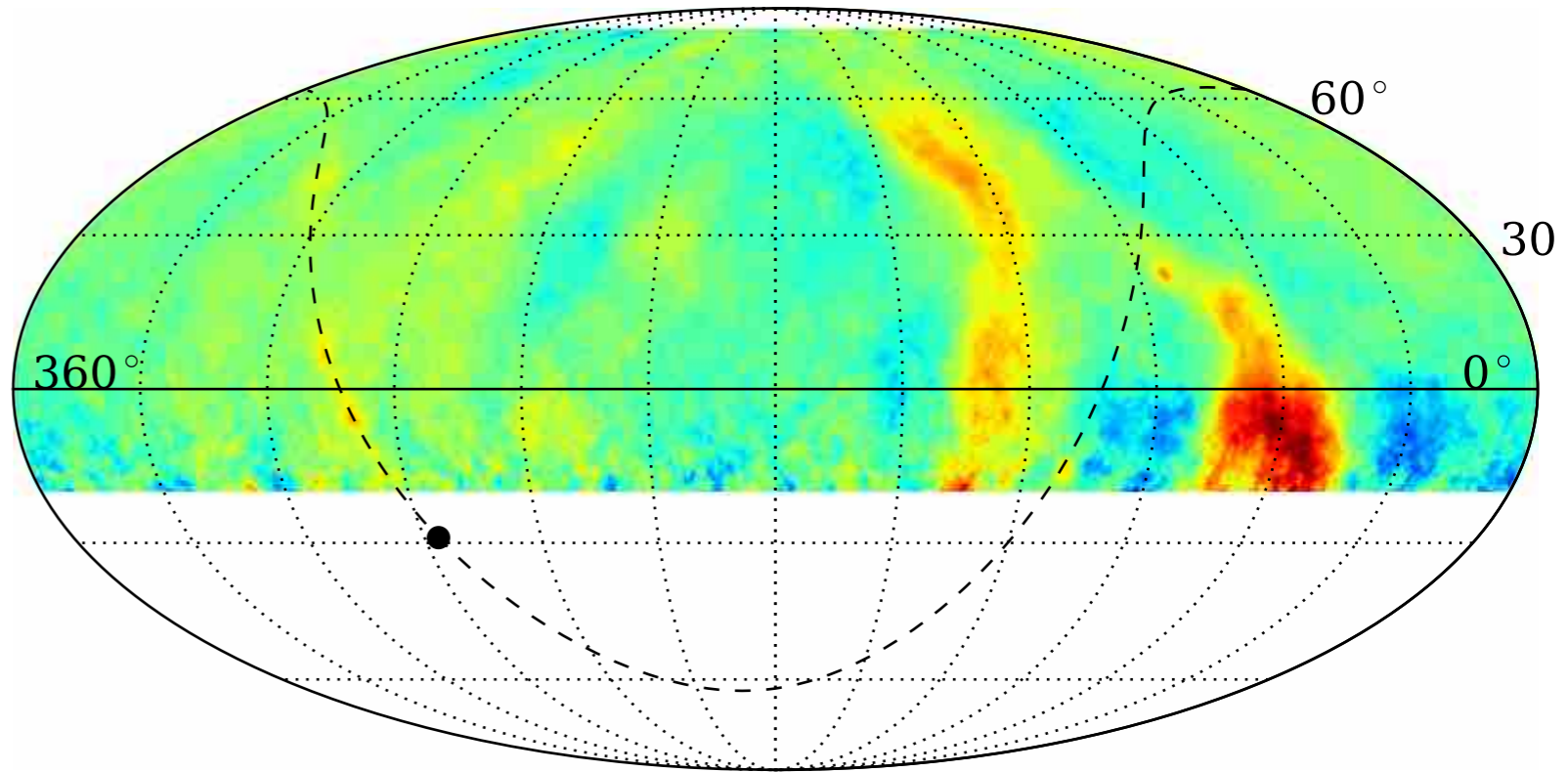
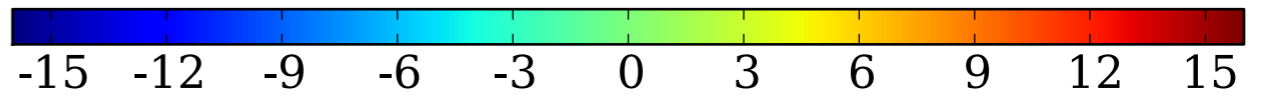
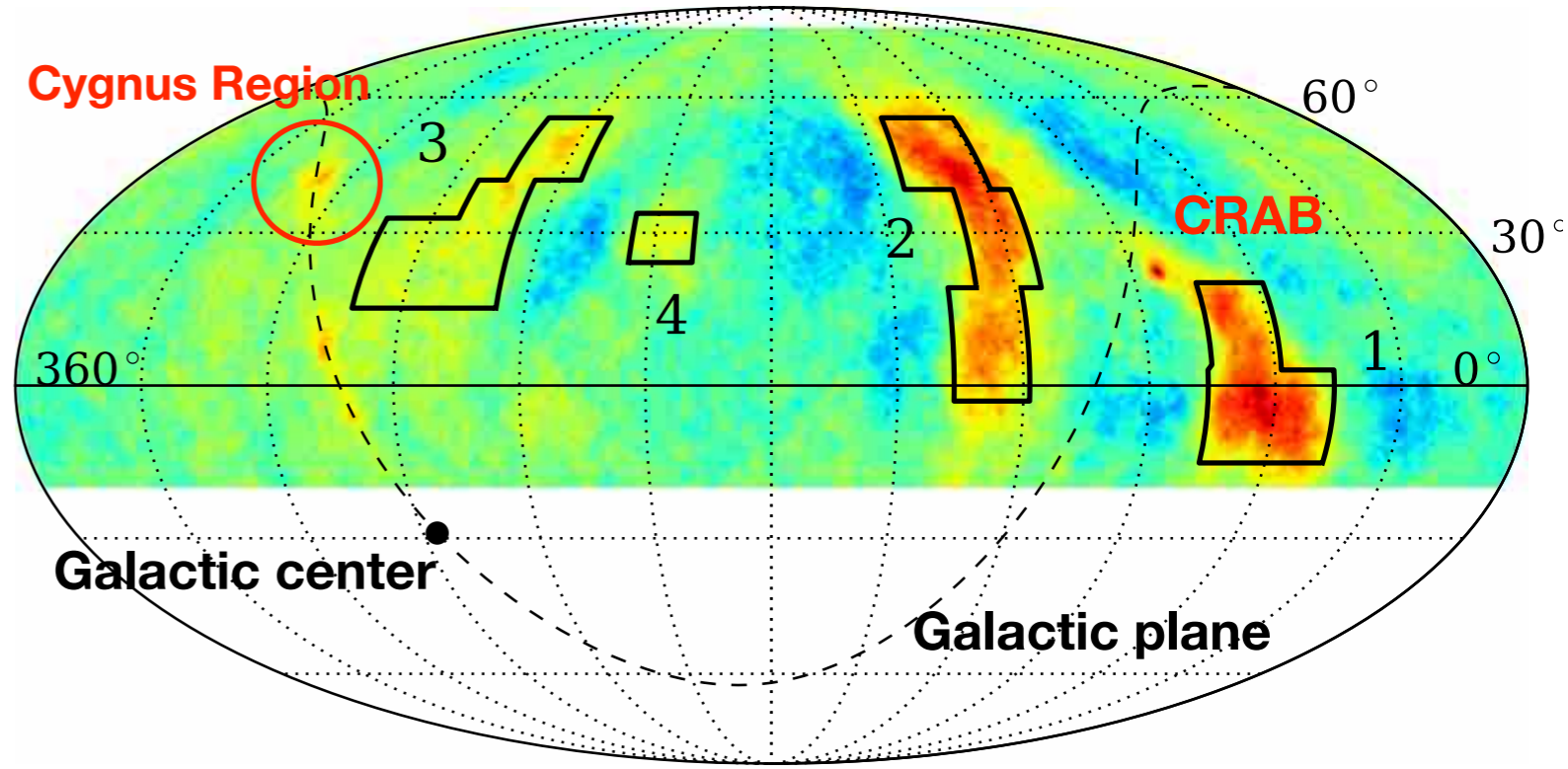
Map smoothed with the detected PSF for CRs,  
 obtained with the Moon Shadow analysis

**Proton median energy  $\approx 1$  TeV**

**CRs excess  $\approx 0.1$  %  
 with significance up to 15 s.d.**

Phys. Rev. D 88 (2013) 082001

ApJ 809 (2015) 90



# Take Home Message - 2

---

- Energy range  $10^{14}$  -  $10^{17}$  eV crucial
- **Experimental results conflicting !**
- **The origin of the observed anisotropies at different angular scales is still unknown**

## Homework

- ✓ **Spectra of individual mass groups !!**
- ✓ Multi-parameter EAS measurements to validate hadronic interaction models
- ✓ Absolute energy scale calibration: low energy threshold → High altitude !
- ✓ **Composition dependent anisotropy studies !!!**
- ✓ **High statistics** in a large energy range (→  $10^{16-17}$  eV)

# The LHAASO experiment

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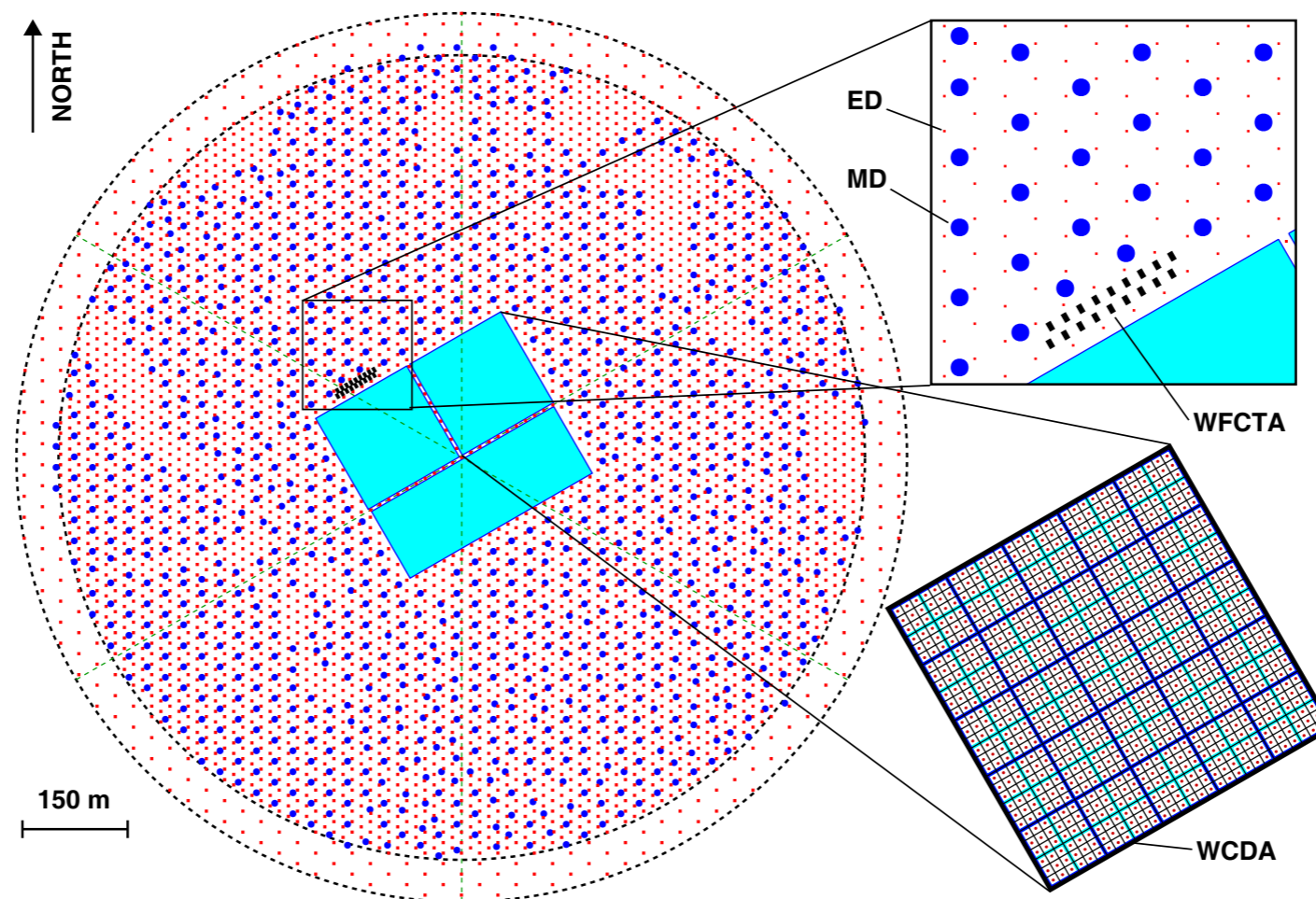
**LHAASO** (Large High Altitude Air Shower Observatory), a new generation EAS array strategically built to cover the exploration of several energy decades with a unique installation, with **20x trigger rate**, will be able to deepen and extend these observations.

LHAASO will enable studies in **cosmic ray physics** and **gamma-ray astronomy** that are unattainable with the current suite of instruments:

- LHAASO will monitor '*all the sky all the time*' performing an *unbiased sky survey of the Northern hemisphere* in the 100 GeV - 1 PeV range.
- LHAASO will open for the first time the 100 -1000 TeV range to the *direct observation of the high energy CR sources*.
- LHAASO, observing the gamma diffuse emission, will be able to *constrain the possible Galactic origin of a fraction of the IceCube neutrinos*.
- LHAASO, studying CRs in a *unprecedented wide energy range  $10^{11} - 10^{18}$  eV*, will clarify the observations of Galactic CRs and will give a *solid foundation for understanding CR physics at energies  $>10^{17}$  eV*.
- LHAASO *will look for signatures of WIMPs as candidate particles for DM* probing the PeV-mass DM scenario as a possible source of IceCube neutrinos.

# LHAASO layout

- 1 km<sup>2</sup> array, including 5195 scintillator detectors 1 m<sup>2</sup> each, with 15 m spacing.
- An overlapping 1 km<sup>2</sup> array of 1171, underground water Cherenkov tanks 36 m<sup>2</sup> each, with 30 m spacing, for muon detection (total sensitive area  $\approx$  42,000 m<sup>2</sup>).



- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m<sup>2</sup>.
- 18 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors → **Yuri Stenkin talk**

# The LHAASO site

The experiment will be located at **4400 m asl (600 g/cm<sup>2</sup>)** in the **Haizishan** (Lakes' Mountain) site, Sichuan province

Coordinates: 29° 21' 31'' N, 100° 08' 15'' E

700 km to Chengdu

50 km to Daocheng City (3700 m asl, guest house)

**10 km to the highest airport in the world**



# Status of LHAASO

---

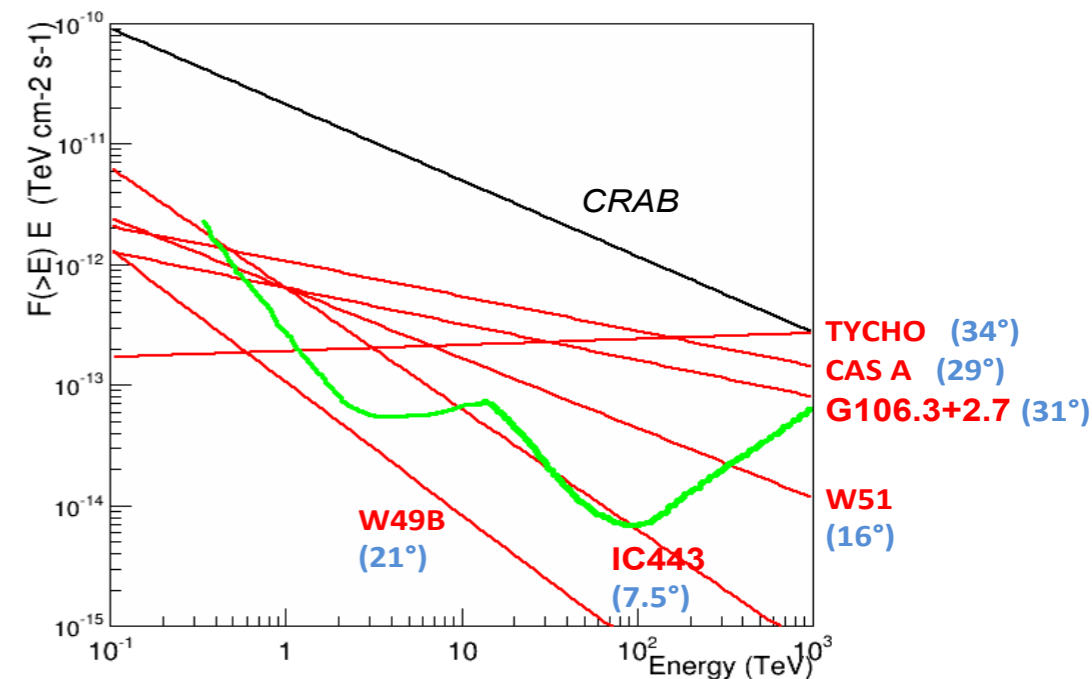
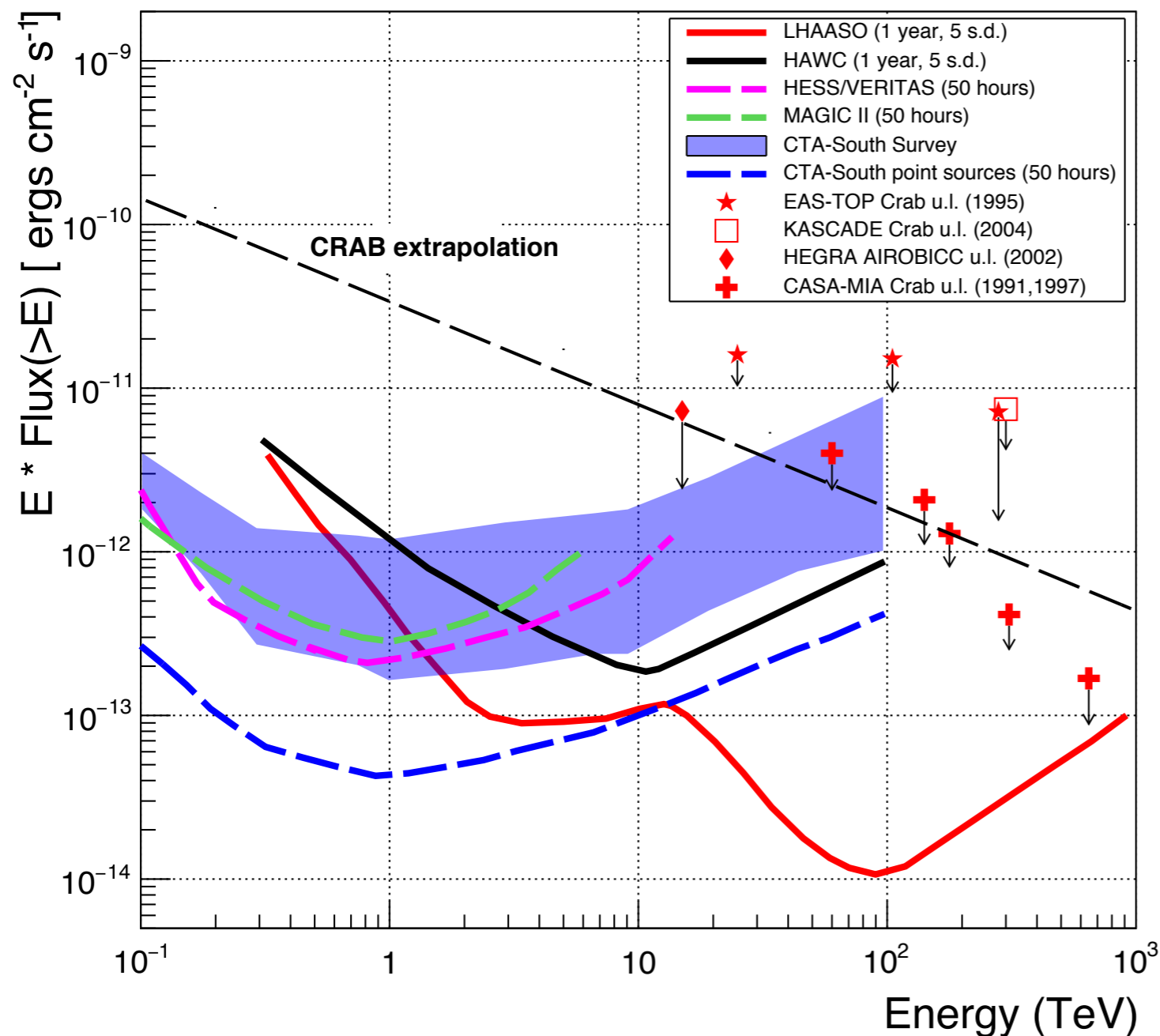
- LHAASO is finally approved and funded for detectors and infrastructures
- 2015: geo survey and **final layout fixed**.
- Installation of detectors started in September 2015 for tests.
- **July 30th: starting ceremony of the big construction** at the site: power station at the site, a power line of 29 km to the nearest major power line in the national grid, the roads in the field, data center and living base.
- **April 2017: Construction of first pond and MD tanks**
- ★ **By the middle of 2018, the first quarter of the whole array**, i.e. 22,500 m<sup>2</sup> water Cherenkov detector, surrounded by 300 MDs and 1200 scintillator counters, and 6 *wide FoV Cherenkov telescopes* **will be put in operation**.
- ★ **2021**: conclusion of installation of main components.



Construction of muon detectors

# Gamma-Ray Astronomy with LHAASO

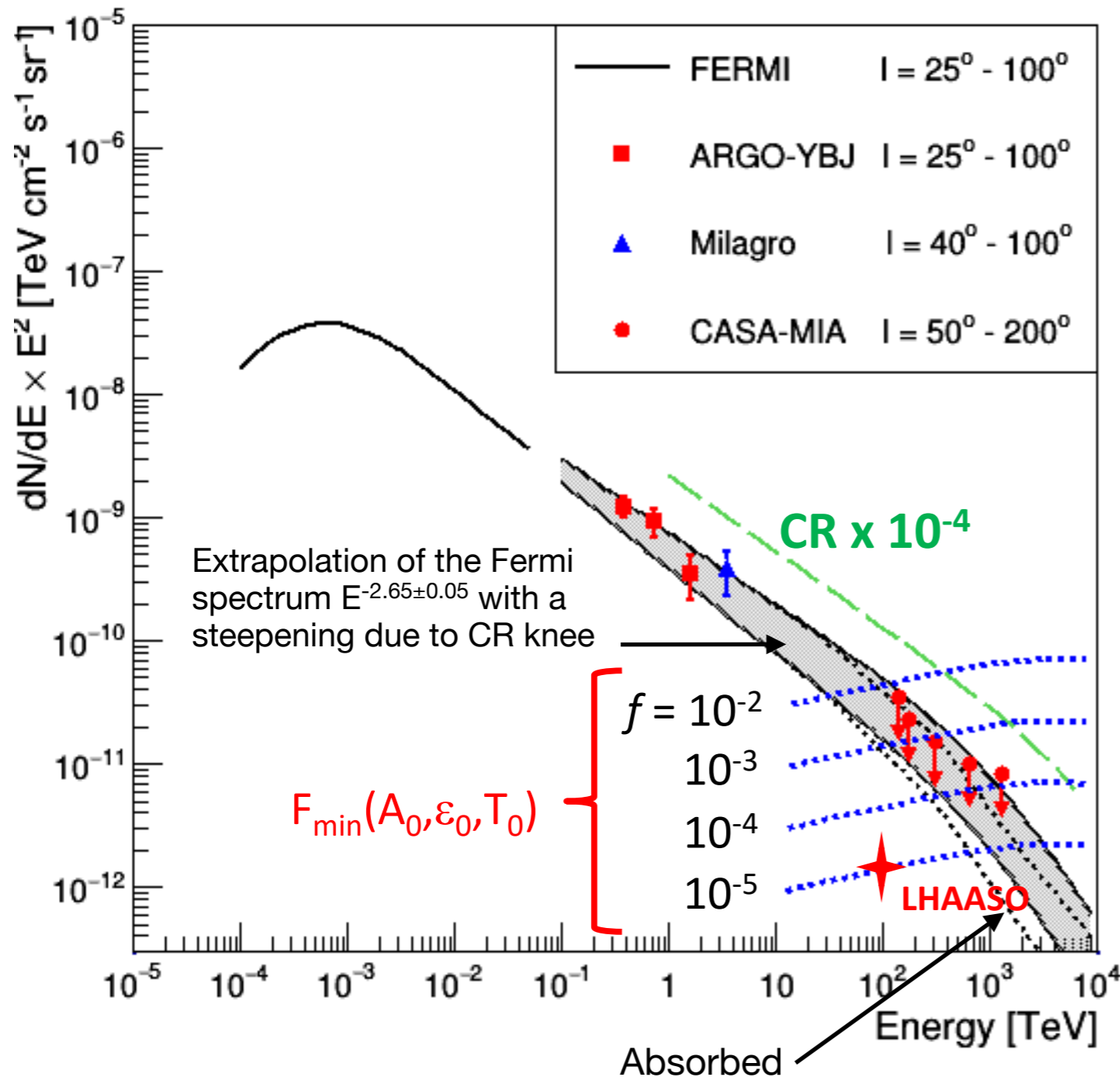
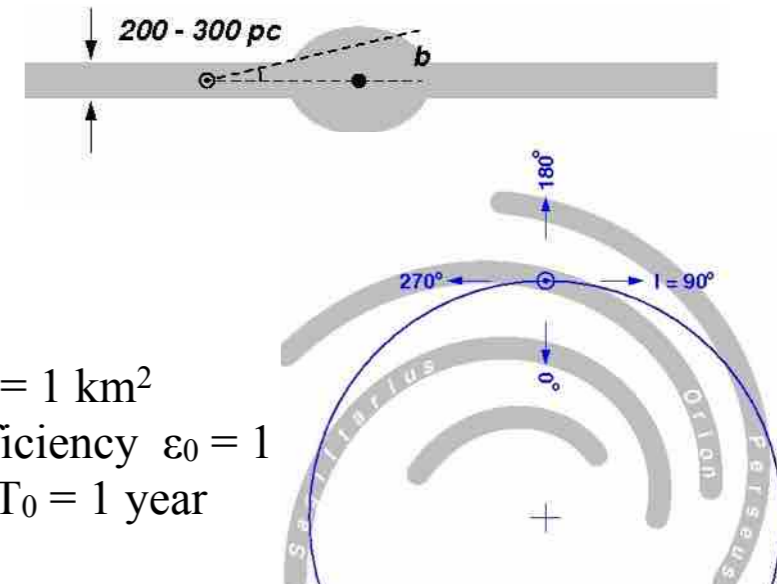
(1) To open for the first time the  $10^2 - 10^3$  TeV range to the direct observation of the Cosmic Ray sources (“PeVatrons”). LHAASO's wide field of view provides a unique discovery potential.



LHAASO will observe at TeVs, with high sensitivity, >40 of the sources catalogued by Fermi-LAT at lower energy, monitoring the variability of >20 AGNs.

# LHAASO sensitivity to diffuse $\gamma$ -ray flux

Diffuse gamma ray flux in the disk region  $l = 25^\circ - 100^\circ$  and  $|b| < 5^\circ$



Detector features:

- Effective area  $A_0 = 1 \text{ km}^2$
- $\gamma$ -ray detection efficiency  $\epsilon_0 = 1$
- Observation time  $T_0 = 1 \text{ year}$
- Latitude  $30^\circ \text{ N}$
- Maximum zenith angle  $45^\circ$

Minimum observable flux ( $5 \sigma$ )

$F_{\min}(A_0, \epsilon_0, T_0)$  for different values of  $f$

$f$  = background rejection factor

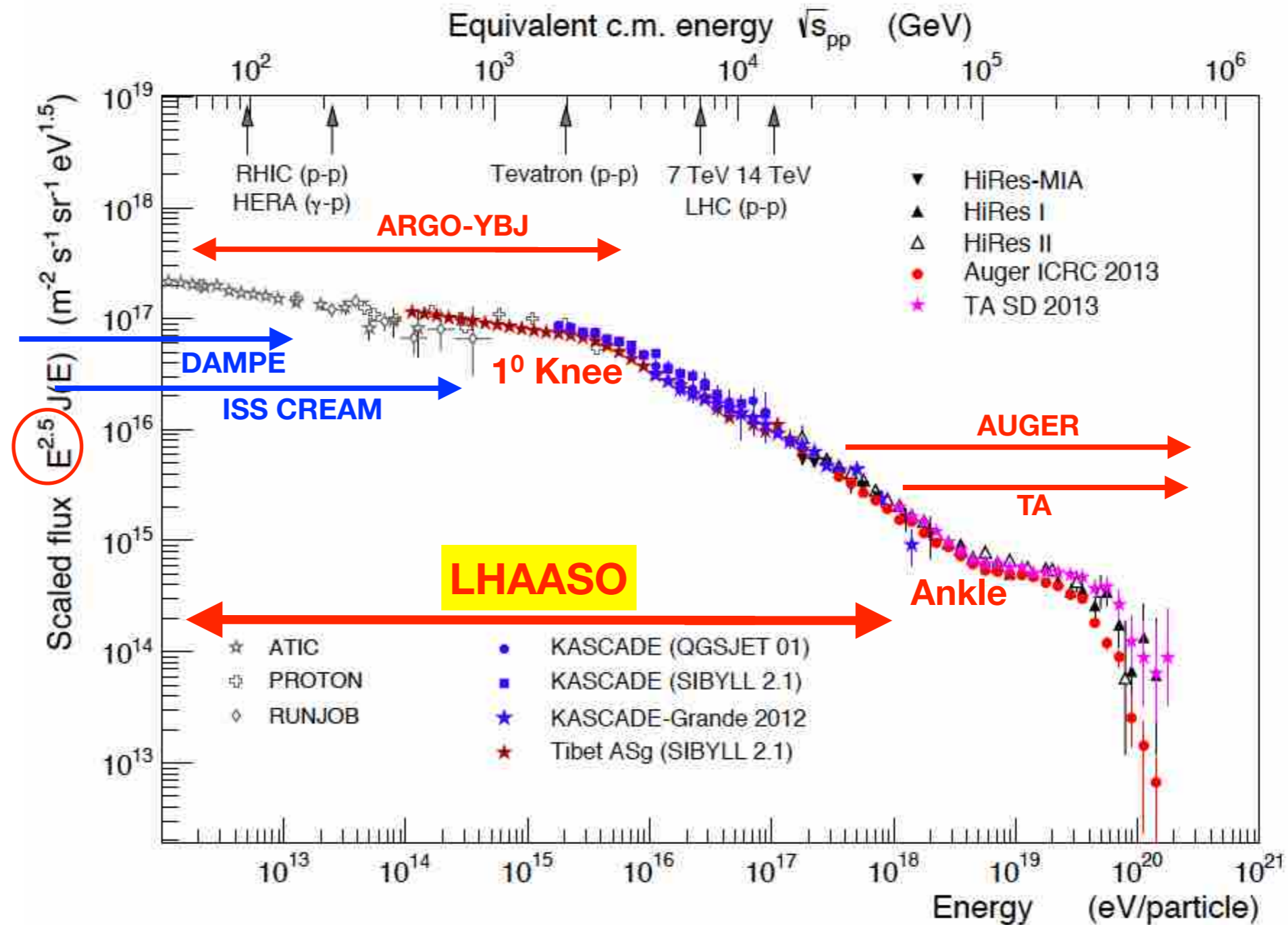
Minimum flux for any  $A$ ,  $\epsilon$  and  $T$ :

$$F_{\min}(A, \epsilon, T) = F_{\min}(A_0, \epsilon_0, T_0) \sqrt{\frac{A_0 T_0}{AT}} \frac{\epsilon_0}{\epsilon}$$

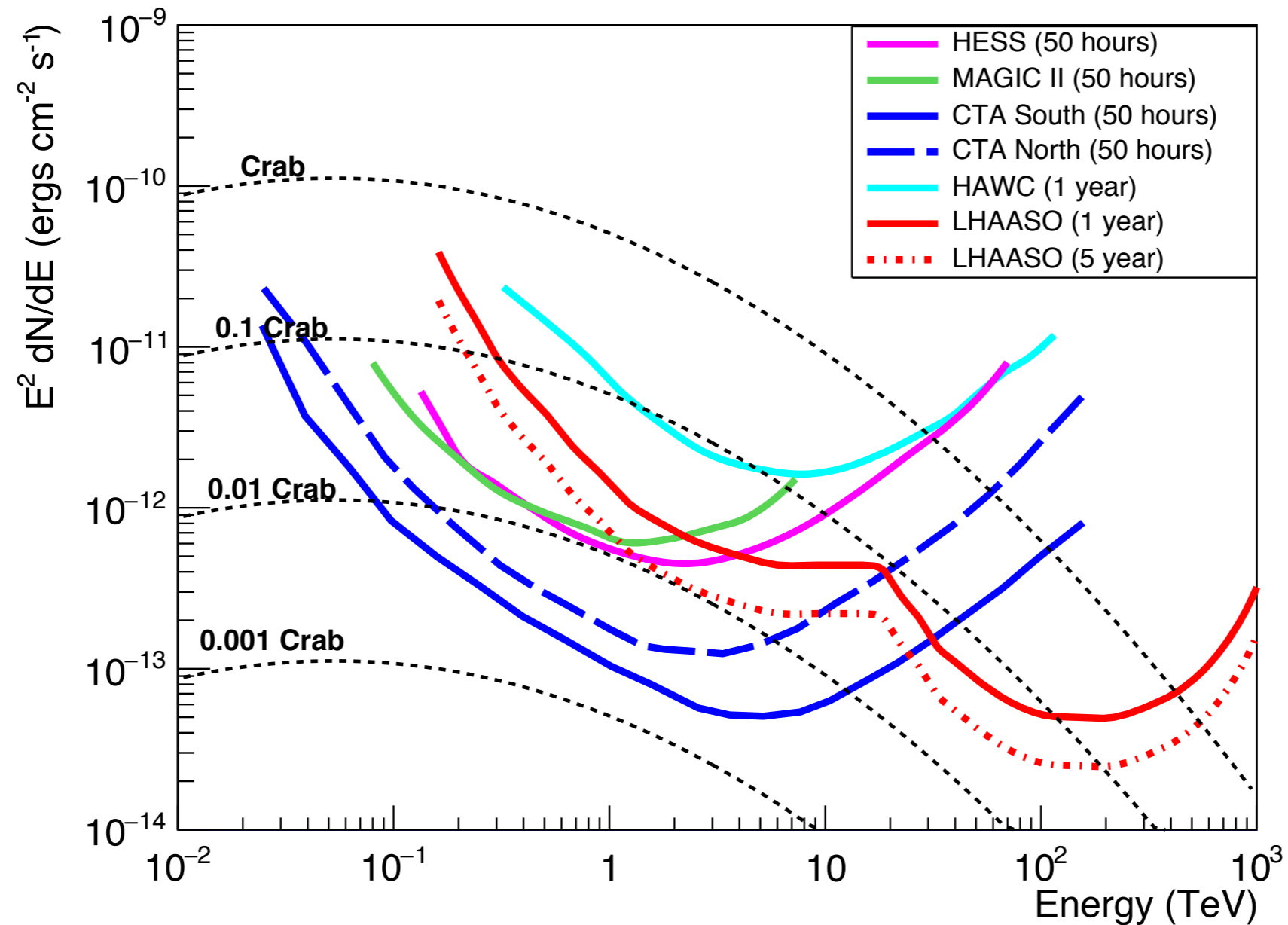
by P. Lipari & S. Vernetto: RICAP 2016

# Cosmic Ray Physics with LHAASO

(2) To fill the gap in the CR detection between the low and the very high energy ranges with a single experiment.



# IACTs and LHAASO/HAWC

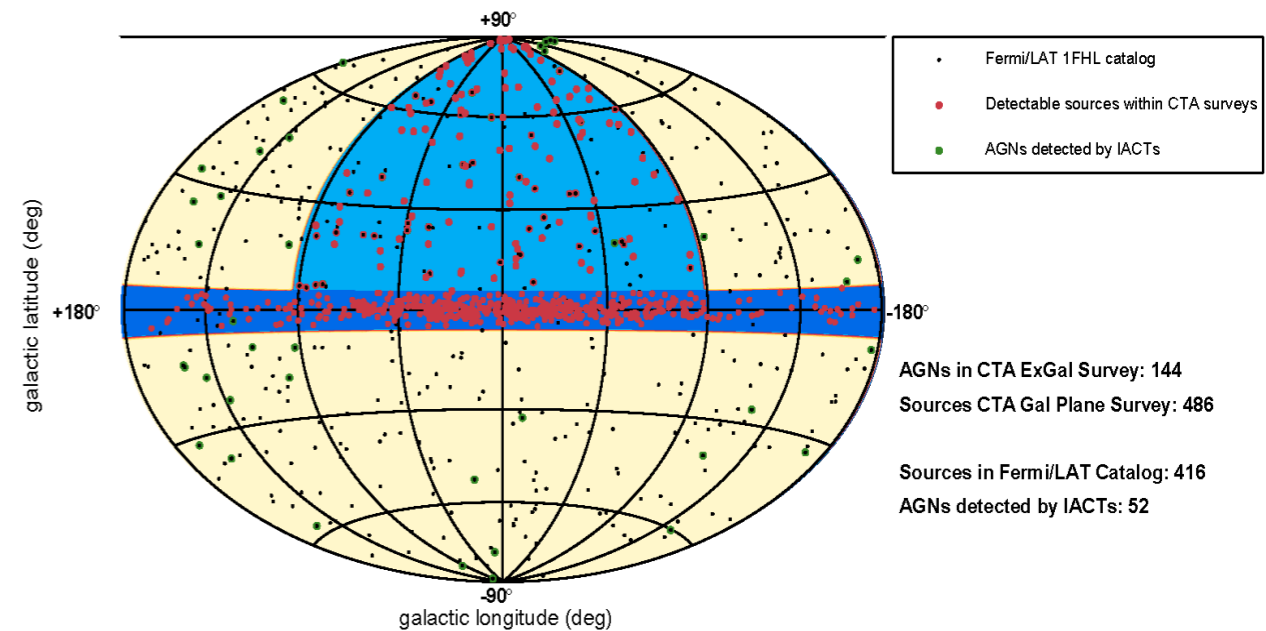


LHAASO (and HAWC) sensitivity is well matched to current generation of IACTs (HESS, VERITAS, MAGIC)

# CTA Sky Survey Plans

CTA:

- ★ Survey of entire Galactic Plane to  $\approx 2 - 4$  mCrab
- ★ Unbiased survey of 1/4 sky to  $\approx 6$  mCrab



from R. Ong, 2015

## • Previous Surveys:

Experiment	Hemisphere	Galactic Plane Coverage	Energy (GeV)	Sensitivity (mCrab)
H.E.S.S.-I	S	$-70^\circ < l < 60^\circ,  b  < 2^\circ$	$> \sim 300$	10 – 30
VERITAS	N	$67^\circ < l < 83^\circ, -1^\circ < b < 4^\circ$	$> \sim 300$	20 – 30
ARGO-YBJ	N	Northern Sky	$> 300$	240 – 1000
HEGRA	N	$-2^\circ < l < 85^\circ,  b  < 1^\circ$	$> 600$	150 – 250
Milagro	N	Northern Sky	$> 10,000$	300 – 500

## • Present/Future Surveys:

from CTA Science Case, 2015

Observatory	Hemisphere	Energy Threshold	Angular Resolution	Pt. Source Sensitivity
CTA	N, S	125 GeV	$\sim 0.07^\circ$ at 1 TeV	2 – 4 mCrab
HAWC	N	2 TeV	$0.30^\circ$	20 mCrab (5 yr)
LHAASO	N	$\approx 500$ GeV	$\approx 0.30^\circ$ at 1 TeV	10 mCrab (1 yr)

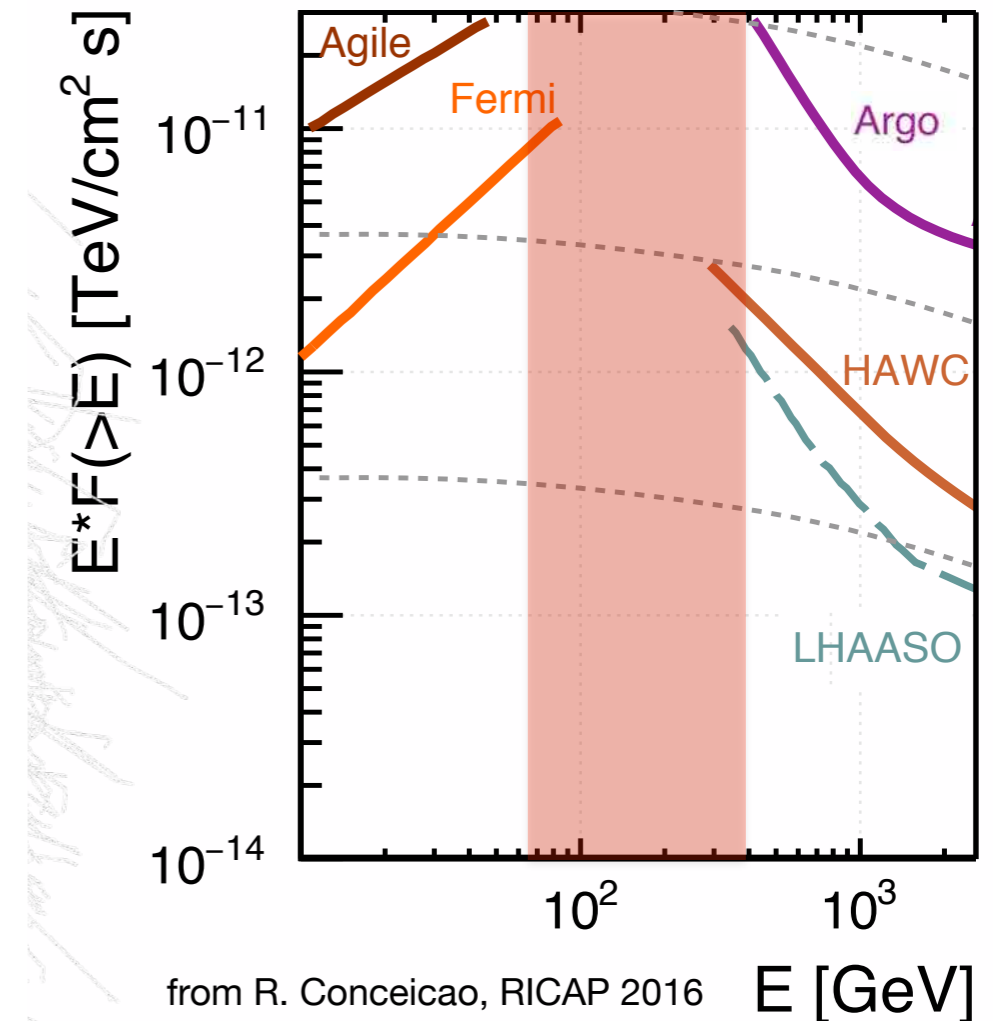
# Why a new Wide FoV detector in the CTA era ?

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- ◆ Multi-Messenger Instrument (by definition)
- ◆ “Finder” telescope for CTA
- ◆ Galactic/Extragalactic unbiased survey
- ◆ Extended objects (PWN, diffuse gamma-ray emission)
- ◆ High exposure for flaring activity (AGN, GRBs, solar flares)
- ◆ High mass dark matter ( $> 10$  TeV)
- ◆ “Classical” Cosmic Ray Physics (energy spectrum, elemental composition, anisotropy, hadronic interactions)

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No Wide FoV experiment to:

- Explore the 100 GeV energy region
- Survey the Galactic Center (GC)

# CTA and a new Wide FoV observatory

A future Wide FoV Observatory to be useful to CTA needs:

- $\approx 5x - 10x$  greater sensitivity below TeV
- Lower energy threshold ( $\approx 100$  GeV)
- Ability to detect extragalactic transient (AGN, GRBs)
- Southern hemisphere site

★ Is this possible ?

Minimum Detectable Gamma-Ray Flux:

$$\Phi_{\gamma}^{MDF} \propto \sqrt{\Phi_B} \cdot \frac{1}{R \cdot \sqrt{A_{eff}^{\gamma}}} \cdot \psi_{70} \cdot \frac{1}{Q_f}$$

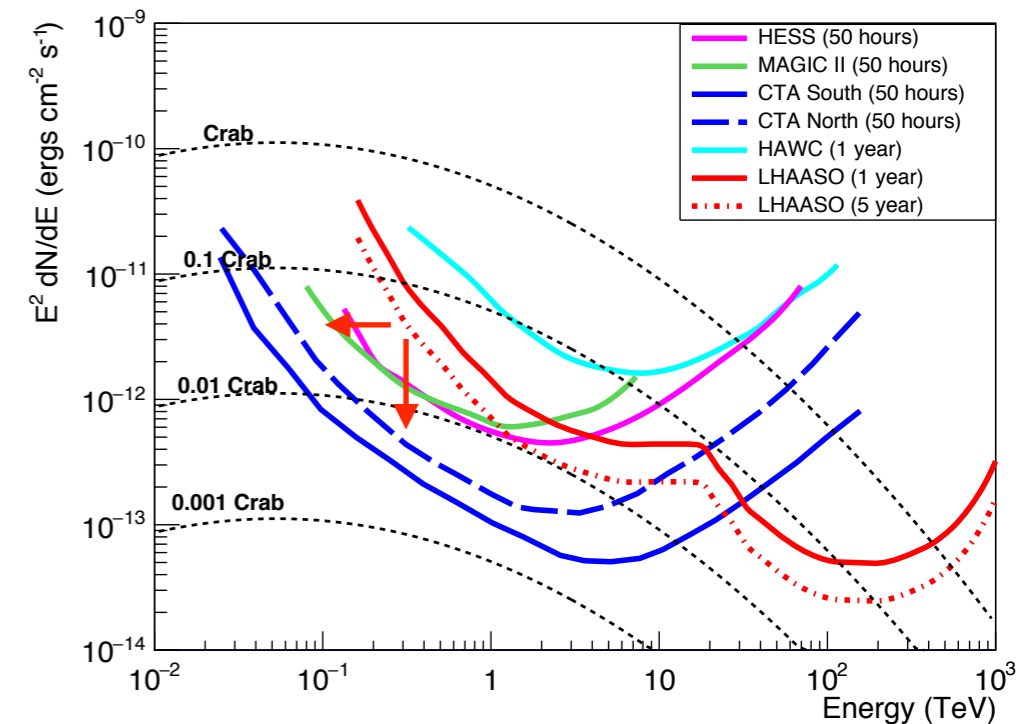
$\Phi_B$  = background flux

$\psi_{70}$  = opening angle

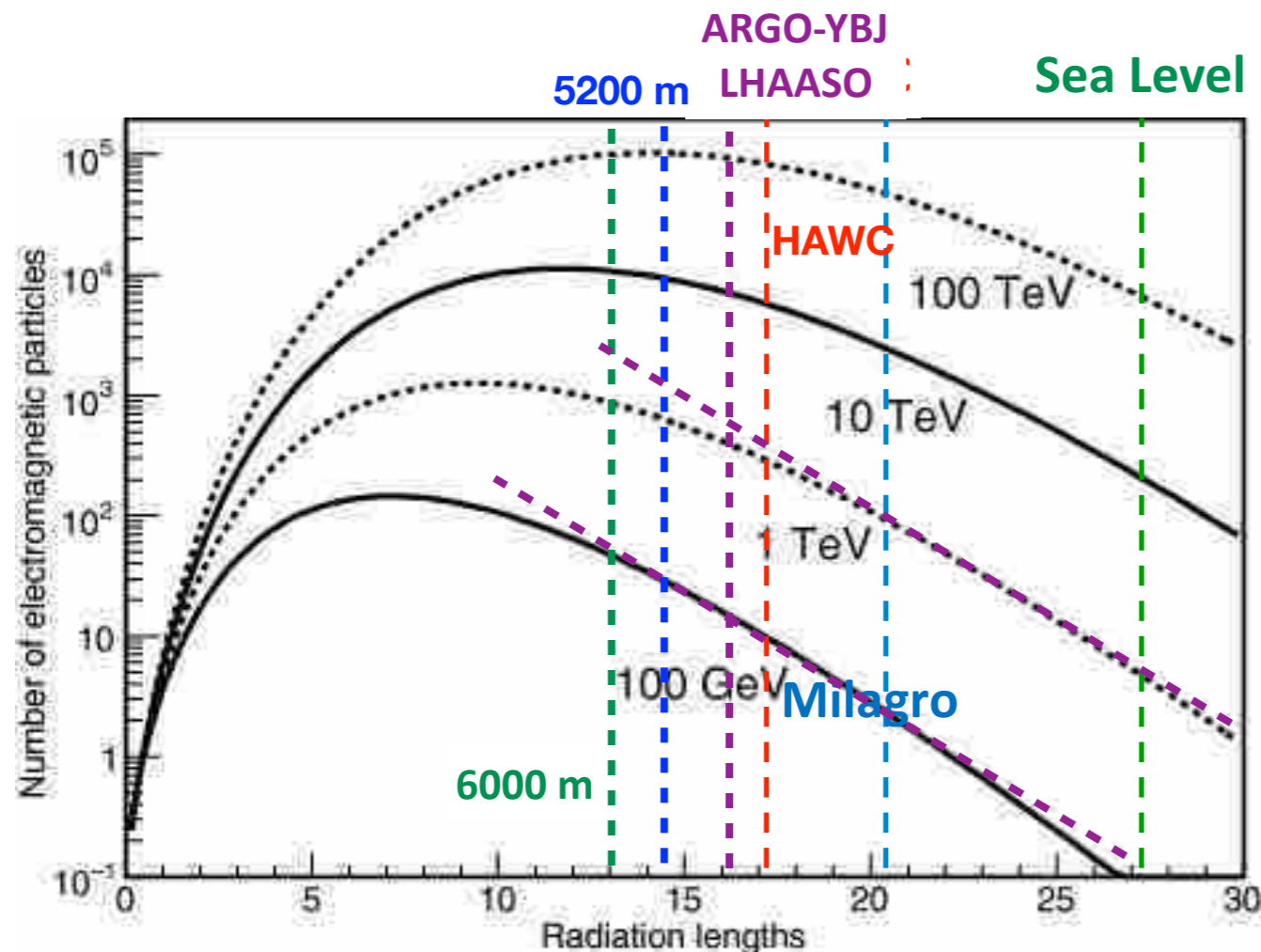
$A_{eff}^{\gamma,p}(E)$  = effective area

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

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



# Lowering the energy threshold: extreme altitude



Showers of all energies have the same slope after shower maximum:  $\approx 1.65x$  decrease per r.l. .

So, for all energies, if a detector is located one radiation length higher in atmosphere, the result will be a  $\approx 1.65x$  increase in the energy observable.

HAWC (4100 m asl)

ARGO-YBJ/LHAASO (4400 m asl) = 1, 1 energy thr.

Chacaltaya (5200 m asl)  $\approx 2x$ ,  $\approx 3x$  energy thr.

6000 m asl  $\approx 3x$ ,  $\approx 5x$  energy thr.

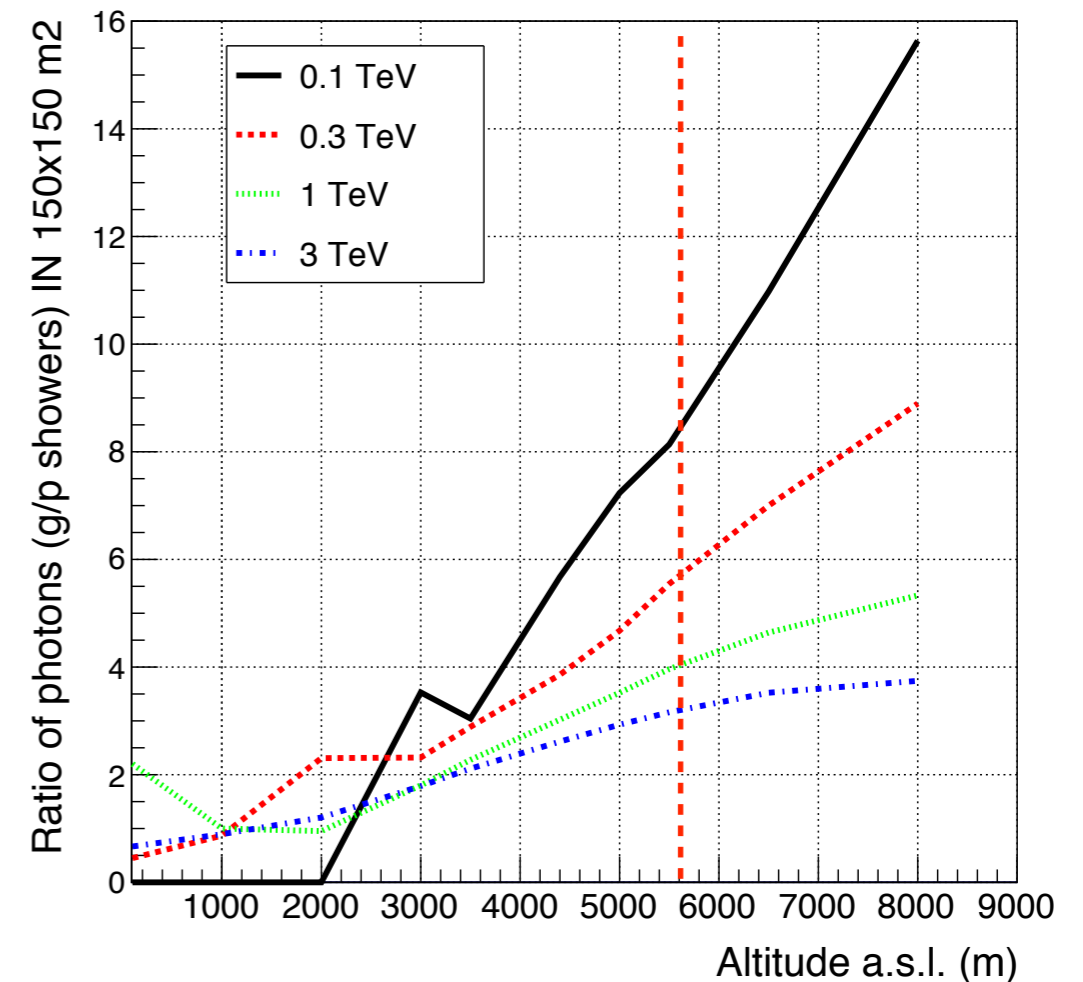
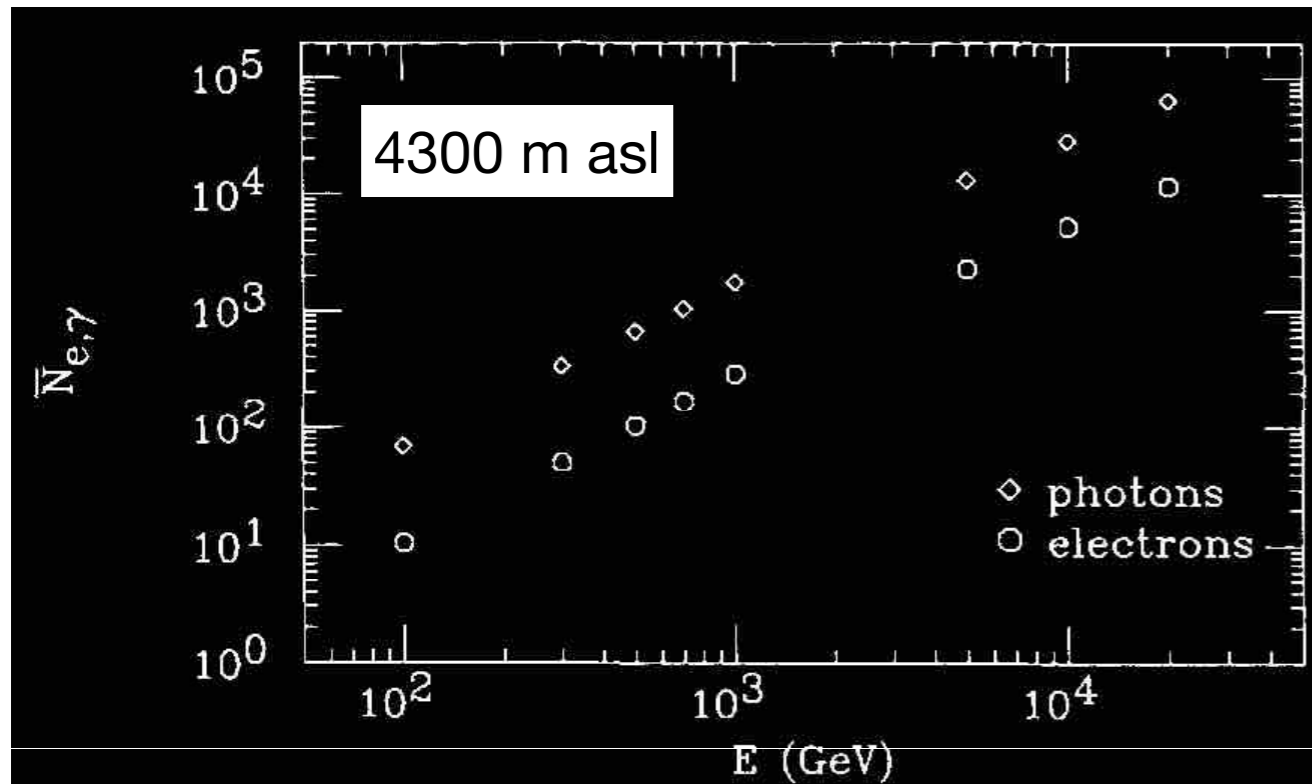
This imply that the effective areas of EAS detectors increases at low energies.

Lowering the energy threshold:

- Extreme altitude ( $>4400$  m asl)
- Detector and layout
- Coverage
- Detection of secondary photons

# Secondary photons

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



In  $\gamma$ -showers the ratio  $N_\gamma/N_{ch}$  decreases if the comparison is restricted to a small area around the shower core. For instance, we get  $N_\gamma/N_{ch} \approx 3.5$  at a distance  $r < 50$  m from the core for 100 GeV showers.

The number of secondary photons in  $\gamma$ -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**

# $\gamma/p$ detection efficiency

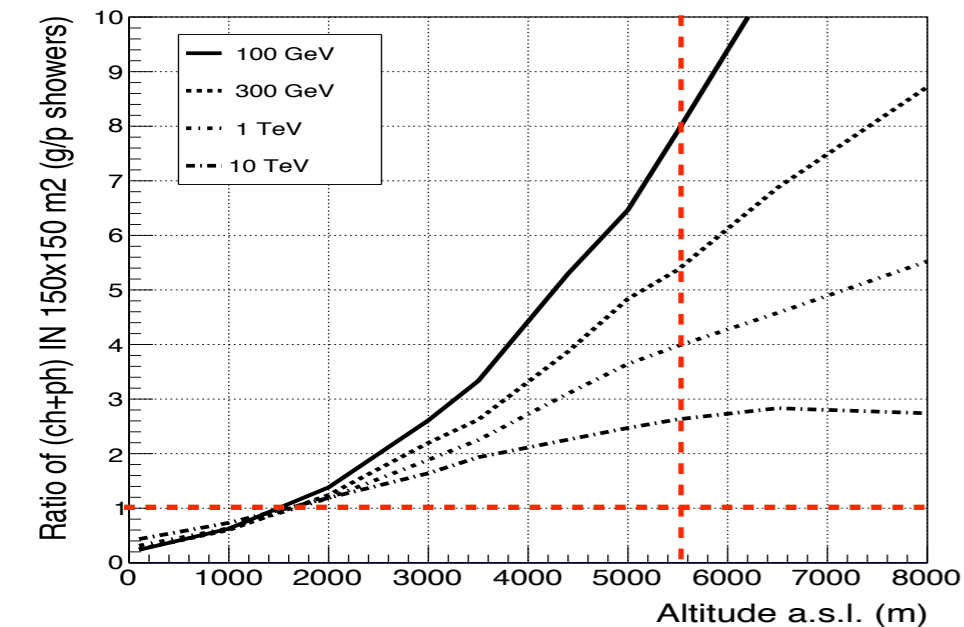
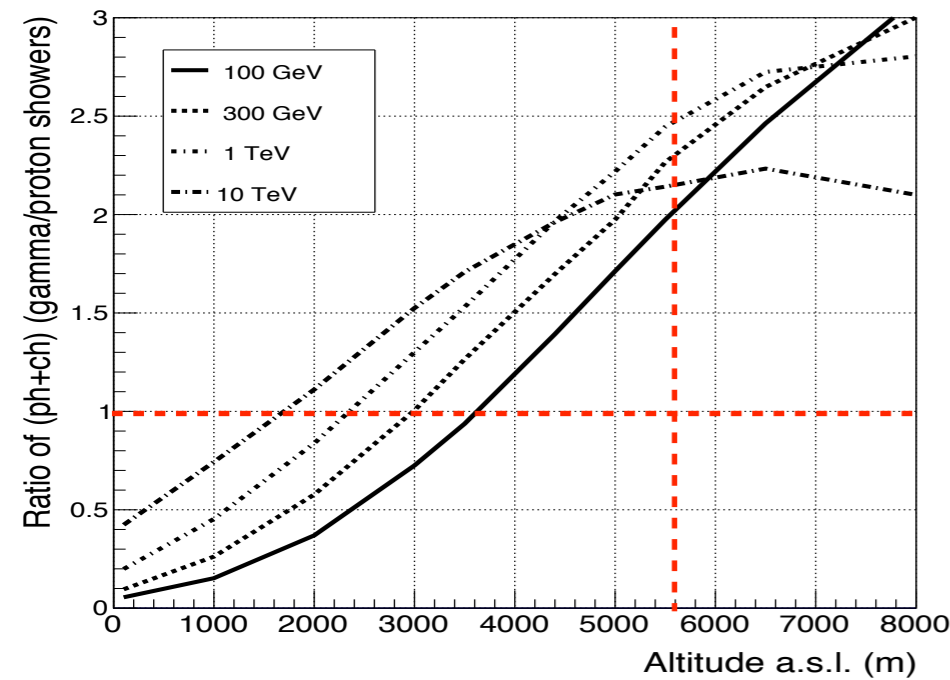
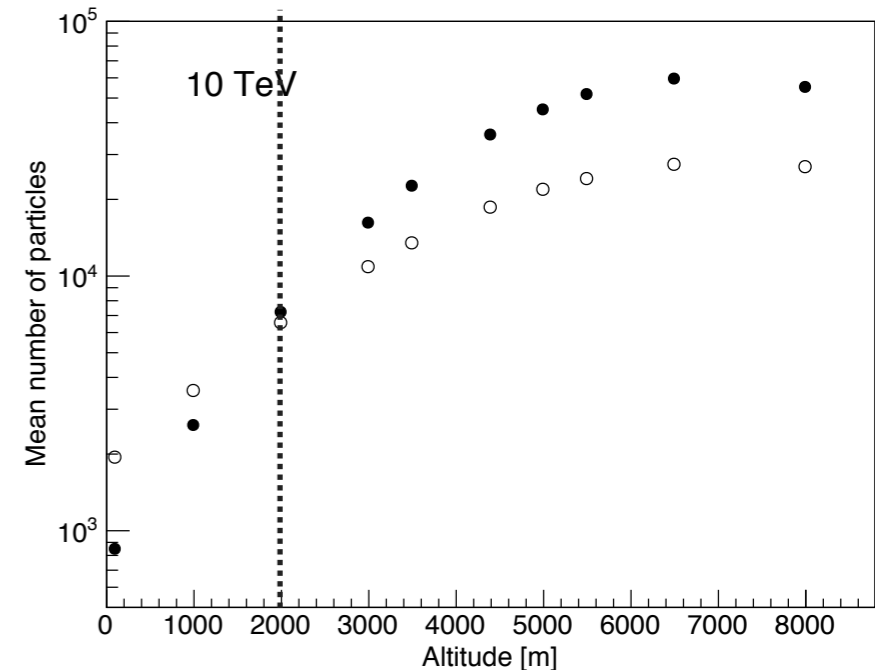
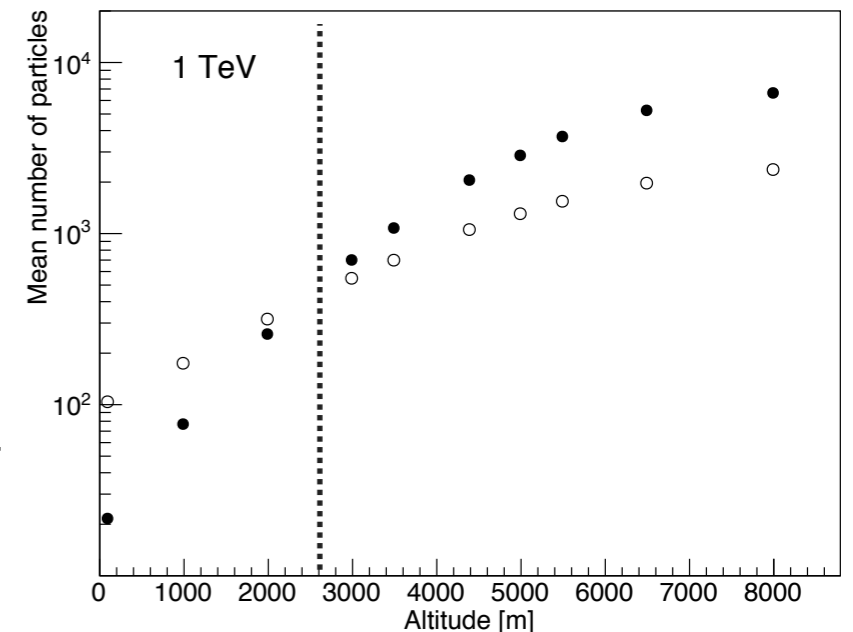
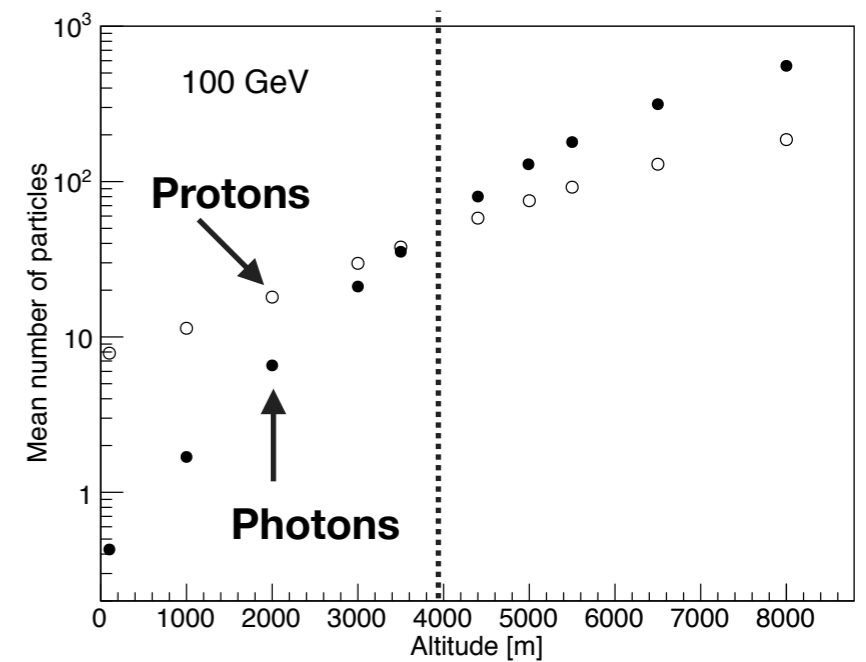
High altitude  $\rightarrow$  rejection of the background 'for free' !

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

$\gamma$ /hadron relative trigger efficiency

The number of particles in  $\gamma$ -showers exceeds the number of particles in p-showers at extreme altitude.

Trigger probability of a detector larger for  $\gamma$ -showers than for p-showers at extreme altitude.



# 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**:

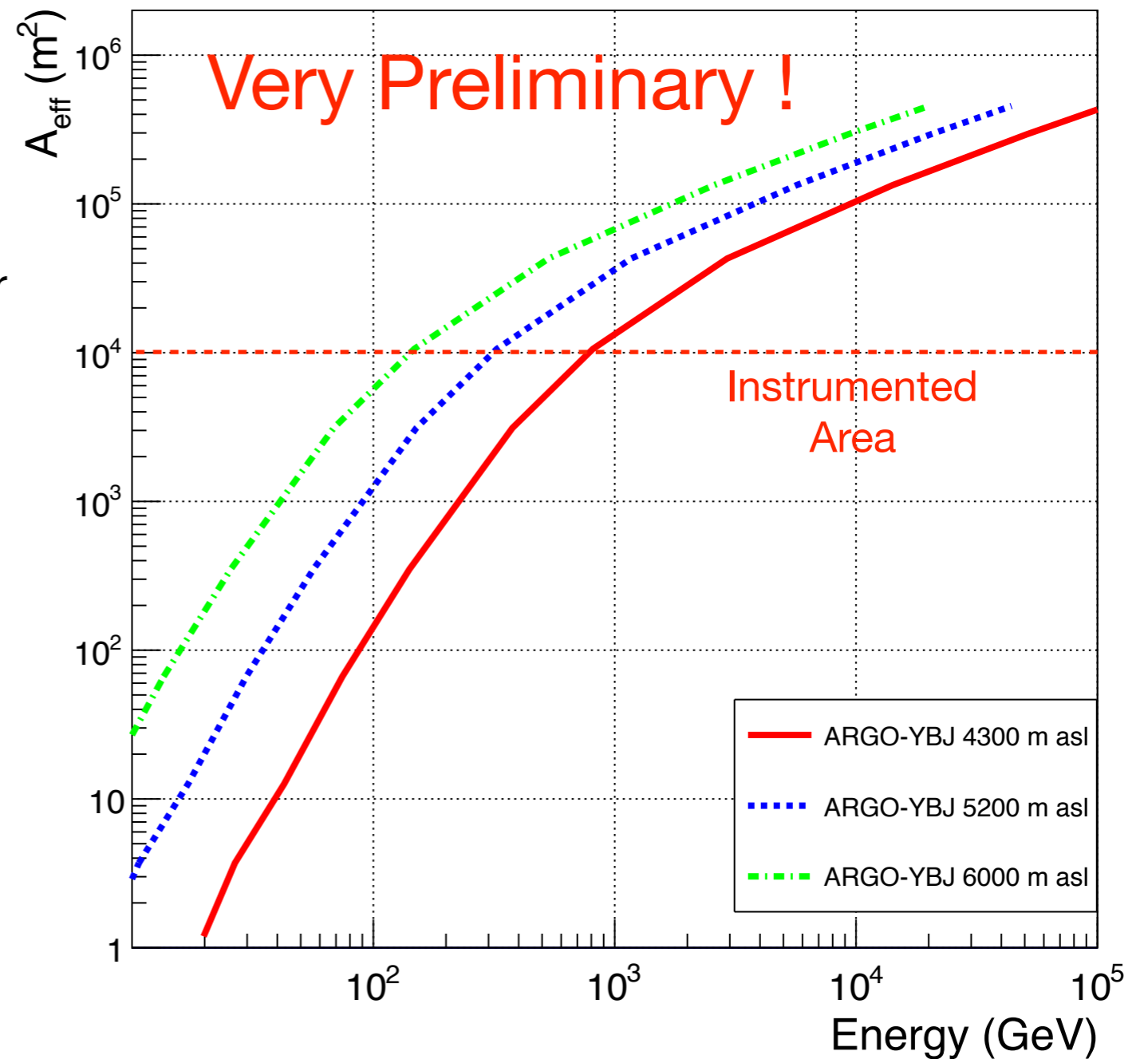
$\approx 1000 \text{ m}^2$  at 5200 m asl

$\approx 5000 \text{ m}^2$  at 6000 m asl

Effective Areas at **300 GeV**:

$\approx 10,000 \text{ m}^2$  at 5200 m asl

$\approx 20,000 \text{ m}^2$  at 6000 m asl



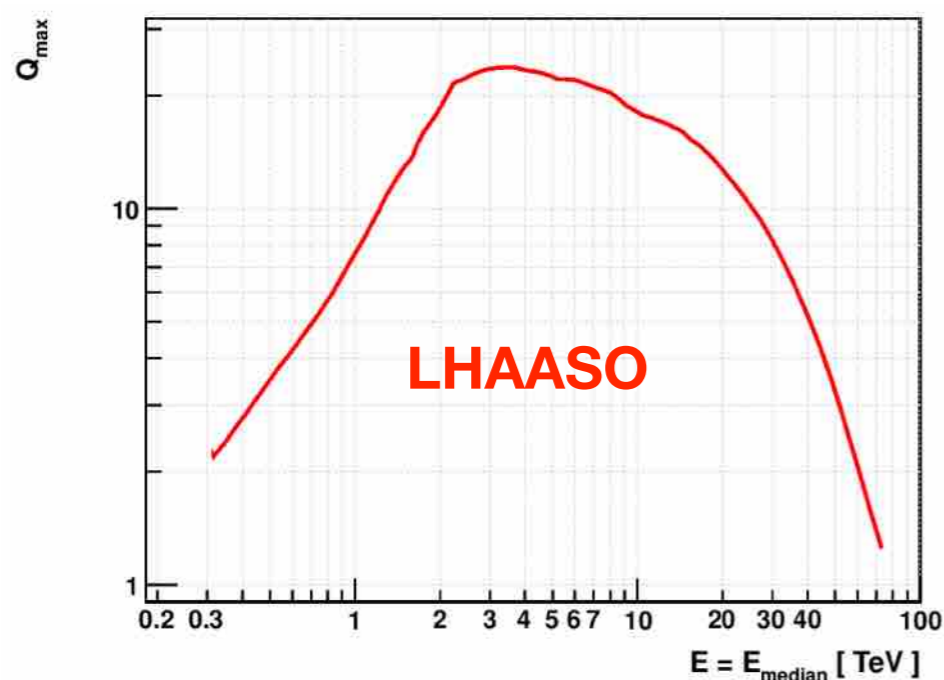
# Gamma/Hadron discrimination

Very difficult at low energy (< 1 TeV)

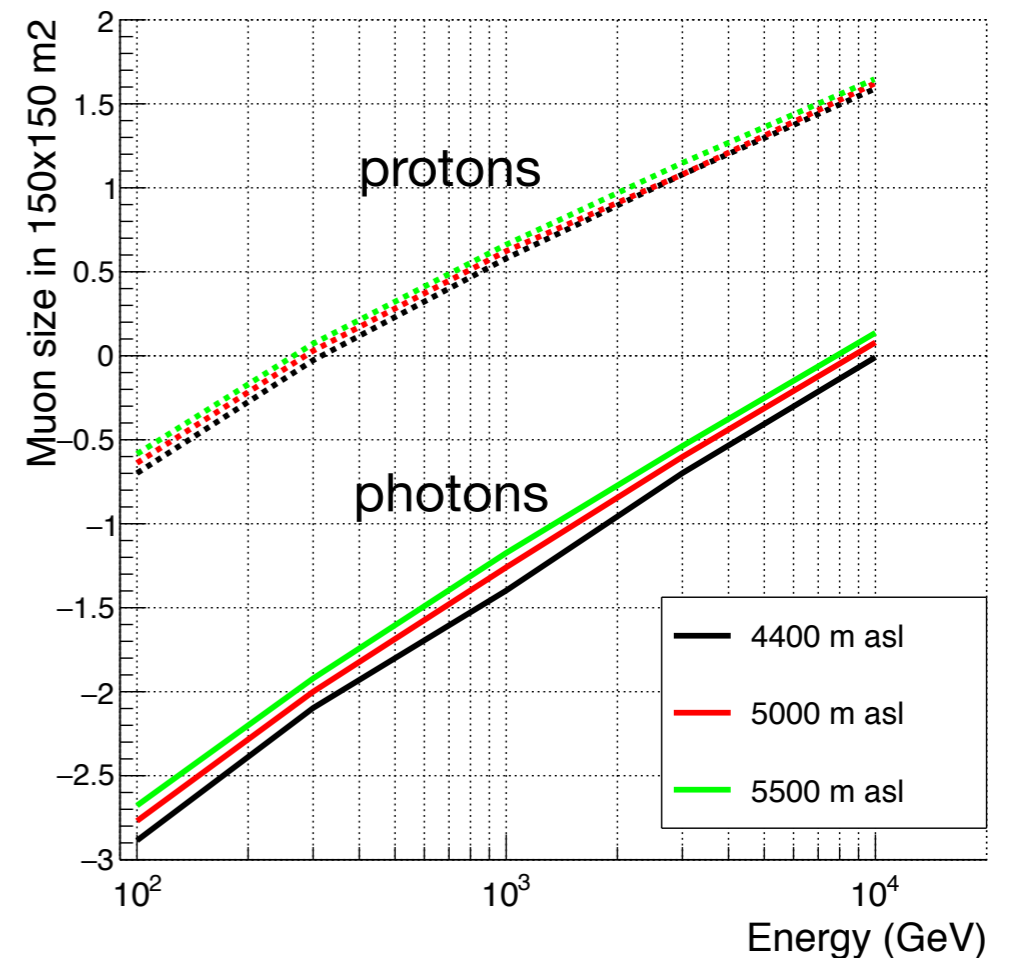
Muon size very small

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



LHAASO Q-factor: 3 at 500 GeV, 7 at 1 TeV, 22 at 5 TeV.



Discrimination depends on detector area  
 → according to HAWC/LHAASO calculations  
 sensitivity  $\approx A_{\text{eff}}^{0.8}$  and not  $A_{\text{eff}}^{0.5}$  up to  $\approx 300 \times 300 \text{ m}^2$   
 at TeV energies

**New ideas ?**

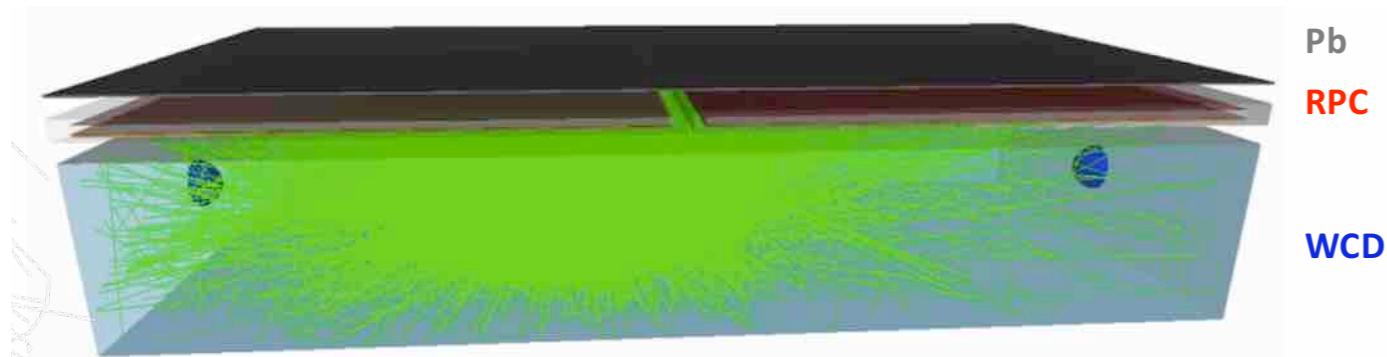
# A hybrid detector: LATTES

arXiv:1607.03051

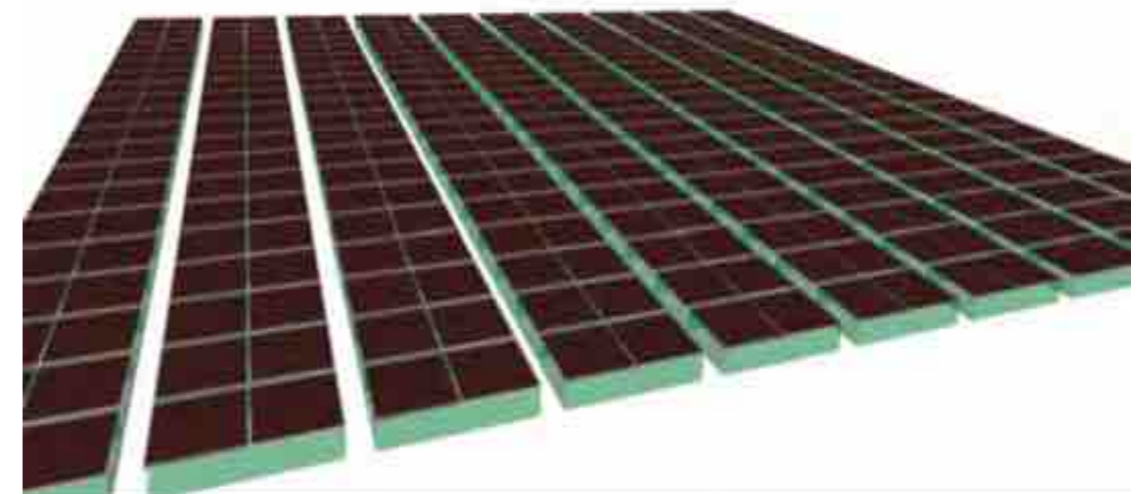
P. Assis, U. Barres de Almeida, A. Blanco, R. Conceicao, B. D'Ettorre Piazzoli, A. De Angelis, M. Doro, P. Fonte, L. Lopes, G. Matthiae, M. Pimenta, R. Shellard, B. Tome'

An **array of hybrid detectors** constituted by

1. one Water Cherenkov Detector (WCD) with a rectangular horizontal surface of 3 m × 1.5 m and a depth of 0.5 m, with signals read by PMTs at both ends of the smallest vertical face of the block.
2. On top of the WCD there are two MARTA RPCs, each with a surface of (1.5 × 1.5) m<sup>2</sup> and with 16 charge collecting pads. Each RPC is covered with a thin (5.6 mm) layer of lead.



- **Thin lead plate (Pb)**
  - 5.6 mm (one radiation length)
- **Resistive Plate Chambers (RPC)**
  - 2 RPCs per station
  - Each RPC with 4x4 readout pads
- **Water Cherenkov Detector (WCD)**
  - 2 PMTs (diameter: 15 cm)
  - Dimensions: 1.5 m x 3 m x 0.5 m

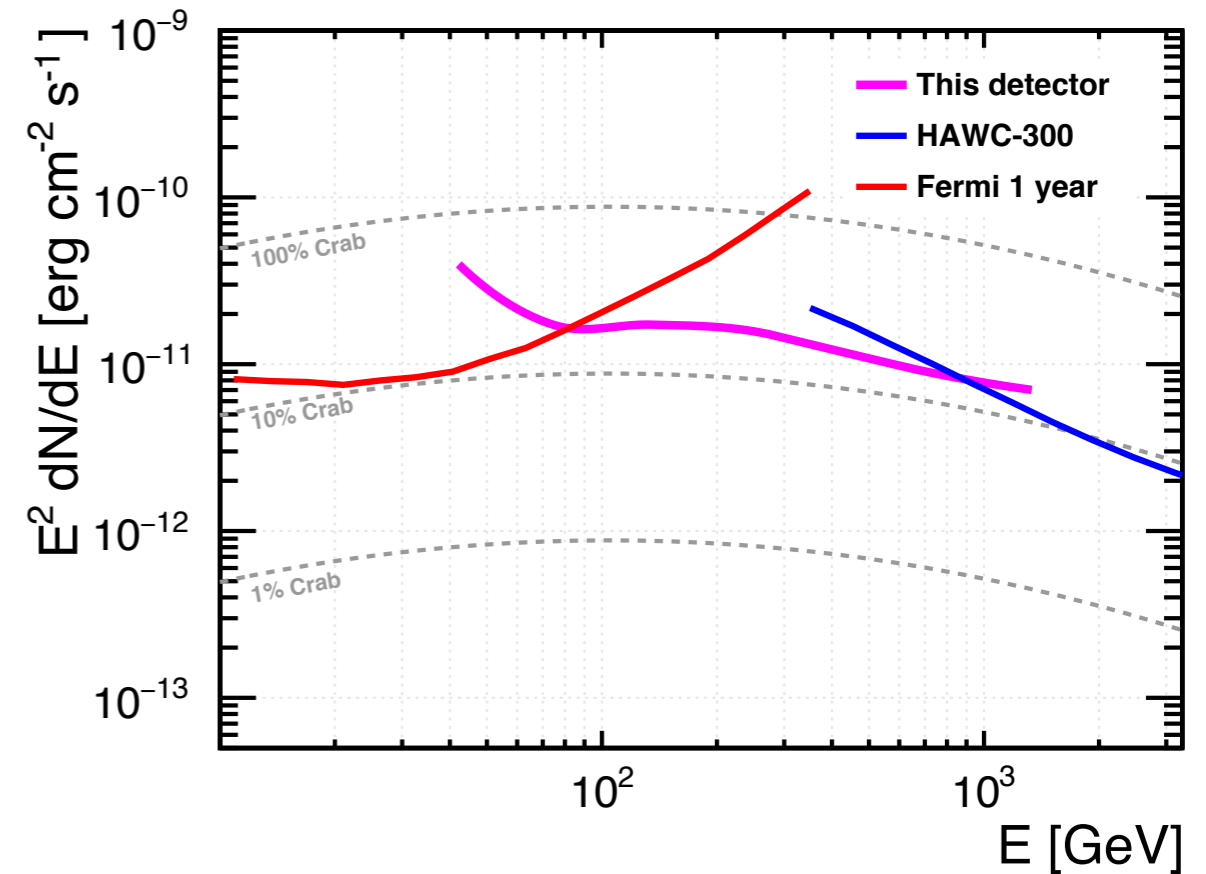
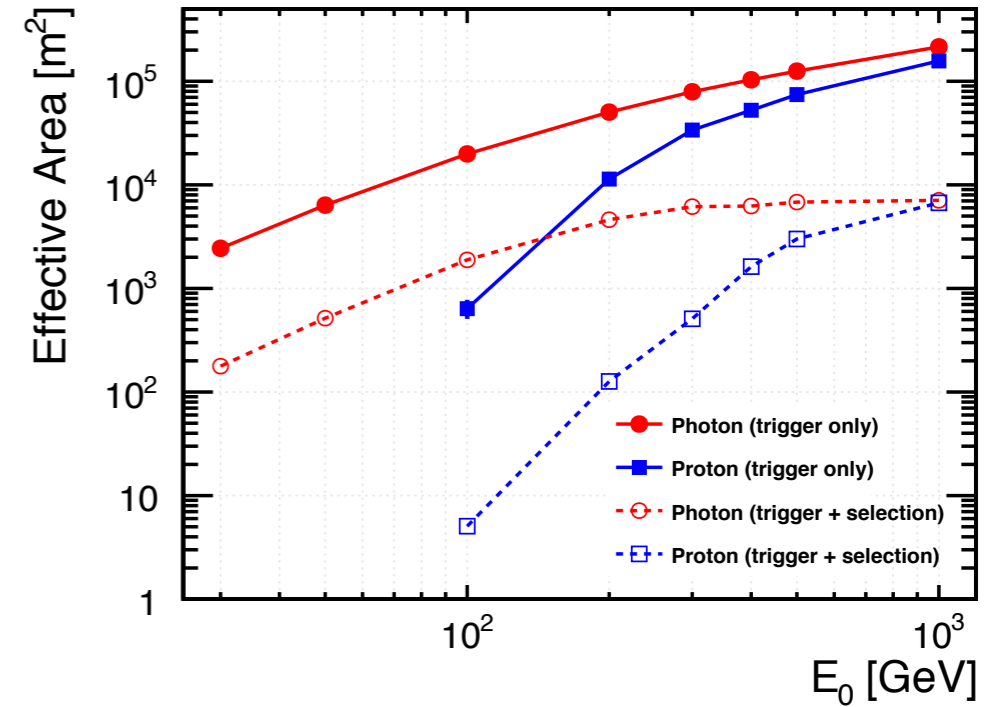
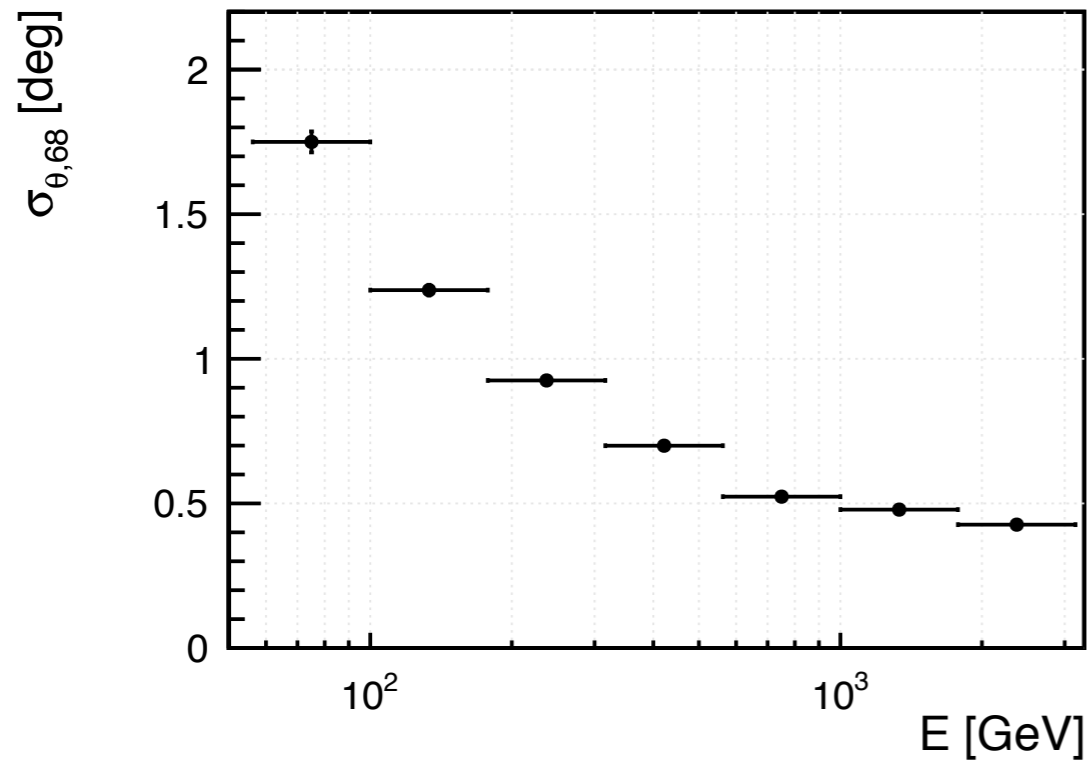


# LATTES performance

Very Preliminary calculations

Baseline configuration with 60 rows and 30 lines,  
instrumented area  $\approx 10,000 \text{ m}^2$ .

Simulated site at 5200 m asl



# Conclusions

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Open problems in cosmic ray physics push the construction of **new generation EAS arrays to study**, in the  $10^{11} - 10^{18}$  eV energy range, **at the same time photon- and charged-induced events**.

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

Benefits of RPCs in ARGO-YBJ:

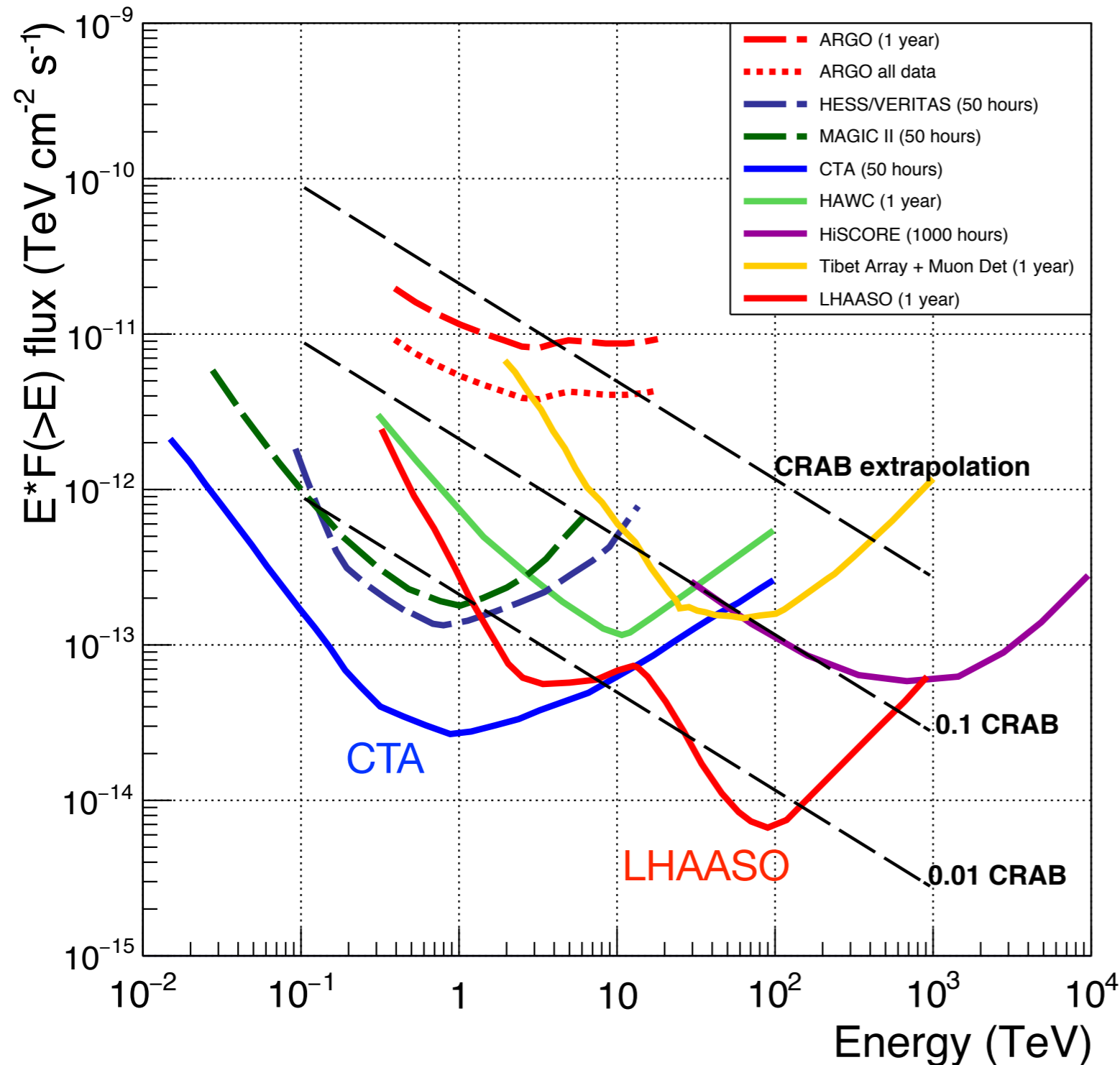
- **dense sampling** → low energy threshold ( $\approx 300$  GeV)
- **wide energy range** (with charge read-out):  $\approx 300$  GeV → 10 PeV
- **high granularity of the read-out** → good angular resolution and unprecedented details in the core region

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

- With CTA coming a future all-sky array should have  $\sim 5x$  increase in sensitivity over LHAASO at least.
- Extragalactic transient detection requires low threshold,  $\approx 100$  GeV.
- **Extreme altitude** (5500 m asl) and **high coverage** are key.
- New detector ideas are under study to improve the bkg rejection below TeV.



# Sensitivity to gamma point sources



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.

The big advantage of EAS arrays

- High Energy (>10 TeV)
- Sky Survey

# (p+He) spectrum below 300 TeV: data selection

Analysis of **digital RPC** data (strip multiplicity) and **statistical** measurement of the energy spectrum by using a **bayesian approach**.

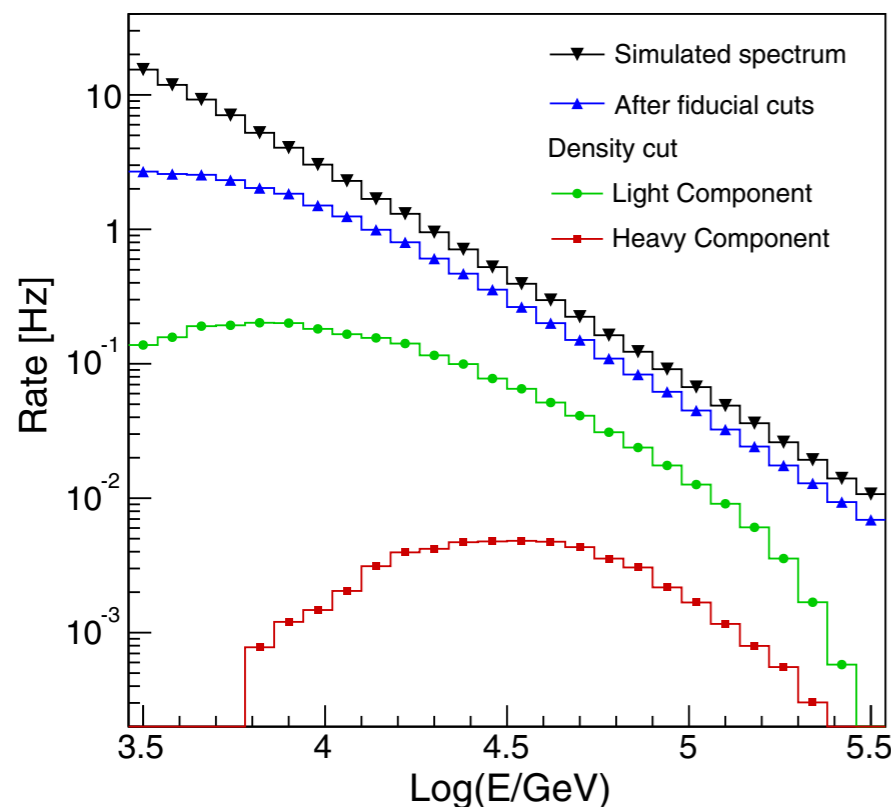
Data collected between Jan. 2008 and Dec. 2012  $\approx 8 \times 10^{10}$  high quality events

- $M \leq 50,000$
- Zenith Angle  $\leq 35^\circ$
- Highest density cluster in  $40 \times 40 \text{ m}^2$
- **Light Component (p+He) selection:**

$$\rho_{A20} > 1.25 \rho_{A42}$$

A20 = 20 innermost clusters

A42 = 42 outermost clusters



Fraction of selected events:

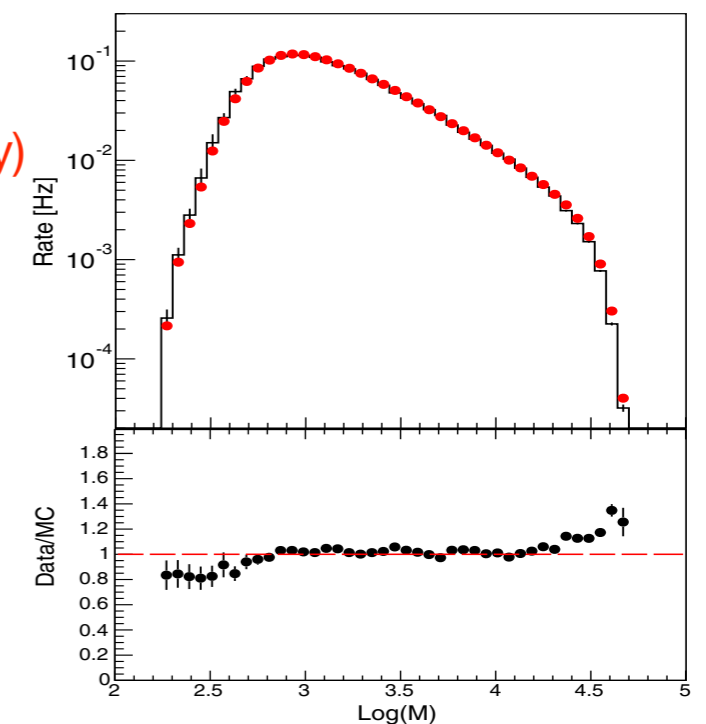
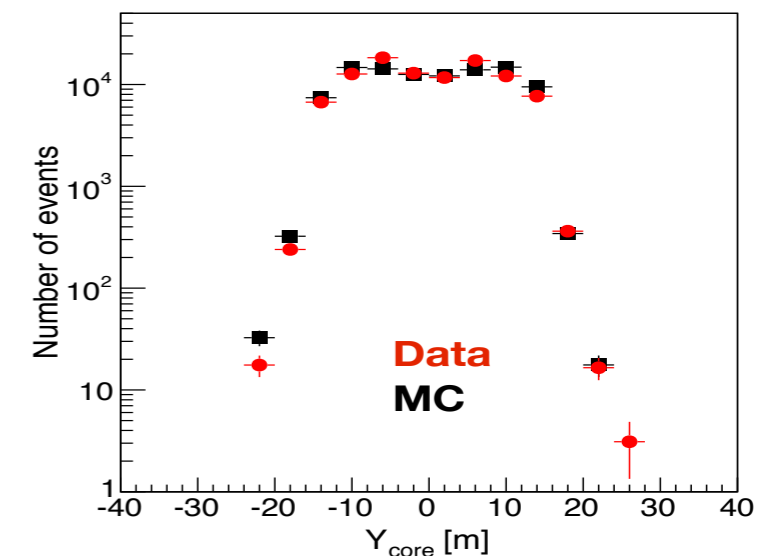
30 TeV  $\rightarrow$  18%

115 TeV  $\rightarrow$  24%

Shower size distribution on the central carpet, **M** (strip multiplicity)

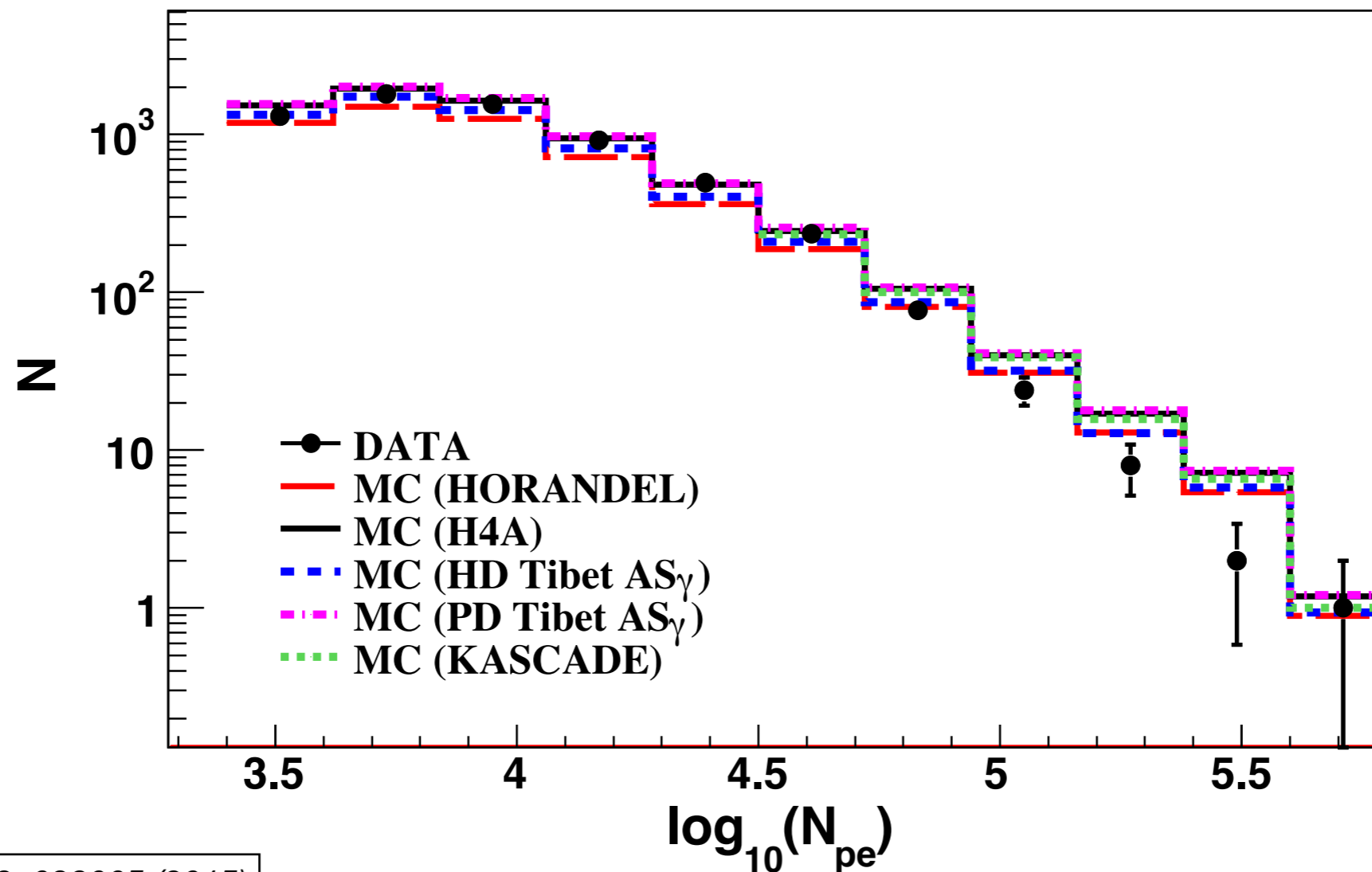
Phys. Rev. D85, 092005 (2012)  
Phys. Rev. D91, 112017 (2015)

Reconstructed shower core position



# ARGO-YBJ/WFCTA: All-particle spectrum

Distribution of the number of Cherenkov photo-electrons measured by the telescope compared to expectations according to different all-particle spectra



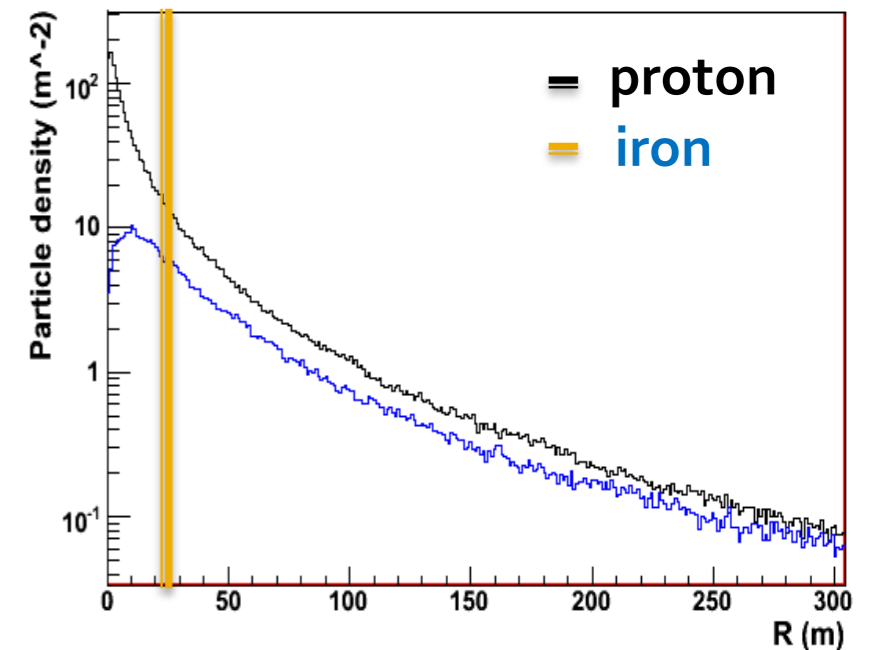
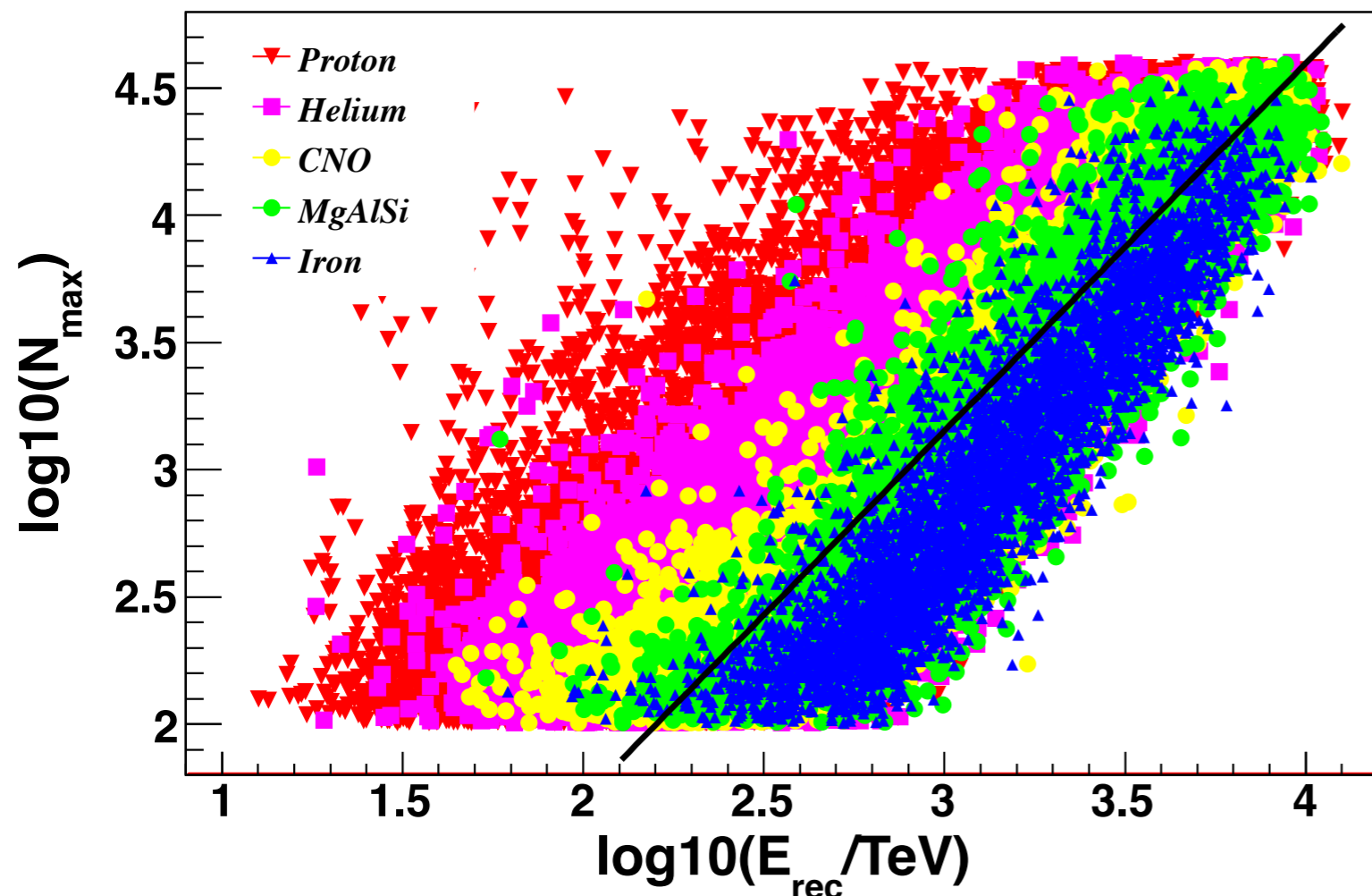
*Phys. Rev. D 92, 092005 (2015)*

# Light component (p + He) selection - (1)

According to MC, the largest number of particles  $N_{\max}$  recorded by a RPC in an given shower is a useful parameter to measure the particle density in the shower core region, i.e. within 3 m from the core position.

$N_{\max}$  is a parameter useful to select different primary masses

$N_{\max} \propto E_{\text{rec}}^{1.44}$ , where  $E_{\text{rec}}$  is the shower primary energy reconstructed using the Cherenkov telescope.



We can define a new parameter to reduce the energy dependence

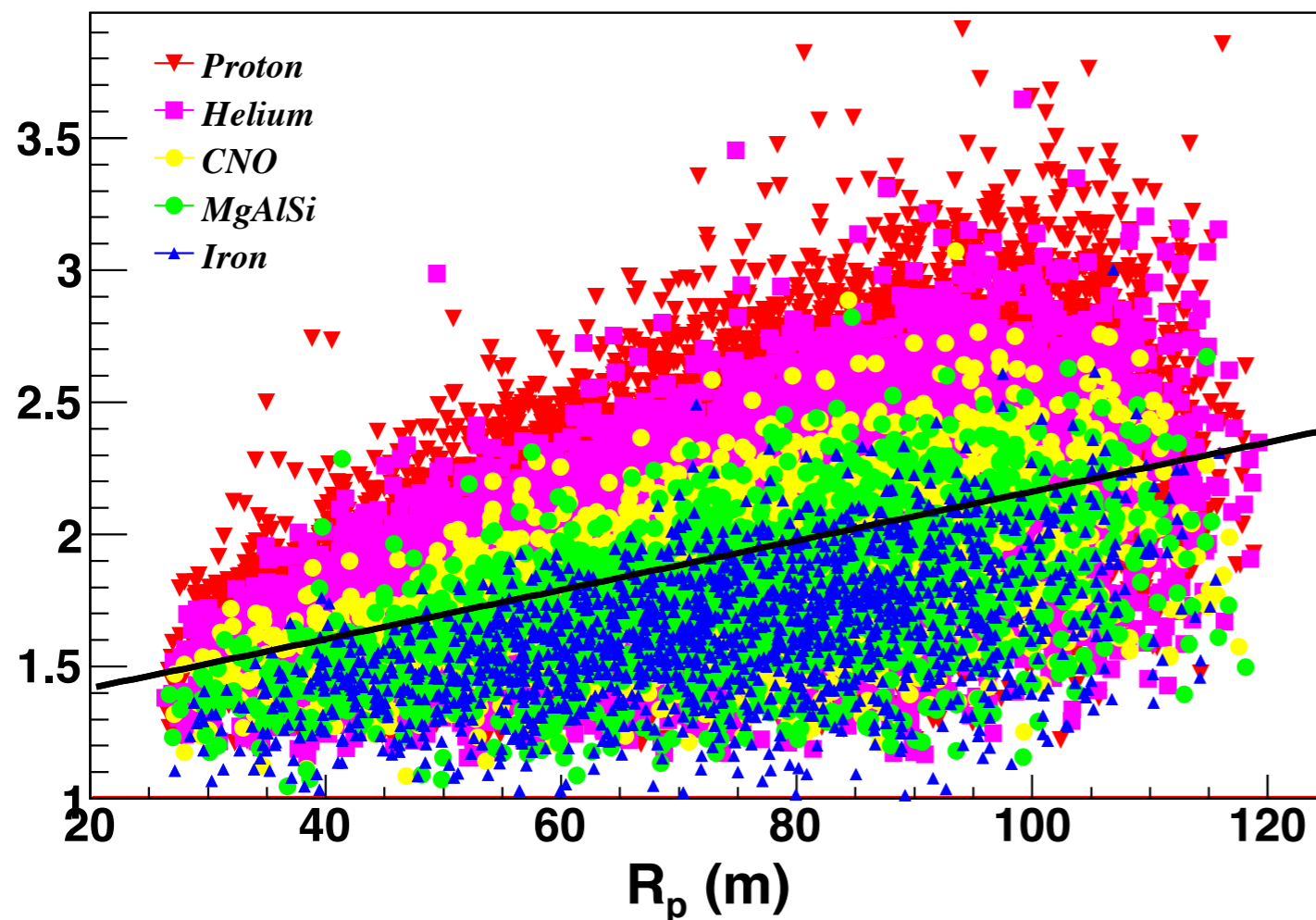
$$p_L = \log_{10}(N_{\max}) - 1.44 \cdot \log_{10}(E_{\text{rec}}/\text{TeV})$$

Chin. Phys. C 38, 045001 (2014)

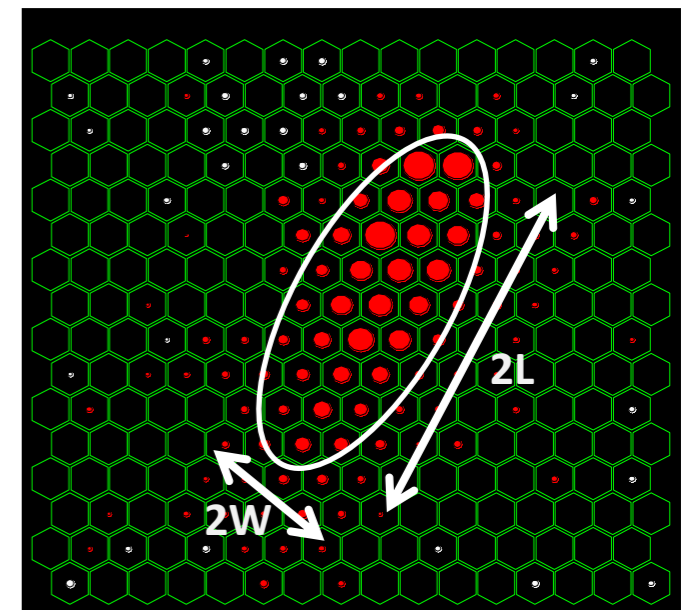
# Light component (p + He) selection - (2)

According to MC, the ratio between the length and the width (L/W) of the Cherenkov image is another good estimator of the primary mass.

Elongation of the shower image proportional to impact parameter  $L/W \sim 0.09 (R_p / 10m)$



Typical Cherenkov footprint



The shower impact parameter  $R_p$  is calculated with 2 m resolution exploiting the ARGO-YBJ characteristics.

We define a new parameter to reduce the  $R_p$  and energy dependence

$$p_C = L/W - 0.0091(R_p/1 m) - 0.14 \cdot \log_{10}(E_{rec}/TeV)$$

Chin. Phys. C 38, 045001 (2014)