ARGO-YBJ results

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Outline

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The ARGO-YBJ detector

A very simple approach to Air Shower detection.

The ARGO-YBJ Physics

Gamma-Ray Astronomy

- Study of the Cygnus region: the Cygnus Cocoon
- Diffuse γ-ray emission
- Flaring TeV γ-ray sky

Cosmic Ray Physics

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

Presentation based on **G. Di Sciascio's talk at ISVHECRI2016**, Moscow (some slides too nice to modify: just copied and pasted!)

ARGO-YBJ did a lot of good Physics in the last decade: quoting all results would take more than 20 mins. I will focus on most important and recent achievements. Biased selection: personal taste as well as credited presentation.

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

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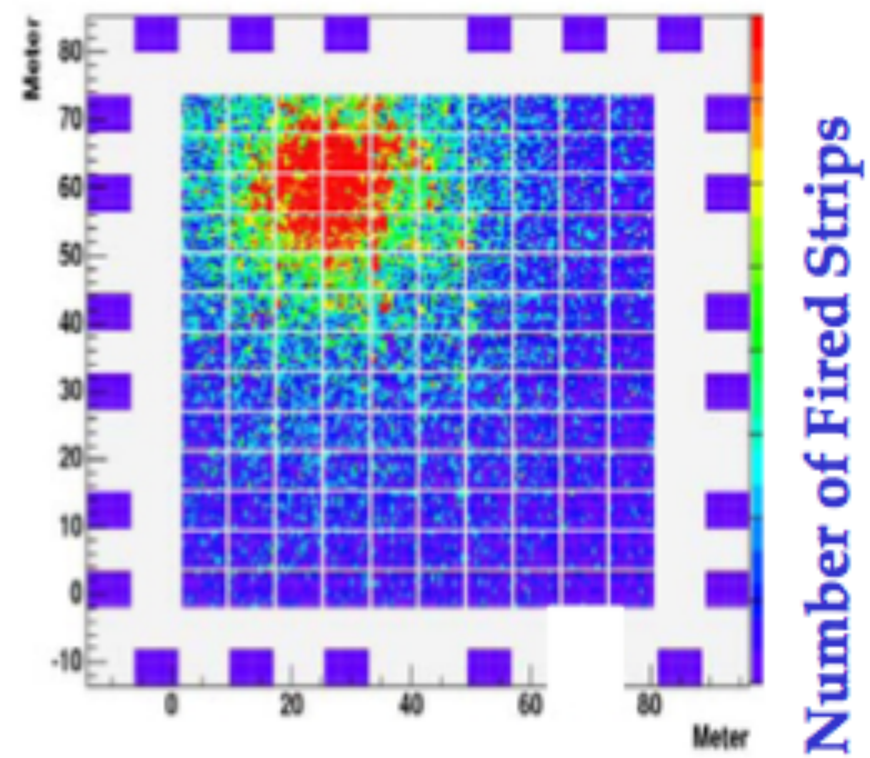
90s: a novel approach

The concept dates back to late 80s – early 90s:

- TeV gamma ray astrophysics almost unexplored and very promising to understand the origin of cosmic rays.
- Need for exposures unconceivable for satellites at that time.
- Shower detection is the only way (particles or Cerenkov).
- The TeV threshold is 10-100 times lower than traditional apparatuses for air showers.



❖ HIGH ALTITUDE SITE

(YBJ - Tibet 4300 m asl - 600 g/cm2)

❖ FULL COVERAGE

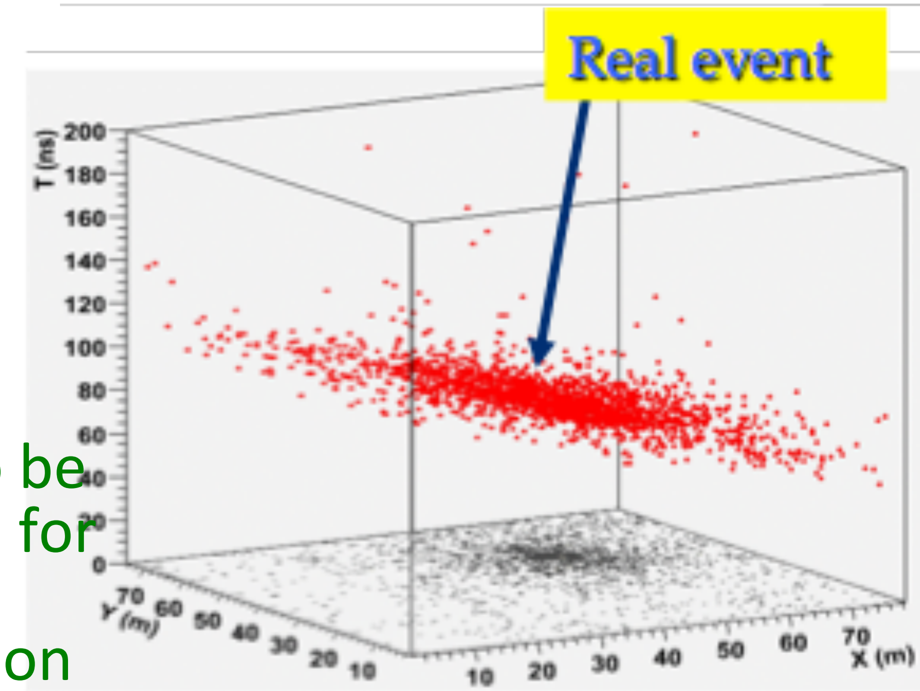
(RPC technology, 92% covering factor)

❖ HIGH SEGMENTATION OF THE READOUT

(small space-time pixels)

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

Intended to be of some use for primary identification



The ARGO-YBJ experiment

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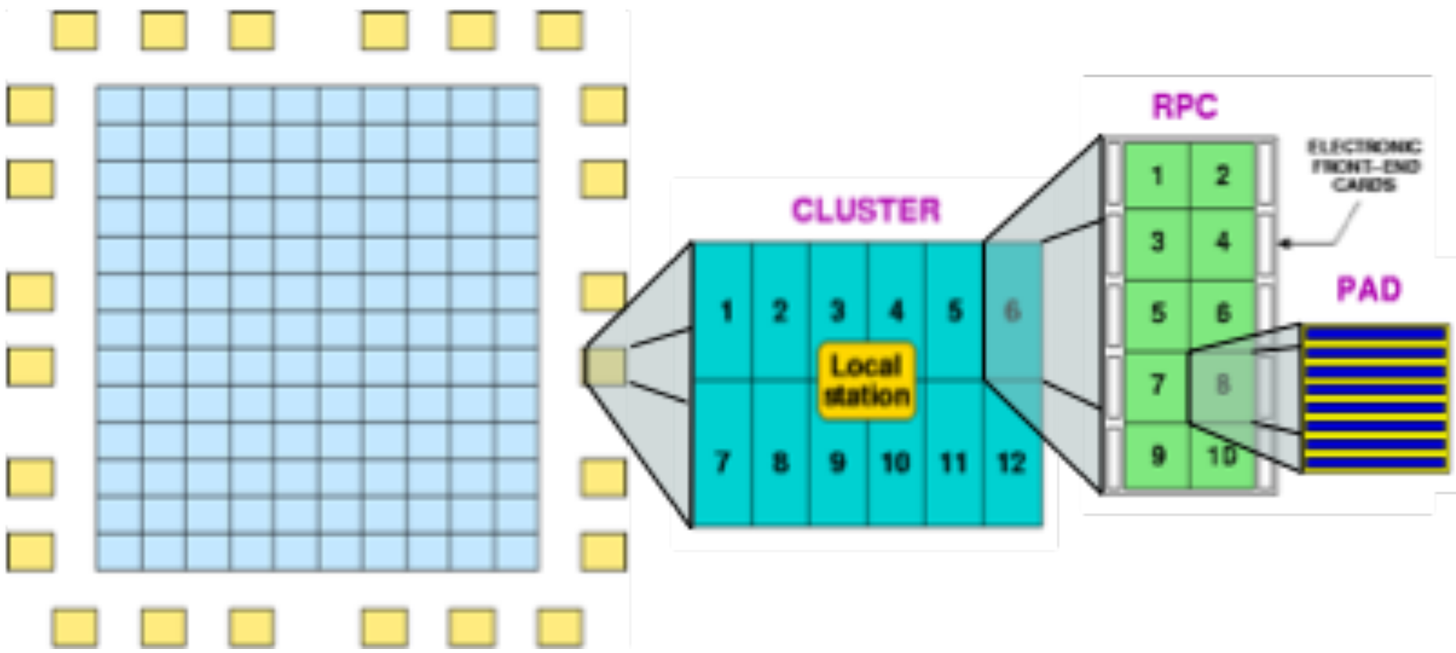
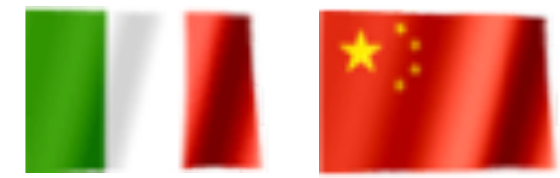
ARGO-YBJ is a telescope optimized for the detection of small size air showers



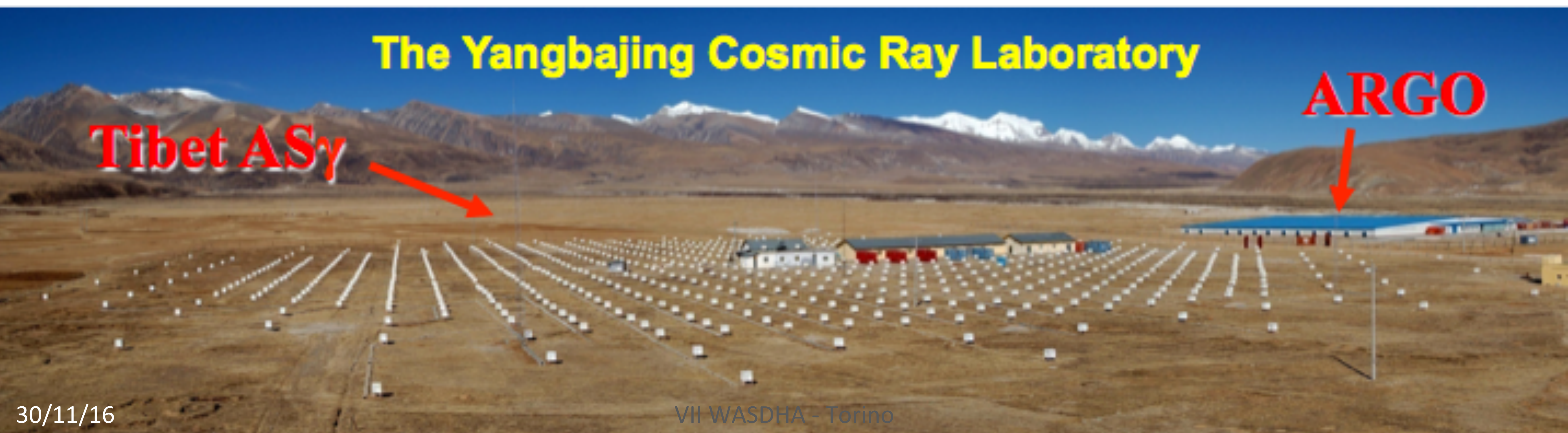


INFN IHEP/CAS

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

90 km North from Lhasa (Tibet)

4300 m above sea level
$\sim$ 600 g/cm^2



The ARGO-YBJ layout

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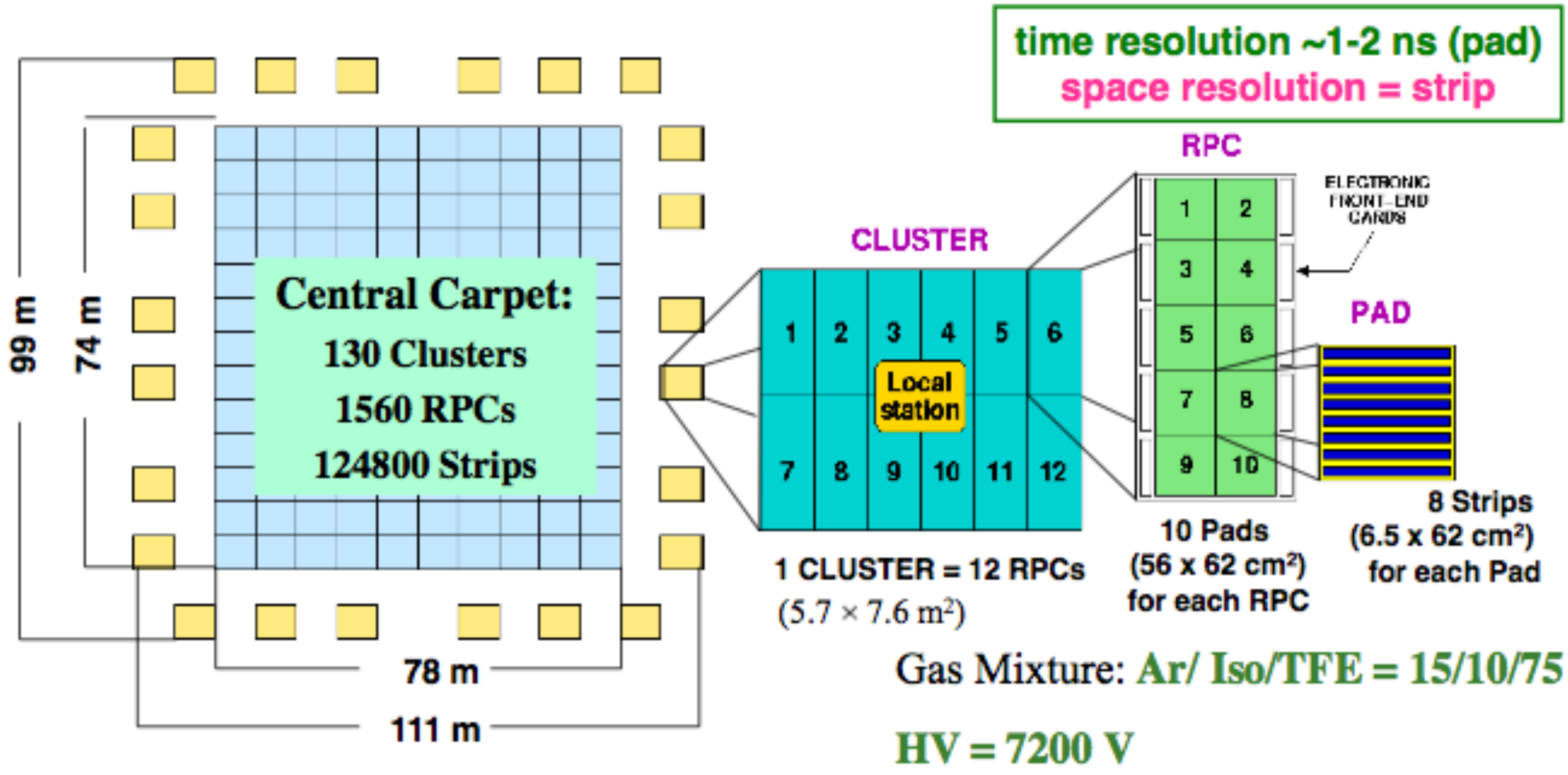

Single layer of Resistive Plate Chambers (RPCs)
with a full coverage (92% active surface) of a large area (5600 m²)
+ sampling guard ring (6700 m² in total)

The RPC charge readout

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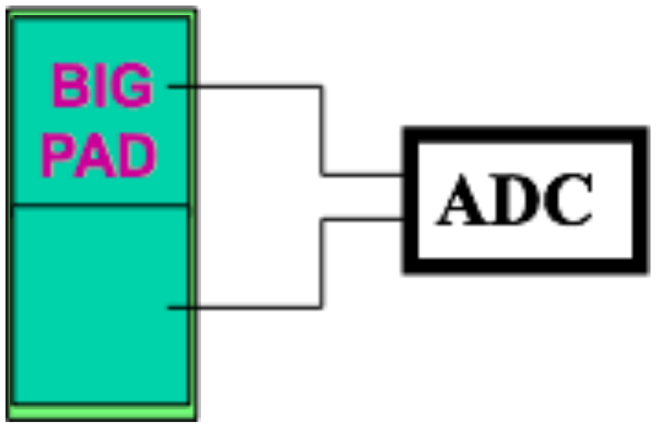
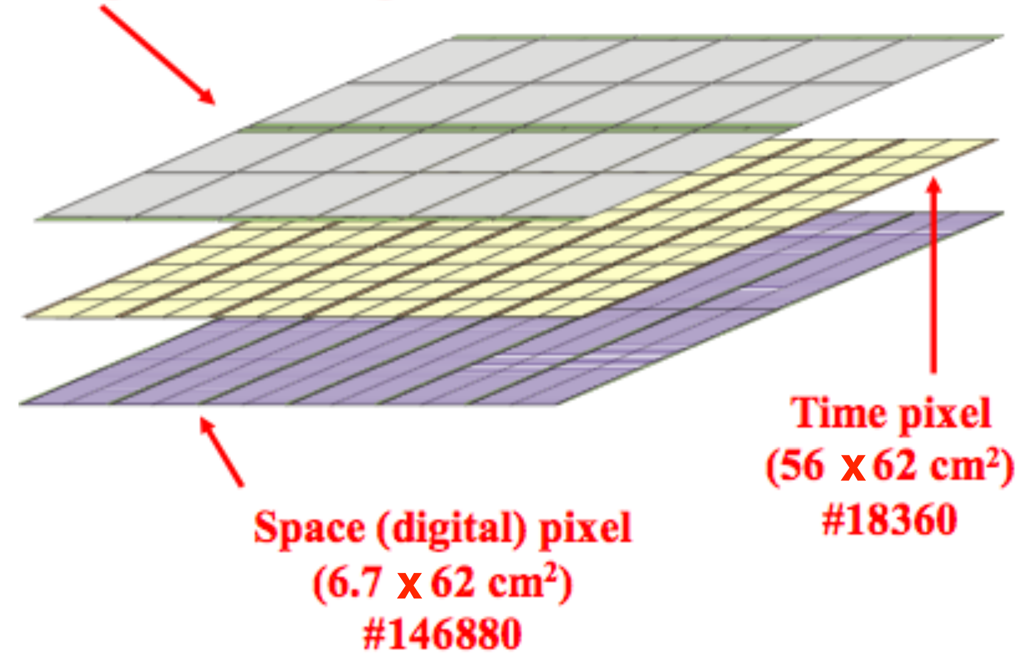


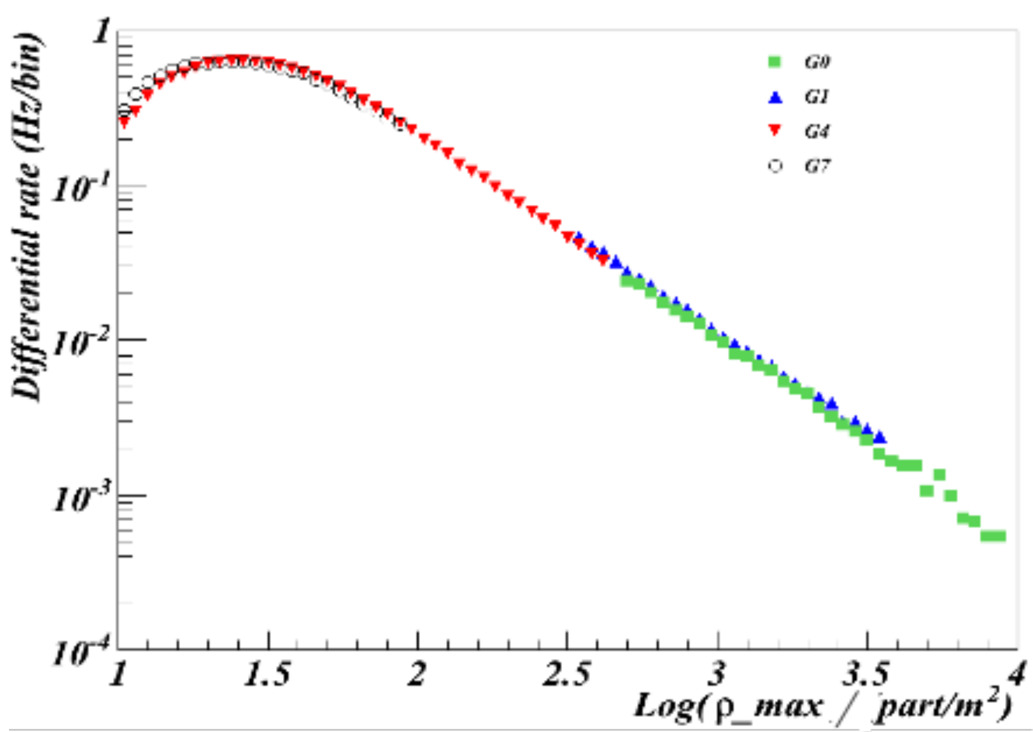
4 different gain scales used to cover a wide range in particle density:

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

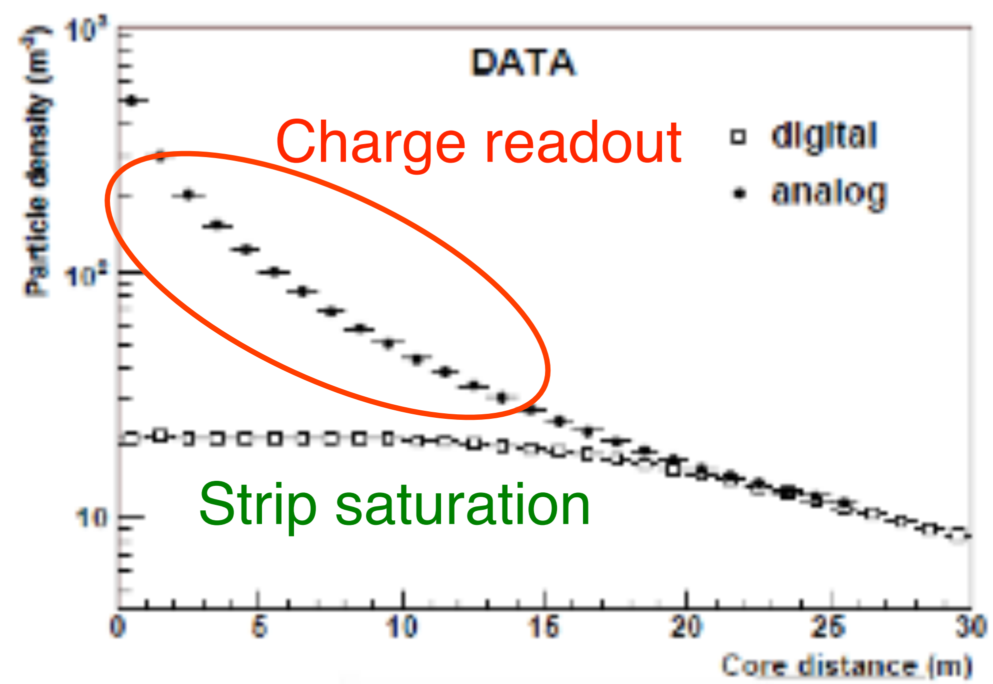
$\rho_{max-analog} \approx 10^4$ particles/m^2



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



Astrop. Phys. 67 (2015) 47



Intrinsic linearity: test at the BTF facility

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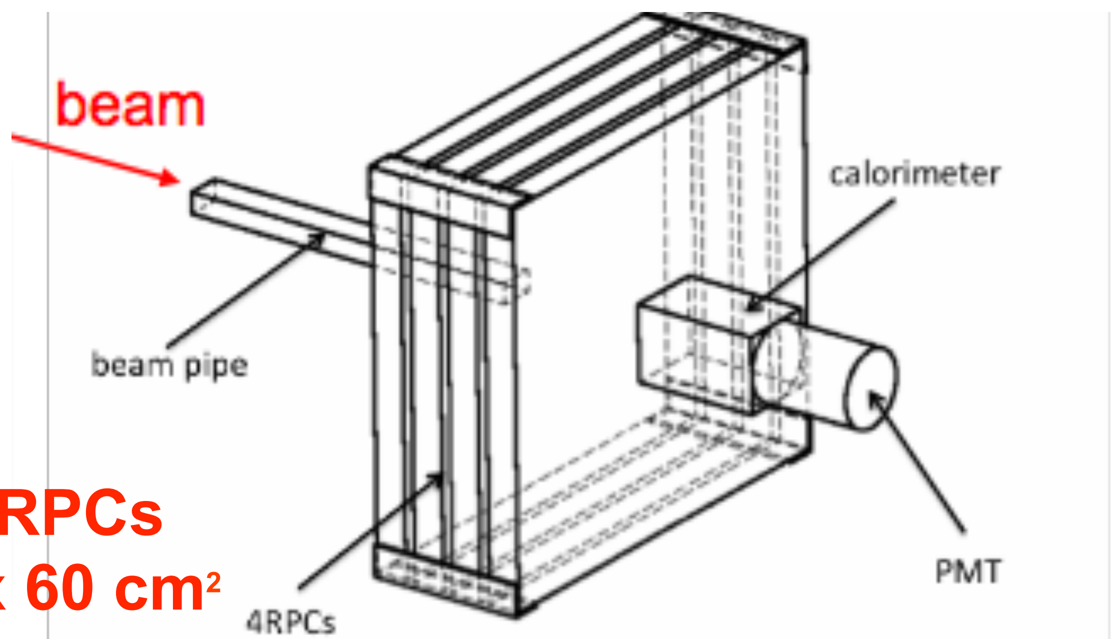
Linearity of the RPC @ BTF in INFN Frascati Lab:

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

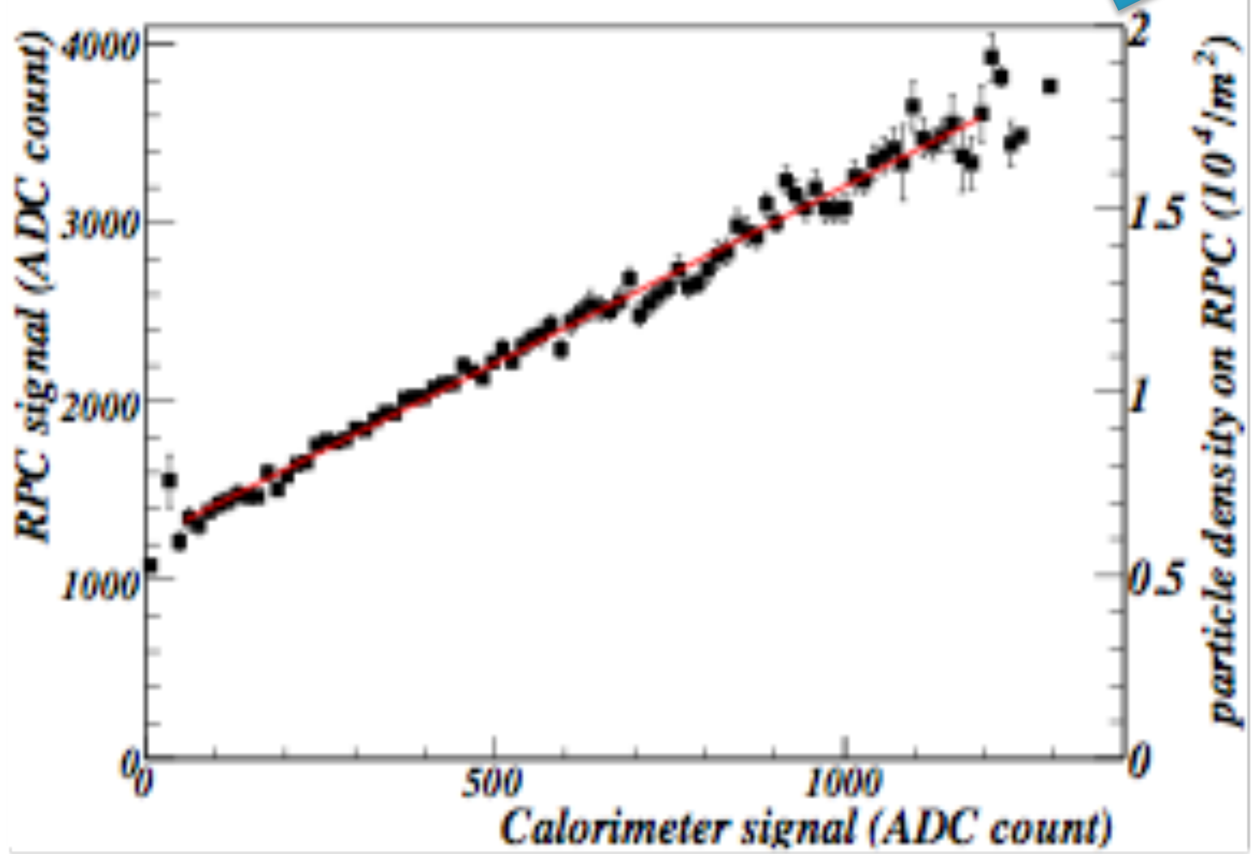
RPCs operated in streamer mode: intrinsic limit given by the transverse size of the electrode zone interested by the local discharge: few mm2 at most. In avalanche mode at least a factor of 100 less.



4 RPCs
60 x 60 cm^2

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

The RPC signal vs the calorimeter signal



→ Linearity up to ≈ 2 • 10^4 particle/m^2

Diary of board

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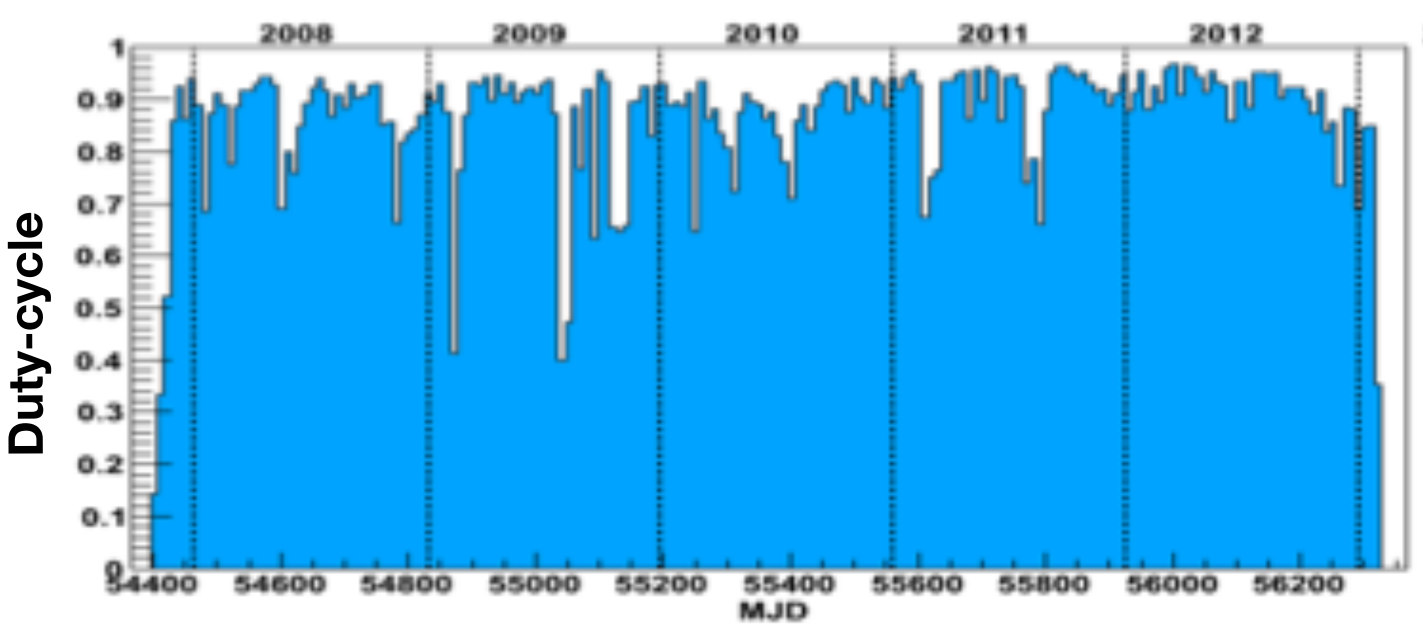
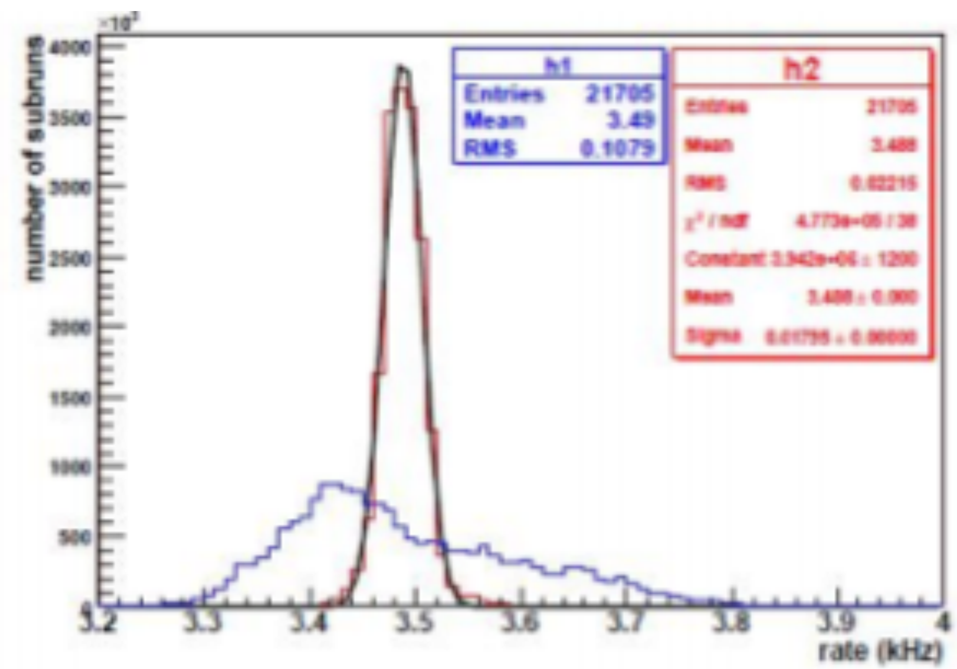
- In data taking since July 2004 (with increasing portions of the detector)
- Commissioning of the central carpet in June 2006
- Stable data taking full apparatus since November 2007
- End/Stop data taking: February 2013

- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data





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

Stability

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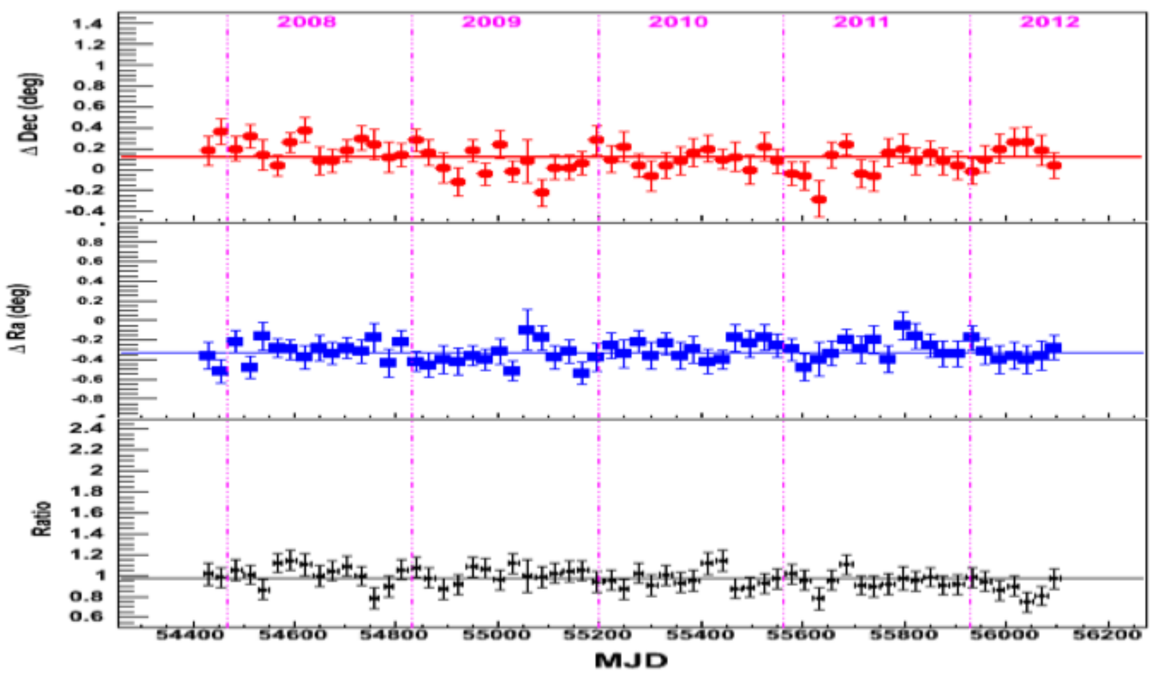
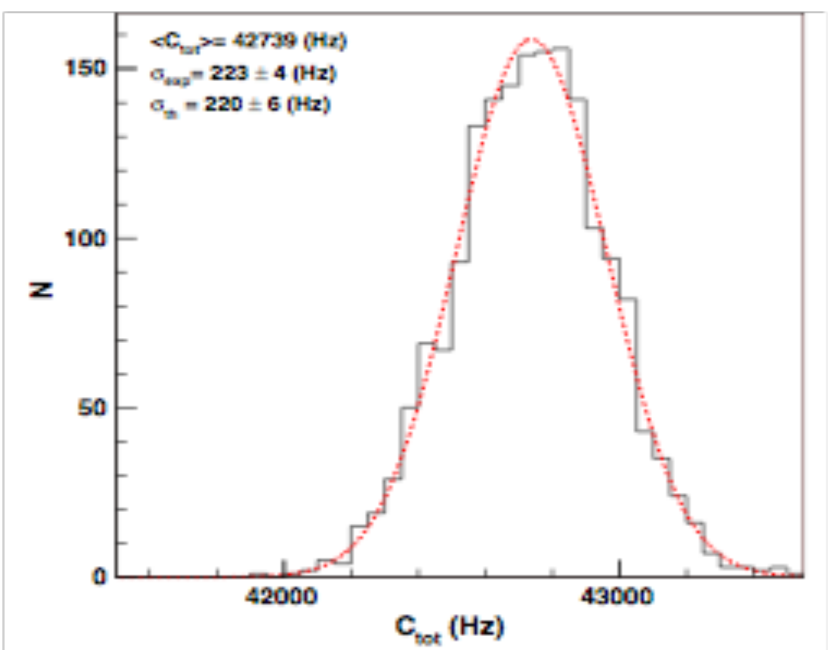
Stability of angular resolution and pointing accuracy (TeV)



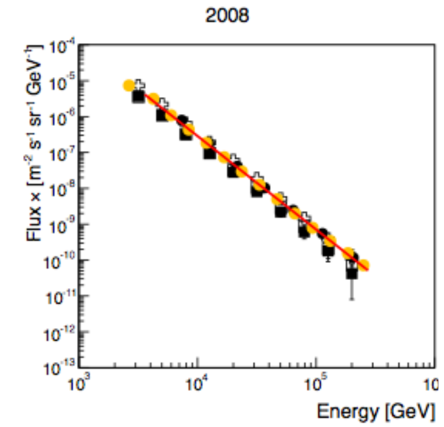
5%

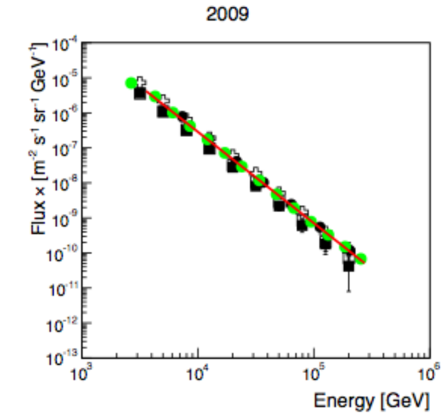
Distribution of particles hitting a cluster (GeV)

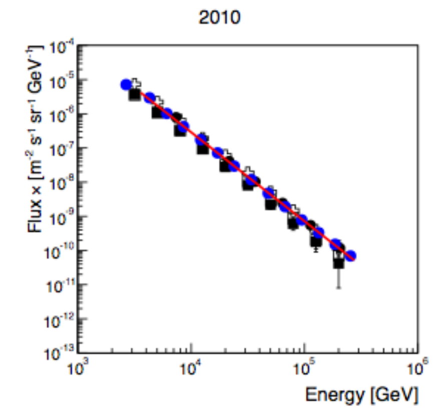


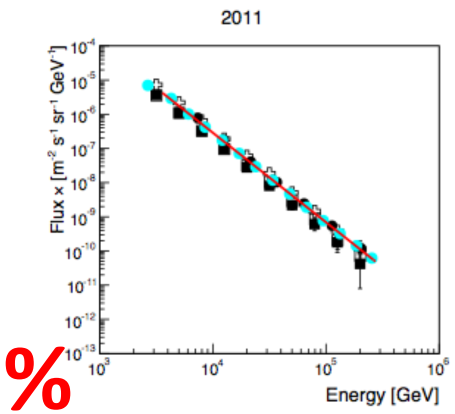
2%

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

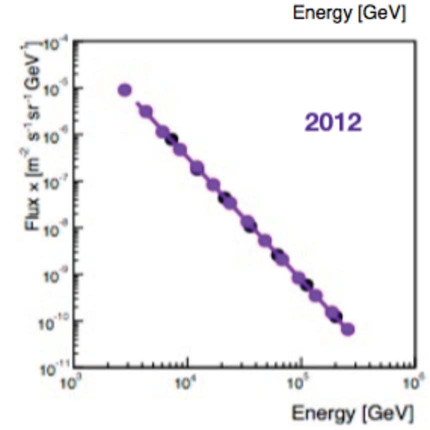






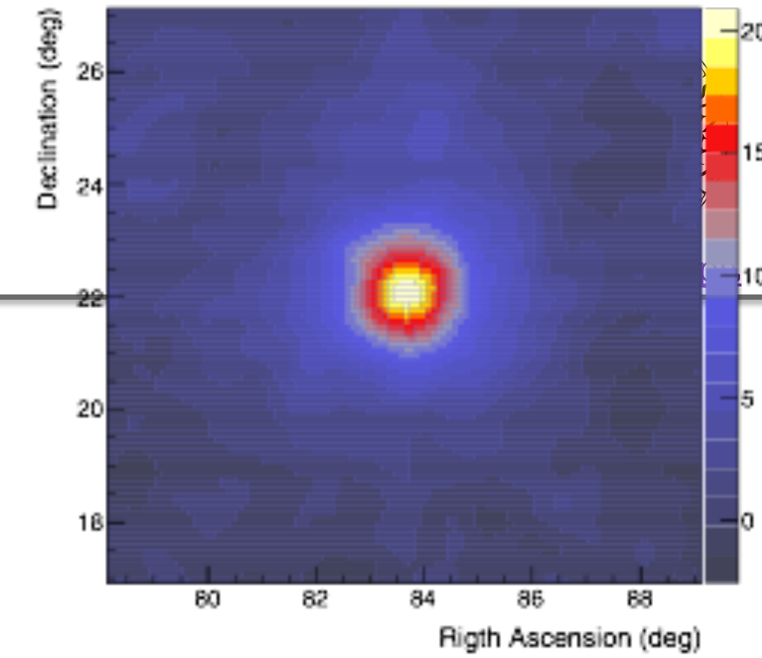


5%

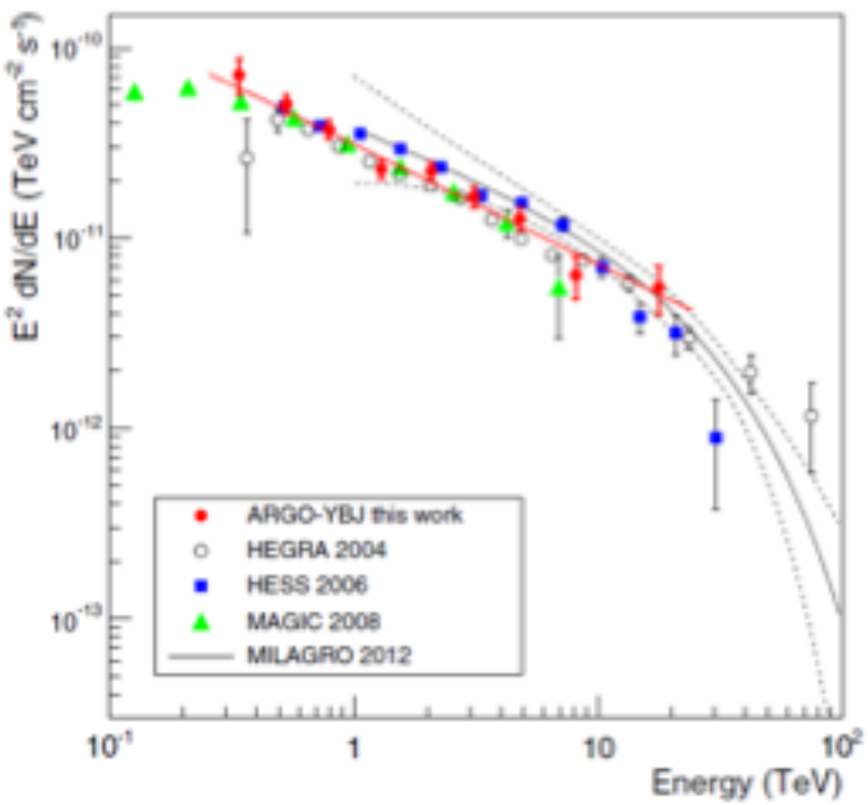


year	Gamma
2008	2.61±0.02
2009	2.61±0.02
2010	2.61±0.02
2011	2.62±0.02
2012	2.63±0.02

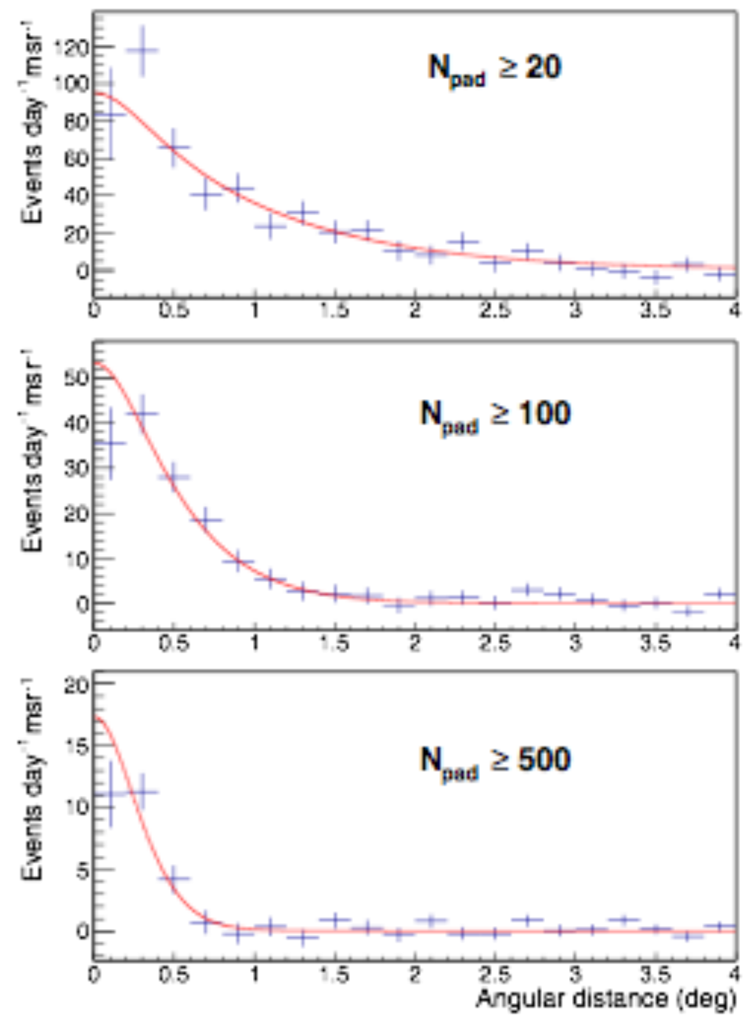
The Crab Nebula

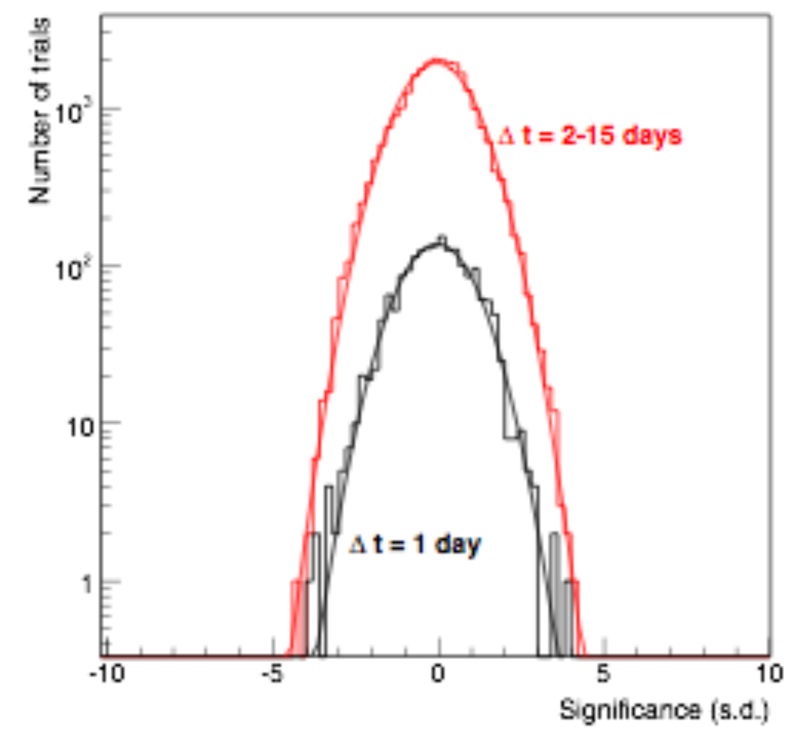


$$dN/dE = (5.2 \pm 0.2)\cdot 10^{-12}\cdot (E/2\ \mathrm{TeV})^{(-2.63 \pm 0.05)}\ \mathrm{cm^{-2}\,s^{-1}\,TeV^{-1}}$$



PSF: data vs MC simulation





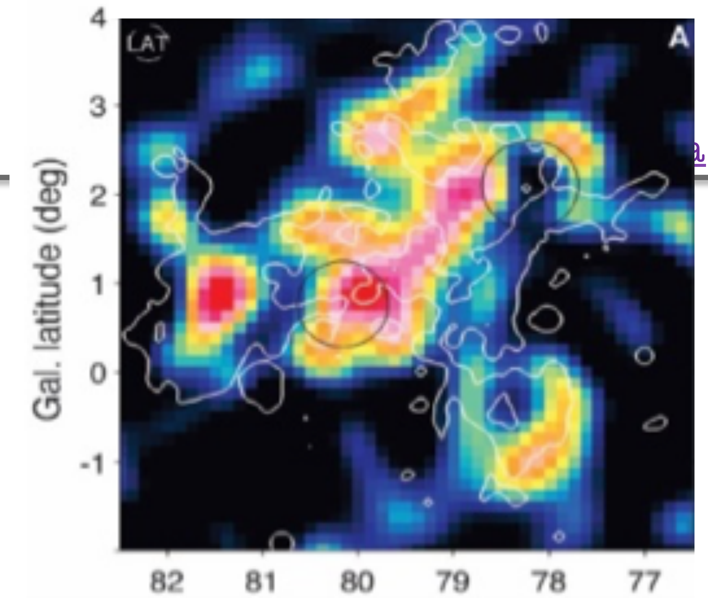
- Energy spectrum in 0.3–20 TeV in agreement with other experiments
- Light curve over five years compatible with a steady emission

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

ApJ 798 (2015) 119

ARGO J2031+4157 as the Cygnus Cocoon

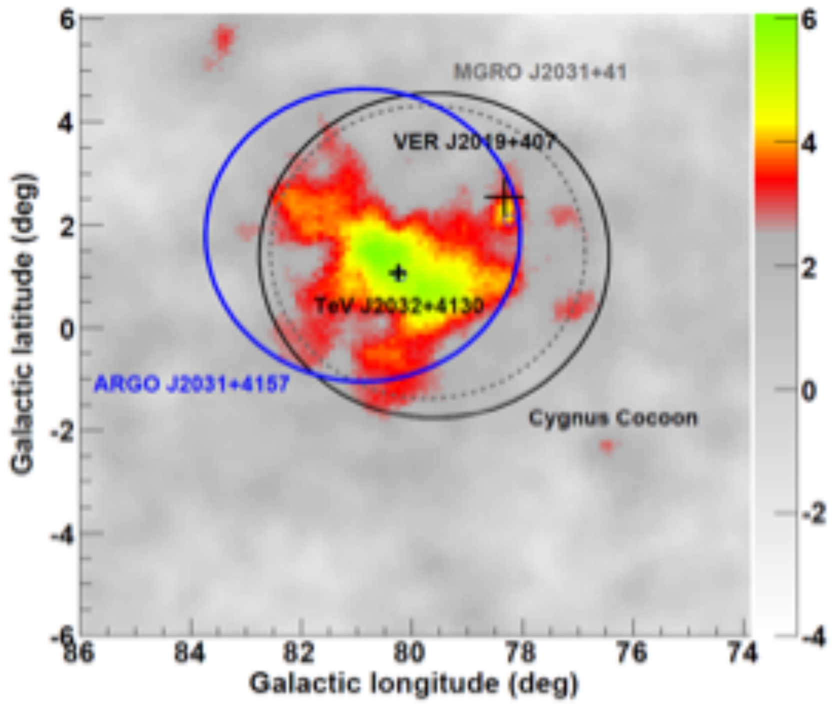
The Fermi/LAT view
in the 10-100 GeV band



Science 334 (2011) 1103

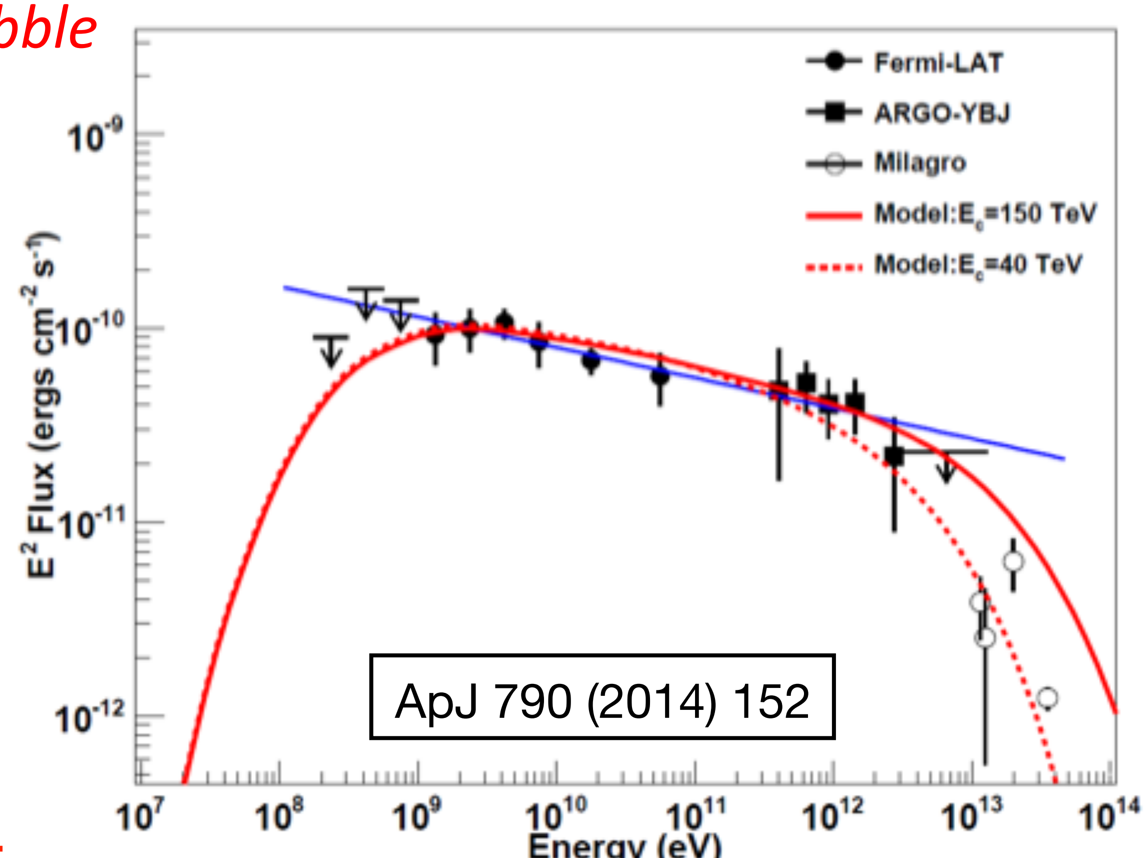
The emission of ARGO J2031+4157 can be identified as the counterpart of Cygnus Cocoon at TeV energies.

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



S_{max} = 6.1 s.d.
σ_{ext} = 1.8°±0.5°

such a large extended emission is likely due to the collective action of multiple shocks in a superbubble



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

Spectrum of ARGO J2031+4157: $dN/dE \propto E^{-2.62\pm0.27}$
Combined LAT&ARGO spectrum: $dN/dE \propto E^{-2.16\pm0.04}$

Diffuse γ-rays from the Galactic Plane

Roberto Iuppa

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.

THE ASTROPHYSICAL JOURNAL, 806:20 (11pp), 2015 June 10

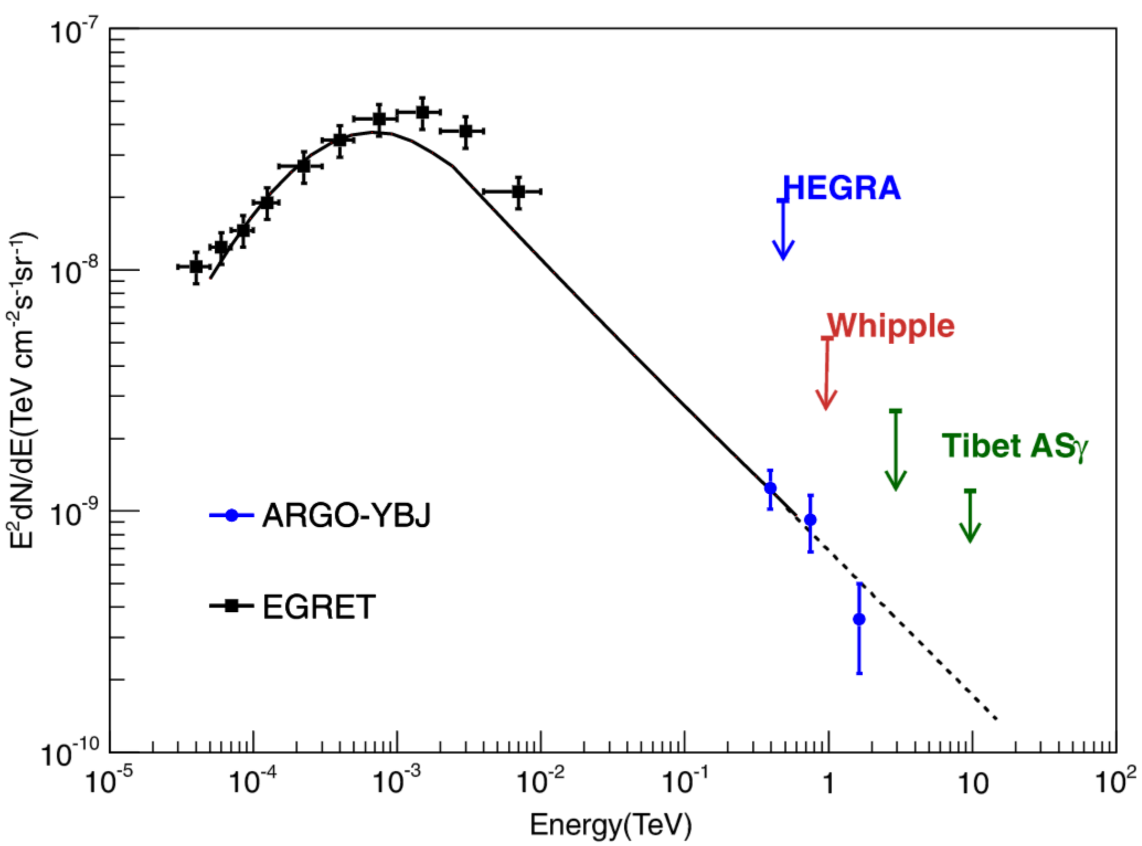
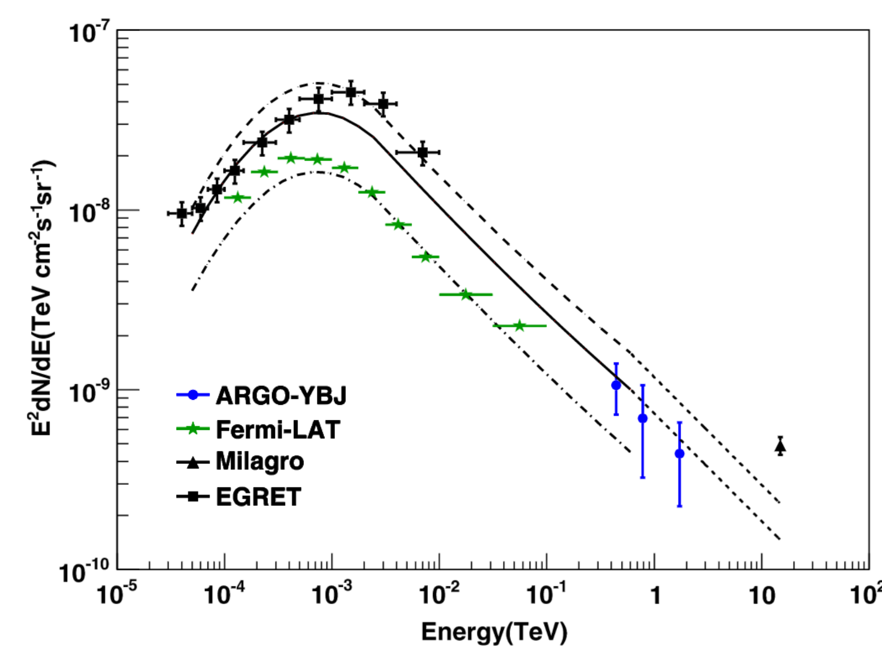


Figure 3. Energy spectrum of the diffuse gamma-ray emission measured by ARGO-YBJ in the Galactic region $25° < l < 100°$, $|b| < 5°$ (dots). The solid line shows the flux in the same region according to the *Fermi*-DGE model. The short-dashed line represents its extension following a power law with spectral index −2.6. The EGRET results (squares) in the same Galactic region $25° < l < 100°$, $|b| < 5°$ and the upper limits quoted by HEGRA (99% C.L., $38° < l < 43°$, $|b| < 2°$), Whipple (99.9% C.L., $38.5° < l < 41.5°$, $|b| < 2°$), and Tibet ASγ (99%C.L., $20° < l < 55°$, $|b| < 2°$) are also shown.

These results are 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 importance of source masking cannot be sufficiently stressed. For instance, the TeV diffuse flux in the Cygnus region (longitude 65° -85°) 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.



Diffuse γ Emission

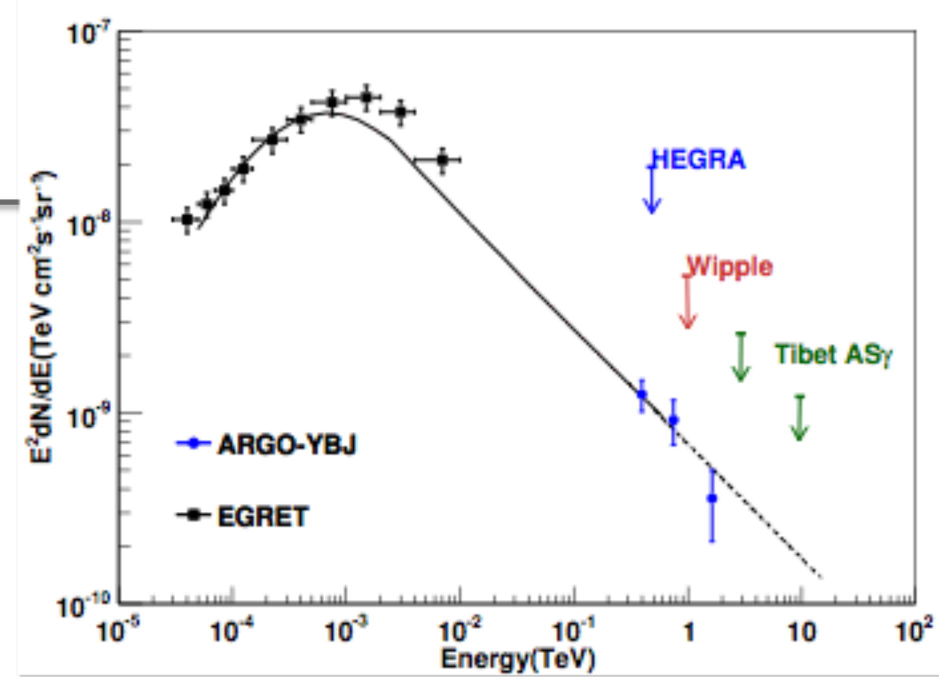
Diffuse gamma-ray emission from the Galactic plane for |b| < 5°

l Intervals	Significance	Spectral index	Energy(GeV)	Flux[a]
$25^\circ < l < 100^\circ$	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
$40^\circ < l < 100^\circ$	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
$65^\circ < l < 85^\circ$	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
$25^\circ < l < 65^\circ$ & $85^\circ < l < 100^\circ$	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
$130^\circ < l < 200^\circ$	-0.5 s.d.	–	–	< 5.7[c]

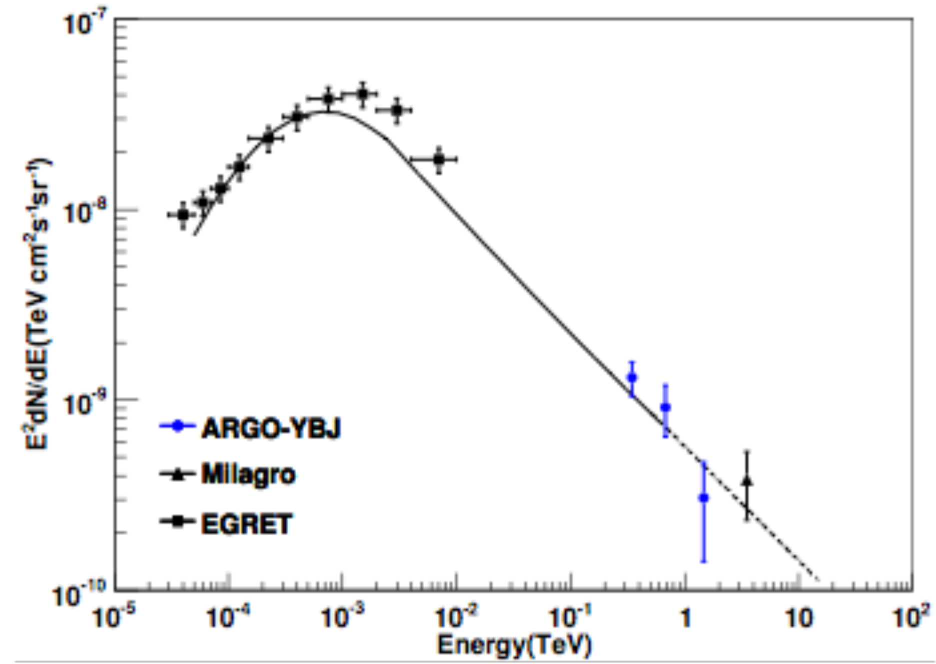
[a]In units of 10^{-9} TeV^{-1} cm^{-2} s^{-1} sr^{-1}.

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.

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



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



Towards the idea of a LOCAL measuments: *liason* TeV-gamma's/CRs mandatory

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

Roberto Iuppa

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)**

Cherenkov data exist for limited periods

By analysing the public data, we have evaluated:

- Light curves
- SEDs

for 4.5 years

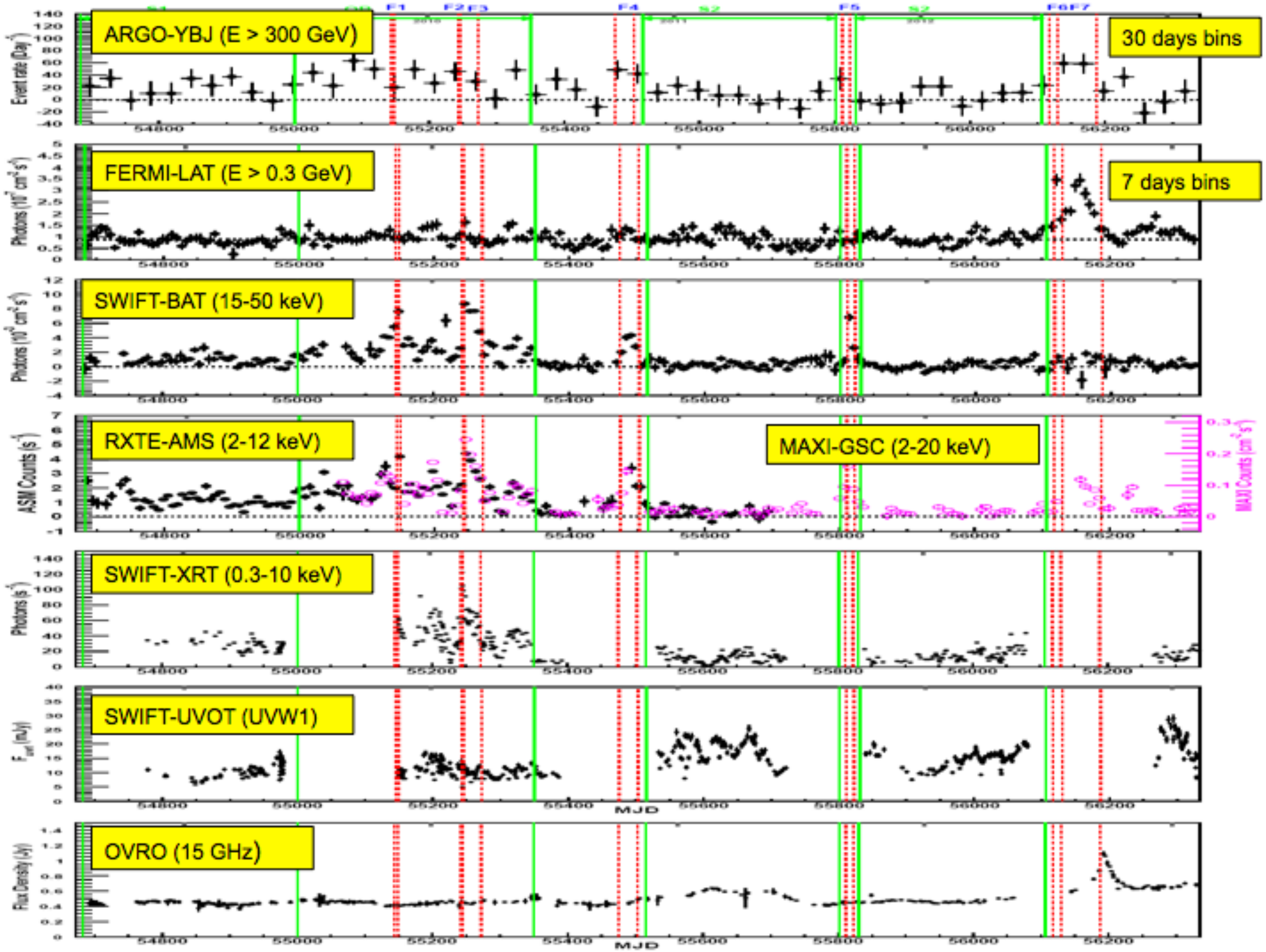
ApJ Supplement, 222 (2016) 6

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

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

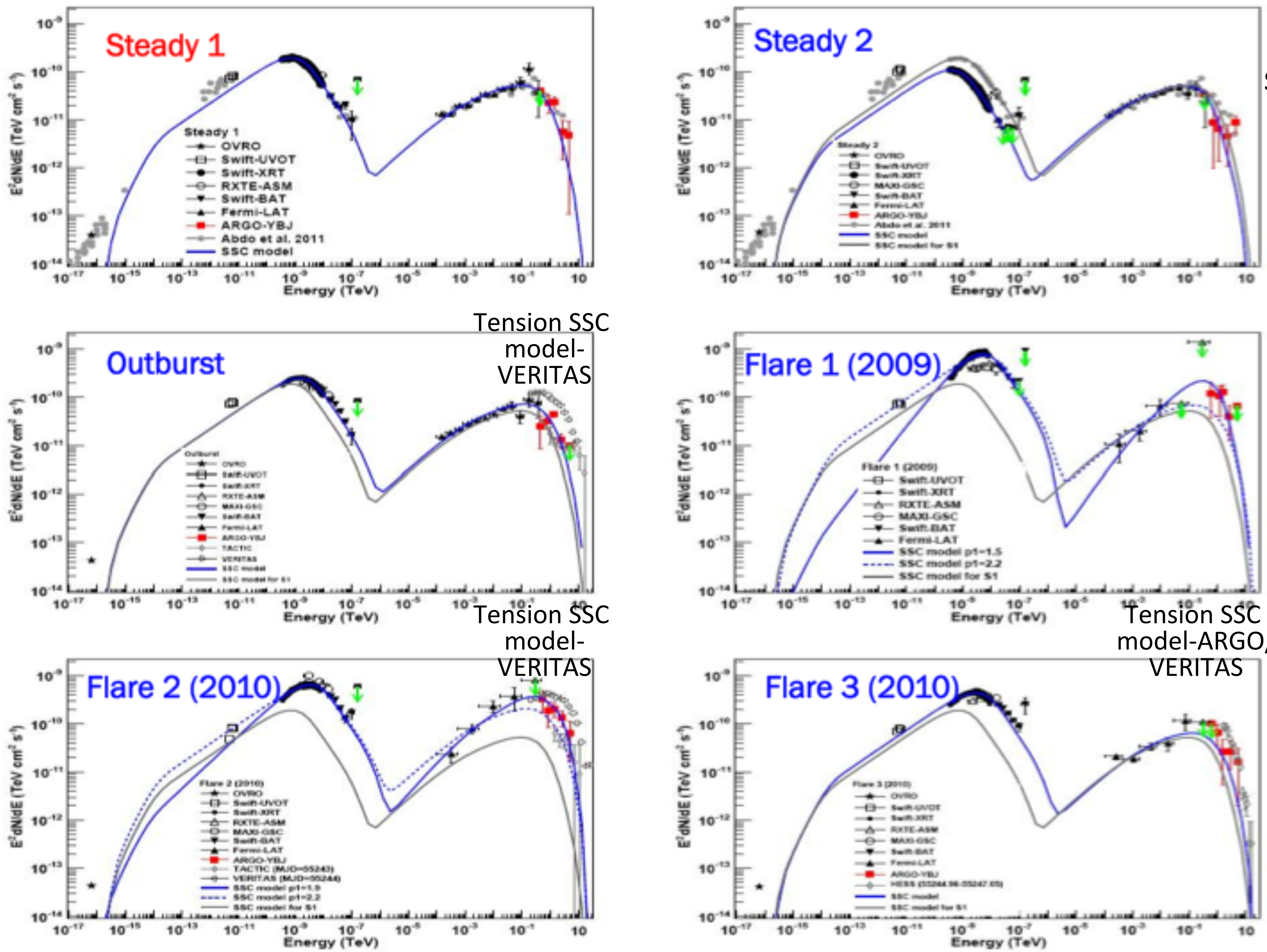
Mrk421 emission

Roberto Iuppa



One-zone Synchrotron Self-Compton model

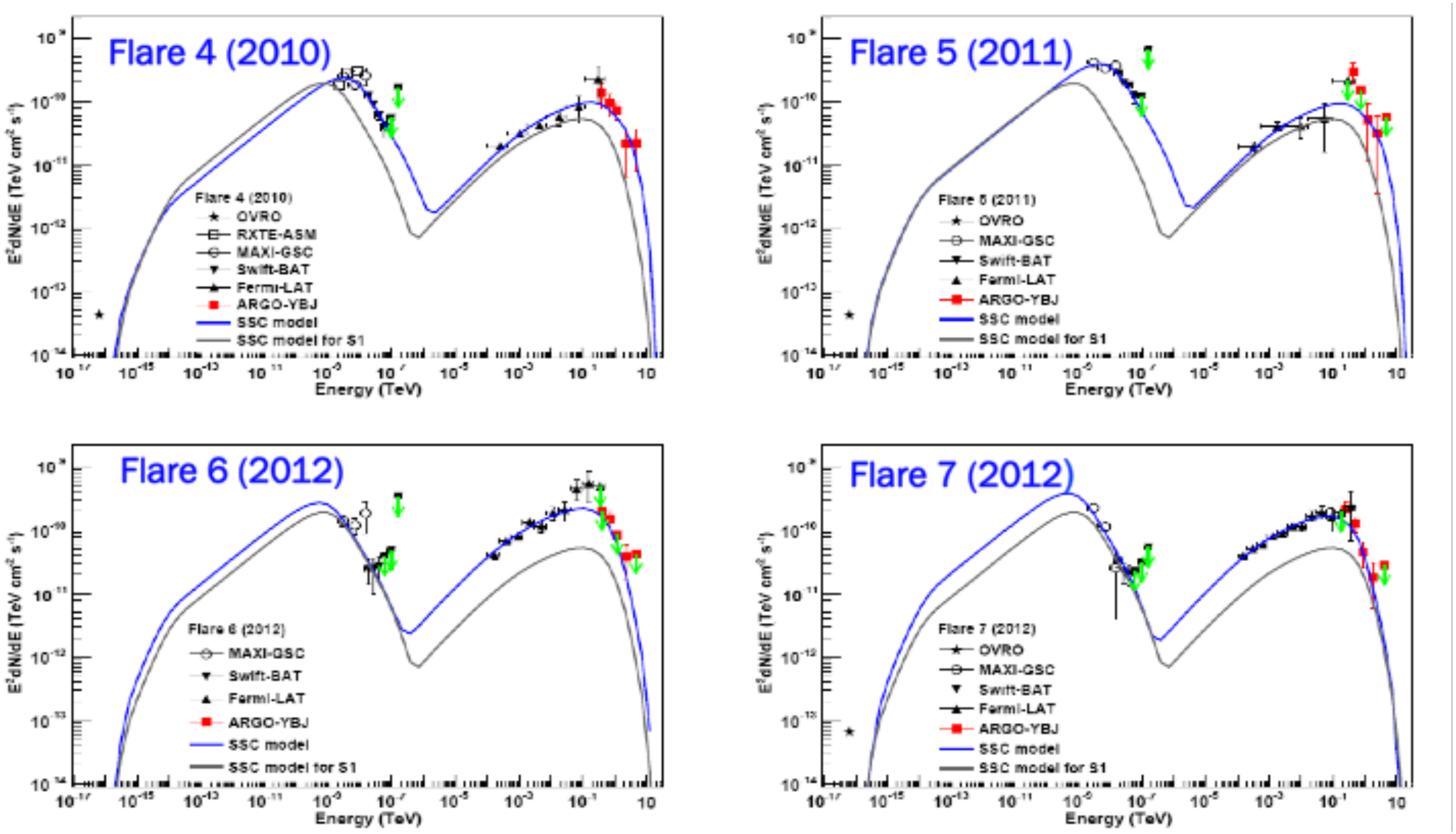
Roberto Iuppa



gray line: steady1 flux reference

One-zone Synchrotron Self-Compton model

Roberto Iuppa



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

ApJ Supplement, 222 (2016) 6

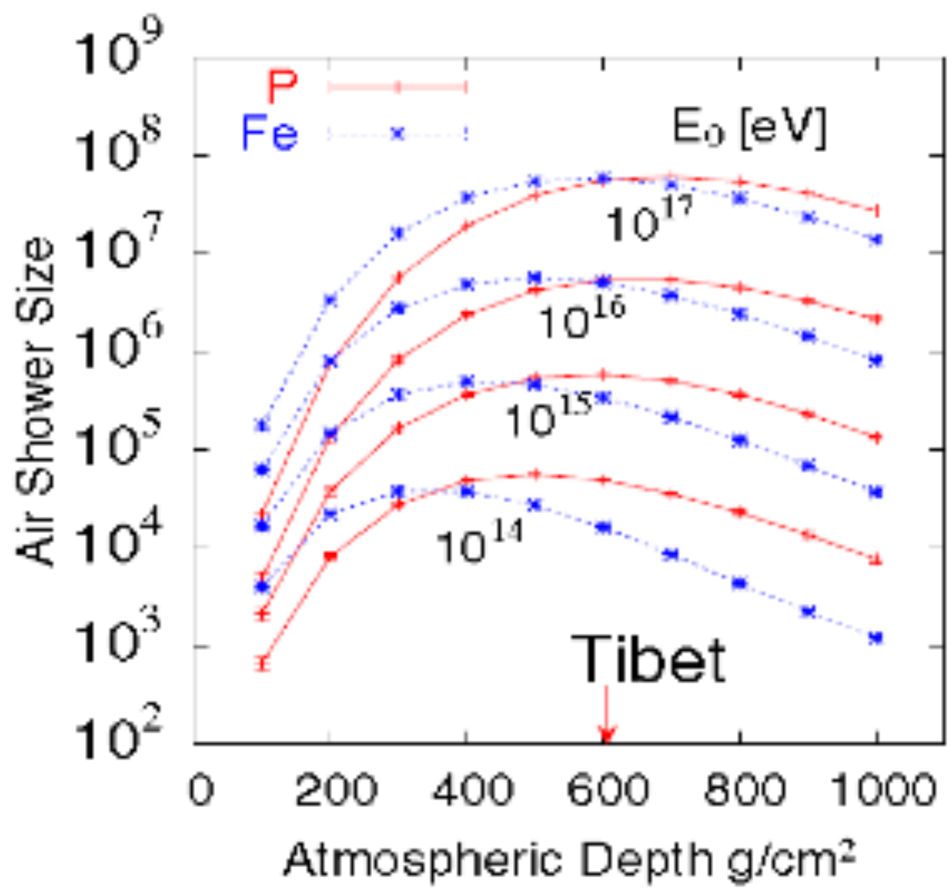
Measurement of CR energy spectrum with ARGO-YBJ

Roberto Iuppa

- 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

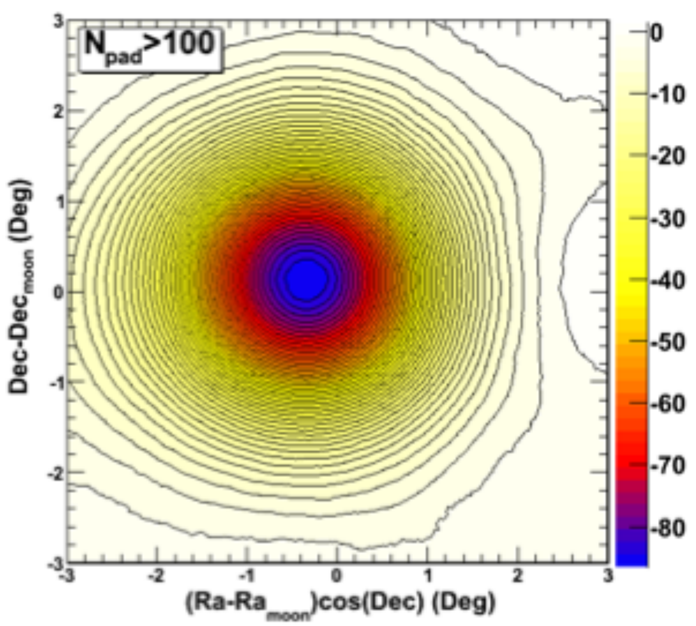
- Working at high altitude (4300 m asl):

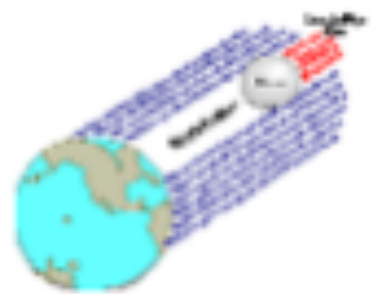
  1. p and Fe produce showers with similar size
  2. Small fluctuations: shower maximum
  3. Low energy threshold: absolute energy scale calibration with the Moon Shadow technique and overposition with direct measurements



Calibration of the energy scale

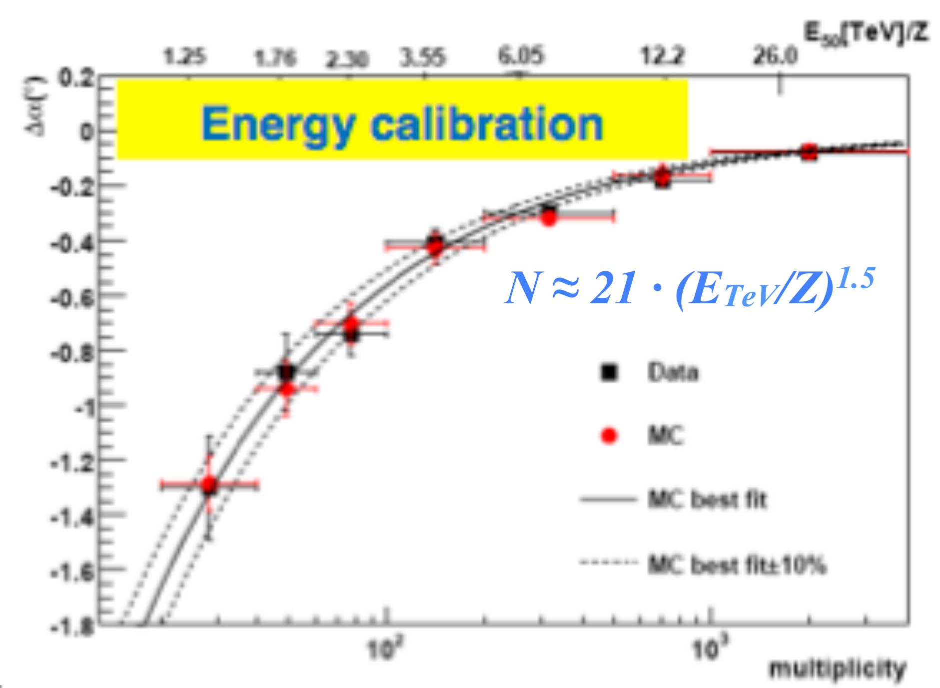
ARGO-YBJ: *Moon shadow* tool



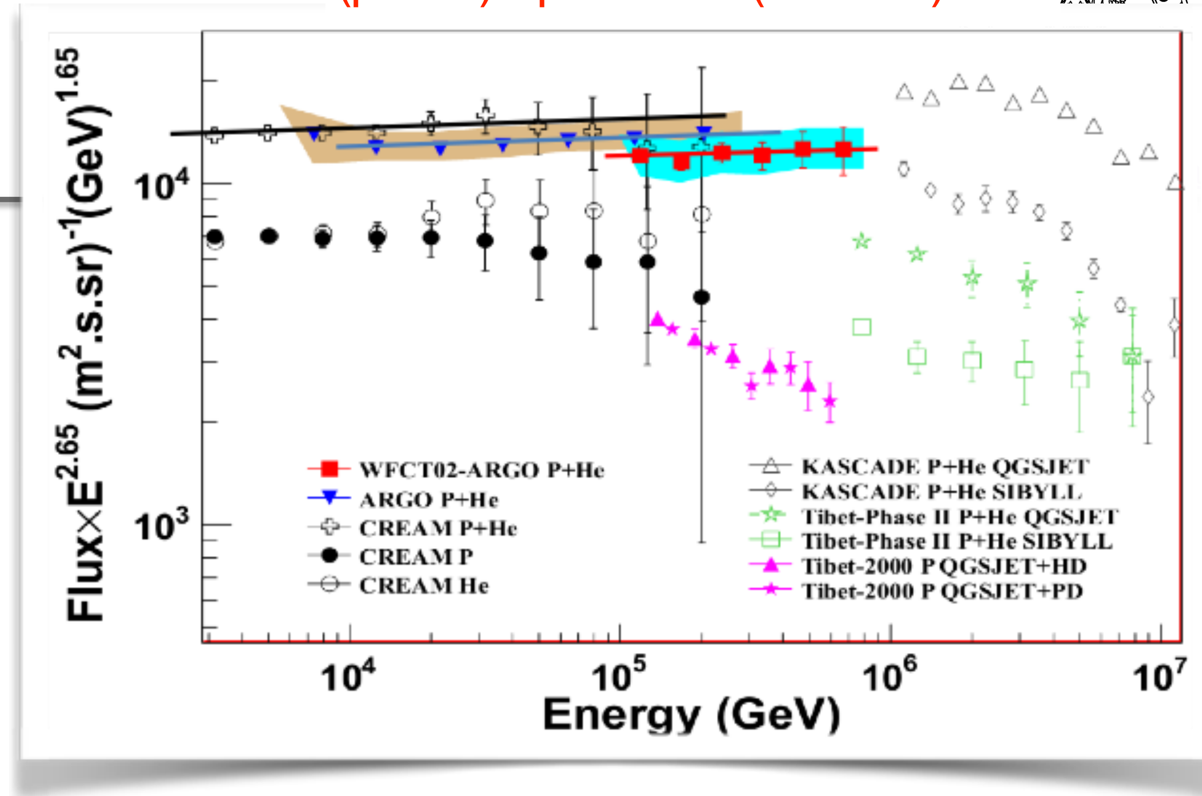


PRD 84 (2011) 022003

The energy scale uncertainty is estimated at 13% 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 TeV)$^{-2.62}$
- ARGO-YBJ: 1.95×10^{-11} (E/400 TeV)$^{-2.61}$
- Hybrid: $0.92 \times 1.95 \times 10^{-11}$ (E/400 TeV)$^{-2.63}$

Single power-law: 2.62 ± 0.01

Flux at 400 TeV:

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

The 9% difference in flux corresponds to a difference of 14% in energy scale between different experiments.

All-particle energy spectrum by ARGO-YBJ

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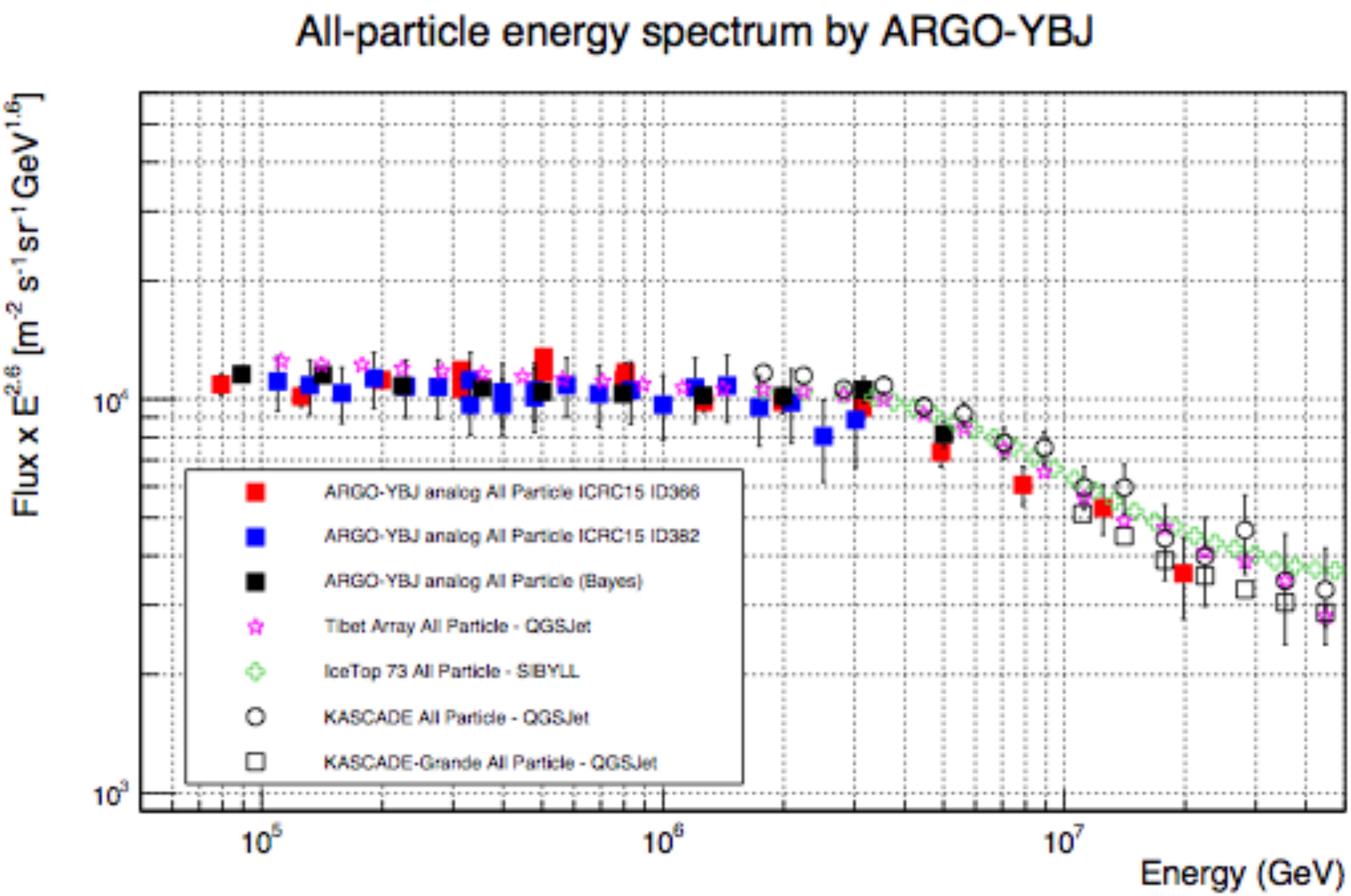
ARGO-YBJ reports evidence for the all-particle knee at the expected energy



Selection of light (p+He) component

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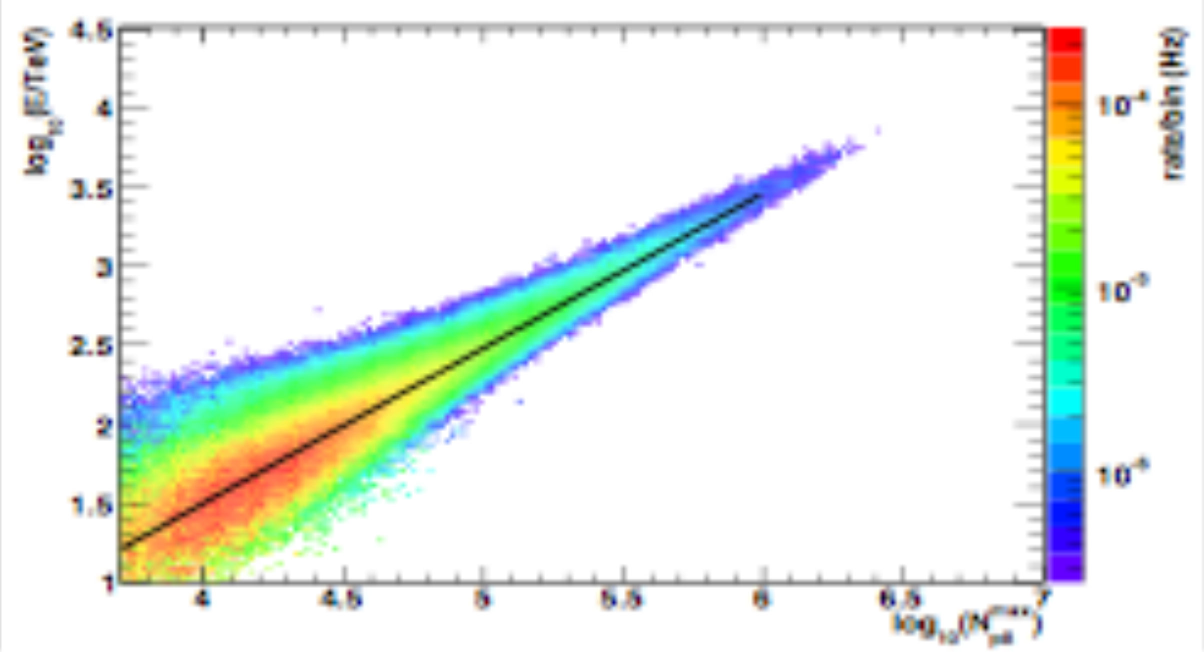
- Selection of (p+He)-induced showers: **NOT** by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an event-by-event basis exploiting showers topology, i.e. the lateral distribution of charged secondary particles.

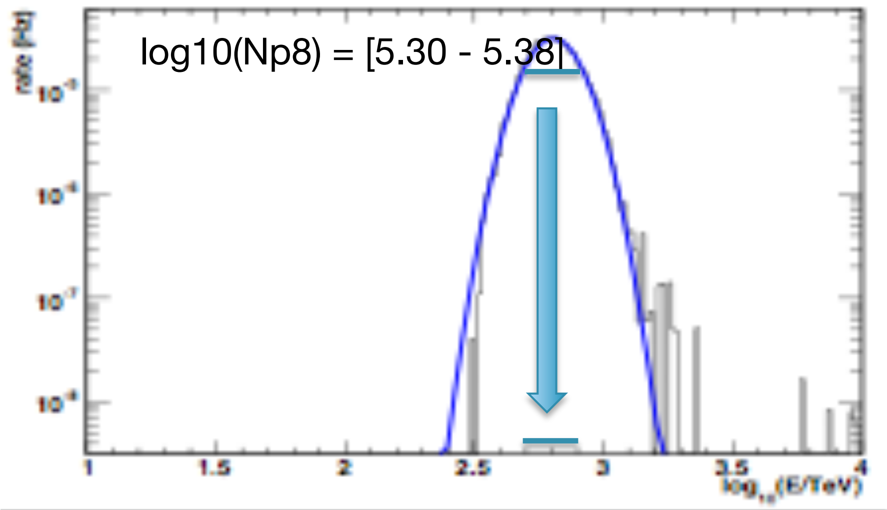
- Energy reconstruction is based on the N_p^{8m} parameter: the *number of particle within 8 m from the shower core position.*

This truncated size is

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



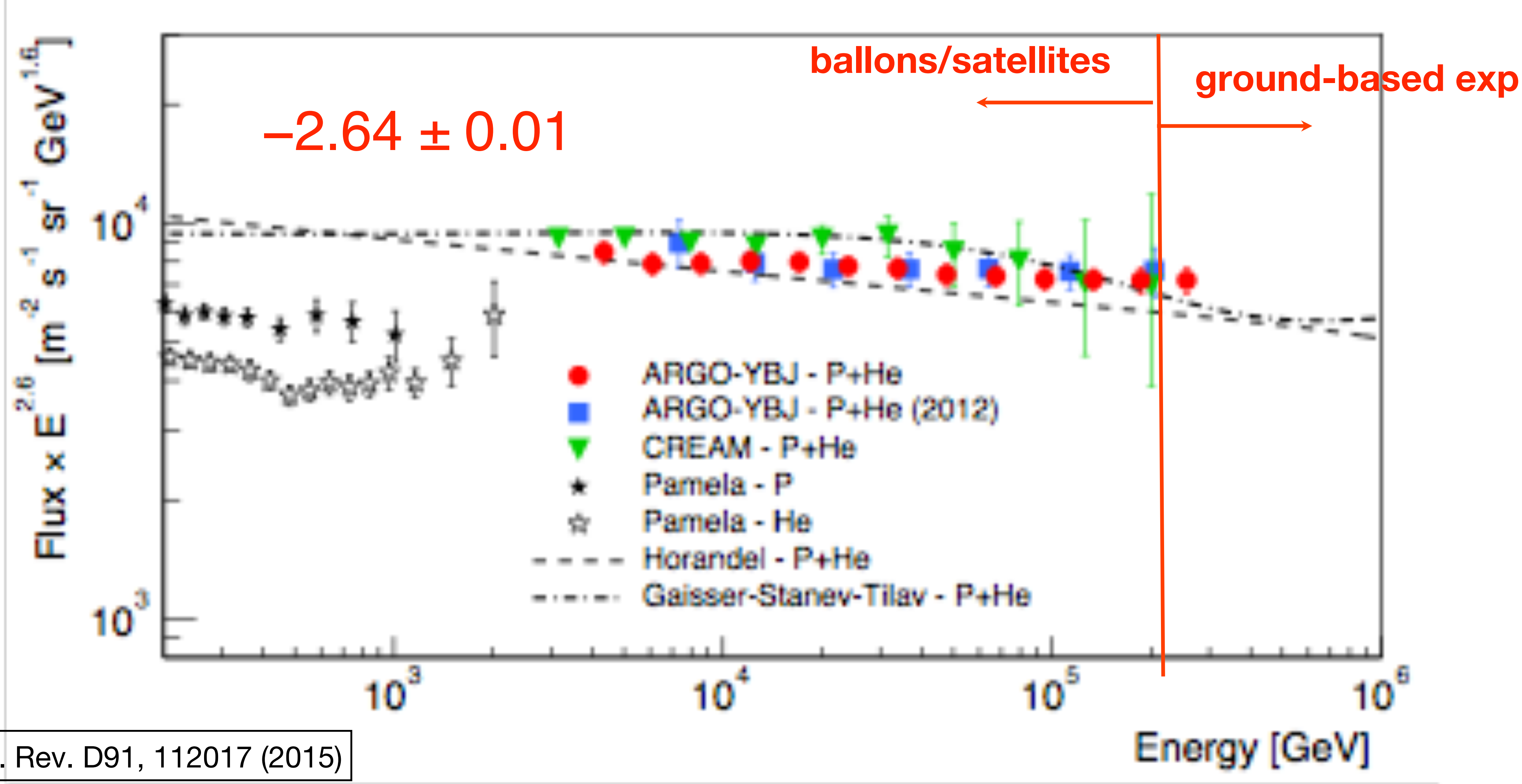
(i) *Density cut:* the average particle density (ρ_{in}) measured by the central area (20 inner clusters) of the detector must be higher than the particle density (ρ_{out}) measured by the outermost area (42 outer clusters): ($\rho_{in} > 1.25\rho_{out}$). This selection criteria based on the lateral particle distribution was introduced in order to discard events produced by nuclei heavier than helium. In fact, in showers induced by



The light-component spectrum (2.5 - 300 TeV)

Roberto Iuppa

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

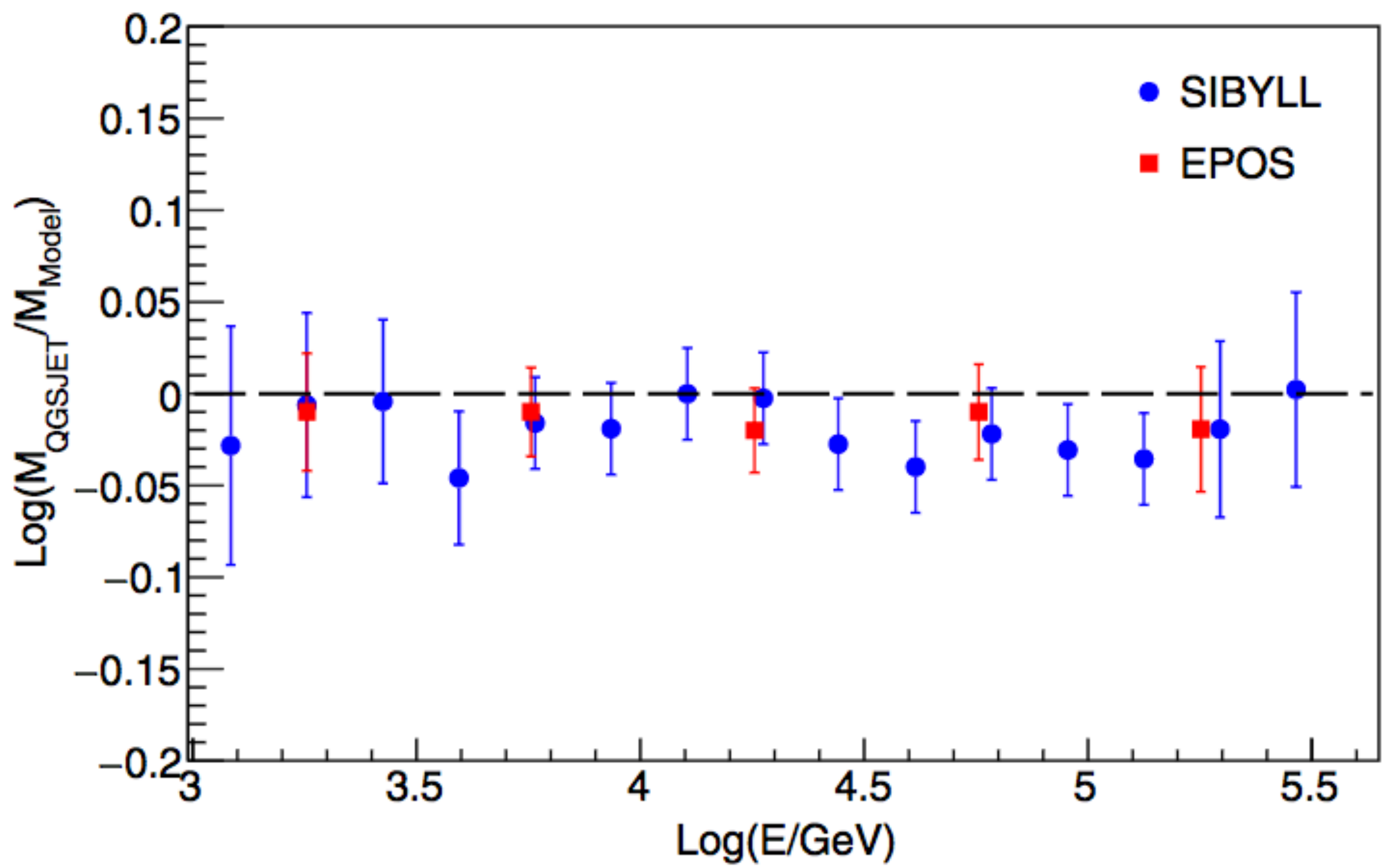
Roberto Iuppa

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

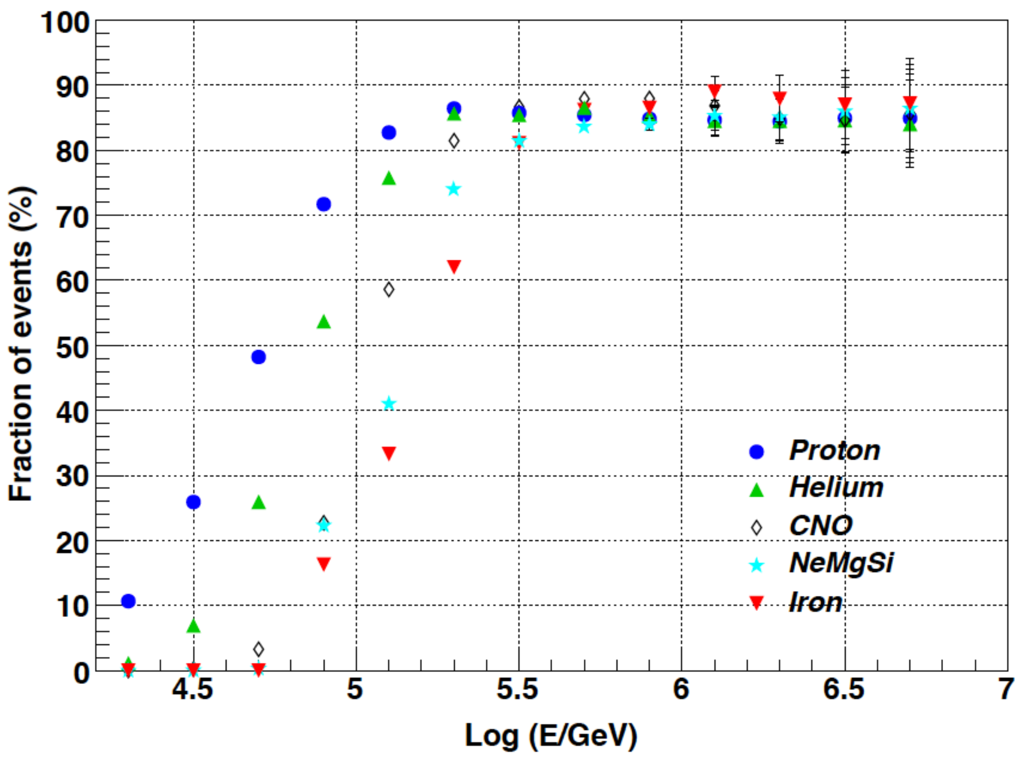
Ratio beetwen multiplicity distributions obtained with different models



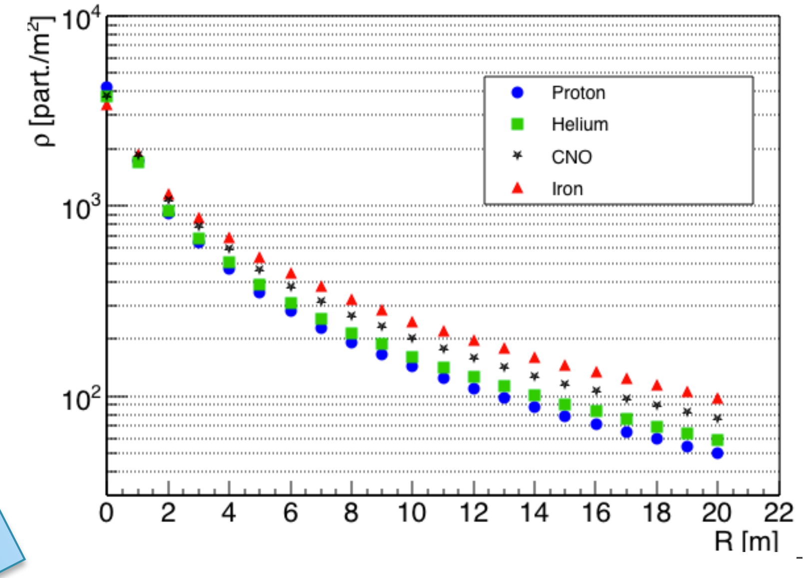
The light-component spectrum (0.3 - 5 PeV)

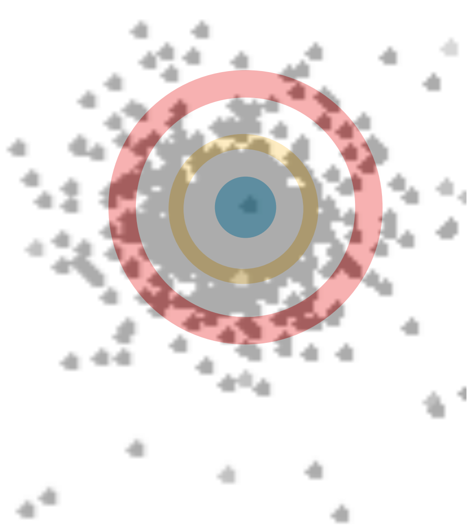
Roberto Iuppa

No mass selection applied: same efficiency for all elements above 100 TeV: quasi "unbiased" all particle measurement



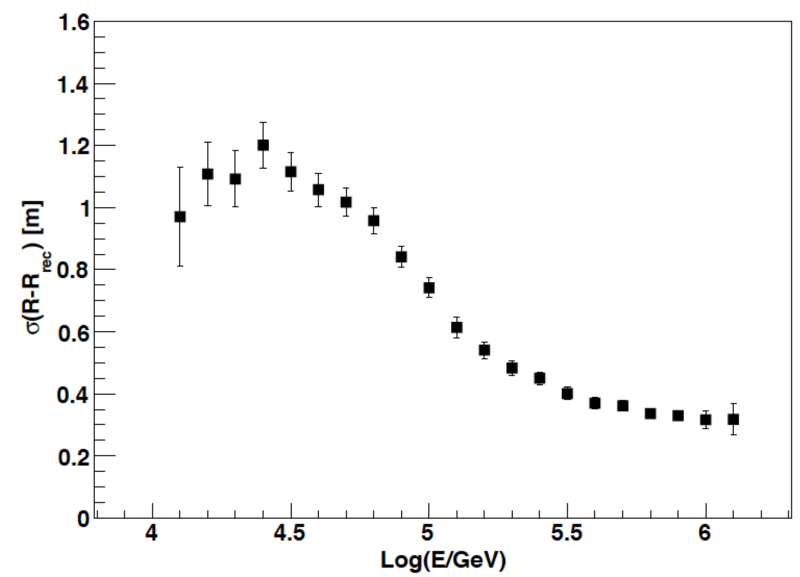
The high segmentation of the read-out allows to access the LDF down to the shower core. Discrimination Light/Heavy based on the measurement of the LDF at different distances from the core





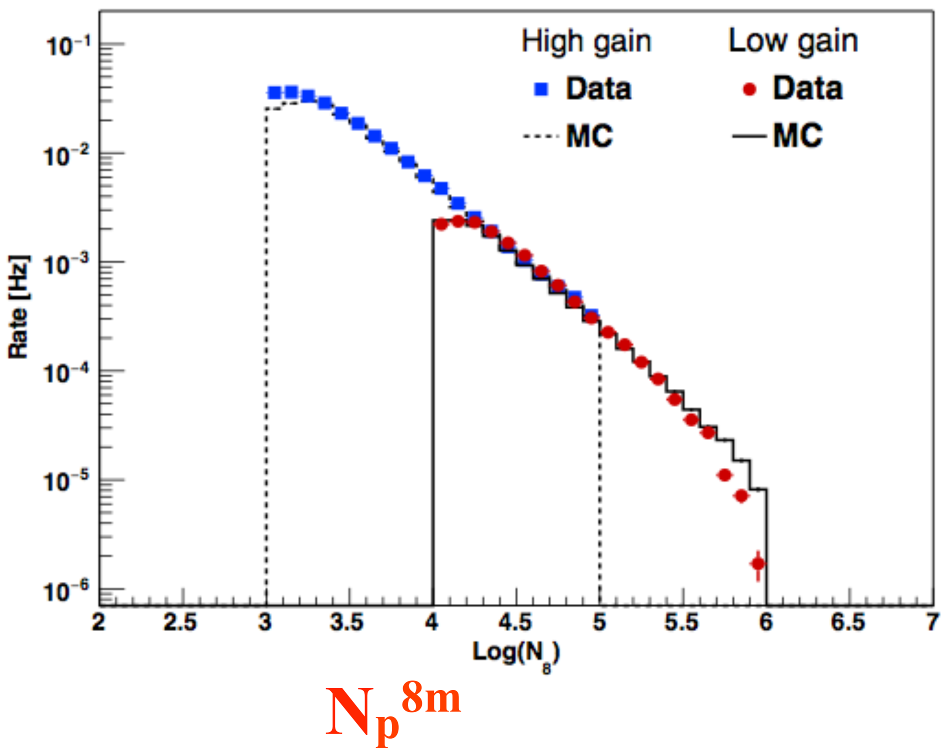
$$\beta_5 = \rho_5/\rho_0$$

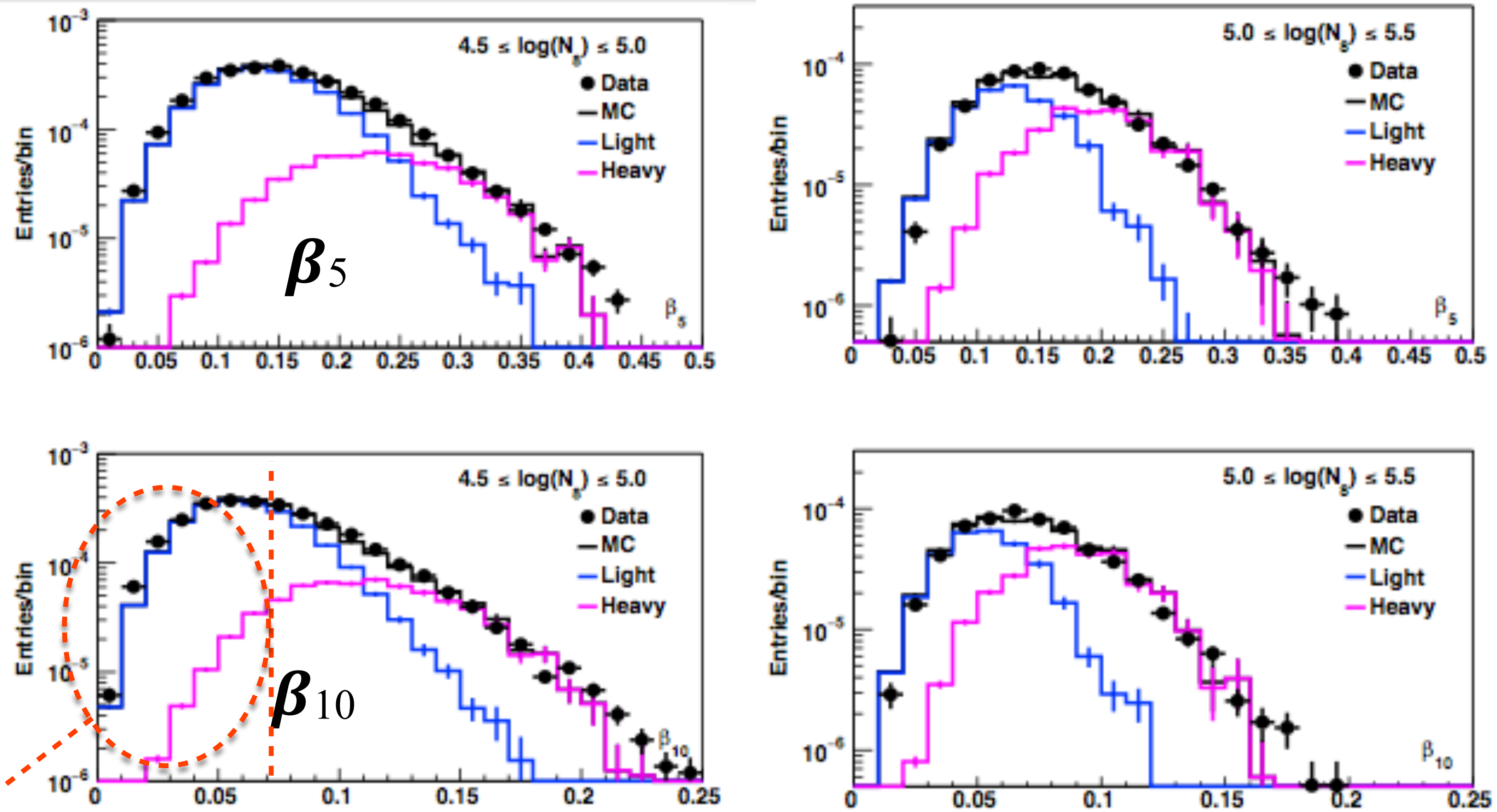
$$\beta_{10} = \rho_{10}/\rho_0$$

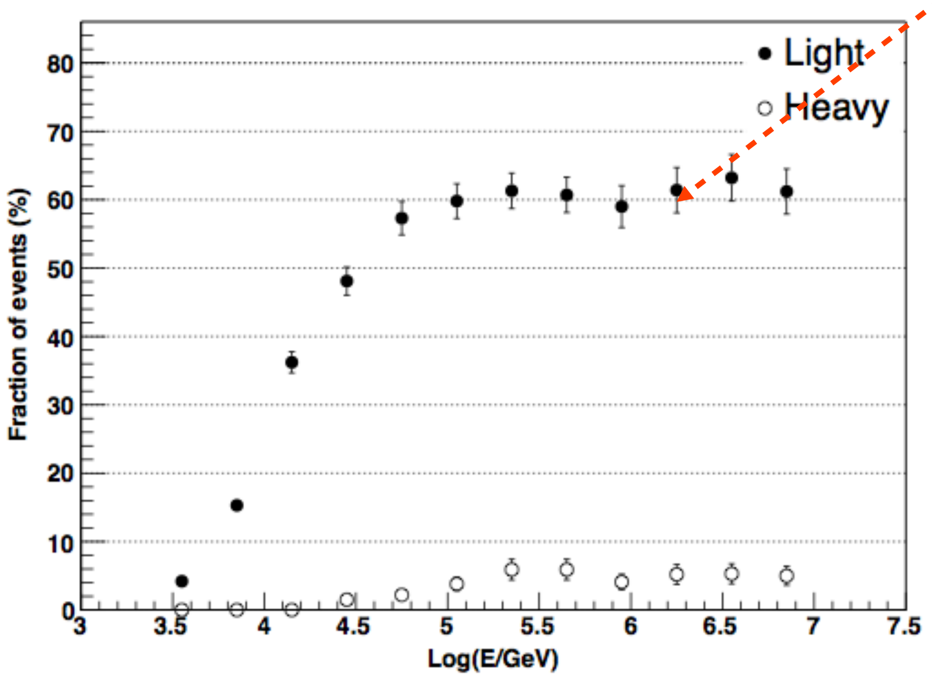


Light/Heavy discrimination

Roberto Iuppa





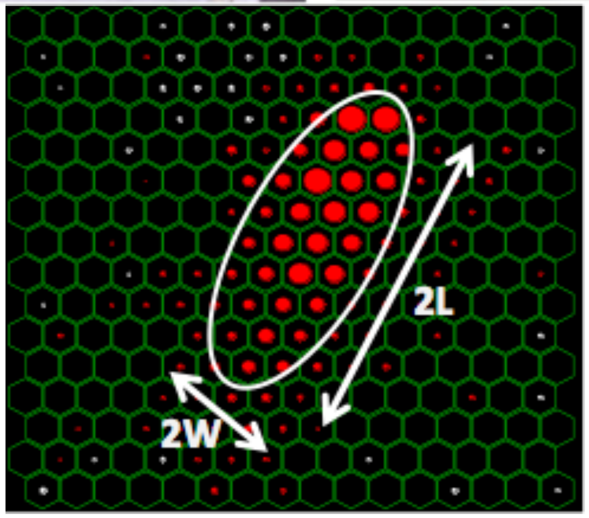


Fraction of events in the Light-selected sample only:
above ≈100 TeV ≈60% of all Light and ≈5% of all Heavy are selected

ARGO-YBJ + WFCTA

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

- 4.7 m^2 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°

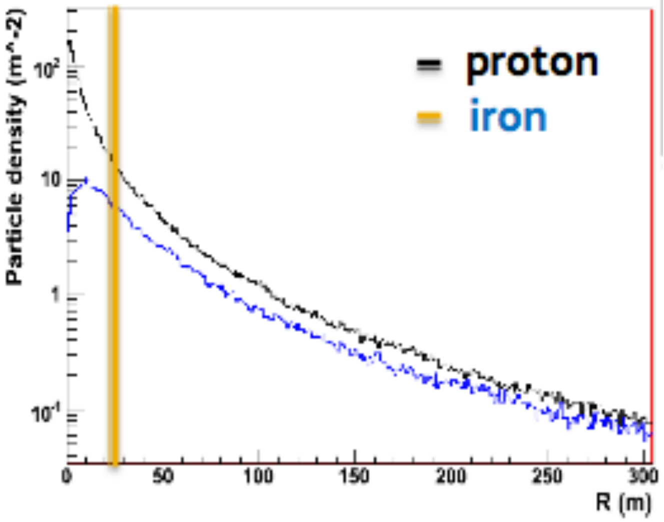


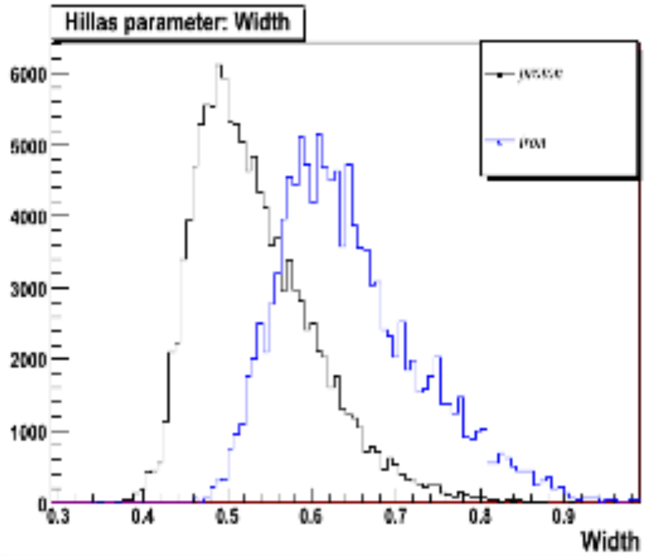
❖ *ARGO-YBJ:* core reconstruction & lateral distribution in the core region

→ mass sensitive

❖ *Cherenkov telescope:* longitudinal information

Hillas parameters → mass sensitive





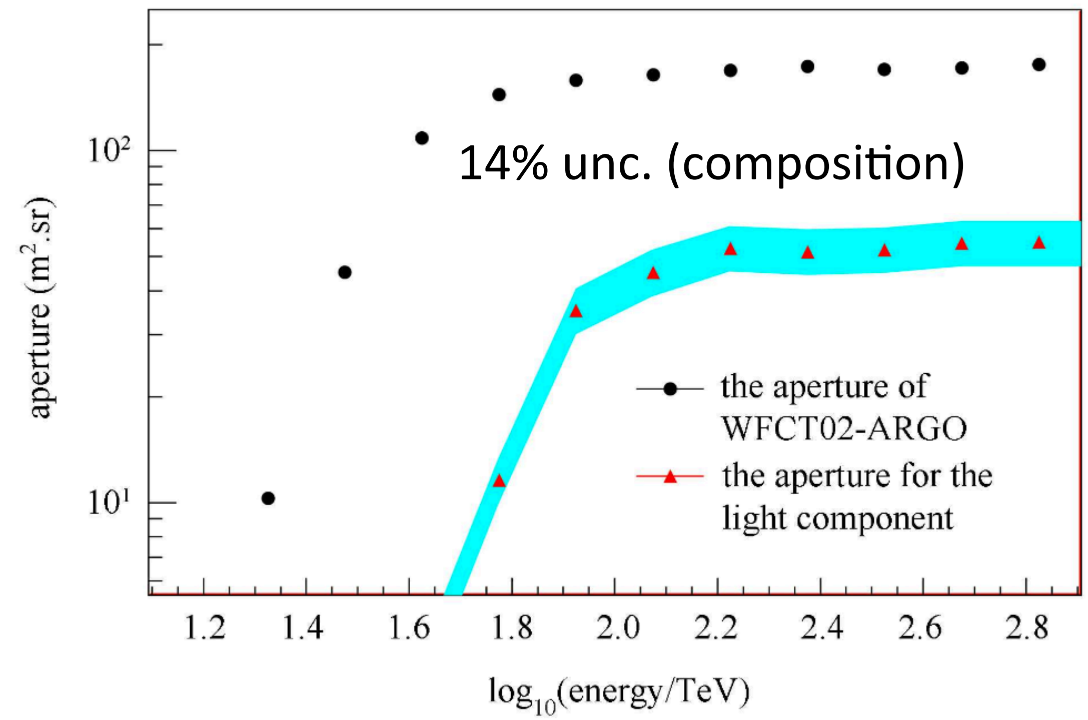
- angular resolution: 0.2°
- shower core position resolution: 2 m

Phys. Rev. D 92, 092005 (2015)

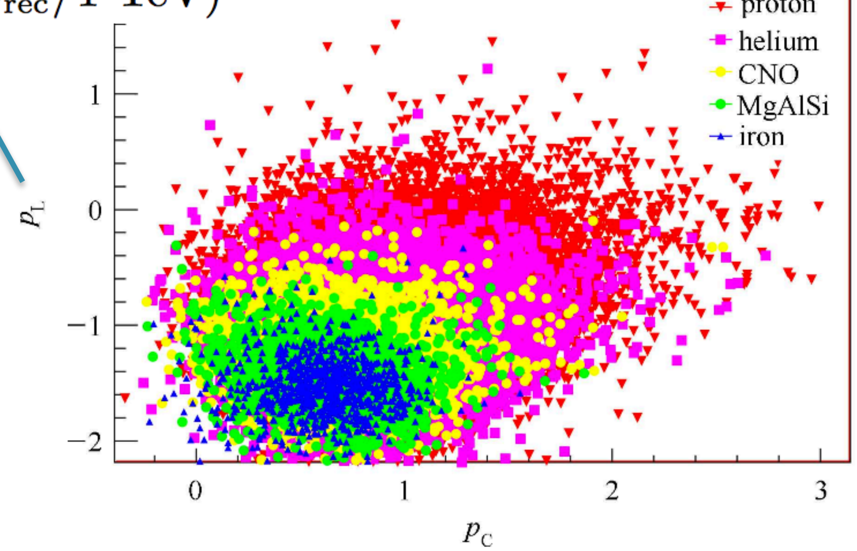
Light component (p + He) selection

Roberto Iuppa

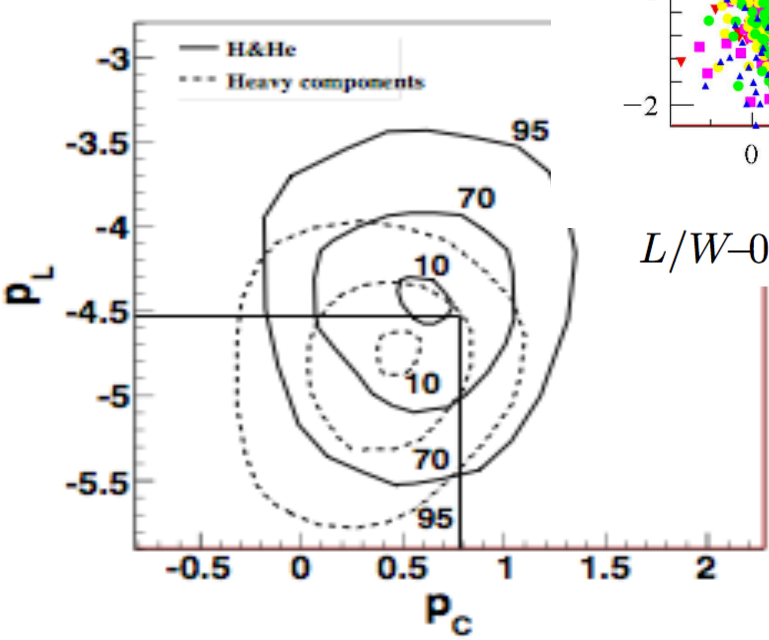
- Contamination of heavier component ≈10 %
- Energy resolution: ~25% constant with energy
- Uncertainty : ~25% on flux



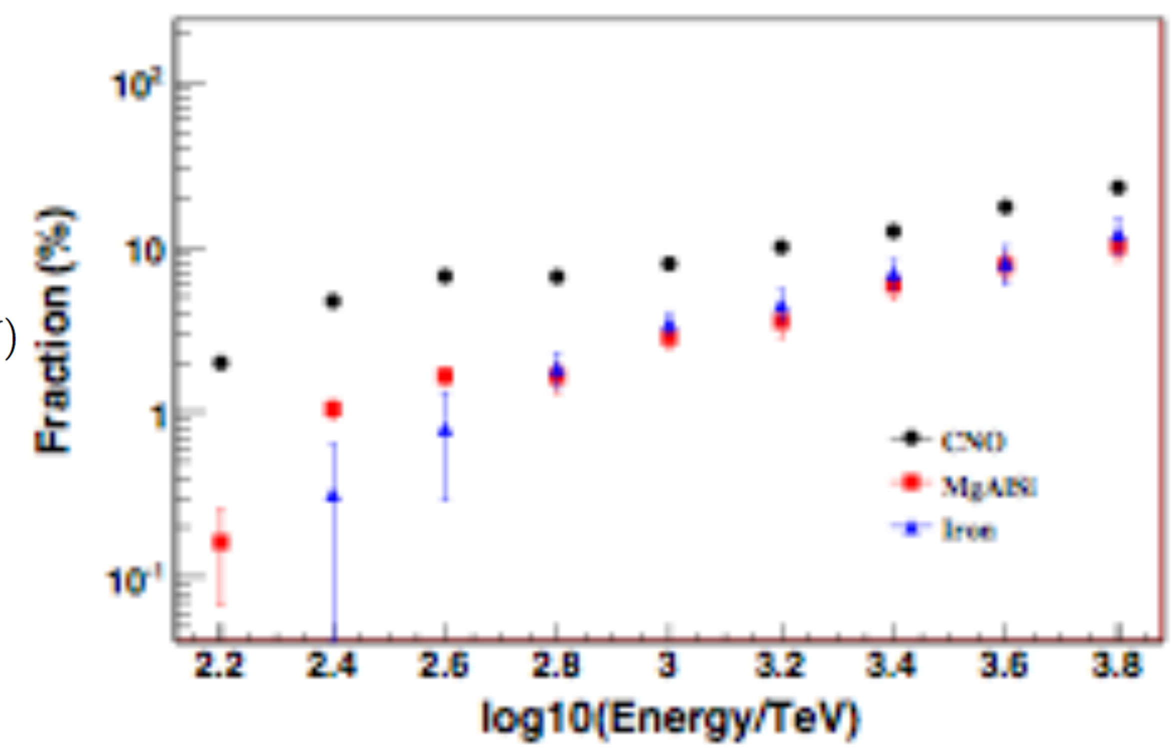
$\log_{10}N_{\rm max}$-$1.44\log_{10}(E_{\rm rec}/1\ {\rm TeV})$



L/W–$0.0091\times(R_p/1\ {\rm m})$–$0.14\log_{10}(E_{\rm rec}/1\ {\rm TeV})$



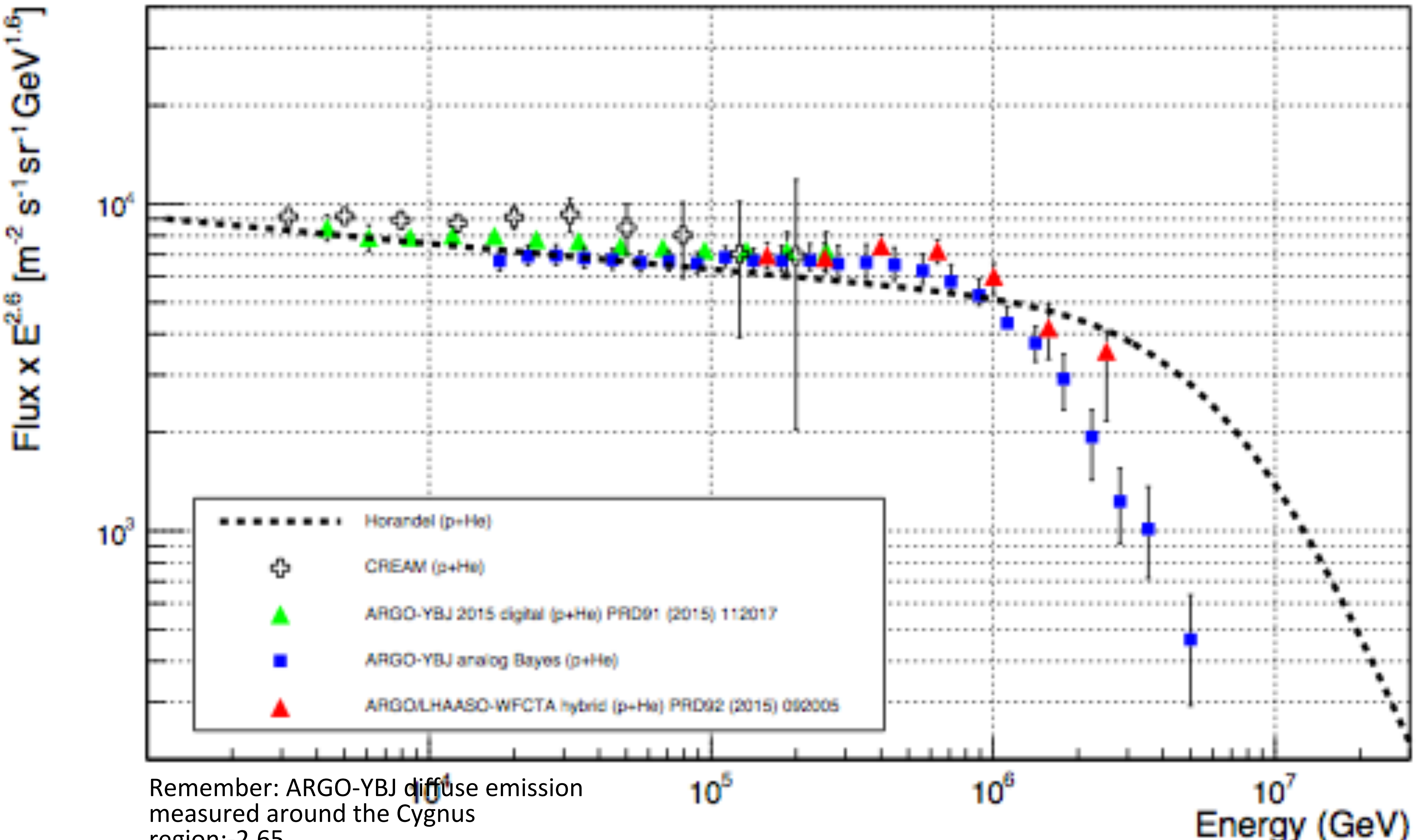
Events for which
$p_L \le -4.53$ and $p_C \le 0.78$
are rejected



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

Roberto Iuppa

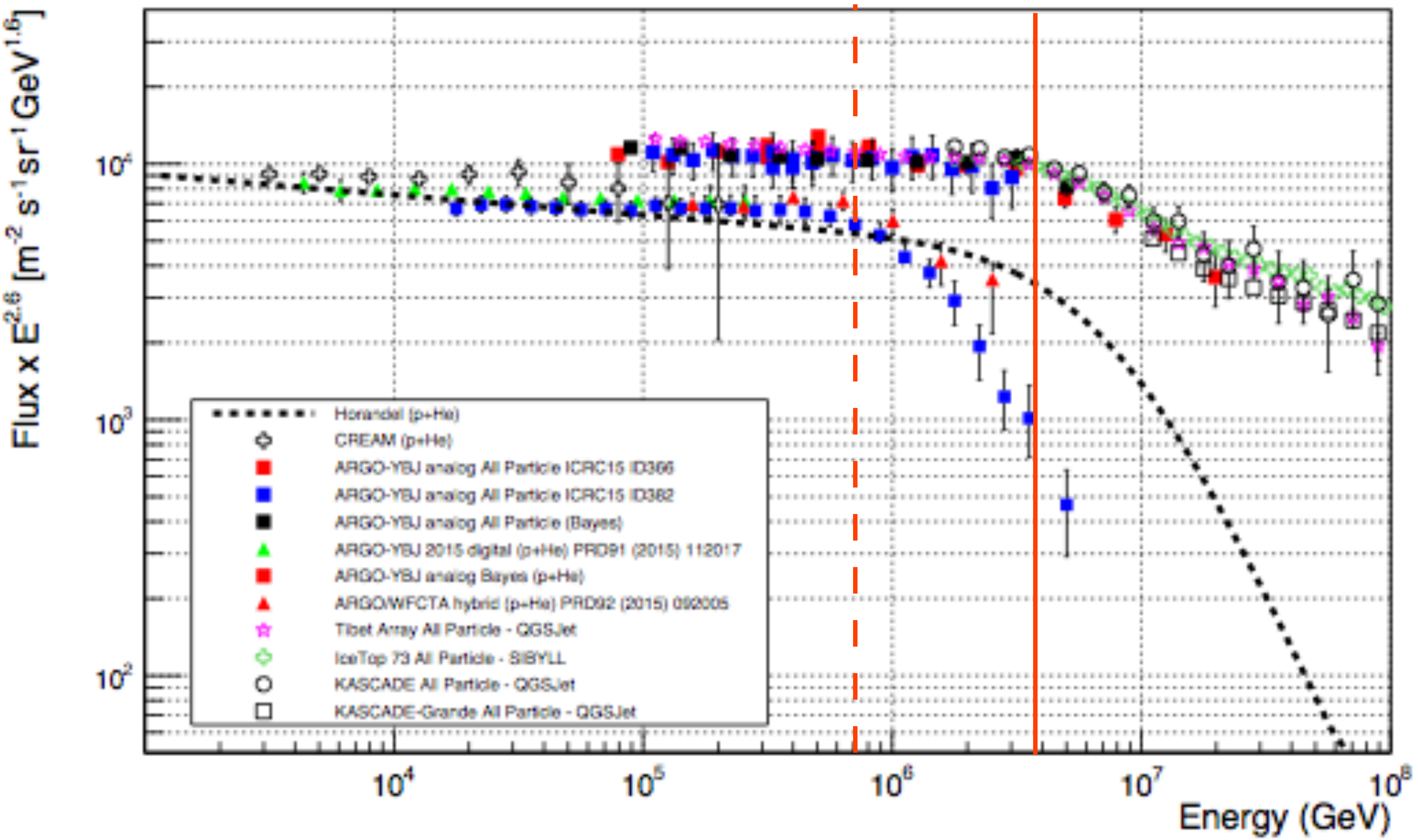
ARGO-YBJ reports evidence for a proton knee starting at about 700 TeV



Remember: ARGO-YBJ diffuse emission measured around the Cygnus region:-2.65

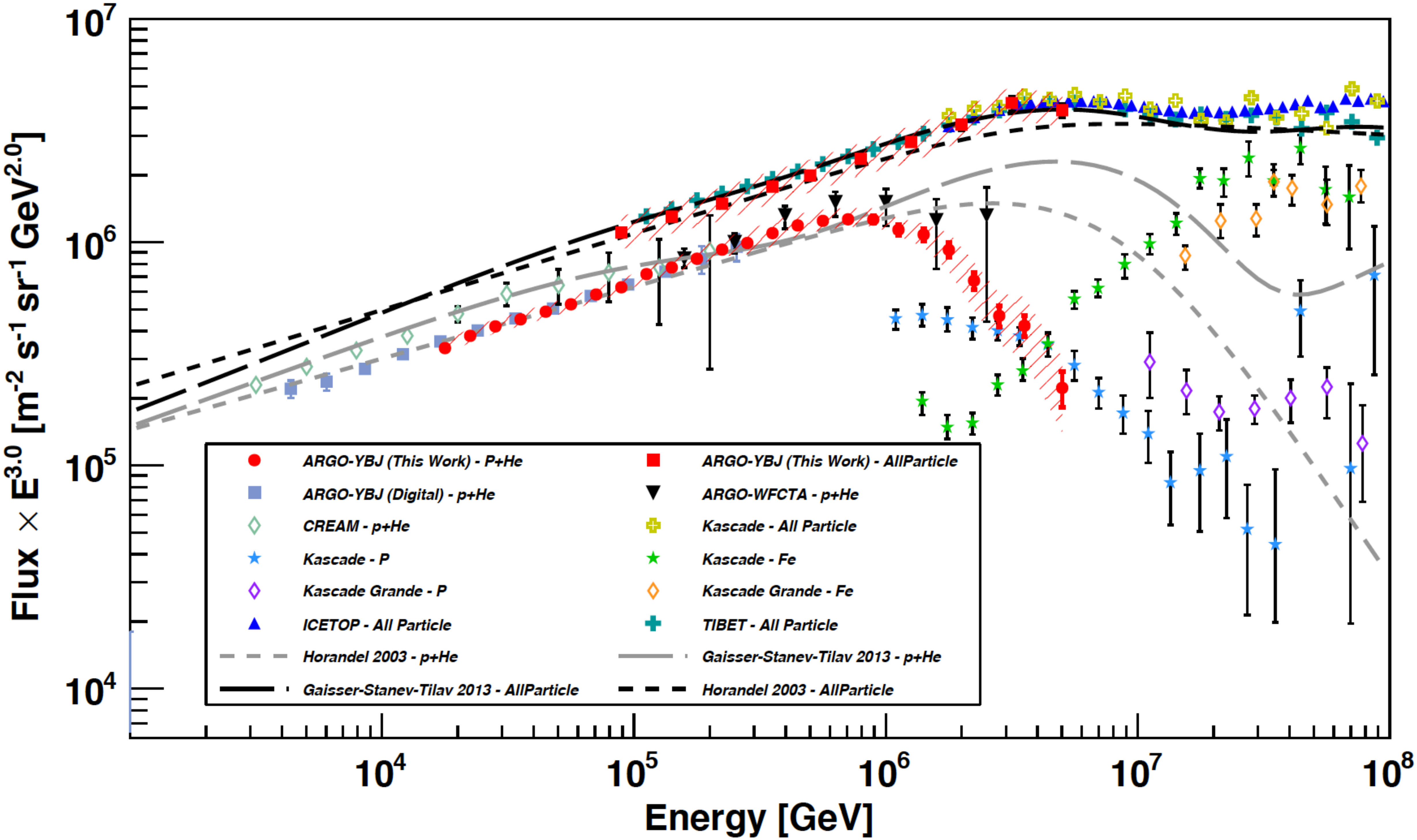
The overall picture

Roberto Iuppa



Comparison with other experiments

Roberto Iuppa



Medium/Small Scale Anisotropy

Roberto Iuppa

Data: November 8, 2007 - May 20, 2012 ≈ 3.70×10^{11} events

PHYSICAL REVIEW D **88,** 082001 (2013)

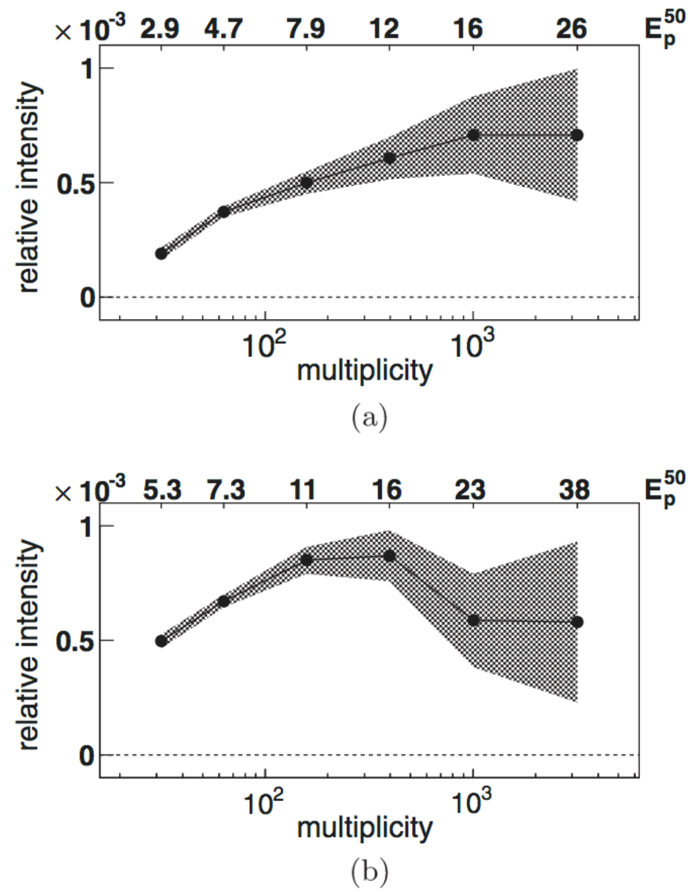
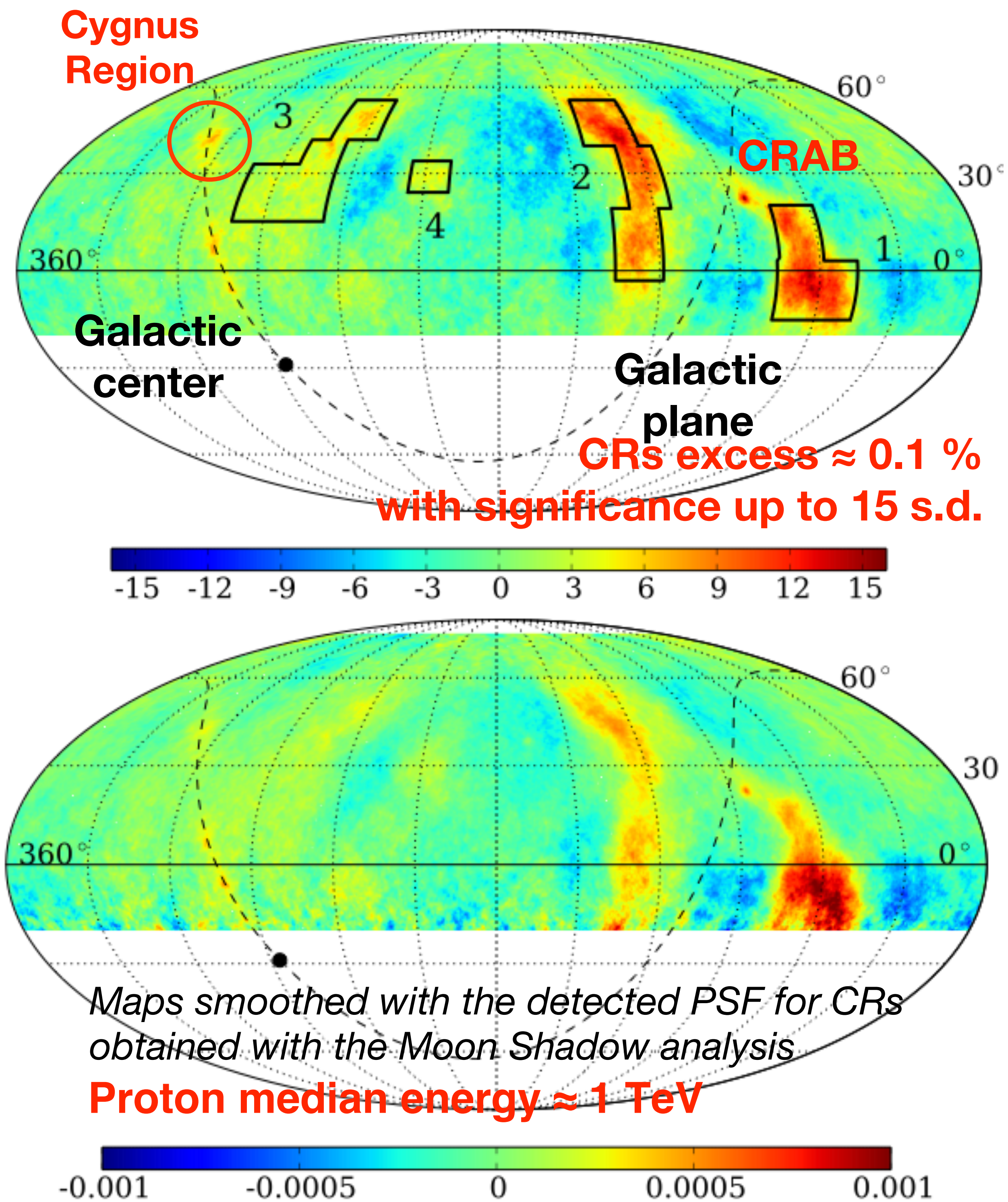


FIG. 7. Multiplicity spectra of the subregions 1U (a) and 1L (b). The vertical axis represents the relative excess $(e - b)/b$. The upper horizontal scale shows the corresponding proton median energy (TeV). Six multiplicity intervals were used instead of the five described in Sec. III; see the text for details.

Towards the idea of a LOCAL measuments: *liason* TeV-gamma's/CRs mandatory

ApJ 809 (2015) 90

Phys. Rev. D 88 (2013) 082001



Conclusions

Roberto Iuppa

- ARGO-YBJ has been a forerunner in Air Shower detection at High Altitude.
- The insight to lower the energy threshold to TeV exploiting high altitude and full coverage was realized with RPCs.
- High granularity was hoped to be of great help in gamma/hadron separation, but turned out to be more useful for mass composition in cosmic-ray Physics (analog readout).
- High-duty cycle and ~sr FOV made it possible important achievements in gamma ray astropnomy, i.e. on flaring source monitoring (MWL campaigns) and for extended sources/diffuse emission.
- High-quality result obtained in CR Physics: anisotropies (LS and MS), all particle spectrum and mass composition, with puzzling results on the knee energy.
- The idea of LOCAL measurements with the same experiment should be pursued as much as possible: it allows to cross-calibrate systematics among different messengers.

ARGO-YBJ: a full coverage detector

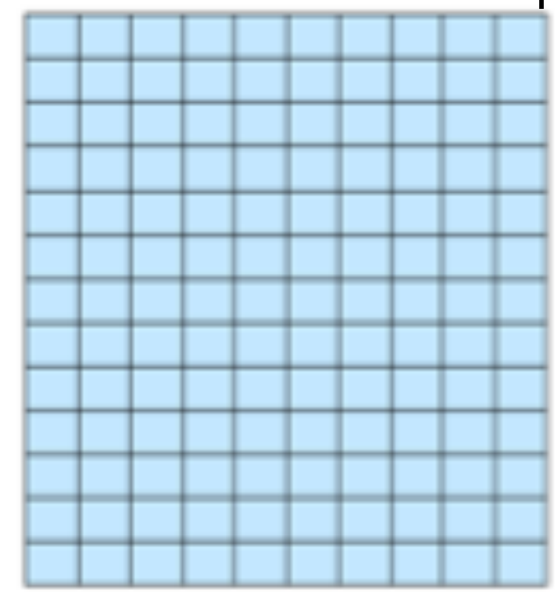
Roberto Iuppa

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 ≈10^5 m^2

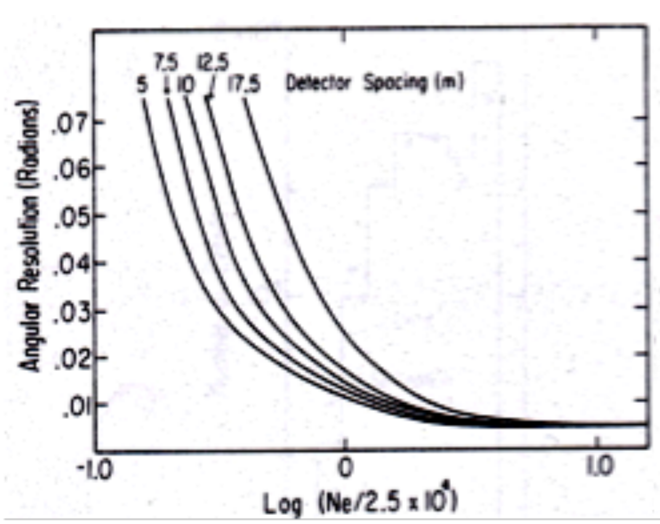
coverage factor (sensitive area/instrumented area) ≈ 10^{-3} - 10^{-2}

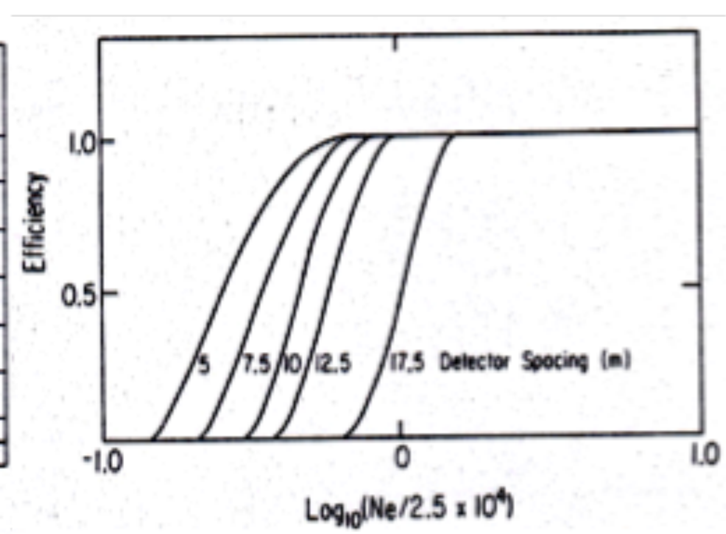
ARGO-YBJ central carpet



a continuous carpet of detectors

coverage factor ≈ 0.92



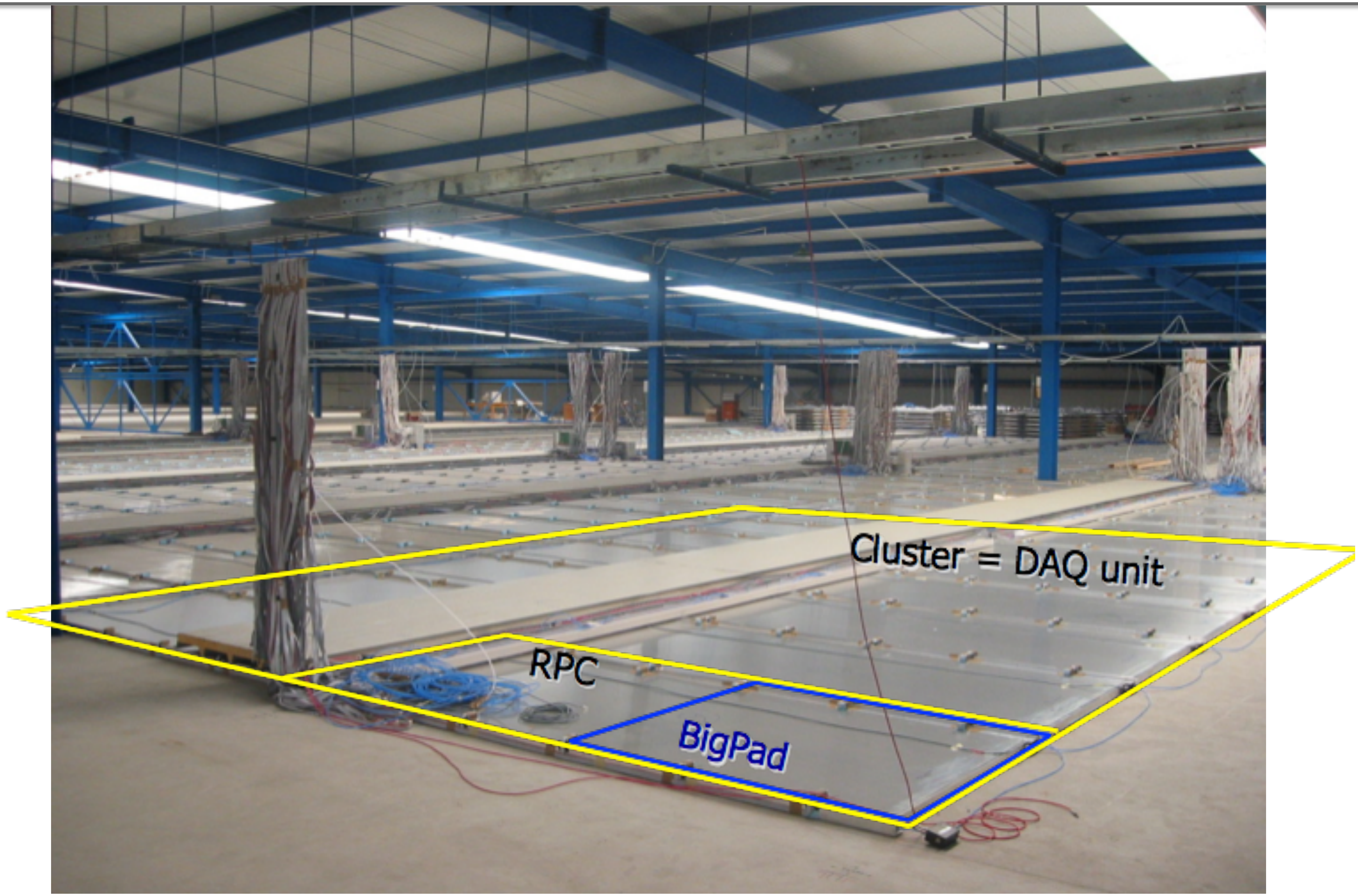


Increasing the sampling (~1% ➜100%)

- Improves angular resolution
- Lowers energy threshold

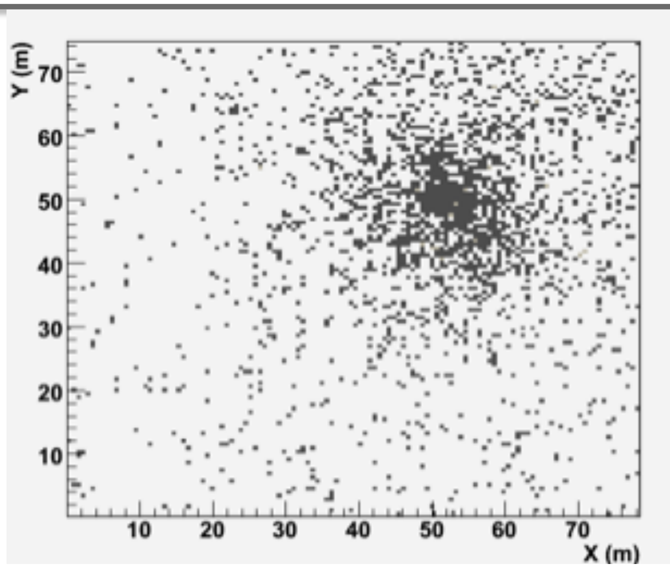
The experimental hall

Roberto Iuppa

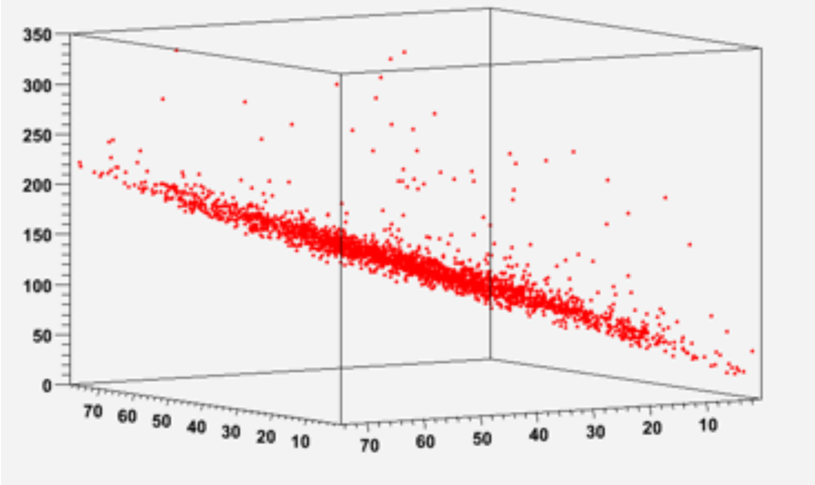


Shower detection

Roberto Iuppa

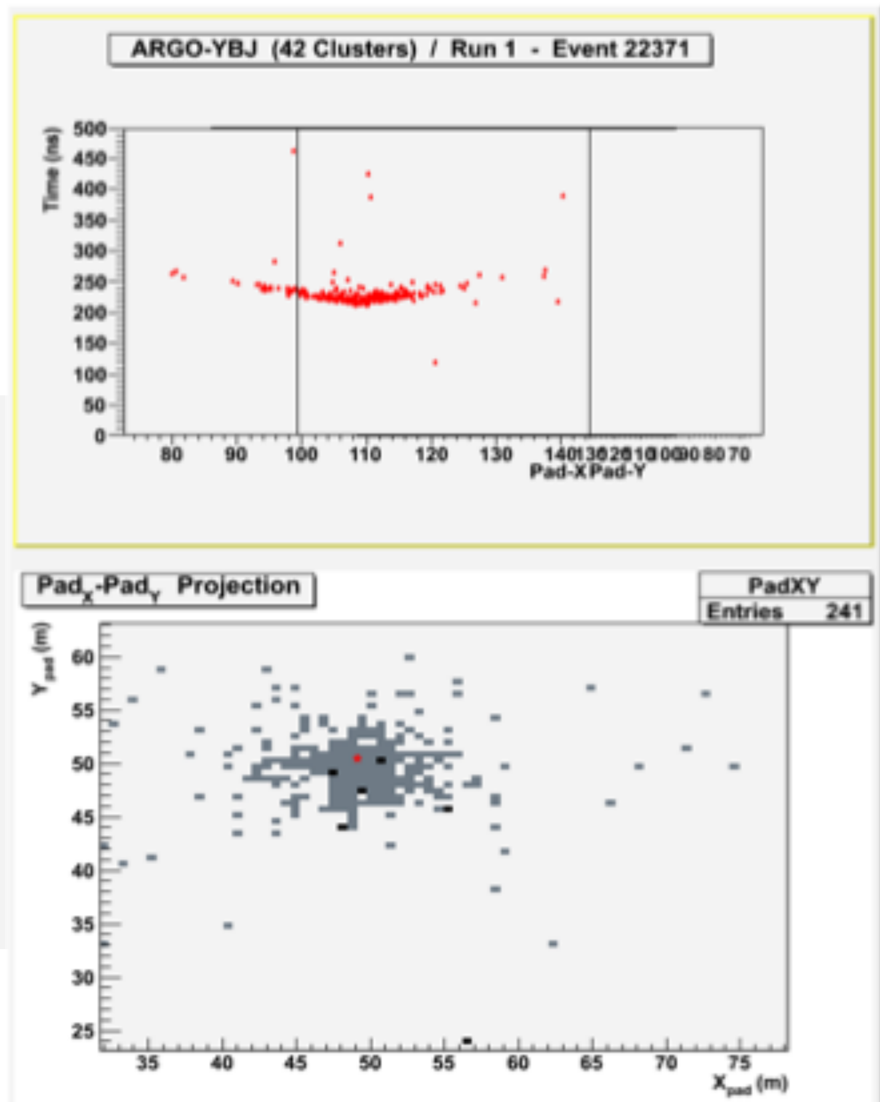


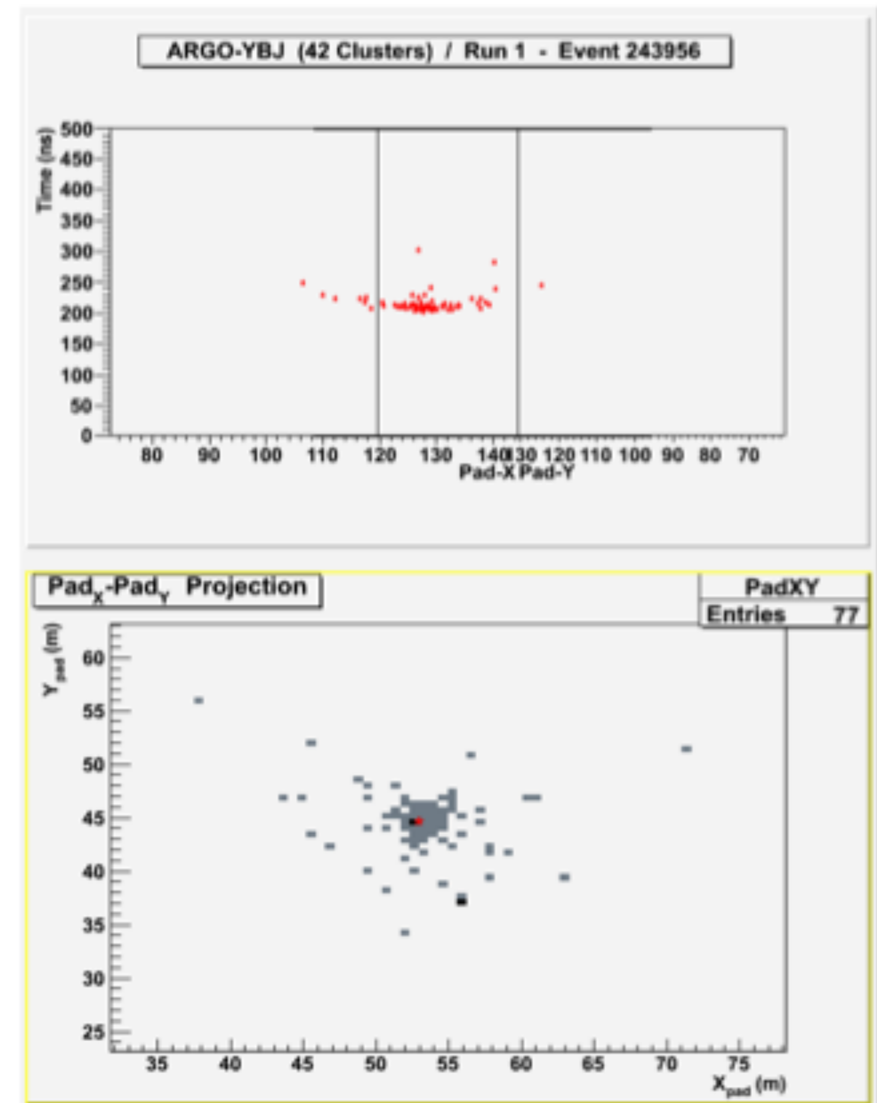
Fired pads on the carpet



Arrival time vs position

Small and compact events





ARGO-YBJ: a multi-purpose experiment

Roberto Iuppa

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

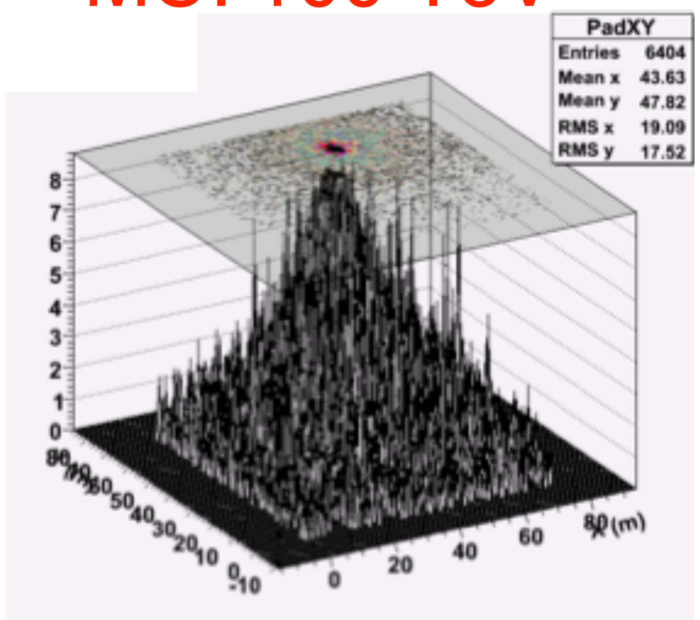
- Sky survey -10% $\leq \delta \leq$ 70% (γ-sources, diffuse emission)
- High exposure for flaring activity (γ-sources, GRBs, solar flares)
- CR 1 TeV ➜ 10^4 TeV
  - p + He energy spectrum
  - Proton *"knee"*
  - Composition at the *knee*
  - Anisotropies
- Antip/p at TeV energies
- Solar and heliospheric physics
- Hadronic interactions, cross sections

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

The RPC charge readout: the core region

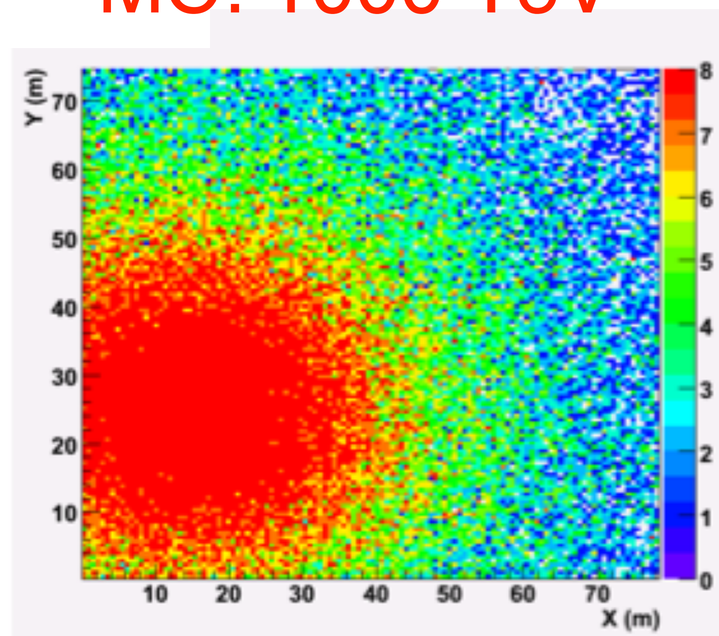
Roberto Iuppa

MC: 100 TeV



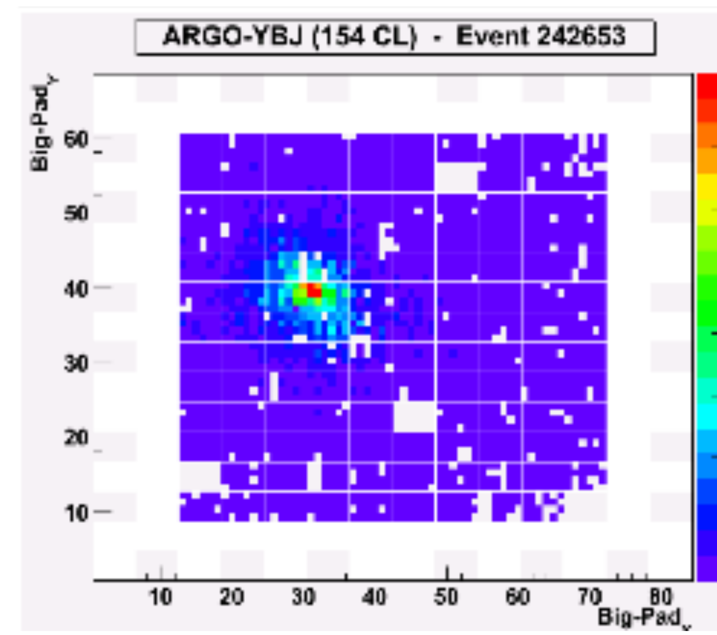
Strip read-out

MC: 1000 TeV

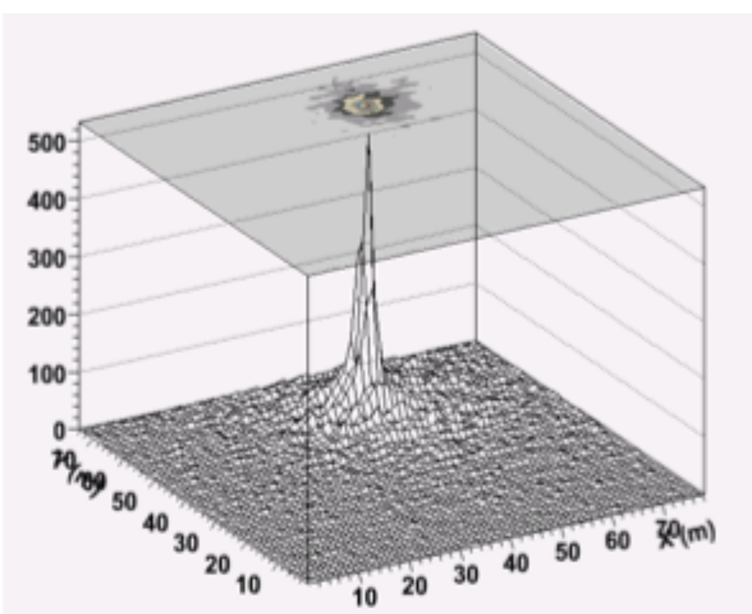


Strip read-out

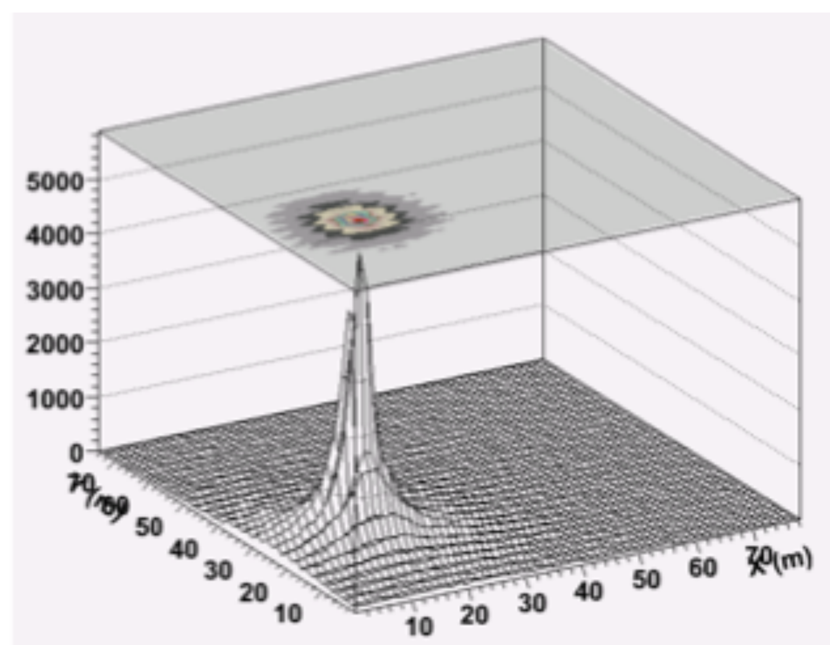
Data



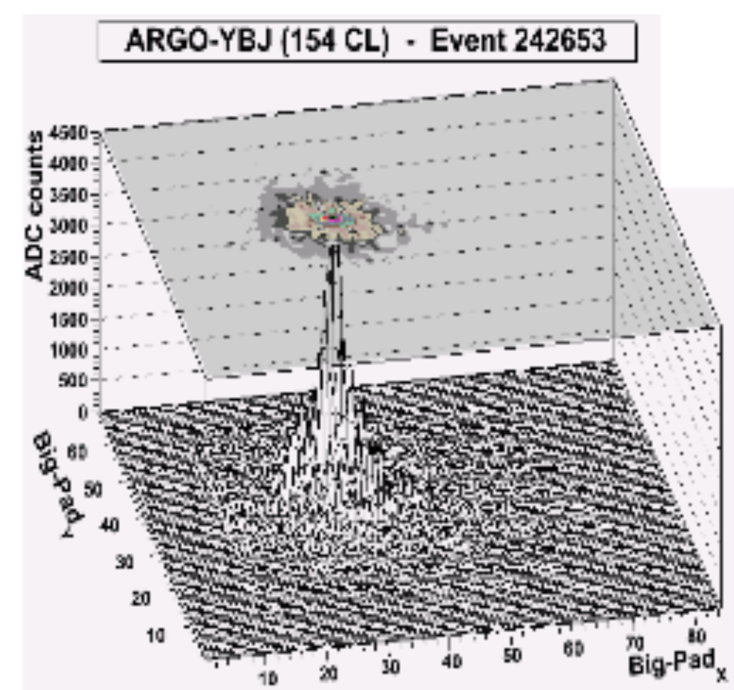
Strip read-out



Charge read-out



Charge read-out

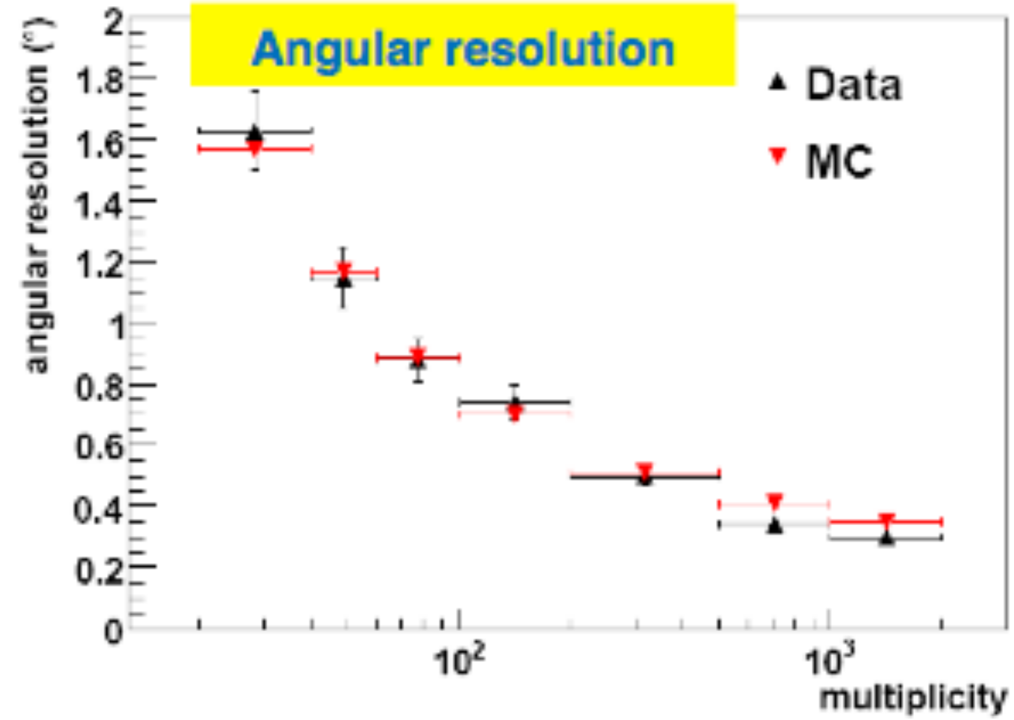


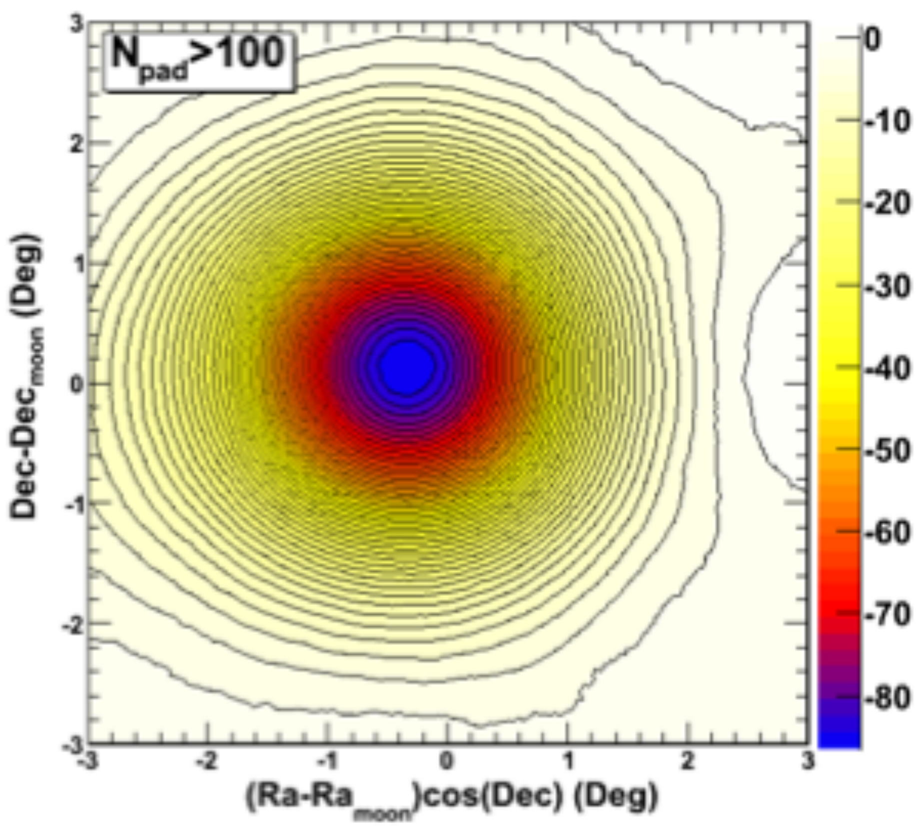
Charge read-out

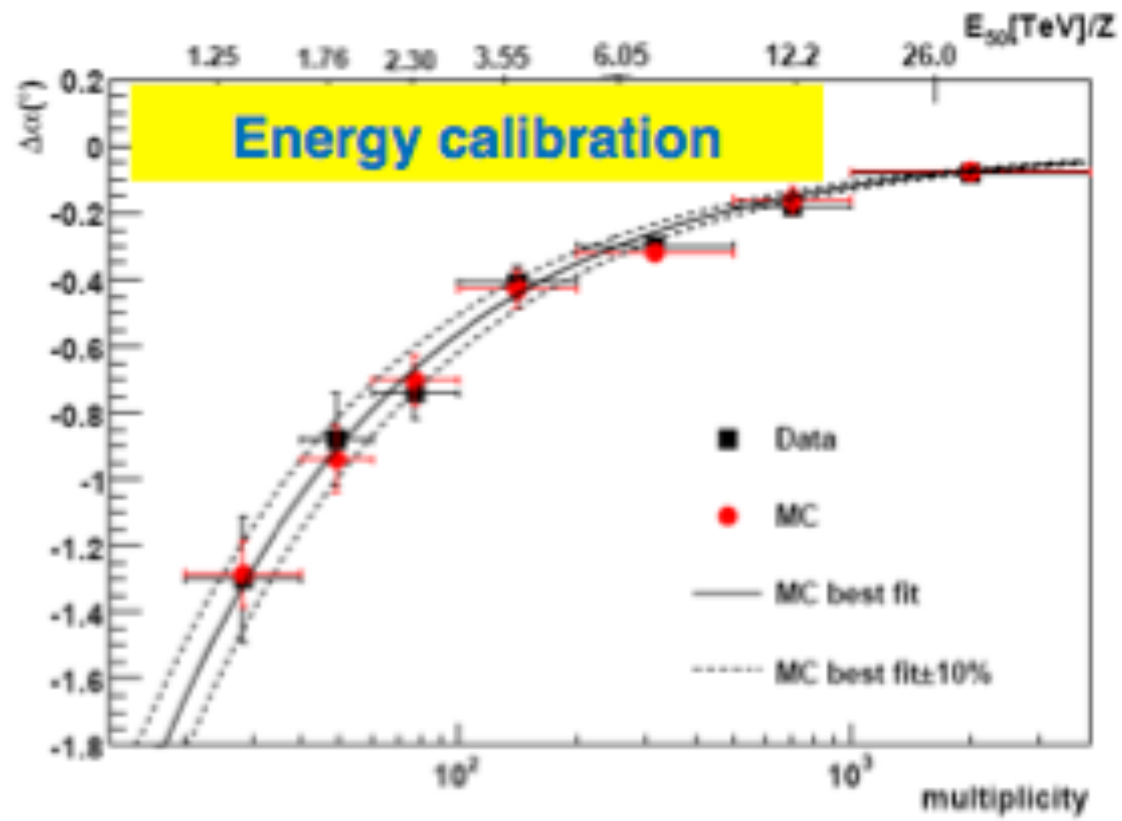
The *Moon shadow* analys

★ 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).

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

Roberto Iuppa

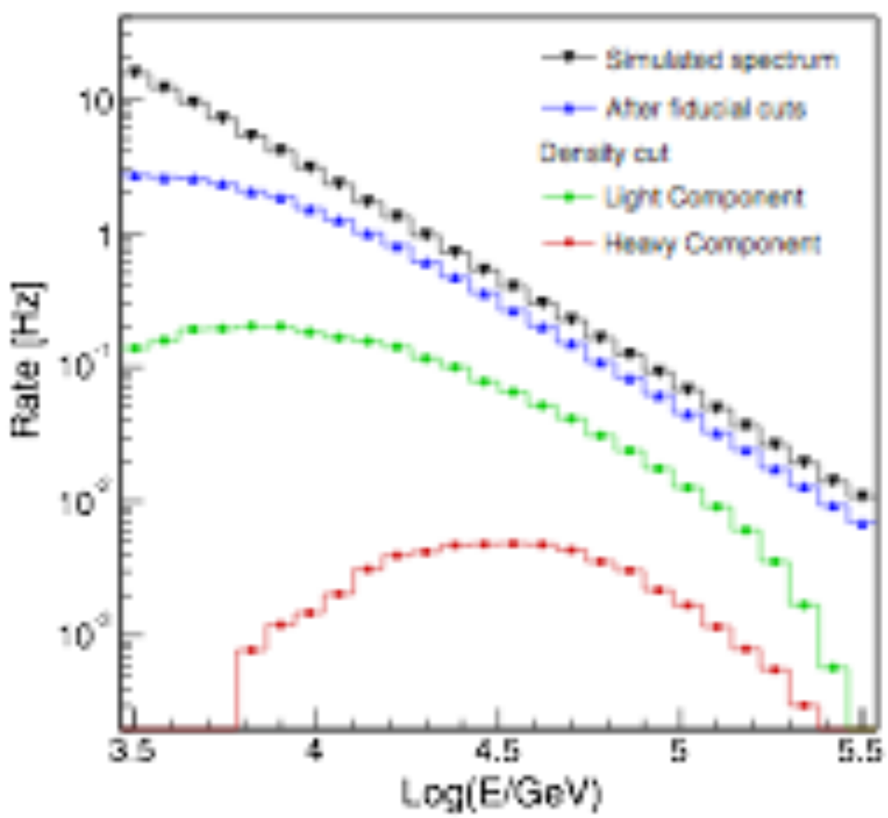
Analysis of **digital RPC** data (strip multiplicity) and **statistical** measurement of the energy spectrum by using a **bayesian approach.**

Data collected between Jan. 2008 and Dec. 2012 ≈ 8×10^{10} high quality events

- M ≤ 50,000
- Zenith Angle ≤ 35°
- Highest density cluster in 40 × 40 m^2

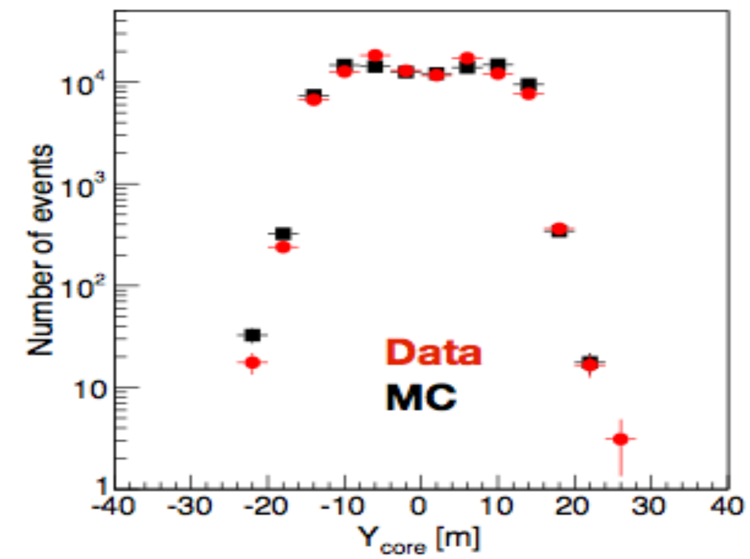
- Light Component (p+He) selection:
  $\rho_{A20} > 1.25\ \rho_{A42}$

A20 = 20 innermost clusters
A42 = 42 outermost clusters

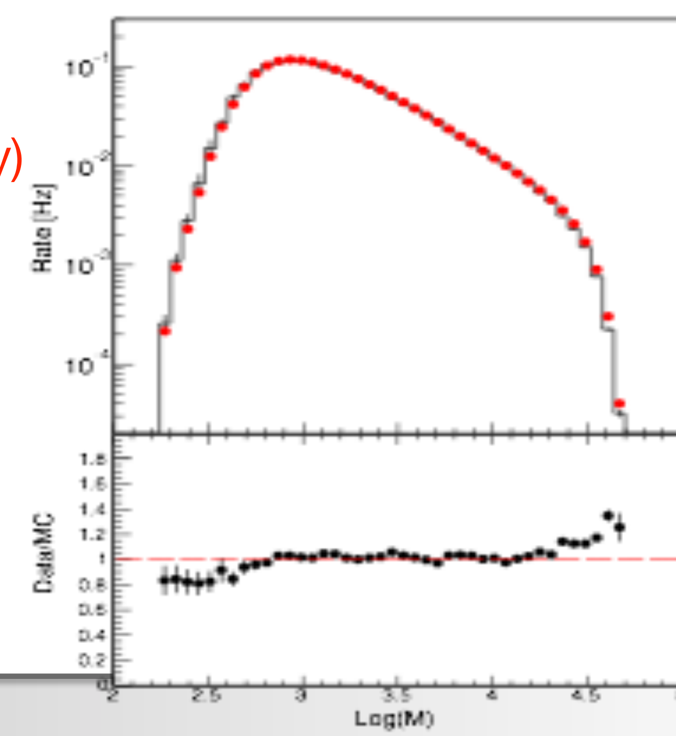


Fraction of selected events:
30 TeV → 18%
115 TeV → 24%

Reconstructed shower core position



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

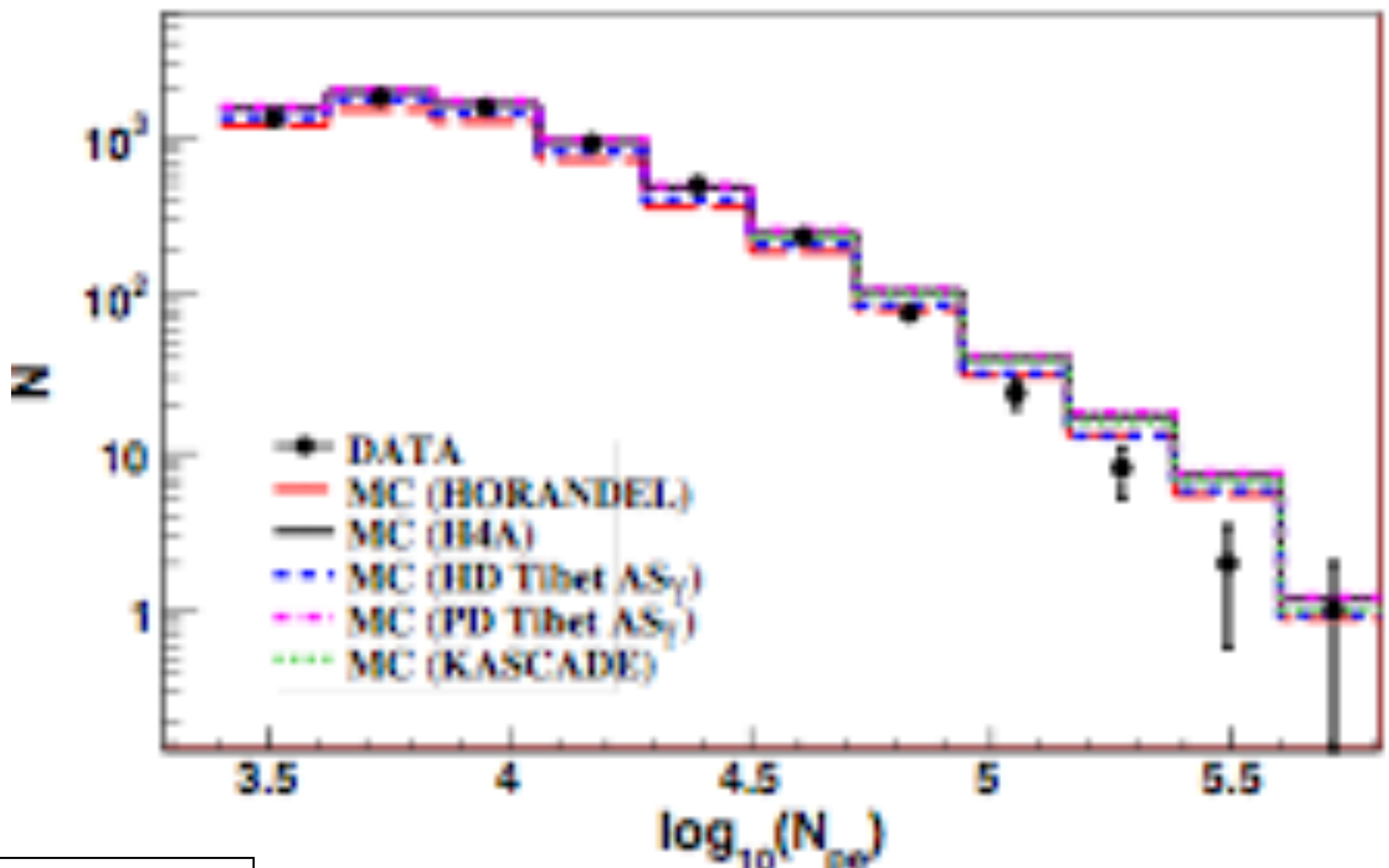


Phys. Rev. D85, 092005 (2012)
Phys. Rev. D91, 112017 (2015)

ARGO-YBJ/WFCTA: All-particle spectrum

Roberto Iuppa

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)

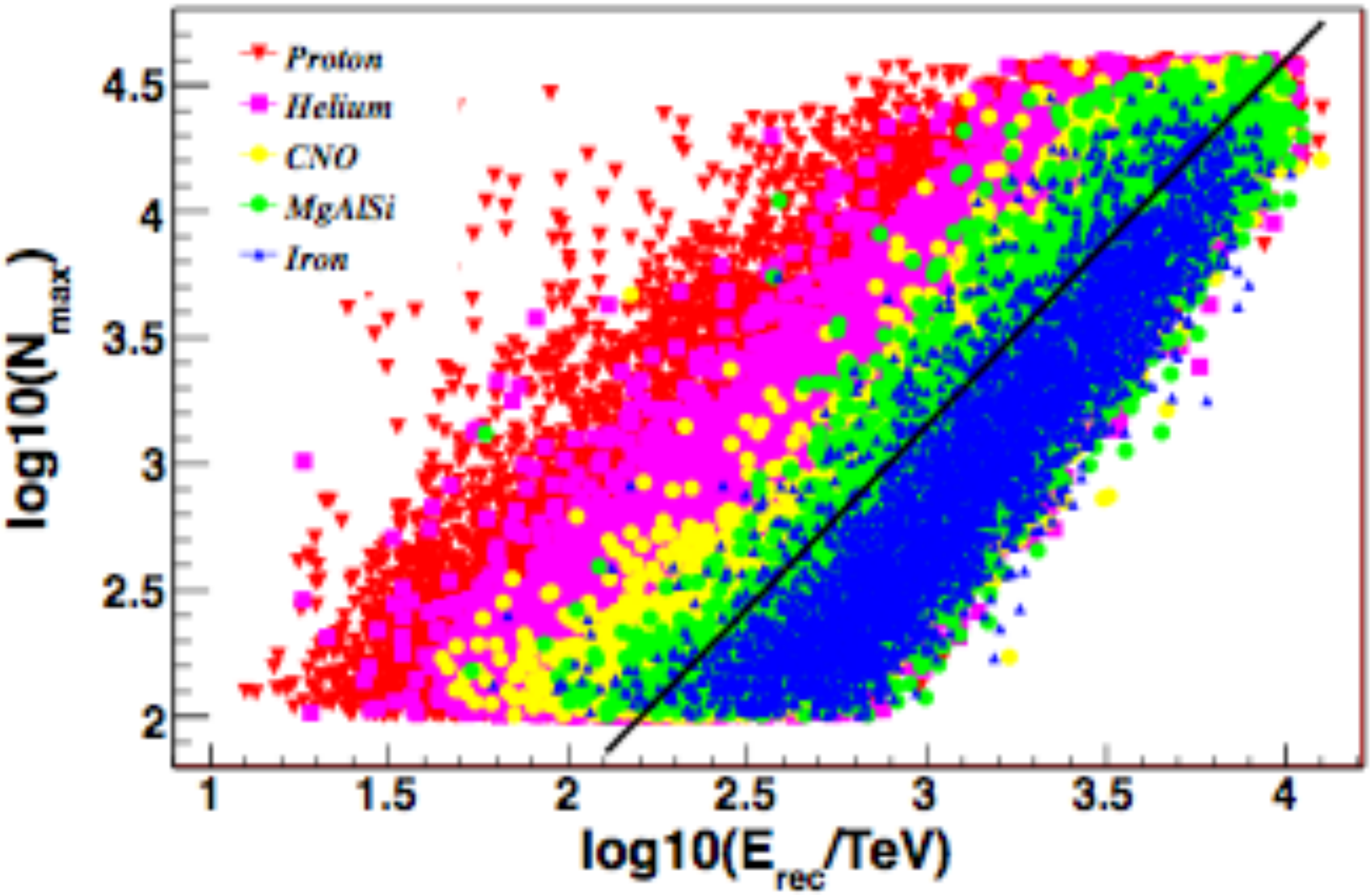
Light component (p + He) selection - (1)

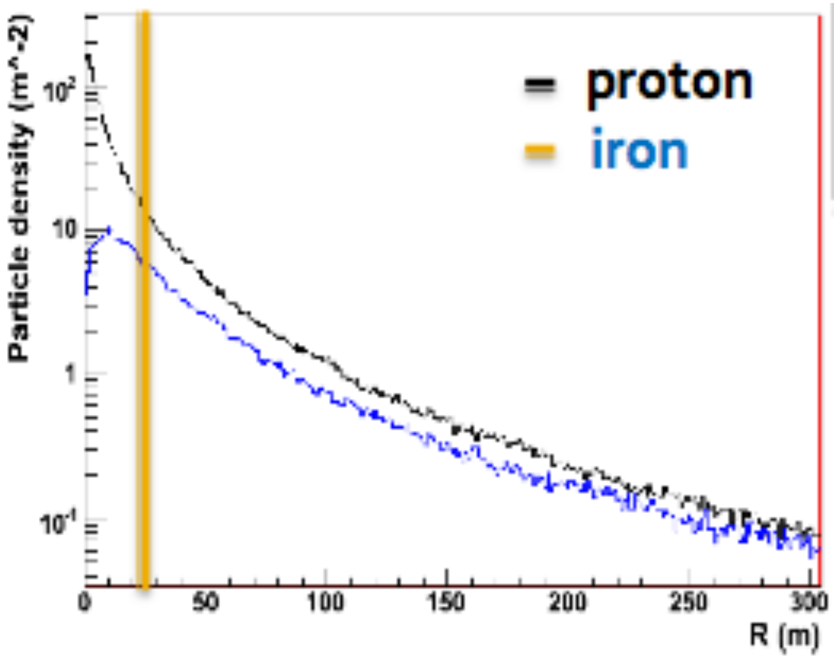
Roberto Iuppa

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

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





We can define a new parameter to reduce the energy dependence

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

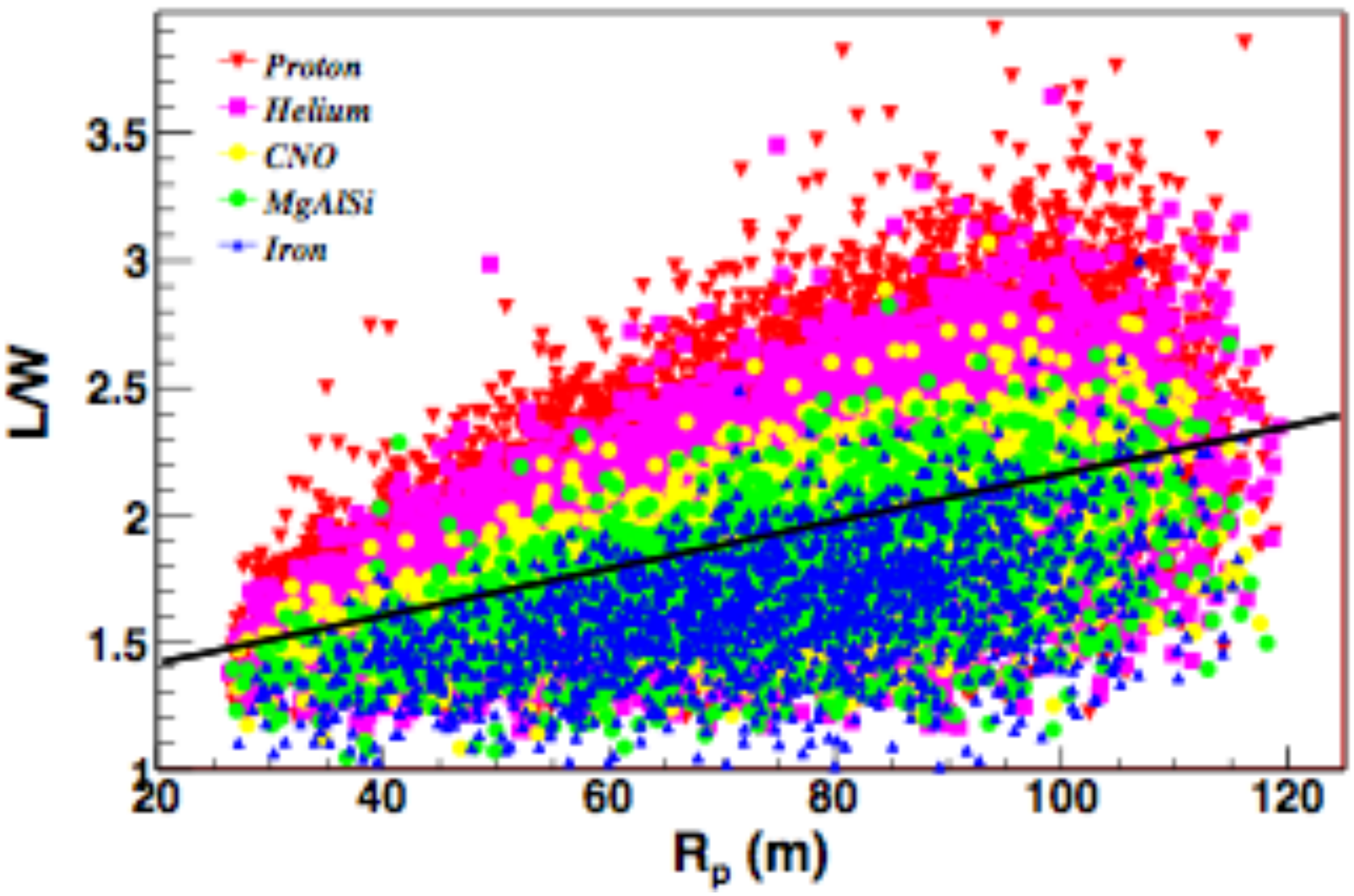
Chin. Phys. C 38, 045001 (2014)

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

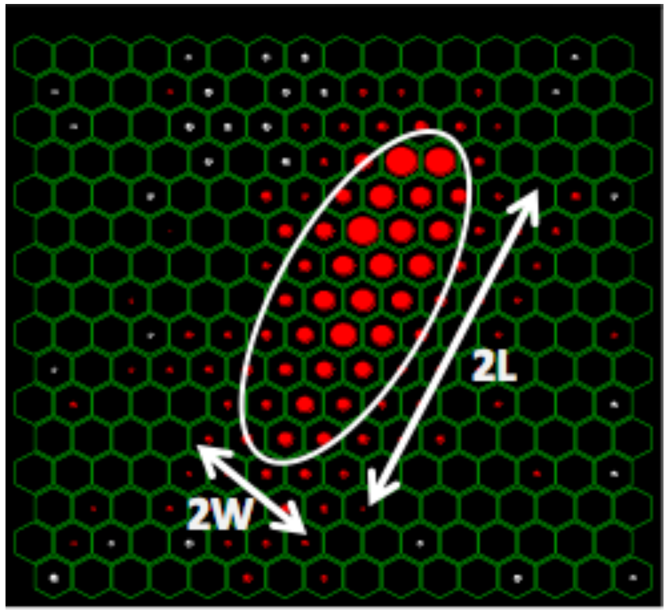
Roberto Iuppa

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 ~ 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)