The Scientific Legacy of ARGO-YBJ

G. Di Sciascio on behalf of the ARGO-YBJ Collaboration
INFN Sezione Roma Tor Vergata
disciascio@roma2.infn.it

XIV International Conference on Topics in Astroparticle and Underground Physics

7-11 September 2015 – Torino – Italy

The ARGO-YBJ experiment

ARGO-YBJ is a full coverage EAS-array capable of acting simultaneously as a Cosmic Ray Detector and a Gamma Ray Telescope to face the open problems in Galactic CR physics.

✦ Cosmic Ray Sources: *"PeVatrons"*

accelerators

"astronomy" (gamma, neutrino) but also *anisotropy* !

old nearby sources: no photons but CRs → anisotropy !

✦ Proton energy spectrum: *"proton knee"*

acceleration mechanisms, propagation, neutrinos, background

The ARGO-YBJ experiment

ARGO-YBJ is a full coverage EAS-array capable of acting simultaneously as a Cosmic Ray Detector and a Gamma Ray Telescope to face the open problems in Galactic CR physics.

✦ Cosmic Ray Sources: *"PeVatrons"*

accelerators

"astronomy" (gamma, neutrino) but also *anisotropy* !

old nearby sources: no photons but CRs → anisotropy !

✦ Proton energy spectrum: *"proton knee"*

acceleration mechanisms, propagation, neutrinos, background

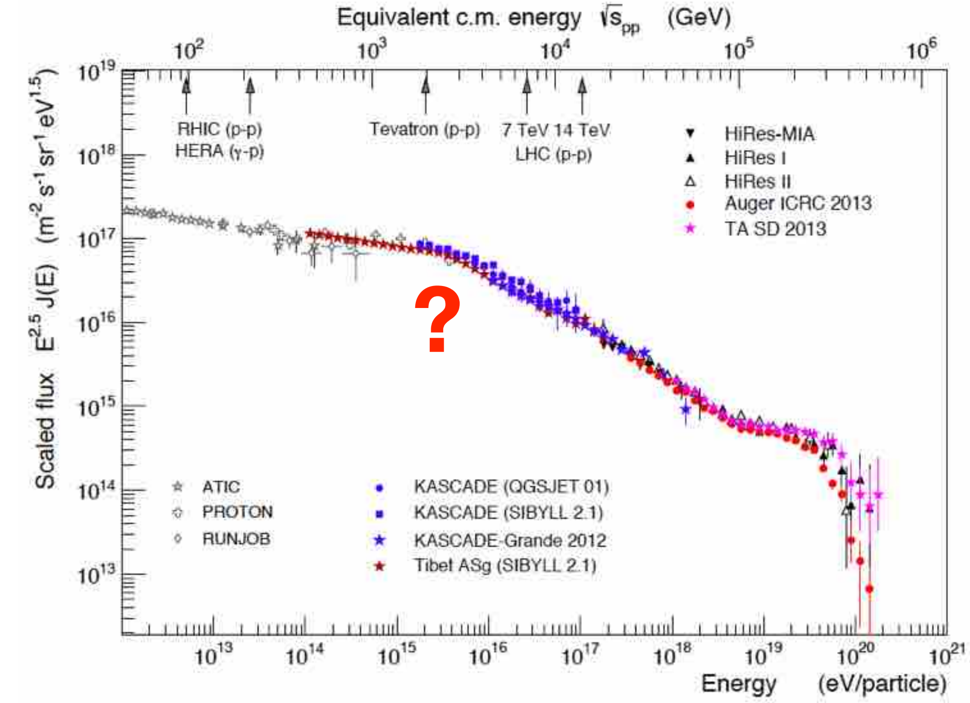
- Energy spectrum, elemental composition, anisotropy in the knee energy region

  3 fragments of a *"Rosetta stone"* crucial for understanding origin, acceleration and propagation of the radiation

- Gamma-ray diffuse emission

  to trace the location of the CR sources and the distribution of interstellar gas.

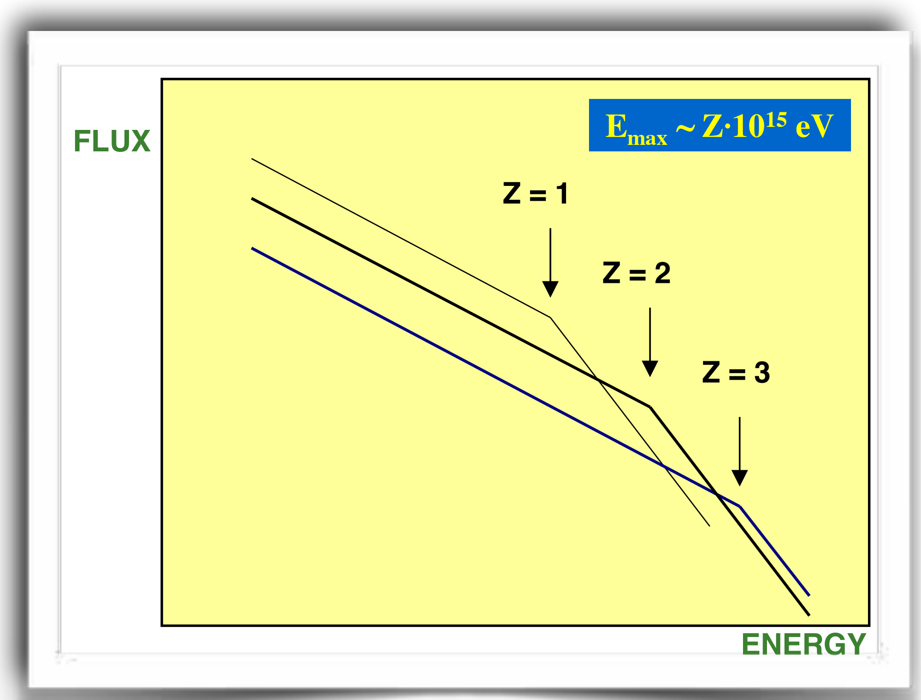
Approaching the knee



The origin of the *knee* in the all-particle spectrum of CRs is inextricably connected with the issue of the end of the Galactic CR spectrum and the transition to extragalactic CRs.

The standard model:

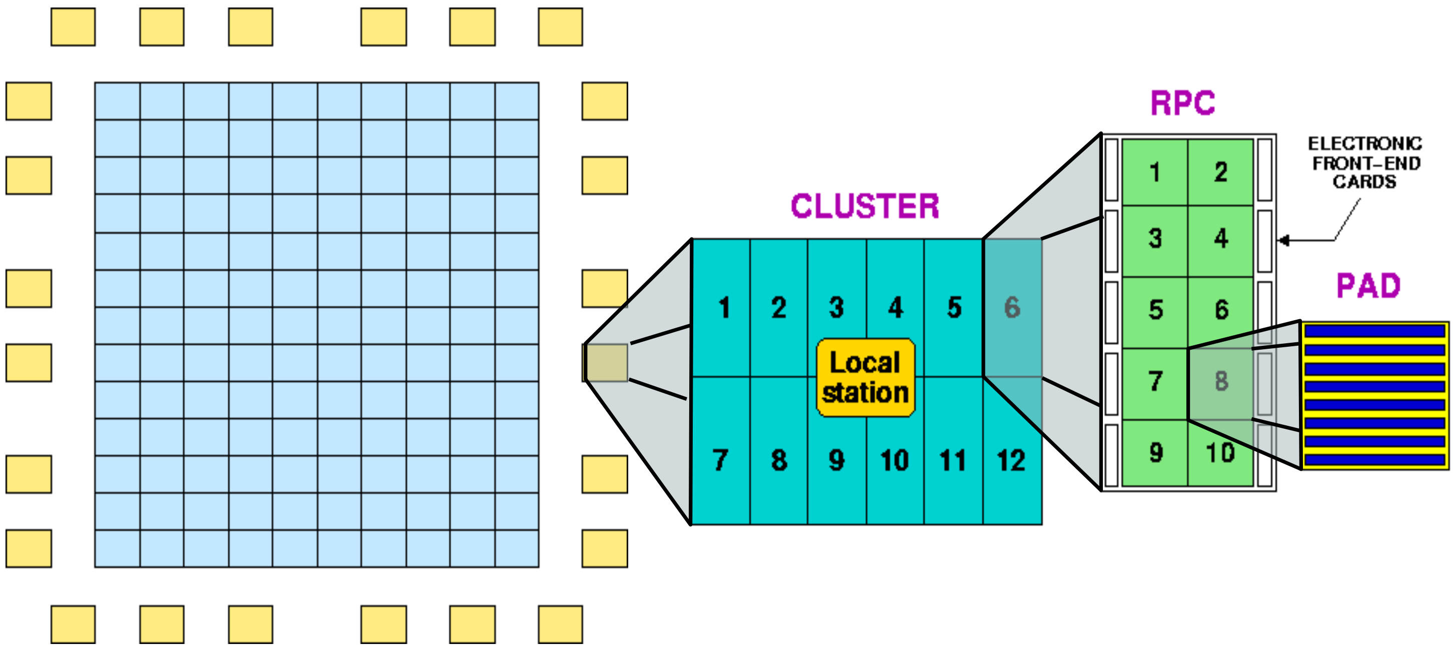
- Knee attributed to light (proton, helium) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge $E_Z = Z \times 4.5$ PeV
- The sum of the flux of all elements with their individual cut-offs makes up the all-particle spectrum.
- Not only does the spectrum become steeper due to such a cutoff but also heavier.

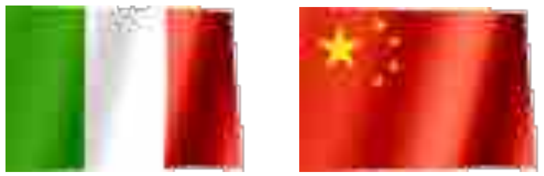


E_{max}(iron) = 26 · E_{max}(proton)

Experimental results still conflicting !

The ARGO-YBJ experiment



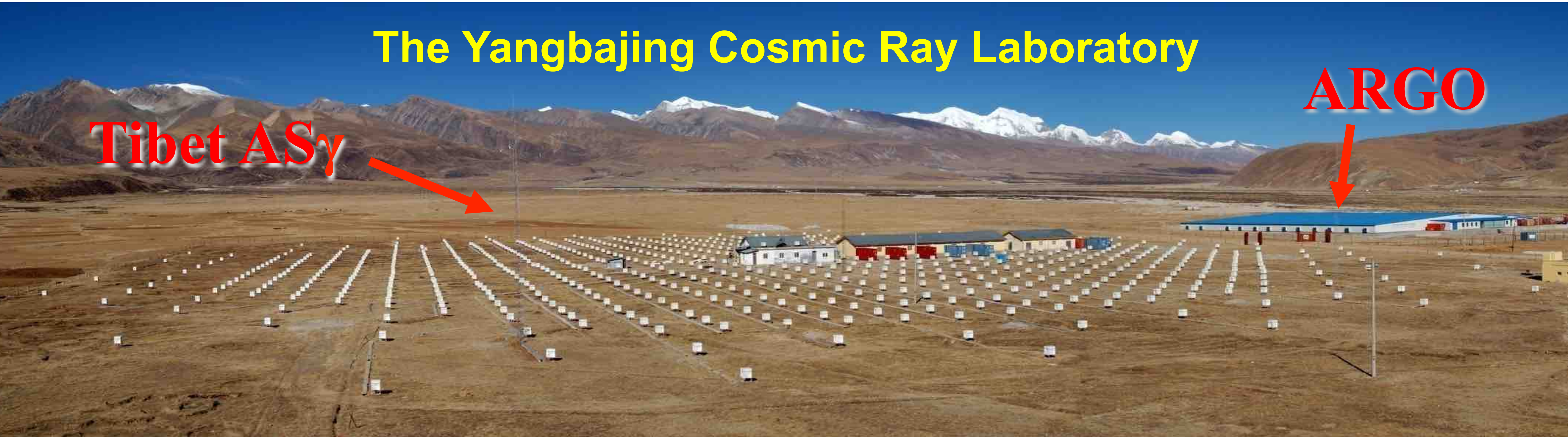


INFN IHEP/CAS

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

90 km North from Lhasa (Tibet)

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



The basic concepts

…for an unconventional air shower detector

❖ HIGH ALTITUDE SITE
(YBJ - Tibet 4300 m asl - 600 g/cm2)

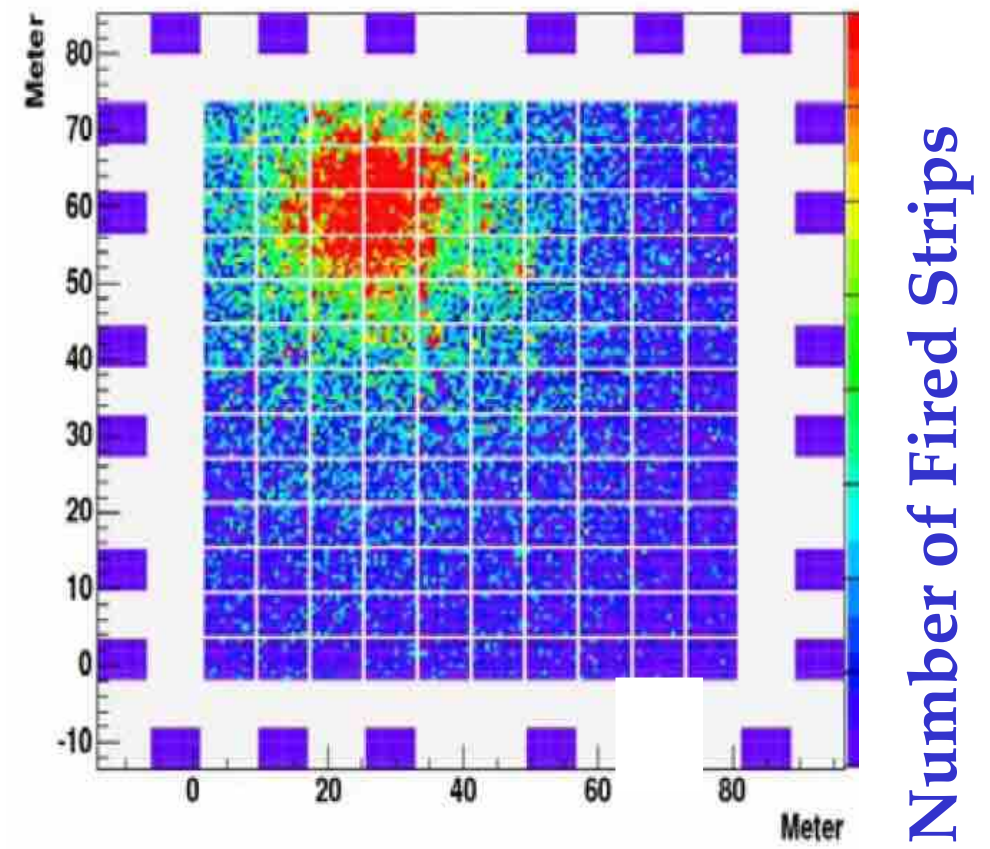
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

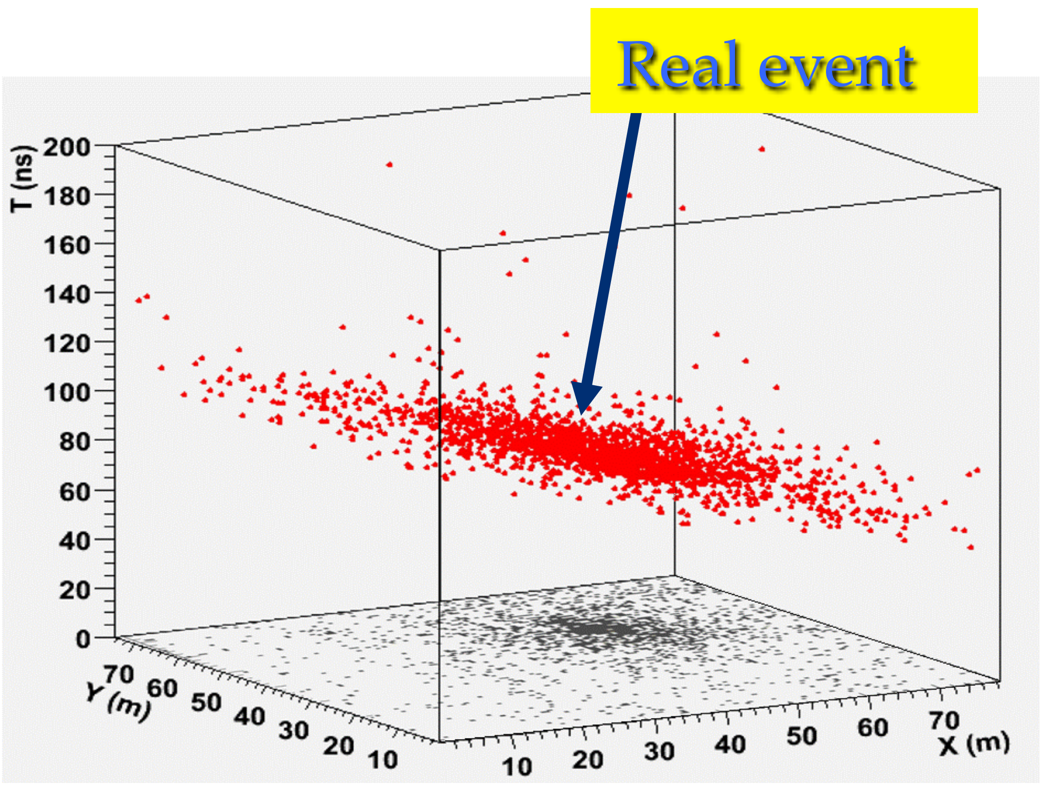
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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

… in order to

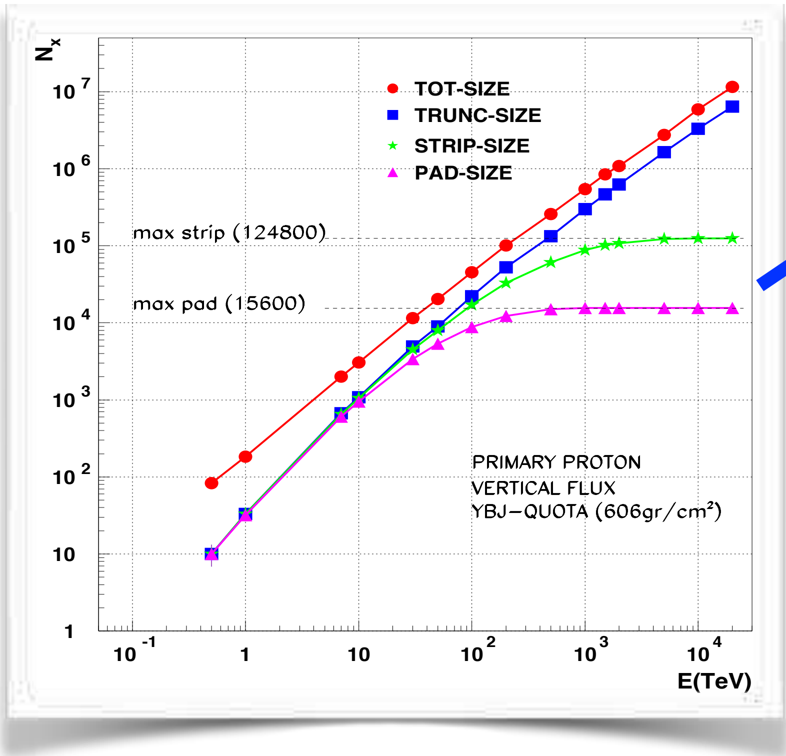
- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV

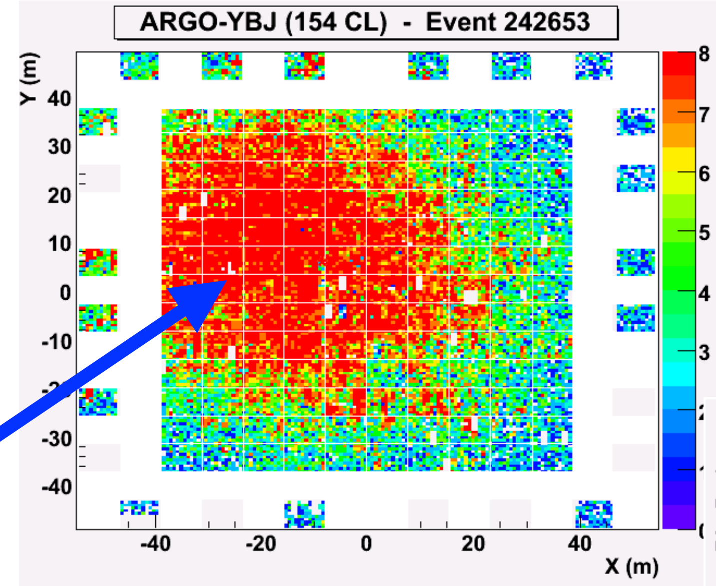




The RPC analog readout

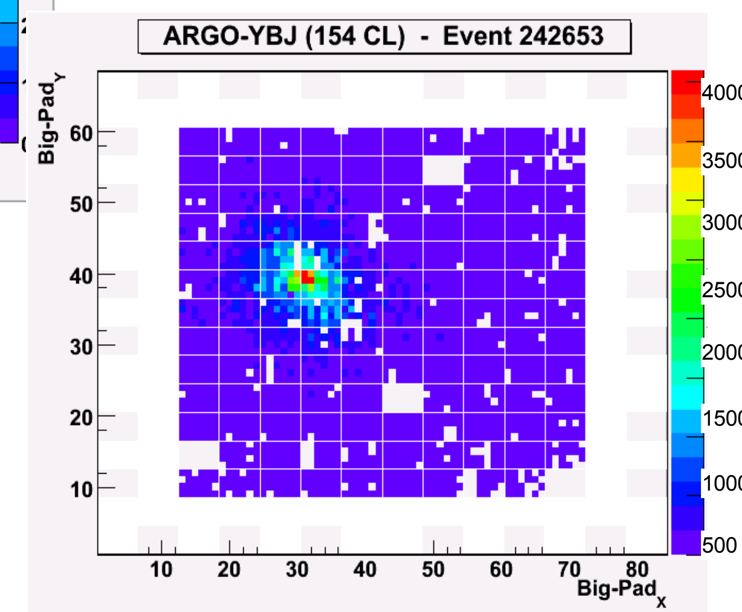
…extending the dynamical range up to PeV

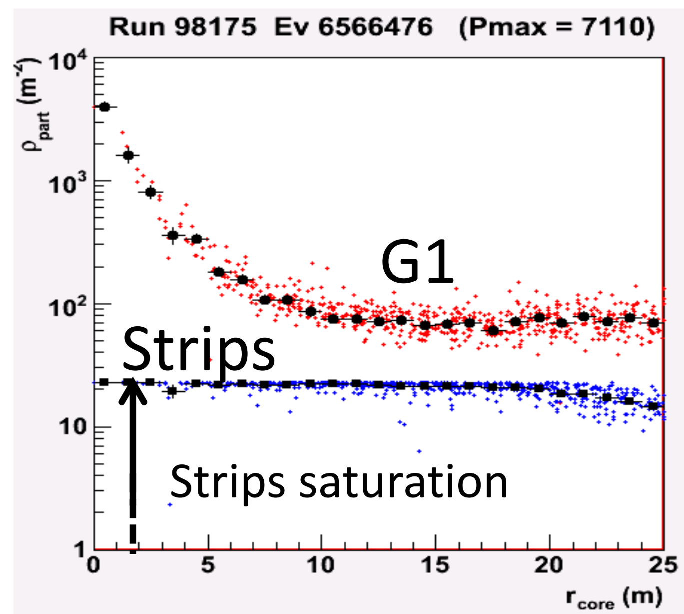


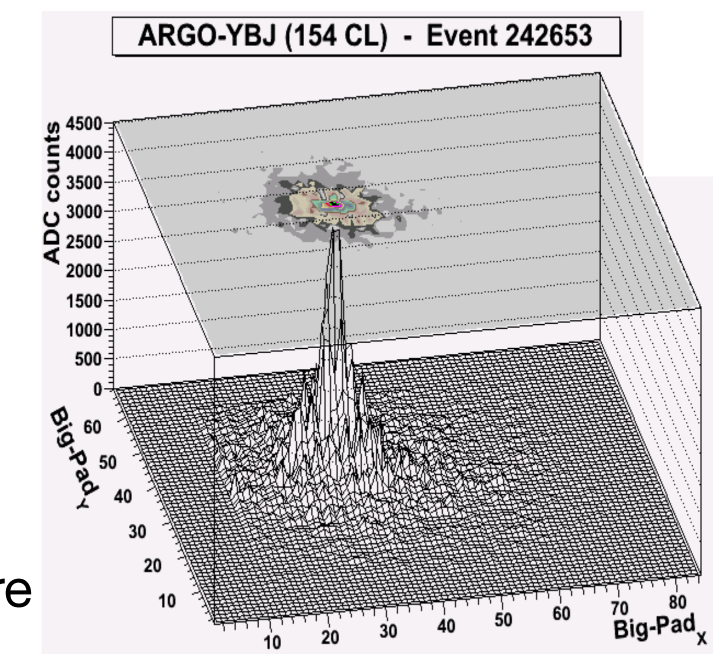


Strips (digital)

Big Pads (analog)







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

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

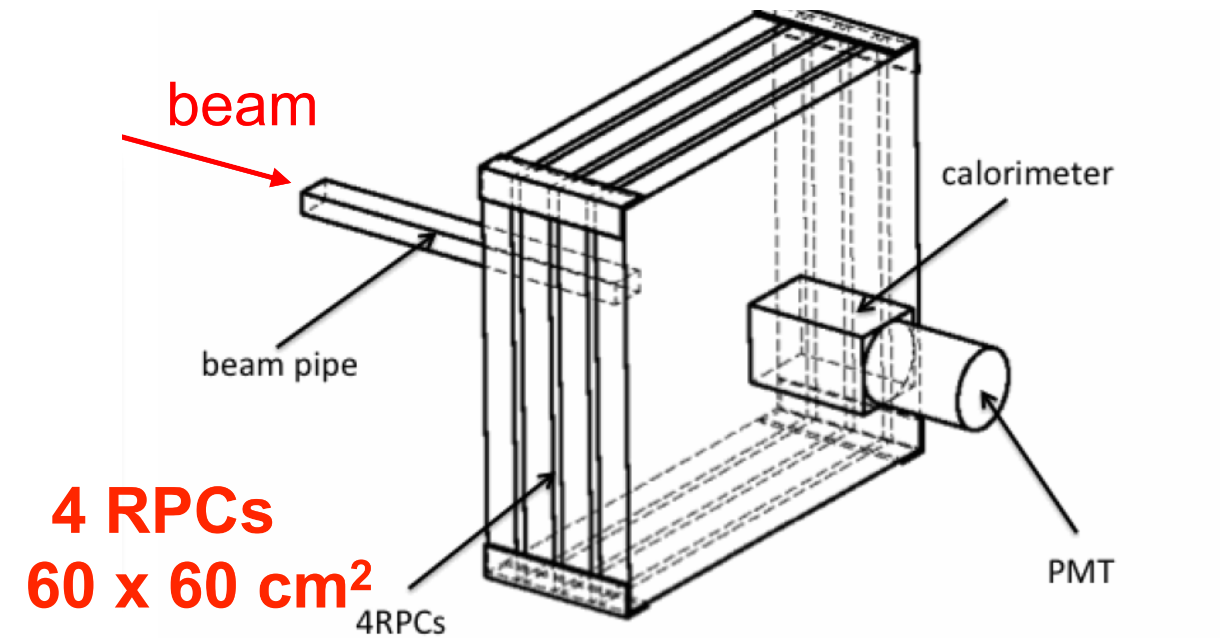
$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

- Extend the covered energy range
- Access the LDF in the shower core
- Sensitivity to primary mass
- Info/checks on hadronic interactions

Intrinsic linearity: test at the BTF facility

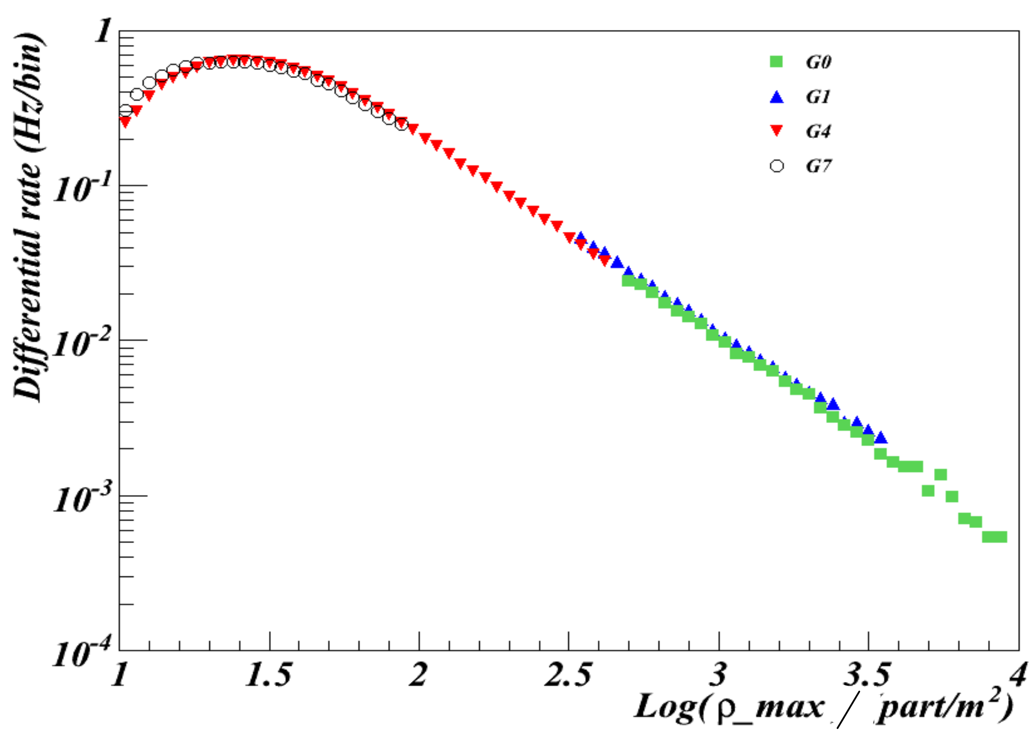
Linearity of the RPC @ BTF in INFN Frascati Lab:

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

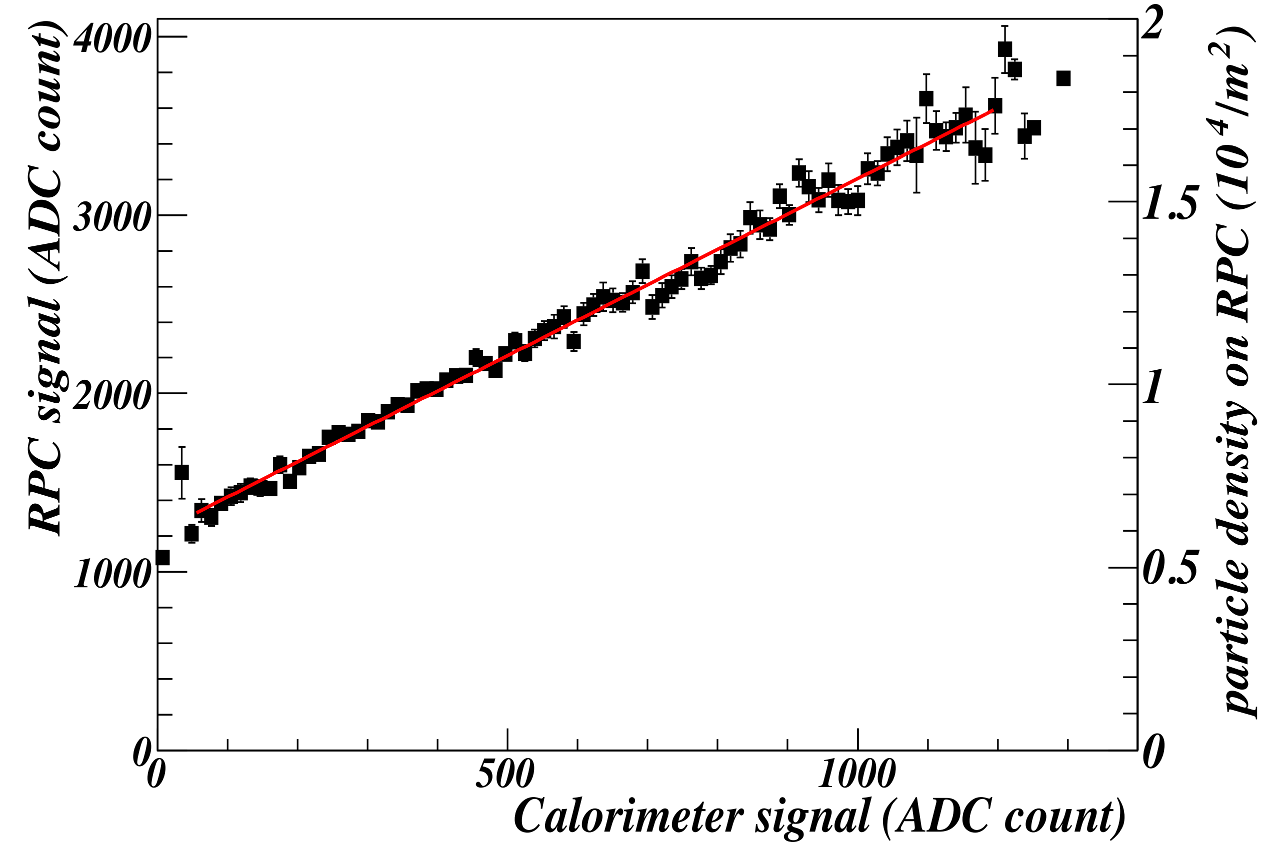


Calorimeter: lead glass block from OPAL, PMT a Hamamatsu R2238.

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



The RPC signal vs the calorimeter signal

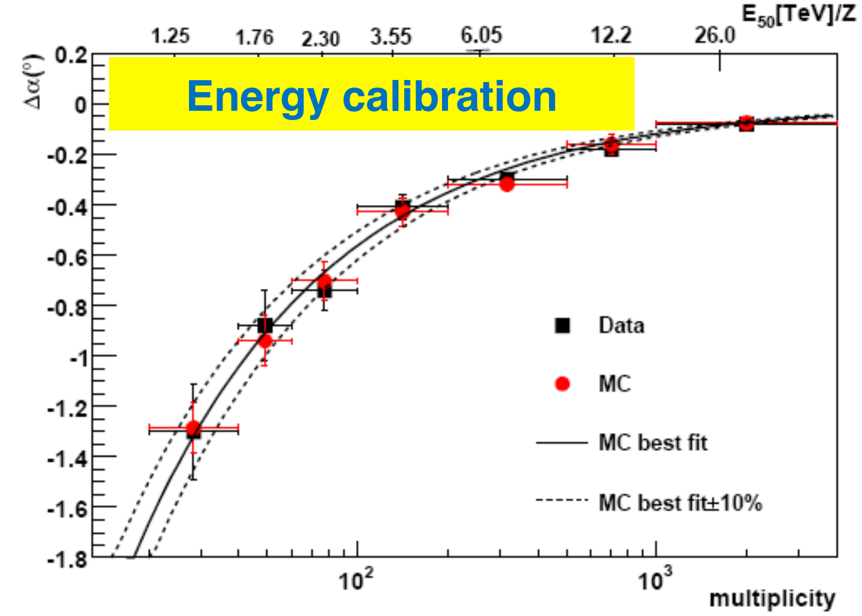


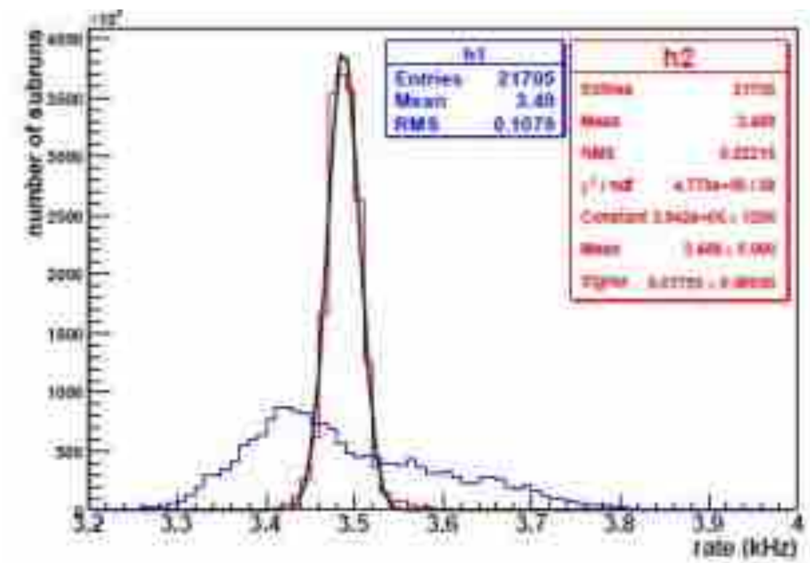
Astrop. Phys. 67 (2015) 47

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

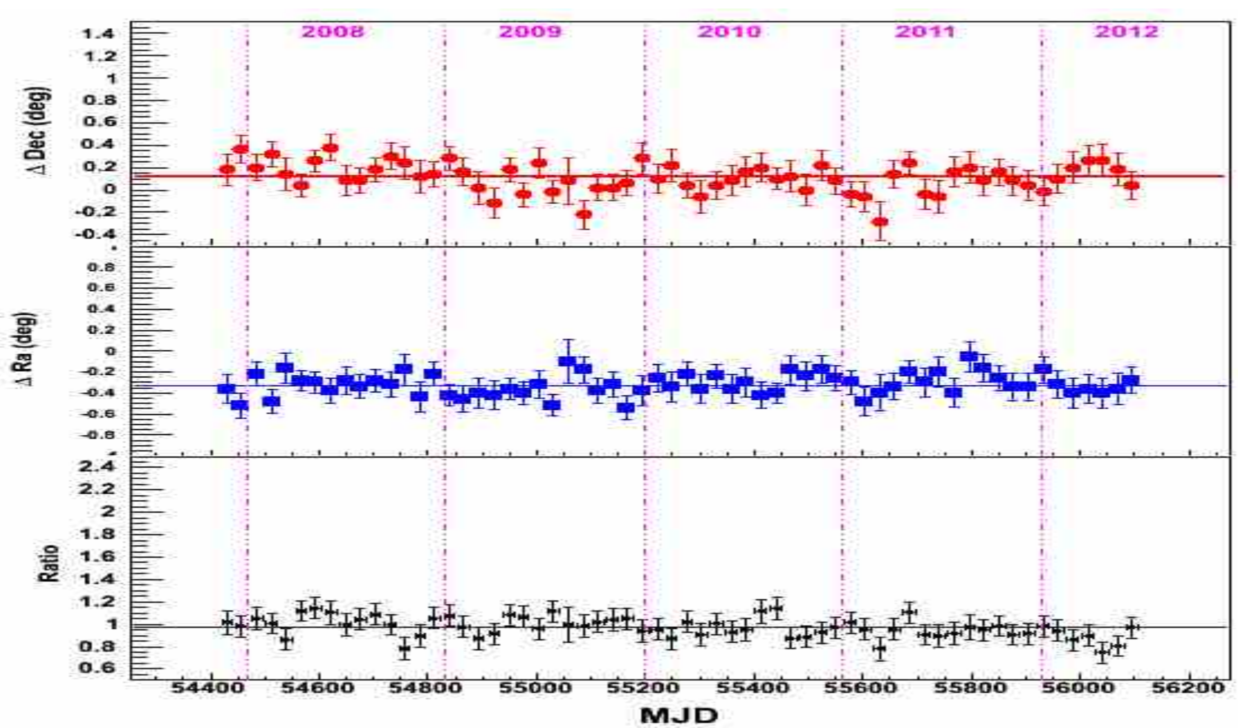
Status and performance

- In observation since July 2004 (with increasing portions of the detector)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5\cdot10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data

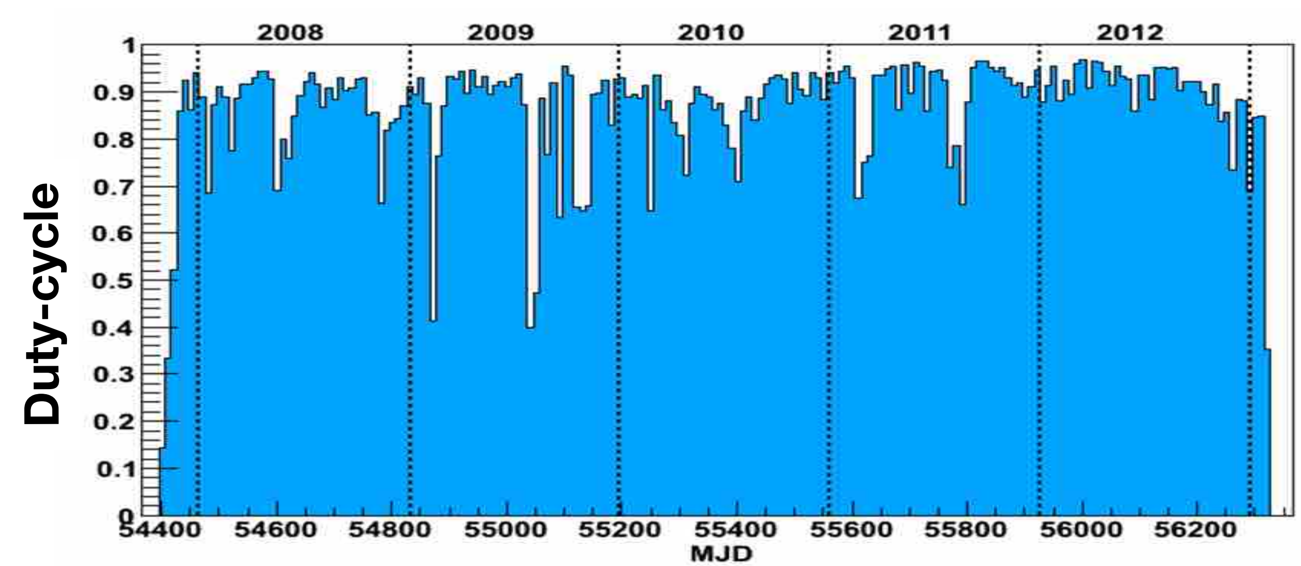




Intrinsic Trigger Rate stability 0.5%
(after corrections for T/p effects)



stability of angular resolution and pointing accuracy

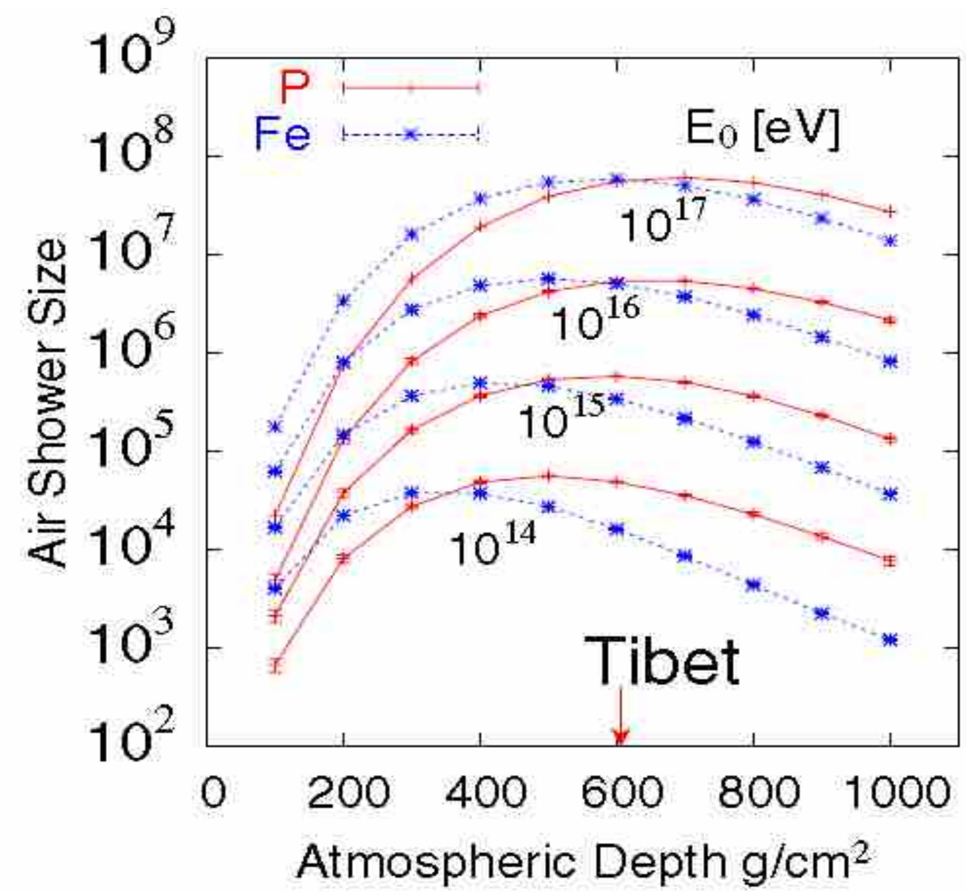


Measurement of CR energy spectrum with ARGO-YBJ

- 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

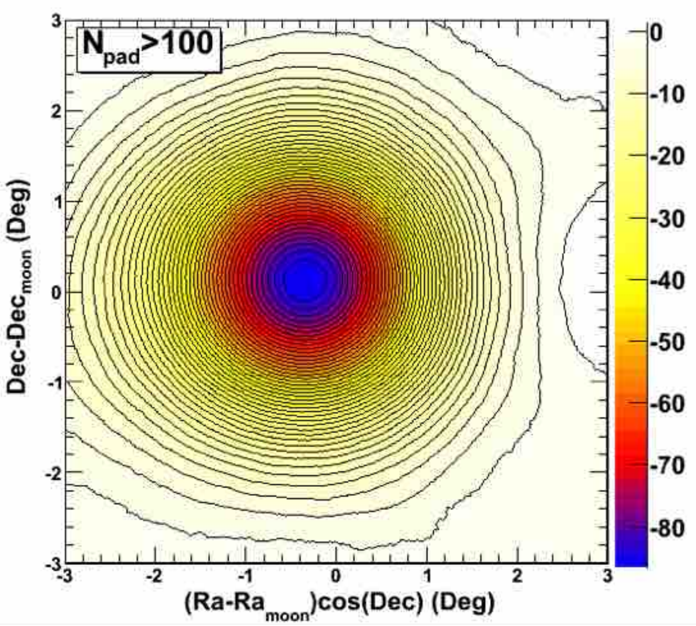
- Working at high altitude (4300 m asl):

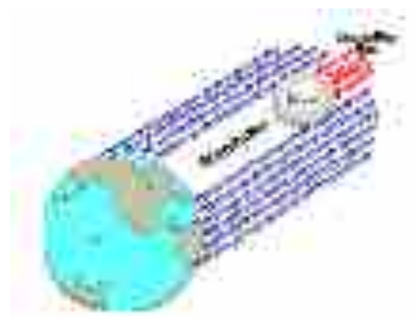
1. p and Fe produce showers with similar size
2. Small fluctuations: shower maximum
3. Low energy threshold: absolute energy scale calibration with the Moon Shadow technique and overposition with direct measurements



Calibration of the energy scale

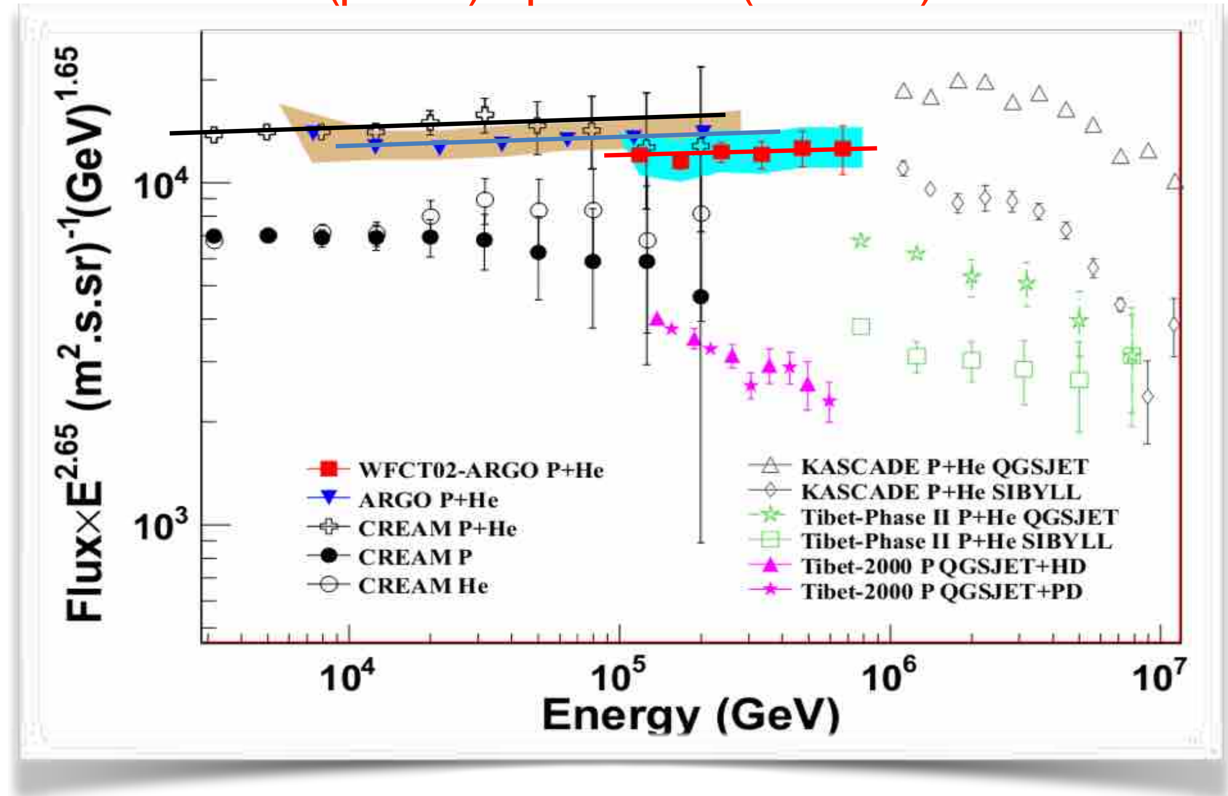
ARGO-YBJ: *Moon shadow* tool





PRD 84 (2011) 022003

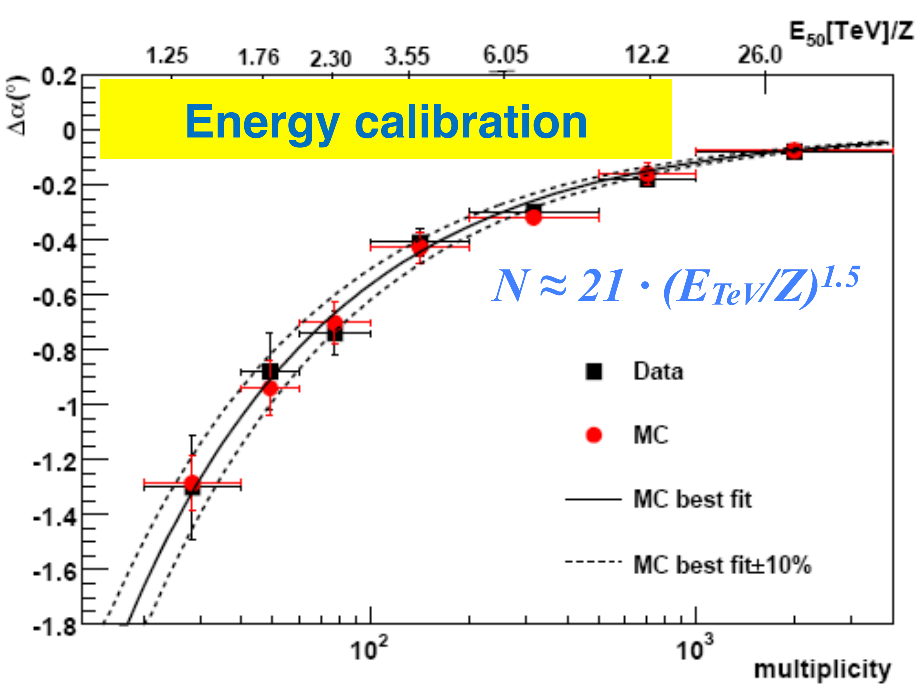
(p+He) spectrum (2 - 700) TeV



Chin. Phys. C 38, 045001 (2014)

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

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



Single power-law: 2.62 ± 0.01

Flux at 400 TeV:

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

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

(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 ≈ 8×10^{10} high quality events

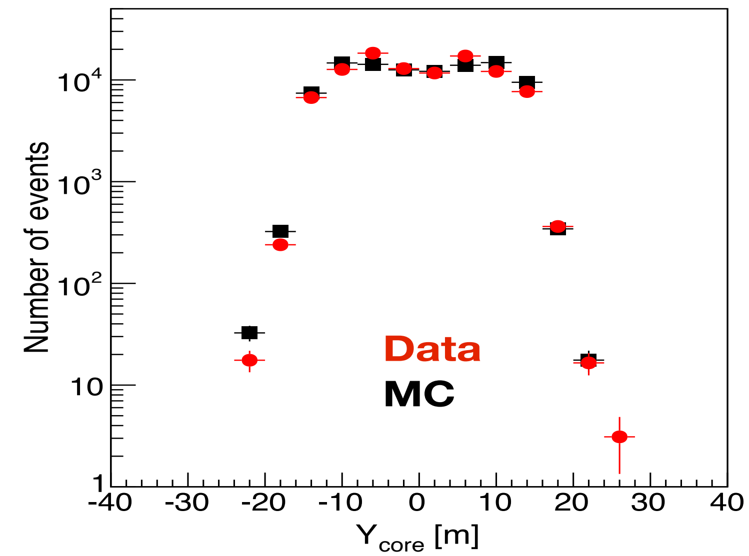
- M ≤ 50,000
- Zenith Angle ≤ 35°
- Highest density cluster in 40×40 m^2

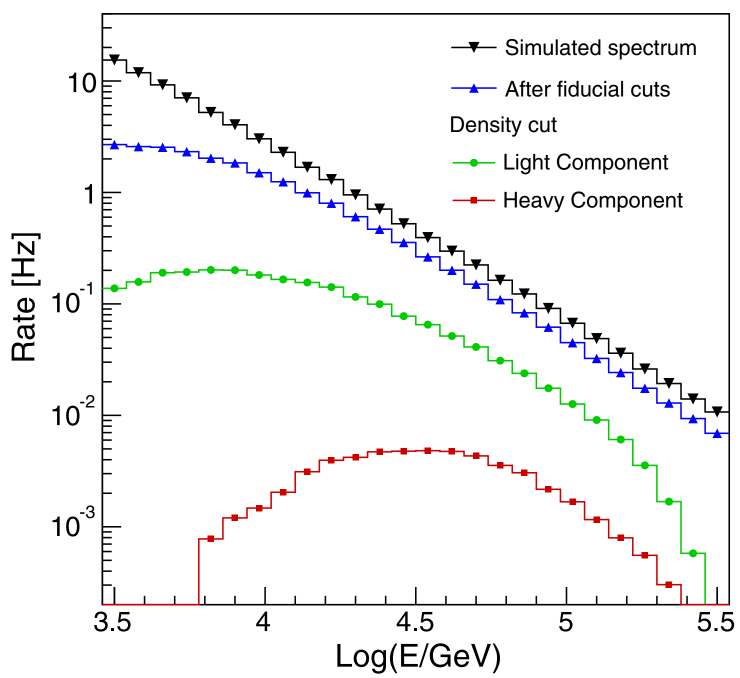
- Light Component (p+He) selection:

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

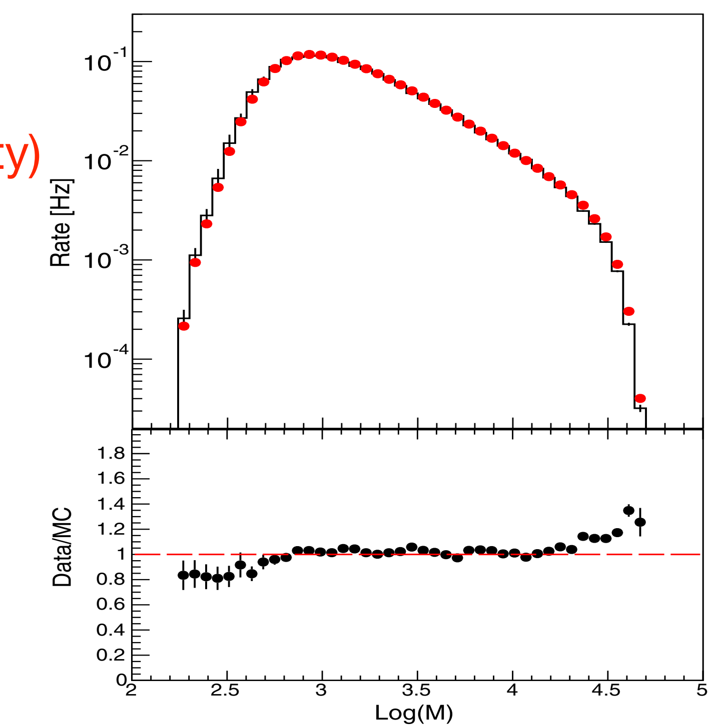
A20 = 20 innermost clusters
A42 = 42 outermost clusters

Rconstructed shower core position



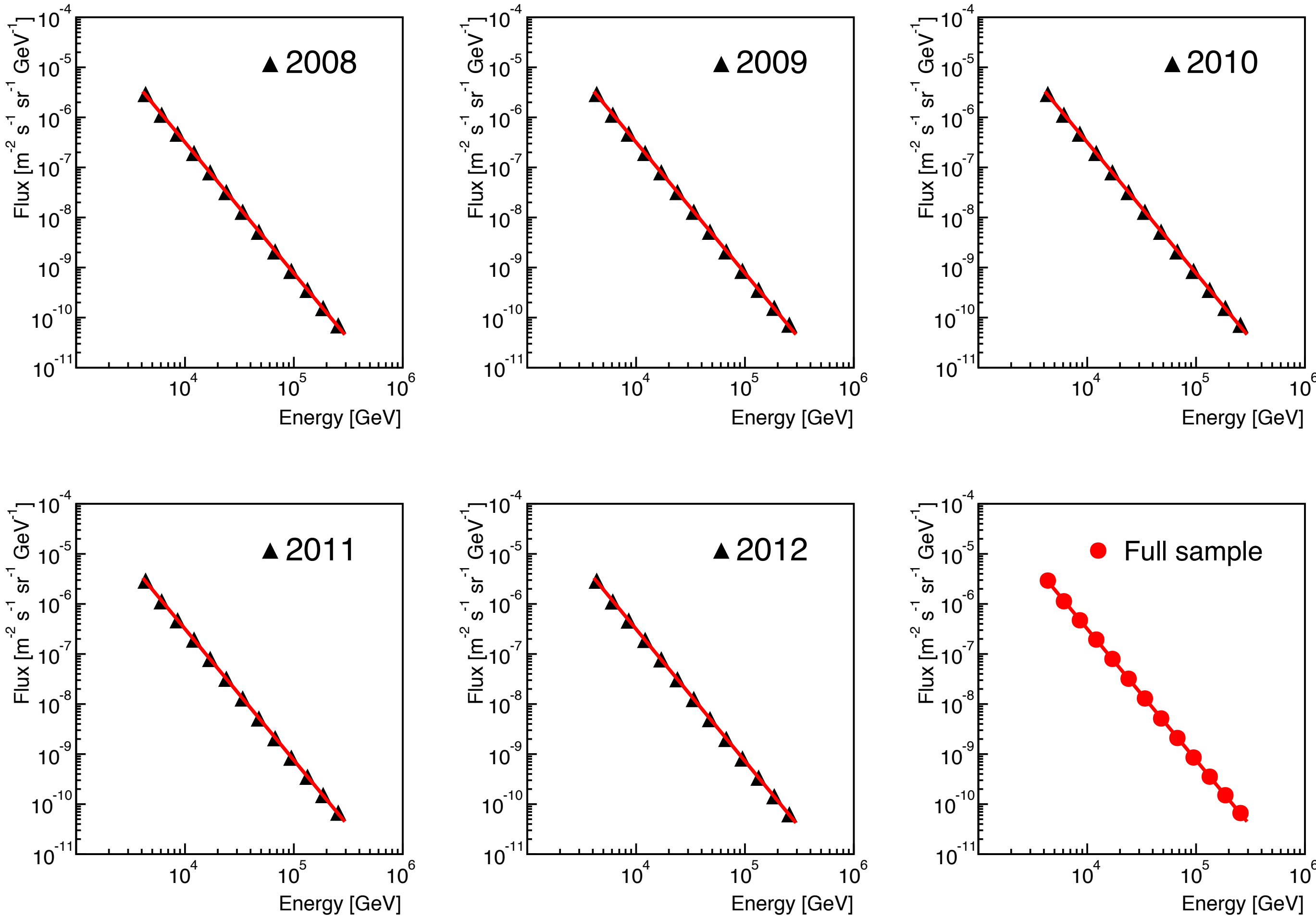


Shower size distribution on the central carpet, **M** (strip multiplicity)



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

Stability of the CR flux measurement



Phys. Rev. D91, 112017 (2015)

Year	Events	Gamma
2008*	7.5×10^{7}	2.61 ± 0.04
2008	5.57×10^{10}	2.63 ± 0.01
2009	5.65×10^{10}	2.63 ± 0.01
2010	5.56×10^{10}	2.63 ± 0.01
2011	5.64×10^{10}	2.64 ± 0.01
2012	5.69×10^{10}	2.65 ± 0.01
Full sample	2.81×10^{11}	2.64 ± 0.01

TABLE I. Proton plus helium flux measured at 5.0×10^{4} GeV.

Year	Flux $\pm$ tot. error [m^{-2} s^{-1} sr^{-1} GeV^{-1}]
2008	$(4.53 \pm 0.28) \times 10^{-9}$
2009	$(4.54 \pm 0.28) \times 10^{-9}$
2010	$(4.54 \pm 0.28) \times 10^{-9}$
2011	$(4.50 \pm 0.27) \times 10^{-9}$
2012	$(4.36 \pm 0.27) \times 10^{-9}$

p+He flux difference at 5% level

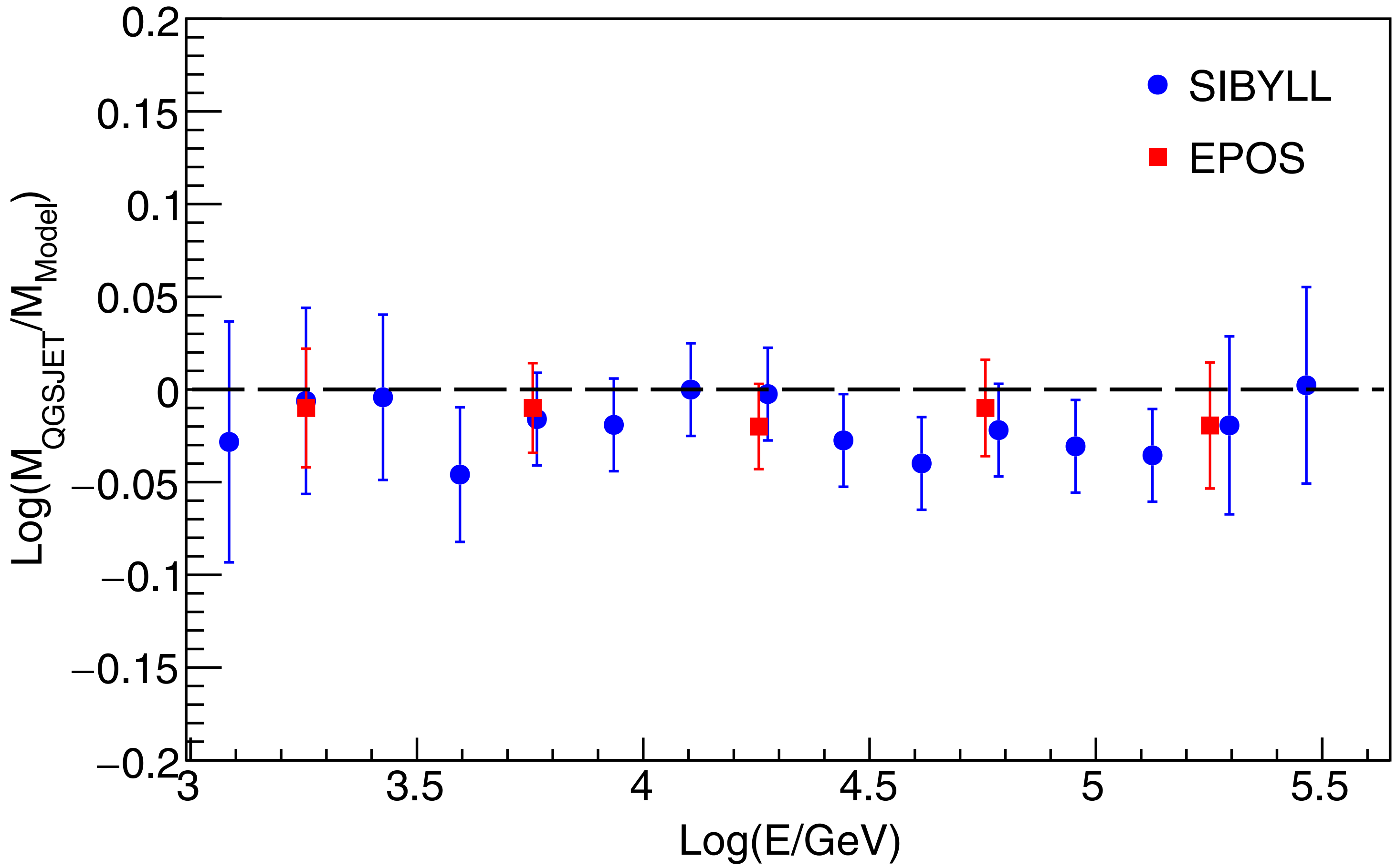
Hadronic Interaction Models

Phys. Rev. D91, 112017 (2015)

Corsika v 6980 + Fluka + EGS4
- QGSJET II.03
- SIBYLL 2.1
- EPOS 1.99

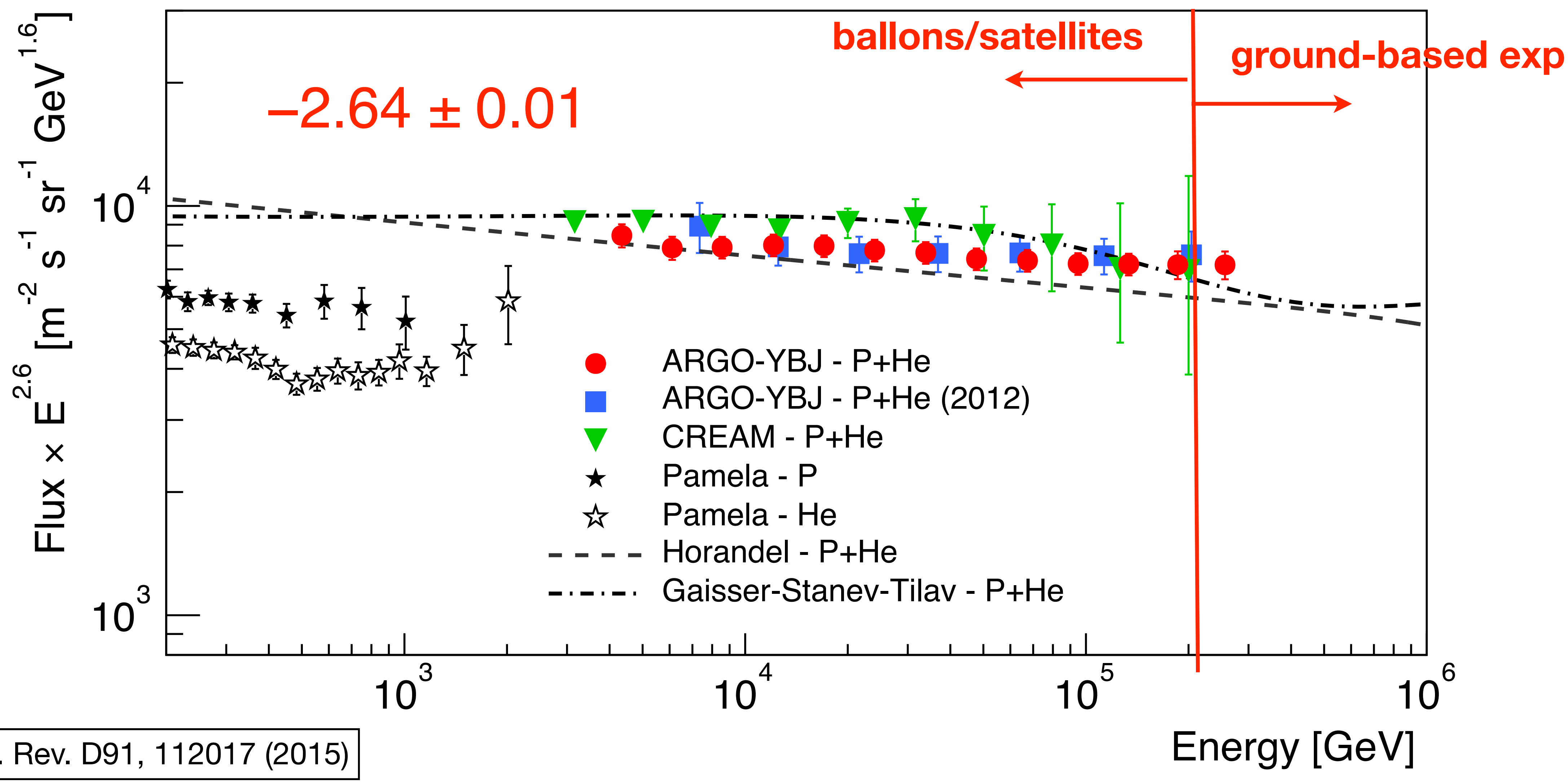
Not muons but lateral distribution ➜ topology

Ratio beetwen multiplicity distributions obtained with different models



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.

ARGO-YBJ + WFCTA

Wide Filed of View Cherenkov Telescope: a prototype of the future LHAASO telescopes

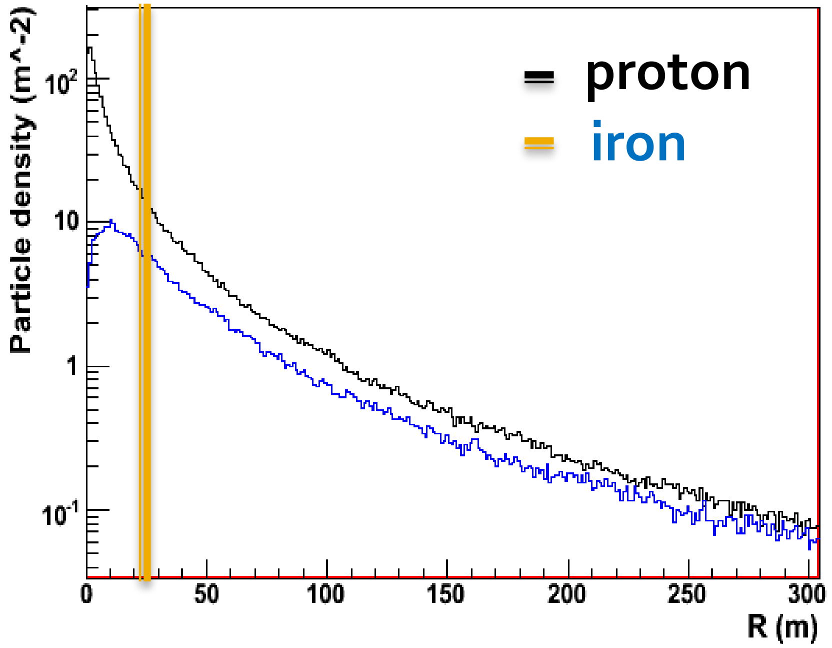
- 5 m^2 spherical mirror
- 16 $\times$ 16 PMT array
- pixel size 1°
- FOV: 14° $\times$ 14°
- Elevation angle: 60°

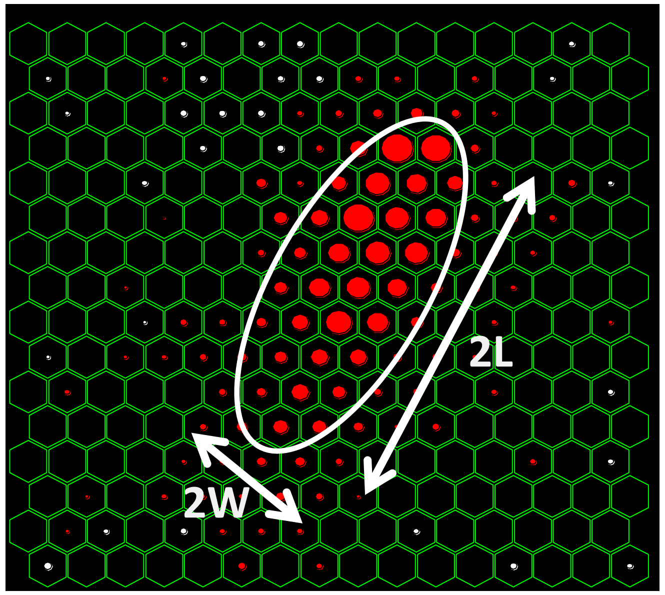
❖ *ARGO-YBJ:* core reconstruction & lateral distribution in the core region → mass sensitive

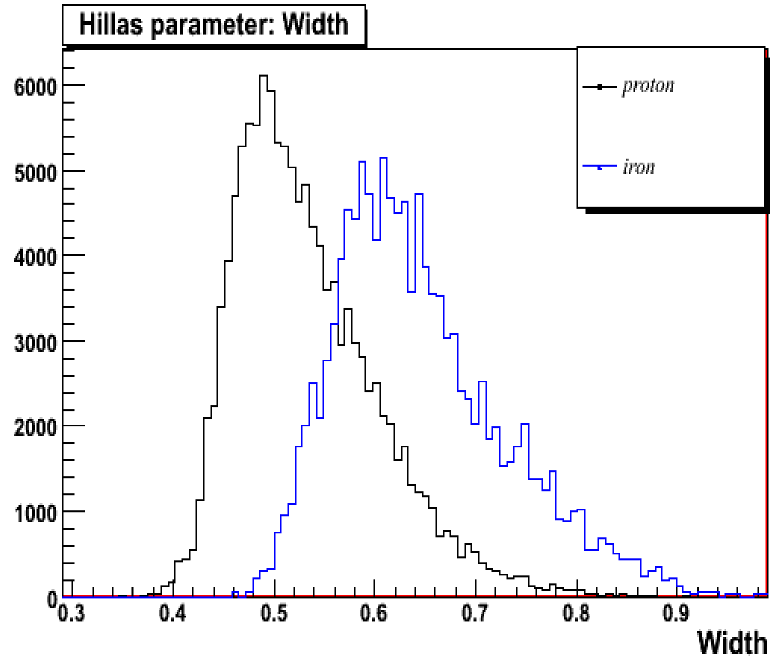
❖ *Cherenkov telescope:* longitudinal information Hillas parameters → mass sensitive

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

Chin. Phys. C 38, 045001 (2014)







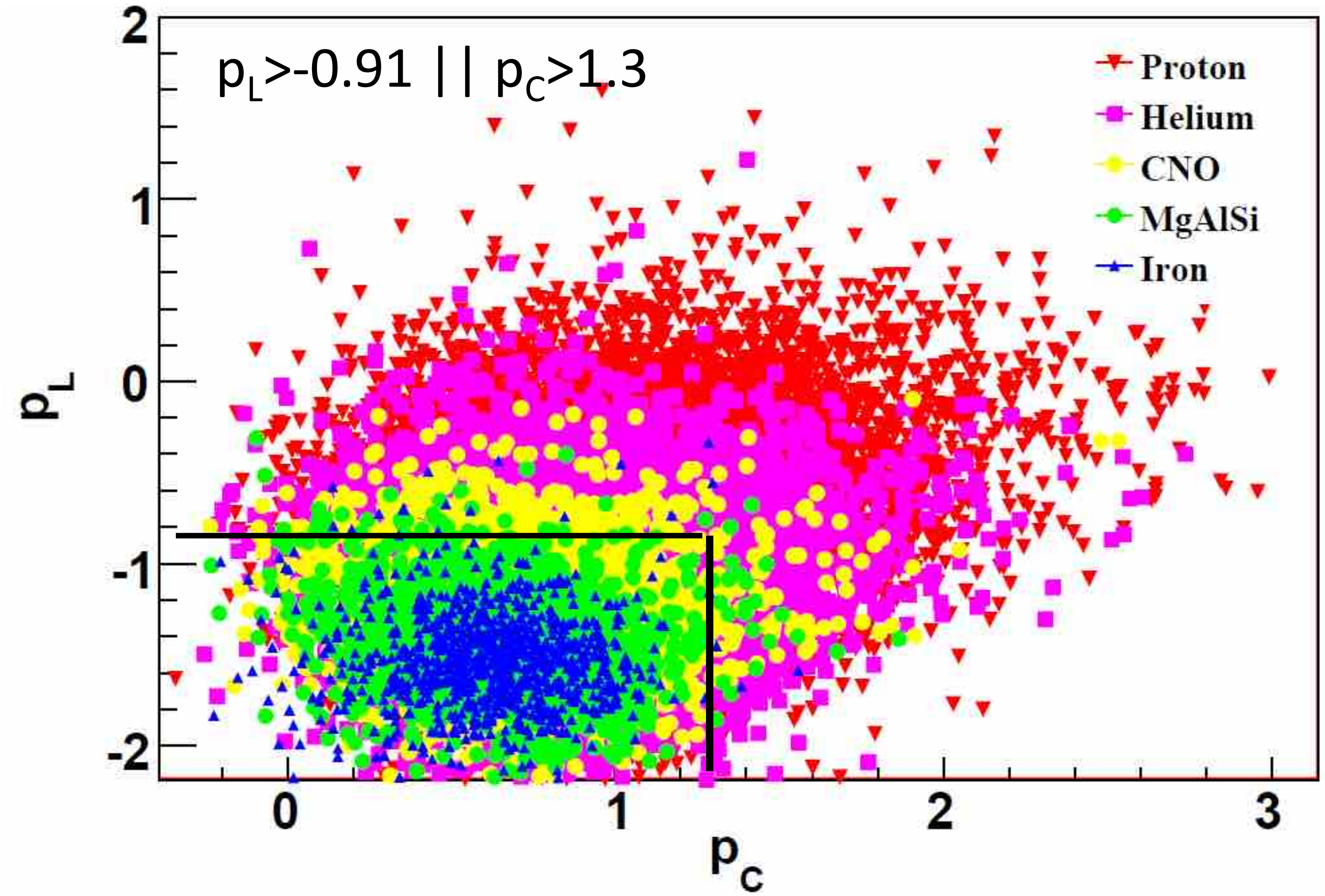
Light component (p + He) selection

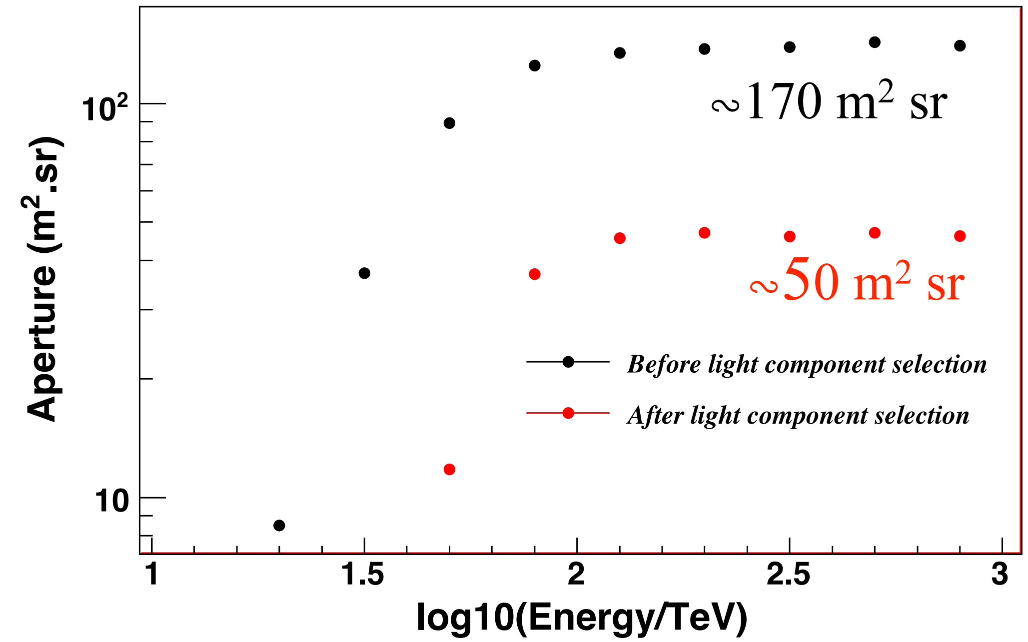
- Contamination of heavier component < 5 %
- Energy resolution: ~25% constant with energy
- Uncertainty : ~25% on flux

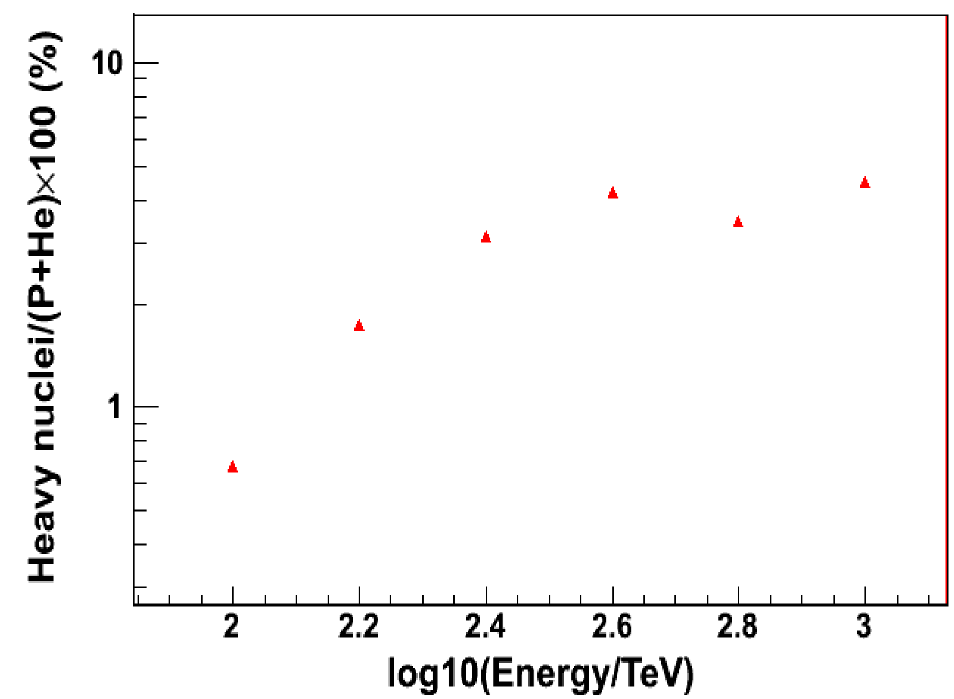
$$\boxed{p_L = log_{10}(N_{max}) - 1.44 \cdot log_{10}(E_{rec}/TeV)}$$

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

Events for which $p_L \leq -0.91$ and $p_C \leq 1.3$ are rejected



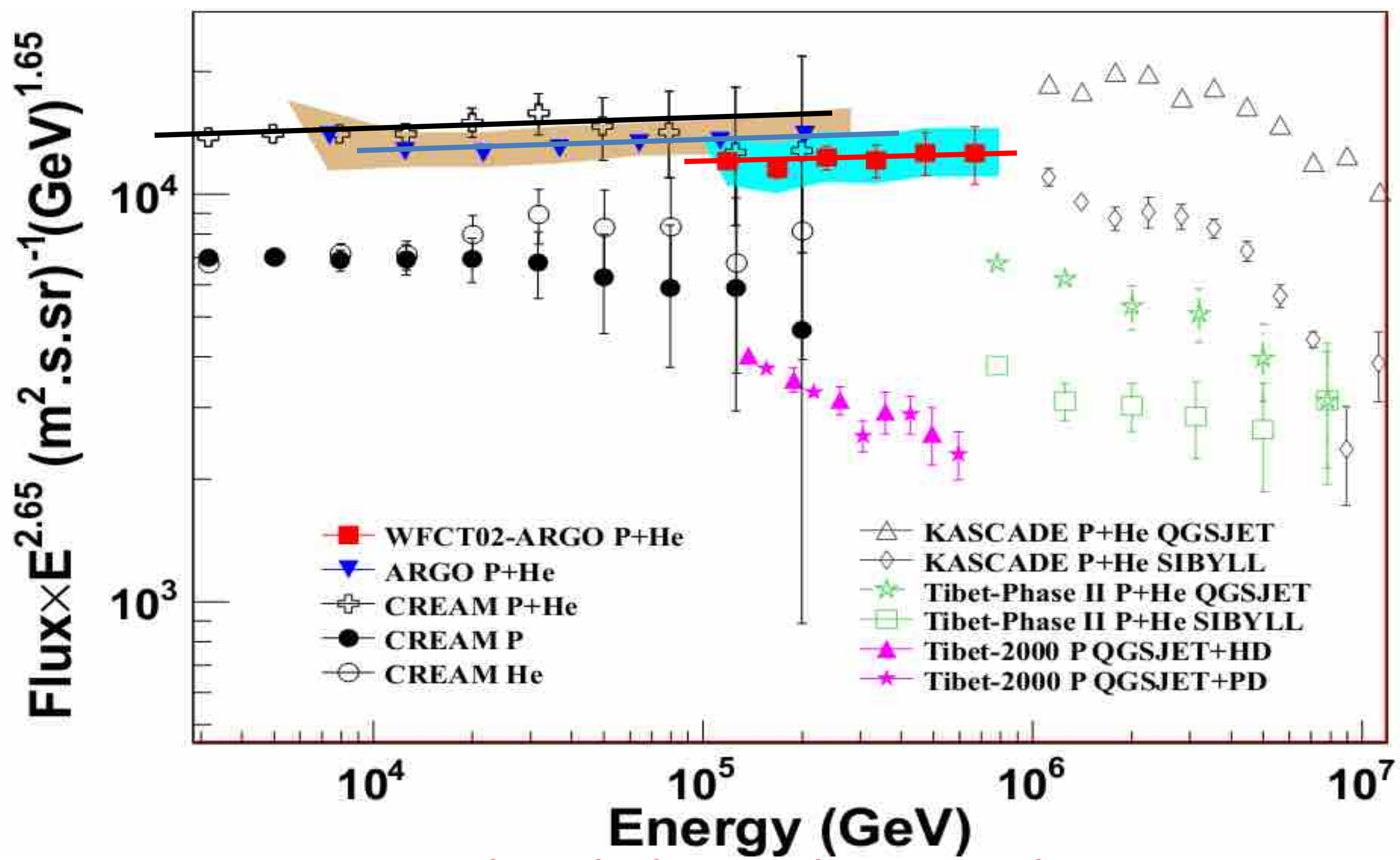




The light-component (p+He) spectrum (2 - 700) TeV

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

Single power-law: 2.62 ± 0.01



Flux at 400 TeV:

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

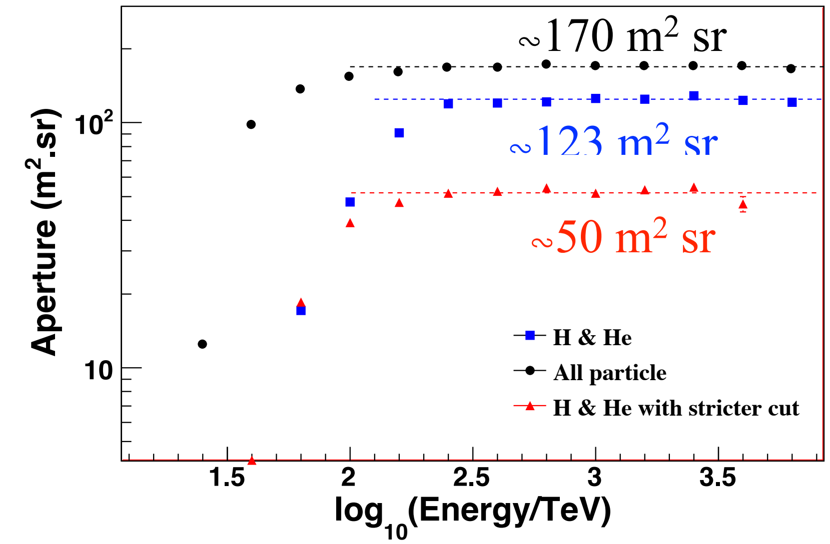
Chin. Phys. C 38, 045001 (2014)

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

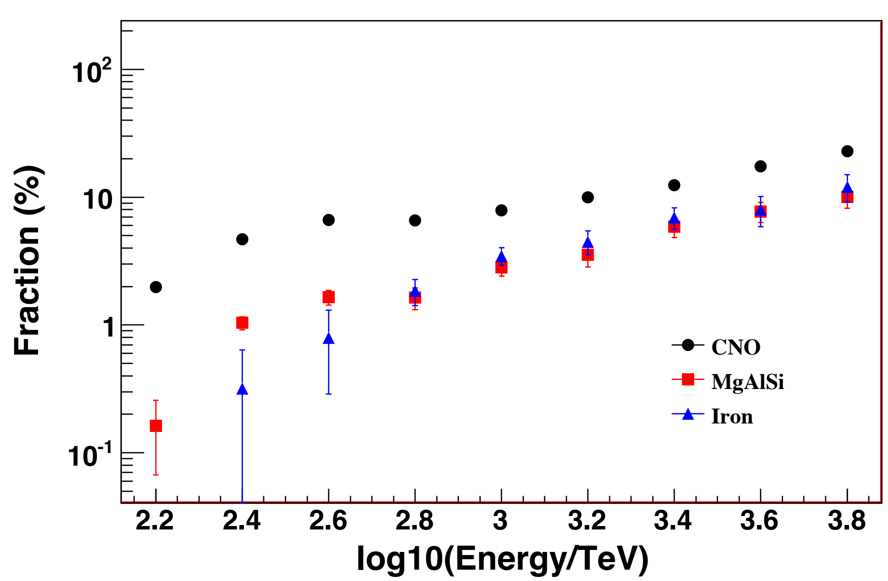
Approaching the all-particle knee

To extend the measurement of the ARGO-YBJ/WFCTA hybrid experiment to the PeV, we modified the selection cuts in the p_L - p_C space: events for which $p_L \leq -4.53$ and $p_C \leq 0.78$ are rejected.

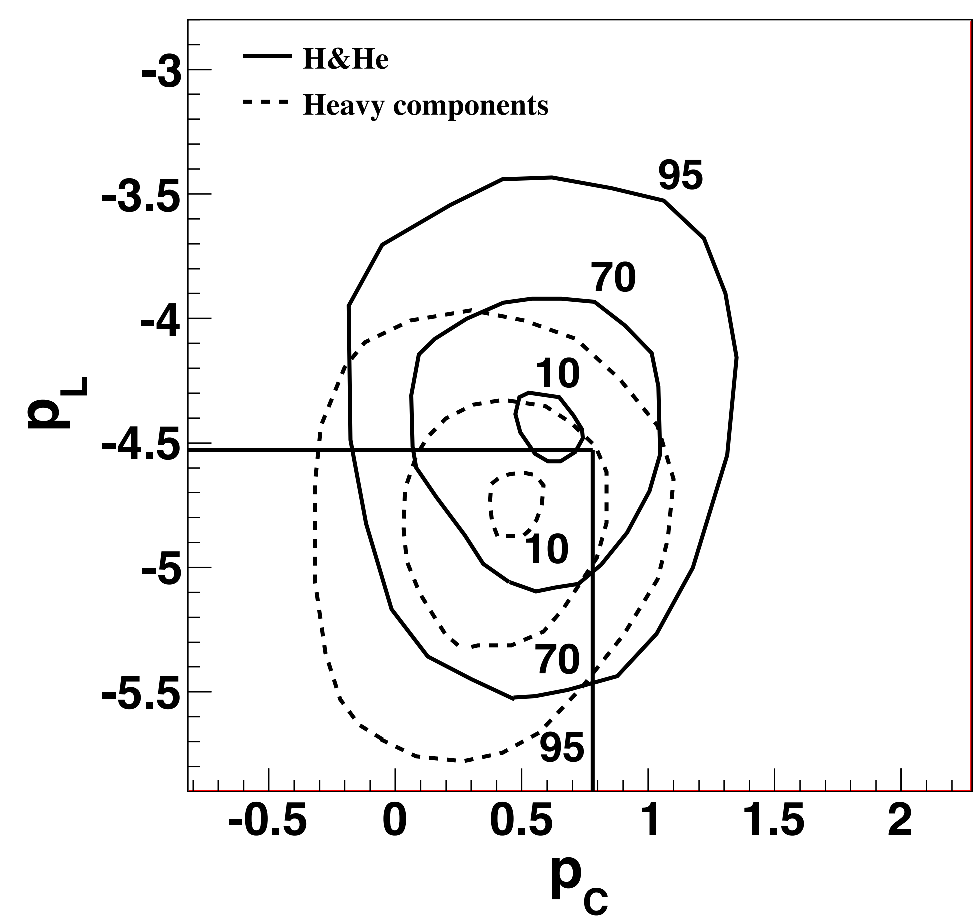
The aperture increases by a factor of 2.4 and the number of (p+He) events increases from 490 to 1162 above 200 TeV.



The contamination increase and the purity of the p+He sample below 700 TeV reduces to 93% with respect to 98% estimated with the original cuts.
At 1 PeV the contamination is less than 13%. About 72% of p+He events survive the selection criteria.

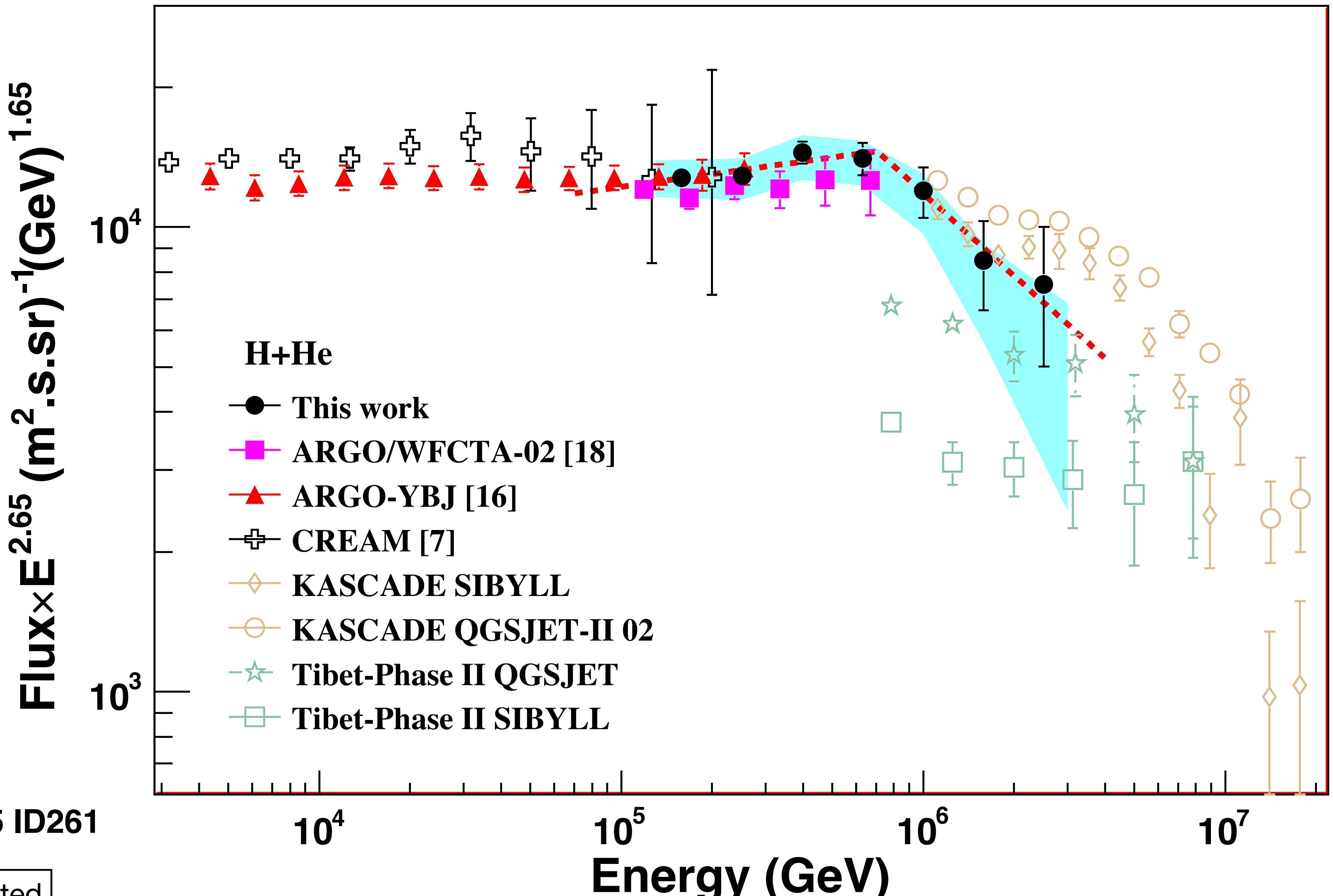


Calculations based on the Horandel spectrum



Light component knee with ARGO-YBJ / WFCTA

Observation of knee-like structure starting around 700 TeV



ICRC 2015 ID261

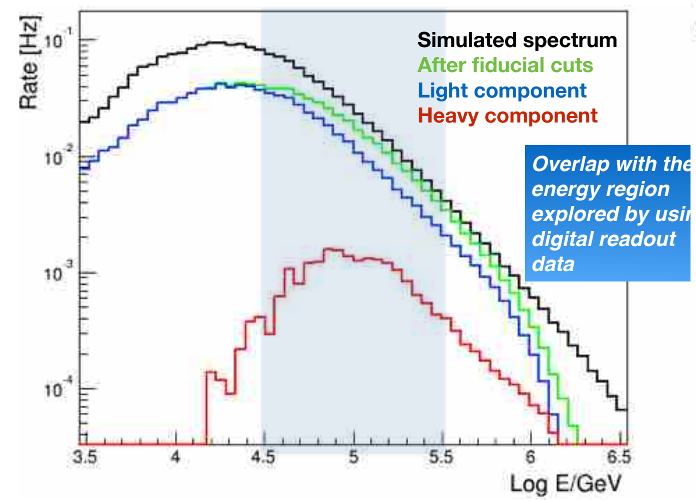
PRD submitted

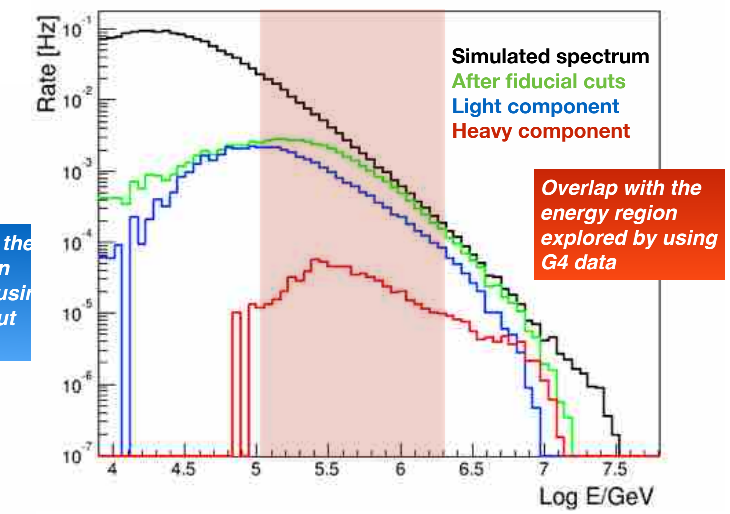
Light Component with ARGO-YBJ

★ Analysis of **analog RPC** data alone and **statistical** measurement of the energy spectrum by using a **bayesian approach**:

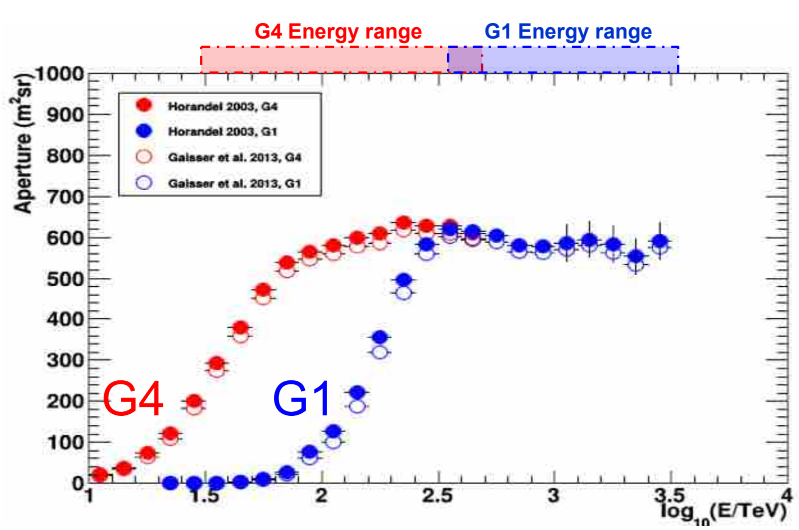
Light - Heavy discrimination *based on the LDF:*
ρ₅/ρ₀, ρ₁₀/ρ₀

ICRC 2015 Mari&Montini





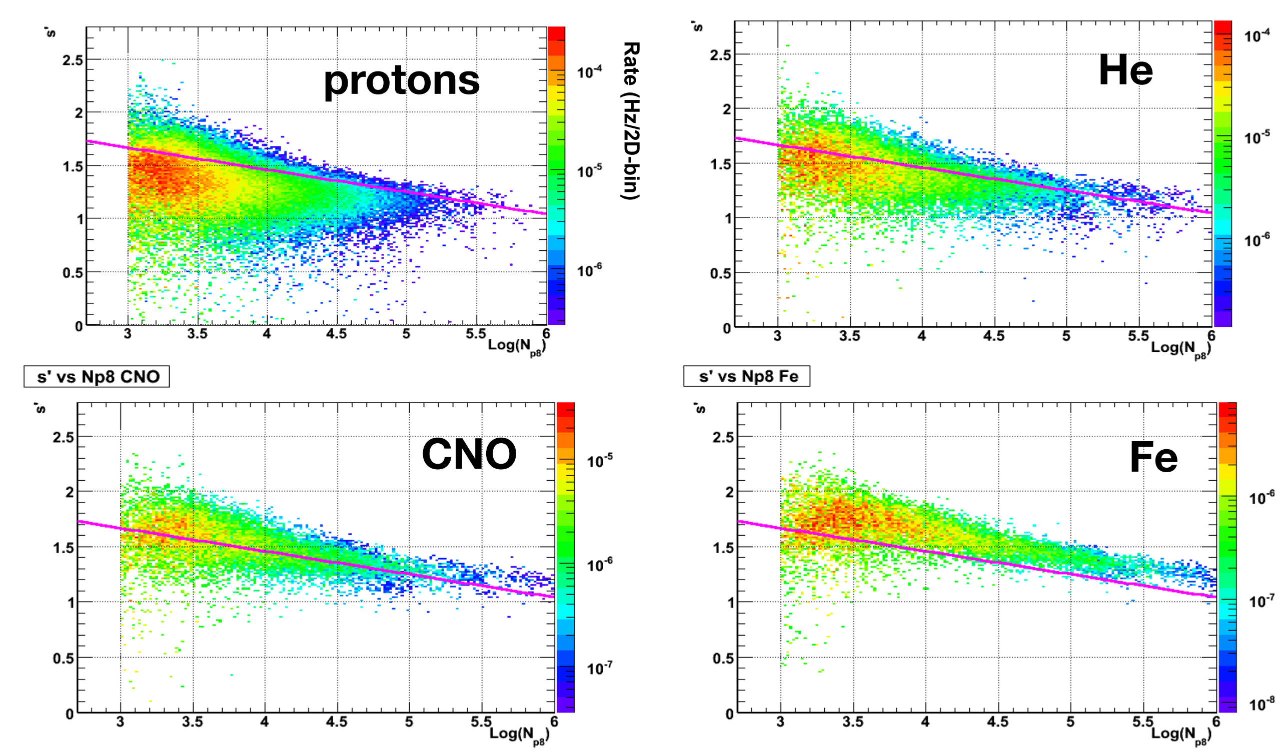
★ Analysis of **analog RPC** data alone and energy determination on an **event by event basis**:



Analysis based on the N_p^{8m} parameter (*number of particle within 8 m from the shower core position*) *and on the LDF slope s'*

ICRC 2015 ID366

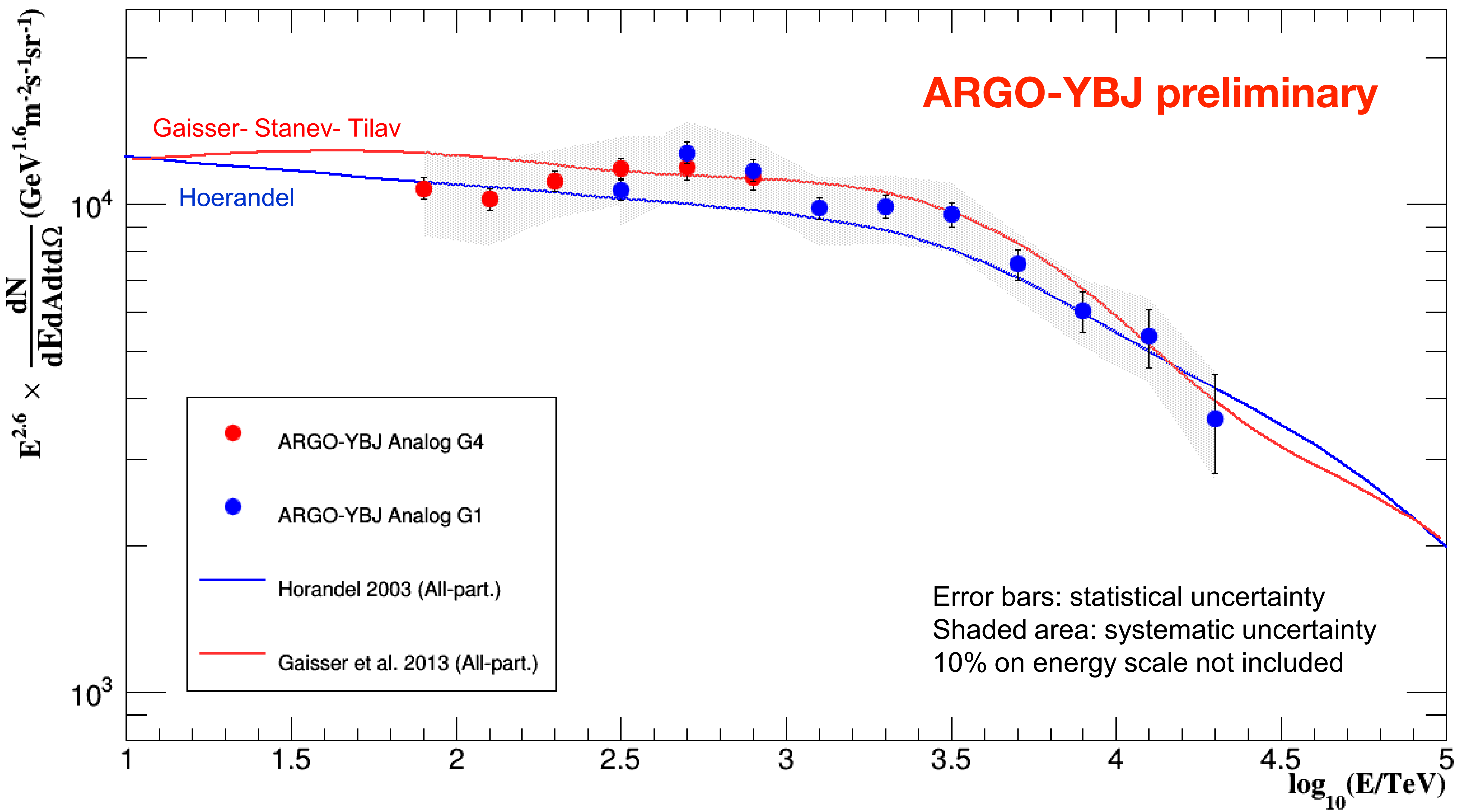
A simple cut in the plane s' vs Np8



Contamination > He: ≈ 15%

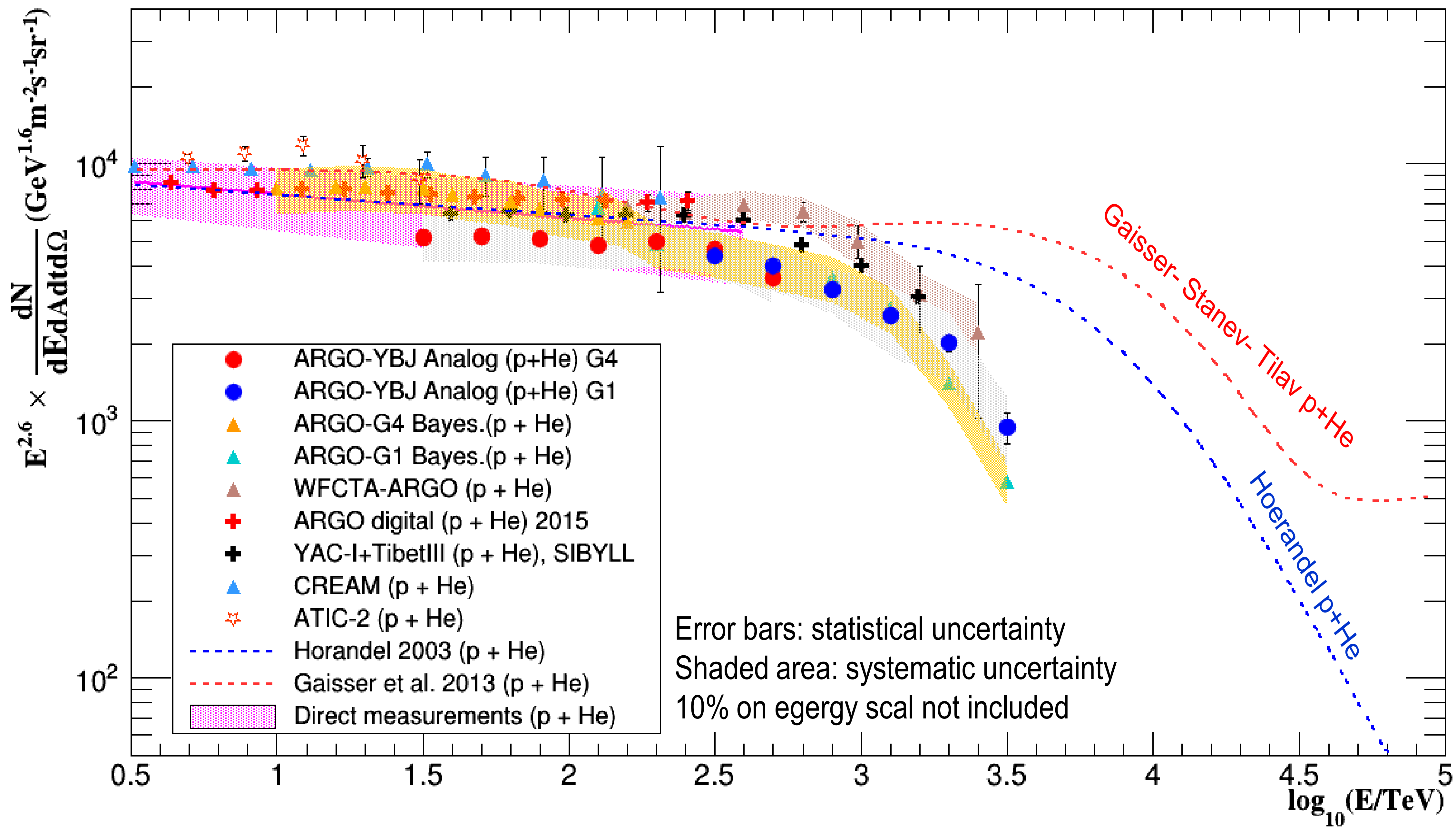
All-particle spectrum by ARGO-YBJ

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



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

ARGO-YBJ reports evidence for a proton knee starting at about 700 TeV and not at 4 PeV ("standard model")

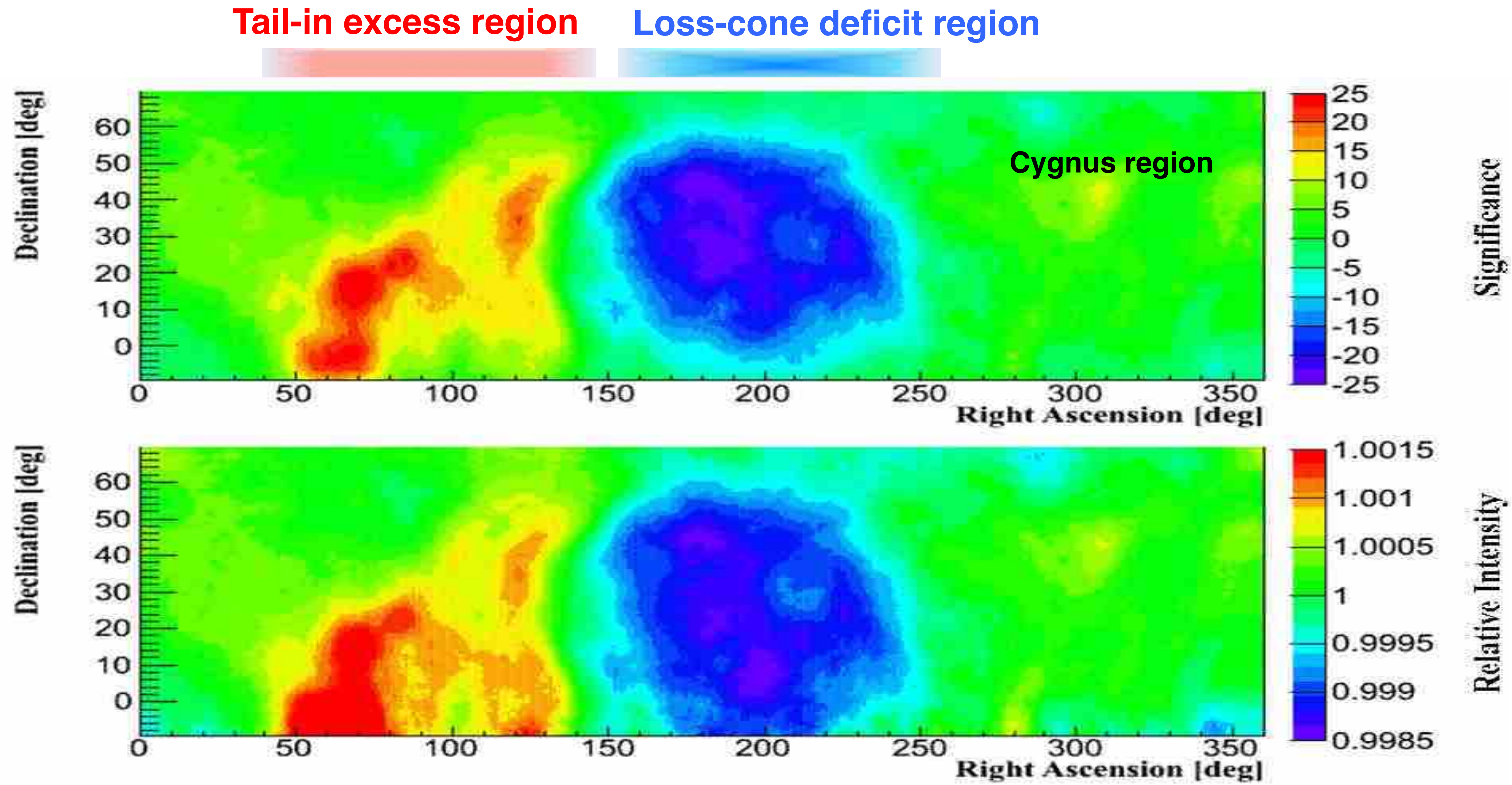


Implications of this results: Cardillo, Amato & Blasi, APP 69 (2015) 1

Large scale anisotropy by ARGO-YBJ

2 years data: 2008 - 2009, during minimum of solar activity

E ≈1 TeV, 3.6×10^{10} events in the declination band -10° < δ < +70°



What this observation tell us ?

- "Tail in" and "loss cone" regions are observed with high stat. significance (> 20 s.d.)
- Anisotropy regions observed in the Cygnus region (13 s.d. level) due to γ-ray emission (TeV counterpart of the *Cygnus Cocoon*)
- R.A. profile of anisotropy can be described with 2 harmonics

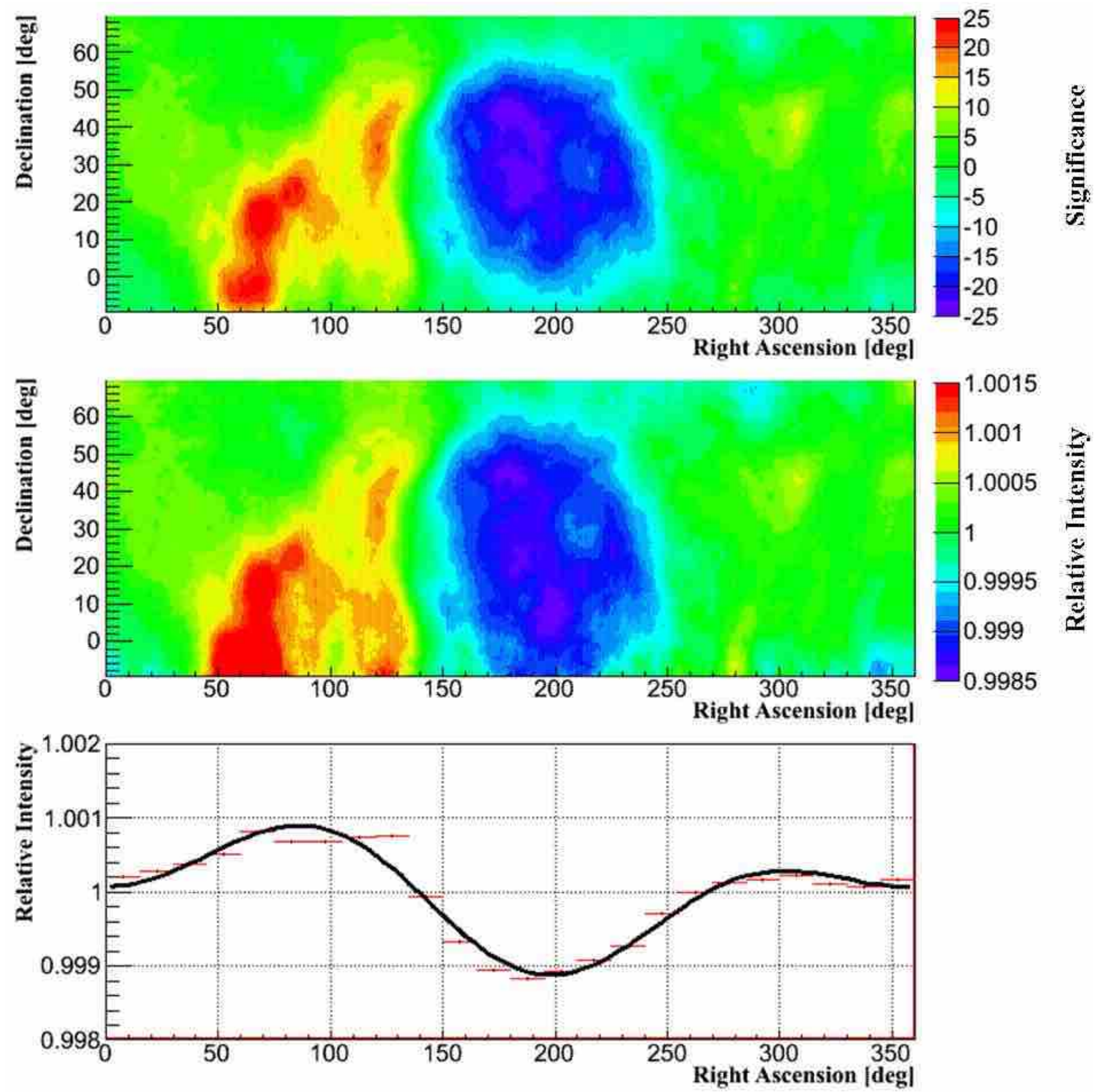
$$I = 1 + A_1 cos[2\pi(x-\phi_1)/360] + A_2 cos[2\pi(x-\phi_2)/180]$$

$A_1 = 6.8\times10^{-4}$, $\Phi_1 = 39.1°$
$A_2 = 4.9\times10^{-4}$, $\Phi_2 = 100.9°$

- The LSA cannot be described by a simple dipole.
- Data rule out the hypothesis of the sidereal Compton-Getting effect be the dominant anisotropy component.

→ CRs corotate with GMF

ApJ 809 (2015) 90



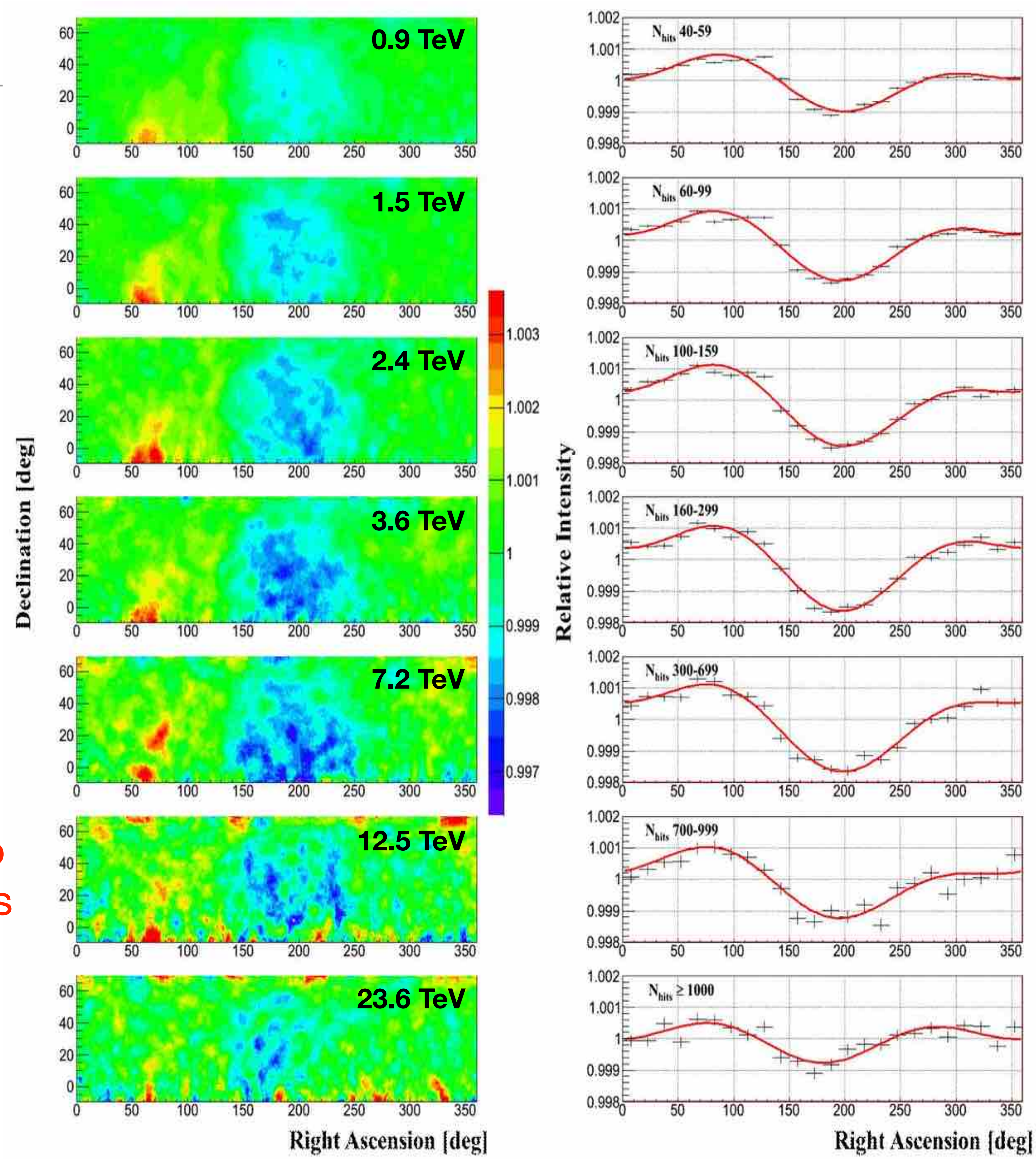
Galactic CG expectations:
$A_{CG} = 3.5\times10^{-3}$, much larger than observations
maximum in the direction of the Galactic Center (R.A.=315° and δ=49°)
minimum at R.A.=135° and δ=-49°

Anisotropy vs energy

First measurement with an EAS array in an energy region so far investigated only by underground muon detectors.

Structures with complex morphologies are visible in all the maps, changing shape with energy.

The tail-in broad structure appears to dissolve to smaller angular scale spots with increasing energy.



ApJ 809 (2015) 90

Medium/Small Scale Anisotropy

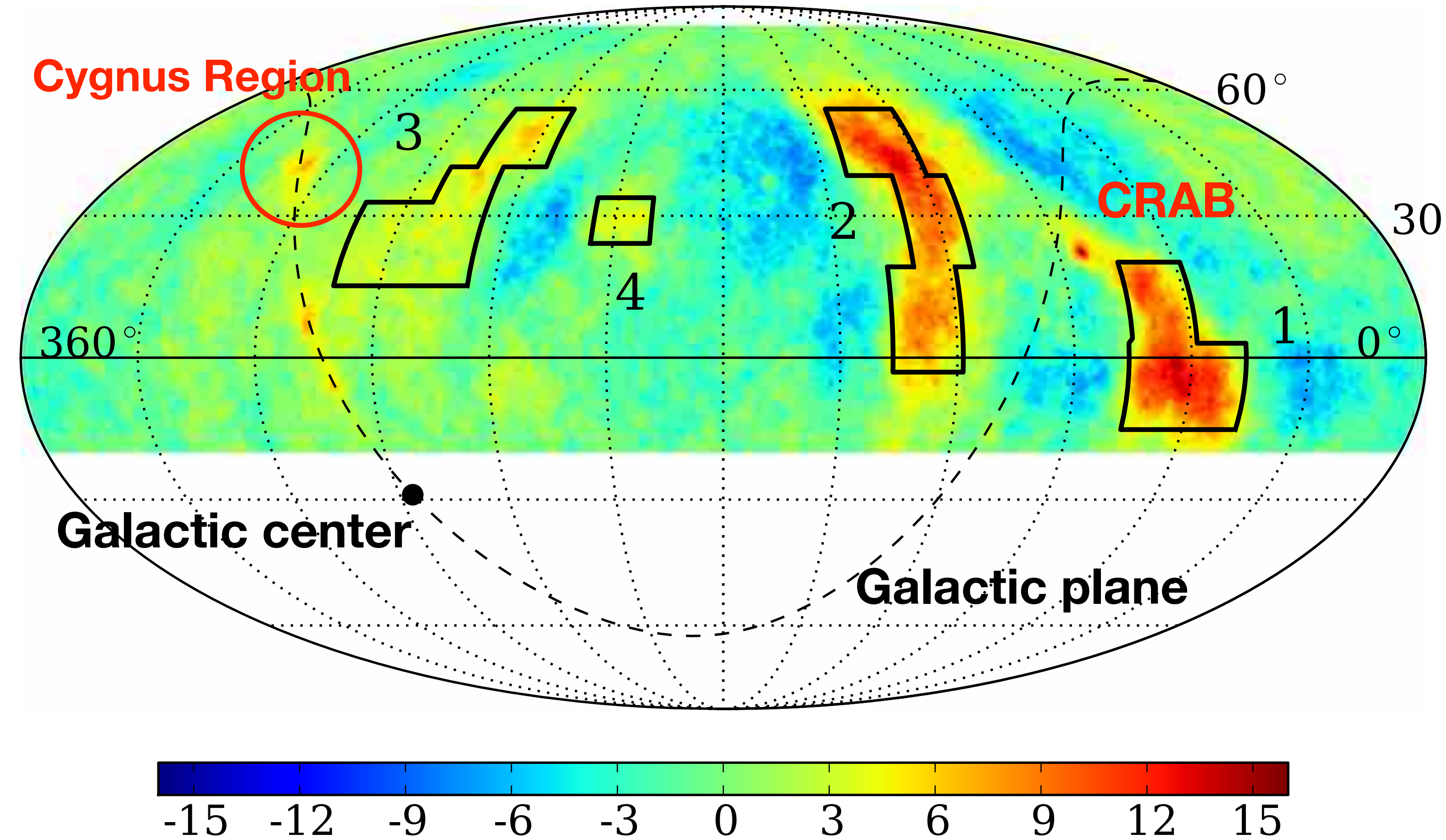
Data: November 8, 2007 - May 20, 2012
≈ 3.70×10^{11} events

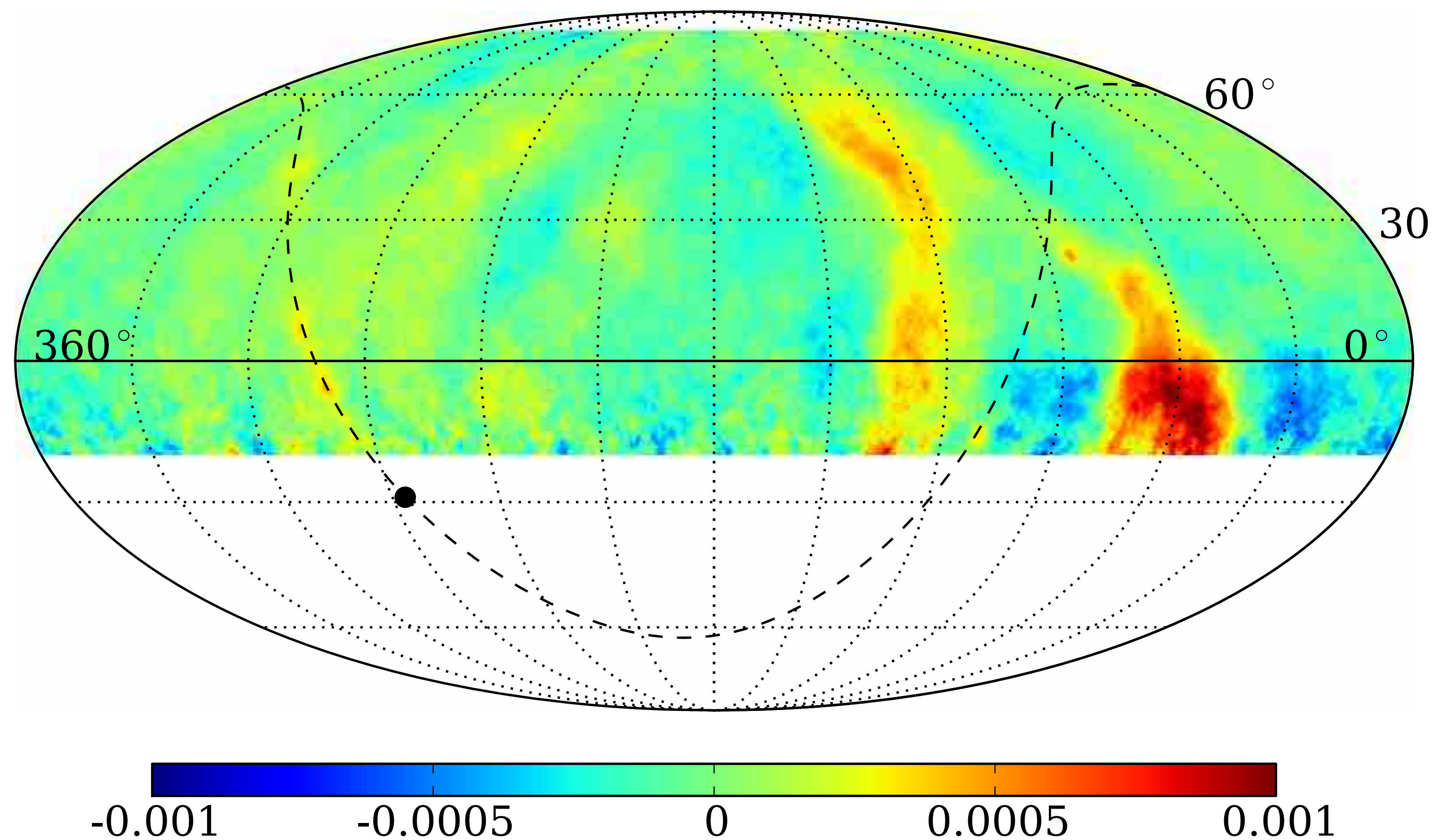
dec. region δ ~ -20°÷ 80°

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

Proton median energy ≈ 1 TeV

**CRs excess ≈ 0.1 %
with significance up to 15 s.d.**





Phys. Rev. D 88 (2013) 082001

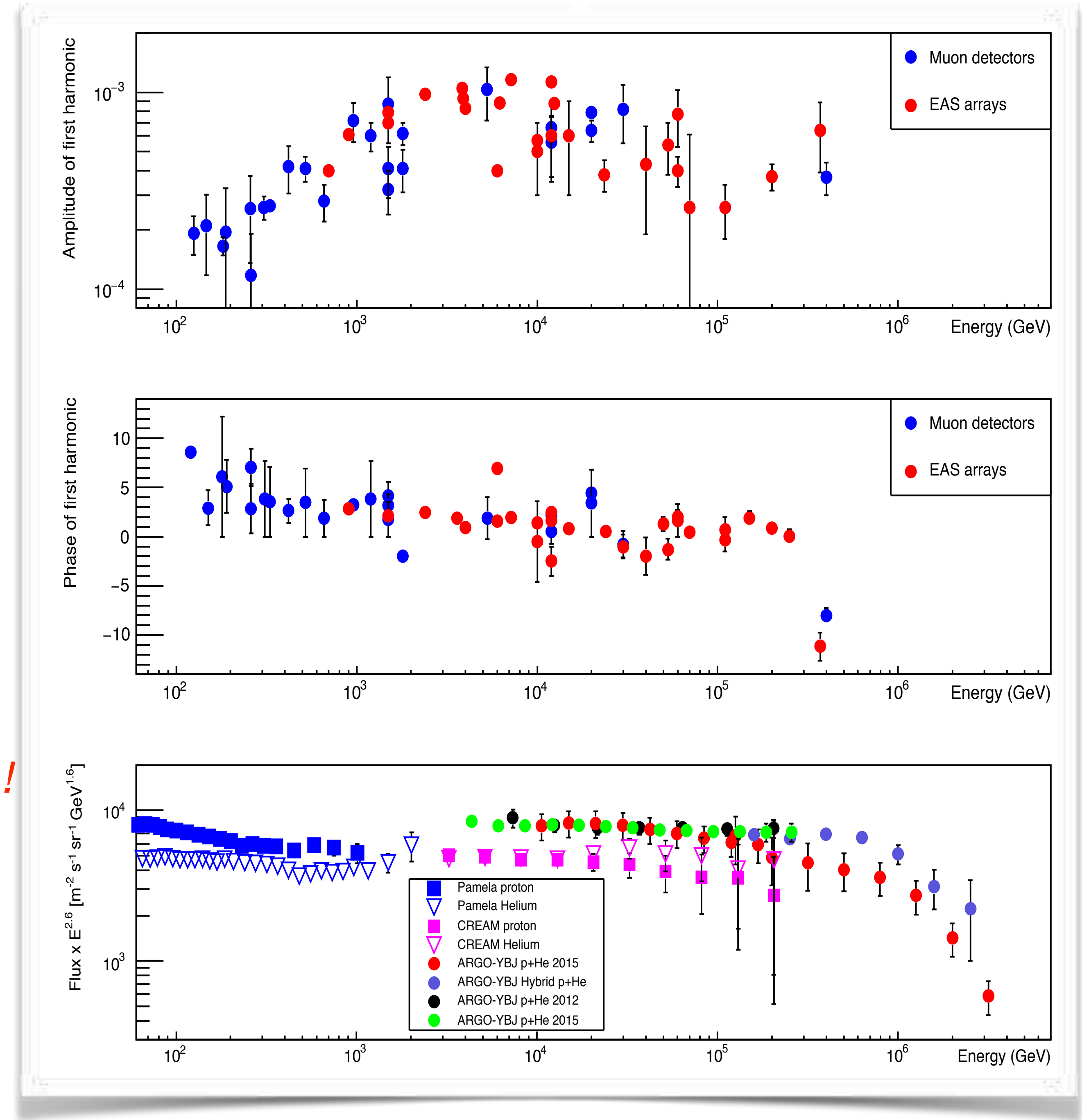
Energy Spectrum, Anisotropy & Mass Composition

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

In fact, propagation of CRs in the galactic medium is known to affect their spectrum and direction distribution.

➡ study **correlation** between anisotropy & spectral features vs **primary mass**

Anisotropy for different primary particle masses crucial !



Anisotropy for p+He nuclei: method

No experiment measured the anisotropy for a particular mass selection, because:

- mass selections are difficult to implement and any contamination may result in a large bias for an anisotropy measurement. To control contamination you may have to suppress statistics too much.
- systematic effects induced by background methods for anisotropy studies may be too large to accomplish a reliable mass selection as a function of the direction in the sky.

The ratio method

The basic idea of this approach is that to measure the anisotropy of a particular subset of events (a selection of them, LIGHT), the complete set of events (ALL) could be taken as reference for the estimation of the background.

With this method we measure the LIGHT anisotropy relative to the ALL anisotropy

The ratio is an observable less subject to systematic effects than time-averages or equi-zenith symmetrisations, because biases may only come from variations affecting LIGHT in a different way than ALL.

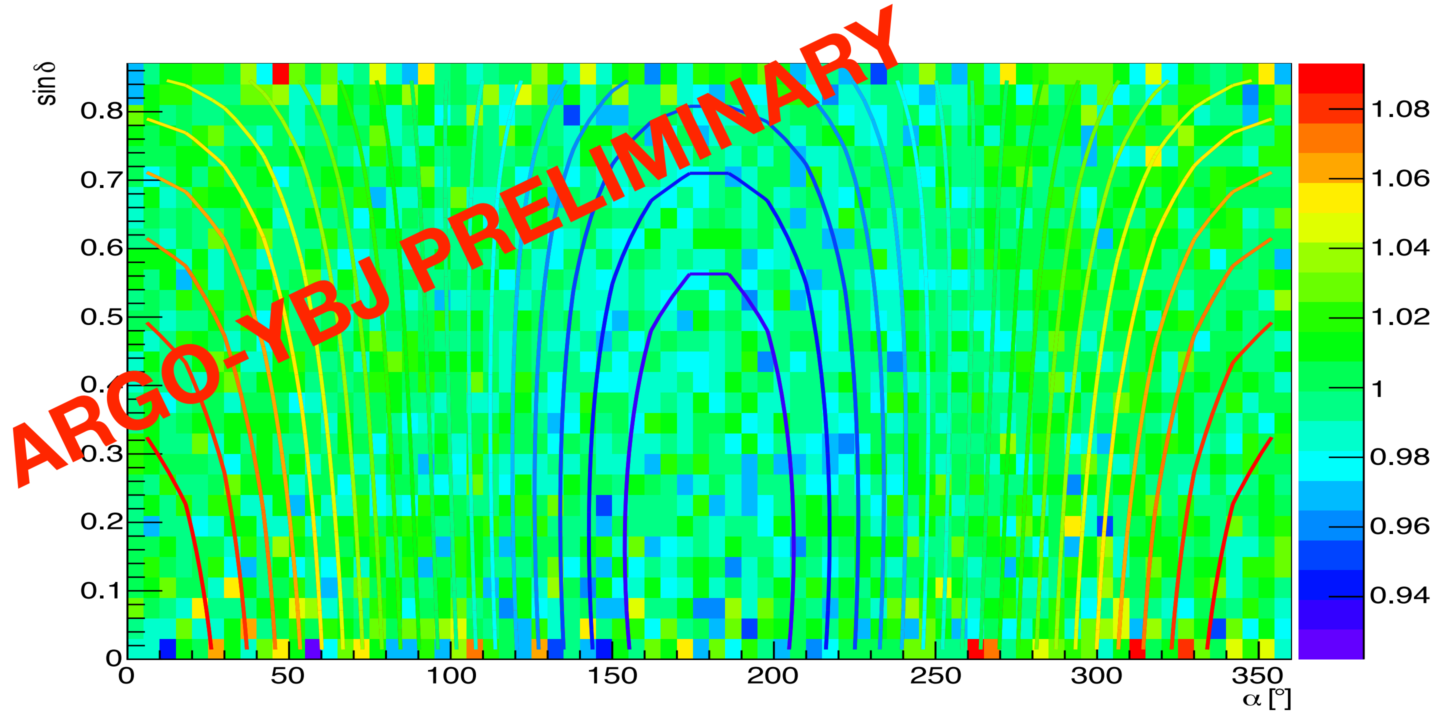
For all other issues, determining global or local changes in time periods whatever long, everywhere in the sky the LIGHT acquisition will exhibit the same variations as the ALL will, leaving unchanged the ratio.

Light component selection: same for CR spectrum with digital data below 300 TeV

p+He energy: 3 - 30 TeV
zenith angle less than 30°

ICRC 2015 ID 524

Anisotropy for p+He nuclei: results



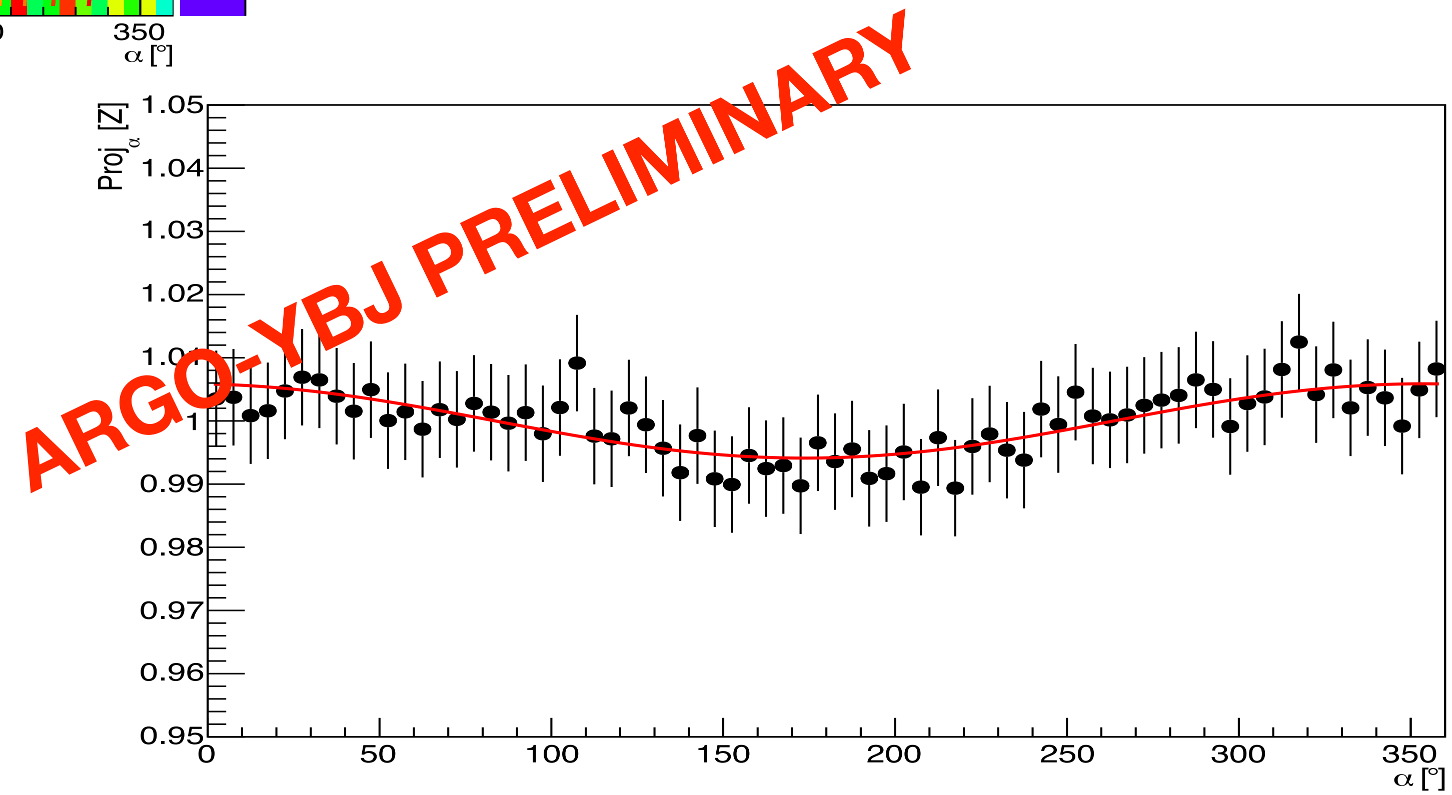
ICRC 2015 ID 524

The significance estimator suggested to fit a dipole function to the observed distribution.

Statistics really poor.

(p+He)-induced dipole amplitude less than 2% at 90% C.L

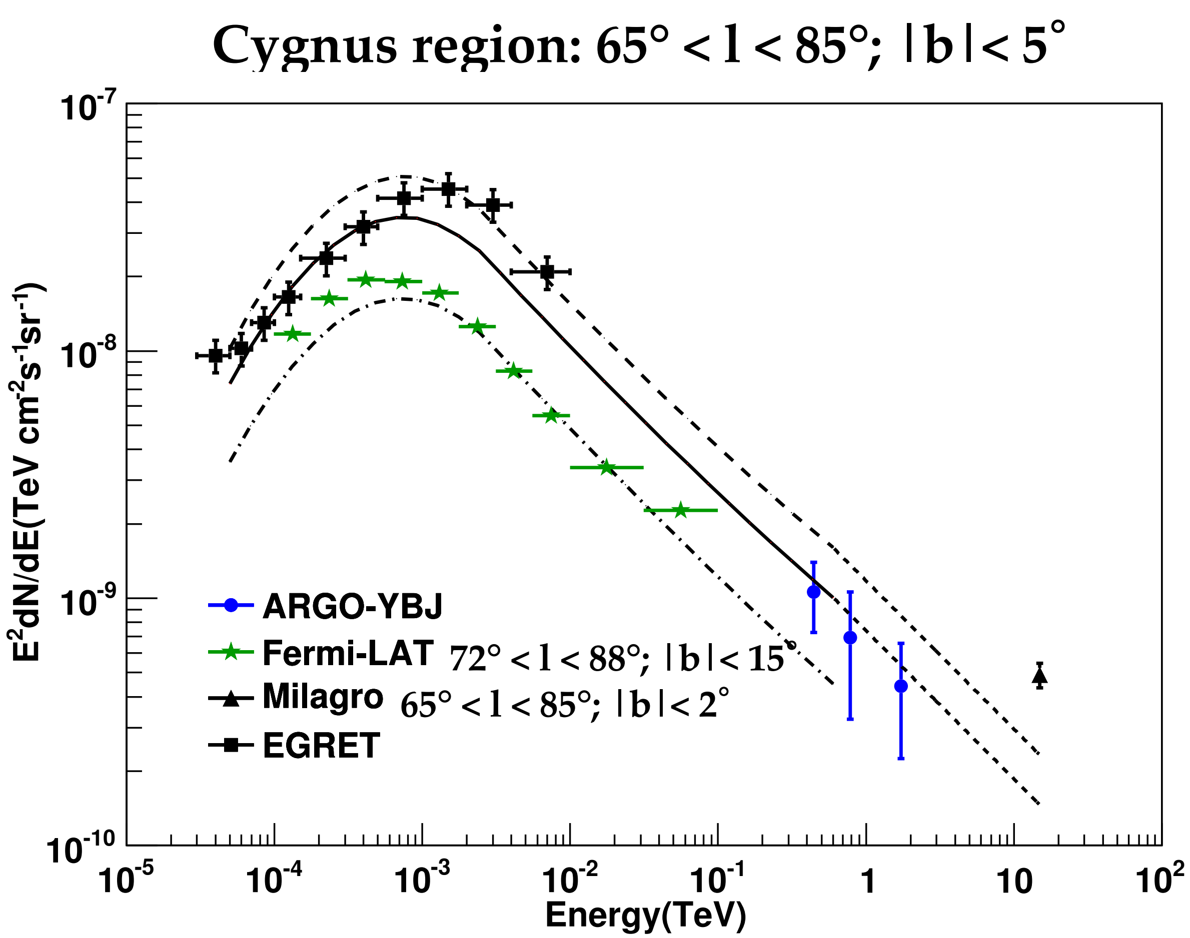
phase in right ascension: -6° ± 10°
(minimum coincident with the loss cone)



The analysis, yet at a preliminary stage, showed an interesting potential, outlining possible correlations between the known LSA structures and LIGHT-induced deviations from isotropy.

Diffuse γ-rays from the Galactic Plane

Diffuse γ-rays are produced by relativistic electrons by bremsstrahlung or inverse Compton scattering on bkg radiation fields, or by protons and nuclei via the decay of π^o produced in hadronic interactions with interstellar gas.
The space distribution of this emission can trace the location of the CR sources and the distribution of interstellar gas.



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.

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.

ApJ 806 (2015) 20

Diffuse γ Emission

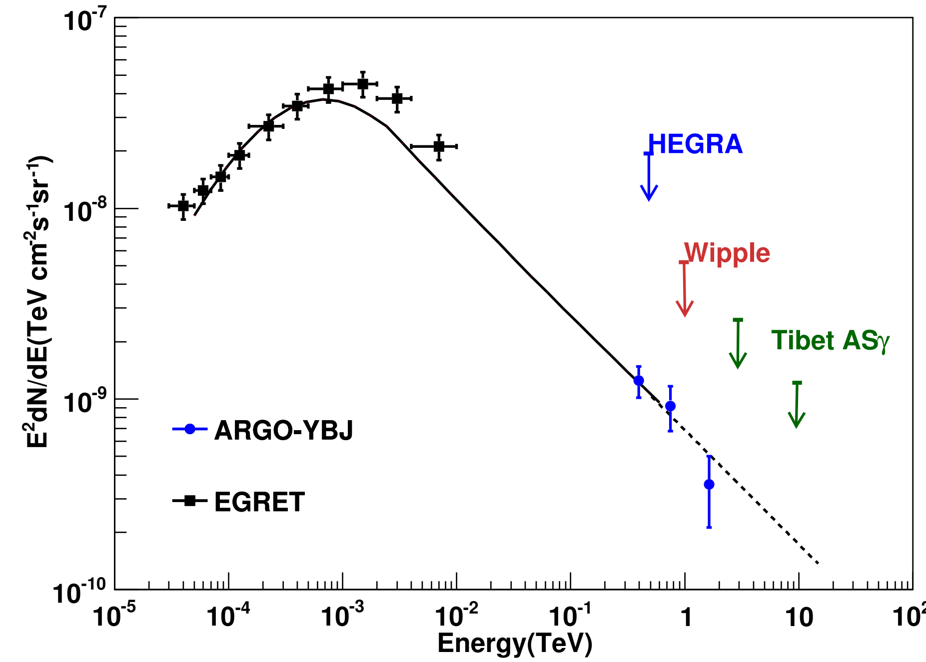
Diffuse gamma-ray emission from the Galactic plane for |b| < 5°

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

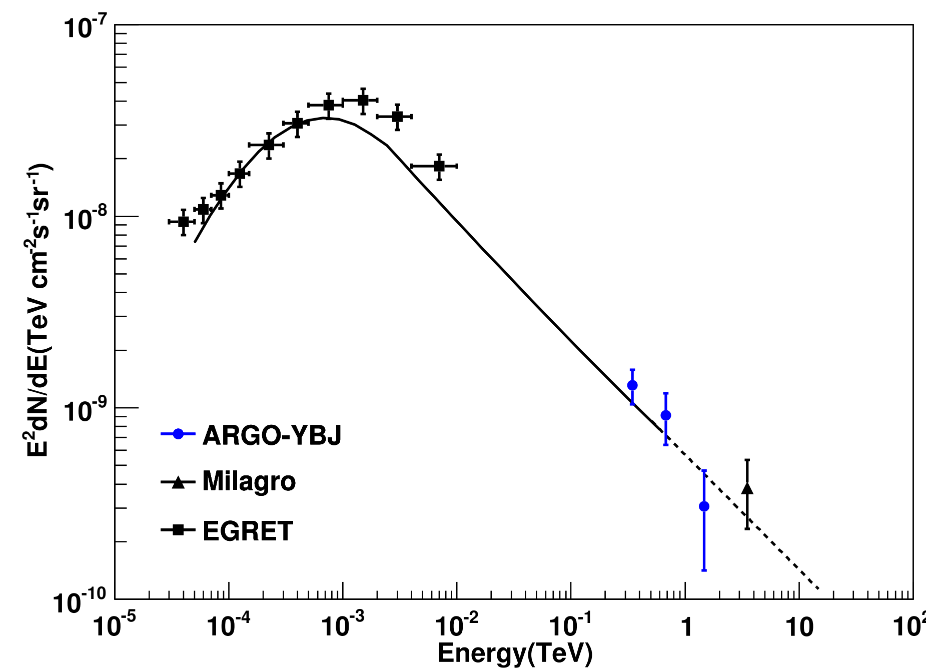
[a]In units of 10^{-9} TeV^{-1} cm^{-2} s^{-1} sr^{-1}.

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.

$25° < l < 100°;\ |b| < 5°$



$40° < l < 100°;\ |b| < 5°$



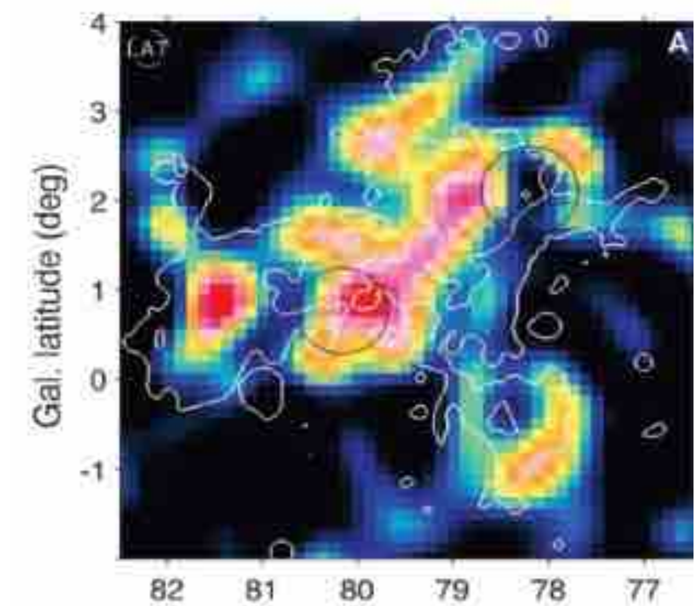
A precise comparison of the spectrum of young CRs, as those supposed in the Cygnus region, with the spectrum of old CRs resident in other places of the Galactic plane, could help to determine the distribution of the sources of CRs.

ApJ 806 (2015) 20

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.

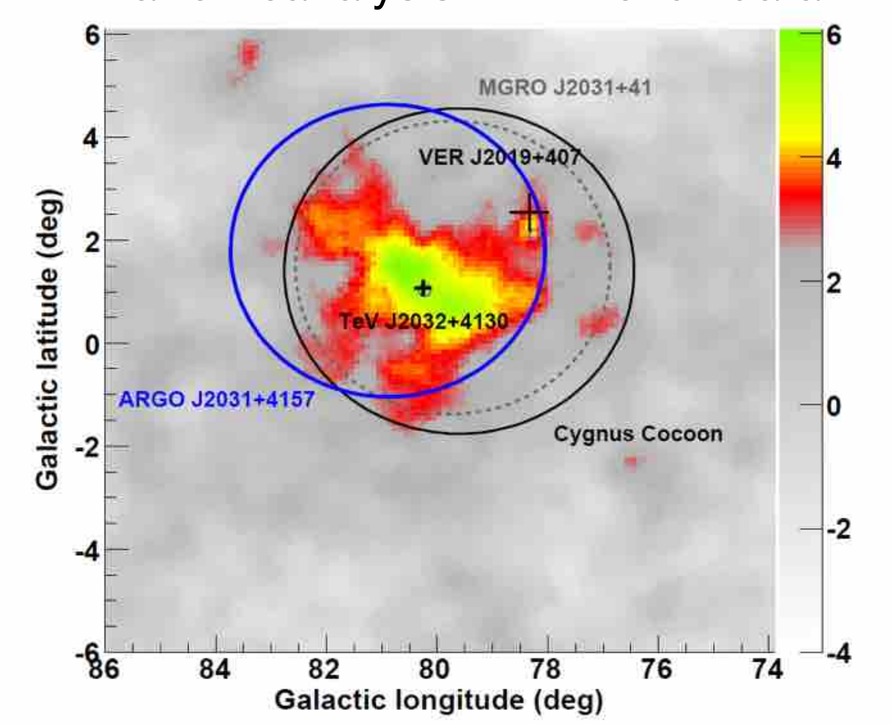
The Fermi/LAT view in the 10-100 GeV band



Science 334 (2011) 1103

The ARGO-YBJ view at TeV energies

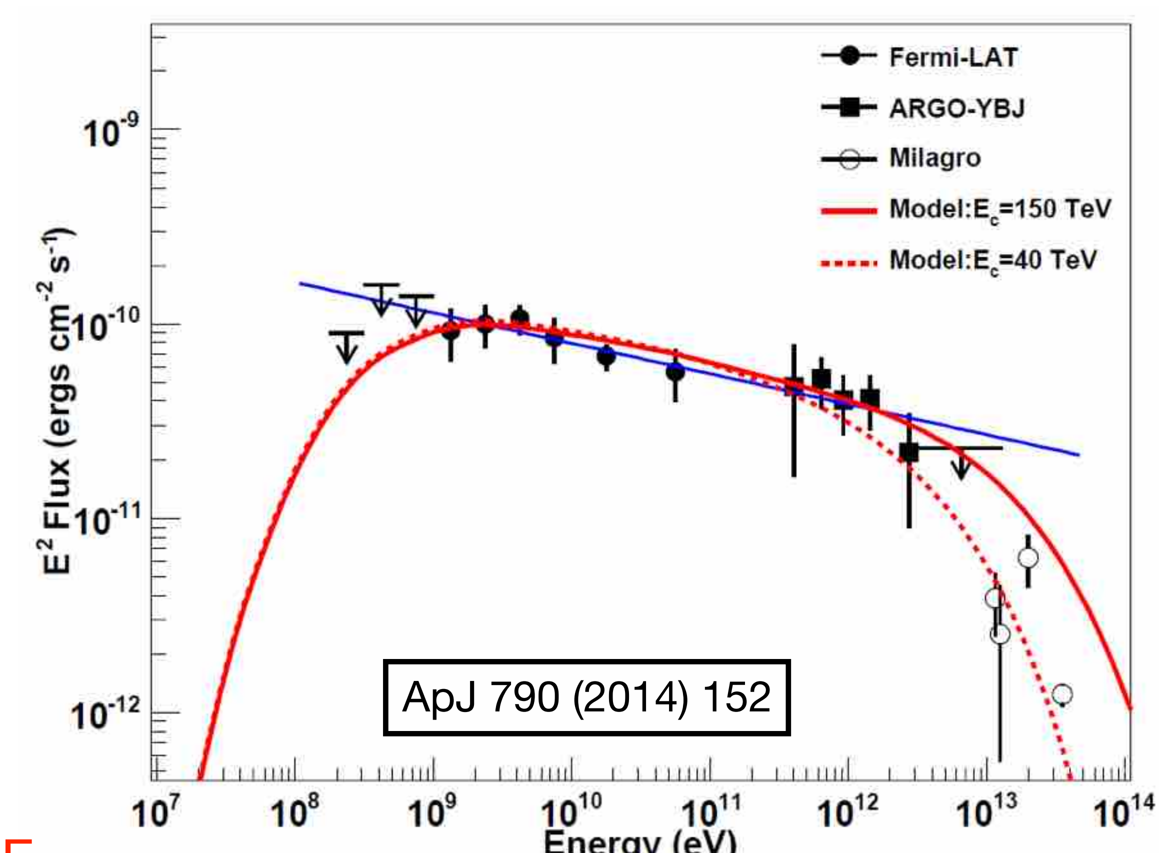
after reanalysis with the full data



S_{max} = 6.1 s.d.

σ_{ext} = 1.8°±0.5°

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: $dN/dE \propto E^{-2.62\pm0.27}$

Combined LAT&ARGO spectrum: $dN/dE \propto E^{-2.16\pm0.04}$

Conclusions

The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout is imaging the front of atmospheric showers with unprecedented resolution and detail.

The digital and analog readout are allowing a deep study of the CR physics in the wide TeV - PeV range.

A number of interesting results have been obtained

- First Northern sky survey ($-10° < \delta < 70°$) at 0.25 Crab Units
- Observation of the TeV counterpart of the Cygnus Cocoon
- Measurement of γ-rays diffuse emission from Galactic Plane
- Detailed study of flaring and extended TeV gamma-ray sources

- Measurement of CR all-particle and light component energy spectrum up to PeVs
- Study of EAS phenomenology up to PeVs
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in the TeV energy range
- Measurement of the p-air and p-p cross sections up to 100 TeV

New generation EAS arrays like LHAASO, with 20x trigger rate, will be able to deepen and extend these observations.

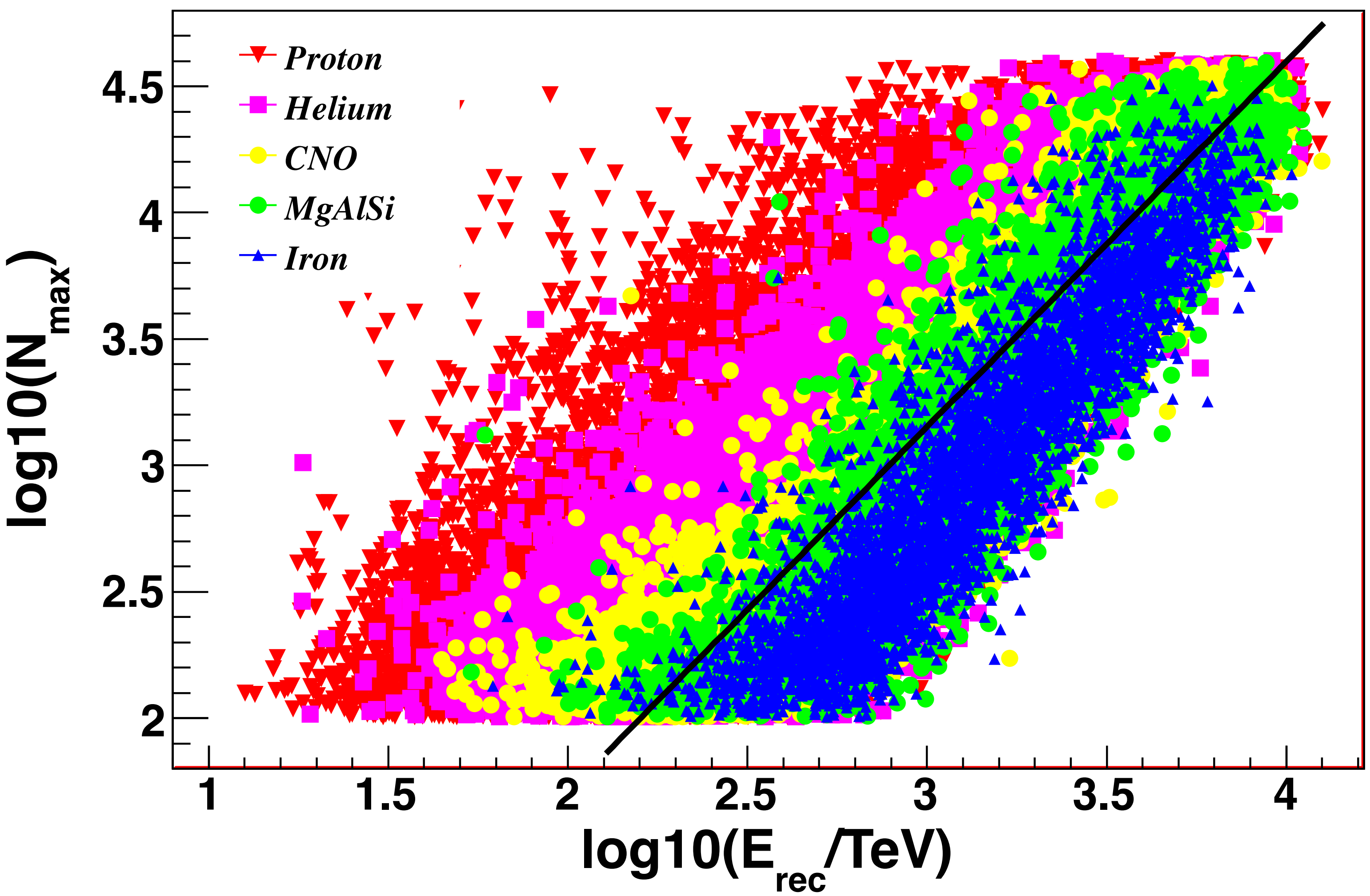
"Main physics results of the ARGO-YBJ experiment", review, Int. J. of Mod. Phys. D23 (2014) 1430019

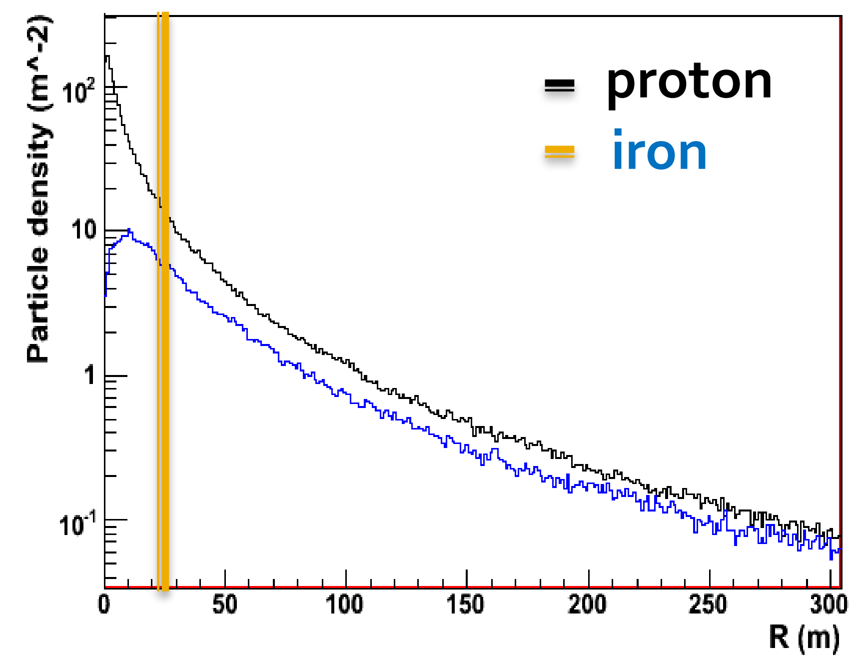
Light component (p + He) selection - (1)

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

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





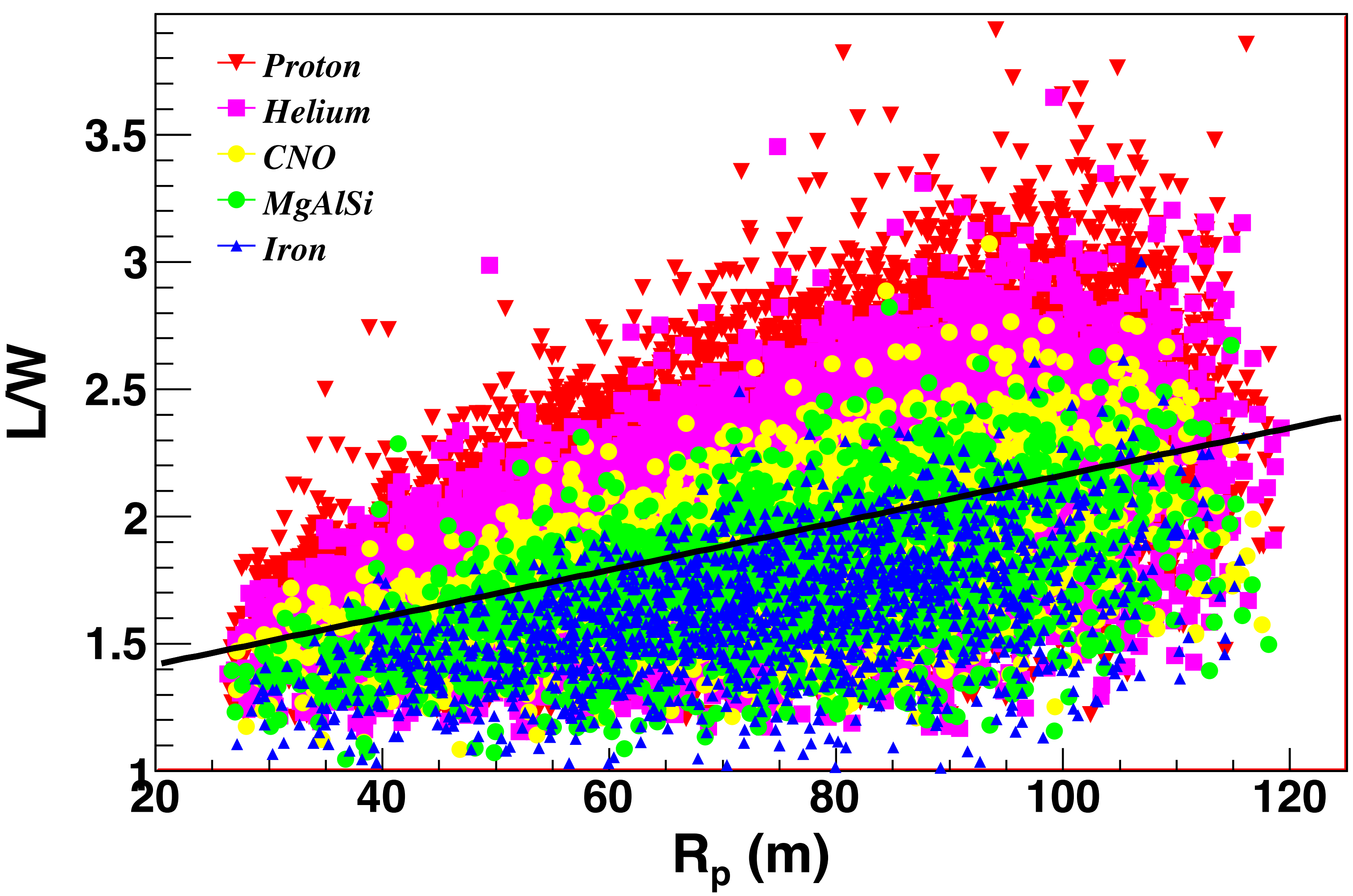
We can define a new parameter to reduce the energy dependence

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

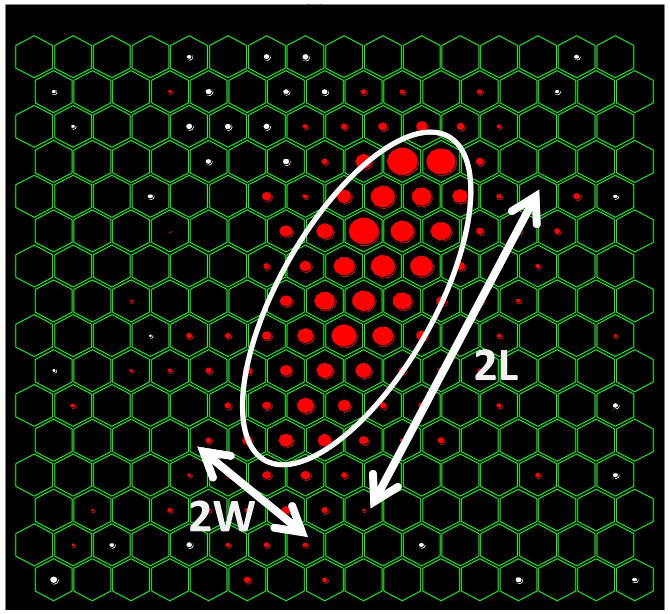
Light component (p + He) selection - (2)

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 ~ 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

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

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