Cosmic Ray Physics with ARGO–YBJ

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INFN - Roma Tor Vergata

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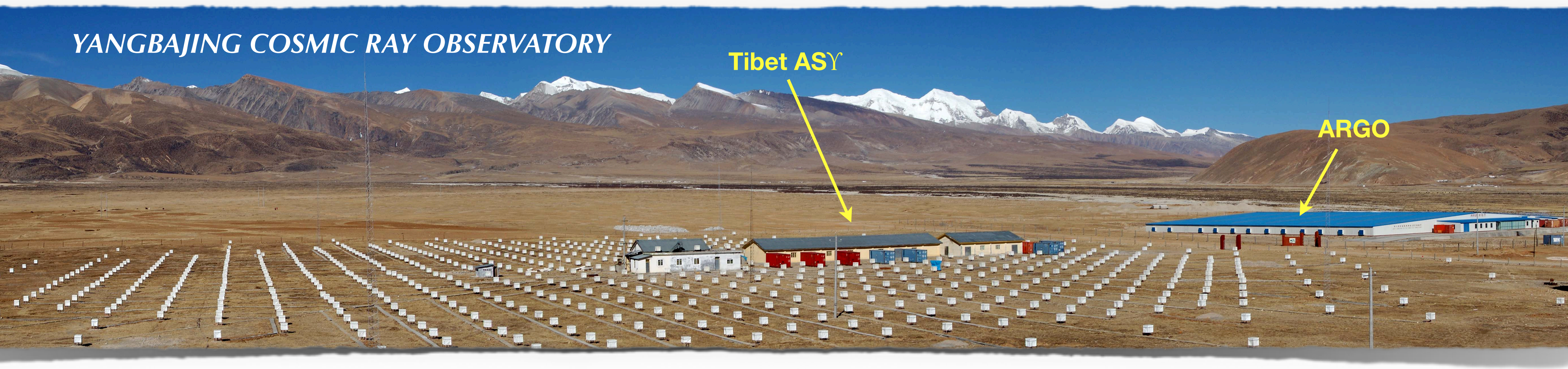
The ARGO—YBJ Experiment

Istituto Nazionale di Fisica Nucleare (INFN) - Chinese Academy of Science (CAS)

(**A**strophysical **R**adiation with **G**round-based **O**bservatory at **Y**ang**B**a**J**ing)

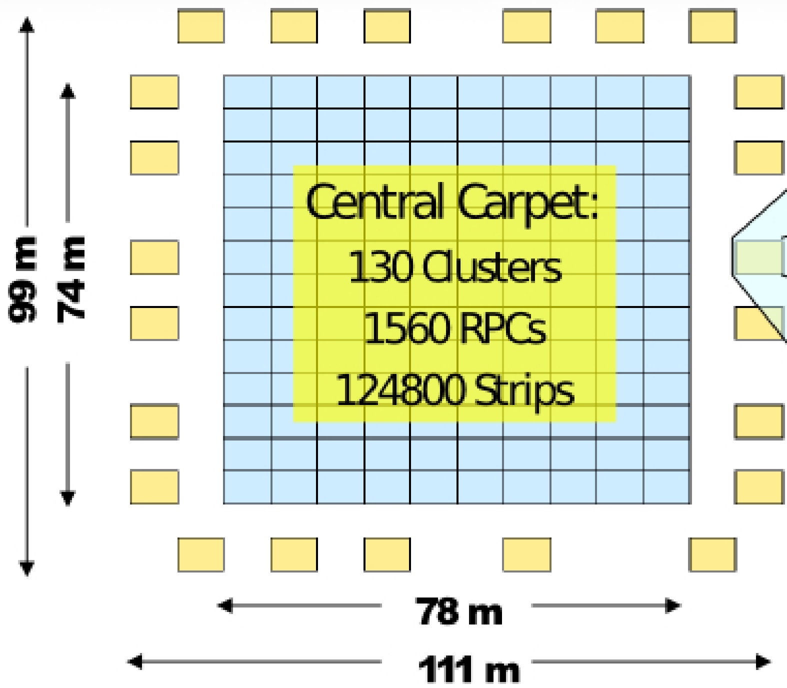
- *COSMIC RAY PHYSICS*
- *GAMMA RAY ASTRONOMY*

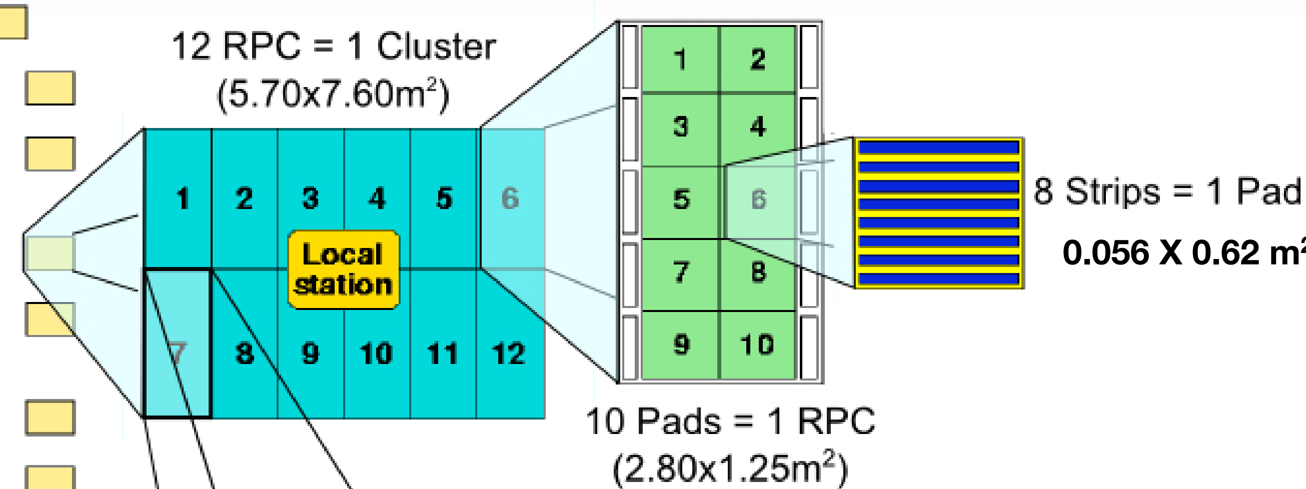
- **Longitude 90° 31′ 50″ East**
- **Latitude 30° 06′ 38″ North**
- **Altitude 4300 m a.s.l.(approx 600 g/cm^2)**

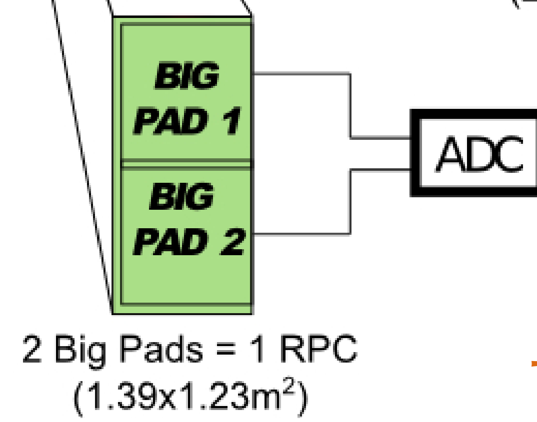


THE DETECTOR

Single layer of Resistive Plate Chambers (RPCs)



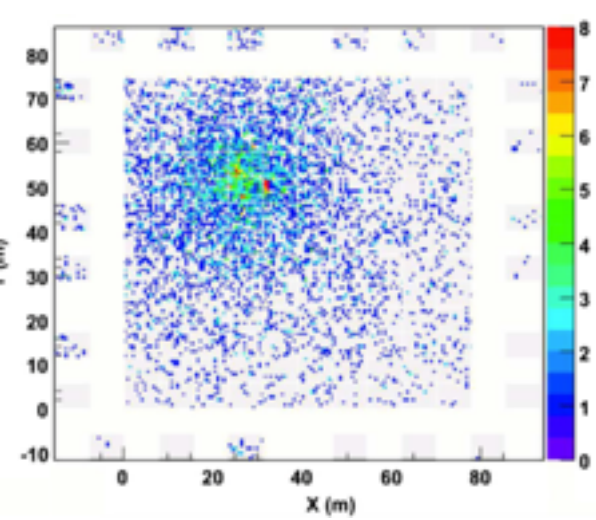


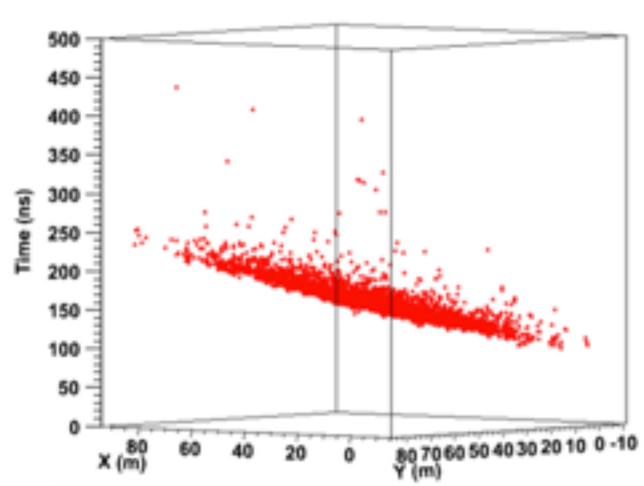


- High Altitude
- Full Coverage
- High segmentation

- time resolution ~ 1 ns
- space pixel = 5.6 x 62 cm^2
- Angular resol. = 0.5° ($N_{hit} \geq 500$)

- IMAGE THE SHOWER WITH UNPRECENDENTED DETAIL





Two independent readout systems

- DIGITAL READOUT
- ANALOG READOUT
- COVERS THE ENERGY RANGE 1-5000 TeV

THE DETECTOR

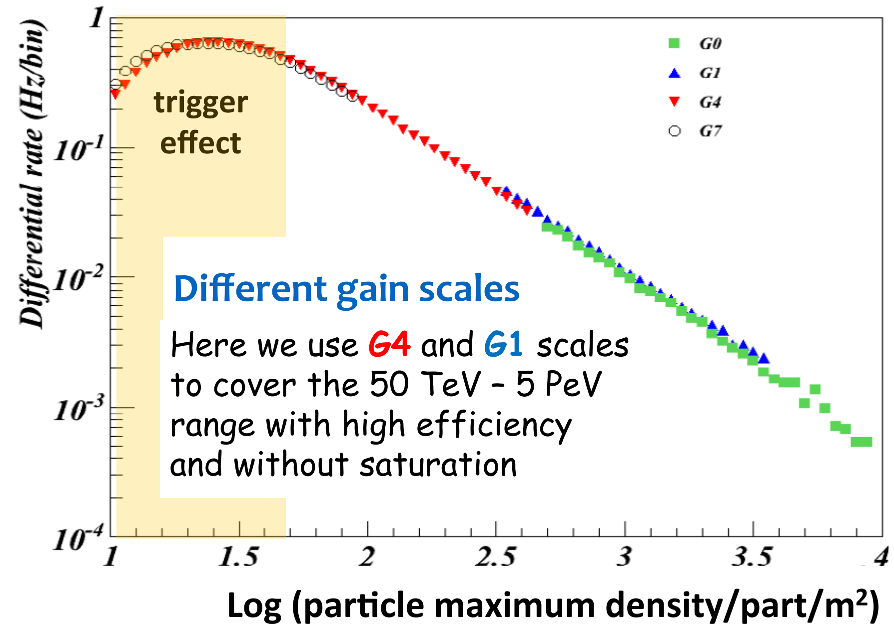
ANALOG READOUT

Extend the maximum energy range up to the PeV region

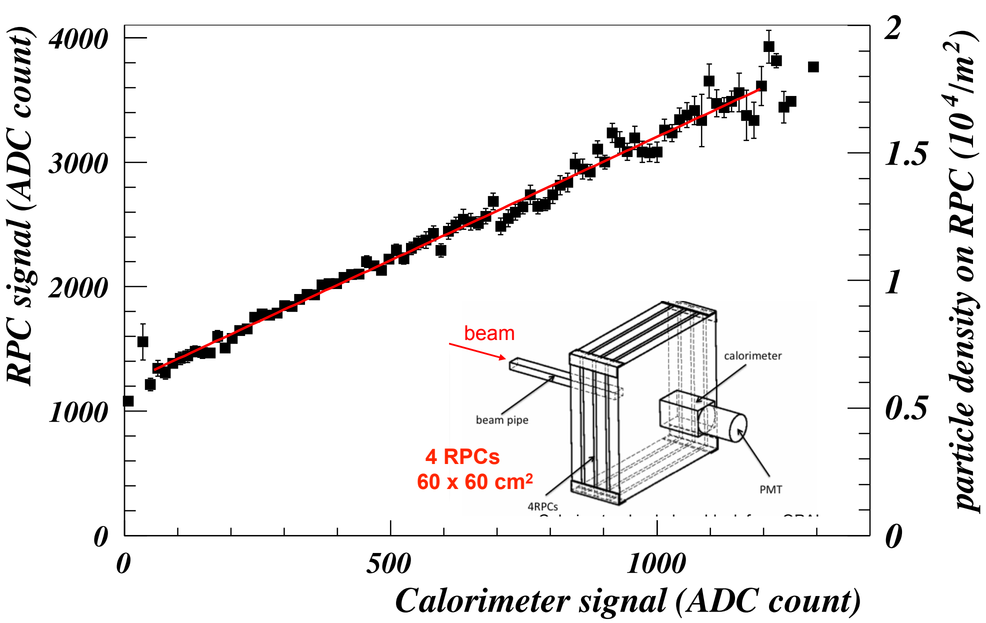
- Extend the covered energy range
- Access the LDF down to the shower core
- Sensitivity to primary mass
- info/checks on Hadronic Interactions

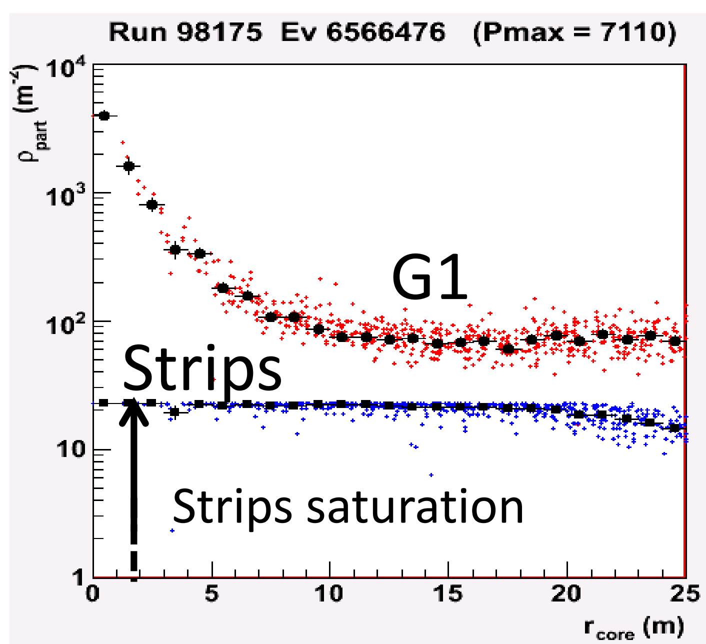
Digital readout:
Showers up to ~23 particles/m²

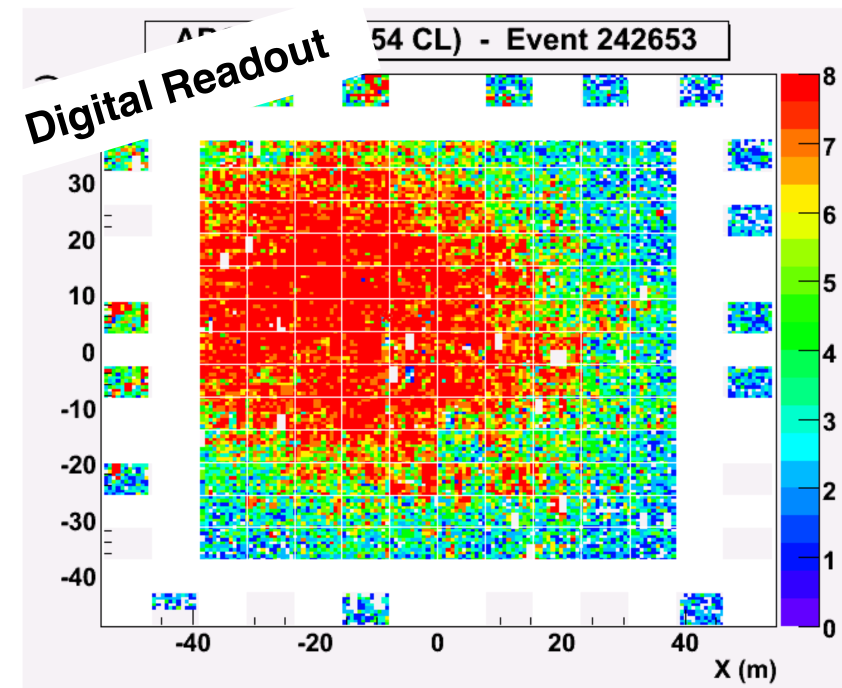
Analog readout:
Showers up to ~10⁴ particles/m²

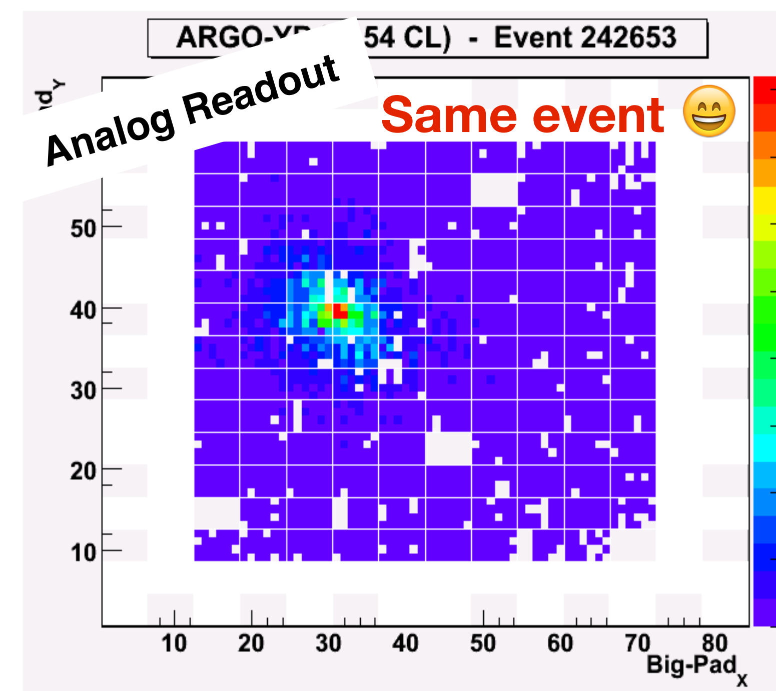


➔ Linearity up to ≈ 2 • 10⁴ particle/m²





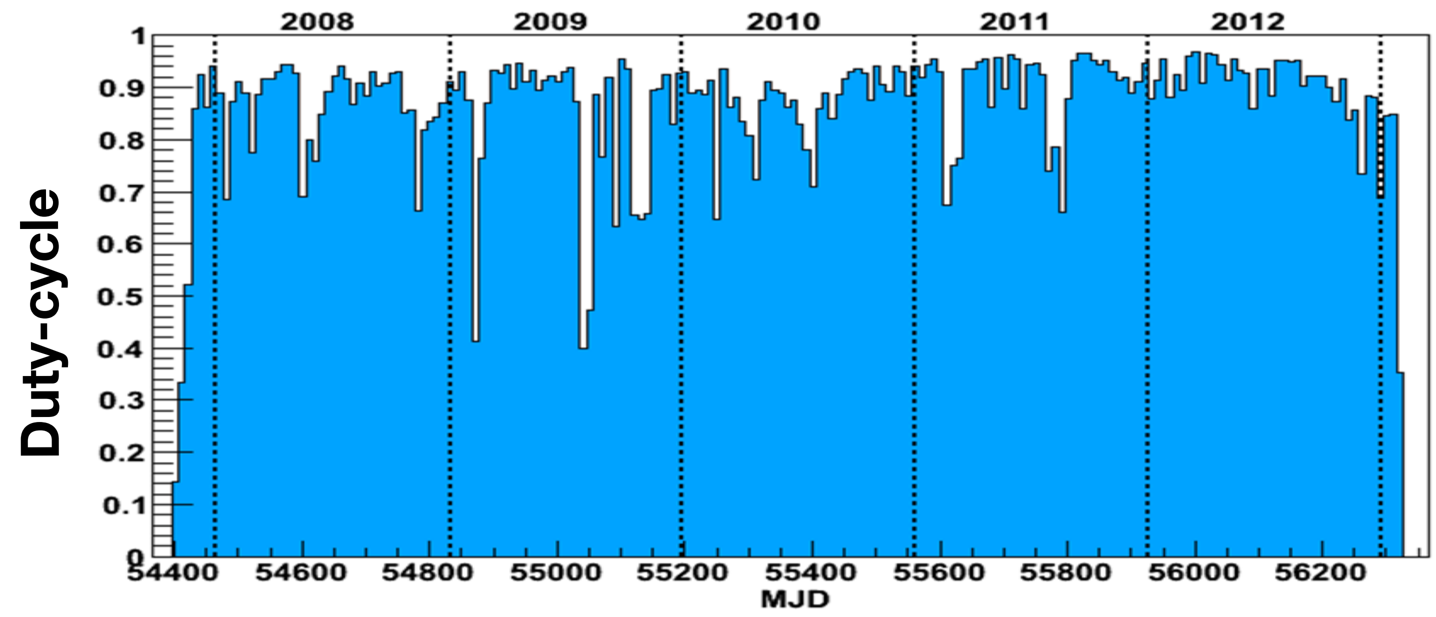


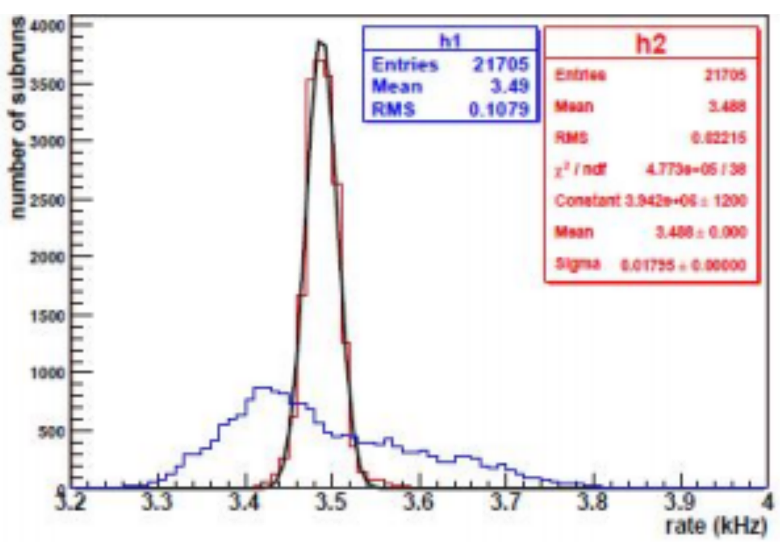


Astropart Phys 67 (2015) 47
NIM A 783 (2015) 68

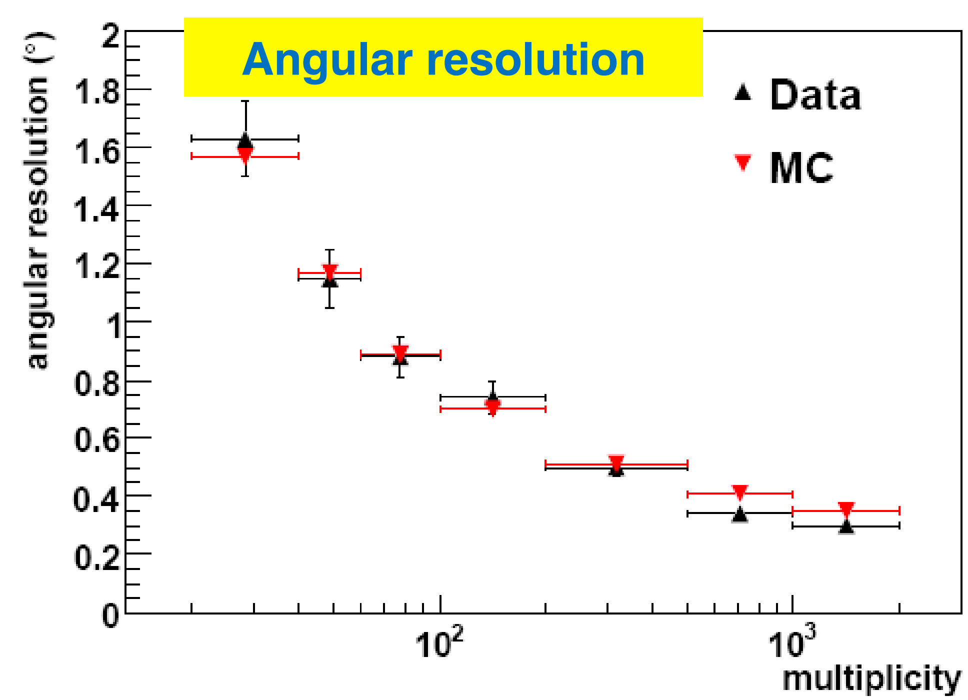
Status and Performances

- Full and stable data taking since Nov. 2007
- End of data taking in Feb. 2013
- Average duty cycle ~87%
- Trigger rate ~ 3.5 kHz @ 20 Pad threshold
- ~ 5 x 10^{11} events recorded
- ~ 100 TB/year





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



Main Results in Cosmic Ray Physics

- **COSMIC RAY ANISOTROPY**
- **COSMIC RAY ENERGY SPECTRUM**
  - ALL-PARTICLE
  - PROTON + HELIUM
- **ANTIPROTON-PROTON RATIO** [Phys. Rev. D 85 (2012) 022002]
- **P-AIR CROSS SECTION** [Phys. Rev. D 80 (2009) 092004]
- **GEOMAGNETIC EFFECTS** [Phys. Rev. D 89 (2014) 052005]
- **SHOWER TIME STRUCTURE**

Large Scale Anisotropy

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

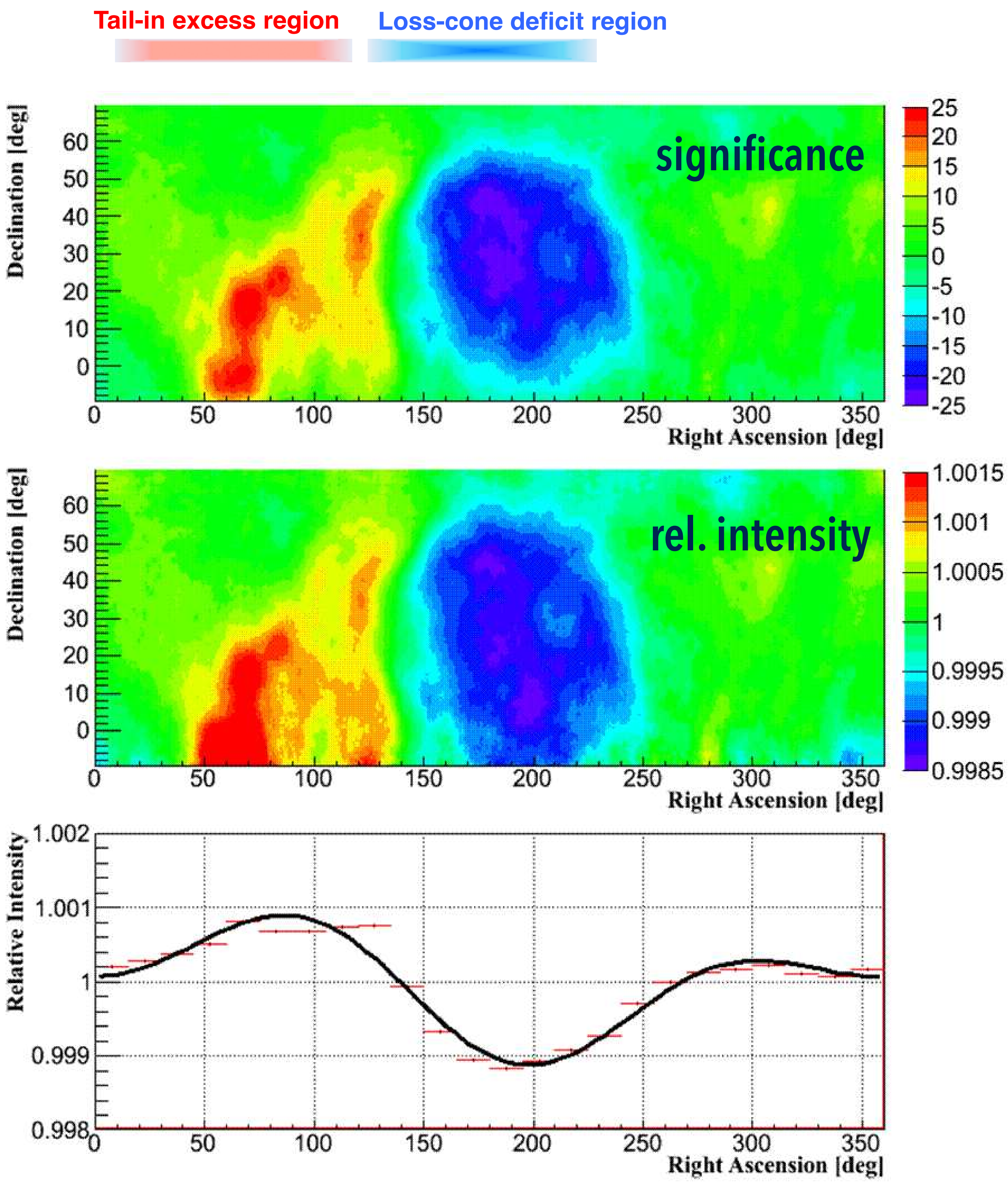
E ≈1 TeV, 3.6×10^{10} events in the declination band $-10^o < \delta < +70^o$

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

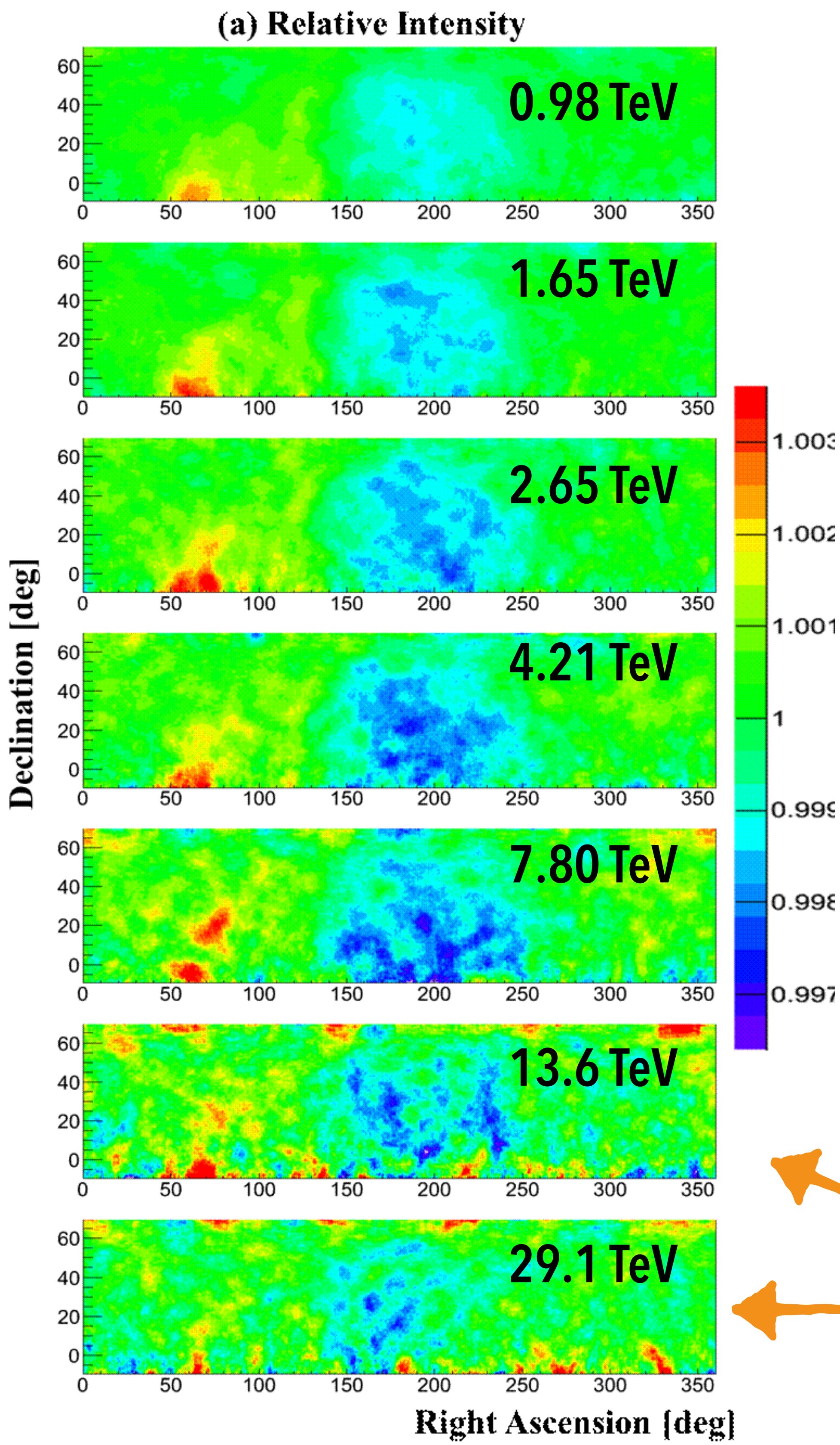
R.A. profile of anisotropy can be described with 2 harmonics

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

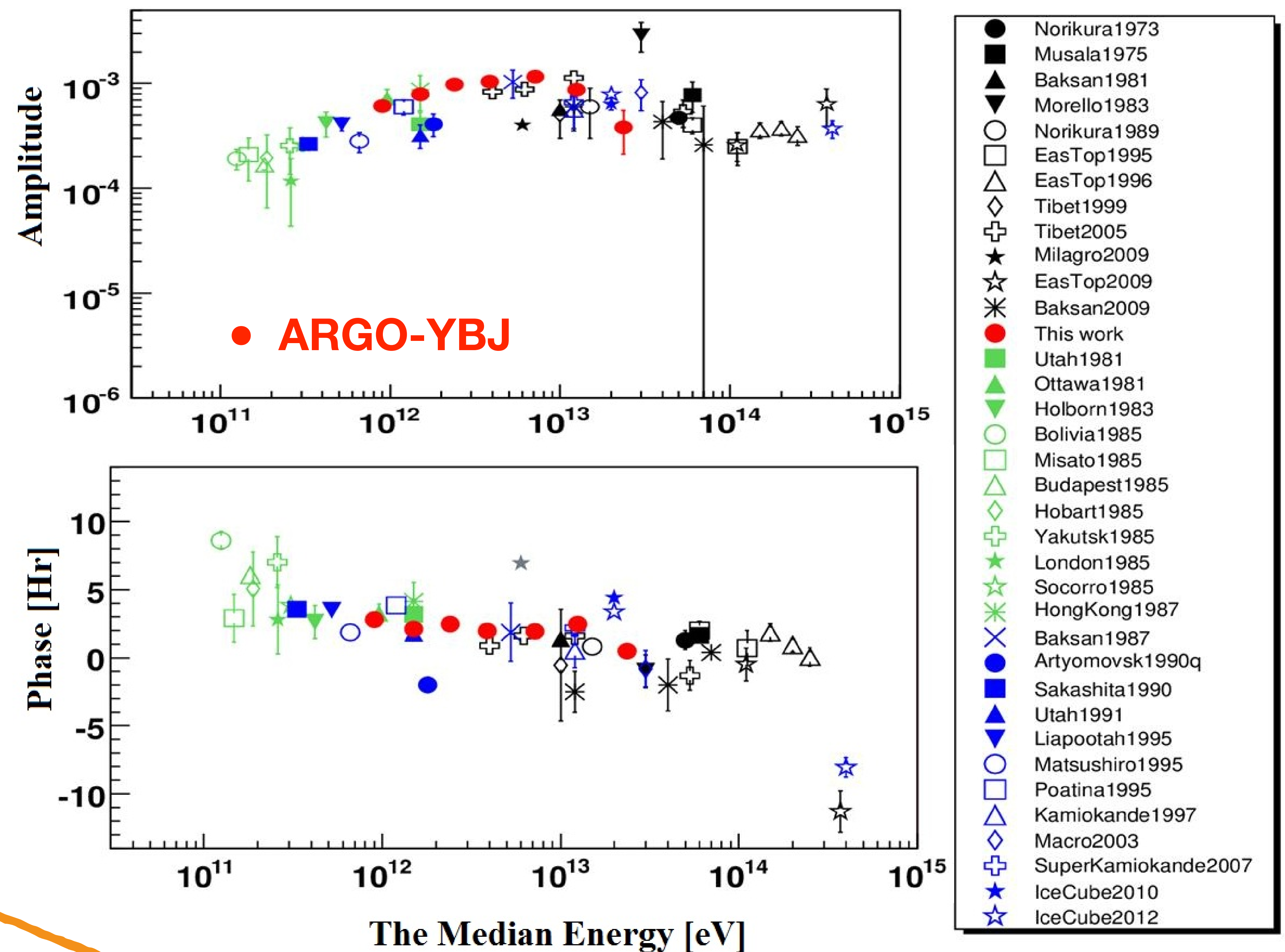
Ap. J. 809:90 (2015)



Large Scale Anisotropy



Good agreement with other experiments



Structures appear to dissolve to a smaller angular scale at high energy

Ap. J. 809:90 (2015)

MEDIUM SCALE ANISOTROPY

Data: November 8, 2007 - May 20, 2012

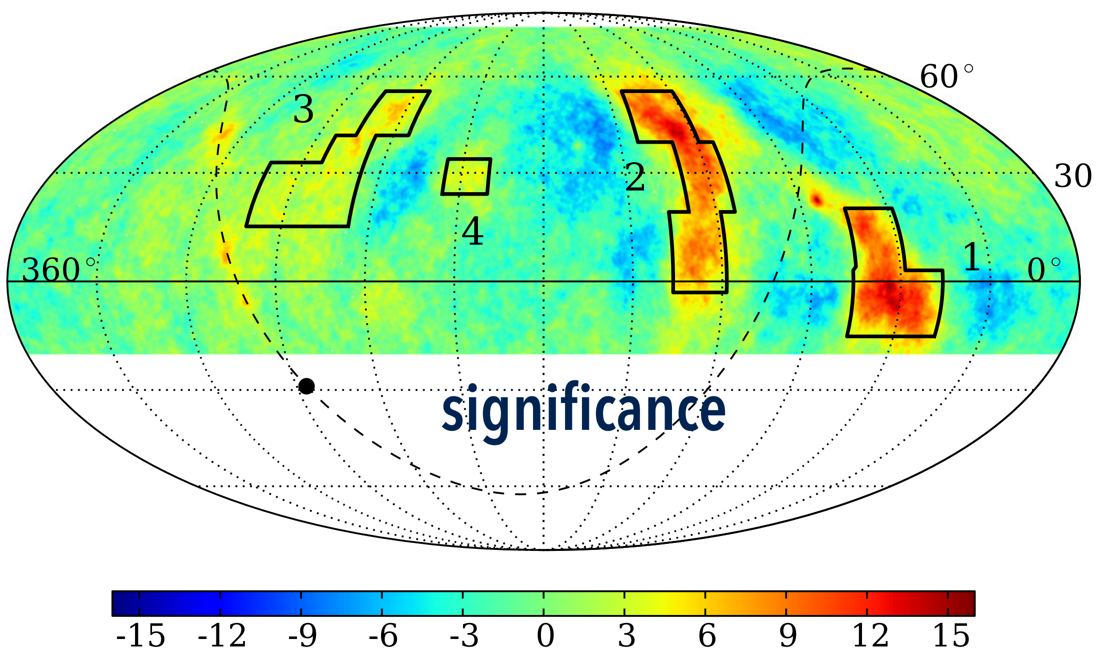
CRs excess ≈ 0.1 % with significance up to 15 s.d.

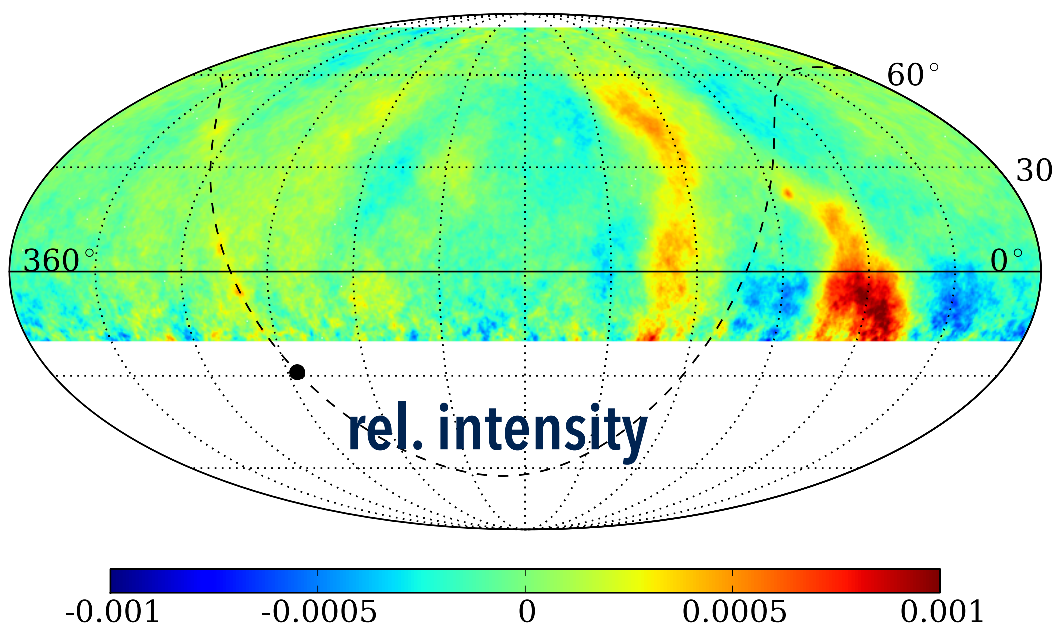
≈ 3.70×10^{11} events dec. region $\delta \sim -20° \div 80°$

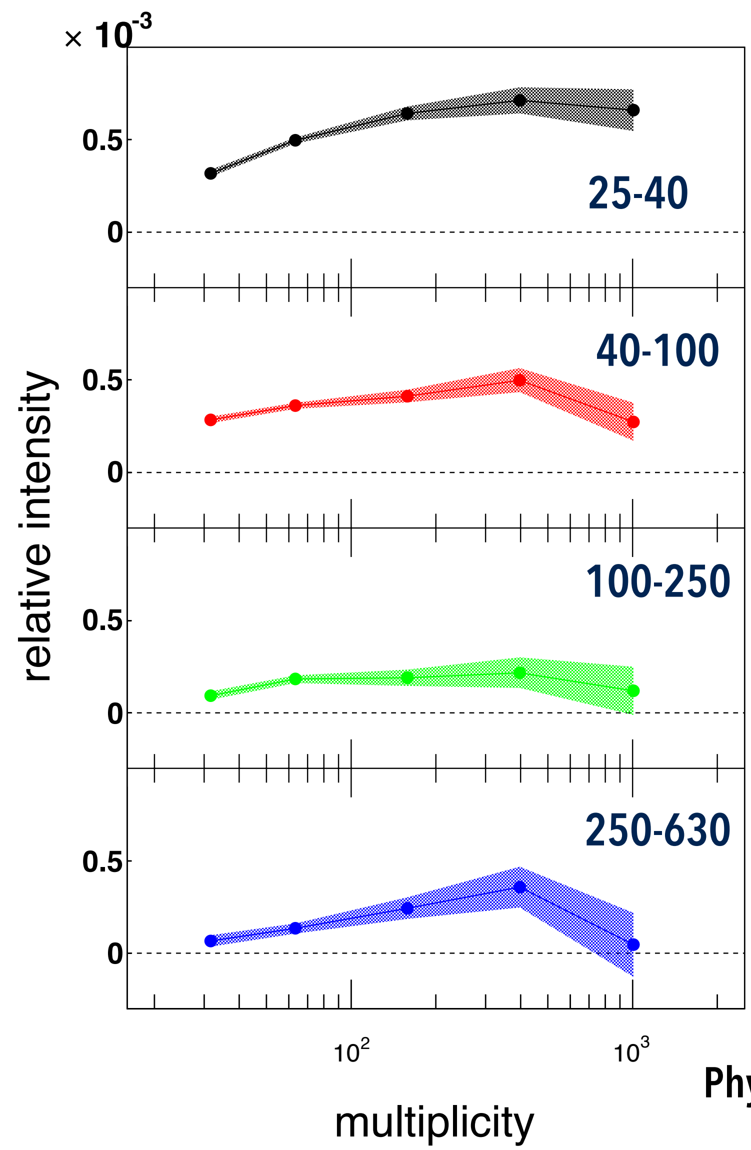
Map smoothed with the detected PSF for CRs

Proton median energy ≈ 1 TeV

Strip-multiplicity interval	number of events		E_p^{50} [TeV]
25 – 40	1.1409×10^{11}	(38%)	0.66
40 – 100	1.4317×10^{11}	(48%)	1.4
100 – 250	3.088×10^{10}	(10%)	3.5
250 – 630	8.86×10^{9}	(3%)	7.3
more than 630	3.52×10^{9}	(1%)	20







The size spectra look quite harder than the CR isotropic flux

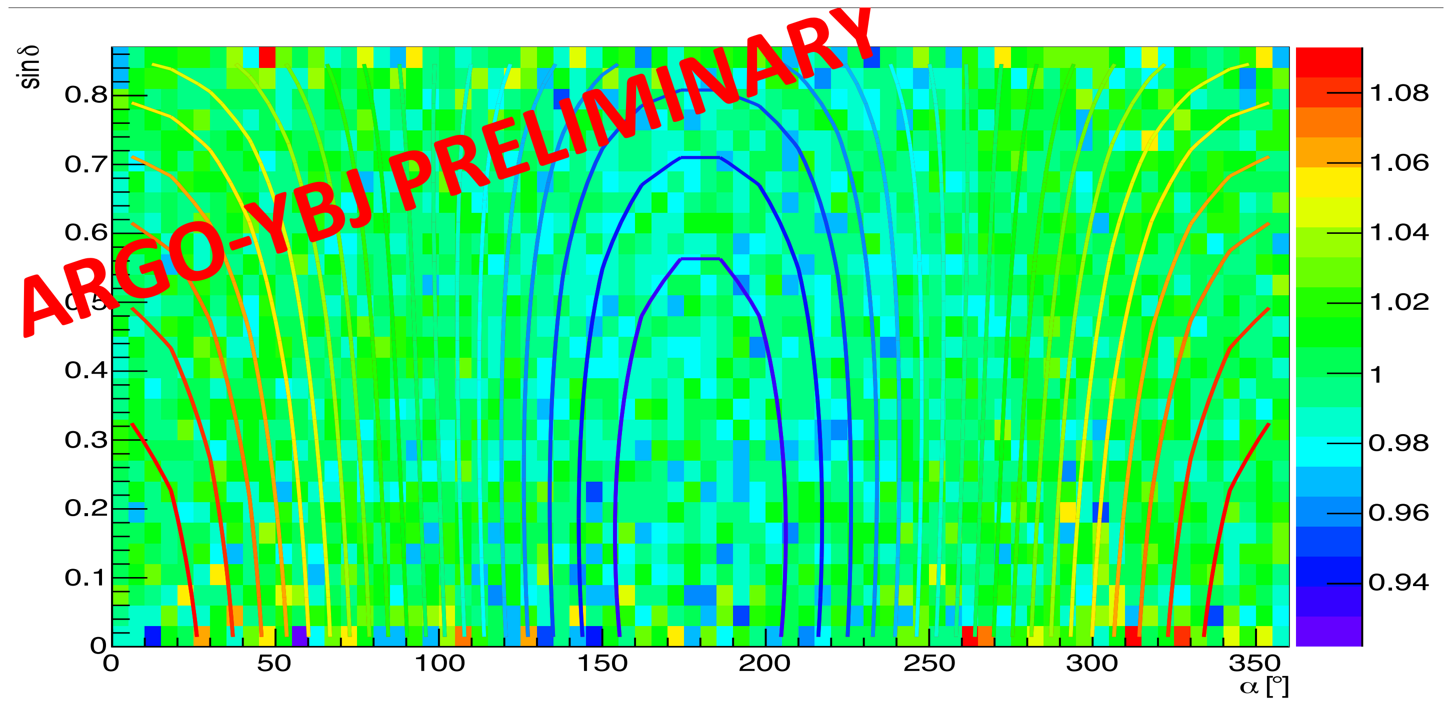
Phys. Rev. D 88 082001 (2013)

Anisotropy of Light Elements

"ratio-method"

use the complete set of events as reference for the estimation of the background of a particular subset of events. The idea is to measure the *local* fraction of *selected* to *all* events

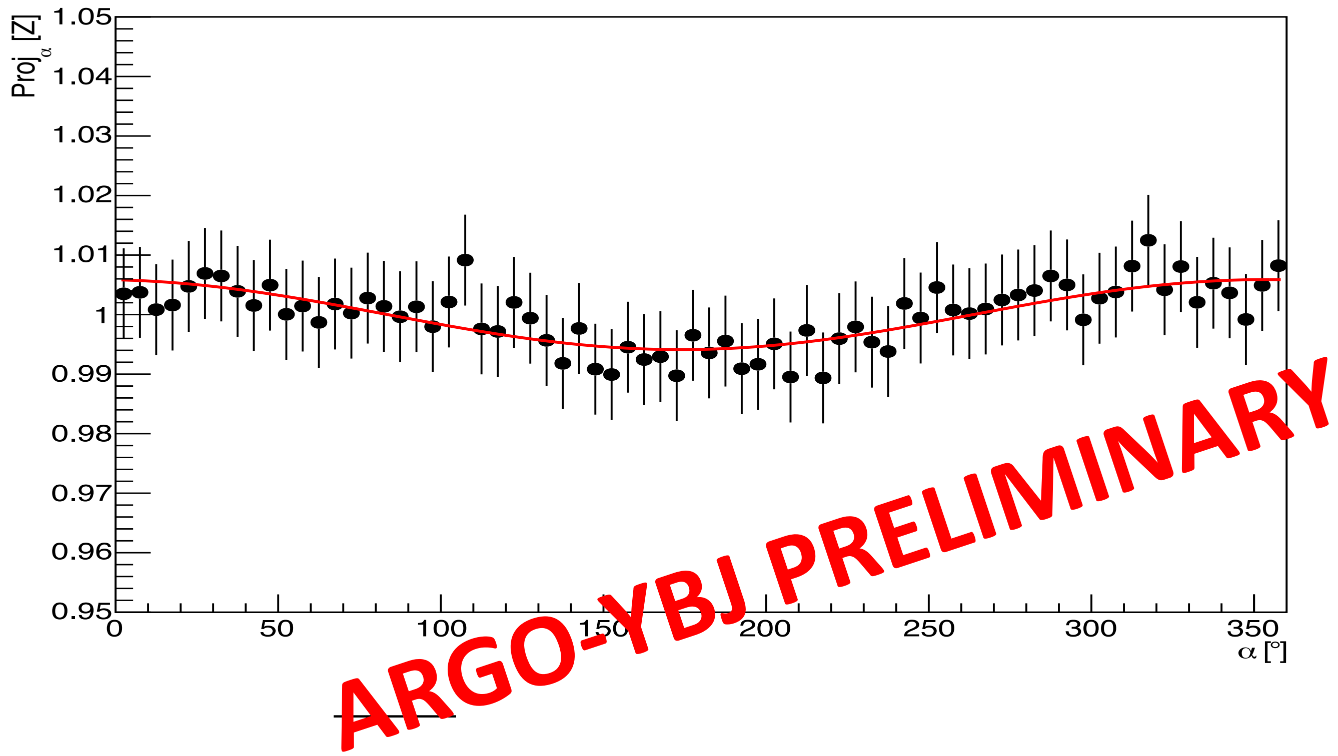
Data: January 1, 2008 - December 31, 2012



Selection of light elements

Same criteria used for the light component energy spectrum analysis

In the energy region below 10 TeV the contamination does not exceed 0.3%, in the range(10–100) TeV is 4.2% and at energies higher than 100 TeV it has been evaluated as 9%.



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

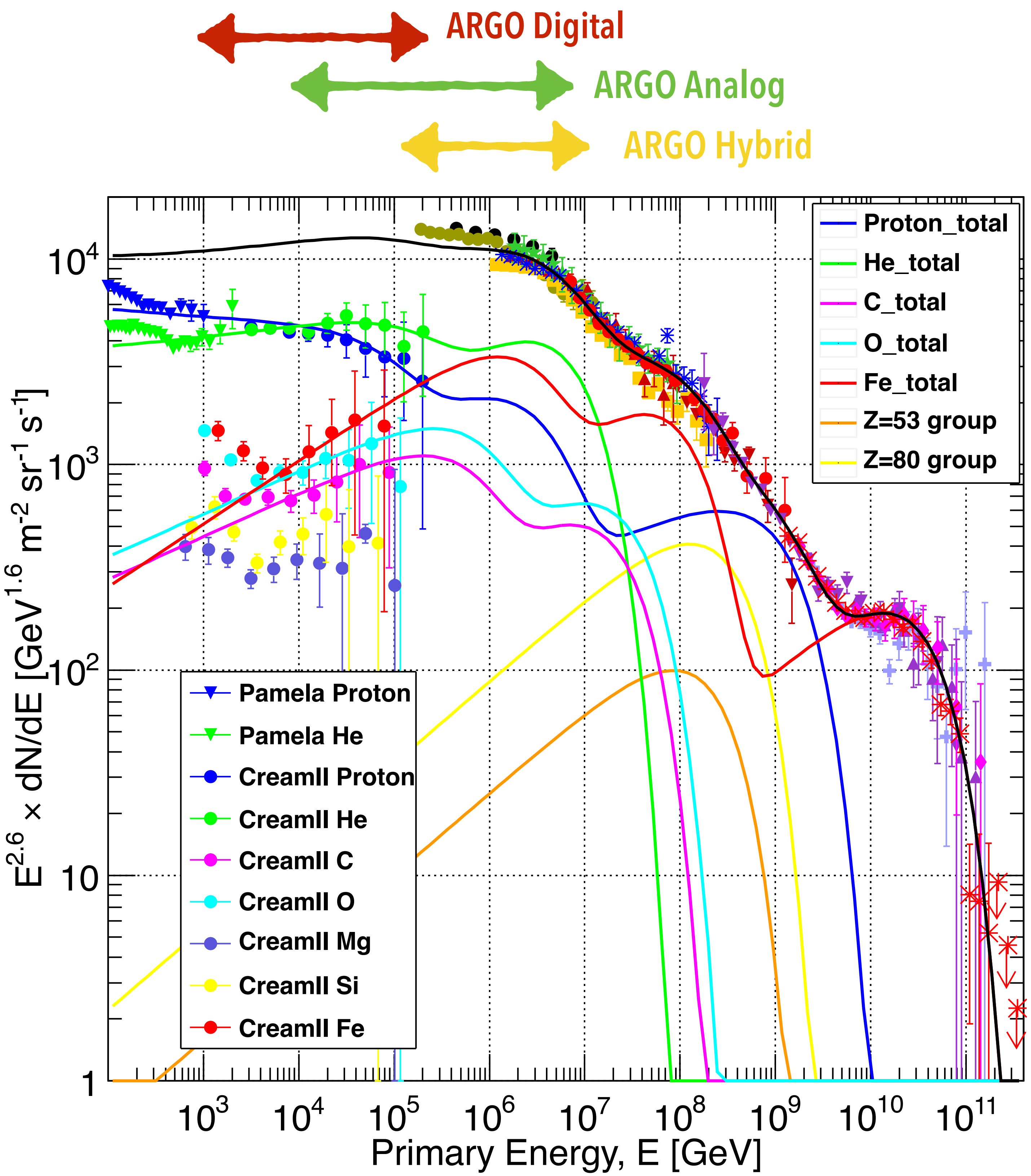
phase in right ascension: -6° ± 10° (minimum in coincidence with the loss cone)

R. Iuppa, PM, et al ICRC 2015 ID 290

Cosmic Ray Energy Spectrum

Different approaches & data sets

- Analysis of digital RPC data alone and statistical measurement of the energy spectrum by using a bayesian approach: p+He spectrum
- Analysis of analog RPC data alone and statistical measurement of the energy spectrum by using a bayesian approach: all particle and p+He spectra
- Analysis of analog RPC data alone and energy determination on an event by event basis: all-particle and p+He spectra
- Hybrid technique by using data from an imaging Cherenkov telescope in addition to analog RPC information: p+He spectrum



Digital Data – P+He Spectrum

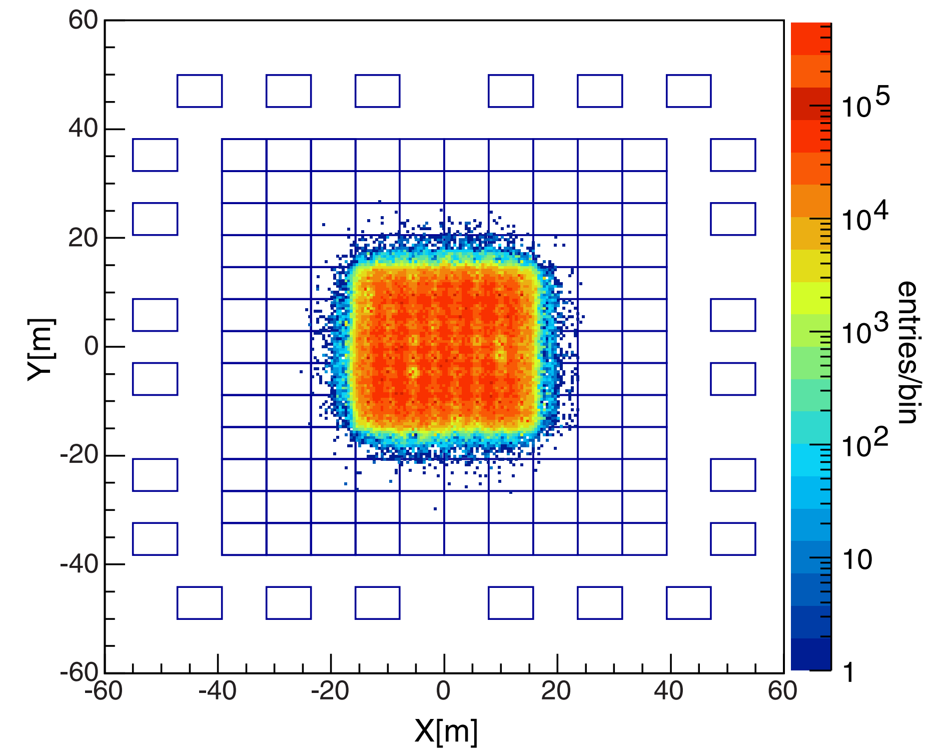
3 - 300 TeV energy range

Bayesian Approach

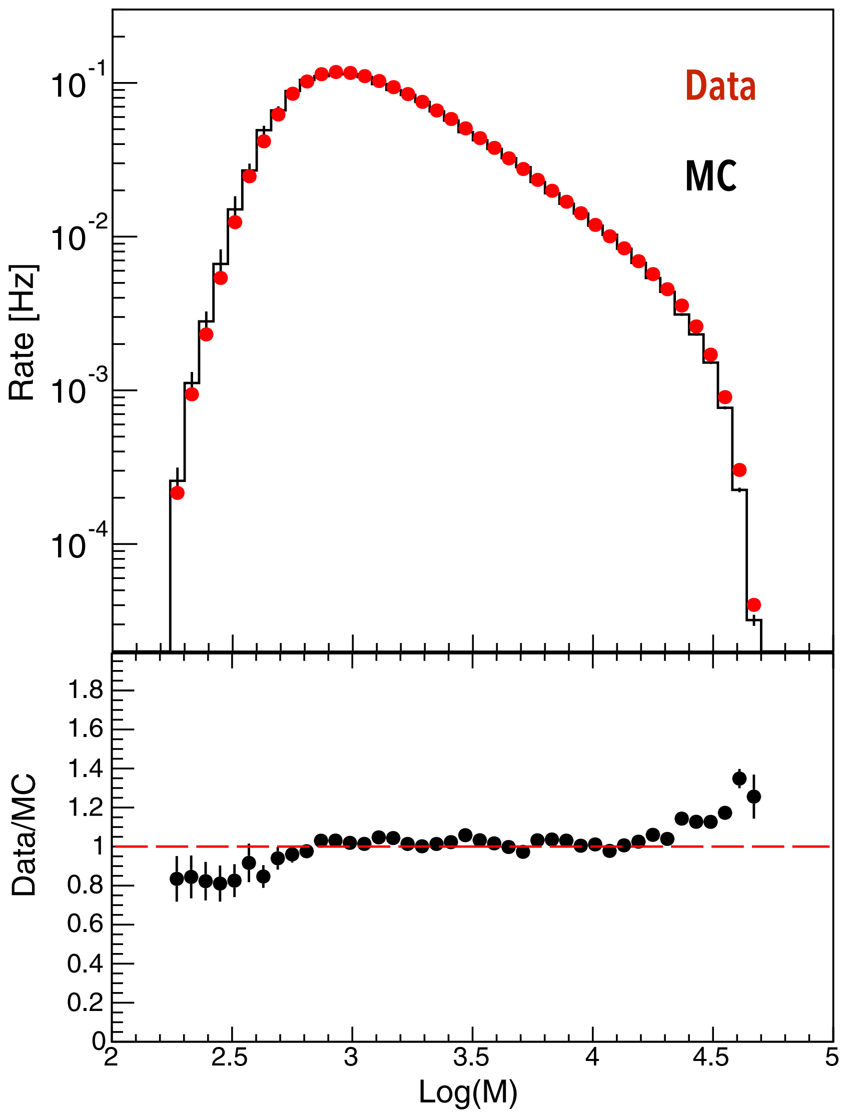
Event selection based on:

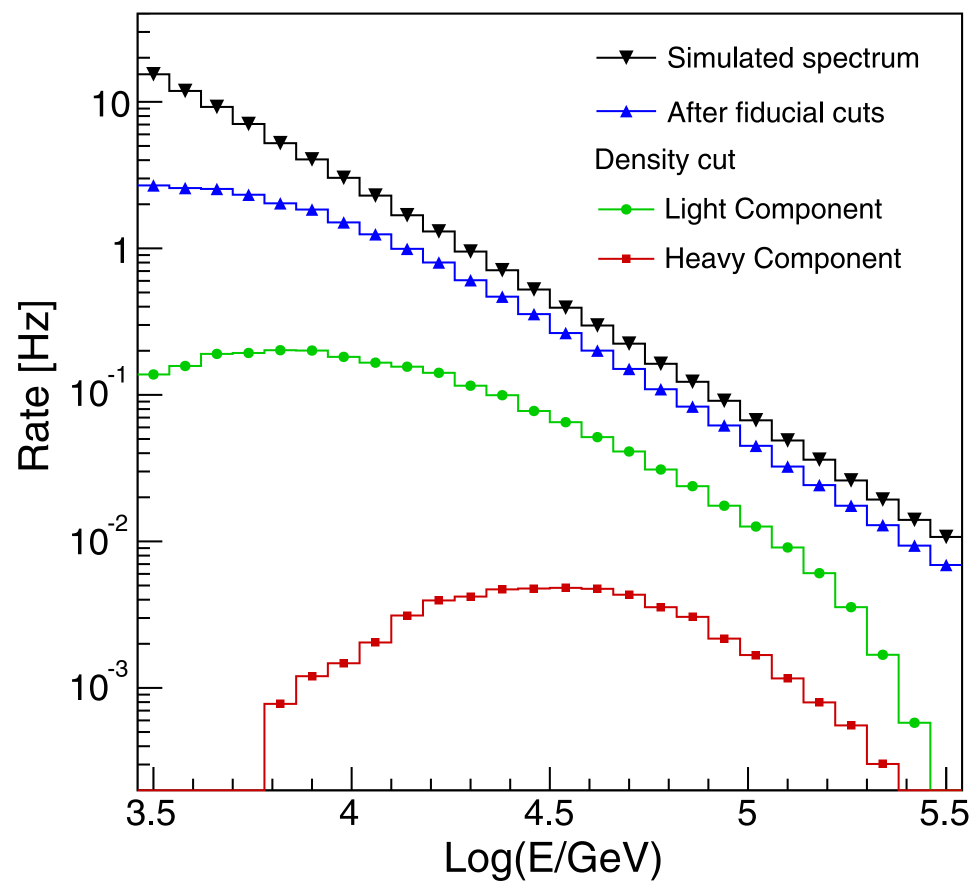
- ➡ Shower size on detector, M (strip multiplicity)
- ➡ Reconstructed zenith angle
- ➡ Core Position

Phys. Rev. D 85 092005 (2012)
Phys. Rev. D 91 112017 (2015)



Five years of data taking
~3 x 10^{11} events





Light - Heavy discrimination

Constraint on strip density (ρ) in the innermost and outermost area of the detector

The cut based on the particle density on the detector surface selects showers with well-shaped core

Mainly produced by light elements

The P+He Spectrum

3 - 300 TeV energy range   Bayesian Approach

➡ Excellent stability over a long period

➡ Overlap with direct measurements in a wide energy region

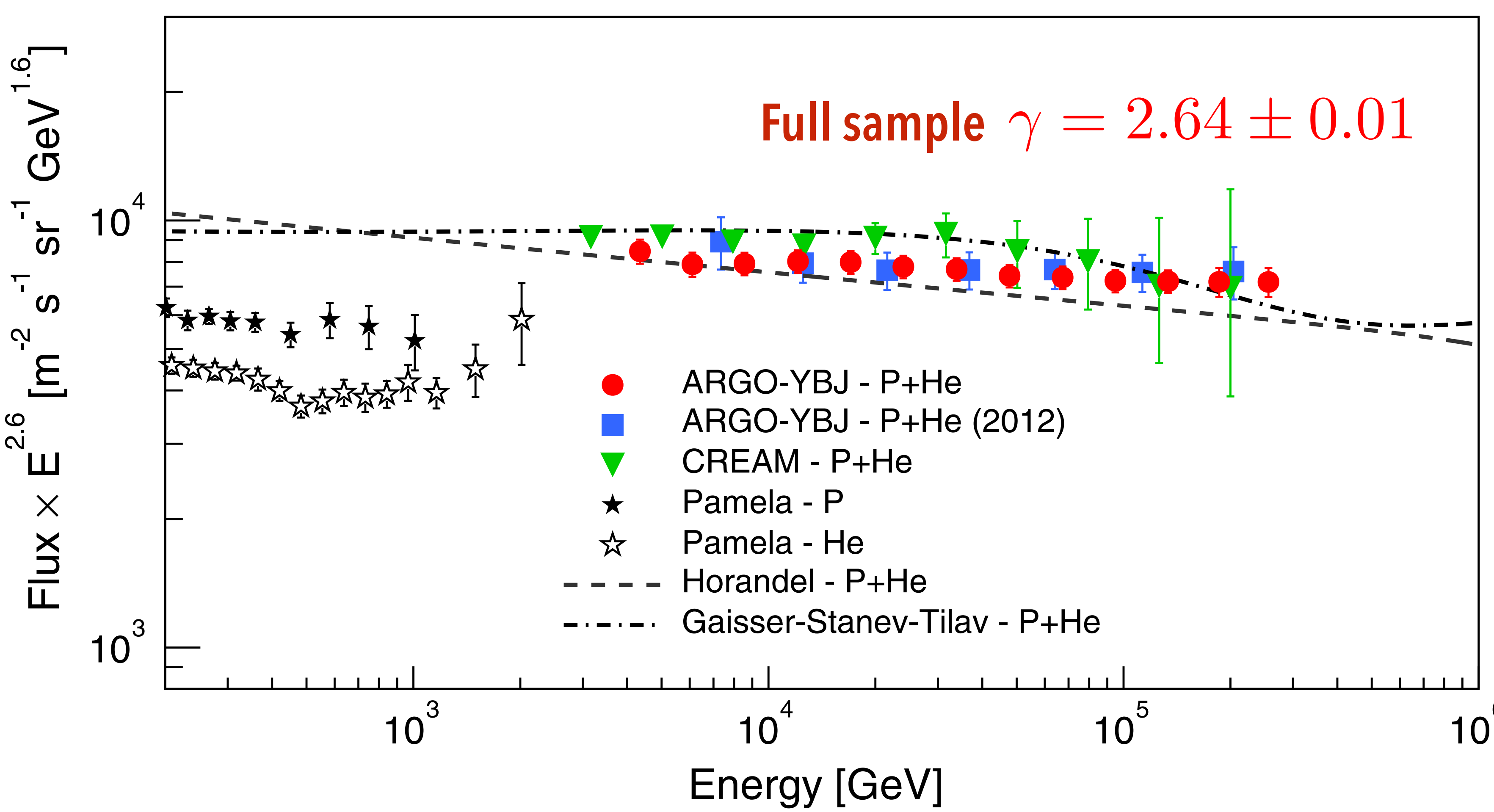
➡ Total systematic uncertainty ~ 5%

YEAR	Gamma
2008	2.63 ± 0.01
2009	2.63 ± 0.01
2010	2.63 ± 0.01
2011	2.64 ± 0.01
2012	2.65 ± 0.01

FLUX @ 50 TeV

YEAR	Flux x 10^{-9} ± tot. err
2008	4.53 ± 0.28
2009	4.54 ± 0.28
2010	4.54 ± 0.28
2011	4.50 ± 0.27
2012	4.36 ± 0.27

Extension of the previous ARGO-YBJ light component spectrum measurement in the low energy region



Phys. Rev. D 85 092005 (2012)

Phys. Rev. D 91 112017 (2015)

Analog Data — All Particle & P+He

10 - 3000 TeV energy range

Fiducial cuts

- ➡ Reconstructed zenith angle
- ➡ Core Position
- ➡ Shower size on detector, M

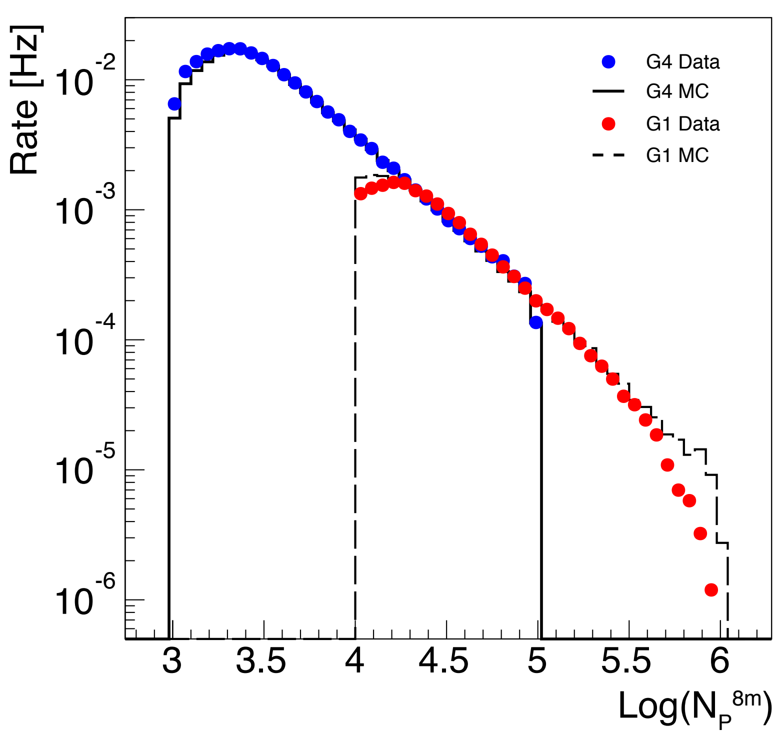
G1

P+He 100 - 3000 TeV

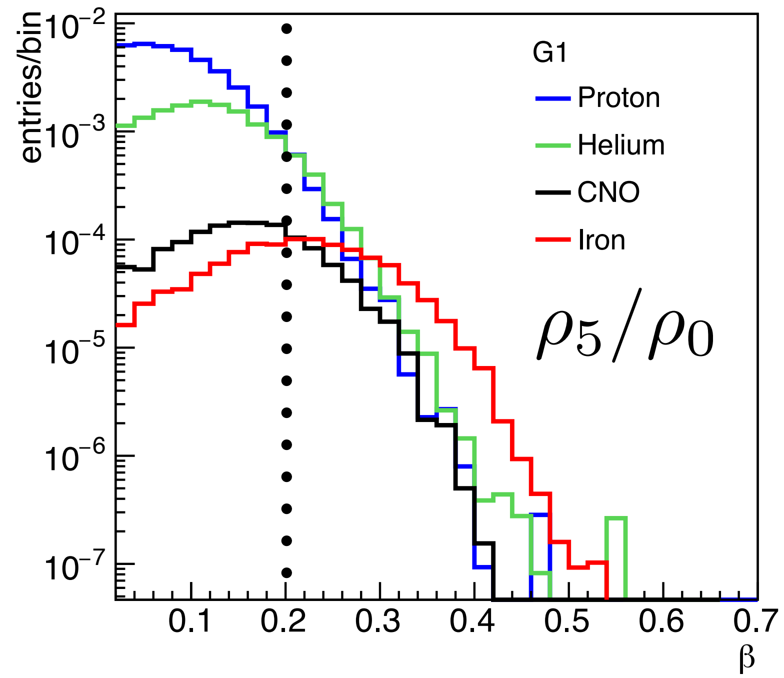
G4

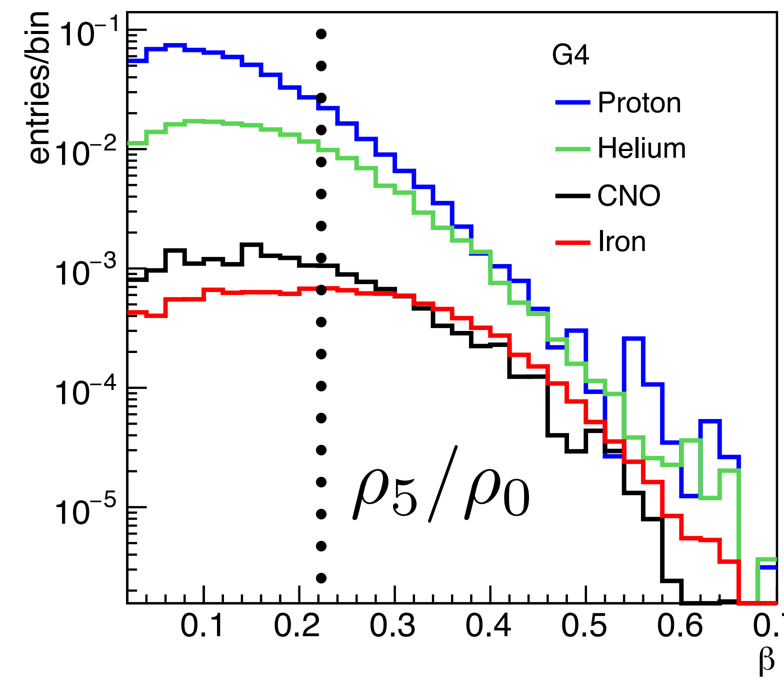
ALL-PARTICLE 40 - 800 TeV

P+He 10–100 TeV

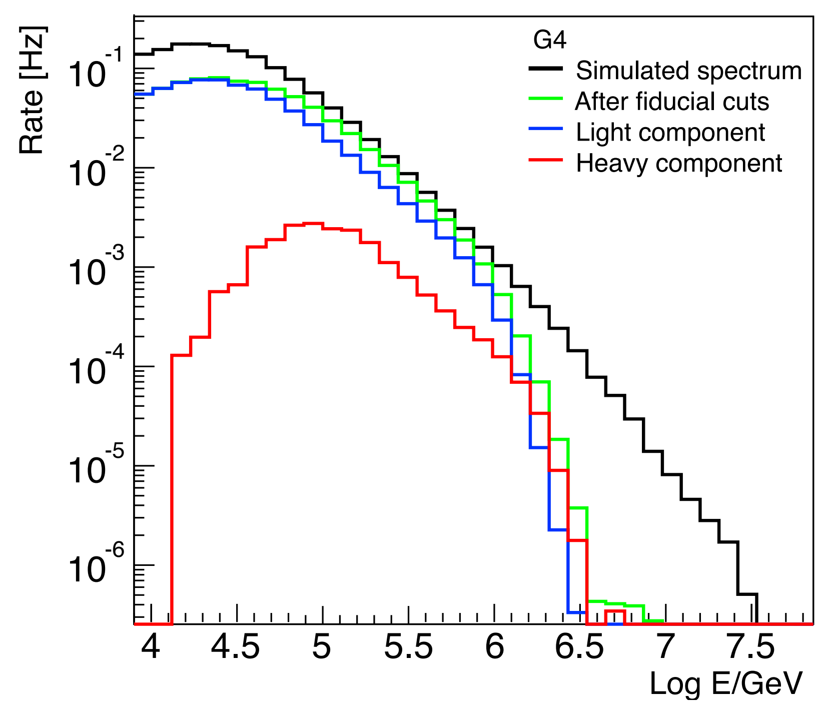


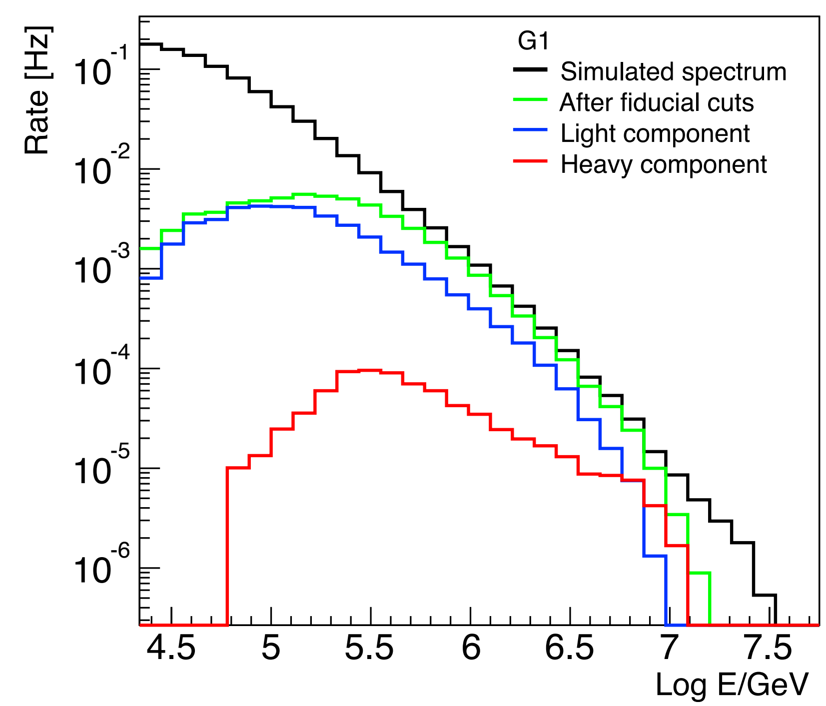
Light/Heavy discrimination based on the LDF





Showers mainly produced by light elements





ALL PARTICLE & P+HE

➡P+HE SPECTRUM

➡Overlap with direct measurements in a wide energy region

➡ Gradual change of the spectral index at E ~ 700 TeV

➡Consistent with the Digital Readout data (different data set)

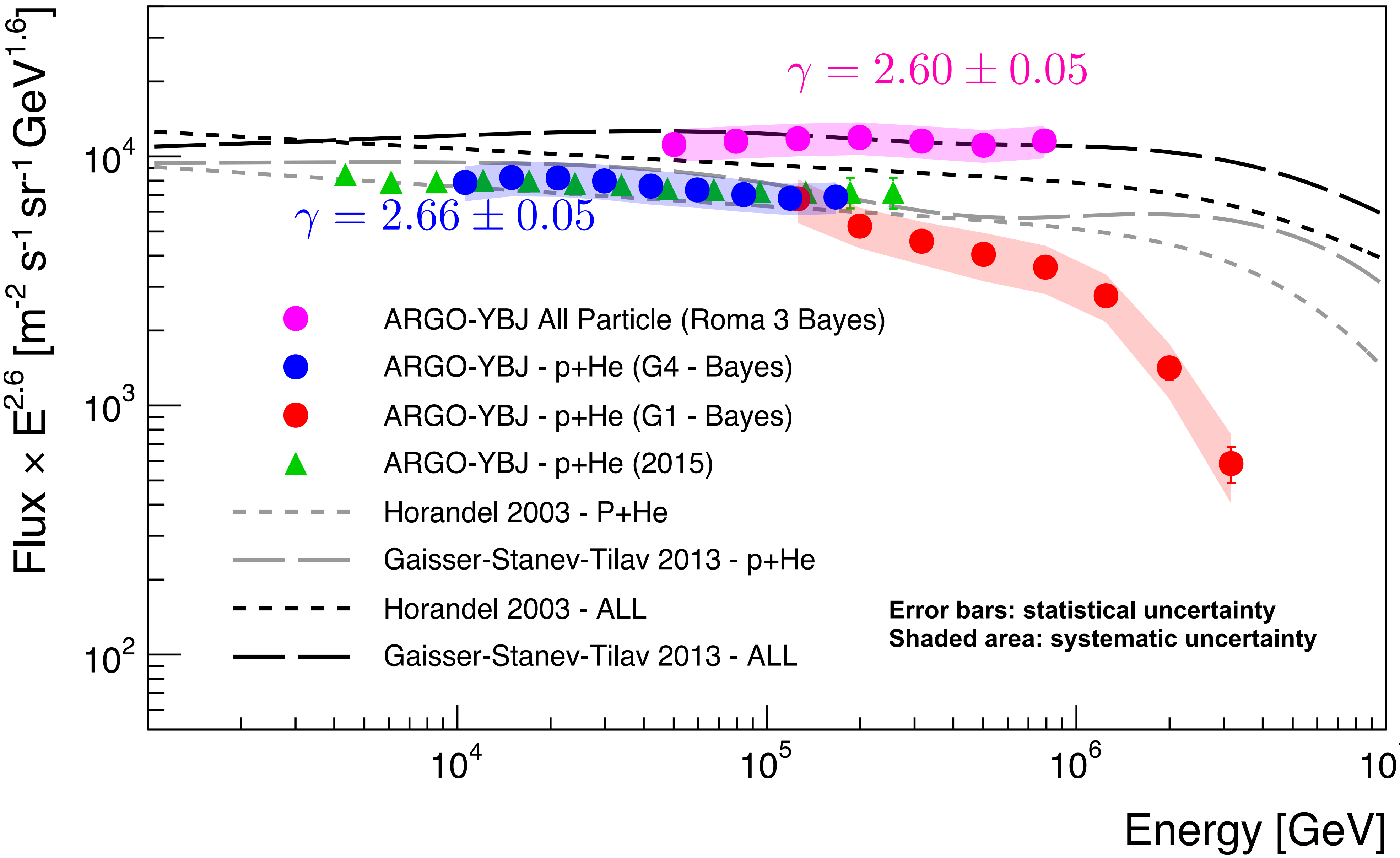
➡Systematics ~10%

➡ ~10-12% of contamination of heavy elements (mainly CNO) at the highest energies

➡ ALL-PARTICLE SPECTRUM

➡ Good agreement with other experiments

➡Systematics ~10%



Mass Independent Energy Reconstruction

The truncated size as (mass dependent) energy estimator

Np_8 (number of particles within 8m from the core):

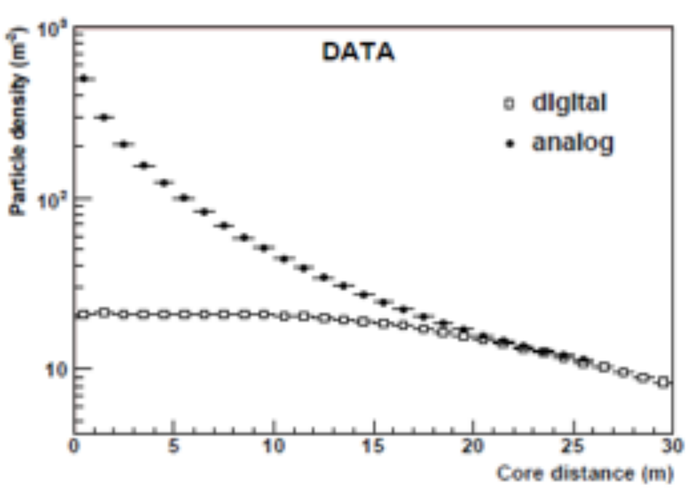
- well correlated with primary energy
- not biased by finite detector size effects
- weakly affected by shower fluctuations

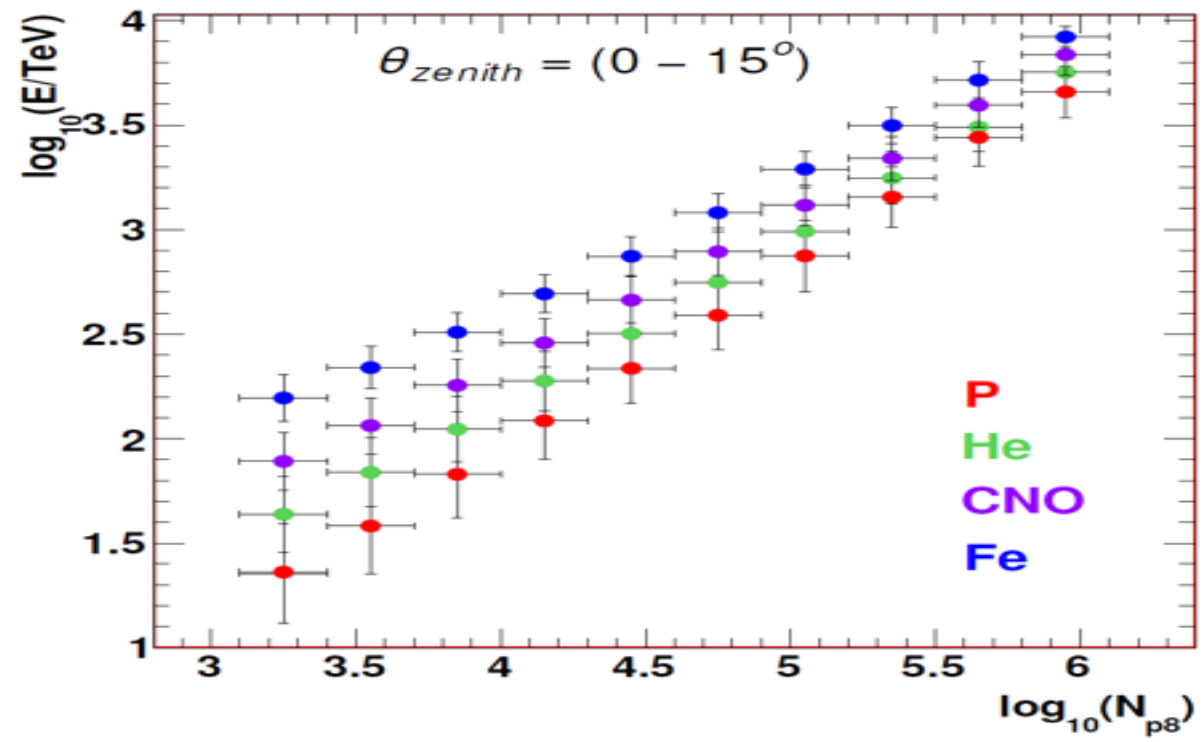
Look for information on the shower age in order to have a mass independent energy estimator.

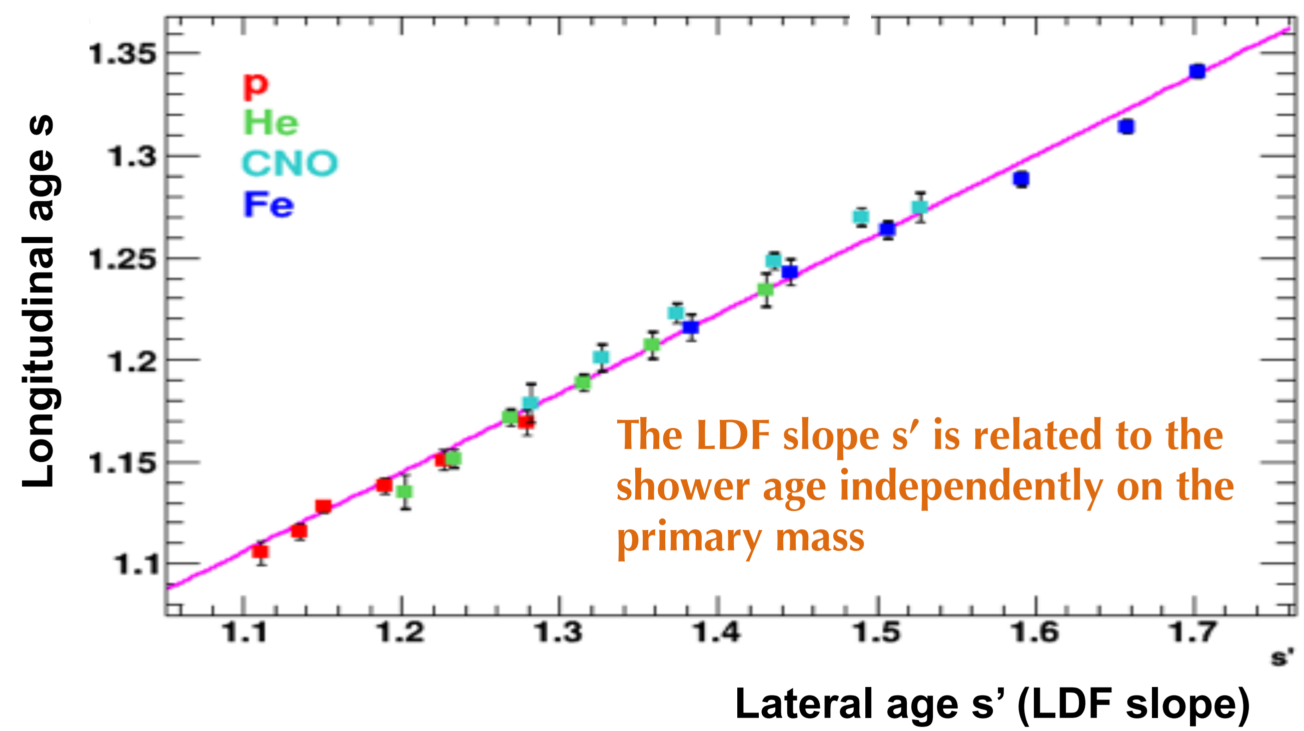
$$\rho_{NKG} = A \cdot \left(\frac{r}{r_0}\right)^{s'-2} \cdot \left(1 + \frac{r}{r_0}\right)^{s'-4.5}$$

Assume an exponential absorption after the shower maximum Get the correct signal at maximum (Np8max) by using Np8 and s' measurements for each event.

$$N_{p8}^{Max} \approx N_{p8} \cdot e^{\frac{h_0 \sec\vartheta - X_{max}(s')}{\lambda_{abs}}}$$



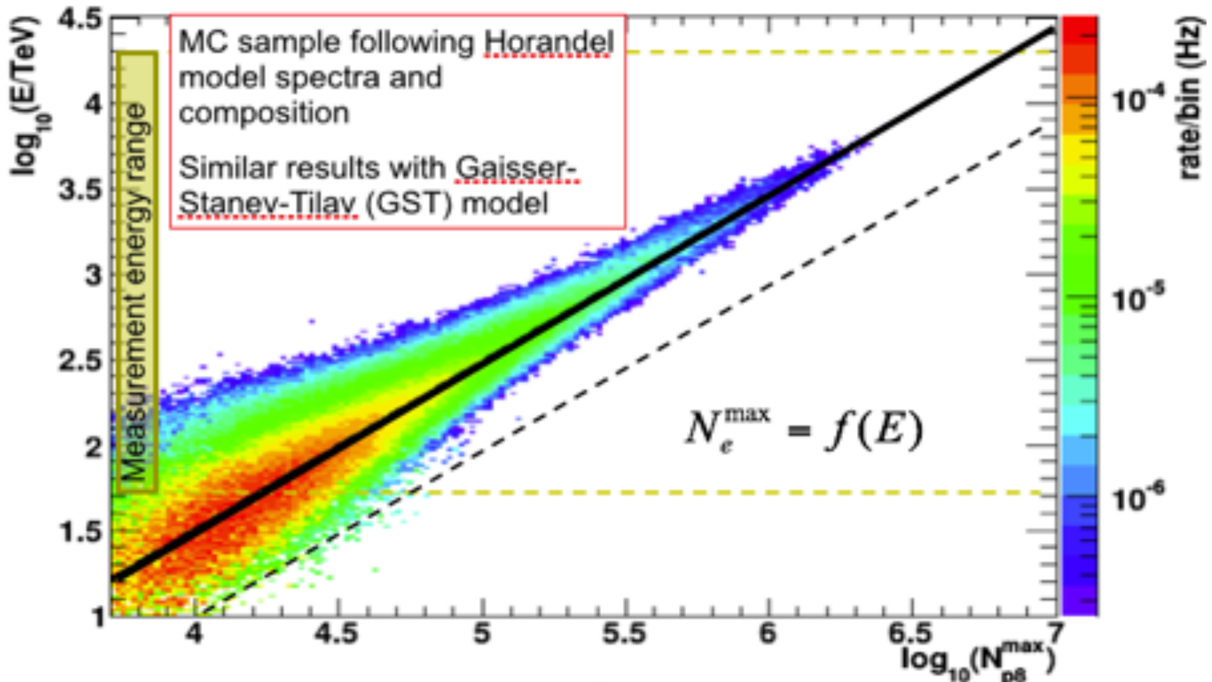


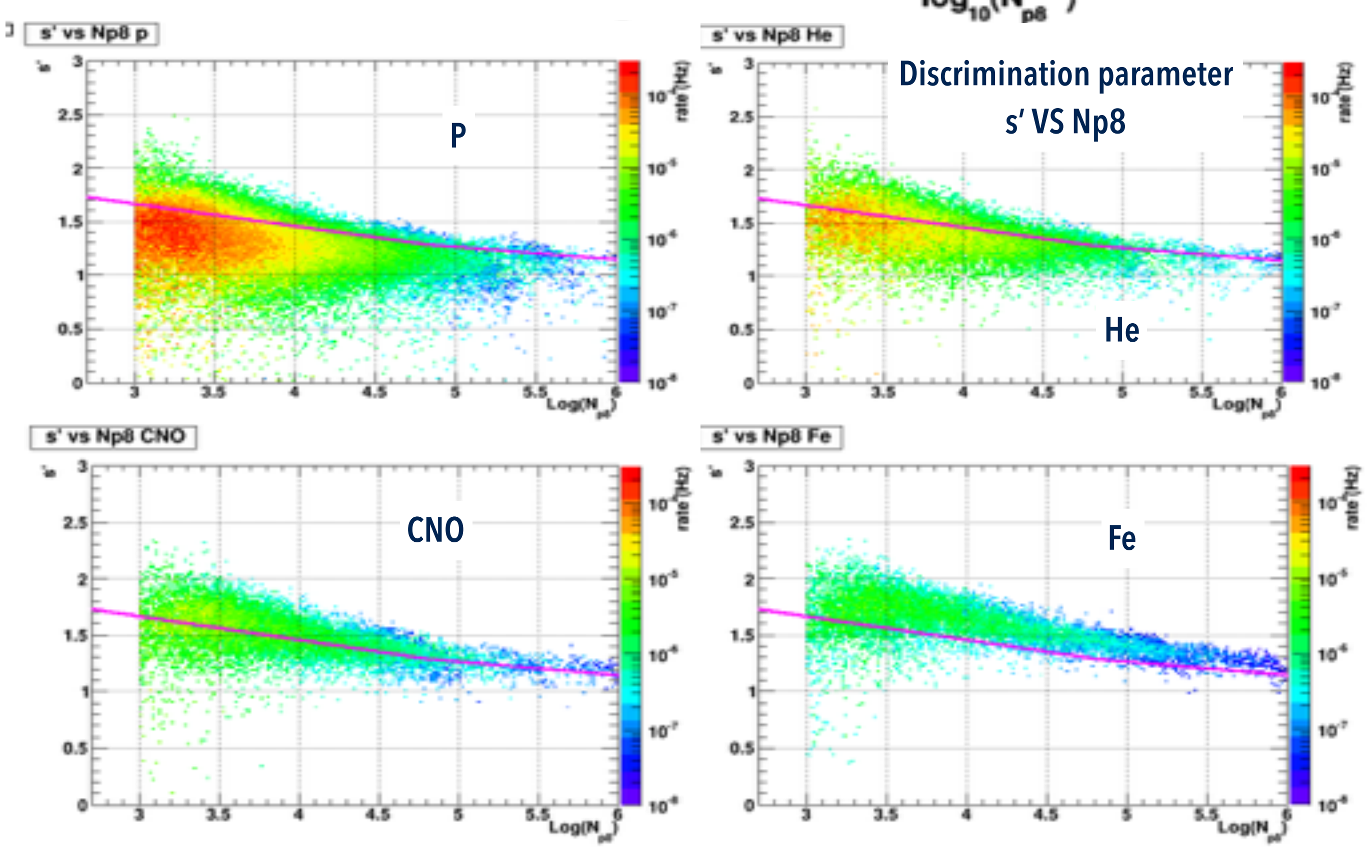


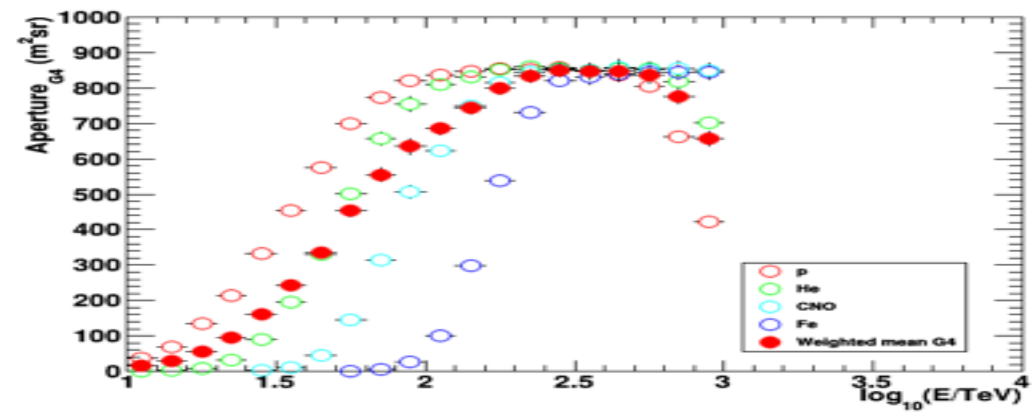
Mass Independent Energy Reconstruction

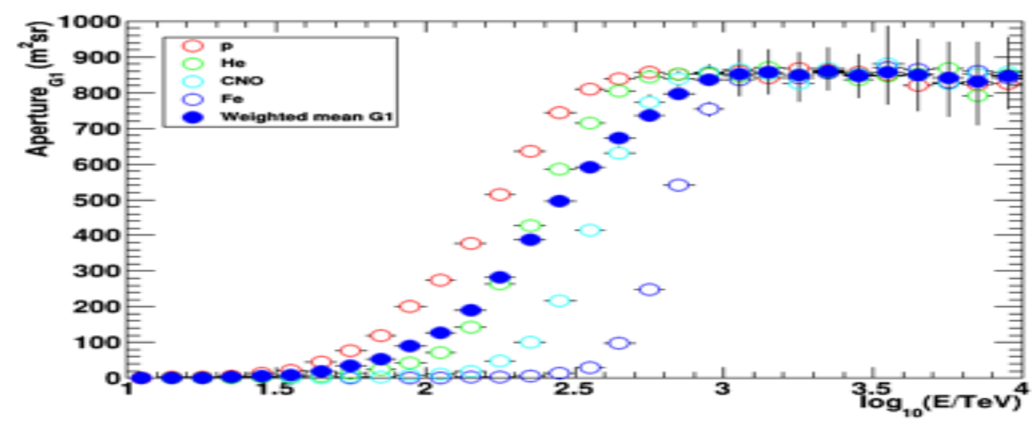
The measurement of Np8 and the (age correlated) LDF slope allows estimating the truncated size at the shower maximum.

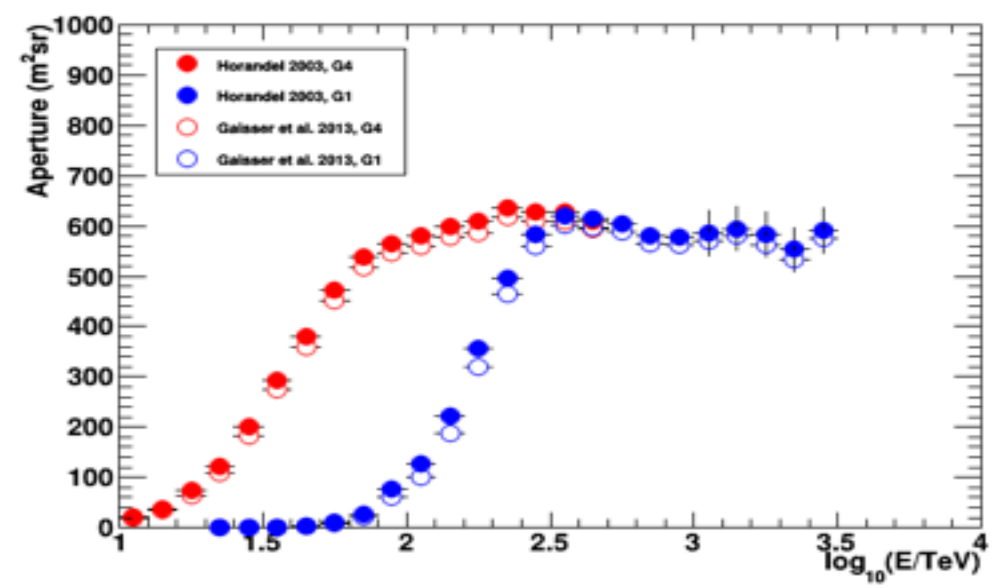
This ensures a mass independent Energy determination.







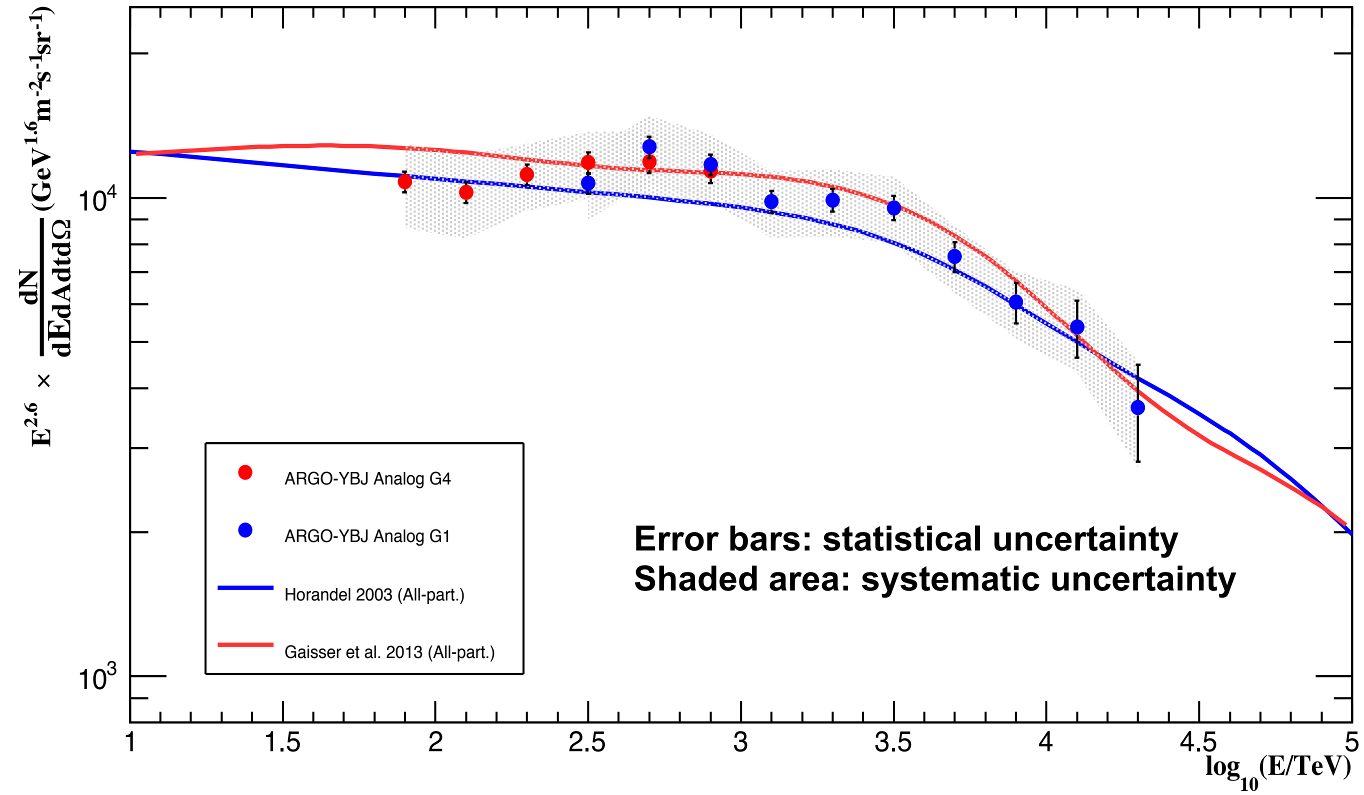




All—Particle & P+He Spectra

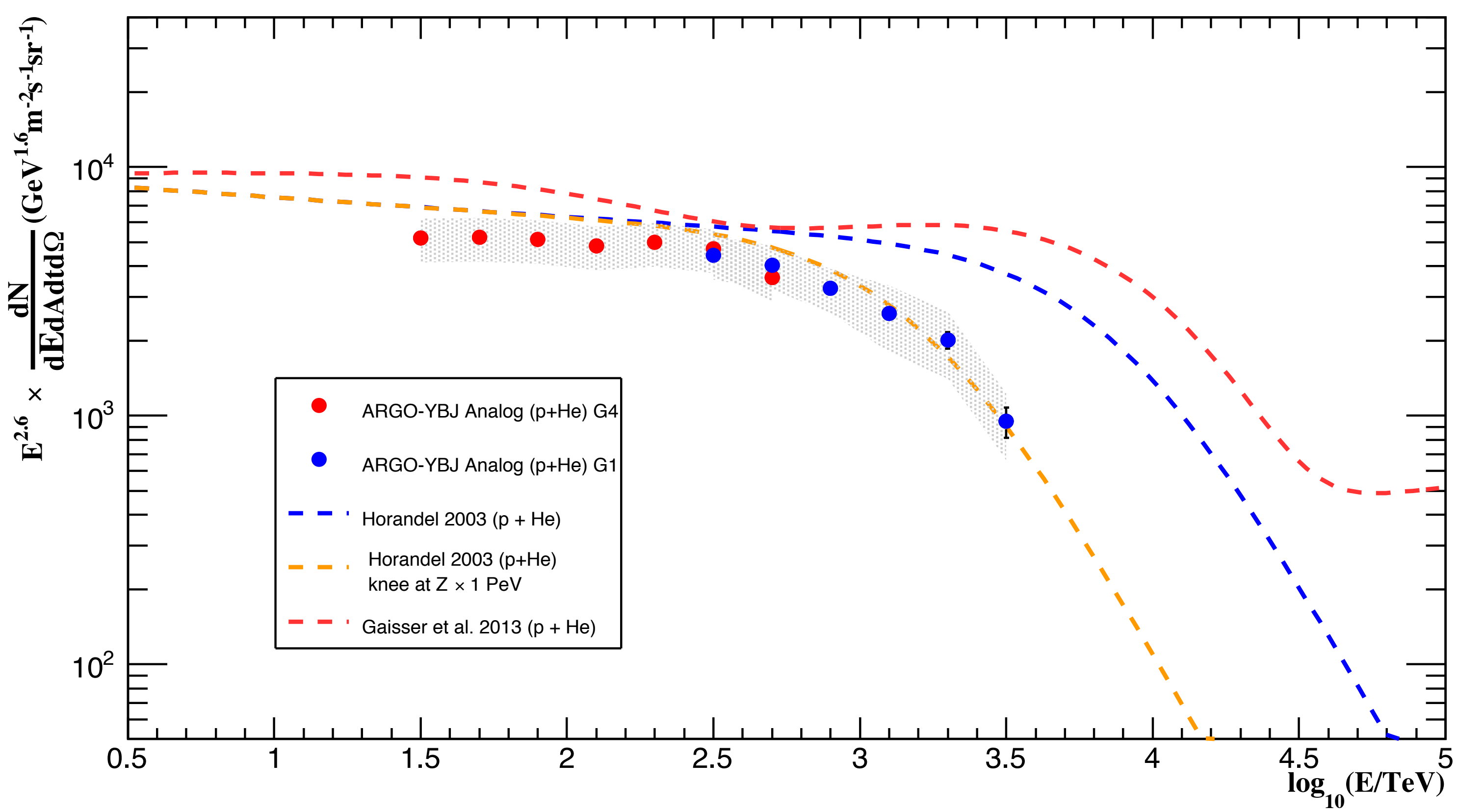
ALL-PARTICLE SPECTRUM

- Consistent picture with models and previous measurements
- Cross check with another ARGO-YBJ analysis
- Nice overlap with the two gain scales (different data set,…)
- Suggest spectral index of -2.6 below 1 PeV and smaller at larger energes



P+He SPECTRUM

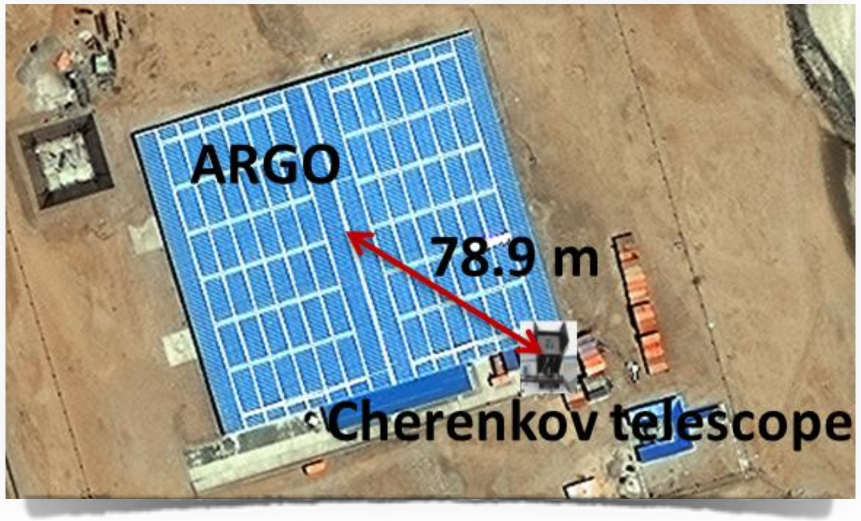
- Same considerations as for the all-particle spectrum
- Gradual change of the slope starting around 700 TeV
- Agreement with other two ARGO-YBJ independent analyses
- Overlap with direct measurements at low energy
- Flux systematics as for the all particle spectrum ⊕ < 15% mainly for the CNO contamination ➔ Overall < 20 %

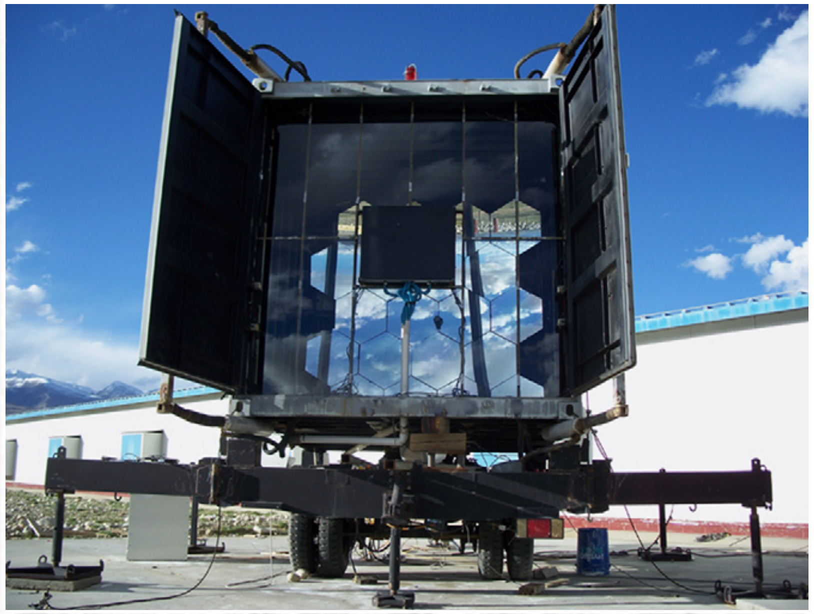


HYBRID ANALYSIS

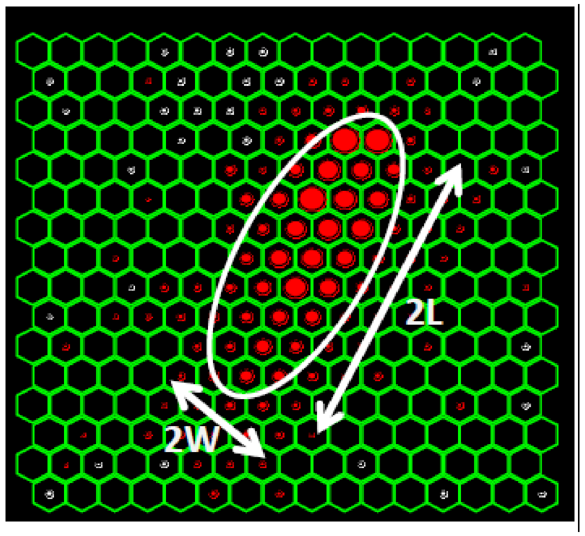
WFCTA - Wide FoV Cherenkov Telescope Array

- 5 m^2 spherical mirror
- 16 X 16 PMT Array
- Pixel size 1°
- FOV: 14°X16°
- Elevation angle: 60°

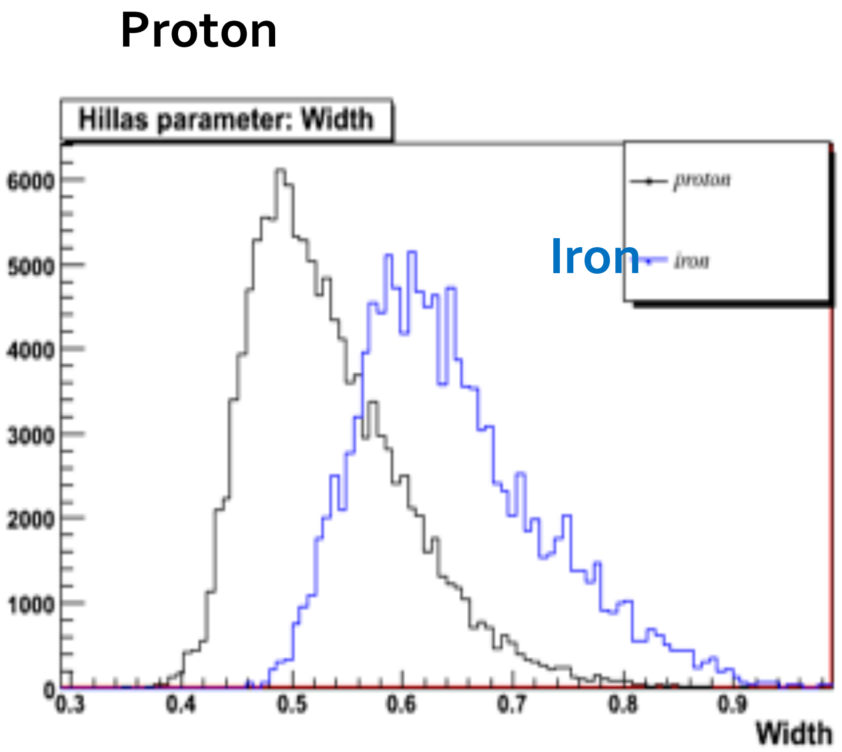




Energy measurement obtained by using the shower geometry reconstructed by ARGO–YBJ and the Cherenkov signal



- ARGO–YBJ: N_{Max} – Lateral distribution
- WFCTA: Longitudinal distribution → Hillas parameters (composition sensitive)



- From 2010.12 ~ 2012.02: Coincidence events;
- Good weather selection: 7.28×10^5 sec.

Hybrid Analysis

N_0^{pe} is the total number of photo-electrons normalized to $R_p = 0$ and $\alpha=0°$

R_p: the impact parameter;

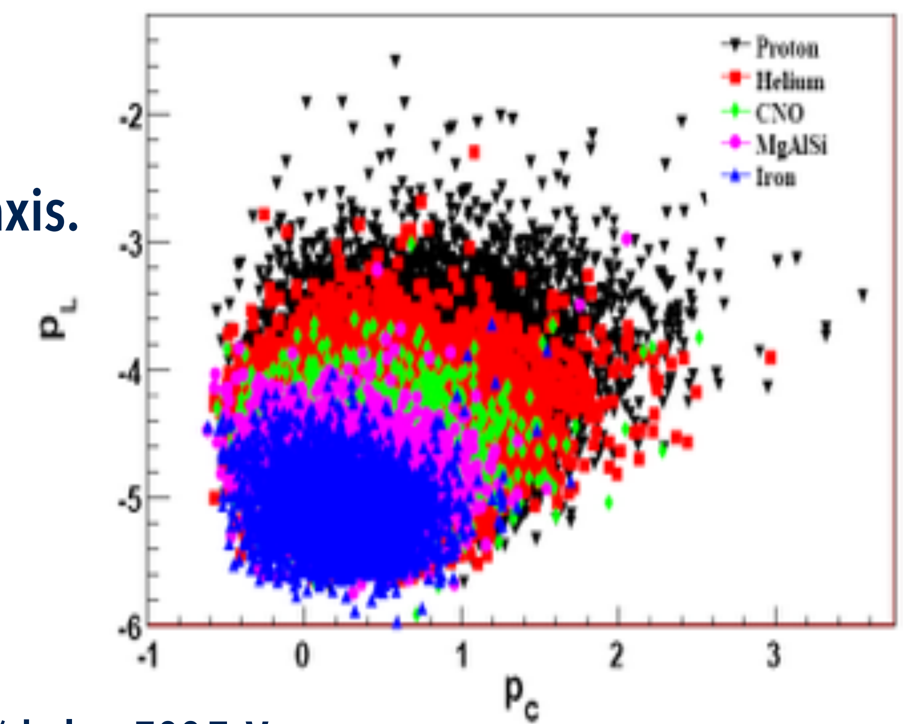
α: the space angle between shower direction and Cherenkov telescope main axis.

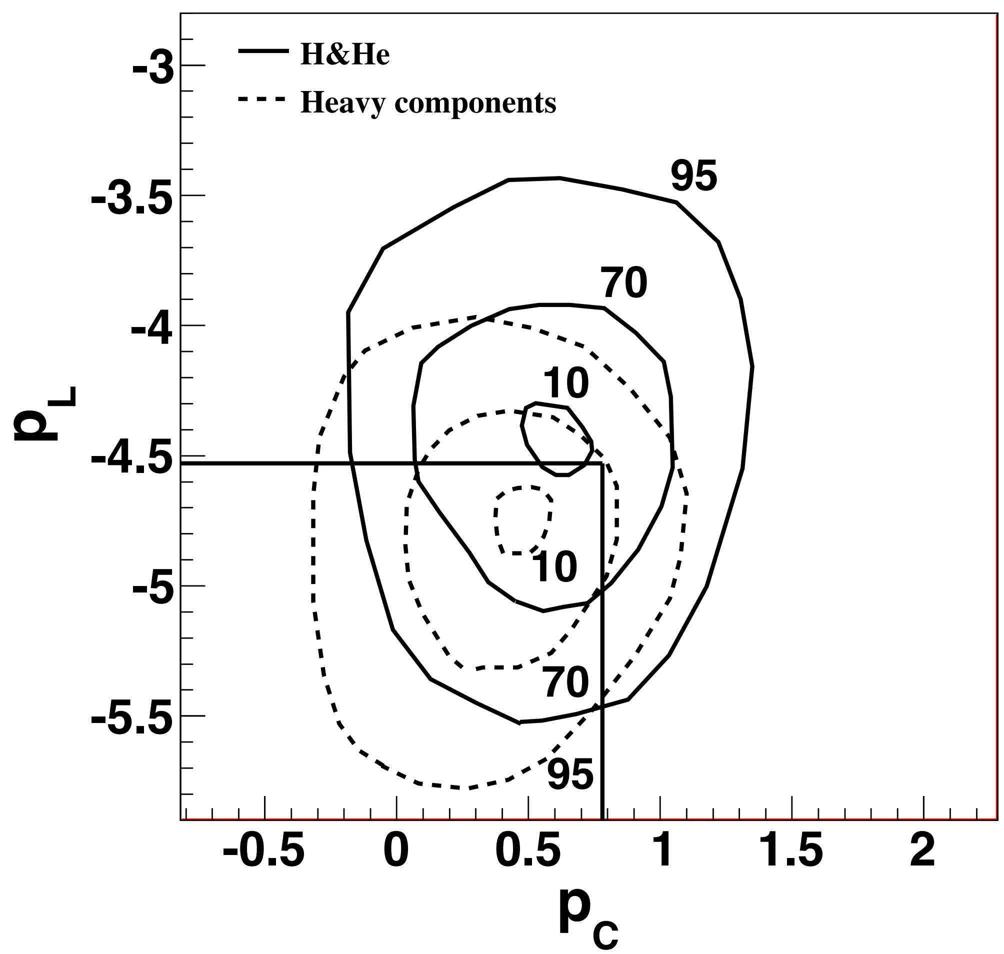
$$p_c = L/W - R_p/109.9\mathrm{m} - 0.1\log_{10} N_0^{pe}$$

$$p_L = \log_{10} N_{max} - 1.44\log_{10} N_0^{pe}$$

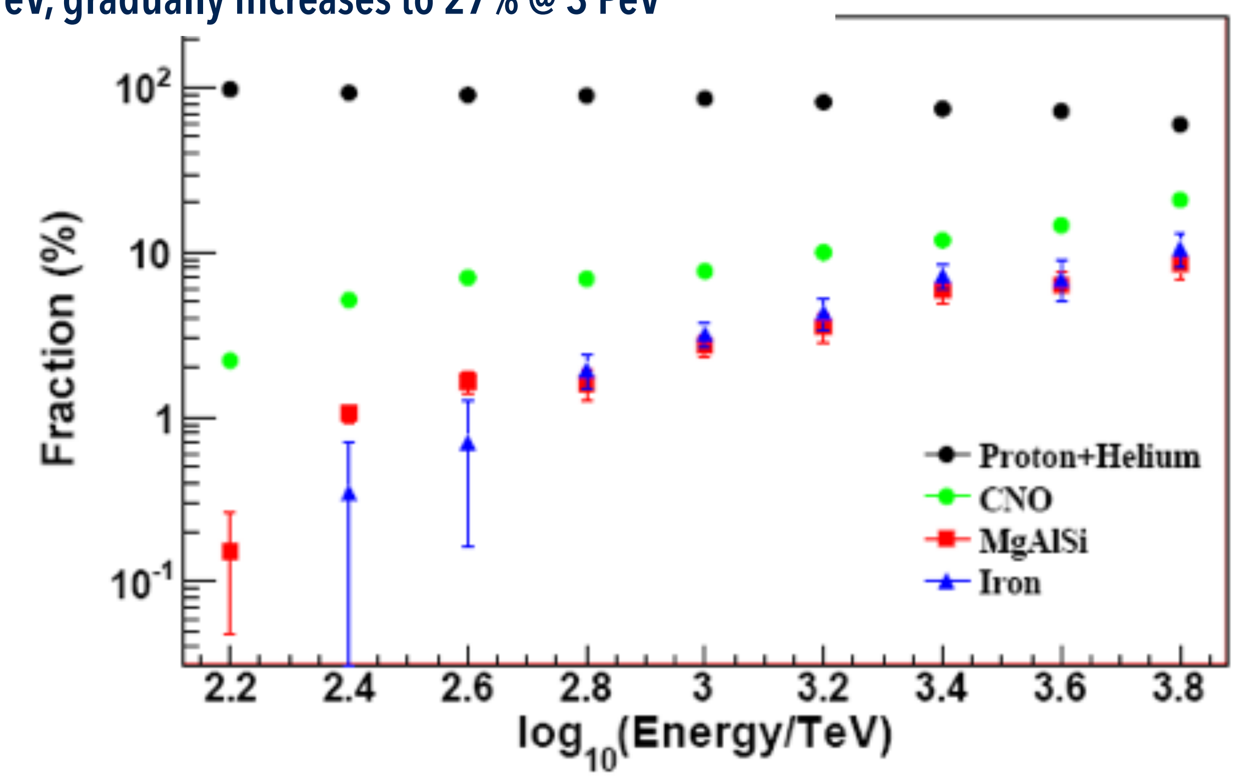
H&He selection criteria : $p_L>-4.53$ & $p_C>0.78$

Energy reconstruction based on $\sum N_{pe}$ in the Cerenkov image





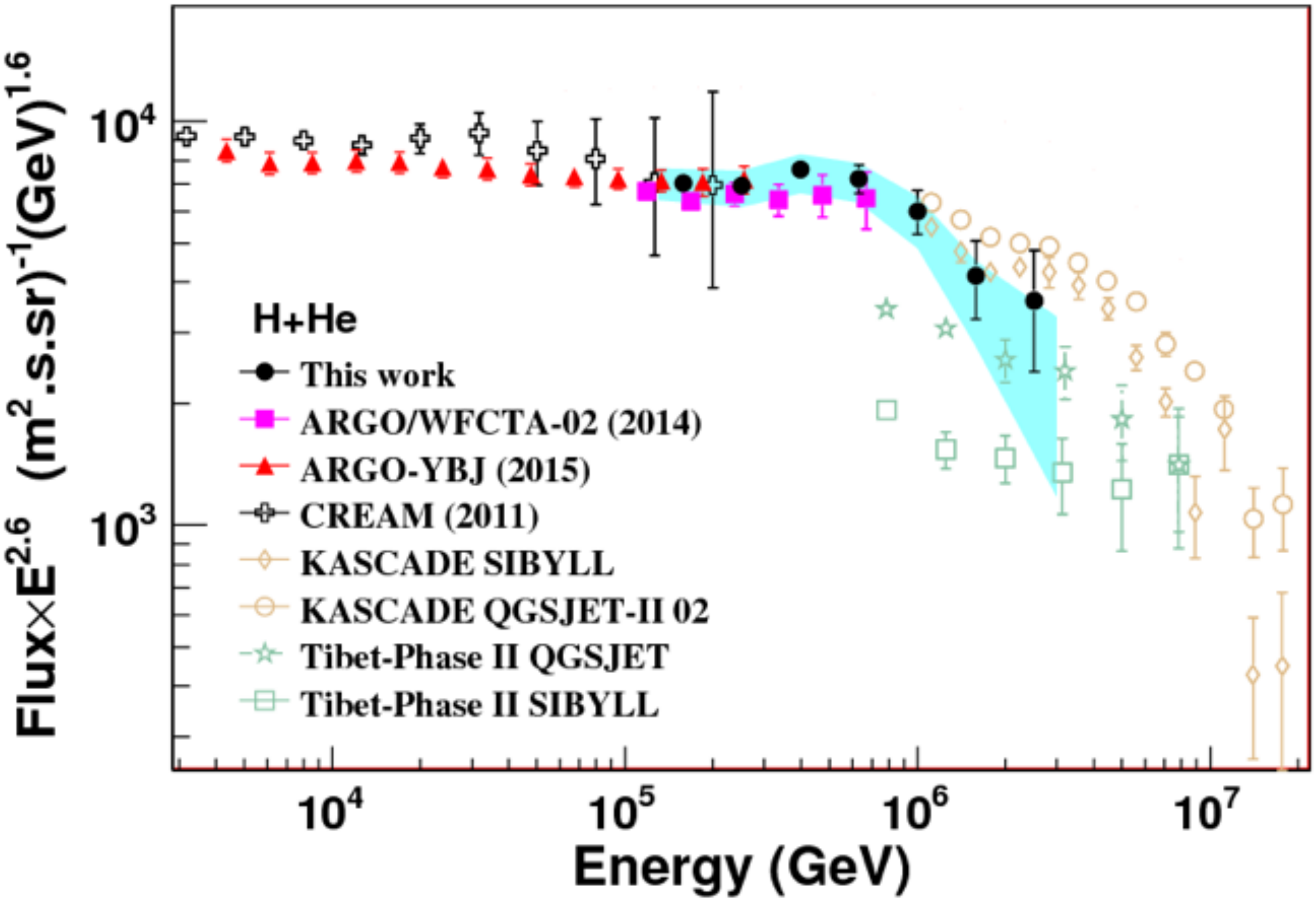
- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV



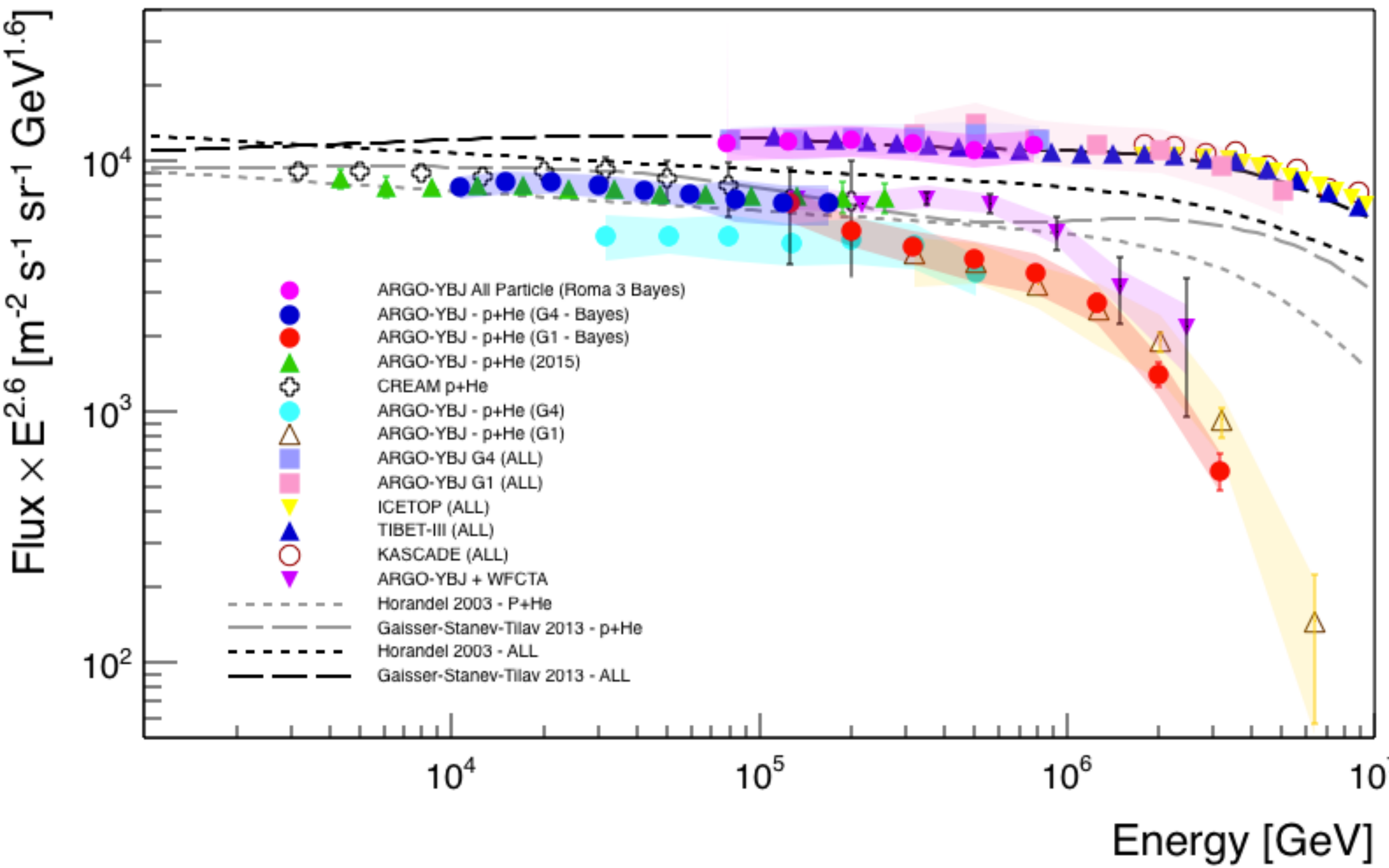
THE P+HE SPECTRUM

100-2500 TeV energy range

- The knee of H&He spectrum at (700±230) TeV is clearly measured
- Broken power law fits data well with indices
- -2.56 ± 0.05 and -3.24 ± 0.36 below and above the knee
- Consistent with other two independent analyses



P+He & All-Particle: The Overall Picture



Conclusions

- Cosmic Ray Anisotropy
    - Large scale anisotropy: 2 harmonic profile - agreement with other experiments
    - Measurement of the medium scale anisotropy
    - First attempt of measuring the anisotropy of light elements

- P+He spectrum in the energy range 3-300 TeV
    - Analysis of ~5 years of digital readout data
    - Excellent detector stabilty over a long period

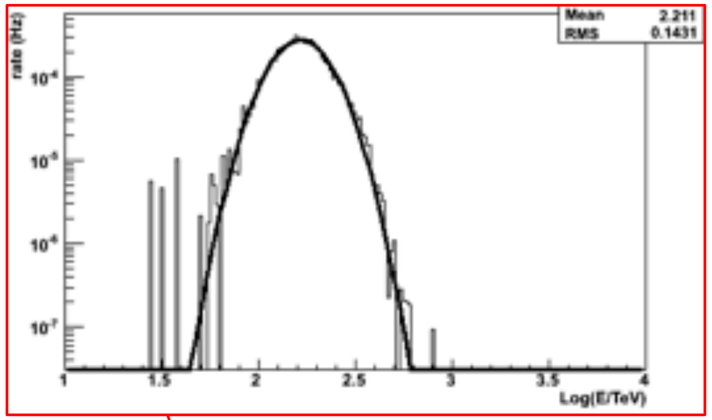
- P+He spectrum by using the analog readout data
    - 10-100 TeV energy range
        - Good agreement with the digital analysis
    - 100-3000 TeV energy range
        - Evidence of a gradual change of the spectral index at energies around 700 TeV
        - Good agreement with two other independent analysis within systematic errors

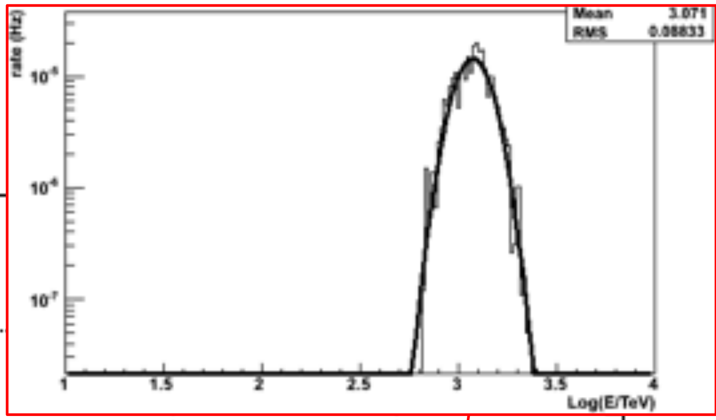
- All–particle spectrum in the energy range 40–800 TeV
    - Good agreement with other experiments

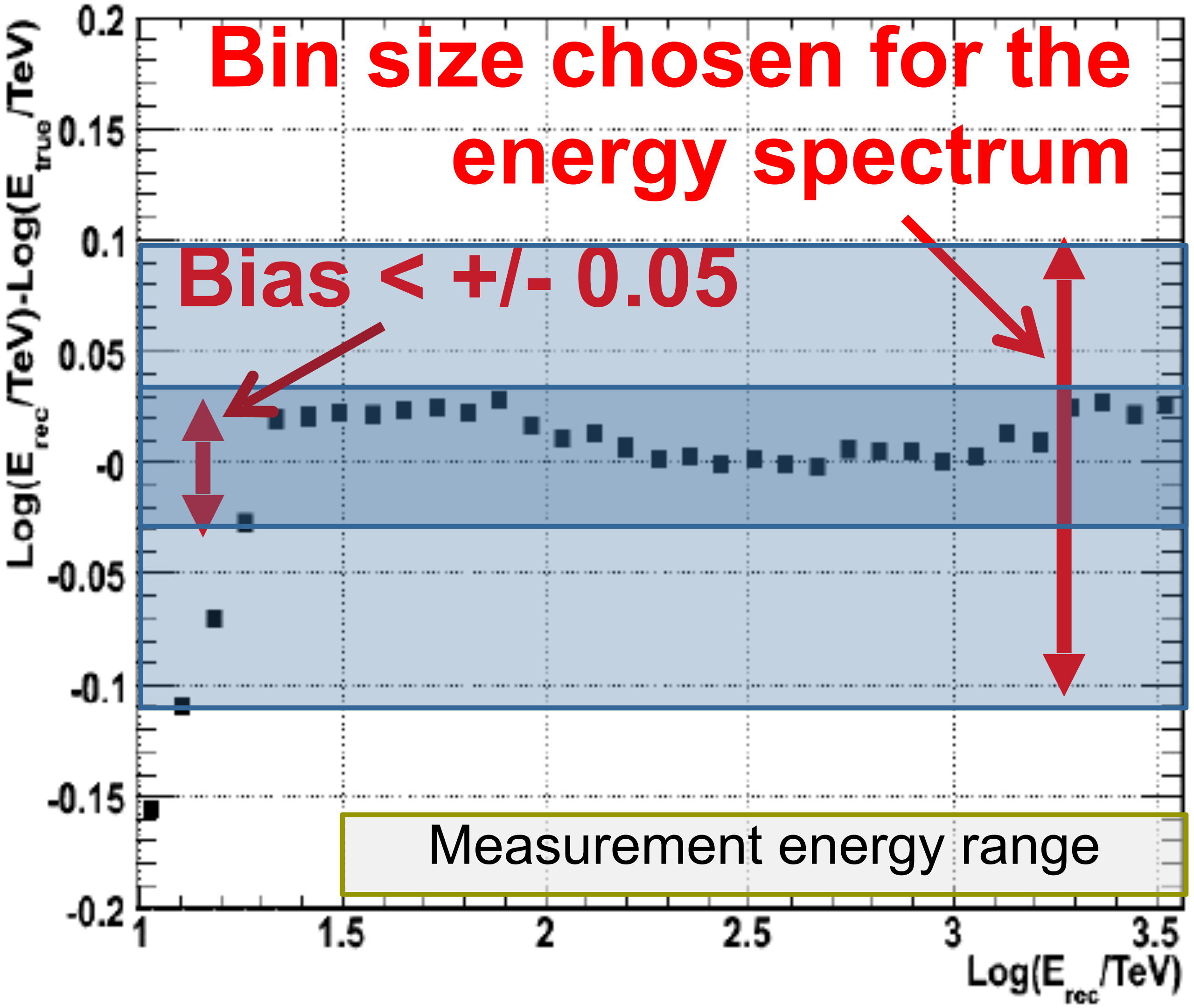
More Stuff

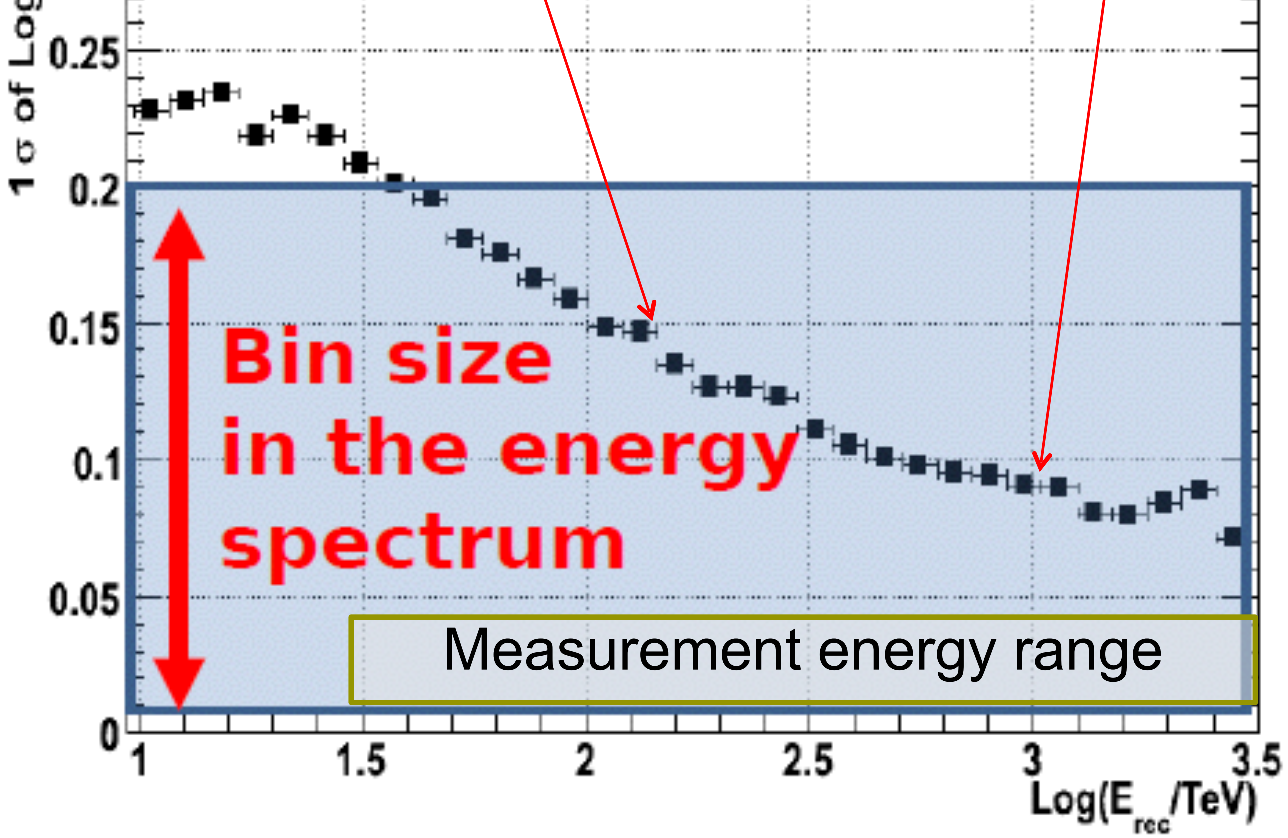
Energy reconstruction: bias and resolution

The response function is gaussian in LogE.
The spectra are then given in LogE bins, much larger than the estimated bias and well above the LogE resolution, in the considered energy range.



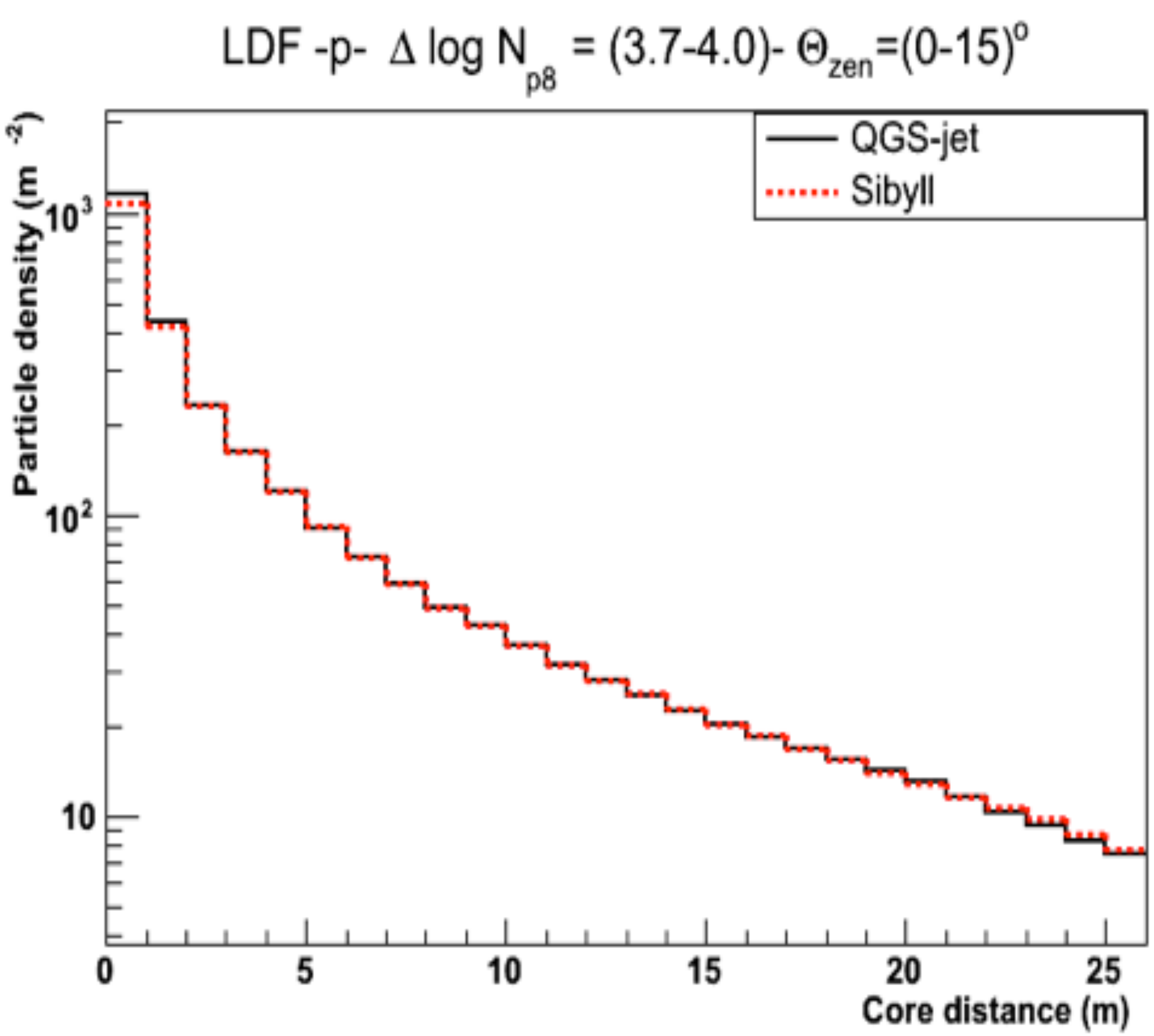


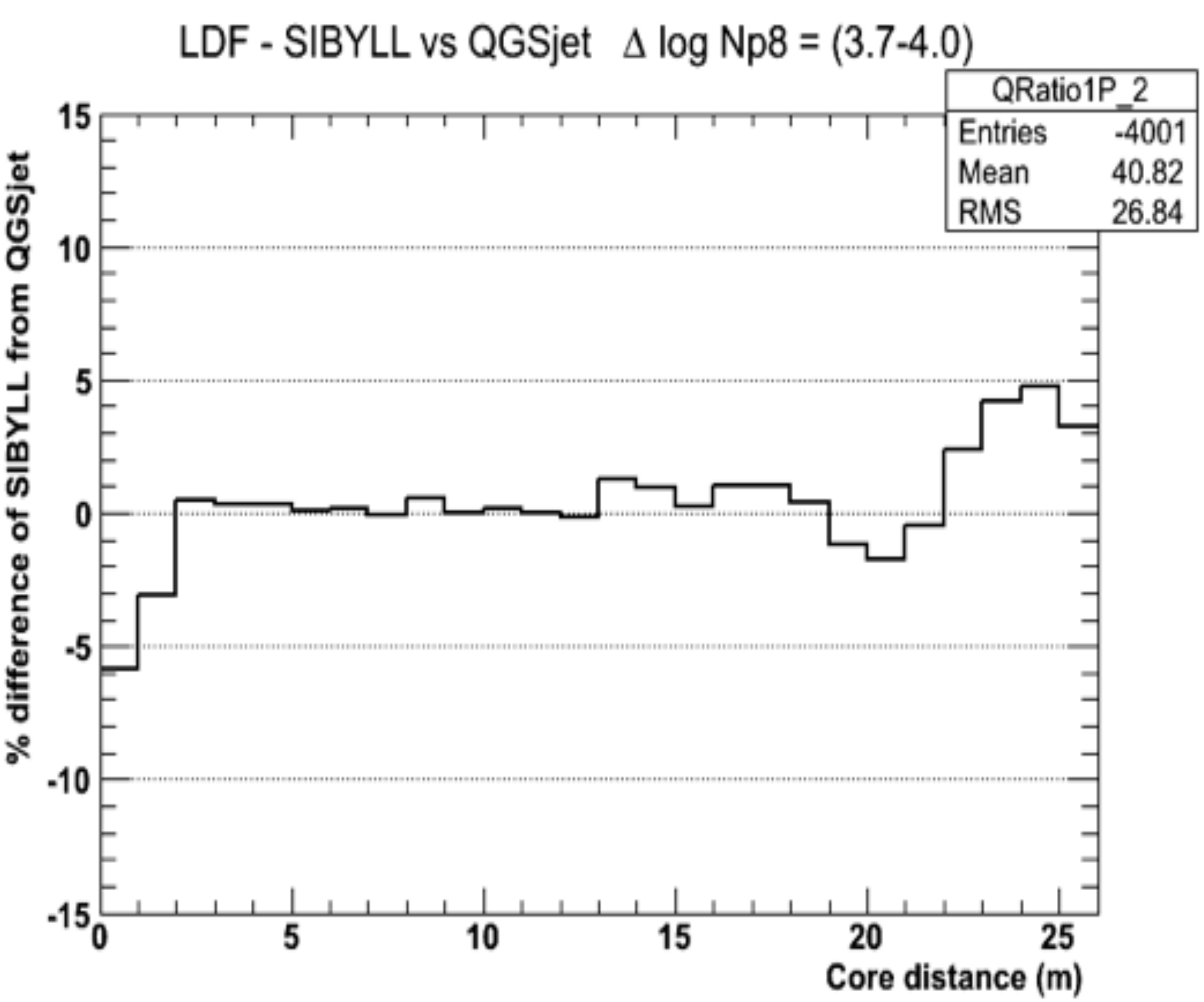




Systematics from the hadronic interaction models

The dependence on the adopted hadronic interaction model is small.
The differences among the QGSJET-II.03 and Sibyll-2.1 are within few percent in the explored energy range (no bias due to muon number).
All further results shown here were obtained with QGSJET-II.03.



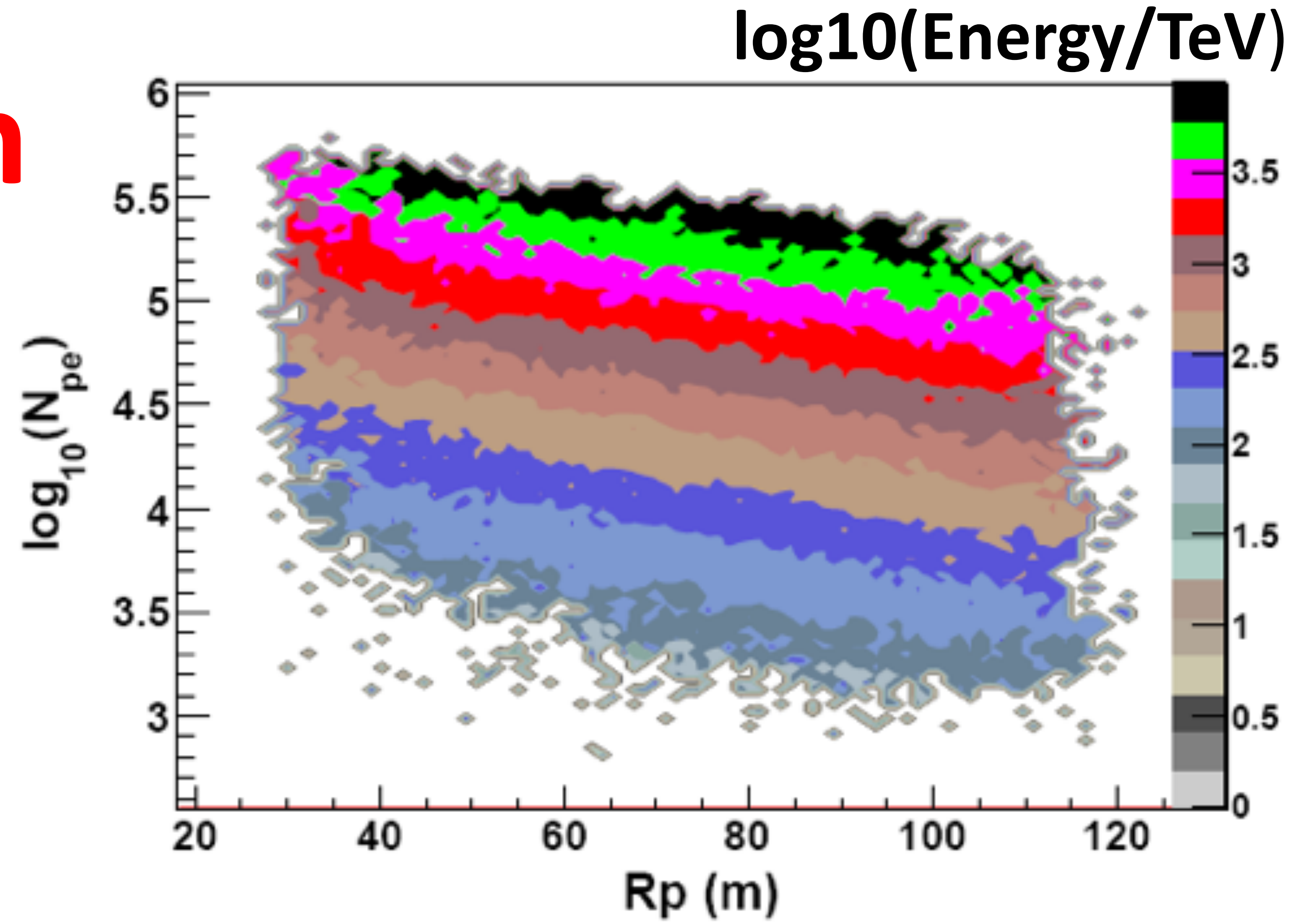


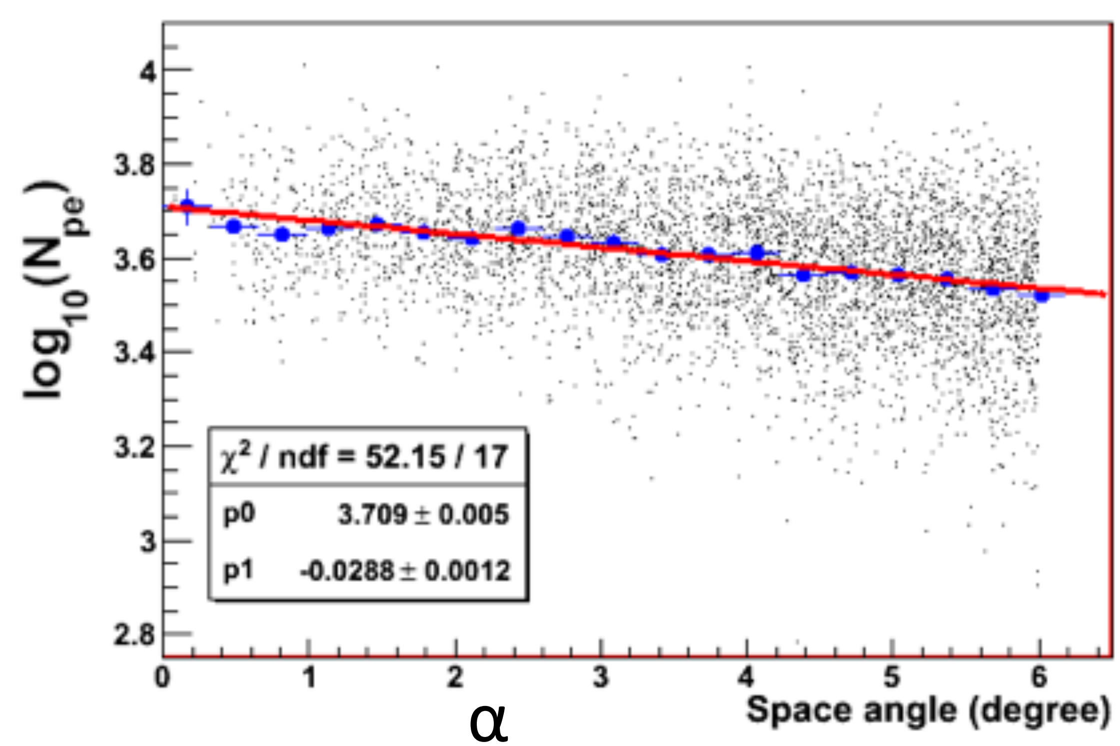
Energy reconstruction

Using $\sum N_{pe}$ in Cherenkov image

➢ **Look-up table:**
light component only

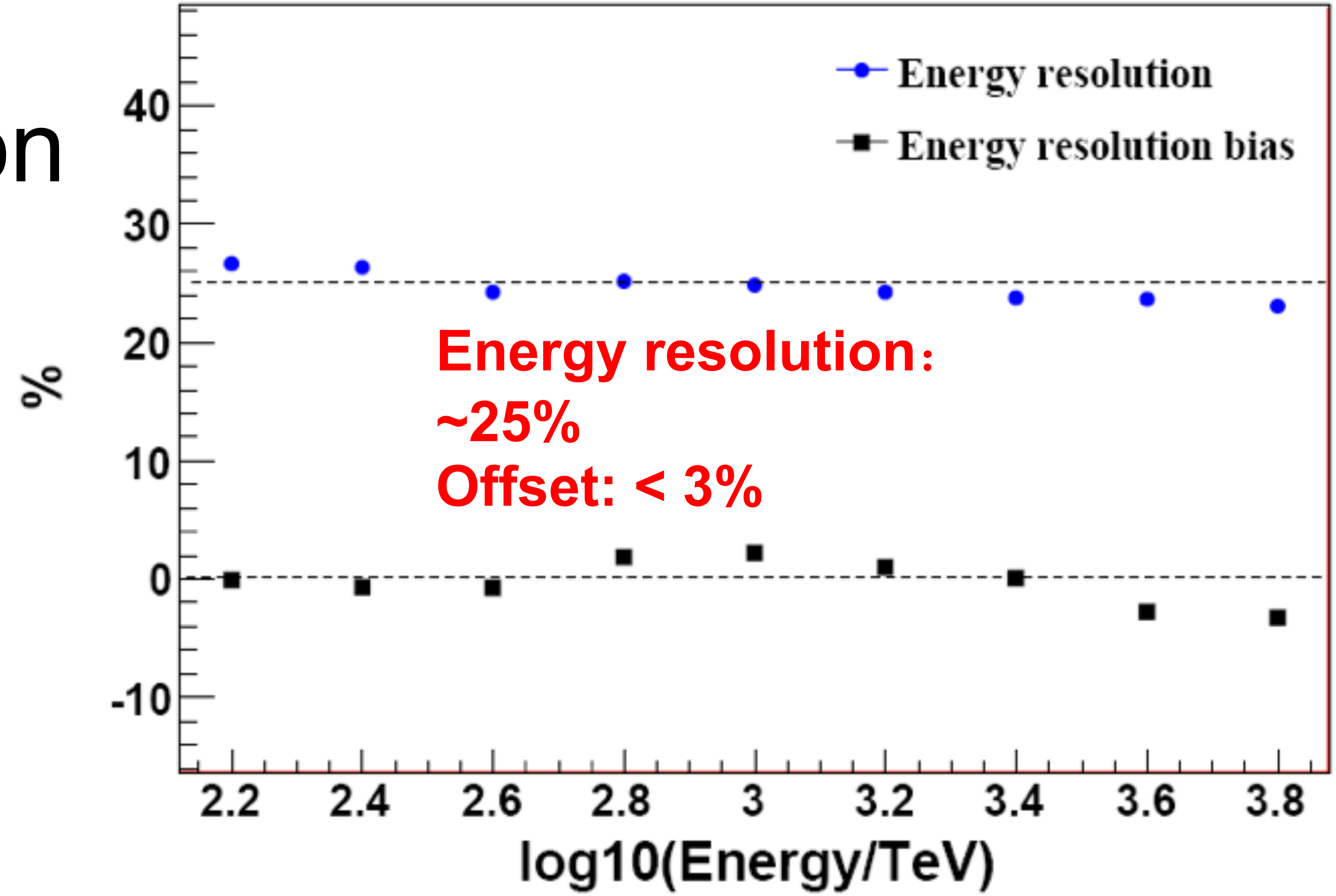
- Impact parameter (R_p): 5m/bin
- Log(total N_{pe}) bin: 0.1/bin
- R_p bin： linear interpolation
- α bin: linear interpolation
- Total N_{pe} bin： quadratic curve interpolation

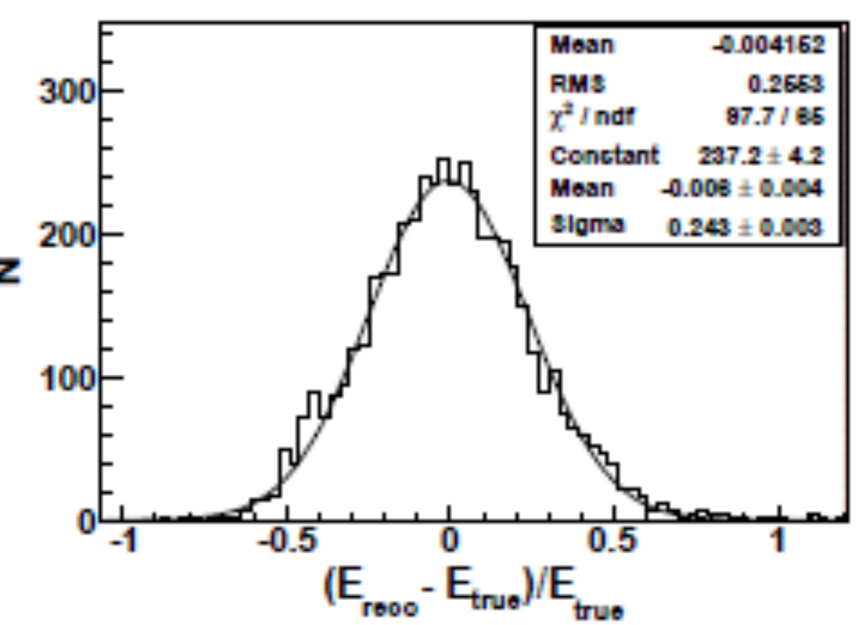




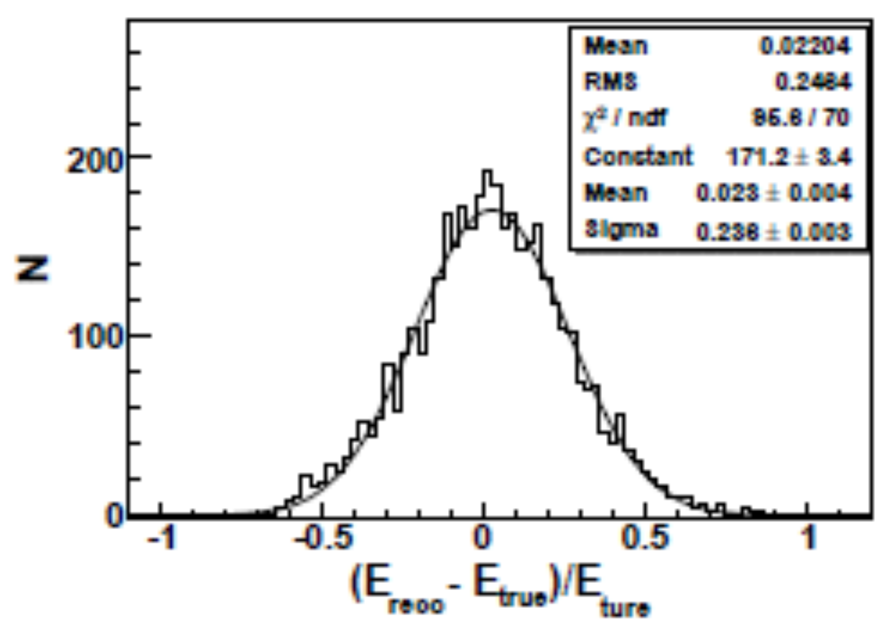
E-reconstruction

- Systematic bias: <3%
- Constant resolution: 25%
- Gaussian

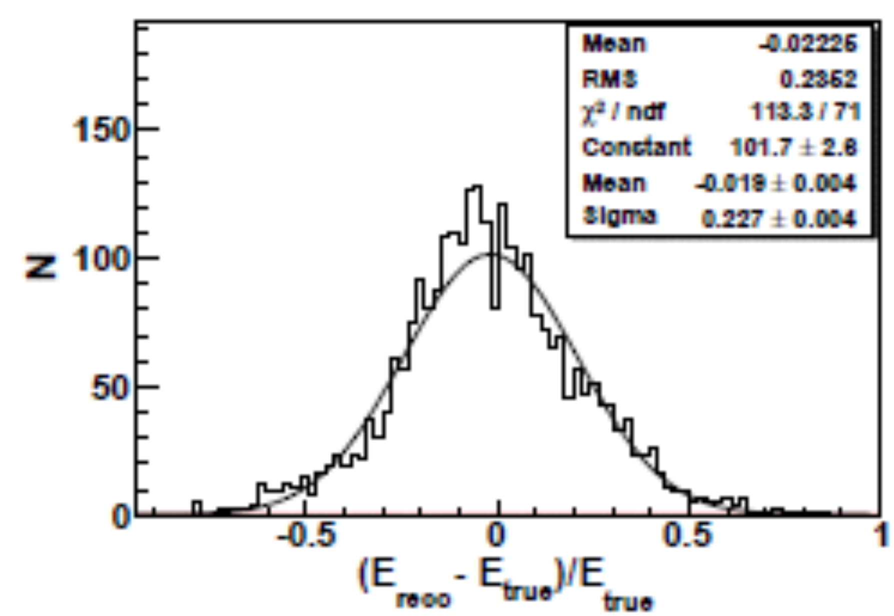




300 TeV



1 PeV

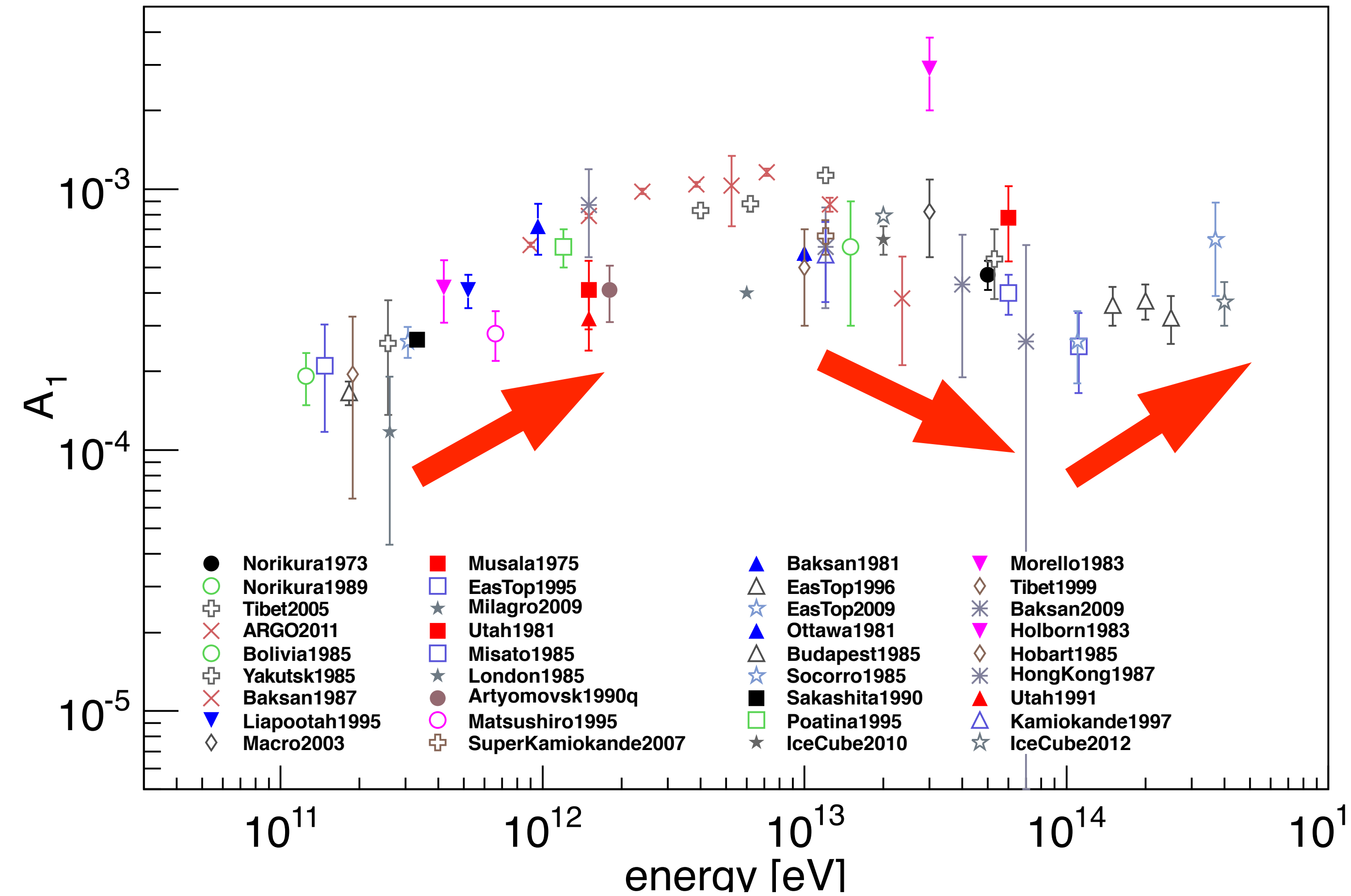


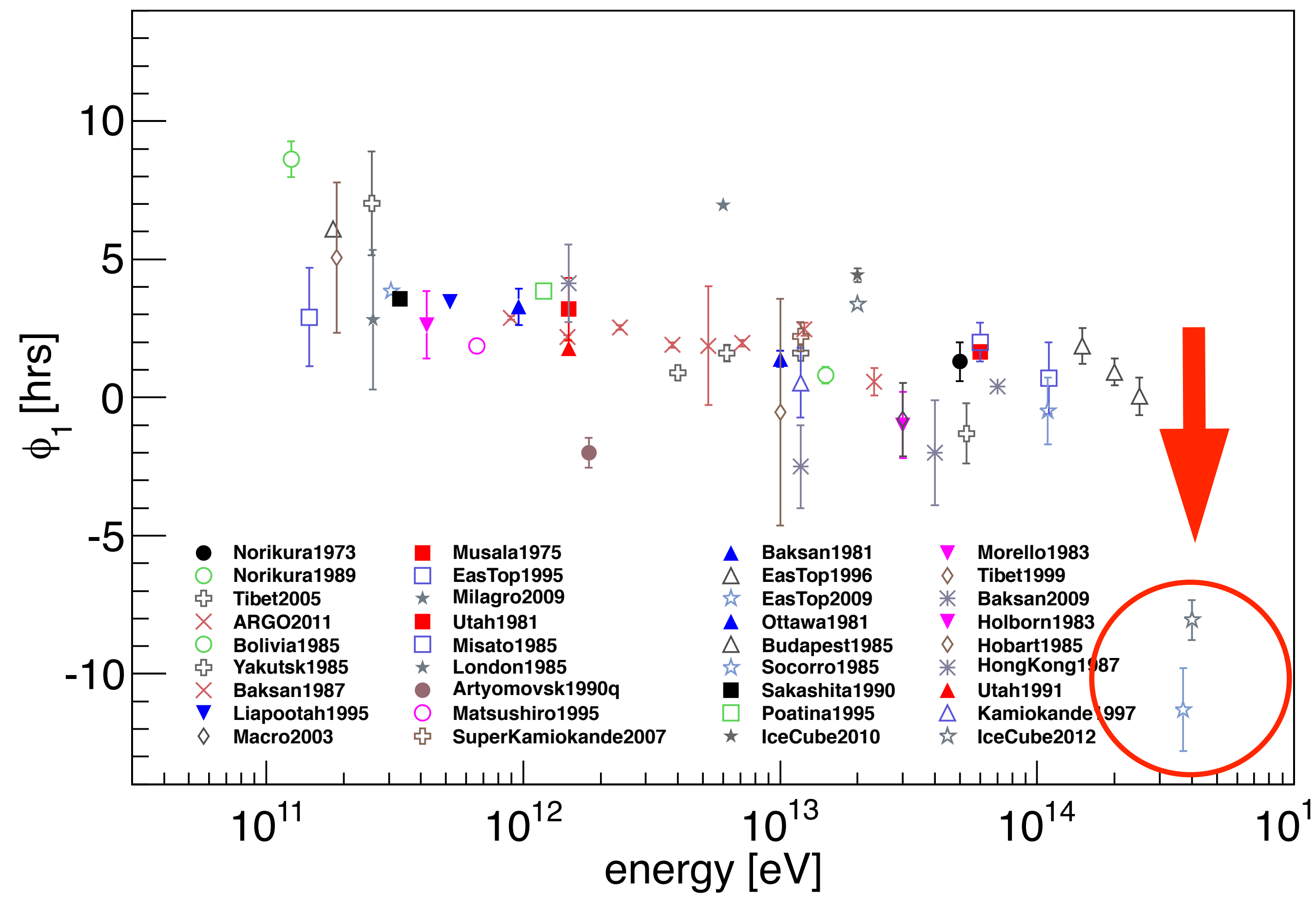
3 PeV

Amplitude and Phase of the first harmonic

dipole component as a tracer of the CR source distribution

- Consistency between different sets of data up to PeV.
- Extremely small amplitude: 10^{-4} — 10^{-3}
- Slow increase of A_1 with increasing energy to a maximum around 10 TeV.
- Slow fall of A_1 to a minimum at about 100 TeV.
- Evidence of increasing A above 100 TeV.
- Phase nearly constant (slowly decreasing) around 0 hrs.
- Dramatic change (decrease) of phase above 100 TeV.



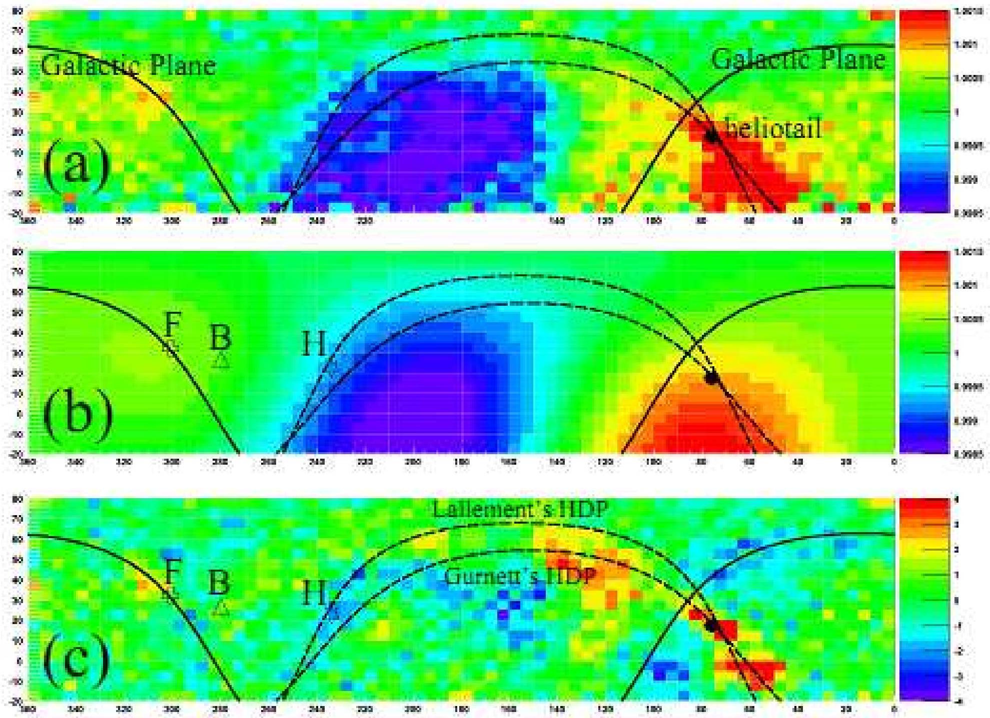


G. Di Sciascio and R. Iuppa, arXiv:1407.2144

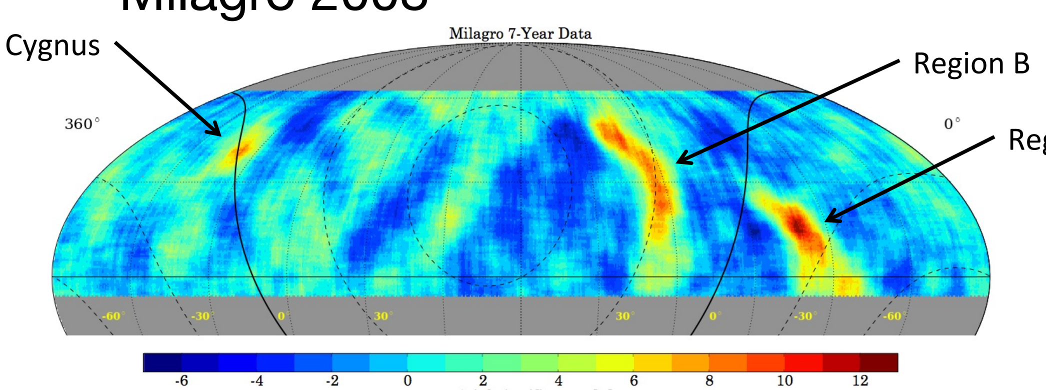
Medium Scale Anisotropy

CR anisotropy is **not a dipole**

Tibet ASγ 2007

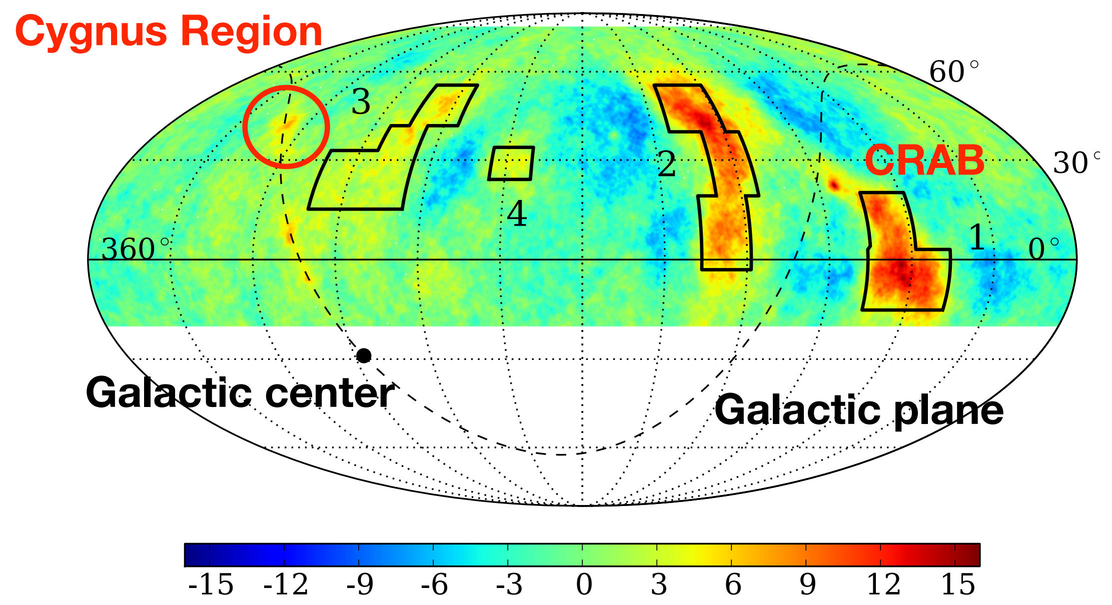


Milagro 2008

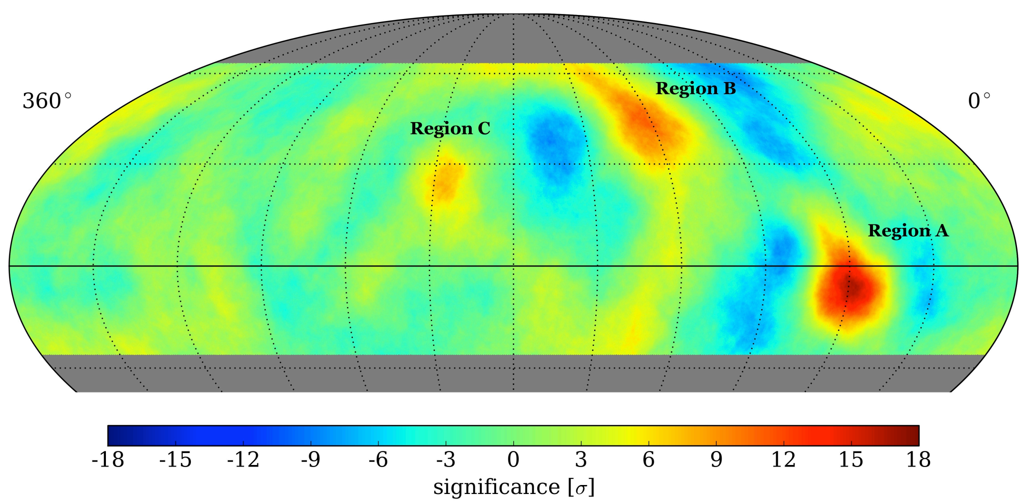


A. Abdo et al., PRL **101**:221101, 2008

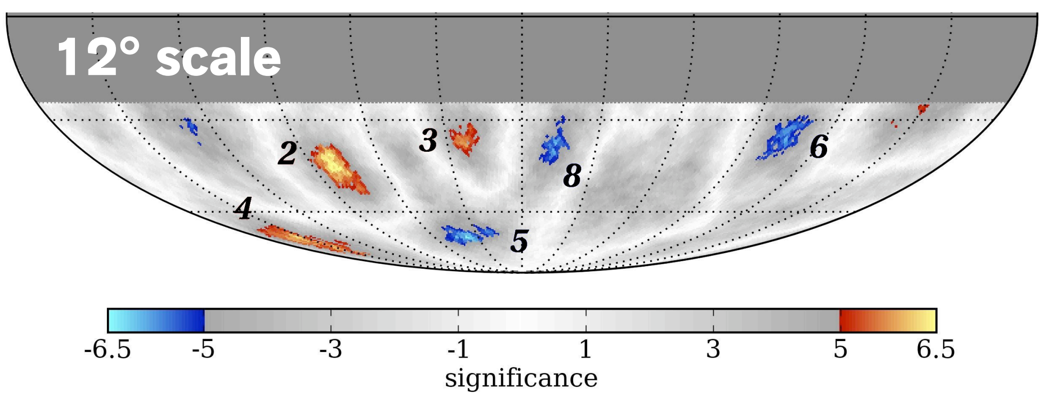
ARGO-YBJ



HAWC



IceCube

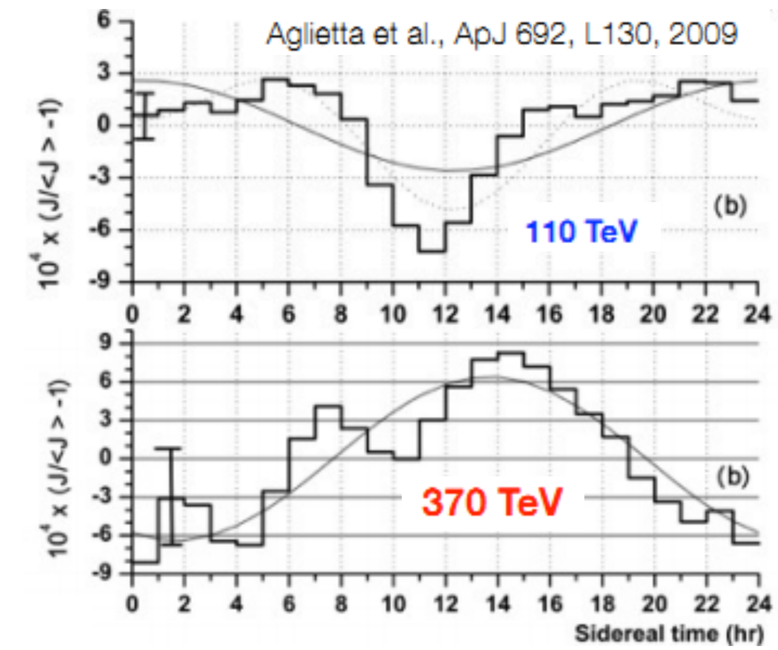


IceCube: large scale anisotropy

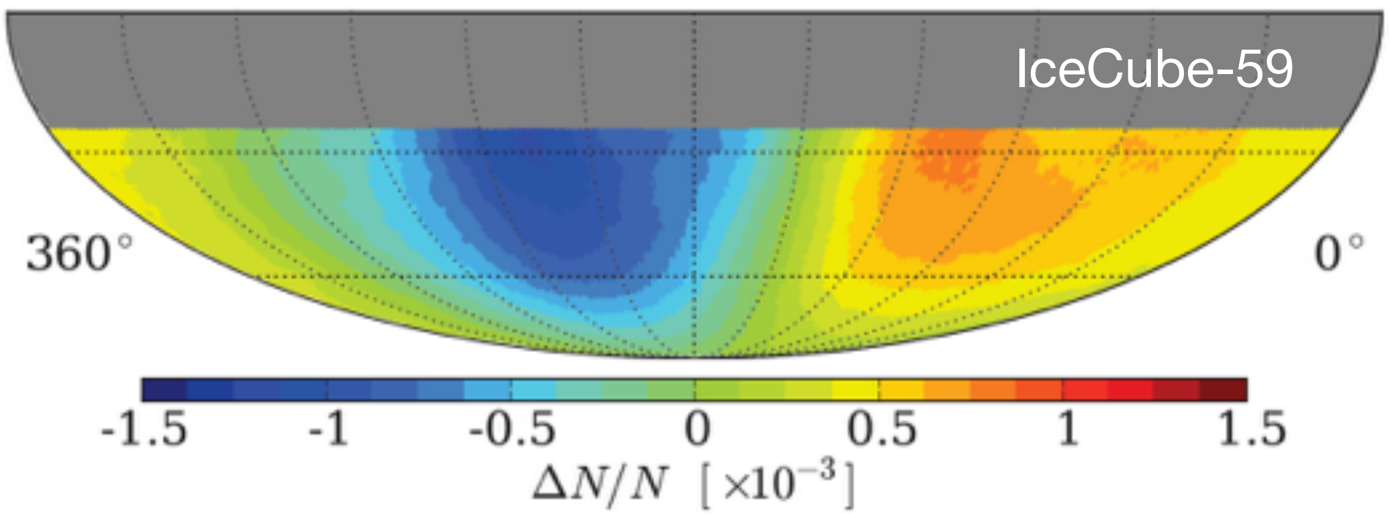
NOTE: anisotropy is not a dipole !

topology changes above ≈ 100 TeV

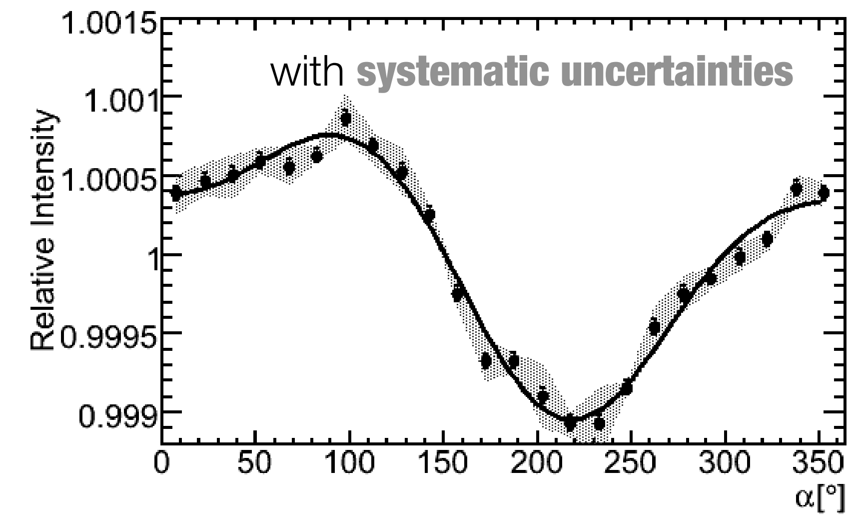
EAS-TOP

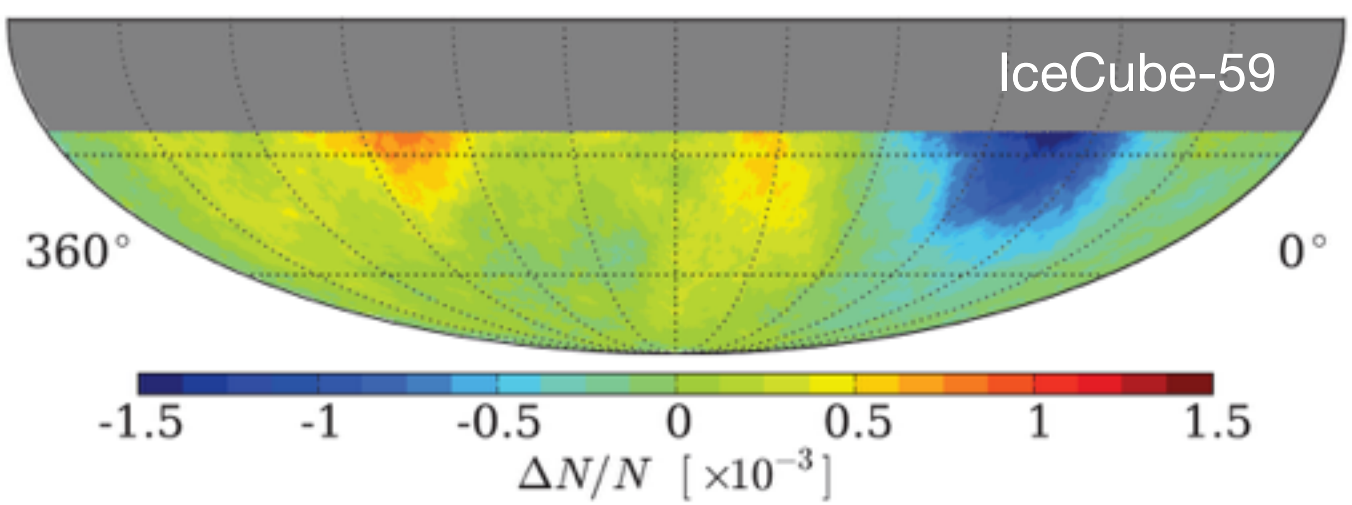


relative intensity equatorial coordinates



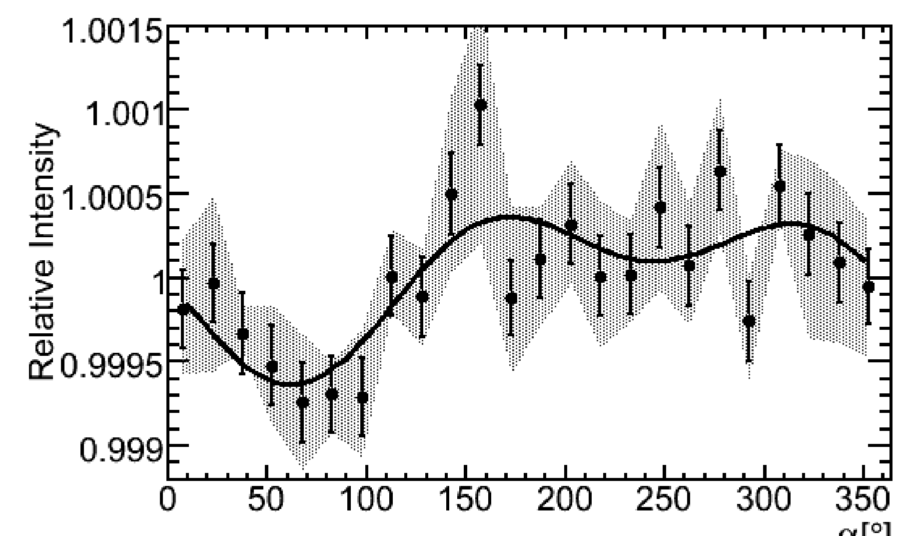
20 TeV





400 TeV

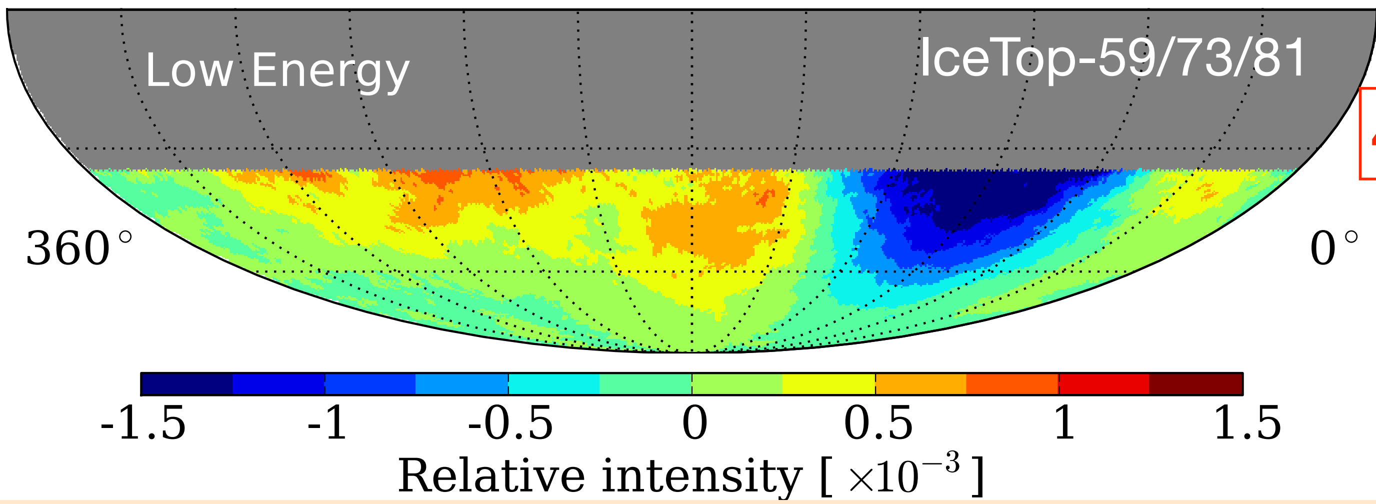
deficit
6.3 σ_{post}



IC59 Abbasi et al., ApJ, **746**, 33, 2012
IC22 Abbasi et al., ApJ, **718**, L194, 2010

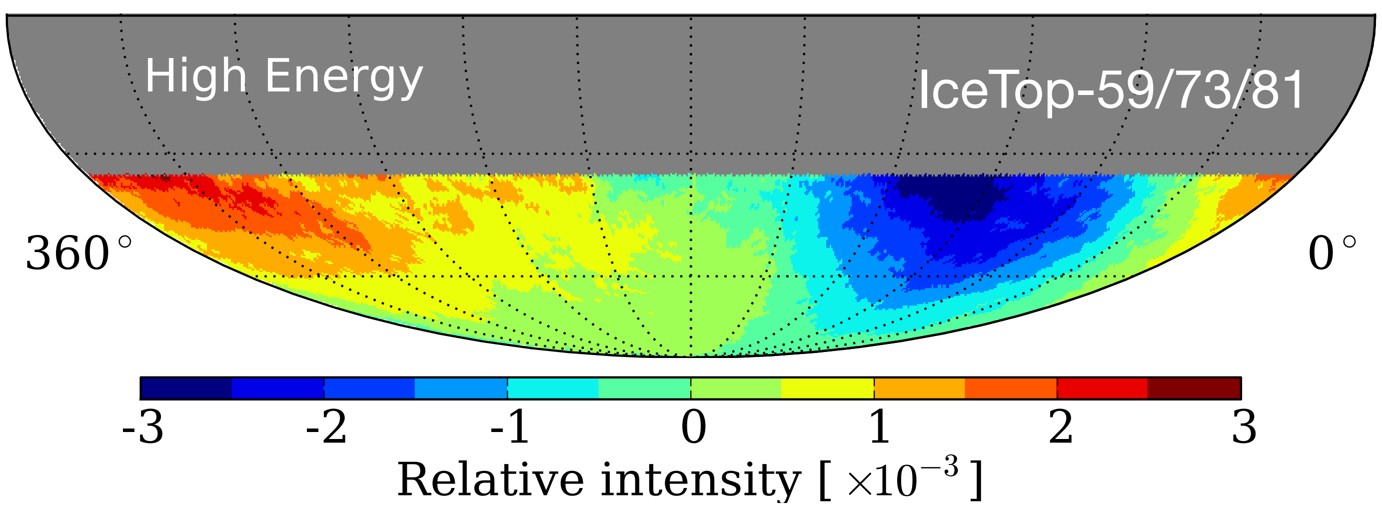
IceTop: large scale anisotropy

relative intensity - equatorial coordinates

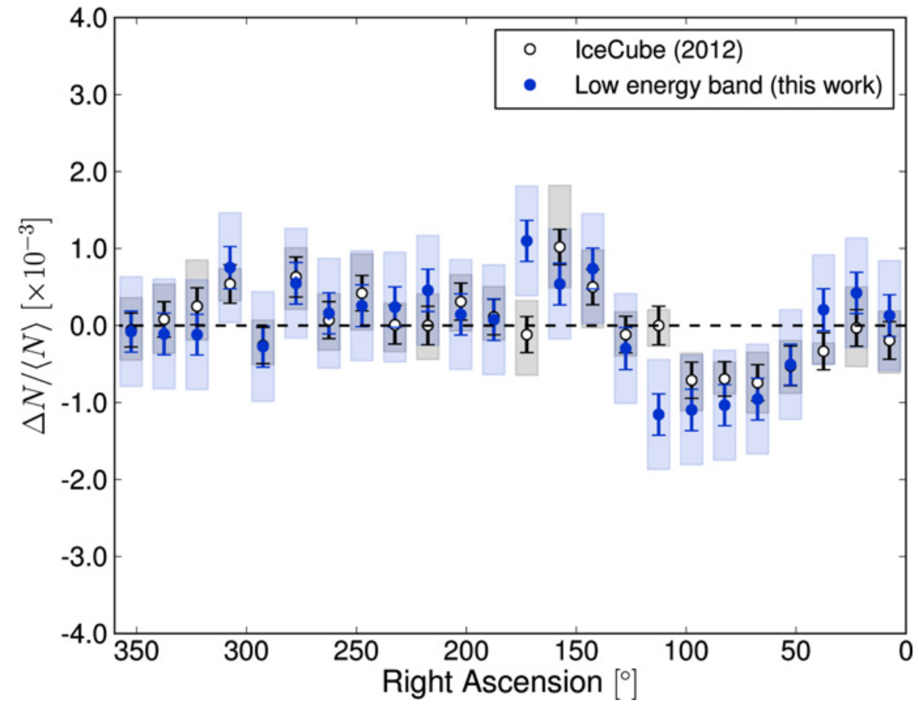


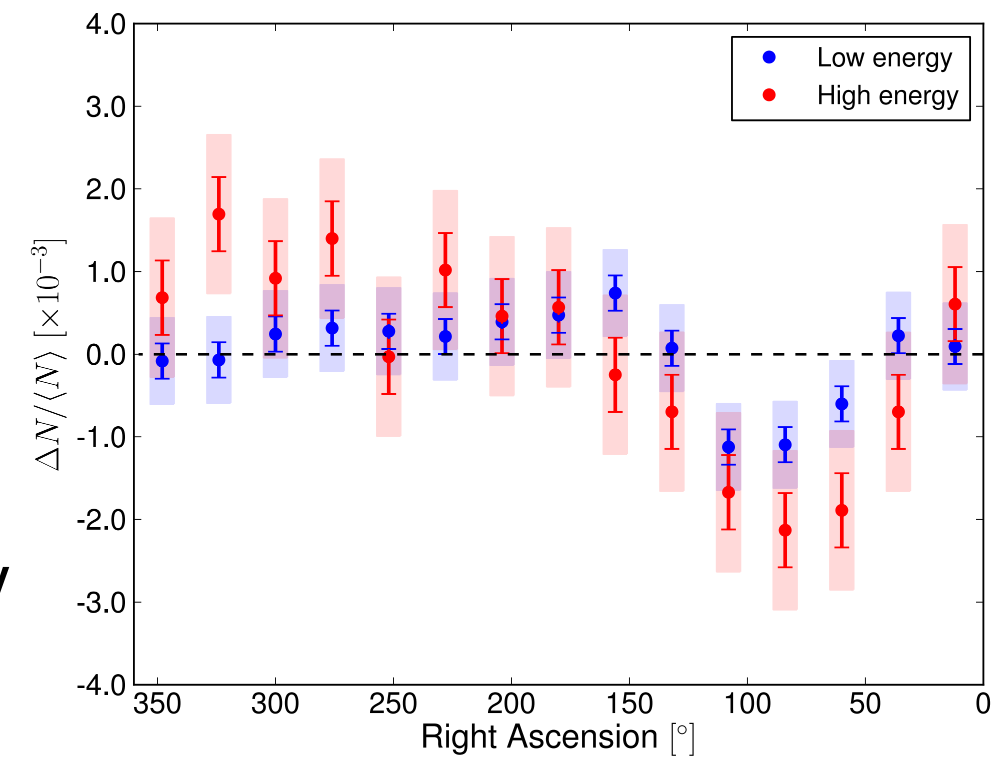
deficit
7 σ_{post}

400 TeV



2 PeV





NOTE: global topology does not change above ≈ 400 TeV

deficit amplitude increases with energy

AArtsen et al., ApJ, **765**, 55 (2013)