Recent Highlights from ARGO-YBJ

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INFN Sezione Roma Tor Vergata

24th European Cosmic Ray Symposium
1-5 September 2014, Kiel, Germany

Outline

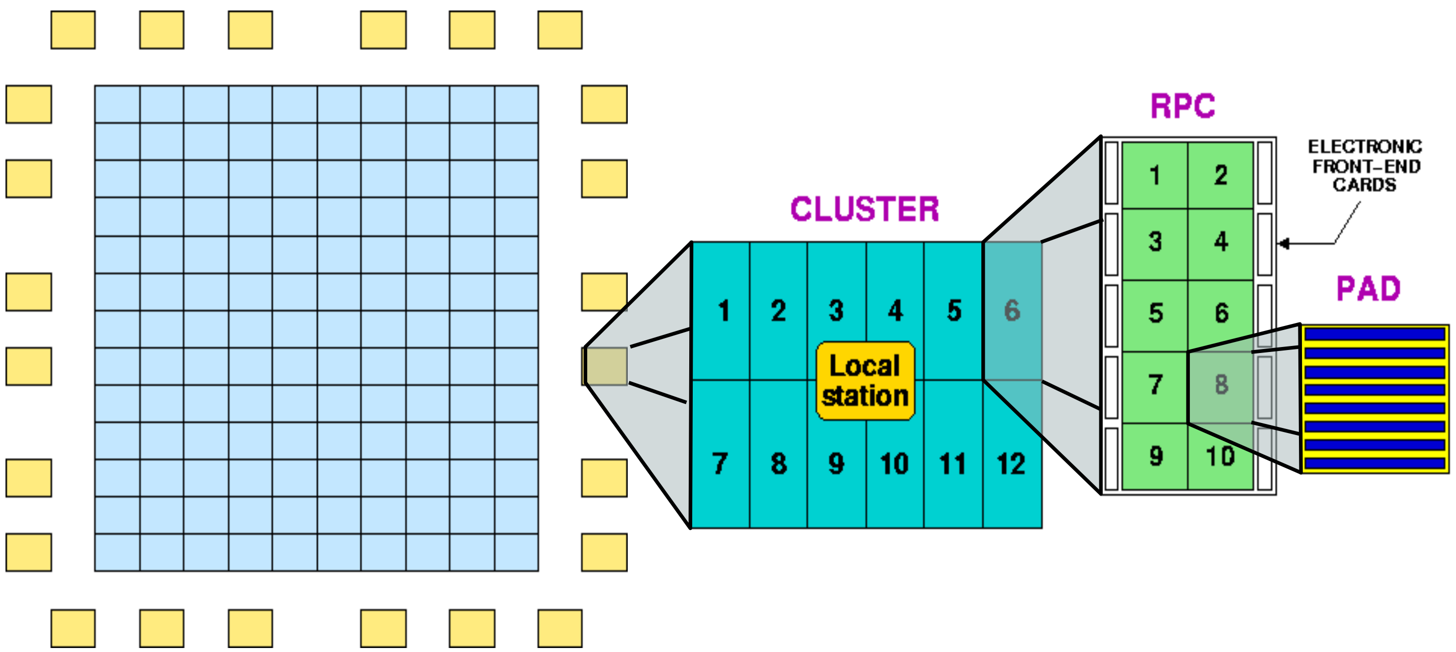
★ Gamma-Ray Astronomy

- Northern sky survey ($-10° < \delta < 70°$) at TeV photon energies at 0.25 Crab units
- Study of the Cygnus region (Cygnus Cocoon and diffuse emission)

★ Cosmic Ray Physics

- CR Light component (p+He) Energy Spectrum (2.5 TeV - 5 PeV)
- Hybrid measurement ARGO-YBJ / WFCTA

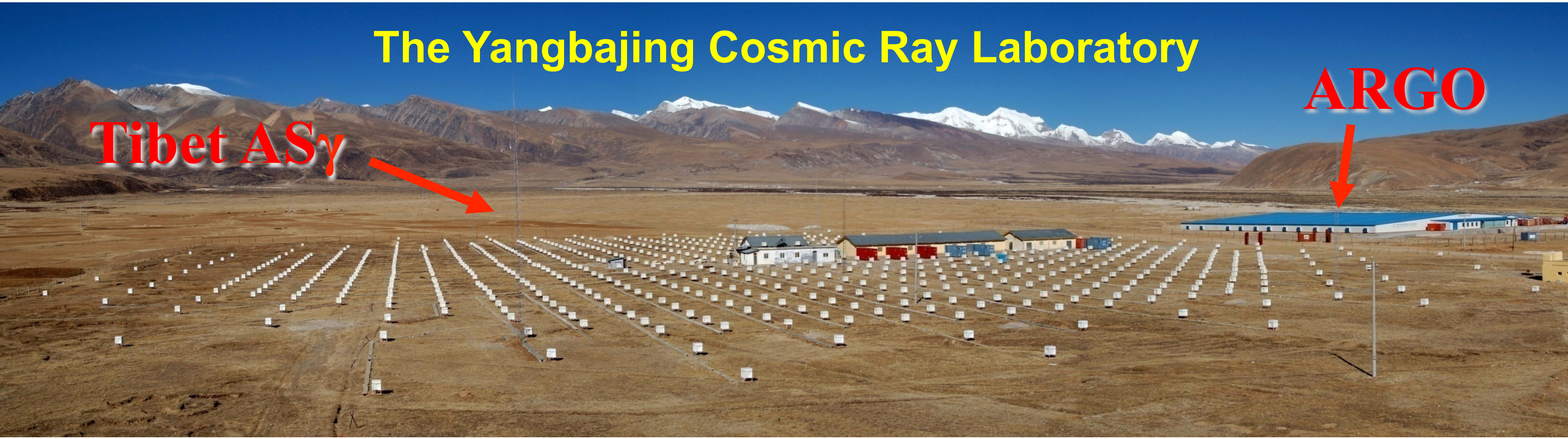
The ARGO-YBJ experiment



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

90 Km North from Lhasa (Tibet)

4300 m above the sea level
~ 600 g/cm²



The basic concepts

…for an unconventional air shower detector

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

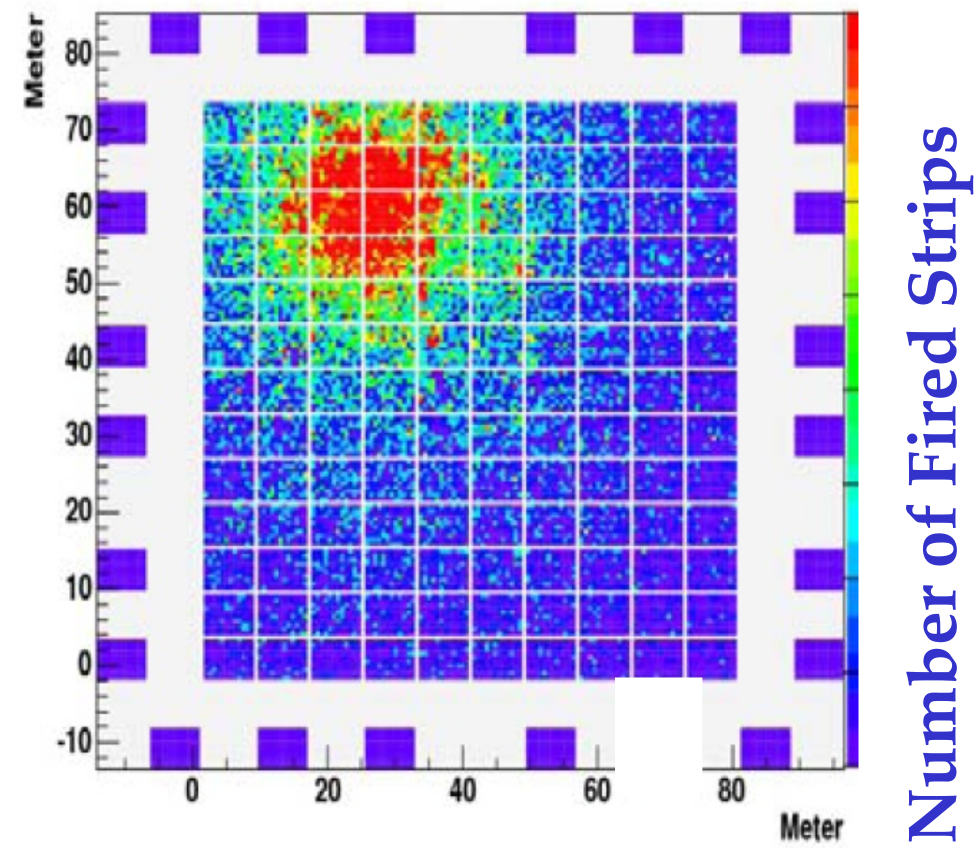
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

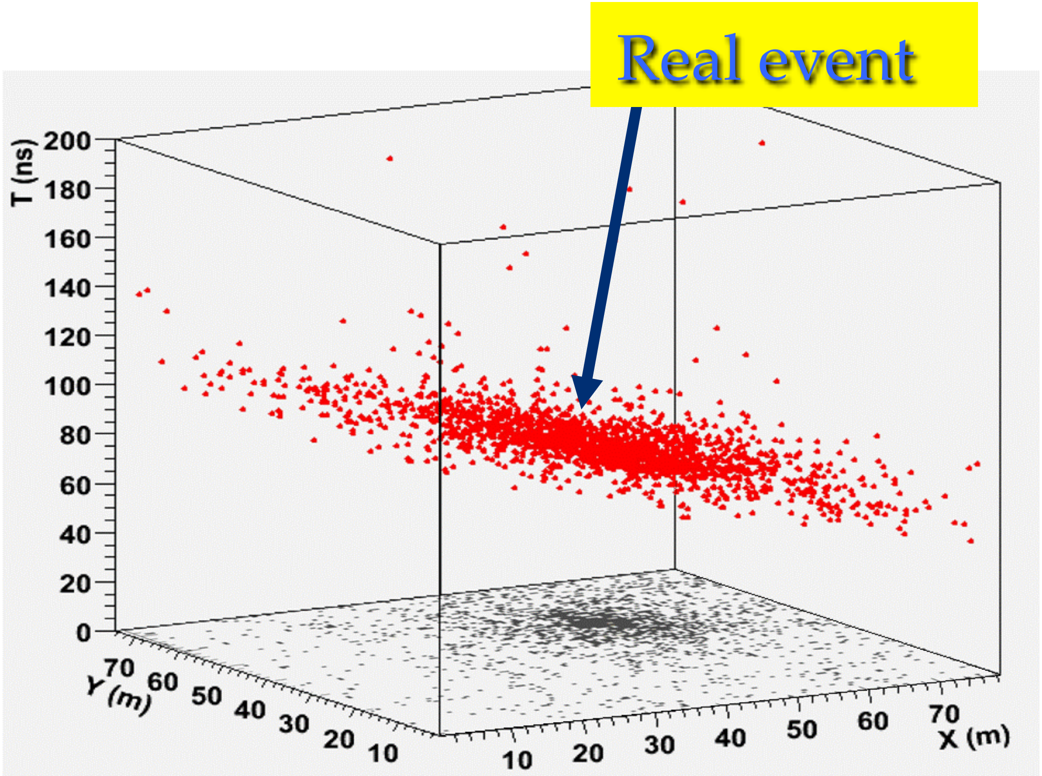
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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

… in order to

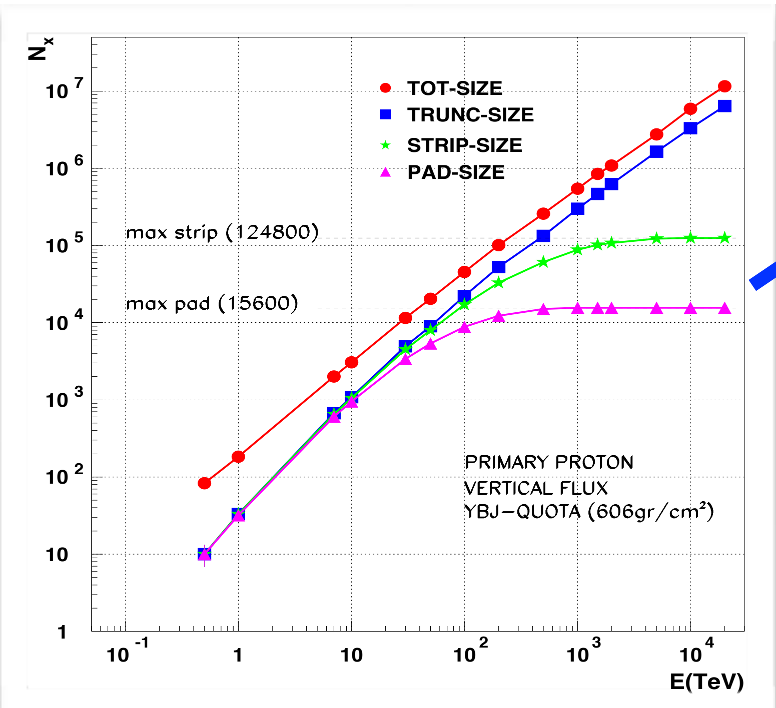
- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV

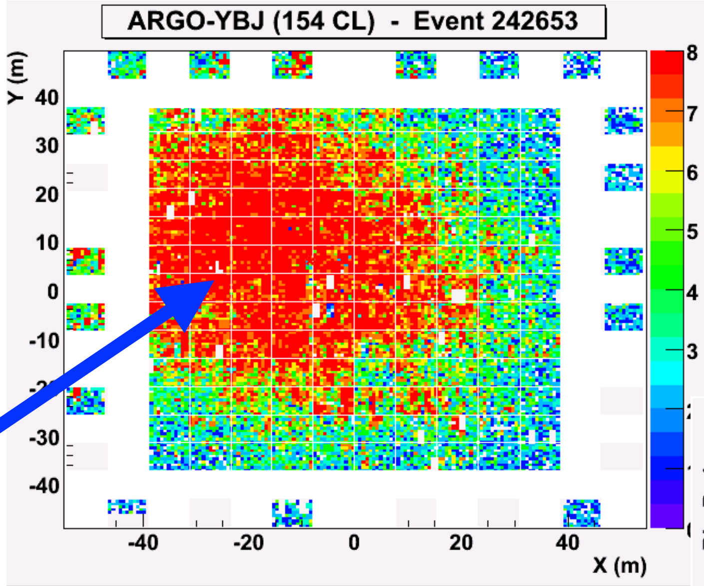




The RPC analog readout

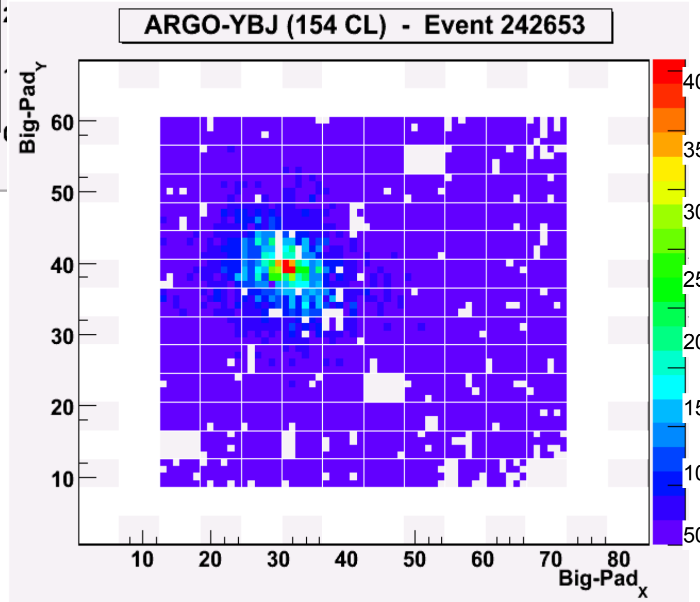
…extending the dynamical range up to PeV

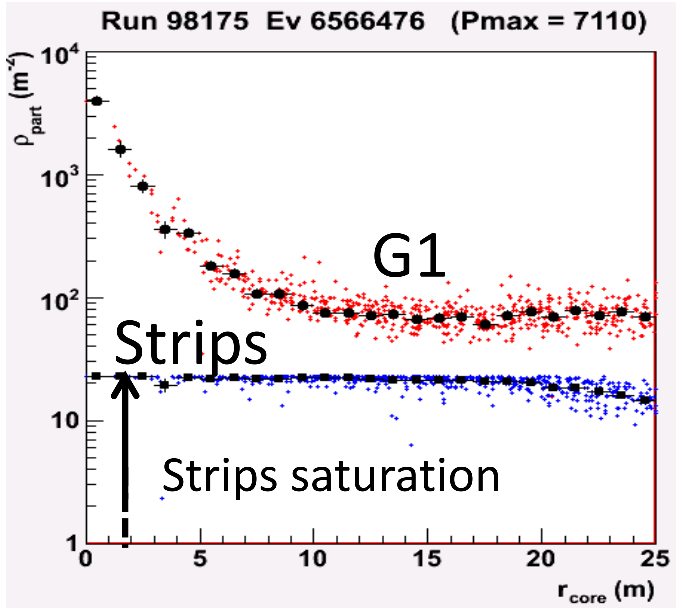


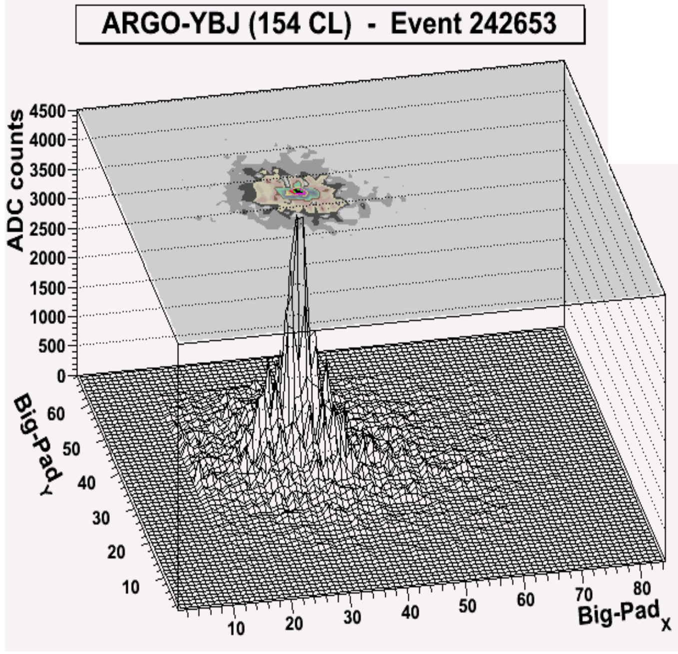


Strips (digital)

Big Pads (analog)







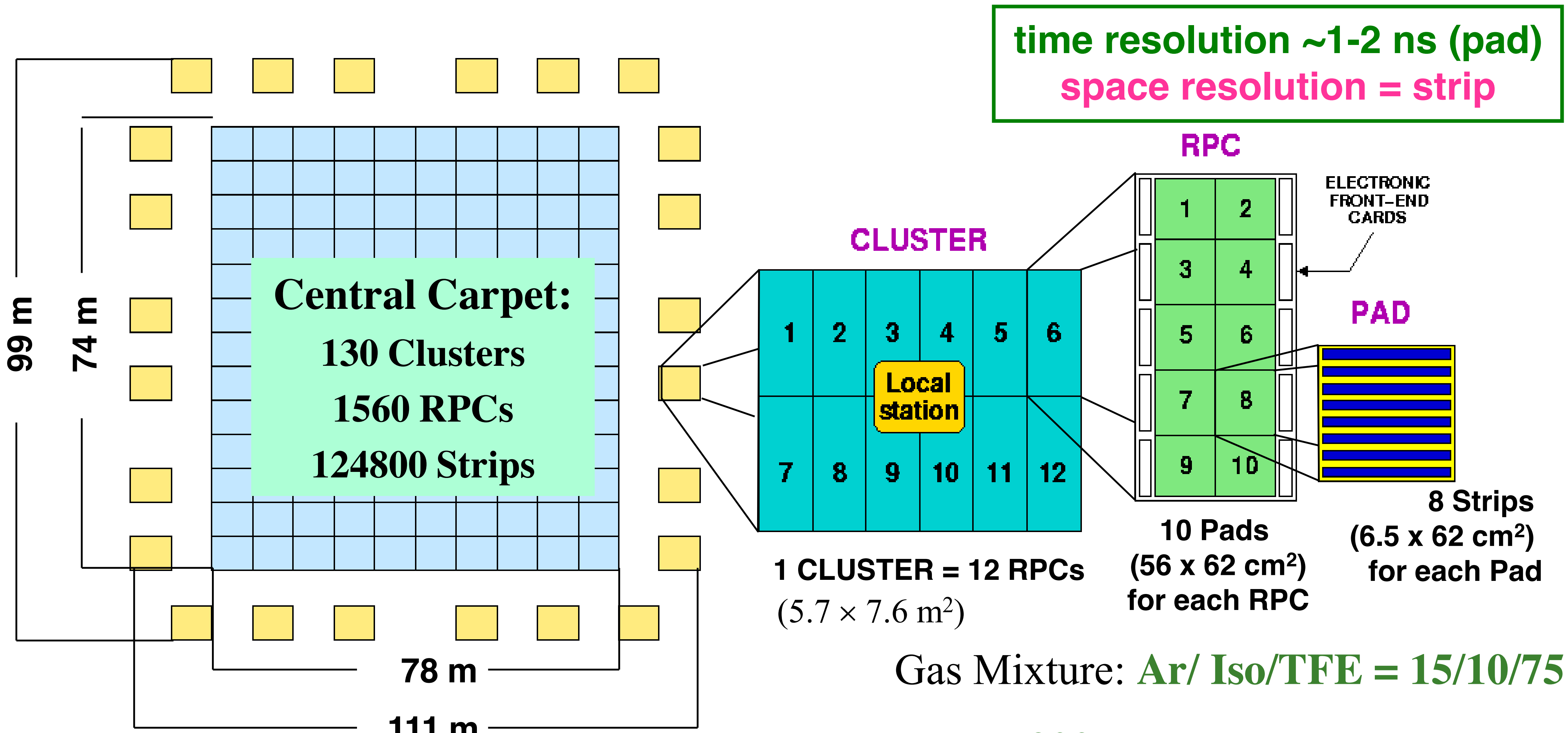
4 different gain scales used to cover a wide range in particle density:

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

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

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

The ARGO-YBJ layout



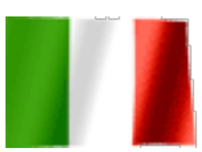
Gas Mixture: **Ar/ Iso/TFE = 15/10/75**

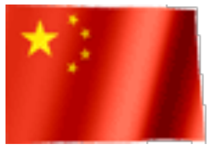
HV = 7200 V

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

The ARGO-YBJ Collaboration

Collaboration Institutions:
- Chinese Academy of Sciences (CAS)
- Istituto Nazionale di Fisica Nucleare (INFN)

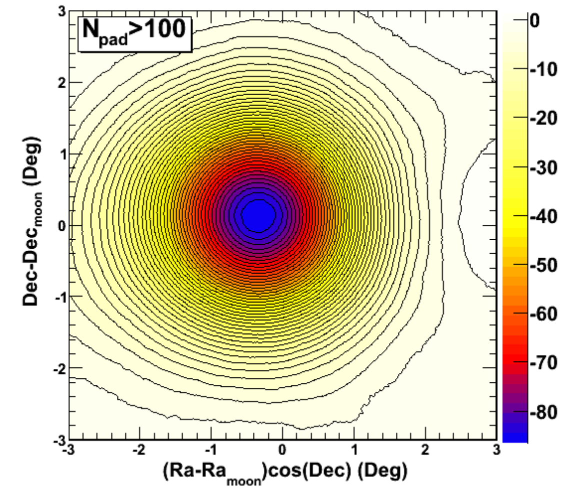


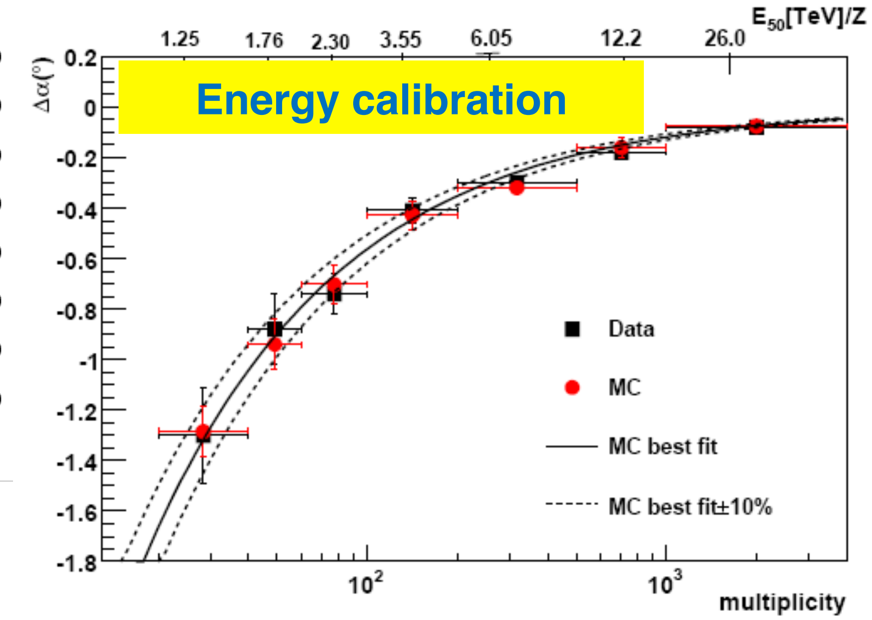




INAF/IASF, Palermo and INFN, Catania
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino

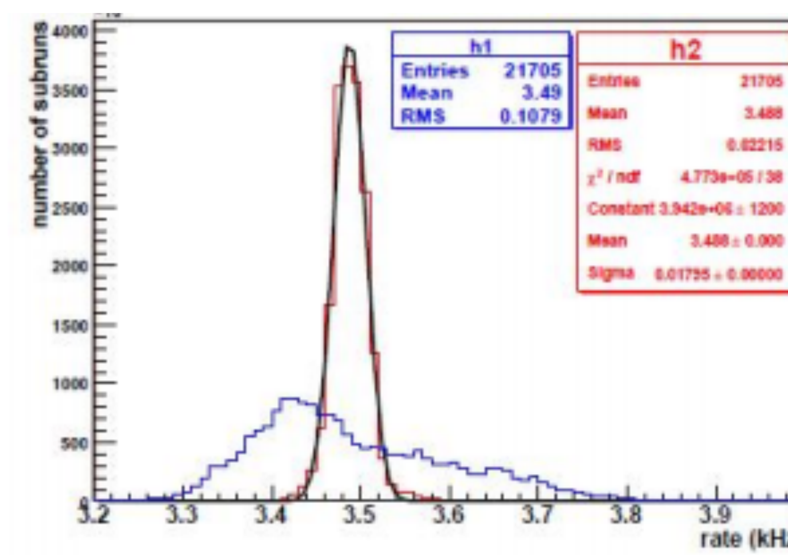
IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming
Hebei Normal University, Shijiazhuang

Status and performance

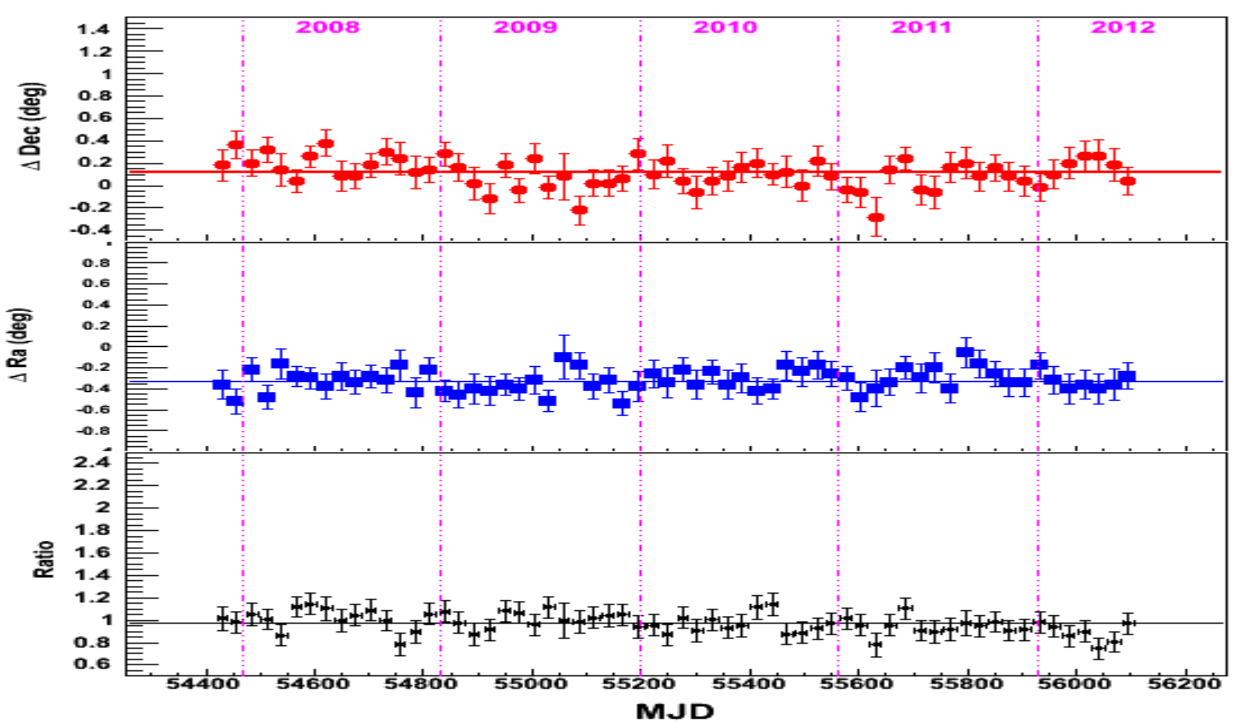


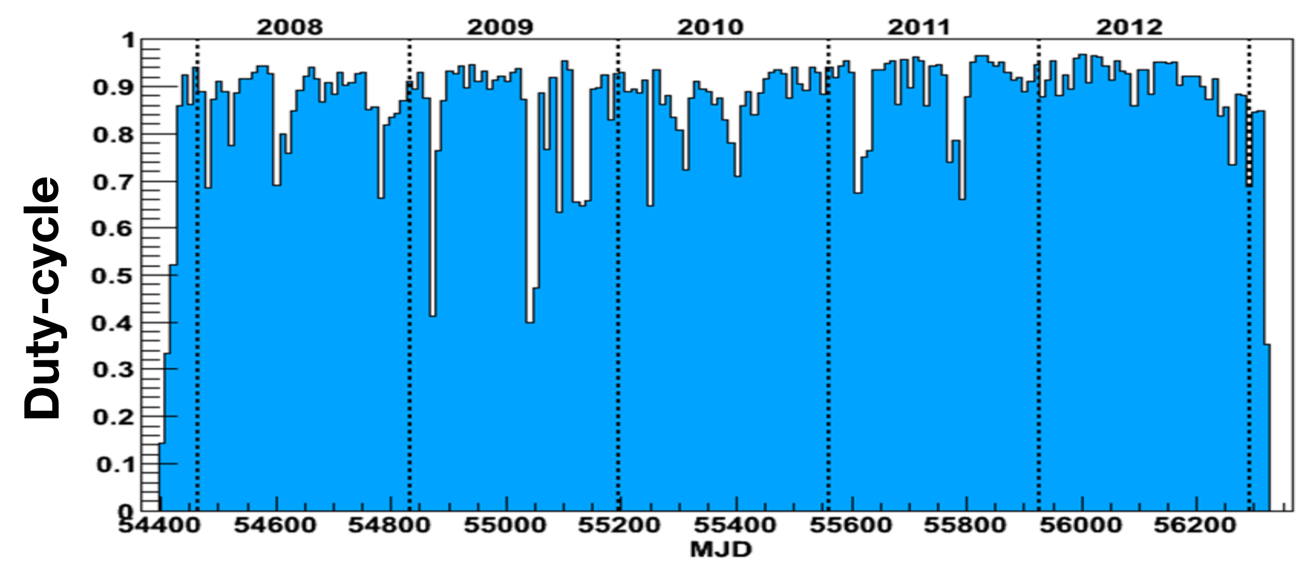


- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to PeV
- 100 TB/year data



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





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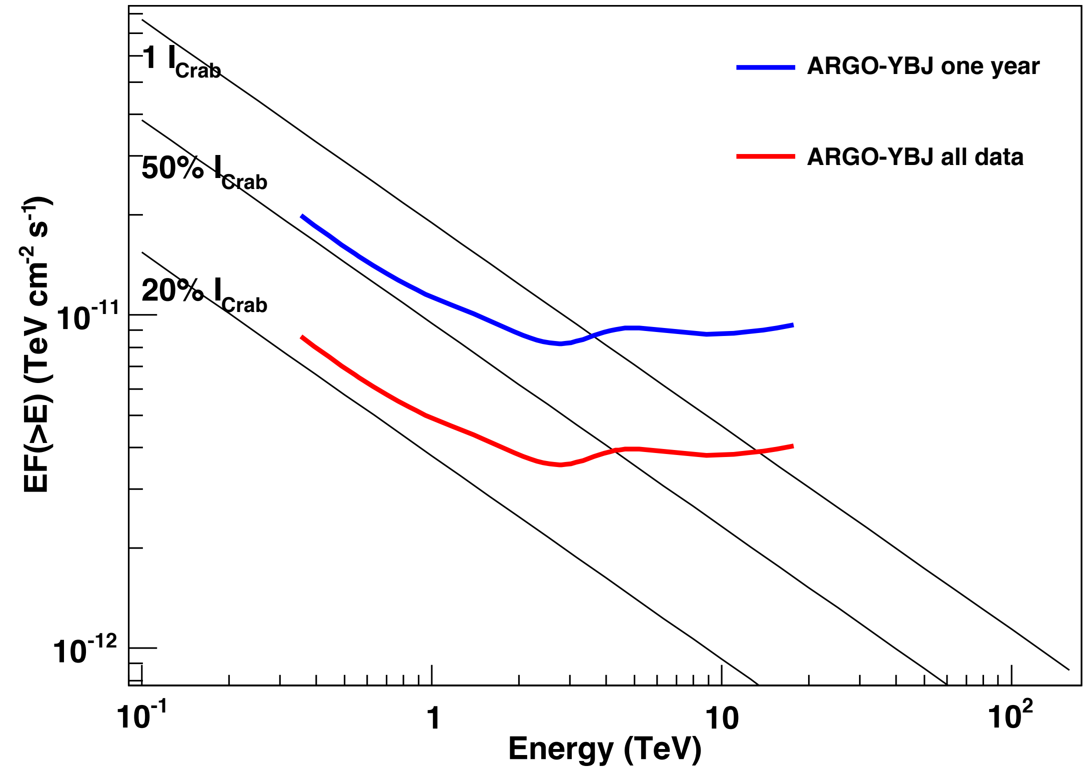
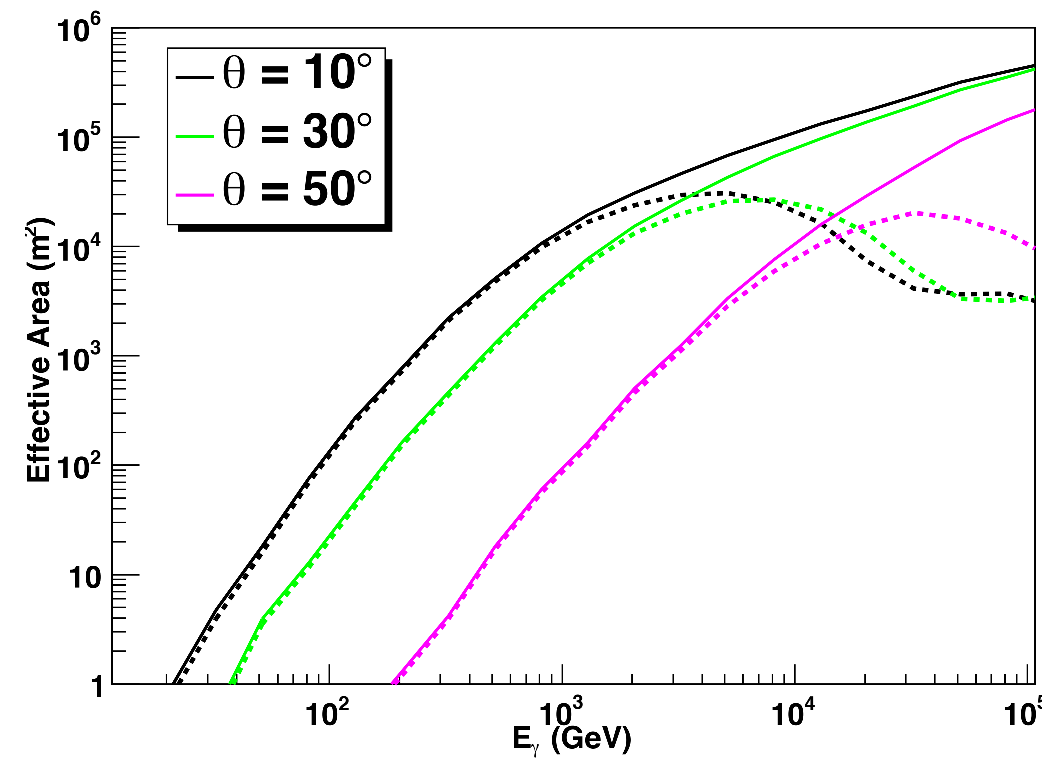
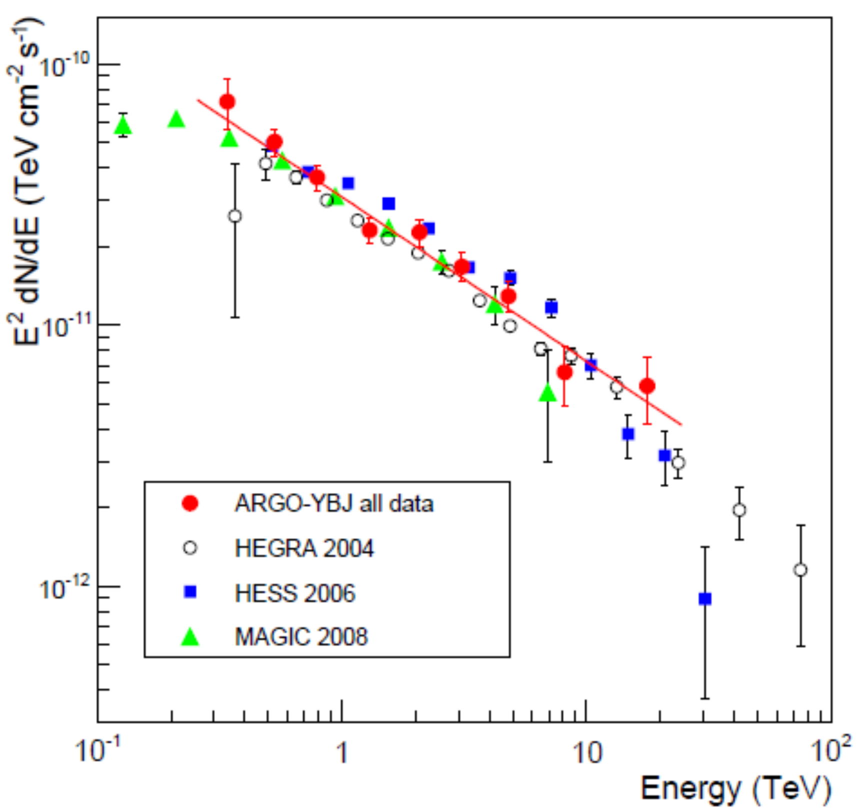
Gamma-Ray Astronomy with ARGO-YBJ

- Energy threshold: few hundreds of GeV
  → Overlaps with Cherenkov detectors
- Large duty cycle: 86%
- Large field of view: ~2 sr
- Declination band from -10° to 70°
- Integrated sensitivity in 5 y at ~1 TeV:
  0.25 Crab for dec 15° - 45°







Crab Nebula 5 years data

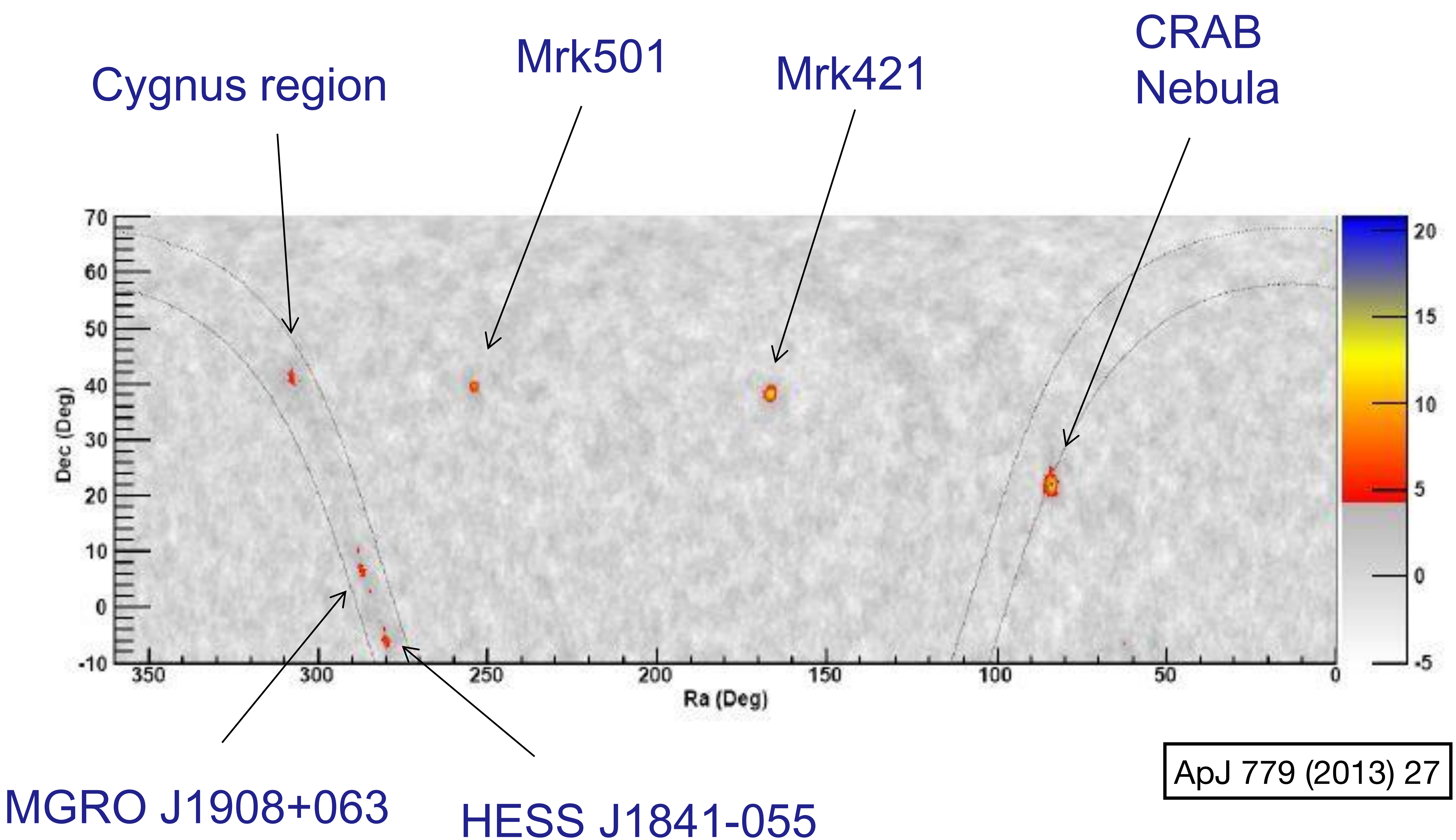
$$dN/dE = (5.2 \pm 0.2)\cdot 10^{-12}\cdot (E/2\ \mathrm{TeV})^{(-2.63 \pm 0.05)} \quad \mathrm{cm^{-2}\ s^{-1}\ TeV^{-1}}$$

(0.3–20 TeV)

paper submitted to ApJ

ARGO-YBJ 5-years survey of the Northern Sky

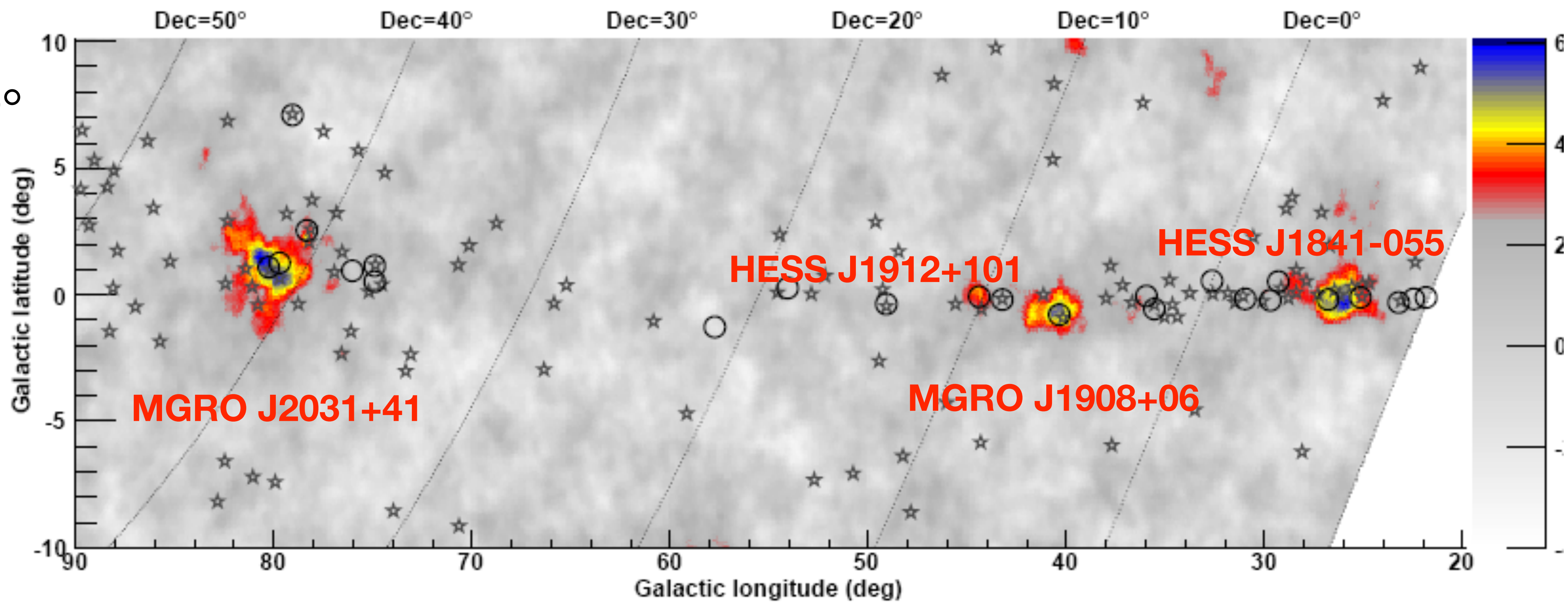
- Integrated sensitivity in 5 y at ~1 TeV: 0.25 Crab for dec 15° - 45°



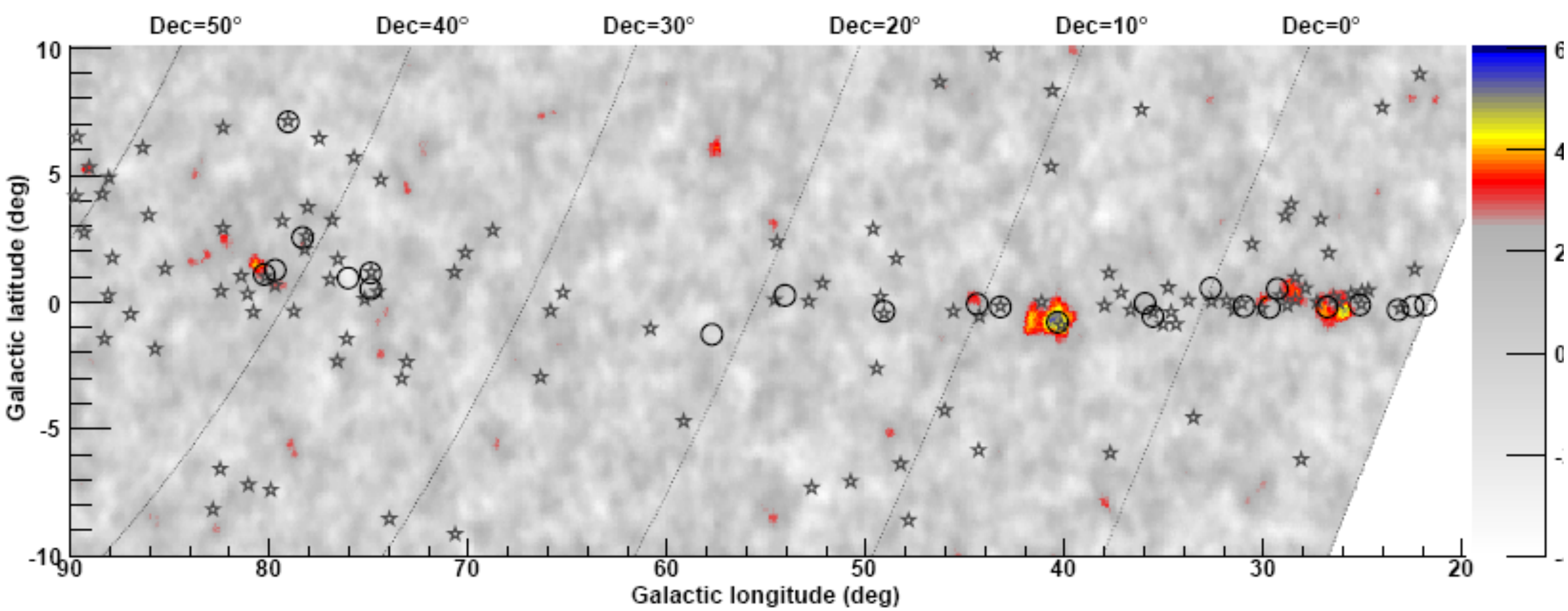
ApJ 779 (2013) 27

ARGO-YBJ 5-years Survey of Inner Galactic Plane

$20° < l < 90°, |b| < 10°$



$E_{50} \approx 0.7$ TeV



$E_{50} \approx 1.8$ TeV

Detected Sources

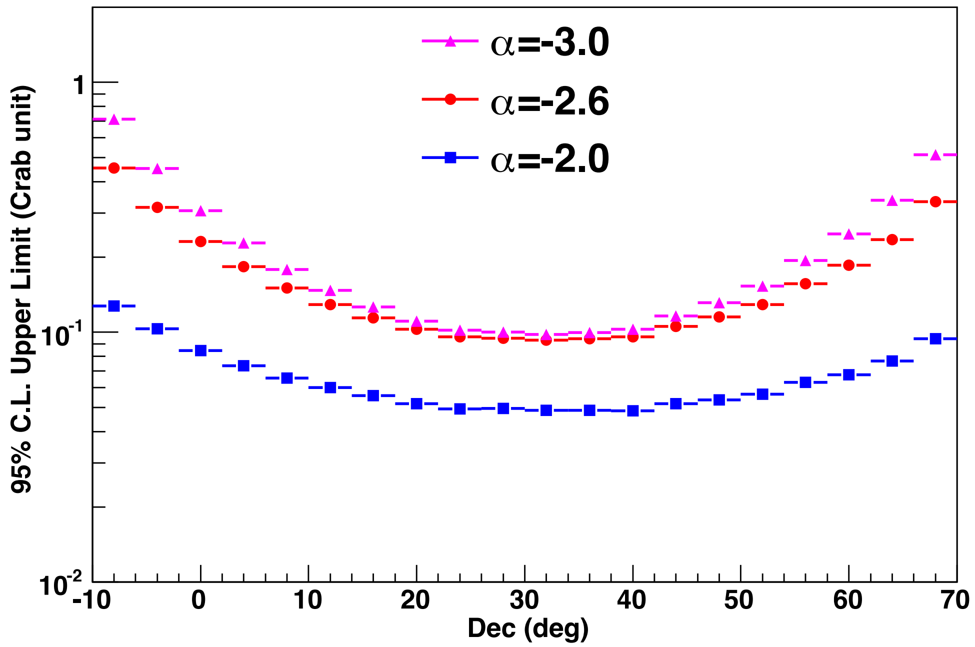


Fig. 4: Average 95% C.L. flux upper limit at energy above 500 GeV, averaged on the right ascension direction, as a function of declinations. Different curves indicate sources with different power-law spectral indices −2.0, −2.6 and −3.0. The Crab unit is 5.77×10^{-11} cm^{-2} s^{-1} .

Table 2. Location of the excess regions

ARGO-YBJ Name	Ra (deg)	Dec (deg)	l (deg)	b (deg)	S (s.d.)	Associated TeV Source
ARGO J0409−0627	62.35	-6.45	198.51	-38.73	4.8	
ARGO J0535+2203	83.75	22.05	184.59	-5.67	20.8	Crab Nebula
ARGO J1105+3821	166.25	38.35	179.43	65.09	14.1	Mrk 421
ARGO J1654+3945	253.55	39.75	63.59	38.80	9.4	Mrk 501
ARGO J1839−0627	279.95	-6.45	25.87	-0.36	6.0	HESS J1841−055
ARGO J1907+0627	286.95	6.45	40.53	-0.68	5.3	HESS J1908+063
ARGO J1910+0720	287.65	7.35	41.65	-0.88	4.3	
ARGO J1912+1026	288.05	10.45	44.59	0.20	4.2	HESS J1912+101
ARGO J2021+4038	305.25	40.65	78.34	2.28	4.3	VER J2019+407
ARGO J2031+4157	307.95	41.95	80.58	1.38	6.1	MGRO J2031+41 TeV J2032+4130
ARGO J1841-0332	280.25	-3.55	28.58	0.70	4.2	HESS J1843−033

ApJ 779 (2013) 27

The Cygnus Region

Very important region populated by many unidentified strong sources

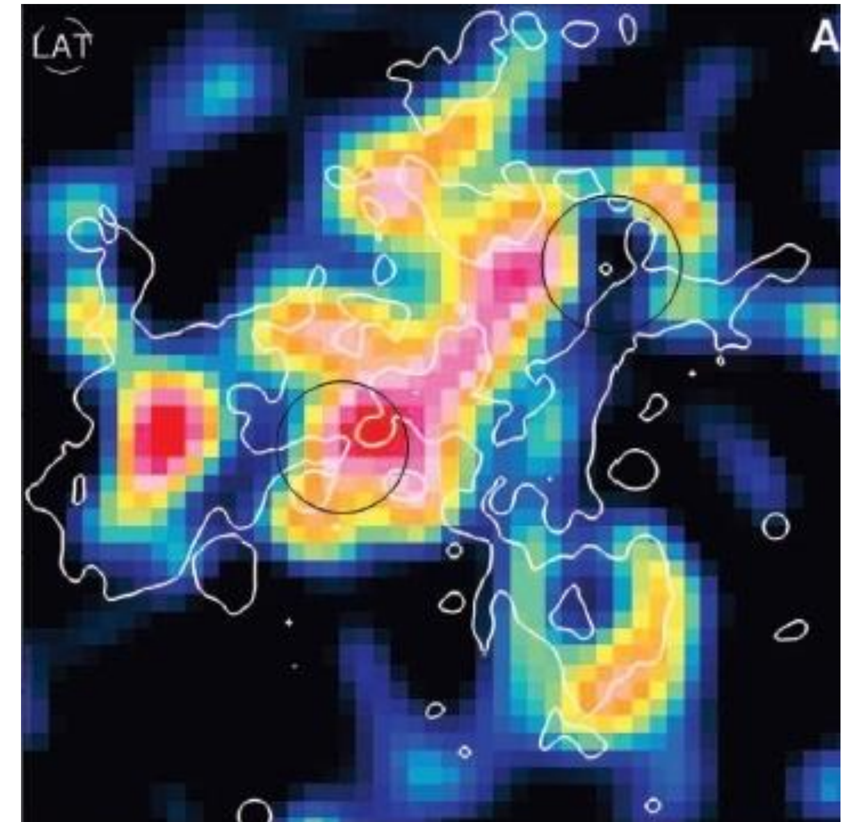
- The brightest diffuse γ-rays source in the northern hemisphere
- 9 supernova remnants
- >20 Wolf-Rayet starts
- 6 OB associations
- shocked gas

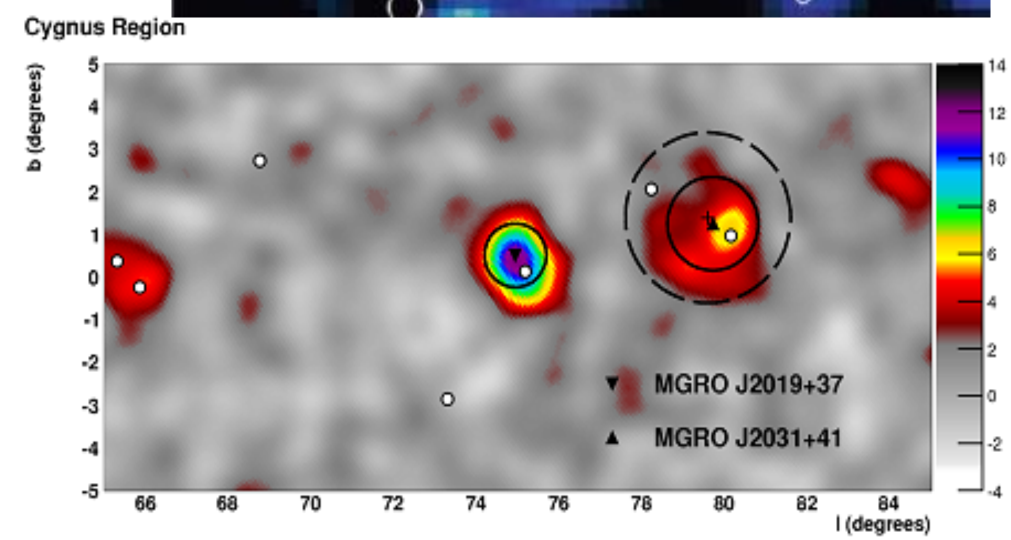
Natural site for cosmic-ray acceleration

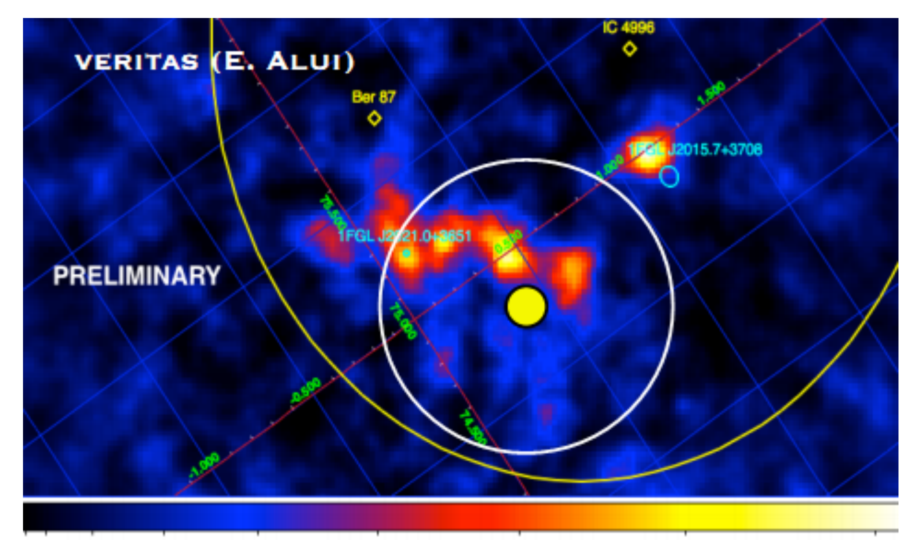
★ Fermi data (1-100 GeV):
A cocoon of freshly accelerated CRs ?

★ Milagro detected 2 sources at 20 TeV
✓ MGRO J2019+37 (12.4 σ)
✓ MGRO J2031+41 (7.6 σ)
Both consistent with Fermi source locations

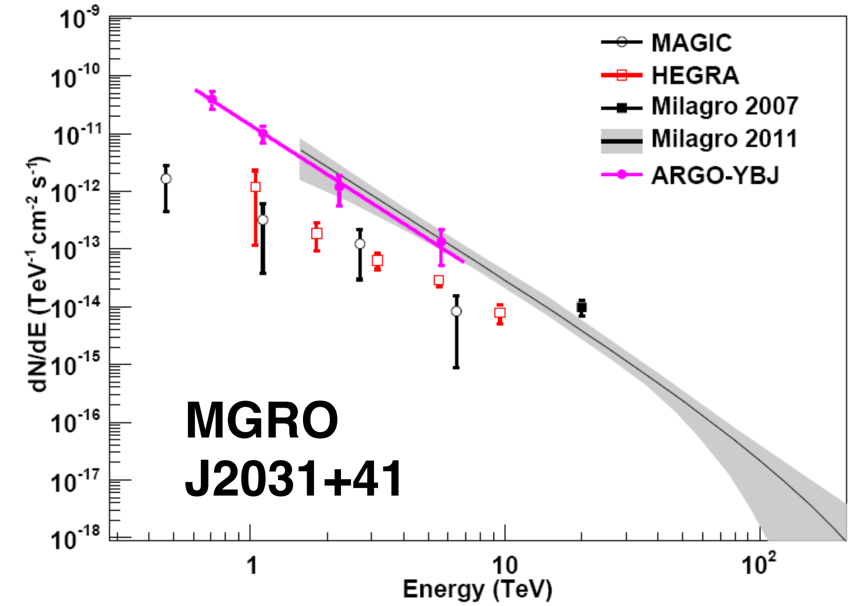
★ Complex emission observed by VERITAS consistent with location of MGRO J2019+37



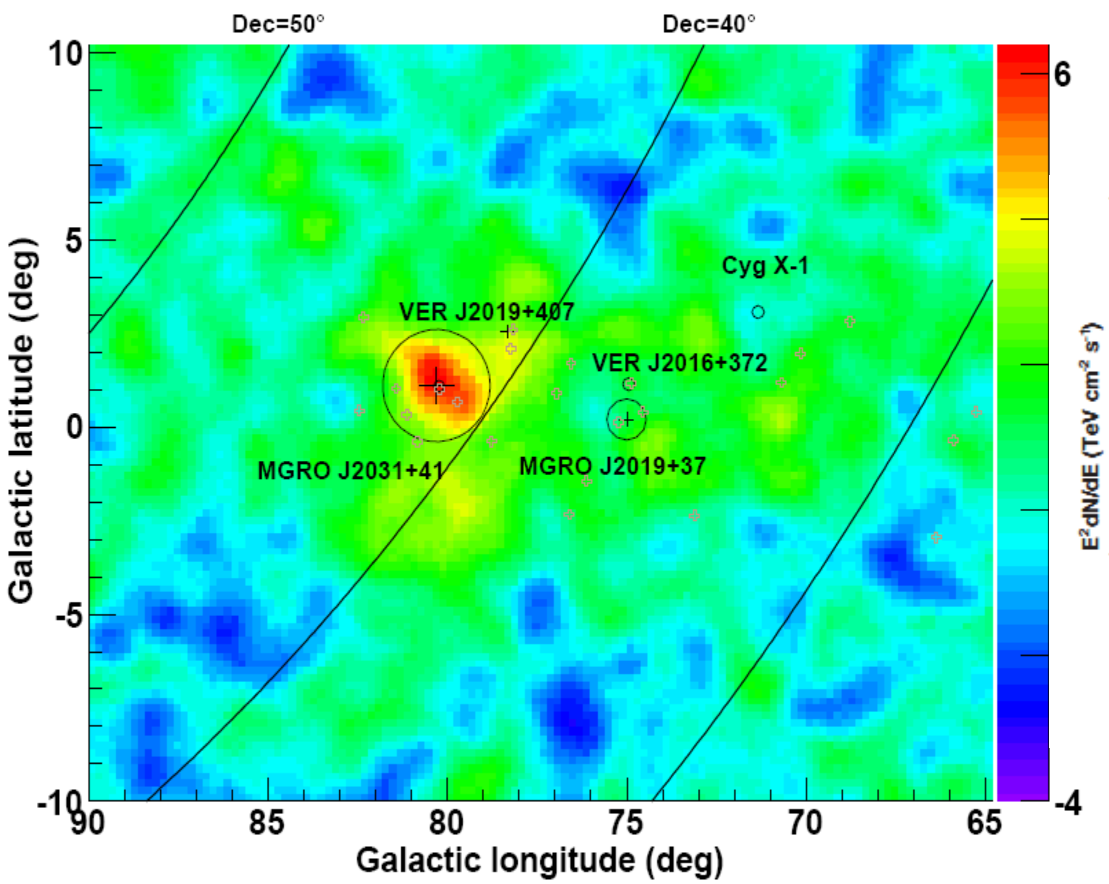


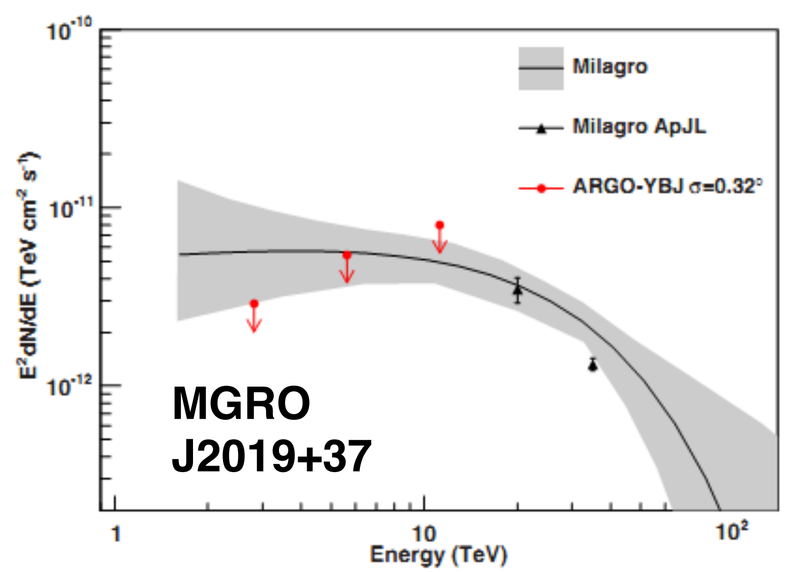


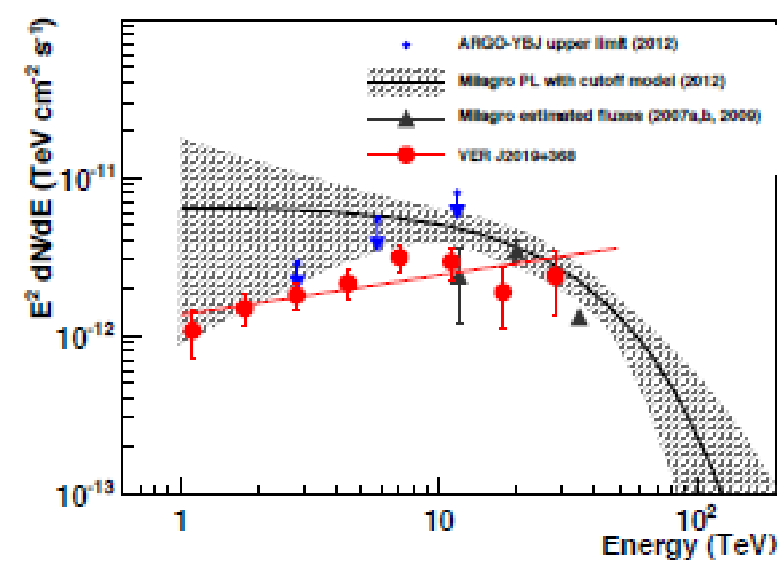
The Cygnus Region by ARGO-YBJ



ApJL 745 (2012) L22







NO signal from the MGRO J2019+37 below 10 TeV

- ✓ Insufficient exposure above 5 TeV ?
- ✓ Variability ?

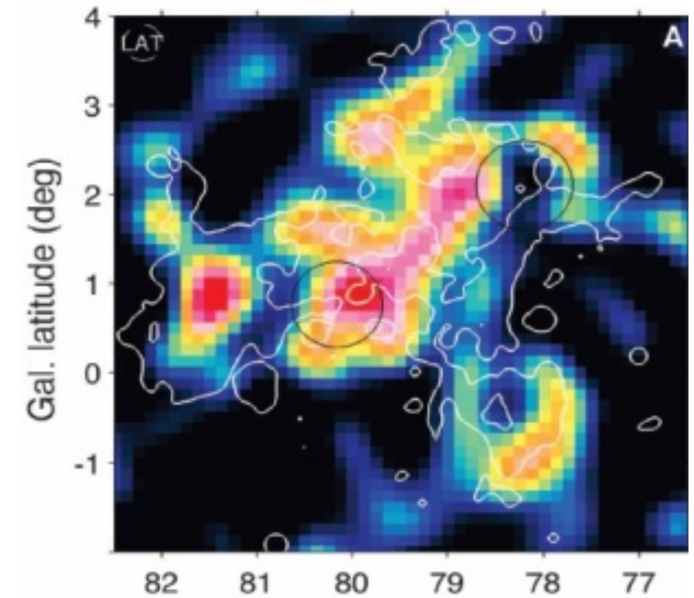
VERITAS recently resolved it in two different sources: the faint point-like VER J2016+371 and the extended (~1°) VER J2019+368

VER J2019+368 likely contributes to the bulk of the emission observed by Milagro and coincides with the PSR J2021+3651 and the star formation HII region Sh2-104

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.

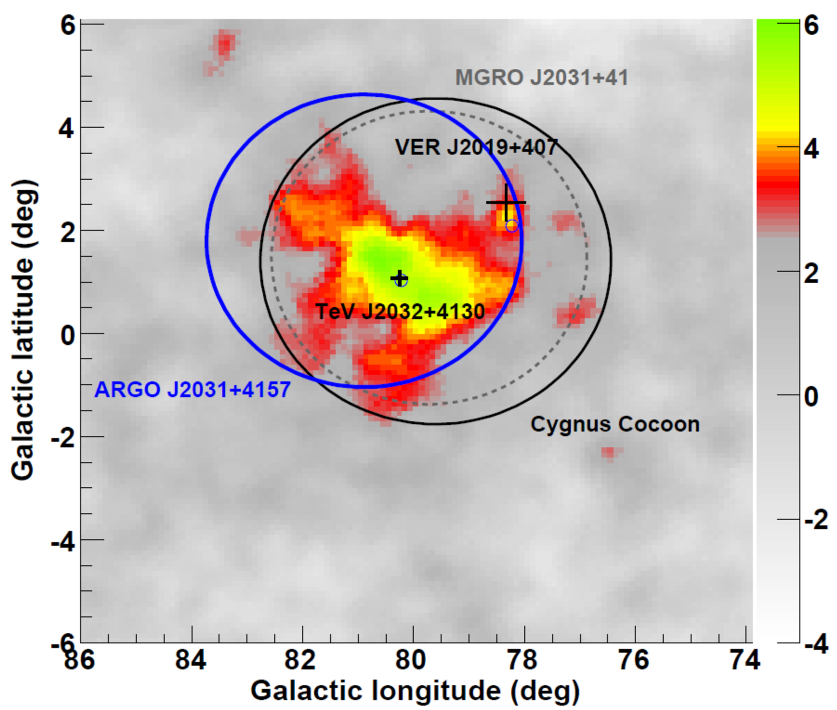
The Fermi/LAT view in the 10-100 GeV band



Science 334 (2011) 1103

The ARGO-YBJ view at TeV energies

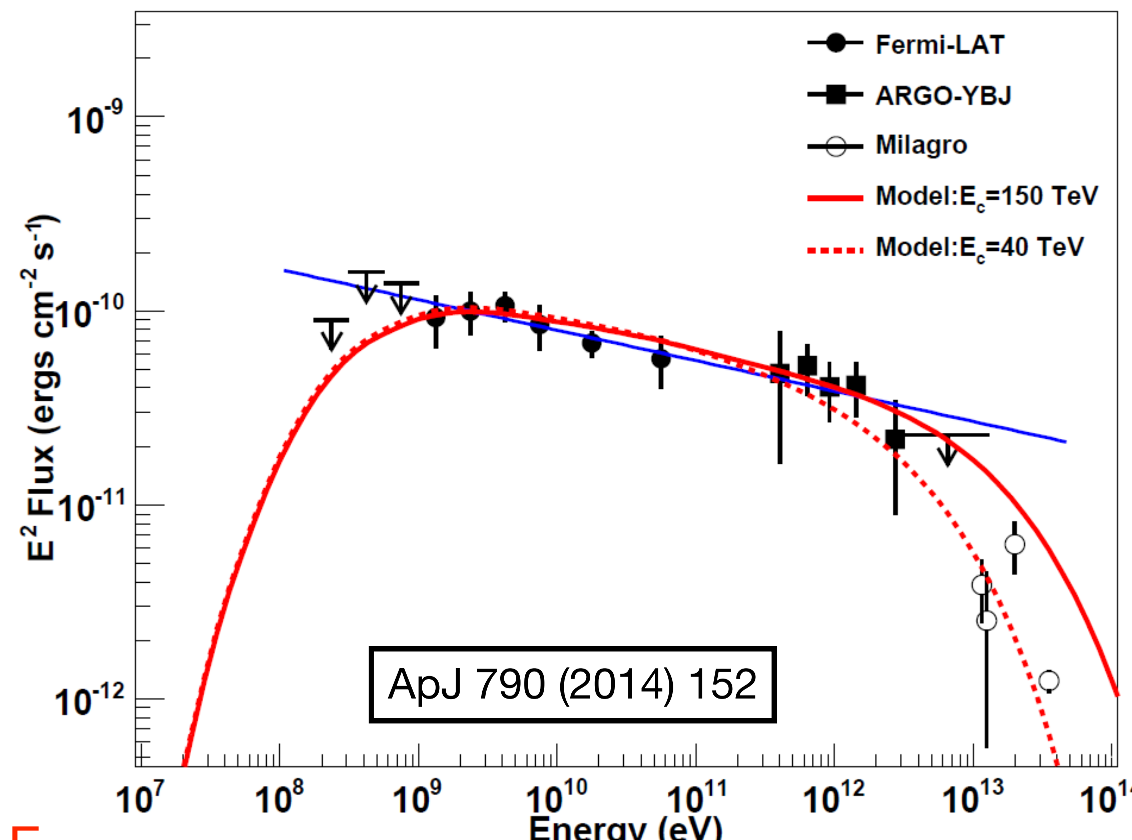
after reanalysis with the full data



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

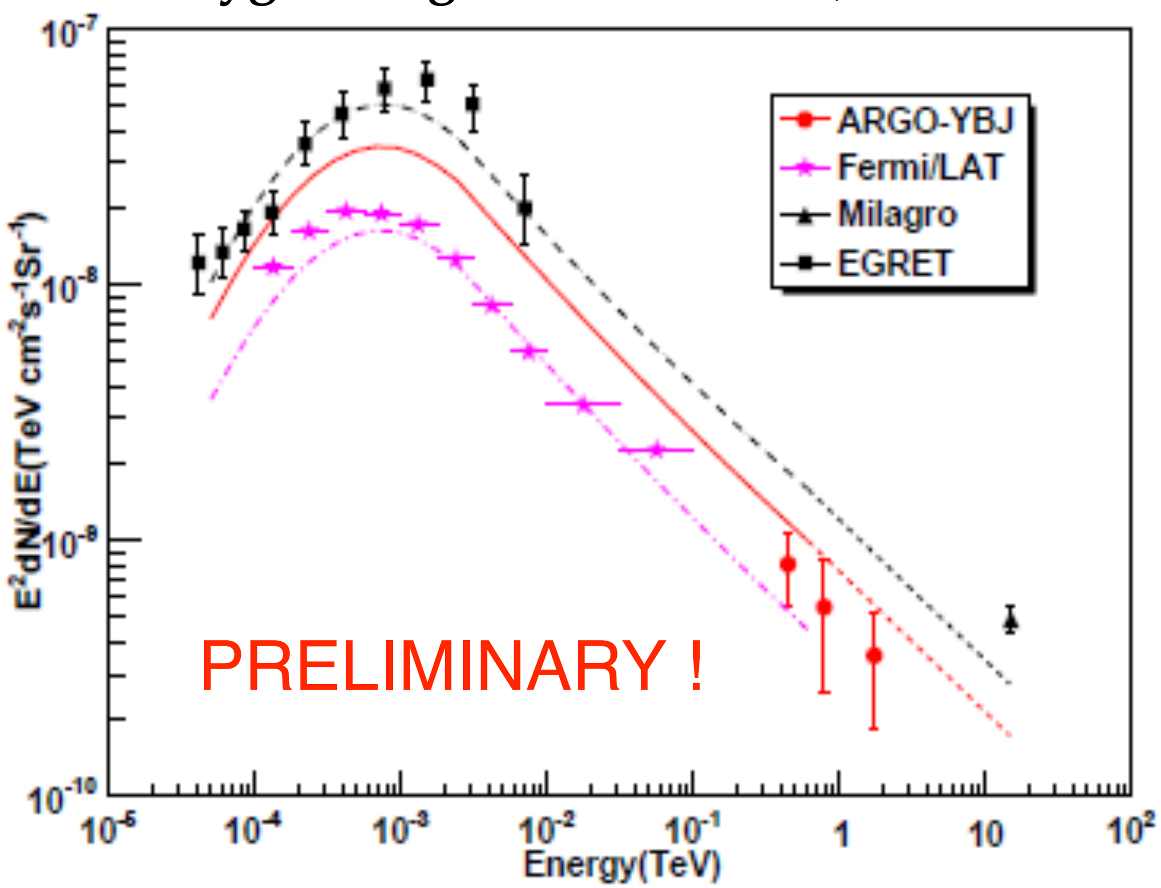
Spectrum of ARGO J2031+4157: $dN/dE \propto E^{-2.62\pm0.27}$

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

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.

Cygnus region: 65° < l < 85°; |b| < 5°



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.

paper in preparation

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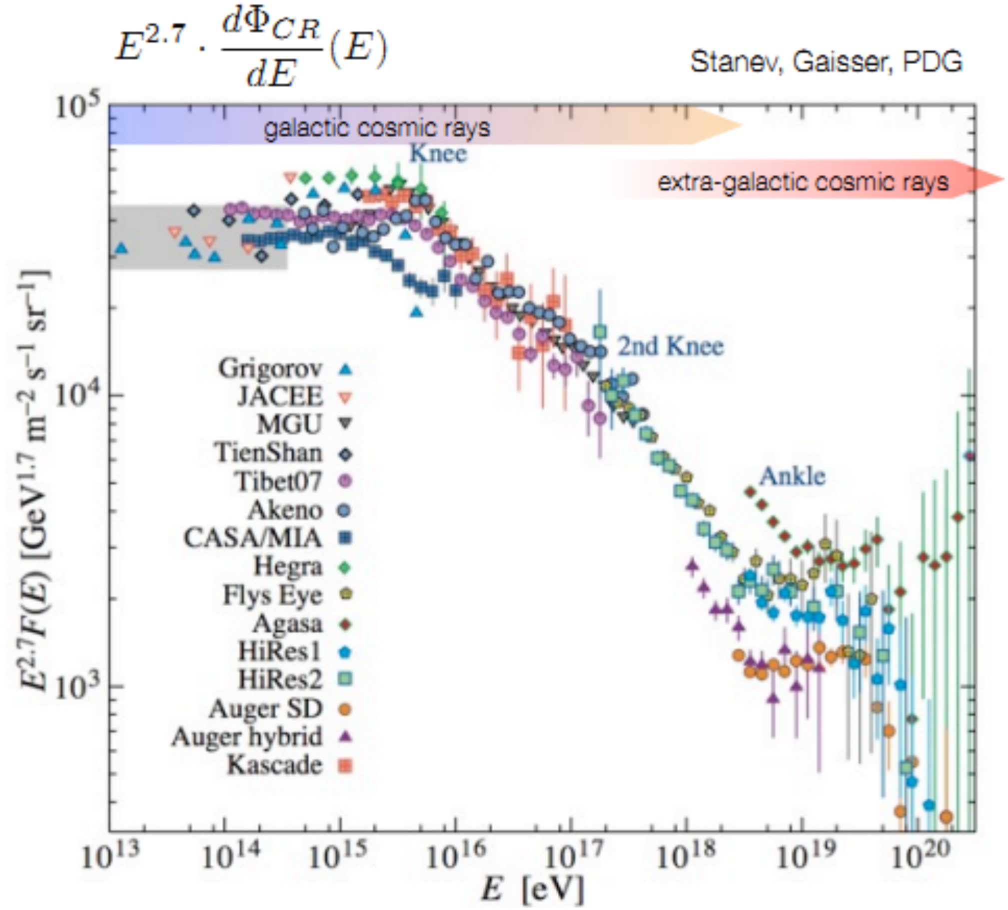
Galactic Cosmic Rays

- CRs below 10^{17} eV are predominantly galactic.
- The bulk of CR is produced by shock acceleration in SN explosions.
- Diffusion of accelerated CRs through non-uniform, non-homogeneous ISM.
- Galactic CRs are scrambled by galactic magnetic field over very long time.



The main feature: the ‘knee’ in the all-particle spectrum

Different models to explain the ‘knee’ and different signature…

- **Acceleration in SNRs:**
  finite lifetime of shock E_{max} $Z \cdot 10^{15}$ eV
  - Eknee $\propto Z$
  - No anisotropy change
- **Diffusion process:**
  probability of escape from Galaxy = f(Z)
  - Eknee $\propto$ Z
  - Anisotropy $\propto E^{\delta}$
- **Interaction with bckg particles:**
  Photo-disintegration - interaction with in galactic halo etc.
- **Change in particle interaction**
  - Eknee $\propto$ A

Key elements: mass composition and anisotropy

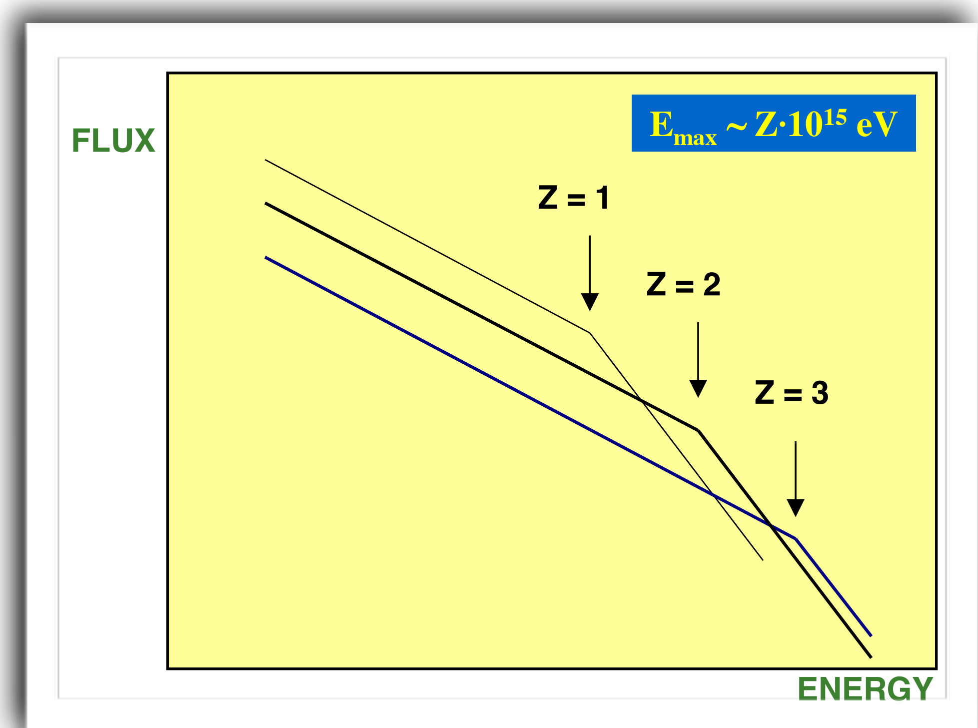
Approaching the knee

How well do we know the structure of the primary spectrum around the knee ($10^{14} – 10^{16}$ eV) ?

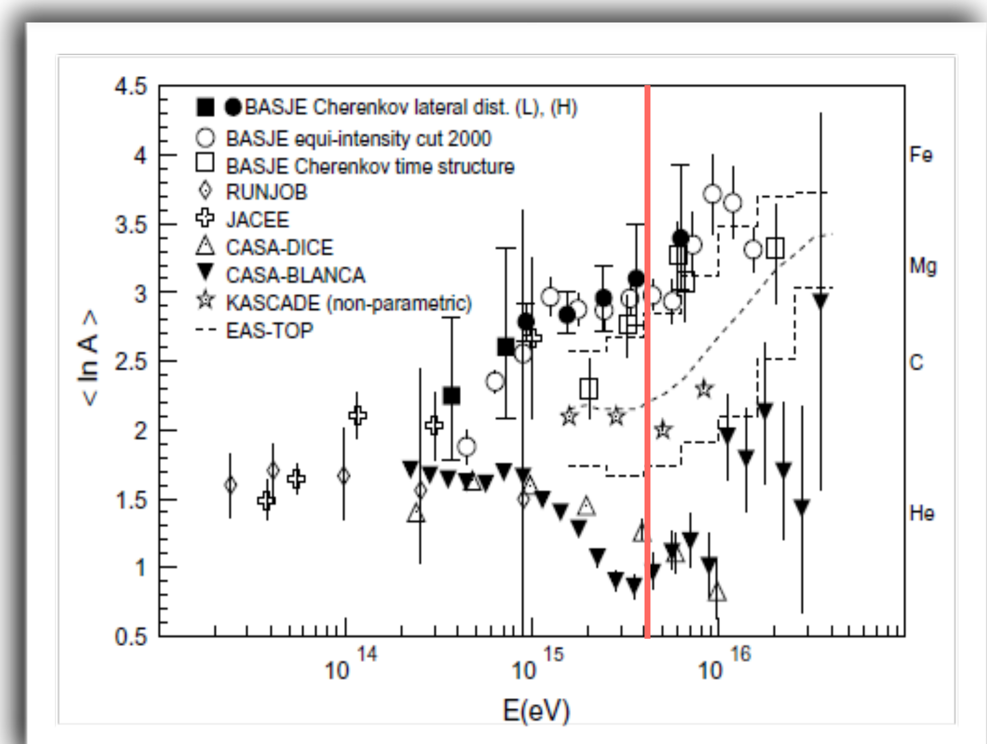
The standard model:

- Knee attributed to light (proton) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge
  $E_Z = Z \cdot 4.5$ 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.

Experimental results still conflicting !



$E_{max}(\text{iron}) = 26 \cdot E_{max}(\text{proton})$

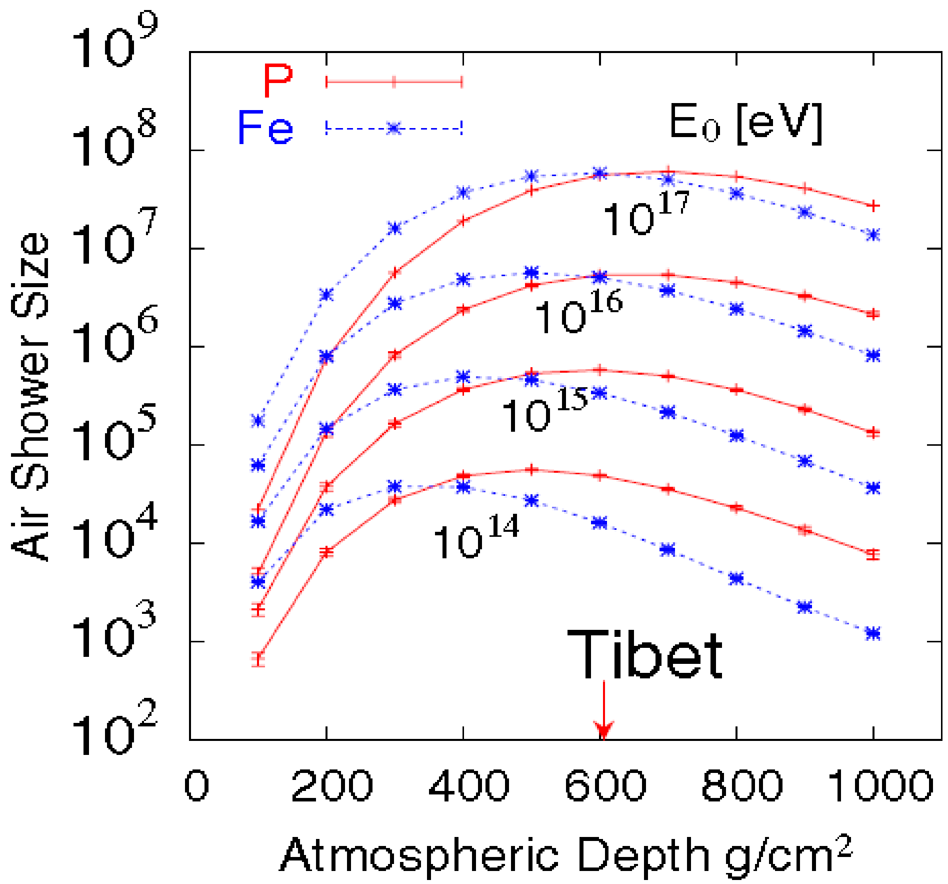


Outline

- Measurement of the CR energy spectrum (all-particle and light component) in the energy range few TeV - 5 PeV by ARGO-YBJ with *different 'eyes'*
  - 'Digital readout' (based on *strip multiplicity*) below 200 TeV
  - 'Analog readout' (based on the *shower core density*) up to 10 PeV → talk by De Mitri
  - Hybrid measurement with a Wide Field of view Cherenkov Telescope 200 TeV - PeV

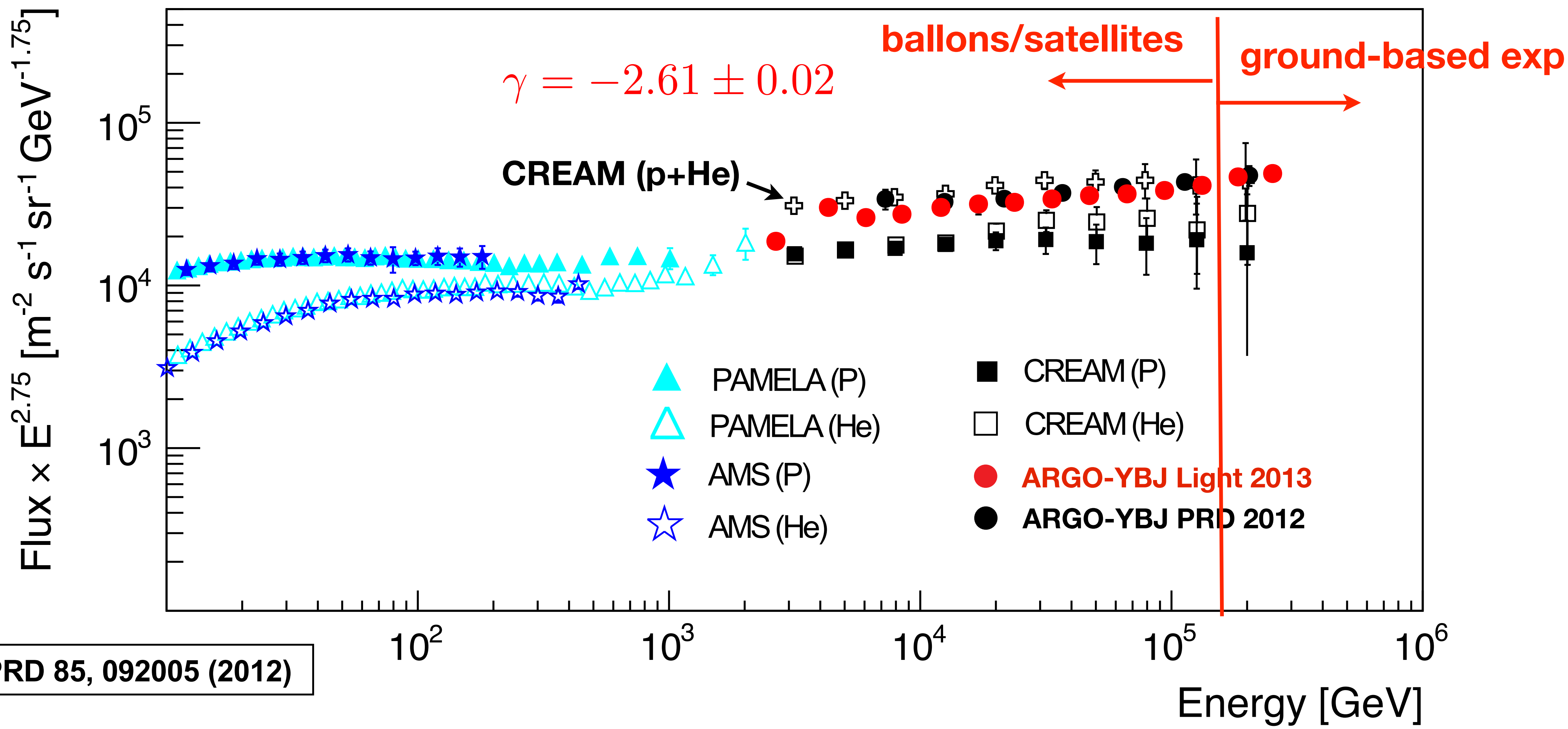
- Working at high altitude (4000 m asl):

1. p and Fe produce showers with similar size
2. Small fluctuations: shower maximum
3. Low energy threshold: overposition with direct measurements → check of the energy scale



The light-component spectrum (2.5 - 300 TeV)

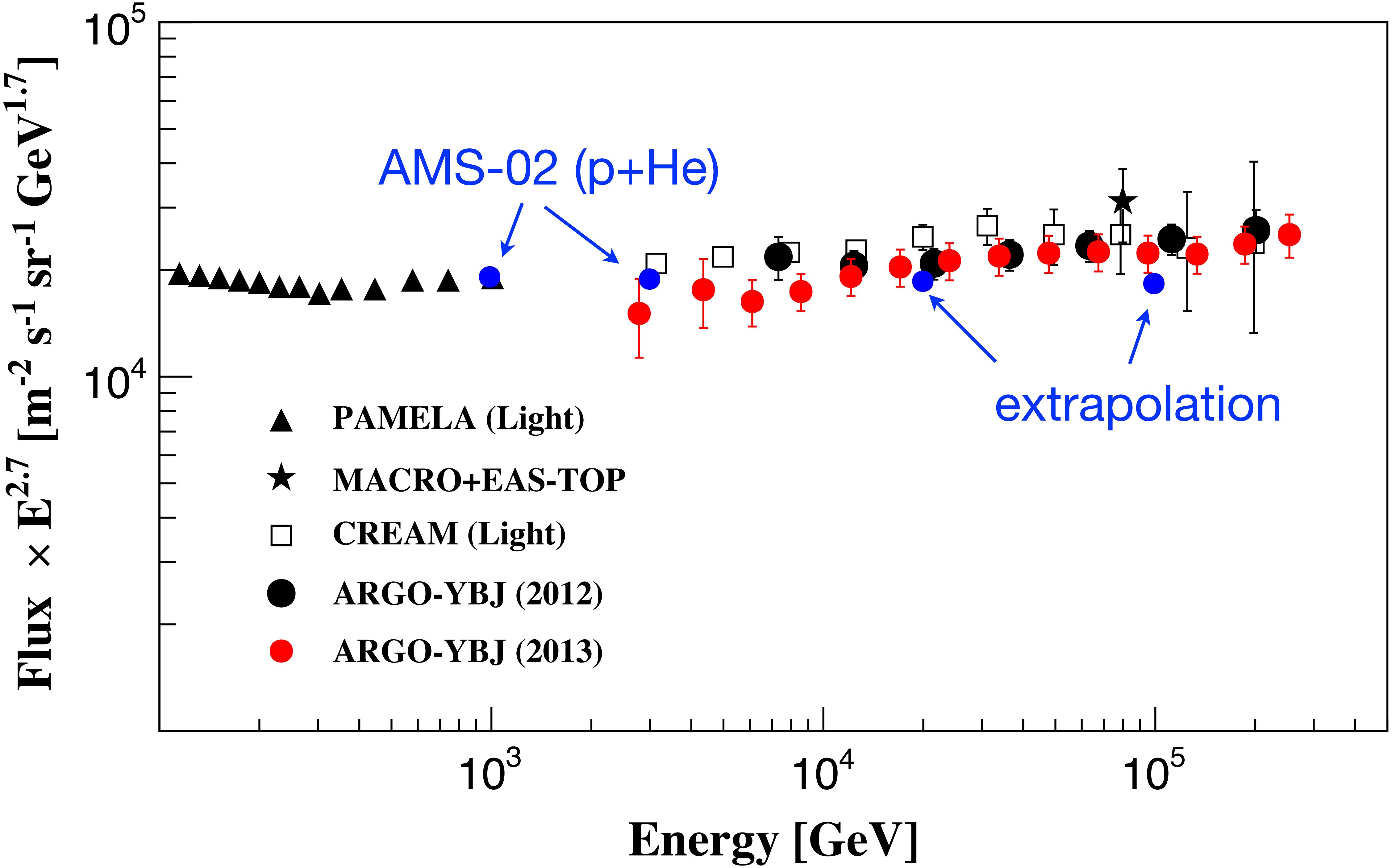
Measurement of the light-component (p+He) CR spectrum in the energy region (2.5 – 300) TeV via a Bayesian unfolding procedure



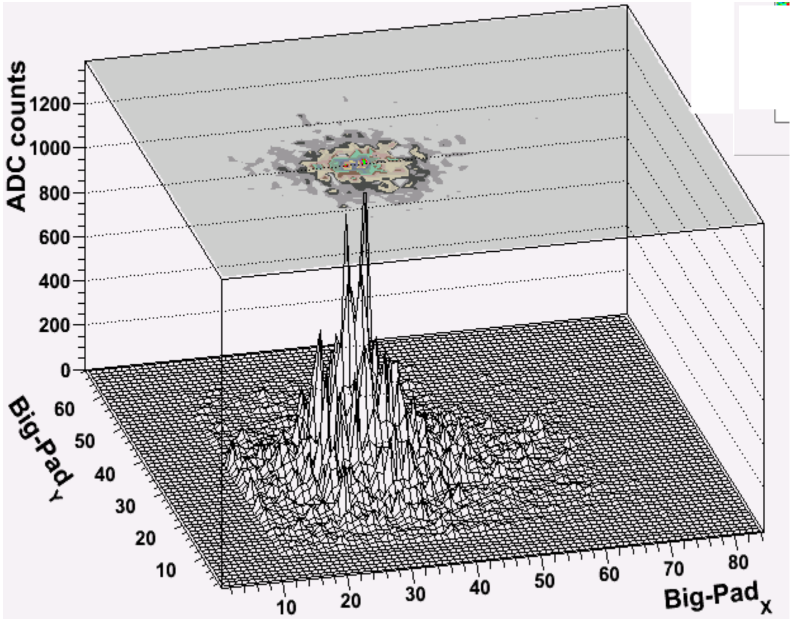
PRD 85, 092005 (2012)

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

ARGO-YBJ and AMS-02 (ICRC13)

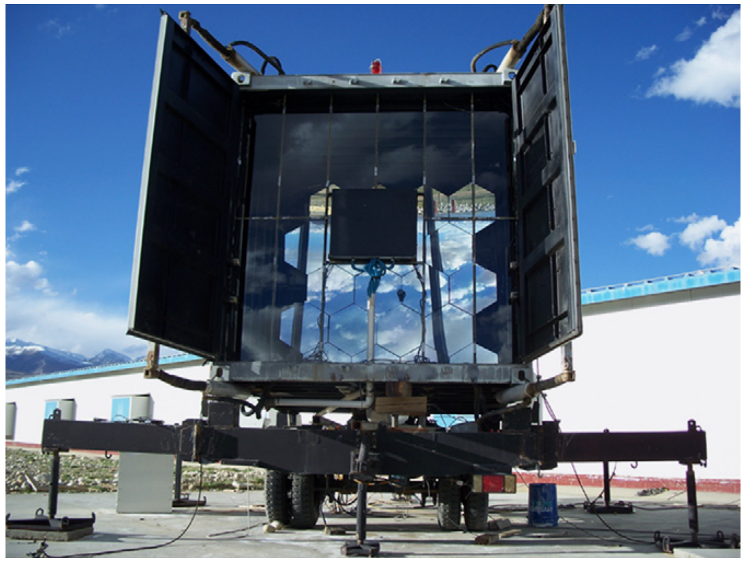


Extending the energy range



To extend the energy range up to 10 PeV we use *different eyes*:

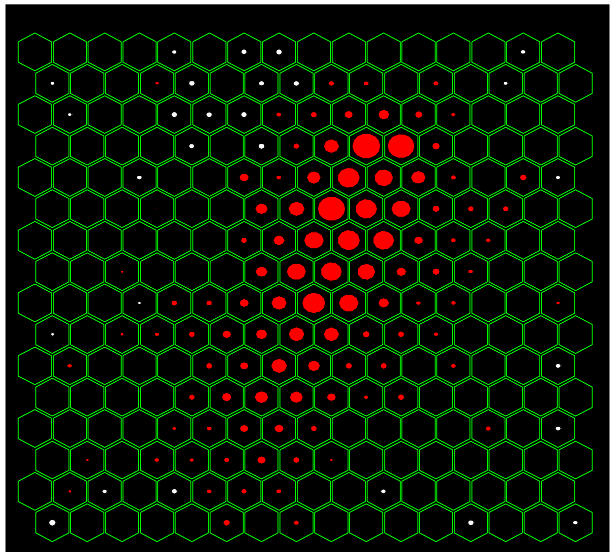
- ❖ ARGO-YBJ Analog Readout
- ❖ Wide Field of view Cherenkov Telescope (WFCTA)
  - 5 m^2 spherical mirror
  - 16 × 16 PMT array
  - pixel size 1°
  - FOV: 14° × 14°
  - Elevation angle: 60°



…to performe 2 different analysis:

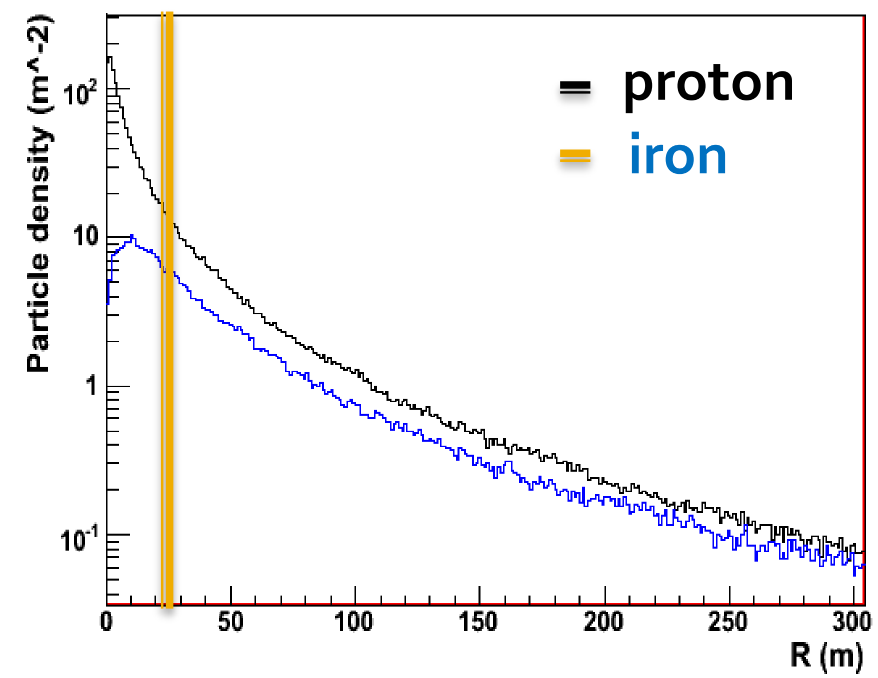
- ❖ ARGO-YBJ Analog Readout alone → talk by De Mitri
- ❖ Hybrid measurement ARGO-YBJ/WFCTA

arXiv:1408.6739



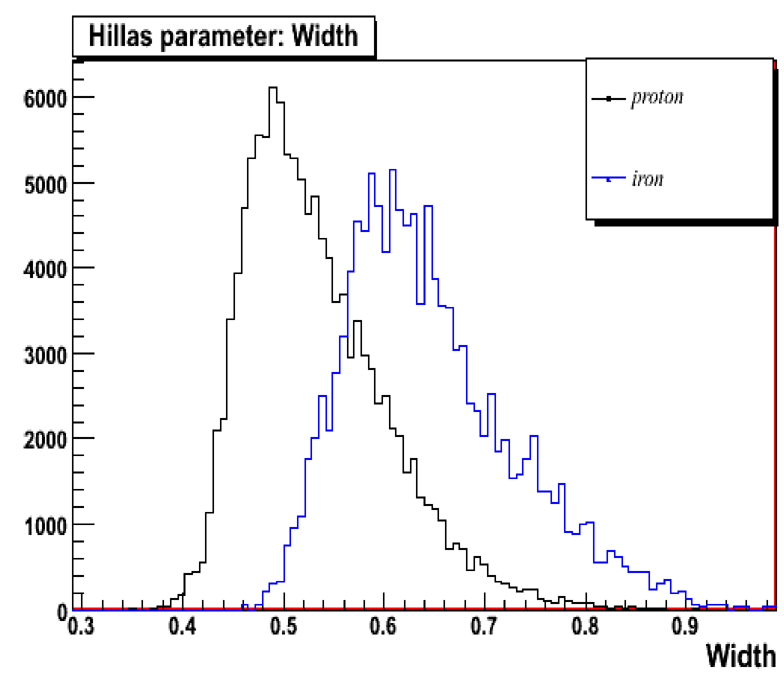
ARGO-YBJ + WFCTA

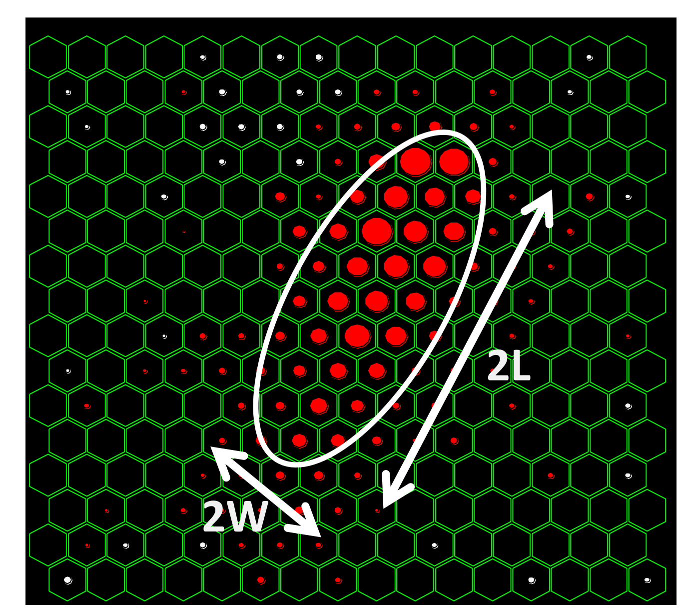
- *ARGO-YBJ:* lateral distribution
  In the core region → mass sensitive



- *Cherenkov telescope:* longitudinal information
  Hillas parameters → mass sensitive
  Better energy resolution

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





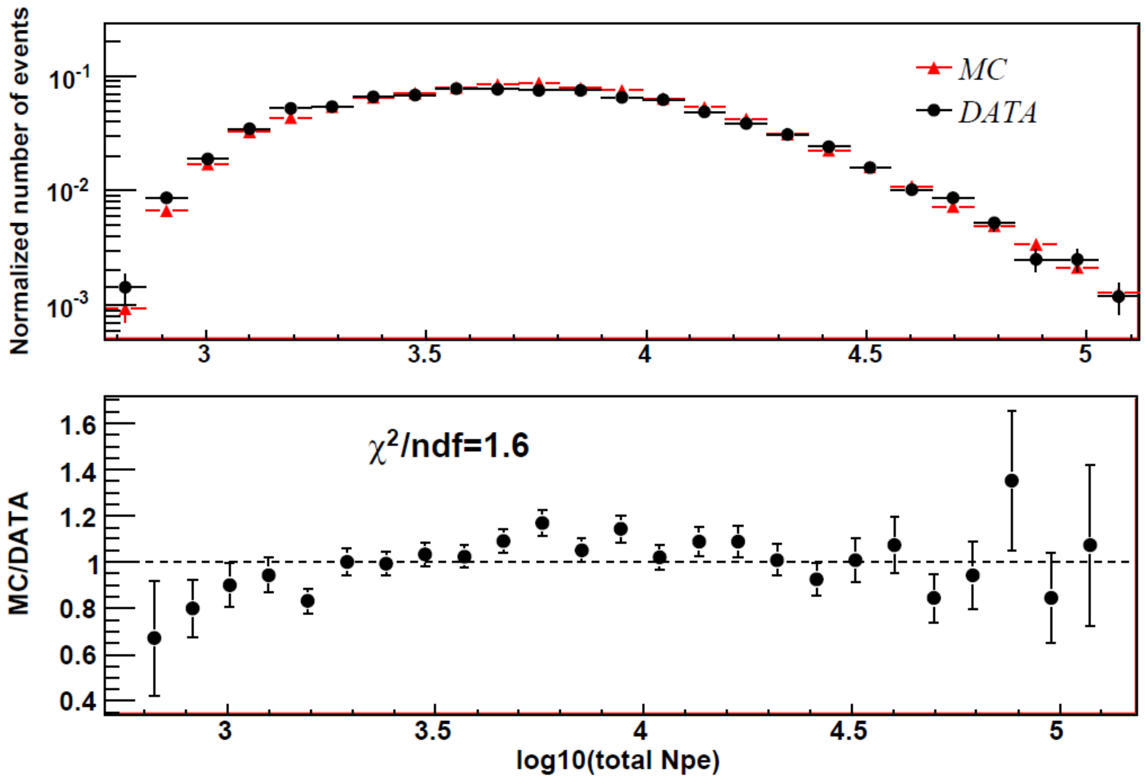
Hybrid observation data set

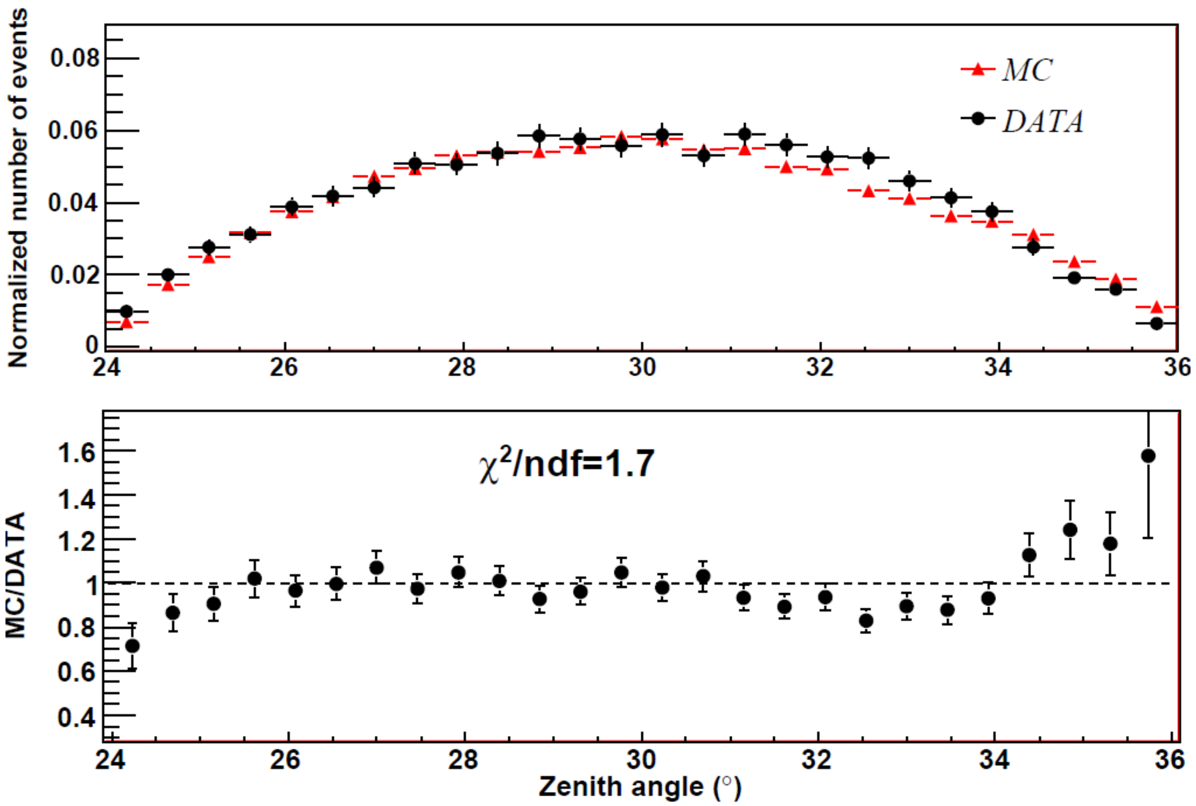
- Period
  - Dec 2010 → Feb. 2012
  - Good wheater: 728,000 sec
- Criteria for reconstruction
  - Shower cores well inside the ARGO-YBJ central carpet
  - Cherenkov images well contained in the telescope, i.e. space angle with respect to the telescope axis < 6°
  - Number of fired PMTs ≥ 6
- Cherenkov image cleaning
  - Single channel threshold: S/N>3.5.
  - Arrival time: all triggered pixels in a window of Δt = 240 ns.
  - Isolated pixels rejected

➡ 8218 events well reconstructed above 100 TeV

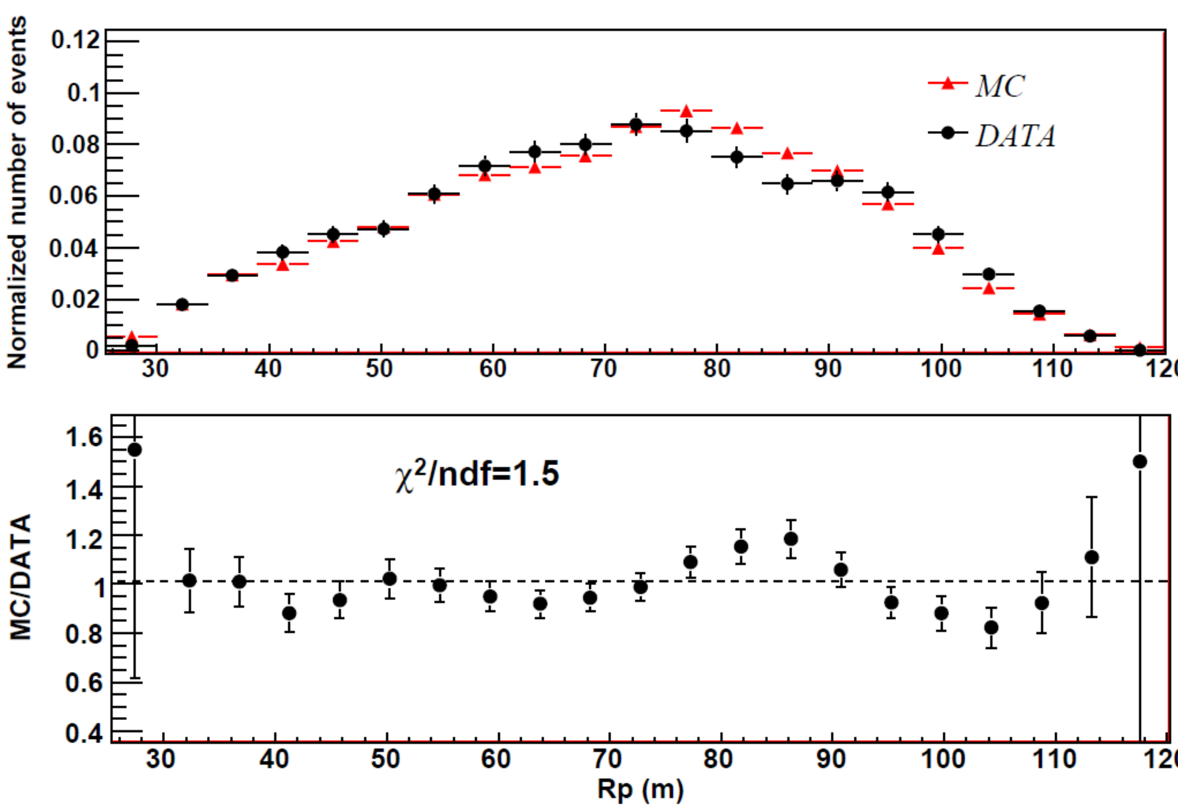
Comparison Data-MC

Total number of photo-electrons





Zenith angle of the shower arrival direction



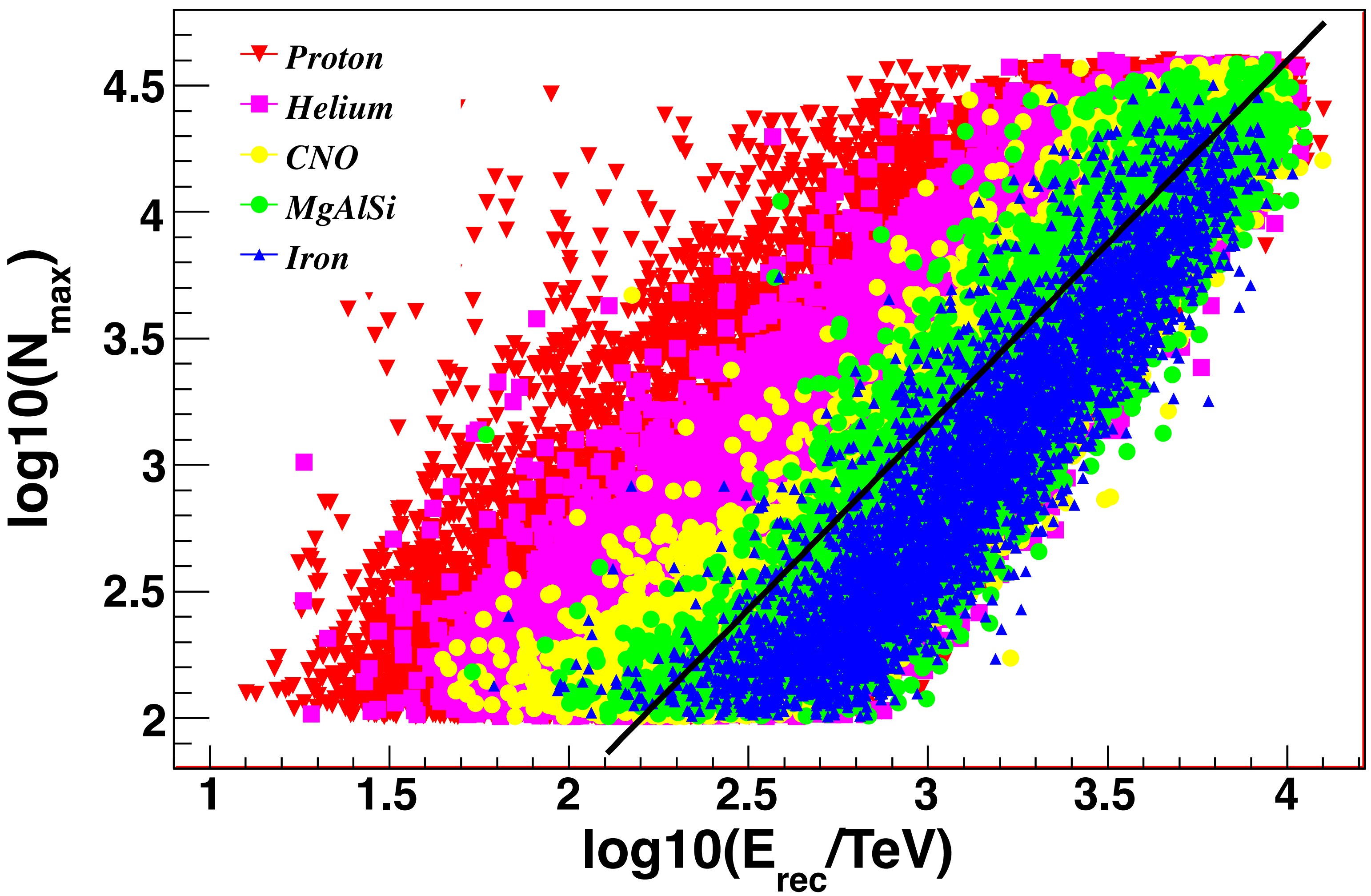
Distance between shower core position and Cherenkov telescope

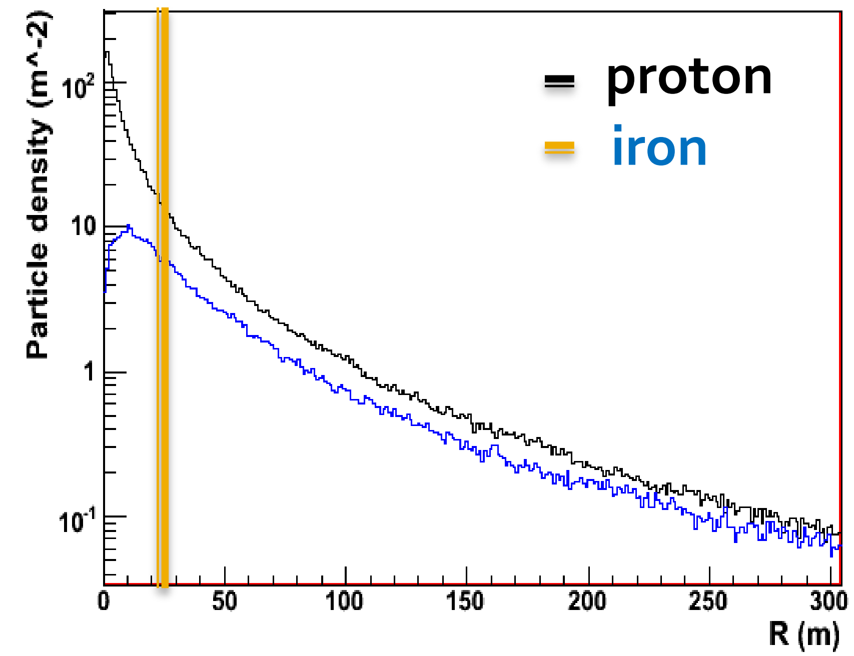
Light component (p + He) selection - (1)

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.

Nmax 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.





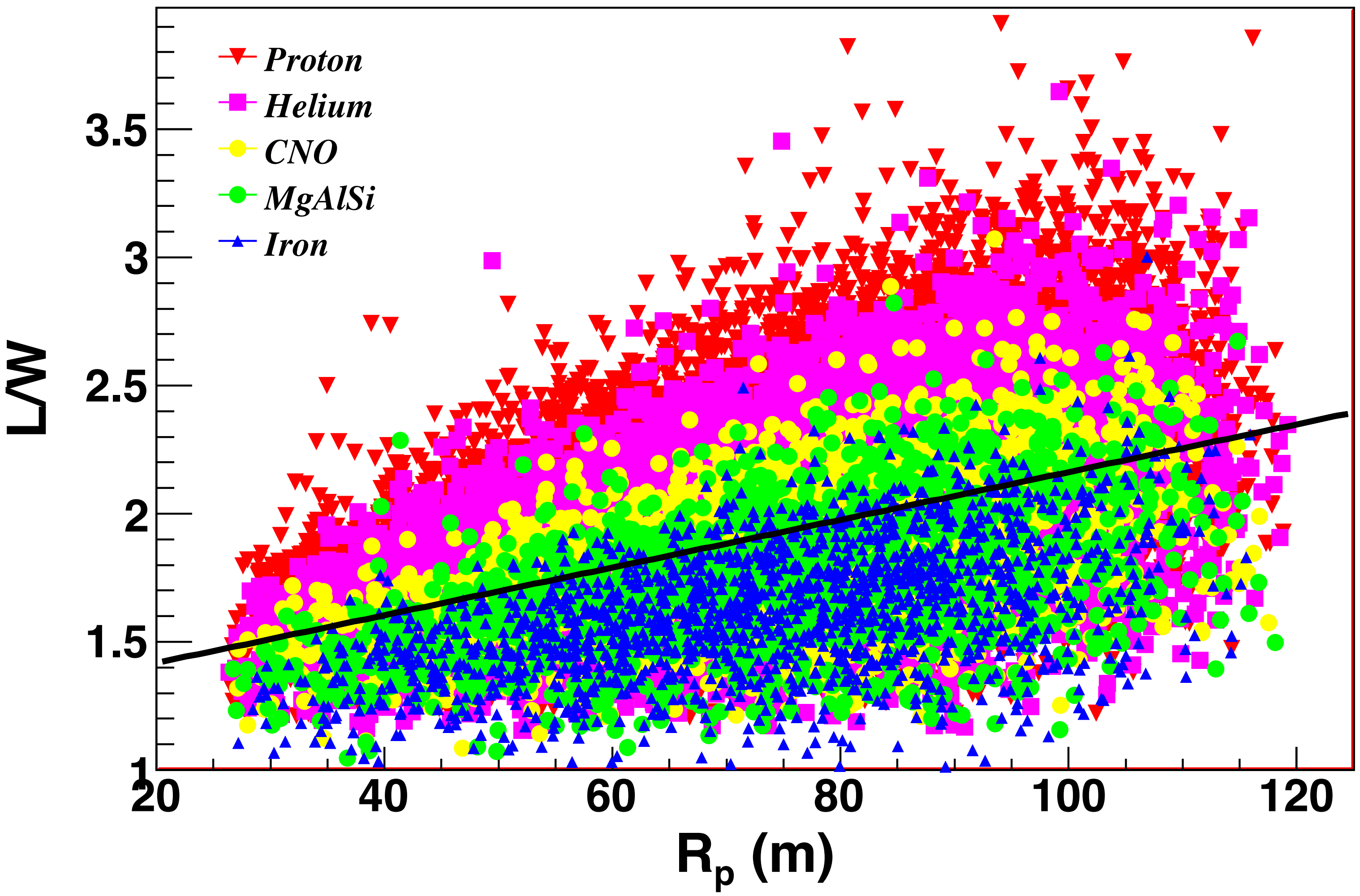
We can define a new parameter to reduce the energy dependence

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

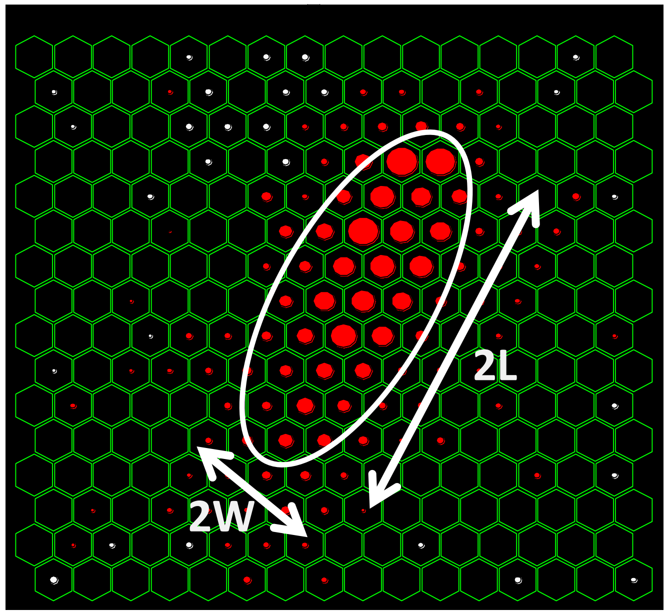
Light component (p + He) selection - (2)

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

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

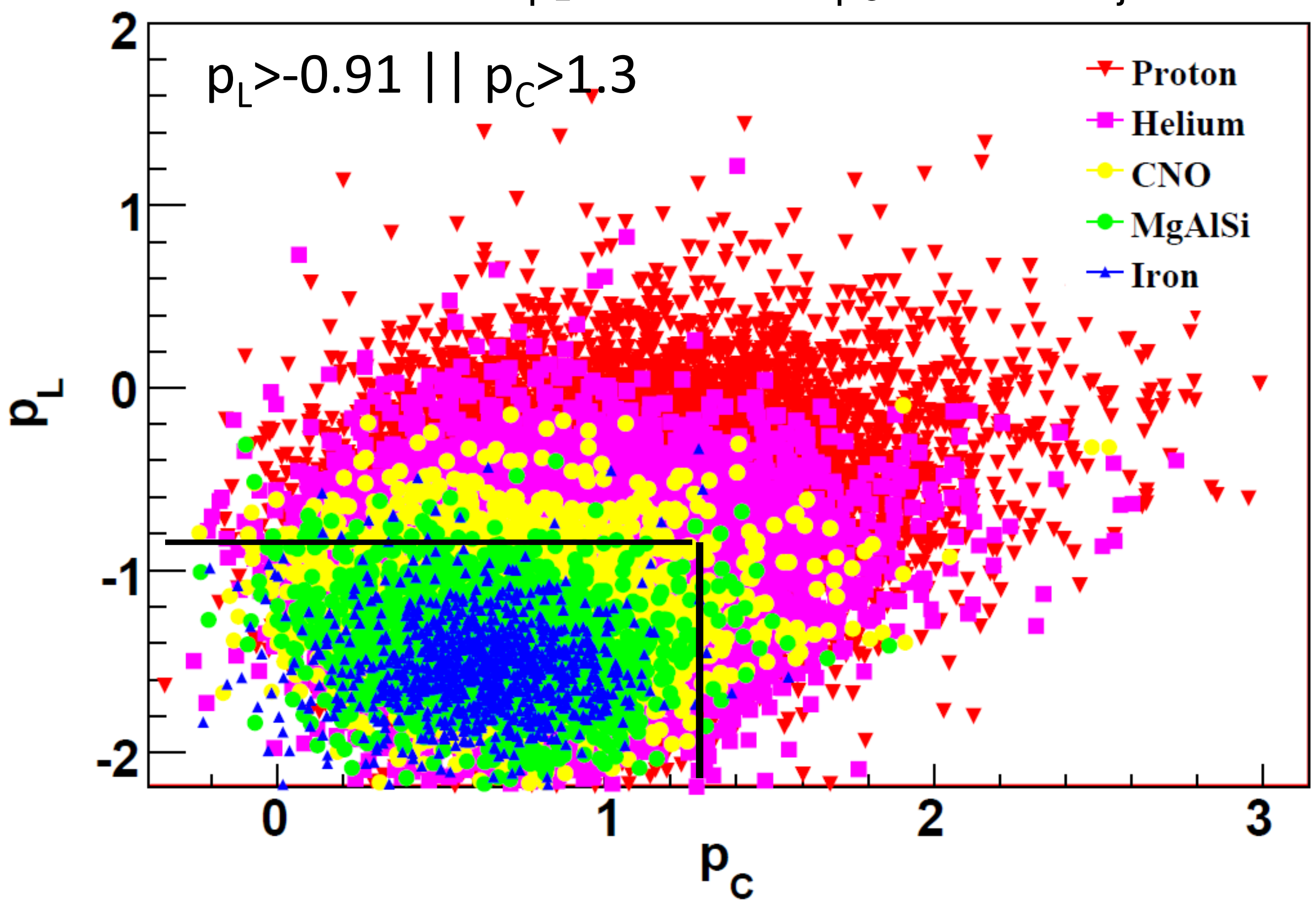
Light component (p + He) selection - (3)

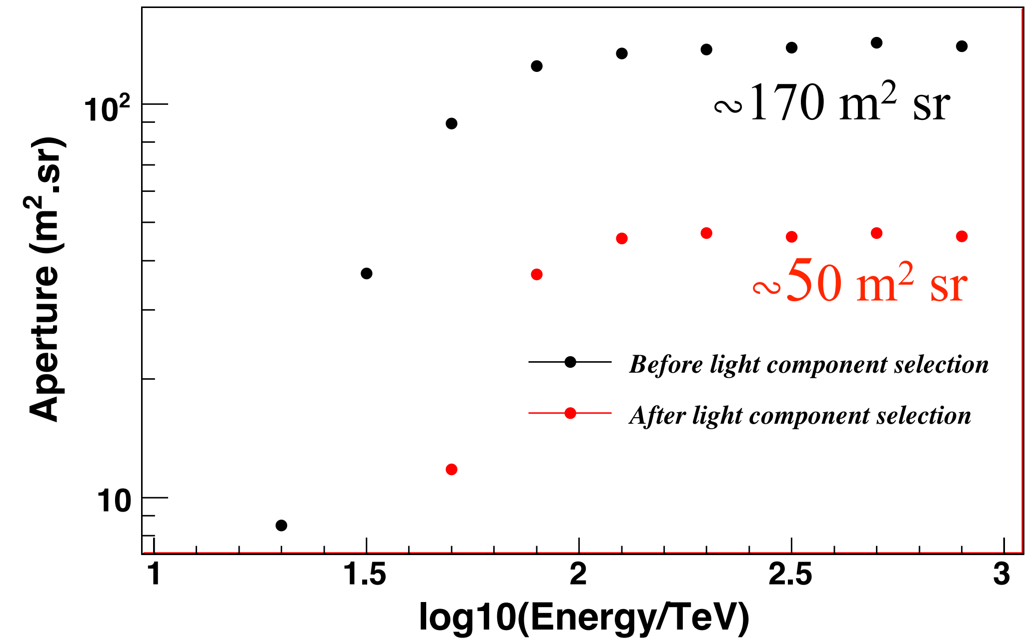
- Contamination of heavier component < 4 %
- Energy resolution: ~25% constant with energy
- Uncertainty : ~25% on flux

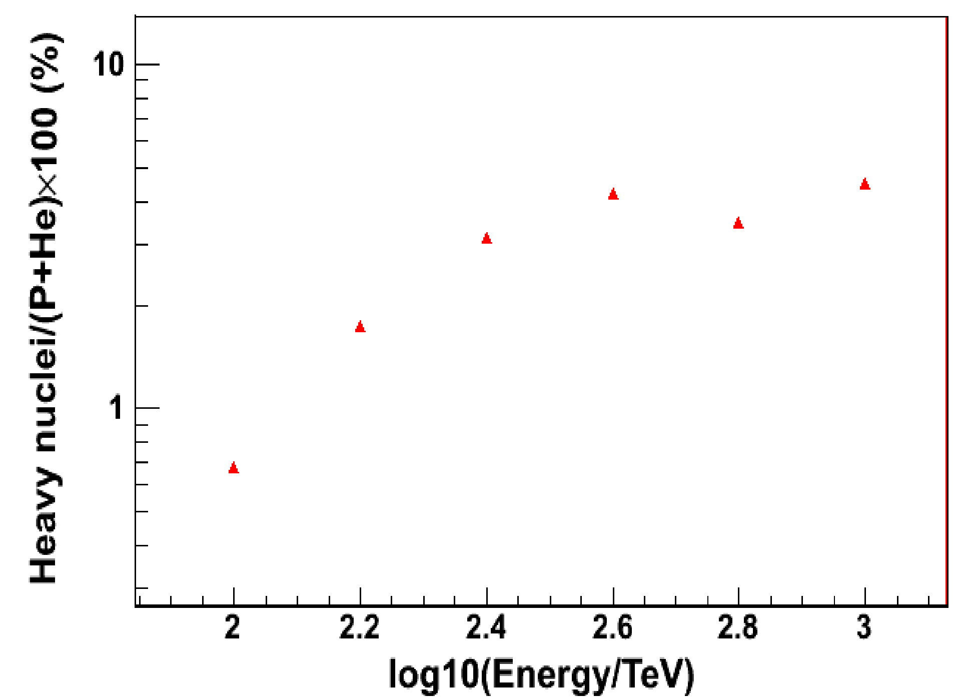
$$\boxed{p_L = log_{10}(N_{max}) - 1.44 \cdot log_{10}(E_{rec}/TeV)}$$

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

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

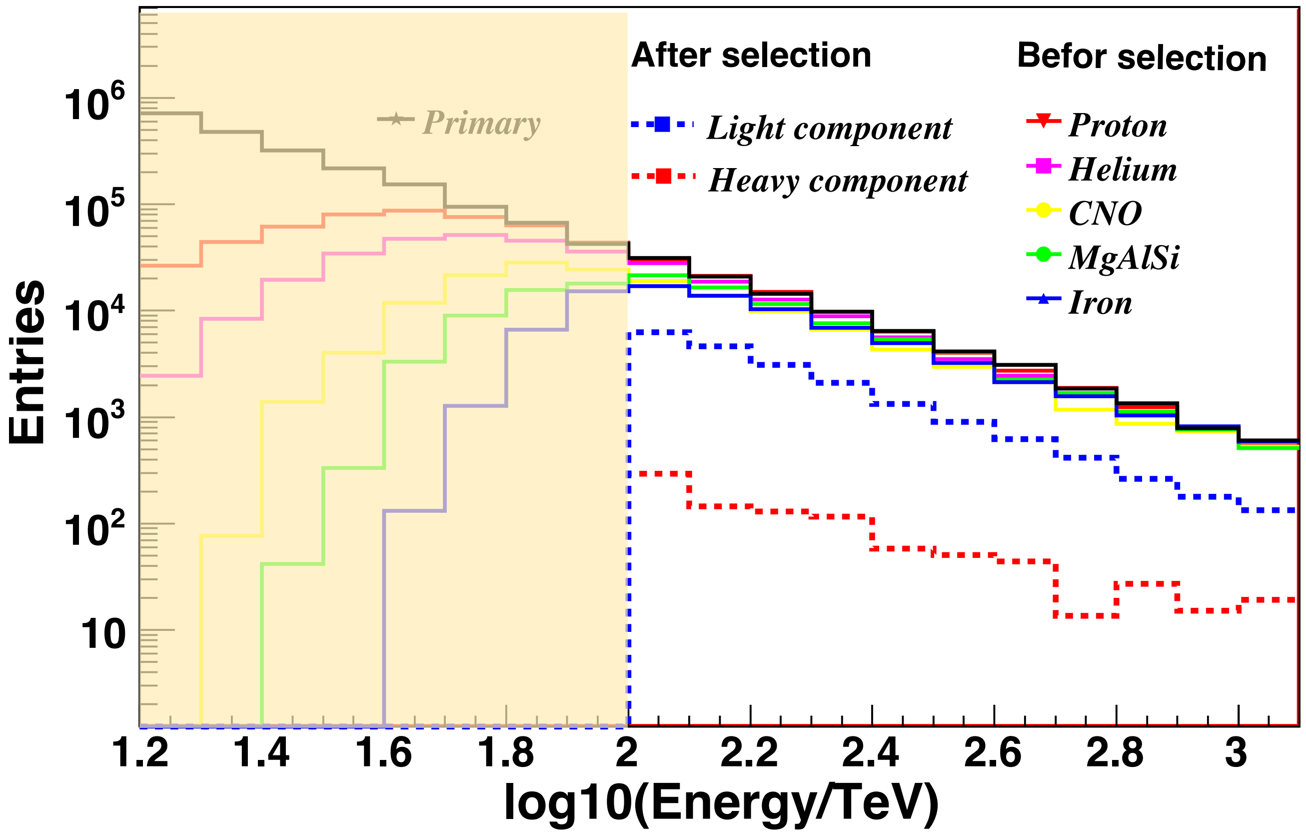


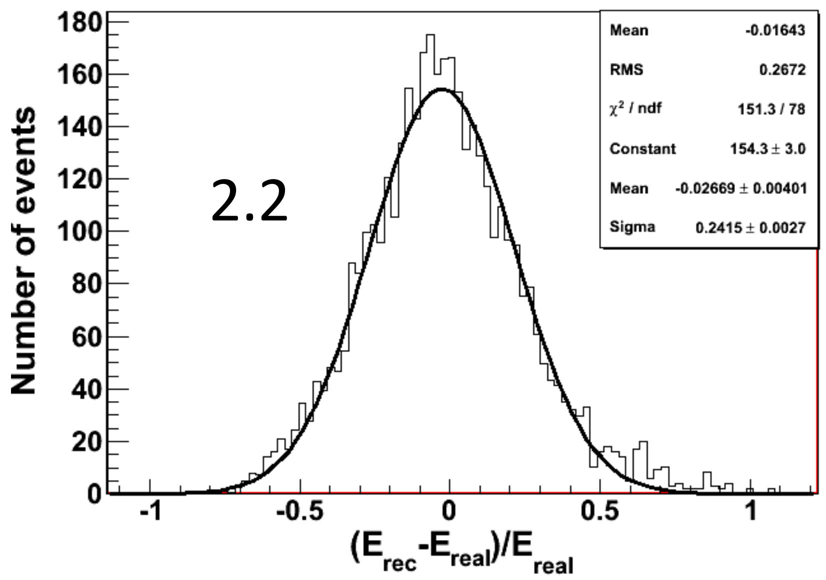


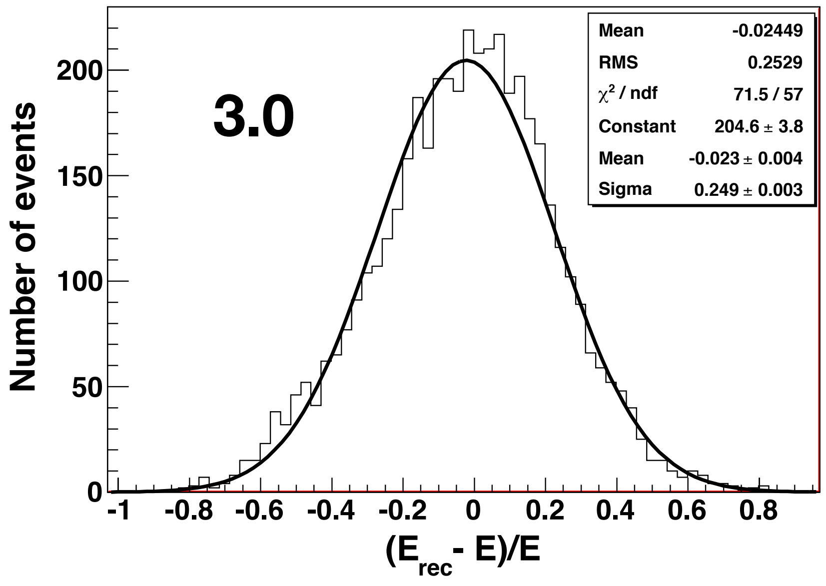


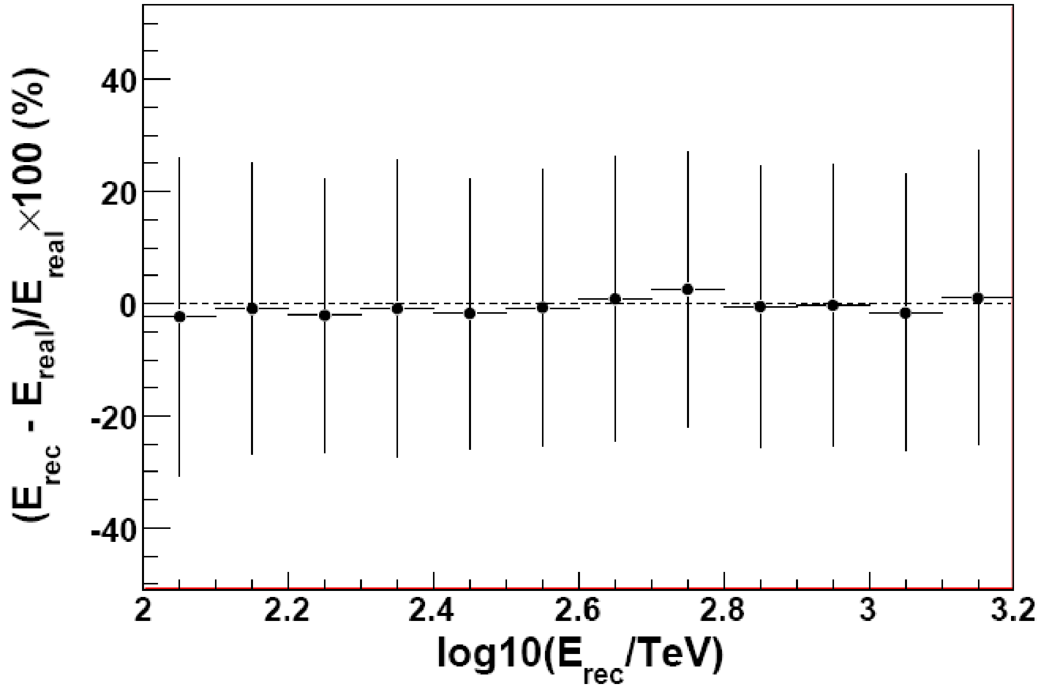
Bartoli et al., Chin. Phys. C 38, 045001 (2014)

Light component (p + He) selection - (4)





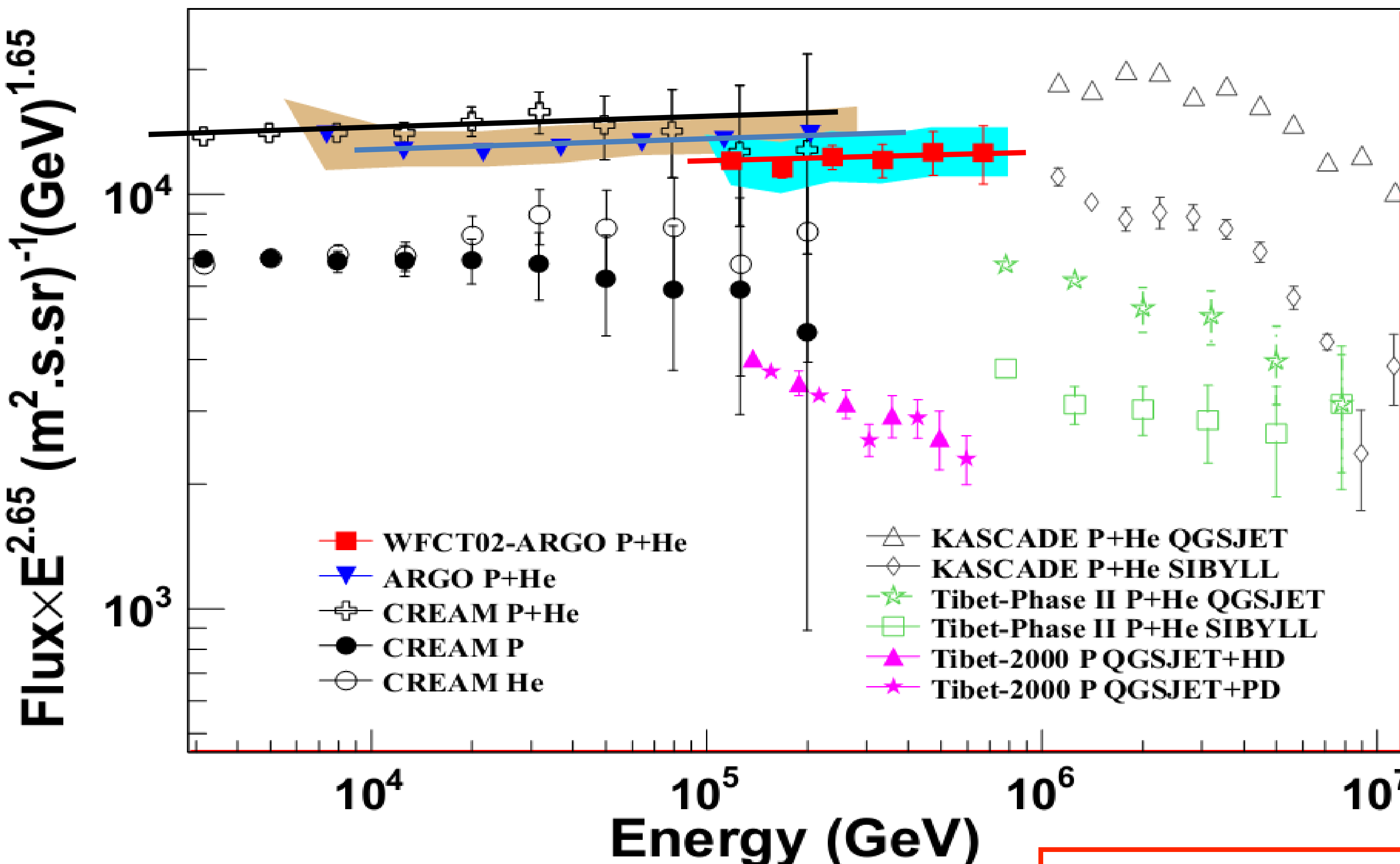




The light-component (p+He) spectrum (2 - 700) TeV

- 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})

Bartoli et al., Chin. Phys. C 38, 045001 (2014)

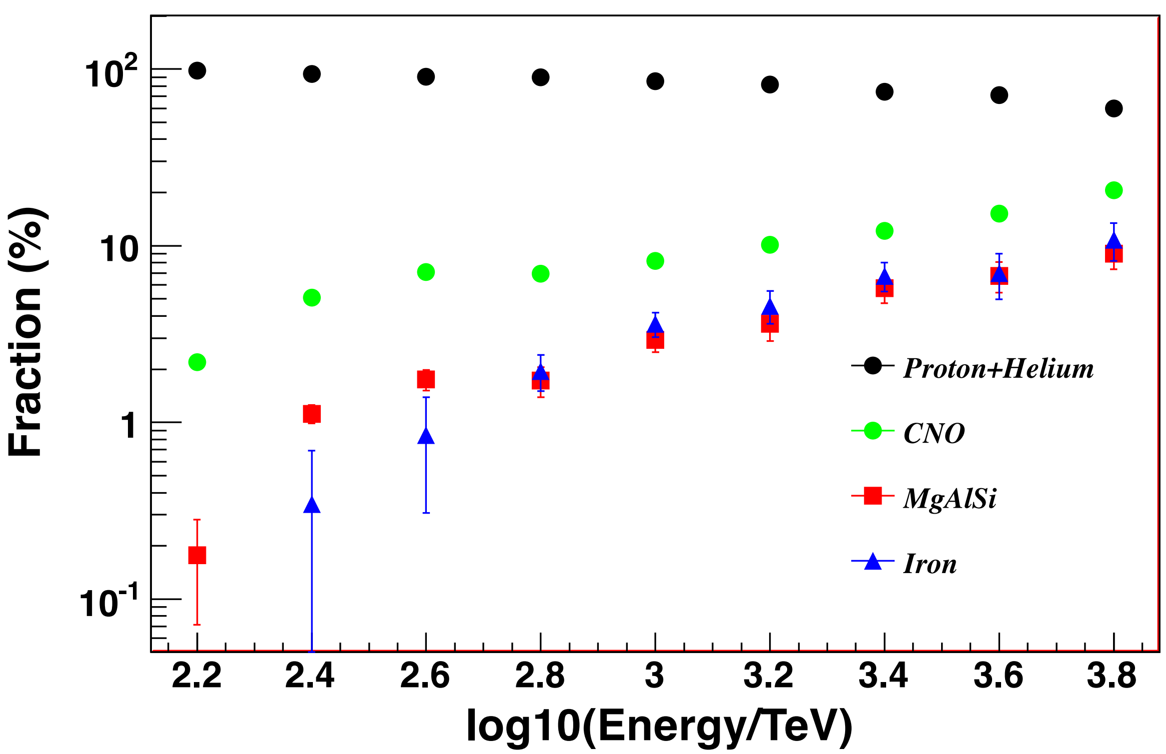
The 9% difference in flux corresponds to a difference of ± 4% in energy scale between different experiments.

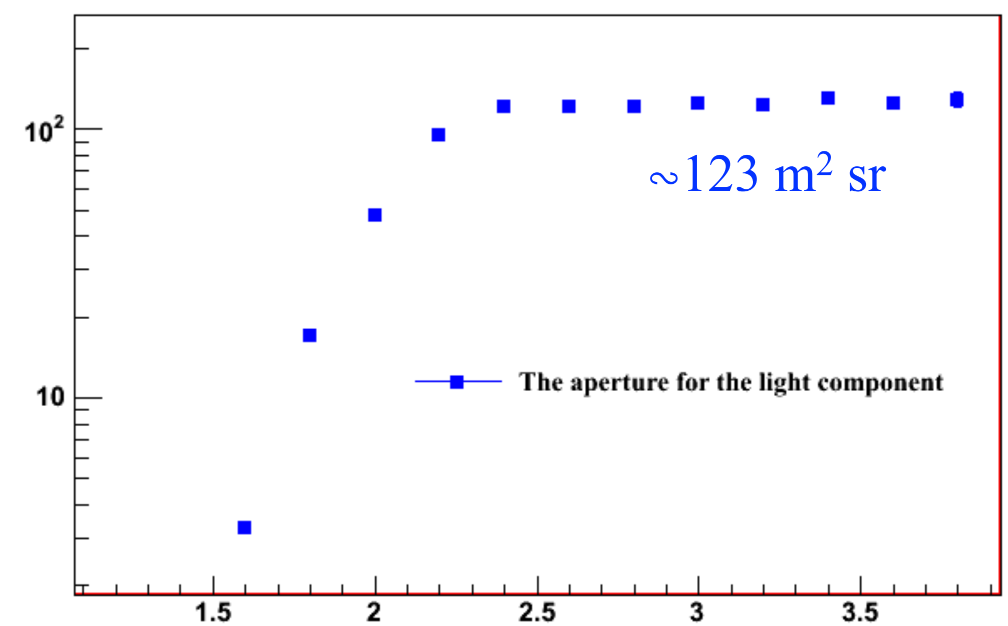
Approaching the all-particle knee

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 $p_L \leq -1.25$ and $p_C \leq 1.1$ 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.

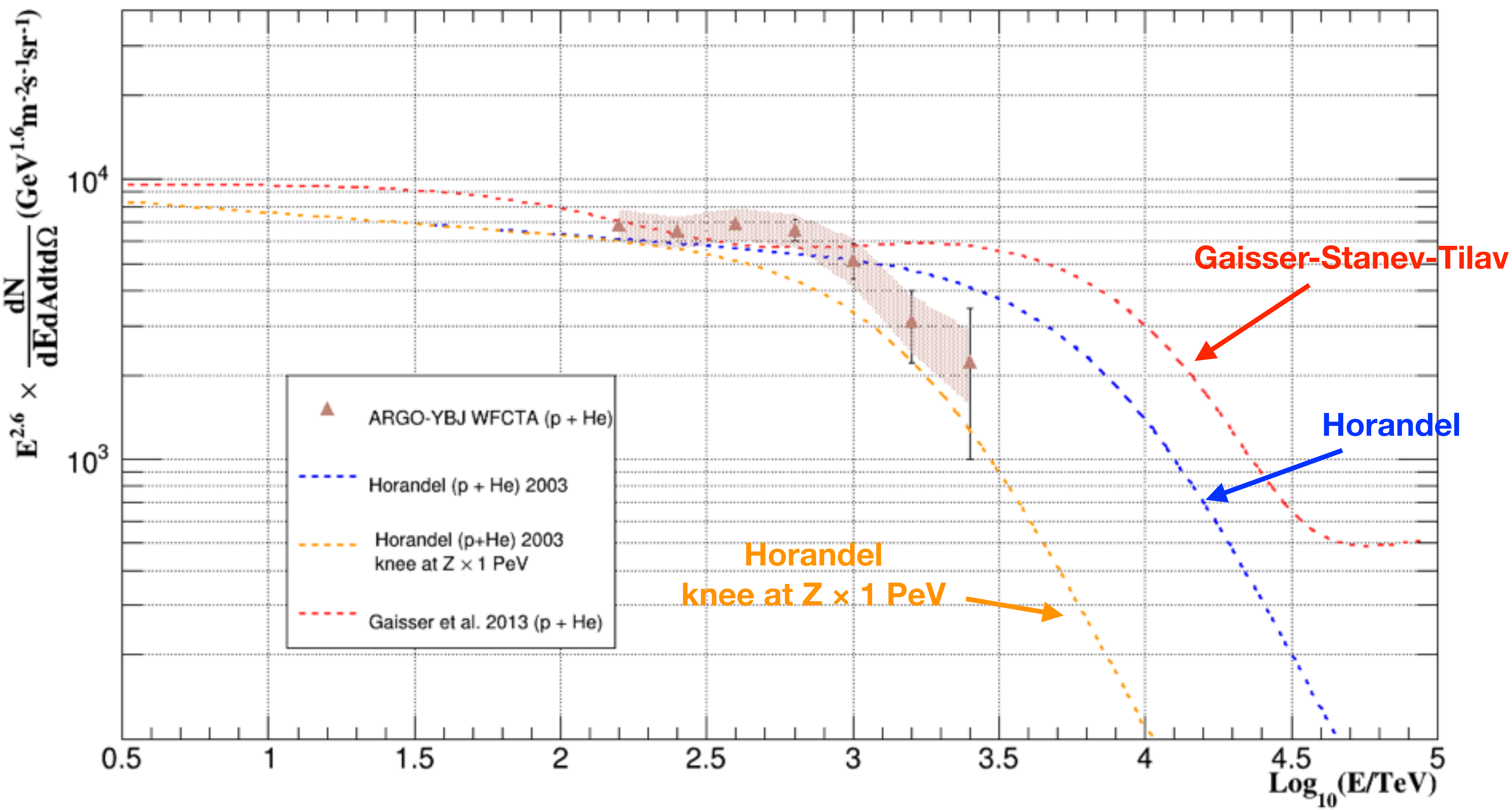




Calculations based on the Horandel spectrum

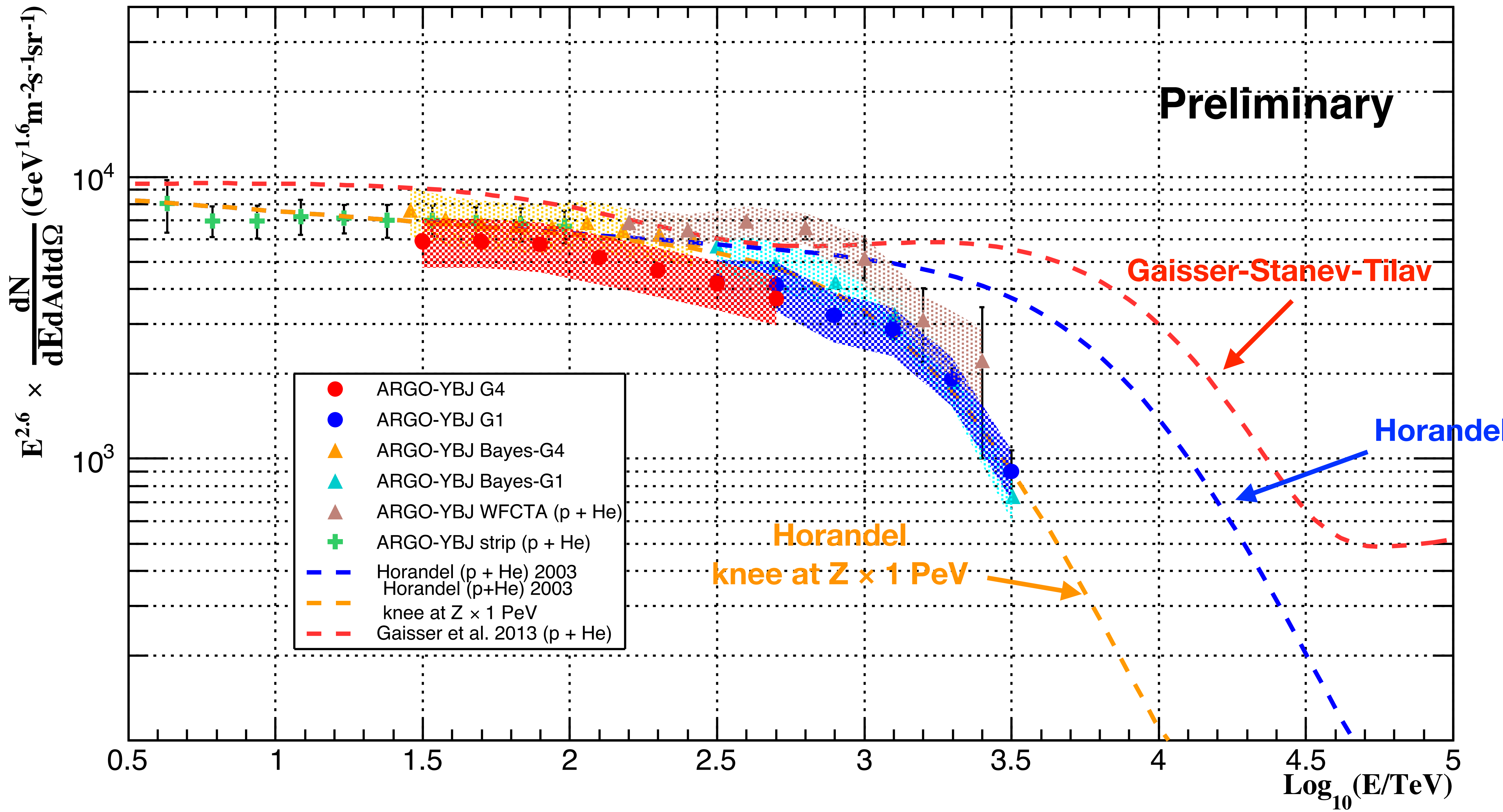
Light component knee with ARGO-YBJ / WFCTA

Observation of gradual change of the slope starting around 700 TeV



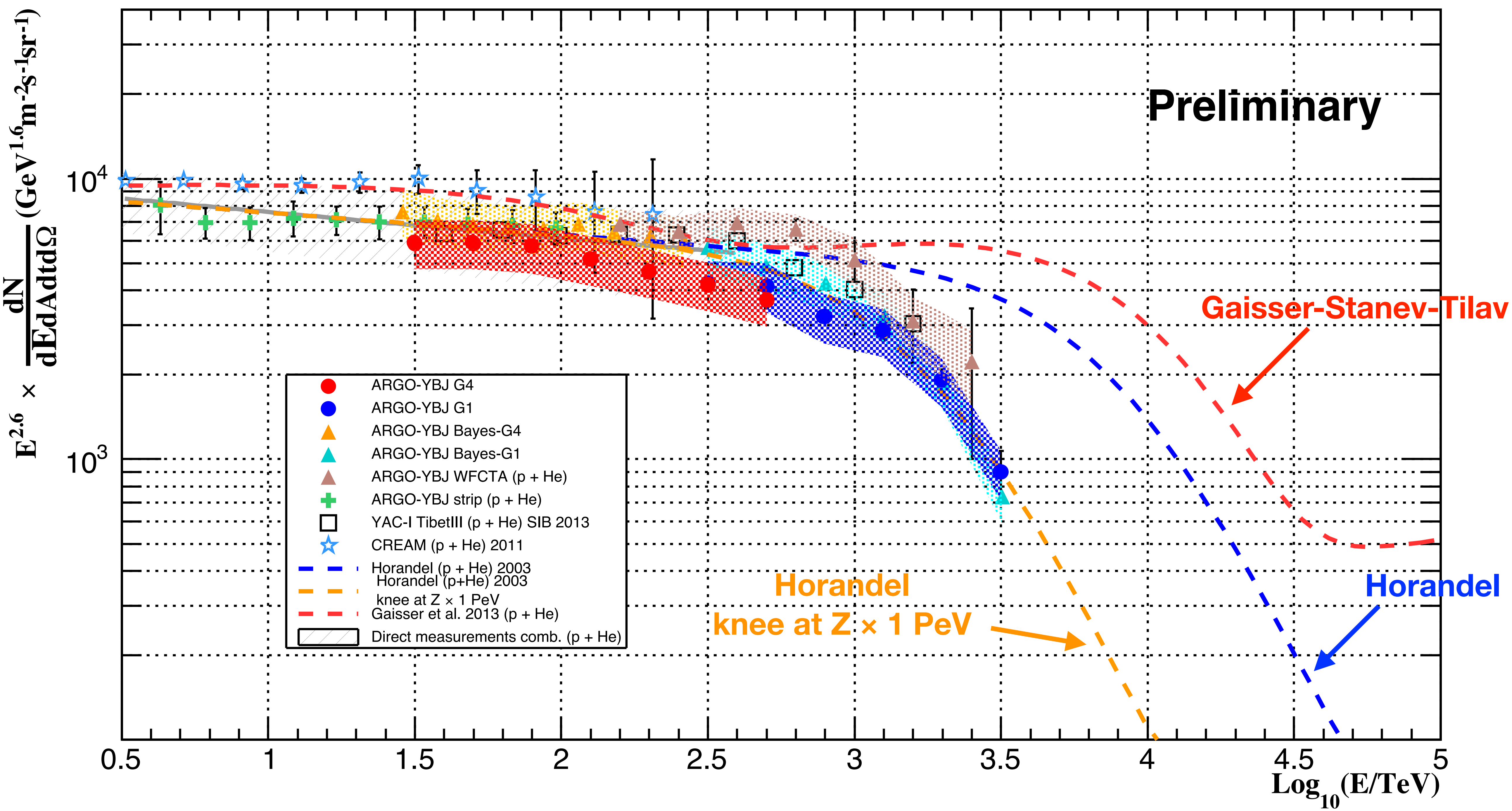
Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Observation of gradual change of the slope starting around 700 TeV

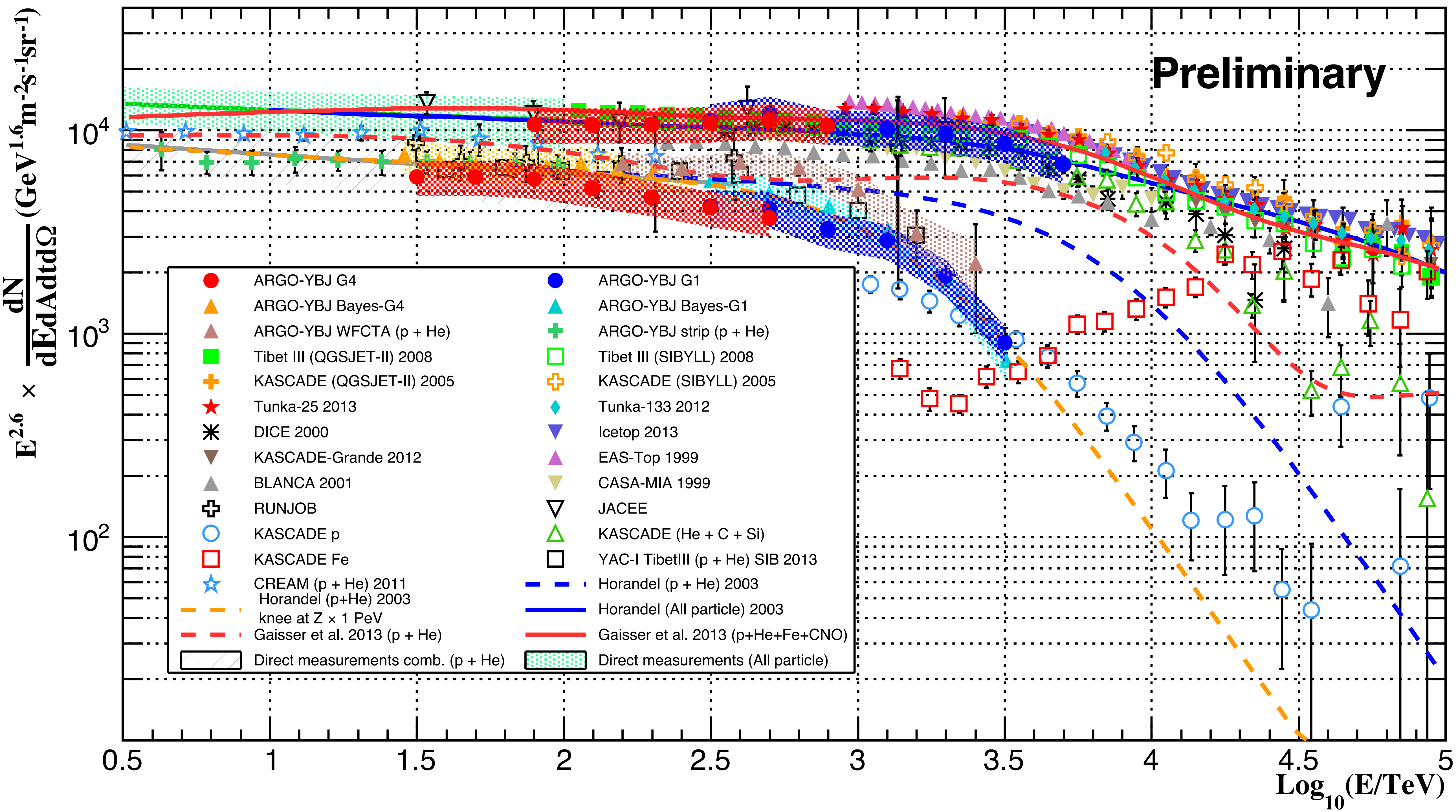


Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Comparison with direct measurements and with Tibet ASgamma (SYBILL)



The overall picture



Some conclusions on CR spectra measurements

- The CR energy spectrum has been studied by the ARGO-YBJ experiment in a wide energy range (TeVs → PeVs) exploiting different approaches.
- The light component (p+He) energy spectrum measured below 200 TeV is in good agreement with the CREAM results.
- The Moon shadow technique and the overposition with the CREAM data allow to fix/check the absolute energy scale of ARGO-YBJ down to 4\% level.
- The all-particle spectrum measured in the energy range 100 -- 3000 TeV is in good agreement with well-known parametrizations, making us confident about the selection and reconstruction of the analog data.
- The light component (p+He) has been reconstructed up to about 5 PeV.
- The ARGO-YBJ results show an indication of a knee-like structure starting at about 700 TeV.
- The results obtained with a hybrid measurement is consistent with the measurements carried out by ARGO-YBJ.
- Preliminary results obtained with the last analog gain scale (able to extend the energy range of the charge readout by a factor of 2 at least) are consistent with the results obtained at lower energies.

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 energy range.

A number of interesting results have been obtained

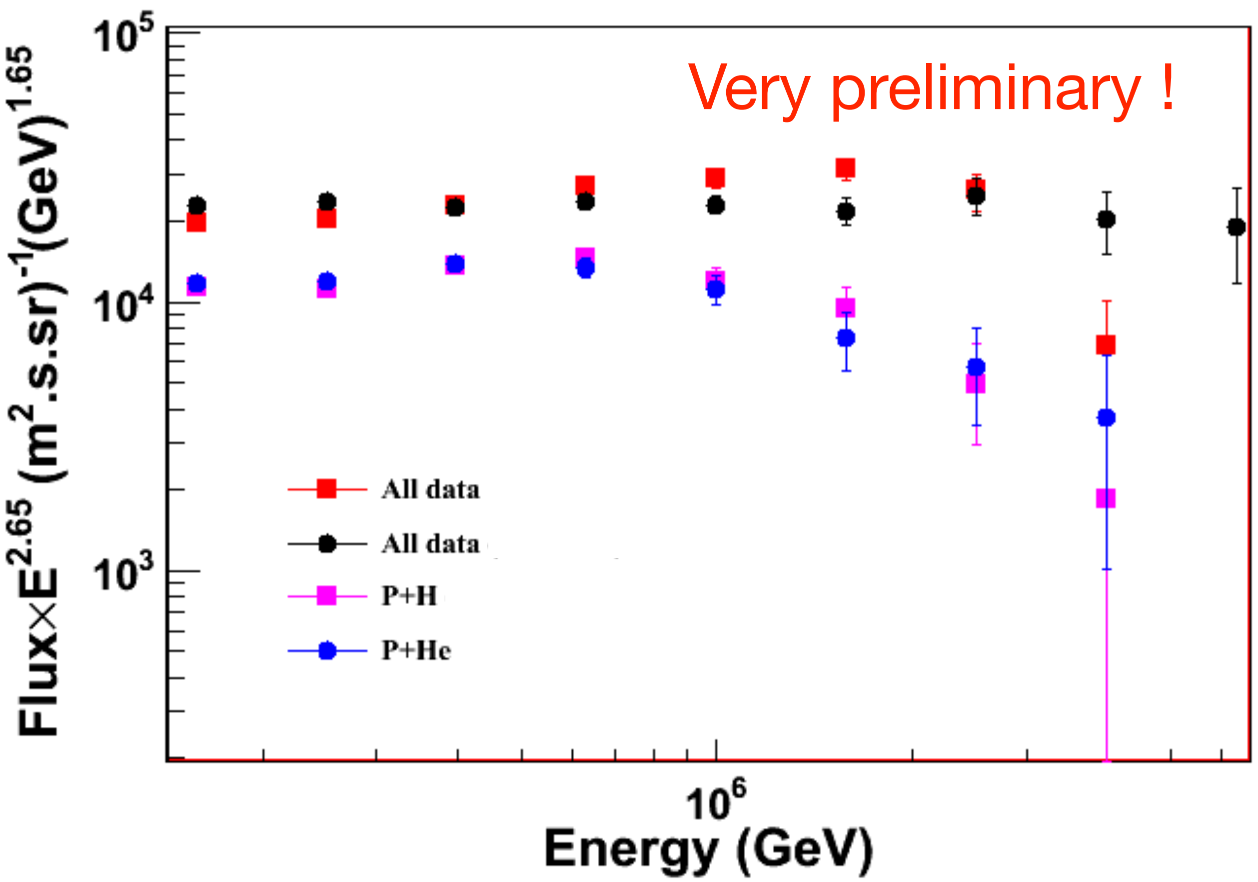
- First Northern sky survey ($-10° < \delta < 70°$) at 0.25 Crab Units
- Observation of the TeV counterpart of the Cygnus Cocoon
- Measurement of γ-rays diffuse emission from Galactic Plane
- Detailed study of flaring and extedend TeV gamma-ray sources

- 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

"Main physics results of the ARGO-YBJ experiment", 80 pages, invited review, Int. J. of Mod. Phys D, in press

ARGO-YBJ + WFCTA: all-particle spectrum

Analysis under way with different event selections

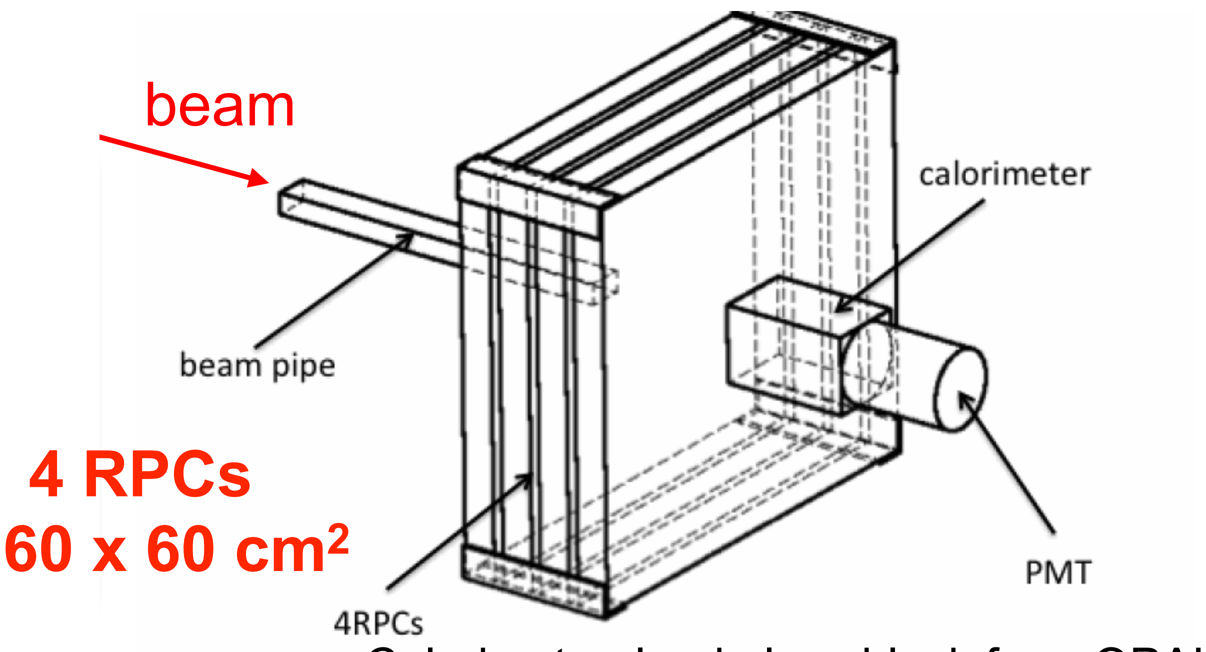


Intrinsic linearity: test at the BTF facility

Linearity of the RPC @ BTF in INFN Frascati Lab:

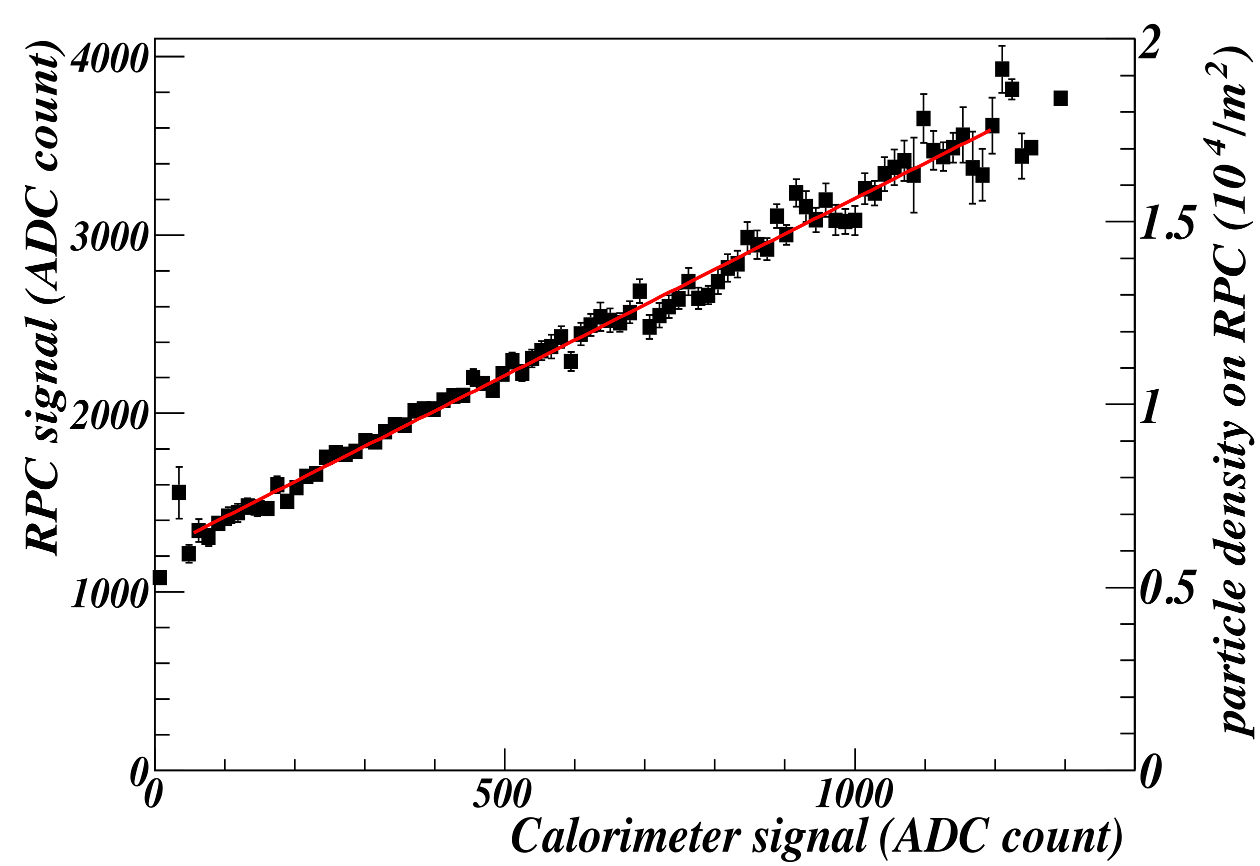
- *electrons (or positrons)*
- *E = 25-750 MeV (0.5% resolution)*
- *<N>=1÷10^{8}particles/pulse*
- *10 ns pulses, 1-49 Hz*
- *beam spot uniform on 3×5 cm*

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



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

The RPC signal vs the calorimeter signal



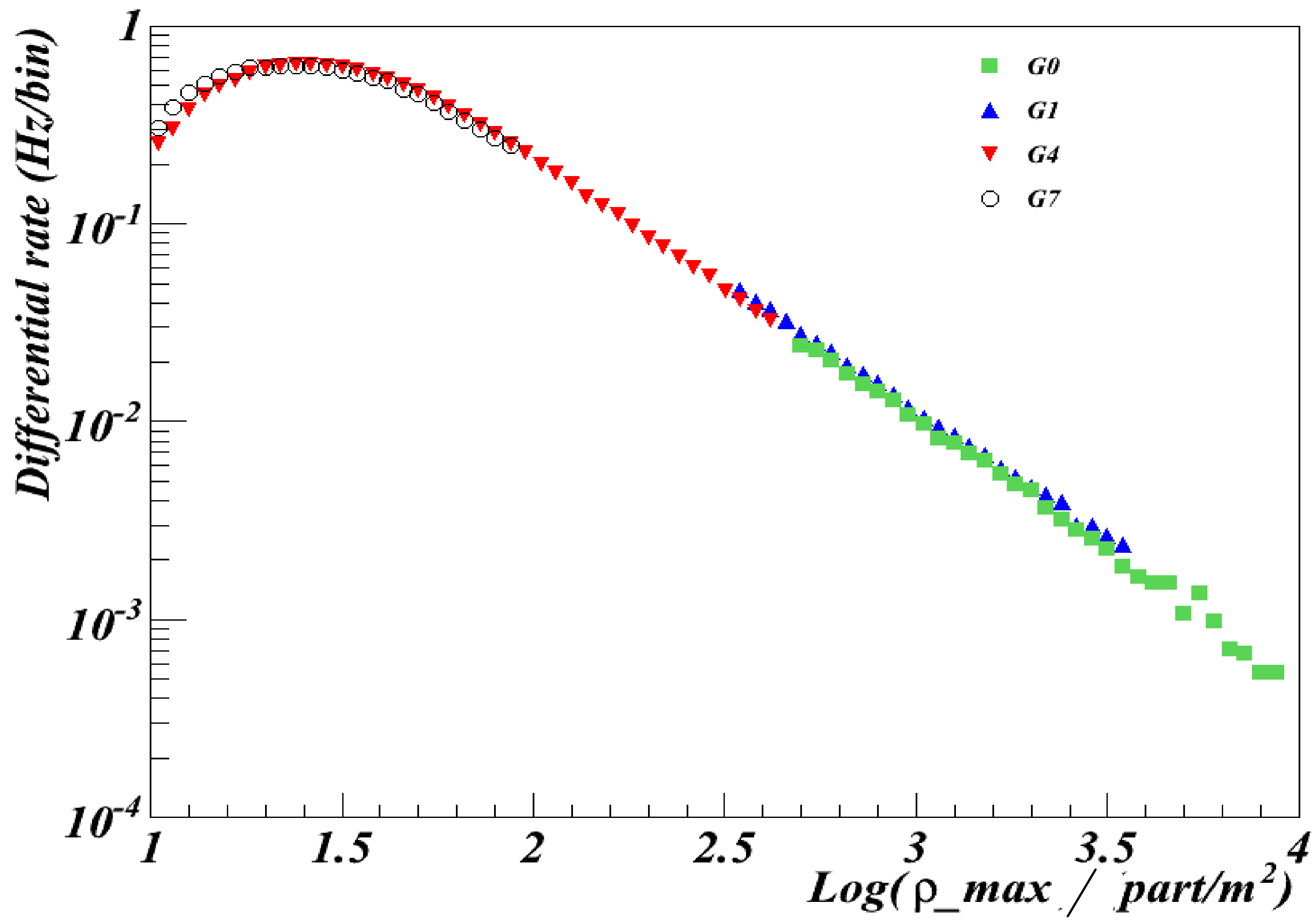
Astroparticle Physics submitted

Performance evaluation

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



4 data sample:

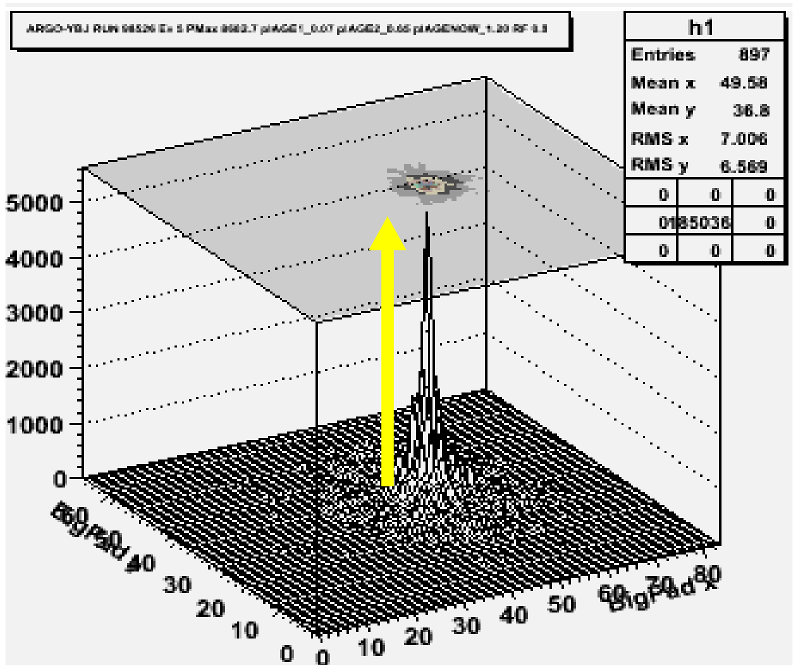
ρ: 10 → 10^4 part/m^2

Event selection:

- Core reconstructed in a fiducial area of 2400 m^2
- Zenith angle < 15°

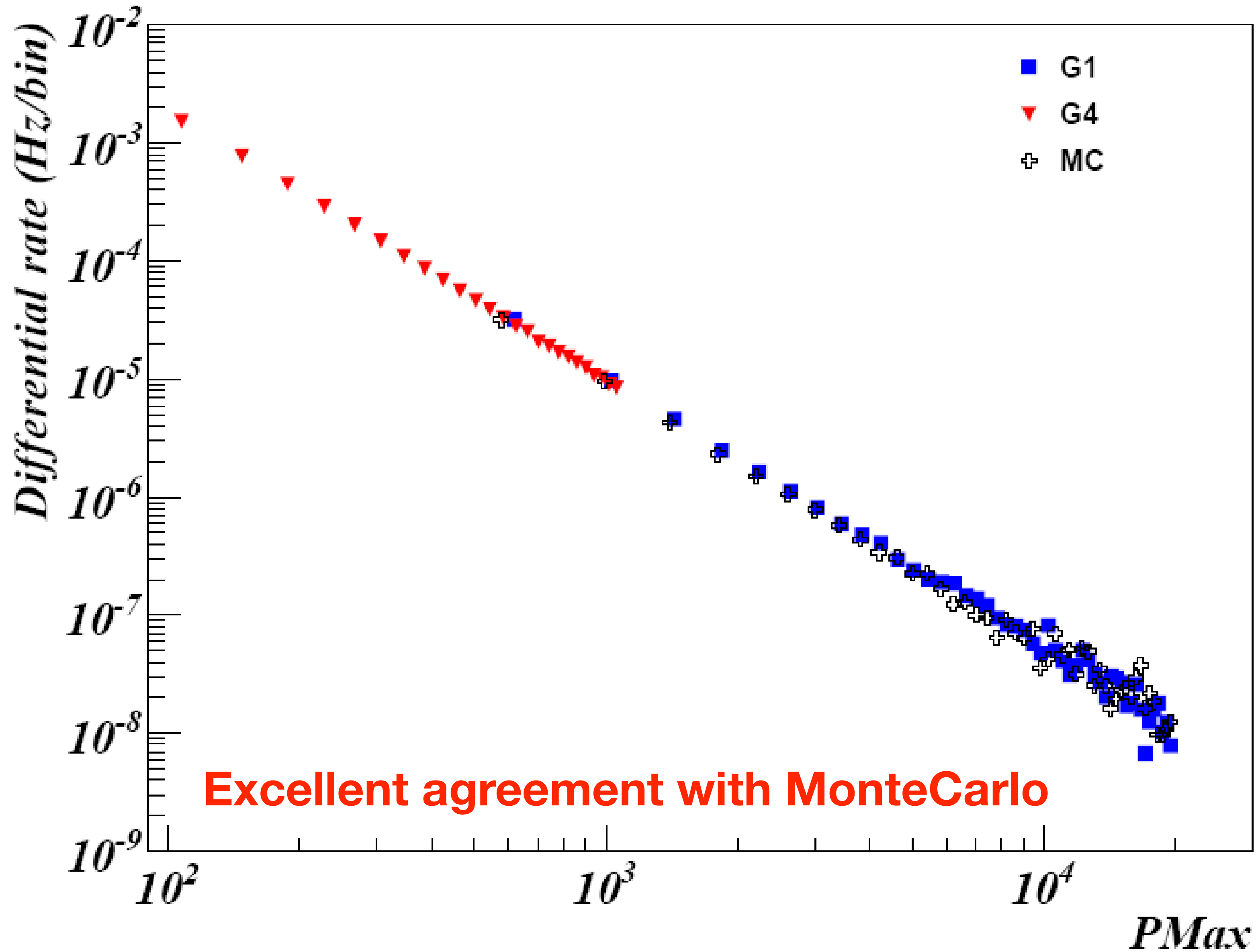
Good overlap between 4 scales with the maximum density of the showers spanning over three decades

Absolute comparison Data - MonteCarlo



J.R. Horandel , Astrop. Phys. 19 (2003) 193

Differential rate of Pmax, shower core density, for 2 gain scales



Event selection:

★ Core reconstructed in a fiducial area of 2400 m^2

★ Zenith angle < 15°

Pmax spans over two and half decades, while the event frequency runs over five decades.