Measurement of the (p+He) energy spectrum with ARGO-YBJ

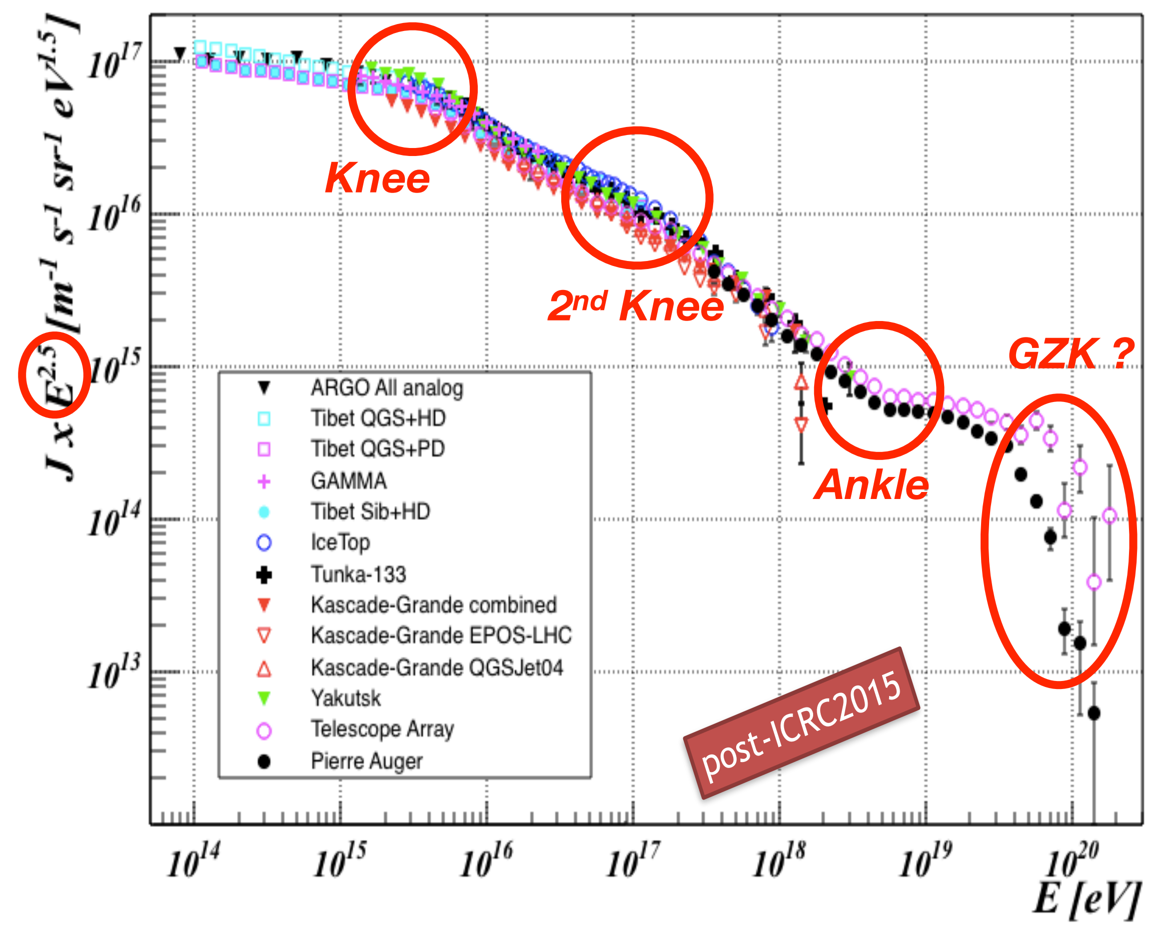
G. Di Sciascio
INFN - Roma Tor Vergata
disciascio@roma2.infn.it

Searching for the Sources of Galactic cosmic rays
APC, Paris - December 11-14, 2018

Galactic Cosmic Rays

- CRs below 10^{17} eV are predominantly Galactic.
- ***Standard paradigm***: *Galactic CRs accelerated in SuperNova Remnants*
  ➜ *But smoking gun still missing !!!*
- Galactic CRs via *diffusive* shock acceleration ?
  $n_{CR} \propto E^{-\gamma}$ (at source), $\gamma \approx 2.1$
- Energy-dependent *diffusion* through Galaxy
  $n_{CR} \propto E^{-\gamma-\delta}$ (observed), $\delta \approx 0.6$

all-particle energy spectrum



- Galactic CRs are scrambled by galactic magnetic field over very long time
  ➜ arrival direction *mostly isotropic*
- Transition to extragalactic CRs occurs somewhere between 10^{17} and 10^{19} eV

The key questions

✦ ***Origin of Cosmic Rays***: what are ***the sites*** that can accelerate particles up to > 10^{20} eV ? How many classes of sources at work ? Which cosmic accelerators dominate the CR flux in which energy range ?

- which *acceleration* mechanism? ➜ injection spectrum
- total energy in CRs
- *maximum energy of accelerated particles: the 'proton knee'*

  The description of how particles escape from a SNR shock has not been completely understood yet, the reason being the uncertainties related to *how particles reach the maximum energies.*

✦ ***Cosmic Ray propagation***: How do CRs propagate ?

- injected ➜ observed spectrum
- Diffusion coefficients
- Why are CR confined in the Galaxy ? ➜ magnetic field in the Galaxy
- spatial distribution of sources
- spatial distribution of CRs ➜ anisotropy

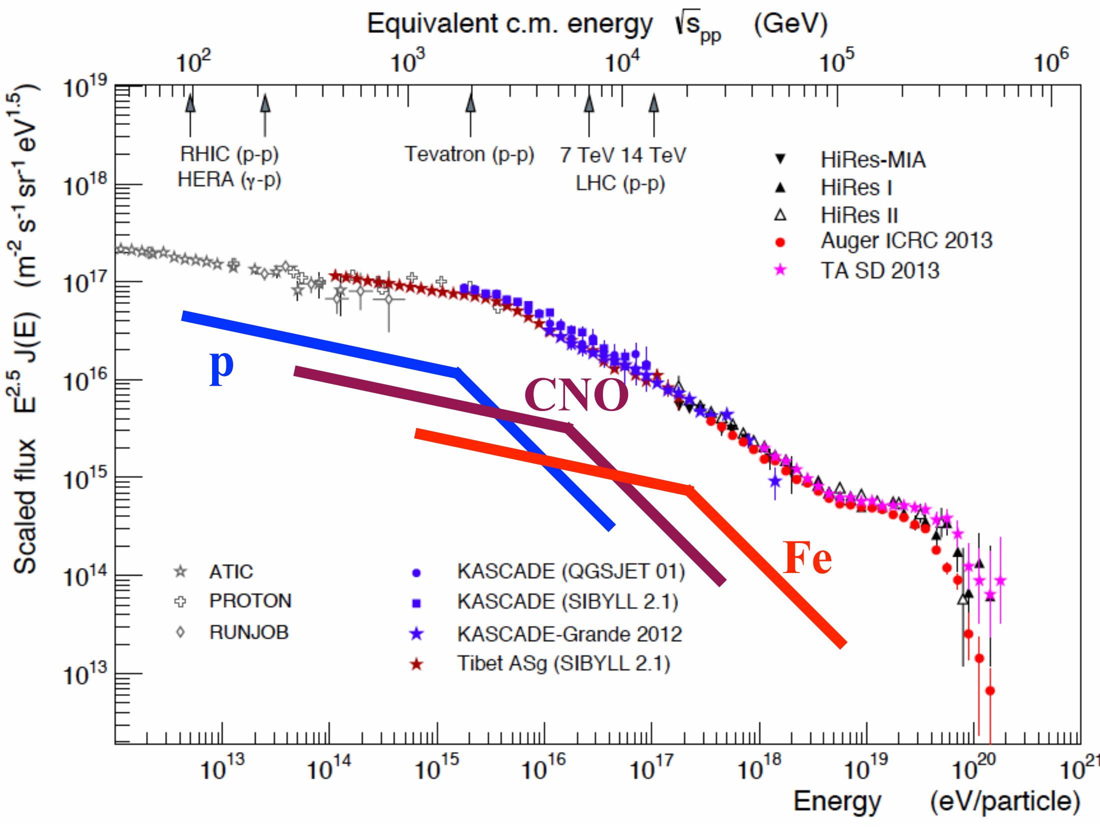
✦ What is the ***elemental composition*** of the radiation as a function of the energy ?

Approaching the '*knee*'

Understanding the origin of the "knee" is the key for a comprehensive theory of the origin of CRs up to the highest observed energies.

The standard model (mainly driven by KASCADE results):

- Knee attributed to light (proton, helium) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge $E_Z = Z \times 4$ 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.



If the mass of the knee is *light* according to the standard model
➜ Galactic CR spectrum is expected to end around 10^{17} eV

If the composition at the knee is *heavier* due to CNO / MgSi
➜ we have a problem !

Experimental results still conflicting !

Cosmic Ray physics with EAS arrays

Experiment	g/cm^2	Detector	ΔE (eV)	e.m. Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
ARGO-YBJ	606	RPC/hybrid	$3 \cdot 10^{11} - 10^{16}$	6700	11,000	0.93 (central carpet)
BASJE-MAS	550	scint./muon	$6 \cdot 10^{12} - 3.5 \cdot 10^{16}$		10^4	
TIBET ASγ	606	scint./burst det.	$5 \cdot 10^{13} - 10^{17}$	380	3.7×10^4	10^{-2}
CASA-MIA	860	scint./muon	$10^{14} - 3.5 \cdot 10^{16}$	1.6×10^3	2.3×10^5	7×10^{-3}
KASCADE	1020	scint./mu/had	$2 - 90 \cdot 10^{15}$	5×10^2	4×10^4	1.2×10^{-2}
KASCADE-Grande	1020	scint./mu/had	$10^{16} - 10^{18}$	370	5×10^5	7×10^{-4}
Tunka	900	open Cher. det.	$3\cdot10^{15} - 3 \cdot 10^{18}$	-	10^6	-
IceTop	680	ice Cher. det.	$10^{16} - 10^{18}$	4.2×10^2	10^6	4×10^{-4}
LHAASO	600	Water C scintill/muon/hadron Wide FoV Cher. Tel.	$10^{12} - 10^{17}$	5.2×10^3	1.3×10^6	4×10^{-3}

Muon detectors

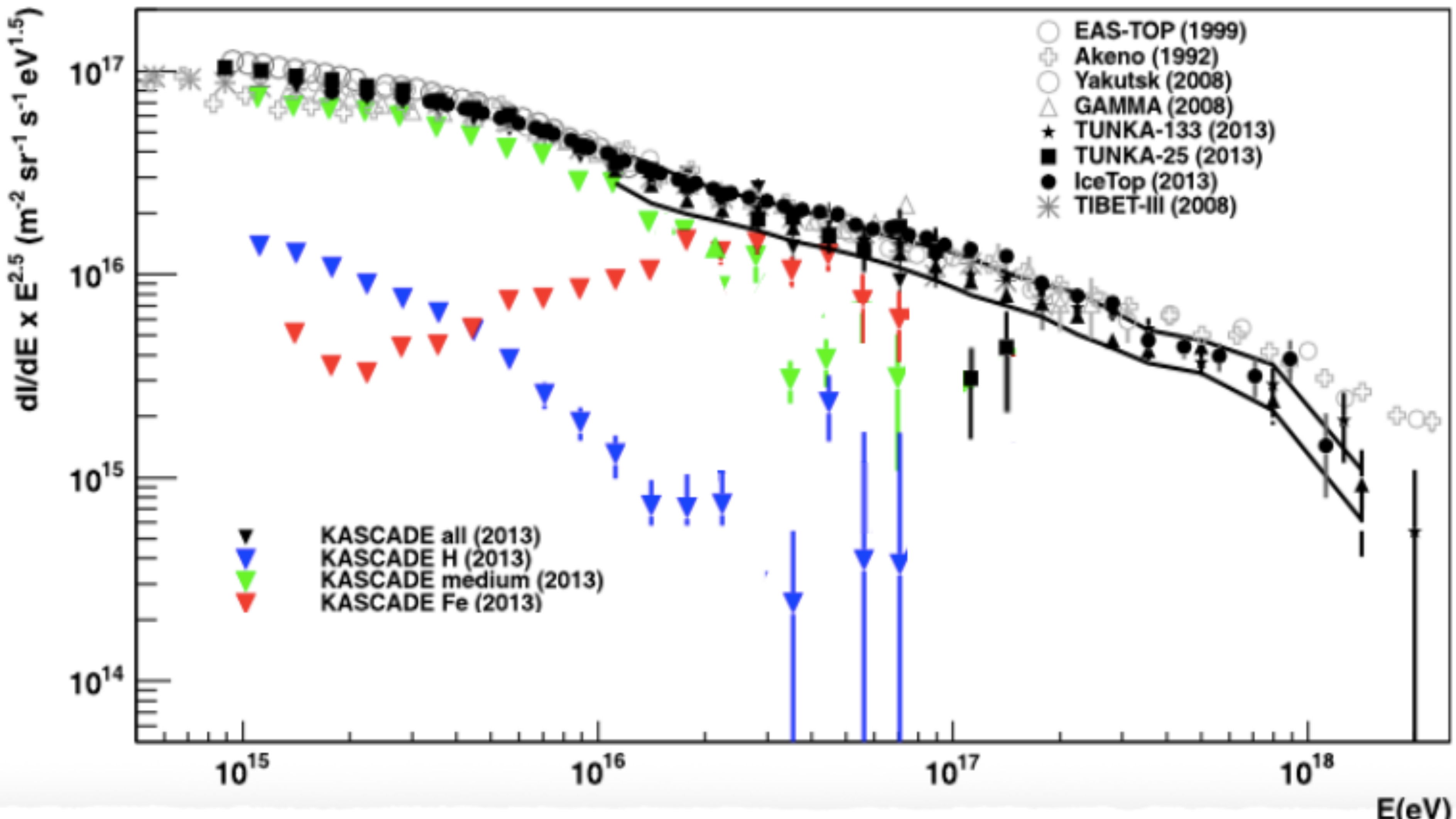
Experiment	m asl	μ Sensitive Area (m^2)	Instrumented Area (m^2)	Coverage
LHAASO	4410	4.2×10^4	10^6	4.4×10^{-2}
TIBET ASγ	4300	4.5×10^3	3.7×10^4	1.2×10^{-1}
KASCADE	110	6×10^2	4×10^4	1.5×10^{-2}
CASA-MIA	1450	2.5×10^3	2.3×10^5	1.1×10^{-2}

The "*knee*" region according to KASCADE

Separation based on N_e/N_μ unfolding

Energy threshold ≈ PeV

sea level



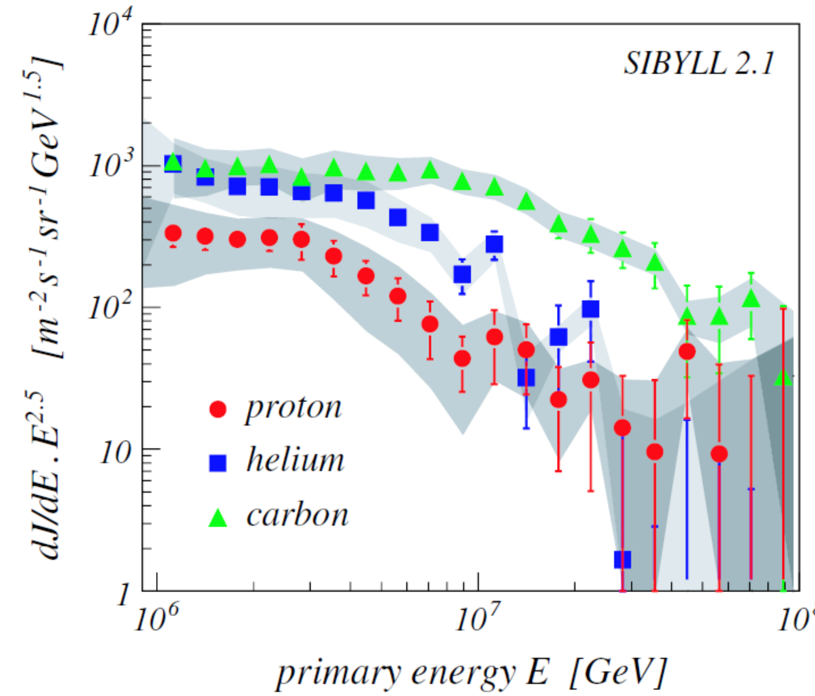
- ✓ All-particle knee at about 4×10^{15} eV
- ✓ *(p+He) knee at few PeV*, heavier knee not visible (low statistics ?)
- ✓ If Peter's cycles, $E_k(Fe)$ must be found at ≈7-10 × 10^{16} eV ➜ evidence with KASCADE-Grande

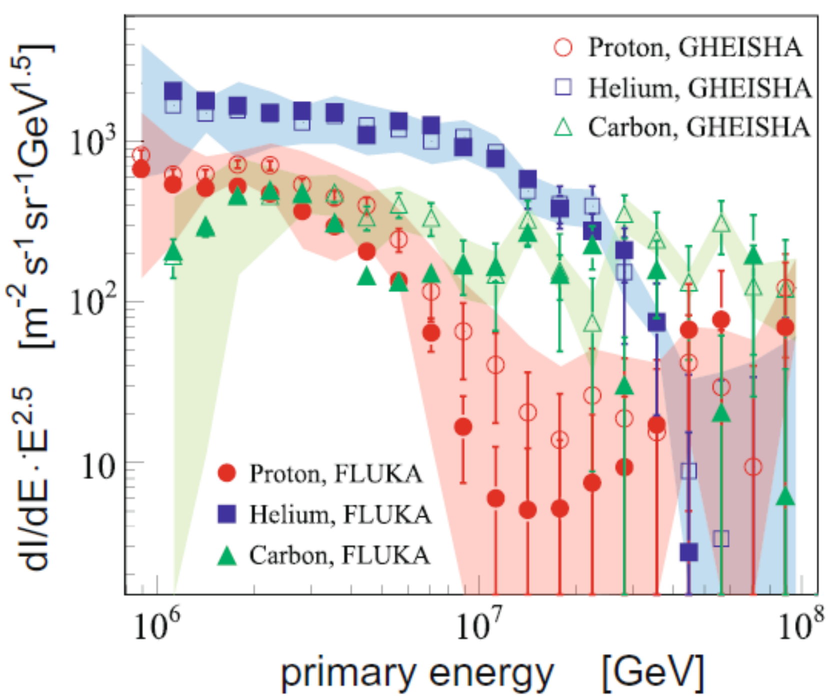
KASCADE results

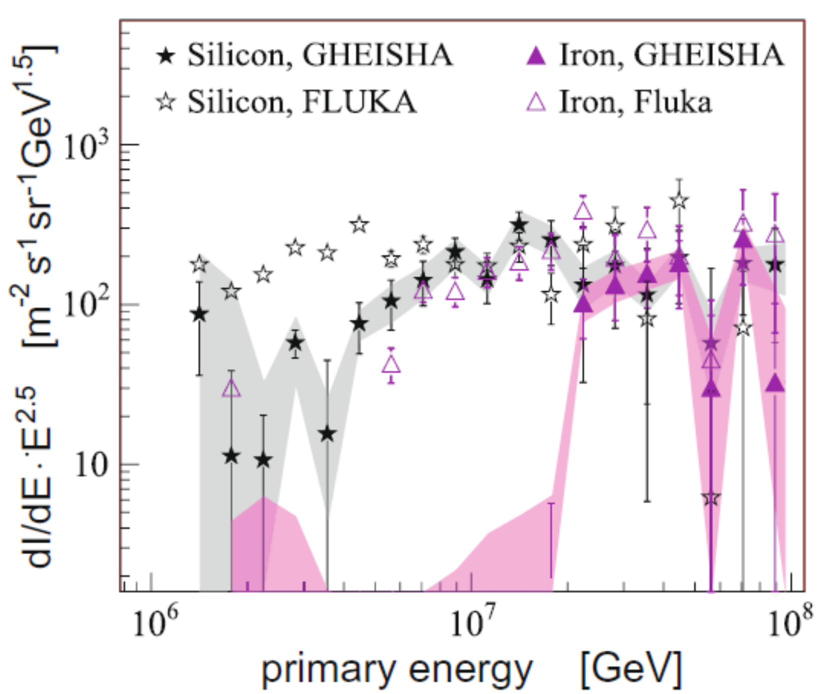
Results depend on the high energy hadronic interaction models

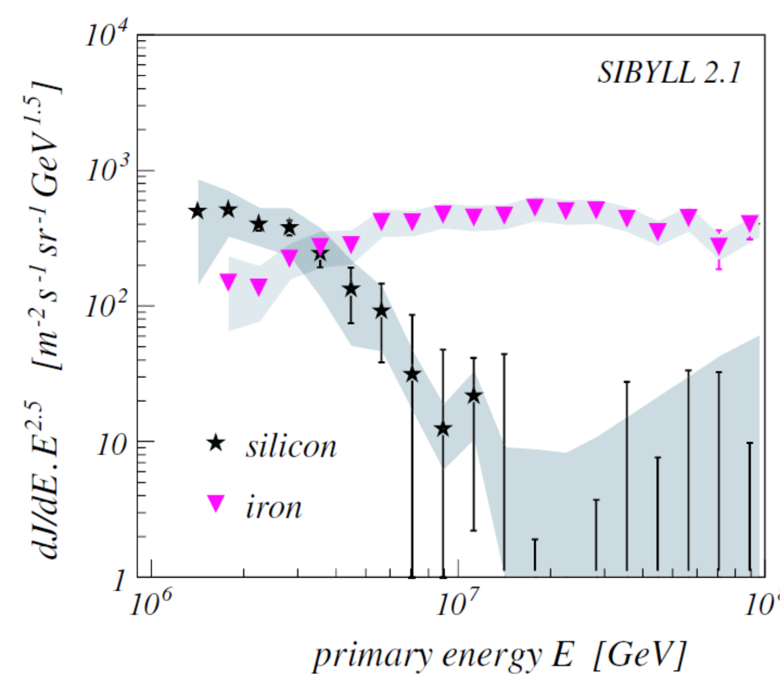
- QGSJet ➜ *He more abundant element at the knee*
- SIBYLL 2.1 ➜ *C more abundant element at the knee*

✓ Knee energy increases with primary mass
✓ Fe knee not observed
✓ Strong indication for a rigidity-dependent knee







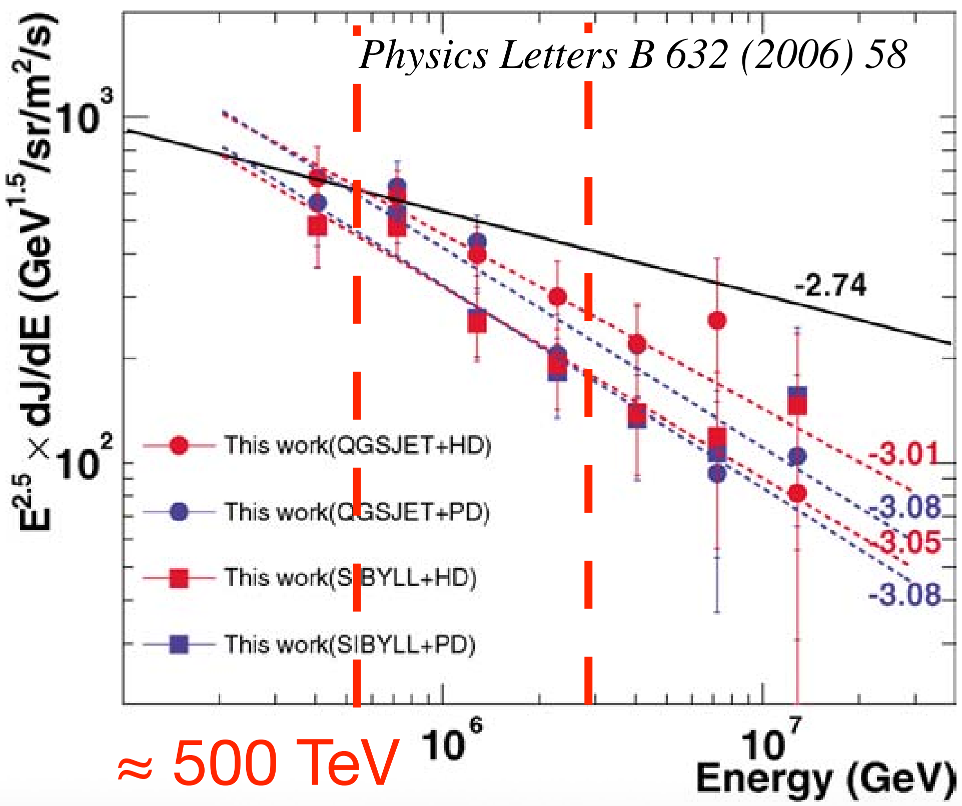


Astroparticle Physics **24** (2005) 1
Astroparticle Physics **31** (2009) 86

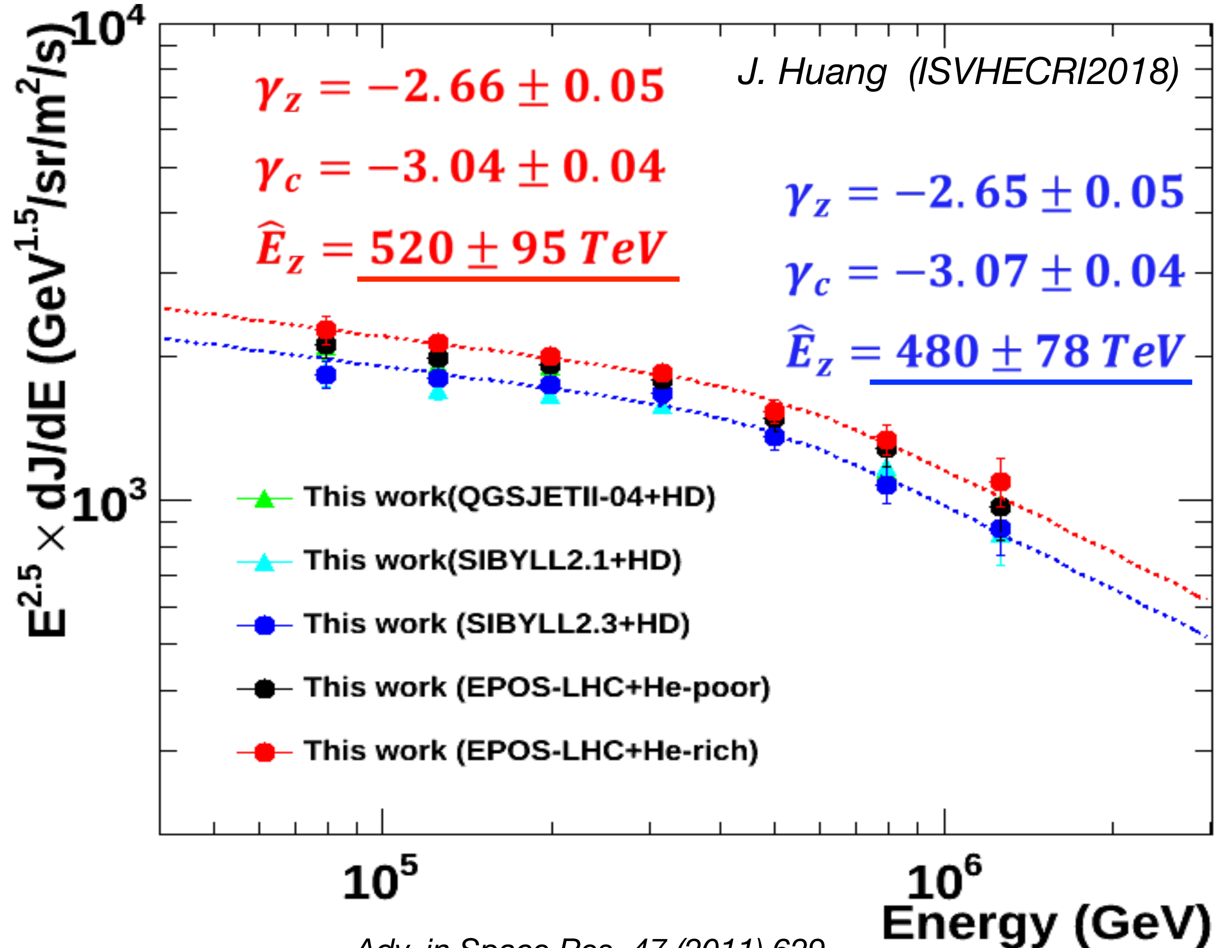
The "*knee*" region according to Tibet ASγ

Energy threshold ≈ 300 TeV   Tibet - 4300 m asl

Separation based on shower core characteristics
(burst detectors)



≈ 500 TeV

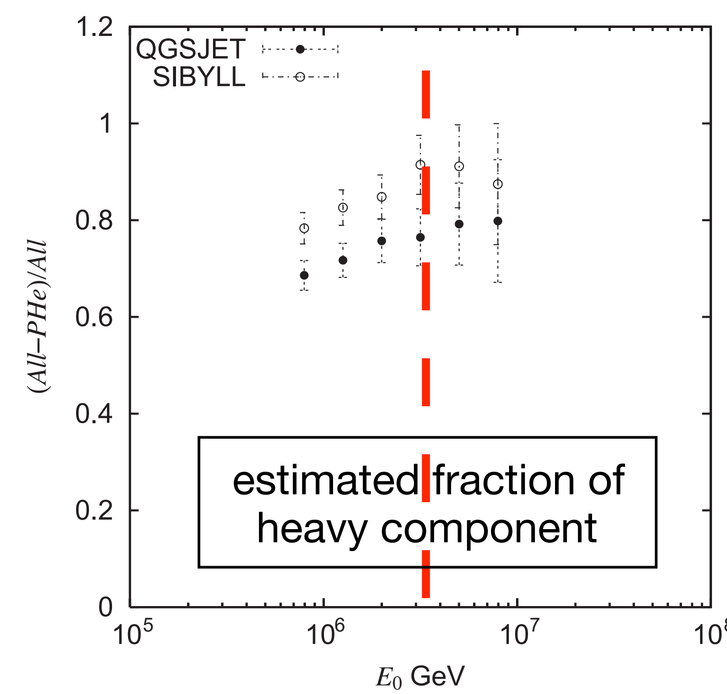


(1) *The power index is steeper than that of all-particle spectrum before the knee*, suggesting that the light component has the break point at lower energy than the knee.

(2) *The fraction of the light component to the all-particles is less than 30%* which tells that *the main component responsible for the knee structure is heavier than helium.*

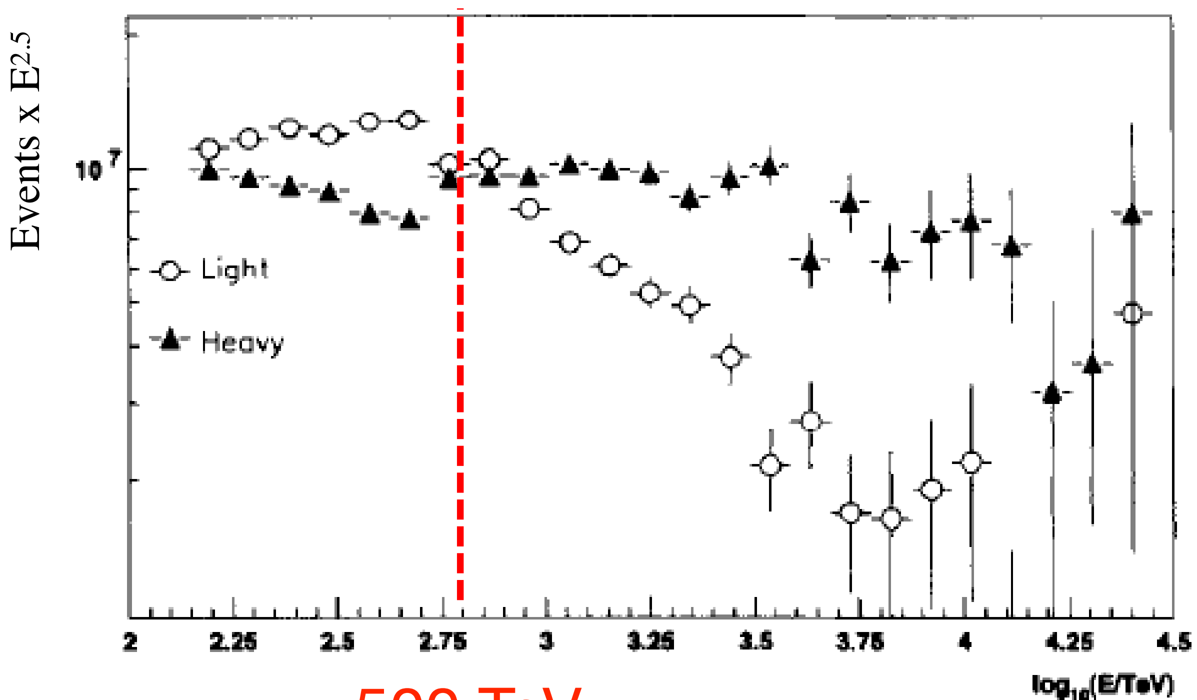
Astrophys. Space Sci. Trans., 7 (2011) 15

Adv. in Space Res. 47 (2011) 629

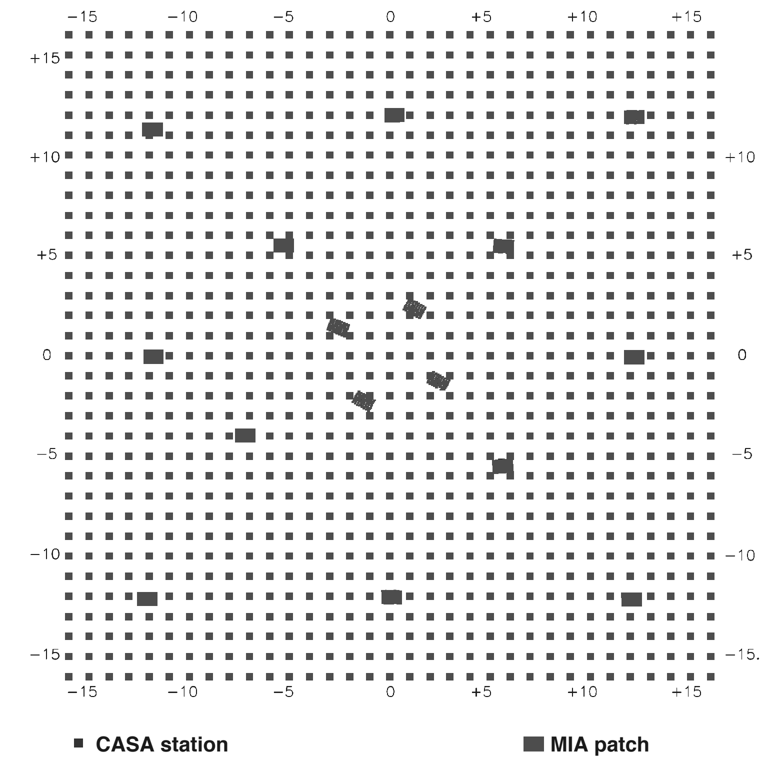


Composition at the knee: CASA-MIA

Energy threshold ≈ 100 TeV   1400 m asl



≈ 500 TeV

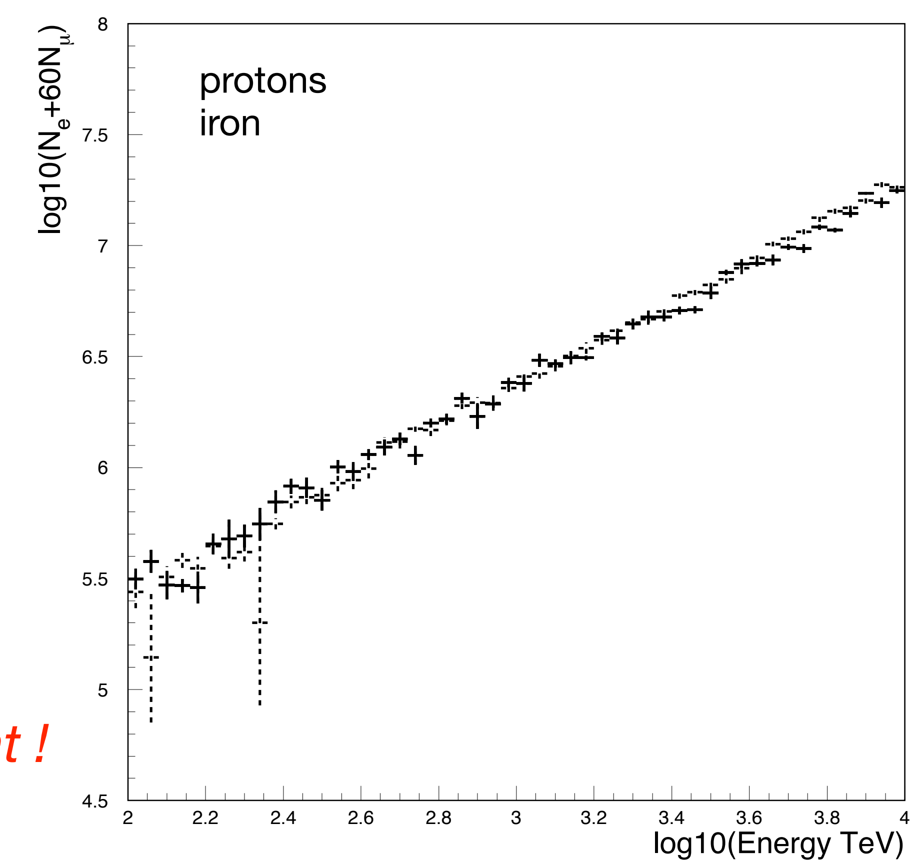


> The spectra of the heavy and light components appear similar below 500 TeV, at which point the lighter component's spectral index steepens. The heavier component shows no such "knee" at that energy.

Astroparticle Physics 12 (1999) 1–17

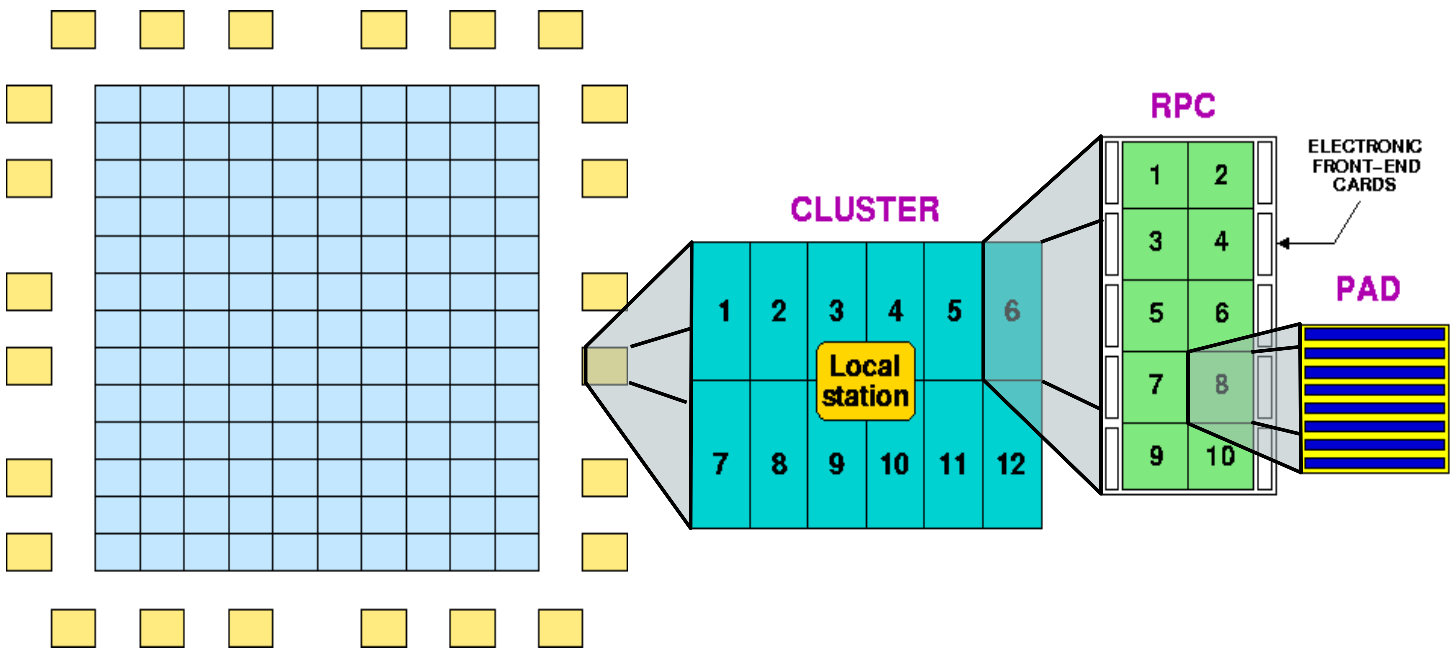
$$E_0 \approx A + B \cdot (N_e + K \cdot N_\mu)$$

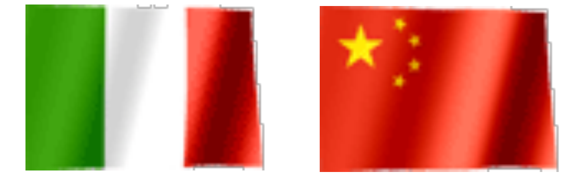
The energy reconstruction is *compositionally independent !*



The ARGO-YBJ experiment

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



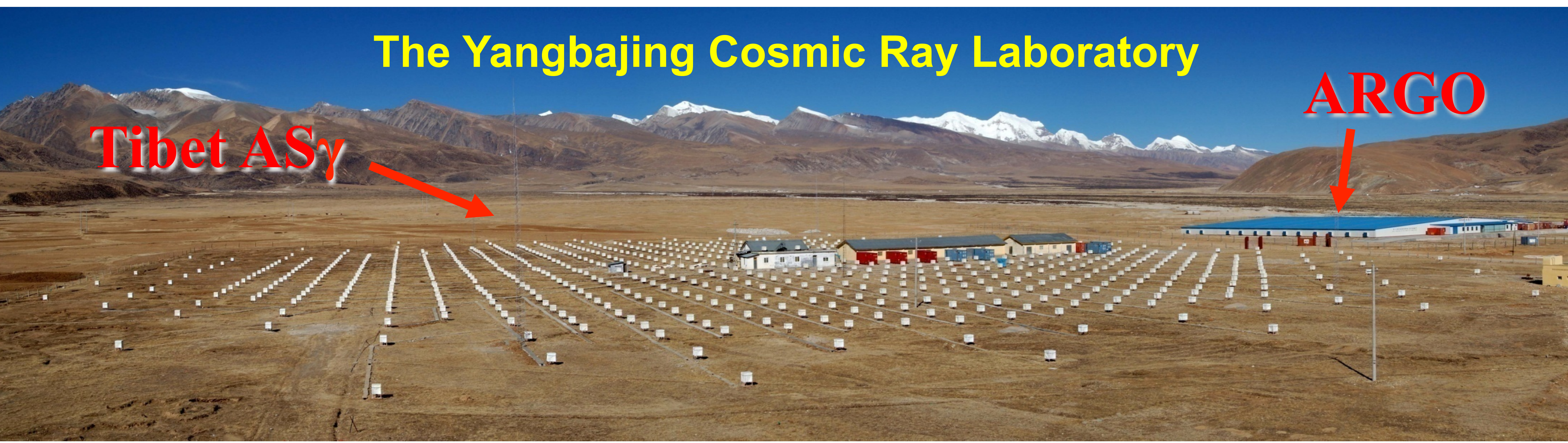


INFN IHEP/CAS

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

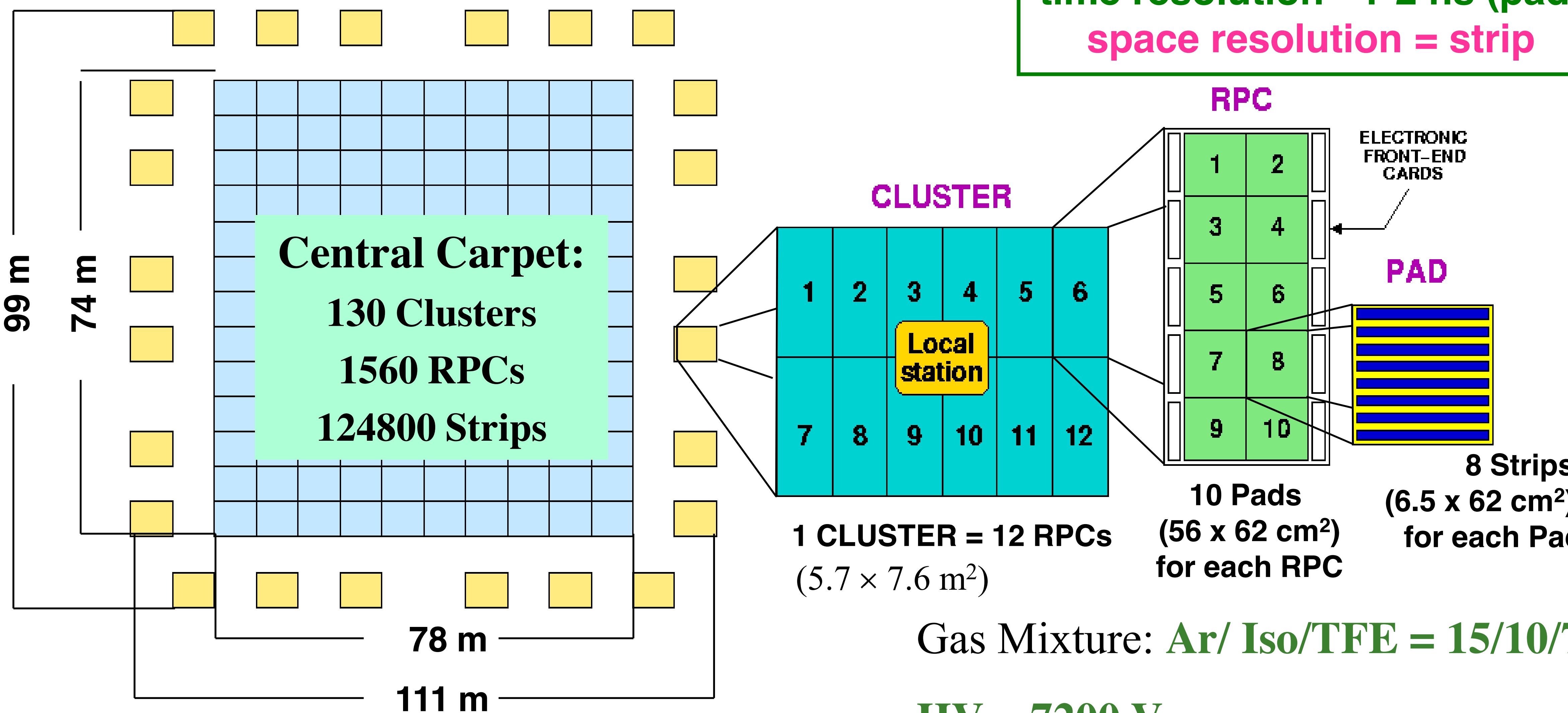
90 km North from Lhasa (Tibet)

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



The ARGO-YBJ layout

time resolution ~1-2 ns (pad)
space resolution = strip



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 m²)
+ sampling guard ring (6700 m² in total)

The basic concepts

…for an unconventional air shower detector

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

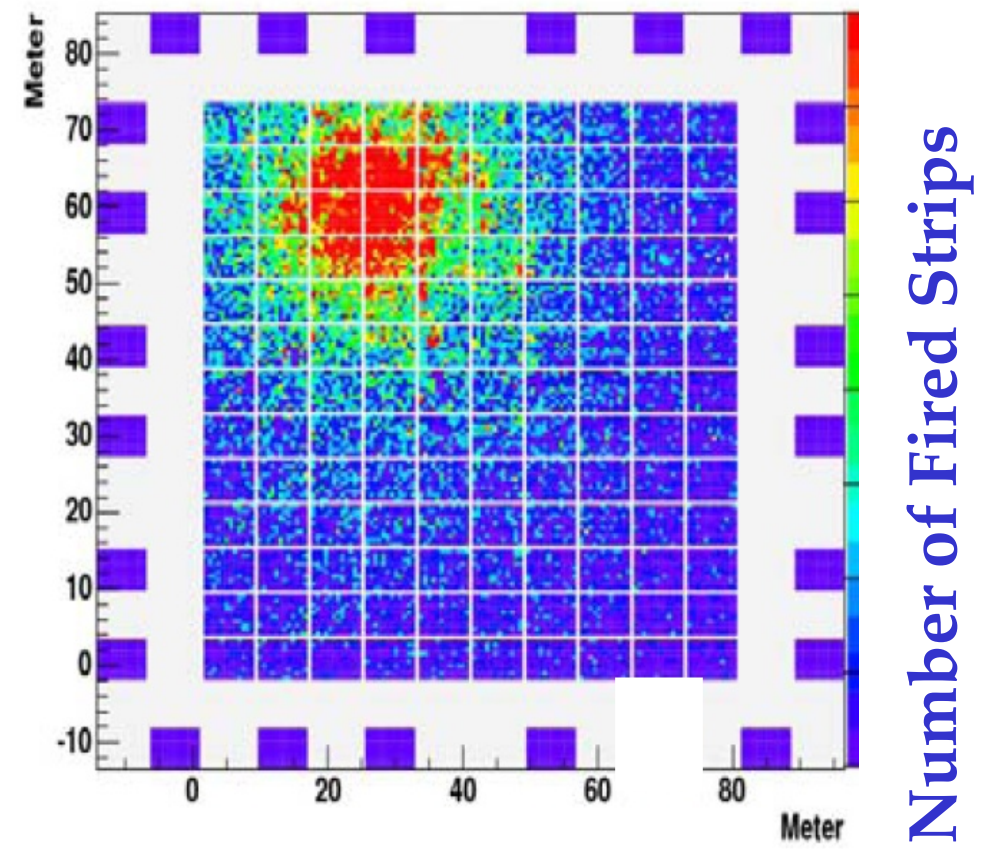
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

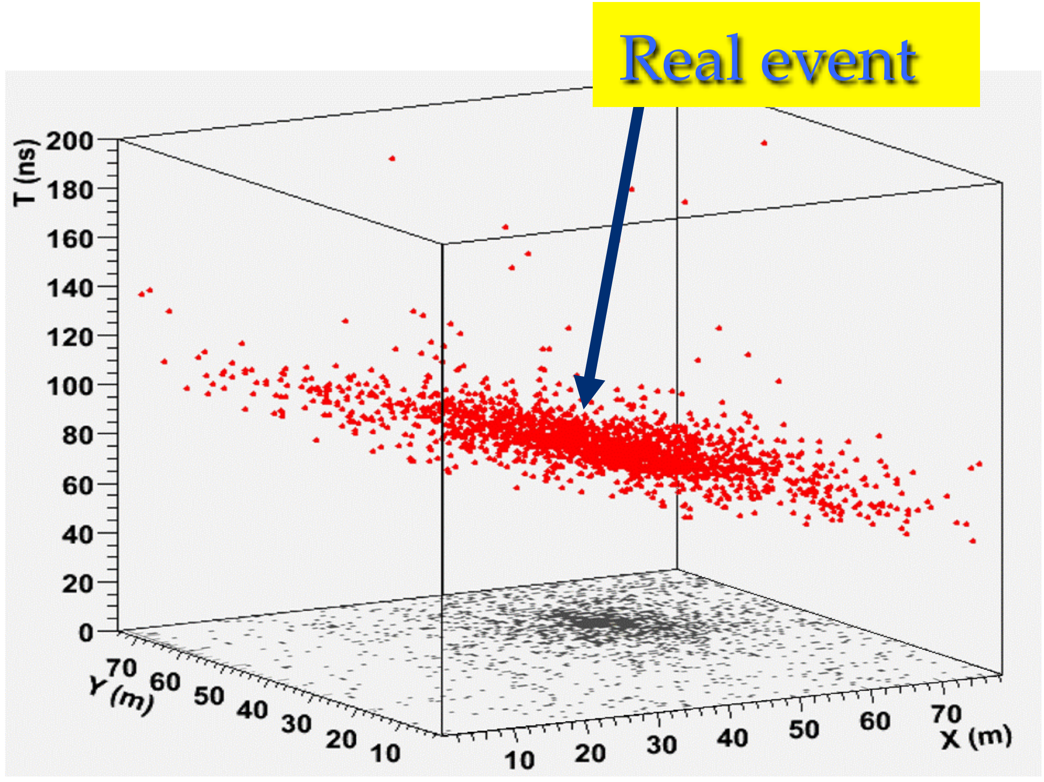
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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

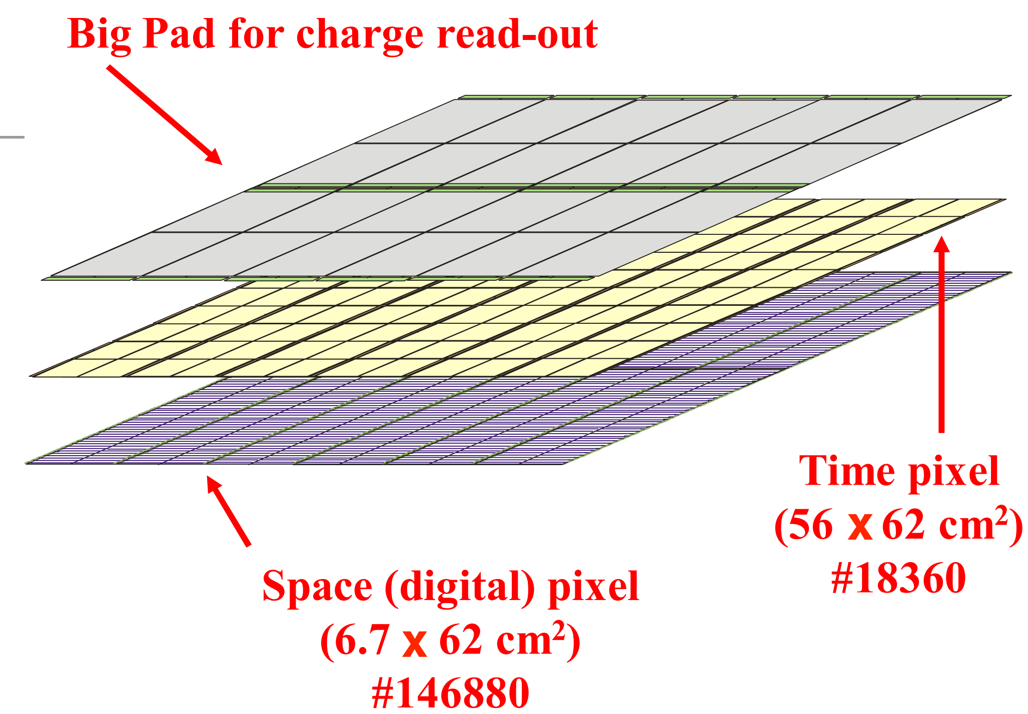
… in order to

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

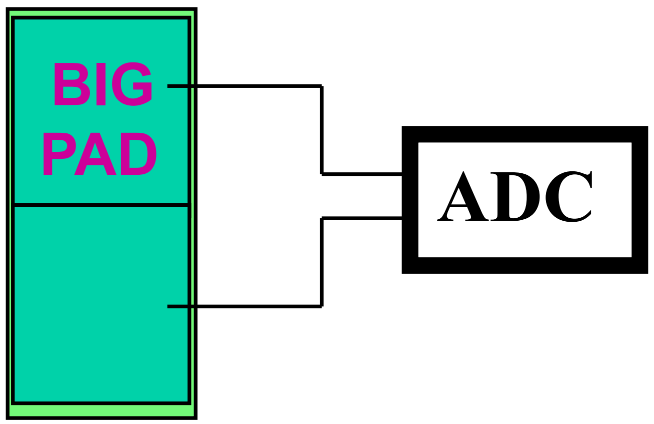




The RPC charge readout



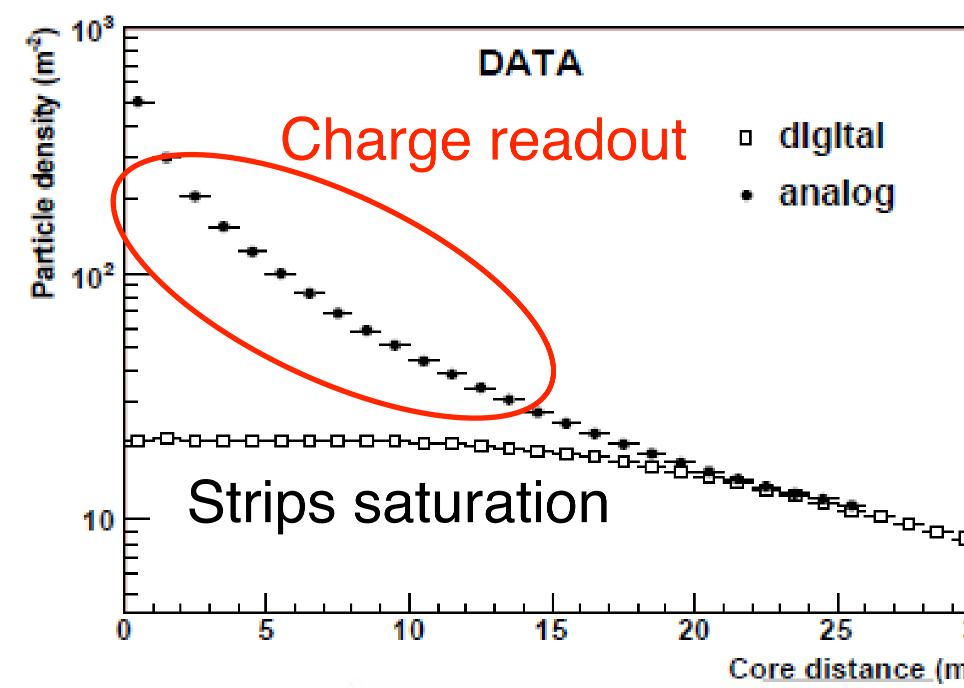
…extending the dynamical range up to 10 PeV

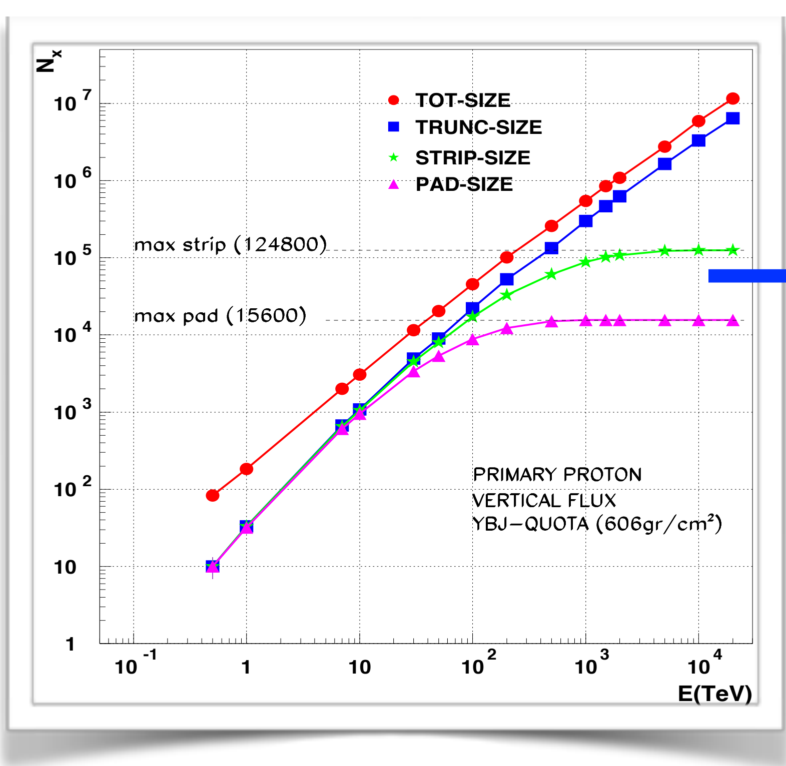


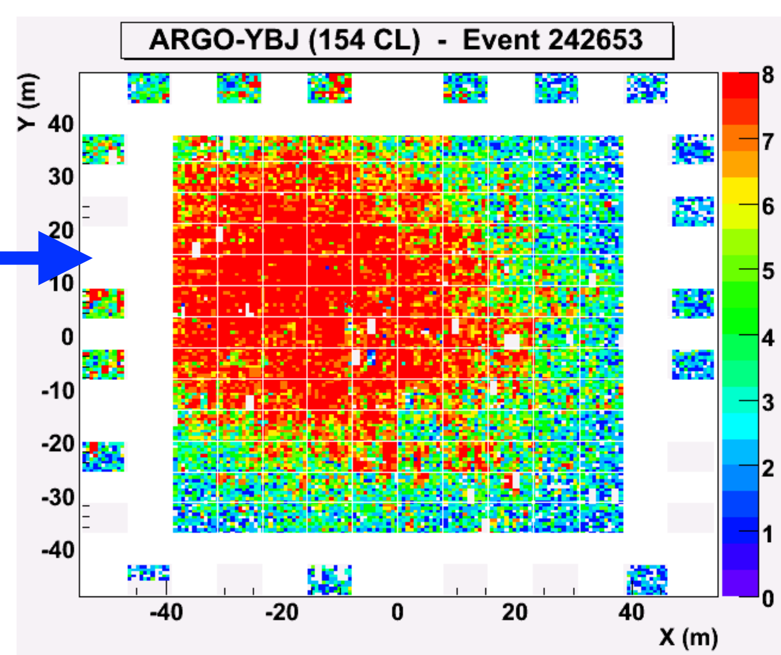
4 different gain scales used to cover a wide range in particle density:

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

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



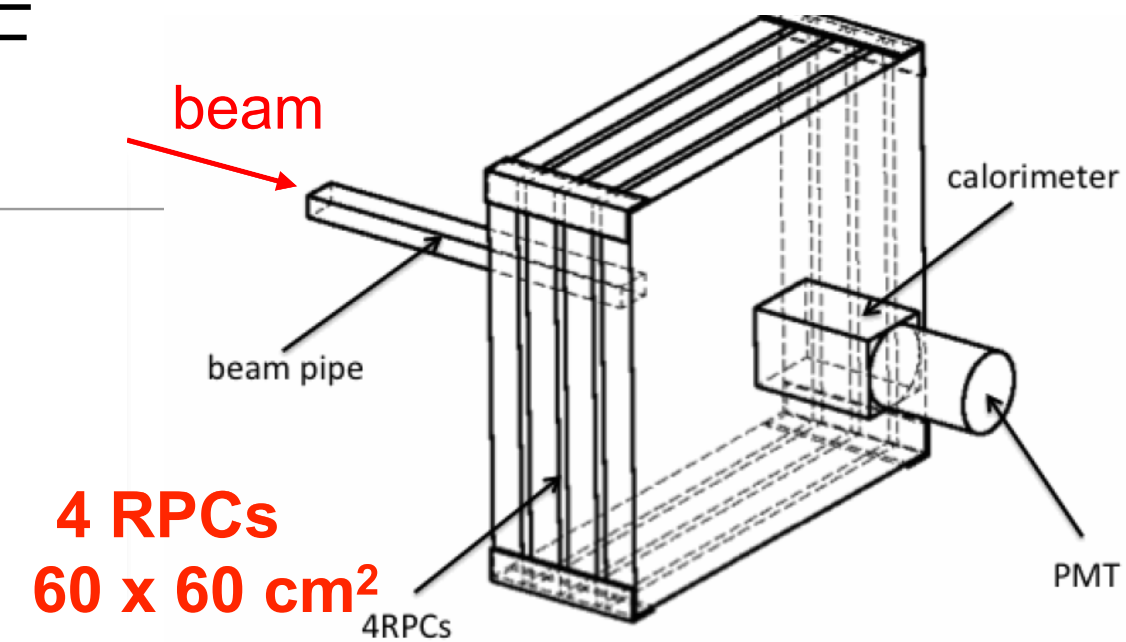




Intrinsic linearity: test at the BTF facility

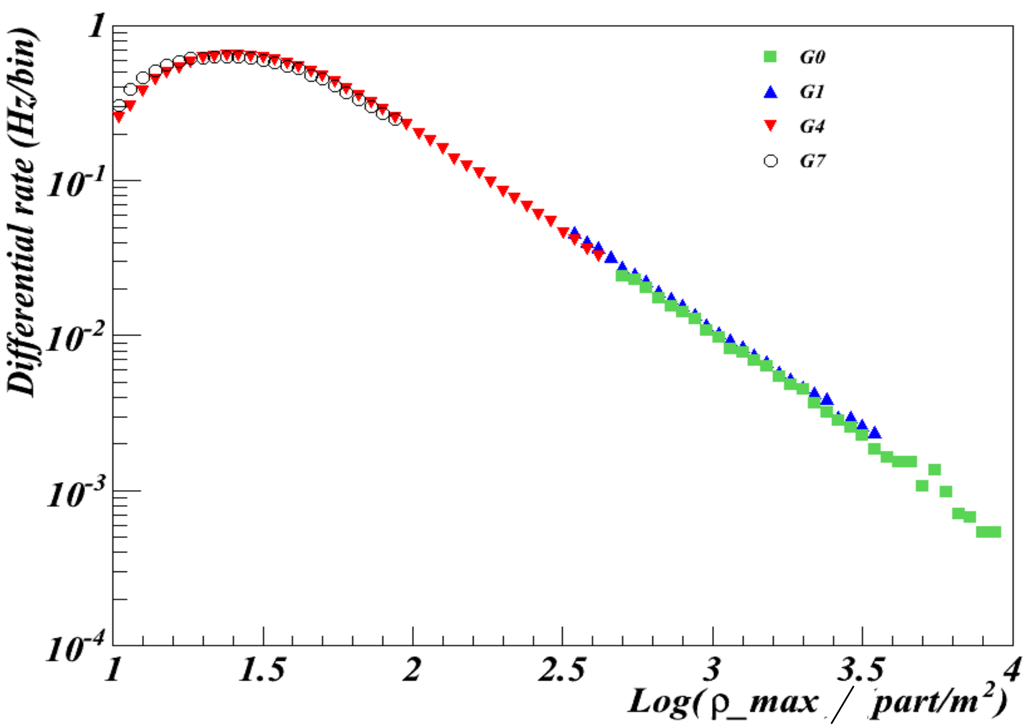
Linearity of the RPC @ BTF in INFN Frascati Lab:

- *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*



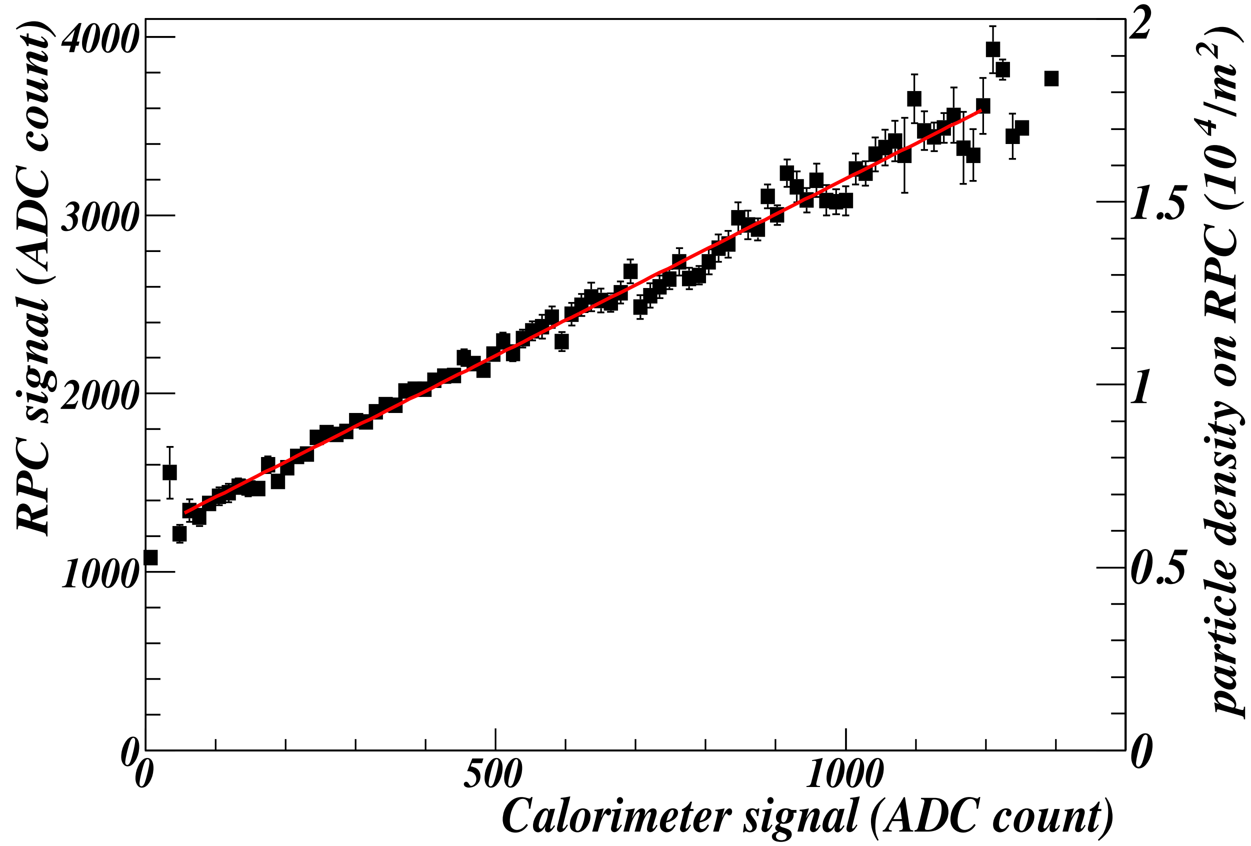
Calorimeter: lead glass block from OPAL, PMT a Hamamatsu R2238.

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



Astrop. Phys. 67 (2015) 47

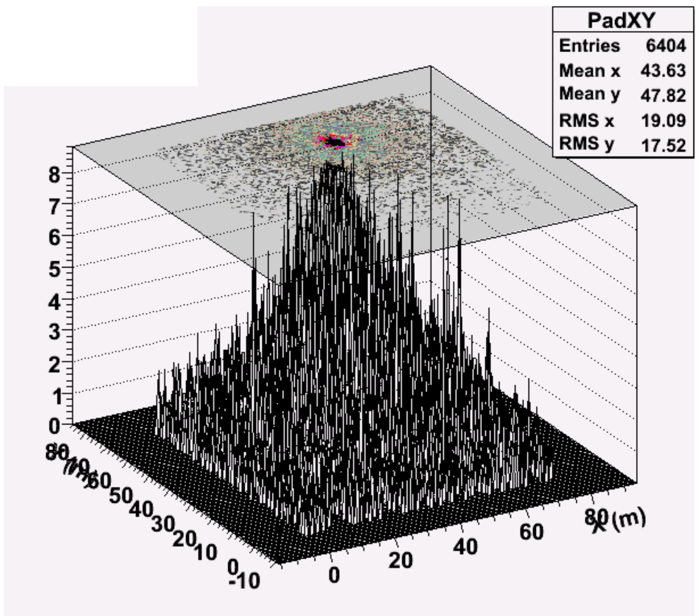
The RPC signal vs the calorimeter signal



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

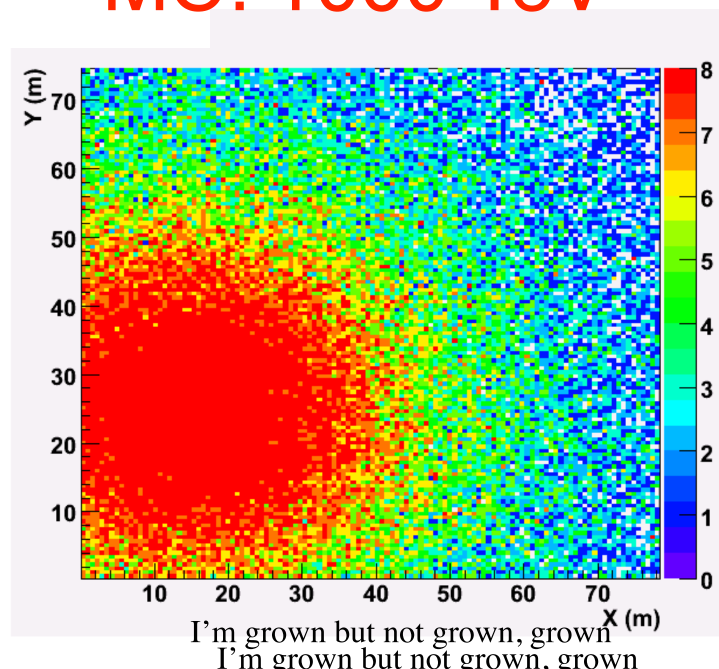
The RPC charge readout: the core region

MC: 100 TeV



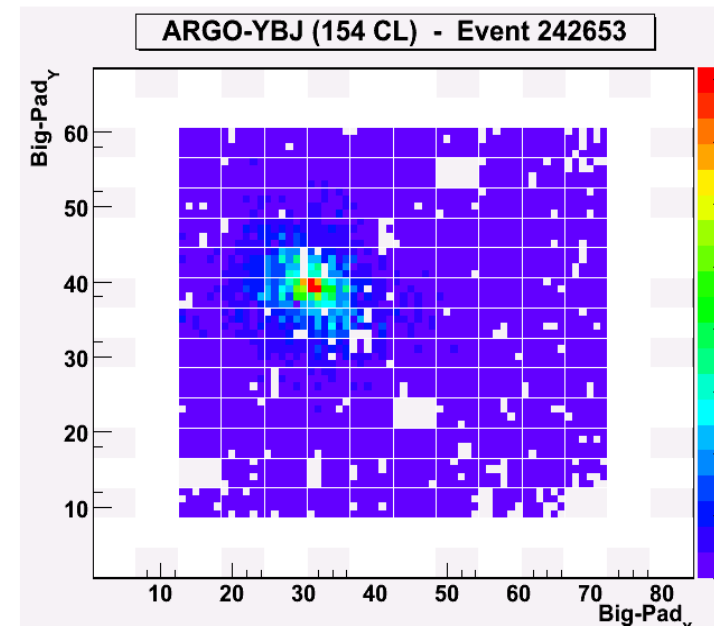
Strip read-out

MC: 1000 TeV

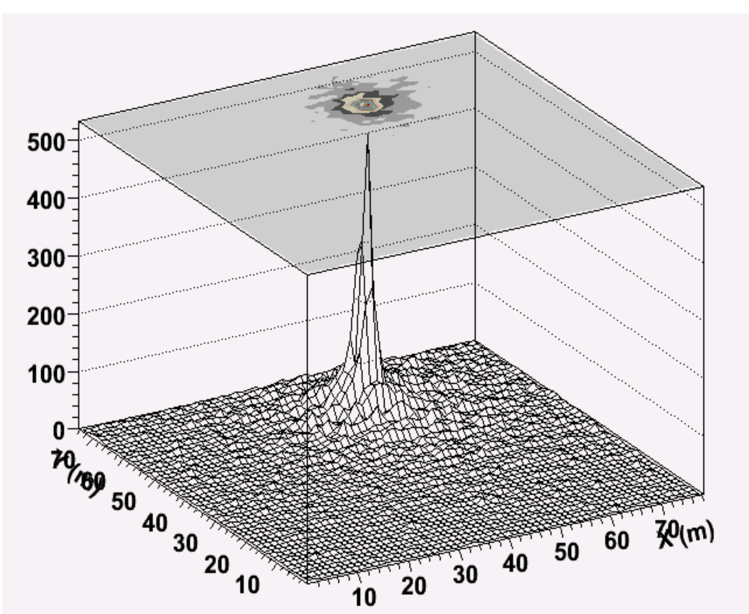


Strip read-out

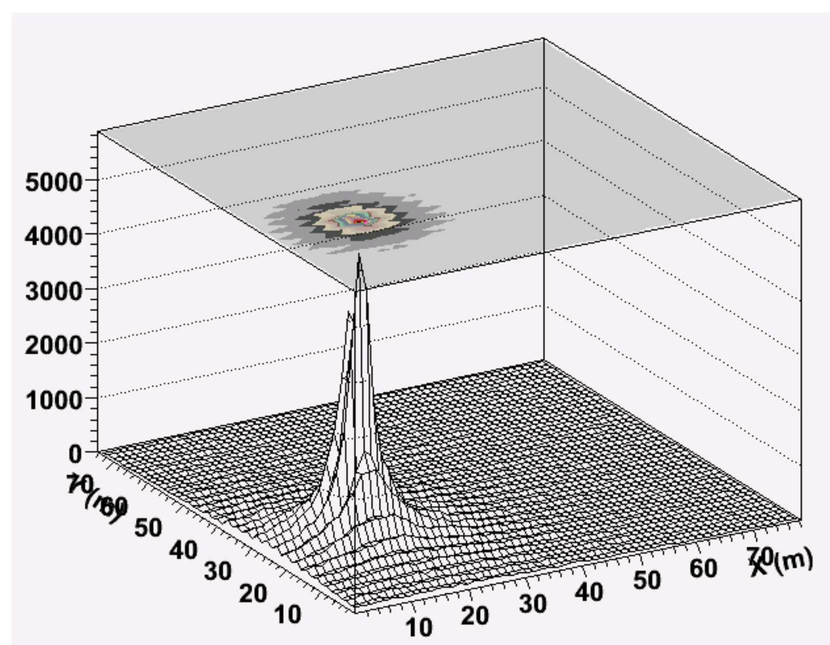
Data



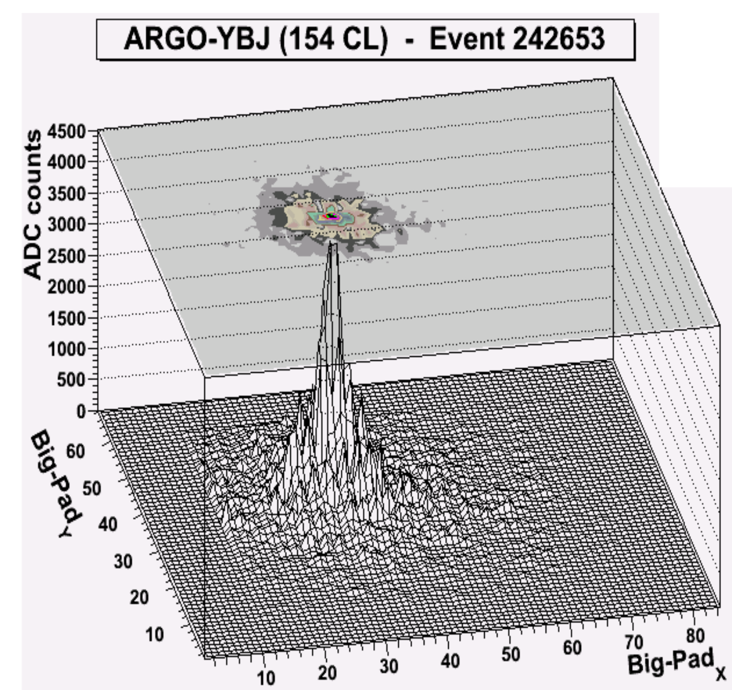
Strip read-out



Charge read-out



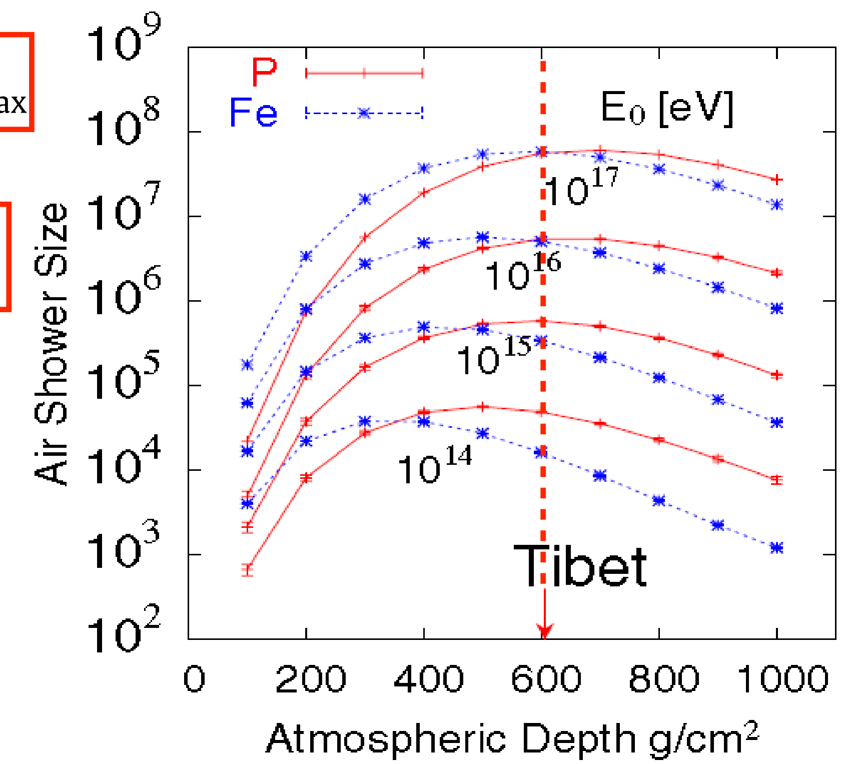
Charge read-out

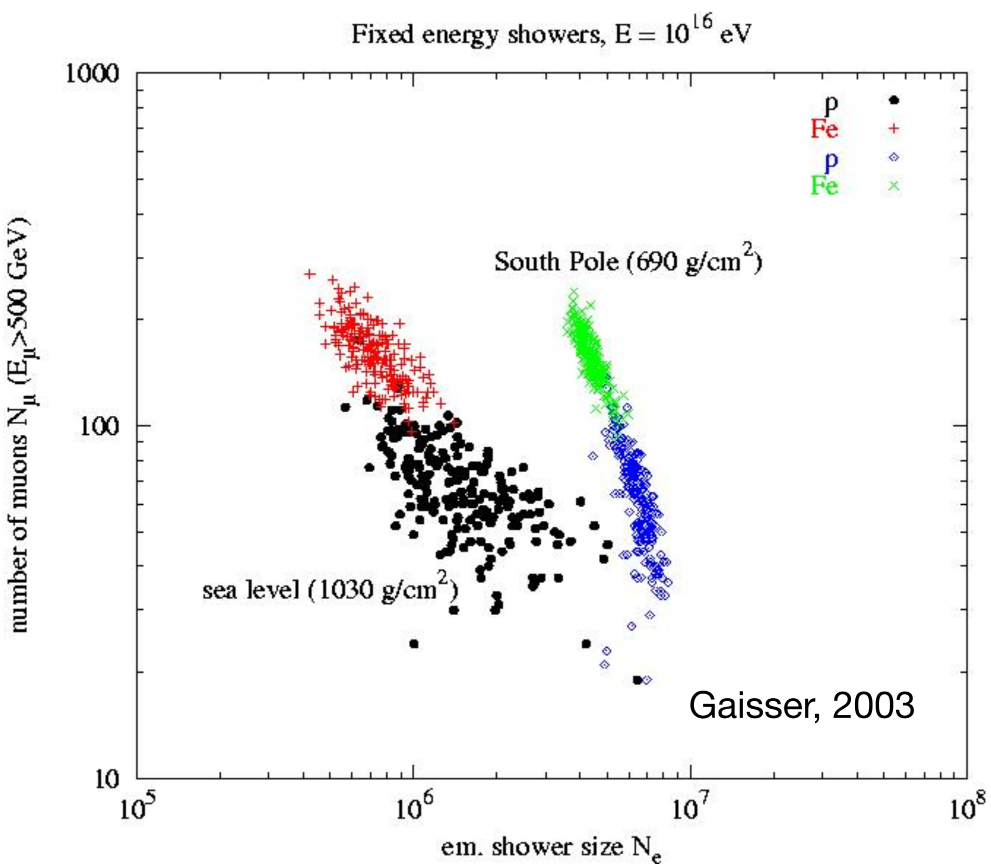


Charge read-out

Extreme Altitude (>4000 m asl)

1. *All nuclei produce showers with similar size in the knee region* $N^{A}_{e,max} \approx N^{p}_{e,max}$
2. *Unbiased trigger threshold* for all nuclei
3. Primary *energy reconstruction mass-independent* $Ne(E_0, A) = \alpha(A) \cdot E^{\beta(A)}$
4. *Small fluctuations:* shower maximum
5. *Low energy threshold: absolute energy scale calibration* with the Moon Shadow technique and overposition with direct measurements
6. Trigger probability larger for γ-showers than for p-showers





Fluctuations smaller but *reduced sensitivity of the N_e/N_μ technique in selecting primary masses*

➜ Different technique to select primary masses: ARGO-YBJ, Tibet ASγ, BASJE-MAS exploited *characteristics of the shower core region.*

No muons ? ➜ results nearly independent on hadronic interaction models !

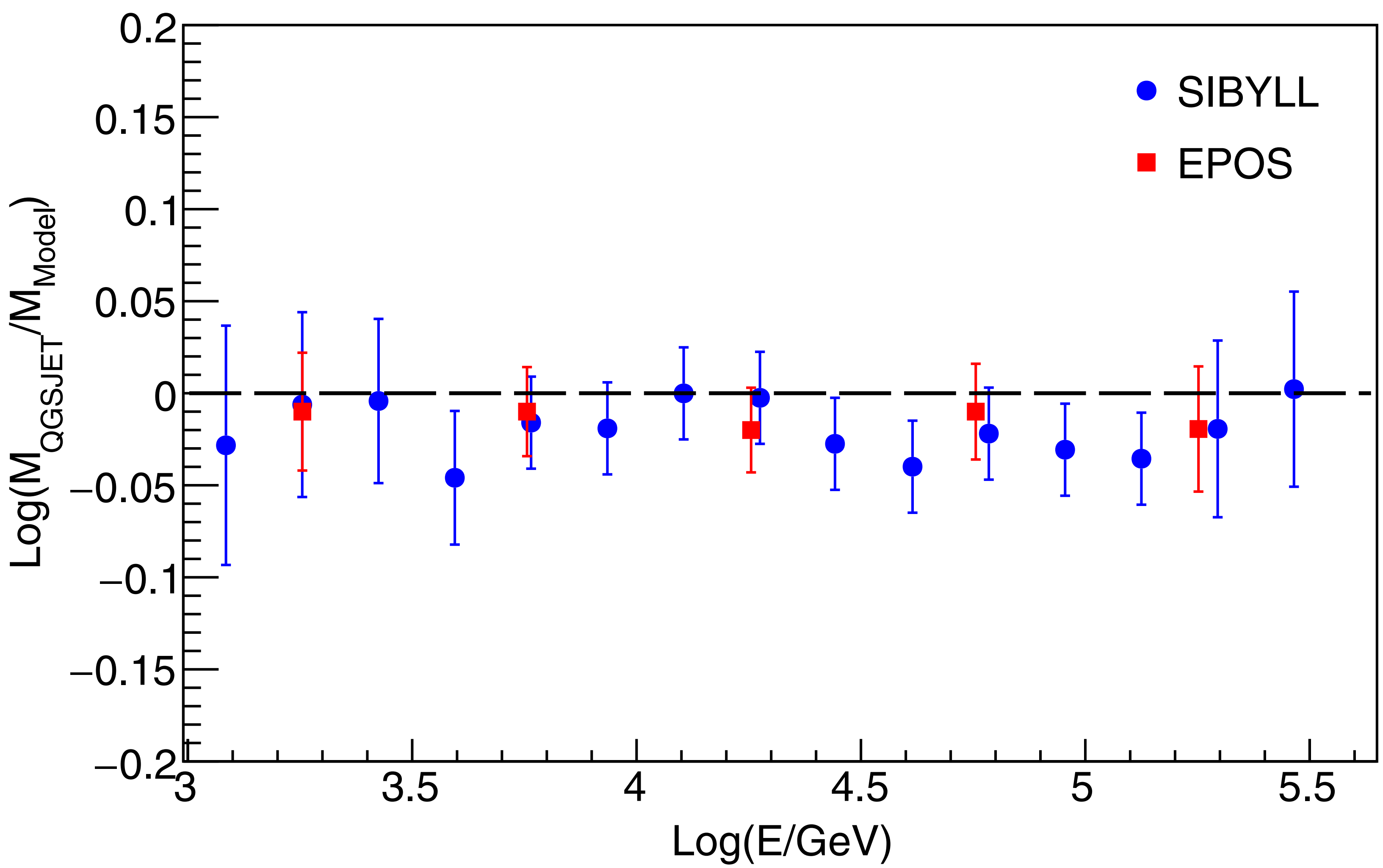
Hadronic Interaction Models

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

Phys. Rev. D91, 112017 (2015)

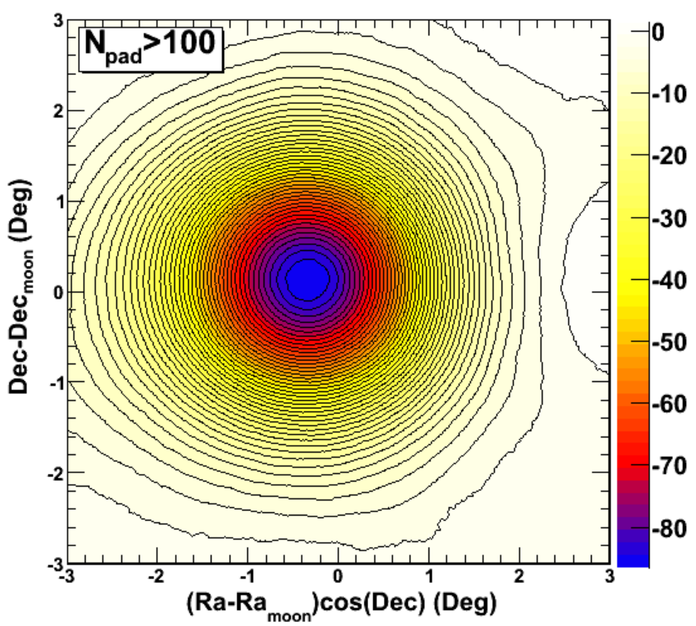
Not muons but lateral distribution ➜ topology

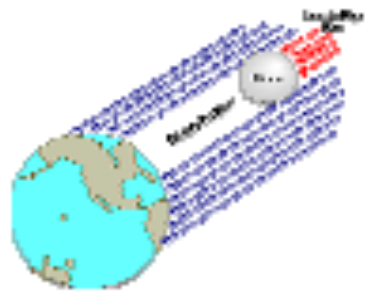
Ratio beetwen multiplicity distributions obtained with different models



Calibration of the absolute energy scale

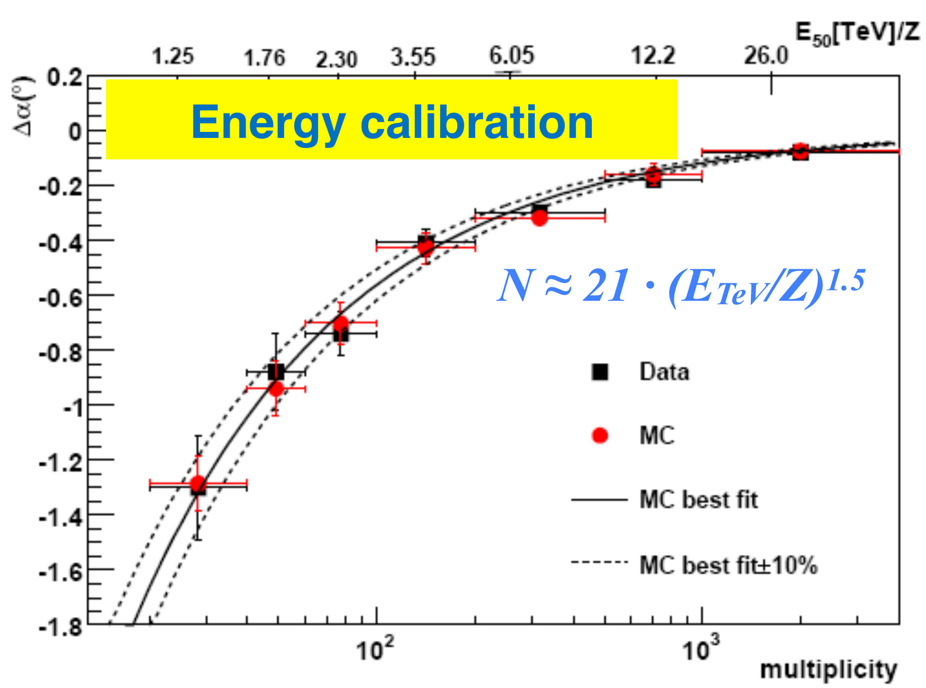
ARGO-YBJ: *Moon shadow* tool



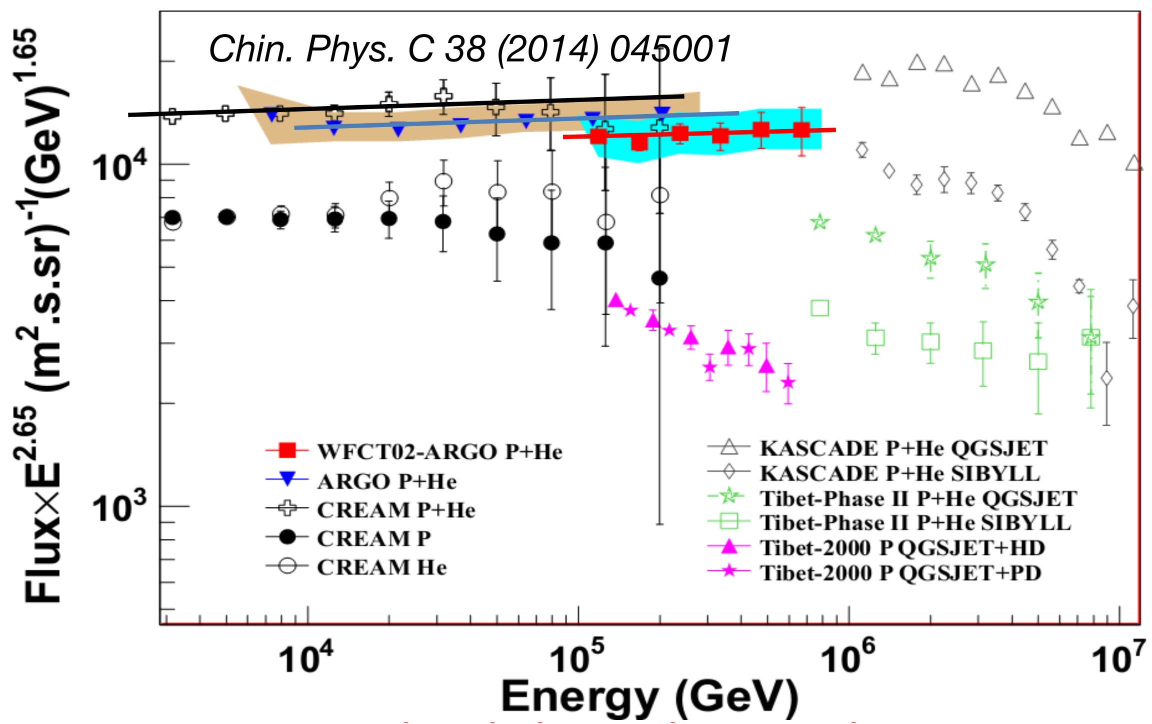


PRD 84 (2011) 022003

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



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



- 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

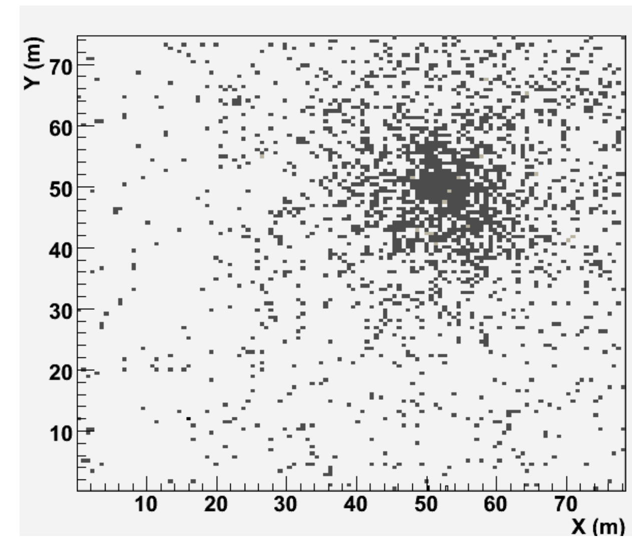
Flux at 400 TeV:

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

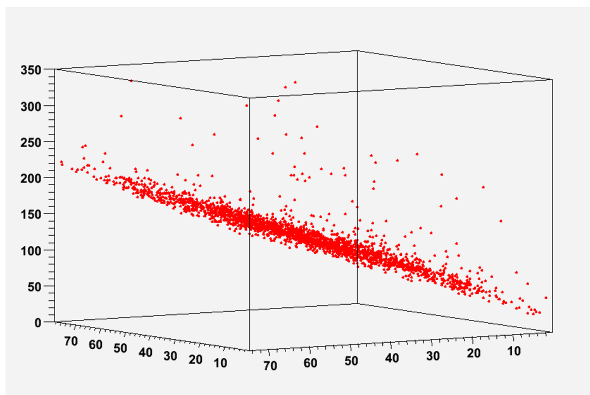
The 9% difference in flux corresponds to a difference of ± 4% in energy scale between different experiments.

CR energy spectrum with ARGO-YBJ

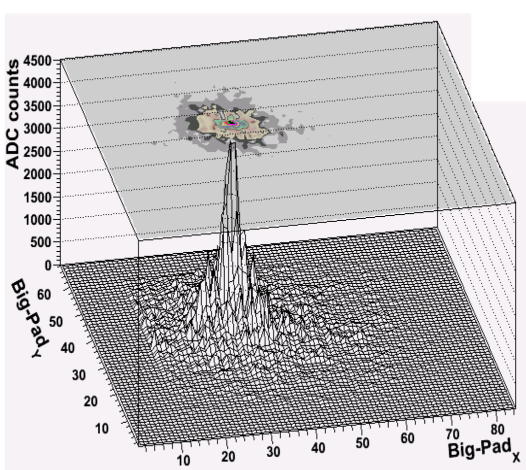
- Measurement of the CR energy spectrum (all-particle and light component) in the energy range *≈10^{12} - 10^{16} eV* by ARGO-YBJ with *3 different ‘eyes’*



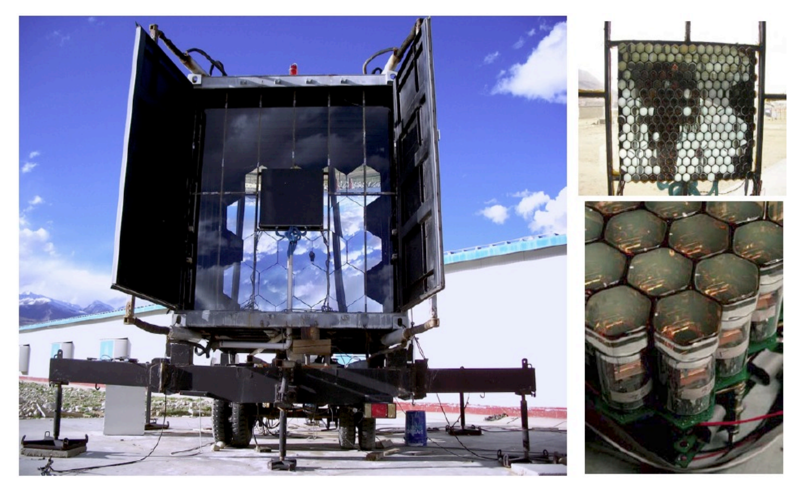
(1) *‘Digital readout’* (based on *strip multiplicity*) below 200 TeV



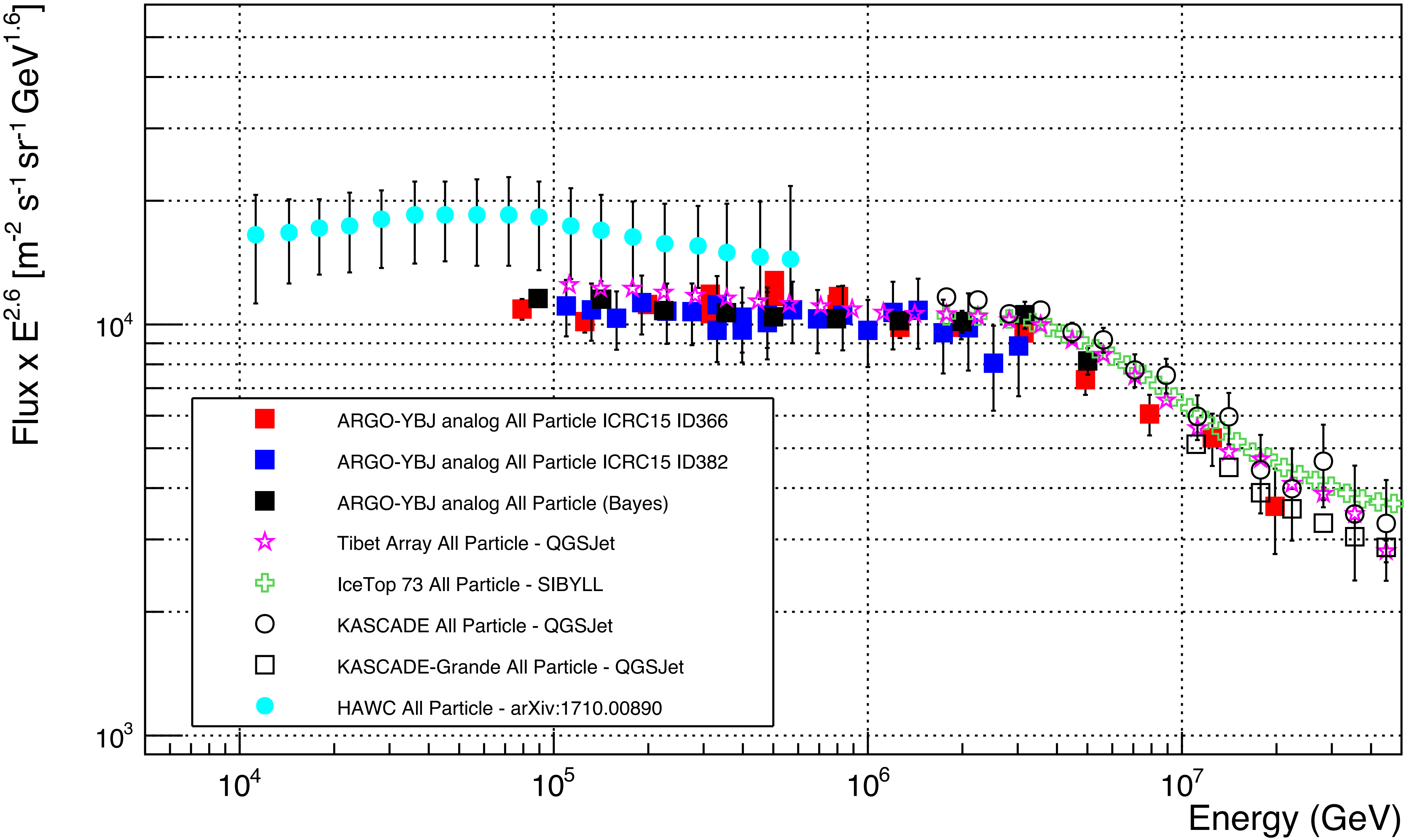
(2) *‘Charge readout’* (based on the *shower core density*) up to ≈10 PeV



(3) '*Hybrid measurement*' with a *Wide Field of view Cherenkov Telescope*: 200 TeV - PeV



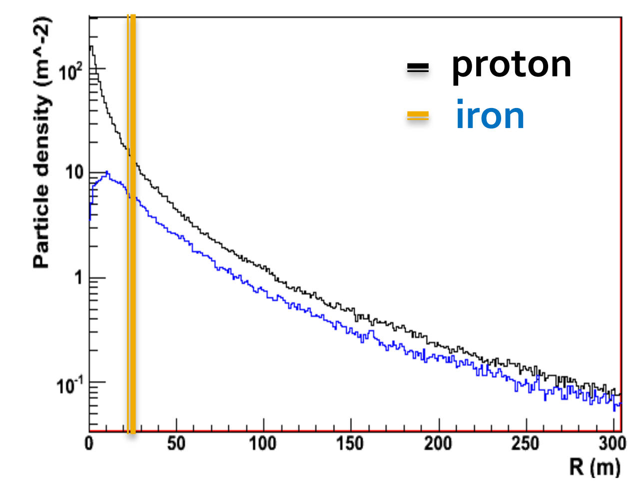
All-particle energy spectrum in the knee region



Selection of light (p+He) component

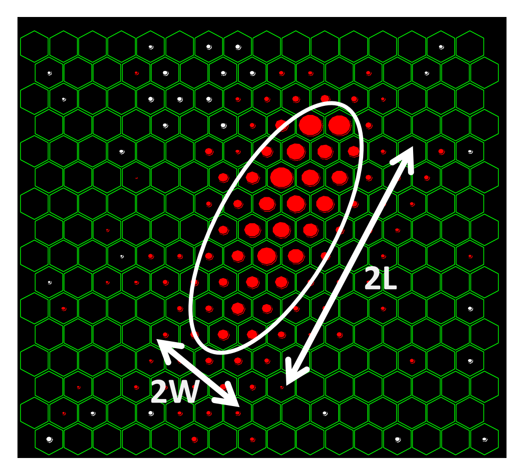
In the ARGO-YBJ experiment the selection of (p+He)-induced showers is performed **not** by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an event-by-event basis exploiting showers topology, i.e. the lateral distribution of charged secondary particles.

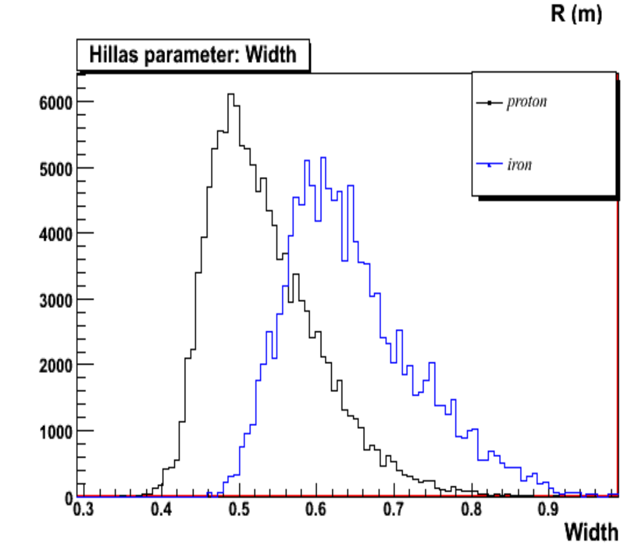
This approach is made possible by the full coverage of the central carpet, the high segmentation of the read-out and the high altitude location of the experiment that retains the characteristics of showers lateral distribution in the core region (< 30 m).



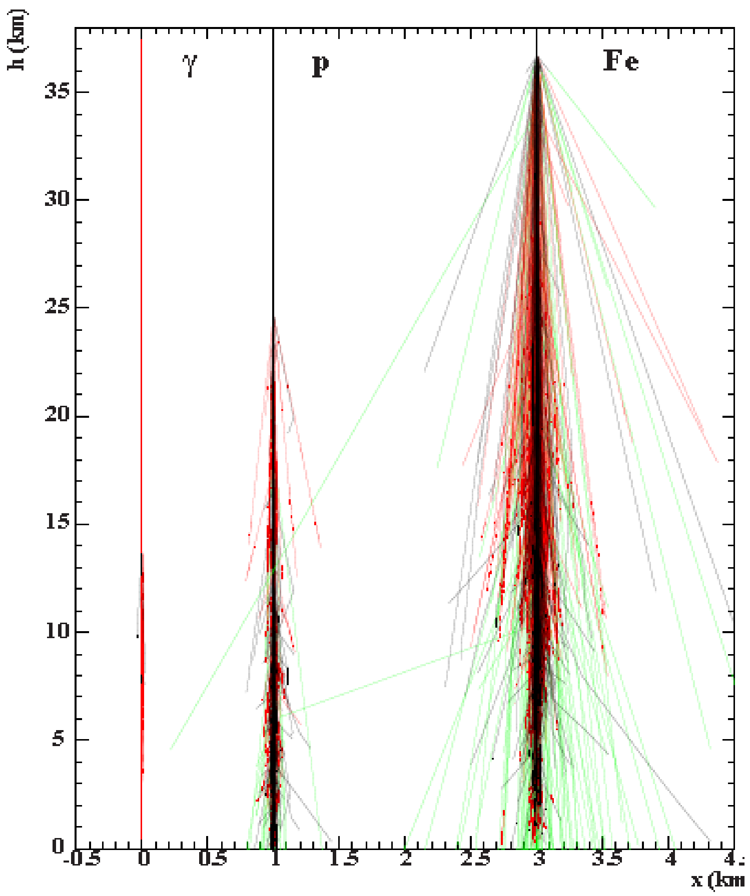
Hybrid measurement

- ❖ *ARGO-YBJ:* core reconstruction & lateral distribution in the core region → mass sensitive
- ❖ *Cherenkov telescope:* longitudinal information Hillas parameters → mass sensitive





Lateral distribution

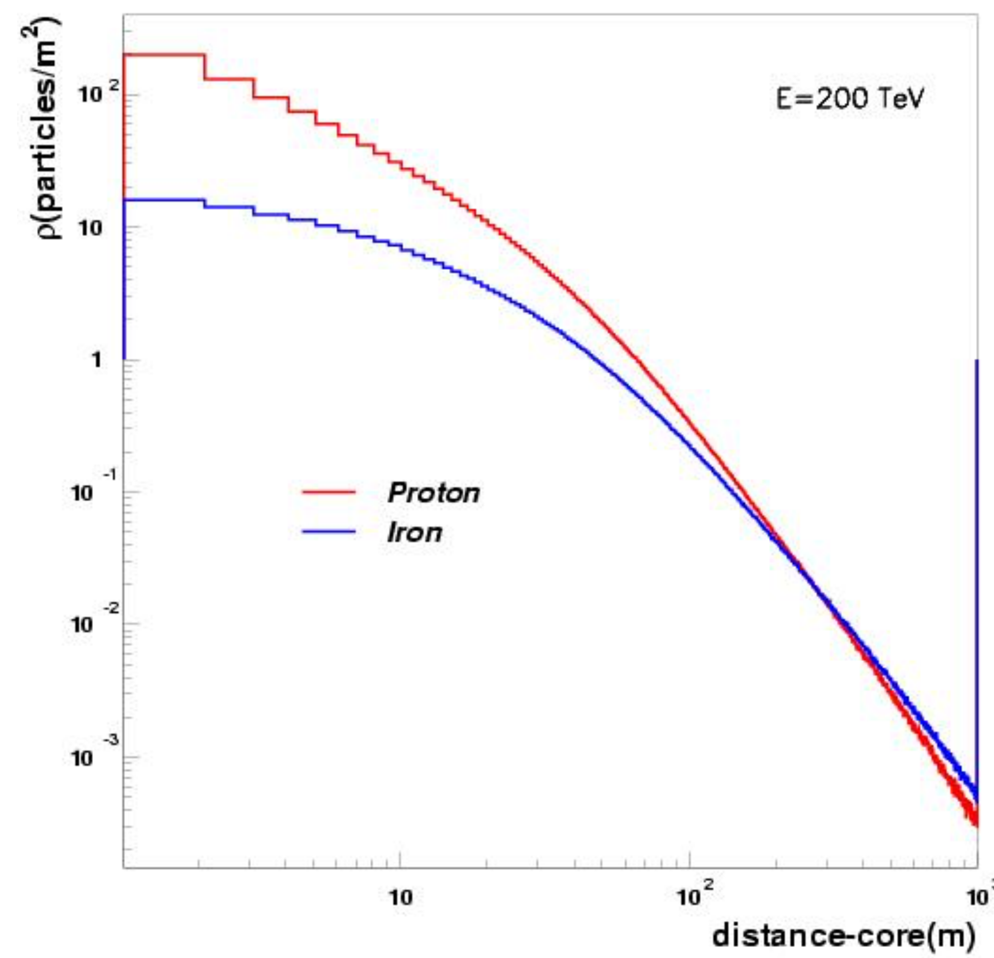


Fe showers develop higher in atmosphere than protons → Fe lateral distribution is slightly broader compared to p-showers

Increasing the mass A:

Larger deflection angles → flatter lateral distributions of secondary particles

J. Matthews, Astrop. Phys. 22 (2005) 387
J. Linsley, 15th ICRC, 12 (1977) 89.



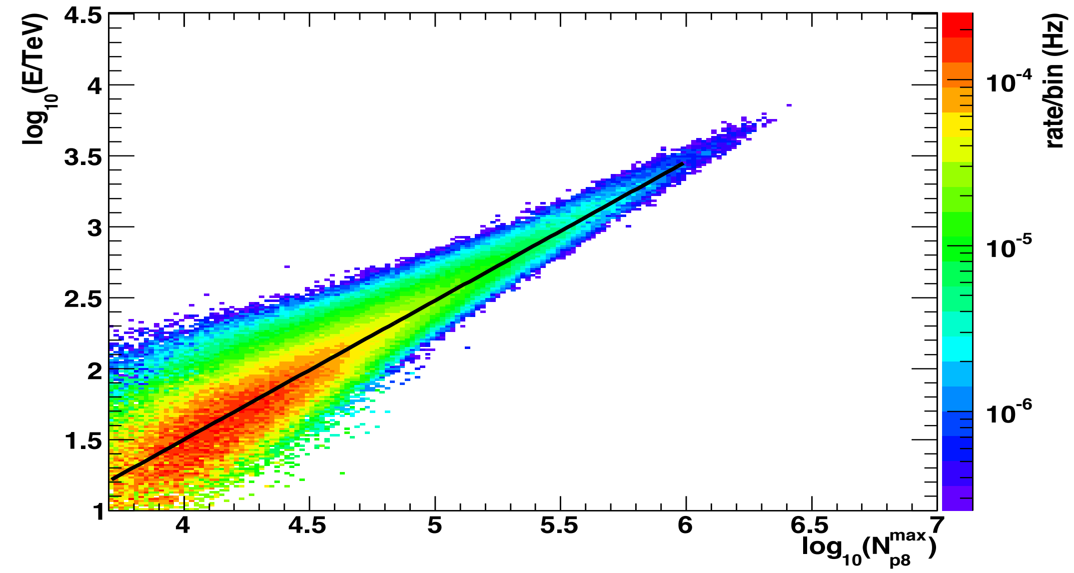
The showers can be classified in terms of the density ratio at two distances from the shower core

$$\rho(25\text{-}35\text{m}) \,/\, \rho(0\text{-}10\text{m})$$

Energy spectrum with '*charge read-out*'

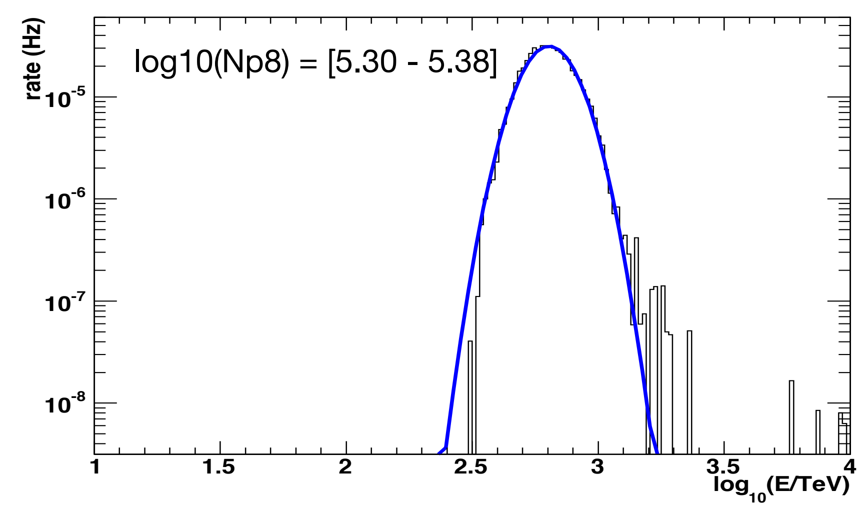
- Selection of (p+He)-induced showers in ARGO-YBJ: **NOT** by means of an unfolding procedure after the measurement of electronic and muonic sizes, but on an *event-by-event basis exploiting showers topology*, i.e. the lateral distribution of charged secondary particles.

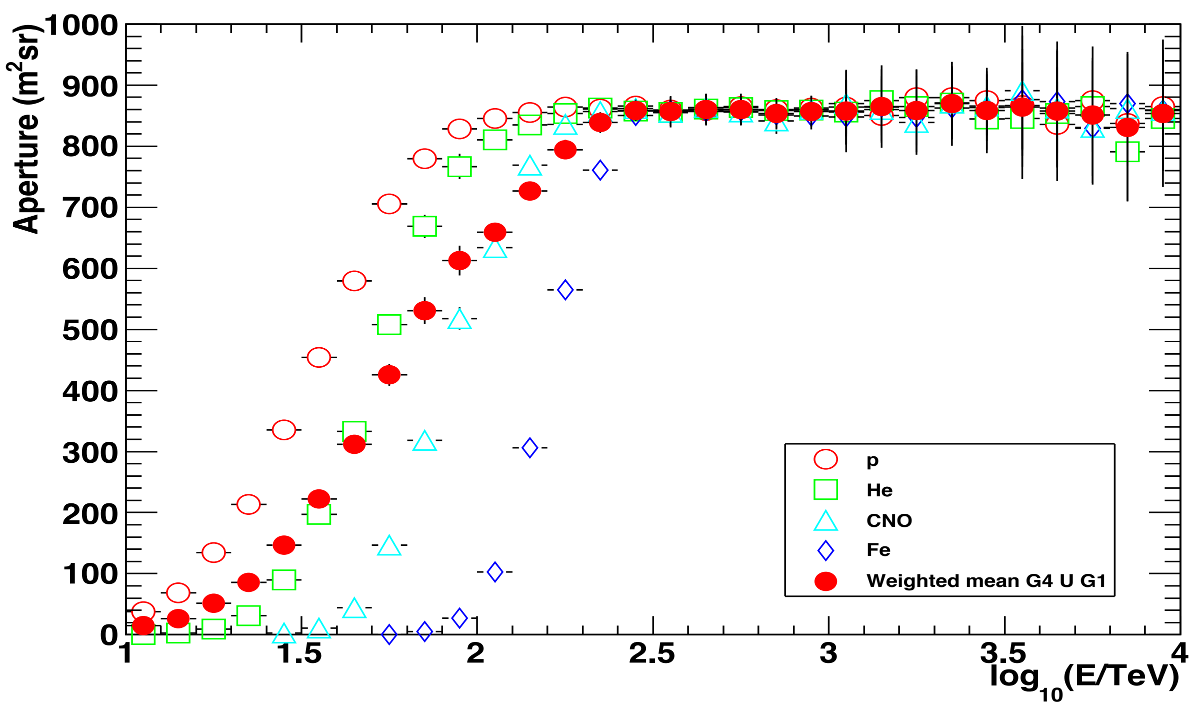
- Energy reconstruction is based on the N_p^{8m} parameter: the *number of particle within 8 m from the shower core position.*

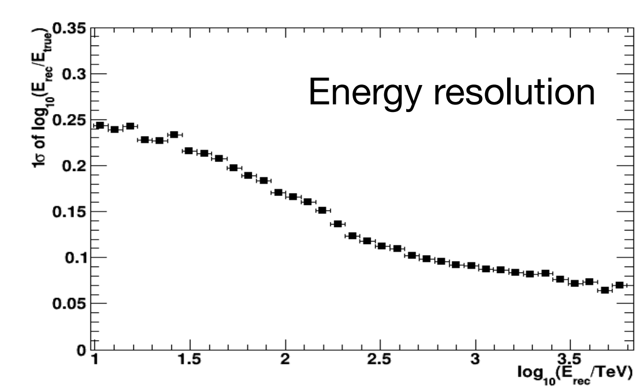


This truncated size is

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







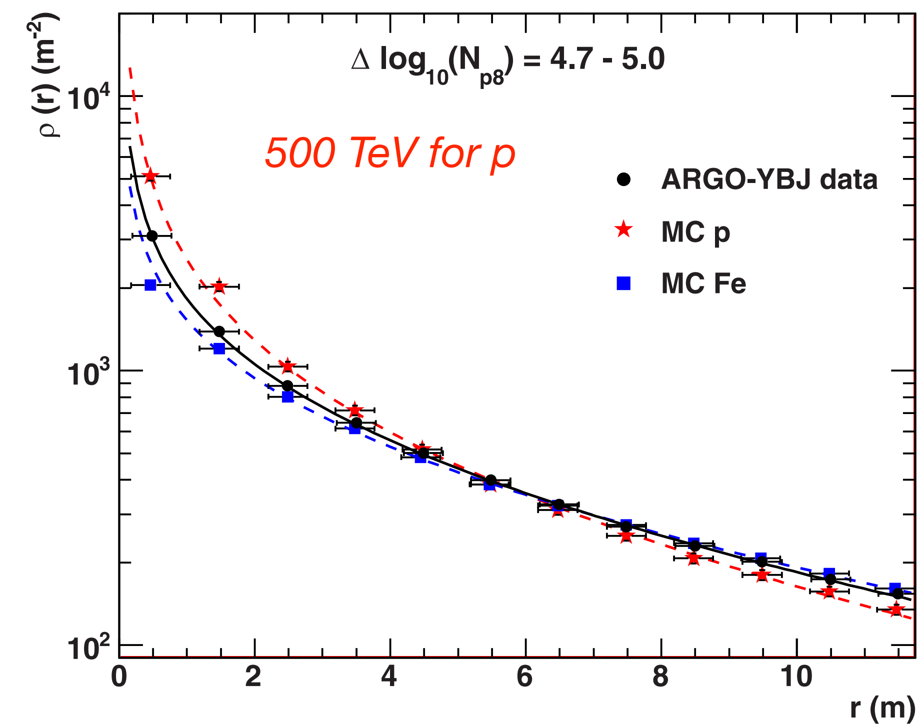
Lateral distribution by ARGO-YBJ

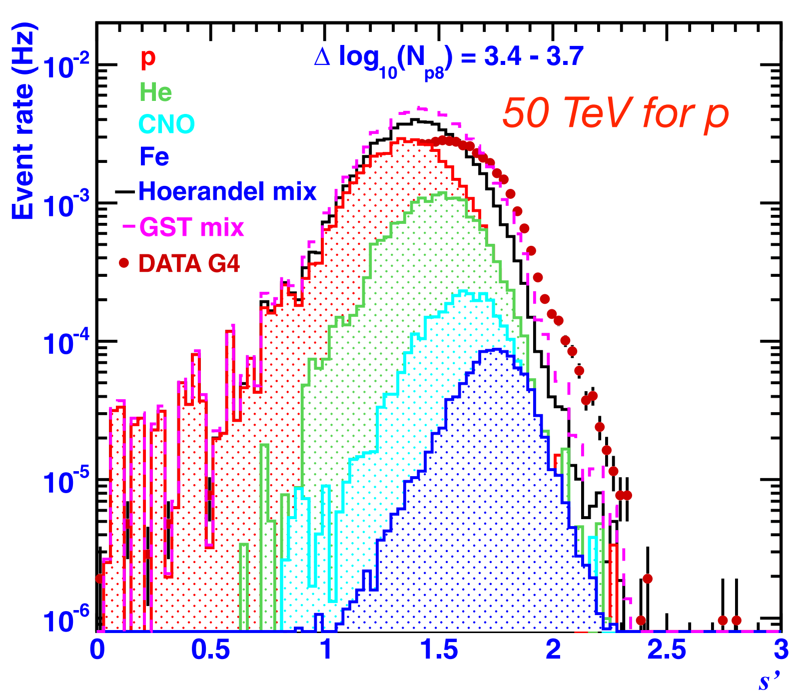
Shower selection in terms of the N_p^{8m} parameter

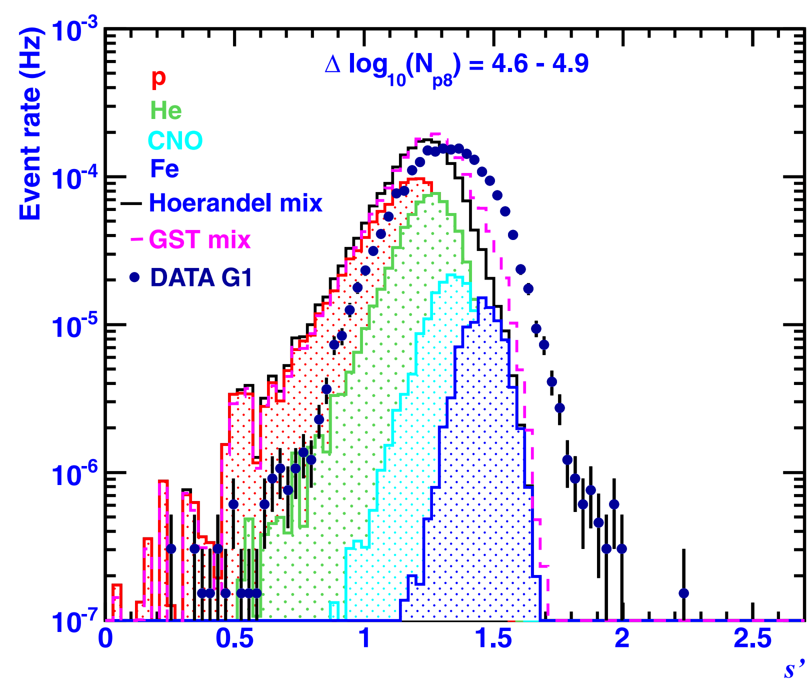
Description of the LDF with a modified NKG form

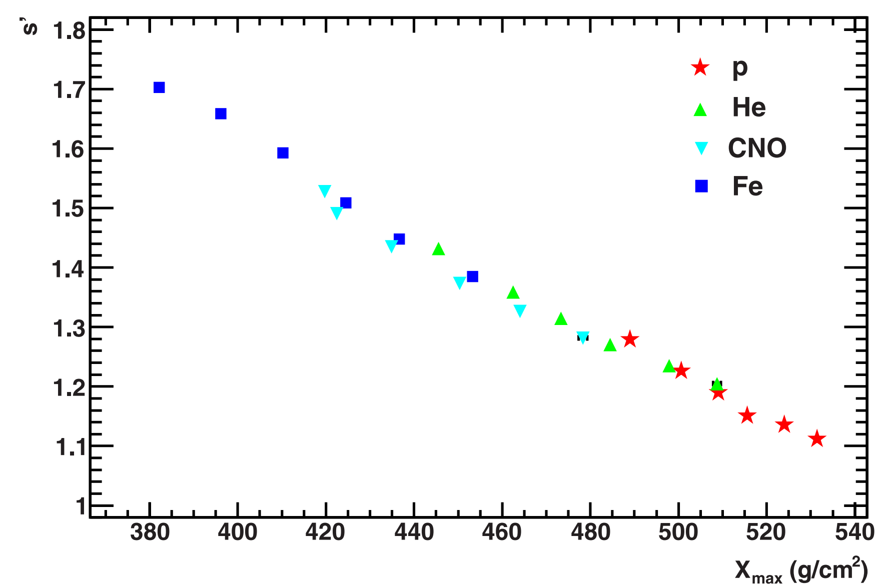
$$\rho(r) = A\left(\frac{r}{r_0}\right)^{s'-2}\left(1+\frac{r}{r_0}\right)^{s'-4.5}$$

A = normalisation factor
s'= shape parameter ➜ *lateral age*
r_0 = constant scale radius





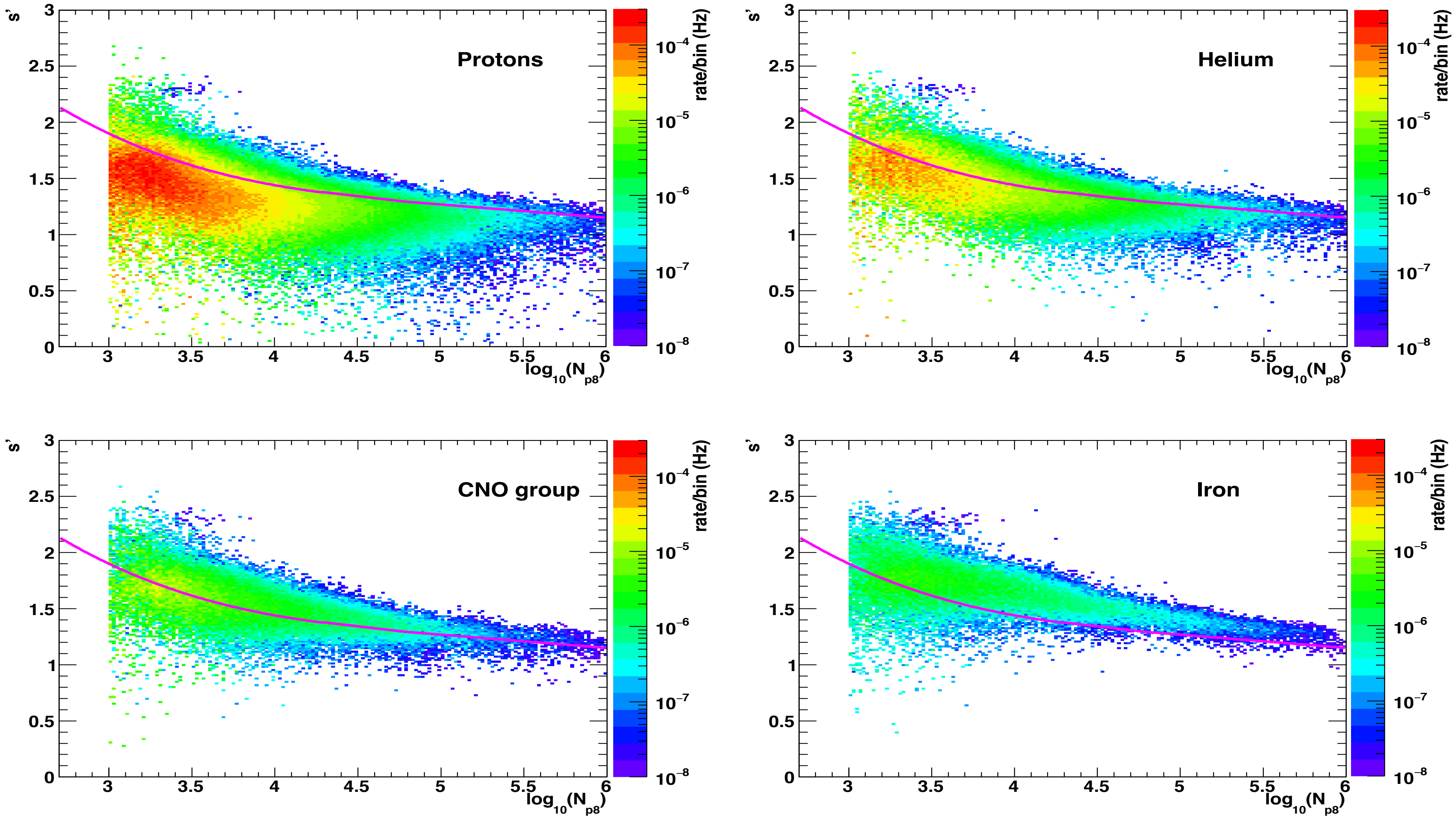




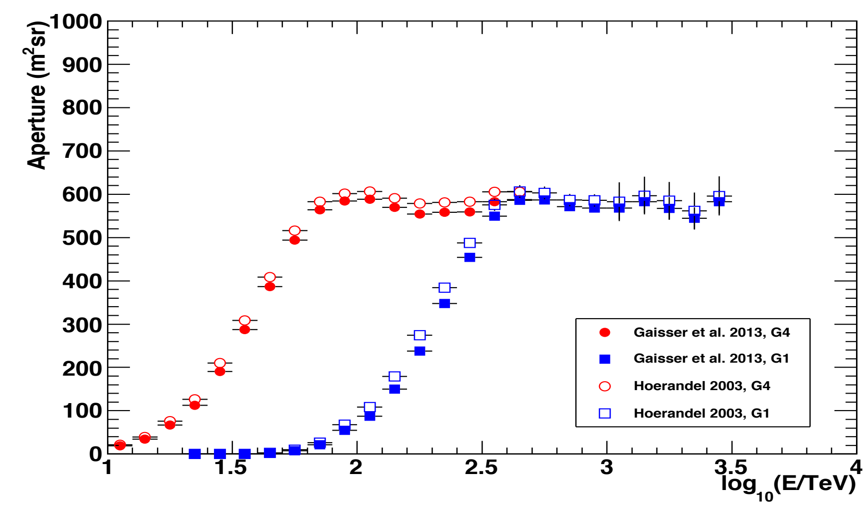
Astroparticle Physics 93 (2017) 46–55

Selection of p+He component by ARGO-YBJ

The LDF slope s' as a function of the truncated size N_{p8} as reconstructed for showers initiated by different nuclei. The p+He selection cut is shown by the pink line.



The *efficiency in selecting p and He* initiated showers and the *heavier elements contamination* are at the level of *85%* and *15%* respectively,



Apertures for G4 and G1 data samples for the measurement of the light-component energy spectrum.

Wide Field of View Cherenkov Telescopes

The goal: *measurement of the CR energy spectrum and composition above 10^{14} eV*

Why Wide FoV Cherenkov telescopes at high altitude ?

High altitude:

(1) Measure EASs near maximum development points t*o reduce fluctuations*.

(2) Use an *unbiased trigger threshold for heavy components* of primaries.

(3) *Low energy threshold* and wide energy range ($10^{13} \rightarrow 10^{18}$ eV).

Cherenkov signal:

(3) *Low energy threshold* and wide energy range ($10^{13} \rightarrow 10^{18}$ eV).

(4) Measure the *electromagnetic component* which is *less dependent on hadronic interaction models* than the muon component.

(5) *Good separation capability* between the different masses.

(6) *Good energy resolution* (≈25 %).

Chin. Phys. C 38, 045001 (2014)
Phys. Rev. D 92, 092005 (2015)

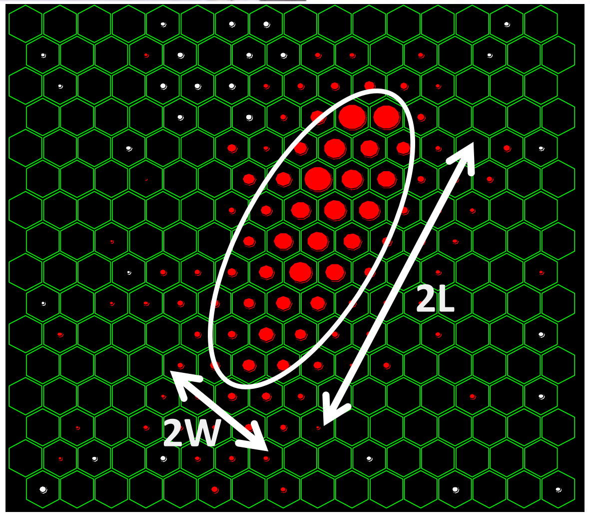
First example of *hybrid measurement*: Cherenkov telescope + EAS array (ARGO-YBJ)

➡ *feasibility study for LHAASO*

ARGO-YBJ + WFCTA

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

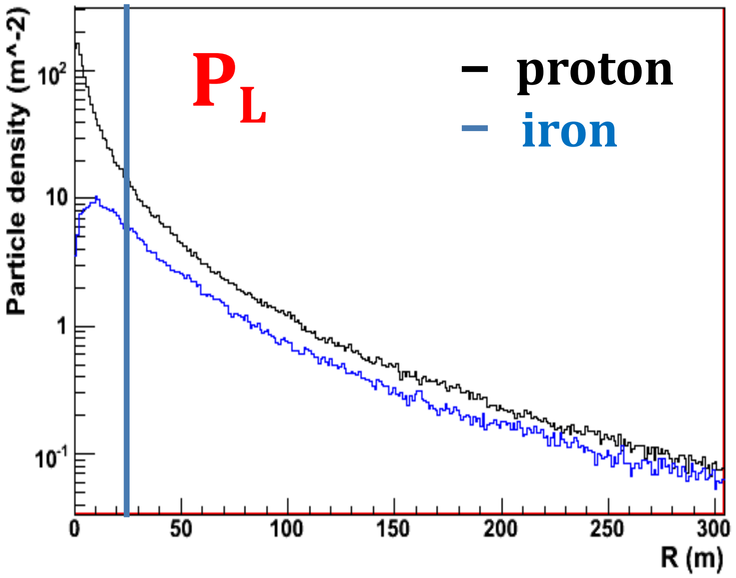
- 4.7 m² spherical mirror composed of 20 hexagon-shaped segments
- 256 PMTs (16 × 16 array)
- 40 mm Photonis hexagonal PMTs (XP3062/FL)
- pixel size 1°
- FOV: 14° × 14°
- Elevation angle: 60°

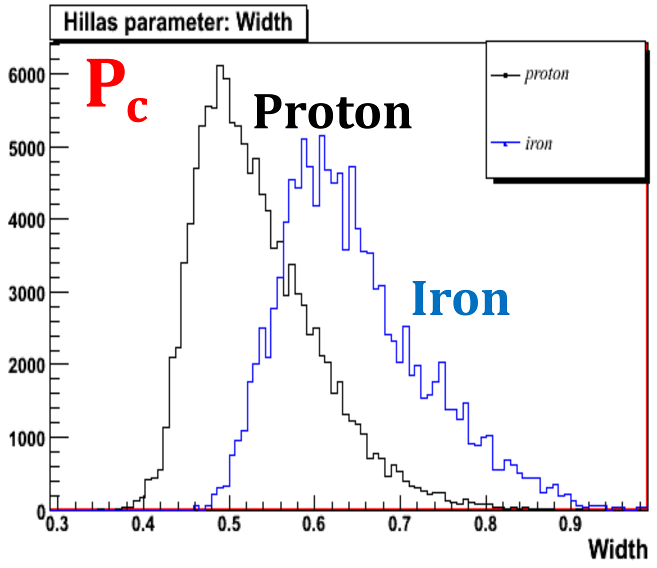


- *ARGO-YBJ:* core reconstruction
  lateral distribution in the core region → mass sensitive
- *Cherenkov telescope:* longitudinal information
  Hillas parameters → mass sensitive
  Energy reconstruction

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

Phys. Rev. D 92, 092005 (2015)



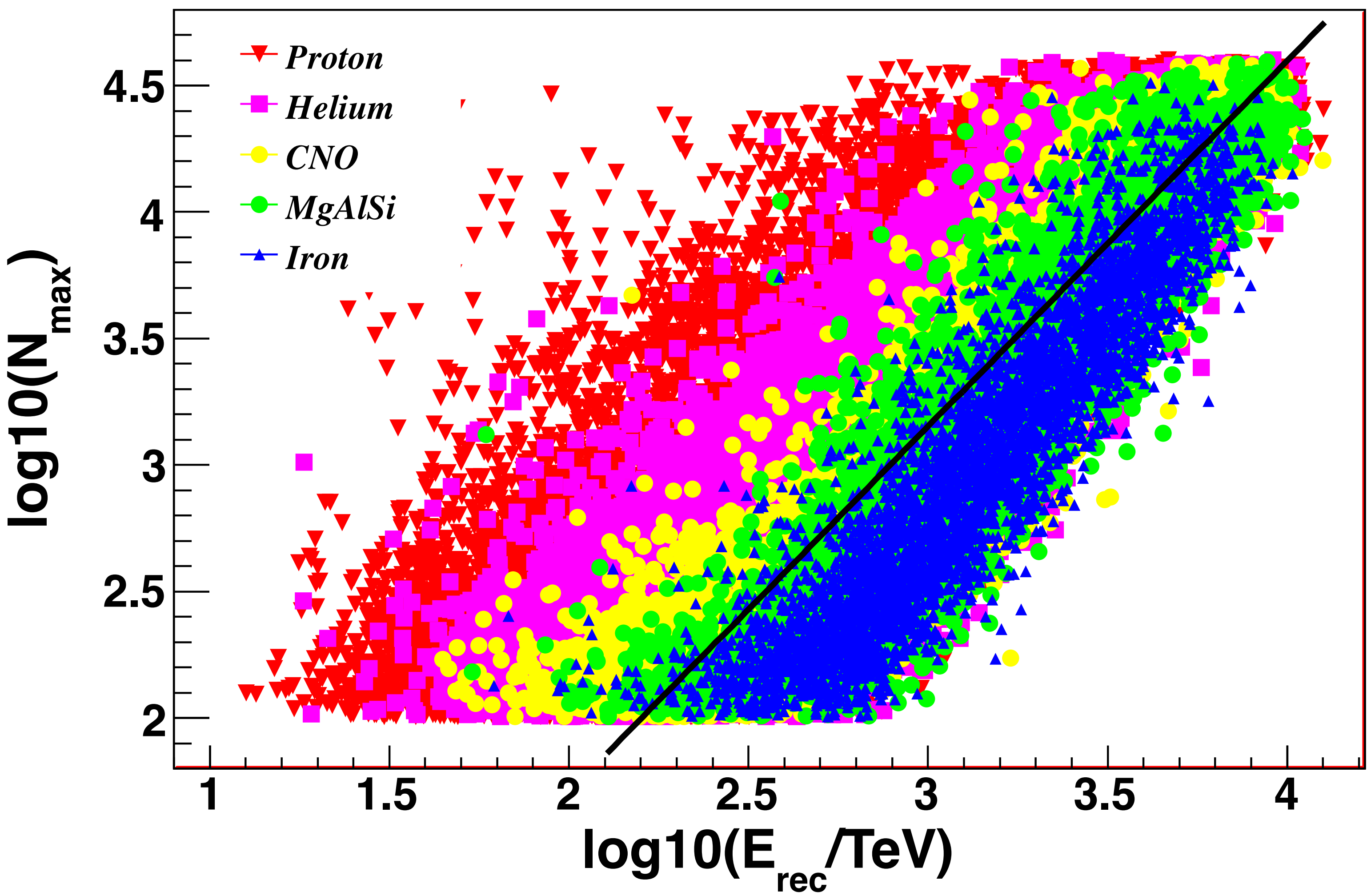


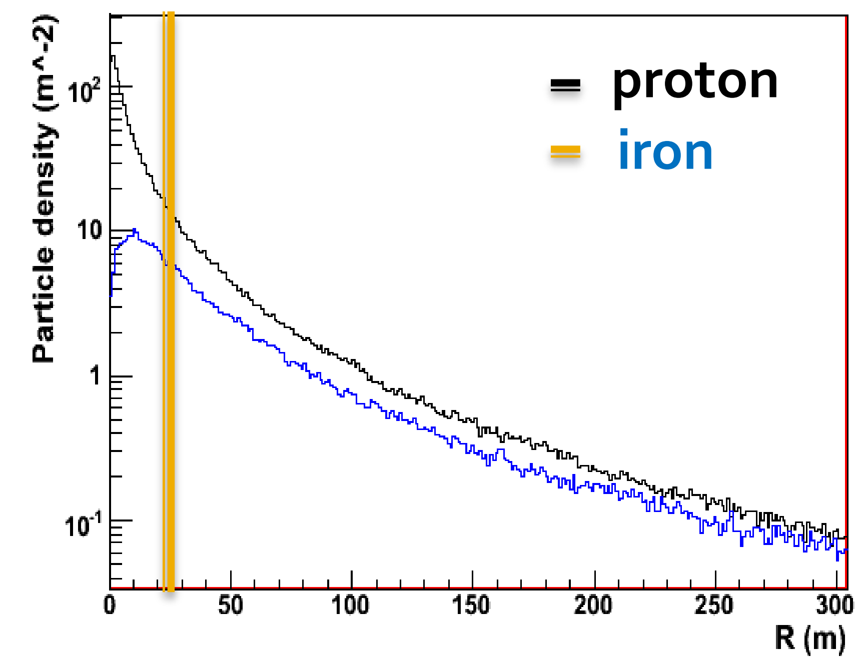
Light component (p + He) selection - (1)

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

N_{max} is a mass sensitive parameter

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





We can define a new parameter to reduce the energy dependence

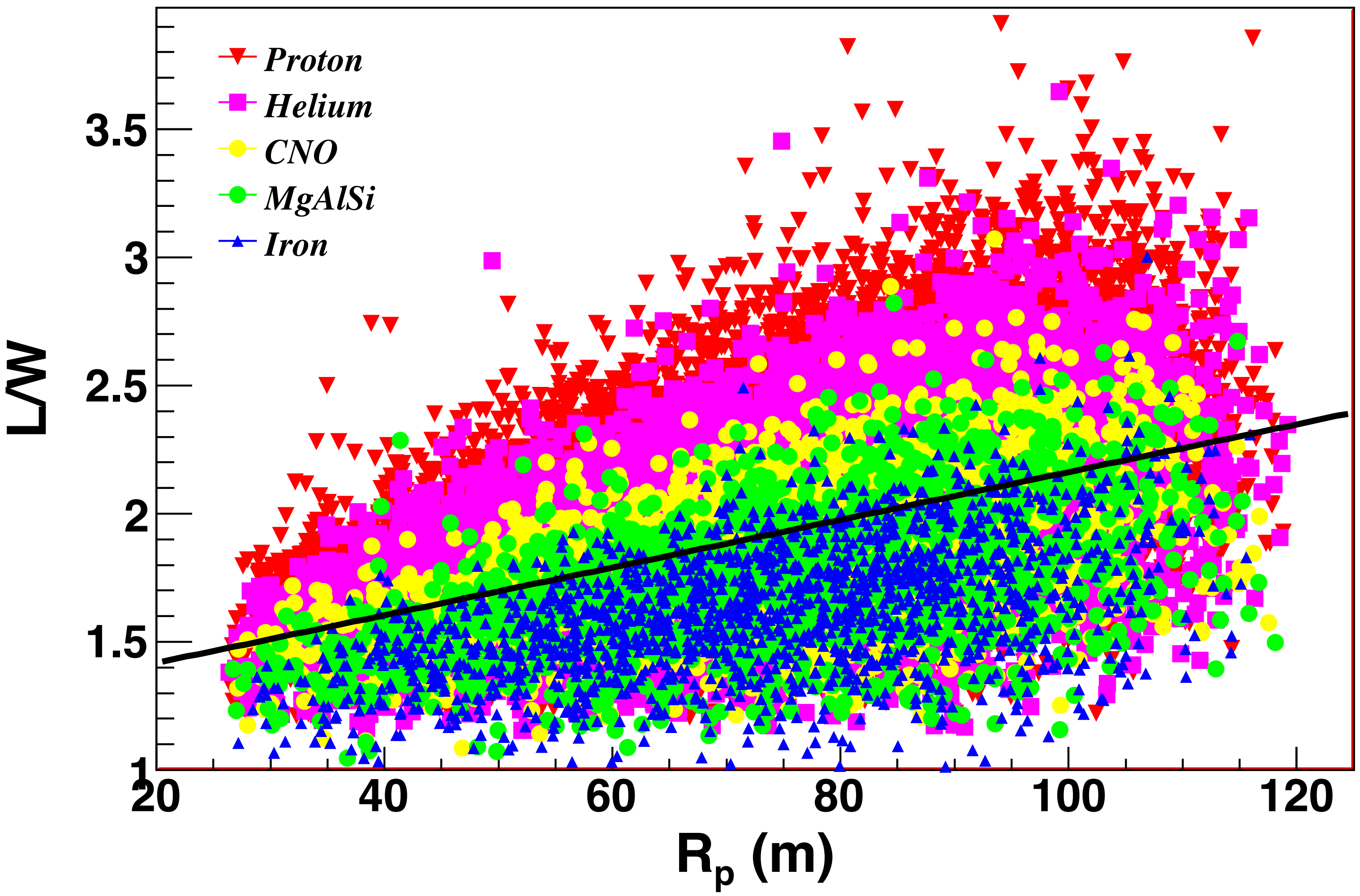
$$p_L = log_{10}(N_{max}) - 1.44 \cdot log_{10}(E_{rec}/TeV)$$

Chin. Phys. C 38, 045001 (2014)

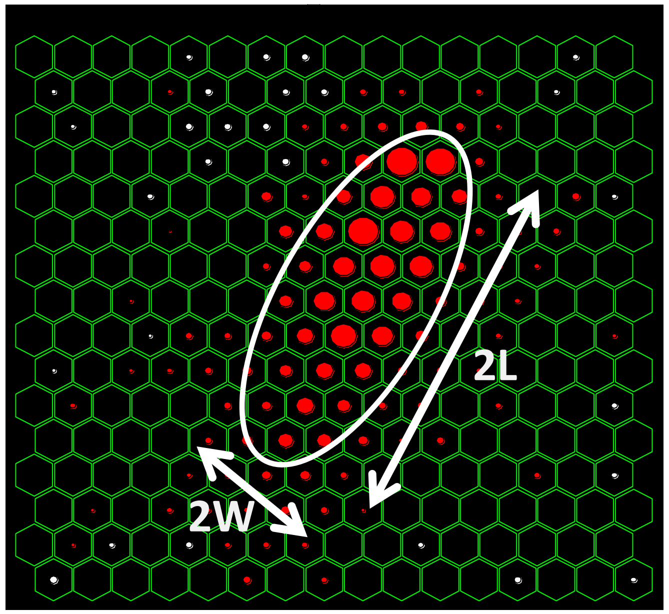
Light component (p + He) selection - (2)

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

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



Typical Cherenkov footprint



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

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

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

Chin. Phys. C 38, 045001 (2014)

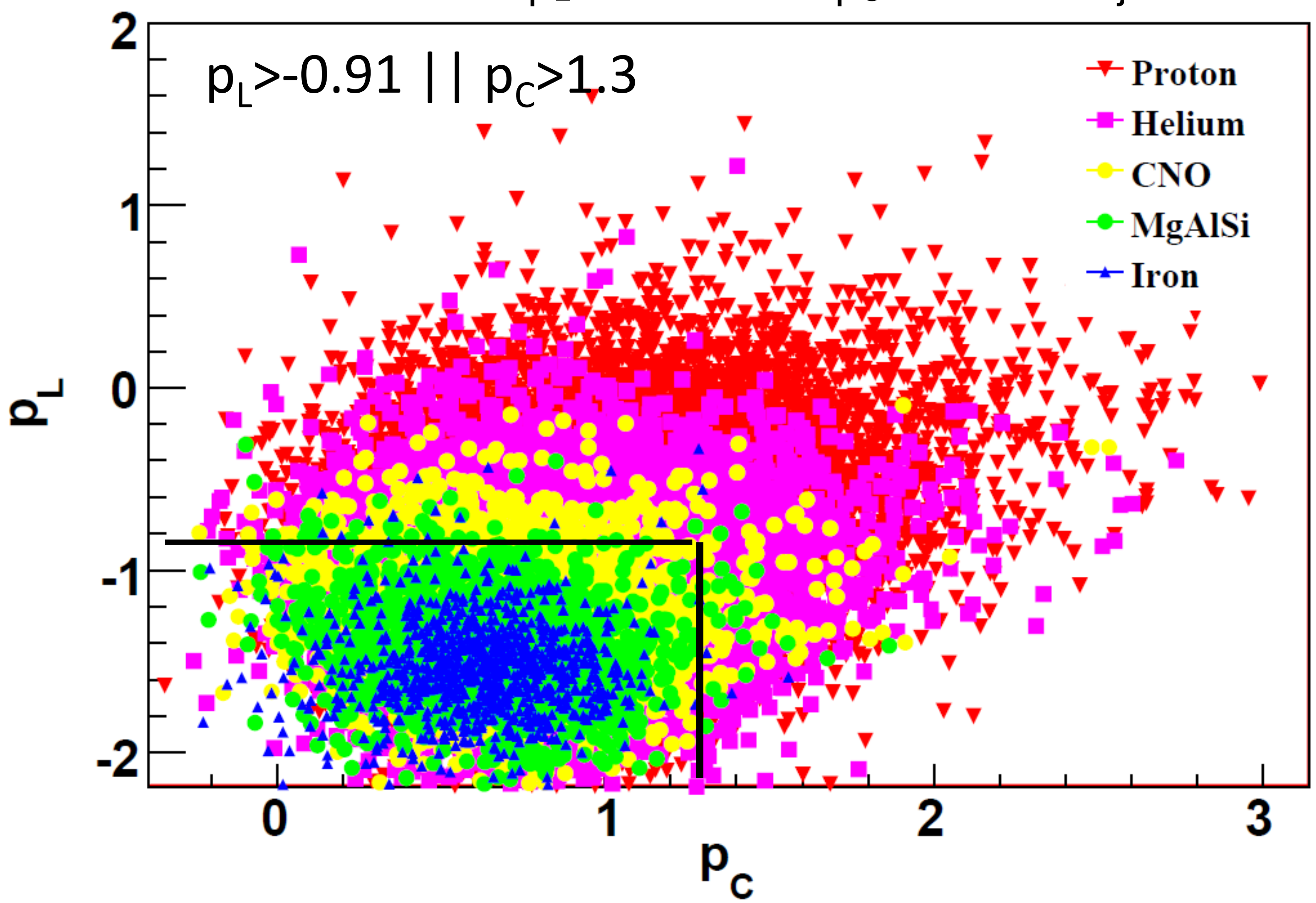
Light component (p + He) selection

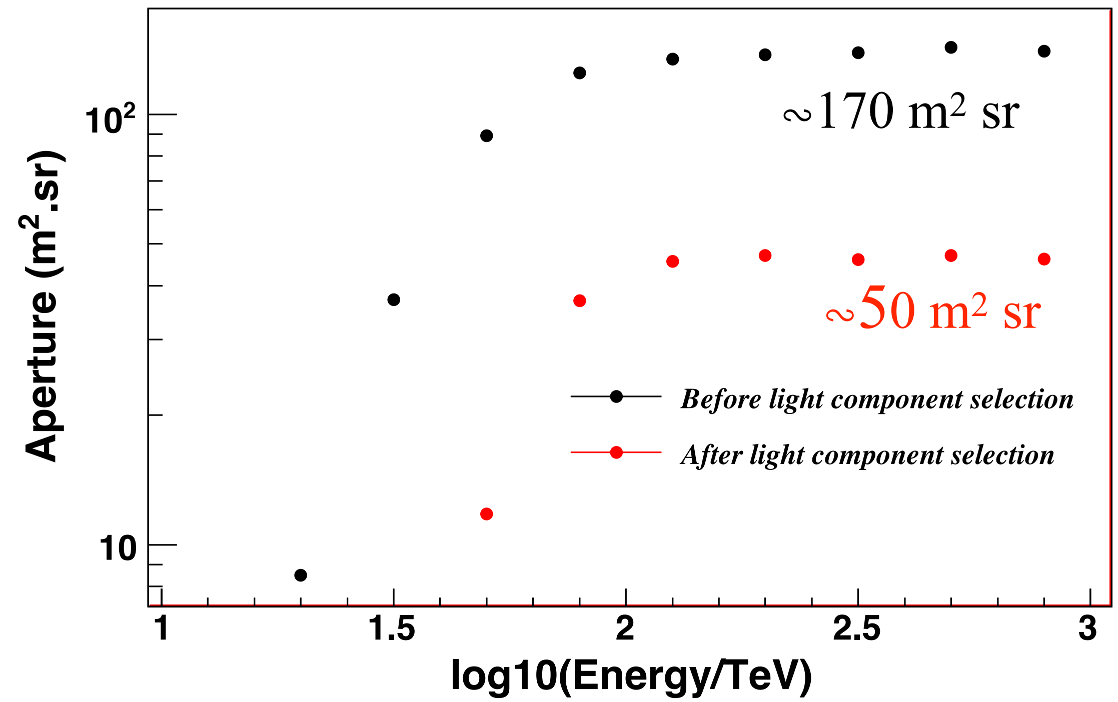
- Contamination of heavier component < 5 %
- Energy resolution: ~25% constant with energy
- Uncertainty : ~25% on flux

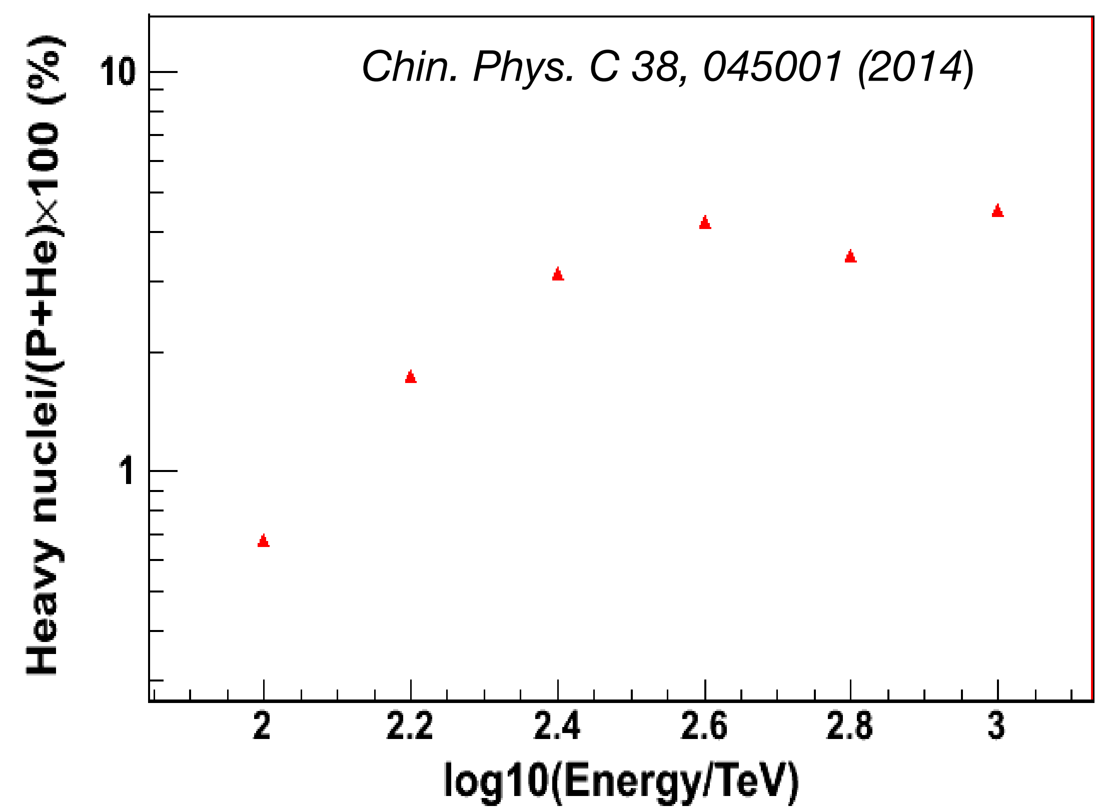
$$p_L = log_{10}(N_{max}) - 1.44 \cdot log_{10}(E_{rec}/TeV)$$

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

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

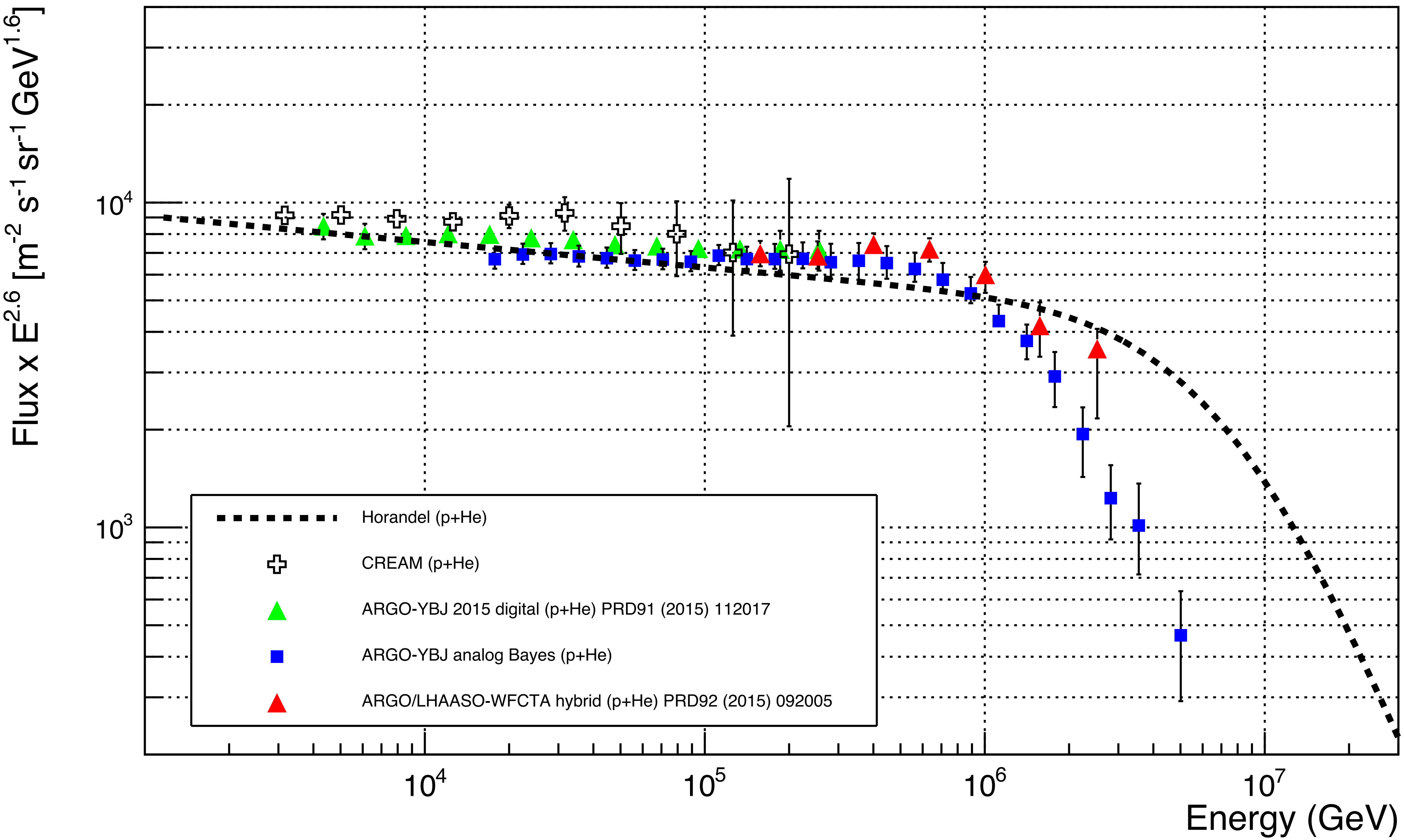




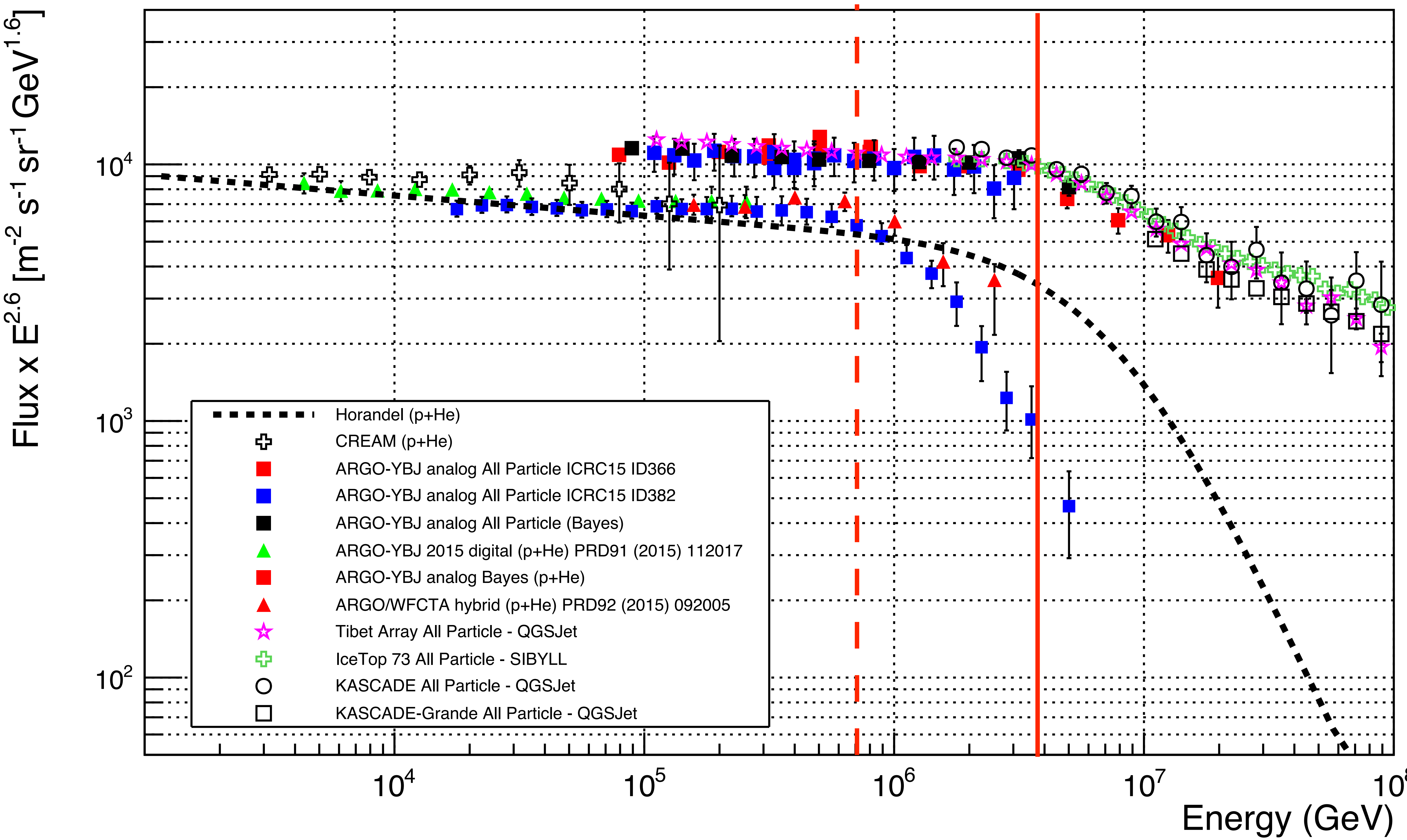


Composition at the knee: ARGO-YBJ

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

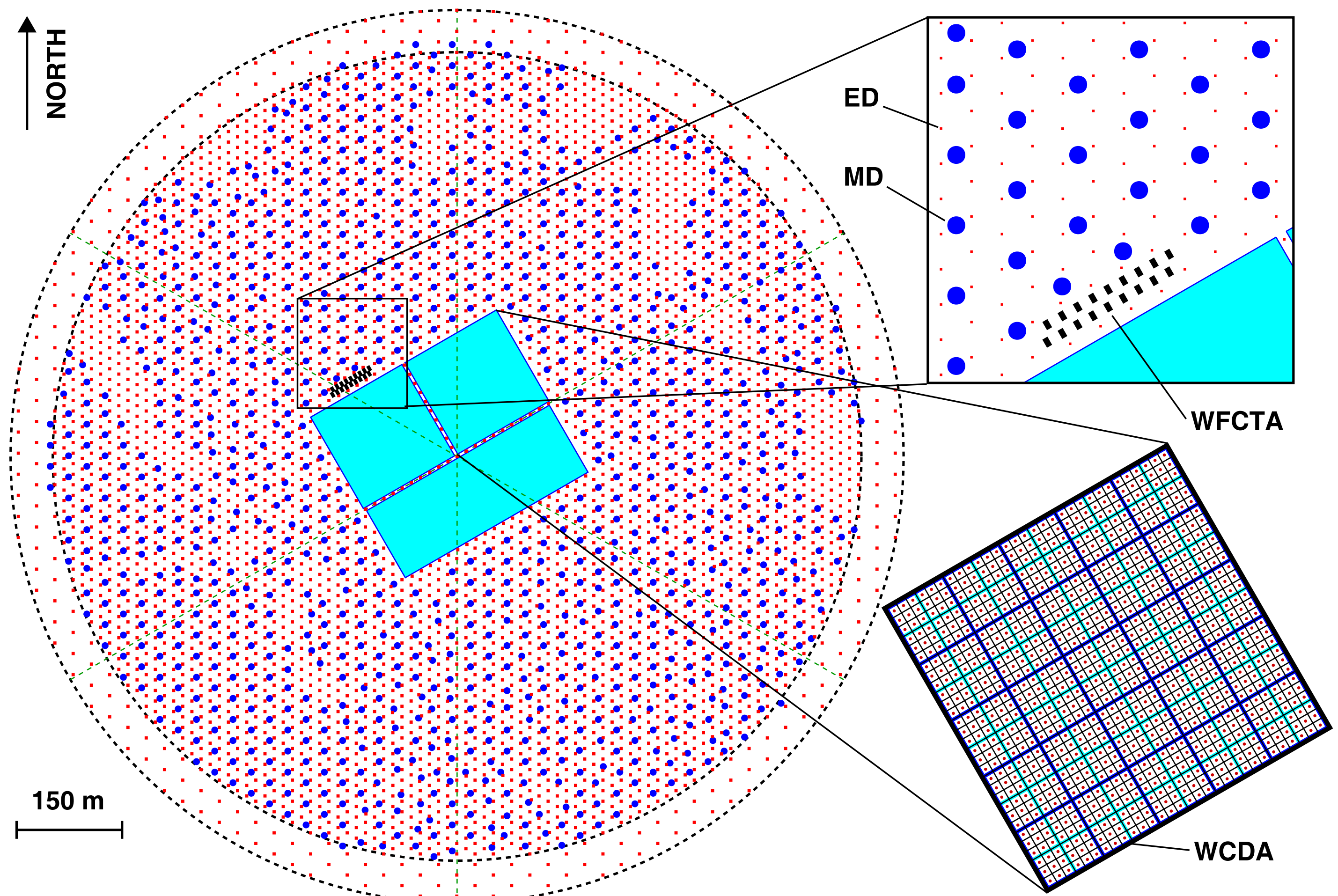


The overall picture



What’s next ? LHAASO

- 1.3 km² array, including 5195 scintillator detectors 1 m² each, with 15 m spacing.
- An overlapping 1 km² array of 1171, underground water Cherenkov tanks 36 m² each, with 30 m spacing, for muon detection (total sensitive area ≈ 42,000 m²).



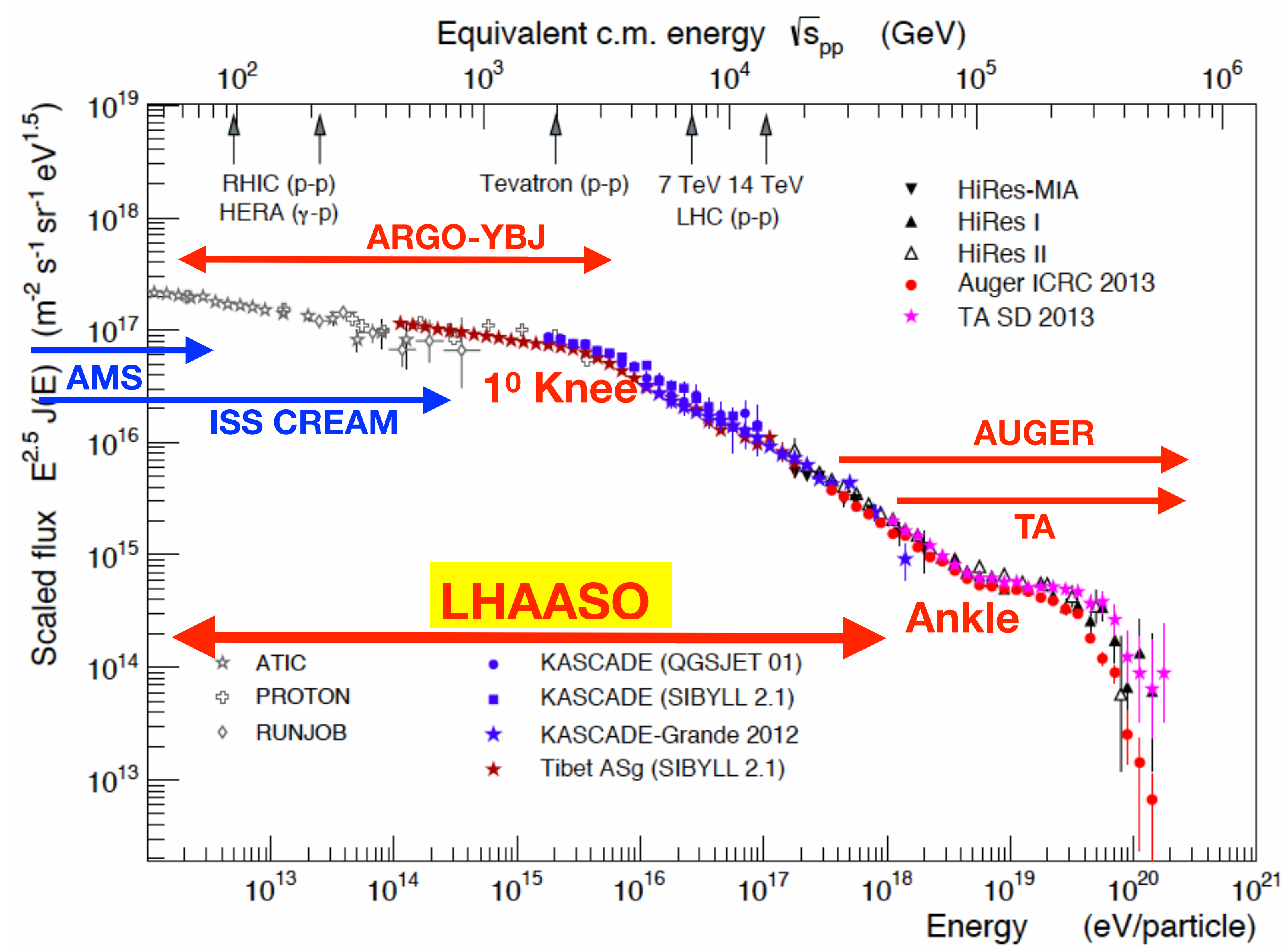
- A close-packed, surface water Cherenkov detector facility with a total area of 80,000 m².
- 12 wide field-of-view air Cherenkov (and fluorescence) telescopes.
- Neutron detectors

Cosmic Ray Physics with LHAASO

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

- Water Cherenkov Detector Array
- Scintillator Array
- Muon Detector Array
- Cherenkov/Fluorescence Telescopes
- Neutron (Hadron) Detectors

The capability of Water Cherenkov facilities in extending the energy range to PeV and in selecting primary masses must be investigated

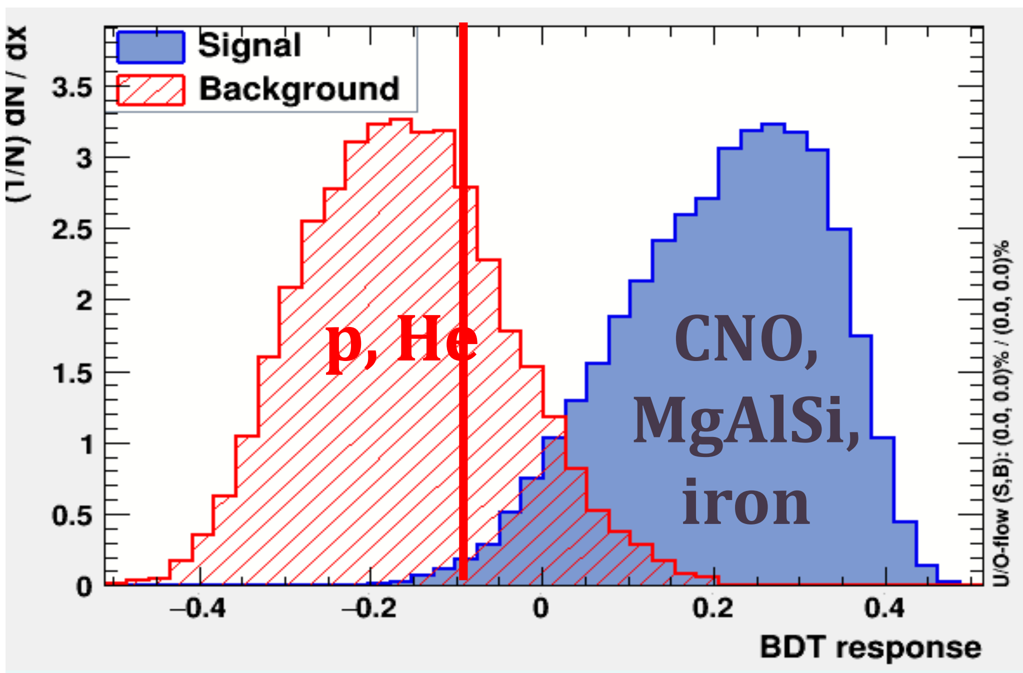


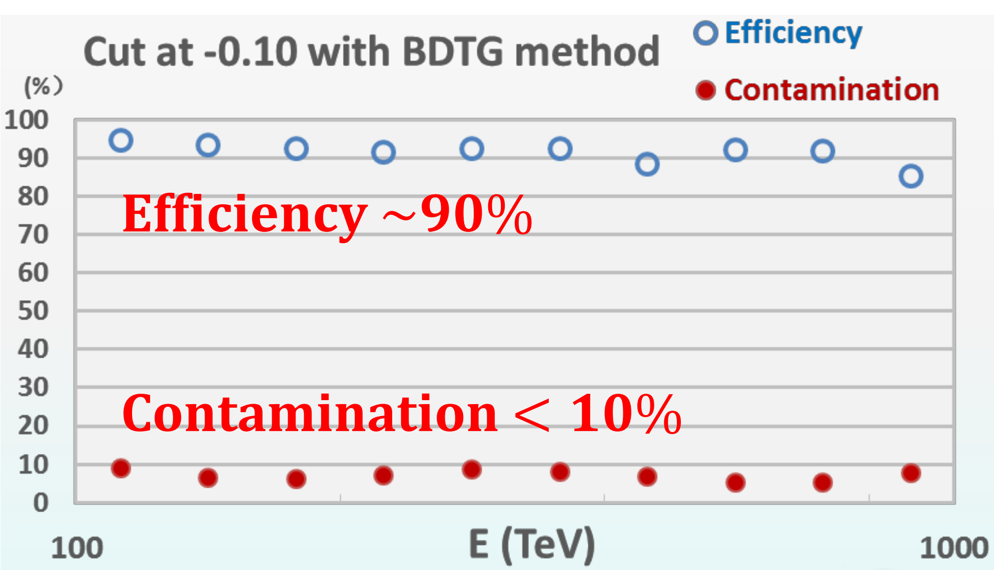
If Water Cherenkov facilities are not able to select primary masses, the measurements of light component is precluded to HAWC and will be possible to LHAASO only with WFCTA, but only starting above 100 TeV.

Elemental composition with WFCTA

0.1-10 PeV in 2019

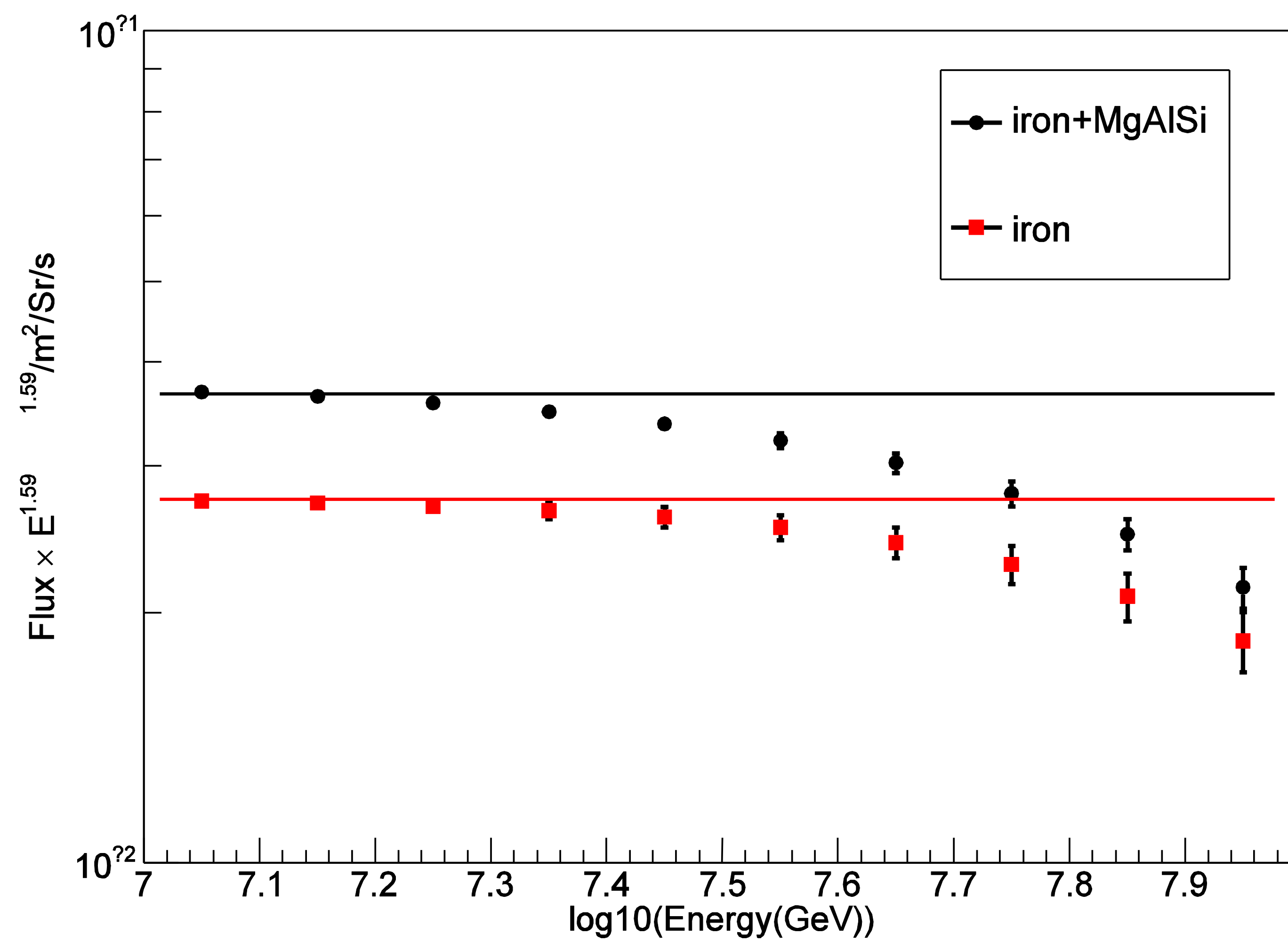
- pure proton and pure Helium spectra
- 6 C-Tel's (60° in elevation) + 1st pool





1-100 PeV in 2021

- pure iron and heavy nuclei (MgSi + Fe)
- 12 C-Tel's (45° in elevation) + scint. + Md array



Conclusions

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

- We measured the CR energy spectrum in the TeV - 10 PeV energy range.
- Evidence for a bending in the p+He spectrum starting around 700 TeV (6 s.d. level).
- The measured all-particle spectrum in agreement with other experiments.
- Different analysis consistent with a hybrid measurement carried out with a wide field of view Cherenkov telescope.
- Results nearly independent from hadronic models: no muons, particle density in the core

What's next ?

★ *High statistics measurement of energy spectra of different nuclei up to 10^{17} eV*

★ *Evolution of the anisotropy across the knee separately for different primary masses*

Cosmic Ray mass dependency ?

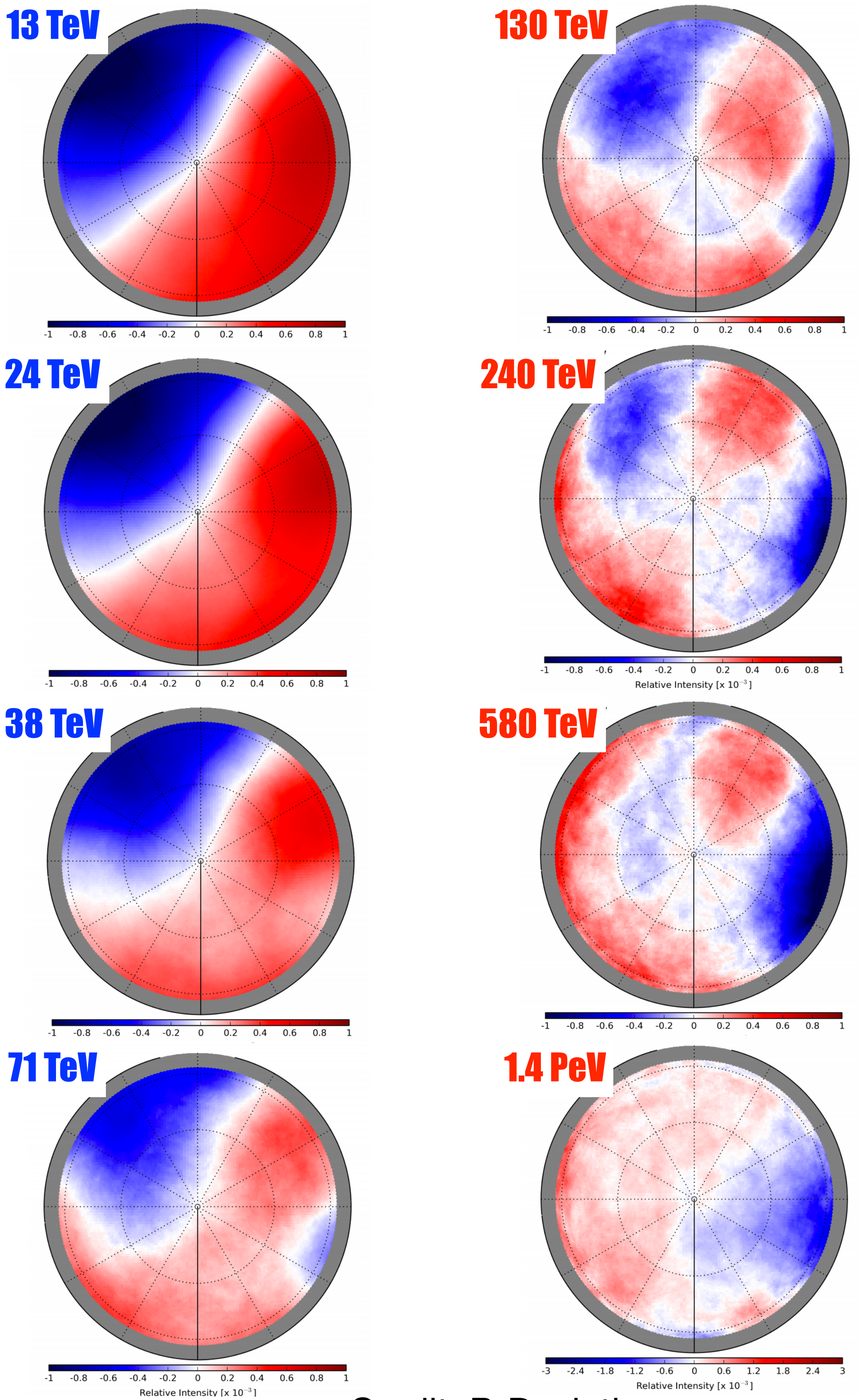
Energy dependency (< knee)

Anisotropy depends on primary energy

CR composition changes as well with energy

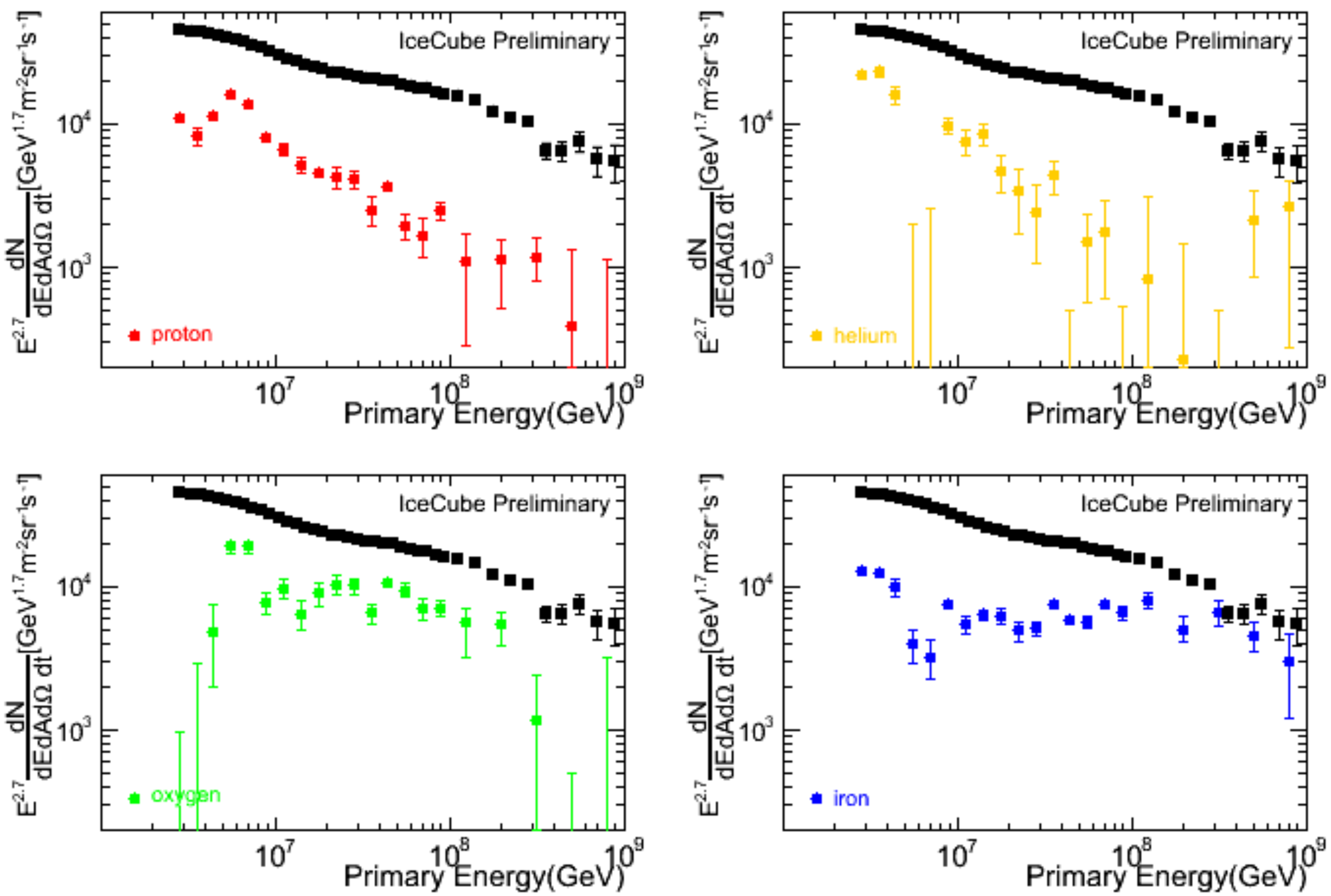
Provide anisotropy observations vs CR particle rigidity !

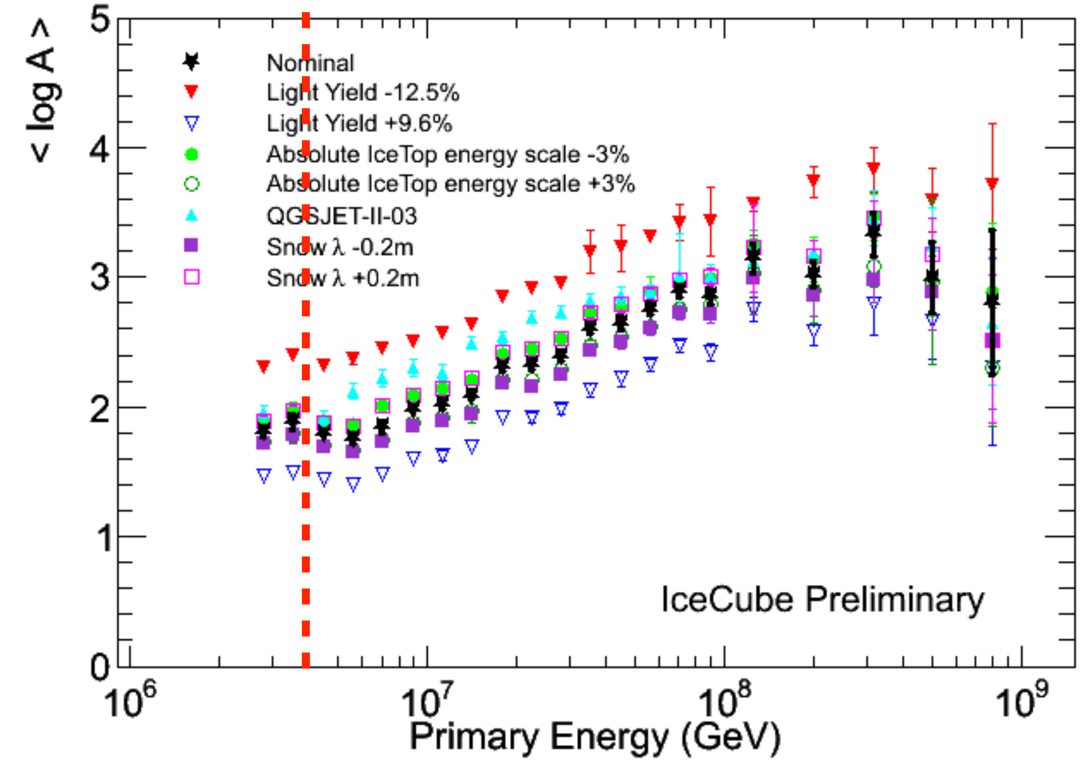
A *combined measurement* of CR energy spectrum, mass composition and anisotropy inevitably probes the properties and spatial distribution of their sources as well as of the long propagation journey through the magnetized medium.



Credit: P. Desiati

Composition at the knee: IceCube/IceTop





EPJ Web Conf. 145 (2017) 01003

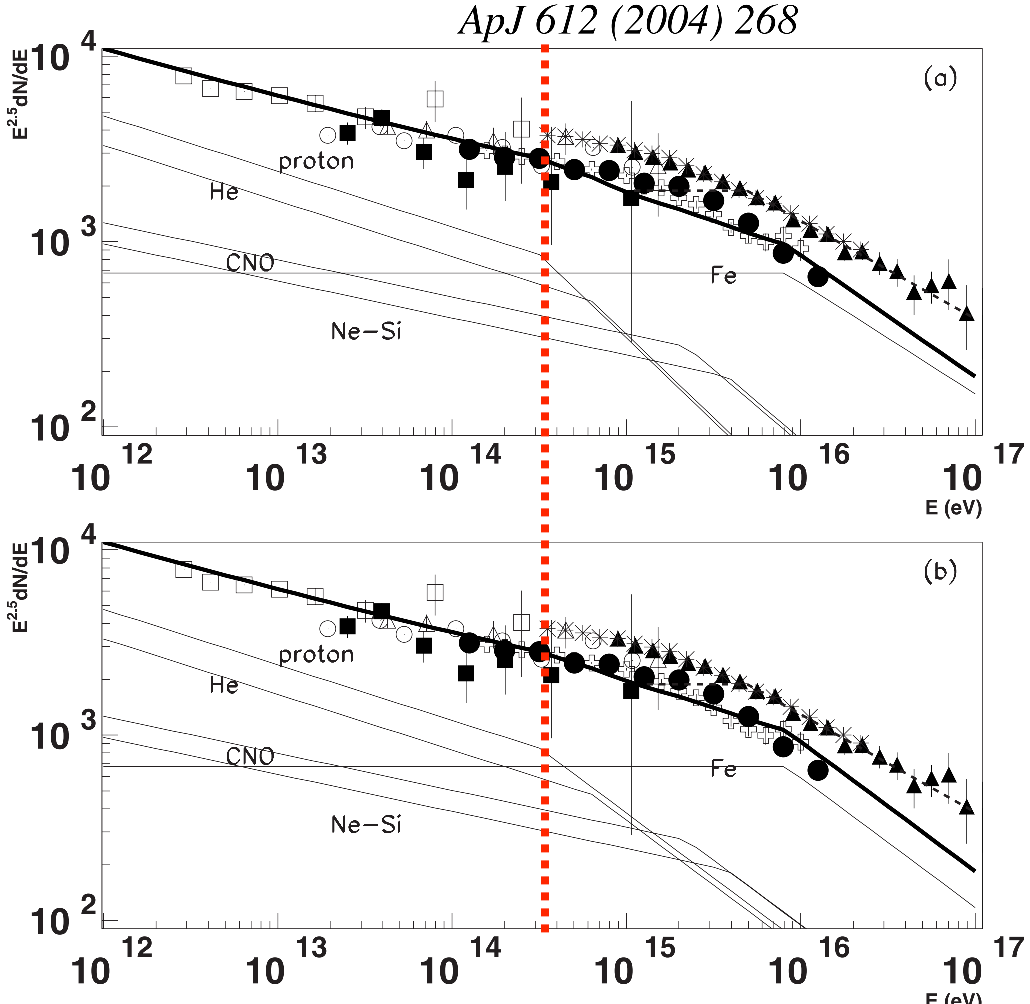
IceCube observes *an initially light composition that becomes increasingly heavy as the energy increases, then stabilizes around 100 PeV.*

The measurement indicates a *heavier composition around 1 EeV than measurements from Auger* based on the depth of shower maximum.

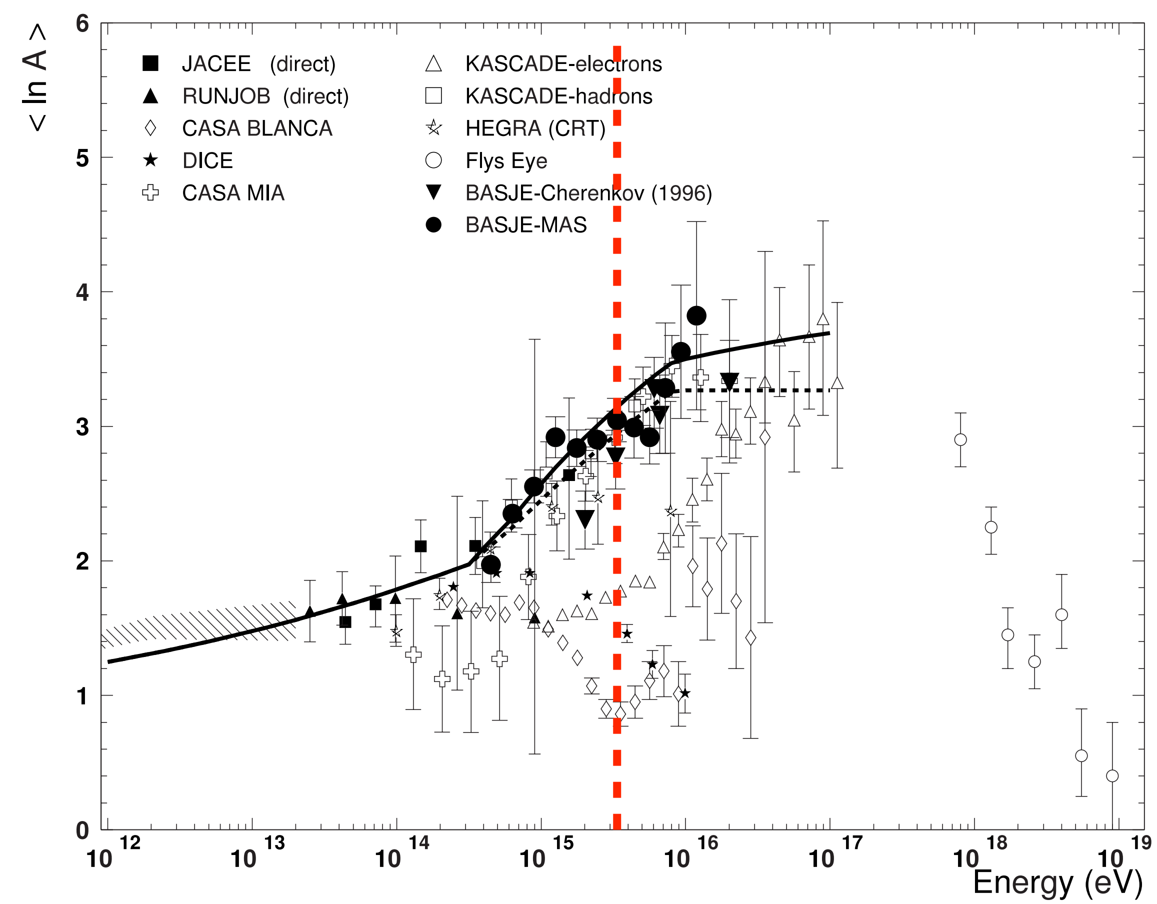
A sudden drop in the helium and iron spectra around 6 PeV is observed, with corresponding elevated levels of proton and oxygen. This feature is under intense study. The most likely explanation is a statistical fluctuation.

Composition at the knee: BASJE - MAS

ApJ 612 (2004) 268



≈ 400 TeV



The measured $\langle \ln A \rangle$ increases with energy over the energy range of $10^{14.5}-10^{16}$ eV. This is consistent with our former Cerenkov light observations and the measurements by some other groups. The observed $\langle \ln A \rangle$ is consistent with the expected features of a model in which the energy spectrum of each component is steepened at a fixed rigidity of $10^{14.5}$ V.

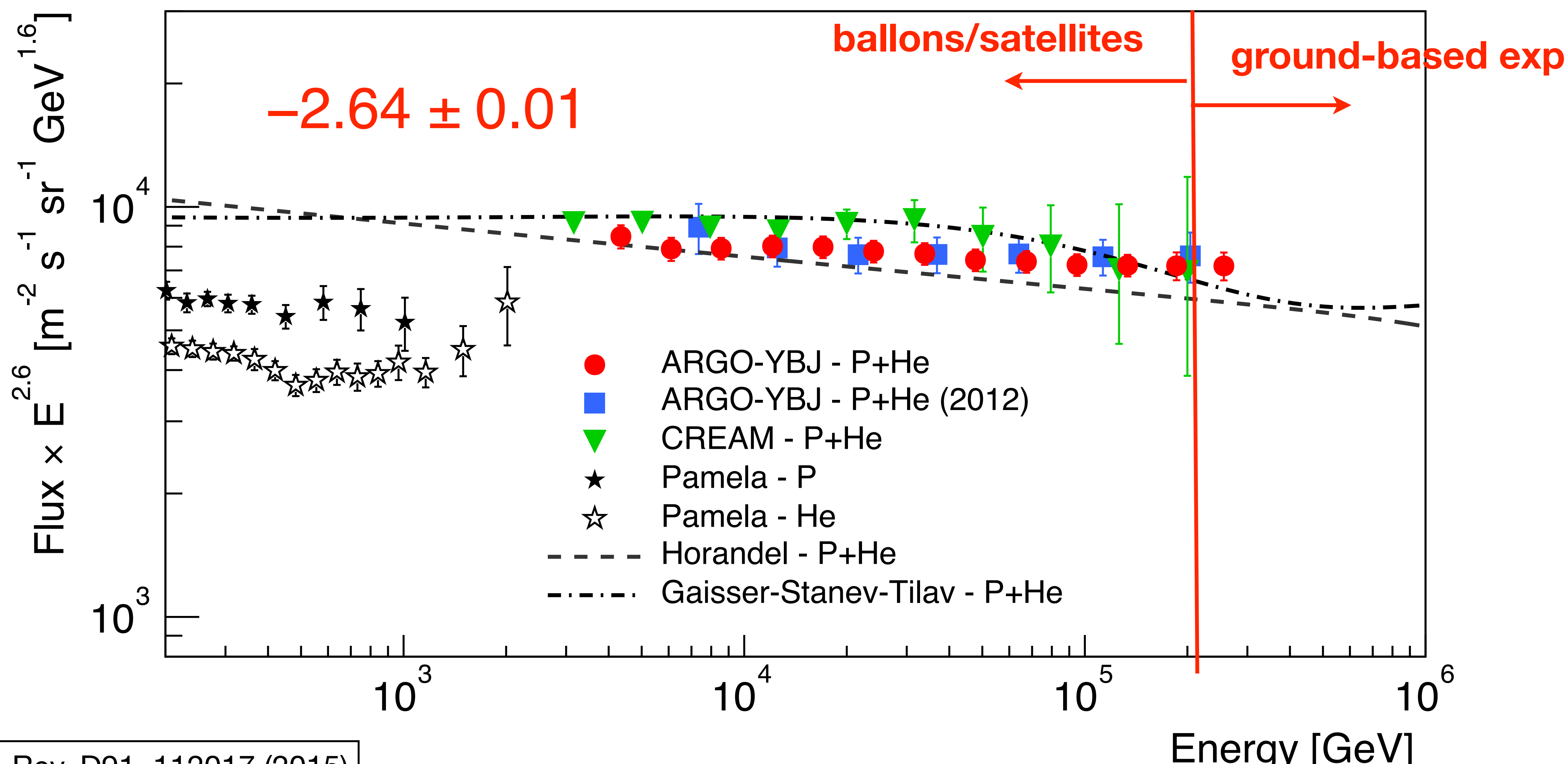
Finally, we conclude that the actual model suggests that the dominant component above 10^{15} eV is heavy and that the $\langle \ln A \rangle$ increases with the energy to about 3.5 at 10^{16} eV.

Chacaltaya 5200 m asl

Energy threshold ≈ 10 TeV

The light-component spectrum (2.5 - 300 TeV)

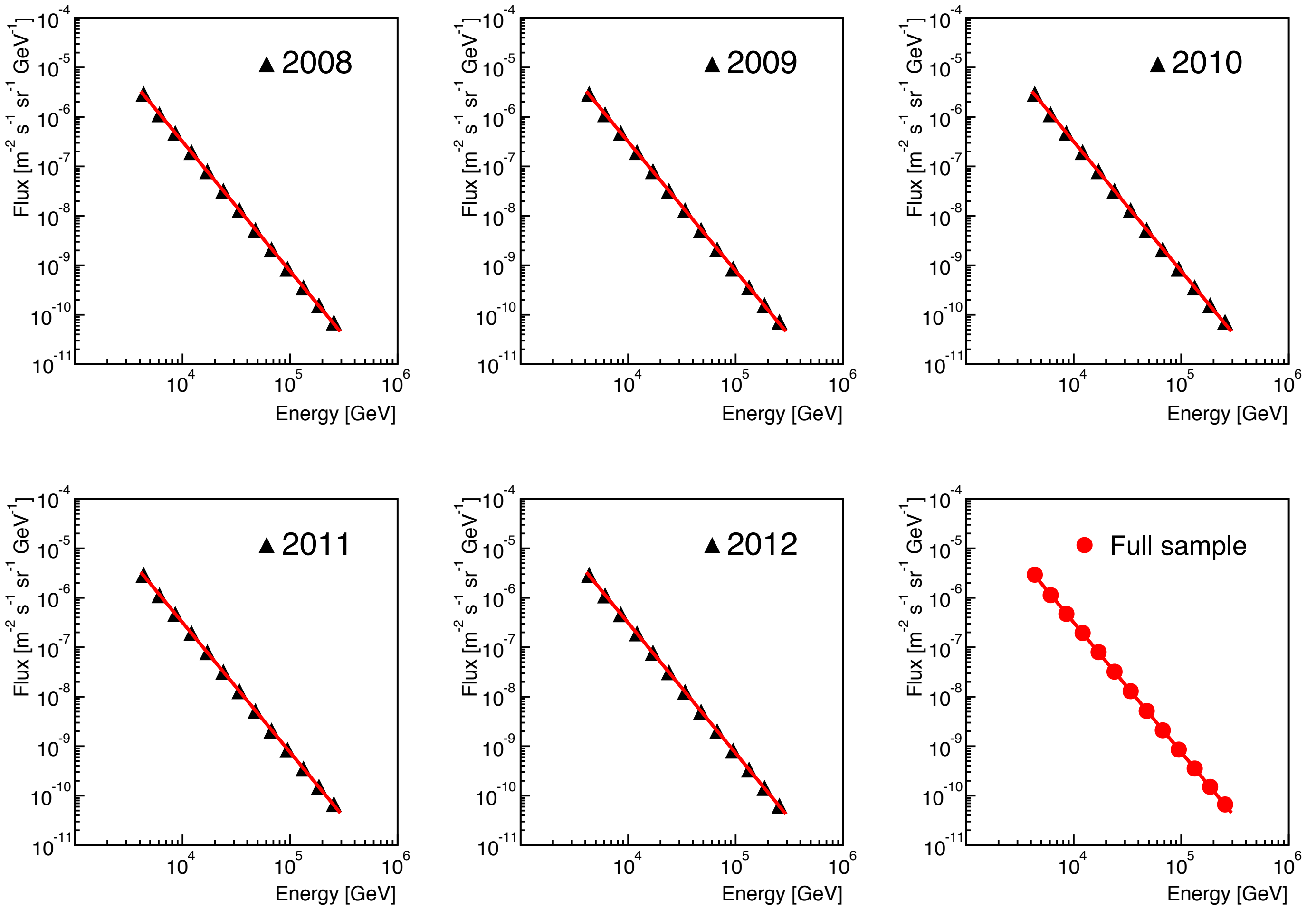
Measurement of the light-component (p+He) CR spectrum in the energy region (2.5 – 300) TeV via a Bayesian unfolding procedure



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.

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

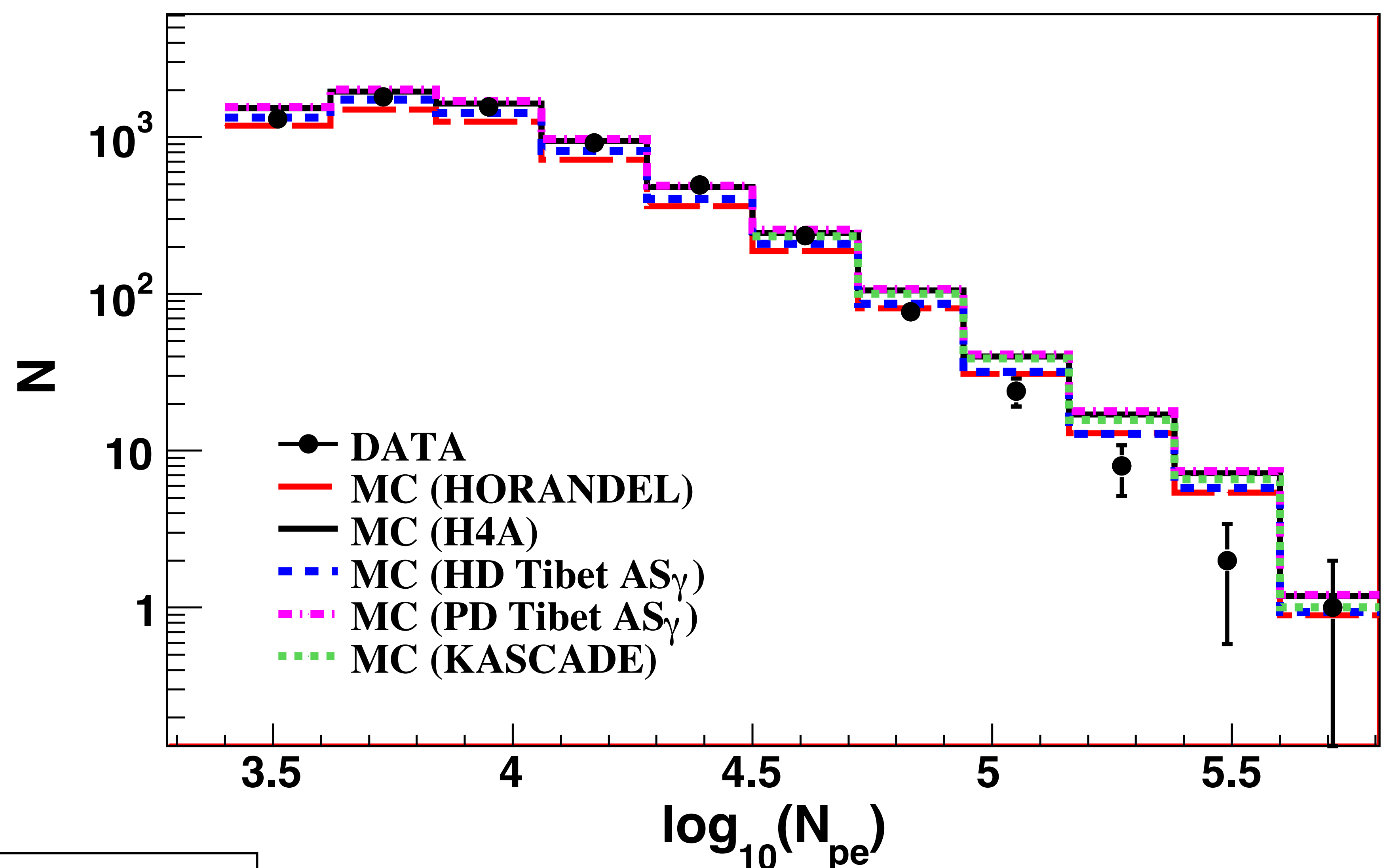
TABLE I. Proton plus helium flux measured at 5.0×10^4 GeV.

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

ARGO-YBJ/WFCTA: All-particle spectrum

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



Phys. Rev. D 92, 092005 (2015)