INFN
Istituto Nazionale
di Fisica Nucleare


# Recent Highlights from ARGO-YBJ

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*Fifth Workshop on Air Shower Detection at High Altitude*

*26-28 May 2014 Paris (France)*

# Outline

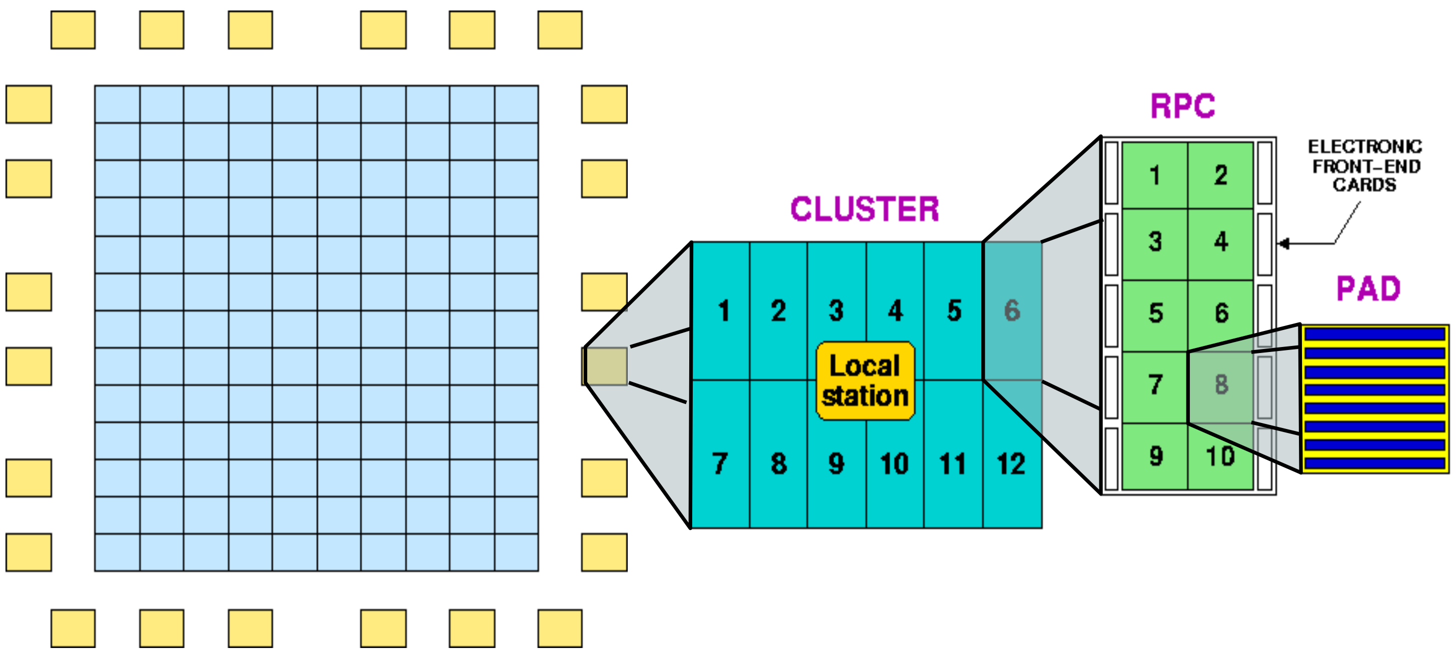
## ★Gamma-Ray Astronomy

- First Northern sky survey (-10° $< \delta <$ 70°) at 0.25 Crab Units
- Study of extended sources

## ★Cosmic Ray Physics

- CR Light component (p+He) Energy Spectrum  (3 TeV - 5 PeV)
- Elemental composition approaching the knee: the ‘proton' knee

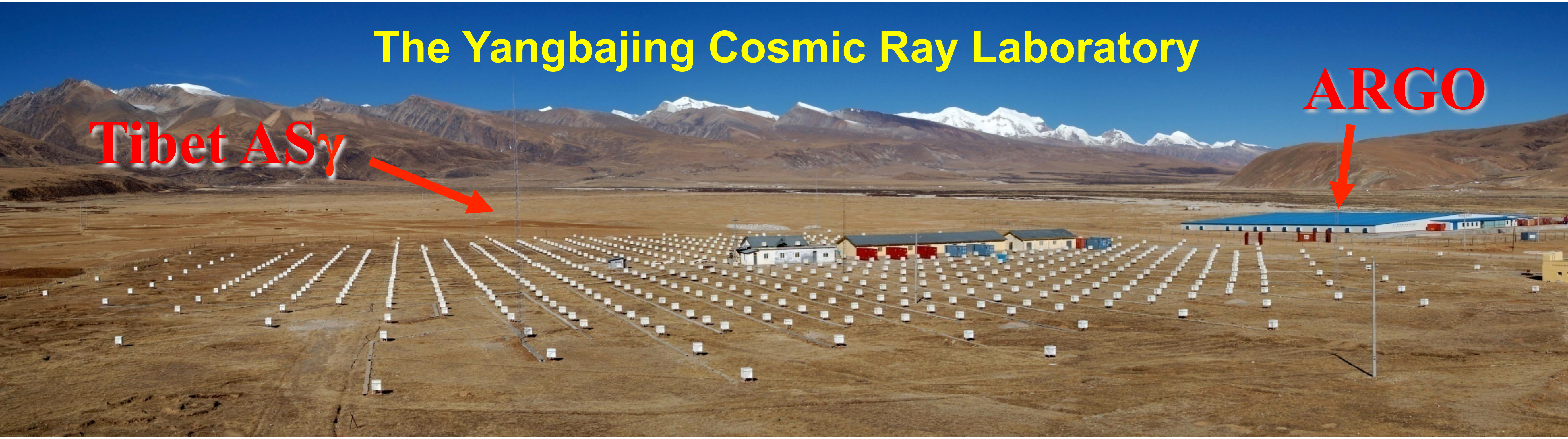
# The ARGO-YBJ experiment




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

**90 Km North from Lhasa (Tibet)**

**4300 m above the sea level**
**~ 600 g/cm$^2$**



# The basic concepts

*…for an unconventional air shower detector*

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

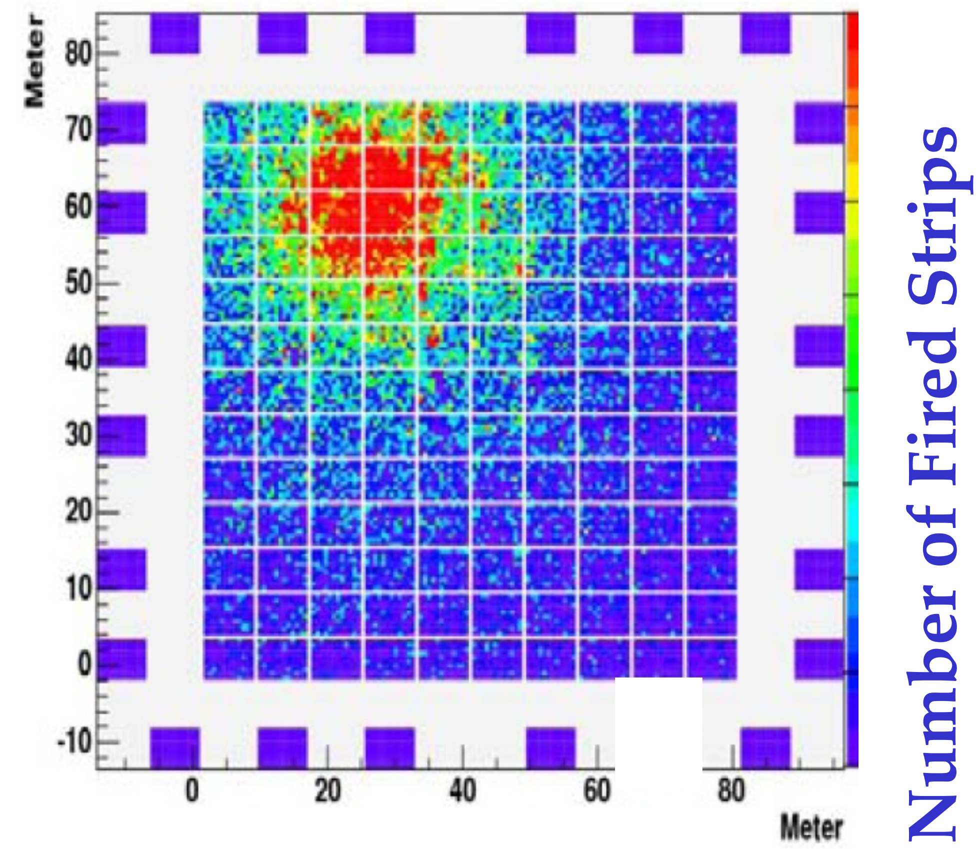
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

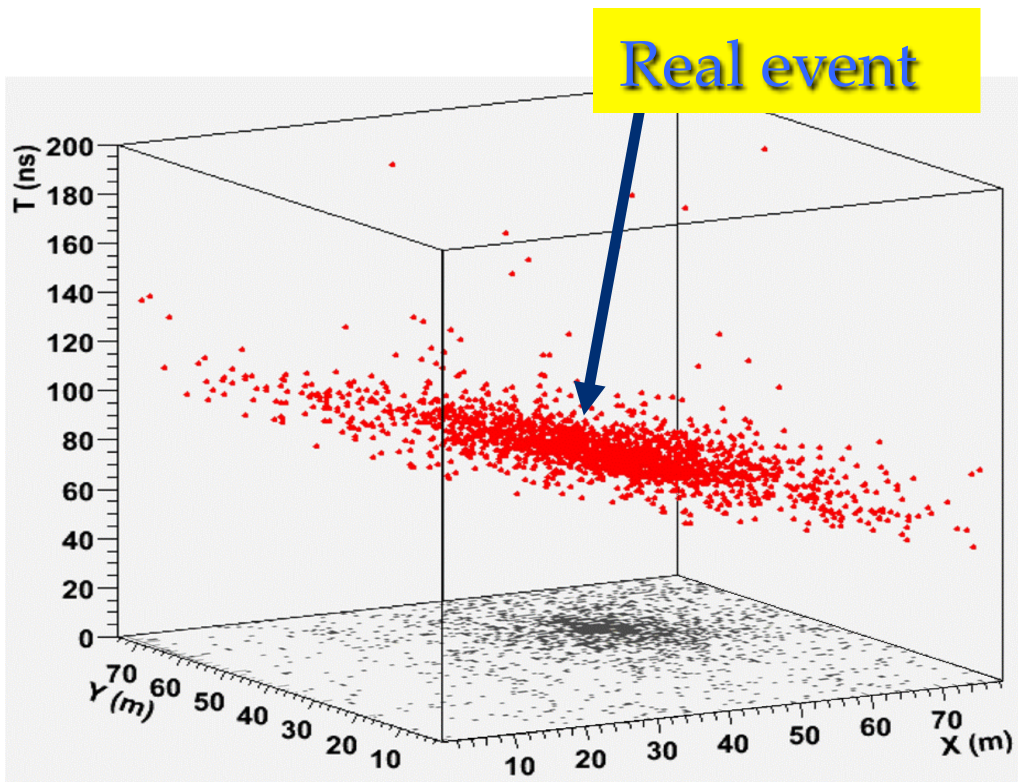
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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

*… in order to*

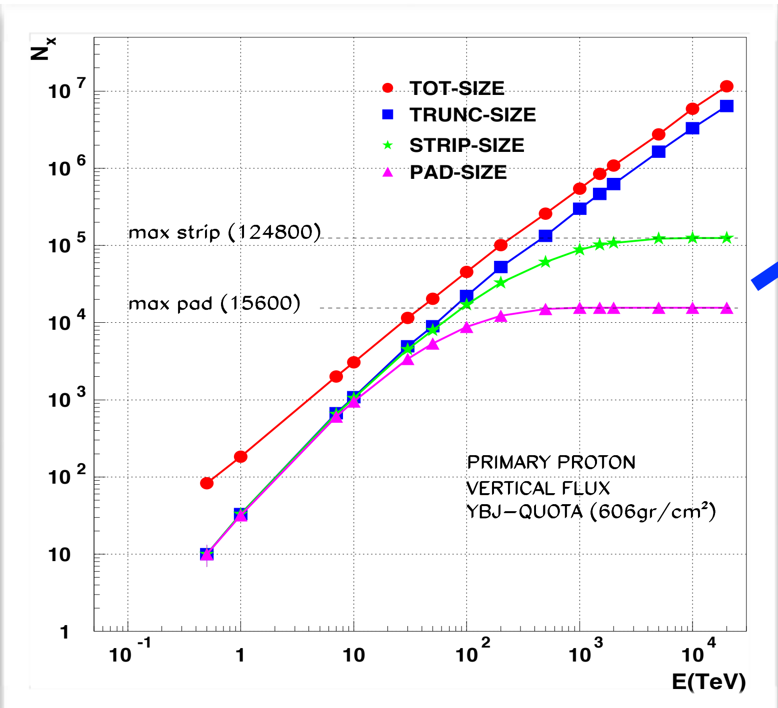
- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV



# The RPC analog readout

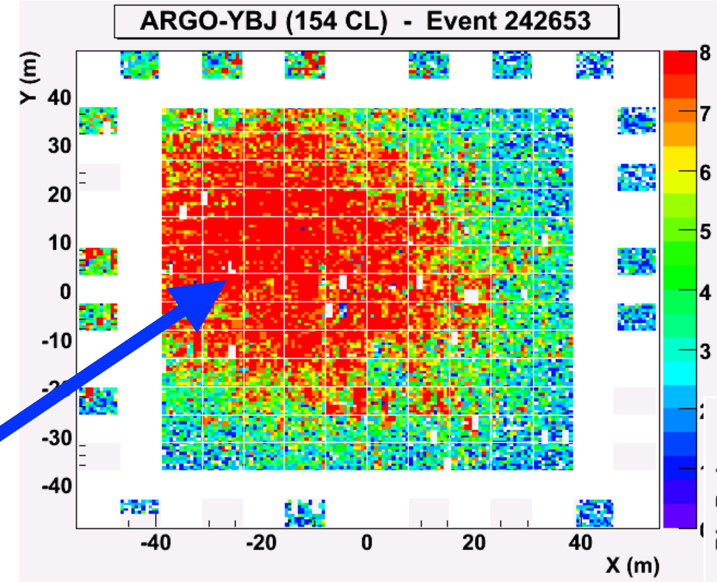
*…extending the dynamical range up to PeV*




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

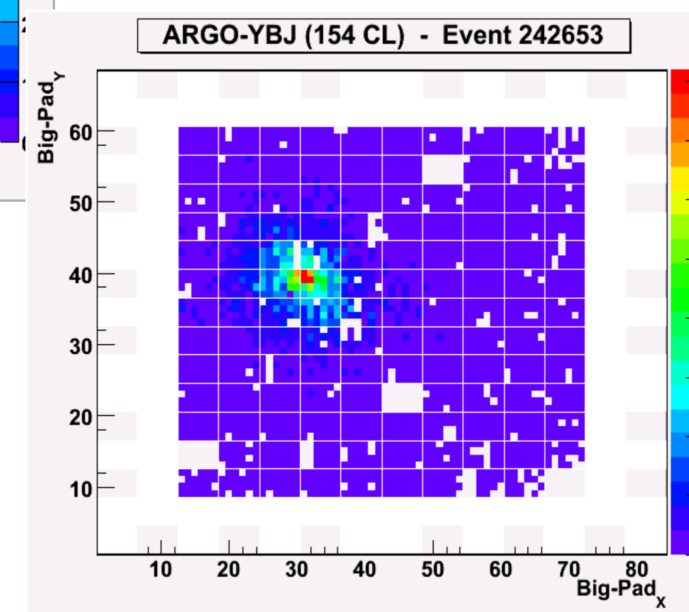
$$\rho_{max-strip} \approx 20 \text{ particles/m}^2$$

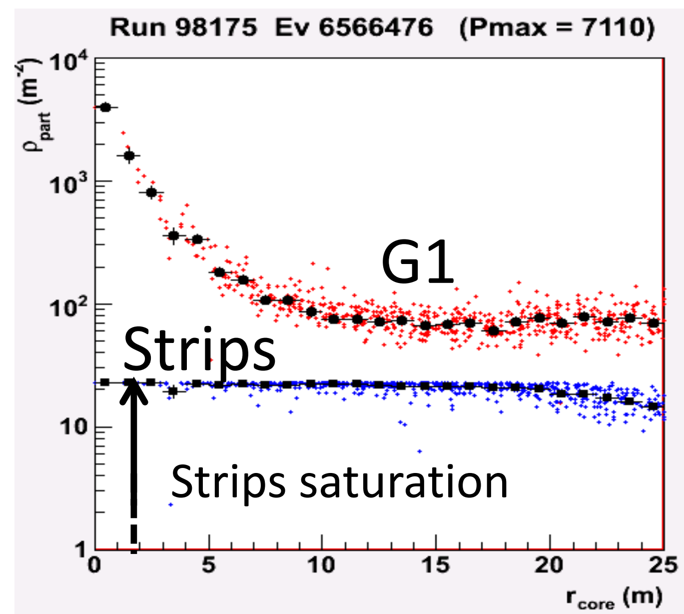
$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

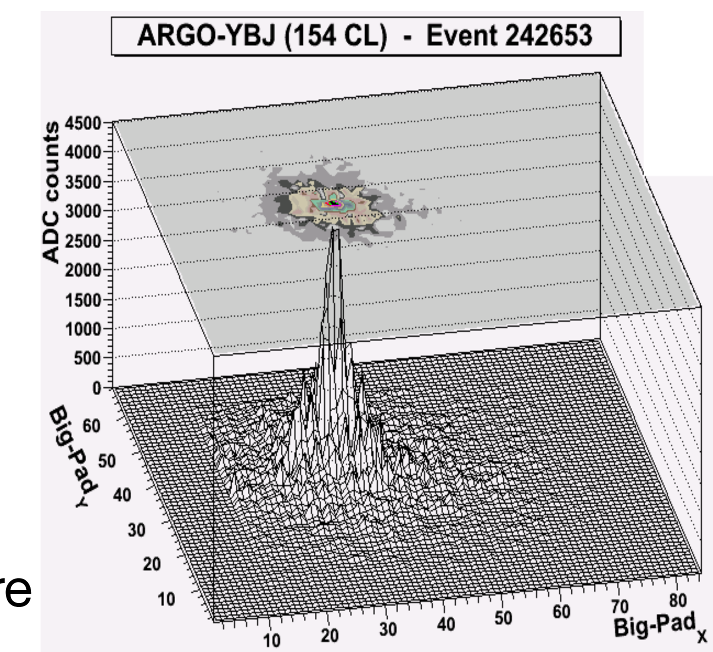



Strips (digital)

Big Pads (analog)



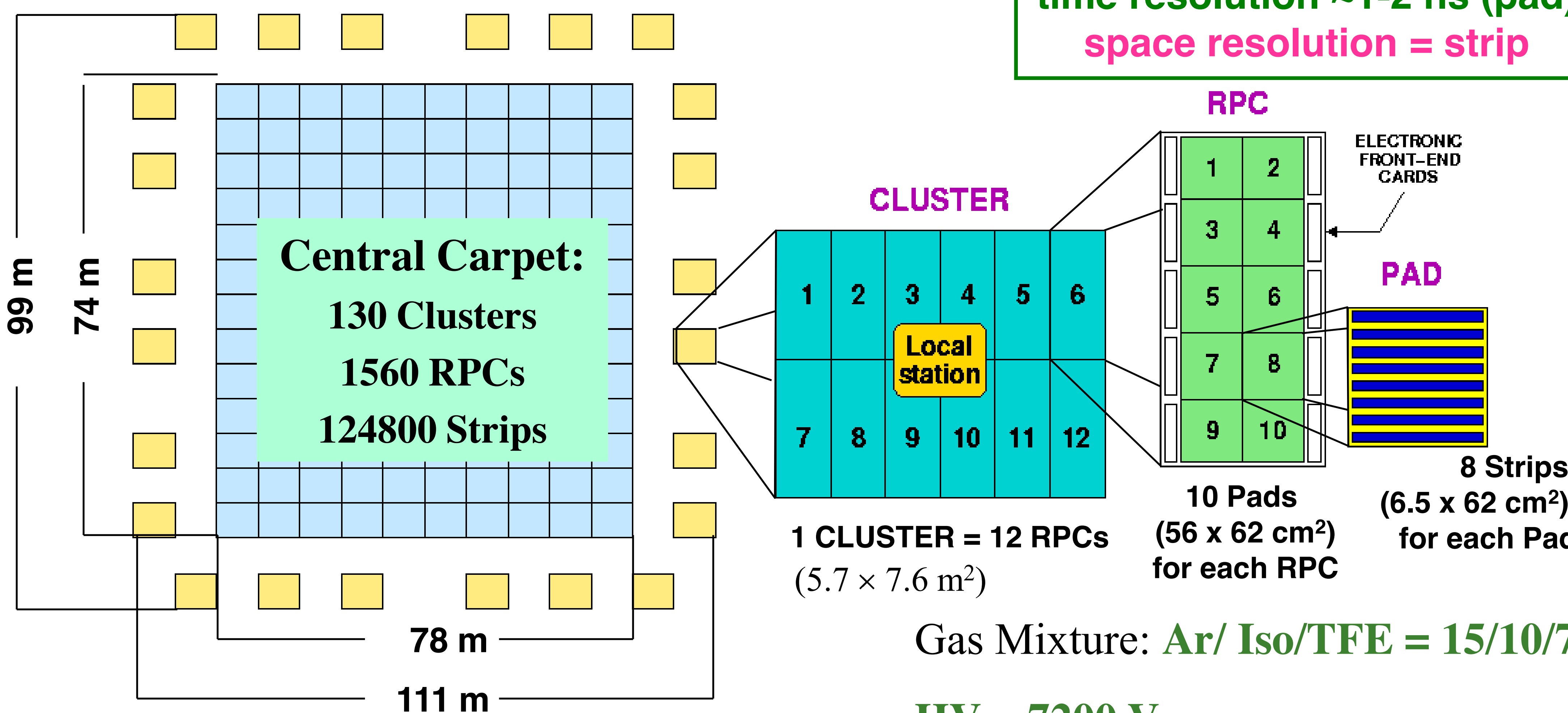




- Extend the covered energy range
- Access the LDF in the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions

# The ARGO-YBJ layout

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



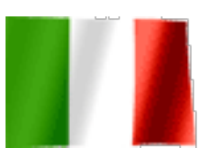

Gas Mixture: Ar/ Iso/TFE = 15/10/75

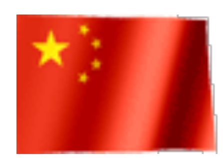
HV = 7200 V

**Single layer of Resistive Plate Chambers (RPCs) with a full coverage (92% active surface) of a large area (5600 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*

# The birth of an idea

**Detection of small size air showers at high altitude: the expected performances of an RPC's carpet**

**B. D'Ettorre Piazzoli[(1)], G. Di Sciascio[(1)], E. Pompei[(2)], A. Surdo[(3)]**

**Experimental set-up**

An RPC's carpet of $120 \times 120\ m^2$ has been considered with a 95% active area. Moreover a 95% efficiency has been take into account. Each RPC ($1 \times 2\ m^2$) is equipped with a read-out system of 3 cm wide, 50 cm long strips. Signals from the strips are OR-ed in order to get the time of the first particle hitting each $50 \times 50\ cm^2$ 'pad'. This time is smeared out with the detector response and assigned

**Conclusions**

Preliminary calculations indicate that an RPC's carpet operating at high altitude could achieve excellent performances in detecting air showers initiated by photons of energy $\geq 300 GeV$. At this energy the minimum detectable integral flux at $4\sigma$ level in 1 yr of data taking is expected to be about $6 \cdot 10^{-11} \cdot \left(\frac{\psi(70\%)}{0.6^0}\right) \cdot \frac{1}{Q}\ cm^{-2}s^{-1}$, comparable to fluxes expected from extragalactic sources. Here $Q$ is a rejection factor resulting

**THE FIRST**

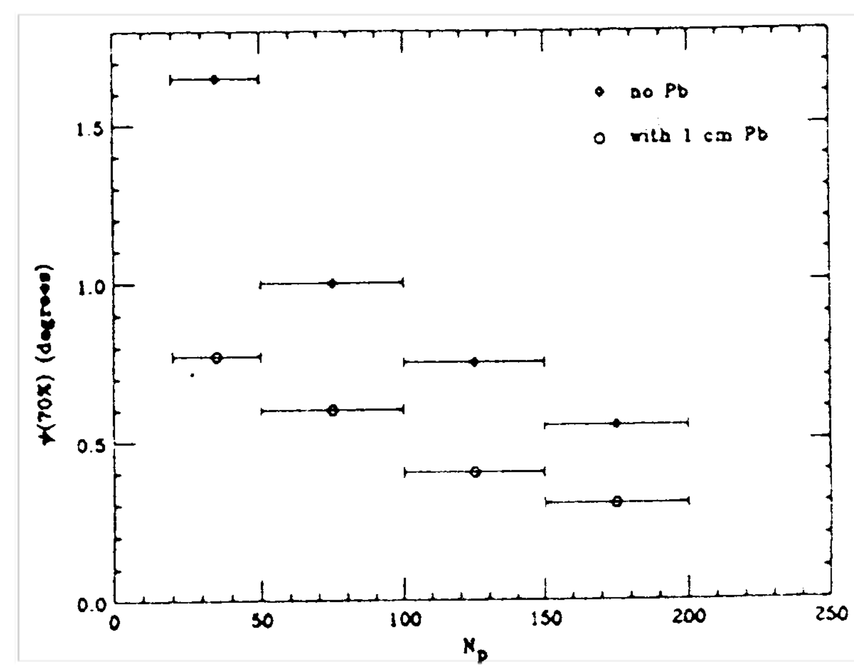
**INTERNATIONAL SYMPOSIUM**

**ON COSMIC RAY PHYSICS**

**IN TIBET**

August 12—17, 1994 LHASA, CHINA

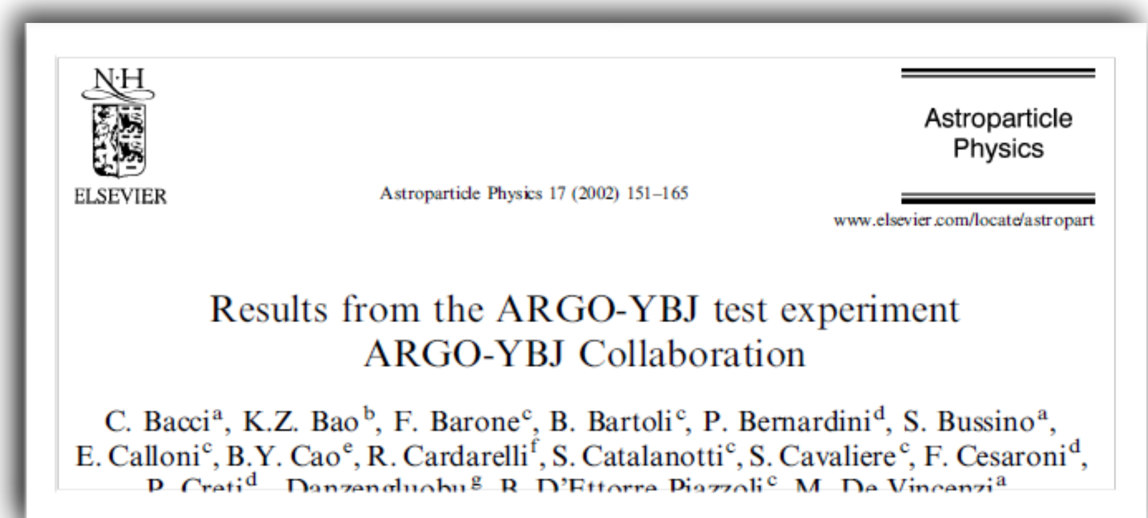
HAWC: ≈ $140 \times 140\ m^2$



# The main stages

- ARGO proposal (1996)
- Approval of a successfull test in Tibet (ARGO-TEST, 1997-1998)
- Approval of the ARGO-YBJ experiment (1999)
- Inauguration of the ARGO-YBJ laboratory (June 2001)
- Central carpet in data taking (2006)
- Full layout in stable data taking (2007)

- End/Stop data taking: January 2013



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ELSEVIER

Astroparticle Physics 17 (2002) 151–165

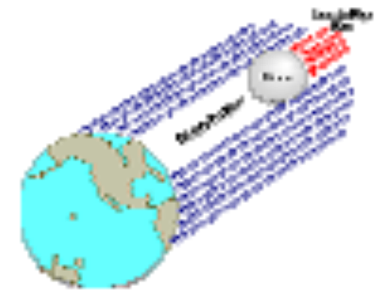
Astroparticle Physics

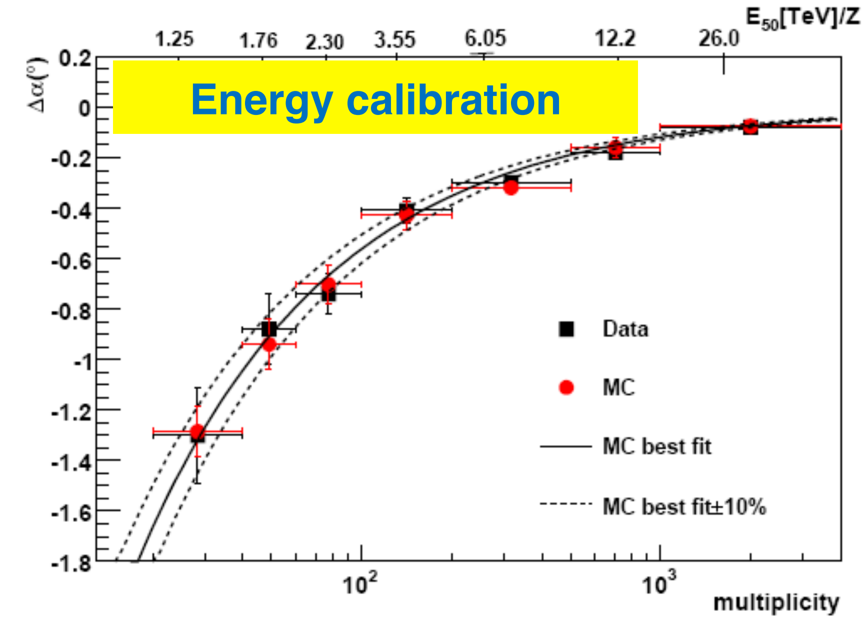
www.elsevier.com/locate/astropart

Results from the ARGO-YBJ test experiment
ARGO-YBJ Collaboration

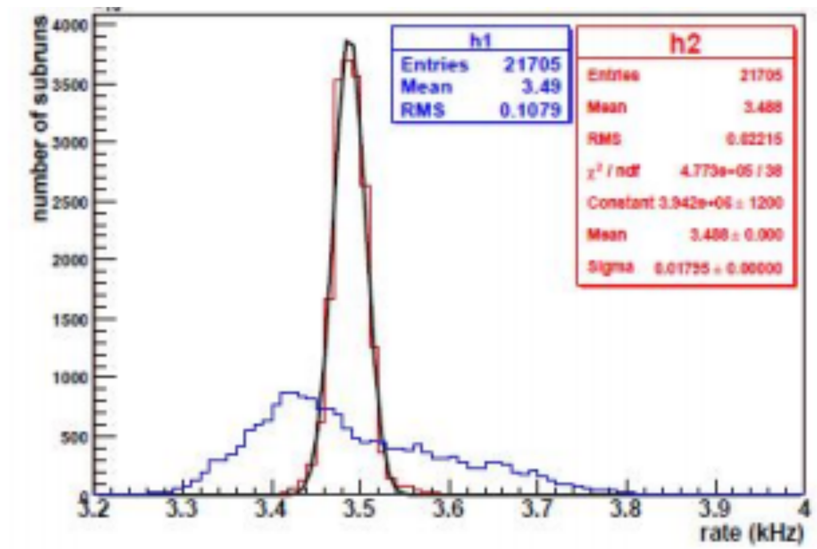
C. Bacci[a], K.Z. Bao[b], F. Barone[c], B. Bartoli[c], P. Bernardini[d], S. Bussino[a], E. Calloni[c], B.Y. Cao[e], R. Cardarelli[f], S. Catalanotti[c], S. Cavaliere[c], F. Cesaroni[d],

# Status and performance

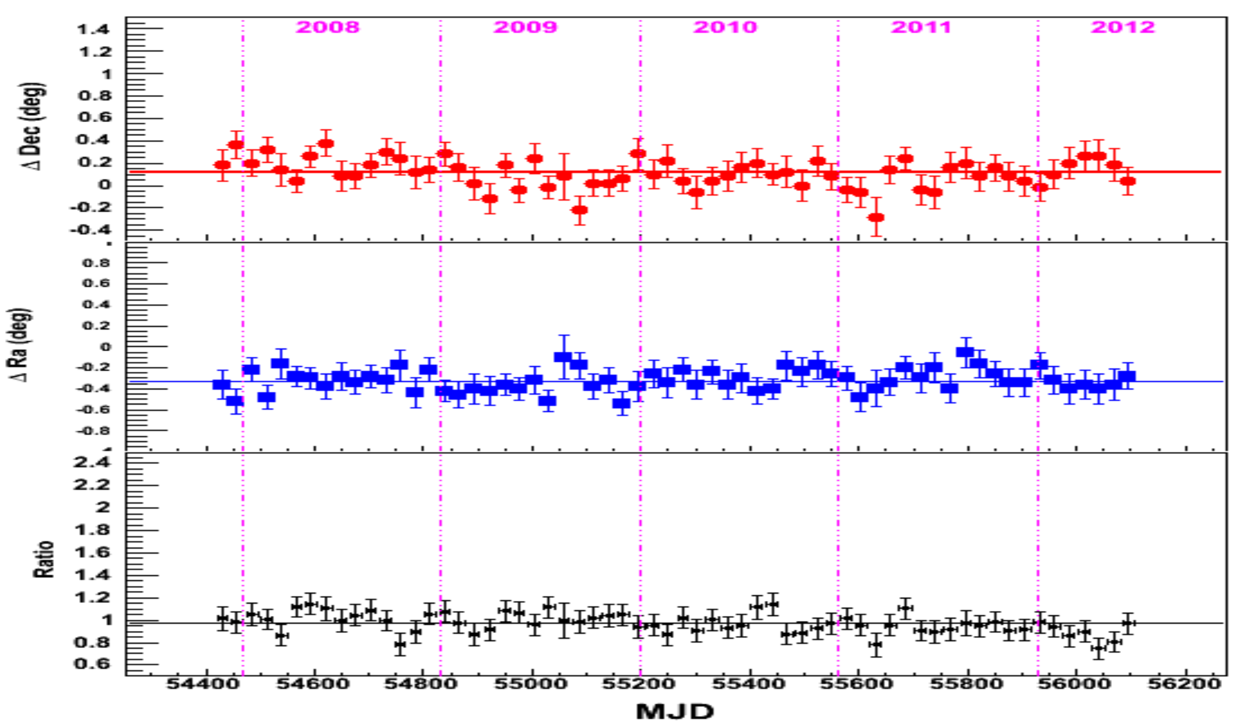


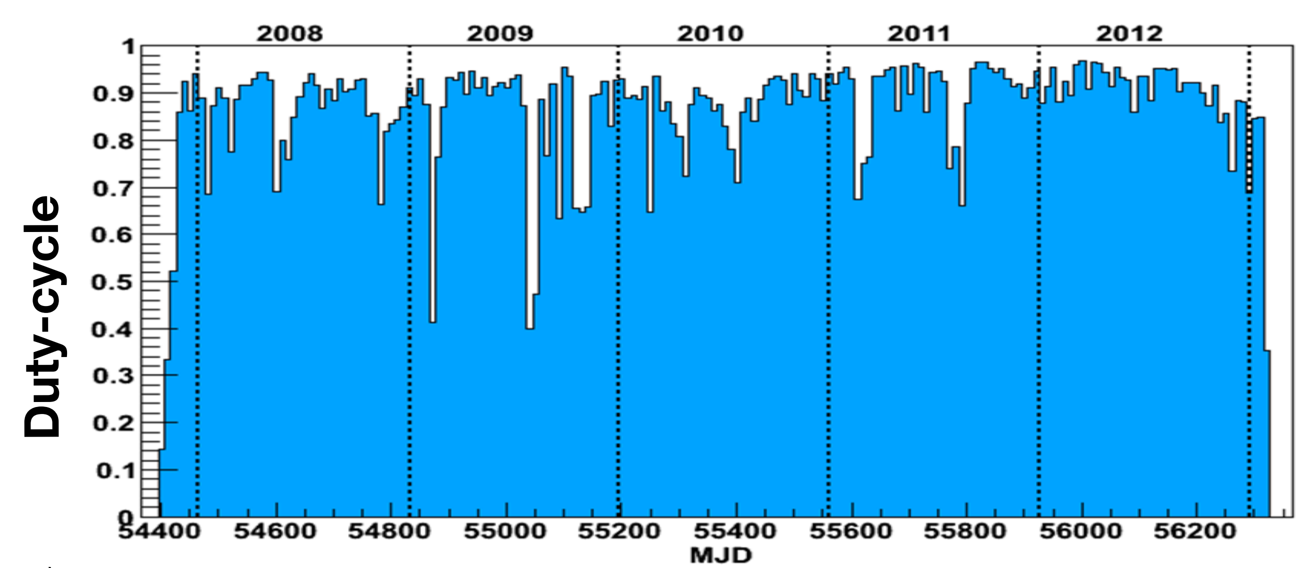



- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data




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



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# Cosmic Rays and γ-Ray Astronomy connection

★ Hadro-production (CR sources)

$p + p/\gamma \Rightarrow n \ (\pi^{+} + \pi^{-} + \pi^{0}) + h$

$\gamma$ **Gamma-Ray Astronomy**

$\nu$ **Neutrino Astronomy**

**CRs, photons and neutrinos strongly correlated**

**ONLY charged CRs observed at E > $10^{14}$ eV so far !**

Recent observations of PeV neutrinos by Icecube

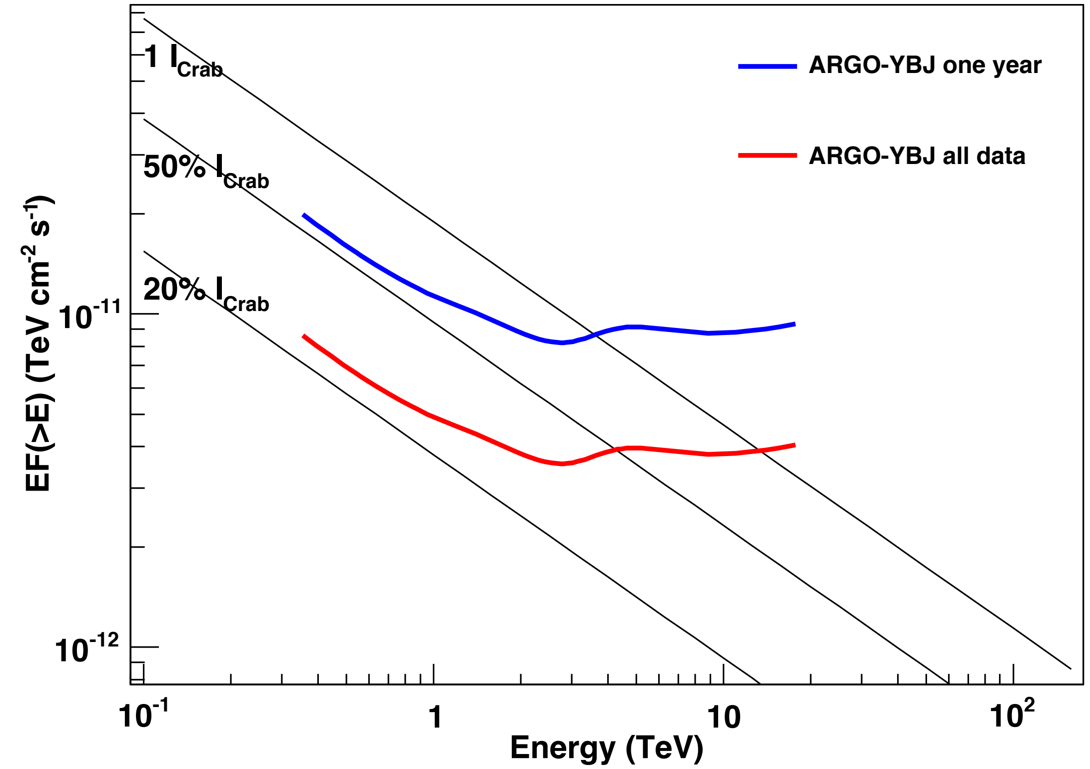
★ Electro-production (Inverse Compton)

$e + \gamma \Rightarrow e' + \gamma'$

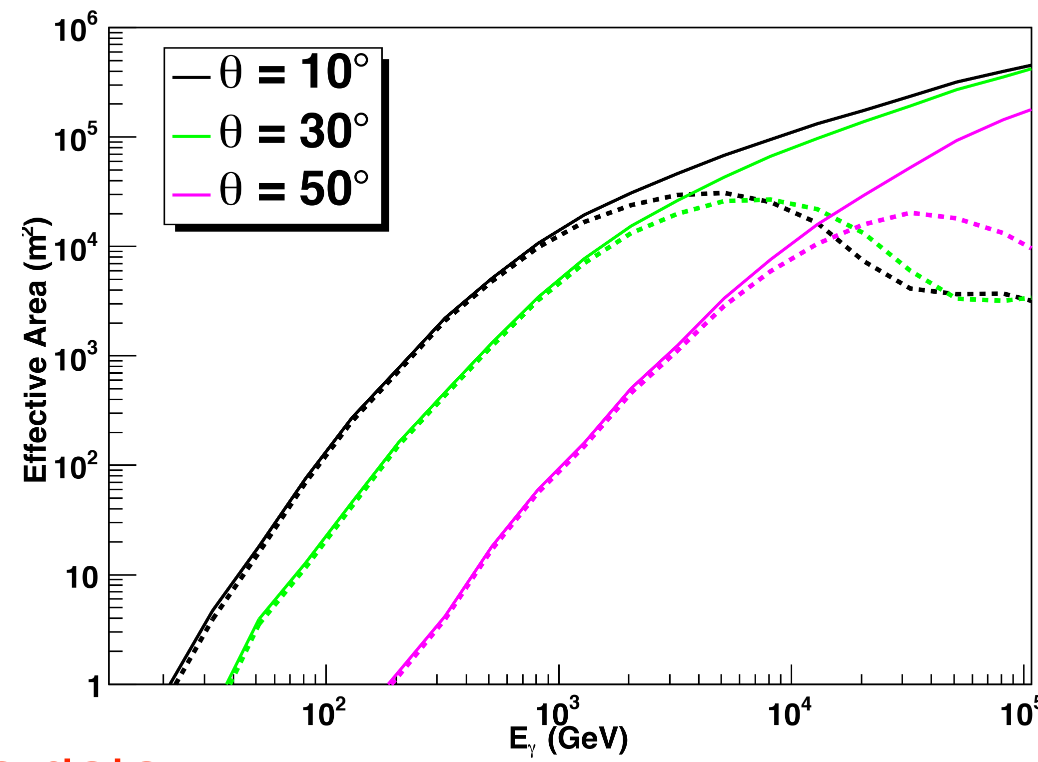
*SSC model: photons radiated by high energy ($10^{15}$ eV) electrons boosted by the same electrons*

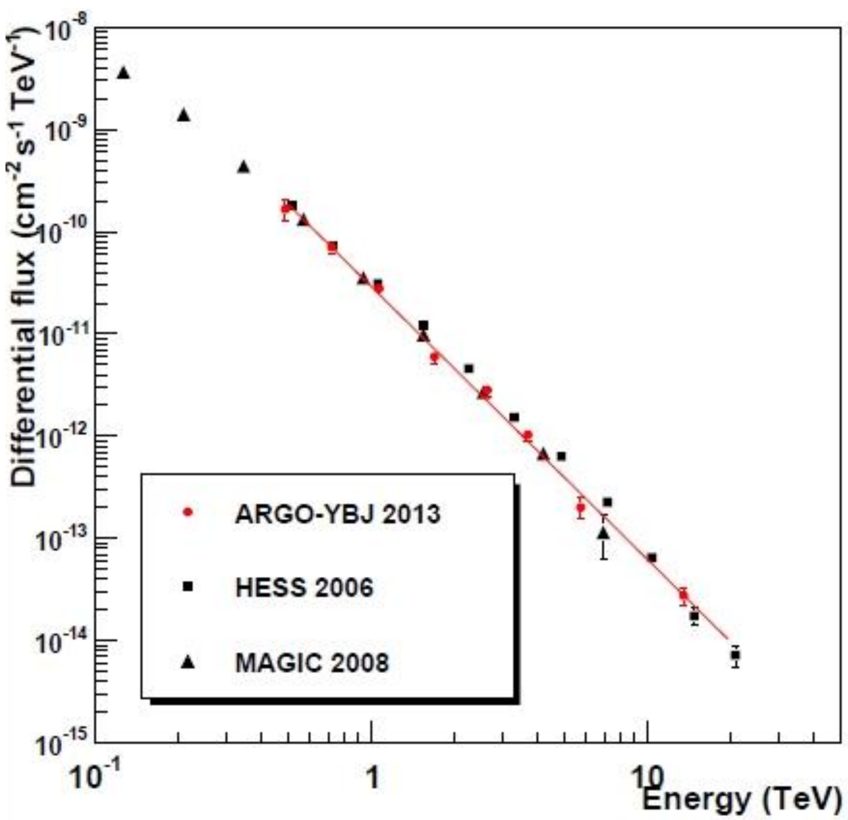
Gammas (and neutrinos) point back to their sources (SNR, PWN, BS, AGN ..)

# 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

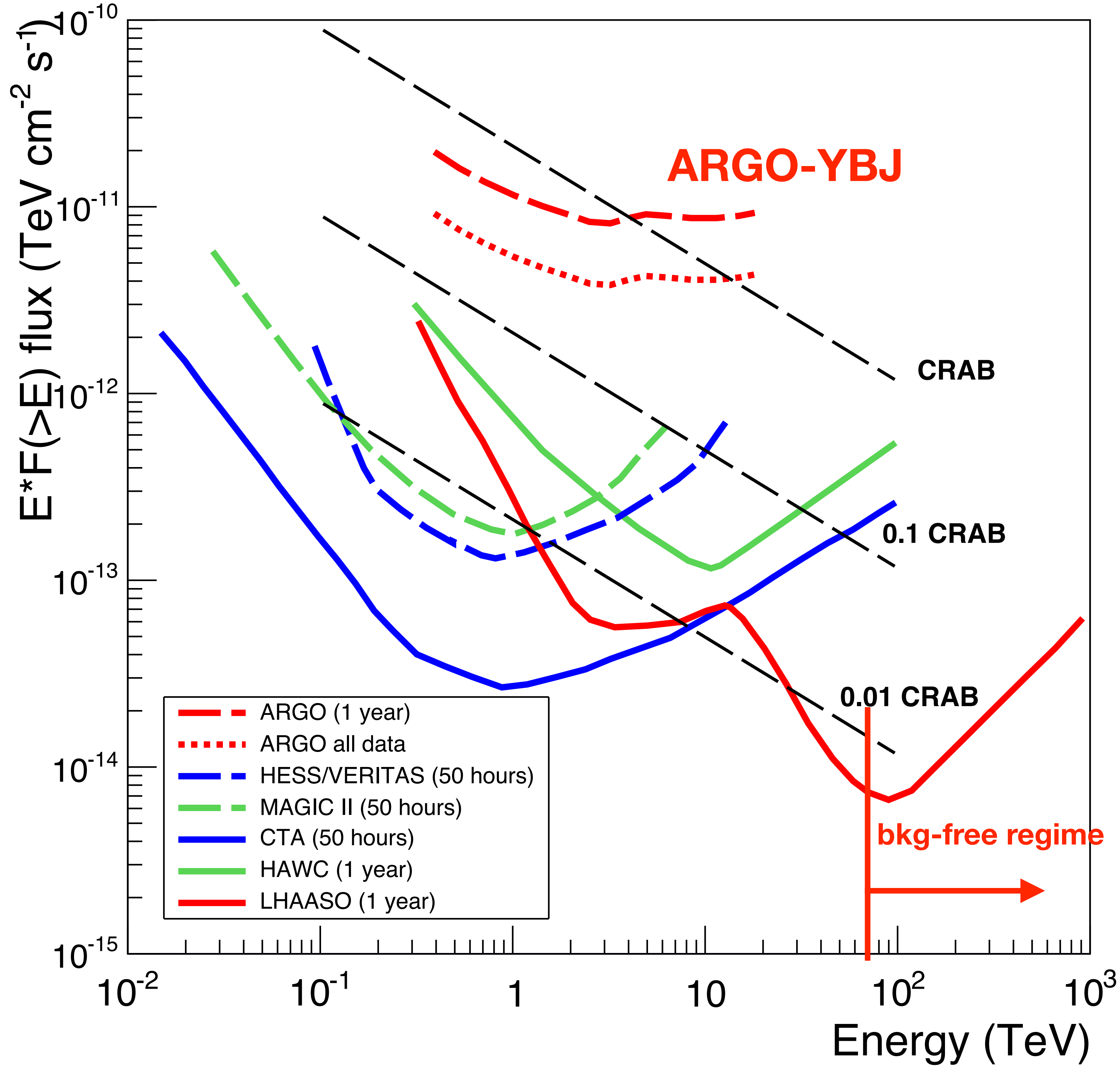
$$\frac{dN}{dE} = (2.94 \pm 0.20_{stat}) \times 10^{-11} \left(\frac{E}{1\,\mathrm{TeV}}\right)^{(-2.67 \pm 0.06_{stat})} \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$$

**(0.5 – 10) TeV**

# Sensitivity to gamma point sources

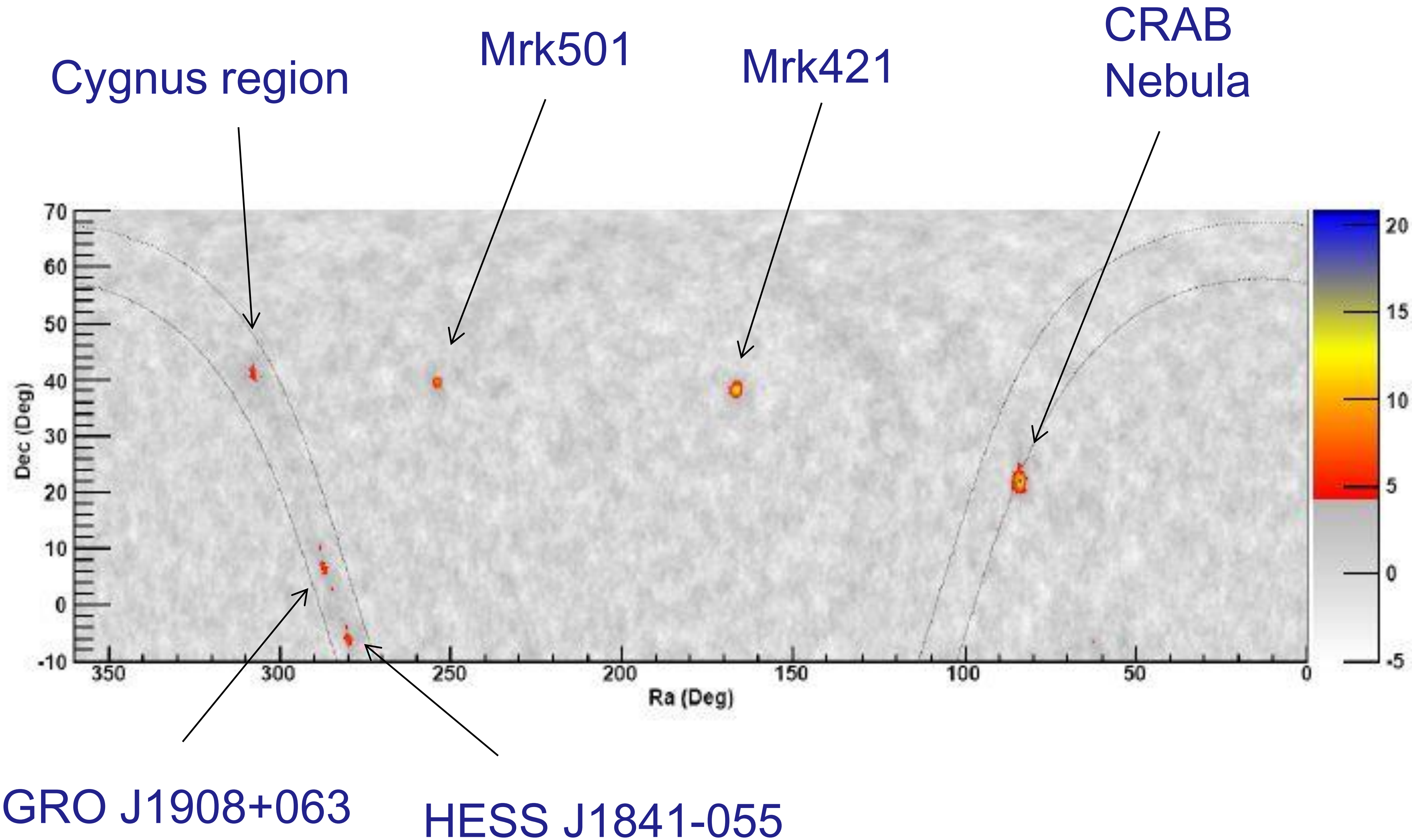
EAS-array: 5 s.d. in 1 year

Cherenkov: 5 s.d. in 50 h on source



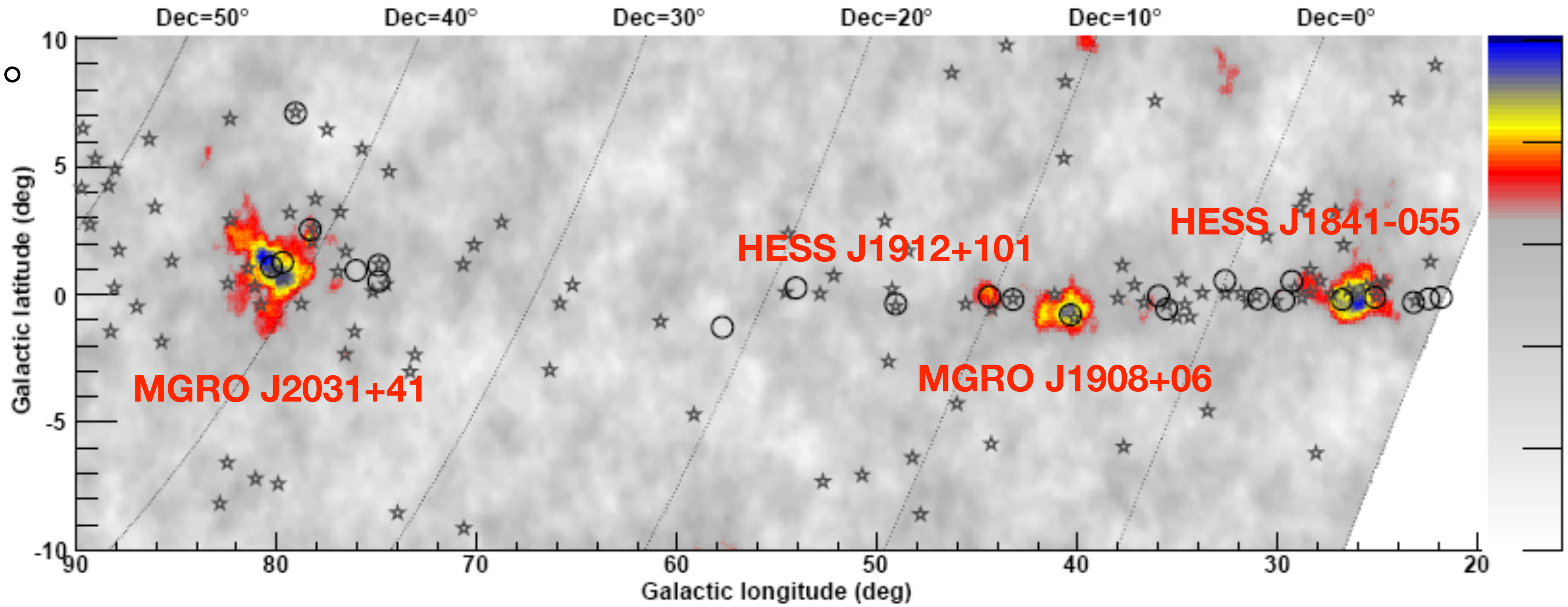
# ARGO-YBJ Sky Survey at 1 TeV

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

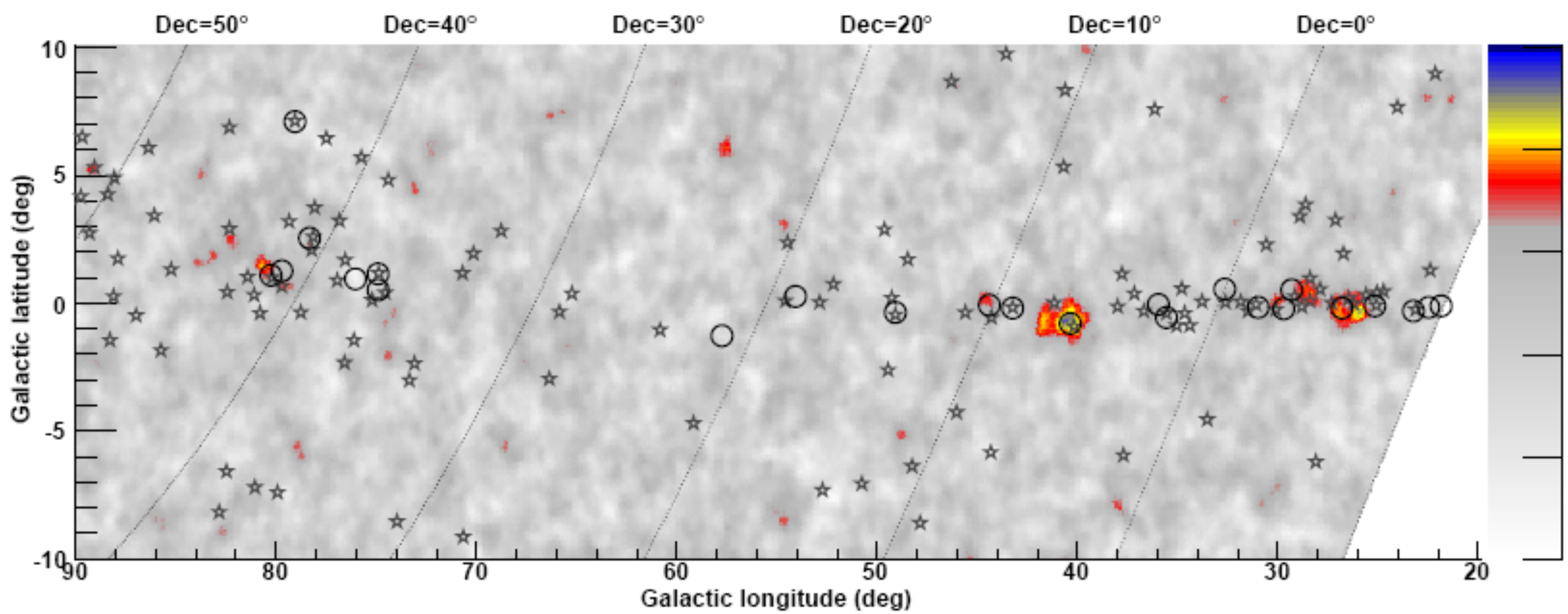


# ARGO-YBJ 5-years Survey of Inner Galactic Plane

$20° < l < 90°, |b| < 10°$




$E_{50} \approx 0.7$ TeV




$E_{50} \approx 1.8$ TeV

# Detected Sources

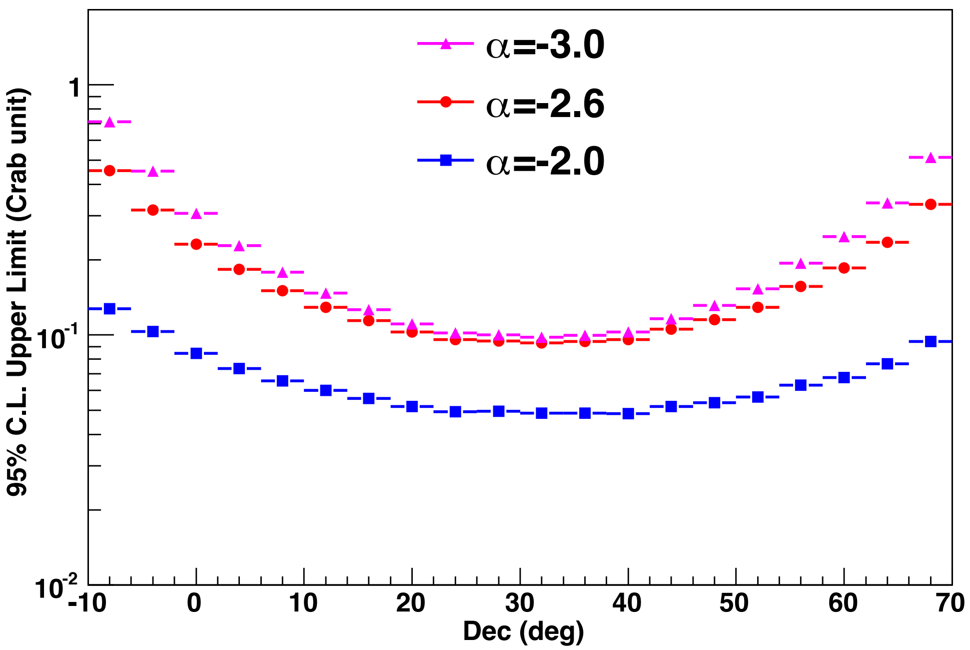



**Fig. 4**: Average 95% C.L. flux upper limit at energy above 500 GeV, averaged on the right ascension direction, as a function of declinations. Different curves indicate sources with different power-law spectral indices −2.0, −2.6 and −3.0. The Crab unit is $5.77\times10^{-11}$ cm$^{-2}$ s$^{-1}$ .

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

# Why gamma-ray extended sources ?

- TeV gamma-ray extended sources an important tool to investigate the sources of cosmic rays.
- The observed degree-scale extended emission could be produced by high-energy cosmic rays escaping from the source and diffusing in the interstellar medium. The gamma-ray emission should result from the interaction of these cosmic rays with the ISM particles.
- 80% of TeV galactic gamma ray sources are extended.
- Many of them are still unidentified.
- To study degree-scale sources we need instruments with a large field of view and able to correctly evaluate the cosmic ray background over a large solid angle
- Sensitivity to an extended source is relatively better for an EAS than an IACT because angular resolution is not as important

$$S_{\mathrm{extended}} \approx S_{\mathrm{point}} \frac{\sigma_{\mathrm{source}}}{\sigma_{\mathrm{detector}}}$$

# 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

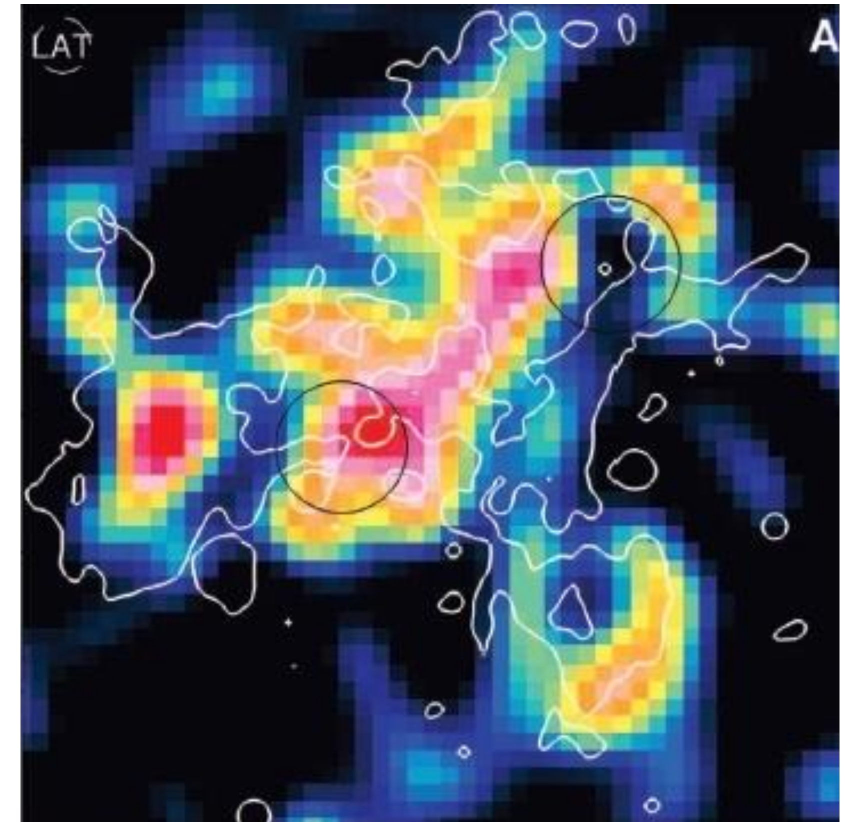
## Natural site for cosmic-ray acceleration

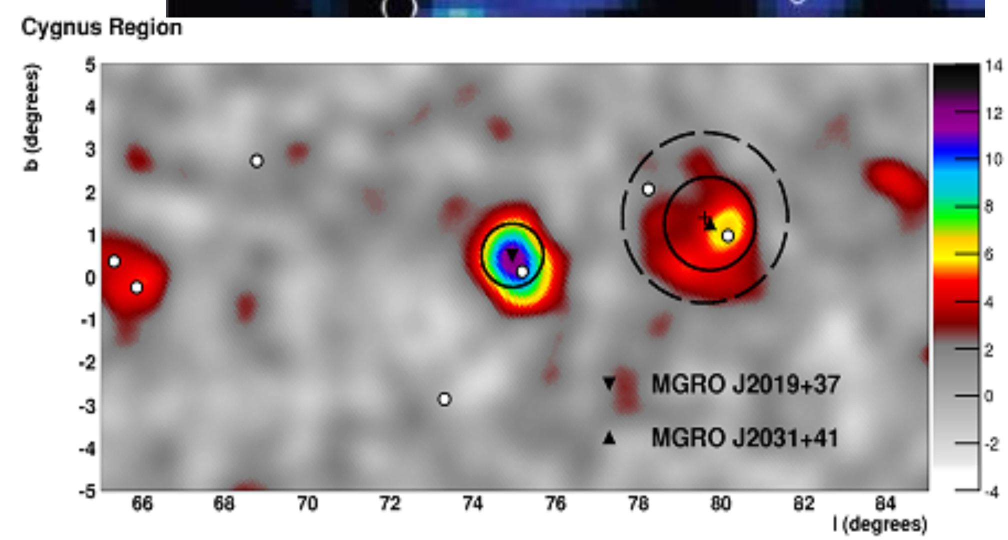
★ Fermi data (1-100 GeV):
A cocoon of freshly accelerated CRs ?

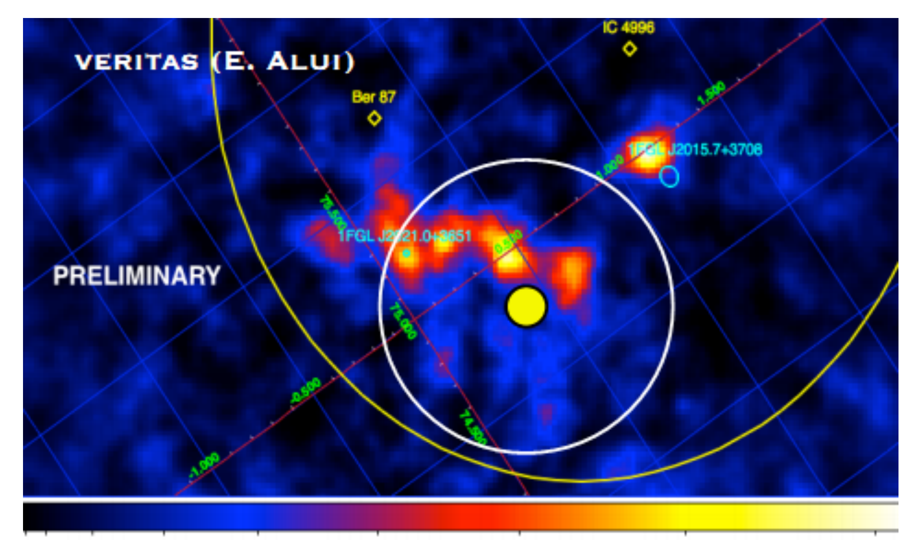
★ Milagro detected 2 sources at 20 TeV
- ✓ MGRO J2019+37 (12.4 σ)
- ✓ MGRO J2031+41 (7.6 σ)

Both consistent with Fermi source locations

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

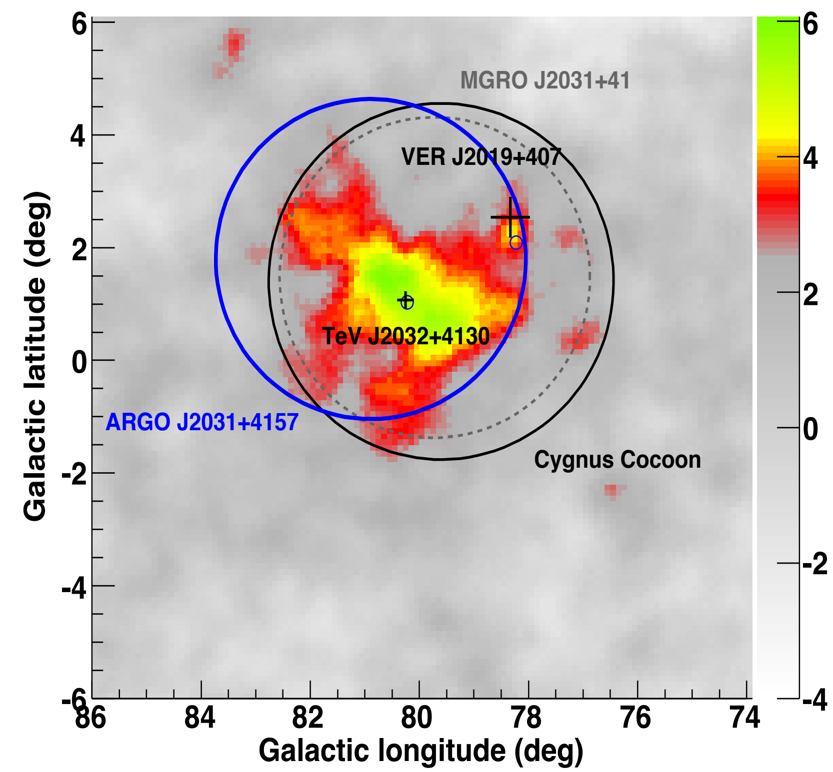


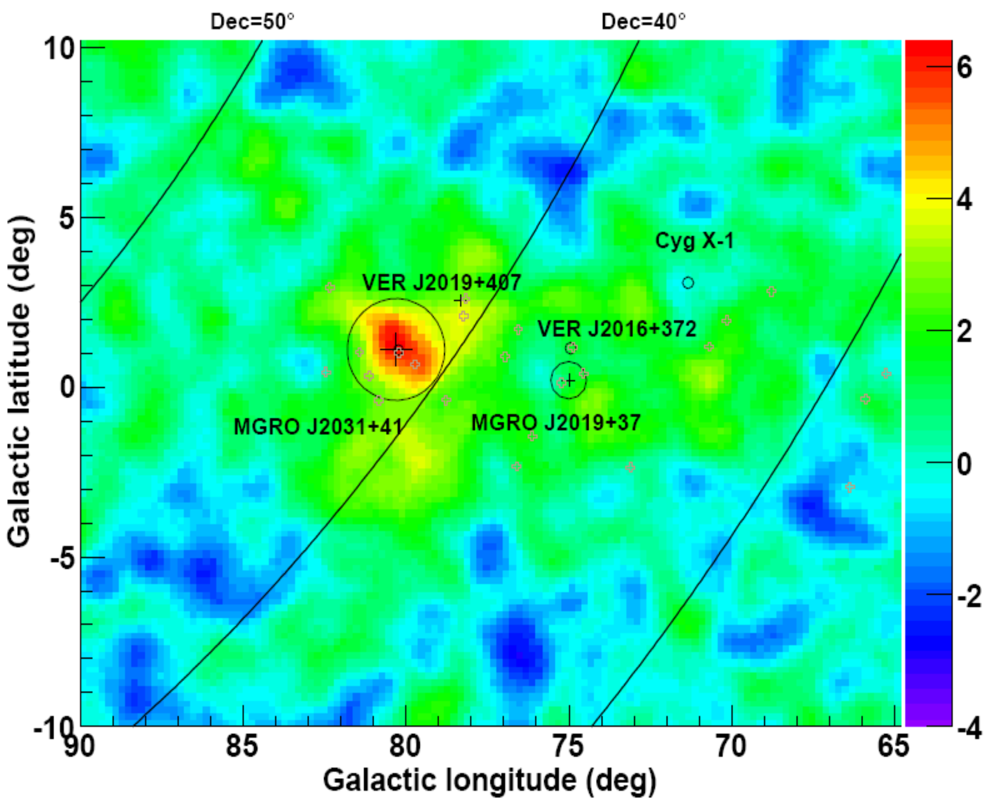



# The Cygnus Region by ARGO-YBJ

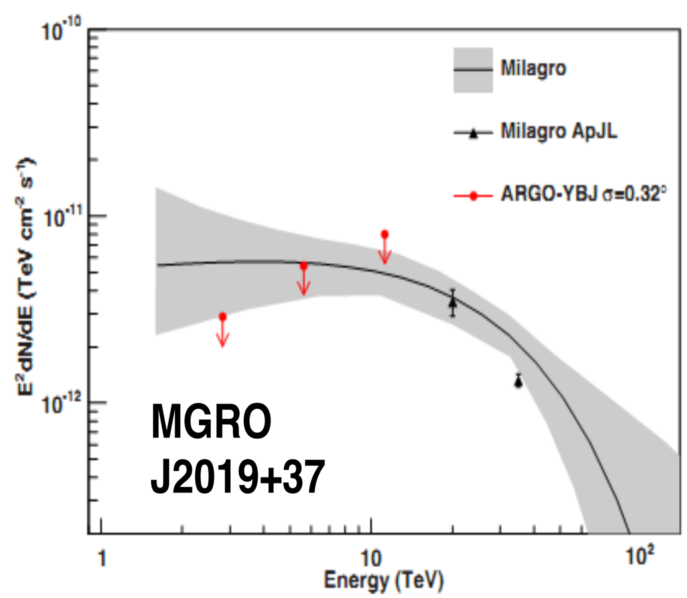
*The Fermi Cocoon*



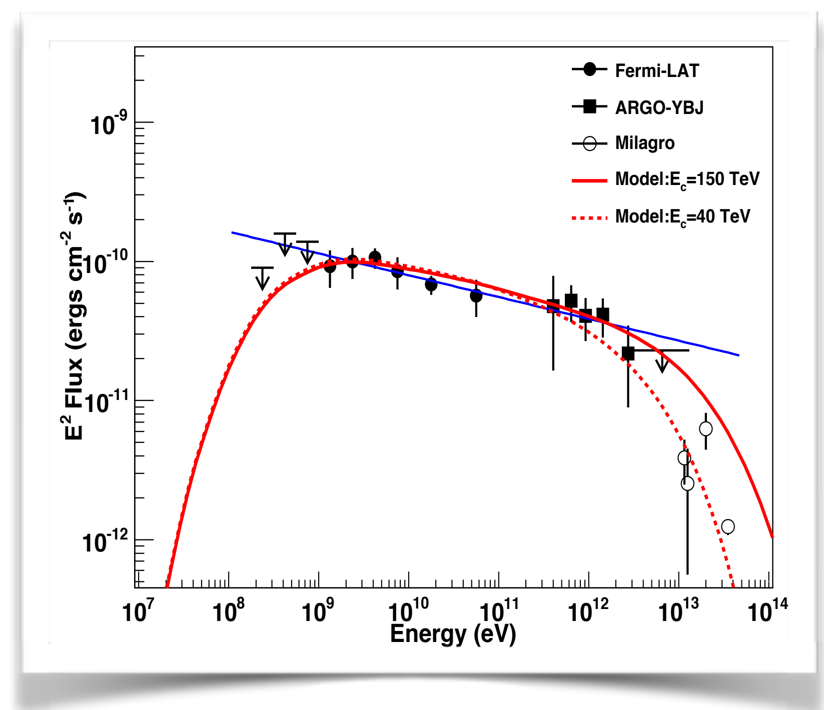

**ApJL 745 (2012) L22**




A cocoon of freshly accelerated cosmic rays by hadronic mechanism ?



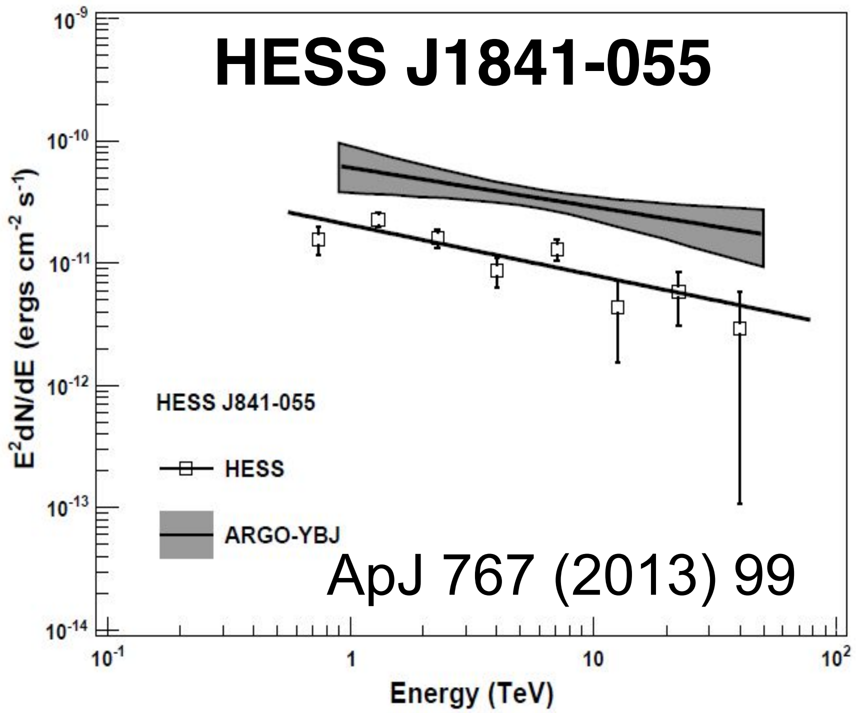

The TeV counterpart of the Fermi Cocoon

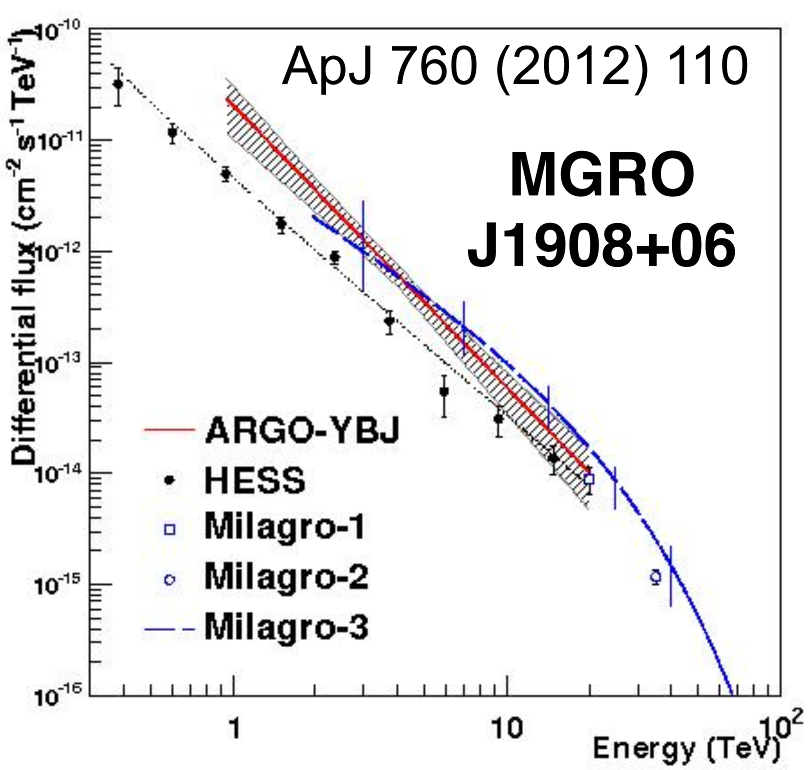


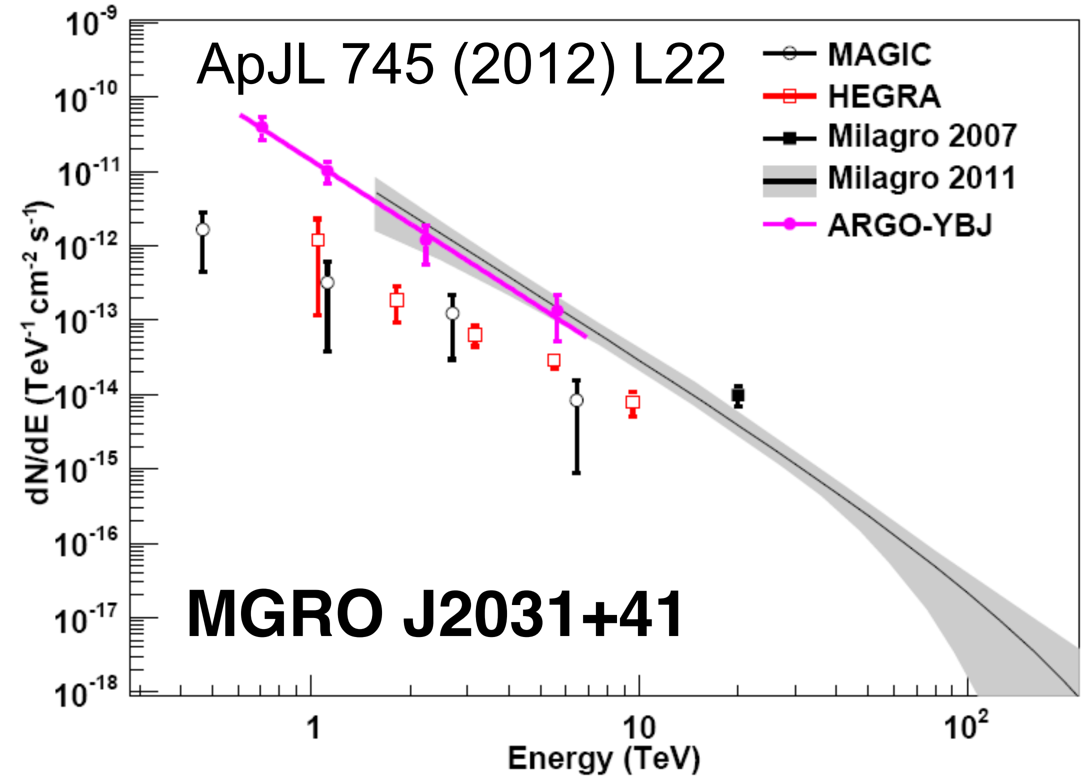

**NO signal from the MGRO J2019+37 below 10 TeV**

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

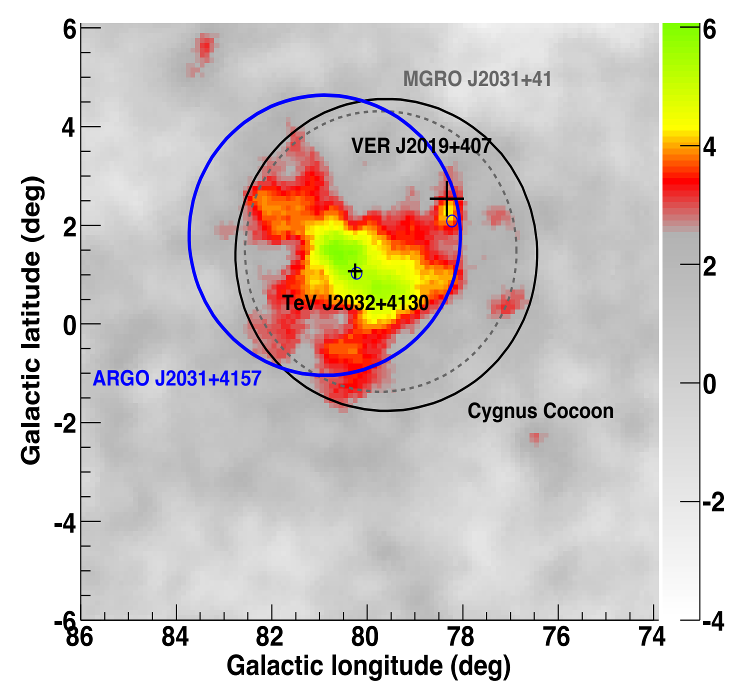
# Observation of extended sources with ARGO-YBJ

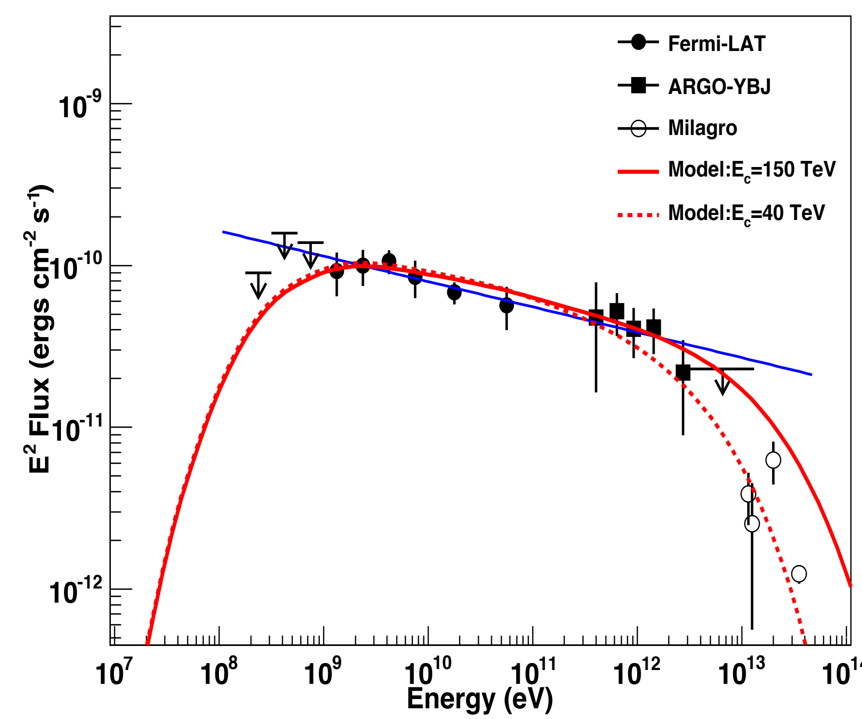



*The Fermi Cocoon*

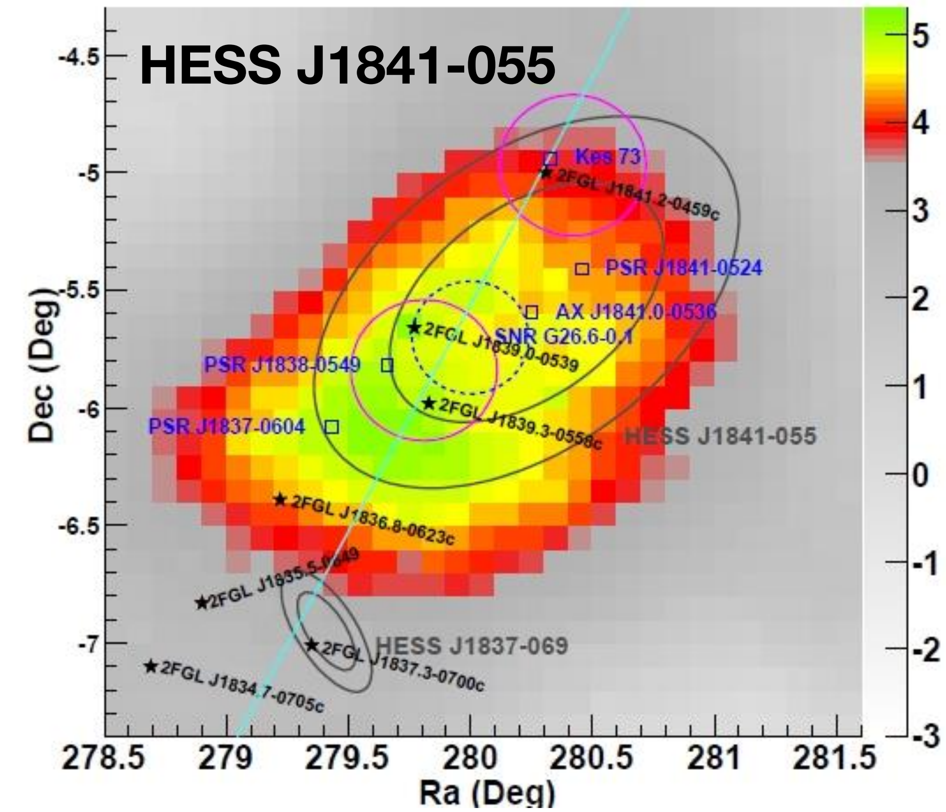



ApJ submitted

# Comments on extended sources

| | | |
|---|---|---|
| • CRAB | point source | flux agrees with IACTs |
| • MGRO J2031+41 | extended | flux ~ 10 X IACTs |
| • MGRO J1908+06 | extended | flux ~ 4 X IACTs |
| • HESS J1841-055 | extended | flux ~ 3 X IACTs |




**ARGO-YBJ Coll., ApJ 767 (2013) 99**

Systematic disagreement for extended sources !
ARGO-YBJ (and MILAGRO) measure higher fluxes

## Possible systematics in ARGO-YBJ

- CR background evaluation: checked with the distribution of the excesses (Gauss with s=1)
- Pointing accuracy (at 0.1° level checked with the Moon Shadow)
- Error in energy scale < 13%
- Contribution from the diffuse emission of the Galactic plane < 15%

**Overall systematics on the flux < 30%**

★The discrepancy could origin from the different techniques used in the background estimation for extended sources.
★Maybe the extended excess is due to the contribution of different sources

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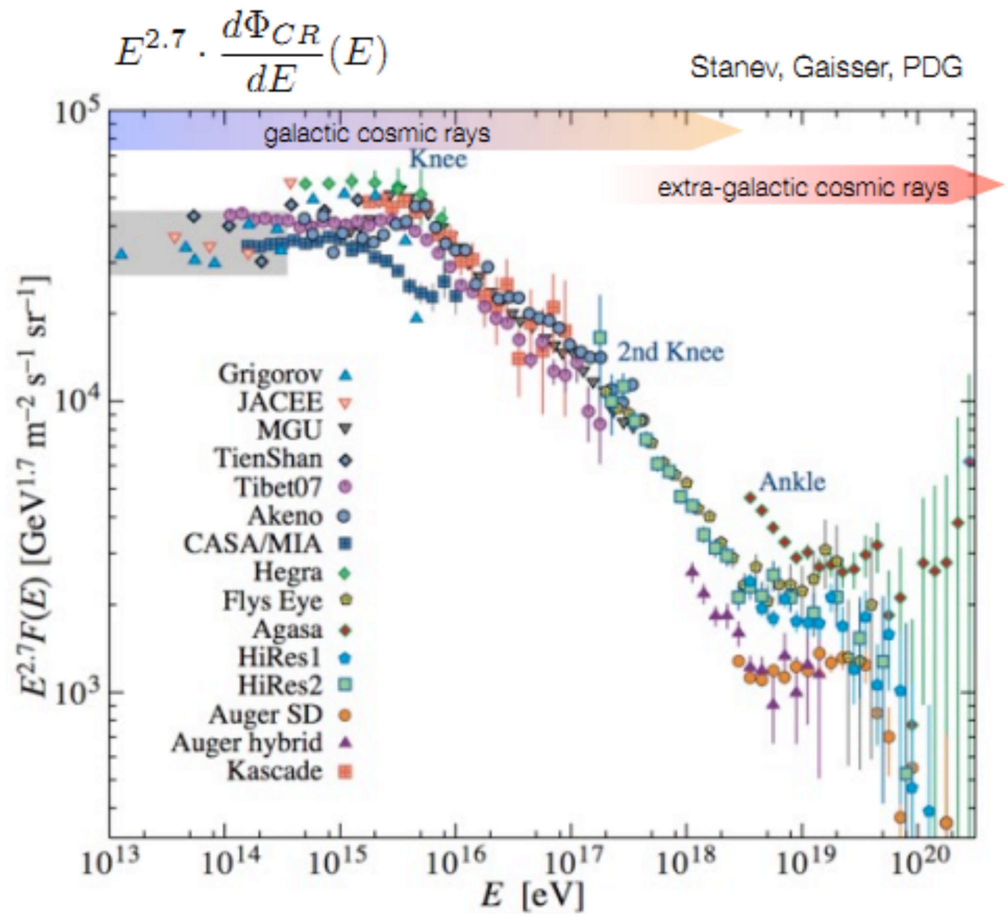
- Elemental composition approaching the knee: the 'proton' knee

# 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 · $10^{15}$ eV → - Eknee ∝Z - No anisotropy change
- **Diffusion process:** probability of escape from Galaxy = f(Z) → - Eknee ∝ Z - Anisotropy $\propto E^{\delta}$

- **Interaction with bckg particles:** Photo-disintegration - interaction with in galactic halo etc.
- **Change in particle interaction**

- Eknee ∝ A

Key elements: mass composition and anisotropy

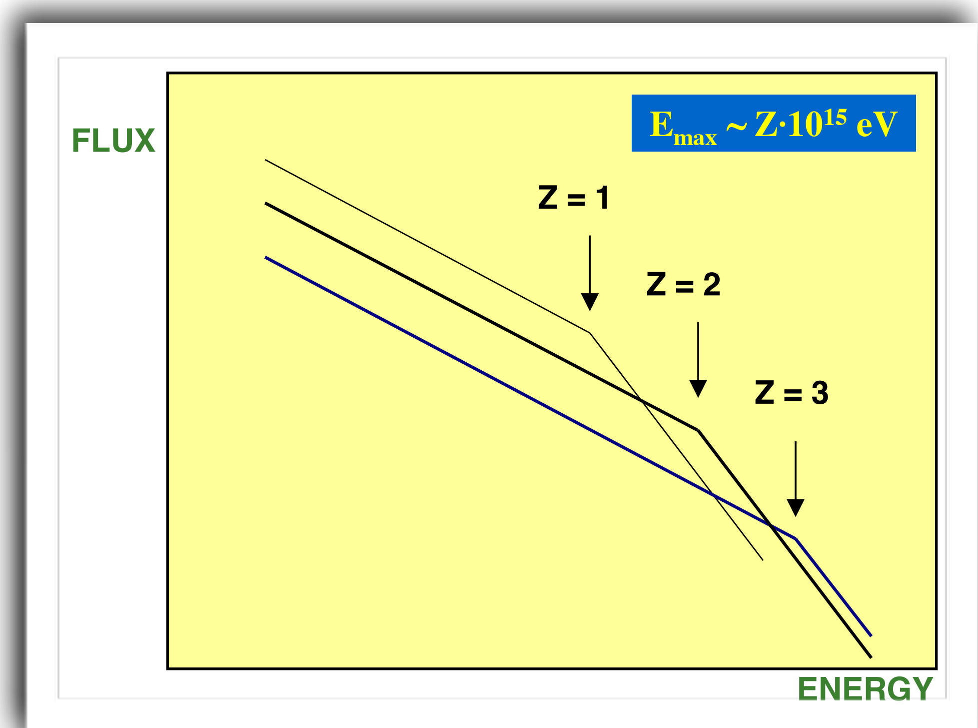
# Approaching the knee

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

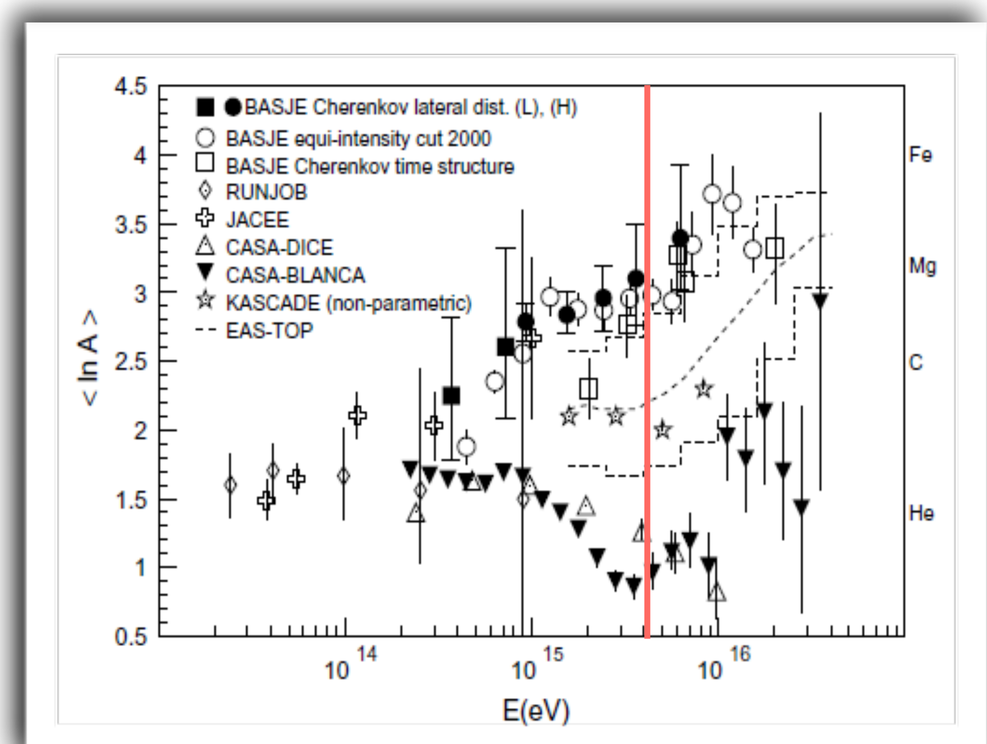
The standard model:

- 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 conflicting




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

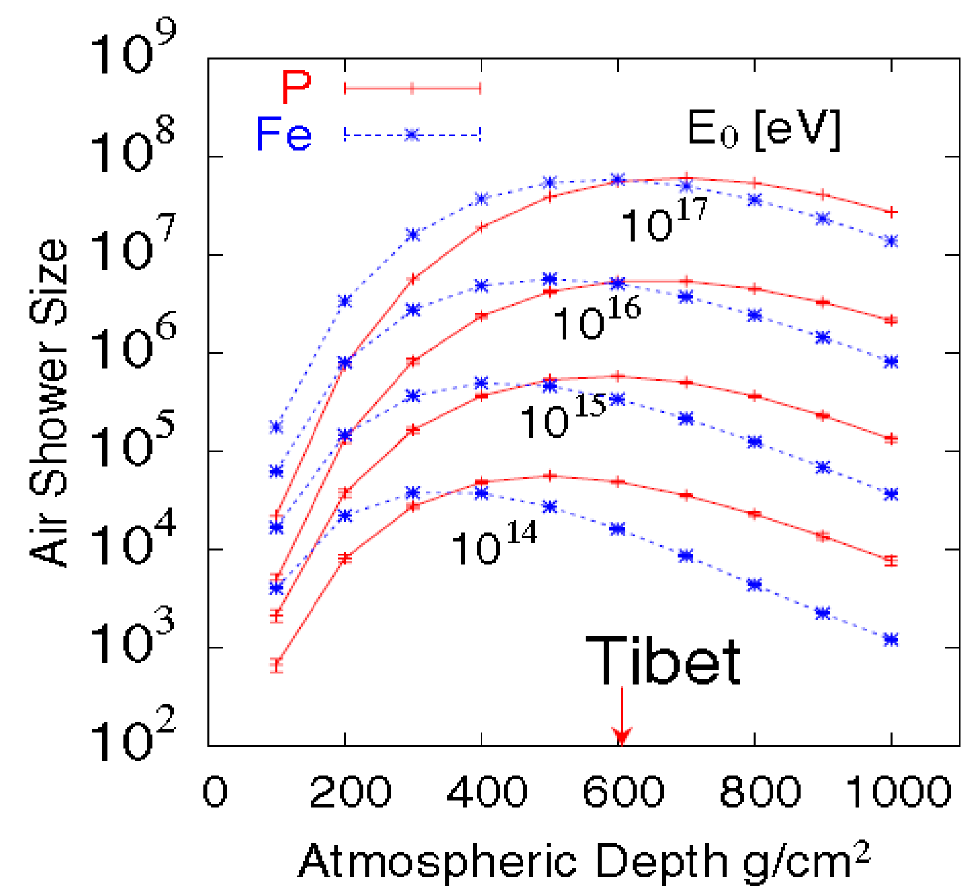


# Measurement of the CR spectrum

- 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
  - Hybrid measurement with a Wide Field of view Cherenkov Telescope 200 TeV - PeV
    → talk by Cao Zhen

- 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



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

Digital readout: strip multiplicity

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

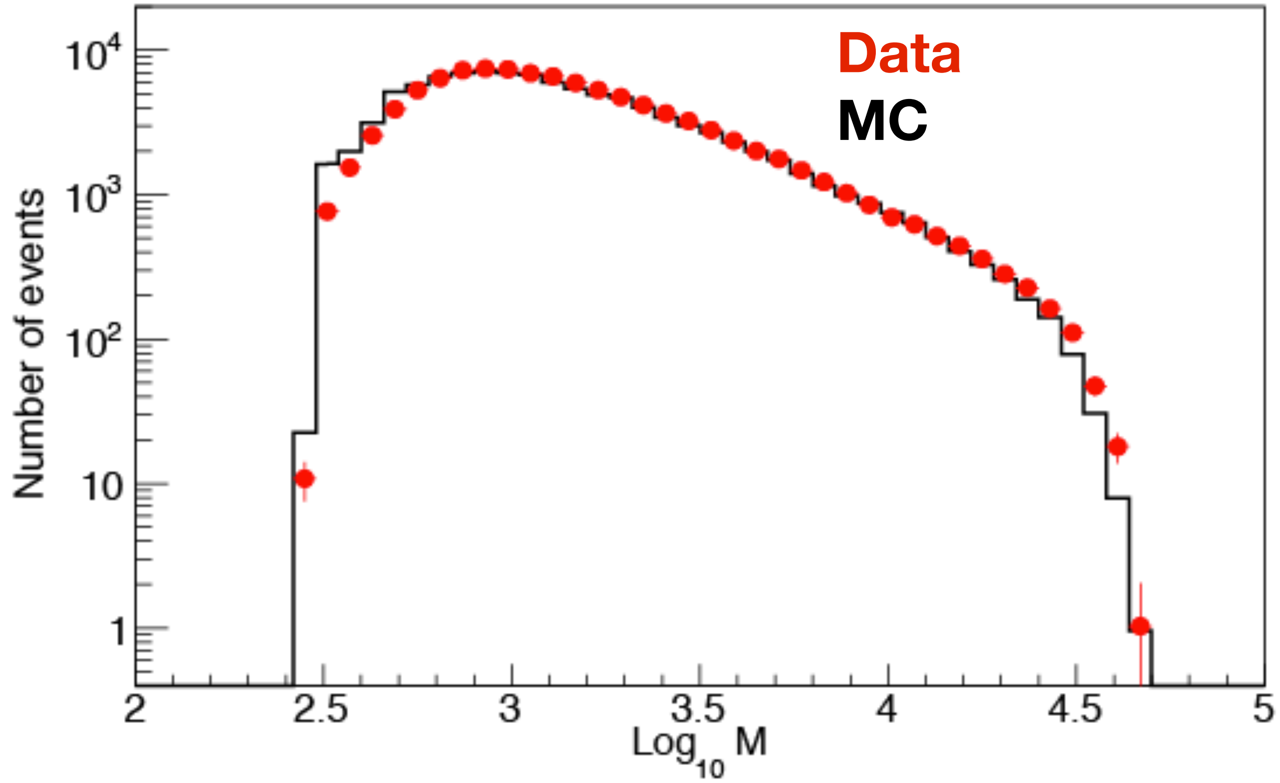
- $M \leq 50{,}000$
- Zenith Angle ≤ 35°
- Highest density cluster in $40 \times 40$ m$^2$

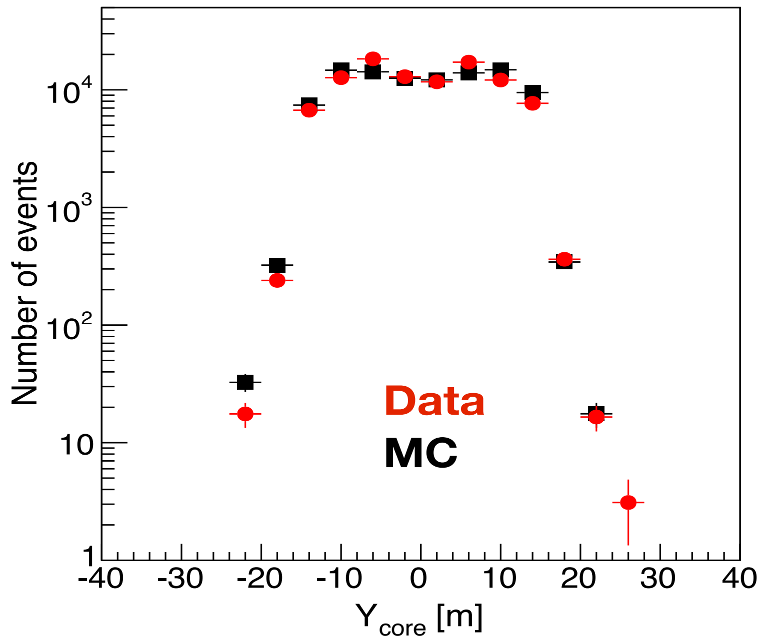
Light Component (p+He) selection:

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

A20 = 20 innermost clusters
A42 = 42 outermost clusters

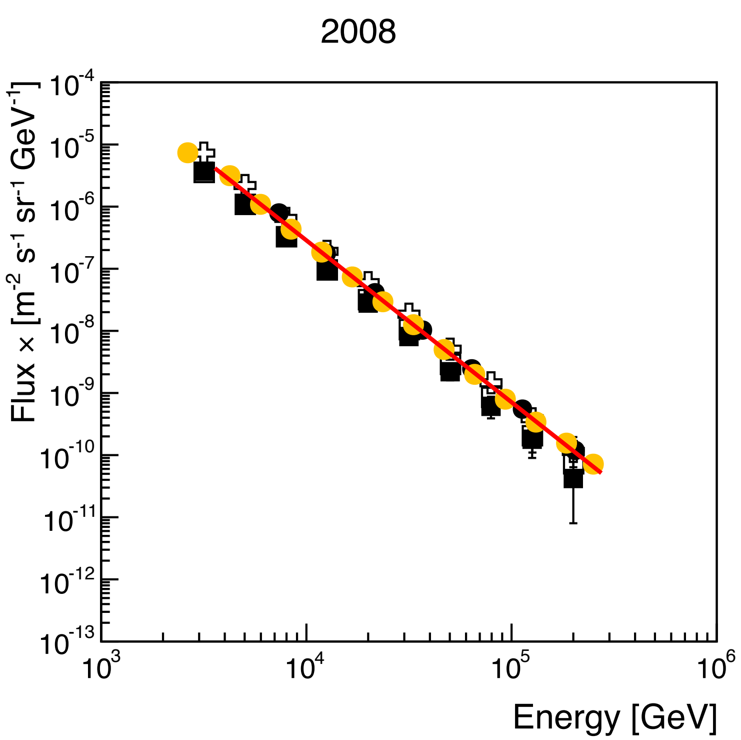
Shower size distribution on the central carpet, **M** (strip multiplicity)

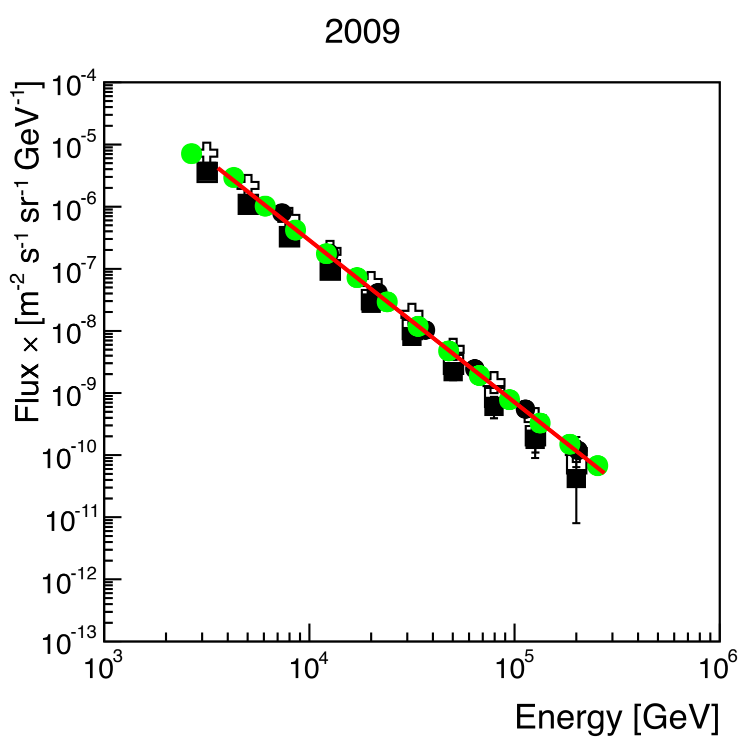


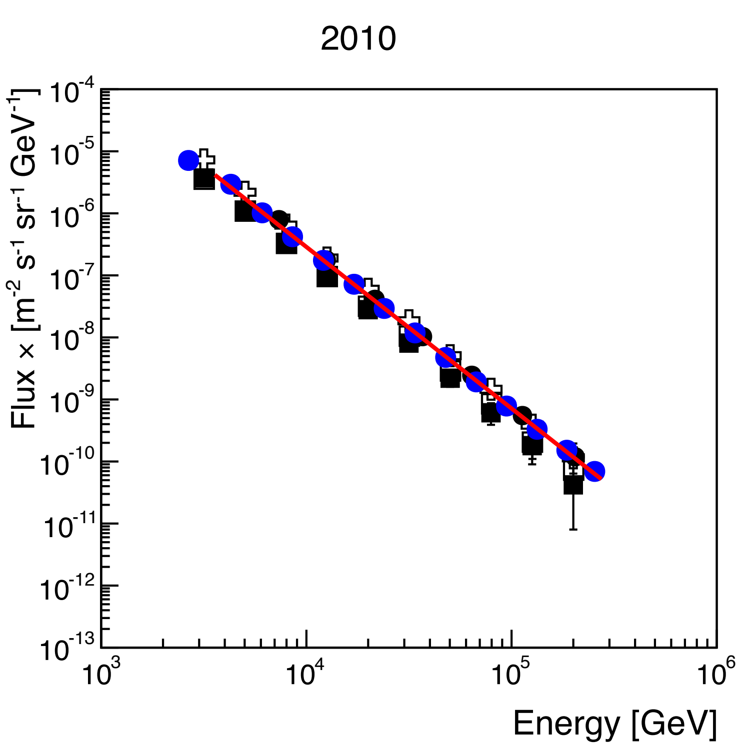



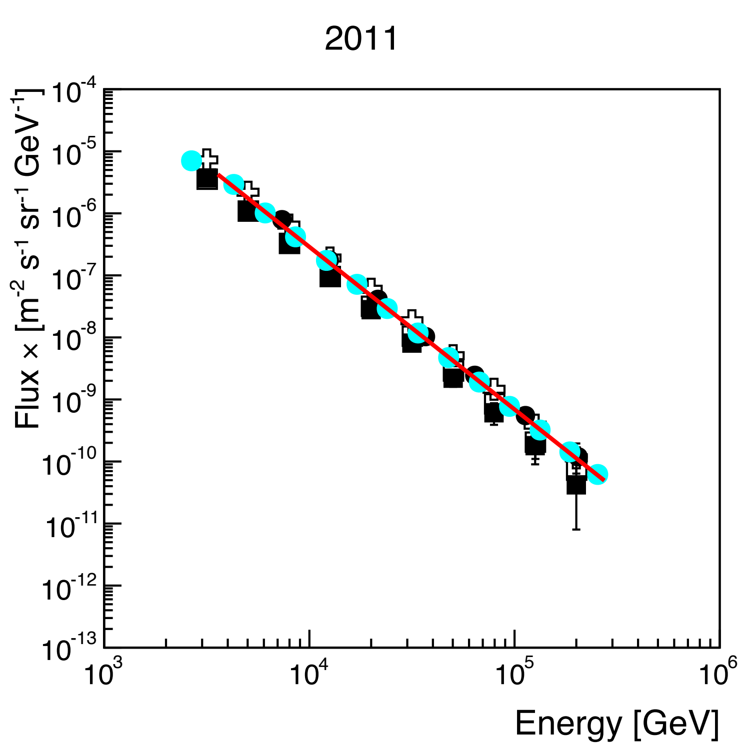

Rconstructed shower core position

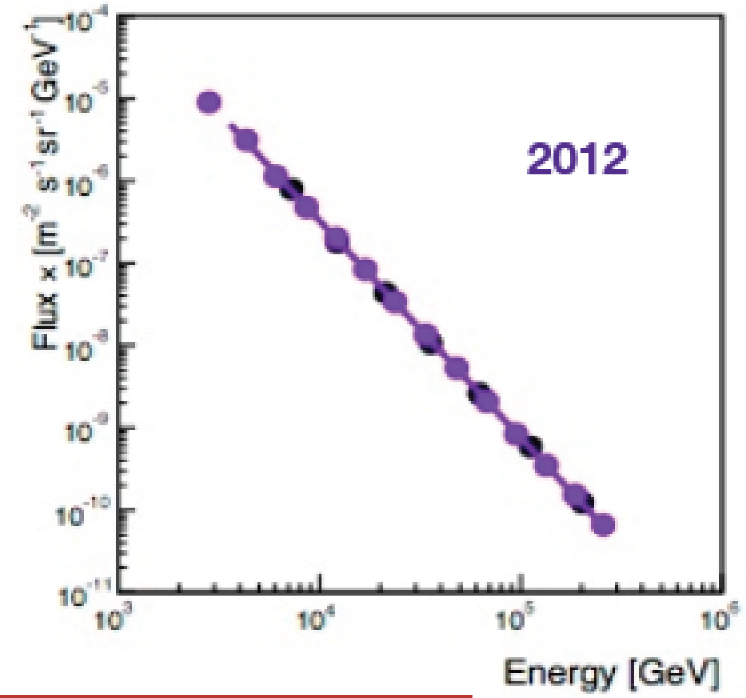
# Light component spectrum



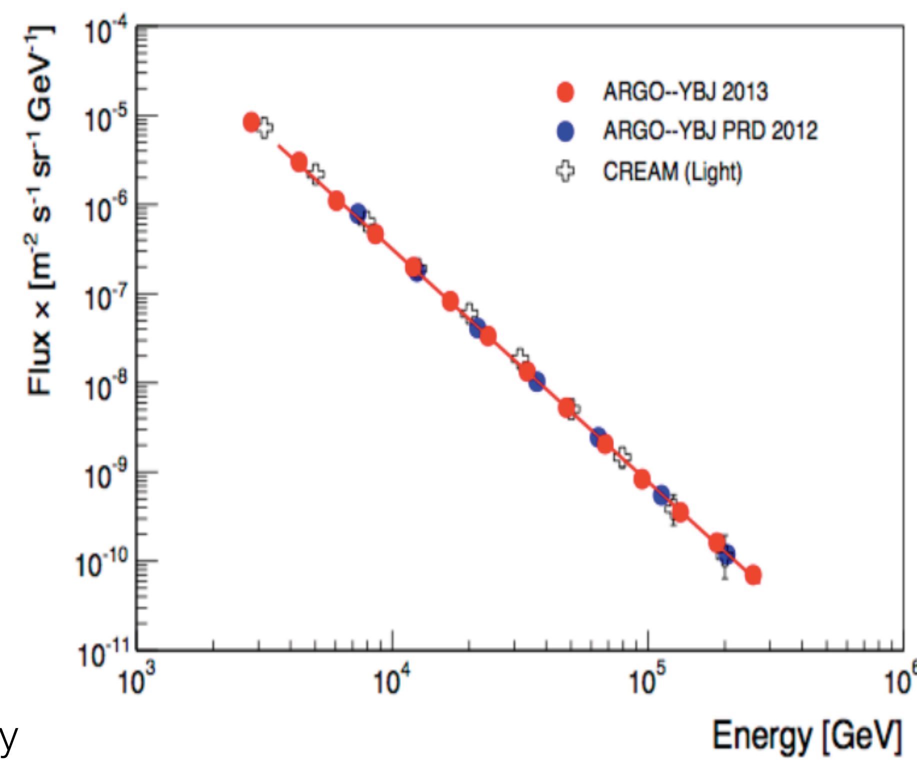



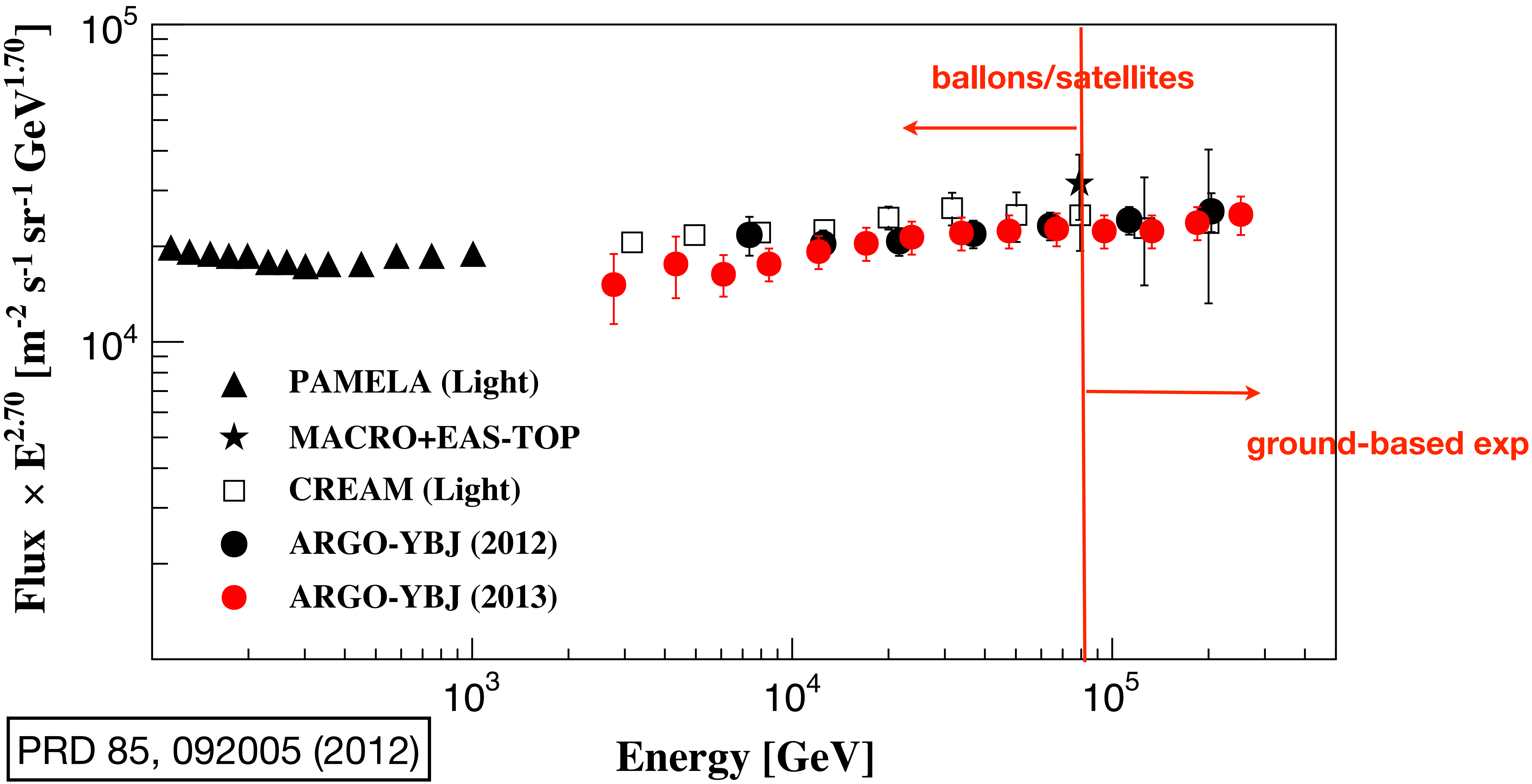




| year | Gamma |
|---|---|
| 2008 | 2.61±0.02 |
| 2009 | 2.61±0.02 |
| 2010 | 2.61±0.02 |
| 2011 | 2.62±0.02 |
| 2012 | 2.63±0.02 |



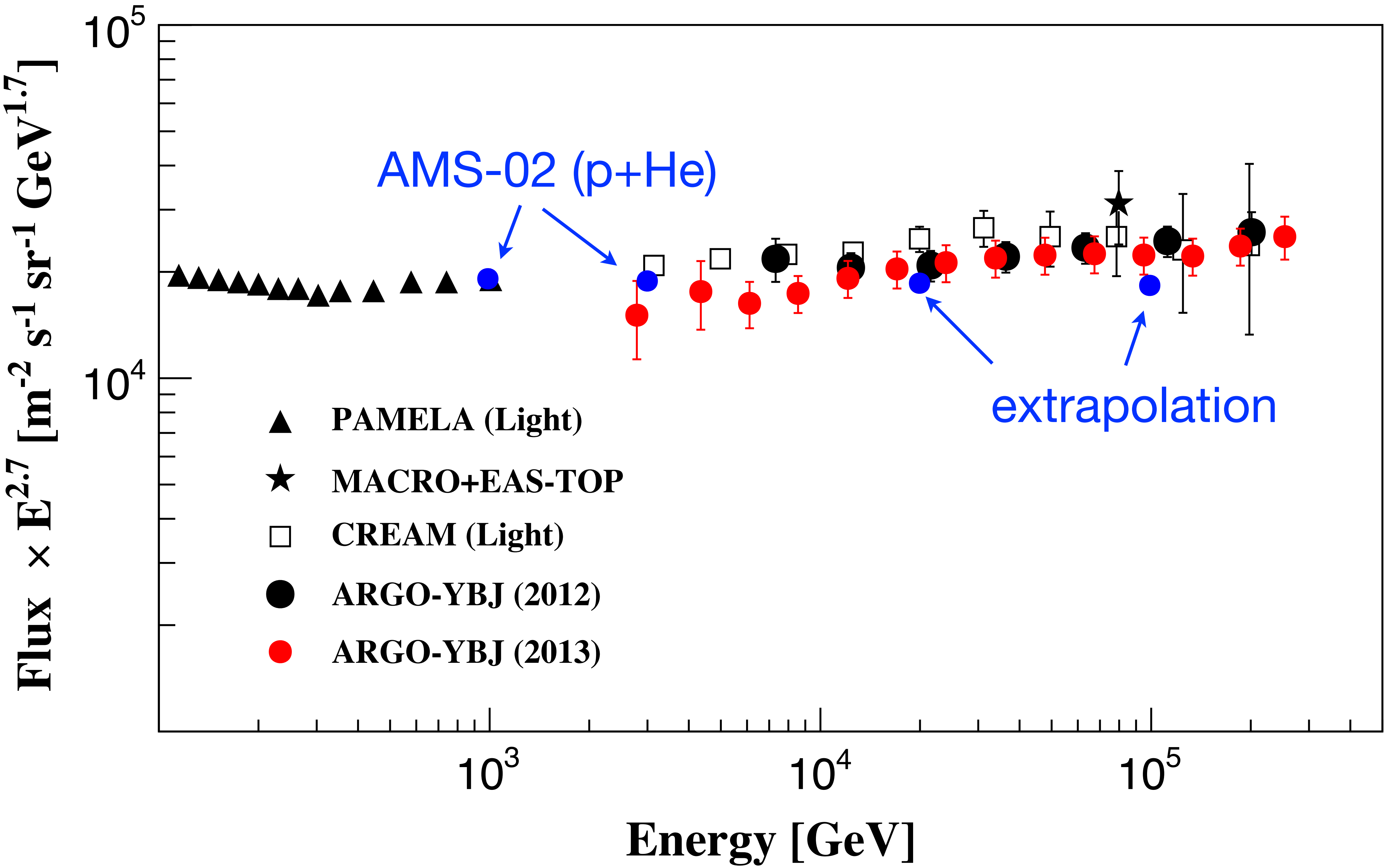
# The light-component spectrum (3 - 300 TeV)

Measurement of the light-component (p+He) CR spectrum in the energy region (3 – 300) TeV via a Bayesian unfolding procedure




PRD 85, 092005 (2012)

# ARGO-YBJ and AMS-02 (ICRC13)



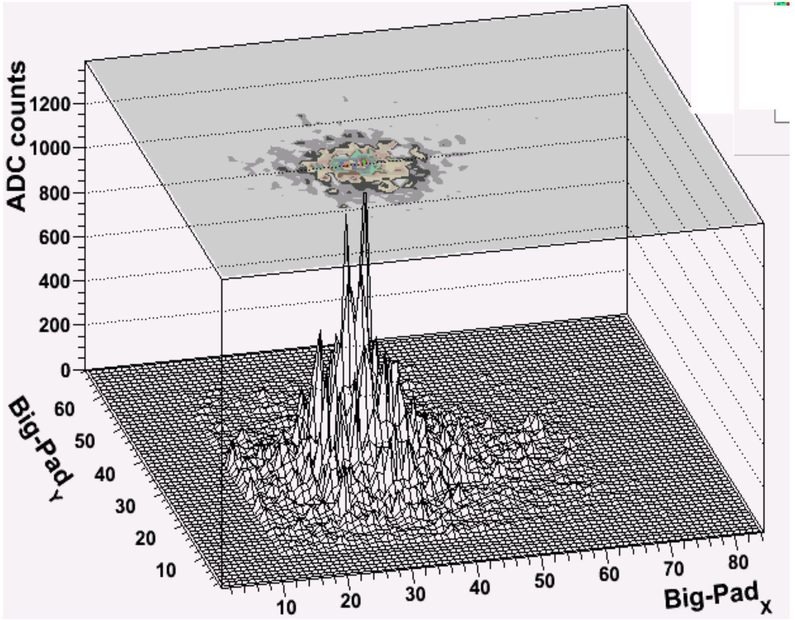
# Extending the energy range

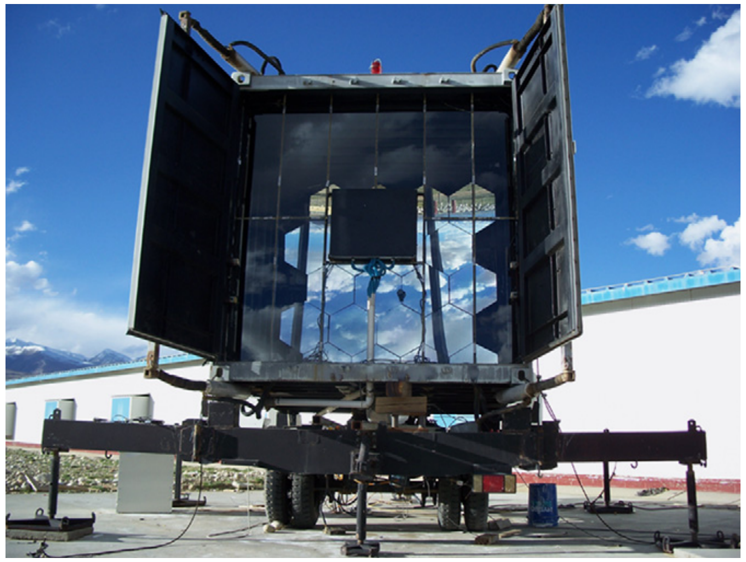
To extend the energy range up to 10 PeV we use *different eyes*:

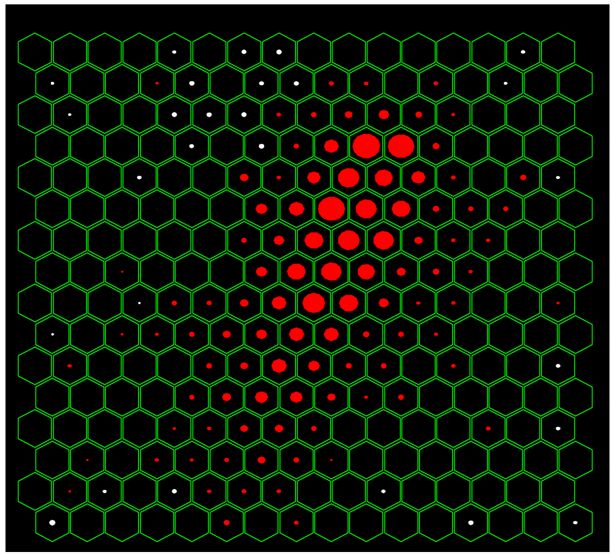
❖ ARGO-YBJ Analog Readout

❖ 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°





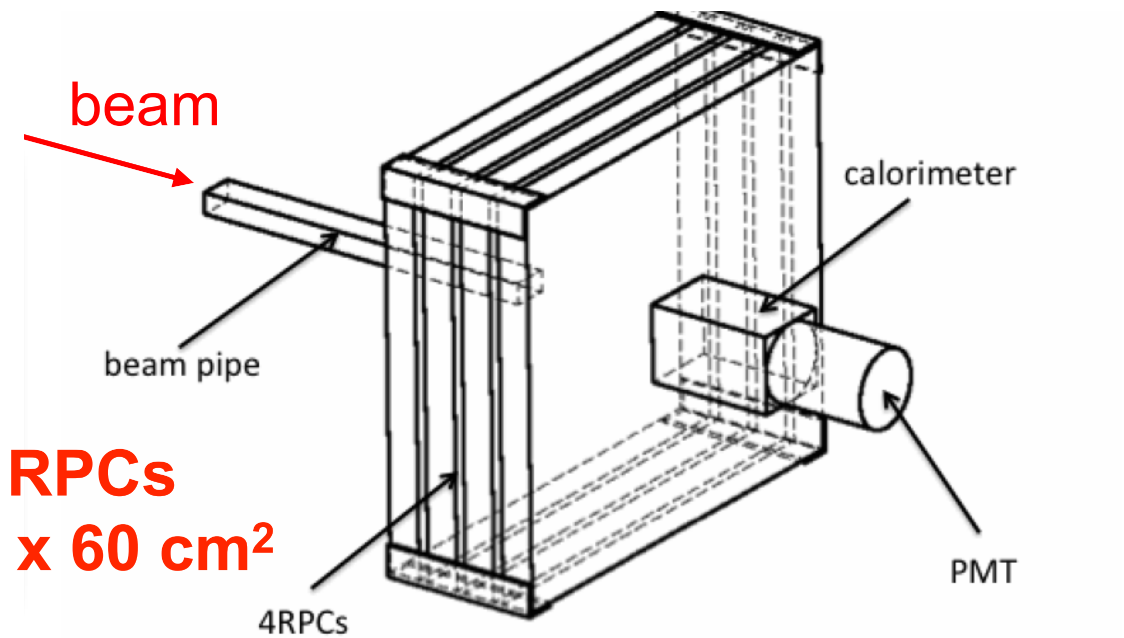
…to performe 2 different analysis:

❖ ARGO-YBJ Analog Readout alone

❖ Hybrid measurement ARGO-YBJ/WFCTA

Talk by Zhen Cao

# Intrinsic linearity: test at the BTF facility



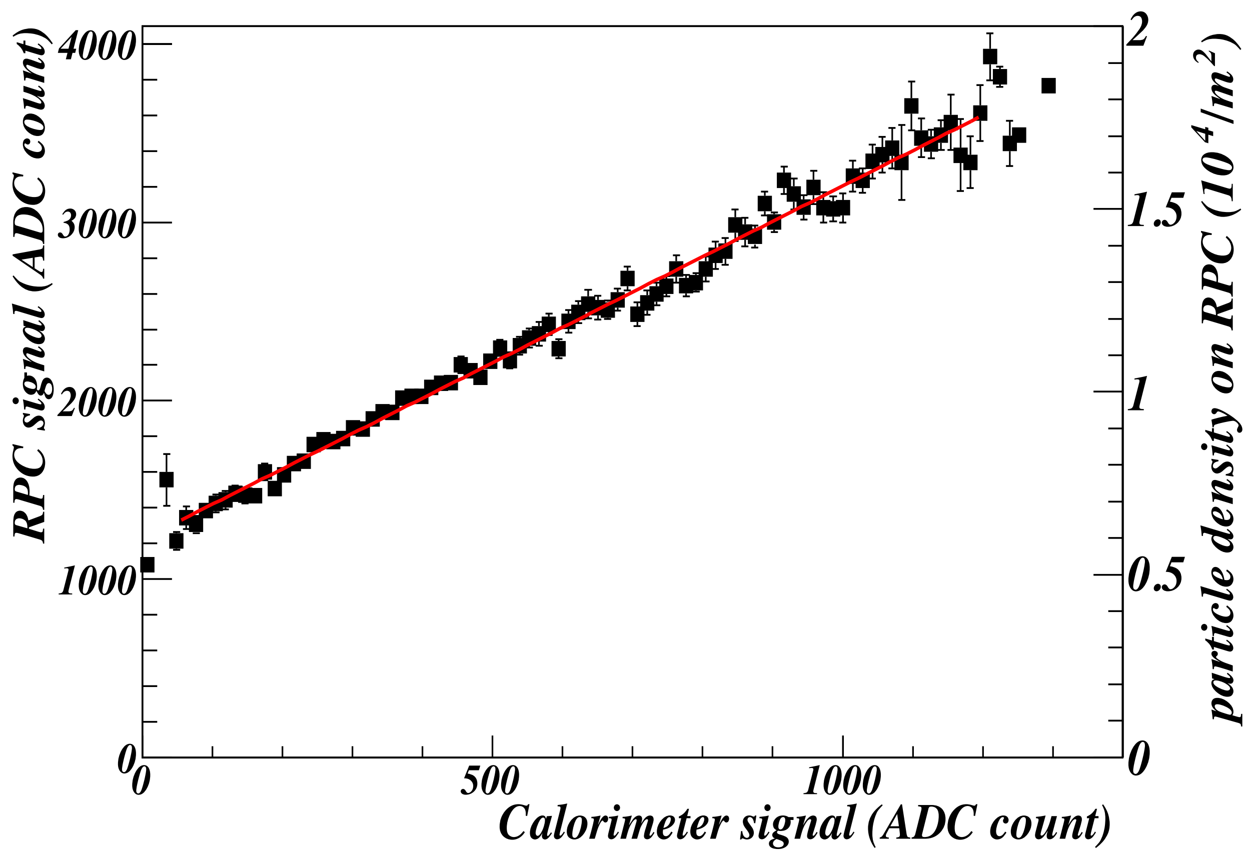

**4 RPCs**
**60 x 60 cm²**

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

**Linearity of the RPC @ BTF in INFN Frascati Lab:**

- *electrons (or positrons)*
- *E = 25-750 MeV (0.5% resolution)*
- *<N>=1÷10⁸particles/pulse*
- *10 ns pulses, 1-49 Hz*
- *beam spot uniform on 3×5 cm*

The RPC signal vs the calorimeter signal




**➔ Linearity up to ≈ 2 • $10^4$ particle/m²**

Astroparticle Physics submitted

# Performance evaluation

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

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

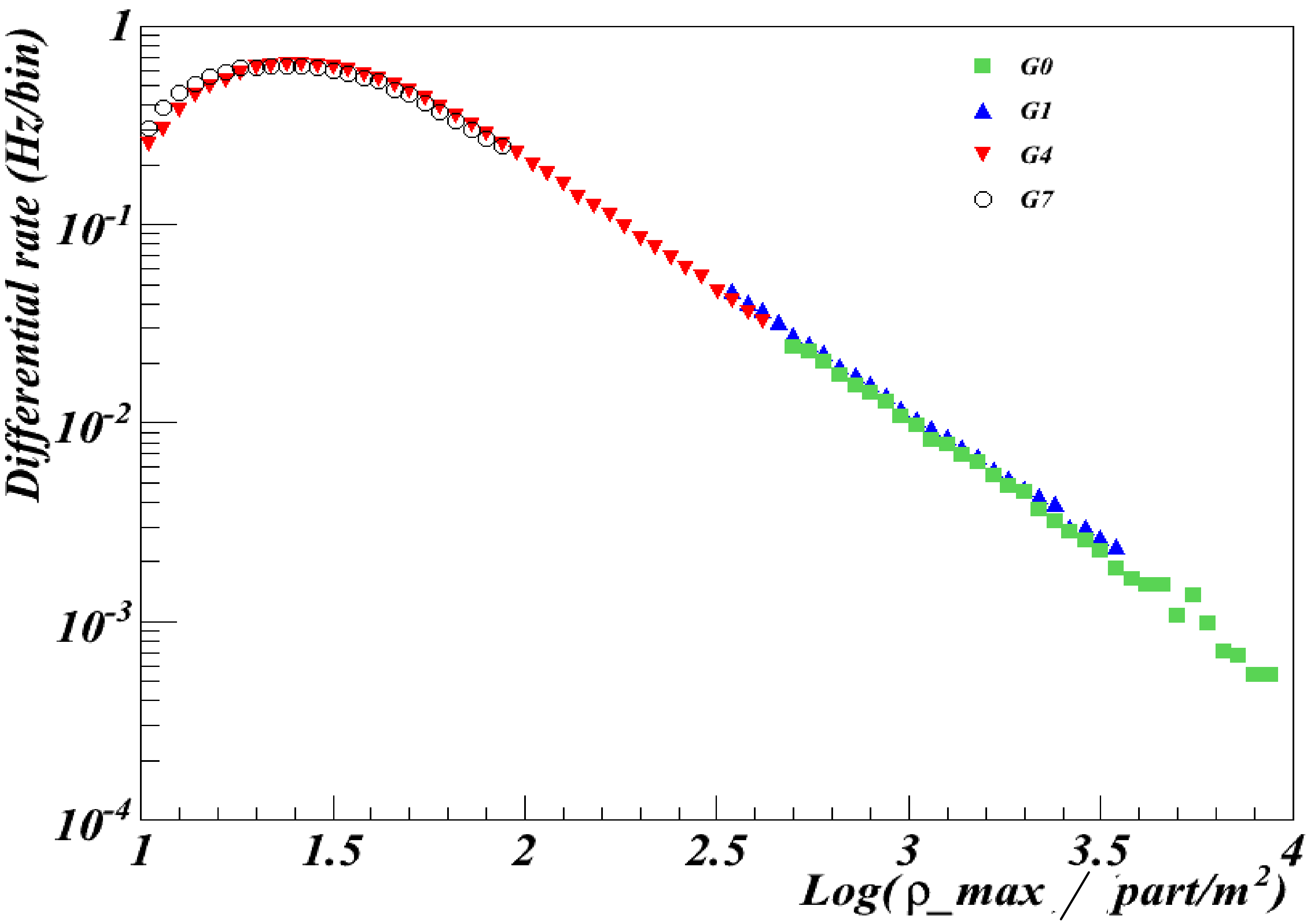
$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

4 data sample:

$\rho$: 10 → $10^4$ part/m$^2$

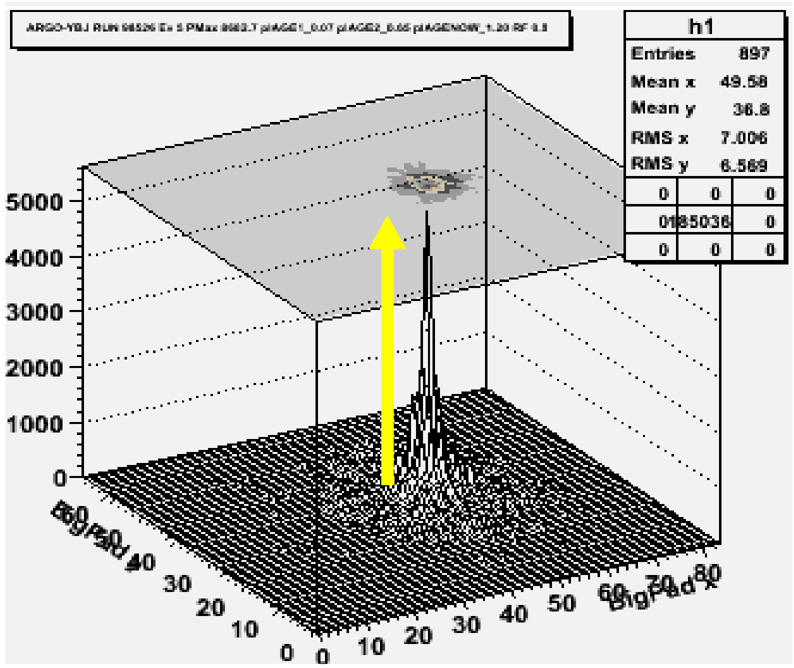
Event selection:

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



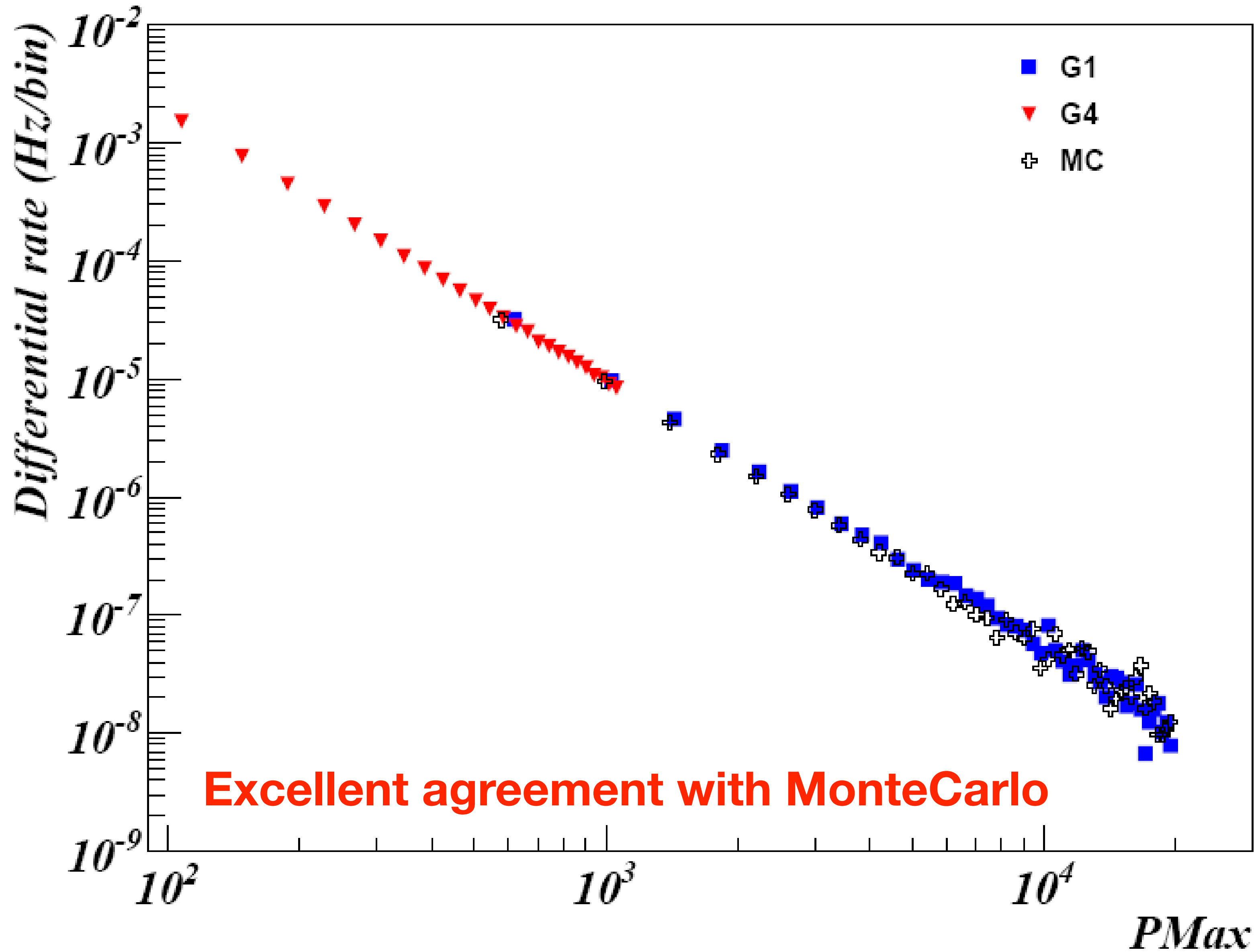

*Good overlap between 4 scales with the maximum density of the showers spanning over three decades*

# 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$^2$

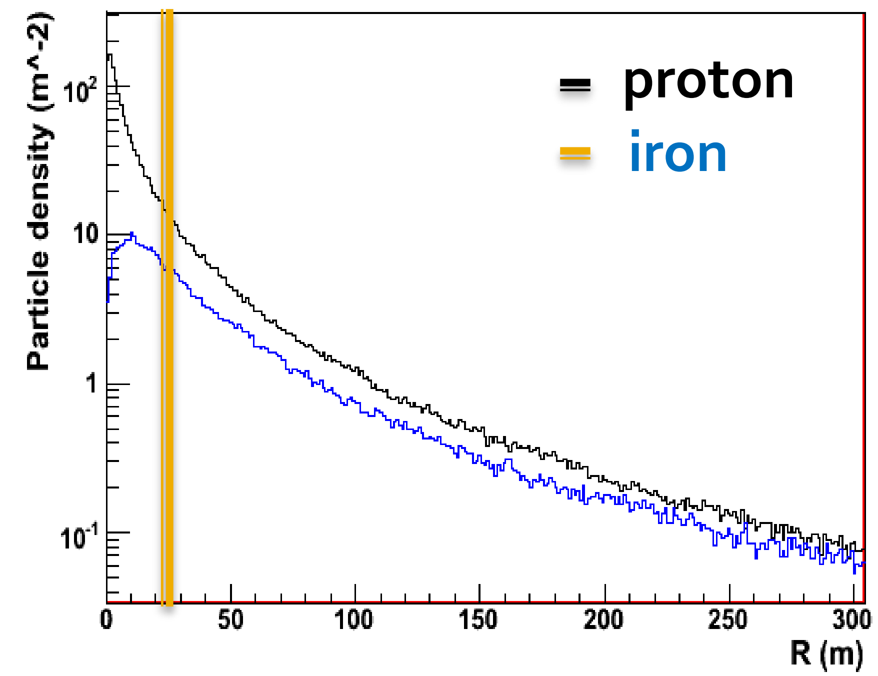
★ Zenith angle < 15°

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

# ARGO-YBJ + WFCTA


❖ *ARGO-YBJ:* lateral distribution

In the core region → mass sensitive

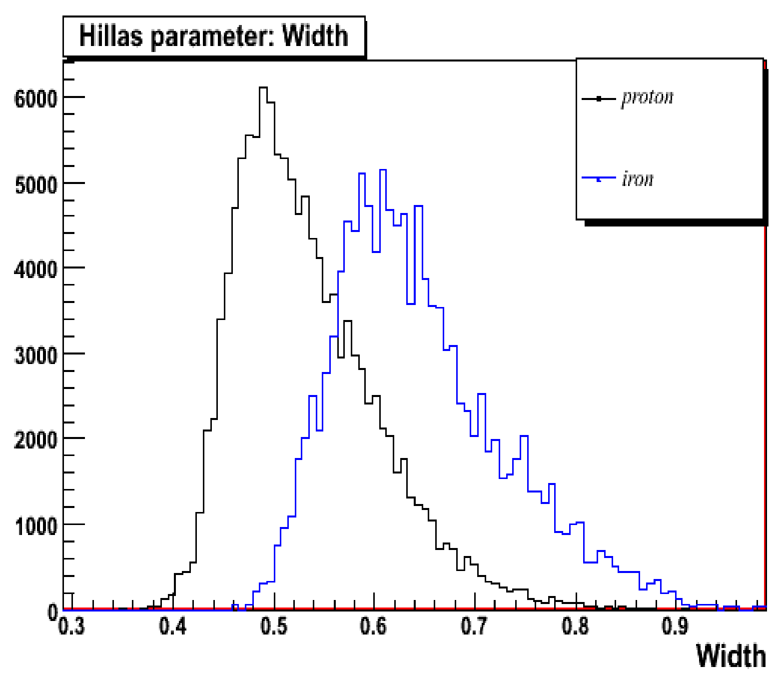


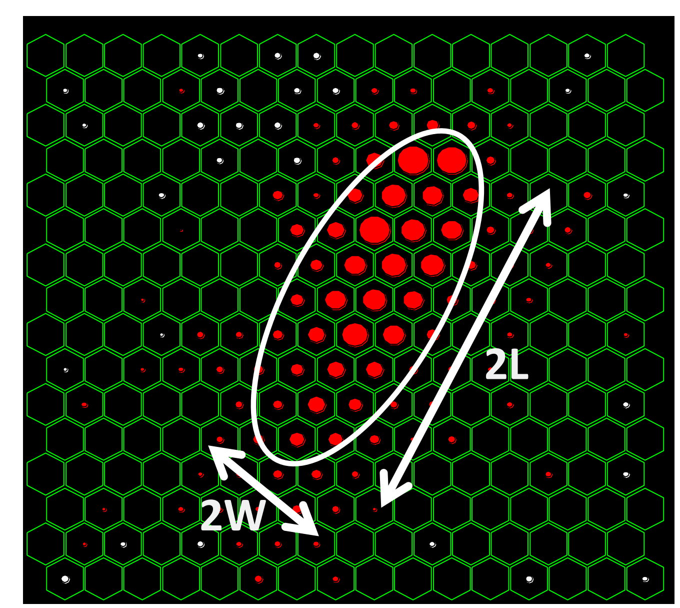

❖ *Cherenkov telescope:* longitudinal information

Hillas parameters → mass sensitive

Better energy resolution

- angular resolution: 0.2°
- 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 < $6^{o}$
  - Number of fired PMTs ≥ 6

- Cherenkov image cleaning
  - Single channel threshold: S/N>3.5.
  - Arrival time: all triggered pixels in a window of $\Delta t$ = 240 ns.
  - Isolated pixels rejected

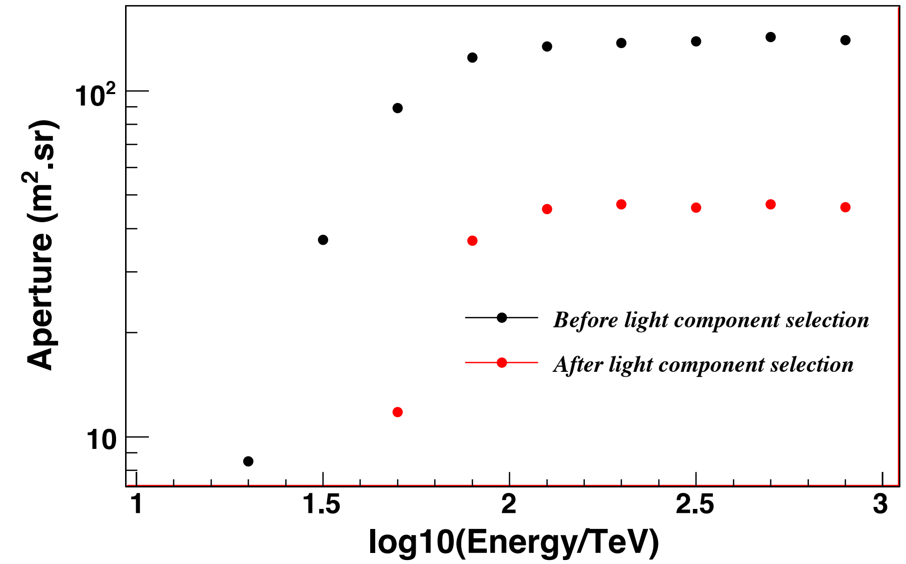
➡ 8218 events well reconstructed above 100 TeV

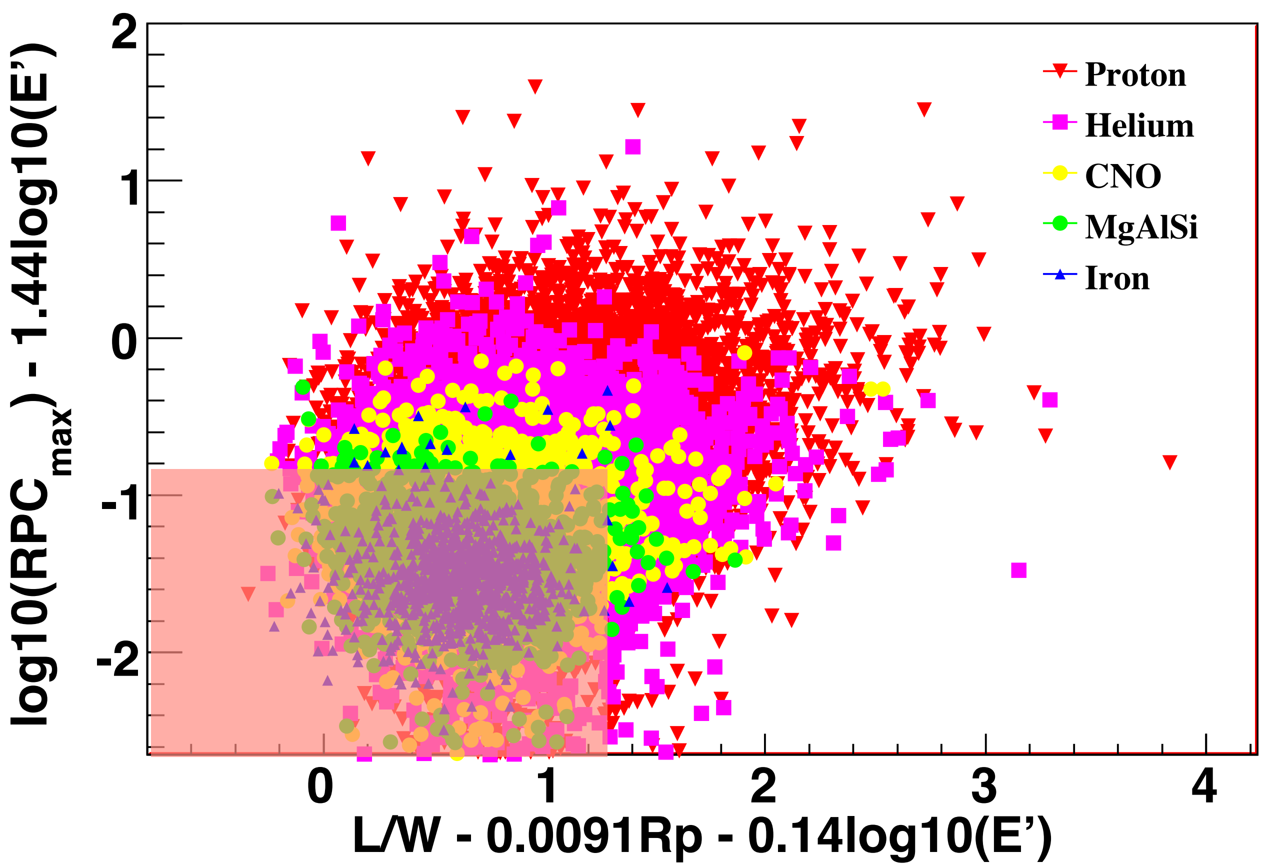
# Light-component (p+He) selection

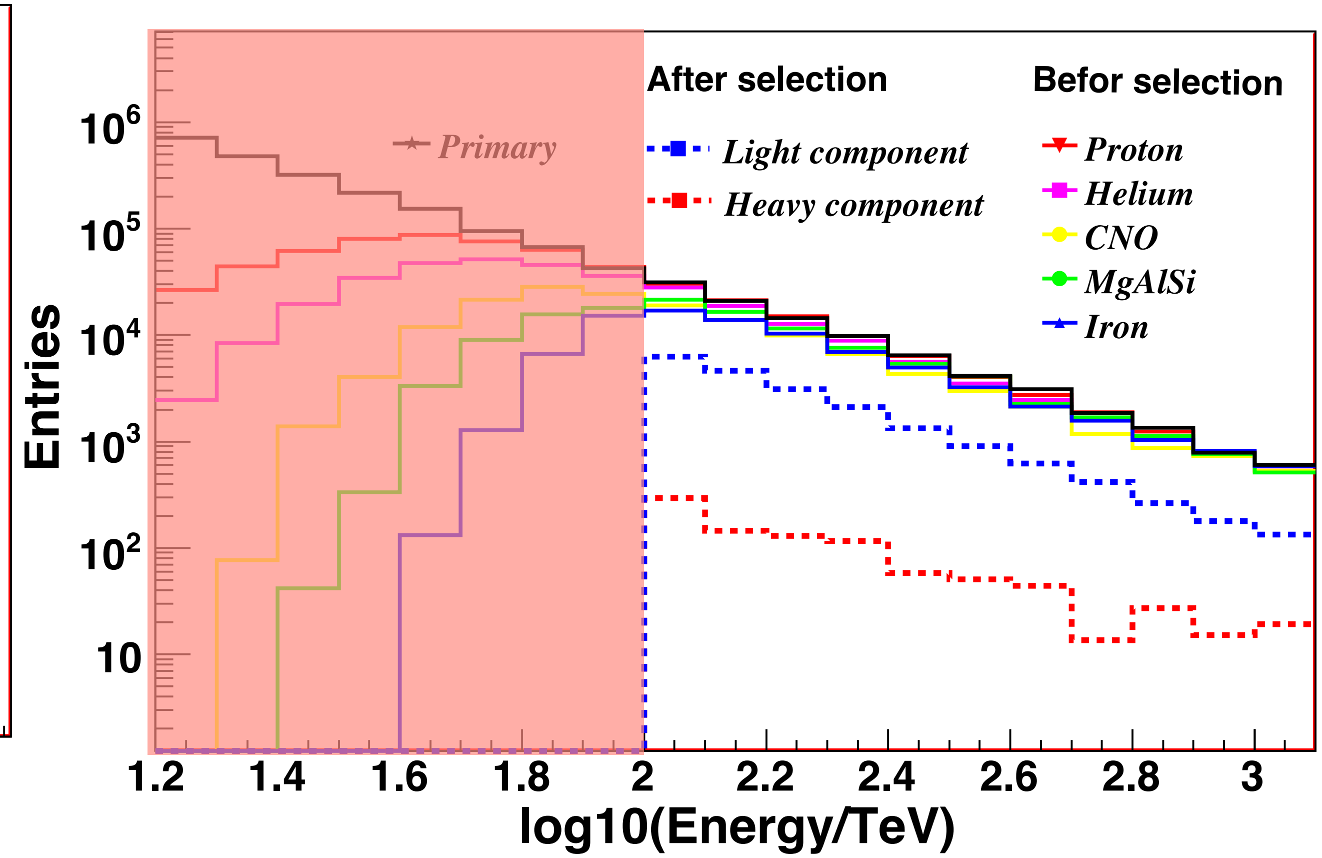
Talk by Zhen Cao

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

| | Proton | Helium | CNO | MgAlSi | Iron | SUM |
|---|---|---|---|---|---|---|
| The initial fractions | 20% | 20% | 20% | 20% | 20% | 100% |
| The fractions after composition selection | 69.1% | 25.8% | 3.8% | 1.1% | 0.2% | 100% |
| The selection efficiency | 51.0% | 19.1% | 2.7% | 0.8% | 0.1% | |



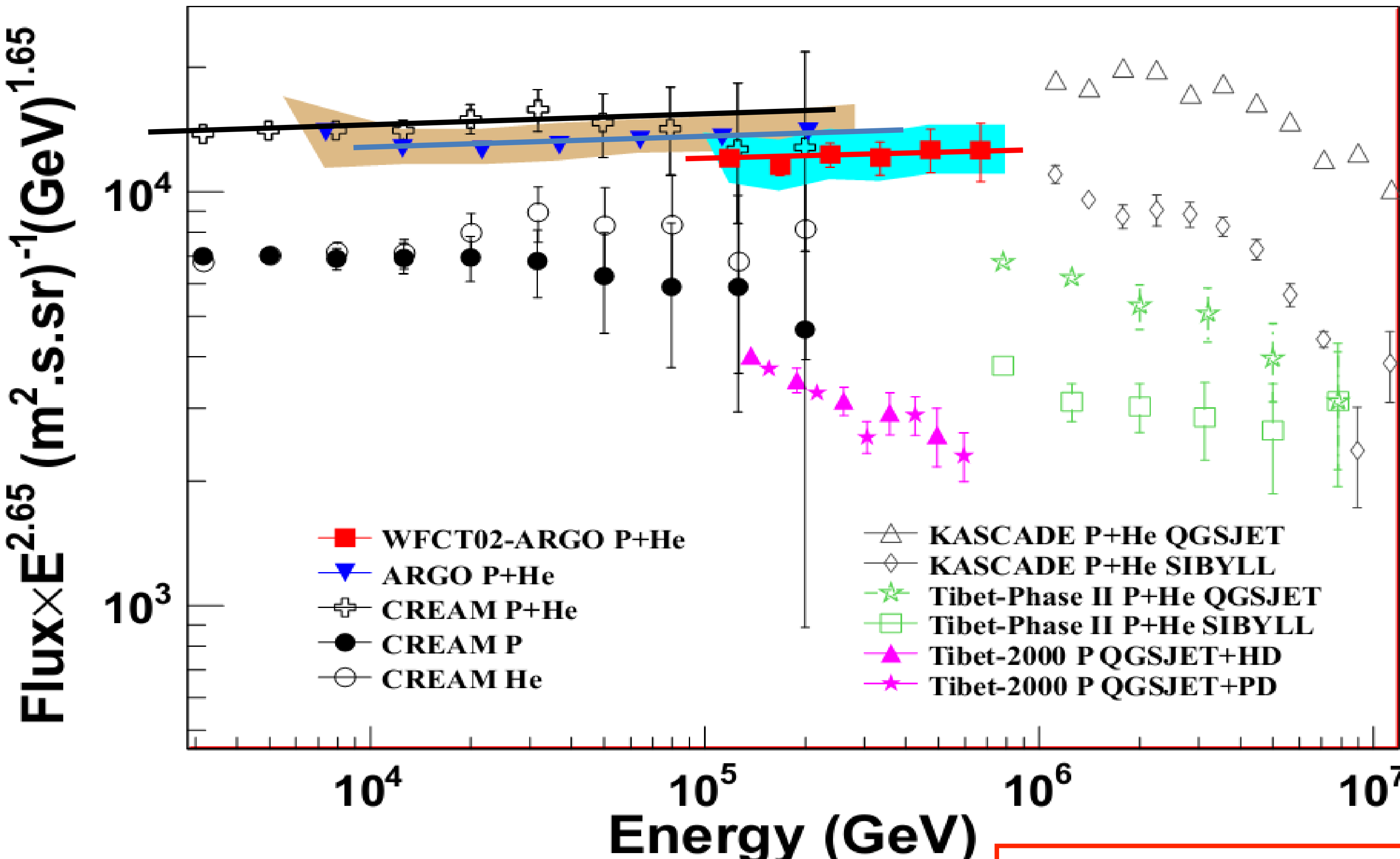



# The light-component (p+He) spectrum (2 - 700) TeV

- 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:

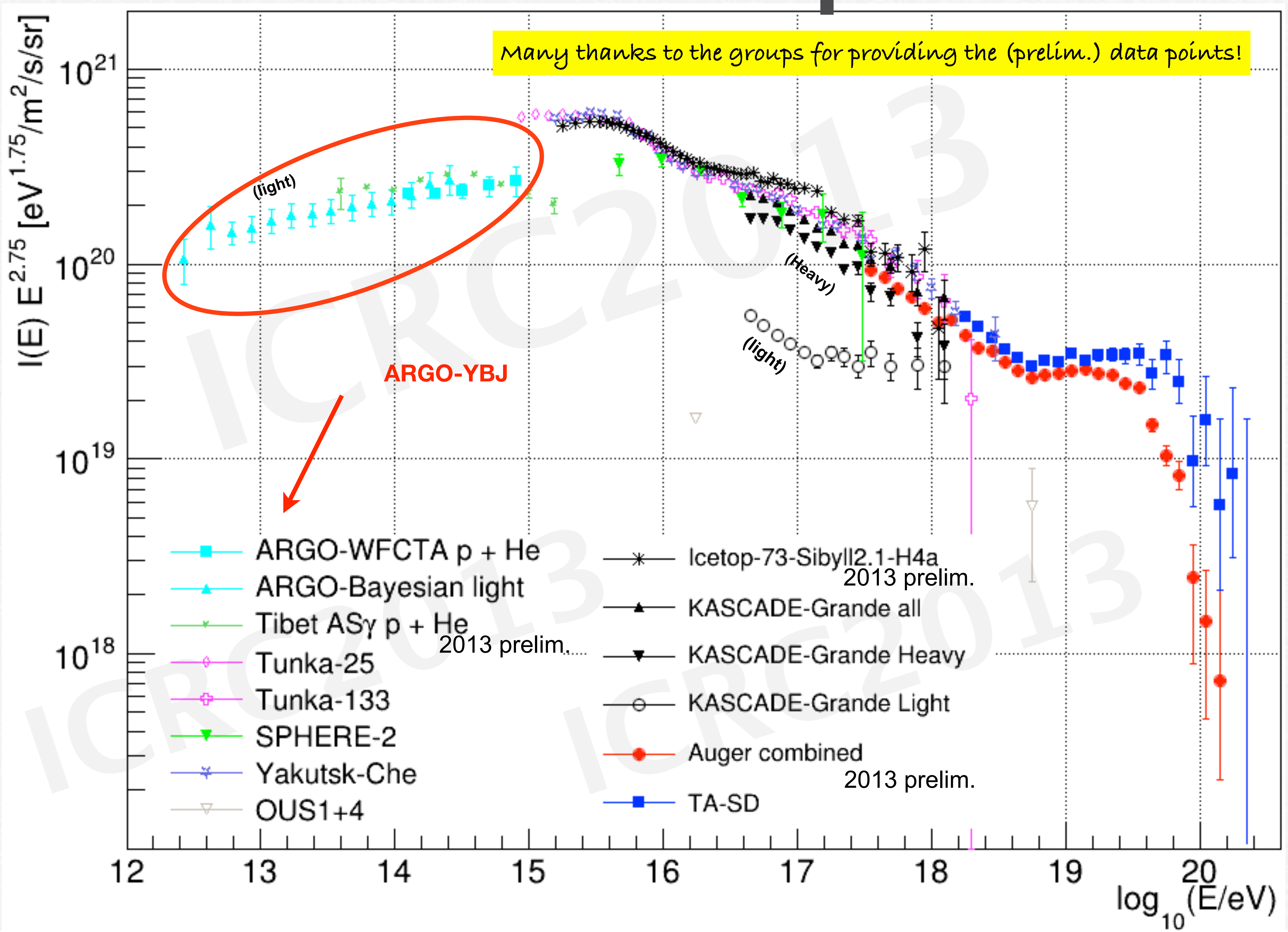
1.95 × $10^{-11}$ ± 9% (GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$)

Energy calibration ok !

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

The 9% difference in flux corresponds to a difference of ± 3.5% in energy scale between different experiments.

# HE-CR: ICRC2013 Spectra

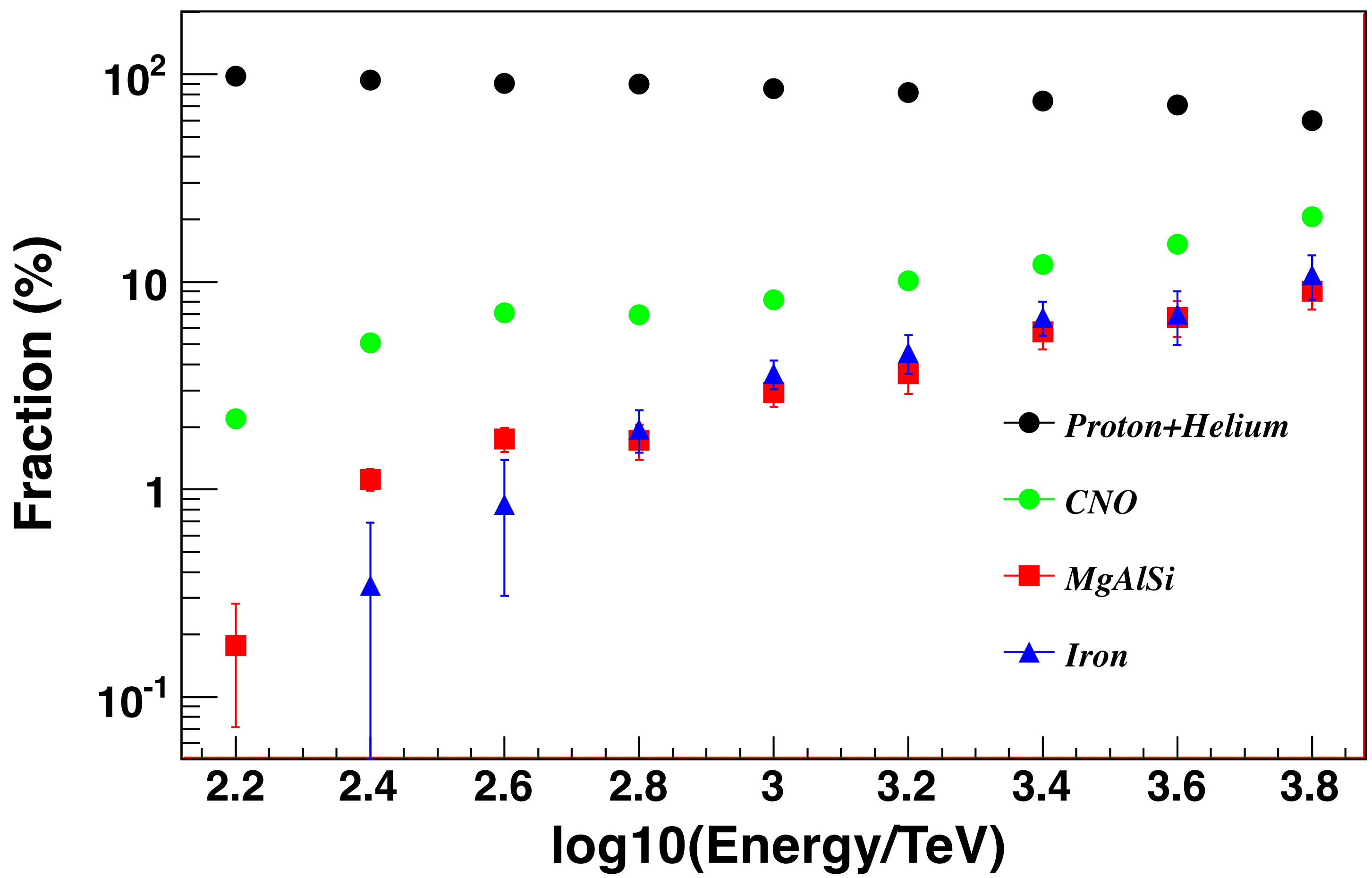


# Approaching the all-particle knee

We modified the selection criteria to increase the statistics above 700 TeV with tolerable contamination from heavier nuclei.

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 increases from 3% to 7% below 700 TeV and the purity worsens from 98% to 93%.



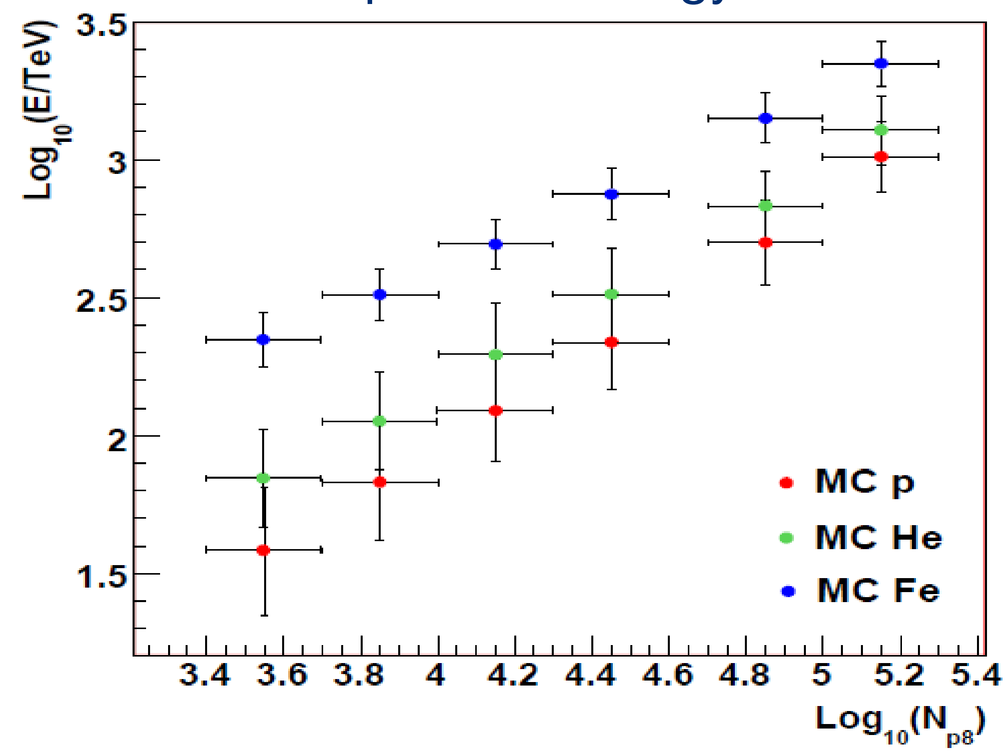

Talk by Zhen Cao

# Analysis with ARGO-YBJ analog data

Analysis 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

mass dependent energy estimator

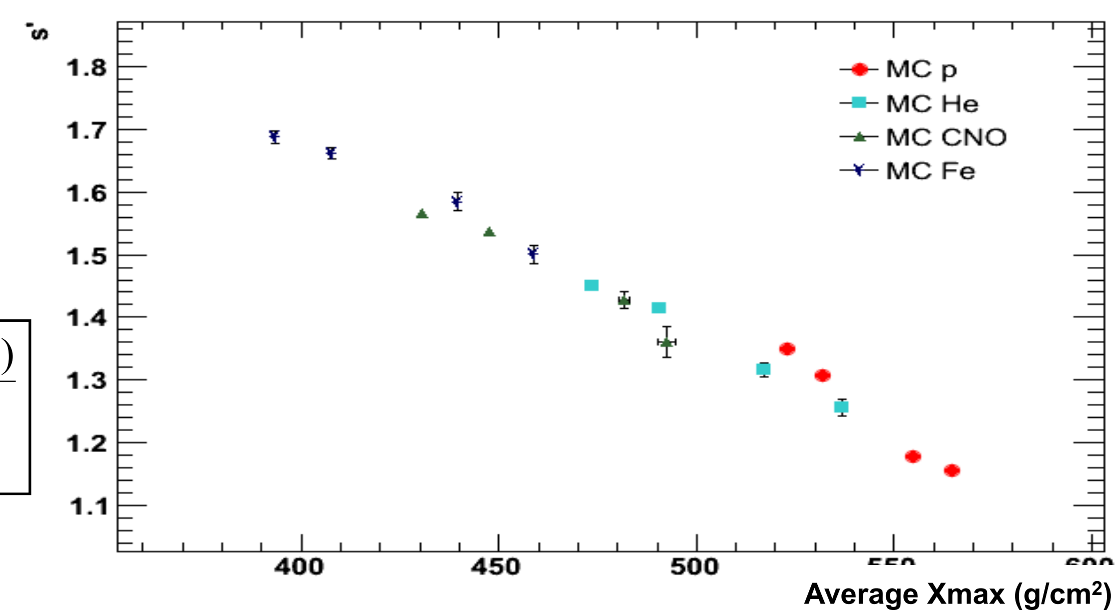



Look for information on the shower age in order to have a mass independent energy estimator.

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

$R_0 = 30$ m

s' is NOT the shower age. It is correlated to it.



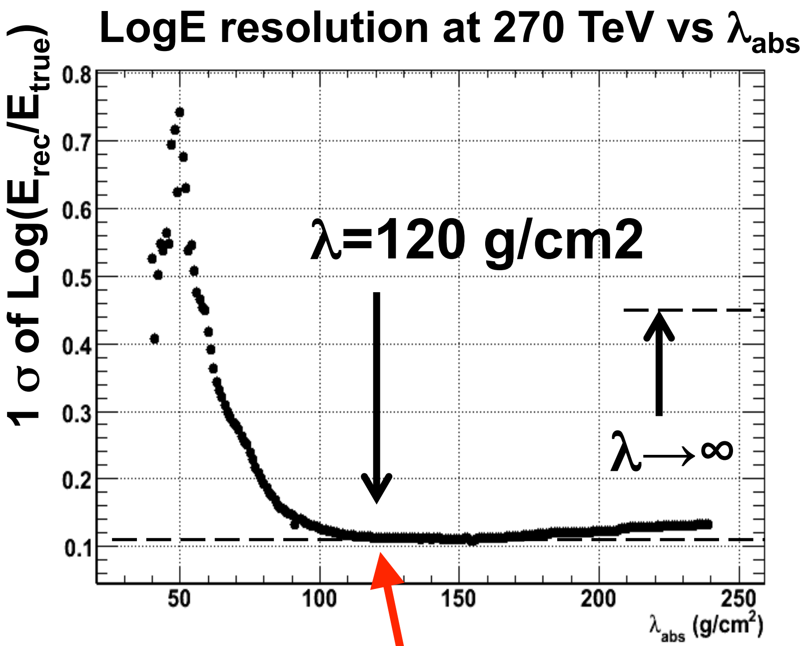

Assume an exponential absorption after the shower maximum. Get the correct signal at maximum (Np8max) by using Np8 and s' measurements for each event.

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

Also checks with Gaisser-Hillas profile

The LDF slope s' is $\langle X_{max} \rangle$ estimator mass-independent

# Finding the best $\lambda_{abs}$ parameter

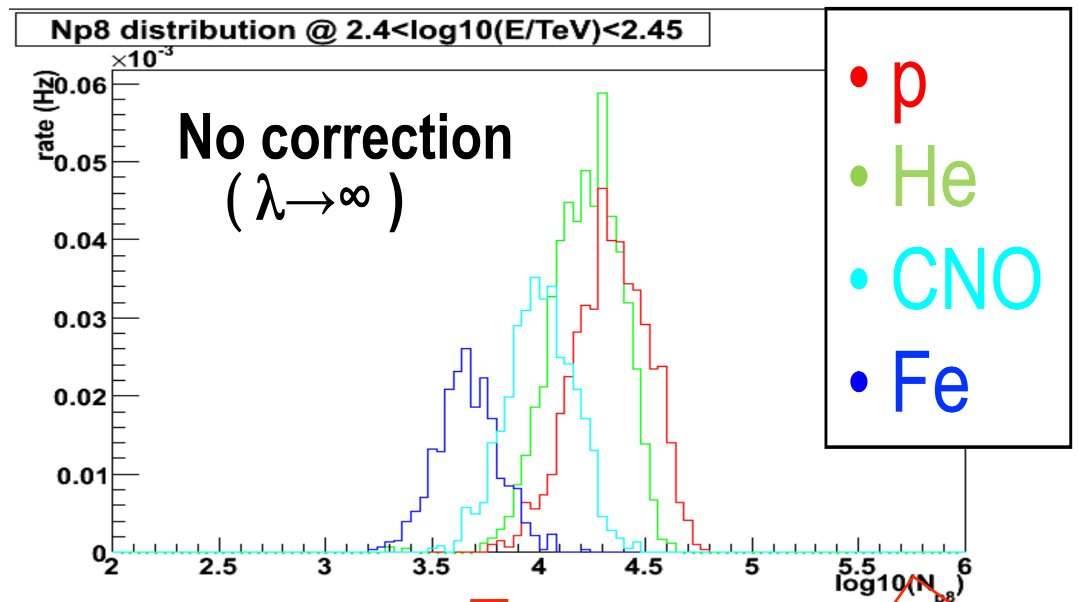



Results from the ARGO-YBJ test experiment

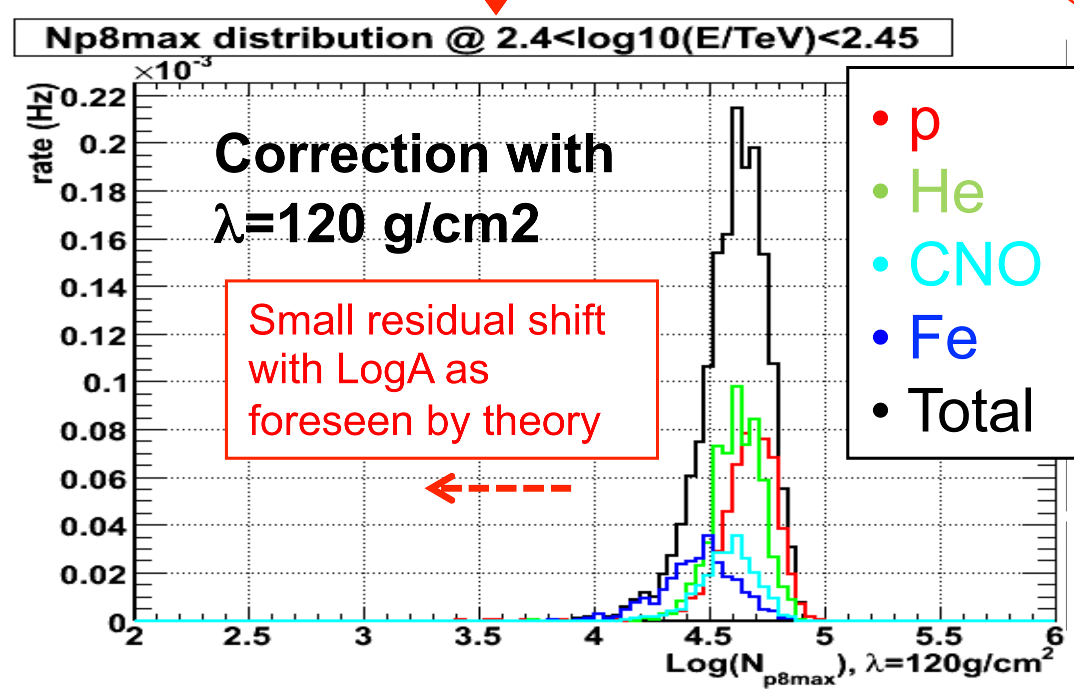
Astroparticle Physics 17 (2002) 151–165

According to numerous measurements from sea level to an altitude of about 4 km, $\Lambda_{att}$ lies between 120 g/cm² and 150 g/cm² for showers with moderate size [15,19]. Thus the exponent of the angular

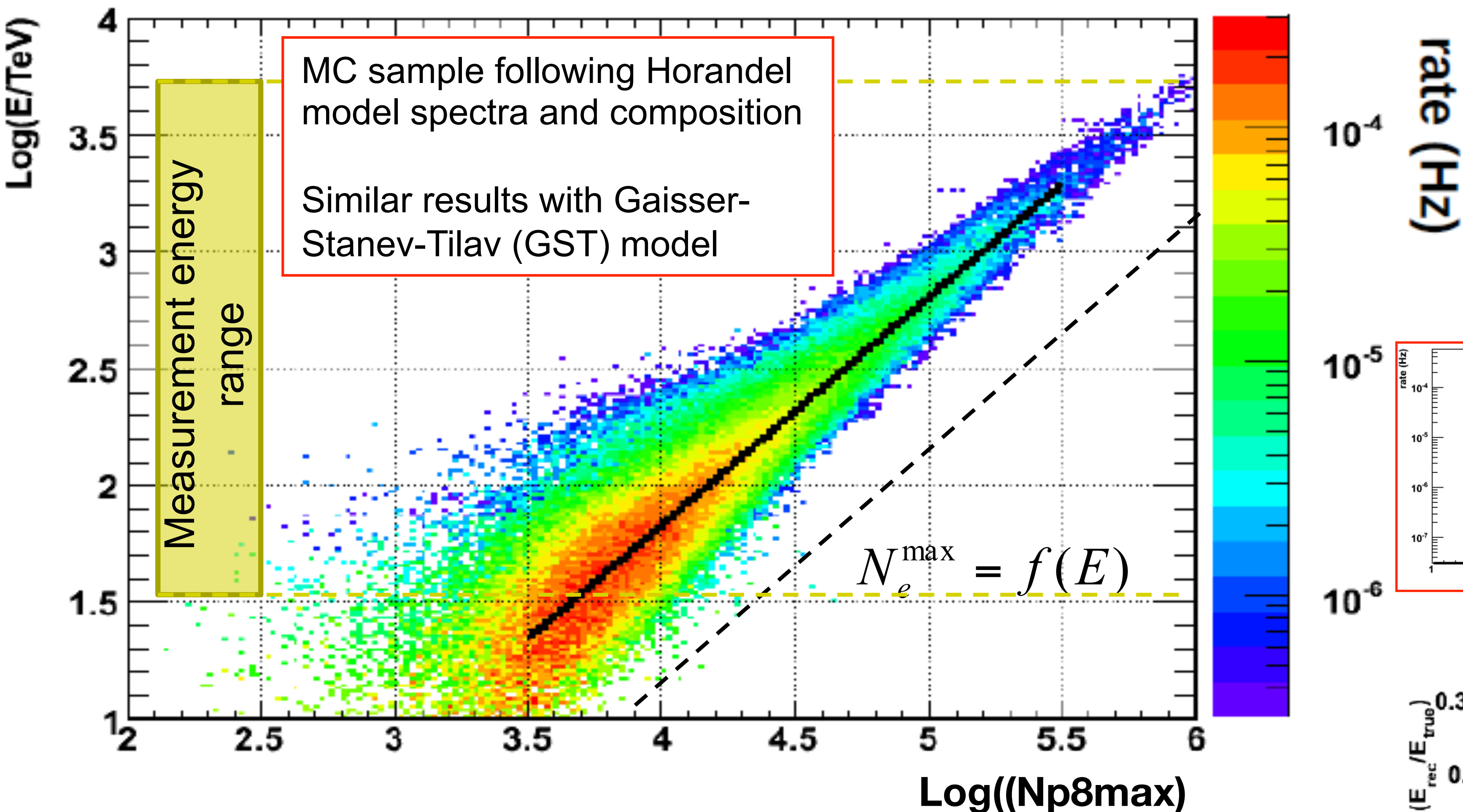
(sec $\theta - 1$)] law. The parameter $\alpha$ is found to be $4.88 \pm 0.45$, so that $\Lambda_{att} = (124 \pm 11)$ g/cm², in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is $4.11 \pm 0.37$. For angles greater than



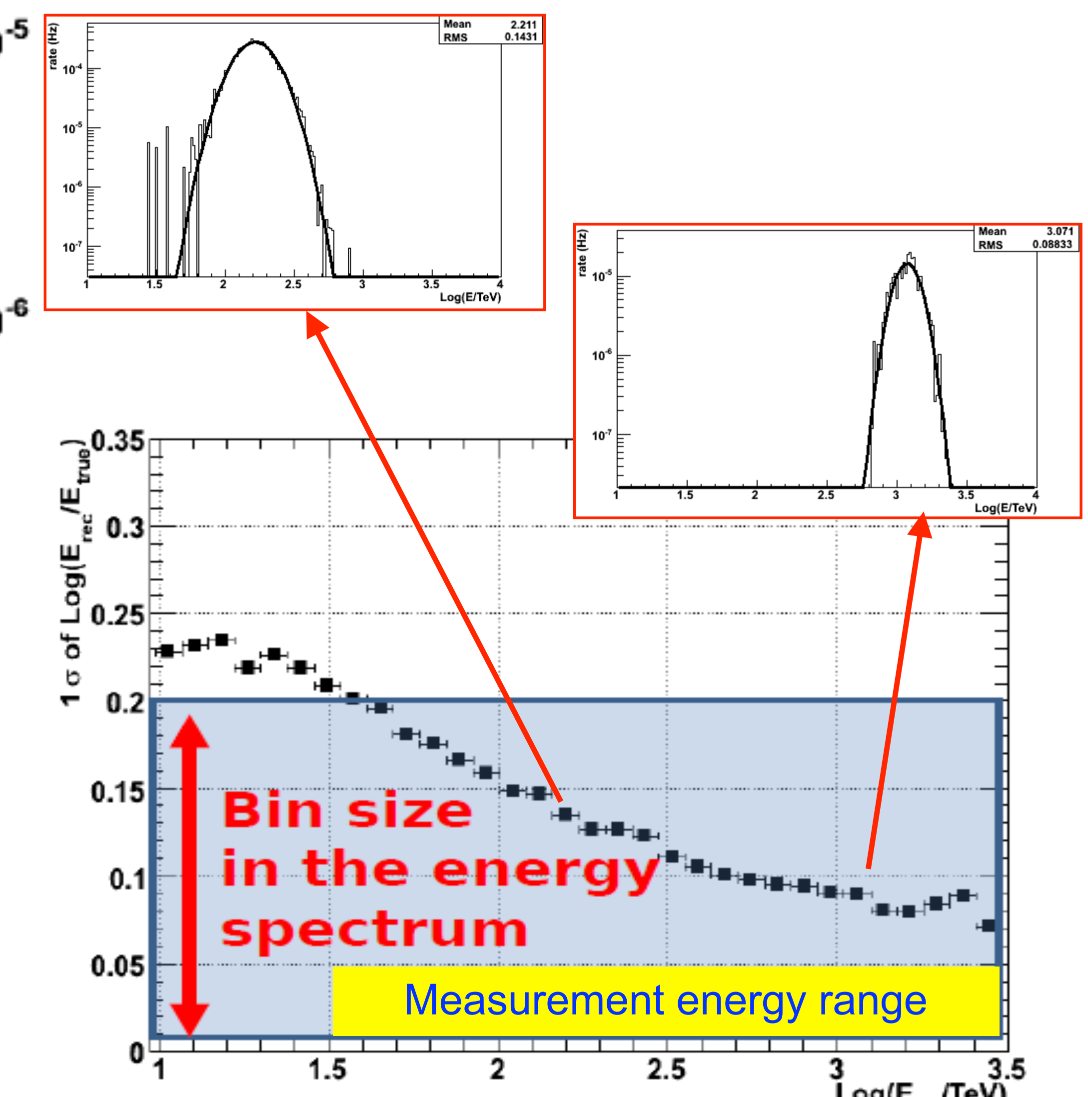

Further improvements in progress



# Mass independent energy reconstruction



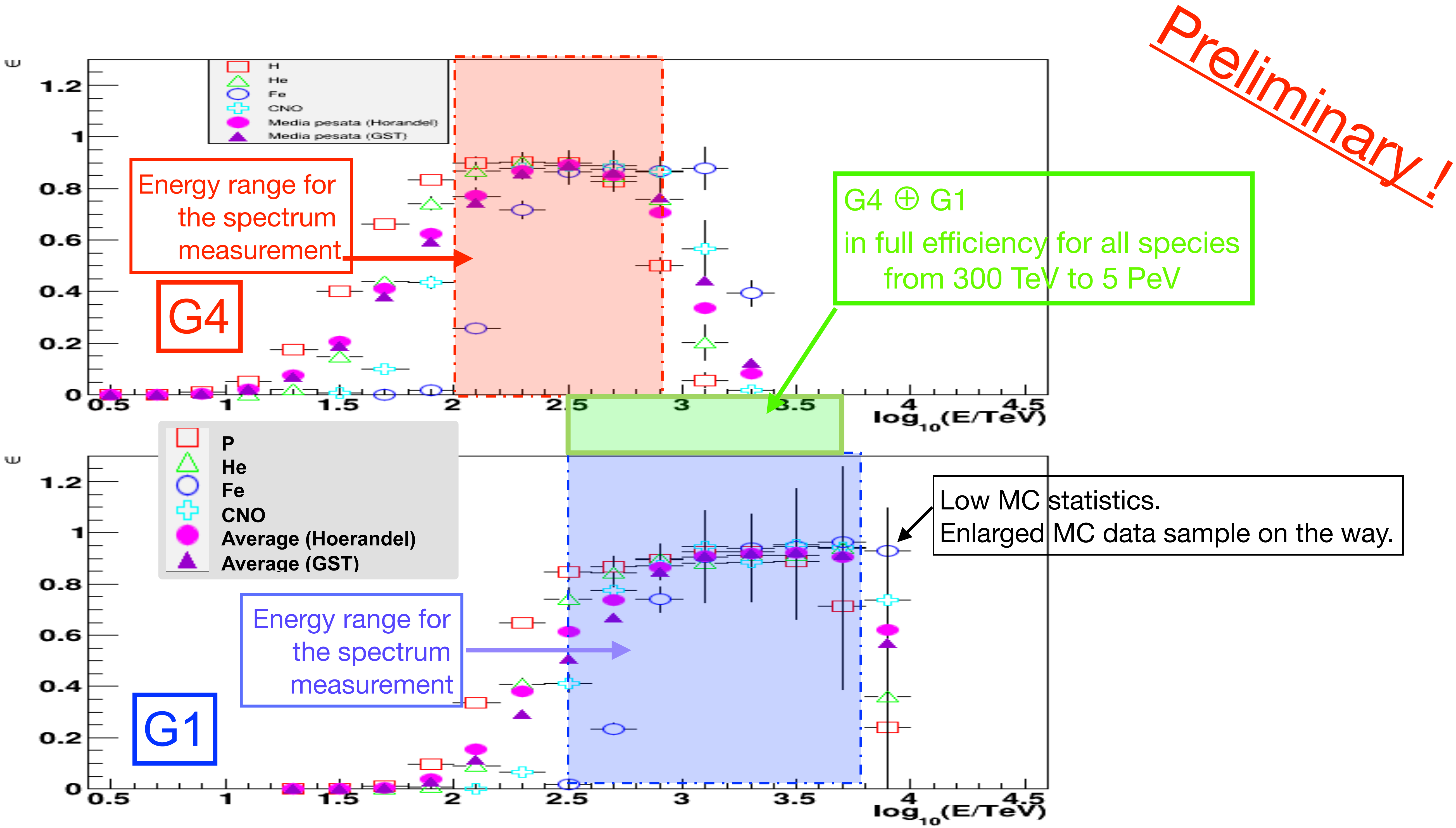

In excellent agreement with total-size vs E theoretical plot.
The shift is simply due to the fact that we are using the truncated size.




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 spectrum: trigger and selection efficiencies



# Systematic uncertainty evaluations

Preliminary !

## Flux:

Geometrical Aperture : (5 % in/out contamination)  (2.5% angular contamination) =5.6 %
Efficiency: (5% from MC samples)  (<10% efficiency estimation of the mixture) = 5.0-11.2 %
Unfolding: 3%
Hadronic interaction model < 5%
**TOTAL: 8.1% - 13.8 %**
**TOTAL: (conservative) = 14%**

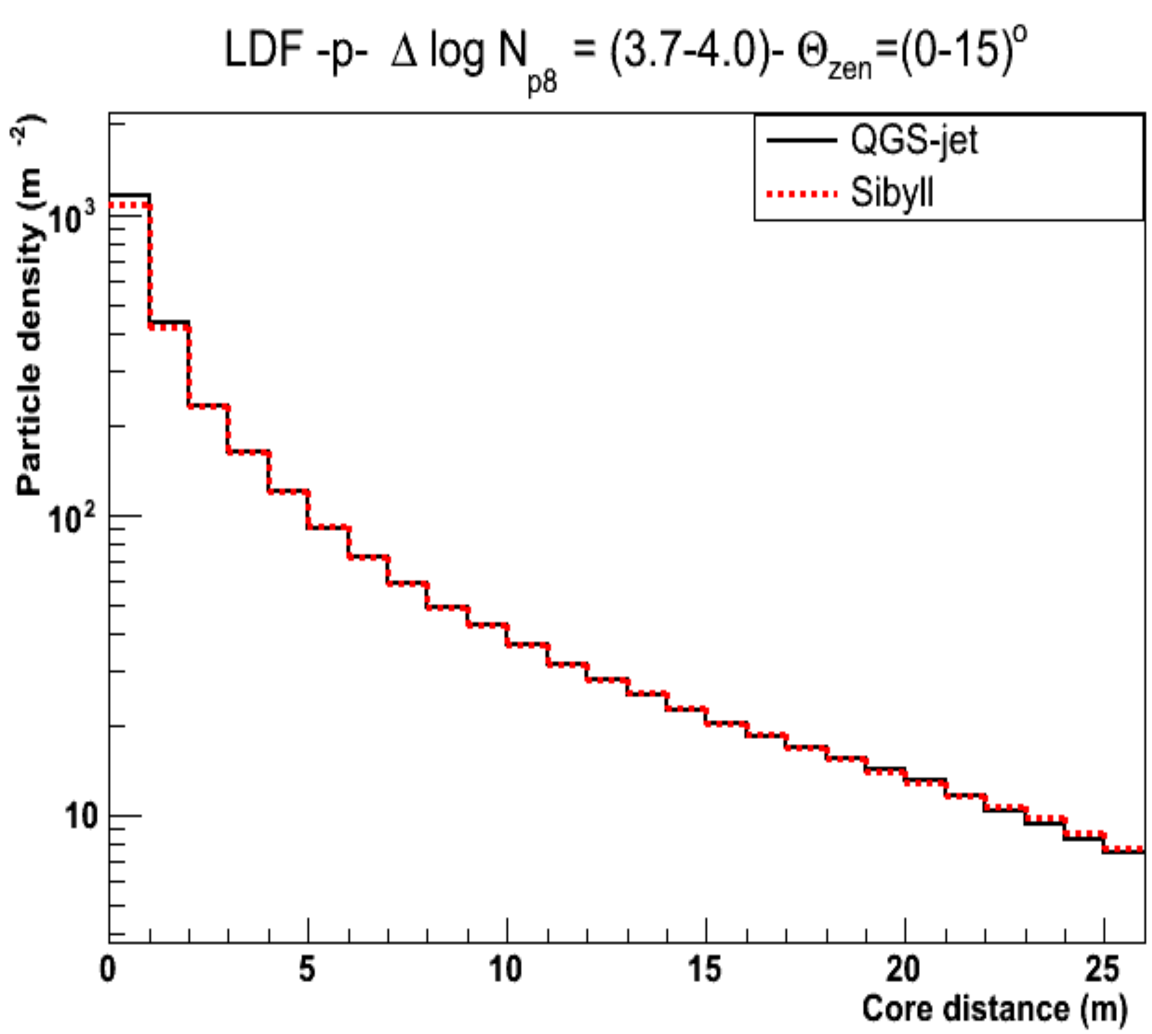
## Energy scale:

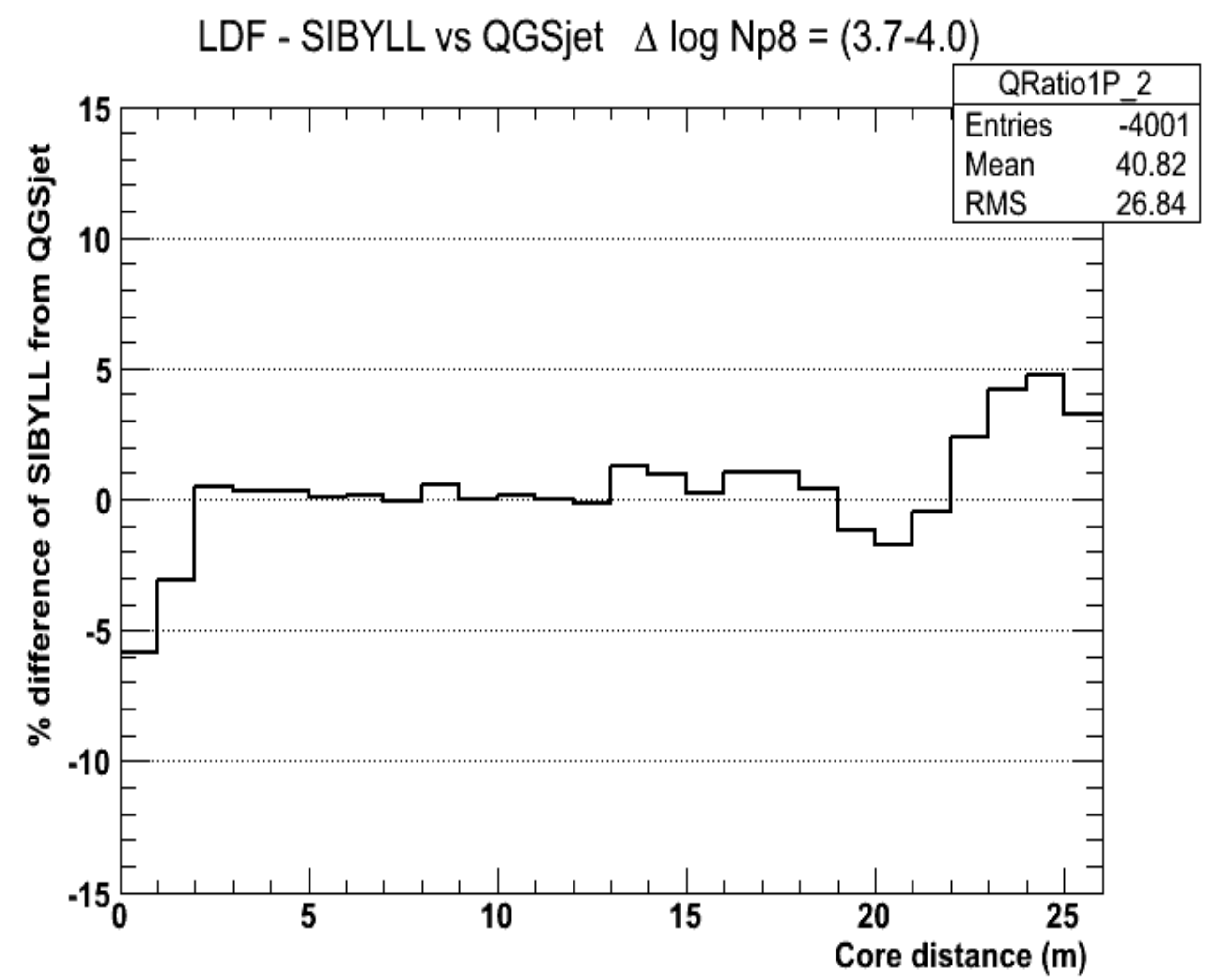
Gain of the analog system: 3.7 %
Energy calibration: 0.03 in LogE = 6.9%
Hadronic interaction model: 5%
**TOTAL: 9.3 %**
**TOTAL: (conservative) =  10%**

In the following plots an over-conservative ±14% shaded area has been temporarily drawn on the flux measurements.
Error bars show the statistical uncertainties.

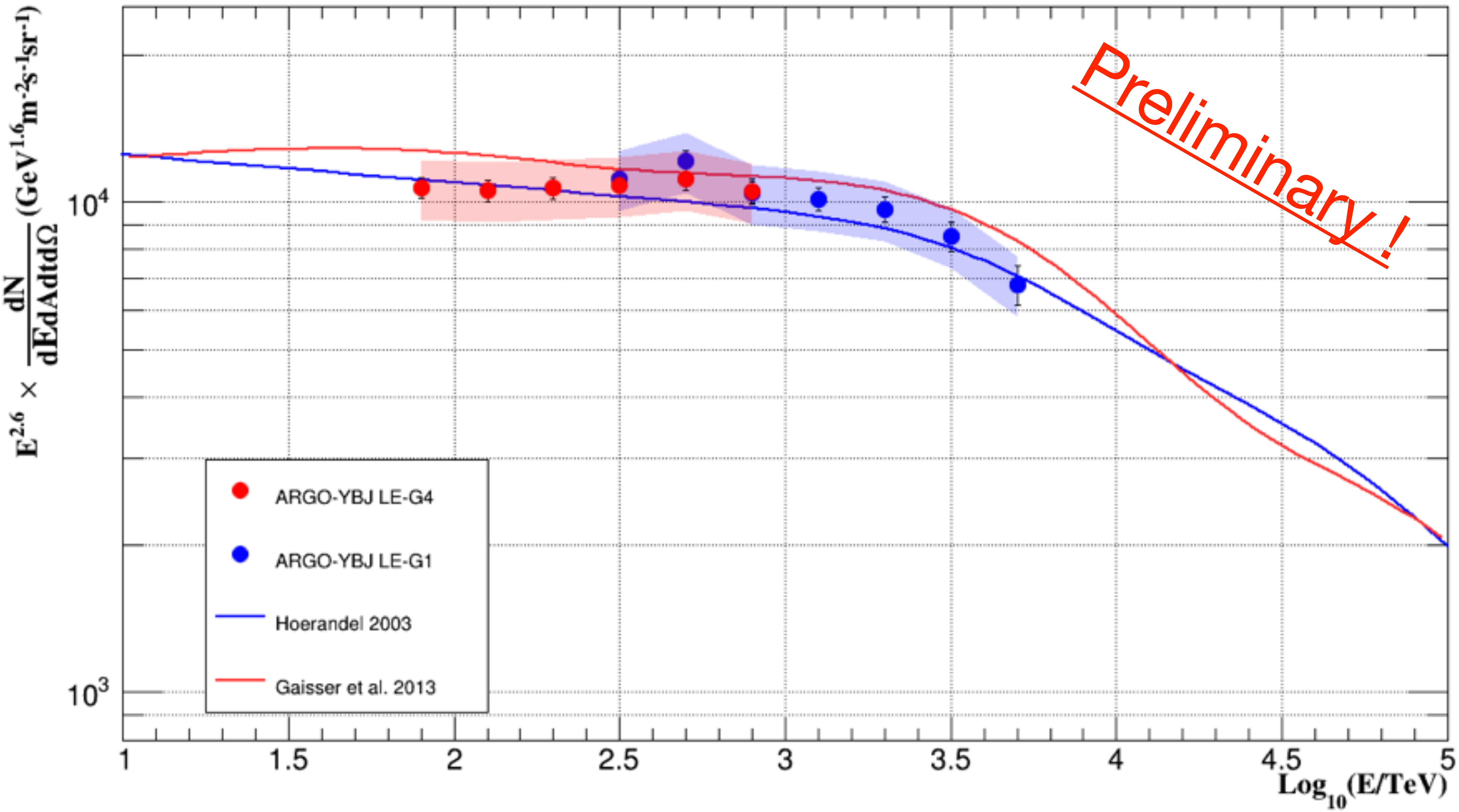
# Systematics from hadronic interaction models

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.



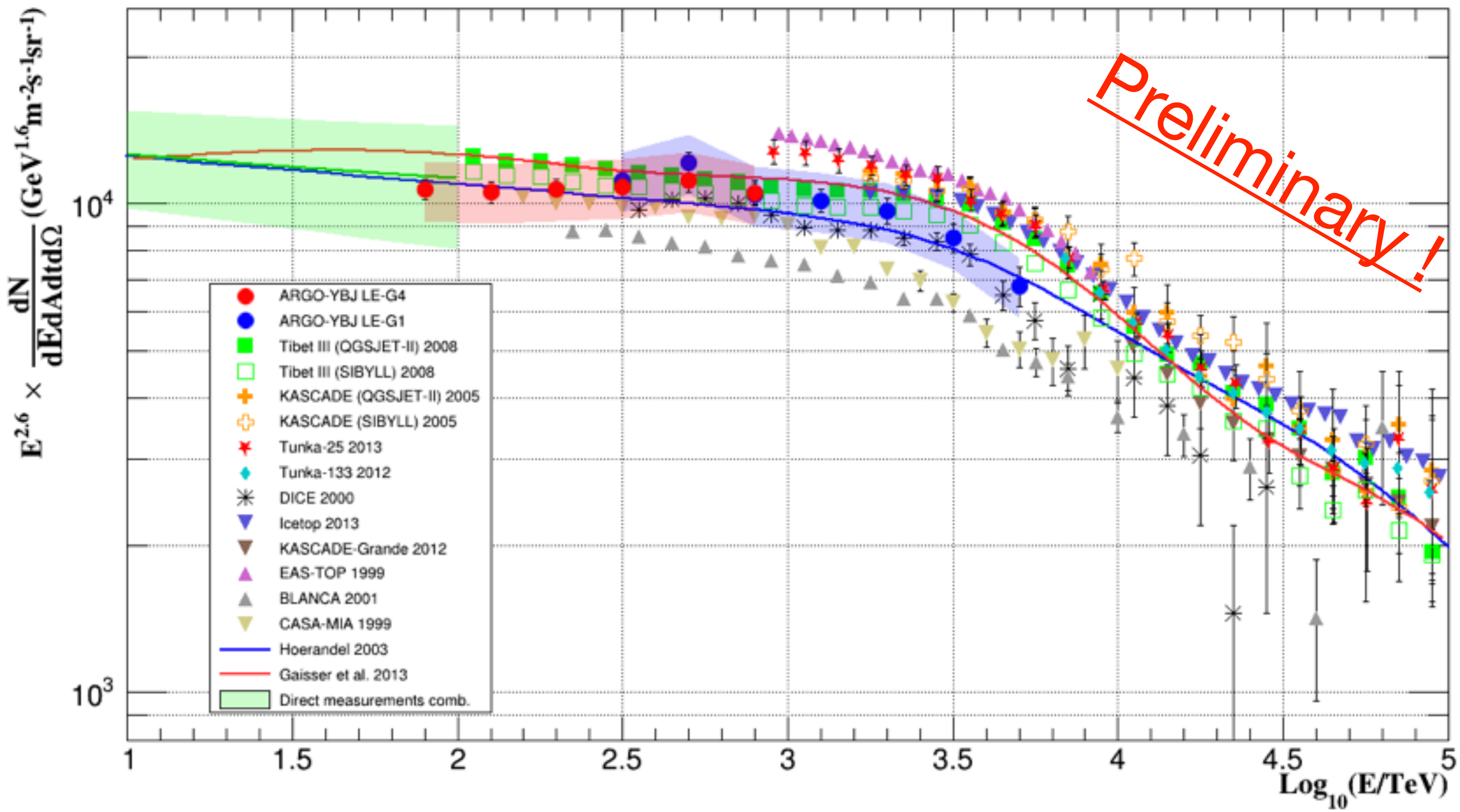



# The "all-particle" spectrum by ARGO-YBJ



# The “all-particle” spectrum by ARGO-YBJ

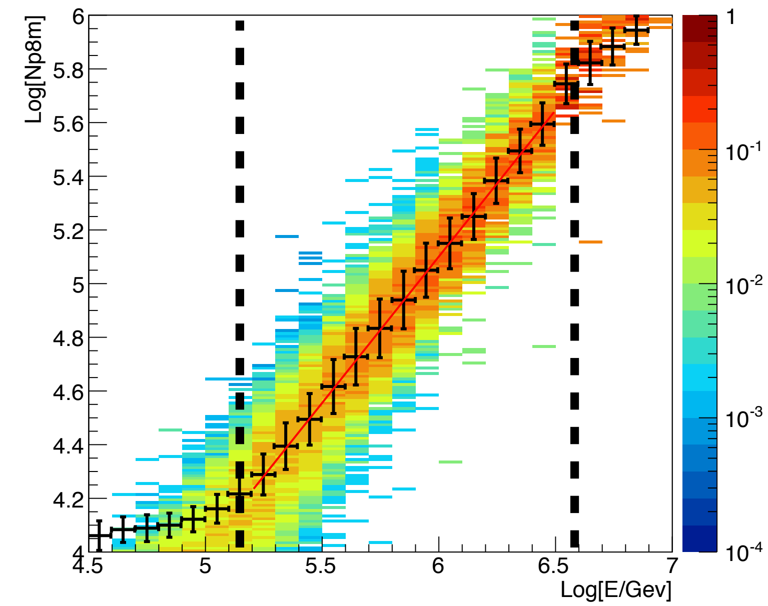
- Consistent picture with models and previous measurements
- Overlap with the two gain scales (different data,…)
- Suggest spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV



# The light component spectrum by ARGO-YBJ (1)

The Bayesian unfolding method used for the analysis of data below 200 TeV is adapted to the ARGO-YBJ analog data.

- NPmax > 500
- $10^4 < Np8 < 10^6$
- Theta ≤ 35°
- Reconstructed shower core position in a fiducial area 40 X 40 $m^2$ centered on the central carpet

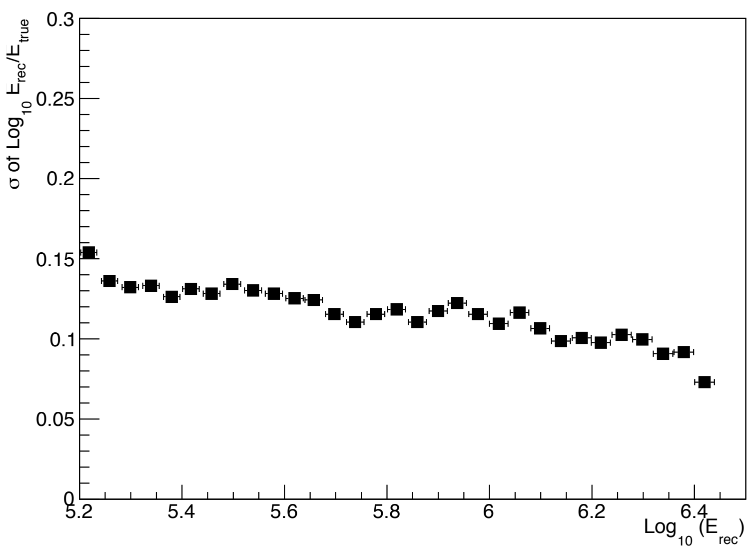



Selection of the light component: shower topology

Light Component (p+He) selection:

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

A20 = 20 innermost clusters
A42 = 42 outermost clusters

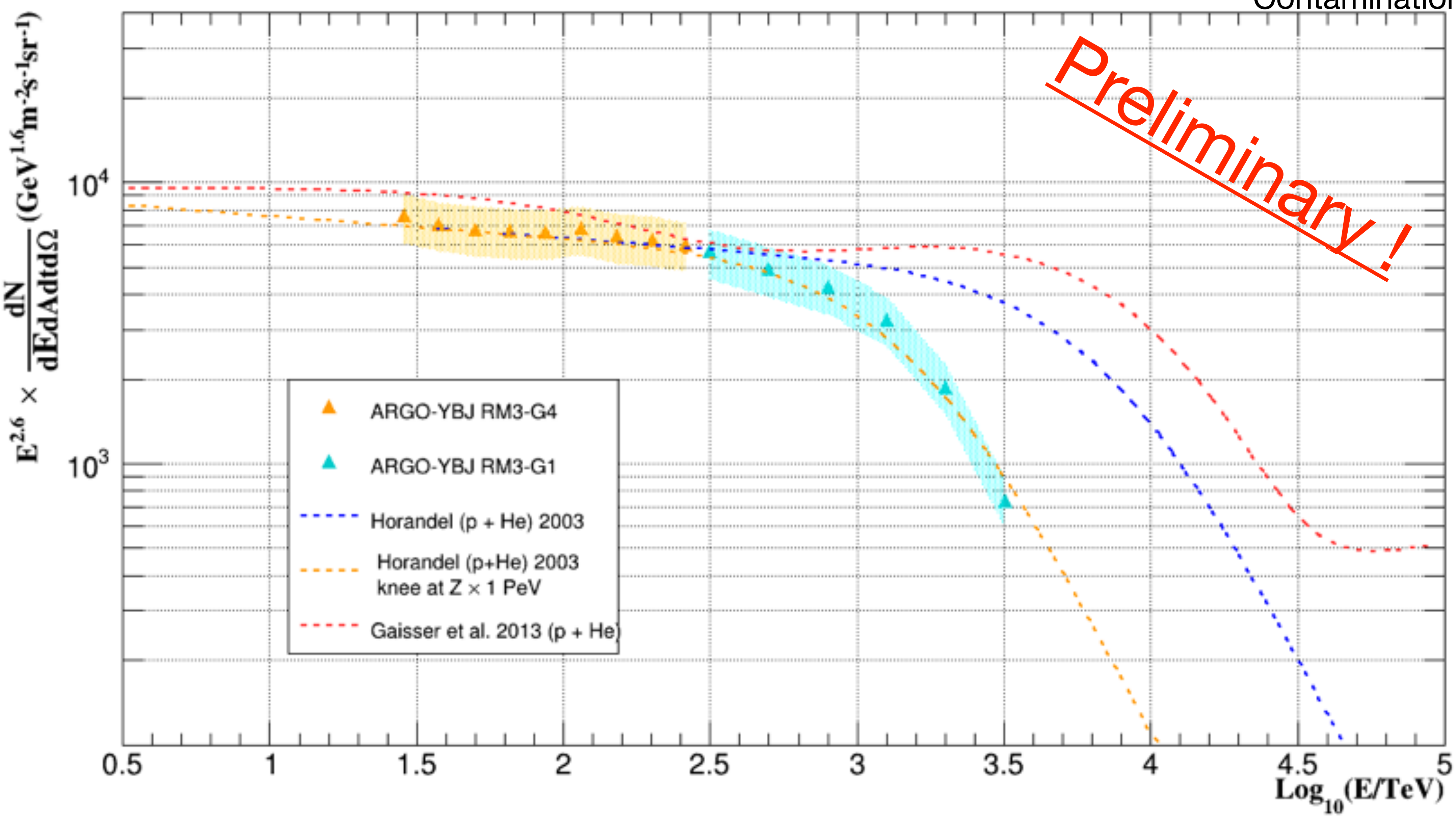


# The light component spectrum by ARGO-YBJ (1)

The Bayesian unfolding method used for the analysis of data below 200 TeV is adapted to the ARGO-YBJ analog data.

Observation of gradual change of the slope starting around 650 TeV

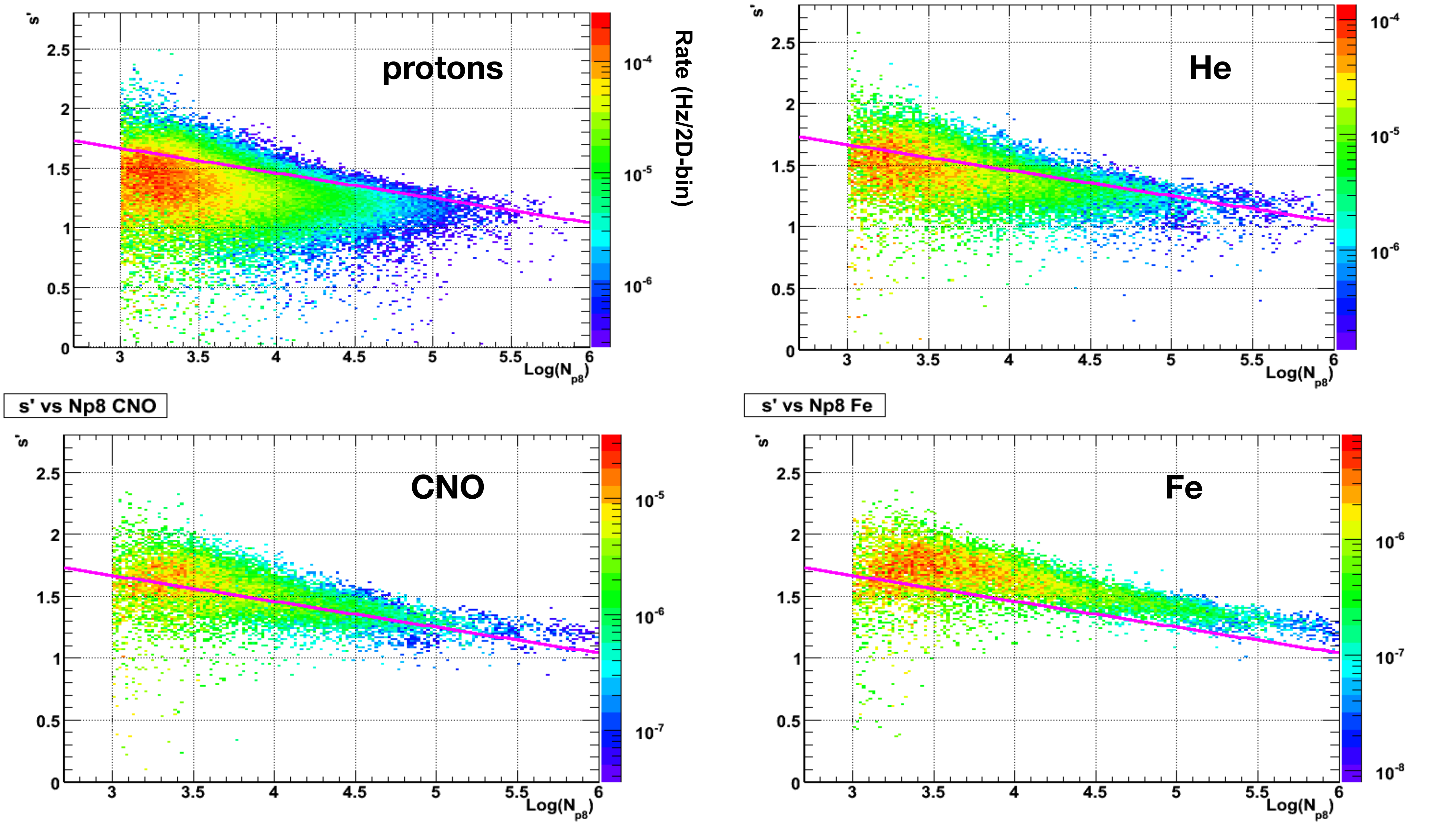
Contamination ≥ CNO: ≈ 15%



# p and He selection

A simple cut in the plane s’ vs Np8

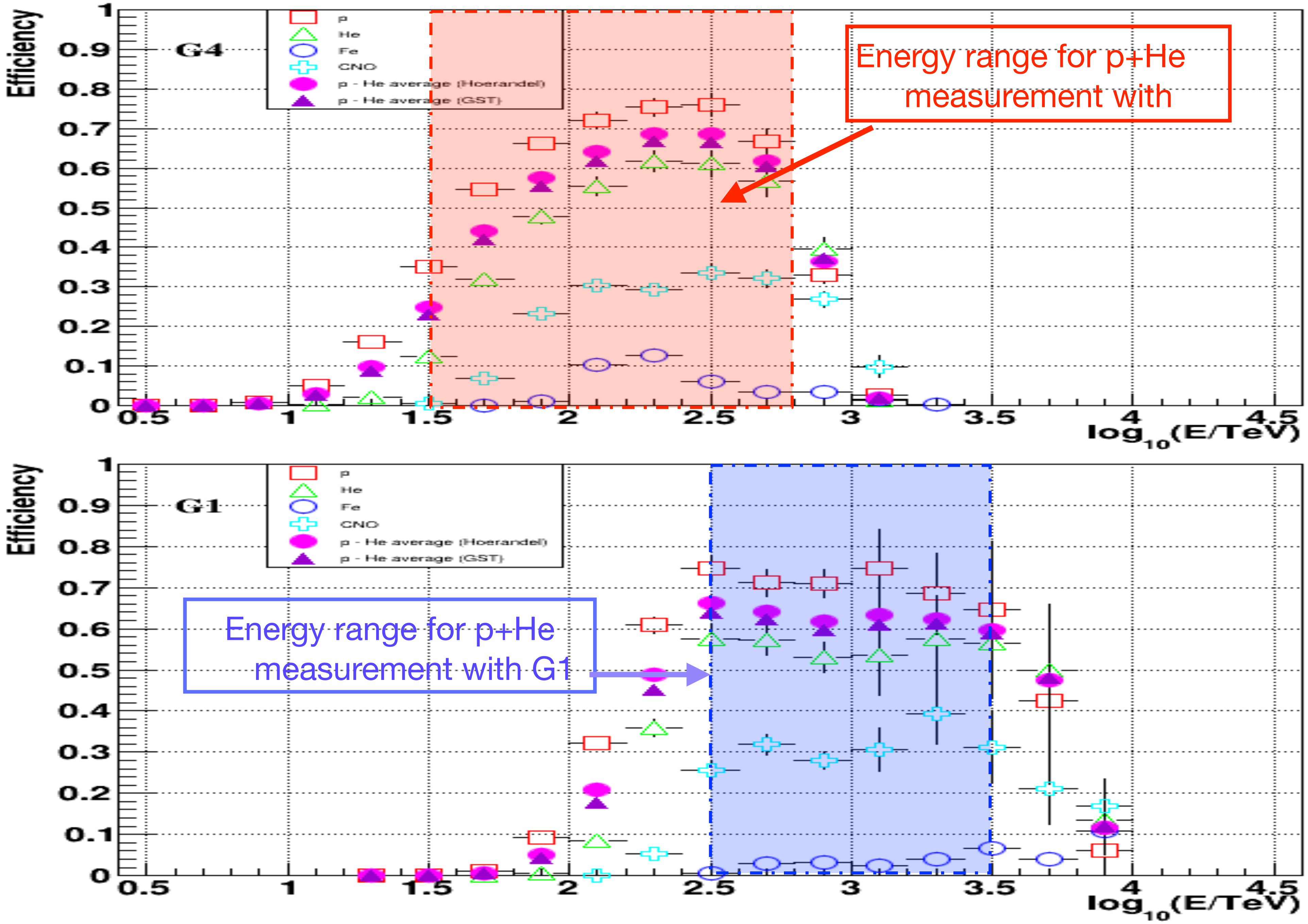
Contamination ≥ CNO: ≈ 15%




MC Horandel spectra and normalizations

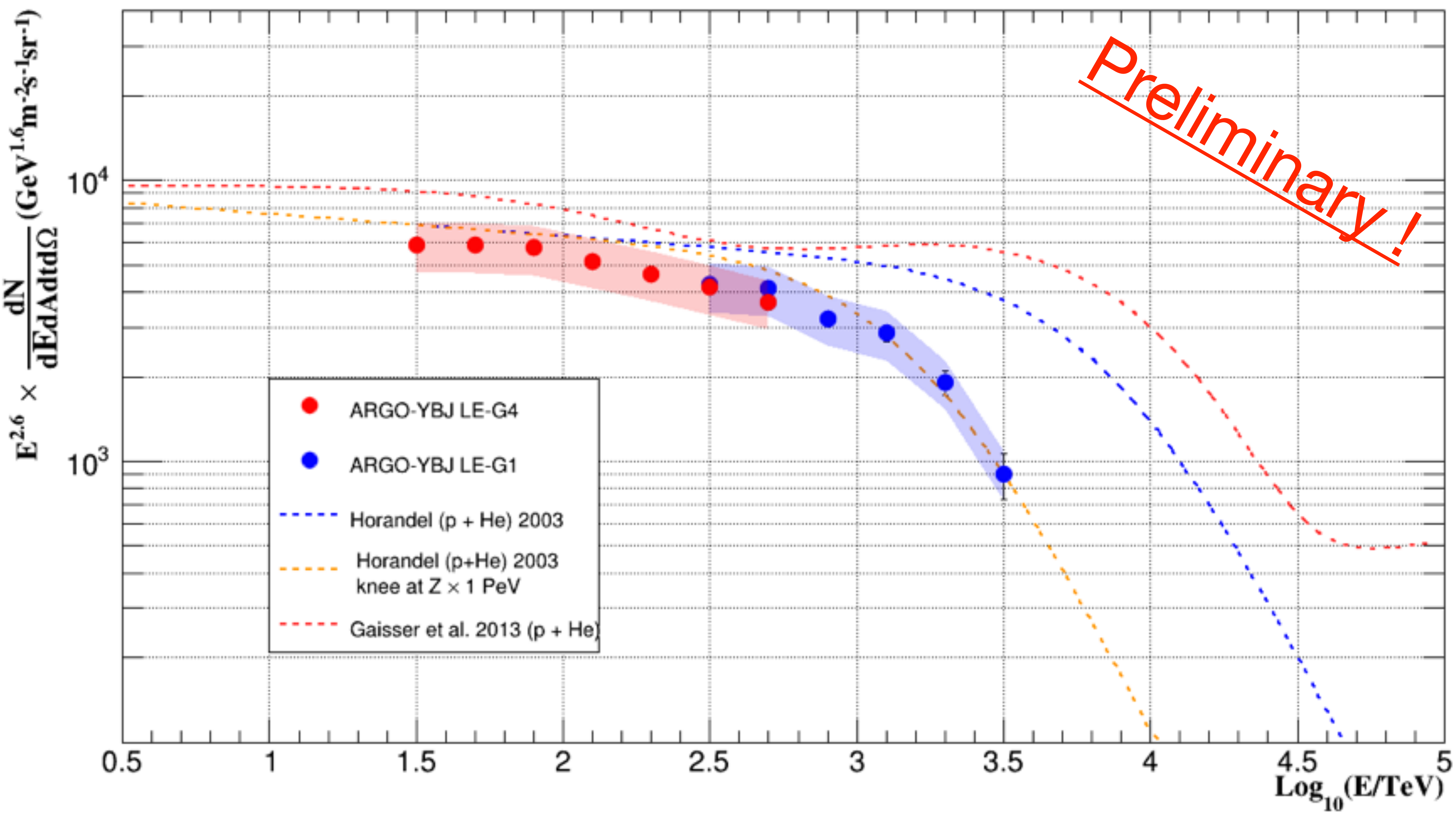
# p+He: trigger and selection efficiencies

**On the efficiency plateau above 200 TeV**



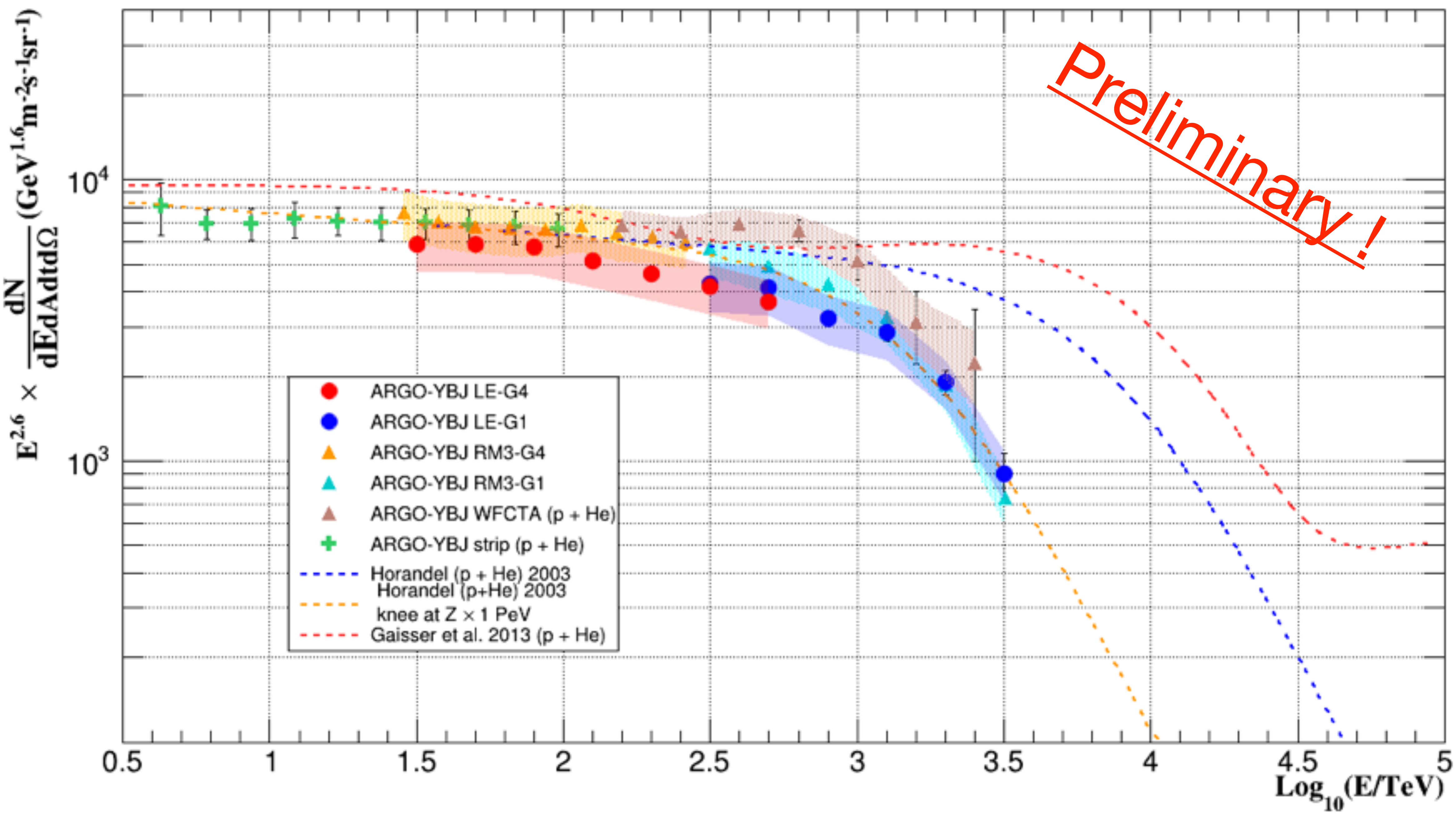
# The light component spectrum by ARGO-YBJ (2)

Observation of gradual change of the slope starting around 650 TeV



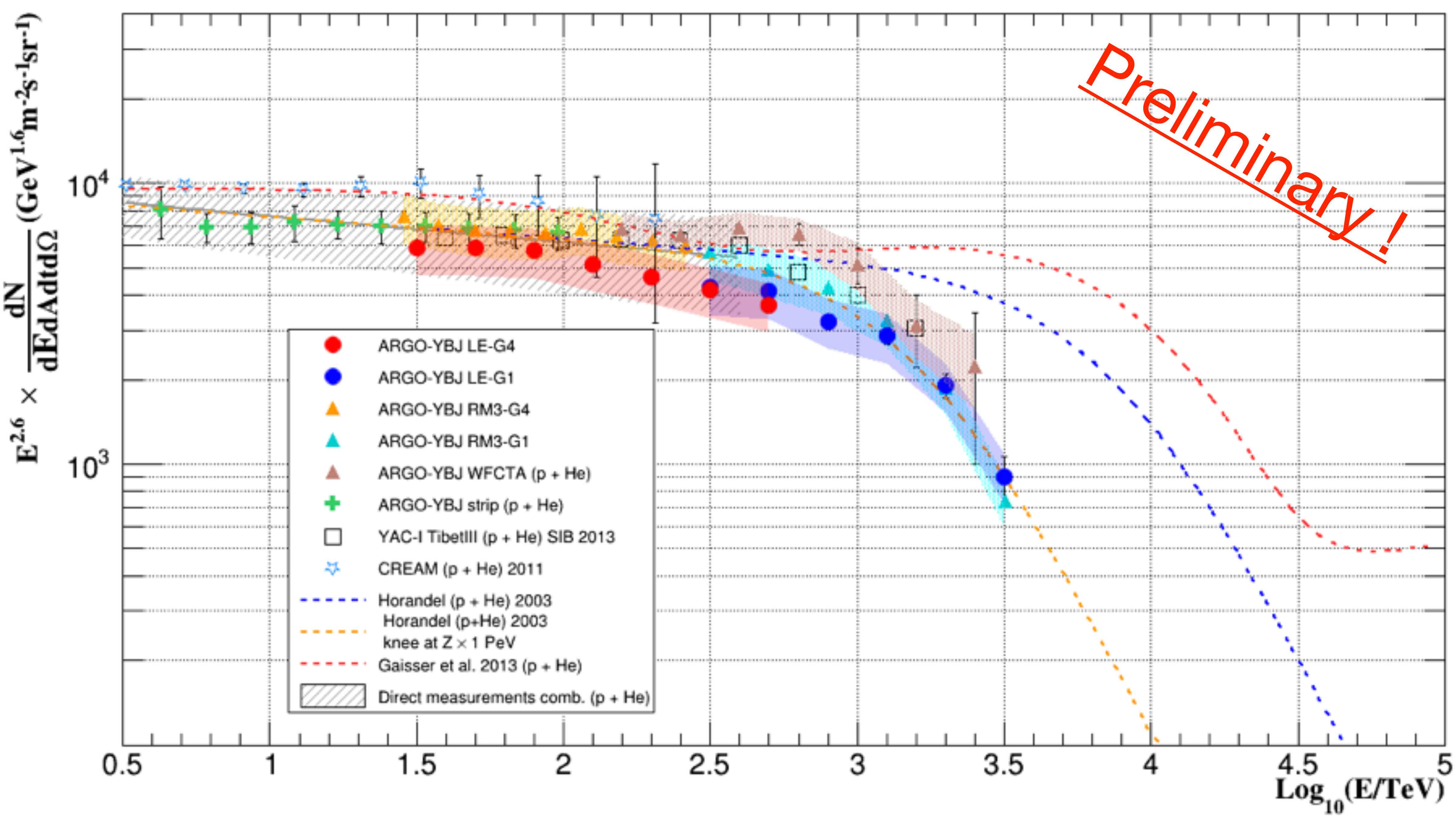
# Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Good overposition with the digital readout < 300 TeV
Observation of gradual change of the slope starting around 650 TeV



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

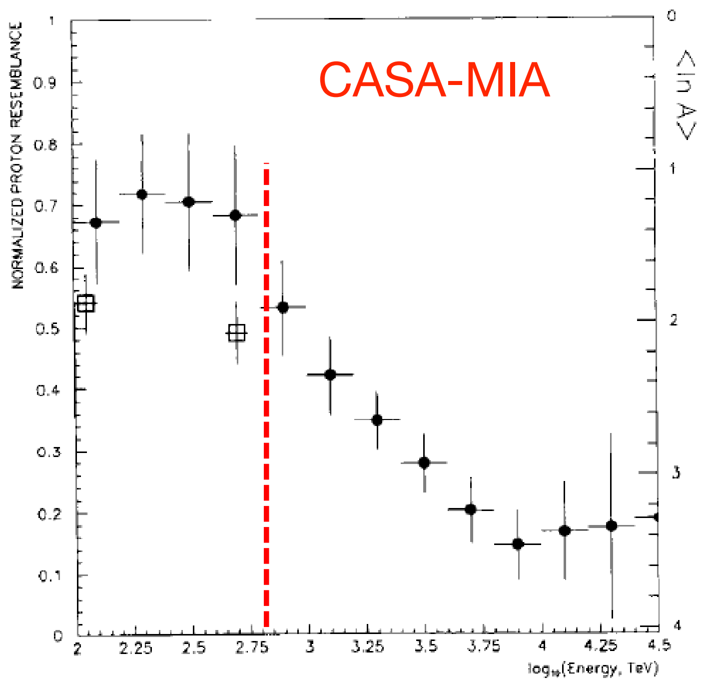
Comparison with direct measurements and with Tibet ASgamma (SYBILL)

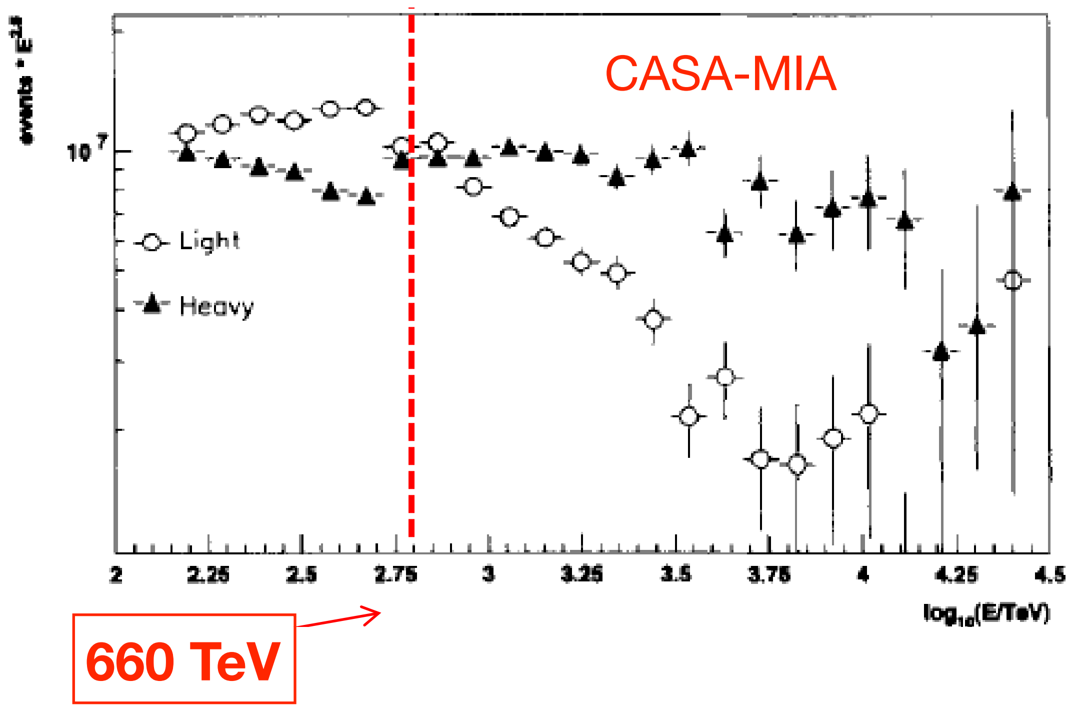


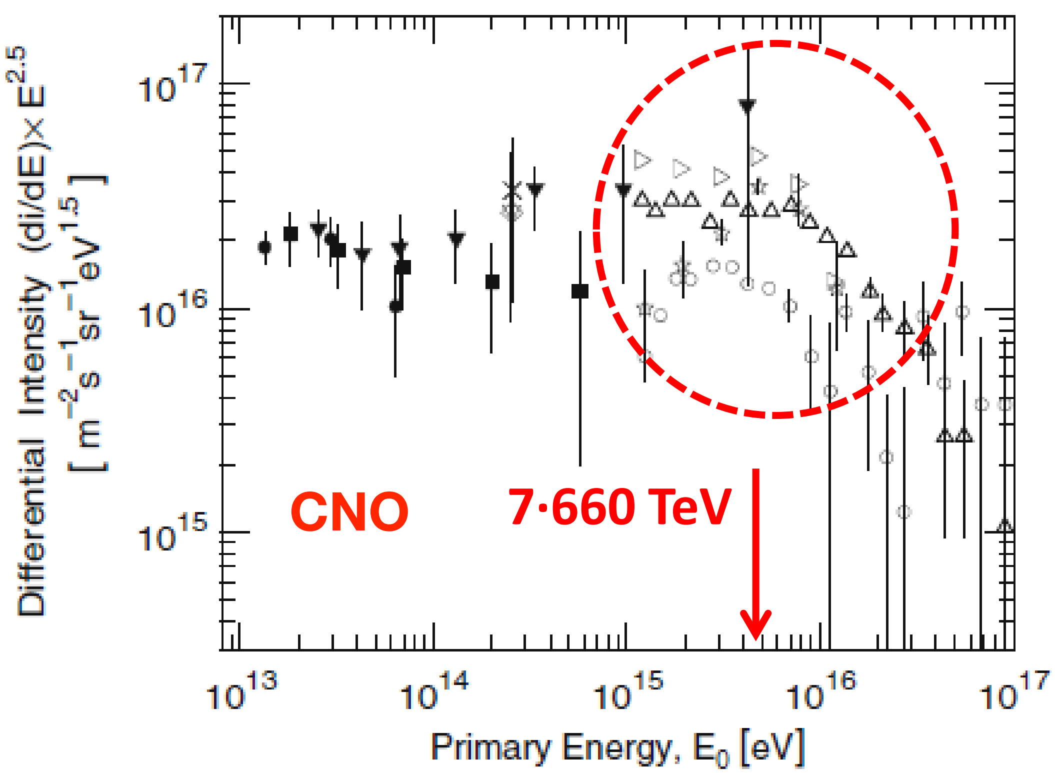
# Other results

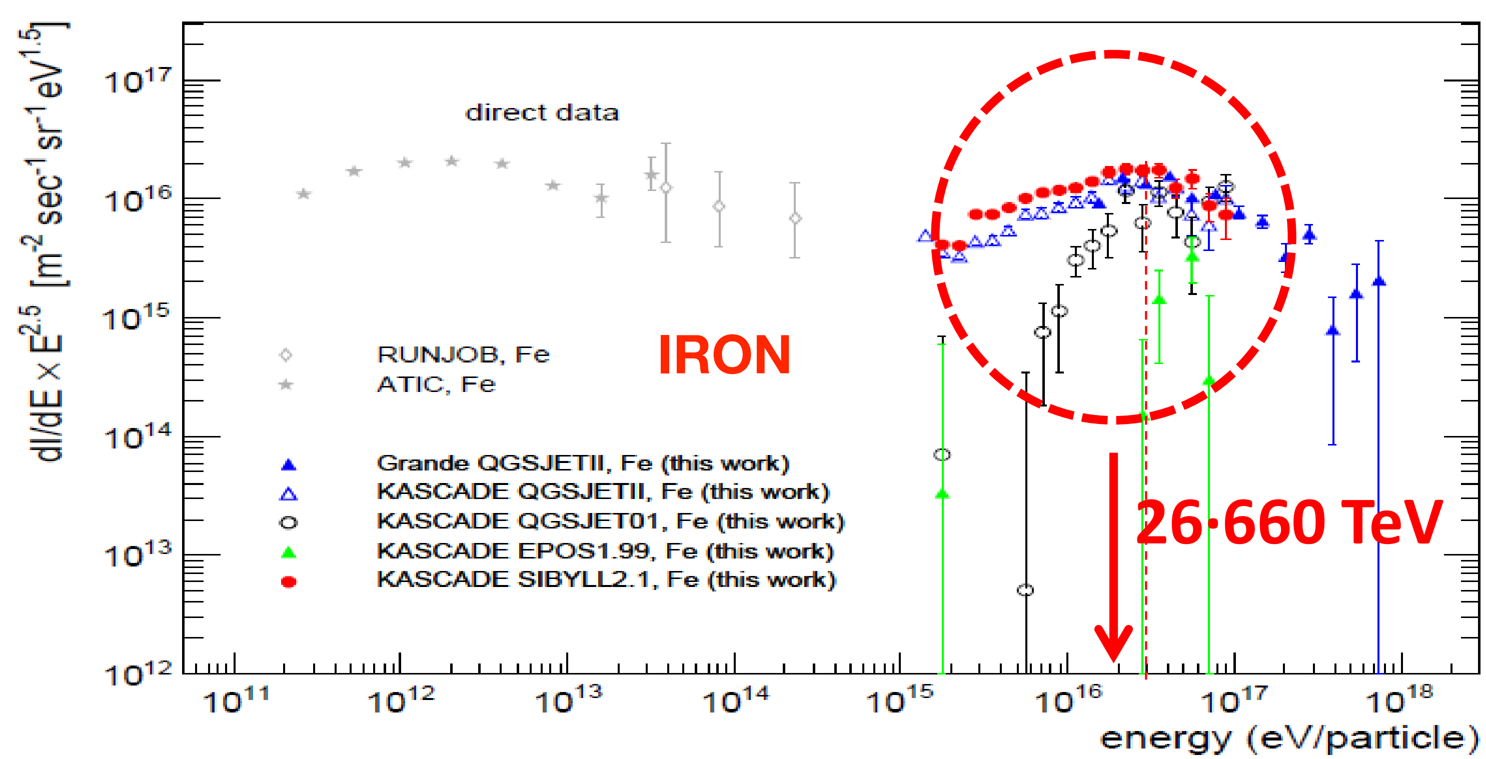
The cosmic ray composition between $10^{14}$ and $10^{16}$ eV

M.A.K. Glasmacher [a], M.A. Catanese [a,1], M.C. Chantell [b], C.E. Covault [b], J.W. Cronin [b], B.E. Fick [b], L.F. Fortson [b,2], J.W. Fowler [b], K.D Green [b,3], D.B. Kieda [c], J. Matthews [a,4], B.J. Newport [b,5], D.F. Nitz [a,6], R.A. Ong [b], S. Oser [b], D. Sinclair [a], J.C. van der Velde [a]

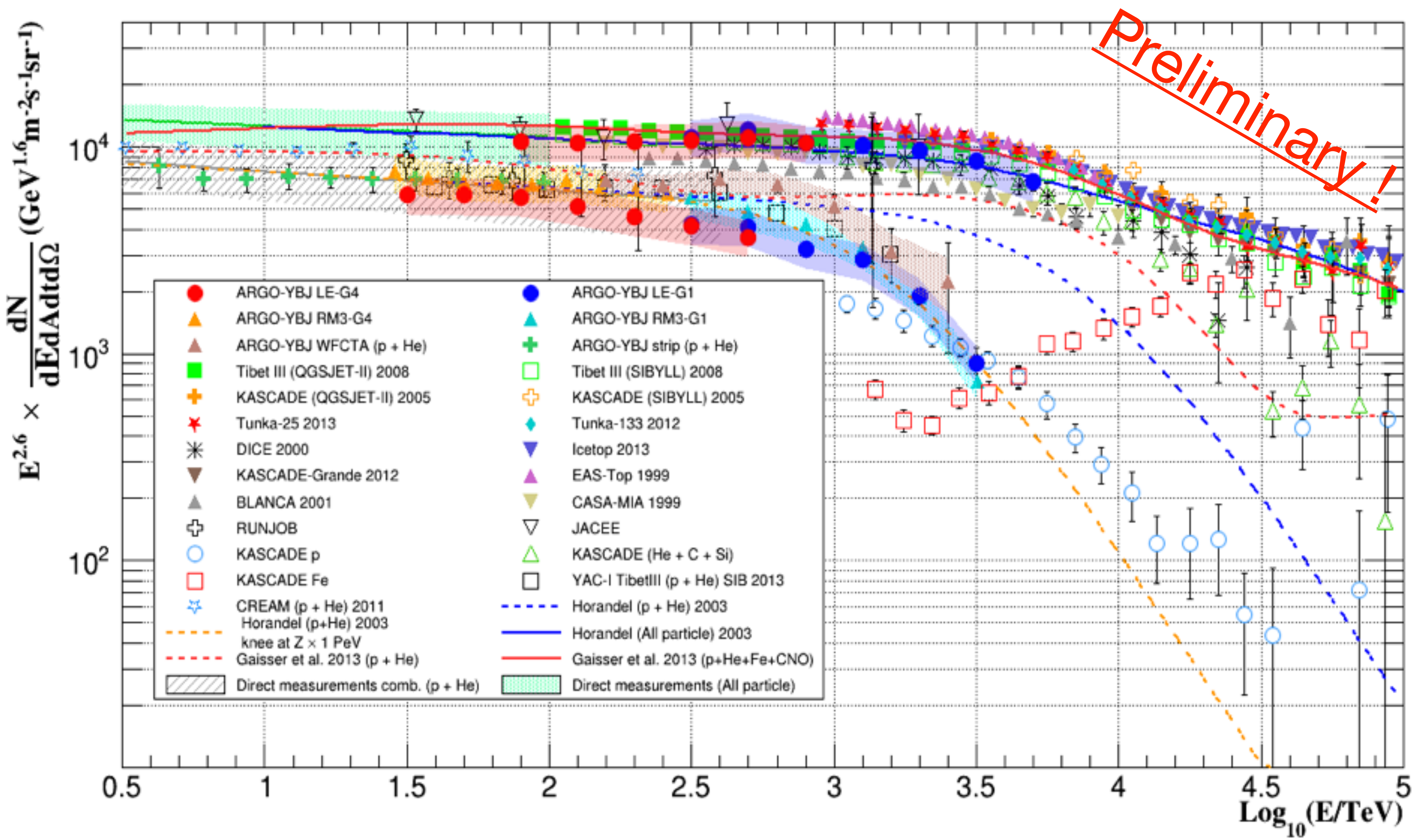


# The overall picture



# 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.
- Observed TeV gamma-ray emission from 6 sources above 5 s.d.
- Detailed study of flaring and extedend TeV gamma-ray sources

- Measurement of CR energy spectrum (all-particle and light component) up to 5 PeV
- Study of EAS phenomenology up to PeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Measurement of the p-air and p-p cross sections up to 100 TeV

- Detailed study of the Sun shadow in correlation with the solar activity

# Backup slides

# ARGO-YBJ + WFCTA: p+He