Istituto Nazionale di Fisica Nucleare

Measurement of the Cosmic Ray Energy Spectrum with ARGO-YBJ

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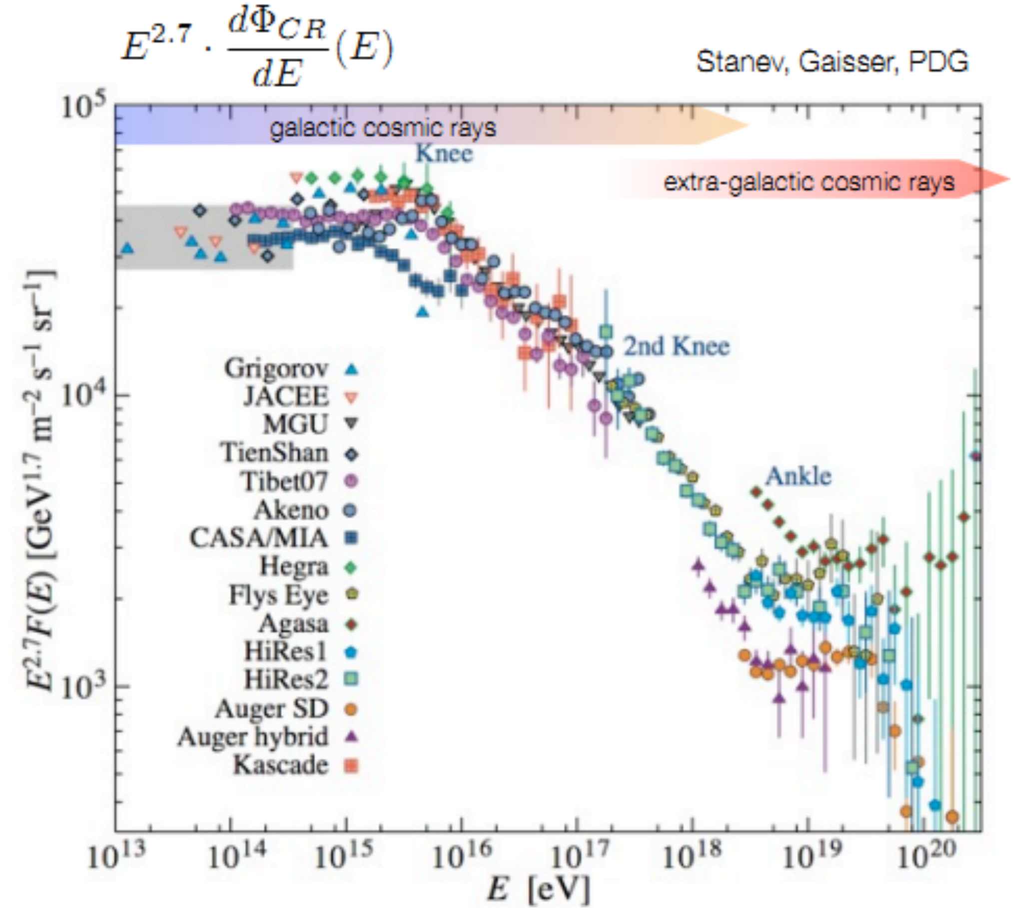
Vulcano Workshop 2014 - *Frontier Objects in Astrophysics and Particle Physics*
Vulcano, 18th - 24th, May 2014

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

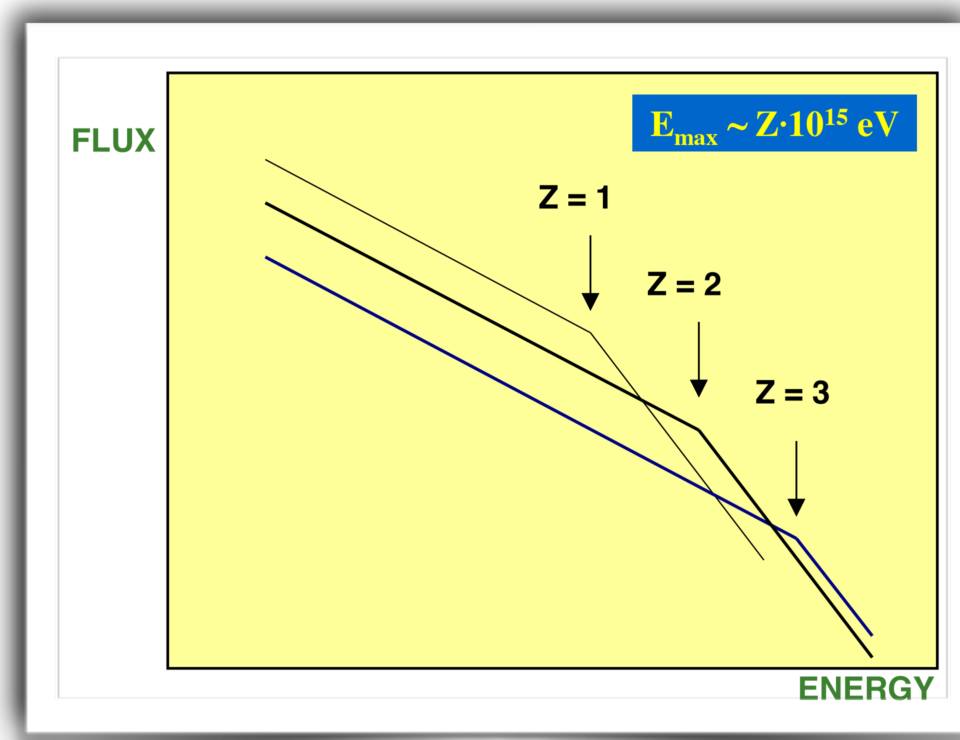
Approaching the knee

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

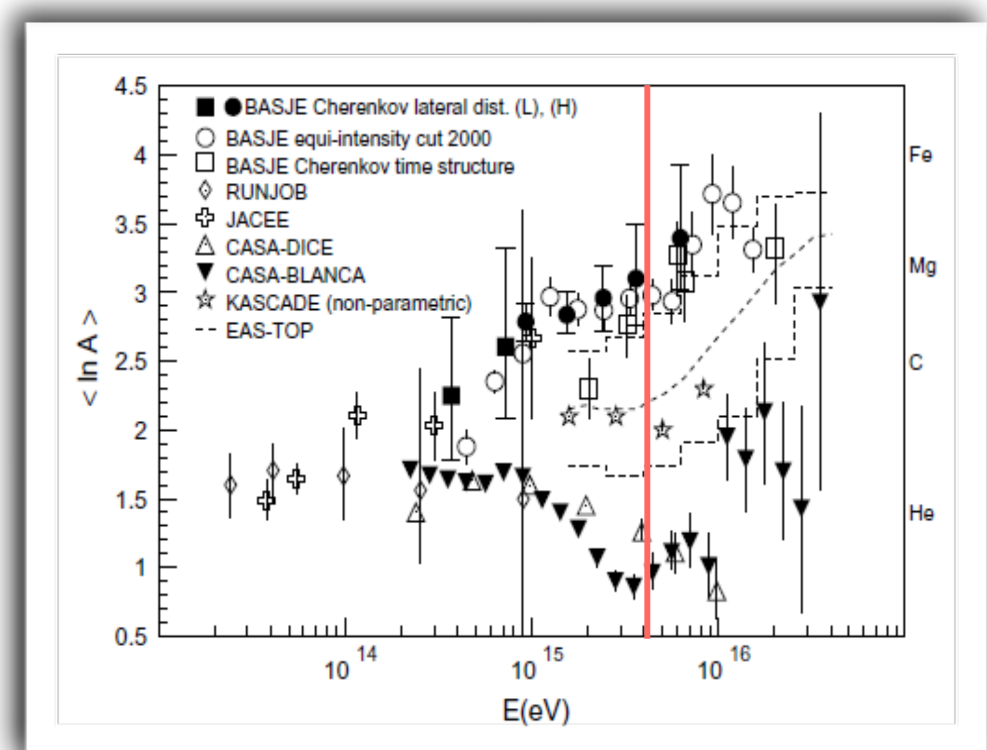
The standard model:

- 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}(iron) = 26 · E_{max}(proton)

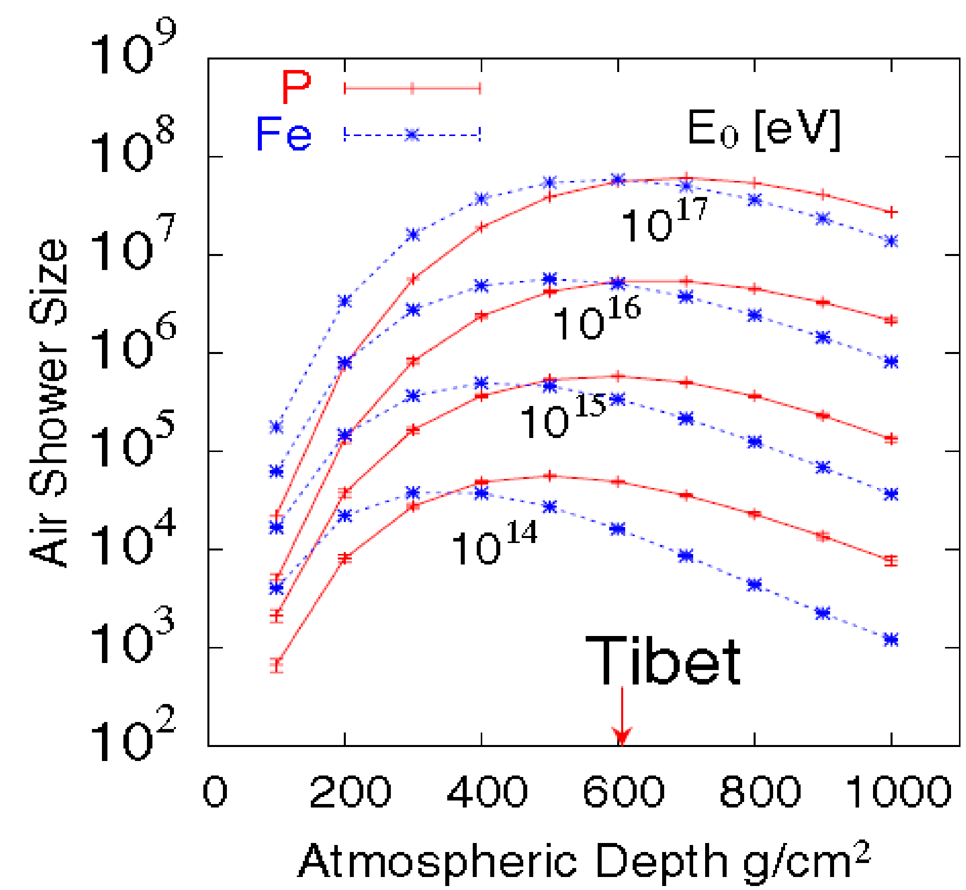


Outline

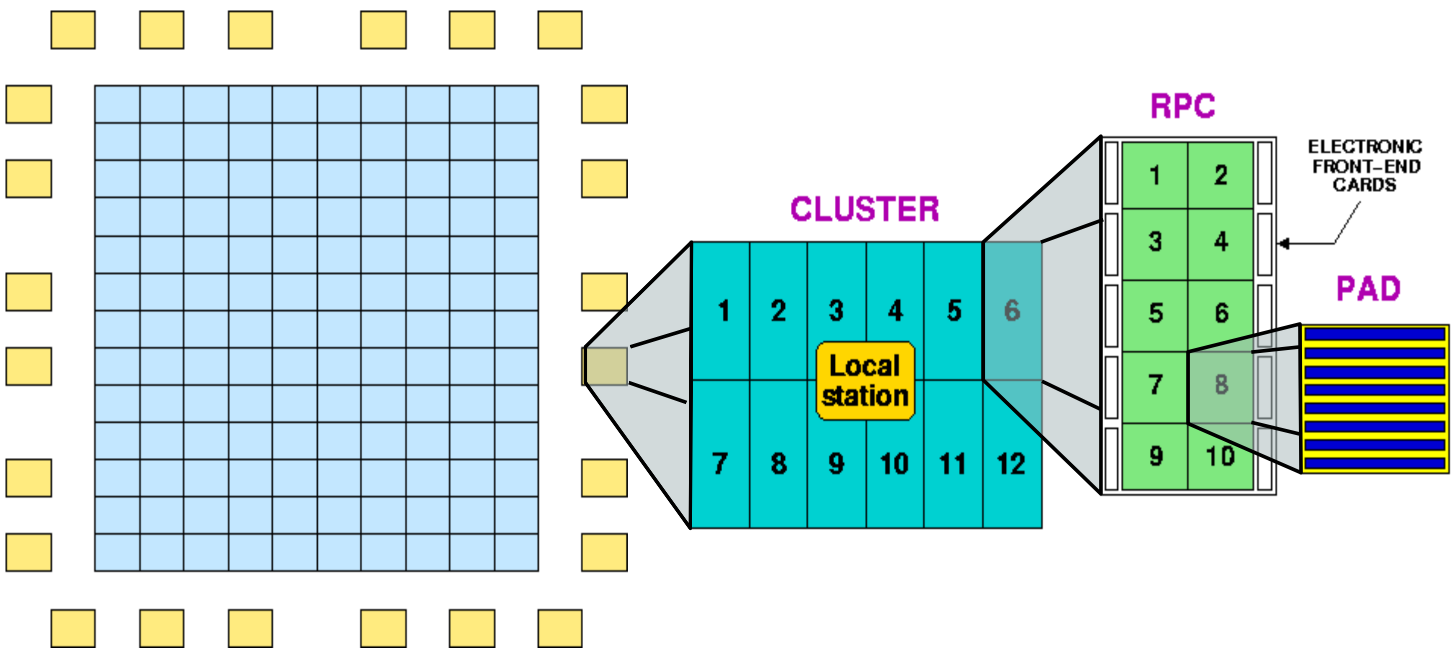
- Measurement of the CR energy spectrum (all-particle and light component) in the energy range few TeV - 5 PeV by ARGO-YBJ with *different 'eyes'*
  - 'Digital readout' (based on *strip multiplicity*) below 200 TeV
  - 'Analog readout' (based on the *shower core density*) up to 10 PeV
  - Hybrid measurement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



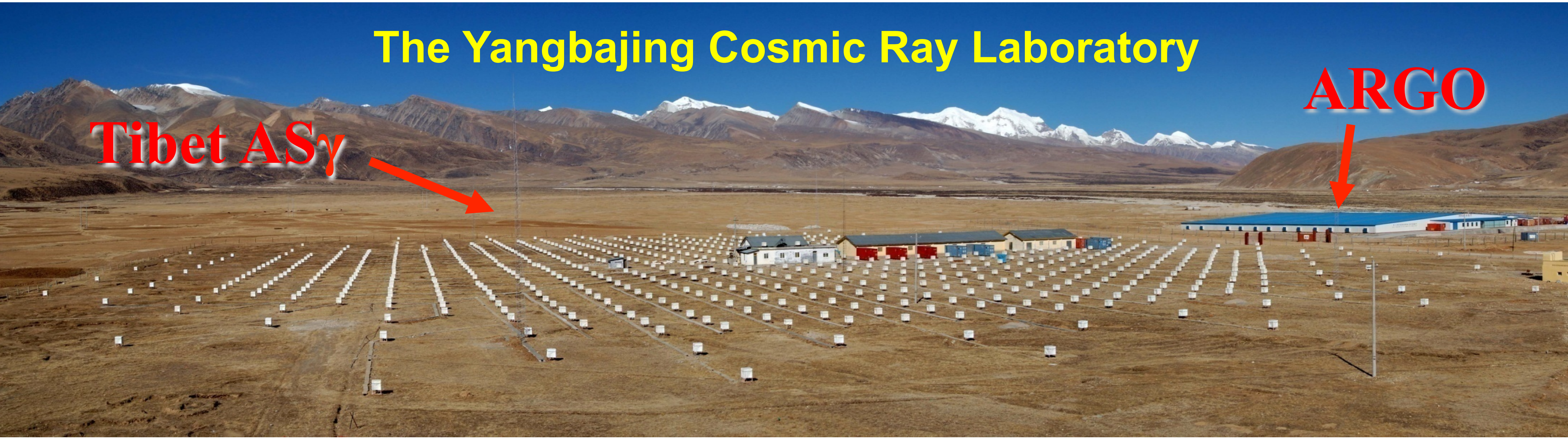
The ARGO-YBJ experiment



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)

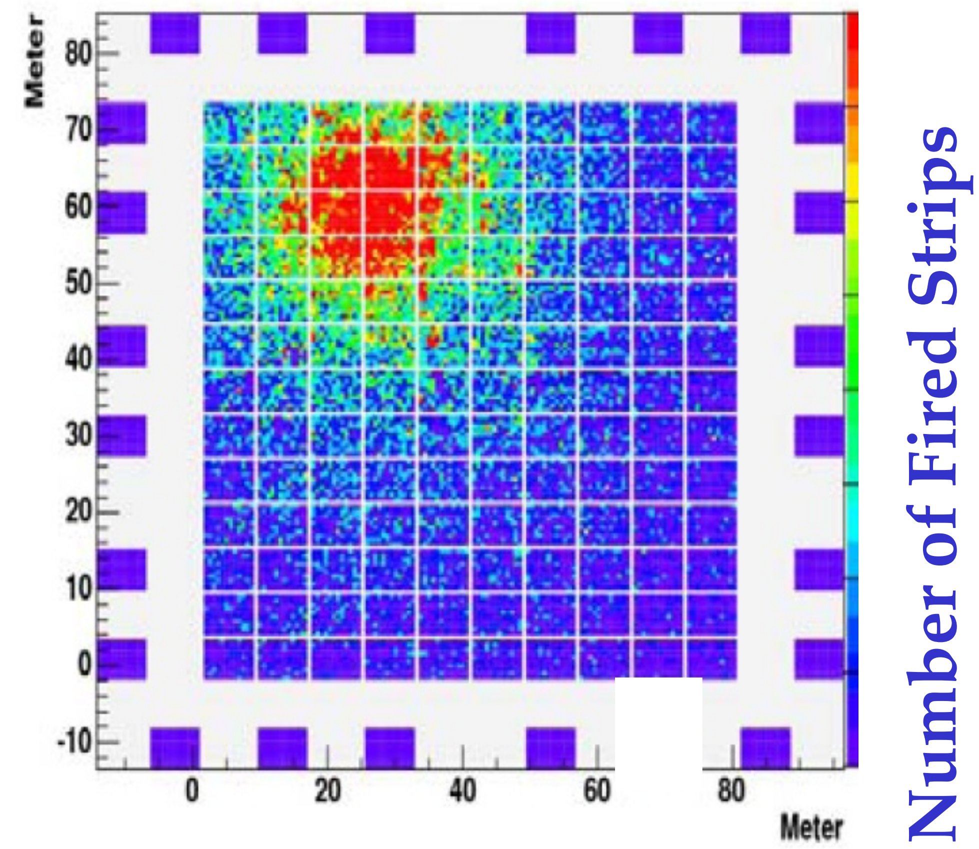
❖ FULL COVERAGE
(RPC technology, 92% covering factor)

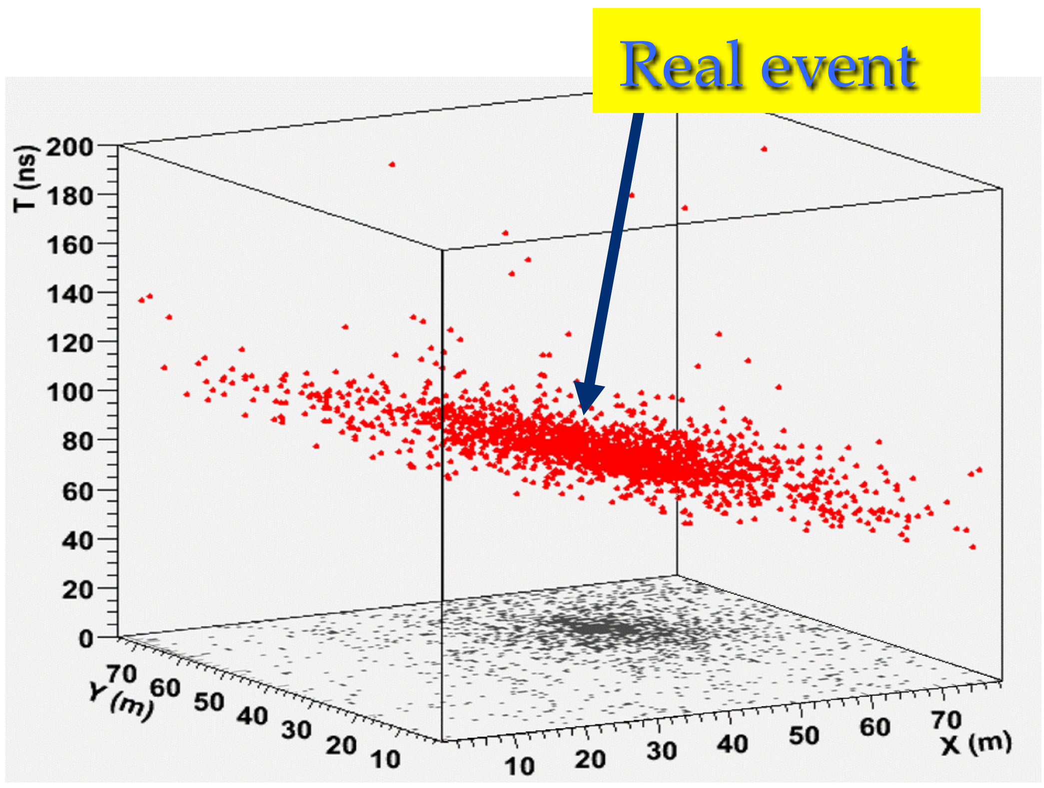
❖ HIGH SEGMENTATION OF THE READOUT
(small space-time pixels)

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

… in order to

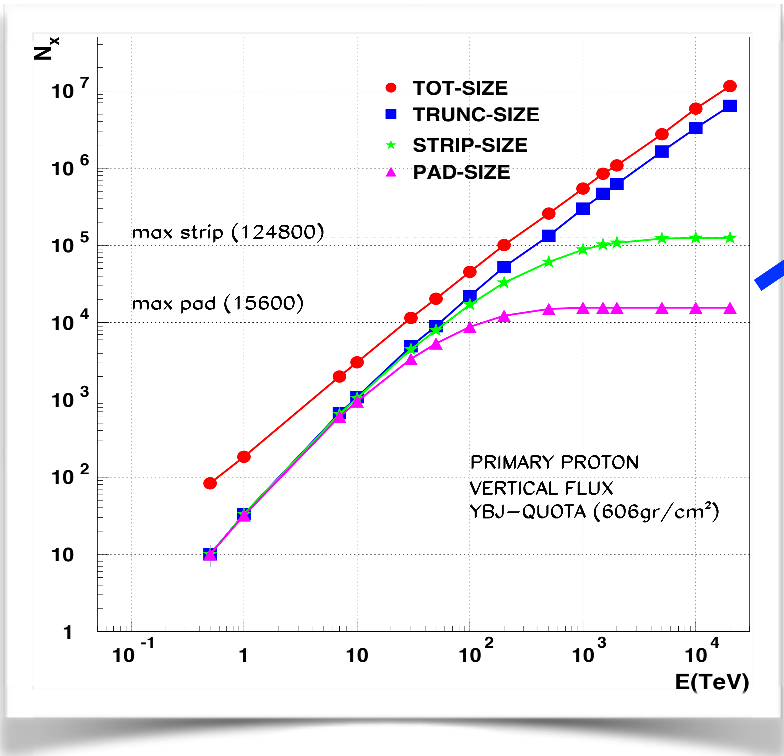
- image the shower front with unprecedented details
- get an energy threshold of a few hundreds of GeV

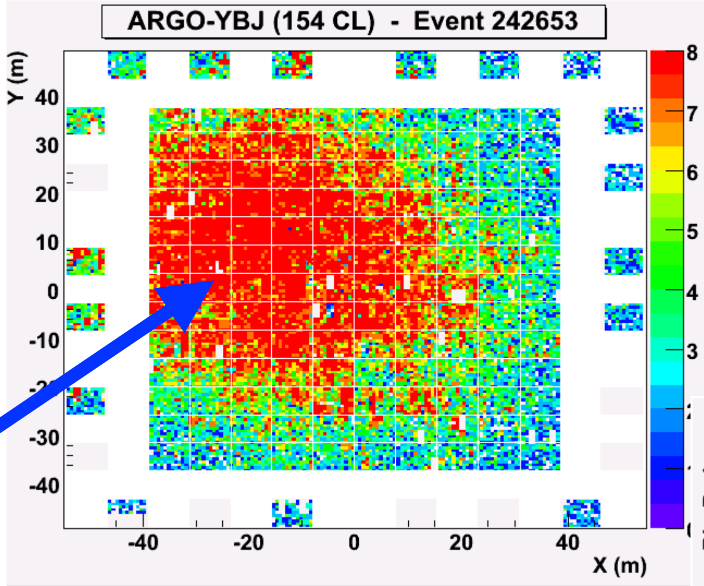




The RPC analog readout

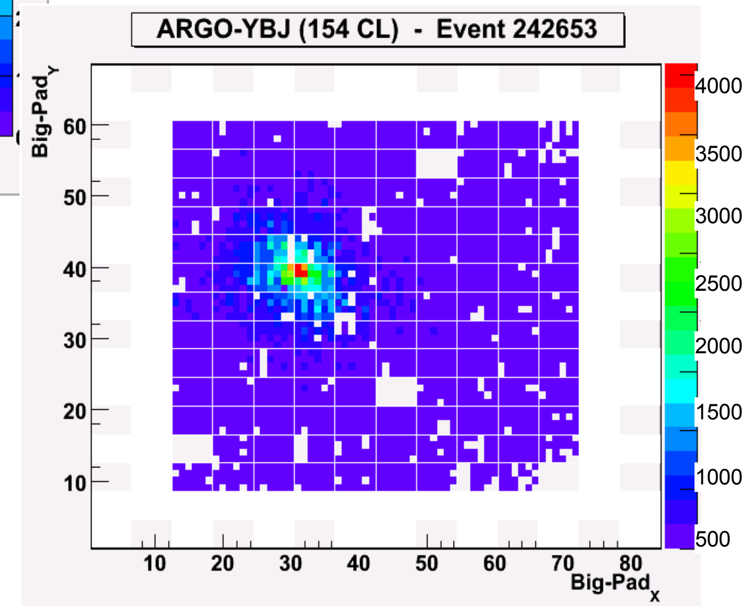
…extending the dynamical range up to PeV

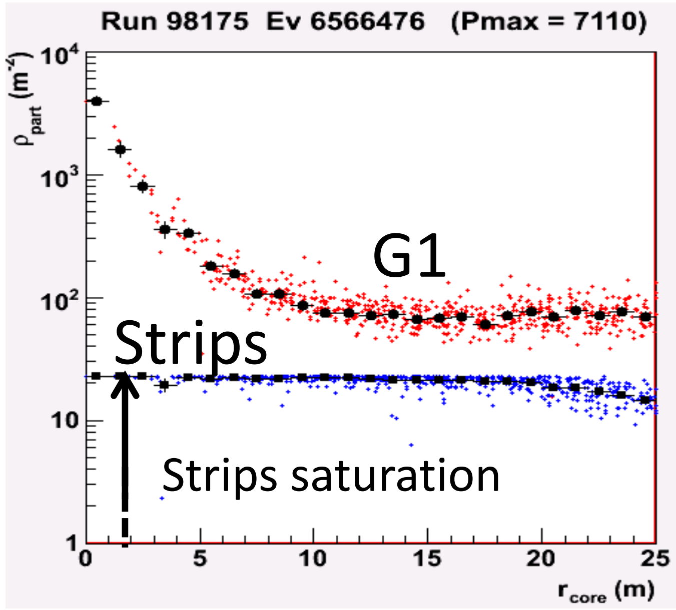


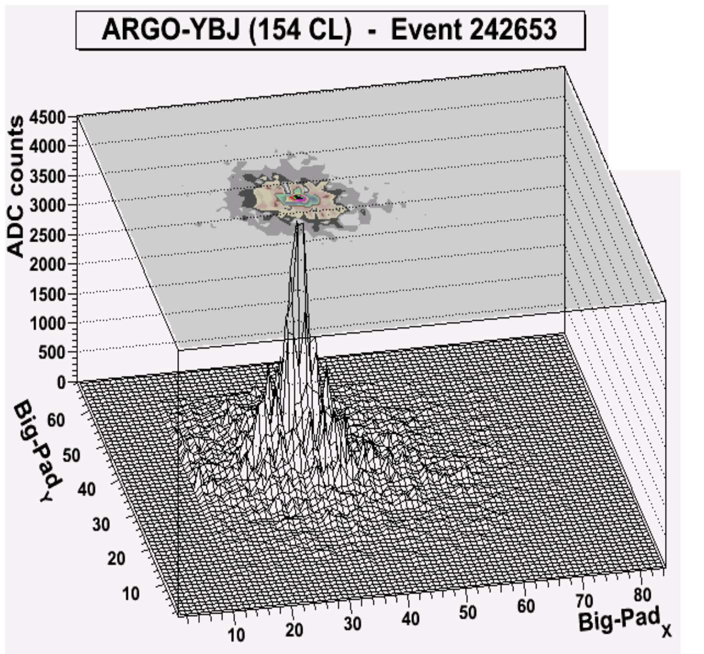


Strips (digital)

Big Pads (analog)







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

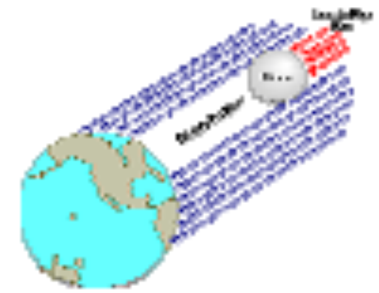
$$\rho_{max-strip} \approx 20 \text{ particles/m}^2$$

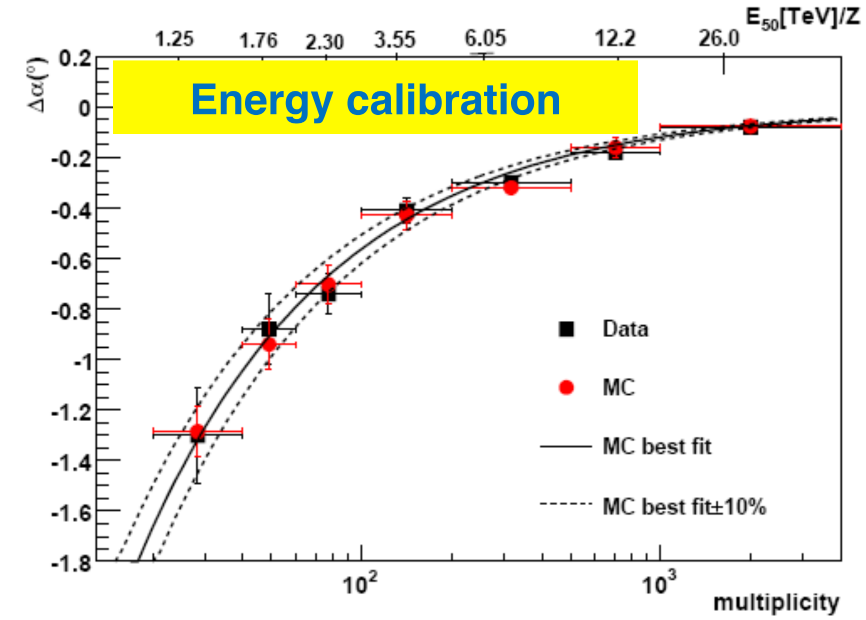
$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

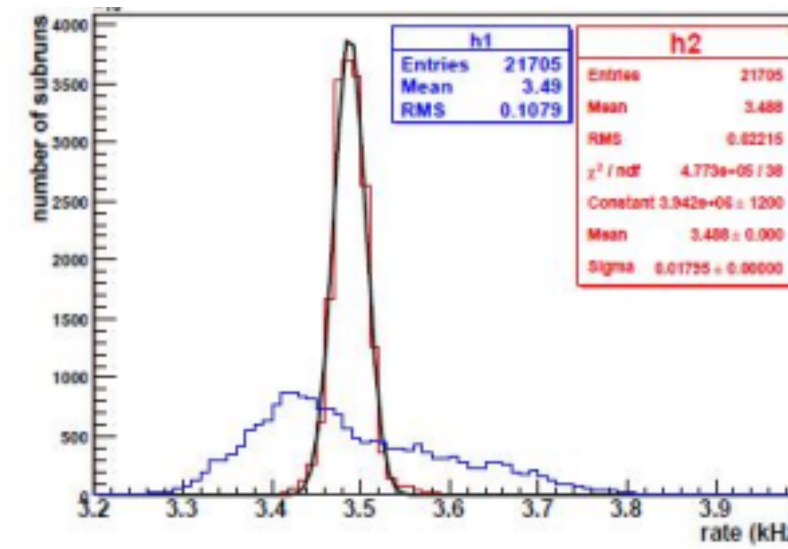
- Extend the covered energy range
- Access the LDF in the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions

Status and performance

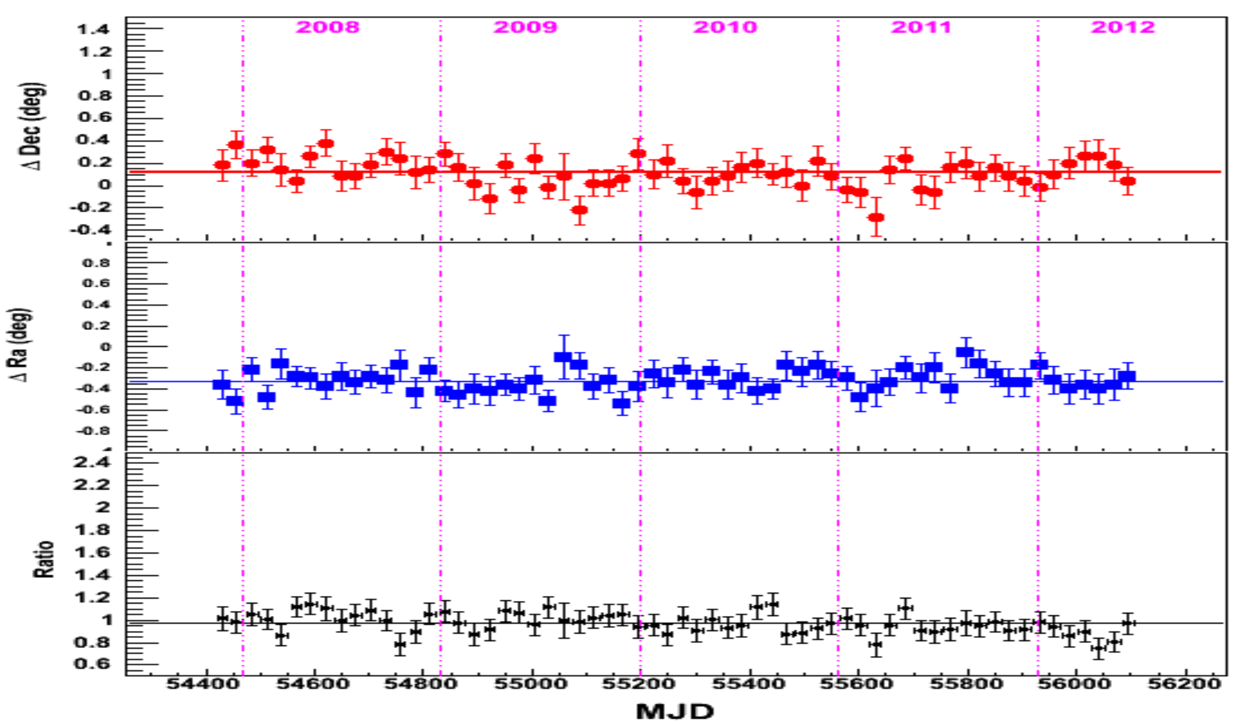
- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data

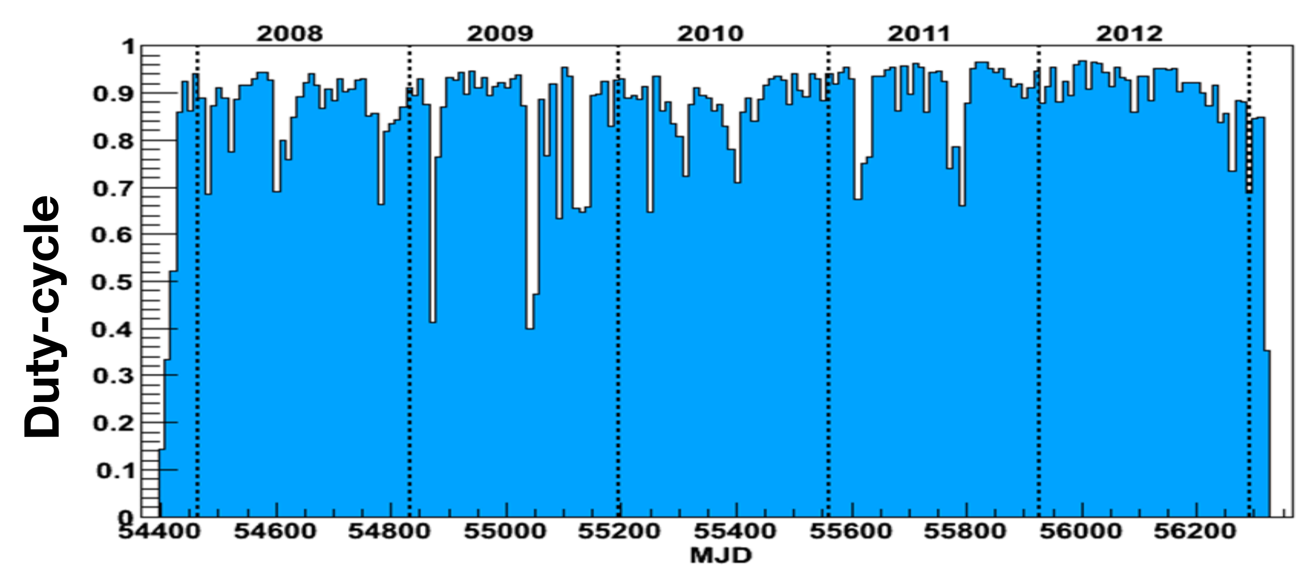






Intrinsic Trigger Rate stability 0.5%
(after corrections for T/p effects)





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

Digital readout: strip multiplicity

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

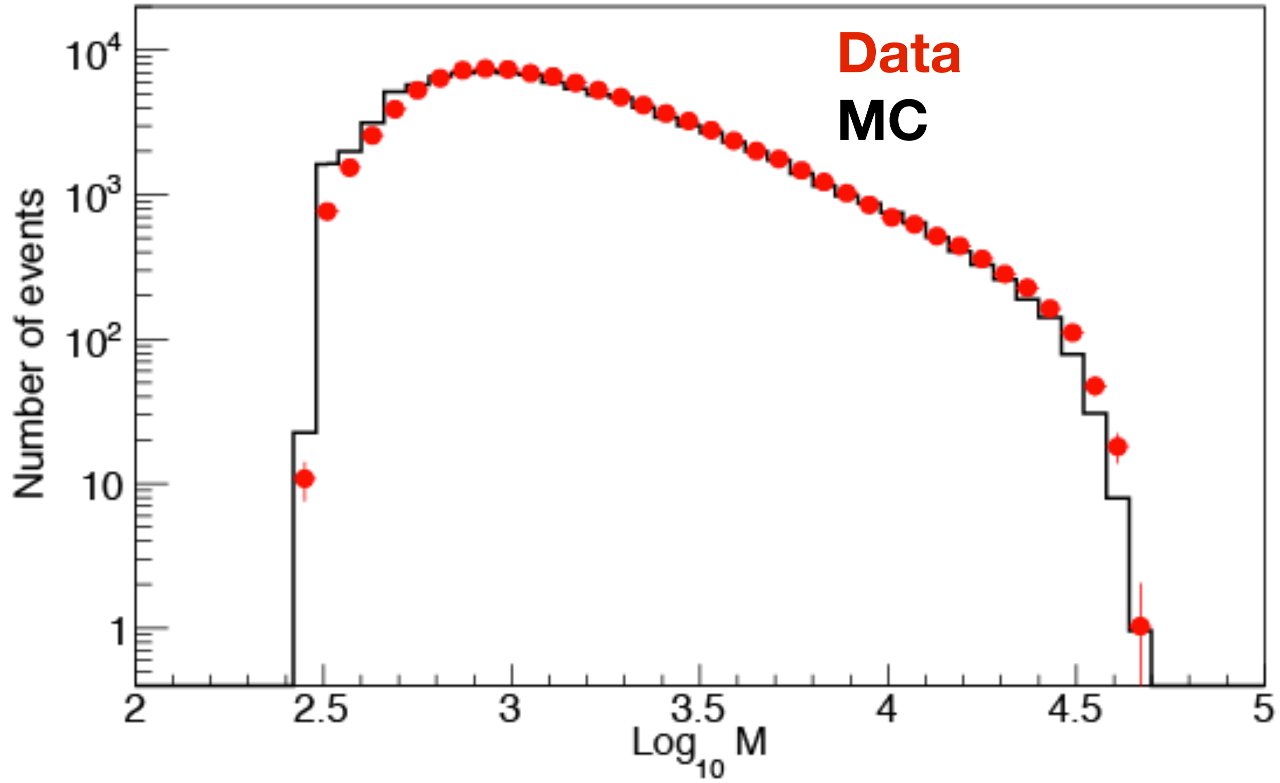
- M ≤ 50,000
- Zenith Angle ≤ 35°
- Highest density cluster in 40 × 40 m^2

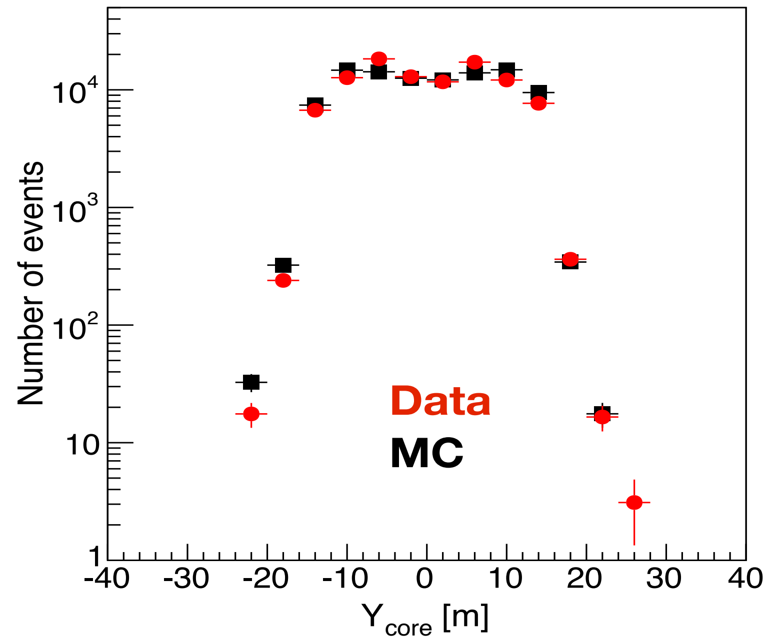
Light Component (p+He) selection:

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

A20 = 20 innermost clusters
A42 = 42 outermost clusters

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

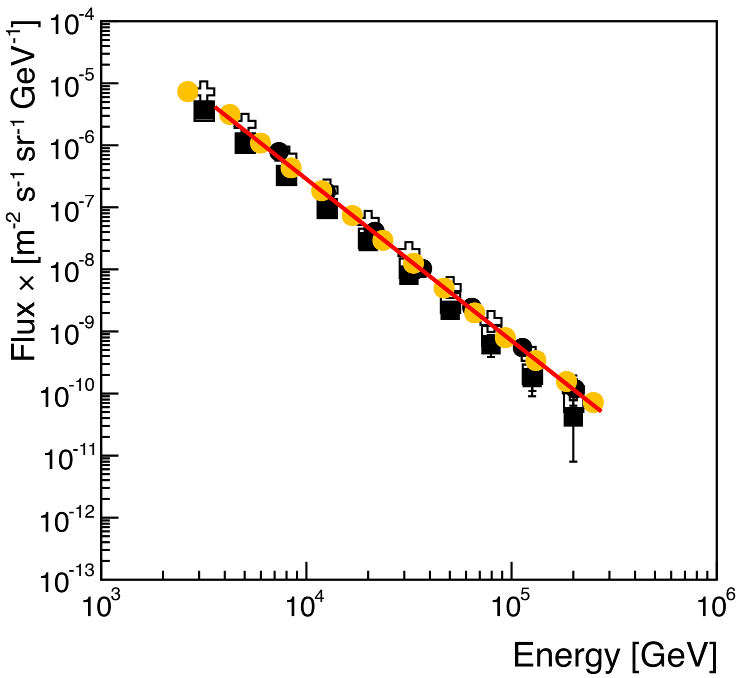




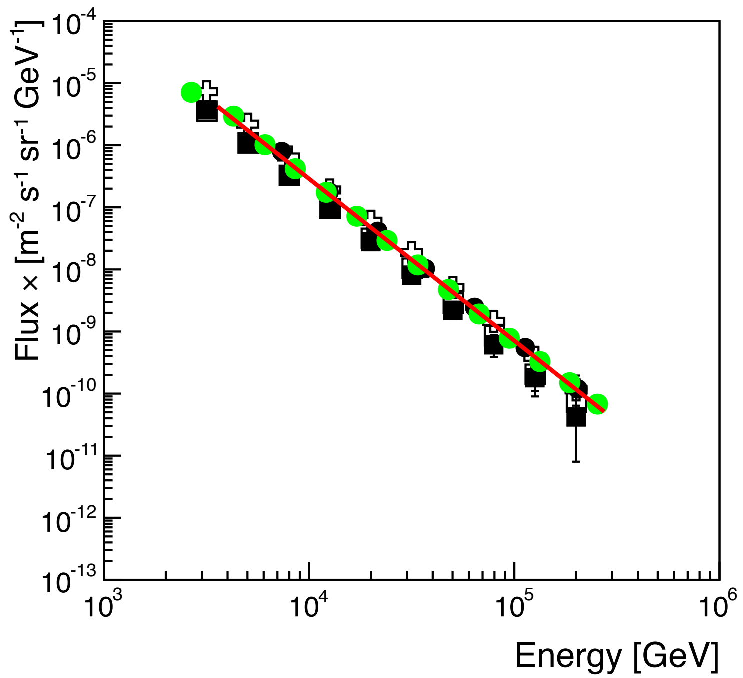
Rconstructed shower core position

Light component spectrum

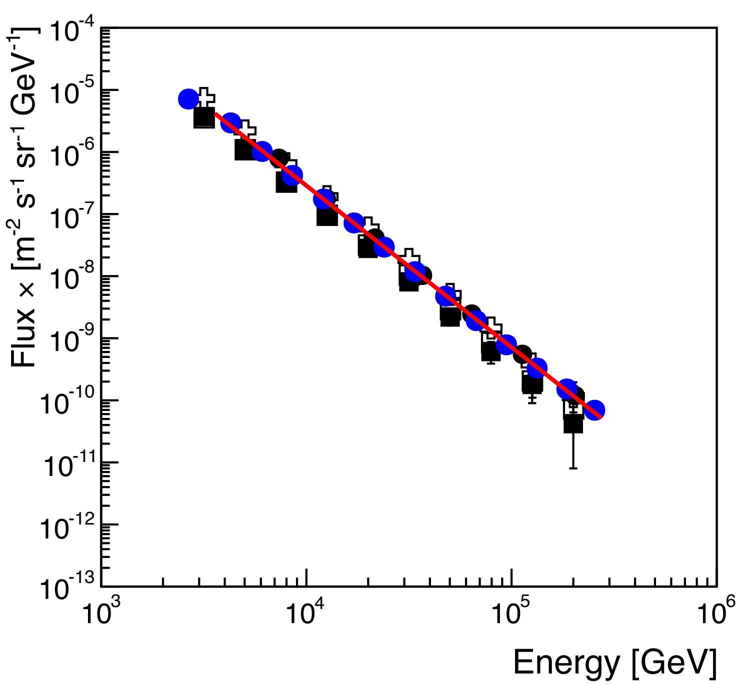
2008



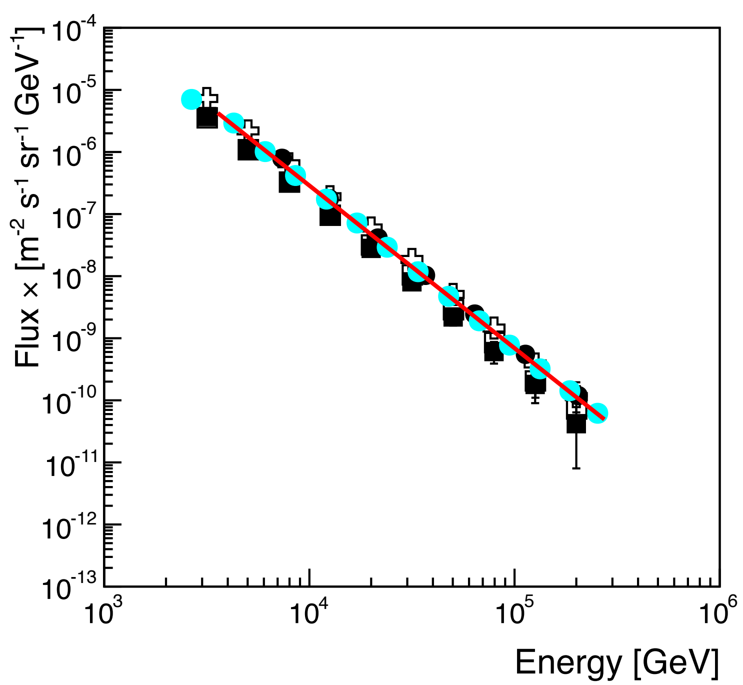
2009

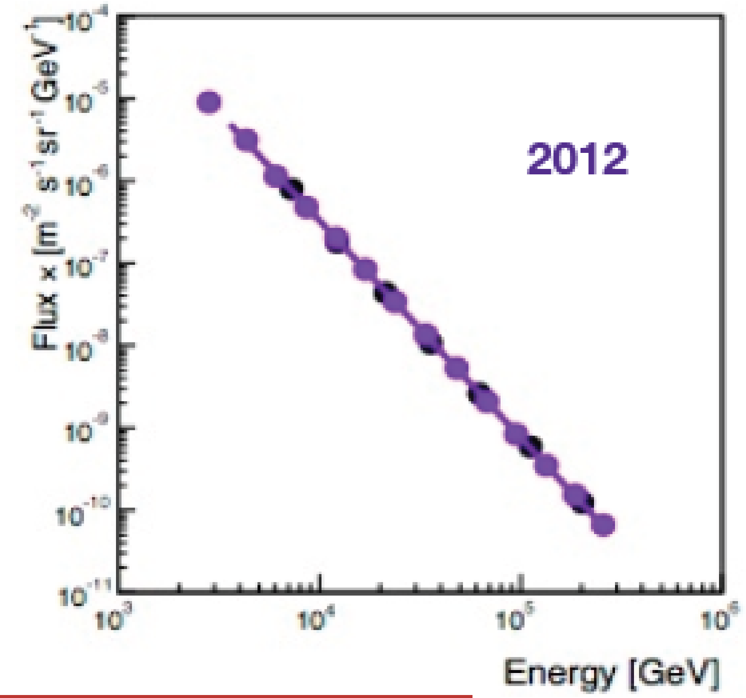


2010

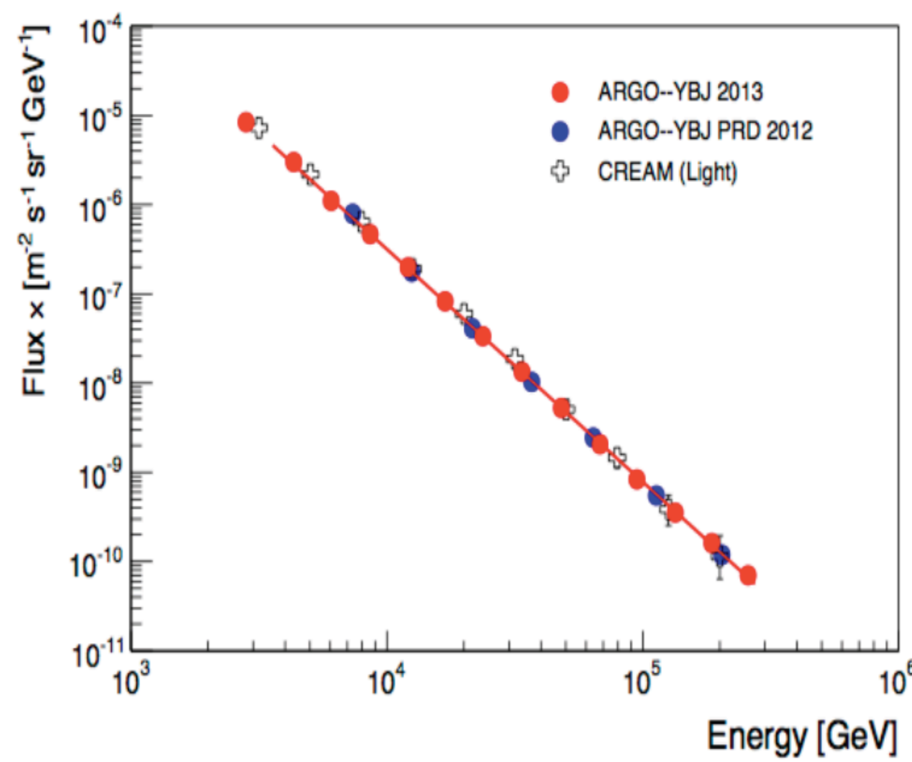


2011



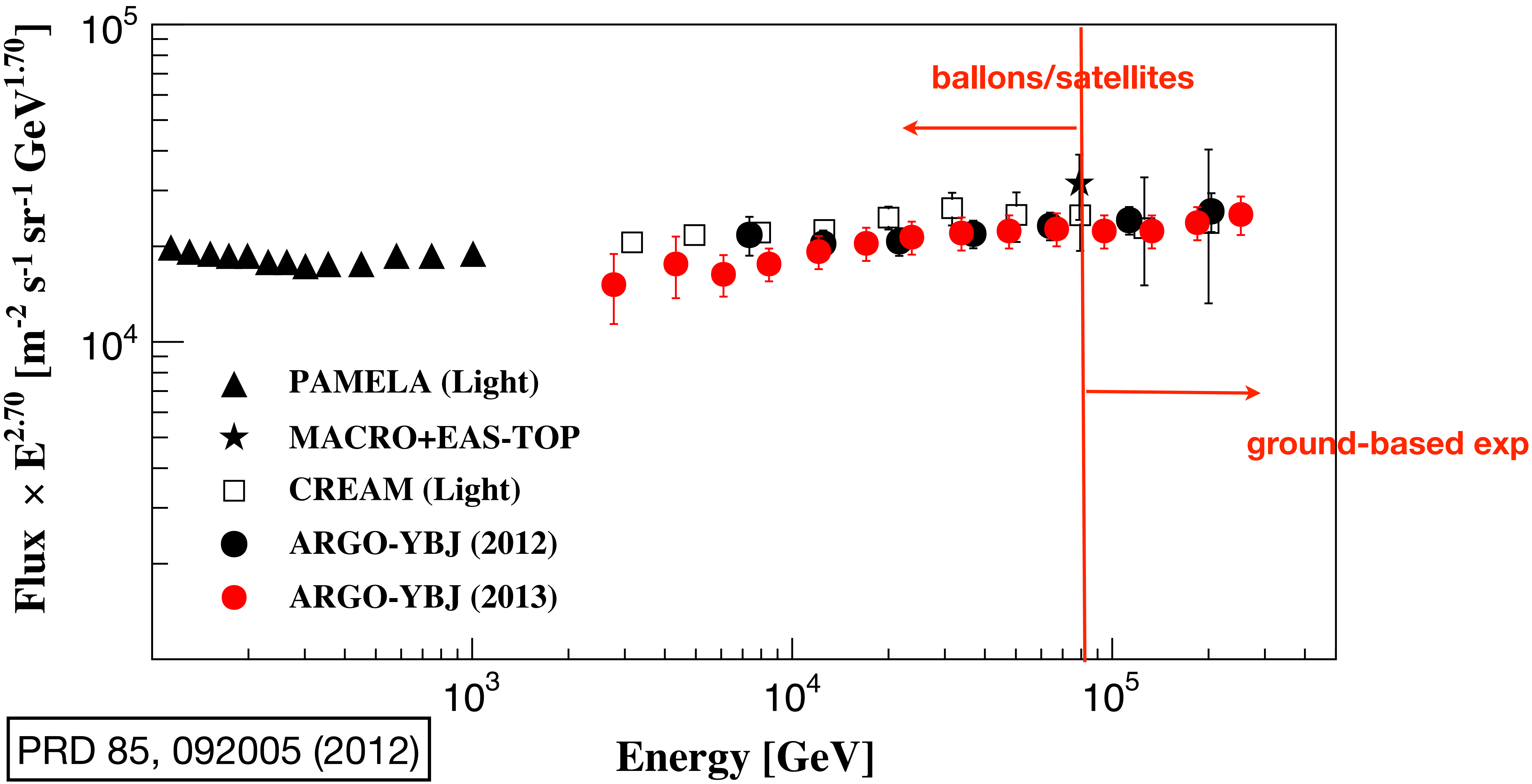


year	Gamma
2008	2.61±0.02
2009	2.61±0.02
2010	2.61±0.02
2011	2.62±0.02
2012	2.63±0.02



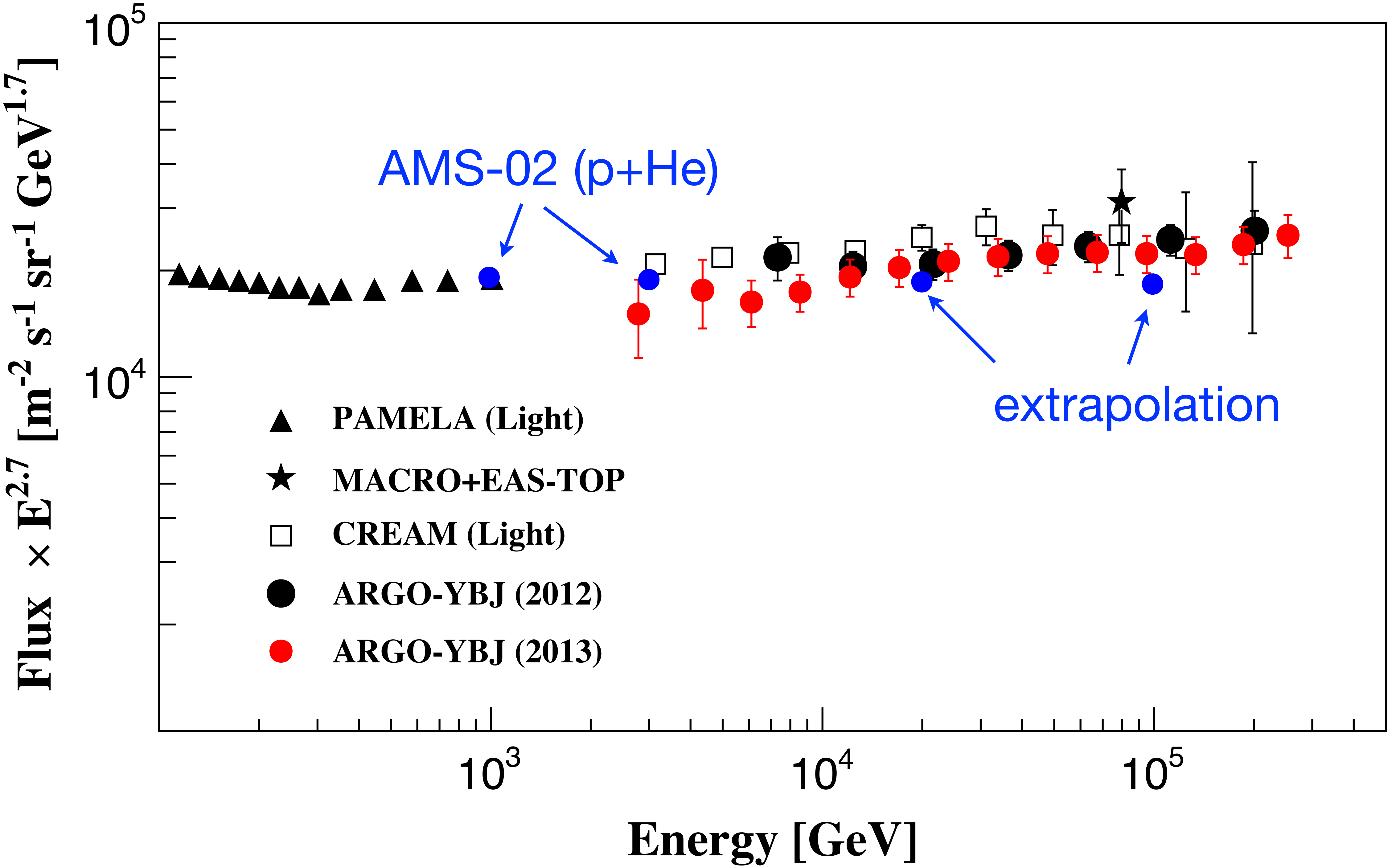
The light-component spectrum (3 - 300 TeV)

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

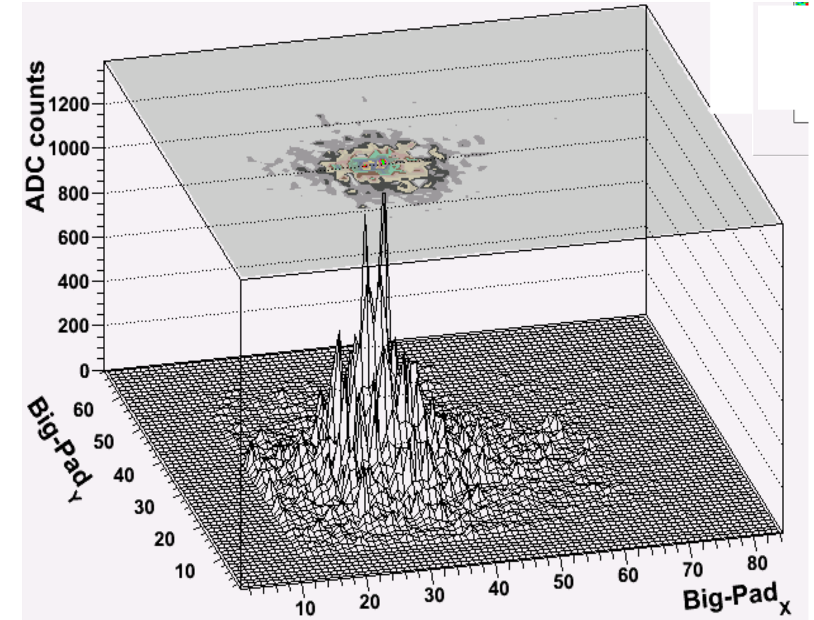


PRD 85, 092005 (2012)

ARGO-YBJ and AMS-02 (ICRC13)

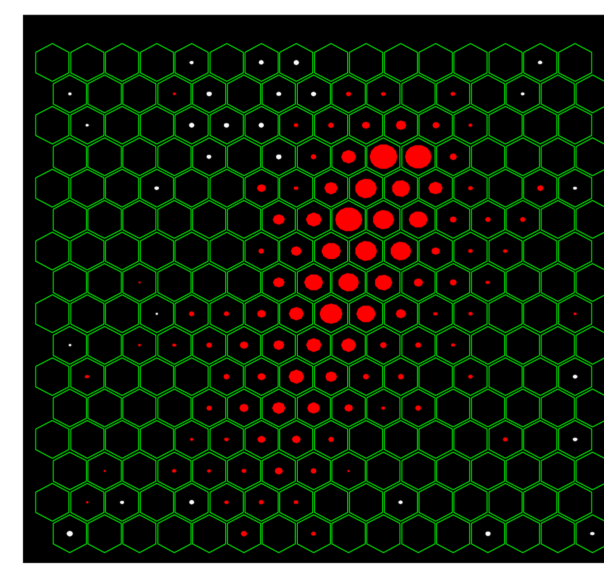


Extending the energy range



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: $14° \times 14°$
  - Elevation angle: 60°

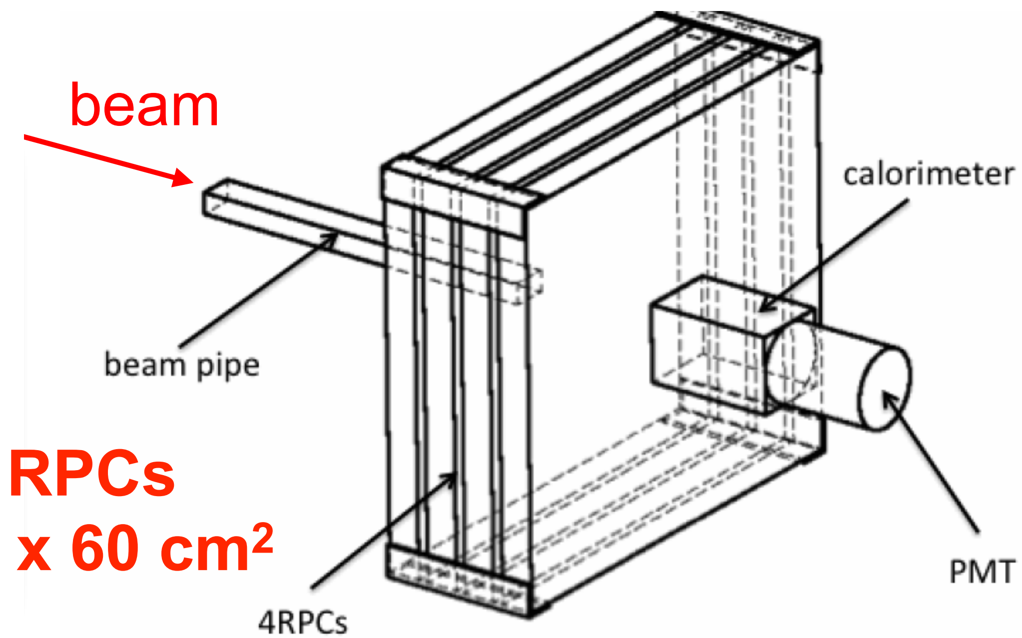


…to performe 2 different analysis:

- ❖ ARGO-YBJ Analog Readout alone
- ❖ Hybrid measurement ARGO-YBJ/WFCTA

Next talk by Zhen Cao

Intrinsic linearity: test at the BTF facility

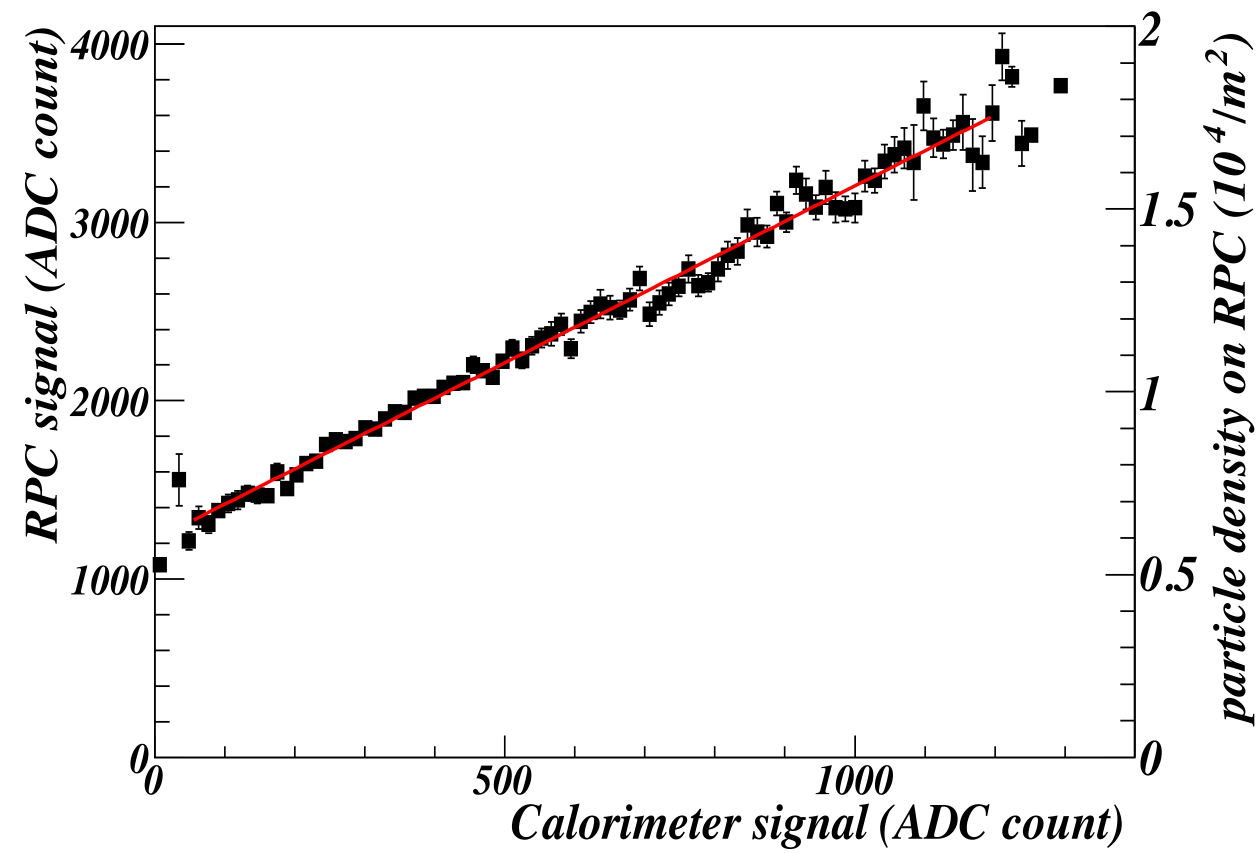


Calorimeter: lead glass block from OPAL,
PMT a Hamamatsu R2238.

Linearity of the RPC @ BTF in INFN Frascati Lab:

- *electrons (or positrons)*
- *E = 25-750 MeV (0.5% resolution)*
- *<N>=1÷10^8particles/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:

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

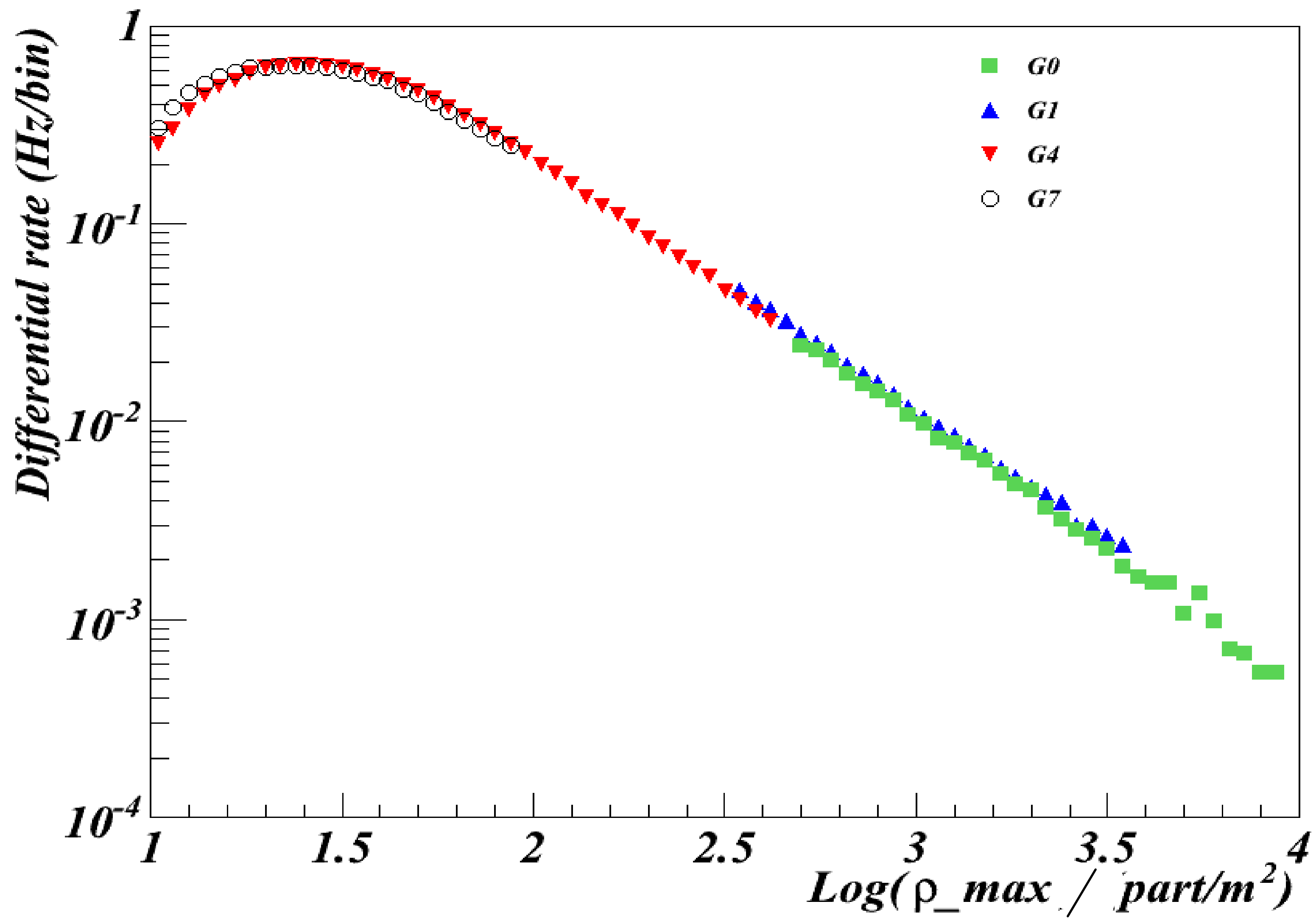
$$\rho_{max-analog} \approx 10^4 \text{ particles/m}^2$$

4 data sample:

ρ: 10 → 10^4 part/m^2

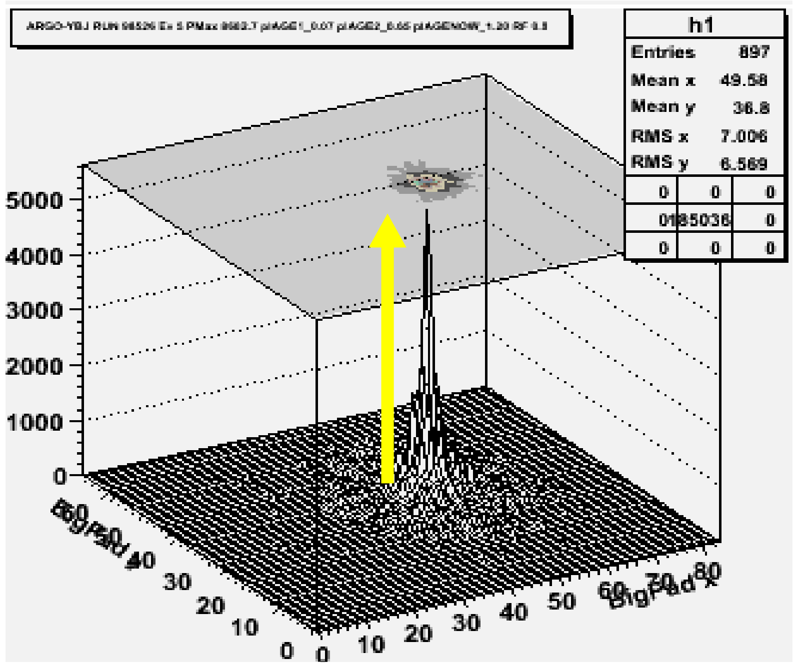
Event selection:

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



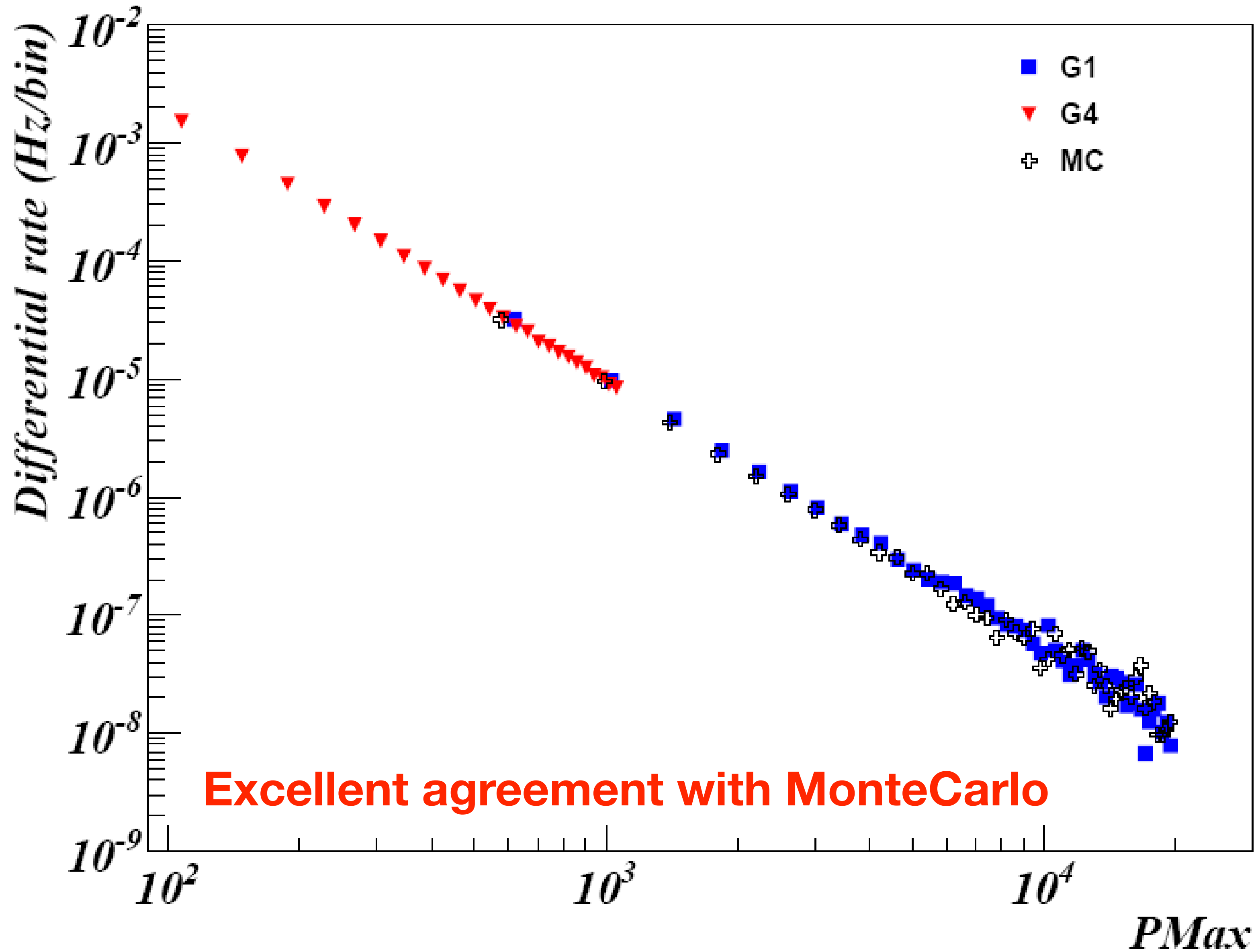
Good overlap between 4 scales with the maximum density of the showers spanning over three decades

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°

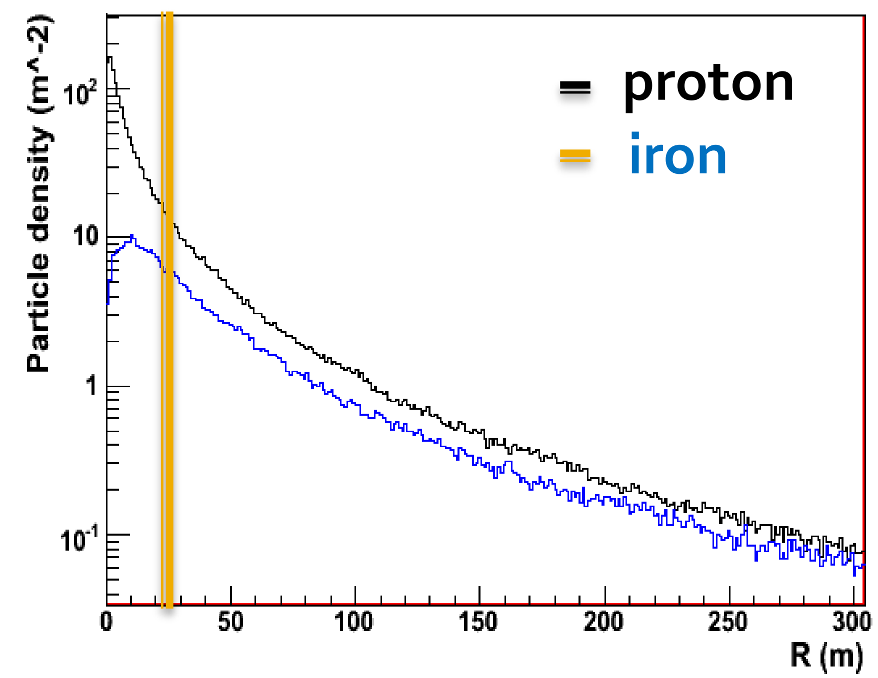
Pmax spans over two and half decades, while the event frequency runs over five decades.

ARGO-YBJ + WFCTA

Next talk by Zhen Cao

- *ARGO-YBJ:* lateral distribution

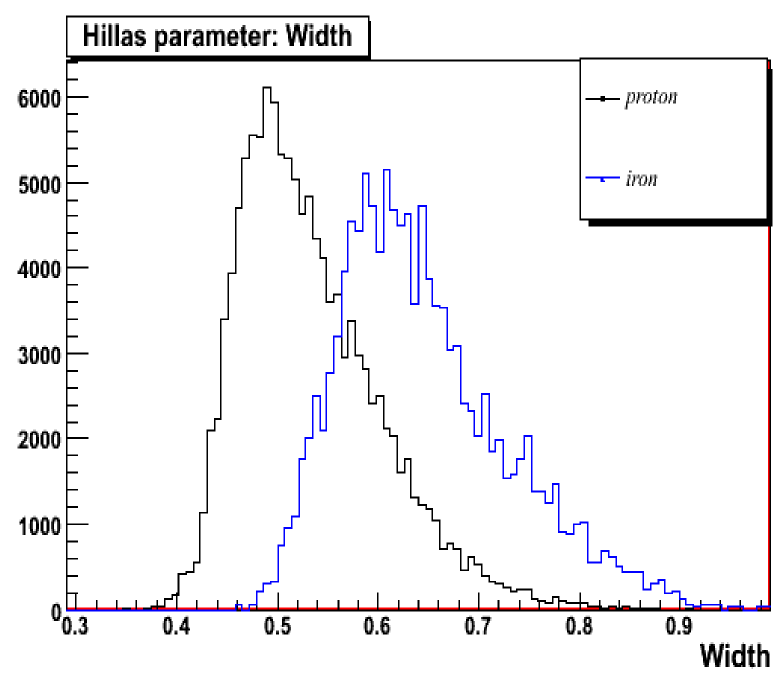
  In the core region → mass sensitive

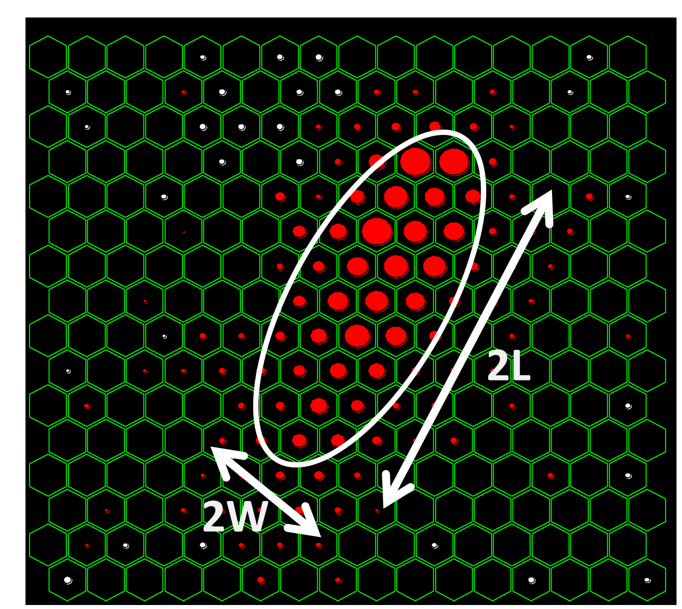


- *Cherenkov telescope:* longitudinal information

  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°
  - 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

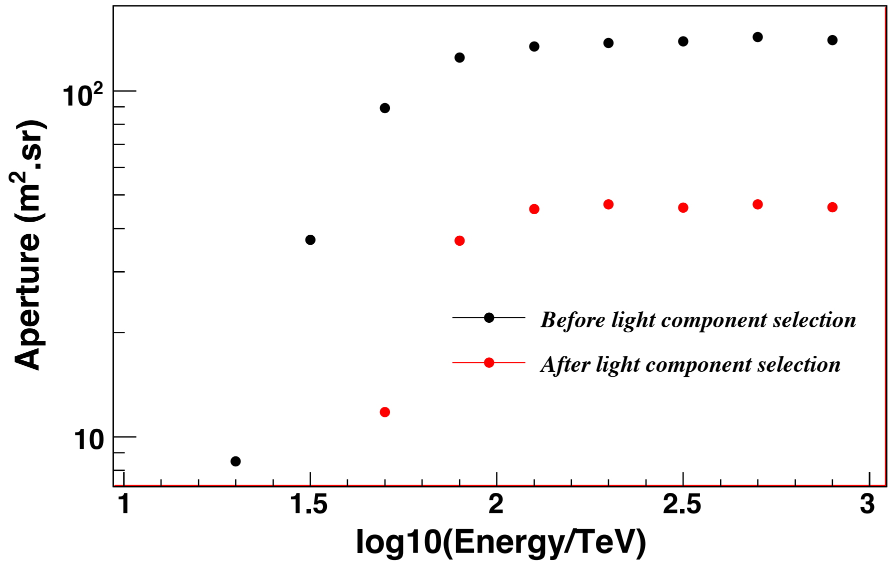
➡ 8218 events well reconstructed above 100 TeV

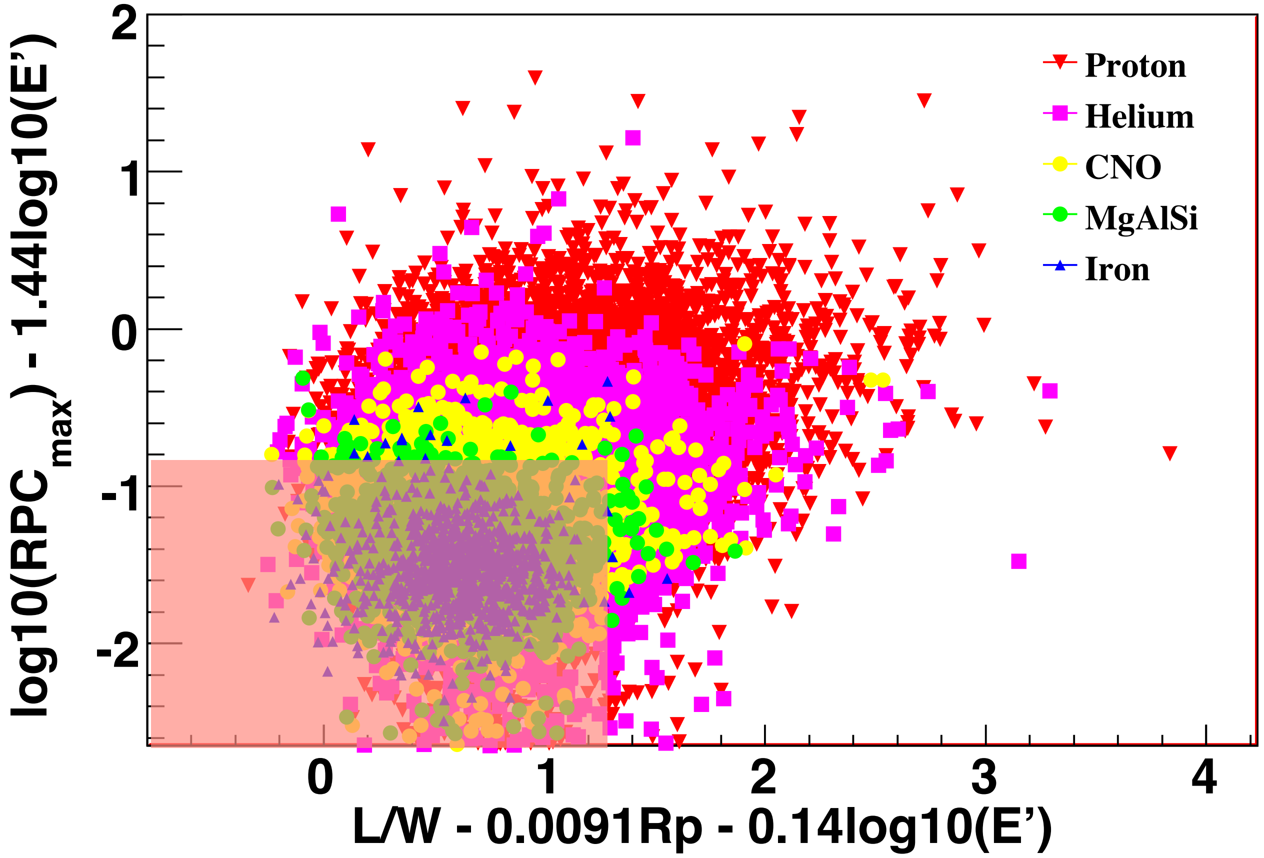
Light-component (p+He) selection

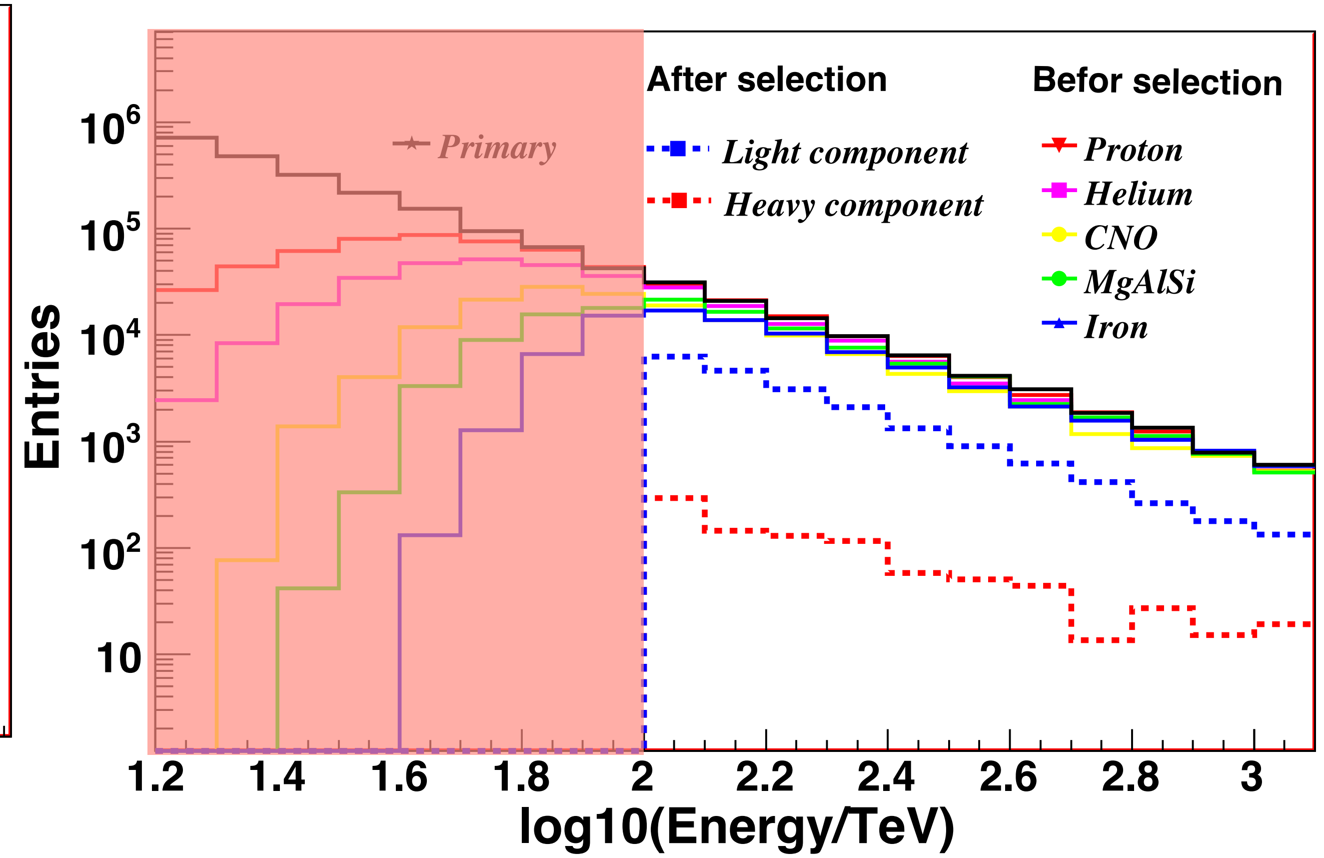
Next talk by Zhen Cao

- 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%	



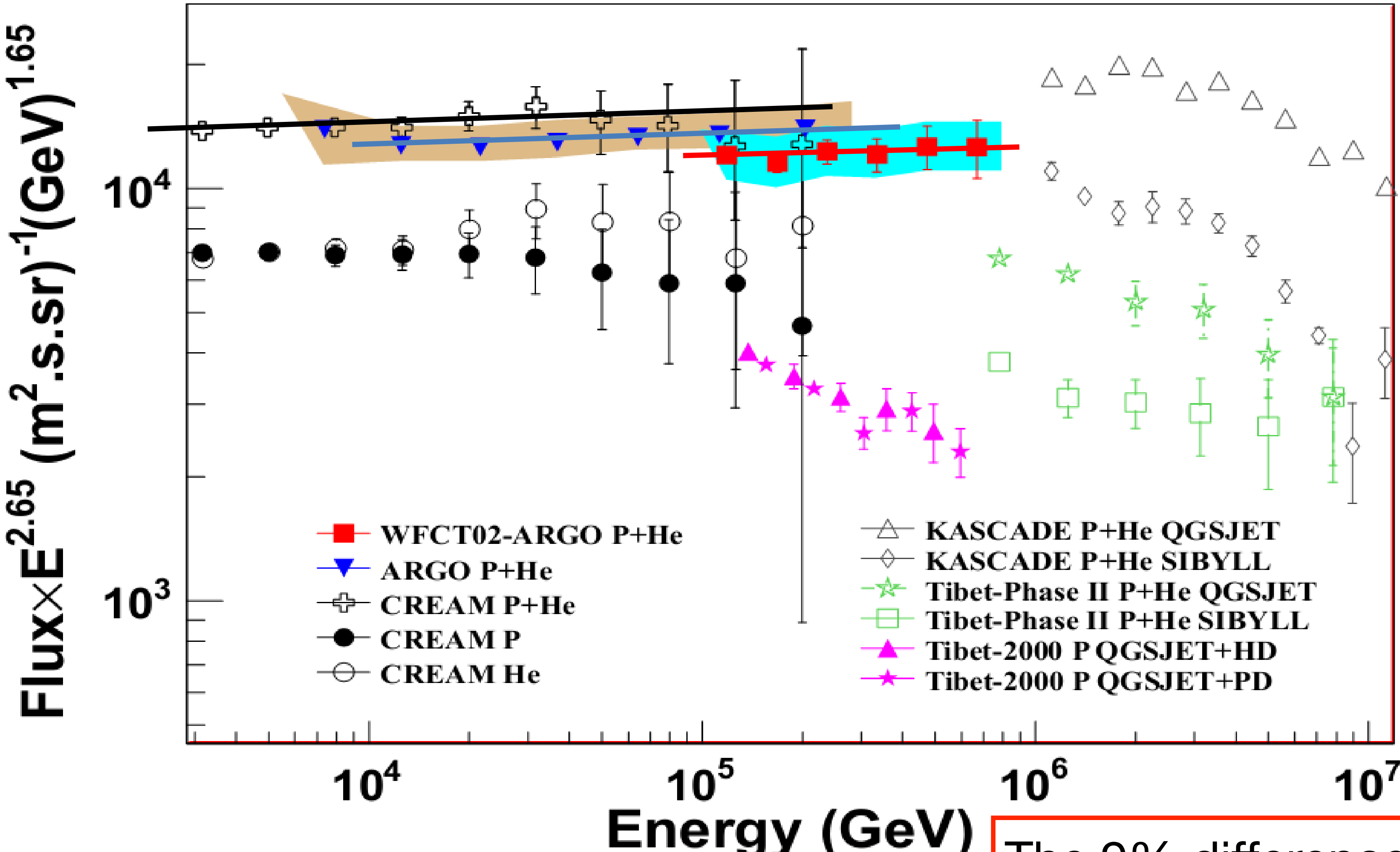




The light-component (p+He) spectrum (2 - 700) TeV

- 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})

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

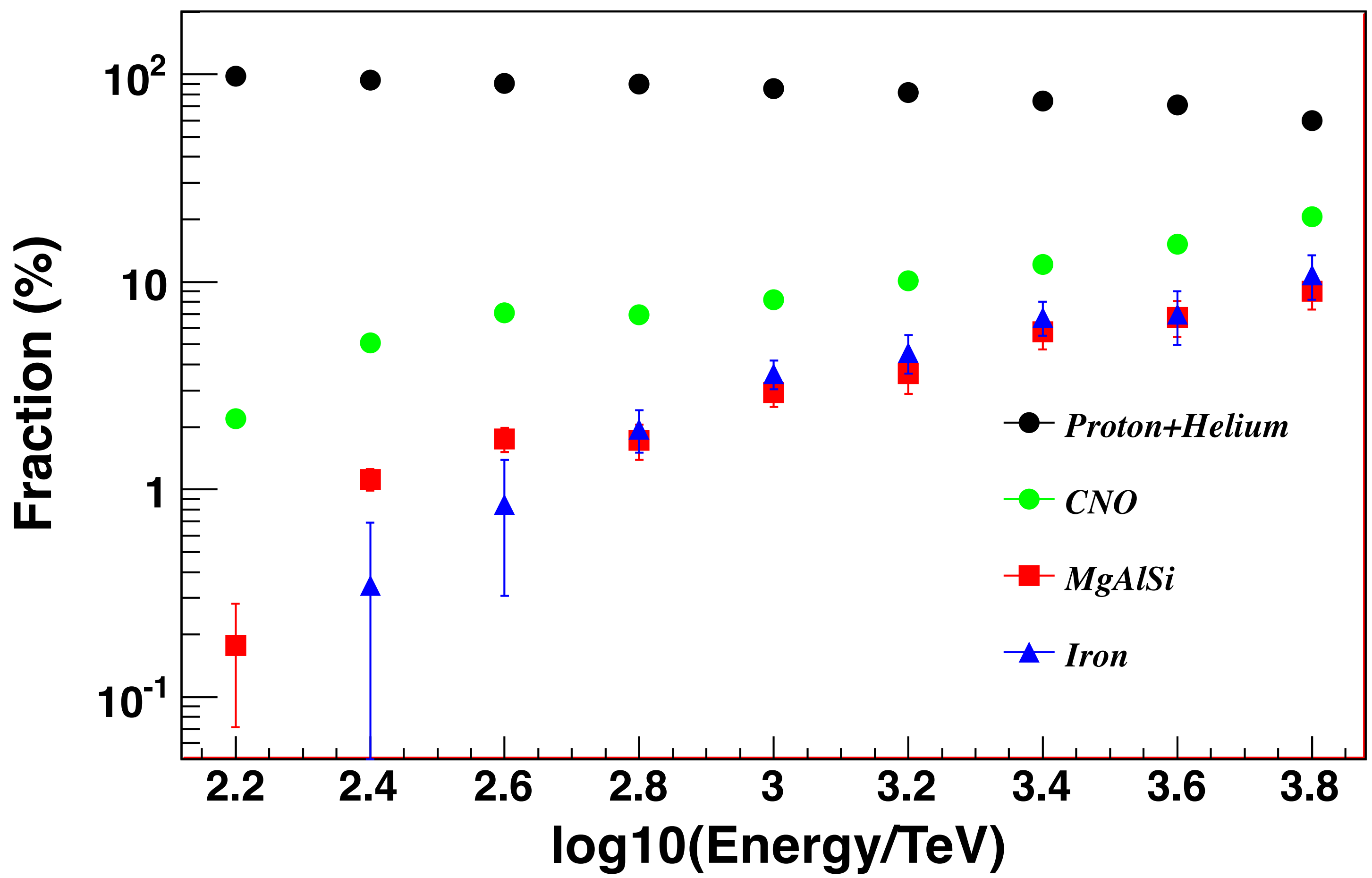
Bartoli et al., Chin. Phys. C 38, 045001 (2014)

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%.



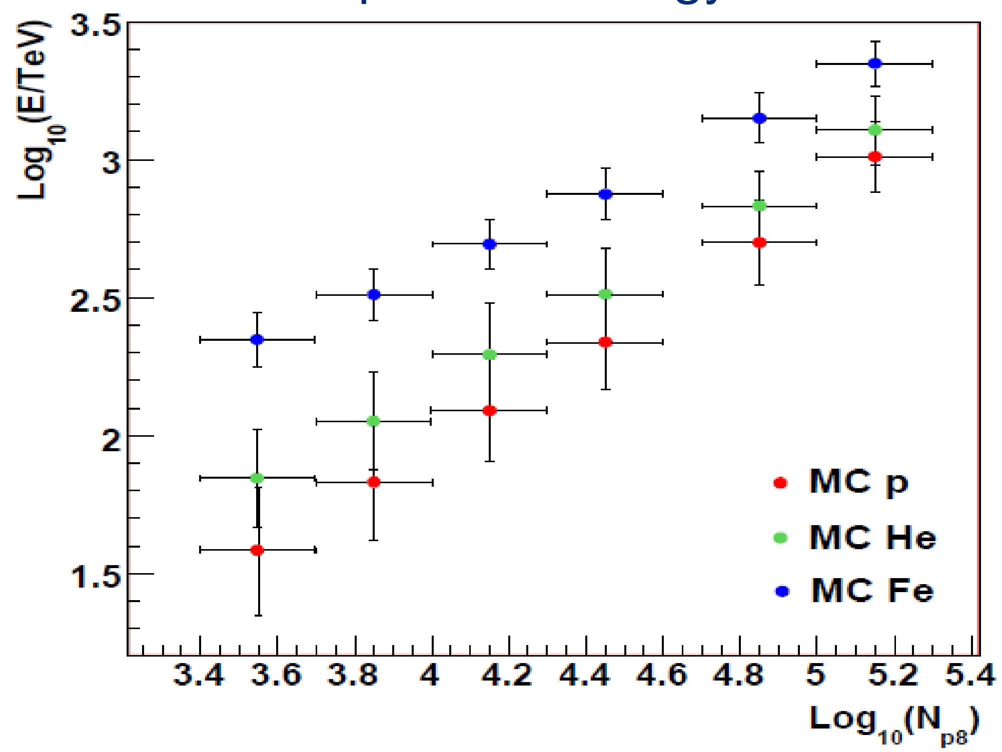
Next talk by Zhen Cao

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

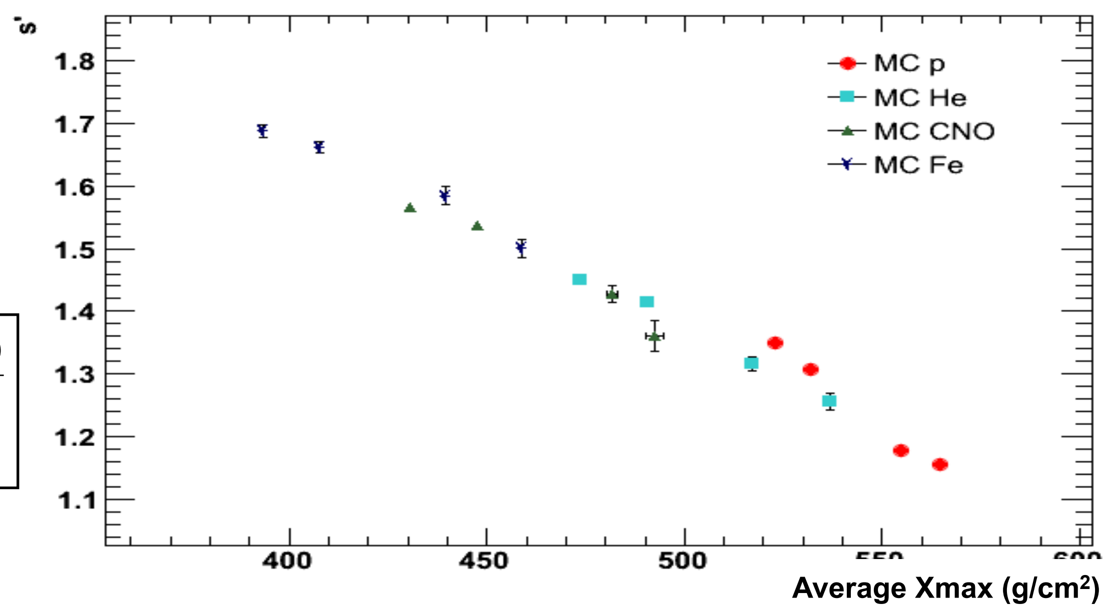


Look for information on the shower age in order to have a mass independent energy estimator.

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

$R_0 = 30$ m

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



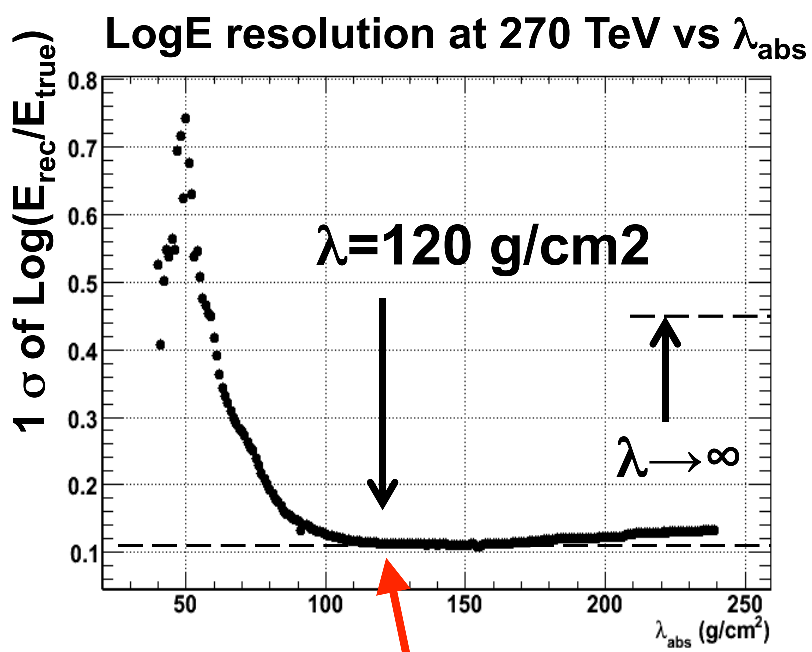
Assume an exponential absorption after the shower maximum. Get the correct signal at maximum (Np8max) by using Np8 and s' measurements for each event.

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

Also checks with Gaisser-Hillas profile

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

Finding the best λ_{abs} parameter

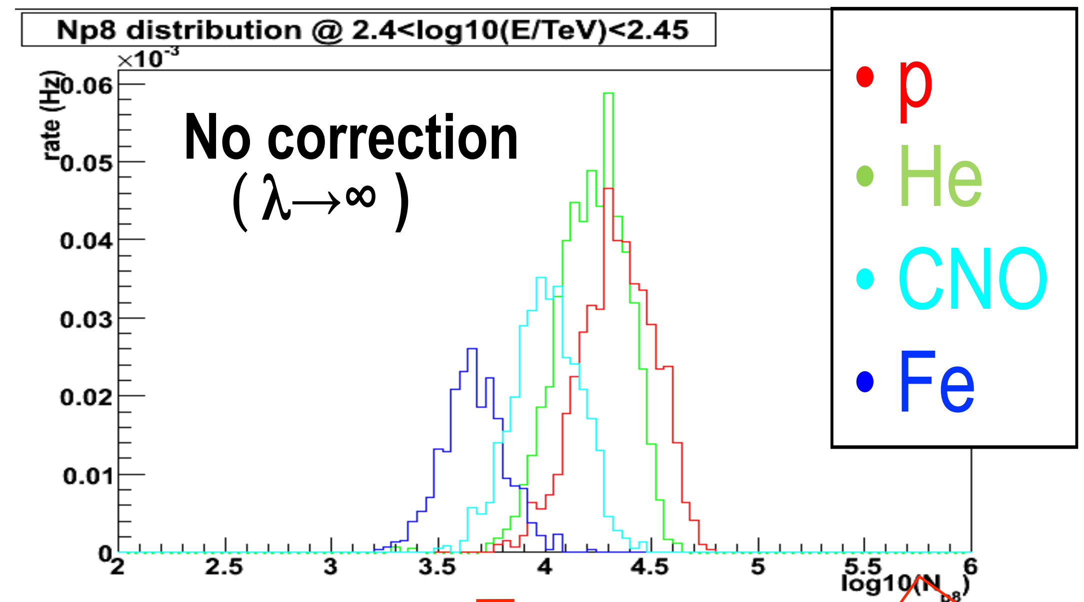


Results from the ARGO-YBJ test experiment

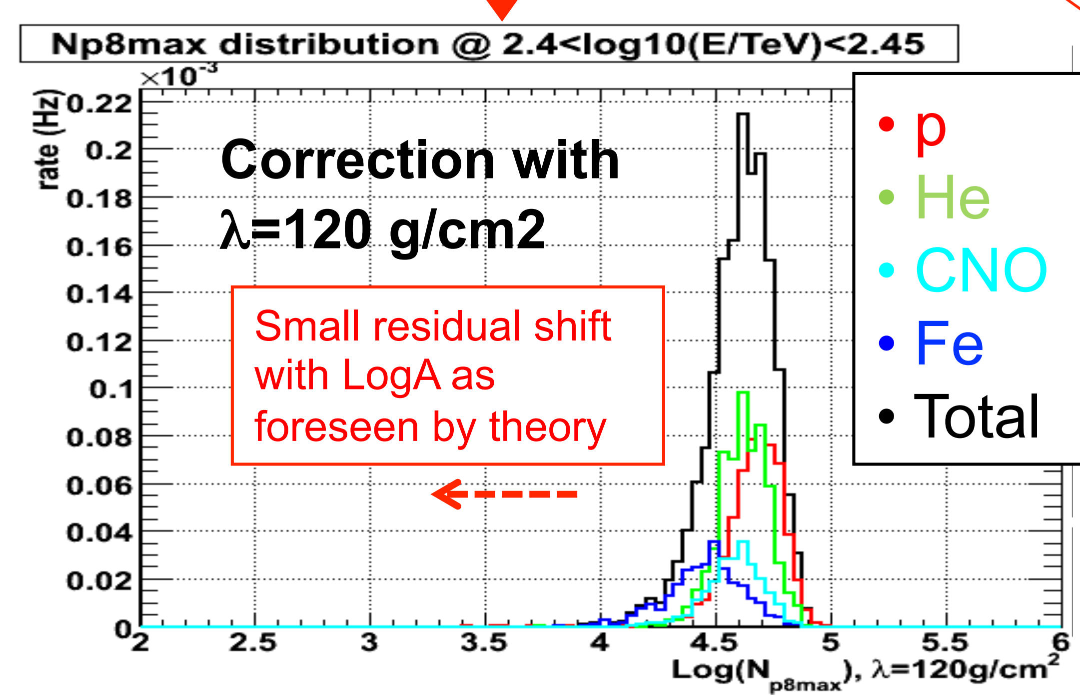
Astroparticle Physics 17 (2002) 151–165

According to numerous measurements from sea level to an altitude of about 4 km, Λ_{att} lies between 120 g/cm^2 and 150 g/cm^2 for showers with moderate size [15,19]. Thus the exponent of the angular

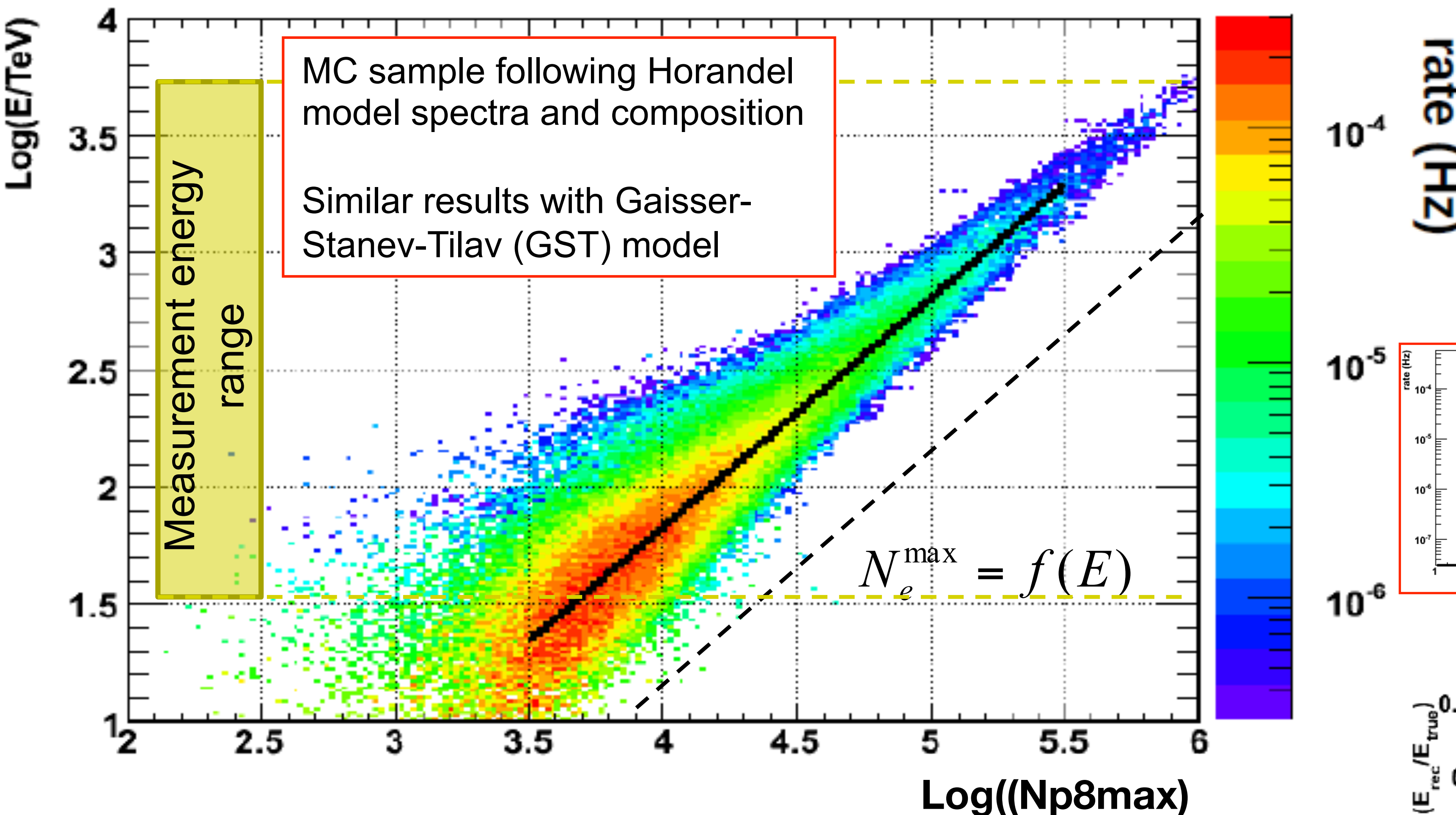
(sec $\theta - 1$)] law. The parameter α is found to be 4.88 ± 0.45, so that $\Lambda_{att} = (124 \pm 11)$ g/cm^2, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 ± 0.37. For angles greater than



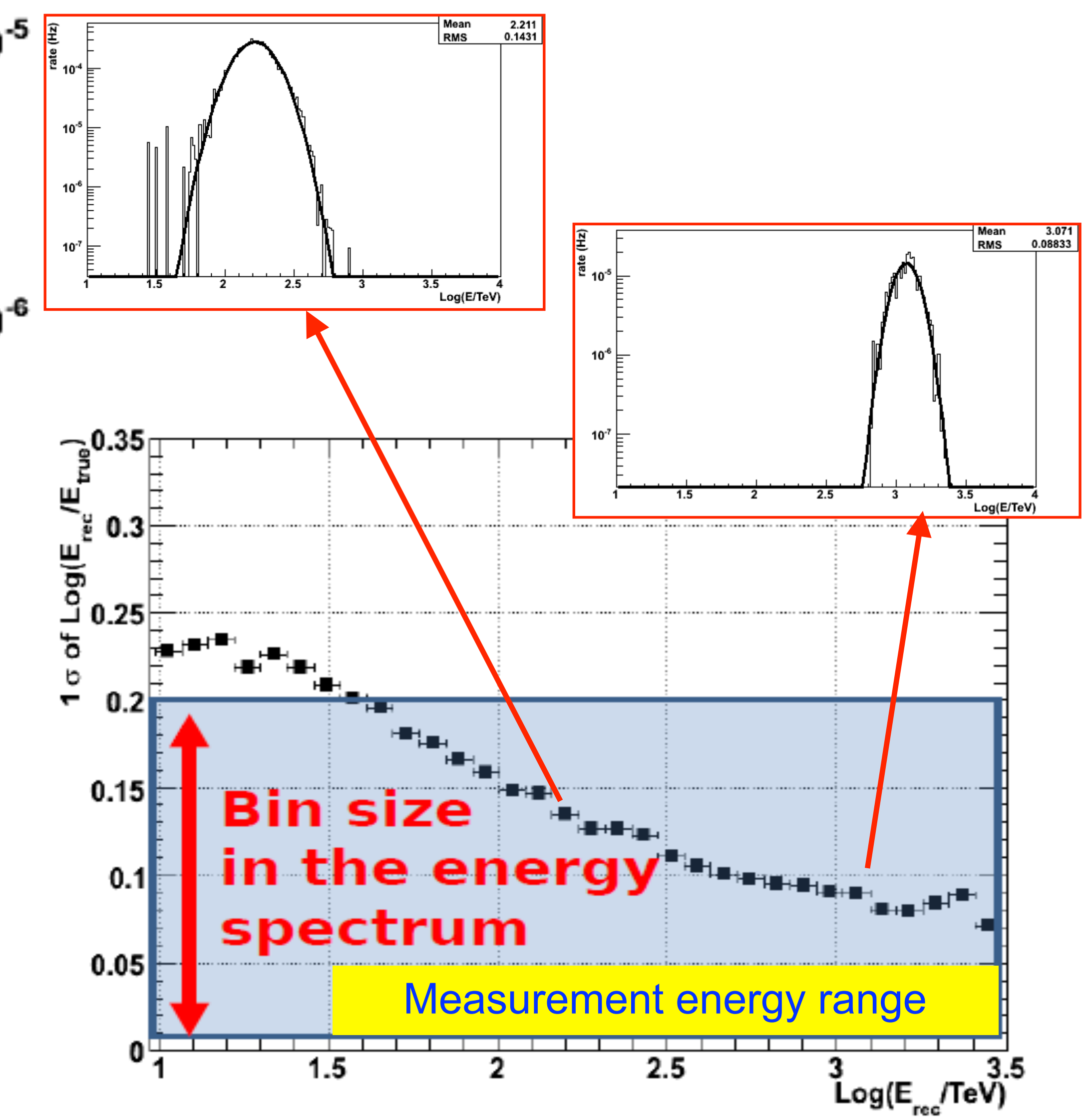
Further improvements in progress



Mass independent energy reconstruction



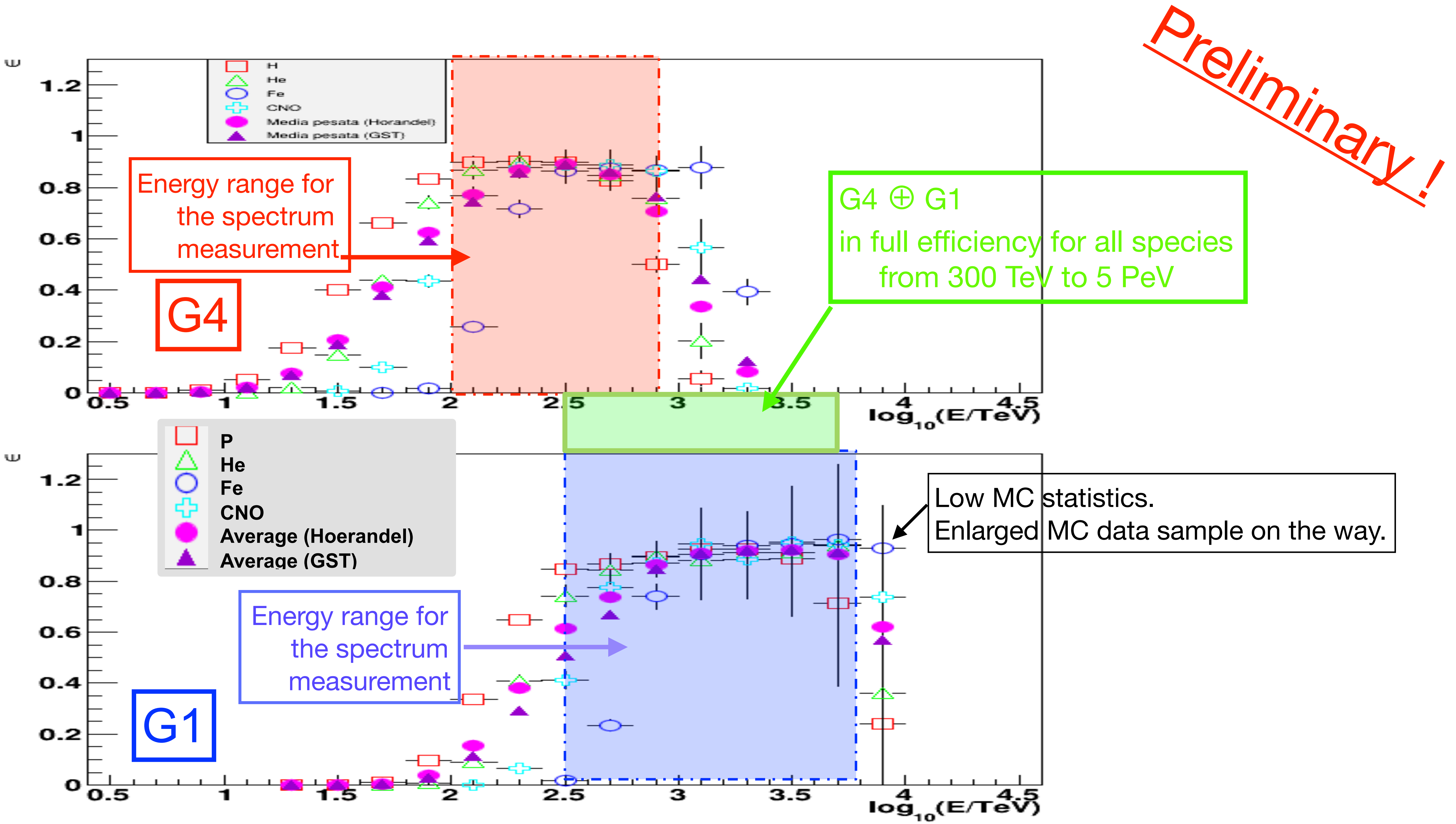
In excellent agreement with total-size vs E theoretical plot.
The shift is simply due to the fact that we are using the truncated size.



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:

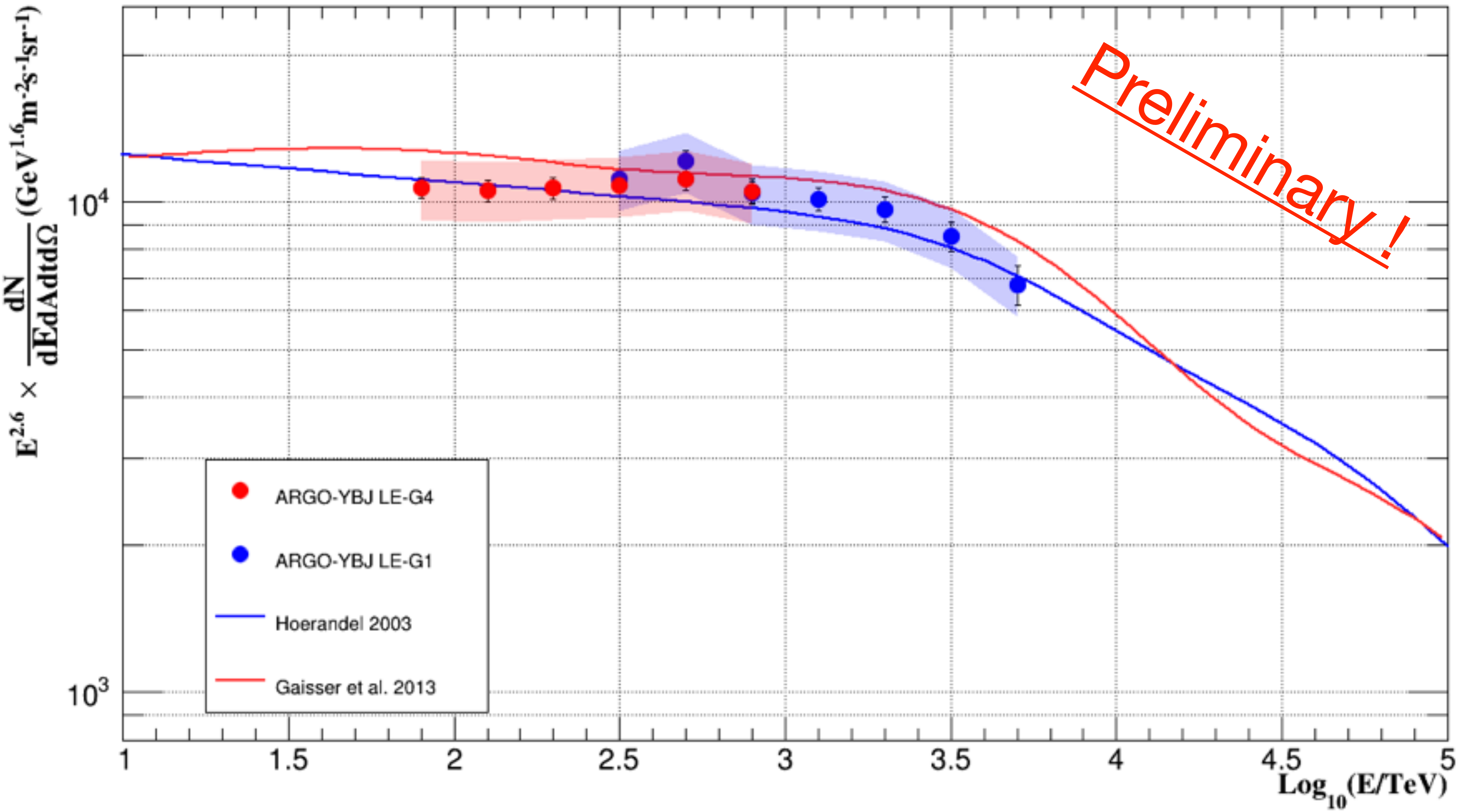
Geometrical Aperture : (5 % in/out contamination) (2.5% angular contamination) =5.6 %
Efficiency: (5% from MC samples) (<10% efficiency estimation of the mixture) = 5.0-11.2 %
Unfolding: 3%
Hadronic interaction model < 5%
TOTAL: 8.1% - 13.8 %
TOTAL: (conservative) = 14%

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%

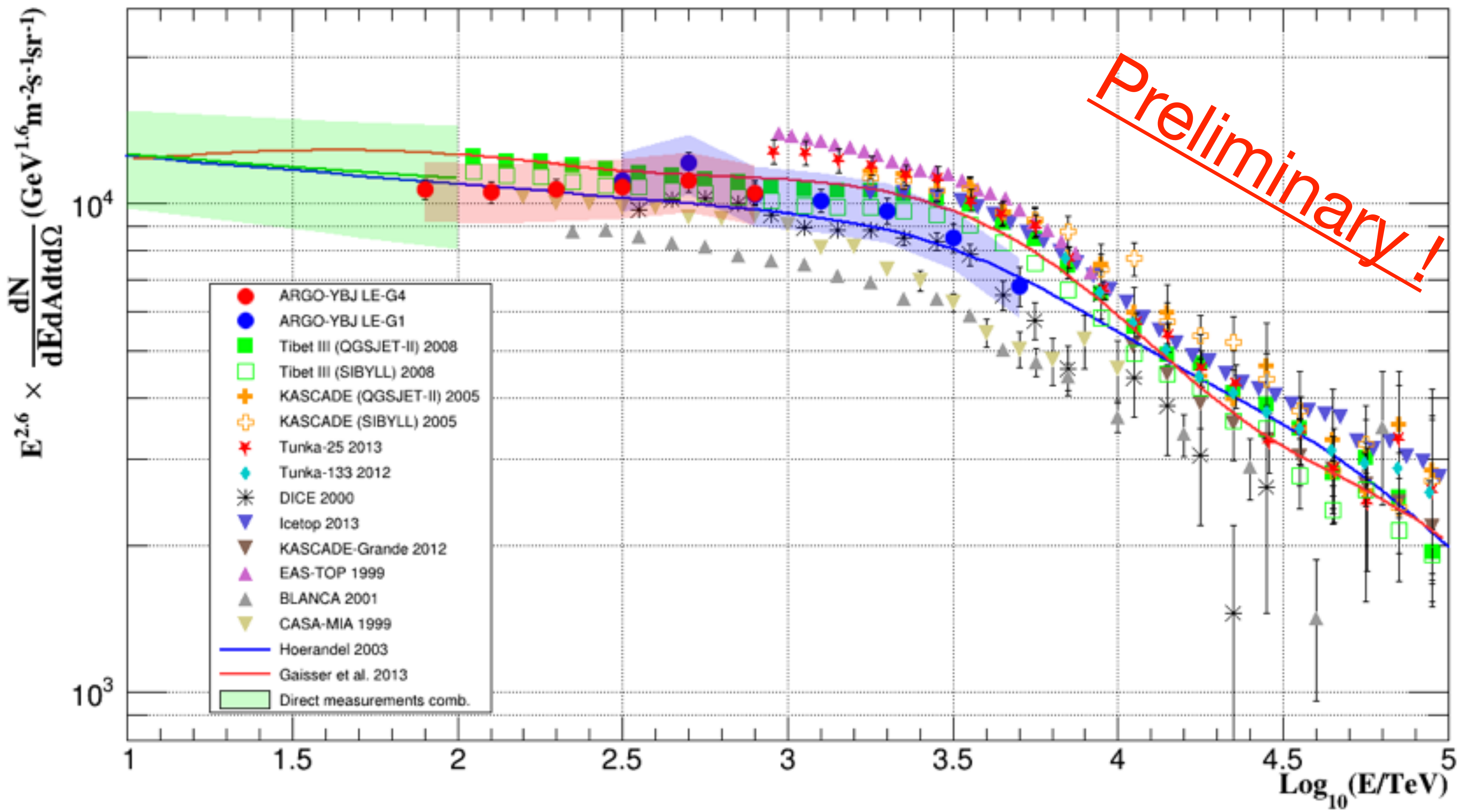
In the following plots an over-conservative ±14% shaded area has been temporarily drawn on the flux measurements.
Error bars show the statistical uncertainties.

The “all-particle” spectrum by ARGO-YBJ



The “all-particle” spectrum by ARGO-YBJ

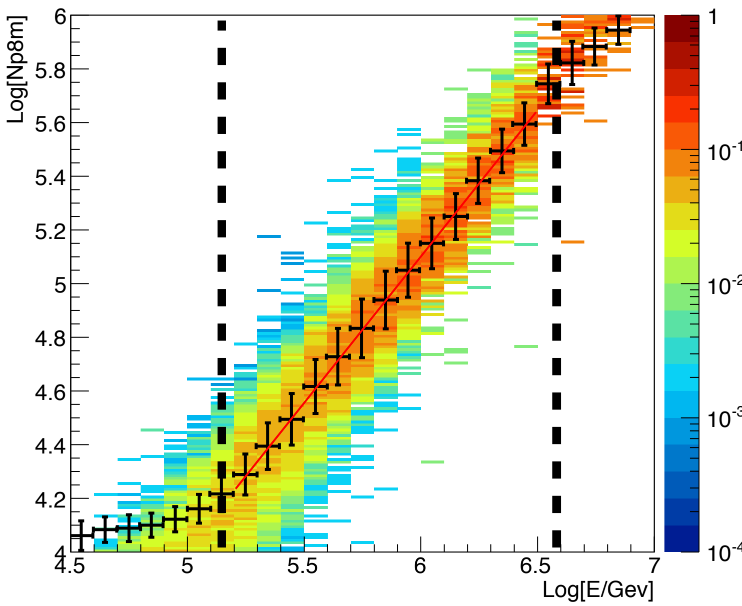
- Consistent picture with models and previous measurements
- Overlap with the two gain scales (different data,…)
- Suggest spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV



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

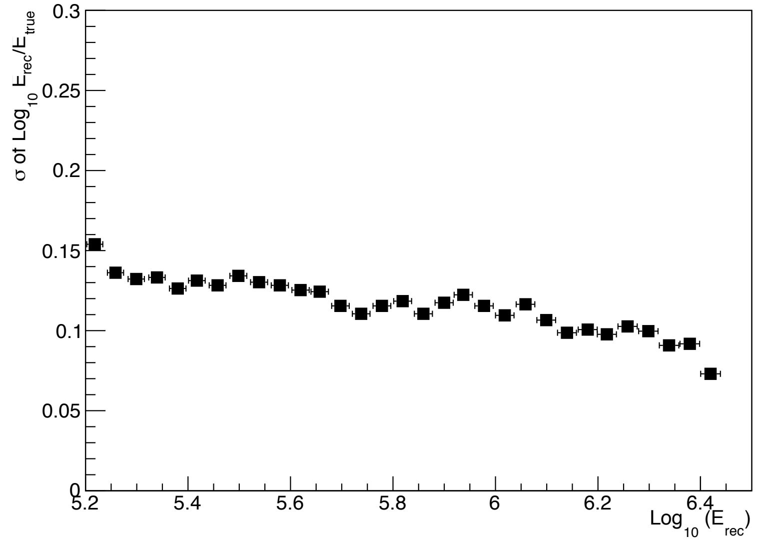


Selection of the light component: shower topology

Light Component (p+He) selection:

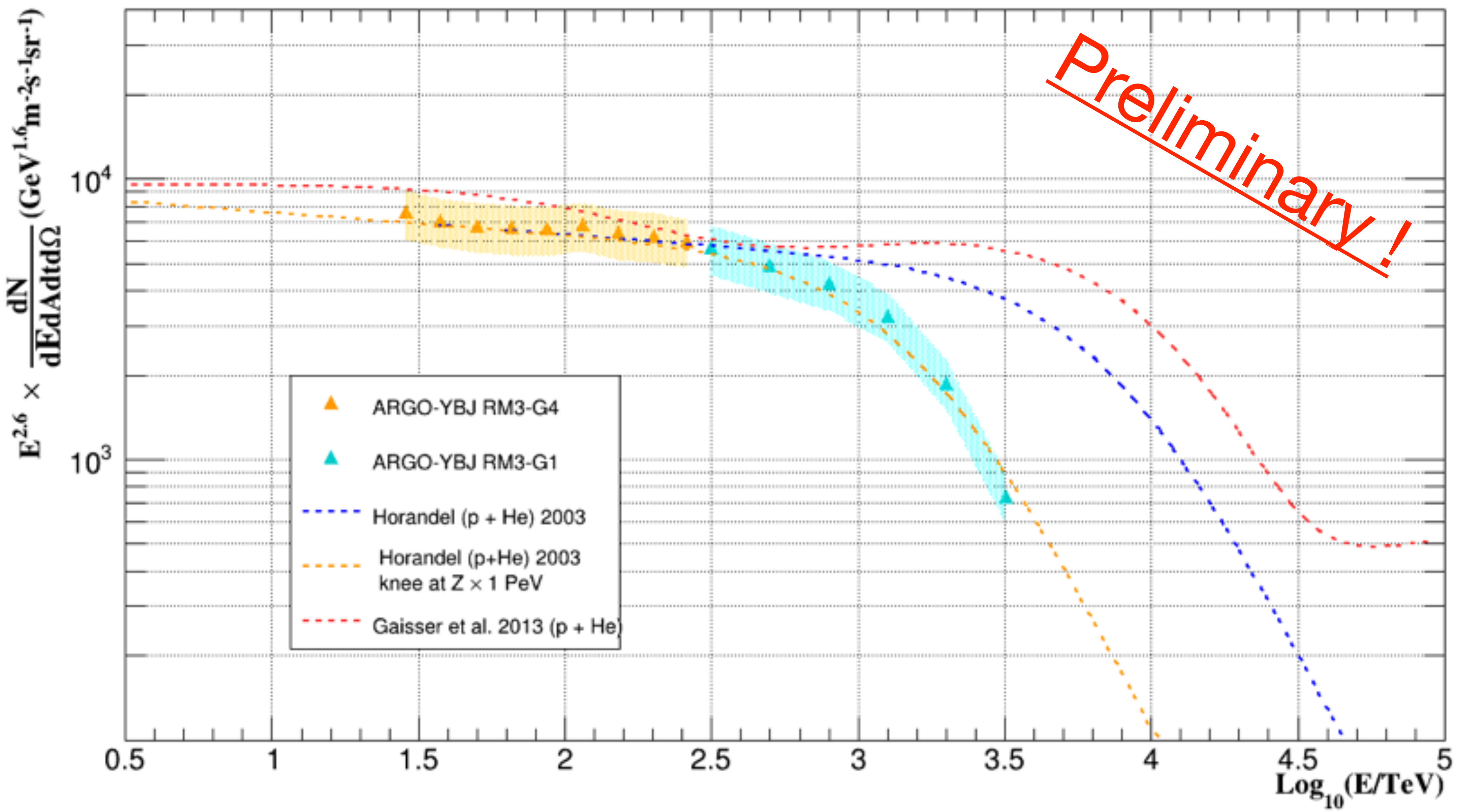
$$\rho_{A20} > \rho_{A42}$$

A20 = 20 innermost clusters
A42 = 42 outermost clusters



The light component spectrum by ARGO-YBJ (1)

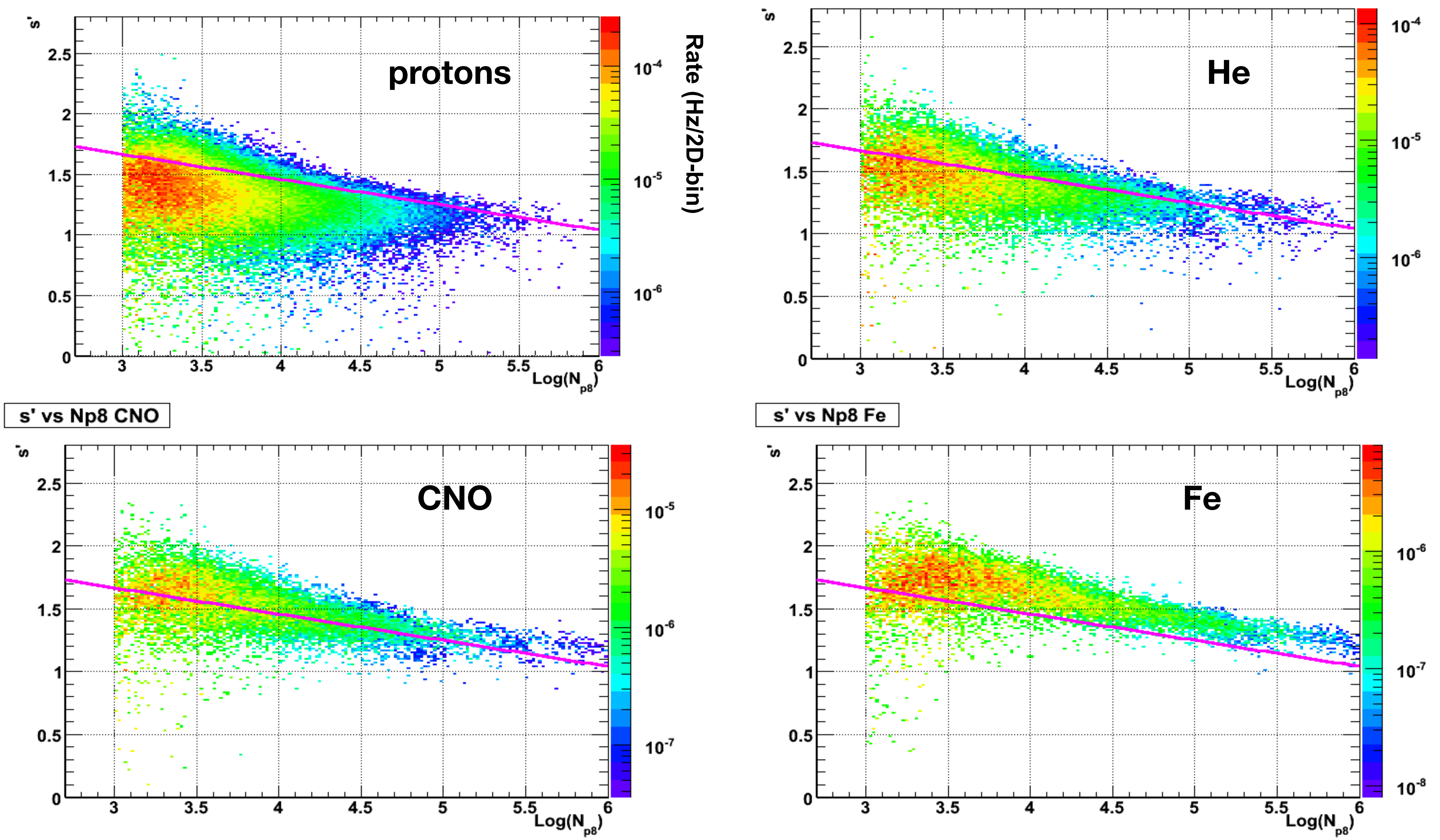
The Bayesian unfolding method used for the analysis of data below 200 TeV is adapted to the ARGO-YBJ analog data.



p and He selection

A simple cut in the plane s' vs Np8

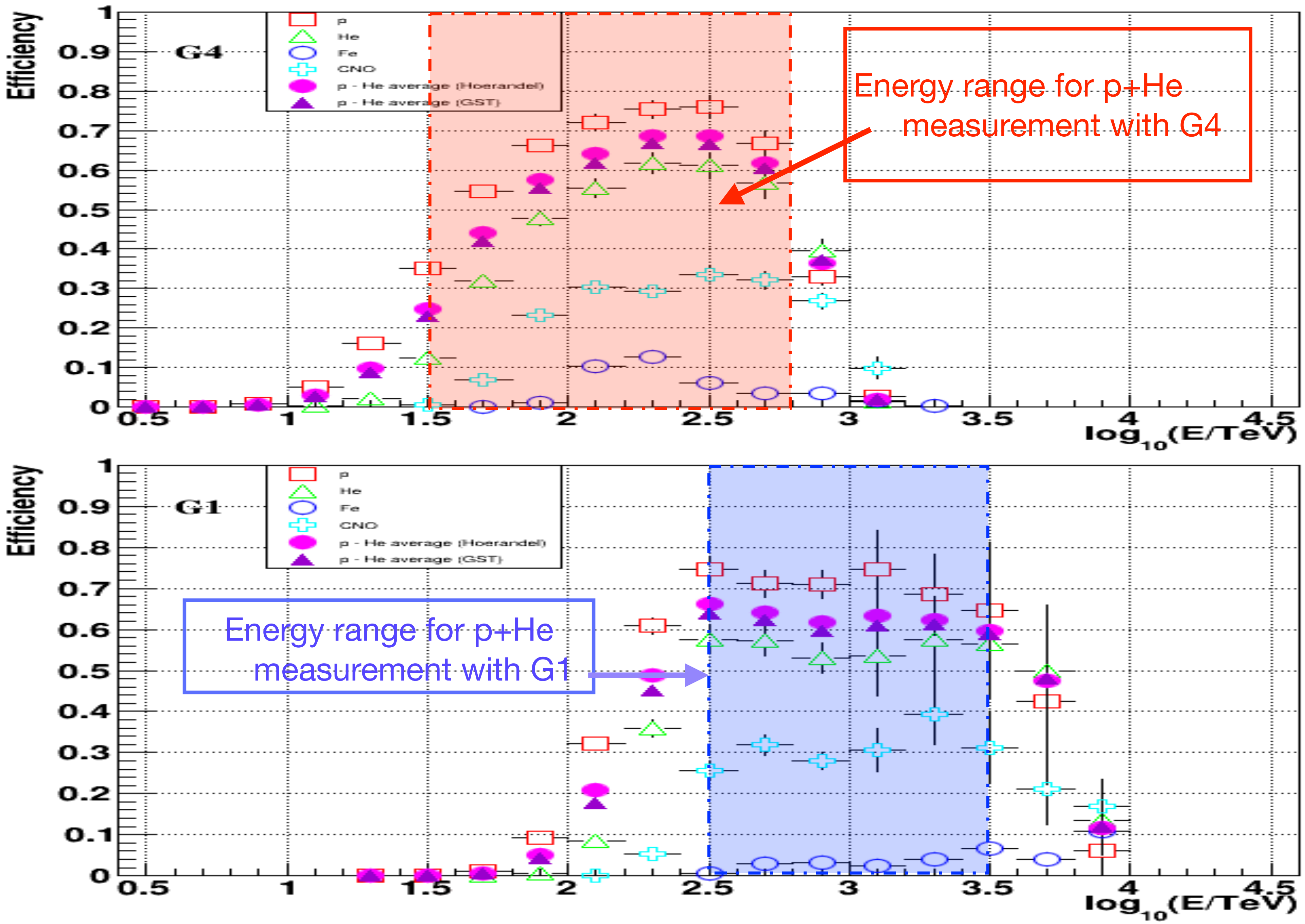
Contamination > CNO: ≈ 15%



MC Horandel spectra and normalizations

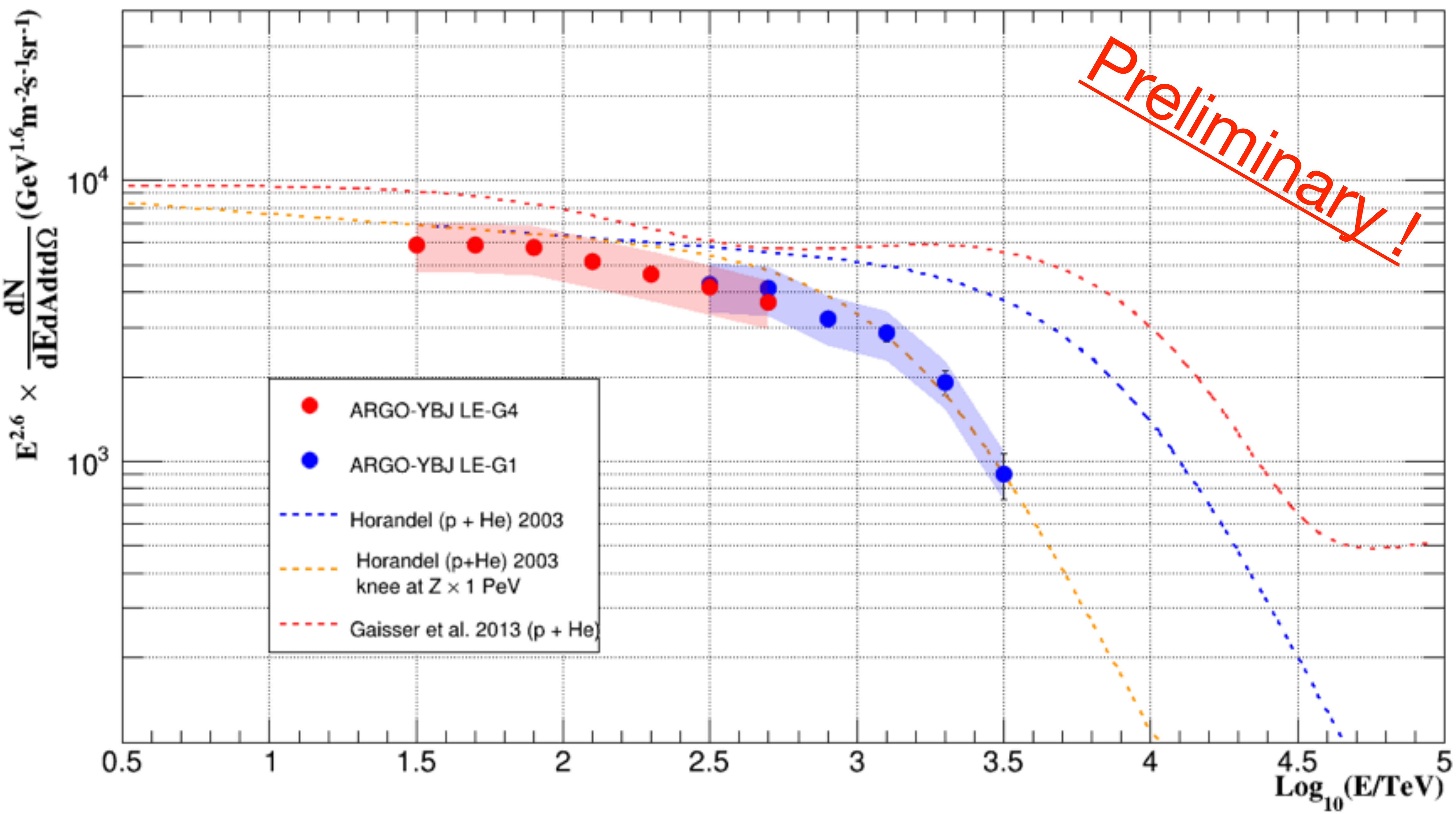
p+He: trigger and selection efficiencies

On the efficiency plateau above 200 TeV



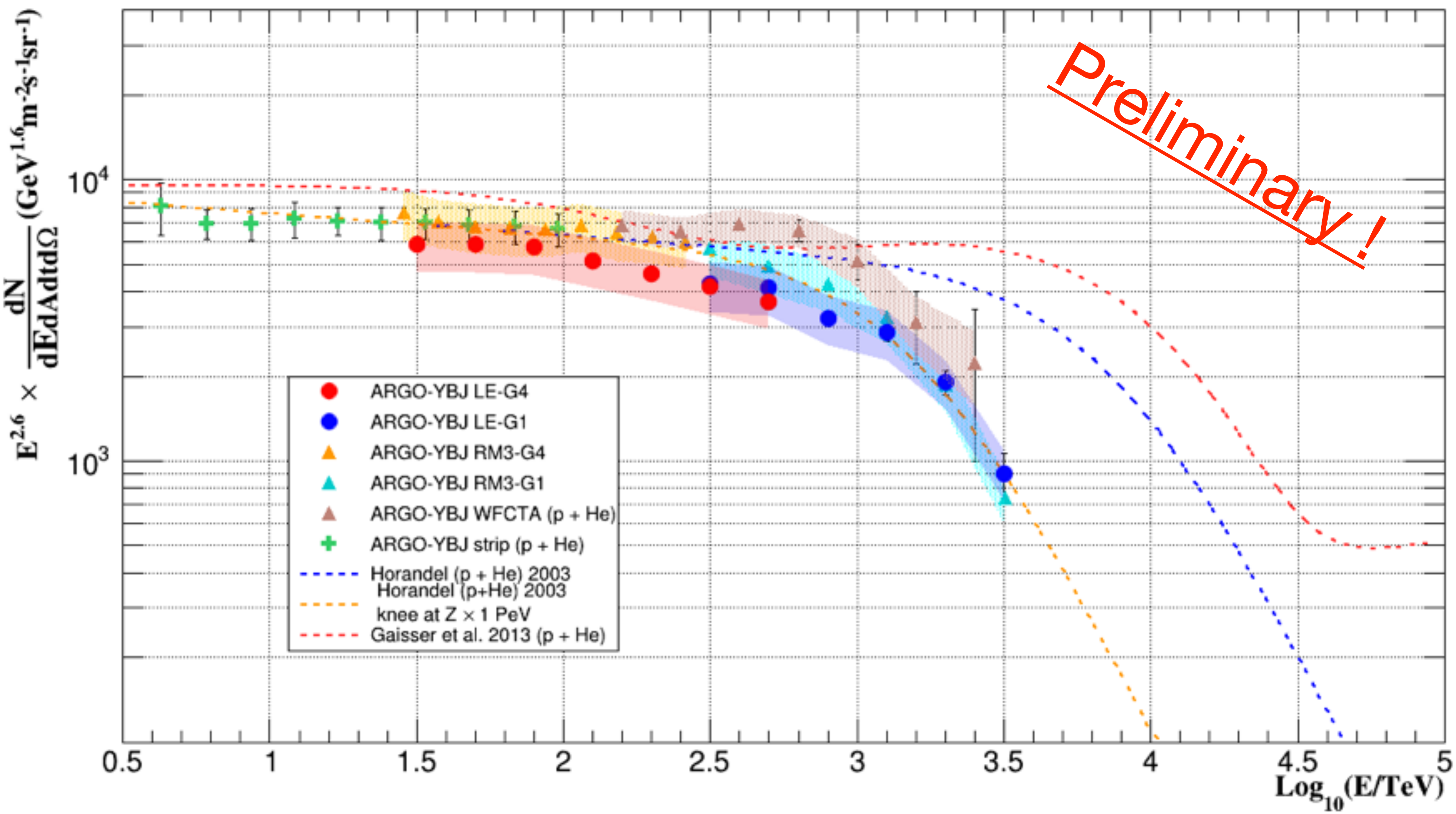
The light component spectrum by ARGO-YBJ (2)

Observation of gradual change of the slope starting around 650 TeV



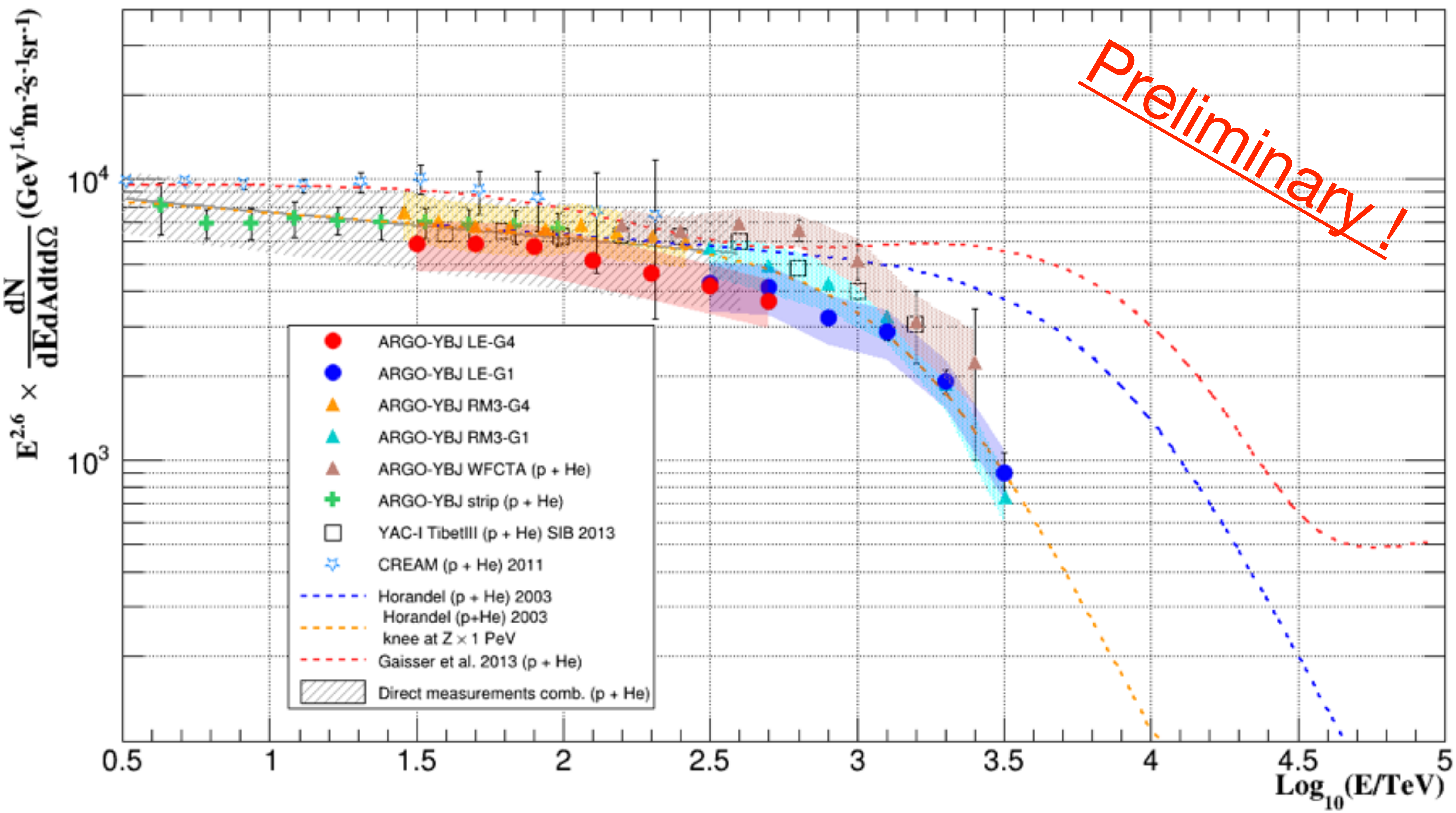
Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Observation of gradual change of the slope starting around 650 TeV



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

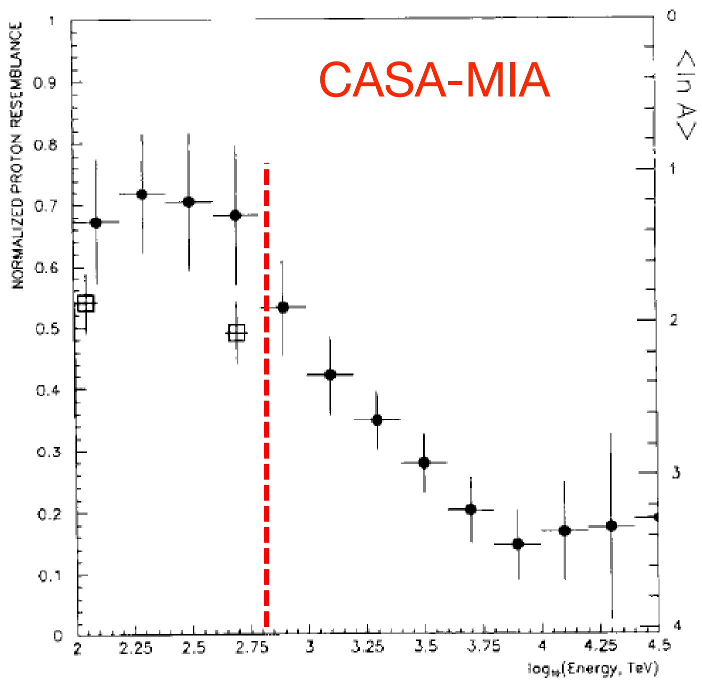
Comparison with direct measurements and with Tibet ASgamma (SYBILL)

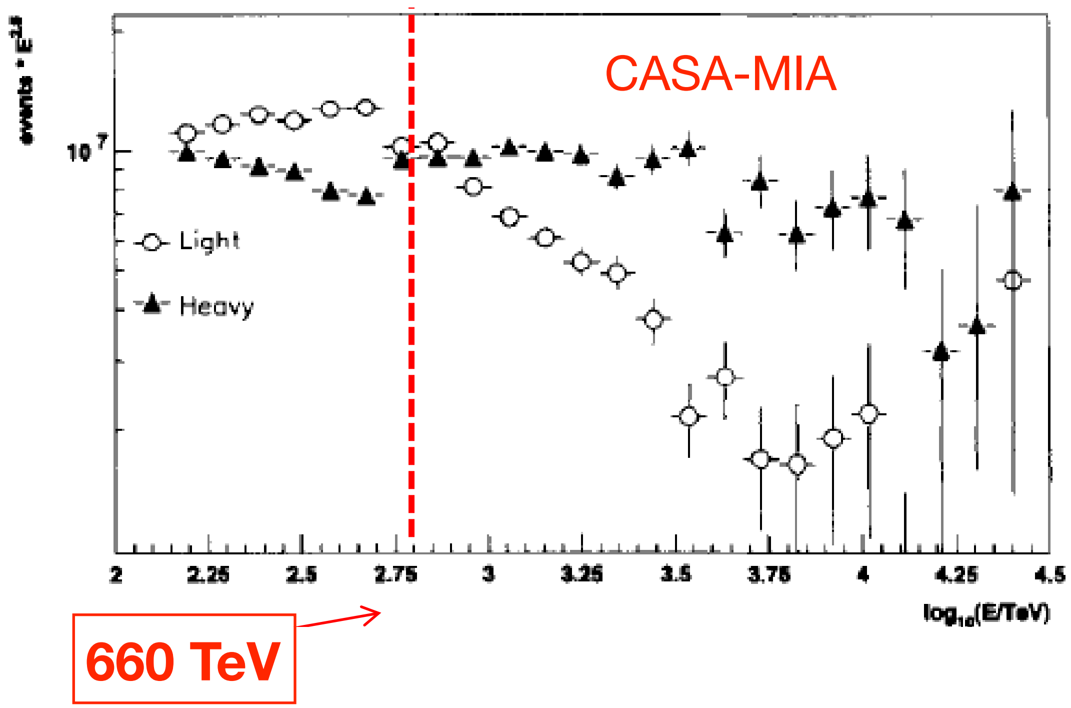


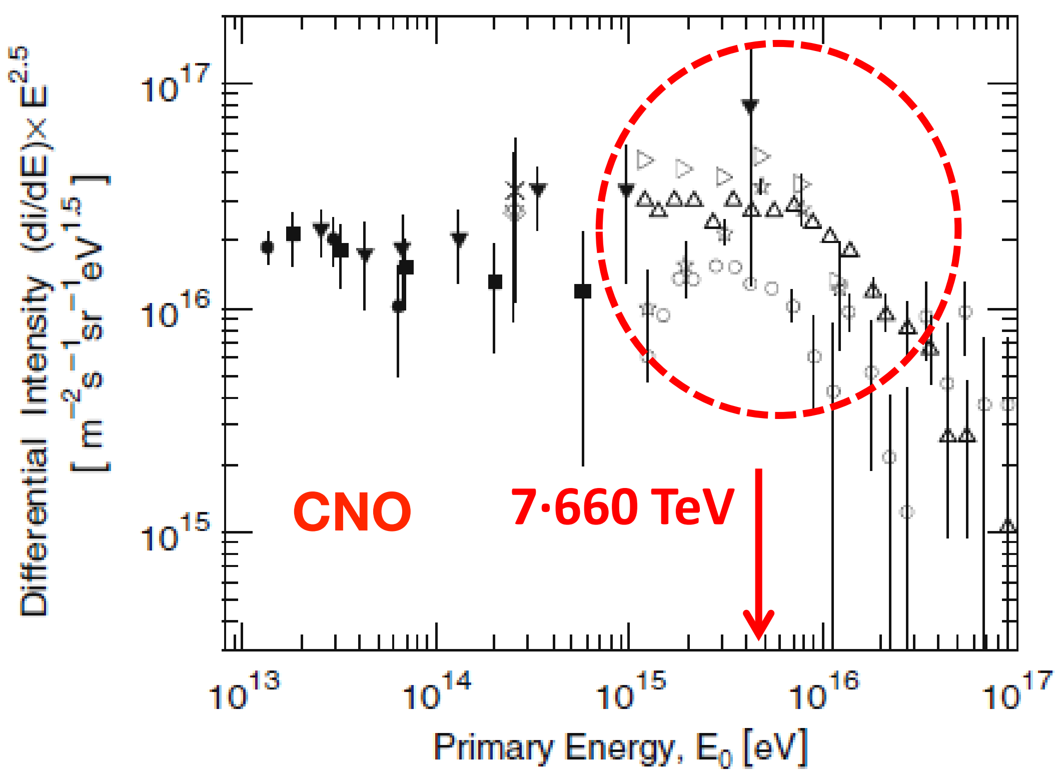
Other results

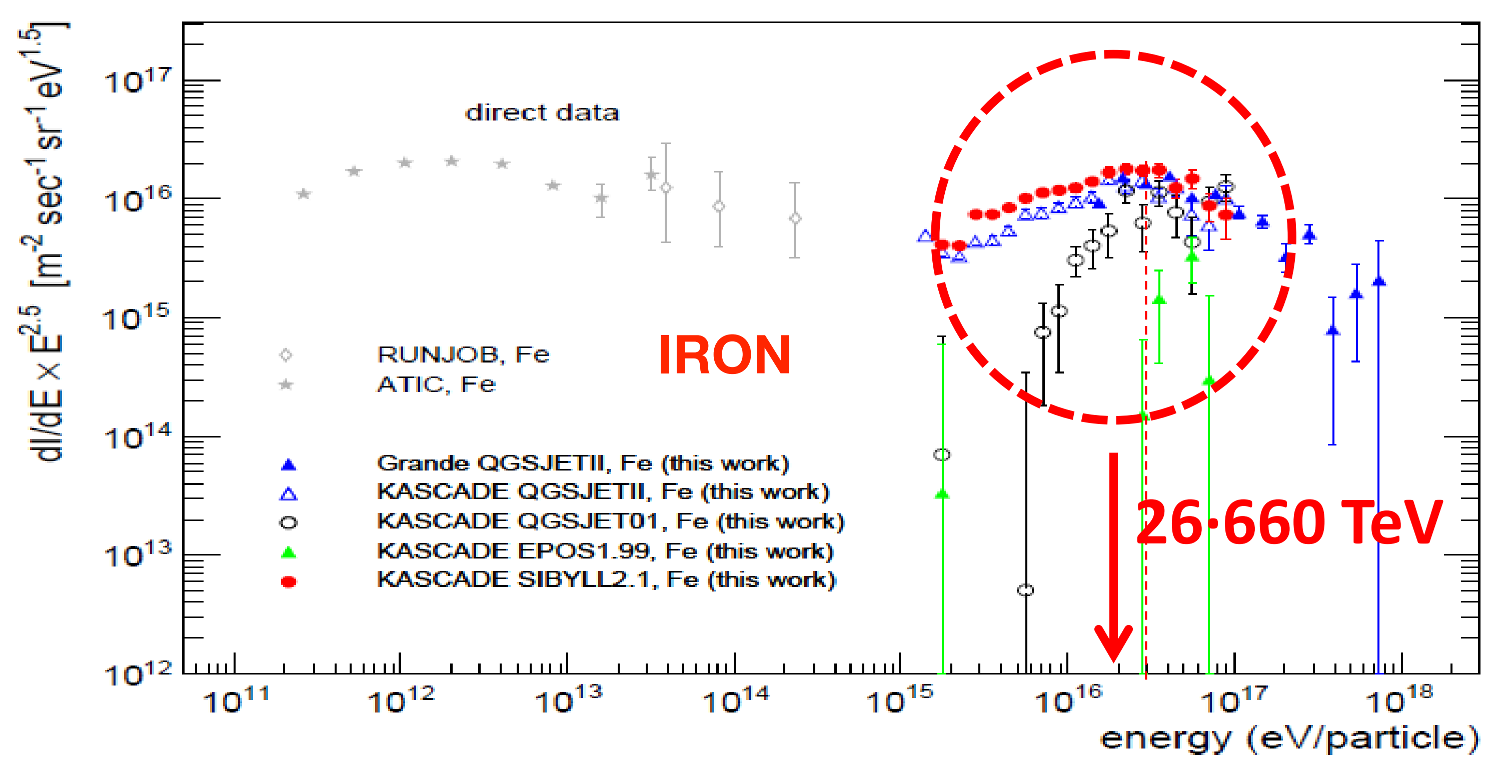
The cosmic ray composition between 10^{14} and 10^{16} eV

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]

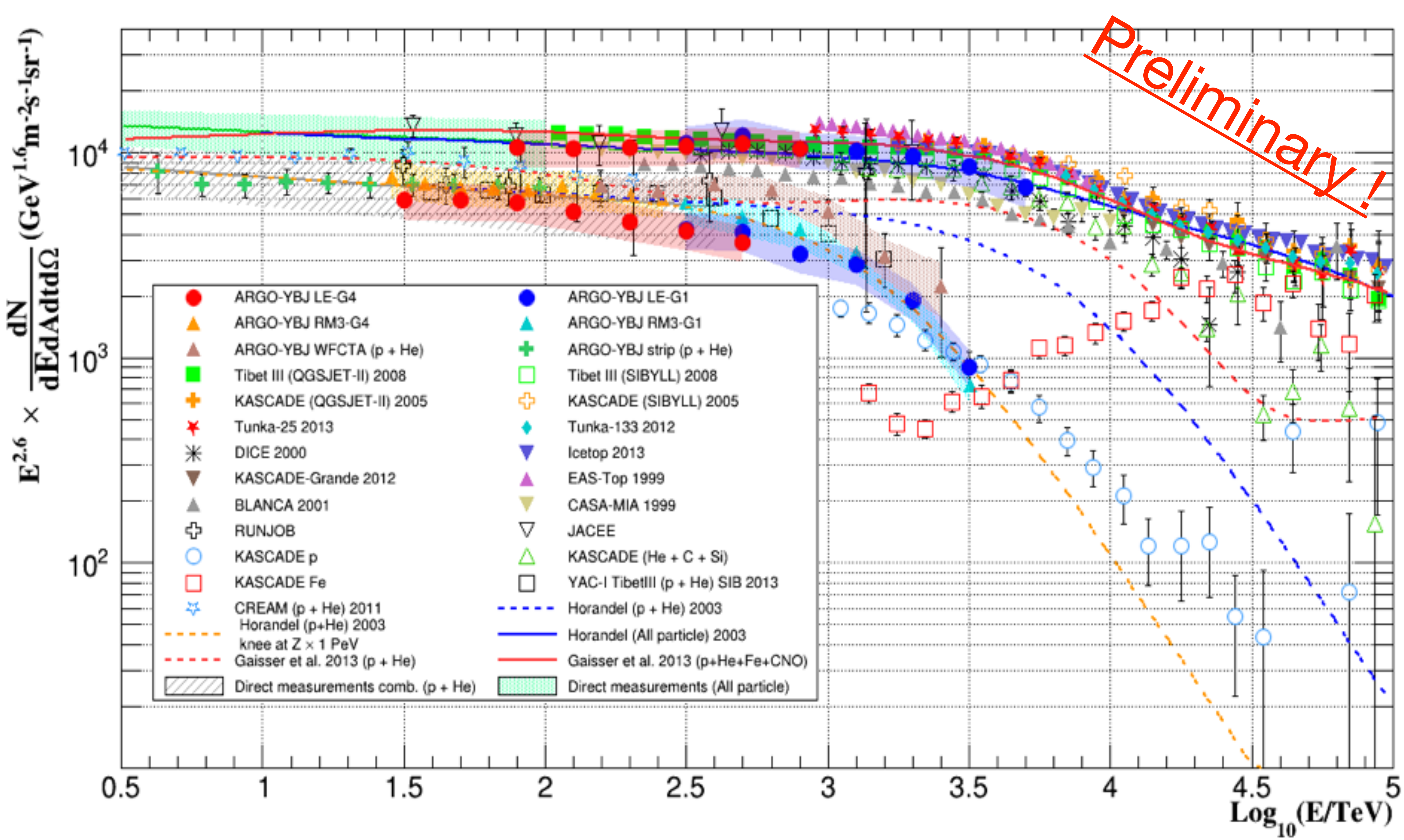








The overall picture



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.

- We measured the CR energy spectrum in the TeV - 10 PeV energy range.
- Evidence for a bending in the p+He spectrum around 650 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
- Many cross check made and improvements on the way.
- Analysis with the full statistics under way. Further gain scale under calibration but preliminary results consistent