Istituto Nazionale di Fisica Nucleare

THE COSMIC RAY SPECTRUM IN THE ENERGY REGION BETWEEN 10^{12} AND 10^{16} eV MEASURED BY ARGO-YBJ

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RICAP 16
6th Roma International Conference on AstroParticle Physics

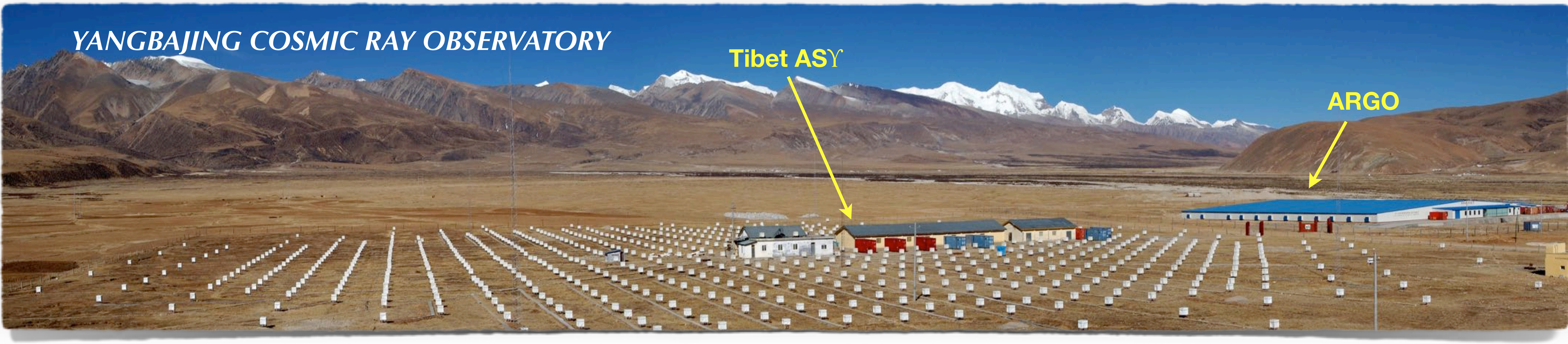
THE ARGO-YBJ EXPERIMENT

ASTROPHYSICAL RADIATION WITH GROUND BASED OBSERVATORY AT YANGBAJING

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

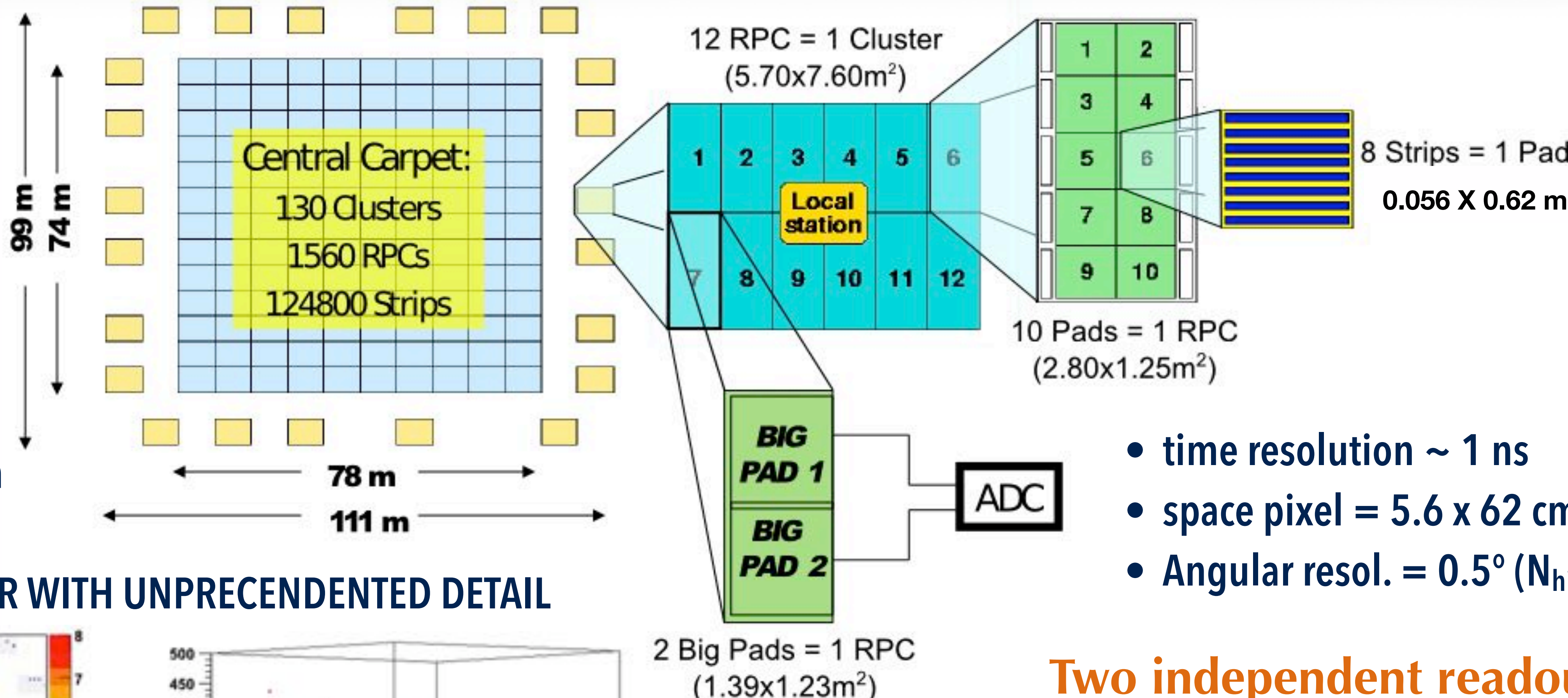
- COSMIC RAY PHYSICS
- GAMMA RAY ASTRONOMY

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

THE ARGO-YBJ EXPERIMENT

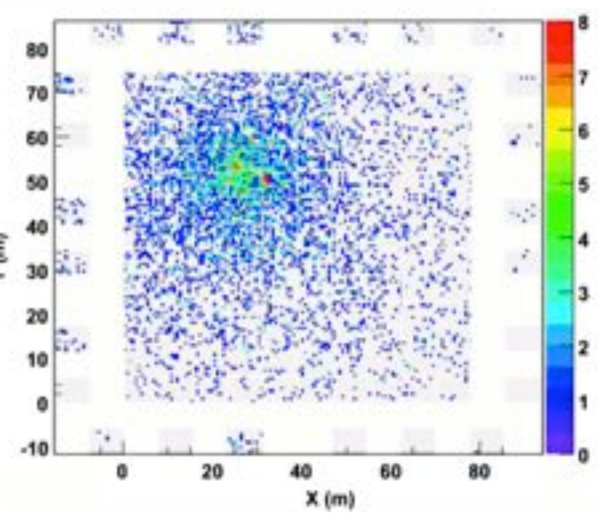
DETECTOR LAYOUT

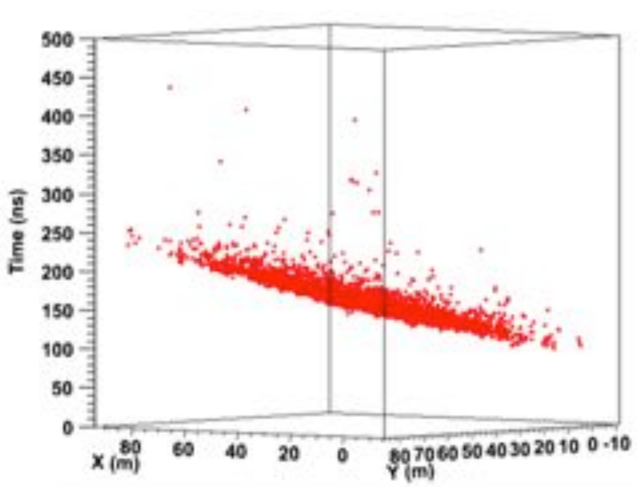


- High Altitude
- Full Coverage
- High segmentation

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

- IMAGE THE SHOWER WITH UNPRECENDENTED DETAIL



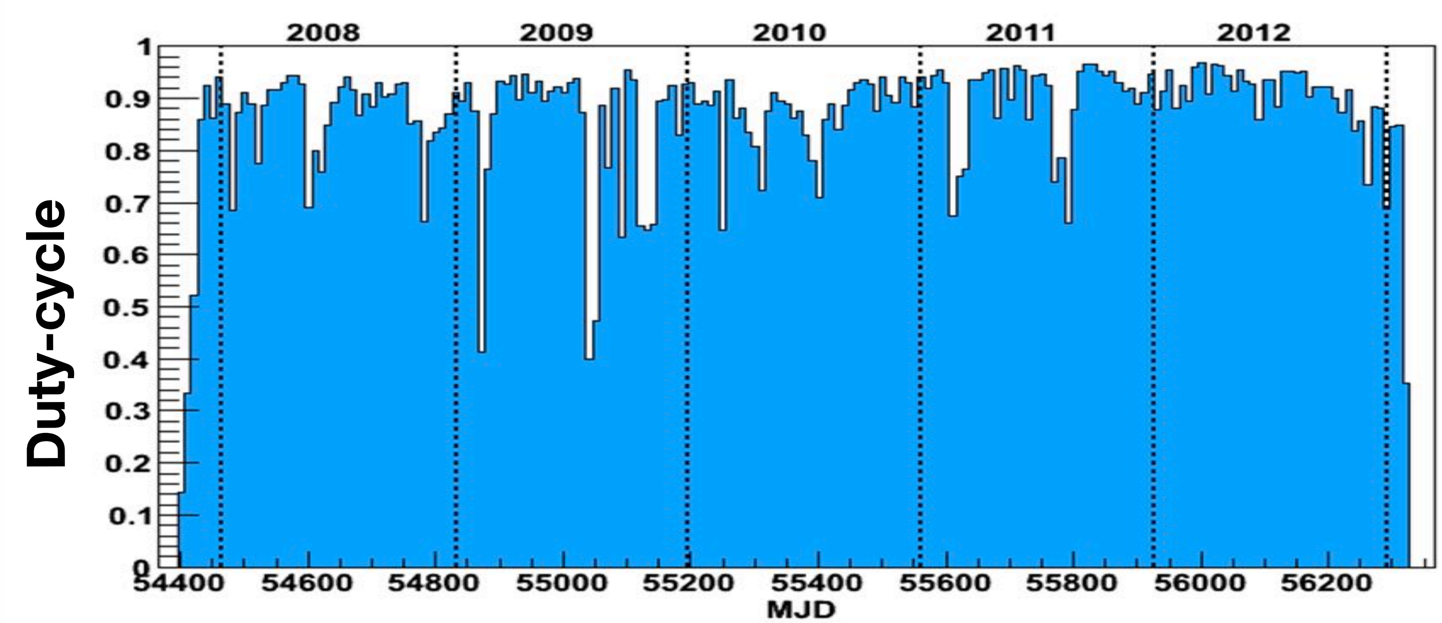


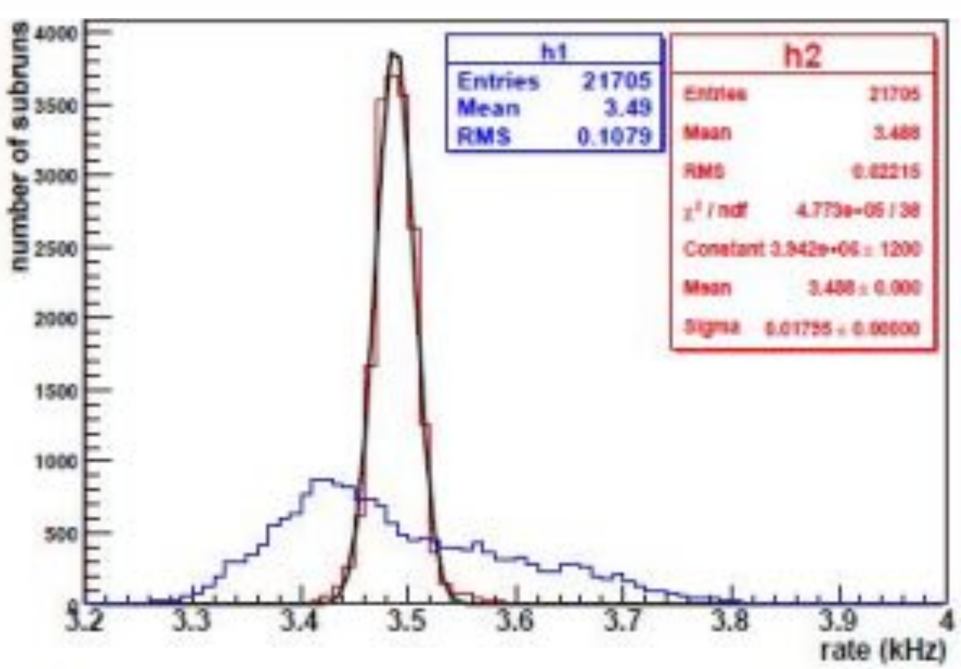
Two independent readout systems

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

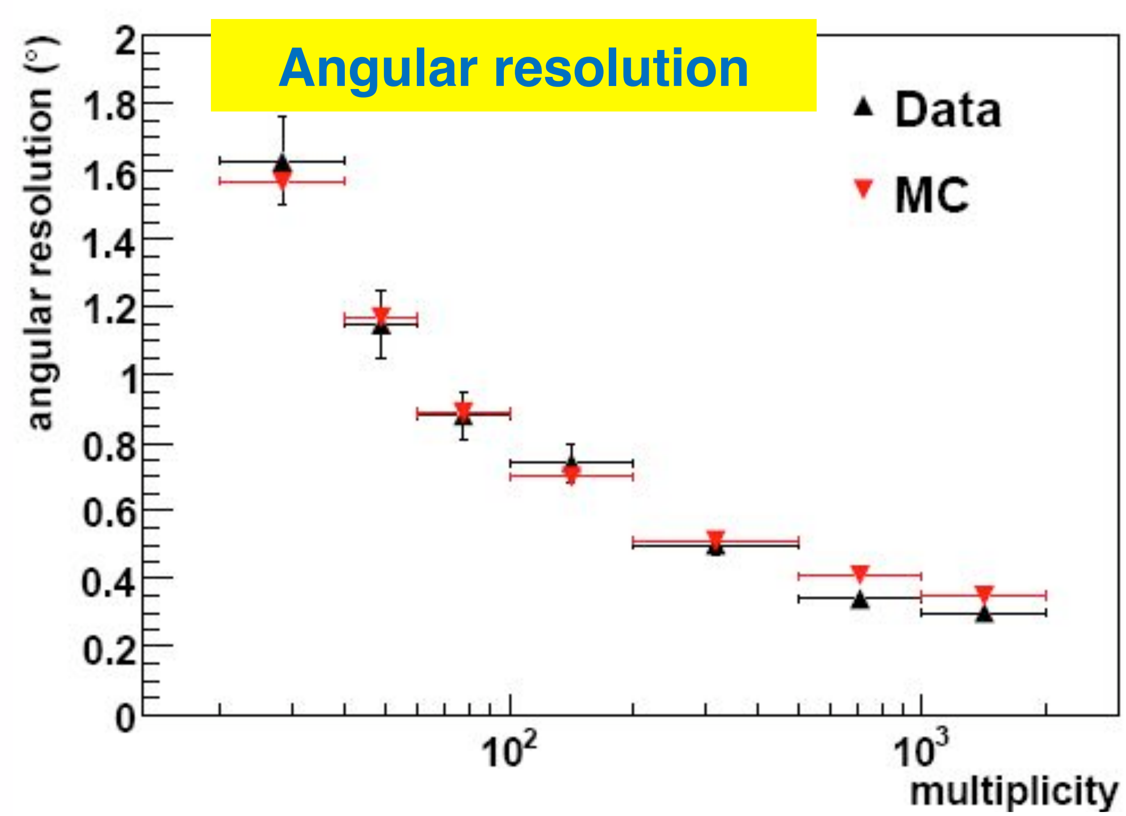
THE ARGO-YBJ EXPERIMENT

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





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



THE ARGO-YBJ EXPERIMENT

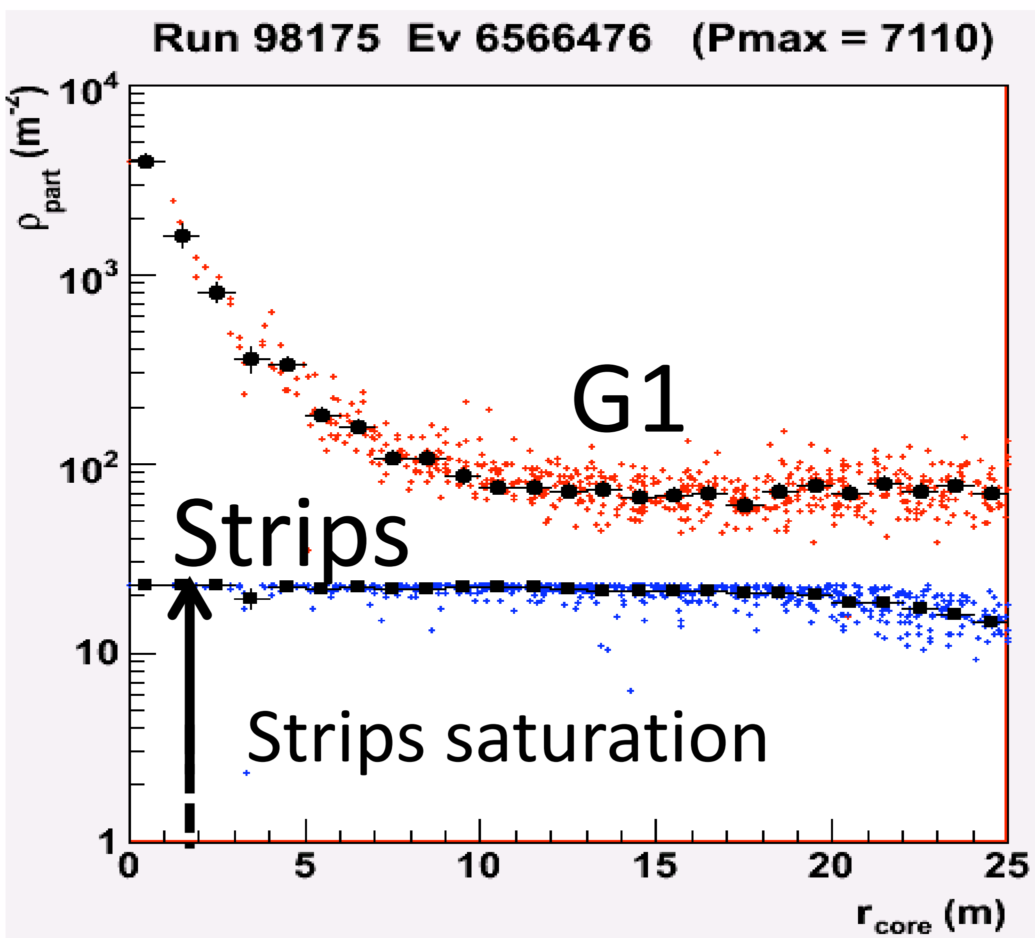
ANALOG READOUT

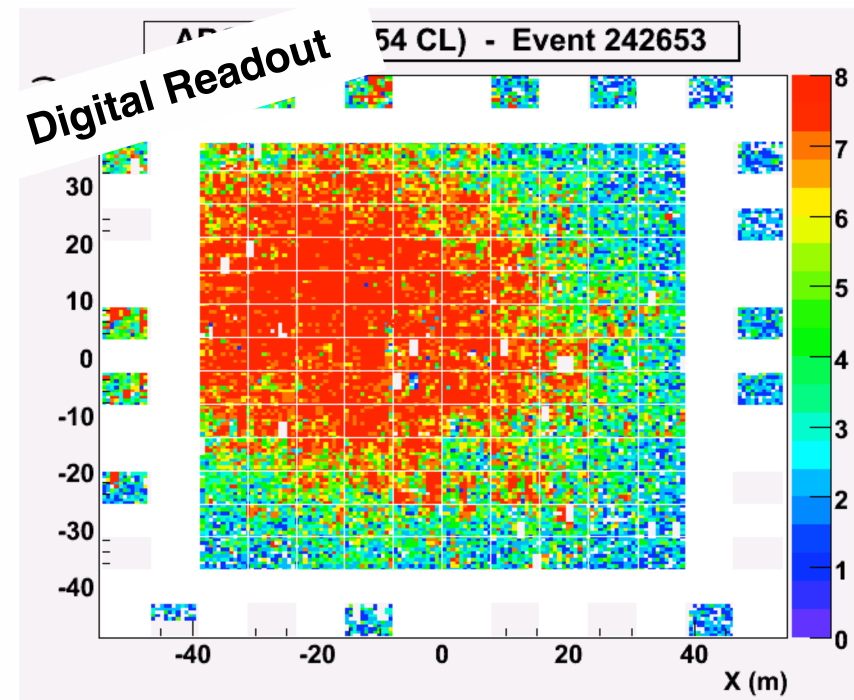
Astropart Phys 67 (2015) 47
NIM A 783 (2015) 68

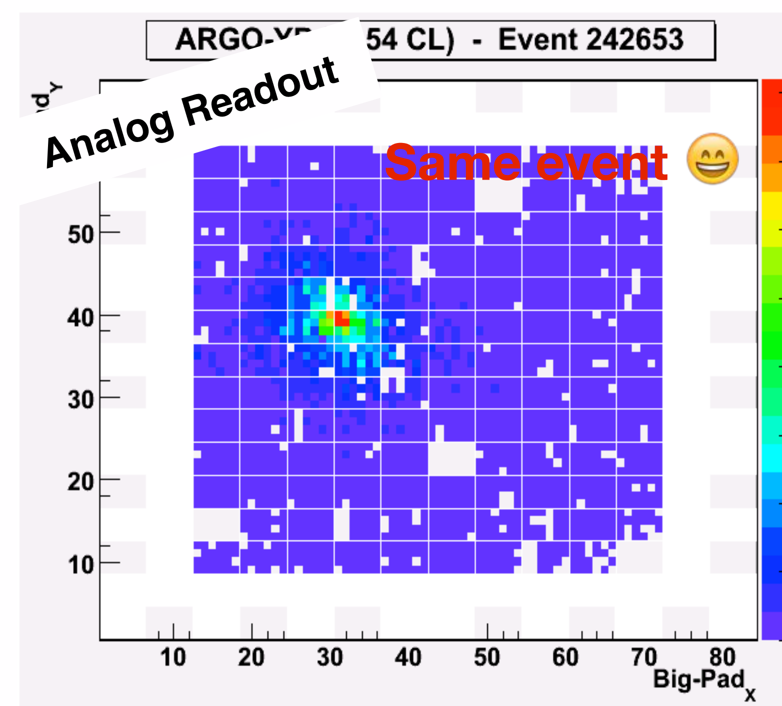
- EXTEND THE MAXIMUM ENERGY RANGE UP TO THE PeV REGION
  - Access the LDF down to the shower core
  - Sensitivity to primary mass
  - info/checks on Hadronic Interactions

Digital readout:
Showers up to ~23 particles/m^2

Analog Readout
Showers up to ~10^4 particles/m^2







THE ARGO-YBJ EXPERIMENT

ANALOG READOUT

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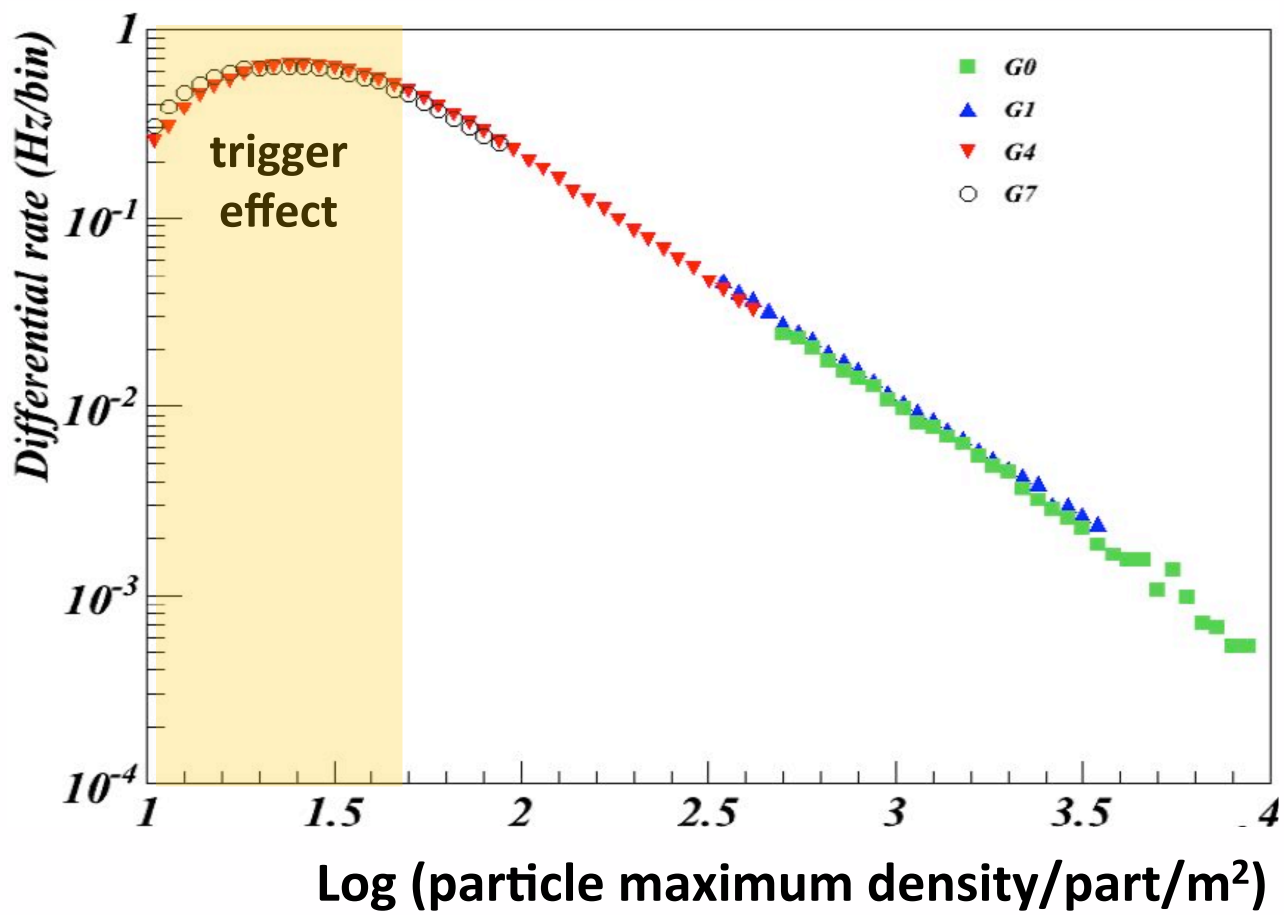
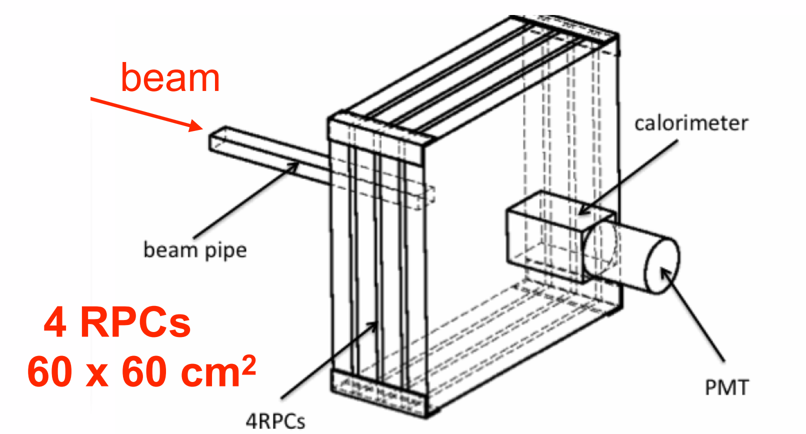
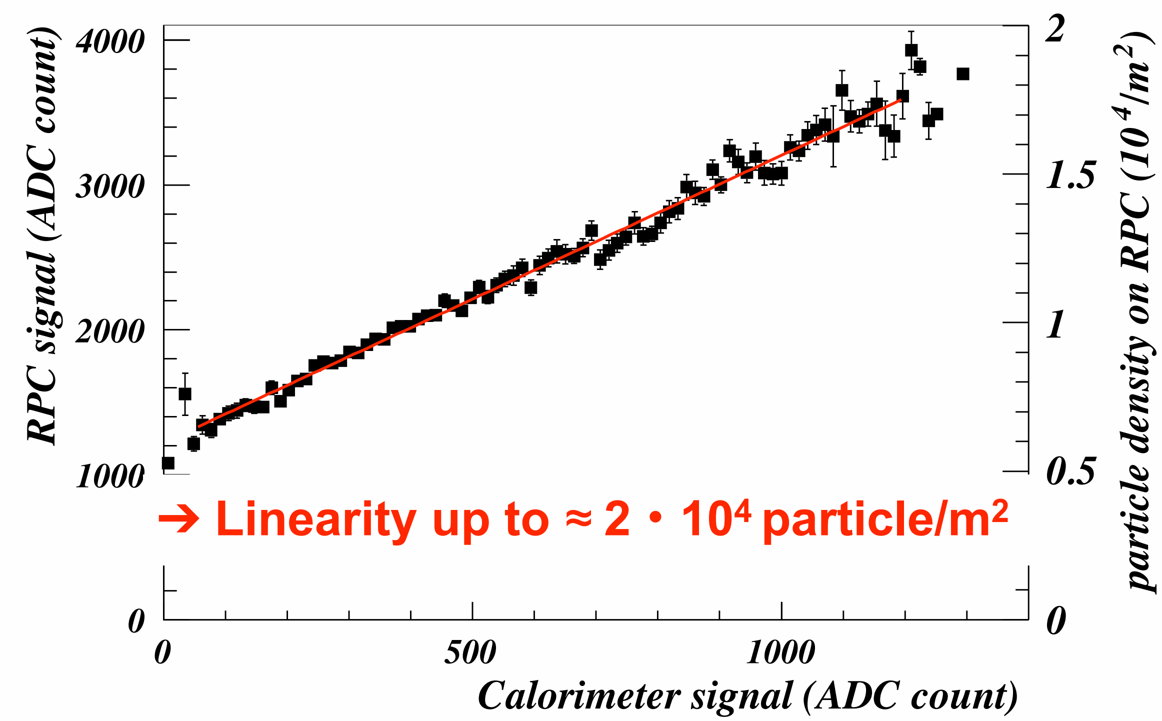
8 Different gain scales: G0…G7

HERE WE USE G4 AND G1 SCALES TO COVER A LARGE ENERGY RANGE BETWEEN 10 TeV and 5 PeV



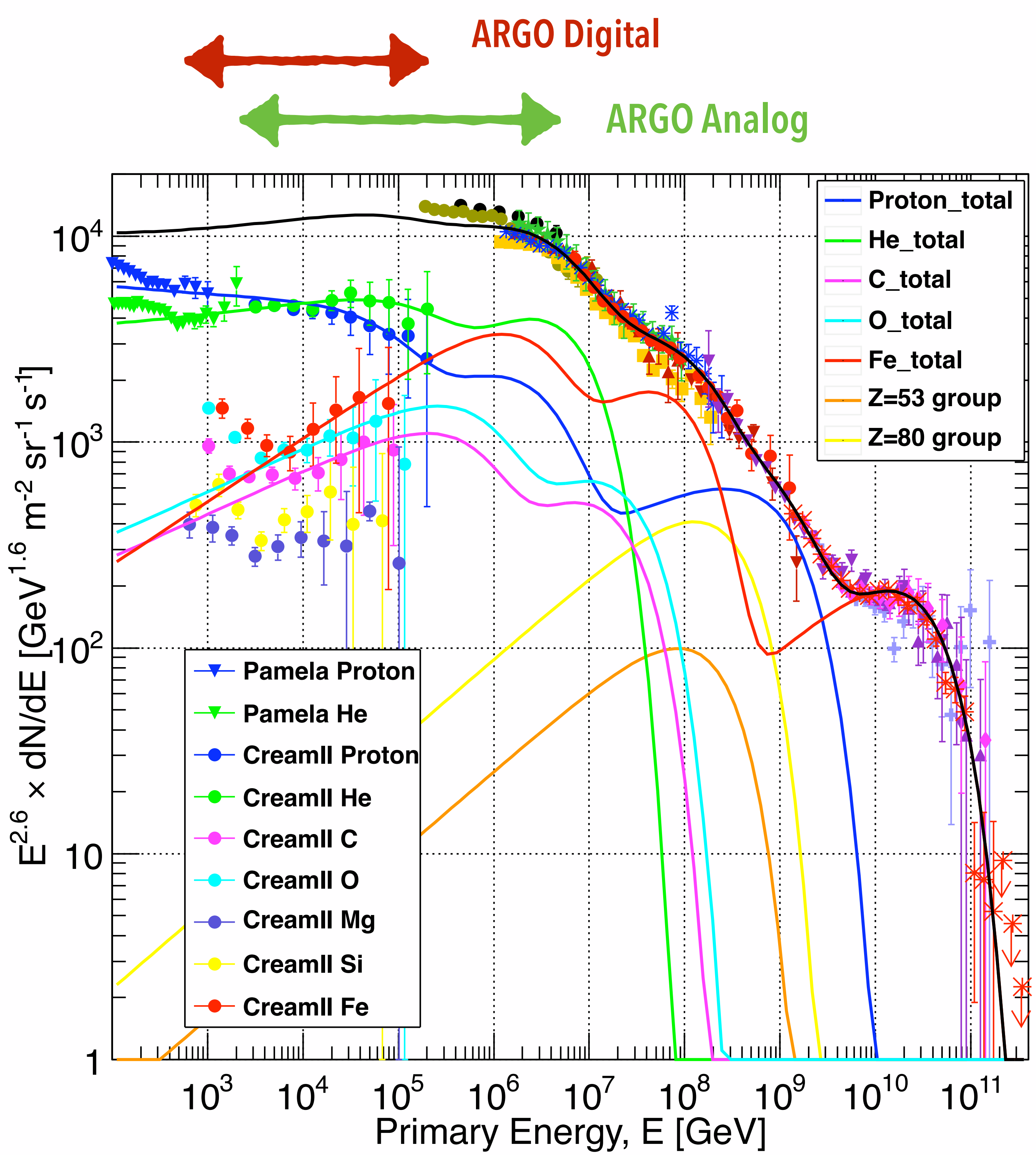
TEST BEAM @ LNF





MAIN GOALS IN CR PHYSICS

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



STRATEGY

- **Learn information about the energy spectrum from the experimental data by using probability theory**

Analysis based on the N^8 parameter: the number of particle within 8 m from the shower core position.

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

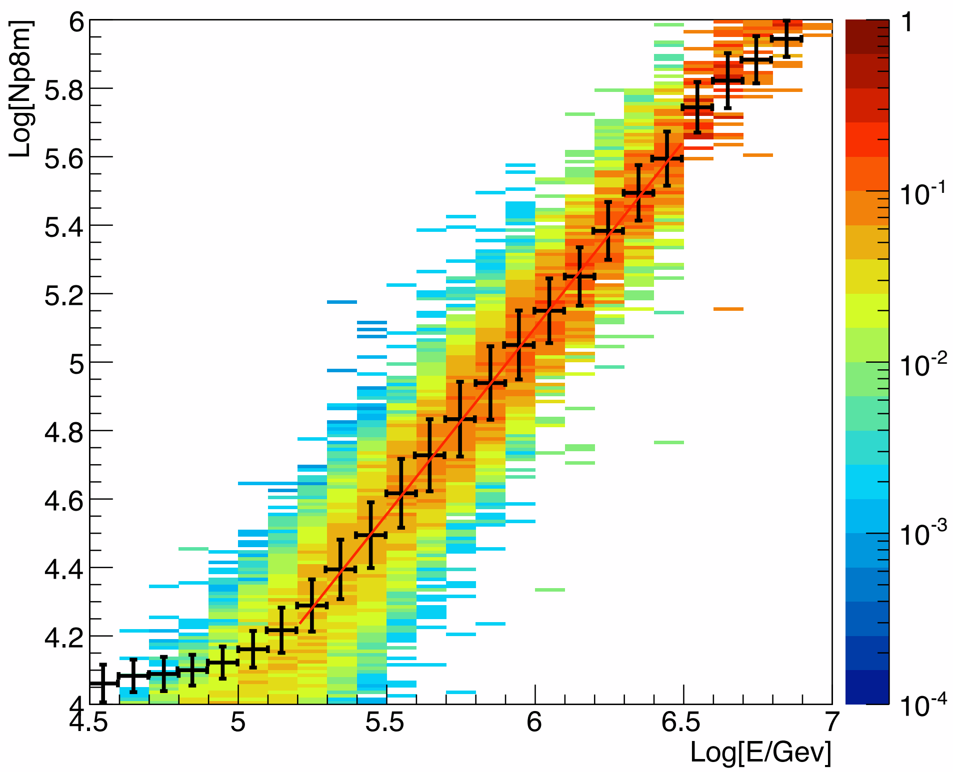
$$N(E, ID) = P(E, A|N^8, LDF) \cdot N(N^8, LDF)$$

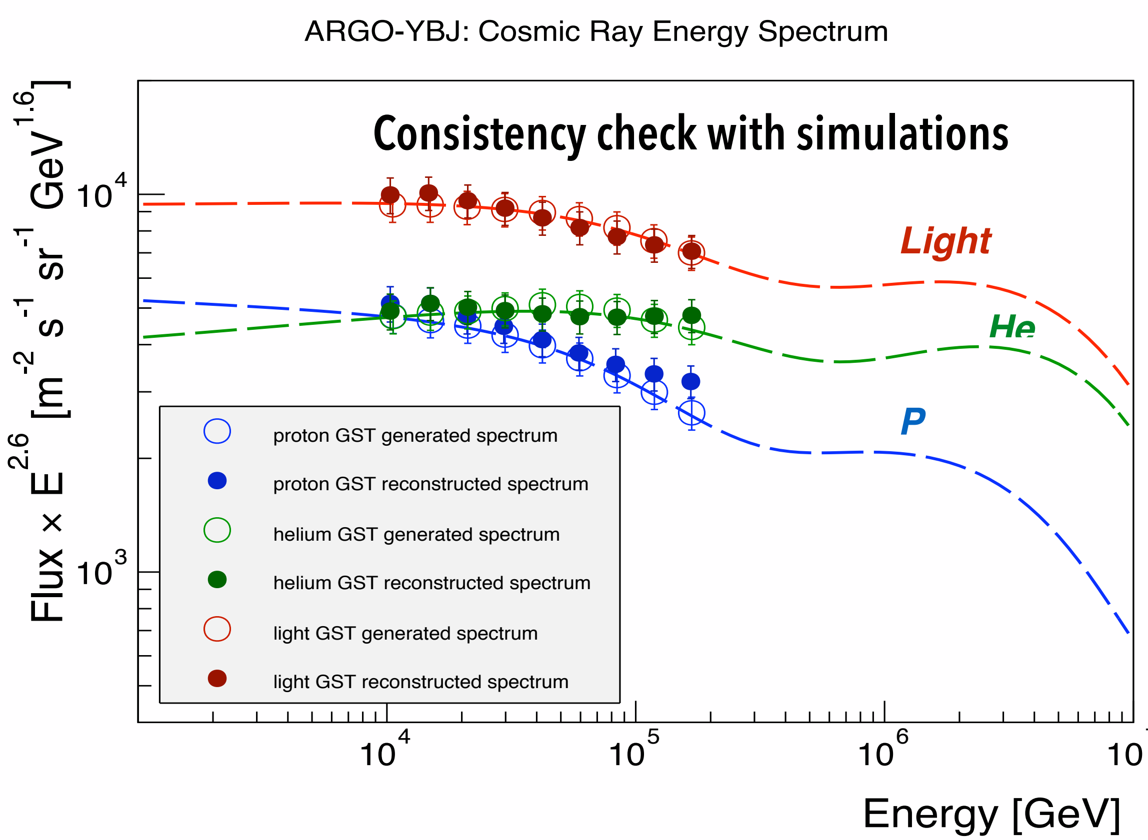
MC + Bayes

Light/Heavy discrimination based on the analysis of the LDF

$N^8 \rightarrow$ ENERGY

LDF $\rightarrow$ COMPOSITION



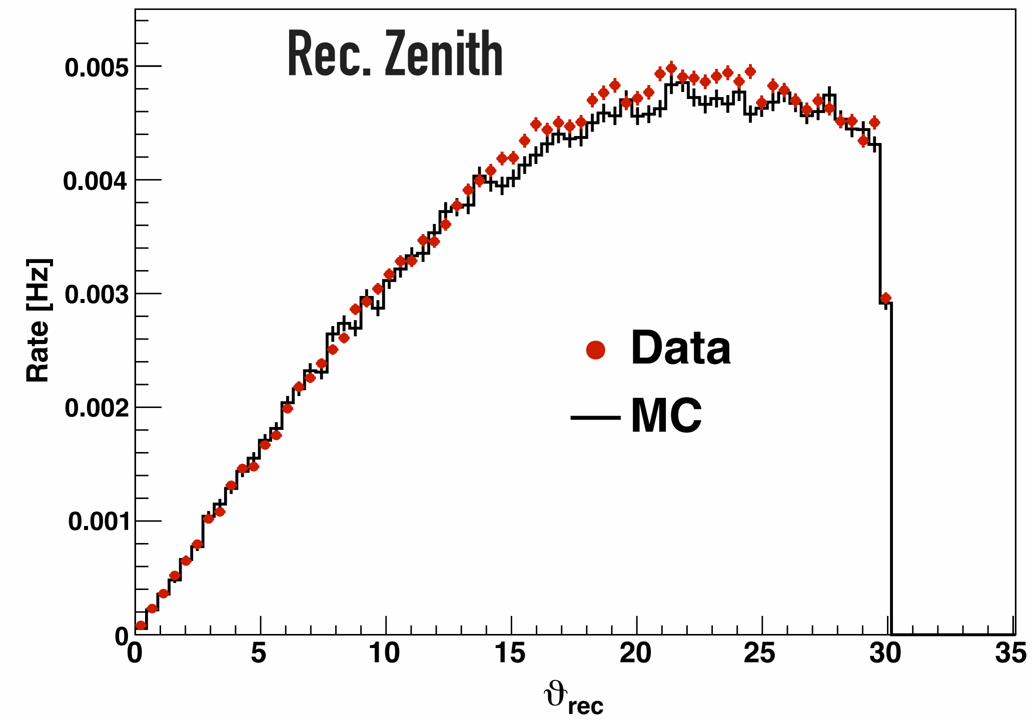


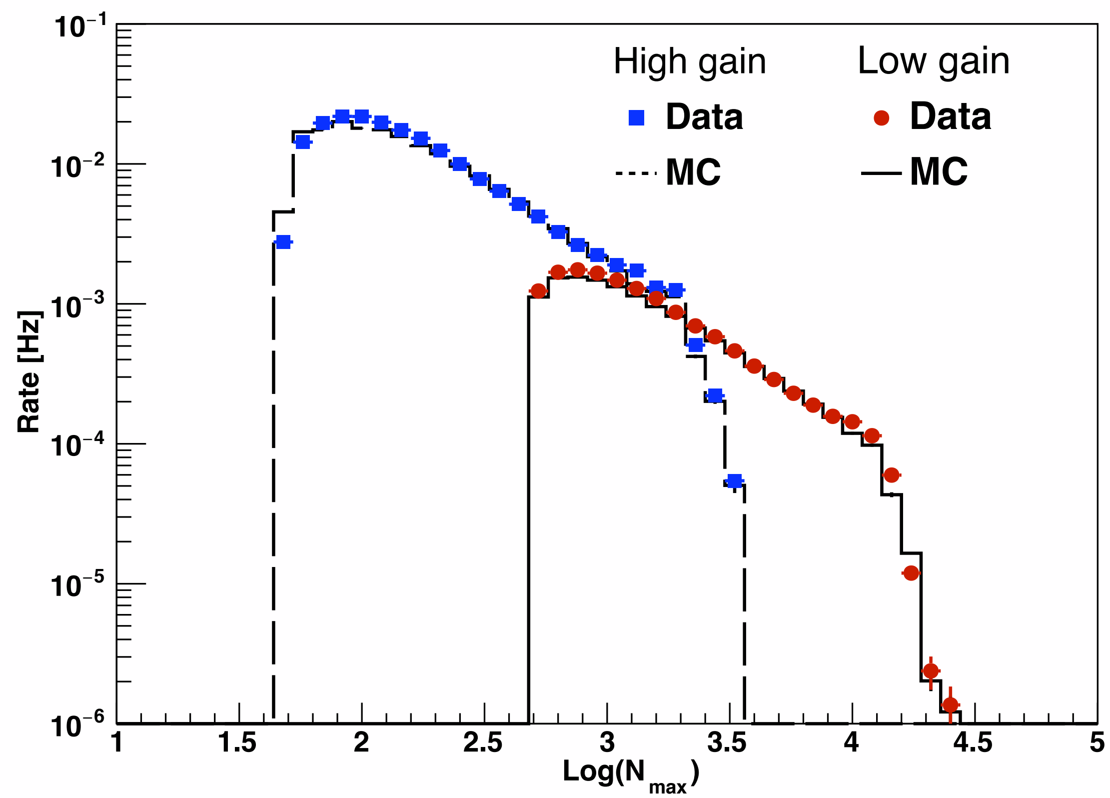
ANALOG DATA: ALL-PARTICLE & P+HE ENERGY SPECTRA

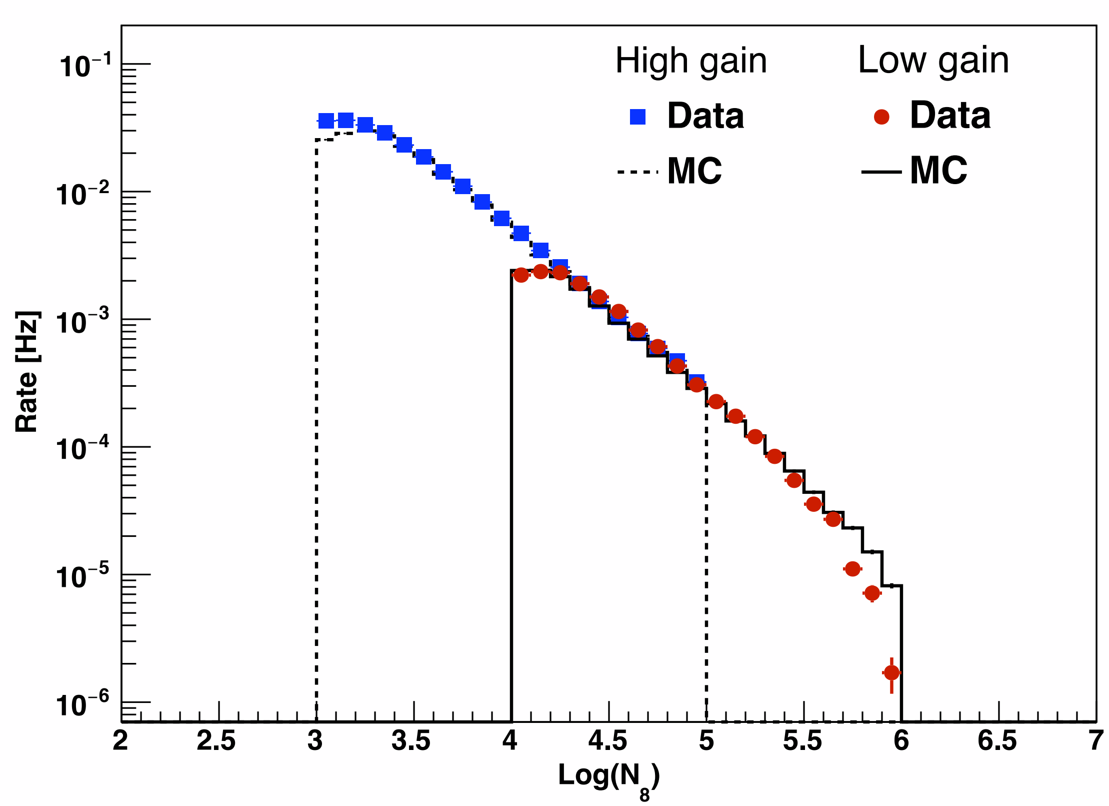
- Shower Core Pos.
- Rec. Zenith Angle
- N_{Max}, N_8

Good consistency between Data & MC

Cut	Data Surviving fraction (%)	Cumulative (%)	Monte Carlo Surviving fraction (%)	Cumulative (%)
Direction	70.2	70.2	68.7	68.7
Containment	40.3	28.3	43.3	29.7
Size	61.8	17.5	62.0	18.4
Maximum	91.7	16.0	89.0	16.4

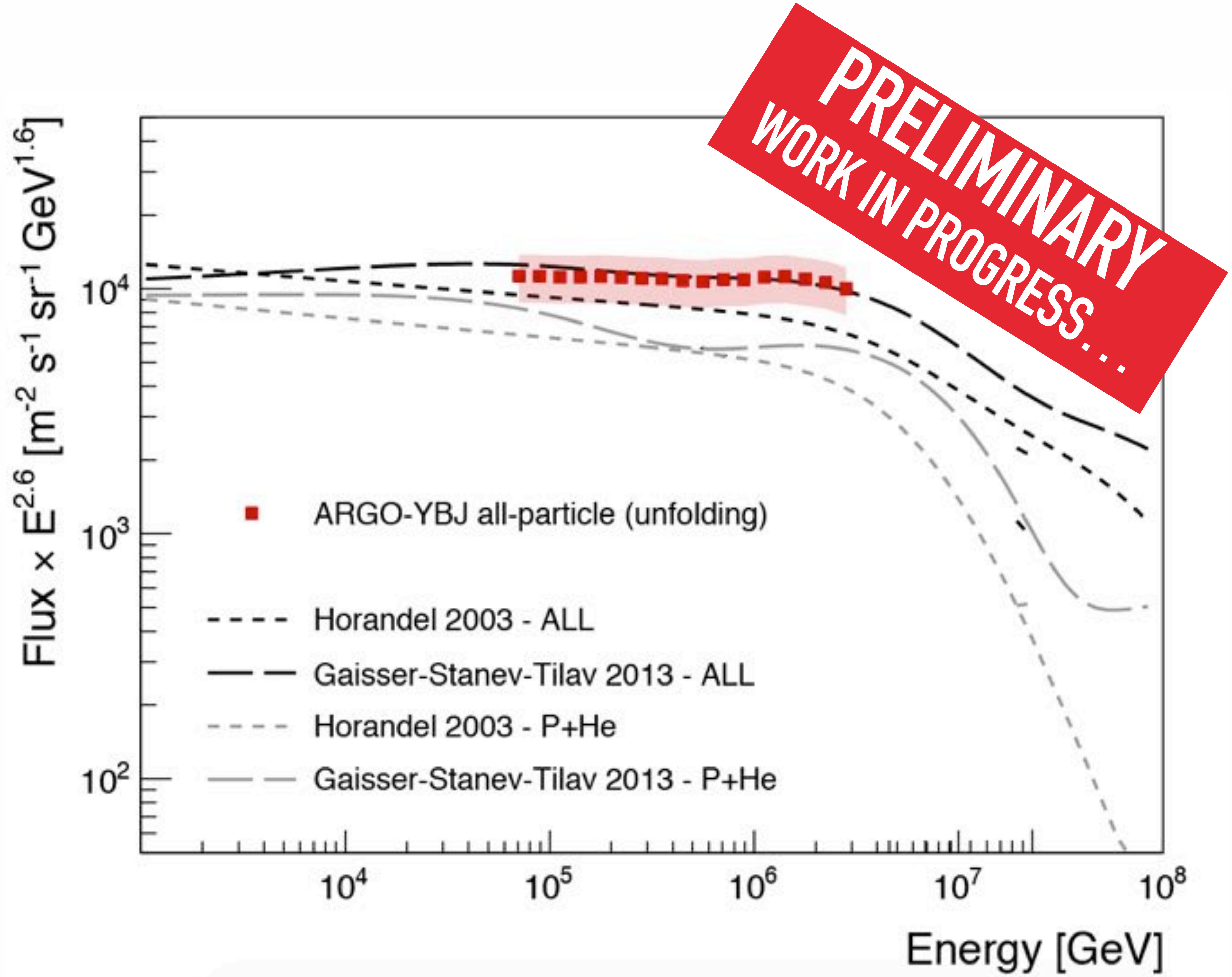






ALL-PARTICLE SPECTRUM

➡ CONSISTENT PICTURE WITH MODELS AND OTHER EXPERIMENTS

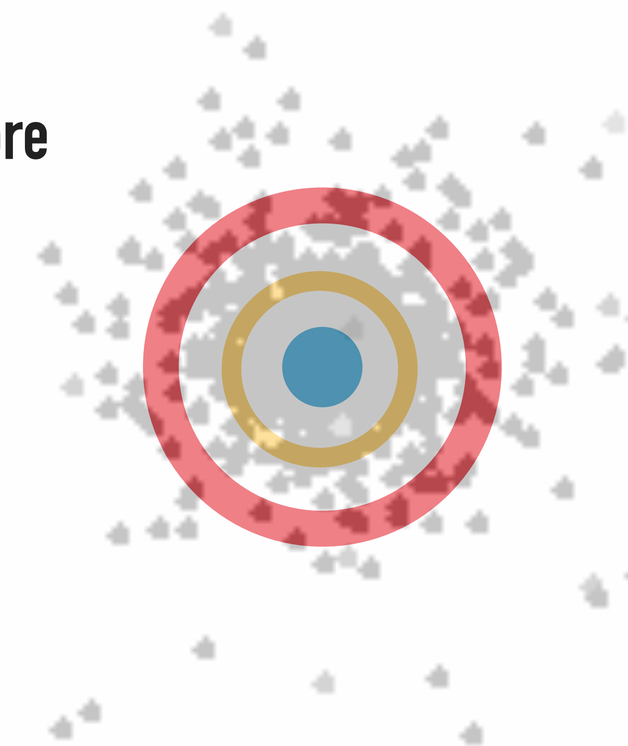


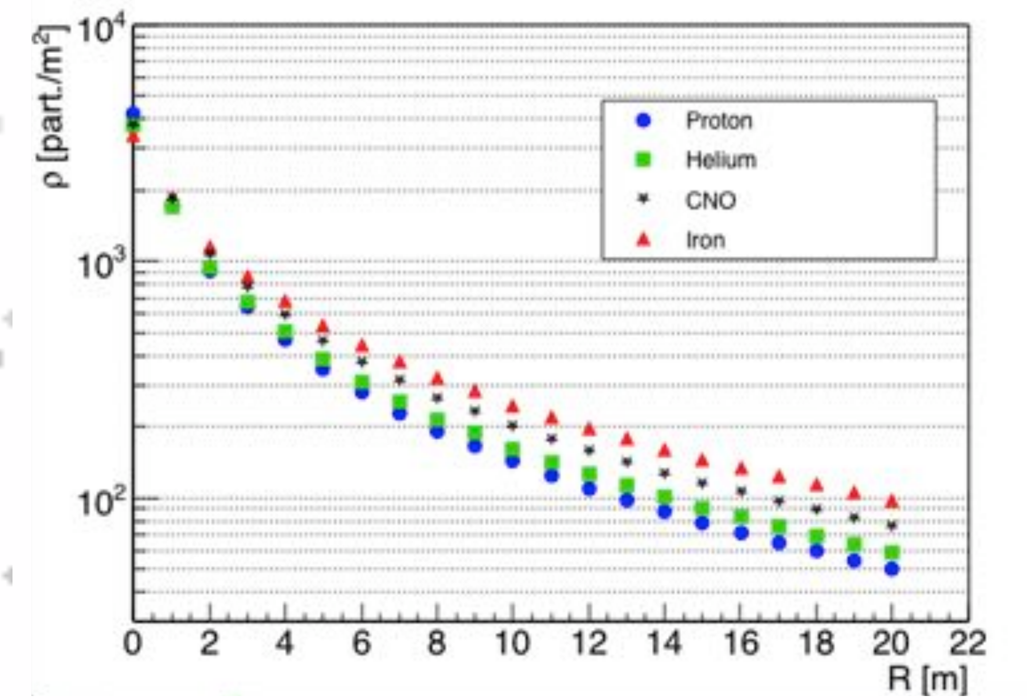
LIGHT/HEAVY DISCRIMINATION

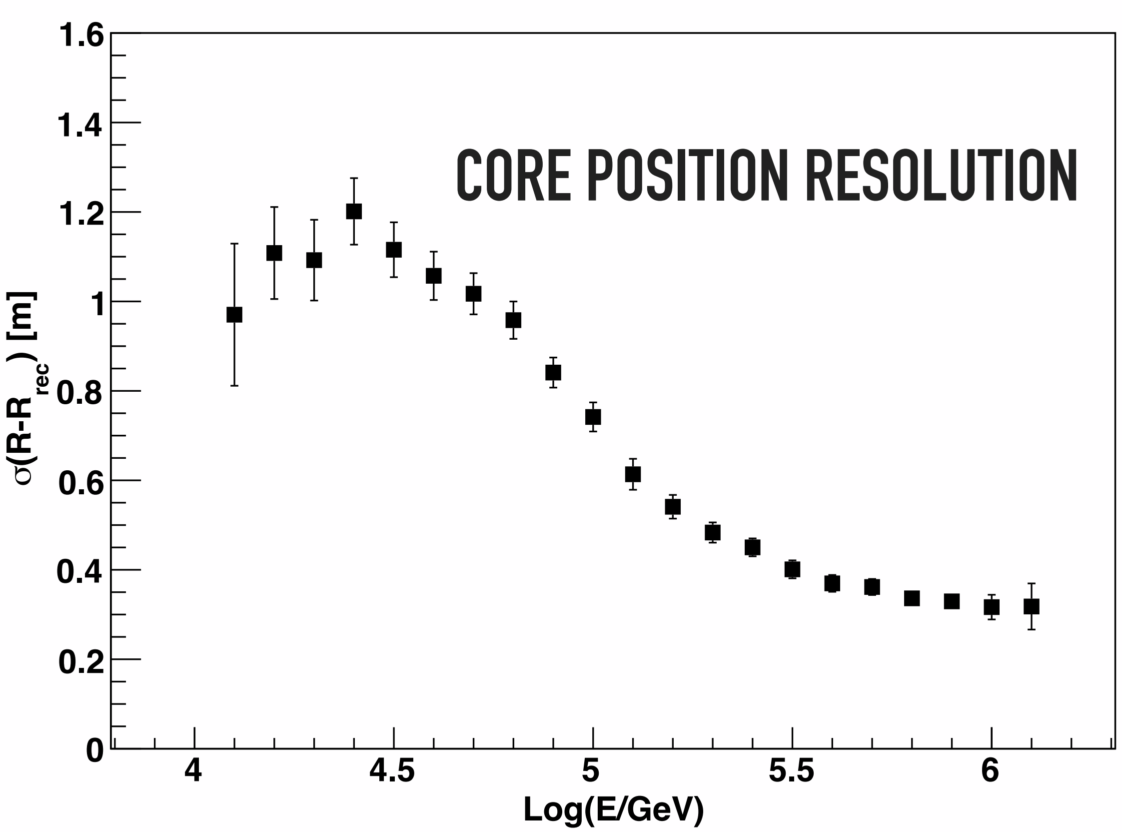
- High segmentation
- Access the LDF down to the shower core
- Precision measurement of the LDF at several distance from the core

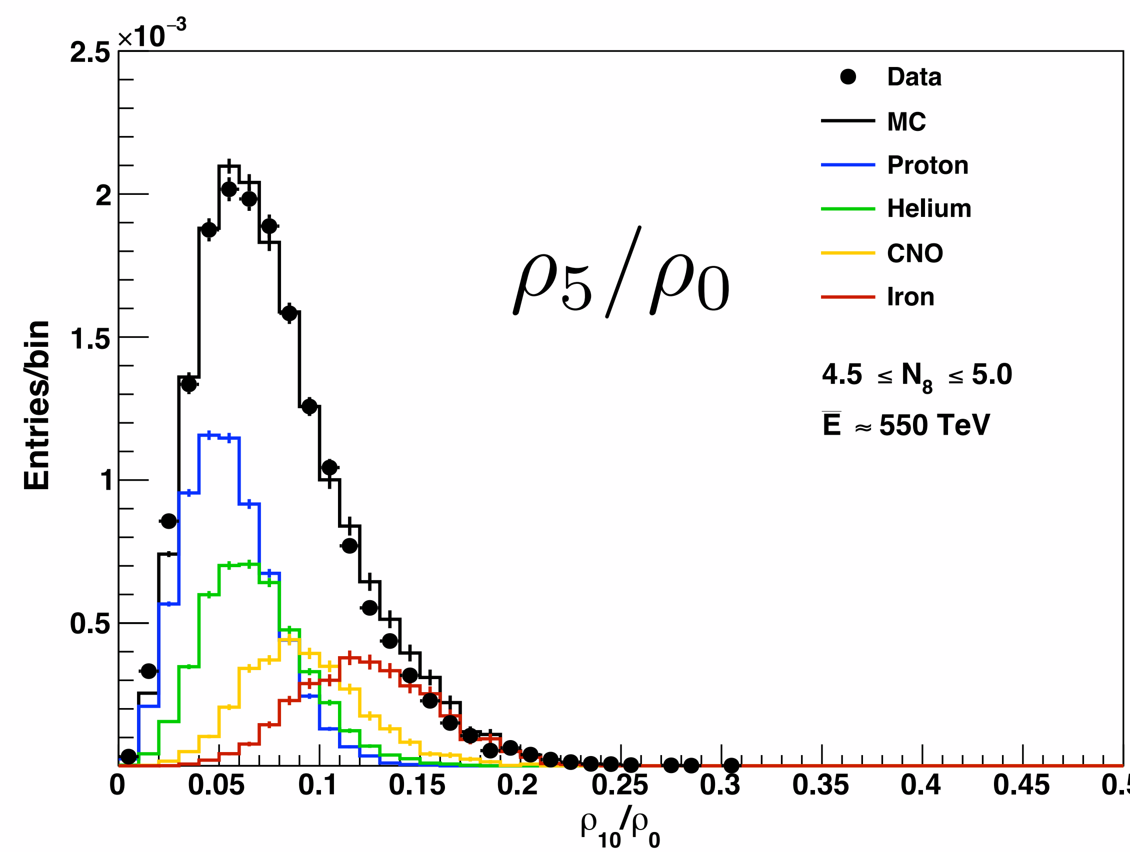
$$\beta_5 = \rho_5 / \rho_0$$

$$\beta_{10} = \rho_{10} / \rho_0$$

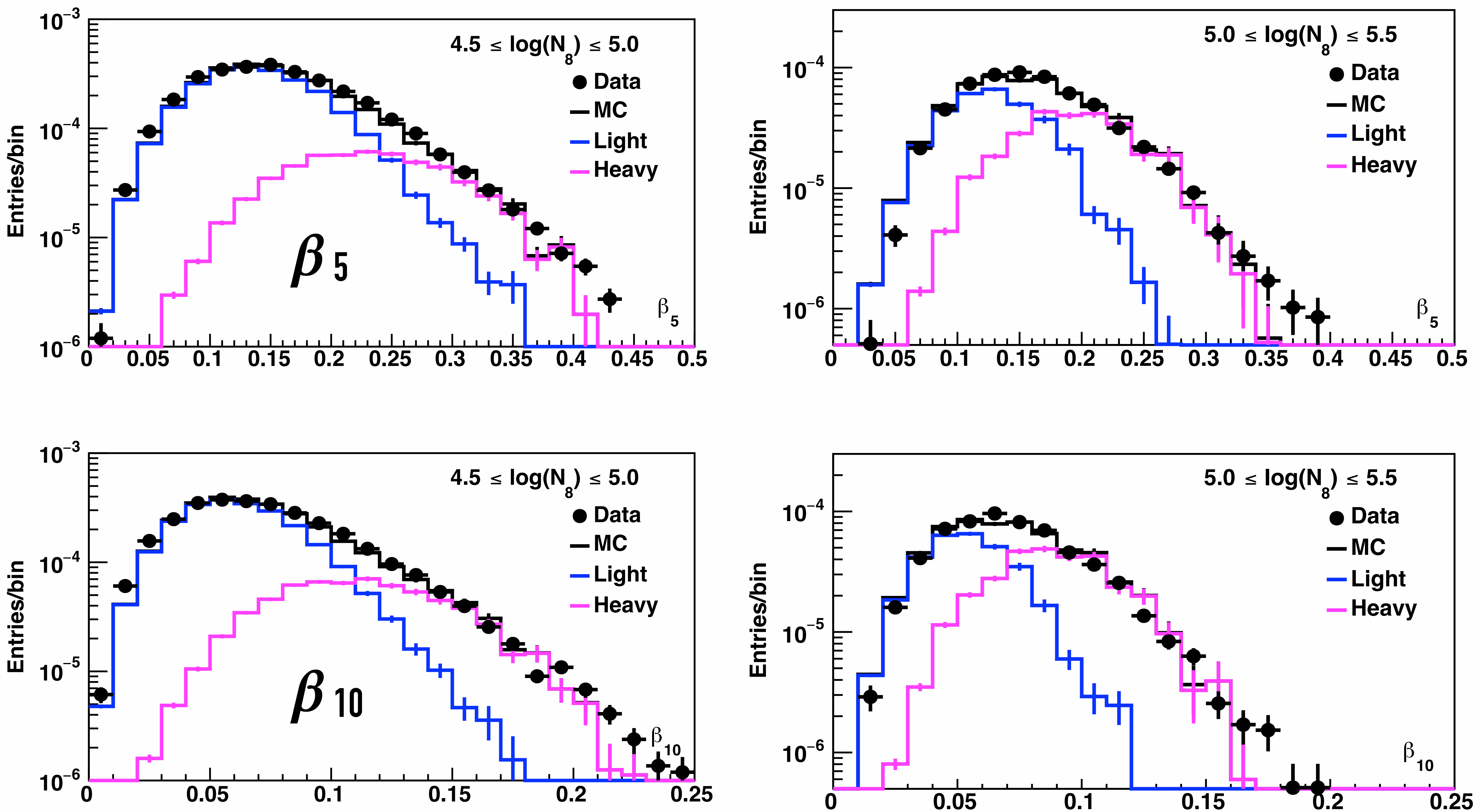








LIGHT/HEAVY DISCRIMINATION



LIGHT/HEAVY DISCRIMINATION

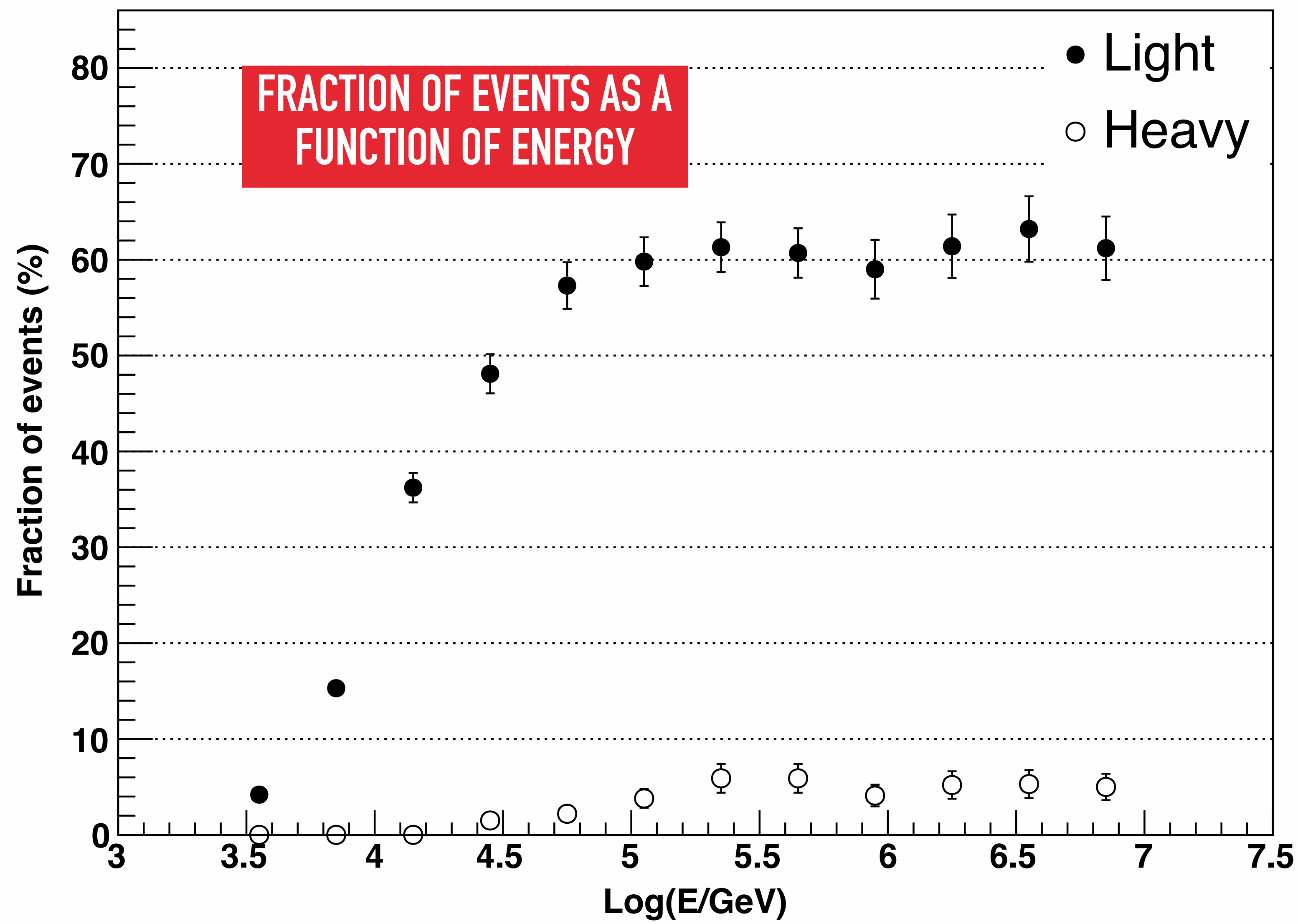
$$N(E_l, A_m) = \sum_{i,j,k} P(E_l, A_m | N_{8,i}, \beta_{5,j}, \beta_{10,k}) \cdot N(N_{8,i}, \beta_{5,j}, \beta_{10,k}).$$

Energy & Mass group

Simulations & Bayesian unf.

Mass group estimators

- Find a range of mass group estimators that correspond to light primaries
- In these bins a large fraction of events is produced by light primaries



P+HE ENERGY SPECTRUM

UNCERTAINTIES

SYSTEMATIC

- SELECTION CRITERIA
  - ± 2.5% over the whole energy range
- HADRONIC INTERACTION MODEL
  - Check with SIBYLL hadr. interaction model + (4 - 10)%
- RESPONSE MATRIX
  - ~10% @ E < 300 TeV
  - ~5% @ 300 TeV < E < 500 TeV
  - Gradually increase up to ~20% @ PeV energies
- UNFOLDING
  - < 1%
- FLUX MODEL IN SIMULATIONS
  - < 1%

STATISTICAL ERRORS

1% @ E ~ 10 TeV Up to

18% @ E ~ 1 PEV

TOTAL SYSTEMATIC:

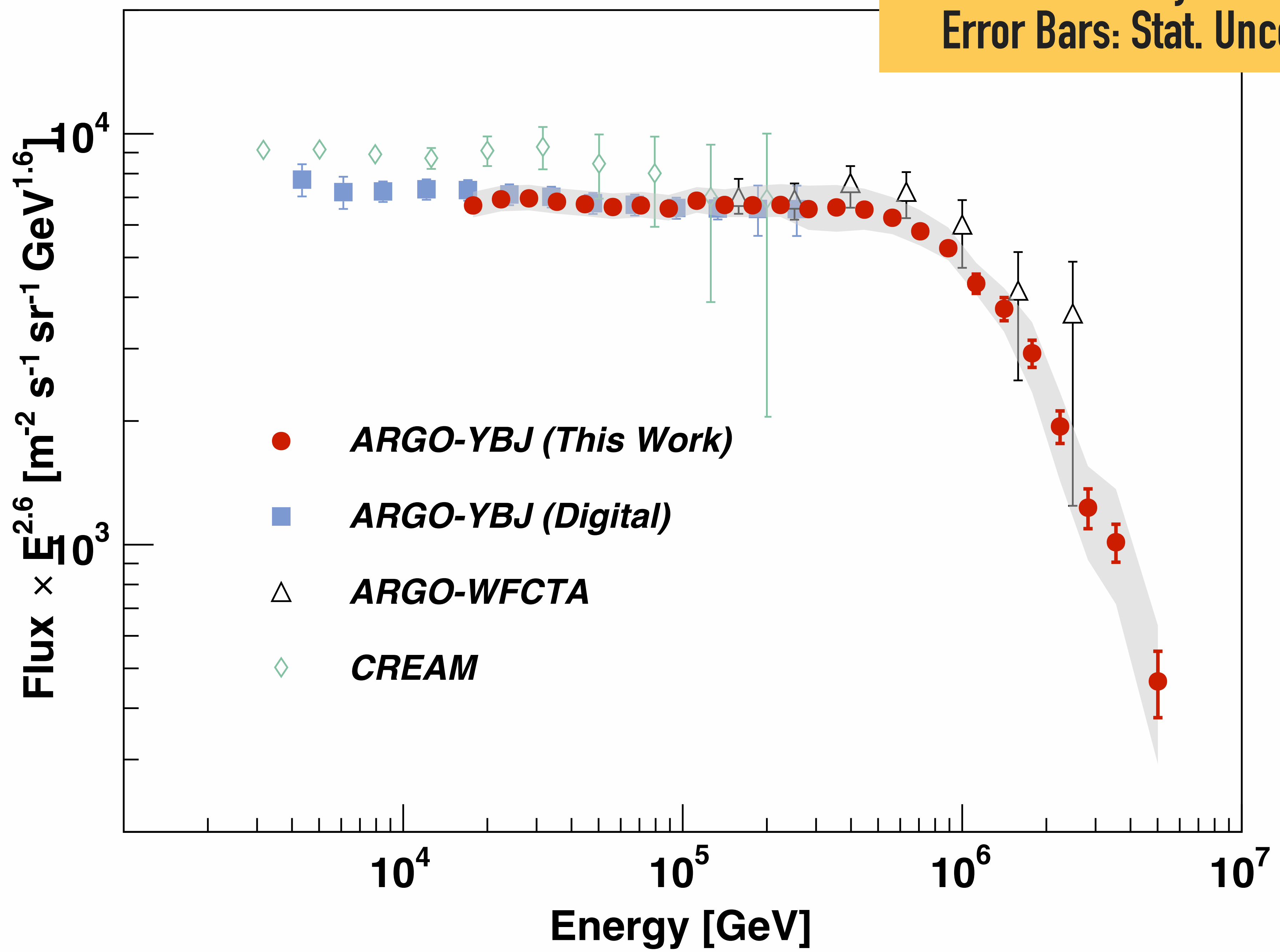
-5.8% +7% @ E< 600 TEV

-20.2% + 22.5% @ E> 1 PEV

P+HE ENERGY SPECTRUM

- Gradual change of the spectral index at E ~ 1 PeV
- Consistent with the Digital Readout data (different data set)
- Hybrid measurement gives consistent results

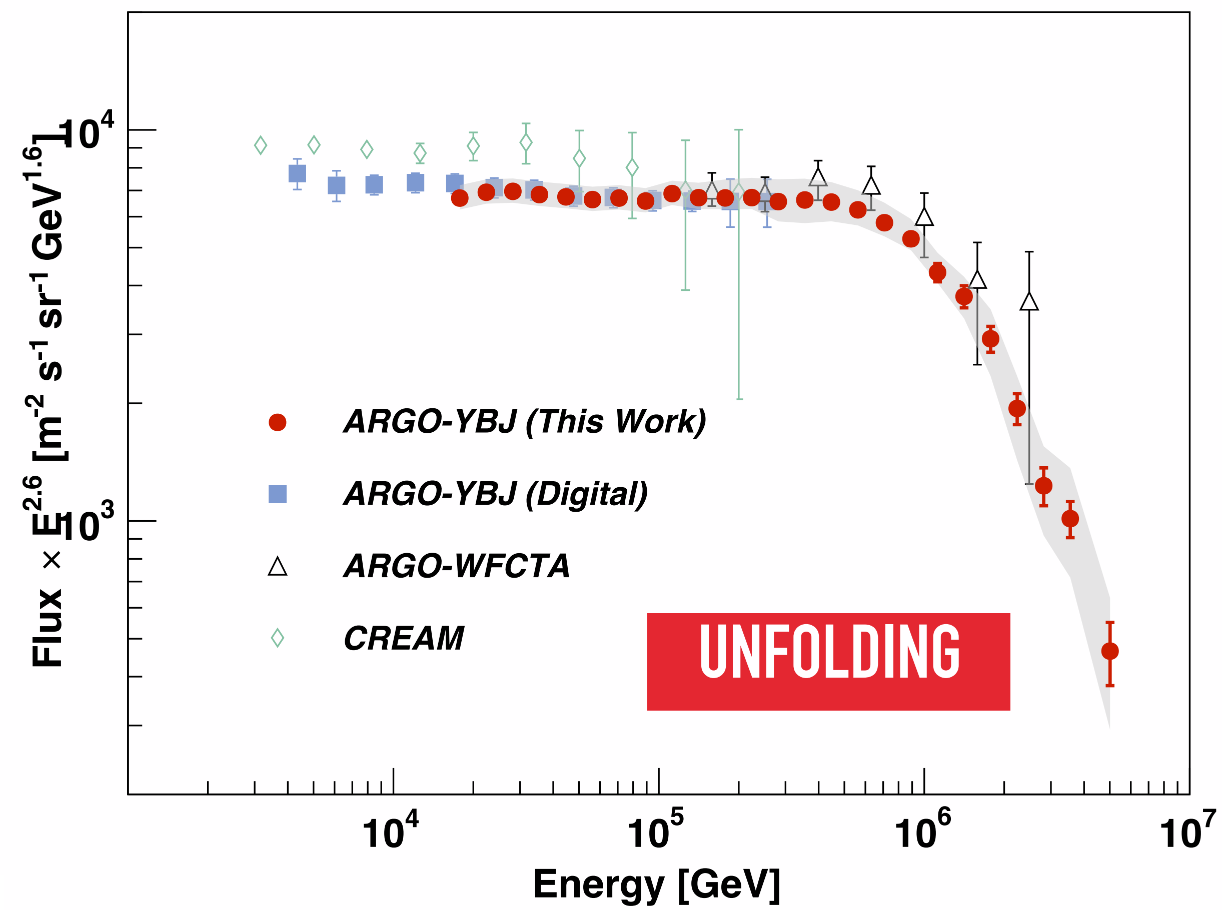
Shaded Area: Sys. Uncertainties
Error Bars: Stat. Uncertainties

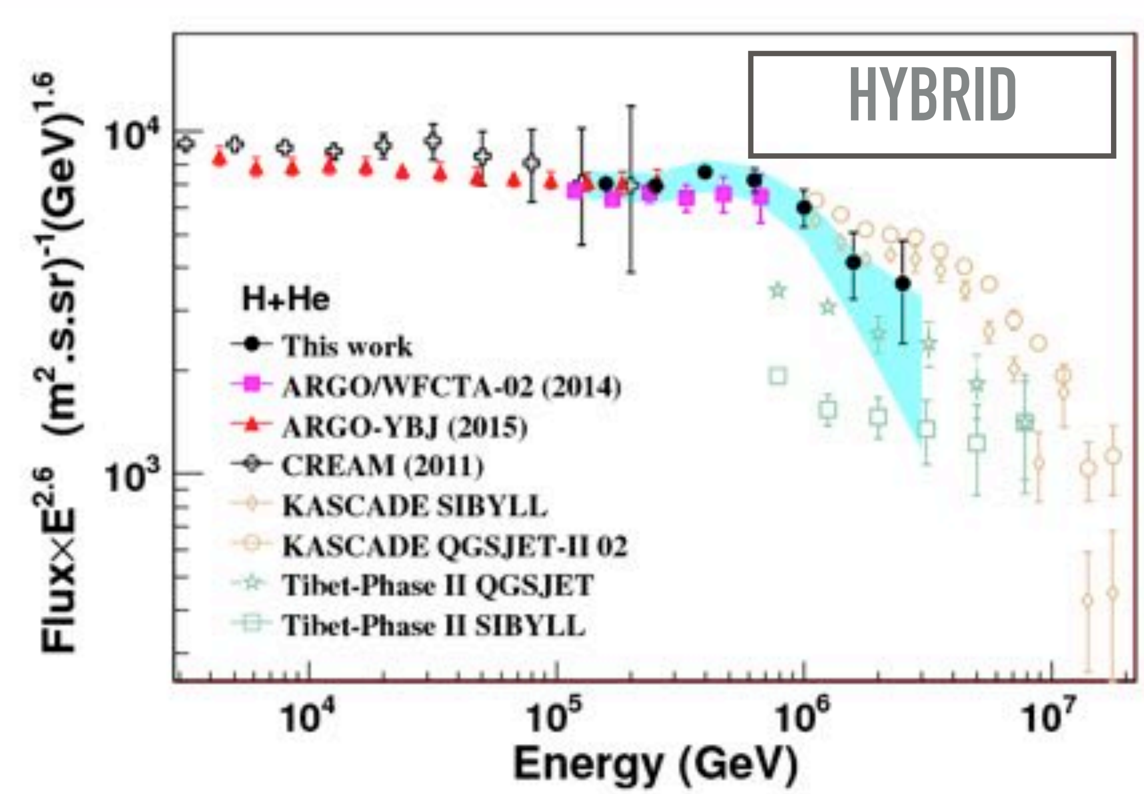


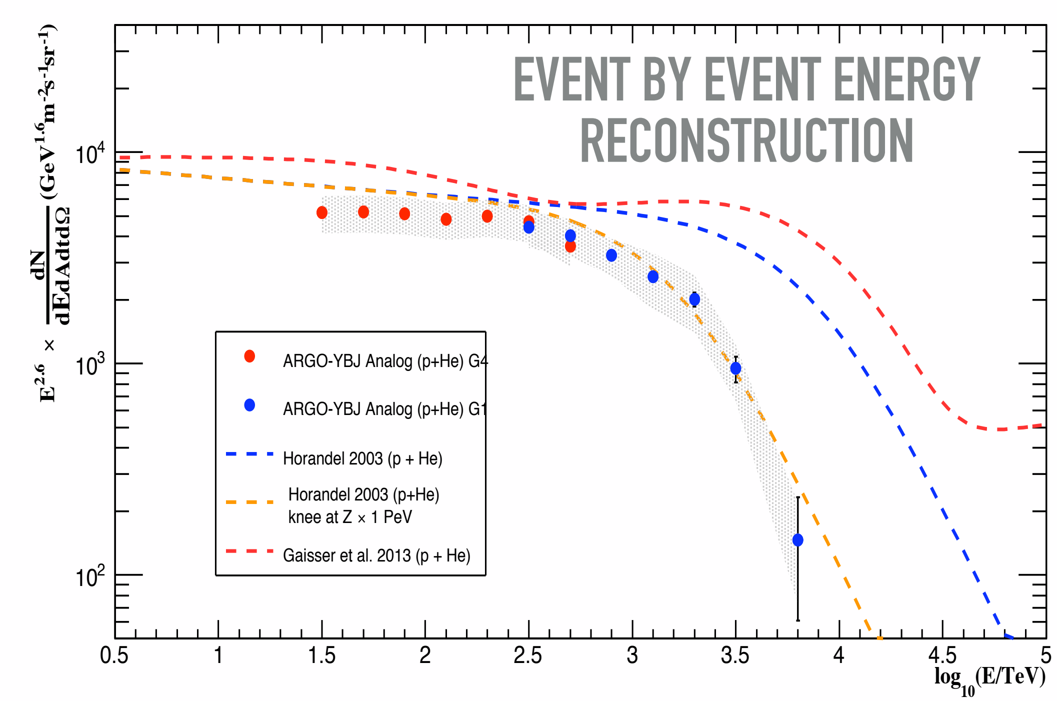
P+HE ENERGY SPECTRUM

SUMMARY OF ALL ARGO RESULTS

- Independent measurements
- Different Analysis technique
- Results are quite consistent within systematic errors







CONCLUSIONS

- ARGO-YBJ has been taken data for more than 5 years
  - Excellent stability of the detector
  - 2 Independent readout systems
  - Covers a very wide energy range: TeV ➟ PeV

- P+He spectrum
  - 10-100 TeV energy range
    - Good agreement with previous analysis
    - 100-3000 TeV energy range
    - Evidence of a gradual change of the spectral index at energies around 1 PeV
    - Good agreement between independent analyses within systematic errors

- All–particle spectrum
  - Good agreement with other experiments

MORE STUFF…

P+HE ENERGY SPECTRUM: DIGITAL READOUT

3 – 300 TeV energy range

Bayesian Approach

➡ Excellent stability over a long period

➡ Overlap with direct measurements in a wide energy region

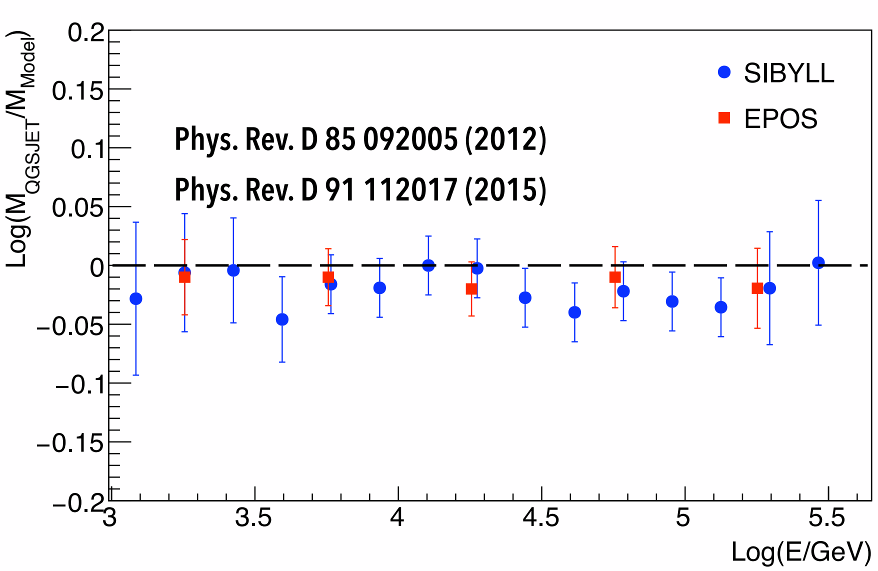
➡ Total systematic uncertainty ~ 5%

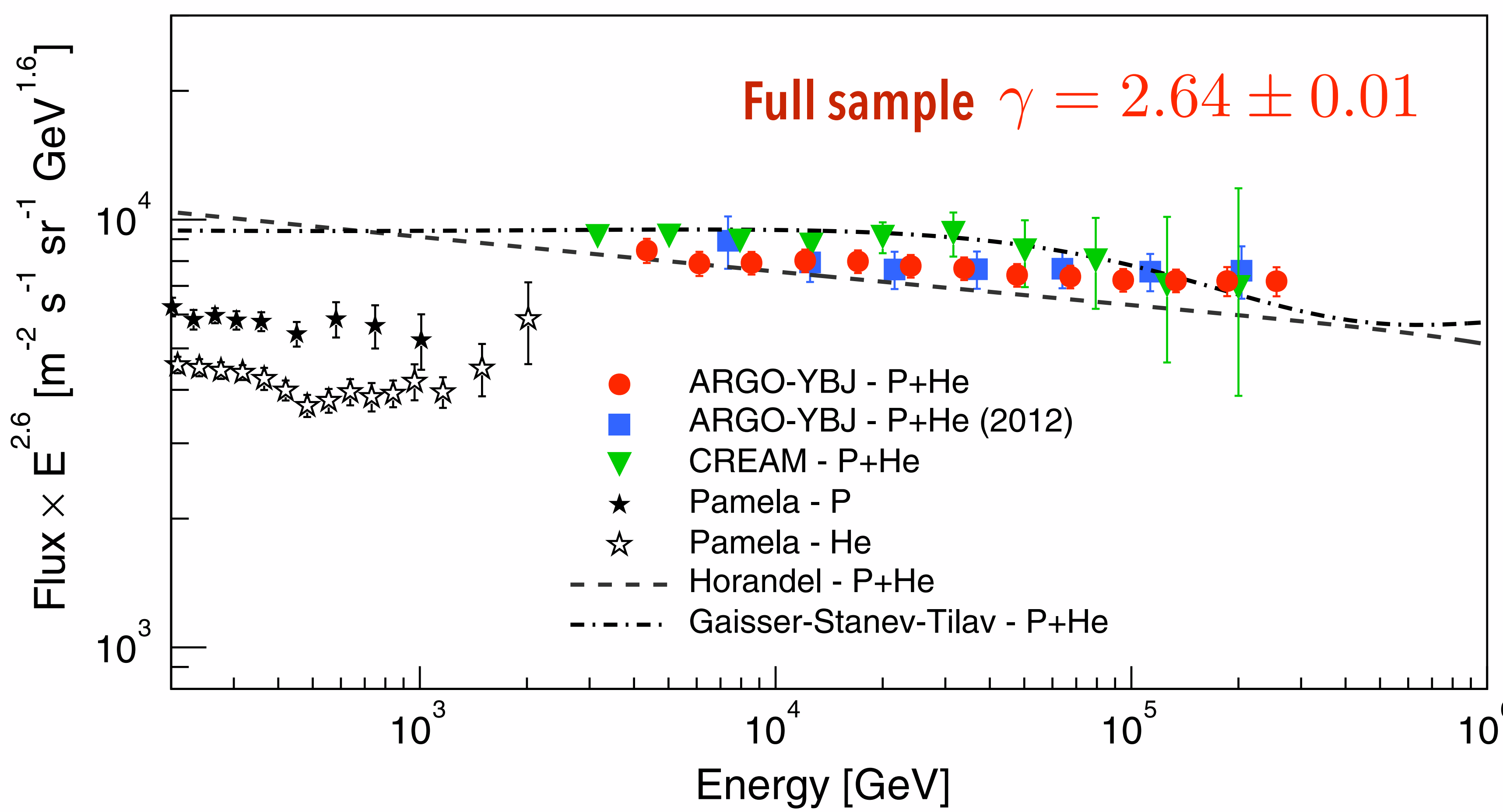
YEAR	Gamma
2008	2.63 ± 0.01
2009	2.63 ± 0.01
2010	2.63 ± 0.01
2011	2.64 ± 0.01
2012	2.65 ± 0.01

FLUX @ 50 TeV

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

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





Hybrid Analysis

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

R_p: the impact parameter;

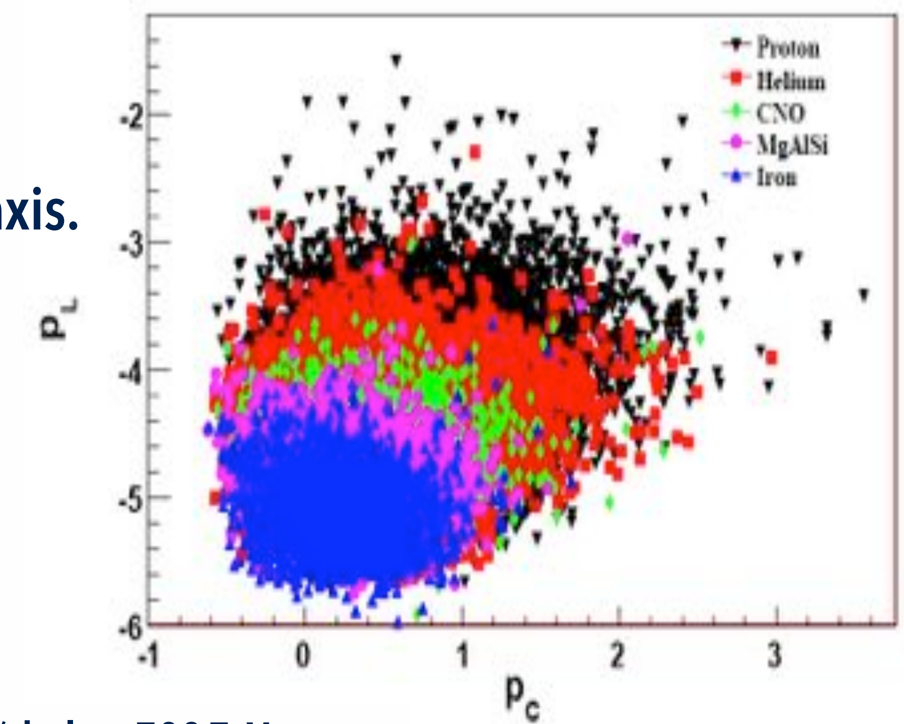
α: the space angle between shower direction and Cherenkov telescope main axis.

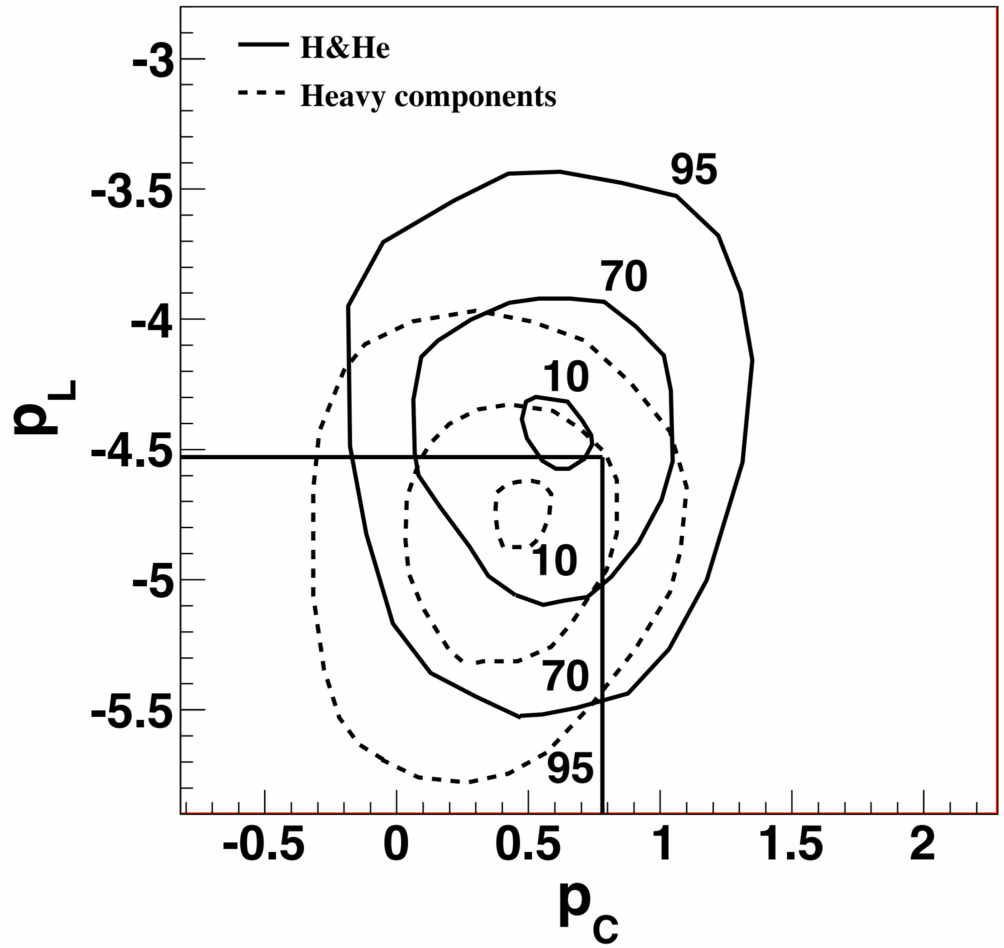
$$p_c = L/W - R_p/109.9\mathrm{m} - 0.1\log_{10} N_0^{pe}$$

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

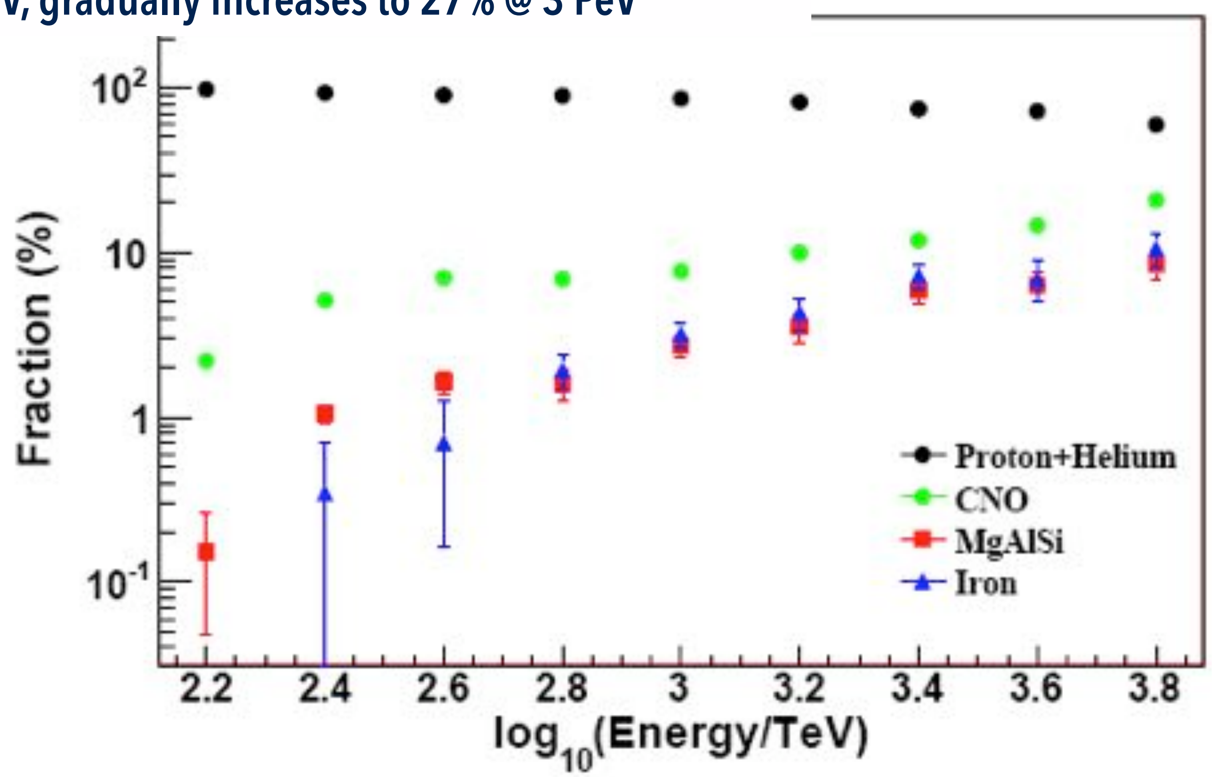
H&He selection criteria : p_L>-4.53 & p_C>0.78

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





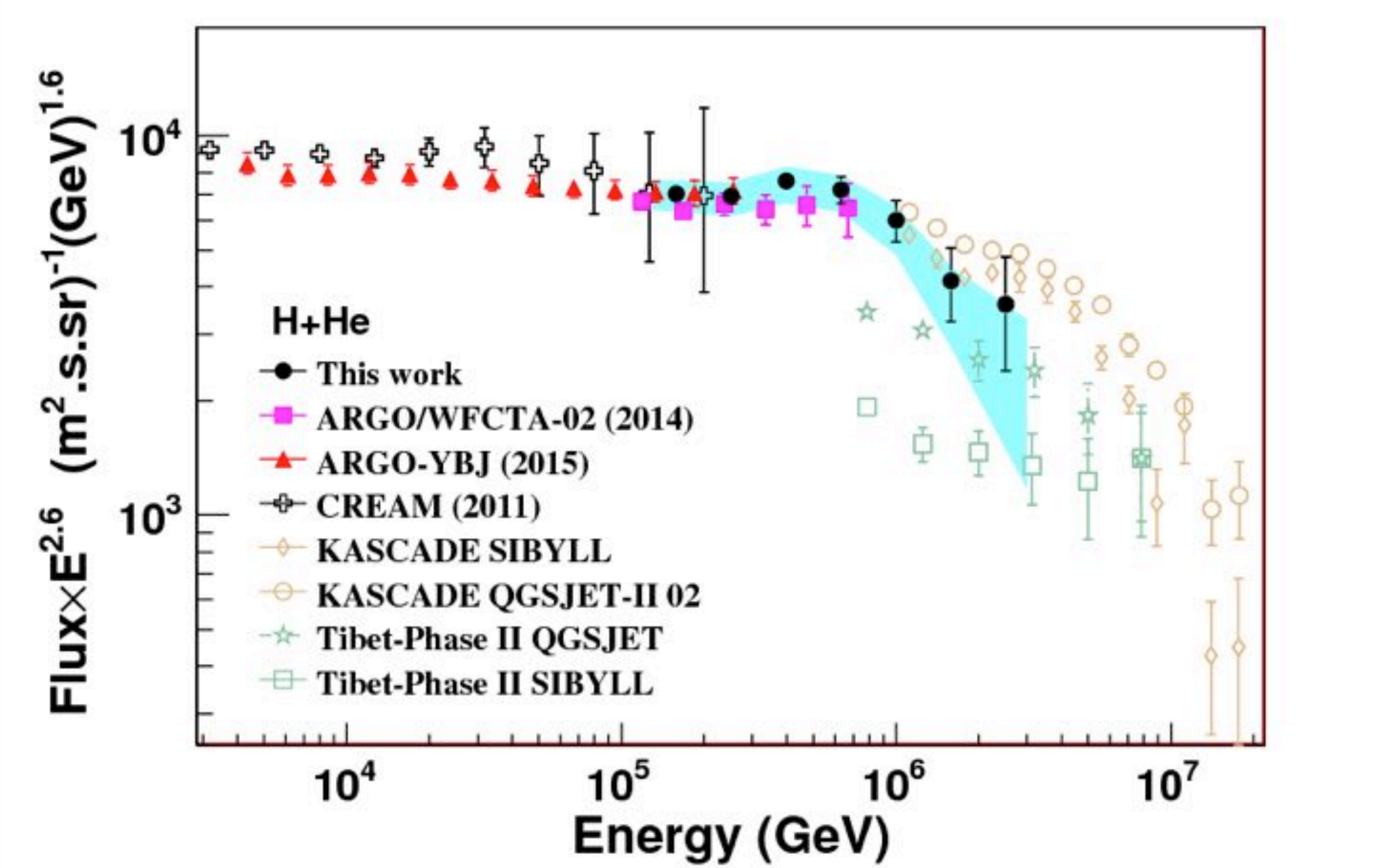
- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV



THE P+HE SPECTRUM

100-2500 TeV energy range

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

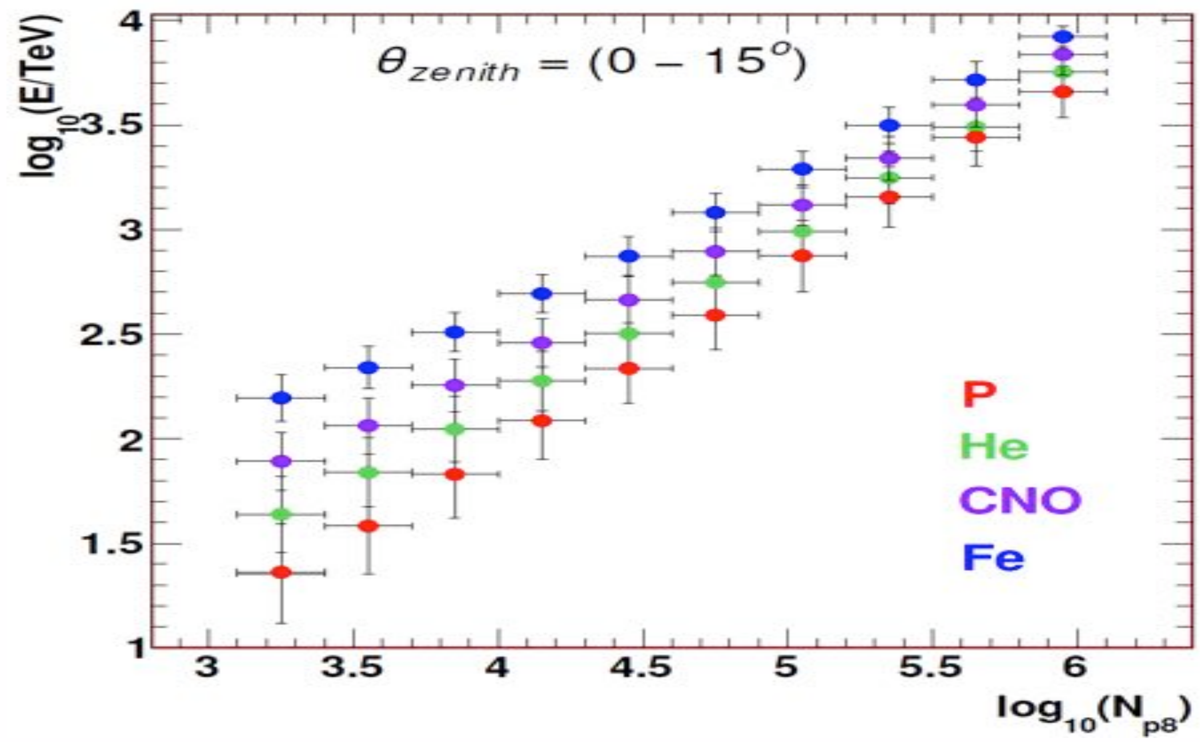


Mass Independent Energy Reconstruction

The truncated size as (mass dependent) energy estimator

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

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

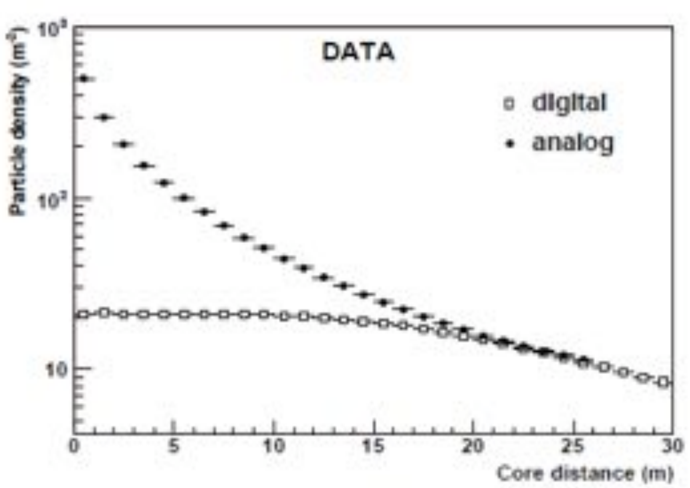


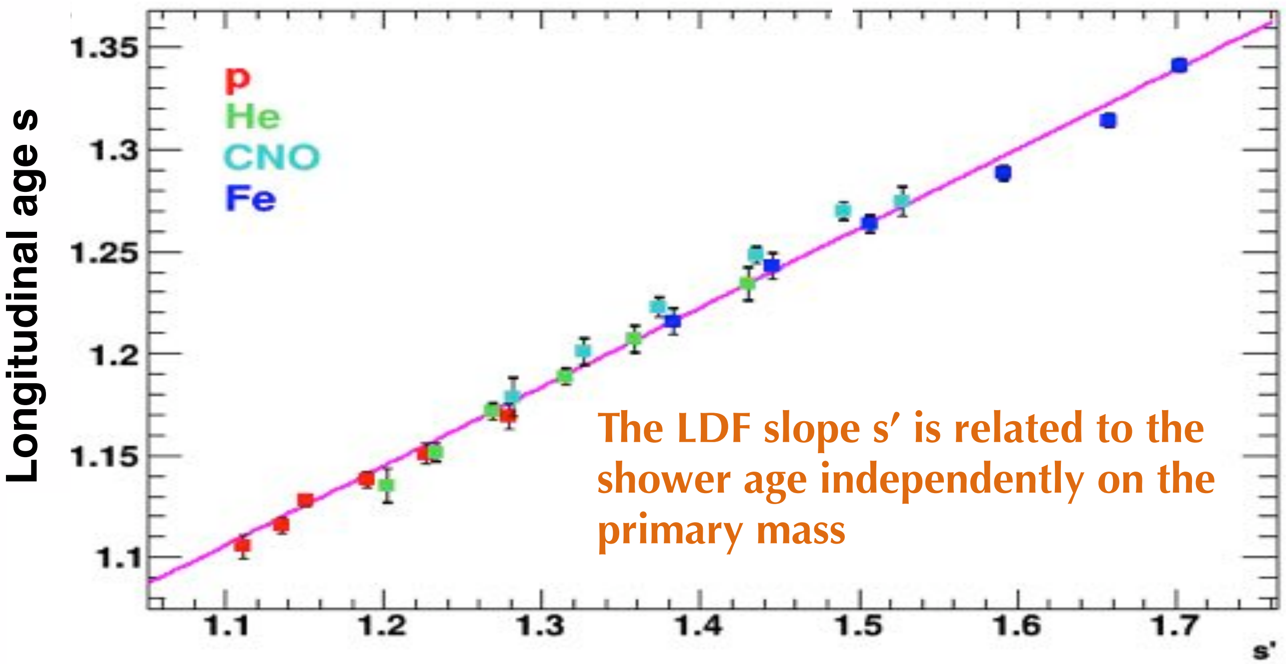
Look for information on the shower age in order to have a mass independent energy estimator.

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

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

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





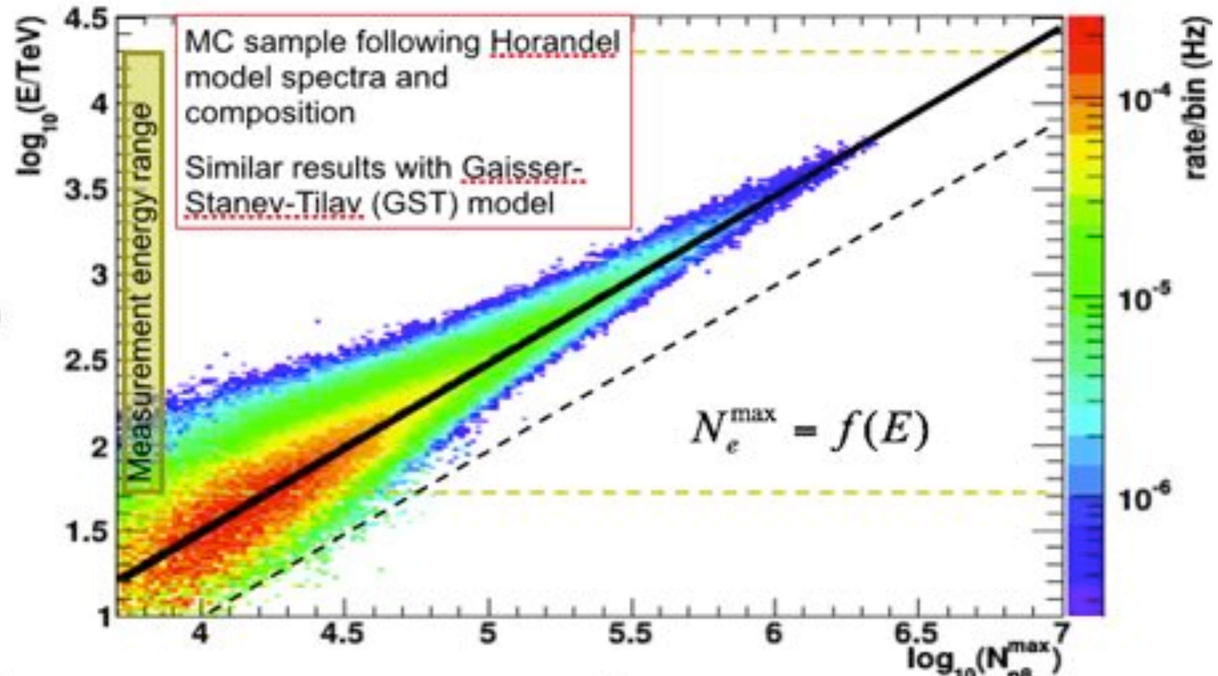
The LDF slope s′ is related to the shower age independently on the primary mass

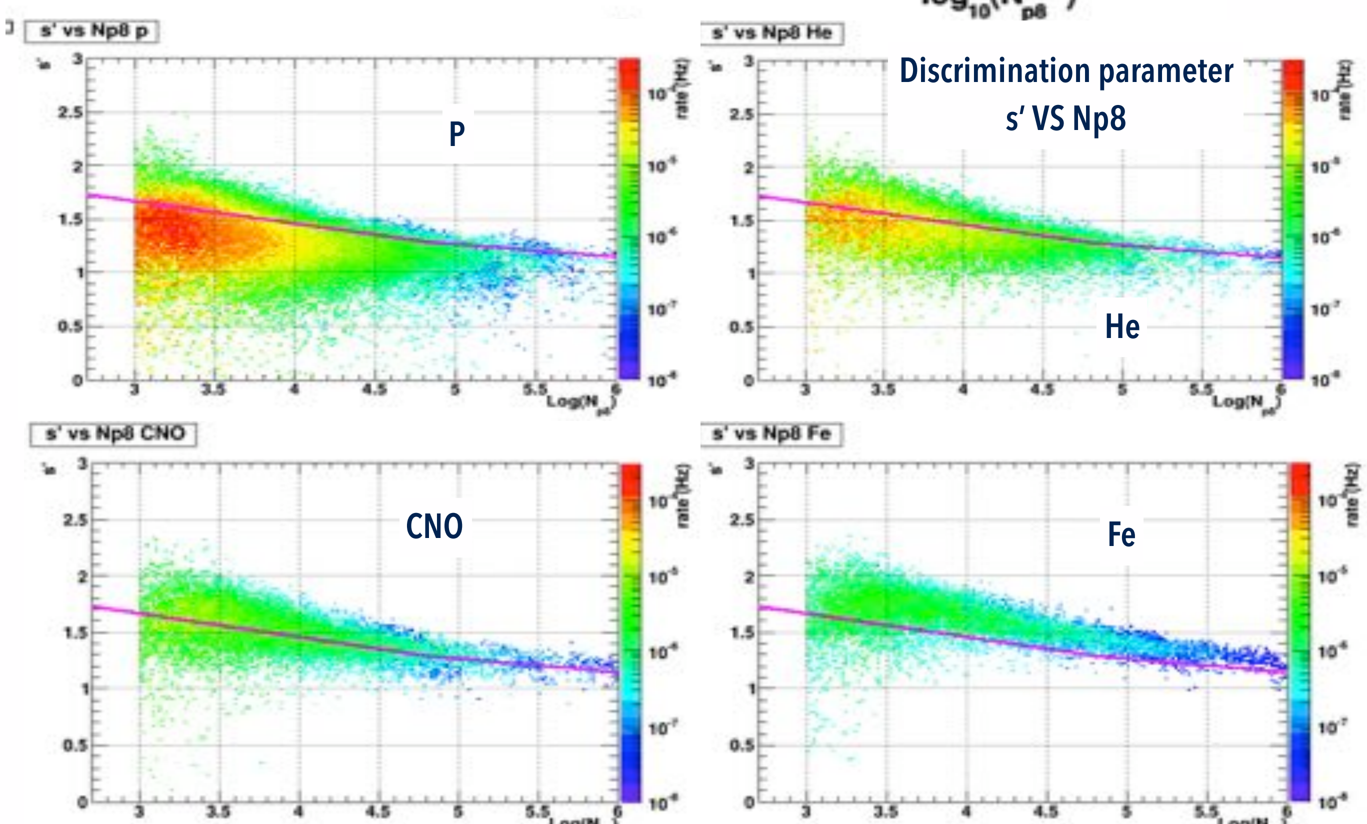
Lateral age s’ (LDF slope)

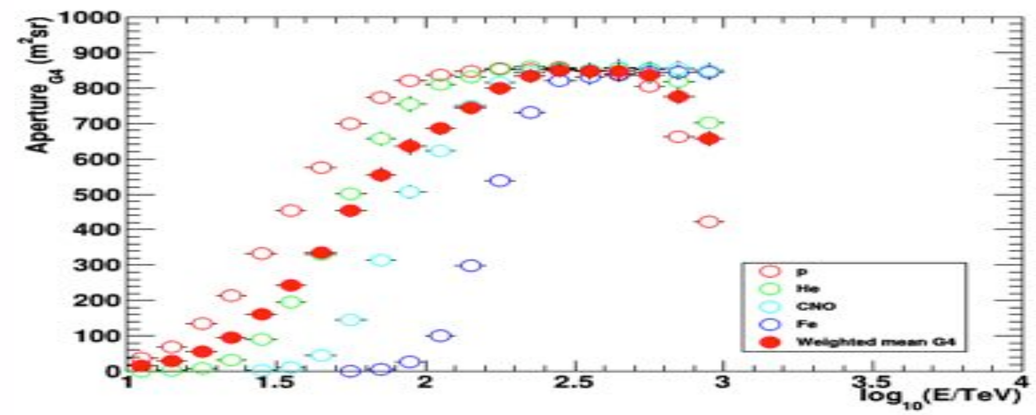
Mass Independent Energy Reconstruction

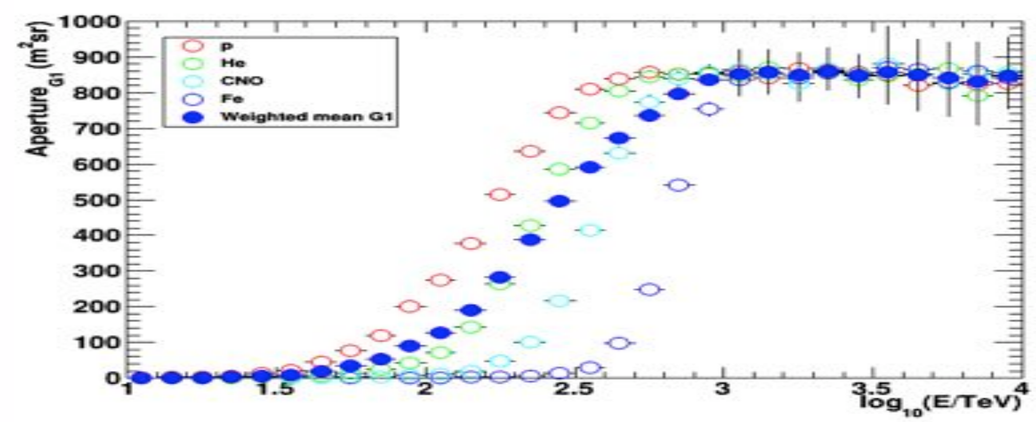
The measurement of Np8 and the (age correlated) LDF slope allows estimating the truncated size at the shower maximum.

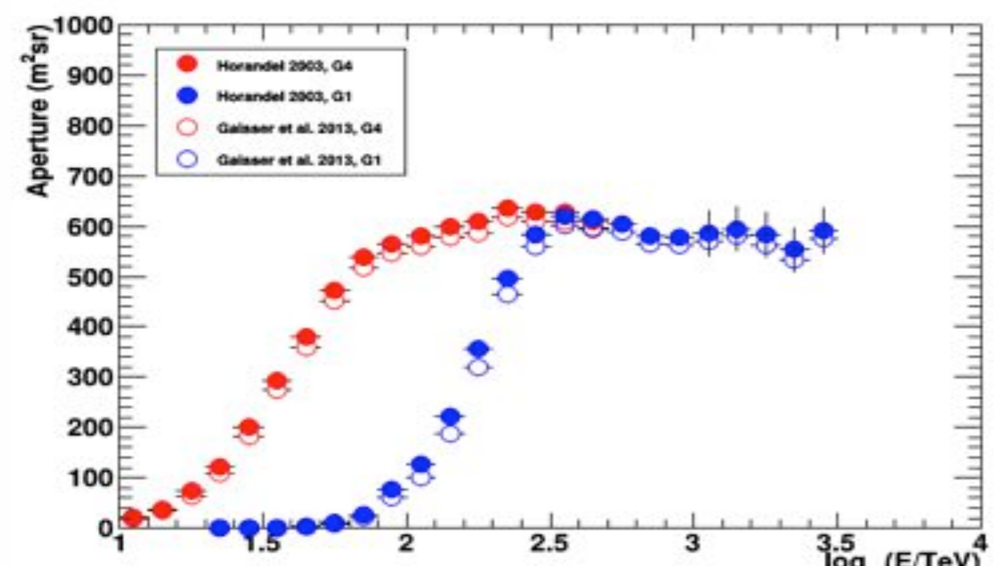
This ensures a mass independent Energy determination.







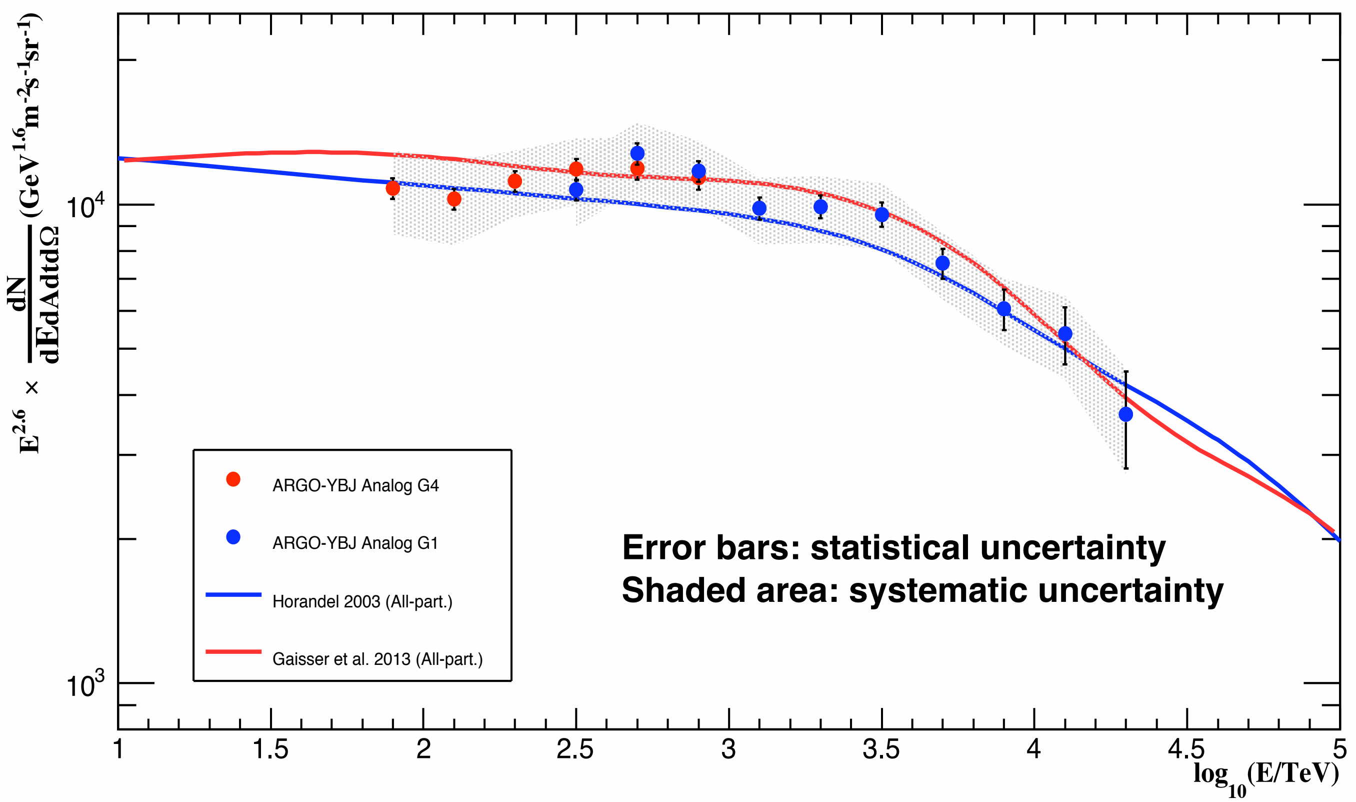




ALL—PARTICLE & P+HE SPECTRA

ALL-PARTICLE SPECTRUM

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



P+He SPECTRUM

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