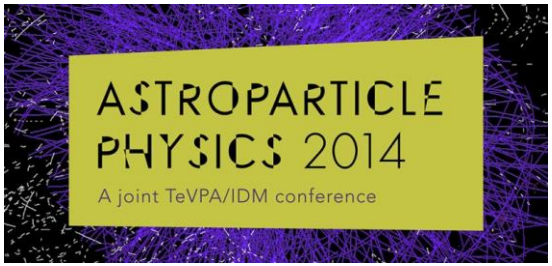


Amsterdam, June 23, 2014

Measurements of the Cosmic Ray energy spectrum with the ARGO-YBJ experiment

Paolo Bernardini

Università del Salento &
Istituto Nazionale di Fisica Nucleare
Lecce, Italy

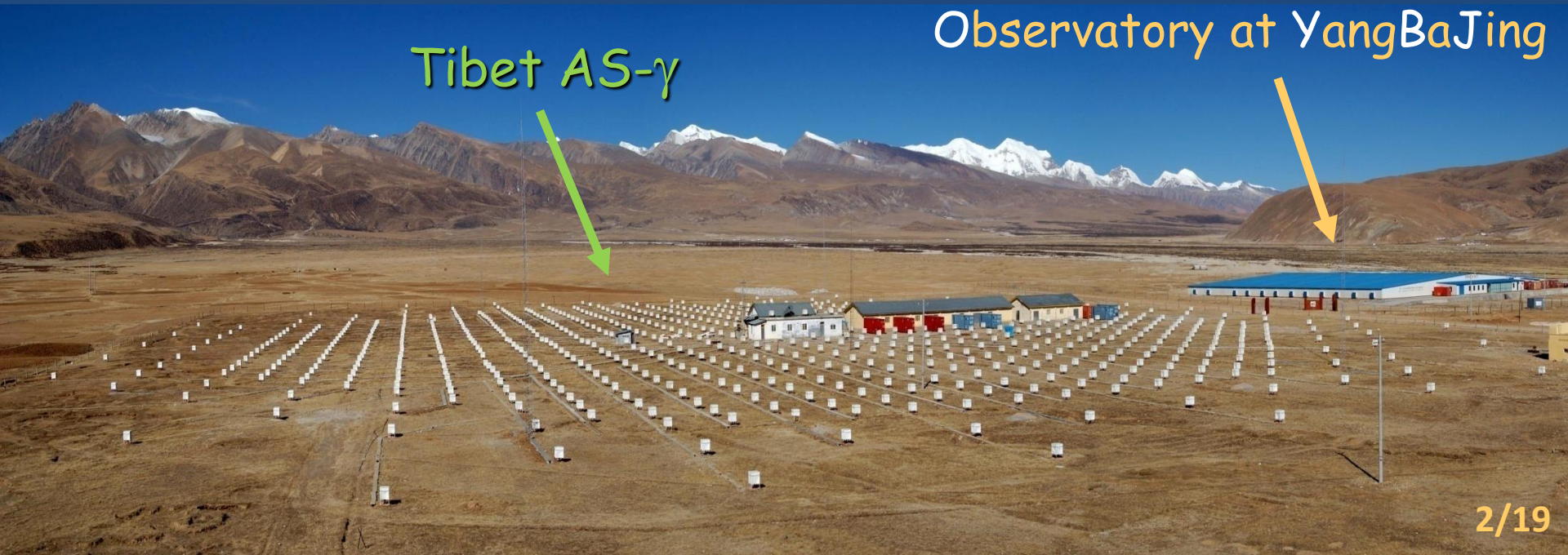
(on behalf of the ARGO-YBJ Collaboration)

The YangBaJing Cosmic Ray Observatory (Tibet, China)

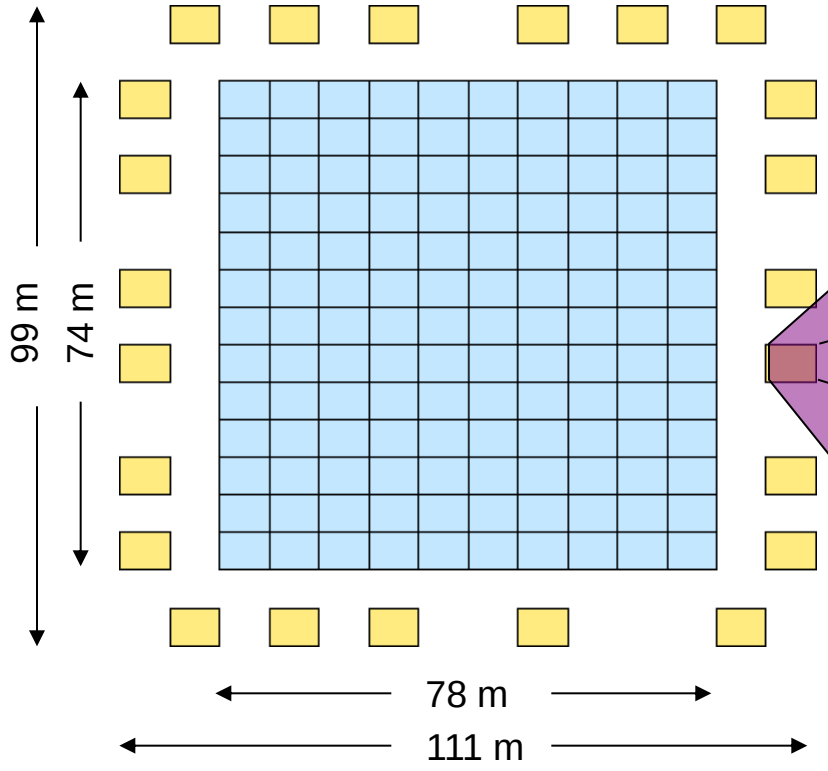
Altitude 4300 m a.s.l. (~ 600 g/cm^2)

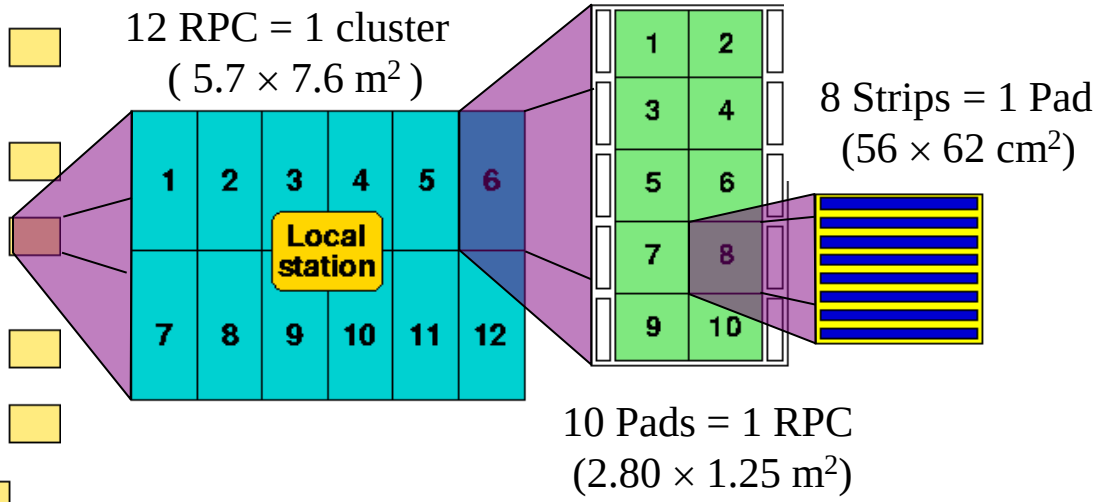
ARGO-YBJ → cosmic-ray physics
→ γ-astronomy

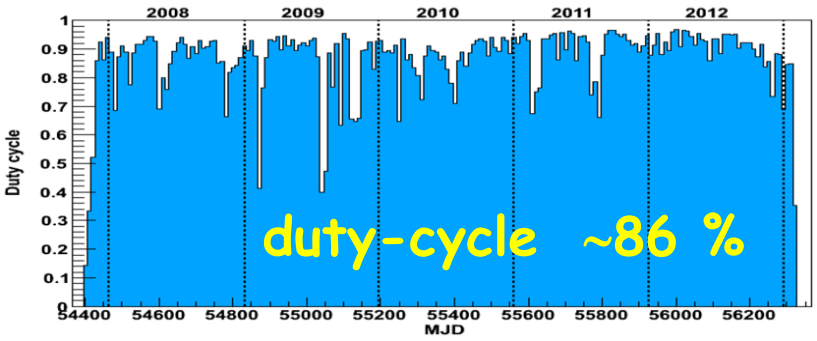
Astrophysical Radiation with Ground-based Observatory at YangBaJing



Layer of Resistive Plate Chambers (RPC)

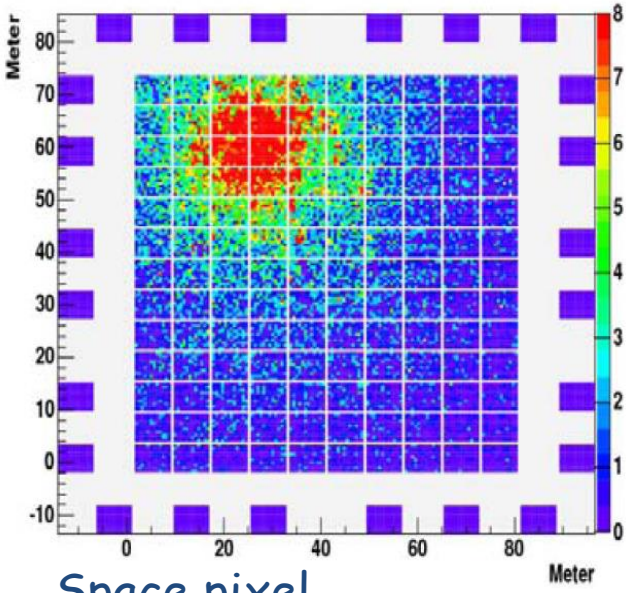






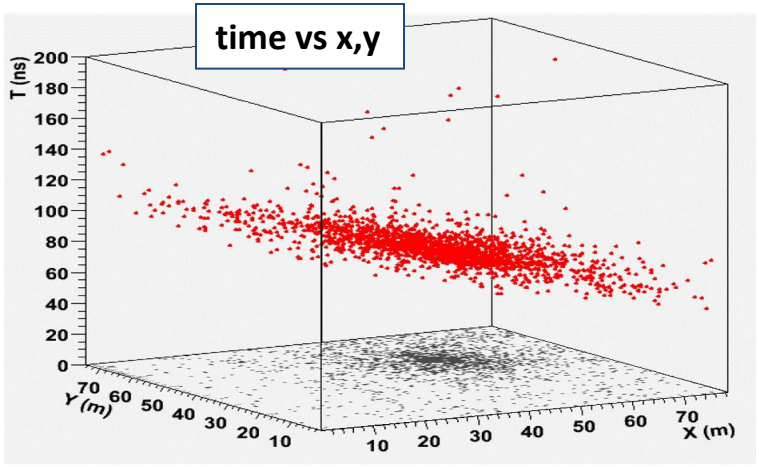
- Full coverage and high segmentation
- Digital and analog readout
- Active area :
  - central carpet ~ 5600 m²
  - sampling guard-ring ~ 1000 m²
- Data taking with complete setup:
  November 2007 – February 2013

The digital readout



Space pixel

single strip (7 × 62 cm^2)



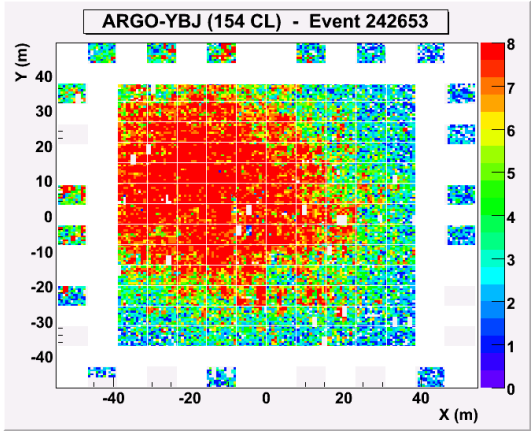
Time pixel

pad (56 × 62 cm^2) is the OR of 8 strips, with a resolution of ~1.8 ns

RPC

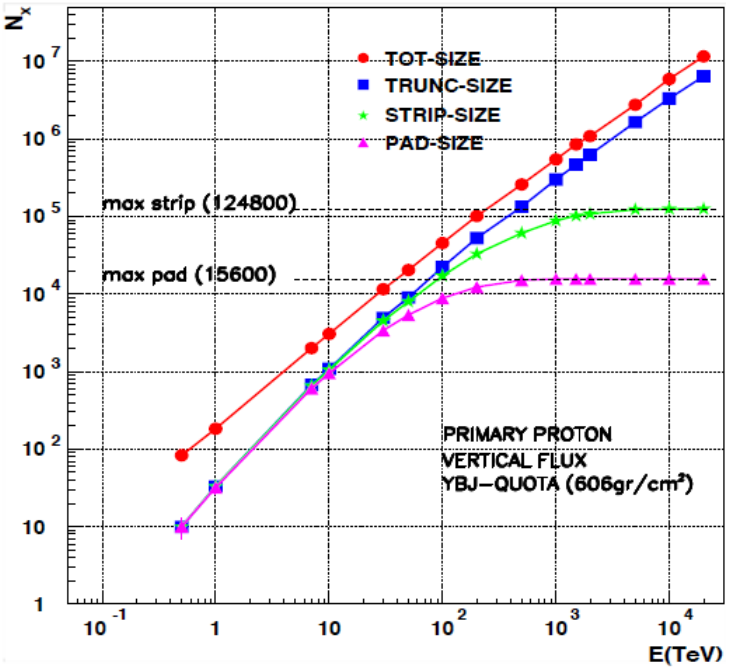
The RPC analog readout (I)

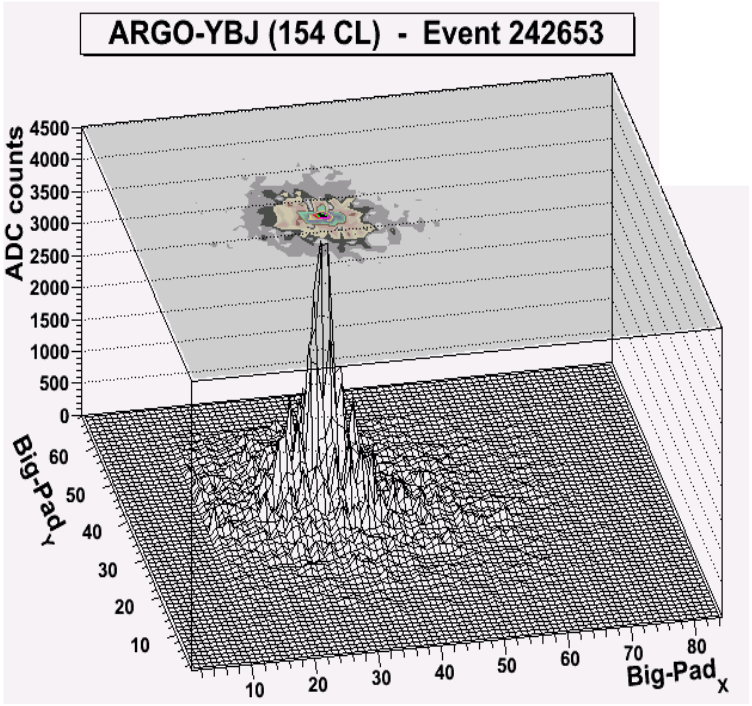
- ✓ Pixel = BigPad (half RPC chamber)
- ✓ Extended energy range
- ✓ Access to the LDF down to the shower core
- ✓ Sensitivity to primary mass
- ✓ Info/checks on Hadronic Interactions



Saturated digital signal

Same event in analog view



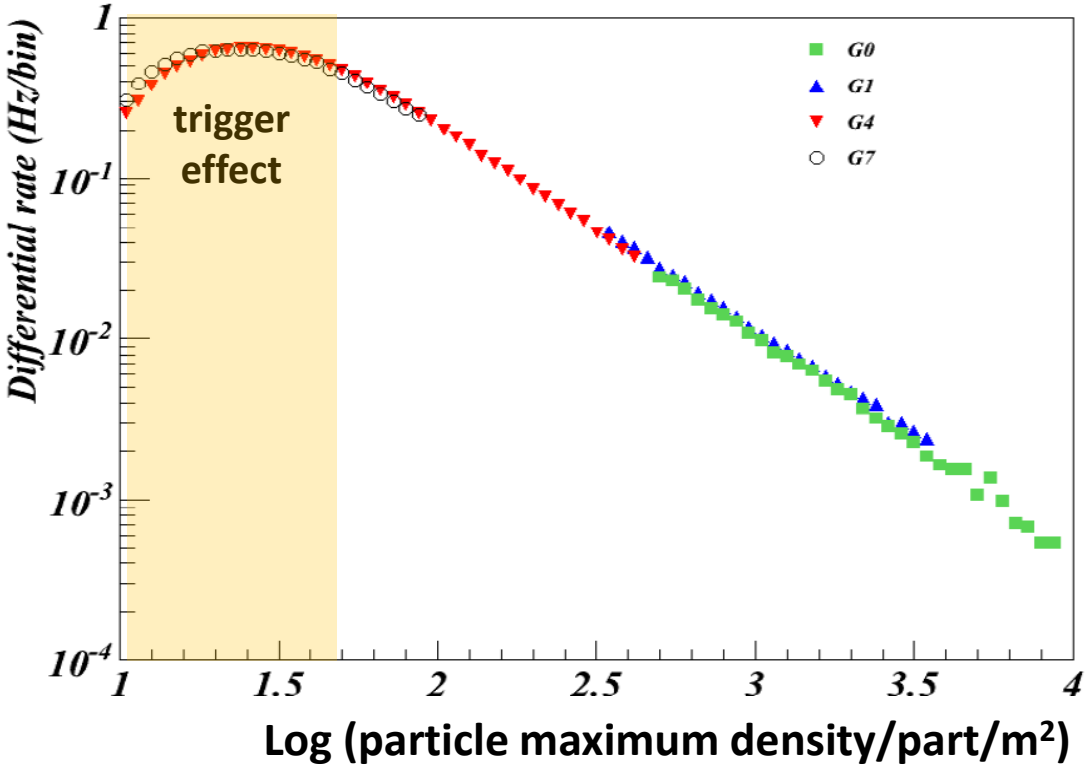


The RPC analog readout (II)

Eight gain scales (G0, G1, … G7) to get good linearity up to about 2 x 10^4 particles/m^2

G7 data overlap the digital-mode linearity range, and have been used for intercalibration and cross checks

Here we use **G4** and **G1** scales to cover the 50 TeV – 5 PeV range with high efficiency and without saturation

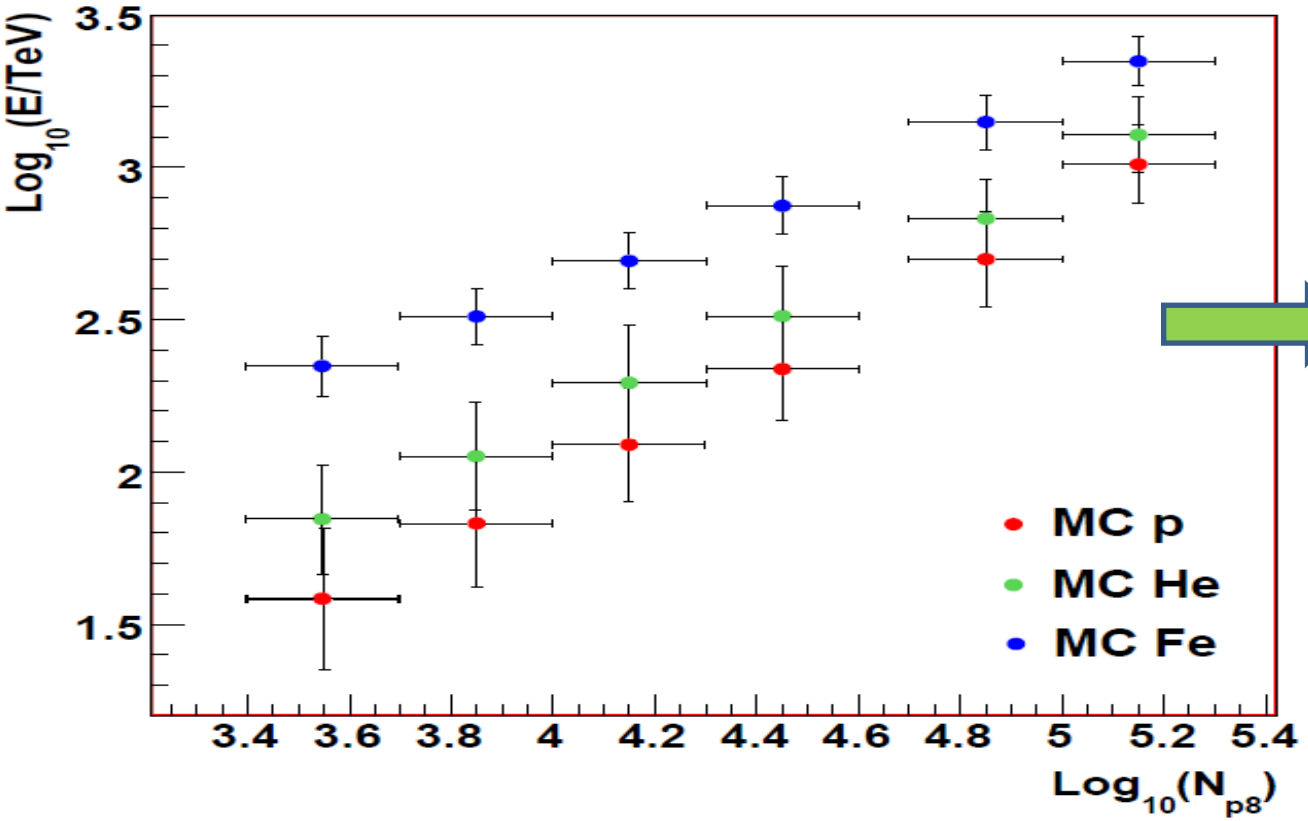


The truncated size as energy estimator (mass dependent)

Np8 (number of particles within 8 m from the core):

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

Only events with zenith angle lower than 15° in this analysis



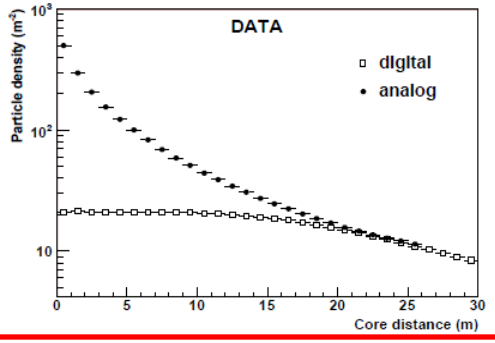
Looking for information on the shower age in order to get a mass independent energy estimator

Lateral Distribution Function (LDF) and shower age

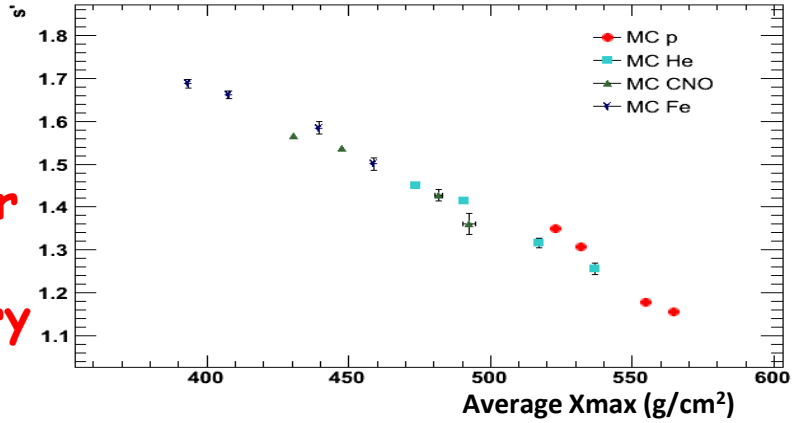
LDF is well fitted by a modified NKG function

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

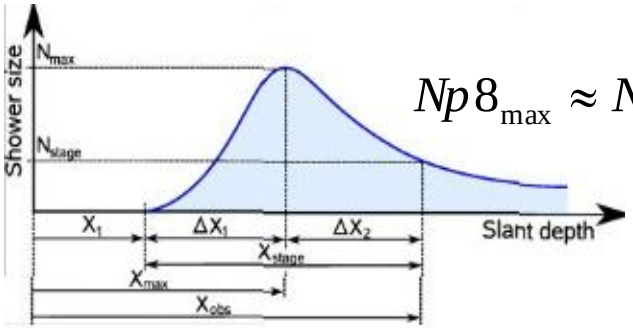
With the analog data the LDF can be studied near the core without saturation



The LDF slope (s') is related to the shower age and does not depend on the primary mass



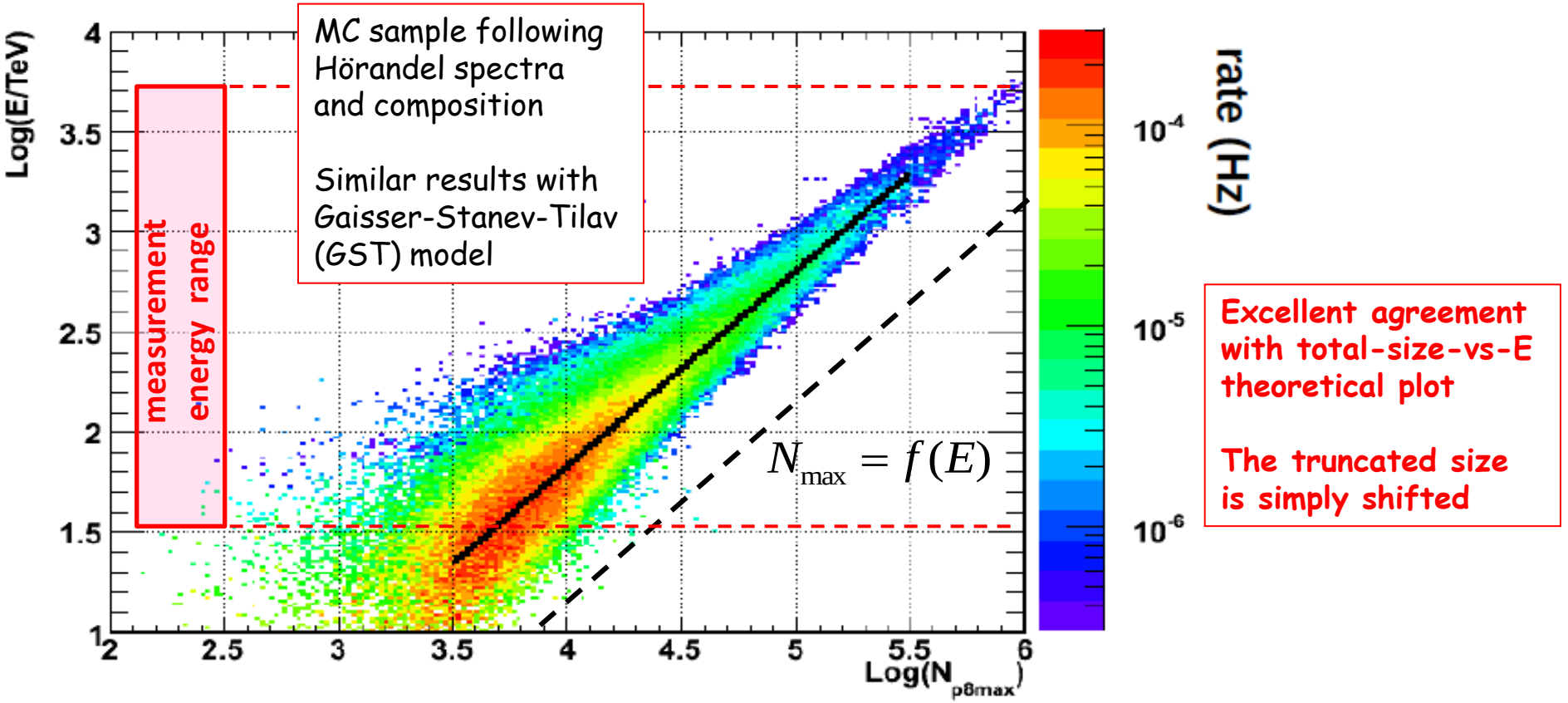
Assuming an exponential absorption after the maximum, the signal at maximum ($Np8_{max}$) can be estimated as a function of Np8 and s'



$$Np8_{\max} \approx Np8 \cdot e^{\frac{h_0 \sec\theta - X_{\max}(s')}{\lambda_{abs}}}$$

Checks in progress with Gaisser-Hillas profile

Mass-independent Energy reconstruction



Excellent agreement with total-size-vs-E theoretical plot

The truncated size is simply shifted

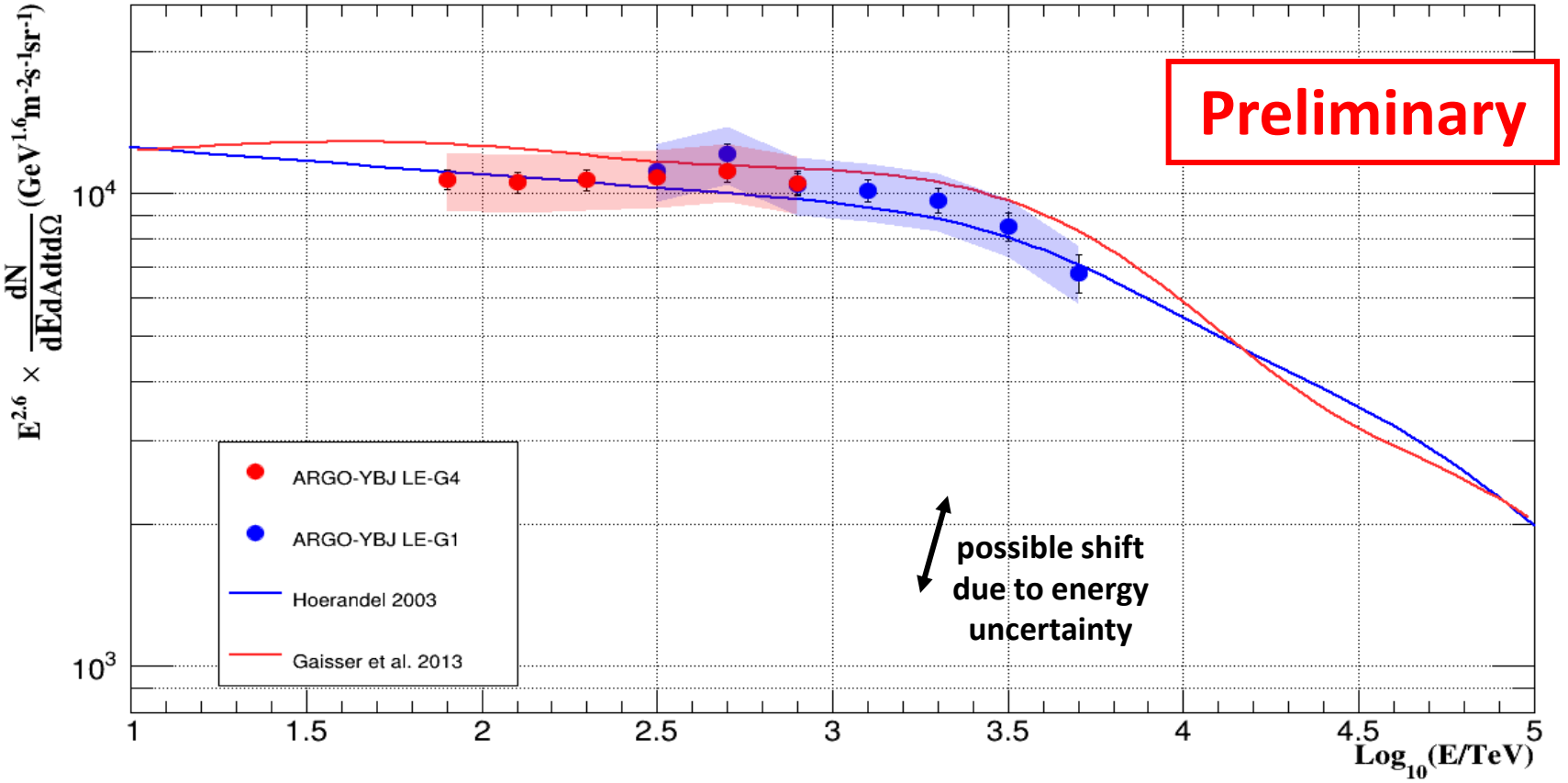
The measurements of Np8 and LDF slope (s') allow estimating the truncated size at the shower maximum ($Np8_{max}$)

↳ Estimate of Mass independent Energy

The all-particle spectrum

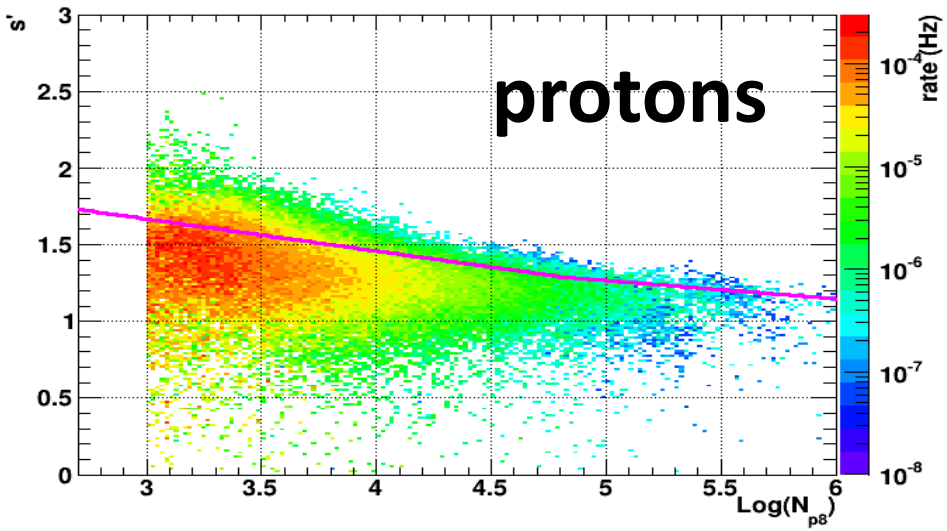
- Picture consistent with models and previous measurements
- Nice overlap with the two gain scales (and different data)
- The plot suggests spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV

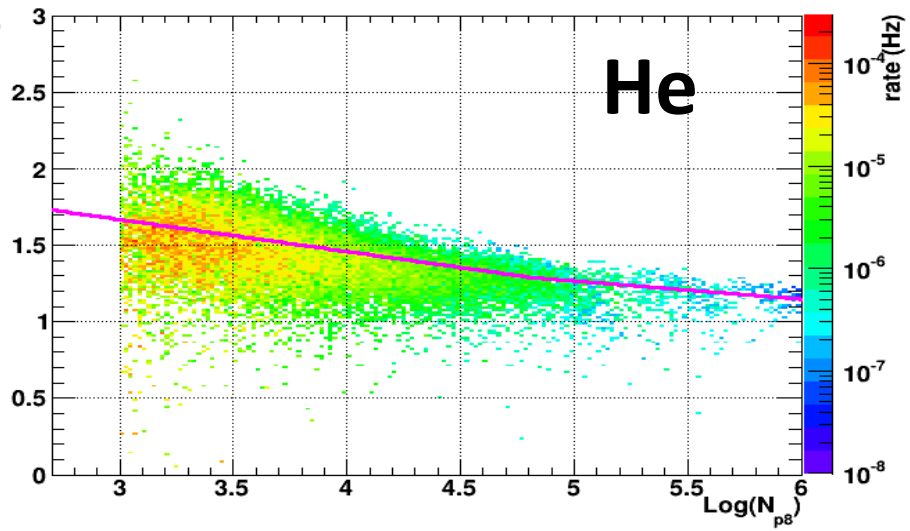
- G0 would extend the energy range up to ~15 PeV
- About a factor 5 should be gained by considering inclined events
- The higher energies would be the subject of a future work

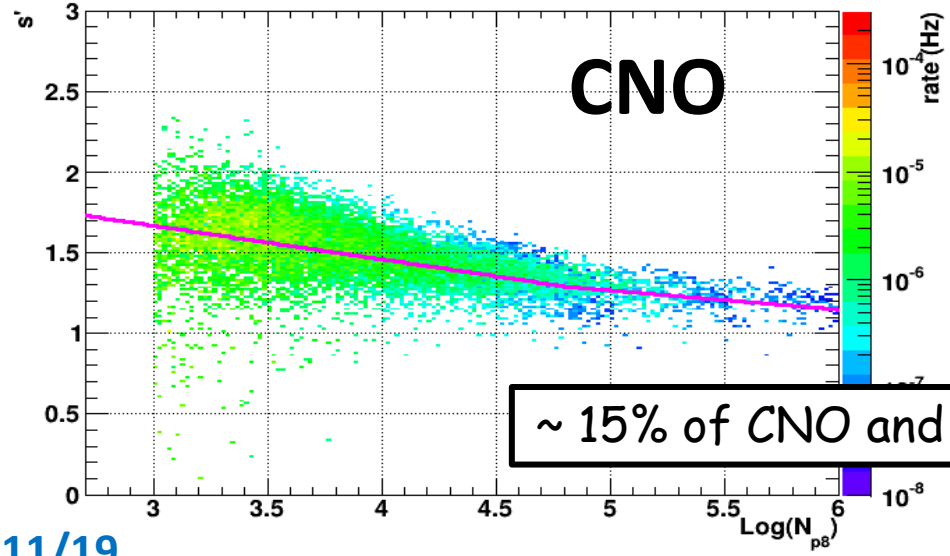


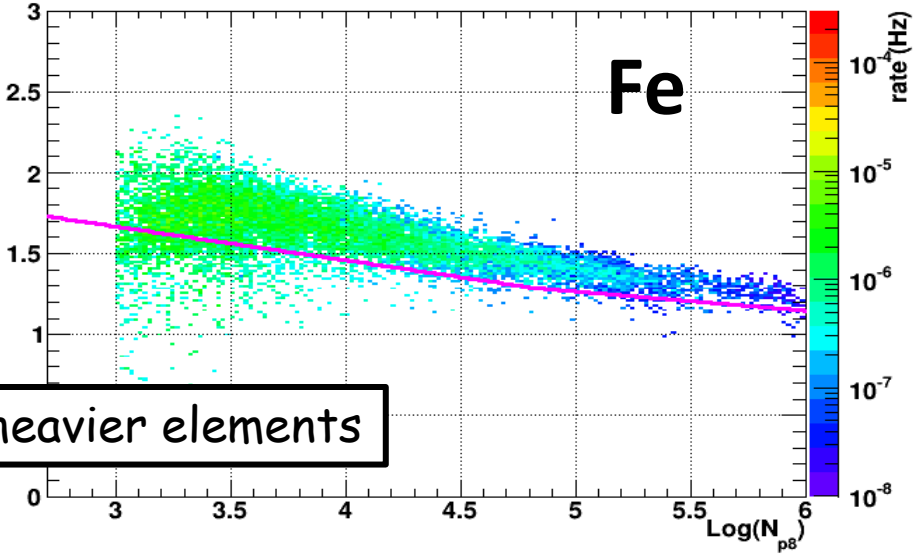
s' vs Log(Np8)

Simple cut to select protons and He (MC with Hörandel spectra)





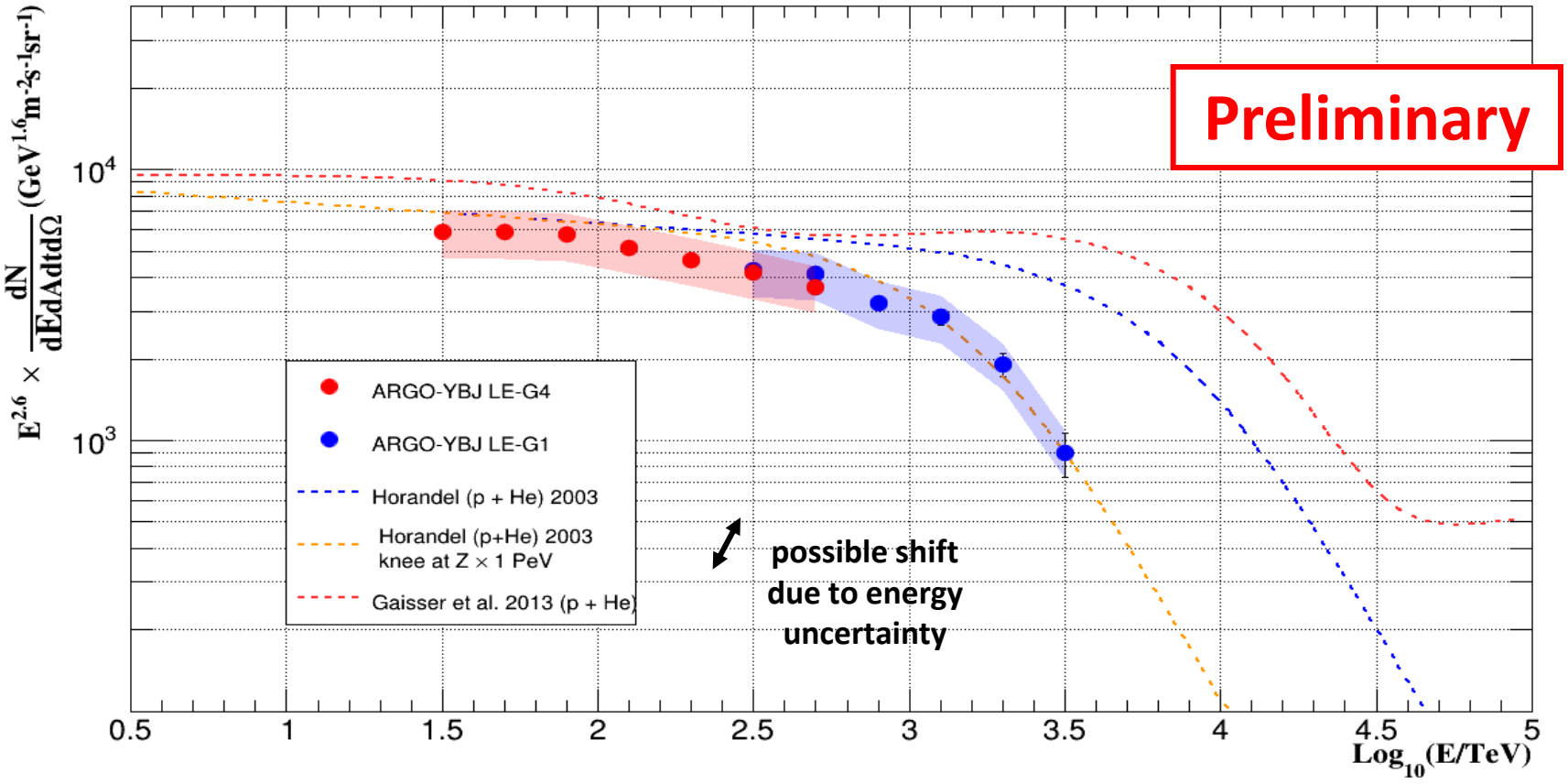




~ 15% of CNO and heavier elements

The 1st light spectrum (p+He)

- Overlap of the points with different gain scales
- Overlap with direct measurements at low energy
- Gradual change of the slope starting around 700 TeV: possible proton knee !!!
- Consistent with previous hints (MACRO, CASA-MIA, Chacaltaya, EAS-TOP …) and YAC-Tibet spectrum
- Flux systematics + CNO contamination ➔ Overall uncertainty < 20 %



Phys. Rev. D 85, 092005 (2012)
Bayesian analysis
for ARGO-YBJ digital data

2nd p+He spectrum: Bayesian unfolding of analog data

The link of primary energy (E) and mass (ID) with observable quantities (Np8, D_5 , D_{10}) has been simulated and studied

$$D_5 = \rho_5 / \rho_{max}$$
$$D_{10} = \rho_{10} / \rho_{max}$$

Simulation

$P(E,ID|Np8,D_5,D_{10}) = P(Np8,D_5,D_{10}|E,ID)\ P(E,ID)$

Bayesian theorem

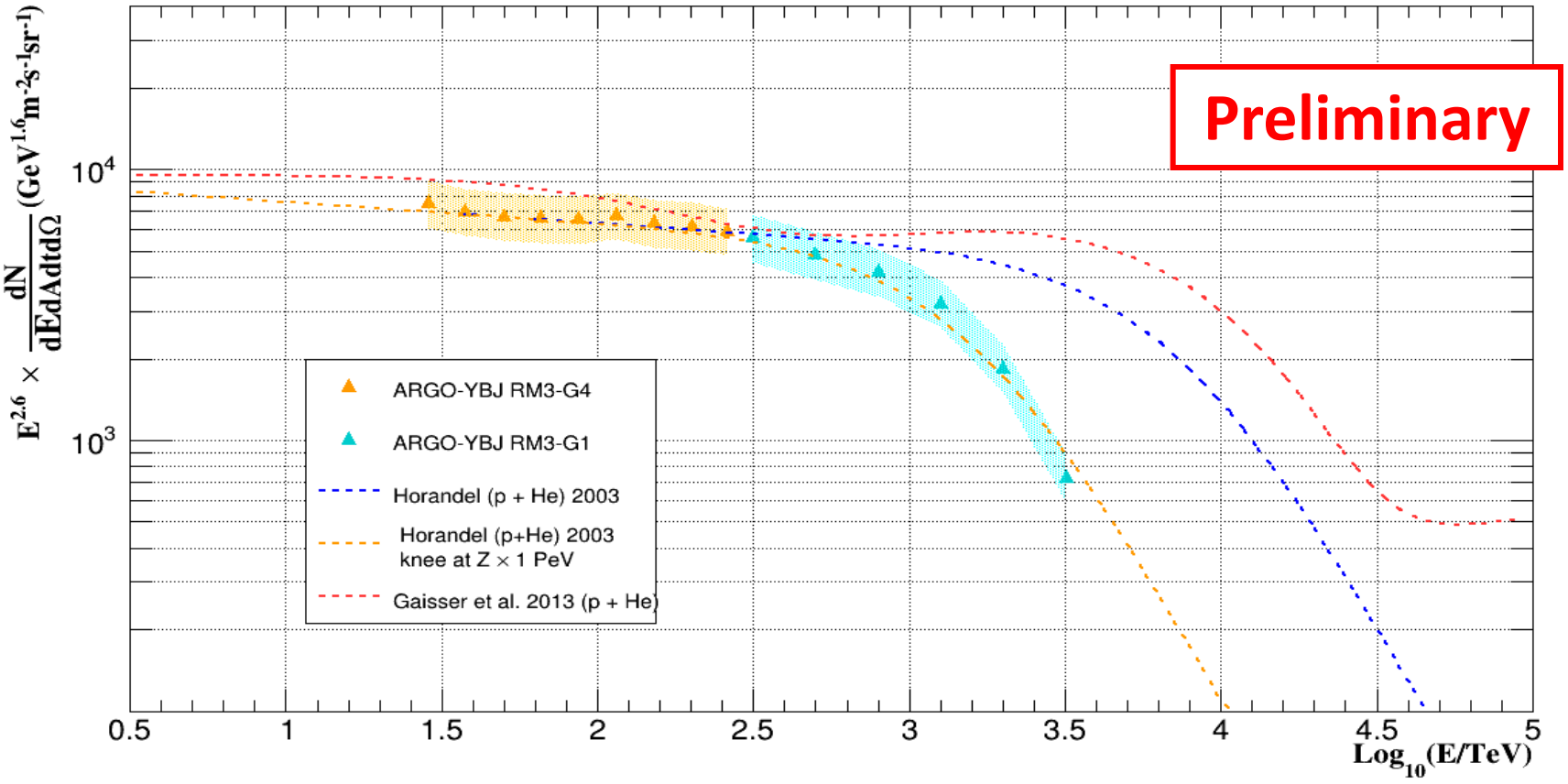
Iterative procedure

$P(E,ID|Np8,D_5,D_{10})\ N(Np8,D_5,D_{10}) = N(E,ID)$

Experimental data

2nd p+He spectrum: Bayesian analysis of analog data

- The results are consistent with previous analysis
- The approach is fully Bayesian
- Different fiducial cuts, also more inclined events ($\theta < 35°$)

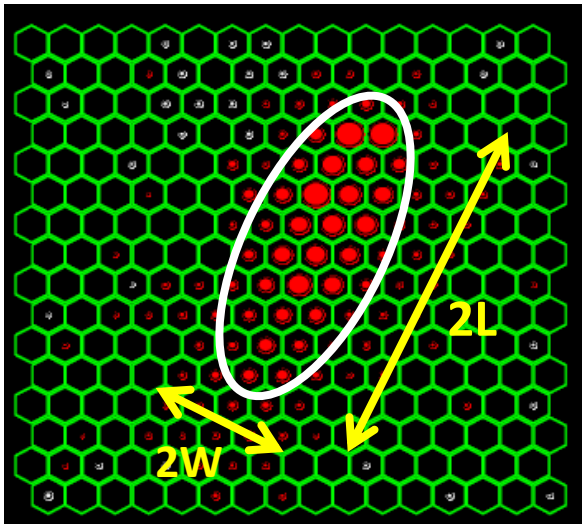


p+He hybrid measurement (3rd): Cerenkov telescope + ARGO-YBJ array

Wide Field of view Cerenkov Telescope Array (WFCTA)

5 m² spherical mirror
16×16 PMT array
Field of View: 14° × 16°
Elevation angle: 60°

Chinese Phys. C 38 (2012) 045001
Hybrid analysis for lower energy showers



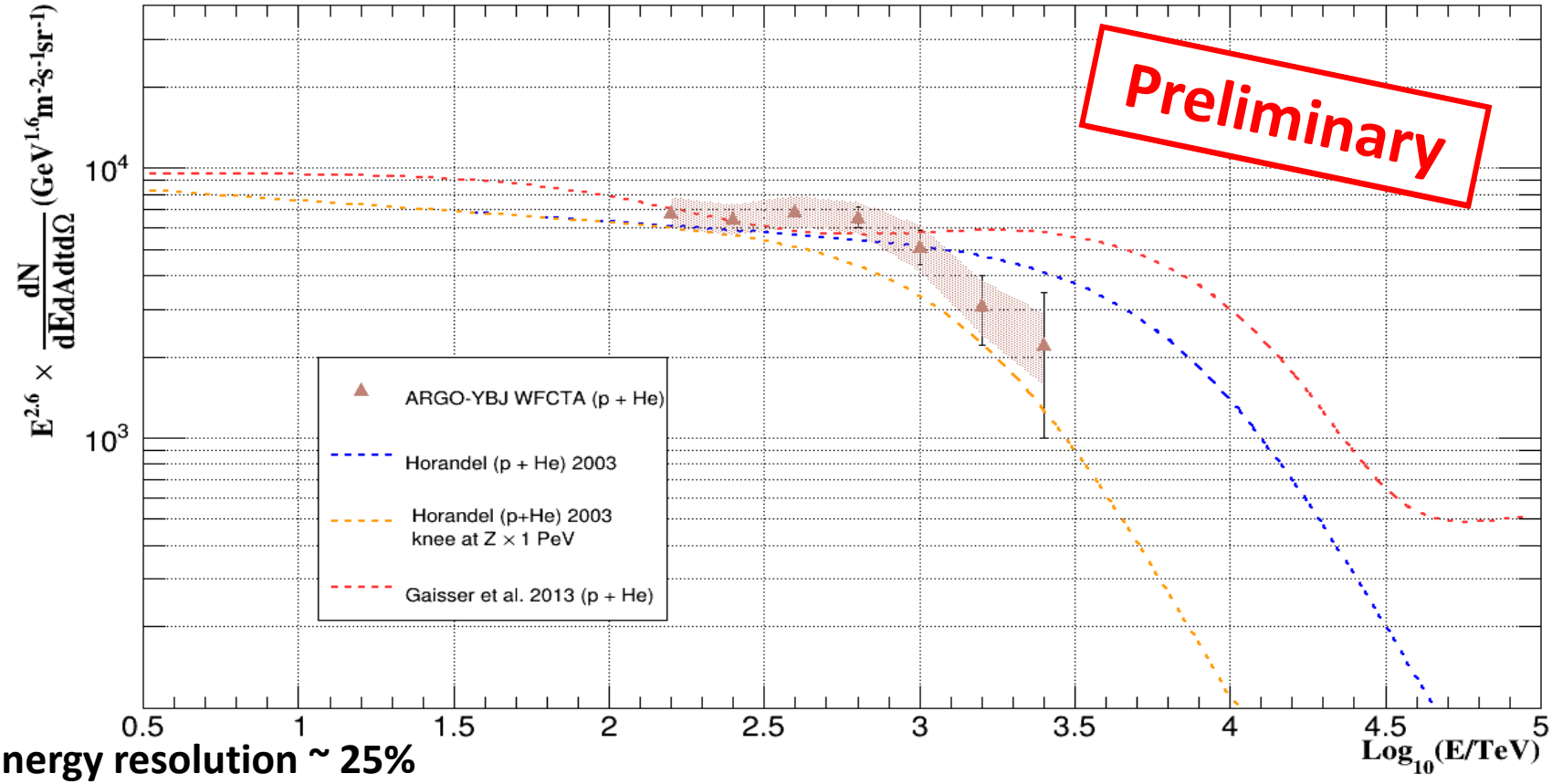
Cerenkov signal: energy measurement
Hillas parameters

ARGO-YBJ analog data: core position
particle number at maximum
shower direction

Light elements are selected according to particle density near the core and shape of the Cerenkov image (L, W)

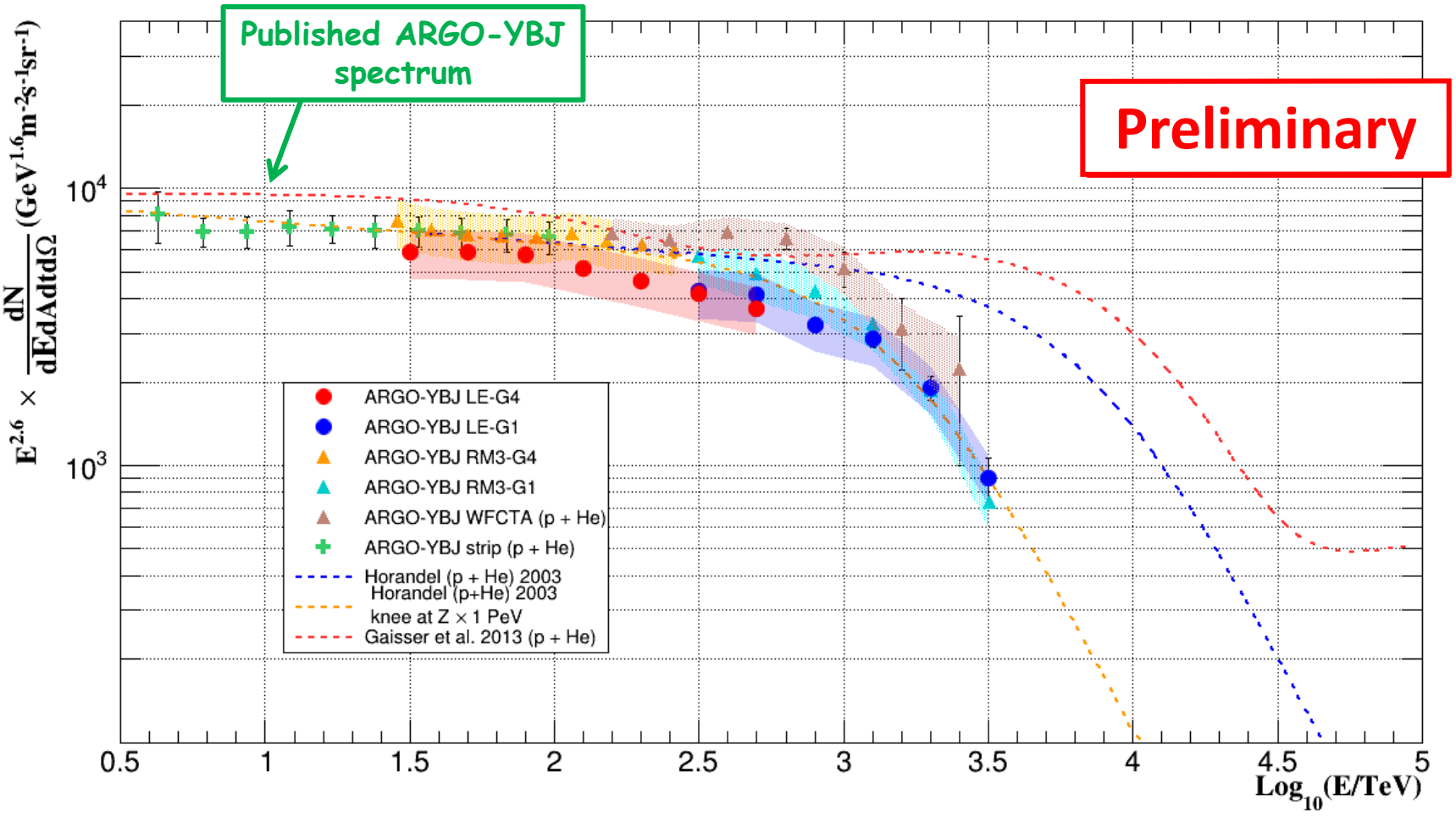
Hybrid measurement (3rd): Cerenkov telescope + ARGO-YBJ array

- The results are consistent with previous analyses
- Possible shape difference
- Different data sample and introduction of another detector
- Different analysis cuts (also inclined events)



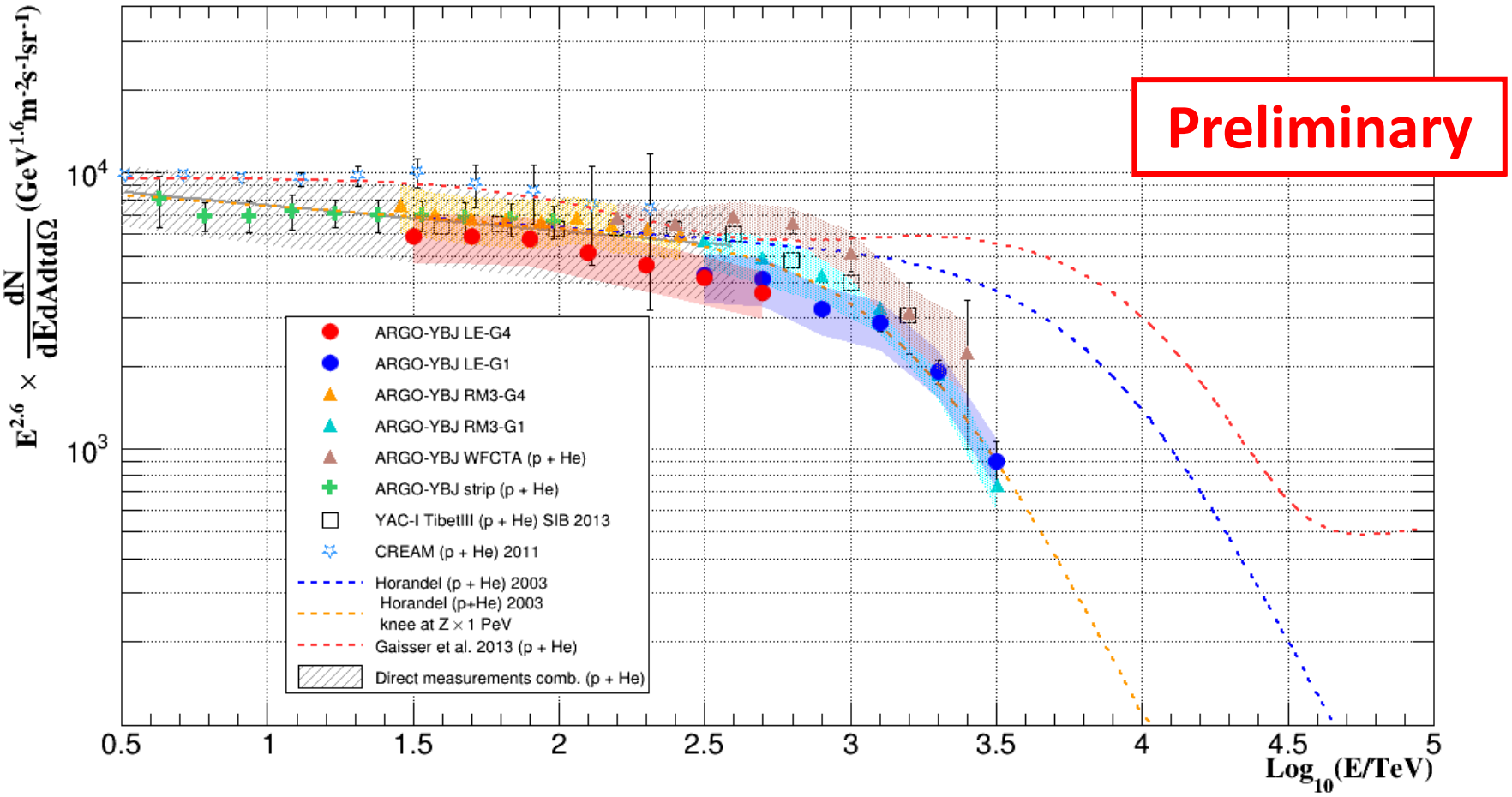
Energy resolution ~ 25%

ARGO-YBJ (+ WFCTA): p+He spectrum



- The results are consistent with published ARGO-YBJ measurement (lower energies)
- The 3 new analyses are consistent within systematics (further cross-checks in progress)

Comparison with some other p+He measurements

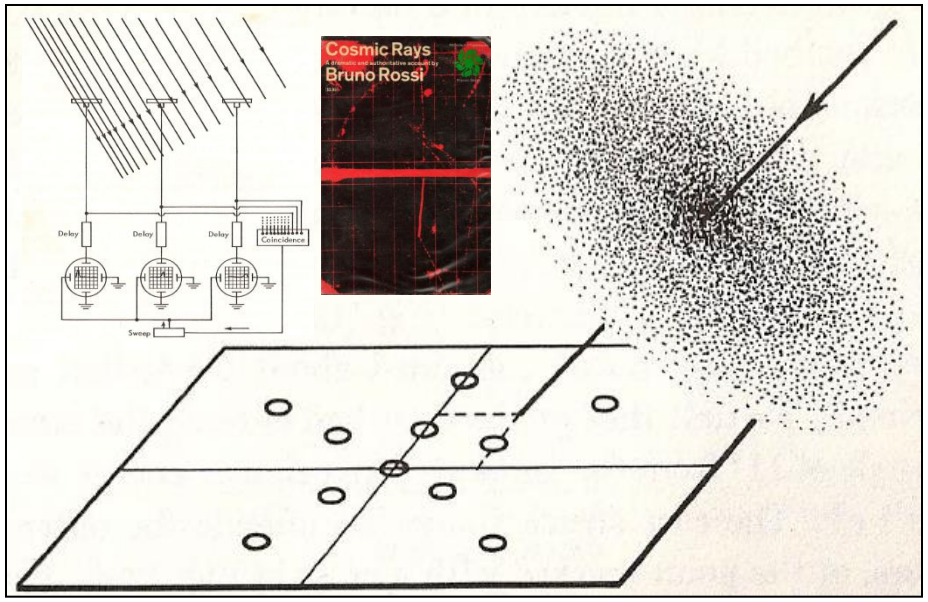


These results are consistent with direct (i.e. below 200 TeV) and YAC-Tibet measurements

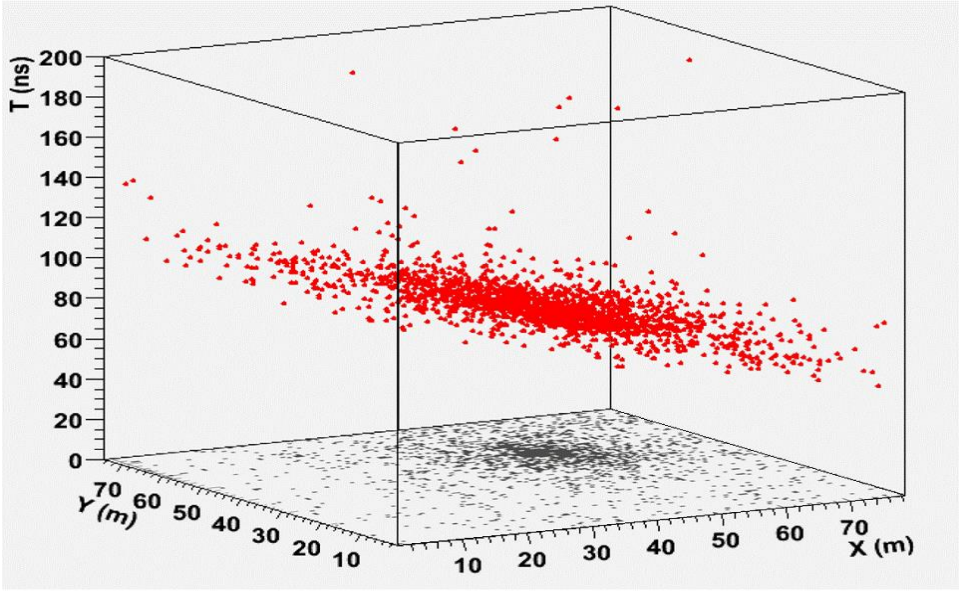
Summary and Outlook

- The analog readout allows to reconstruct the EAS front with unprecedent resolution
- Measured the CR spectrum in the TeV – 10 PeV range. All-particle spectrum consistent with other experiments
- Evidence for a bending in the p+He spectrum below 1 PeV (two different analyses of ARGO-YBJ data in agreement within quoted uncertainties)
- Consistent results from a third independent hybrid analysis (RPC + Cerenkov signal)
- Further cross checks, larger data sample and MC statistics for the final results

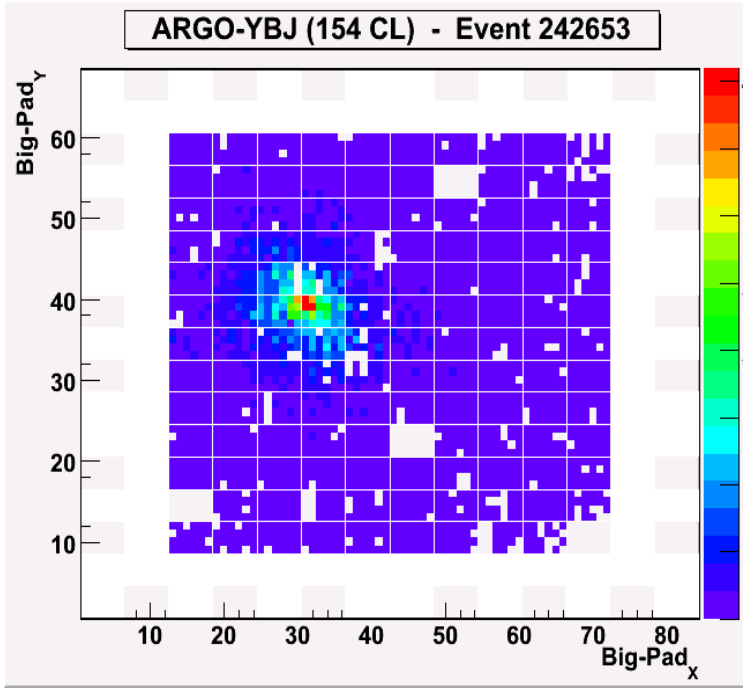
More Stuff



Bruno Rossi conceptual EAS detector

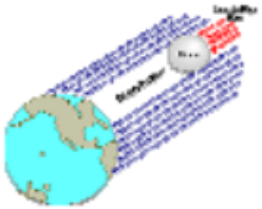


3-D view of a shower detected in ARGO-YBJ

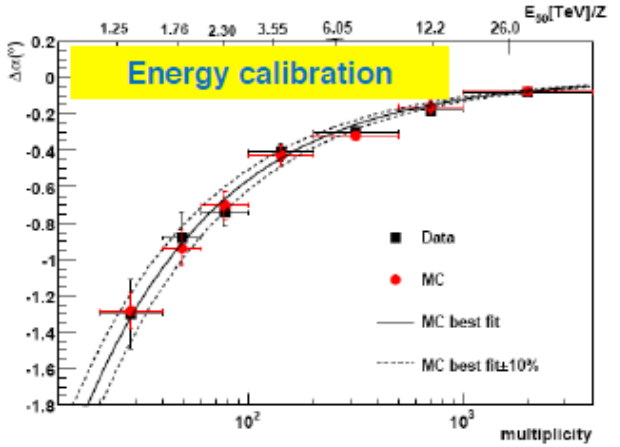


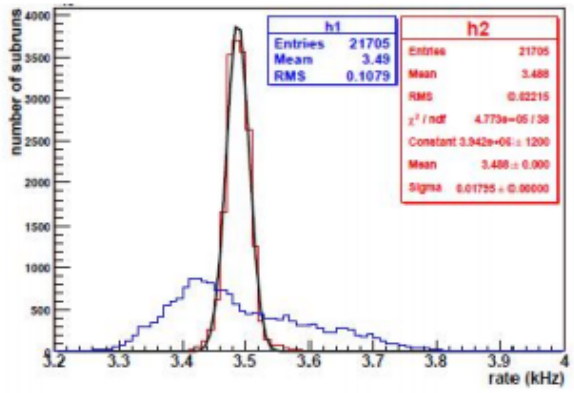
Analog view of a shower

Status and performance

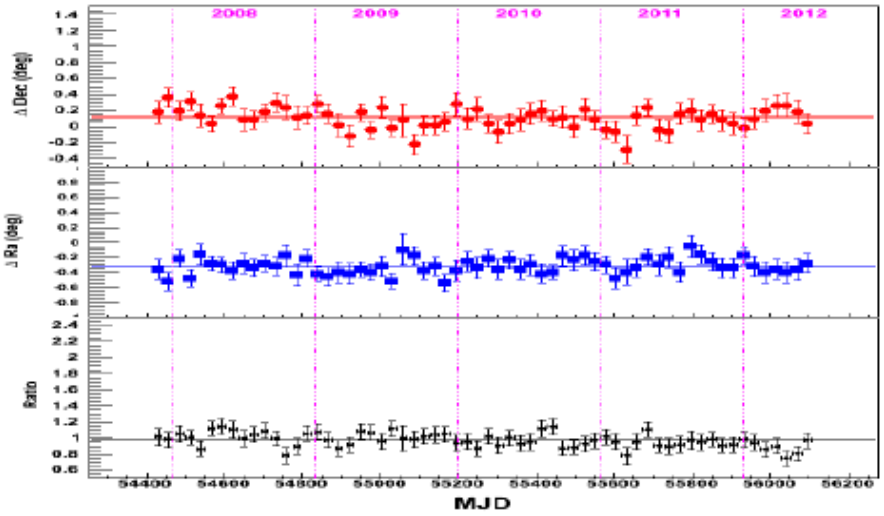


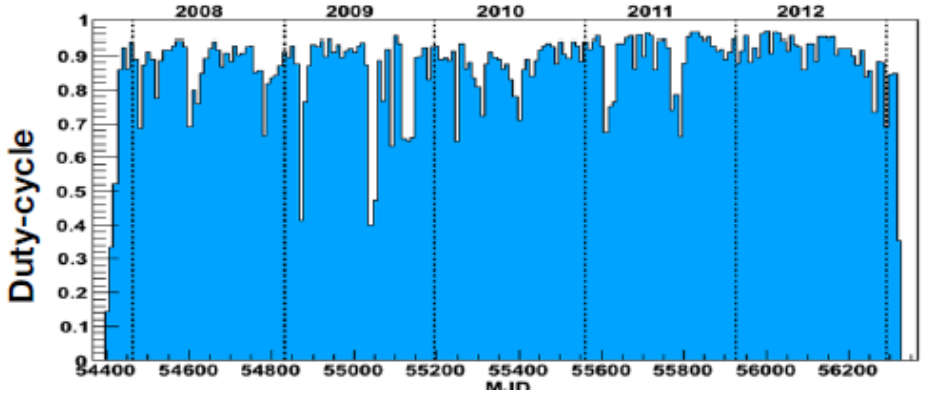
- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data





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





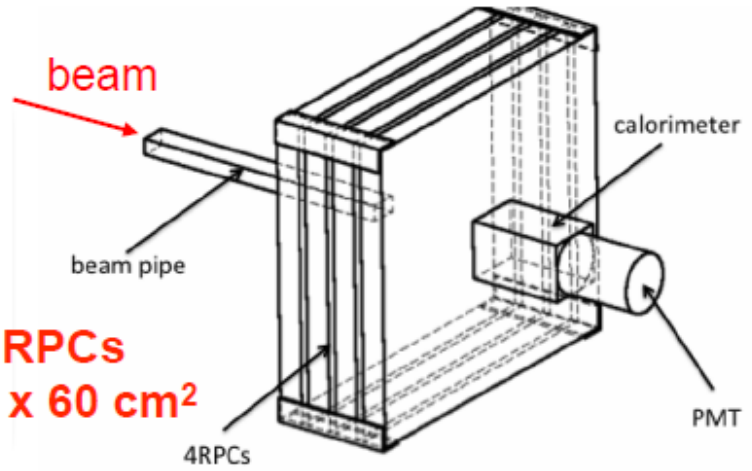
Intrinsic linearity: test at the BTF facility

Linearity of the RPC @ BTF in INFN Frascati Lab:

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

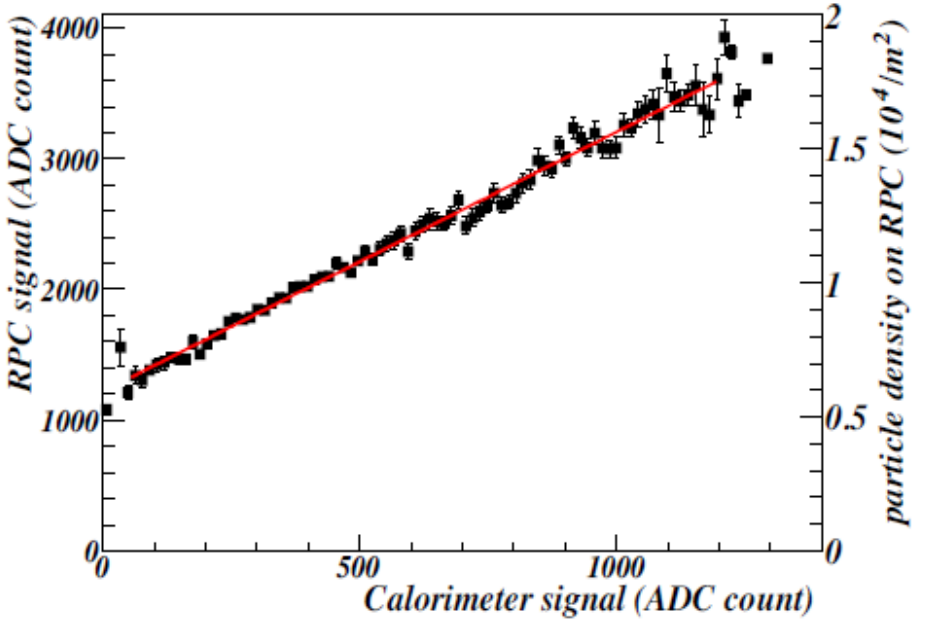
→ Linearity up to ≈ 2 • 10⁴ particle/m²

Astroparticle Physics submitted

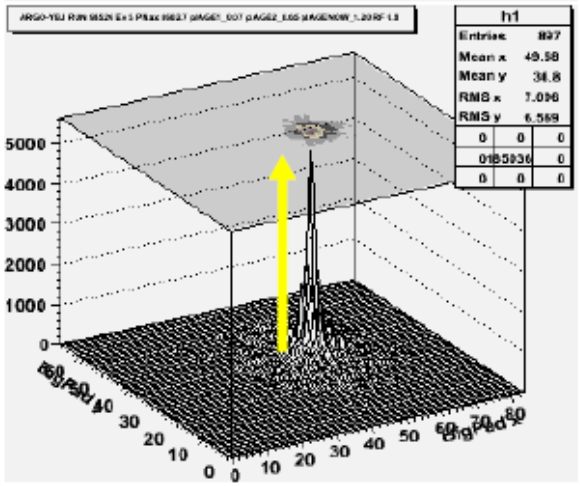


Calorimeter: lead glass block from OPAL,
PMT a Hamamatsu R2238.

The RPC signal vs the calorimeter signal



Absolute comparison Data - MonteCarlo



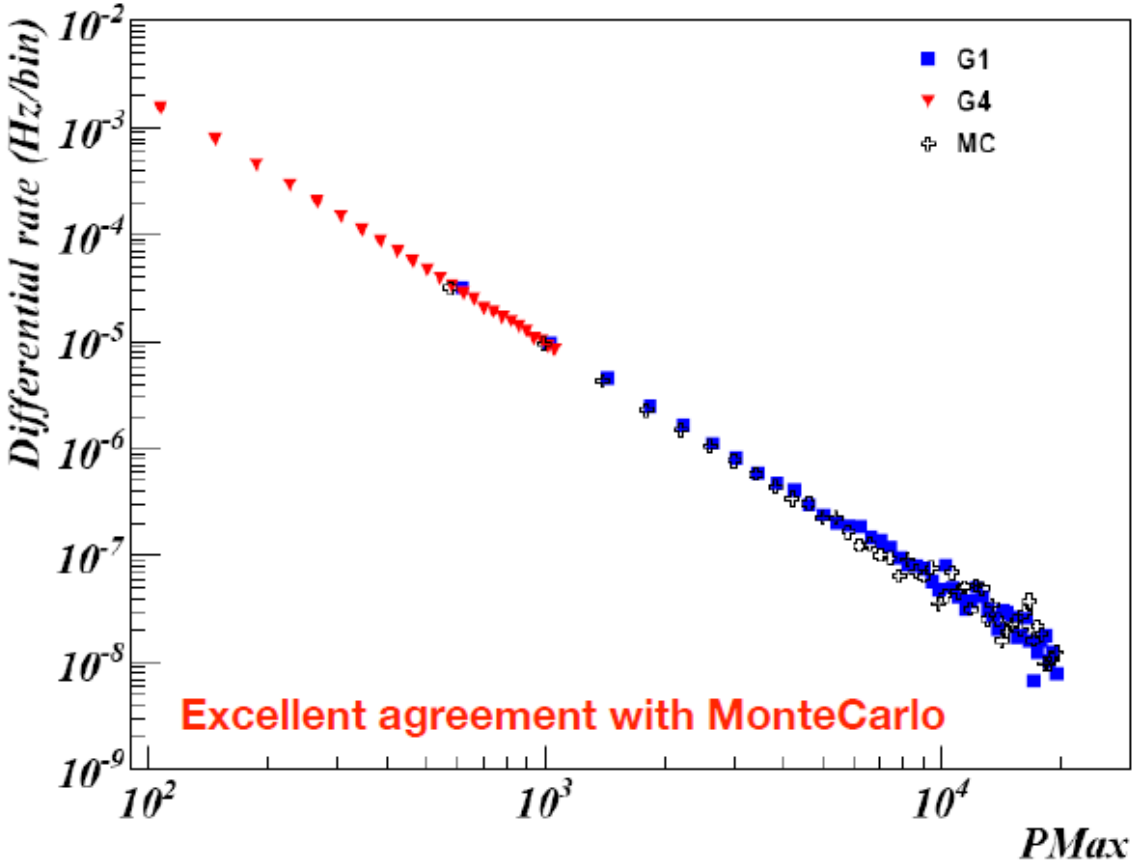
J.R. Horandel , Astrop. Phys. 19 (2003) 193

Event selection:

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

★ Zenith angle < 15°

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



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

The analog readout system

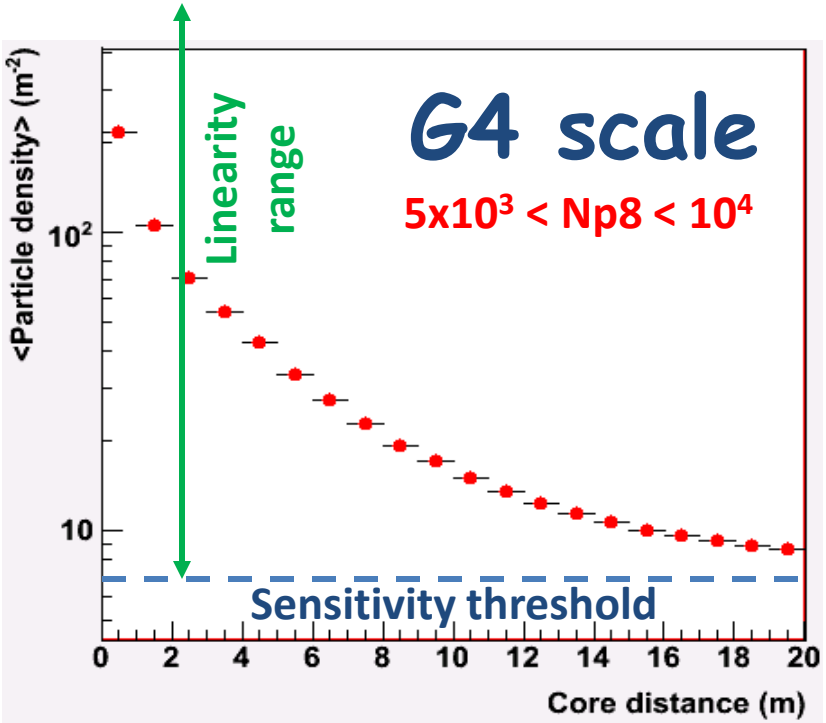
Eight gain scales (G0, G1, … G7) ensure good linearity up to about 2 x 10^4 particles/m^2

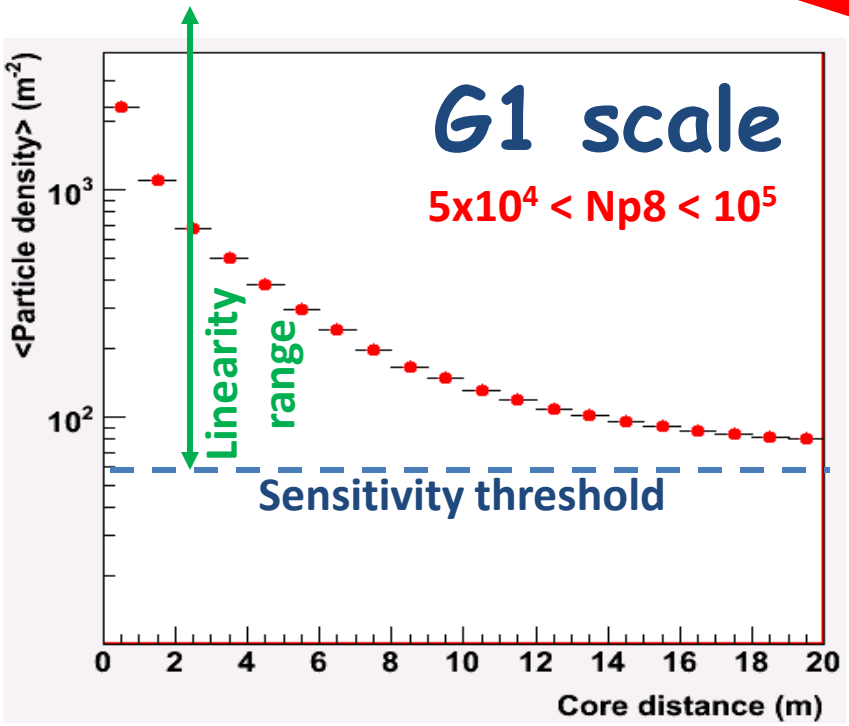
G7 data overlap the digital-mode linearity range, and have been used for intercalibration and cross checks

Here we use G4 and G1 scales to cover the 50 TeV – 5 PeV range with high efficiency and without saturation

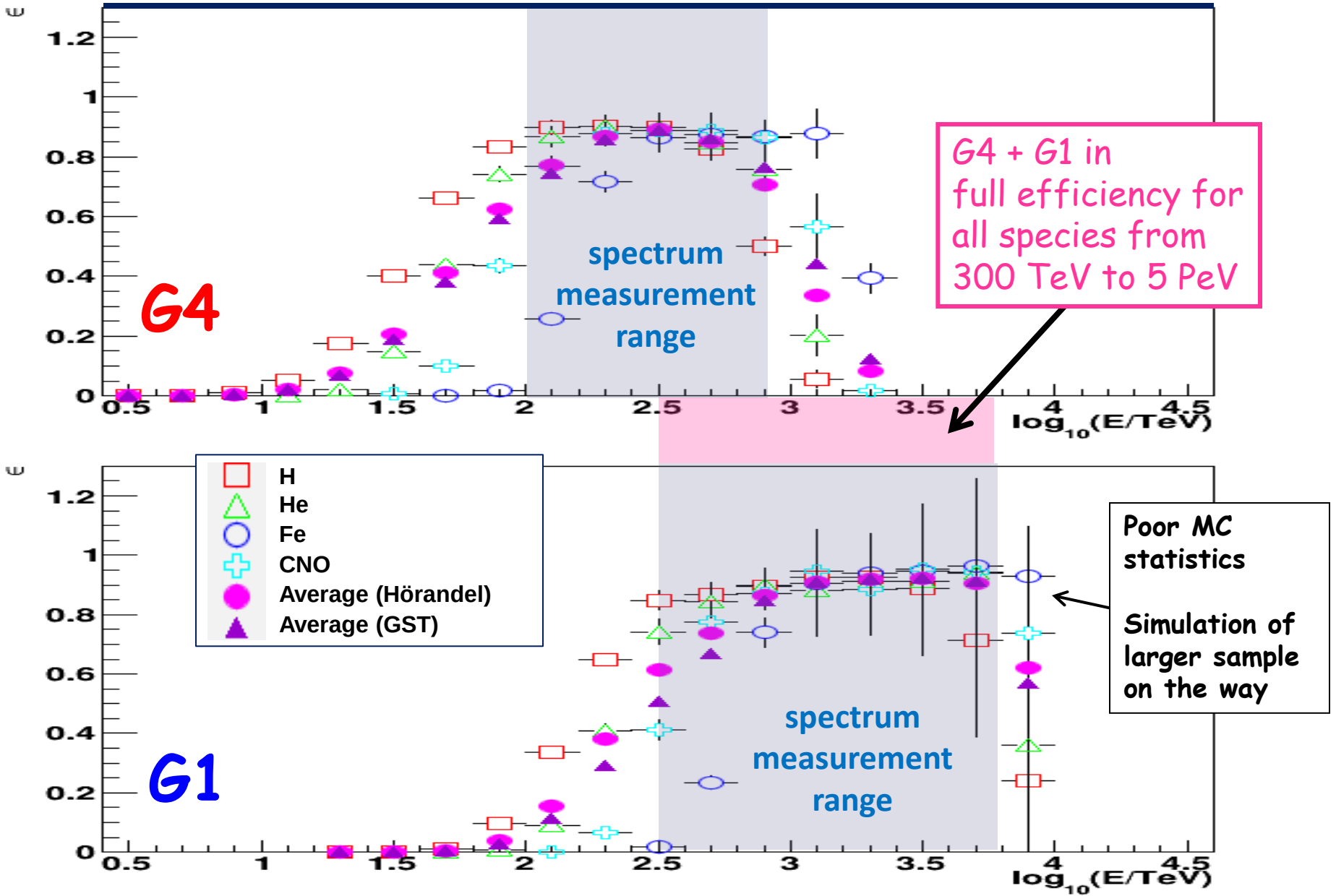
Np8 = how many particles within 8 m from the core

Lateral Distribution Function (LDF)





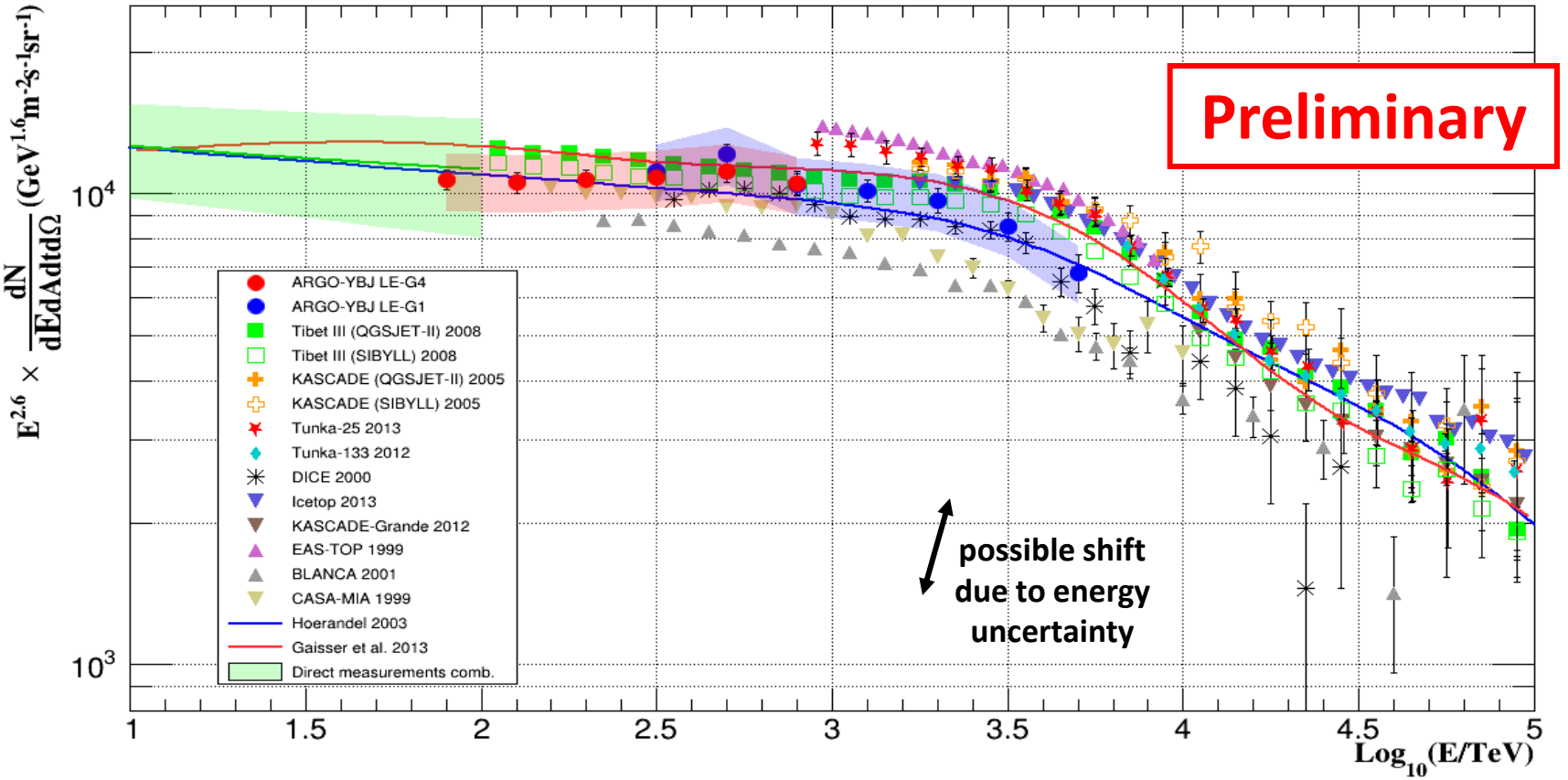
Efficiency of trigger and event selection for the all-particle spectrum



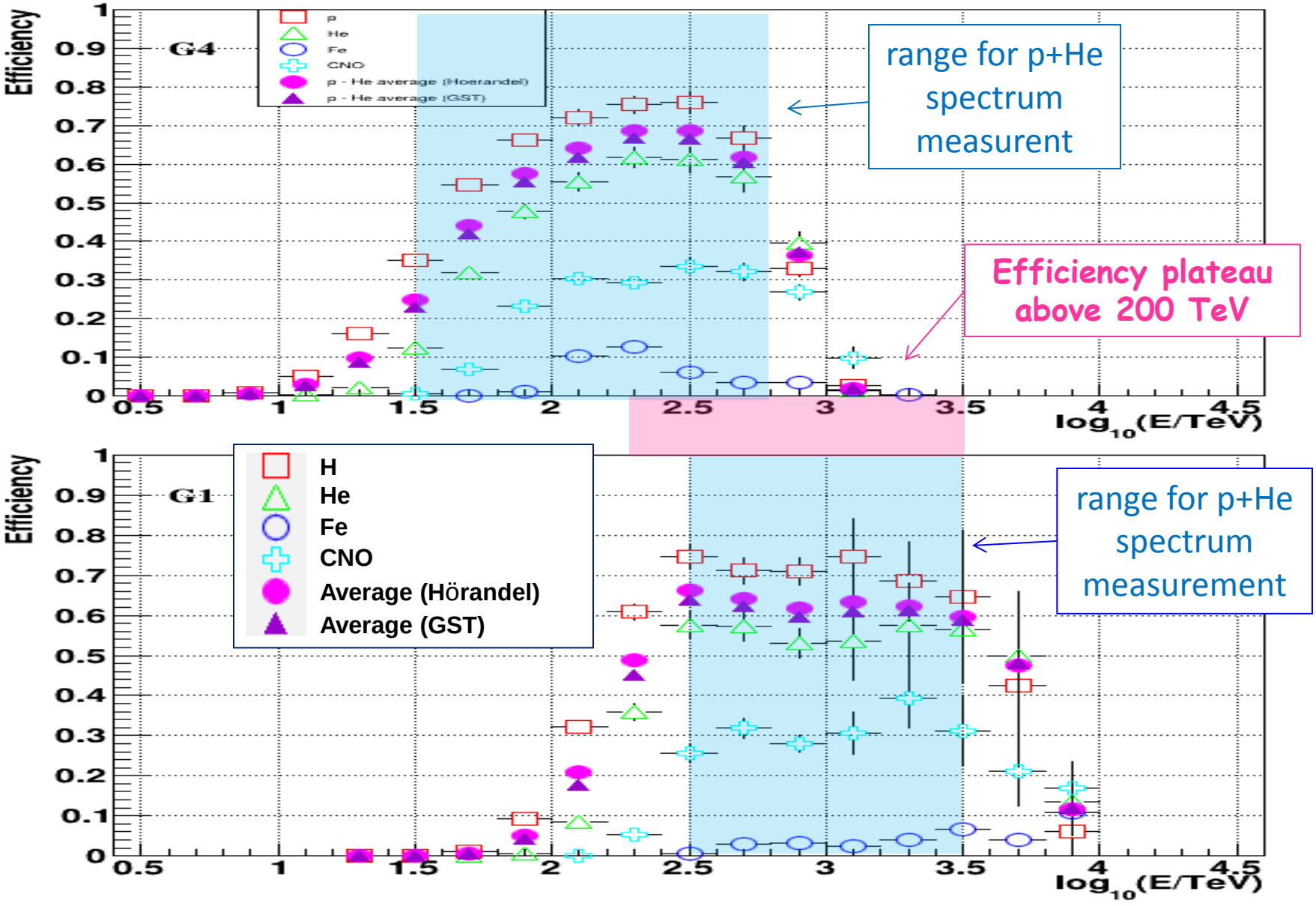
The all-particle spectrum (II)

- Picture consistent with models and previous measurements
- Nice overlap with the two gain scales (and different data)
- The plot suggests spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV

- GO would extend the energy range up to ~15 PeV
- About a factor 5 should be gained by considering inclined events
- The higher energies would be the subject of a future work



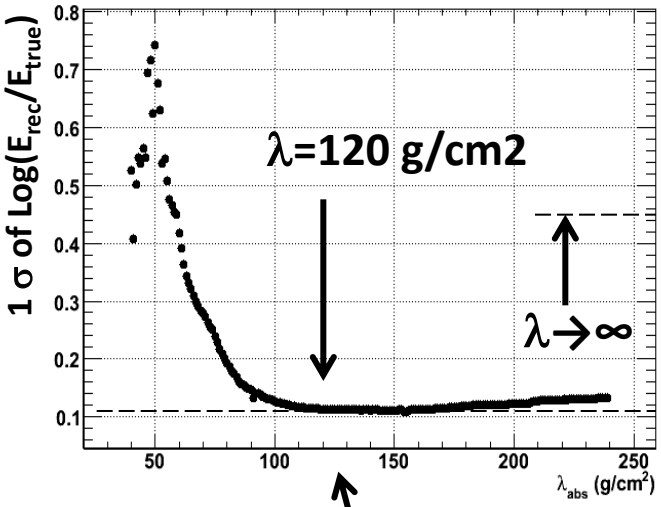
Efficiency of trigger and event selection for the p+He spectrum



Finding the best λ_{abs} parameter

Further improvements in progress

LogE resolution at 270 TeV vs λ_{abs}

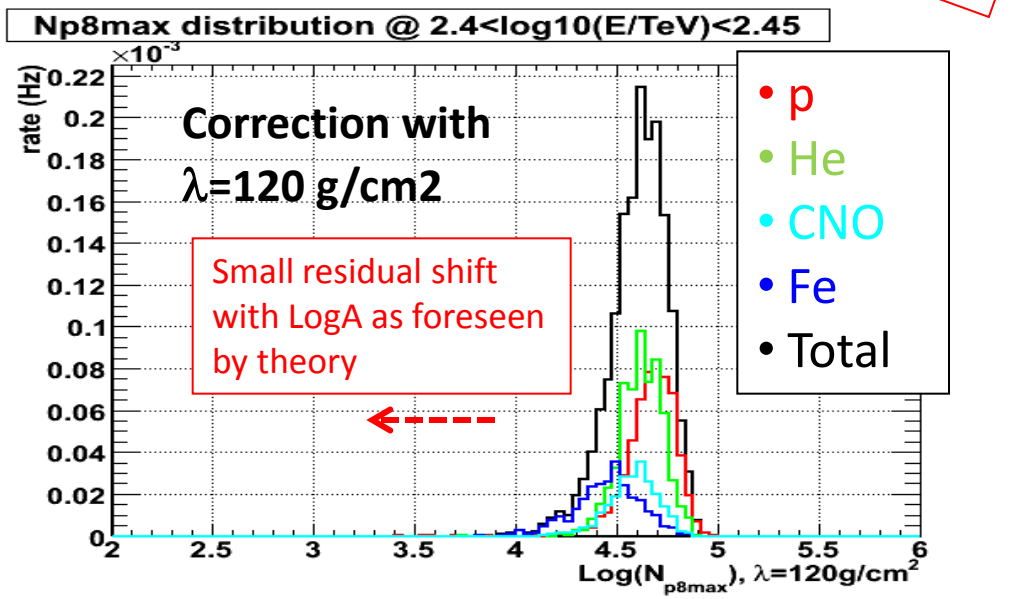


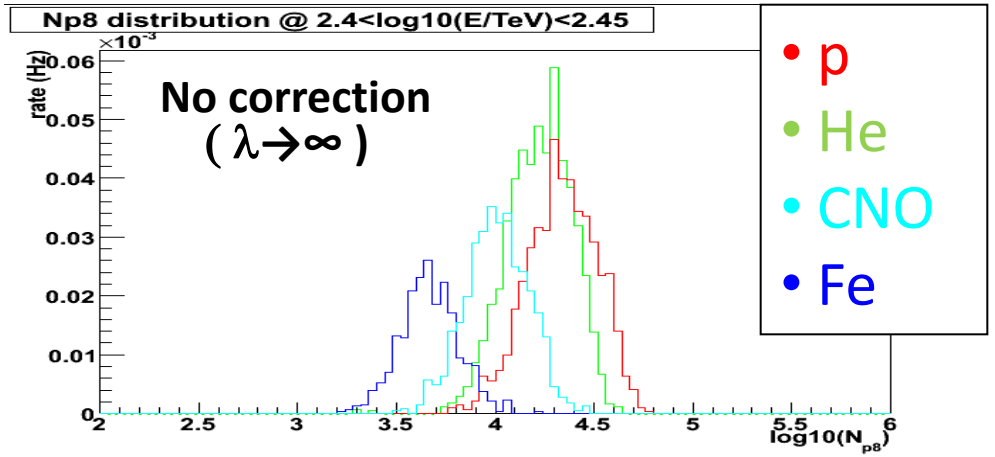
Results from the ARGO-YBJ test experiment

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].

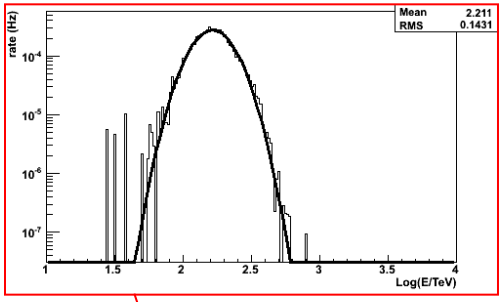
The parameter α is found to be 4.88 ± 0.45, so that $\Lambda_{att} = (124 \pm 11)$ g/cm^2, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 ± 0.37.

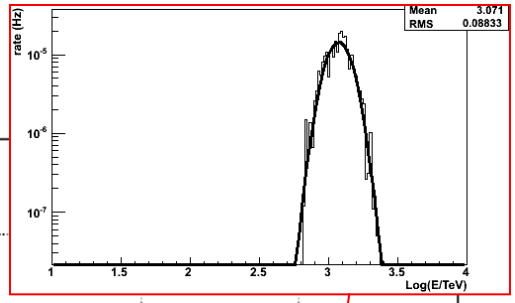


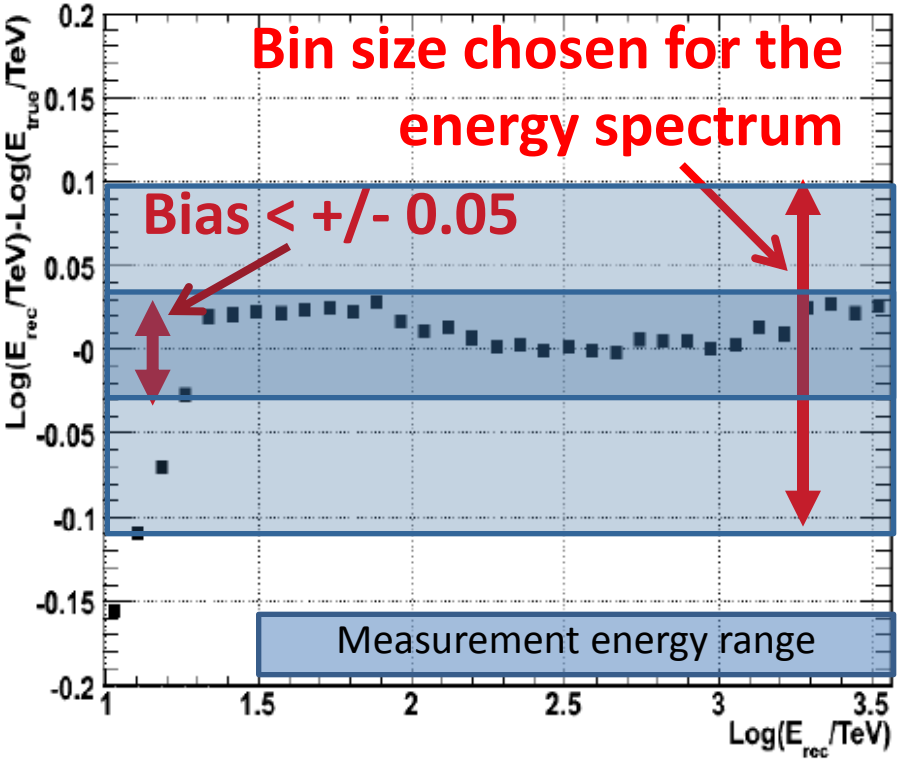


Energy reconstruction: bias and resolution

The response function is Gaussian in LogE.
The spectra are then given in LogE bins, much larger than the estimated bias and well above the LogE resolution, in the considered energy range.





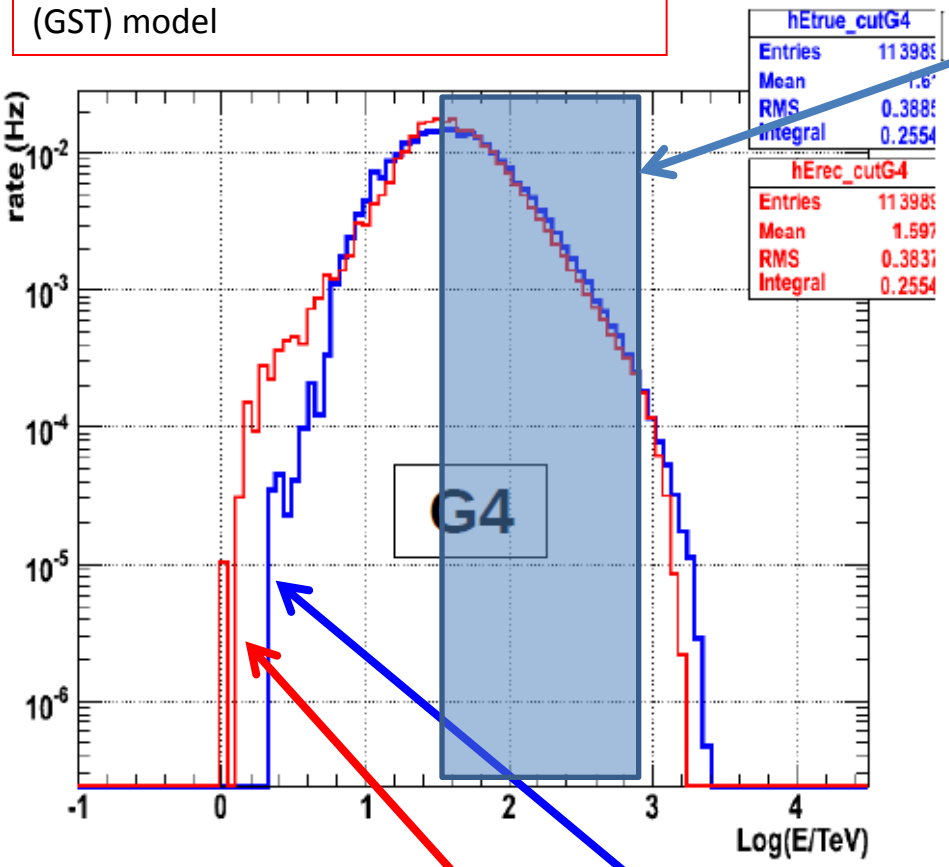


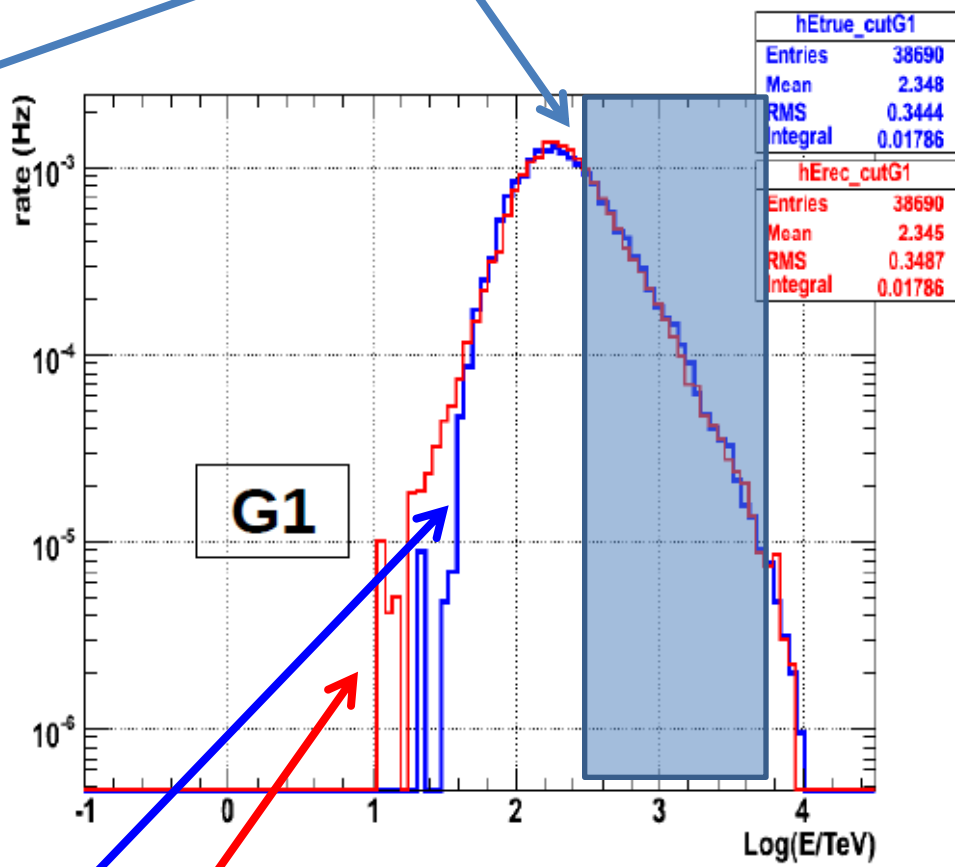
MC Energy distributions

MC sample following Horandel model spectra and composition

Similar results with Gaisser-Stanev-Tilav (GST) model

Measurement energy ranges





MC true energy

MC reconstructed energy

Systematic uncertainty evaluations

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

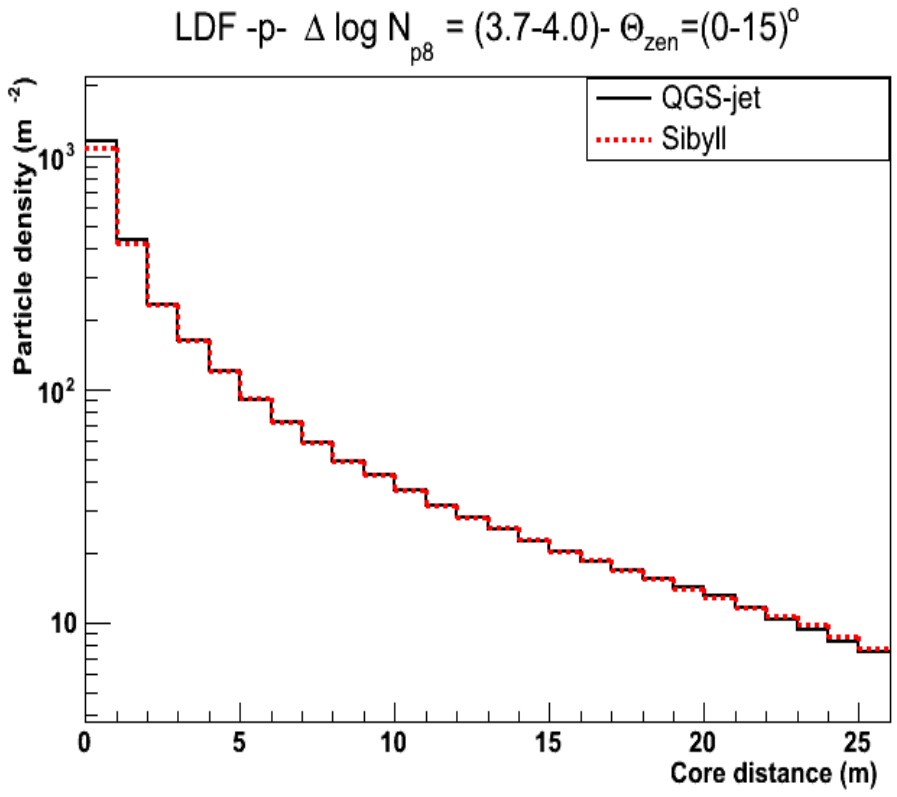
- Gain of the analog system: 3.7 %
- Energy calibration: 0.03 in LogE = 6.9 %
- Hadronic interaction model: 5 %
- **TOTAL: 9.3 %** **TOTAL (conservative) = 10%**

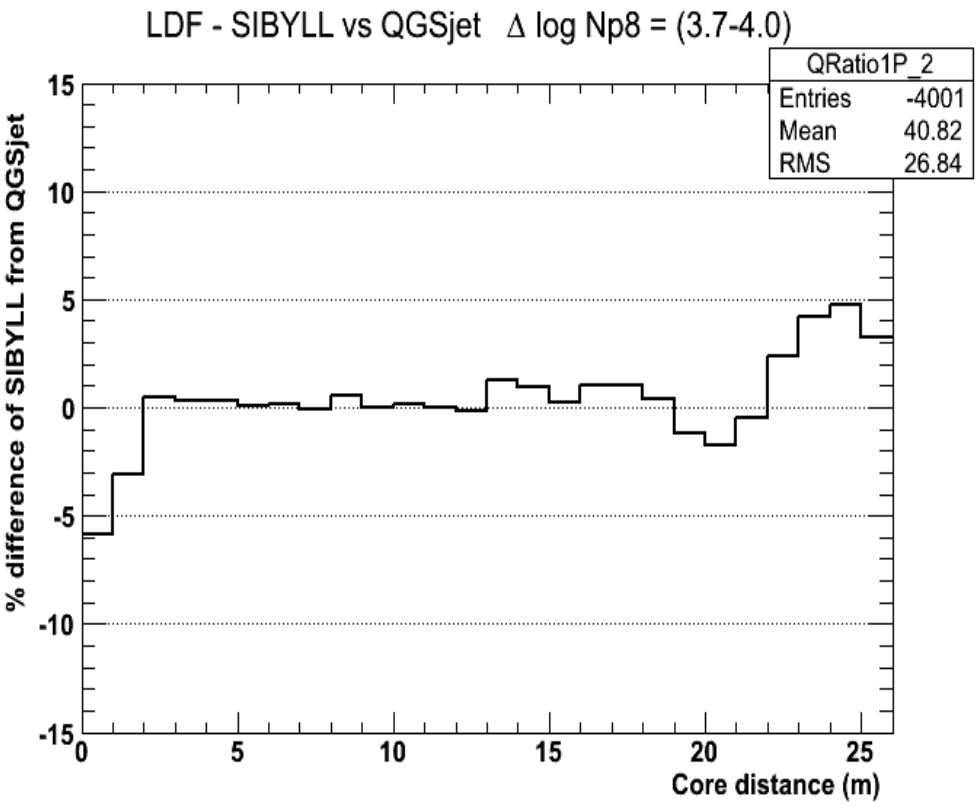
In the flux plots an over-conservative ± 14% shaded area has been temporarily drawn on the flux measurements

Error bars show the statistical uncertainties

Systematics from the hadronic interaction models

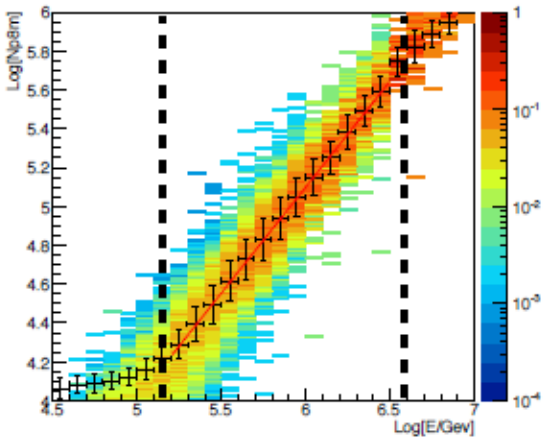
The dependence on the adopted hadronic interaction model is small.
The differences among the QGSJET-II.03 and Sibyll-2.1 are within few percent in the explored energy range (no bias due to muon number).
All further results shown here were obtained with QGSJET-II.03.





The 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

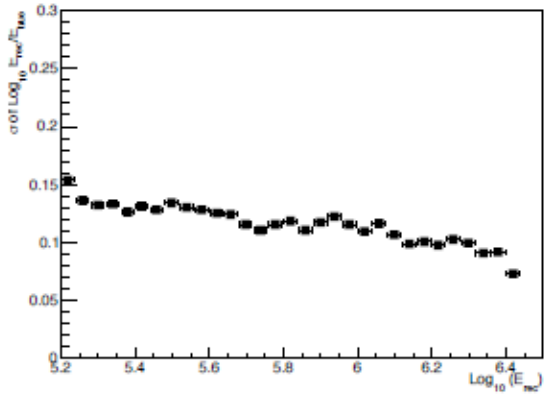


Selection of the light component: shower topology

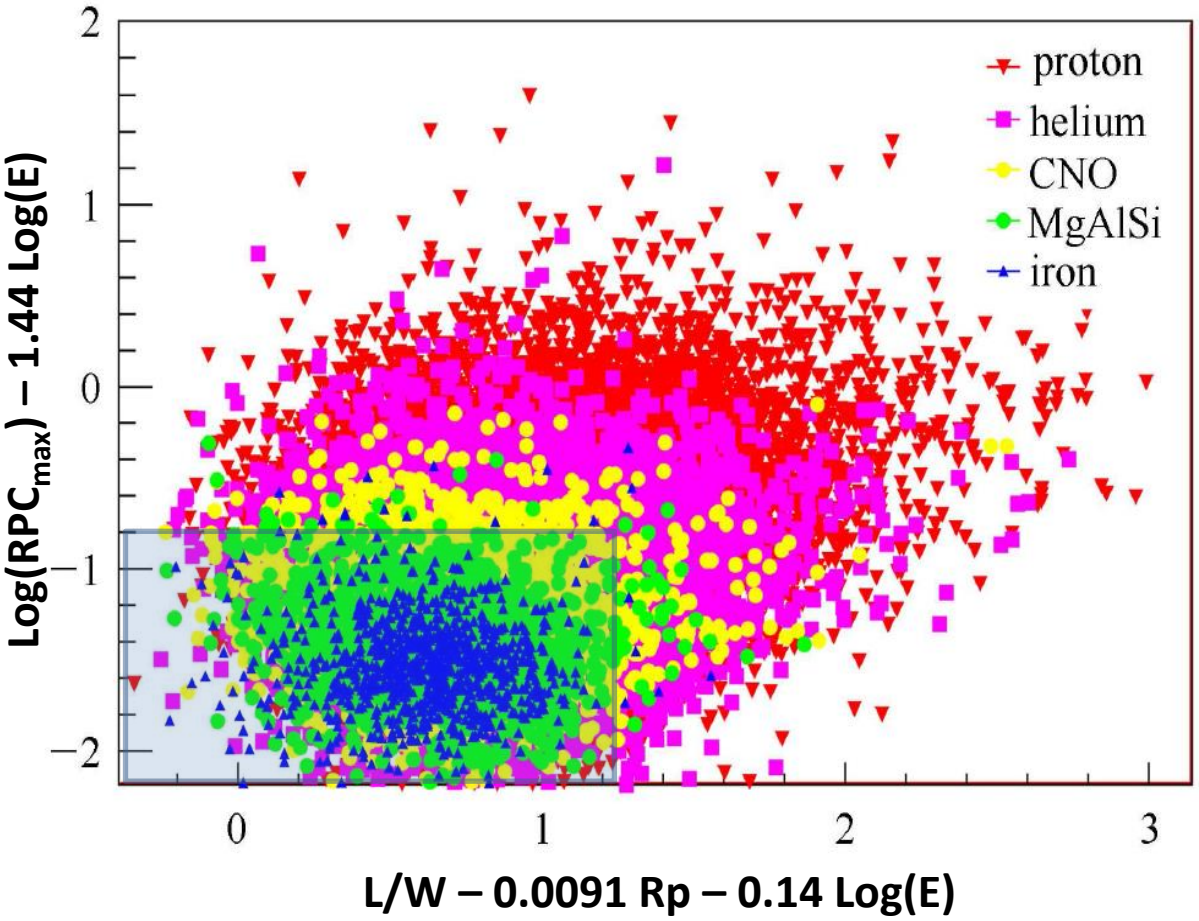
Light Component (p+He) selection:

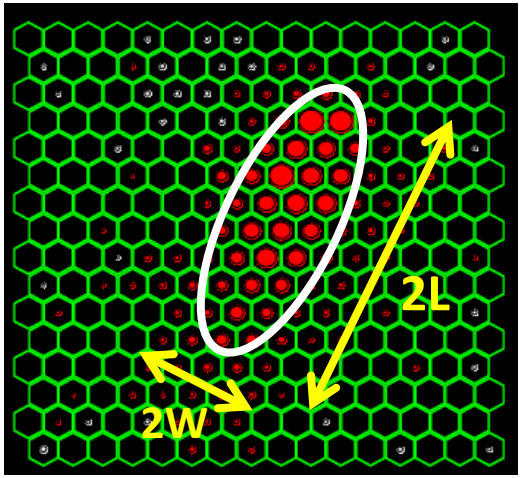
$$\rho_{A20} > \rho_{A42}$$

A20 = 20 innermost clusters
A42 = 42 outermost clusters



Mass selection for the hybrid measurement

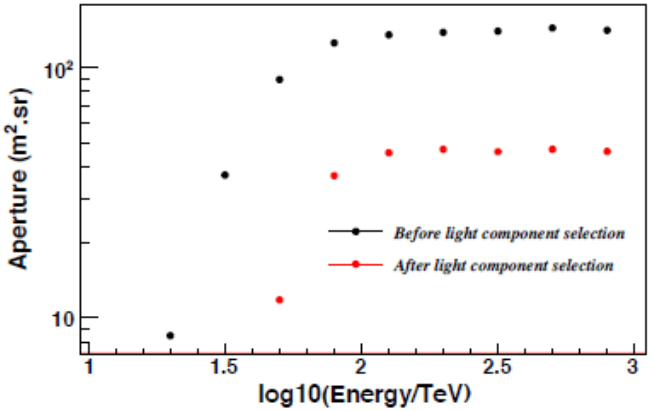


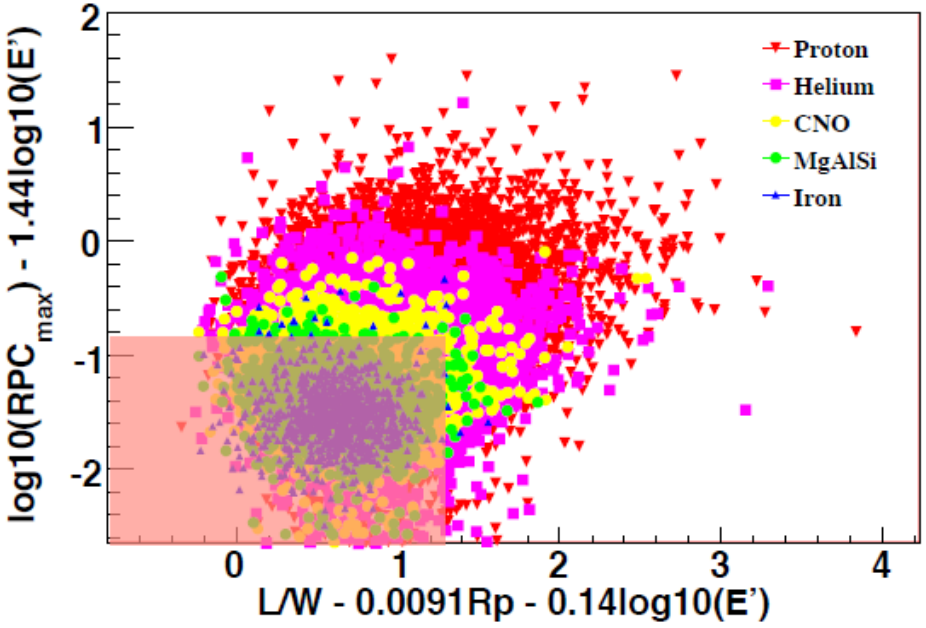


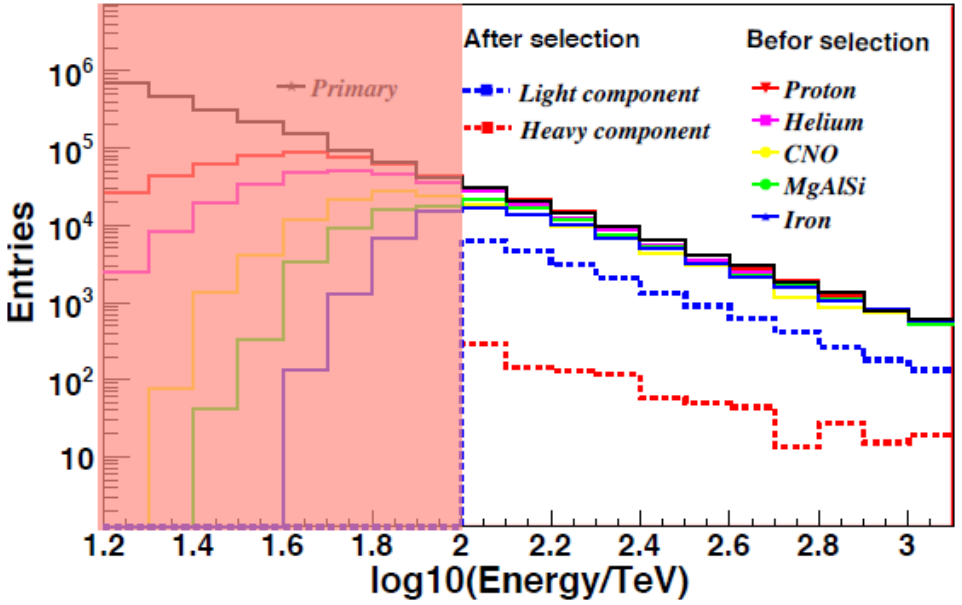
Rp – shower impact parameter
E – reconstructed energy
RPC$_{max}$ – maximum RPC signal

- 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%	



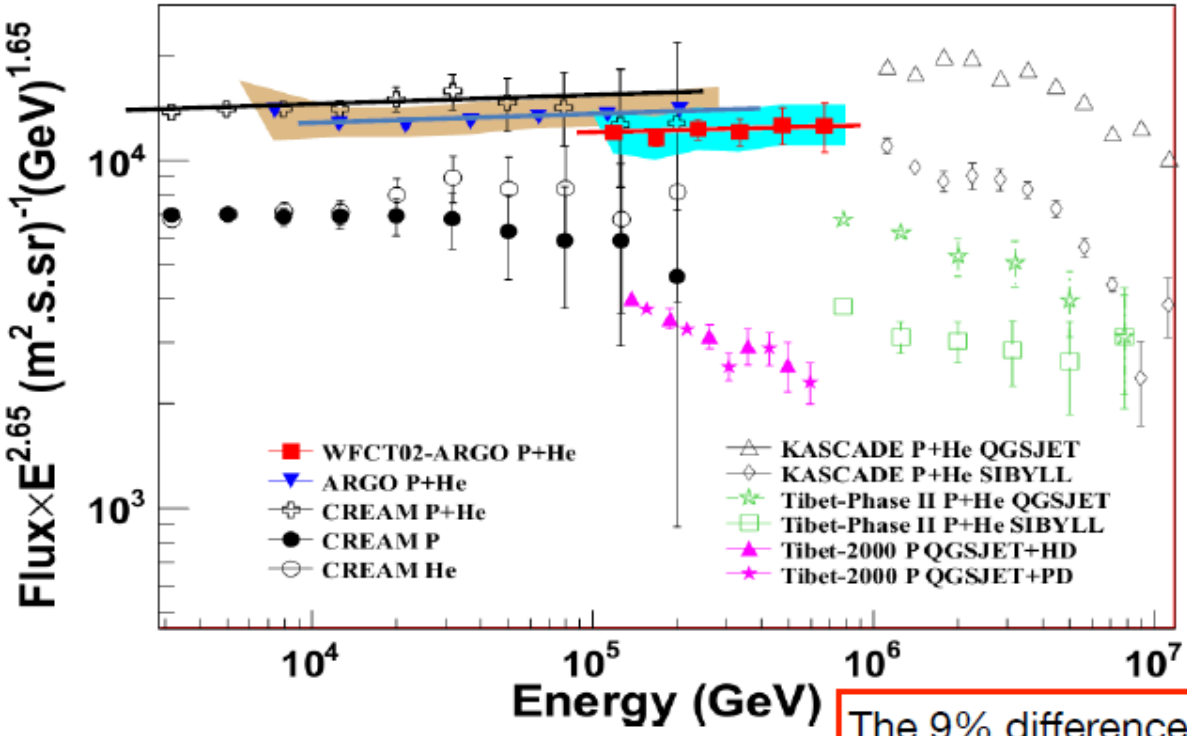




The light-component (p+He) spectrum (2 - 700) TeV

- **CREAM** 1.09 x 1.95 x 10^{-11} (E/400 TeV)$^{-2.62}$
- **ARGO-YBJ** 1.95 x 10^{-11} (E/400 TeV)$^{-2.61}$
- **Hybrid** 0.92 x 1.95 x 10^{-11} (E/400 TeV)$^{-2.63}$

Single power-law: 2.62 ± 0.01



Flux at 400 TeV:

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

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

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

The overall picture