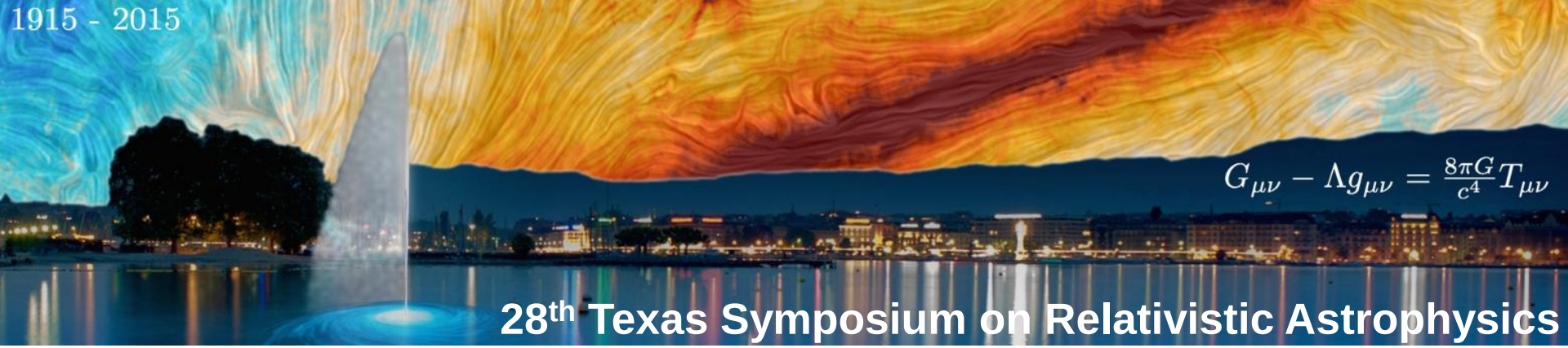


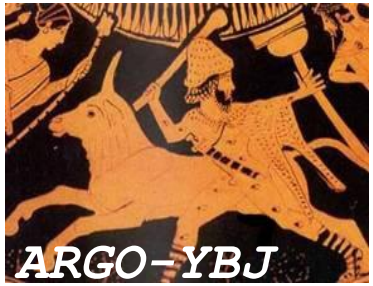
Geneva, 13-18 December 2015

Study of the Galactic Cosmic Ray energy spectrum with the ARGO-YBJ experiment

Antonio Surdo

Istituto Nazionale di Fisica Nucleare
Lecce, Italy
(surdo@le.infn.it)

for the ARGO-YBJ Collaboration



The ARGO-YBJ experiment

Astrophysical Radiation with Ground-based Observatory at YangBaJing

ARGO-YBJ

Kaijiaguo

© 2013 Mapabc.com

High Altitude Cosmic Ray Observatory @ YangBaJing, Tibet, China

Site Altitude: 4,300 m a.s.l. , ~ 606 g/cm^2

ARGO-YBJ physics

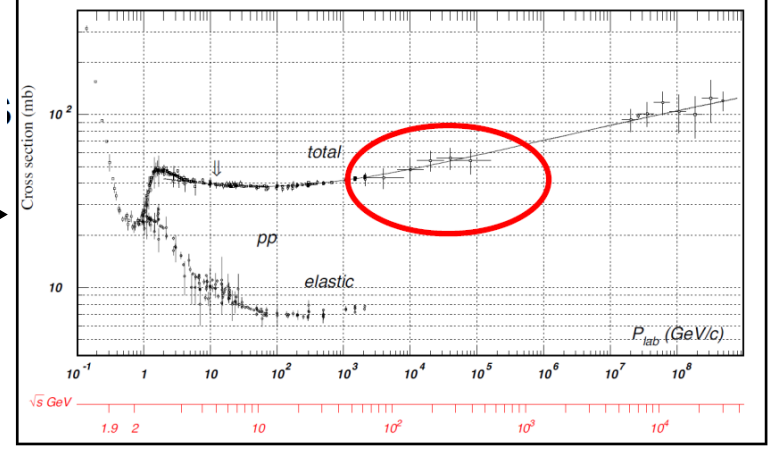
- **VHE γ-Ray Astronomy**:

  point-like and extended (galactic and extra-galactic) sources, diffuse γ rays (few hundreds GeV energy thresh.) *ApJ 760:110 (2012), ApJ779:27 (2013), ApJ767:99 (2013), ApJ790:152 (2014), ApJ798:119 (2015), ApJ806:20 (2015), arXiv:1511.06851v1[astro-ph.HE], …*

- **Cosmic ray physics**:
  - **energy spectrum and composition**
  - flux anisotropies at different angular scales

    PhRevD 88:082001 (2013), ApJ 809:90 (2015)
  - hadronic interaction (p-air, p-p cross section) →
  - anti-p/p ratio at TeV energy *PhRevD 85:022002 (2012)*
  - geomagnetic effects on EAS *PhRevD 89:052005 (2014)*

PDG particle data group — *PhRevD 80:092004 (2009)*



- **Search for GRB's** (full GeV / TeV range)

  AstropartPh 32:47 (2009), ApJ 794:82 (2014)

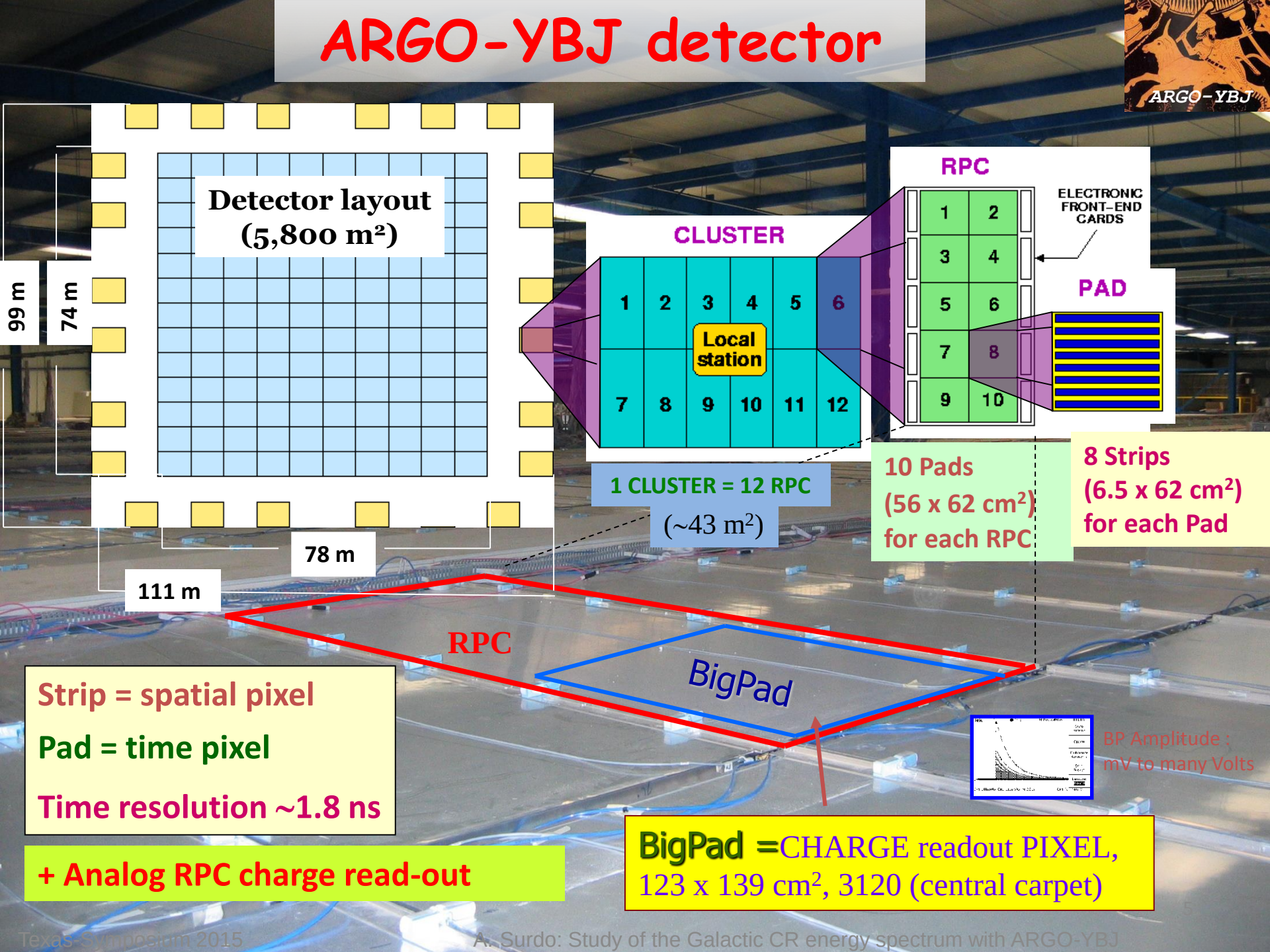
- **…**

through the…

Observation of *Extensive Air Showers* produced in the atmosphere by primary γ's and nuclei

ARGO-YBJ detector

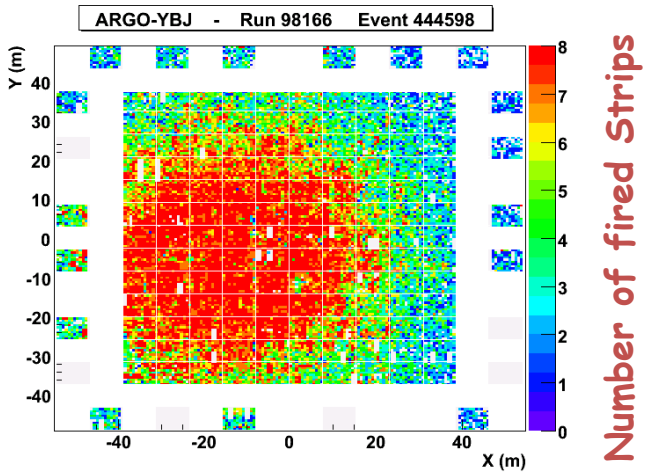
ARGO-YBJ detector

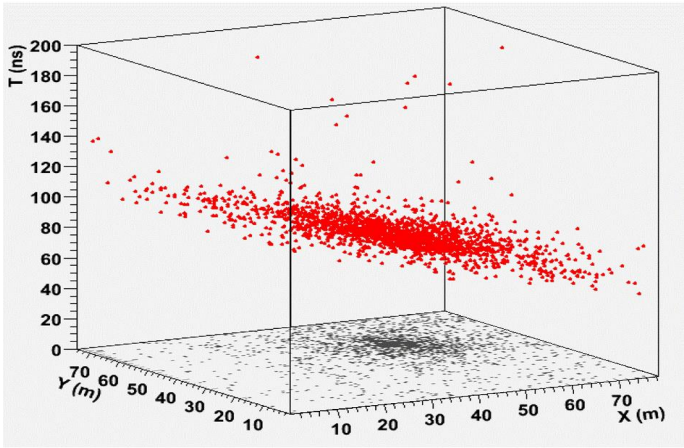


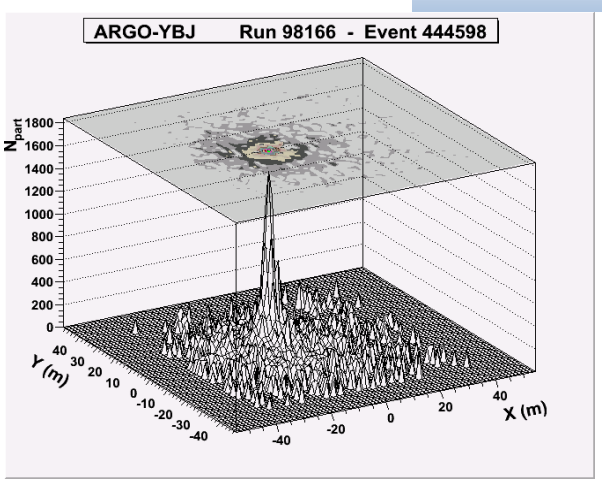
EAS reconstruction with digital …

Space/time granularity + full coverage

EAS imaging and reconstruction with unprecedented details







… and analog (RPC charge) readout

- ✓ Access lateral particle distributions down to the shower core (densities > $10^4/m^2$) thus overcoming the strip saturation
- ✓ Extend energy range (above 100 TeV)
- ✓ Sensitivity to Hadronic Interaction details and CR primary mass

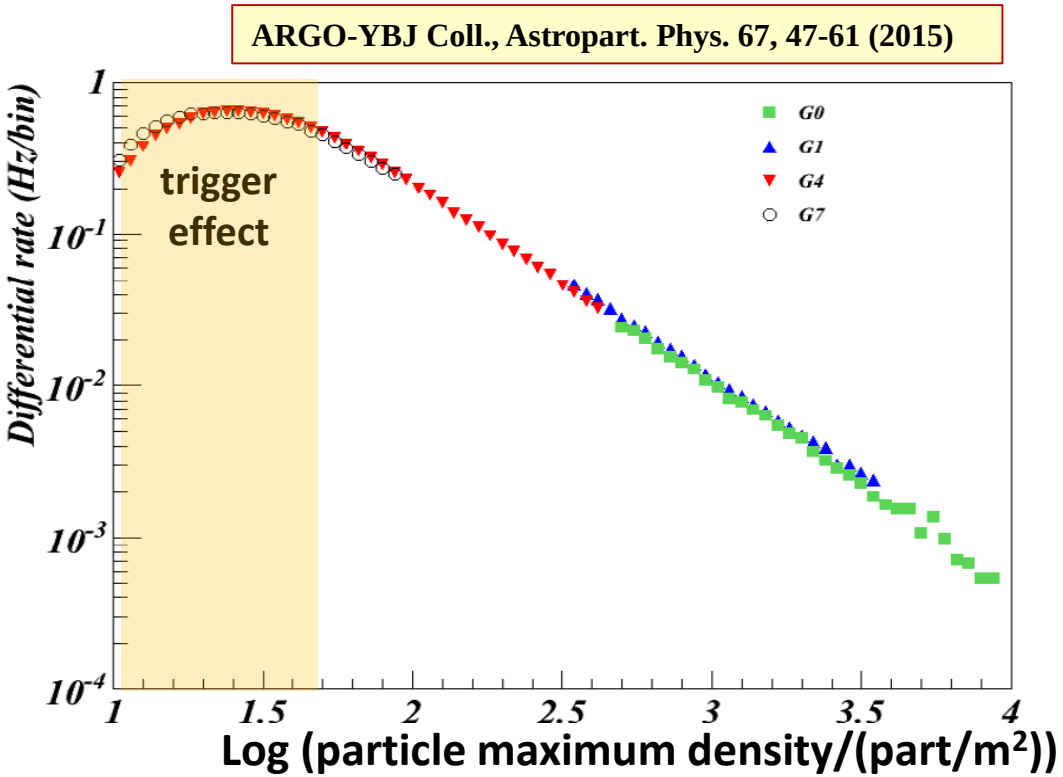
The RPC analog readout

- Eight gain scales (G0, G1, … G7) ensure good linearity up to ~ 2 x 10^4 particles/m^2
- G7 data overlap the digital-mode linearity range → used for intercalibration and cross checks
- G0 allows to cover the energy range up to ~20 PeV and above

Here we use **G4** and **G1** scales to cover the 50 TeV – 10 PeV range with high efficiency and without saturation

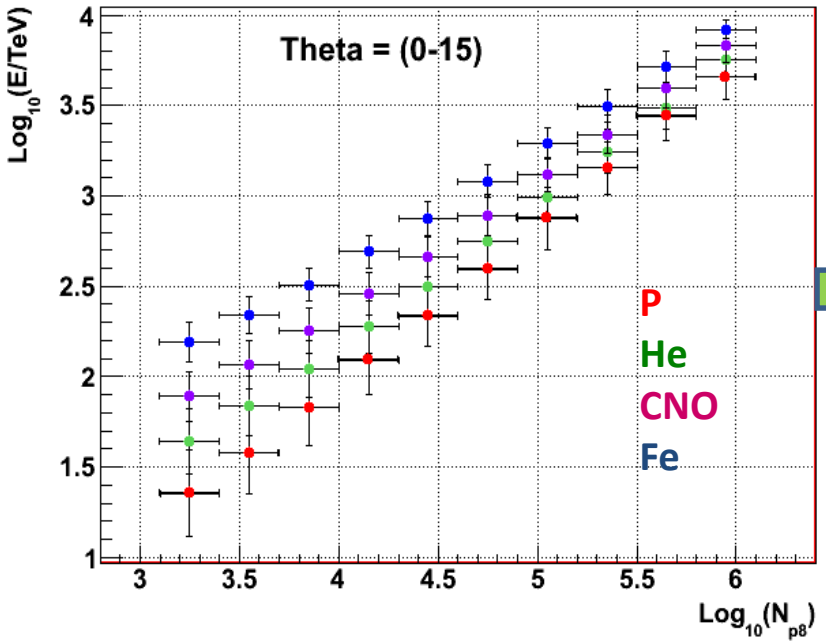
Event selection:

- Core reconstructed in a central detector fiducial area
- Reconstructed zenith angle <15°



MC: the truncated size Np_8 as (mass dependent) energy estimator

- **Event selection: Core in a central detector fiducial area, zenith angle <15°**
- **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

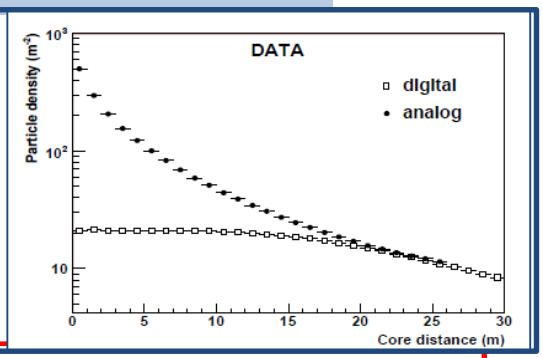
Lateral Distribution Function (LDF) and shower age

Modified NKG function: LDF to fit the lateral particle distribution

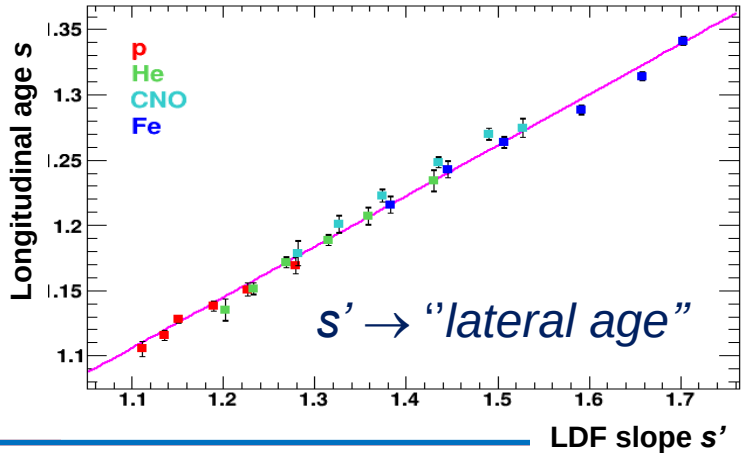
$$\rho'_{NKG} = A\left(\frac{r}{r_0}\right)^{s'-2}\left(1+\frac{r}{r_0}\right)^{s'-4.5}$$

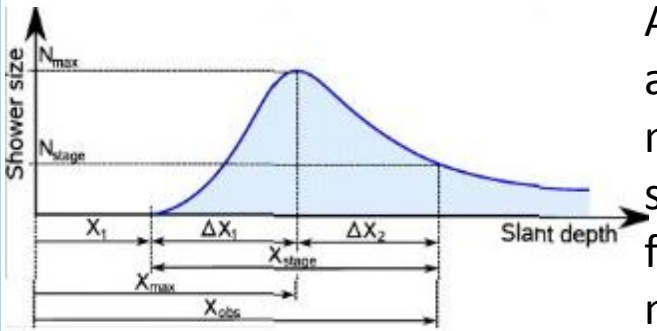
s' plays the role of 'lateral age'

With analog data, the particle density can be studied near the shower core without saturation



The LDF slope (*s'*) is related to X_{max}, then to the shower age *s*, independently on the primary mass ('**universality property**')



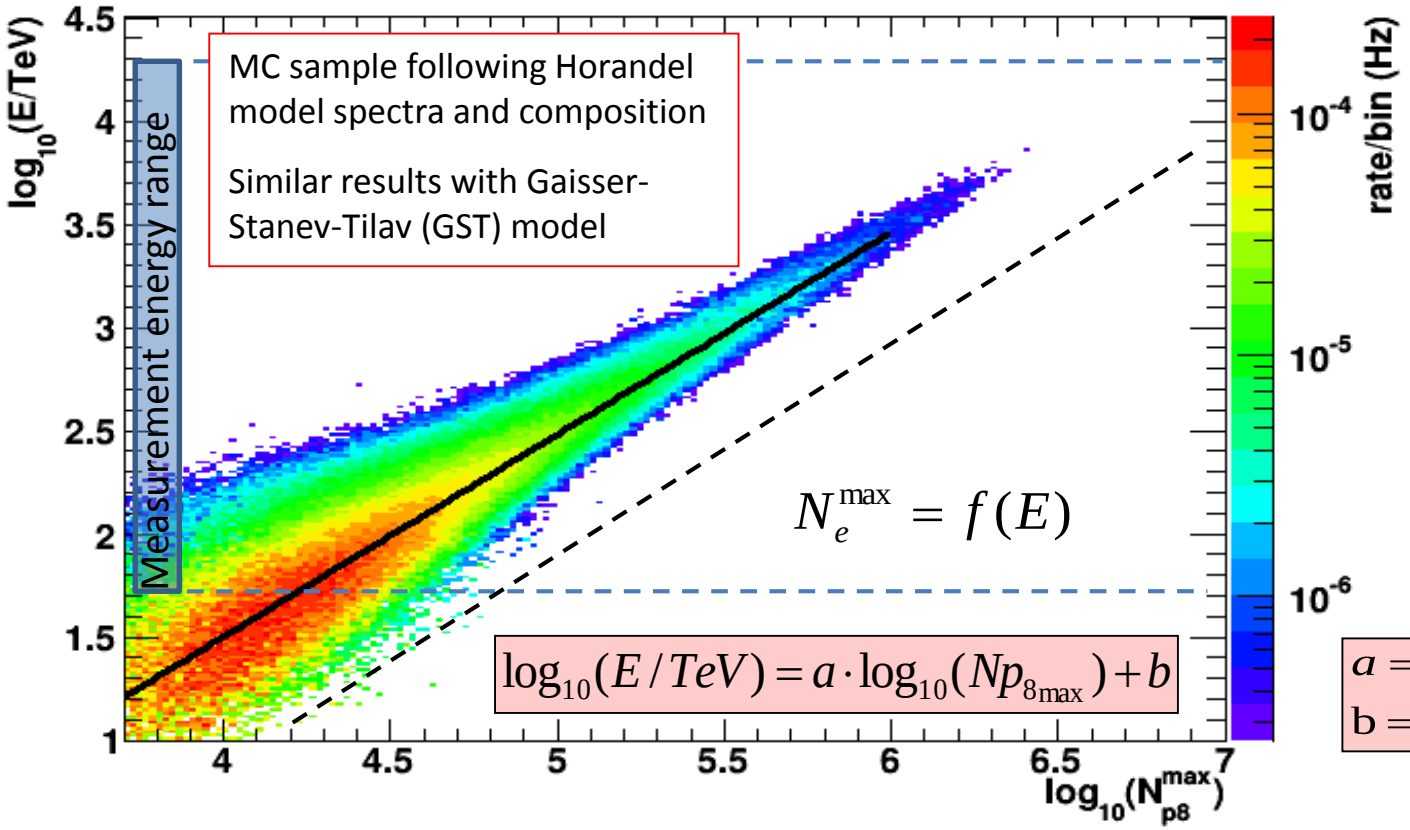


Assume an exponential absorption after the shower maximum → Get the correct signal at maximum (Np_{8max}) from Np_8 and *s'* (fit parameter) measured for each event

$$Np_{8\max} \approx Np_8 \cdot e^{\frac{h_0 \sec\theta - X_{\max}(s')}{\lambda_{abs}}}$$

$$X_{\max}(s') = \frac{1}{2} h_0 \sec\theta \left(\frac{3}{s(s')} - 1\right)$$

Mass independent Energy reconstruction



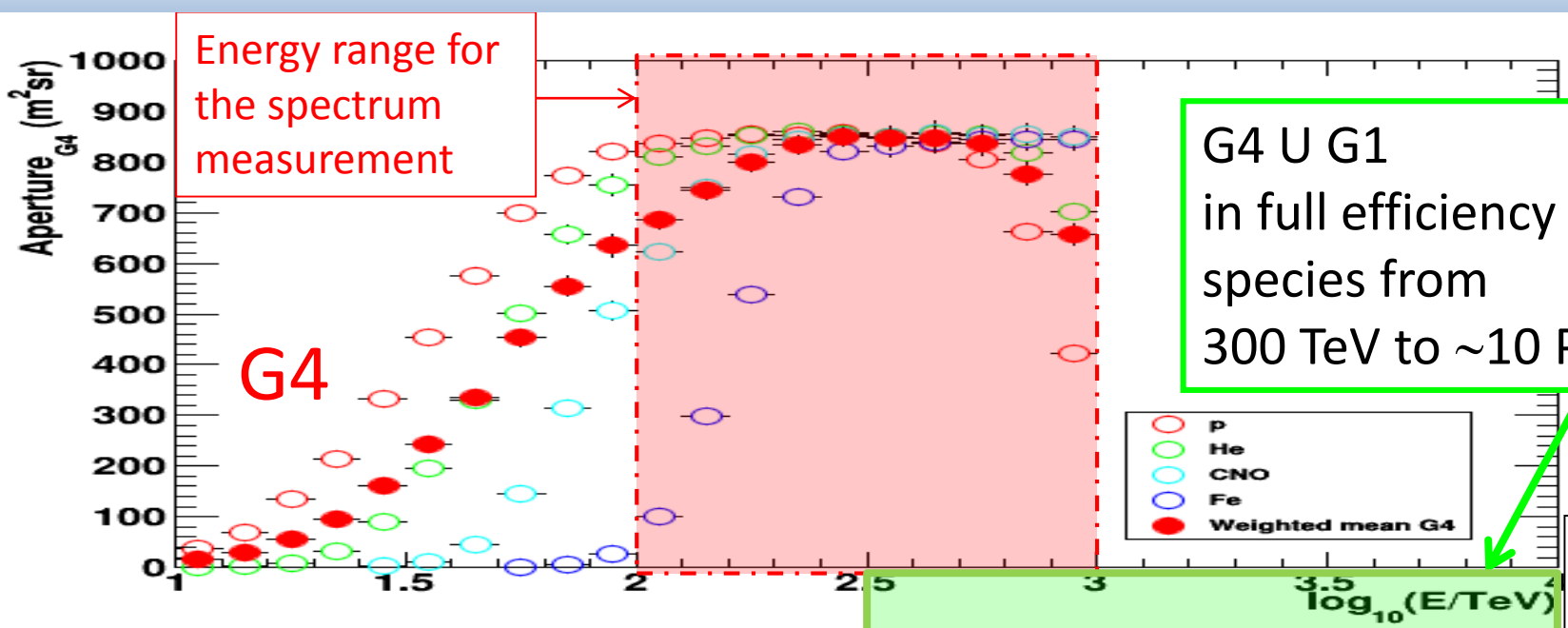
In excellent agreement with total-size-vs-E theoretical plot. The shift is simply due to the fact that we are using the truncated size

$a = (0.98 \pm 0.01)$
$b = (-2.42 \pm 0.05)$

The measurement of Np_8 and the (age correlated) LDF slope *s'* allows estimating the truncated size at the shower maximum Np_{8max}

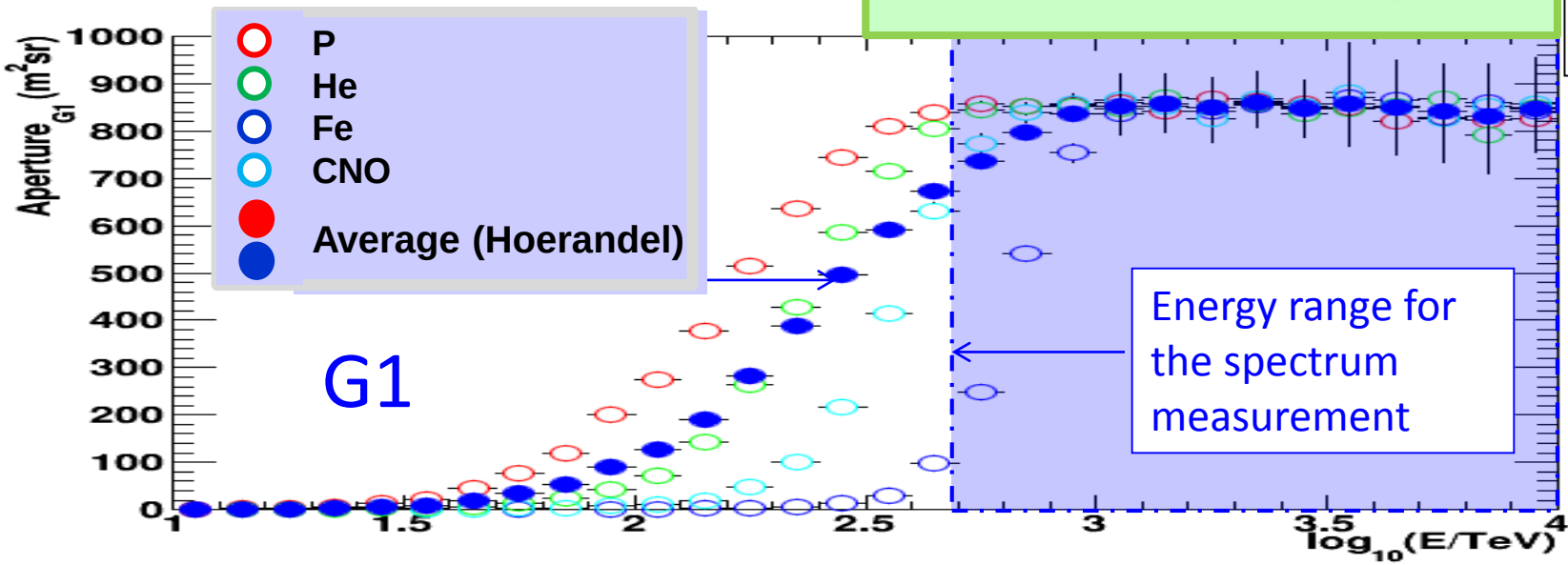
This ensures a mass independent Energy determination.

Aperture for the all particle spectrum



G4 U G1
in full efficiency for all species from
300 TeV to ~10 PeV

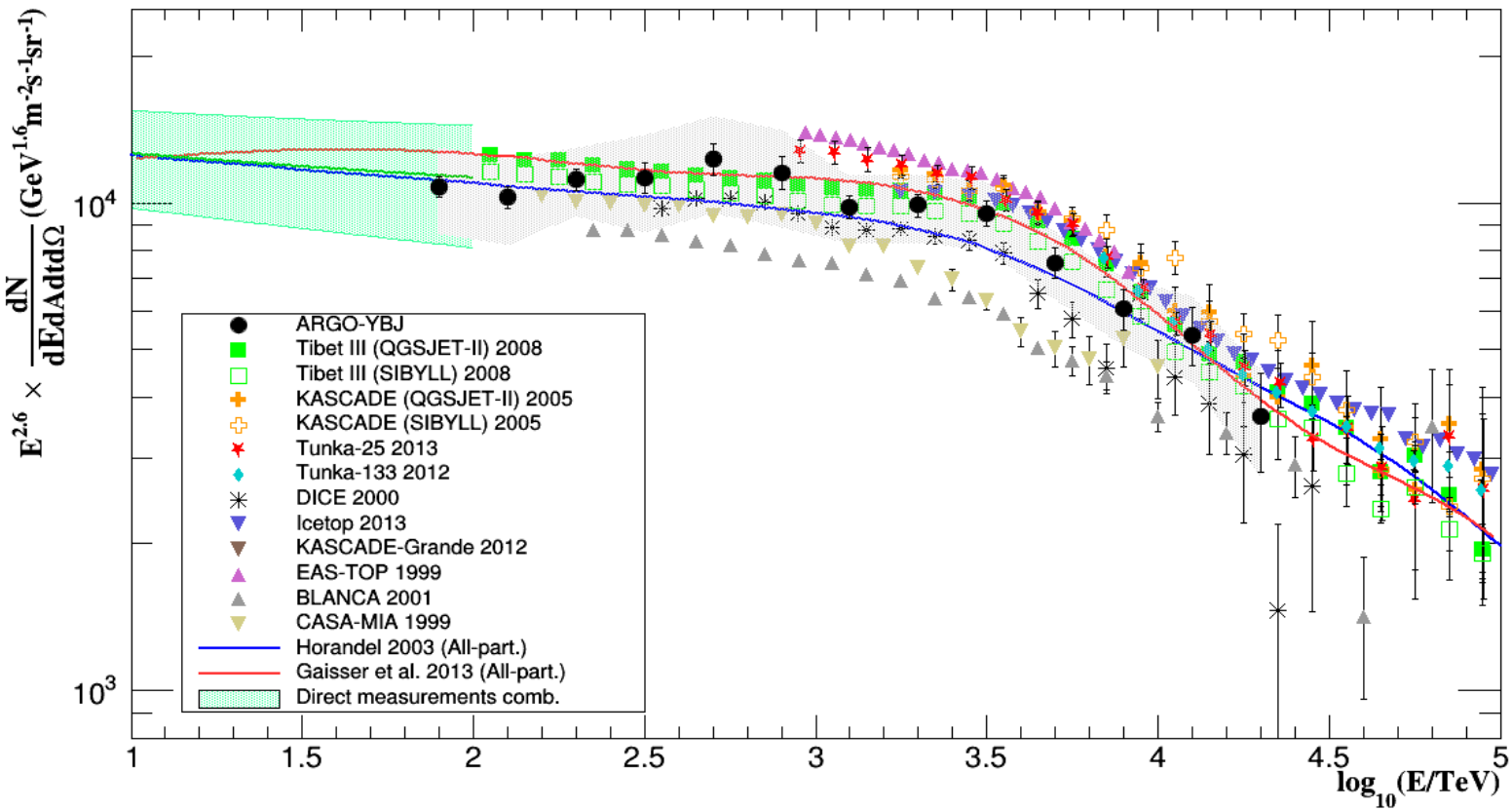
Fit with Fermi functions.



The all particle spectrum

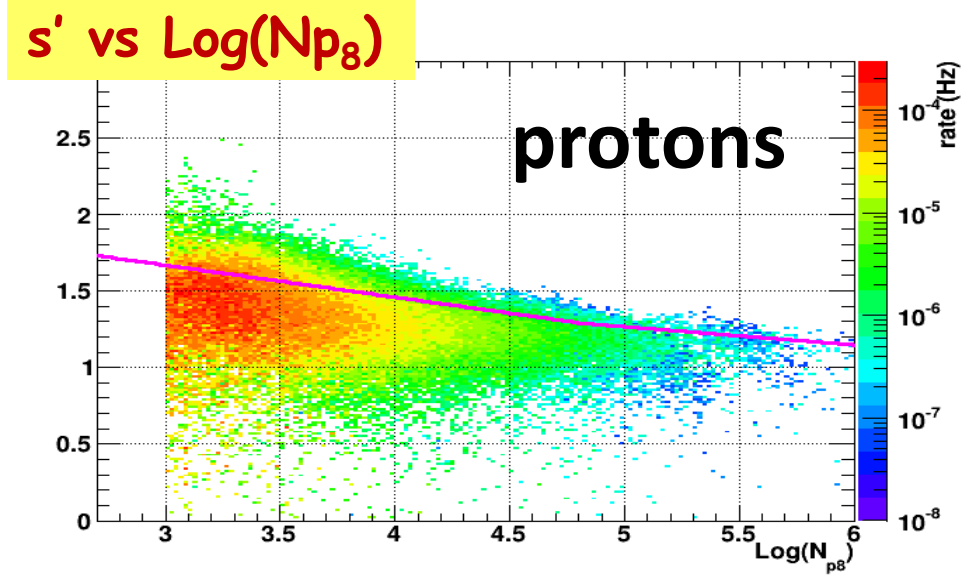
- Picture consistent with models and previous measurements
- Nice overlap between the two gain scales (different data samples, …)
- Results suggest spectral index -2.6 below ~3 PeV and -2.8 above
  (extensions to higher energy → subject of a future work)

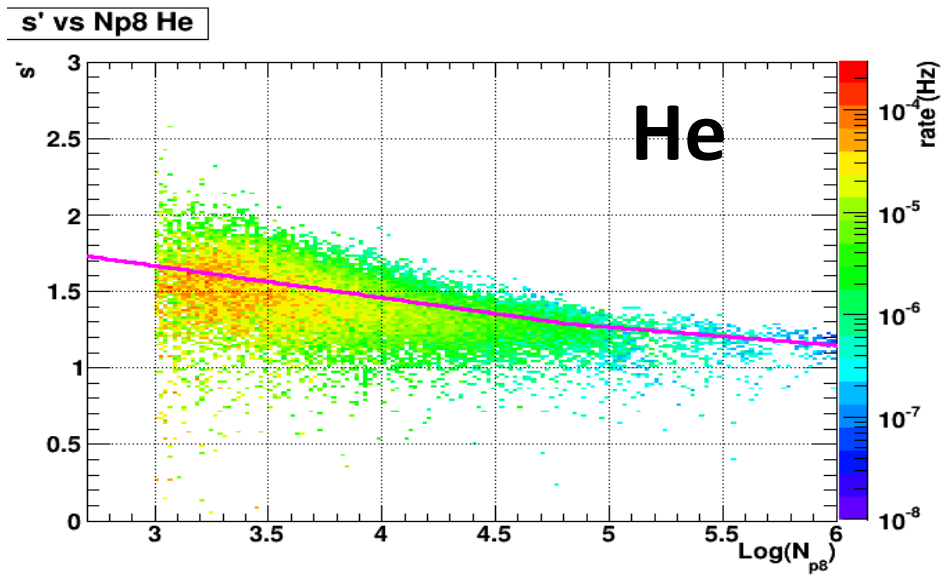
Comparison with other experiment results

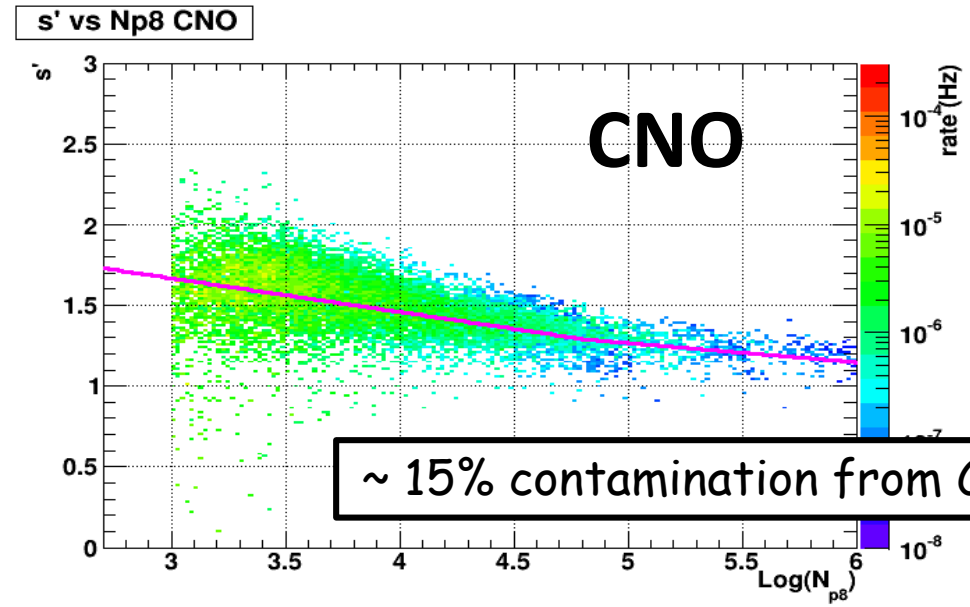


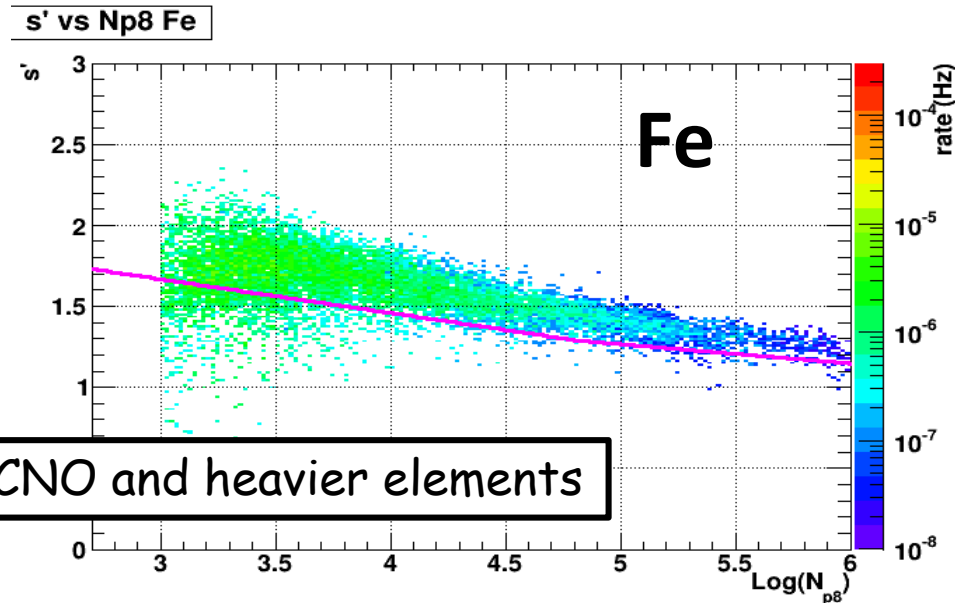
p and He selection
(MC Hoerandel spectra and normalizations)

s' vs Log(Np_8)





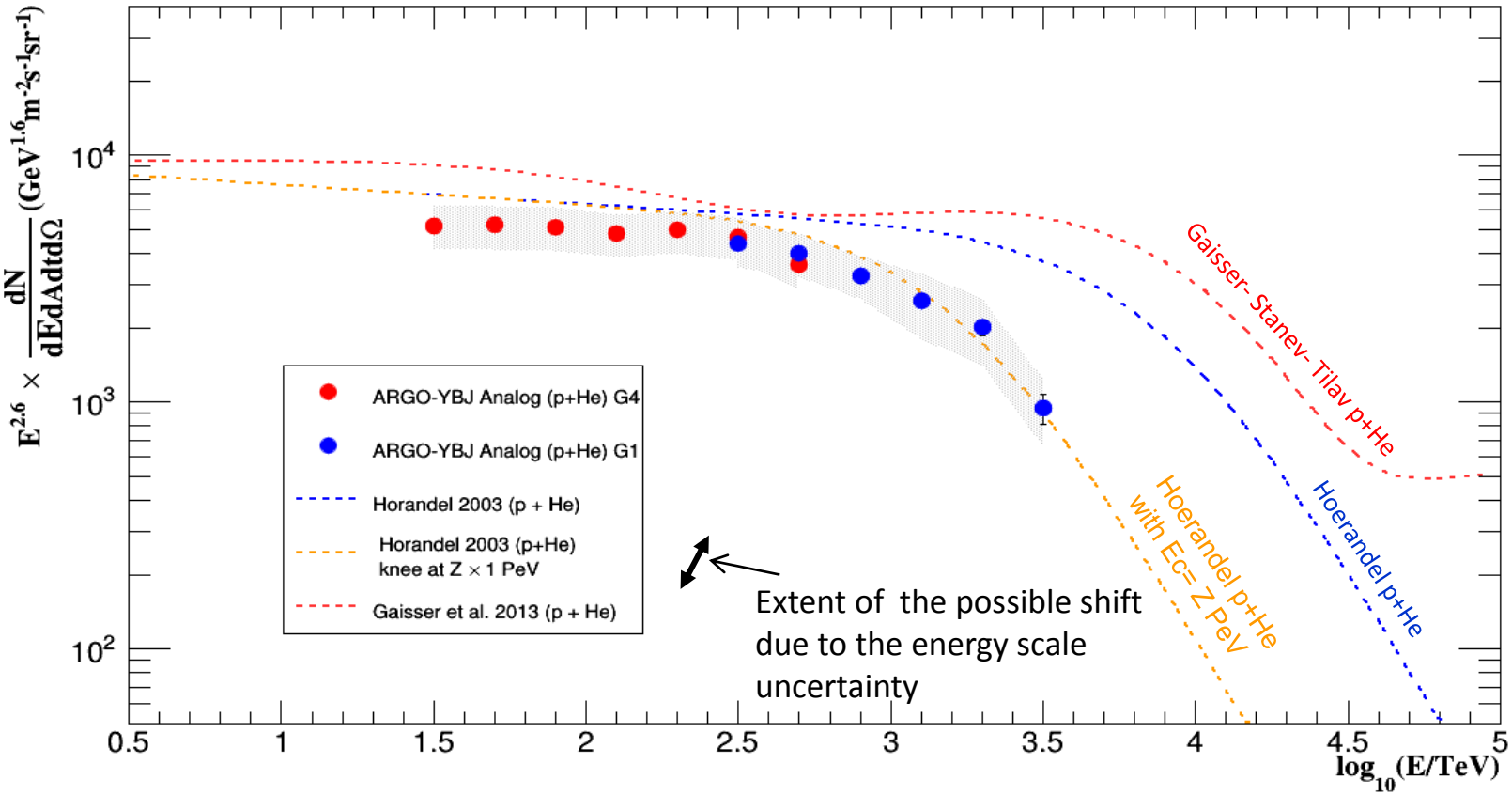




~ 15% contamination from CNO and heavier elements

The p+He spectrum (1st)

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



2nd Analysis - Bayesian Approach

Digital Data — p+He spectrum

- Excellent stability over a long period
- Overlap with direct measurements in a wide energy region
- Total systematic uncertainty ~ 5%

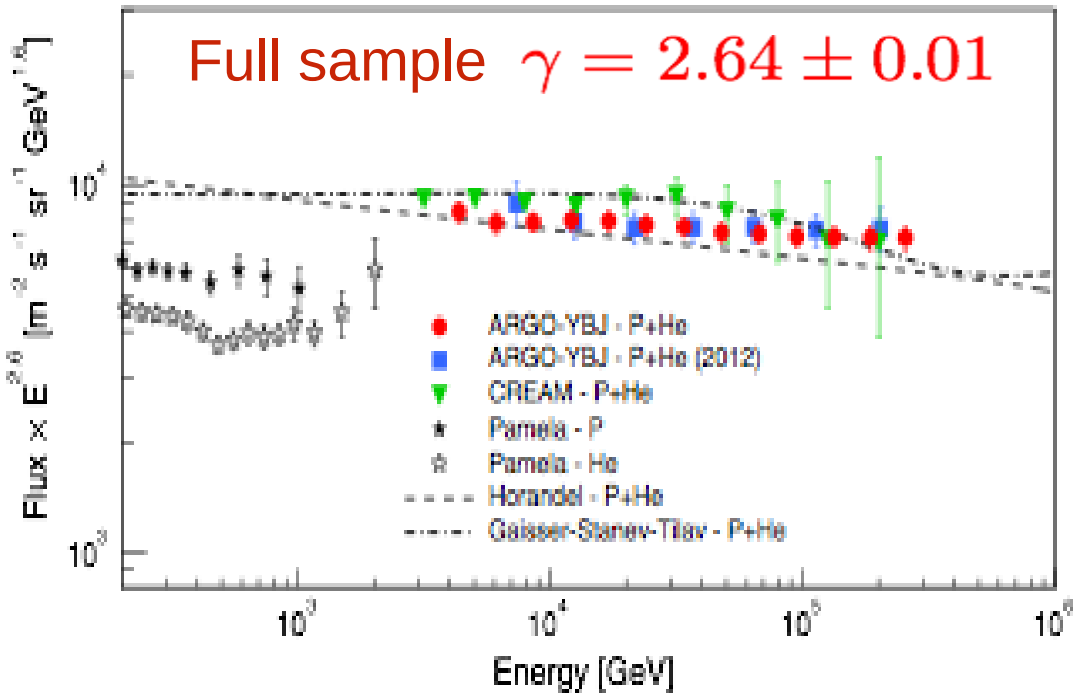
3 - 300 TeV energy range:

Extension of the previous ARGO-YBJ light spectrum measurement

Phys. Rev. D 91, 112017 (2015)

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



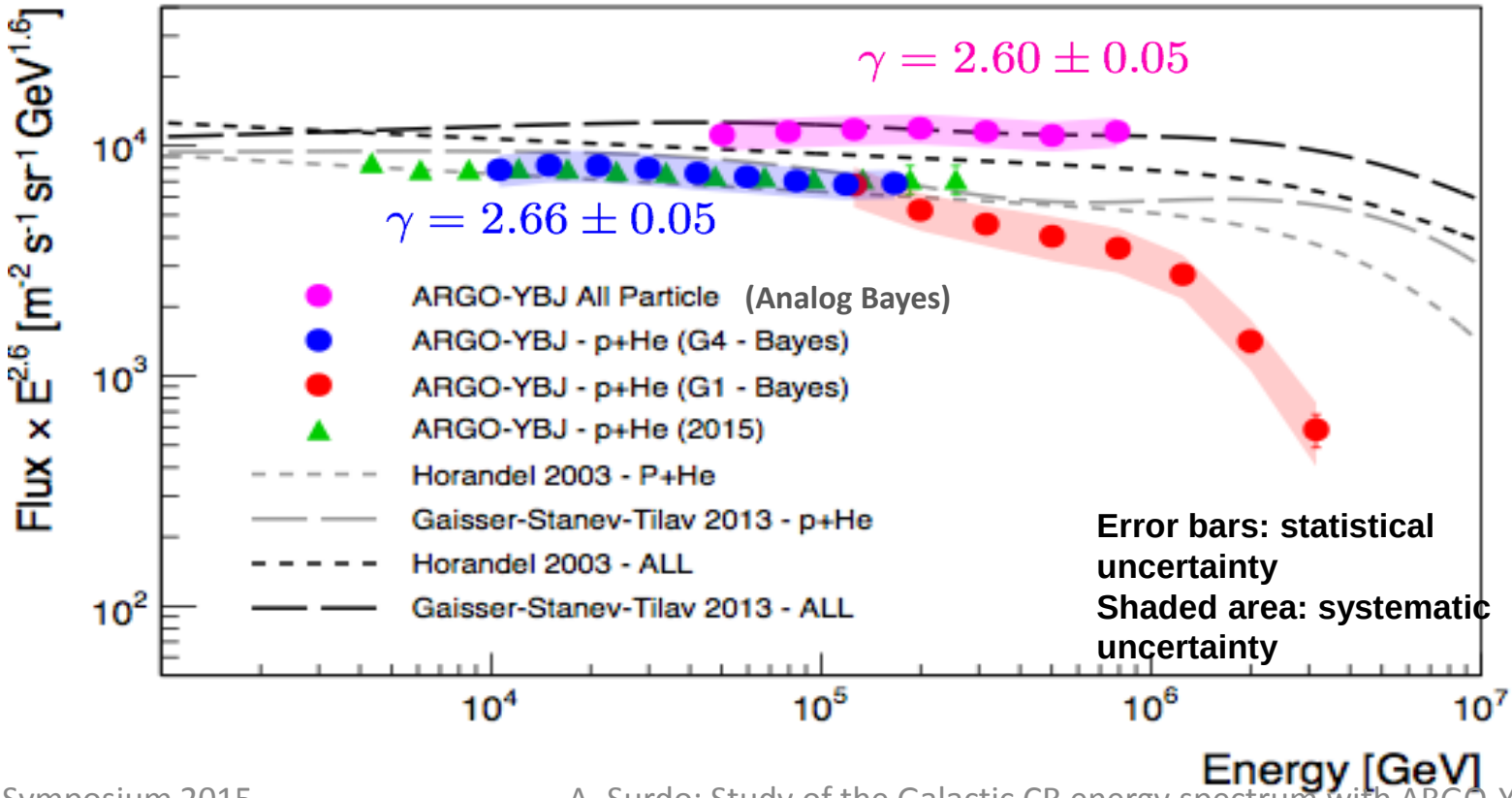
All-particle & p+He spectrum (2nd)
- Bayesian method applied to Analog Data

ALL-PARTICLE SPECTRUM

- ➞ Good agreement with other experiments
- ➞ Systematics ~10%

P+HE SPECTRUM

- ➞ Overlap with direct measurement energy region
- ➞ Consistent with the Digital Readout data
- ➞ Gradual change of the spectral index at E ~ 700 TeV
- ➞ ~12% contamination of heavy elements (mainly CNO)

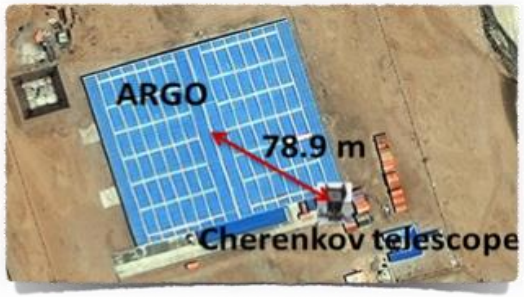


3rd Analysis - Hybrid

ARGO-YBJ array + Cerenkov telescope

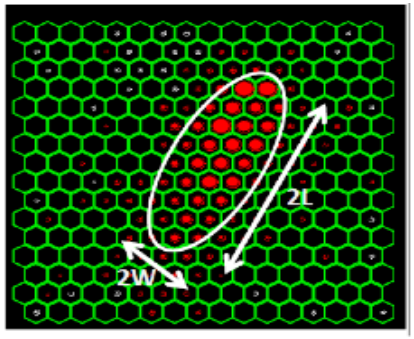
WFCTA - Wide FoV Cherenkov Telescope Array

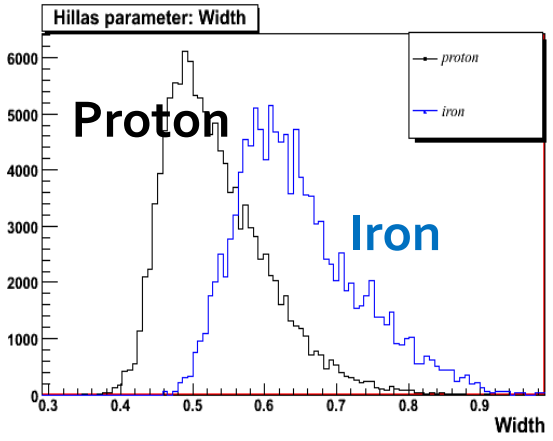
- 5 m^2 spherical mirror
- 16 X 16 PMT Array
- Pixel size 1°
- FOV: 14°X16°
- Elevation angle: 60°



Energy measurement obtained by using the shower geometry reconstructed by ARGO—YBJ and the Cherenkov signal

❖ **Energy resolution ~25%**





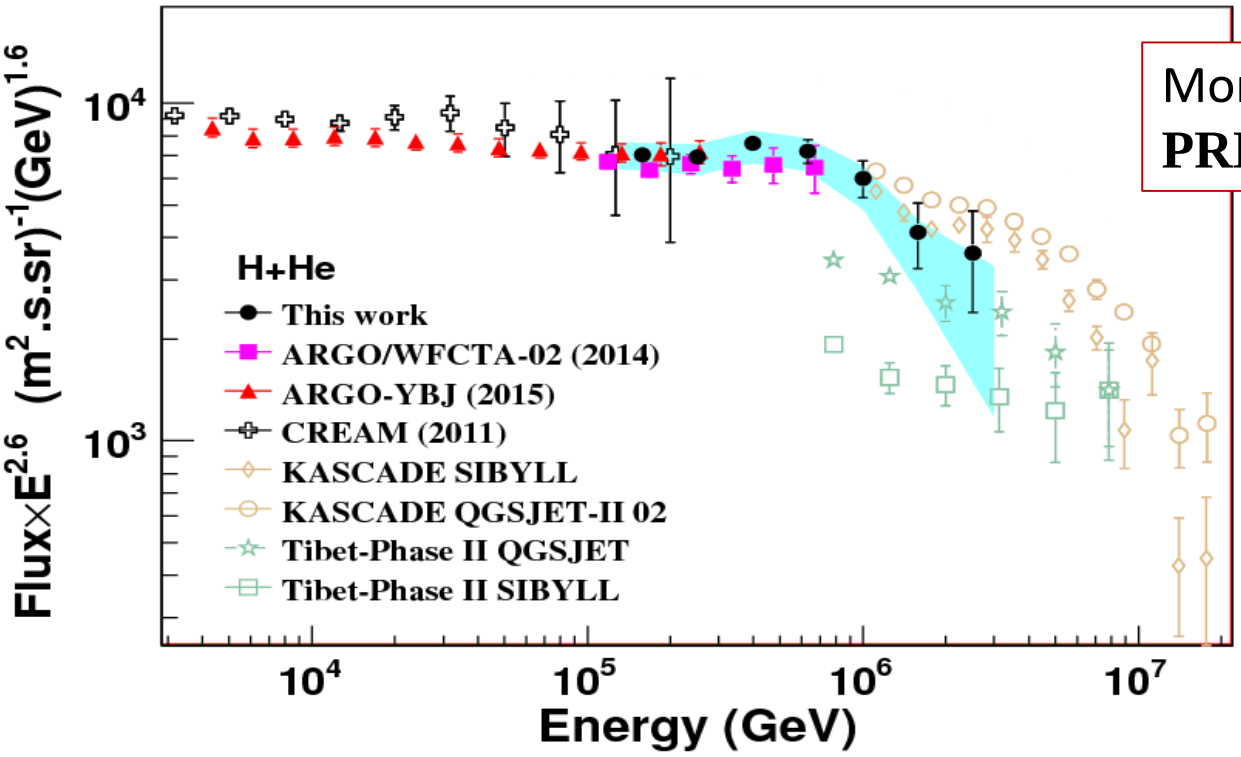
- ARGO—YBJ: N_{Max} — Lateral distribution
- WFCTA: Longitudinal distribution

  → Hillas parameters (composition sensitive)

The p+He Spectrum (3rd)

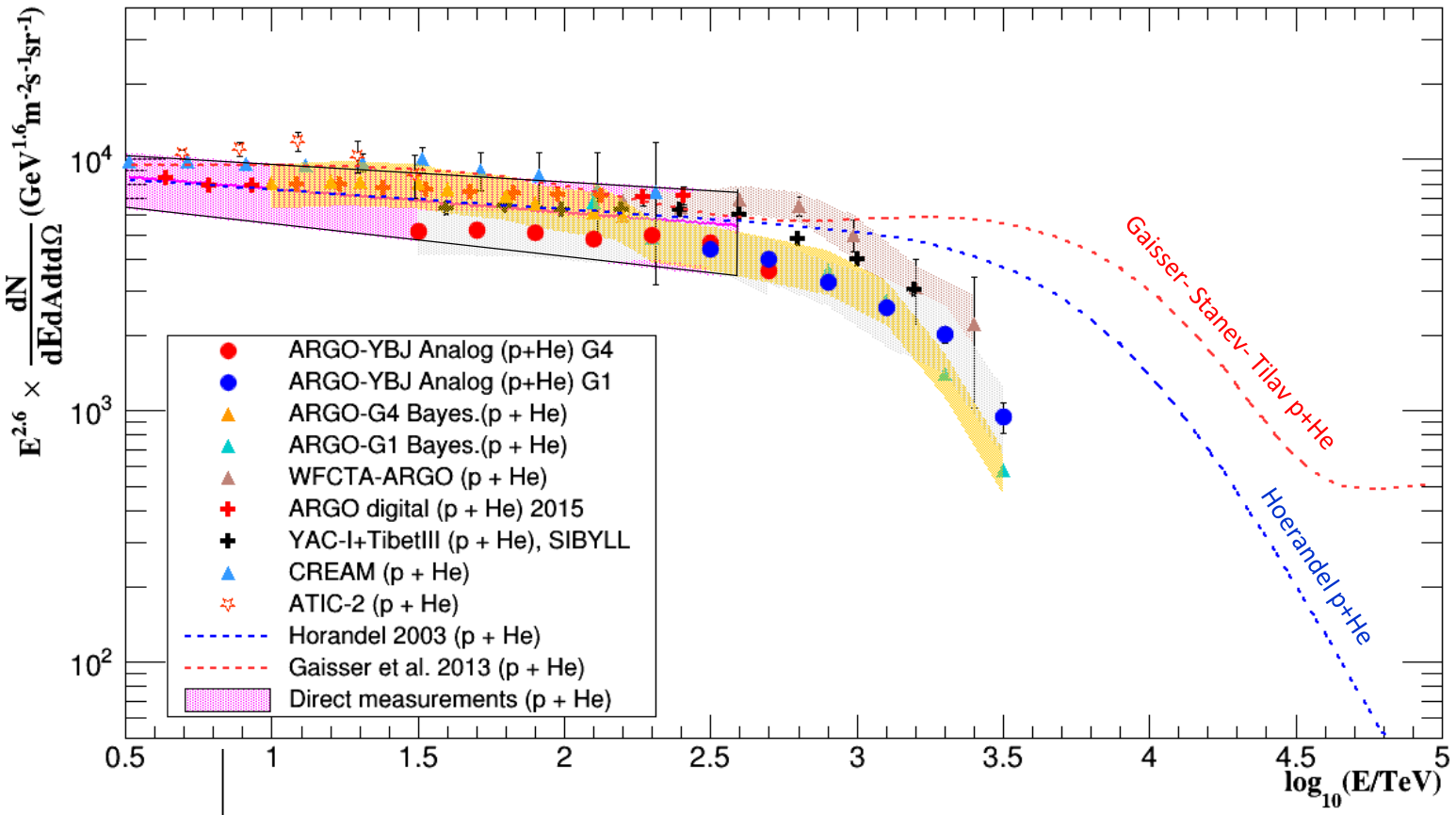
100-2500 TeV energy range

- The knee of p+He spectrum at (700±230) TeV clearly measured
- Broken power law fits well the data
- Indexes -2.56 ± 0.05 and -3.24 ± 0.36 below and above the knee
- Consistent with previous analyses (different data set and detector setup)



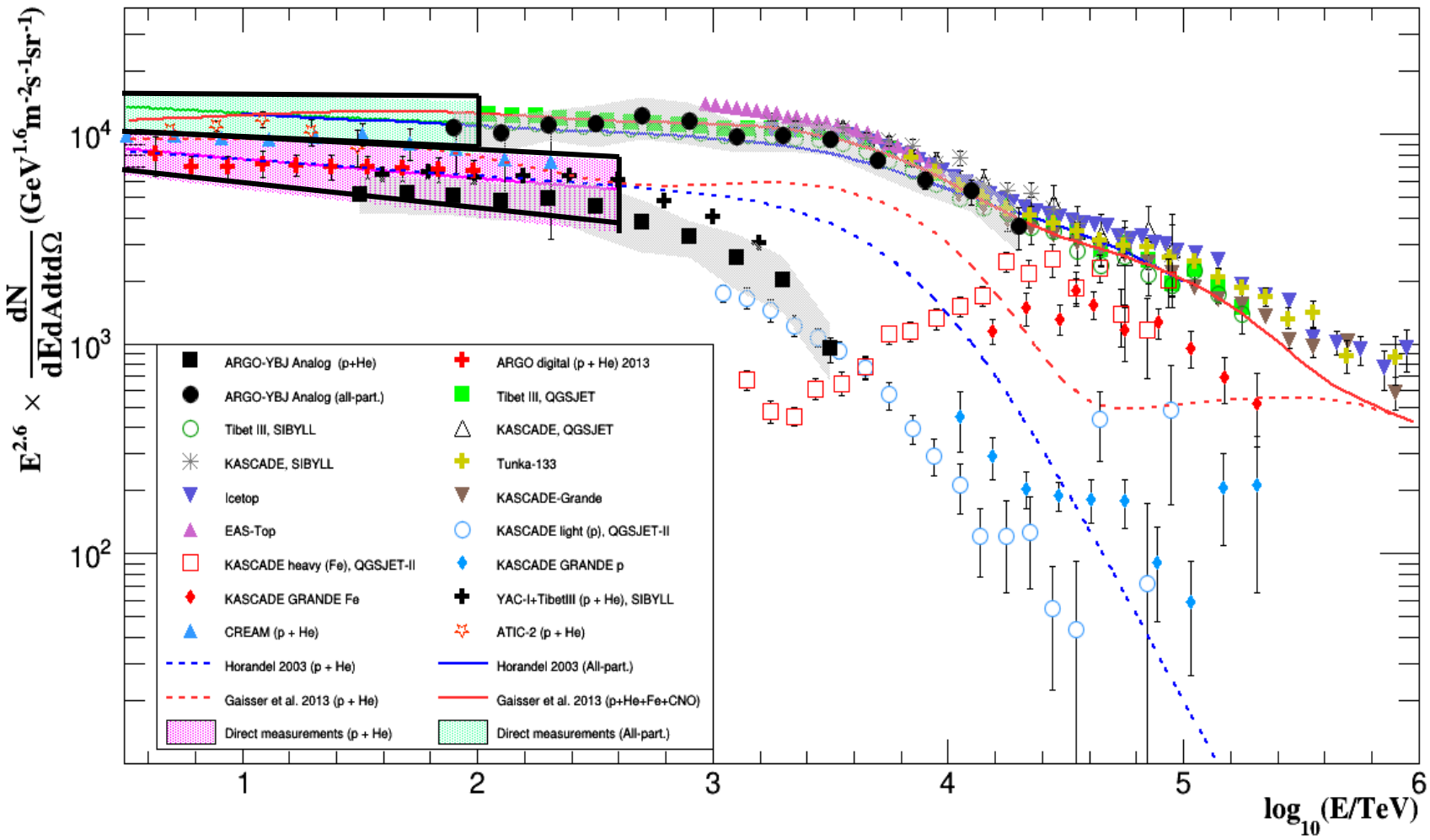
More details in:
PRD 92, 092005 (2015)

ARGO-YBJ: p+He spectrum compared with other measurements



- Different analyses of ARGO-YBJ data give results in agreement within systematics (further cross-checks in progress)
- ARGO-YBJ results consistent with direct (i.e. below 200 TeV) and YAC-Tibet measurements

The overall picture



Summary

ARGO-YBJ measured the CR spectrum in the TeV – 20 PeV range using the analog readout

- **All-particle spectrum in the energy range (80 – 20) PeV**
  - **Good agreement with other experiments**
- **p+He spectrum in the (3-3000) TeV energy range**
  - **Good agreement with the digital analysis (3-300 TeV)**
  - **Evidence of a spectrum bending just below 1 PeV**

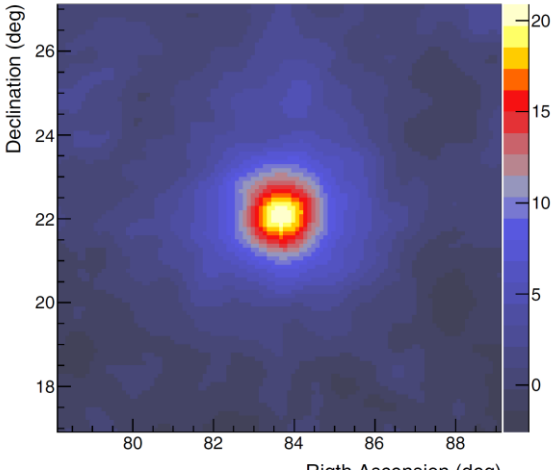
    - Two different ARGO-YBJ data analyses + a third (hybrid) one, using also the Č light signal, give consistent results.

⇒ **New relevant inputs to acceleration/propagation models for galactic cosmic rays**

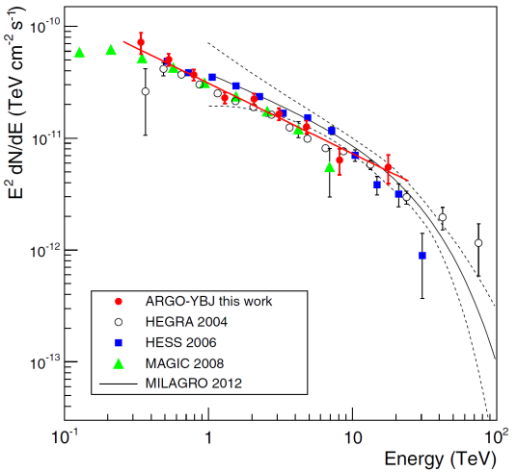
Backup slides

γ-ray astronomy with ARGO-YBJ

The Astrophys. Jour. 798:119 (2015)

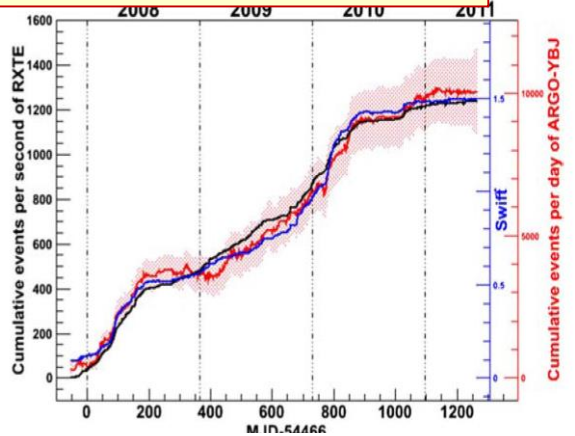


Significance map of the Crab Nebula region from ARGO-YBJ data



Spectrum of the Crab Nebula measured by ARGO-YBJ and other experiments

arXiv: 1511.06851v1 [astro-ph.HE] (2015)

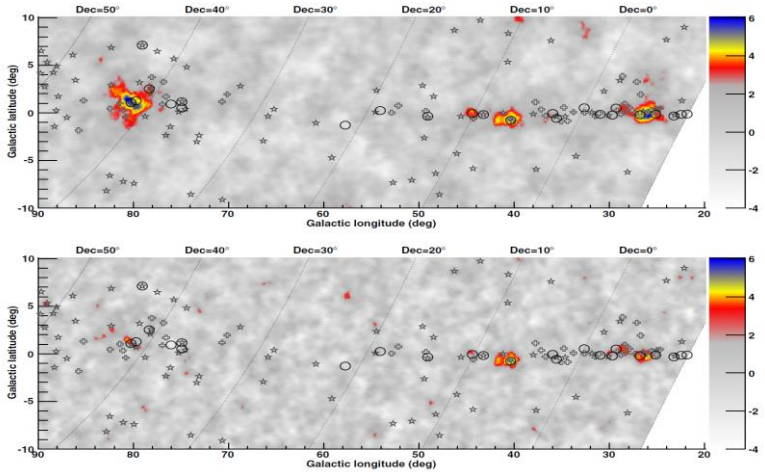


Mrk421: Cumulative light curve measured by ARGO-YBJ compared with RXTE/ASM and Swift X-ray data

Table 1. Location of the excess regions observed by ARGO-YBJ.

ARGO-YBJ name	Ra (deg)	Dec (deg)	S (s.d.)	Associated TeV source
J0409−0627	62.35	−6.45	4.8	
J0535+2203	83.75	22.05	20.8	Crab Nebula
J1105+3821	166.25	38.35	14.1	Mrk 421
J1654+3945	253.55	39.75	9.4	Mrk 501
J1839−0627	279.95	−6.45	6.0	HESS J1841−055
J1907+0627	286.95	6.45	5.3	HESS J1908+063
J1910+0720	287.65	7.35	4.3	
J1912+1026	288.05	10.45	4.2	HESS J1912+101
J2021+4038	305.25	40.65	4.3	VER J2019+407
J2031+4157	307.95	41.95	6.1	MGRO J2031+41 TeV J2032+4130
J1841−0332	280.25	−3.55	4.2	

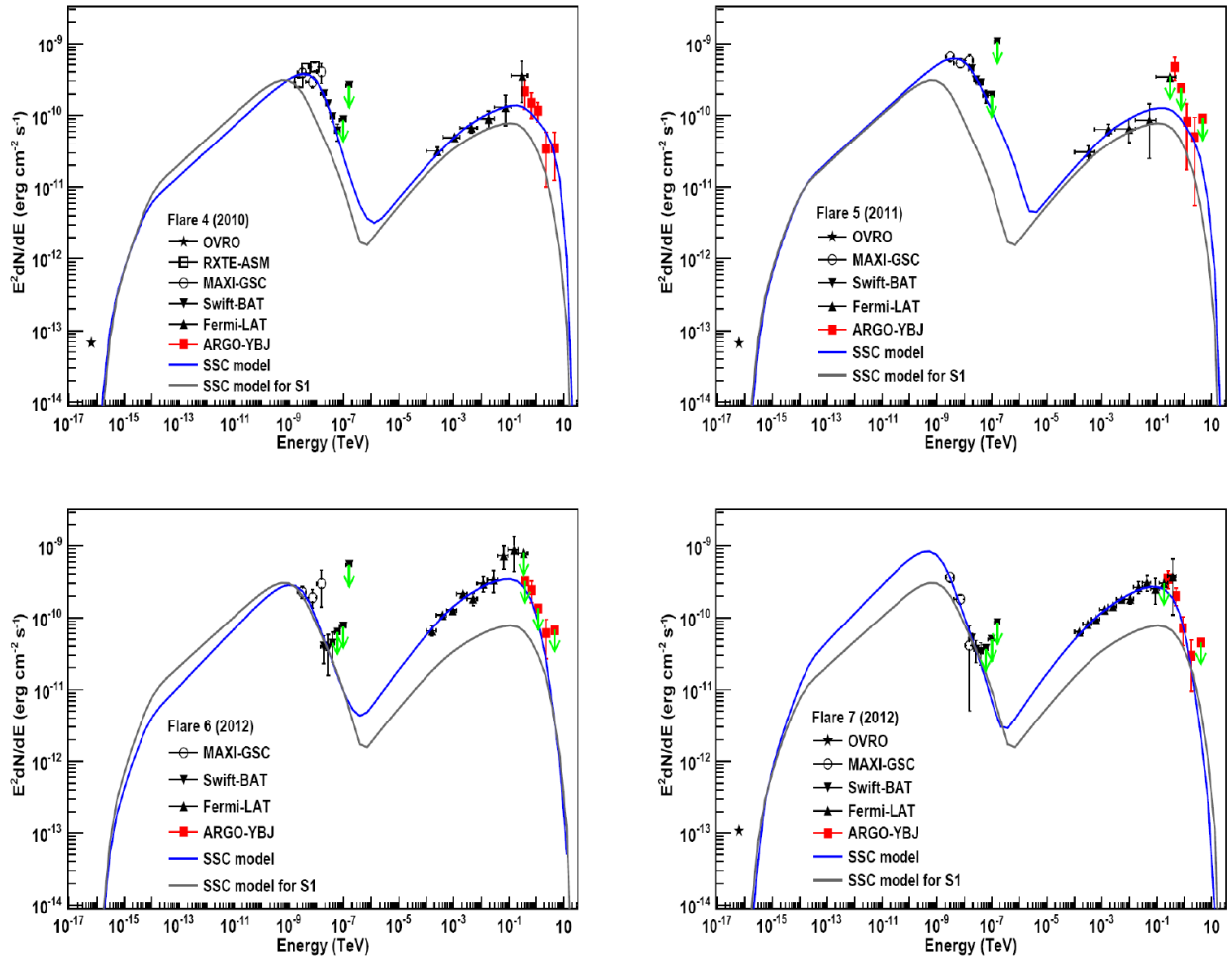
The Astrophys. Jour. 779:27 (2013)



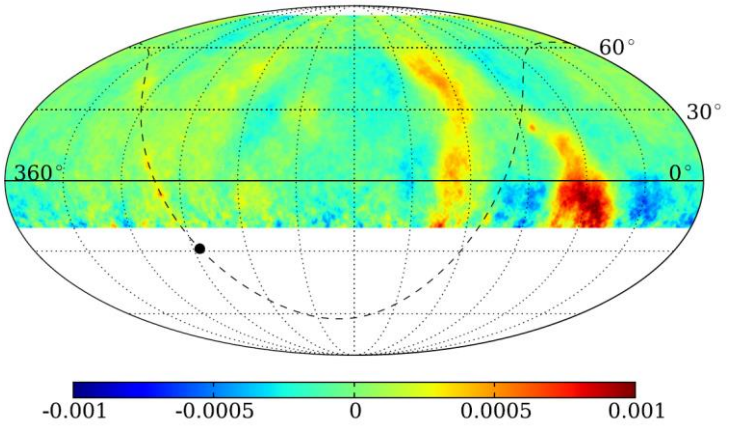
Significance map of the Galactic Plane region observed by ARGO-YBJ (hit multiplicity thresholds: 20 and 100).

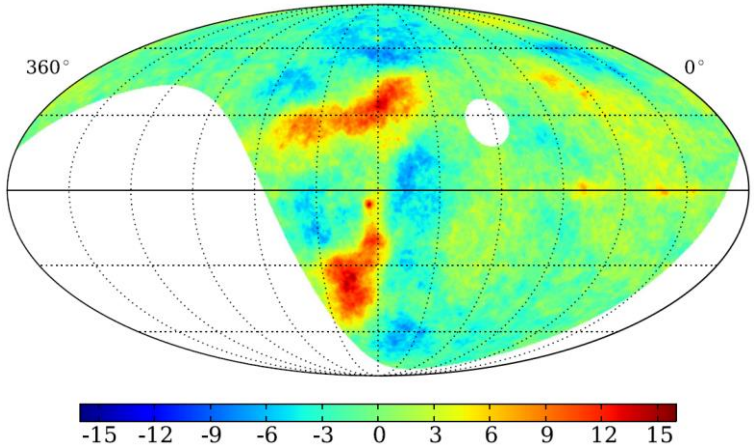
Observation of Mrk421 by ARGO-YBJ

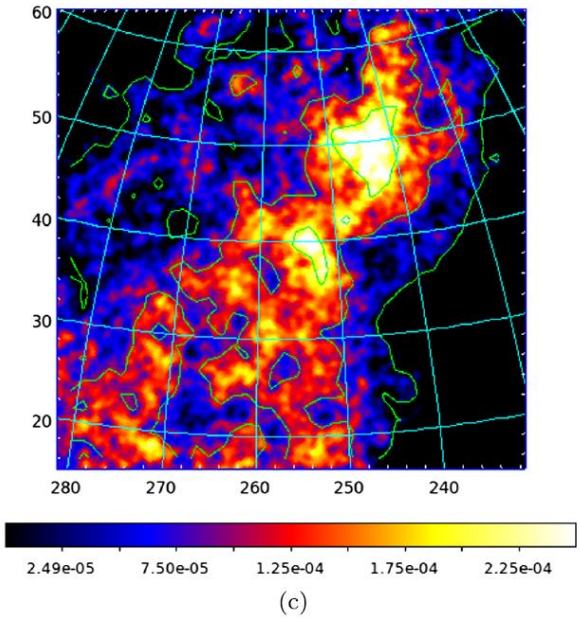
Spectral enrgy distribution of Mrk421 in four states.
Solid line: best fit to the data assuming a homogeneus one-zone SSC model.

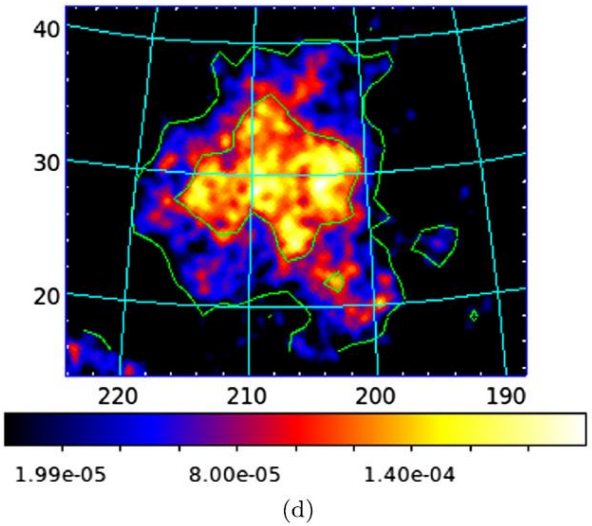


Medium scale anisotropies in CR by ARGO-YBJ

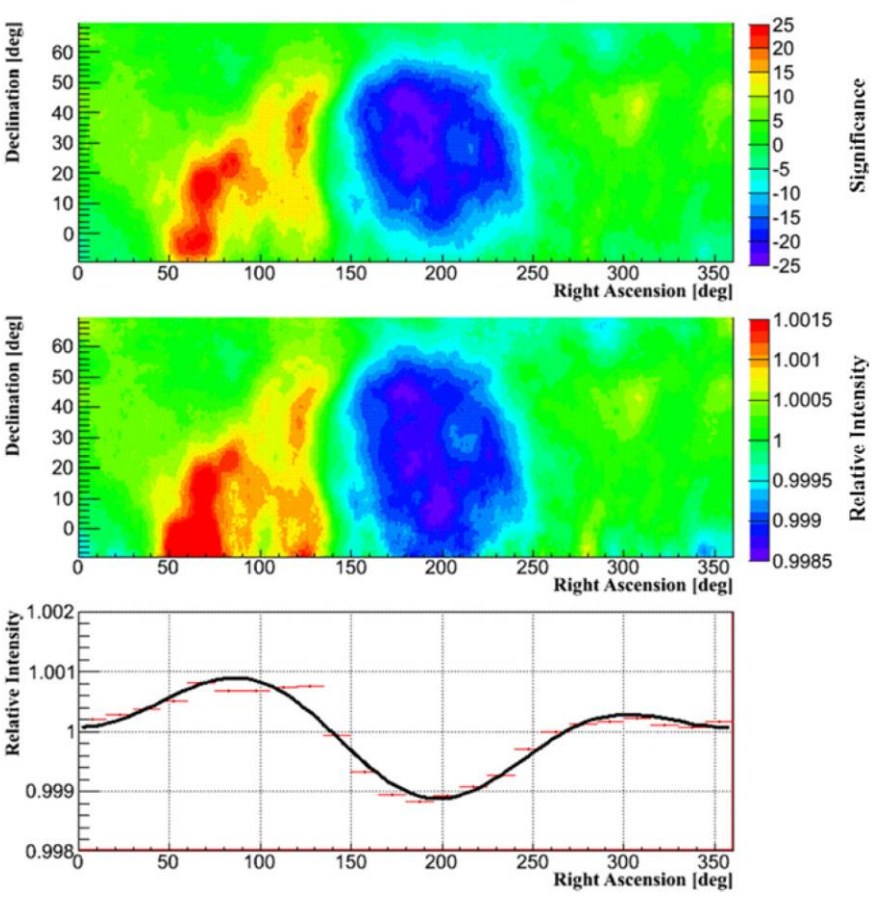


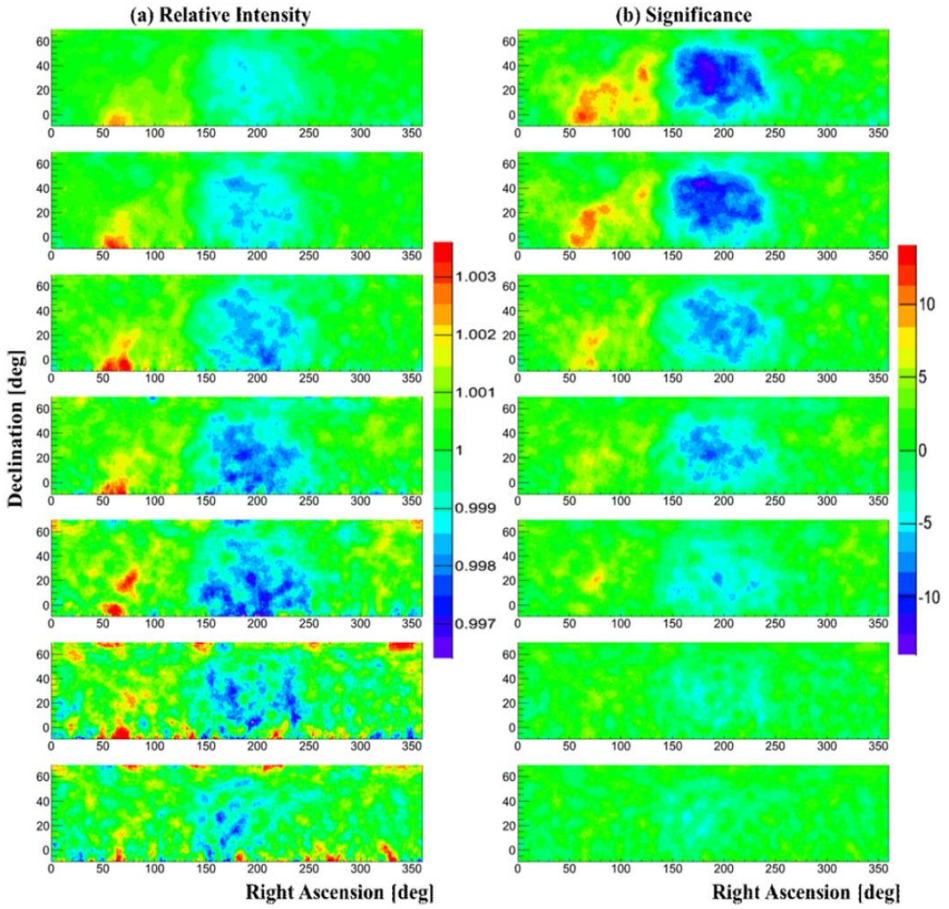


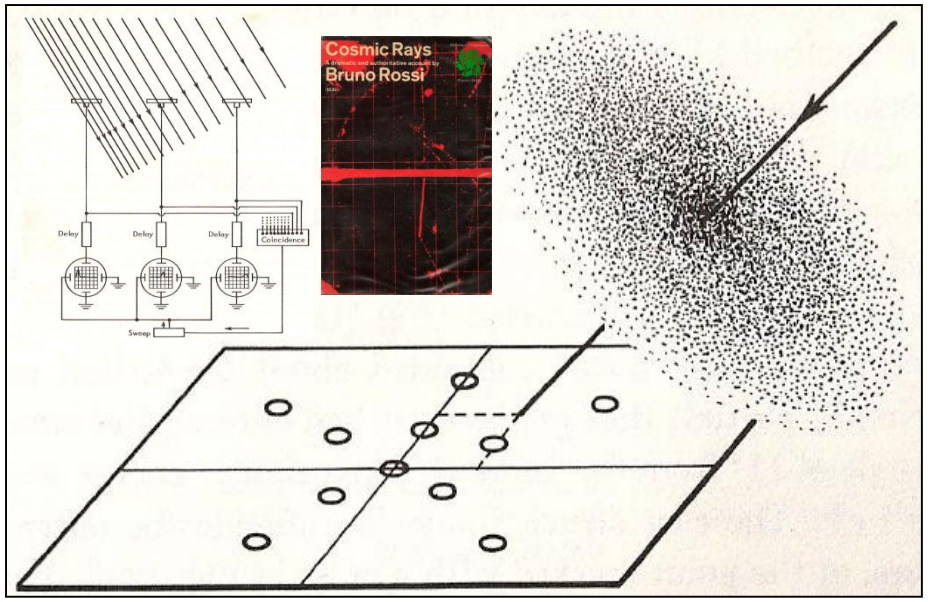




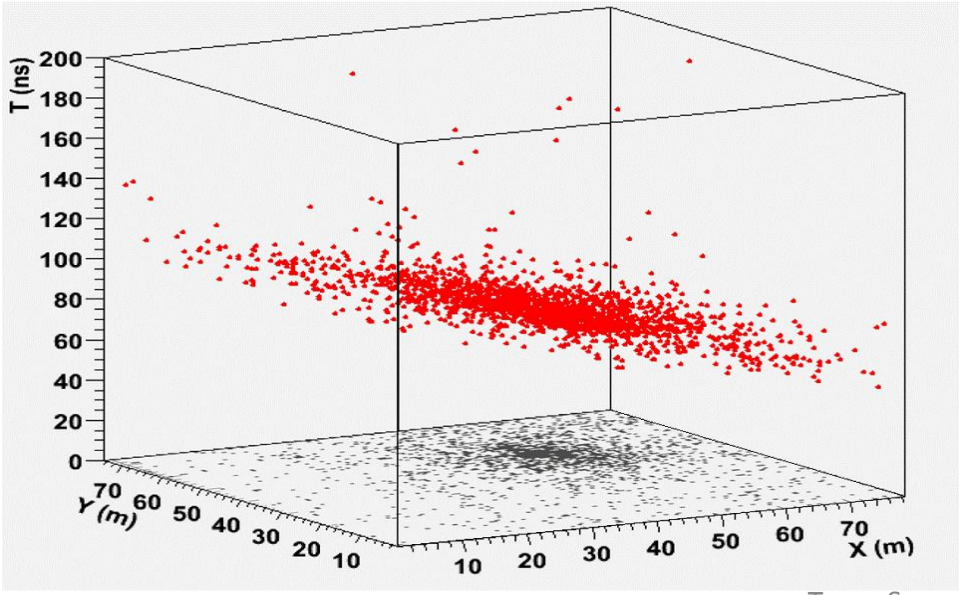
Large scale anisotropies in CR by ARGO-YBJ



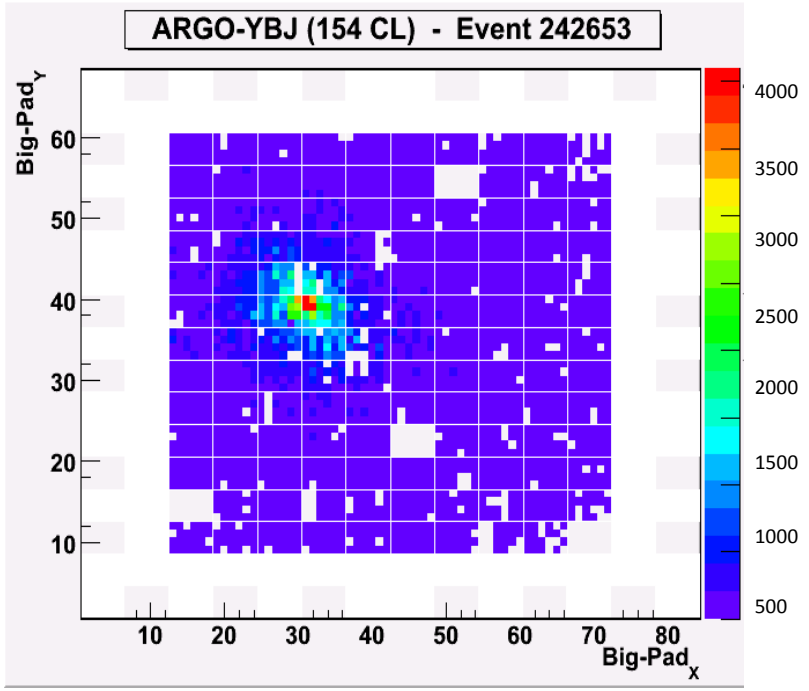




Bruno Rossi conceptual EAS detector



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

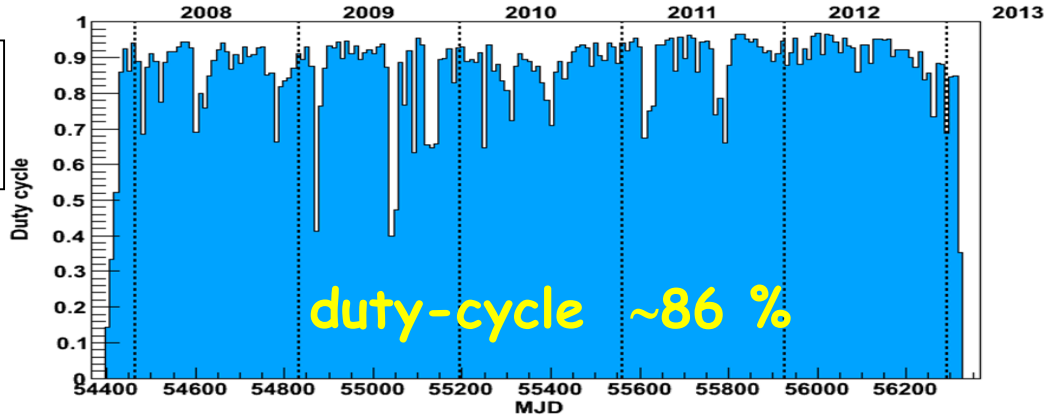


Analog view of a shower

EAS reconstruction by digital readout

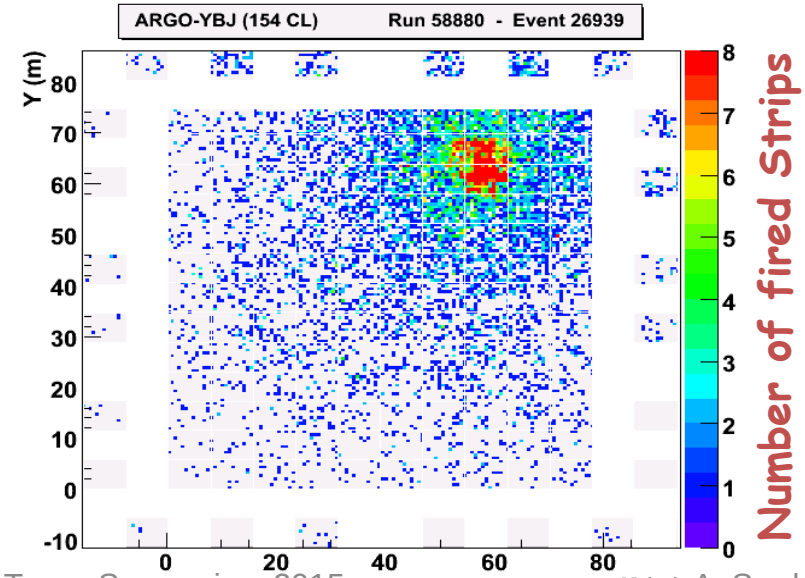
Data taking with full configuration:
November 2007- February 2013

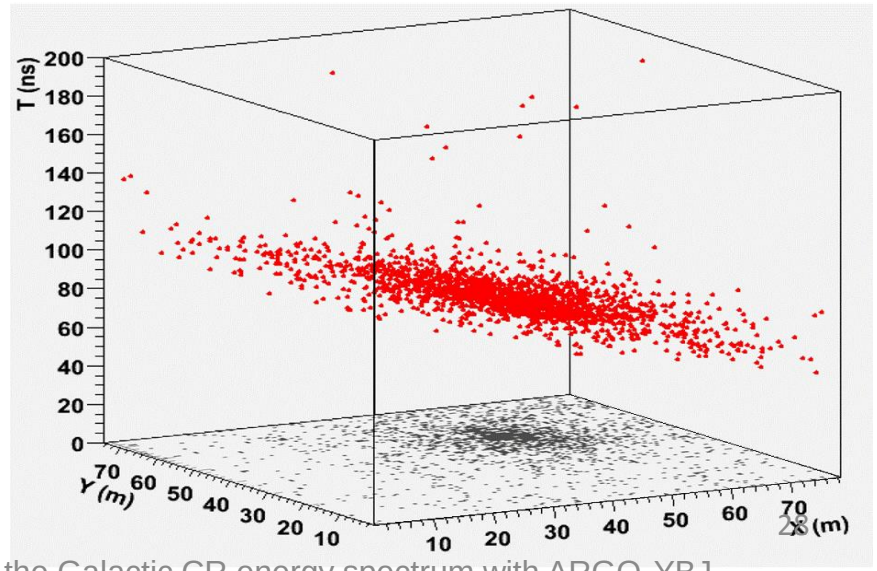
Event Rate ~ 3.5 kHz for $N_{hit} \geq 20$
- Duty cycle ~ 86% - 10^{11} evts/yr



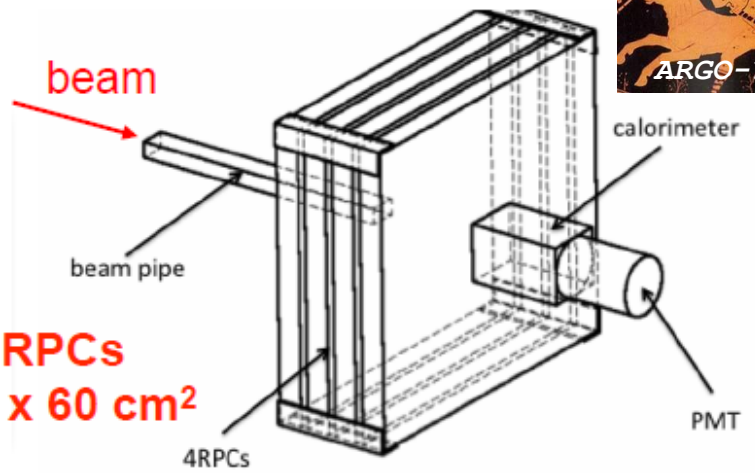
Space/time granularity
+ full coverage
+ high altitude

event imaging and EAS space/time structure study with unprecedented details





Intrinsic linearity: test at the BTF facility



4 RPCs
60 x 60 cm²

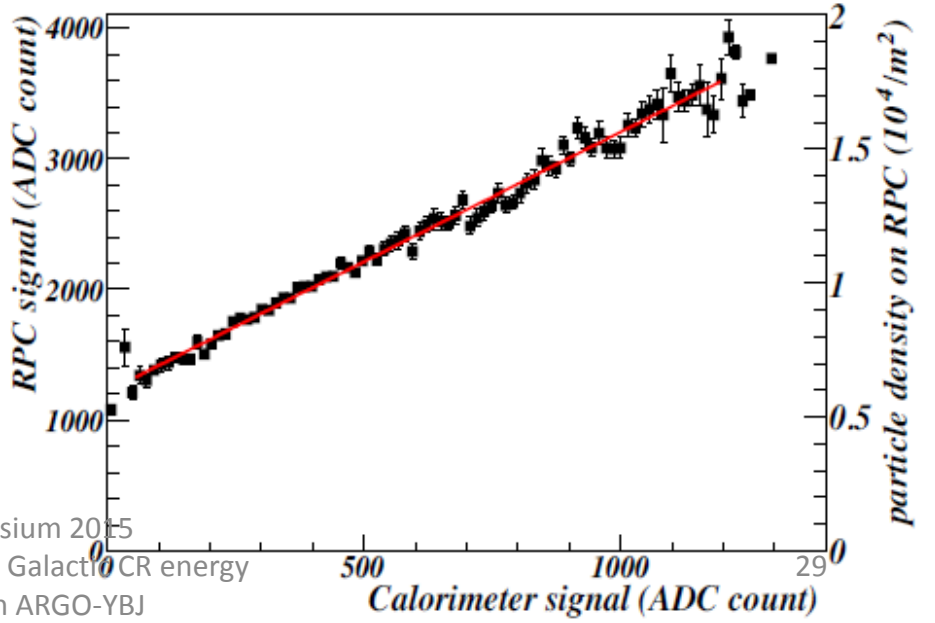
Calorimeter: lead glass block from OPAL,
PMT a Hamamatsu R2238.

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*

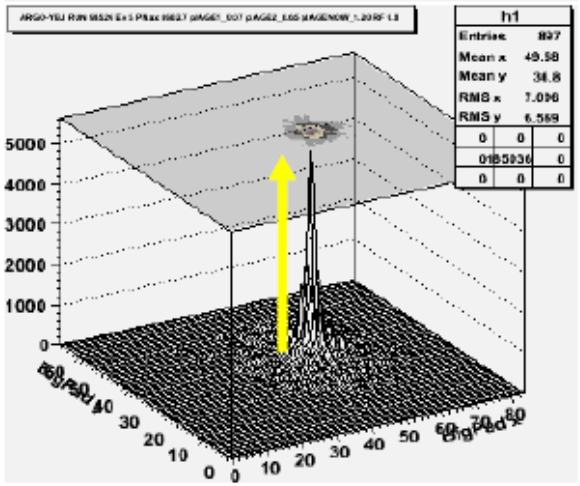
→ Linearity up to ≈ 2 • 10⁴ particle/m²

The RPC signal vs the calorimeter signal



Astroparticle Physics submitted

Absolute comparison Data - MonteCarlo



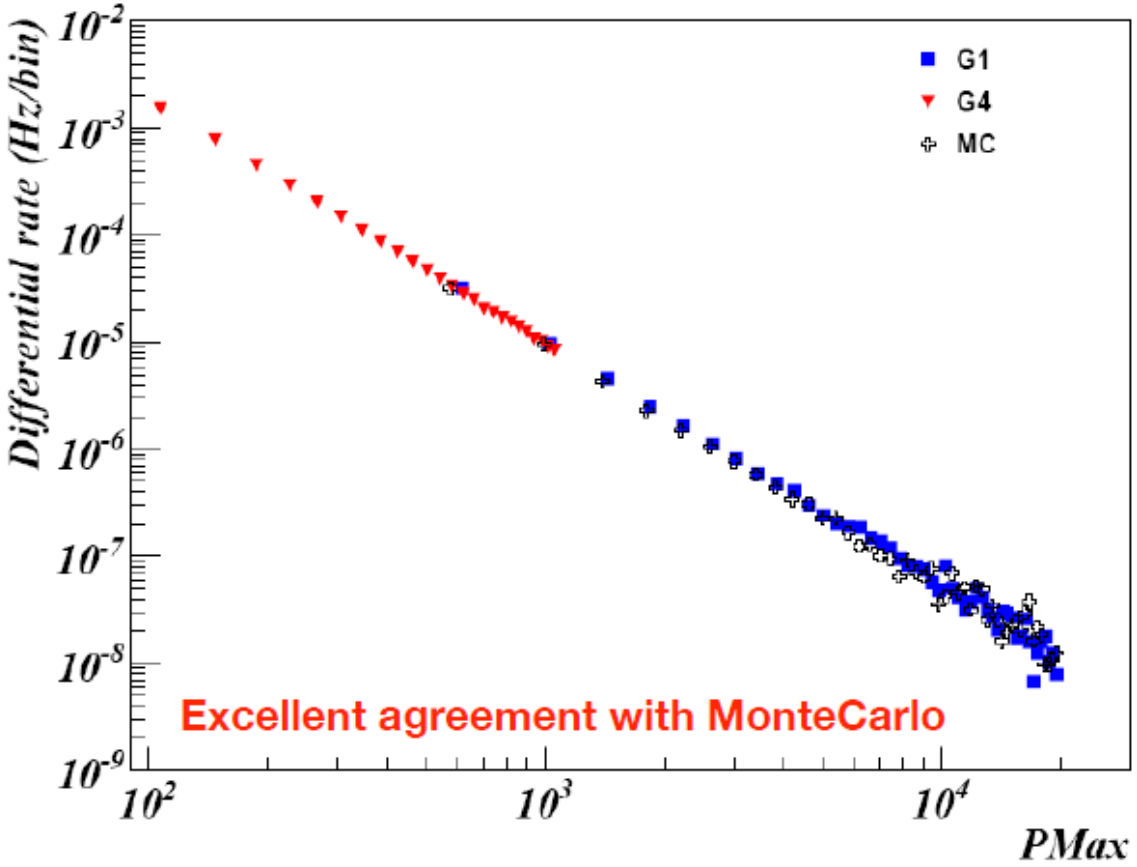
J.R. Horandel , Astrop. Phys. 19 (2003) 193

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

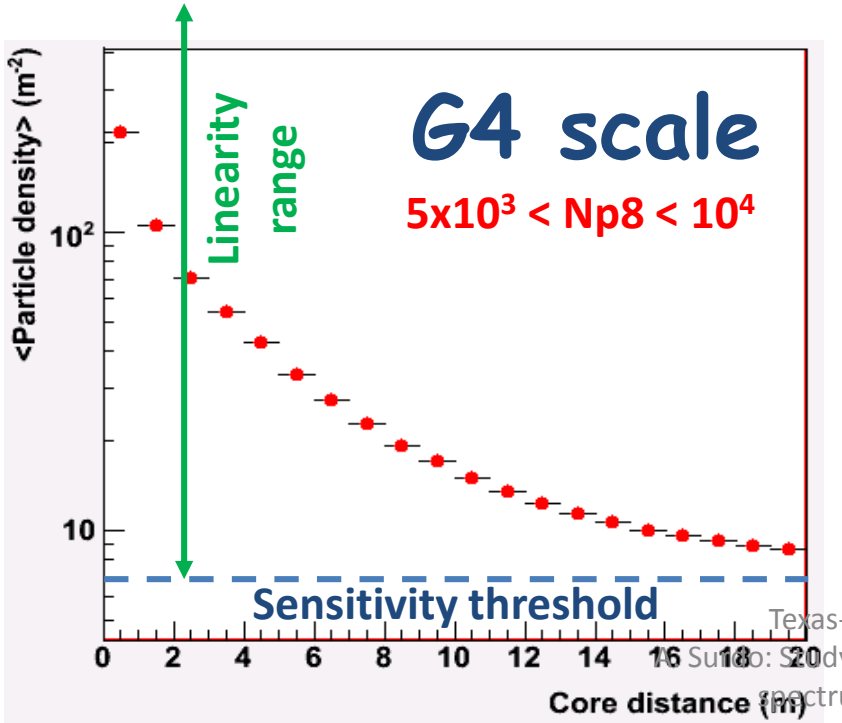
Eight gain scales (G0, G1, … G7) ensure good linearity up to about 2 x 10^4 particles/m^2

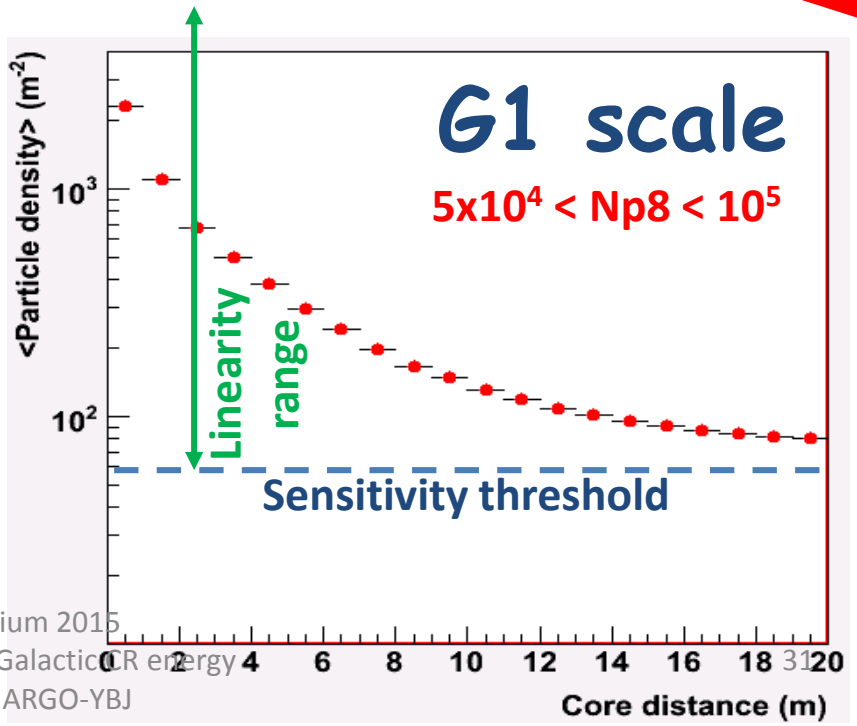
G7 data overlap the digital-mode linearity range, and have been used for intercalibration and cross checks

Here we use G4 and G1 scales to cover the 50 TeV – 10 PeV range with high efficiency and without saturation

Np_8 = how many particles within 8 m from the core

Lateral Distribution Function (LDF)



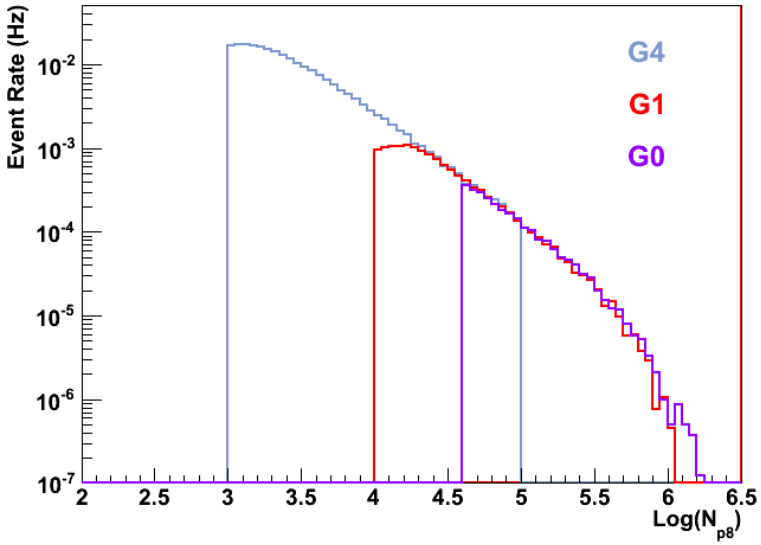


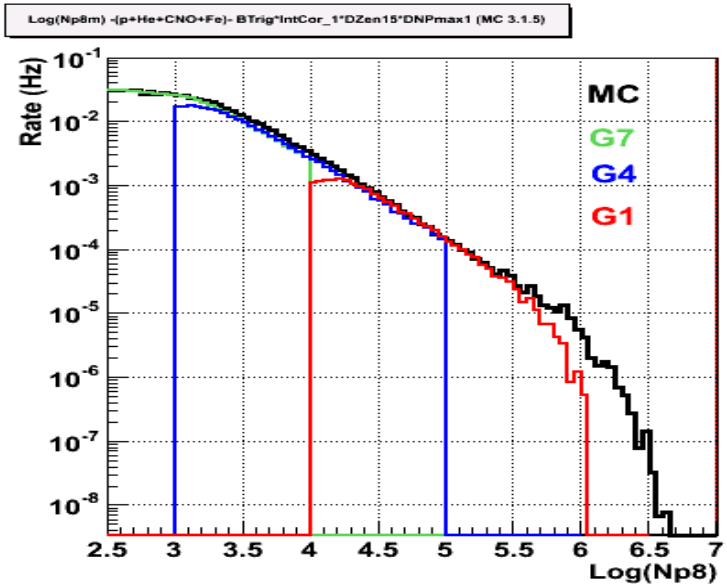
Truncated particle size

Np_8 :particle size truncated at 8m of core distance

Not affected by possible saturation of Analog System

Log(Np8) distributions for DATA from G4, G1, and G0 scales





MC simulation

- **Simulated air shower samples:**

  (a) p showers (1- 30,000)TeV, Theta<45°
  (b) He showers (1- 10,000)TeV, "
  (c) CNO showers (1- 30,000)TeV, "
  (d) Fe showers (1- 10,000)TeV, "

  produced using *CORSIKA* code (*QGSJET-II.03 + Fluka*)

- **Also p and He showers (1- 10,000)TeV, Theta<45°**

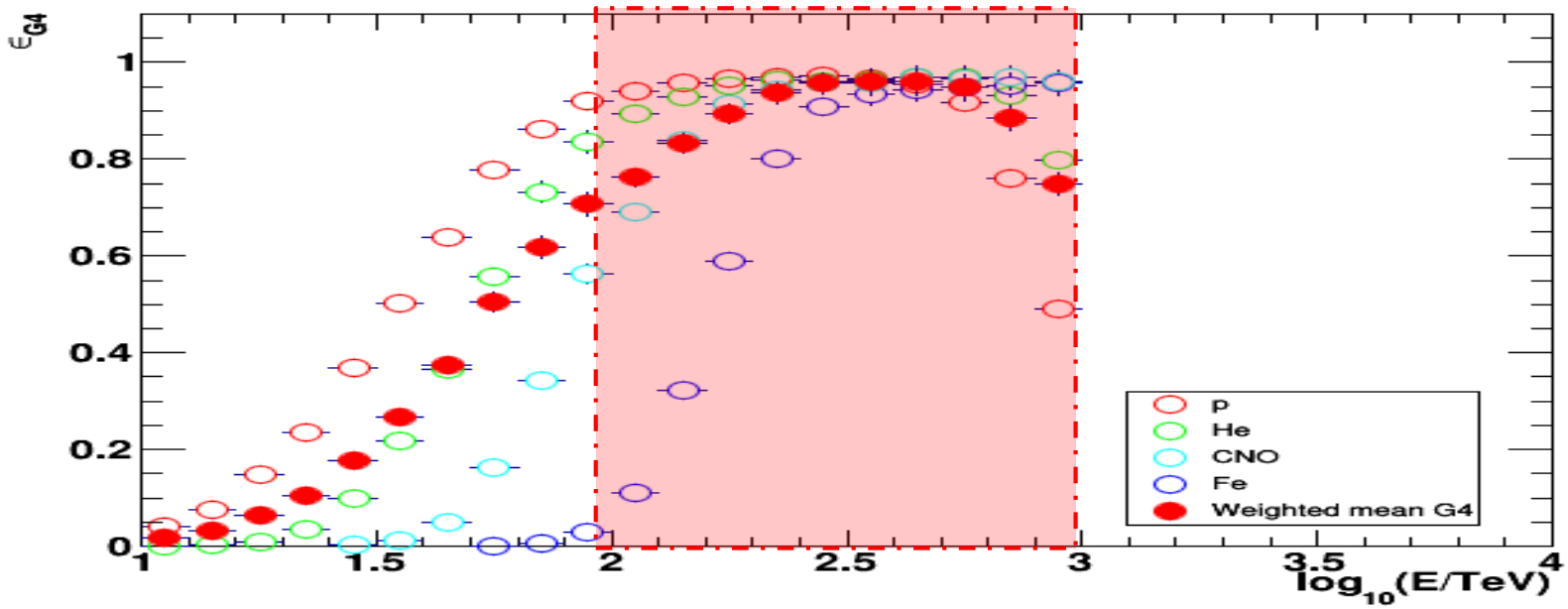
  produced using *a different hadronic model: SIBYLL-2.1 (+ Fluka*)

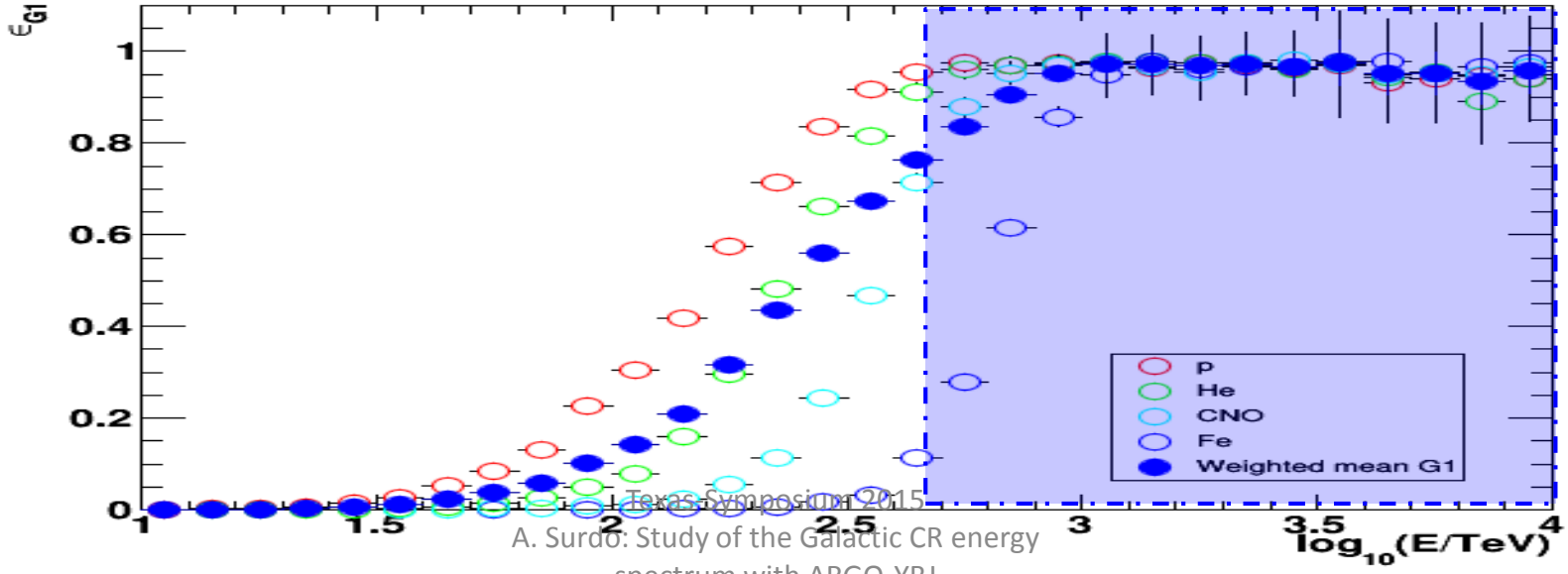
- **Simulated showers (sampled on large areas) given in input to the ARGO MC (based on *Geant*-3) fully simulating the detector response (analog charge trigger and readout system included)**

- **MC data reconstructed by using the same program as for real data.**

- **Event selection: core inside a fiducial area A_{fid} = (64 x 64) m^2 (θ_{zen} < 15° used in this analysis)**

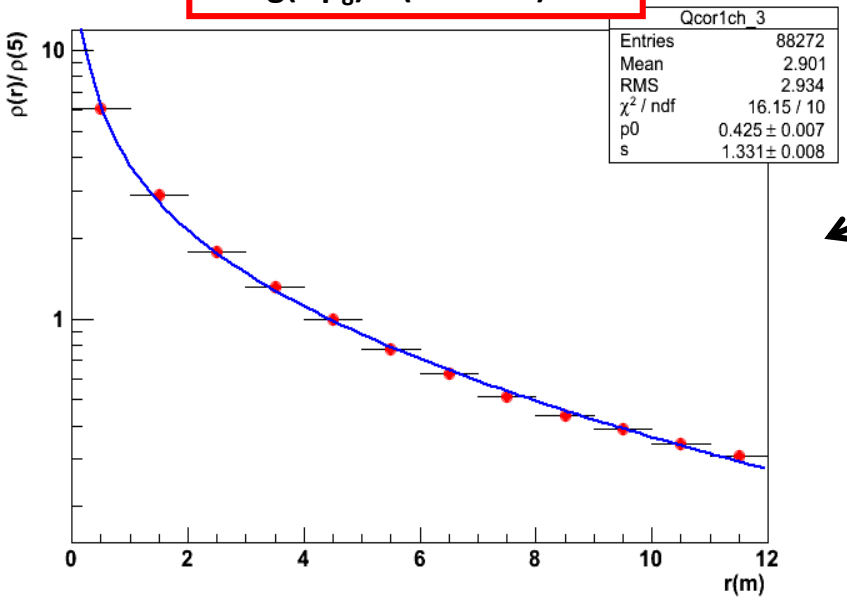
Trigger and event selection efficiencies for the all particle spectrum



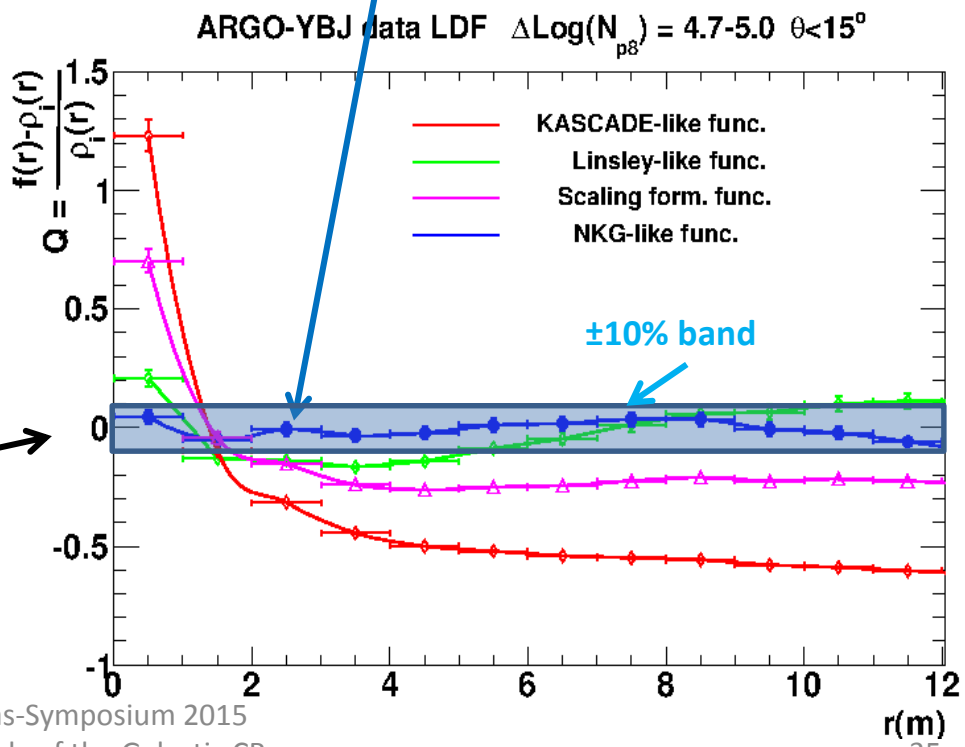


ARGO-YBJ data: LDF fits

ΔLog(Np_8) = (4.7 - 5.0)



Fit with ρ'_{NKG}



Comparison of residuals from different function fits:

Lateral Distribution Function (LDF) and shower age

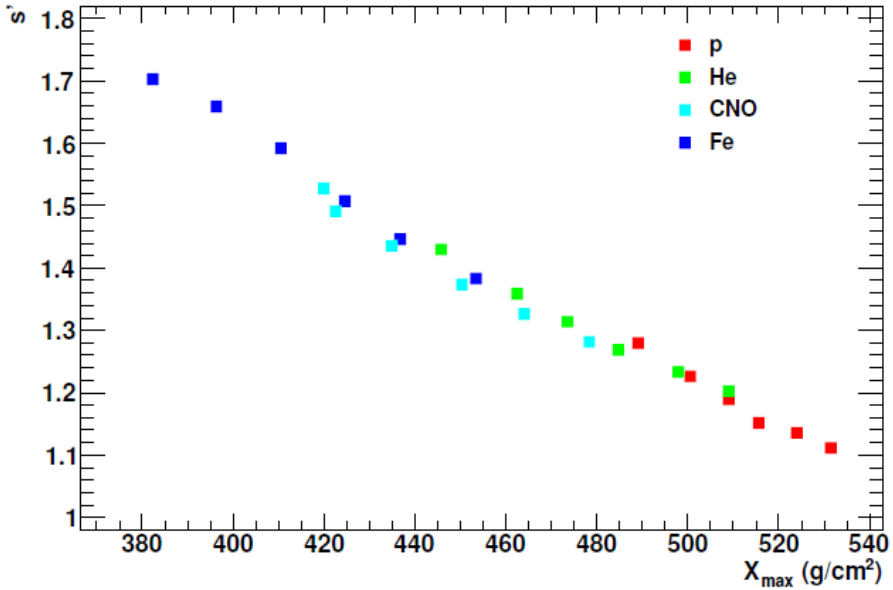
Modified NKG function: LDF to fit the lateral particle distribution

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

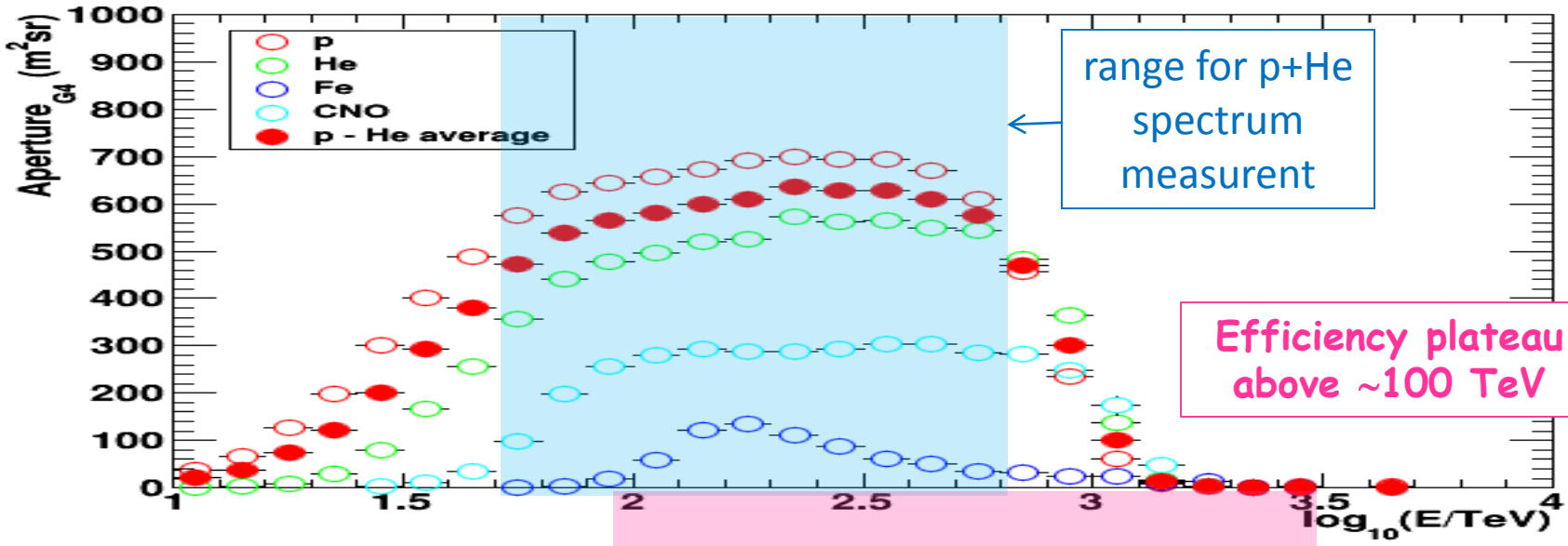
s' plays the role of 'lateral age'

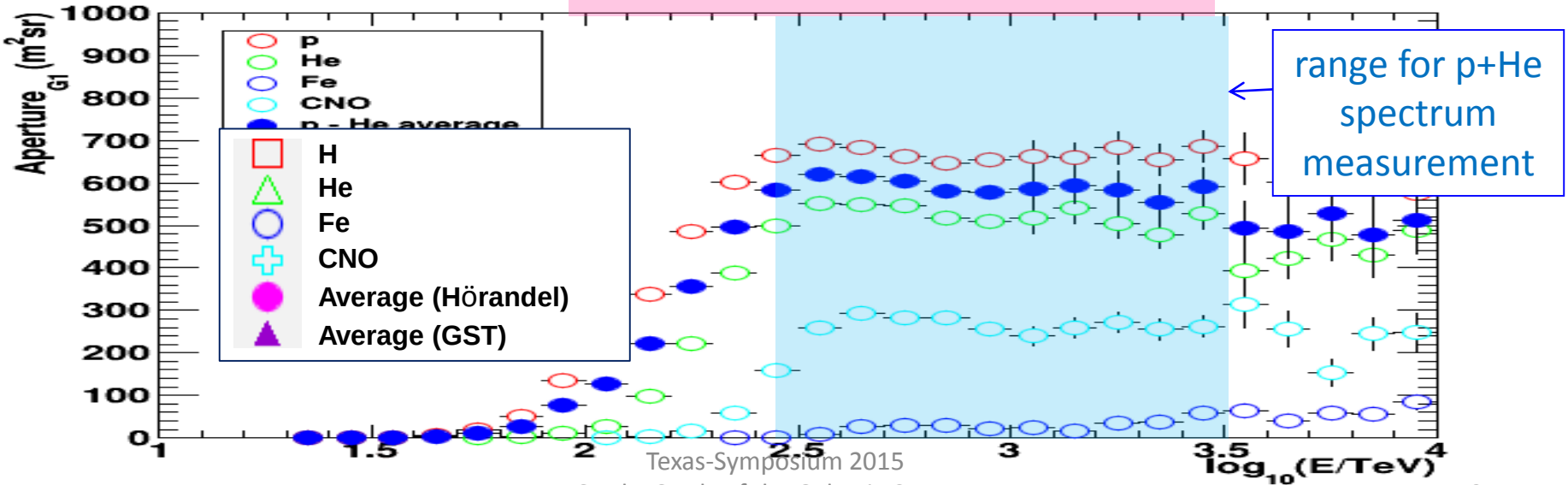
The LDF slope (*s'*) is related to X_{max}, then to the shower age s, independently on the primary mass ('**universality property**')

$$s = \frac{3h_0 \sec\theta}{h_0 \sec\theta + 2X_{\max}}$$



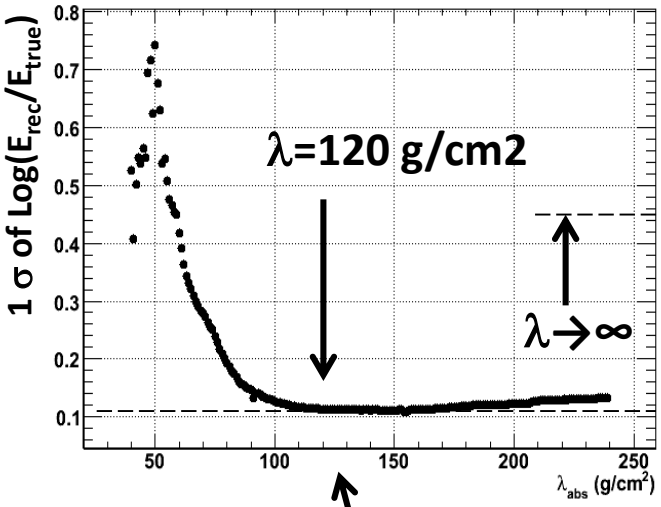
Aperture for p+He event selection





Finding the best λ_{abs} parameter

LogE resolution at 270 TeV vs λ_{abs}

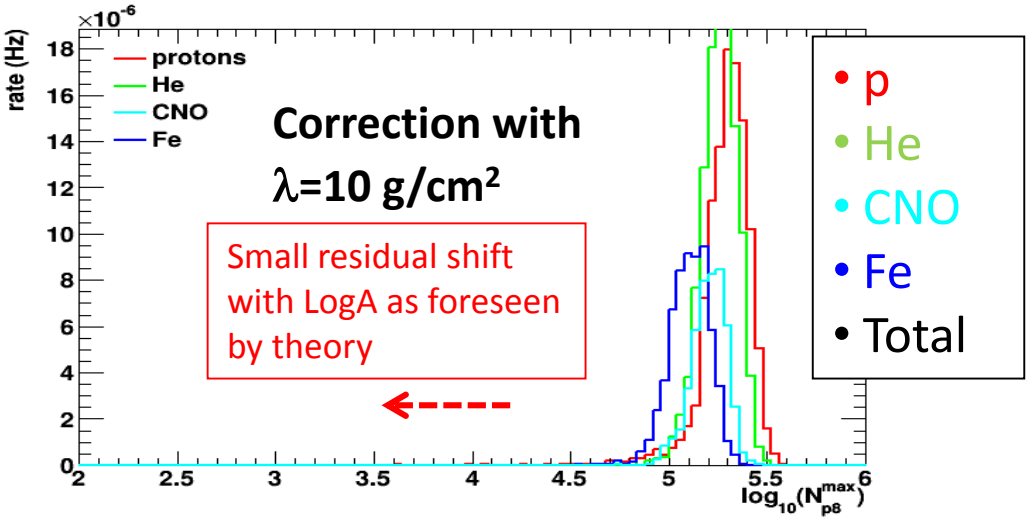


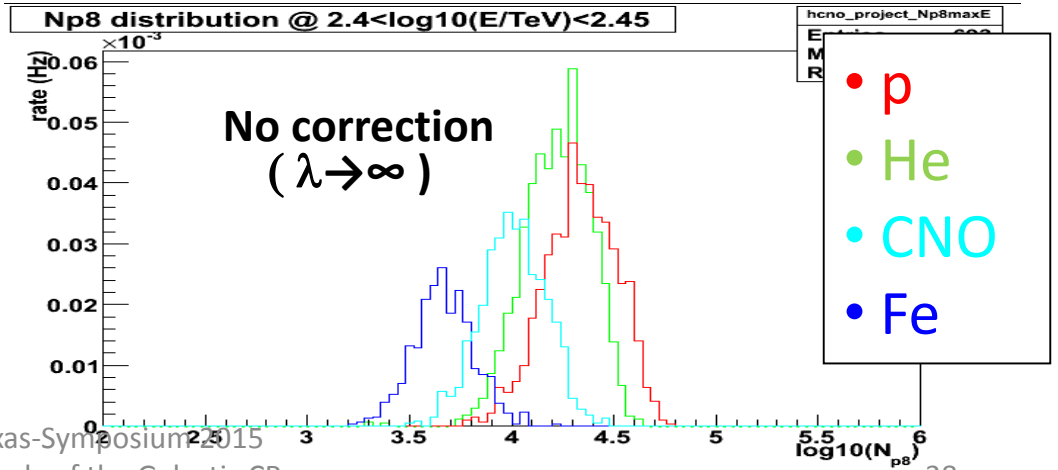
Results from the ARGO-YBJ test experiment

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].

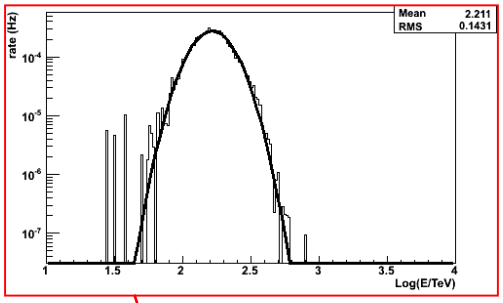
The parameter α is found to be 4.88 ± 0.45, so that $\Lambda_{att} = (124 \pm 11)$ g/cm^2, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 ± 0.37.

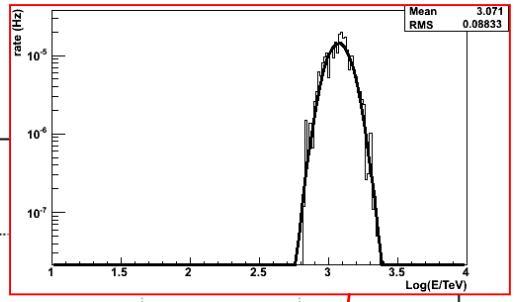


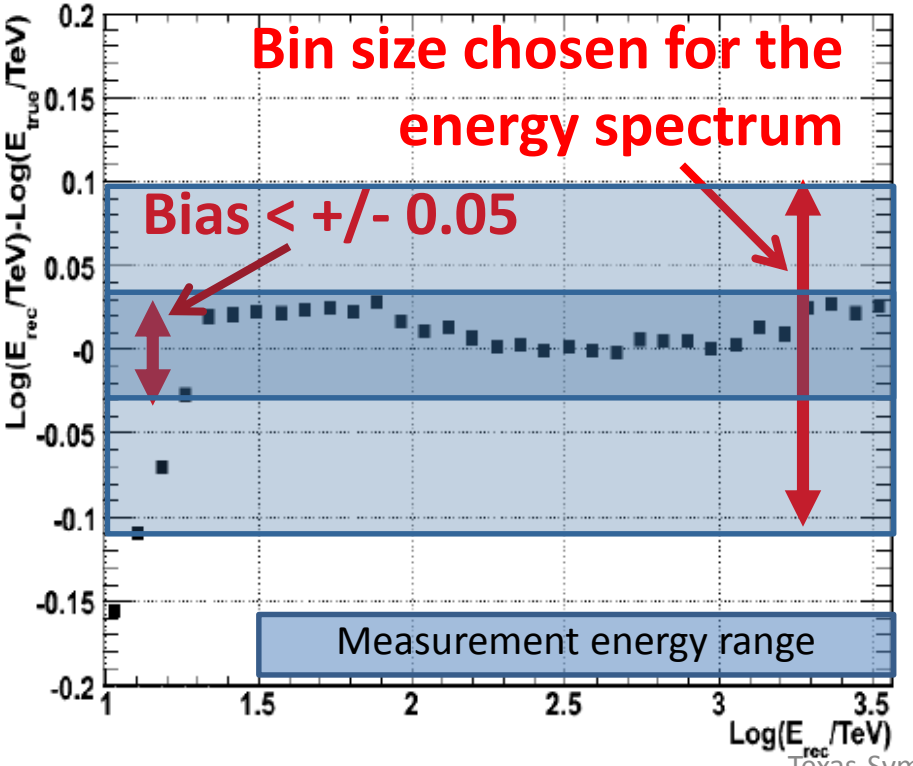


Energy reconstruction: bias and resolution

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.





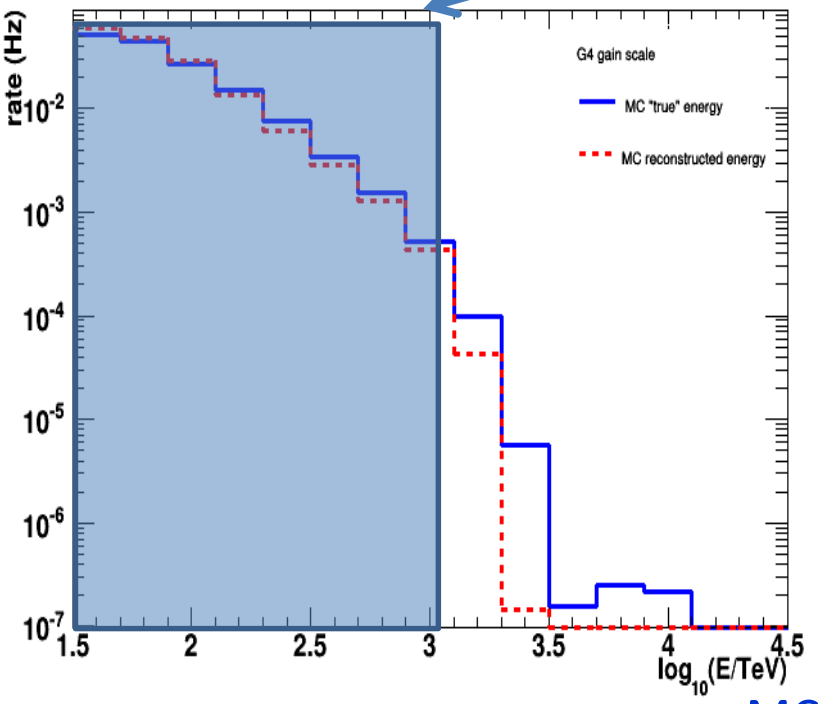


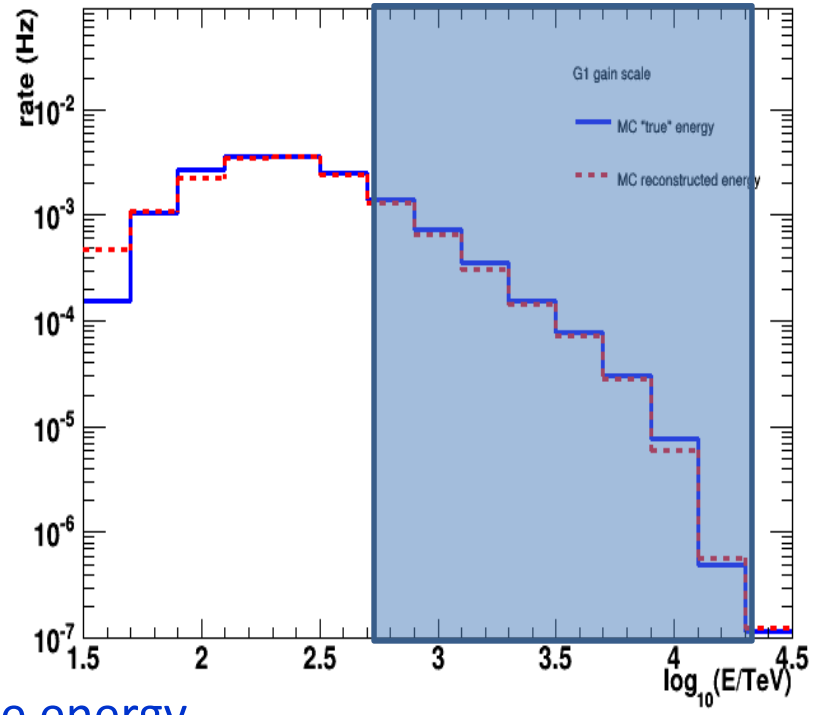
MC Energy distributions

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 %**

Light component (p+He)

- Residual contamination of heavier nuclei after selection: 15-20 %
  (CNO → 14 %, Fe → 4 %)

Combined (p+He) = 20-25 %

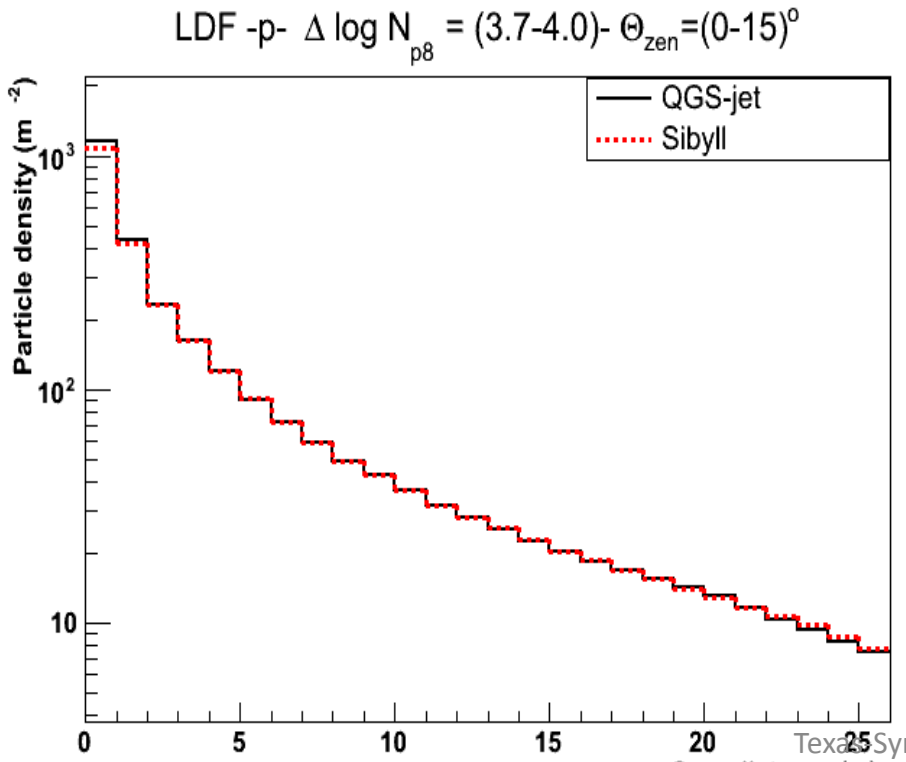
Energy scale

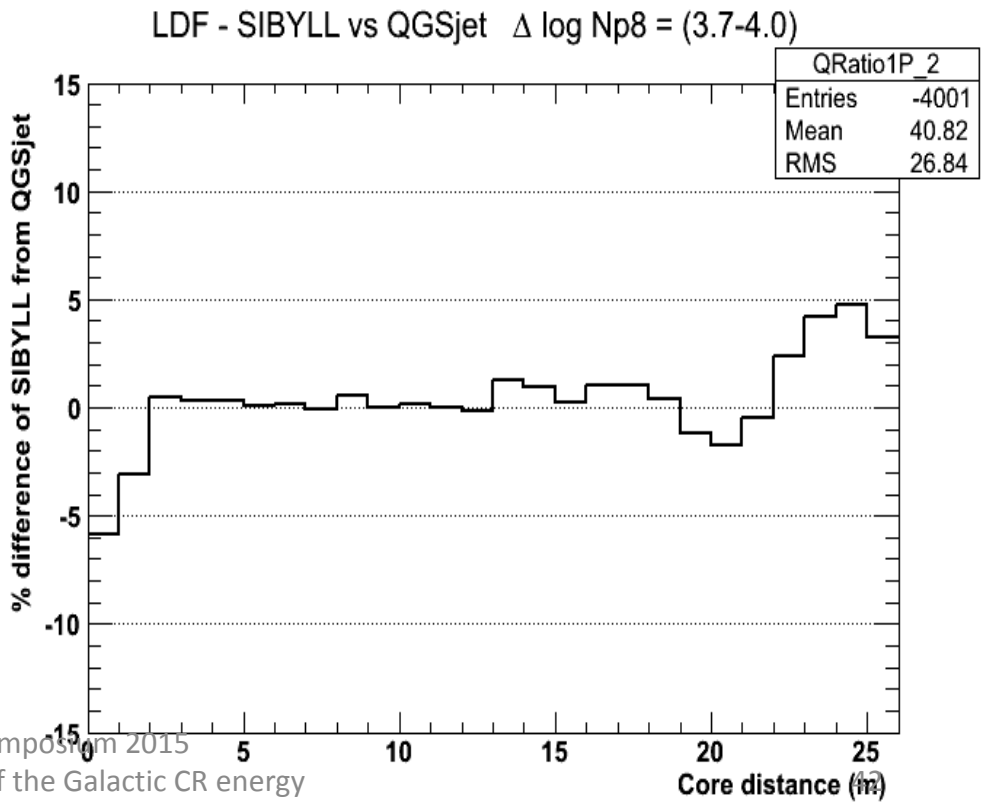
- Gain of the analog system: 3.7 %
- Energy calibration: 0.03 in LogE = 6.9 %
- Hadronic interaction model: 5 %
- **TOTAL: 9.3 %** **TOTAL (conservative) = 10%**

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.





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

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

Direct link between observables and primary energy and mass

- Causes: $\{E_i,\ldots..E_n;\ ID_i,\ldots\ldots ID_n\}$
- Effects: $\{Np8_i,\ldots.,Np8_n;\ D_i,\ldots.,D_n\}$

Experimental data → **Probability theory** → **Energy Spectrum Composition**

CR Flux

$$N(E,ID) = P(E,ID|NP_8,D_1,D_2)\cdot N(NP_8,D_1,D_2)$$

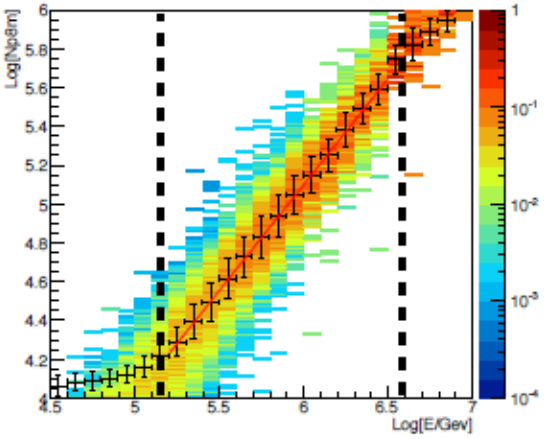
Exp. Data

Bayes

Simulations $P(NP_8,D_1,D_2|E,ID)\cdot P_0(E,ID)$

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

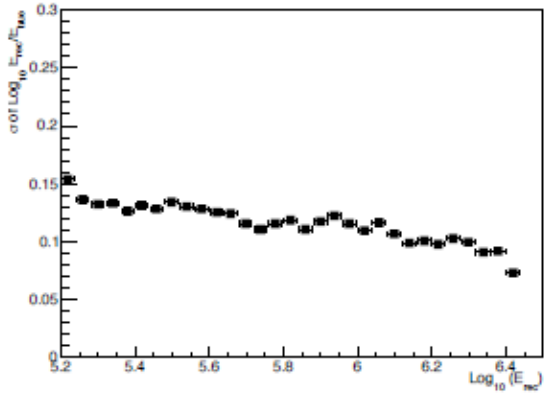


Selection of the light component: shower topology

Light Component (p+He) selection:

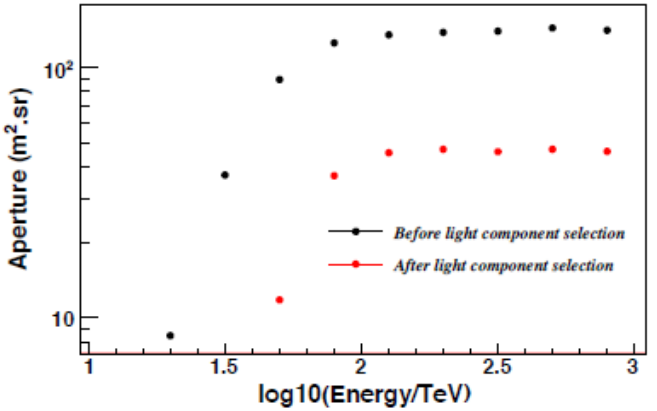
$$\rho_{A20} > \rho_{A42}$$

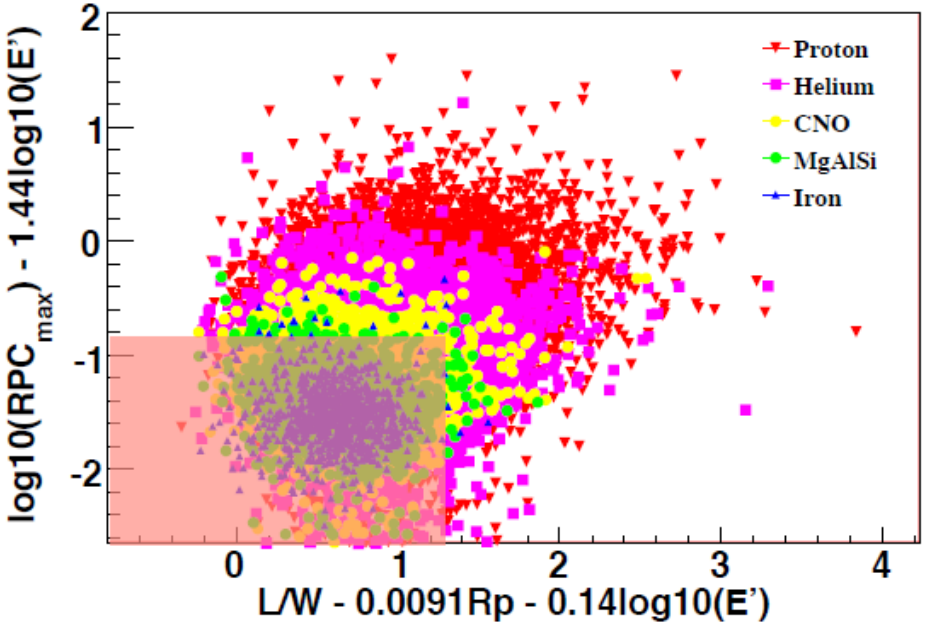
A20 = 20 innermost clusters
A42 = 42 outermost clusters

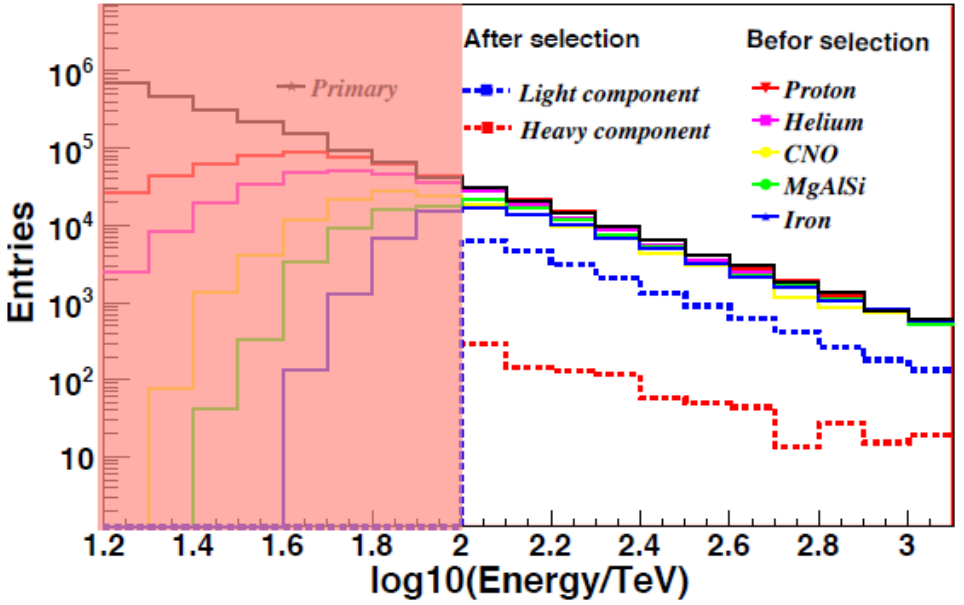


- Contamination of heavier component < 5 %
- Energy resolution: ~25%
- Uncertainty : ~25% on flux

	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 p+He spectrum index

Preliminary ARGO-YBJ analog data (G4 and G1)