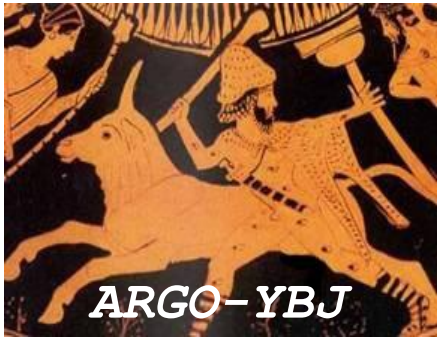


EPS-HEP 2015

Observation of a knee in the Cosmic Ray p+He energy spectrum below 1 PeV with the ARGO-YBJ experiment

A. Surdo

Istituto Nazionale di Fisica Nucleare (INFN)
Sezione di Lecce, Italy

(on behalf of the ARGO-YBJ Collaboration)

The ARGO-YBJ experiment

High Altitude Cosmic Ray Observatory @ YangBaJing, Tibet, China

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

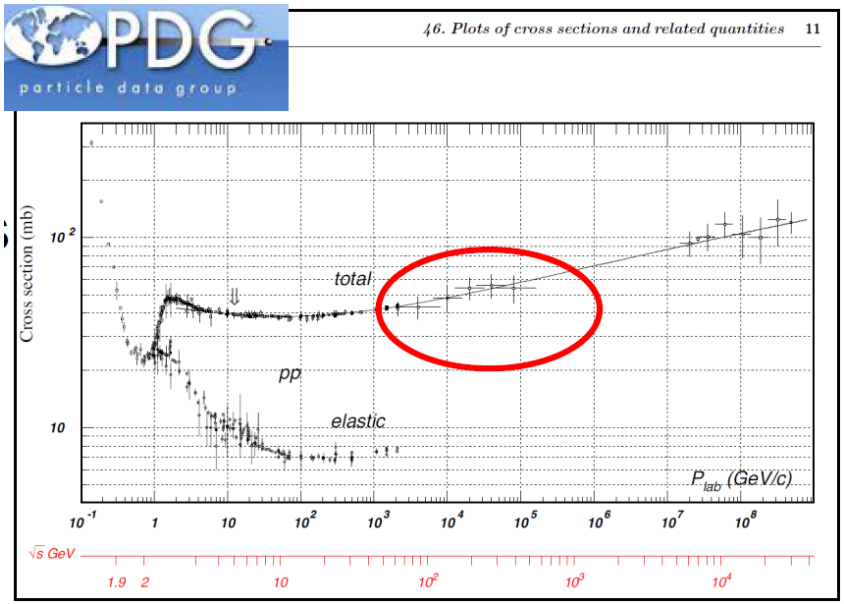
ARGO-YBJ physics

- **VHE γ-Ray Astronomy**:

  study of point-like (and diffuse) galactic and
  extra-galactic sources with few hundreds GeV energy threshold

- **Cosmic ray physics**:
  - **energy spectrum and composition**
  - study of the shower space-time structure
  - flux anisotropies at different angular scales
  - p-Air cross section measurement →
  - hadronic interaction studies
  - anti-p / p ratio at TeV energies,
  - geomagnetic effects on EAS

  .....



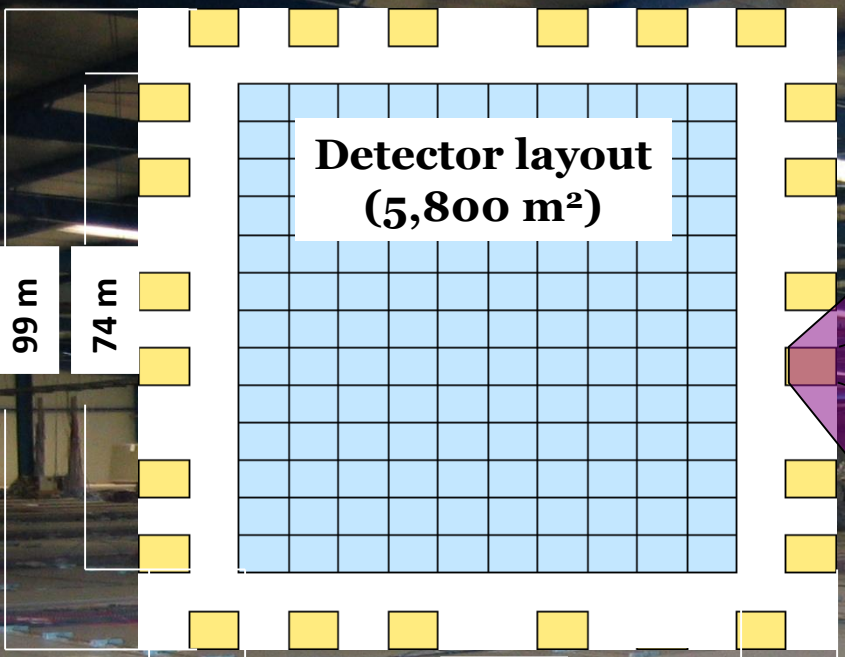
- **Search for GRB's** (full GeV / TeV energy range)
- **...**

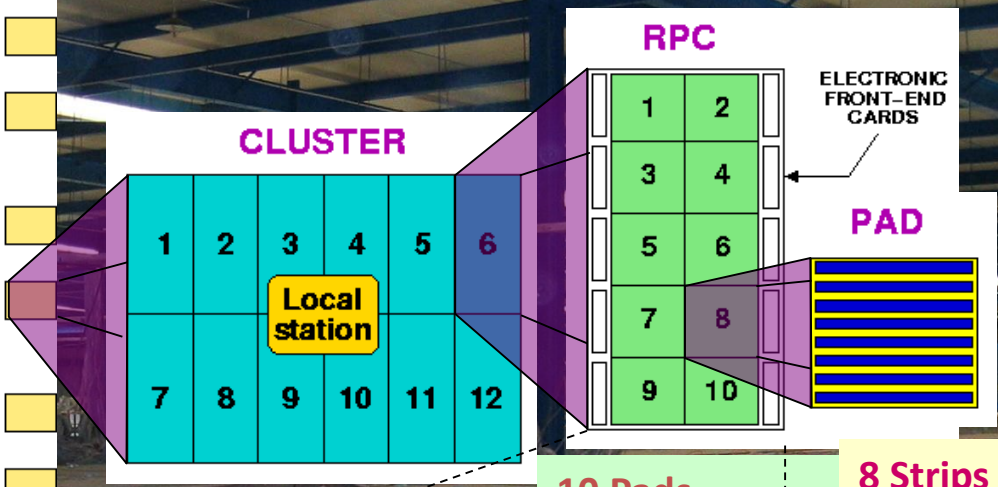
through the...

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

ARGO-YBJ detector

ARGO-YBJ detector

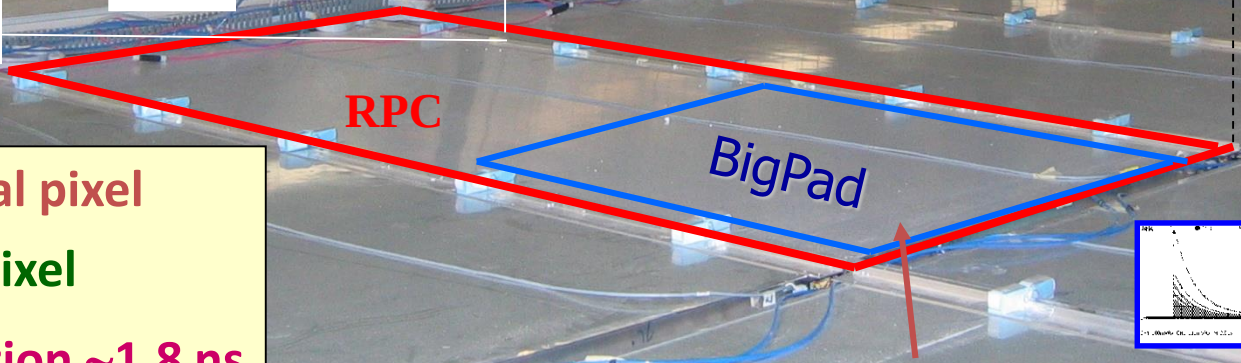




1 CLUSTER = 12 RPC
(~43 m²)

10 Pads
(56 x 62 cm²)
for each RPC

8 Strips
(6.5 x 62 cm²)
for each Pad



BP Amplitude :
mV to many Volts

Strip = spatial pixel

Pad = time pixel

Time resolution ~1.8 ns

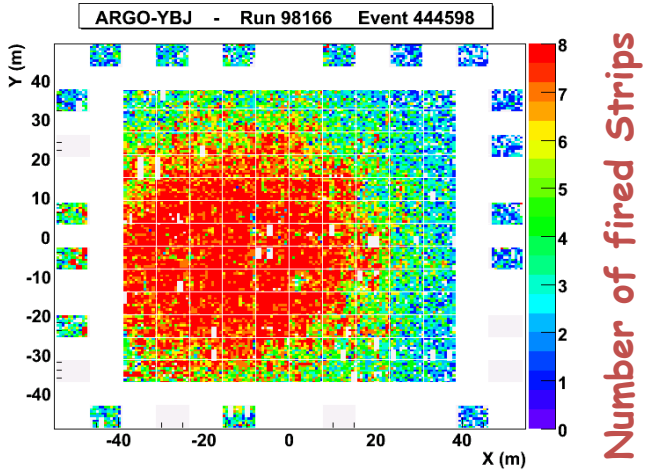
+ Analog RPC charge read-out

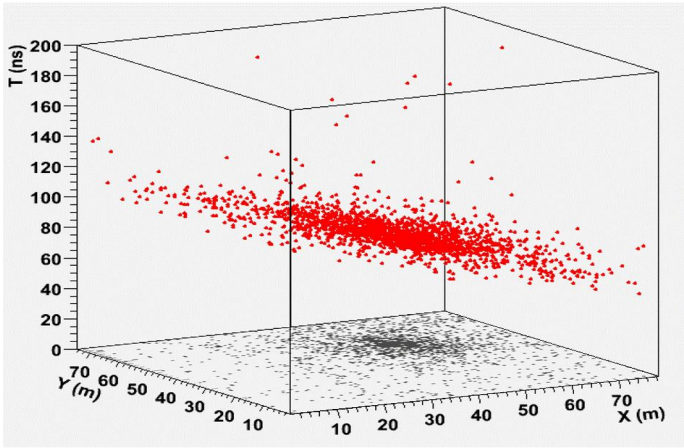
BigPad =CHARGE readout PIXEL,
123 x 139 cm², 3120 (central carpet)

EAS reconstruction with digital …

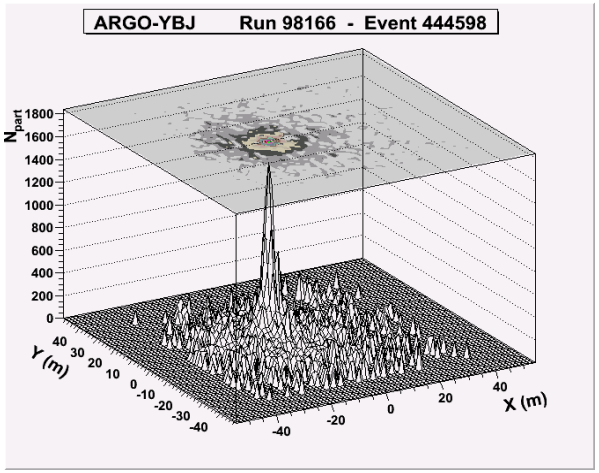
Space/time granularity + full coverage

EAS imaging and reconstruction with unprecedented details





… and analog (RPC charge) readout

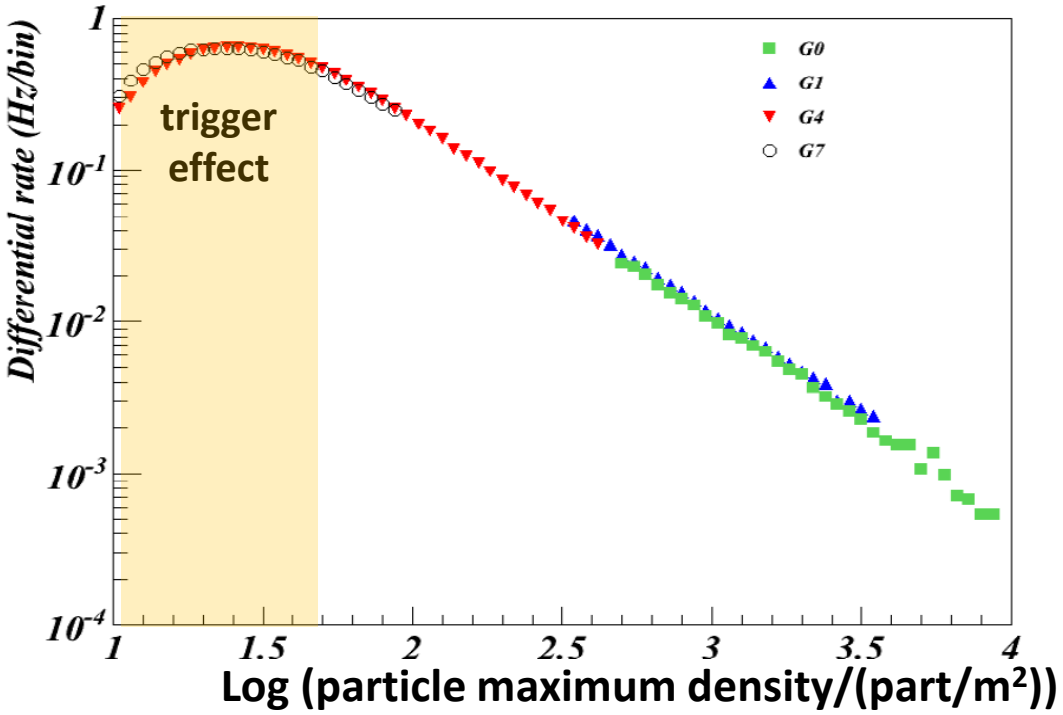


- ✓ Access lateral particle distributions down to the shower core (densities > $10^4/m^2$) thus overcoming the strip saturation
- ✓ Extend energy range (above 100 TeV)
- ✓ Sensitivity to Hadronic Interaction details and CR primary mass

The RPC analog readout

- Eight gain scales (G0, G1, … G7) ensure good linearity up to about 2×10^4 particles/m^2
- G7 data overlap the digital-mode linearity range, and have been used for intercalibration and cross checks
- G0 allows to cover the energy range up to ~30 PeV
  $\Rightarrow$ important region for the estimation of atmosferic ν flux

Here we use **G4** and **G1** scales to cover the 50 TeV – 20 PeV range with high efficiency and without saturation



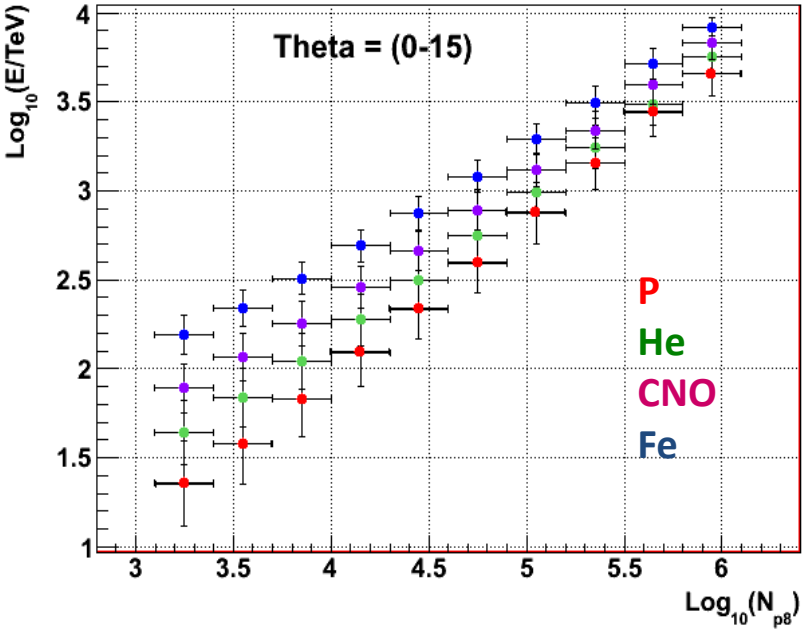
Event selection:

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

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

- **Event selection:** - Core reconstructed in a central detector fiducial area
  - Reconstructed 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

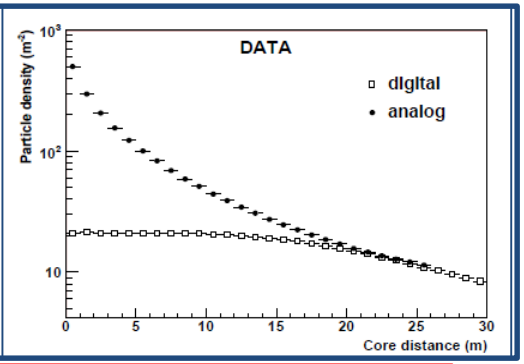
Lateral Distribution Function (LDF) and shower age

Modified NKG function: LDF to fit the lateral particle distribution

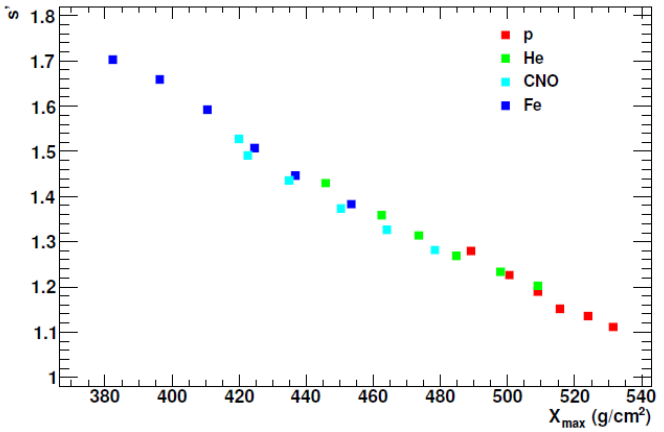
$$\rho'_{NKG} = A\left(\frac{r}{r_0}\right)^{s'-2}\left(1+\frac{r}{r_0}\right)^{s'-4.5}$$

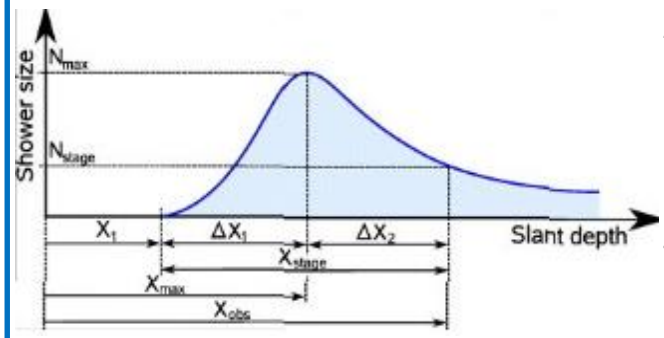
s' plays the role of 'lateral age'

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



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

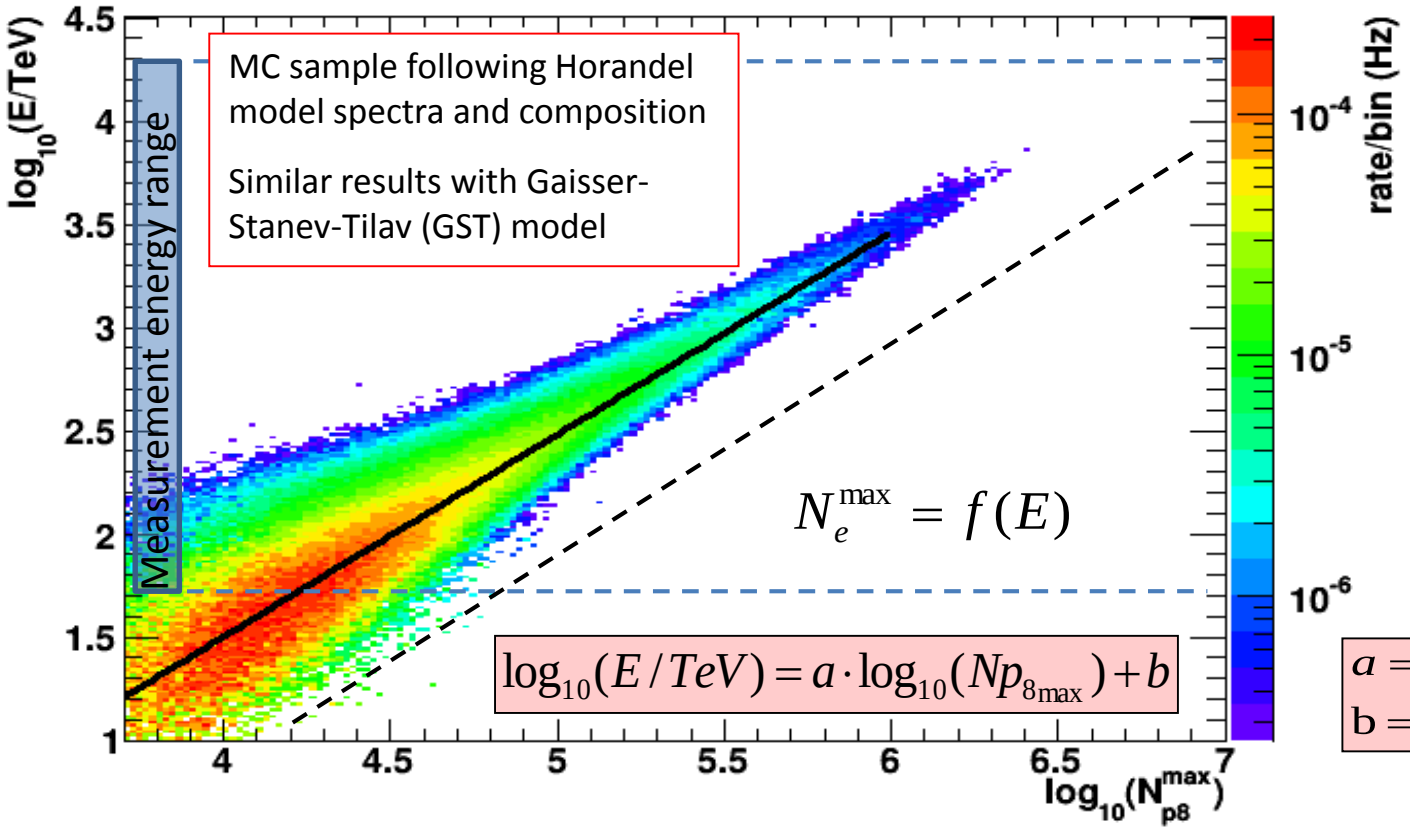




Assume an exponential absorption after the shower maximum → Get the correct signal at maximum (Np_{8max}) from Np_8 and *s'* (fit parameter) measured for each event

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

Mass independent Energy reconstruction



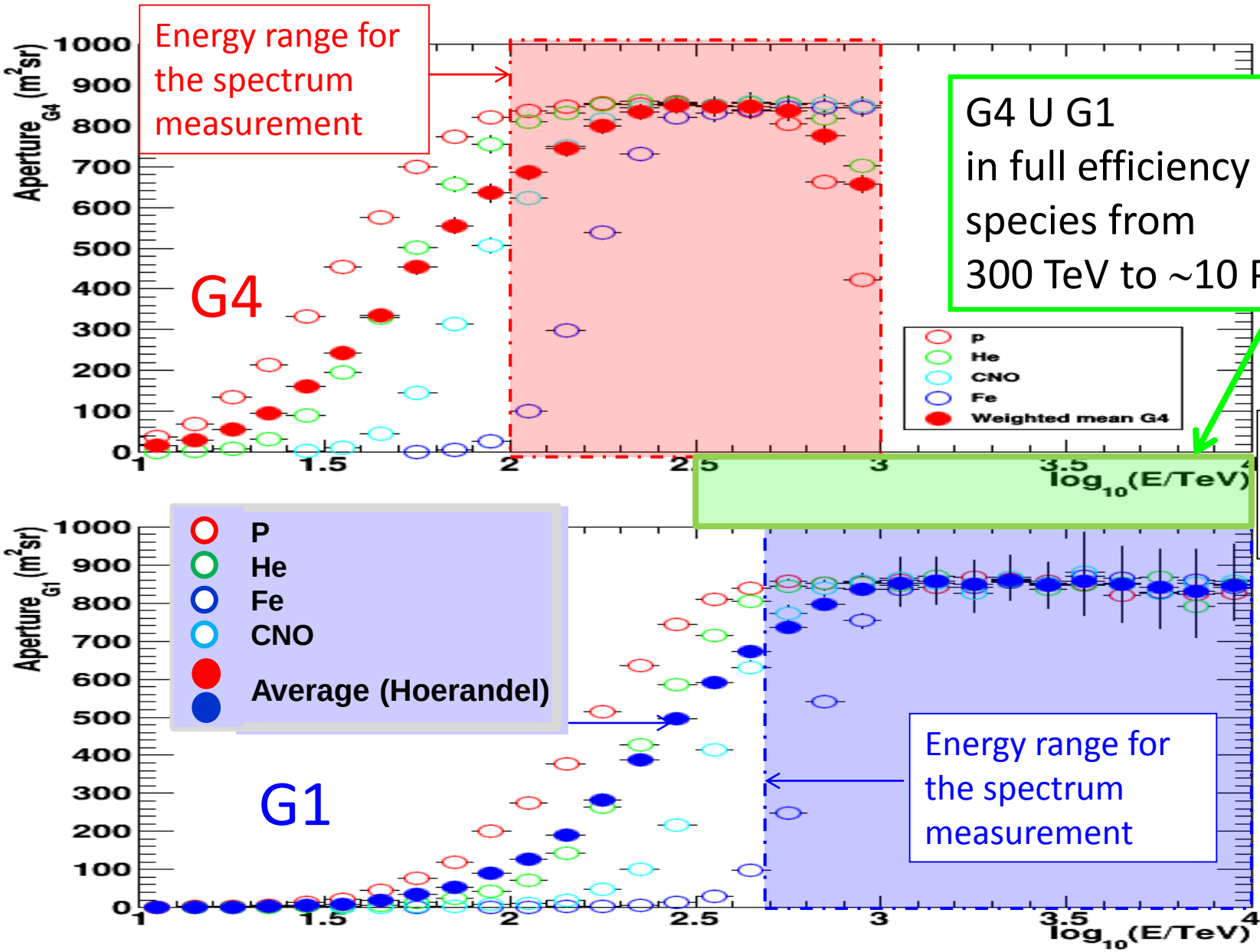
In excellent agreement with total-size-vs-E theoretical plot. The shift is simply due to the fact that we are using the truncated size

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

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.

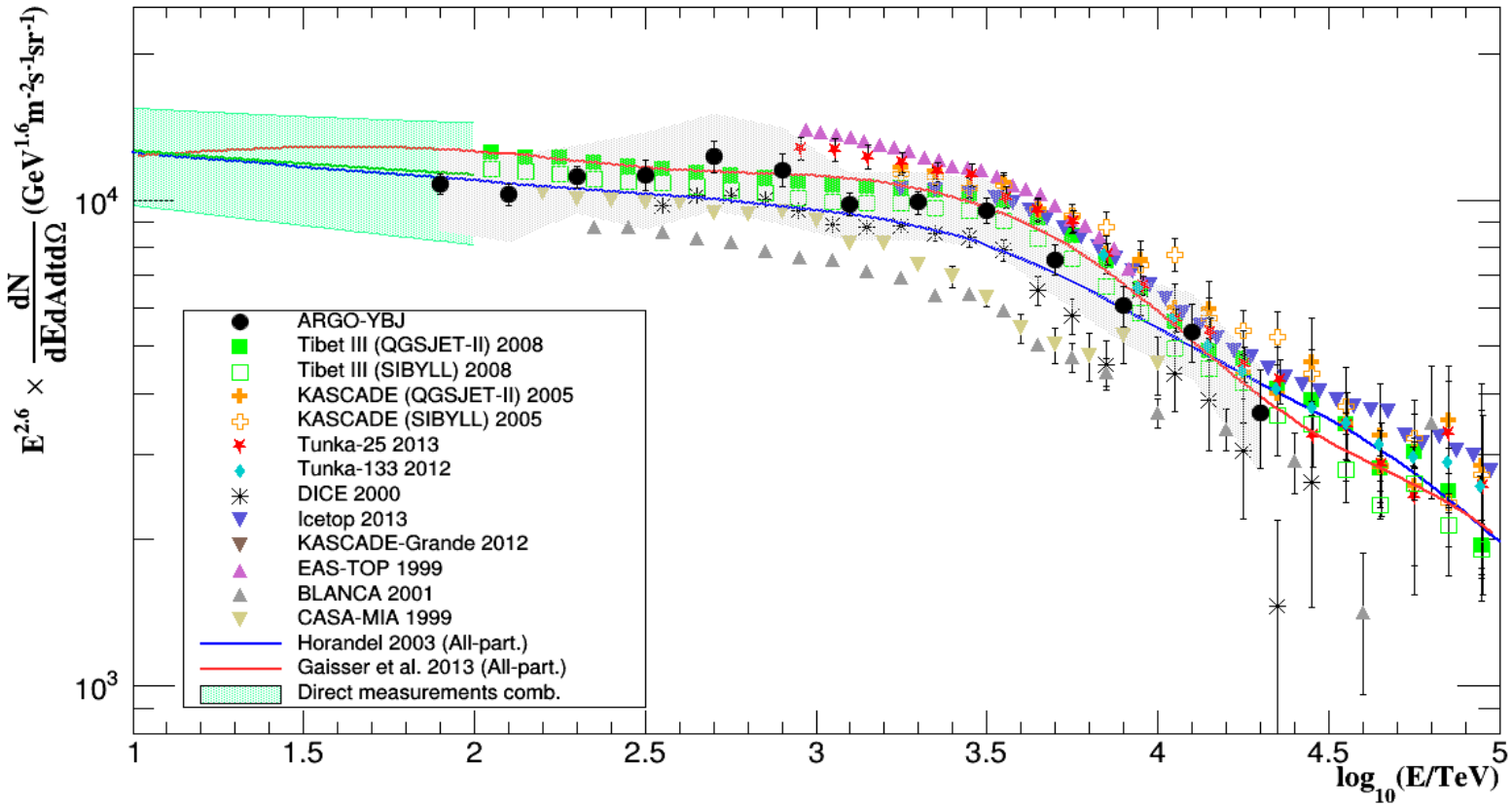
Aperture for the all particle spectrum



The all particle spectrum

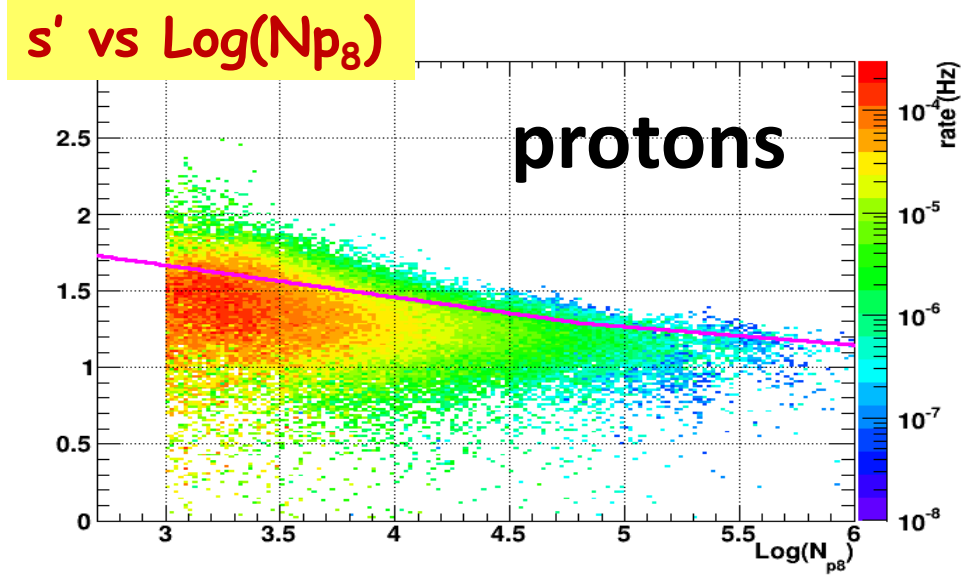
- Picture consistent with models and previous measurements
- Nice overlap between the two gain scales (different data samples, …)
- Results suggest spectral index -2.6 below ~1 PeV and -2.8 from 1 to ~20 PeV

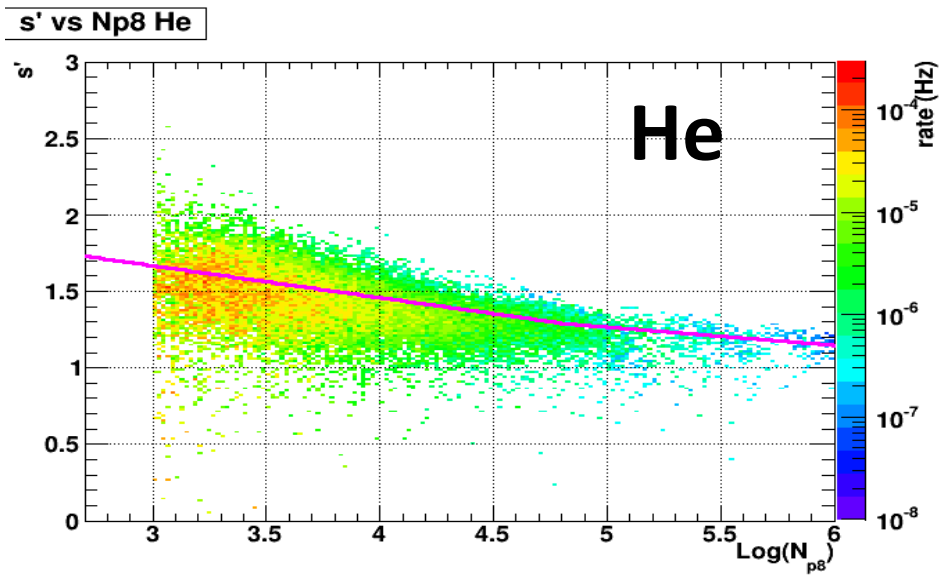
- A significant energy range extension should be gained by considering G0 scale data and inclined events (about a factor 5)
- The extensions to higher energy would be the subject of a future work

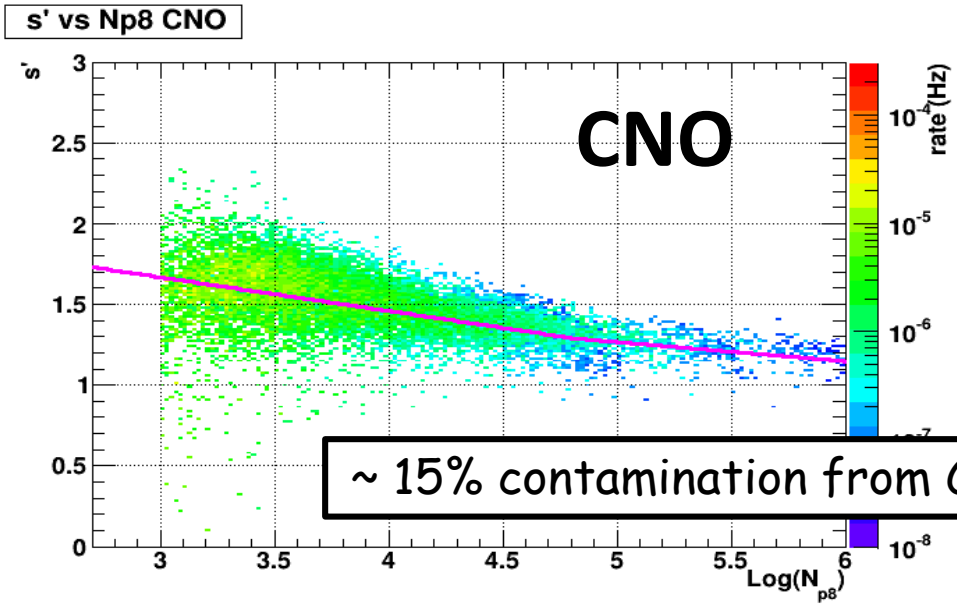


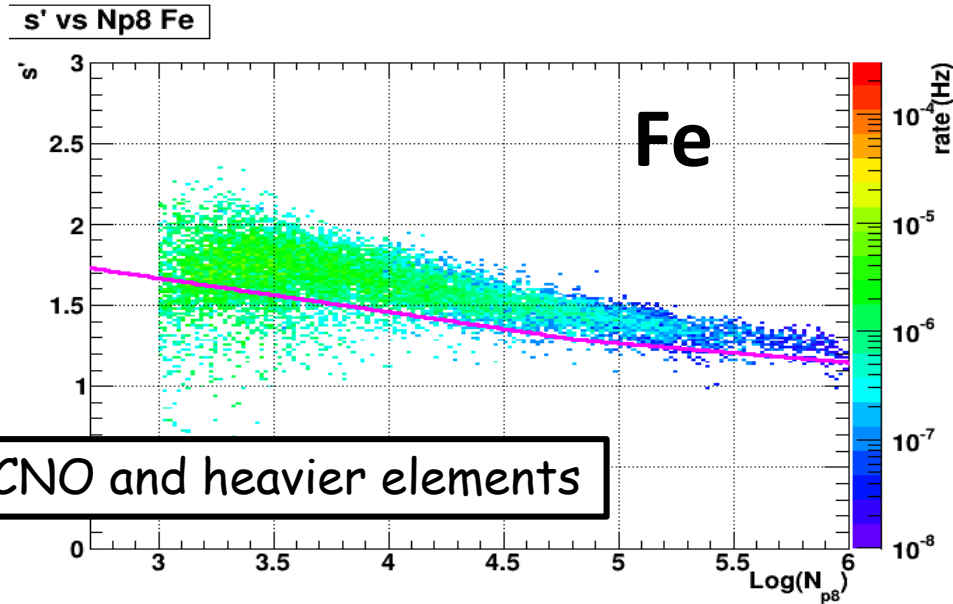
p and He selection
(MC Hoerandel spectra and normalizations)

s' vs Log(Np_8)





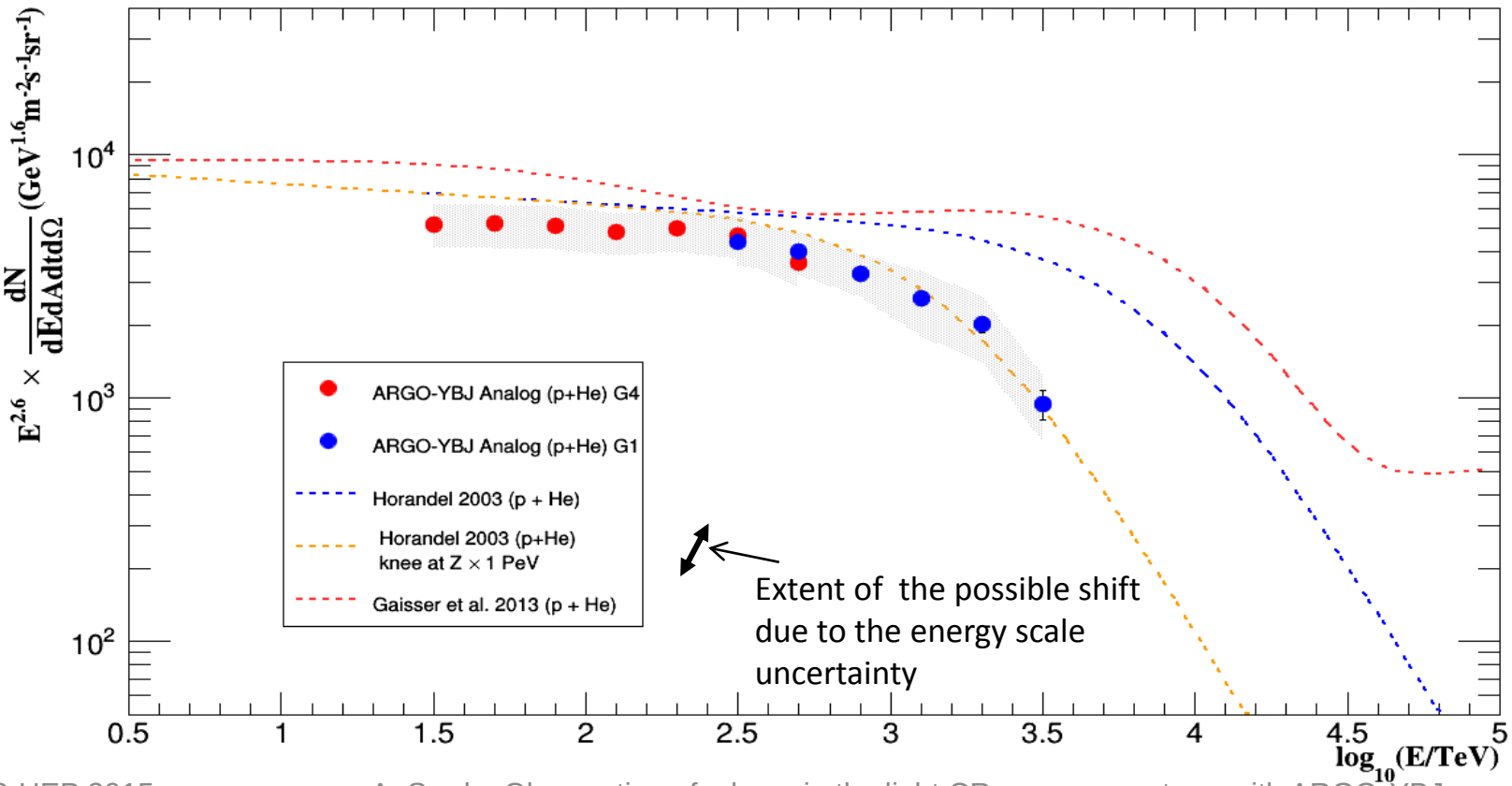




~ 15% contamination from CNO and heavier elements

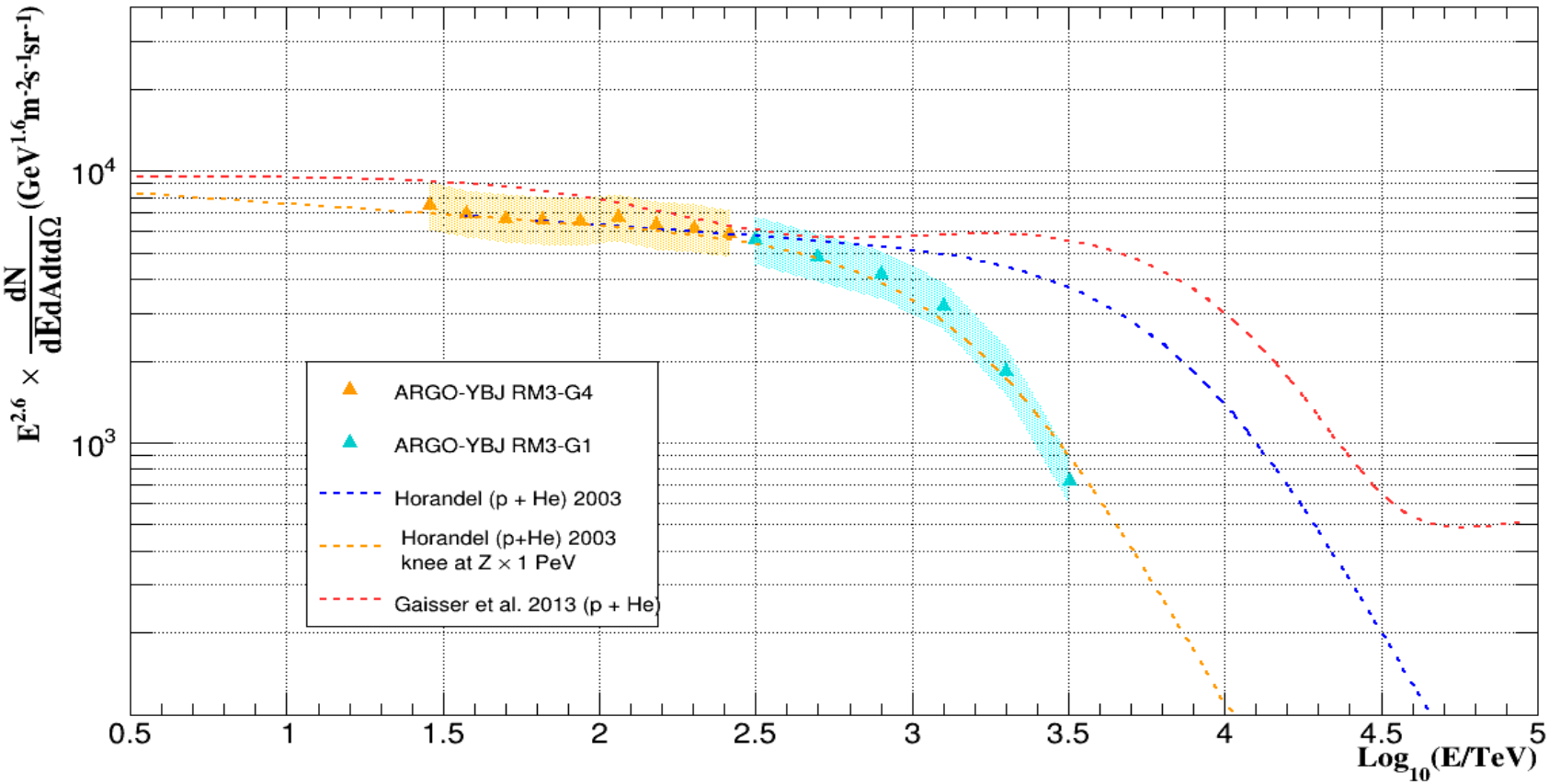
The p+He spectrum (1st)

- Overlap of the points with different gain scales
- Overlap with direct measurements at low energy
- 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 %



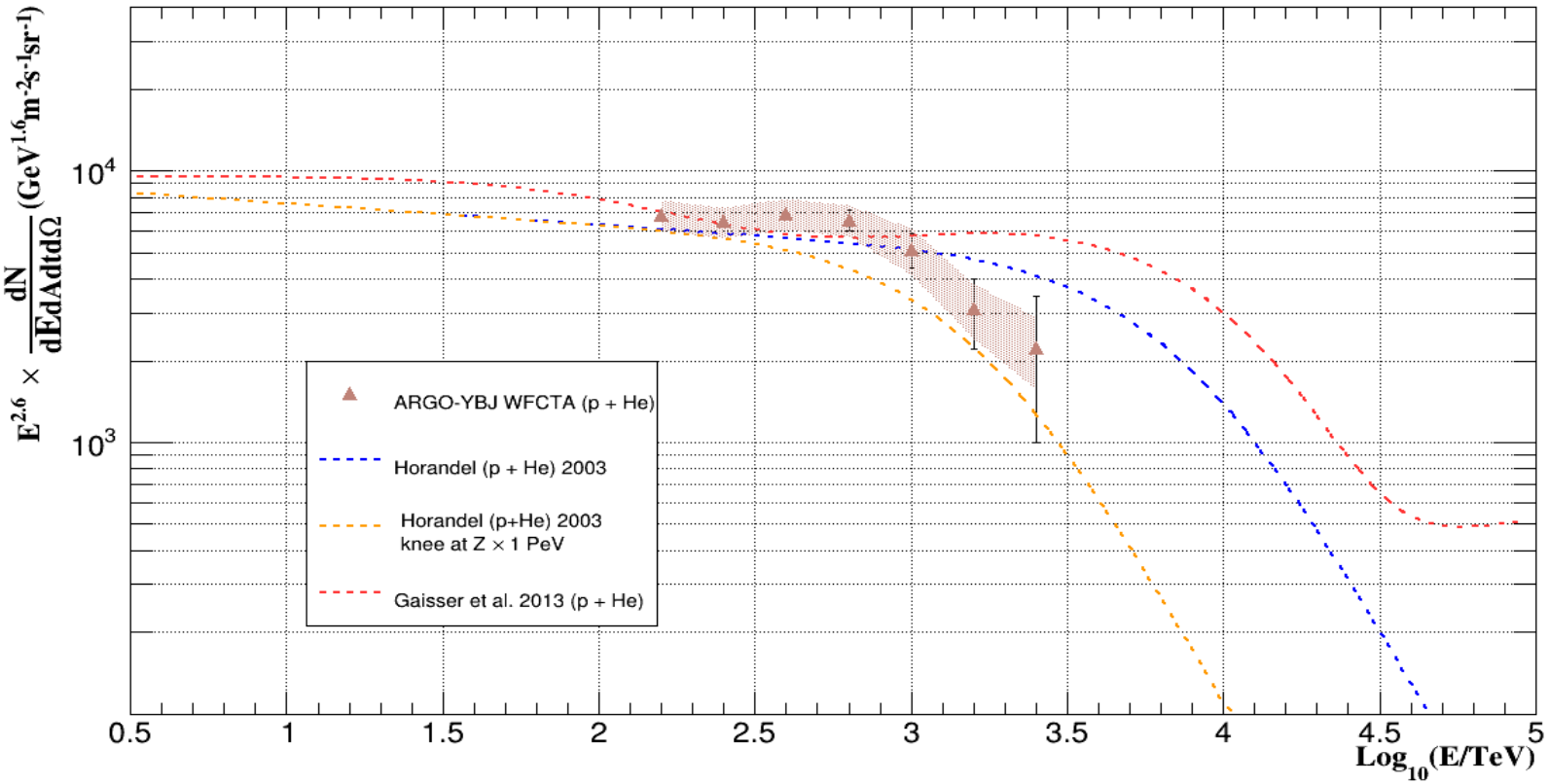
p+He spectrum (2nd): Bayesian analysis of analog data

- The results are consistent with previous analysis
- The approach is fully Bayesian
- Different fiducial cuts, also more inclined events (θ_{zenith}<35°)

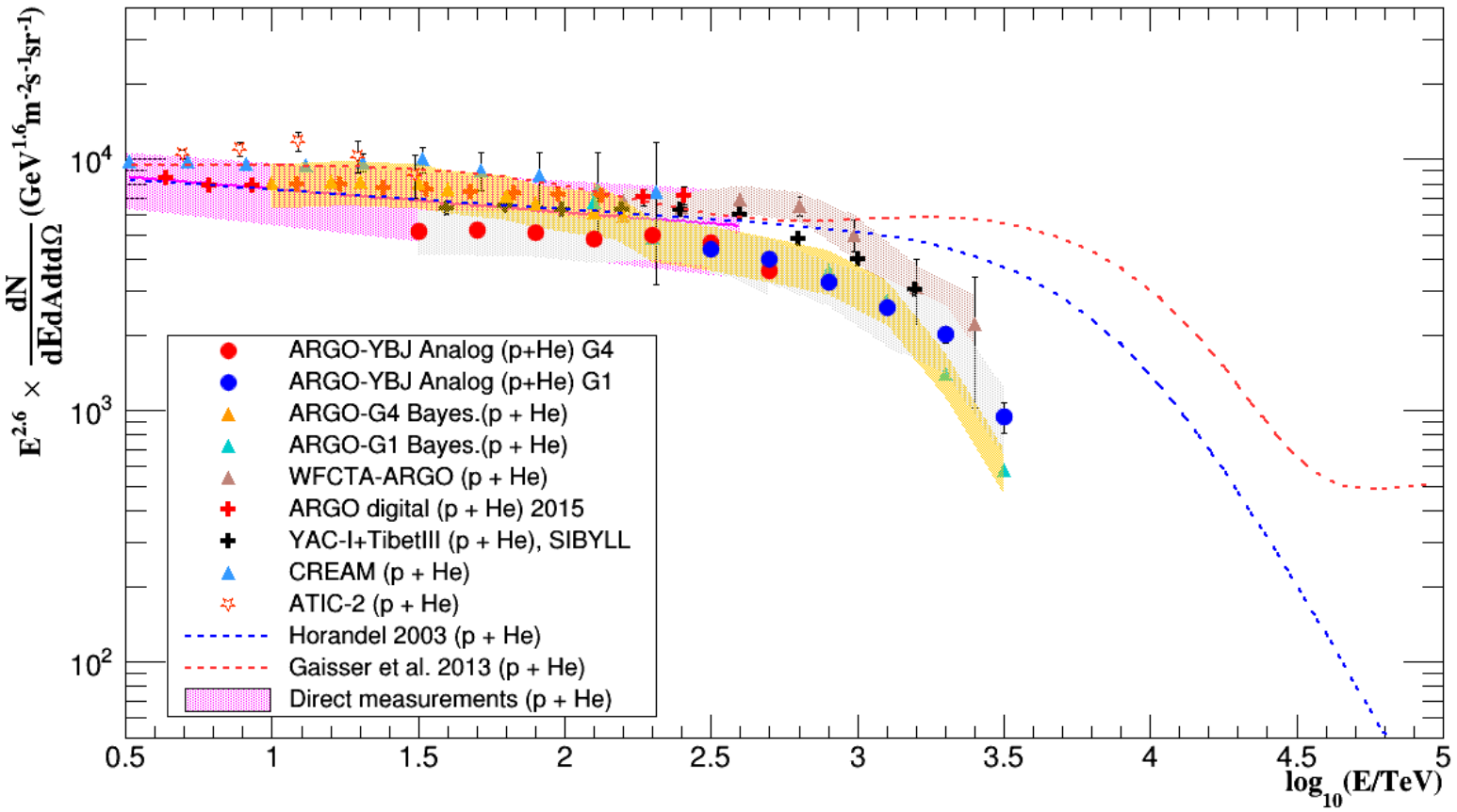


Hybrid measurement (3rd): Cerenkov telescope + ARGO-YBJ array

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



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

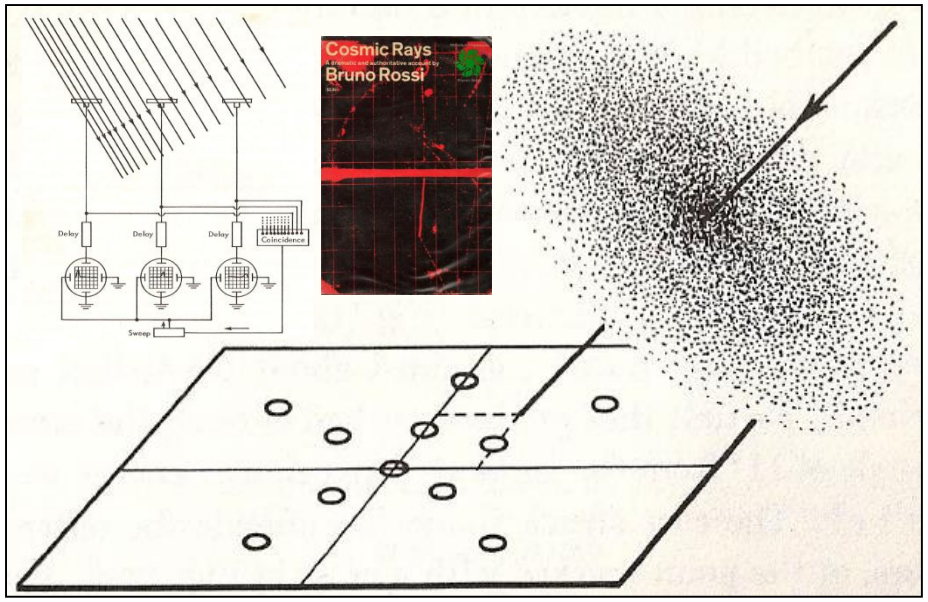


- Different analyses of ARGO-YBJ data give results in agreement within systematics (further cross-checks in progress)
- ARGO-YBJ results consistent with direct (i.e. below 200 TeV) and YAC-Tibet measurements

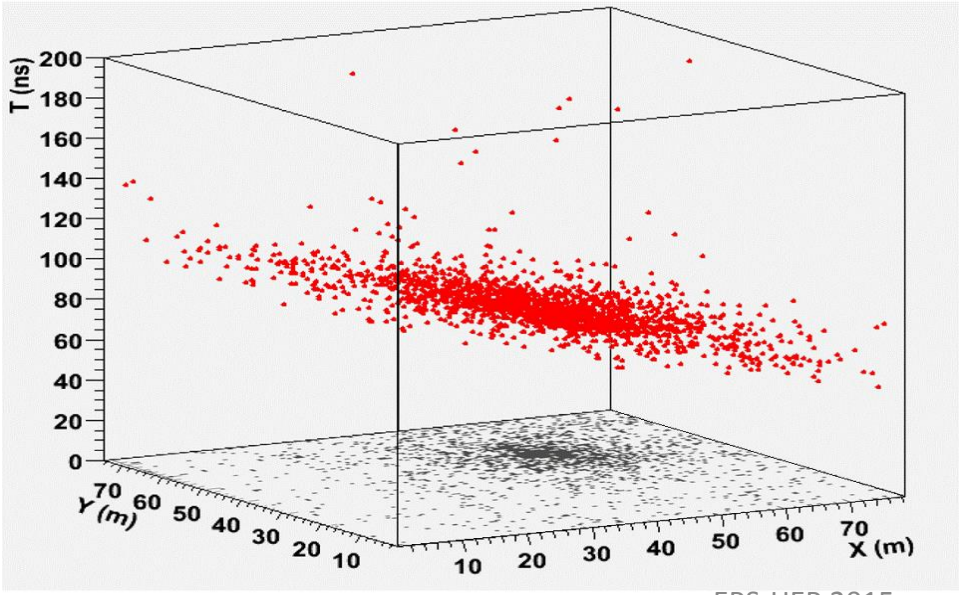
Summary and Outlook

- ARGO-YBJ measured the CR spectrum in the TeV – 20 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 and full data samples for final results
- Possibility to study the details of hadronic interaction features in the very forward kinematic region

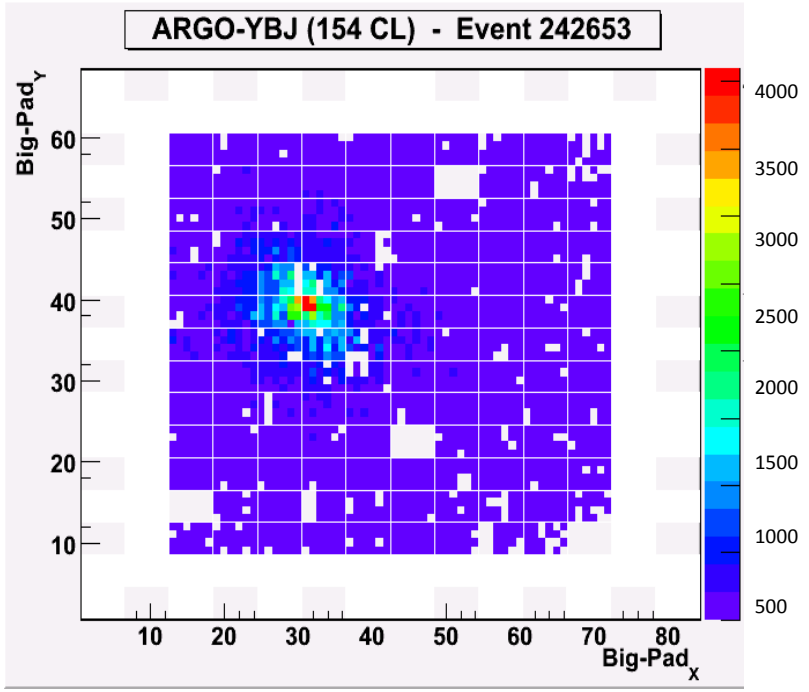
Backup slides



Bruno Rossi conceptual EAS detector



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

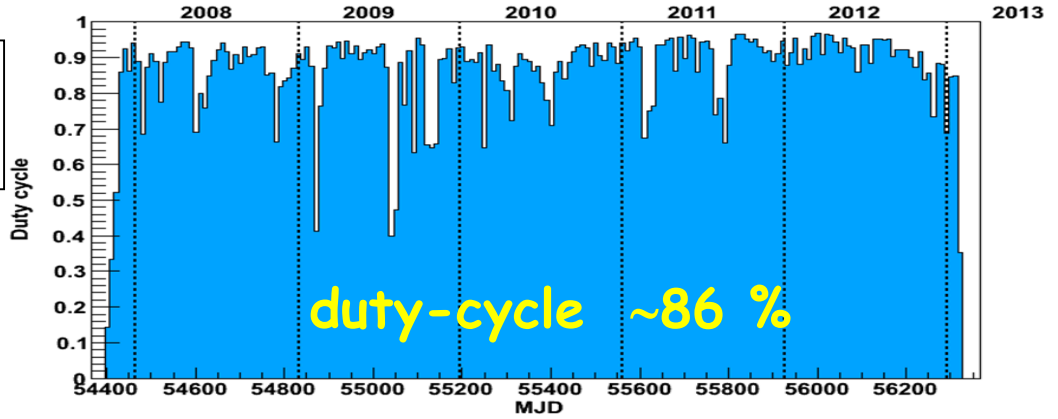


Analog view of a shower

EAS reconstruction by digital readout

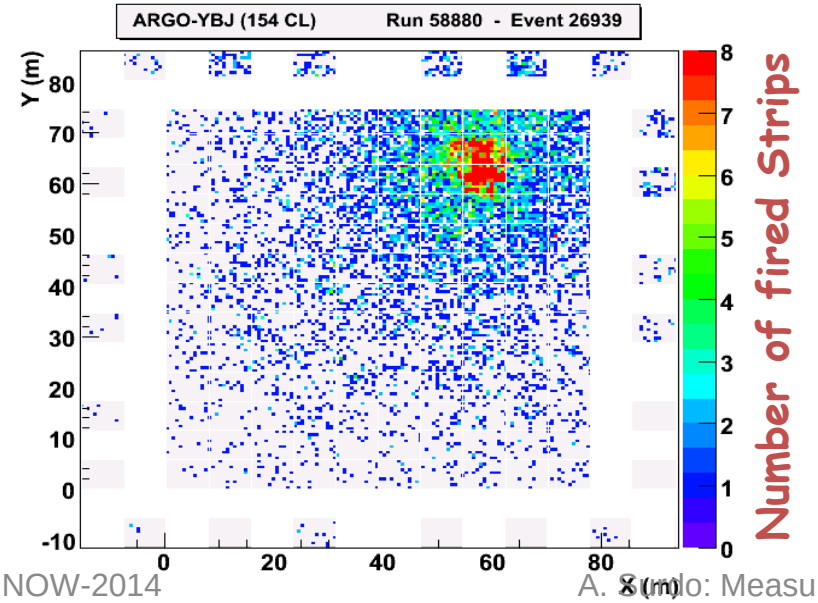
Data taking with full configuration:
November 2007- February 2013

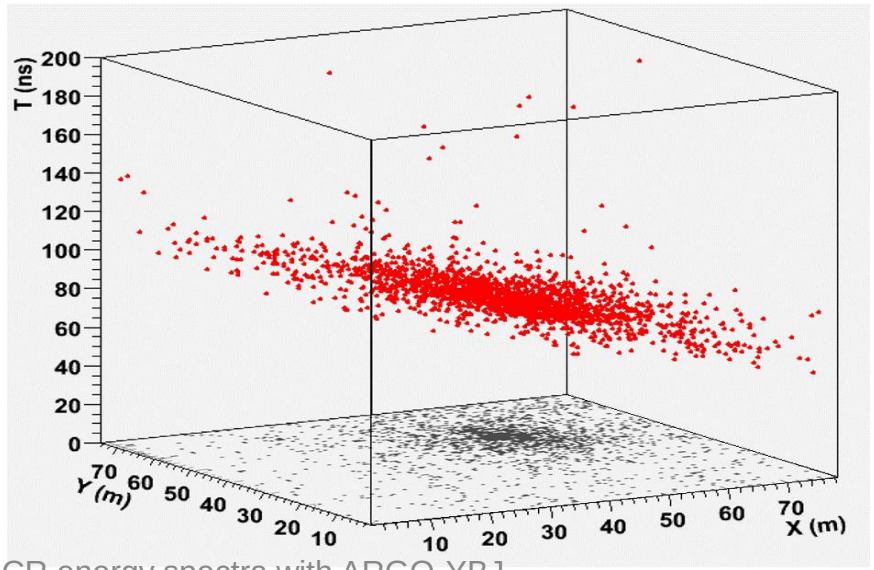
Event Rate ~ 3.5 kHz for $N_{hit} \geq 20$
- Duty cycle ~ 86% - 10^{11} evts/yr



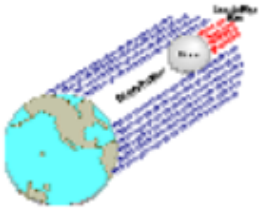
Space/time granularity
+ full coverage
+ high altitude

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

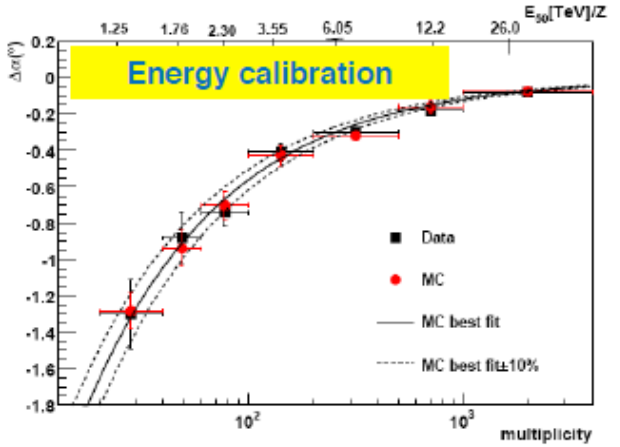


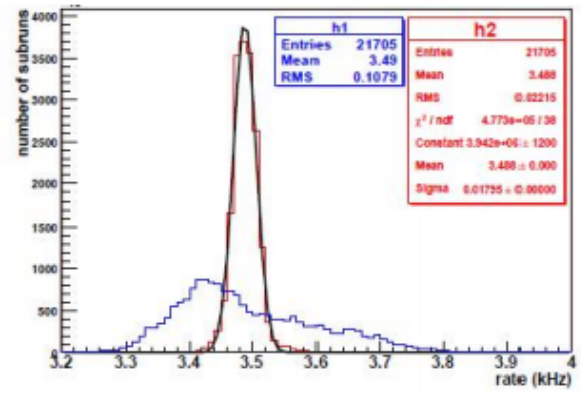


Status and performance

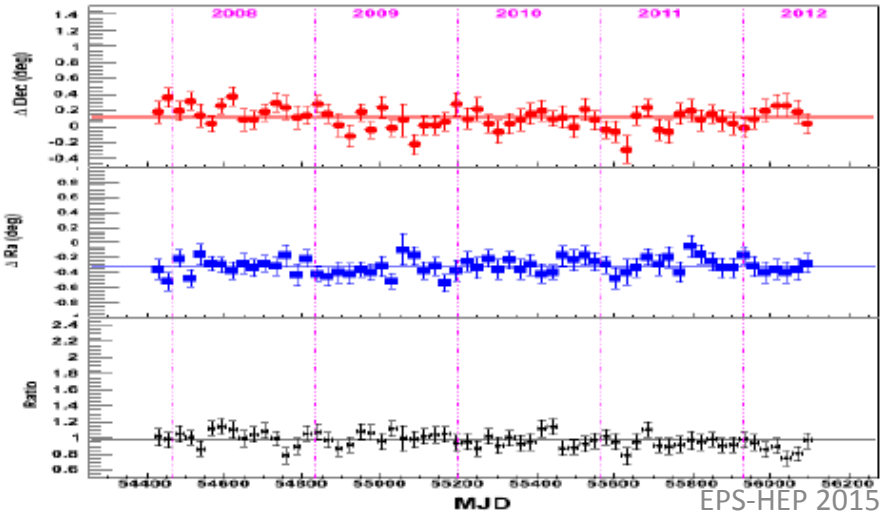


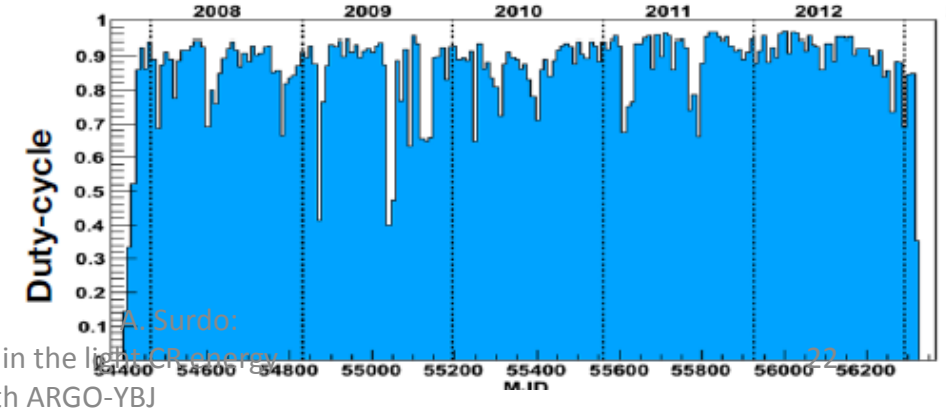
- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: ≈ $5 \cdot 10^{11}$ from 100 GeV to 10 PeV
- 100 TB/year data



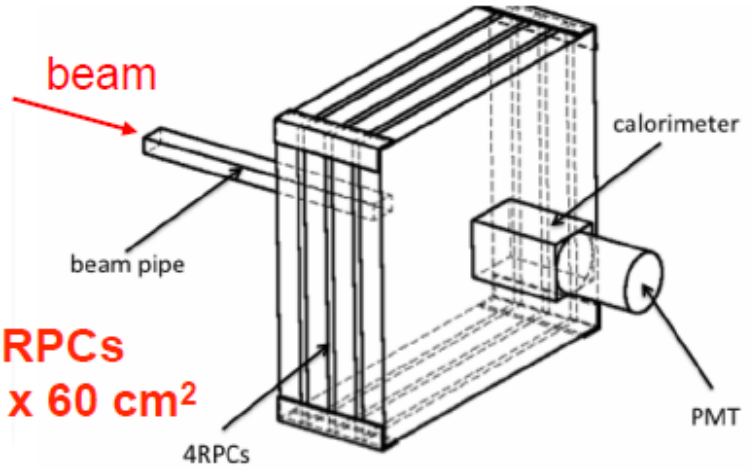


Intrinsic Trigger Rate stability 0.5%
(after corrections for T/p effects)





Intrinsic linearity: test at the BTF facility



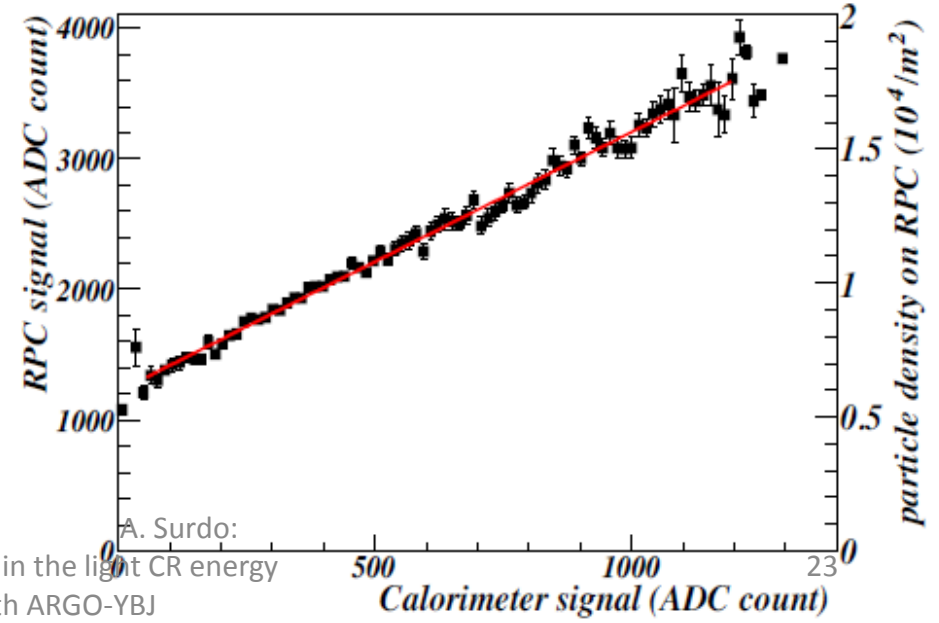
Calorimeter: lead glass block from OPAL,
PMT a Hamamatsu R2238.

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*

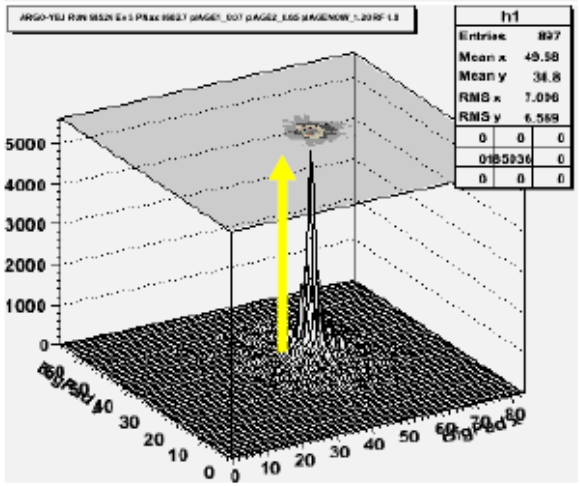
→ Linearity up to ≈ 2 • 10⁴ particle/m²

The RPC signal vs the calorimeter signal



Astroparticle Physics submitted

Absolute comparison Data - MonteCarlo

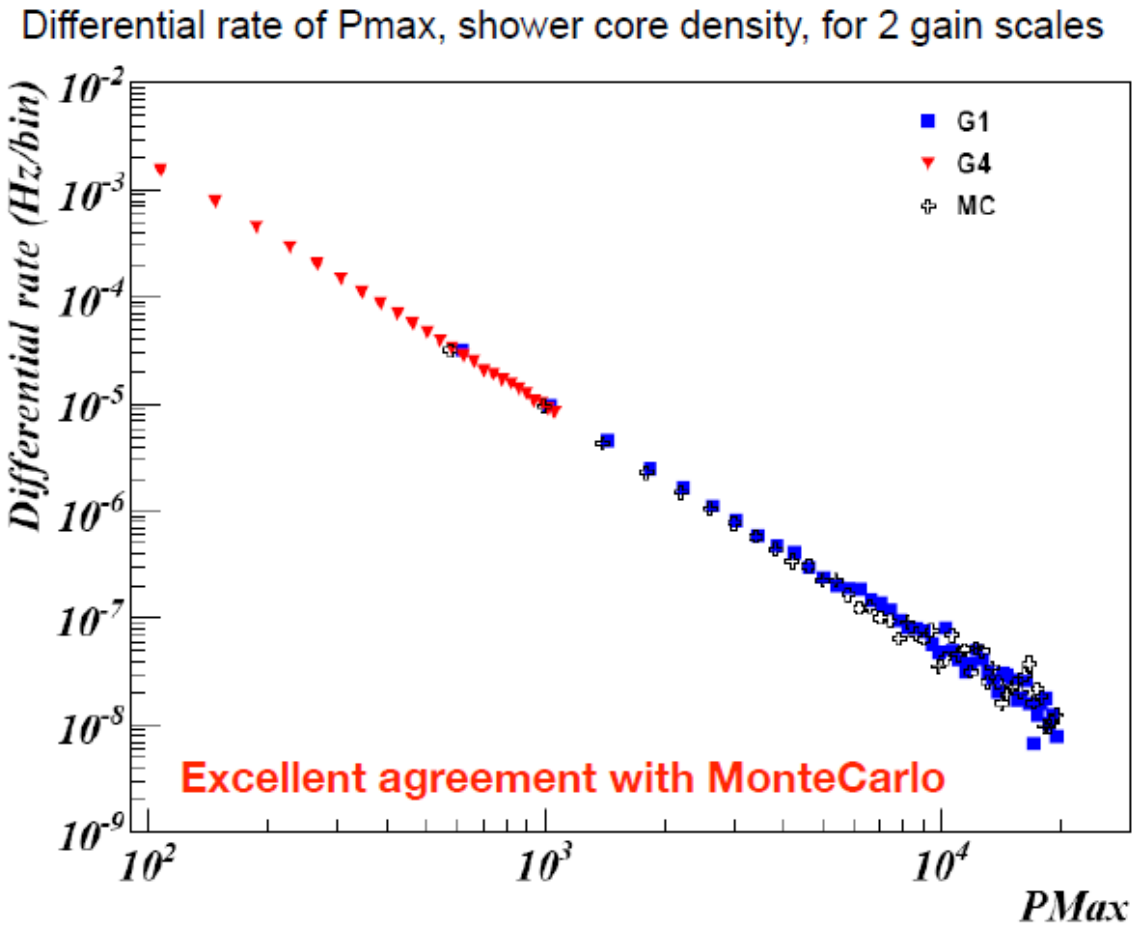


J.R. Horandel , Astrop. Phys. 19 (2003) 193

Event selection:

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

★ Zenith angle < 15°



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

The analog readout system

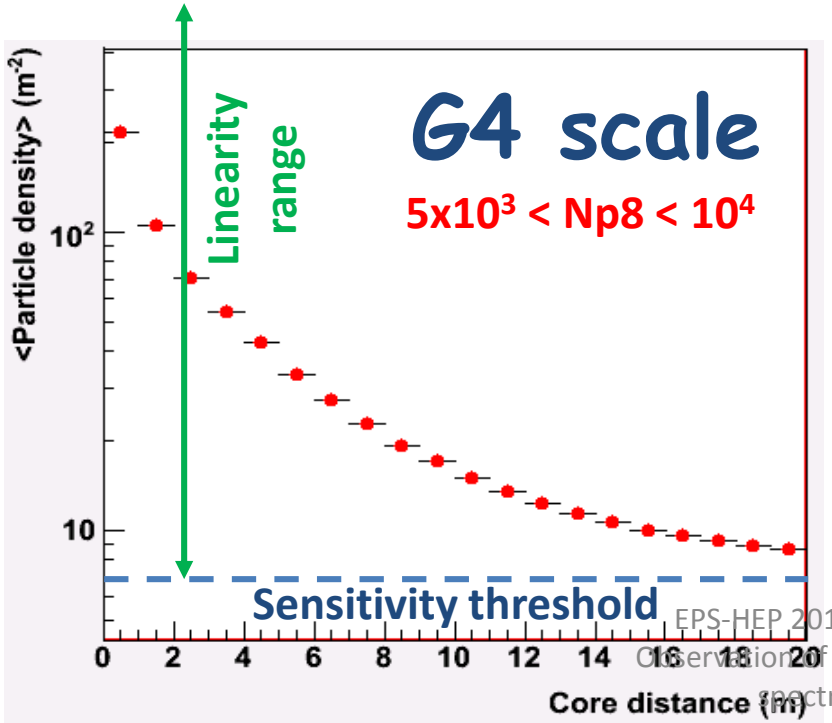
Eight gain scales (G0, G1, … G7) ensure good linearity up to about 2 x 10^4 particles/m^2

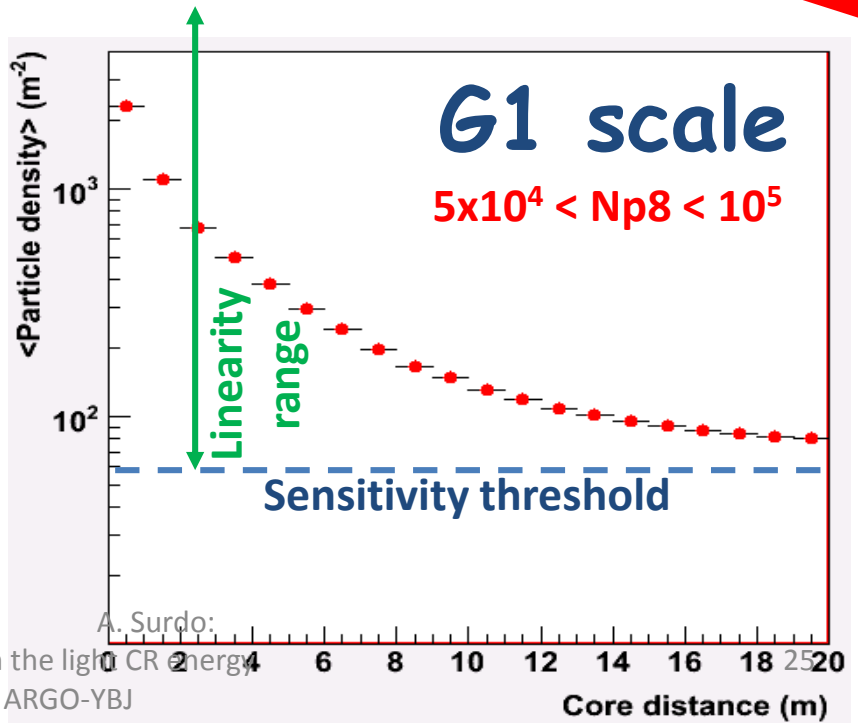
G7 data overlap the digital-mode linearity range, and have been used for intercalibration and cross checks

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)



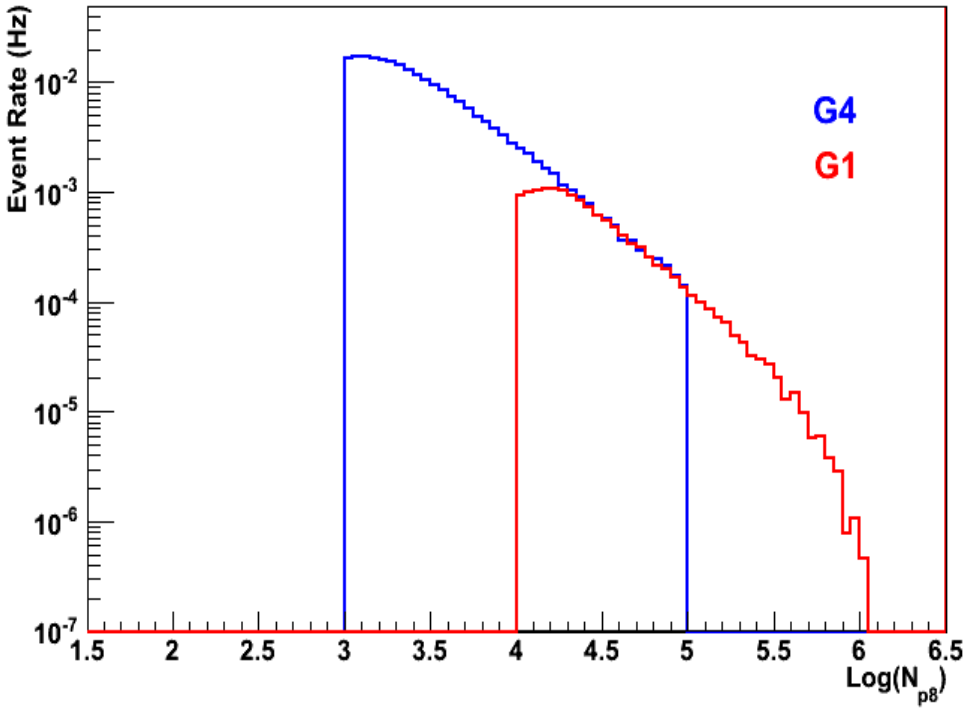


Truncated particle size

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 and G1 scales

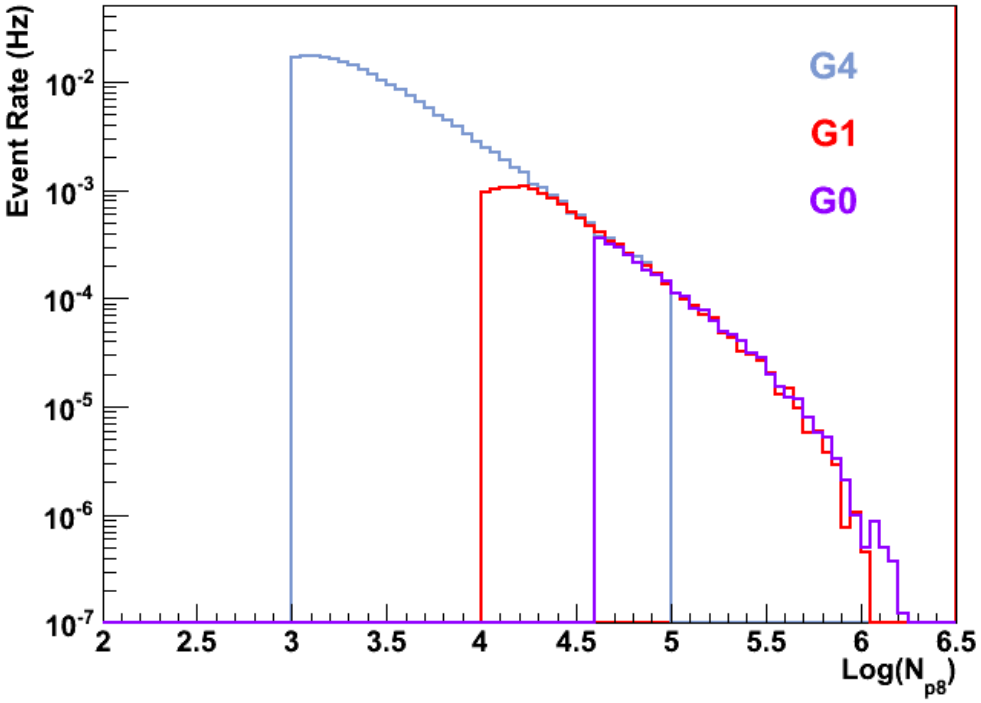


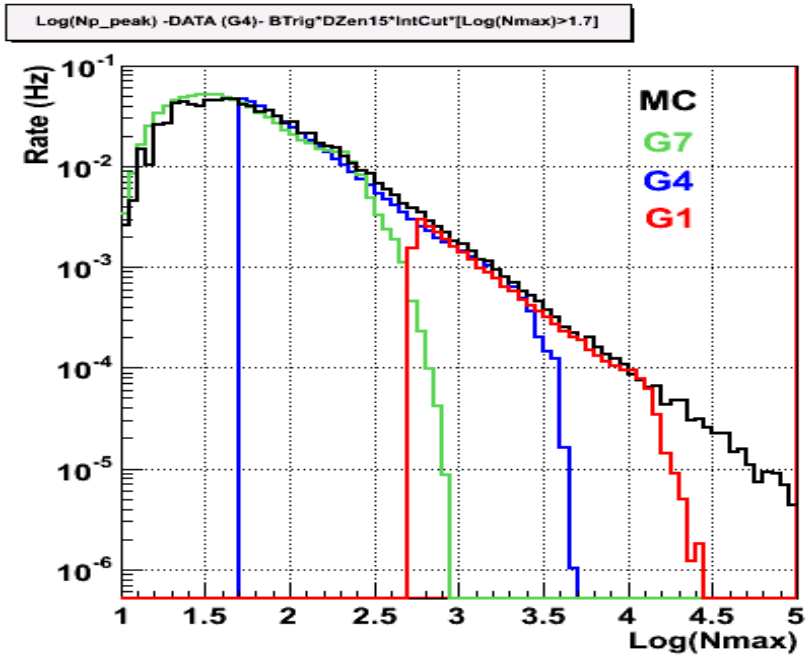
Truncated particle size

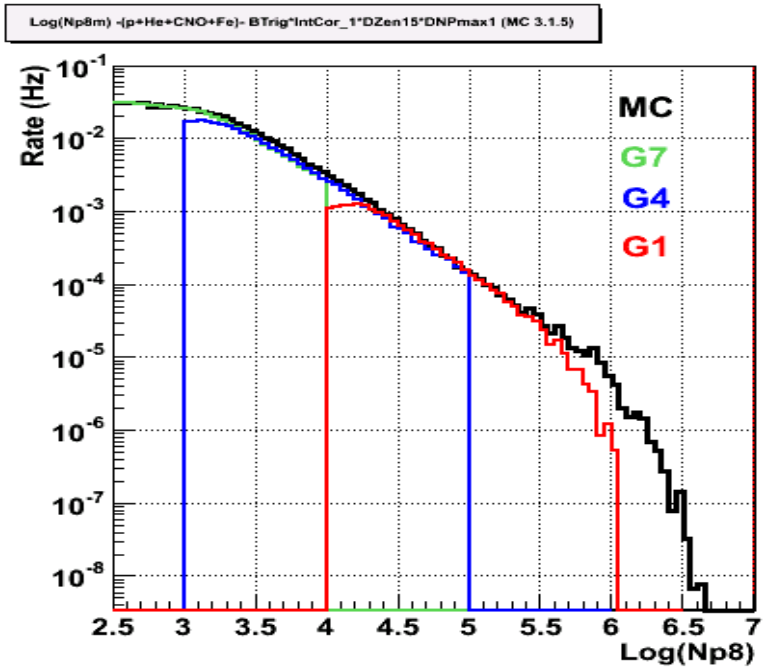
Np_8 :particle size truncated at 8m of core distance

Not affected by possible saturation of Analog System

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




Log(Np_peak) -DATA (G4)- BTrig*DZen15*IntCut*[Log(Nmax)>1.7]
Rate (Hz)
Log(Nmax)
MC
G7
G4
G1


Log(Np8m) -(p+He+CNO+Fe)- BTrig*IntCor_1*DZen15*DNPmax1 (MC 3.1.5)
Rate (Hz)
Log(Np8)
MC
G7
G4
G1

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°**

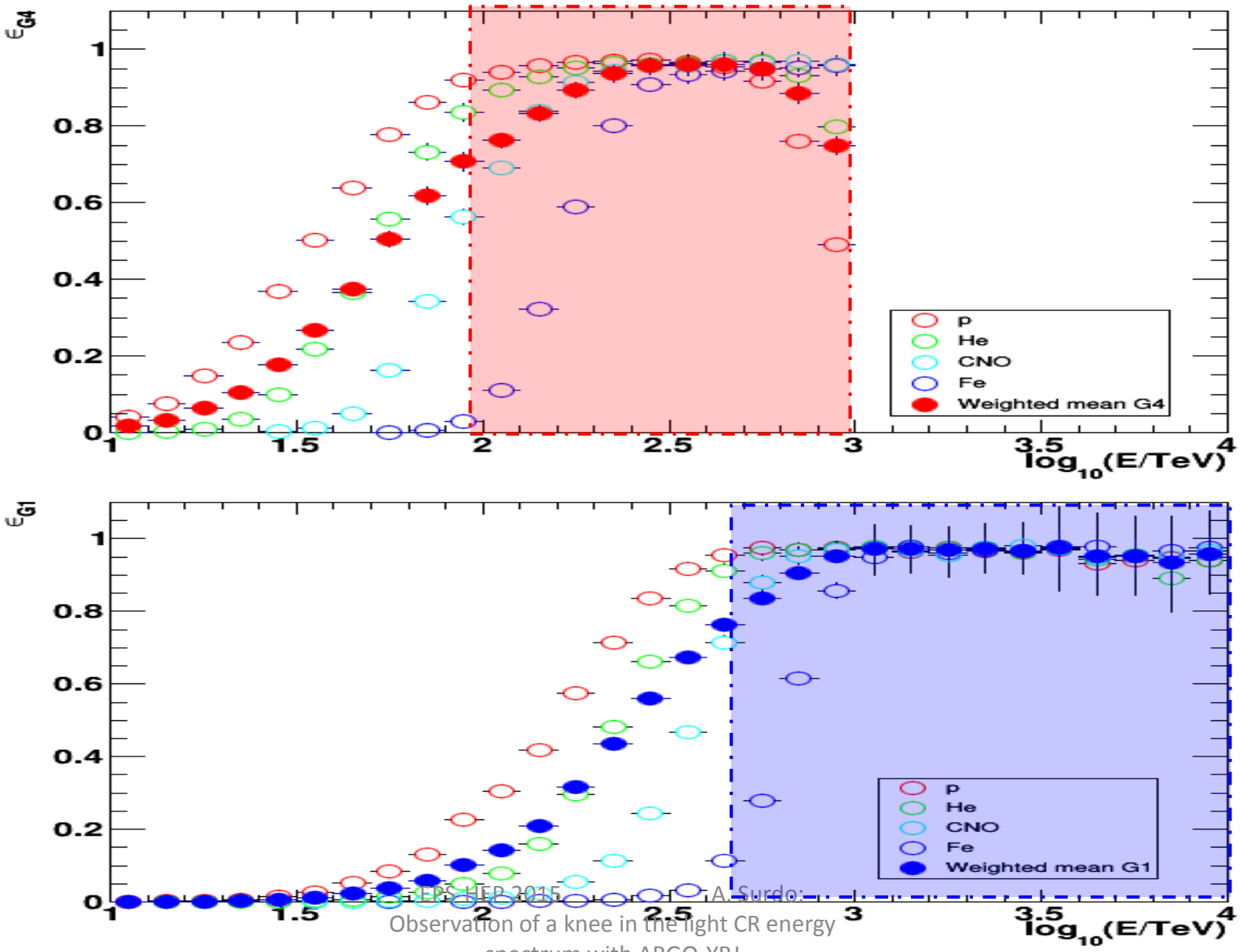
  produced using *a different hadronic model: SIBYLL-2.1 (+ Fluka*)

- **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.**

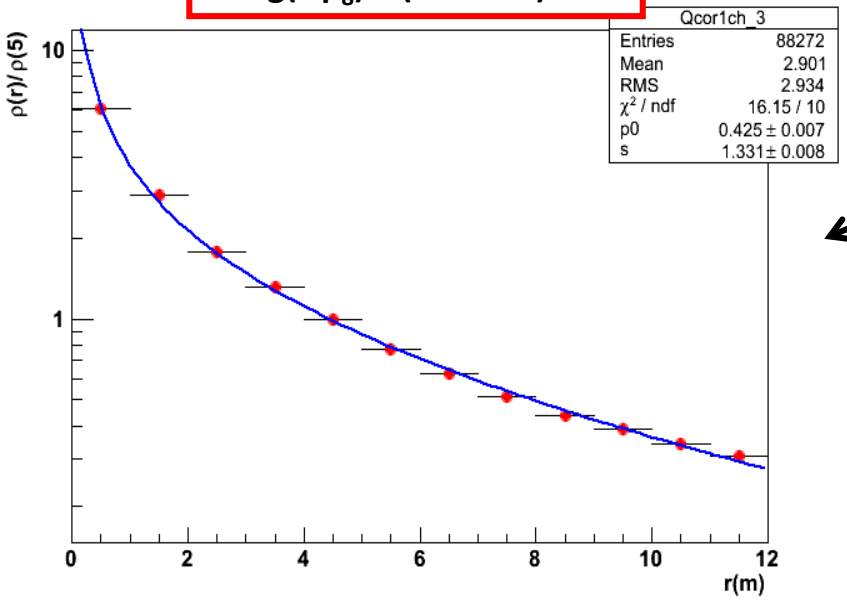
- **Event selection: core inside a fiducial area A_{fid} = (64 x 64) m^2 (θ_{zen} < 15° used in this analysis)**

Trigger and event selection efficiencies for the all particle spectrum

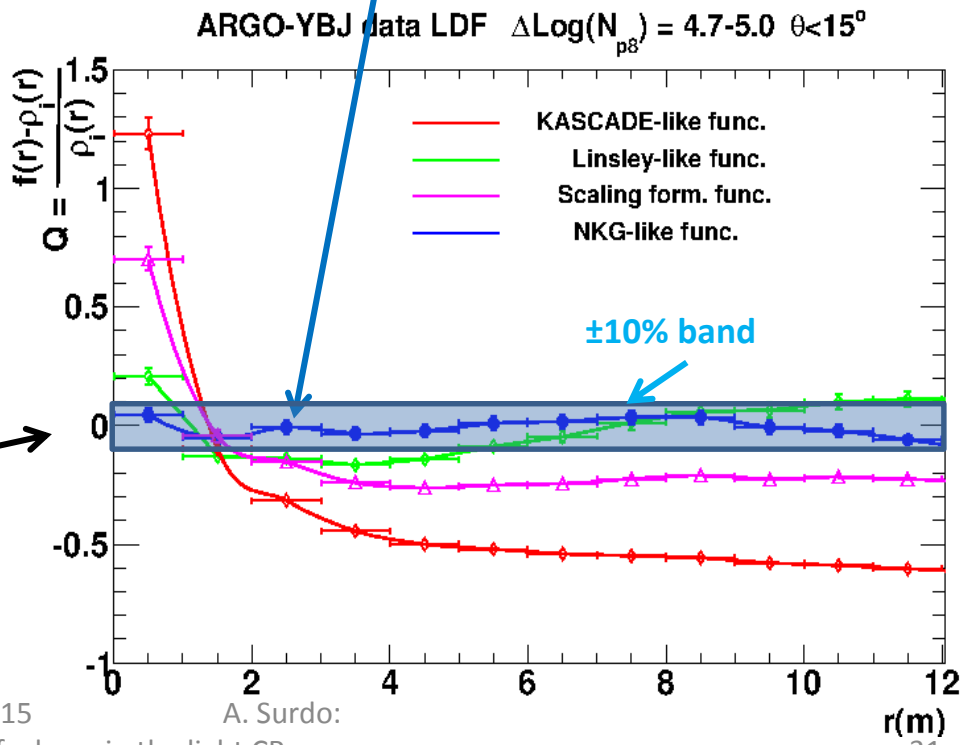


ARGO-YBJ data: LDF fits

ΔLog(Np_8) = (4.7 - 5.0)



Fit with ρ'_{NKG}

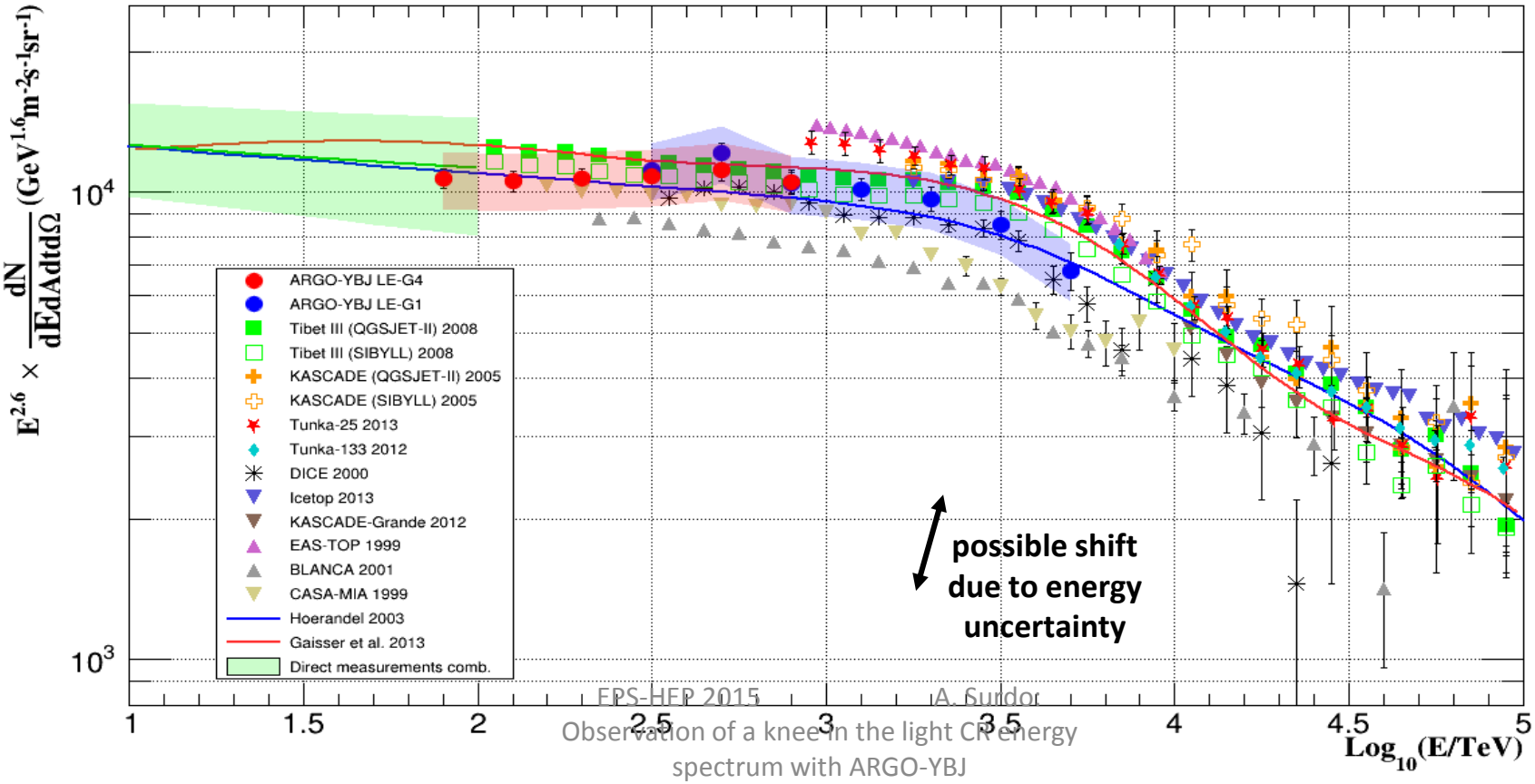


Comparison of residuals from different function fits:

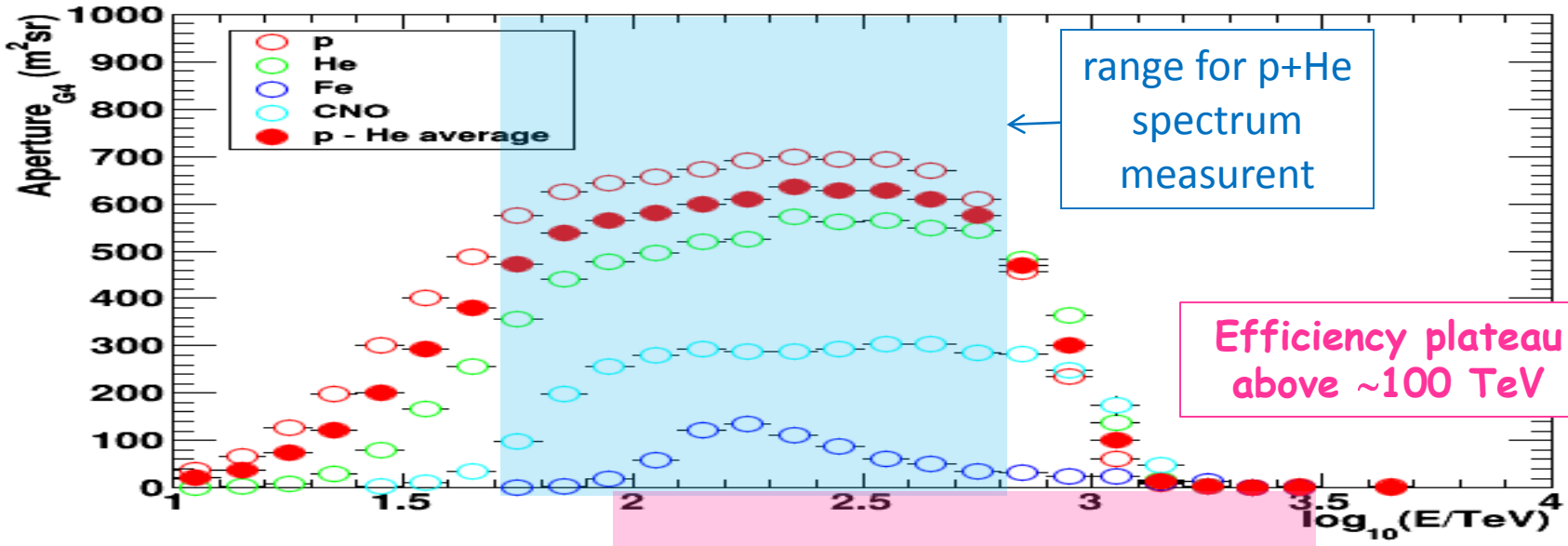
The all-particle spectrum (II)

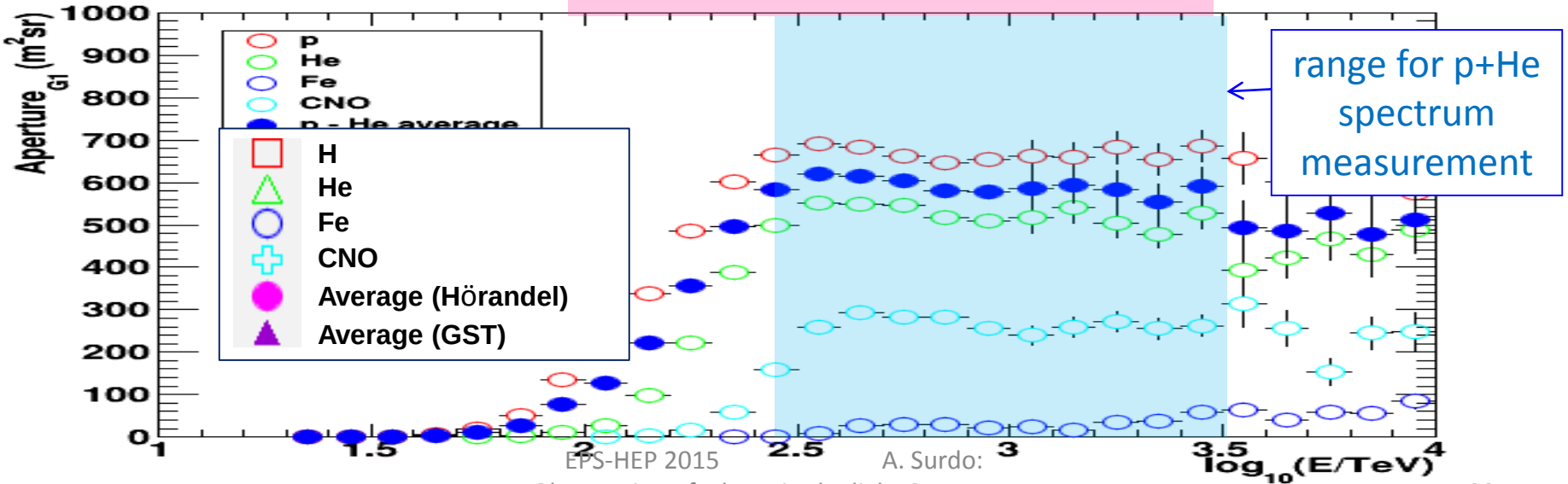
- Picture consistent with models and previous measurements
- Nice overlap with the two gain scales (and different data)
- The plot suggests spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV

- 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



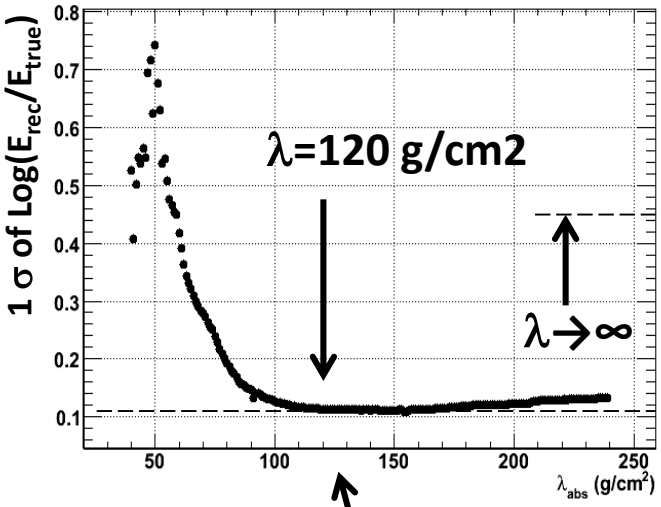
Aperture for p+He event selection





Finding the best λ_{abs} parameter

LogE resolution at 270 TeV vs λ_{abs}

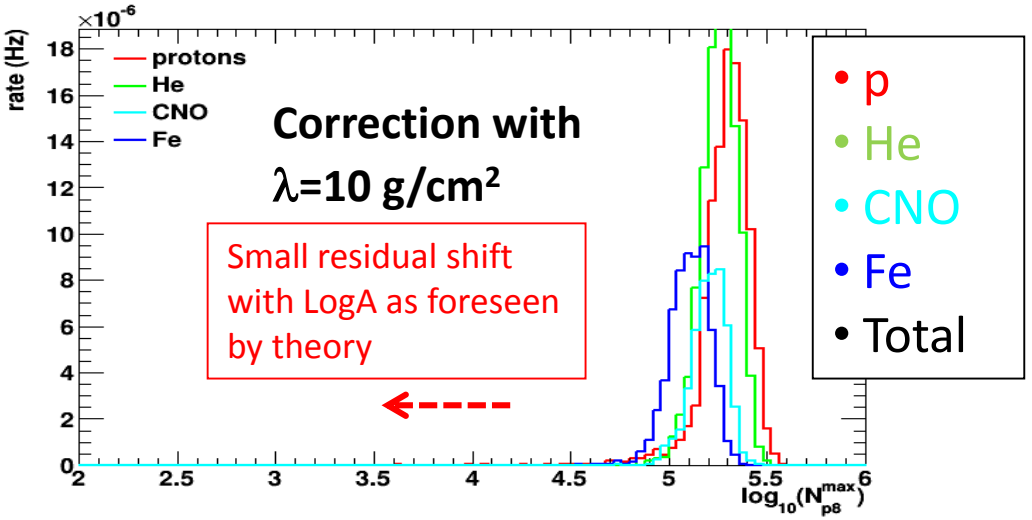


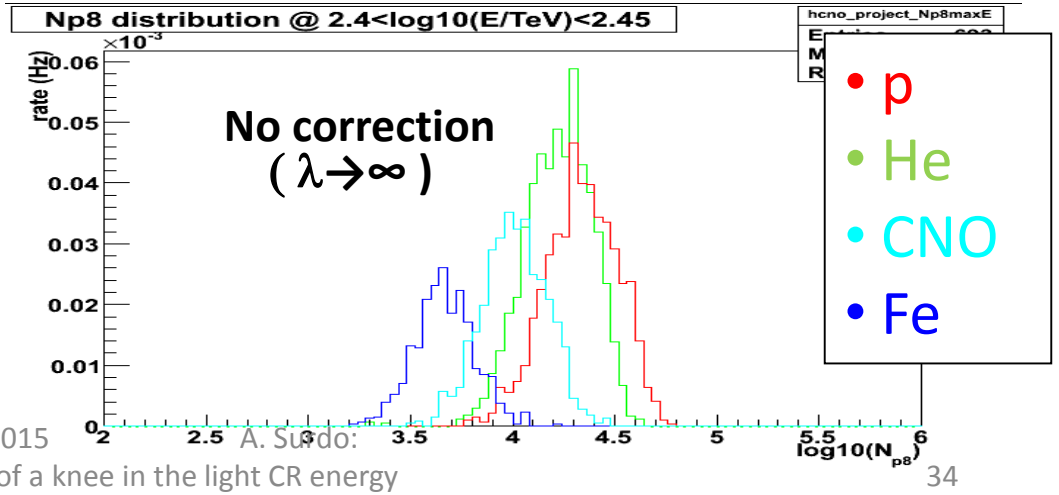
Results from the ARGO-YBJ test experiment

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].

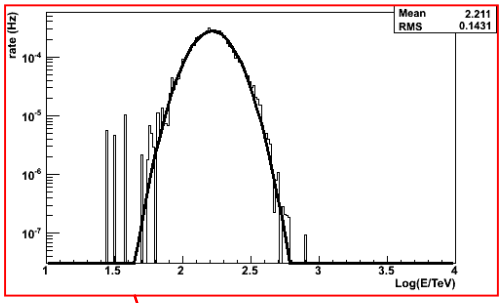
The parameter α is found to be 4.88 ± 0.45, so that $\Lambda_{att} = (124 \pm 11)$ g/cm^2, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 ± 0.37.

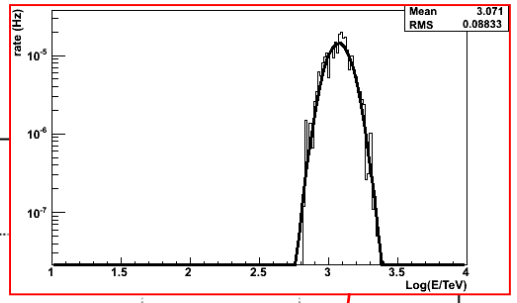


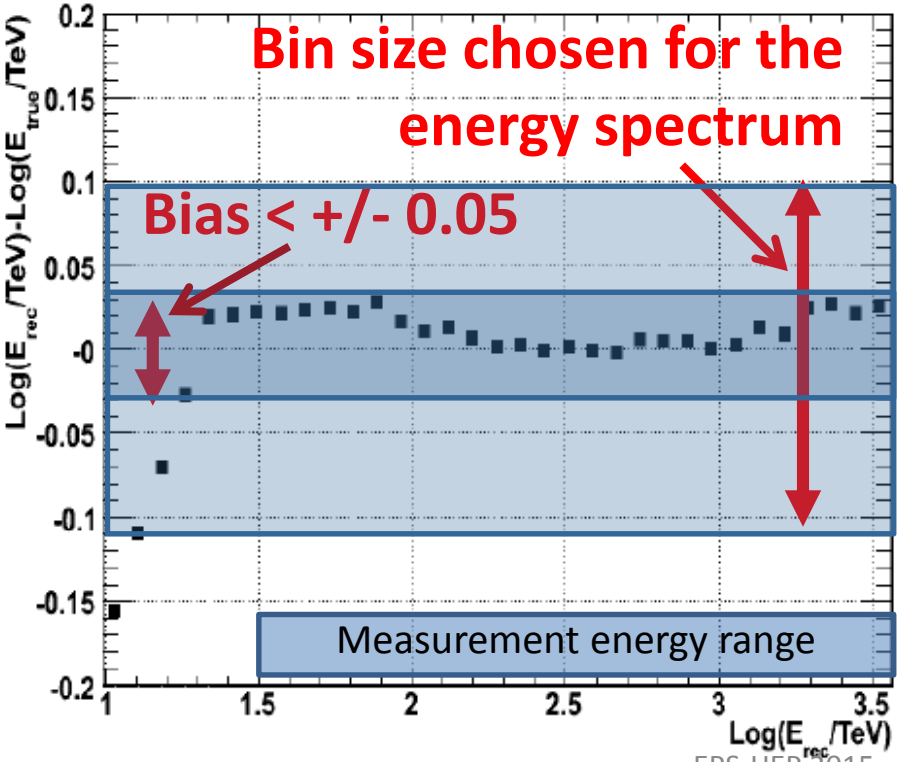


Energy reconstruction: bias and resolution

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.





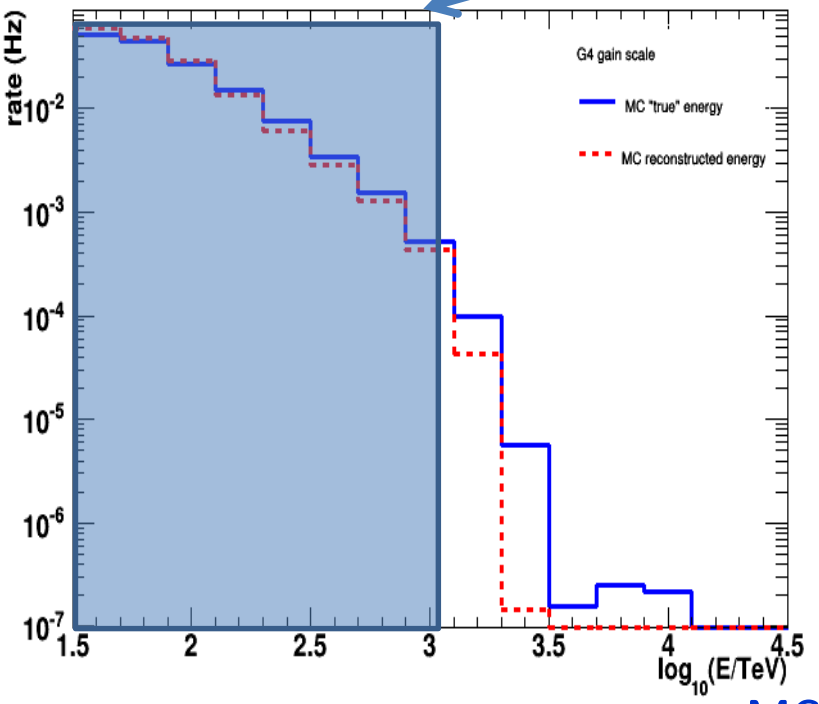


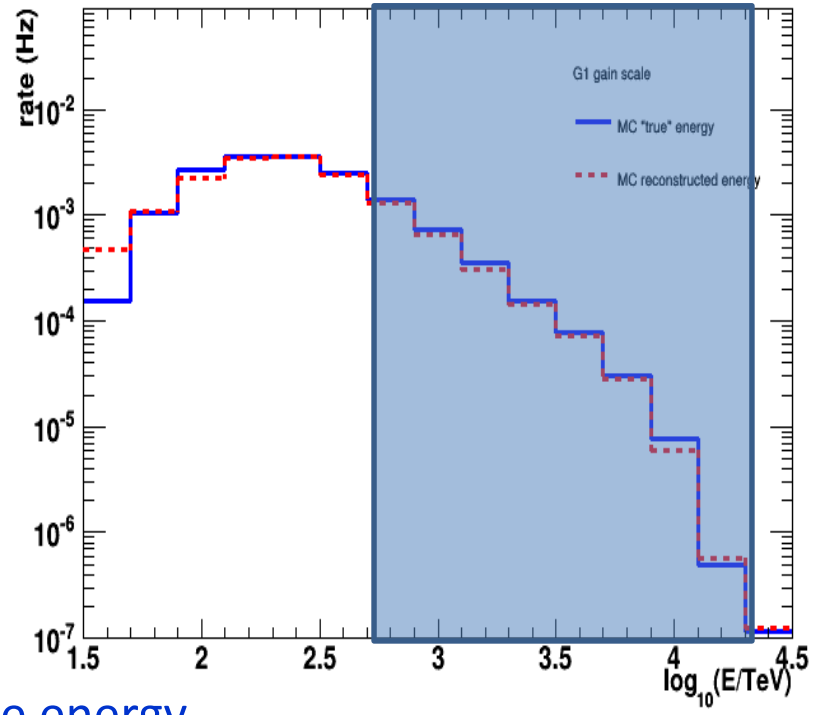
MC Energy distributions

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 %

⇒ Shaded area In the flux plots

Error bars show the statistical uncertainties

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

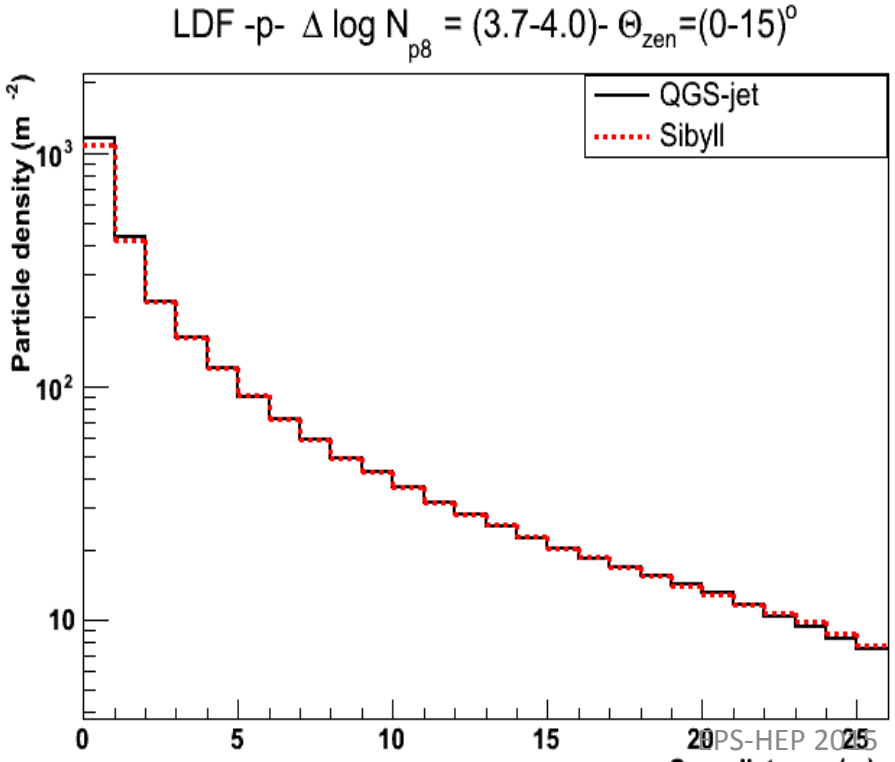
- Gain of the analog system: 3.7 %
- Energy calibration: 0.03 in LogE = 6.9 %
- Hadronic interaction model: 5 %
- **TOTAL: 9.3 %** **TOTAL (conservative) = 10%**

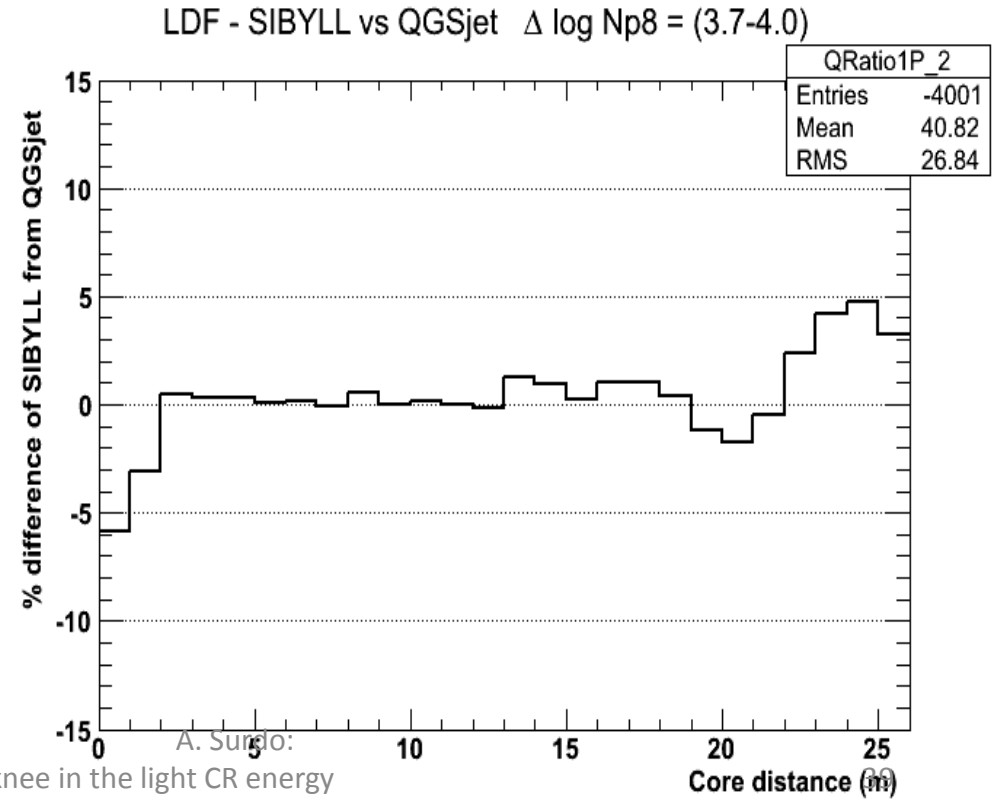
In the flux plots an over-conservative ± 14% shaded area has been temporarily drawn on the flux measurements

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.





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

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

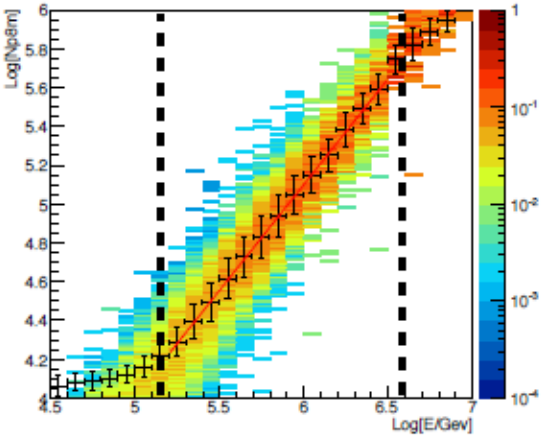
Exp. Data

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

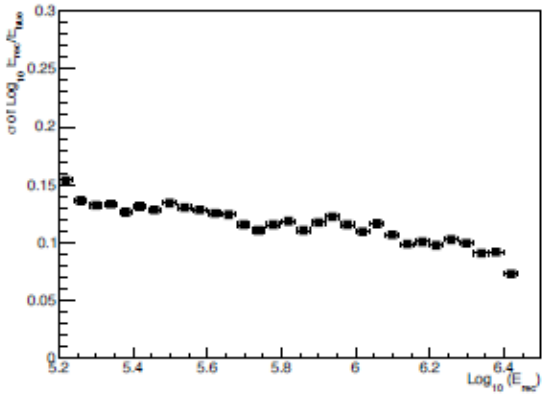


Selection of the light component: shower topology

Light Component (p+He) selection:

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

A20 = 20 innermost clusters
A42 = 42 outermost clusters

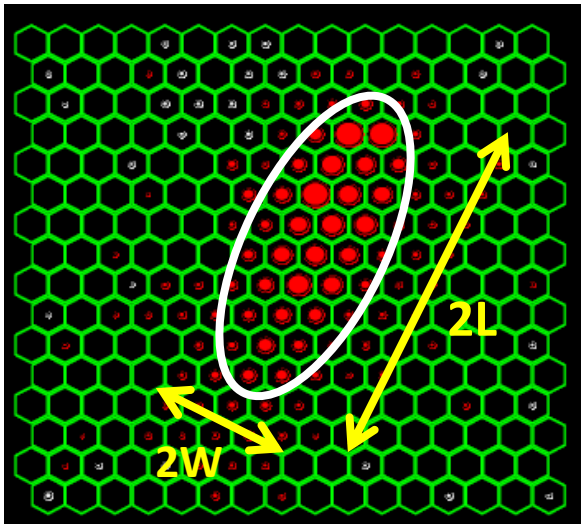


p+He hybrid measurement (3rd): Cerenkov telescope + ARGO-YBJ array

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 (2014) 045001
Hybrid analysis for lower energy showers

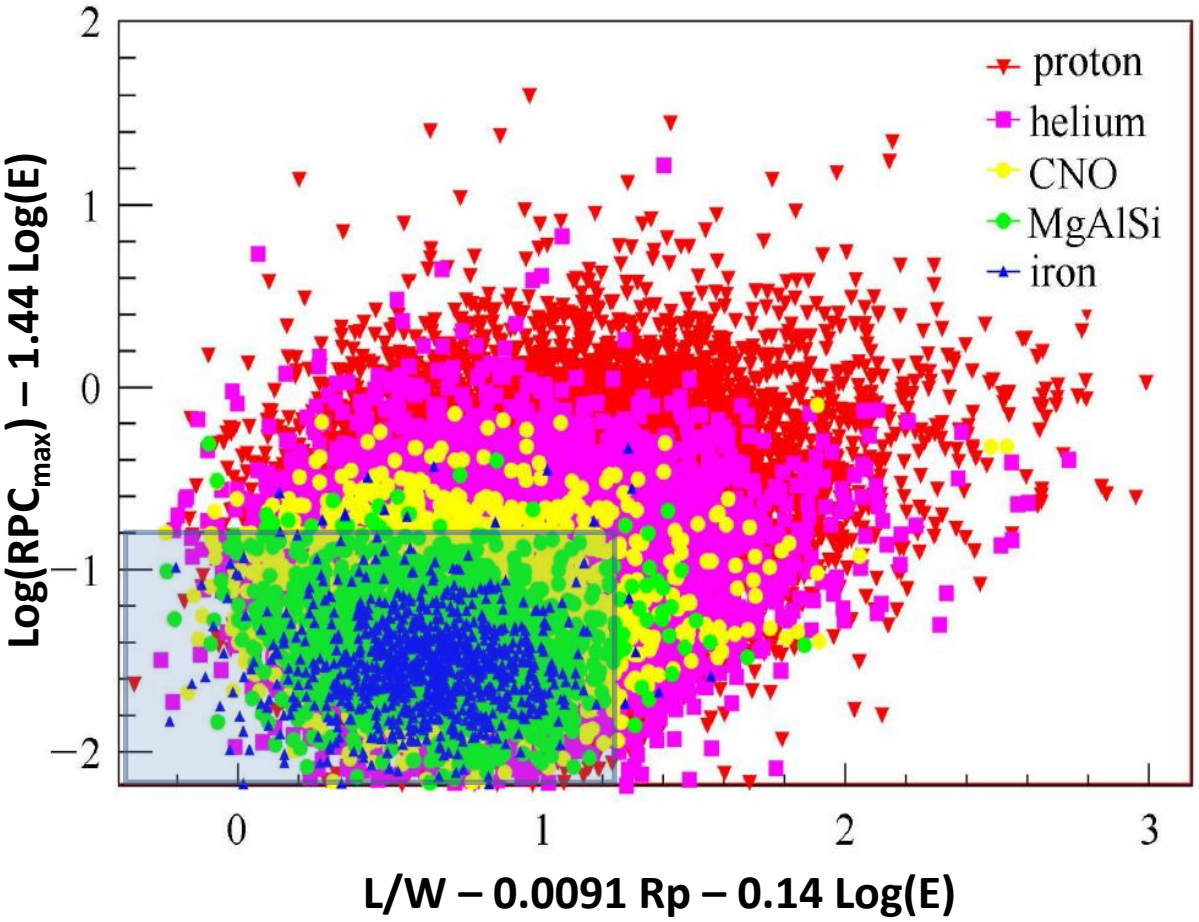


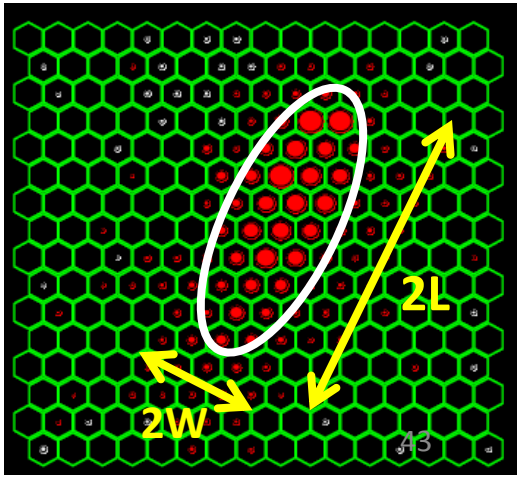
Cerenkov signal: energy measurement
Hillas parameters

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)

Mass selection for the hybrid measurement

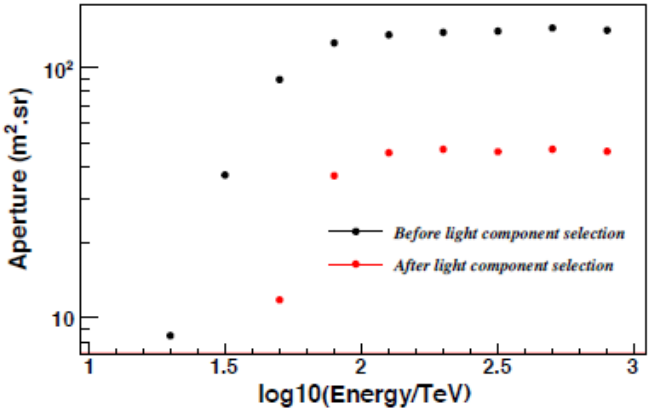


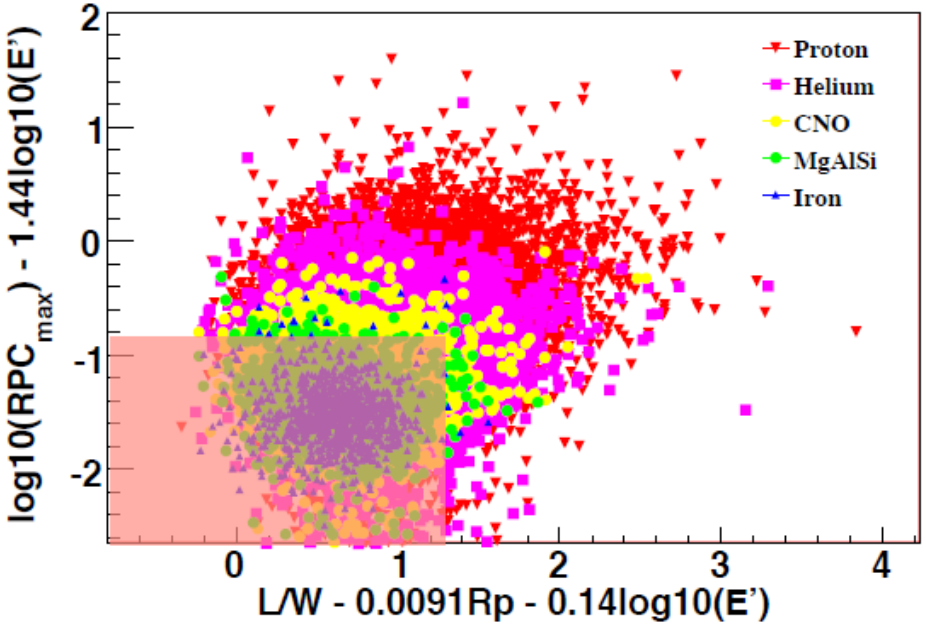


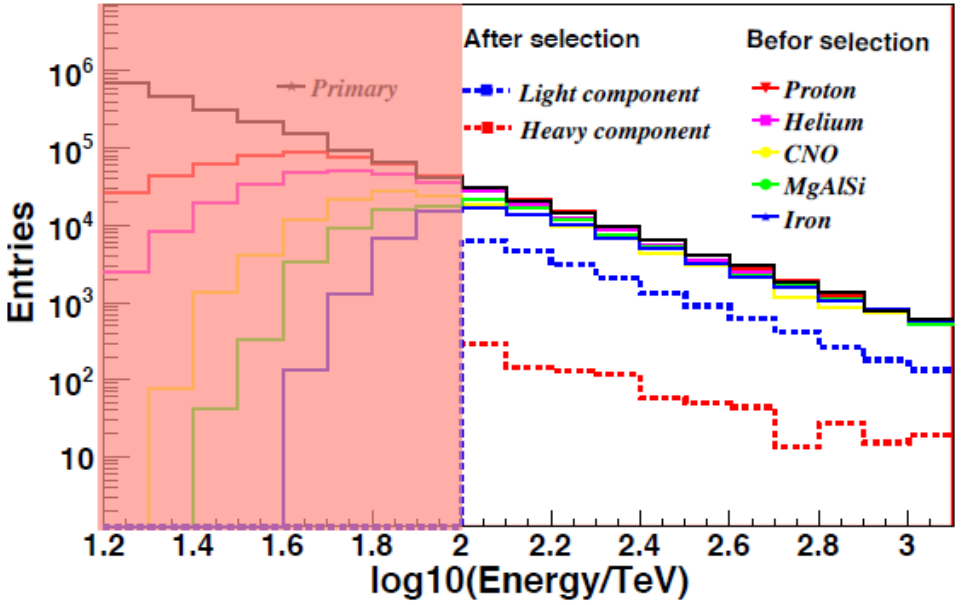
Rp – shower impact parameter
E – reconstructed energy
RPC_{max} – maximum RPC signal

- 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%	

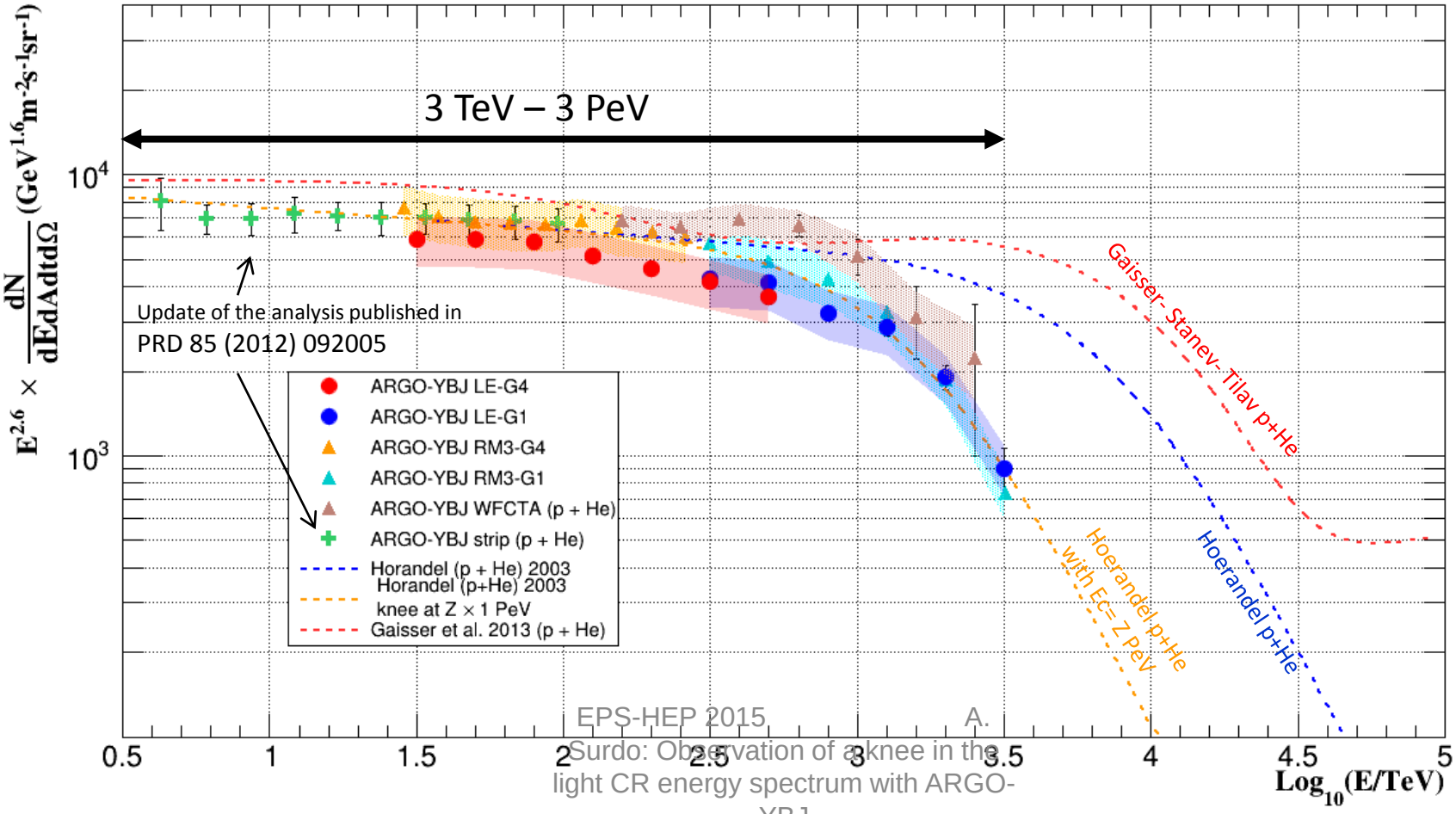






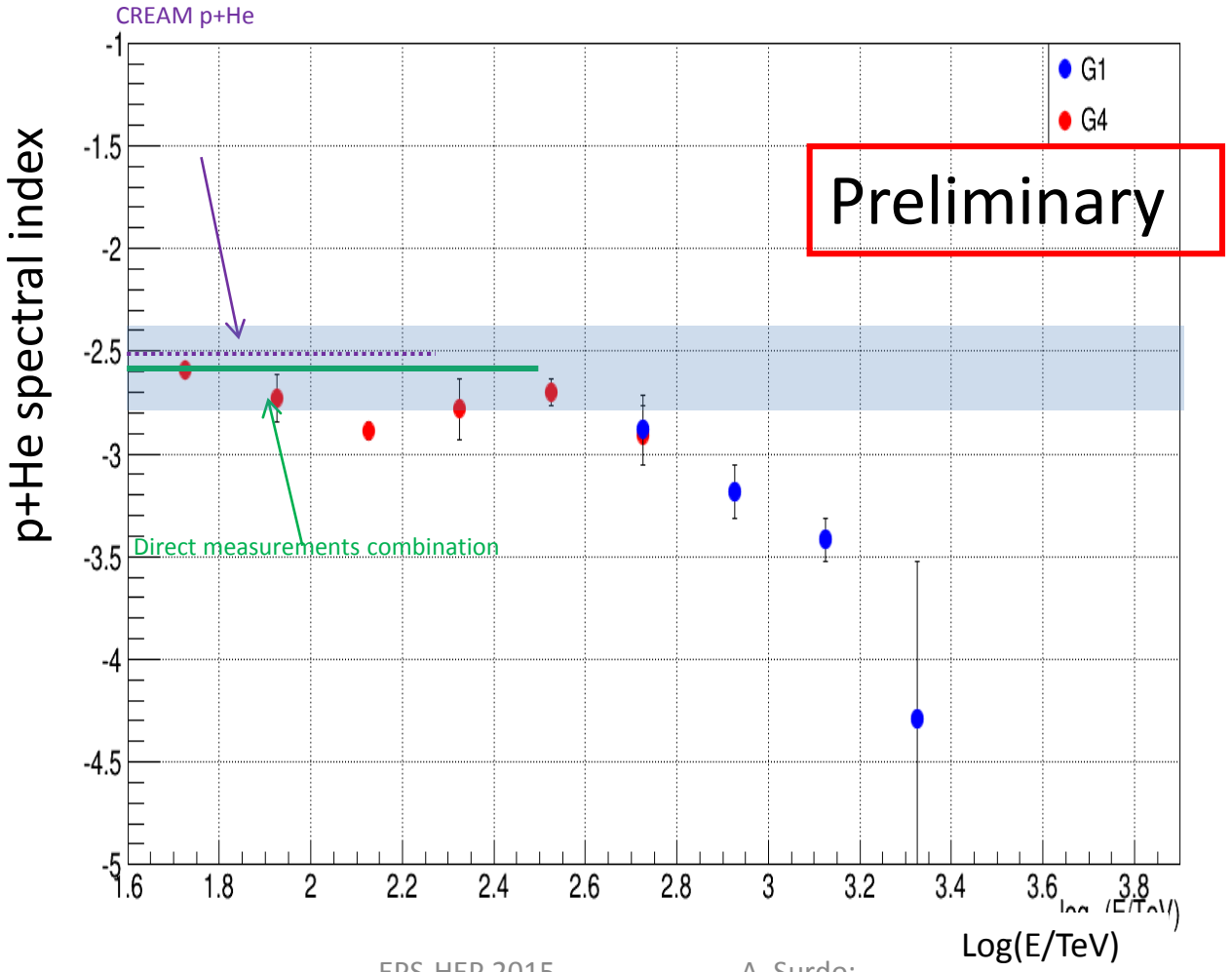
The ARGO-YBJ measurements of the p+He spectrum

Results also consistent with measurement at lower energies, done with the strip data. Consistent picture within systematics. Further cross-checking still ongoing.



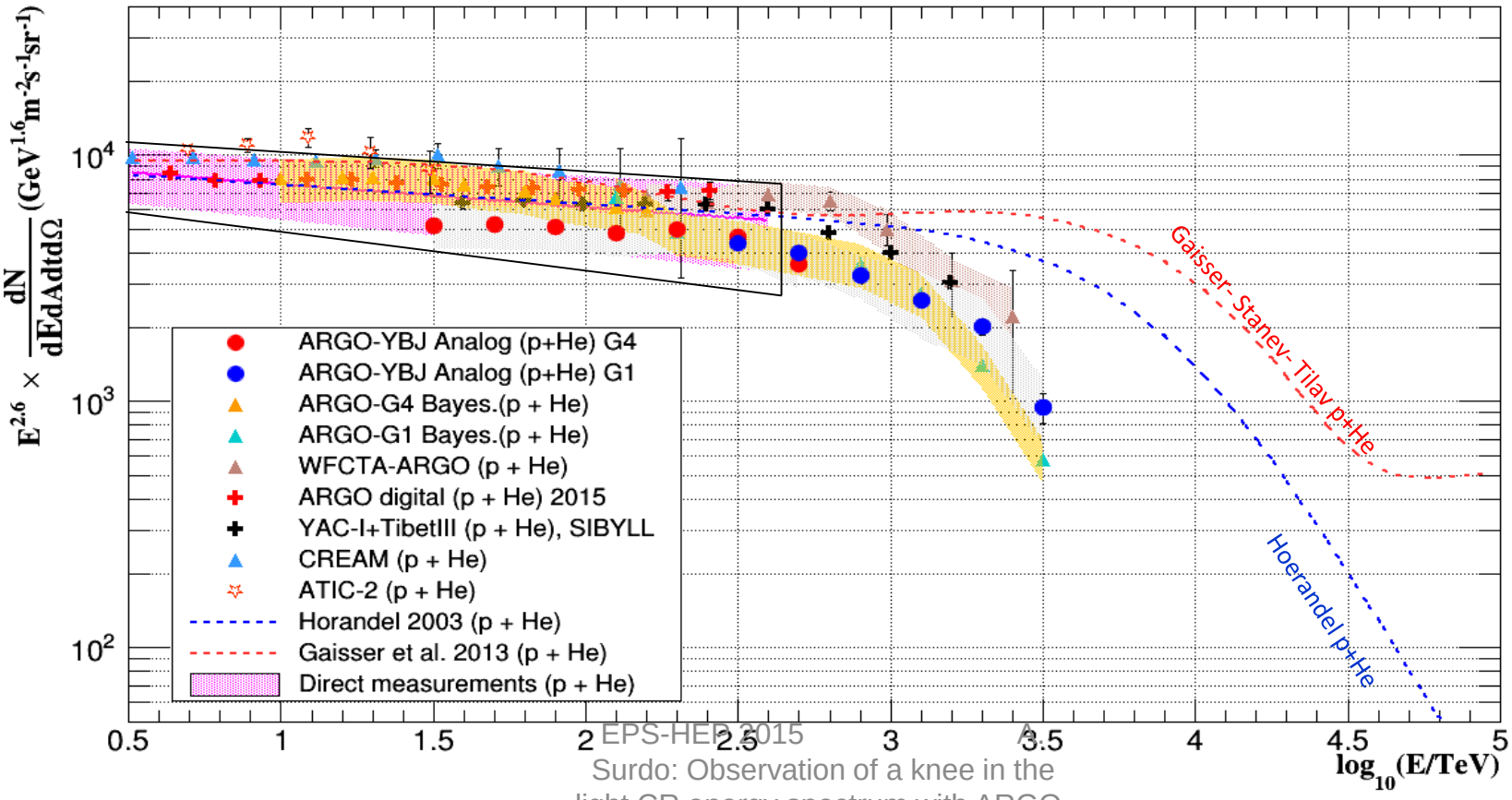
The p+He spectrum index

Preliminary ARGO-YBJ analog data (G4 and G1)

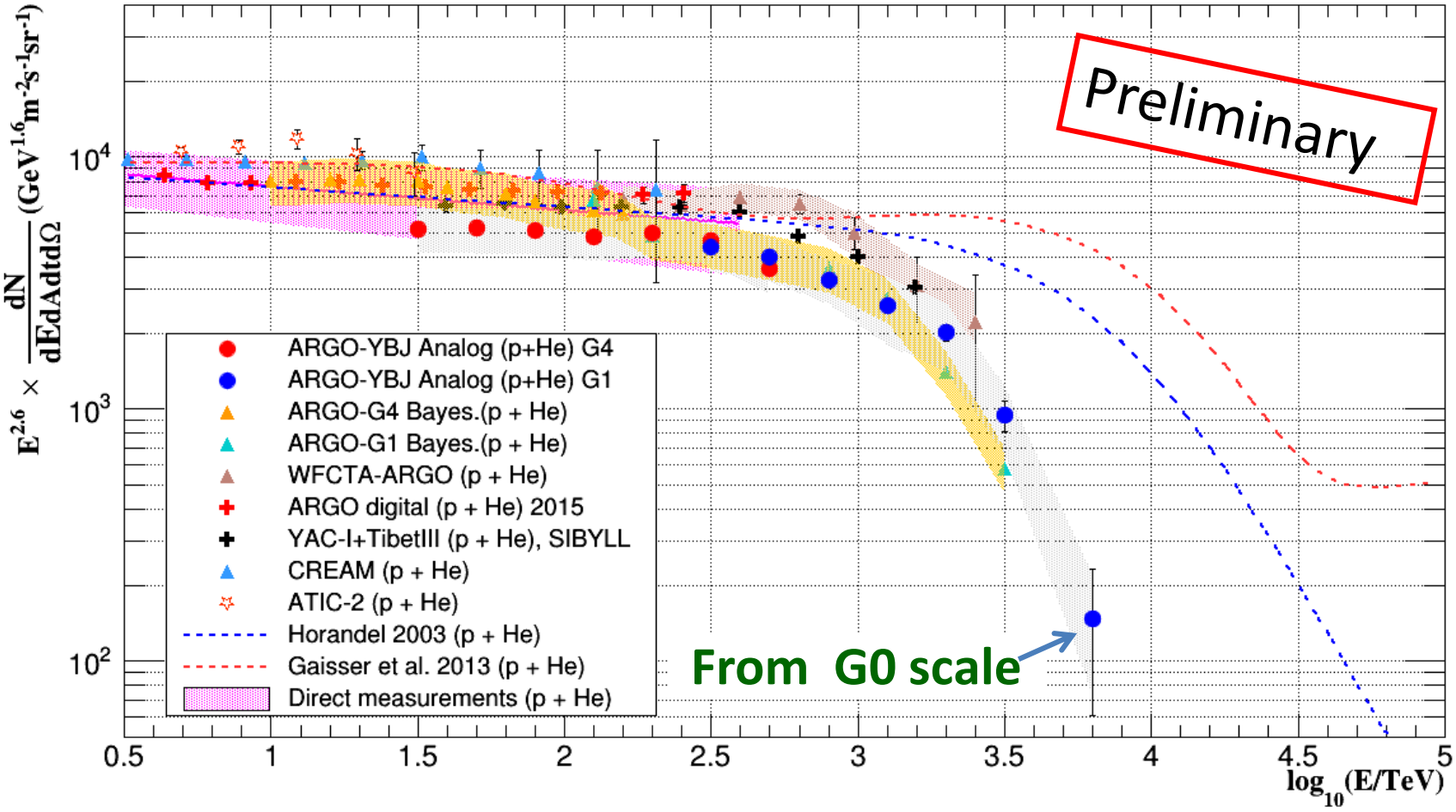


Comparison with other p+He measurements

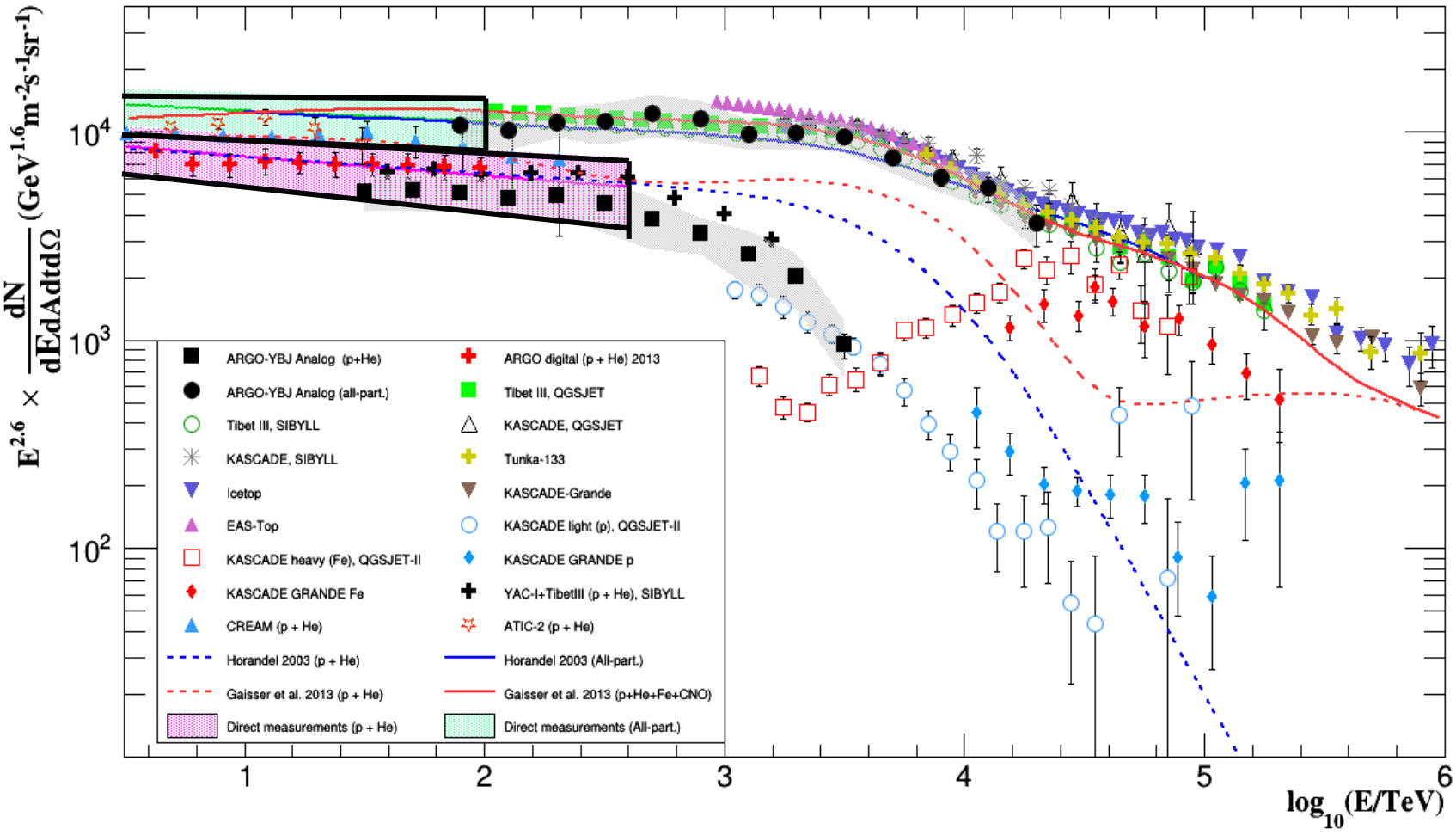
Consistent results with direct measurements (i.e. below 200 TeV) and YAC-Tibet



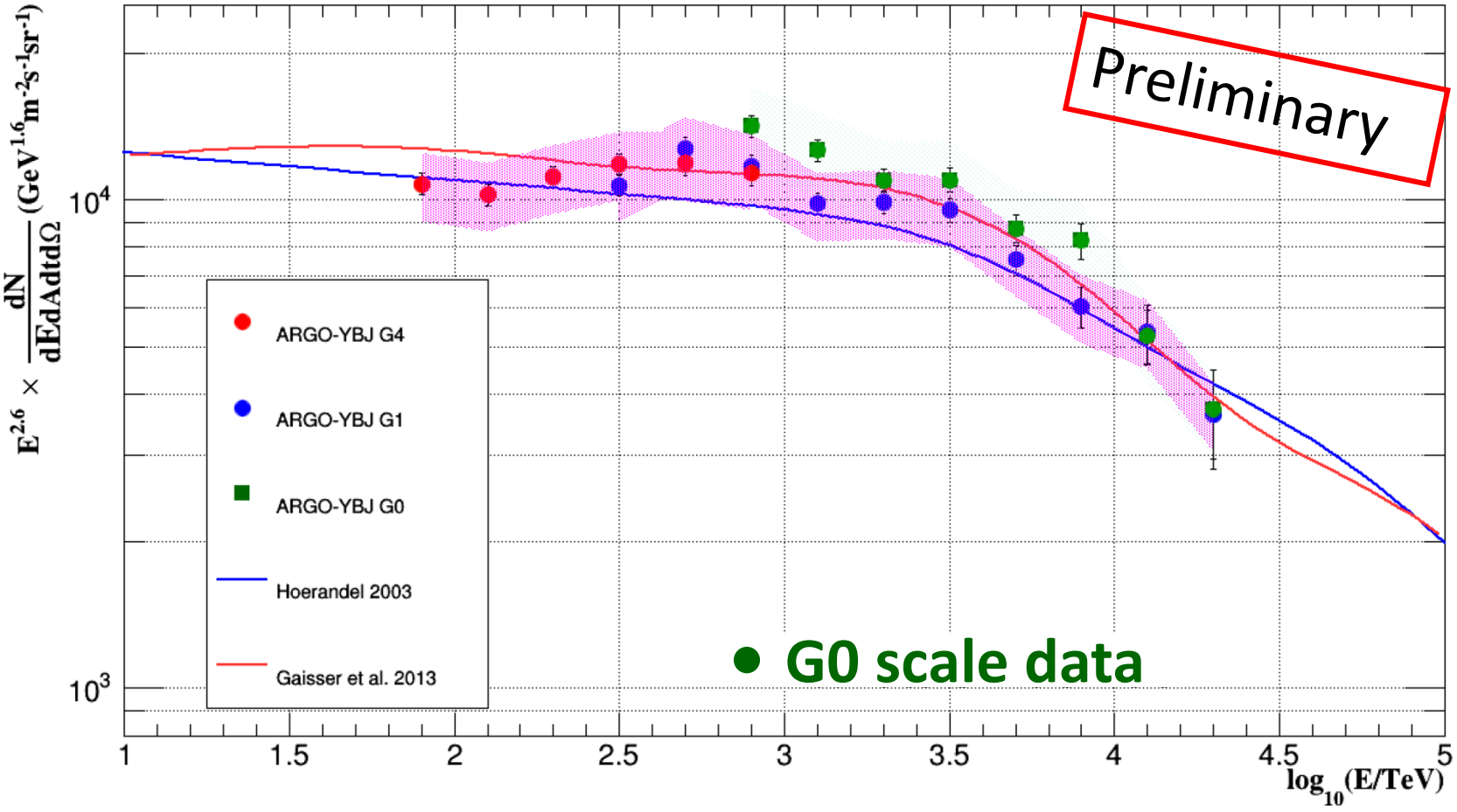
Extension of the ARGO-YBJ p+He spectrum measurements



The overall picture



The all particle spectrum: cross-check using G0 scale



The overall picture with the extended p+He spectrum