Measurement of the Cosmic Ray all-particle and light-component energy spectra with ARGO-YBJ

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On behalf of the ARGO-YBJ Collaboration

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International Symposium on Very High Energy Cosmic Ray Interactions
CERN, August 18-22, 2014

The ARGO-YBJ experiment

High Altitude Cosmic Ray Observatory @ YangBaJing, Tibet, China

Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm^2

ARGO-YBJ physics

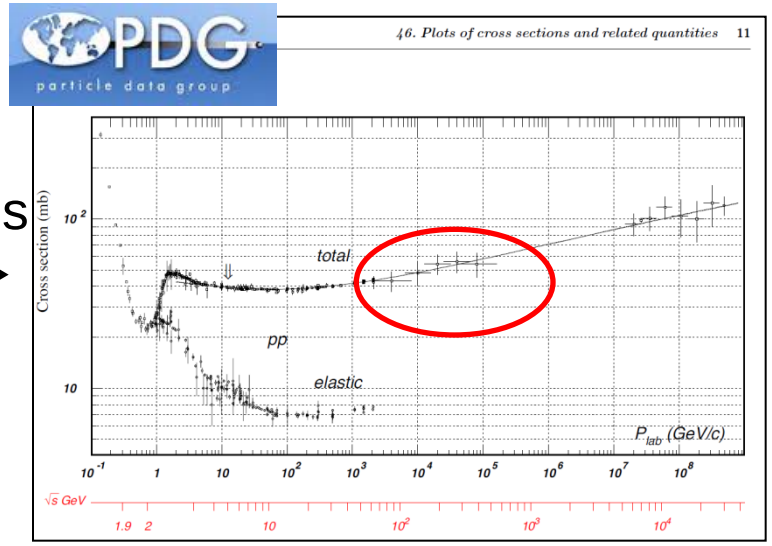
- **VHE γ-Ray Astronomy**:

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

- **Cosmic ray physics**:

  Talks and posters at this workhop

  - **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

Proton Break
240 GeV

He Break
2 X 240
= 480 GeV

Fe Break
26 X 240
= 6240 GeV

Air Shower Experiments

?

region explored by ARGO-YBJ

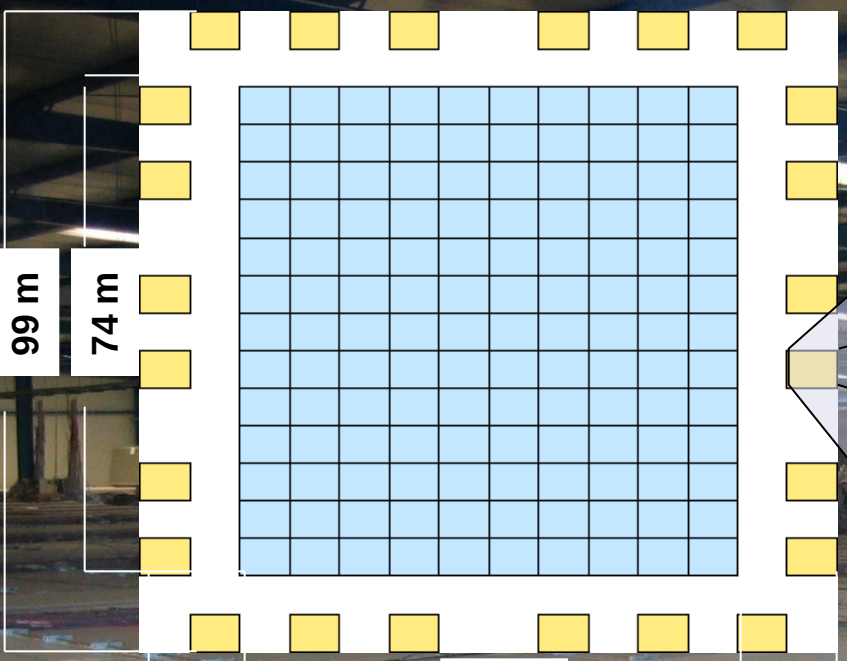
S. Tilav
(this workshop)

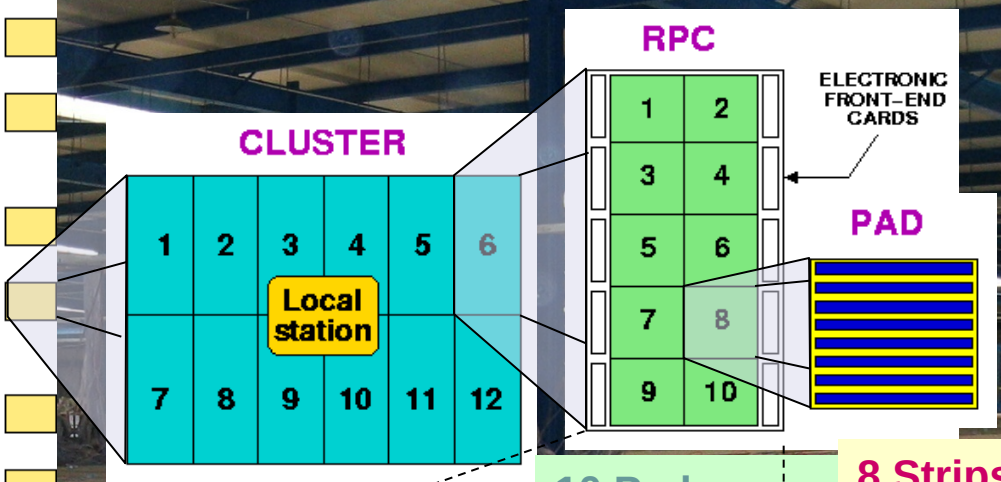
$E^{2.6} \times dN/dE$ [GeV$^{1.6}$ m^{-2} sr^{-1} s^{-1}]

Primary Energy, E [GeV]

Pamela Proton
Pamela He
CreamII Proton
CreamII He
CreamII C
CreamII O
CreamII Mg
CreamII Si
CreamII Fe

The ARGO-YBJ detector





1 CLUSTER = 12 RPC

(~43 m^2)

10 Pads (56 x 62 cm^2) for each RPC

8 Strips (6.5 x 62 cm^2) for each Pad

RPC

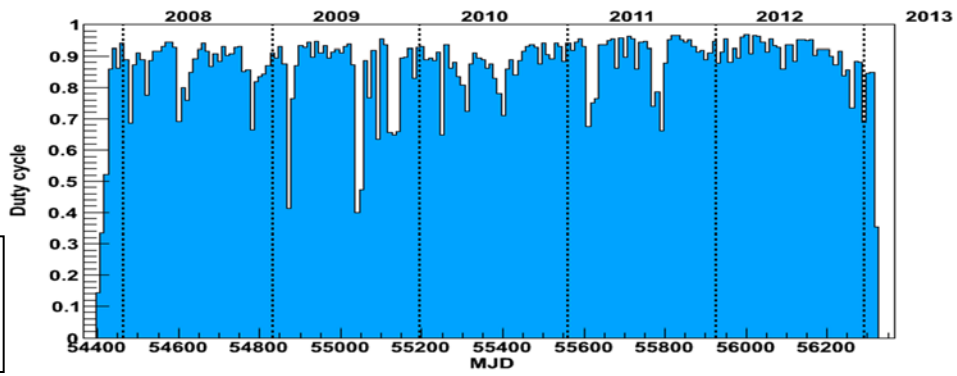
Strip counting

Pad = space-time pixel

Time resolution ~1.8 ns

+ Analog charge read-out on "Big Pads"

EAS reconstruction

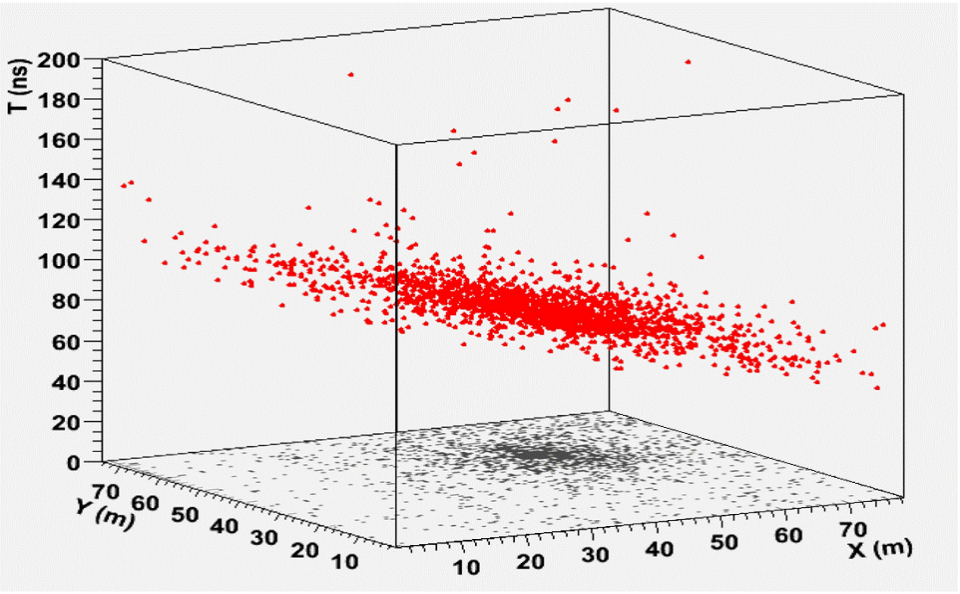


Data taking with full configuration:
November 2007- February 2013

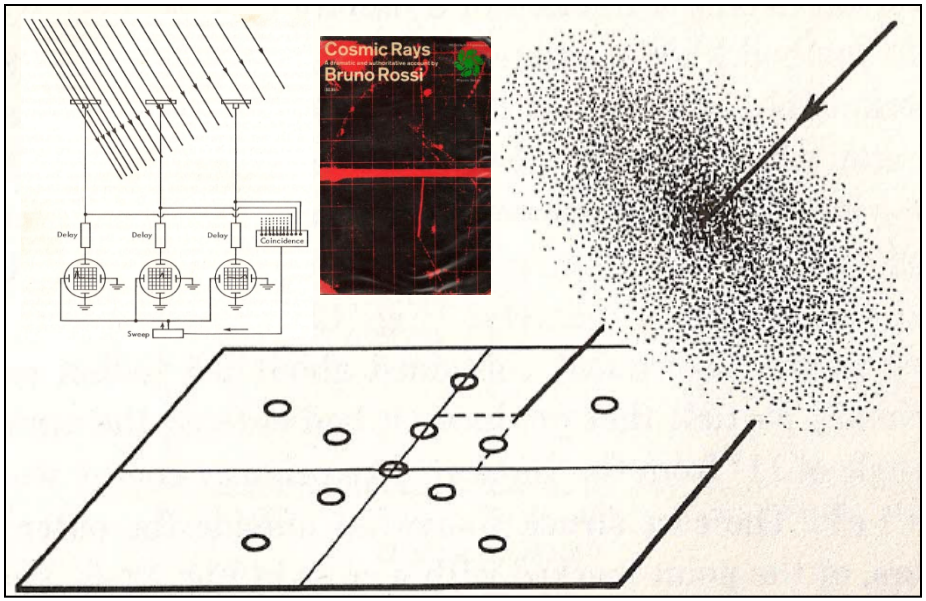
Event Rate ~ 3.5 kHz for N_{hit} >20 - Duty cycle ~ 86% - 10^{11} evts/yr – 100TB/yr

High space/time granularity
+ Full coverage
+ High altitude

detailed study on the EAS space/time structure with unique capabilities

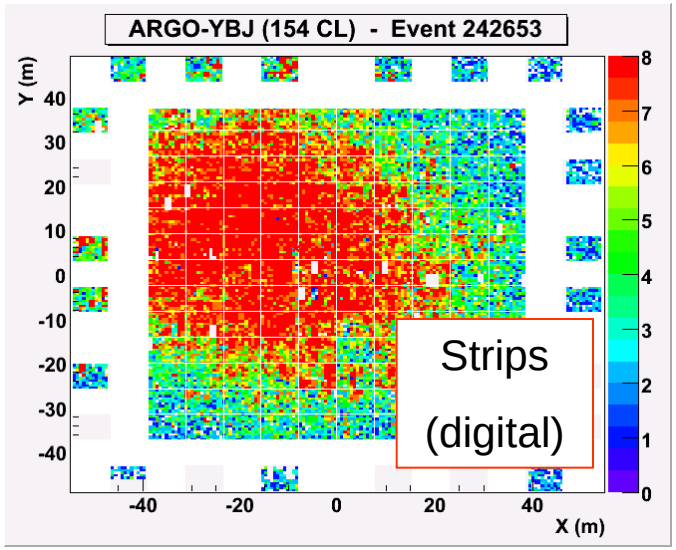


3-D view of a detected shower



Bruno Rossi conceptual EAS detector

The RPC analog readout

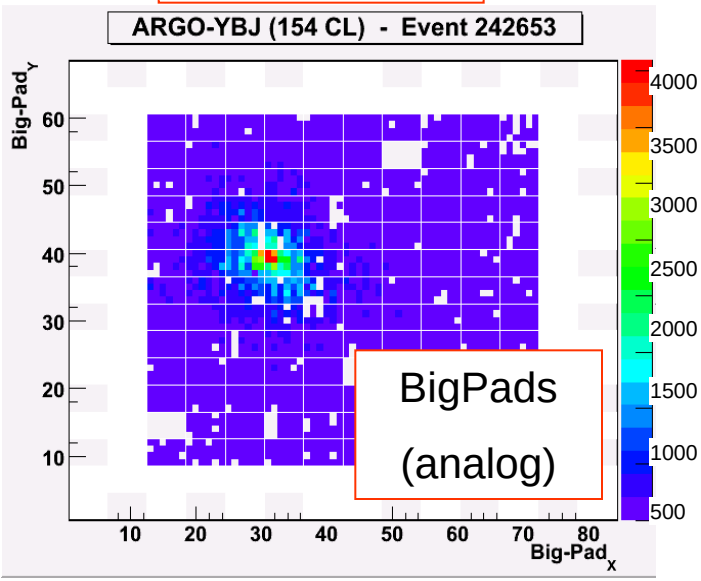


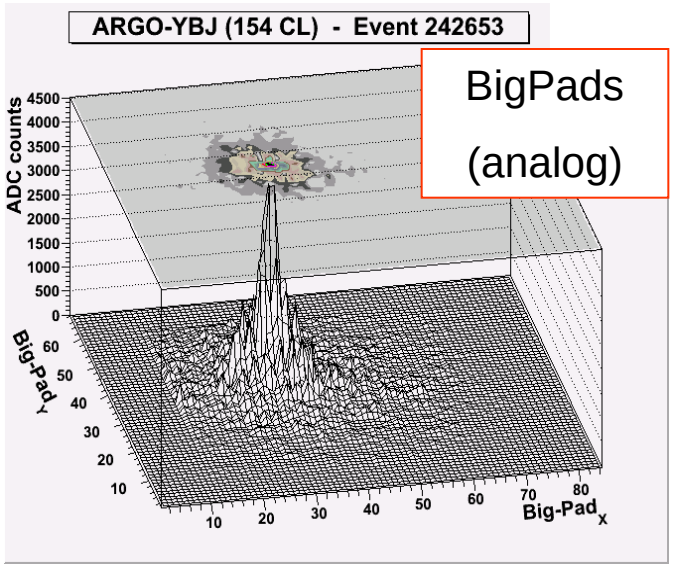
- ✓ **Extend the explored energy range**
- ✓ **Access the LDF down to the shower core**
- ✓ **Sensitivity to primary mass**
- ✓ **Info/checks on Hadronic Interactions**

Eight different gain scales (G0, G1, …..,G7) ensure a good linearity up to about $2 \cdot 10^4$ particles/m^2.

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

Real event



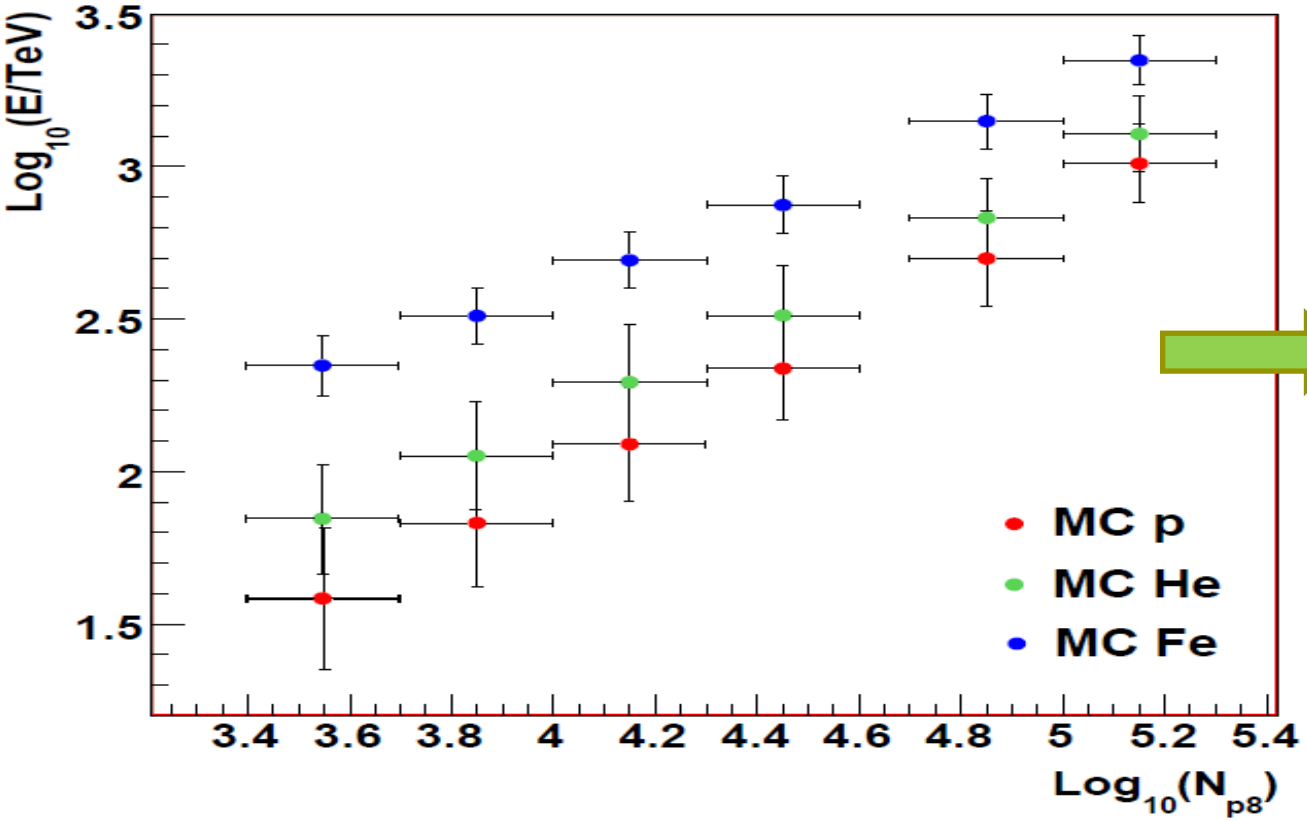


In this study we used data taken with G4 and G1 scales that allow covering the 50TeV – 5PeV energy range with high efficiency and no saturation.

The truncated size as (mass dependent) energy estimator

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

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



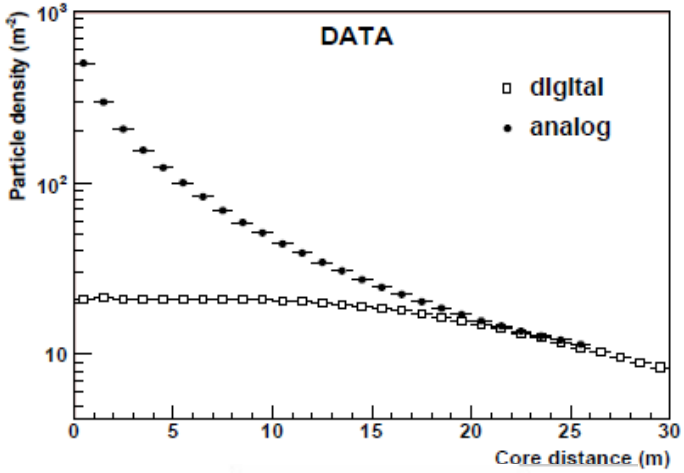
Only events with zenith angle less athn 15 degrees in this work

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

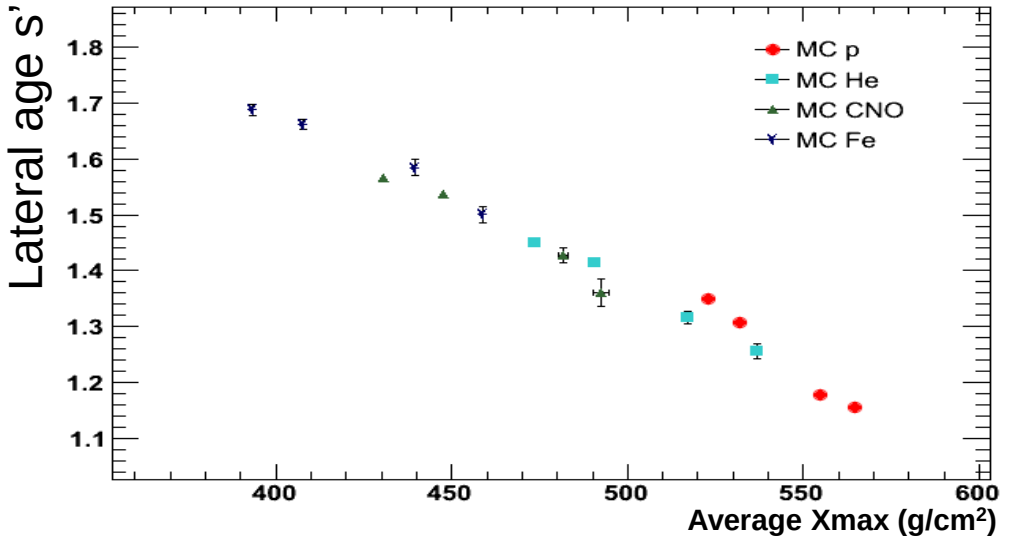
LDF and shower age

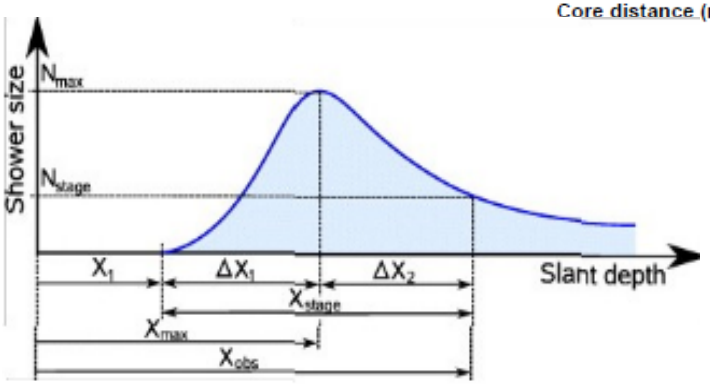
With the analog data we can study the LDF without saturation near the core. It is well fitted by a modified NKG function

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



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



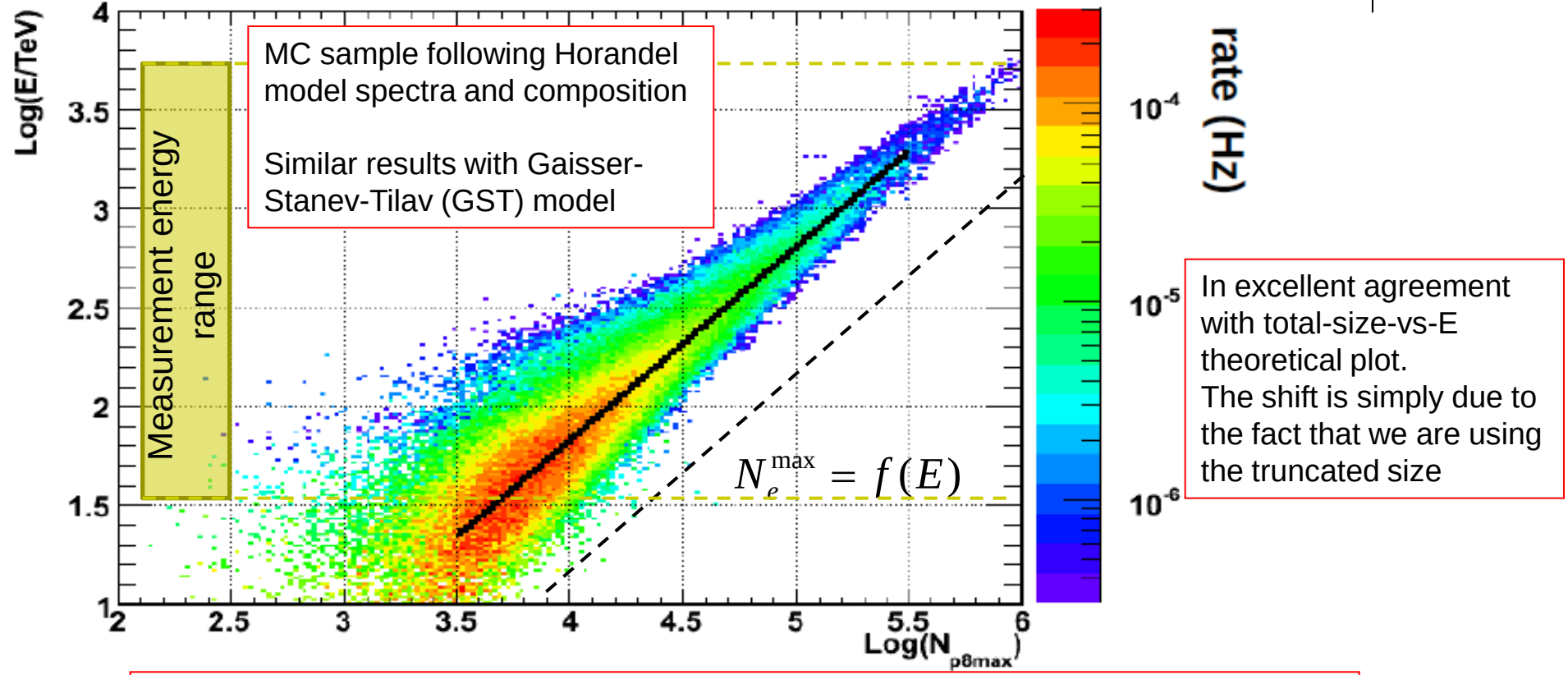


Assume an exponential absorption after the shower maximum. Get the correct signal at maximum (Np8max) by using Np8 and s' measurements for each event

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

Also checks with Gaisser-Hillas profile

Mass independent Energy reconstruction



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

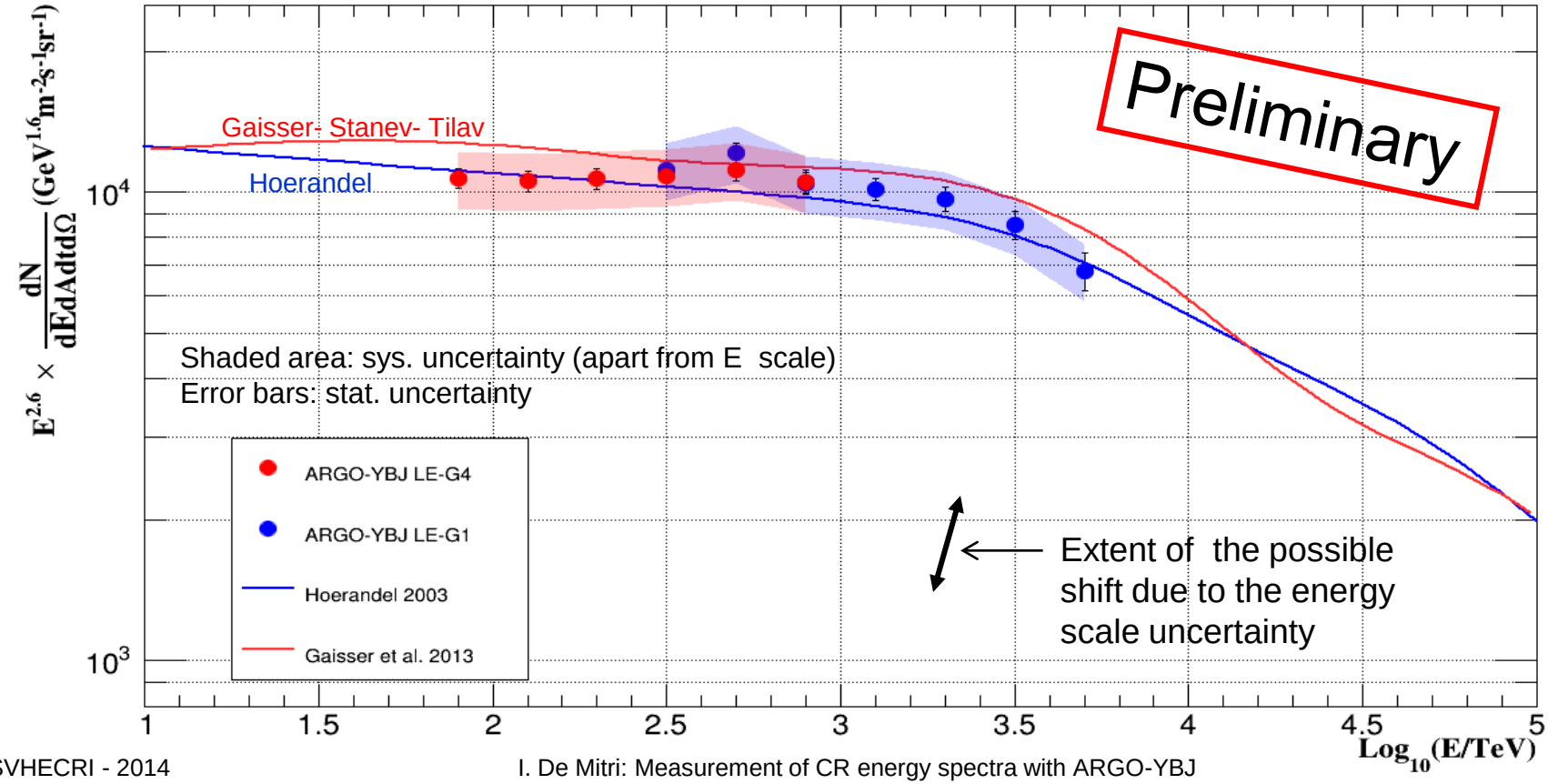
The measurement of Np8 and the (age correlated) LDF slope allows estimating the truncated size at the shower maximum.

This ensures a mass independent Energy determination.

The all particle spectrum

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

- **Ongoing extension to about 10 PeV thanks to more statistics and G0 and inclined data**



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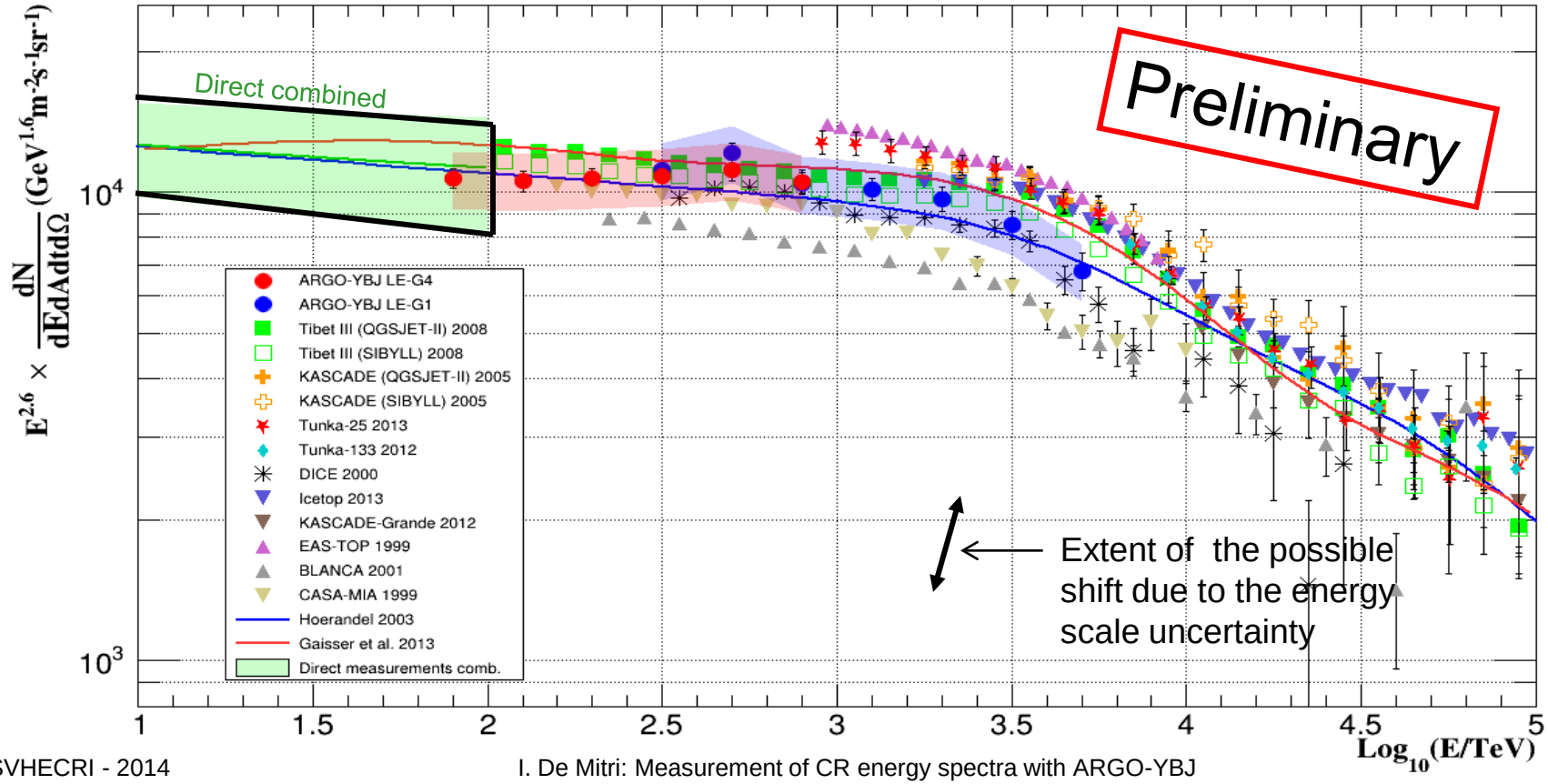
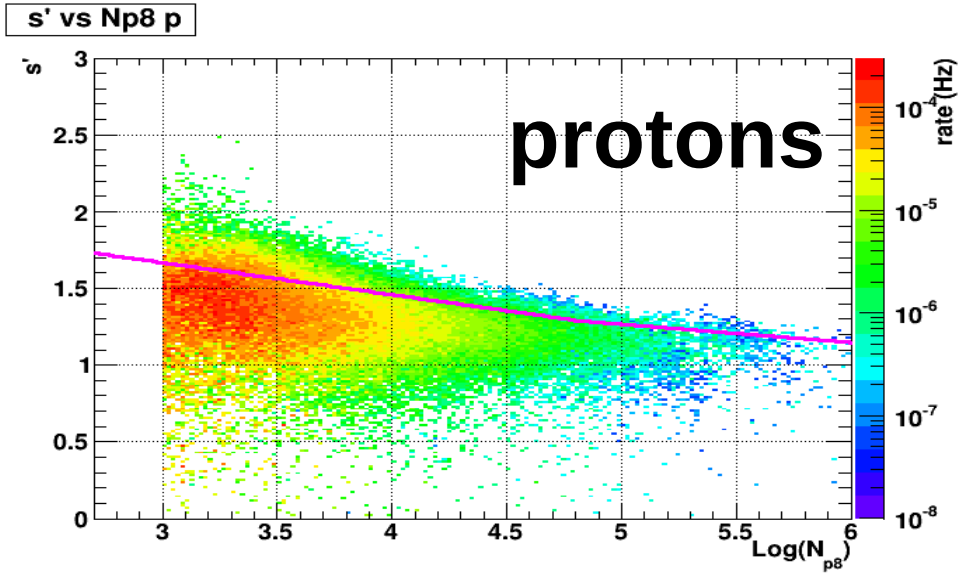
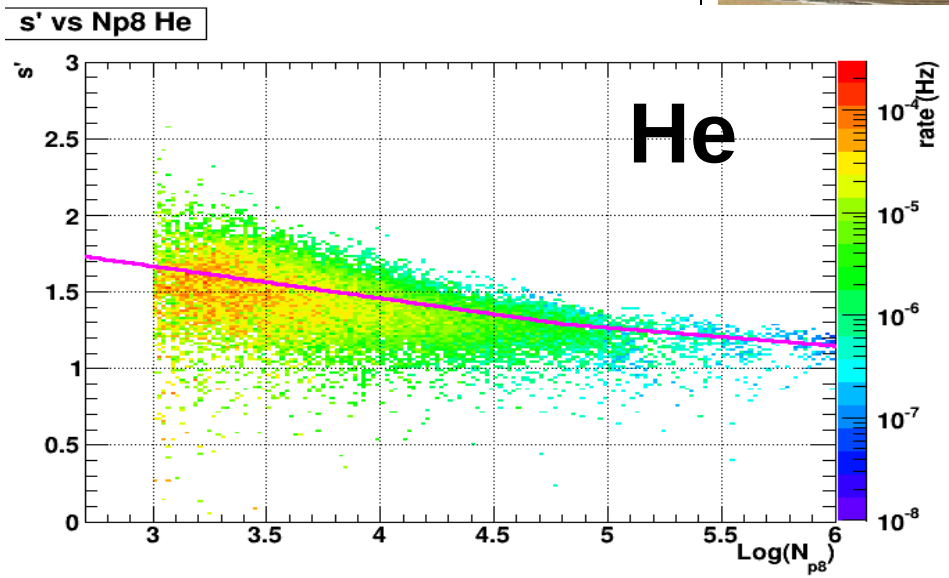
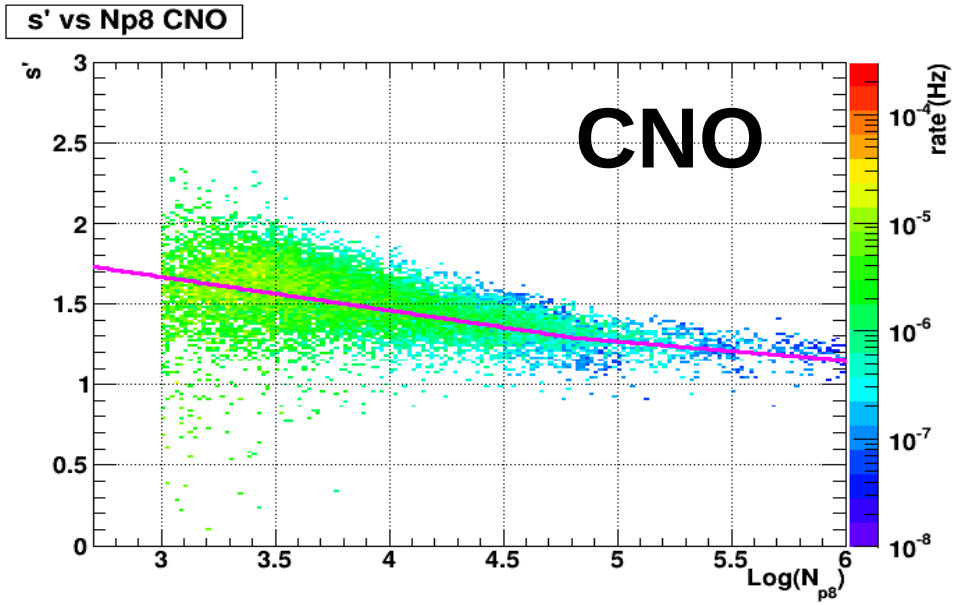
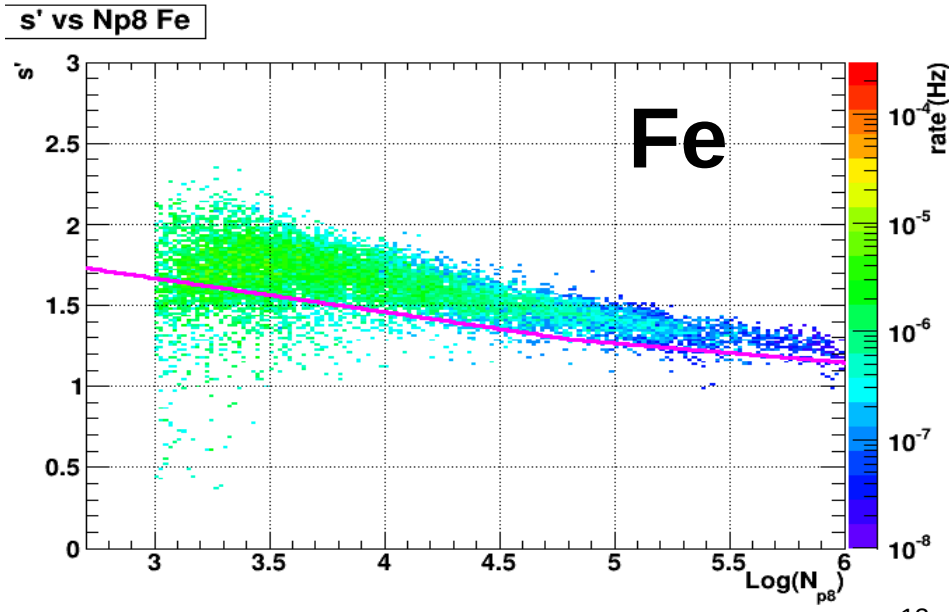


p and He selection
(MC Hoerandel spectra and normalizations)



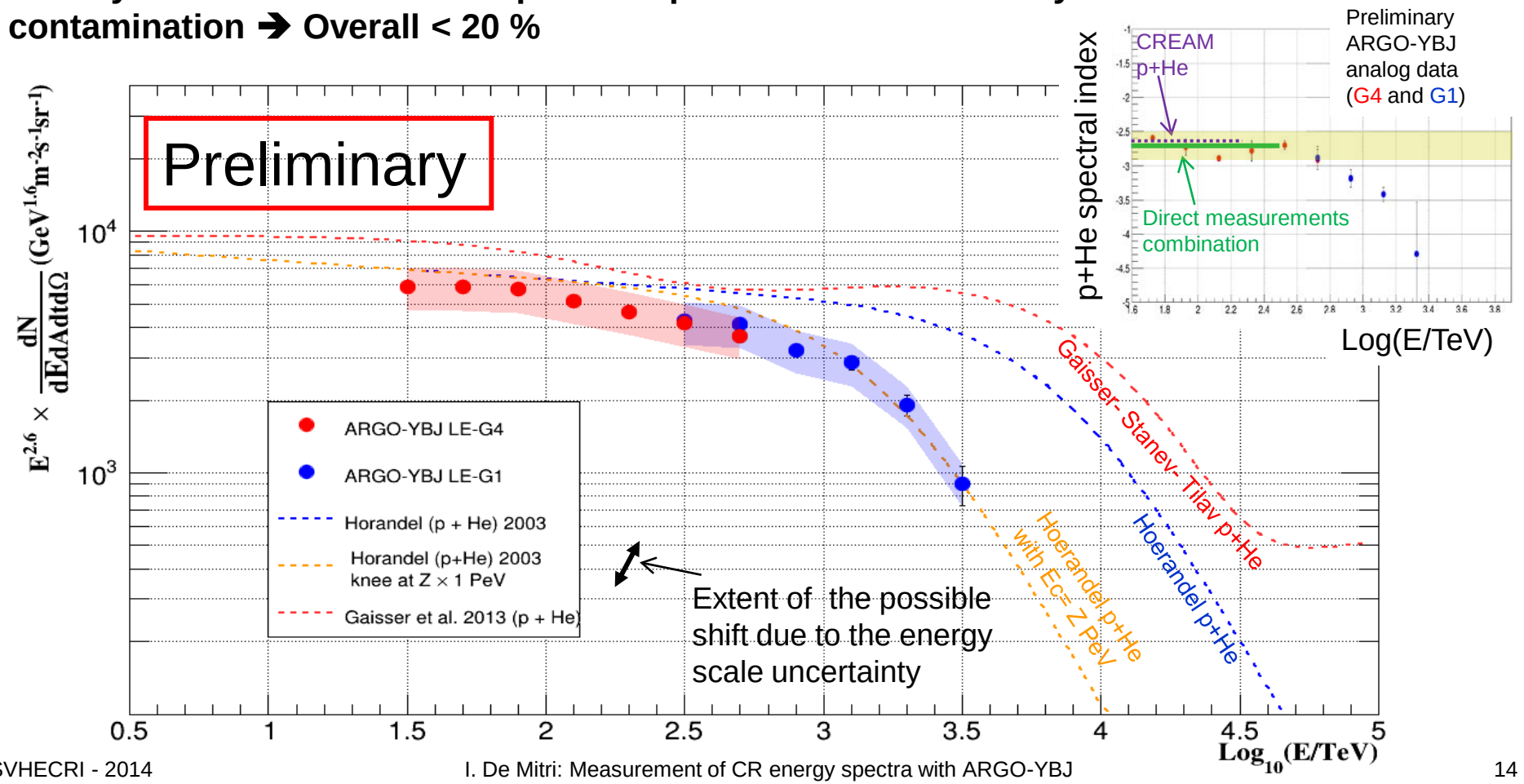






The p+He spectrum

- Same considerations as for the all-particle spectrum
- Gradual change of the slope starting around 700 TeV
- Agreement with other two ARGO-YBJ independet analyses (see next two slides)
- Consistent with previous hints (MACRO, CASA-MIA, Chacaltaya, EAS-TOP,...) and YAC-Tibet spectrum
- Overlap with direct measurements at low energy
- Flux systematics as for the all particle spectrum ⊕ < 14% mainly for the CNO contamination ➔ Overall < 20 %



p+He spectrum: bayesian analysis of analog data

Direct link between observables and primary energy and mass

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

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

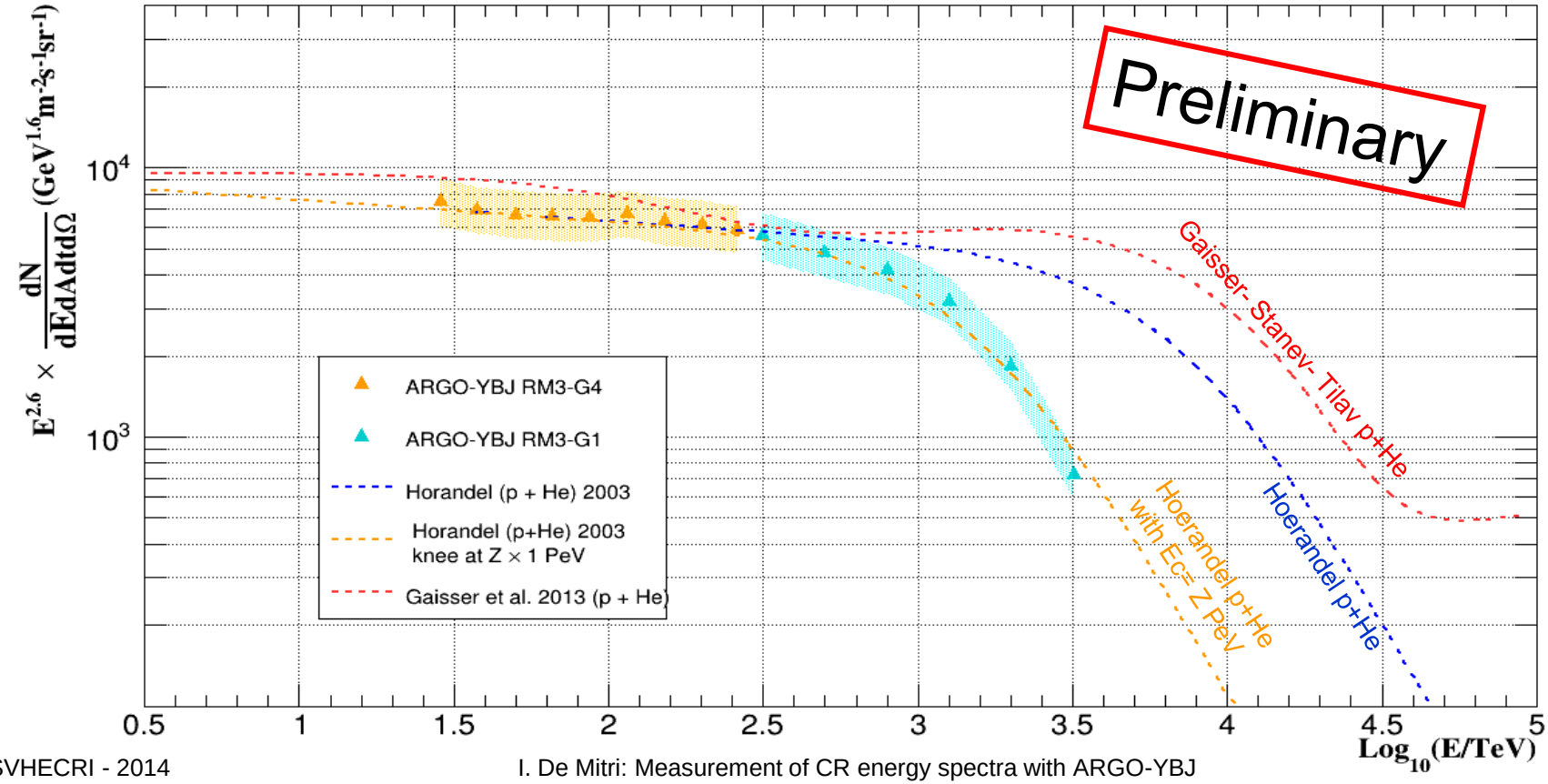
Bayes

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

p+He spectrum: bayesian analysis of analog data

Results are consistent with previous analysis.

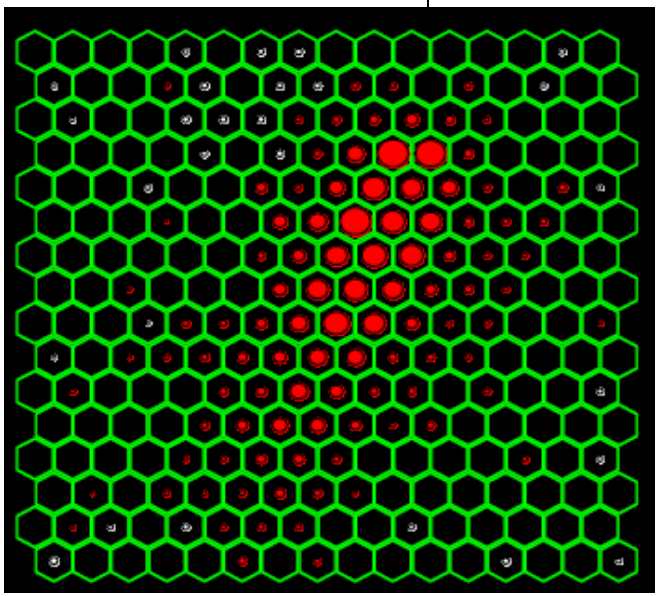
Different fiducial cuts, also inclined events, fully bayesian approach,…



p+He spectrum: measurement of Cerenkov light

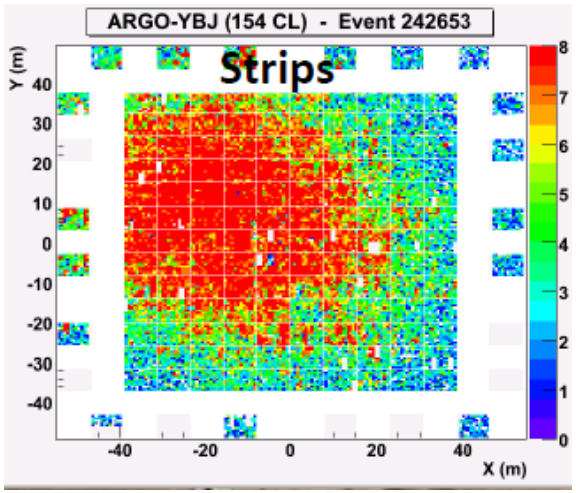
Wide Field of View Cerenkov Telescope (Array): (WFCTA)

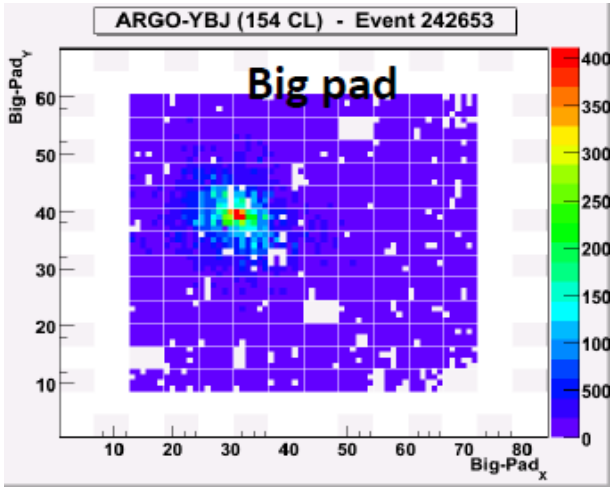
$5m^2$ spherical mirror
16×16 PMT array
14° ×16° Field Of View
Elevation angle: 60°



Energy easurement by using the Cerenkov signal and the shower geometry as reconstructed with the ARGO-YBJ analog data.

Light elements are selected by using information of particle desity near the core (ARGO-YBJ) and the shape of the Cerenkov image
Chin. Phys. C 38 (2014) 045001

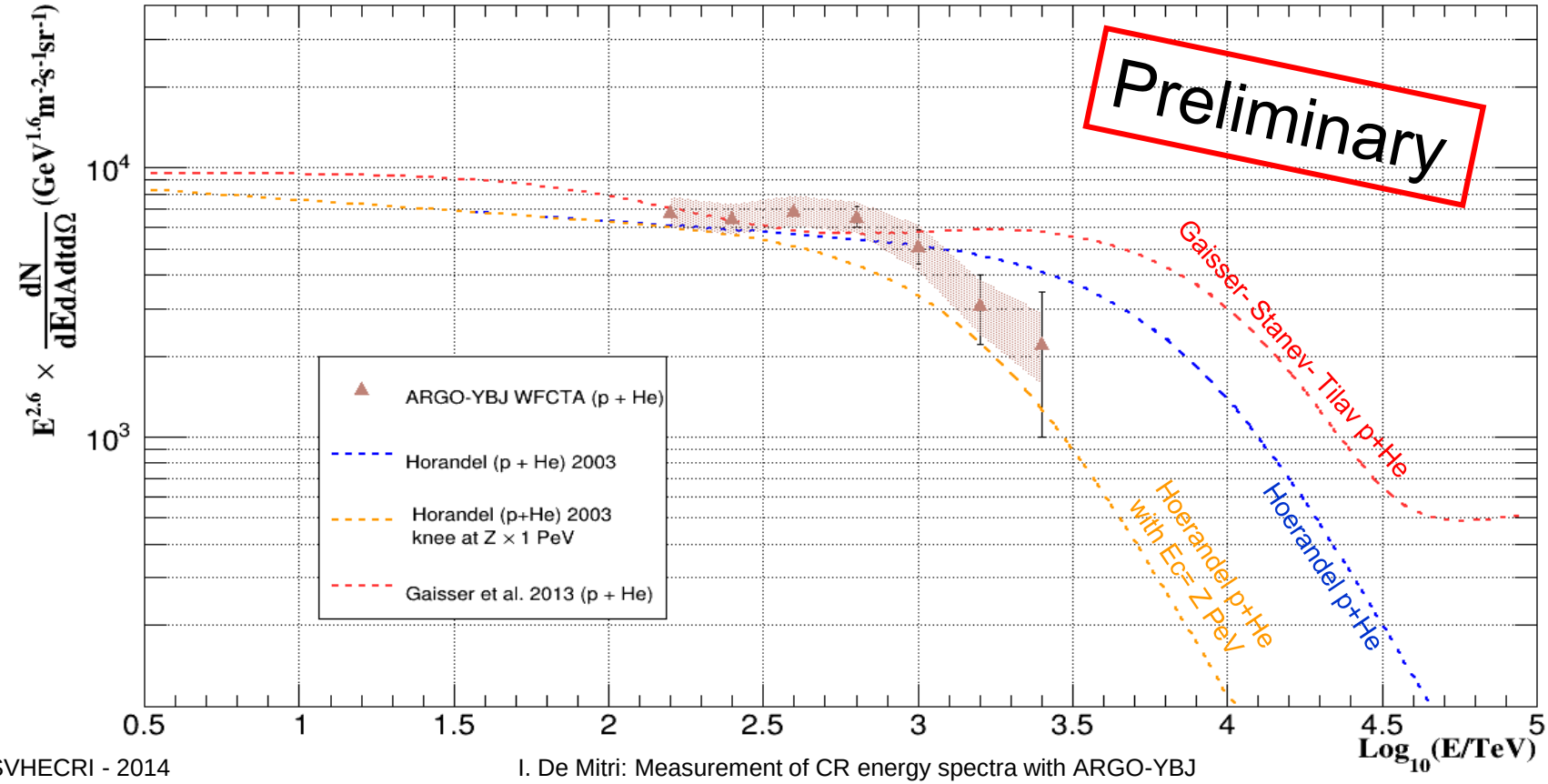




p+He spectrum: measurement of Cerenkov light

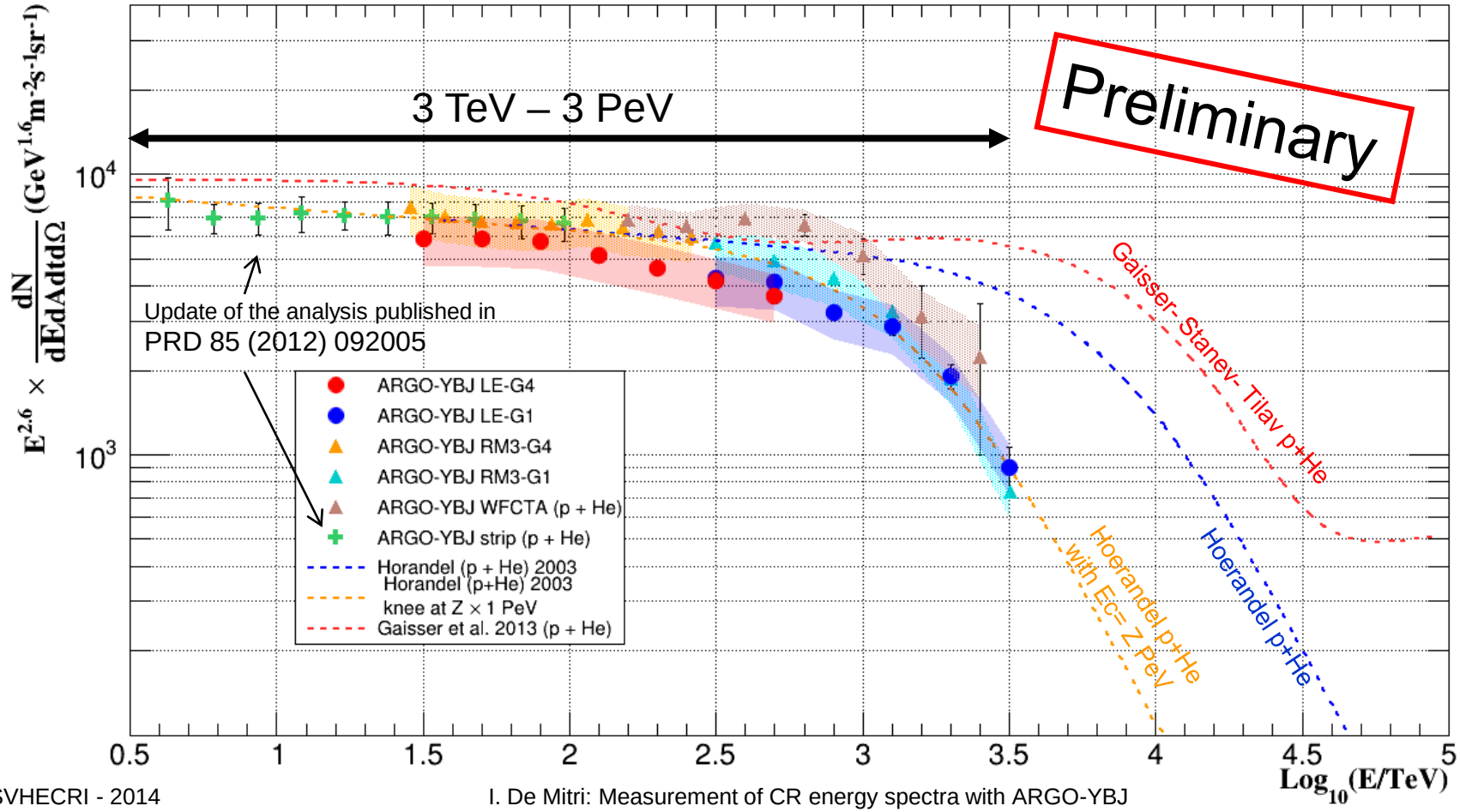
Results are consistent with previous analyses. May be different shape.

Different data/detector, different fiducial cuts, inclined events,…



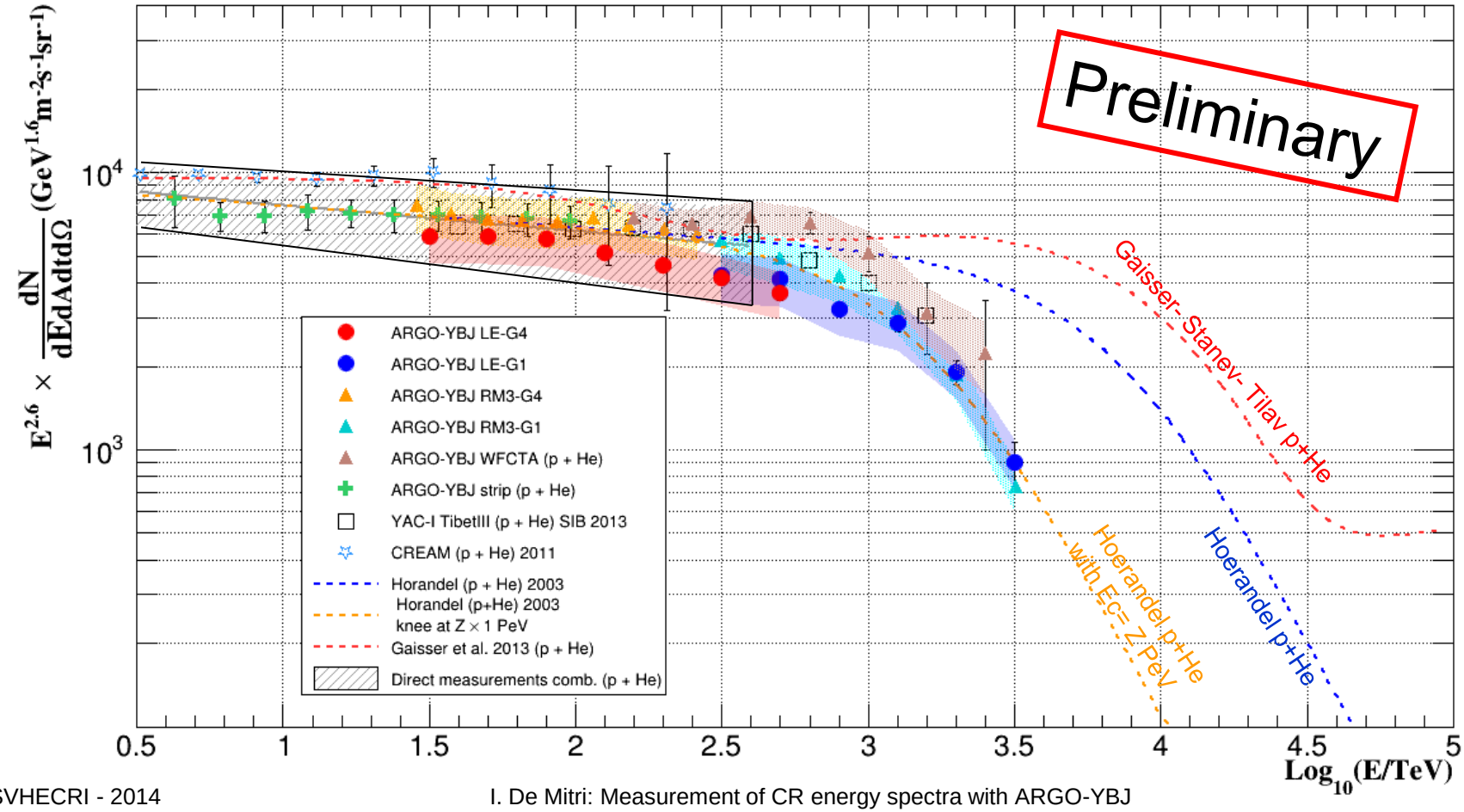
The ARGO-YBJ measurements of the p+He spectrum

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

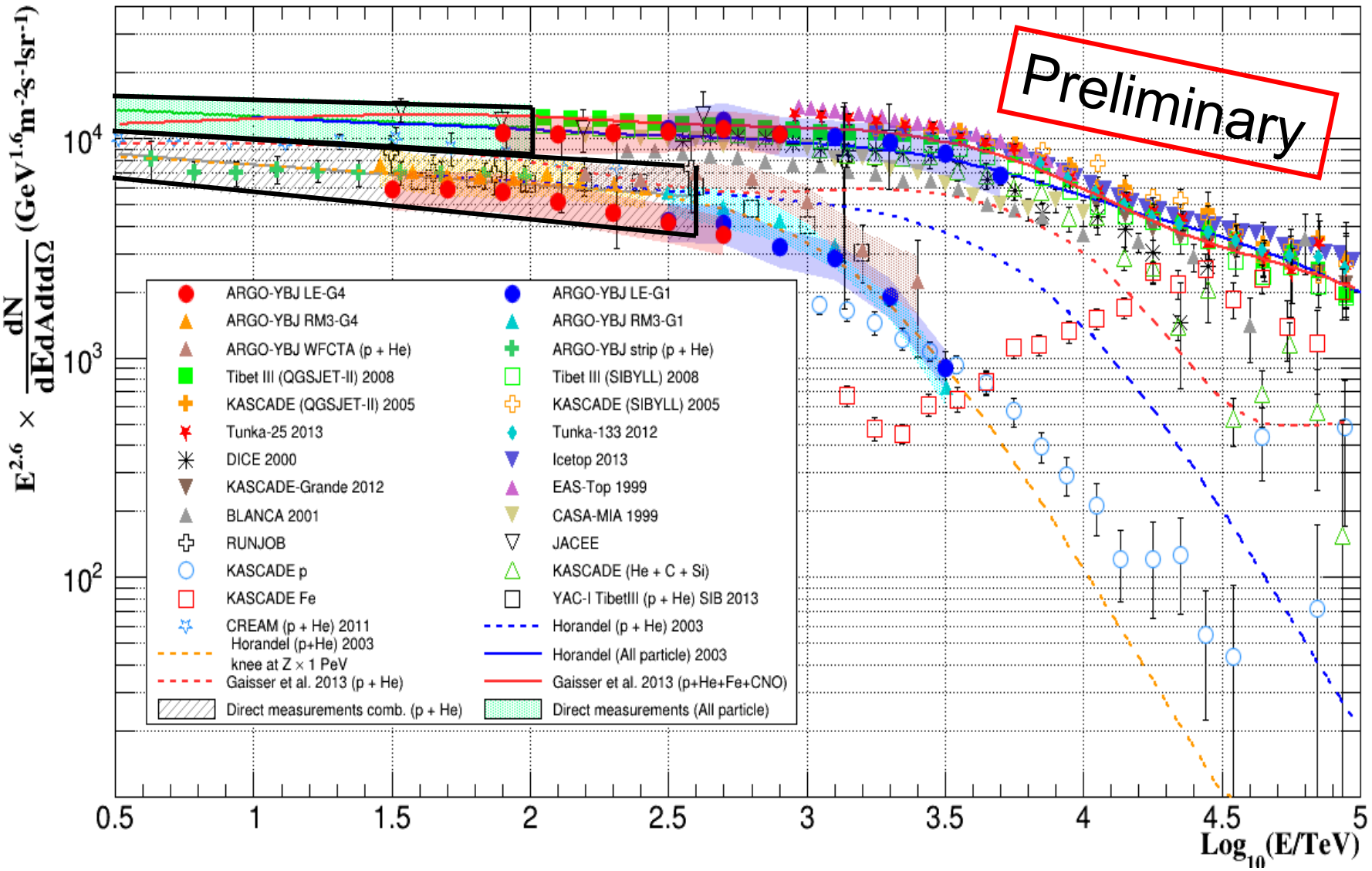


Comparison with other p+He measurements

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



The overall picture



Summary

- Measurement of the all-particle spectrum from 50TeV to 5 PeV consistent with both direct and indirect experiments
- Measurement of the p+He component from 3 TeV to 3 PeV
- Evidence for a bending in the p+He spectrum (just) below 1 PeV
- Two different (p+He) analyses of ARGO-YBJ data in agreement within quoted uncertainties. A third independent (hybrid) analysis, using also the Cerenkov light signal, gives consistent results.
- Many cross check made and improvements on the way (e.g. different hadronic interaction models, no big differences expected).
- Now extending data set and MC statistics for the final results

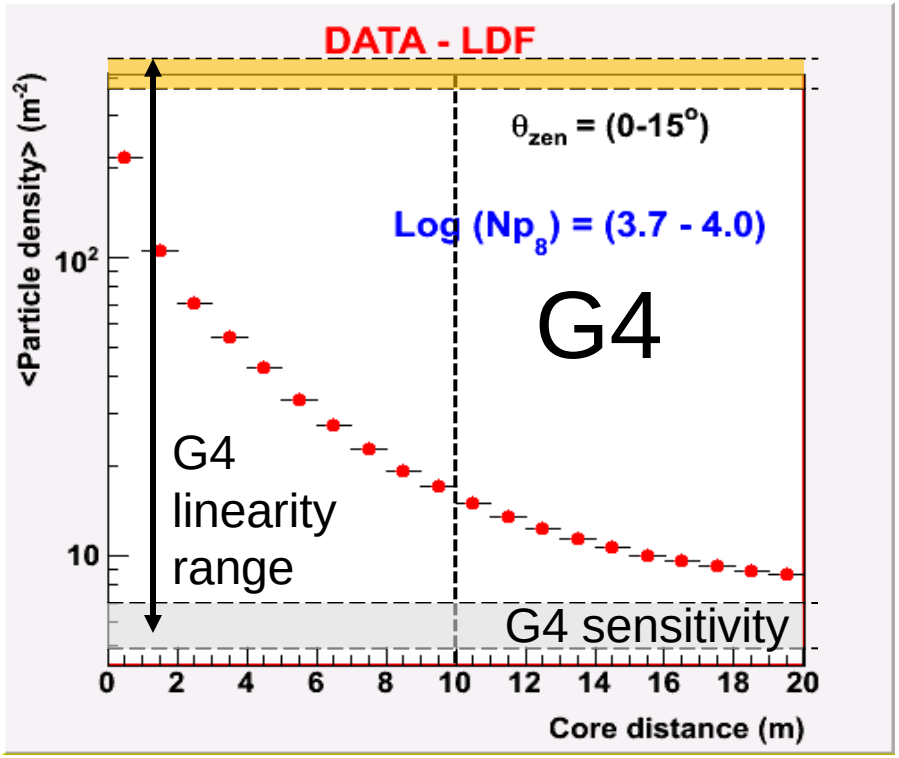
More Stuff

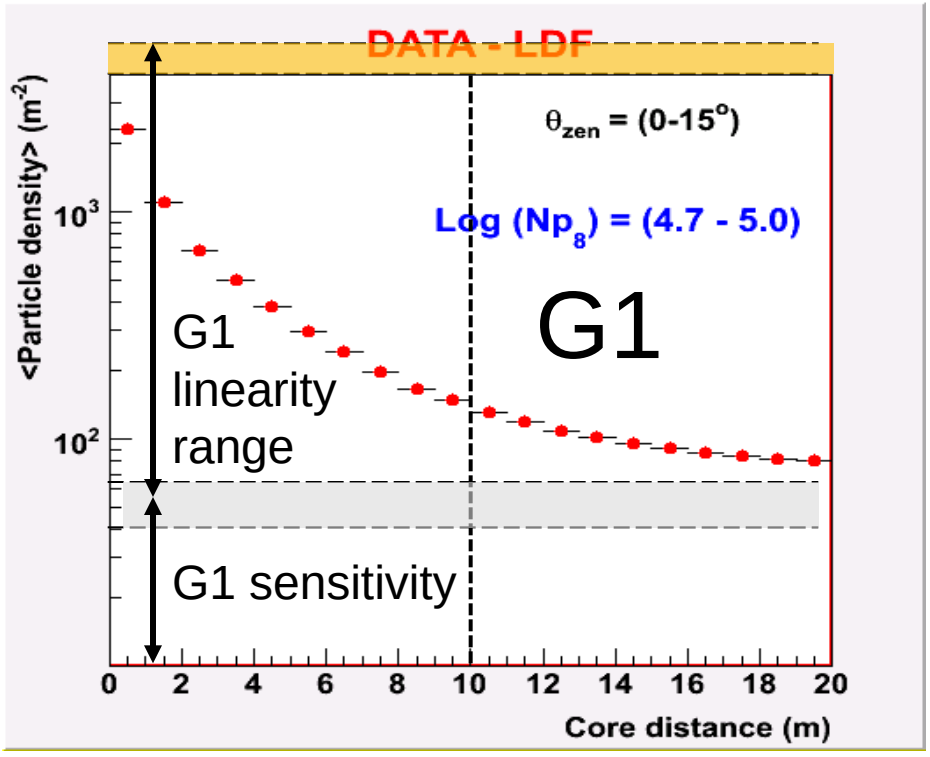
On the analog readout system

Eight different gain scales (G0, G1, …..,G7) ensure a good linearity up to about $2 \cdot 10^4$ particles/m^2.

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

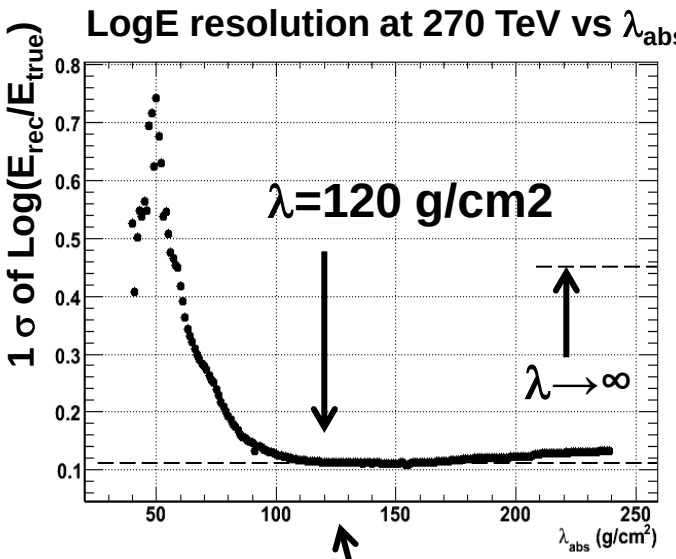
In this study we used data taken with G4 and G1 scales that allow covering the 50TeV – 5 PeV energy range with high efficiency and no saturation.





Finding the best λ_{abs} parameter

Further improvements in progress

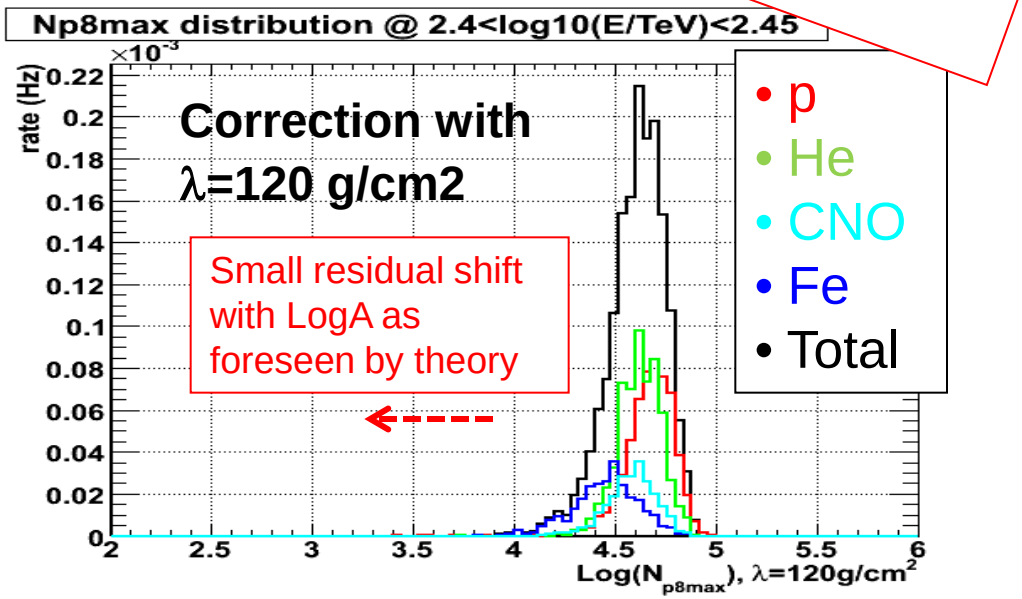


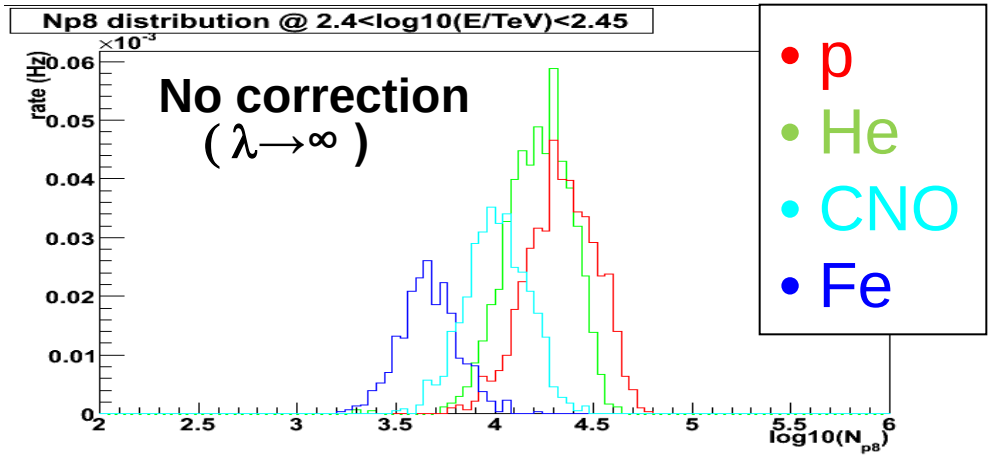
Results from the ARGO-YBJ test experiment

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].

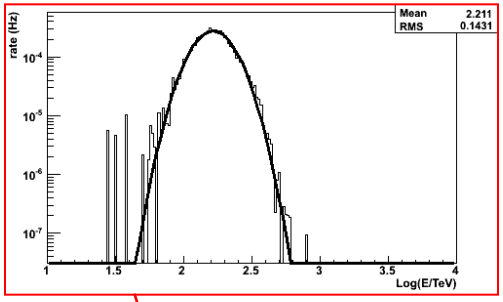
The parameter α is found to be 4.88 ± 0.45, so that $\Lambda_{att} = (124 \pm 11)$ g/cm^2, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 ± 0.37.

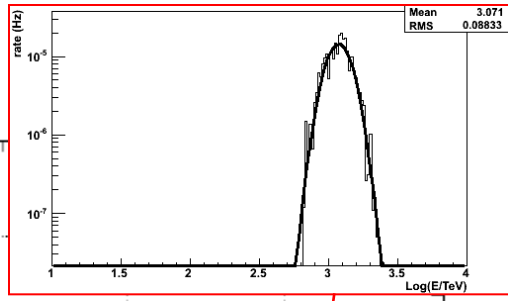


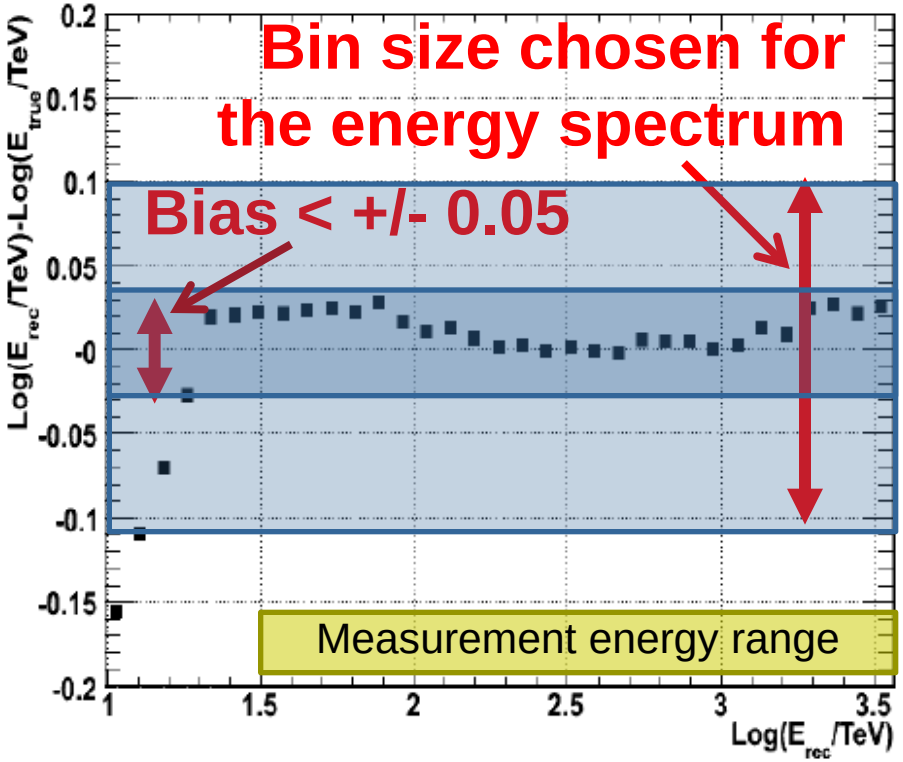


Energy reconstruction: bias and resolution

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.





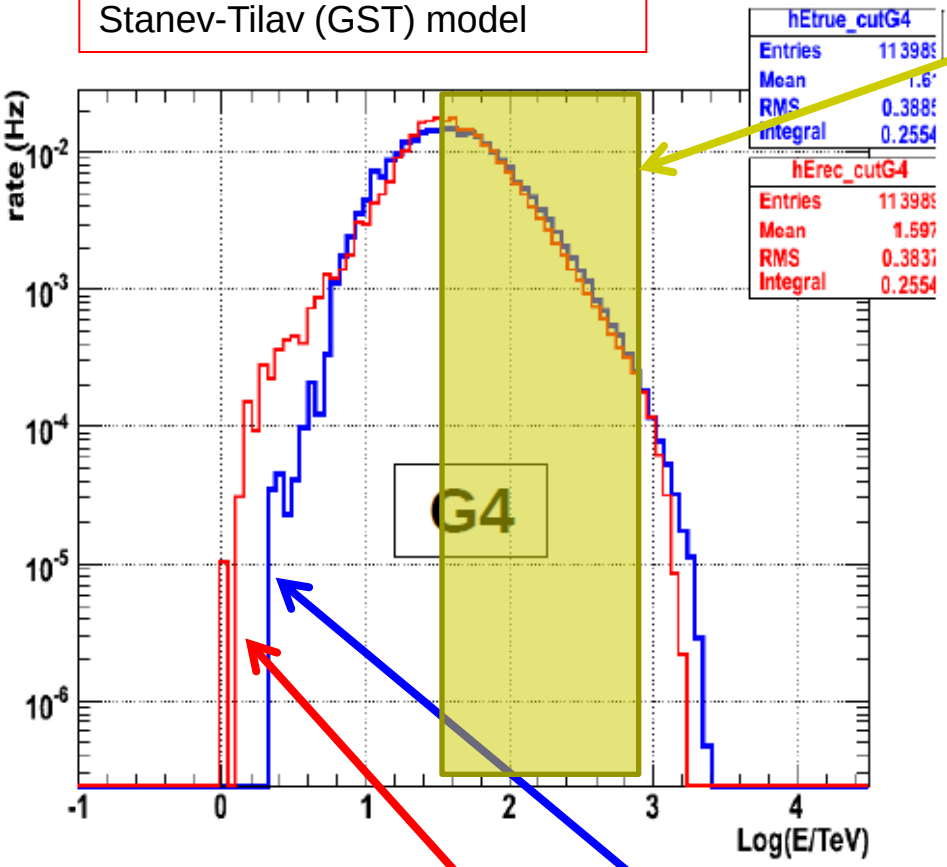


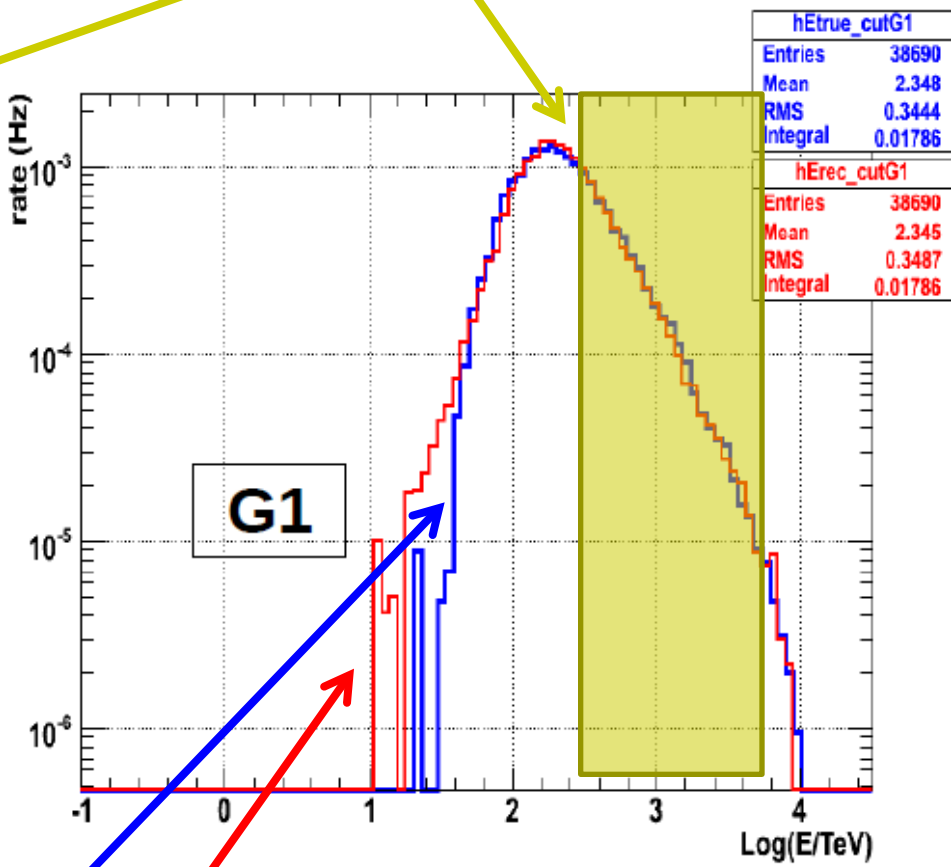
MC Energy distributions

MC sample following Horandel model spectra and composition

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

Measurement energy ranges

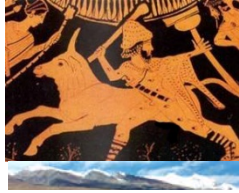


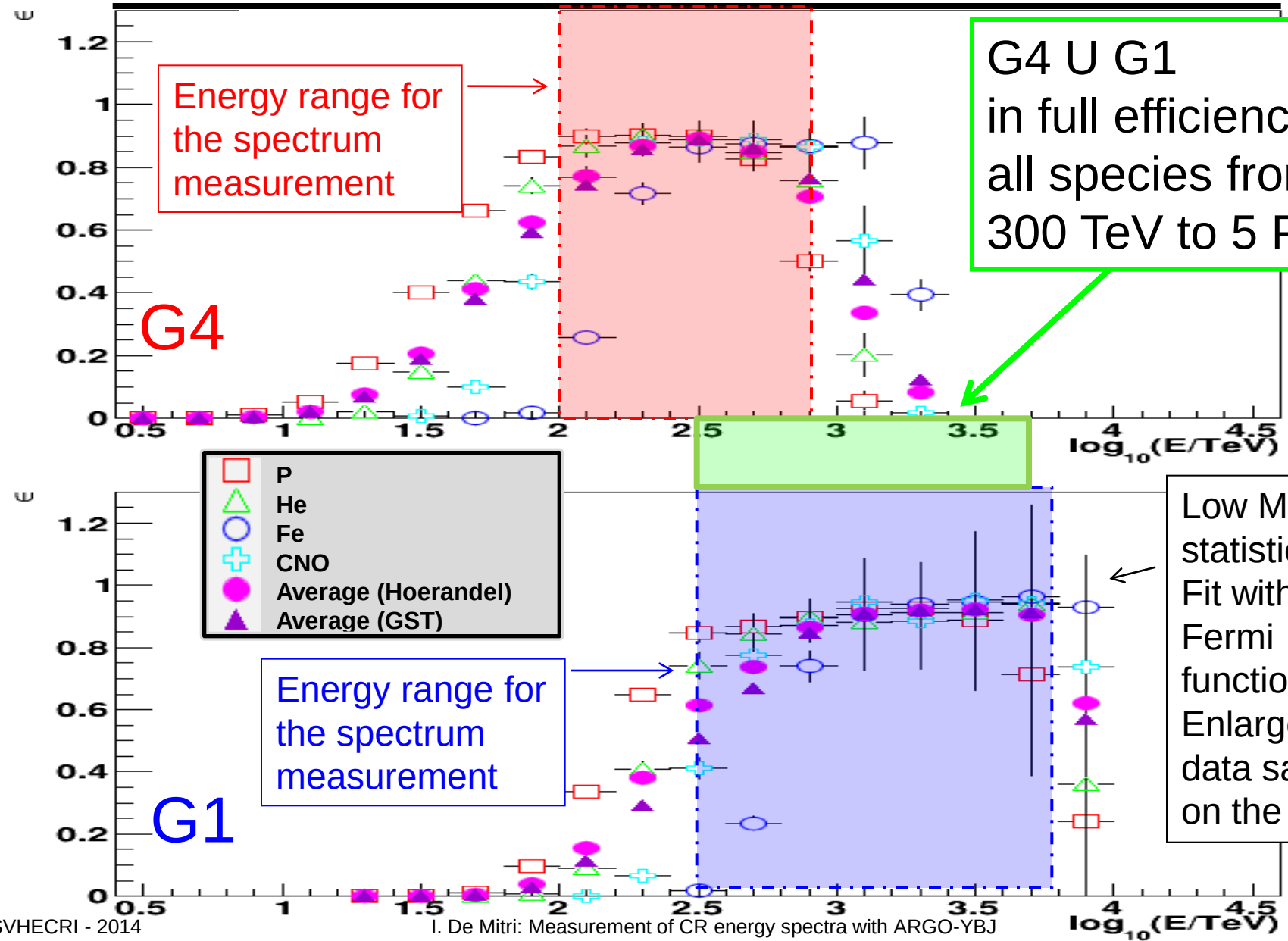


MC true energy

MC reconstructed energy

Trigger and event selection efficiencies for the all particle spectrum





Systematic uncertainty evaluations for the all-particle spectrum

For the flux:

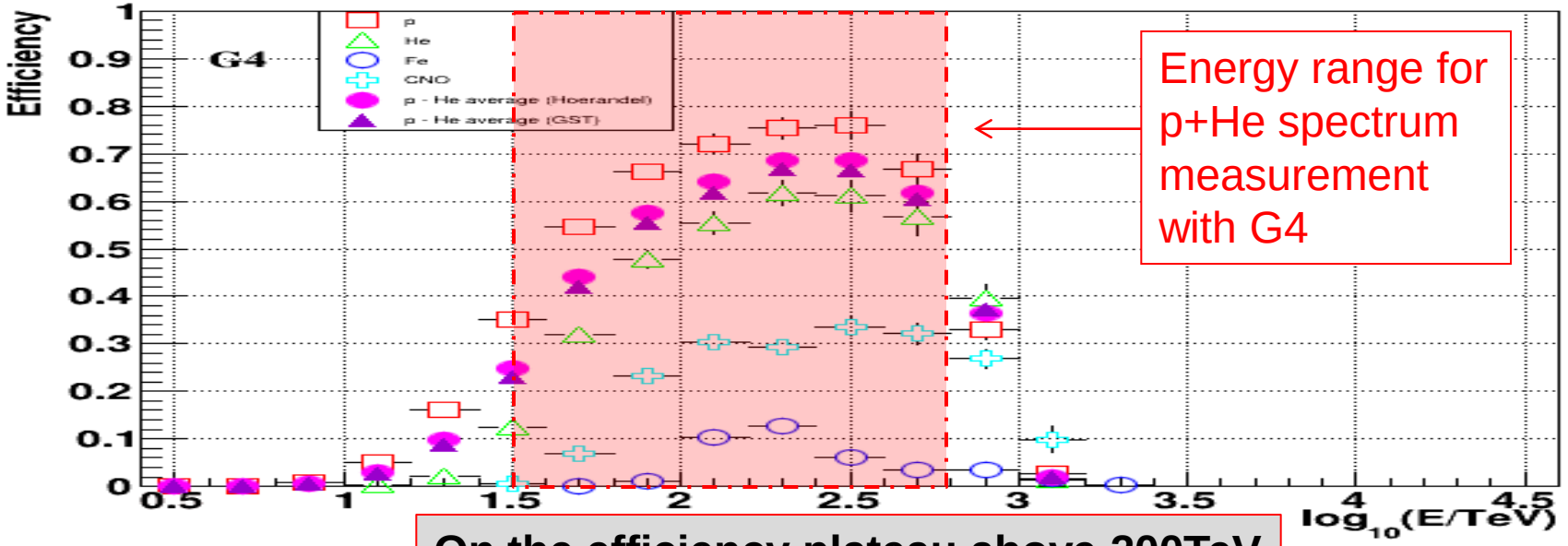
- Geometrical Aperture : (5 % in/out contamination) ⊕ (2.5% angular contamination) =5.6 %
- Efficiency: (5% from MC samples) ⊕ (<10% efficiency estimation of the mixture) = 5.0-11.2 %
- Unfolding: 3%
- Hadronic interaction model < 5%
- **TOTAL: 8.1% - 13.8 %**
- **TOTAL: (conservative) = 14%**

For the energy scale:

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

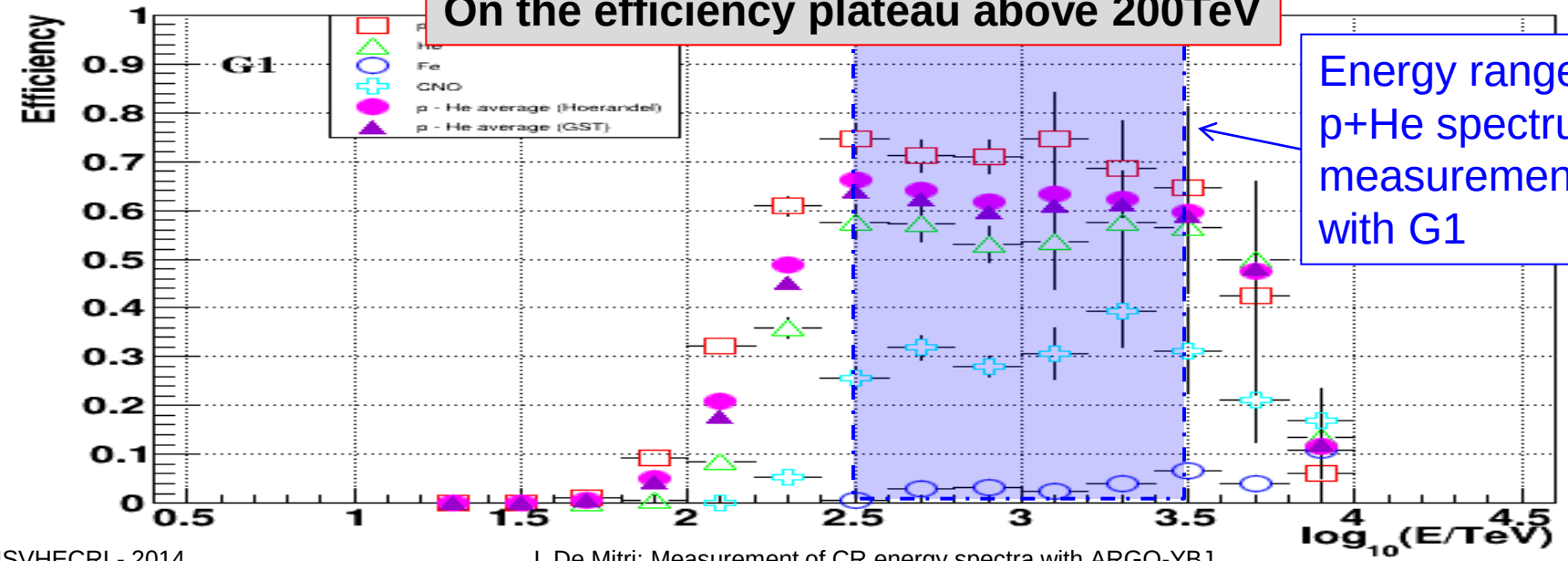
In the following plots an over -conservative +/- 14% shaded area has been temporarily drawn on the flux measurements.
Error bars show the statistical uncertainties.

Trigger and selection efficiencies for the p+He measurement



Energy range for p+He spectrum measurement with G4

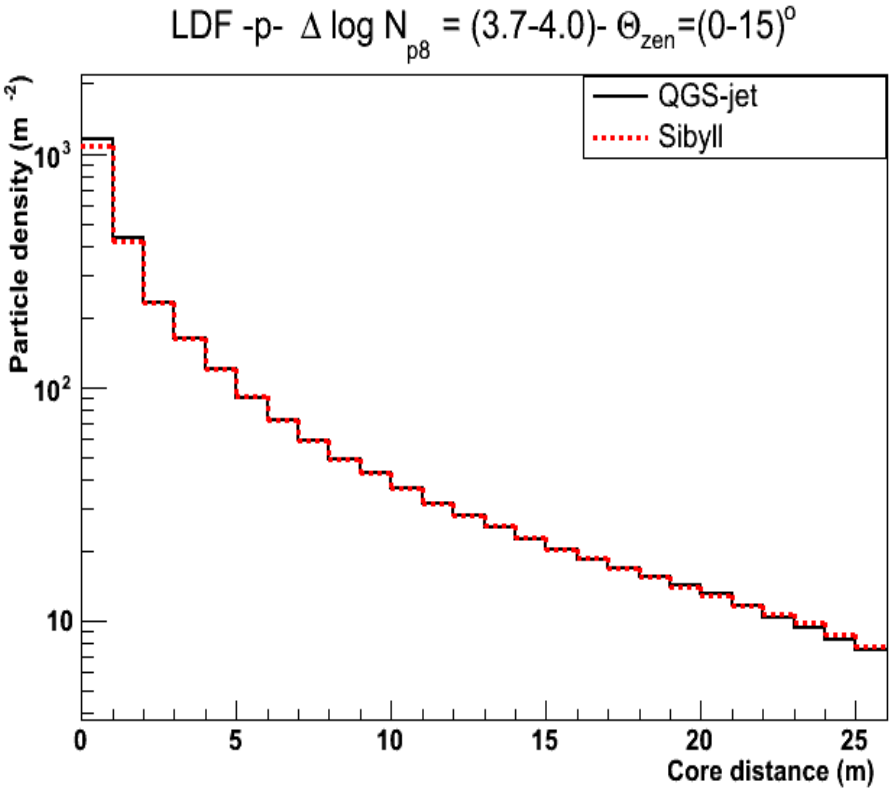
On the efficiency plateau above 200TeV

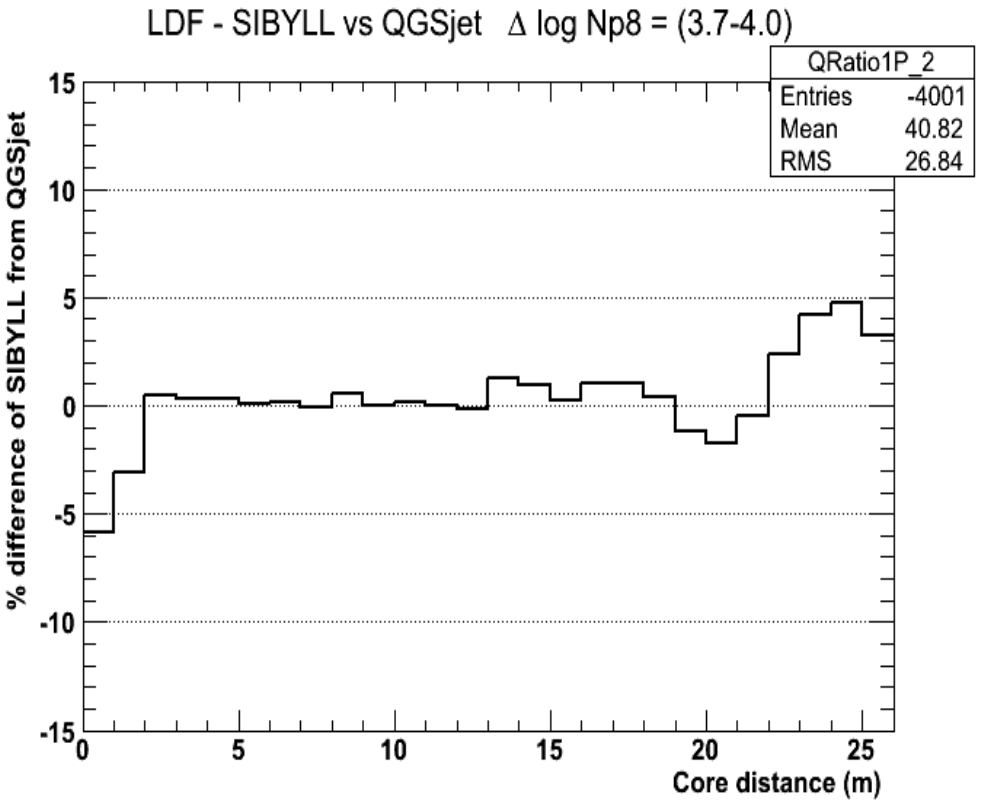


Energy range for p+He spectrum measurement with G1

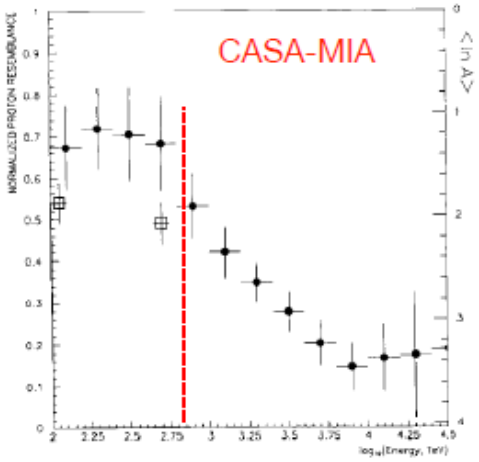
Systematics from the hadronic interaction models

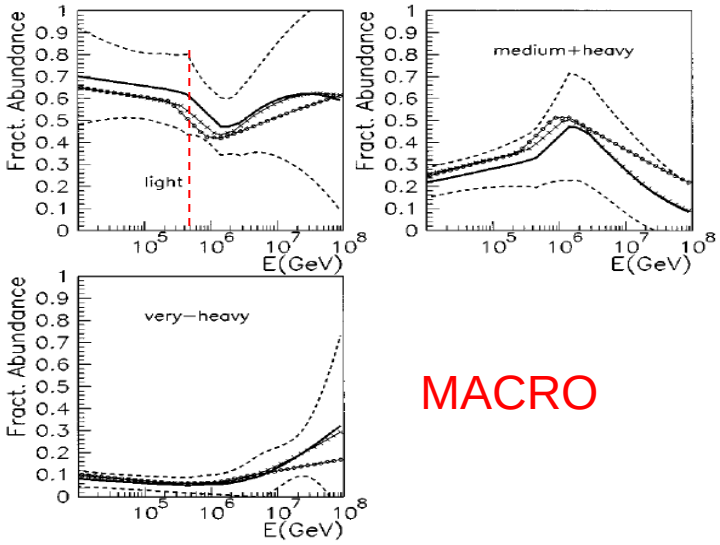
The dependence on the adopted hadronic interaction model is small.
The differences among the QGSJET-II.03 and Sibyll-2.1 are within few percent in the explored energy range (no bias due to muon number).
All further results shown here were obtained with QGSJET-II.03.





(Some of the) Previous hints





MACRO

- CASA-MIA
- CHACALTAYA
- MACRO
- EAS-TOP + MACRO
- Delayed hadrons
- …….