The cosmic ray energy spectrum in the range 10^{16} - 10^{18} eV measured by KASCADE-Grande

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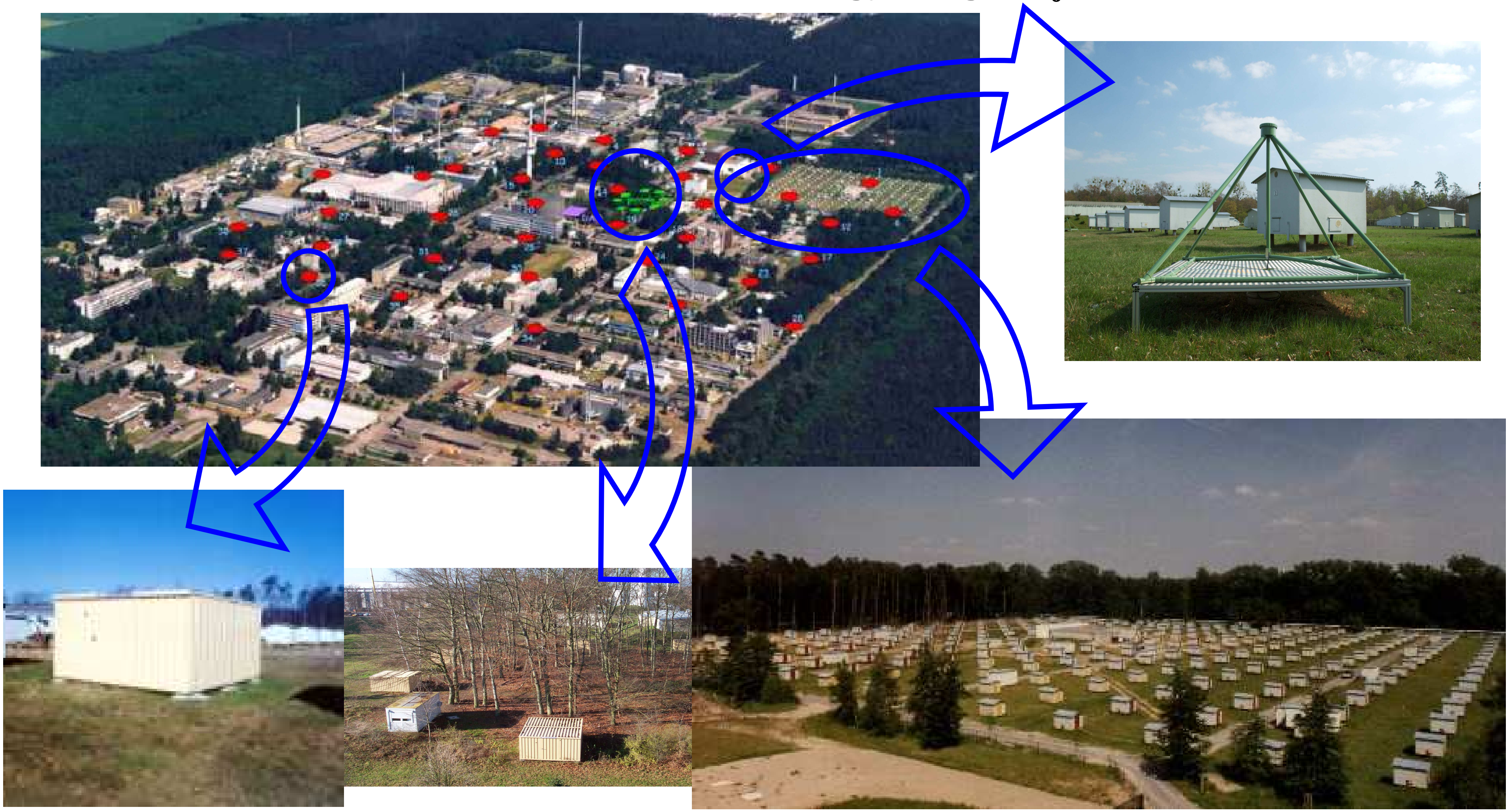
*deceased

KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

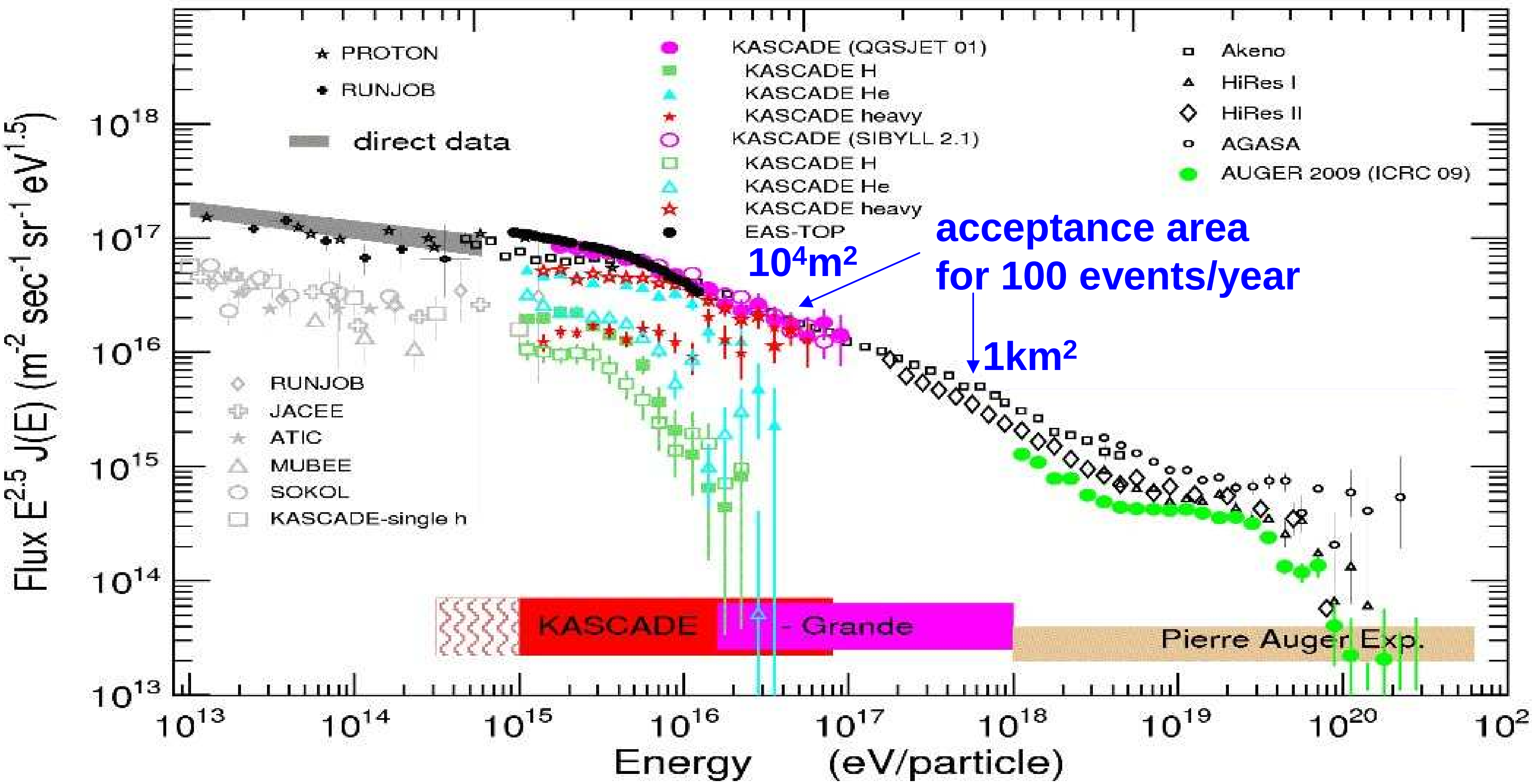
Measurements of air showers in the energy range E_0 = 100 TeV - 1 EeV



Motivations for the KASCADE-Grande experiment

The range $10^{16} - 10^{18}$ eV is crucial for different reasons:

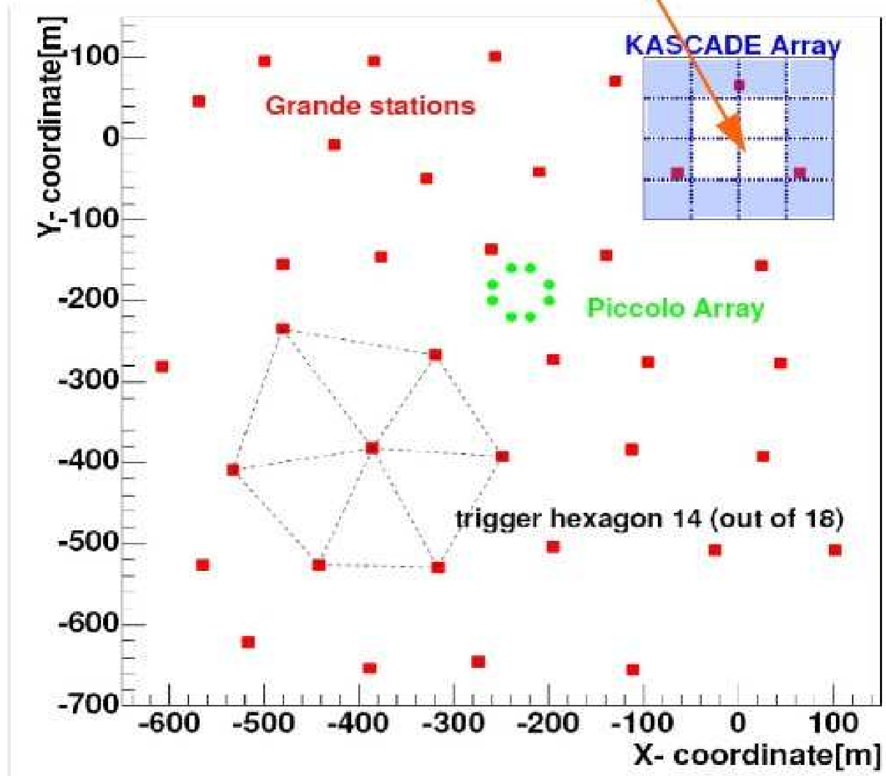
- complete “knee” studies
- investigate galactic-to-extragalactic transition
- hadronic interactions
- anisotropies



KASCADE-Grande features and performances

- KASCADE:
  → energy range $10^{14} – 10^{16}$ eV
  → 252 detector stations over 200x200 m^2
  → in a station: measurement of e and μ separately with two co-located types of detector scintillators

- Grande:
  → 37 detector stations 10 m^2 each spread over 700 x 700 m^2
  → in a station: measurement of all-charged e + μ
  → 18 hexagonal clusters. 7 out-of-7 coincidence triggers data acquisition



Upper view and Bottom view of a Grande station

A standard event

- Recorded on July 8 2005 at 12:11 UTC
- Core: (-155, -401) m
- $\log_{10}(N_{ch}) = 7.0$
- $\log_{10}(N_{\mu}) = 5.7$
- Zenith : 24.2°
- Azimuth: 28.4°

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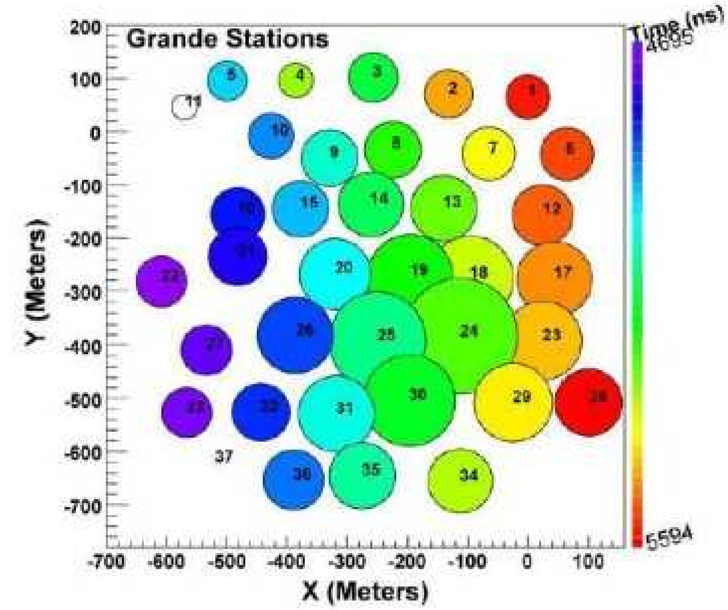
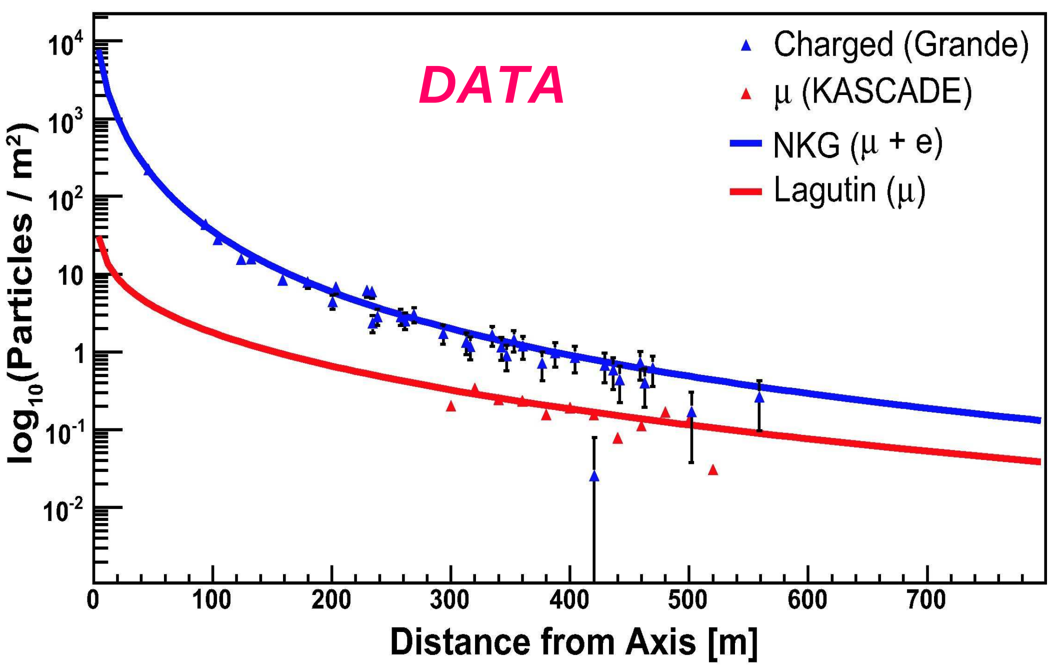
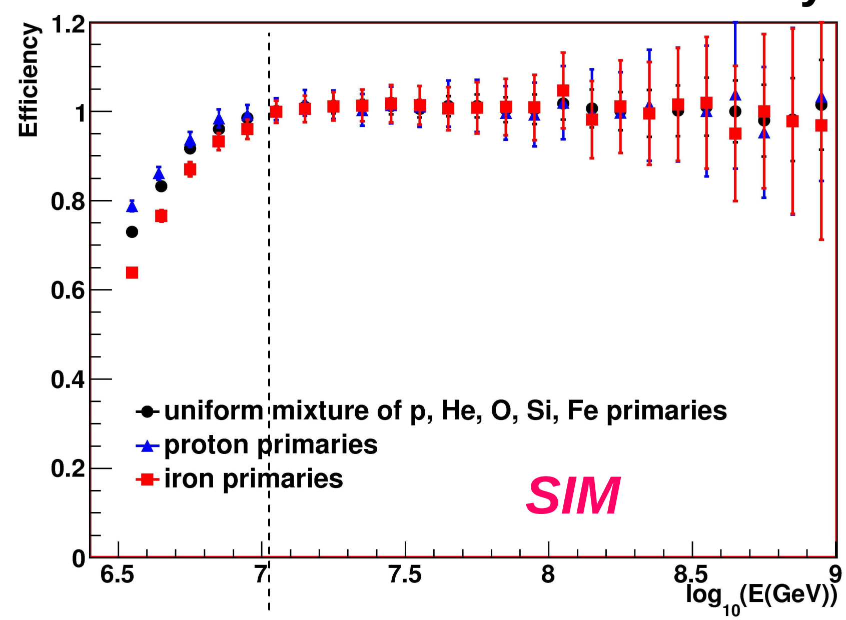


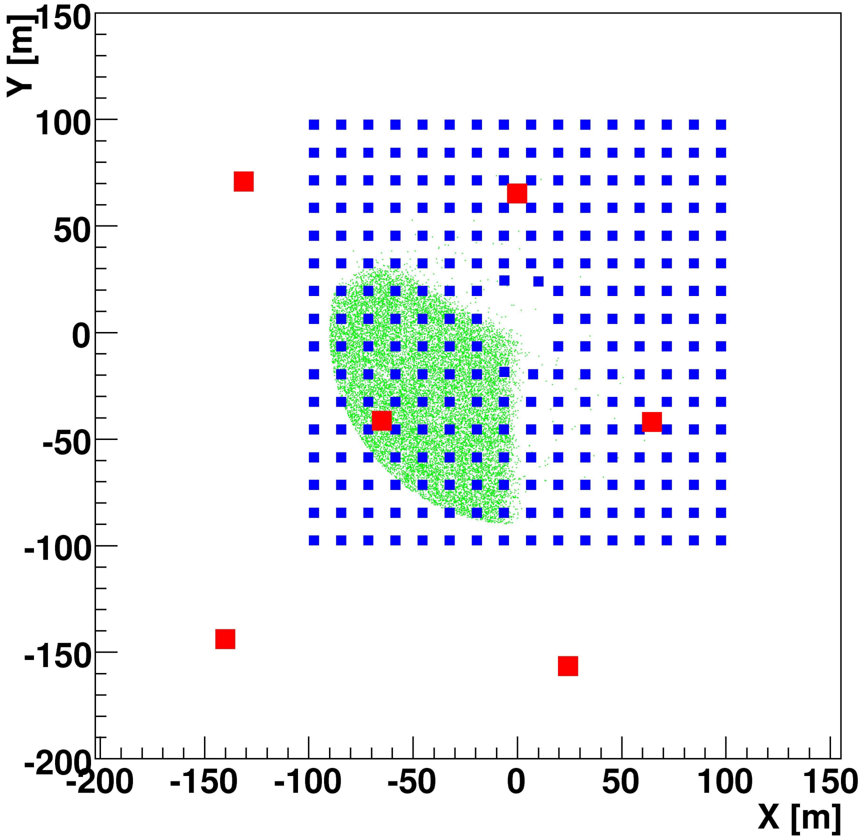


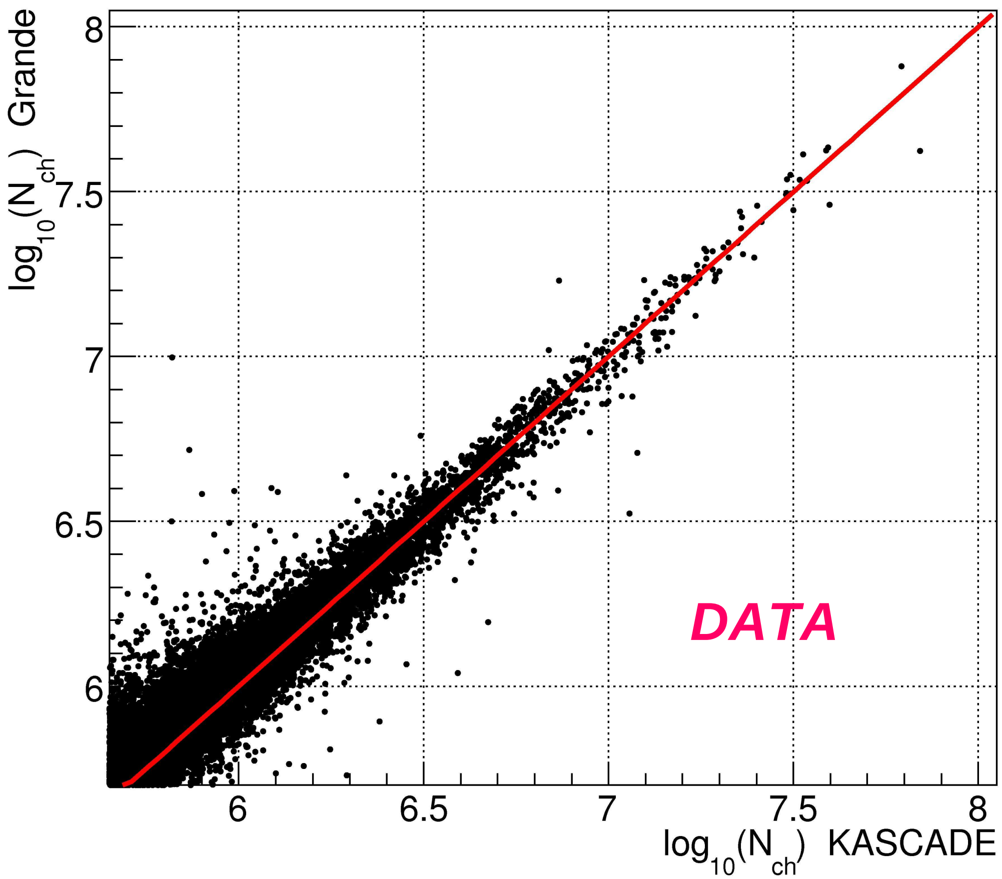
KASCADE-Grande efficiency



10^{16}eV

Cross-check between KASCADE and Grande





■ KASCADE stations

■ Grande stations

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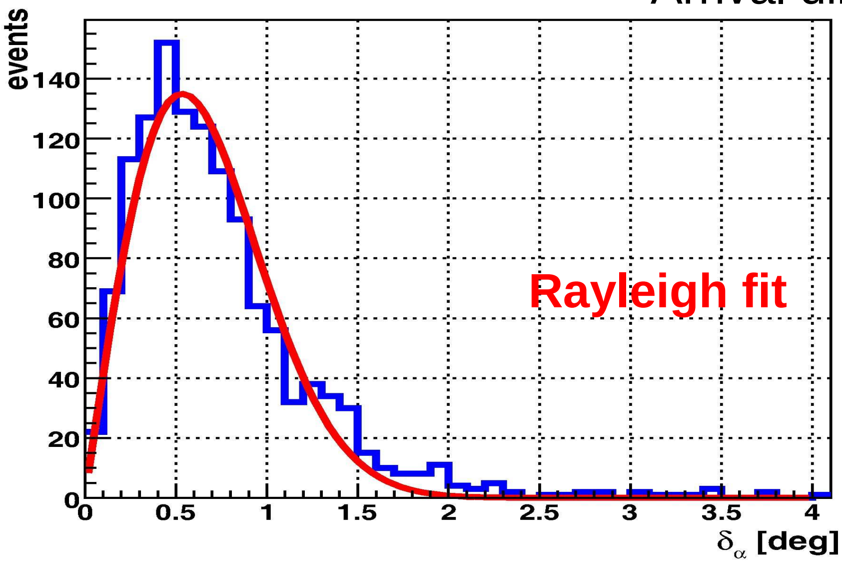
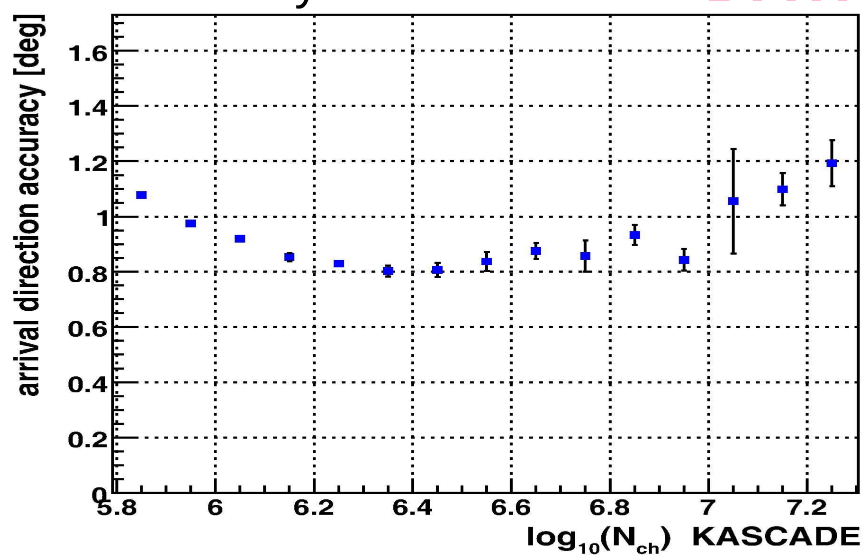
Good agreement between the reconstruction accuracies of the 2 detectors

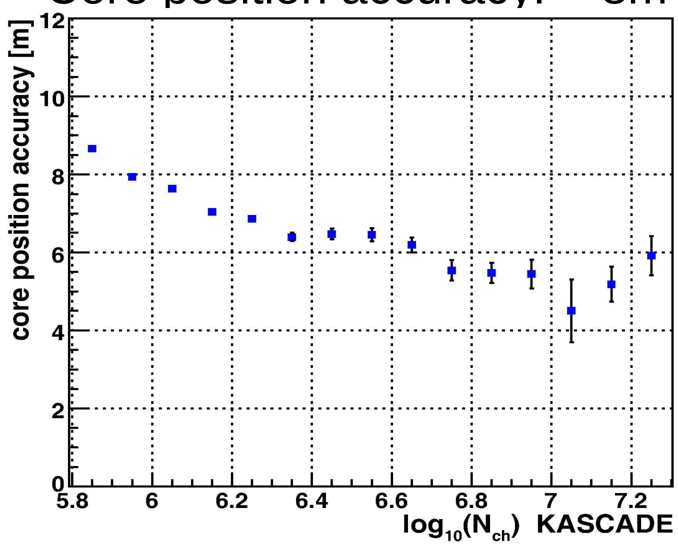
Arrival direction accuracy <1°

DATA

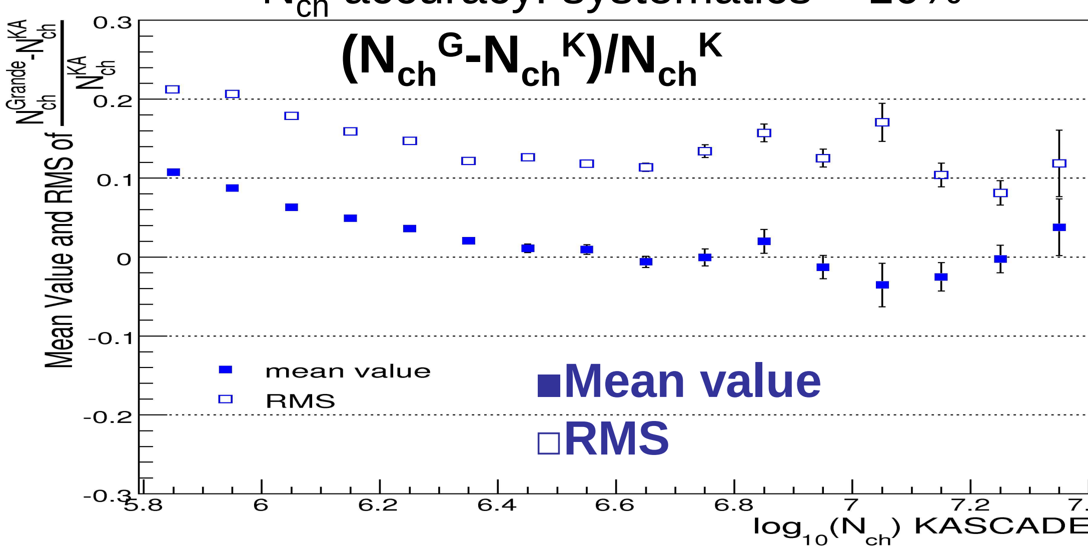




Core position accuracy: < 8m



N_{ch} accuracy: systematics < 10%



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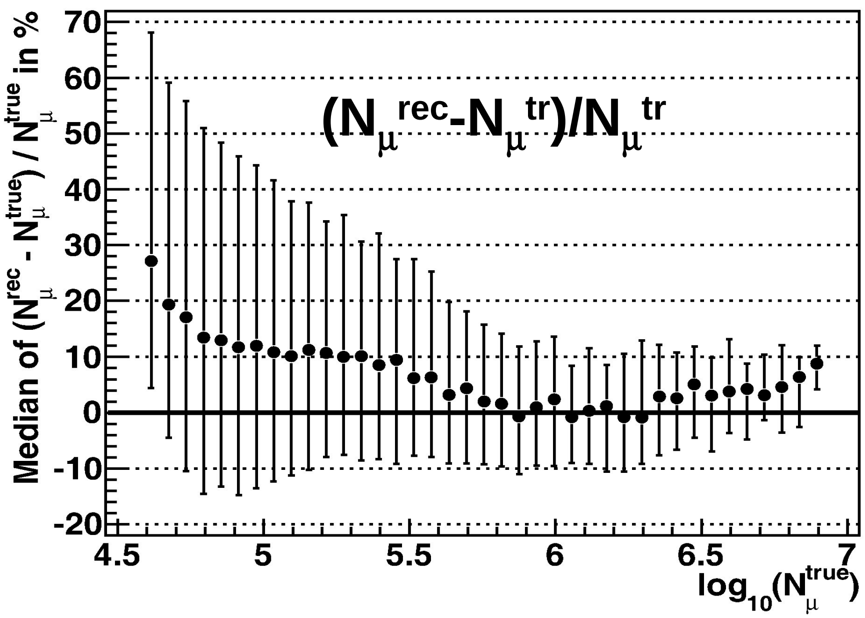
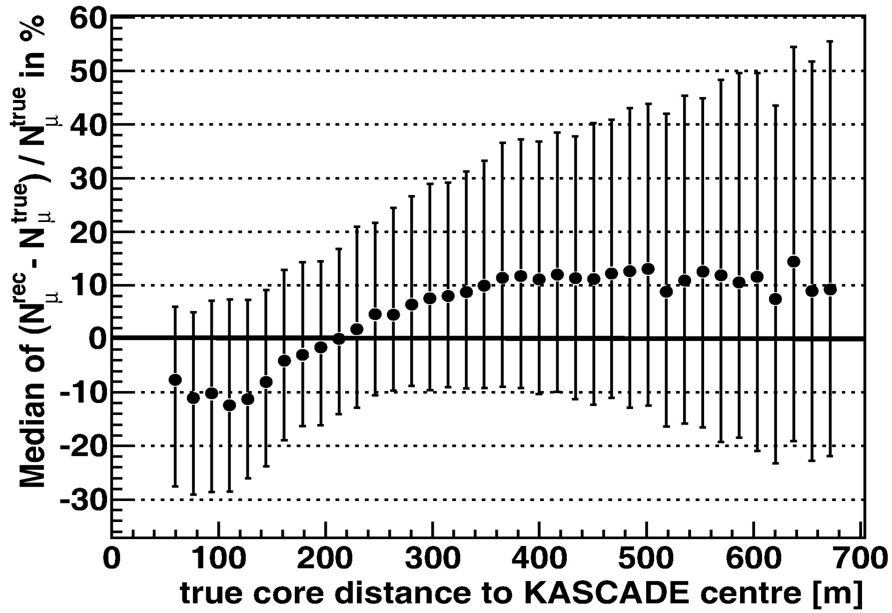
Muon reconstruction (from simulation QGSjet II & FLUKA)

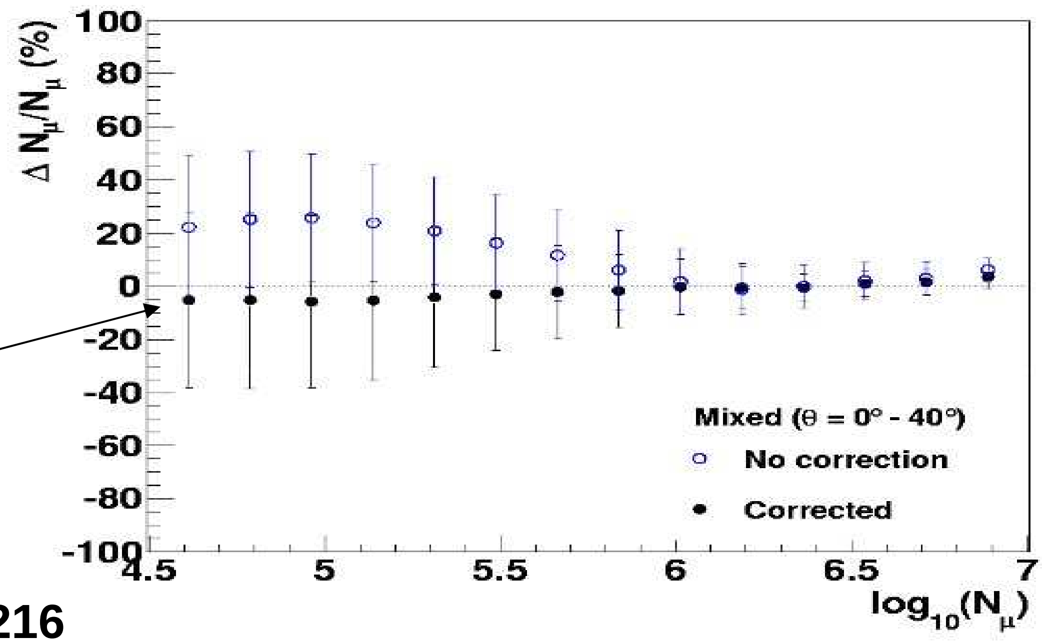




$(N_\mu^{rec}-N_\mu^{tr})/N_\mu^{tr} < 20\%$

SIMULATION

After applying
muon correction functions



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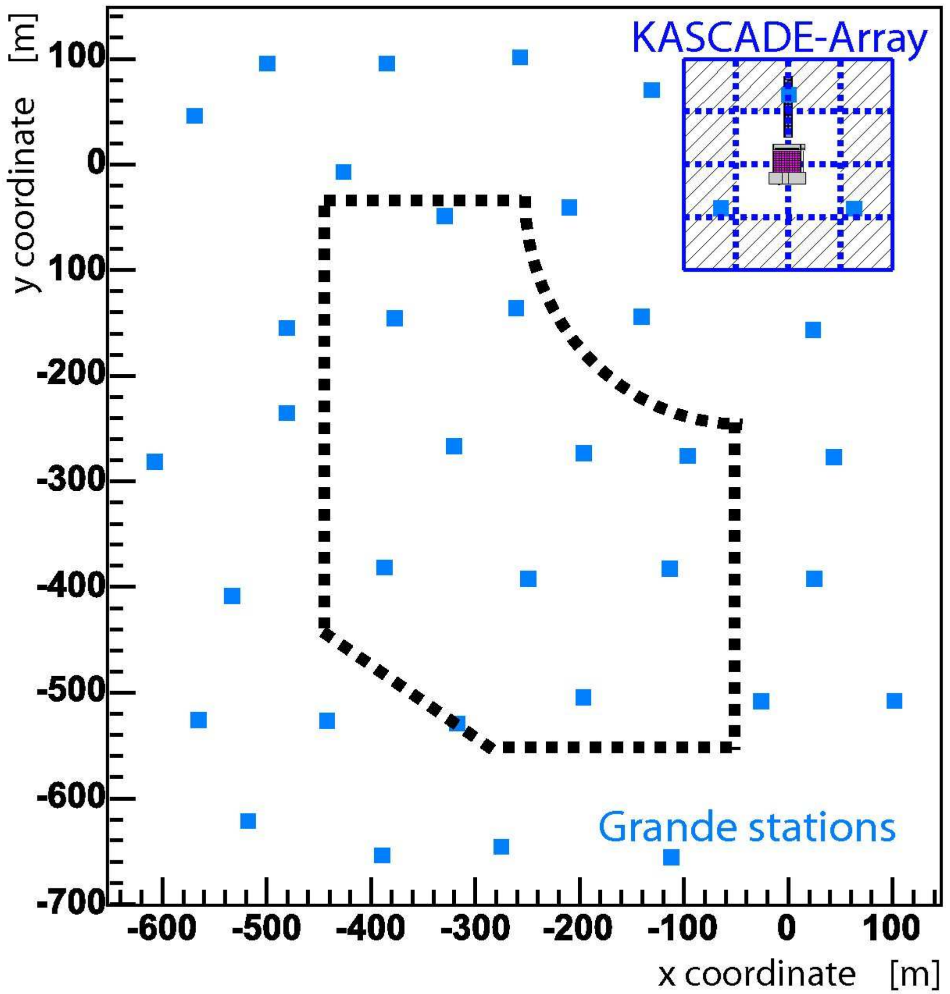
Selection area for the energy spectrum



- **1173 days of effective DAQ time.**
- **Performance of reconstruction and detector is stable.**
- **$\theta < 40°$**
- **Exposure: $2 \cdot 10^{17}$ $cm^2 \cdot s \cdot sr$**

Reconstruction of the energy spectrum

We use three different methods:

- **N_{ch} as observable**
- **N_{μ} as observable**
- **Combination of N_{ch} and N_{μ} as observables**

↓

- **Cross check of reconstruction procedures**
- **Cross check of systematic uncertainties**
- **Test sensitivity to composition**
- **Cross check of validity of hadronic interaction models**

If not explicitly mentioned in the following CORSIKA QGSjetII/FLUKA interaction model is used

***additional method to reconstruct the energy spectrum employs the particle density at 500 m (S500) (see G. Toma's poster on Thursday's morning - Session 4)**

Pro & cons of the methods

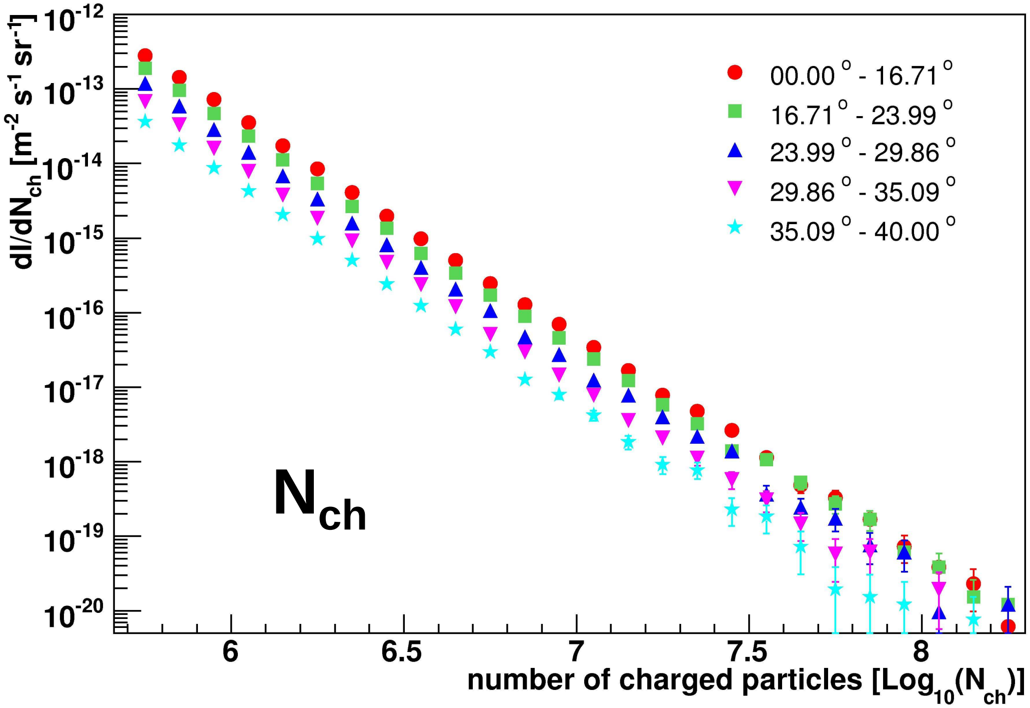
N_{ch} or N_{μ} alone:

- **Constant intensity cut method**
- **Correction for atmospheric attenuation is model independent**
- **Calibration function QGSjet II: shower size (N_{ch} or N_{μ}) vs E**
- **Composition dependent**

N_{ch} & N_{μ} combined:

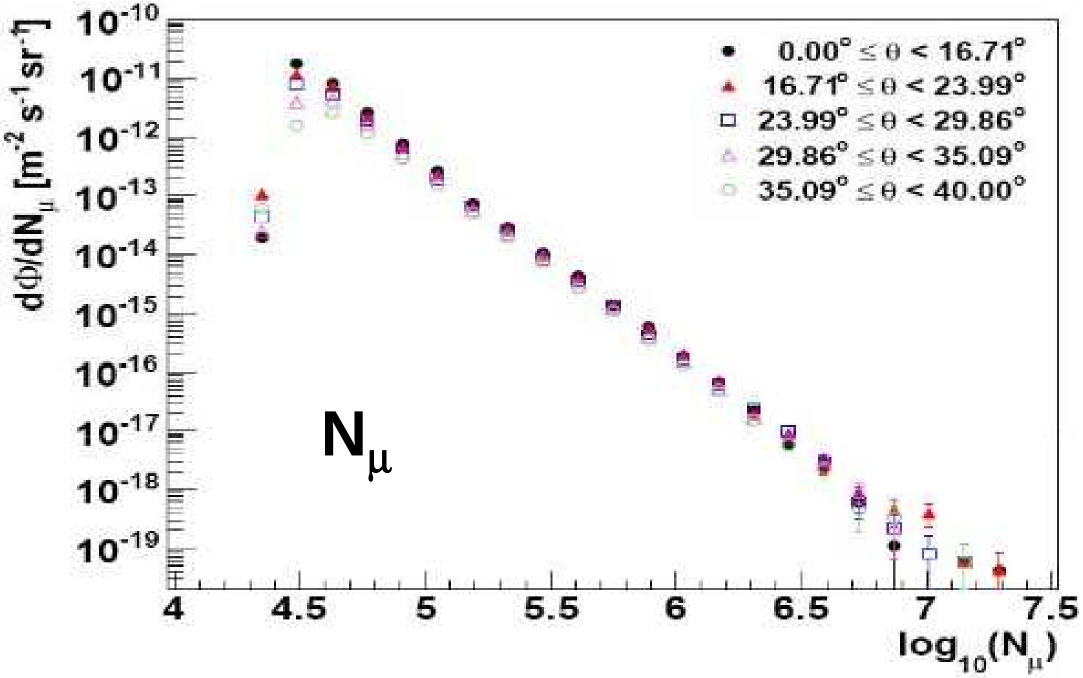
- **Composition independent**
- **Correction for atmospheric attenuation is model dependent**
- **Calibration function is N_{ch}-N_{μ} vs E**

Size spectra

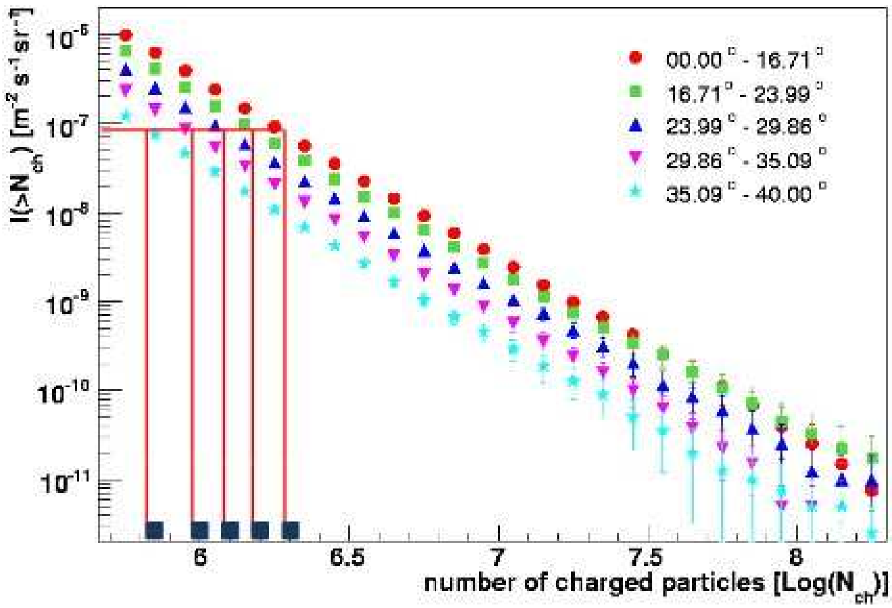


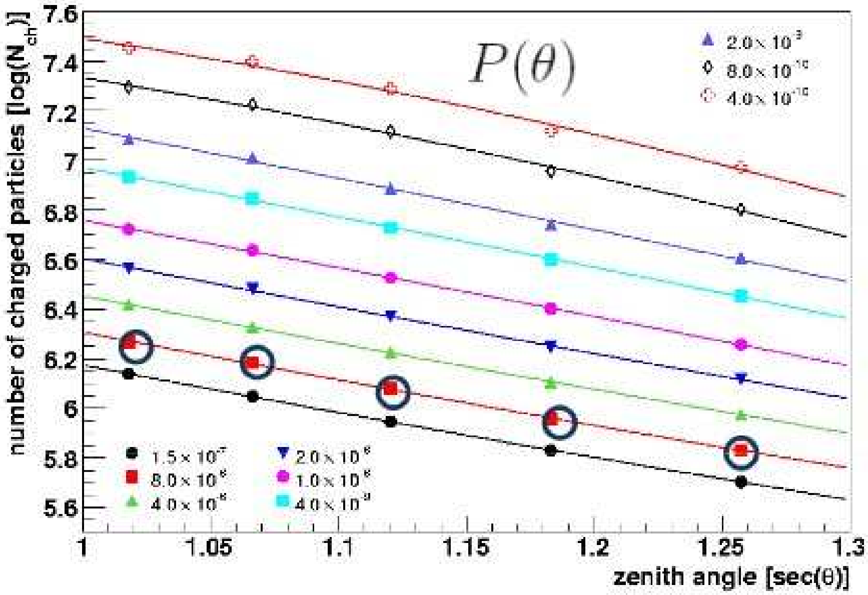
to be corrected for attenuation curves

DATA



The Constant Intensity Cut Technique



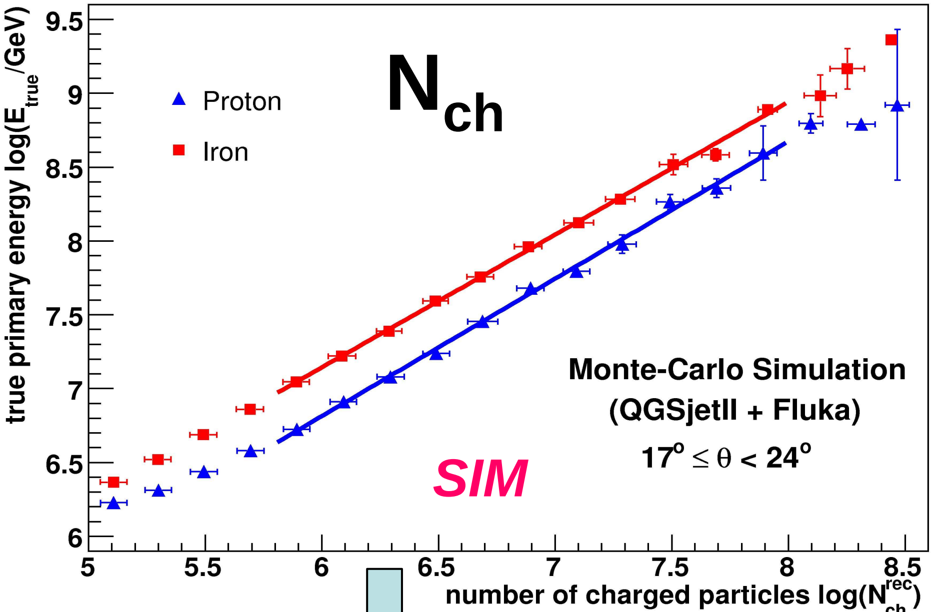


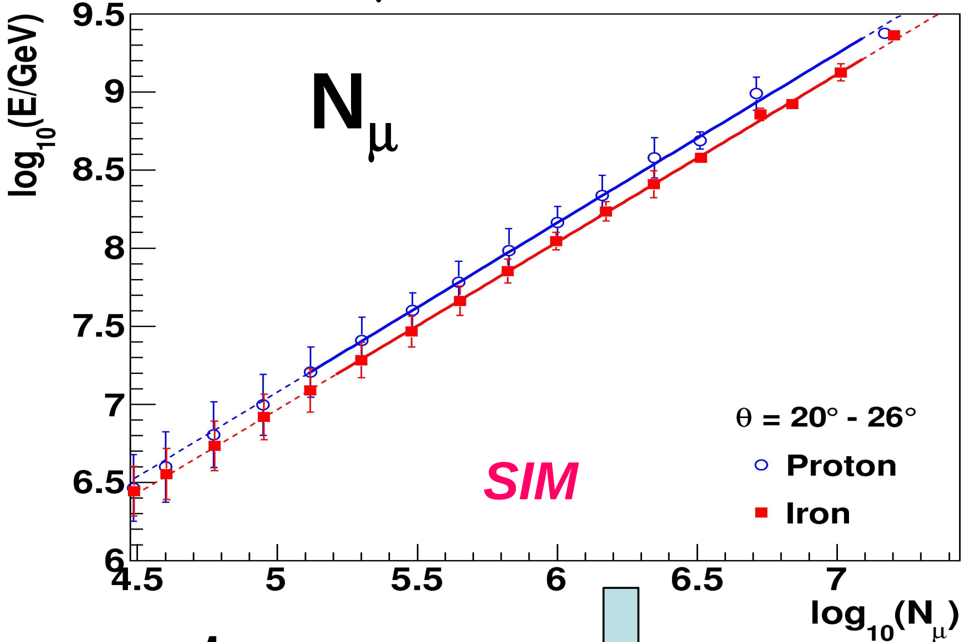
$$N_{ch(\mu)}(\theta_{ref}) = N_{ch(\mu)}(\theta) \exp\left[P(\theta_{ref}) - P(\theta)\right]$$

Shower size is normalized at a specific angle (around 20 deg.)

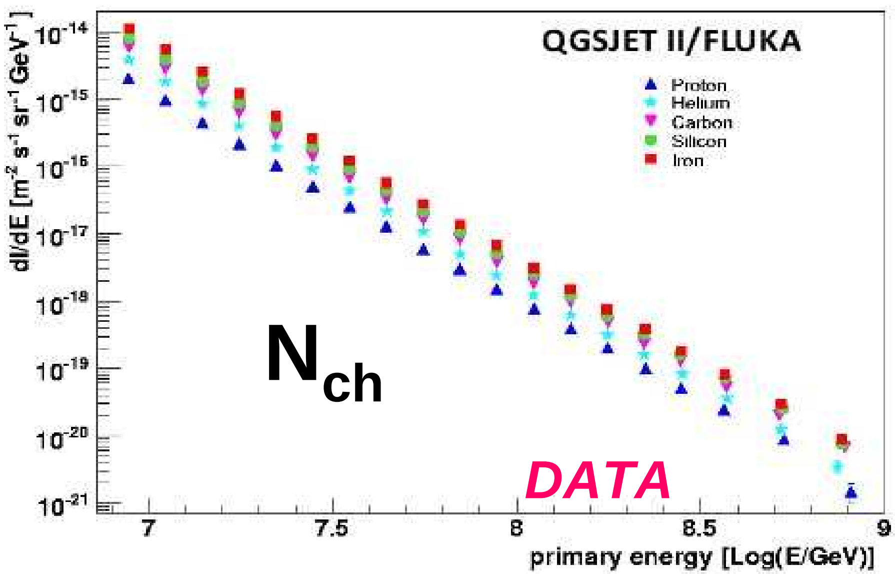
DATA

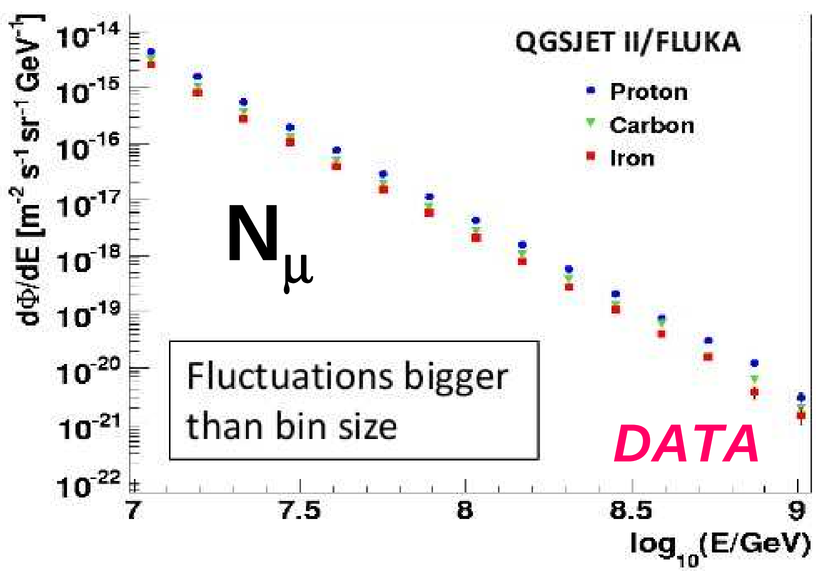
$E = a + b \cdot \log_{10}(N_{ch,\mu})$





Energy spectra

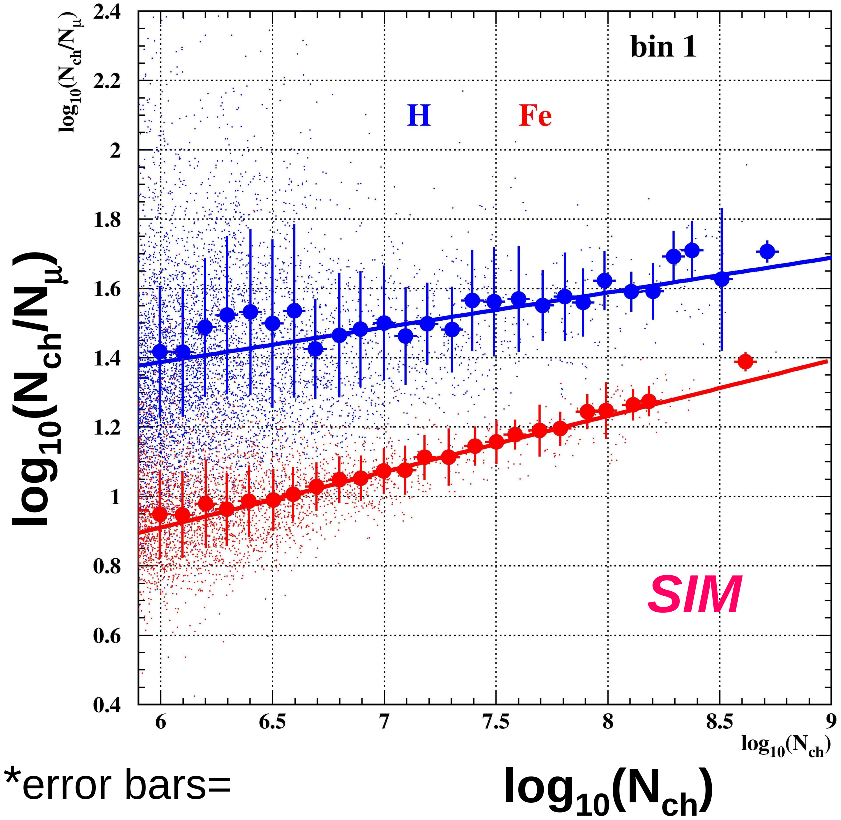




$N_{ch} - N_\mu$ technique

5 angular bins treated independently

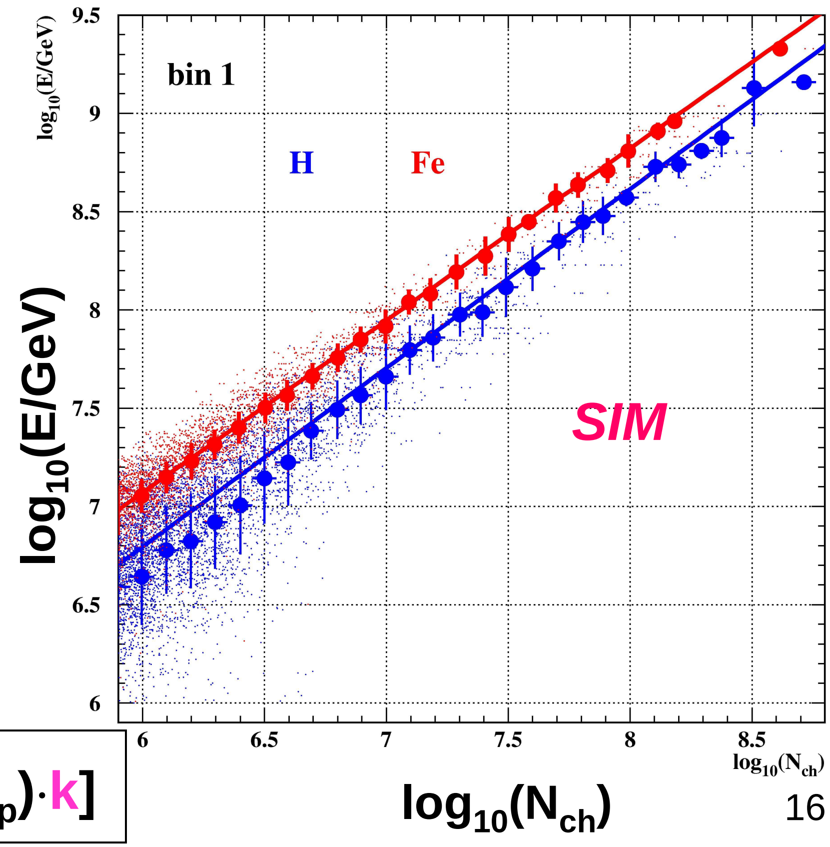
$$\log_{10}(N_{ch}/N_\mu)_{p,Fe} = c_{p,Fe}\log_{10}N_{ch} + d_{p,Fe}$$



*error bars=
RMS of distributions

$$k = \frac{\log_{10}(N_{ch}/N_\mu) - \log_{10}(N_{ch}/N_\mu)_p}{\log_{10}(N_{ch}/N_\mu)_{Fe} - \log_{10}(N_{ch}/N_\mu)_p}$$

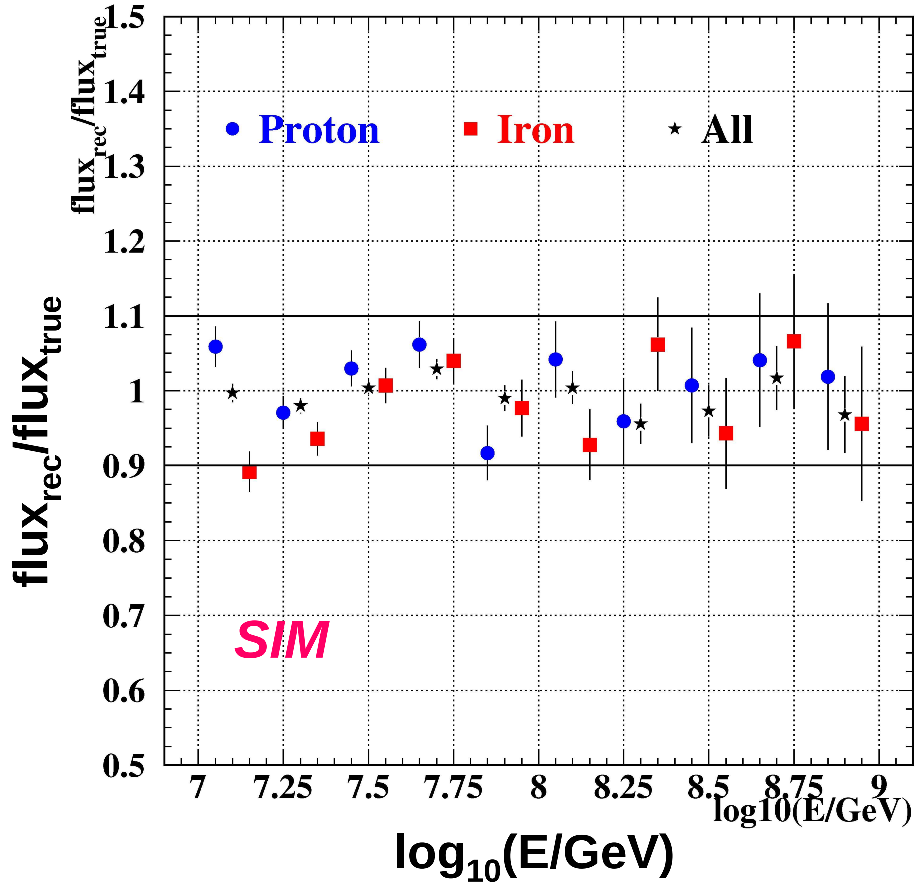
$$\log_{10}E_{p,Fe} = a_{p,Fe}\log_{10}N_{ch} + b_{p,Fe}$$

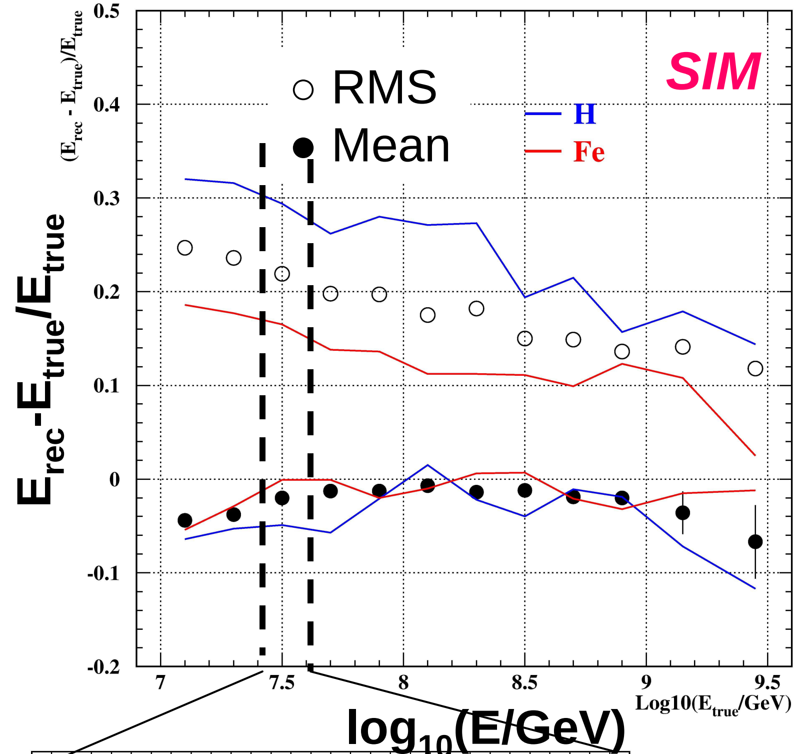


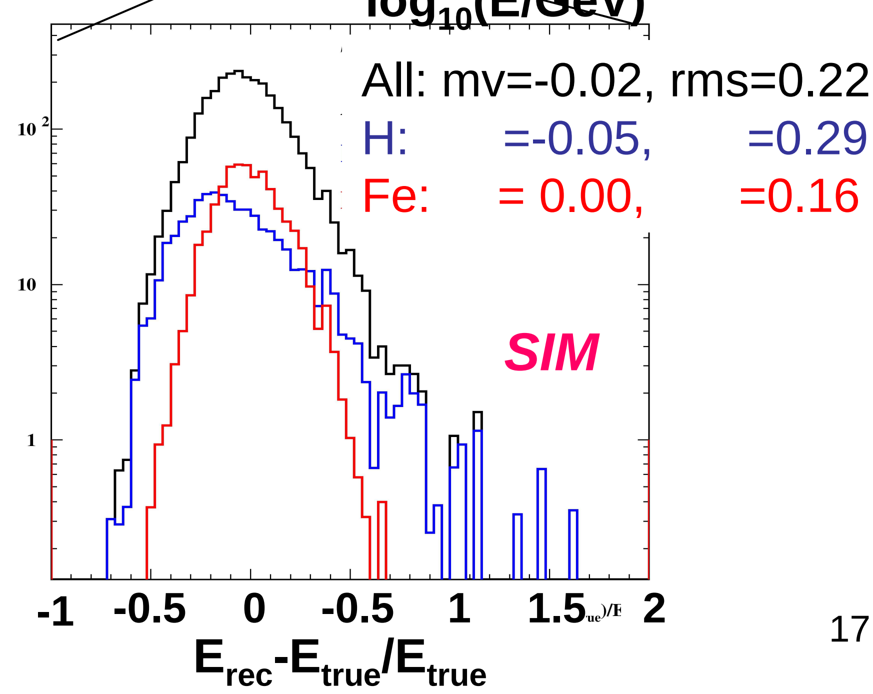
$$\log_{10}E = [a_p + (a_{Fe} - a_{,p})]\cdot k \cdot \log_{10}(N_{ch}) + [b_p + (b_{Fe} - b_p)\cdot k]$$

Check of resolutions and systematics using MC simulations

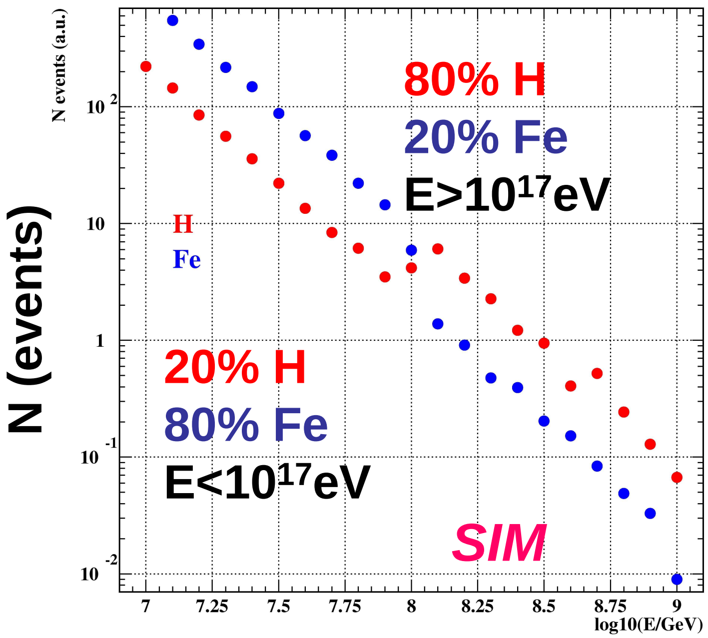
Reconstructed/True flux

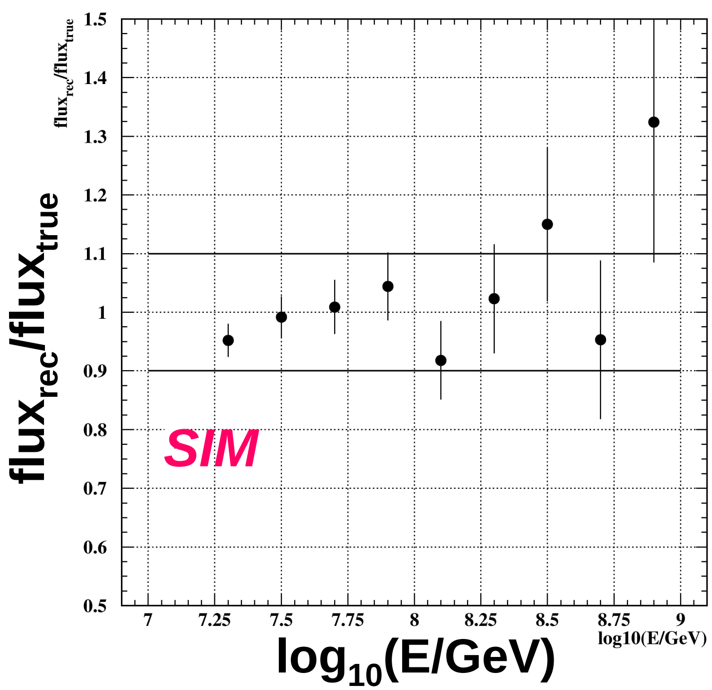






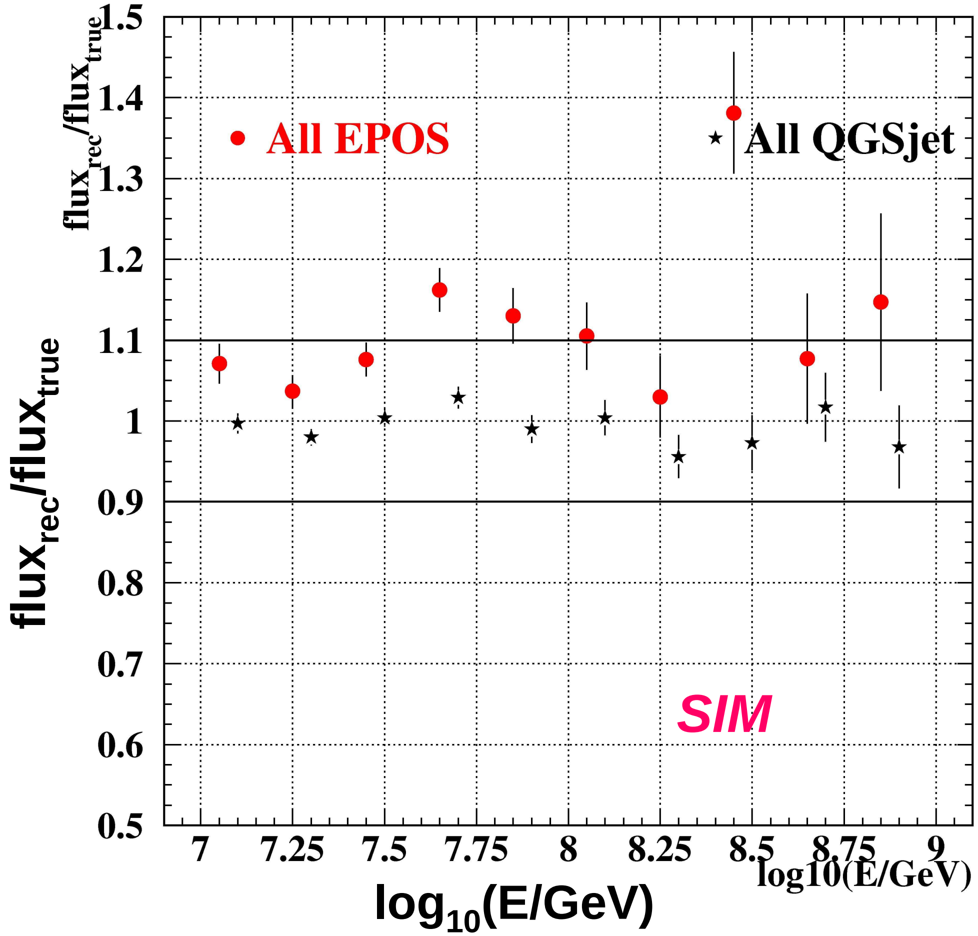
Simulation: extreme case



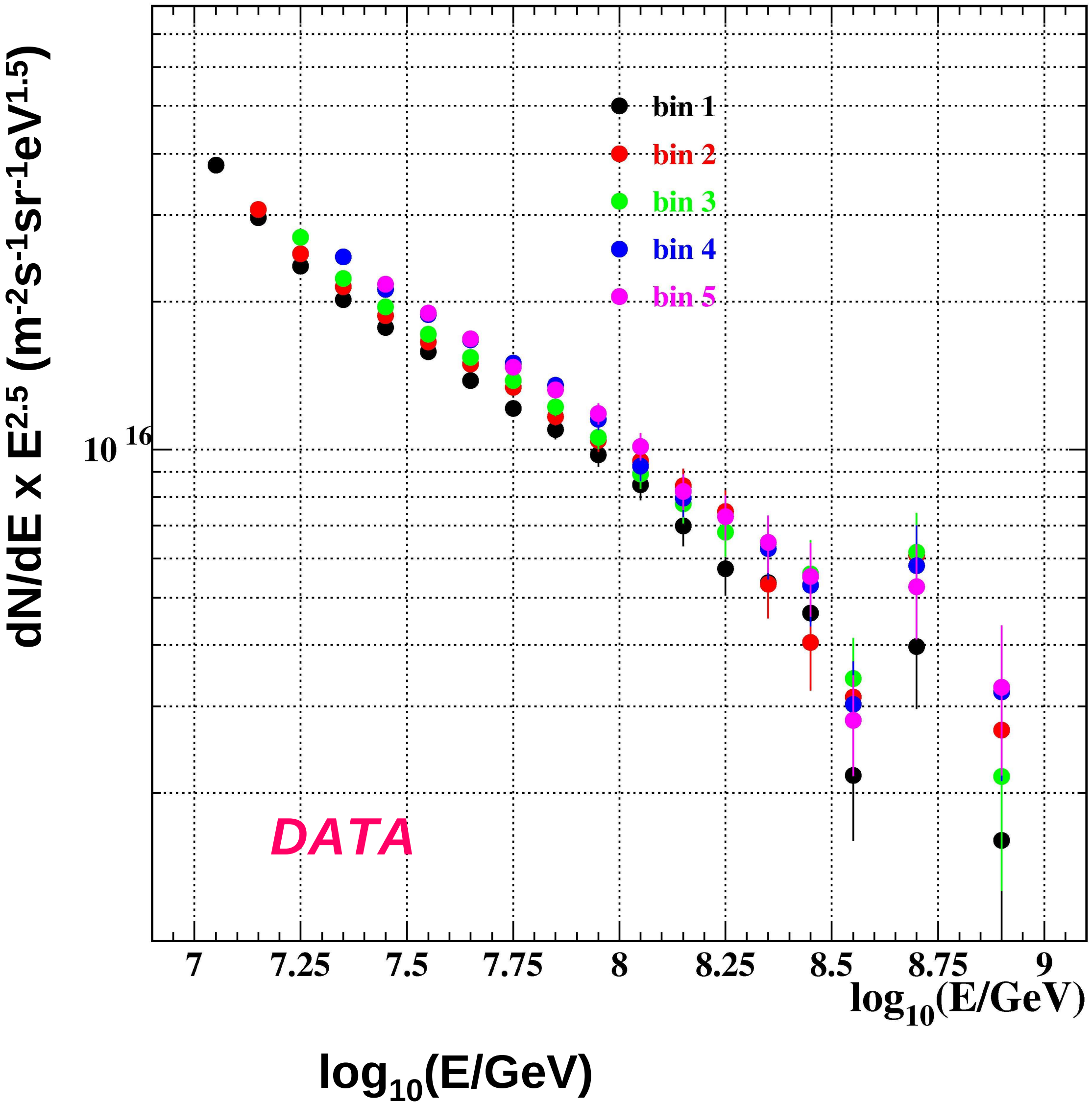


SIMULATIONS

Effect of Hadronic interaction model: EPOS data treated as exp. data and analyzed using QGSjet II



Experimental data

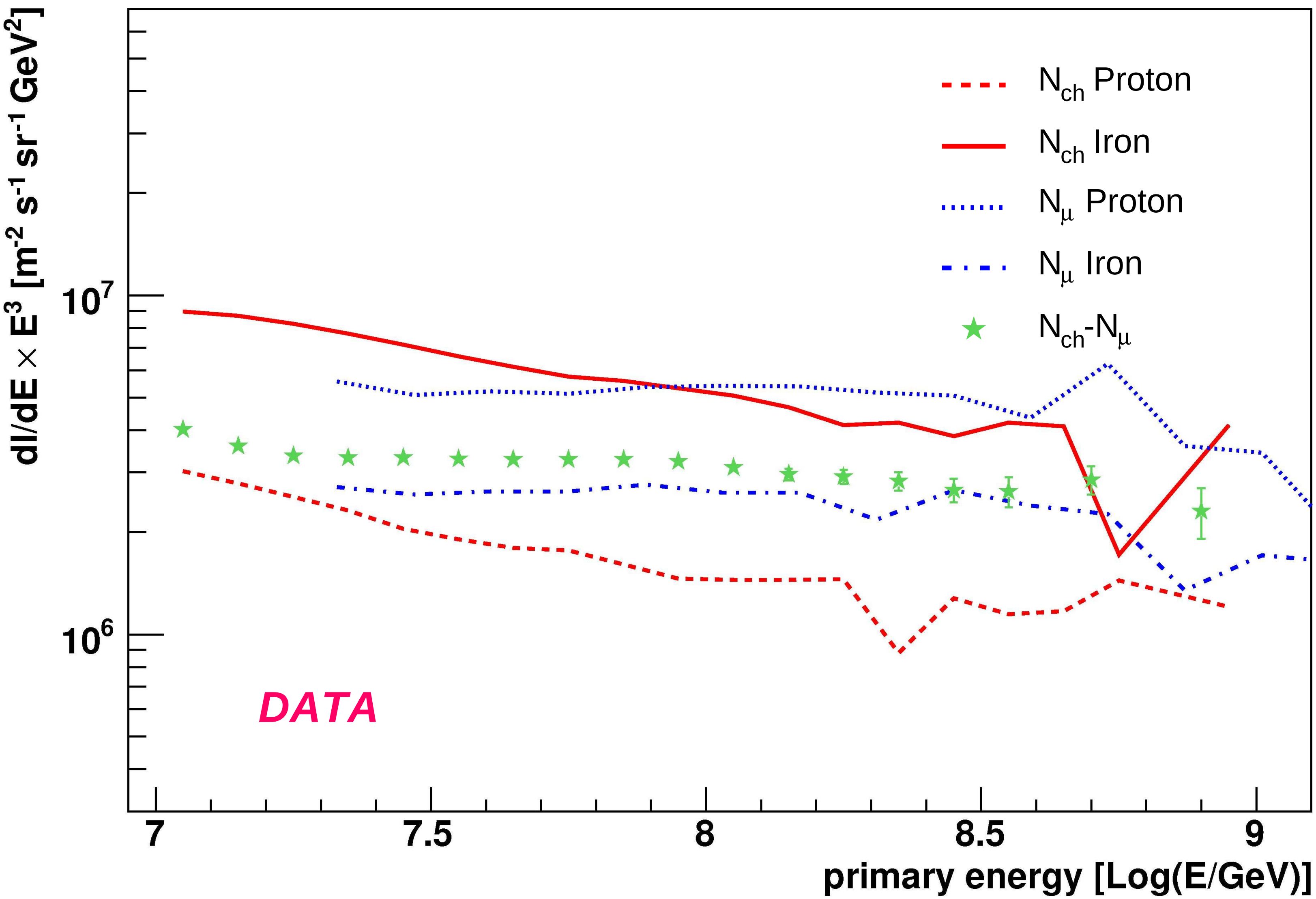


Bin 1 0.0 < θ < 16.7
Bin 2 16.7 < θ < 24.0
Bin 3 24.0 < θ < 29.9
Bin 4 29.9 < θ < 35.1
Bin 5 35.1 < θ < 40.0

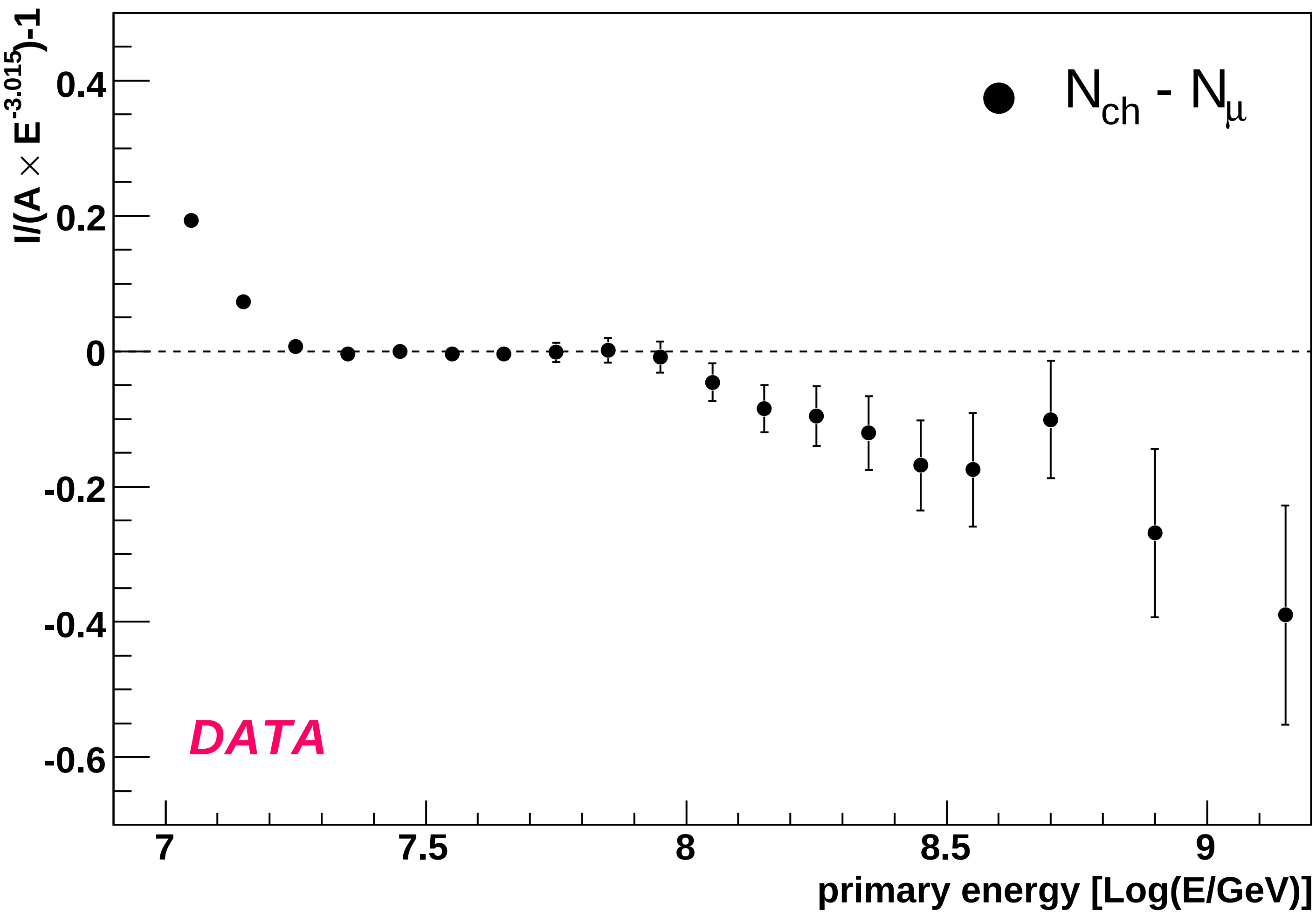
Table of systematics on the flux

Source of uncertainty	**10^{16}eV (%)**	**10^{17}eV (%)**	**10^{18}eV (%)**
Intensity in different angular bins (attenuation)	10.2	9.3	13.0
Calibration & composition	10.8	7.8	4.4
Slope of the primary spectrum	4.0	2.0	2.1
Reconstruction (shower sizes)	0.1	1.3	6.6
TOTAL	**15.4**	**12.4**	**14.7**
Other uncertainties	**%**	**%**	**%**
Sudden knee structures (extreme cases)		<10	
Hadronic interaction model (EPOS-QGSjet)	-5.4	-12.3	-9.5
Statistical error	**0.6**	**2.7**	**17.0**
Energy resolution (mixed primaries)	**24.7**	**18.6**	**13.6**

Comparing the 3 methods (dI/dE x E^3)



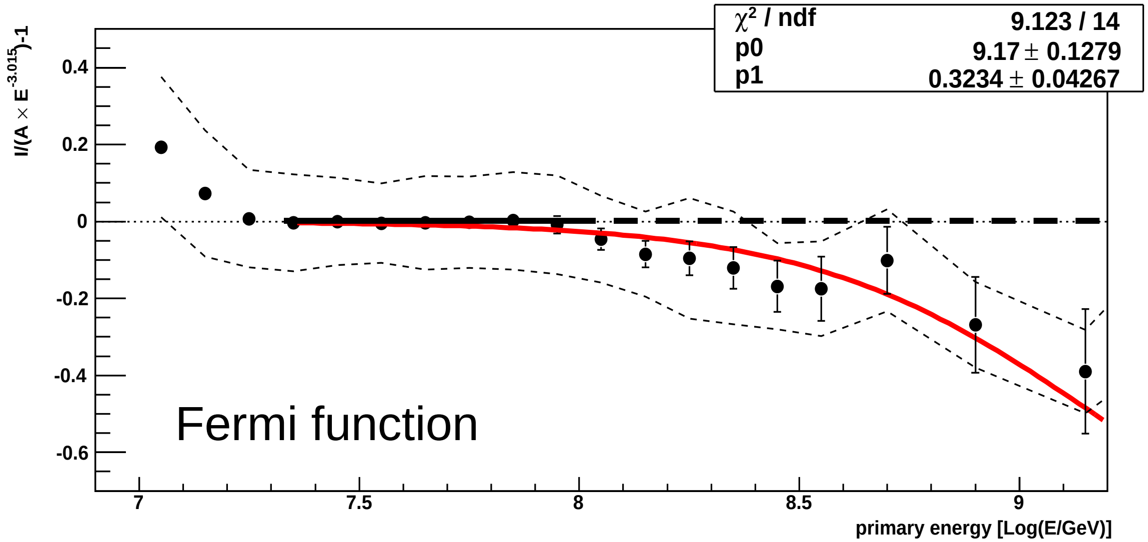
Residual plot



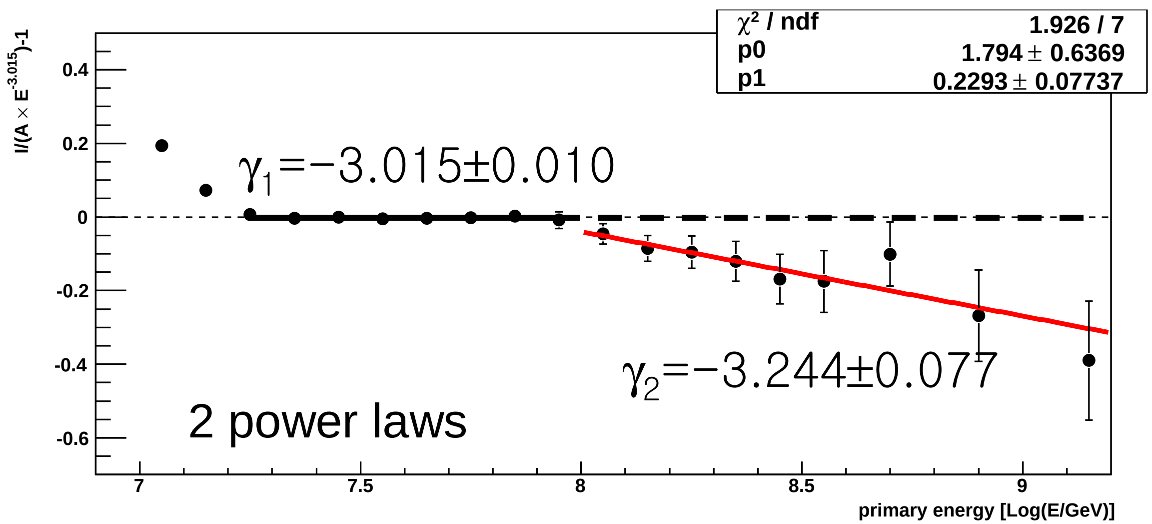
$F_{test} = (\chi^2_{single\ power\ law} / m) / (\chi^2_{function} / n)$, with m,n = ndf single power-law, function

Variance = $2n^2(m+n-2) / m(n-2)^2(n-4)$

Significance in units of the standard deviation = $F_{test} / \sqrt{Variance}$

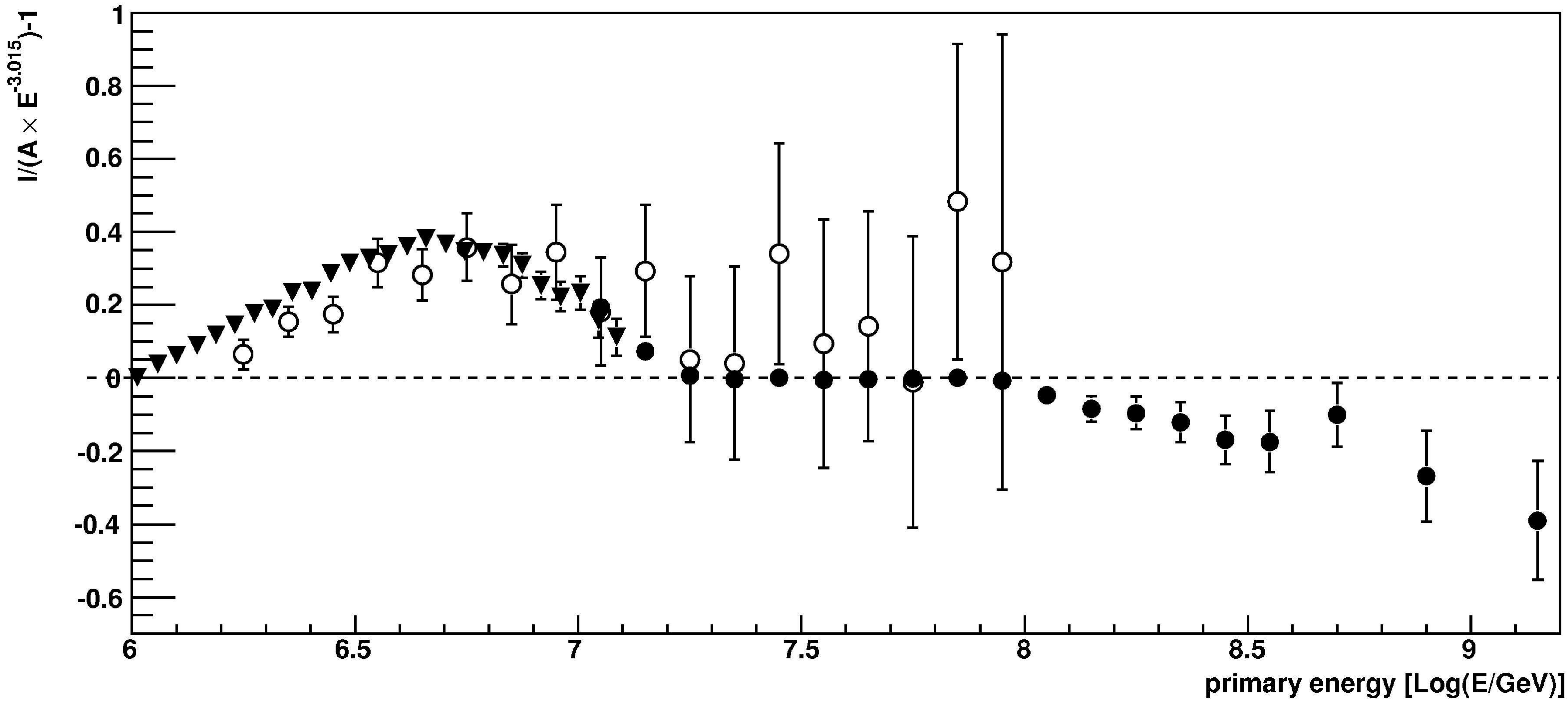


$\chi^2_{single\ power\ law}$ / ndf =2.97
χ^2_{fermi} / ndf =0.65
F_{test} = 4.56
Variance = 0.51
Significance = 6.4 σ



$\chi^2_{single\ power\ law}$ / ndf =2.97
$\chi^2_{2\ power\ laws}$ / ndf =0.49
F_{test} = 6.09
Variance = 0.62
Significance = 7.7 σ

Comparison with KASCADE & EAS-TOP

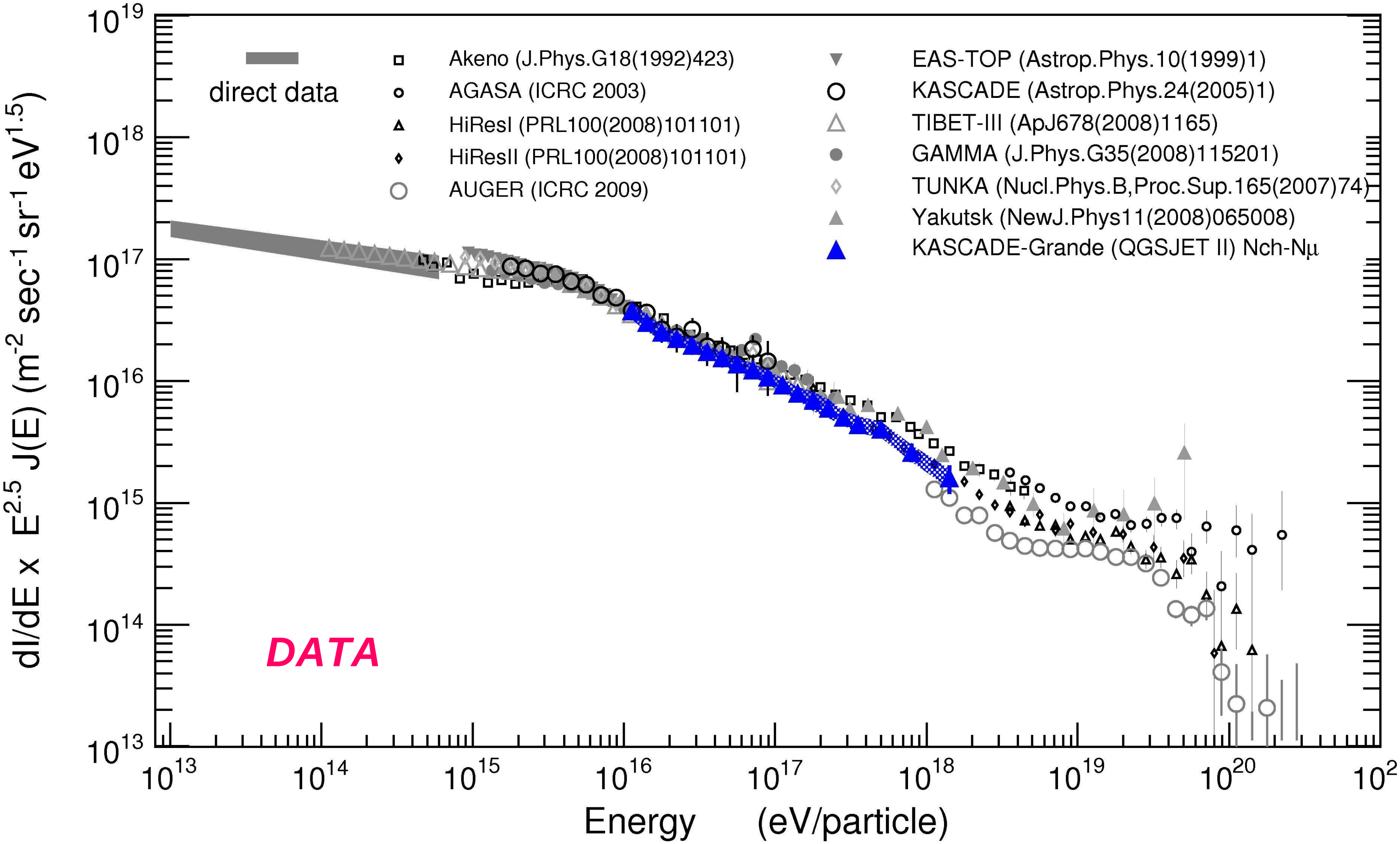


○ KASCADE QGSjet01

▼ EAS-TOP

● KASCADE-Grande QGSjet2

The all-particle energy spectrum



Towards the composition

- The Energy spectrum shows interesting structures.
- The composition analysis is crucial to try to understand their origin.
- The composition analysis is under study using different approaches (all based on N_{ch}-N_{μ} observables and QGSjet model) like we did for the Energy spectrum to have a coherent result and check systematics for each technique:
  - K parameter
  - Separation in light & heavy spectra
  - KNN technique
  - N_{μ}/N_{ch} distributions in bins of N_{ch}
  - unfolding

Conclusions

KASCADE-Grande has collected high quality data in the region 10^{16} – 10^{18} eV region which will be the basis to look for the iron knee and the galactic-extragalactic transition in the cosmic ray spectrum

Recent results of Kascade-Grande regarding the all-particle energy spectrum:

•Agreement with KASCADE & EAS-TOP results at the threshold

•Agreement between different reconstruction approaches

•No single power law

•Structures at the threshold and around 10^{17} eV

•Medium or heavy composition is preferred assuming QGSjetII model

Work is in progress for the composition studies using different approaches:

PLEASE STAY TUNED!