Results from KASCADE-Grande

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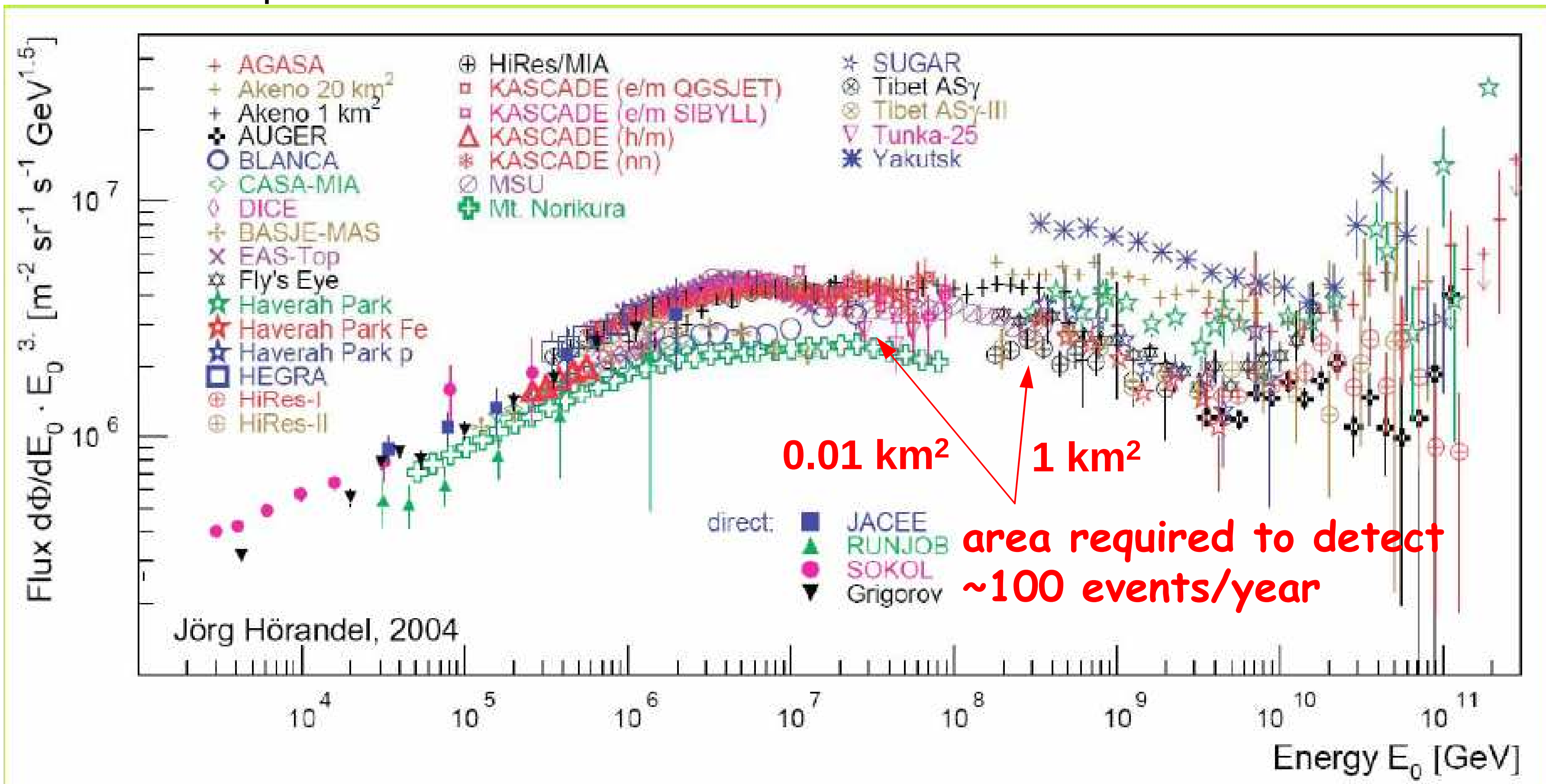
Motivations for the KASCADE-Grande experiment

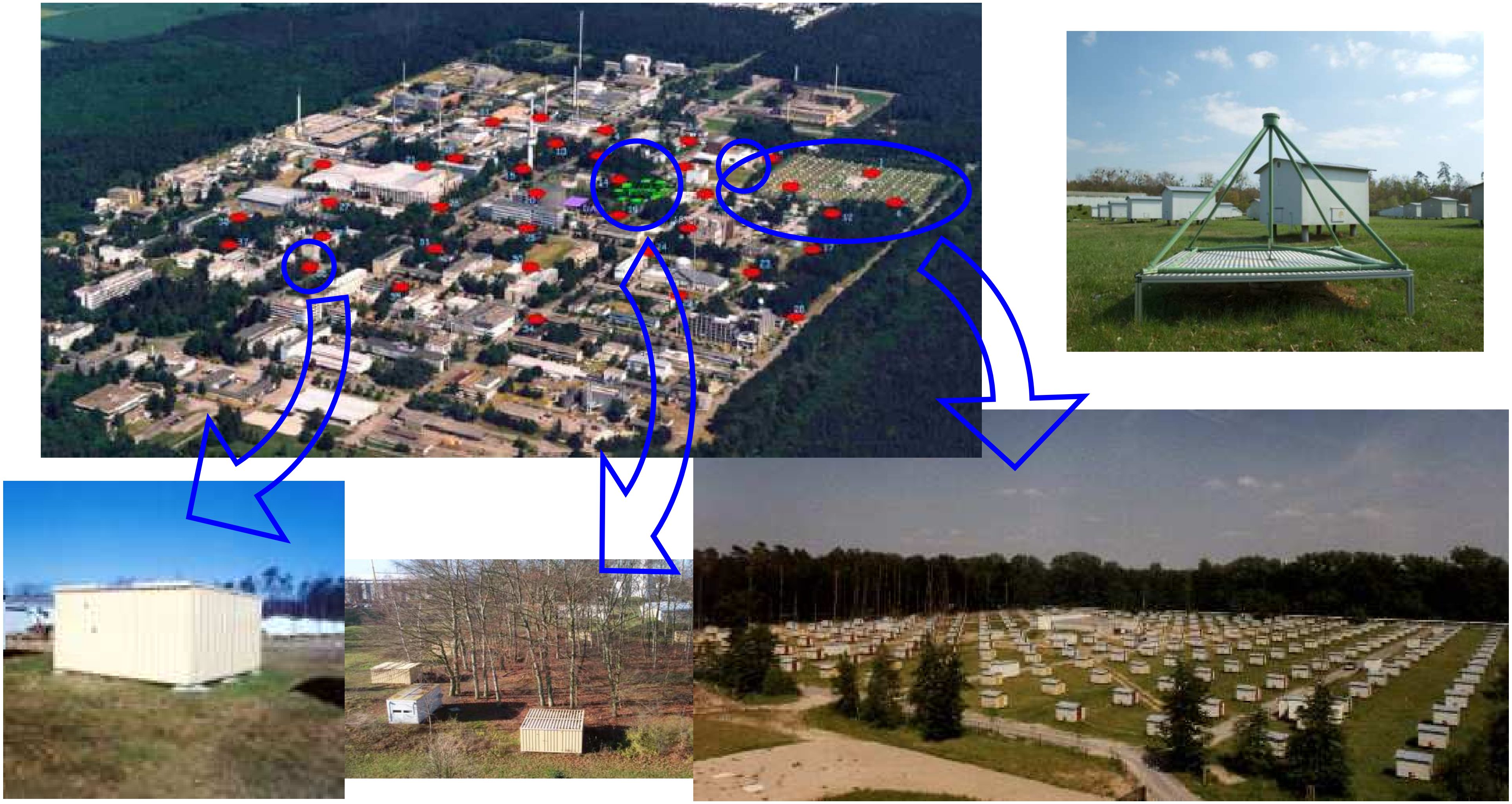
The range $10^{16} – 10^{18}$ eV is crucial for different reasons:

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



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

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



KASCADE-Grande Collaboration

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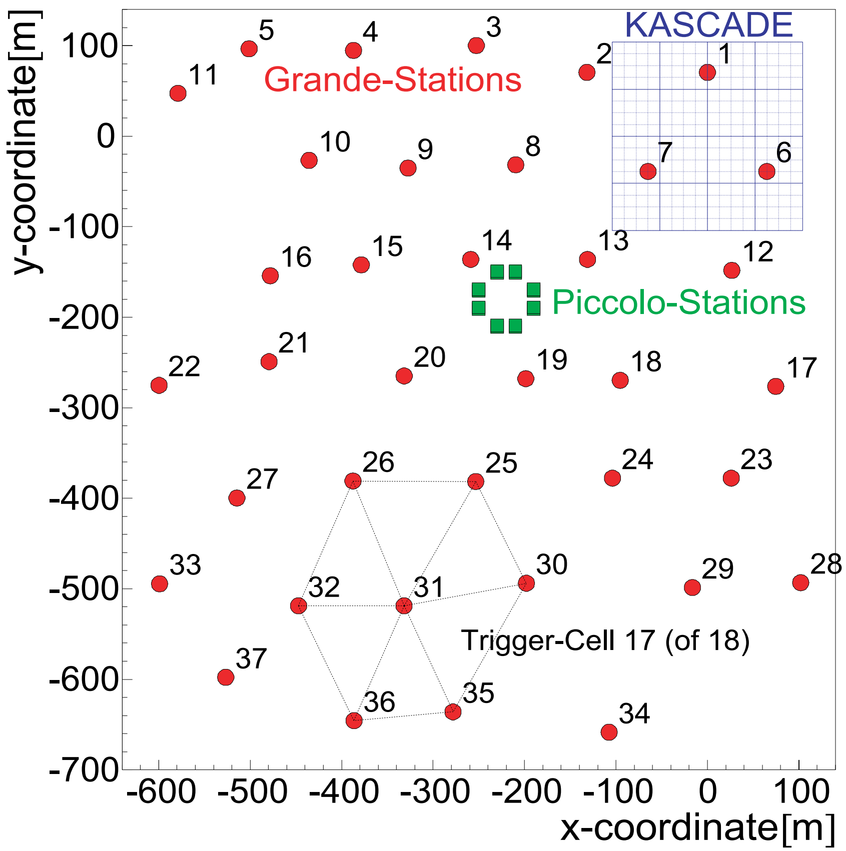
*deceased

KASCADE-Grande detectors & observables



Detector	Detected EAS compone nt	Detection Technique	Detect or area (m^2)
Grande	Charged particles	Plastic Scintillators	37x10
KASCADE array e/γ	Electrons, γ	Liquid Scintillators	490
KASCADE array μ	Muons ($E\mu^{th}$=230 MeV)	Plastic Scintillators	622
MTD	Muons (Tracking) ($E\mu^{th}$=800 MeV)	Streamer Tubes	4x128

- Shower core and arrival direction
  - Grande array
- Shower Size (N_{ch} number of charged particles)
  - Grande array
    - Fit NKG like ldf

- μ Size (E_μ>230 MeV)
  - •KASCADE array μ detectors
    - •Fit Lagutin Function
- μ density & direction (E_μ>800 MeV)
  - •Streamer Tubes

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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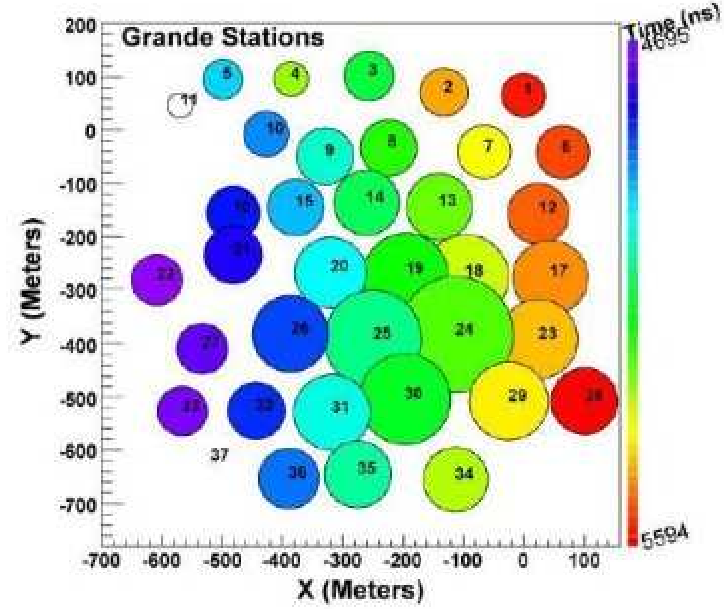
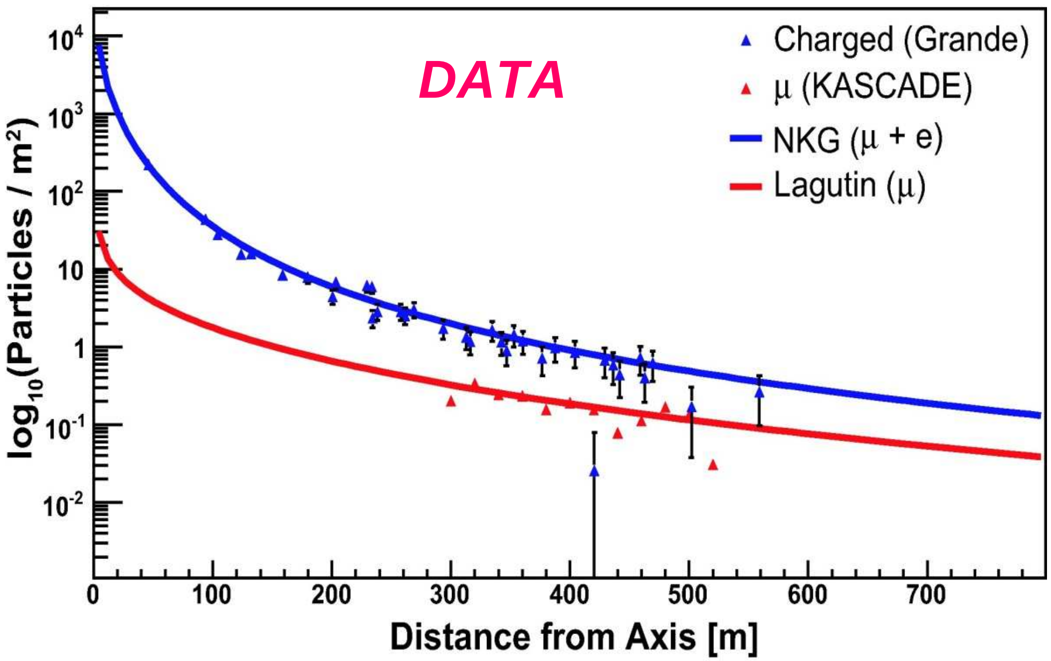
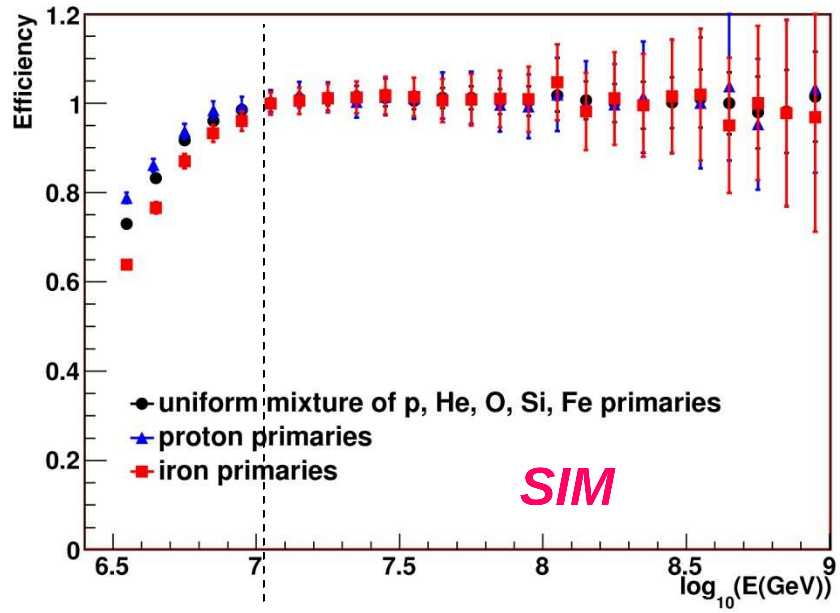


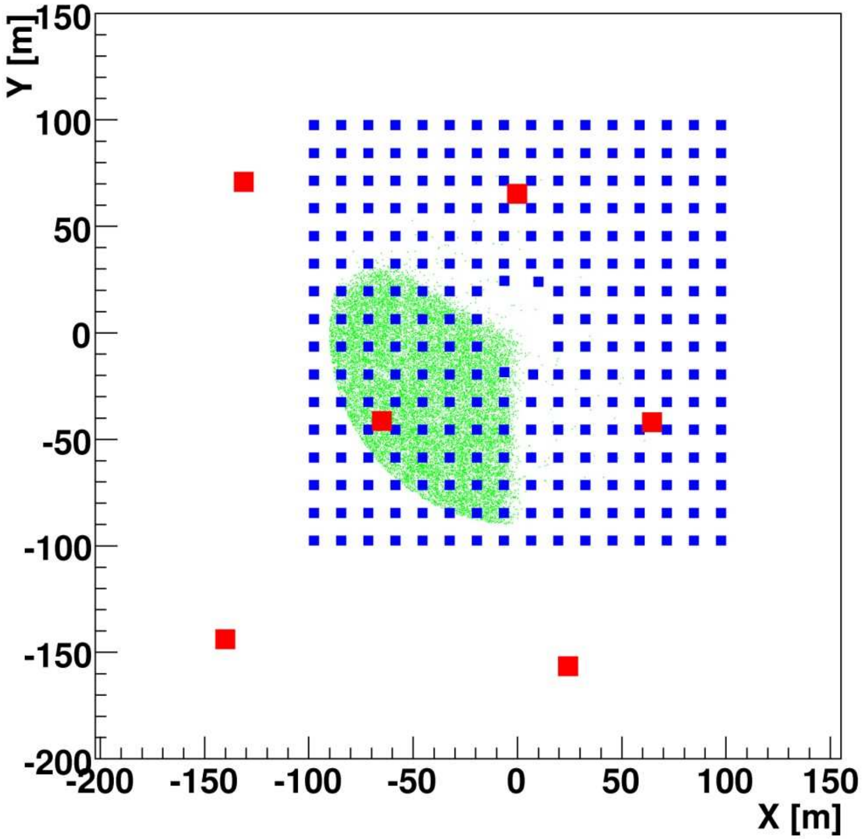


KASCADE-Grande efficiency

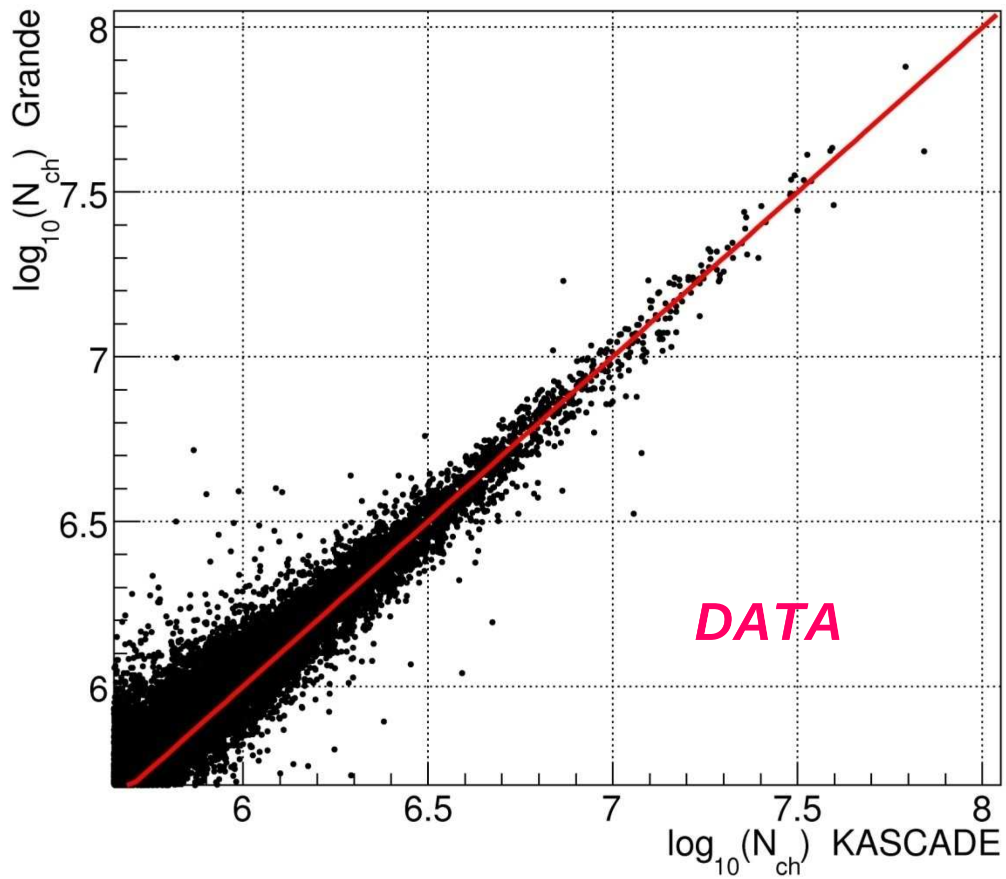


10^{16}eV

Cross-check between KASCADE and Grande



■ KASCADE stations
■ Grande stations



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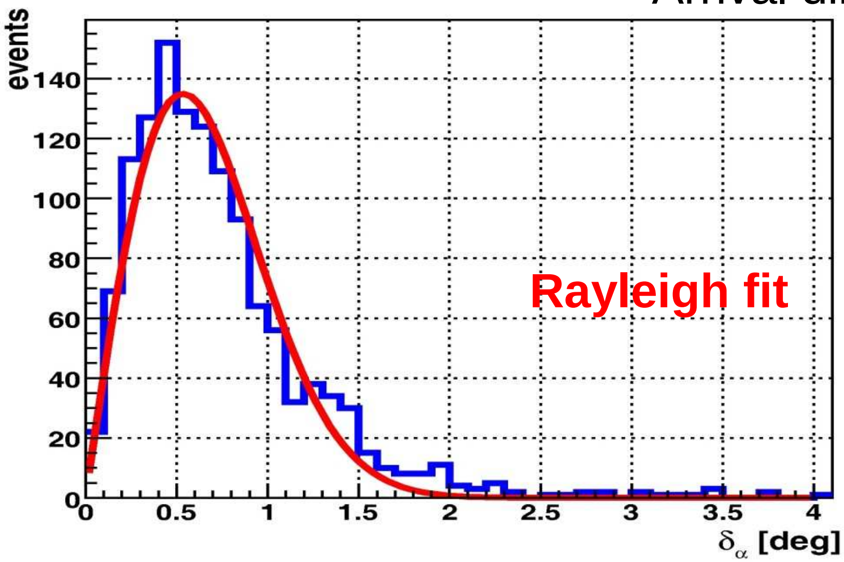
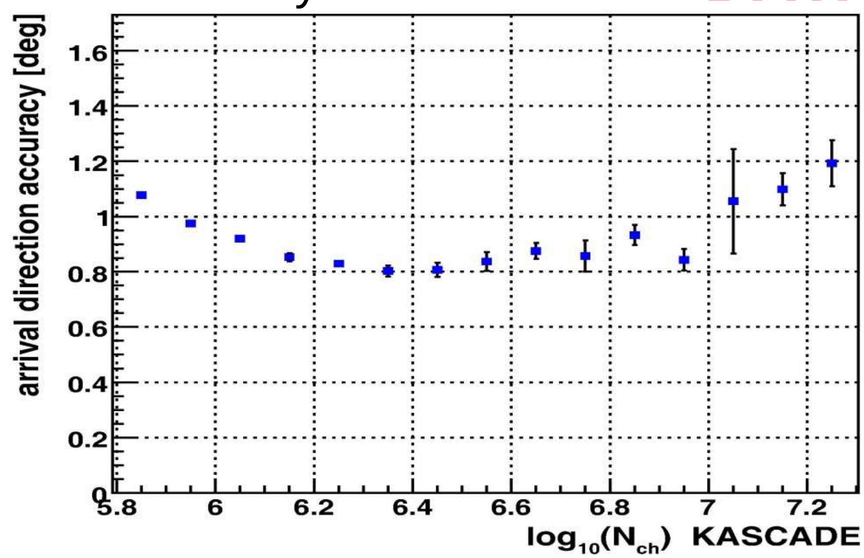
Good agreement between the reconstruction accuracies of the 2 detectors

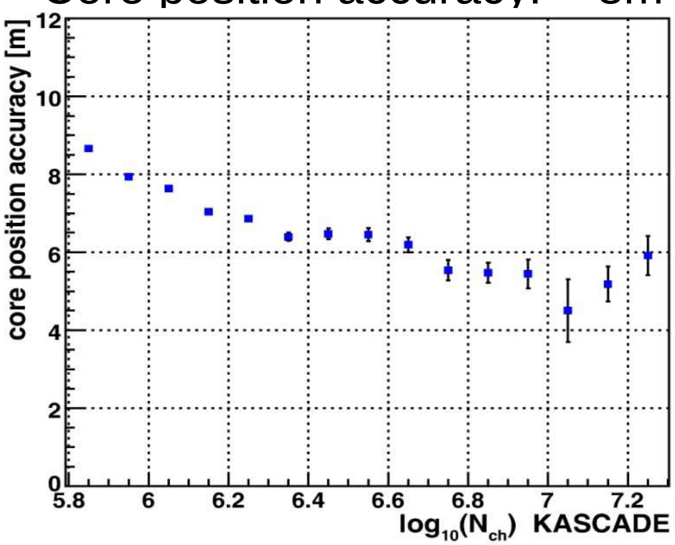
DATA



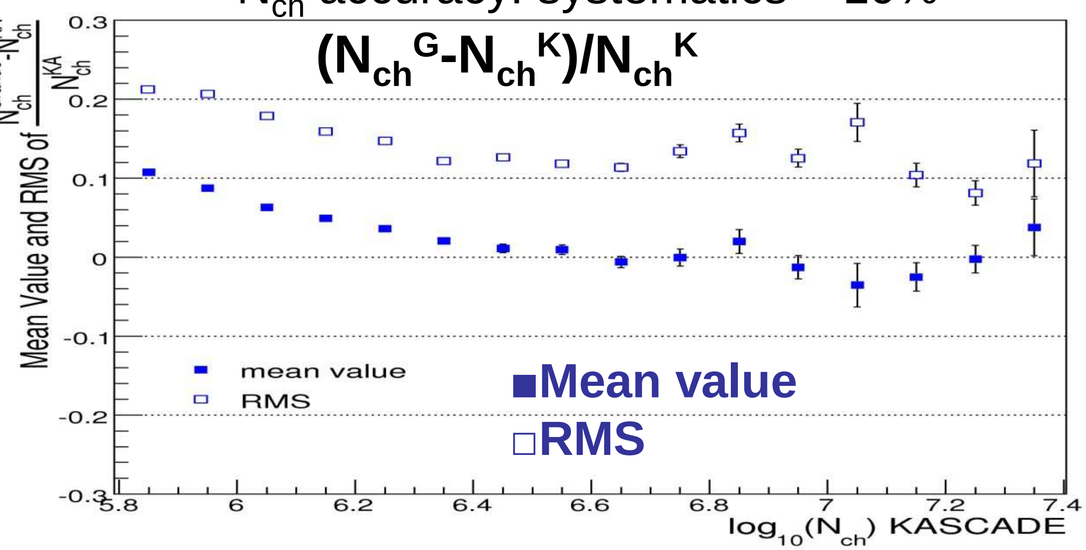
Arrival direction accuracy <1°



Core position accuracy: < 8m



N_{ch} accuracy: systematics < 10%



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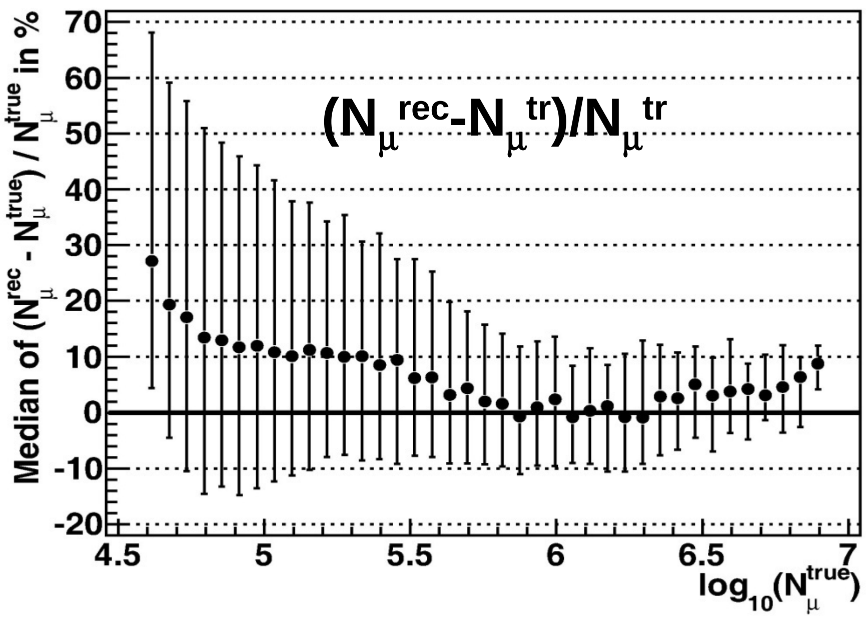
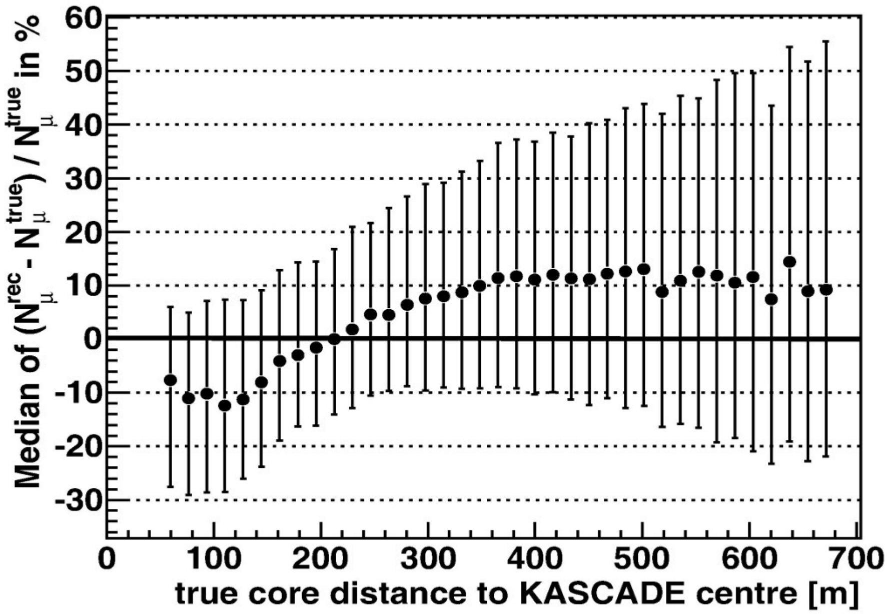
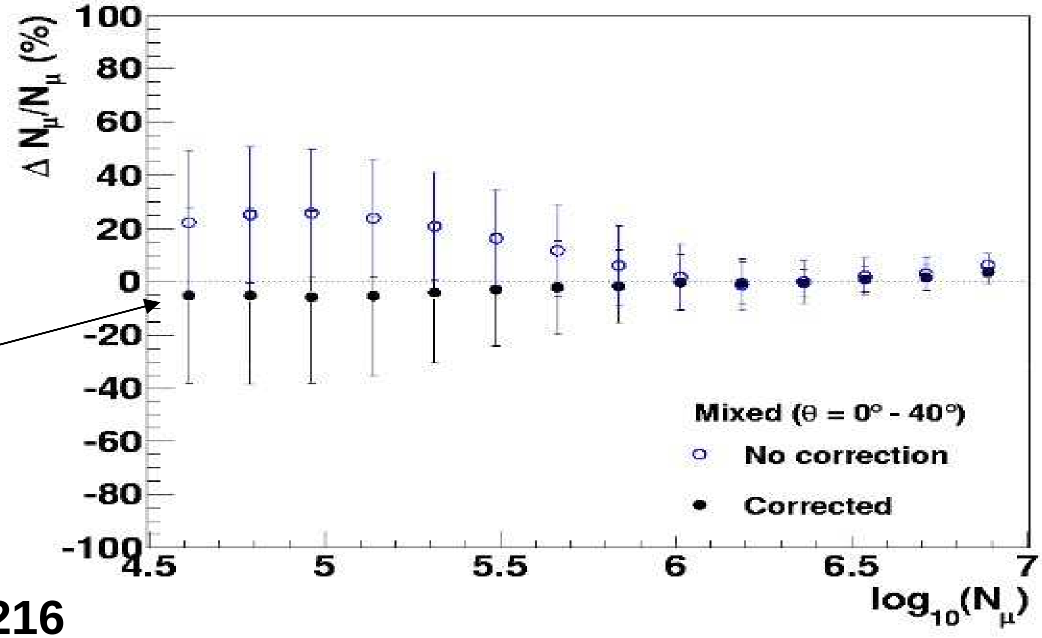
Muon reconstruction (from simulation QGSjet II & FLUKA)





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

SIMULATION



After applying muon correction functions

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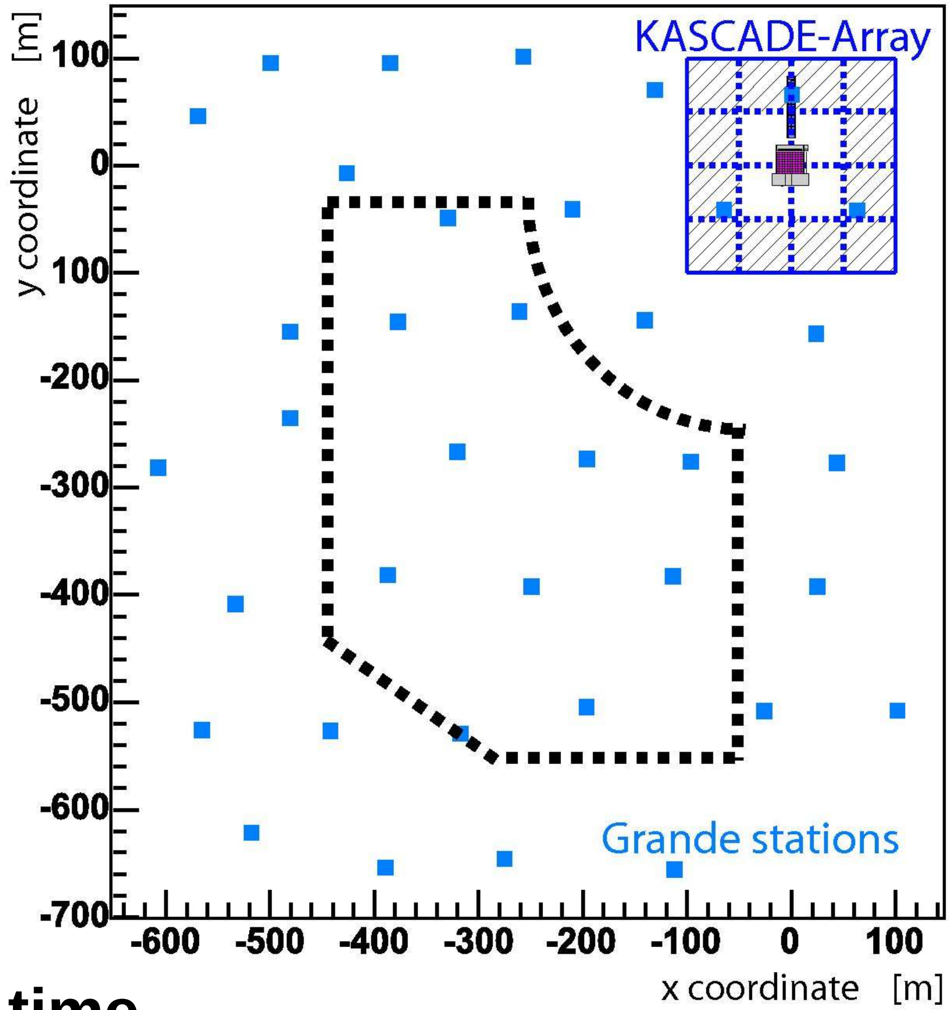
First Results:

- All particle Energy spectrum
- Towards Mass Groups spectra



- 1173 days of effective DAQ time.
- Performance of reconstruction and detector is stable.
- $\theta < 40°$
- $250\ \mathrm{m} < r_{KAS} < 600\ \mathrm{m}$

Reconstruction of the energy spectrum

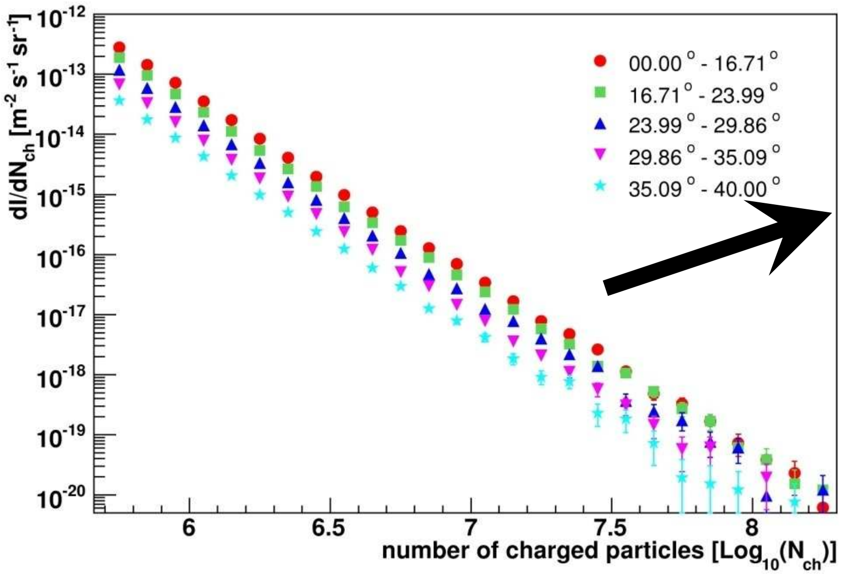
We use three different methods:

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

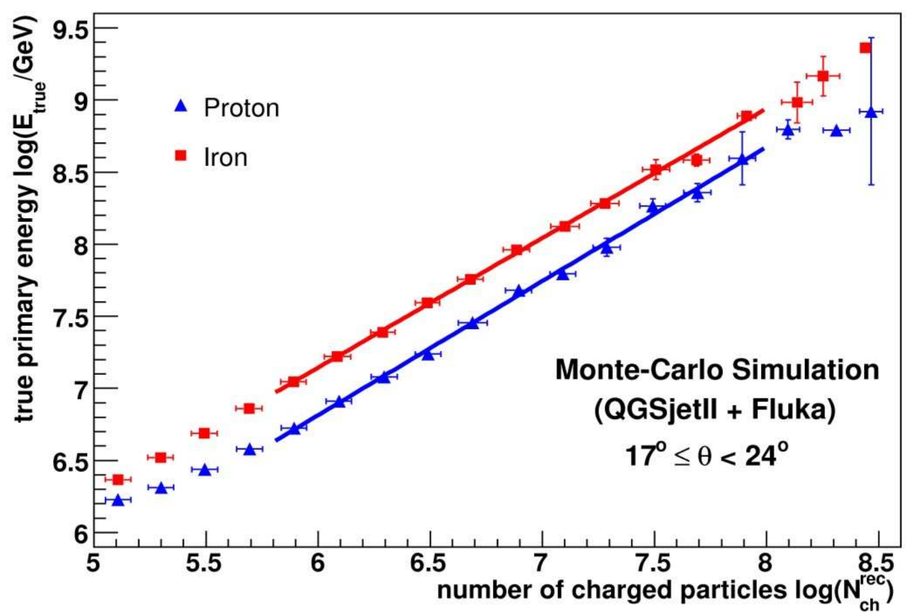
$$\Downarrow$$

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

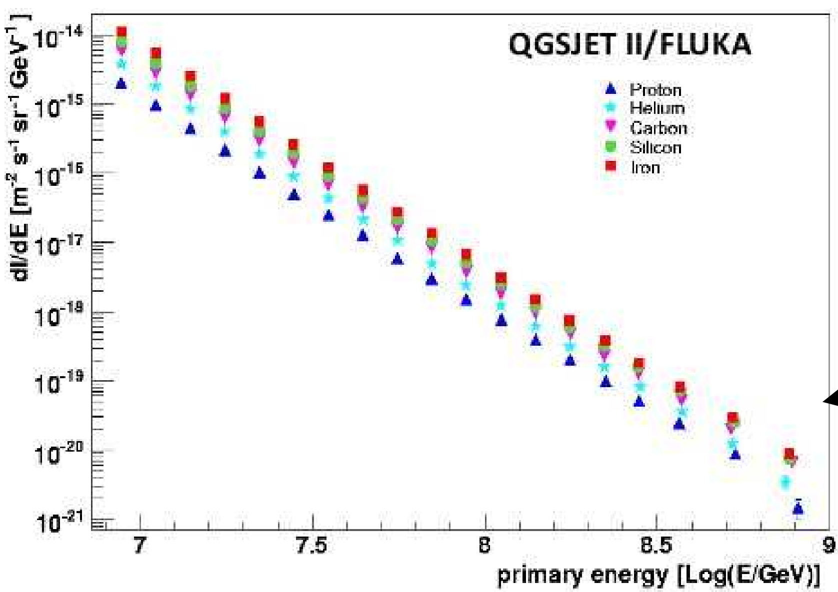
If not explicitly mentioned in the following CORSIKA QGSjetII/FLUKA interaction model is used



1) $N_{ch,\mu}$ Spectra measured at different angles
2) $N_{ch,\mu}(\theta) \rightarrow N_{ch,\mu}(\theta_{ref})$
CIC to correct for atmospheric attenuation → model independent



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

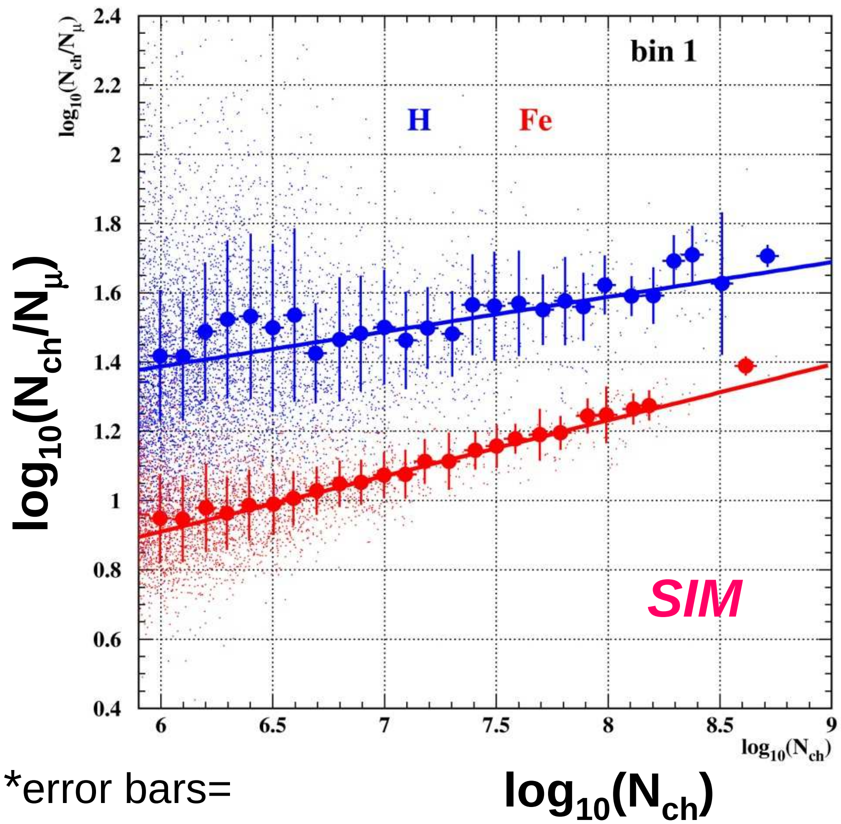


Energy spectra →
model & composition dependent

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

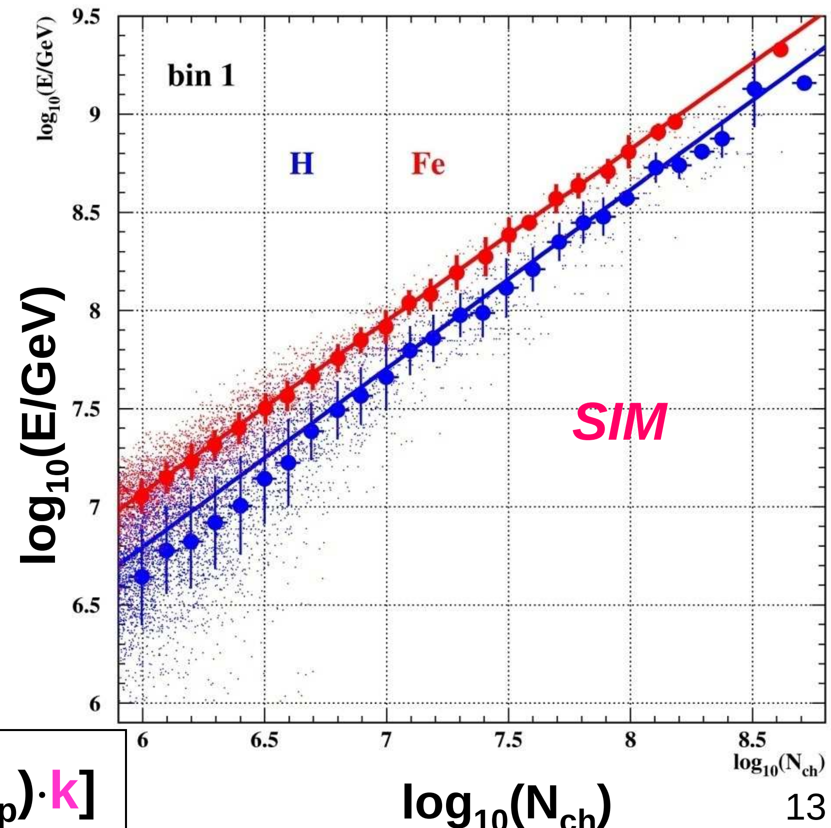
$N_{ch} – N_{\mu}$ technique

5 angular bins treated independently



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

*error bars=
RMS of distributions



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

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

Pro & cons of the methods

N_{ch} or N_{μ} alone:

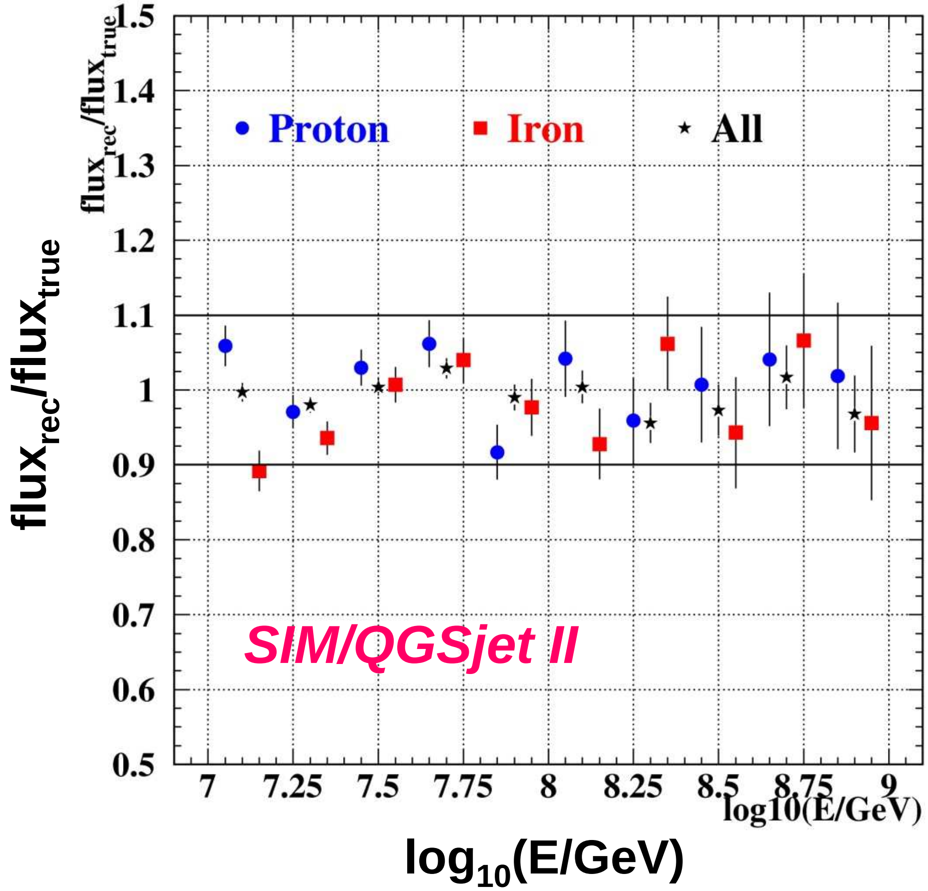
- **Constant intensity cut method**
- **Correction for atmospheric attenuation is model independent**
- **Calibration function QGSjet II: shower size (N_{ch} or N_{μ}) vs E**
- **Composition dependent**

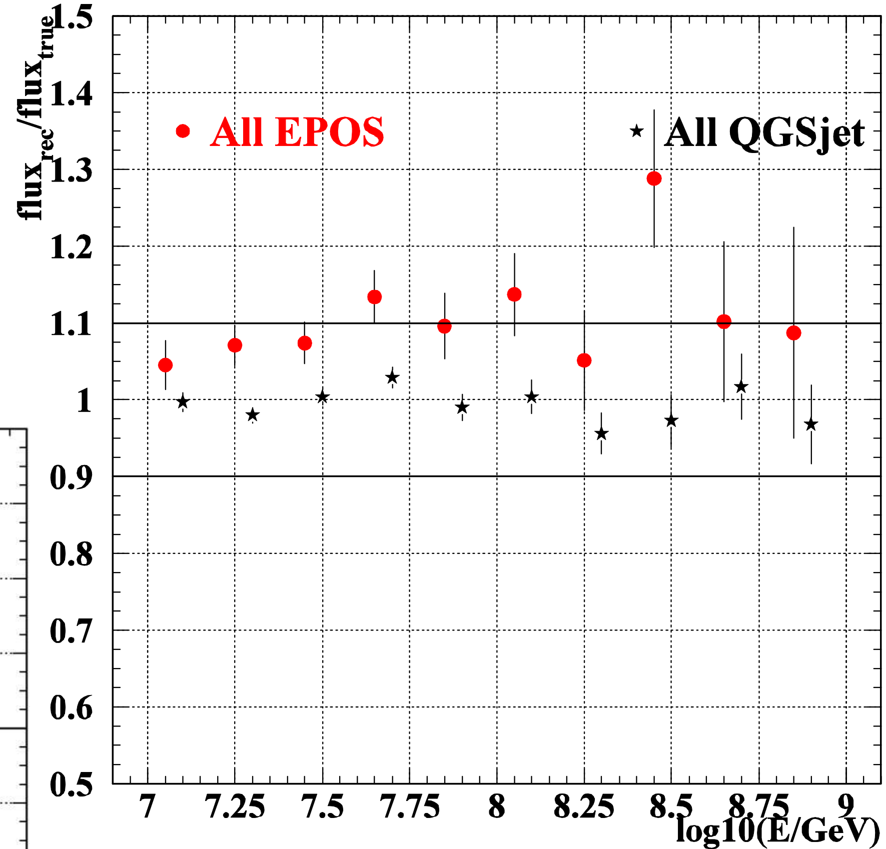
N_{ch} & N_{μ} combined:

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

Check of resolutions and systematic errors using MC simulations

Reconstructed/True flux



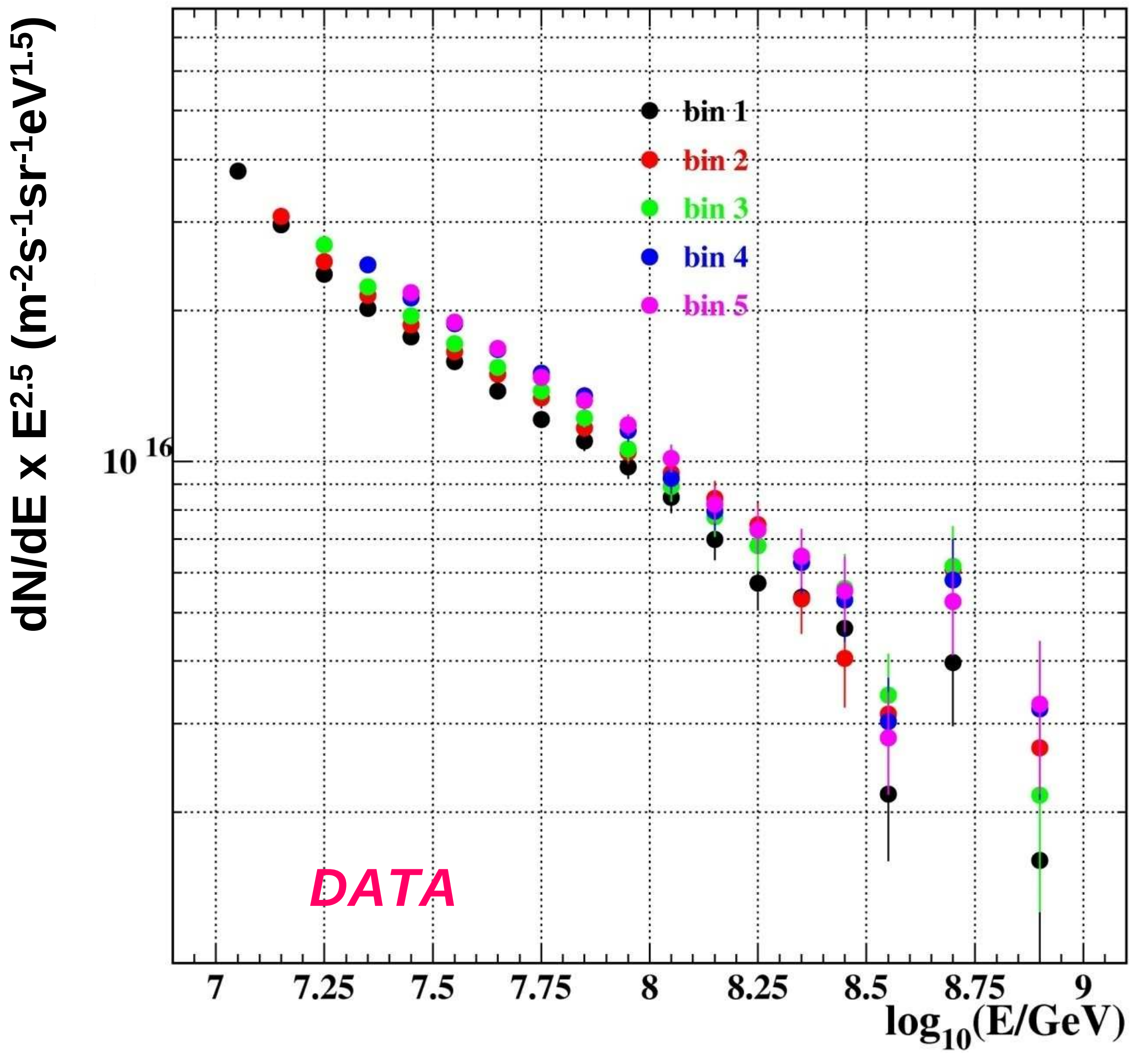


Effect of Hadronic interaction model: EPOS data treated as exp. data and analyzed using QGSjet II

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)	-5.3	-14.0	-9.5
Statistical error	**0.6**	**2.7**	**17.0**
Energy resolution (mixed primaries)	**24.7**	**18.6**	**13.6**

Experimental data



$\log_{10}(E/GeV)$

$0° < \theta < 16.7°$

$16.7° < \theta < 24.0°$

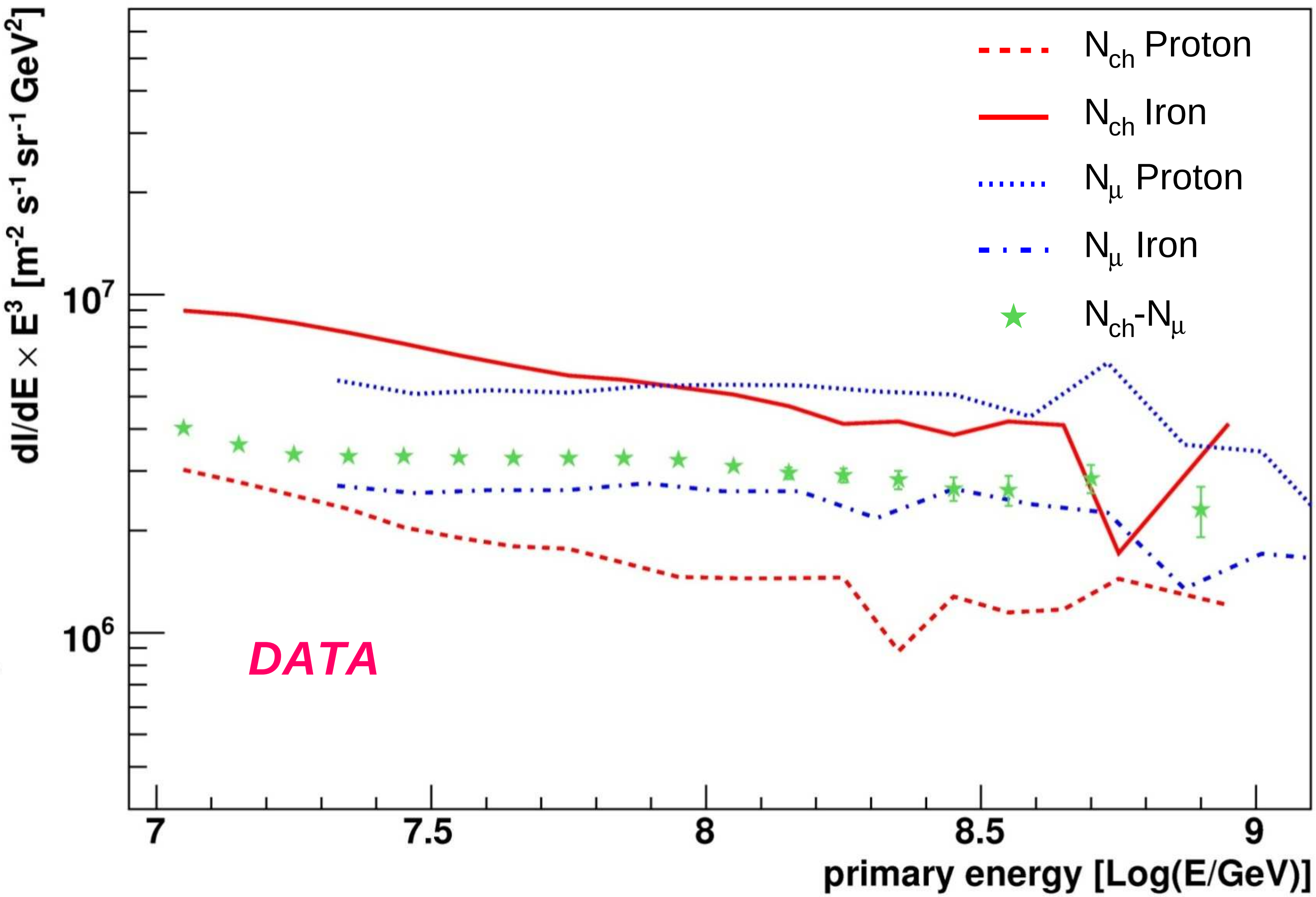
$24.0° < \theta < 29.9°$

$29.9° < \theta < 35.1°$

$35.1° < \theta < 40.0°$

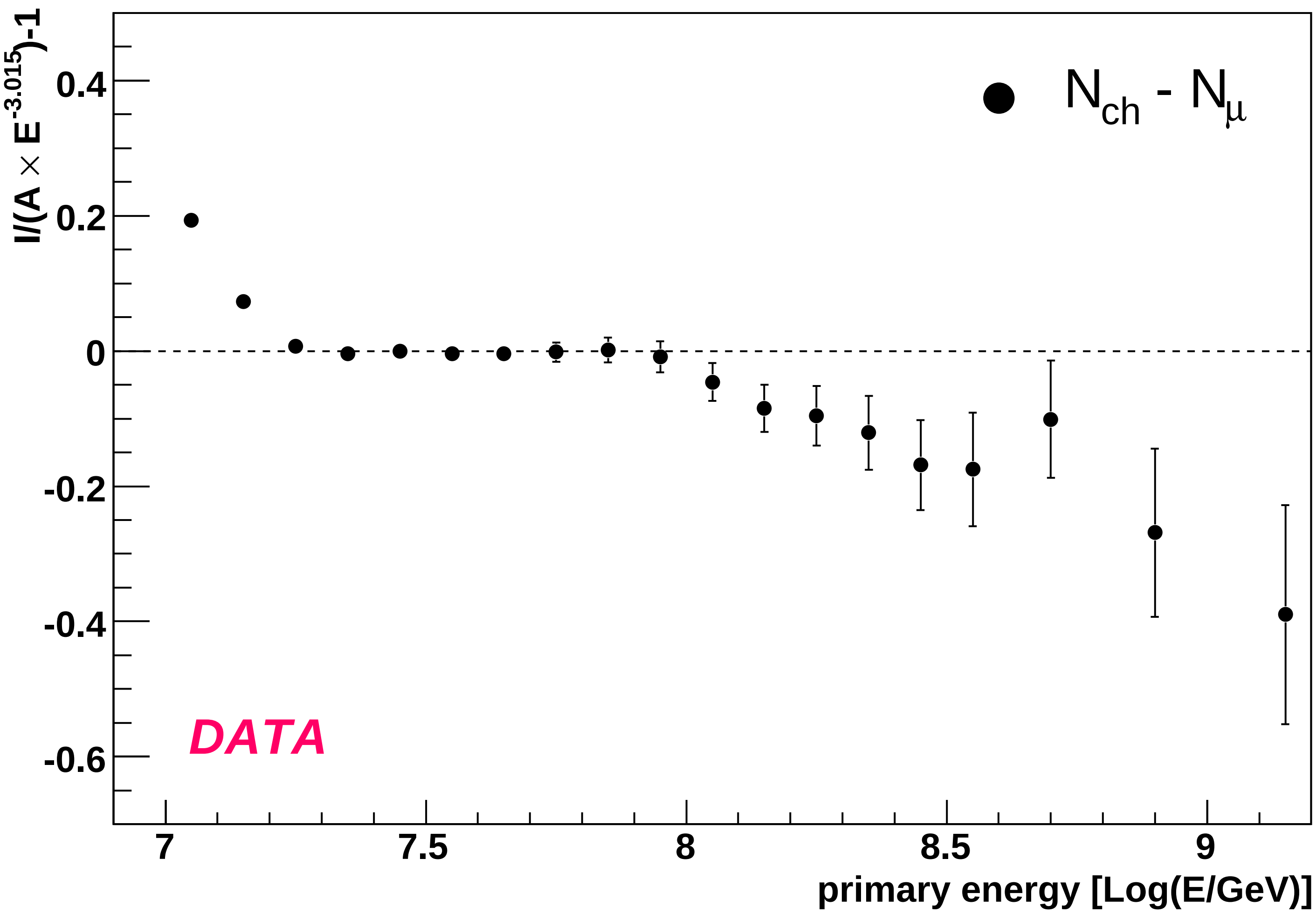
The measured fluxes are different→ EAS development in atmosphere not correctly described by the simulation?

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



Spectrum measured with the N_{ch}-N_{μ} technique lies in the allowed region by the CIC analysis performed both with N_{ch} and with N_{μ}

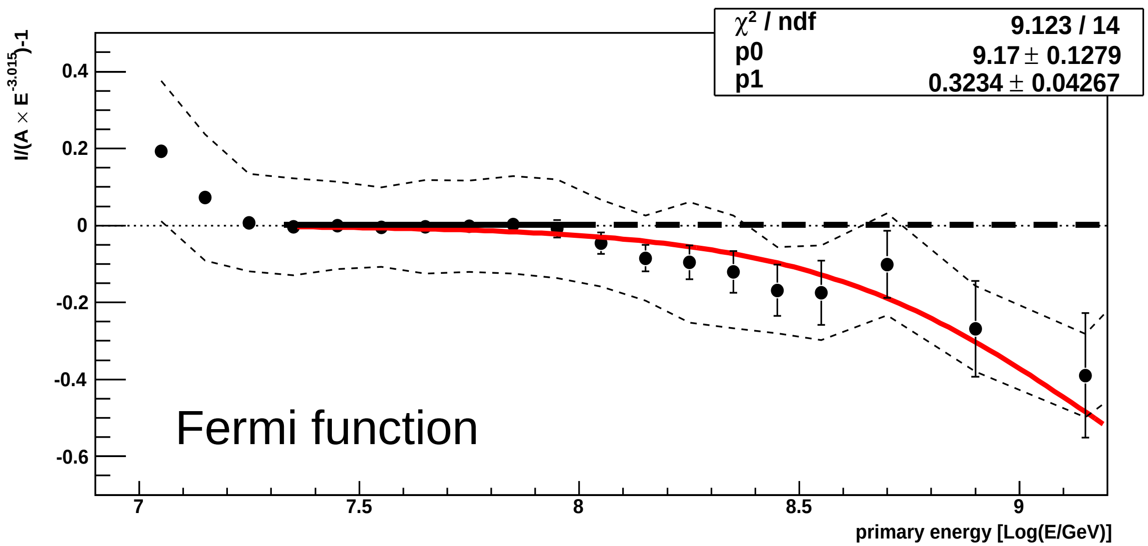
Residual plot



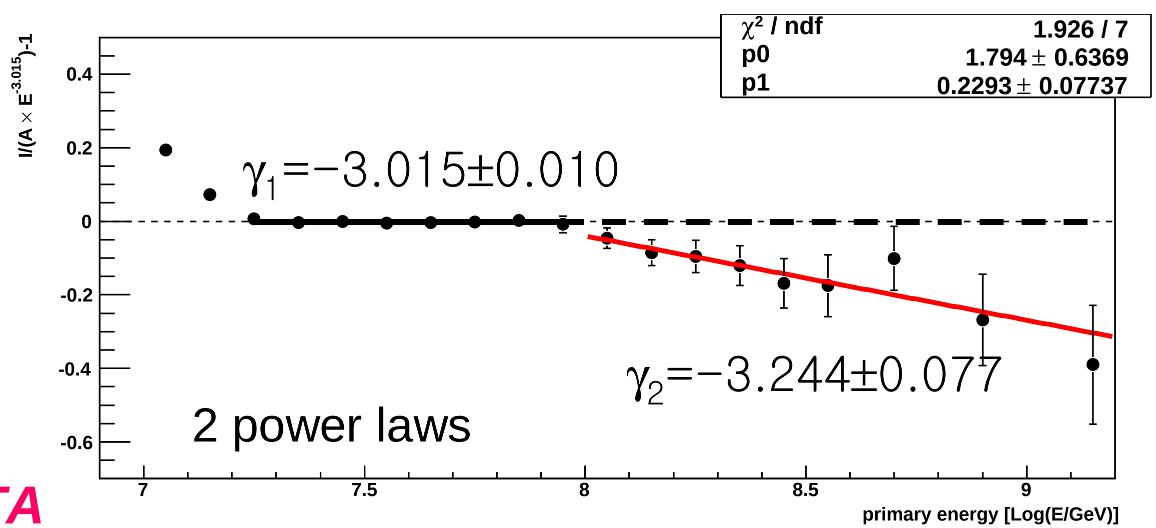
$F_{test} = (\chi^2_{single\ power\ law} / m) / (\chi^2_{function} / n)$, with m,n = ndf single power-law, function

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

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



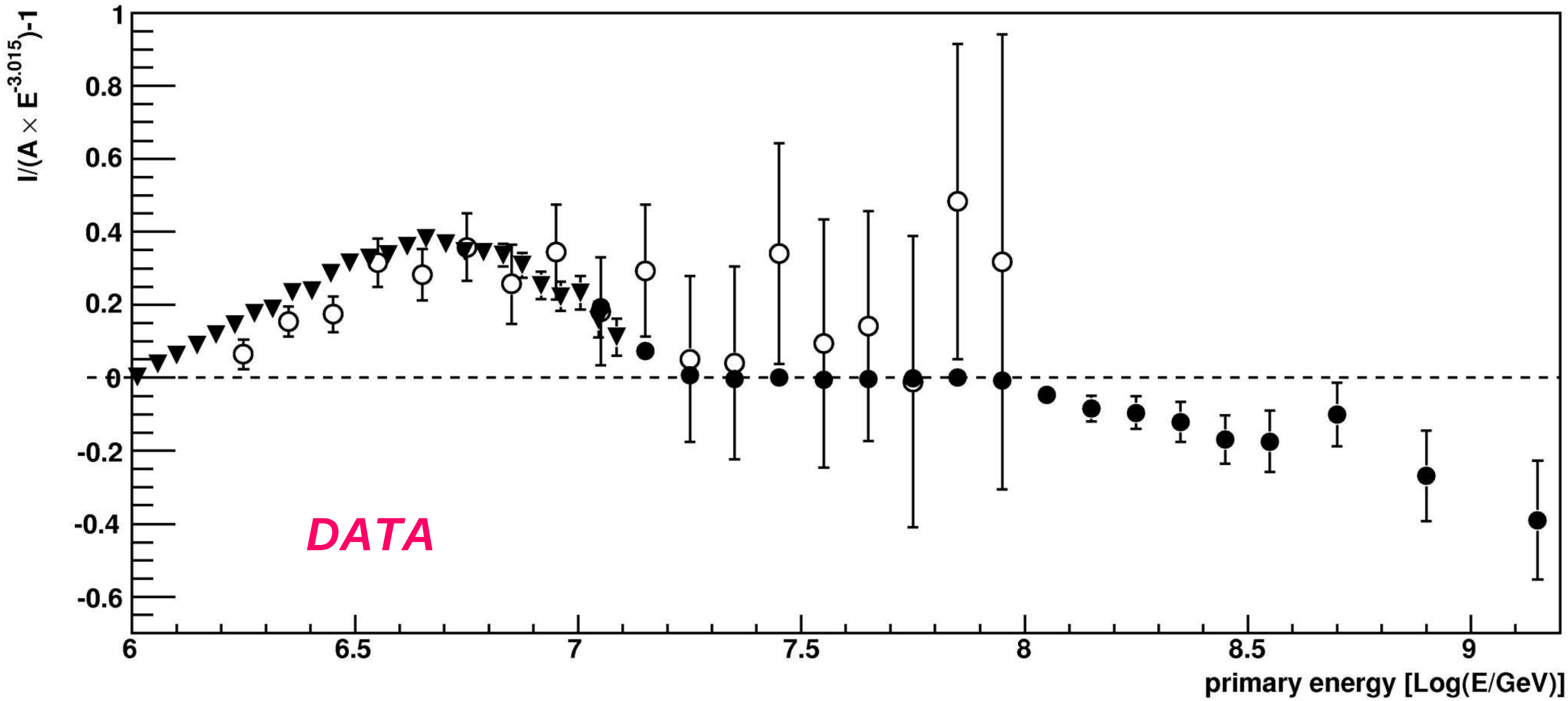
$\chi^2_{single\ power\ law}$ / ndf =2.97
χ^2_{fermi} / ndf =0.65
F_{test} = 4.56
Variance = 0.51
Significance = 6.4 σ



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

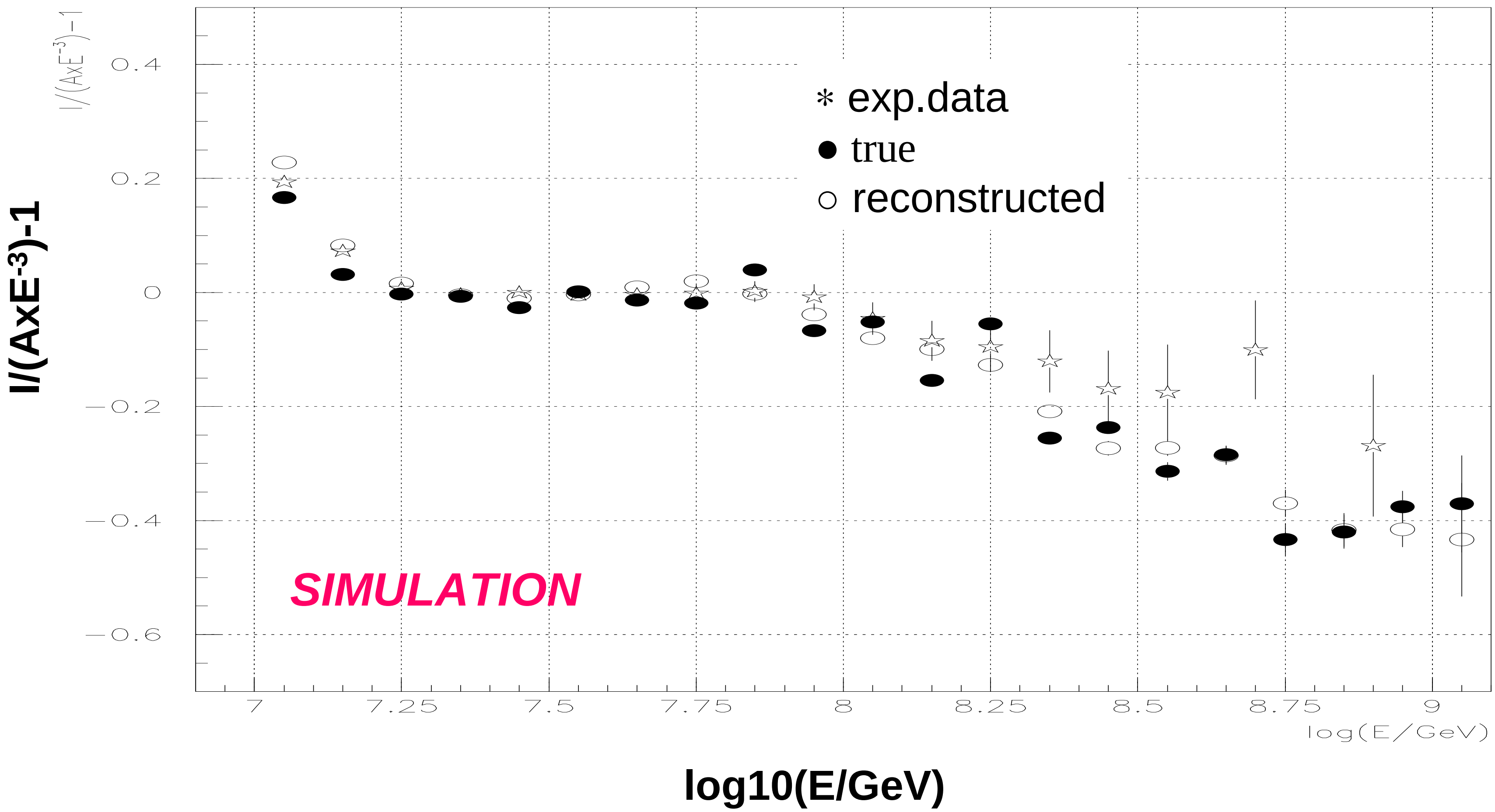
DATA

Comparison with KASCADE & EAS-TOP

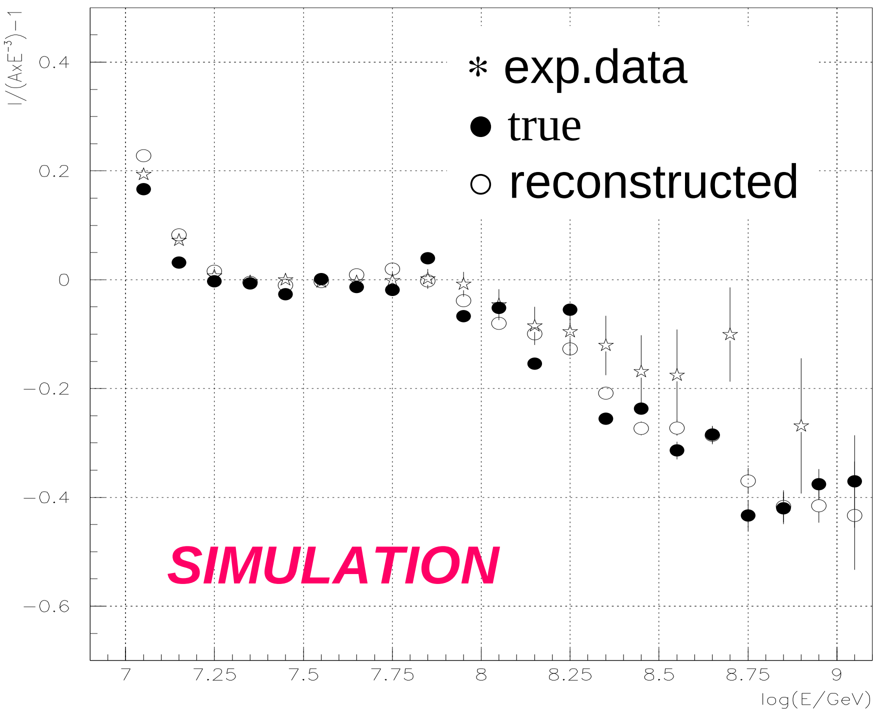


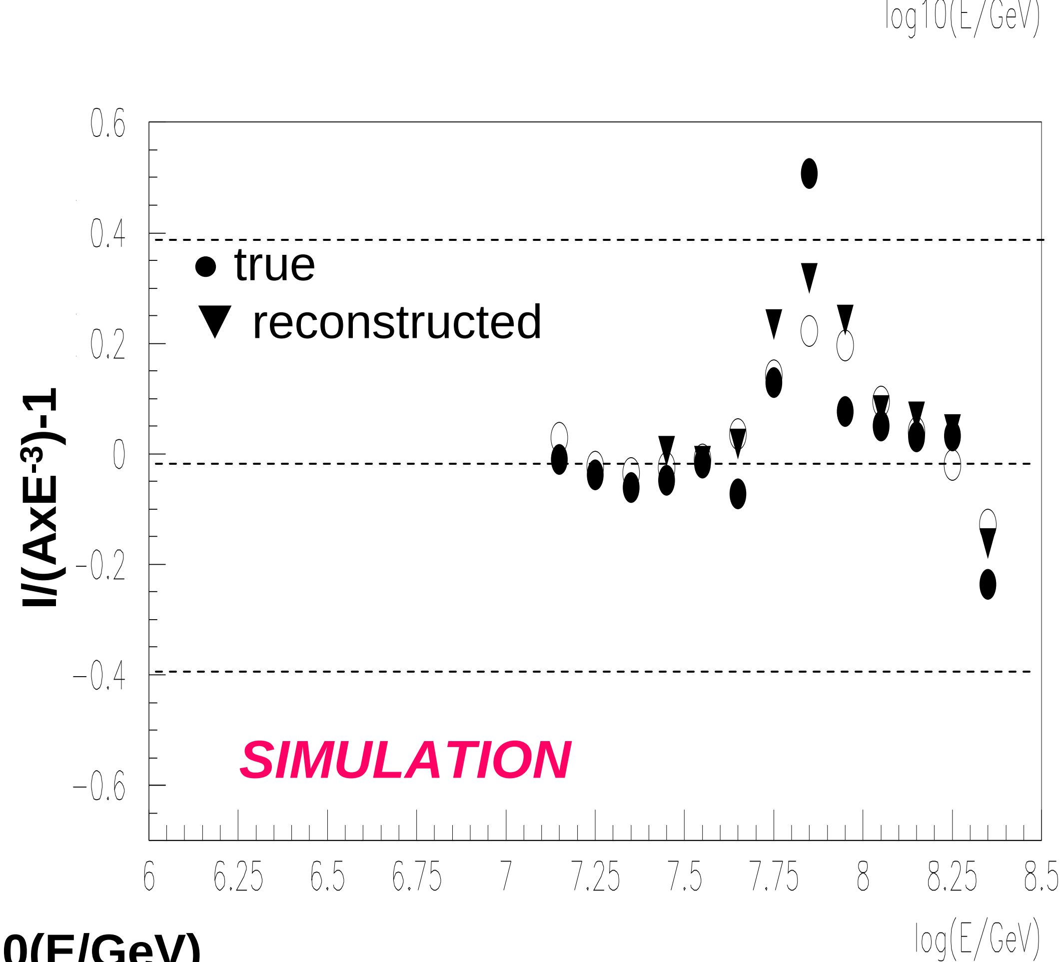
○ KASCADE QGSjet01
▼ EAS-TOP
● KASCADE-Grande QGSjet2

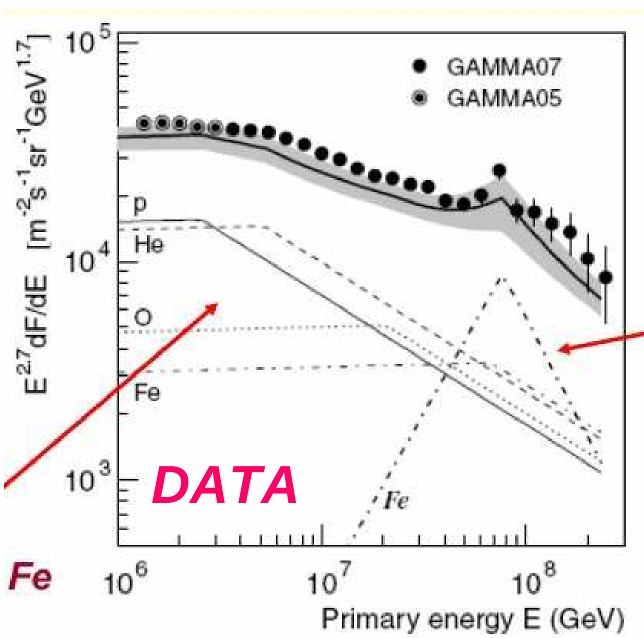
Simulated spectrum similar to the experimental one



The features of the spectrum are properly reproduced.
Only slight overestimation (~7%) of the flux at the threshold





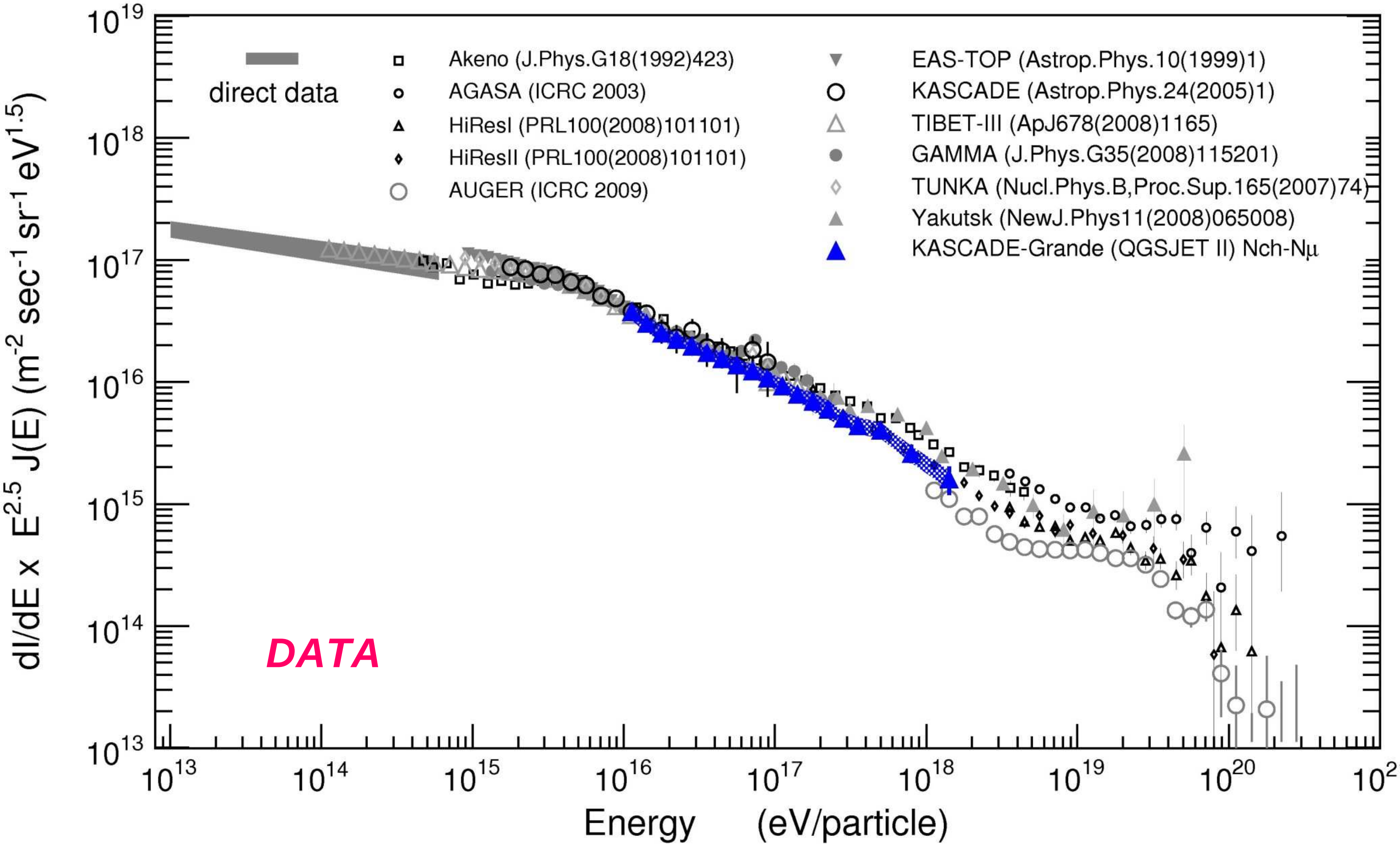


log10(E/GeV)

J.Phys.G35(2008)115201

A feature like the one claimed by the GAMMA collaboration would have been detected. Even if broaden by KASCADE-Grande resolution and EAS development in atmosphere

The all-particle energy spectrum

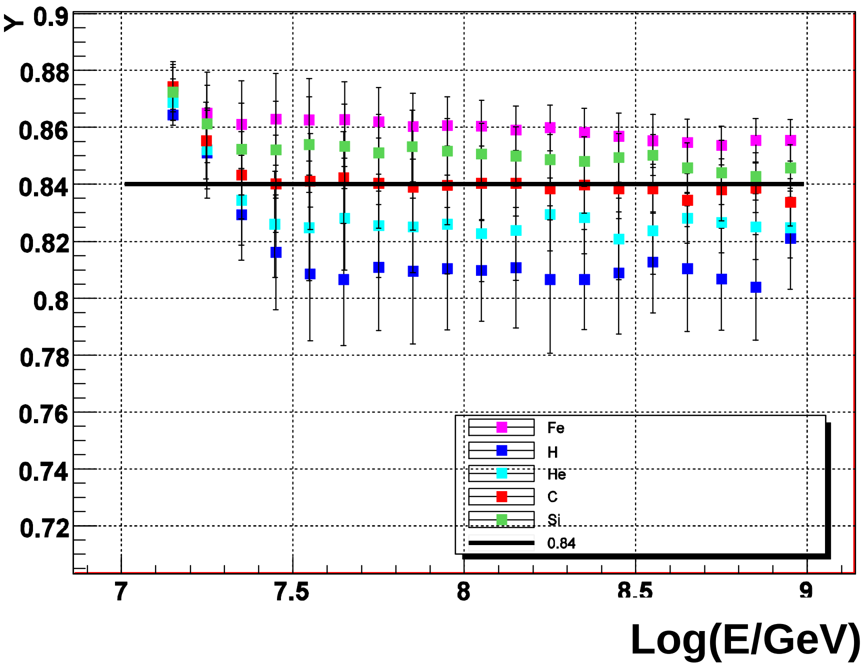


- The Energy spectrum shows structures.
- The composition analysis is crucial to try to understand their origin.
- The composition studies are approached with different techniques (all based on N_{ch}-N_{μ} observables and QGSjet model) like we did for the Energy spectrum to have a cross check of the results and in order to study the systematic errors of each technique:
  - N_{μ}/N_{ch} distributions in bins of N_{ch} (χ^2)
  - unfolding
  - k parameter
  - $Y^{CIC} = \log N_{\mu} / \log N_{ch}$

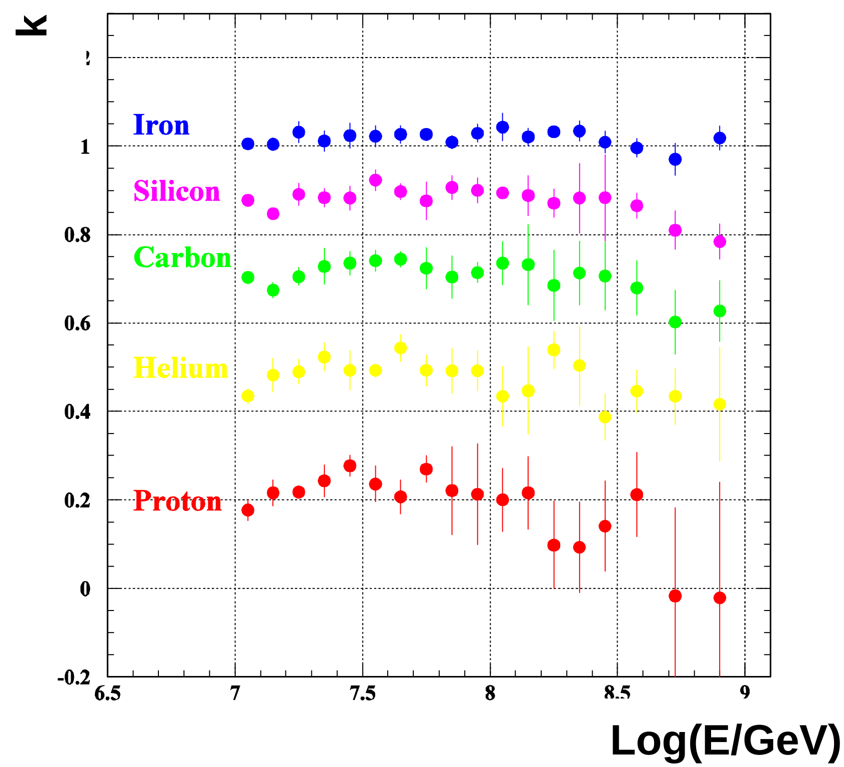
- The goal of the Y^{CIC} and “k parameter” algorithm is to separate the events into samples originated by primaries belonging to different “mass groups”
  - $Y^{CIC} = \log N_{\mu}(\theta_{ref}) / \log N_{ch}(\theta_{ref})$
  - $k = (\log(N_{ch}/N_{\mu}) - \log(N_{ch}/N_{\mu})_p) / (\log(N_{ch}/N_{\mu})_{Fe} - \log(N_{ch}/N_{\mu})_p)$
- χ^2 and unfolding algorithm have the goal of measuring the spectra of single mass groups through statistical analysis of the two dimensional (N_{ch}, N_{μ}) spectra

Performances of the Y^{CIC} and "k parameter" algorithm. Calculated in the frame of CORSIKA full EAS simulation with QGSJet II interaction model.

Y^{CIC}



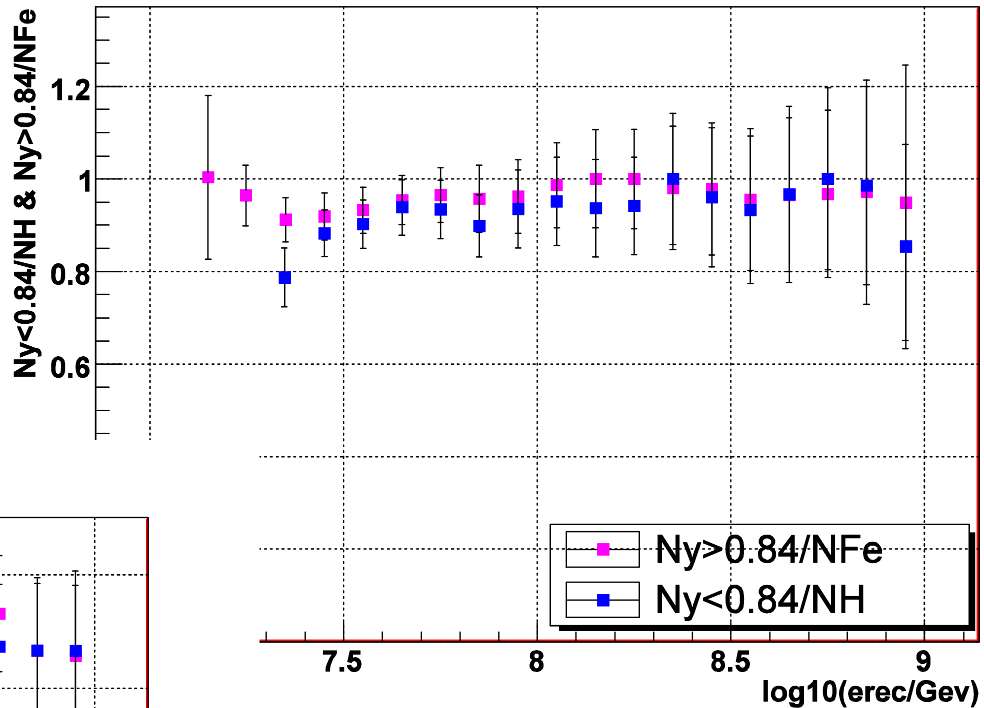
k paramater



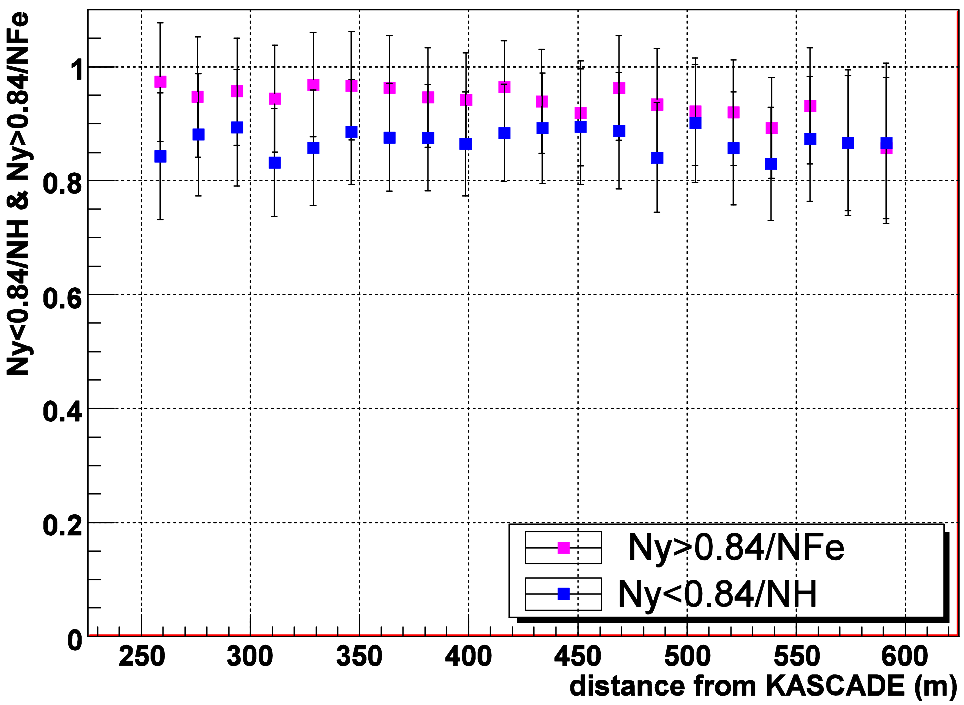
SIMULATION

$N_{y<0.84}/N_H$ & $N_{y>0.84}$ $/N_{Fe}$

yCIC



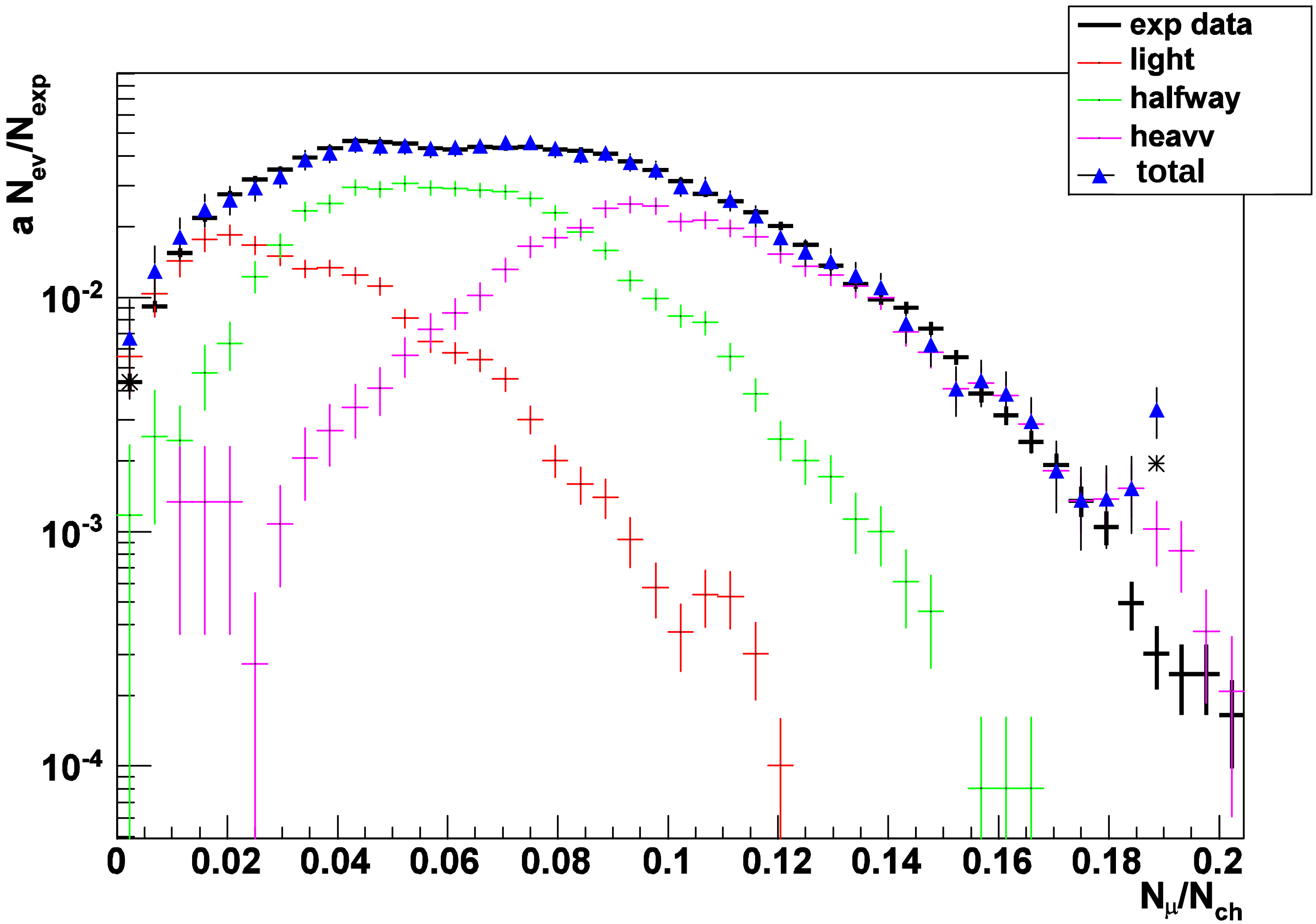
Vs. Distance from KASCADE



vs. Primary Energy

SIMULATION

χ^2 method
N_μ/N_{ch} distributions in bins of N_{ch}



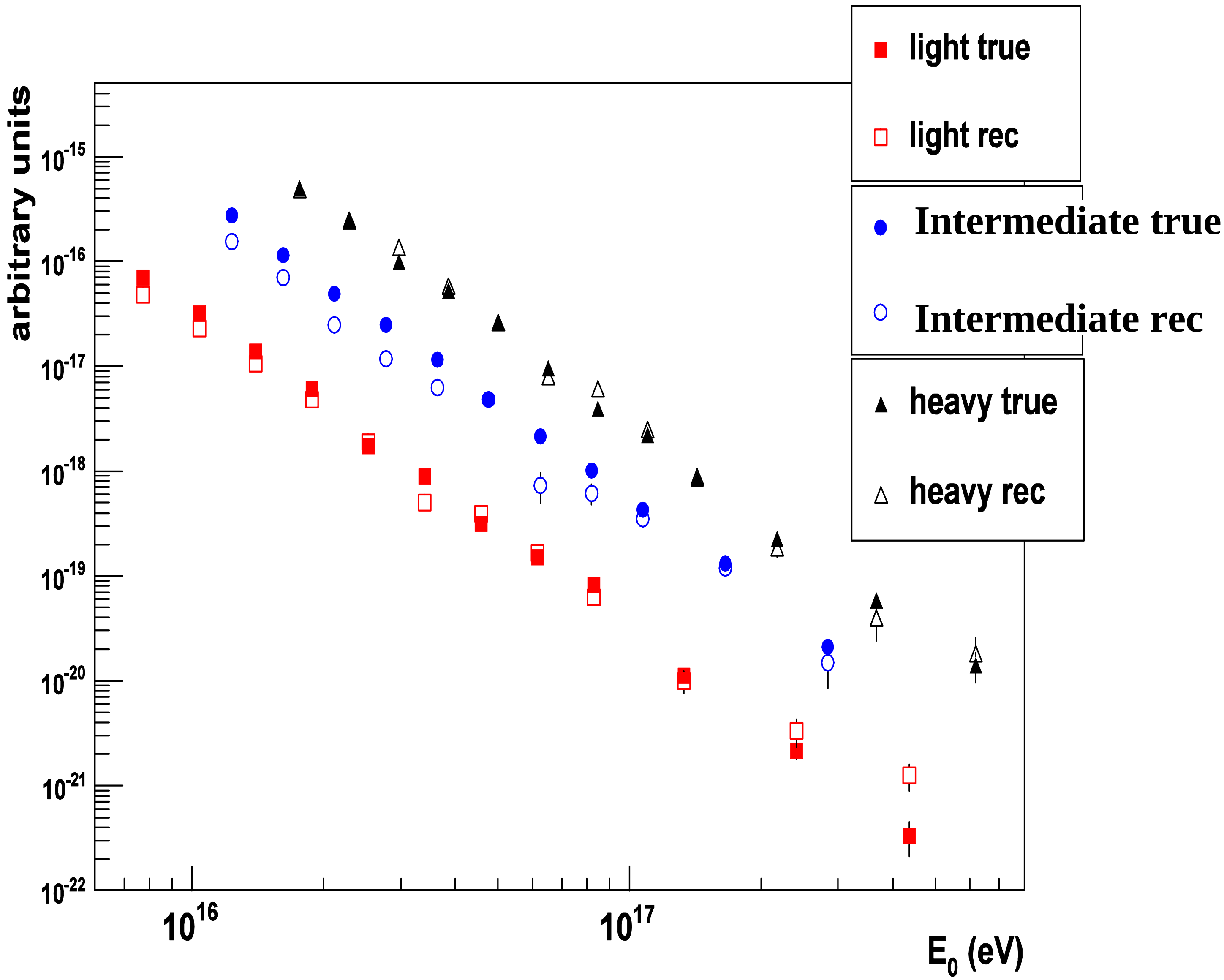
SIMULATION/DATA

N_μ/N_{ch} distributions in bins of N_{ch}

- $F_{sim}(i) = \Sigma_j \alpha_j f_{sim,j}(i) \quad \Rightarrow \quad \Sigma_j \alpha_j = 1$
- $\chi^2 = \Sigma_i (F_{sim}(i)-F_{exp}(i))^2/\sigma^2(i)$
- It has already been shown that:
  - KG can separate three mass groups:
    - Light (H), Intermediate (He+C), Heavy (Si+Fe)
  - QGSJet II gives a good description of the measured N_μ/N_{ch} distributions in the whole N_{ch} range
  - Light and Heavy mass groups are needed to describe the distributions measured in all N_{ch} intervals

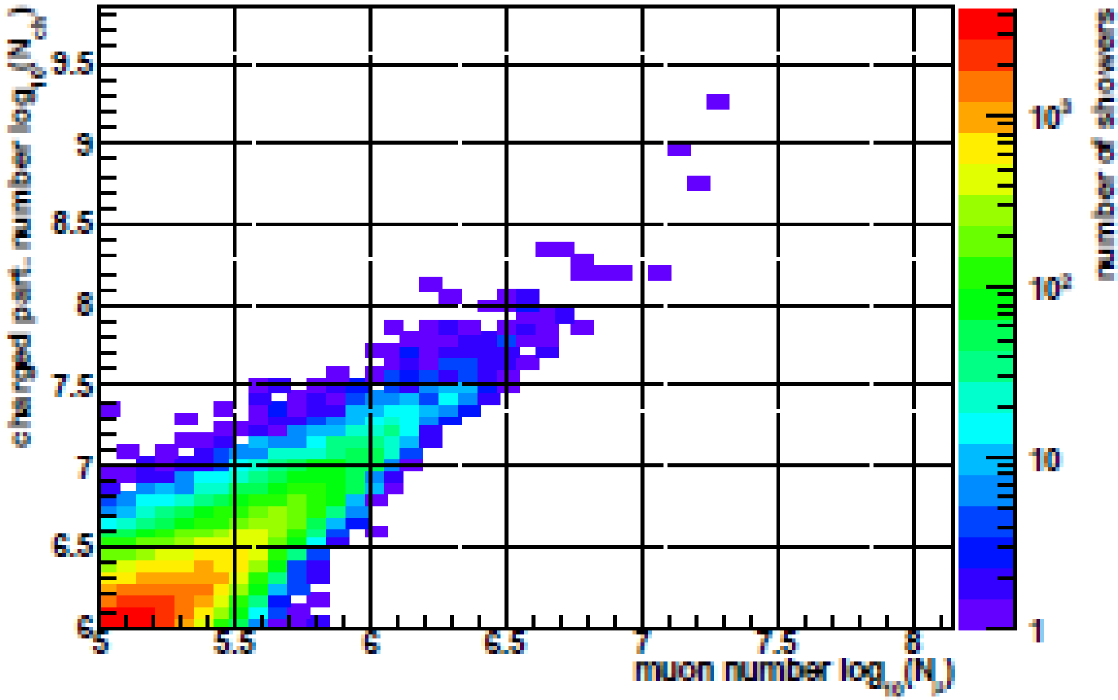
From α_j to mass groups energy spectra

- Analyzing the N_μ/N_{ch} distributions in the k^{th} N_{ch} interval we obtain the abundances $\alpha_j(k)$ of different mass groups.
- $N_j(k) = \alpha_j(k)\, N_{exp}(k)$
- From $N_j(k)$ we can calculate the flux in the k^{th} N_{ch} interval.
- By a full simulation we convert N_{ch} into primary energy. We calculate the differential energy fluxes of single mass group
- Results heavily depend on the QGSjet II interaction model



Test spectra of the three mass groups reconstructed with the χ^2 analysis.
The results are not yet corrected for migration effects.
No spectral breaks are introduced by the algorithm.

Unfolding



Number of events N_i in the cells of the two dimensional spectra are given by:

$$N_i = \sum_{n=1}^{N_n} \int_{T_m} \int_{\Omega_{tot}} \int_{A_f} \int_{E} \frac{\mathrm{d}J_n}{\mathrm{d}\lg E}\, p_n \, \mathrm{d}\lg E \;\cos\theta \, \mathrm{d}A \, \mathrm{d}\Omega \, \mathrm{d}t,$$

Where p_n is the conditional probability of measuring an event in the Log N_μ, log N_{ch} cell if the shower was induced by a particle of type *n* and primary energy E

$$p_n = p_n\left((\lg N_{ch}, \lg N_\mu)_i \mid \lg E\right) \; .$$

Conclusions

- KASCADE-Grande operates in the 10^{16}-10^{18} eV energy range
- <1° arrival direction, <10 m core position, ~15% N_{ch} , >20% N_{μ} resolutions
- **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 ~10^{17} eV

•Toward mass groups energy spectra

- Resolve three mass groups
- Mass group spectra will be soon presented