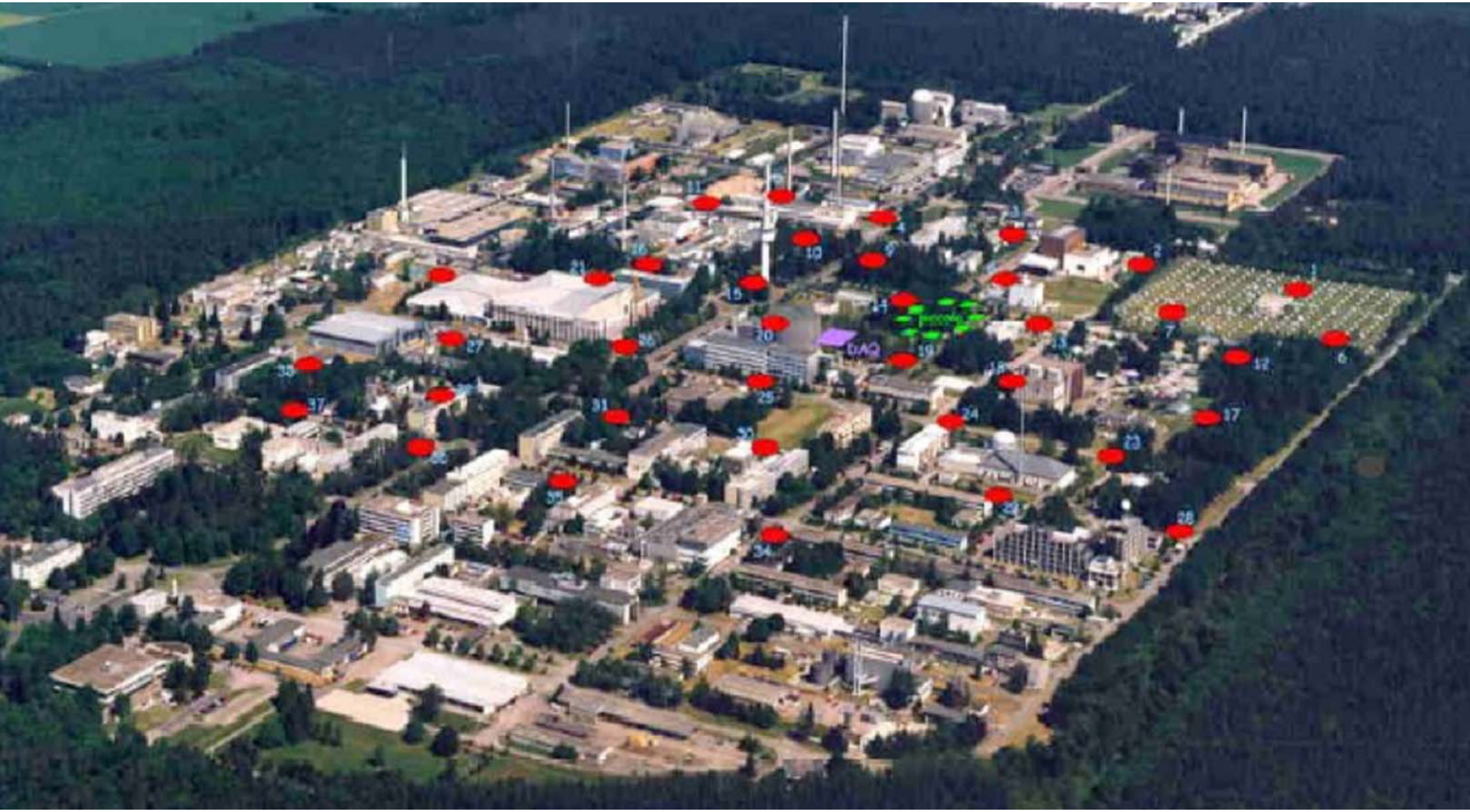
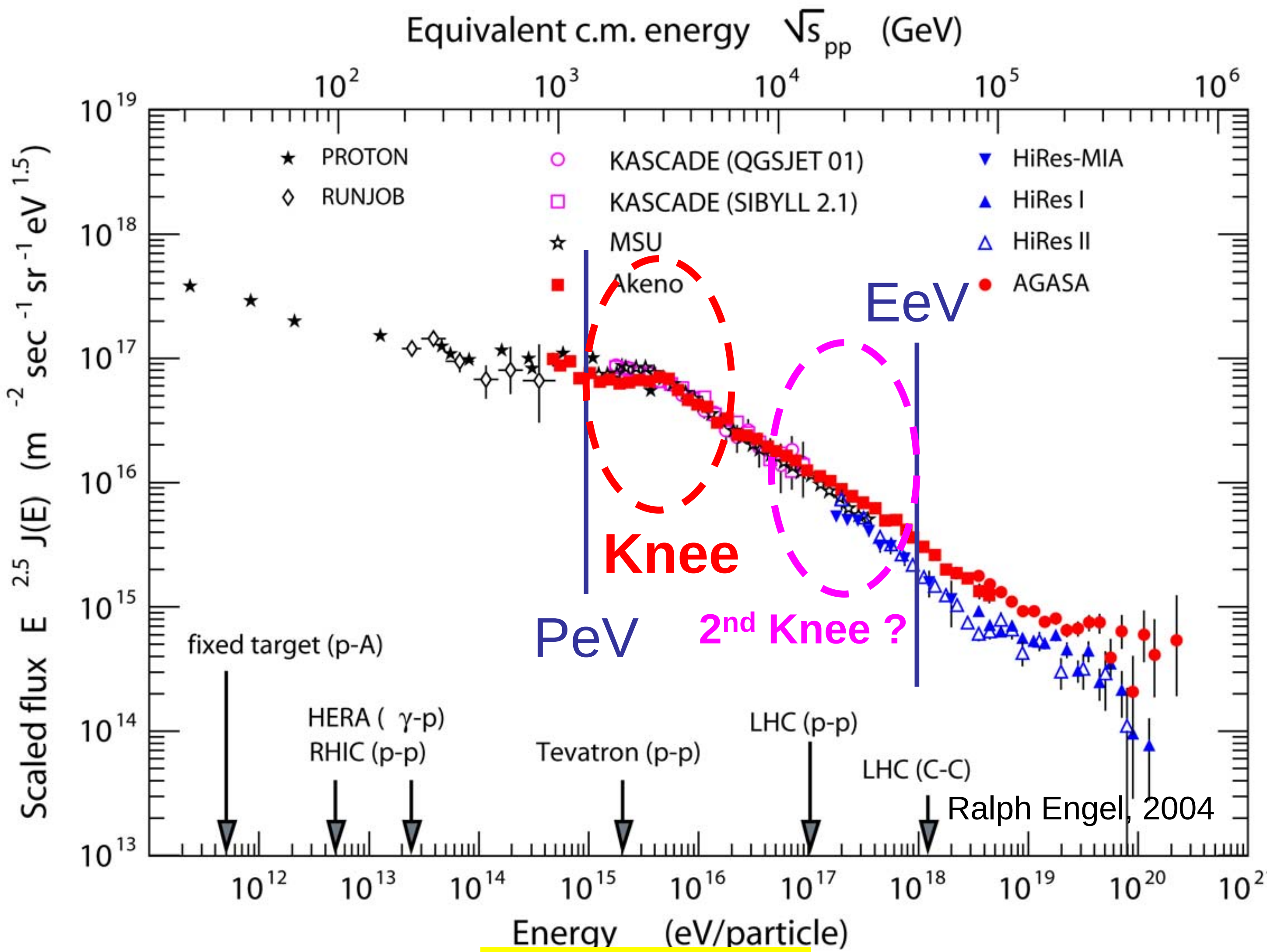
The air-shower experiment
KASCADE-Grande



Cosmic Rays around the knee(s) ➔ galactic origin of CR

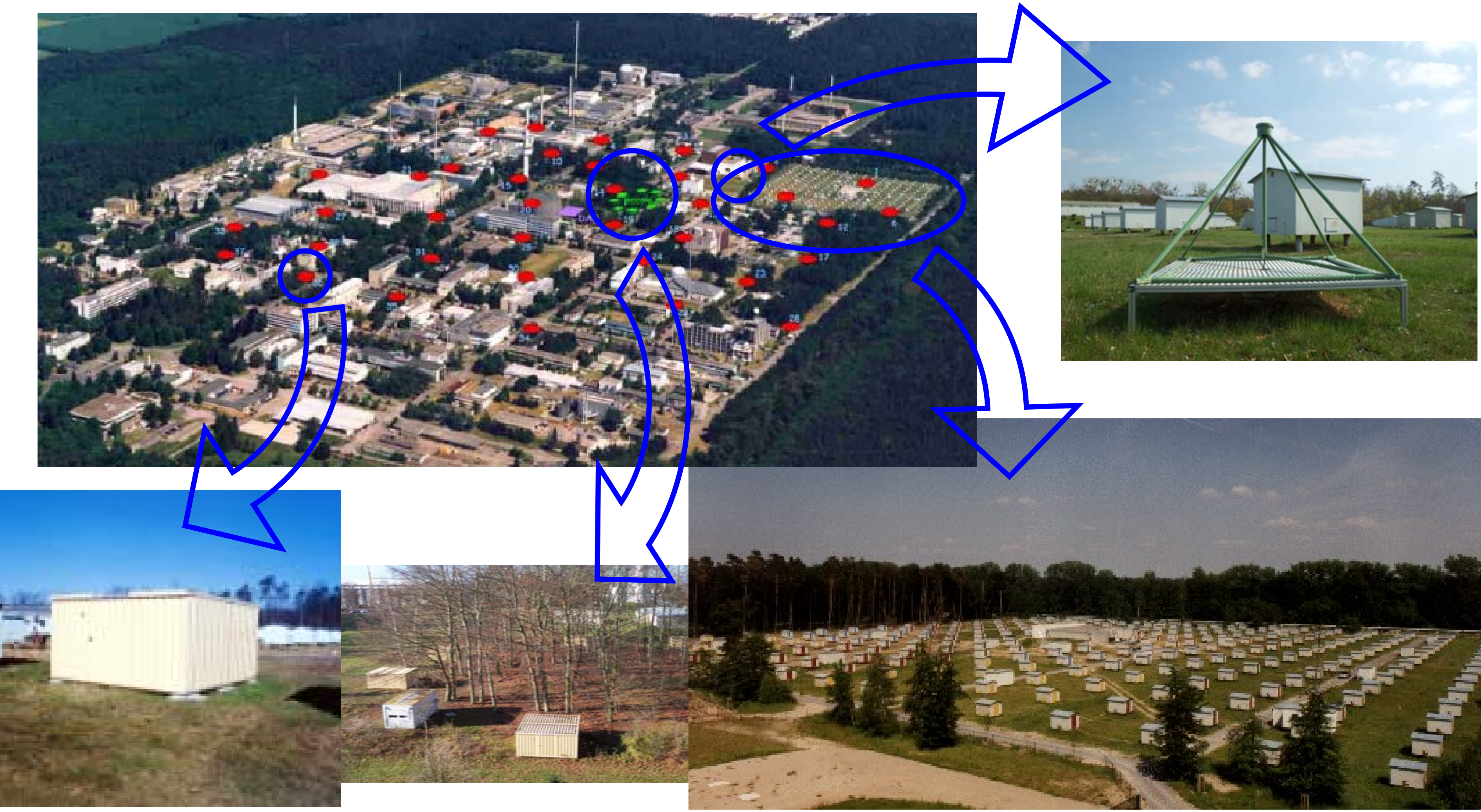


KASCADE 1995-2009 **-Grande 2003-2009**

Experiment: KASCADE-Grande

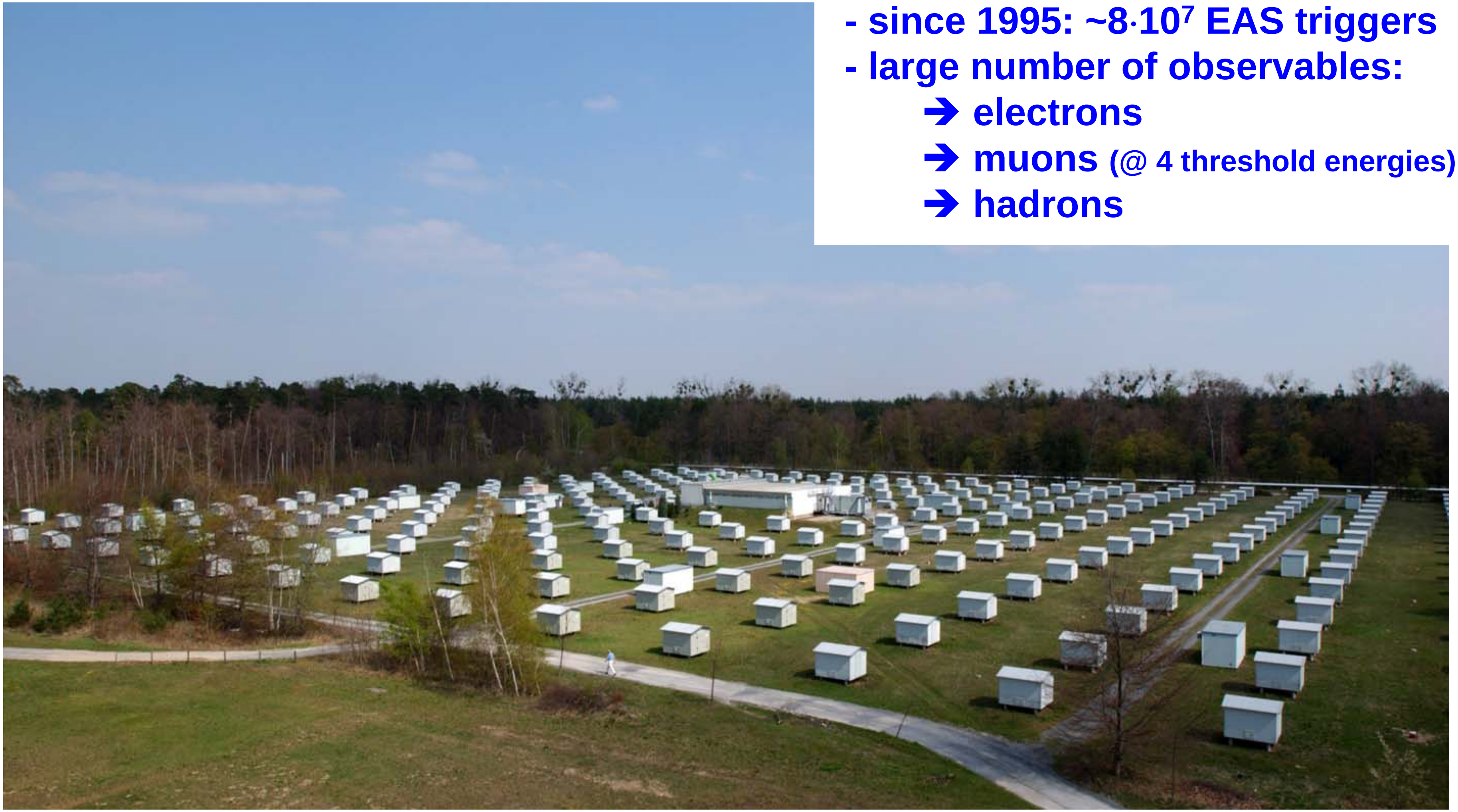
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

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

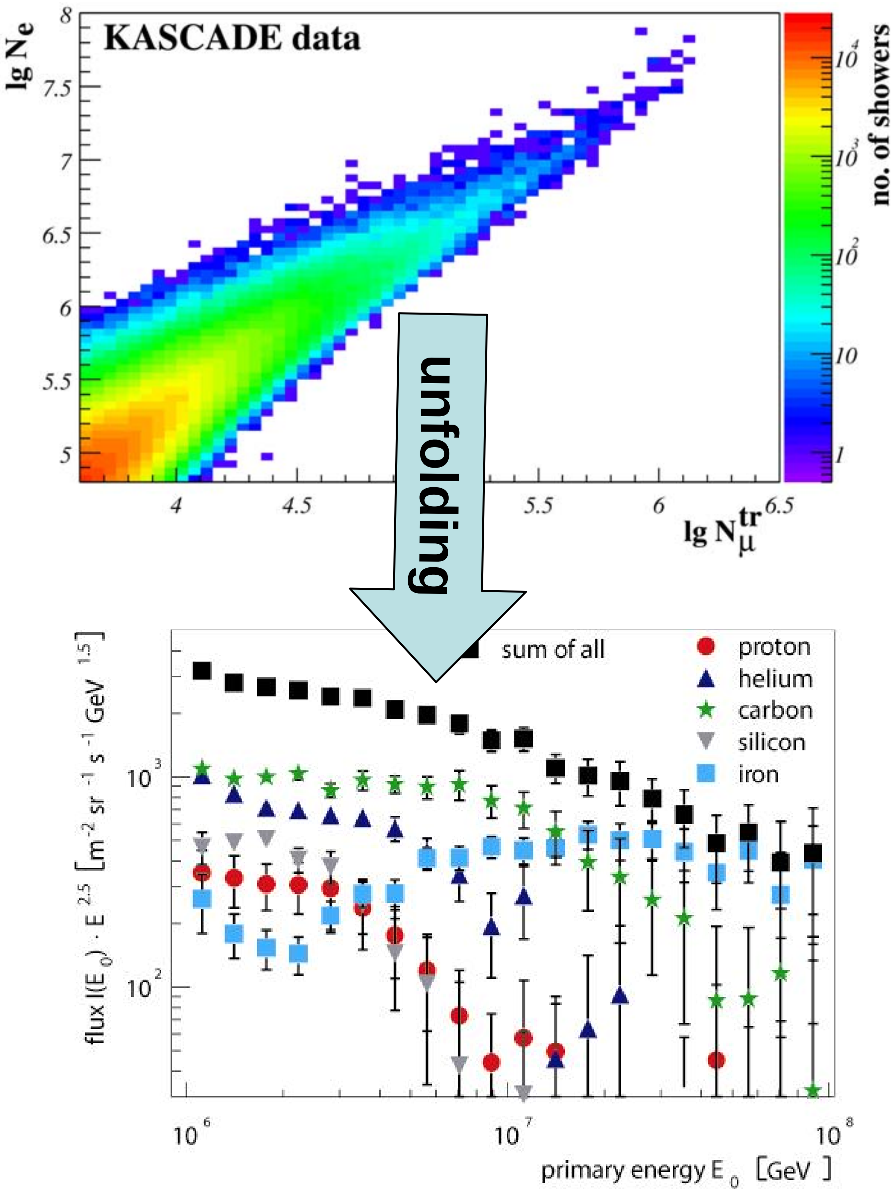


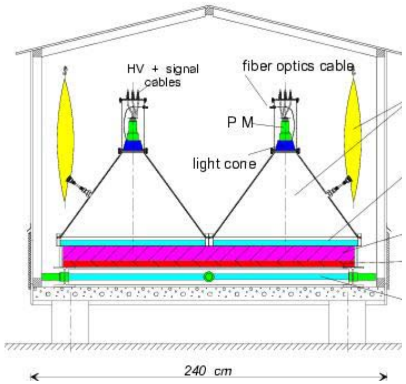
KASCADE :
multi-parameter measurements

- energy range 100 TeV – 80 PeV
- since 1995: ~$8 \cdot 10^7$ EAS triggers
- large number of observables:
  - ➔ electrons
  - ➔ muons (@ 4 threshold energies)
  - ➔ hadrons



KASCADE : energy spectra of single mass groups





Measurement:
KASCADE array data
900 days;
0-18° zenith angle
0-91m core distance
lg N_e > 4.8;
lg N_μ^{tr} > 3.6
➔ 685868 events

Searched:
E and A of the Cosmic Ray Particles
Given:
N_e and N_μ for each single event

➔ solve the inverse problem

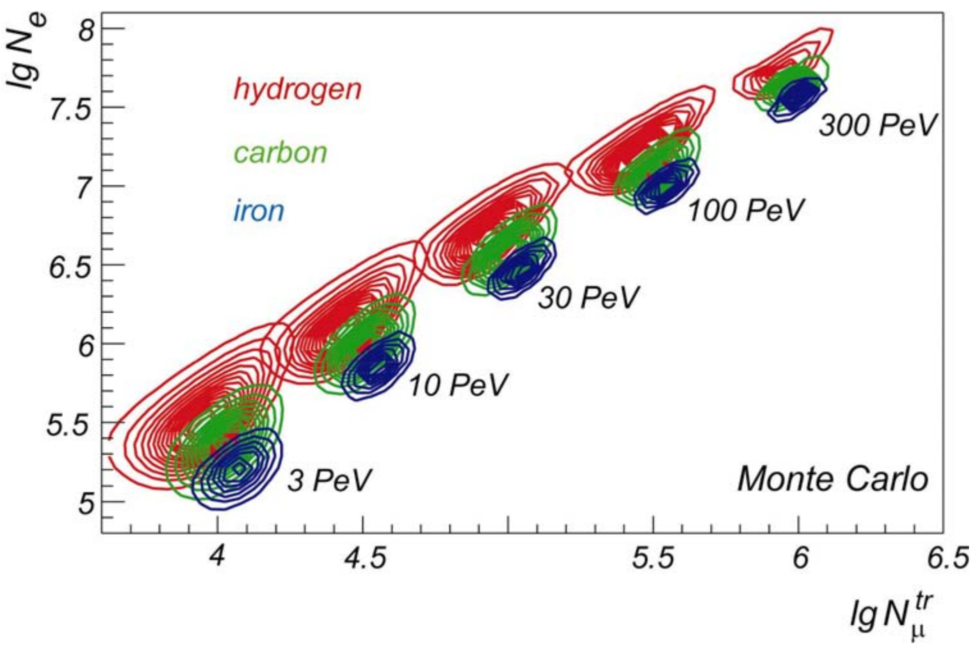
$$g(y) = \int K(y,x)p(x)dx$$

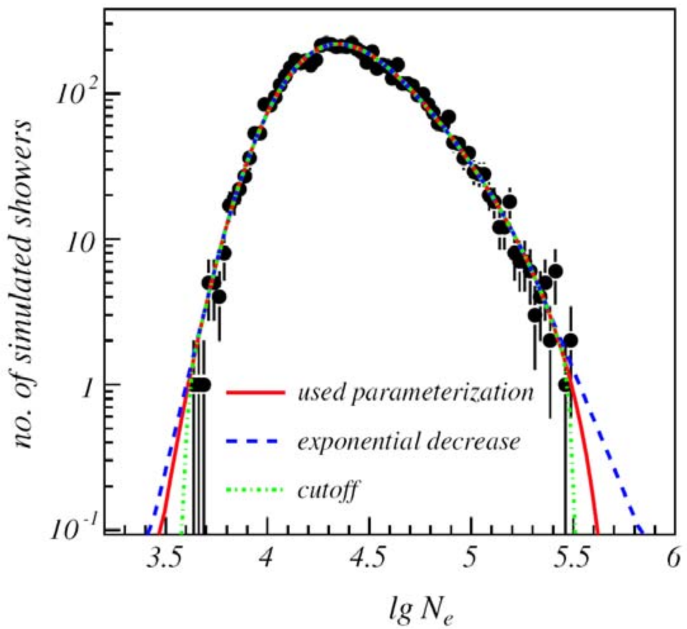
with $y=(N_e,N_\mu^{tr})$ and $x=(E,A)$

KASCADE Unfolding procedure

$$\frac{dJ}{d\lg N_e \, d\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E} \, p_A(\lg N_e, \lg N_\mu^{tr} \mid \lg E) \, d\lg E$$

- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution



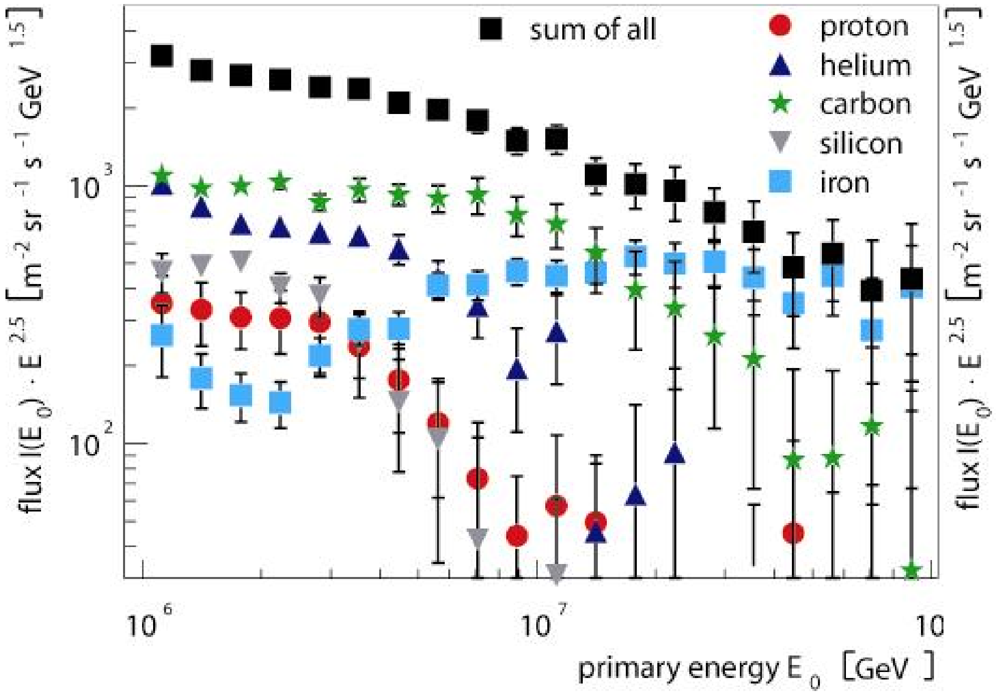


KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

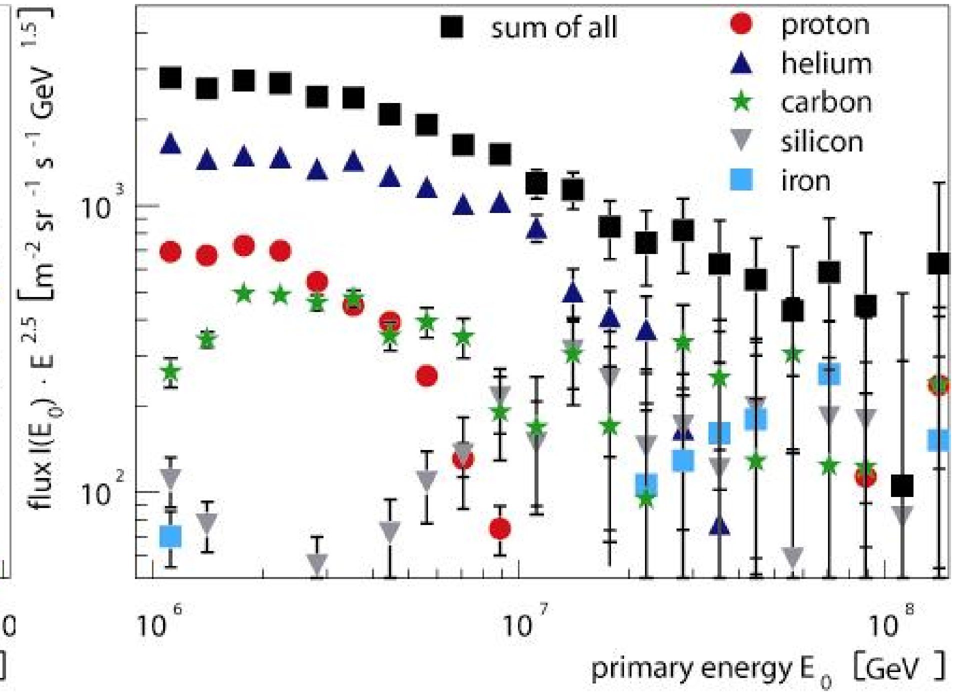
KASCADE results

- same unfolding but based on two different interaction models:
- SIBYLL 2.1 and QGSJET01 (both with GHEISHA 2002) all embedded in CORSIKA

SIBYLL

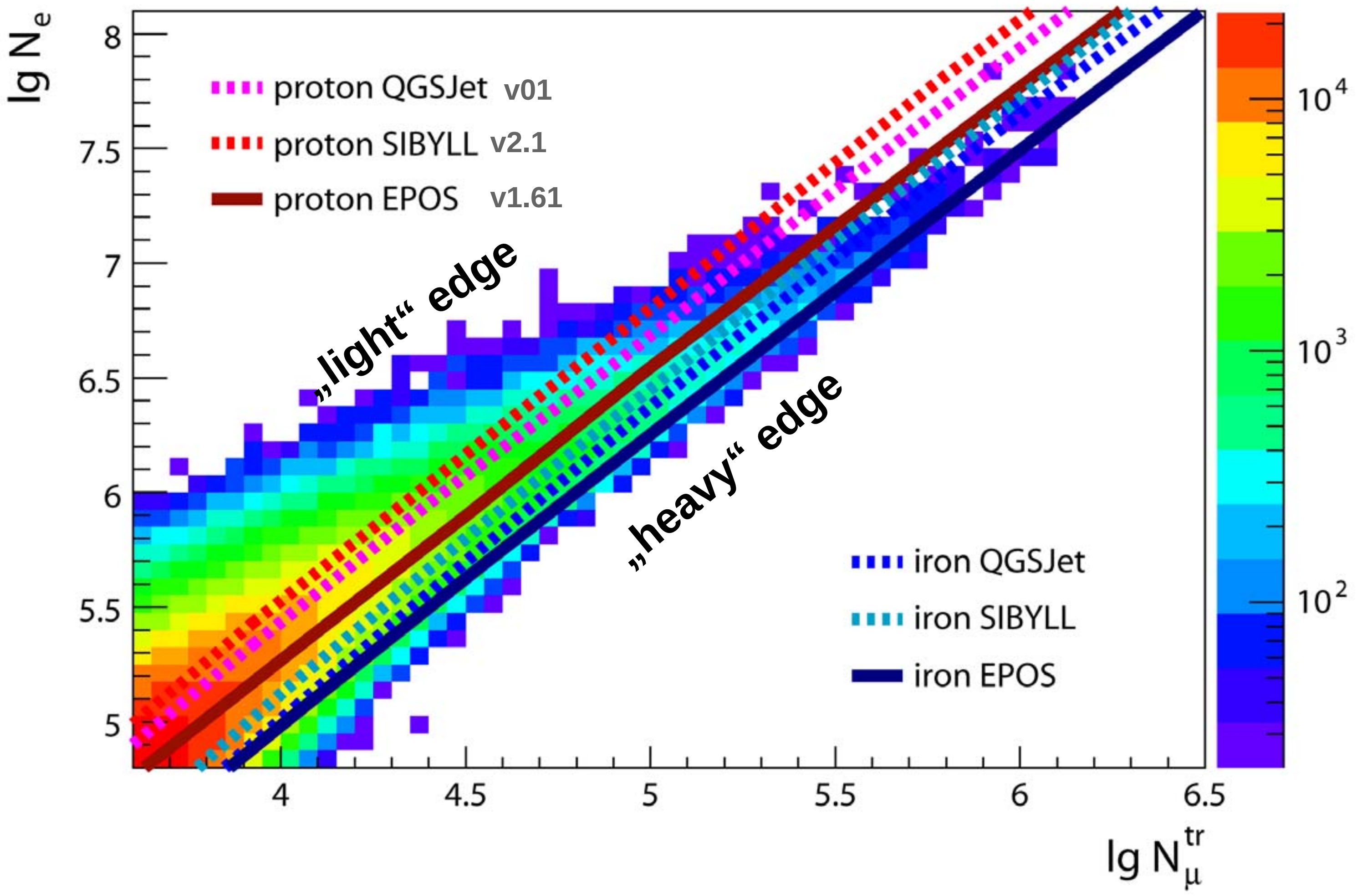


QGSJet

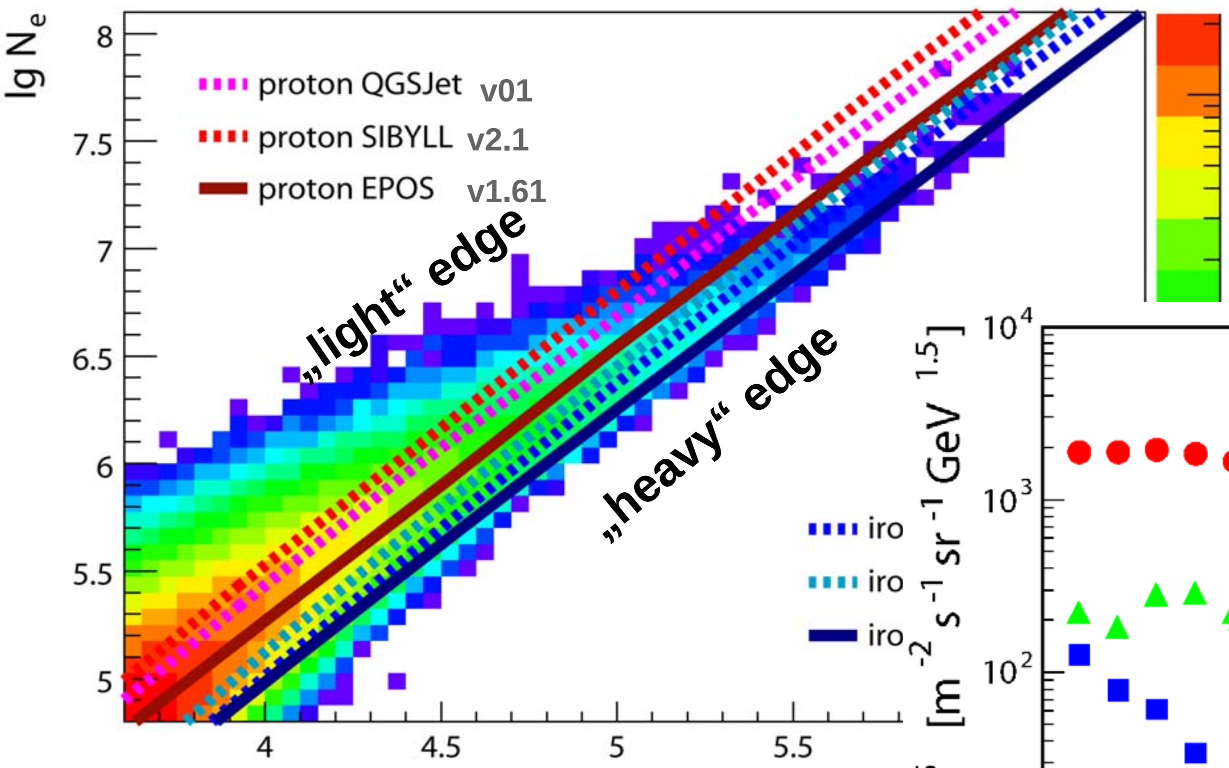


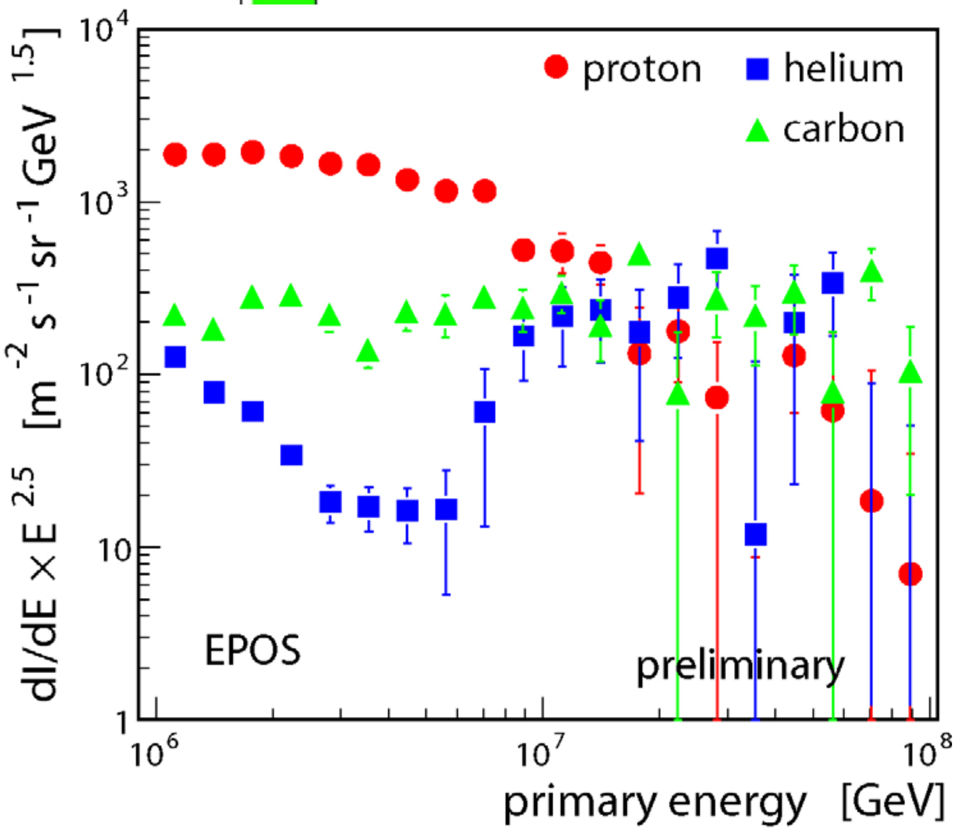
KASCADE collaboration, Astroparticle Physics 24 (2005) 1-25, astro-ph/0505413

KASCADE : sensitivity to hadronic interaction models



KASCADE : sensitivity to hadronic interaction models

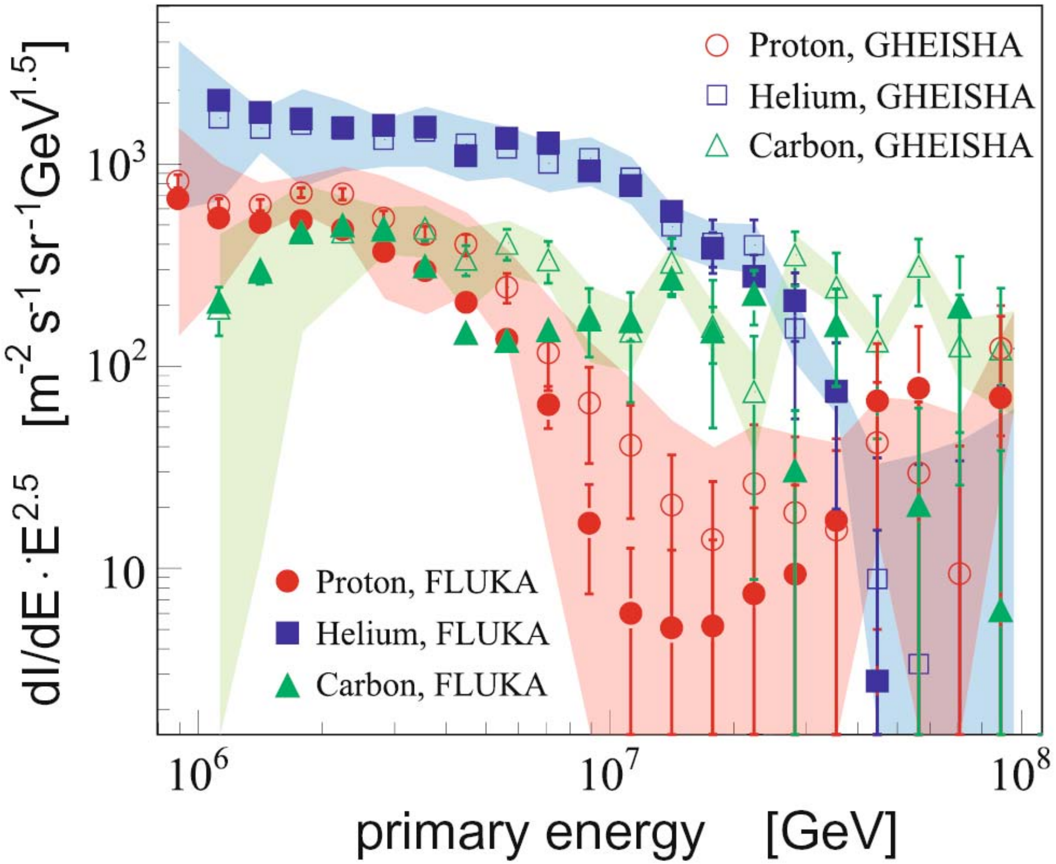




EPOS 1.61
-) very proton dominant, but knee caused by light primaries
-) no iron needed

KASCADE results: low-energy models

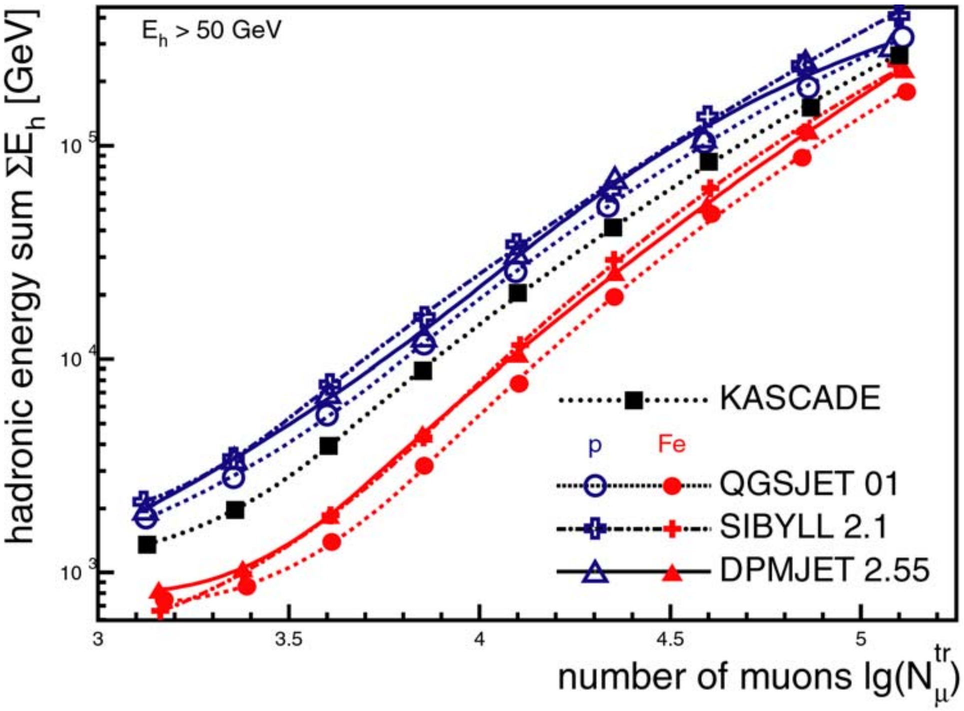
- same unfolding but based on two different low energy interaction models: GHEISHA 2002 and FLUKA (both with QGSJET01 and 0-18º)

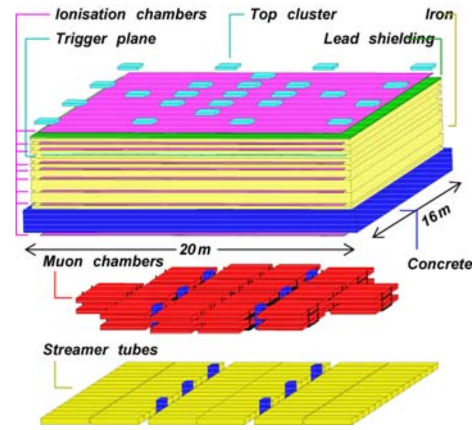


- Less dependence for unfolding based on different low energy hadronic interaction models

KASCADE collaboration, Astroparticle Physics 31 (2009) 86–91

KASCADE data analyses:
shower observable correlations





Example:
hadrons vs. muons

correlation of observables:

<u>no hadronic interaction model describes data consistently !</u>

➔ tests and tuning of hadronic interaction models !

➔ close co-operation with theoreticians

(CORSIKA including QGSJET, SIBYLL, FLUKA, GHEISHA,…..)

KASCADE collaboration, J Phys G (3 papers)

Shower observable correlations: Model tests

QGSJET 98
~~VENUS~~
~~SIBYLL 1.6~~

J. Phys. G: Nucl. Part. Phys. 25 (1999) 2161

DPMJET II.55
QGSJET 01
SIBYLL 2.1
~~NEXUS 2~~

~~DPMJET II.5~~

J. Phys. G: Nucl. Part. Phys. 34 (2007) 2581

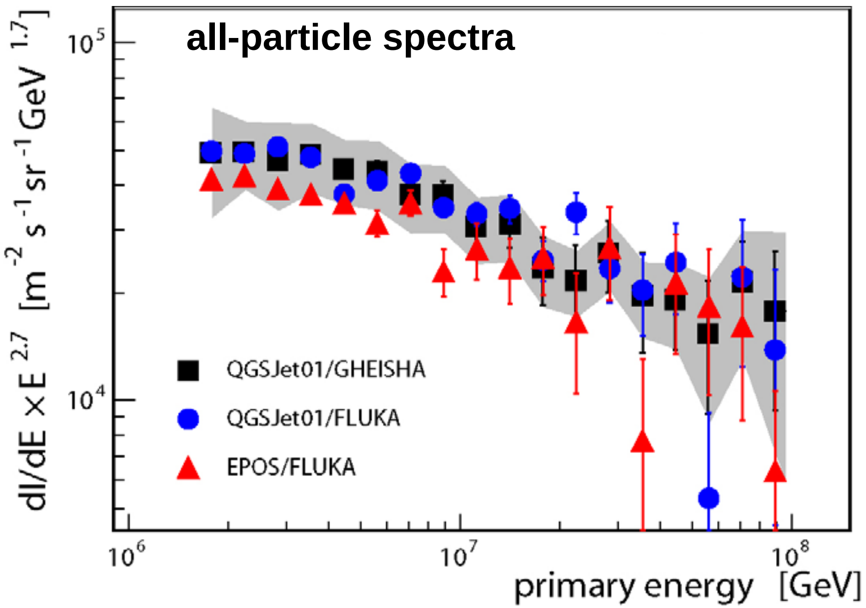
~~EPOS 1.6~~
QGSJET II

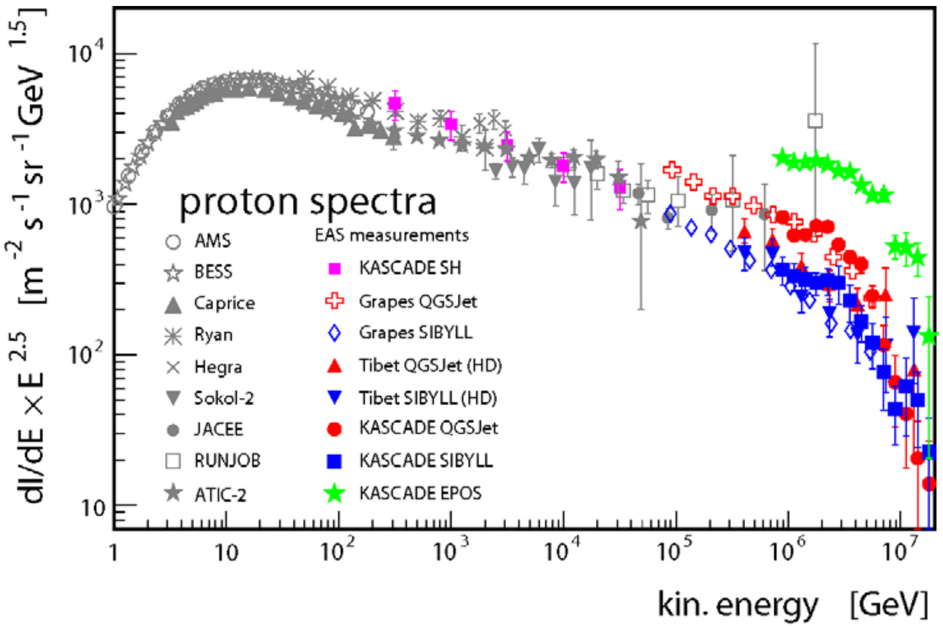
J. Phys. G: Nucl. Part. Phys. (2009) 035201

- **EPOS 1.6 is not compatible with KASCADE measurements**
- **QGSJET-II has some deficiencies**
- **QGSJET 01and SIBYLL 2.1still most compatible models**

➔ **New models are welcome for cross-tests with KASCADE data**

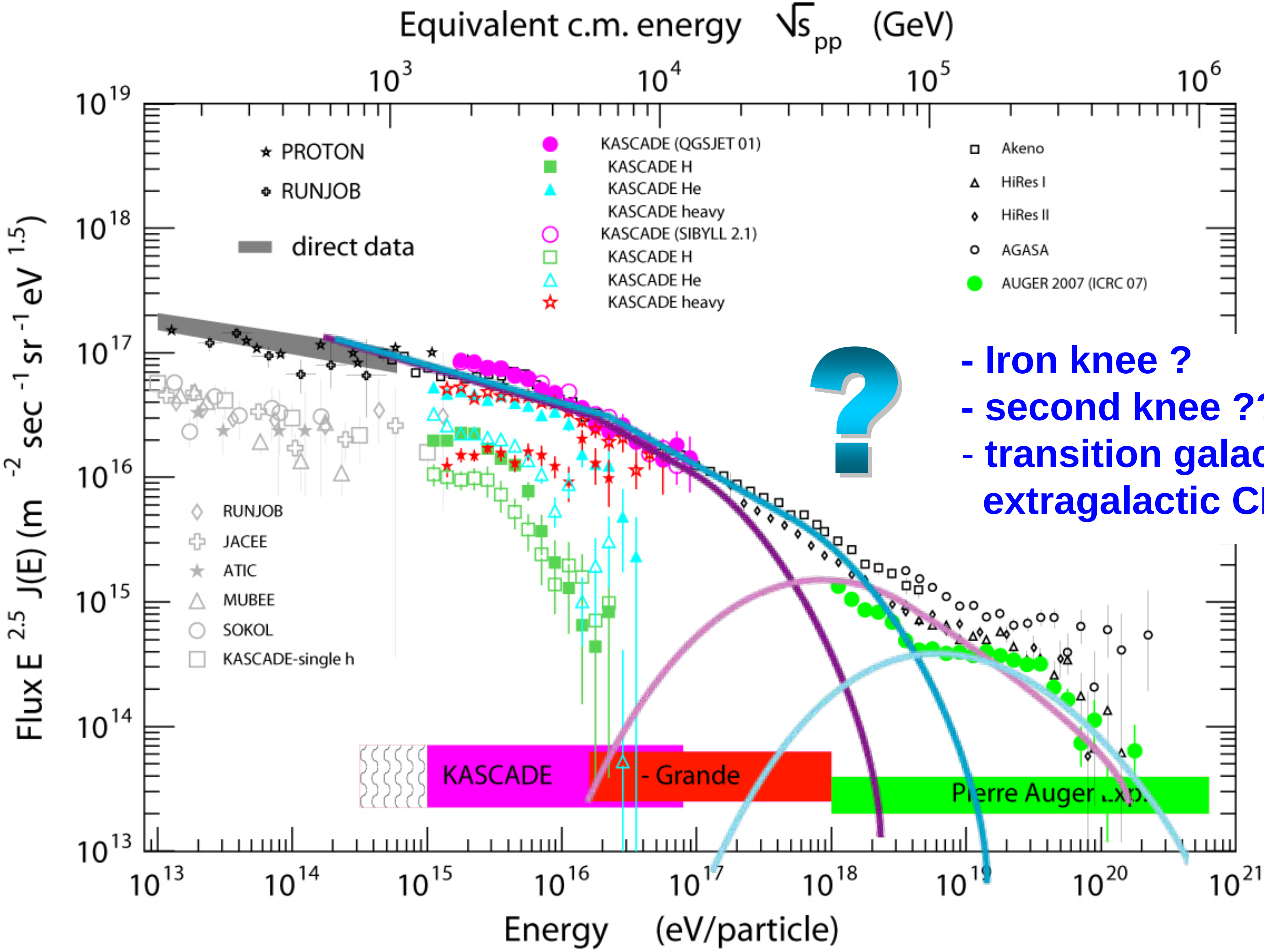
KASCADE Summary





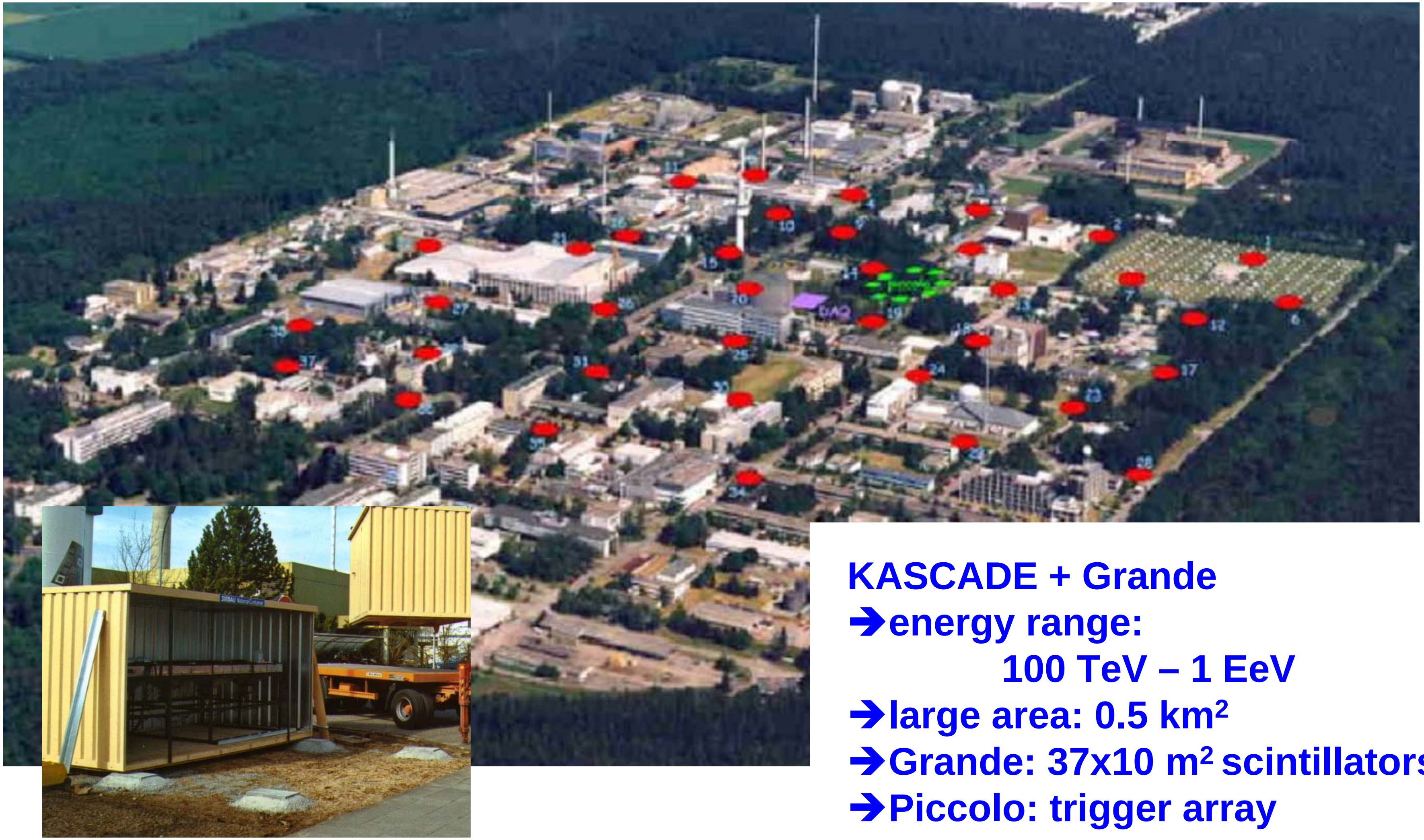
- -) **knee caused by light primaries ➔ composition gets heavier across knee**
- -) **positions of knee vary with primary elemental group**
- -) **relative abundancies depend strongly on high energy interaction model**
- -) **result only weakly dependent on low energy interaction model**
- -) **result consistent for different data sets**
- -) **no (interaction) model can describe the data consistently**
- -) **all-particle spectra agree inside uncertainties** (EPOS1.6 a bit lower)
- -) **proton spectra agree with direct measurements** (not for EPOS1.6)

Motivation for measurements 100 – 1000 PeV



- Iron knee ?
- second knee ??
- transition galactic-extragalactic CR ??

KASCADE-Grande : extension to higher energies

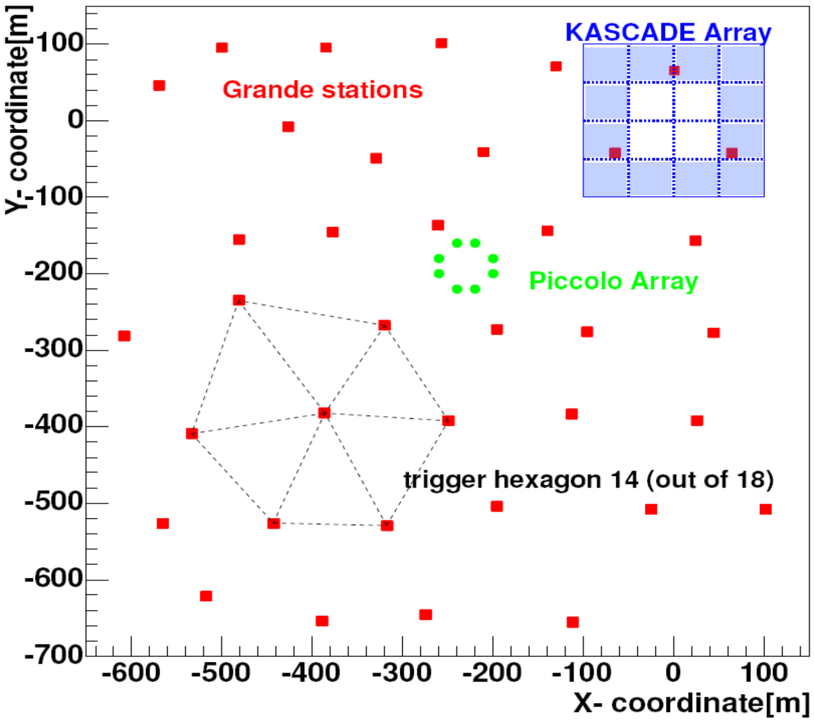


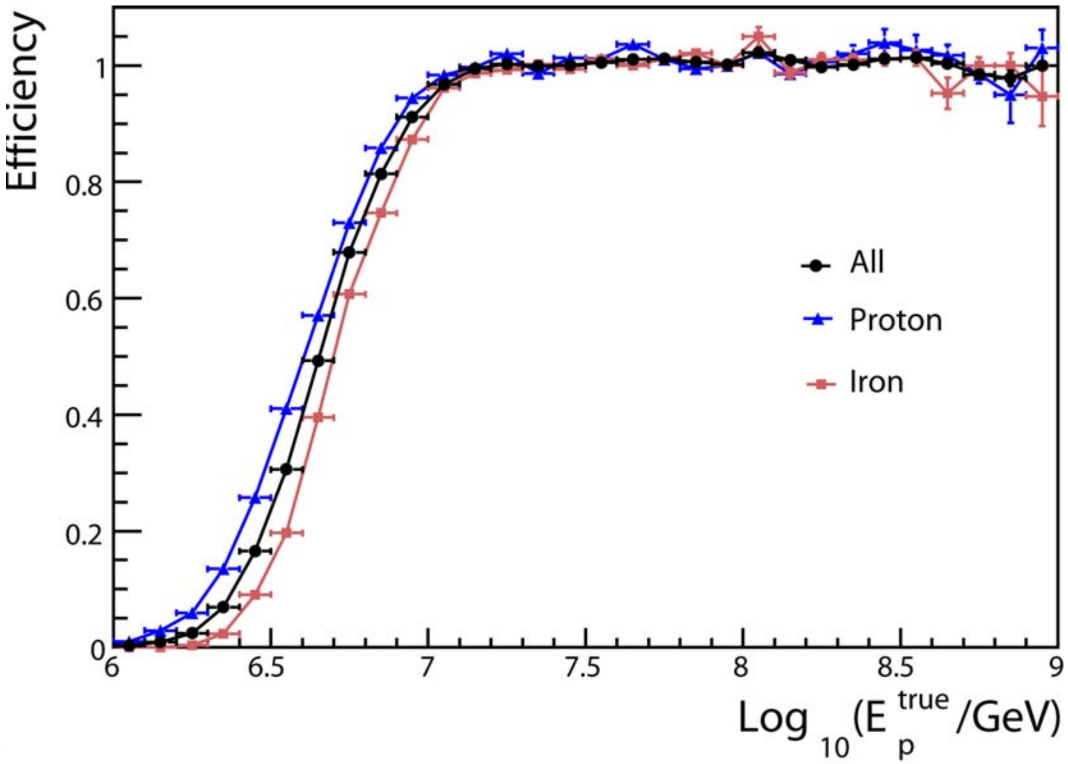
KASCADE + Grande

- ➔**energy range:**
  100 TeV – 1 EeV
- ➔**large area: 0.5 km²**
- ➔**Grande: 37x10 m² scintillators**
- ➔**Piccolo: trigger array**

KASCADE-Grande : Efficiency

- Common events (all detector components) measure since December 2003
- Trigger: 7of 7 stations at one of 18 hexagons





KASCADE-Grande: Reconstruction

1) core position and angle-of-incidence
from Grande array data

➔

2a) shower size (charged particles)
from Grande array data

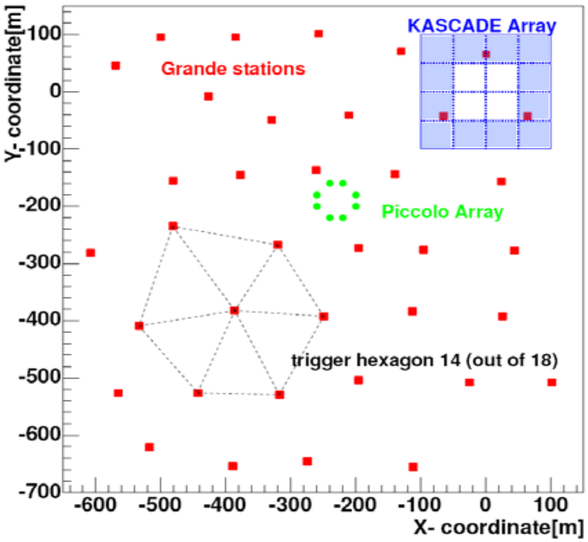
2b) muon number
from KASCADE muon detectors

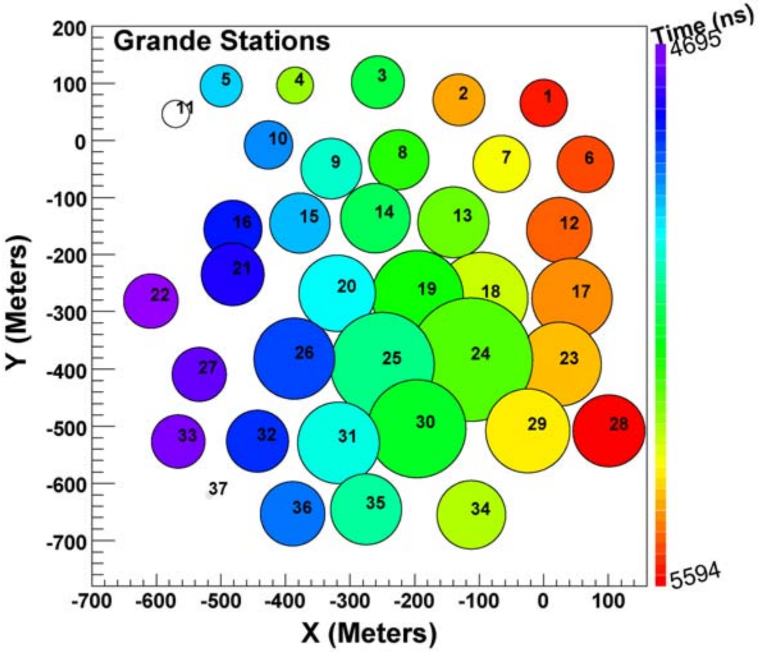
➔

3) electron number
from Grande by subtraction of muon content

➔

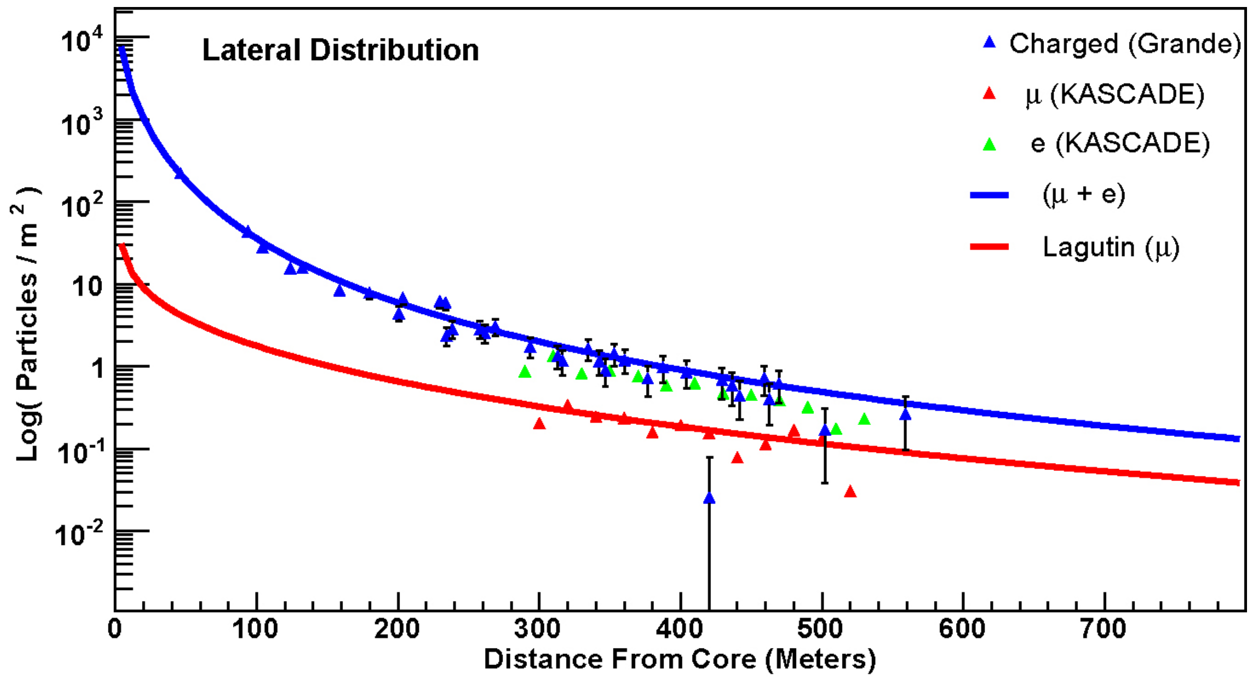
4) two dimensional size spectrum
for the unfolding analysis



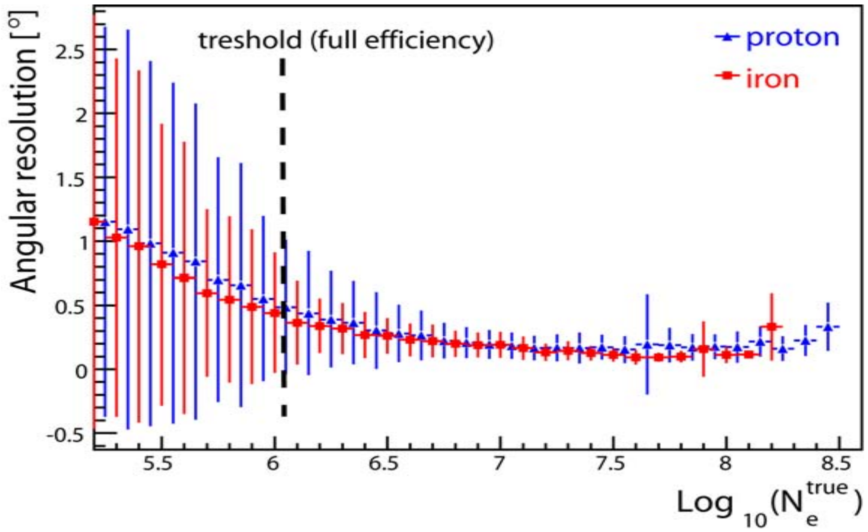


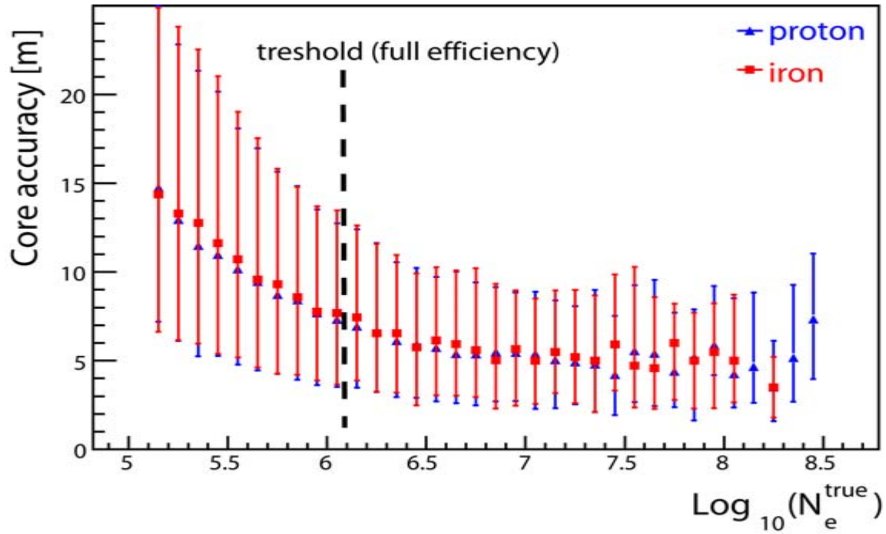
KASCADE-Grande : Single event reconstruction

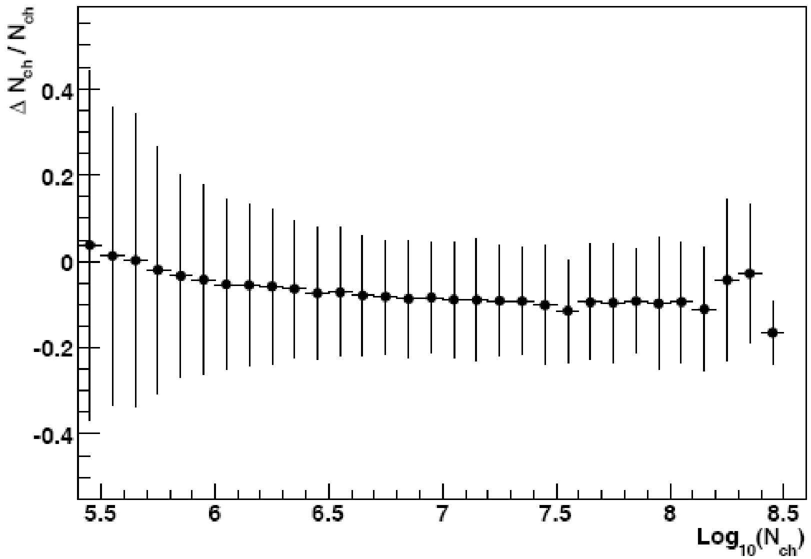
a single event measured by KASCADE-Grande:
core (-155,- 401) m
log10(Size) : 7.0
log10(Sizm) : 5.7
No saturation
Zenith: 24.2 degrees
Azimuth: 284 degrees
Recorded on 8 July 2005 at 12:11 (UTC)



KASCADE-Grande : Reconstruction angular, core & shower size (N_{ch}) resolution







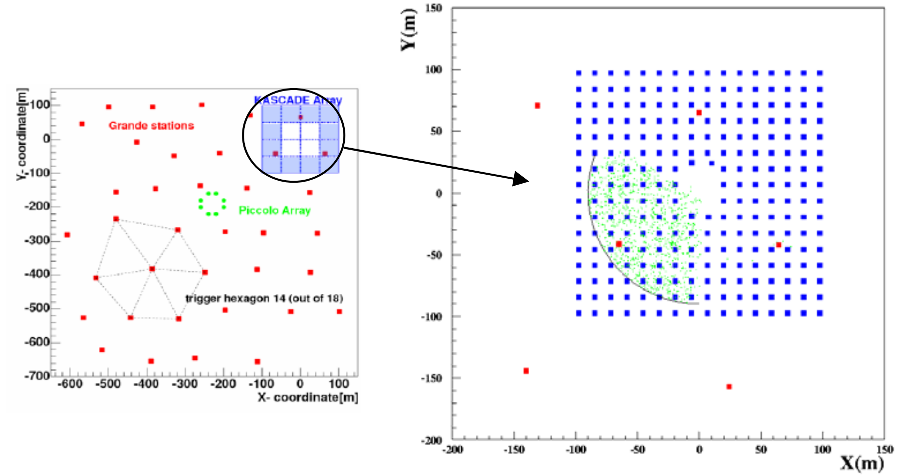
Monte-Carlo studies (QGSJet II / FLUKA):

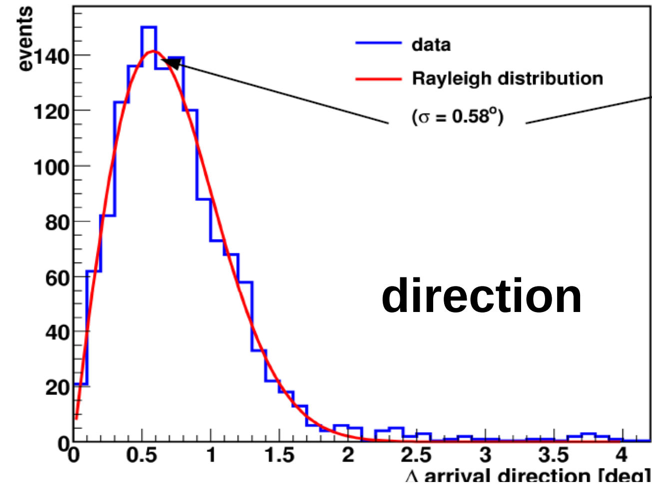
- **σ ~ 0.4º angular resolution**
- **σ ~ 5m core resolution**
- **Sufficient (~15%) reconstruction accuracies for shower size**
- **Small overestimation (5-10%) and small energy (size) dependence**

KASCADE-Grande : Accuracies

with subsample of common events KASCADE + Grande

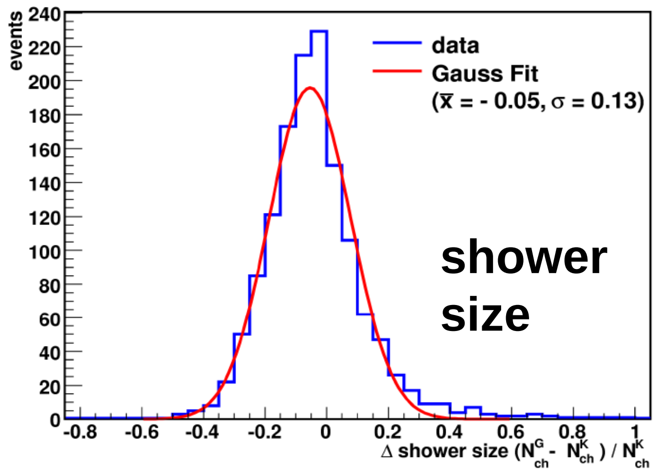
$$\Delta\psi = \arccos(\cos(\theta_K)\cdot\cos(\theta_G)+\sin(\theta_K)\cdot\sin(\theta_G)+\cos(\phi_K-\phi_G))$$





accuracy: $\Delta\psi$ = 0.58°

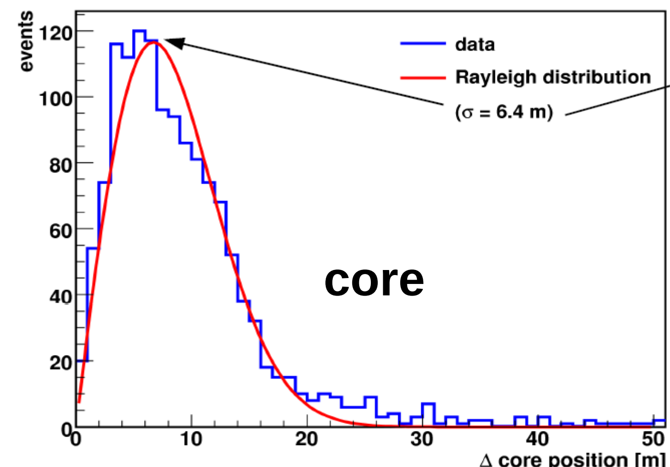
$$x = (N_{ch}^{G} - N_{ch}^{K}) / N_{ch}^{K}$$



systematic shift: $\bar{x}$ = - 0.05

event by event fluctuation: σ_x = 0.13

$$\Delta r = \sqrt{(x_K - x_G)^2 + (y_K - y_G)^2}$$



accuracy: Δr = 6.4 m

KASCADE-Grande collaboration (F. Di Pierro), ICRC 09

KASCADE-Grande
Reconstruction of the energy spectrum

Application of different methods:

-Using the shower size (N_{ch}) as observable

-Using the muon size (N_{μ}) as observable

-Using the density at 500m (S_{500}) as observable

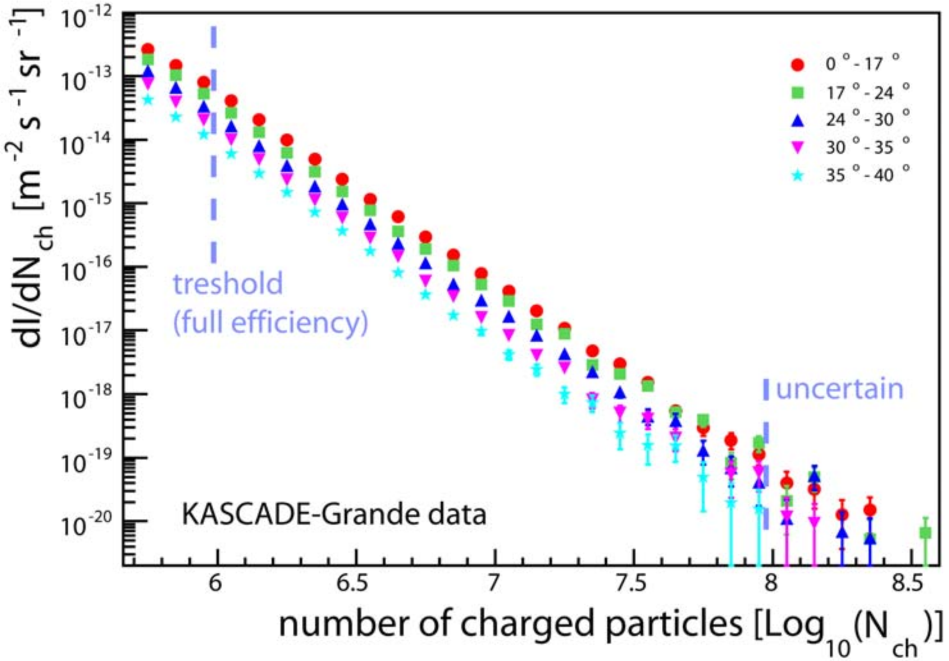
-Using combination of N_{μ} and N_{ch} as observables

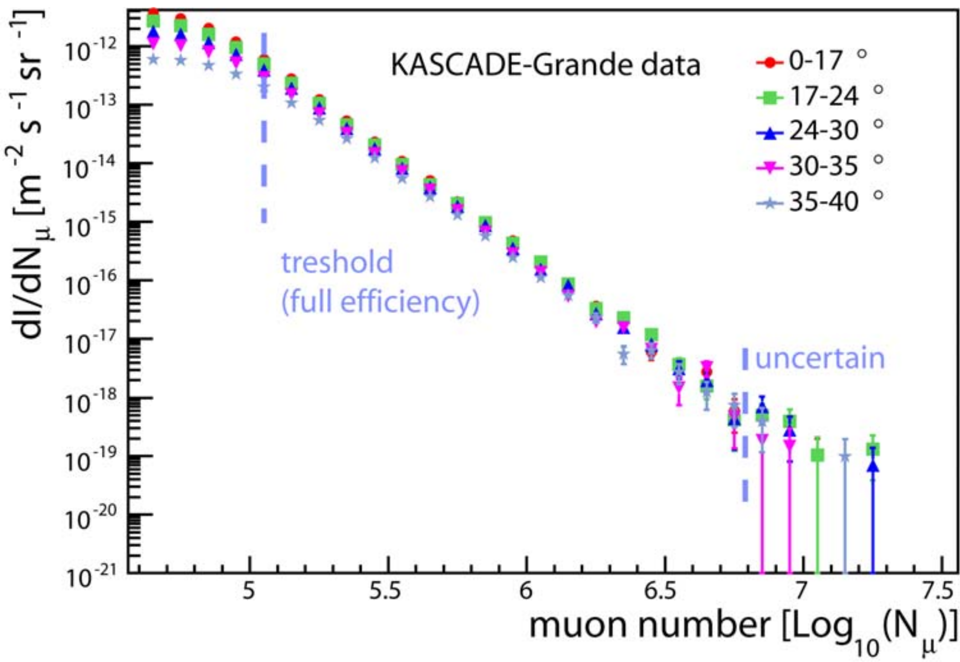
→

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

size spectra
(charged particles)

muon number spectra
(N_μ ; E_μ>230MeV)

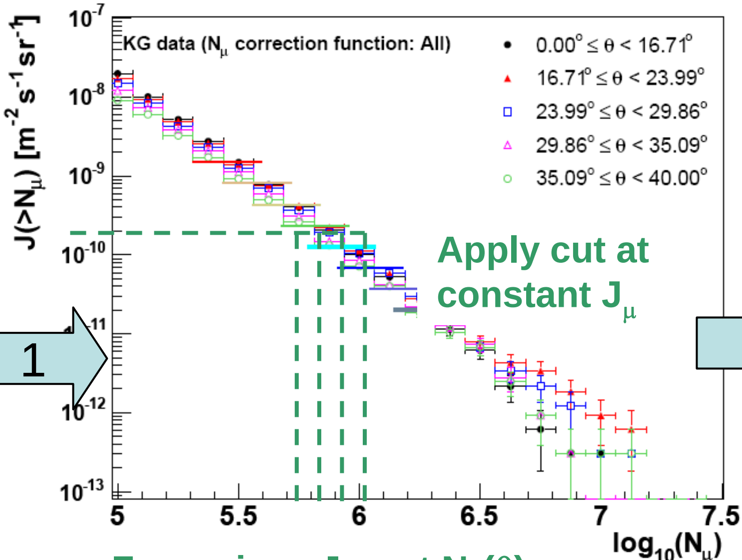




-stable data taking since 2004, c. 900 days effective DAQ time
-performance of reconstruction (and detector) is stable

constant intensity cut method CIC (N_μ, N_{ch}, S_{500}) = correct for the attenuation from data

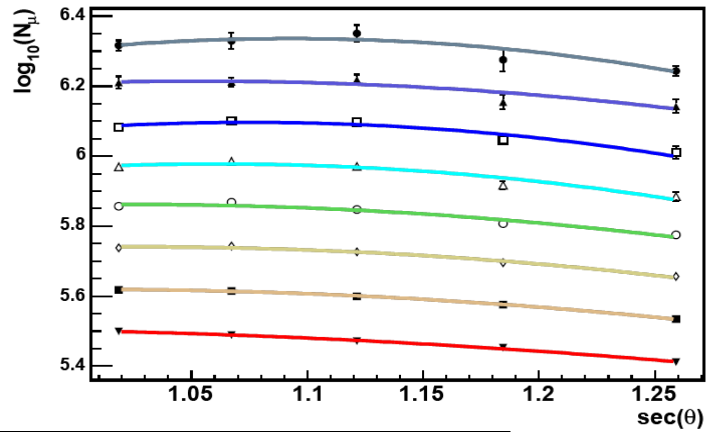
1



For a given J_μ, get $N_\mu(\theta)$

2

$$\log_{10} N_\mu = a_0 + a_1 \cdot Sec(\theta) + a_3 \cdot Sec^2(\theta)$$

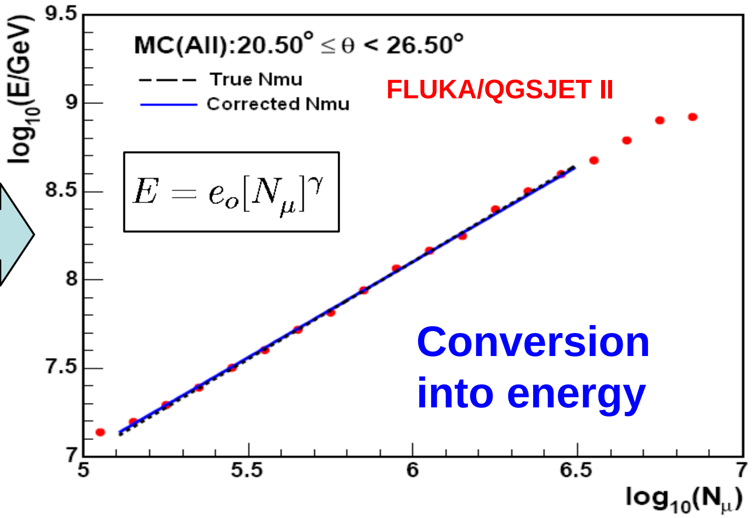


Get attenuation curves

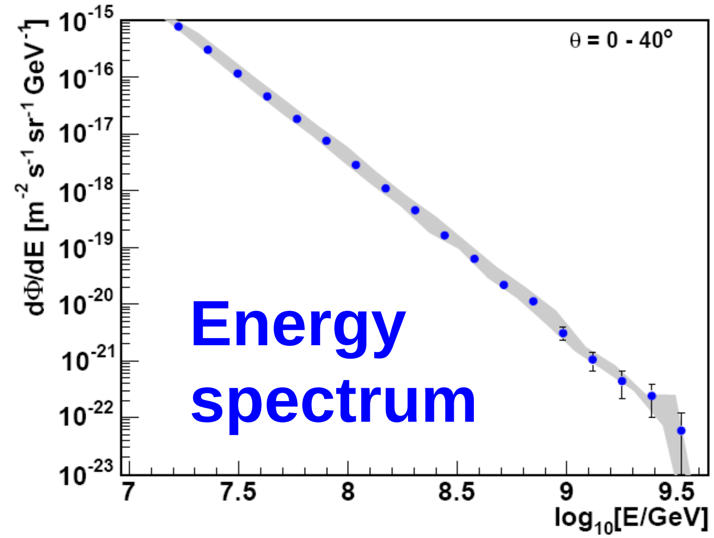
3

$N_\mu(24^\circ)$ of each event

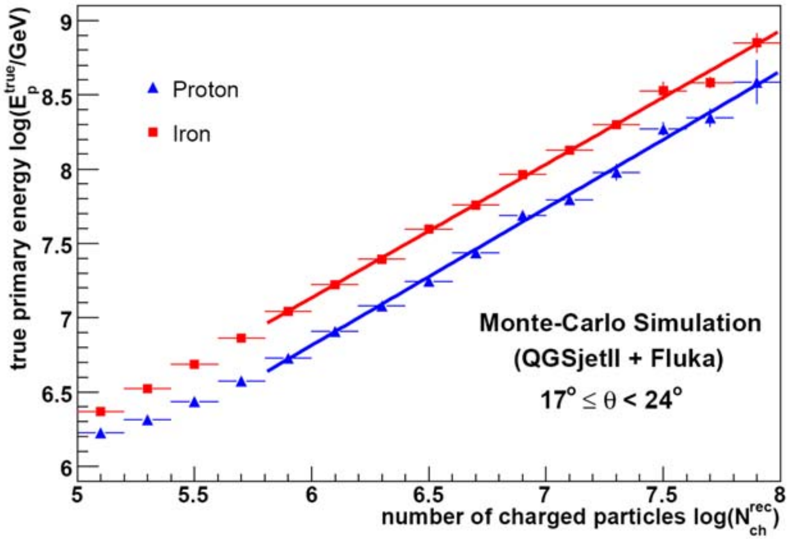
4



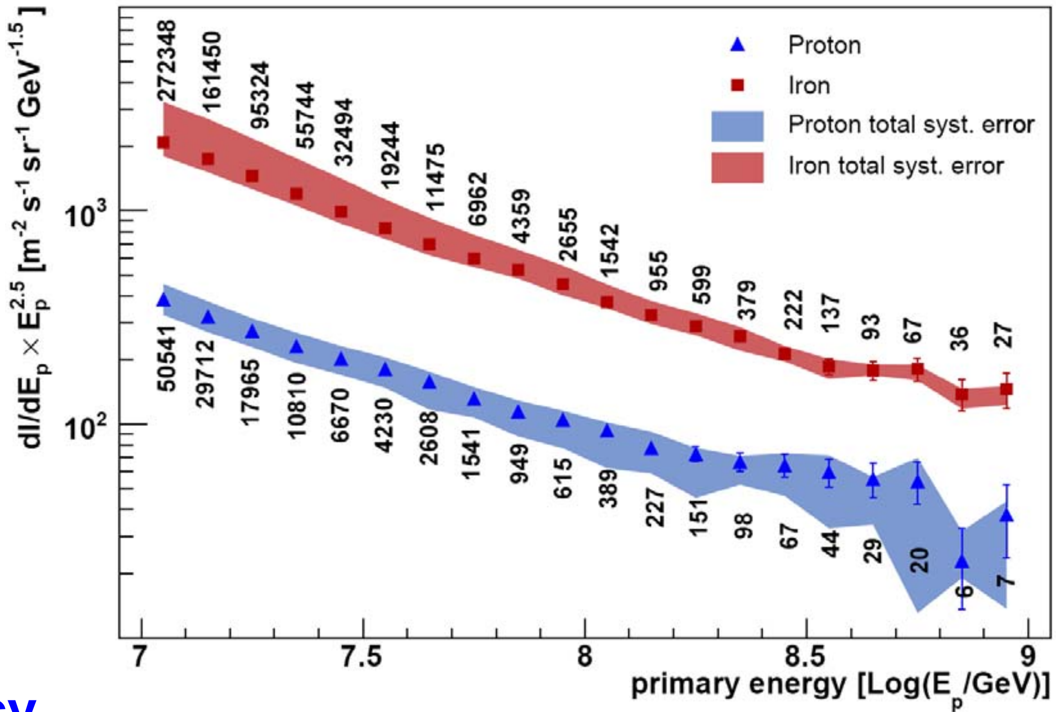
5



Way to all particle energy spectrum : via shower size (N_{ch})



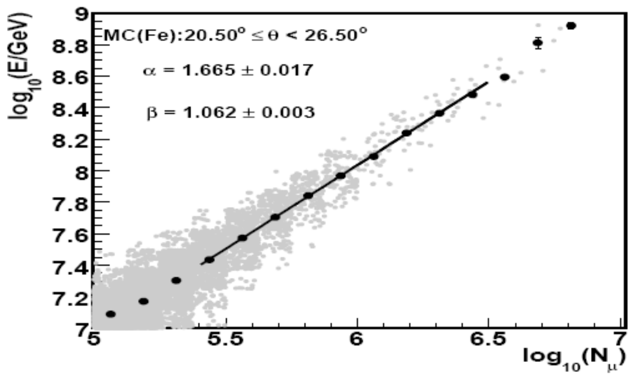
QGSJET II hadronic interaction model

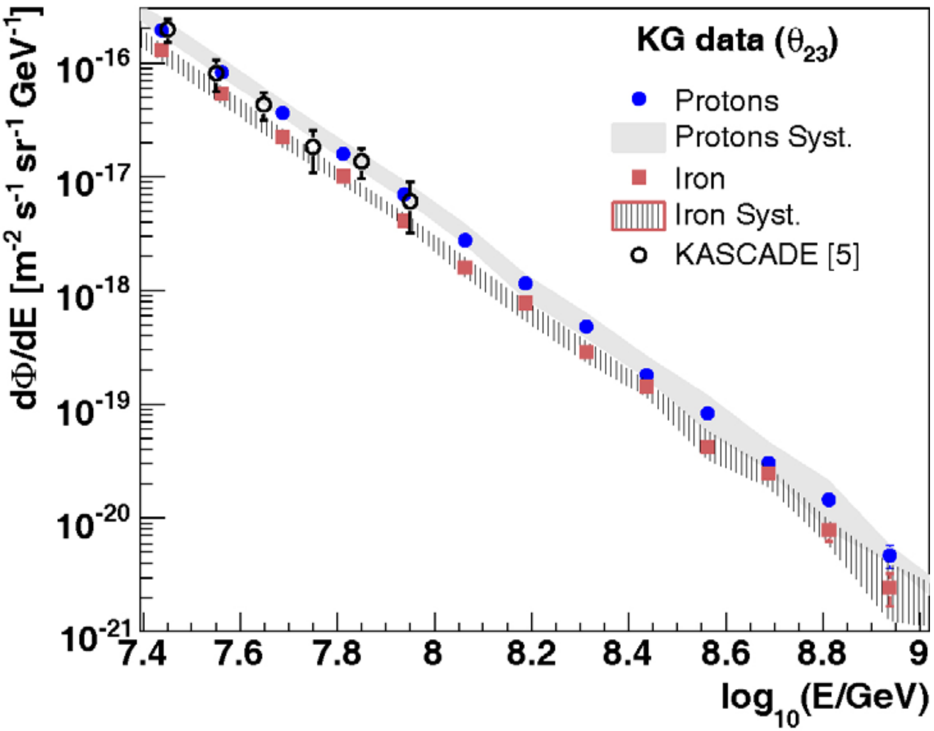


-Good reconstruction accuracy
-Very composition dependent
(need assumption of primary type)
-careful checks of systematic effects

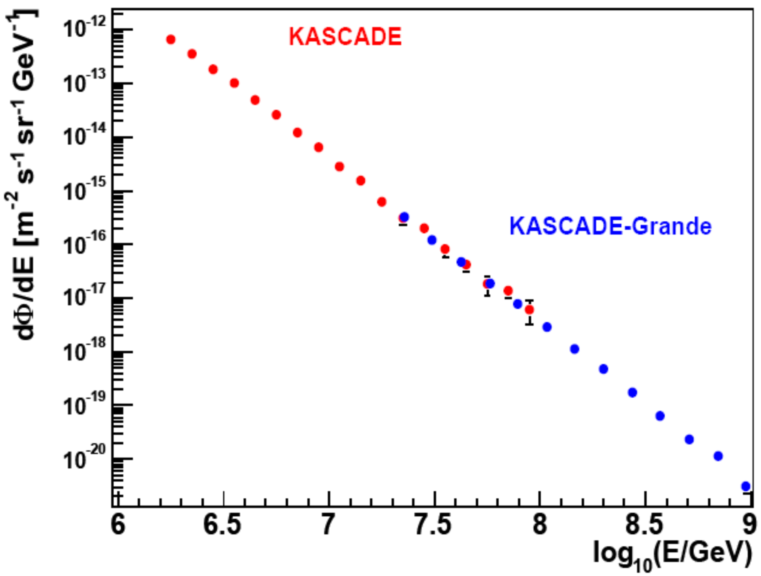
KASCADE-Grande collaboration (D.Kang), ICRC 09

Way to all particle energy spectrum : via muon number (N_μ)





QGSJET II hadronic interaction model



-Less good reconstruction accuracy

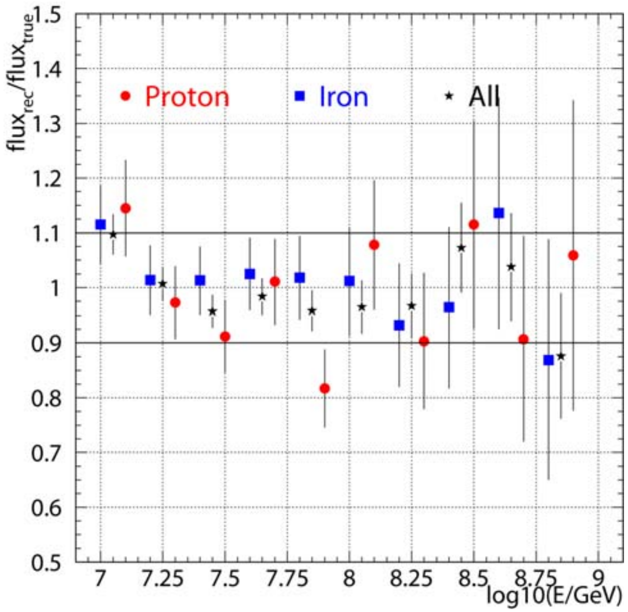
-Less composition dependence

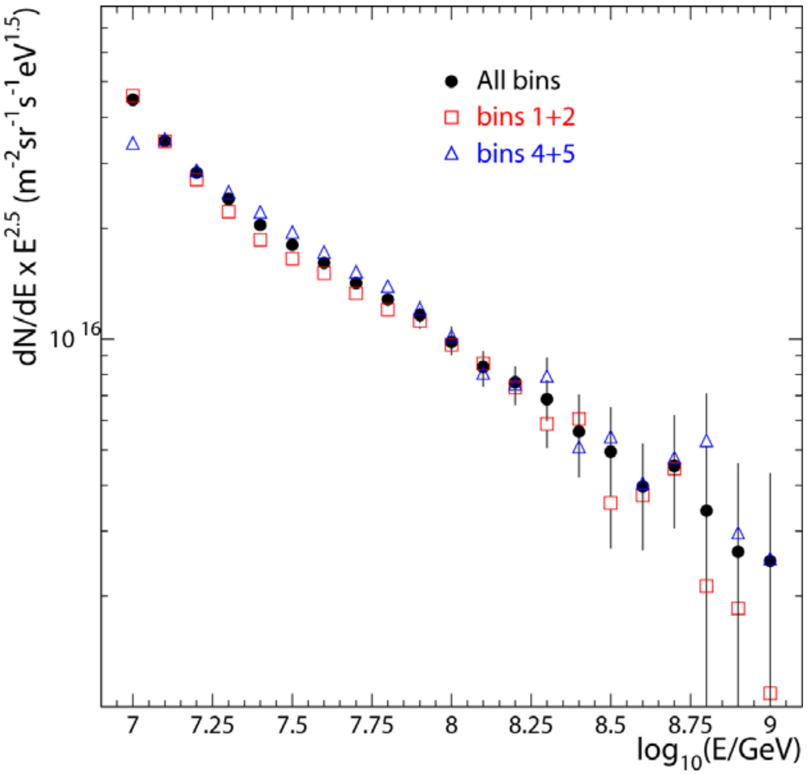
KASCADE-Grande collaboration (J.C.Arteaga-Velazquez), ICRC 09

Way to all particle energy spectrum : via combination of N_μ and N_{ch}

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

$$k = (\log_{10}(N_{ch}/N_\mu) - \log10(N_{ch}/N_\mu)_p) / (\log10(N_{ch}/N_\mu)_{Fe} - \log10(N_{ch}/N_\mu)_p)$$

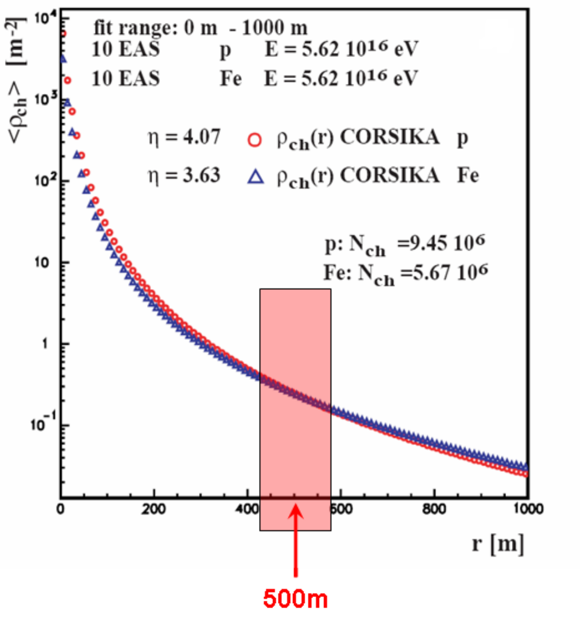


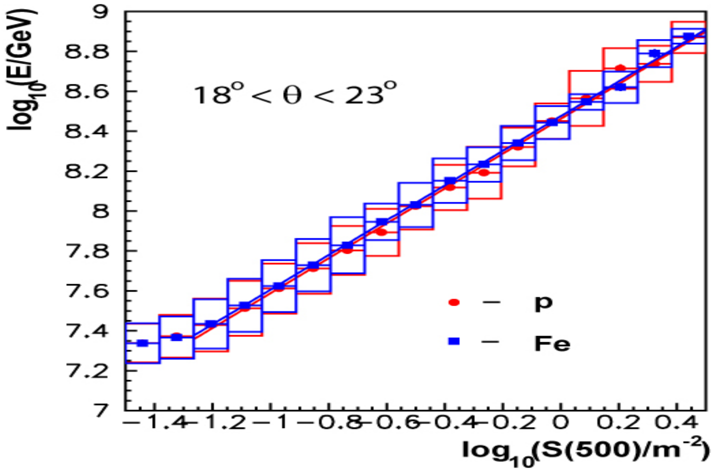


-different zenith angle bins
-no composition dependence

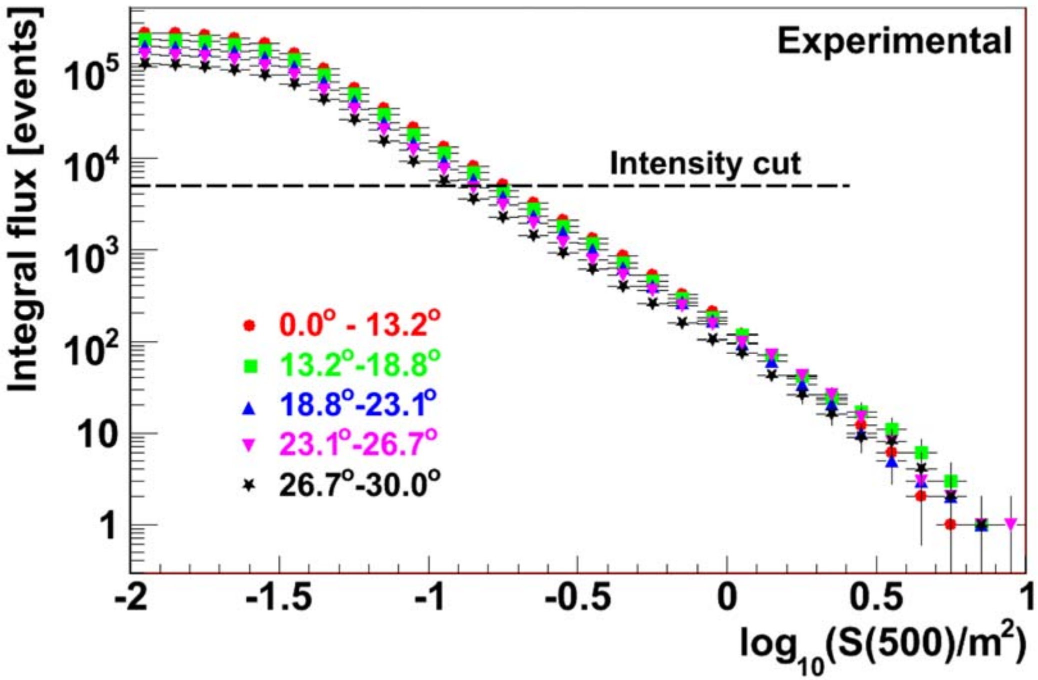
KASCADE-Grande collaboration (M.Bertaina), ICRC 09

Way to all particle energy spectrum : via S(500)





QGSJET II hadronic interaction model

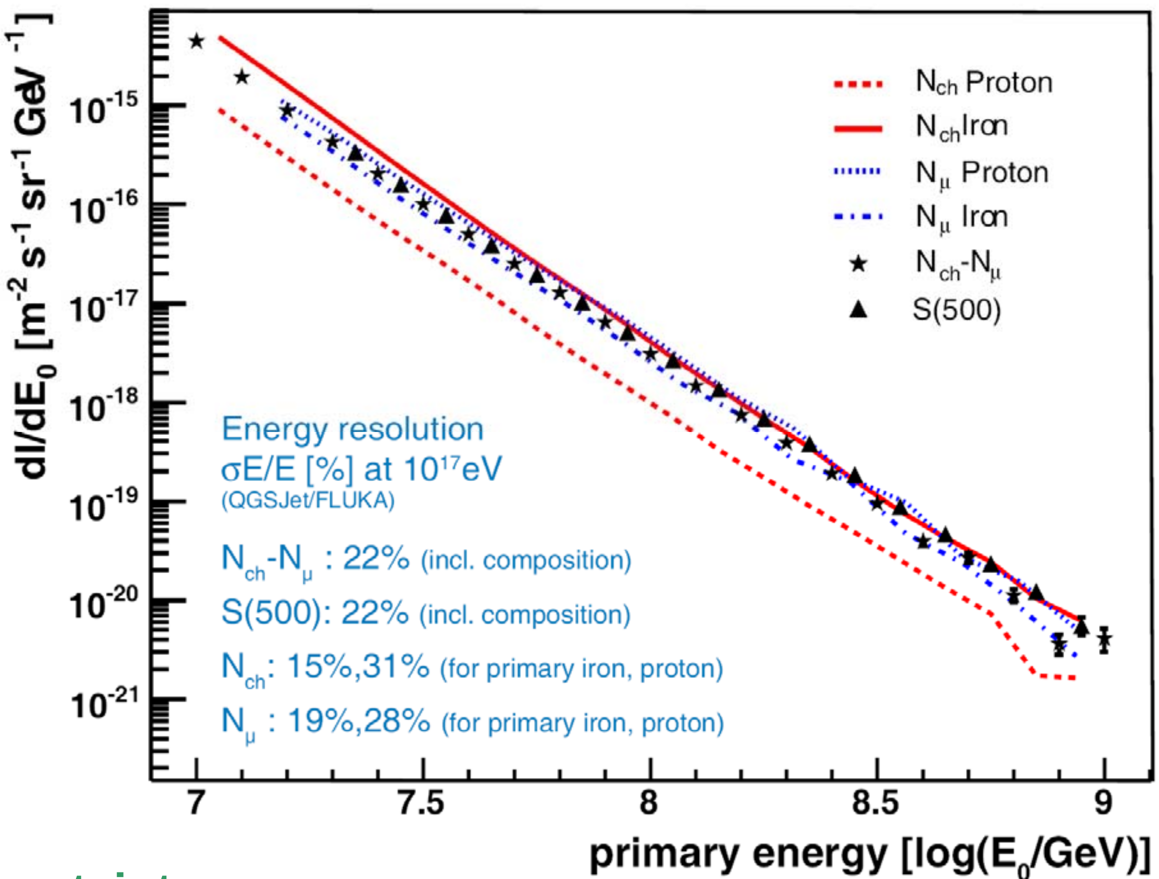


-Problem reconstruction accuracy

-No composition dependence

KASCADE-Grande collaboration (G.Toma), ICRC 09

The all-particle energy spectrum



Sources of uncertainty:

1) Observable reconstruction

2) CIC method, attenuation

3) Energy vs N_μ relation

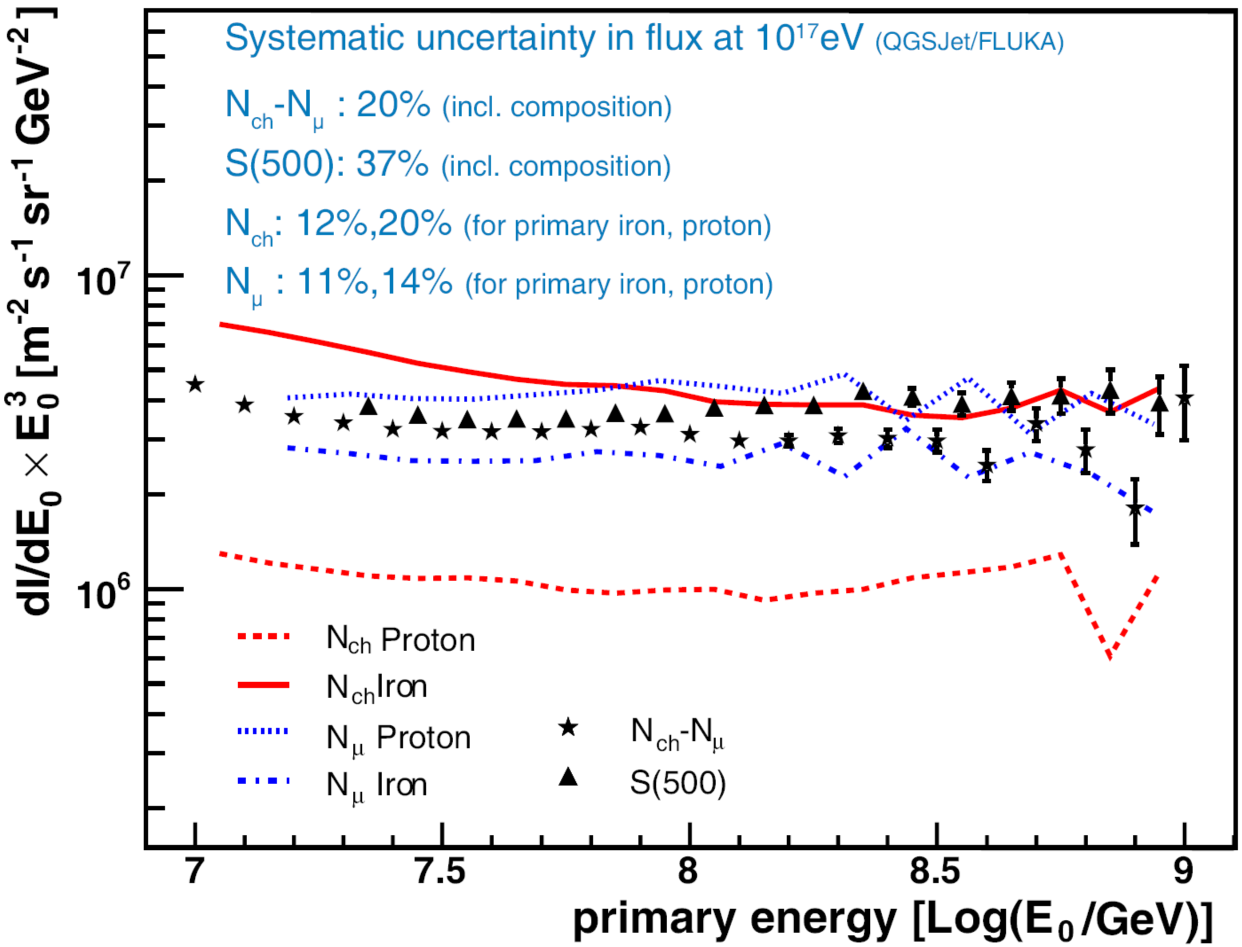
4) Influence of MC statistics

5) Spectral index in MC sample

6) Composition assumption

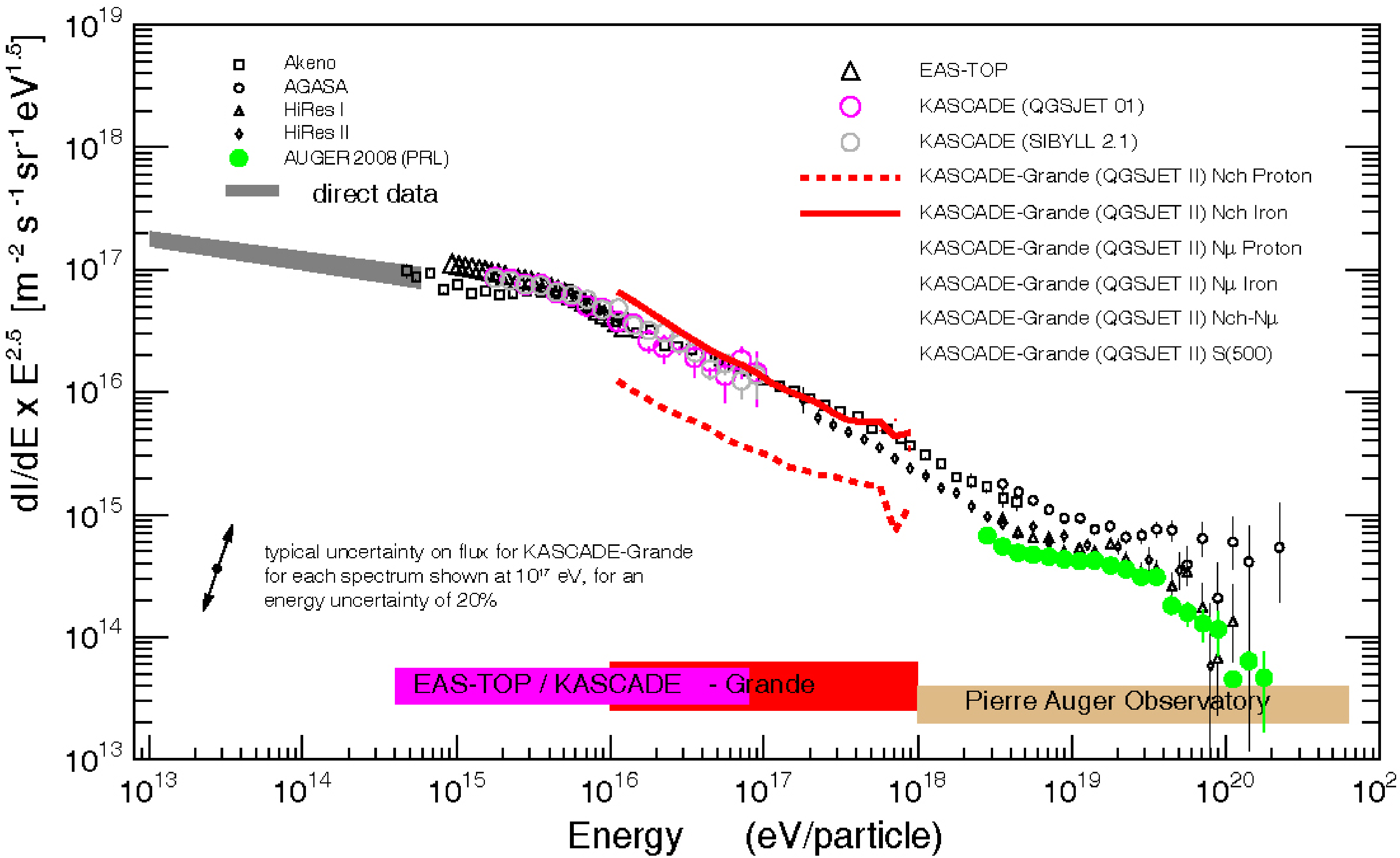
…..

KASCADE-Grande
Reconstruction of the energy spectrum

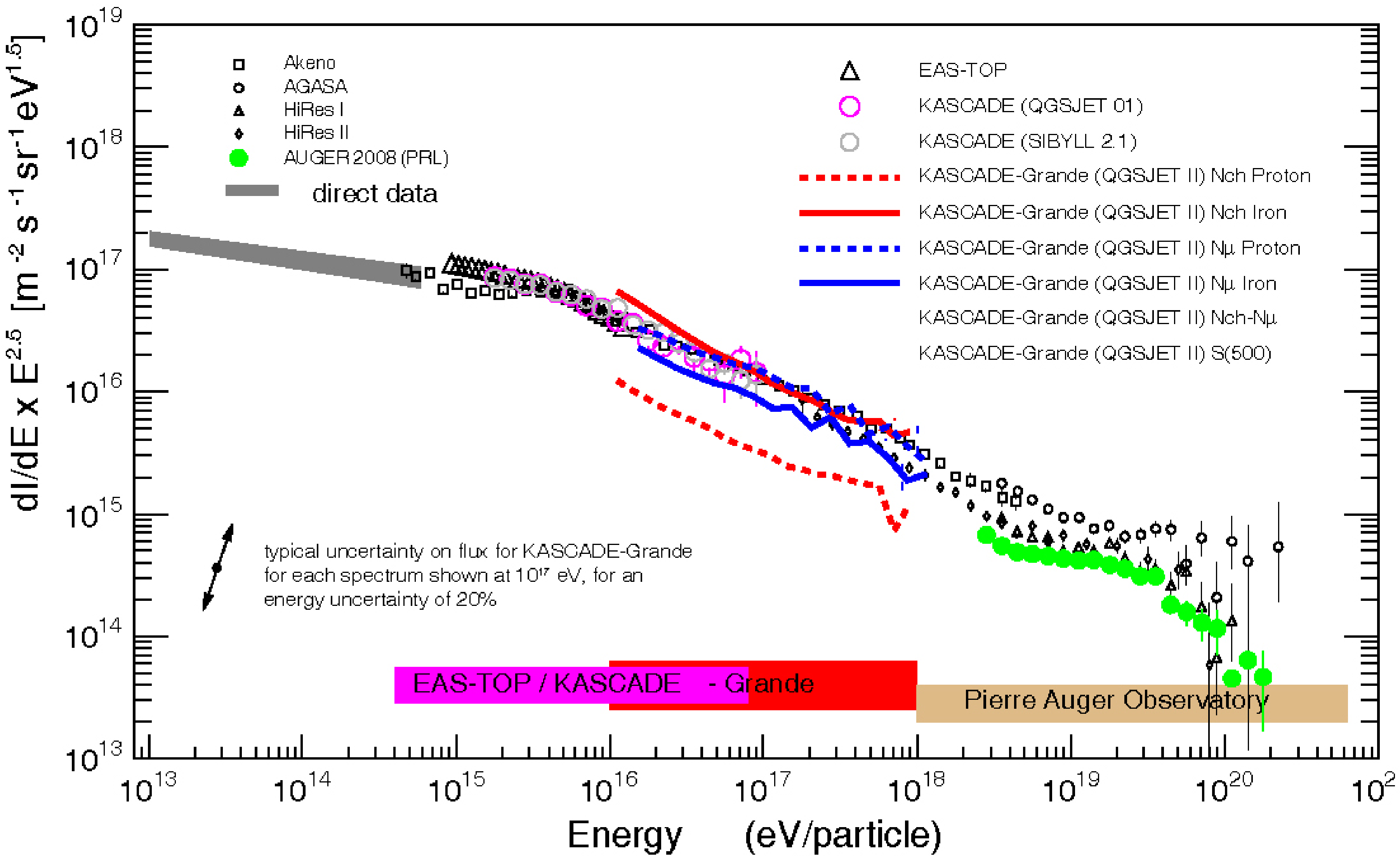


- Differences due to different sensibility to composition?

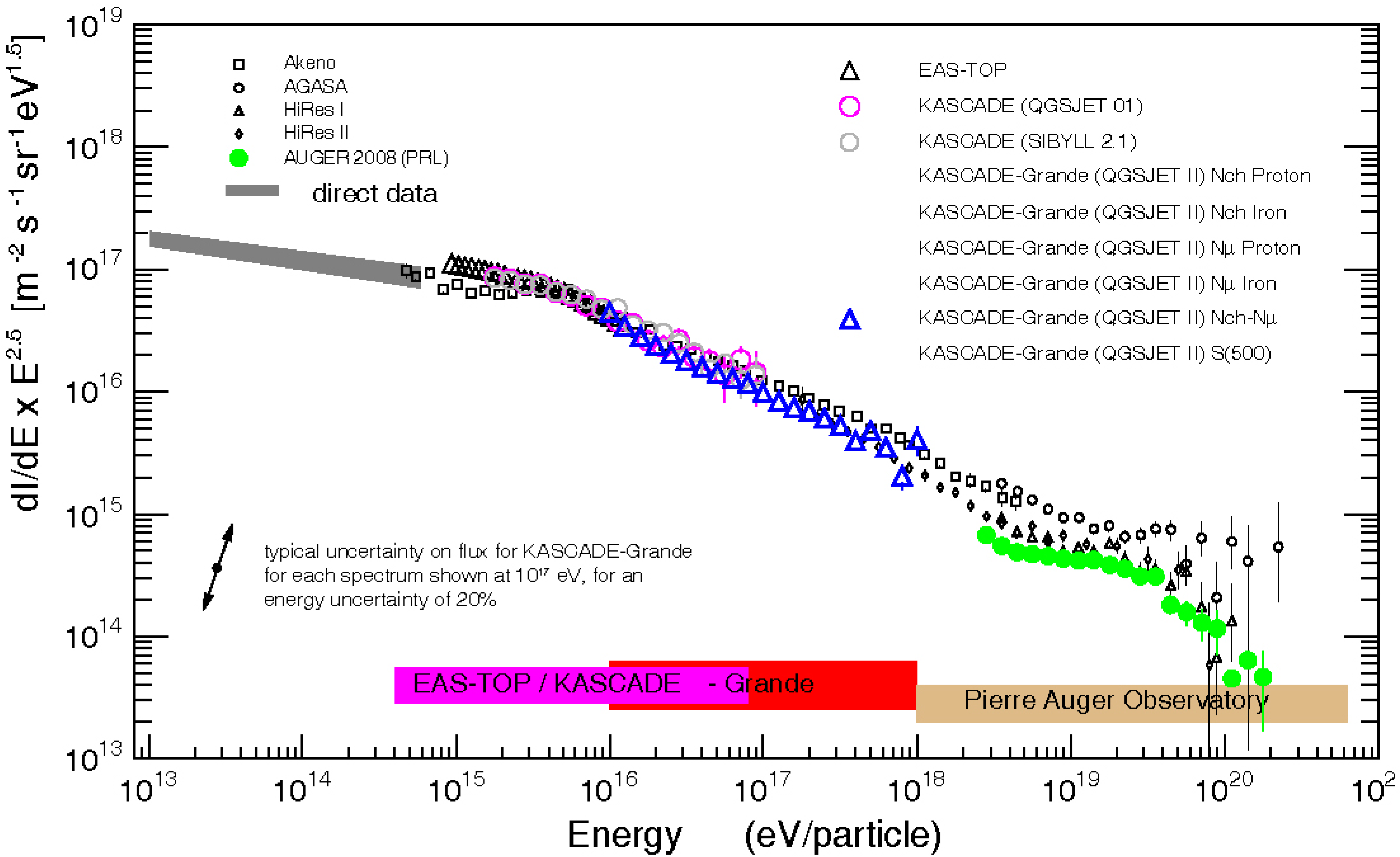
KASCADE-Grande all-particle energy spectrum



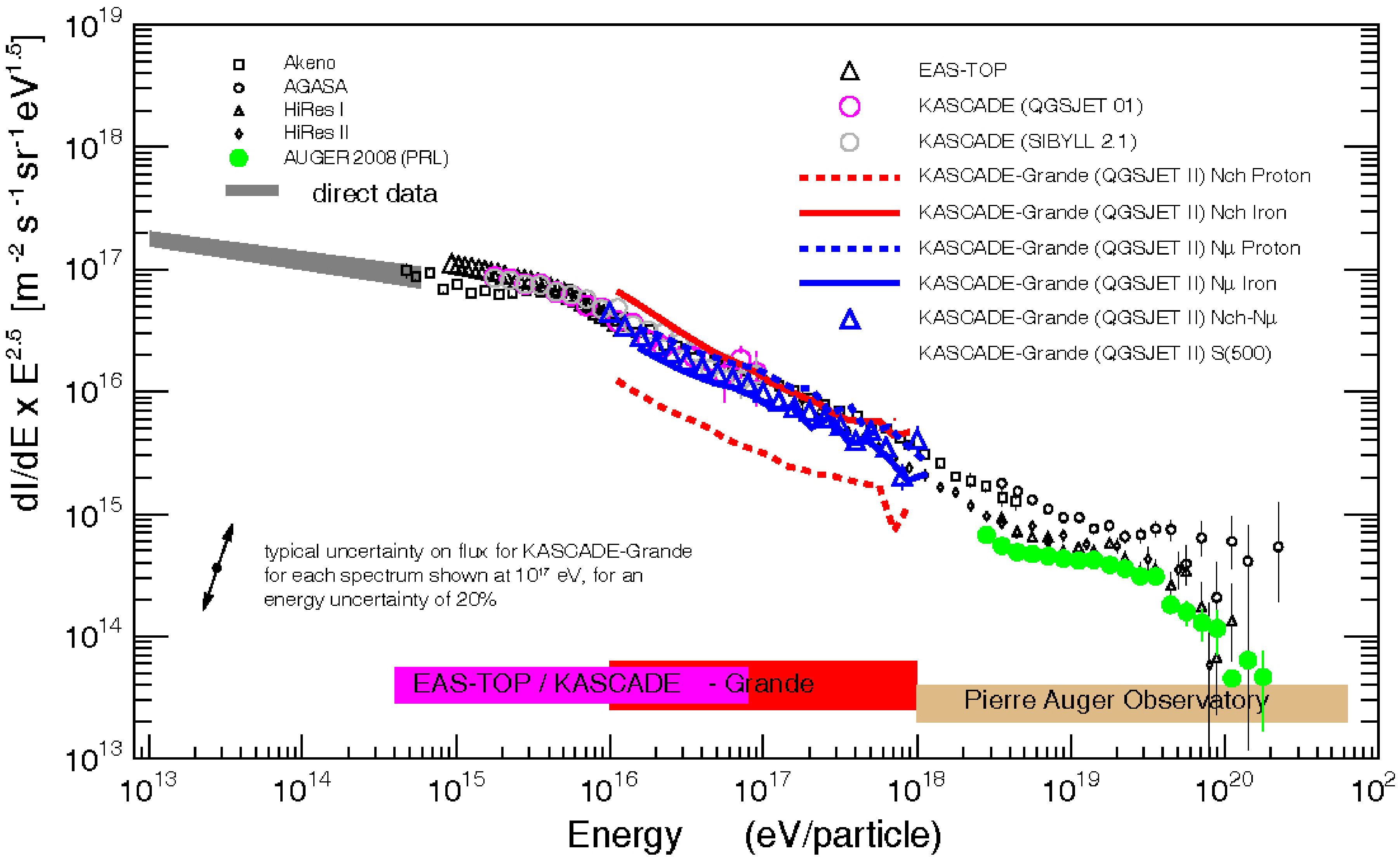
KASCADE-Grande all-particle energy spectrum



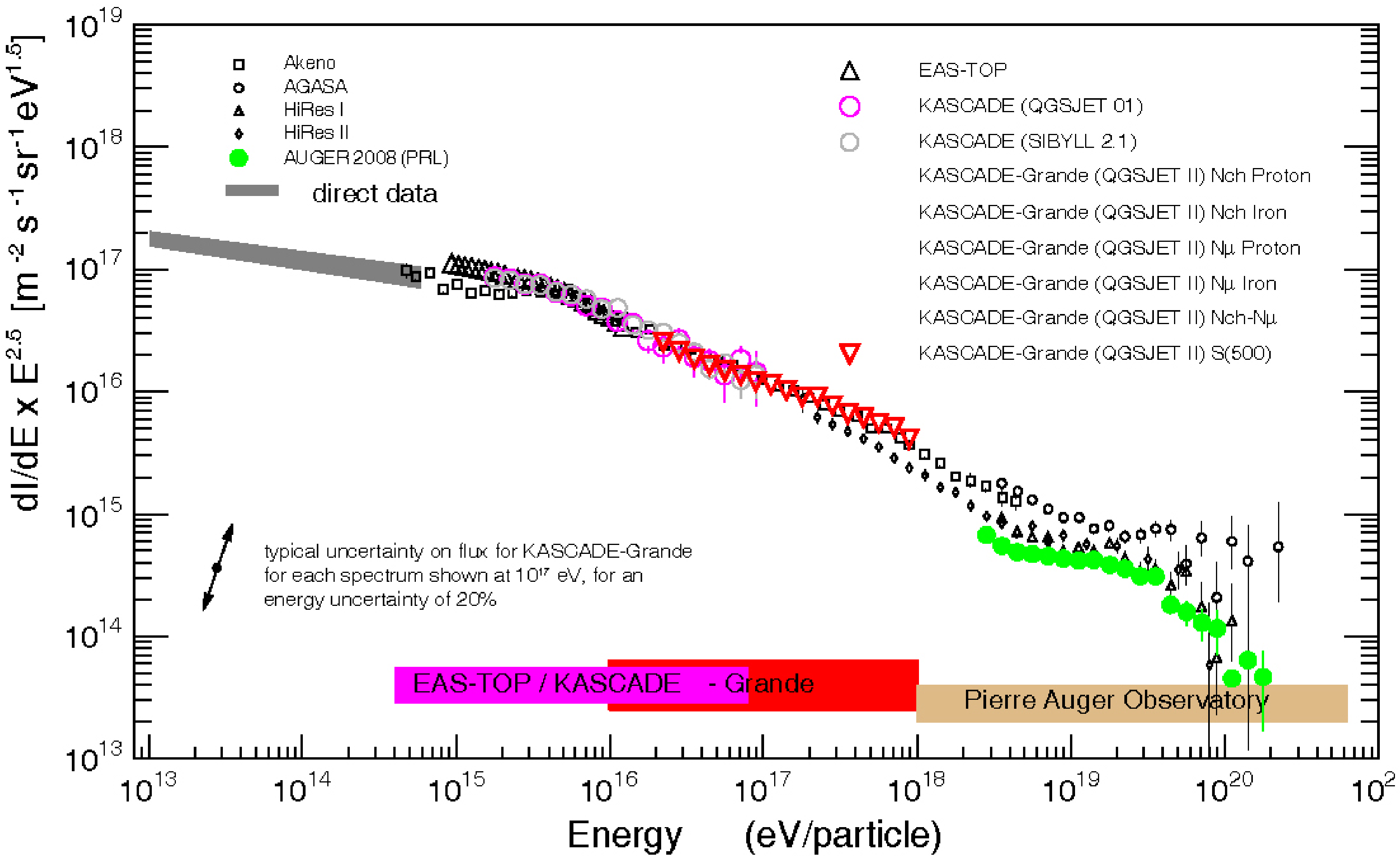
KASCADE-Grande all-particle energy spectrum



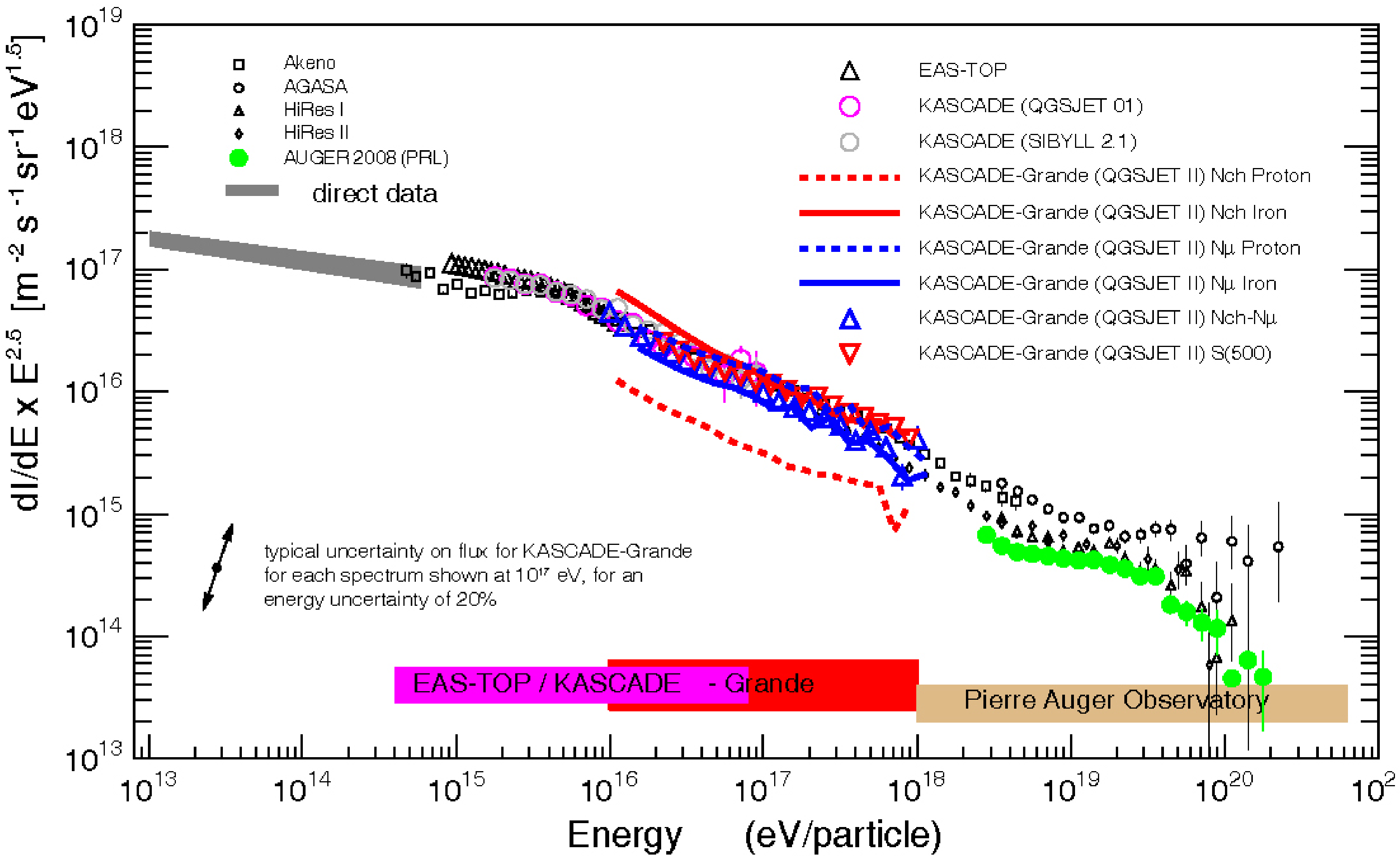
KASCADE-Grande all-particle energy spectrum



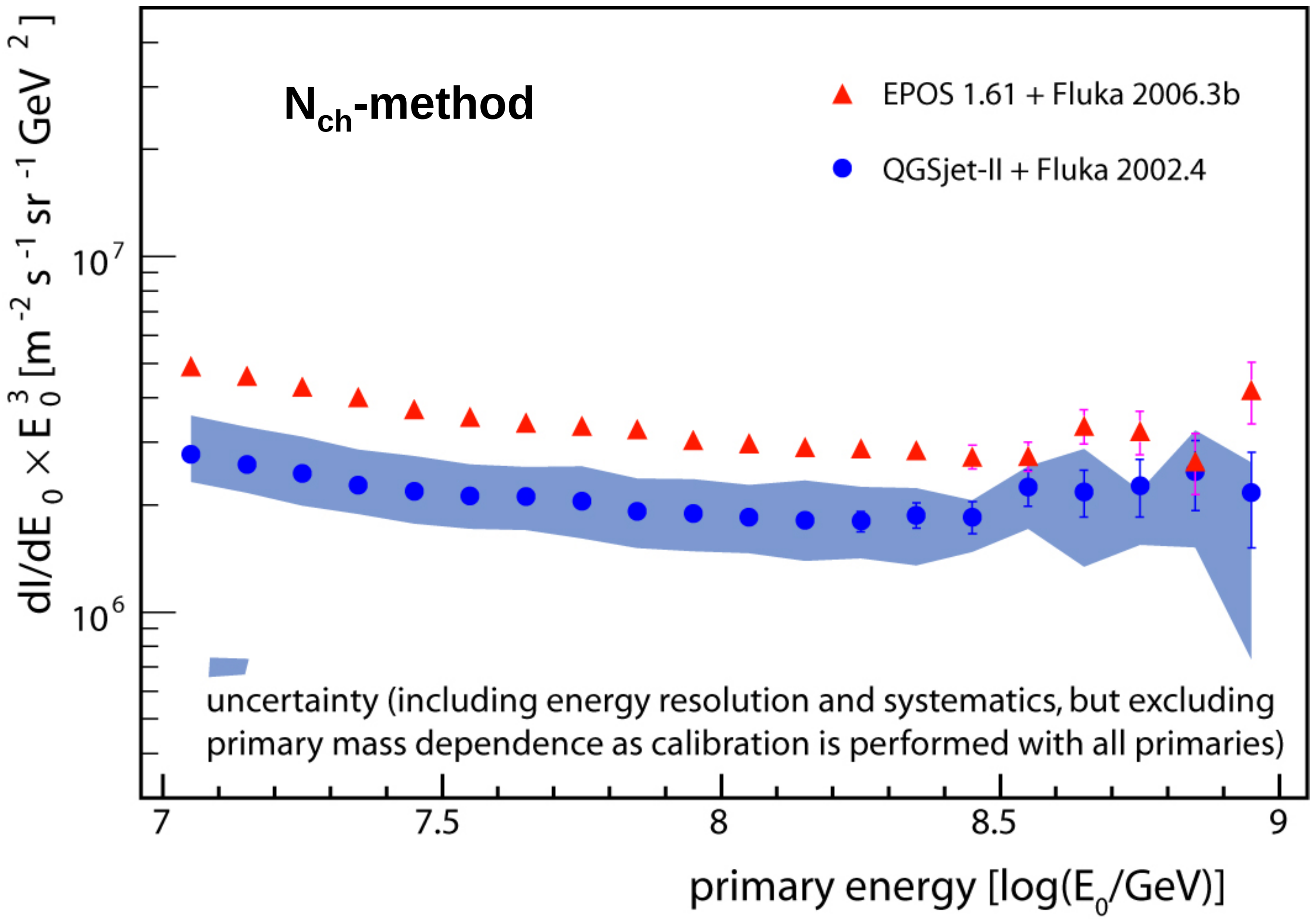
KASCADE-Grande all-particle energy spectrum



KASCADE-Grande all-particle energy spectrum



systematic checks: hadronic interaction model

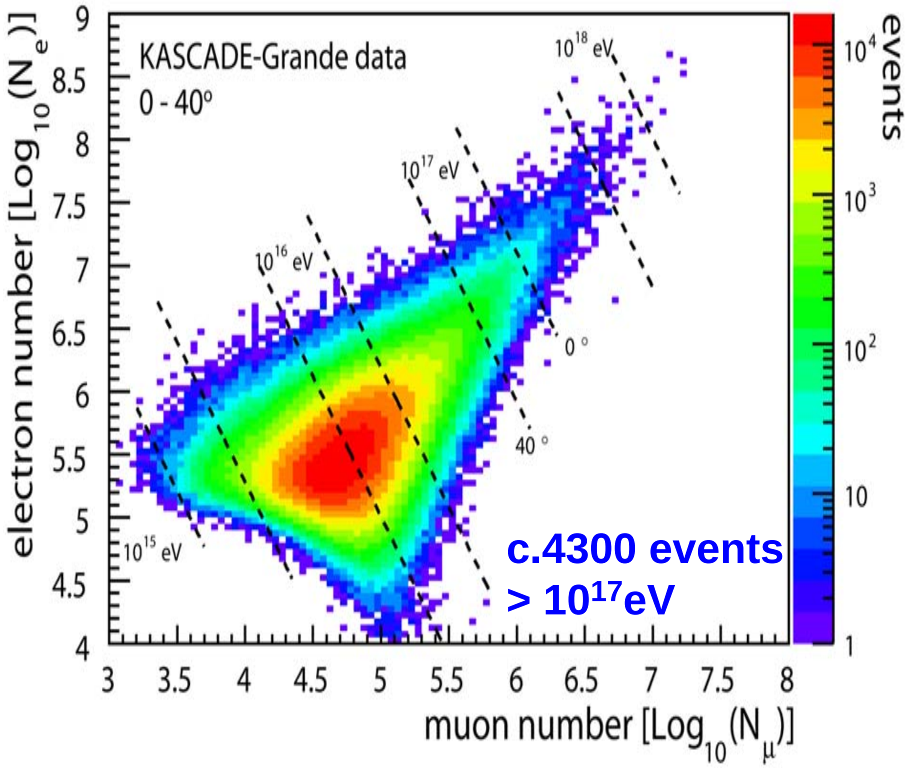


KASCADE-Grande collaboration (A.Haungs), ICRC 09

Ways to elemental composition :

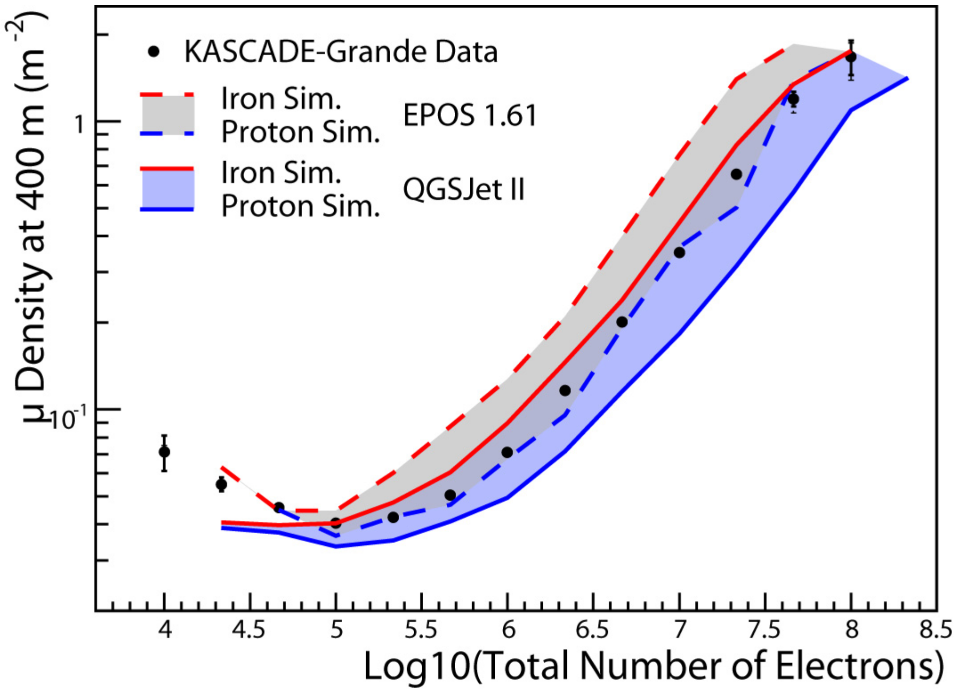
Application of different methods:

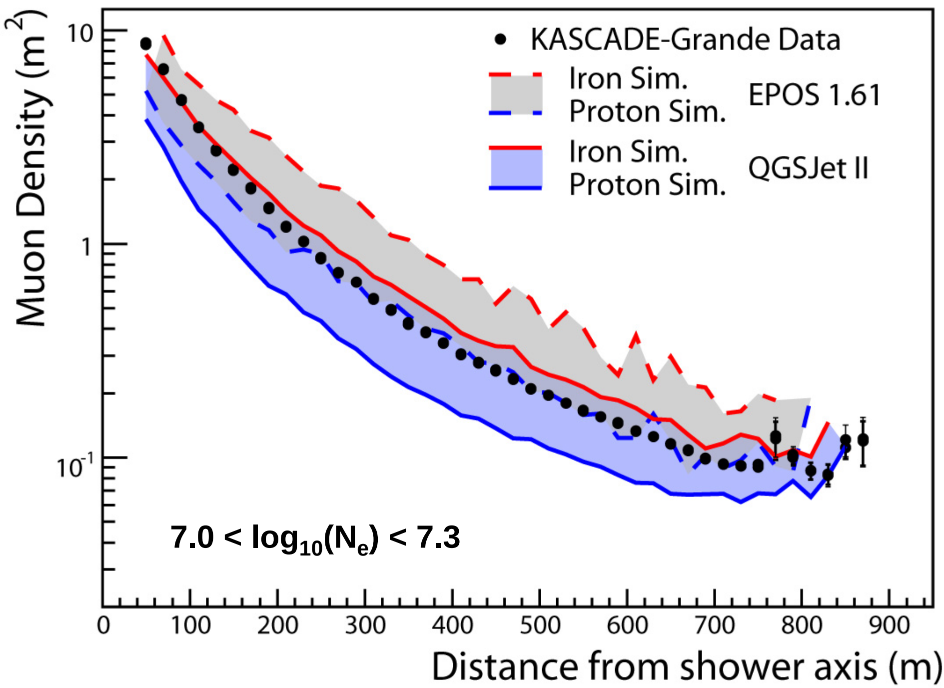
- **Local muon densities**
- **High-energy muon investigations**
- **Parametric combination of N_{ch} , N_{μ}**
- **kNN method**
- **Fit of N_{μ}/N_{ch}-ratios in fixed size/ energy bins**
- **Unfolding of the 2-dimensional shower size spectrum**



→ **energy & composition**
→ **still improvements in systematics needed**
→ **higher statistics**

Way to elemental composition : muon density investigations





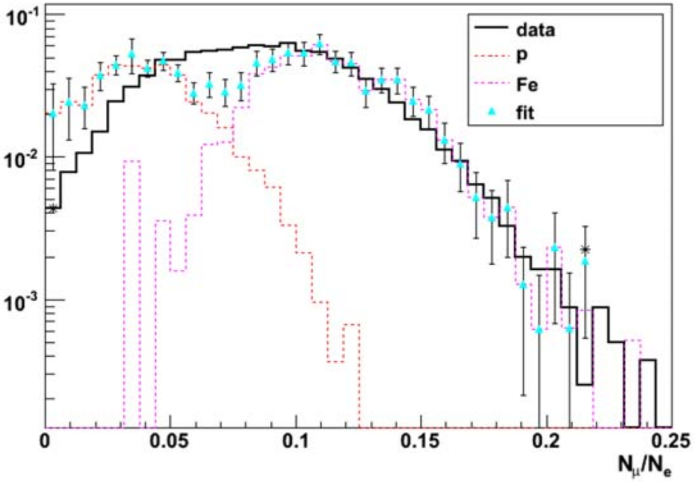
- muon (local) density reconstruction for different, but fixed distances

➔ composition sensitivity

➔ model tests

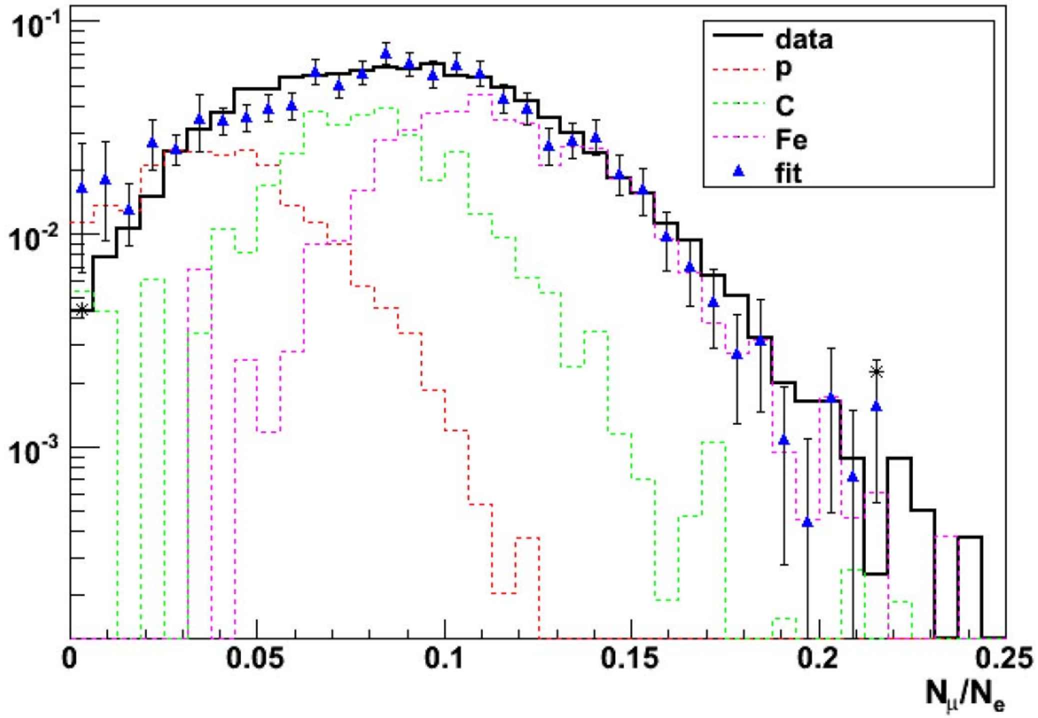
KASCADE-Grande collaboration
(V. de Souza), ICRC 09

Way to elemental composition : N_μ / N_{ch}-ratio



6.5 < log₁₀(Nₑ) < 6.75

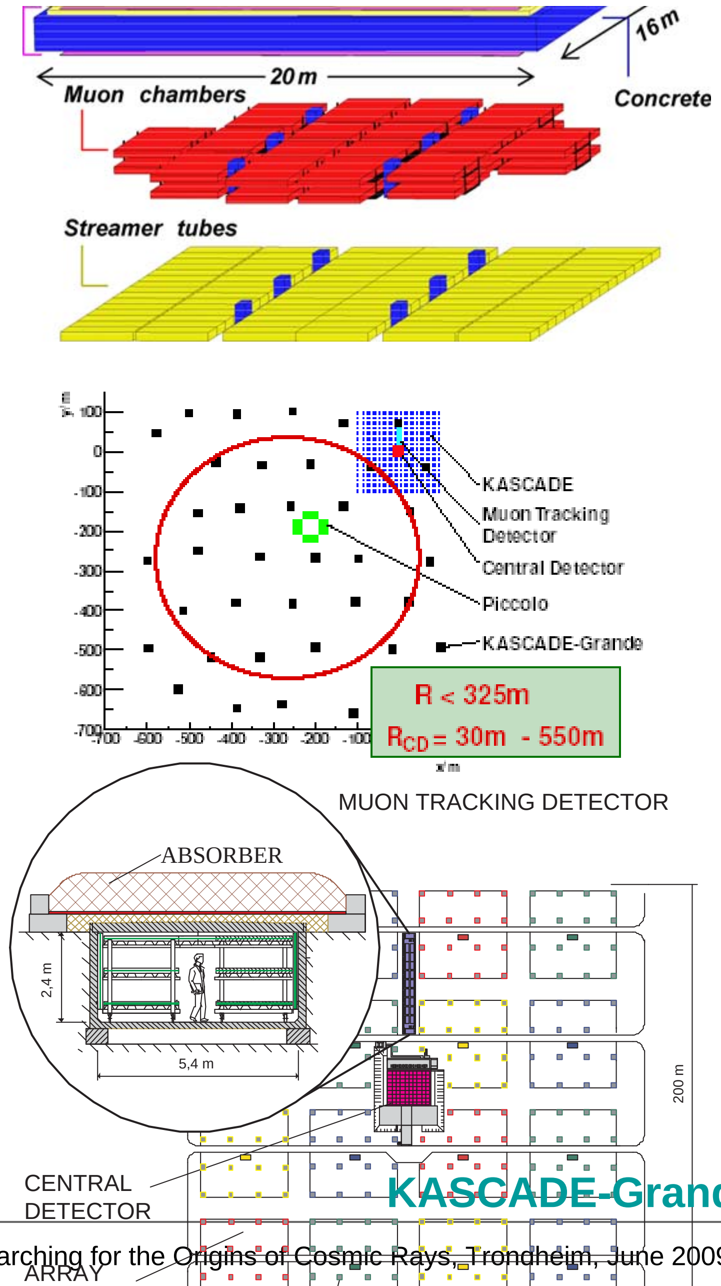
QGSJET II hadronic interaction model



- shower size ratio:
investigation of mean and rms
➔ composition sensitivity
more than 2 components needed;
consistent with KASCADE in overlapping range

KASCADE-Grande collaboration (E. Cantoni), ICRC 09

HE Muon Measurements at KASCADE-Grande



- **Central Detector muon facility**

  E_μ^{thresh} = 2400 MeV

  ➔ **Muon Density measurements** $\rho_\mu^{2.4GeV}$

  ➔ **Lateral distributions**

  ➔ **Model tests (muon energy spectrum)**

  $R_\rho^{2.4/0.23} = \rho_\mu^{2.4GeV} / \rho_\mu^{0.23GeV}$

- **Muon Tracking Detector**

  E_μ^{thresh} = 800 MeV

  ➔ **Measurement of radial and tangential angles** ρ_μ, τ_μ

  ➔ **Muon production height**

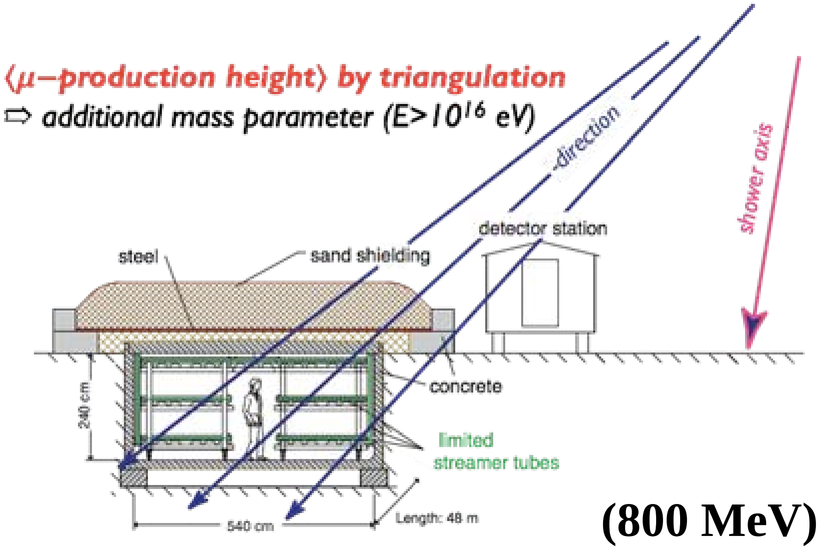
  ➔ **Lateral distributions**

  ➔ **Model tests** (pseudorapidity)

  $\eta_\mu = -\ln(\zeta/2) \quad \zeta = p_t/p_{||} = \mathrm{sqrt}(\rho^2 + \tau^2)$

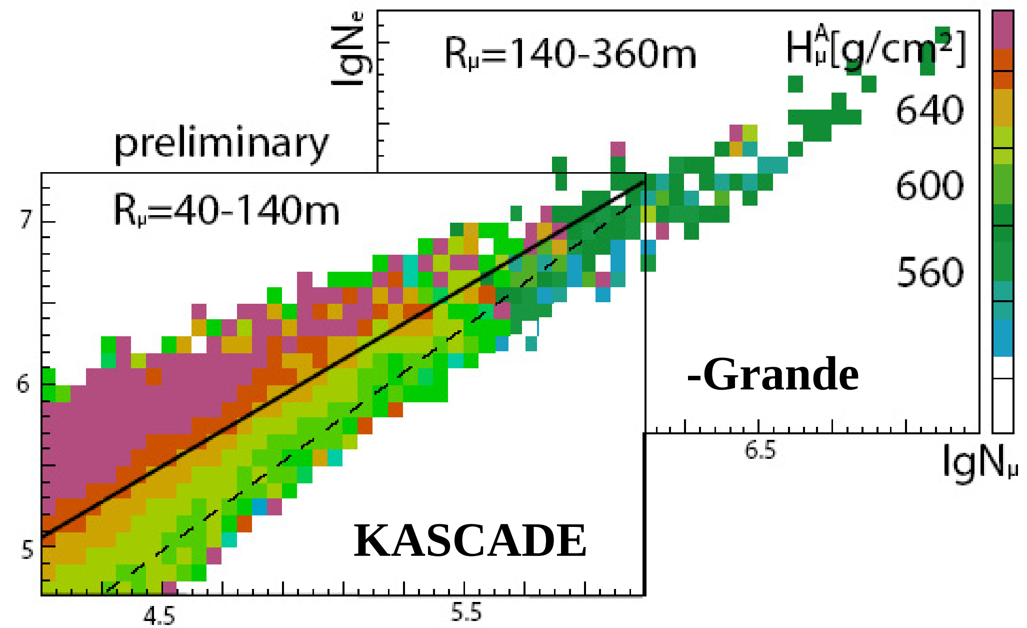
KASCADE-Grande collaboration (J.Zabierowski, P.Luczak), ICRC 09

Muon Tracking Detector

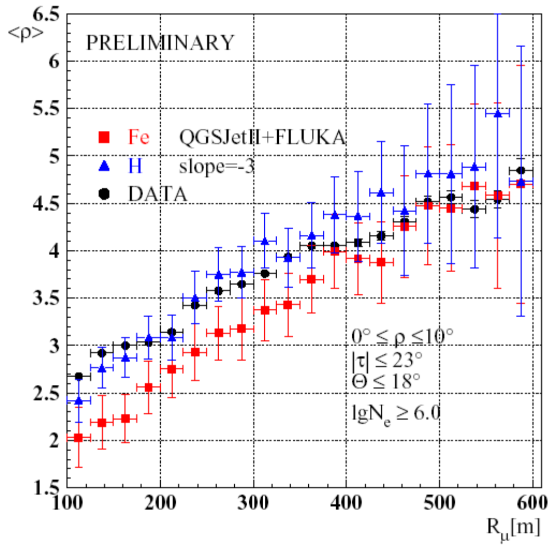


(800 MeV)

Angular resolution 0.35 deg



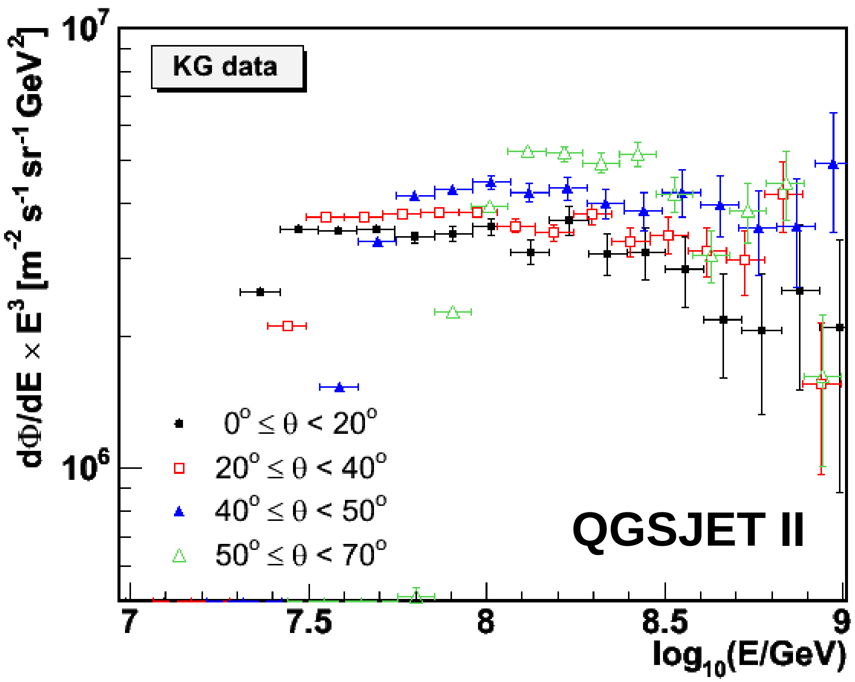
- **muon tracking:**
➔ **composition sensitivity**
Mean production height
➔ **model tests**
pseudorapidity



KASCADE-Grande collaboration (J.Zabierowski, P.Doll), ICRC 09

Muon reconstruction at inclined showers

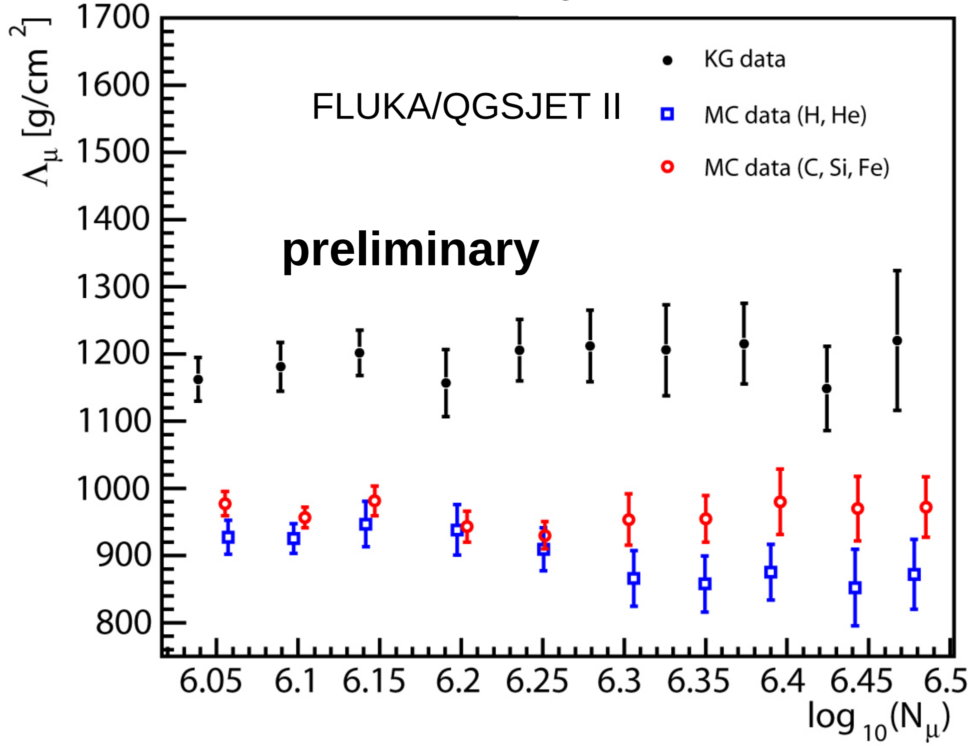
Energy reconstruction without CIC



Discrepancy between energy spectra from vertical and inclined showers

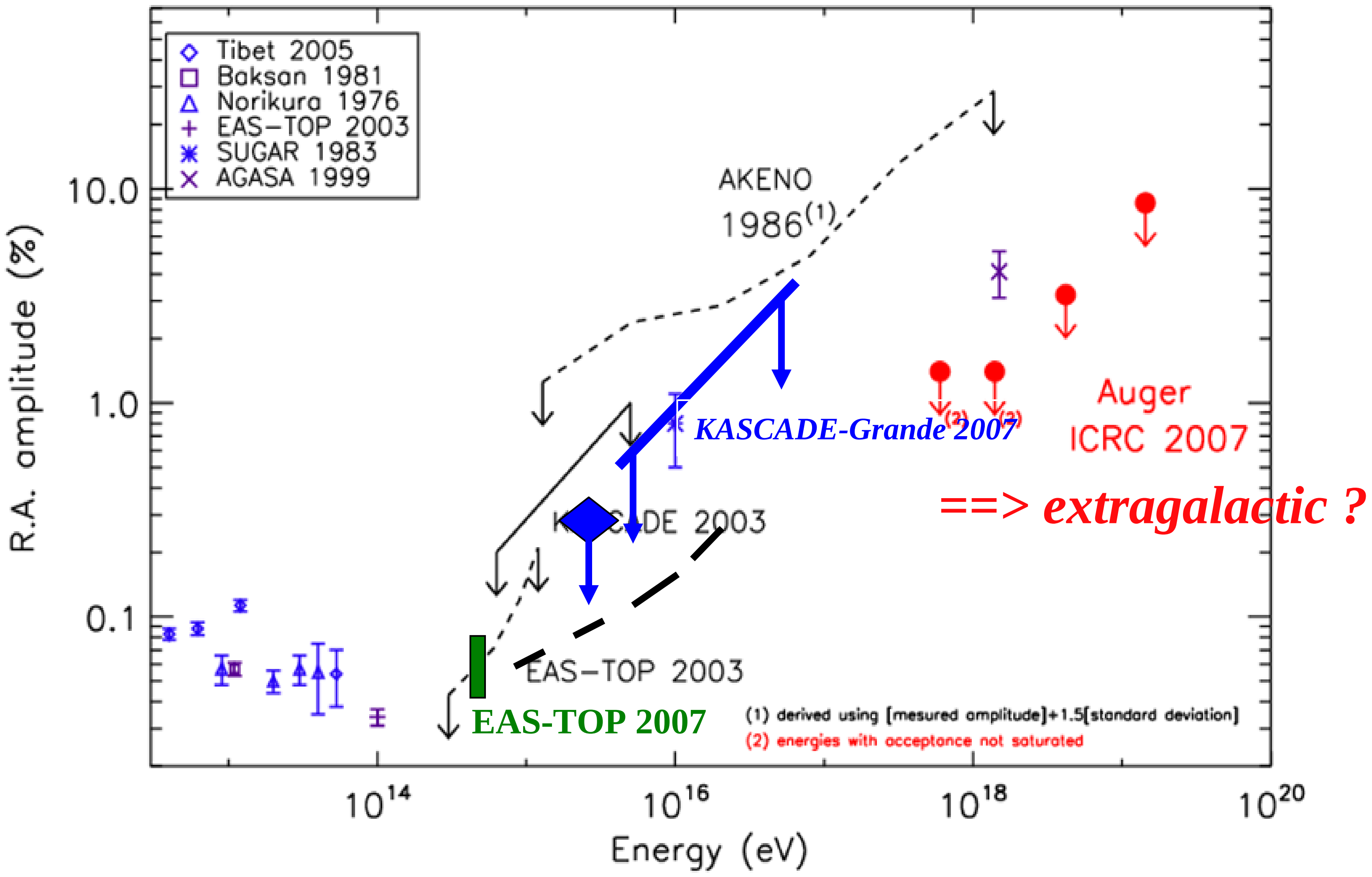
Muon shower size attenuation length

$$N'_\mu = N_\mu e^{-X_0 Sec\theta/\Lambda_\mu}$$



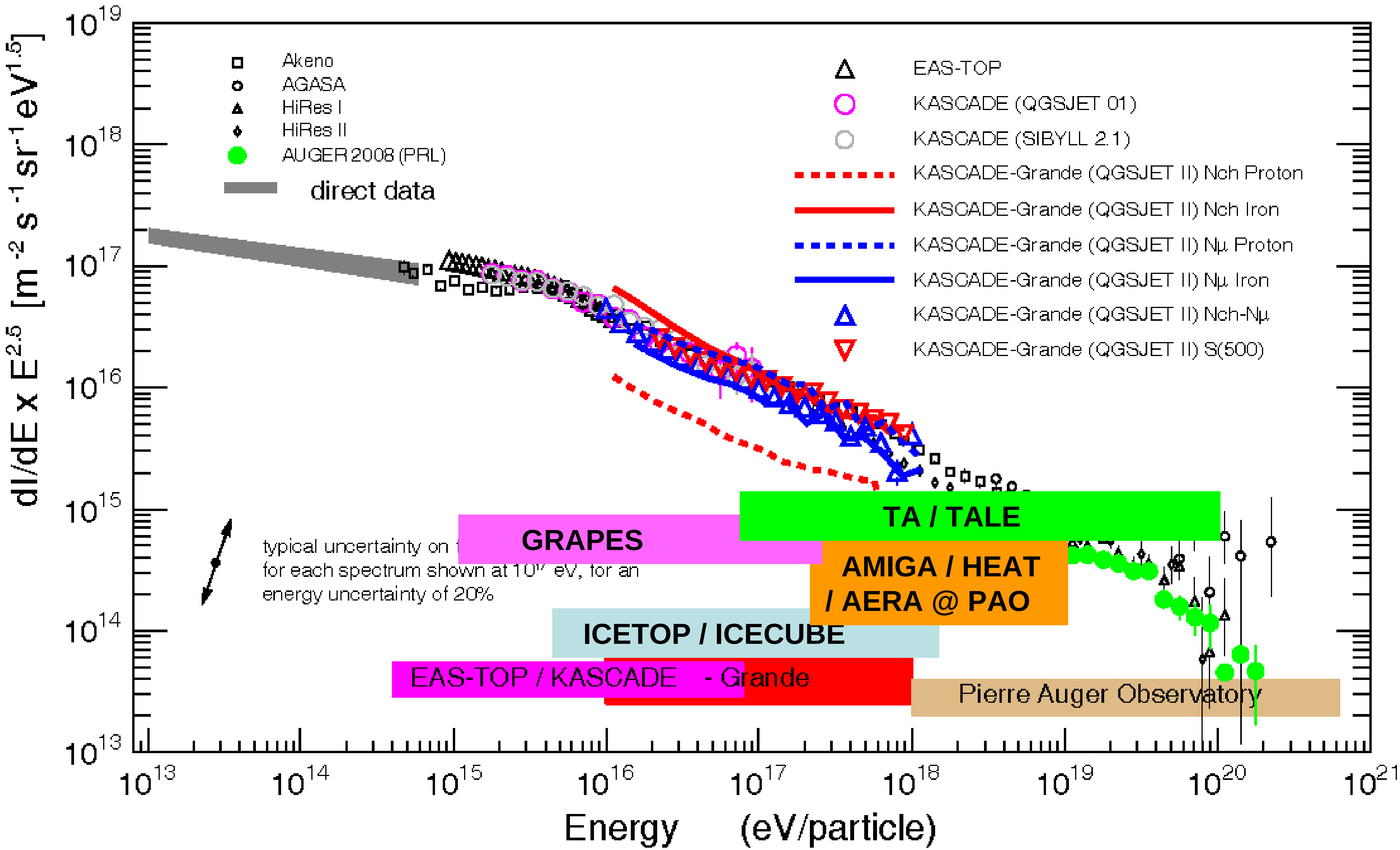
Difference between MC and KASCADE-Grande muon attenuation lengths

Anisotropy



Tibet 2005
Baksan 1981
Norikura 1976
EAS−TOP 2003
SUGAR 1983
AGASA 1999
AKENO
1986(1)
KASCADE-Grande 2007
Auger
ICRC 2007
==> extragalactic ?
KASCADE 2003
EAS−TOP 2003
EAS-TOP 2007
(1) derived using [mesured amplitude]+1.5[standard deviation]
(2) energies with acceptance not saturated
R.A. amplitude (%)
Energy (eV)

KASCADE-Grande



KASCADE-Grande

- around knee KASCADE results:
  - ➔knee is caused by light primary elements
  - ➔cosmic rays are isotropic around the knee
  - ➔interaction models have to be further improved (w/o new physics)

- now: high quality data at 10-1000 PeV by KASCADE-Grande to identify the „iron"-knee and transition galactic–extragalactic cosmic rays!

- KASCADE-Grande: energy spectrum :
  - ➔no distinct structure well below 10^{18}eV
  - elemental composition
    - ➔no abrupt change below 10^{18}eV
    - ➔more than one component around 10^{17}eV
  - anisotropy studies ➔no anisotropy?
  - interaction models ➔muon attenuation etc…

MORE AT ICRC 2009

- 30/03/2009: KASCADE-Grande closure symposium
  KASCADE-Grande ➔ EAS test facility

- new detection techniques? ➔ LOPES – radio detection of air showers

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