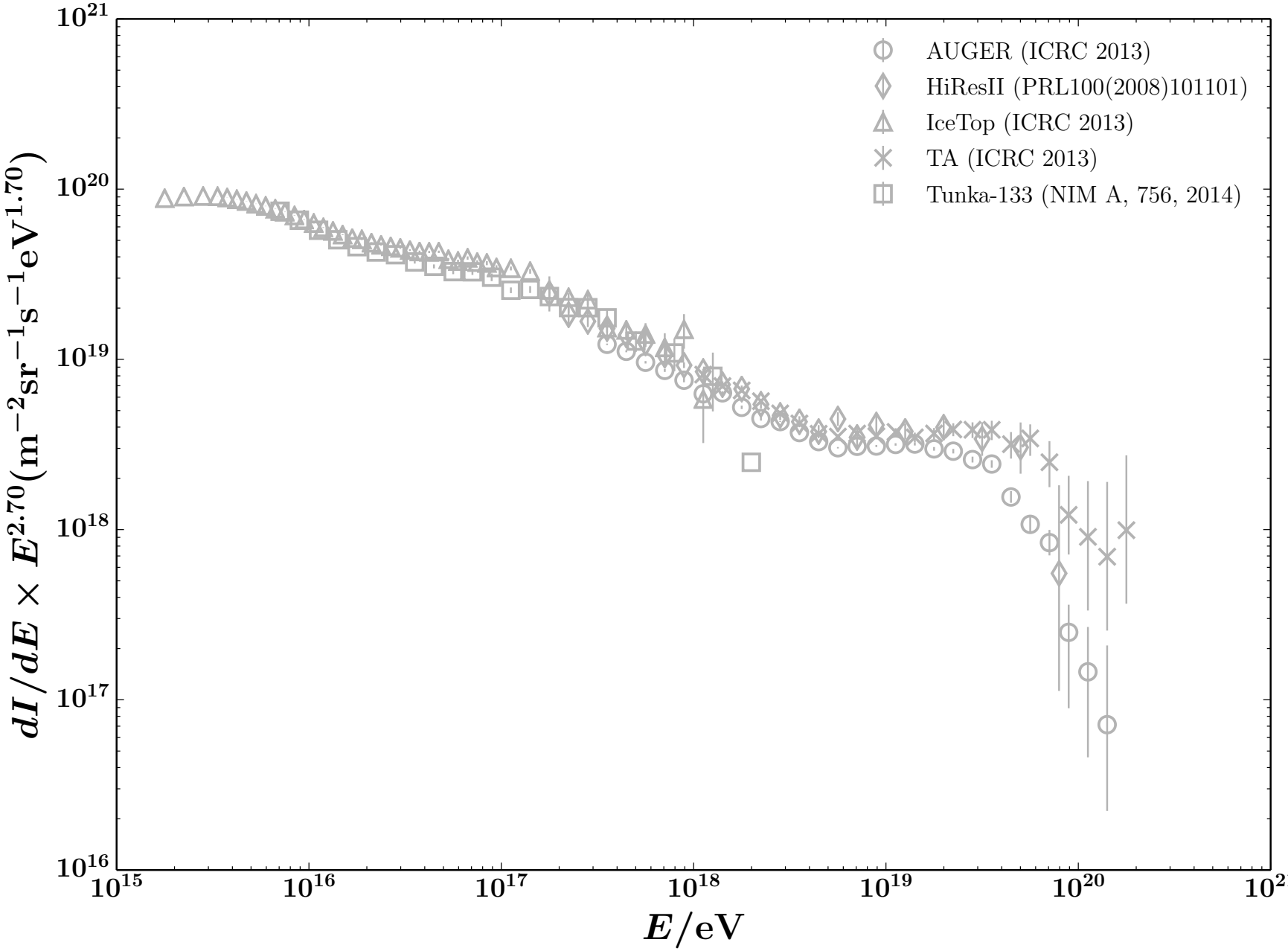
The spectrum of cosmic rays in the energy range of $10^{14} - 10^{18}$ eV

Sven Schoo

Karlsruher Institut für Technologie - Institut für Kernphysik

02.09.2014


AUGER (ICRC 2013)
HiResII (PRL100(2008)101101)
IceTop (ICRC 2013)
TA (ICRC 2013)
Tunka-133 (NIM A, 756, 2014)
$dI/dE \times E^{2.70} (\mathrm{m^{-2} sr^{-1} s^{-1} eV^{1.70}})$
E/eV
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}

252 Detector Stations organized in 16 Clusters

observable: Nch

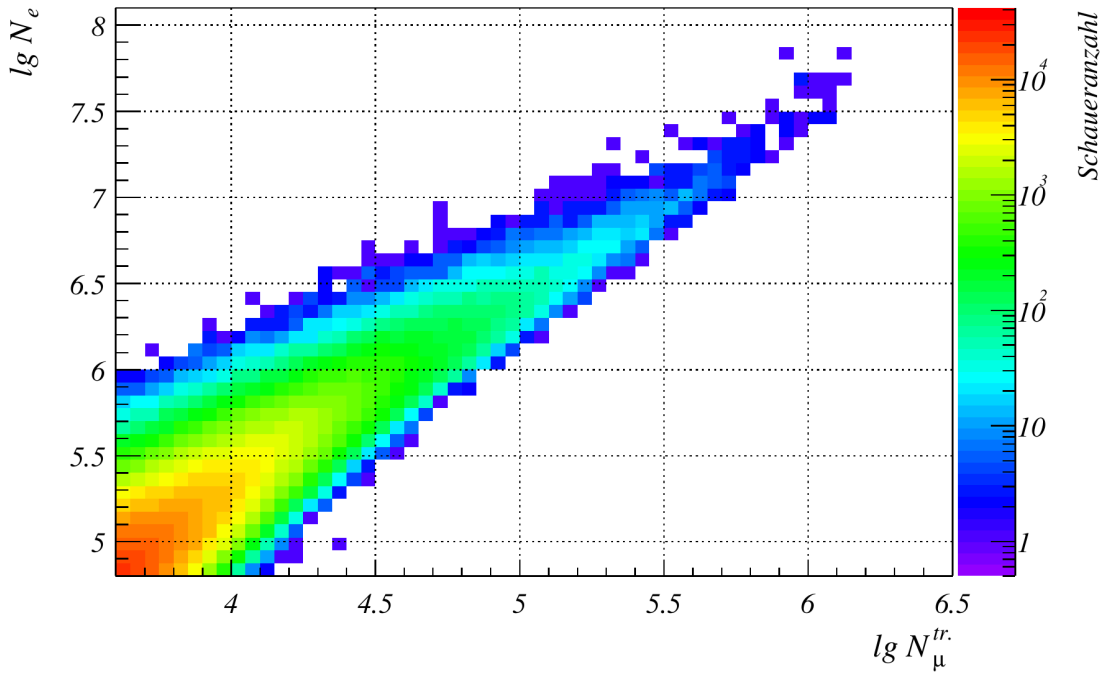
192 Detector Stations with shielded scintillators

observable: Nμ

KASCADE

Scintillator Array

KASCADE Analysis

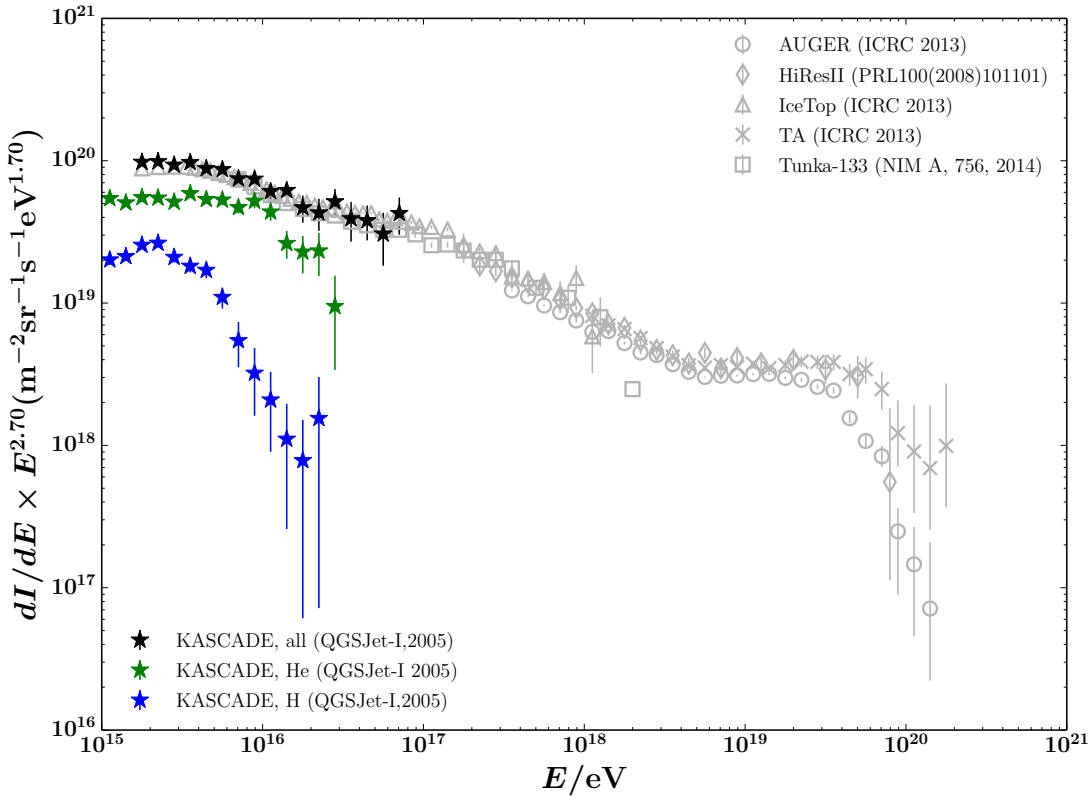


[doi: 10.1016/j.astropartphys.2005.04.001]

- $\frac{\mathrm{d}J}{\mathrm{d}\log_{10} N_\mathrm{e}\,\mathrm{d}\log_{10} N_\mu^\mathrm{tr}} = \Sigma_{n=1}^{N_\mathrm{nucl}} \int \frac{\mathrm{d}J}{\mathrm{d}\log_{10} E} p_\mathrm{n}(\log_{10} N_\mathrm{e}, \log_{10} N_\mu^\mathrm{tr} \mid \log_{10} E)\mathrm{d}\log_{10} E$
- p_n takes into account the probability...
  - that a nucleus n with an energy E induces EAS with $N_\mathrm{ch}^\mathrm{true}$ and N_μ^true
  - that the event gets triggered and properly reconstructed
  - that $N_\mathrm{ch}^\mathrm{true}$ and N_μ^true are reconstructed as the N_ch and N_μ of the cell i

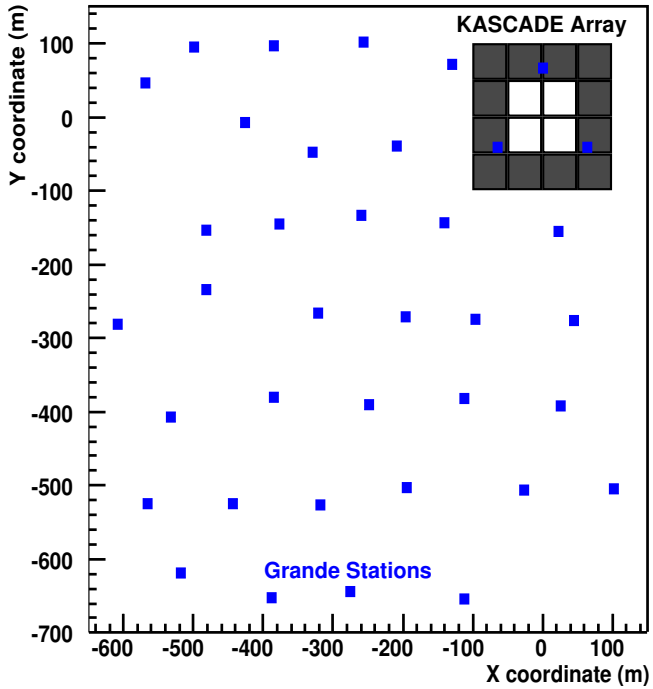
KASCADE Results (QGSJet-1)

- helium more abundant compared to proton (For QGSJet-1)
- proton knee: ∼2-3 PeV
- helium knee: ∼4-6 PeV? if yes, knee maybe Z-dependent
- helium knee: ∼8-12 PeV? if yes, knee maybe A-dependent
- take a look also at e.g. iron to get a clearer picture



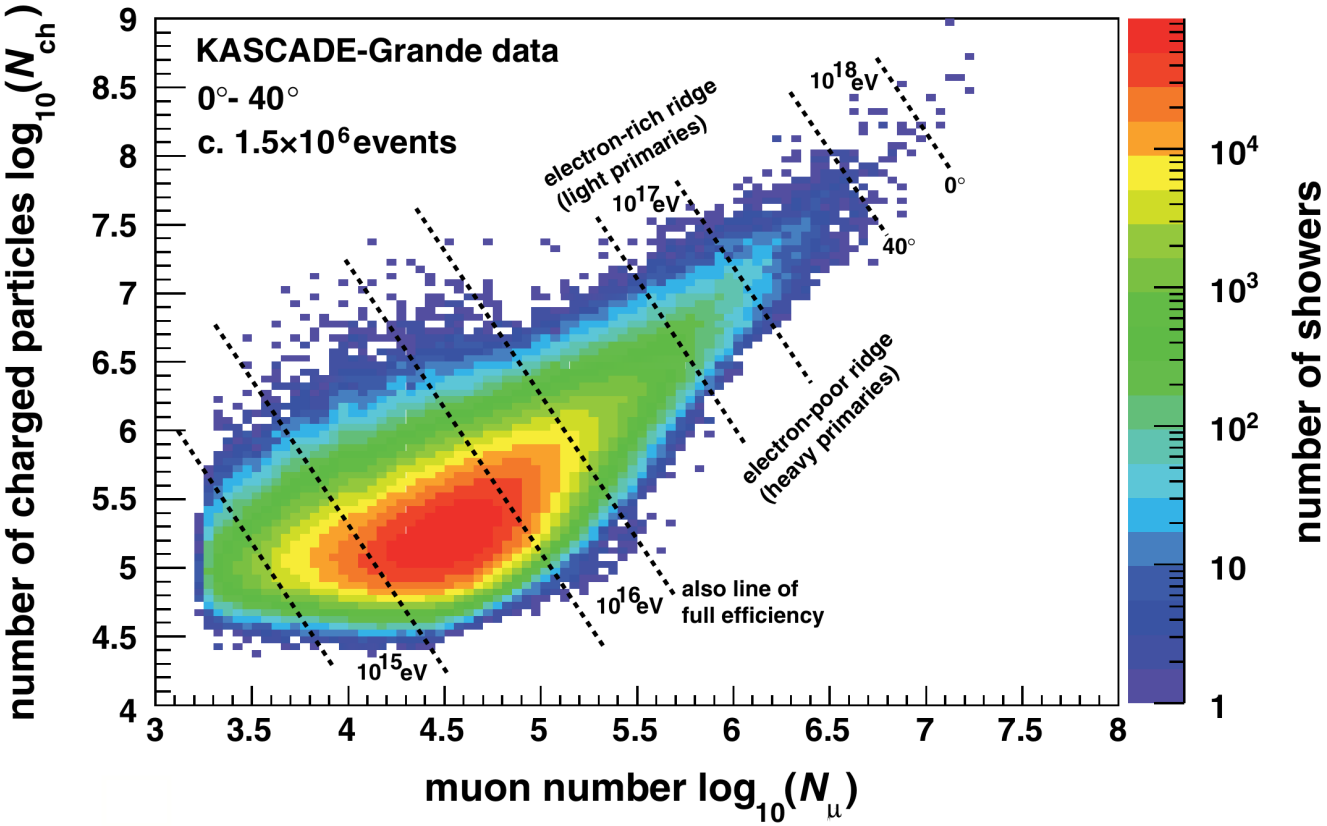
KASCADE-Grande Setup

- location: extension of the KASCADE-Array
- 37 additional stations (unshielded only)
- N_μ: derived using KASCADE
- area: $700 \times 700\,\mathrm{m}^2$
- spacing: $137\,\mathrm{m}$



[http://www-ik.fzk.de/KASCADE_home.html/]

2 dimensional shower size spectrum

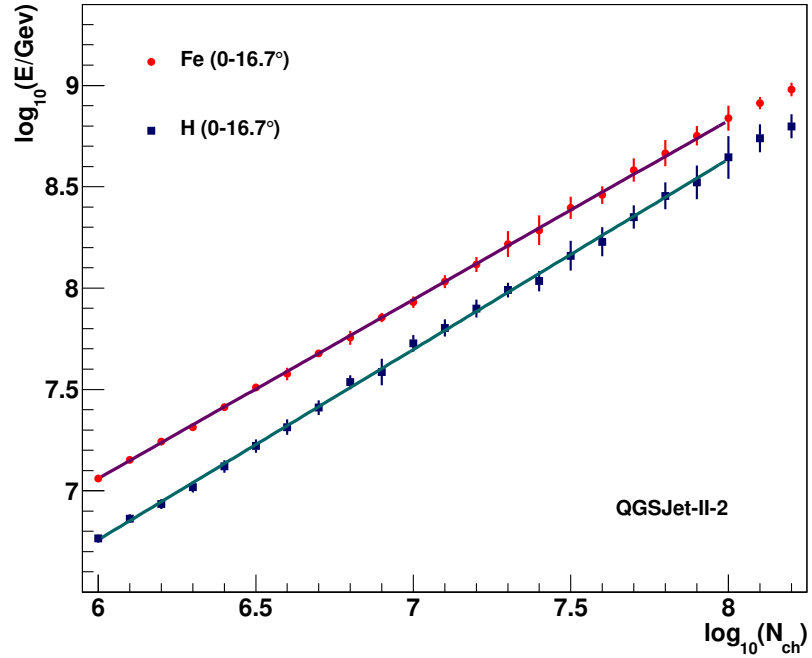


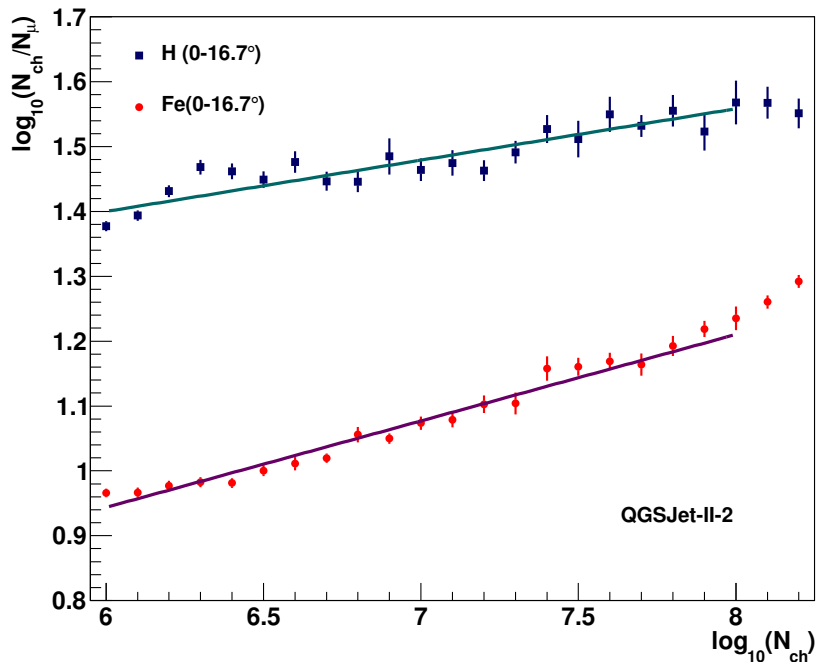
[doi: 10.1103/PhysRevLett.107.171104]

- again basis of the analysis
- lower statistics towards upper energy limit ($10^{18}\,\mathrm{eV}$) problematic for unfolding analysis $\rightarrow$ use different approach for the whole energy range
- used to separate events into mass groups

KASCADE-Grande Energy reconstruction

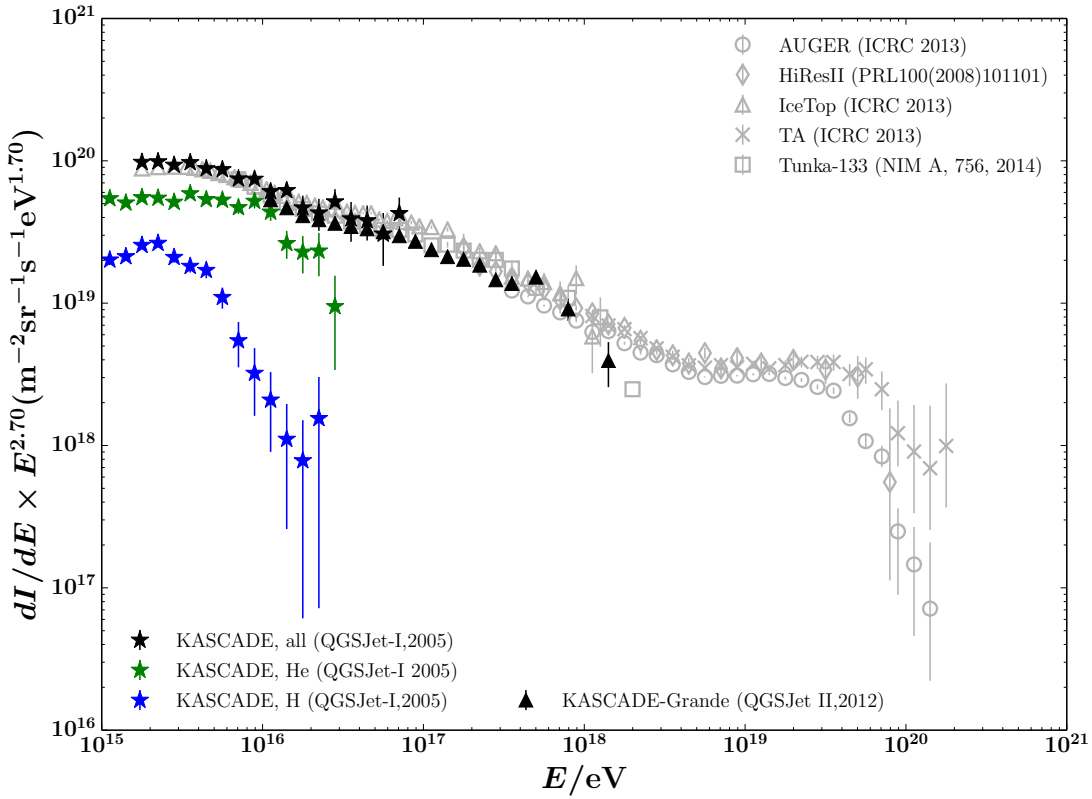
- N_{ch} is used to estimate the energy of an event.
- $\log_{10}(E/\mathrm{GeV}) = (a_{\mathrm{H}} + (a_{\mathrm{Fe}} - a_{\mathrm{H}}) \cdot k) \cdot \log_{10}(N_{\mathrm{ch}}) + b_{\mathrm{H}} + (b_{\mathrm{Fe}} - b_{\mathrm{H}}) \cdot k$
- k is used to correct the obtained energy for the mass dependence
- $k = \frac{log_{10}(N_{\mathrm{ch}}/N_{\mu}) - log_{10}(N_{\mathrm{ch}}/N_{\mu})_{\mathrm{H}}}{log_{10}(N_{\mathrm{ch}}/N_{\mu})_{\mathrm{Fe}} - log_{10}(N_{\mathrm{ch}}/N_{\mu})_{\mathrm{H}}}$
  proton: $k \to 0$,iron: $k \to 1$





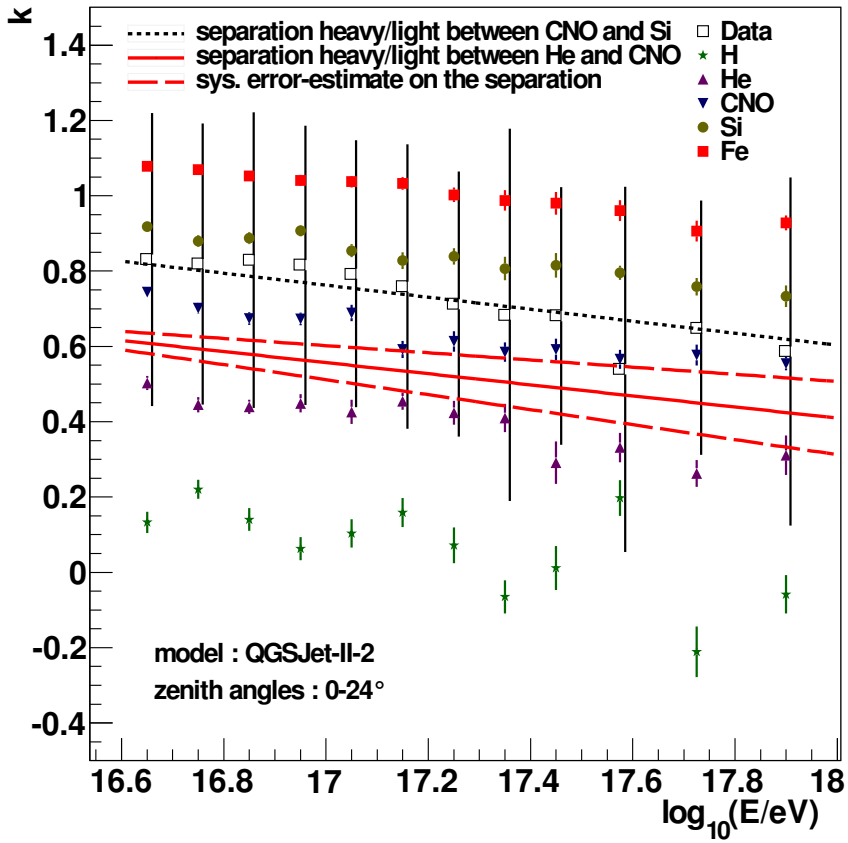
KASCADE-Grande All-Particle Spectrum

- all-particle spectra (K/KG) show same structures, but absolute flux different
- KG spectrum corrected for bin-to-bin migrations
- correction is of the order of a few percent
- all-particle spectrum does not follow single power law



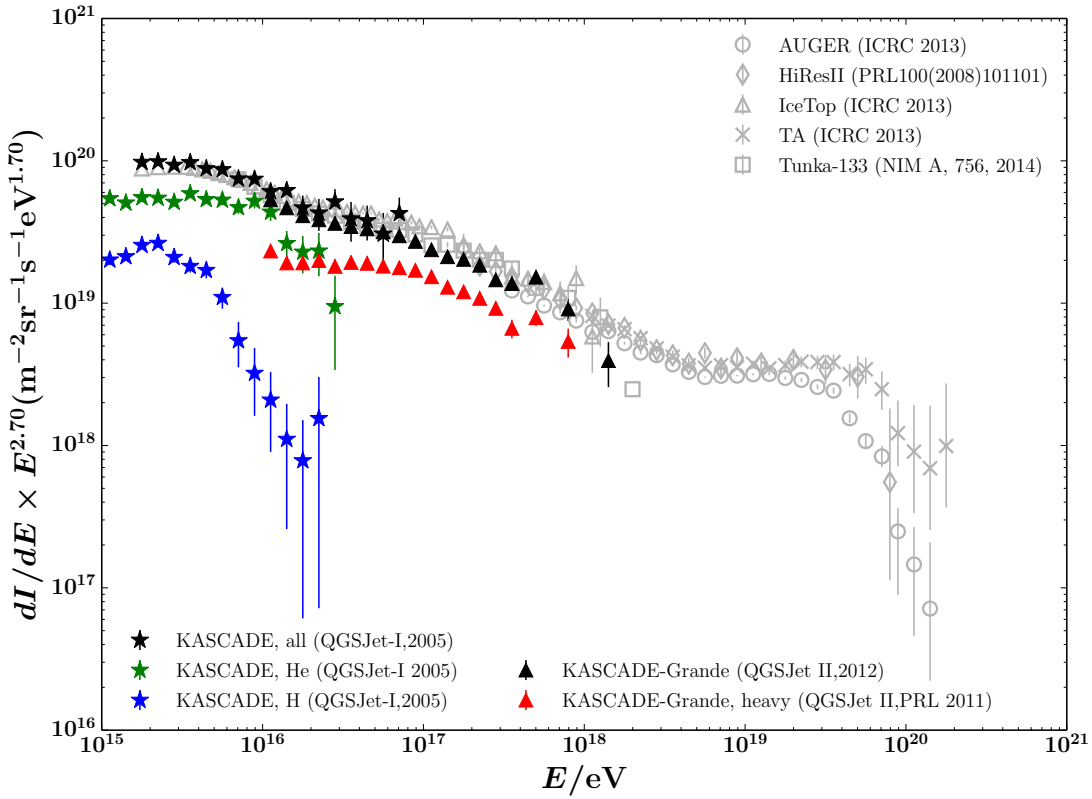
Separation into mass groups

- separation lines are fitted to mean k-values
- k-value(event) below separation line
  $\rightarrow$ light primary, else
  $\rightarrow$ heavy primary
- dotted line was used to put emphasis on the heavy component (search for a possible heavy knee)
- continuous line was used to put emphasis on the light component (search for a recovery of the light component)



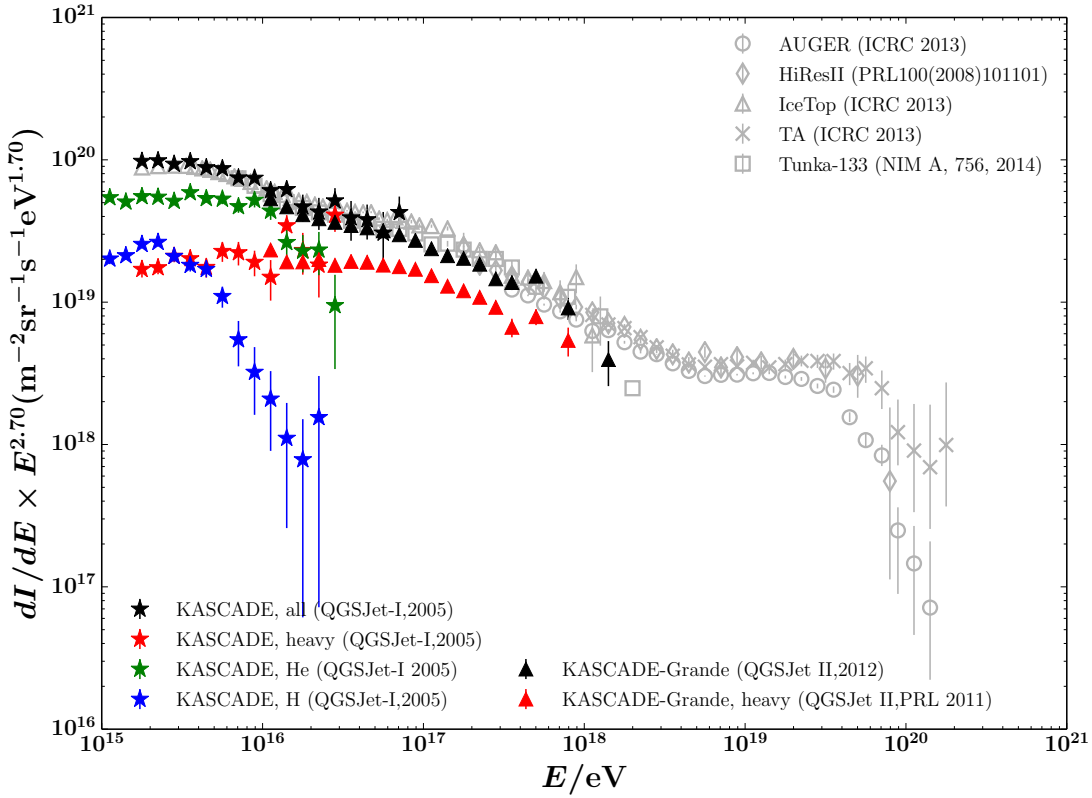
KASCADE-Grande The heavy knee

- heavy knee observed at $10^{16.92 \pm 0.04}\,\mathrm{eV}$
- indication for Z-dependent knee positions (Heavy == Iron?)
- significance: $3.5\,\sigma$



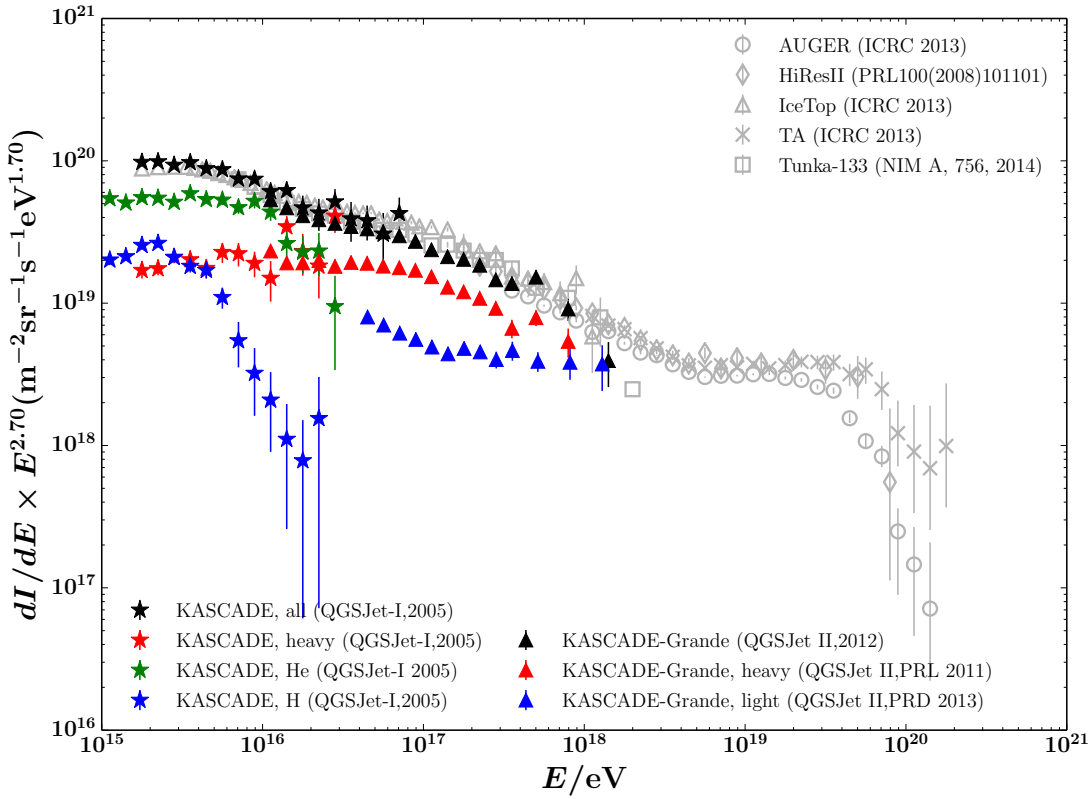
KASCADE-Grande The heavy knee

- heavy knee observed at $10^{16.92 \pm 0.04}\,\mathrm{eV}$
- indication for Z-dependent knee positions (Heavy == Iron?)
- significance: $3.5\,\sigma$
- KASCADE spectrum for heavy component connects to the one from KASCADE-Grande



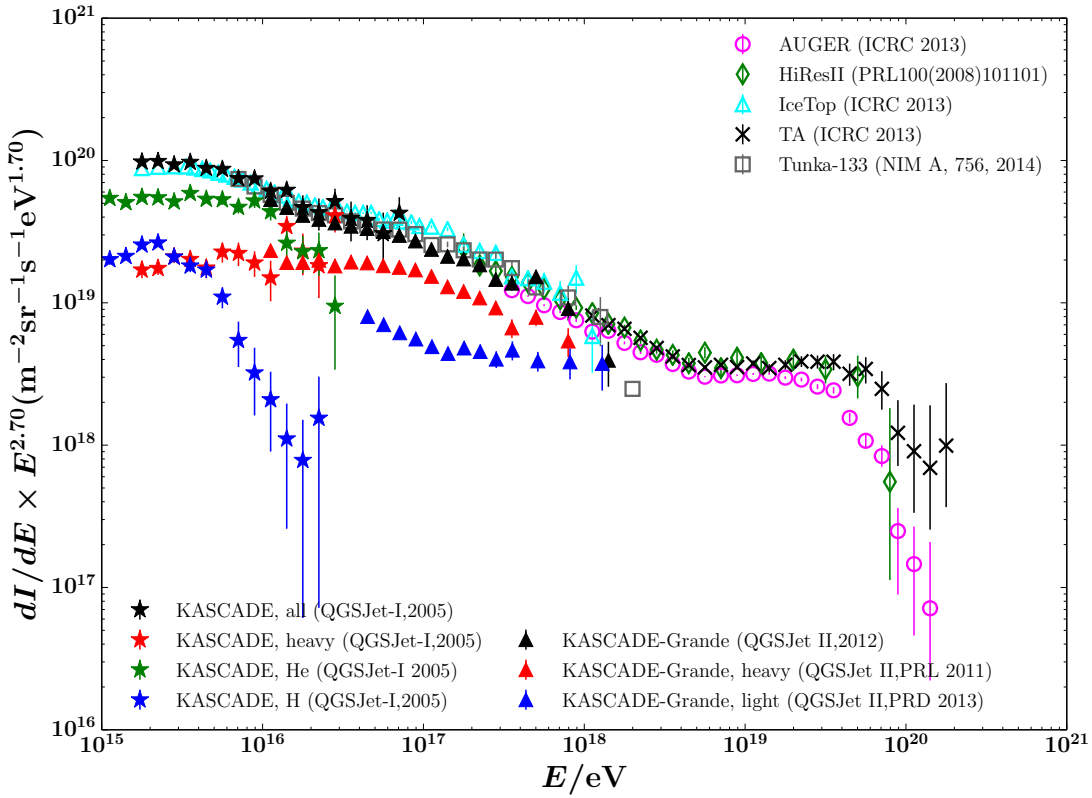
KASCADE-Grande The light ankle

- light ankle observed at $10^{17.08 \pm 0.08}\,\mathrm{eV}$
- possible transition from galactic to extragalactic origin starts at this energy?
- significance: $5.8\,\sigma$
- medium component not shown (e-poor + e-rich != all-particle)



Comparison

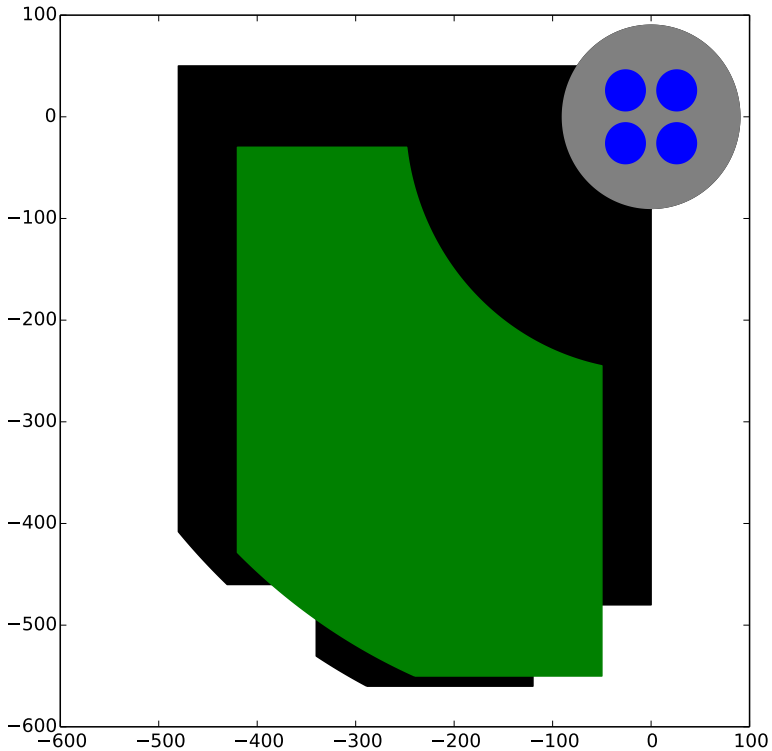
- absolute flux slightly different
- heavy mass spectra seem to fit reasonably well
- what is the composition of the light spectrum below and above the ankle-like feature?
- KASCADE He-flux may be too steep. Need another component? Should we expect another bending at around $10^{16.5}\,\mathrm{eV}$?
- galactic KASCADE proton flux is too low



- change of composition before and after the light ankle possible
- composition at higher energies needed, connection to direct measurements desirable

Combined Analysis

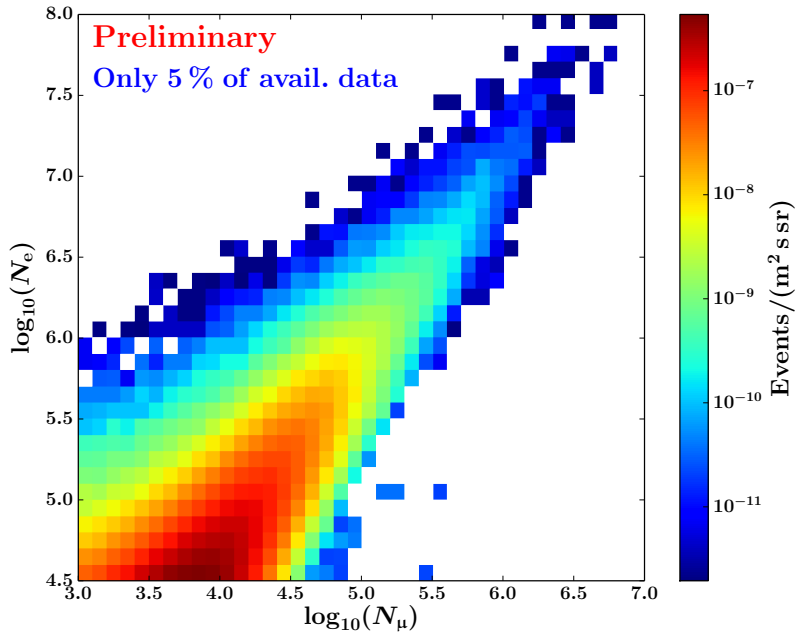
- Idea: Use e/γ detectors of both arrays together instead of separately
- Reconstruction of observables even more accurate
- The consistent reconstruction over the whole range eliminates systematic differences due to different reconstruction procedures
- Significant increase in number of events by increased measurement time and fiducial area
- Sub-KASCADE area might help to reach down to $10^{14}\,\mathrm{eV}$



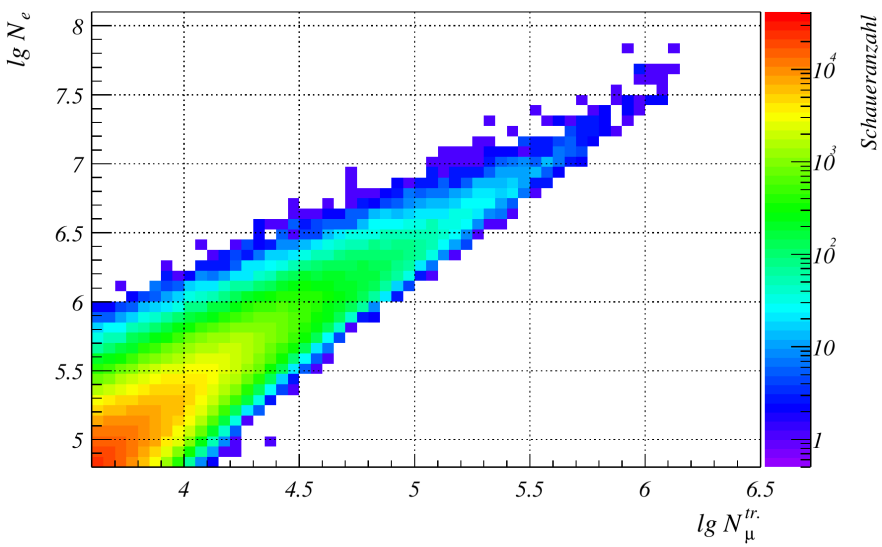
- Standard Area: $152202\,\mathrm{m}^2$
- KASCADE Area: $25447\,\mathrm{m}^2$
- Sub-KASCADE Area: $5027\,\mathrm{m}^2$
- Combined Area: $282057\,\mathrm{m}^2 (\sim 1.84 \times \mathrm{Std.\,Area})$

- First tests with about 5% of the avail. data look very promising.
- The recontruction using both arrays simultaneously works as expected.
- Next: process the whole dataset, apply energy-reconstruction procedures to combined data

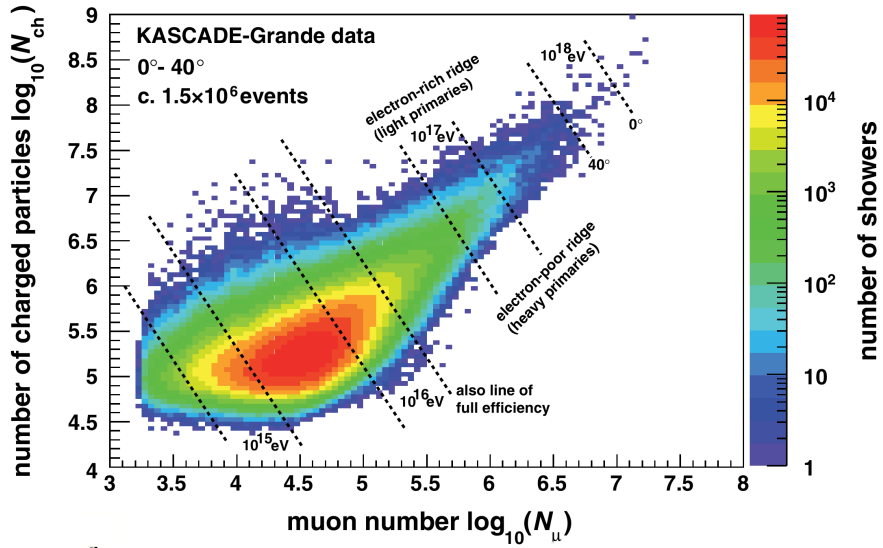
Combined



KASCADE



KASCADE-Grande



KASCADE-Grande Collaboration

Institut für Kernphysik & Institut für Experimentelle Kernphysik
KIT - Karlsruhe Institute of Technology

W.D.Apel, K.Bekk, J.Blümer, H.Bozdog, F.Cossavella, K.Daumiller, P.Doll, R.Engel, J.Engler, B.Fuchs, H.J.Gils, A.Haungs, D.Heck, D.Huber, T.Huege, D.Kang, H.O.Klages, K.Link, H.-J.Mathes, H.J.Mayer, J.Milke, J.Oehlschläger, N.Palmieri, T.Pierog, H.Rebel, M.Roth, H.Schieler, S.Schoo, F.G.Schröder, H.Ulrich, A.Weindl, J.Wochele

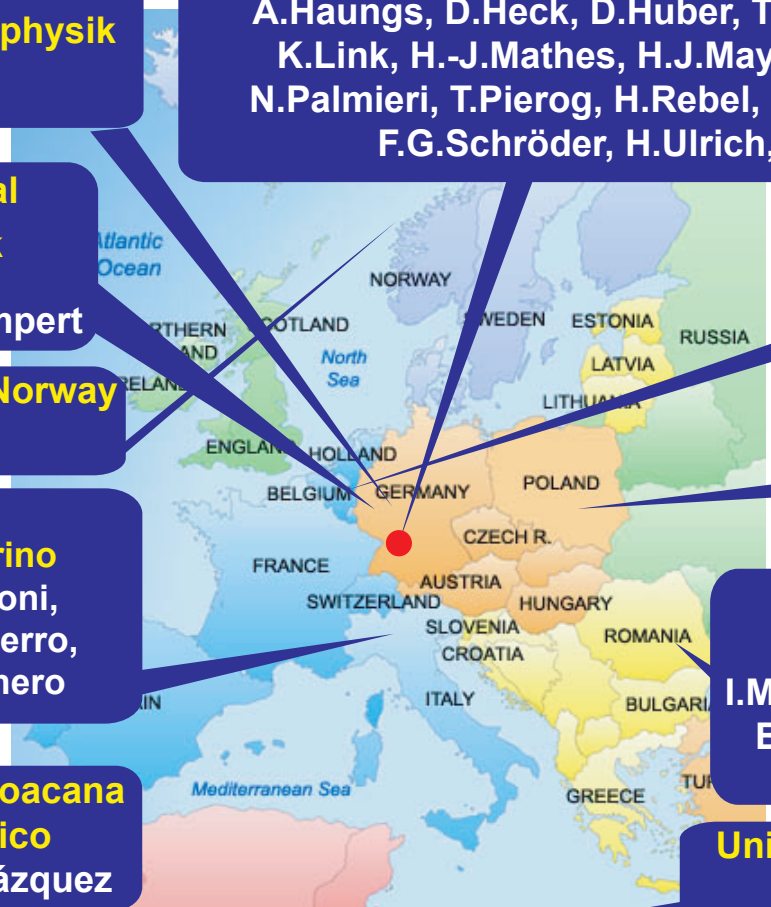
Universität Siegen
Experimentelle Teilchenphysik
C.Grupen

Universität Wuppertal
Fachbereich Physik
D. Fuhrmann,
R. Glasstetter, K-H. Kampert

University Trondheim, Norway
S. Ostapchenko

IFSI, INAF
and University of Torino
M. Bertaina, E. Cantoni,
A. Chiavassa, F. Di Pierro,
C. Morello, G. Trinchero

Universidad Michoacana
Morelia, Mexico
J.C. Arteaga-Velázquez



Radboud University
Nijmegen
J.R.Hörandel

National Centre for
Nuclear Research, Lodz
P. Łuczak, J. Zabierowski

IFIN Horia Hulubei and
University Bucharest
I.M. Brancus, A. Gherghel-Lascu,
B. Mitrica, M. Petcu, O. Sima,
G. Toma

Universidade Sao Paulo, Brasil
V. de Souza

https://web.ikp.kit.edu/KASCADE/

email spokesperson: haungs@kit.edu