KASCADE-Grande

...from PeV to EeV: investigating the knee(s)
Measurement Techniques: Air-Shower

- **energy**
- **mass**
- **arrival directions**
- **interaction mechanism**

First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Measurement of Cherenkov light with telescopes or wide angle pmts

Some of the particles reach the ground

Measurement with scintillation counters

Measurement of fluorescence light

Measurement of low energy muons with scintillation or tracking detectors

Measurement of high energy muons deep underground
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

- core and direction (from Grande)
- shower size (charged particles)
- muon number (from KASCADE)
- local muon density (from KASCADE)
- local charged particle density $S(500)$
- ...
2-dimensional shower size spectrum

- determination of primary energy
- separation in “electron-rich” and “electron-poor” event
All-particle energy spectrum:

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

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

- different zenith angle bins
- no composition dependence

Astroparticle Physics 36 (2012) 183
KASCADE-Grande all-particle energy spectrum

Astroparticle Physics 36 (2012) 183

- spectrum not a single power law
- hardening of the spectrum above $10^{16}$eV
- steepening close to $10^{17}$eV ($2.1\sigma$)

~15% systematic uncertainty in flux (energy independent)
KASCADE-Grande: Spectra of individual mass groups

\[ k = \frac{\log_{10}(N_{ch}/N_\mu) - \log_{10}(N_{ch}/N_\mu)_p}{\log_{10}(N_{ch}/N_\mu)_Fe - \log_{10}(N_{ch}/N_\mu)_p} \]

- spectra of individual mass groups:

→ steepening close to \(10^{17}\)eV (2.1\(\sigma\)) in all-particle spectrum

→ steepening due to heavy primaries (3.5\(\sigma\))

→ spectrum of more enhanced heavy sample has harder spectrum before break.

→ light+medium primaries show steeper spectrum, but fit by power law okay

→ possibility for hardening above \(10^{17}\)eV

KASCADE-Grande: spectrum of light primaries

- re-investigation of the spectrum of light primaries:
  ➔ increased area (higher threshold)
  ➔ 1 year more data
  ➔ improved selection cut

Phys.Rev.D (R) 87 (2013) 081101
KASCADE-Grande: spectrum of light primaries

observation of a „light“ ankle at $1 - 2 \cdot 10^{17} \text{ eV}$

hardening at $10^{17.08} \text{ eV}$ (5.8σ) in light spectrum

slope change from $\gamma = -3.25$ to $\gamma = -2.79$!

Phys.Rev.D (R) 87 (2013) 081101
Validity of Hadronic Interaction Models

First, high energy interaction: LHC + multiparameter measurements EAS

Secondary interactions: Fix target experiments + multiparameter measurements EAS

particle flow

energy flow

All particles

neutral
KASCADE-Grande: model dependence

- Structures of all-particle, heavy and light spectra similar
  ➔ knee by light component and heavy component; ankle by light component
- relative abundances different for different high-energy hadronic interaction models

Advances in Space Research (2013) accepted - dx.doi.org/10.1016/j.asr.2013.05.008
Present Main Experiments $10^{16}$-$10^{18}$eV

- **KASCADE-Grande**
- **IceTop (IceCube)**
- **Tunka**
Measurement Techniques of Air Showers

KASCADE-Grande

IceTop

Tunka

First interaction (usually several 10 km high)

Air shower evolves (particles are created and most of them later stop or decay)

Some of the particles reach the ground

Measurement of fluorescence light

Measurement with scintillation counters

Measurement of radio emission

Measurement of particles with tracking detectors or calorimeters

Measurement of low energy muons with scintillation or tracking detectors

Measurement of high energy muons deep underground

Measurement of Cherenkov light with telescopes or wide angle pmts
All-particle spectra

- Structures of all-particle spectra similar (in the level of 15%)
KASCADE-Grande results

- **KASCADE**: knee of light primaries at $\sim 3 \cdot 10^{15}$ eV
- Hardening at $10^{16}$ eV due to knee of medium component
- **KASCADE-Grande**: knee of heavy primaries at $\sim 9 \cdot 10^{16}$ eV
- Heavy knee less distinct compared to light knee
- Mixed composition for $10^{15}$ to $8 \cdot 10^{17}$ eV
- Light ankle at $1-2 \cdot 10^{17}$ eV
Light and Heavy Knees, Ankles, and Transition

Questions:
- which astrophysical scenario (model) describes the data?
- exact energy and mass scale?
- spectral forms?
KASCADE-Grande: Next

• KASCADE + KASCADE-Grande
  finally closed end 2012
  presently dismantled

• combined analysis
  for coherent spectrum and
  composition $10^{14}$-$10^{18}$ eV

• detailed data analysis (20y high-quality data)
  testing hadronic interaction models
  anisotropy studies
  radio (LOPES and CROME)

• KCDC
  KASCADE Cosmic ray Data Center
• KCDC = publishing research data from the KASCADE experiment

• Motivation and Idea of Open Data: general public has to be able to access and use the data the data has to be preserved for future generations

• Web portal: providing a modern software solution for publishing KASCADE data for a general audience In a second step: release the software as Open Source for free use by other experiments

• Data access: 4.5\cdot10^8 EAS events in first data release planned October 2013
Summary

GRAPES / ASγ / GAMMA

ICETOP / ICECUBE

TUNKA

TA / TALE

Yakutsk

AMIGA / HEAT / AERA

JEM-EUSO

AUGER

KASCADE, KASCADE-Grande

answers only by combining all information: stay tuned!
KASCADE-Grande Collaboration

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

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

W.D. Apel, K. Bekk, J. Blümer, H. Bozdag, F. Cossavella,
K. Daumiller, P. Doll, R. Engel, J. Engler, M. Finger, B. Fuchs,
H. J. Gils, A. Haungs, D. Heck, D. Huber, T. Huege, D. Kang,
H. O. Klages, K. Link, M. Ludwig, H.-J. Mathes, H. J. Mayer,
M. Melissa, 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, M. Wommer

Radboud University
Nijmegen
J. R. Hörandel

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

Institute of Physics and Nuclear Engeneering and University
Bucharest
I. M. Brancus, B. Mitrica,
M. Petcu, O. Sima, G. Toma

Universidade Sao Paulo, Brasil
V. de Souza

http://www-ik.fzk.de/KASCADE-Grande/

email spokesperson: haungs@kit.edu
**KASCADE : energy spectra of single mass groups**

Searched:
E and A of the Cosmic Ray Particles

Given:
$N_e$ and $N_\mu$ for each single event

$\Rightarrow$ solve the inverse problem

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

- kernel function obtained by Monte Carlo simulations (CORSIKA)
- contains: shower fluctuations, efficiencies, reconstruction resolution
Unfolding results: KASCADE and KASCADE-Grande

spectra of individual mass groups:
proton medium (He+C+Si) iron
⇒ all spectra overlap and agree well!
⇒ all three show a knee-like feature!!

Astroparticle Physics (2013) accepted
arXiv:1306.6283
Tunka-133

- Energy range: 100TeV – 1EeV
- Area: >1 km²; 675m asl
- Cherenkov-experiment: LDF
- 2011: Tunka-133 is extended by 6 distant external clusters
IceTop

- Energy range: PeV – 1EeV
- Area: 0.5 km²
- 2835m altitude (680 g/cm²)
- 79 ice cherenkov stations
- LDF + particle density at 125m
- in-ice high-energy muons