Recent Results from KASCADE-Grande

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Outline

• Motivation

• Update on KASCADE results
  EAS measurements $10^{14}$ eV $\div 8 \cdot 10^{16}$ eV

• KASCADE-Grande status
  EAS measurements $3 \cdot 10^{16}$ eV $\div 10^{18}$ eV

• Conclusion and Outlook
### Origin of the Knee

- **AGASA**
- **Akeno 20 km²**
- **Akeno 1 km²**
- **AUGER**
- **BLANCA**
- **CASA-MIA**
- **DICE**
- **BASJE-MAS**
- **EAS-Top**
- **Fly's Eye**
- **Haverah Park**
- **Haverah Park Fe**
- **Haverah Park p**
- **HEGRA**
- **HiRes-I**
- **HiRes-II**

- **HiRes/MIA**
- **KASCADE (e/m QGSJET)**
- **KASCADE (e/m SIBYLL)**
- **KASCADE (h/m)**
- **KASCADE (nn)**
- **MSU**
- **Mt. Norikura**
- **SUGAR**
- **Tibet ASγ**
- **Tibet ASγ-III**
- **Tunka-25**
- **Yakutsk**

#### Flux $\frac{d\Phi}{dE} \propto E^{3.2}$

#### $E_{\text{max}} \propto R \cdot B \cdot A$ ?

- **Direct:**
  - **JACEE**
  - **RUNJOB**
  - **SOKOL**
  - **Grigorov**

#### Cannon Ball Model

- Maximum energy of accelerators?
- Diffusion Losses from Galaxy?
- New type of interaction?

- **Development of cosmic-ray air showers**
  - Primary particle (e.g., nucleon)
  - First interaction
  - First nucleon interaction
  - Phenomenological
  - second interaction
  - New interaction mechanisms??
Is there a 2\(^{nd}\) Knee?

Flux \(\frac{d\phi}{dE_0} \cdot E_0^{-3} \text{ [m}^2 \text{sr}^{-1} \text{GeV}^{-1}]\)

Energy \(E_0 \text{ [GeV]}\)

Fe knee?

Akeno+HiRes Data

Karl-Heinz Kampert – KASCADE-Grande Collaboration
Where is the transition? Is this the cause of the ankle?
Measurements of EAS in the energy range $E_0 = 100 \text{ TeV} - 1 \text{ EeV}$
KASCADE : multi-parameter measurements

- energy range 100 TeV – 80 PeV
- up to 2003: $4 \cdot 10^7$ EAS triggers
- large number of observables:
  - electrons
  - muons (@ 4 threshold energies)
  + tracking
  - hadrons

Antoni et al., NIM A513 (2003) 490
KASCADE-Grande
= KArlsruhe Shower Core and Array DEtector + Grande and LOPES

**Key-Parameters:**

- **Data Taking started in 2004**
- **Covered E-range:** 100 TeV - 1 EeV
- **Instrumented area:** KASCADE 0.04 km$^2$; Grande: 0.45 km$^2$
- **Number of Stations:** KASCADE: 252 á 3.8 m$^2$; Grande: 37 á 10 m$^2$
- **Detected particles:**
  - electrons (1200 m$^2$ instrumented area)
  - muons (1100 m$^2$ @ E ≥ 230, 490, 800, 2400 MeV)
  - muon tracking (150 m$^2$ instrumented area)
  - hadrons (≥ 80 GeV; 320 m$^2$ instrumented area)
  - best sampling of all EAS expts. in this E-range
- **Radio Antennas (LOPES)** (☞ A. Haungs, yesterday)
KASCADE: Electrons & Muons in a single event

- **Electrons**: 
  - Graph showing density vs. core distance.
  - Data points and trend line.

- **Muons**: 
  - Graph showing density vs. core distance.
  - Data points and trend line.

- **Arrival Times**: 
  - Graph showing time vs. core distance.
  - Data points and trend line.

**Notes:**
- $e/\gamma$
- $20X_0$
- $\mu$
\[(N_e, N_\mu) \Leftrightarrow \text{(Energy, Mass)}\]

**CORSIKA Simulations**

- 3 PeV
- 100 PeV
- 10 PeV
- Fe, 100 PeV
- Fe, 30 PeV
- H, 100 PeV
- H, 30 PeV

**Data**

- Islands of fixed E & M

2-dim \(N_e-N_\mu\) distribution \(\Leftrightarrow\) system of coupled Fredholm-Equations

\[
\frac{dJ}{d\log N_e \, d\log N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{dJ_A}{d\log E} p_A(\log N_e, \log N_\mu^{tr} | \log E) \, d\log E
\]
Result of Unfolding: QGSJet01

(GHEISHA 2002 for low energy interactions)

Antoni et al., APP 24 (2005) 1
Result of Unfolding: Sibyll 2.1

(GHEISHA 2002 for low energy interactions)

More CNO & Iron with Sybill based unfolding
? E/Z or E/A ?

GQSJET

original

SYBILL

$\frac{dN}{dE} \cdot E^{2.5}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1.5}$]

$\frac{dN}{dE} \cdot E^{2.5}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1.5}$]

primary energy $E$ [GeV]

primary energy $E$ [GeV]

- proton
- helium
- carbon

Antoni et al., APP 24 (2005) 1
? E/Z or E/A ?

GQSJET vs. SYBILL

? E/Z or E/A ?

QGSJet 01

SIBYLL 2.1

 primary energy $E$ [GeV]

$\frac{dN}{dE} \cdot E^{2.5}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1.5}$]

- proton
- helium
- carbon

 primary energy $E$ [GeV]

$\frac{dN}{dE} \cdot E^{2.5}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1.5}$]

- proton
- helium
- carbon
? E/Z or E/A ?

GQSJET

$E_{\text{He}/4}$

SYBILL

$\frac{dN}{dE} \cdot E^{2.5}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1.5}$]

primary energy $E$ [GeV]

- proton
- helium
- carbon

$QGSJet 01$

$SIBYLL 2.1$
All-Particle Spectra

QGSJet & Sibyll based unfolding results agree well

Most experiments agree
Sensitivity to hadronic interaction models

\[ \Sigma \chi^2 \approx 2.8 \]
Main results robust against method or model:
- knee caused by light primaries
- positions of knee vary with primary elemental group
- no (interaction) model can describe the data consistently

(\(N_e, N_\mu\)) \(\iff\) \(N_h\): Consistent Inconsistencies

**QGSJET 01**

Number of hadrons vs. number of muons

- **rel. dev. \(N_h\)**
  - **p**
  - **Fe**

- **\(E_h > 100\ \text{GeV}\)**
  - **p**
  - **Fe**

**\(\chi^2\) distribution**

\(N_e-N_\mu\) data + QGSJet

\(\implies\) predicts too few hadrons @ low \(E\)
\((N_e, N_\mu) \Leftrightarrow N_h: \text{Consistent Inconsistencies}\)

**SIBYLL 2.1**

Number of hadrons vs. number of muons

- \(E_h > 500\ \text{GeV}\)
- \(p\) (proton)
- \(Fe\) (iron)

\[\text{rel. dev. } N_h\]

- \(\text{SIBYLL 2.1 (with composition)}\)

\[\text{number of muons } \log(N_{\mu}^{tr})\]

\[\chi^2\] distribution

\(N_e-N_\mu\) data + Sybill

\(\implies\) predicts too many hadrons @ high \(E\)
**Compare to µ-production height**

Idea:
Use composition from Ne-Nµ as input and simulate expected µ-production height and compare with data

Preliminary Result:
Showers penetrate deeper than expected at all energies
Model tests by muon density measurements

model sensitive parameters:

\[ R_{\rho}^{2.4/0.49} = \frac{\rho_\mu^{2.4\text{GeV}}}{\rho_\mu^{0.49\text{GeV}}} \]

\[ R_{\rho}^{2.4/0.23} = \frac{\rho_\mu^{2.4\text{GeV}}}{\rho_\mu^{0.23\text{GeV}}} \]

\[ R_{\rho}^{0.49/0.23} = \frac{\rho_\mu^{0.49\text{GeV}}}{\rho_\mu^{0.23\text{GeV}}} \]

\[ E_{\text{thr}}^{\mu} = 230\ \text{MeV} \]

\[ 490\ \text{MeV} \]

\[ 2400\ \text{MeV} \]

\[ R = 30\text{m} - 71\text{m} \]
Model tests by muon density measurements

Haungs et al, ICRC 2005

Results in terms of the muon energy spectrum in EAS:
-deviation between measurements and predictions increases with energy
-large deviations in the width of the distributions (shower to shower fluctuations)
Comparison with direct experiments

Systematic uncertainties in p and He spectra comparable to uncertainties of direct measurements!
**Analysis of large scale anisotropy of cosmic rays**

Different astrophysical models for the origin of the knee can be distinguished by their predictions of anisotropy.

KASCADE collaboration


**Anisotropy:**

- No large scale anisotropy observed
- Limits in Rayleigh amplitude
Search for point sources of cosmic rays

Point sources: not expected at these energies, but needs to be checked. Muon poor events is a sample enriched by possible gamma induced showers.

Li-Ma significances $E_0 > 10^{14.5} \text{eV}$

no positive signal from point sources

KASCADE collaboration
Primary photons: point directly to the source of cosmic rays
EAS are $\mu$-poor, i.e. small ratio of $\mu$ to electron number

- no photon signal observed
- best limits for diffuse flux

KASCADE collaboration, paper in preparation
F. Feßler, ICRC 2005
What did KASCADE tell us?

- Knee is caused by light primaries
- Knee marks a change from light ➔ heavy
- E/A vs E/Z cannot be sufficiently well separated
- Interaction models still unsatisfactory;
  10-15% deviations in EAS observables really matter ...
- KASCADE provides important clues to interaction models
- LHC data in forward region will be highly welcome
- But still more data to come from KASCADE
- no global anisotropies observed
- no point sources observed
- upper limit on γ-flux deduced
Towards higher Energies: KASCADE-Grande

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

→ measure higher energies!
Is there a transition galactic - extragalactic? If yes, where is it?

Fe-knee $\sim 10^{17}$ eV
gal-eg transition $\sim 10^{17.7}$ eV
Ankle due to $e^+e^-$ pair production

Fe-knee $\sim 10^{18}$ eV
Ankle = gal-eg transition $\sim 10^{19}$ eV

Cannonball model:
Accounts for CRs of all E (knee= elastic magnetic scattering)
KASCADE-Grande :
multi-parameter measurements
KASCADE-Grande:
multi-parameter measurements

KASCADE + Grande

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

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

100 % efficient above $2 \times 10^{16}$ eV

$10^{16}$ eV

$600 \times 600 \text{m}^2$ $<42^\circ$
KASCADE-Grande: Single event measurement

lateral distribution of a single event measured by KASCADE-Grande: $E_0 \approx 2 \times 10^{17} \text{eV}, \Theta = 33^\circ$

Event ID160542

particle density [m$^{-2}$]

KASCADE electron detectors

Grande detectors

KASCADE muon detectors

core distance [m]

$N_\alpha = 9.5 \times 10^6$

$N_\mu = 1.2 \times 10^6$

deposited energy [MeV/m$^2$] arrival time [ns]
KASCADE-Grande: Observables

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
2c) muon production height from KASCADE muon tracking detector

3) electron number from Grande by subtraction of muon content

4) two dimensional size spectrum for the analysis
Monte-Carlo studies:

- Sufficient reconstruction accuracies for
  - core (≤ 8 m)
  - direction (≤ 0.5°)
  - shower size, and
  - muon number (≈ 8%)

Reconstruction Accuracy (Full EAS & detector MC, w/o electronics)

Cuts: A = 500 × 600 m², 0.4 < s < 1.4, NGR > 19, θ < 18°, σΔt = 2 ns
\[
\rho = N_e \cdot \tilde{c}(s) \cdot \left( \frac{r}{r_0} \right)^{s-\alpha} \cdot \left( \frac{1 + r}{r_0} \right)^{s-\beta}
\]

Modified NKG-function
(\(\alpha = 1.5\), \(\beta = 3.6\), \(r_0 = 40\) m)

\(\Theta < 18^\circ\); core inside Grande array

\(\Rightarrow\) Averaged electron lateral distribution
\(\Rightarrow\) Averaged muon lateral distribution per
- reconstructed total muon number
- electron shower size
KASCADE-Grande : first analyses

Glasstetter et al, ICRC 2005

Unfolding of 2-dimensional shower size spectrum possible
\[ \Rightarrow \text{composition} \]
KASCADE-Grande: all-particle energy spectrum

Combination of muon and electron number
⇒ primary energy

⇒ all angular bins show same flux in energy

⇒ still improvements in systematics needed

Estimated primary energy $\log(E_{\text{est}}/\text{GeV})$

Flux uncertainty $\approx 20\%$

Threshold constant increase in atm. thickness by 50 g/cm²
First energy spectrum (by muon number only)

KASCADE-Grande: E-Spectrum from $\mu$-number estimate and 1-dim unfolding

preliminary
KASCADE-Grande: first analyses: Anisotropies

Large scale anisotropy?

✉ Distributions of events in galactic coordinates

Point sources?

✉ Angular differences between two events
KASCADE-Grande : Flash ADC system

• Flash-ADC system for the Grande array

  with optical links and a ring buffer system
  ➔ self triggering  ➔ full signal information of the detectors
  ➔ high time resolution ➔ intrinsic electron muon separation

⇒ High precision data from Grande array
Summary & Conclusions

• 'Revival' of research activities in knee- & ankle region
• Comparison of data and models has become more quantitative; we are discussing 10-15%-effects!
• Limitations are by EAS-simulations and by data itself
• KASCADE-Grande just about to start delivering high-quality data from the knee up to the ankle
• A true understanding of CRs requires:
  – origin of the knee (E/Z vs E/A)
  – answer question about Fe-knee
  – transition galactic-extragalactic
  – (astro)physics of the ankle
  – GZK-existence
KASCADE-Grande Collaboration

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