Test of the SIBYLL 2.3 high-energy hadronic interaction model using the KASCADE-Grande muon data

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Outline

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3. The KASCADE-Grande detector
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5. Analysis
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7. Summary
Cosmic rays are produced in HE astrophysical sources (SNR’s, AGN’s, etc?).

Primaries with $E > 1$ PeV are detected at Earth through air shower (EAS) observation.

EAS data is interpreted with hadronic models to study energy and composition.

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Hadronic interaction models:

1. Phenomenological models inspired in QCD.

3. Calibrated with accelerator data.

4. Extrapolated to high energies (HE’s) and forward region ($p_T \sim 0$).

Soft physics (low $Q^2$) is relevant for CR interactions

Model uncertainties produce uncertainties in predictions of EAS parameters
Differences in EAS observables due to uncertainties in the models

T. Pierog, EPJ web of conferences 145, 18002 (2017)
Introduction

Dependence of **relative abundances** and **spectrum** of CR’s with hadronic interaction models:


**Composition and energy scale are affected by model uncertainties**

**Imperative to check validity of hadronic models**
Use CR observatories to constrain/test models:

- **KASCADE-Grande**
  \[ E_{CR} = 10^{15} - 10^{18} \text{ eV} \]
  \[ E_{th,\mu} = 230 \text{ MeV}, 490 \text{ MeV}, 800 \text{ MeV}, 2.4 \text{ GeV} \]

- **ICECUBE/ICETOP**
  \[ E_{CR} = 10^{15} - 10^{17} \text{ eV} \]
  \[ E_{th,\mu} = 0.2 \text{ GeV} \]

- **EAS-MSU**
  \[ E_{CR} = 10^{17} - 10^{18} \text{ eV} \]
  \[ E_{th,\mu} = 10 \text{ GeV} \]

- **Pierre Auger**
  \[ E_{CR} > 10^{18} \text{ eV} \]
  \[ E_{th,\mu} = 1 \text{ GeV} \]

**Employ muons for tests:**

- Penetrating particles/less atmospheric attenuation.
- Keep information from early stage of EAS development.
- Sensitive to hadronic processes.
- Used in composition studies.

Proton @ \( 10^{15} \text{ eV} \), Corsika simulation, F. Schmidt & J. Knapp
Muon measurements:
- Energy spectrum
- μ⁻/μ⁺ Charge ratio
- Multiplicity
- Zenith angle dependence
- Lateral distributions
- Production height
- Pseudorapidites

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Proton @ 10^{15} \text{ eV. Corsika simulation, F. Schmidt & J. Knapp}
Motivation

KASCADE-Grande EAS muon data

Muon attenuation length ($\Lambda_\mu$):

1. Parameterizes dependence of number of $\mu$'s in EAS with the atmospheric depth:

   $$N_\mu = N_\mu^0 e^{-X/\Lambda_\mu}$$

2. Correct data for attenuation in the atmosphere.

3. Affected by details of shower production:

   - $\pi$ energy spectrum, cross section, $p_\pi$ distribution,
   - $\pi^\pm/\pi^0$ ratios,
   - Baryon/resonance production,
   - Multiplicity $<N>$
   - Inelasticity (y), etc.

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Motivation

KASCADE-Grande EAS muon data

Muon attenuation length ($\Lambda_{\mu}$):

Measured muon attenuation length ($E_{\text{CR}} \sim 10^{16} - 10^{17} \text{ eV}$) is above MC predictions from:

- SIBYLL 2.1
- QGSJET-II-02

Pre-LHC models (~ 2 $\sigma$):

- SIBYLL 2.1
- QGSJET-II-02

Post-LHC models (~ 1.34 $\sigma$ to 1.48 $\sigma$):

- EPOS-LHC
- QGSJET-II-04

Better agreement with post-LHC models.

Does SIBYLL 2.3* perform better?

*F. Riehn et al., PoS(ICRC2015) 558

J.C. Arteaga et al., Astropar. Phys. 95 (2017) 25

Less effective attenuation in exp. data

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The KASCADE-Grande detector

\[ J(E) = E^{-\gamma} \]

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1. What is the origin of the features in the spectrum?

2. Where do they come from?

3. What is their nature?

4. How do they get accelerated?

5. Are there nearby sources?

6. Where is the galactic to extragalactic transition?

$J(E) = E^{-\gamma}$

$\gamma = -2.7$

$\gamma = -3.0$

$\gamma \sim -3.3$

$\gamma = -2.6$
The KASCADE-Grande detector

December 2003 - November 2012

1. **Location:** KIT-Campus North, Karlsruhe, Germany

![Karlsruhe, Germany
110 m a.s.l., 49° N, 8° E](image)
The KASCADE-Grande detector

KASCADE (200 x 200 m$^2$) + Grande (0.5 km$^2$)

E = 1 PeV - 10$^{18}$ eV

Grande array

KASCADE array

37 plastic scintillator detectors

252 shielded/unshielded scintillator detectors, muon tunnel, calorimeter.

W.D. Apel et al., NIMA 620 (2010) 490

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The KASCADE-Grande detector

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H. Falcke et al., Nature 435 (2005) 313

W.D. Apel et al., NIMA 620 (2010) 490

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The KASCADE-Grande detector

1. Grande provides
   \( N_{\text{ch}} \): Number of charged particles

2. KASCADE provides
   \( N_{\mu} \): Number of muons

Fit to data:

\[
\rho_{\text{ch}}(r) = N_{\text{ch}} \cdot f_{\text{ch}}^{\text{NKG}}(s, r)
\]

Fit to data:

\[
\rho_{\mu}(r) = N_{\mu} \cdot f_{\mu}^{\text{Lagutin}}(r)
\]

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The KASCADE-Grande detector

Unfolding methods capable of reconstructing spectra of elemental groups:

- **Knee** at \( E \sim 10^{15} \) eV due to a break in the spectrum of light components

- **Spectral features independent** of the hadronic interaction models

- **Iron knee** around 80 PeV

Knee positions \( \propto Z \)

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The KASCADE-Grande detector

- **Knee structure around 80 PeV in the heavy component**

- **Ankle-like** feature at 120 PeV in the light component

Galactic-extragalactic transition?
Experimental data

1. Effective time: 1434 days

2. Area: $8 \times 10^4$ m$^2$

3. Exposure: $2.6 \times 10^{12}$ m$^2$ s sr

4. Cuts (reduction of EAS uncertainties):
   - Central area
   - $\theta < 40^\circ$
   - Instrumental & reconstruction cuts
   - Optimized for $E = [10^{16}, 10^{17}]$ eV

Efficiency:
\[
\log_{10} (E/\text{GeV}) = 7 \pm 0.20
\]
\[
\log_{10} (N_{\mu}) = 5 \pm 0.20
\]
**Data & simulations**

**MC data (CORSIKA/Fluka)**

1. **HE hadronic interaction**
   - Model: SIBYLL 2.3

2. **Simulation:** H, He, C, Si, Fe, mixed;
   - $\gamma = -3, -3.2, -2.8$
   - $\theta < 42^\circ$
   - $E = 10^{14} - 3 \times 10^{18}$ eV

3. **Systematics:**
   - $\Delta N_{\text{ch}} < 12\%$  \(\Delta N_\mu < 20\%\)
   - $\Delta \theta < 0.6^\circ$
   - $\sigma_{\text{core}} < 10$ m

$N_\mu$ data corrected for systematic errors $\Delta N_\mu^\text{corrected} < 10\%$
Analysis

Shower content at same Energy (E) is attenuated with atmospheric depth (X):
Large X  —> High zenith angles (θ)

\[ N_\mu = N_\mu^0 \exp\left[-X_0 \sec(\theta)/\Lambda_\mu\right] \]
Analysis

- Constant Intensity Cut method: Quantify zenith-angle evolution of data.
- Method is independent of MC model.

![Diagram]

**Constant intensity cut method**

100 % detector efficiency + Isotropy

$\rightarrow J[N_\mu(0)] = J[N_\mu(\theta)]$
Data divided in five $\theta$ intervals with equal exposure.

$$J(>N_\mu) = \int_{N_\mu}^{\infty} \Phi_\mu(N_\mu) dN_\mu$$

1. Apply cuts at fixed frequencies

$$N_\mu = N_\mu^0 \exp[-X_0 \sec(\theta)/\Lambda_\mu]$$

2. Get attenuation curves

3. Apply a fit to get $\Lambda_\mu$
Discrepancy between SIBYLL 2.3 and measurement is small, but large uncertainty from composition
Results

Reduce error due to composition uncertainties:

- $\chi^2$ fit to measured data with 4 mass groups: H, He, C, Si+Fe (50% mixture).
- Use double power-law for energy spectrum of each mass group.
- Employ templates from SIBYLL 2.3 for each mass group.

\[ \chi^2 = \sum_{i,j} \frac{[n_{ij}^{\text{exp}} - \sum_{A} n_{ijA}^{MC}(p_A)]^2}{(\sigma_{ijA}^{MC})^2} \]

$A$: atomic mass
Results

Composition model obtained from measured data using SIBYLL 2.3

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Results

\[ \Lambda_{\mu} \text{ (g/cm}^2) \]

\[ \theta = 0^\circ - 40^\circ \]

\[ QGSJET \text{ II-2} \quad QGSJET \text{ II-04} \quad SIBYLL 2.1 \quad SIBYLL 2.3 \quad EPOS \text{ LHC} \]

\[ \Delta \Lambda_{\mu} \quad QGSJET-II-2 \quad QGSJET-II-4 \quad SIBYLL 2.1 \quad SIBYLL 2.3 \quad SIBYLL 2.3 \quad EPOS-LHC \]

\[ \sigma \quad +2.04 \quad +1.48 \quad +1.99 \quad +1.06 \quad +1.52 \quad +1.34 \]

SIBYLL 2.3 has also problems to describe the data

*Errors on SIBYLL 2.3 are preliminary

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Results

Muon lateral densities

J.C. Arteaga & D. Rivera et al., (KG Collab.) PoS (ICRC2017) 316

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Results

$N_\mu$ - $N_{ch}$ correlation

![Graph showing $N_\mu$ - $N_{ch}$ correlation with three different zenith angle ranges: $\theta \in [0^\circ, 16^\circ]$, $\theta \in [24^\circ, 30^\circ]$, and $\theta \in [35^\circ, 40^\circ]$. The graph plots $\log_{10} N_\mu$ against $\log_{10} N_{ch}$ with lines for protons, Fe, and KG data.]

J.C. Arteaga & D. Rivera et al., (KG Collab.) PoS (ICRC2017) 316

Tests of SIBYLL 2.3 using KG data - J.C. Arteaga

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1. The measured $\Lambda_{\mu}$ at KASCADE-Grande is above predictions of HE hadronic interaction models: QGSJET-II-02, QGSJET-II-04, EPOS-LHC and SIBYLL 2.3.

2. Post-LHC models predict a $\Lambda_{\mu}$ value higher than that predicted by Pre-LHC models.

3. The models might need:
   - a harder $\mu$ energy spectrum,
   - a decrease of elasticity in pion interactions,
   - a reduction of forward production of baryon/antibaryon pairs, etc.,

to agree with the data.
Thank you!