Tests of HE hadronic interaction models with the muon attenuation length in KASCADE-Grande

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1) The Problem

• Preliminary studies show that **zenith angle dependence of the muon content of EAS is not described** by hadronic interaction models.

• **Attenuation length of muons** in the atmosphere seems to be **higher than** that predicted by simulations.

\[ \Lambda_\mu^{\text{exp}} > \Lambda_\mu^{\text{MC}} \]

• **How statistically significant are the results?** Need a complete study of statistical and systematic errors.
2) The objective

• Look for statistical/systematic errors that may be responsible for the origin of the discrepancy.

• If no error can explain the difference, how significant is the result?
3) Experiment and data

KASCADE-Grande:

- **KASCADE** (200 x 200 m$^2$) + Grande (0.5 km$^2$)
- **EAS detector**: $E = 10^{15}-10^{18}$ eV.
- **Total $N_\mu (E_\mu > 230$ MeV)**: $\rho_\mu(r)$ data from 192 KASCADE $\mu$ detectors
4) Data and systematics

Data sample:
- Effective observation time: 1434 days
- Total exposure: $1.3 \times 10^3 \text{ m}^2 \text{ s sr}$

Selection cuts:
- Central area: $370 \times 520 \text{ m}^2$.
- $\theta < 40^\circ$ ($N_\mu \geq 3.98 \times 10^4$).
- Reconstruction & experimental cuts.

Advantages:
- Reduction of muon uncertainties, avoid punch-through bias and edge effects,
- Remove events with under- and over-estimated muon numbers, poor muon reconstruction, etc.
4) Data and systematics

MC sample:
- QGSJET-II-02
- EPOS 1.99
- SIBYLL 2.1
- QGSJET-II-04
- EPOS LHC

Simulated spectra:
- Composition: H, He, C, Si, Fe & Mixed
- \( E^\gamma, \gamma = -2.8, -3, -3.2 \)

Mean accuracy (in region of full efficiency):
- \( \Delta N_\mu < 20\% \)
- \( \Delta N_{ch} < 15\% \)
- \( \Delta \theta < 0.6^\circ \)
- \( \sigma_{Core} < 10 \, \text{m} \)
4) Data and systematics

- All muon data is corrected for systematic errors (using a correction function derived from QGSJET-II-02)

No dependence with core position, zenith angle and muon shower size
5) The method

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

![Graphs showing the relationship between J and N_μ](image)

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

- Apply cuts at fixed frequencies.
- Attenuation curves -> Global Fit -> Λ_μ.
6) The results

<table>
<thead>
<tr>
<th>QGSJET-II-02</th>
<th>EPOS 1.99</th>
<th>SIBYLL 2.1</th>
<th>EPOS LHC</th>
<th>QGSJET-II-04</th>
<th>KG data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_\mu$ (g/cm²)</td>
<td>706$^{+87}_{-108}$</td>
<td>564$^{+49}_{-79}$</td>
<td>743$^{+54}_{-205}$</td>
<td>823$^{+153}_{-148}$</td>
<td>735$^{+78}_{-145}$</td>
</tr>
</tbody>
</table>

Error bars: Syst. & Stat. errors.

MC (CORSIKA/FLUKA): Include errors from: $\gamma = -2.8$, -3.0, -3.2
H, Fe and mixed composition

| J.C. Arteaga – Muons and model tests in KG | 34th ICRC, The Hague, Holland, 3.08.15 |
6) The results

Deviations and C.L. for agreement between model predictions and experimental data

<table>
<thead>
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<td>$1256^{+283}_{-258}$</td>
</tr>
<tr>
<td>Deviation($\sigma$)</td>
<td>+2.02</td>
<td>+2.63</td>
<td>+1.94</td>
<td>+1.44</td>
<td>+1.93</td>
<td></td>
</tr>
<tr>
<td>C.L .(%)</td>
<td>2.17</td>
<td>0.43</td>
<td>2.62</td>
<td>7.49</td>
<td>2.68</td>
<td></td>
</tr>
</tbody>
</table>

- Probability of agreement between experiment and MC is low.

- Measurements and predictions are not consistent.
6) The results

<table>
<thead>
<tr>
<th>Systematic/Statistical uncertainties of the measured $\Delta_\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction/Analisys method</td>
</tr>
<tr>
<td>+9%/-2%</td>
</tr>
<tr>
<td>Muon systematics</td>
</tr>
<tr>
<td>+13%/-10%</td>
</tr>
<tr>
<td>Correction function</td>
</tr>
<tr>
<td>+6%/-9%</td>
</tr>
<tr>
<td>Statistical fluctuations</td>
</tr>
<tr>
<td>+9%/-9%</td>
</tr>
<tr>
<td>EAS core position</td>
</tr>
<tr>
<td>+12%/-11%</td>
</tr>
</tbody>
</table>

- Aging of detectors is not the origin of the discrepancy

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<th>Period</th>
<th>Effective time (s)</th>
<th>$\Delta_\mu$ (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1 20/12/2003 – 07/11/2006</td>
<td>$3.3 \times 10^7$</td>
<td>1233 ± 89</td>
</tr>
<tr>
<td>Sample 2 07/11/2006 – 11/04/2009</td>
<td>$5.2 \times 10^7$</td>
<td>1295 ± 85</td>
</tr>
<tr>
<td>Sample 3 11/04/2009 – 31/10/2011</td>
<td>$3.9 \times 10^7$</td>
<td>1219 ± 89</td>
</tr>
</tbody>
</table>
6) The results

• Studying systematics with MC

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluctuations on $\rho_\mu(r)$</td>
<td>+15%</td>
</tr>
<tr>
<td>core position, arrival angle and $\rho_\mu(r)$ reconstruction</td>
<td>±3%</td>
</tr>
<tr>
<td>Shape of lateral distribution function</td>
<td>+5%/ -4%</td>
</tr>
</tbody>
</table>

• Other discarded sources:
  - Flat atmosphere in MC
  - Atmosphere model
  - Local variations of air pressure and temperature.
Differences can be tracked down to the evolution of lateral muon densities in atmosphere.

QGSJET-II-02 and QGSJET-II-04 predictions for Fe+Si/H+He bracket the measurements.
6) The results

EPOS 1.99 and EPOS LHC predictions for Fe+Si/H+He also bracket KASCADE-Grande measurements.
6) The results

SIBYLL 2.1 predictions for Fe+Si/H+He are smaller than the measured data at HE for inclined EAS.

Vertical EAS

Inclined EAS

LE

HE

Heavy

Light

ρμ(r)[m⁻²]

$log_{10} N_{IC}^{IC} = 6.55 - 6.80$

$\Delta \theta = [0.00, 18.71]^\circ$

$log_{10} N_{IC}^{IC} = 6.80 - 7.04$

$log_{10} N_{IC}^{IC} = 7.04 - 7.28$

200 300 400

r[m]

200 300 400

r[m]
• The observed zenith angle evolution of the muon content in the atmosphere is not consistent with predictions from the models: QGSJETII-02, QGSJET-II-04, EPOS 1.99, EPOS LHC and SIBYLL 2.1.

• Statistical/Systematics errors do not explain the observed deviation.

• Deviations are tracked down to the different evolution of the muon density distributions of real data with the atmospheric depth.

• Measured EAS have more muons than the predictions of SIBYLL 2.1 for heavy/light nuclei at high energies and zenith angles.