Particle-physics aspects in air shower measurements with the Pierre Auger Observatory

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Photo by S.J. Saffi, University of Adelaide
Composition and hadronic interactions: a vicious circle

Pure beams are needed to study hadronic interactions

Selecting pure beams requires detailed understanding of hadronic interactions

![Graph showing the maximum range of muons in iron compared to protons.](image-url)
Air showers recorded at Auger

15% duty cycle :-(

Lateral distribution

\[ S_{1000} \propto E \]

Longitudinal profile

\[ E \propto \int \frac{dE}{dX} \, dX \]
Correlation between $X_{\text{max}}$ and SD Signal

$18.5 < \lg(E/\text{eV}) < 19.0, \frac{X^*_{\text{max}}}{S^*(1000)}$: scaled to $10^{19}$ eV

Pure compositions
$\Rightarrow$ correlation $\approx 0$

Ranking coefficient $r_G$ [R. Gideon, R. Hollister, JASA 82 (1987) 656]
The key idea

Heavier nuclei produce shallower showers with larger signal (more muons)

General characteristics of air showers / minor model dependence

Correlation more negative $\Rightarrow$ composition becomes more mixed

Correlation $r_G$ in data

$\rho(G(X_{\text{max}},S^*(1000))$ for protons

<table>
<thead>
<tr>
<th>Model</th>
<th>$r$ (Epos-LHC)</th>
<th>$r$ (QGSJetII-04)</th>
<th>$r$ (Sibyll 2.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epos-LHC</td>
<td>0.00</td>
<td>+0.08</td>
<td>+0.07</td>
</tr>
<tr>
<td>QGSJetII-04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sibyll 2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\approx 5\sigma \approx 8\sigma \approx 7\sigma$

Difference is larger for other pure beams

Systematics plays only a minor role $\sigma_{\text{syst}}(r_G) \approx 0.01$

due to invariance of $r_G$ to additive and multiplicative scale transformations

Relation of $r_G$ to dispersion of masses $\sigma(\ln A)$

Mixtures of $p$, He, O, Fe
(step in fractions $\Delta f_i = 0.1$)

pure beams, $r_G \geq 0$

preliminary

$0.5p - 0.5Fe$
Relation of $r_G$ to dispersion of masses $\sigma(\ln A)$

$E_{\text{pos-LHC}}$  
Auger 2015, preliminary

$r_G = -0.125 \pm 0.024$
$\lg(E/\text{eV}) = 18.5 - 19.0$
Relation of $r_G$ to dispersion of masses $\sigma(\ln A)$

$\sigma(\ln A)$

Sibyll 2.1

Auger 2015, preliminary

$r_G = -0.125 \pm 0.024$

$\lg(E/eV) = 18.5 - 19.0$
Relation of $r_G$ to dispersion of masses $\sigma(\ln A)$

$\sigma(\ln A)$ vs $r_G$ with data from QGSJetII-04 and Auger 2015.

$r_G = -0.125 \pm 0.024$

$\lg(E/\text{eV}) = 18.5 - 19.0$
Relation of $r_G$ to dispersion of masses $\sigma(\ln A)$

Data are compatible with dispersion of masses $\sigma(\ln A) \lesssim 1$

Muons in air showers

\[ X_{\text{max}} \text{ is dominated by first interaction} \]

R. Ulrich, APS 2010

muons are produced late in the shower cascade
→ number of generations \( \sim 6 \) at \( 10^{19} \text{ eV} \)
→ amplified sensitivity to hadronic interactions
Muon number in hybrid events with $\theta<60^\circ$

- $E = 10^{18.8} - 10^{19.2}$ eV
- Zenith angles $[0^\circ, 60^\circ]$
- 411 hybrid events after quality cuts
Muon number in hybrid events with $\theta<60^\circ$

\[
S_{\text{resc}} = R_E \, S_{\text{EM}} + R_{\text{had}} \, R_E^\alpha \, S_{\text{had}}
\]

$\alpha \approx 0.9$

Systematic uncertainties on $R_E$ and $R_{\text{had}}$: 10%
Muons in highly inclined events

\[ \rho_\mu(\text{data}) = N_{19} \cdot \rho_\mu(\text{QGSJETII03, } p, E = 10^{19} \text{ eV}, \theta) \]

\[ R_\mu = \frac{N^\text{data}_\mu}{N^\text{MC}_\mu} \]

- \( E > 4 \times 10^{18} \text{ eV} \)
- Zenith angles \([60^\circ, 80^\circ]\]
- 174 hybrid events after quality cuts
- Systematic uncertainty on \( R_\mu \): 11%
Data at variance with simulations

- $\langle R_\mu \rangle$ higher than MC iron predictions
- Tension between the $X_{\text{max}}$ and muon measurements
- Older versions of QGSJet model are at odds with data taking into account the large systematic uncertainty
The average muon content and the muon gain with energy

<table>
<thead>
<tr>
<th>Model</th>
<th>$\langle \ln R_\mu \rangle (10^{19} \text{eV})$</th>
<th>$\frac{d}{d \ln E} \langle \ln R_\mu \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger data</td>
<td>0.601 ± 0.016, 0.169 ± 0.203 (sys.)</td>
<td>1.029 ± 0.024, 0.030 (sys.)</td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>0.482 ± 0.007, 0.039 (sys.)</td>
<td>0.928 ± 0.006, 0.017 (sys.)</td>
</tr>
<tr>
<td>QGSJET II-04</td>
<td>0.453 ± 0.007, 0.037 (sys.)</td>
<td>0.925 ± 0.006, 0.017 (sys.)</td>
</tr>
<tr>
<td>QGSJET II-03</td>
<td>0.258 ± 0.007, 0.043 (sys.)</td>
<td>0.922 ± 0.006, 0.018 (sys.)</td>
</tr>
<tr>
<td>QGSJET01</td>
<td>0.370 ± 0.004, 0.047 (sys.)</td>
<td>0.922 ± 0.006, 0.020 (sys.)</td>
</tr>
<tr>
<td>$p$</td>
<td>0.197</td>
<td>0.944</td>
</tr>
</tbody>
</table>

Muon deficit from 30% to 80% at $10^{19}$ eV depending on the model:
Best case for EPOS-LHC (minimum deviation of 1.4 $\sigma$)

Deviations from a constant proton (iron) composition observed at the level of 2.2 (2.6) $\sigma$
Composition Fit ($X_{\text{max}}$ distribution)
Surface detector data recorded with Auger

- **Time structure**

- **Lateral distribution**

- $S_{1000} \propto E$
Muon Production Depth distribution (MPD) in a nutshell

Inclined events to avoid EM contamination:

Geometric delay of arriving muons:

\[ c \cdot t_g = l - (z - \Delta) \]
\[ = \sqrt{r^2 + (z - \Delta)^2} - (z - \Delta) \]

Mapped to muon production depth:

\[ z = \frac{1}{2} \left( \frac{r^2}{ct_g} - ct_g \right) + \Delta \]
Muon Production Depth

- $E > 10^{19.3} \text{ eV}$ (enough muons/event)
- Zenith angles $[55°, 65°]$ (low EM contamination)
- Distances from the core $[1700 \text{ m}, 4000 \text{ m}]$
- 481 events after quality cuts
- Systematic uncertainties: $17 \text{ g/cm}^2$

Resolution:
- $100 \ (80) \text{ g/cm}^2$ at $10^{19.3} \text{ eV}$ for $p$ (Fe)
- $50 \text{ g/cm}^2$ at $10^{20} \text{ eV}$
Comparison of $\langle \ln A \rangle$ from $X_{\text{max}}$ and $X_{\text{max}}^\mu$

InA (FD) from *Phys. Rev. D* 90 (2014) 12

QGSJetII-04: Compatible values within 1.5 $\sigma$
EPOS-LHC: Incompatibility at a level of at least 6 $\sigma$
Summary

- $\langle X_{\text{max}} \rangle$, $\sigma(X_{\text{max}})$, $r_G(X_{\text{max}}/S(1000))$
  - Mixed composition around and above the ankle (if LHC-inspired extrapolations are ok)

- Muon number
  - At odds with predictions for mixed composition
  - Muon deficit in simulations

- Muon production depth vs. $X_{\text{max}}$
  - QGSjetII-04: marginally compatible
  - EPOS-LHC: incompatible

Auger is going to extend the composition measurements up to highest energies measuring $e^\pm/\gamma$ & muons with 2 arrays: AugerPrime

(szintillators accompanying WCDs; see Tiina’s talk)
Measurement of the UHE Proton+Air Cross section

tail of $X_{\text{max}}$ distribution:

\[ \left\langle E \right\rangle = 10^{17.90} \text{ eV} \]

\[ \left\langle E \right\rangle = 10^{18.22} \text{ eV} \]

\[ 10^{17.8} < E < 10^{18} \text{ eV} \]

\[ \Lambda_i = 60.7 \pm 2.1 \text{ g/cm}^2 \]

\[ 10^{18} < E < 10^{18.5} \text{ eV} \]

\[ \Lambda_i = 57.4 \pm 1.8 \text{ g/cm}^2 \]
Measurement of the UHE Proton+Air Cross section

Equivalent c.m. energy $\sqrt{s_{pp}}$ [TeV]

Energy [eV]

Lower energy point $457.5 \pm 17.8 \text{(stat)} +19/-25 \text{(syst)}$

Higher energy point $485.8 \pm 15.8 \text{(stat)} +19/-25 \text{(syst)}$

Ralf Ulrich for the Pierre Auger Collaboration

Fit: $\langle R_\mu \rangle = a(E/10^{19} \text{ eV})^b$

174 Auger hybrid events

stdev $0.20 \pm 0.01$