Measurement of the muon content in air showers at the Pierre Auger Observatory (id=336)

Laura Collica¹ for the Pierre Auger Collaboration²

¹INFN Torino, Italy
²Av. San Martín Norte 304, 5613 Malargüe, Argentina

(full author list: http://www.auger.org/archive/authors_2015_06.html)
Outline

- **Measurement of muon number in highly inclined air showers**

  Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events
  A. Aab *et al.* (Pierre Auger Collaboration)

- **Measurement of muon number in hybrid events with zenith angles < 60°**

  Testing hadronic interactions at ultra-high energy using air showers measured at the Pierre Auger Observatory
  The Pierre Auger Collaboration
  [to be published]

- **Measurement of muon production depth**

  Muons in air showers at the Pierre Auger Observatory: Measurement of atmospheric production depth
  A. Aab *et al.* (Pierre Auger Collaboration)
Measuring muons with Auger SD

The muon content of EAS is sensitive to the primary composition and to the hadronic interaction properties.

- In inclined showers, the EM component is largely absorbed before reaching the ground.
- The EM signal decreases with the distance from the core.
Testing hadronic interactions at ultra-high energy using air showers measured at the Pierre Auger Observatory
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- Measurement of muon production depth
- Measurement of muon number in hybrid events with zenith angles < 60°

Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events
A. Aab et al. (Pierre Auger Collaboration)

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[to be published]
Muons in highly inclined events

The number of muons per unit area at the ground level has a shape which is almost independent of energy, composition or hadronic model.

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

The measured muon scale factor \(N_{19}\) with respect to muon reference density profiles is converted to

\[ R_\mu = \frac{N_{\mu, \text{data}}}{N_{\mu, \text{MC}}} \]

Analysis details:

➤ data set: 01/2004 - 12/2013
➤ E > 4 \times 10^{18} \text{ eV} (100\% SD trigger)
➤ zenith angles \([62^\circ, 80^\circ]\) (low EM contamination)
➤ 174 hybrid events after quality cuts

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Mean Muon Scale $<R_\mu>$

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

- 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) $\sigma$
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Muons with zenith angles < 60°

Hybrid events used to test LHC-tuned hadronic models

Ground signal modified in MC to fit the one in the data

Rescaling factors:

- $R_E$ → primary energy
- $R_{\text{had}}$ → hadronic contribution to the ground signal

Analysis details:

- data set: 01/2004 - 12/2012
- $E = 10^{18.8} - 10^{19.2}$ eV
- zenith angles $[0°, 60°]$
- distances from the core, $r = 1000$ m
- 411 hybrid events after quality cuts
Muon number in hybrid events with $\theta<60^\circ$

- No energy rescaling is needed
- The observed muon signal is a factor 1.3 to 1.6 larger than predicted by models
- Smallest discrepancy for EPOS-LHC with mixed composition, at the level of 1.9 $\sigma$
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Muon Production Depth (MPD)

The muon longitudinal profile could be estimated from the muon arrival times at the ground

Two assumptions:
♦ Muons are produced in the shower axis
♦ Muons travel following straight lines

Muon production height given by:

\[ z \approx \frac{1}{2} \left( \frac{r^2}{c(t - \langle t_\epsilon \rangle)} - c(t - \langle t_\epsilon \rangle) \right) + \Delta - \langle z_\pi \rangle \]

where
\[ \langle t_\epsilon \rangle \] — mean kinematic delay
\[ \langle z_\pi \rangle \] — pion decay length

\[ \rightarrow \text{MPD} \quad X^\mu = \int_z^{\infty} \rho(z') dz' \]
Muon Production Depth (MPD)

Analysis details:

➤ data set: 01/2004 - 12/2012
➤ $E > 10^{19.3}\,\text{eV}$ (more muons/event)
➤ zenith angles [55°, 65°] (low EM contamination)
➤ distances from the core [1700 m, 4000 m]
➤ 481 events after quality cuts

➤ resolution:
100 (80) g/cm² at $10^{19.3}\,\text{eV}$ for p (Fe)
50 g/cm² at $10^{20}\,\text{eV}$

Example of a real event
with: $E = (33 \pm 1)\,\text{EeV}$
$X_{\mu \text{max}}$ vs. energy

- QGSJetII-04: data bracketed by predictions
- EPOS-LHC: predictions above data

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Comparison of $\ln A$ from $X^{\mu}_{\text{max}}$ and $X_{\text{max}}$

In $\ln A$ (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 $\sigma$

see talk by T. Pierog on EAS and pion interactions (id=803)

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Summary

Muon number measurement:

➤ we observe a muon deficit in the simulation
  ▪ similar conclusions are obtained for the events with $\theta < 60^\circ$
➤ our data disfavor light composition at $10^{19}$ eV

Muon production depth measurement:

➤ $X_{\mu_{\text{max}}}$ below prediction for iron EPOS-LHC, inconsistent with $\langle \ln A \rangle$ from $X_{\text{max}}$
➤ conclusions on composition cannot be drawn due to sys. uncertainties but discrepancy with models is large enough to put new constrains on hadronic interactions

None of the interaction models recently tuned to LHC data provides a consistent description of both the EM and muonic shower profiles as measured by Auger