AugerPrime – the Upgrade of the Pierre Auger Observatory

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Key results of the Auger Observatory

1. Very strong flux suppression
2. Top-down scenarios ruled out
3. Challenging level of isotropy (but ~7% dipole at E > 8x10^{18} eV)
4. Unexpected mass composition or change of hadronic interactions for E > 10^{18.5} eV
5. Air showers have surprisingly high number of muons (not yet understood)

(see Auger contributions to ICRC2015, arXiv:1509.03732)
New questions and puzzles

Interpretation: model scenario without GZK effect preferred, many alternative scenarios considered (neutron stars, photo-disintegration in sources, negative source evolution…)

1. Origin of flux suppression (GZK energy loss vs. maximum injection energy)
2. Proton contribution at highest energies (E > 6x10^{19} eV), particle astronomy?
3. New particle physics beyond the reach of LHC?

Auger Collab: maximum rigidity scenario

(Di Matteo, Auger, ICRC 2015)
Auger Upgrade: composition sensitivity at $E > 6 \times 10^{19} \text{ eV}$

Complementarity of particle response used to discriminate em. and muonic components

$S_{\mu,\text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}}$

$S_{\text{em},\text{WCD}} = c S_{\text{WCD}} + d S_{\text{SSD}}$

(AugerPrime design report 1604.03637)
Matrix-based muon reconstruction

(i) Single station analysis

\[ S_{\mu, \text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}} \]

(ii) Lateral distribution analysis

Resolution at \(10^{19.8} \text{ eV}\)

\[ \frac{\sigma[S_{\mu}(800)]}{\langle S_{\mu}(800) \rangle} \bigg|_{\text{proton}} \approx 22\% \]

\[ \frac{\sigma[S_{\mu}(800)]}{\langle S_{\mu}(800) \rangle} \bigg|_{\text{iron}} \approx 14\% \]

Model-independent: average muon number

Figure of merit

\[ f_{p,Fe} = \frac{|\langle S_{Fe} \rangle - \langle S_{P} \rangle|}{\sqrt{\sigma(S_{Fe})^2 + \sigma(S_{P})^2}} \approx 1.5 \]
Universality-based event reconstruction w/o FD data

(iii) Full event reconstruction

\[ S_{\text{tot}} = S_{\text{em}}(r, DX, E) + N_{\mu}^{\text{rel}} \left[ S_{\mu}^{\text{ref}}(r, DX, E) + S_{\text{em}}^{\mu}(r, DX, E) \right] + (N_{\mu}^{\text{rel}})^{\alpha_{\text{slow-energy}}}(r, DX, E) \]

Distance to ground – DX

Performance of \( X_{\text{max}} \) and muon number reconstruction (simulated)

<table>
<thead>
<tr>
<th>Model</th>
<th>Energy</th>
<th>Composition</th>
<th>Zenith angle</th>
<th>( f_{\text{MF}}^{\text{Rec}} )</th>
<th>( f_{\text{MF}}^{\text{MF}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>QGSJetII-04</td>
<td>63 EeV</td>
<td>Proton-Iron</td>
<td>21°</td>
<td>2.08</td>
<td>1.56</td>
</tr>
<tr>
<td>QGSJetII-04</td>
<td>63 EeV</td>
<td>Proton-Iron</td>
<td>38°</td>
<td>1.97</td>
<td>1.67</td>
</tr>
<tr>
<td>QGSJetII-04</td>
<td>63 EeV</td>
<td>Proton-Iron</td>
<td>56°</td>
<td>2.14</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Note: \( X_{\text{max}} \) and \( N_{\mu} \) reconstructed from surface detector data only!
Physics reach: mass sensitivity & discrimination of scenarios

Illustration with two benchmark scenarios

(note: these are not physics models)

(AugerPrime 1604.03637)
Physics reach: detection of 10% proton contribution

- Standard scenario 1 (no protons at high energy)
- Scenario 1 with 10% protons added

(AugerPrime 1604.03637)
Photon and neutrino flux limits

Expected improvements compared to current limits (ICRC 2015)

- increased exposure
- improved low-energy trigger (low-energy threshold)
- improved separation power (needs still to be evaluated)

(AugerPrime 1604.03637)
Physics reach: composition-enhanced anisotropy

Modified Auger data set 
(E > 4x10^{19} eV, 454 events, 

$X_{\text{max}}$ assignment according to 
maximum rigidity scenario

10% protons added, half of 
which from within 3° of AGNs

(AugerPrime 1604.03637)
Physics reach: generic composition-enhanced anisotropy

Generic source correlation study: 75% of the protons in the data correlate with sources, sources+correlation radius cover $p_{\text{iso}}$ of sky (folded with exposure)

Merit factor of 1.5 for discrimination light/heavy assumed

(AugerPrime 1604.03637)
Results on muon number of showers still not understood, important effect missing in models?


Example of power of upgraded detectors

Correlations between $X_{\text{max}}$ and muon density

(Allen & Farrar, 1307.7131)
Overview of AugerPrime: items needed to make things work

1. Installation of 1700 scintillation detectors (3.8 m², 1cm thick)

2. Installation of new electronics (additional channels, 40 MHz -> 120 MHz, better GPS timing)

3. Installation of small PMT in water-Cherenkov detectors for increasing dynamic range: typical lateral distance of saturation reduced from ~500 m (E > 10^{19.5} eV) to 300 m

4. Cross checks of upgraded detectors with direct muon detectors shielded by 2.3 m of soil (AMIGA, 750 m spacing, 61 detectors of 30 m², 23.4 km²)

5. Increase of FD exposure by ~50% (lowering HV of PMTs)

(AugerPrime 1604.03637)
1. Scintillation Surface Detector (SSD)

Water-Cherenkov detector (WCD)

Two modules in one box per station, readout by one PMT, area ~3.8 m²

Read-out of scintillators with WLS fibers

Both WCD and SSD to be connected to new 120 MHz electronics

Simple and robust construction of detector module and mounting frame, double roof for thermal insulation
1. Scintillation Surface Detector: construction

- Two LED flashers
- HAMAMATSU PMT 1.5" R9420
- Kuraray Y11 (300) BSJ 1mm
- 2 x 24 scintillator bars with two holes, 5x1x160 cm³
- Al profile with corner inserts
- Glued cookie
- 2 SiPMs (5x5 mm², 25 µm)
1. Scintillation Surface Detector: performance

Uniformity typically better than ±5%

30 PE per vert. MIP

Spatial resolution ~1cm
2. Upgraded unified board (UUB) and 3. Small PMT (sPMT)

- Processes signals from WCD and SSD (now 10 ADC channels)
- Increased the data quality
- Faster sampling of ADC traces, 40 -> 120 MHz
- Better timing accuracy, from 12 ns to 4 ns
- Increased dynamic range
- Enhanced the local trigger and processing capabilities (with a more powerful local station processor, FPGA)
- Improved calibration and monitoring capabilities of the surface detector stations.

Small PMT installed in un-used filling port

Use of ADC channels:
- 2 x 3 for 9" PMTs, 2 x 1 for SSD PMT, 1 for small PMT, 1 spare
4. Direct muon measurement – underground muon detectors (UMD)

MINOS type scintillator

Dow Styron 663W doped w/ PPO and POPOP

Trigger from surface detector (WCD)

Muon peak counting plus one channel integrated signal (320 MHz)

Readout by 64-anode PMT or SiPM

Module sizes: 10 m² and 5 m²
5. Extended duty cycle of fluorescence telescopes

Each ultra-high-energy shower measured with FD of great importance

Extend measurement time by reducing PMT HV (gain by factor 10 lowered)

Increase of uptime by 50% (FD shifts operated remotely)
11 Conclusions

The design of the UC muon counters has been shown to function successfully within expectations. The mechanical design of the modules has shown quality results regarding mechanical and functional stability, performance of the couplings with PMTs, light and water tightness, and temperature stability.

No major mechanical damage or module losses were suffered during the construction and deployment of the 38 modules of the UC, the twin detectors, and other prototypes.

First longitudinal and lateral muon profiles have been reconstructed and are currently under further analysis. The stable and quality performance of the AMIGA muon counters is reflected in the analysis of events recorded thus far. Important advances in the engineering of the muon counters’ logistics (i.e., fabrication procedures, transportation, and deployment techniques) have been achieved, which have allowed for much progress during the re-design phase for module mass.

2.3 m of soil (550 g/cm$^2$, $E_\mu > 1$ GeV)
Putting things together – SSD Engineering Array (i)

Engineering Array: 12 stations

- SSD w. PMT & CAEN HV
- SSD w. PMT & Isog base
- SSD w. SIPM
- Regular SD w/o SSD

- Jaco
- Generalife
- Nuria
- Cristian
- Peteroa
- Perú
- Svenja
- Ruca Malén
- Pichi Peñi Hue
- Kathy Turner
- Clais
- Trak
- Didi @Assembly Building

(SSD EA Layout - 2016-09-20)

Deployment fast: ~ 5 - 10 stations per day

2016-09-15: first station in field
Putting things together – SSD Engineering Array (ii)

SSD with PMT (R9420)

SSD peak distribution

small PMT (R8619)

SiPM (S13360-6025PE)

SSD with PMT (R9420)

small PMT (R8619)

SiPM (S13360-6025PE)
Putting things together – SSD Engineering Array (ii)

**SSD with PMT (R9420)**

![SSD with PMT (R9420)](image)

**SSD peak distribution**

![SSD peak distribution](image)

**small PMT (R8619)**

![small PMT (R8619)](image)

**SiPM (S13360-6025PE)**

![SiPM (S13360-6025PE)](image)

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**Photomultiplier**

- **Ham. R9420-100**
- **Ham. R8619**
- **Size** 1.5" 1"
- **Photocathode** super-bialkali
- **min. E**
- **effective Area [mm]**
  - 34
  - 22
- **Dynode Structure/Stages**
  - lin. focused/8
  - lin. focused/10
- **Gain**
  - 3
  - 7
  - 10
- **Supply Voltage [V]**
  - typ. 1300
  - 1000
  - max. 1500
  - 1500
- **Dark Current [nA]**
  - typ. 10
  - 2
  - max. 100
  - 15
- **Cathode Sens. [mA/W]**
  - 110
  - 90
- **Q.E. at peak wavelength**
  - 35%
  - 27%
- **Rise Time [ns]**
  - 1.6
  - 2.5

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**Entries**

- **137244**
- **Mean**
  - 0.1518
- **Std Dev**
  - 0.09242
- **χ^2**
  - 485.1 / 392
- **Constant**
  - 2.53 ± 45.32
- **MPV**
  - 0.0093 ± 0.7521
- **Sigma**
  - 0.0064 ± 0.1199
- **Constant (exp)**
  - 2.000 ± 8.677
- **Decay (exp)**
  - 0.66 ± 2.81

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![Amplitudes](image)

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**A. Castellina**

**Karlsruhe Analysis Meeting, June 2016**

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**Amplitudes**

- **Entries**
  - 137900
- **Mean**
  - 0.143
- **Std Dev**
  - 0.01138
- **χ^2**
  - 260.6 / 148
- **Constant**
  - 12.5 ± 1910
- **Gain**
  - 0.00019 ± 0.01728
- **Offset**
  - 0.0002 ± 0.1333
- **Sigma**
  - 0.000191 ± 0.003137
- **Noise**
  - 0.000199 ± 0.003743
- **Crosstalk**
  - 0.00151 ± 0.08344
Summary and outlook

Main aims of Auger Upgrade
1. Origin of flux suppression and mass composition in suppression region
2. Proton contribution of more than 10% at $E > 6 \times 10^{19}$ eV, particle astronomy?
3. New particle physics beyond the reach of LHC?

Timeline and exposure

April 2015: preliminary design report
Fall 2016: engineering array
Spring 2017-18: deployment
2019-25: data taking (40,000 km$^2$ sr yr)

Total cost (WBS): $15M

| $\log_{10}(E/\text{eV})$ | $dN/dt|_{\text{infill}}$ | $dN/dt|_{\text{SD}}$ | $N|_{\text{infill}}$ | $N|_{\text{SD}}$ |
|---------------------|----------------------|----------------------|----------------------|----------------------|
|                     | [yr$^{-1}$]          | [yr$^{-1}$]          | [2018-2024]          | [2018-2024]          |
| 17.5                | 11500                | -                    | 80700                | -                    |
| 18.0                | 900                  | -                    | 6400                 | -                    |
| 18.5                | 80                   | 12000                | 530                  | 83200                |
| 19.0                | 8                    | 1500                 | 50                   | 10200                |
| 19.5                | ~1                   | 100                  | 7                    | 700                  |
| 19.8                | ~9                   | -                    | ~60                  | ~9                   |
| 20.0                | -                    | ~1                   | -                    | ~9                   |

AugerPrime well-suited to address these questions

Similar event statistics as collected so far will be reached with upgraded detectors