Upgrade of the Pierre Auger Observatory

Karl-Heinz Kampert for the Pierre Auger Collaboration

- Why doing an upgrade?
- Technical Realisation and Expected Performance
- Timeline & Costs
Observation of Flux Suppression


\[ E^3 J(E; E > E_a) \propto E^{-\gamma} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \]

\[ E_{\text{ankle}} = 5 \cdot 10^{18} \text{ eV} \]

\[ E_{\text{50\%}} = 4 \cdot 10^{19} \text{ eV} \]

130,000 events

\[ \gamma_1 = 3.23 \pm 0.07 \]

\[ \gamma_2 = 2.63 \pm 0.04 \]
Do we see the GZK-Effect?


\[ J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \]

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

**GZK-effect**

**exhausted sources**

**p-sources**

**Fe-sources**

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p**

**He**

**N**

**Fe**

Allard et al. 2011

Auger 2013 preliminary

10^18 10^19 10^20

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p-sources**

**Fe-sources**

**k=5, 4 masses**

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

**k=5, 4 masses**

**Fe-sources**

**GZK-effect**

**exhausted sources**

**p-sources**

**Fe-sources**

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p**

**He**

**N**

**Fe**

Allard et al. 2011

Auger 2013 preliminary

10^18 10^19 10^20

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

**k=5, 4 masses**

**Fe-sources**

**GZK-effect**

**exhausted sources**

**p-sources**

**Fe-sources**

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p**

**He**

**N**

**Fe**

Allard et al. 2011

Auger 2013 preliminary

10^18 10^19 10^20

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

**k=5, 4 masses**

**Fe-sources**

**GZK-effect**

**exhausted sources**

**p-sources**

**Fe-sources**

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p**

**He**

**N**

**Fe**

Allard et al. 2011

Auger 2013 preliminary

10^18 10^19 10^20

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]

**k=5, 4 masses**

**Fe-sources**

**GZK-effect**

**exhausted sources**

**p-sources**

**Fe-sources**

\( J(E; E > E_a) \propto E^{-\gamma_2} \left[ 1 + \exp \left( \frac{\log_{10} E - \log_{10} E_{1/2}}{\log_{10} W_c} \right) \right]^{-1} \)

**p**

**He**

**N**

**Fe**

Allard et al. 2011

Auger 2013 preliminary

10^18 10^19 10^20

\( E \) [eV]

\( E^3 J(E) \) [eV^2 km^-2 sr^-1 yr^-1]
E_{\text{max}}\text{-model supported by RMS}(X_{\text{max}})\ldots

\begin{align*}
\text{PRD 2014 in press} & \\
\text{no composition data yet} & \\
\end{align*}
...and by $\langle X_{\text{max}} \rangle$
Decomposition of $X_{\text{max}}$-Distributions

- Sibyll 2.1
- QGSJET II-4
- EPOS-LHC

PRD 2014 in press

suppression region
no sign. anisotropy seen

Equatorial Coordinates - 15° smoothing

Auger & TA: 

UHECR Sky highly isotropic

hot/warm spot


TA (5σ pre-trial)

Auger (3σ pre-trial)
Science Goals of Auger Upgrade

1. Elucidate the origin of the flux suppression, i.e. GZK vs. maximum energy scenario
   ➔ fundamental constraints on UHECR sources
   ➔ galactic vs extragalactic origin
   ➔ reliable predictions of GZK $\nu$- and $\gamma$ fluxes

2. Search for a flux contribution of protons up to the highest energies at a level of $\sim 10\%$
   ➔ proton astronomy up to highest energies
   ➔ prospects of future UHECR experiments

3. Study of extensive air showers and hadronic multi-particle production above $\sqrt{s}=70$ TeV
   Need to study composition event-by-event into the flux suppression region!
assume present statistics: N=146 events (E>57 EeV), P_{iso}=0.21
and study correlation significance when protons correlate, but Fe does not

![Diagram](image-url)

white lines: contour levels at sigma = 1, 2, 3, ...

simulations by M. Unger
assume present statistics: \(N = 146\) events \((E > 57\) EeV\), \(P_{\text{iso}} = 0.21\)
and study correlation significance when protons correlate, but Fe does not
Add 20% isotropic background: catalog incompleteness, distant sources, …
assume present statistics: $N=146$ events ($E>57$ EeV), $P_{\text{iso}}=0.21$
and study correlation significance when protons correlate, but Fe does not
Add 50% isotropic background: catalog incompleteness, distant sources, …
Disentangling Int.-Models from Composition

Muon deficit in models
(see M. Unger, tomorrow)

Conservative Approach:
Composition enhanced Anisotropy does not need to know absolute \( \mu \)-numbers, just select X % of most \( \mu \)-poor an most \( \mu \)-rich events

More ambitious:
want to know if \( \mu \)-poor events are compatible with protons...
Disentangling Int.-Models from Composition

$\langle \rho_\mu \rangle$ and RMS($\rho_\mu$) in a mixed composition changes distinctly different with $X_{\text{max}}$ as compared to models of a pure p-composition.

Note: p-dominated composition at $10^{18.3}$ eV serves as benchmark for Fe at $10^{19.7}$ eV (superposition model)
Rational of Auger Upgrade

Enhancing the surface detector array for better e/µ separation will boost the science of Auger

- factor of \(\sim 10\) in statistics for composition measurements
- discriminate GZK vs maximum energy scenario
- composition enhanced anisotropy (\(\sim 10\%\) protons?)
- learn about global features of hadronic interactions at \(\sqrt{s} > 70\) TeV
- decisive prediction of UHE (cosmogenic) \(\nu\)-fluxes
- decisive for next generation UHECR Experiments

Auger Observatory is in place to address all these questions now
$N_{\mu}^{\text{max}}$ vs $X_{\text{max}}$

Muons may even outperform $X_{\text{max}}$ at highest energies!
1) New Electronics for Surface Detector
   ➞ faster sampling, better triggers, larger dynamic range, more channels

2) Enhanced Muon-Counting in Surface Detector
   Two options (out of five originally) under study:
   a) introduce vertical segmentation of tanks
   b) add scintillator on top of each tank

3) Extended operation of fluorescence telescopes
   may double observation time

4) High Precision Array with shielded muon detectors
1) New SD-Electronics

Purpose:
- facilitate the readout of new electronic channels (PMTs)
- faster sampling (40→120 MHz) for better timing and $\mu$-identification
- enhanced dynamic range (by adding a small PMT)
- faster data processing and more sophisticated triggers
- better data monitoring

- design is ready
- prototypes are now being produced
2a) Enhanced Muon Counting: LSD

a) longitudinally segmented tanks (LSD)

Linear system of equations:

\[
\begin{pmatrix}
S_{\text{top}} \\
S_{\text{bot}}
\end{pmatrix} =
\begin{pmatrix}
a_{\text{em}} & a_{\mu} \\
1 - a_{\text{em}} & 1 - a_{\mu}
\end{pmatrix}
\begin{pmatrix}
S_{\text{em}} \\
S_{\mu}
\end{pmatrix}
\]

\[
\begin{pmatrix}
S_{\text{top}} \\
S_{\text{bot}}
\end{pmatrix} \approx
\begin{pmatrix}
0.6 & 0.4 \\
0.4 & 0.6
\end{pmatrix}
\begin{pmatrix}
S_{\text{em}} \\
S_{\mu}
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
S_{\text{em}} \\
S_{\mu}
\end{pmatrix}
\]

Letessier-Selvon et al., NIM A767 (2014) 41
Figure 2: The fraction of the number of photoelectrons in the upper liner. The mean values are between the height and the radius of the tank.

In the particular case of the Auger WCD, particles entering from the side wall of the station cannot go to 1 while the radius also large so that the side contributions can still be neglected.

Cosmogenic (QGSJet II.04 [17]) as high energy interaction models and FLUKA [18] at low energy have been simulated with the CORSIKA code [15], using EPOS-LHC [16] and LSD, simulations of the detector response have been performed. Air showers from different primary type (proton, helium, nitrogen and iron) and in two energy intervals (from 8 to 13 EeV and from 40 to 60 EeV, uniformly distributed in the logarithm of energy).

The most remarkable property of the LSD is that the coefficients $a_e, a_{em}, a_{mu}$... as a fct of zenith angle... no model dependency!
Construction & Commissioning of LSD Tank
LSD Protoype Results

Reconstructed muon and electron lateral distribution

Muon peak → calibration

Figure 6: Electromagnetic and muonic LDFs for the three prototypes, derived applying a matrix with $a = 0.6$ and $b = 0.4$ to the top and bottom LDFs shown in figs 4 and 5.

Electron lateral distribution

Muon lateral distribution

Electron reconstructions

Muon reconstructions
2b) Enhanced Muon Counting: ASCII

1 cm thick scintillator read out by green WLS

ASCII: Auger Scintillator for Composition II

Scintillator on top of tank
4 m² ASCII prototype
Performance of ASCII

Method of matrix inversion works again, similar to LSD; for 4 m² ASCII:

\[
\begin{pmatrix}
S_{\text{Scin}} \\
S_{\text{WCD}}
\end{pmatrix} = \begin{pmatrix}
0.54 & 0.3 \\
0.46 & 0.7
\end{pmatrix}
\begin{pmatrix}
S_{\text{em}} \\
S_{\mu}
\end{pmatrix}
\]
Prototype experiences accompanied by detailed performance estimates

CORSIKA Shower libraries were generated with different
- energies (fixed and continuous)
- primaries
- zenith angles
- interaction models

performance then studied
- per station and
- per event

Merit Factor (discrimination power):

\[
f_{p,Fe} = \frac{|\langle S_{Fe} \rangle - \langle S_p \rangle|}{\sqrt{\sigma^2_{Fe} + \sigma^2_p}}
\]

Note: enhanced SD helps also improving photons and neutrino detection

→ M. Settimo, tomorrow
3) Extended Operation of FD-Telescopes

Present FD data taking:
- illuminated fraction of moon < 70%
- longer than 3 hrs below horizon
⇒ 22% theoretical uptime
  (-5% bad weather -2% short nights)
~ 15% effective uptime

Future plan:
- astronom. (nautical) twilight:
  sun 18° (12°) below horizon
  moon >5° from telescope
~30 % effective uptime

<table>
<thead>
<tr>
<th>condition</th>
<th>$I_A$ ($\mu A$)</th>
<th>$\sigma^2$ (ADC$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no moon</td>
<td>0.5</td>
<td>25</td>
</tr>
<tr>
<td>1/4 moon</td>
<td>5</td>
<td>250</td>
</tr>
<tr>
<td>full moon</td>
<td>50</td>
<td>2500</td>
</tr>
</tbody>
</table>

will reduce HV to reduce aging
(effective increase of threshold)

test setup to aging/noise studies
4) High Precision Complementary Array

**Primary Aims:**
- Complementary (and high-precision) measurement of $S_{em} / S_{\mu}$ for fraction of events
- Cross-check of $S_{em} / S_{\mu}$ separation of individual upgraded detector stations
- Improve understanding of particle physics models

**Particle energy spectra at 1000m**

- Electrons and photon distributions universal to very good degree
- Muon energy distribution highly variable (and model dependent)

(Simulations by Tanguy Pierog)
High Precision Array: Optimal E-range

\[ E_{\text{CM}} = 3 \cdot E_{\text{LHC}} \]

Proton dominated

Study \( X_{\text{max}} \), em-, \( \mu \)-component in detail

→ change of composition or change of hadron interaction?

\( E_p @ 5 \cdot 10^{18} \text{ eV} \) anchor point for \( E_{\text{Fe}} @ 10^{20} \text{ eV} \)

e.g. \( O(100 \text{ km}^2) \) ⇒ 30/yr @ \( \geq 10^{19} \text{ eV} \)

61 stations @ infill + 40 @ 1500 m
High Precision Array

Scintillators shielded by tank and concrete...

Two options considered

... or by 1.5 m soil
Plan for a Proposal to Upgrade the Pierre Auger Observatory

Pierre Auger Collaboration

October 28, 2013

Submitter: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martin Norte 304,
5613 Malargüe,
Argentina

Proposal for Detector Upgrade

OVERVIEW

Pierre Auger Collaboration

October 27, 2013

Submitter: Pierre Auger Collaboration
Observatorio Pierre Auger,
Av. San Martin Norte 304,
5613 Malargüe,
Argentina
### Time Line

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science Proposal subm.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Review of Science Proposal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototyping in field</td>
<td></td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
</tr>
<tr>
<td>Selection of Prototype</td>
<td></td>
<td>⨲</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submission of TDR</td>
<td></td>
<td></td>
<td></td>
<td>⨲</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>⨲</td>
<td></td>
</tr>
<tr>
<td>Seeking funds / construction</td>
<td></td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
<td>⨲</td>
</tr>
<tr>
<td>take data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>upgrade finished</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>⨲</td>
</tr>
</tbody>
</table>

- Selection of full array upgrade option very soon
- Data taking into 2023 will double the statistics of all data up to 2015
Estimates of Costs (investment and personnel)

WBS-Estimates: ~ **10-12 M€**

This includes (at least part of) prototyping and engineering

Nearly all of the materials, services and effort to implement the upgrade will be provided by in-kind contributions from the collaborating countries

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Funding Upg (M€)</td>
<td>0,0</td>
<td>0,5</td>
<td>4,0</td>
<td>4,0</td>
<td>2,5</td>
<td>0,5</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
<td>0,0</td>
<td>11,5</td>
</tr>
<tr>
<td>Operation (M€)</td>
<td>1,4</td>
<td>1,4</td>
<td>1,5</td>
<td>1,5</td>
<td>1,6</td>
<td>1,6</td>
<td>1,6</td>
<td>1,6</td>
<td>1,6</td>
<td>1,6</td>
<td>1,6</td>
<td>16,9</td>
</tr>
<tr>
<td>Researchers</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>525</td>
<td>16,9</td>
</tr>
<tr>
<td>Engineers (FTE)</td>
<td>1,5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1,5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
</tbody>
</table>
Summary: Auger Upgrade

Precise UHECR measurements lead to many surprising results and new questions

Need to resolve open puzzles

Observatory in unique position and collaboration is ready to go

Decisive for future experiments