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Towards AugerPrime: the upgrade of Pierre Auger Observatory

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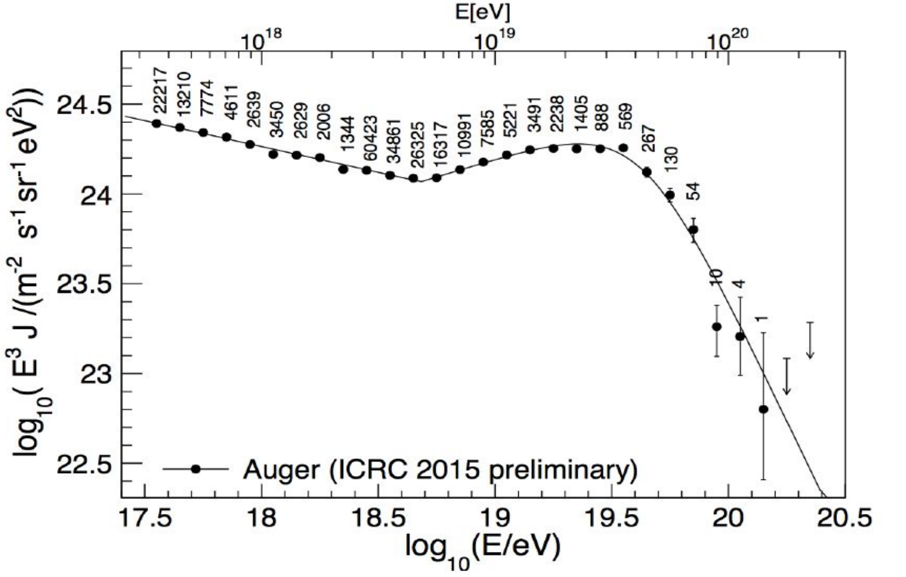
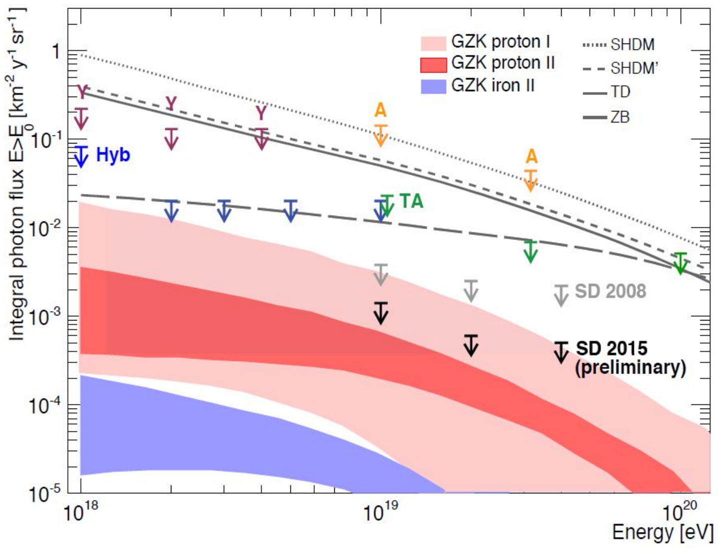
Scientific results from the PAO

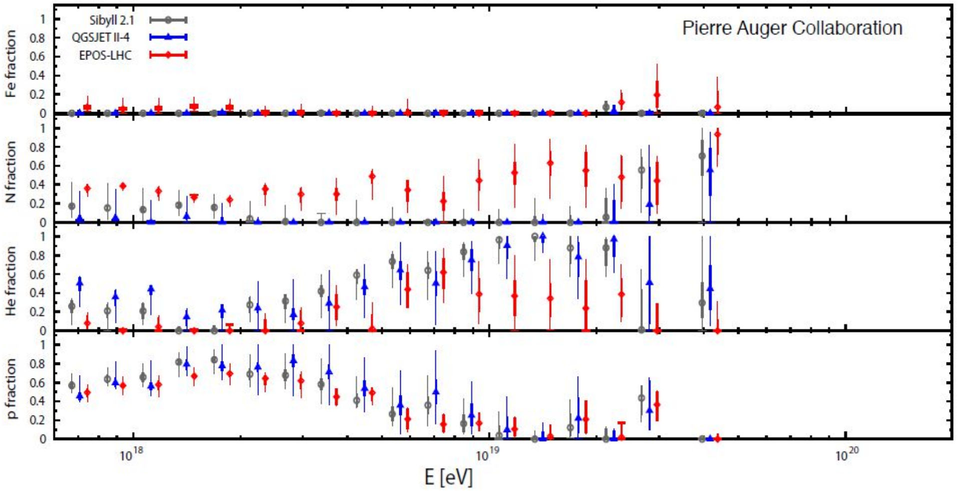
(see *M. Bohacova talk*)

Strong flux suppression above 5×10^{19}eV



Photon and neutrino upper limits
(exclusion of top-down models)





Mass composition change
(but no data above 5×10^{19} eV)

The upgrade Science Case

The data collected after 2017 must provide additional measurements to allow us to address the following key objective:

1. The mass composition and the origin of flux suppression at the highest energies
   - Understanding the origin of the flux suppression will provide fundamental constraints on the astrophysical sources and will allow a more reliable estimates of neutrino and gamma-ray fluxes at UHE.
2. Proton contribution in the flux suppression region ($E > 5x\ 10^{19}$ eV)
   - Estimate the physics potential of existing and future cosmic ray, neutrino and gamma-ray detectors; Search of proton astronomy
3. Fundamental particle physics at energies beyond reach of man-made accelerators.
   - Study extensive air showers and hadronic multiparticle production.

Mass composition measurement above 5×10^{19} eV with a sensitivity to the proton flux as small as 10%.

The strategy

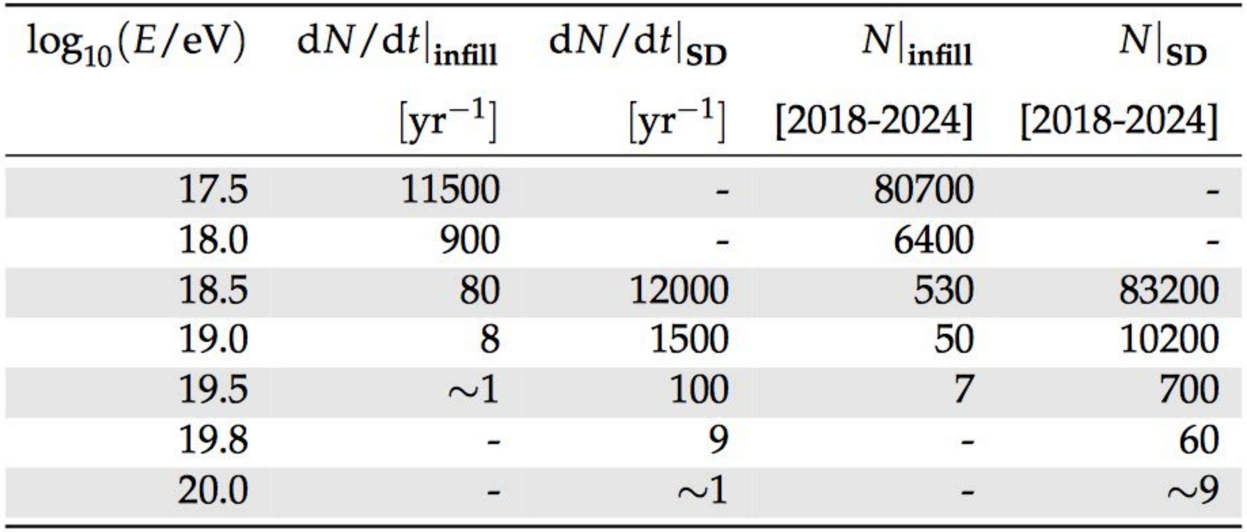
Measure with the Pierre Auger Observatory until 2025.

(MOUs have been signed in Nov 2015)

Proposed upgrades:

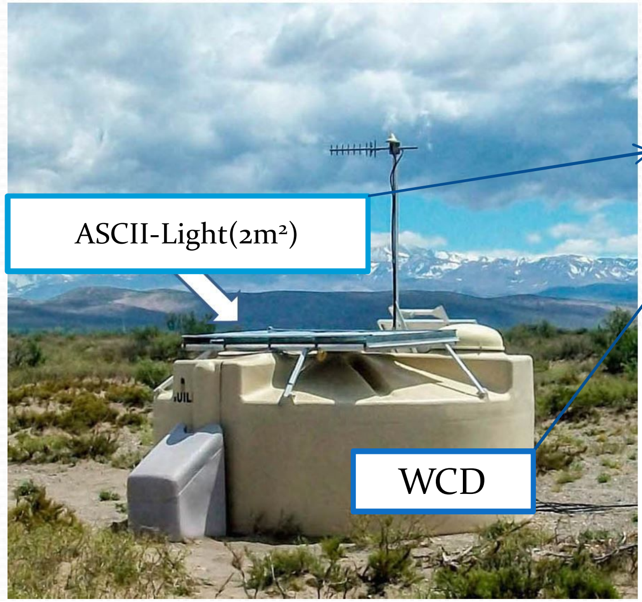
1. Scintillator SD (SSD) to measure the mass composition with 100% duty cycle
2. Upgrade Surface Detector (SD) electronics and introduce a small PMT
3. Underground Muon Detector with AMIGA to have a direct muon measurement
4. Extended FD operation

Event statistics for the upgraded array in a data taking period from 2018-2024 (events up to zenith angle θ<60°) for both the 750 m array and the 1500 m array.



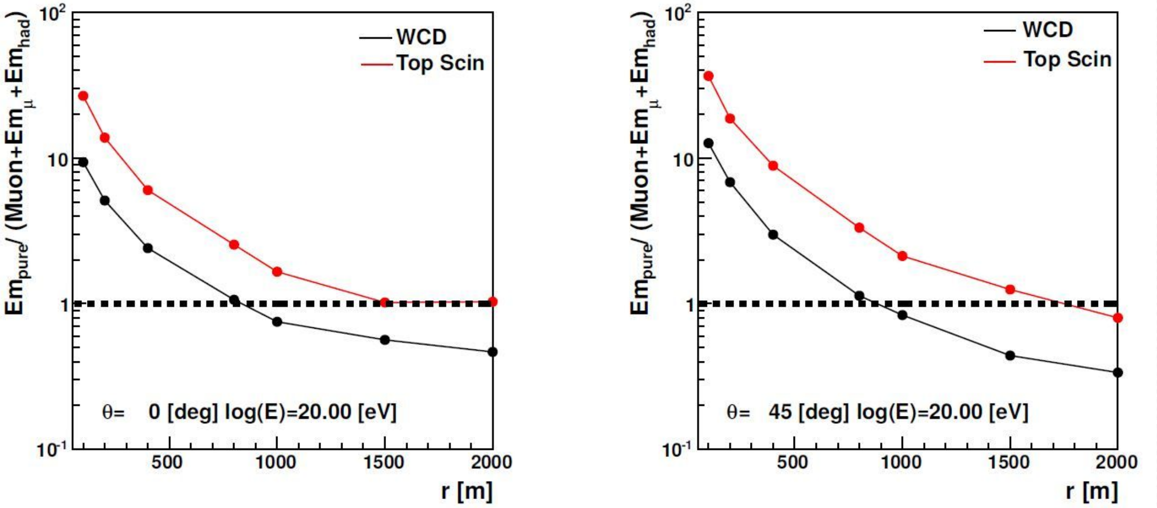
$\log_{10}(E/\mathrm{eV})$	$\mathrm{d}N/\mathrm{d}t\vert_{\text{infill}}$ [yr^{-1}]	$\mathrm{d}N/\mathrm{d}t\vert_{\text{SD}}$ [yr^{-1}]	$N\vert_{\text{infill}}$ [2018-2024]	$N\vert_{\text{SD}}$ [2018-2024]
17.5	11500	-	80700	-
18.0	900	-	6400	-
18.5	80	12000	530	83200
19.0	8	1500	50	10200
19.5	$\sim$1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

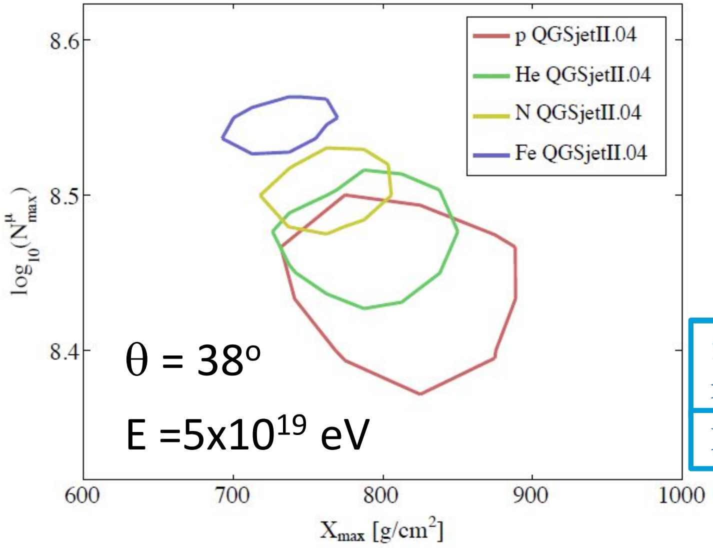
Scintillator Surface Detector Measurement



100% duty cycle

Complementarity of particle response used to discriminate electromagnetic and muonic components of air showers

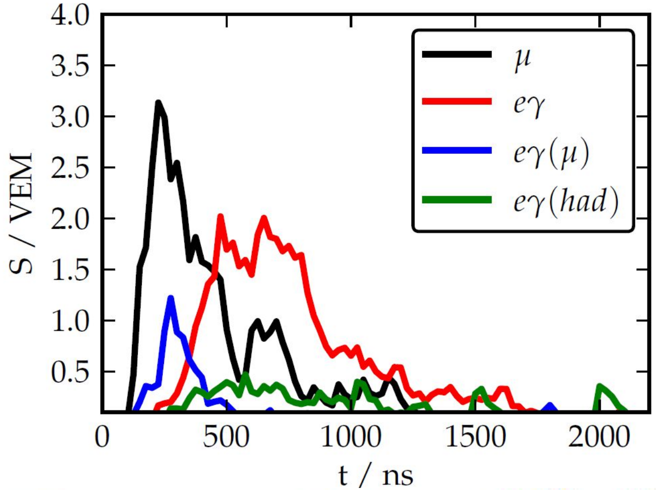




1σ contour of the number of muons at maximum of the muon shower development

Measure muon component for composition

SSD Measurement: Universality approach



The shower universality method **predicts for the** entire range of **primary masses the air-shower** characteristics on the ground **using only three** parameters: ***E, Xmax and Nµ***

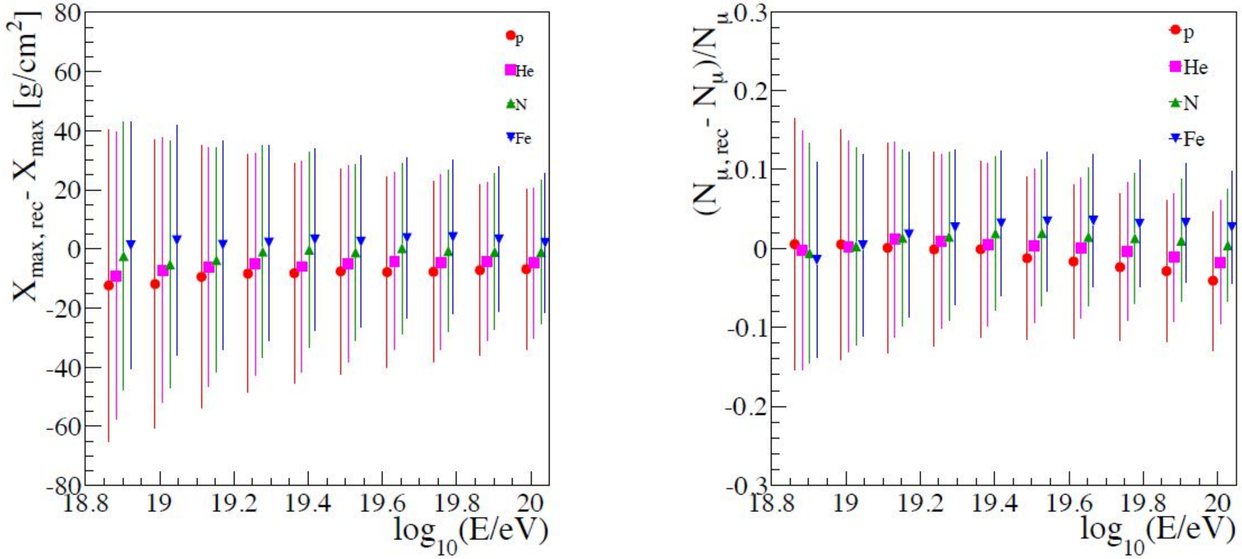
The parameter could be **estimated from the integrated signal and the temporal structure** of the signal measured in individual stations. Event by event basis

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

Applying the Universality method it is possible to take into account the **correlation between the WCD and the SSD. The parameters now are more (**Xµmax ,Xmax, Nµ) in the model.

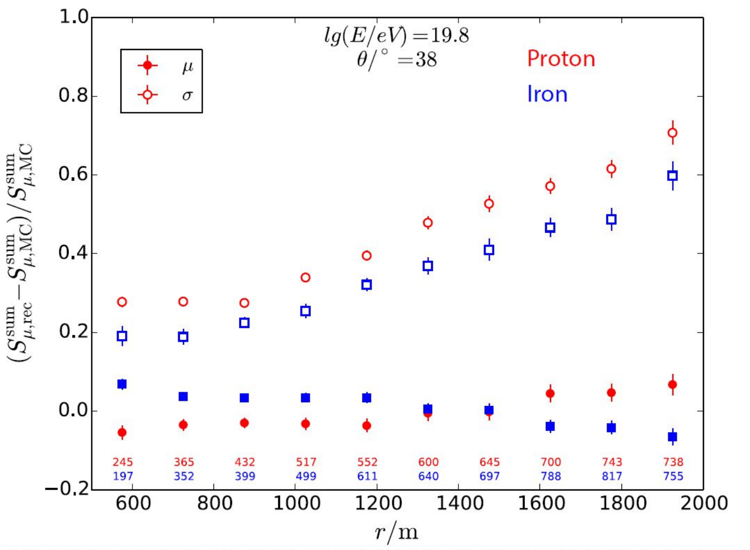
This allows a measurement of the **number of muons on a event by event basis and the relation** between Xµmax ,Xmax and Nµrel can be calibrated.

The **resolutions of the method are obtained from parameterizations and interpolations of EPOS-LHC** simulations at fixed energies and zenith angles and are shown for events up to 60º.



SSD: Matrix Inversion Method

Single Station Analysis

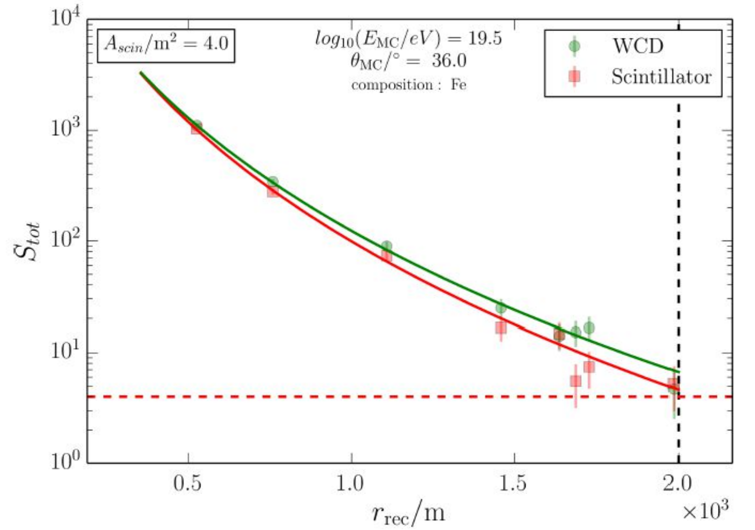


$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

Lateral Distribution Analysis

A **parameterization of the LDF for the SSD** was done using simulation.

Simulated Fe LDFs fit for WCD and SSD

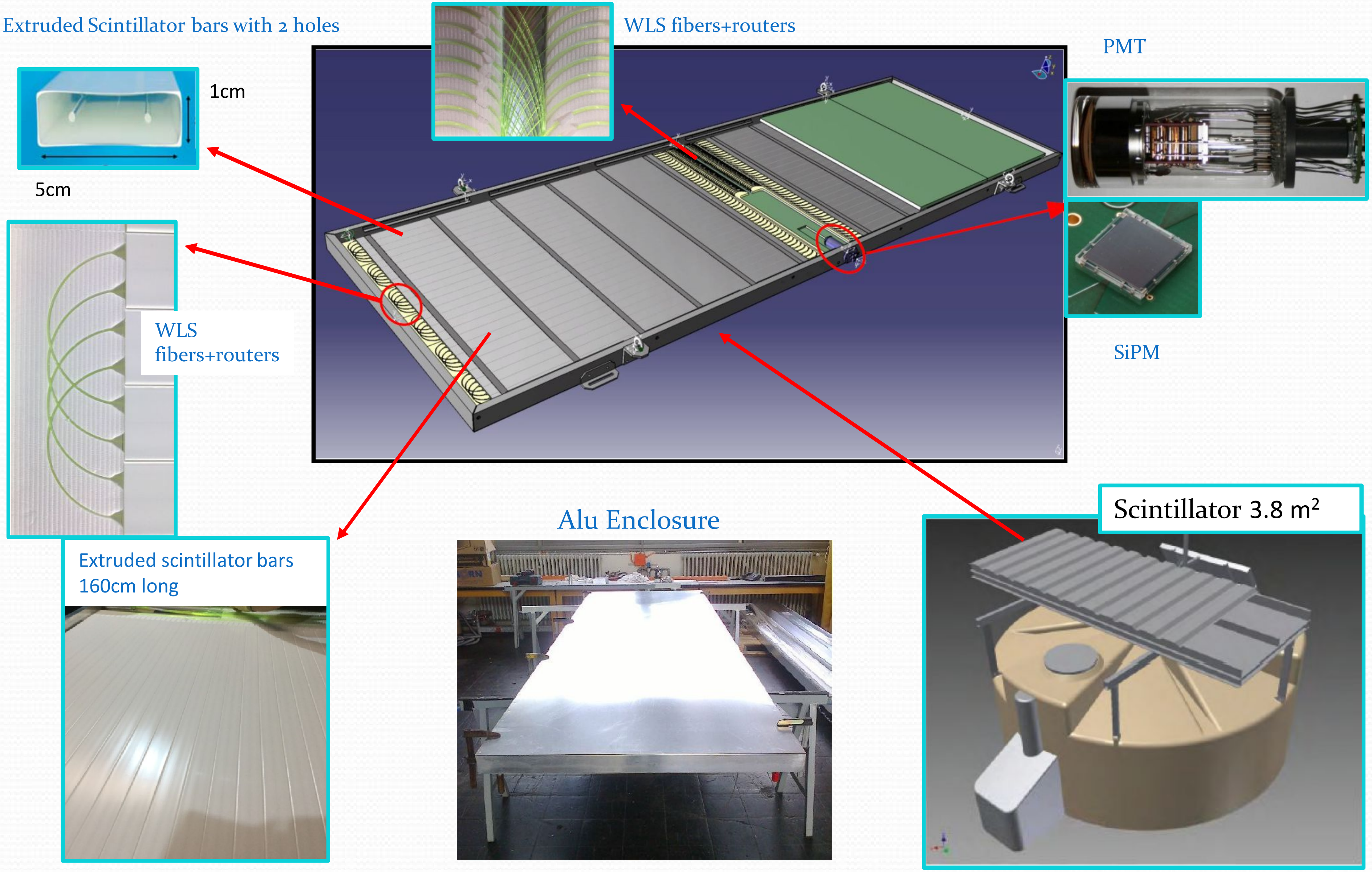


The **matrix inversion algorithm is then applied** to the LDF values for the WCD and SSD to calculate the **muonic signal expected in a WCD at 800 m core distance**, *Sμ(800)*.

$$f_{\mathrm{p,Fe}} = \frac{|\langle S_{\mathrm{Fe}}\rangle - \langle S_{\mathrm{p}}\rangle|}{\sqrt{\sigma(S_{\mathrm{Fe}})^2 + \sigma(S_{\mathrm{p}})^2}} \sim 1.5$$

Figure of merit

SSD:The detector



Extruded Scintillator bars with 2 holes

1cm

5cm

WLS fibers+routers

PMT

SiPM

WLS fibers+routers

Extruded scintillator bars 160cm long

Alu Enclosure

Scintillator 3.8 m^2

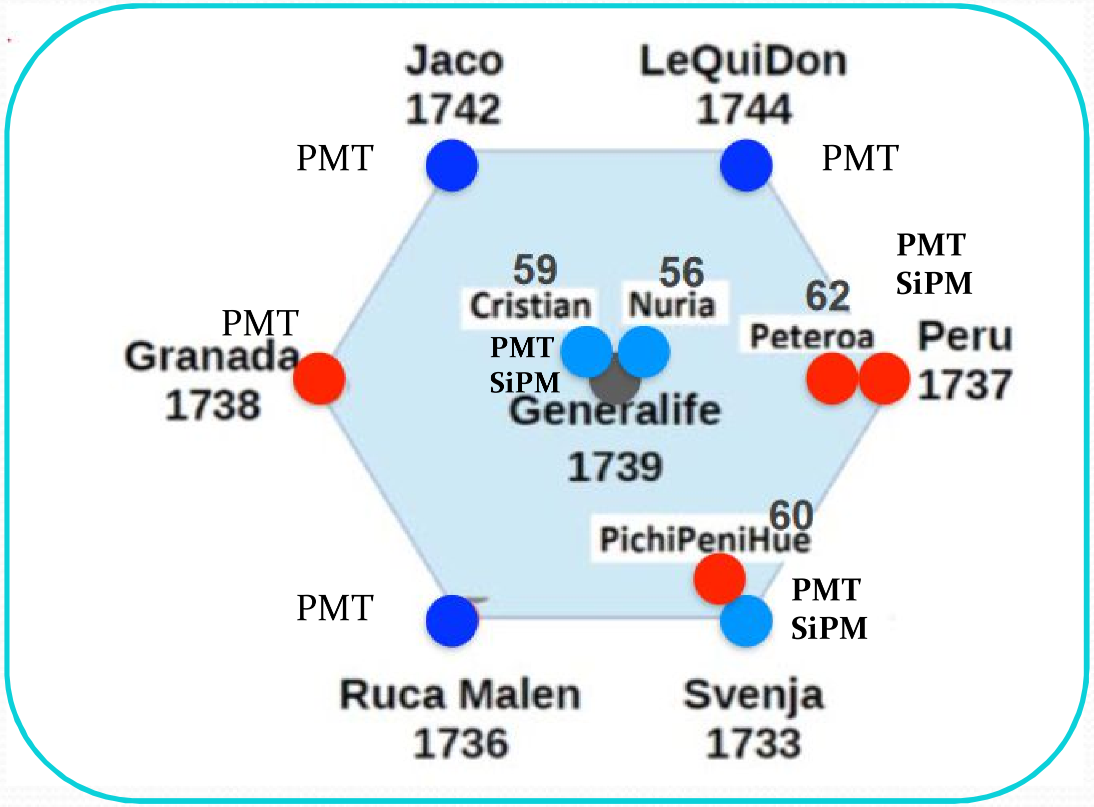
SSD:The Engineering Array

12 SSD EA Module ready!
On their way to PAO.

Located in infill array

Infill
● PMT
● PMT

Located in standard array



Twin stations will allow to verify particle number resolution

SD Electronics

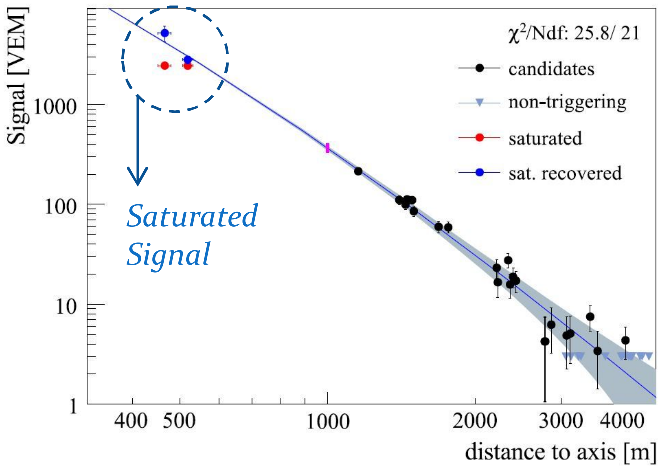
Auger electronics based on a 15 years old design

1. Increase of the data quality (better timing, dynamic range and μ identification):
    a) faster sampling of ADC traces (40 → 120 MHz)
    b) more precise absolute timing accuracy (new GPS receiver)
    c) increase the dynamic range by adding a 1” PMT (SD PMTs are 9”) small PMT
2. Faster data processing and more sophisticated local triggers
    a) more powerful processor and FPGA
3. Improved calibration and monitoring capabilities
4. New components:
    1. Connection to the SSD and any additional (R&D) detectors
    2. Prolong lifetime and reduce failure rate

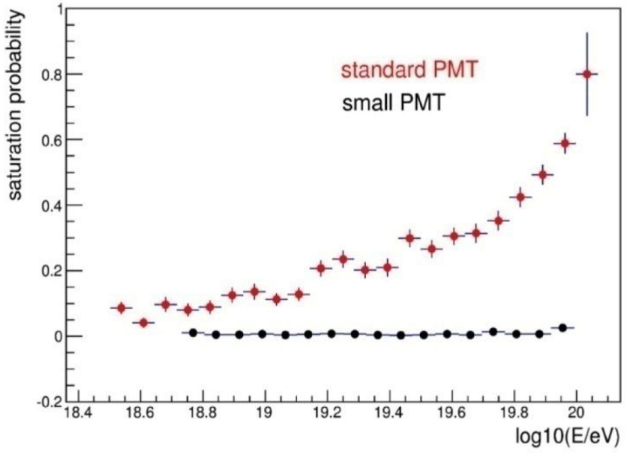
Can be swapped in place with old design
(same power communications, hardware interfaces…)

The Upgrade Unified Board (prototype)

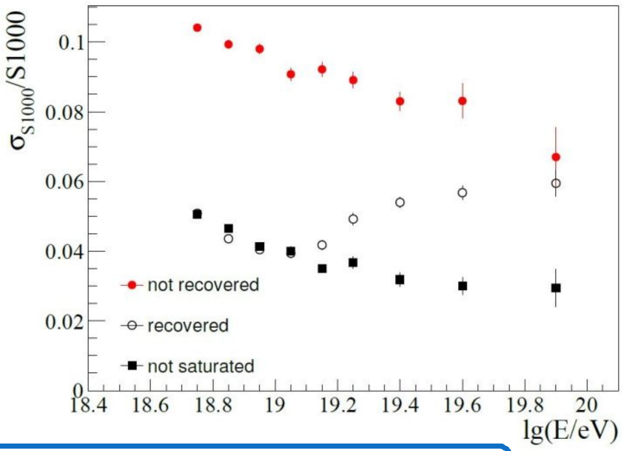
SD Electronics: small PMT



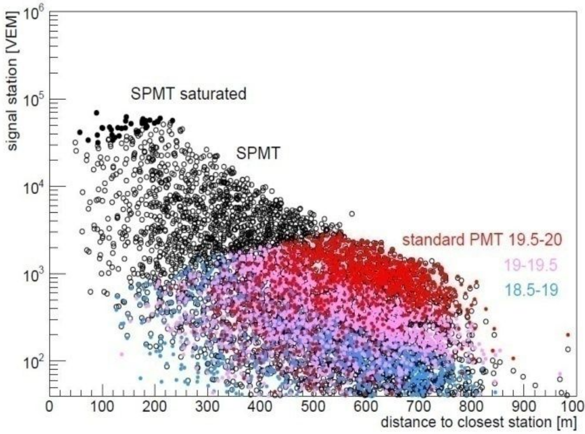
Lateral Distribution of the signal sizes recorded in SD detectors



Probability of having at least one saturated station in an event as function of energy, obtained from simulation for standard and small PMT



Resolution of the Reconstructed S(1000)



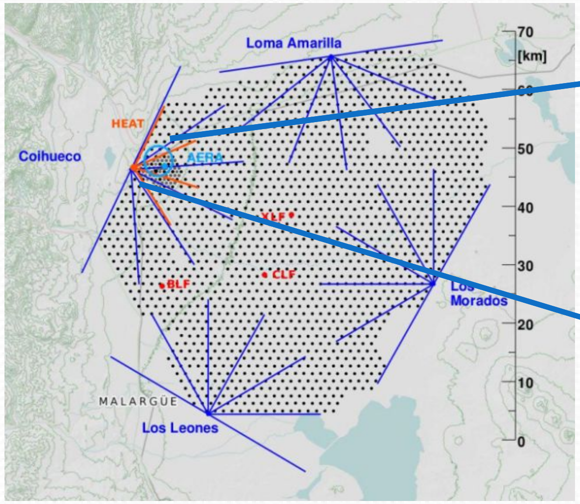
The distribution of the expected signals as a function of the distance between the shower axis and the closest SD station

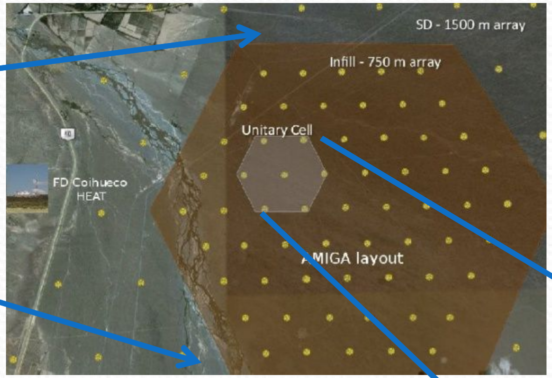
The Underground Muon Detector

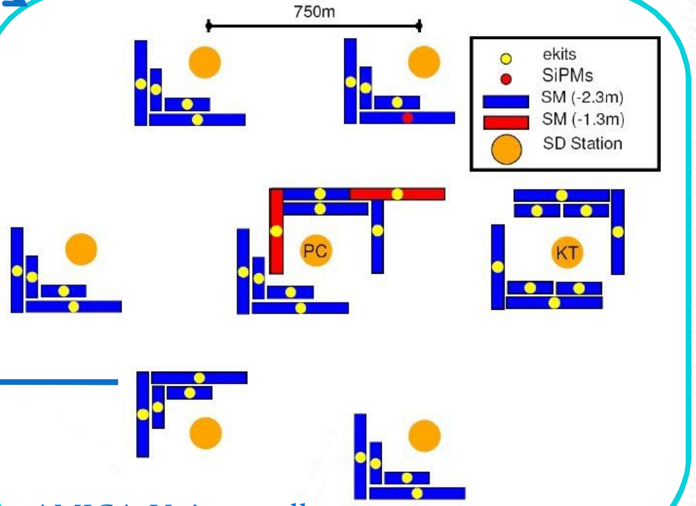
The UMD is required in the existing SD infill area of 23.5 km² in order to provide important direct measurements of the shower muon content and its time structure while serve as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements.

61 AMIGA muon detectors (30 m²) are planned to be deployed on a 750m grid (a total area of 23.5 km²)

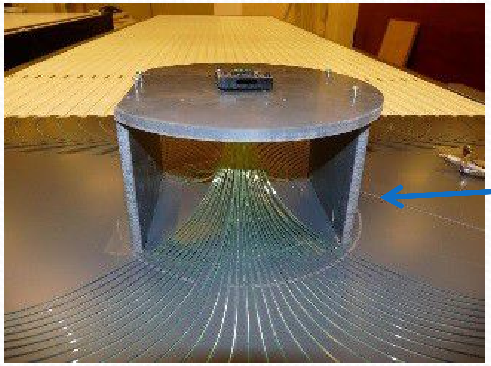
AMIGA layout: an infill of surface stations with an inter-detector spacing of 750 m. Plastic scintillators of 30m² are buried under 280 g/cm² of vertical mass to measure the muon component of the showers. The Unitary Cell indicates the prototype area of the muon detector.







AMIGA-Unitary cell



Fluorescence Detector Operation

- The FD provides exceptional information about extensive air showers (model-independent energy reconstruction and direct measurement of the longitudinal development profiles)
- The main limitation of the FD is the duty cycle, currently at the level of 15%.

Duty cycle 15%

↓

Increase by 50%

Increase the exposure for cosmic ray events above 10^{19} eV by extending the FD measurement into hours with high night sky background (NSB)

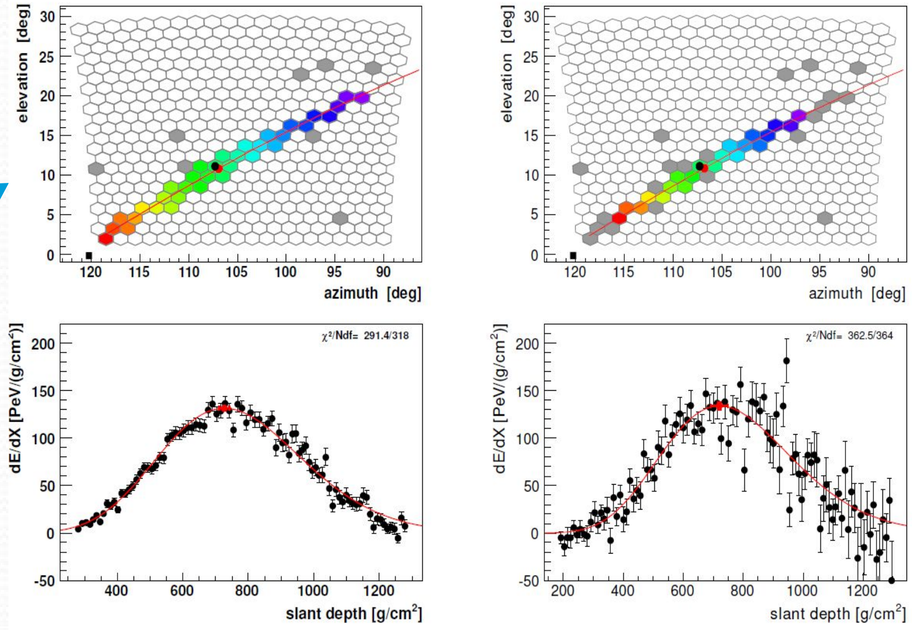
A significant increase of the duty cycle is possible by the extension of the FD operation to times at which a large fraction of the moon in the sky is illuminated. During such operations the PMT gain must be reduced (lower HV) to avoid an excessively high anode current.

10x reduced PMT gain by reducing supplied HV

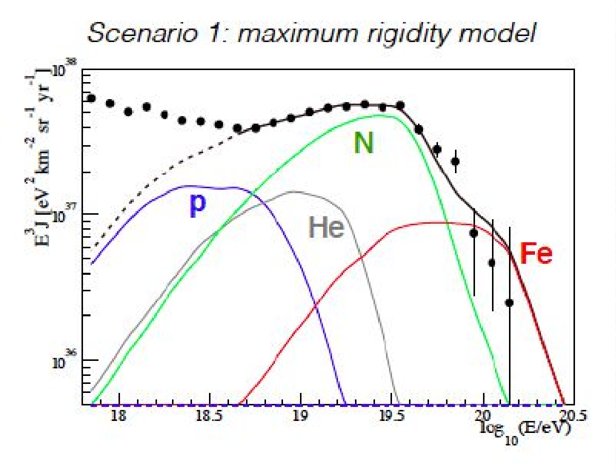
satisfy linearity, stability and lifetime

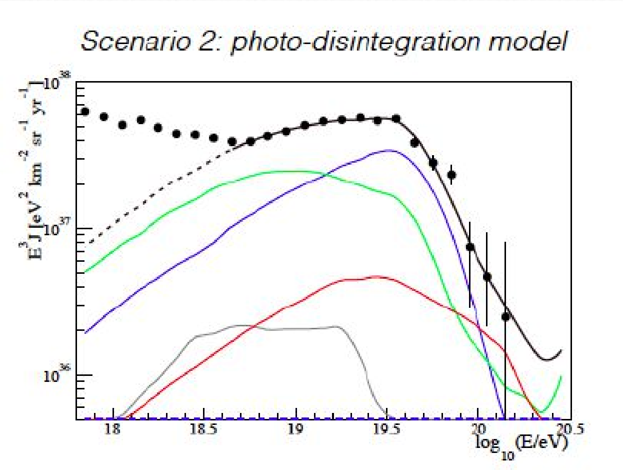
Existing measured air showers have been analyzed with the standard reconstruction chain after adding random noise to the ADC traces.

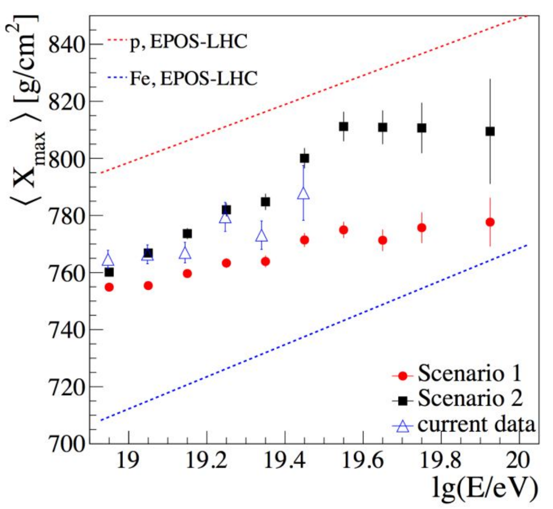
keep very high selection efficiency and reconstruction.

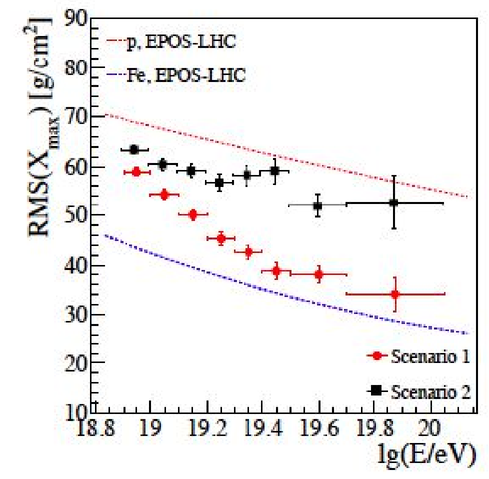


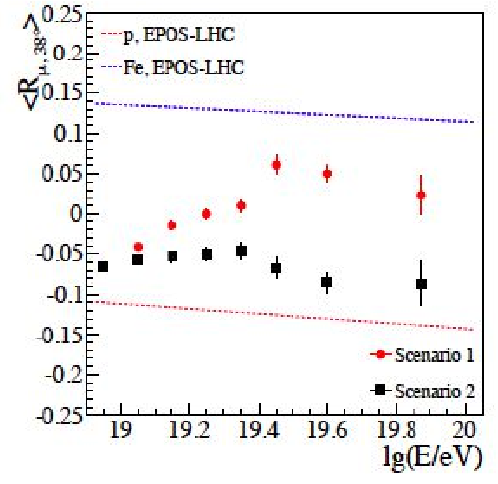
Science Impact of upgrade


Scenario 1: maximum rigidity model


Scenario 2: photo-disintegration model

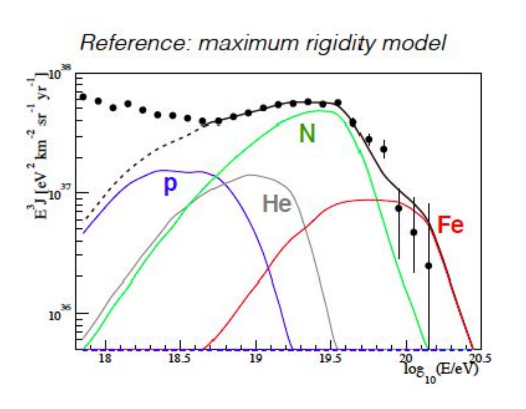




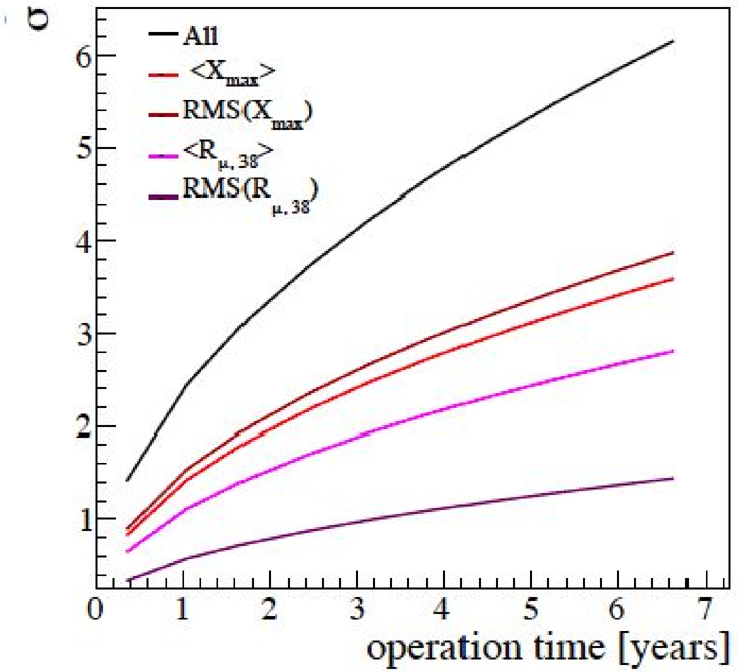


Science Impact of upgrade

- Physics reach: detection of 10 % proton contribution
- Significance of distinguishing scenarios with and without 10% of protons



•Standard scenario 1 (almost no protons)
• Scenario 1 with 10 % protons added



Timeline for new SDE and SSD

- July 2016: Engineering Array (12 stations) ready!
- Nov 2016: Evaluation of detectors
- 2017-2018: Deployment
- Till 2025: Data taking (up to 40,000 km^2 sr yr)
- Similar event statistics as collected so far will be reached with upgraded detectors.

Summary and Outlook

- AugerPrime will allow a study of mass composition above 5×10^{19} eV and address:
  - Origin of the flux suppression (GZK energy loss Vs. maximum energy of sources)
  - Proton contribution of more than 10% above 5×10^{19} eV?
    (particle astronomy, GZK γ and ν fluxes → future experiments)
  - New particle physics beyond the reach of LHC?

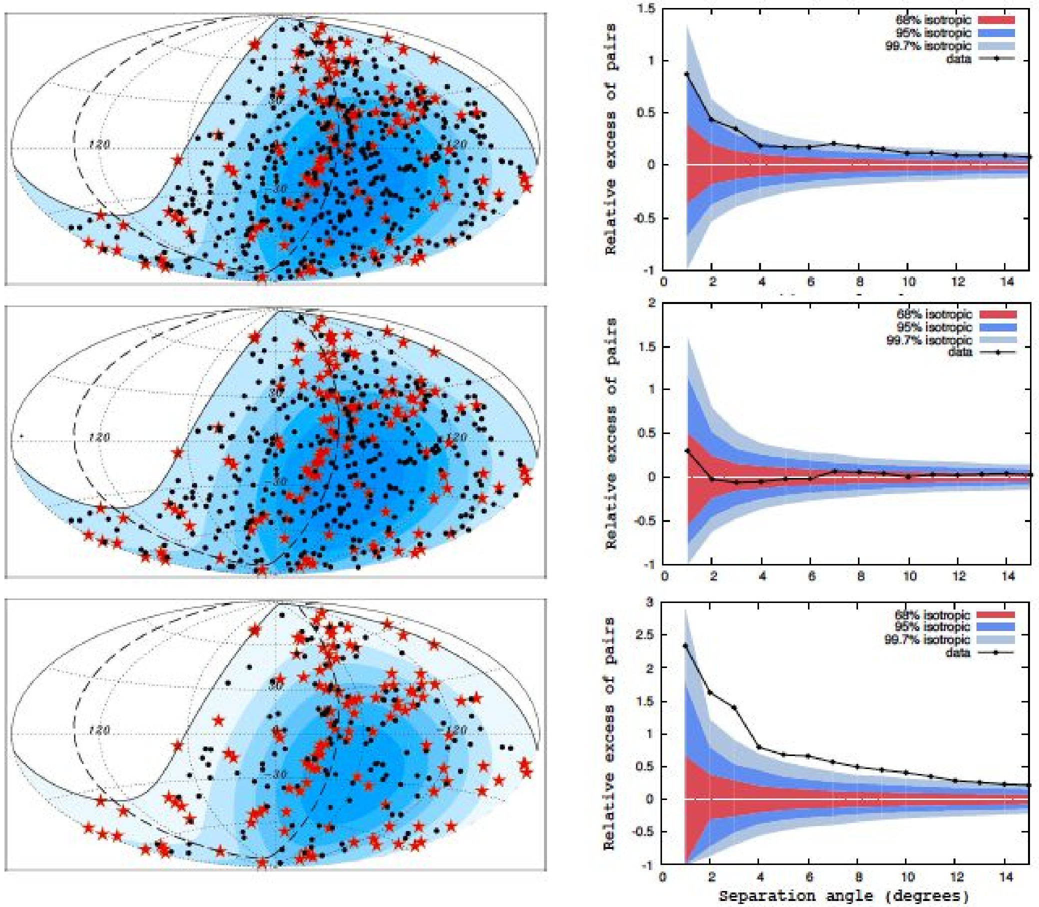
Backup slides

Science Impact of upgrade: composition-enhanced anisotropy

Modified Auger data set
($E > 4 \times 10^{19}$ eV, 454 events)

X_{max} assignment according to maximum rigidity scenario

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



all 454 events

proton depleted data set (326)

proton enhanced data set (128)

Science impact of upgrade: photon and neutrino flux limits

Expected sensitivity on the flux of photons and neutrinos.
In addition to the conservative estimates based on the increase of statistics, also the projected photon sensitivity for the ideal case of being able to reject any hadronic background due to the upgraded surface detector array is shown.