14th-16th September 2015, Gallipoli, ITALY

Cosmic Ray International Seminar 2015

The Pierre Auger Observatory Upgrade Program

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Pierre Auger Collaboration

Istituto Nazionale di Fisica Nucleare

PIERRE AUGER OBSERVATORY

NIM A 798 (2015) 172–213

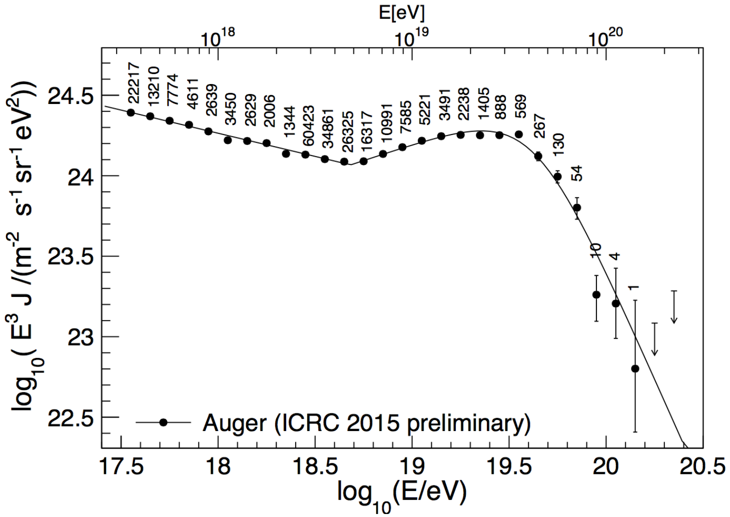
Outlook

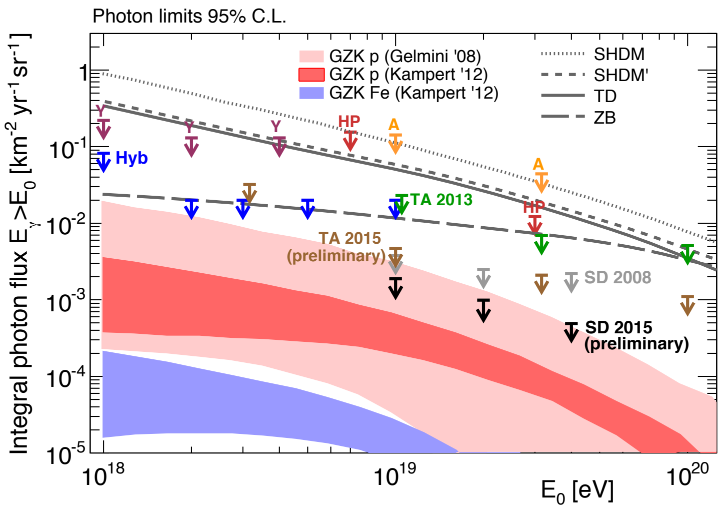
- Key results
- New questions and open challenges
- Auger Upgrade program
  - **S**cintillator **S**urface **D**etector
  - Surface Detector Upgrade
  - **U**nderground **M**uon **D**etector
  - Fluorescence Detector DAQ extension time
- AUGER PRIME performances

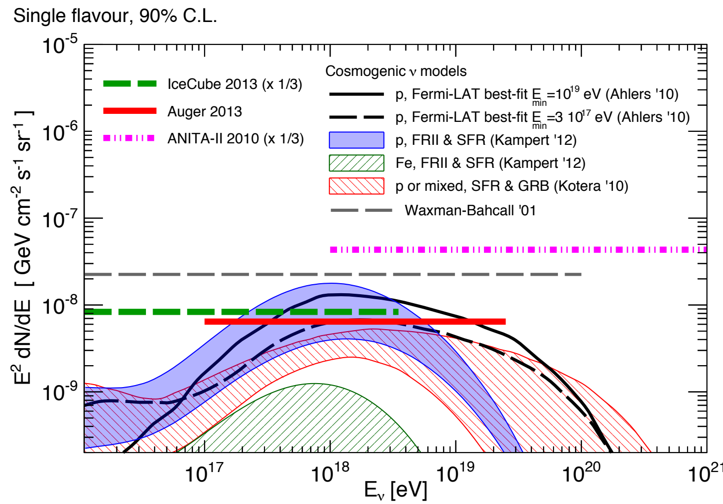
Present results from the Pierre Auger Observatory

- The suppression of the flux around 5×10^{19} eV

- Strong limits have been placed on the photon and neutrino components of the flux indicating that "top-down" source processes, such as the decay of super-heavy particles, cannot account for a significant part of the observed particle flux.







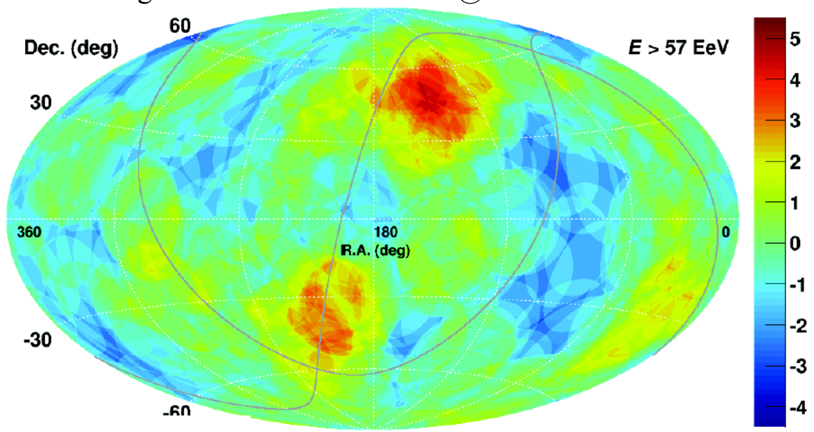
PRD 91 (2015) 092008

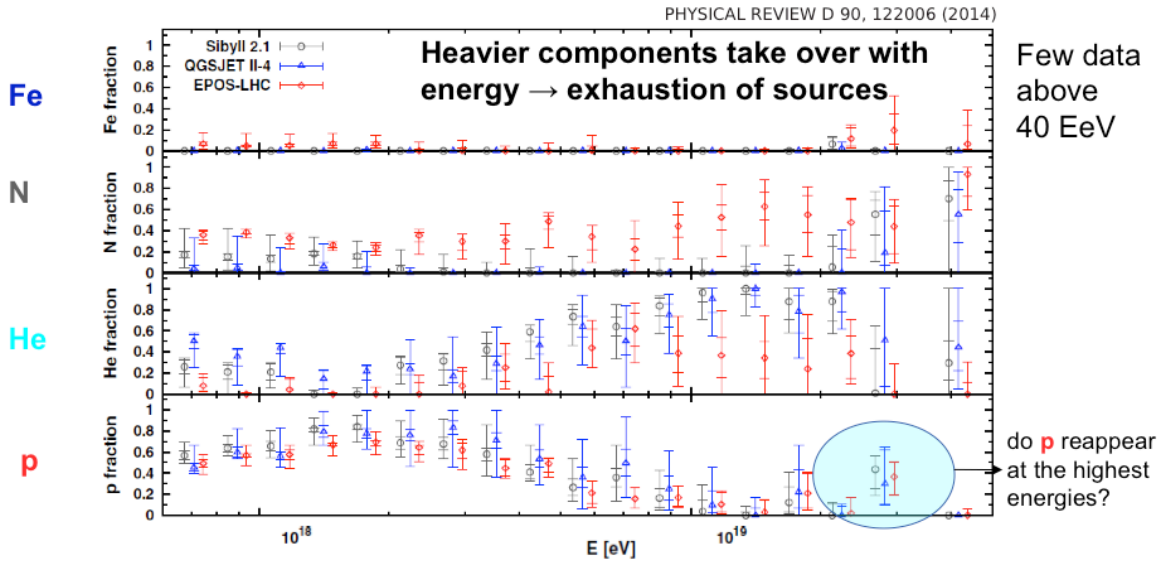
(**Highlights from the Pierre Auger Observatory** Prof. Stephane Coutu this conference)

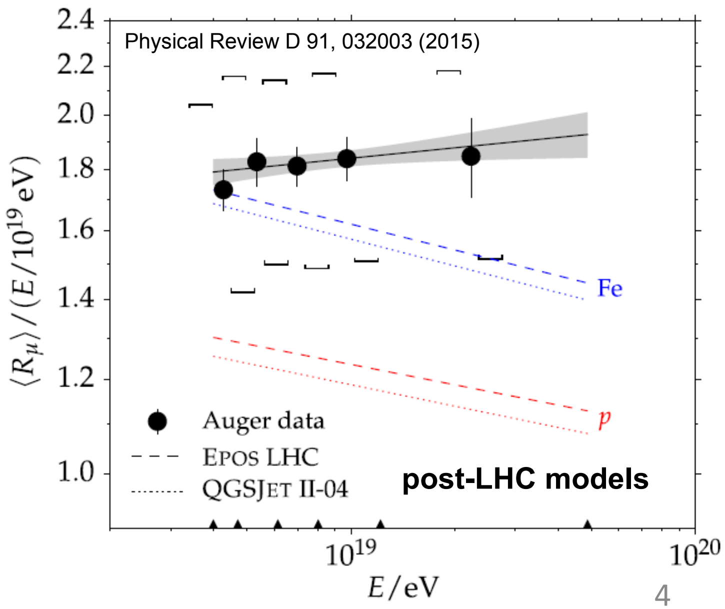
Present results from the Pierre Auger Observatory

- A large-scale dipole anisotropy of about 7% amplitude has been found for energies above 8x10^{18} eV.
- In addition there is an indication a large scale anisotropy below the ankle.
- Unexpected mass composition or change of hadronic interactions for E > 10$^{18.5}$ eV
- Air showers have surprisingly high number of muons respect the models.

Auger and TA Collaborations @ **ICRC 2015**







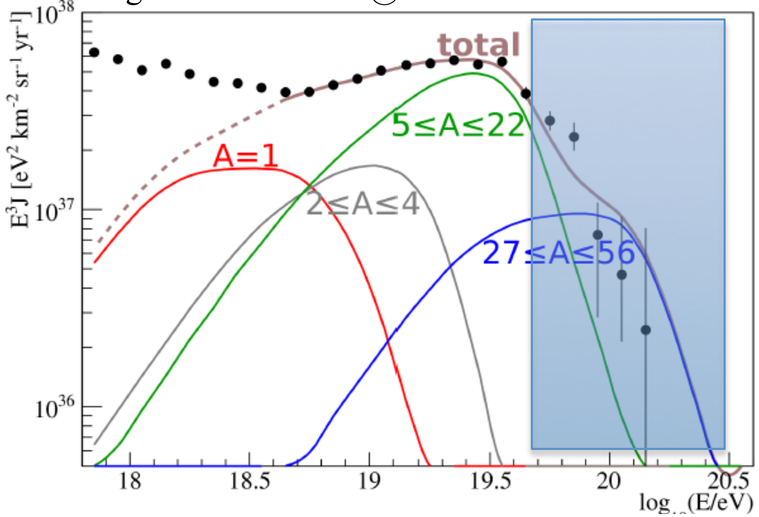
Motivation for the upgrade of the Pierre Auger Observatory

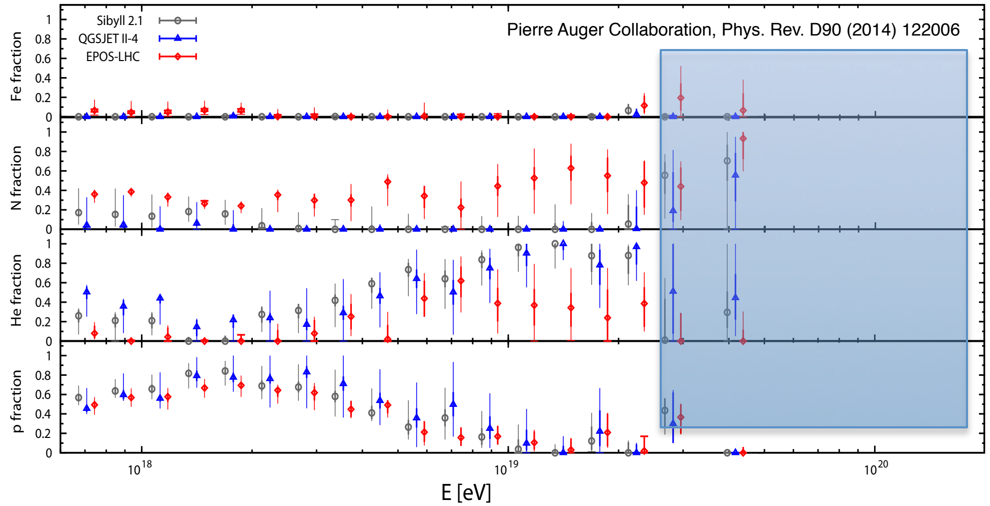
- Explain the mass composition and the origin of the flux suppression at the highest energies, (energy loss effects due to propagation vs the maximum energy of particles injected by astrophysical sources).

- We aim to reach a **sensitivity to a contribution as small as 10%** in the flux suppression region.

- Measurement of **the fraction of protons is the decisive ingredient for estimating the physics potential of existing and future cosmic ray**, neutrino, and gamma-ray detectors.

Auger Collaboration @ **ICRC 2015**





Motivation for the upgrade of the Pierre Auger Observatory
AUGER PRIME

Primary cosmic **R**ay **I**dentification with **M**uons and **E**lectrons

- Operation planned until 2024, event statistics will more than double compared with the existing Auger data set, with the critical added advantage that every event will now have mass information.

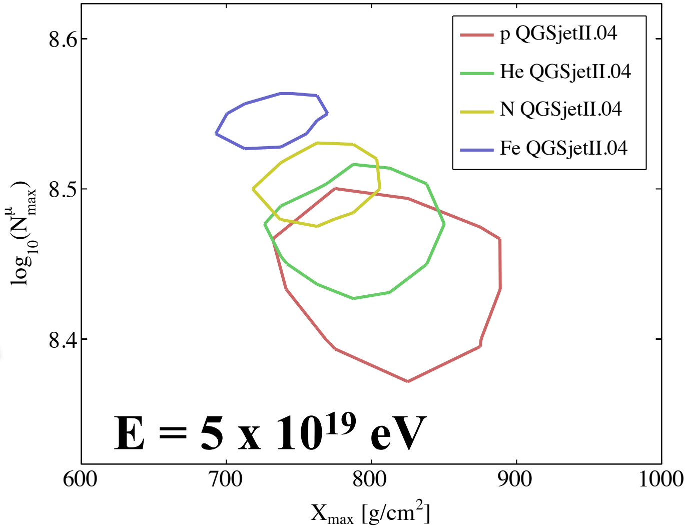
- Obtaining additional composition-sensitive information will not only help to better reconstruct the properties of the primary particles at the highest energies, but also improve the measurements in the important energy range just above the ankle .

- New detectors will help to reduce systematic uncertainties related to modeling hadronic showers and to limitations of reconstruction algorithms.

- This improve the knowledge on the air shower physics.

The upgrade of the Pierre Auger Observatory

100%



15%

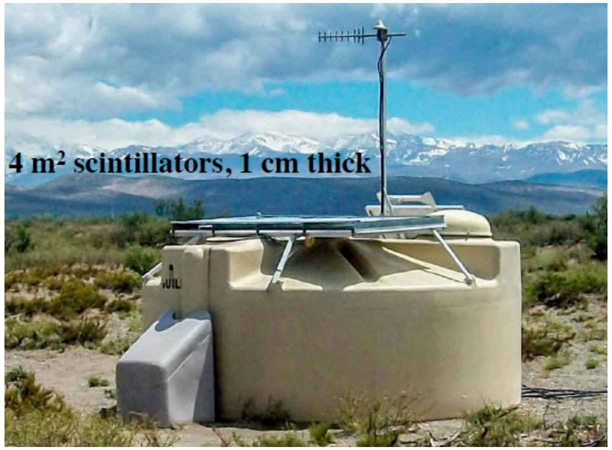
- To obtain this sensitivity it's necessary to discriminate the e.m. and the muonic components in the air shower.
  - Installing a Scintillator Surface Detector (SSD)
  - Upgrading the Surface Detector Elettronics Upgrade (SDEU)
  - Installing a small PMT to increase the dynamic range
  - Installing a sub array of Underground Muon Detector (UMD) to check the method.

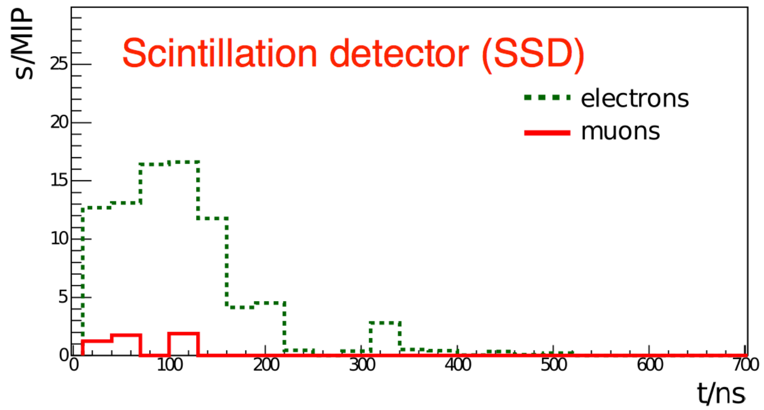
- Increase the FD statistics.

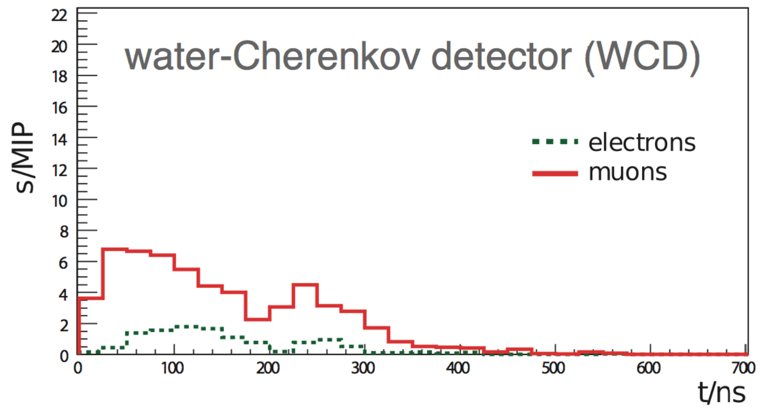
The Surface Scintillator Detectors (SSD): Methodology

- A complementary measurement of the shower particles will be provided by a plastic scintillator plane above the existing Water-Cherenkov Detectors (WCD).

- This allows the sampling of the shower particles with two detectors having different responses to muons and electromagnetic particles.

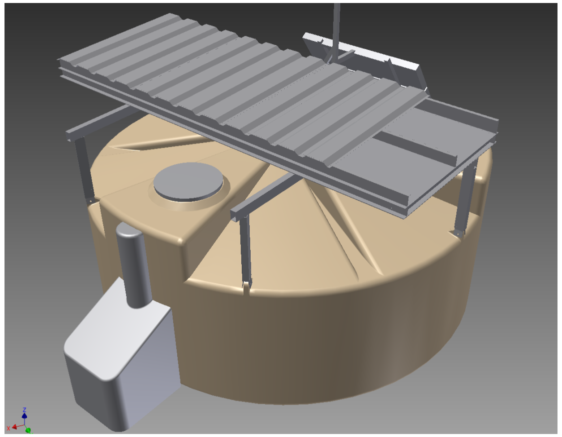


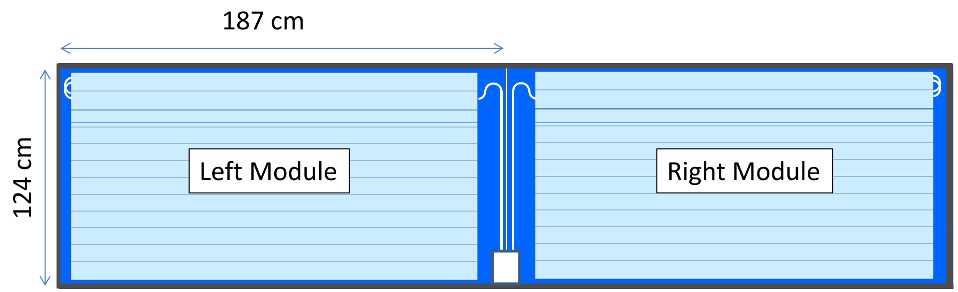




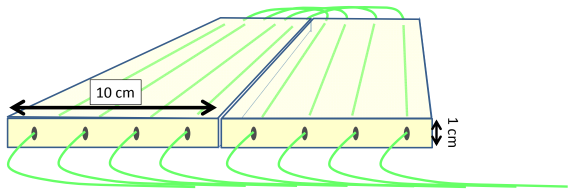
$$S_{\mu,\mathrm{WCD}} = a\,S_{\mathrm{WCD}} + b\,S_{\mathrm{SSD}}$$

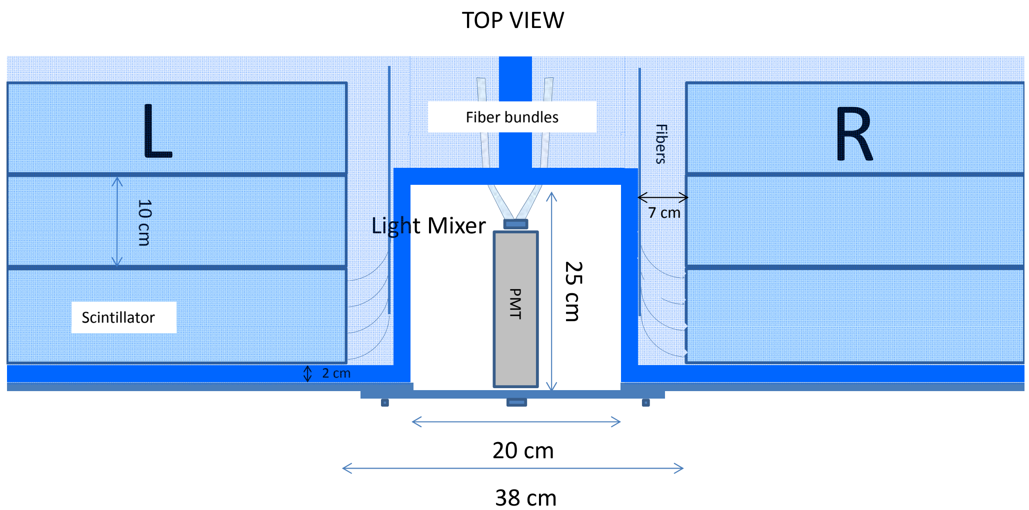
The Surface Scintillator Detectors (SSD): The detector

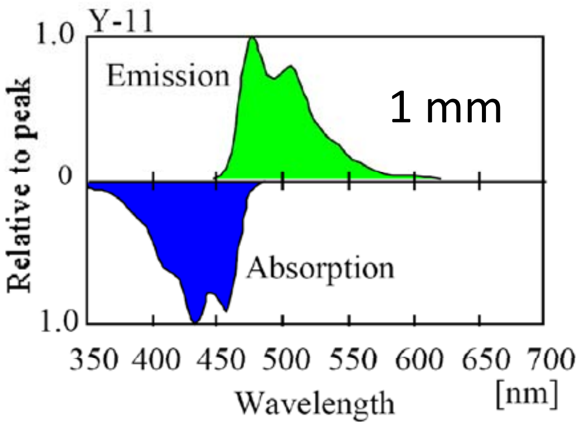




Schematic view of the two modules in the extruded polystyrene foam vessel.





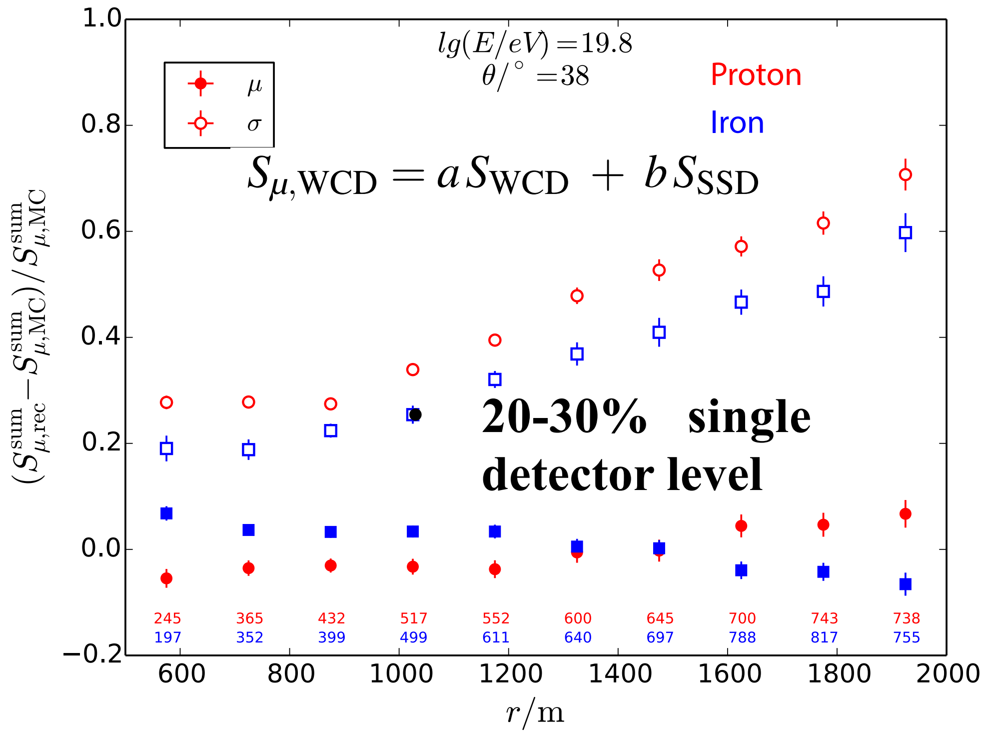


Hamamatsu R9420, head-on type, 8-stage PMT with a 38 mm bialkali photocathode. (Q.E. 20%, good linearity)

The Surface Scintillator Detectors (SSD): the matrix method

NIM A767 (2014) 41–49

- Derive the **muon density** for stations close to the shower core.
- almost **model-independent** way
- The values of ***a*** **and** ***b*** were calculated from showers **simulated**.



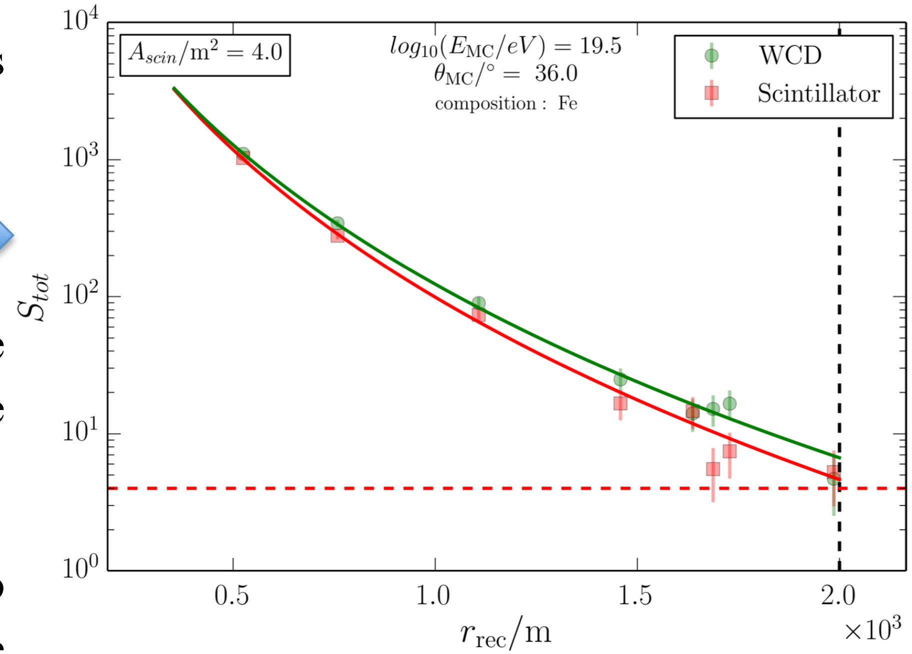
- A small **dependence on the mass** of the primary and on the hadronic interaction model **could impact the resolution** and a mass-dependent **bias** in the reconstruction could be introduced for the muon density for individual detector stations.

- The reconstruction **bias** (solid symbols) and **resolution** (open symbols) of the muonic signal contribution for individual detector stations is shown.

The Surface Scintillator Detectors (SSD): LDF_{SSD} + the matrix method

- A **parameterization of the LDF** for the SSD was done using simulation.
- Simulated Fe LDFs fit for WCD and SSD
- The horizontal dashed line indicates the single station trigger threshold and the vertical line the range up to which stations are used in the LDF fit.
- The **matrix inversion algorithm** is then applied to the LDF values for the WCD and SSD to calculate the **muonic signal expected in a water-Cherenkov detector at 800 m core distance**, $S_\mu(800)$.
- A reconstruction resolution of the muonic signal for example at E =$10^{19.8}$ eV and θ = 38 º:

$$\left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\text{proton}} \approx 22\% \qquad \left.\frac{\sigma[S_\mu(800)]}{\langle S_\mu(800)\rangle}\right|_{\text{iron}} \approx 14\%$$

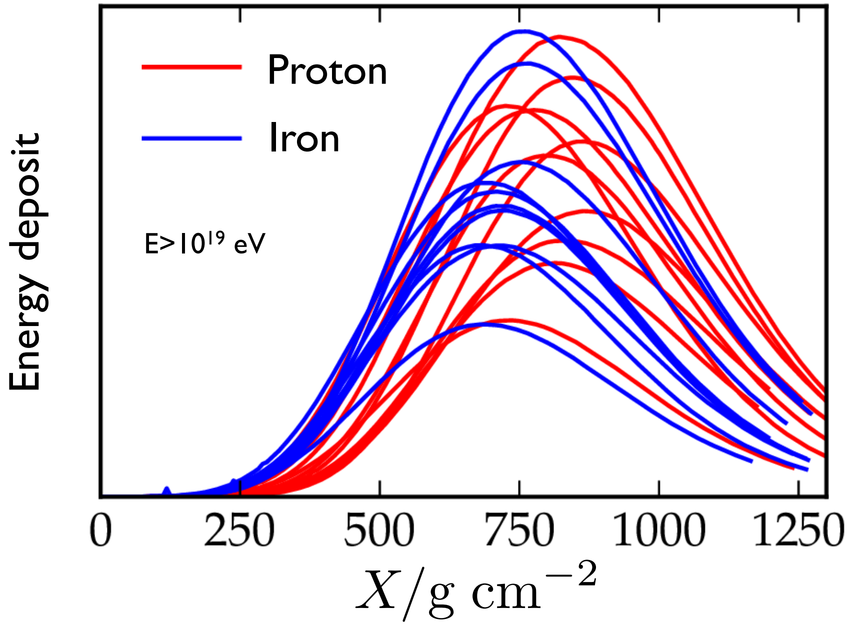


Using $S_\mu(800)$ as composition estimator, the **merit factors** for distinguishing between proton and iron primaries are above **1.5 at energies E > $10^{19.5}$ eV** and small zenith angles.

Event by Event basis.

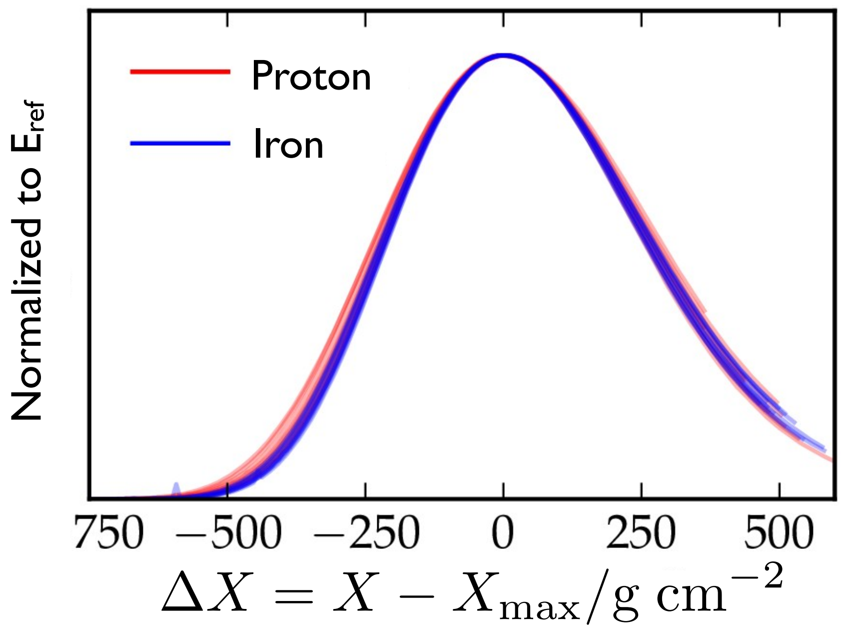
The Surface Scintillator Detectors (SSD): Universality

- The longitudinal profile depend on E and on the distance to X_{max} $(\Delta X = X - X_{max})$ ***but not on mass***.



Simulated energy deposit along shower axis

Large fluctuation in shower development apparent



Universal longitudinal profile

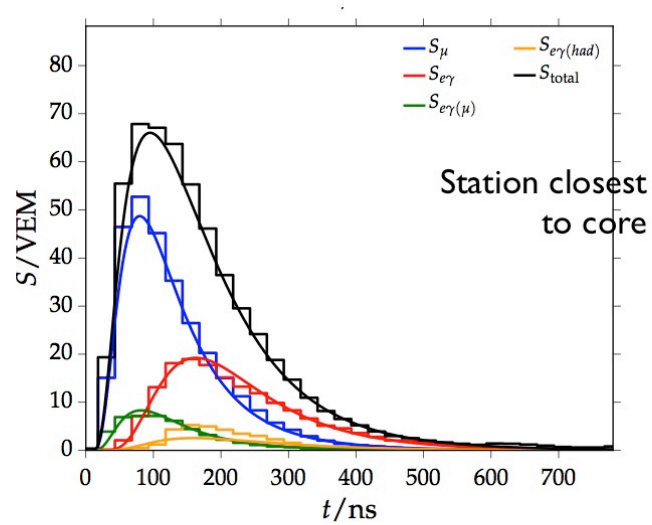
M. Roth @ ICRC 2015

M. Ave, R.A. Vazquez, E. Zas, Astropart. Phys. 14 (2000) 109
M. Giller et al., J. Phys. G 31 (2005) 947
M. Giller, H. Stojek, G. Wieczorek, Int. J. of Modern Physics A 20 (2005) 6821
F. Nerling, J. Blümer, R. Engel, M. Risse, Astropart. Phys. 24 (2006) 421
D. Góra, R. Engel, D. Heck, et al., Astropart. Phys. 24 (2006) 484
P. Billoir, C. Roucelle, J.-C. Hamilton, astro-ph/0701583
F. Schmidt, M. Ave, L. Cazon, A. Chou, Astropart. Phys. 29 (2008) 355
P. Lipari, Phys. Rev. D79 (2008) 063001
S. Lafebre, et al., Astropart. Phys. 31 (2009) 243
M. Ave, .J. Gonzalez, D. Maurel,, M.Roth ICRC 2011 Beijing, 1025

The Surface Scintillator Detectors (SSD): Universality

- The shower universality method **predicts** for the entire range of **primary** masses the air-shower characteristics on the ground **using** only three parameters: ***E*, *X*$_{\mathbf{max}}$ and *N*$_{\boldsymbol{\mu}}$**

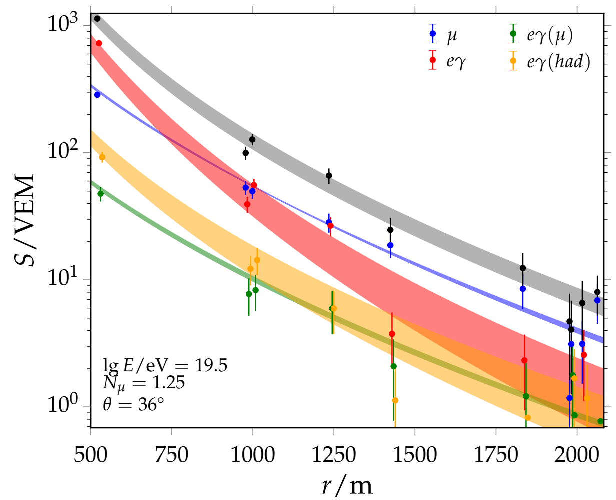
- The parameters could be **estimated from the integrated signal and the temporal structure** of the signal measured in the individual stations . Event-by-event basis.



$$
\begin{aligned}
S_{\text{tot}} =& S_{\text{em}}(DX, E) + \\
& N_\mu^{\text{rel}} S_\mu^{\text{QGS}}(DX, E) + \\
& N_\mu^{\text{rel}} S_{\text{em}}^{\mu}(DX, E) + \\
& (N_\mu^{\text{rel}})^\alpha S_{\text{em}}^{\text{jet}}(DX, E)
\end{aligned}
$$

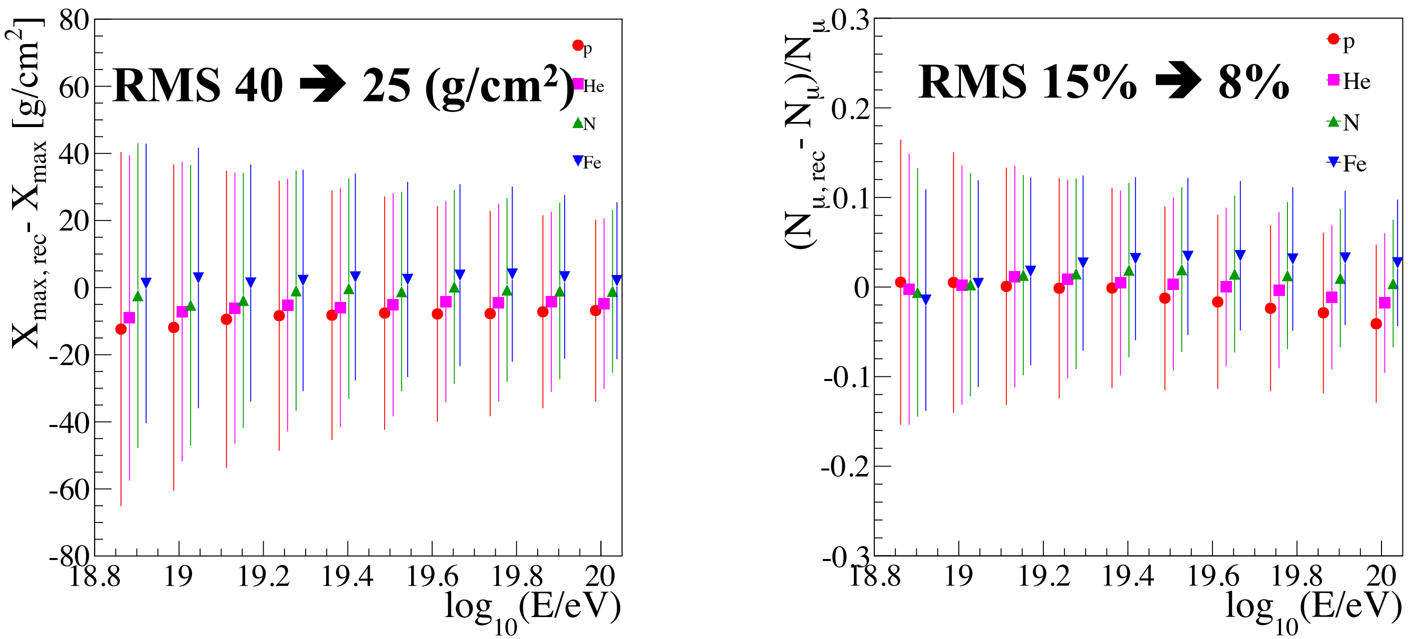
- Pure electromagnetic
- Muons
- Electromagnetic from muon decay
- Electromagnetic jets from hadrons

$$
N_\mu^{\text{rel}} = \frac{S_\mu(DX, r, E)}{S_\mu^{\text{QGS}}(DX, r, E)}
$$



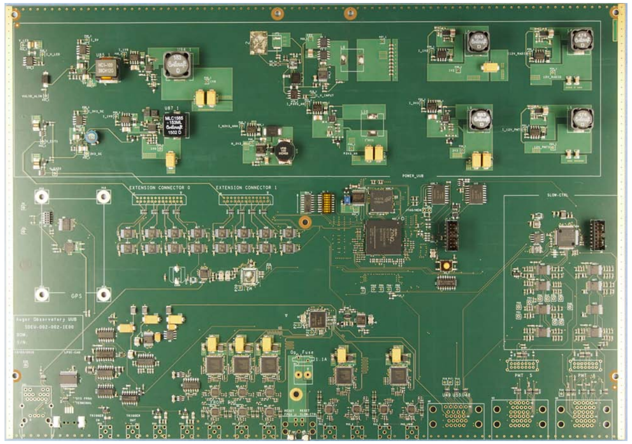
The Surface Scintillator Detectors (SSD): Universality

- Applying the Universality method it's possible to take in to account the **correlation between the WCD and the SSD**. The parameters now are more (X^{μ}_{max} ,$X_{max,}$ N_{μ}) in the model.
- This allow a measurements of the **number of muons event by event basis** and the relation bewteen X^{μ}_{max} ,X_{max} and N_{μ}^{rel} coul 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 60°.



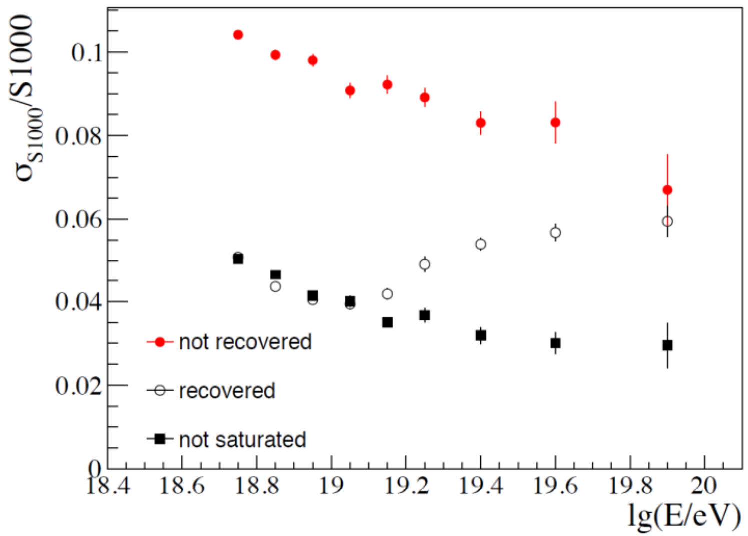
The upgrade of the Water-Cherenkov Detectors (WCD): SDEU

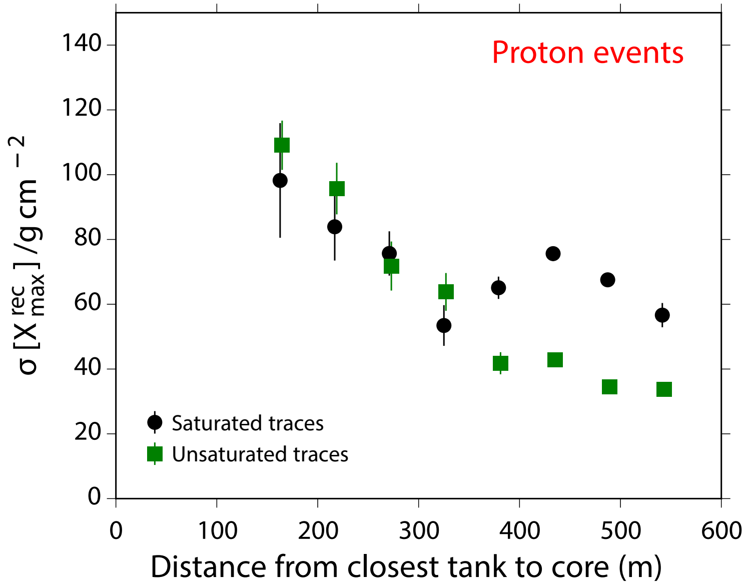
- The surface detector stations will be upgraded with **new electronics** that will process both WCD and SSD signals.
- Increase the **data quality** (with faster sampling of ADC traces, better timing accuracy).
- Increased **dynamic range**, to enhance the local trigger and processing capabilities (with a more powerful local station processor and FPGA)
- To improve calibration and **monitoring capabilities** of the surface detector stations.
- The *surface detector electronics upgrade* (SDEU) can be easily deployed, and will have only **minimal impact** on the continuous data taking of the Surface Detector.

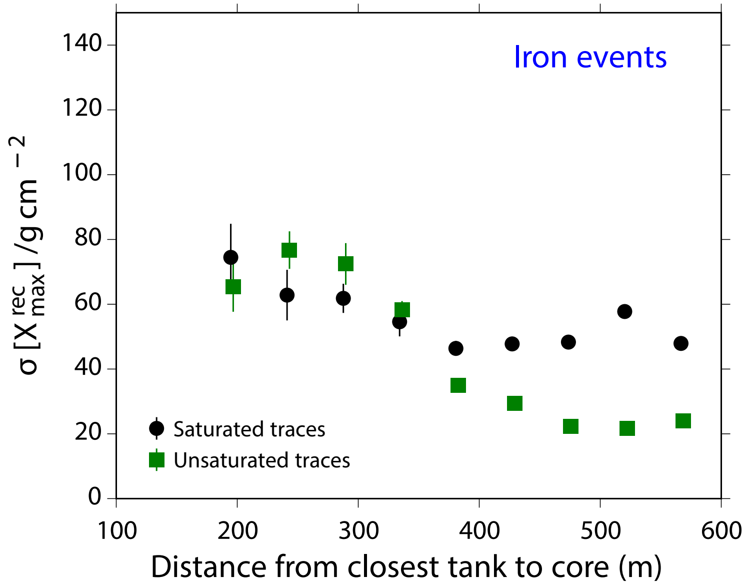


The upgrade of the Water-Cherenkov Detectors (WCD): SPMT

- The new electronics allow to install a **small PMT** in the tank.
- Installed in water-Cherenkov detectors for increasing dynamic range.
- Typical lateral distance of saturation ~500 m (E > $10^{19.5}$ eV) reduced to 300 m.

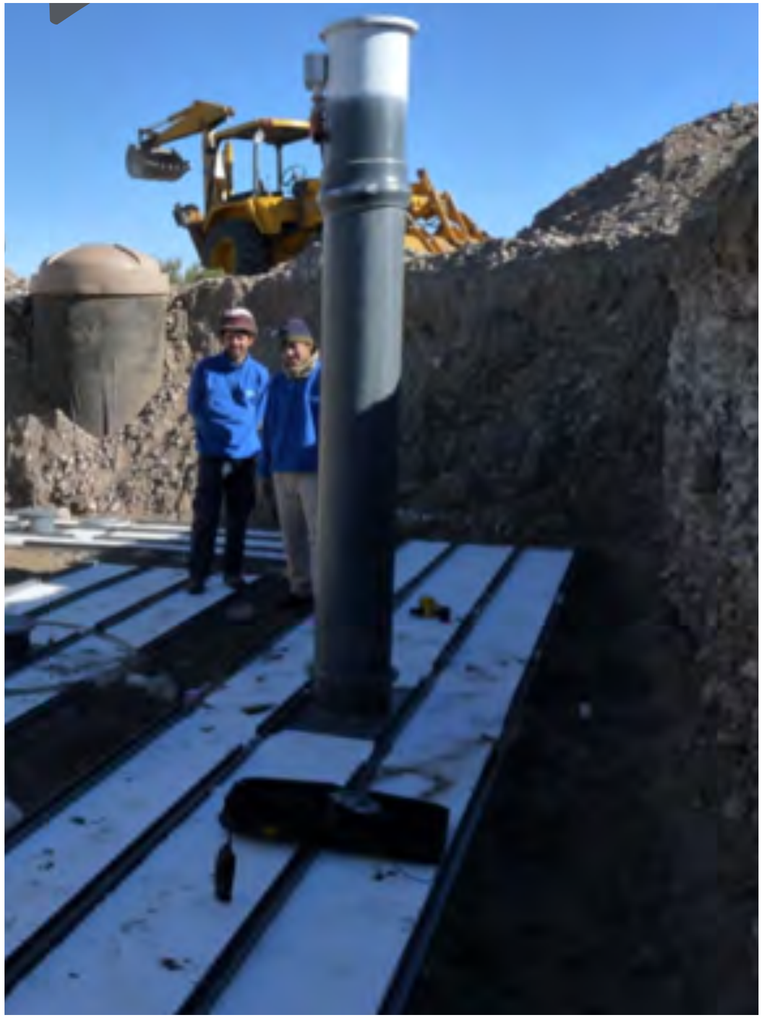






The Underground Muon Detector (UMD)

- An **Underground Muon Detector (UMD)** is required in the existing SD infill area of 23.5 km^2.
- The UMD will provide important **direct measurements of the shower muon content** and its time structure.
- UMD serving as **verification** and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements.
- The performance and characteristics of the **AMIGA** match these requirements, and thus the completed AMIGA array will serve as the UMD.
- Muon detectors shielded by 1.3 m of soil (AMIGA, 750 m spacing, 63 detectors of 30 m^2)



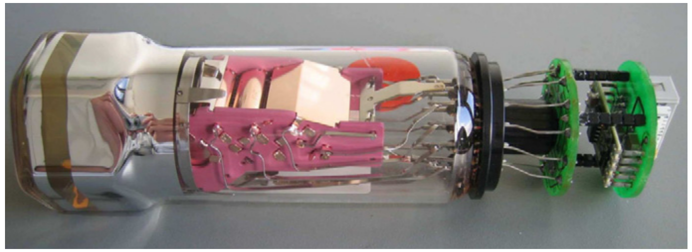
The Fluorescence Detector Operation Upgrade

- **Safety limits** on the long and short term illumination of PMTs by the NSB, and particularly scattered moonlight, define the data taking period of the current FD operation.

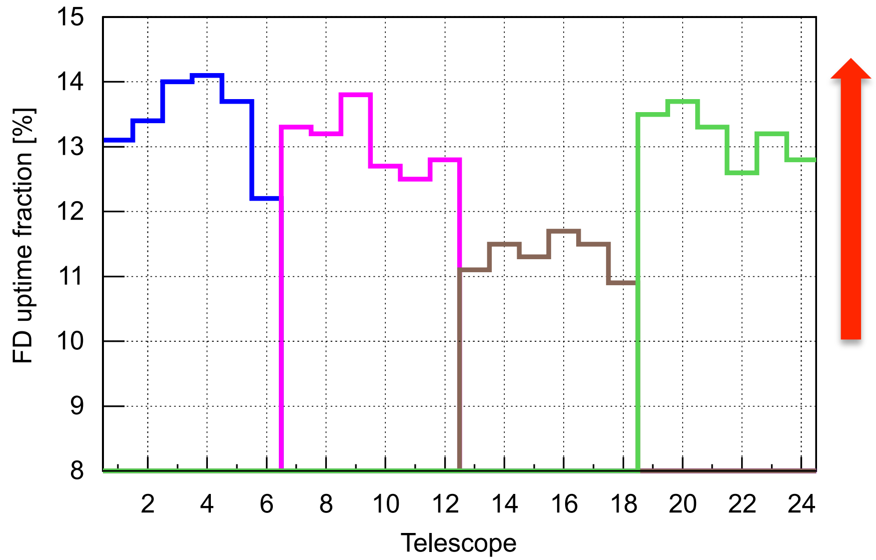
- The **extension** of the FD operation to times at which a large fraction of the moon in the sky is illuminated is possible

- **Reducing the PMT gain** by lowering the supplied high voltage (HV) to avoid an excessively high anode current leading to an irreversible deterioration of the PMT sensitivity.

- The HV power supplies installed in the FD buildings allow **switching between two high voltage** levels and the PMTs can be operated at the nominal gain and a lower gain.



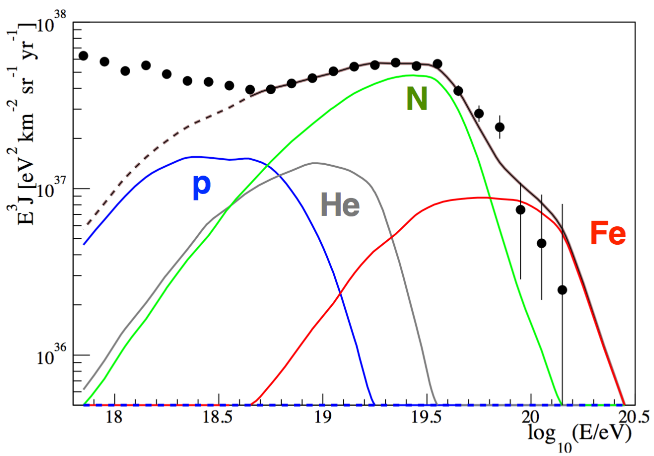
NIM A 620 (2010) 227–251



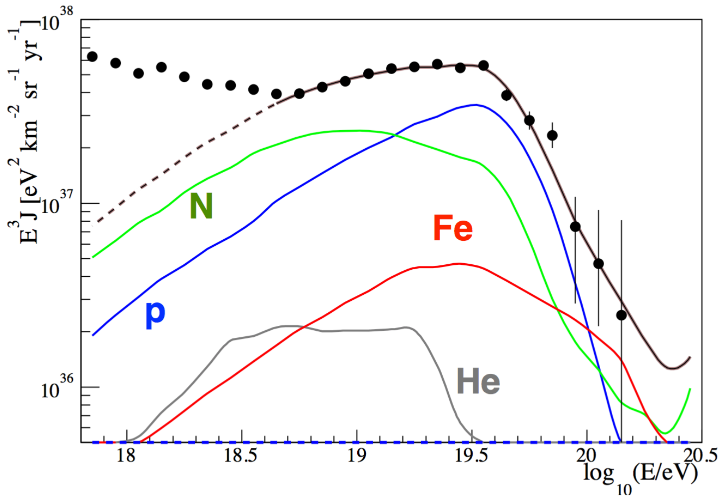
This Upgrade will allow an increase in the current 15% duty cycle of the FD to over 20%

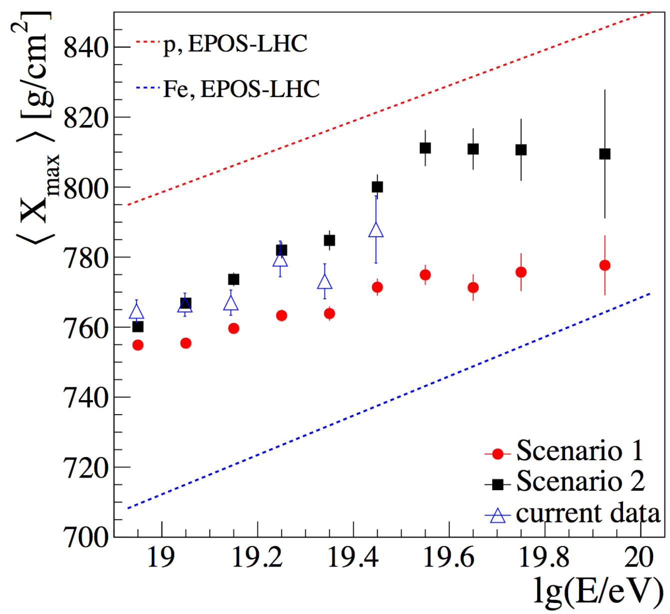
Example of the expected performances

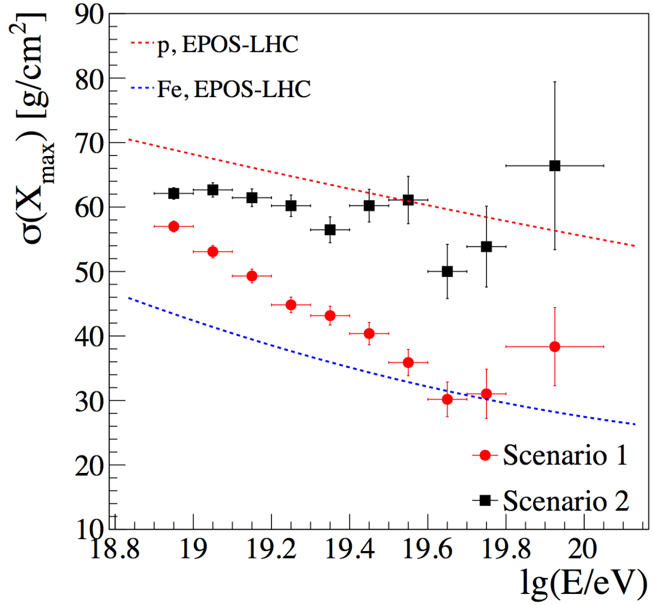
Scenario 1: maximum rigidity model

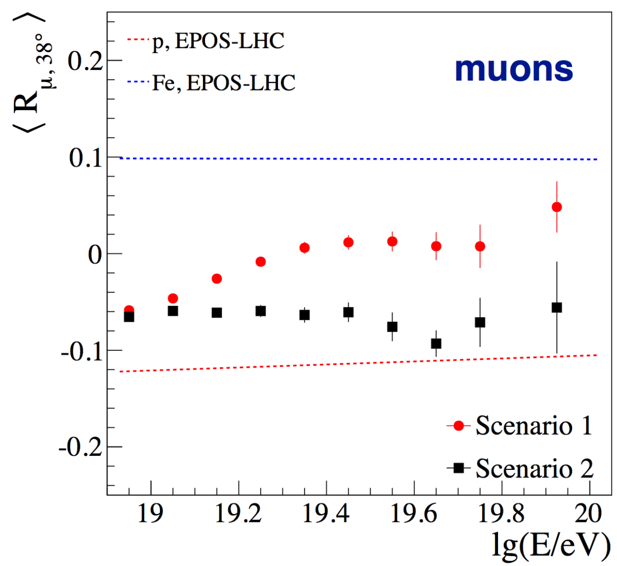


Scenario 2: photo-disintegration model









R. Engel @ ICRC15

Example of the expected performances

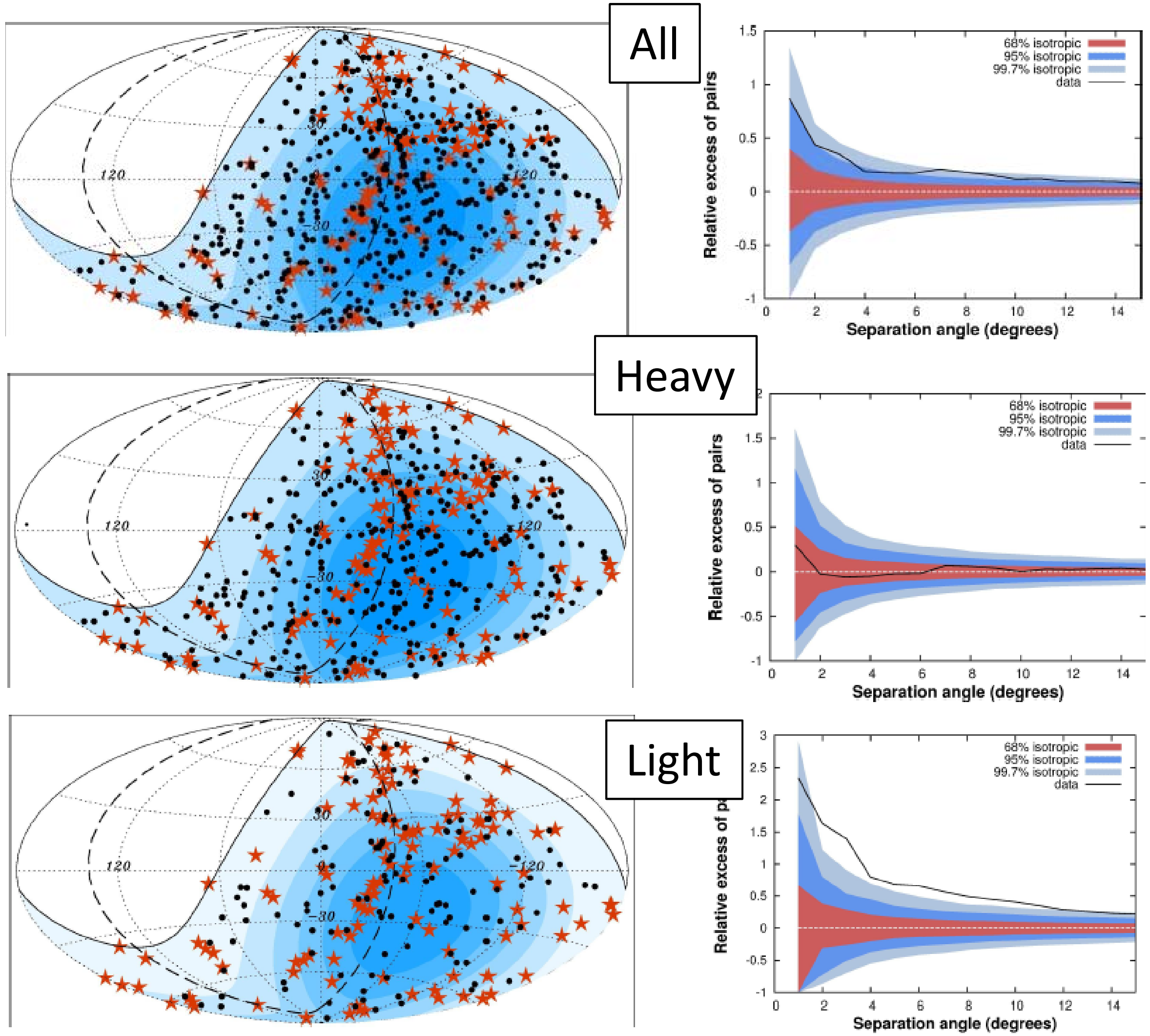
- **Event-by-Event** primary **mass identification** could provide the possibility to do the anisotropy analysis with data sample selected by the mass of the primary

- Example 454 events with

  E > 4x10^{19}eV

  X_{max} Scenario 1

10% protons and half correlate with near AGN (<100 Mpc)



Summary

- A brief summary of the precise Pierre Auger Observatory results that call for an AUGER Upgrade are shown.

- The Primary Mass Identification using the electronic and muonic componets it was described and different metodologies are discussed.

- The complete upgrade program of the Pierre Auger Observatory it was shown and the expected performances are briefly discussed.

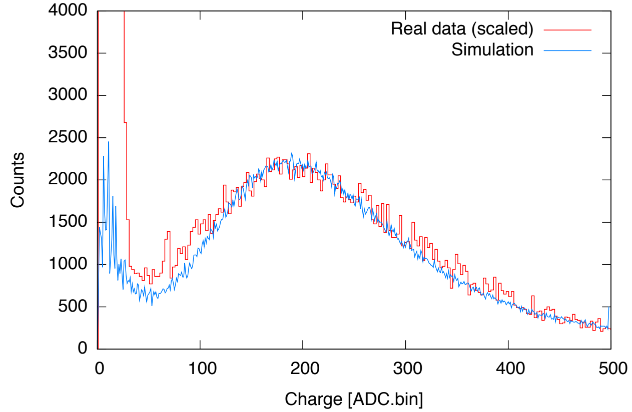
- The upgraded observatory will take data until 2024

- We will show in CRIS 2025 the results obtained by the upgrade.

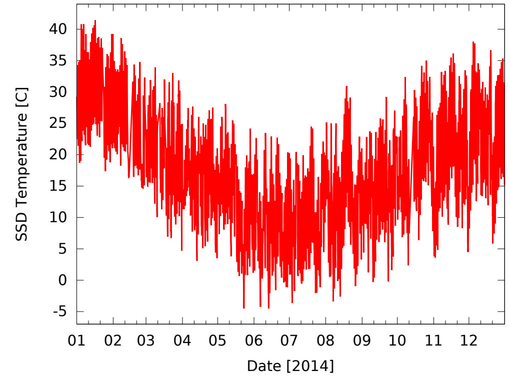
Back-up

Prototype development and testing

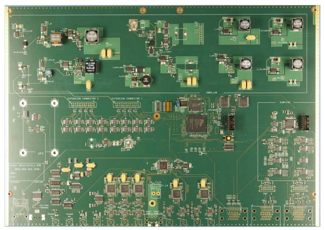
MIP calibration curve

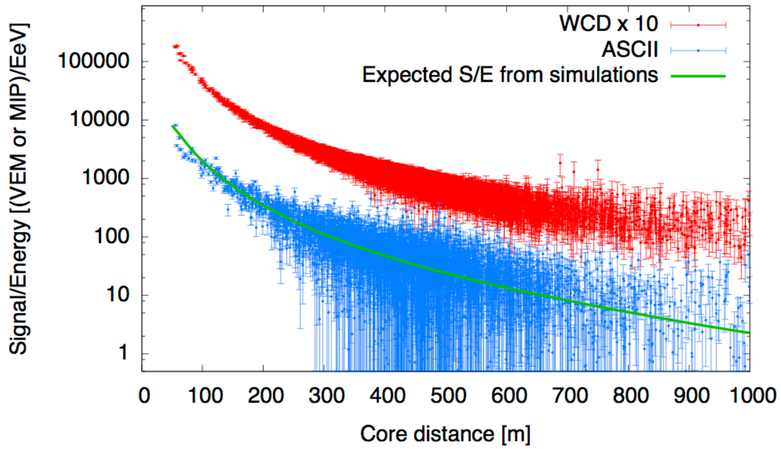


Temperature variation one year



Electronics prototypes (120 MHz)





Rescaled lateral distribution

The upgrade of the Pierre Auger Observatory

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

- A complementary measurement of the shower particles will be provided by a plastic scintillator plane above the existing Water-Cherenkov Detectors (WCD).

- The surface detector stations will be upgraded with new electronics that will process both WCD and SSD signals. Use of the new electronics also aims to increase the data quality (with faster sampling of ADC traces, better timing accuracy, increased dynamic range), to enhance the local trigger and processing capabilities (with a more powerful local station processor and FPGA) and to improve calibration and monitoring capabil- ities of the surface detector stations. The surface detector electronics upgrade (SDEU) can be easily deployed, and will have only minimal impact on the continuous data taking of the Surface Detector.
- An Underground Muon Detector (UMD) is required in the existing SD infill area of 23.5 km2. The UMD will provide important direct measurements of the shower muon content and its time structure, while serving as verification and fine-tuning of the meth- ods used to extract muon information with the SSD and WCD measurements. The per- formance and characteristics of the AMIGA underground muon detectors, now being deployed, match these requirements, and thus the completed AMIGA array will serve as the UMD.

Increasing the FD statistics

- In parallel with the Surface Detector upgrade, the operation mode of the Fluorescence Detector (FD) will be changed to extend measurements into periods with higher night sky background. This will allow an increase in the current 15% duty cycle of the FD to over 20%
- Auger upgrade will not affect the continuous data taking and maintenance of the existing detectors.