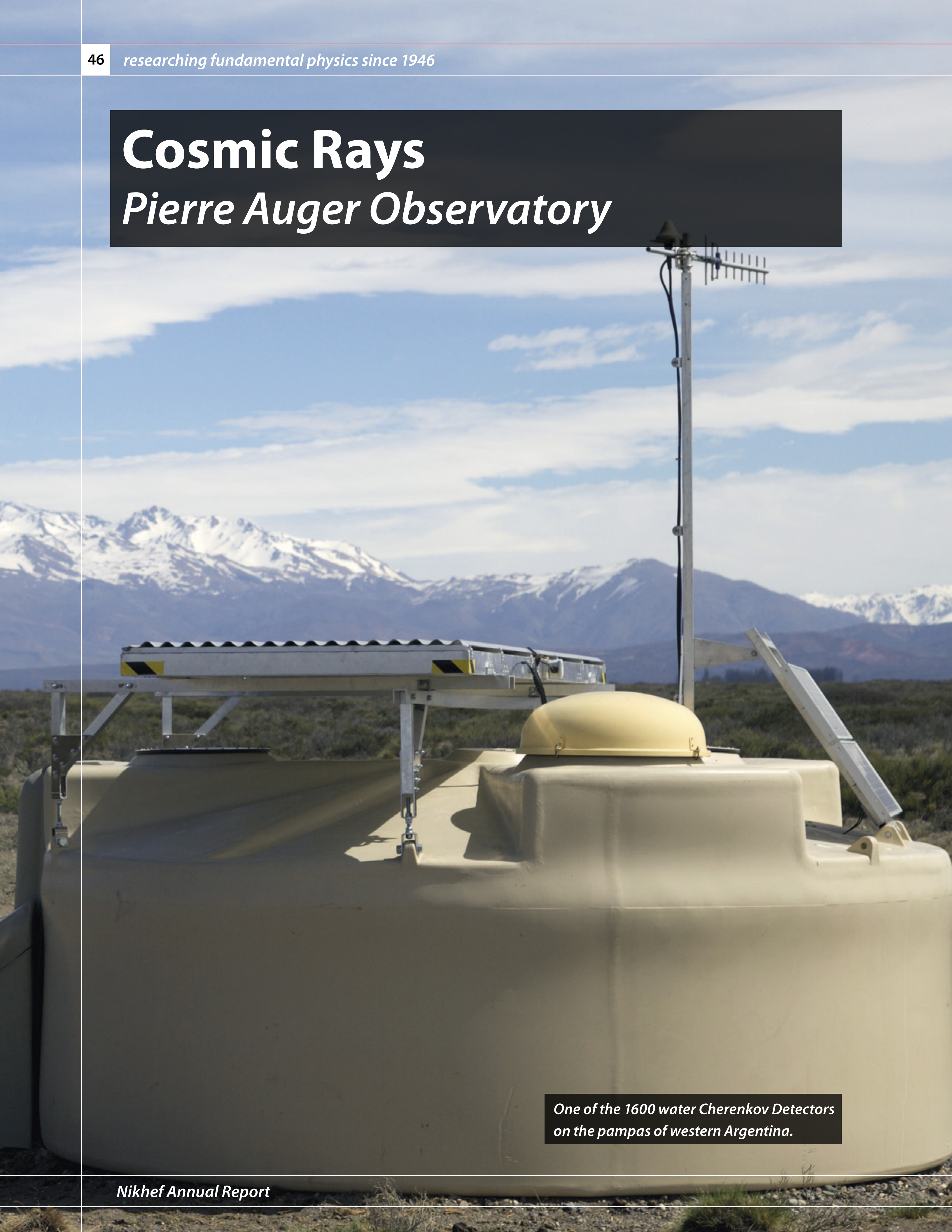
Cosmic Rays
Pierre Auger Observatory



One of the 1600 water Cherenkov Detectors on the pampas of western Argentina.

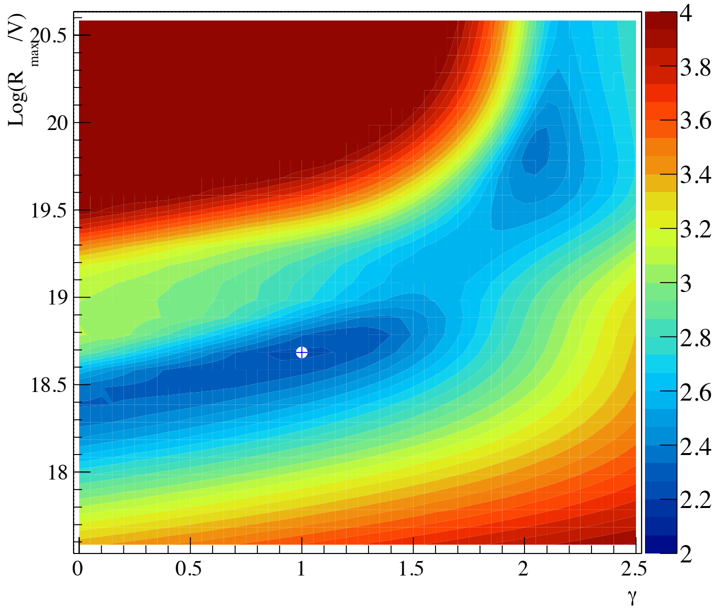


Figure 1. Fit to Auger ultra-high-energy cosmic ray data with models as a function of the model parameters injection index γ and maximum rigidity R_{max}. The fit quality ranges from good in blue to very bad in red. The two best, equally likely fit positions correspond to a normal injection index spectrum with high rigidity cut-off, which is the GZK scenario, and a hard injection spectrum with low rigidity cut-off, which corresponds to a maximum attainable energy of the cosmic accelerators.

Management
prof.dr. S. de Jong

Ultra-high-energy cosmic rays are the most energetic particles we know, exceeding the LHC energy by many orders of magnitude. Yet we neither know their sources, the physics that is needed to generate them, nor the physics that governs their interactions with the air in our atmosphere. The Pierre Auger Observatory was built to resolve these mysteries. It is the world's largest cosmic ray observatory located on 3000 km^2 near Malargüe in the province of Mendoza in Argentina.

The origin of ultra-high-energy cosmic rays

The Pierre Auger Collaboration had already definitively shown that the energy spectrum of cosmic rays exhibits a sharp drop around 10^{20} eV. This drop is compatible with the Greisen-Zatsepin-Kuz'min (GZK) cut-off, above which ultra-high-energy cosmic rays interact with photons of the 2.7 °K cosmic microwave background and will loose their energy when traveling over inter-galactic distances. Due to the different interactions strengths with the cosmic microwave background, the end of the spectrum is expected to be dominated by protons.

However, another reason for the cut-off of the spectrum can be that there is a maximum energy that can be reached by the cosmic accelerators. In that case a heavy composition is expected. Recently, the Pierre Auger Collaboration confirmed a mixed mass composition at energies one order of magnitude below the cut-off energy, *i.e.* at $10^{18.5}$–10^{19} eV.

A more elaborate fit of all available information for ultra-high-energy cosmic rays is shown in Fig. 1, which shows that the two scenarios are about equally likely given the available data.

The AugerPrime upgrade of the Pierre Auger Observatory is aimed at an event-by-event determination of the cosmic ray composition up to the highest energy. This will clearly distinguish between the two presented scenarios. The Nikhef group is strongly involved in the design and production of the SSD modules. The Nikhef group is also a main drivers of the novel technique of radio detection of cosmic rays in the Pierre Auger Observatory.

AugerPrime

The Auger Surface Detector consists of about 1,660 water Cherenkov tanks of 12 ton water each. These tanks are spaced by 1.5 km to cover a surface of 3,000 km^2 in total. When high-energy particles at the end of the air showers pass through the water they make Cherenkov radiation that is observed by three photomultipliers that look down in the water of the tank. For ultra-high-energy cosmic rays, many tanks are hit. The particle flux in a collection of tanks is fit as a lateral density profile and its normalisation renders the energy of the incoming cosmic ray. Depending on the direction of the incoming cosmic ray, the water tanks are hit at different times by the air shower front. From timing reconstruction the arrival direction of the incoming cosmic ray can be determined.

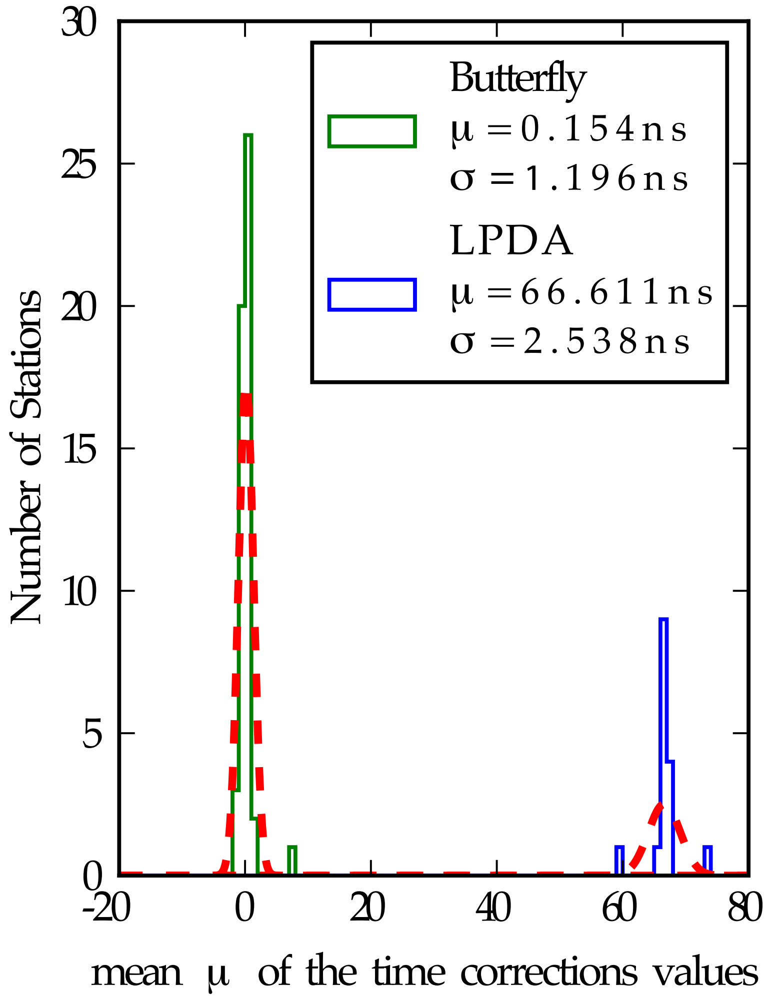


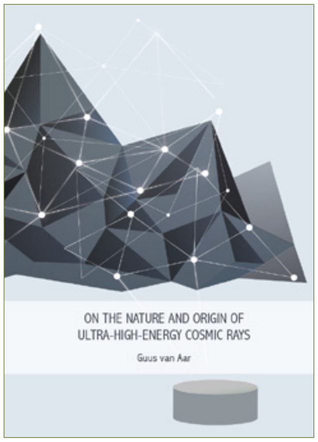
Figure 2. Histogram of the mean μ of the time correction values. The standard deviations σ of the distributions provide a measure for the average agreement between the beacon and airplane methods. The values stated in the statistics box are from fitted Gaussians (dashed lines).

At the same energy light and heavy cosmic ray particles have different interactions with the atmosphere. Light particles, in extremum protons, have a smaller cross section with air molecules than heavy elements, such as nitrogen or even iron nuclei. Therefore, light cosmic rays have the development of their shower deeper into the atmosphere than heavier nuclei. Moreover, the interactions with heavier cosmic rays invoke a more rapid shower development than with lighter ones. In addition, heavier elements tend to produce significantly more muons, especially also at the early stage of the shower, than light cosmic rays.

The AugerPrime upgrade aims at

- elucidating the mass composition and the origin of the flux suppression at the highest energies, *i.e.* the differentiation between the energy loss effects due to propagation, and the maximum energy of particles injected by astrophysical sources;
- searching for a flux contribution of protons up to the highest energies, with a sensitivity down to less than a 10% proton fraction. This is a decisive ingredient for estimating the physics potential of existing and future cosmic ray, neutrino, and gamma-ray detectors. It will predict the flux of secondary gamma-rays and neutrinos due to proton energy loss processes; and
- studying extensive air showers and hadronic multiparticle production at energies beyond those accessible at man-made accelerators, and the derivation of constraints on new physics phenomena, such as Lorentz invariance violation or extra dimensions.

Stefan Jansen
13 April 2016



Guus van der Aar
19 October 2016

These goals will be achieved by

- A complementary measurement of the shower particles will be provided by Surface Scintillator Detectors (SSD) 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 and thereby being able to measure these components separately;
- A surface detector electronics upgrade (SDEU) 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 capabilities of the surface detector stations;
- An Underground Muon Detector (UMD) 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, while serving as verification and fine-tuning of the methods used to extract muon information with the SSD and WCD measurements; and
- a changed operation mode of the Fluorescence Detector (FD) to extend measurements into periods with higher night sky background, to allow an increase in the current 15% FD duty cycle to over 20%.

The biggest and most important part of the AugerPrime upgrade are the Scintillating Surface Detector modules that will be installed on top of the existing Surface Detector tanks. Nikhef has designed the mounting frame for these modules and is an important partner in designing the modules. A production of a substantial number of SSD modules is planned at Nikhef to start in the second half of 2017.

Progress in radio detection of Cosmic Rays

In 2016 a proof of principle for the timing calibration of the radio detector stations was demonstrated (see Fig. 2). The calibration was based on the use of a beacon, while it was verified using commercial airplanes that flew over the AERA set-up and emitted pulses in the right frequency range for detection by the AERA stations. The timing precision could thus be verified to be about 1 ns for the butterfly antennas and about 2 ns for the Log Periodic Dipole Antennas. Such a precision corresponds in principle to a pointing accuracy of much less than one degree for cosmic rays that are measured by the radio detector.