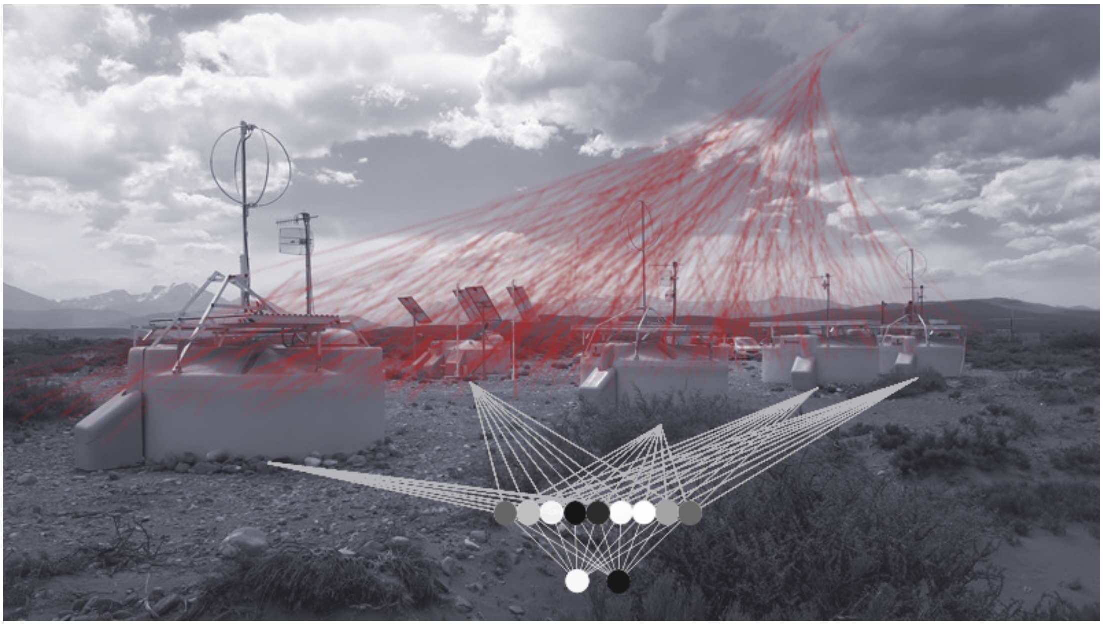
Karlsruhe Institute of Technology

PIERRE AUGER OBSERVATORY

# Harry Potter and the Neural network triggers for the surface detector of the Pierre Auger Observatory: A plausibility



Master's thesis by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# Review and Declaration

This thesis has been accepted by the first reviewer of the master thesis.

*Karlsruhe, TBD*

Prof. Dr. Ralph Engel

I declare that the work in this thesis was carried out in accordance with the requirements of the university's regulations and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others is indicated as such.

*Karlsruhe, TBD*

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# Contents

# 1 Introduction

# 2 Physical background

This chapter aims to introduce the general physical principles underlaying the analysis presented in this work. For this purpose, an overview of the origin, composition and energy spectrum of cosmic rays is given in section 2.1. Their interactions with other matter, and consequently possible detection methods are listed in section 2.2.

## 2.1 Cosmic rays

### 2.1.1 History

A first hint at the existance of high-energy particles in the upper atmosphere was given by Hess in 1912, who found that the discharge rate of an electroscope is altitude-dependant. Millikan coined the term cosmic "rays" for these particles, as he argued the ionizing radiation must be part of the electromagnetic spectrum [1]. This was later - at least partially - falsified with the discovery of the east-west effect [2]. Hess' observation however withstood the tests of time and was ultimately recognized with the Nobel prize in physics in 1936 [3]. Two years later, in 1938, Pierre Auger showed via coincidence measurements that cosmic rays originate from outer space, and gave a first description of extensive air showers. Another 60 years later, the Pierre Auger collaboration would adopt his experimental setup and name in their search for cosmic rays of the highest energies.

Numerous other discoveries have helped advance our knowledge in both astro- and particle physics in the meantime. These include (but are not limited to)

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### 2.1.2 Origin

Cosmic rays whose kinetic energy far exceeds their rest energy must originate from some of the most extreme environments in space. In particular, regions with a large (either in field strength or spatial extent) electromagnetic field, where charged particles are accelerated to speeds very close to the speed of light, , via e.g. the Lorentz force.

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#### Acceleration mechanisms

### 2.1.3 Composition

### 2.1.4 Energy spectrum

## 2.2 Extensive air showers

Consider an incident particle of sufficiently high energy such that

### 2.2.1 Heitler Model

### 2.2.2 Heitler-Matthews Model

# 3 The Pierre Auger Observatory

Located on the argentinian high-plains of Pampa Amarilla, the Pierre Auger observatory is a hybrid detector designed to detect and study cosmic rays of the highest energies. With an effective area of 3000 $km^2$ it is by far the largest experiment of its kind [4].

Altough first proposed in 1992, it took 18 years until the idea of a large scale experiment to detect cosmic rays matured and construction of the first prototype started near Mendoza [5]. Some further 20 years later, the Pierre Auger collaboration has co-authored over publications and continues to advance research in astroparticle physics. It does this via a hybrid approach, combining measurements of a surface detector (SD) as well as a flouresence detector (FD). Additional machinery, such as the e**X**treme (XLF) and **C**entral **L**aser **F**acility (CLF), is installed and monitors atmospheric variables. This improves the overall systematic accuracy of predictions made by the experiment. An overview of the site can be seen in Figure 3.1. Data measured by the FD, SD and the atmospheric monitors is sent to a **C**entral **D**ata **A**cquisition **S**ystem (CDAS) located in the nearby town of Malargüe.

This chapter offers a brief look into the measurement principle and setup of the observatory. Information regarding the fluoresence detector can be found in section 3.1. The SD is described in section 3.2. A more in depth read on detector specifications and design choices is represented by the Pierre Auger observatory design report [4], where a lot of information stated in this chapter is conglomerated from. Notes on the event reconstruction are listed in section 3.3 and summarized from [6] and [7].

## 3.1 Fluoresence Detector (FD)

The FD consists of a total of 27 fluoresence telescopes (eyes) at 4 different sites. Each eye monitors a 30° x 30° window of the sky at a resolution of $\approx 0.5\,\frac{\mathrm{px}}{\mathrm{deg}^2}$. This results in an effective FOV of roughly 180° x 30° per FD station, with an exception of Coihueco, where three additional telescopes - HEAT (**H**igh **E**levation **A**uger **T**elescope) - are installed to enable monitoring of higher zenith angles ($30° \leq \theta \leq 60°$) and increase sensitivity for showers of lower energies (compare chapter 2).

The individual telescopes consist of 3.6 m by 3.6 m, convex mirrors. They reflect incoming light onto a set of 440 photomultipliers (PMTs), each corresponding to one pixel in the resulting image seen by an eye. Since the setup needs to be extremely sensitive to UV light in order to detect flouresence caused by extensive air showers, its operation is limited to the relatively noise free moonless astronomical nights (Sun

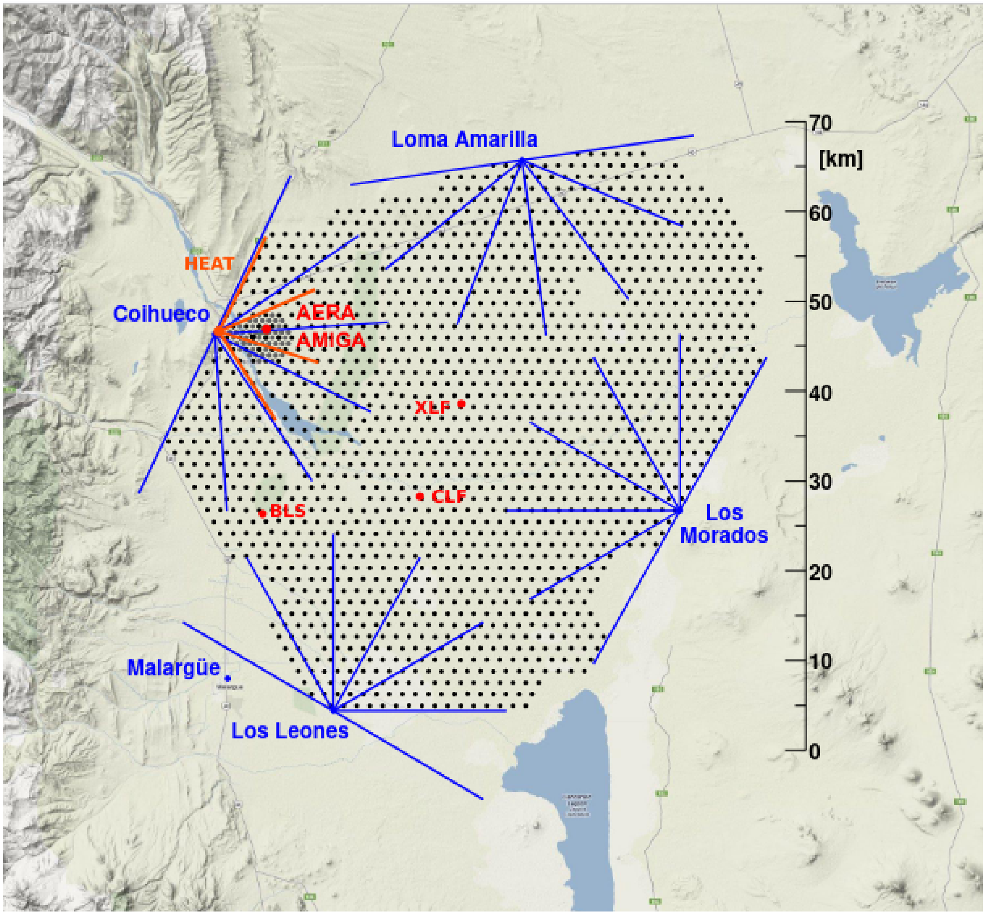


**Figure 3.1:** Overview of the Pierre Auger observatory. The four different FD sites (respective FOV shown with blue lines) sit at the edge of the detector area and monitor the night sky above the SD array consisting of 1600 water tanks (black dots). A denser spacing of stations near Coihueco is equipped with additional electronics such as e.g. radio antennas (AERA) and muon detectors (AMIGA).

$\measuredangle$ Horizon $\lesssim -18°$). When the FD is operational, this allows the observation of the longitudinal propagation of a shower instead of just its' footprint (as seen by the SD).

## 3.2 Surface Detector (SD)

The SD consists of 1600 individually operating stations, spaced apart on a hexagonal grid with a standard 1.5 km spacing. Each station is made up of a main tank filled with 12 000 L of purified water and reflective inner walls, a solar panel and batteries for power management, as well as an antenna for communication. Within each tank three PMTs detect Cherenkov light originating from shower particles, these are together with the tank referred to as **W**ater **C**herenkov **D**etectors (WCDs). With the (at the time of this work) ongoing AugerPrime upgrade, each station is additionally equipped with a **S**urface **S**cintillator **D**etector (SSD), and radio antenna atop the tank. This allows for finer separation of electromagnetic and muonic shower component and detection of highly inclined air showers respectively [**horandel2020precision**, 8].

Onboard electronics, the **U**pgraded **U**nified **B**oard (UUB), or more precisely six 10-bit **F**lash **A**nalog-to-**D**igital-**C**onverters (FADCs) read out measurement data from the PMTs at a sampling rate of 120 MHz ($\approx$ 8.33 ns binning) [**verzi2013energy**]. This is done in a two-fold way. Three FADCs digitize the PMTs dynode voltage, resulting in the **H**igh**G**ain (HG) output. Three FADCs monitor the anode voltage to form the **L**ow **G**ain (LG) output, which can be analyzed if the HG output exceeds a value of $2^{10}$ ADC counts and becomes saturated. This effectively enables the measurement of both large ($\geq \mathcal{O}(10^3)$ particles hitting the tank) as well as small shower signals ($\mathcal{O}(1)$ particle hitting the tank) with sufficient accuracy. Once an FADC bin has been recorded and checked for possible triggers (c.f. subsection 3.2.2) it is written to a ring buffer. If a trigger is issued, the corresponding chunk in the ring buffer (600(? ) bins before and 23409857 bins after the latch bin, where the trigger was raised) can be analyzed in order to calibrate a station in the array (subsection 3.2.1) or processed by a higher-level CPU for event reconstruction purposes (section 3.3).

### 3.2.1 Calibration

While each station is equipped with the same electronics and runs the same analysis software, variables like the position in the field, station age or slight changes in the manufacturing/installation process cause different stations to age differently. Over the lifetime of the array such differences can sum into potentially drastic discrepancies in gathered data. Put simply, an extensive air shower will look different to a station compared to the same shower one year later. To account for this, measurements are standardized for all stations. ADC counts are related to a **V**ertical **E**quivalent of through-going **M**uons (VEM) that would result in the same signal strength. In this fashion, the maximum response that is generated by a PMT from a vertically through-going muon is defined as 1 $\mathrm{VEM}_{\mathrm{Peak}}$. The total deposited charge (equivalent to the integral over response) is defined as 1 $\mathrm{VEM}_{\mathrm{Ch.}}$. The conversion factor between ADC counts and $VEM_{Peak}$ and $VEM_{Ch.}$ is estimated from data and continuously updated via the algorithms detailed below. Note that the used methods differ for calibration in the field (Online algorithm) and event reconstruction (Oflline algorithm). Both approaches are listed here and discussed in more detail in [9, 10].

#### Baseline estimation

First and foremost, the average noise level of each PMT needs to be determined

#### Rate based estimation of peak and charge

#### Histogram based estimation of peak and charge

### 3.2.2 Trigger procedure

## 3.3 Event Reconstruction

# 4 SD Station Triggers

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