Measurement of the efficiency of the SD1500 with the SD750

Gabriel Brichetto Orquera and Diego Ravignani

ITeDA (CNEA, CONICET, UNSAM), Buenos Aires, Argentina

Abstract

In order to report the spectrum, it is required that the Surface Detector is fully efficient ($< 97\%$). We propose a fully experimental method to determine the efficiency of the SD1500 as a function of the energy and the zenith angle using the events simultaneously detected by the SD750. The energy threshold we found is 2.5×10^{18} eV in accordance with the current used value. We also found that this threshold improves to 10^{18} eV when reconstructing including the ToTd and MoPS triggers and using events with zenith angle below 45°.

1 Introduction

The Surface Detector of the Pierre Auger Observatory consists of three hexagonal arrays of Water Cherenkov Detectors (WCD) nested one within another. The first array to be deployed was the 1500-metre detector (SD1500) which consists in 1600 stations. Later, 73 stations were added between the SD1500 stations in order to form the 750-metre detector near the Cohihueco site (fig. 1). Finally, in 2019 a third array was completed by adding 12 stations with a separation of 433 metres (SD-433) to form a 7 hexagon array in order to reach lower energies.

In order to have an accurate measurement of the spectrum, Auger requires for the detector to be fully efficient: the acceptance of the detector must be independent of the mass and energy of the primary cosmic ray. The full efficiency threshold used for practical purposes is 97%. Since the SD750 is nested within the SD1500 and has a lower energy

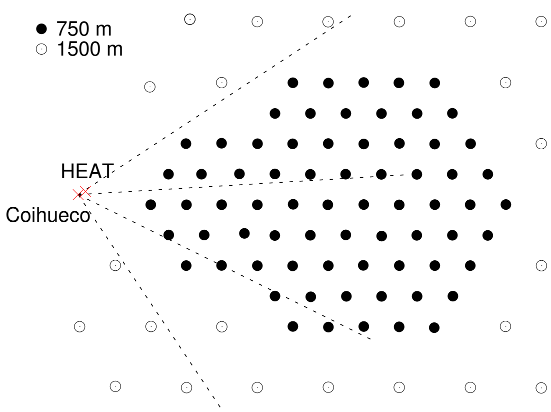

Figure 1: Schematic view of the 1500-metre surface detector (SD1500) and the 750-metre detector(SD750) nested within.

threshold, we propose a completely experimental method to study the efficiency for the SD1500. For this we reconstructed the event set of the SD750 and the SD1500 using the rev 33753 of the Offline framework.

For the cosmic ray spectrum, the SD1500 uses events with zenith angle lower than 60°. As a consequence we also studied the zenith angle dependency of the efficiency.

The spectrum is currently reported using only the ToT and TH2 station level triggers. However, in 2014 two new triggers were added [1], the ToTd and MoPS. These new triggers are designed to be more sensitive to the electromagnetic component of the showers which is more present in the lower energy events. We studied the efficiency of the SD1500 including these triggers in the reconstruction in order to lower energy threshold of the detector.

2 Efficiency of the 1500-metre array

The idea of this work is to study the SD1500 efficiency using that the SD750 is nested within the SD1500. For WCD arrays it is expected that after a certain energy it will be able to detect the signal of the air shower produced by the primary cosmic ray. After that, the efficiency will start to increase and plateau at 100% (full efficiency). The energy at which this occurs will depend on the distance between the stations, the nearer the stations, the lower the energy where full efficiency is reached. But this is a constant compromise with the exposure of the detectors, since the CR flux decays exponencially. In Auger, currently the full efficiency threshold for the SD1500 is taken at 2.5×10^{18} eV while for the SD750 is 10^{17} eV [3]. Since the SD750 is fully efficient at the energy range where the SD1500 starts to detect, the SD750 events can be used as a reference and estimate the efficiency by seeing the subset of events mutually detected. For the SD1500 spectrum currently Auger only uses the reconstruction using the original ToT and TH2 triggers, but with the inclusion of the new more sensitive to the electromagnetic component of the shower triggers, it is expected to be able to have a fully efficient detector at a lower energy.

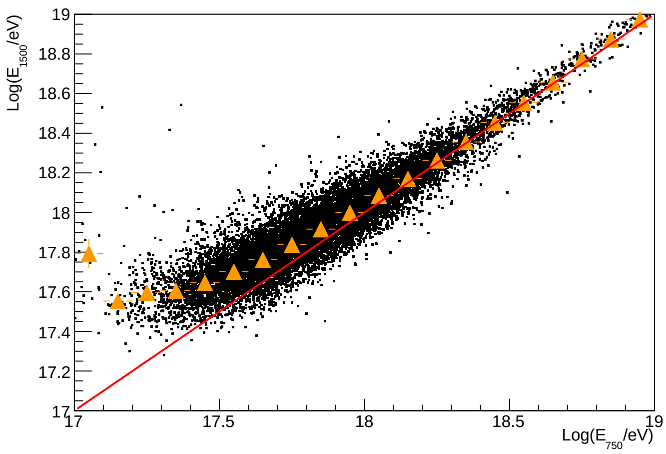

Figure 2: Energy measured by the SD1500 as a function of the SD750 energy. In red it can be seen the identity function and the bin average.

In order to compare the efficiency both reconstructing only with the original triggers and including the new triggers, the time period of the analysis ranges from the inclusion of the new triggers, Jan 1st 2014 up to the AMIGA comm crisis, Aug 31st 2018 [4].

The first step was to measure the dependence of the efficiency with the energy. To avoid mismatch between energy bins in the different arrays which would lead to wrong measurements of the efficiency, a robust estimator of the energy of an event was needed. Figure 2 shows the energy of the SD1500 events as a function of the SD750 energy and the average of each bin. There is no significant bias in the energy range of interest ($10^{17.5}$ eV to 10^{20} eV). As a consequence, the SD750 energy is used as the energy estimator for both detectors.

Since the events are independant, the probability of detecting k events with the SD1500 of n SD750 events with success rate p is binomial. In this case, the probability p corresponds to the efficiency of the detector. To estimate the efficiency we used the Maximum Likelihood Estimator (MLE). The likelihood of a binomial distribution is:

$$L(p|n,k) = \binom{N}{k} p^k (1-p)^{n-k} \tag{1}$$

The maximum likelihood estimator $\hat{p} = k/n$ was used as the efficiency estimator, since it is unbiased and with minimum variance. To measure the confidence intervals of the efficiency, the 95% confidence Wilson scored intervals were used, which have a good coverage probability and avoids overshooting when the full efficiency is reached.

First we proceeded with the analysis of the efficiency of the SD1500 including only the original triggers in the whole range of zenith angle. The reconstruction used for vertical events in the SD1500 ranges for $0° \leq \theta \leq 60°$. Figure 3 shows the efficiency of the SD1500 for zenith angle lower than 60°.

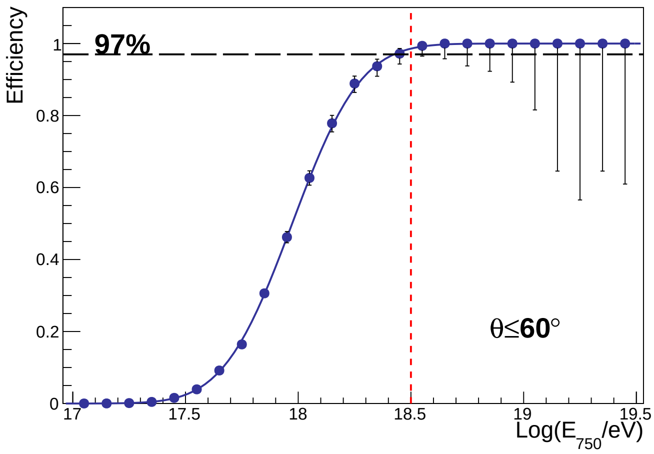

Figure 3: SD1500 efficiency measured with the SD750 event set. The error bars show the 95% confidence Willson score interval. The 97% efficiency threshold is reached at 2.5×10^{18} eV.

The proposed phenomenological model of the efficiency as a function of the energy is a sigmoid function with two free parameters, E_0 and b. The election of the error function as the representation of the function is in order to make the results comparable with [2]:

$$\varepsilon(E) = \frac{1}{2} + \frac{1}{2}\text{erf}\left(\frac{\log_{10}(E_{750}/\text{eV}) - E_0}{b}\right) \tag{2}$$

Using the Minuit routine for a χ^2 method the parameters $E_0 = 17.97$ and $b = 0.393$ were obtained.

For this measurement the threshold 97% efficiency is reached for events with energy higher than 2.5×10^{18} eV which is in accordance with the current value used by Auger.

3 Zenith angle dependence of the efficiency

The next step is to analyse the dependency of the efficiency with the zenith angle of the events. We divided the events with zenith angles $\leq 60°$ in twelve zenith bins equispaced in $\sin^2(\theta)$ in order to have approximately the same exposure. Based on [2] we propose a combined model of the efficiency consisting in a sigmoid function, just like eq. (2) but including the dependency on the zenith angle in the parameters E_0 and b:

$$\varepsilon(E, \theta) = \frac{1}{2} + \frac{1}{2}\mathrm{erf}\left(\frac{\log_{10}(E_{750}/\mathrm{eV}) - E_0(\theta)}{b(\theta)}\right) \tag{3}$$

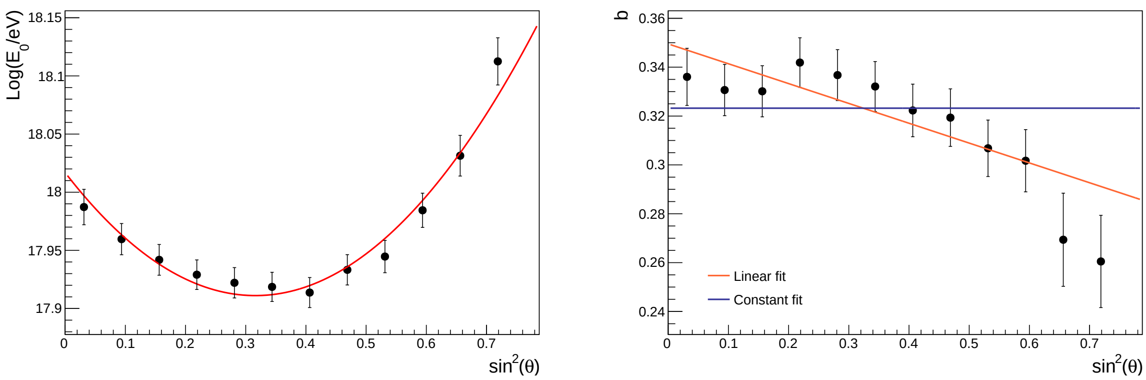

Figure 4: Parameter dependency with $\sin^2(\theta)$ for the preliminary fit. E_0 shows a quadratic dependence and b is modeled by a constant function and a linear function.

In order to see the functional form of $E_0(\theta)$ and $b(\theta)$ we propose a preliminary analysis where the efficiency is measured for each $\sin^2(\theta)$ bin separately. Figure 4 shows a quadratic dependency of E_0 while for b, two models are proposed, one of constant b and other linear in $\sin^2(\theta)$. In consequence two parametrizations of the efficiency as a function of the energy and the zenith angle are proposed: one of 4 parameters with $E_0(\theta) = p_0 + p_1 \sin^2(\theta) + p_2 \sin^4(\theta)$ and $b = b_0$ and one of 5 parameters with the same E_0 but $b = b_0 + b_1 \sin^2(\theta)$. With the fitted parameters for the single bins as initial values, we made a simultaneous χ^2 fit of the efficiency for the 4 parameter and the 5 parameter models. Results are shown in table 1.

In order to compare the results, the 4 and 5 parameter fits were evaluated in the centre of each zenith angle bin. As an example, fig. 5 shows the results for the bin $56.0 \leq \theta \leq 60.0$. For further reference, fig. 10 in the appendix shows this data for all the zenith angle bins. For the more vertical bins, both the 4 and 5 parameter fits show accordance with the measured efficiency but for the more inclined events, the 5 parameter description adjust better the data. Seeing 1 can give an explanation for this. Both parameters in the 5 parameter and 4 parameter fits are very similar, the extra linear term in $\sin^2(\theta)$ can be seen as a correction that's specially relevant for the more inclined events. In consequence, our proposed model of the efficiency is the 5 parameter one:

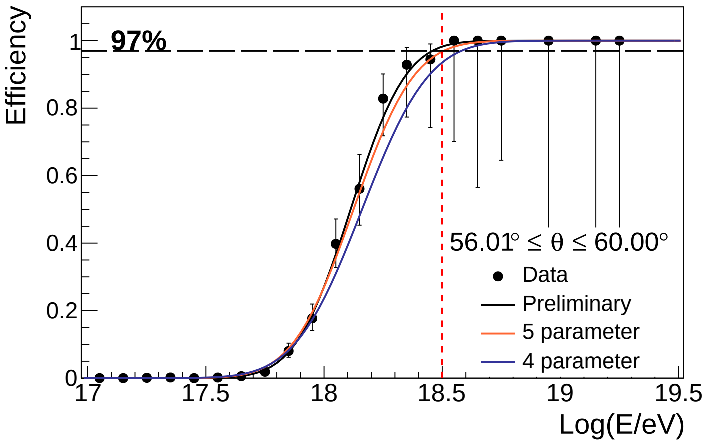

Figure 5: Efficiency for the 56.0° − 60.0° zenith angle bin together with the preliminary fit and the 4 and 5 parameter models.

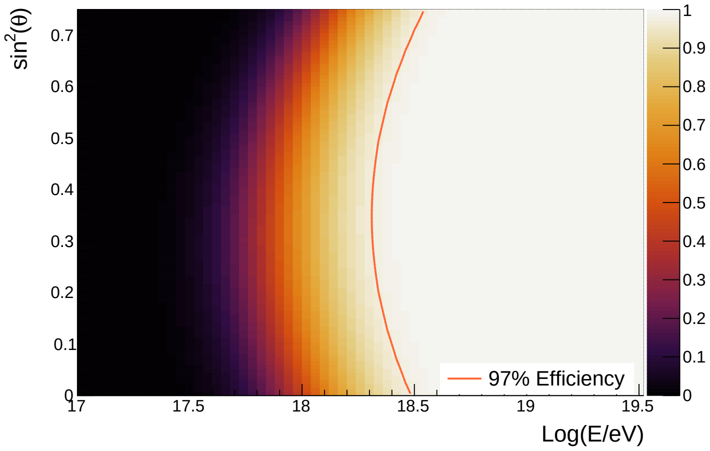

Figure 6: Efficiency as function of the Energy and zenith angle and the 97% surface level.

$$\varepsilon(E,\theta) = \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{\log_{10}(E/\mathrm{eV}) - (p_0 + p_1 \sin^2(\theta) + p_2 \sin^4(\theta))}{b_0 + b_1 \sin^2(\theta)}\right)\right) \tag{4}$$

with $p_0 = 18.03$ $p_1 = -0.91$, $p_2 = 1.45$, $b_0 = 0.336$, $b_1 = -0.068$. We are working to have a better understanding of the errors associated with this adjustment.

Figure 6 shows the surface plot of the efficiency as a function of the energy and the zenith angle. The efficiency is lower for the vertical events, increasing and reaching a maximum at approximately 30° and then decreasing for the most inclined events. The 97% efficiency threshold ranges from $10^{18.5}$ eV improving to almost $10^{18.3}$ eV at 30° and then decreases. This behaviour is in accordance to the model proposed in [2].

	p_0	p_1	p_2	b_0	b_1
Preliminar	18.01	-0.67	1.1	0.350	-0.08
5 parameter	18.03	-0.92	1.45	0.336	-0.07
4 parameter	18.01	-0.83	1.44	0.315	-

Table 1: Parameter results for the preliminary analysis and the 4 and 5 parameter models proposed.

4 Inclusion of the ToTd and MoPS triggers

Since 2013 two new station level triggers were included in the acquisition system for the surface detectors of the Pierre Auger Observatory. However, the SD1500 spectrum currently reconstructs events only using the original ToT and TH2 triggers. These triggers are more sensitive to the electromagnetic component of the shower which is more dominant at lower energies. Since our method is limited only by the full efficiency threshold of the SD750, we propose to use our analysis for the SD1500 dataset reconstructed including these electromagnetic triggers. In order to do that, the events were reconstructed using the Trunk version 33753 of the Offline framework for the same time period. This reconstruction results in 74853 simultaneous events in both SD arrays, a 500% increase with respect to the reconstruction only with the old triggers.

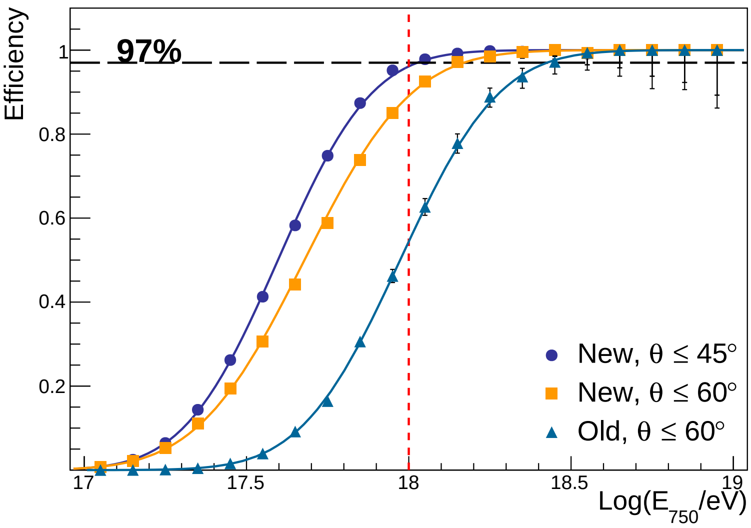

Figure 7: SD1500 efficiency including the new triggers for $\theta \leq 60°$ and $\theta \leq 45°$. The 97% efficiency threshold is reached at $10^{18.2}$ eV and 10^{18} eV respectively.

When including the new triggers in the whole zenith range, from 0° to 60° the efficiency increases and the full efficiency starts at 1.25×10^{18} eV, three energy bins lower than using only the original triggers. When the zenith angle dependency is brought into consideration, the efficiency shows a stronger dependency with the inclusion of the new triggers. This is expected, since the electromagnetic component of the shower suffer stronger attenuation because of the further distance travelled in the atmosphere. From this, we propose a modification in the acceptance angle for the events, lowering the maximum zenith angle to 45°. Figure 7 shows the efficiency including the new triggers with and without the new acceptance angle, compared to the reconstruction only including the original triggers. This modification yields to being able to report the spectrum from 10^{18} eV, gaining four bins with respect to the current spectrum measurements.

5 Efficiency correction of the SD1500 Spectrum

The spectrum measured by Auger with the SD1500 is reported only including events where the acceptance of the detector is independent of the mass and energy of the primary particle. However, having a fully experimental measurement of the energy, we propose to introduce an efficiency correction to the SD1500 spectrum in order to gain data for the lower energies. Using our reconstructions made for the efficiency analysis, we made the event histogram of the SD1500 for the original triggers and zenith angle below 60°. Also, we made the same histogram for including the new triggers with the new 45° acceptance angle. To make the histograms comparable, we used as a reference the SD750 event histogram. In first place, the histogram including the new triggers was scaled by 1.5 to have into account the difference of angular exposure with respect to the original triggers histogram. Then, the efficiency correction was introduced by dividing the number of events in each bin by the efficiency measured for that bin. Lastly, all fluxes were scaled to match the flux of the SD750 at $10^{18.4}$ eV, where the detectors are fully efficient to take into account de geometric factors.

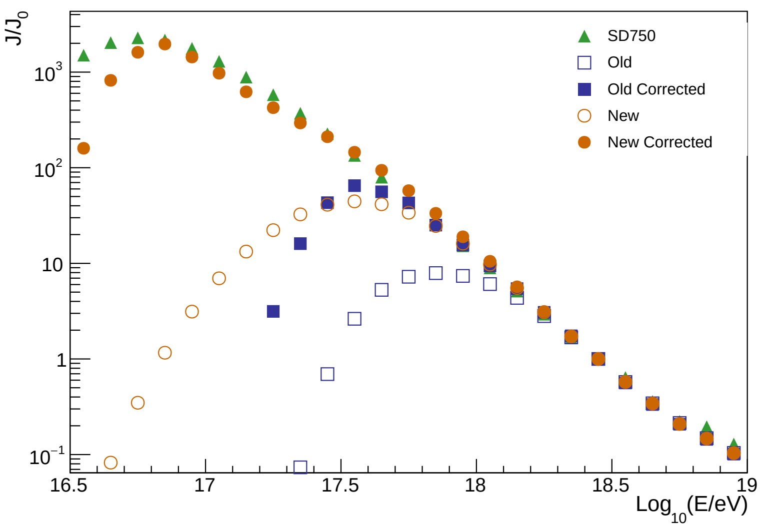

Figure 8: Raw flux measured by the SD1500 using old and new triggers and it's efficiency correction. The fluxes were normalized to $J_{18.2} = 1$.

Figure 8 shows the fluxes both before and after the efficiency correction was introduced. For energies above the full efficiency threshold, the SD1500 fluxes before the correction behave like the SD750. However, for energies below the full efficiency the difference between the measurements quickly increases. With the introduction of the efficiency correction, the SD1500 follows the behaviour of the SD750 for energies lower than full efficiency until the correction factor is too big to have a good estimation of the flux. For the SD1500 including the new triggers the results are very remarkable, the fluxes being similar for energies as low as 10^17eV. The relative difference between the flux of the

SD1500 and the SD750 is shown in fig. 9 both before and after the efficiency correction. This preliminary analysis for a possible improvement of the SD1500 spectrum for lower energies shows very promising results. The difference between the fluxes for energies lower than 10^{18} eV increases up to about 100% at 10^{17} eV if it is not corrected. However with the inclusion of the correction the data shows differences of about 25% for this energy range.

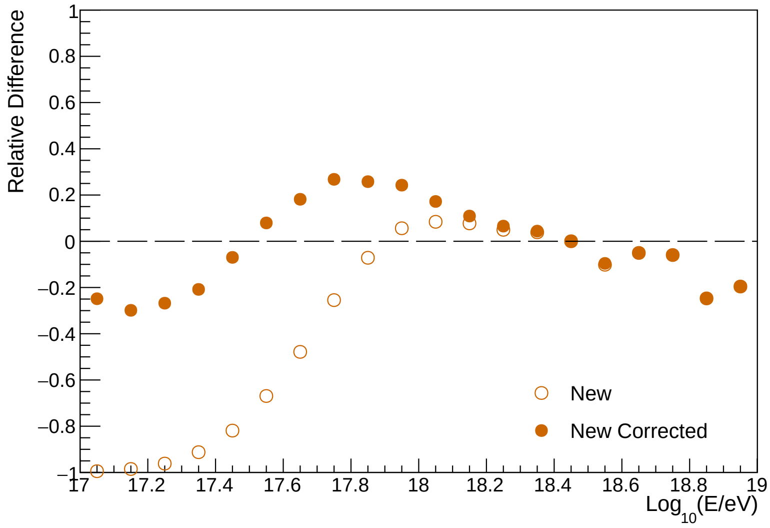

Figure 9: Relative difference between SD1500 flux and the SD750 for the old trigger reconstruction and after efficiency correction.

Conclusions

We provide a fully experimental measurement of the SD1500 efficiency using the SD750 dataset. The efficiency measured shows that the detector acceptance becomes independent of the mass and energy of the primary particle for events with energies higher than 2.51×10^{18} eV which is in accordance with the current threshold used by Auger. By studying the dependence of the efficiency as a function of the energy and zenith angle we propose a 5 parameter model of the efficiency. When including the new station level triggers in the reconstruction the efficiency improves and the 97% efficiency threshold is reached for energies above 1.4×10^{18} eV. However, given the stronger dependence of the efficiency on the zenith angle, we propose a new acceptance angle of 45° which leads to a spectrum starting at 10^{18} eV. Finally we propose the tentative inclusion of an efficiency correction to the SD1500 in order to report the spectrum to even lower energies, having satisfactory results for energies even in the 3.16×10^{17} eV range.

Appendix: Zenith angle dependency of the Efficiency

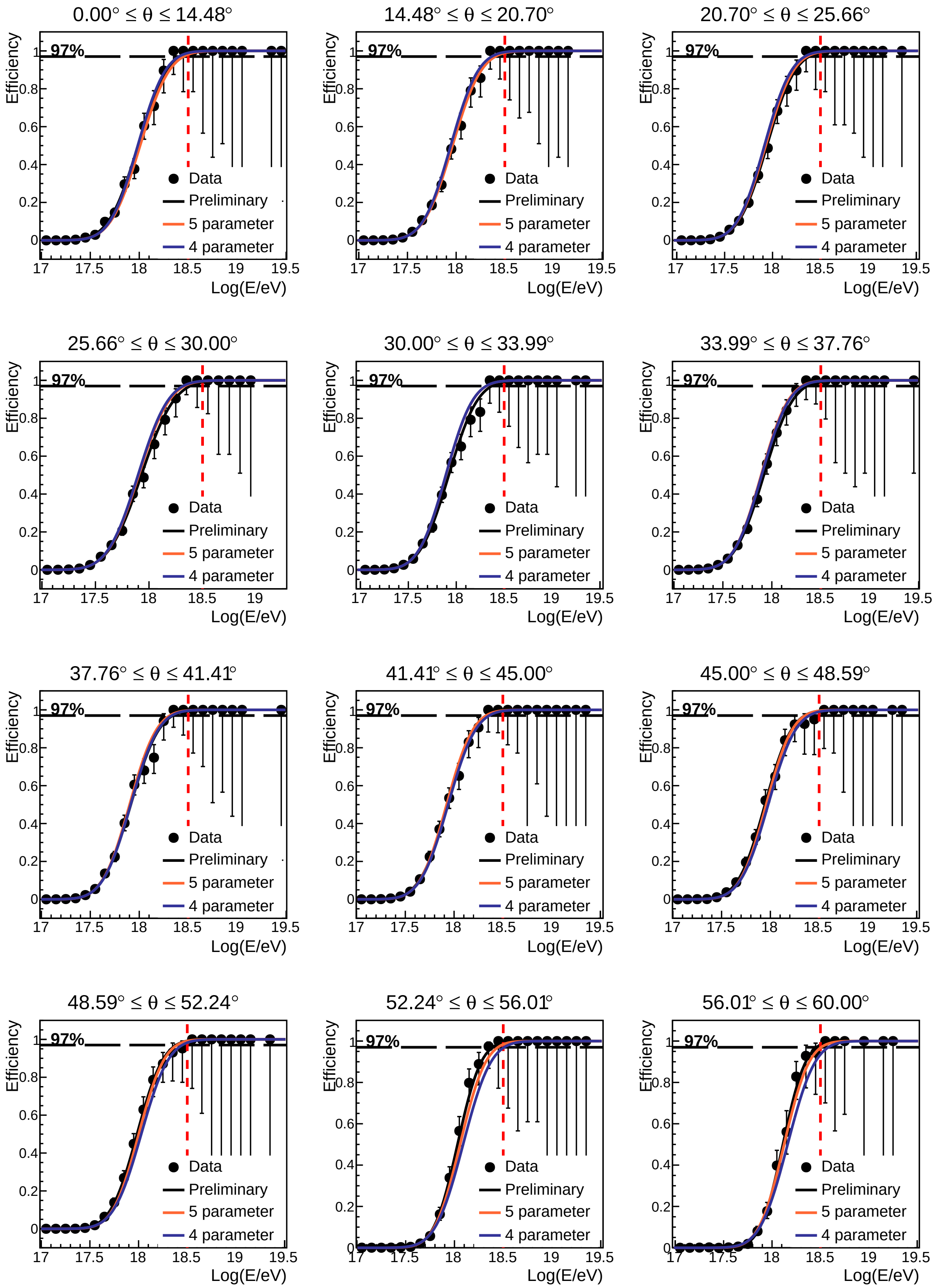

Figure 10: SD1500 efficiency for zenith angle bins and the 4 and 5 parameter fittings proposed together with the preliminary fit.

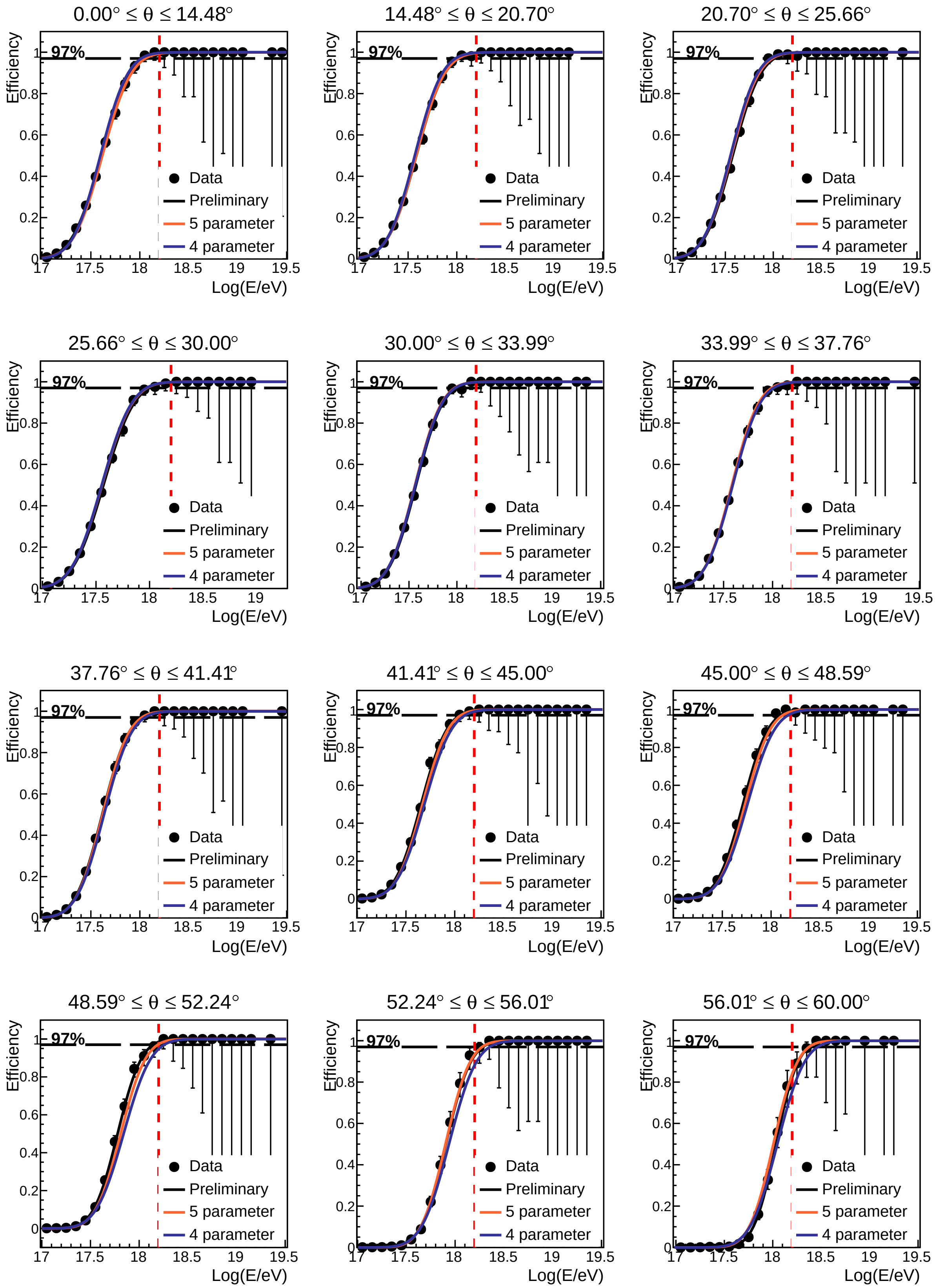

Figure 11: Efficiency for the zenith angle bins for events reconstructed including the new triggers and it's parametrizations.

References

[1] A. Coleman. *Measurement of the cosmic ray flux above 100 PeV at the Pierre Auger Observatory*. PhD thesis, Pennsylvania State University, 2018.

[2] The Pierre Auger Collaboration. Measurement of the cosmic-ray energy spectrum above 2.5×10^{18} eV using the Pierre Auger Observatory. *Phys. Rev. D*, 102(6):062005, 2020.

[3] The Pierre Auger Collaboration. The energy spectrum of cosmic rays beyond the turn-down at 10^{17} ev as measured with the surface detector of the pierre auger observatory. accepted in Eur. Phys. J. C, 2021.

[4] I. Lhenry-Yvon and R. Sato. The 2018 - 2019 infill comms crisis.impact on the data set and the proposal to fix it. *GAP-Note 2021-007*.