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Classification and Reconstruction of single and multiple ELVES in AUGER

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Abstract. ELVES have been regularly studied since 2013 with the twenty-four telescopes of the Pierre Auger Observatory, exploiting a dedicated trigger and extended readout. A large fraction of the observed events shows double ELVES within the time window, and, in some cases, even more complex structures are observed. We classify double ELVES using the radial variation of the time gap and the photon flux ratio between flashes. Such parameters may be related to the different types of lightning in which they originated. We will review the cross correlations of the ELVES light emissions with the radio waves detected by the antennas of the ENTLN network, active in Argentina since late 2018. Further improvements of our detection and classification algorithms were achieved by detecting ELVES from closer lightning: since December 2020, the ELVES trigger was extended to the three High Elevation Auger Telescopes (HEAT), which observe the night sky at elevation angles between 30 and 60 degrees, with an enhanced time resolution (50 ns time binning). Both single and double ELVES are recorded with unprecedented time and space resolution. Events from the first year of data taking will be shown.

Introduction

The Pierre Auger Observatory is the world's largest infrastructure for the study of ultra high energy cosmic rays. Besides its main activity, the Observatory has started a program of cosmo geophysics studies, which exploit some of the unique features of its detectors. ELVES are transient luminous events occuring at the base of the ionosphere, when a strong electromagnetic pulse (EMP) is emitted by a lightning. These phenomena, theoretically predicted a few years before [1], were photographed for the first time in 1990 from the Space Shuttle [2]. For an observer at ground, ELVES appear as rapidly expanding rings, smoothly fading towards the horizon, and can be observed at distances farther than 250 km from our fluorescence detector (FD) [3]. The events triggered by Auger are produced by lightning sources far enough from the FD, such that the earth curvature prevents the direct light from reaching our sensors. Since 2013, we developed a dedicated trigger and readout scheme to study these events, using the twenty-four FD Telescopes [4,5,6]. In December 2020, we implemented the ELVES trigger and readout in the data taking of the three additional high elevation telescopes (HEAT) located in the proximity of the Coihueco site.

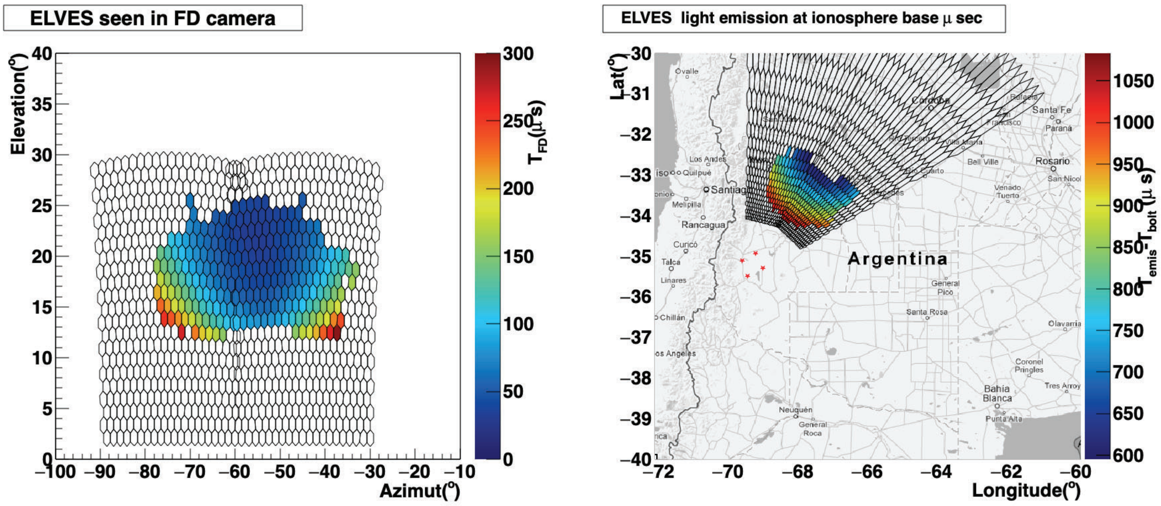

Figure 1. A typical ELVES event: the time evolution (in color) is shown (left) as seen in the FD telescopes , and (right) as projected at the emission layer at the base of the ionosphere, after correcting for the transit time from the emission layer to the FD. The four red stars show the FD sites.

Parametrization of double ELVES

It is known that the ELVES is produced by the EMP emitted during the lightning return stroke or in initial breakdown stages of the discharge. The conditions that favor the production of two or more ELVES rings in less than one millisecond are not yet clear. In Auger, we have observed that the fraction of multi ELVES events peaks in April [7]. Ground reflection is the most common explanation for the double ELVES.

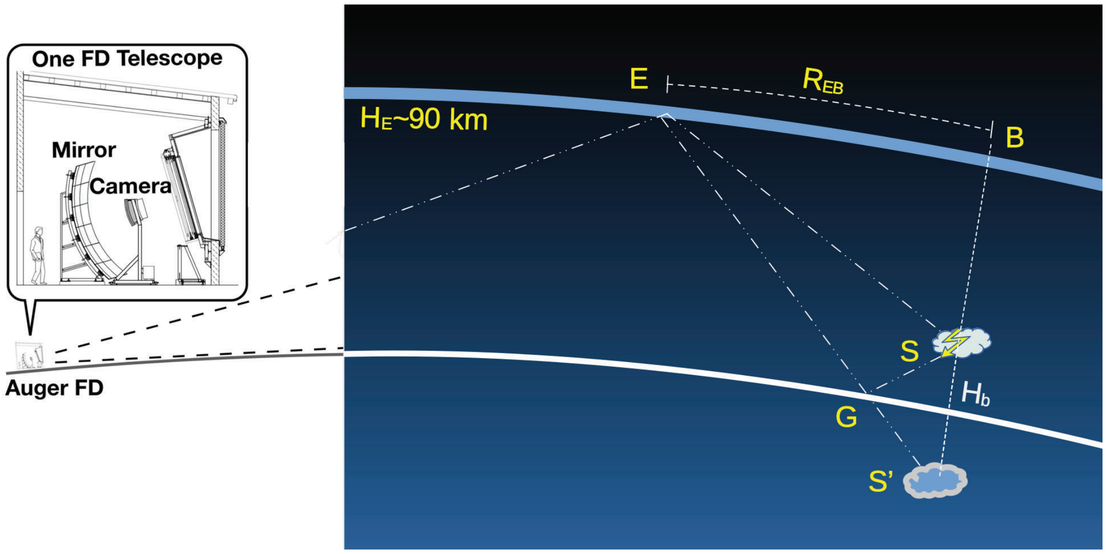

Figure 2. Geometric model for the calculation of the time gap between the first (light path: SED) and the second pulse (light path:S'ED, equivalent to SGED) observed in a given pixel, pointing towards E.

Therefore we wrote a simple model to calculate the time gap between the first and second flash as a function of the region at the base of the ionosphere where the EMP is converted into the UV light which we observe in a given pixel of our camera. If the primary source is assumed to be at an altitude H_b, therefore at a distance $R_{earth}+H_b$ from the center of Earth, we can idealize the second pulse as if coming from a source located at the same latitude and longitude, but at a radius $R_{earth}-H_b$, as shown in Figure 2. From the symmetry of the problem, we expect the time gap to be constant at a fixed arc distance $ArcR=R_{EB}$ at the base of the ionosphere between the region emitting the light and the lightning location.

In Figure 3, the relation between time gap and ArcR is shown. In a typical ELVES caused by a lightning at a distance of 400 km from the FD telescopes, the first triggered pixel is about 200 km from the vertical of the lightning, which correspond to a time gap of 12 (25) μs for a source at H_b=5(10) km. This limits the observation of double ELVES from EMP bounce to lightning sources not exceeding 400 km. The colored markers in Figure 3, left plot, are consistent with the *bounce* hypothesis, for an ELVES observed by two sites. Events like this are rare: most double ELVES exhibit patterns like the one shown in Figure 3, right plot, with a time gap which is flat for most of the field of view.

Another class of events are the triple ELVES: Auger has published the first observation of such events [5], which exhibit a narrow gap, maybe due to ground reflection, and a broader one. A paper by Liu et al. [8] suggests that Terrestrial Gamma Flashes (TGFs for short) which originate at the top of thunderstorm clouds may produce three or four distinct ELVES.

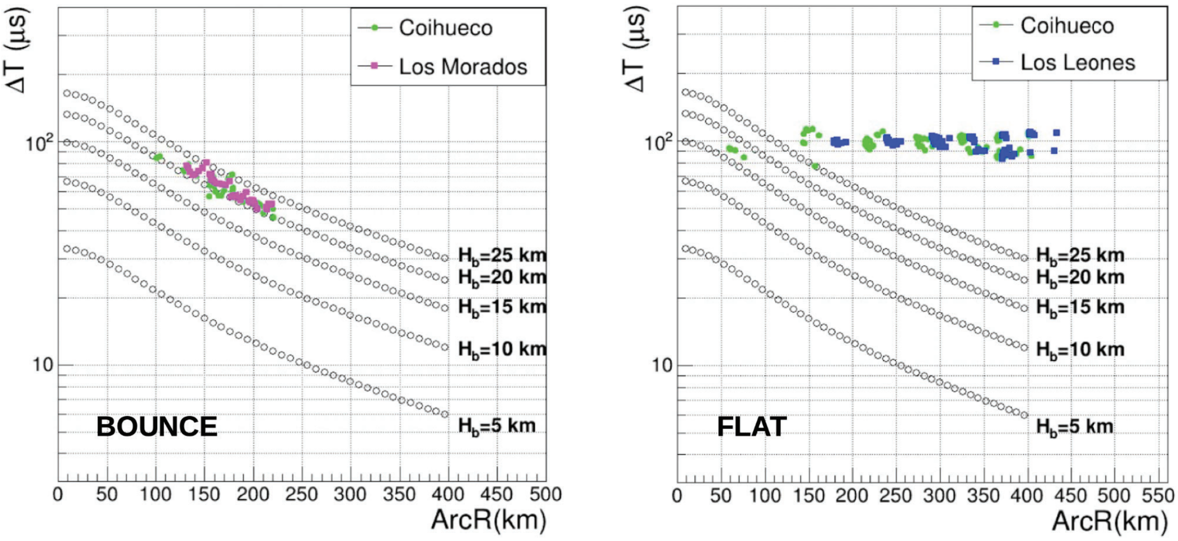

Figure 3. Classification of double ELVES according to time gap vs arc distance. Ground reflections (nicknamed *bounce* events) on the left are much less frequent than *flat* events (on the right). Both examples are observed by two telescopes.

The second parameter that can be studied to compare different models is the ratio between the total amount of light from the first peak (Q_{1tot}) and the one of the second peak (Q_{2tot}), for each pixel. In Figure 4, we show the ratio profile Q_{2tot}/Q_{1tot} vs ArcR for double ELVES detected on April 28,2020, the night with the largest number of flat double ELVES in the period 2014-20. Such an observable is plotted as a function of the arc distance ArcR from the lightning for all events in one storm. All pixels from the same event have the same color. We observe a significant number of events consistent with the empirical relation $\log(Q_{2tot}/Q_{1tot}) = k\ ArcR+m$, where k is a positive constant. Other events show more complex functional relations with ArcR which may be reconstruction artifacts, and deserve further studies. The large fraction of events in our sample of double ELVES which are observed by more than one FD site is useful to discard artifacts due to clouds in the foreground.

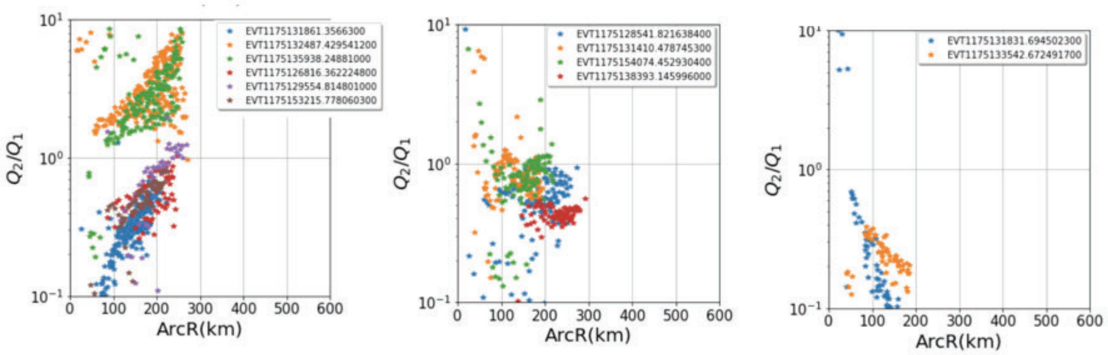

Figure 4. Study of the arc distance dependence of the ratio between the light intensity of the second flash and the first one. All events were detected on the same night (April 28,2020): most show clear increasing (left) or decreasing patterns (right), but some (center) have more complex features.

Reconstruction of close ELVES detected by HEAT

Starting in January 2021, the ELVES trigger has been implemented also in the three HEAT telescopes located in the proximity of the Coihueco FD site. These three fluorescence detectors are meant to extend the dynamic range of the Observatory, detecting lower

energy cosmic ray showers. The three detectors are identical in size and aperture to the other 24 FD telescopes, but the optical axis of their mirrors can be tilted to an elevation angle of 45 degrees. The field of view of these three detectors is shown in Figure 5: the red hexagons show the pixel edges in operation mode, the green hexagons show them in the calibration mode, to cross calibrate the observed events with the ones seen in Coihueco. During the year 2020, the HEAT telescopes were operated in calibration position from July to September, and we exploited the rare thunderstorms which occurred in this period to check alignments and trigger efficiency.

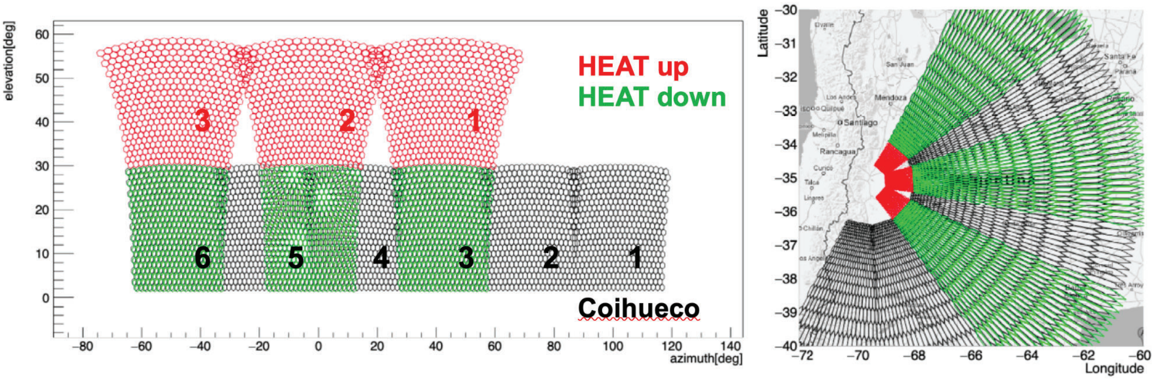

Figure 5. Field of view of the three HEAT telescopes, compared with the ones in the near site of Coihueco. The camera views are shown on the left, and the projections of each pixel at the base of the ionosphere are shown in the map on the right.

In the standard Auger FD's, triggering of ELVES from lightning closer than 250 km is prevented by the arrival of the direct light from the thunderstorm at ground which overwhelms the emission from the base of the ionosphere, and, due to multiple scattering, does not follow the time pattern which is typical of each ELVES. Given the large elevation angle, the HEAT telescopes can observe the light from much closer lightning, as the direct light from the bolt is prevented from reaching the camera by the tilted entrance window. Such a feature allows one to observe the region of maximum emission, which typically has a radius of about 80 km around the vertical of the lightning, with unprecedented resolution. The HEAT electronics is two times faster than the one of the standard FD's, and each trace is made of 2000 bins to cover the same time window of the FD traces (100 μs). The ELVES trigger is programmed to acquire a maximum of three consecutive pages, for a total trace length of 300 μs. In comparison, ELVES traces in standard FD reach up to 900 μs [9].

Because of the tilted geometry, HEAT can only see a portion of the full ELVES: the vertical of the causative lightning is often contained in the field of view of one of the standard telescopes. Very few events trigger simultaneously HEAT and the standard FD telescopes.

Reconstruction of ENTLN waveforms in coincidence with the Auger ELVES

In a previous publication [5] we used ELVES events in coincidence with lightning detected by global detection networks (WWLLN, GLD360) to estimate the resolution and bias of our lighting detection algorithm. Recently, we have analyzed the ELVES correlated with lightning located by GLD360, and compared the distribution of correlated events as a function of current and polarity.

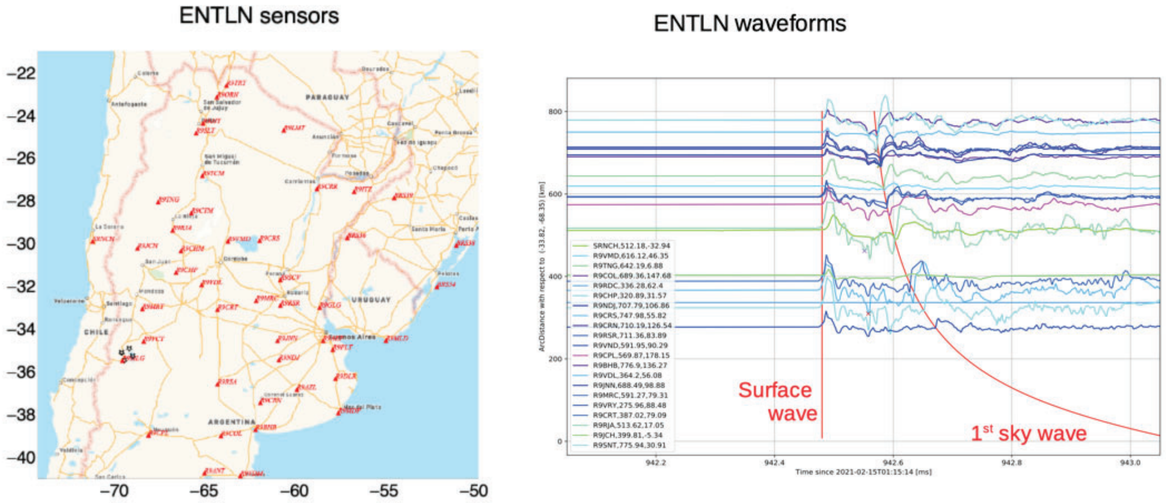

Figure 6. Left: Location of the ENTLN antennas in Argentina; four black stars identify the Auger site. **Right:** Reconstruction of ENTLN traces using the reconstruction of the ELVES detected by Auger to calculate the time delays between antenna signals.

The result is shown in ref.[7] , and proved that double ELVES are more frequently generated in negative lightning strikes. To further investigate this subject, we started comparing our ELVES data with the waveforms detected by the Earth Networks Lightning Network (ENTLN) , which is operational in Argentina since 2018 [10,11] and provides high bandwidth data, which allow accurate determination of the lightning type, distinguish between cloud-to-ground and intracloud lightning. A map of the ENTLN antennas deployed over South America is shown in Figure 6. We have written a minimization algorithm to compare the source location obtained synchronizing the ENTLN traces with the result of our time fit. One example is shown in Figure 7. The two best fits are less than 6km apart from each other.

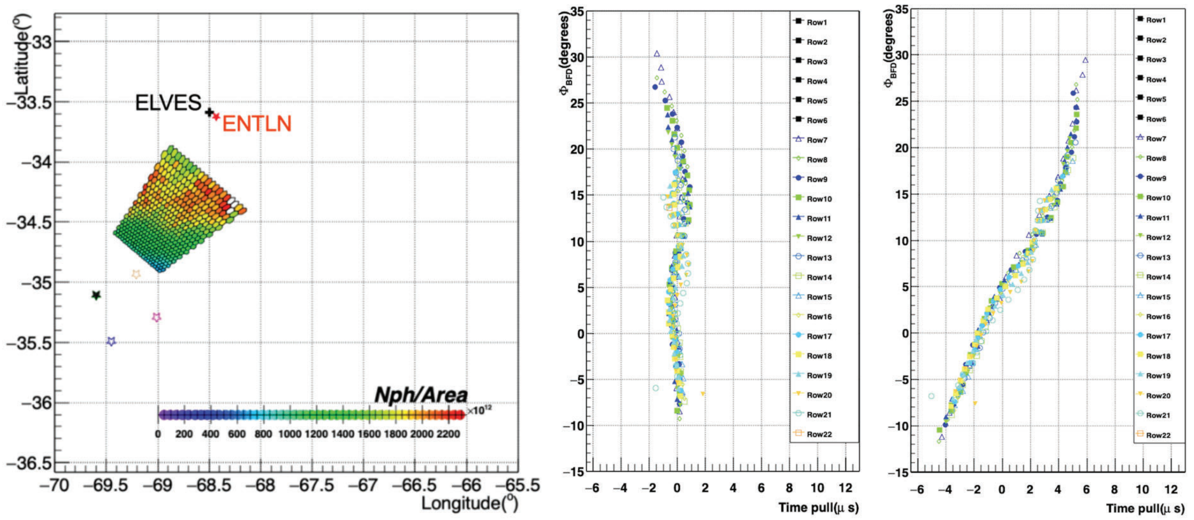

Figure 7. Left: surface density of photon emission at the base of the ionosphere, and EMP source location, as reconstructed by ELVES (black) and by ENTLN (red). **Center:** pulls vs pixel azimuth (Y axis) and row number (color) from the time fit of ELVES signals using best fit longitude and latitude. **Right:** same pulls, using ENTLN best fit for the source coordinates.

Conclusions

Multiple ELVES have been frequently observed since 2014 by the Auger Observatory, thanks to the high time resolution of our PMTs. By studying the dependence of the time gap between flashes in each pixel, we have found that a large fraction of double ELVES cannot be explained as ground reflections of the EMP which generated them. We have started then to study the ratio between the intensity of the two flashes, where a variety of patterns are observed, suggesting that multiple ELVES are due to diverse causes. With the introduction of the new trigger on the HEAT telescopes, we have access to closer lightning, with better time and space resolution. This will allow better studies on double ELVES from lower clouds that cannot be resolved in the other telescopes. Furthermore, the comparison of ELVES light curves with the signals from ENTLN antennas, deployed in Argentina in 2018, will allow us to correlate the features of double ELVES with the polarity of intracloud lightning and return strokes.

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