PROCEEDINGS OF SCIENCE

Search for very high energy gamma-ray bursts based on LHAASO-WCDA triggered data

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Water Cherenkov Detector Array (WCDA), a part of Large High Altitude Air Shower Observatory(LHAASO), is a very sensitive gamma source detector in hundreds GeV to dozens TeV due to its effectvie gamma-proton discriminating capability. Triggered data is always preserved for long term, which makes long time analysis for gamma-ray bursts (GRBs) possible. Based on LHAASO-WCDA triggerd data, we searched GRB signal using location and corresponding time extracted from GCN website if GRB bursts in view from March 5, 2021 to February 1, 2023 manually. Alert automatic analysis program is deployed in April, 2023, which will give analysis results within 2 days automatically. Trial number is considered to avoiding misjudging. In this contribution we will introduce searching strategy, alert automatic analysis workflow and present the total searching results.

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1. Introduction

GRBs are irregular pulses of gamma-ray radiation lasting less than serveral thousands seconds at random direction in the sky. They are usually regarded as production of compact binary star merger or massive star collapse. However, observation in TeV energy is still rare and some detail about the process remains a mystery.

Detection on VHE emission of GRB is one of the key scientific goals of LHAASO. Simulation on observation of GRB with LHAASO-WCDA under spercific condition is performed in [2] and it predicts LHAASO-WCDA observes 1 GRB per year. LHAASO consists of three kinds of arrays: the Kilometer Square Array (KM2A), which is a ground-based particle detector array covering one square kilometer and composed of 5,216 electromagnetic particle detectors and 1,188 muon detectors; the Water Cherenkov Detector Array (WCDA), which covers 78,000 square meters and comprises of 3,120 detection cells; and the Wide Field-of-view Cherenkov Telescope Array (WFCTA), consisting of 18 telescopes. LHAASO-WCDA provides triggerless data, which includes all infomation recorded in detection cells in the time around GRB, and triggered data, which contains less noise and be saved to disk forever.

Triggered data is analysed for GRB signals, as gamma-proton discrimination parameters like $Pincness$ work well, which make LHAASO-WCDA more sensitive. Triggered data is also suitable for long term afterglow analysis, on condition it comes into field of view. We open a series time windows according to the location and burst time given by GCN, calculate significance and analyse the trial number limit. We show the final searching result using data from April 2021 to July 2023.

2. Analysis method

2.1 Searching strategy

Analysis begins with a prior known location and bursting time from GCN. We collect data around the GRB position, and divide data into pieces by time. For data within 45 minutes after GRB, the cumulative map is generated every minutes. If GRB keeps in view, then map is accumulated every 5 minutes, till 2 hours after bursting. Accumulation continues every hour until GRB goes out of view, which is defined region where zenith angle is less than 60deg for observation. If more data is accessible, cumulative map is calculated evergy day when GRB again goes out of view. After above, cumulative map is subtracted by the previous one to get a time windows. As such generated window is independent to each other, the number of these plus 1 (the first cumulative window) is regarded as lower limmit of trial number. We then sum up neighboring two independent window to generate more. Suming continues based on previous sum windows, until no more window could be gnerated. The total number of time window we get is used as upper limit of trial number. Figure 1 shows a real time window for GRB 221009A. Each horizontal stripe illustrate one time window, with its left end and right end corrsponding to begin time and end time. Light background green color area means time GRB 221009A stay in view.

In each time window, we count events 0.5 deg within GRB, which is inspired by PSF of LHAASO-WCDA, as N_{on}. events in the same declination but in shifting time are counted as N_{off} while area 3 deg near GRB are always masked. Considering the possible event correlation between

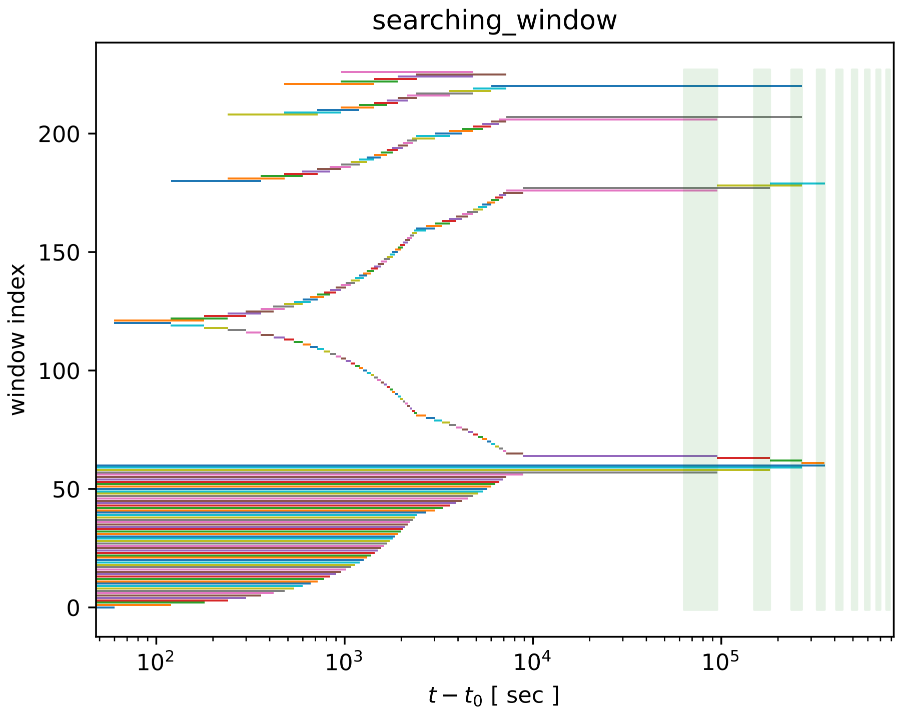

Figure 1: searching time windows of GRB 221009A. We use data within 5 days after bursting. Windows with index ranging from 0 to 39 cumulates data evergy miniuts. Those ranging from 40 to 55 cumulates data evergy 5 minutes. 56 to 60 corresponds windows day by day. 61 to 120 is from accumulated window by subtracting it's prior window. 121-179 is generated by combine neighboring two windows from 61 to 120. Windows with index more than 179 are genrated in similar way. Trial number is reported between 61 and 227.

off events, the final α, which is the ration of expected cosmic background in N_{on} and N_{off}, is less than 0.01. Significance is calculated with

$$s = \sqrt{2}\sqrt{N_{on}log(\frac{1+\alpha}{\alpha}(\frac{N_{on}}{N_{on}+N_{off}})) + N_{off}log((1+\alpha)(\frac{N_{off}}{N_{on}+N_{off}}))} \quad (1)$$

given by [3]. Window with N_{off} equal to 0 is ignored. As data may correlated to each other among the time windows, trial number is hardly precisely calculated but we report its upper limit and lower limit. Trial number differs, denpending on the zenith angle when a GRB occurs, usually less than 300.

2.2 Alerts automatic analysis

In order to get observed resutls timely, analysis program based on information from GCN alerts runs automatically every day. First it checks whether there is alerts to analyse and whether there is enough reconstructed data. If everything is ready, program searches signals in about 9 hours after the burst without manual intervention. Analysis takes 2 to 10 hours, depending on the server's working envrionment. Results are sent to everyone interested by email for further checking. Figure

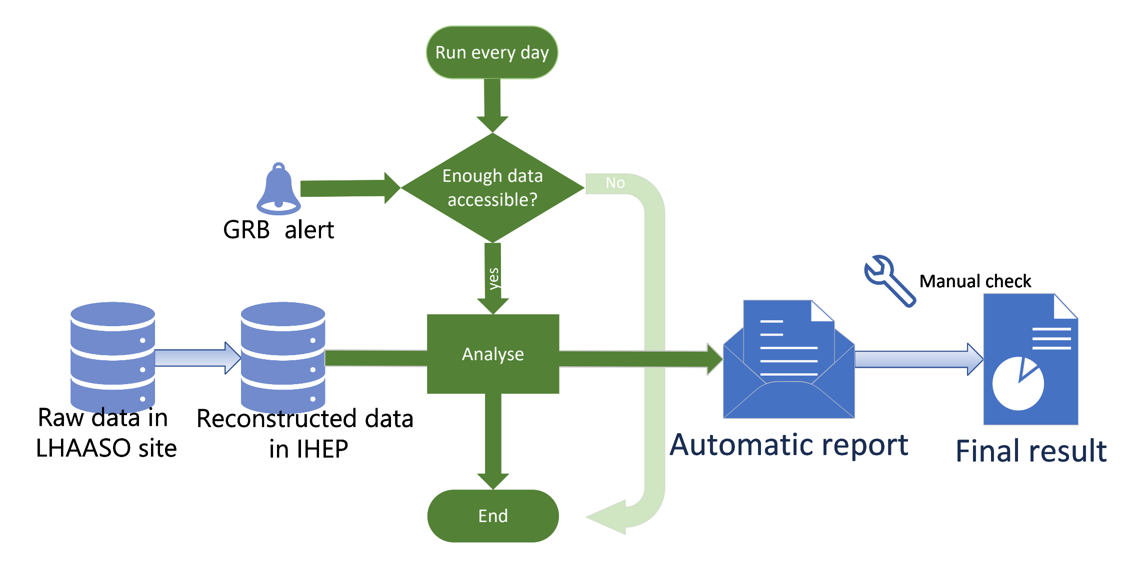

Figure 2: Alerts searching workflow. Green color shapes illustrate workflow of alert automatic analysis program. Alert automatic program produces email report with reconstructed data and GRB alert information.

2 gives a brief illustration on how data processed (blue shapes) and how program works (green shapes). The whole preocess including recording data from GRB, reconstructing direction and rough energy, analysing and manual checking, usually finishes in 2 days.

3. Results

We manually analyse 356 GRBs occur in view, or come into view later, using data from March 5, 2021 when LHAASO-WCDA full array begin to work, to February 1, 2023. Location is chosen to be roughly the most precise one and time is checked to be the earliest one from GCN email list. For alert automatic program, every alert with position and bursting time triggers a seraching. Alert automatic program is deployed in April and scheduled to run every morning. All 262 alerts in view from January 1, 2023 to July 11, 2023 are already analysed.

Among all the above searching, GRB 221009A shows confident excess, with significance up to 170.526 σ, while no signal is found in others. Figure 3 shows all result significance excluding GRB 221009A. Each time window provides a significance number. The results follow normal distribution, with its maximum less than 3.5 σ.

Figure 4 shows significance map of GRB 221009A using data that begins at time given by [6] and ends 1136 seconds later. Trial number searching along time is estimated to be larger than 61 and smaller than 227. The final significance considering trial number is between 170.494 and 170.502 σ.

We calculate the sensitivity of LHAASO-WCDA for GRB, as shown in Figure 5. Assumping GRB emission lasts for 600 seconds, with spectrum index without extragalactic background light (EBL) fixed to 2.4, and EBL model follows as [5], the least flux at 3 TeV that satisfies 5 σ significance using LHAASO-WCDA triggered data depends on distance (reprented by redshift), and zenith angle. We apply these factors by reweight standard Monte Carlo gamma events of LHAASO-WCDA. GRB

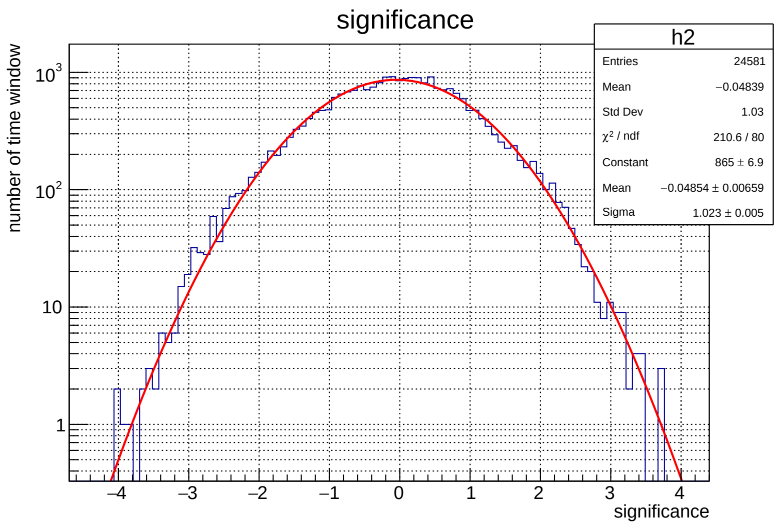

Figure 3: Searching results without GRB 221009A. Results include analysis GRB by GRB from March 5,2021 to February 1, 2023 and alert by alert from January 1,2023 to July 11, 2023. Searching during unstable period is discarded. Only windows with estimated background more than 4 are shown.

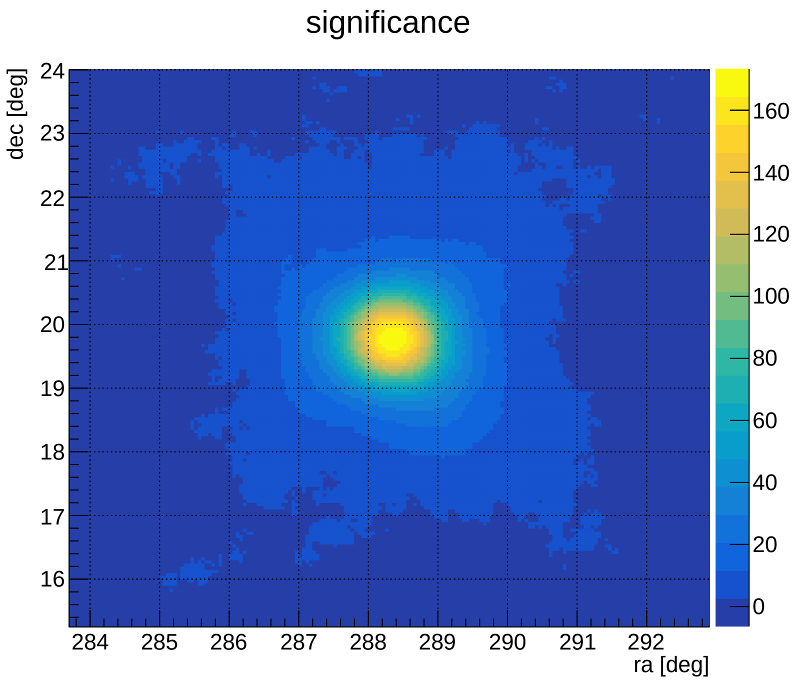

Figure 4: significance of GRB 221009A, data is collected from 0 to 1137 seconds after the burst. In our searching, only the center significance value is used.

221009A has a feature time about hundreds seconds, spectrum index close to our assumption, and redshift equal to 0.151, so we plot it on figure 5. Compared to the blue curve, it is hundreds higher than the given sensitivity by LHAASO-WCDA.

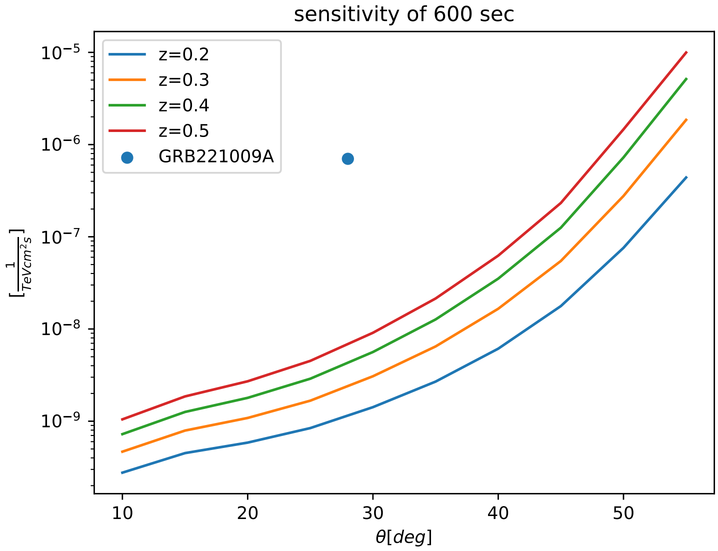

Figure 5: Least flux at 3 Tev satisfying 5 σ detection if burst lasts 600 seconds. Specturm index is fixed to 2.4. GRB221009A is detected with redshift 0.151 according to [8] and spectrum index approximately according to [1]. All the results are based on Monte Carlo data.

4. Summary

LHAASO-WCDA triggered data is sensitive due to it's descrimination of gamma and proton. Based on the location and bursting time from GCN, we search GRB signal in different time window after the bursting and develop a software to automatically begin analysis with alert. We search 356 GRB from March 5, 2021 to February 1, 2023 extracted from GCN email list and alert automatic analysis program search 262 GRB alerts with data from January 1, 2023 to July 11, 2023. GRB 221009A shows extremely signifcant signal exceeding 170.494 σ while others are not observed. We also make a simulation to get the sensitivity for GRB with different redshift and spectrum index.

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