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Joint Observation of the Galactic Center with MAGIC and CTA-LST-1

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MAGIC is a system of two Imaging Atmospheric Cherenkov Telescopes (IACTs), designed to detect very-high-energy gamma rays, and is operating in stereoscopic mode since 2009 at the Observatorio del Roque de Los Muchachos in La Palma, Spain. In 2018, the prototype IACT of the Large-Sized Telescope (LST-1) for the Cherenkov Telescope Array, a next-generation ground-based gamma-ray observatory, was inaugurated at the same site, at a distance of approximately 100 meters from the MAGIC telescopes. Using joint observations between MAGIC and LST-1, we developed a dedicated analysis pipeline and established the threefold telescope system via software, achieving the highest sensitivity in the northern hemisphere. Based on this enhanced performance, MAGIC and LST-1 have been jointly and regularly observing the Galactic Center, a region of paramount importance and complexity for IACTs. In particular, the gamma-ray emission from the dynamical center of the Milky Way is under debate. Although previous measurements suggested that a supermassive black hole Sagittarius A* plays a primary role, its radiation mechanism remains unclear, mainly due to limited angular resolution and sensitivity. The enhanced sensitivity in our novel approach is thus expected to provide new insights into the question. We here present the current status of the data analysis for the Galactic Center joint MAGIC and LST-1 observations.

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1. Introduction

The central part of the Milky Way Galaxy is one of the most studied regions in the sky. Along the Galactic plane, sub-PeV diffuse gamma-ray emission has been detected by the Tibet Air Shower Array [1] and, more recently, neutrino emission has been identified by the IceCube Neutrino Observatory [2]. Both detections are consistent with a scenario of the presence of the "PeVatron" in our Galaxy. With very-high-energy (VHE) gamma-ray observations of diffuse ridge emission spanning about 200 pc in the Galactic Center region, H.E.S.S. argued that the supermassive black hole Sagittarius A* (Sgr A*) supplied PeV Galactic cosmic rays in the past [3].

The Galactic Center has been also observed by MAGIC, a system of two Imaging Atmospheric Cherenkov Telescopes (IACTs) designed to detect VHE gamma rays and operating in stereoscopic mode since 2009 at the Observatorio del Roque de Los Muchachos in La Palma, Spain. The system attains the integral sensitivity of $(0.66 \pm 0.03)\%$ of the Crab Nebula flux above 220 GeV in 50 hours for the standard zenith angle [4].

The previous MAGIC study using 100 hours of data on the Galactic Center reported a 2σ-level hint of the existence of a spectral cut-off of the diffuse emission at 20 TeV [5]. This result may challenge the idea of PeV hadron acceleration of Sgr A*. To address this potential contradiction in the TeV regime, deeper observations of the Galactic Center leading to better statistics especially above 10 TeV are necessary.

Besides, the Galactic Center has the highest local density of the Weakly Interacting Massive Particles (WIMPs), and thus should be one of the brightest sources of dark matter. Although, likewise H.E.S.S., the spectral line search based on the 223 hours of MAGIC data imposed, on super-symmetric wino, a stringent constraint or even its rejection in an optimistic scenario, a model rejection in the entire accessible energy range has neither been achieved nor a definite discovery [6–8]. Further enhancement in sensitivity or a wider energy coverage is required to probe the uncharted parameter space.

In 2018, the prototype IACT of the Large-Sized Telescope (LST-1) for the Cherenkov Telescope Array (CTA), a next-generation ground-based gamma-ray observatory, was inaugurated at the same site, at a distance of approximately 100 meters from the MAGIC telescopes. Using joint observations between MAGIC and LST-1, we developed a dedicated analysis pipeline and established the threefold telescope system via software, achieving the highest sensitivity in the northern hemisphere.

Aiming at further advancement, not only by collecting data but also by better observation, data of the Galactic Center are jointly under accumulation and analysis. This contribution presents results of the joint analysis using the currently available Galactic Center data.

2. Method

The joint analysis requires quality data both for MAGIC and LST-1, while enabling to check ambient conditions from both perspectives. Following the standard procedure [9, 10], the data quality is verified mainly by ensuring the atmospheric transmission, the night-sky background, and the shower image quality. After the data selections, the dataset in this analysis amounts to about 8-hour livetime. All the data were taken at the so-called wobble mode with the offset angle of 0.5 deg in 2021. As shown in Fig.1, the MAGIC and LST-1 observation of the Galactic Center is

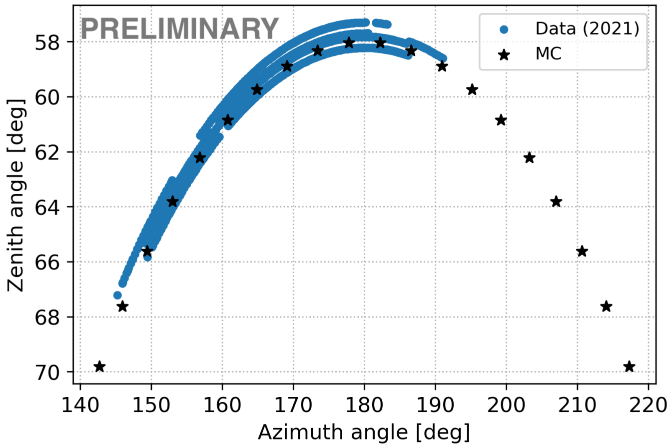

Figure 1: Distribution of telescope pointing directions in the horizontal coordinate system. For observation data, a mean position of MAGIC pointing directions in each subrun is plotted.

carried out at the large zenith angle: Zd $\gtrsim$ 57 deg, which increases the gamma-ray collection area (proportional to the gamma-ray rate) by one order of magnitude, as compared with the standard low zenith angles (Zd $\lesssim$ 30 deg) [11, 12].

Employing our newly developed software `magicctapipe`[1] (v0.2.0), the data are processed from the telescope-wise data into the Data Level 3 (DL3): a list of gamma-ray-like candidates after the reconstruction of the energy, the arrival direction and the particle type, following the standard analysis procedure [13]. In this study, signals are counted within 0.1 deg around Sgr A*, instead of a dynamic arrival-direction cut, in order to avoid a contamination of other gamma-ray signals in the signal or background control regions. Finally, the gamma-ray flux is estimated from the DL3 files through a standard point-source spectral analysis in `gammapy` [14].

3. Results

Fig.2 compares the detection significance between MAGIC-only stereo analysis and the joint MAGIC and LST-1 analysis, demonstrating that the joint analysis yields a clearer detection. This rapid significance evolution, aided by the larger collection area of the large zenith angle, will play a key role in observing a short time variability of gamma-ray emission. In particular, although it has not been discovered yet, Sgr A* might be a time variable on a minute or hour scale [15]. The joint analysis will thus serve an important function of verifying this prediction.

Fig.3 (the so-called theta-square plot) illustrates the radial profile of the gamma-ray-like events. The angle θ is measured between an arrival direction and the centers of the ON and OFF regions: The ON center is at Sgr A* and the three OFF centers are perpendicularly situated with the pointing positions as the center. The peak at $\theta = 0$ deg clearly shows signals from the position at Sgr A*. Within 0.02 deg^2 from the source, the significance against the null hypothesis is 20σ: the detection is clearly shown. Notably, the baseline of this plot contains not only the irreducible hadronic background, but potentially also the diffuse gamma-ray emission or the gamma rays from

[1]https://github.com/cta-observatory/magic-cta-pipe/tree/v0.2.0

(a) Counts **(b)** Significance

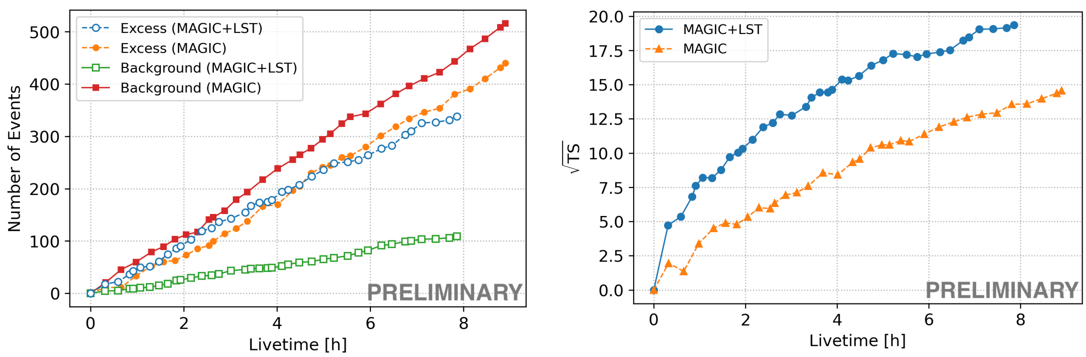

Figure 2: Time evolution of (a) counts and (b) significance for the MAGIC+LST joint analysis and the MAGIC-alone analysis. The cut conditions are met in the two analyses; the dynamic gammaness cut at a 90% gamma-ray efficiency is applied, and events within 0.1 deg around Sgr A* are extracted. Although a common list of runs is used between the two, the MAGIC-alone livetime is longer than the joint one, as the two operations are not completely in coincidence.

sources near or in the OFF regions. This contamination effect induces a background overestimation, and is more emergent especially for the situation of low background (that is, a small background uncertainty). An alternative analysis, including more sophisticated spatial models, is required to alleviate the contamination.

From the signals in Fig.3 obtained by subtracting the OFF counts from the ON counts within 0.1 deg around the source, the spectral energy distribution (SED) of Sgr A* are reconstructed. In this study, the power law spectral model with an exponential cut-off is used to describe the SED: $\mathrm{d}N/\mathrm{d}E = N_0(E/E_{\mathrm{ref}})^{-\alpha} \times \exp(-E/E_{\mathrm{cut}})$, where $E_{\mathrm{ref}} = 1\,\mathrm{TeV}$. The best-fit values are given by $N_0 = (4.83 \pm 0.65) \times 10^{-13}\ \mathrm{cm^{-2}\ s^{-1}\ TeV^{-1}}$, $\alpha = 2.19 \pm 0.13$, $E_{\mathrm{cut}} = 18.1^{+35.4}_{-7.2}$ TeV, where all the errors do not include a systematic uncertainty but only show the statistical one.

4. Conclusion and Outlook

The joint analysis between MAGIC and LST-1 being established, data of the Galactic Center is jointly accumulated and analyzed. This study provides the first results by the joint analysis using the Galactic Center data of about 8 hours taken in 2021. Fig.2 confirms that the joint analysis technique brings the fast significance evolution to the gamma-ray observation. On top of this enhanced performance, the squared-theta plot in Fig.3 clearly exhibits an excess at Sgr A*, providing 20σ of significance within a radius of 0.02 deg around the source. The reconstructed SED is consistent with results from the current telescopes, though a relatively wide energy binning has to be used due to the currently limited statistics. These results illustrate the successful analysis even between different-performance telescopes.

This study will be improved by adopting all available data including archival MAGIC data and LST-1 data taken in a monoscopic mode. As with MAGIC, the LST-1 single view of the Galactic Center already functions in shape [16]. In addition, underpinned by the swift evolution of the significance as shown in Fig.2 and the one-order-of-magnitude enhancement of the collection area by the large zenith angle observation, the joint analysis is suitable to probe a time variability on

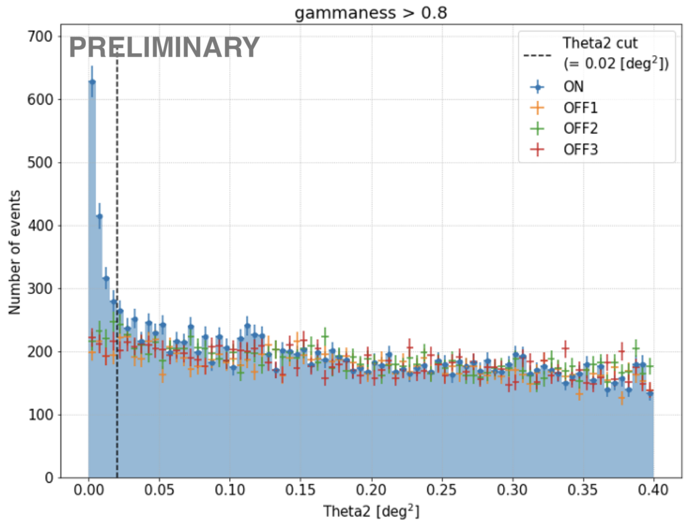

Figure 3: Distribution of the squared distance between the arrival directions and the region center. The OFF centers are given by rotating the ON (source) position with respect to the pointing positions in the camera coordinates. The detection significance of 20σ is yielded within a circle of 0.02 deg^2 radius (black dashed line) around Sgr A*.

a scale of a few tens of minutes in the TeV energy range. This capability is almost not feasible at the standard low zenith angle because of the limited collection area; however it may be crucial to investigate phenomena in the vicinity of the central supermassive black hole. Detailed results through the new analysis here presented with the comprehensive data set will be reported elsewhere.

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