

Prospects on detection of the Fermi Bubbles with the Cherenkov Telescope Array Observatory

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In 2010, the Fermi Gamma-ray Space Telescope observed two gamma-ray emitting structures, the Fermi Bubbles (FBs), which extend up to 55° above and below the Galactic plane and that seem to emanate from the Galactic center region. Although the spectrum at latitudes $|b| > 10^\circ$ has a softening or a cutoff around 100 GeV, the one at the base of the FBs, $|b| < 10^\circ$, extends up to ~ 1 TeV without a significant cutoff in the *Fermi*-LAT data. The mechanism behind the FBs production is currently under debate. More observations of the FBs at different energies are required to improve our understanding of their origin.

Recently, H.E.S.S. and HAWC observatory have set upper limits on the FBs. In this work, we assess the sensitivity of the Cherenkov Telescope Array Observatory (CTAO) using the "Alpha configuration" in the South site to detect the FBs and investigate the optimal strategies for their detection at low latitudes. We simulate the observations using the official CTAO science tool *gammapy*, considering several benchmark models for the FBs and the interstellar emission and test different observational strategies taking advantage of the proposed CTAO consortium surveys. We use these simulations to estimate the CTAO sensitivity to the FBs.

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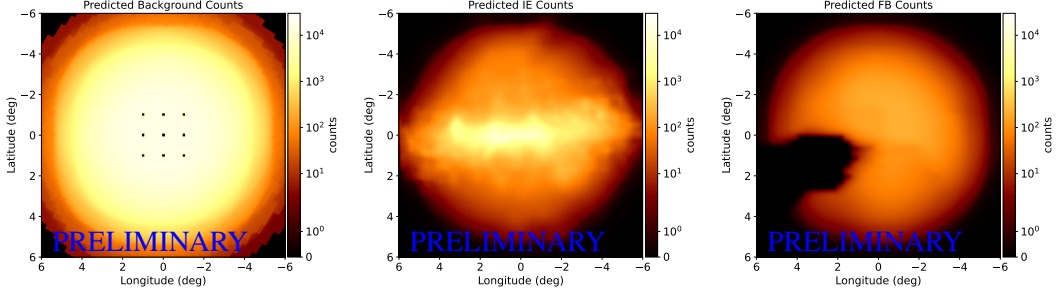


Figure 1: **Left:** Counts map for CR Background including the pointing positions of the GC survey. **Center:** Counts map for the Interstellar Emission (IE), corresponding to the VariableMin benchmark model. **Right:** Counts map for the FBs. All of the plots show the sum of counts over the whole considered energy range.

1. Introduction

The Fermi Bubbles (FBs) were first identified in 2010 through the observations of the *Fermi* Large Area Telescope (LAT) [1]. These large-scale gamma-ray structures extend roughly 55° above and below the Galactic plane (GP), originating from the Galactic center (GC). The two lobes are approximately symmetric, though slight asymmetries were observed within the innermost $\sim 6^\circ$. At low latitudes ($|b| < 10^\circ$), the emission is brighter and characterized by a hard spectrum with a spectral index of ~ 2 , whereas at higher latitudes ($|b| > 10^\circ$) the intensity decreases and the spectrum exhibits a softening around ~ 100 GeV [2]. Despite targeted searches to observe gamma-ray emission from the FBs with Imaging Atmospheric Cherenkov Telescopes (IACTs), no detection has yet been claimed. The upper limits obtained from H.E.S.S. observations [3] suggest a possible cutoff in the low latitude spectrum near ~ 1 TeV. The presence of such a cutoff, however, remains highly uncertain. Probing the FBs in the vicinity of the GC at energies around ~ 1 TeV is therefore essential to address the existence of a spectral cutoff and provide key insights into their morphology.

The Cherenkov Telescope Array Observatory (CTAO) represents the next generation of IACTs, designed to operate from 20 GeV to 300 TeV (with peak sensitivity near ~ 1 TeV), with an expected increase in sensitivity of one order of magnitude compared to current IACTs¹. CTAO will be able to scan the whole sky thanks to its two placements: La Palma (Spain) for CTAO North and the Atacama Desert (Chile) for CTAO South. Owing to its unprecedented sensitivity and planned surveys of the GC region, CTAO has the potential to detect the FBs emission at high energies, complementing the low energy detection by *Fermi*-LAT [4]. In this contribution, we evaluate the sensitivity of the CTAO-South array to detect gamma-ray emission from the low latitude FBs.

2. Methodology

Simulations. Our study on the low latitude FBs is based on simulations of observations using the GC survey, consisting of 9 pointings between $b, l = -1, 0, 1^\circ$ with a total time of 525 hours. We define the region of interest (RoI) as $12^\circ \times 12^\circ$ centered in the GC (as depicted in the left panel of Figure 1). For this study we consider CTAO South in the "Alpha configuration". We employ the latest instrument response functions (IRFs), "prod5v0.1" [5], which account for this configuration.

¹<https://www.ctao.org/for-scientists/performance/>

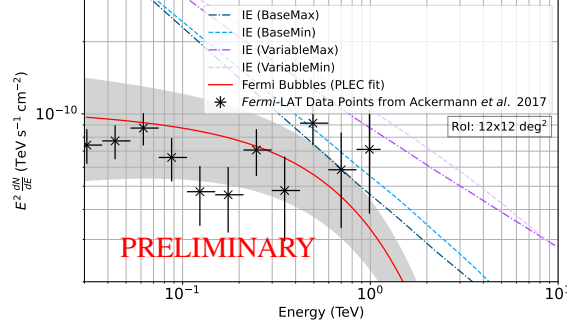


Figure 2: Models for the different emission components in our RoI. The FBs model is obtained by fitting the low latitude spectrum in [2] (black stars). We take the Max and Min benchmarks for both the Base and Variable IE models of [6] (4 models in total).

Parameter	Value
Amplitude, N_0 , ($\text{cm}^{-2} \text{s}^{-1} \text{TeV}^{-1}$)	$(9 \pm 2) \times 10^{-11}$
Spectral Index, γ	2.03 ± 0.05
Cutoff Energy, E_{cut} , (TeV)	1.0

Table 1: Value of the parameters for the PLEC obtained from fitting the low latitude FB data points from [2] with a fixed cutoff energy.

To assess the detection capabilities of early intermediate CTAO configurations, we simulate the same set-up with a reduced observation time of 50 hours. In this study, the following emission components are included (their counts maps and spectra are shown in Figures 1 and 2 respectively):

- *Fermi Bubbles:* We use the FBs component from the *Fermi*-LAT observations from [2] to derive a model based on a power law with exponential cut-off (PLEC), given as $\frac{dN}{dE} = N_0 \left(\frac{E}{1 \text{ GeV}}\right)^{-\gamma} e^{-E/E_{\text{cut}}}$, where N_0 is the normalization, γ is the index and E_{cut} is the cutoff energy. The fitted parameters are shown in Table 1.
- *Interstellar Emission:* The IE, originated from the production of gamma-rays from the interstellar medium in the galaxy, is included using the benchmark models established in [6]. Through these benchmark models we quantify the impact on the uncertainty in the cosmic-ray (CR) diffusion coefficient of the IE for our results.
- *Instrumental Cosmic Ray Background:* An estimation for the instrumental CR background is taken into account using the model provided by the IRFs, developed within the CTAO Consortium in [5].

To generate the mock observations we use Gammapy (v.1.2) [7], the official CTAO analysis tool, considering 55 logarithmically spaced energy bins between 30 GeV and 100 TeV. We mask the inner $|b| < 1.5^\circ$ of the GP to reduce contamination from other emission components (check Figure 1).

Statistical Framework. We perform the analysis using a template fitting approach applied to the simulated observations, with the likelihood based on Poisson statistics for the distribution of the

counts. The predicted counts are defined as $\mu_{ij}(A_i^{FB}, A_i^{IE}, A_i^{CR}) = A_i^{FB} \mu_{ij}^{FB} + A_i^{IE} \mu_{ij}^{IE} + A_i^{CR} \mu_{ij}^{CR}$ where the parameters $A_i^{FB,IE,CR}$ are the normalizations (for each energy bin, labeled as i), and the labels are chosen according to the which model they account for (FBs, IE or CR background). Then, we define the test statistics (TS) as:

$$TS(A_i^{FB}) = 2 \ln \left[\frac{\mathcal{L}(\mu(A_i^{FB}, \hat{A}_i^{IE}, \hat{A}_i^{CR})|n)}{\mathcal{L}(\mu(0, \hat{A}_i^{IE;0}, \hat{A}_i^{CR;0})|n)} \right], \quad (1)$$

where $\hat{A}_i^{IE,CR}$ represents the norms optimized for a given value of A_i^{FB} (with $\hat{A}_i^{IE,CR;0}$ being optimized for $A_i^{FB} = 0$), while n represents the mock (simulated) data. The TS compares hypothesis H_0 , where $A_i^{FB} = 0$, to H_1 , where $A_i^{FB} \neq 0$. These specify that the parameters live respectively in sets Θ_0 and Θ_1 . Wilk's theorem states that the TS will then tend to a χ^2 distribution with $\nu = \dim(\Theta_0 \cup \Theta_1) - \dim(\Theta_0)$ degrees of freedom. Since $\nu = 1$ here, we require a threshold of $TS > 4$ for detected points in each bin, roughly equivalent to a 2σ detection. To compute the mean expected value $\langle A_i^{FB} \rangle$, we employ a representative dataset, the Asimov dataset, which corresponds to the expected number of counts in the limit of an infinitely large sample of Poisson realizations.

We further study the impact of correlated systematic uncertainties. To this end, we introduce the scaling parameters α_{ij} and β_i . α_{ij} represents the differential acceptance uncertainties (which vary through energy and spatial bins), while β_i describes the systematic uncertainties for a given energy bin. We assume Gaussian nuisance likelihoods for α_{ij} and β_i with respective standard deviations σ_α and σ_β [8]. The likelihood is then given by:

$$\mathcal{L}(\mu|n) = \prod_i \frac{1}{\sqrt{2\pi}\sigma_\beta} e^{-\frac{(1-\beta_i)^2}{2\sigma_\beta^2}} \prod_j \frac{(\mu_{ij}\alpha_{ij}\beta_i)^{n_{ij}}}{\sqrt{2\pi}\sigma_\alpha n_{ij}!} \times e^{-\mu_{ij}\alpha_{ij}\beta_i} e^{-\frac{(1-\alpha_{ij})^2}{2\sigma_\alpha^2}}, \quad (2)$$

where:

$$\alpha_{ij} = \frac{1}{2} \left(1 - \sigma_\alpha^2 \mu_{ij} \beta_i + \sqrt{1 + 4\sigma_\alpha^2 n_{ij} - 2\sigma_\alpha^2 \mu_{ij} \beta_i + \sigma_\alpha^4 \mu_{ij}^2 \beta_i^2} \right). \quad (3)$$

We therefore examine the effect of fixing $\beta_i = 1$ for all i , leaving only σ_α as a free parameter.

Estimation of the energy cutoff. Finally, we investigate the capability of CTAO to constrain the energy cutoff of the low latitude FBs emission. We simulate observations fixing the cutoff energy and spectral index of the PLEC to $E_{cut} = 1, 3, 10, 30, 100, 300$ TeV and $\gamma = 1.94, 2.00, 2.10$ respectively, then proceed with the likelihood fit as previously explained. Then, we perform a least χ^2 global fit to the resulting points using a PLEC and a Power Law (PL). Since the only additional parameter in the PLEC with respect to the PL is the cutoff energy, the difference in reduced χ^2 between the two fits should follow a χ^2 distribution with one d.o.f., providing a suitable proxy for the TS as an estimate of CTAO capability to recover the energy cutoff.

3. Results and Conclusions

Recovery of the FBs. The preliminary results indicate that CTAO should be able to detect the FBs from ~ 60 GeV to ~ 5 TeV for a model with a cutoff at 1 TeV assuming no systematic uncertainties. CTAO is further expected to constrain the FBs energy cutoff at the 3σ level for cutoff values in the range between ~ 1 TeV to ~ 150 TeV (see the left panel in Figure 3). For larger spectral

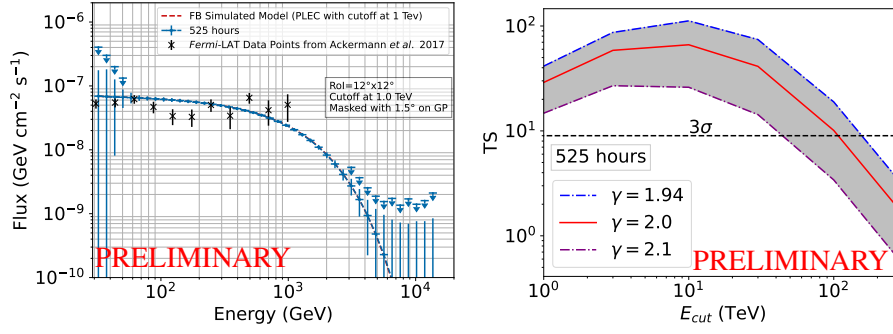


Figure 3: **Left:** Recovery of the injected FBs spectrum for 525 hours in our RoI. Upper limits are shown together with 1σ uncertainties for each point. **Right:** Capability of CTAO to recover the energy cutoff for different spectral indices.

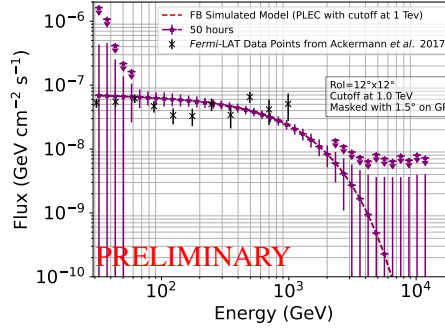


Figure 4: Recovery of the injected FBs spectrum for 50 hours in our RoI. Upper limits are shown together with 1σ uncertainties for each point.

indices the PLEC better resembles a PL, lowering the ability of CTAO to differentiate between the two models (check the right panel in Figure 3). Reducing the observation time by a factor of 10 still enables a detection from ~ 200 GeV to ~ 1 TeV for the same injected model. In this case, the uncertainties grow on average by a factor of $\sim 20\%$, as shown in Figure 4. All the results shown were obtained using the VariableMin benchmark IE model.

Systematic Uncertainties. In this study we keep the systematic uncertainties to the benchmark values $\sigma_\alpha = 1\%$, 3% , 10% . This impacts our results as an average decrease of 4% , 36% , 77% in the TS , respectively. In particular, for $\sigma_\alpha = 10\%$, the FBs model is recovered above ~ 200 GeV, with an associated increase up to $\sim 30\%$ in the flux uncertainty (as seen in the left panel in Figure 5). The impact on the cutoff estimation is comparatively modest, degrading the TS by up to $\sim 10\%$, as can be seen in the right panel of Figure 5.

Summary and future prospects. Our results show that the CTAO is expected to successfully detect the emission from the FBs. The FBs can be recovered from ~ 60 GeV without systematic uncertainties, and from ~ 200 GeV for $\sigma_\alpha = 10\%$ for an injected model with a PLEC with a cutoff at 1 TeV.

Future work will focus on assessing in greater detail the prospects for an early detection of the FBs and the characterization of a potential spectral cutoff. We will also investigate the sensitivity of CTAO subarrays, and extend our analysis to the high latitude FBs.

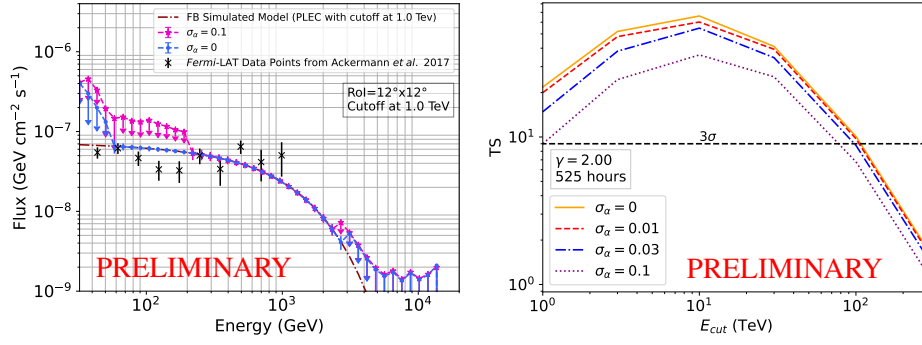


Figure 5: Left: Impact of systematic uncertainties on the recovery of the FBs. **Right:** Impact of systematic uncertainties on the estimation of the energy cutoff.

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