A maximum-likelihood-based technique for detecting extended gamma-ray sources with VERITAS

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1. Motivation

Gamma-ray observations from hundreds of MeV to tens of TeV are valuable for studying galactic particle accelerators: supernova remnants, pulsar wind nebulae, and star-forming regions. These source types are often largely extended and have unknown morphology at very high energies. These factors, combined with the limited field of view (FOV) of imaging atmospheric-Cherenkov telescopes (IACTs), make detection challenging; background emission regions near the source cannot be found. There are multiple extended sources detected by instruments operating in lower and higher ranges of the gamma-ray spectrum with projected spectral parameters indicating they are visible to VERITAS. For this reason a different approach must be implemented to VERITAS data on extended sources.

2. The VERITAS Instrument

VERITAS is an array of four 12-meter IACTs, with a 3.5° diameter FOV, located at the Fred Lawrence Whipple Observatory in southern Arizona. They operate in the energy range from 100 GeV to >30 TeV, with an energy resolution between 15-25% and an angular resolution <0.1° at 1 TeV for 68% containment. The array can detect flux at the level of 1% Crab in ~25 hrs.

4. Background Modeling

Mean scaled width (MSW) and mean scaled length (MSL) are parameters defining the Cherenkov shower image shape. The MSW and MSL distributions are very different for hadrons vs gamma-rays, as shown in Fig. 1. Thus, they are used in both standard IACT analysis and in the 3D-MLM to separate background events from gamma-ray signal, crucial for detecting largely extended sources.

Simulations are used to model the MSW/MSL distribution of pure gamma-rays. The background emission is derived from gamma-ray quiet fields. The MSW/MSL shape also changes due to other observing parameters: zenith, azimuth, energy, noise, and camera offset. The plan is to use singular value decomposition on 2D MSL vs MSW histograms, to create a set of matrices which characterize the dependence on these parameters.

References

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3. 3D Maximum Likelihood Method

A 3D-maximum likelihood method (MLM) is under development for analysis of extended sources observed by VERITAS. The method gives the likelihood values ($\mathcal{L}$) that a model consisting of a set of probability distribution functions (PDFs), predict a region of emission[1].

$$\mathcal{L} = \prod_{i=1}^{N} P_i .$$

The likelihood PDFs include instrument response functions (IRFs), which predict the response of the VERITAS instrument on observed parameters[2]. In the 3D-MLM, the IRFs are effective area, energy dispersion, and point spread function. The 3D-MLM IRF equation is the same as the formulation implemented in Gammapy[5].

The predicted gamma-ray signals are derived from simulations. The likelihood must also include models for background emission, dominated by cosmic rays. In the 3D-MLM, background models are derived from source-free data samples. The following sections go into the details of creating instrument response functions and background models.

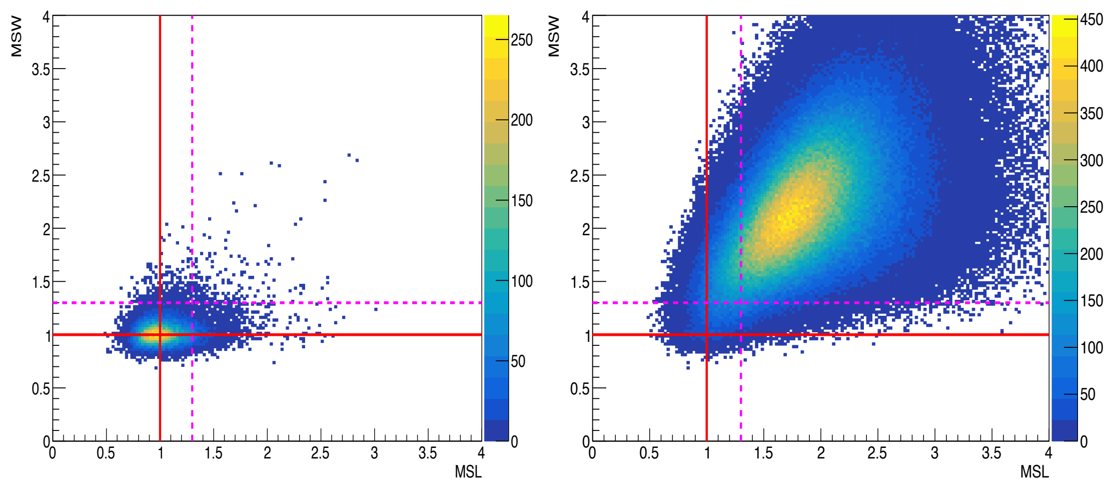

Fig 1 *MSL versus MSW distributions of (left) gamma-ray simulations and (right) background emission from dark matter target Segue1.The red solid lines mark the peak of gamma-ray distribution. The dashed line marks the upper boundary used in the 3D-MLM.*

5. Point Spread Function Modeling

In the 3D-MLM, the point spread function is modeled with the King-function[4].

$$PSF(x,y) \propto \left(1-\frac{1}{\lambda}\right)\left[1+\left(\frac{1}{2\lambda}\right)\cdot\left(\frac{x^2}{\sigma_x^2}+\frac{y^2}{\sigma_y^2}\right)\right]^{-\lambda}$$

Initially, validations of the King-function to the 2D spatial distribution of gamma-ray simulations were performed with a fixed value of λ and $\sigma_x = \sigma_y$. However, for bright sources, such as the Crab Nebula, subtracted sky maps show residual bias pattern that changed with MSW. The PSF depends on MSW and in order to address this, two separate bins of MSW, 0.8-1.1 and 1.1-1.3, are introduced to the binned likelihood[3].

Initial modeling of the PSF was performed with the symmetric King-function. However, inconsistences were observed between the data and the function after fitting, correlated with increasing camera offset and energy. This is shown visually in Fig. 2. The PSF is broader in the direction of offset. The integrated difference of the core PSF between the gamma-ray simulations and the King-function should be close to 1 and the same value for integration in 2D and both projections. As shown in Fig. 3, this is not the case for the symmetric fit and is true for the asymmetric fit. The asymmetric King-function is the best function to model the spatial distribution of VERITAS gamma-ray events.

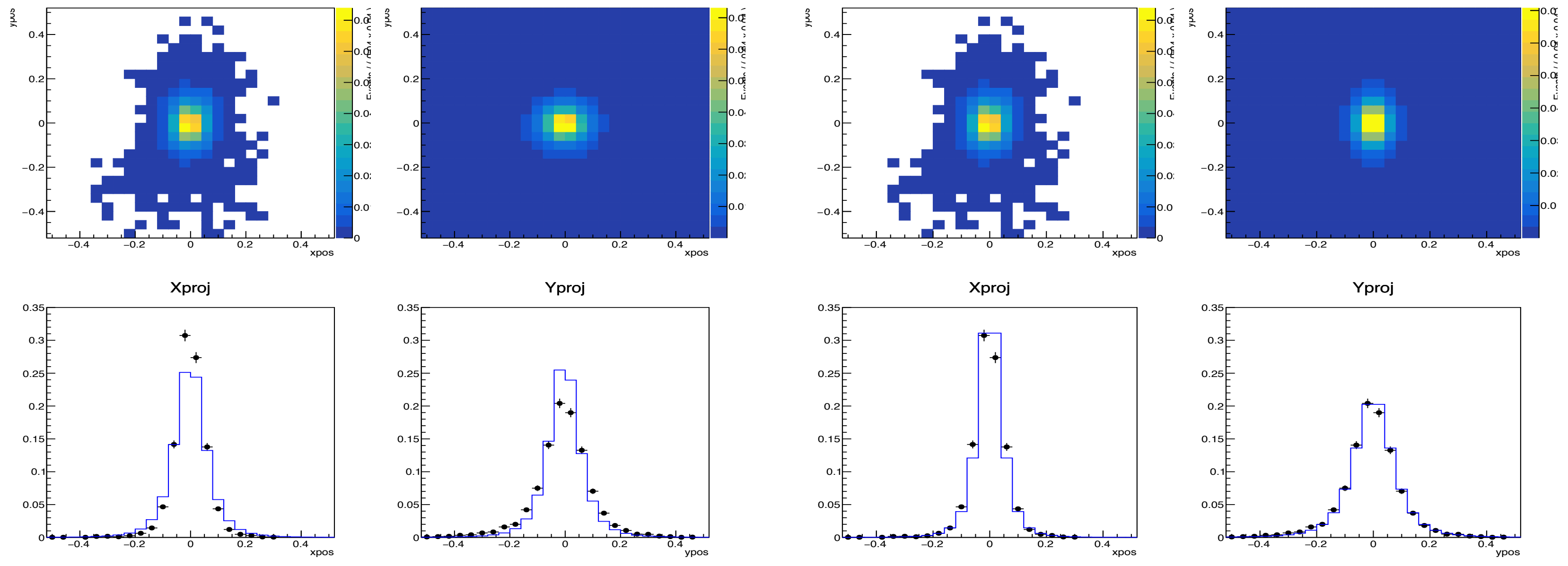

Fig 2 Gamma-ray simulations at 1 TeV, all azimuths, 1.5° *offset after fitting with a King-function. The left set of plots shows results of the symmetric fit and the right set the asymmetric fit. Top row: 2D plot of the spatial distribution of simulated events and 2D plot of the King-function after the fit. Bottom Row: 1D projection plots of simulated events with overlaid King-function.*

Core Containment Fraction

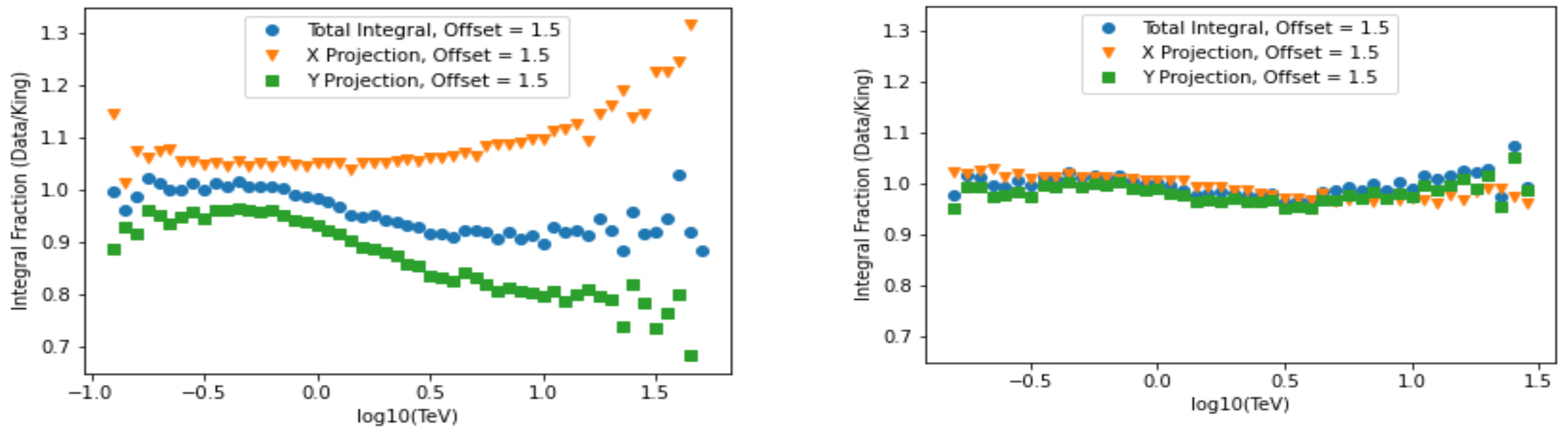

Fig 3 *The integrated difference of the core PSF between gamma-ray simulations at 1.5° offset and the King-function after fitting. The integrated difference is calculated over the 2D PSF and both projections. Left: With symmetric King-function Right: With asymmetric King-function*

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