Towards multi-instrument and reproducible gamma-ray analysis

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A **Python** package for **gamma-ray** astronomy

Introduction

Analysis and combination of data from different gamma-ray instruments involve the use of collaboration proprietary software and case-by-case methods. By defining a common format for high-level gamma-ray data, named Data Level 3 (DL3) with a preliminary version available at [1], we allow multi-instrument analysis within the context of open-source software, in this case the gammapy science tools [2]. This project aims at:

- performing the first fully-reproducible, multi-instrument very-high-energy gamma-ray analysis,
- combining data from Fermi-LAT, and from the four existing imaging air Cherenkov telescopes (IACTs), to produce a joint fit of the Crab Nebula spectrum.

Datasets

For this project, each IACT collaboration produced a small data sample of the Crab Nebula in DL3 format, containing event lists and instrument response functions (IRFs). H.E.S.S. and FACT datasets are already publicly available at [3, 4].

Dataset	time	obs. mode	E_{min}/TeV	E_{max}/TeV
Fermi-LAT	8 years	sky survey	0.03	2
MAGIC	40 mins	pointing	0.08	30
VERITAS	40 mins	pointing	0.15	30
H.E.S.S.	3 hours	pointing	0.50	30
FACT	10 hours	pointing	0.40	30

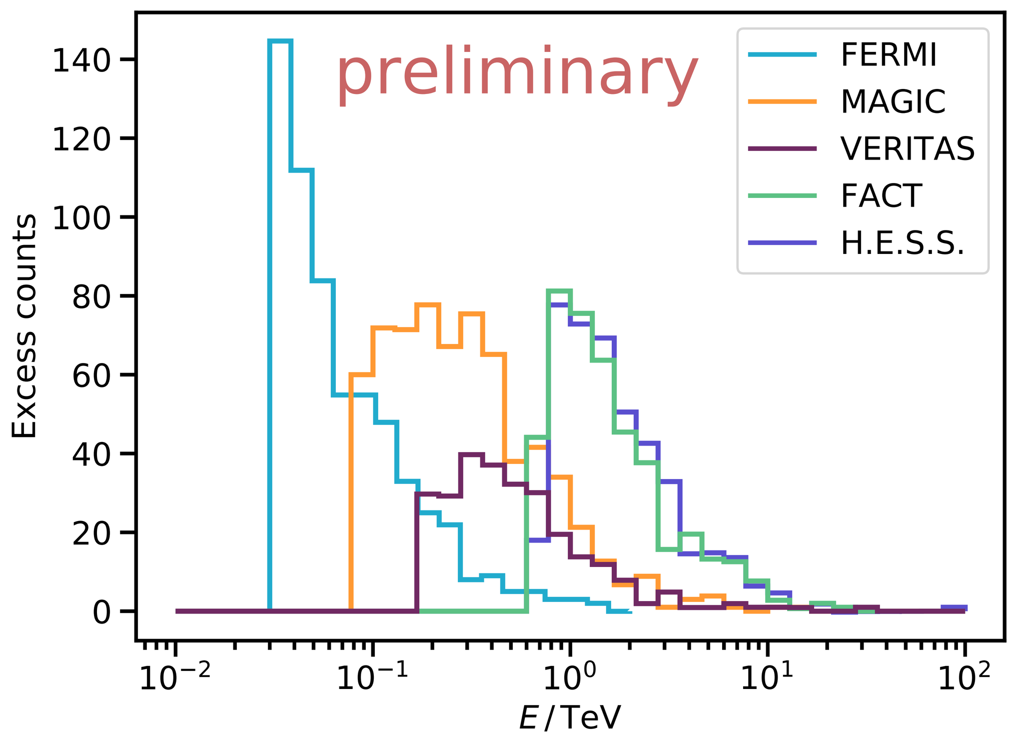

Figure 1: Histogram of the excess counts per each instrument.

Analysis

A one dimensional (energy dependent) spectral likelihood fit is performed. A Poisson likelihood is built extracting the observed counts from the datasets with aperture photometry techniques and computing the predicted counts folding the assumed spectral model with the IRFs. The assumed model for all the datasets is a log-parabola:

$$\frac{d\phi}{dE} = \phi_0 \left(\frac{E}{E_0}\right)^{-\Gamma-\beta\log_{10}\left(\frac{E}{E_0}\right)} \tag{1}$$

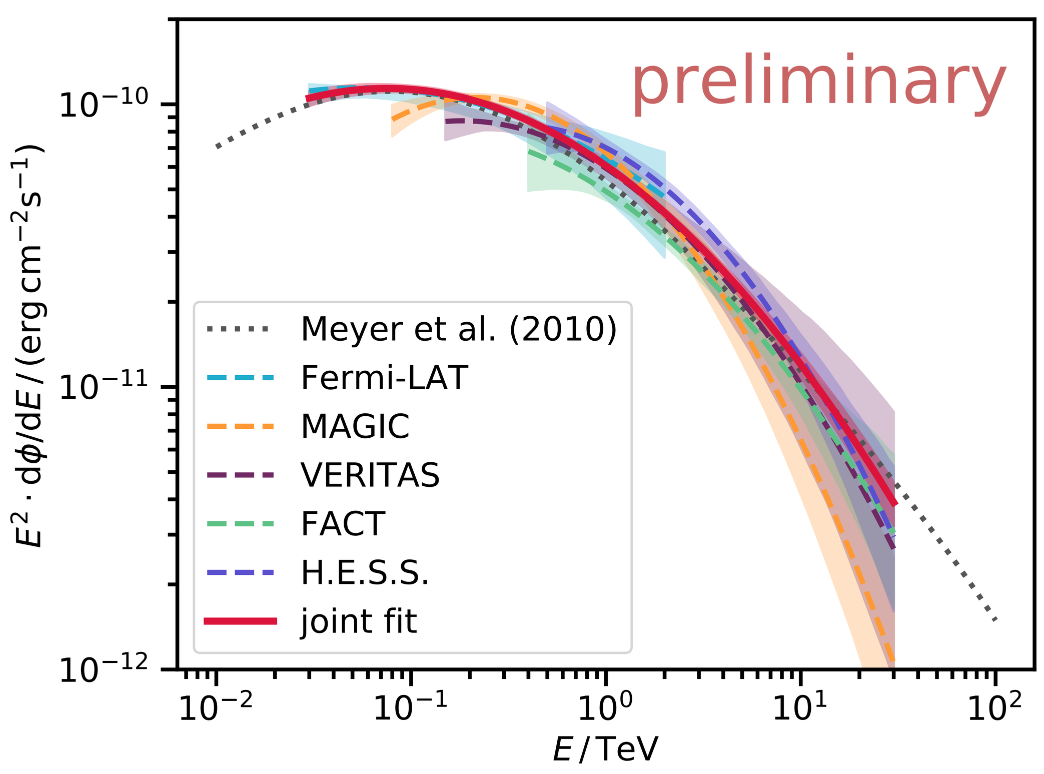

Figure 2: Resulting Crab Nebula spectral energy distribution (SED) from individual instruments and from the joint fit. Only statistical error bands are displayed.

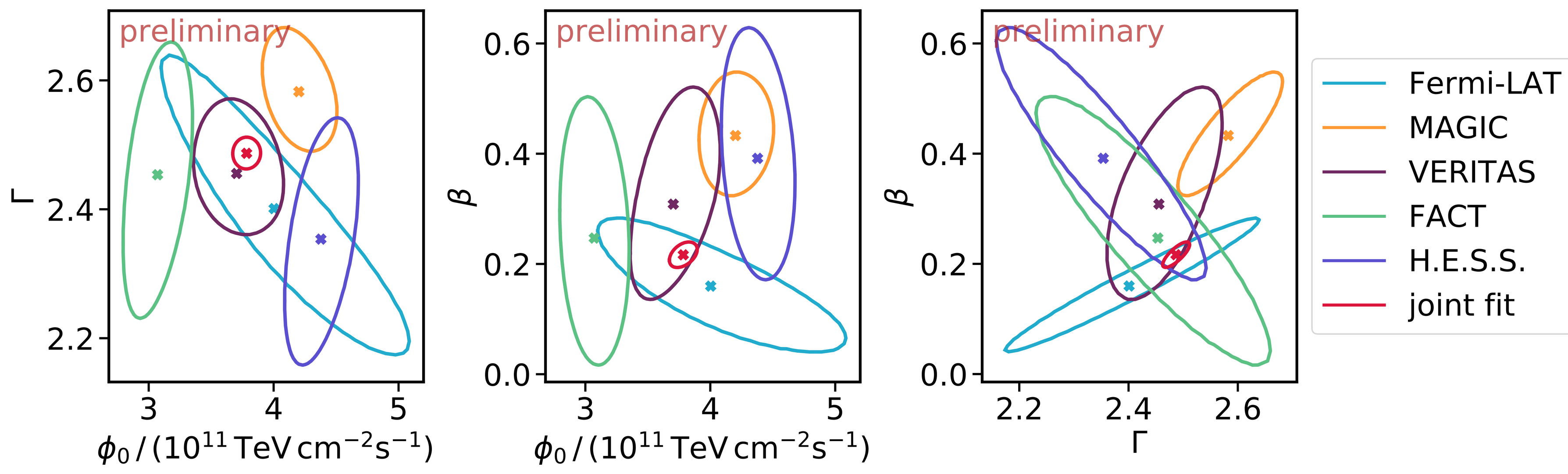

Figure 3: Likelihood 1-σ contours for the fitted parameters of the log-parabola for individual instruments and the joint fit.

Systematic uncertainties

To account for the systematic uncertainties on the energy scale of the different instruments while performing the joint likelihood fit we introduce a nuisance parameter, as shown in [5], $z = \frac{\tilde{E}-E}{E} = \frac{\tilde{E}}{E} - 1$ relating the reconstructed ($\tilde{E}$) and true (E) energy per instrument. The differential energy flux model is modified in:

$$\frac{d\tilde{\phi}}{d\tilde{E}} = \phi_0\left(\frac{E/(1+z_{instr})}{E_0}\right)^{-\Gamma+\beta\log\left(\frac{E/(1+z_{instr})}{E_0}\right)} \times \left(\frac{1}{1+z_{instr}}\right) \tag{2}$$

The global likelihood function is extended with the distributions of the nuisance parameters z_{instr} assumed to be Gaussian with mean 0 and variance δ_i, i.e. the uncertainty in the energy reconstruction estimated by each instrument

$$-2\sum_{\text{all instruments}} \ln\mathcal{L}(\phi_0,\Gamma,\beta,z_{instr}|N_{ON\,instr},N_{OFF\,instr}) + \left(\frac{z_{instr}}{\delta_{instr}}\right)^2 \tag{3}$$

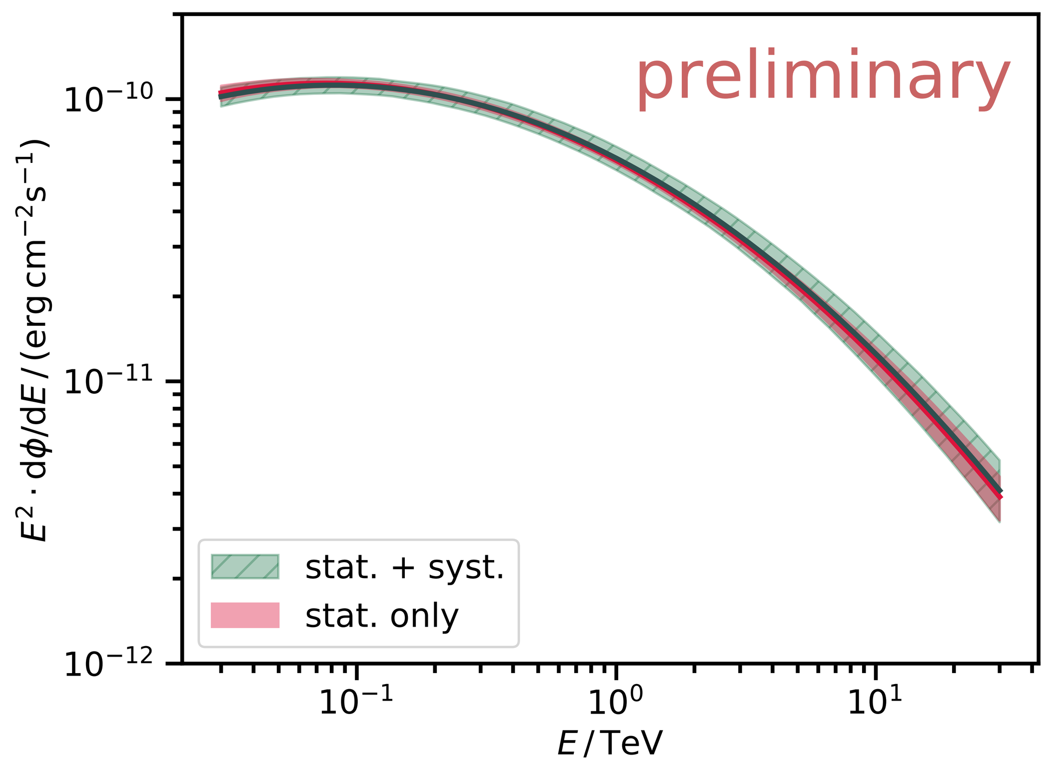

Figure 4: Resulting Crab Nebula SED from the joint fit including both statistical and systematic error bands.

Conclusions

- DL3 format allows for the first time to run a multi-instrument analysis using data from *Fermi*-LAT and all the existing IACTs,
- this format, proposed for the future Cherenkov Telescope Array (CTA), allows reproducible science in the very-high-energy (VHE) field relying on open-source software,
- Datasets, scripts and Jupyter notebooks will be provided in a GitHub repository together with a Docker image published in DockerHub. This will allow any user to reproduce the results in a playable environment. All these assets will be published and linked in Zenodo with a technical publication (in progress).

Acknowledgements

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References

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[5] Dembinski, H. et al, arXiv:1711.11432