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# Interpolation of Instrument Response Functions for the Cherenkov Telescope Array in the Context of `pyirf`

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The Cherenkov Telescope Array (CTA) will be the next generation ground-based very-high-energy gamma-ray observatory, constituted by tens of Imaging Atmospheric Cherenkov Telescopes at two sites once its construction and commissioning are finished. Like its predecessors, CTA relies on Instrument Response Functions (IRFs) to relate the observed and reconstructed properties to the true ones of the primary gamma-ray photons. IRFs are needed for the proper reconstruction of spectral and spatial information of the observed sources and are thus among the data products issued to the observatory users. They are derived from Monte Carlo simulations, depend on observation conditions like the telescope pointing direction or the atmospheric transparency and can evolve with time as hardware ages or is replaced. Producing a complete set of IRFs from simulations for every observation taken is a time-consuming task and not feasible when releasing data products on short timescales. Consequently, interpolation techniques on simulated IRFs are investigated to quickly estimate IRFs for specific observation conditions. However, as some of the IRFs constituents are given as probability distributions, specialized methods are needed. This contribution summarizes and compares the feasibility of multiple approaches to interpolate IRF components in the context of the `pyirf` python software package and IRFs simulated for the Large-Sized Telescope prototype (LST-1). We will also give an overview of the current functionalities implemented in `pyirf`.

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## 1. Introduction

Instrument Response Functions (IRFs) are crucial in analyzing data taken by Imaging Air Cherenkov Telescopes (IACTs) as they relate the reconstructed information and the true ones for incomming gamma rays. The first VHE gamma-ray observatory, the under construction Cherenkov Telescope Array Observatory (CTAO), will consist of tens of telescopes in two arrays located at the Northern and Southern Hemisphere [1]. As CTAO is designed to detect gamma rays with energies between 20 GeV and 300 TeV with unprecedented angular and energy resolution, it has stringent requirements on systematic uncertainties which are dominated by how well the derived IRFs reproduce the actual response of the telescopes. To manage this, extensive, time- and resource-consuming, Monte Carlo simulations will be needed to generate the data necessary for the computation of the final IRFs. In settings where time and resources are constrained, creating simulations tailored to each pointing position is infeasible. In these cases, IRF interpolation may offer a solution. In CTAO's software ecosystem, both IRF computation and interpolation are managed by the `pyirf` software package.

This proceeding aims to give a brief overview of the `pyirf` package with a focus on IRF interpolation in `pyirf`. For this, section 2 will give a more thorough introduction to IRFs and section 3 will introduce `pyirf` and its main interpolation functionalities. Results of these methods on IRFs will be shown in section 4 and section 5 will summarize this proceeding.

## 2. Instrument Response Functions

While IACT experiments employ advanced machine learning methods to reconstruct the observed air showers as-good-as-possible, the result always has a finite accuracy. Trying to estimate energy $\hat{E}$, origin as right ascension and declination $(\hat{\alpha}, \hat{\delta})$ and arrival time $\hat{t}$ of a gamma-ray signal, deviations from the true values $E, \alpha$ and $\delta$ are inevitable and that some events are not recorded or successfully reconstructed at all. For most applications, the time measurement can be assumend to be precise so that $t = \hat{t}$ holds. In its most general form, an IRF $R$ is the conditional probability relating the observed distribution of events $g(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$ to the true gamma-ray signal arriving at Earth $f(E, \alpha, \delta, t)$ with a background $b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$ by

$$\underbrace{g(\hat{E}, \hat{\alpha}, \hat{\delta}, t)}_{\text{Observed distribution}} = \iiint \overbrace{R(\hat{E}, \hat{\alpha}, \hat{\delta} | E, \alpha, \delta, t)}^{\text{Instrument Response}} \cdot \underbrace{f(E, \alpha, \delta, t)}_{\text{True gamma-ray signal}} \, \mathrm{d}E \, \mathrm{d}\Omega \, \mathrm{d}t + \overbrace{b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)}^{\text{Background}} \tag{1}$$

with the solid angle differential $\mathrm{d}\Omega = \sin\delta \, \mathrm{d}\alpha \, \mathrm{d}\delta$. Even when assuming a sufficiently correct knowledge of $b(\hat{E}, \hat{\alpha}, \hat{\delta}, t)$, the IRF is a six-dimensional, time-dependent quantity $R(\hat{E}, \hat{\alpha}, \hat{\delta} | E, \alpha, \delta, t)$. As IRFs are generated from Monte Carlo simulations, where after processing both the true and the reconstructed values are known, it is infeasible to generate the amount of events needed to compute $R$ in this general form. Since it is nevertheless needed to solve (1) and, with it, correctly reconstruct spectral and spatial information, a dimension reduction by factorization

$$R(\hat{E}, \hat{\alpha}, \hat{\delta} | E, \alpha, \delta, t) = \underbrace{A_{\text{eff}}(E, \alpha, \delta, t)}_{\text{Effective Area}} \cdot \overbrace{M(\hat{E} | E, \alpha, \delta, t)}^{\text{Energy Migration}} \cdot \underbrace{\text{PSF}(\hat{\alpha}, \hat{\delta} | E, \alpha, \delta, t)}_{\text{Point Spread Function}} \tag{2}$$

is commonly applied and IRFs are expressed as parametrizations or discretized tables of these components. Thus, the

- Effective Area (`AEFF`), the combination of the experiment's sensitive area and the probability of a gamma ray with some true properties to be present in the data as a gamma ray after all analysis steps,
- Energy Migration (`EDISP`), the conditional probability to reconstruct a gamma ray of some true properties with a certain energy $\hat{E}$ and
- Point Spread Function (`PSF`), the conditional probability to reconstruct a gamma ray of some true properties at a certain origin $(\hat{\alpha}, \hat{\delta})$

constitute an IRF that is applicable to all analysis use-cases. Further simplifications can be made for the case of a point source, where events can be selected around the assumed point source position using potential $\hat{E}$-dependent radii. In this case, the full PSF is not needed and instead the effective area is reduced by the amount of non-selected events. The used radii are linked to the IRFs and must be stored along-side in so-called `RAD_MAX`-tables. All these components are usually assumed constant over some time window and further depend on observation conditions like telescope pointing or weather. As the telescope performance is not constant over the whole field of view (FoV), all components are typically computed in more than one bin of FoV offset.

Allthough the process of simulating sufficient events to compute IRFs is time and resource-consuming, it assures the best possible results. On the other hand, there are circumstances where IRFs are needed on short time scales for next-day or even real-time analyses. This might be the case when observing an unexpected, transient event, and a preliminary analysis is needed to alert other experiments for follow-up observations. Interpolation between IRFs, precomputed for some observation conditions, is a possible solution in these cases and, if sufficiently performant, the less resource intensive solution to IRF computation.

## 3. The `pyirf` Package

The open-source software package `pyirf` [2] is a python library to compute IRFs and, derived from them, sensitivities. It is developed on Github[1] and released to PyPI[2] and conda-forge[3]. While the main use case will lie within CTAO's analysis framework, `pyirf` does not rely on specialized input formats but rather `astropy`'s `QTable` [3] and is thus, by design, usable with any IACT experiment. The internal representation of IRFs and, with this, `pyirf`'s output is, on the other hand, compatible with the *data formats for gamma-ray astronomy* (GADF) [4]. In the CTA software ecosystem, `pyirf` processes the so-called DL2 stage of gamma-ray Monte Carlo simulations containing reconstructed air-shower events generated by `ctapipe` [5] to obtain IRFs. With the initial DL2 data and observatory metadata, IRFs are issued to the scientific users of CTA as DL3 data and are ready for usage with CTA's science tools like `gammapy` [6]. Alongside the computation of IRFs, `pyirf` also provides sensitivity and significance calculation and IRF interpolation, the focus of this proceeding.

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[1] https://github.com/cta-observatory/pyirf

[2] https://pypi.org/project/pyirf

[3] https://anaconda.org/conda-forge/pyirf

### 3.1 Interpolate IRFs from Existing IRFs

To interpolate IRFs and contrary to other `pyirf` functionalities, the user does not have to supply reconstructed shower events but computed IRFs on a grid in some observation parameters that influence the telescope performance and, therefore, the IRFs. One such choice might be a grid in zenith angular distance and the angle between the telescope pointing direction and the geomagnetic field. Both parameters influence shower development in the atmosphere. Currently, `pyirf` supports the interpolation of `AEFF`, `EDISP`, `PSF` and `RAD_MAX` quantities according to the GADF definitions and with that both full enclosure and point like IRFs.

While `AEFF` and `RAD_MAX` are simple, unconnected quantities, i.e., each bin holds a value that is not correlated to its neighboring bins, simple, e.g. linear, interpolation can be applied. Contrary, `EDISP` and `PSF` represent discretized probability density functions; therefore, both need specialized methods to maintain their internal consistency. Such methods have already been employed in high-energy particle physics, `pyirf` offers two, Quantile Interpolation [7, 8] and Moment Morphing [9].

In short summary, Quantile Interpolation utilizes that there exist points $x_i$ where the template distribution's cumulative distribution functions (CDF) $F_i$ give the same value $F_i(x_i) = y$. The target distribution's CDF is then constructed to also return this value at a linear interpolation of the $x_i$. However, to obtain this position, the template distribution's quantile functions are needed and ultimately interpolated. The second method, Moment Morphing, is based on a Taylor expansion on the parameter grid used to find suitable interpolation coefficients. These, in return, are used to construct a linear combination of the template distributions; the interpolated result. To do so correctly, it is necessary to account for the template distribution's varying mean and standard deviation by transforming them to common values first. Both methods need to be adapted to be usable with discretized distributions. For Quantile Interpolation, this includes the usage of empirical distribution functions and linear interpolation to obtain an estimate for the quantile functions. Moment Morphing needed approximating versions of mean and standard deviation computation and a look-up method to evaluate the template distributions at the transformed values.

While `pyirf`'s Quantile Interpolation can, in principle, be applied to arbitrary parameter grid dimensions if the function interpolating the quantiles is chosen appropriately, Moment Morphing is currently limited to one or two-dimensional grids as the computation of the interpolation coefficients is dimension-dependent. On the other hand, our adapted version of Moment Morphing offers the possibility to extrapolate beyond the parameter grid convex hull. For this, two methods are implemented for extrapolation: Nearest Simplex and Visible Edges Extrapolation. The first one extrapolates from the nearest triangular simplex as seen from a point outside the parameter grid, resulting in a non-continuous extrapolation function. This is solved by the second method, which computes extrapolations from all visible simplices, computing coefficients according to visible edges blending as discussed in [10] and then again using these coefficients in the Moment Morphing procedure to compute the actual estimation by combining all extrapolations. While a continuous extrapolation is desirable, we provide both methods to leave it to the user's discretion to utilize the additional assumptions needed for visible edges blending. For one-dimensional parameter grids, both methods are equivalent. The same holds for points outside two-dimensional grids where only one edge and thus triangular grid simplex is visible. In all cases, we advise caution, as

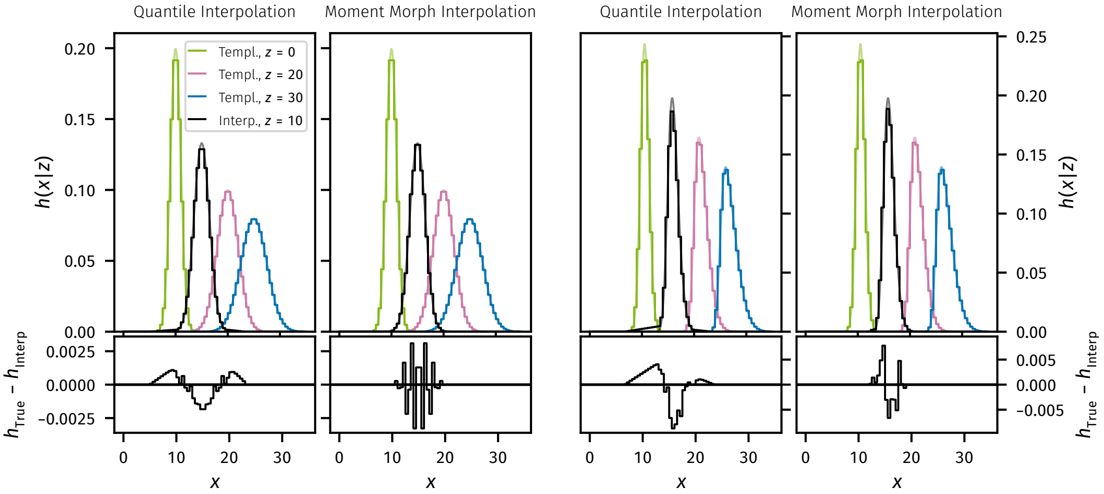

**Figure 1:** Interpolation algorithms applied to Gaussian (**left**) and skewed Gaussian (**right**) distributions whose parameters vary linearly with $z$. Three template histograms were created from the distribution's CDFs and used to interpolate to the black distribution. True distributions are given as solid lines.

our extrapolation implementations are extensions of the Moment Morphing procedure that utilize negative interpolation coefficients. It is easily possible for bin entries to become negative and thus ill-defined when overlaying the template distributions with negative coefficients. While this effect is minor and, to some extent, accountable by cutting off affected bins for small extrapolation distances, high extrapolation distances result in meaningless estimations. Extrapolation should thus be avoided by extending the template distribution grid to include all desired target points. For convenience, we also provide dummy extrapolation using the nearest neighbor approach.

Quantile Interpolation and Moment Morphing have been applied to one-dimensional Gaussians and skewed Gaussians in Fig.1, performing well in this simple demonstration. However, skewed distributions seem harder to interpolate, which is easily explainable for Moment Morphing as it only accounts for first and second-order moments by design. The good performance holds for comparably small extrapolation distances, as shown in Fig.2. As expected, the result worsens with increased distance.

## 4. IRF Interpolation

In addition to the benchmark presented in the previous section, performance measures on actual IRFs were performed. To do so, we used a subset of an IRF grid produced for the Large-Sized Telescope prototype LST-1 [11]. As mentioned in section 3.1, the grid is produced in zenith distance $\theta$ and the angle between telescope pointing and the geomagnetic field $\delta_{\mathrm{mag}}$. This angle is not to be confused with the astronomical declination introduced in section 2, although they share a common symbol. To better reflect the physical development of an air shower, we use $\cos\theta$ (dependency of the atmospheres density profile and thus Cherenkov light absorption) and $\sin\delta_{\mathrm{mag}}$ (measure of the geomagnetic field effect on the shower development). Other choices, especially for transformations of $\theta$, are possible, e.g., $(\cos\theta)^{-1}$, to reflect the atmospheric depth along the shower's line of sight.

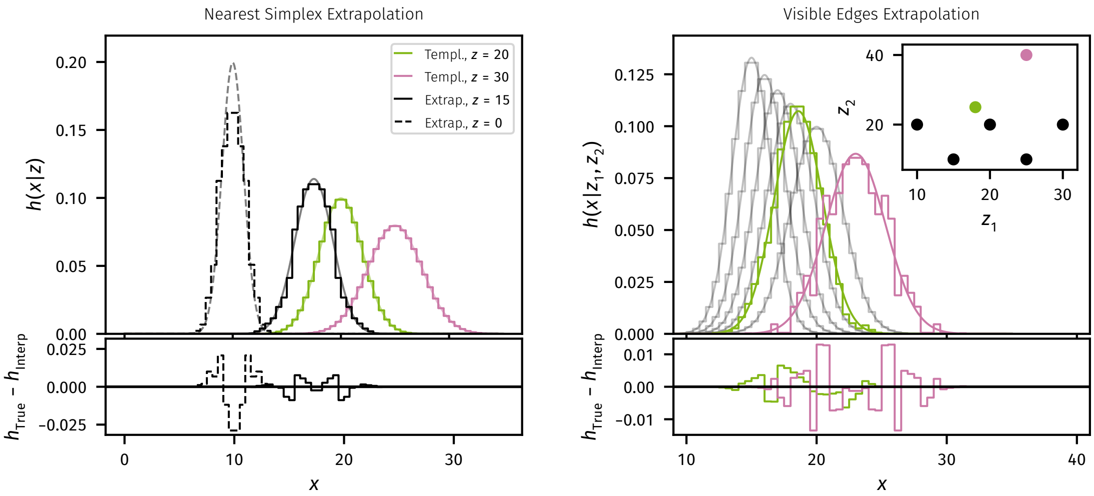

**Figure 2:** Extrapolation applied to Gaussian on a one- (**left**) and two-dimensional grid (**right**). Gaussian distributions whose parameters vary linearly with $z$ and $z_1$ and $z_2$, respectively. Two and five template histograms were created from the distribution's CDFs and used to extrapolate to the black distribution.

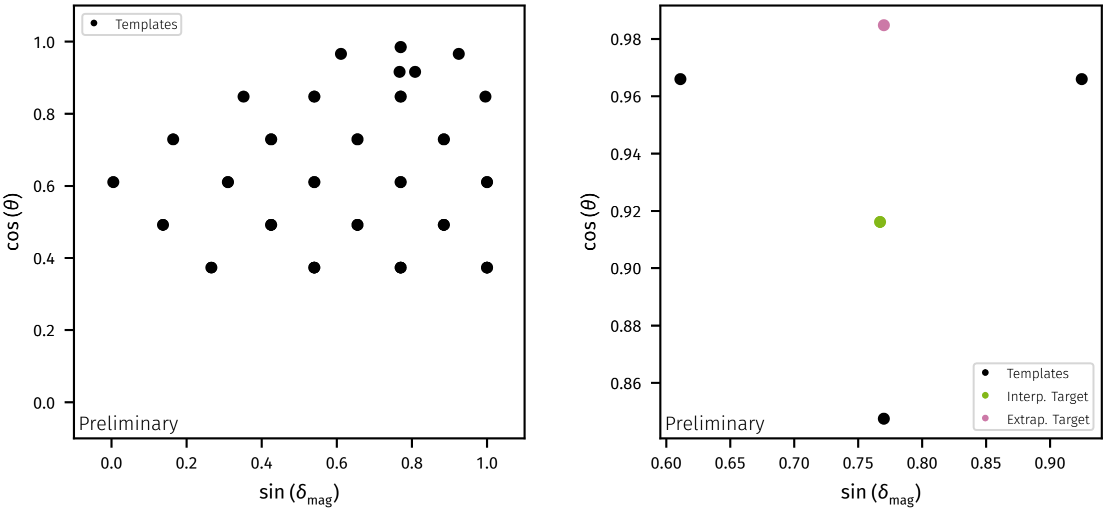

**Figure 3:** Full grid (**left**) of IRFs produced for LST-1 and the subset (**right**) selected to showcase both interpolation and extrapolation results.

The full grid and a selected part used for the following showcase are displayed in Fig. 3. Multiple grid nodes exist in this representation, where more than one Monte Carlo production has been made for different azimuth pointings. In these cases, the nodes closest to the target's azimuth pointing have been selected as interpolation templates.

Testing the interpolation on the selected subset of the full grid, we find good agreement between simulated and estimated energy dispersions, as shown in Fig. 4. The estimated results outperform a nearest-neighbor approach, especially for low- and high energies, and extrapolation, in this case, is feasible. It can be seen in the extrapolation case of Fig. 4 that the lowest true energy bin is

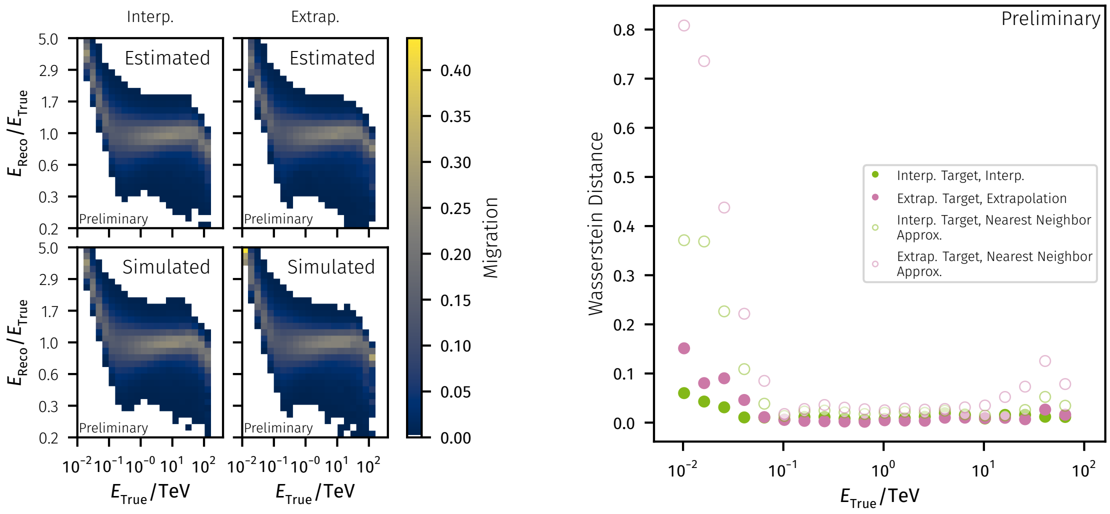

**Figure 4:** Inter- and Extrapolated energy dispersions (**left**) with corresponding Wasserstein distances (**right**). A simple next-neighbor interpolation was added for reference.

missing in the estimation. This occurs when one of the used templates has, due to a higher energy threshold, no corresponding IRF values drived in the respective bin. This is caused by an increasing zenith angle as the amount of atmosphere traversed by a gamma ray grows and thus the possibility for the primary particle to interact before reaching the telescope increases. Primary particles of these energies are thus less and less often detected until these energies are lost. Consequently, this problem is more frequent when high interpolation distances along the zenith angle are chosen. A densely populated grid thus minimizes the effect, although there will always be translations in the grid's parameter space where one bin becomes empty.

As for the estimation of AEFF and RAD_MAX tables (see Fig. 5), we find that especially effective areas are estimated with minor errors compared to the actual values. As with the energy dispersions, the lowest energy bin was missing in some templates and could not be computed. RAD_MAX tables, on the other hand, with errors in the order of 10 %, perform worse than other components. We account this to the nature of producing these values, optimizing a cut-value instead of comparing simulated and reconstructed quantities. RAD_MAX tables thus violate the assumption of being dependent on the chosen set of grid parameters. It is, however, to be checked, if these interpolation results in a meaningful IRF at all as it is not guaranteed that AEFF and RAD_MAX values are matching afterwards.

## 5. Conclusion

In this proceeding, we have given a brief overview of `pyirf` and explicitly discussed the therein-provided IRF inter- and extrapolation methods. We have shown IRF inter- and extrapolation to be usable with toy data sets and actual IRFs. Especially for quantities independent from any user optimization, like effective area and energy dispersion, the generated IRFs are reasonable estimations of the truth and outperform simple, next-neighbor approaches. Errors are minor but present, especially in low- or high-energy bins, and increase with inter- or extrapolation distance.

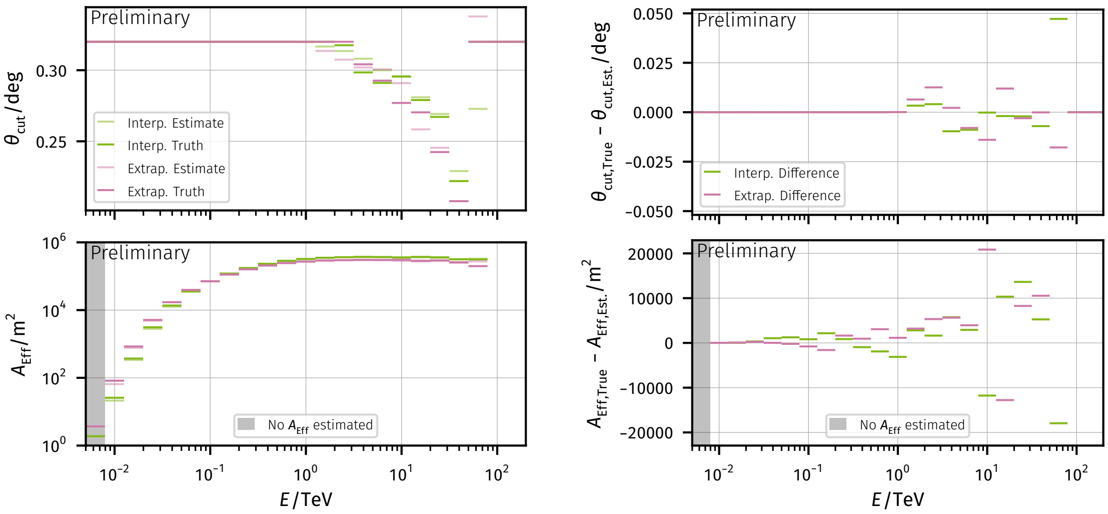

**Figure 5:** Inter- and Extrapolated `RAD_MAX` and `AEFF` tables (**left**) with inter- and extrapolation error (**right**).

Edge effects may occur if the interpolation templates partially miss some energy ranges, e.g., low true energy entries missing in energy dispersions for high zenith angles. User optimized quantities, like `RAD_MAX`-tables, are less suited for interpolation. In general, however, IRF interpolation has the potential to produce sufficiently accurate results for short time scale analyses.

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