To search for ultra-high-energy photons in primary cosmic rays, air shower observables are needed that allow a good separation between primary photons and primary hadrons. We present a new observable, $F_\gamma$, which can be extracted from ground-array data in hybrid events, where simultaneous measurements of the longitudinal and the lateral shower profile are performed. The observable is based on a template fit to the lateral distribution measured by the ground array with the template taking into account the complementary information from the measurement of the longitudinal profile, i.e. the primary energy and the geometry of the shower. $F_\gamma$ shows a very good photon-hadron separation, which is even superior to the separation given by the well-known $X_{\text{max}}$ observable (the atmospheric depth of the shower maximum). At energies around 1 EeV (10 EeV), $F_\gamma$ provides a background rejection better than 97.8 % (99.9 %) at a signal efficiency of 50%. Advantages of the observable $F_\gamma$ are its technical stability with respect to irregularities in the ground array (i.e. missing or temporarily non-operating stations) and that it can be applied over the full energy range accessible to the air shower detector, down to its threshold energy. Furthermore, $F_\gamma$ complements nicely to $X_{\text{max}}$ such that both observables can well be combined to achieve an even better discrimination power, exploiting the rich information available in hybrid events.

**Keywords:** Photons, Cosmic Rays, Hybrid Detector, Lateral Distribution Function, LDF

1. Introduction

The discovery of ultra-high-energy (UHE) photons, i.e. photons with an energy larger than $\sim 10^{18} \text{ eV} = 1 \text{ EeV}$, in primary cosmic rays would be of particular interest not only for the field of astroparticle physics, but also for related fields such as particle physics, astrophysics and fundamental physics [1]. For example, UHE photons are tracers of the Greisen-Zatsepin-Kuzmin (GZK) process, i.e. the interactions of UHE protons, propagating through the Universe, with photons from the cosmic microwave background (CMB). In these interactions, neutral pions are produced via the Delta resonance ($p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$). These pions subsequently decay into pairs of UHE photons with energies at typically 10 % of the energy of the primary UHE proton. If these predicted GZK photons are observed on Earth, it would be an indicator for the GZK process being the reason for the observed suppression in the energy spectrum of UHE cosmic rays (UHECR) [2].

Observing UHE photons could also help to pinpoint the very sources of UHECR, since photons, unlike charged cosmic rays, are not deflected by magnetic fields. The attenuation length for photons in the EeV range varies between some 100 kpc at 1 EeV and a few Mpc at 10 EeV [3], encompassing possible galactic and nearby extragalactic sources. The detection of UHE photons is of great interest for fundamental physics as well. For instance, the registration of a single photon in the EeV range could improve existing bounds on Lorentz invariance violation in the context of a modified Maxwell theory by several orders of magnitude [4]. In addition, observing the particle cascade initiated by a UHE photon in the atmosphere allows testing particle interactions at extreme energies and searching for new physics [1, 5].

Due to their small incoming flux (less than one particle per square kilometer per year), UHE cosmic particles impinging on the Earth can only be detected indirectly through the measurement of the air showers they initiate when entering the Earth’s atmosphere. For the identification of primary photons in the recorded air shower data, the challenge is to separate photon-induced showers from those initiated by hadrons. Thus, the differences between these two classes of air showers are of great importance. Air showers initiated by UHE photons develop, on average, deeper in the atmosphere than air showers of the
same primary energy initiated by hadrons. This can be expressed through the observable $X_{\text{max}}$, which describes the atmospheric depth of the shower maximum (see Fig. 1). At larger energies, additional effects like the Landau-Pomeranchuk-Migdal (LPM) effect and preshower processes above the atmosphere, which further influence the shower development, have to be taken into account [1]. $X_{\text{max}}$ has become a key observable for current cosmic-ray research, mostly due to the fact that it can be accessed directly using the air-fluorescence technique. Current air shower experiments like the Pierre Auger Observatory [12] or the Telescope Array [13] are following a hybrid approach, where fluorescence detectors are complemented by a ground array of particle detectors. The typical $X_{\text{max}}$ resolution of e.g. the Pierre Auger Observatory is better than 26 g cm$^{-2}$ at energies around $10^{17.8}$ eV, improving with energy to about 15 g cm$^{-2}$ above $10^{19.3}$ eV [14]. This is much smaller than the differences in the average $X_{\text{max}}$ between photon- and hadron-induced air showers at these energies ($\sim 100$ g cm$^{-2}$ at $10^{18}$ eV and $\sim 160$ g cm$^{-2}$ at $10^{19}$ eV, cf. Fig. 1).

To fully exploit this hybrid approach and to improve the photon-hadron separation power, it is useful to complement the observable $X_{\text{max}}$ with an additional observable that is based on the data from the ground array. In the past, observables such as the curvature of the shower front or the risetime of the signals in the detectors of the ground array have been used in the context of the search for photons [15, 16]. However, such observables can only be reliably estimated when a minimum number of detectors of the ground array have triggered. For example, at least five detectors are needed to determine the curvature of the shower front with acceptable accuracy. This effectively places a lower limit—for past analyses typically at 10 EeV—on the energy region that can be accessed with an analysis based on these observables. At lower energies, i.e. in the eV range, the observable $S_b$ [17] has been successfully used in past analyses [15, 19, 20, 3]. $S_b$ is based on the sum of the signals $S_i$ measured in the individual detectors $i$ of the ground array, weighted by the distances $r_i$ of the detectors to the shower axis:

$$S_b = \sum_i S_i \left( \frac{r_i}{1000 \text{m}} \right)^b,$$

with the free parameter $b$, which has to be fixed for a given analysis [21].

Air showers initiated by photons have, on average, a smaller $S_b$ than air showers induced by hadrons of the same primary energy [21]. However, an observable like $S_b$ can be significantly affected by any incompleteness in the detector array, which would lead to an underestimation of the true value. Such an incompleteness may be due to the borders of the array, due to missing detectors (important e.g. during the deployment phase of the array), or due to temporarily non-operating detectors. As an example for the latter effect, let us assume that at any time, 1% of the detectors from the ground array are temporarily non-operating. For an array geometry where the detectors are arranged on a hexagonal grid, this means that 6% of all events contain at least one non-operating detector in the first hexagon around the detector measuring the largest signal. When also the second hexagon is considered, about 18% of all measured events are affected. Special care must then be taken, e.g. in the event selection, to prevent an underestimation of the $S_b$ value for a given event due to these incompletenesses, which could mimic the expected behaviour of a photon-induced air shower. This holds especially at energies not far from the energy threshold of the experiment, where usually only very few detectors of the ground array are triggered and an omission of a signal from a detector can alter the $S_b$ value substantially.

In this paper, we describe a new observable, called $F_{\gamma}$, which can be used at all energies down to the threshold set by the shower array. This observable exploits, similarly to $S_b$, the lateral distribution of the density of secondary particles from the air shower on ground level and is, as will be discussed later, complementary to $X_{\text{max}}$. Unlike $S_b$, missing stations will not alter the central value of $F_{\gamma}$ (but only increase its uncertainty), leading to an improved stability of the observable. The lateral distribution can be described by a lateral distribution function (LDF), which can be determined from the ground-array data. The shape of the LDF depends on the type of the primary particle initiating the air shower: for photon-induced air showers, which on average exhibit a smaller number of secondary muons and a larger $X_{\text{max}}$ compared to hadron-induced air showers of the same primary energy, the LDF is steeper, leading
2. Description of the observable

2.1. General idea

The observable $F_\gamma$ is based on a template fit of an LDF to the data recorded by the ground array. In this fit, we assume the primary particle initiating the air shower was a photon, and we determine the expected signal recorded in a detector of the ground array at a reference distance under this assumption. In this fit, two things will be different between photon- and hadron-induced showers with the same primary energy. First, the LDF fit will better describe the lateral particle distributions for primary photons than for primary hadrons. Second, the signal at a certain distance from the shower core will be smaller for showers initiated by photons than for those initiated by hadrons, as is known from air shower physics. We exploit the second difference. We normalize the expected signal obtained from the fit to the average signal expected for hadron-induced air showers of the same primary energy and zenith angle, and we call the resulting quantity $F_\gamma$, In short, the sequence to determine $F_\gamma$ for a given air shower event is as follows:

- From hybrid observations, in particular of the longitudinal shower profile, the energy $E$ and zenith angle $\theta$ of the event are reconstructed;
- Using $E$ and $\theta$ as an input, a photon LDF template is fit to the ground-array data of the event. The template is prepared in advance using extensive photon simulations. The fit determines the LDF normalization $S_{1000|\gamma}$, the only remaining free parameter of the template;
- The average ground signal $\langle S_{1000} \rangle$ in case of hadron-induced air showers expected for this event is calculated using $E$ and $\theta$. The relation between these quantities is known from the standard energy calibration of the ground array;
- $F_\gamma$ for this event is then given by the ratio $S_{1000|\gamma}/\langle S_{1000} \rangle$.

2.2. Specific implementation

In the following section, we describe a specific realization of the observable $F_\gamma$. In particular, we use a given functional form to describe the LDF. However, the core concept of the observable as described above does not depend on the very choice of a functional form for the LDF or even a particular experimental setup, but it can be applied to different functional forms and adapted to different experiments.

To describe the LDF—i.e. the signal $S$ measured in a detector at a perpendicular distance $r$ from the shower axis—, we use an NKG-type function, which has the following form:

$$S(r) = k \left( \frac{r}{r_{\text{opt}}} \right)^{\beta} \left( \frac{r + r_s}{r_{\text{opt}} + r_s} \right)^{\beta},$$

where $r_{\text{opt}}$ is the optimum distance at which the characteristic parameters of the air shower can be determined to reduce e.g. uncertainties due to a lack of knowledge about the true LDF, $r_s$ is a scaling parameter, $k$ is a normalization parameter equal to the signal at the optimum distance, and $\beta$ is the slope of the LDF. The choice of the optimum distance depends on the geometrical properties of the ground array. For the experimental setup of the Pierre Auger Observatory—which is assumed from now on—with its hexagonal grid and a spacing of 1500 m between the individual detectors, $r_{\text{opt}} \simeq 1000$ m is found [22]. The normalization parameter $k$ is then commonly referred to as $S_{1000}$— and given in units of vertical equivalent muon (VEM) —, and the scaling parameter $r_s$ is chosen as $r_s = 700$ m. The determination of the LDF is thus reduced to determining $S_{1000}$ and $\beta$.

When only data from the ground array are available, the normalization parameter $S_{1000}$ is used to estimate the energy of the primary particle initiating the recorded air shower. In hybrid events, however, the primary energy as well as other shower parameters such as the shower geometry can be determined from the data recorded by the fluorescence detectors. With this knowledge, we can introduce the template, or “photon-optimized”, fit of the LDF, which is the basis for the observable $F_\gamma$. In this fit, we fix the slope parameter $\beta$ to the average value expected for a photon-induced air shower that has the same primary energy $E$ and the same zenith angle $\theta$ as reconstructed from the fluorescence detector data. In general, the type of the primary particle that initiated the recorded air shower is not known. Hence, we use the photon energy $E_\gamma$, i.e. the calorimetric energy determined from the fluorescence detector data corrected for the missing energy expected for a photon-induced air shower (about 1 % of the calorimetric energy [23]) as reference energy for all events in the application of the observable. Since the slope of the LDF is fixed in the photon-optimized LDF fit, only the normalization parameter, which we denote as $S_{1000|\gamma}$, has to be
determined from the fit. The function that is fitted to the data from the ground array thus reads

\[ S(r) = S_{1000|\gamma}(\frac{r}{1000\text{ m}})^{\beta(E, \theta)}(\frac{r + 700\text{ m}}{1700\text{ m}})^{\beta(E, \theta)}. \] (3)

Since only a single parameter of the LDF has to be determined, the photon-optimized fit can also be applied to lower-energy events in the EeV range, where perhaps even only one detector from the ground array is triggered. On a technical note, we use a maximum-likelihood method to determine the photon-optimized LDF, which enables us to use not only the information from the triggered detectors in the fit, but also from non-triggering but active detectors. These effectively place an upper limit on the signal at the corresponding distance to the shower axis, and it is another advantage of the $F_{\gamma}$ observable that this piece of information can be taken into account in a straightforward way.

To fix the slope parameter $\beta$, we use a phenomenological parameterization that has been derived from MC simulations of photon-induced air showers in the energy range between 1 and 10 EeV (referring to the true MC energy) and in the zenith angle range between 0 and 60°:

\[ \beta(E_{\gamma}, \theta) = a_0(E_{\gamma}) + a_1(E_{\gamma}) (\sec(\theta) - 1)^3, \] (4)

with

\[ a_0(E_{\gamma}) = b_0 + b_1 \log_{10}(E_{\gamma}\text{ [eV]}), \]
\[ a_1(E_{\gamma}) = c_0 + c_1 \log_{10}(E_{\gamma}\text{ [eV]}) + c_2 \log_{10}(E_{\gamma}\text{ [eV]})^2. \]

The five parameters $b_0$, $b_1$, $c_0$, $c_1$ and $c_2$ are:

\[ b_0 = -0.695 \pm 0.098, \]
\[ b_1 = -0.107 \pm 0.005, \]
\[ c_0 = 506.72 \pm 0.11, \]
\[ c_1 = -53.159 \pm 0.006, \]
\[ c_2 = 1.3972 \pm 0.0003. \]

In Fig. 2 the parameterized $\beta$, following Eq. 4, is given as a function of the energy $E_{\gamma}$ for three different fixed zenith angles $\theta$. Due to the dependence on secant cubed of the zenith angle, the curves for $\theta = 0°$ and $30°$ are very similar. Only at larger zenith angles, the curves change significantly.

An example for the application of the photon-optimized fit to two simulated air shower events with the same primary energy ($E_{\text{MC}} \sim 3.5\text{ EeV}$) and zenith angle ($\theta \sim 45°$), but different primary particle types (photon in blue, proton in red). Non-triggering stations that are included in the photon-optimized LDF fit are indicated as upper limits (at 95% C.L.) on the expected signals at the corresponding distances.

The observable $F_{\gamma}$ is eventually obtained by normalizing the $S_{1000|\gamma}$ that is determined from the photon-optimized fit of the LDF to the value of $S_{1000}$ that is expected for an average (hadron-induced) air shower with the same primary energy and the same zenith angle. Thus, $F_{\gamma}$ is defined as

\[ F_{\gamma} = \frac{S_{1000|\gamma}}{(S_{1000})(E_{\gamma}, \theta)}. \] (5)
In hybrid events, the primary energy \( E \) and the zenith angle \( \theta \) are determined from the data from the fluorescence detectors, hence \( \langle S_{1000} \rangle \) can be calculated from the reconstructed energy and zenith angle by inverting the formulas for the energy calibration (for the dependence on the energy) and the Constant Intensity Cut (CIC) function (for the dependence on the zenith angle) [21]. As before, we use the photon energy \( E_{\gamma} \) for all events. For the two example events shown in Fig. 3, the \( F_{\gamma} \) values are 0.34 ± 0.08 for the photon event and 0.54 ± 0.12 for the proton event.

3. Performance

3.1. \( F_{\gamma} \) alone

To evaluate the performance of the observable for photon-hadron discrimination, a set of photon- and proton-induced air showers has been simulated with CORSIKA [25], version 7.4000, using QGSJET-II-04 [11] and Fluka2011.2b.6 [26] as hadronic interaction models at high and low energies, respectively. In total, 20,000 air showers have been simulated in ten energy bins (equidistant in \( \log_{10} E \)) as hadronic interaction models at high and low energies. This in the energy range between 1 and 10 EeV for each of the two primary particle types. As stated before, we use the setup of the Pierre Auger Observatory as an example for the application of the observable. Hence, we use the Offline software framework of the Auger collaboration [28] to simulate the detector response of the fluorescence detectors and the individual detectors of the ground array. For the air shower simulations, we use \( 10^{-6} \) optimum thinning [29, 30]. For the unthinning, we use the standard routines implemented in the Offline software framework, which are based on [31]. Each CORSIKA shower is resampled five times with the core position of the shower randomly distributed over the area of the ground array. The total data set of simulated air shower events contains 200,000 events. Several cuts are applied to the data set to ensure that only events of sufficient quality, i.e. with a well-reconstructed geometry and shower profile following the selection criteria from [20], enter the analysis. Overall, this event selection retains about 30% (33%) of all triggered photon (proton) events at energies around 1 EeV, increasing to 42% (69%) around 10 EeV. The differences between the selection efficiencies for primary photons and protons can be attributed to the differences between air showers initiated by the two particle types as discussed in Sec. 1.

In Fig. 4 (left column), the \( F_{\gamma} \) distributions for three different energy bins between \( E_{\rm MC} = 1 \) EeV and \( E_{\rm MC} = 10 \) EeV are shown. The average values of the distributions are roughly as expected from the definition of the observable (see Eq. 5) around 0.8 for the proton distributions (since \( S_{1000} \) from the photon-optimized LDF fit underestimates the “true” \( S_{1000} \) by construction, while \( \langle S_{1000} \rangle (E_{\gamma}, \theta) \) is close to the “true” \( S_{1000} \)) and around 0.4 for the photon distributions (\( S_{1000} \) is, on average, close to the “true” \( S_{1000} \) of photons, but \( \langle S_{1000} \rangle (E_{\gamma}, \theta) \) is much larger than the “true” \( S_{1000} \)). Qualitatively, it can be seen that the distributions are well-separated. The separation gets larger with increasing energy. To quantify the separation between proton- and photon-induced air shower events, we use the merit factor \( \eta \) as a measure for the separation power of an observable. The merit factor is defined as

\[
\eta = \frac{|\mu_{\gamma} - \mu_{p}|}{\sqrt{\sigma_{\gamma}^2 + \sigma_{p}^2}},
\]

with \( \mu_{\gamma} \) and \( \mu_{p} \) (\( \sigma_{\gamma} \) and \( \sigma_{p} \)) denoting the mean values (standard deviations) of the photon and proton distributions, respectively. For the case of the distributions shown in Fig. 4, merit factors of 1.40, 2.12 and 2.41 are obtained in the three different energy bins. The increase in the merit factor comes mostly from the smaller widths of the distributions at higher energies. With increasing energy, more stations are triggered and enter the LDF fit. Thus, fluctuations in the signals are mitigated in the fit, leading eventually to a narrower \( F_{\gamma} \) distribution. The mean values of the distributions do not change significantly. This is expected from the definition of the observable, since the energy dependence is largely removed by dividing \( S_{1000} \) by \( \langle S_{1000} \rangle (E_{\gamma}, \theta) \).

For comparison, the merit factors of the corresponding \( X_{\max} \) distributions for the same data set have been calculated. Merit factors of 1.28, 1.76 and 1.97 have been obtained for the three energy bins. The merit factors calculated here are in good agreement with what is expected from parameterizations of the \( X_{\max} \) distributions for primary photons and protons at the corresponding energies [32].

For the same conditions, the separation power of \( F_{\gamma} \) in terms of \( \eta \) is thus larger than the separation power of the observable \( X_{\max} \) over the full energy range considered here. For the observable \( S_{b} \) with \( b = 4 \)—the value that has been used in [20]—a merit factor around 2 is found in [21] for energies averaged between 10^{17.5} eV and 10^{19.6} eV and a hexagonal grid with 1500 m spacing (cf. the merit factor of 2.41 for \( F_{\gamma} \) around 10^{19} eV). For other choices of \( b \), the merit factor might be higher, but it should be noted that in [21], a semi-analytical approach was employed instead of a full MC simulation of the detector response. Overall, it can be stated that \( F_{\gamma} \) is at least on par with \( S_{b} \) in terms of the merit factor over the energy range considered here.

It should be noted however, that the merit factor takes into account only the mean and the width of the distributions and not the full shape. As an example, one could imagine a long tail in the proton distribution reaching beyond the bulk of the photon distribution. Proton events in this tail will very likely be misidentified as photon events, even though the bulk of the distributions may be well-separated, leading to a large merit factor. Hence, we employ a second measure for the separation power: the background rejection, i.e. the fraction of events in the proton.
Figure 4: Performance of $F_\gamma$ in three different energy bins between $E_{\text{MC}} = 1$ EeV and $E_{\text{MC}} = 10$ EeV. Left column: distributions of $F_\gamma$ for primary photons (blue) and protons (red). The mean values $\mu$ and the standard deviations $\sigma$ of the distributions as well as the merit factors $\eta$ calculated from these values are indicated in the plots. Right column: background rejection as a function of the signal efficiency, calculated from the $F_\gamma$ distributions. The background rejection at a signal efficiency of 50% is indicated by the dashed red lines.
distribution rejected by a given cut value on the observable, as a function of the signal efficiency, i.e. the fraction of events in the photon distribution that pass the given cut. The resulting curves are shown in Fig. 4 (right column). As reference value for the separation power, the background rejection at a signal efficiency of 50% (i.e. the cut value corresponds to the median of the photon distribution) is usually taken. From the three curves shown in Fig. 4, values of 97.83%, 99.77% and 99.94% are obtained for the three energy bins. As before, the corresponding values for the observable \( X_{\max} \) have also been determined for comparison. In the three energy bins, values of 92.60%, 97.57% and 98.48% were calculated.

In Fig. 5 the performance of the \( F_\gamma \) observable in comparison with \( X_{\max} \) is shown over the full energy range from 1 to 10EeV. In terms of the merit factor, the separation power of both observables increases linearly with the logarithm of the energy, albeit with a larger slope for \( F_\gamma \). In terms of the background rejection, both curves converge exponentially towards 100%. However, the \( F_\gamma \) curve converges much faster: already around \( 10^{18.4} \) eV, the curve is above 99.5%, while the \( X_{\max} \) curve is still below 98.5% around \( 10^{19} \) eV.

### 3.2. Combination with \( X_{\max} \)

In a realistic application, \( F_\gamma \) will not be used as a stand-alone observable, but rather in combination with some other observable, e.g. \( X_{\max} \), to fully exploit the information available in hybrid events. Hence, we will now discuss the potential performance of the combination of the two observables \( F_\gamma \) and \( X_{\max} \). In Fig. 6 scatter plots of the two observables in three different energy bins are shown. Within the individual data sets, the two observables are largely uncorrelated, with the correlation coefficients close to zero. Comparing the photon and the proton data sets, it can be seen that the two observables complement each other well. The distributions are well separated in the \( (F_\gamma, X_{\max}) \) space, with the separation increasing with energy as before. Especially at higher energies, only very few proton events are found in the regions where the bulk of the photon distribution is located. Already by applying simple cuts on the two observables, it is possible to reach a background rejection very close to 100% (i.e. comparable to the background rejection quoted above for \( F_\gamma \)), but at a much larger signal efficiency.

Another possibility is to combine the two observables in a Multi-Variate Analysis (MVA). To illustrate the potential of an MVA combining \( F_\gamma \) and \( X_{\max} \), we use a simple linear Fisher discriminant analysis \[34\]. The Fisher analysis has the advantages that it can be calculated analytically and that it provides robust and very good event classification for uncorrelated input observables, as is the case for \( F_\gamma \) and \( X_{\max} \). In Fig. 7 the distribution of the Fisher discriminant is shown exemplarily for the first energy bin. As expected from the scatter plots, the distributions are very well separated. The overlap between the photon and the proton distributions is smaller than for \( F_\gamma \) alone. Consequently, the merit factor increases to 2.0, while the background rejection at a signal efficiency of 50% increases to 99.39%. In other words, the combination of both observables can reduce the background contamination at this signal efficiency and in this energy bin by more than a factor of 3 compared to \( F_\gamma \) alone and more than a factor of 12 compared to \( X_{\max} \) alone. At higher energies, the combination of the two observables performs similarly well (see also Fig. 5). The merit factors increase to 2.82 and 3.10 in the second and third energy bin from Fig. 4 respectively. The values for the background rejection rise to 99.94% in the second energy bin and 100% (within the limited statistics available in the data sets used here) in the third energy bin.

![Figure 5: Separation power of \( F_\gamma \) (red) between \( E_{\text{MC}} = 1 \) EeV and \( E_{\text{MC}} = 10 \) EeV, compared to the separation power of \( X_{\max} \) (blue). Top: merit factor \( \eta \); bottom: background rejection \( \rho \) at 50% signal efficiency. The uncertainties on \( \eta \) and \( \rho \) have been determined using the bootstrapping method \[33\]. The red and blue lines have been included to guide the eye, while the gray lines indicate the separation power of a possible combination of the two observables in a simple Fisher analysis (cf. Sec. 3.2).](image-url)
4. Discussion

In summary, we introduced a new observable, called $F_\gamma$, to improve the photon-hadron separation in air shower events measured simultaneously by fluorescence detectors and a ground array. $F_\gamma$ shows very good separation power and complements nicely to $X_{\text{max}}$. Combining both observables in an MVA leads to a background rejection of 99.39\% at 50\% signal efficiency at energies around $10^{13}$ eV, improving further with increasing energy. In other words, the observable allows one to reach a nearly background-free regime while still keeping a significant fraction of the signal. A particular advantage of $F_\gamma$ is its reconstruction stability: it can be applied also at energies close to the energy threshold of the experiment, where perhaps even just a single detector from the ground array is triggered. The absence of a signal measured in an active station can be taken into account as well. In addition, the observable is not affected significantly by incompletenesses of the ground array, e.g. at the borders of the array or due to temporarily non-operating detectors. We explicitly checked this by removing triggered stations from a (simulated) event and repeating the photon-optimized LDF fit without these stations. On average, the deviation of the resulting $F_\gamma$ value from the one obtained with all stations included in the fit is in the order of a few percent only, which is within the average uncertainties on $F_\gamma$. Especially if only one or two stations are removed, the deviation is practically negligible. We also note that the observable is not significantly affected by uncertainties in the hadronic interaction models used in air shower simulations. This is because the template used in the photon-optimized LDF fit is based only on photon simulations, where the impact of the choice of the hadronic interaction model is practically negligible (cf. Fig. 1). The method of the LDF template fit can be easily adapted to other experimental setups than the case of the Pierre Auger Observatory discussed in this paper. This includes mixed configurations as well, where e.g. a part of the ground array has a denser arrangement of detectors.

In this work, we discussed the application of the $F_\gamma$ ob-
servable for hybrid data, i.e. data where simultaneous measurements from both a fluorescence detector and a ground array are available. However, the observable is not limited to the particular combination of a fluorescence detector and a ground array. Only the reconstructed shower geometry and primary energy are needed in addition to the data from the ground array to determine $F_\gamma$. This additional information could also be obtained from e.g. radio measurements of air showers, which may start to develop into a viable possibility to measure the longitudinal development of air showers in the atmosphere without the limitations in detector uptime that the air-fluorescence technique faces.\footnote{35}

The method of the LDF template fit could also be applied to mass composition studies, since the characteristic differences between proton-induced and iron-induced air showers are similar to the differences between air showers initiated by photons and protons (i.e. larger $X_{\text{max}}$, cf. Fig.\[1\]) and smaller number of muons). A preliminary study of the proton-iron separation using $F_\gamma$ without any changes to the observable compared to this work leads to merit factors comparable to those obtained with $X_{\text{max}}$ at energies around $10^{19}$ eV. In a real application, the template used in the LDF fit should be adapted, i.e. the fit should be optimized to e.g. primary iron nuclei. If the appropriate template is used, it can be expected that the performance of an $F_\gamma$-like observable for proton-iron separation is even higher.

So far, we used a basic event selection to ensure that only events of sufficient reconstruction quality enter the analysis. The overall photon-hadron separation could be improved further by introducing additional event selection criteria, optimized for the specific experimental setup. Such criteria could be based for example on the goodness of the LDF fit. In general, it is expected that the photon-optimized LDF doesn’t fit proton-induced air shower events well (see the two example events shown in Fig.\[3\]). Hence, the goodness of the fit could in principle be used to select photon-like events and to further improve the search for UHE photons.

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