# Some observable parameters of Cherenkov photons in Extensive Air Showers of different primaries at various zenith angles

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We have studied the density and angular distributions of Cherenkov photons in extensive air showers initiated by $\gamma$-ray and proton primaries at different energies and at different zenith angles. The study of this kind is important to distinguish the $\gamma$-ray initiated showers from hadronic showers by understanding the nature of $\gamma$-ray and hadronic showers. In this work, we used CORSIKA 6.990 simulation package. For the high energy hadronic interaction part, QGSJET-II and EPOS hadronic interaction models are used whereas for low energy interaction FLUKA model is used. Here we are going to report the result of this work.

## 1. Introduction

For ground based detection of $\gamma$-rays in the range of few hundred GeV to few TeV, the Atmospheric Cherenkov Technique (ACT) is the most extensively used technique which is based on detection of Cherenkov photons emitted in the Extensive Air Showers (EASs) created during the process of interaction between the primary $\gamma$-rays and earths atmosphere [1]. It should be noted that, the sources which emit $\gamma$-rays also emit Cosmic Rays (CRs). As the CRs are mostly charged particles they got deflected by the intergalactic magnetic fields and hence they loose their directional property, whereas $\gamma$-rays being neutral, retain their direction of origin. So the detection of $\gamma$-rays can lead to the estimation of the locations of such astrophysical objects.

ACT, being an indirect process of $\gamma$-ray detection and due to the presence of huge CR background, a detailed Monte Carlo simulation studies of atmospheric Cherenkov photons have to be carried out for detection and proper estimation of their energy from the observational data of experiments based on ACT. Although both $\gamma$-ray and CR can generate EAS, the nature of two are different as the former is purely electromagnetic in nature whereas the later is a mixture of electromagnetic and hadronic cascades. Many studies have already been carried out on the density, arrival time and angular distributions of Cherenkov photons in EASs using available detailed simulation techniques [2, 3, 4, 5, 6, 7], however not many studies have been done on model dependent behaviour of density and angular distributions of Cherenkov photons initiated by $\gamma$-ray and hadronic particles incident at various zenith angles, particularly at high altitude observation levels. Consequently, in this work we have studied the angular and density distributions of Cherenkov photons at different energies and at different zenith angles on a high altitude observation level, using two different high energy hadronic interaction models, viz., QGSTJETII and EPOS with FLUKA low energy hadronic interaction model available in the CORSIKA simulation package [8].

CORSIKA is a detailed Monte Carlo simulation package to study the evolution and properties of extensive air showers in the atmosphere. This allows to simulate interactions and decays of nuclei, hadrons, muons, electrons and photons in the atmosphere up to energies of some $10^{20}$eV. For the simulation of hadronic interactions, presently CORSIKA has the option of seven high energy hadronic interaction models and three low energy hadronic interaction models. It uses EGS4 code [9] for the simulation of electromagnetic component of the air shower [8]. This paper is organized as follows. In the section 2, we discuss briefly about the simulation process. The section 3 contains the analysis and results of the simulated data. The summary of the work with conclusion is put in the section 4.

## 2. Simulation of the Extensive Air Showers

The simulation of the Cherenkov photons in EASs is carried out by using the CORSIKA 6.990 simulation package. As mentioned earlier, we have used two high energy hadronic interaction models, viz., QGSJETII.3 and EPOS 1.99 with the low energy hadronic interaction model FLUKA to generate EASs for the monoenergetic $\gamma$-ray and proton primaries incident vertically as well as inclined at zenith angle $10^o$, $20^o$ and $30^o$. The QGSJETII and EPOS high energy hadronic interaction models are preferred because QGSJETII is the improved version of the model

QGSJET01 and EPOS is based on quantum mechanical multiple scattering approach based on partons and strings, which performed better compared to RHIC data [10]. By using QGSJETII-FLUKA and EPOS-FLUKA model combinations, the following numbers of showers were generated at different energies and at different zenith angles for the $\gamma$-ray and proton primaries as given in Table 1.

**Table 1.** Number of showers generated at different energies and at different zenith angles for different primaries using QGSJETII-FLUKA and EPOS-FLUKA model combinations.

| Primary particle | Energy | Number of Showers |
|---|---|---|
| $\gamma$-ray | 100 GeV | 10000 |
| | 250 GeV | 7000 |
| | 500 GeV | 5000 |
| | 1 TeV | 2000 |
| | 2 TeV | 1000 |
| Proton | 250 GeV | 10000 |
| | 500 GeV | 8000 |
| | 1 TeV | 5000 |
| | 2 TeV | 2000 |
| | 5 TeV | 800 |

The energies of the primaries selected for this work are the typical ACT energy range of respective primaries in terms of the equivalent number of Cherenkov photons yield. The altitude of HAGAR experiment at Hanle (longitude: $78^o\ 57'\ 51''$ E, latitude: $32^o\ 46'\ 46''$ N, altitude: 4270 m) is used as the observational level in the generation of these showers. The cores of the EASs is considered to be at the centre of the detector array. The detector geometry is set as a horizontal flat detector array, where there are 25 telescopes in each of the E–W direction and the N–S direction with a separation of 25 m in between two telescopes. The mirror area of each telescope is taken as 9 m$^2$. Details of the simulation parameters can be obtained in our earlier work in [7].

## 3. Analysis and results

The density of the Cherenkov photon is obtained by counting the numbers of photons incident on each detector for each of the shower, while the angular distribution of Cherenkov photons is obtained by counting the number of photons produced per angular bin with respect to the shower axis. For angular distribution the numbers of photons are then normalized to one photon ($\frac{1}{N}\frac{dN}{d\theta}$ (degree$^{-1}$)) with averaged over azimuth. The analysis has been done on the ROOT software [11] platform by using C++ programs developed by us. The results of this work are discussed in the following subsections:

### 3.1 Cherenkov photon density

Fig. 1 shows the variation of average Cherenkov photon density $\rho_{ch}$ as a function of core distance $r$ (in meter) in the EASs initiated by the $\gamma$ and proton primaries of various energies incident at zenith angles $0^o$ and $30^0$. The hadronic interaction model combination used here is the EPOS-FLUKA. In Fig. 2 the density distributions for $\gamma$-ray and proton primaries have been plotted for fixed energies but for different zenith angles. It is seen that the density distribution has an exponential fall with increasing core distance for both the primaries at all energies [7] and at all zenith angles. It is clear that with increasing zenith angle, the $\rho_{ch}$ decreases sufficiently upto a certain core distance depending upon the primary particle type and energy. This effect of zenith angle decreases with increasing energy of primary particle. For $\gamma$-ray primaries at energy 100 GeV, the characteristic hump is visible at a core distance of about 100 m.

### 3.2 Angular distribution

Fig. 3 shows the angular distributions of Cherenkov photons for $\gamma$-ray and proton primaries at different energies and incident at zenith angles $0^o$ and $30^o$. It can be seen that for both $\gamma$-ray and proton primaries, the Cherenkov

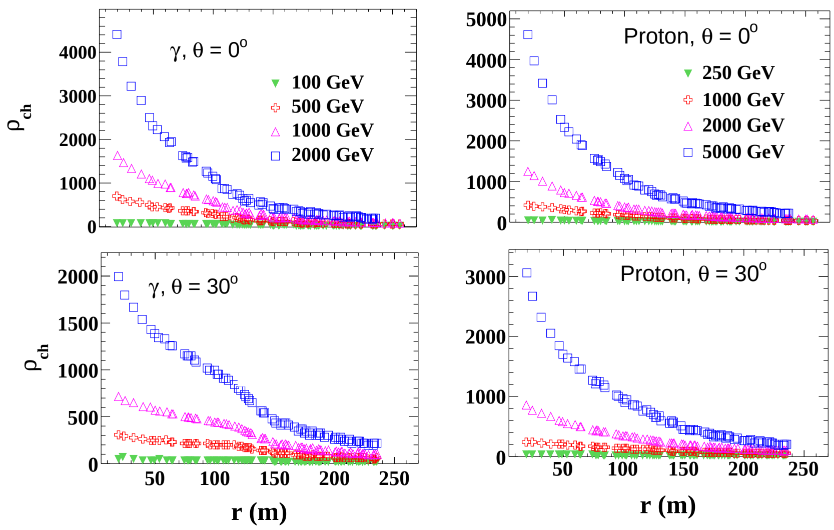


**Figure 1.** Density distributions of Cherenkov photons in EASs of $\gamma$-ray and proton primaries at different energies and incident at angles $0^o$ and $30^o$.

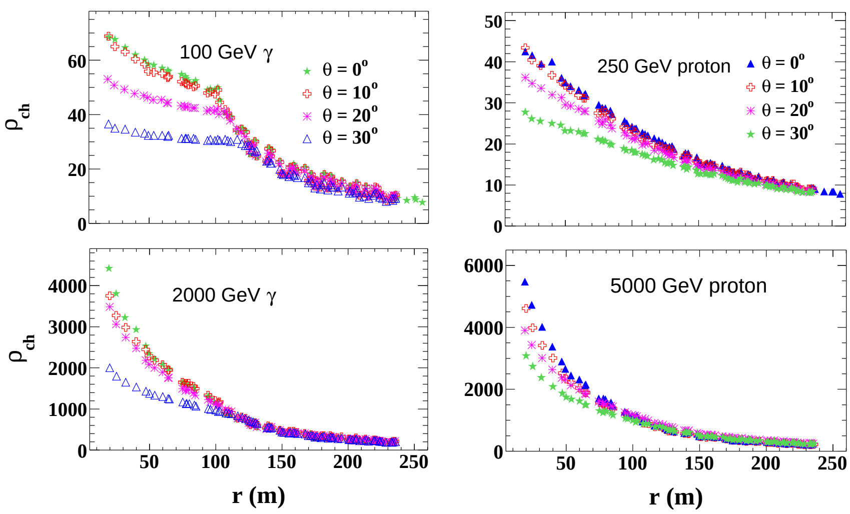


**Figure 2.** Density distributions of Cherenkov photons in EASs of $\gamma$-ray and proton primaries at two different energies incident at angles $0^o$, $10^o$, $20^o$ and $30^o$.

photons are distributed on average within $1^0$ to $30^o/40^o$ from the shower axis. Most of the photons are scattered within $1^o$ to $2^o$ from the shower axis after which there is a rapid fall in the number of particles scattered at larger angles. For each of the angle of incidence, the pattern has become flatter with increase in energy of the incident primary. Further, for larger value of the angle of incidence the distribution profile has become steeper as well as symmetric for all values of energy. For proton primaries, the distribution follows a rather linear fall than in comparison to the exponential fall for the $\gamma$-ray. Moreover, the distributions for the $\gamma$-ray at higher zenith angles are more symmetric than that for the proton primary.

### 3.3 Dependence on hadronic interaction model

Fig. 4 and 5 show the angular distributions of Cherenkov photons initiated by $\gamma$-ray of energy 100 GeV and 1000 GeV and proton primaries of energy 250 GeV and 2000 GeV respectively as obtained by using two hadronic

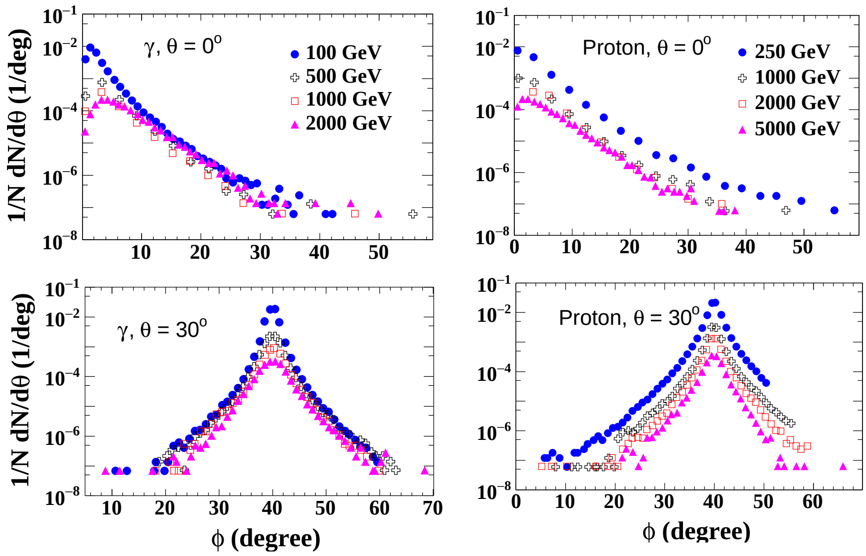


**Figure 3.** Angular distributions of Cherenkov photons in EASs of $\gamma$-ray and proton primaries at different energies incident at zenith angles $0^o$ and $30^o$.

interaction model combinations viz. EPOS-FLUKA and QGSJETII-FLUKA for four different zenith angles under consideration. It is seen from the distributions that both the model combinations produce similar results except for the 250 GeV proton where the EPOS-FLUKA combination seems to have generated slightly higher numbers of Cherenkov photons than the QGSJETII-FLUKA model combinations.

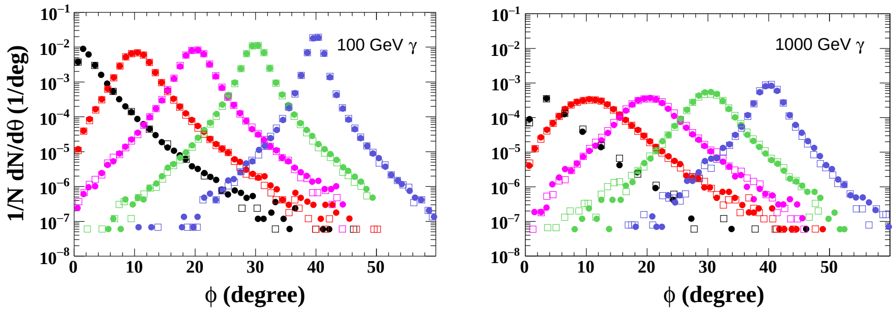


**Figure 4.** Angular distribution of Cherenkov photons initiated by $\gamma$-rays of energy 100 GeV and 1000 GeV incident at various zenith angles obtained by using EPOS-FLUKA and QGSJETII-FLUKA model combinations. In the respective plots, different coloured ● and □ indicate the EPOS-FLUKA and QGSJETII-FLUKA model combinations respectively. Plots with peaks from left to right represent the showers with zenith angles from $0^o$ to $30^o$ respectively.

## 4. Summary and conclusion

Considering the importance of effective gamma-hadron separation techniques and the lack of sufficient studies in this context, we have studied the density and the angular distributions of Cherenkov photons in EASs produced by $\gamma$-ray and proton primaries at different energies and at different zenith angles using the CORSIKA 6.990 simulation package [8]. The density of Cherenkov photons in EASs of both primaries is the increasing function of energy of primary particle, but the decreasing functions the zenith angle and the distance from the shower core. The decreasing effect of the zenith angles decreases with increasing energy of primary particle. Most of the Cherenkov photos are scattered within $1^o$ to $2^o$ with respect to the shower axis. Angular distributions of Cherenkov photons for $\gamma$-ray and proton primaries have slightly different patterns. A detail study on the difference in the patterns of

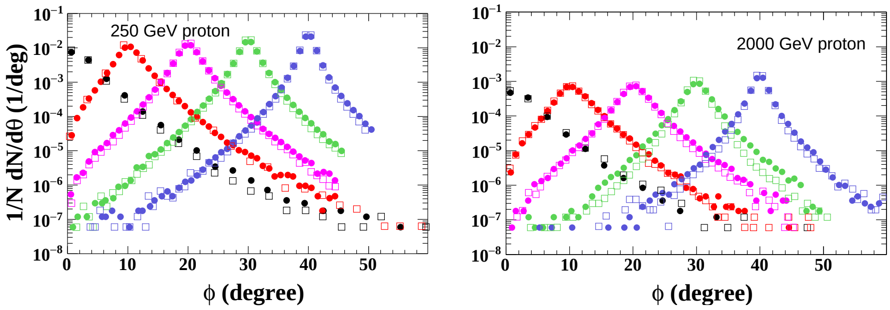


**Figure 5.** Angular distribution of Cherenkov photons initiated by proton primaries of energy 250 GeV and 2000 GeV incident at various zenith angles obtained by using EPOS-FLUKA and QGSJETII-FLUKA model combinations. In the respective plots, different coloured ● and □ indicate the EPOS-FLUKA and QGSJETII-FLUKA model combinations respectively. Plots with peaks from left to right represent the showers with zenith angles from $0^o$ to $30^o$ respectively.

distributions of Cherenkov photons obtained from EASs of $\gamma$-ray and proton primaries may be useful for distinguishing the $\gamma$-rays from the CR background. The angular distributions of Cherenkov photons are found to be model independent for both $\gamma$-ray and proton primaries in the range of 100 GeV to 100 TeV.

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