Detection of primary photons in high energy cosmic rays using \v{C}erenkov imaging and surface detectors

\lettrine[nindent=0em,lines=3]{D}iscovered by Hess during some experiments about air ionization, cosmic rays are constituted by particles coming from the space. In the past, cosmic rays allowed the development of Particle Physics; indeed, thanks to their high energy not achievable in laboratories, they enabled new particles discovery. Today, interest about this radiation concerns both Astrophysics and Particle Physics. Indeed on the one hand, their knowledge allows formulation about new models of Universe structure and evolution or to acquire new knowledge about final objects of stars evolution; on the other hand cosmic rays allows us to study fundamental processes, as for example acceleration and interaction mechanisms of particles at energies not achievable in laboratories. Although it has passed more than a century after their discovery, there are many questions to which it isn't possible to answer yet or to which there isn't certainty about formulated theories. Some examples are about objects that can accelerate particles to high energy and acceleration mechanisms; indeed, even if there are some theories, we don't have experimental certainty. Moreover, although measured in many experiments, energy spectrum shows, especially in the region called "Knee", some differences between measuring made by experiments. Since magnetic fields deflect charged particles, their observation doesn't allow to go back to the source, so in cosmic rays study it's very important γ rays observation because they aren't deflected by magnetic fields. In 1989 \textit{\textbf{Whipple}} experiment allowed to observe, for the first time,
$unitTeV$ energy γ rays coming from Crab Nebula. Thanks to many experiments made to answer questions about cosmic rays, more than 100 \textit{\textbf{\ac{VHE}}} γ rays sources were observed since then; 60 out of 100 have galactic origin, as for instance Supernova Remnants or Pulsars; for the rest, apart from those not identified, they have extra-galactic origin. In this perspective, \textit{\textbf{\ac{LHAASO}}} experiment is currently in planning phase; it will be composed by \ac{LHAASO-KM2A} (it will be composed by \textit{\textbf{\ac{ED}}} and \textit{\textbf{\ac{MD}}}) to measure number and arrival time of particles, \ac{LHAASO-WCDA} a water \v{C}erenkov detector to study cosmic rays of energies higher than
$unit[1]TeV$ and \ac{LHAASO-WFCTA} a \v{C}erenkov telescope system to measure longitudinal development of cosmic rays and to obtain information about primary cosmic rays. After the building at Daochen in China, \ac{LHAASO} will allow to study the \textit{"High Energy Universe"}, allowing observation of γ rays of energies in the range
$unit[300]GeV \div$
$unit[1]PeV$ observing secondary particles of showers called \textit{\textbf{\ac{EAS}}}, result of interaction between primary particles and atmosphere. One other important experiment, currently in planning phase, it's \textit{\textbf{\ac{CTA}}}. It will be built in two sites, at La Palma in Spain and at Parana in Chile. It will be the biggest \v{C}erenkov imaging telescope array built so far and, although using different kind of detectors, \ac{CTA} final goals are the same of \ac{LHAASO}. Improving instrumentation respect to current and past experiments, they will allow observations not possibile up to now and they will improve results as well. To allow observation of γ rays of energies in the range
$unit[20]GeV \div$
$unit[300]TeV$, \ac{CTA} will be composed by three kind of telescopes, the \textit{\textbf{\ac{LST}}} to make observations in the range
$unit[20]GeV \div$
$unit[100]GeV$, the \textit{\textbf{\ac{MST}}} for observations in the range
$unit[100]GeV \div$
$unit[10]TeV$ and the \textit{\textbf{\ac{SST}}} for observations in the range
$unit[10]TeV \div$
$unit[300]TeV$. Although \ac{LHAASO} and \ac{CTA} will have same final goals, since they will have different detectors, they will offer distinct opportunities to Astroparticle Physics; for example, \ac{LHAASO} will have a better resolution at energies higher than
$unit[30]TeV$ and it will allow observation of high section of the sky, \ac{CTA} at energies approximately
$unit[1]TeV$ and focused about single source. Thanks to specific simulation software it's possible to simu-

late \ac{EAS} on the basis of theoretical models and to use simulations both to study detector performances during fulfillment phase and to compare simulation results to experimental data in order to prove models during detector data acquisition; one of these software is, for example, \textit{\textbf{\ac{CORSIKA}}}. Since in γ astronomy experiments it's very important adrons rejection, some simulations made by \ac{CORSIKA} were analyzed to compare \ac{EAS} induced by protons in the range
$unit[1]GeV \div$
$unit[1000]GeV$ and power law $\frac{dN}{dE} \propto E^{-2}$ to \ac{EAS} induced by γ in the same energetic range and same power law. First of all, it was studied first interaction height of primary particles showing that, due to different values of radiation length about electromagnetic showers and interaction length about adronic showers, γ rays interact previous to protons in atmosphere; in addition, by calculating mean values of first interaction heights in the ranges $[unit[20]GeV \div unit[50]GeV]$, $[unit[50]GeV \div unit[100]GeV]$, $[unit[100]GeV \div unit[200]GeV]$, $[unit[200]GeV \div unit[350]GeV]$, $[unit[350]GeV \div unit[600]GeV]$ and $[unit[600]GeV \div unit[1000]GeV]$ it was showed that first interaction height of gamma rays is almost constant in energy; instead, due to pp cross section, protons first interaction height mean values are a bit higher for energies $E <$
$unit[100]GeV$ than for higher energies. Later, concentration was focused about \ac{EAS} to study differences between the showers on the basis of primary particle. For this reason, first of all, arbitrarily choosing two primary particles energies $E \sim$
$unit[150]GeV$ and $E \sim$
$unit[1]TeV$, it was plotted secondary particles distributions at observation level (setted on
$unit[4300]m$ above sea level); by plots we can see that secondary particles of γ rays showers are arranged on surfaces centered in \ac{EAS} core smaller than particles of proton showers. Later it was observed the difference between number of secondaries $e^{\pm}$ and $\mu^{\pm}$ produced by γ rays showers and proton showers; by plots it's clear that $\frac{e^{\pm}}{\mu^{\pm}}$ ratio is higher for γ rays showers than for proton showers, because in proton showers we have higher $\mu^{\pm}$ than in γ rays showers. Additionally, calculating $e^{\pm}$ and $\mu^{\pm}$ mean values in energy ranges, it was showed their increasing production for higher primary particles energies. Very important is the difference about lateral development of the \ac{EAS}; indeed, to confirm what showed by plots about distributions at observation level, it was calculated particles density in circular crowns centered in the \ac{EAS} core up to $unit[10]Km$ from it. Plots showed that, increasing distance from core, density decreasing of secondary particles produced by γ rays showers is faster than secondary particles produced by proton showers, so probability to find particles of γ rays showers faraway from the core is smaller than to find particles of proton showers. Lastly, arbitrarily choosing 3 distances from the core
$unit[10]m$,
$unit[100]m$ and
$unit[600]m$ it was calculated particles density for energy ranges of primary particles $[unit[20]GeV \div unit[50]GeV]$, $[unit[50]GeV \div unit[100]GeV]$, $[unit[100]GeV \div unit[200]GeV]$, $[unit[200]GeV \div unit[350]GeV]$, $[unit[350]GeV \div unit[600]G$
and $[unit[600]GeV \div unit[1000]GeV]$; as result it's clear that for fixed distances, increasing primary particles energy, secondary particles density increases too. Obtained results are based on theoretical models of interaction processes between cosmic rays and atmosphere; for the future, when \ac{LHAASO} and \ac{CTA} will start to take data, it will be important to compare simulation data to experimental data. It's essential a careful experimental test that, thanks to improvements that \ac{LHAASO} and \ac{CTA} will have compared to current \ac{SD} and \textit{\textbf{\ac{IACT}}}, it will allow to acquire new knowledge about cosmic rays, their acceleration in galactic and extragalactic sources, propagation in Universe and interaction in atmosphere. However, obtained results are important because analysis of γ rays showers and proton showers, produced by \ac{CORSIKA}, it allows us to test teories at the basis of \ac{LHAASO} and \ac{CTA} realization, that is thanks to algorithms based on differences between lateral developments of showers in atmosphere, lateral distribution at observation level about charged and neutral particles around shower core, number of $\mu^{\pm}$, it will be possible to discern γ rays showers from proton showers ($\frac{proton ac EAS}{\gamma \quad ac EAS} \sim 100$) to acquire events and to reject adronic background. Finally, comparing experimental data to obtained mean values of studied physical quantities in function of primary particles energies, it will be possible to estimate the latter.

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