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Monte Carlo Simulation of the Milagro Gamma-ray Observatory

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Abstract: The Milagro gamma-ray observatory is a water-Cherenkov detector capable of observing air showers produced by very high energy gamma-rays. The sensitivity and performance of the detector is determined by a detailed Monte Carlo simulation. Observations of γ-ray sources and of the isotropic cosmic-ray background are used for verification of the simulation. CORSIKA is used for simulating the extensive air showers produced by either hadrons (background) or γ-rays (signal). A GEANT4 based application is used for simulating the response of the Milagro detector to the air shower particles reaching the ground. The detector's simulation includes a detailed description of the optical properties of its components and of the photomultiplier tubes' response.

Introduction

Milagro [1] is a water-Cherenkov detector at an elevation of 2650 m (750 g/cm^2 of overburden) at the Jemez mountains near Los Alamos, NM. It consists of a central rectangular 60 m x 80 m x 7 m reservoir filled with purified water and surrounded by a sparse 200 m x 200 m array of 175 "outrigger" (OR) tanks. The reservoir is covered by light barrier and is instrumented with two layers of 8" photomultiplier tubes (PMTs). The top "air-shower" (AS) layer consists of 450 PMTs under $\sim$1.4m of water, while the bottom "muon" (MU) layer has 273 PMTs located $\sim$6m below the surface. Each outrigger tank contains $\sim$4000 l of water and one PMT. The PMTs collect the Cherenkov light produced by the air shower particles, as they transverse the detector's water volume. The AS layer allows the measurement of the air shower particle arrival times and is used for direction reconstruction and triggering. The outrigger array improves the accuracy of the core location reconstruction and the angular resolution of the detector by providing a longer lever arm and better curvature correction with which to reconstruct events. The greater depth of the muon layer ($\sim$17 radiation lengths) is used to distinguish deeply penetrating muons and hadrons, which are common in hadron induced air showers, from electrons and γ-rays.

The Monte Carlo Simulation

CORSIKA v6.5021 [2] is used for simulating the development of γ and hadron initiated Extensive Air Showers (EAS). The low energy (E<80GeV) hadronic interactions are simulated with FLUKA v2005.6, the high energy hadronic interactions (E>80GeV) are simulated with NEXUS v3.972, and the electromagnetic interactions are simulated with EGS4. The energy distribution of the primary particles extends from 20 GeV to 500 TeV and is a pure power law. The spectral index for primary γ rays is assumed to be γ =-2.62, whereas charged primaries follow the known cosmic-ray spectra [3]. The zenith angles (θ) extend from zero to 60^o for gammas and from zero to 70^o for hadrons.

The response of the Milagro detector to the EAS particles reaching the ground is simulated using a GEANT4 [4] (v4.8) based MC simulation.

A full optical model[1] of the PMTs is used in the simulation. This model includes the simulation of reflection, absorption and transmission of the Cherenkov photons from all parts of the PMT. The corresponding probabilities for each physical process are either calculated from Fresnel's laws using the refractive indices of the materials or are estimated. By using the complex refractive index of

1. http://neutrino.phys.ksu.edu/ GLG4sim

the photocathode material [5], the model can calculate the photocathode's quantum efficiency for any angle of incidence and photon energy. The collection efficiency (CE) is treated as being dependent only on the photocathode position that the photon absorption took place. At the center of the photocathode, the CE is assumed to be 100%, while for off-center positions experimental measurements [6] are used. The pulse height assigned to each detected photon is derived from measured pulse height distributions [6].

We have created GEANT4 code for the simulation of Mie scattering. This code can simulate scatterings with an angular distribution and a scattering length provided by our measurements of the Milagro's water properties.

Comparison between simulation results and real data

With our current simulation, events very close to the trigger threshold are not being simulated with high accuracy. This is mainly because the trigger conditions are not completely stable in the apparatus. To study the simulation results without these uncertainties, a cut that rejects events with less than 80 AS layer PMTs hit was used. This cut is just over our hardest trigger condition which corresponds to about 70 AS PMTs hit.

γ-hadron discrimination variables

The Milagro background rejection was initially based on the compactness parameter X2[7] and later on the parameter A4[8]. X2 and A4 are calculated using the number of photoelectrons (PEs) registered by the MU layer PMT with the most PEs (fig. 1), the number of PMTs used in the direction reconstruction fit (fig. 2), the number of MU layer PMTs that have registered more than two photoelectrons (fig. 3(b)), and the fraction of PMTs in the AS layer and OR array hit (figs. 3(a) and 3(c)).

In figs.4(a) and 4(b) the distributions of X2 and A4 are shown for real data, and for a simulation of hadronic showers.

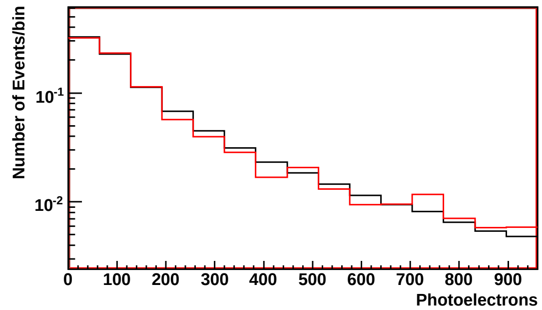


Figure 1: Distribution of the number of PEs registered by the MU layer PMT with the most PEs. Black for data and red for simulation of hadronic showers.

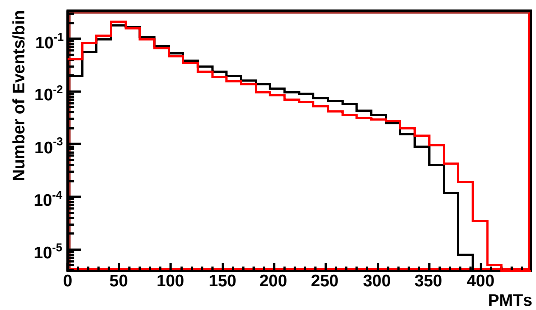


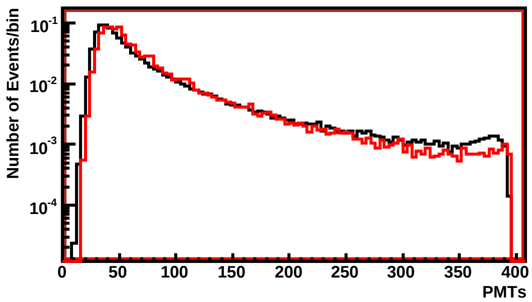
Figure 2: Distribution of the number of PMTs participating in the direction reconstruction fit. Black for data and red for simulation of hadronic showers.

Results from the reconstruction

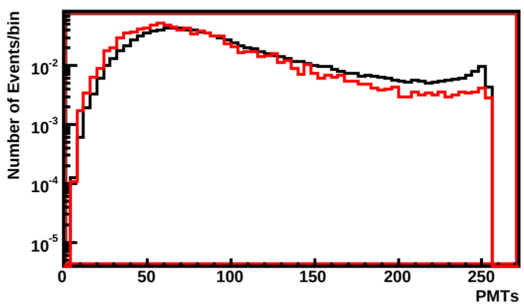
The reconstructed zenith angles and the distance of the shower cores from the center of the pond are shown in figures 5 and 6 respectively. To verify the predictions on the performance of Milagro's angular reconstruction by the simulation, the profile from the γ-ray signal from the Crab is compared with the one derived from the simulation (fig. 7).

Other results

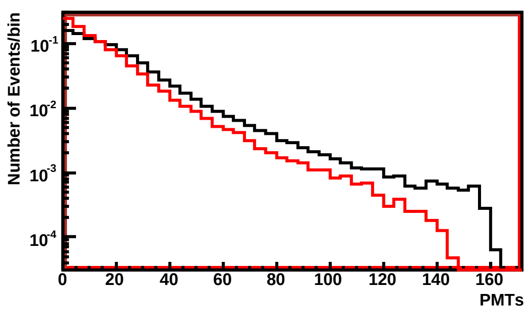
Many other results from the simulation have been cross checked against data. Some of the quantities with good agreement between MC and data are: the number of PEs a high energy (E>1 GeV) atmospheric muon creates in the PMTs of the MU



(a) Air shower layer



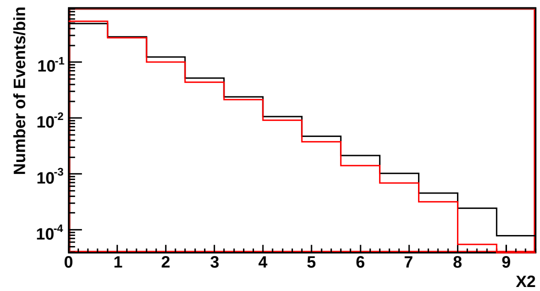
(b) Muon layer



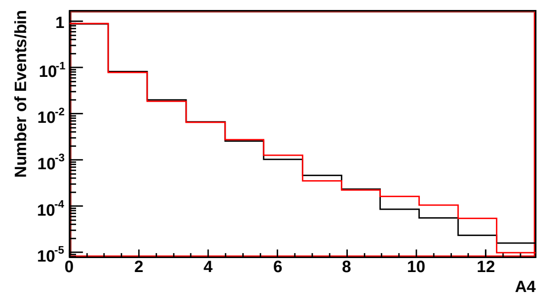
(c) Outrigger array

Figure 3: Distribution of the number of PMTs hit with more than 2 PEs, per event. Black for data and red for simulation of hadronic showers.

layer, the total number of PEs registered by the PMTs of each layer, the number of PEs registered by the hottest PMT of each layer, the number of PMTs of the AS and OR layers participating in the reconstruction fit, and the cosmic-ray trigger rate.The parameters that don't have a good agreement between MC and data yet are the number of any layer PMTs hit that register less than two PEs, the number of MU layer PMTs hit and the rate of triggers caused by big cosmic-ray events.



(a) X2



(b) A4

Figure 4: γ-hadron discrimination variables. Black for data and red for simulation of hadronic showers.

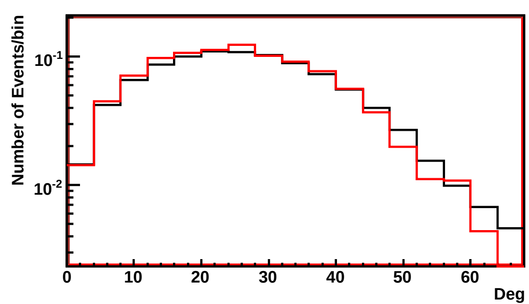


Figure 5: Distribution of the reconstructed zenith angles. Black for data and red for simulation of hadronic showers.

Conclusion

The Milagro experiment has a very detailed Monte Carlo simulation. In order to improve the agreement between the simulation results and the experimental data, there has been a systematic effort to identify the factors with the biggest influence on the data and to improve the parts of the simula-

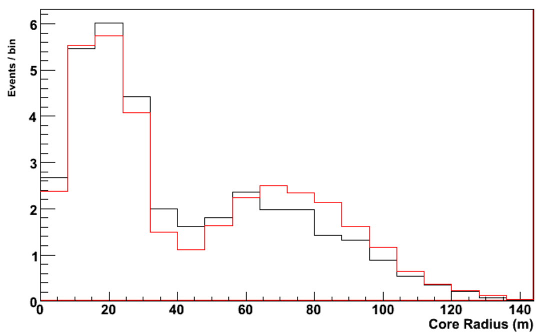


Figure 6: Distribution of the reconstructed distance of the shower cores from the center of the pond. Black for data and red for simulation of hadronic showers.

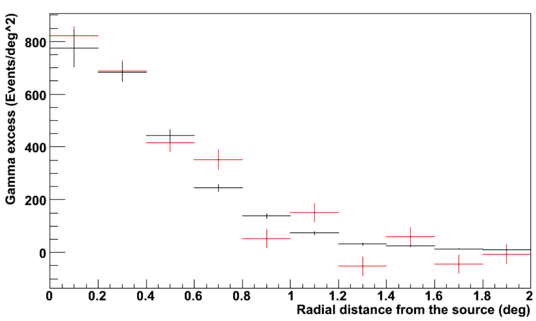


Figure 7: Profile of the γ-ray signal from the Crab. The plot was produced by data from a 8σ image of the Crab, obtained using a relatively soft γ-hadron rejection cut (A4>3). Black for data and red for simulation of hadronic showers.

tion corresponding to them. For that reason, a very detailed PMT model has been incorporated into the simulation, experimental tests have been carried out to measure the PMT properties, GEANT4 code has been written to simulate new physical processes, and in general a strong effort from all the collaboration has been carried out in order to better understand our simulation. Many experimental quantities ranging from low-level ones such as the number of PMTs hit per event, the number of PEs detected per event or per PMT to higher-level ones such as the results of the reconstruction or the γ-hadron discrimination variables already have very good agreement with the simulation. We have identified the last types of simulation results not in agreement with the data and we are working on improving them too.

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