Monte Carlo Simulation of the Milagro Gamma-ray Observatory

V. VASILEIOU[1] FOR THE MILAGRO COLLABORATION
[1]*Department of Physics, University of Maryland, College Park, MD*
vlasisva@umd.edu

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 gamma-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 [4] 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 and to provide a calorimetric view of the energy deposition in the detector.

The Monte Carlo Simulation

CORSIKA v6.5021 [6] is used for simulating the development of γ and hadron initiated Extensive Air Showers (EAS). The low energy (E<80 GeV) hadronic interactions are simulated with FLUKA v2005.6, while the high energy hadronic interactions (E>80 GeV) are simulated with NEXUS v3.972. 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 [5]. The zenith angles (θ) extend from zero to 45^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 [2] (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

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

ICRC 2007 Proceedings - Pre-Conference Edition

the refractive indices of the materials (photocathode [7], glass, vacuum) or are estimated. By using the complex refractive index of the photocathode material, the model can calculate the photocathode's quantum efficiency (QE) for any angle of incidence. The PMTs detection efficiency is equal to the QE times the collection efficiency (CE). The 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 our experimental measurements [8] are used. Finally, a pulse height is assigned to each detected photon using our measured pulse height distributions [8].

A strong factor influencing the data is the scattering of the Cherenkov photons from the water molecules (Rayleigh scattering) or from dissolved particles (Mie scattering). For optical photons, the Rayleigh scattering length is very long ($L_{scat} \simeq$100 m for $\lambda =$350 nm) and increases with λ^4. We have measured the water properties of the Milagro's water and have found that the scattering length is $L_{scat}\simeq$26m and that the majority of the scattering is forward. For that reason, we believe that the dominant scattering process in the Milagro water is small-angle (Mie) scattering. GEANT4 currently contains code for only the simulation of Rayleigh scattering. Code for the simulation of Mie scattering has been written by us. This code can simulate scatterings with an angular distribution and a scattering length provided by our measurements of the Milagro's water properties.

Another factor with some influence on the data is the amount of scattering from the surface of the pond. In periods with high rainfall, water accumulates on the pond's cover and pushes the air under the cover away. In such a case, the cover is in optical contact with the surface of the water and the surface's reflectivity is minimal. In the winter, the surface of the water can freeze or in dry periods, air can accumulate under the cover causing the photons to undergo total internal reflection. In both of these latter cases, the reflectivity of the surface becomes considerably higher than in the first case. The effect can be easily seen in the distributions of the Milagro data and in the trigger rate. We have simulated the detector with various amounts of air under the cover or with a water surface reflectivity similar to the one of ice. The properties of the Milagro data affected by the different water surface reflecitivities have been identified and special care has been taken to account for their seasonality at the Milagro's data analysis.

Comparison between simulation results and real data

In the 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 70 PMTs participating in the direction reconstruction fit has been applied.

γ-hadron discrimination and energy estimation variables

The Milagro background rejection was initially based on the compactness parameter X2[3] and later on the parameter A4[1]. X2 and A4 are calculated using the following quantities:

- The number of MU layer PMTs that have registered more than two photoelectrons (PEs) ,
- the number of PEs registered by the MU layer PMT with the most PEs (see fig. 1),
- the fraction of PMTs in the AS layer and OR array hit(see figs. 2(a) and 2(b)), and
- the number of PMTs used in the direction reconstruction fit (see fig. 3).

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

Milagro's energy estimation algorithm [9] depends on the variable ξ calculated using:

- the number of PMTs in the AS layer and OR array hit (see figs. 2(a) and 2(b)), and
- the reconstructed zenith angle of the event (see fig. 5).

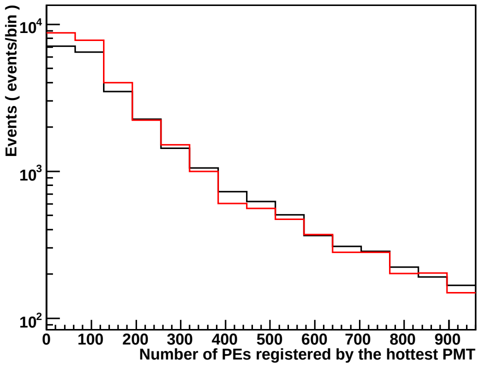


Figure 1: Distribution of the number of PEs registered by the MU layer PMT with the most PEs

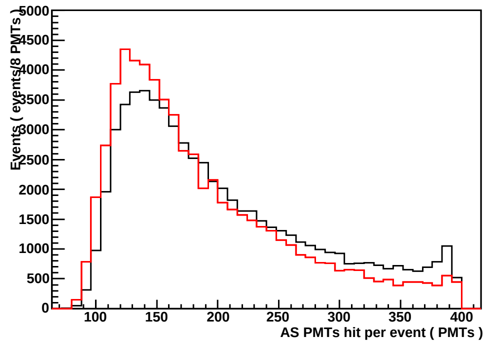
Other results

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 (>1 GeV) atmospheric muon creates in the PMTs of the MU 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, the distribution of the reconstructed shower-core locations on the ground and the cosmic-ray trigger rate.

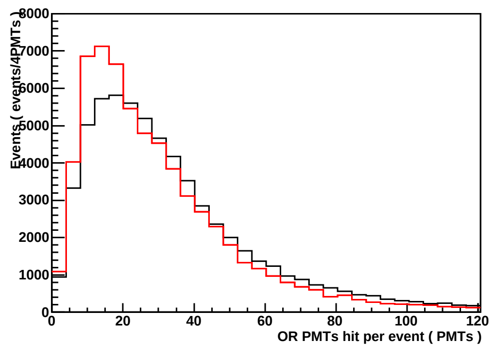
The parameters with not good agreement between MC and data are the number of any layer PMTs hit that register less than two PEs, the number of MU layer PMTs hit and the rate of triggers caused by big cosmic-ray events.

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 simulation 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. We have identified the last types of simulation results not in agreement with the data and we are working on improving them too.



(a) Air shower layer



(b) Outrigger array

Figure 2: Distribution of the number of PMTs hit per event in the AS layer and OR array. The black line is from data and the red line is from the simulation.

Acknowledgments

We acknowledge Scott Delay and Michael Schneider for their dedicated efforts in the construction and maintenance of the Milagro experiment. This work has been supported by the National Science Foundation (under grants PHY-0245234,

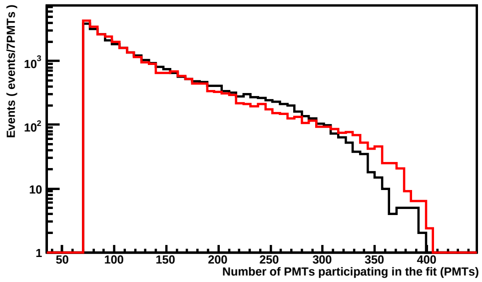


Figure 3: Distribution of the number of PMTs participating in the direction reconstruction fit

-0302000, -0400424, -0504201, -0601080, and ATM-0002744) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics.

References

[1] Abdo, A.A. et al. Discovery of tev gamma-ray emission from the cygnus region of the galaxy. *ApJ*, 658:L33, 2007.

[2] Agostinelli, S. et al. Geant4: A simulation toolkit. *NIM*, A506:250–303, 2003.

[3] Atkins, R. et al. Observation of TeV Gamma Rays from the Crab Nebula with Milagro Using a New Background Rejection Technique. *ApJ*, 595:803–811, October 2003.

[4] Atkins, R.W. et al. Tev gamma-ray survey of the northern hemisphere sky using the milagro observatory. *ApJ*, 608:680–685, 2004.

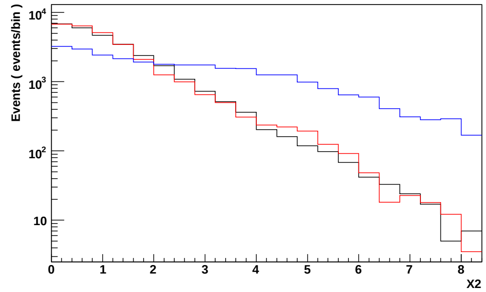
[5] Haino, S. et al. Measurements of primary and atmospheric cosmic-ray spectra with the bess-tev spectrometer. *Phys. Lett. B*, 594:35, 2004.

[6] Heck, D. et al. Corsika: A monte carlo code to simulate extensive air showers. *FZKA*, page 6019.

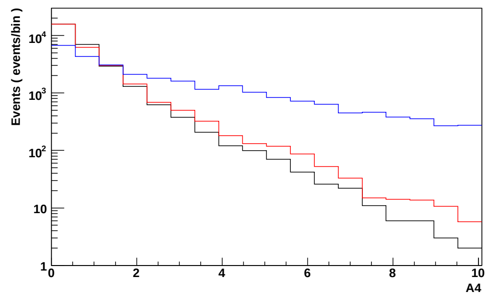
[7] Motta, D. et al. Optical properties of bialkali photocathodes. *NIM A*, 539:217, 2005.

[8] Vasileiou, V. et al. Photocathode-uniformity tests of the hamamatsu R5912 photomultiplier tubes used in the milagro experiment. 30th ICRC, Merida, Mexico, 2007.

[9] Allen B. et al. Yodh, G.B. Energy spectrum



(a) X2



(b) A4

Figure 4: γ-hadron discrimination variables. The distributions of X2 and A4 for real data (black line), simulation of a hadronic signal (red line) and simulation of a γ-ray signal (blue line) are shown.

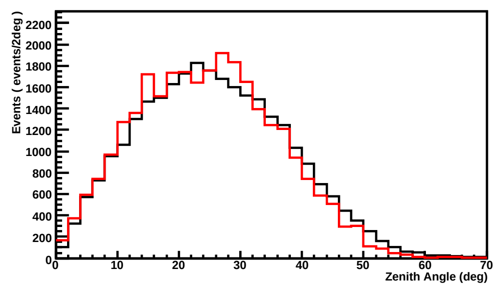


Figure 5: Distribution of the reconstructed zenith angles of triggered events. The black line is from data and the red line is from the simulation.

of gamma rays from the crab nebula from 1 to 100 tev with the milagro telescope. 30th ICRC, Merida, Mexico, 2007.