Cosmic Ray Induced Backgrounds in the Mu2e Experiment

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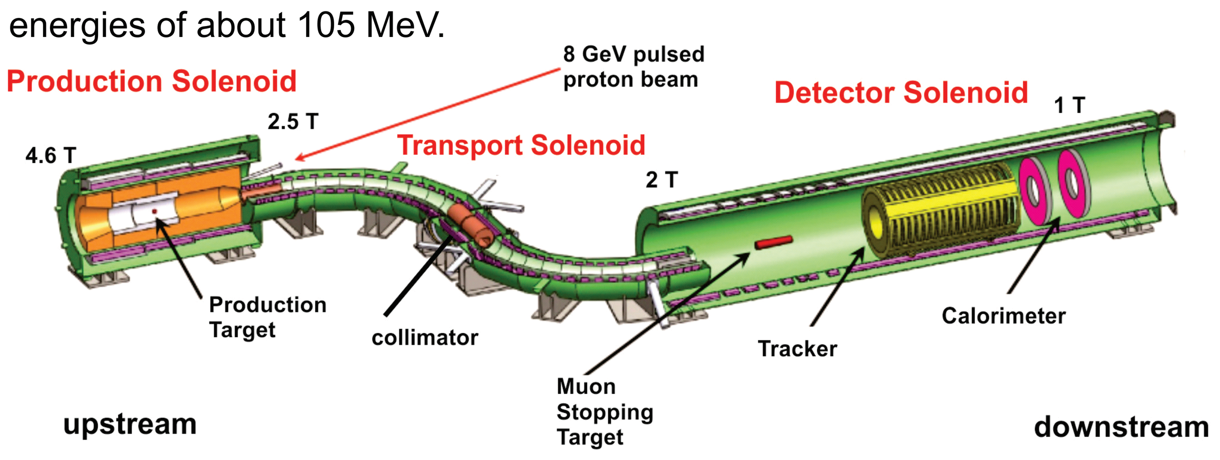
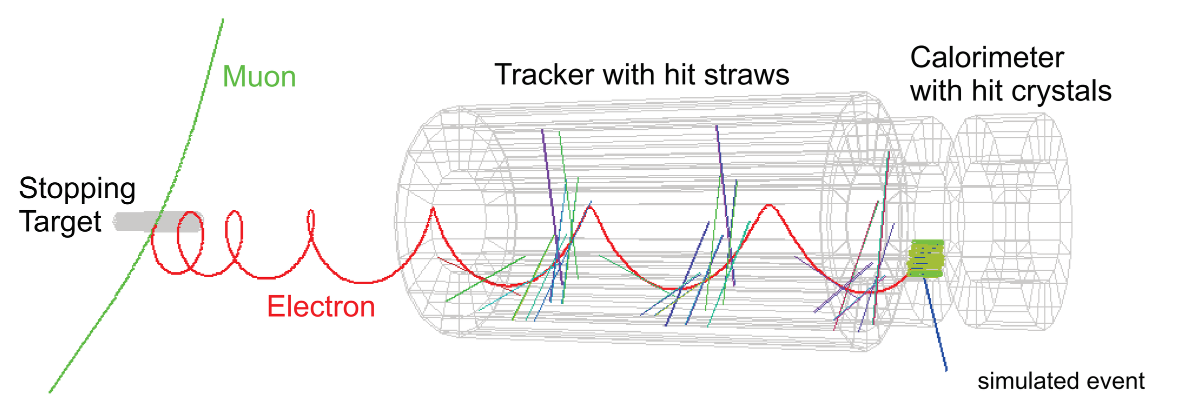
Overview

The Mu2e experiment will look for neutrinoless, coherent muon to electron conversions in the orbit of aluminum atoms: $\mu^- + N \rightarrow e^- + N$. The observation of such a process would be unambiguous evidence of new physics beyond the Standard Model. The electrons from such conversions would have energies of about 105 MeV.

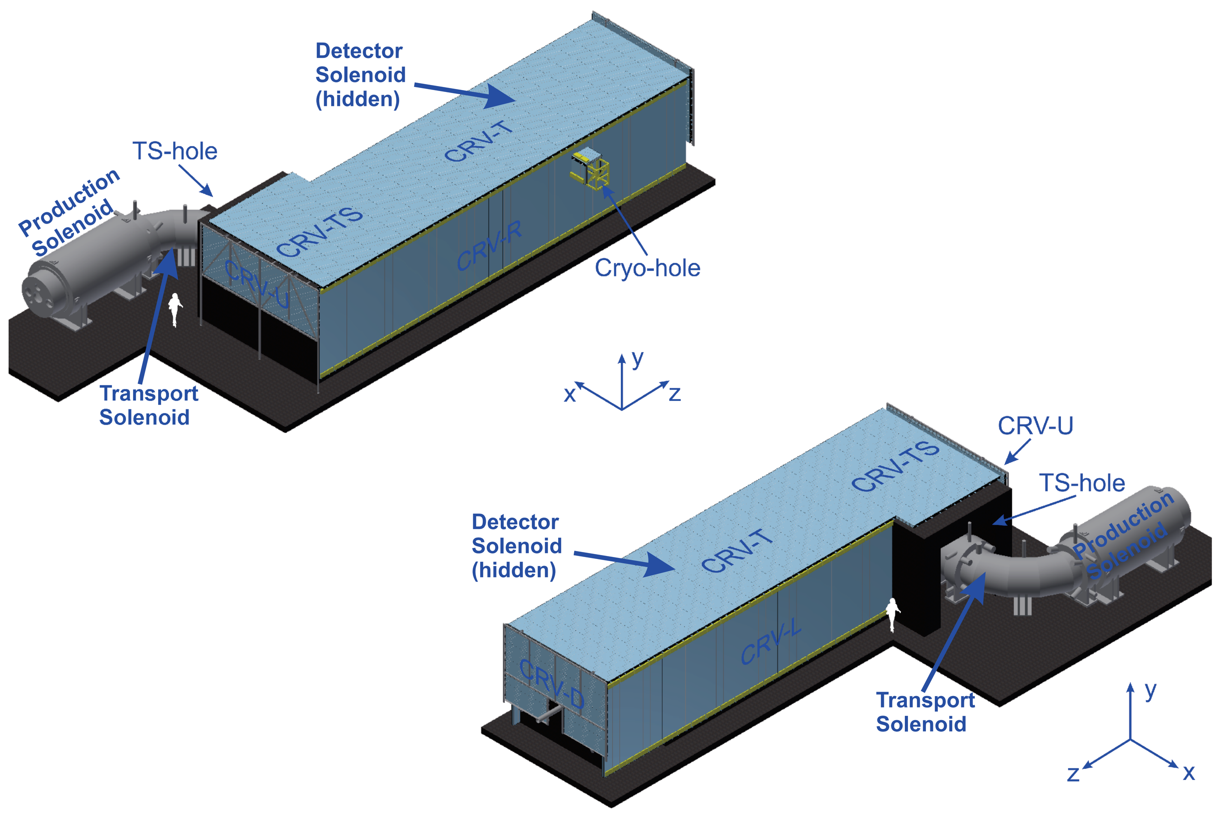


A major source of background comes from cosmic rays, which can produce particles that mimic conversion electrons. In order to exclude these background events, a cosmic ray veto system (CRV) has been designed. This CRV consists of an active detector which will be placed around the Mu2e spectrometer. Conversion-like electrons in coincidence with a cosmic ray muon detected by the CRV will be vetoed in the offline analysis.

An example of a cosmic-ray background event is shown below: A cosmic-ray muon created an electron of about 105 MeV by ionizing an atom in the stopping target. The event appears identical to a real conversion electron.

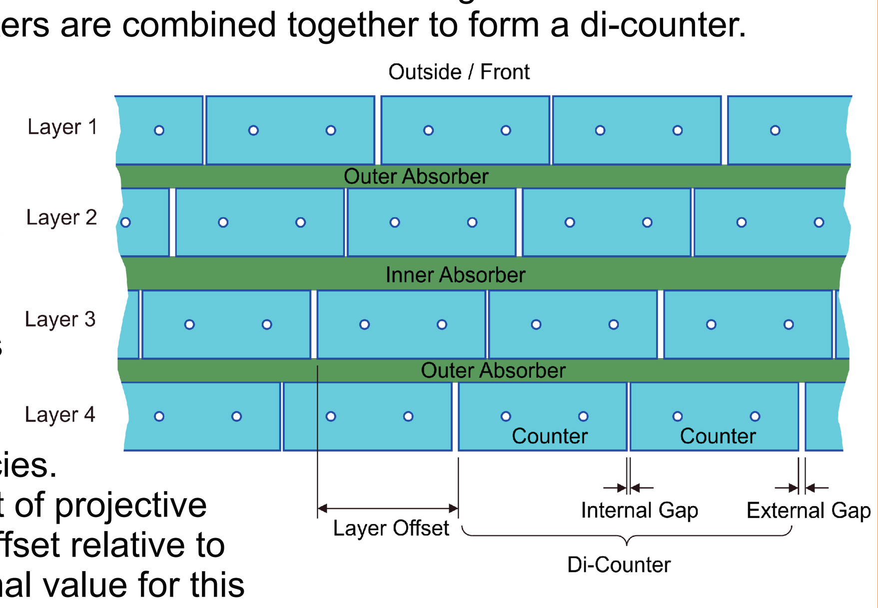


The Cosmic Ray Veto System



The CRV encloses the detector solenoid and parts of the transport solenoid (TS). The CRV modules are made of four layers of scintillator counters. Each counter has two embedded wavelength-shifting fibers, which are read out on both ends by a SiPM. The counters have a thickness of 20 mm, and a width of 50 mm and lengths between 0.9 m and 6.6 m. Two counters are combined together to form a di-counter.

The counters are grouped together in modules, 16 counters per layer. Unavoidable gaps between counters in a di-counter, counters in a module, and between modules can lead to inefficiencies. To minimize the effect of projective gaps the layers are offset relative to each other. The optimal value for this offset is determined by a simulation.



Cosmic Ray Simulations

Simulations were done to determine:
- The required efficiency and coverage of the CRV.
- The various types of backgrounds induced by cosmic-ray muons.
- The required veto time windows following a CRV hit

Two types of simulations have been done:
- One "general simulation" in which muons were generated over the entire Detector Solenoid region.
- Four "targeted simulations" in which the muons were generated in regions with less than ideal coverage – in particular the TS hole.

Total number of generated events (general+targeted simulations): 3.7 trillion
Computer resources: 13 million CPU hours, 515 TB disk space

	General Simulation	Targeted Simulations			
		TS Hole	Upstream	Downstream	Cryo Hole
ProductionArea [m²]	800	100	100	100	16
Orientation	horizontal	vertical	vertical	vertical	vertical
Cosmic Rate* [s⁻¹]	$9.35\cdot10^{4}$	$2.93\cdot10^{3}$	$2.93\cdot10^{3}$	$2.93\cdot10^{3}$	$4.69\cdot10^{2}$
Number of Simulated Events	$5.00\cdot10^{11}$	$1.00\cdot10^{12}$	$9.99\cdot10^{11}$	$9.99\cdot10^{11}$	$2.00\cdot10^{11}$
Simulated Time [s]	$5.35\cdot10^{6}$	$3.41\cdot10^{8}$	$3.41\cdot10^{8}$	$3.41\cdot10^{8}$	$4.26\cdot10^{8}$
Simulated Experiment's Live Times**	4.04	257	257	257	322

*For the energy range of the cosmic-ray muons from 0.5 GeV to 5000 GeV.
**These numbers are based on the experiment's live time of $1.06\cdot10^{7}$s, and an additional factor of 8, since a signal momentum interval of 10 MeV/c is considered which is 8 times larger than the experiment's signal momentum interval of 1.25 MeV/c.

References
[1] M. Guan et al., Muon simulation at the Daya Bay site, 2006
[2] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update, 28. Cosmic Rays

Acknowledgements
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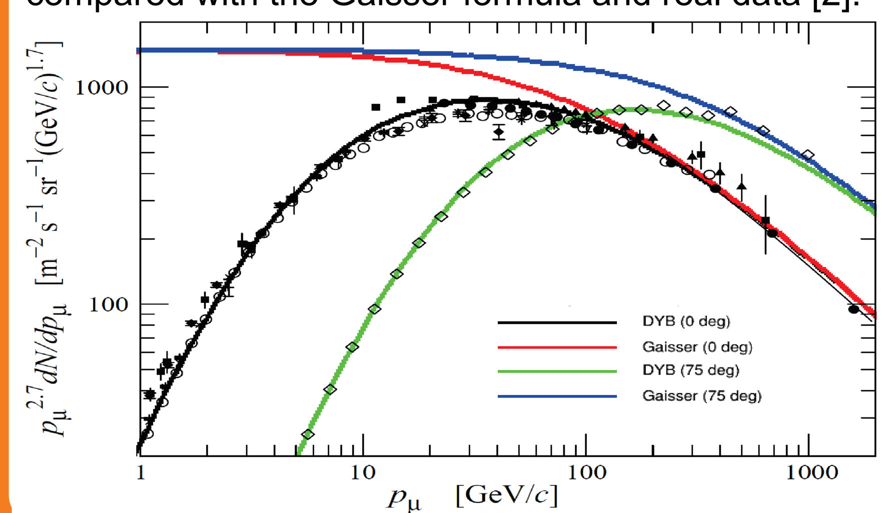
Cosmic Ray Event Generator

The cosmic-ray muons are generated with an energy and angular distribution based on the Daya Bay formula [1]. This formula has been compared with the Gaisser formula and real data [2].

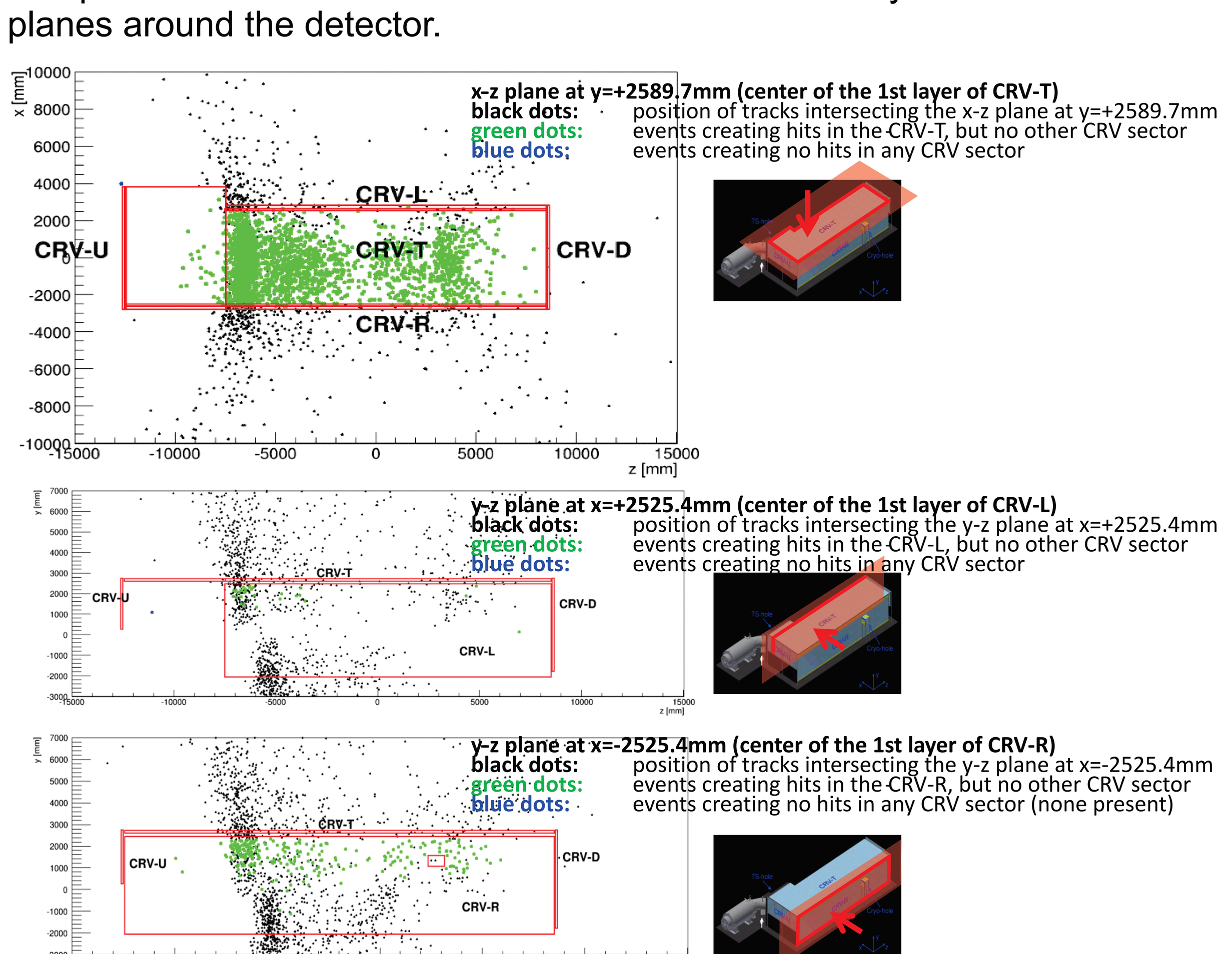


Spectrum of muons at θ=0° ♦ [50], ■ [56], ▼ [57], ▲ [58], ×, + [52], ○ [53], ● [54], and θ=75° ◊ [59]
The references are the references in [2].

General Simulation

In the general simulation, 3170 events were found to have conversion-like electrons, which corresponds to 785 conversion-like electrons for the experiment's live time (about 1 conversion-like electron per day). Only one of these events missed the CRV, since it came through the opening at the transport solenoid. (The expected number of events coming through this hole is studied in more detail with the targeted simulation.) The remaining 3169 events had tracks going through at least one CRV sector.

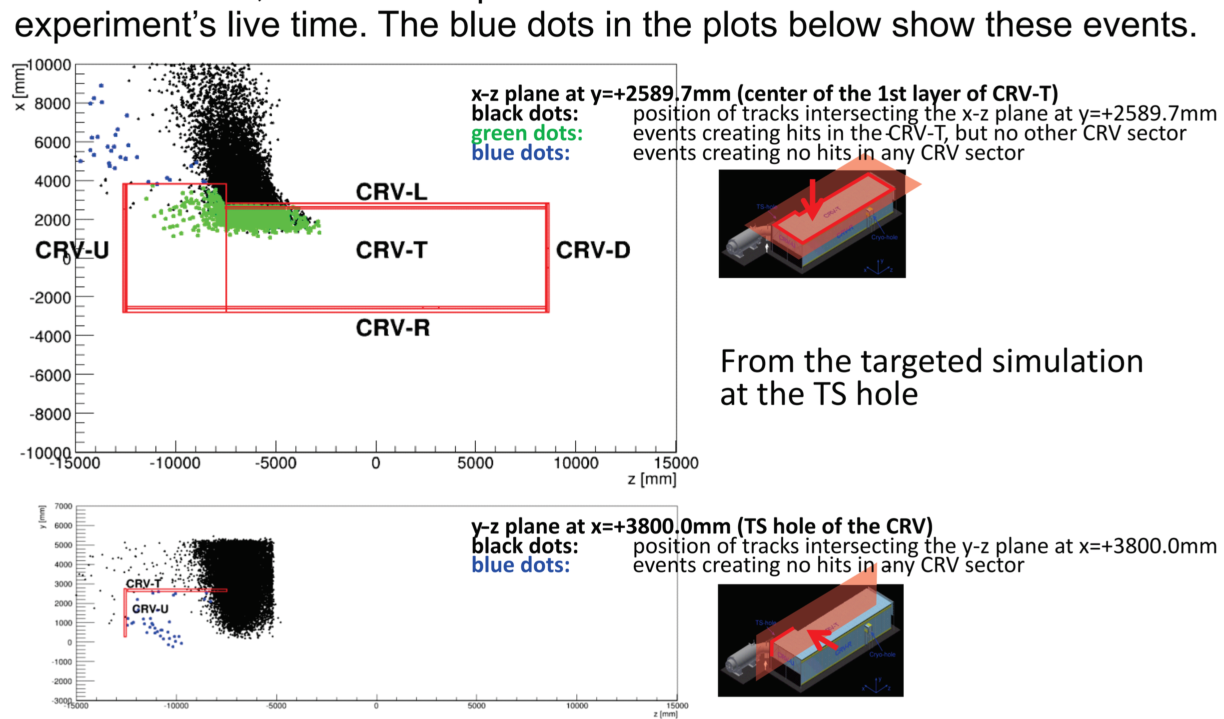
The plots below show the intersections of the cosmic-ray muon tracks on the planes around the detector.



Targeted Simulations

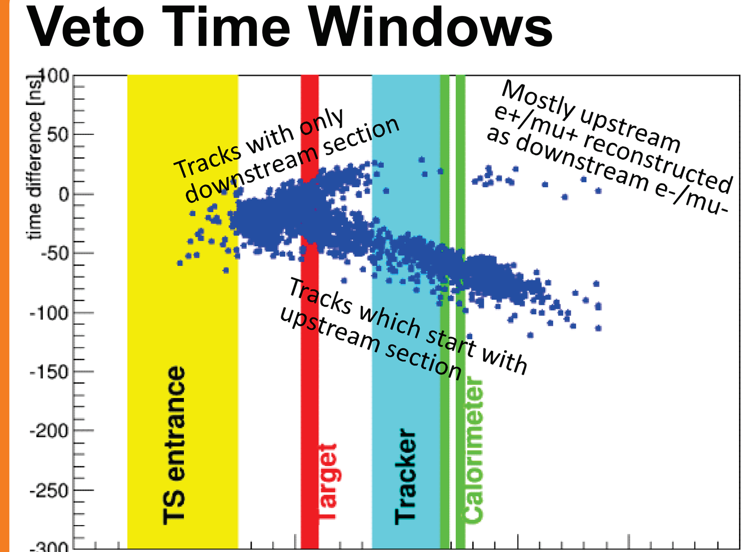
The targeted simulations revealed a few additional sources. Some of them can be eliminated by small changes of the CRV design, or by modifications of the CRV coincidence finder.

However, the major source of these background events cannot be reduced: Cosmic-ray muons coming through the hole in the CRV coverage at the transport solenoid entrance. The targeted simulation for this region showed 39 such events, which correspond to 0.152 events when scaled to the experiment's live time. The blue dots in the plots below show these events.



From the targeted simulation at the TS hole

Veto Time Windows



These time differences determine the required veto time windows around the CRV coincidences.

vertical axis: time differences between the time of the first CRV coincidence hit and the time when the track reaches the center of the tracker

horizontal axis: z-position of the CRV coincidence hit

Required Efficiency

The table below shows how many conversion-like events created hits each CRV sector (if multiple sectors are hit, the first sector is counted). It also shows the required sector-by-sector CRV inefficiency to keep the total number of events which the CRV fails to veto to below 0.1 for the experiment's live time. The number of events in each sector multiplied by the CRV inefficiency is the expected number of conversion-like events which will not be vetoed by the CRV. This leads to a total number of non-vetoed events of 0.075 events during the experiment's live time.

CRV Sector	CRV-R	CRV-L	CRV-TS	CRV-T	CRV-D	CRV-U	CRV-Cryo
Number of events	120	71	12	578	0.6	0.1	1.6
CRV inefficiency	$6\cdot10^{-5}$	$6\cdot10^{-5}$	$5\cdot10^{-4}$	$1\cdot10^{-4}$	$1\cdot10^{-4}$	$5\cdot10^{-4}$	$1\cdot10^{-4}$
Expected number of non-vetoed events	$7.2\cdot10^{-3}$	$4.3\cdot10^{-3}$	$5.8\cdot10^{-3}$	$5.8\cdot10^{-2}$	$6.2\cdot10^{-5}$	$4.7\cdot10^{-5}$	$1.6\cdot10^{-4}$

These numbers are scaled to the experiment's live time.

Simulation of the Response of the CRV

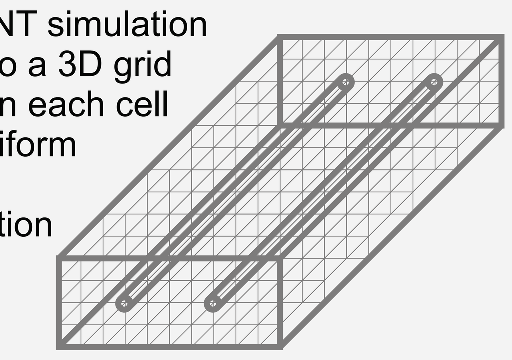
Particle Simulation by GEANT

The simulation of particles going through the detector is handled by GEANT, which determines the energy depositions, particle positions, and particle speeds inside of the CRV counters.

CRV Photon Generator

A full GEANT simulation of the CRV would require the propagation of a large number of photons through the scintillator counters and optical fibers to the SiPMs. Since this is too time consuming, lookup tables are used to simulate the photons arriving at the SiPMs.

Lookup Tables
- generated by a standalone GEANT simulation
- divides the scintillator counter into a 3D grid
- 100,000 photons are generated in each cell (uniform direction distribution, uniform polarization distribution, energy distribution based on the scintillation spectrum) which are propagated by GEANT
- material parameters for lookup tables are tuned so that the results agree with data from test beam measurements
- lookup tables store for each cell: arrival probability at each SiPM, travel time (excluding decay times in the scintillator and fiber which can be adjusted later), number of re-emissions in the fiber
- additional tables for Cerenkov radiation in the fibers with additional lookup parameters (particle direction, speed) on which the photon energy, direction and polarization distributions depend



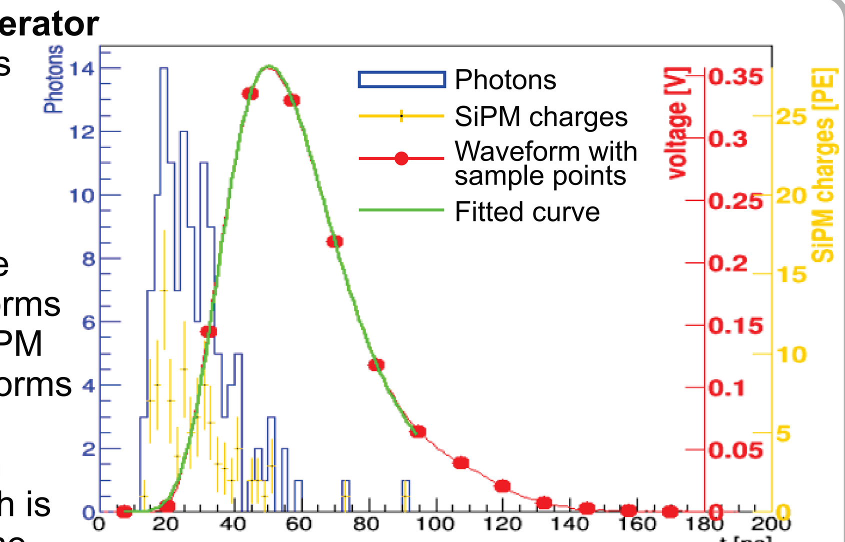
In each cell which a particle enters, the number of generated scintillation photons is based on the deposited energy, while the number of Cerenkov photons is based on the particle speed. The lookup tables are used to determine how many of these photons arrive at each SiPM and at what times.

CRV SiPM Response Generator

The photons arriving at each SiPM are distributed to the individual pixels where saturation effects may occur. The responses of each pixel is simulated including the pixel recharge curve, cross talk, after pulses, and thermal noise.

CRV Waveform Generator

The SiPM response is used to generate full waveforms based on the behavior of the electronics. This is done by adding single photoelectron waveforms for every released SiPM charge. These waveforms are digitized, i.e. the voltage is recorded in steps of 12.5ns, which is the CRV sampling time.



Reconstruction of the Response of the CRV

CRV Hit Reconstruction

A fit is done on the digitized waveforms to reconstruct the CRV hits to determine the numbers of photo electrons (PEs), the pulse time, and the pulse width.
The fit function is a modified version of the Gumbel distribution.

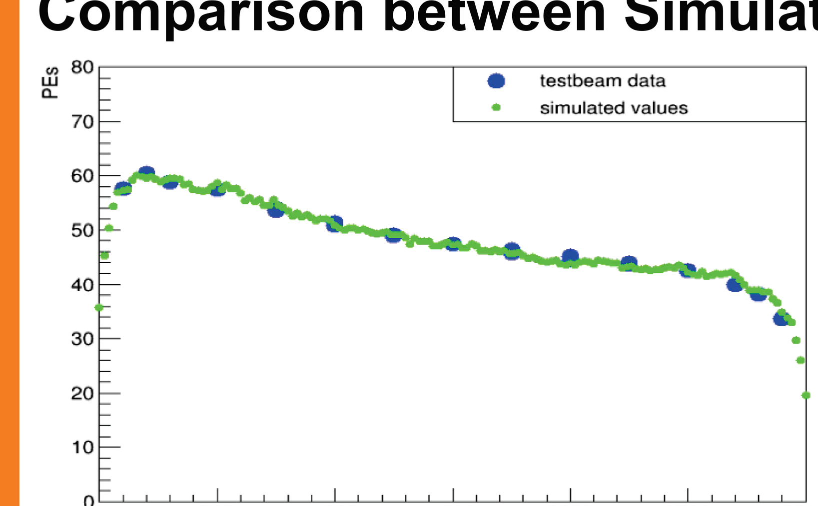
$$f(t) = A \cdot e^{-\frac{t-\mu}{\beta} - e^{-\frac{t-\mu}{\beta}}}$$

Pulse height: A/e
Peak time: μ
Pulse area: $A \cdot \beta$
Pulse width: $\beta\pi/\sqrt{6}$

CRV Coincidence Finder

The CRV's purpose is to issue a veto every time a cosmic ray went through the CRV. However, the CRV is located in an intense radiation environment where the high rate of neutrons and gammas creates many fake signals in the CRV. In order to avoid a high rate of false vetoes, a veto is issued only if the reconstructed hits satisfy certain coincidence conditions, e.g. at least 3 out of the 4 layers need to have hits above a certain PE threshold within a certain time window.

Comparison between Simulation and Data



The simulated PE distribution as a response to muons going through different locations along a 3 m long CRV counter has been compared with data obtained from a test beam study at Fermilab.

CRV Efficiency Studies

Simulations for each CRV sector were done to find the best combination of layer offsets, required PE yields of the counters, PE thresholds, and coincidence time window for the CRV coincidence finder. For every combination of these variables a simulation with one million cosmic-ray muons (with an energy and angular distribution based on the Daya Bay formula [1]) was done to determine the CRV efficiency. The CRV efficiency is the fraction of events which satisfy a set of CRV coincidence requirements. The maximum allowed CRV inefficiency of each CRS sector was chosen based on the results of the cosmic ray simulations.