Muon reconstruction in Double Chooz

M Strait
High Energy Physics, University of Chicago, 5640 S Ellis Ave, Chicago IL 60637
E-mail: strait@hep.uchicago.edu

Abstract. We describe a muon track reconstruction algorithm for the reactor anti-neutrino experiment Double Chooz. The Double Chooz detector consists of two optically isolated volumes of liquid scintillator viewed by PMTs, and an Outer Veto above these made of crossed scintillator strips. Muons are reconstructed by their Outer Veto hit positions along with timing information from the other two detector volumes. In the ideal case of a through-going muon intersecting the center of the detector, the resolution is \( \sim 40 \) mm in each transverse dimension.

1. Introduction
Double Chooz is a reactor anti-neutrino experiment designed to measure the mixing parameter \( \theta_{13} \) by observing inverse beta decay events, \( \bar{\nu}_e p \rightarrow e^+ n \). Due to its overburden, 300 meters water equivalent, the Double Chooz far detector has a muon rate of 46 Hz. Consequently, reconstruction of muons is very helpful for suppressing cosmogenic backgrounds. The most important of these is \( ^9\text{Li} \), a \( \beta^-\text{n} \) emitter.

The design details of the detector have been described in Ref. [1]. It consists of four concentric cylindrical volumes and the Outer Veto (OV). The inner three volumes form a single optical volume isolated from the fourth and are collectively called the Inner Detector (ID). The innermost two volumes, the Neutrino Target (NT) and Gamma Catcher (GC), are filled with scintillator and are treated as a single undifferentiated volume for muon reconstruction purposes.

They are surrounded by the Buffer, a volume of non-scintillating oil in a steel vessel in which 390 10-inch PMTs are placed. Outside this is the Inner Veto (IV), a volume of scintillator with 78 8-inch PMTs. Above these is the OV, a segmented plastic scintillator detector that provides \( (x, y) \) position information in 25 mm steps. It has a lower panel 1.1 m above the IV, and an upper panel 3.9 m above the lower. When a muon crosses both the upper and the lower, a high-resolution OV track is formed.

The characteristics of a muon event depend on which detector volumes the muon intersects. Consider muons that pass through the NT. As it traverses the ID, it first emits only Cherenkov light, then isotropic scintillation light, and then only Cherenkov again. Muons can also intersect only the IV and Buffer, or only the IV, and they can stop in any volume. In any of these cases, a muon can intersect zero, one, or two OV panels. All such combinations of through-going muons are handled by this reconstruction, as is the case of muons stopping in the ID scintillator.

2. Algorithm
Each ID and IV PMT in Double Chooz is read out using a 500 MHz flash-ADC with a readout window of 256 ns. A special pulse reconstruction is used for muons that is separate from that
used for other events. It defines a start time with an error, a rise time and integrated charge for each pulse. To be selected for use in the fit, IV PMTs must satisfy charge and risetime cuts to remove hits resulting from reflections. In the ID, the selection criteria are varied continuously with energy. For low-energy events, a loose selection is done that optimizes resolution for Cherenkov light. For high-energy events, a more stringent selection is used.

A $\chi^2$ fit function is used, which minuit [2] minimizes. The contribution to the $\chi^2$ from the ID is calculated either under the assumption of light mostly from Cherenkov or mostly from scintillation, depending on the event characteristics. The $\chi^2$ is built from the selected PMTs’ pulse start times and their associated errors, with unselected PMTs ignored. When OV hits are present, they are used as a spatial constraint. Since one of the goals of muon reconstruction is to look for muons with high d$E$/d$x$, we do not use the total reconstructed energy in the fit function for through-going muons. If the amount of light in the ID corresponds to $<30$ MeV, the code assumes a Cherenkov-dominated event. If it is $>180$ MeV, it is assumed to be scintillation-dominated. Between these, it tries both and chooses the one with the better $\chi^2$. These criteria were tuned on data, using OV positions to check the results.

If fitting under the Cherenkov-dominated hypothesis, the PMT timings are calculated for a simple Cherenkov cone, and penalty terms are used for hits that are not intersected by the cone.

For the scintillation-dominated hypothesis, the light pattern is more complex, as shown in Fig. 1. As the muon traverses the scintillator it emits light isotropically. Due to the muon’s motion, this light forms a cone similar to that of Cherenkov radiation. In addition to the cone, a sphere of light is produced behind the point where the muon enters the scintillator. The same occurs at the exit point. Cherenkov light near the entry point can generally be neglected (if significant, it is detected by the algorithm and removed), but near the exit point it is intense and overwhelms the scintillation light.

An effective shape for the wavefront is used to account for the fact that a sharp boundary between the cone and sphere shown in Fig. 1 is physically unrealistic, since it implies that an infinitesimal volume of scintillator at the entry point produces enough light to be seen by every PMT that lies above the region intersected by the scintillation cone. We parametrize a corrected shape as shown, where the difference between the ideal and realistic wavefronts is controlled by a single parameter related to the muon’s d$E$/d$x$. The effective speed of scintillation light is also allowed to float in the fit.

Under either fit hypothesis, IV timing information is used in the same way. Since the IV
is relatively thin, an approximation is used in which the scintillation light is treated as coming from a single point for the muon’s entry position and another for its exit. The expected times are calculated using these points; whichever gives a smaller $\chi^2$ for each PMT is used. Penalty terms are added if the intersection points are not directly visible to PMTs with hits.

If the muon deposited an unusually low amount of energy in the IV, it is a stopping muon candidate. The stopping muon fit function that MINUIT minimizes is the same as the through-going scintillation-dominated fit, except that (1) light is only expected from the entry point into the IV, (2) an additional free parameter is added for the stopping point and no light is generated past this point in the model, and (3) the track energy is used to constrain the track length.

For the through-going fits, if there is OV data, the fit with the OV is usually judged to be better, but the fit without the OV is selected if it has a dramatically better $\chi^2$. If a stopping muon fit was done, it is chosen as the best answer if the IV energy is consistent with a single IV crossing, given the reconstructed length of IV scintillator traversed.

3. Resolution

The resolution of the fit is tested using data-driven methods, primarily in events with OV tracks. We find that the resolution is about 40 mm in the ideal case of a muon intersecting a large amount of ID scintillator (see Fig. 2). For the median energy muon in Double Chooz, the limiting factor in this resolution is multiple Coulomb scattering, which violates the reconstruction’s assumption of a perfectly straight track. With an $(x, y)$ coordinates in one OV panel, the resolution is improved substantially, compared to the case of no OV data, at the top of the detector, but only marginally at the bottom.

The resolution gradually worsens as the muon’s path length through the detector decreases. For shorter paths, the resolution increases by up to a factor of two from the timing-based ideal described above. For the lowest quality tracks, muons passing only through the IV, the resolution is 250 mm. Resolution for showering muons is typically 10–40% worse than for minimum ionizing muons, depending on the extent of the shower. The most important application of muon tracking in Double Chooz, $^9$Li identification, is affected by this loss of resolution since $^9$Li is produced by showering muons. However, the typical physical distance between the muon and the $^9$Li production is still greater than the resolution, so the ability to identify the $^9$Li remains excellent.

The resolution for stopping muons is 150 mm in each of $x$, $y$ and $z$, as tested by comparing to the following Michel electron.

[1] Abe Y et al. (Double Chooz Collaboration) 2012 Phys.Rev. D86 052008
[2] James F and Roos M 1975 Comput.Phys.Commun. 10 343–367