Constraining Muon Internal Bremsstrahlung as a Contribution to the MiniBooNE Low Energy Excess

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Using a cleanly tagged data sample of ν_μ charged current events, it is demonstrated that the rate at which such events are mis-identified as ν_e's is accurately simulated in the MiniBooNE $\nu_\mu \to \nu_e$ analysis. Such mis-identification, which could arise from muon internal bremsstrahlung, is decisively ruled out as a source of the low energy electron-like events reported in the MiniBooNE search for $\nu_\mu \to \nu_e$ oscillations. This refutes the conclusions of a recent paper which postulates that hard bremsstrahlung could form a substantial background to the MiniBooNE ν_e sample.

The MiniBooNE Collaboration has reported the results of a search for $\nu_\mu \to \nu_e$ oscillations at $\Delta m^2 \sim 1$ eV^2. In this search, no significant excess of events was observed above background for reconstructed neutrino energies above 475 MeV, but $96 \pm 17(stat) \pm 20(sys)$ excess events were reported between 300 and 475 MeV [1]. The data are not consistent with two-neutrino oscillations and the source of the excess is, at present, undetermined.

A recent paper [2] suggests that the source of the low energy excess is muon internal bremsstrahlung associated with the ν_μ charged current quasi-elastic (CCQE) interaction, $\nu_\mu n \to \mu^- p + \gamma$, as depicted in Fig 1. The issue of bremsstrahlung of muon neutrino CCQE events was raised in an earlier paper [3] and brought to MiniBooNE's attention in the course of the oscillation analysis [4], prompting the study presented here.

Reference [2] asserts that $\nu_\mu n \to \mu^- p + \gamma$ events can be mis-classified as ν_e CCQE signal events if the final state muon is below Čerenkov threshold, since the radiated photon may imitate a final state electron. Even when the muon escapes direct detection, however, its presence may be revealed by the Michel electron from the muon decay. Making use of this Michel electron tag, the present paper demonstrates that the misidentification of ν_μ events caused by muon internal bremsstrahlung cannot be the

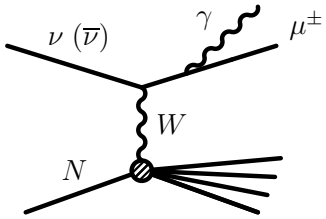

FIG. 1: Feynman diagram for muon internal bremsstrahlung.

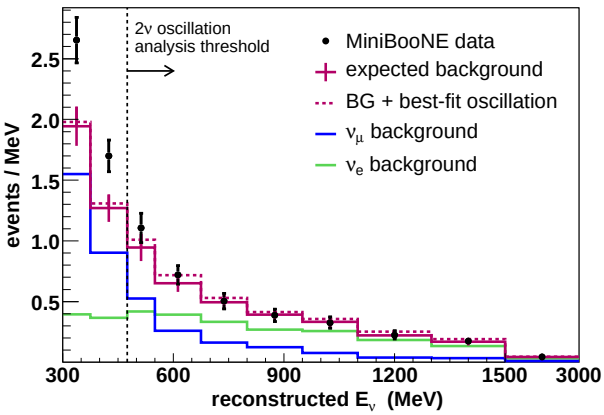

FIG. 2: Reconstructed neutrino energy distribution of *one* subevent events passing ν_e selection cuts. The data are shown as points with statistical errors and the Monte Carlo prediction is shown as a histogram with systematic errors. This figure is a reproduction of Fig. 2 in [1].

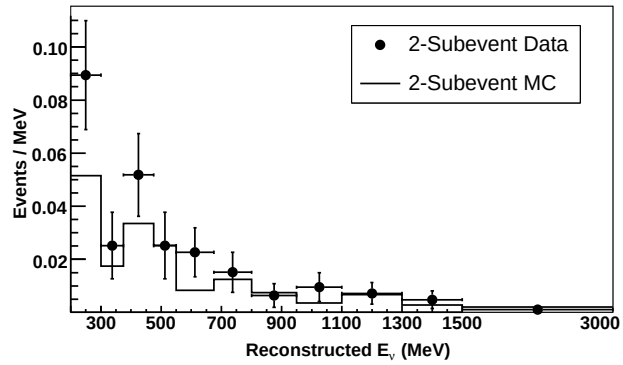

FIG. 3: Reconstructed neutrino energy distribution of *two* subevent events passing ν_e selection cuts. The data are shown as points with statistical errors and the Monte Carlo prediction is shown as a histogram. No systematic uncertainty has been evaluated for this sample. Normalization of both data and Monte Carlo is to the rate of ν_μ CCQE events with no observed Michel. If muon internal bremsstrahlung were the source of the low energy excess in the oscillation sample (Fig. 2), then the same excess would also be observed in this figure, but is not.

source of the observed low energy excess and is not a significant background to the MiniBooNE $\nu_\mu \to \nu_e$ oscillation search. Rather than relying on Monte Carlo simulation of this process, data are used to directly constrain the contribution of the muon bremsstrahlung diagram. The study was conducted prior to the unblinding of the data for the oscillation analysis and the results were incorporated into the estimated backgrounds at that time. Because the study showed that the background to the oscillation analysis from muon internal bremsstrahlung was extremely small, it was deemed unnecessary to add such internal radiative effects to the simulation. The analysis makes use of an event sample in which the presence of a muon is tagged strictly by the presence of the Michel electron from the decay of the muon:

$$\nu_\mu + n \to \mu^- + p, \qquad \mu^- \to e^- + \nu_\mu + \bar{\nu_e}.$$

The MiniBooNE detector and trigger [1] are particularly well suited for such identification. The MiniBooNE trigger creates a 19.2 μs time window surrounding the 1.6 μs beam spill. When events are reconstructed, periods of time in which light is produced in the tank are identified as "subevents". Subevents are separated by looking for gaps between PMT hit times larger than 10 ns, and are typically ∼100 ns in length.

In 82% of the cases where a muon is contained in the detector, a second subevent from the Michel electron is produced. The 18% without a second subevent splits into 8% that result from μ^- capture in oil (this rate has been separately measured [5]), 2% where simulation predicts the Michel electron creates too few PMT hits to be clearly seen (<10 hit PMTs), and 8% where the muon decays sufficiently quickly that the decay cannot be time-resolved from the initial interaction.

To study the rate at which ν_μ charged current interactions are mis-identified as ν_e's, events with two subevents are first selected. The two subevents must be separated by at least 1500 ns to avoid any instrumental effects causing the second subevent. No cuts are placed on the first subevent, but the second subevent must have fewer than 6 veto hits to ensure containment and reject cosmic muons and fewer than 200 main tank hits to ensure an energy consistent with a Michel electron. Having created, in this way, a sample of events tagged as being from a ν_μ charged current interaction, the second subevent and its hits are discarded. The full set of ν_e selection cuts, identical to those used in the oscillation result, are then applied to this artificial one subevent sample. The resulting sample is a direct, *in situ* measurement of the bulk of the ν_μ charged current contribution to the background in the ν_e sample, including that from muon internal bremsstrahlung. The only ν_μ charged current background component this measurement misses is that due to muon decay so rapid that the Michel electron cannot be time separated from the parent muon. This background is constrained and checked in other ways.

The ν_e selection cuts [1] include precuts to isolate a clean neutrino event sample: the event must have just one subevent within the 1.6 μs beam window and have fewer than 6 veto hits to remove incoming cosmic rays and exiting muons from neutrino events in the detector. Each event must also have more than 200 tank hits to reject Michel electrons from stopped cosmic rays which can enter the tank prior to the trigger window and therefore avoid the veto.

After the precuts, the same "track-based" algorithm used in the oscillation analysis [1] reconstructs the vertex position, angle, energy, and time of the event, assuming the light comes from an extended, straight line source.

The vertex and projected track endpoint must lie within the fiducial volume of the detector and the visible energy in the tank must be $E_{vis} > 140$ MeV.

Events are identified as ν_e CCQE based on likelihoods which are built from phototube charge and time probability distribution functions. For each event, using a single-track hypothesis, the likelihood is calculated that it is an electron (L_e) or a muon (L_μ). The event is then reconstructed under a two track hypothesis, where the invariant mass is forced to be 135 MeV, and a π^0 likelihood (L_π) is formed. Finally, the event is reconstructed by finding the best two track fit allowing the invariant mass to float. This yields a best-fit mass ($M_{\gamma\gamma}$). Visible energy-dependent cuts on $\log(L_e/L_\mu)$, $\log(L_e/L_\pi)$ and $M_{\gamma\gamma}$ are then applied to isolate a ν_e CCQE signal sample. The neutrino energy is then determined using the reconstructed lepton energy and direction and assuming the interaction is ν_e CCQE.

Fig. 2 shows the spectrum of the originally-published ν_e candidate sample subject to this selection [1]. The excess of events between 300 and 475 MeV is clearly visible. Fig. 3 shows the results of the same cuts applied to the tagged ν_μ data sample. In this case, the normalization has been adjusted to correct for the Monte Carlo determined rates of one subevent and two subevent ν_μ charged current interactions and for the requirement that the two subevents be separated by more than 1500 ns. Fig. 3 is therefore a direct prediction and measurement of the ν_μ charged current contribution to Fig. 2. The Monte Carlo prediction for the rate at which these processes pass the ν_e selection agrees well with the data. Furthermore, the abscissa of these two figures shows that ν_μ charged current processes account for only a tiny fraction of the background in Fig. 2. Muon internal bremsstrahlung (or any ν_μ charged current process that can lead to muon decay at rest) therefore cannot be the source of the low energy data excess.

Muon bremsstrahlung events should be efficiently rejected by the ν_e selection. Muon tracks are considerably longer than electron tracks for the same visible energy in the MiniBooNE detector. For events where the muon energy lies above Čerenkov threshold, the additional track length leads to a significantly different charge and hit structure, particularly in the center of the Čerenkov ring. One would therefore expect the presence of the muon to pull the charge and time likelihoods of the events away from an "electron-like" hypothesis.

In this paper, ν_μ charged current events are identified through the presence of a Michel electron and then subjected to the MiniBooNE oscillation analysis cuts. The rate of misidentification of these events as ν_e's is accurately modeled by the Monte Carlo and is not the source of the low energy excess in MiniBooNE.

It should be noted that this study says nothing about the total rate of muon internal bremsstrahlung in MiniBooNE, just the rate at which this process occurs in the ν_e sample. It may be possible to relax or adjust the ν_e selection cuts to make a measurement of muon internal bremsstrahlung at some time in the future.

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