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Systematic Errors of MiniBooNE

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Abstract. Modern neutrino oscillation experiments use a ‘near to far’ ratio to observe oscillation; many systematic errors cancel in a ratio between the near detector’s unoscillated event sample and the far detector’s oscillated one. Similarly, MiniBooNE uses a ν_e to ν_μ ratio, which reduces any common uncertainty in both samples. Here, we discuss the systematic errors of MiniBooNE and how the ν_μ sample constrains the ν_e signal sample.

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INTRODUCTION

MiniBooNE, a short-baseline neutrino experiment designed to test ν_μ to ν_e oscillations[1], published first results this year. Because MiniBooNE employed a ‘blind’ analysis, the ν_e potential signal and backgrounds had to be understood without direct observation of the signal region. The constraints on some of the ν_e backgrounds– misidentified neutral current single pion events (NCπ^0), out of tank (“dirt”) events and intrinsic electron neutrinos in the beam– are discussed. The implementations of the constraints in the final appearance analysis are also detailed.

Constraining the NCπ^0 background

The largest reducible background in the ν_e sample are NCπ^0 interactions which are misidentified as ν_e events. The pion can decay asymmetrically and, if one of the decay photons is very low energy, only a single, electron-like ring is observable in the tank. Such events are almost indistinguishable from a true ν_e. To constrain this sample, we measure well reconstructed two ring events which is a sample of high purity π^0 events. We compare the observed rate to the MiniBooNE simulation, and correct the simulation’s normalization of these events in π^0 momentum bins. The normalization correction is propagated to the misidentified π^0 in the signal ν_e sample.

Constraining the dirt events

Events from interactions in the rock surrounding MiniBooNE produce photons which pass the veto and give events in the inner tank, called “dirt” events. Pions which decay near the edge of the tank can lose a photon to the outside of the tank, and also appear as a single electron-like ring. An enhanced sample of dirt events is selects events at high radius, low energy and in time with the beam with minimal veto activity. The spatial distribution and energy spectrum of these events sets their normalization.

Constraining ν_e from μ^+ decay

The largest single source of background in the ν_e sample are events which are really ν_e, but are inherent to the beam. Charged pions are the main source of neutrinos in MiniBooNE. A π^+ decay produces both a ν_μ and a μ^+, and the μ^+ can decay into a ν_e. However, because the pion decay is very forward for neutrinos detected in MiniBooNE, the ν_μ reconstructed energy spectrum measures the parent π^+ spectrum very well, and consequently constrains the ν_e from μ^+ background in the signal region.

IMPLEMENTATION OF CONSTRAINTS

In this way, the ν_μ sample serves as the “near detector” sample. An expected oscillation would give an unobservable 0.25% disappearance in the ν_μ sample, but, due to the large size of the potential ν_e signal relative to background, we can observe a noticeable excess.

MiniBooNE employed two independent ν_e selection criterion: a simple, log-likelihood analysis comparing electron to muon to pion like rings, and a boosted decision tree method which takes multiple weaker variables in concert to create a single, powerful classifier. The two ν_e analyses also had two different methods to include ν_μ information in the final oscillation fit, either by reweighting of ν_e sample or by a simultaneous fit to both samples.

In the likelihood-based analysis, the ν_e reconstructed neutrino energy spectrum is reweighted based on the observed ν_μ spectrum. For example, in the case of flux errors, a matrix is made to relate the ν_μ observed energy spectrum to the π^+ energy spectrum. This is a correction based on data applied to the π^+ of the ν_e from π^+. A second correction maps ν_μ reconstructed neutrino energy to true neutrino energy, and this is applied to the potentially oscillated events from ν_μ, along with any ν_μ induced interaction not already weighted. Then, just the ν_e are fit for oscillation. The second method, used by the boosted decision tree analysis, is discussed in more detail here. In it, both the ν_μ and ν_e reconstructed neutrino energy spectra are fit simultaneously; the ν_μ spectrum assumes no oscillation and constrains the errors on the ν_e backgrounds, and the total ν_e sample provides the oscillation parameters.

Oscillation Fit Details

To compare data to a prediction, one can form a simple χ^2 distribution,

$$\chi^2 = \sum_{i,j=1}^{bins} \Delta_i M_{ij}^{-1} \Delta_j \qquad (1)$$

with $\Delta_i = Data_i - Prediction_i$, the difference between data and prediction in energy bin i. M_{ij}^{-1} is the inverse of the error matrix, which contains all systematic and statistical uncertainties.

If M_{ij} were just statistical error, it would contain the number of data events in each bin along the diagonal, and zero in all other entries (assuming negligible simulation statistical error). Uncorrelated systematic errors, with no bin to bin correlations across reconstructed energy bins would have the sum of the α sources of error on the diagonals:

$$M_{ij} = \sum_{\alpha=1}^{systematics} \sigma^2{}_{ij}(\alpha)\delta_{i,j} \qquad (2)$$

Most sources of systematic error can have correlations between different bins in energy. Eq. 3 shows the error matrix for a single source of systematic error:

$$M_{ij} = \begin{pmatrix} \sigma_1^2 & \rho_{21}\sigma_2\sigma_1 & ... & \rho_{N1}\sigma_N\sigma_1 \\ \rho_{12}\sigma_Z 1\sigma_2 & \sigma_2^2 & ... & \rho_{N2}\sigma_N\sigma_2 \\ ... & ... & ... & ... \\ \rho_{1N}\sigma_1\sigma_N & \rho_{2N}\sigma_2\sigma_N & ... & \sigma_N^2 \end{pmatrix} \qquad (3)$$

where $\rho_{i,j}$ corresponds to the correlation between the systematic error in those bins, σ_i and σ_j.

The final important detail of the fit is that it is a simultaneous to both ν_e and ν_μ reconstructed neutrino energy. The error matrices in the final oscillation fit contain not just ν_e energy bins, but also include the ν_μ energy bins as well. So the error matrix contains sections which have correlations between the ν_μ and ν_e bins. When the fit is done, the bins which contain the error and correlation between ν_μ and ν_e bins will reduce the overall error on the ν_e sample.

As an example of how the ν_μ rate can constrain the error on the ν_e, consider the error matrix for one ν_μ bin and one ν_e bin,

$$M_{ij} = \begin{pmatrix} N_e + \sigma_e^2 & \rho\sigma_e\sigma_\mu \\ \rho\sigma_\mu\sigma_e & N_\mu + \sigma_\mu^2 \end{pmatrix} \qquad (4)$$

After minimizing the χ^2 with this M_{ij}, the uncertainty on the signal will be:

$$\sigma_{signal}^2 = N_e + \sigma_e^2 \left(1 - \frac{\rho^2}{(N_\mu/\sigma_\mu + 1)}\right) \qquad (5)$$

If the two bins are highly correlated, $\rho \to 1$ or $\rho \to -1$, and if the ν_μ has large statistics, $\frac{N_\mu}{\sigma_\mu} \to 0$, the error on the fitted signal becomes N_e. The error on the signal in the fit is therefore limited by the statistical, not systematic error of the ν_e sample. In the case of no correlation ($\rho \to 0$), then the ν_e sample has no extra information on the systematics, and suffers from the full statistical and systematic error. The high statistics ν_μ sample, with perfect correlations, fixes the systematic error of the ν_e; any lack of correlation will bring with it associated unconstrained systematic error.

Building an error matrix

To form an error matrix, we sum the error matrices from each independent source of error. In the final fit, we consider errors from the production of charged pions and kaons, neutral kaons, our target/beam model, the neutrino cross section, the NCπ^0 rate measurement, events from outside the tank, light propagation in the detector (optical model) and DAQ electronics model. The next section goes into more detail on the flux and optical model uncertainties and the construction of those two error matrices.

Pion production uncertainties

We compare the existing pion production data from HARP[2] to a Sanford-Wang parameterization function of the differential cross section[3]:

$$\frac{d^2\sigma}{dpd\Omega} = c_1 p^{c_2}\left(1 - \frac{p}{p_{beam} - c_9}\right) exp\left[-c_3 \frac{p^{c_4}}{p_{beam}^{c_5}} - c_6\theta(p - c_7 p_{beam} cos^{c_8}\theta)\right] \qquad (6)$$

where p_{beam} is the proton beam energy, p is the momentum of the produced pion, and θ is the angle with respect to the beam direction of the pion. The Sanford-Wang parameterization has 9 variables, c_i, correlated in accord with the functional form of the parameterization. The fit to the HARP data provides the best fit for each parameter, and a corresponding error matrix.

We then throw, many times (≈ 1000), the c_i according to their covariance matrix from the fit to HARP data. By comparing these throws to our central-value (CV) prediction of our simulation, we can form an error matrix (Eq. 7). As the underlying flux changes, the neutrino energy distribution changes, and the RMS of that fluctuation for each energy bin sets the error.

$$M_{ij}^{\pi^+ prod} = \frac{1}{(throws-1)} \sum_{k=1}^{throws} (N_{cv}-N_k)_i (N_{cv}-N_k)_j \tag{7}$$

Detector light modeling uncertainties

MiniBooNE is a spherical $\sim$ 1kton mineral oil Cherenkov detector. Light in mineral oil is complicated to model; there are multiple sources from Cherenkov and scintillation light which can be attenuated, absorbed and remitted. Additionally, one must include PMT effects. First, a barrage of external measurements of the mineral oil tested the scintillation of the oil using a proton beam and cosmic ray muons, the fluorescence components of the oil, and the attenuation. This resulted in a model with 39 parameters and initial errors.

Each of these parameters were varied independently within initial errors, to produce different ‘universes’, or simulations which had different possible oil configurations. Unlike the flux error matrices, where one can produce many fluctuations of the neutrino energy spectrum simply by reweighting the parent π^+, these universes had to have the simulation fully rerun. Events are generated, the light propagated through the universe’s version of the mineral oil, and then reconstruction and cuts applied. Each of these simulations were then compared to select high-purity calibration samples, such as the muon decay electron sample. Universes with poor χ^2 when compared to the calibration data eliminated certain combinations of parameters. The final allowed space of parameters after calibration constraints were applied was drawn from to form the final error matrix. In this way, external data determined the parameters and initial errors, and MiniBooNE data fixed the correlations and final size of the errors.

CONCLUSION

MiniBooNE, while having no near detector at the time of the oscillation result, was able to constrain many backgrounds in the oscillation sample with the use of correlations between data sets. The rate of well reconstructed π^0 constrains how many can be misreconstructed in the ν_e sample. The ν_μ sample constrains the size of flux and cross section errors possible for the intrinsic ν_e from μ^+ decay. By using the large statistics of the ν_μ sample and strong correlations to the ν_e sample, the effective ν_e systematic error is reduced. A suite of external measurements and *in situ* MiniBooNE calibration data were used to constrain the uncertainties on the predicted ν_e background.

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