BF-2021 transcription

Page 1 (title page): Good morning, everyone. My name is Wenqiang Gu. Today I am going to talk about *Measurement of Energy-dependent Inclusive Muon Neutrino Charged-Current Cross Section at MicroBooNE*.

Page 2: MicroBooNE is an accelerator neutrino experiment at Fermilab, and is a LArTPC with 85 ton of active mass. The two of the main physics goals are to investigate the low-energy excess indicated by MiniBooNE as you have heard from Bonnie in this morning’s session, as well as to measure the neutrino-argon interaction cross section as I will be focusing on in this talk.

Page 3: So why are we interested in the inclusive muon-neutrino charged-current cross section? It is one of the most important systematics for a precision accelerator neutrino oscillation measurement. Additionally, the energy-dependent inclusive cross section is a good test of the overall modeling of all the interaction modes (like CCQE including 2p2h, CCRES), and it can form a good basis for exclusive channels (e.g. people may want to take a ratio measurement between the exclusive and the inclusive to reduce the systematic uncertainty)

Page 4: Today, my talk will be mainly covering on two parts. I will begin with the introduction of the stringent model validation for hadronic missing energy with a conditional constraint formalism. And later we will land on the measurement of the inclusive CC cross section with an unfolding procedure.

Page 5: Let’s begin with the validation of the neutrino energy modeling. It is also critical for neutrino oscillation measurements. The key challenge is to verify the modeling of the undetectable missing hadronic energy (for example, the neutrons that exits the LArTPC). In this study, we overcome the challenge by leveraging the simultaneous measurement of lepton energy and hadronic energy in LArTPC. Finally, we report two differential cross section as a function of muon energy and hadronic energy transfer, as well as a total cross section as a function of neutrino energy.

Page 6 (transion page): To give you some details about this validation, I will be brief on our event selection and systematic uncertainties in the following two slides.

Page 7: MicroBooNE is a near-surface detector, therefore, the key for a clean selection of the candidates is to reject cosmic muon. It is nontrivial as LArTPC is a slow readout detector. With the Wire-Cell reconstruction tool, a neutrino preselection is achieved with a cosmic rejection power of ~140,000. With additional CC selection algorithm, the S/B ratio is further improved with a factor more than 5.

The high-statistics event selection allows for a high-precision …

The figure shows you the reconstructed energy distribution for the CC candidates, overlayed with the MC prediction. The difference between data and MC is covered by the systematic uncertainties in the grey band.

Page 8: For the systematic uncertainty, it has contributions from several components, where the detector modeling uncertainty is dominating the total uncertainty, and the flux, cross section, statistical uncertainty is sub dominating. The other factors e.g., hadron-argon interaction uncertainty and the material modeling surrounding the cryostat is small but not ignored.

Page 9: Now given the full systematics, a covariance matrix is constructed, and a value of chi2/ndf is calculated, providing a goodness-of-fit for the overall model.

For example, the reconstructed neutrino energy distribution is compared with the model prediction. Both the fully contained and partially contained sample are tested. The reasonable chi2/ndf value indicates that the data-MC difference can be well covered by the total systematic uncertainty.

**However, there is a concern. It is possible that part of the uncertainties is overestimated and it could hide the potential bias in the other component of uncertainty. For example, the flux uncertainty is conservative, therefore, it could hide some bias in the cross section interaction model. In this study, we show that this concern can be solved with a formalism of conditional covariance.**

Page 10: To remind you, conditional expectation and covariance has a same backend formular as in the Gaussian Process Regression. It assumes two normally distributed variable vector, given a measurement in one variable, it leads to a constraint of phase space in the other variable. In the other word, this is a data driven model correction on both the mean and variance with auxiliary sidebands. It avoids over-tuning of MC models.

For example, the model prediction of the reconstructed hadronic energy distribution can be constrained with the measured distribution of the reconstructed energy distribution. As a result, the common systematics such as flux are largely reduced, where the correlated statistical uncertainty between hadronic energy and muon energy is estimated with bootstrapping procedure.

Page 11: First, let’s take a look at the overall model validation at the lepton side. The reconstructed energy for muon final state is compared with model prediction, the chi2/ndf value looks reasonable.

Page 12: Next, a data-MC comparison is done for the reconstructed hadronic energy. The overall chi2/ndf looks reasonable, but there is a little excess at low hadronic energy. Could it be a mis-modeling of the hadronic missing energy given the neutrino flux reasonably well known? The total uncertainty at low energy is about 20%, limiting our ability to investigate the potential bias.

The solution is that we can use the kinematic distributions from the muon final state to reduce the total uncertainty from the common systematic components (e.g., flux, cross section).

Page 13: Finally, this is the hadronic energy distribution with a constraint to the muon kinematics …

Page 14: Now you might ask a question: is this new validation method really work? Here, I am showing you two fake data studies. The left one is the fake data generated based on the old version generator GENIE v2. It has been shown that the chi2/ndf is large after the constraint to muon kinematics. The right handed table shows another set of fake data study, where the hadronic energy fraction allocated to protons has been reduced with different percentages, mimicking a variation in the proton-inelastic scattering). It has shown that ch2/ndf increases significantly large with a shift of ~15%, smaller than the more conservatively assigned uncertainty in the GENIE generator.

All these shows that the conditional constraint approach is sensitive to the underlying model difference.

Page 15: Now I would like to move on to the cross section unfolding.

Page 16: Understanding the cross section as a function of energy is also crucial for oscillation measurement. In this study, we measure the energy-dependent total cross section using the Wiener-SVD unfolding. I am not going to expand the details about the technical formalism but Wiener-SVD unfolding simplify the procedure and maximize S/N ratio.

Unfolding is basically a technique to extract the underlying true model given the reconstructed distribution and a proper modeling of the detector response. We can do an extraction of the cross section if we can write down a master equation, where the measured neutrino energy distribution is modeled with the background prediction and the response matrix, and the cross section can be maintained in the signal term.

Page 17/18: To rephrase this problem. Let’s write down the neutrino measurement as a convolution of the number of target, flux , cross section, detector and selection efficiency, as well as background.

(page 18) To simplify the treatment of the systeamatic uncertainty, our signal is defined as the cross section in each energy bin and weigted averaged by flux spectrum.

The advantage of this definition is that it can address a recent concern from the community about the treatment of the flux shape uncertainty.

Page 19: So it brings me to the final result. The data points are shown and overalyed with the central prediction from several state-of-the-art event generators. The wiener regulization is added to the model prediction for a proper data comparison. The GiBUU, NEUT, and the MicroBooNE GENIE tune all give reasonable agreement.

Page 20: Similarly, we also measured two differential cross section. One is as a function of …, the other is … For the muon energy one, a reasonable … For the hadronic energy transfer one, GiBUU gives best agreement at low energy transfer.

Page 21: It brings me to my short summary now. …

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Page2: **Wire-Cell is a software package for LArTPC simulation and reconstruction.** MicroBooNE is a LArTPC operating near the earth surface, therefore, cosmic muon is a major background for the numu CC selection. With the excellent generic neutrino detection, an overall rejection factor of 140,000 has been achieved for the cosmic-muon.

By further incorporating the WireCell pattern recognition, a high-performance numuCC selection is accomplished with 64% efficiency and 93% purity. The high-statistics selection allows for high-precision , multi-dimensional cross-section measurement.

In this figure, the comparison of the data and MC distribution is shown as function of the reconstructed neutrino energy with calorimetry method. A difference between data and central value MC can be seen. In particular, the slope in data/MC ratio suggests us to validate **the modeling of the conversion from the true neutrino energy to the reconstructed energy.**

Page3: This validation is crucial not only for the cross-section measurement, but also for the oscillation measurement. It requires a good understanding of the neutrino-Ar cross section, which is a key challenge because these is no mono-energetic neutrino beam to calibrate the Argon response.

**One idea, known as “NuPRISM”,** proposes to constrain cross section modeling with a series of off-axis measurements.

Here, we propose a new idea based on the calorimetric energy reconstruction. We examine the data-MC comparison of the reconstructed hadronic energy distribution after applying constraints of **the much well-known** muon kinematics distributions. This technique is called “conditional covariance”. Briefly speaking, with two correlated variables, the measurement in one variable gives rise to constraint on the other variable’s mean and covariance. In this case, many common systematics (e.g. flux) are cancelled, providing a more stringent validation of the cross-section modeling.

Page4: Here is the validation result. In this figure, the data-MC comparison is shown as a function of reconstructed hadronic energy. An excess is observed at low hadronic energy, while the excess is covered by the overall systematic uncertainty, **it’s natural to ask whether there is any mis-modeling of missing energy in the hadron final state.**

So we apply the constraints technique. And you can the difference here,

First, the systematic uncertainty has been significantly reduced from 20% to 5%.

Secondly, **there is no more excess** at low hadronic energy.

This demonstrates a **good validation for the modeling of the reconstructed neutrino energy**.

Page5: Also, with enough statistics we can further separate the selection into two sub-channels **without and with protons** in the reconstructed final states. The data-MC comparisons have different behaviors between these two sub-channels. While an overall excess is observed for the 1u0p channel, a deficit is seen at the muon forward angle in the 1uNp channel. The high-statistics numu CC selection enables a future multi-dimensional cross-section measurement.

Page6: So here is my summary.

A high performance inclusive numu CC selection has been achieved using Wire-Cell reconstruction at MicroBooNE

A new technique with conditional covariance matrix provides more stringent validations of the cross-section modeling and neutrino energy reconstruction

With the full dataset of 1.2E21 POT at MicroBooNE, we expect to have more than 200k numu CC events, allowing us to perform multi-dimensional differential cross-section. Please stay tuned for the upcoming results on the nominal flux-averaged cross-section measurement.

**Thank you for listening!**