6th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NUINT 09)

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Book of Abstracts

Contents

Single pion production II / 2

neutrino-induced coherent pion production at low energies

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We present a model for neutrino-induced coherent pion production off nuclei in the energy regime of interest for present and forthcoming neutrino oscillation experiments. It is based on a microscopic model for pion production off the nucleon that, besides the dominant Δ pole contribution, takes into account the effect of background terms required by chiral symmetry. Moreover, the model uses a reduced nucleon-to-Δ resonance axial coupling, which leads to coherent pion production cross sections around a factor two smaller than most of the previous theoretical estimates. In the coherent production, the main nuclear effects, namely medium corrections on the Δ propagator and the final pion distortion, are included. We have improved on previous similar models by taking into account the nucleon motion and employing a more sophisticated optical potential. As found in previous calculations the modification of the Δ self-energy inside the nuclear medium strongly reduces the cross section, while the final pion distortion mainly shifts the peak position to lower pion energies. The angular distribution profiles are not much affected by nuclear effects. We discuss what we think are the deficiencies of the commonly used Rein–Sehgal pion coherent production model when is used for neutrino energies below 2 GeV.

Single pion production II / 3

Neutrino induced pion production at MiniBooNE and K2K within the GiBUU model

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A precise determination of neutrino oscillation parameters demands for an equally precise knowledge of the neutrino nucleus interaction process. Neutrino induced pion production is strongly influenced by nuclear effects. Their understanding is crucial since neutral current $\pi 0$ production is a major background in ν_e appearance experiments, while charged current π^+ production introduces a background to ν_μ disappearance searches.

We have investigated both, charged and neutral current neutrino induced pion production off nuclei, at MiniBooNE and K2K energies within the GiBUU transport model. Assuming impulse approximation, we treat the nucleus as a local Fermi gas of nucleons bound in a density and momentum potential. The outcome of the initial neutrino nucleon reaction undergoes complex hadronic final state interactions where in-medium spectral functions of the particles are taken into account. We present results for neutral current $\pi 0$ and charged current π^+ production and compare to first MiniBooNE and K2K data.

A correct understanding of neutrino induced pion production is also important for the reconstruction of the neutrino energy out of quasi-elastic scattering—events where the pion is absorbed in the nucleus might be misidentified as quasi-elastic and thus, modify the reconstructed energy leading to errors in the oscillation measurements.

Poster session and cocktail reception / **4**

A study of nuclear effects in F_2 and F_3 structure functions in the deep inelastic $\nu(\bar{\nu})$ reactions in nuclei

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We shall present the results for the nuclear effects in $F_2^A(x)$ and $F_3^A(x)$ structure functions in the deep inelastic neutrino(anti-neutrino) induced charged lepton production on some nuclear targets which are being used in the present neutrino oscillation experiments. These theoretical calculations have been done by using a spectral function to describe the momentum distribution of nucleons in the nucleus. The spectral function has been calculated using the Lehmann's representation for the relativistic nucleon propagator and nuclear many body theory is used to calculate it for an interacting Fermi sea in nuclear matter. A local density approximation is then applied to translate these results to finite nuclei. This model takes into account the binding energy, off mass shell and Fermi motion of the nucleons in the nuclear medium. Furthermore, we have taken into account the target mass correction, non-isoscalar nuclear correction and the Q^2 evolution in the parton distribution function. The results obtained by using this spectral function will be compared with the results obtained by using the different spectral functions available in literature. We have also studied the effect of the different parametrizations of the parton distribution function which are presently being used in the literature. Our results will be compared with the recent results available in literature from theoretical and phenomenological analyses of experimental data.

Poster session and cocktail reception / **5**

Prospect of Dimuon Analysis at the MINOS Near Detector

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We present the prospect for a dimuon analysis at the MINOS Near Detector. A sample of about 10M muon-neutrino charged current events has been accumulated with the MINOS Near Detector. The dimuon analysis focuses on neutrino charm-production where the charmed hadron decays into a positive-muon. Estimates of signal efficiency and background, and the sensitivity to physics parameters will be presented.

CC and NC quasi-elastic scattering II / **6**

Quasielastic scattering at MiniBooNE energies

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Charged-current neutrino interactions with carbon nuclei at the typical energies of the MiniBooNE experiment (around 700 MeV) have been investigated. We describe the nucleus as a local Fermi gas of nucleons in a density- and momentum-dependent mean field potential, taking into account nucleon in-medium spectral functions. Polarization effects are included by means of an RPA resumation of particle-hole and Delta-hole states; they cause a considerable reduction of the cross section at low q2. With the same physics input and using the transport techniques of the Giessen BUU model we also obtain the non-CCQE part of the cross section that arises mainly from pion production followed by absorption inside the nucleus. Our CCQE results are compared with the modified Fermi gas ansatz proposed by MiniBooNE as a good fit. Finally, we have investigated how the many body effects present in our description affect the neutrino energy reconstruction.

Poster session and cocktail reception / **7**

Generator of neutrino-nucleon interactions for the {\sc fluka} based simulation code

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An event generator of neutrino-nucleon and neutrino-nucleus interactions has been developed for the general purpose Monte Carlo code {\sc fluka}. The generator includes options for simulating quasi-elastic interactions, the neutrino-induced resonance production and deep inelastic scattering. Moreover, it shares the hadronization routines developed earlier in the framework of the {\sc fluka} package for simulating hadron-nucleon interactions. The simulation of neutrino-nuclear interactions makes use of the well developed {\sc peanut} event generator implemented in {\sc fluka} for modeling of the interactions between hadrons and nuclei.The generator has been tested in the neutrino energy range from 0 to 10 TeV and it is available in the standard {\sc fluka} distribution. Limitations related to some particular kinematical conditions as well as comparison with experimental data are discussed. A number of upgrades is foreseen for the generator which will optimize its applications for simulating experiments in the CNGS beam.

8

Neutrino cross sections within the Continuum Random Phase Approximation

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The description of the energy spectrum above the nucleon emission threshold requires a proper treatment of the continuum part of the single particle configuration space. The Random Phase Approximation equations, written in coordinate space representation, are solved in this work, using an expansion on the Sturmian functions basis. This approach can be applicated also when finite range interactions with tensor channel are used.
The possibility of applying this approach to the study of low-energy neutrino scattering cross-sections will be shown, with the purpose of studying their sensitivity to the tensor components of the interaction.

Poster session and cocktail reception / **9**

Neutrino-induced coherent pion production off nuclei – revisited

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It is pointed out that so far all theoretical estimates of coherent pion production off nuclei induced by neutrinos rely on the 'local approximation' well known in photonuclear physics. The effects of dropping this approximation are discussed. It is found that in a plane wave approximation for the pion the local approximation overestimates the coherent neutrino-induced pion production on nuclei.

Current and future neutrino experiments I / **10**

ArgoNeuT: a liquid Argon TPC for the study of neutrino interactions in the intermediate energy range

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On the way toward massive Liquid Argon Time Projection Chamber (LAr TPC) detectors for future generation long baseline neutrino experiments, a "physics R&D" phase is in act: the ArgoNeuT detector (175 l of LAr active volume) is now going to be exposed on-axis to the NuMI beam at Fermilab, in front of the MINOS Near Detector. By taking measurements in the 0.1 to 10 GeV energy range, ArgoNeuT will produce the first ever data for intermediate energy neutrino interactions in a LAr TPC. Data acquisition is expected to start in spring 2009.
The experiment's research/design goals and physics potentialities, including a charged current quasi-elastic ν_μ cross section and M_A parameter measurement, are reviewed. The ArgoNeuT detector performances during the above-ground commissioning run with cosmic rays and the current status of the experiment are also shown.

CC and NC quasi-elastic scattering II / **13**

Effect of final state interaction and Coulomb distortion of charged current neutrino-nucleus scattering in quasielastic region

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Within the framework of a relativistic single-particle model, final state interaction between outgoing nucleons and residual nuclei and Coulomb distortion of charged current reaction are studied through total cross sections of neutrino-nucleus scattering . The Coulomb effect is almost half of the electron scattering. Furthermore, to investigate the effect of the final state interaction, a relativistic phenomenological optical potential and a real potential for final nucleons are used. We calculate both neutral-current reaction such as (ν, ν') and charged-current reaction like (ν_e, e^-) and (ν_μ, μ^-) with inclusion of the strangeness. In these calculations, ^{12}C is used as a target nucleus and the incident neutrino (antineutrino) energies are exploited up to 2 GeV. We find that the effect of the final state interaction is about 50 \% for the optical potential and is about 15 \% for the real potential.

Current and future neutrino experiments I / 14

Status of the OPERA experiment

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The OPERA experiment aims to observe tau neutrinos in the CNGS mu-neutrino beam using emulsion films packed into bricks based on the Emulsion Cloud Chambers (ECC) technology.
ECC provides a spatial resolution of tracks and vertices on the level of a micrometer which is sufficient to unambiguously identify tau leptons produced in the primary vertex. An important background to a search for tau lepton is due to charmed particles. A precision measurement of charmed particles in the OPERA experiment is an important step in the verification of the ability of the OPERA experiment to identify tau lepton. Also it provides a better understanding of charm production in the neutrino interactions in few the GeV neutrino energy region. We review the current status of the OPERA experiment, focusing on its potential to improve our knowledge on neutrino nucleon interactions in few GeV region.

15

C5A axial form factor predicted from the bubble chamber scattering data

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Analysis of the single pion production data collected in the 12-ft ANL and 7-ft BNL experiments will be presented. It will be shown that successful, simultaneous fit (assuming dipole form of C5A)

to both sets of the data is possible if the flux uncertainties are taken into account. The deuteron structure effects are taken into consideration. The obtained fits of C5A will be applied to the NuWro Monte Carlo (MC) generator and then used to predict $\sigma(CC\pi^+)/\sigma(CCQE)$ ratio for the K2K and MiniBooNE experiments. Eventually, I will also present computation of the cross sections for pi0 production in neutral current neutrino-nucleon scattering for T2K experiment. All predicted observables will be presented together with the uncertainties which are determined from the fit.

Poster session and cocktail reception / **17**

Neutrino interactions with nuclei

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We present a model for neutrino-nucleus scattering in the energy region relevant for present and forthcoming neutrino oscillation experiments.
The model is based on the RPA treatment of the nuclear responses in the quasi elastic and delta region. It includes also in a phenomenological way nucleon knock-out.
It aims at the description in an unique framework of several final state channels i.e. quasi elastic one, incoherent
and coherent one pion production and two or several nucleon knock-out.
It allows to compare easily effects in different nuclei through a local density approximation treatment.
We compare our model results with the recent data from K2K and MiniBooNE discussing the sensitivity on the hadron physics input parameters.

Poster session and cocktail reception / **18**

Charged-Current Neutrino-induced Neutral Pion Production at SciBooNE

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SciBooNE, located in the Booster Neutrino Beam at Fermilab, collected data from June 2007 to August 2008 to accurately measure muon neutrino and anti-neutrino cross sections on carbon below 1 GeV neutrino energy. SciBooNE is studying charged current interactions. Among them, neutral pion production interactions will be the focus of this poster. The experimental signature of neutrino-induced neutral pion production is constituted by two electromagnetic cascades initiated by the conversion of the pi0 decay photons, with an additional muon in the final state for CC processes.

In this poster, I will present how we reconstruct and select charged-current muon neutrino interactions producing pi0's in SciBooNE. For this purpose, data from all three SciBooNE sub-detectors is used. A preliminary measurement of the overall rate for this process to occur in neutrino-mode, as well as distributions in key pi0 observables, will be given. Data will be compared to expectations from two widely-used neutrino event generators: NEUT and NUANCE.

Single pion production II / 19

Dynamical Model Approach to Coherent Pion Production

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We report our recent study on the coherent pion production in the neutrino-nucleus scattering in the sub- and few-GeV region. In our approach, the transition amplitude is calculated by summing elementary amplitudes of a weak pion production off a single nucleon embedded in a nuclear environment. Therefore, it is of primary importance to start with a model which reasonably describes electroweak pion productions off a free single nucleon. The Sato-Lee (SL) model is such a model, and we employ it in our calculation. The SL model contains both resonant and non-resonant mechanisms. For a reaction on a nuclear target, we need to consider medium effects such as the change of the delta-propagation (shifts of the mass and width) and the final-state interactions between the outgoing pion and nucleus. In the energy region of our interest, we may take care of these important medium effects using the delta-hole model. Thus our model is based on a combination of the SL model and the delta-hole model. Our model takes care of non-local effects of the delta propagation in nuclei. All free parameters in our model are optimally fitted to both elastic and total cross sections of the pion-nucleus scattering. First, we calculate the coherent pion photo-production off a nucleus, and then compare the result with data to test the reliability of our approach. We find a reasonable agreement with data, and have a good basis to proceed to the neutrino process. In our presentation, we explain our model and show new numerical results for the charged-current and neutral-current reactions, and the neutrino and antineutrino reactions. We also make a comparison of our result with recent data and other theoretical calculations.

Poster session and cocktail reception / 20

A Two Prong Selection for Quasi-Elastic Muon Neutrino Interactions in MINOS

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The Main Injector Neutrino Oscillation Search (MINOS) is a two detector, long baseline neutrino oscillation experiment that uses the Neutrinos at the Main Injector (NuMI) beam at Fermilab. Both MINOS detectors are iron-scintillator tracking/sampling calorimeters. The MINOS near detector has recorded the world's largest dataset of neutrino interactions in the 0-10 GeV region. This high statistics data set can be used to make high precision measurements of neutrino interaction cross-sections.

The Q squared dependence in quasi-elastic scattering probes the axial form factor of the nucleon/nuclear target, and nuclear effects in neutrino scattering. There are curious discrepancies between recent measurements and older ones taken during the bubble chamber era. Two distinct methods for selecting quasi-elastic enhanced neutrino interactions in the MINOS near detector are presented with the resulting selection efficiency and purity. A method for selecting quasi-elastic enhanced neutrino

interactions in the MINOS near detector which looks for two distinct prongs is presented with the resulting selection efficiency and purity.

Electron scattering and its connection to neutrino-nucleus interactions II / 21

From electron scattering to neutrino physics

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In neutrino scattering off nucleus, the uncertainties of the cross section come from the parameterization of the axial form factor and from nuclear effects. The approach currently applied in neutrino physics is to extract information about the elementary cross section (i.e. axial form factor) from scattering off nuclei. To make it possible, we have to describe nuclear effects in the most accurate way.

In the typical approach to modeling of ~1-GeV neutrino scattering, one assumes that an interacting probe sees the nucleus as a collection of independent nucleons. Without additional assumptions, i.e. in the impulse approximation, the nucleus cross section is a product of the nucleon cross section and the so-called spectral function, describing the distribution of nucleon momenta and energies.

As was shown [Phys. Rev. C 77 044311 (2008)], some electron-scattering data correspond kinematically to neutrino interactions, what allows for precise tests of the accuracy of the used description of nuclear effects. In this indirect way, I want to show accuracy of the spectral functions of argon and calcium in modelling neutrino interactions in quasielastic and delta-production region. Moreover, I will present when the impulse approximation breaks down and what are the consequences of this fact for neutrino observables.

Current and future neutrino experiments I / 22

MicroBooNE: A New Liquid Argon Time Projection Chamber Experiment

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Liquid Argon Time Projection Chamber (LAr TPC) detectors are well suited to study neutrino interactions, and are an intriguing option for future massive detectors capable of measuring the parameters that characterize neutrino oscillations. These detectors combine fine-grained tracking with calorimetry, allowing for excellent imaging and particle identification ability. In this talk the details of the MicroBooNE experiment, a 175 ton LAr TPC which will be exposed to Fermilab's Booster neutrino beamline starting in 2011, will be presented. The ability of MicroBooNE to differentiate electrons from photons gives the experiment unique capabilities in low energy neutrino interaction measurements.

Electron scattering and its connections to neutrino-nucleus interactions I / 23

Relativistic models for electron and neutrino-nucleus scattering

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Relativistic models of electron and neutrino-nucleus scattering in the quasielastic region are presented and compared. For inclusive processes the numerical results obtained with different approaches to describe final-state interactions, in particular the Relativistic Green's Function and the Relativistic Mean Field approaches, are compared. The scaling properties of the different models are also investigated. The scaling functions obtained in the different models for different kinematics are compared with the experimental scaling function extracted from the analysis of (e,e') data.

Shallow to deep inelastic scattering I / 27

Modeling neutrino structure functions at low Q^2

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Shallow to deep inelastic scattering II / 28

Duality and neutrinos

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Shallow to deep inelastic scattering I / 32

Discussion

Shallow to deep inelastic scattering II / 33

Discussion

Confronting theory, models & data / 34

Review of final state interactions

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For neutrino interactions with nuclei, the primary interaction is often sought. However, this character is often masked by interactions of the outgoing hadrons in the residual nucleus. There are many fsi models available. This talk will attempt to give an overview of their properties.

CC and NC quasi-elastic scattering III / 35

Impact of nuclear effects on the determination of the nucleon axial mass

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In this talk I analize the influence of nuclear effects on the determination of the nucleon axial mass from nuclear cross sections computed in the impulse approximation regime. We show that correlation effects, not taken into account by the relativistic Fermi gas model, sizably affect the Q2-dependence of the cross section but do not explain the large values of the axial mass recently reported by the K2K and MiniBooNE collaborations.

CC and NC quasi-elastic scattering III / 36

Kinematic reconstruction of atmospheric neutrino events in a large water Cherenkov detector with proton identification

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We report the development of a proton identification method for the \superk detector. This new tool is applied to the search for events with a single proton track, a high purity neutral current sample of interest for sterile neutrino searches. After selection using a neural network, we observe 38 events in the combined SK-I and SK-II data corresponding to 2285.1 days of exposure, with an estimated signal-to-background ratio of 1.6 to 1. Proton identification was also applied to a direct search for charged-current quasi-elastic (CCQE) events, obtaining a high precision sample of fully kinematically reconstructed atmospheric neutrinos, which has not been previously reported in water Cherenkov detectors. The CCQE fraction of this sample is 55\%, and its neutrino (as opposed to anti-neutrino) fraction is 91.7 ± 3\%. We selected 78 μ-like and 47 e-like events in the SK-I and SK-II data set. With this data, a clear zenith angle distortion of the neutrino direction itself is reported in a sub-GeV sample of μ neutrinos where the lepton angular correlation to the incoming neutrino is weak. Our fit to \mutau oscillations using the neutrino $\frac{L}{E}$ distribution of the CCQE sample alone yields a wide acceptance region compatible with our previous results and excludes the no-oscillation hypothesis at 3 sigma.

CC and NC quasi-elastic scattering I / 37

Overview of neutrino-nucleus quasielastic scattering

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A review of quasielastic neutrino-nucleus scattering will be presented, with emphasis on bringing together the knowledge (and language) of neutrino physics, electron scattering, and nuclear structure communities. Assumptions commonly made which simplify the theoretical calculations will be examined. Finally, an attempt will be made to identify places where improvement from either theoretical or experimental sides would be more significant.

CC and NC quasi-elastic scattering II / 38

A study of quasi-elastic muon (anti)neutrino scattering in the NOMAD experiment

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We have studied the muon neutrino and antineutrino quasi-elastic (QEL) scattering reactions using a set of experimental data collected by the NOMAD collaboration. We have performed measurements of the cross-section of these processes on a nuclear target (mainly Carbon) normalizing it to the total charged current cross-section. The axial mass parameter was extracted from the measured quasi-elastic neutrino cross-section. The corresponding result is M_A = 1.05 \pm 0.02 (stat) \pm 0.06 (syst) GeV. It is consistent with the axial mass values recalculated from the antineutrino cross-section and extracted from the pure Q^2 shape analysis of the high purity sample of neutrino quasi-elastic 2-track events, but has smaller systematic error. Our measured M_A is found to be in good agreement with the world average value obtained in previous deuterium filled bubble chamber experiments. The NOMAD measurement of M_A is lower than those recently published by K2K and MiniBooNE collaborations. However, within the large errors quoted by these experiments on M_A, these results are compatible with the more precise NOMAD value.

CC and NC quasi-elastic scattering I / 39

Preliminary Results for CCQE Scattering with the MINOS Near Detector

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We present preliminary results from a quasielastic enhanced sample of neutrino-iron interactions observed by the MINOS Near Detector in the NuMI neutrino beam at Fermilab. From a shape fit to the Q2 distribution for these events we extract a value for the effective axial-vector mass MA which best describes that distribution. We discuss the very low Q2 behavior of this sample and the most important systematic effects for this measurement.

Poster session and cocktail reception / 40

Challenges in Fitting MiniBooNE Anti-Neutrino data to MC Through M_A, Kappa Parameters

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The anti-neutrino data collected at the MiniBooNE project has many complications not present in neutrino-mode data. Purity is much lower in the sample due to so-called Wrong Sign contamination (neutrinos in the anti-neutrino sample), and there is an additional relevant scattering target in hydrogen. We want to fit the axial parameter M_A and pauli blocking parameter Kappa to our data to improve data-MC agreement in the kinematic variables. There is significant disagreement, especially at low Q^2 and the forward scattering angle, if we use the world values M_A = 1.015, K = 1.000.

54

Q2 discrepancies : data confronts theory

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Electron scattering and its connections to neutrino-nucleus interactions I / 80

Nucleon Form Factors: recent experimental progress.

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Current and future neutrino experiments II / 88

Neutrino Beams

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Current and future neutrino experiments II / 90

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Electron scattering and its connection to neutrino-nucleus interactions II / 91

Empirical Fit to Inclusive Electron Scattering on Nuclei

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An empirical fit has been made to inclusive electron scattering data on nuclei in the kinematic region $0 < W < 4$ GeV and $0 < Q^2 < 10$ GeV^2. Several new high-precision data sets from Jefferson Lab were used to augment the existing world data set. Data on the deuteron and proton were used to obtain a fit to a free neutron target. Simple Fermi-smearing, Coulomb corrections, and a parametrization of the "EMC effect" were used to obtain a "basic" fit for nuclei with $A > 3$, which was adjusted with 25 additional free parameters to fit data on He, berylium, carbon, aluminum, iron, and copoper. The largest adjustments to the basic fit were needed for the transverse cross section in the "dip" region between the quasi-elastic peak and the $\Delta(1232)$ resonance. Approximately 70\% of the data points used lie within 4\% of the fit, and 97\% lie within 10\%. The functional form of the fit was chosen to join smoothly onto fits at higher W and Q^2.

Single pion production I / 93

Neutral Current $1\pi^0$ Production at MiniBooNE

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We detail the analysis involved in the measurement of neutral current single π^0 production cross sections on CH_2 in MiniBooNE and report our most recent measurements for both neutrino and antineutrino induced production.

Confronting theory, models & data / 94

Experimental review – needs from theory and models.

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This will be review of three or four pre-NuInt09 experimental puzzles and how experiments have dealt with them up to now. Rather than a simple review of past NuInt presentations, the focus of the talk will be the connection between models and experiment. Using these recent experimental

puzzles, I will explore how and where improved application of theory can make a significant impact on the understanding of the experimental data.

Single pion production II / 95

PCAC and coherent pion production by low energy neutrinos

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Coherent production of charged and neutral pions in low energy neutrino reactions is discussed in the framework of the partially conserved axial vector current theory (PCAC). The role of lepton mass effects in suppressing the production of charged
pions is included. Instead of using models of pion nucleus scattering,
the available data on pion Carbon scattering are implemented for
an analysis of the PCAC prediction. Our results agree well with the published
upper limits for the production of positively charged pions but are much below the recent MiniBooNE result for neutral pion production.

CC and NC quasi-elastic scattering II / 96

SciBoone CCQE

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The next generation of accelerator neutrino oscillation experiments will require precise neutrino cross-section measurements. SciBooNE is a sub-GeV muon neutrino and anti-neutrino cross-section experiment based at Fermilab, USA, that ran from June 2007 until August 2008 collecting 0.99E20 and 1.53E20 protons on target in neutrino and anti-neutrino mode respectively. Here we will present an introduction to the SciBooNE experiment and preliminary results for two independent muon neutrino CCQE cross-sections analyses covering different neutrino energy regions.

Shallow to deep inelastic scattering II / 98

Hadronization in cold and hot QCD matter

Author: Alberto Accardi[1]

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I will review recent progress in the study of parton propagation, interaction and fragmentation in both cold and hot QCD matter, with emphasis on Deep Inelastic Scattering on nuclear targets. I will highlight theoretical and experimental open issues, the connection with heavy-ion collisions, and the hadronization program at the Electron-Ion Collider.

CC and NC quasi-elastic scattering I / **100**

Measurement of Muon Neutrino Charged Current Quasielastic (CCQE) Double Differential Cross Section in MiniBooNE

Author: Teppei Katori[1]

[1] *Massachusetts Institute of Technology*

The mini-Booster neutrino experiment (MiniBooNE) at Fermi National Accelerator Laboratory (Fermilab) is designed to search for \nu_mu to nu_e appearance neutrino oscillations. Muon neutrino charged current quasielastic (CCQE) interactions make up roughly 40% of our data sample, and are used to constrain the background and cross sections for the oscillation analysis.

Using high-statistics MiniBooNE CCQE data, the muon-neutrino CCQE differential cross section on carbon is measured. The backgrounds are tuned precisely using the MiniBooNE data. This is the first measurement for the double differential cross section in CCQE interaction, and is the most complete information one can obtain from muon-kinematics-based CCQE cross section measurements. Our measurement can be used to study nuclear effects in neutrino interactions, which is critical input for future long baseline neutrino oscillation experiments.

Confronting theory, models & data / **101**

Comparisons of neutrino-nucleus Cross Section Calculations

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The interpretation of experimental data on neutrino-nucleus interactions at low energy relies on predictions of various theoretical models.This session brings together a number of groups working on the theoretical understanding of quasi-elastic scattering and single pion production and compares the predictions of their models for a set of standard conditions. Differences between the models will be discussed.

Confronting theory, models & data / **102**

How much nuclear physics do we need to understand the neutrino-nucleus cross section ?

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Electron scattering experiments have clearly exposed the limits of the shell model description of atomic nuclei.
I will discuss the dynamics leading to the appearance of strong correlation effects, and their impact on the
nuclear cross sections in the impulse approximation regime.

Current and future neutrino experiments II / 103

Short Baseline Neutrino Physics - OscSNS, the BNB, and Beyond

Author: Geoffrey Mills[1]

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This talk will explore the impact of future short baseline experiments at the SNS and the Booster Neutrino Beam (BNB). The Spallation Neutrino Source (SNS), located at the Oak Ridge National Laboratory site near Knoxville, TN, USA, will eventually provide roughly 1.3 MW of proton beam power on a liquid mercury target. The extremely intense beam of neutrinos, largely produced by pions and muons which decay at rest, has a neutrino spectra that is precisely known. The beam's time structure will separate the monochromatic, 30 MeV, pion decay-at-rest neutrinos and allow the C12(1511) state to be cleanly measured. The OscSNS experiment would be sensitive to a host of short-baseline oscillation effects. Further measurements in the BNB could provide a resolution to the exciting low energy excess found by MiniBooNE in neutrino mode.

The path forward: theory vs. experiments needs I / 104

QE Scattering

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In this first topic of the session, we will invite an open discussion on the current situation in measuring and modeling neutrino QE scattering on nuclei. The session will start with a few brief presentations and then the floor will be open for general discussion. Here, we will specifically address whether or not we have a solid understanding of QE scattering on nuclear targets. Do we understand the difference in axial mass measurements from various experiments? Can new theoretical calculations explain what we are seeing in experimental data, both in shape and normalization? Do we need to start seriously considering a non-dipole axial form factor? At low Q2, are there better alternatives to the use of the Pauli blocking scale parameter, kappa, as introduced by MiniBooNE? Do we understand the normalization of the QE cross section? What can we learn from modern NC elastic scattering data? The hope is to leave the workshop with a better understanding of the problem and what to do next.

The path forward: theory vs. experiments needs I / 105

Coherent Pion production

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The second topic of the session will focus on coherent pion production. The session will start with a few brief presentations and then the floor will be open for general discussion. Here, we plan to discuss whether or not we understand the discrepancy between recent NC and CC coherent pion measurements (i.e., the fact that we see evidence for NC coherent pi0 but not CC coherent pi+ production in low energy neutrino experiments). Is there a way to reconcile these results theoretically? Are there alternative measurements or approaches we should be pursuing in the near future to shed further light on the situation? There have also been host of new model predictions in the past year. What are the differences/commonalities between the various theoretical approaches? Is there a preferred approach in certain energy regions? Also, how well do we understand physics of diffractive neutrino scattering in the context of the coherent pion production process? The hope is to leave the workshop with a better global understanding of the coherent pion production mechanism at low neutrino energies.

Poster session and cocktail reception / **112**

Measurement of inclusive p0 production in the charged current interactions of neutrinos in a 1.3 GeV wide band beam in the K2K-Scibar detector

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In this poster we report on the measurement of the rate of the inclusive π production induced by charged-current neutrino interactions in the K2K SciBar detector, at a mean energy of 1.3 GeV in the K2K near detector. Out of a sample of 11,606 charged current neutrino interactions, we select 479 π0 events with two reconstructed photons.
We find that the cross section ratio of the inclusive π0 production to the charged-current quasi-elastic cross section averaged over the K2K neutrino beam is:
σCCp0 / σCCQE = 0.443 ± 0.033(stat.) ± 0.036(syst.) that shows an excess of (49 ± 16)% (statistical and systematic errors added in quadrature) with respect to the prediction of our reference Monte Carlo simulation. Taking the single pion contribution from the charged-current single pi+ production measurement, the results above corresponds to a measurement of the charged-current deep inelastic cross section
σCC−DIS / σCCQE = 0.381 ± 0.013(stat.) ± 0.046(syst.)

Shallow to deep inelastic scattering I / **113**

Global Fits for PDFs at Large-x

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Co-authors: Alberto Accardi [2]; Cynthia Keppel [3]; Eric Christy [2]; Jorge Morfin [4]; Peter Monaghan [2]; Wally Melnitchouk [2]

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Current global fits used to determine parton distribution functions (PDFs) are typically limited to the region of x below about 0.7. In order to extend the range of such fits one, encounters kinematic regions where target mass corrections and higher twist contributions become relevant. Furthermore, Fermi motion corrections for deuterium targets also become significant in this region. I will describe recent global fits which include new treatments of all three of these effects, thereby allowing the x range of the fits to be extended. I will discuss the stability of the resulting PDFs to various choices for the target mass corrections as well as the effects on the PDF errors resulting from the additional data sets used in the fits.

Motivation I / **114**

Neutrino Cross Sections in Astrophysics

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Neutrino cross sections are often a crucial input in understanding a broad range of phenomena ranging from stellar evolution to core-collapse supernovae and gamma-ray bursts. This talk will present an overview of the role of neutrino cross sections in astrophysics and cosmology.

Motivation II / **115**

Neutrino interactions importance to Nuclear Physics

Author: Jose Enrique Amaro[1]

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We review the general interplay between Nuclear Physics and neutrino-nucleus cross sections at intermediate and high energies. As motivation for the more specific talks that will be given on the corresponding workshop sessions, we first introduce the general formalism of neutrino scattering from nuclei and define the observables of interest for nuclear physics such as response functions, asymmetries and polarization observables. Very general and useful properties of cross sections and response functions and their connection to electron scattering and scaling will be briefly described. We then introduce the different nuclear models and theoretical ingredients of relevance for neutrino reactions at the energy regime of interest. Some of the nuclear and reaction mechanism ingredients that will be discussed using those models are electro-weak current matrix elements, long Range nuclear correlations (RPA), final state interactions (FSI), finite-size effects, Coulomb corrections, and relativistic effects. Theoretical results will be shown for different reaction channels, charge-changing and neutral current quasielastic scattering, Delta excitation and coherent pion production, for kinematics going from low to high energy and for different kind of observables and reactions, inclusive

cross sections, integrated cross sections, angular distributions, polarization observables, etc. Nuclear models for which we will show results are Local Fermi Gas (LFG), Relativistic Fermi Gas (RFG), Shell Model (SM), Relativistic Mean Field (RFG) and Super-Scaling Analysis (SuSA) model. Some particular topics that we will briefly discuss are theoretical uncertainties on the ratios of interest for experiments on atmospheric neutrinos, influence of strangeness content inside the nucleon on neutral current scattering, nuclear effects on lepton polarization, and predictions of flux-averaged coherent pion production cross sections at T2K and MiniBoone energies.

Electron scattering and its connections to neutrino-nucleus interactions I / 116

Electron scattering data and its use in constraining neutrino models

Author: Costas Andreopoulos[1]

[1] *STFC, Rutherford Appleton Laboratory*

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We review how electron scattering data are employed by neutrino Monte Carlo generator groups so as to constrain and validate neutrino interaction modeling aspects.

Shallow to deep inelastic scattering II / 117

Minos total cross-section

Author: Michael Kordosky[1]

[1] *William and Mary*

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I will describe measurements of the muon neutrino and anti-neutrino inclusive charged current cross-sections for neutrino energies spanning 3-50GeV. The data were collected with the MINOS near detector, a magnetized steel/scintillator tracking/sampling calorimeter exposed to the NuMI neutrino beam at Fermilab. I will describe selection of a sample of inclusive CC scattering events, estimation of the neutrino flux, treatment of systemtatic errors, and show our preliminary results.

Single pion production III / 118

Search for anti-neutrino charged current coherent pion production at SciBooNE

Author: Hidekazu TANAKA[1]

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The precise measurement of neutrino-nucleus cross-sections in the few GeV energy range is an essential ingredient in the interpretation of neutrino oscillation experiments.
SciBooNE is ~1 GeV muon neutrino scattering experiment based at Fermilab, USA, that ran from

June 2007 until August 2008 in both neutrino and anti-neutrino mode.
We will present a search for charged current coherent pion production in SciBooNE's collected anti-neutrino data.

Current and future neutrino experiments I / **119**

MINERvA

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MINERvA is a dedicated neutrino scattering experiment which will collect data in the NuMI beam at Fermilab. The experiment is designed to measure inclusive and exclusive cross-sections for a wide variety of neutrino reactions over a 1-20 GeV range of neutrino energies. The MINERvA detector is centered around a fully-active, low-density, tracking chamber consisting of plastic scintillator strips. The strips have a novel triangular cross-section to improve position resolution and are read out wavelength shifting fibers coupled to multi-anode photomultiplier tubes. The tracking chamber is surrounded by electromagnetic and hadronic calorimeters. Muons punching through the detector are analyzed in the MINOS near detector which sits just downstream of MINERvA.
The MINERvA collaboration has recently completed construction of a fully functional prototype, representing roughly 20% of the full detector, which is now being operated in the NuMI neutrino beam. The complete MINERvA detector will begin taking data in early 2010. I will describe the goals of the experiment, the construction and calibration of the detector, and early experience operating it in a neutrino beamline.

CC and NC quasi-elastic scattering III / **120**

Neutrino-Nucleus Neutral Current Elastic Interactions in MiniBooNE

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MiniBooNE is an experiment operated at Fermilab looking for neutrino oscillations at $\Delta m^2 \sim 1eV^2$. MiniBooNE uses a neutrino beam produced from 8 GeV protons from the Fermilab Booster incident on a Be target. The Cerenkov detector located 541m from the target is a 12m diameter sphere filled with mineral oil and instrumented with 1280 inner and 240 veto PMTs. Neutral current elastic scattering (NCEL) is one of the most important interactions in MiniBooNE. To date we have recorded about 93K NCEL interactions candidates in neutrino mode with about 62% NCEL purity, which represents the world's biggest sample of such interactions. The MiniBooNE NCEL cross-section has been measured and will be presented as well as the measurement of the the axial vector mass (M_A).

Shallow to deep inelastic scattering I / **121**

Recent and Upcoming Experimental studies at Large Bjorken-x

Author: Eric Christy[1]

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In this talk we briefly review both recent and upcoming experimental studies of nucleon structure functions at large Bjorken-x. In particular, preliminary results on the (nearly) free neutron F_2 structure function measured by the BoNuS experiment performed in Hall B at JLab will be discussed, as well as the approved extension of these measurements to even higher Bjorken-x and Q^2 utilizing the upgraded 11 GeV electron beam planned for the CEBAF accelerator. Estimations of the quality of structure function data, and both flavor and valence/sea separated parton distributions, which would be possible utilizing a hydrogen target in a high flux neutrino beam will also be discussed.

Single pion production I / **122**

SciBooNE's neutral current single pion production measurements

Author: Yoshinori Kurimoto[1]

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The next generation of accelerator neutrino oscillation experiments will require precise neutrino cross-section measurements. Especially the neutral current neutral pion production is the biggest background for the electron neutrino appearance search. SciBooNE is ~1GeV muon neutrino and anti-neutrino scattering experiment based at Fermilab, USA. SciBooNE can reconstruct neutral pions using two gamma rays converted in the SciBar detector, which is full active scintillating tracker, for the measurement of the neutral current neutral pion production. We reports measurement of the neutral current neutral pion production to charged current inclusive cross section ratio with preliminary study of systematic uncertainty.

Current and future neutrino experiments II / **123**

HARP and NA61 (SHINE) hadroproduction experiments

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The hadroproduction experiments HARP and NA61 (SHINE) as well as their implications for neutrino physics are discussed. Recent HARP measurements have already been used for precise predictions of neutrino beams in K2K and MiniBooNE/SciBooNE experiments and are also being used to improve the atmospheric neutrino flux predictions and to help in the optimization of neutrino factory and super-beam designs. First preliminary data from NA61 are of significant importance for a precise prediction of a new neutrino beam at J-PARC to be used for the first stage of the T2K experiment. Both HARP and NA61 provide a large amount of input for validation and tuning of hadroproduction models in Monte-Carlo generators.

Electron scattering and its connection to neutrino-nucleus interactions II / **124**

Nuclear effects in electron reactions and their impact in neutrino processes

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It is suggested that the impact of nuclear dynamics on electron scattering cross sections can be extracted from the data and used to predict neutrino cross sections using the susperscaling properties of (e,e') data. The merits and limits of this approach will be illustrated and discussed.

Shallow to deep inelastic scattering I / 125

Nuclear Effects in neutrino-nucleus DIS

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I will review nuclear effects on neutrino-nucleus deeply inelastic scattering (DIS) and discuss the nuclear parton distributions functions (NPDFs). Due to the weak interaction, heavy nuclear target is needed to get high accuracy of the measurements. The nuclear effects on the structure function must be taken into account. These effects are already known by charged lepton-nucleus DIS experiments. In the ratio of the structure functions obtained by nucleus and deuteron targets; $R^A(x) = F_2^A(x)/F_2^D(x)$, these effects show the following behavior: $R^A(x) < 1$ for $x < 0.07$ (shadowing effect) $R^A(x) > 1$ for $0.1 < x < 0.3$ (anti-shadowing effect) $R^A(x) < 1$ for $0.3 < x < 0.8$ (EMC effect) $R^A(x) > 1$ for $0.8 < x$ (Fermi motion effect) where x is the Bjorken-x. These are interpreted as the effects of parton-nucleon multiple scattering,
nucleon binding and internal motion in the nucleus. Models explained each effect are proposed, however these effect must be comprehensively treated in theoretical prediction for the measurements using nucleus targets. As a way of involving these effects in a similar manner, nuclear parton distribution functions (NPDFs) are investigated. These nuclear effects are contained in the parton distributions, and these distributions are determined by using experimental data with nucleus targets. By using the NPDFs, nuclear effect on the measurements can be discussed quantitatively. In practice, extraction of NPDFs is performed by several analysis groups. I will discuss the NPDFs of these analyses.

Current and future neutrino experiments I / 126

The ND280 near detector of the T2K experiment

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The T2K experiment is a long-baseline neutrino oscillations experiment, designed to improve the sensitivity to θ_{13} by at least one order of magnitude and to determine more accurately the "atmospheric" parameters θ_{23} and Δm^2_{23}. For this purpose a high intensity ν_μ beam (∼700~MeV peak energy) produced at the JPARC accelerator complex will be directed towards the Super-Kamiokande (SK) detector, at a distance of 295~km. A near detector complex (ND280) is also under construction at 280~m

from the production target. The ND280 apparatus is designed to measure the energy spectrum, flavor content and neutral and charged current interaction rates of the unoscillated neutrino beam; this information will be used to predict the unoscillated interaction rates at Super-Kamiokande.

In this talk the physics goals of T2K will be introduced and the role of the ND280 detector in the T2K analysis strategy will be discussed. The ND280 detector is presently under construction, and first neutrino interaction data are expected at the end of this year. The design, expected performance and test-beam studies of the ND280 sub-detectors will be described briefly, together with timescales for construction and initial operation.

Single pion production III / **127**

First CCpi+ Cross Section Results from MiniBooNE

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The MiniBooNE experiment has just completed a measurement of the CCpi+/CCQE cross section ratio as a function of neutrino energy. In addition, a new event fitter has been developed that allows for the reconstruction of not only the final state muon, but the charged pion as well. By using a new particle identification technique, we are able to distinguish muon and pion tracks with an 88% success rate. First results will be presented for an absolute CCpi+ cross section measurement as a function of neutrino energy, as well as several differential cross section measurements of the final state muon and pion kinematics. Double differential cross sections as a function of the direction and energy have been measured for both the muon and pion, and each of the final state muon and pion measurements has also been performed as a function of neutrino energy to decouple the cross section results from the MiniBooNE neutrino energy spectrum.

Single pion production I / **128**

CCπ^0 Event Reconstruction at MiniBooNE

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We describe the development of a fitter to reconstruct ν_μ induced Charged-Current single π^0 events in an oil Cherenkov detector (CH_2). These events are fit using a generic muon and two photon extended track hypothesis from a common event vertex. The development of ring finding and particle identification are described. Comparisons between data and Monte Carlo will be presented for a few kinematic distributions.

Single pion production II / **129**

Coherent Pion production (PCAC)

Author: Emmanuel Paschos[1]

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In the talk I will present results on coherent pion production by neutrinos scattered off nuclei. The method is based on PCAC and uses helicity cross sections for the scattering of weak gauge bosons on nuclei including the lepton mass in the formulas. The process relies on experimental data for elastic pion-nucleus scattering, thus it avoids discussing what is happening within the Nucleus. A detailed analysis of the differential and integrated cross sections is presented for neutral and charged currents, with special emphasis on the regions of integrations. The method is applicable to low and higher energies and has been extended to incident energies of 10.0 GeV. The predictions are consistent with present experimental results and provide a benchmark for measurements in the future.

Single pion production I / **130**

Discussion

Single pion production II / **131**

Discussion

Single pion production III / **132**

Discussion

Motivation I / **134**

Outlook on Neutrino Cross Sections in the next generation of Neutrino Oscillation Experiments

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Following the establishment of neutrino oscillations using both astrophysical and terrestrial neutrino sources, we look forward to an exciting era when precision and high-sensitivity probes will refine our understanding of neutrino oscillations and elucidate their relationship to some of the "Big Questions" that confront the field of particle physics as a whole. Among these include the origins of flavor mixing and masses, why they are so dramatically different in the lepton and quark sectors, and the persistent puzzle of the source of the matter/anti-matter asymmetry of the Universe.
As the projected precision of neutrino oscillation experiments increase, we will rely increasingly on our knowledge and understanding of neutrino-nucleus interactions. As a result, the ongoing collaboration between different
communities that is at the heart of the NuInt Workshops will only become more important.

Confronting theory, models & data / 135

Neutrino Event Generator Review

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Neutrino event generators are a crucial link between theory and experiment and play an important role in the design of new experiments and the analysis of experimental data. These programs have advanced significantly since the start of the NuINT series in 2001. In this talk, I will describe the evolution of this field over the last decade, focusing on the physics content of several widely-used generators. The use of these packages throughout the entire experimental "life-cycle" will be described, and particular attention will be drawn to areas where the content of these programs significantly lags current theoretical work.

Motivation II / 136

Non-Standard Interactions

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In this talk, I will review non-standard interactions in neutrino physics, especially I will emphazise the impact of non-standard interaction on neutrino oscillations. First, I will give a brief introduction about non-standard interactions and what they are. Then, I will present what has been performed in the literature, what I have done in the field, and what could be done in the future. Next, I will discuss how important non-standard interactions are for neutrino cross-sections. Finally, I will give a summary of the field.

Single pion production III / 137

Search for neutrino charged current coherent pion production at SciBooNE

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Single charged pion production via neutrino-nucleus charged current (CC) interaction is a dominant background process for muon neutrino disappearance measurements in a few-GeV energy range, and thus needs to be understood more precisely. The SciBooNE experiment has ability to separate CC coherent pion production from CC resonant pion production by using a fully-active fine-segmented scintillator tracking detector. We have performed a search for neutrino CC coherent pion production on carbon using SciBooNE's full neutrino data set. The results will be presented.

Poster session and cocktail reception / **138**

Measurement of the NuMI Neutrino Flux Using the Accompanying Muon Beam

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To further our understanding of neutrino interactions, it is desirable to measure absolute cross sections on nucleon and nuclear targets. Many past neutrino experiments have measured relative cross sections due to a lack of precise measurements of the incident neutrino flux, normalizing to better established reaction processes, such as quasielastic neutrino-nucleon scattering. Absolute neutrino cross sections, in contrast, are determined via \sigma_nu = N_nu/\phi_nu , where the numerator is the measured number of neutrino interactions in a neutrino detector and the denominator is the flux of incident neutrinos, measured independently. The NuMI beam line has 3 muon monitors which can be used to, indirectly, measure the neutrino flux. The muon flux is related to the neutrino flux because one muon is produced for every muon neutrino in \pi -> \mu \nu and K\pm -> \nu \mu decays. We measure the neutrino flux generated by the NuMI beam line by measuring the daughter muon flux produced in pion and kaon decays. This is an in-situ flux measurement and is completely independent of the observed neutrino interaction rate in a neutrino detector.

The muon monitoring system consists of 3 arrays of 81 helium filled ionization chambers located approximately 720m downstream of the target. Muons must have a minimum energy of 4, 10 and 20 GeV to penetrate muon monitor 1, 2 and, 3, respectively, providing sensitivity to the neutrino flux above E_\nu = 1.6 GeV. Furthermore,
the kinematic distributions of mesons producing neutrinos can be studied by moving the meson production target longitudinally and by varying the current through the focusing horns. These studies provide a mechanism to measure of the muon spectrum which is directly related to the parent pion and kaon flux off of the NuMI target and, in turn, the neutrino flux. The two current experiments utilizing the NuMI beam, MINOS and MINER\nuA, can use this independently determined flux to measure neutrino cross-sections via \sigma_\nu = N_\nu/\phi_\nu , where the numerator is the number of neutrino events seen in the MINOS Near Detector and MINER\nuA Detector. We will present preliminary measurements of the neutrino flux obtained from the muon monitoring system.

CC and NC quasi-elastic scattering III / **139**

Neutrino-Nucleon Neutral Current Elastic Scattering at SciBooNE

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The cross-section for neutrino-nucleon neutral current (NC) elastic scattering contains the axial vector form factor G_A(Q2) as well as electromagnetic form factors unlike electromagnetic interaction. G_A is proportional to strange part of nucleon spin (Δs) in Q2⟶0 limit. Measurement of NC elastic cross-section with smaller Q2 enables us to access Δs. Signal of NC elastic scattering is a single proton track. Analysis for the single proton track events using geometrical and dE/dx information of reconstructed track is performed. NC elastic scattering data sample including$\nu p \longrightarrow \nu p$ and$\nu n \longrightarrow \nu n$ is obtained. We will report the absolute cross-section as a function of nucleon kinetic energy.

Poster session and cocktail reception / 140

Measurement of the numu charged current pi+ production to quasi-elastic cross section ratio on mineral oil in a 0.8 GeV neutrino beam

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Using high statistics samples of charged current interactions, MiniBooNE reports a measurement of the single charged pion production to quasi-elastic cross section ratio on mineral oil (CH2), both with and without corrections for pion re-interactions in the target nucleus. The result is provided as a function of neutrino energy in the range 0.4 GeV < E < 2.4 GeV with 11% precision in the region of highest statistics. The results are consistent with previous measurements and the prediction from historical neutrino calculations.

Single pion production III / 141

Q2 discrepancies : data confronts theory

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The MiniBooNE experiment has collected what is currently the world's largest sample of muon neutrino charged current single charged pion (CC1pi+) interactions, roughly 46,000 events. The purity of the CC1pi+ sample is 87% making this the purest event sample observed in the MiniBooNE detector. The average energy of neutrinos producing CC1pi+ interactions in MiniBooNE is about 1 GeV, therefore the study of these events can provide insight into both resonant and coherent pion production processes. In this talk, we will discuss the long-standing discrepancy in four-momentum transfer observed between CC1pi+ data and existing predictions. Several attempts to address this problem will be presented. Specifically, the Rein-Sehgal model has been extended to include muon mass terms for both resonant and coherent production. Using calculations from recent papers, an updated form for the vector form factor has also been adopted. The results of this improved description of CC1pi+ production will be compared to the high statistics
MiniBooNE CC1pi+ data and to several existing parametrisations of the axial vector form factor. Preliminary results for the value of the axial mass in resonant single pion production will be presented.