The problem we want to solve:

\[ \frac{N_{\text{events}}^{\text{far}}(E_\nu)}{N_{\text{events}}(E_\nu)} = \frac{\int \sigma(E_\nu') \Phi(E_\nu') P(E_\nu | E_\nu') P_{\text{osc}}(E_\nu') dE_\nu'}{\int \sigma(E_\nu') \Phi(E_\nu') P(E_\nu | E_\nu') dE_\nu'} \]

F. Sanchez @ NuPhys2015

QE and 2p2h dominant at T2K kinematics

QE and 2p2h
response

Elastic

N* Nucleon

GR

T2K Flux

Neutrino Energy (GeV)

Maria Barbaro plenary talk

SIS DIS Plenary talk by Jorge Morfin

Tension between event topology and genuine interaction mode
Impact of cross-section modeling on the NOvA oscillation analysis (Gregory Pawlowski in WG1+2)

Oscillation analysis affected by:
- event yields and
- energy reconstruction

**Event Yields**

- Different processes have different selection efficiencies
  - How much 4-momentum goes to the lepton, how much goes to the hadronic system

- Ideally apply same selection in ND and FD, so they have same efficiencies, but the mix of processes is not exactly identical in both detectors

- Flux is different (eg oscillation)
  - Containment is different
Impact of cross-section modeling on the NOvA oscillation analysis

Oscillation analysis affected by:
- event yields and
- energy reconstruction

**Neutrino Energy**

Different processes have different energy resolutions and energy scales:
- How much 4-momentum goes to the lepton, how much goes to the hadronic system
- How much 4-momentum is invisible

Gregory Pawlowski in WG1+2
How do various modeling uncertainties impact oscillation analysis?

**Impact Cross-sections – Joint $\nu_\mu + \nu_e$ Analysis**

Without $p_T$ extrap.  
With $p_T$ extrap.

Biggest cross-section analysis uncertainties affect relative normalization of QE and RES

Biggest cross-section uncertainties for $\delta_{CP}$ related to $\nu_e - \nu_\mu$ differences

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Gregory Pawlowski in WG1+2
We have heard about analysis and generator efforts going hand in hand!

We have heard about theory developments finding their way to generators!

4 talks!

7 talks!

10 talks!

Input from electron scattering constraining theory and generator
➢ See Larry Weinstein’s plenary talk on Monday
➢ Generators implementing e-scattering
➢ Use of electron information in various theory and experimental modeling efforts

4 talks!

Theories

Experiments

Generators
**NuWro updates** (Kajetan Niewczas)

New implementations

- phenomenological 2p2h model with simultaneous fit to T2K and MINERvA CC0π data
- Hyperon production and propagation
- Neutrino-electron scattering
- Electron scattering
- Work towards the implementation of microscopic and exclusive vertex description
New release in preparation including:

- improvements in kinematics determination of the separation energy and 2p2h model,
- alternative axial form factors,
- refinements in the implementation of NC multipion production channels

Introducing new predictions of the Bodek Yang model for SIS and DIS channels

Ongoing project for future releases:

- Implementation of SuSav2 and RMF models, DCC and MK model for single pion production
- Work towards more universal interface and data format to facilitate comparisons between different generators
GENIE v3 : AGKY Hadronization tuning (Julia Tena-Vidal)

- Hadronization mismodeling affects SIS and DIS and there is no information on the uncertainty due to hadronization modelling: e reconstruction, topology, and BG estimation.
- Model consists of an empirical description at low W and PYTHIA 6 for W>3 GeV/c² and has to be validated with data.
- The goal is to improve the charge multiplicity description for neutrino experiments and understand possible tensions between datasets.
- Global fit H+D and only D fit 154 data points.

nu_μ + p on hydrogen.           nu_μ + p on deuterium.           nu_μ + n on deuterium.

- Global fit increases charge multiplicity for W>3 GeV/c² and reveals tension between H and deuterium data sets.
Sebastian Pina-Otey: Neural Net Techniques in Monte Carlo generators
Improve on methods of designing proposal function to make the rejection sampling more efficient
Use Normalizing flows techniques:
- Adapts to a given target density automatically,
- Good acceptance efficiency,
- Grows properly with the number of dimensions,
- Produces exact samples through rejection sampling

Very promising for the efficiency of generators!
MicroBooNE modeling and tuning (Steven Gardiner)

First dedicated GENIE tune for MicroBooNE

- **Adopted list**: two QE and two 2p2h parameters
  - CCQE axial mass and RPA strength
  - CC 2p2h normalization and shape

- **T2K 2016 CC0π data chosen**
  - Independent measurement in a similar beam line
  - Double-differential in muon kinematics

- **Analysis I**: results reported over full angular range
MicroBooNE updates and new results

- MicroBooNE collected the largest sample of neutrino-argon data to date, and
- has updated a series of cross section measurements and analyses
- leading the way for future LArTPC results
- notable improvements concerning the interaction model employed, the reconstruction paradigms, the detector simulation and modeling of the cosmos.

→ WG2 talks by Elena Gramellini on $\nu_e$ and $\nu_\mu$ and CC inclusive and $\Lambda$ production and Samantha Sword-Fehlberg on proton knockout
→ Posters by Afroditi Papadopoulou on differential CCQE, Lu Ren on Neutral Current elastic processes, Chris Thorpe on Lambda production and Wenqiang Gu on CC inclusive
MicroBooNE updates and new results

**νμ CC Inclusive @ BNB: a Sneak Peek at Next Gen Analyses**

**Updates included:**
Better detector understanding:
signal processing from all planes & improved calorimetry

Reduced systematic uncertainties via a data driven method for detector systematics and cosmics modelling
MICROBOONE-NOTE-1075-PUB

Improved neutrino interaction model

**Results:**
- Purity: from 50% to 71.9%
- 3x Reduction of cosmic contamination
- Detector uncertainties from 16.2% to 3.3%

Elena Gramellini
Energy dependent $\nu_\mu$ CC Inclusive @ BNB

New energy-dependent measurement of inclusive $\nu_\mu$ CC interactions:
total and differential in muon energy and energy transfer
Biggest sample of selected $\nu_\mu$ CC interactions on Argon to date: 11528 events.
Improved Purity $\sim$92% & Efficiency $\sim$68% thanks to new tomographic event reconstruction paradigm.

JINST 16, P06043 (2021)

The analysis uses the subset of the data where the muon is fully contained to characterize the muon kinematics and constrain the prediction for missing hadronic energy.

More at CC Inclusive

Elena Gramellini
All signatures show nice agreement with GENIE except for final state leptons in forward region. This is expected to improve with new modelling in GENIE along with MicroBooNE’s dedicated tune done with data from T2K.
MicroBooNE updates and new results

**MicroBooNE**

**CCNP**

- **$d\sigma/dp^*_p (10^{-37} \text{ cm}^2\text{ GeV}/\text{nucleus})**
  - Data
  - GENIE v2, $\chi^2$/dof=5.1/10
  - GENIE v3, $\chi^2$/dof=7.1/10

**CC2P**

- **$\cos(\gamma_{\text{lab}})$**

**Opening angle between protons in lab frame**

**Samantha Sword-Fehlberg on proton knockout**
MicroBooNE updates and new results

- All signatures show nice agreement with GENIE except for final state leptons in forward region. This is expected to improve with new modelling in GENIE along with MicroBooNE’s dedicated tune done with data from T2K.

CCQE-like

Samantha Sword-Fehlberg on proton knockout
T2K updates and new results

See Kenji Yasutome’s talk in WG2+6: updates on T2K WAGASCI near detector and efforts reduce the uncertainty in neutrino interaction modeling:

- First data run finished and analysis ongoing
- Planning combined analysis with ND280 data that has a slightly different flux
- Get sharp neutrino energy spectrum by subtraction
- Investigate the energy dependency of neutrino interaction by using these fluxes in calculation of flux integrated cross section extraction

See also Viet Nguyen’s poster on studies for the T2K ND upgrade and Danaisis Vargas’s study of CCπ⁺ interactions!
Clarence Wret on Neutrino interaction modeling and recent improvements in model and analysis: T2K uncertainty model for neutrino interaction modeling

- 2-ring events for muon selection
- Photon-tagging in ND280 to better separate multi-π and DIS events
- Separating CC0π into CC0πp and CC0πNp

- Combined analyses with SK and NOvA: bring modeling challenges due to the higher neutrino energies that are coming in
Jordan McElwee on removal energy uncertainties improved by using electron scattering data archives

- CCQE modeling - Benhar spectral function
- Development of e-scattering module in NEUT and comparison to data to correct for nucleon removal energies

Naive e-NEUT does not reproduce data well!

- Spectral function and lepton-nucleon interaction factorize
- Effect of influence of nuclear potential on struck nucleon on cross section can be parametrized by shift in binding energy
- Constraint by e-scattering data to fit QE peak position with energy and QE peak width with momentum
T2K updates and new results

Jordan McElwee on Removal energy uncertainties improved by using electron scattering data archives
Jafaar Chakrani on Parametrising CCQE uncertainties in Spectral Function model theory driven freedom to improve agreement between data and semi-inclusive data

- Current models struggle to describe (semi-)inclusive measurements
- Introduce new theory-driven freedoms to improve agreement
- Include systematic uncertainties in modeling (Pauli blocking threshold, SF shape variations, scale amount of events undergoing FSI, strength of optical potential ....) and refit

**T2K CC0pi O & C measurement**

Parameters used in this fit:

- $M_{A}^{QE}$
- Shell occupancies
- $p_{m}$ shape
- SRC norm
- Pauli blocking
- Optical potential correction
- Pion absorption normalization
- 2p2h normalization

Improvement of T2K modeling after new fit, but not for MINERvA
No model describe data well!

Caspar Schloesser on simultaneous fit to neutrino/antineutrino events
Event Selection - Improvements

New selection

Previous selection

• Very similar purity for previous and improved selection
• But efficiency is greatly improved for high angle and backwards going tracks

Caspar Schloesser
T2K updates and new results

Sam Jenkins on improved Pion kinematics reconstruction using Michel electron information

Working well for momentum, pion angle ... Work in progress
NOvA updates and new results

**Leo Soplin** Muon-neutrino charged-current interactions at the NOvA near detector

- (anti)neutrino $\nu_\mu$ - CC with low hadronic activity is actively being analyzed,
- Exclusive channels in progress
NOvA updates and new results

Brian Ramson on interactions with an electromagnetic shower in the final state at the NOvA ND

- Particle ID with ML techniques

Excellent agreement with GENIE!
ARTIE first results (Emilija Pantic in WG2+6):

- measuring neutrino transmission coefficient through liquid argon in the 30-70 keV energy range
- TOF spectroscopy neutron beam at LANL
- Resolving a discrepancy between theory predictions and existing data

**Auxiliary experiments**

- ARTIE Neutron cross section measurements (Emilija Pantic in WG2+6)

Regions of small n-Ar cross section are important for reliable predictions of transportation and shielding of neutrons in a large-scale LAr-based $\nu$ experiments such as DUNE.

- Neutrons from $\nu$ interactions might exit the detector volume and affect the energy resolution. At which rate?
- Background neutrons from detector components and the surrounding rock might enter from the outside. To which penetration depth?
- Will externally-produced neutrons for the calibration of detector probe deep enough?

ARTIE data confirms the existence of the anti-resonance at 57 keV, but not as strong as predicted.

Neutron-argon total cross section in the ROI
Neutron cross section measurements (Guang Yang in WG2+6 on behalf of the joint T2K_DUNE 3D Projection Scintillator R&D group)

- One of the major systematic uncertainties in the neutrino interaction modeling in the long-baseline neutrino experiments is due to blindness to neutrons in the final state, especially in the RHC mode, while neutrons carrying out a large fraction of energy in antineutrino interaction
- LANL LANCSE neutrons 0-800 MeV
- Proof of principle of the capability to use TOF technique to detect neutrons and their kinematics on an event-by-event basis

193 MeV neutron candidate with 123 MeV deposit energy

10 m data, in total we have > 10 hours
CEvNS: rich physics program

See Luis Flores’ talk on prospects for a coherent physics program with LAr scintillating bubble chamber detector at nuclear reactors
- Low thresholds
- Energy resolution
- Allows for stricter limits on new physics signals

See Newton Nath’s talk on constraints
For BSM parameters and generalized neutrino interactions
Huma Haider Weak structure functions in $\nu l-N$ and $\nu l-A$ scattering with nonperturbative and higher order perturbative QCD effects

**Nuclear Model Structure Functions and Data**

- Predictions off Ar,
- medium effects different for electromagnetic and weak interactions!
Noemi Rocco on Lepton-nucleus interactions within the spectral function approach

- Gauge validity of factorization comparing different approaches

- $e-^3H$: inclusive cross section

$E_e = 0.3677$ GeV, $\theta = 54.0$

- Comparisons among QMC, SF, and STA approaches: first step to precisely **quantify the uncertainties** inherent to the factorization of the final state.

- Gauge the role of **relativistic effects** in the energy region relevant for neutrino experiments.
Noemi Rocco Lepton-nucleus interactions within the spectral function approach

- Gauge validity of factorization comparing different approaches
- Extended factorization scheme, including 2-body currents in the hadronic final state

![Graph]

- Good agreement with electron scattering data when all reaction mechanisms are included

![Graph]

$F_2$ predictions for the DIS region. Convolution of the spectral function+nucleon pdf MMHT2014 at LO
Noemi Rocco

Lepton-nucleus interactions within the spectral function approach

- Gauge validity of factorization comparing different approaches
- Extended factorization scheme, including 2-body currents in the hadronic final state
- Semi-classical intra-nuclear cascade with nuclear effects included
Oleksandr Tomalak: QED radiative corrections for CC neutrino-nucleon elastic scattering

- soft and collinear contributions are evaluated in QED
- new model for hard contributions presented
- Higher order corrections are logarithmically enhanced
- Radiative corrections crucial for %-level oscillation program

See also Ryan Plestid’s poster on Coulomb corrections!
Ari Bodek : update Bodek-Yang model
• accounting for differences between axial and vector structure function for electron- and neutrino-nucleon data

Bonus of the model :
• Model also works on-average down to $W>1.4$ GeV, thus providing some overlap with resonance models (and should be used for $W>1.8$).
And more ...

- Shunzo Kumano’s talk on prospects for studying hadron tomography studies at high-energy neutrino facilities, GPD studies complementary to charged-lepton efforts as neutrino cross sections are sensitive to quark flavor
- Dimitrios Papoulias on prospects for detecting axion-like particles with reactor experiments
- Diego RG on the impact of the QCD dynamics on the determination of the high energy astrophysical neutrino flux
- Osamu Sato on Tau neutrino production with nuclear emulsion at CERN-SPS
  - Large uncertainty on tau neutrino flux, wants to
  - Aims at reducing uncertainties on $\nu_\tau$-nucleon cross sections
- Libo Jiang’s talk on Cross Section Measurement of Pion Absorption in ProtoDUNE Single Phase Detector at CERN to study
  - Validate the design of the DUNE far detector and
  - Accumulate test-beam data to understand calibration of the DUNE far detector response
- Many more posters ...
Neutrino interaction uncertainties constitute one of the largest sources of uncertainty in the accelerator-based neutrino program.

In recent years, there has been a lot of theoretical developments in describing inclusive neutrino-nucleus scattering. Progress towards semi-inclusive predictions are needed, they require more detailed modeling and resources.

Neutrino interaction physics in generator has been significantly improved by implementing new models. Comparisons of measurements to event generators show that a lot more work is still needed.

Many neutrino experiments have made a wide range of innovative cross-section measurements. Near-future datasets of neutrino and electron scattering will be critical to build/constrain models before the next generation experiments.

Dedicated cross-community efforts and sustained institutional support is needed for many years in order to achieve global constraints on neutrino-nucleus interaction physics that can enable desired precision in neutrino experiments.
Summary of the summary .... Challenges towards NuFACT 2022!

**Neutrino-Nucleus Interactions: Measurements**

- Near-future data sets will be critical to build/constrain models before DUNE and T2HK.

  - **SBN Program at FNAL (LArTPCs):**
    - MicroBooNE: Already producing interesting measurements
    - ICARUS: Started taking data
    - SBND: SBND will compile data with an unprecedented high event rate

- Lots of exciting measurements to come from T2K, NOvA and MINERvA.

  - **Electron-scattering data:**
    (L. Weinstein’s talk on Monday)
    - E12-14-012 at JLab Hall A
    - e4nu collaboration/CLAS
    - LDMX at SLAC

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Vishvas Pandey
Neutrino-Nucleus Interactions: Generators

- **Challenges and opportunities:**
  
  - Models provide inclusive predictions, generators have to produce energy and momentum of all the final state particles using additional schemes, that leads to inconsistencies.
  
  - Analyzers have to develop experiment-specific interaction model or "tuning", using available cross-sections data and often using internal ND data.
  
  - See Wednesday's WG1+WG2 session.

Vishvas Pandey
Challenges and opportunities:

- Most models up to now have been focused on inclusive reactions, semi-inclusive/exclusive predictions are needed. See Maria Barbaro’s talk from Monday.

- More exclusive processes require more detailed modeling. More response functions enter in the calculations.

- Further development from LQCD community will also improve the situation: nucleon level robust input from LQCD to nuclear model/EFT