WG2 Neutrino Scattering

Summary

Adi Ashkenazi — TEL AVIV UNIVERSITY

Tatsuya Kikawa — KYOTO UNIVERSITY

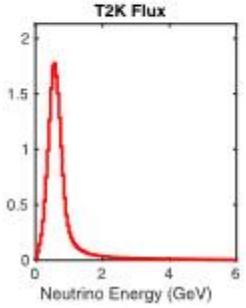
Natalie Jachowicz — GHENT UNIVERSITY

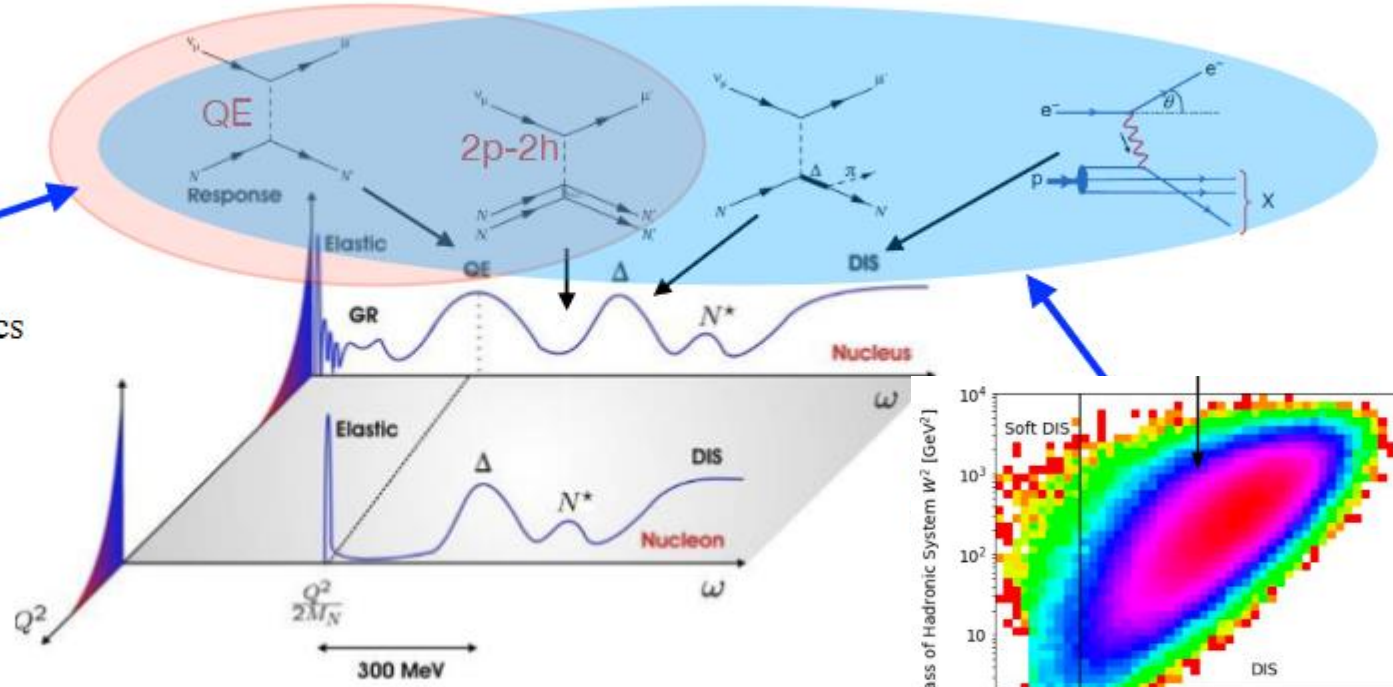
The problem we want to solve :

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

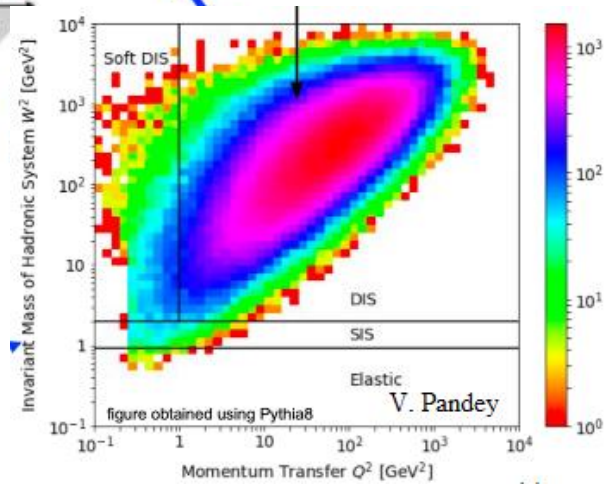
F. Sanchez @ NuPhys2015

QE and 2p2h
dominant at T2K kinematics





Maria Barbaro plenary talk



Tension between event topology and genuine interaction mode

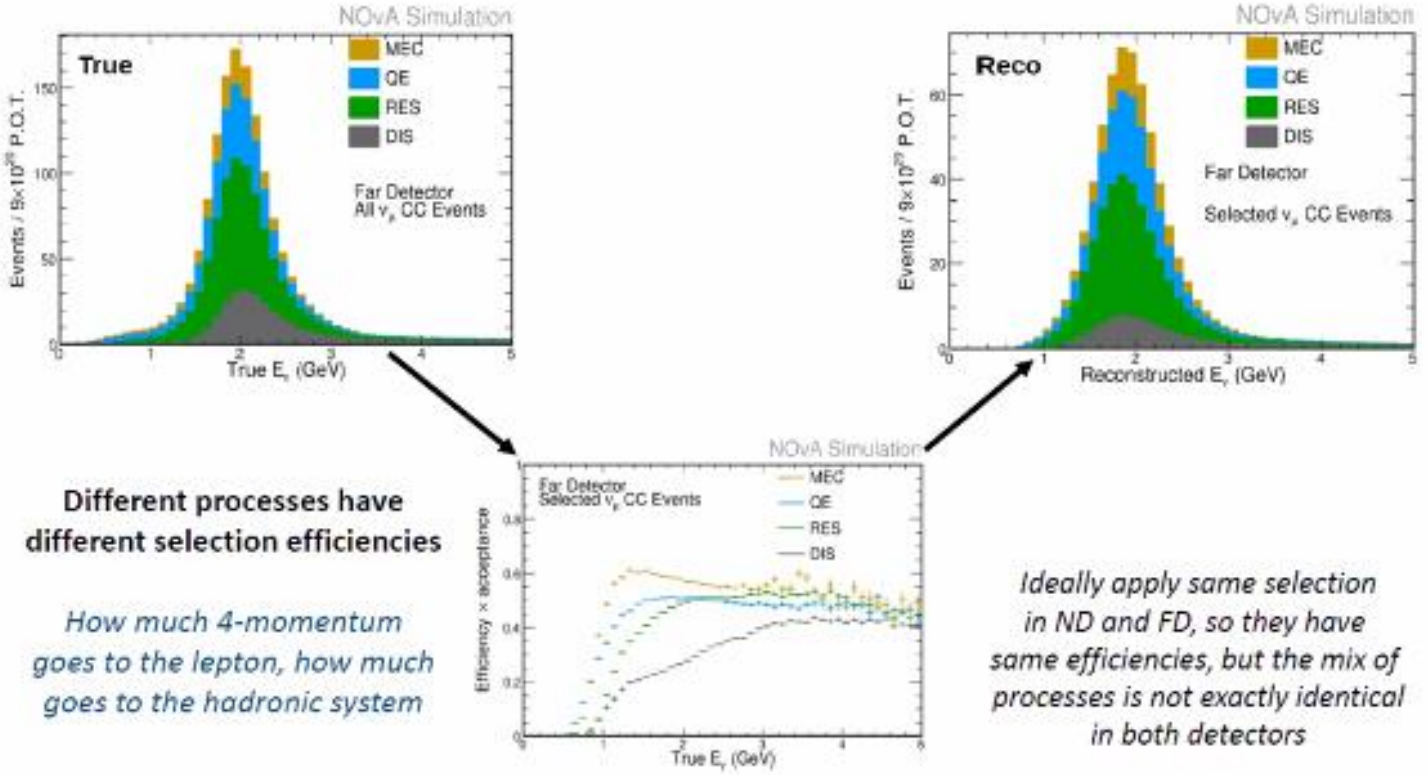
SIS DIS Plenary talk by Jorge Morfin

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

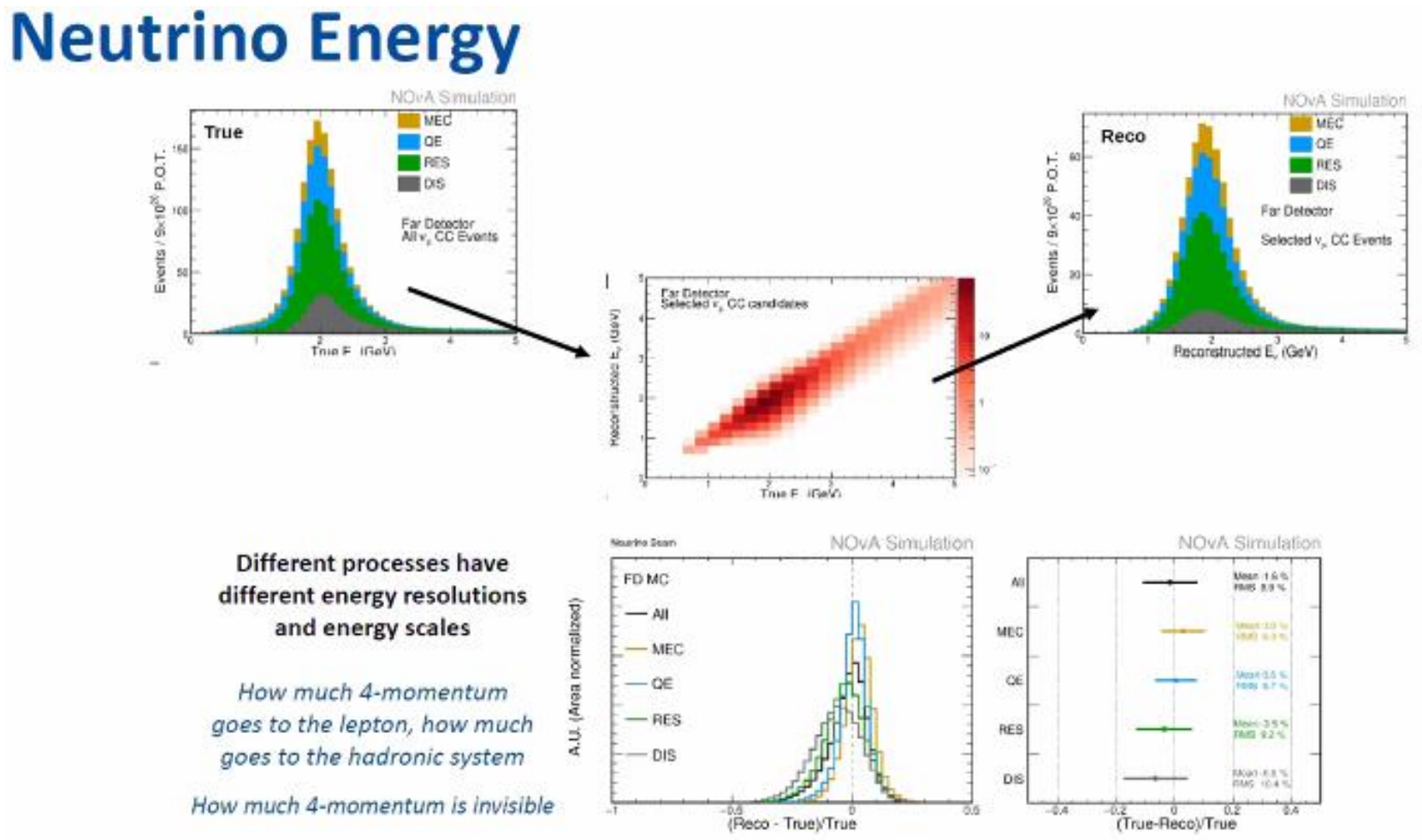
Ideally apply same selection in ND and FD, so they have same efficiencies, but the mix of processes is not exactly identical in both detectors

Flux is different (eg oscillation)
Containment is different

Impact of cross-section modeling on the NOvA oscillation analysis

Oscillation analysis affected by :

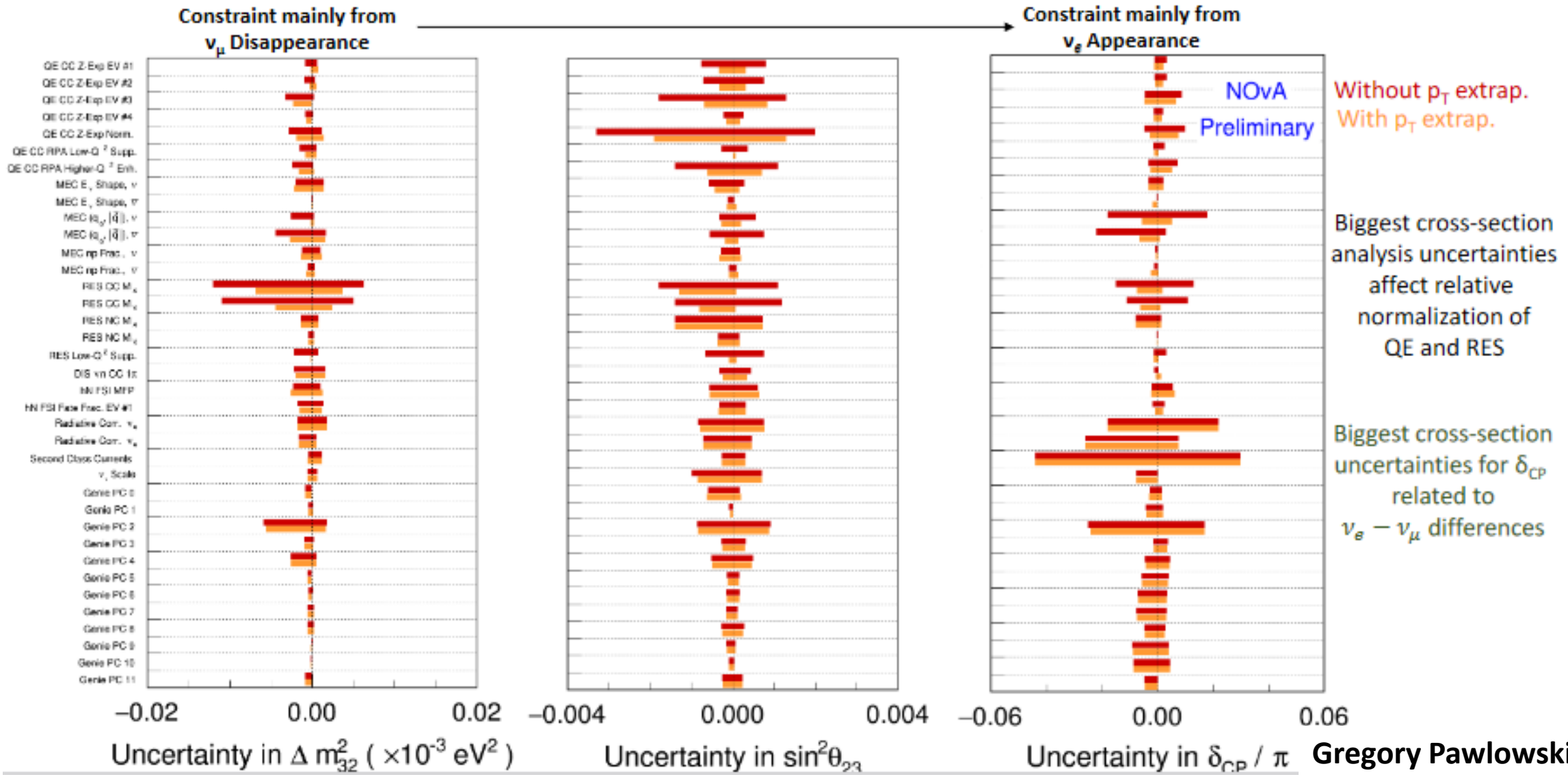
- event yields and
- energy reconstruction



Gregory Pawlowski in WG1+2

How do various modeling uncertainties impact oscillation analysis ?

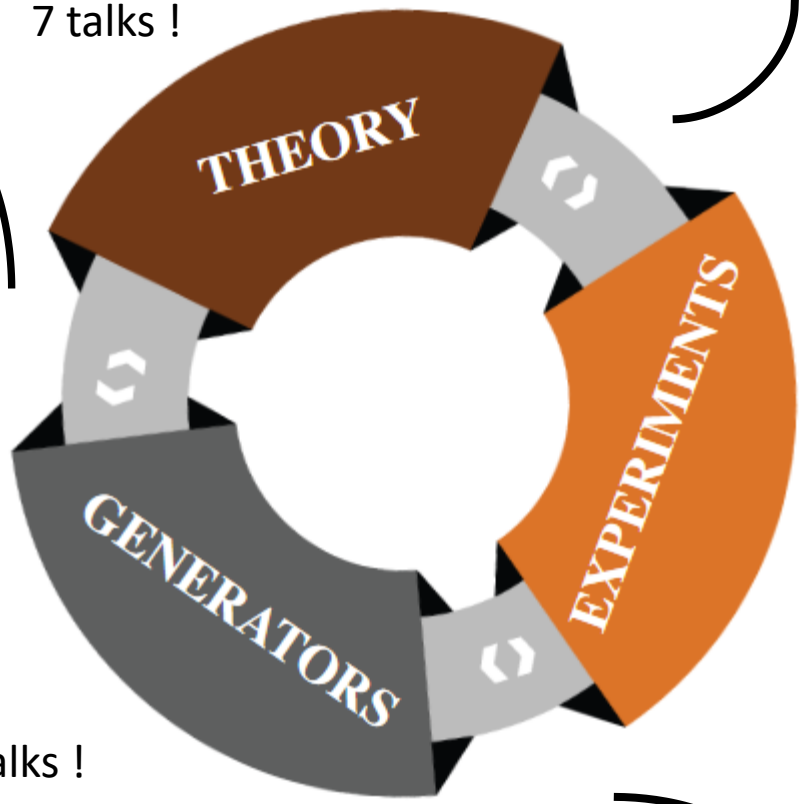
Impact Cross-sections – Joint $\nu_\mu + \nu_e$ Analysis



Gregory Pawlowski in WG1+2

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

7 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

10 talks !

4 talks !

We have heard about analysis and generator efforts going hand in hand !

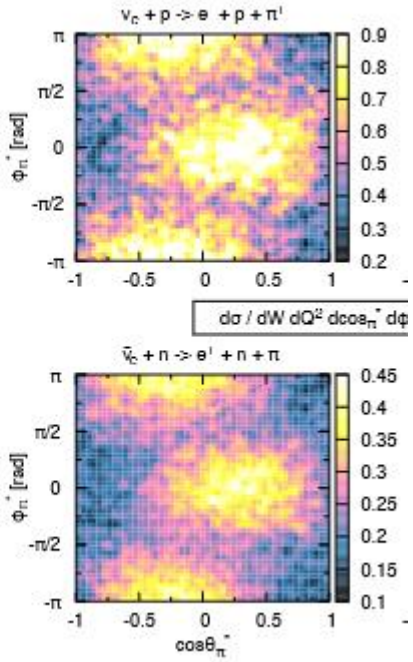
NuWro updates (Kajetan Niewczas)

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

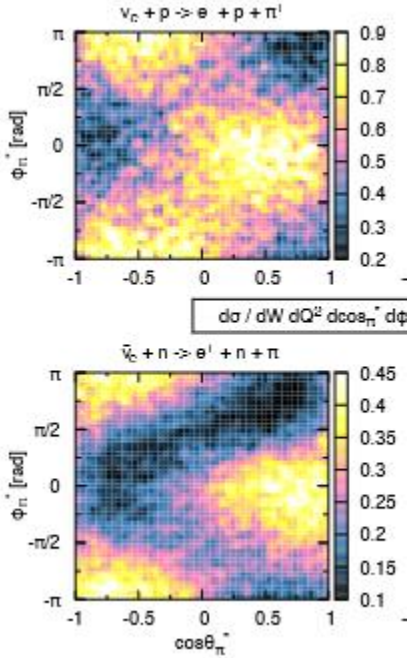
- Default NuWro
- Free nucleon
- Fixed kinematics:

$E = 1$ GeV
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



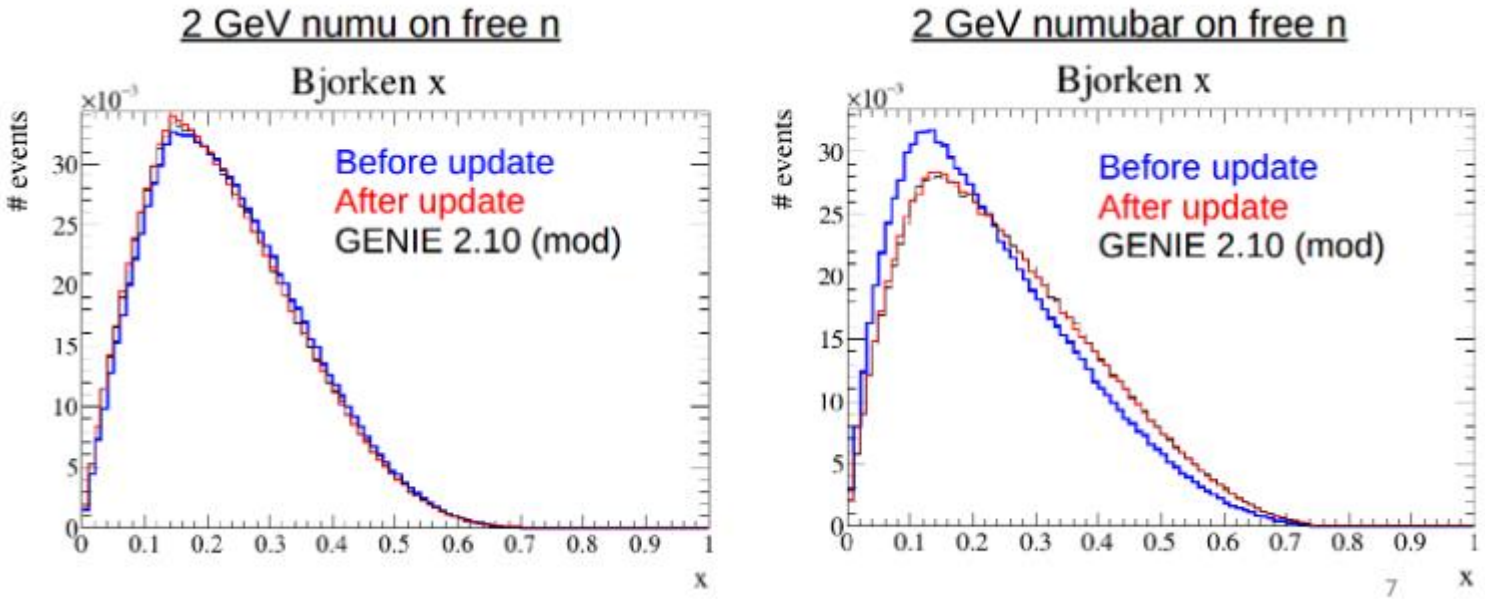
- Ghent LEM
- Free nucleon
- Fixed kinematics:

$E = 1$ GeV
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



NEUT updates and Strategy (Yoshinari Hayato)

- 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

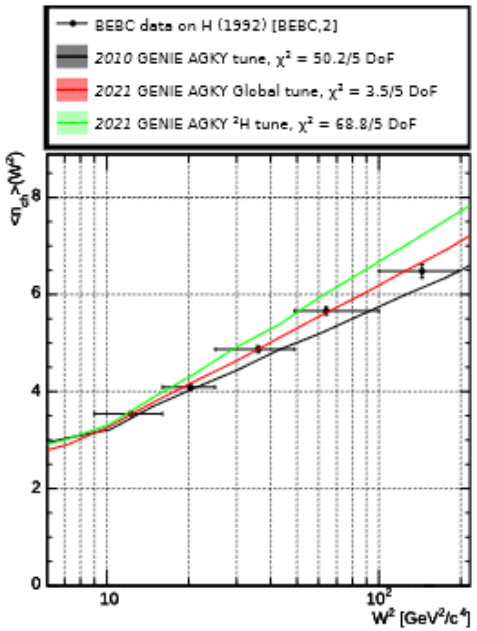


  - introducing new predictions of the Bodek Yang model for SIS and DIS channels

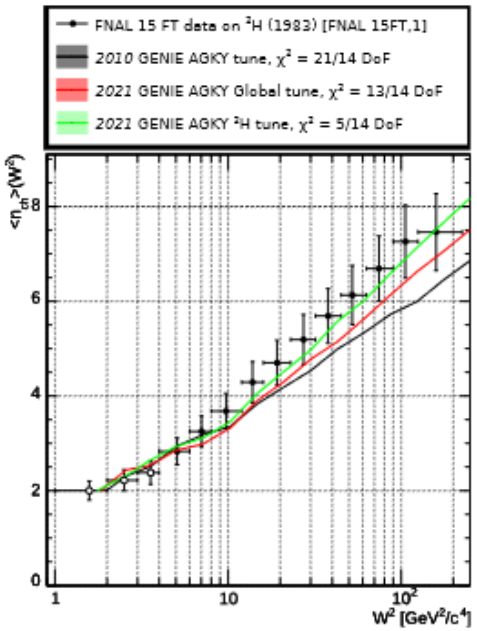
- Ongoing project for future releases :
- Implementation of SuSav2 and RMF models, DCC and MK model for single pion production
- Work towards more universal interface and data format to facilitate comparisons between different generators

GENIE v3 : AGKY Hadronization tuning (Julia Tena-Vidal)

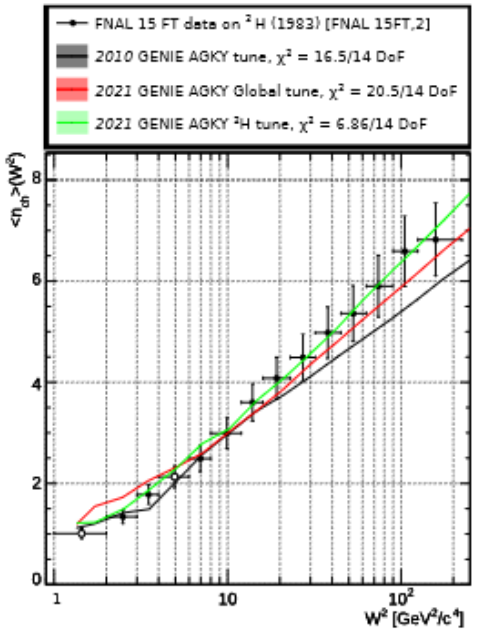
- Hadronization mismodeling affects SIS and DIS and there is no information on the uncertainty due to hadronization modelling : e reconstruction, topology and BG estimation
- Model consists of an empirical description at low W and PHYTHIA 6 for W>3 GeV/c2 and has to be validated with data
- The goal 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



$\nu_\mu + p$ on hydrogen.



$\nu_\mu + p$ on deuterium.



$\nu_\mu + n$ on deuterium.

- Global fit increases charge multiplicity for W>3 GeV/c^2 and reveals tension between H and deuterium data sets

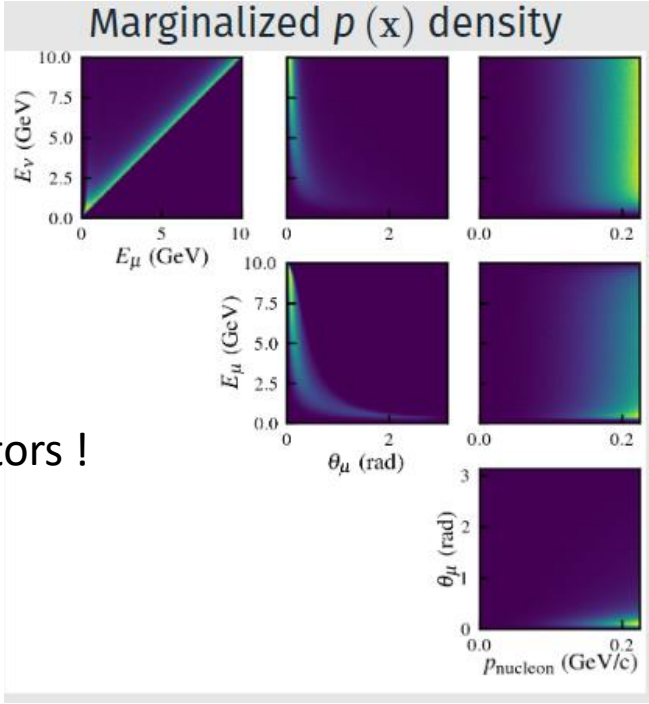
Sebastian Pina-Otey : Neural Net Techniques in Monte Carlo generators

Improve on methods of designing proposal function to make the rejection sampling more efficient

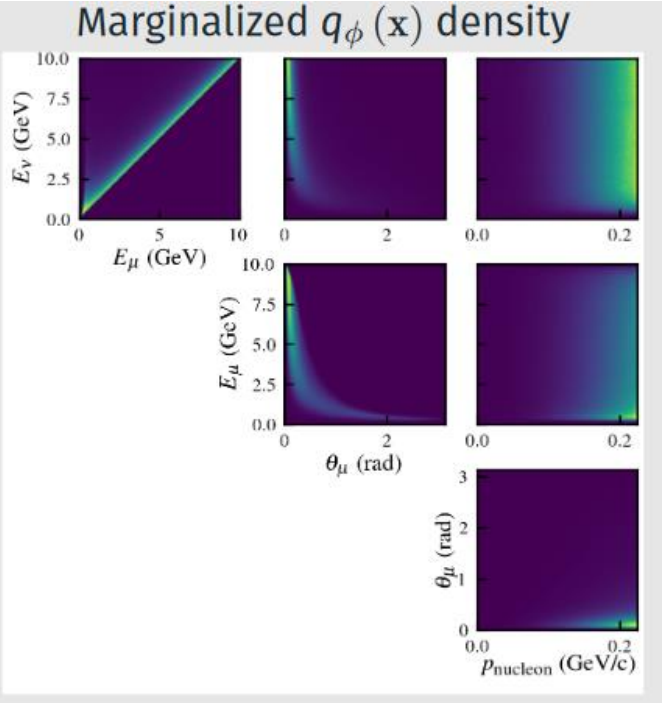
Use Normalizing flows techniques :

- Adapts to a given target density automatically,
- Good acceptance efficiency,
- Grows properly with the number of dimensions,
- Produces exact samples through rejection sampling

Original target



Normalize flow proposal

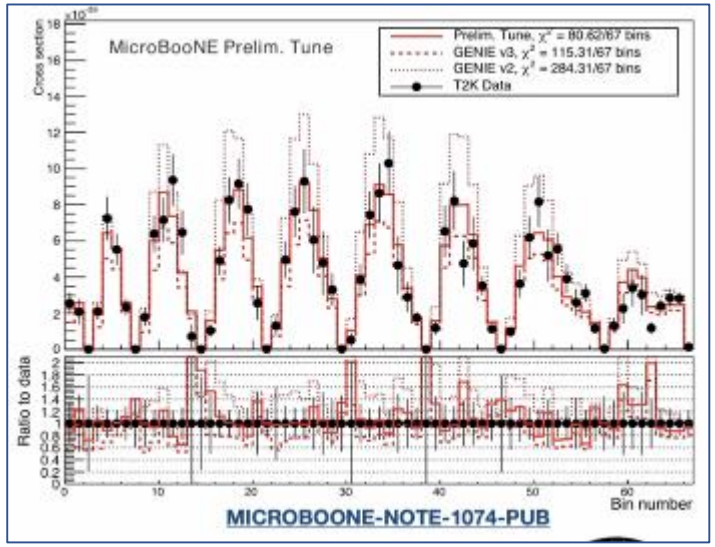


Very promising for the efficiency of generators !

MicroBooNE modeling and tuning (Steven Gardiner)

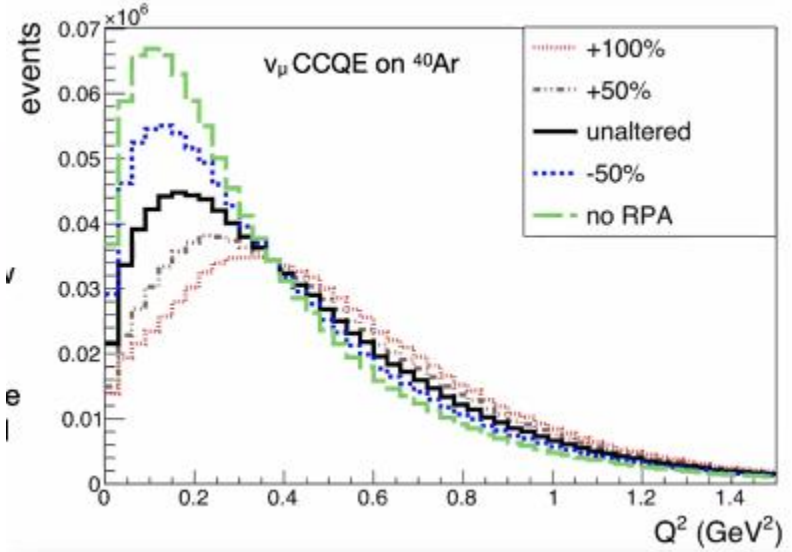
First dedicated GENIE tune for MicroBooNE

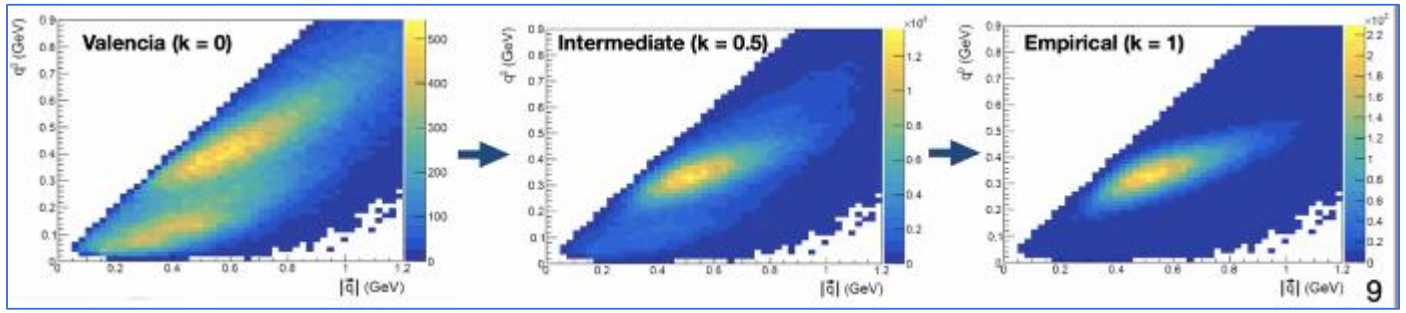
- MicroBooNE has adopted the GENIE v3.0.6 G18_10a_02_11a model as a starting point for a dedicated tune
- **10a**: model set with key theory improvements for low energies
  - Local Fermi gas nuclear model
  - Valencia QE + 2p2h
  - Berger-Sehgal RES, Bodek-Yang DIS
  - Updated FSI treatment (hA2018)
- **02_11a**: Parameter tuning performed by GENIE on bubble-chamber data, focus on RES + DIS



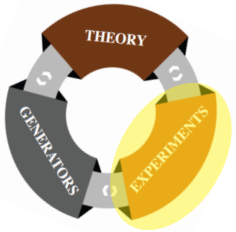
- **T2K 2016 CC0π data chosen**
  - Independent measurement in a similar beam line
  - Double-differential in muon kinematics
- **Analysis I:** results reported over full angular range

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





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 cosmics.

→WG2 talks by Elena Gramellini on ν_e and ν_μ and CC inclusive and Λ 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

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

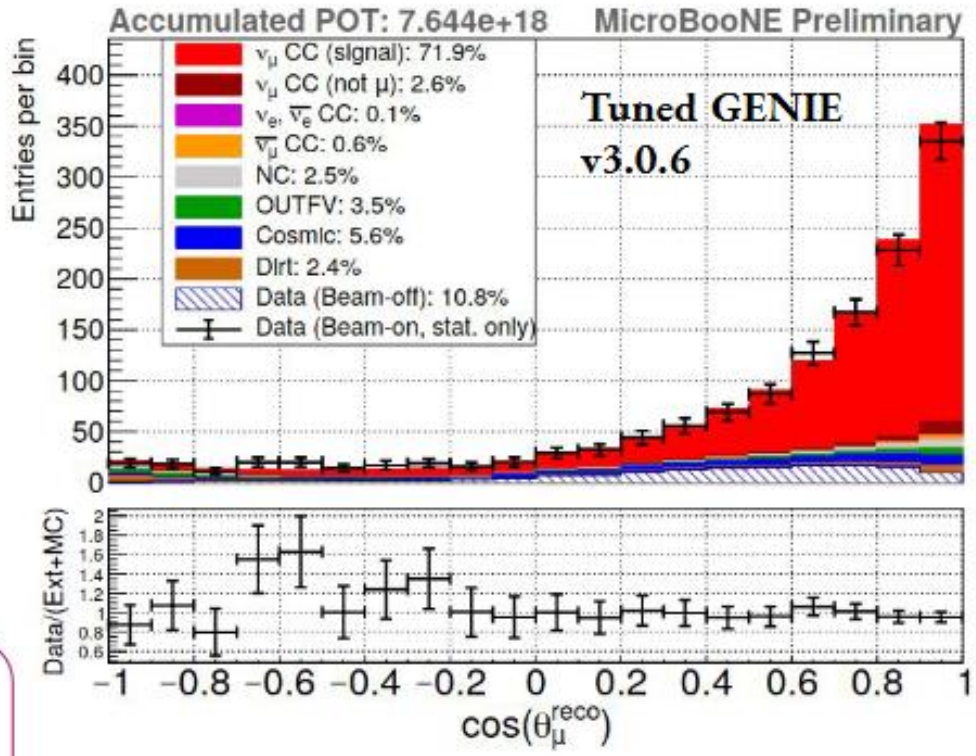
Updates included:

Better detector understanding:
signal processing from all planes & improved calorimetry
JINST 13, P07006 (2018), JINST 13, P07007 (2018)

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 %



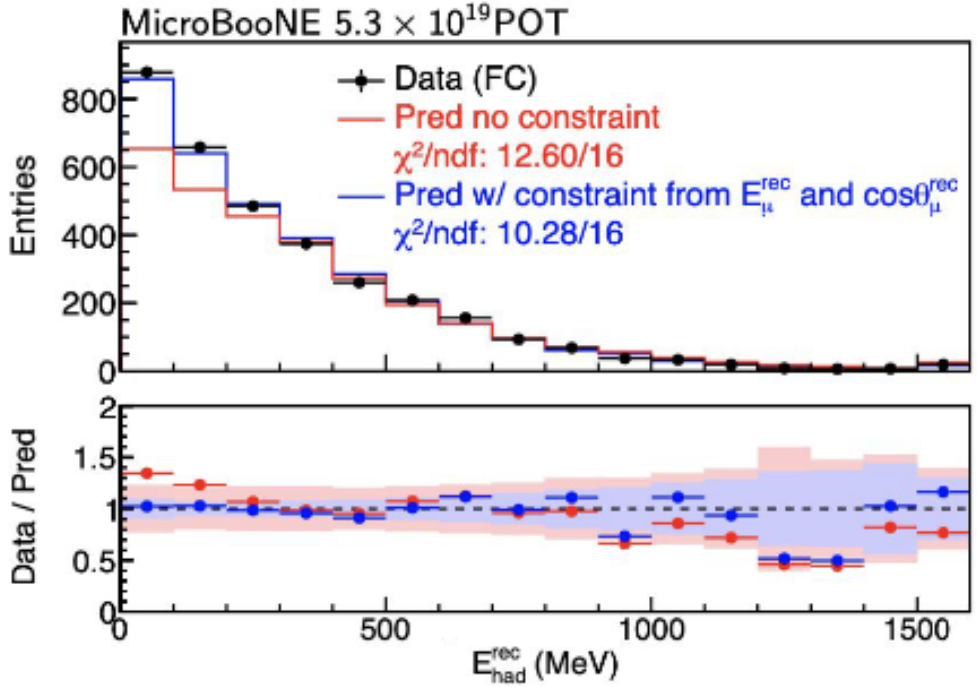
Update measurement
MICROBOONE-NOTE-1069-PUB

Elena Gramellini

Energy dependent ν_μ CC Inclusive @ BNB

NuFact Premiere!

New energy-dependent measurement of inclusive ν_μ CC interactions:
total and differential in muon energy and energy transfer
Biggest sample of selected ν_μ CC interactions on Argon to date: 11528 events.
Improved Purity ~92% & Efficiency ~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

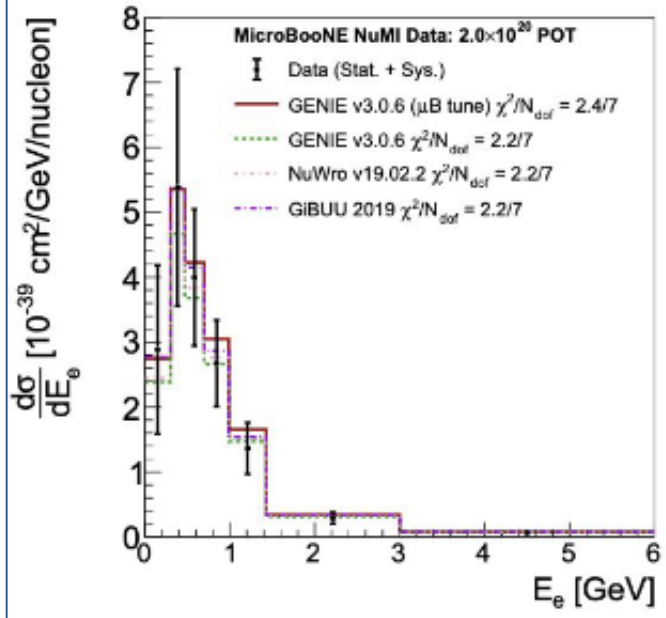
Elena Gramellini

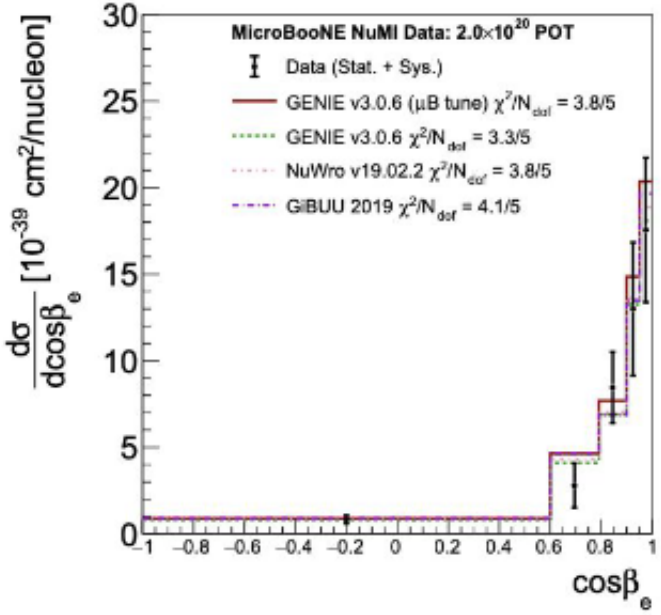
Differential $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

NuFact Premiere!

First Measurement of Inclusive ν_e and $\bar{\nu}_e$ CC differential in Lepton Energy on Argon.

Selection main requirement: at least one shower compatible with electron hypothesis.
Biggest sample of selected ν_e CC interaction on Argon to date: 243 events.
Purity ~70%, Efficiency ~20%. Extracted cross section in good agreement with models.



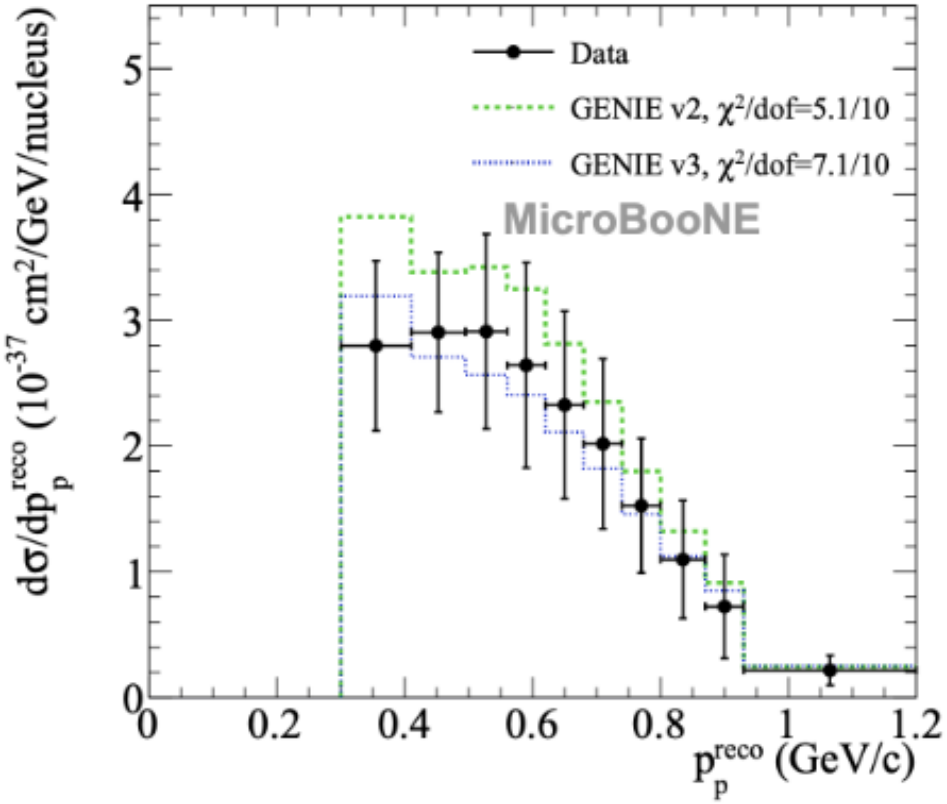


Total cross section compatible with previous measurement, a factor of 2 reduction in uncertainties

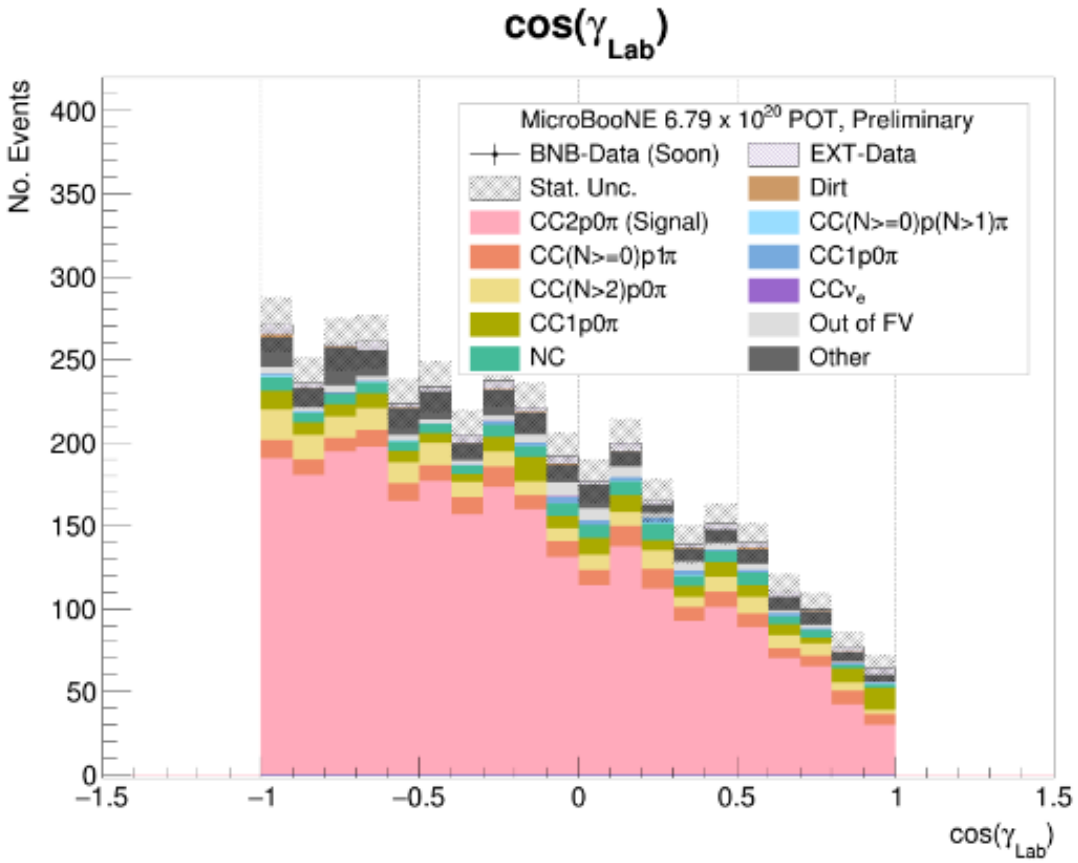
Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

- All signatures shows 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



CCNP

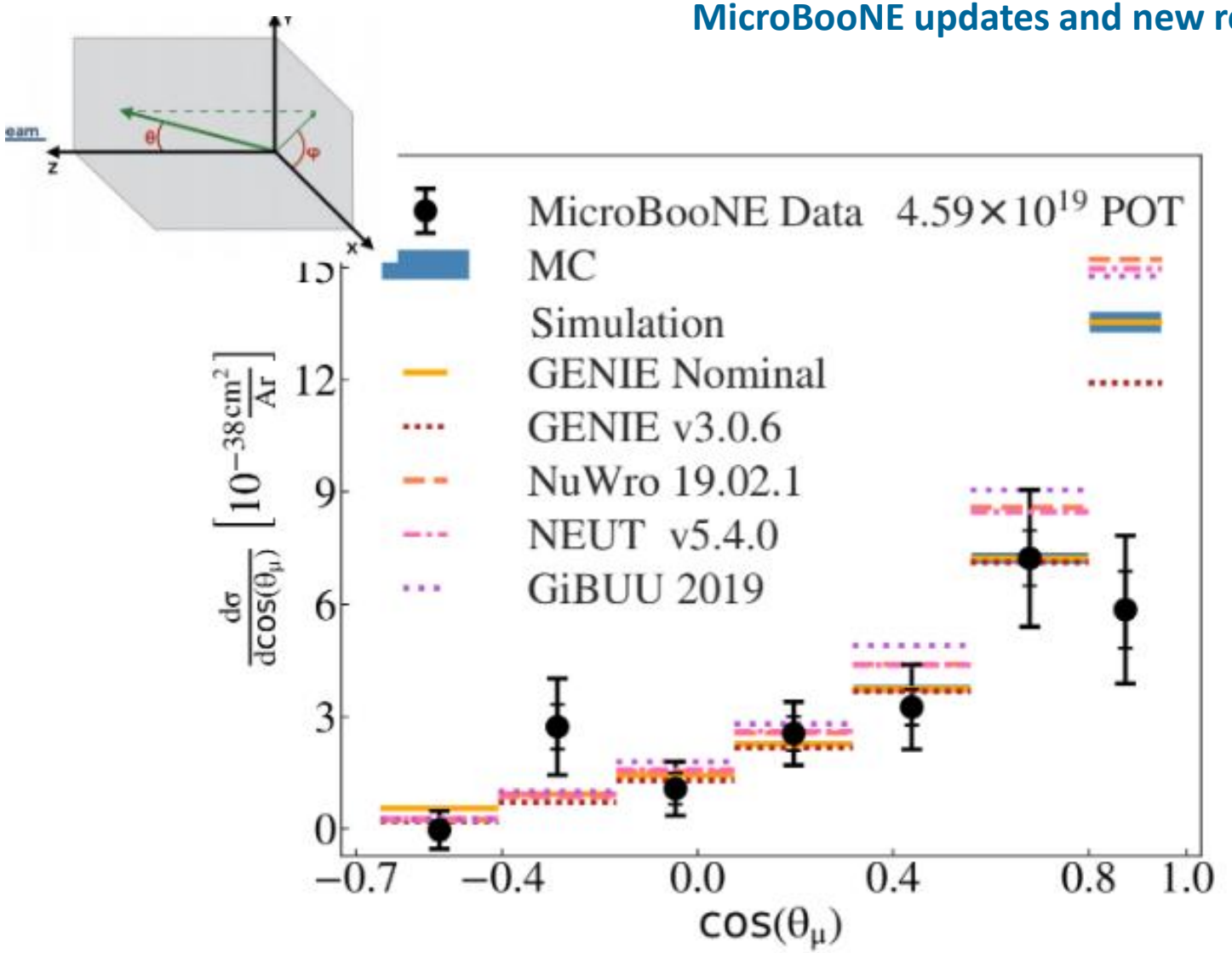


CC2P

Opening angle between protons in lab frame

Samantha Sword-Fehlberg on proton knockout

MicroBooNE updates and new results



CCQE-like

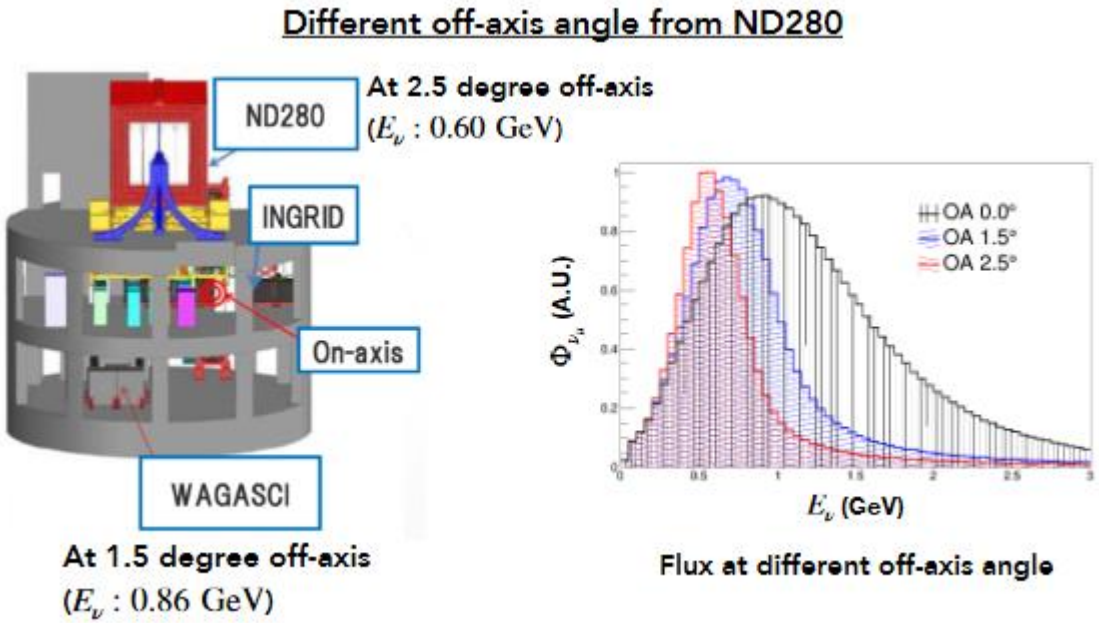
Samantha Sword-Fehlberg on proton knockout

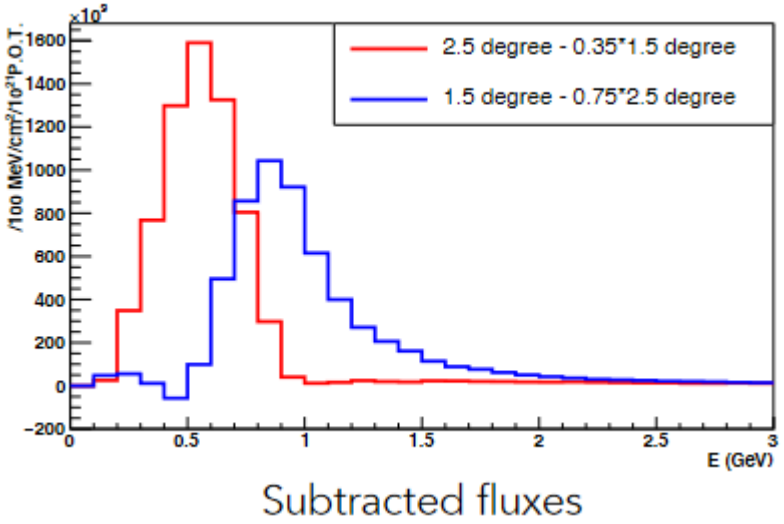
- All signatures shows nice agreement with GENIE except for final state leptons in forward region. This is expected to improve with new modelling in GENIE along with MicroBooNE's dedicated tune done with data from T2K.

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

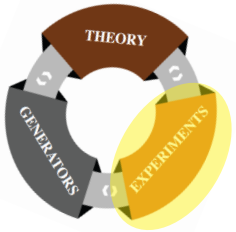




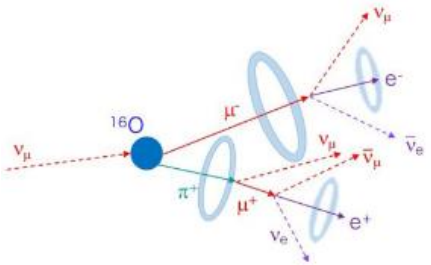
See also Viet Nguyen's poster on studies for the T2K ND upgrade and Danaisis Vargas's study of CCπ^+ interactions!

T2K updates and new results

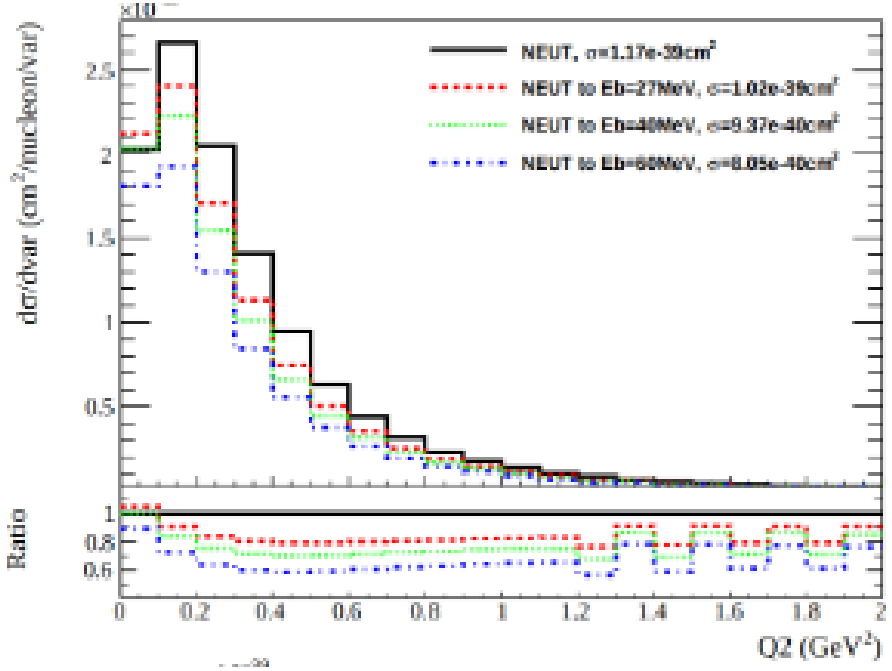
Clarence Wret on Neutrino interaction modeling and recent improvements in model and analysis: T2K uncertainty model for neutrino interaction modeling



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



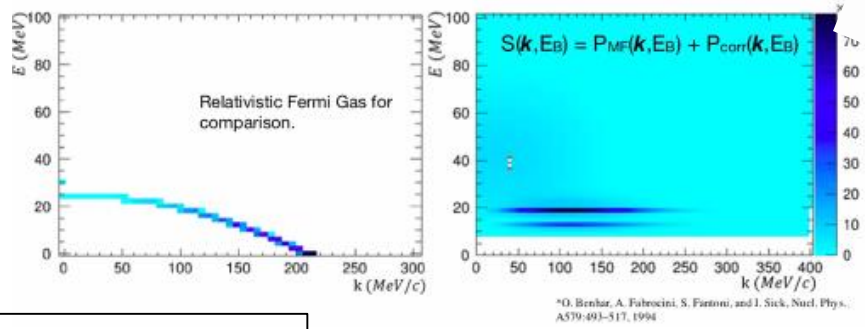
- Combined analyses with SK and NOvA : bring modeling challenges due to the higher neutrino energies that are coming in



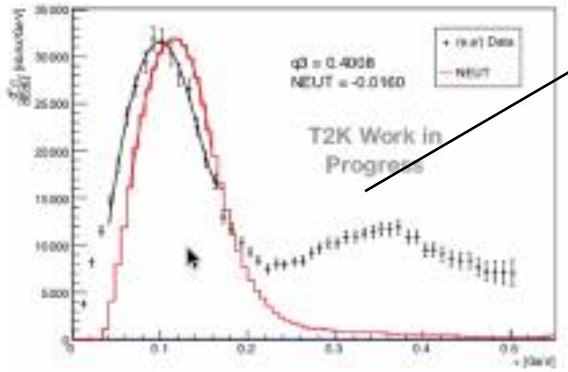
T2K updates and new results

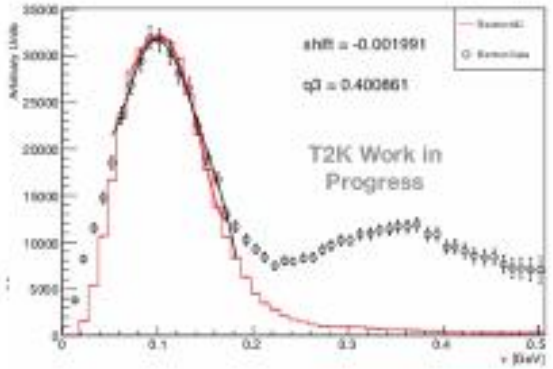
Jordan McElwee on removal energy uncertainties improved by using **electron scattering data** archives

- 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 !

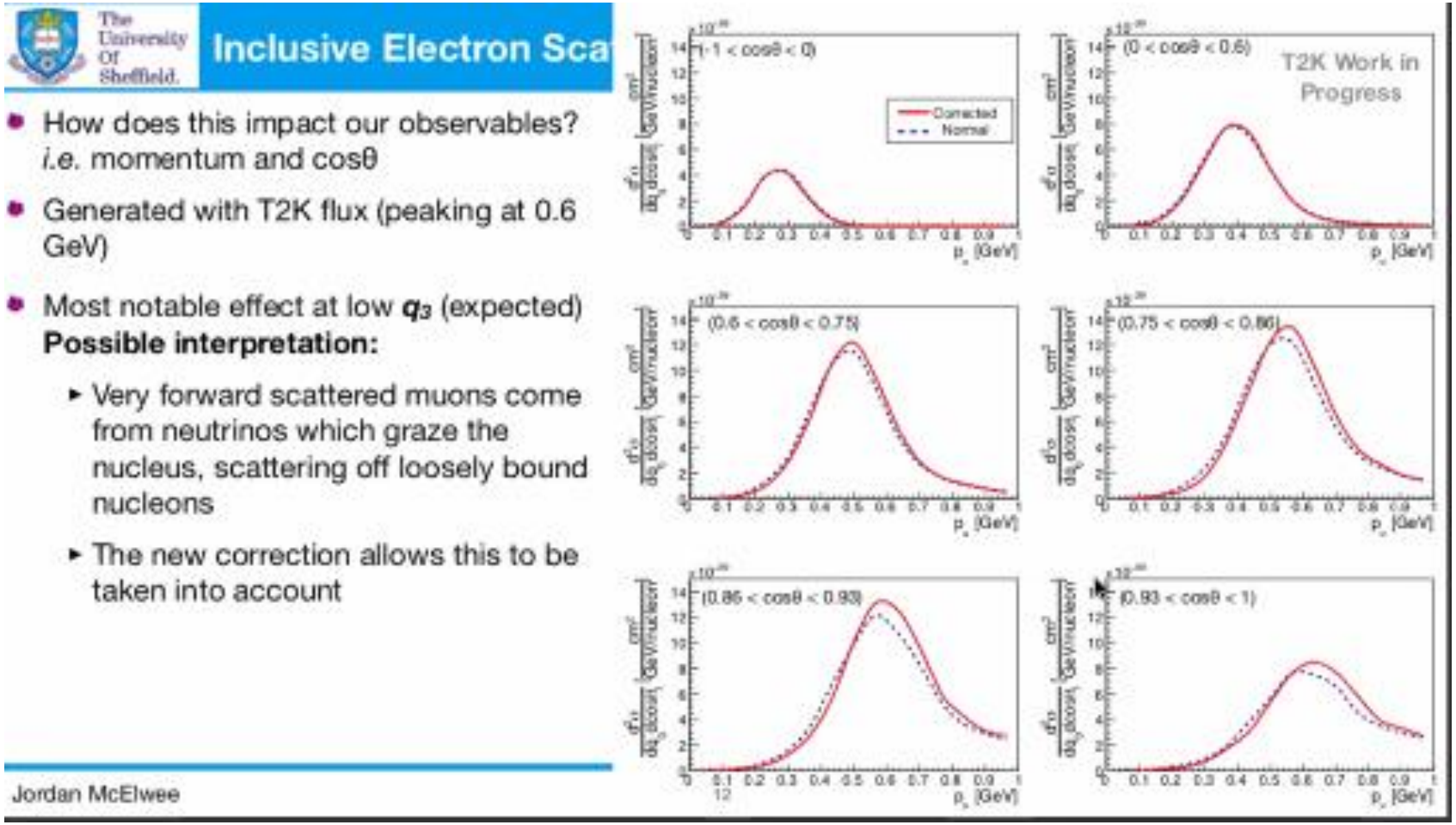




- Spectral function and lepton-nucleon interaction factorize
- Effect of influence of nuclear potential on struck nucleon on cross section can be parametrized by shift in binding energy
- Constraint by e-scattering data to fit QE peak position with energy and QE peak width with momentum

- $E_B \rightarrow$ QE peak position
- $k \rightarrow$ QE peak width

T2K updates and new results



Jordan McElwee on Removal energy uncertainties improved by using **electron scattering data** archives

T2K updates and new results

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

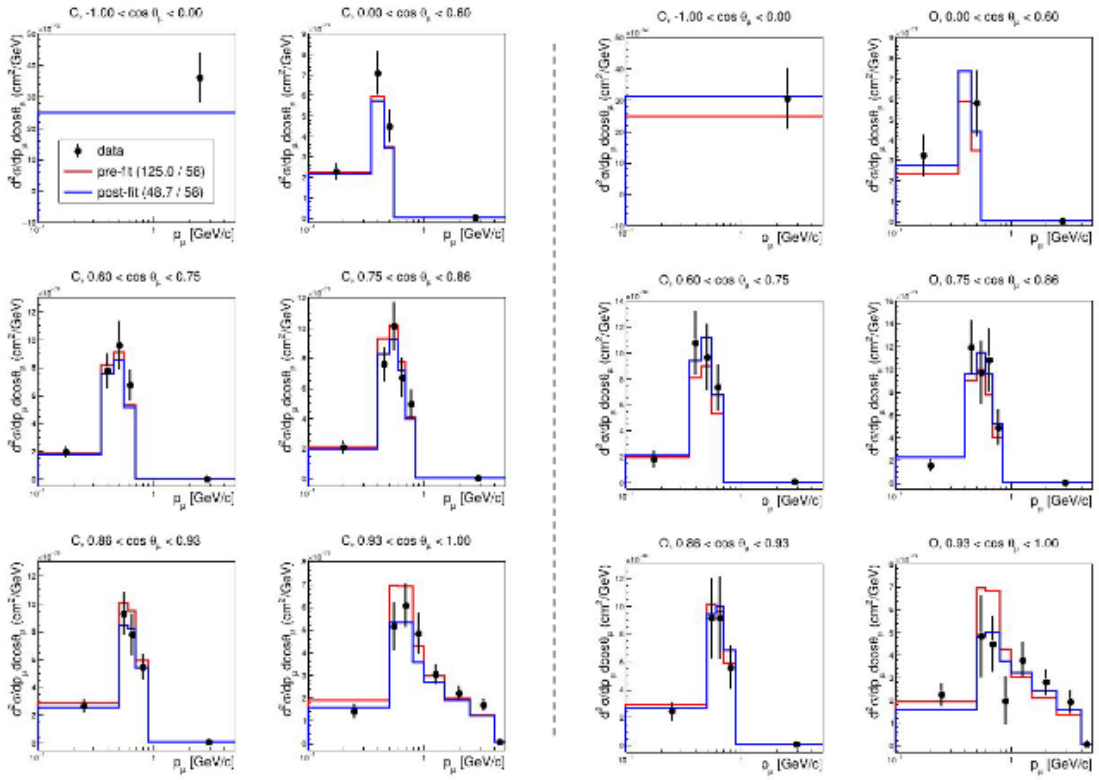
T2K CC0pi O & C measurement

Phys. Rev. D 101, 112004 (2020)

45

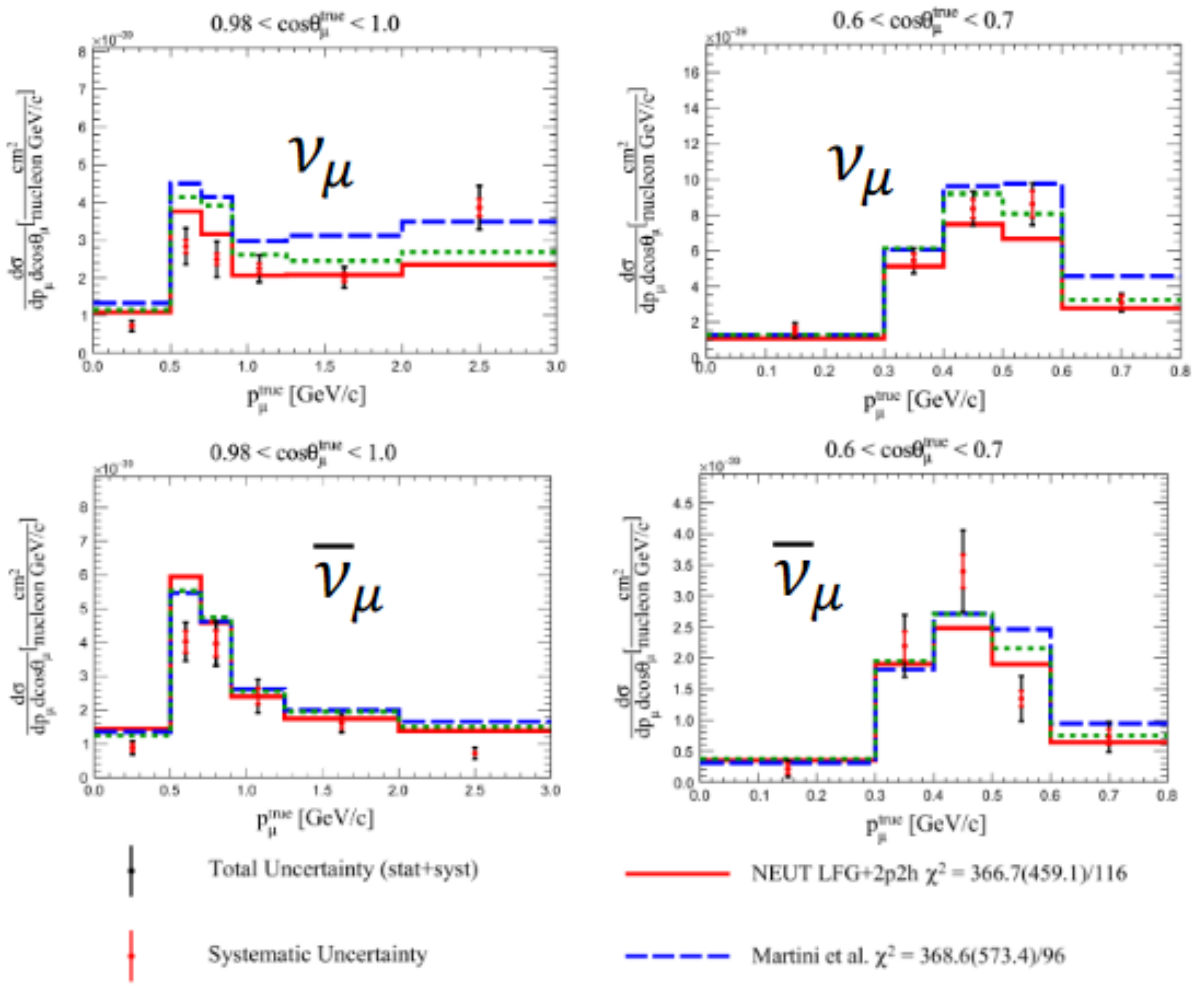
Parameters used in this fit:

- 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

T2K updates and new results



Combined analyses

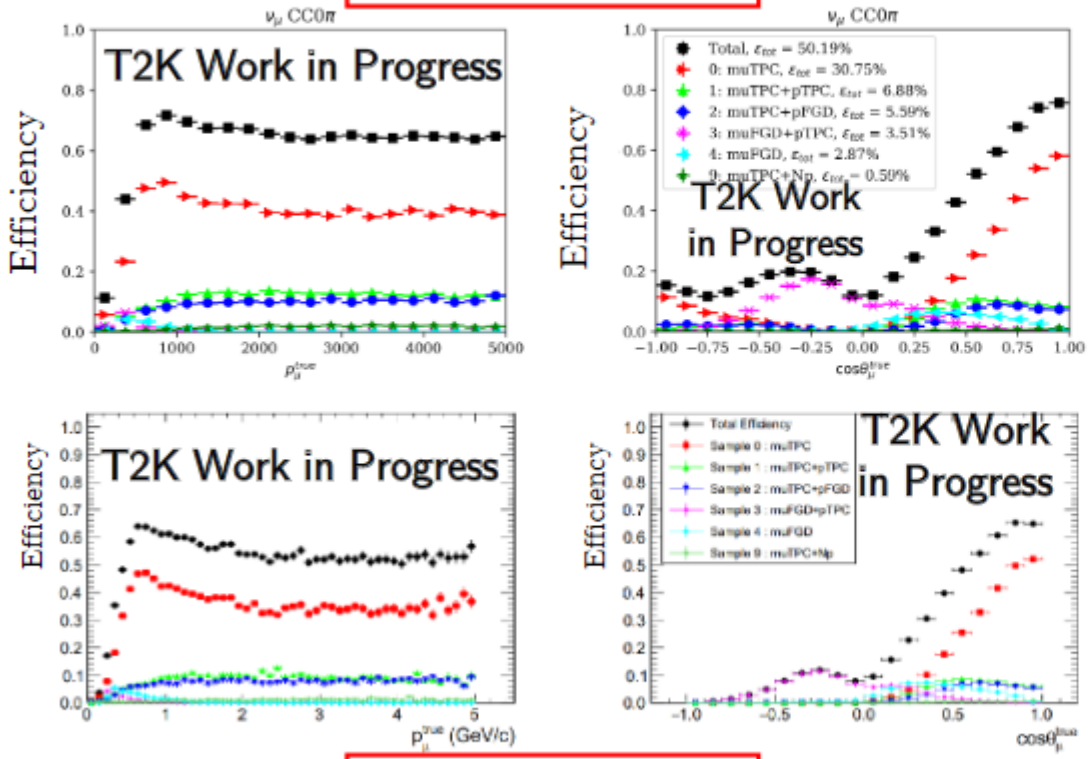
No model describe data well !

Caspar Schloesser on **simultaneous fit to neutrino/antineutrino events**

CC0π combining T2K on and off-axis NDs

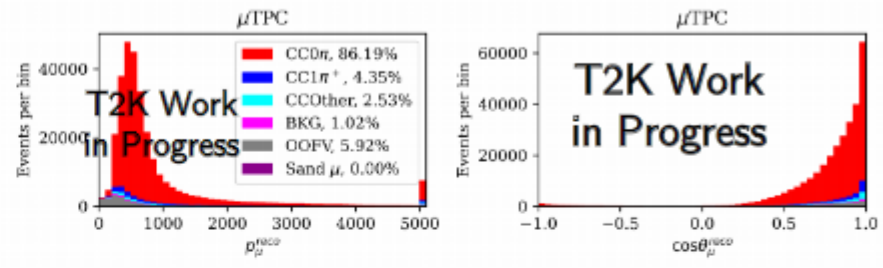
Event Selection - Improvements

New selection

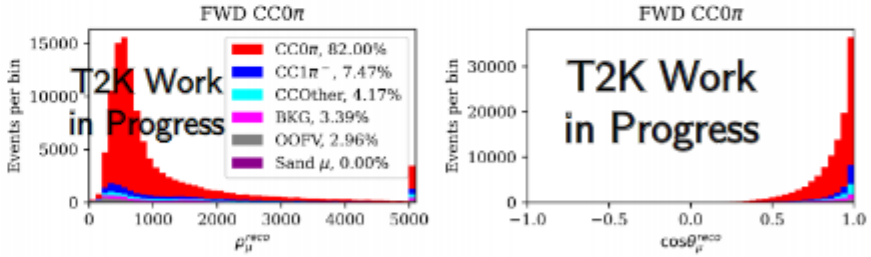


Previous selection

Off-axis ν_μ Selection



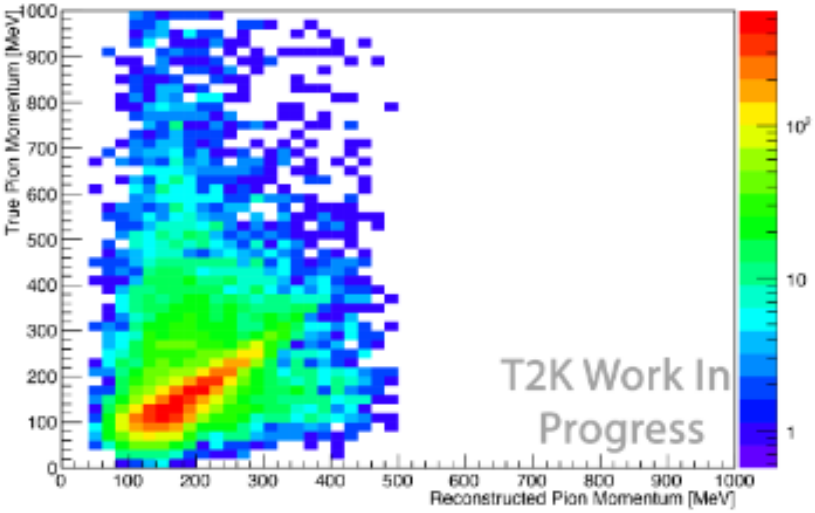
Off-axis $\overline{\nu}_\mu$ Selection

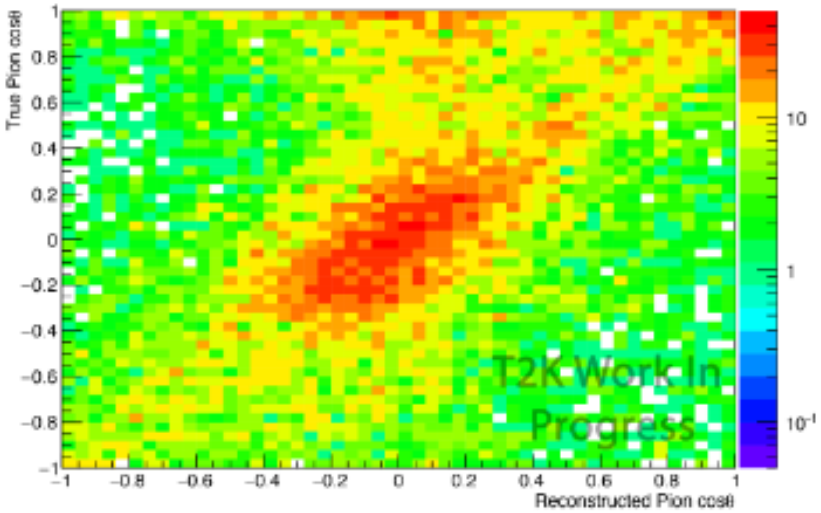


- Very similar purity for previous and improved selection
- But efficiency is greatly improved for high angle and backwards going tracks

Caspar Schloesser

T2K updates and new results



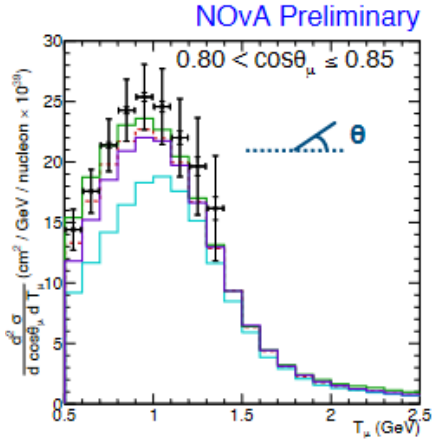


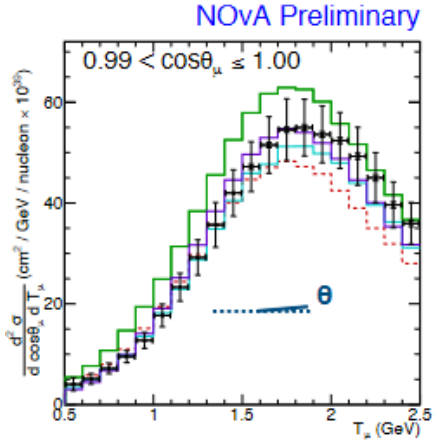
Working well for momentum, pion angle ... Work in progress

Sam Jenkins on improved Pion kinematics reconstruction using Michel electron information

NOvA updates and new results

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





- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

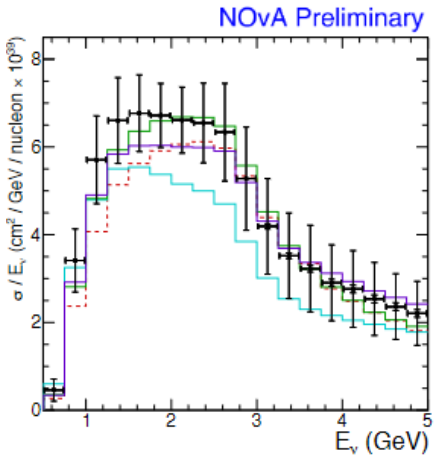
» Out of the box generator comparisons.

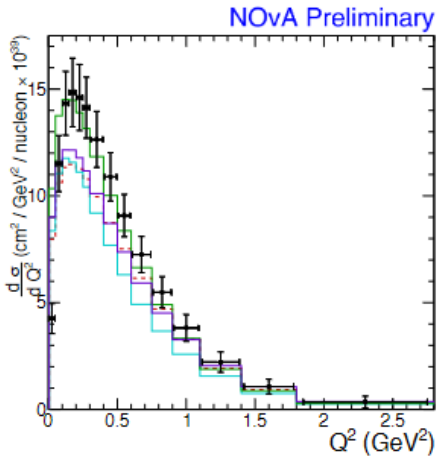
» All generators reproduce well the shape of our data.

» We notice an overall normalization difference in GiBUU.

*N18_10j_02_11a: G18_10j_00_000 and G18_10b_02_11a

Draft publication is under Collaboration review





- Data (Stat. + Syst.)
- GENIE 3.00.06*
- GiBUU 2019
- NEUT 5.4.0
- NuWro 2019

» E_ν and Q^2 are extracted only over the range of muon kinematics reported in the differential measurements.

» Good agreement between data and predictions for E_ν

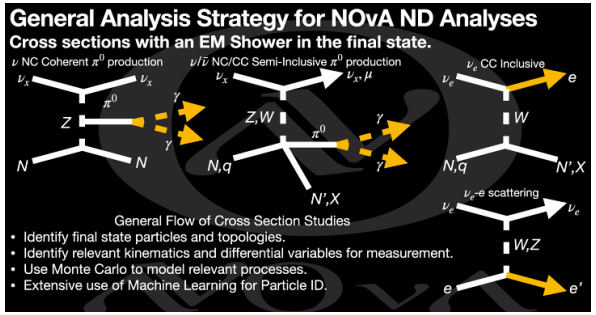
» We observe a low Q^2 suppression that is not well modeled by any generator

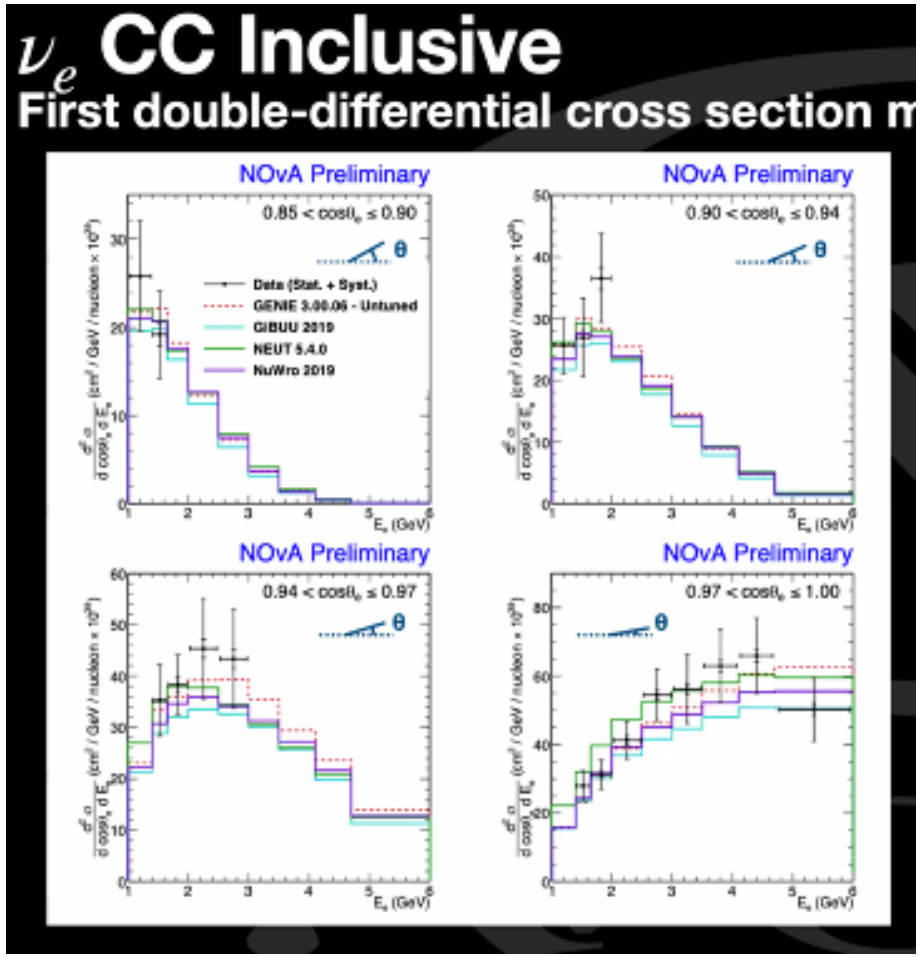
- (anti)neutrino ν_μ - CC with low hadronic activity is actively being analyzed,
- Exclusive channels in progress

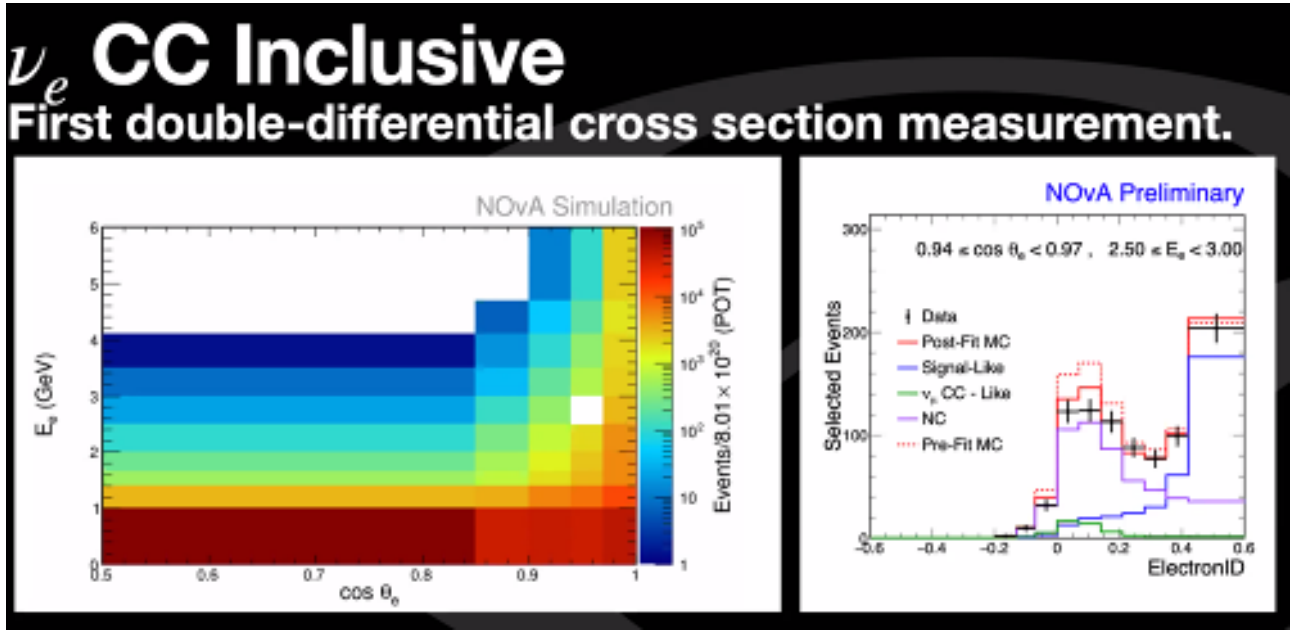
NOvA updates and new results

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

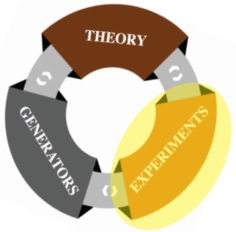
- Particle ID with ML techniques







Excellent agreement with GENIE !



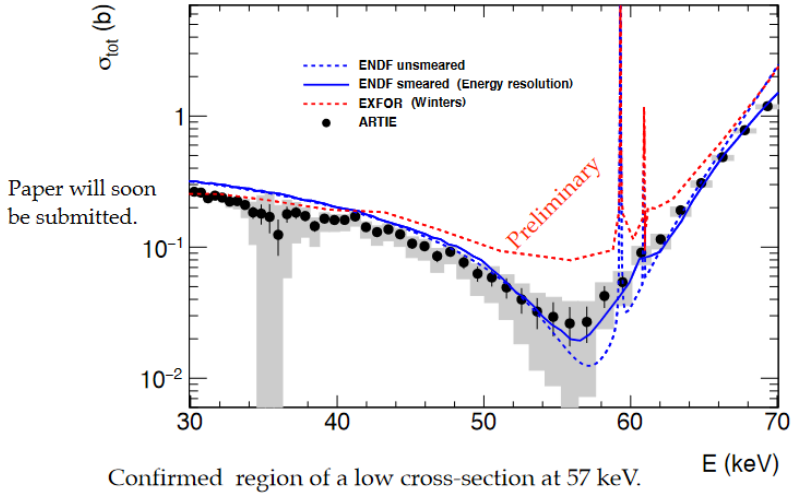
❑ **ARTIE Neutron cross section measurements** (Emilija Pantic in WG2+6)

- 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

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

- Neutrons from ν 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?

Neutron-argon total cross section in the ROI



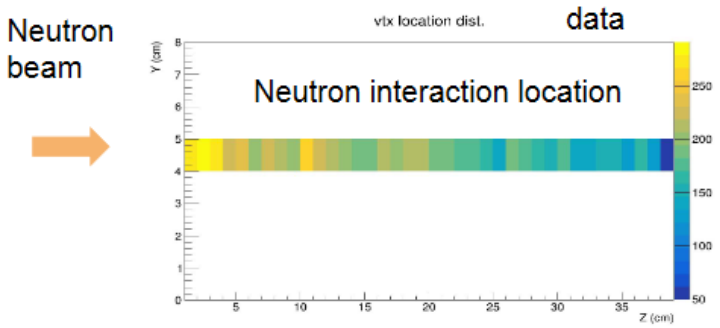
Paper will soon be submitted.

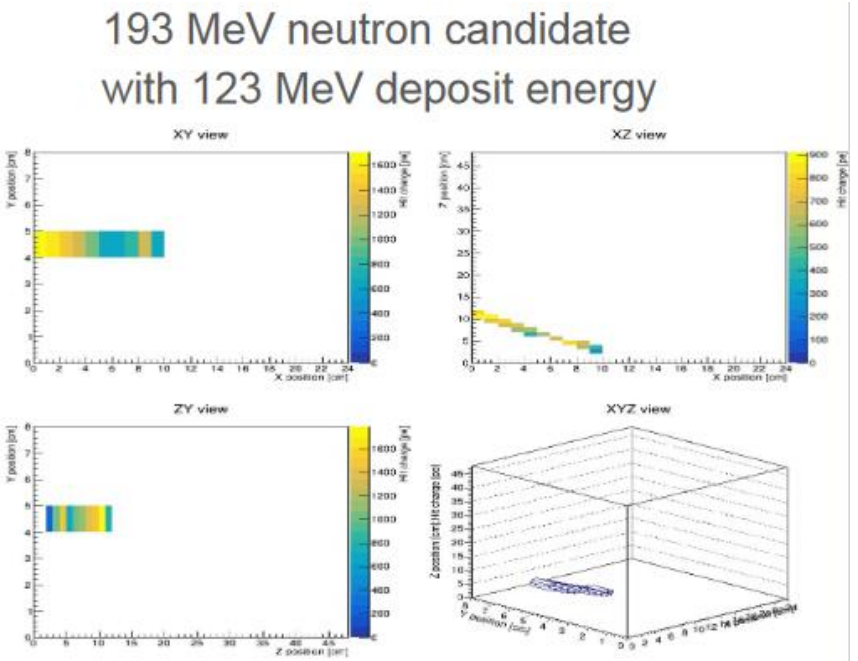
Confirmed region of a low cross-section at 57 keV.

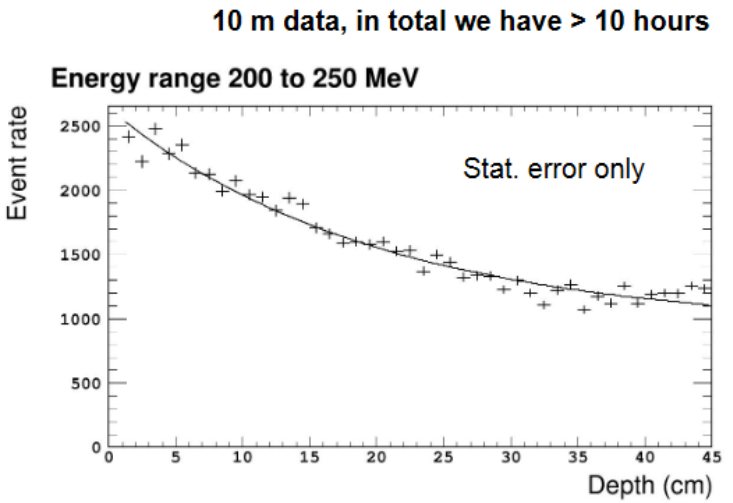
ARTIE data confirms the existence of the anti-resonance at 57 keV, but not as strong as predicted

Auxiliary experiments

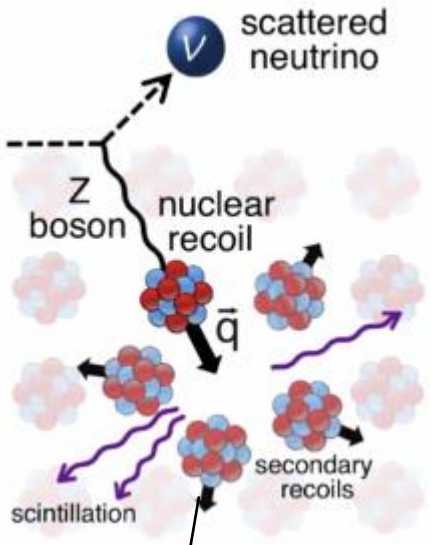
- Neutron cross section measurements (**Guang Yang** in WG2+6 on behalf of the **joint T2K_DUNE 3D Projection Scintillator R&D group**)
  - One of the major systematic uncertainties in the neutrino interaction modeling in the long-baseline neutrino experiments is due to blindness to neutrons in the final 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

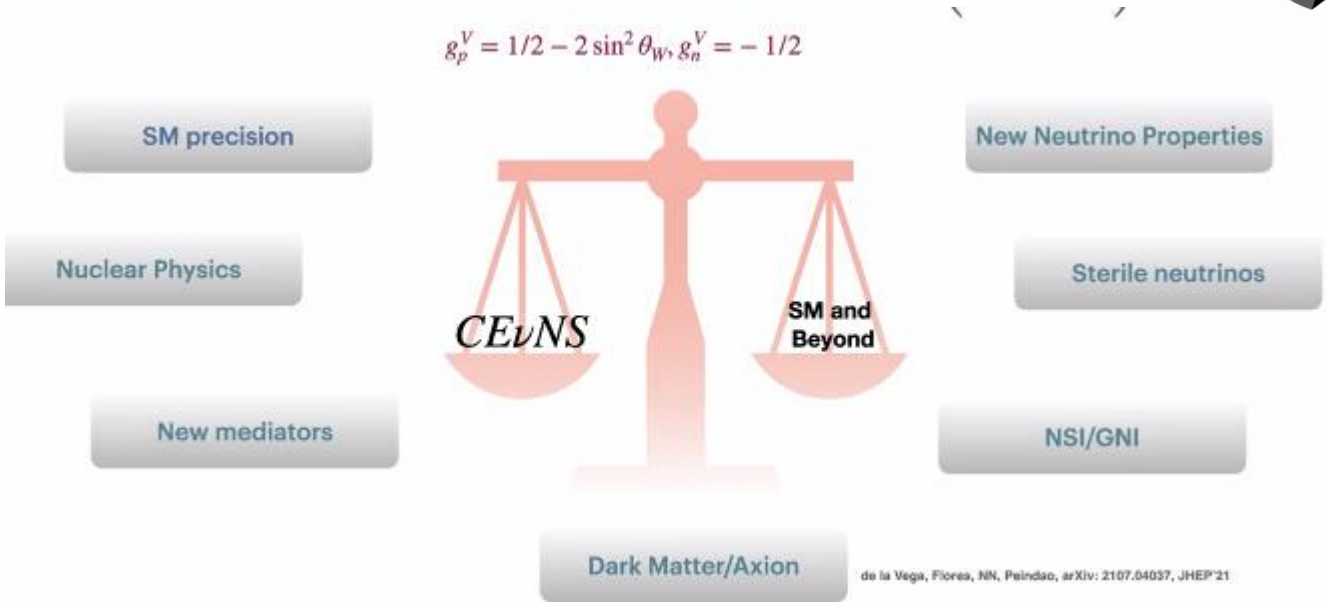






CEvNS : rich physics program



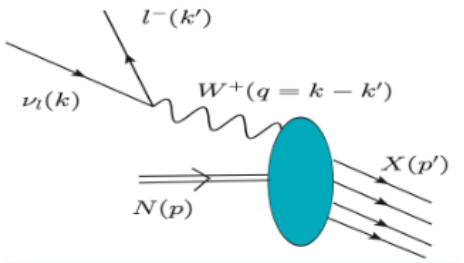


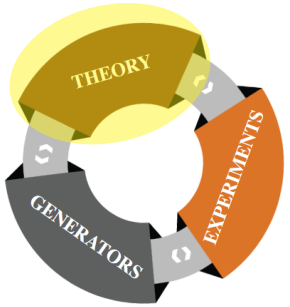
See **Luis Flores**' talk on prospects for a coherent physics program with LAr scintillating bubble chamber detector at nuclear reactors

- Low thresholds
- Energy resolution
- Allows for stricter limits on new physics signals

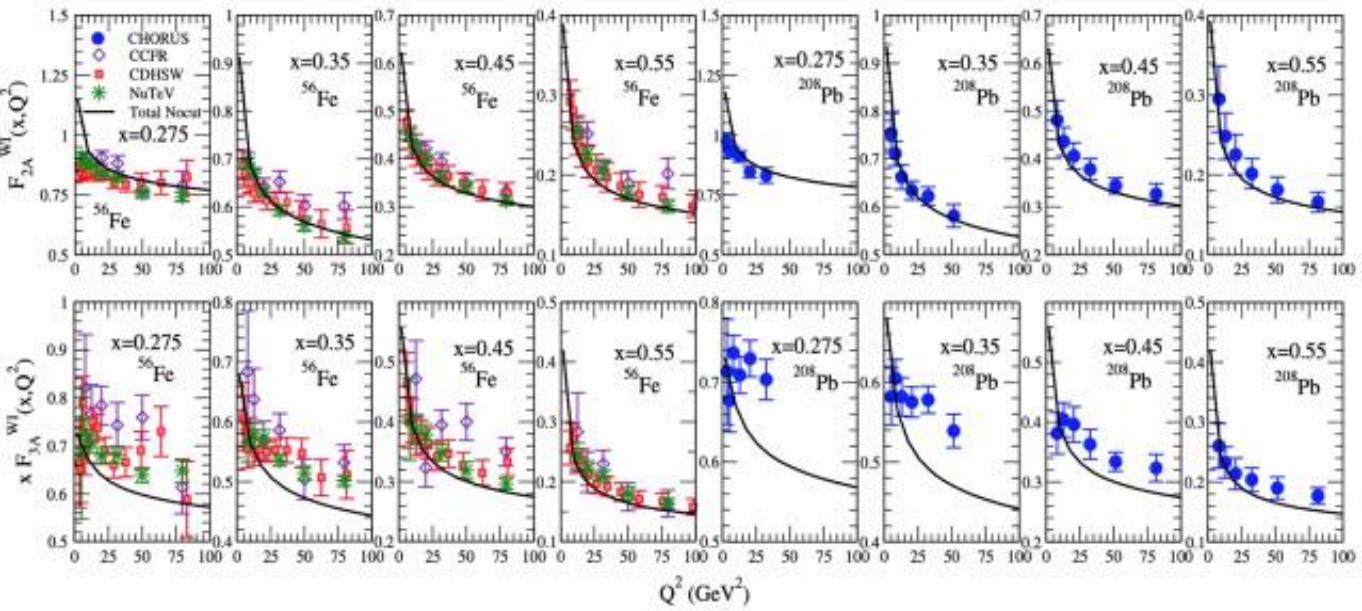
See **Newton Nath**'s talk on constraints For BSM parameters and generalized neutrino interactions

Huma Haider Weak structure functions in νl−N and νl−A scattering with nonperturbative and higher order perturbative QCD effects

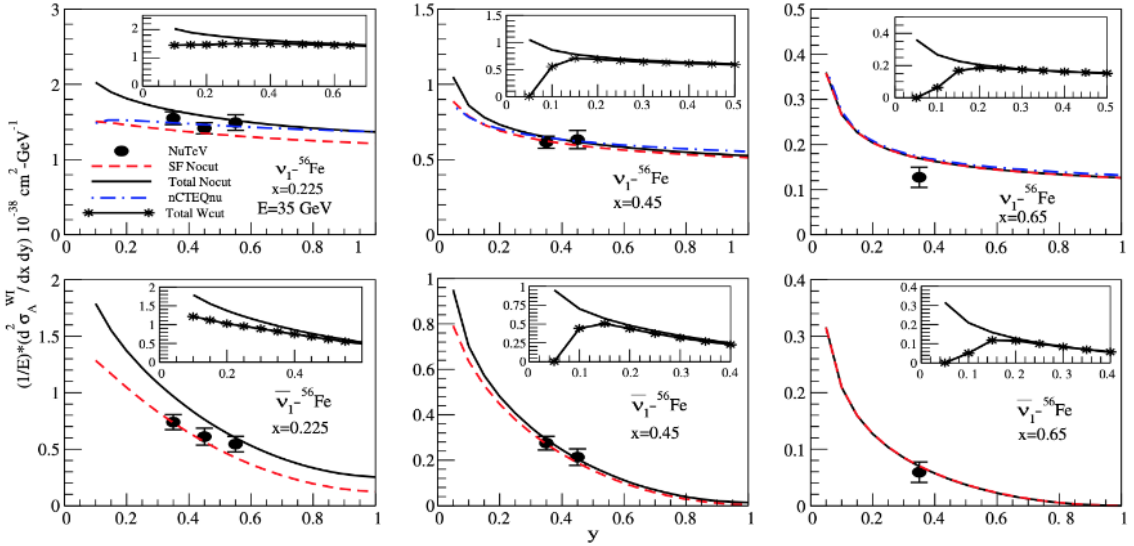




Nuclear Model Structure Functions and Data PHYS. REV. D **101,** 033001 (2020)



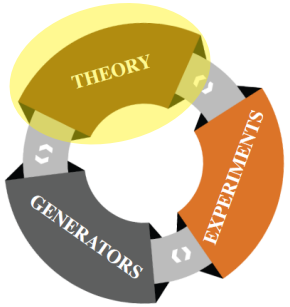
Nuclear Model differential scattering cross sections and nCTEQnu



- Predictions off Ar,
- medium effects different for electromagnetic and weak interactions !

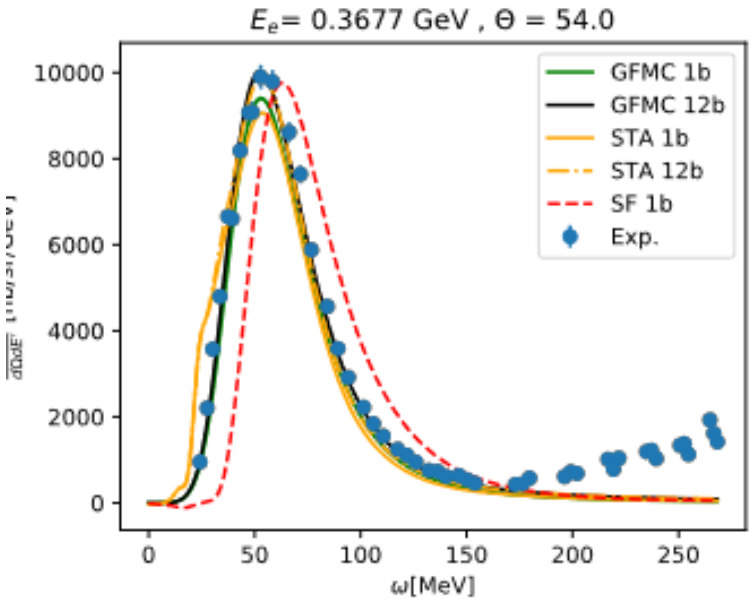
Noemi Rocco on Lepton-nucleus interactions within the spectral function approach

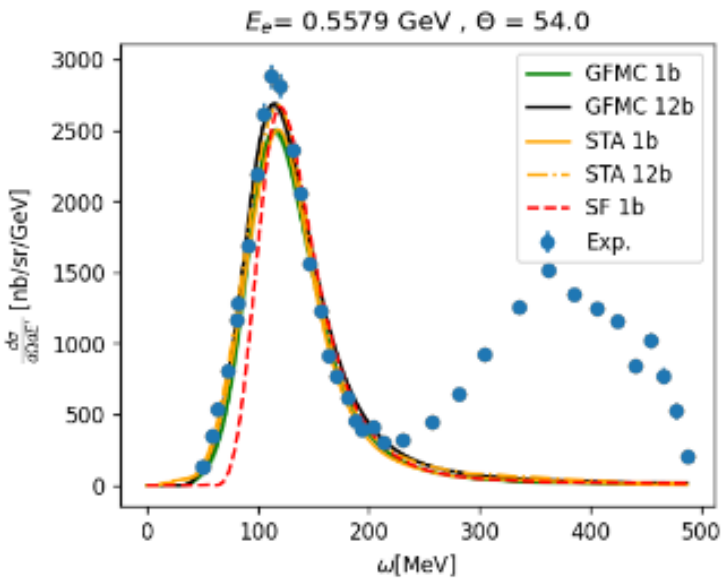
- Gauge validity of factorization comparing different approaches



- e -^{3}H: inclusive cross section

L. Andreoli, J. Carlson, A. Lovato, S. Pastore, NR, arXiv::2108.10824

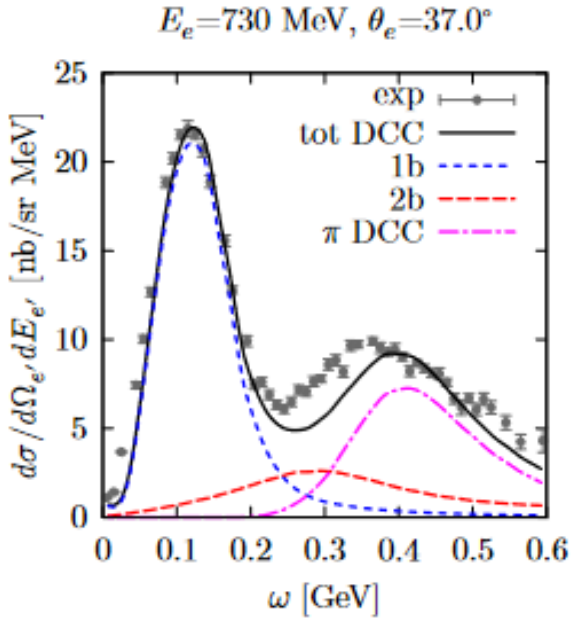




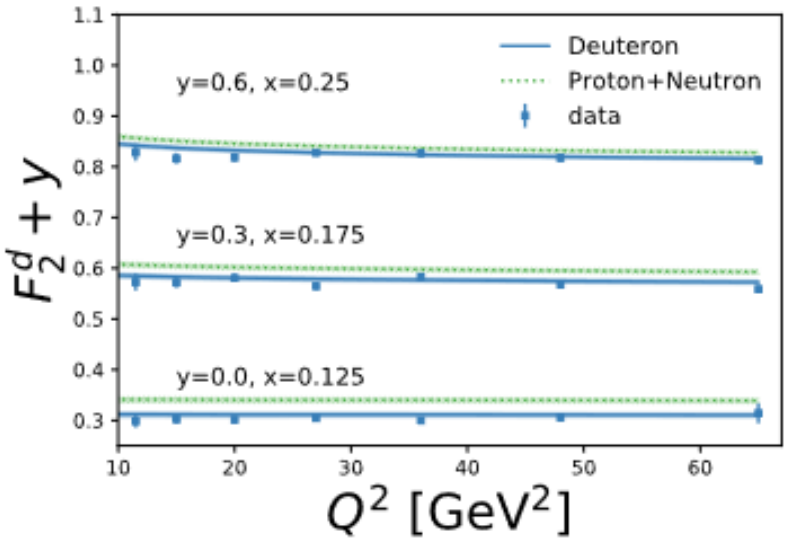
- Comparisons among QMC, SF, and STA approaches: first step to precisely **quantify the uncertainties** inherent to the factorization of the final state.
- Gauge the role of **relativistic effects** in the energy region relevant for neutrino experiments.

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



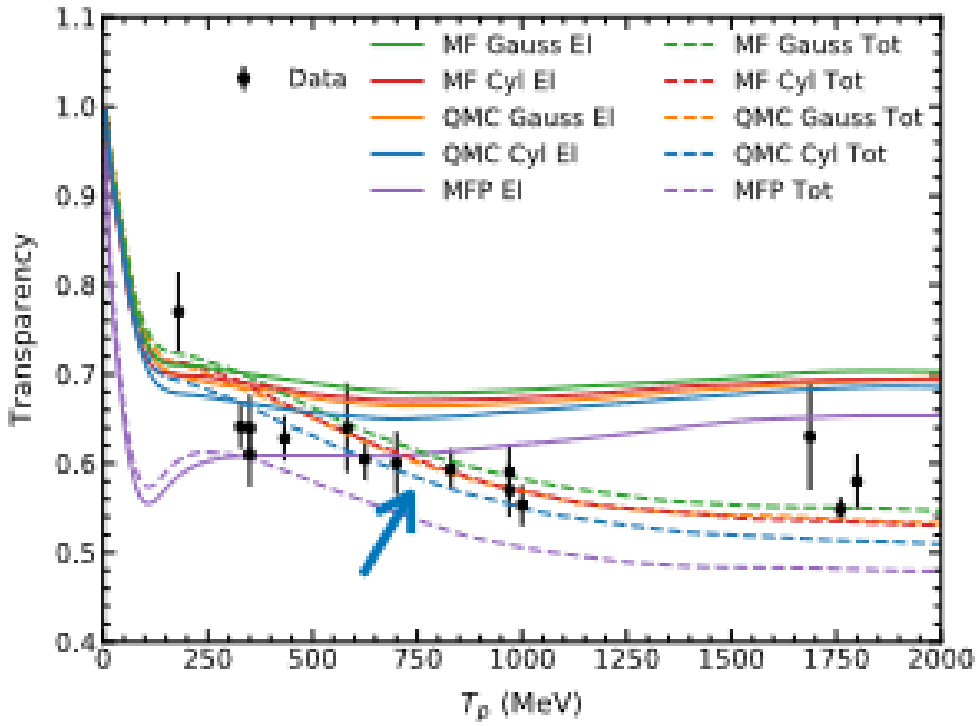
- Good agreement with electron scattering data when all reaction mechanisms are included

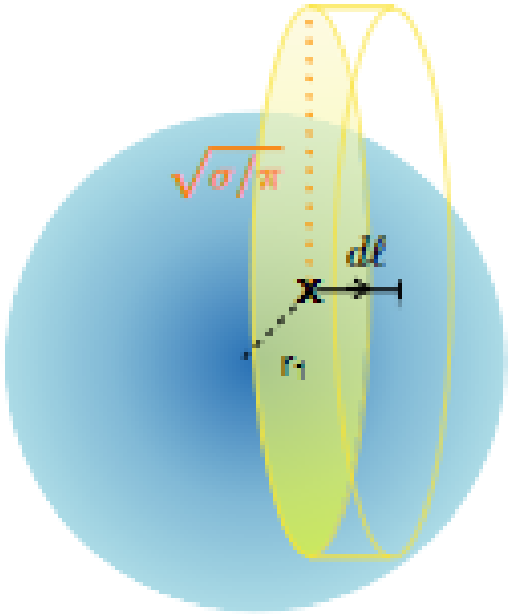


Deuteron electromagnetic structure function F_2 predictions for the DIS region. Convolution of the spectral function+nucleon pdf MMHT2014 at LO

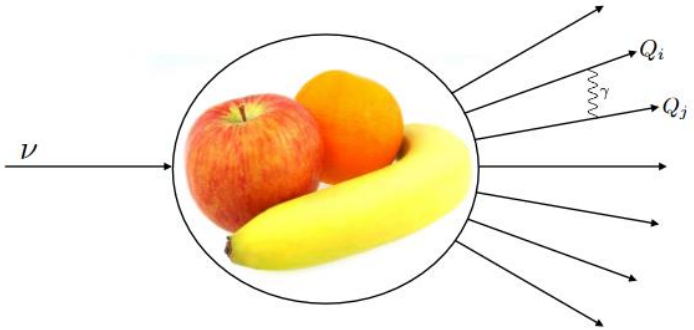
Noemi Rocco Lepton-nucleus interactions within the spectral function approach

- 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

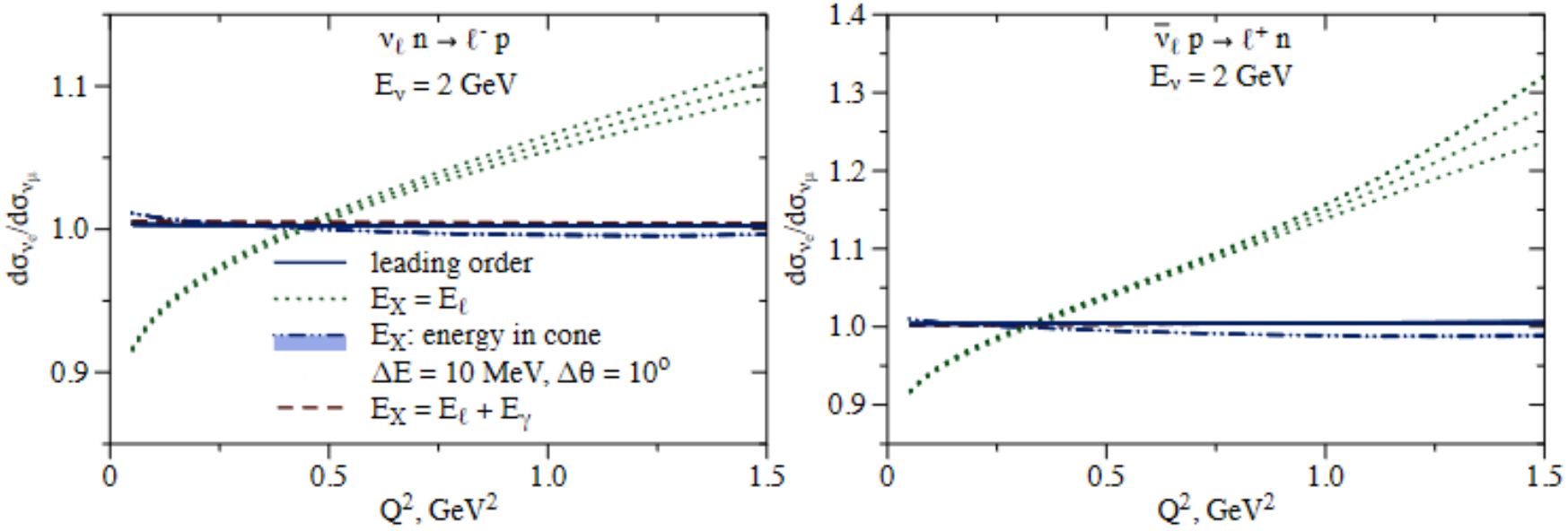




Oleksandr Tomalak : QED radiative corrections for CC neutrino-nucleon elastic scattering



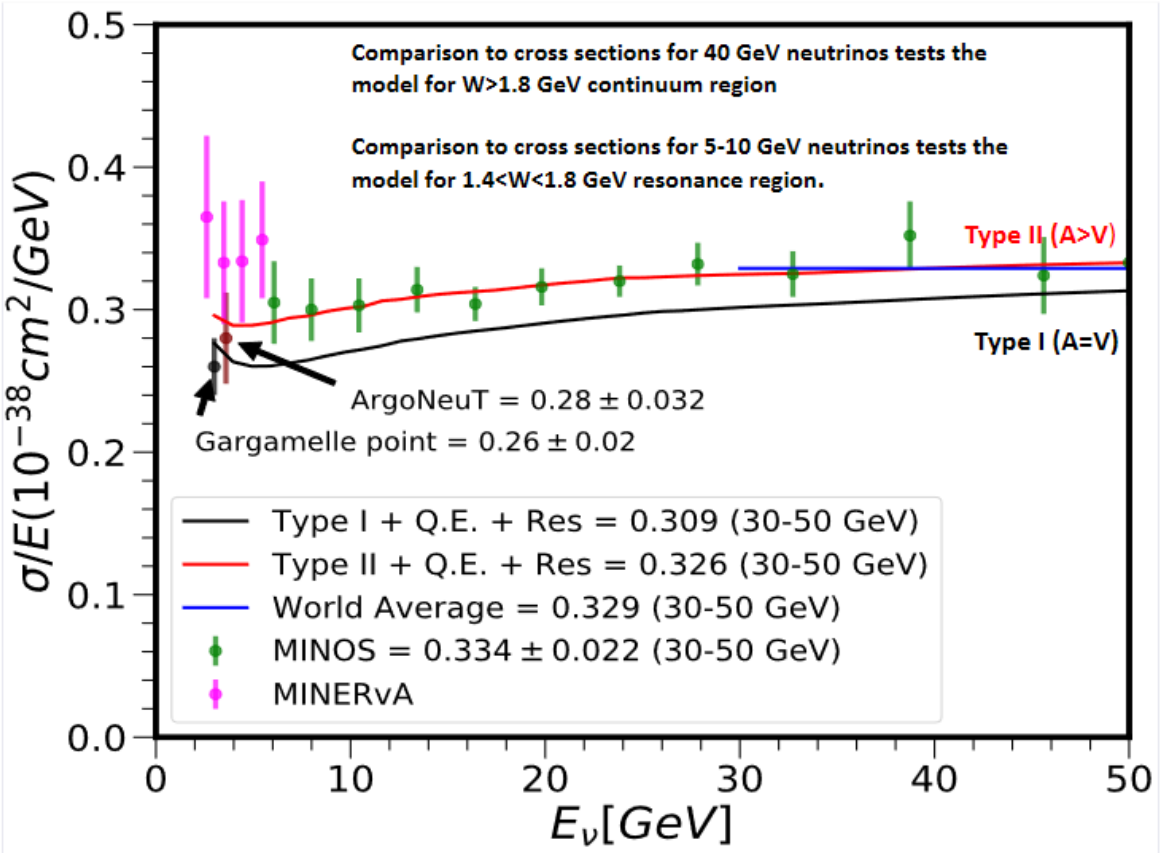
- soft and collinear contributions are evaluated in QED
- new model for hard contributions presented
- Higher order corrections are logarithmically enhanced
- Radiative corrections crucial for %-level oscillation program



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 ν_τ-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 ...**

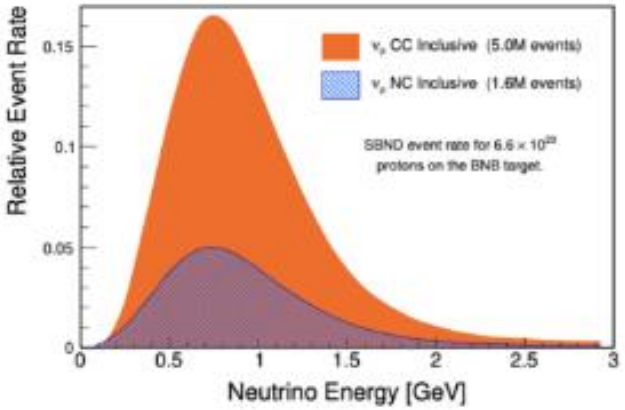
Summary of the summary ....

- 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

Vishvas Pandey

Neutrino-Nucleus Interactions: Measurements

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



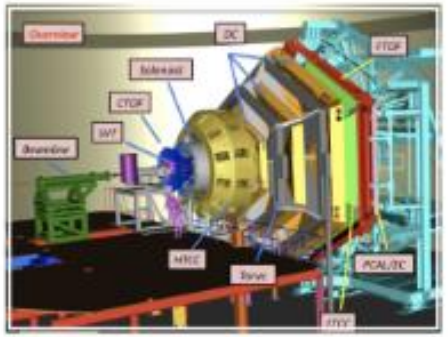
- SBN Program at FNAL (LArTPCs):
  - MicroBooNE: Already producing interesting measurements
  - ICARUS: Started taking data
  - SBND: SBND will compile data with an unprecedented high event rate

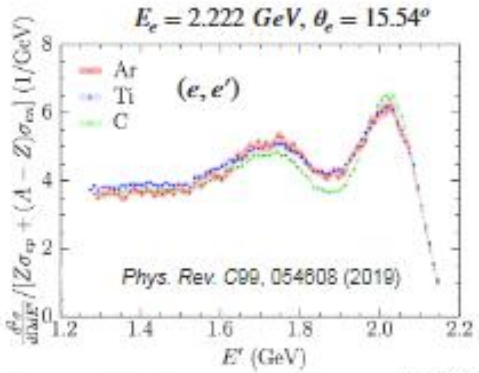
- Lots of exciting measurements to come from T2K, NOvA and MINERvA.

- 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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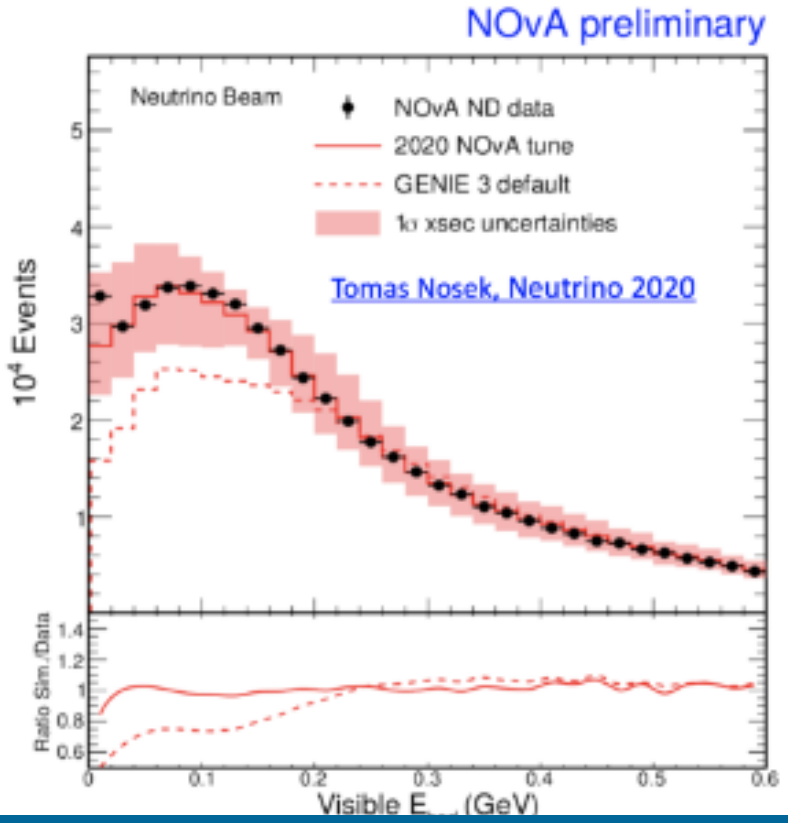
Neutrino-Nucleus Interactions: Generators

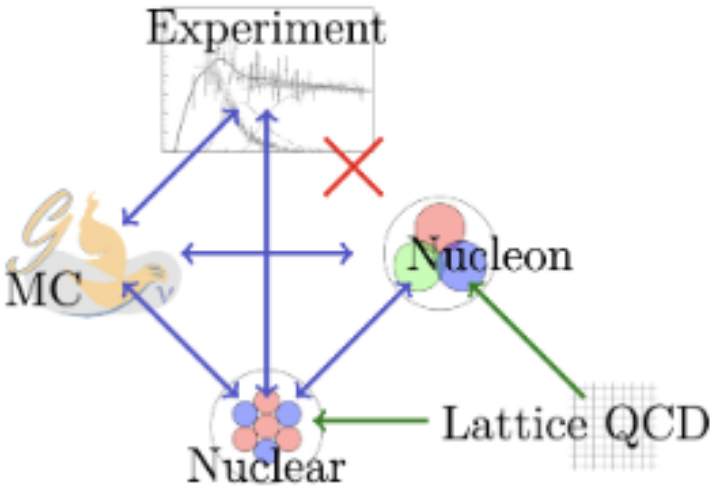
- **Challenges and opportunities:**
  - Models provide inclusive predictions, generators have to produce energy and momentum of all the final state particles using additional schemes, that leads to inconsistencies.
  - Analyzers have to develop experiment-specific interaction model or "tuning", using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



Vishvas Pandey

Neutrino-Nucleus Interactions: Theory Models

- **Challenges and opportunities:**
  - Most models up to now have been focussed 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



A. S. Meyer at a Snowmass Workshop

Vishvas Pandey