24th International Workshop on Neutrinos from Accelerators (NuFACT 2023)

WG2: Neutrino scattering Summary

C. Bronner, R. González Jiménez, E. Gramellini

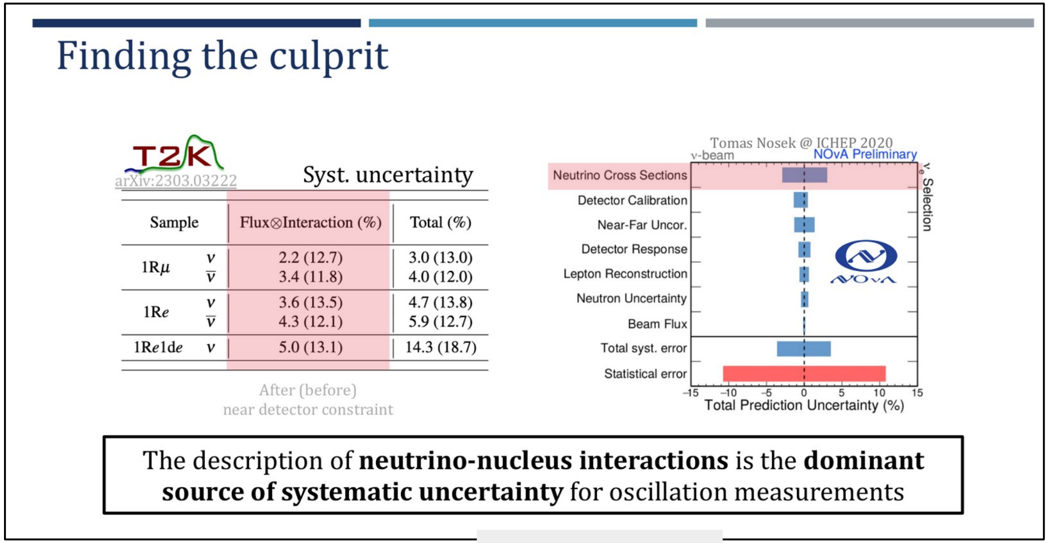
August 26th, 2023

ICRR
Institute for Cosmic Ray Research
University of Tokyo

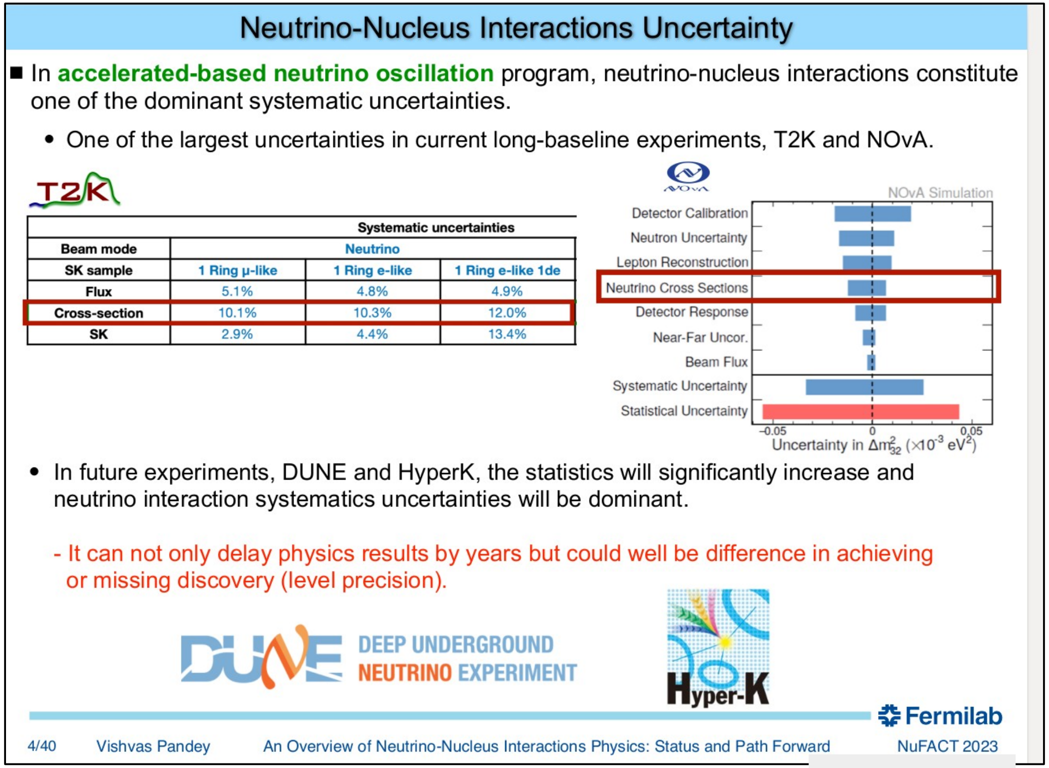
KAMIOKA OBSERVATORY

Introduction

- Active field: 54 abstracts, 4 plenary talks, 33 parallel talks
- Main motivation: importance for future neutrino oscillation measurements and searches for new physics



L. Munteanu

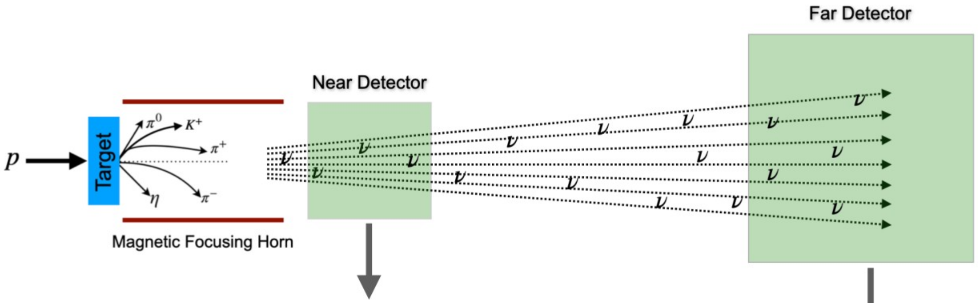


V. Pandey

Joint session with WG1

Ability to describe neutrino scattering critical for precise oscillation measurements, in particular in LBL experiments

Neutrino Oscillations Physics at Accelerator Neutrino Facilities



Measure Event Rate at the Near Detector:

$$N^{\alpha}_{ND}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\alpha(E_\nu)\times\epsilon^i_\alpha(E_\nu)\times S_i(E_\nu;E_{\nu,rec})$$

- Event Rate at Near Detector: Select primarily ν_μ ($\bar{\nu}_\mu$) interactions. Constrain flux and cross sections.

Measure Event Rate at the Far Detector:

$$N^{\alpha\to\beta}_{FD}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\beta(E_\nu)\times P_{\nu_\alpha\to\nu_\beta}(E_\nu)\times\epsilon^i_\beta(E_\nu)\times S_i(E_\nu;E_{\nu,rec})$$

- Event Rate at Far Detector: Select primarily ν_μ ($\bar{\nu}_\mu$) and ν_e ($\bar{\nu}_e$) interactions after the oscillations.

Neutrino Oscillations Physics at Accelerator Neutrino Facilities

- **Extract Oscillation Parameters:**

$$P_{\nu_\alpha\to\nu_\beta}(E_\nu) = \sin^2 2\theta_{ij}\ \sin^2\left(\frac{\Delta m^2_{ij}}{4}\frac{L}{E_\nu}\right)$$

$$\frac{N^{\alpha\to\beta}_{FD}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\beta(E_\nu)\times P_{\nu_\alpha\to\nu_\beta}(E_\nu)\times\epsilon^i_\beta(E_\nu)\times S_i(E_\nu;E_{\nu,rec})}{N^{\alpha}_{ND}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu)\times\sigma^i_\alpha(E_\nu)\times\epsilon^i_\alpha(E_\nu)\times S_i(E_\nu;E_{\nu,rec})}$$

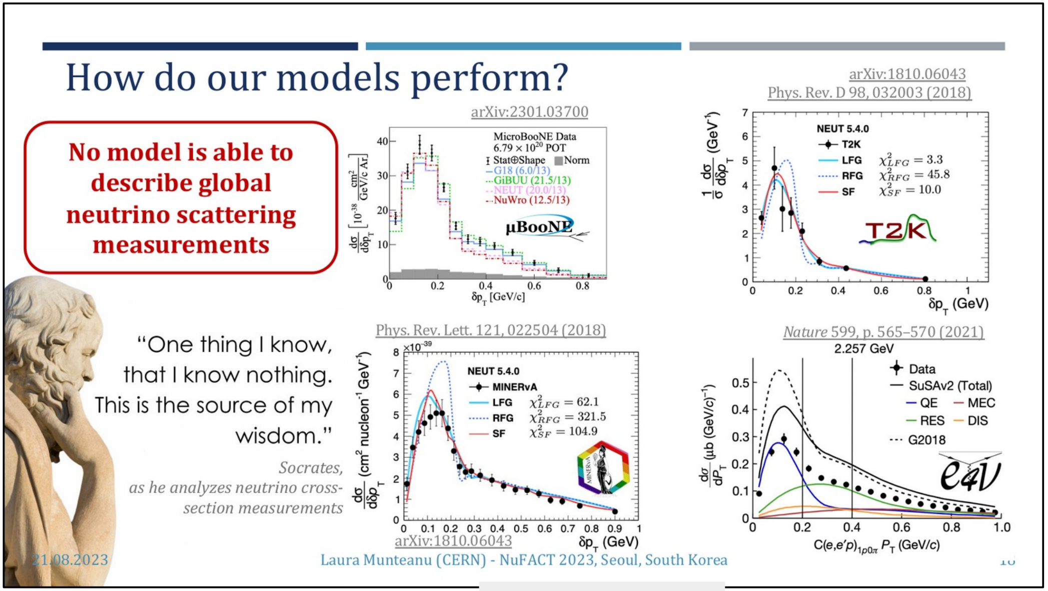
Near to far ratio doesn't fully cancel out neutrino interaction dependencies:

- Flux and cross sections are convoluted
- Different neutrino energy spectrum at near and far detector
- Different neutrino flavor at ND and at FD (appearance)
- Different Near and Far Detector design, acceptance, etc.

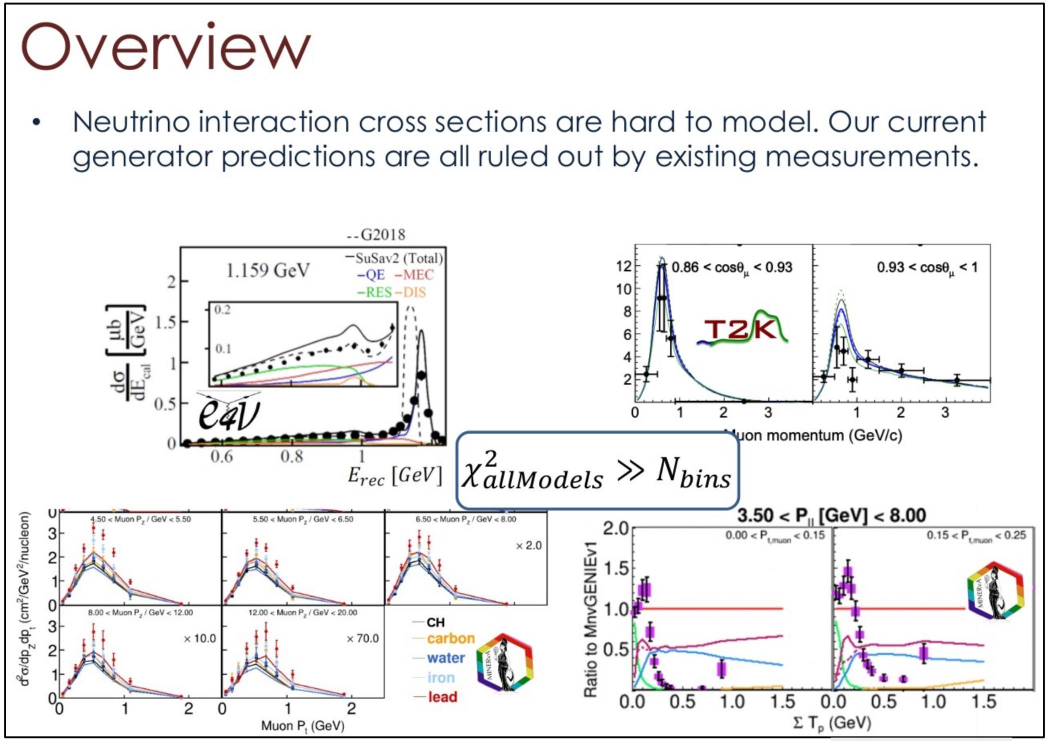
V. Pandey

Describing neutrino scattering data

However, we’re currently not able to do that



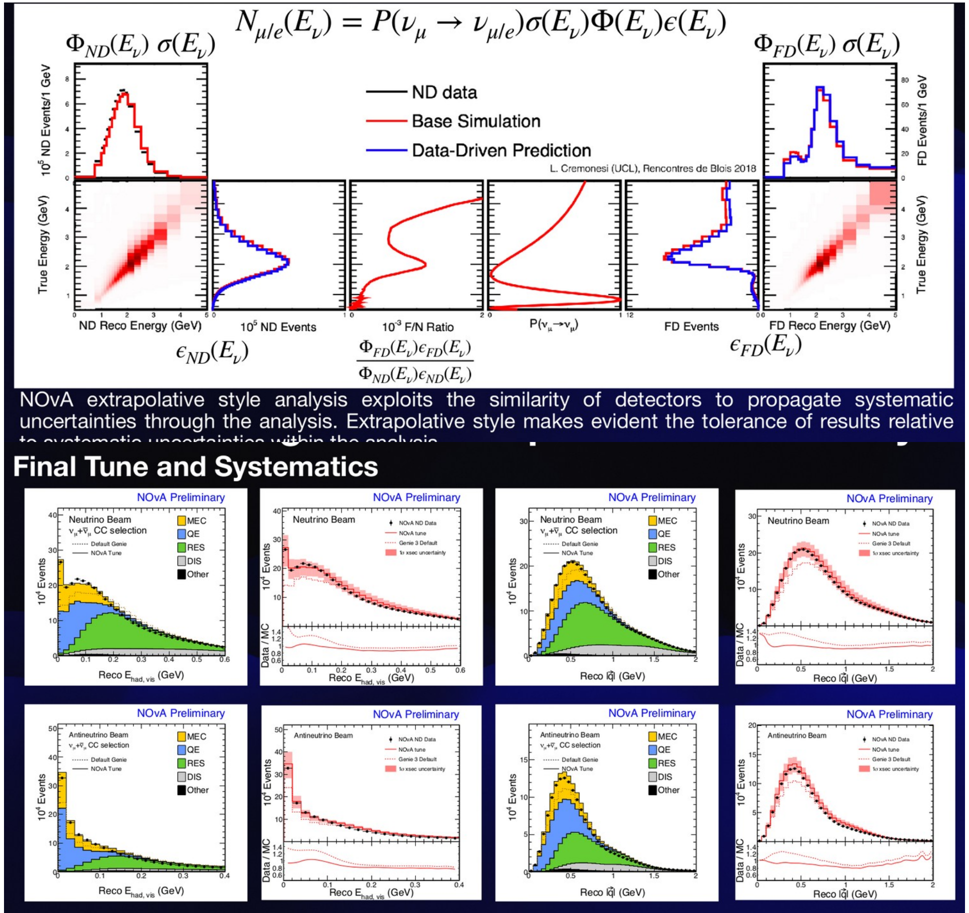
L. Munteanu



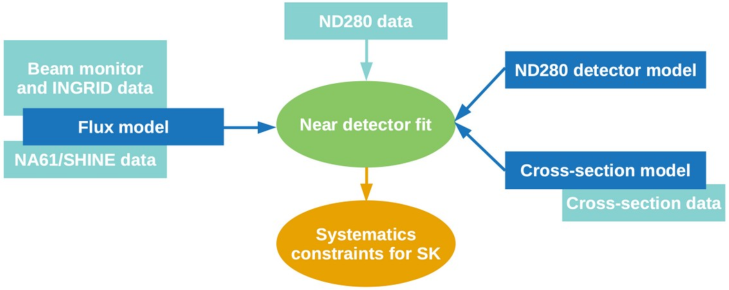
S. Dolan

Tuning with near detectors

NOνA (B. Ramson)

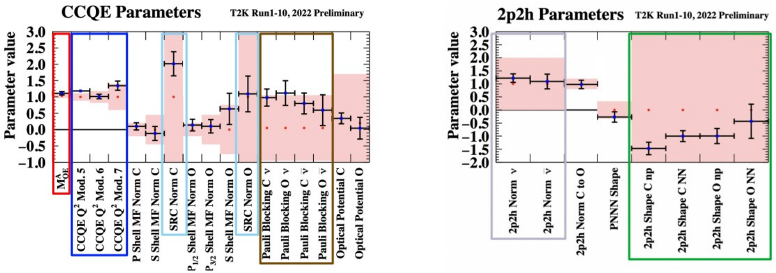


T2K (T. Doyle)



Postfit Constraints on CCQE and 2p2h Parameters

- M_A^{QE} increased above prior, CCQE high Q^2 cross section increased, Short Range Correlations (SRC) normalisation increased
- Pauli Blocking increased
  - → Changes low Q^2 region of CC0π0p with little impact on CC0πNp
- 2p2h normalisation increased by ~20% for ν and ~5% for $\bar{\nu}$
  - → Less than previous analysis due to correlations with SRC
- 2p2h shape parameters pulled towards non-Δ region
  - → Shift 2p2h towards low q_0



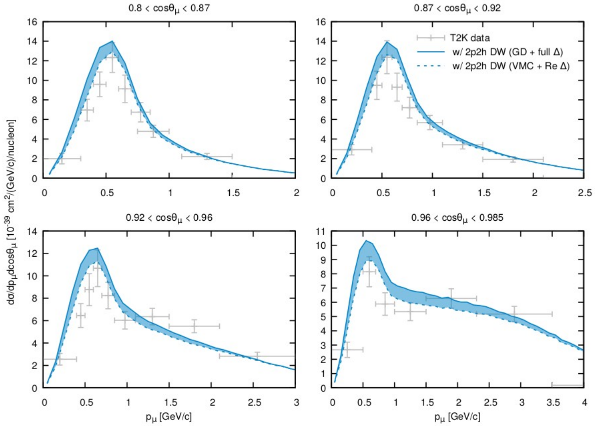
Interaction systematics

ND tuning needs systematic uncertainties for interaction models

1. Improving a model through detailed **theoretical calculations** (extension to a large enough Kinematic regions)
2. Transforming the model to something that could be easily and efficiently **incorporated into event generators**
3. Studying the **systematic uncertainties** of the theoretical model
4. Providing a few adjustable **physics-based parameters**, or "knobs" which can be used in future measurements

M. Kabirnezhad

Comparison to inclusive T2K neutrino data using NuWro

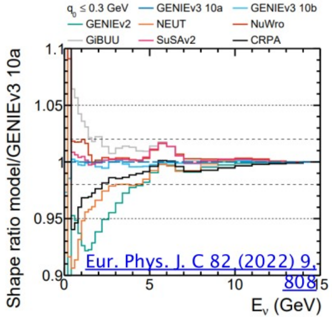


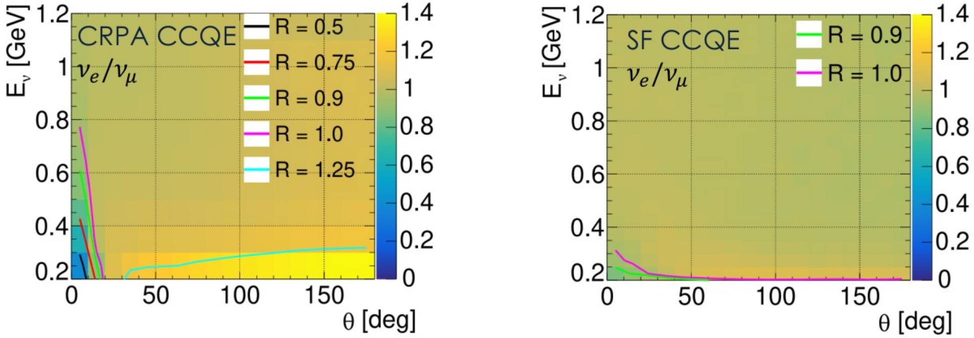
→ Premilinary implementation of the **Ghent model in NuWro**

→ We provide **systematic theoretical uncertainties** on the model

K. Niewczas

- Our systematic uncertainty models are almost certainly incomplete
- Model spread is a useful tool to define or inspire supplementary systematics





Phys. Rev. Lett. **123**, 052501
Phys. Rev. D **108**, L031301
Phys. Rev. C **96**, 035501

Flux integrated impact for Hyper-K:

- ν_e/ν_μ: ~3%, $\bar{\nu}_e/\bar{\nu}_\mu$: ~1.5%, $\nu_e/\bar{\nu}_e$: ~1.5%

S. Dolan

Understanding neutrino interactions

Neutrino-Nucleus Interactions: Wish List

- We need a consistent model of neutrino interaction physics for:
  - wide energy transfer range (10s of MeV to a few GeV)
  - many nuclei (in particular, 12C, 16O and 40Ar)
  - all neutrino and antineutrino flavors
    - For appearance searches: constrain ν_μ to ν_e differences (lepton mass effects, radiative corrections)
    - For CP violation searches: constrain ν to $\bar{\nu}$ differences (especially relevant for an isospin asymmetric nuclei like ^{40}Ar)
  - all final state observables (inclusive and semi-inclusive/exclusive).

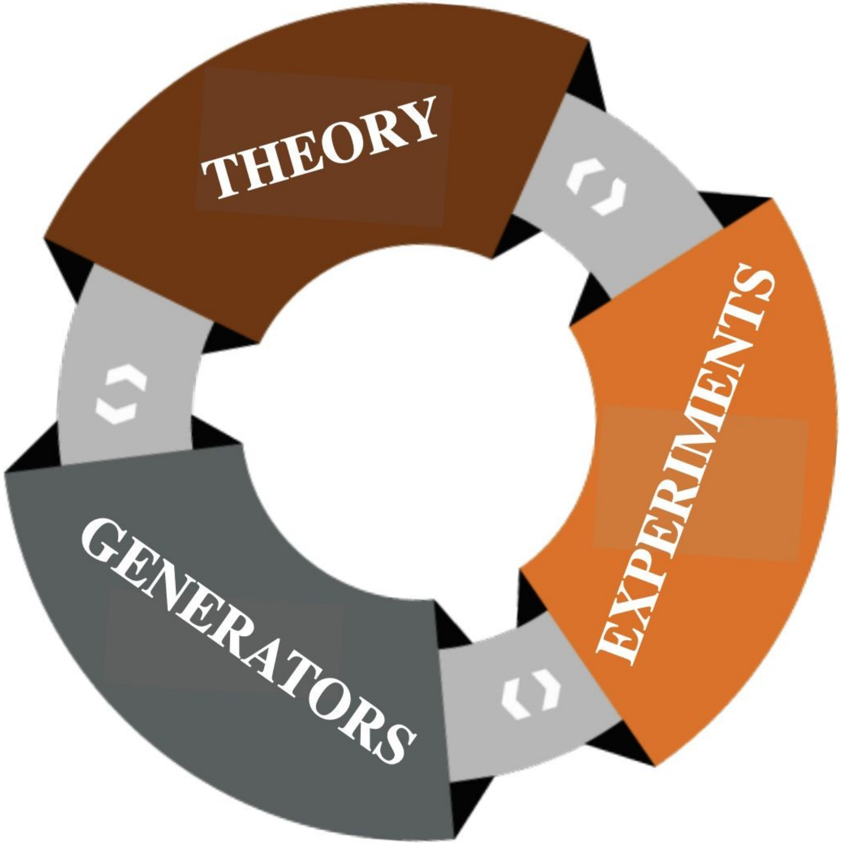
  And, the model

  - is validated against existing data (e.g. electron scattering)
  - allows estimation of theoretical uncertainties
  - allows robust implementation into generators
- This requires development of a combination of lattice QCD, nuclear many body theories, and neutrino event generators with input from neutrino, electron/hadron scattering data.

Fermilab

12/40 Vishvas Pandey An Overview of Neutrino-Nucleus Interactions Physics: Status and Path Forward NuFACT 2023

V. Pandey

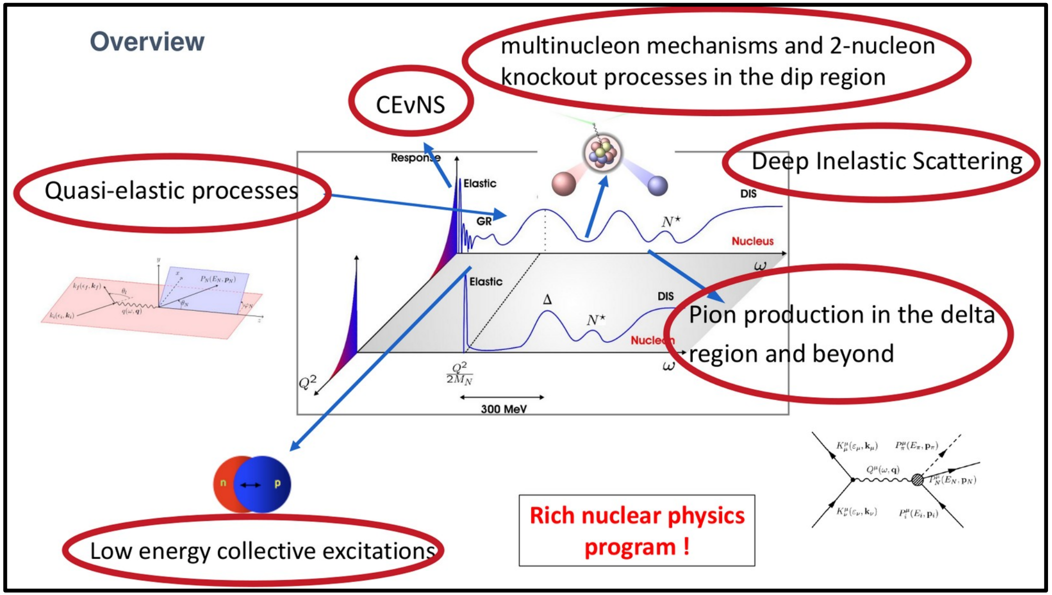


Theory

Plenary: Modeling neutrino-nucleus cross section

Overview of theory models and generators by N. Jachowicz

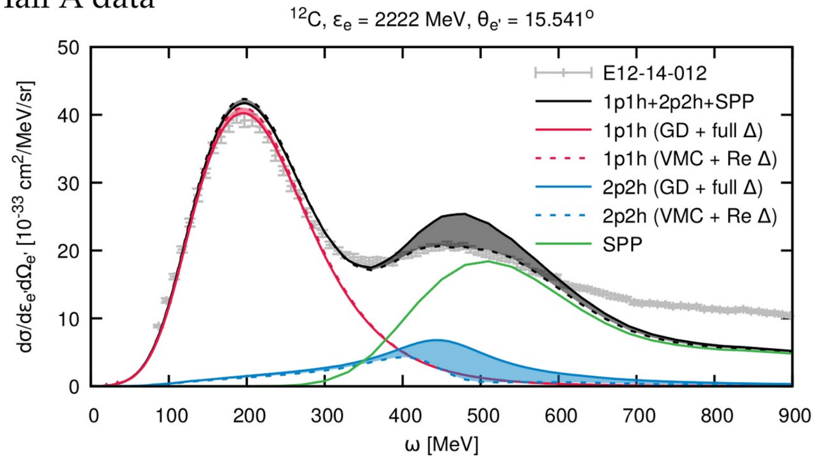
- QE processes are dominating the signal in experiments with average energies of a couple of hundreds of MeVs
- A thorough understanding of the QE cross section is extremely important as it is pivotal for the oscillation analysis
- Correct identification of the reaction mechanism is important but not straightforward



- Coherent Scattering
- Quasi elastic and multinucleon knockout processes
- Models for QE(like) cross sections : Fermi gas approaches
- Models for QE(like) cross sections :SuSA
- Models for QE(like) cross sections : Mean FIeld
- Models for QE(like) cross sections : Spectral function
- Models for QE(like) cross sections : Ab initio
- Models for QE(like) cross sections : Coupled cluster
- Pion Production
- The transition to the Shallow and Deep Inelastic Scattering region
- DIS

Parallel session: Multi-nucleon emission

JLab Hall A data



→ Combining variation in given d.f. provides **flexibility in describing QE and Δ peaks**

Summary

→ We refreshed the **SRC+MEC** Ghent legacy model for **1p1h and 2p2h reactions**

→ We extended the formalism to **neutrino scattering** (Δ-currents)

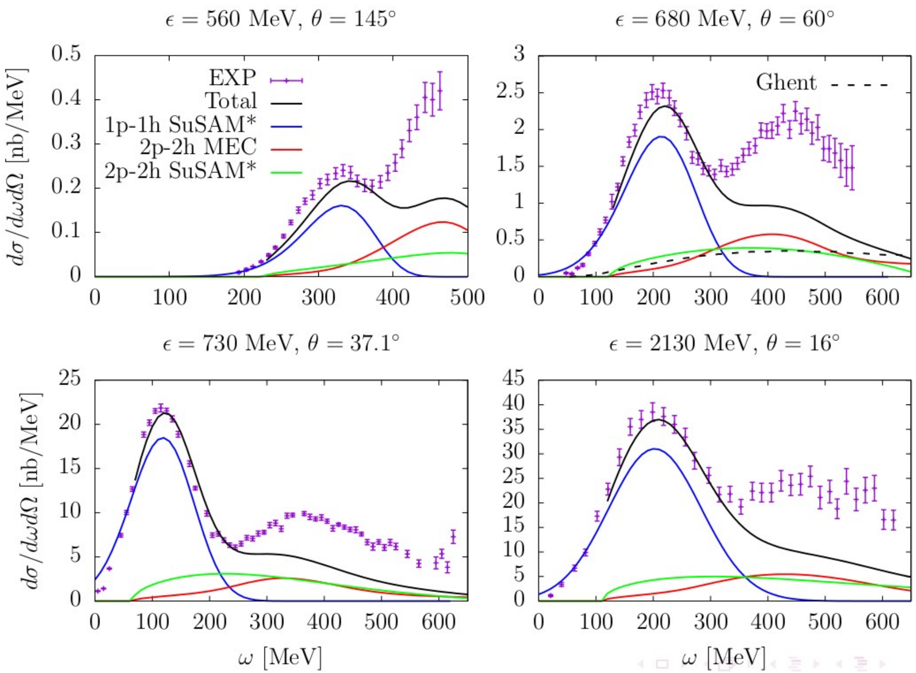
→ We established **vital degrees of freedom** and estimated uncertainties

→ We provide **inclusive**, **semi-inclusive** and **exclusive** two-nucleon knock-out cross sections

→ We performed a preliminary implementation of the **inclusive Ghent 2p2h** model in **NuWro**

Two-Nucleon Emission in Quasielastic Neutrino and Electron Scattering induced by short-range correlations

P.R. Casalé, V.L.M. Consentino, J.E.Amaro, I.R.Simo



K. Niewczas

Mean field models

- ➢ Hartree-Fock **mean field**
- Mean-field models capture a lot of nuclear medium effects in a natural and efficient way
- Can be extended to include long-range RPA correlations

Imperial College London | Implementation progress

- I am currently implementing the nuclear model into the NEUT neutrino event generator framework.
- We seen an in-depth description of NEUT given by Luke in the previous talk. (please see talk).
- The model is now "inside" NEUT and the model is called when it needs to be and produces events.
- Current efforts are being made to ensure the correctness of the events since the model code stems from outside NEUT.

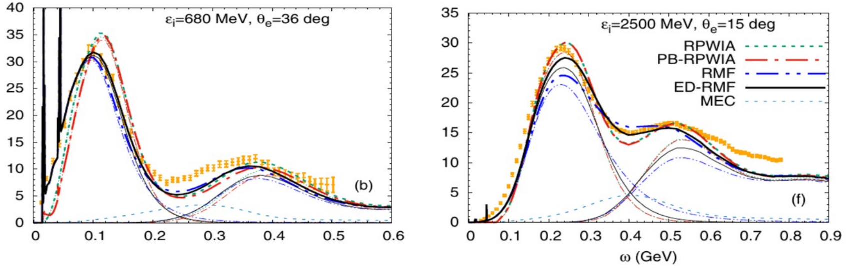
J. McKean

What can **mean-field models** offer?

– Good inclusive cross section with full hadronic information (at the primary vertex).

– Excellent prediction of the **elastic 1p-1h channel**: useful to benchmark cascade models.

Inclusive electron scattering **at intermediate q:**



Distortion of the outgoing nucleon (elastic FSI in a Quantum Mechanical way) is important at intermediate energies too !!!

Model for the primary vertex
RDWIA with real potentials

(Remember it provides good agreem. with inclusive data).

→

CASCADE

The nucleon is propagated through the NEUT cascade.

↓

Signal definition

We select the "only one proton" events (elastic channel).

←

BENCHMARKING the cascade

The output from the cascade should match the predictions from **RDWIA with complex optical potentials.**

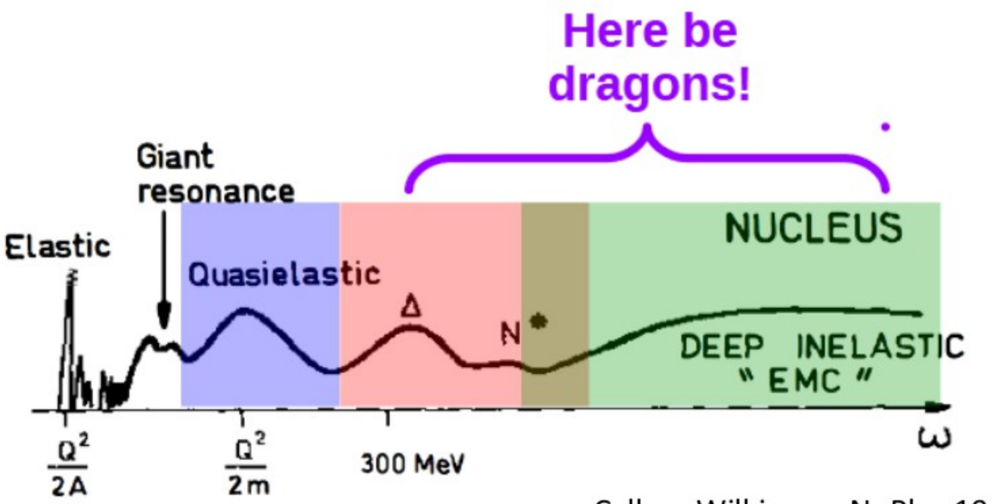
(Remember it provides excellent agreem. with exclusive (e,e'p) data).

R. González Jiménez

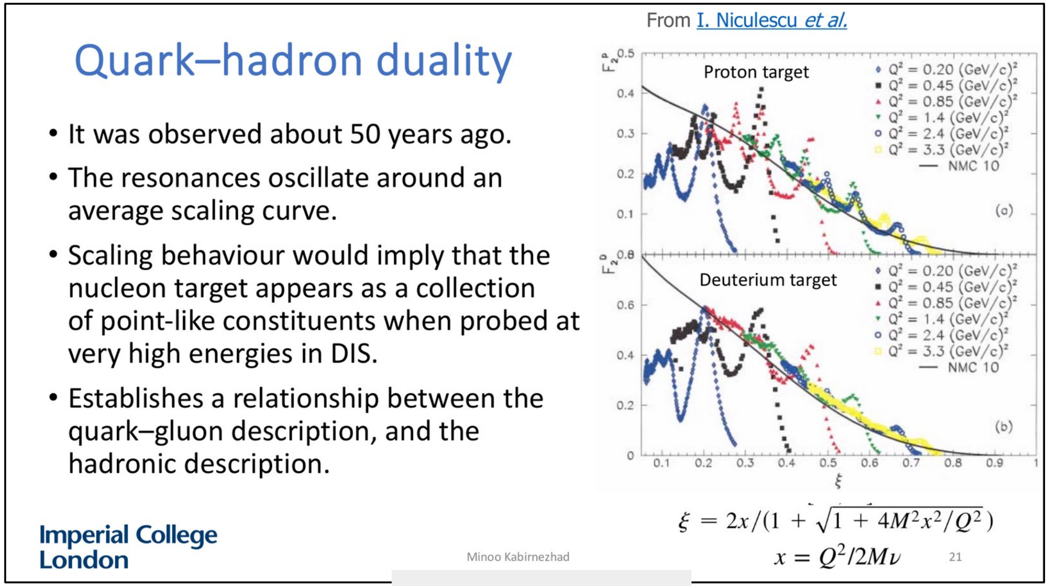
SIS/DIS

- An important challenge for the energy range relevant for DUNE will be reliably bridging the transition from strong interactions described in terms of hadronic degrees of freedom to those among quarks and gluons described by perturbative QCD
- Least understood region (also referred to as dragon region :-))
- There is a strong need for new experimental data of neutrino scattering on nucleons and nuclei as well as theoretical studies of how to consistently model this transition region

V. Pandey



Callum Wilkinson, NuPhys19

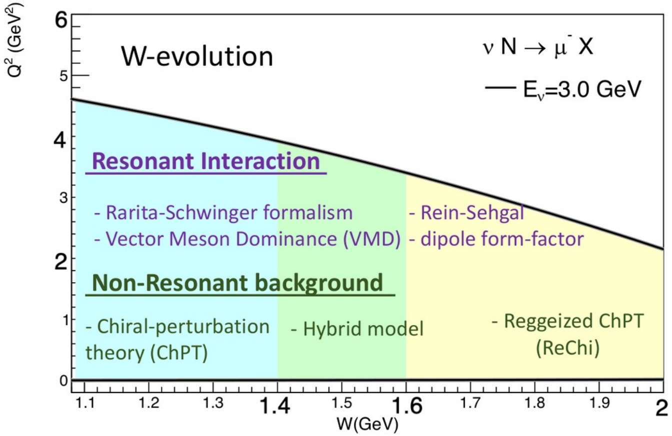


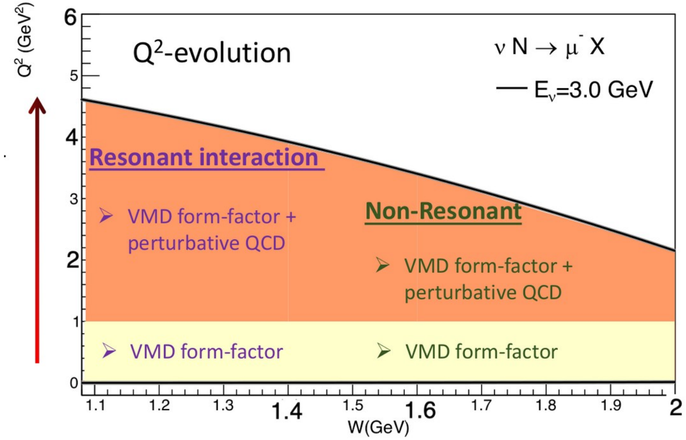
M. Kabirnezhad

Resonant interactions

M. Kabirnezhad presented an update of MK model for single pion production

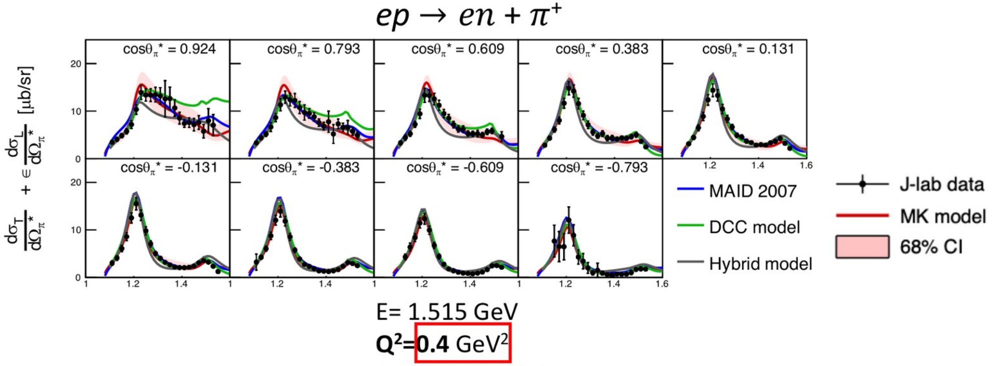
Extended to high Q^2 (6 GeV^2) and W (2 GeV)





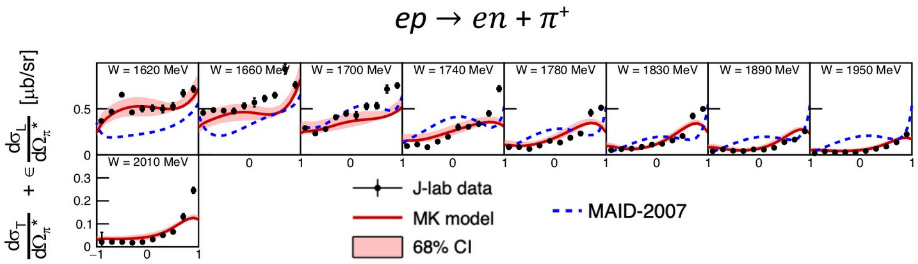
Data/models comparison at low Q^2

M. Kabirnezhad
Phys.Rev.C 107 (2023)



Data/models comparison at high Q^2

M. Kabirnezhad
Phys.Rev.C 107 (2023)



E= 5.449 GeV
Q^2=2.6 GeV^2
1.62 <W< 2.01 GeV
Third resonance region

Imperial College London

Minoo Kabirnezhad 15

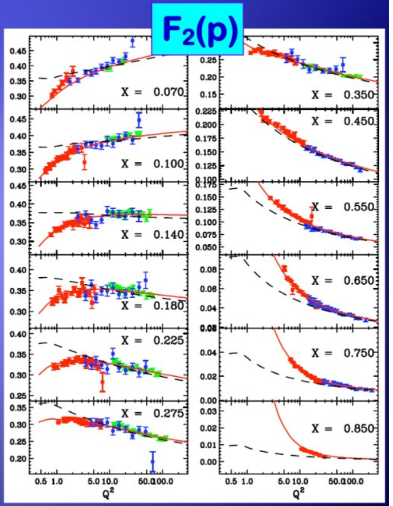
SIS/DIS: models

Bodek-Yang Model

- Bodek-Yang model: describe DIS cross section in all Q^2 regions

Bodek-Yang Effective LO PDFs Model

1. Start with GRV LO PDF (Q^2_{min}=0.80)
2. Replace x_{bj} with a new scaling, ξ_w
3. Multiply all PDFs by K factors for photo prod. limit and higher twist
   [$\sigma(\gamma) = 4\pi\alpha/Q^2 * F_2(x, Q^2)$]
   $Ksea = Q^2/[Q^2+Csea]$
   $Kval = [1- G_D{}^2 (Q^2)] * [Q^2+C_{2V}] / [Q^2+C_{1V}]$
   motivated by Adler Sum rule
   where $G_D{}^2 (Q^2) = 1/ [1+Q^2 / 0.71]^2$
4. Freeze the evolution at $Q^2 = Q^2_{min}$
   - $F_2(x, Q^2 < 0.8) = K(Q^2) * F_2(\xi w, Q^2=0.8)$
5. Fit all DIS F_2(p/D) data:
   SLAC/BCDMS/NMC/HERA data



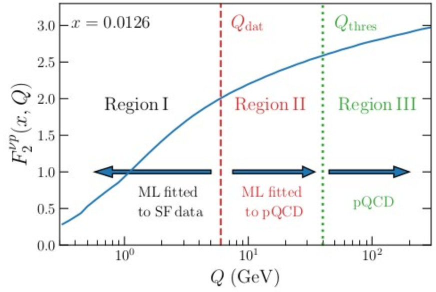
Axial Vector Structure Functions

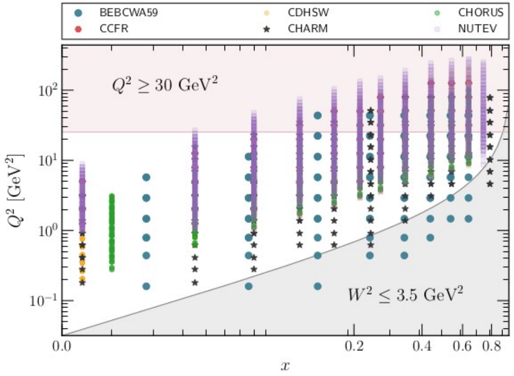
- At high Q^2 , vector and axial vector contribution are same, but not at low Q^2

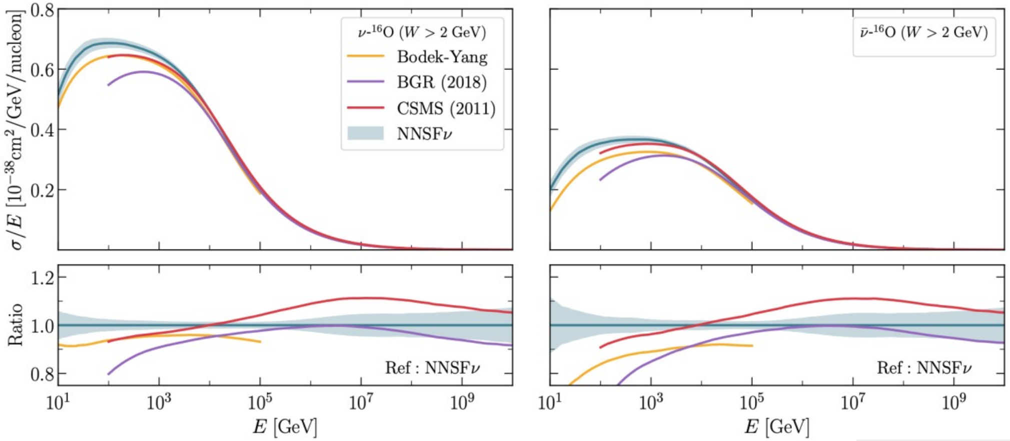
U-K Yang

Develop a new method to account for non-pQCD terms.

- Machine learning parametrisation of low Q using neutrino scattering data.
- High Q region comes from pQCD.
- Account for nuclear effects.







A. Garcia

SIS/DIS: nuclear targets

Target mass corrections

(R. Ruiz)

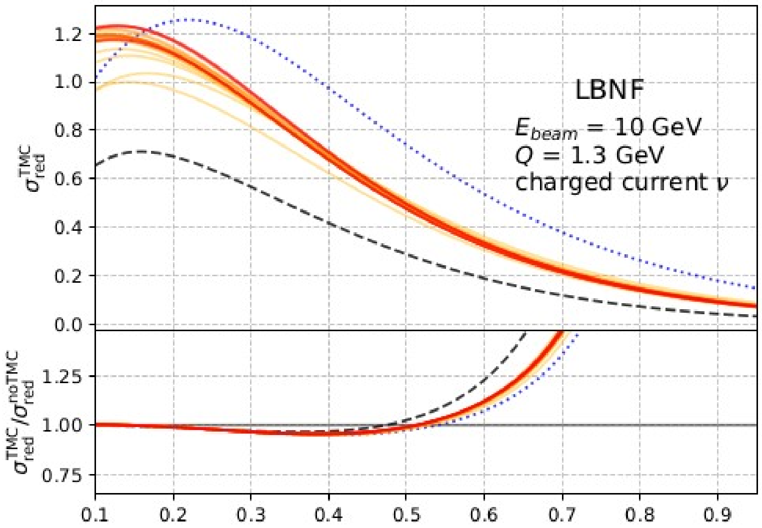
why look into power corrections?

nuclei (A) are not protons $(\mathcal{P})$ ☹

- Starting from OPE, derived TMCs for arbitrary A for $F_1, \ldots, F_6$ ☺

(lenthy appendix to avoid ambiguities in conventions!)

sketched in next few slides!



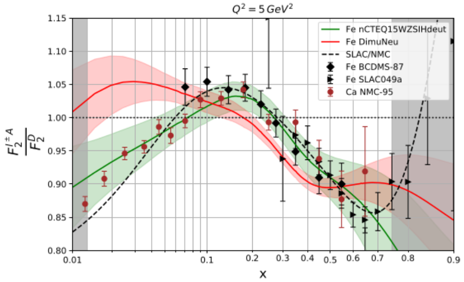
Nuclear Parton Distribution Functions

(Ji-Young Yu)

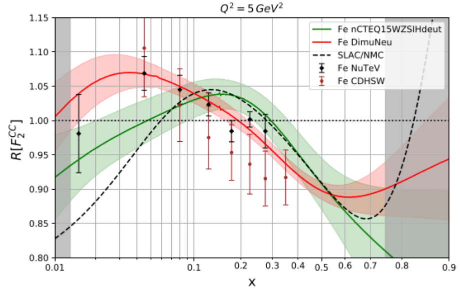
Neutrino DIS vs Charged lepton DIS

Ultimate analysis: " Compatibility of Neutrino DIS data and Its Impact on Nuclear Parton Distribution Functions", arXiv:2204.13157

Data set	Nucleus	$E_{\nu/\bar{\nu}}$(GeV)	#pts	Corr.sys.	Ref.
CDHSW ν CDHSW $\bar{\nu}$	Fe	23 - 188	465 464	No	[48]
CCFR ν CCFR $\bar{\nu}$	Fe	35 - 340	1109 1098	No	[50]
NuTeV ν NuTeV $\bar{\nu}$	Fe	35 - 340	1170 966	Yes	[23]
Chorus ν Chorus $\bar{\nu}$	Pb	25 - 170	412 412	Yes	[27]
CCFR dimuon ν CCFR dimuon $\bar{\nu}$	Fe	110 - 333 87 - 266	40 38	No	[19]
NuTeV dimuon ν NuTeV dimuon $\bar{\nu}$	Fe	90 - 245 79 - 222	38 34	No	[19]



- Most thorough analysis so far (thesis K. F. Muzakka, U Münster): different tools to analyse compatibility of data
- Neutrino data creates significant tensions between key data sets: neutrino vs charged lepton+DY+LHC
- Tensions among different neutrino data sets: iron (CDHSW, NuTeV, CCFR) vs lead (CHORUS)?
- Next nCTEQ analysis will include CHORUS and Di-muon data but not NuTeV, CCFR, CDHSW data



Generators

Generators: introduction

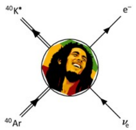
How experiments use models and compare them to data
Active field: many generators, some general some more focused

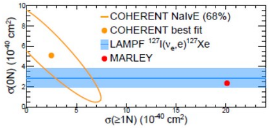
- Number of generators on the market :
  - GENIE, NEUT, NuWro, GIBUU

See Stephen Dolan's WG2 talk on Tuesday !

GiBUU
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- Number of generators on the market :
  - MARLEY : low energy processes (< 100 MeV) S. Gardiner PRC103, 044604 (2021)



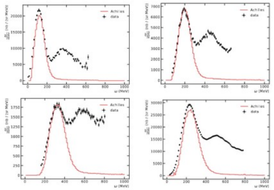


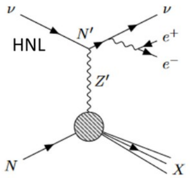
arXiv:2205.06378

- INCL : FSI including nuclear clusters and de-excitation

See Anna Ershova's WG2 talk on Friday !

- Achilles : beyond standard model processes, QMC nuclear input





J. Isaacson et al. PRD 107, 033007 (2023)

N. Jachowicz

March 2023 workshop in FNAL
Summary by A. Papadopoulou

Workshop Overview

- Agenda

- Theory interface (Wednesday afternoon)
- Common flux/geometry drivers (Thursday morning)
- Common event format (Thursday morning)
- **Systematic uncertainties** (Thursday afternoon)
- **Data comparison tools** (Friday)

Conclusions & Outlook

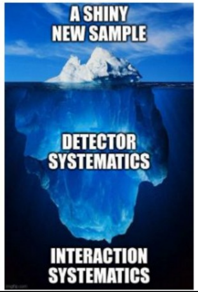
White Paper Plans (1)

- Goals:
  - Similar scope to white paper from 2020 workshop
  - List a set of action items to accomplish in a one to two year time span (aim to meet again to evaluate status as well)
  - Hope to maintain working groups after the workshop to work on action items
  - Notes from the workshop can be found at:

https://docs.google.com/document/d/1wFUCu4o1pkBsvsUW6iQRlQ81rbEjM7qo3Xm6yMnwg64/edit?usp=sharing

White Paper Plans (2)

- Create working groups to focus on each topic
- Looking for volunteers to lead each topic:
  - Theory interface
  - Common flux/geometry drivers
  - Common event format
  - Systematic uncertainties
  - Data comparison tools
- Responsibilities would include:
  - Leading the writing of the given section of the white paper
  - Organizing meetings with other interested parties on establishing plans for future development



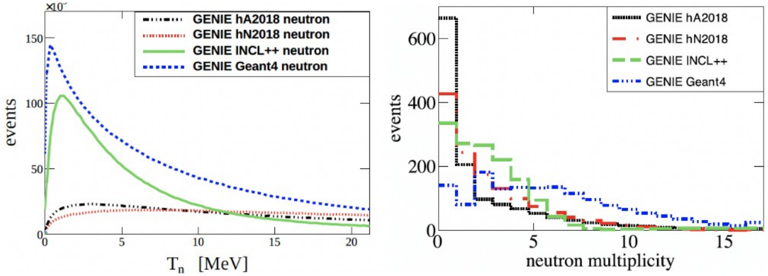
10

Standard generators

GENIE | NEUT | NuWro (Wroclaw Neutrino Event Generator) | GiBUU — The Giessen Boltzmann-Uehling-Uhlenbeck Project

GENIE
C. Andreopoulos

3. Summary of recent developments
4. **Medium energy neutrino scattering** in GENIE
5. **High energy / ultra high energy neutrino scattering** in GENIE
6. **Low energy neutrino scattering** in GENIE
7. New **BSM generators** in GENIE
8. Tuning programme



2 GeV

$\nu_\mu + ^{40}Ar$

- **Substantial developments since the release of v3 in Oct 2018**
- **GENIE v4 on the horizon**
  - Req'd devel: DCC [53, 54], MAID [59], reweighting support for tunes.
  - Will feature a novel but reduced/targeted set of ME physics configurations
  - New tuning campaign and uncertainty evaluation for preferred configurations, including new analyses (TKI and FSI global fits)

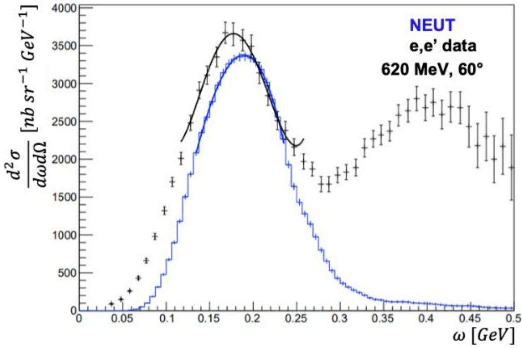
NEUT: L. Pickering

Maintained 'in house' for use on T2K and SK:

- Development targets the needs of the long baseline oscillation and cross-section programmes

Electron Scattering

- New capability to run an e-like mode in NEUT
- Can be used to benchmark nuclear response implementation:



Future: NEUT 6

- Development has begun on NEUT6 - Targeted at HK and final T2K analyses:
  - Significant reorganization of code-base
  - Improved, modern build system
  - Removed dependence on an external CERNLIB2005
  - New TOML-based configuration file
  - Modern C/Fortran interop
  - Automatic C/Fortran interface generation for model integration
- Aim is to release NEUT6 as open source under the GPL before the end of 2023

Generators: focus on some developments

Spectral function in GENIE
N.Steinberg

Incorporating new models into event generators

- Common issue is large time/person investment
  - Translating codes/phase space/form factors/constants/FSI models/etc..

Summary of Workshop on Common Neutrino Event Generator Tools

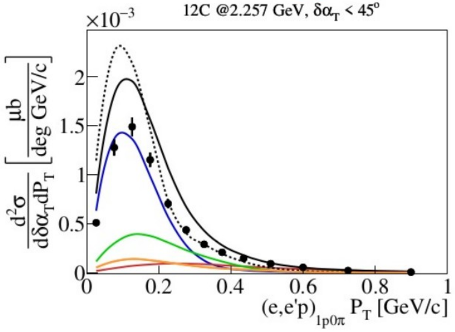
Josh Barrow[1], Minerba Betancourt[2], Linda Cremonesi[3], Steve Dytman[4], Laura Fields[2], Hugh Gallagher[5], Steven Gardiner[2], Walter Giele[2], Robert Hatcher[2], Joshua Isaacson[2], Teppei Katori[6], Pedro Machado[2], Kendall Mahn[7], Kevin McFarland[8], Vishvas Pandey[9], Afroditi Papadopoulou[10], Cheryl Patrick[11], Gil Paz[12], Luke Pickering[7], Noemi Rocco[2,13], Jan

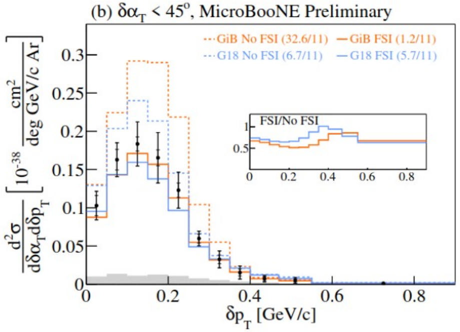
- GENIE Fortran Interface
  - Instead of a pre-computed hadron tensor, compute it on the fly!
  - Use existing Fortran code to compute unintegrated $A^{\mu\nu}$ (different than W!)
    - Fully exclusive

F + Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

e4v e⁻ ⟷ µBooNE ν_μ





FSI with INCL
A. Ershova

Potential

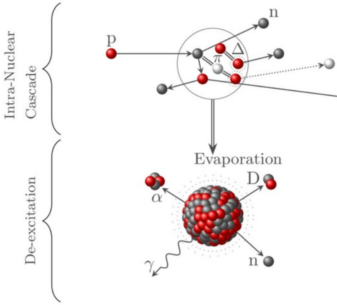
Each nucleon in the nucleus has its **position and momentum** and moves **freely** in a square potential well. Nuclear model is essentially **classical**, with some additional ingredients to mimic quantum effects.

Pauli Blocking

criteria by which the state cannot be occupied

Events inside cascade

- decay/collision
- reflection
- transmission with probability to **leave the nucleus as a nuclear cluster**



Projectiles: baryons (nucleons, Λ, Σ), mesons (pions and Kaons) or light nuclei (A ≤ 18). **No neutrinos** yet! We use neutrino vertex from **NuWro** (widely used ν-nucleus MC generator).

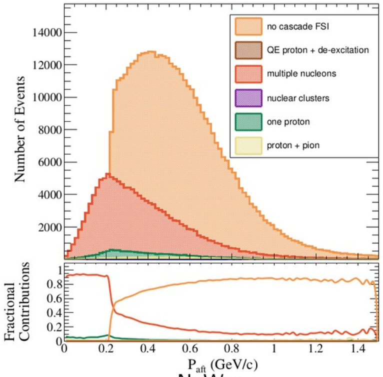
Flexible tool: has been implemented in GEANT4 and GENIE

De-excitation: ABLA, SMM, GEMINI

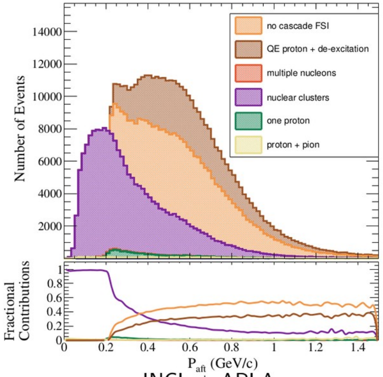
We will use **ABLA**, since it proved to work for the **light nuclei** (Phys. J. Plus 130, 153 (2015))

First neutrino simulation results: Phys.Rev.D 106, 3 (2022)

INCL+ABLA simulation features **massive difference** in nucleon kinematics in comparison to NuWro



NuWro



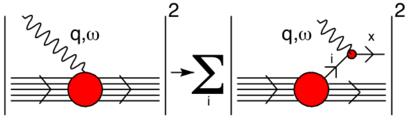
INCL + ABLA

Experiment

Plenary: Determination of the Argon SF from (e,e'p) data

Factorisation of the Nuclear Cross Section

- In the PWIA regime, corresponding to $\lambda \ll d_{\rm NN} \sim 1.5$ fm , nuclear scattering reduces to the incoherent sum of scattering processes involving individual nucleons



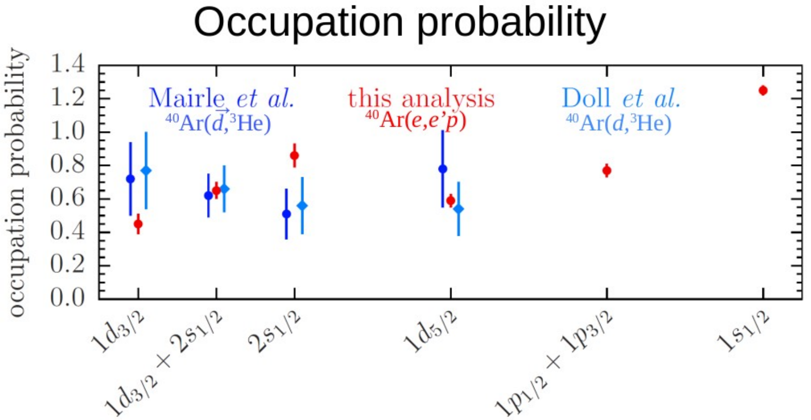
- Basic assumptions
  - $J^\mu_A(q) \approx \sum_i j^\mu_i(q)$ (single-nucleon coupling)
  - $|(A-1)_n, \mathbf{p}'\rangle \approx |(A-1)_n\rangle \otimes |\mathbf{p}'\rangle$ (factorization of the final state)
- As a zero-th order approximation, Final State Interactions (FSI) and processes involving two-nucleon Meson-Exchange Currents (MEC) are neglected. Their effects are included as corrections.

Relevance to Neutrino Experiments

- The approach based on factorisation and the spectral function formalism provides a fully consistent theoretical framework, uniquely suited to meet the challenges posed by the interpretation of neutrino interactions
  - It allows to combine an accurate description of nuclear structure and dynamics—which can be obtained from non relativistic nuclear many-body theory—with a fully relativistic treatment of the variety of the hadronic final states produced in scattering processes involving broad-band neutrino beams
- The spectral functions extracted from $\mathrm{Ar}(e,e'p)$ and $\mathrm{Ti}(e,e'p)$ will be essential for the description of events observed by accelerator-based neutrino experiments using liquid argon detectors

Comparison with Previous Argon Data

- Nucleon knock-out from Argon has been also studied in the proton pick-up reaction ${}^{40}\mathrm{Ar}({}^2\mathrm{H},{}^3\mathrm{He})$ using both inpolarised and polarised deuteron beams



- The results of present analysis turn out to be largely compatible with previous data

O. Benhar

Experimental cross-section results on Ar and non-Ar targets

Keeping pace with experimental progress : semi-inclusive and exclusive cross sections

- Until not too long ago : mainly inclusive data on ^{12}C
- LArTPC detectors : more exclusive data

N. Jachowicz

SUMMARY

Neutrino Cross Section measurements provides a model independent probe on the many assumptions adopted for oscillation and other BSM physics.

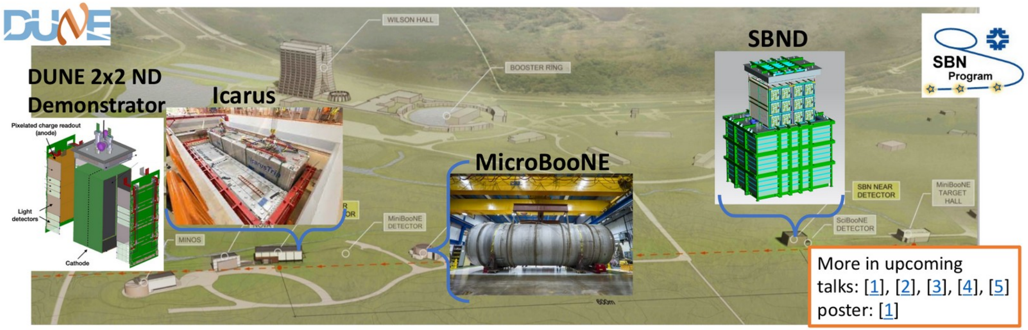
MINERvA and the near detectors of T2K and NOvA have been/are delivering high statistical studies:

- MINERvA explored many different channels and developed MINERvA-informed.
  - Generally observed a need of low Q2 suppression, also observed by others (T2K, NOvA).
  - Factorization in longitudinal and transversal momentum, and the triple differential cross sections provides unvaluable information that is going to take a while to digest.
  - Data preservation plan is pioneering in the community and very welcomed!
- T2K has produced several ratios and simultaneous fit measurements (nu/anti-nu, O/CH,…).
  - Tests over a variety of models (NEUT, GENIE, NuWRO, GiBUU), but no tests on MINERvA tunings.
  - Stay tuned for the T2K ND upgrade!
- NOvA has explored CC inclusive and inclusive π^0 productions.
  A large amount of data has been already explored.

- CEvNS results, on different targets, are already coming. See talks by:
  - **Overview of physics results with coherent elastic neutrino-nucleus scattering data**. Matteo Cadeddu. 8/22/23.
  - **Study of Neutrino Interactions by the COHERENT collaboration**. Yuri Efremenko. 8/25/23.

R. Castillo Fernández

Wealth of New Data Ahead



More in upcoming talks: [1], [2], [3], [4], [5]
poster: [1]

More statistics: better isolation of various final state topologies [1]

SBND expects 20-30 times more data in the BNB than current data sets, average neutrino energy 0.8 GeV SBND NuInt '22

Icarus will measure NuMI neutrinos at ~5 degrees off axis (up to ~2 GeV) in addition to BNB neutrinos Icarus NuINT '22

DUNE 2x2 ND Demonstrator will collect NuMI data on-axis over a range of energies (~2-8 GeV) 2x2 NuINT 2022

Opportunity for high statistics measurements, possibility of NuMI anti-neutrinos in Icarus and DUNE 2x2

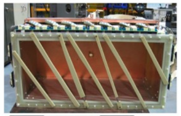
S. Berkman

Experimental cross-section results on Ar targets

ArgoNeuT and MicroBooNE

- Liquid argon time projection chamber detectors
- To date most neutrino-argon cross section measurements are from these experiments

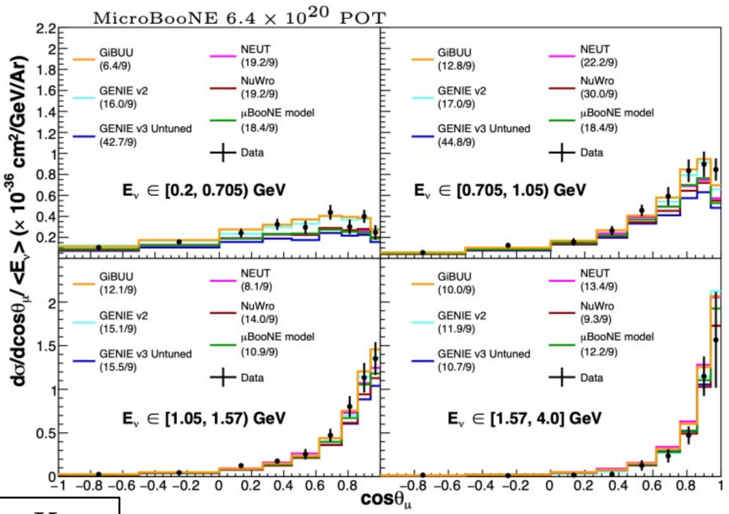
	ArgoNeuT *JINST 7 (2012) P10019*	MicroBooNE *JINST 12 (2017) 02, P02017*
Operation:	2009-2010	2015-2020
Active Volume:	0.25 Ton	85 Ton
Beam Energy:	NuMI (on-axis): neutrino = <4.6 GeV> anti-neutrino = <3.6 GeV>	BNB: neutrino = <0.8 GeV> NuMI (8° off axis): neutrino = ~<0.9 GeV> anti-neutrino = ~<0.9 GeV>




Overview of selected results from these experiments

2023: First triple differential measurement

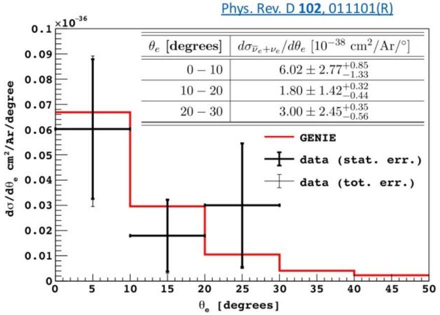
MicroBooNE: arXiv:2307.06413



$$\nu_e + Ar \rightarrow e + X$$

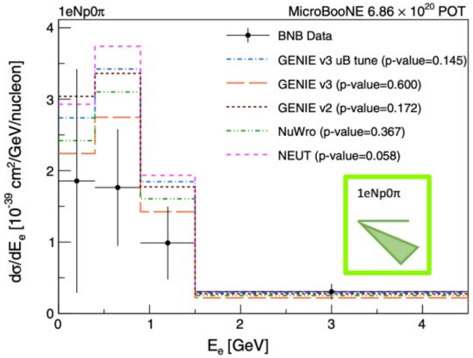
ArgoNeuT: First measurement

Phys. Rev. D **102**, 011101(R)



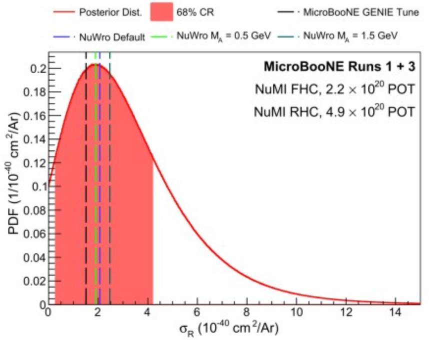
θ_e [degrees]	$d\sigma_{\bar{\nu}_e+\nu_e}/d\theta_e$ [10^{-38} cm^2/Ar/°]
0 – 10	$6.02 \pm 2.77^{+0.85}_{-1.33}$
10 – 20	$1.80 \pm 1.42^{+0.32}_{-0.44}$
20 – 30	$3.00 \pm 2.45^{+0.35}_{-0.56}$

$$\nu_e + Ar \rightarrow e + Np + 0\pi$$

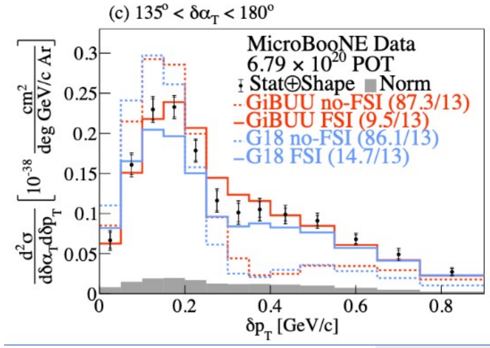


$$\bar{\nu}_\mu + \mathrm{Ar} \rightarrow \mu^+ + \Lambda + X$$

Phys. Rev. Lett. **130**, 231802



MEC/Resonant/FSI Dominated



Experimental cross-section results on non-Ar targets

Disclaimer: On this talk I will mostly focus on recent results from **MINERvA, T2K, NOvA** due to time constraints.

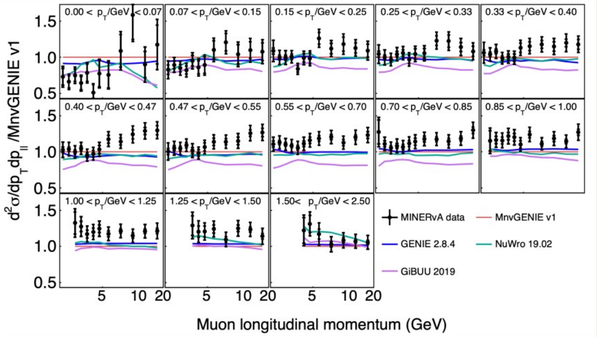
Charged Current Inclusive measurements (CC)

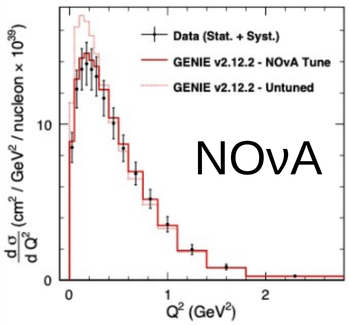
MINERvA

NuMI low energy mode, <E_ν> ~3.5GeV
Flux uncertainty 7% on average (dominant uncertainty)

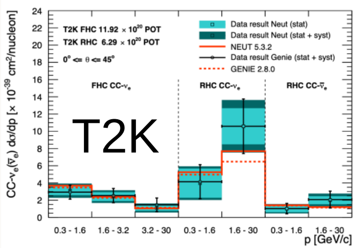
Selected 325,588 events of ν_μ CC on hydrocarbon

Lepton kinematics

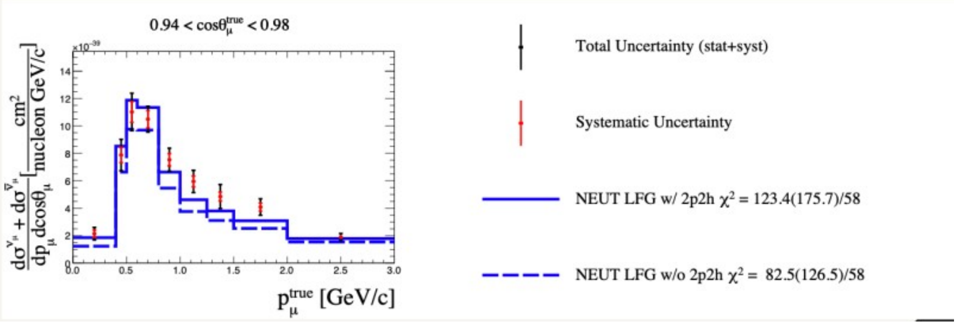




J. High Energ. Phys. 2020, 114 (2020)

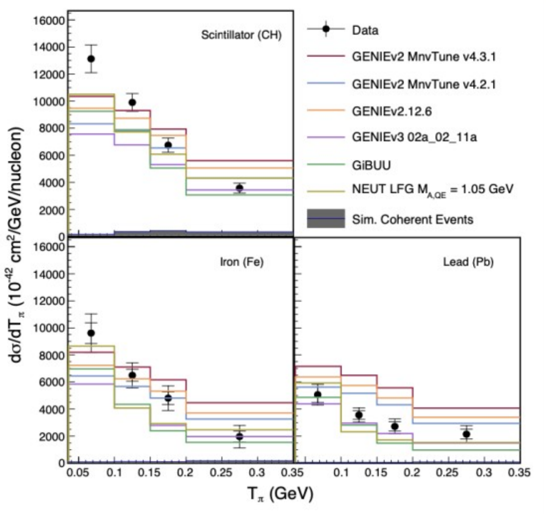


Phys. Rev. D 101, 112001 T2K $\bar{\nu}_\mu$ CC0π



MINERνA CCπ$^+$

Phys. Rev. Lett. 131, 011801



Parallel: experimental cross-section results

Results and perspectives from many experiments presented during workshop
(very) quick overview in the coming slides

Parallel: experimental cross-section results COHERENT

Physics of SN explosion is very rich
99% of explosion energy is emitted by Neutrinos
SN explosion is one of the sources of heavy elements in the universe

Are we ready for the next galactic SN?

What Experimental Data do we have for Low Energy (<100 MeV) Neutrino Interactions on Nuclei?

Isotope	Reaction	Experiment
^{2}H	CC	E31 (LAMPF)
^{12}C	CC, NC	KARMEN (ISIS), LSND (LAMPF), E225 (LAMPF)
^{13}C	CC	KARMEN (ISIS)
^{56}Fe	CC	KARMEN (ISIS)
^{71}Ga	CC	GALEX (Gran Sasso), SAGE (Baksan)
^{127}I	CC	E-1213 (LAMPF), COHERENT 2023 (SNS)
^{208}Pb	CC+NC	COHERENT 2022 (SNS)

What Are Nuclear Targets for the Large Neutrino Detectors?

C, O, Ar, Xe, Pb

Heavy Water Detector to Measure Neutrino Flux and CC on oxygen

S.Nakamura et. al. Nucl.Phys. A721(2003) 549

Prompt NC ν_μ +d → $1.8 \cdot 10^{-41}$ cm²
Delayed NC $\nu_{e\mu\text{-bar}}$+ d → $6.0 \cdot 10^{-41}$ cm²
Delayed CC ν_e + d → $5.5 \cdot 10^{-41}$ cm²

Detector calibration with Michel Electrons from cosmic muons (same energy range)

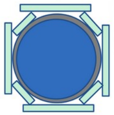
- Neutrino Alley space constraints for the D2O detector are:
  - 1 m diameter x 2.3 m height
- Locations 20 meters from the SNS target

Will do CC measurement on Oxygen for SN

Eli Ward poster on Wednesday

Specifications

- 0.55 tons D_2O within acrylic inner vessel
- Water Cherenkov Calorimetry
- H_2O "tail catcher" for high energy e⁻
- Outer light water vessel contains PMTs, PMT support structure, and optical reflector.
- Outer steel vessel to
- Lead Shielding
- Hermetic veto system

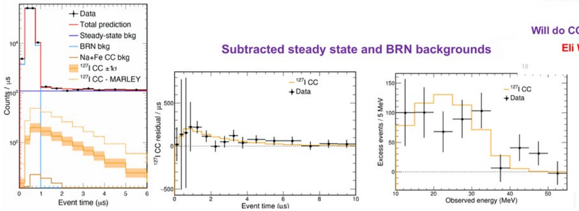


Iodine cross section results

Best fit gives 541^{+121}_{-108} events or 5.8σ evidence of CC

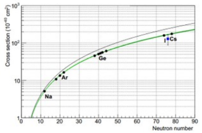
Corresponds to cross section of $9.2^{+2.1}_{-1.8} \cdot 10^{-40}$ cm² or 40% of MARLEY prediction

Subtracted steady state and BRN backgrounds



Future for LAr - 1 ton LAr detector

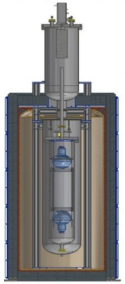
Need high statistics and low background measurements for CEvNS and good energy linearity for CC

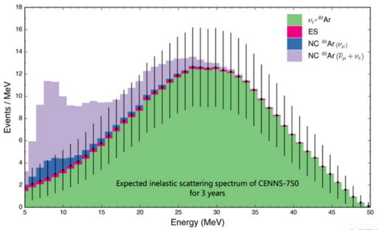


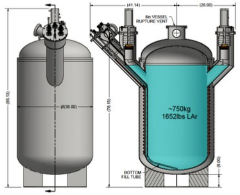
Transition from 22 kg to 1 ton LAr detector.

Can fit at the same place where presently is CENSS-10

Will see 3kt of CEvNS events per year + 400 CC

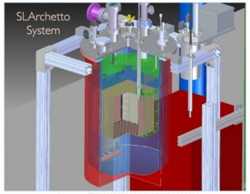






+

R&D on compact TPC SLAC (Yun-Tse-Tsai)



...etector is being build by our Korean collaborators at SNU

See Haemin Jeong talk yearly today

Yu. Efremenko

21

OAK RIDGE National Laboratory

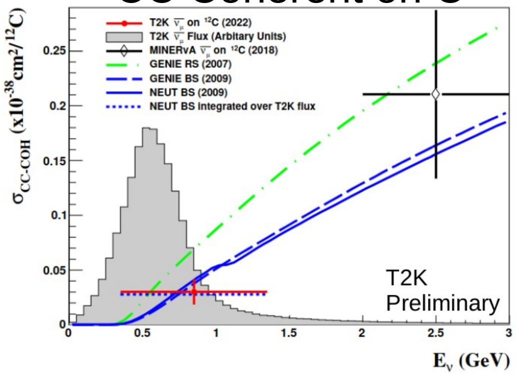
Parallel: experimental cross-section results
ND of LBL experiments: T2K and NOvA

T2K

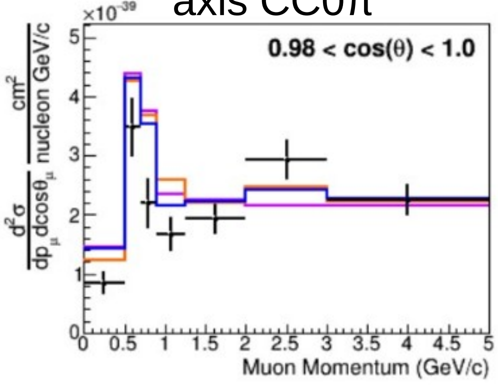
L. Koch

- Recent official results
  - Charged current coherent on carbon
  - Combined on- and off-axis $0\pi^{+/-}$
- Upcoming measurements
  - Intermediate angle $0\pi^{+/-}$ and combination of all angles
  - Kaon production

CC Coherent on C



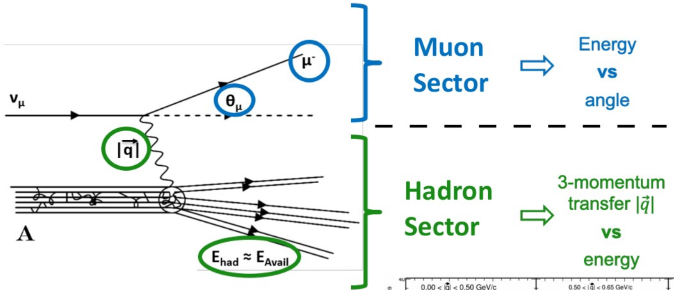
Combined on/off axis CC0π

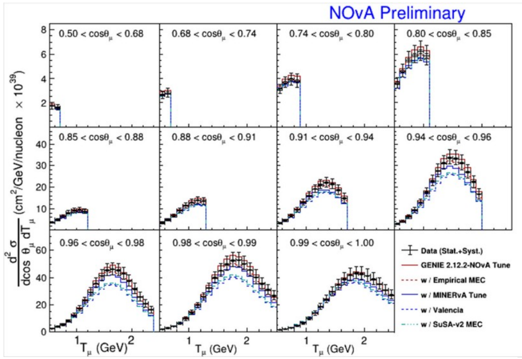


NOνA

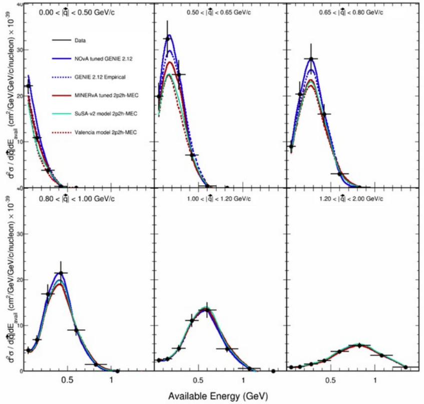
P. Singh

- Both focus on 2p2h interactions





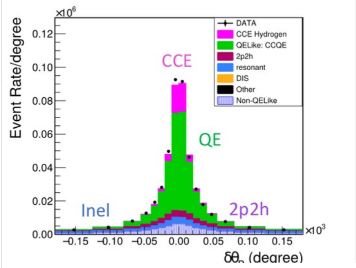
Theory models are underestimating cross sections in 2p2h region

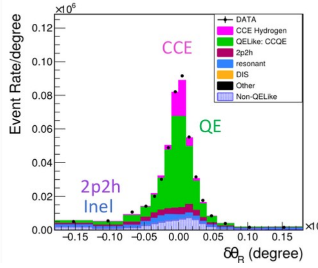


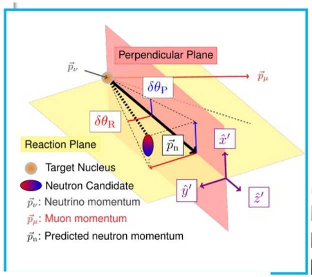
Theory models are underestimating cross section in 2p2h region

Parallel: experimental Results MINERvA

MINERvA recently published (*Nature* 614, 48–53) a high statistics, ~5000 event, measurement of the reaction $\bar{\nu}_\mu p \rightarrow \mu^+ n$, which we call "charged-current elastic scattering".

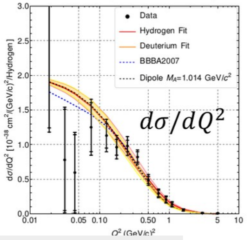


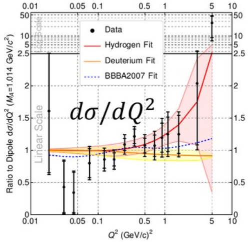


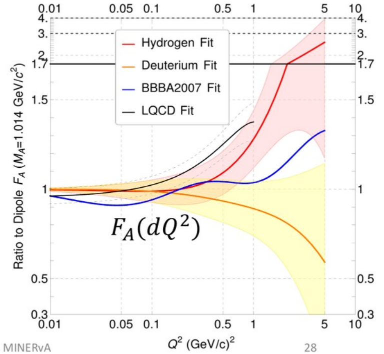


Free Nucleon Axial Form Factor

- We have ~5800 such events on a background of ~12500.
- Shape is not a great fit to a dipole at high Q^2.
- LQCD prediction at high Q^2 is close to this result, but maybe not at moderate Q^2.







K. McFarland

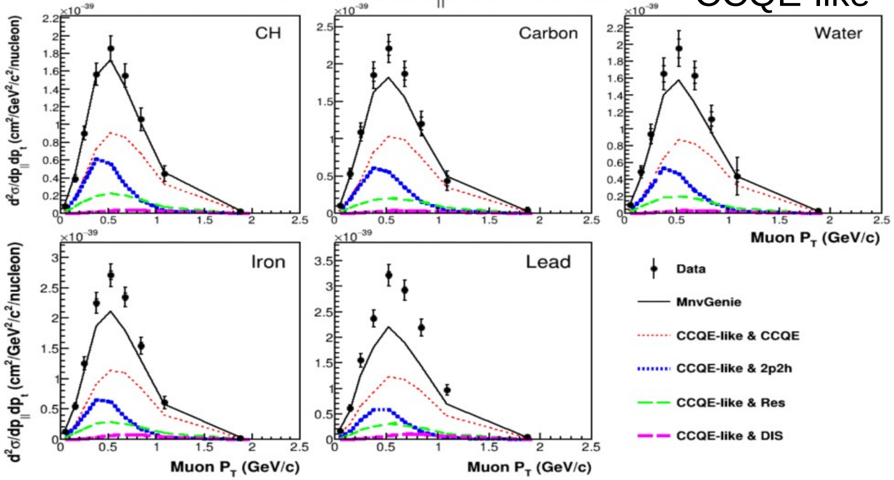
K. McFarland, CC Elastic Scattering on Free Protons @ MINERvA 28

Recent results from MINERνA

V. Ansari

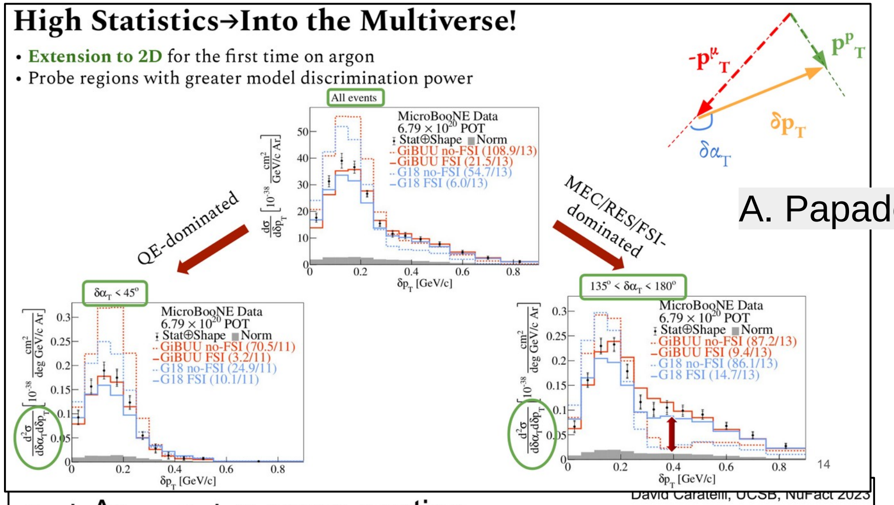
- Nuclear dependence on :
  - Neutrino CCQE-like: A-dependence on C, CH, H_2O, Fe, Pb
  - Neutrino CC1π^+: A-dependence on C, CH, H_2O, Fe, Pb
  - Neutrino CC1π^0: A-dependence on Fe, Pb
- Antineutrino CCQE-like on CH

4.5 < Muon $P_{||}$ / GeV / c < 5.5 CCQE-like

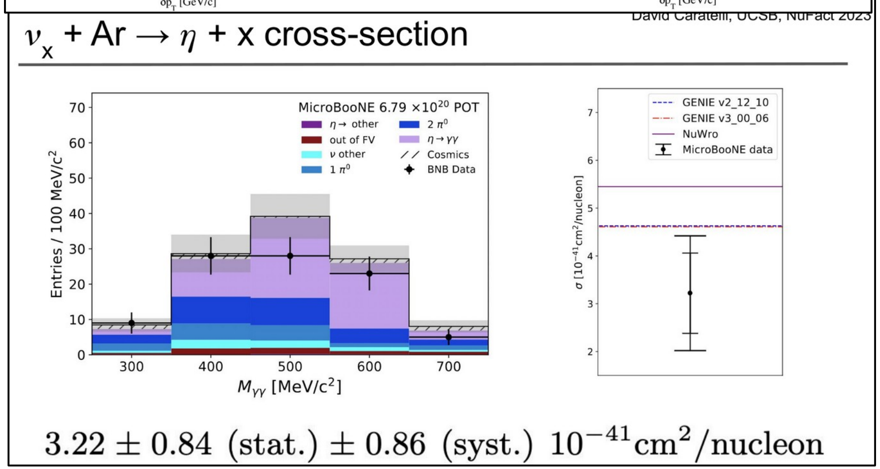


Parallel: experimental cross-section results
Liquid Argon experiments

Details of **MicroBooNE** results



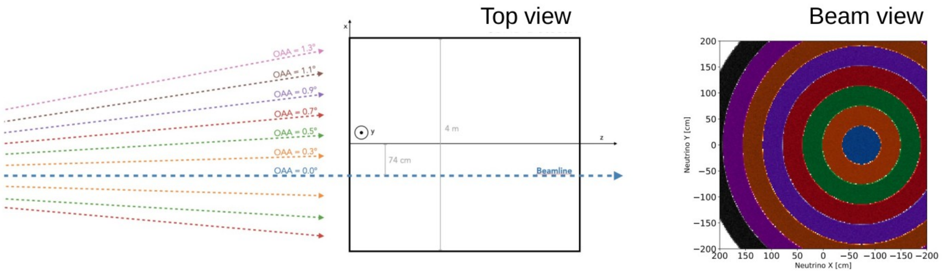
A. Papadopoulou



SBND
A. Furmenski

30x MicroBooNE stats

5M ν_μ CC per year
2M NC per year
12k ν_e CC per year



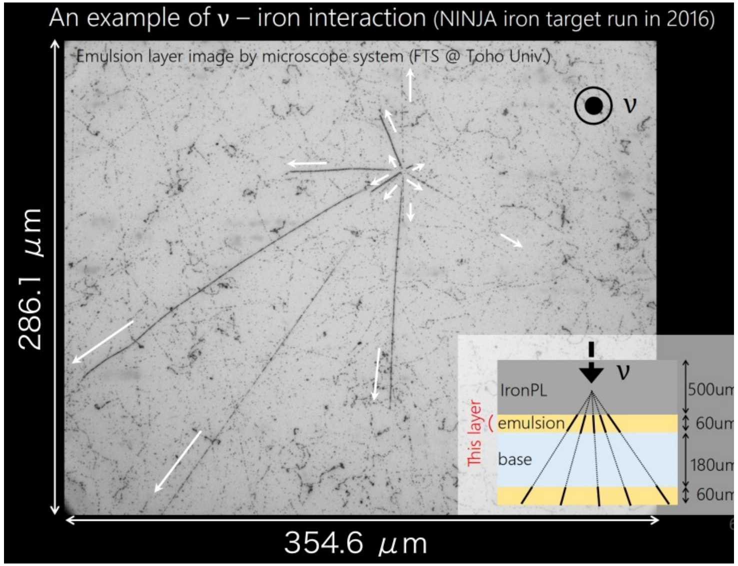
What's Next?

- Argon fill starts soon!
- Cold commissioning, and CRT installation in late 2023 / early 2024
- Initial Physics Run planned for spring 2024
- After that, **one neutrino every six seconds!**

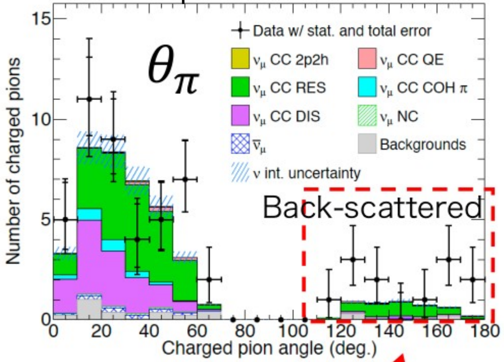
Parallel: experimental cross-section results Emulsion

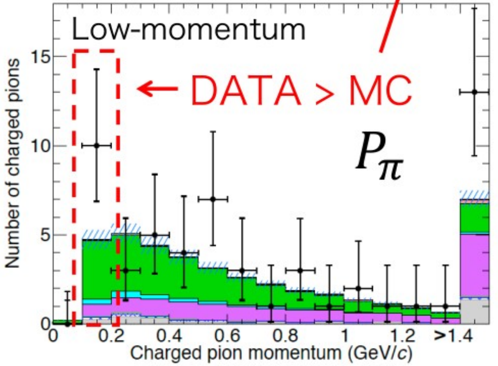
Emulsion technology also allows precise tracking with low thresholds and different target materials

NINJA experiment

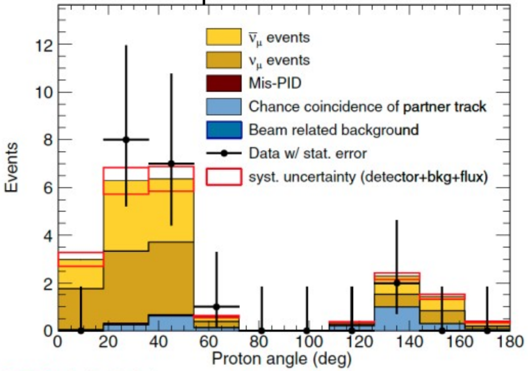


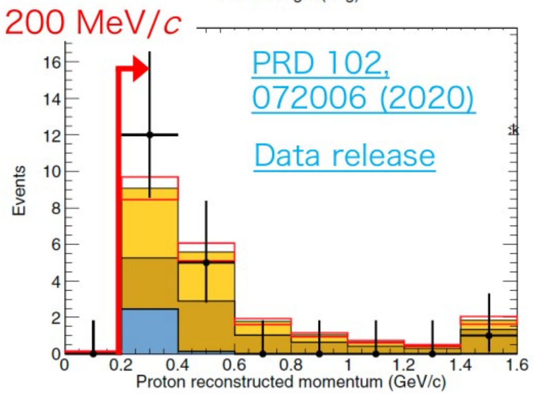
ν_μ on Fe





$\bar{\nu}_\mu$ on water





PRD 102, 072006 (2020)

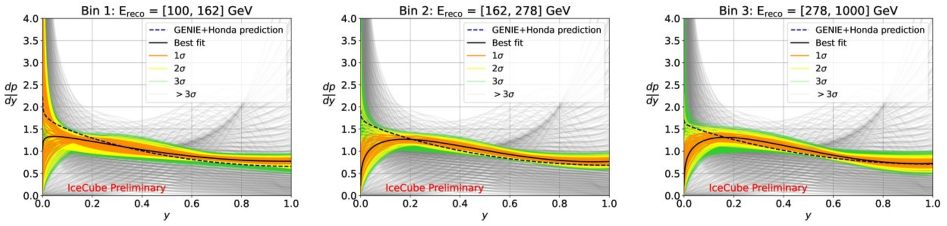
Data release

H. Oshima

Also used for measurement of high energy neutrino produced at LHC (next slide)

Parallel: experimental cross-section results
High energy

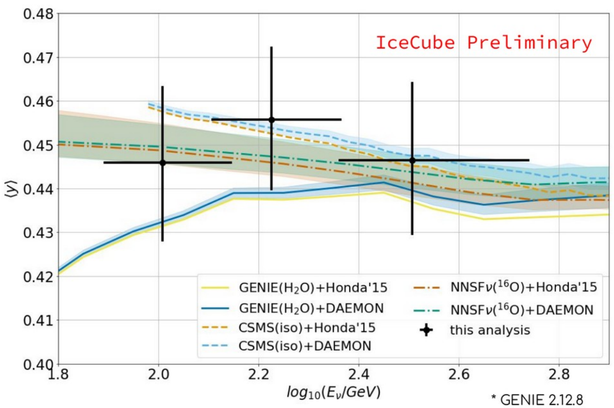
Measurement of the inelasticity distribution of neutrino-nucleon interactions for 100 GeV < E_ν < 1 TeV with IceCube DeepCore



<y> comparison to model predictions

- ★ Calculated p-values for each models
  - ✧ model uncertainties not included
- ★ All tested models in agreement at 1σ level

Model combination	χ^2	p-value
GENIE + Honda'15	2.19	0.53
GENIE + DAEMON	1.91	0.59
CSMS + Honda'15	1.40	0.70
CSMS + DAEMON	1.61	0.66
NNSFν + Honda'15	0.08	0.99
NNSFν + DAEMON	0.13	0.99



* GENIE 2.12.8

[9] J. P. Yañez, A. Fedynitch, "Data-driven muon-calibrated neutrino flux"

[10] A. Candido et al., "Neutrino Structure Functions from GeV to EeV Energies" (thanks to Alfonso Garcia for providing NNSFν cross section!)

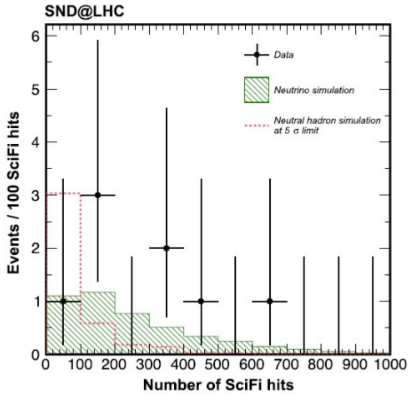
16

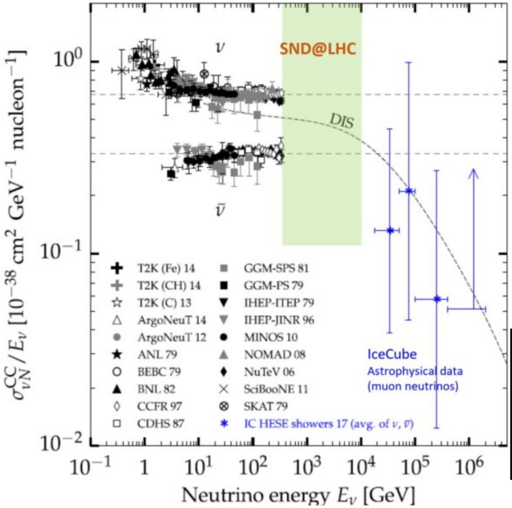
M. Liubarska

Neutrinos from collisions at LHC (ATLAS)

SND: Yeong Gyun Kim

FASERν: Jeremy Atkinson

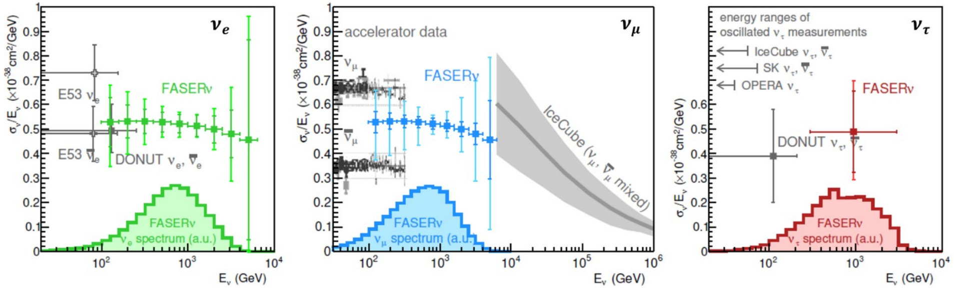




New FASERν Results – (

- 7 selected ν CC events after applying kinematic selection (p_{lep} > 200 GeV) .

Projected precision of FASERν measurement at 14-TeV LHC (150 fb^{-1})

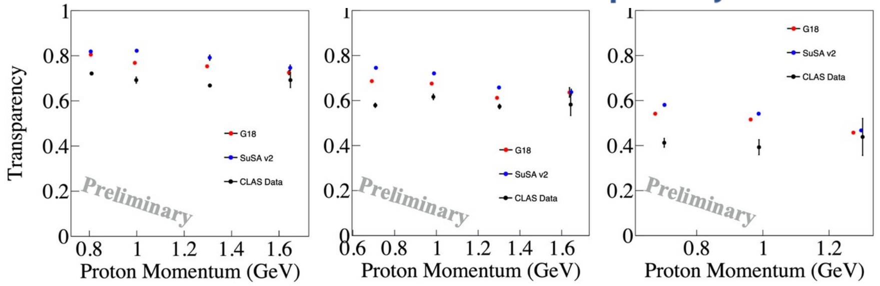


Parallel: experimental cross-section results
Neutron and electrons

Electrons for Neutrinos
N. Steinberg

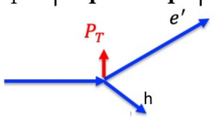
"Any model must work for electrons to work for neutrinos"

New Results – Nuclear Transparency

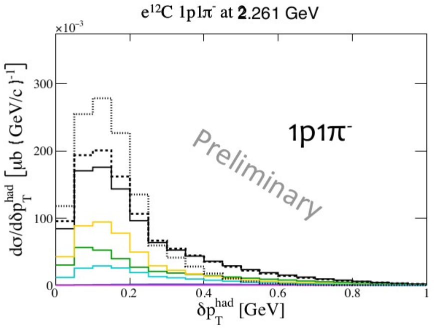


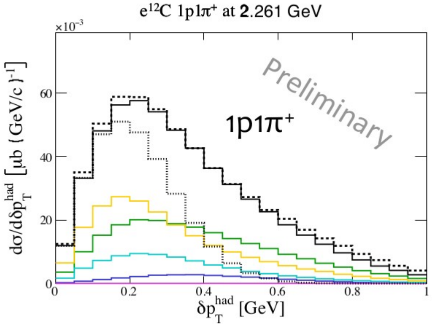
New Results – Single Pion production

$P_T = | \mathbf{P_T}^{e'} + \mathbf{P_T}^{h} |$

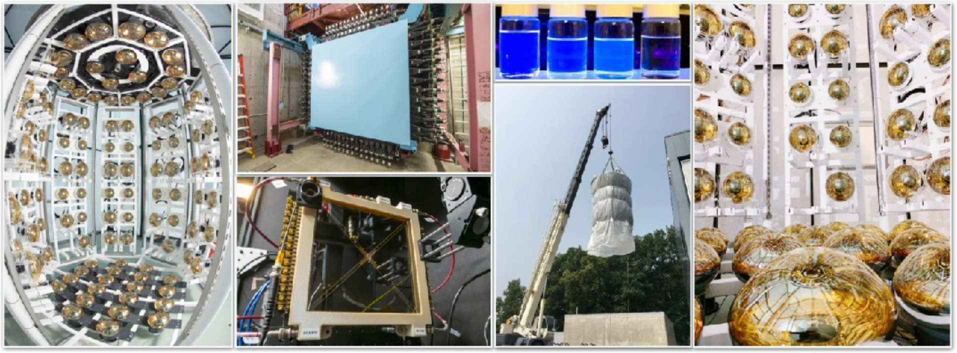


- Simultaenous measurement of 1p1π⁺ and 1p1π⁻
  - GENIE simulation broken down into components
  - G18_10a **hA**, 10b **hN**, G18 **no FSI**



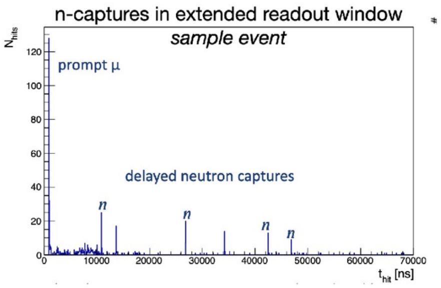


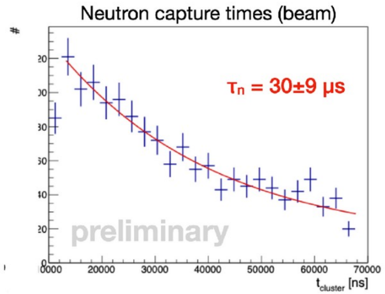
ANNIE
A. Sutton



First beam neutrinos

- Beam spill + high PMT readings define a 2 μs trigger window
- Additional PMT signals open up an extended 70 μs window to detect delayed neutrons
  - Beam neutron capture time agrees with AmBe calibration





Conclusion

- Understanding and being able to describe neutrino scattering critical for future study of neutrino oscillations and a number of BSM searches

- Many challenges, but very active community, many efforts on-going in theory, interaction generators and experiments

- Great problem to have as conveners: so many contributions that it is difficult to make the program for the WG sessions.

- Takeaway from convenors:
  - Growing interest/need for model systematics and a desire for theory-based uncertainties
  - An effort should be make to incorporate state-of-the-art nuclear models in generators. These models (for the primary vertex: QE, RES and 2p-2h) should provide information on the hadrons, which are then propagated through the nucleus with the cascade
  - Many experimental measurements already available, even more expected in the near future: plenty of data to study neutrino scatterings in the coming years