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NEUTRINO SCATTERING – WG2

Christophe Bronner, University of Tokyo
Elena Gramellini, University of Manchester
Raúl González-Jiménez, University of Seville

NuFact 2024, Argonne National Lab, Sep 16, 2024

Goals of the Neutrino Oscillation Program

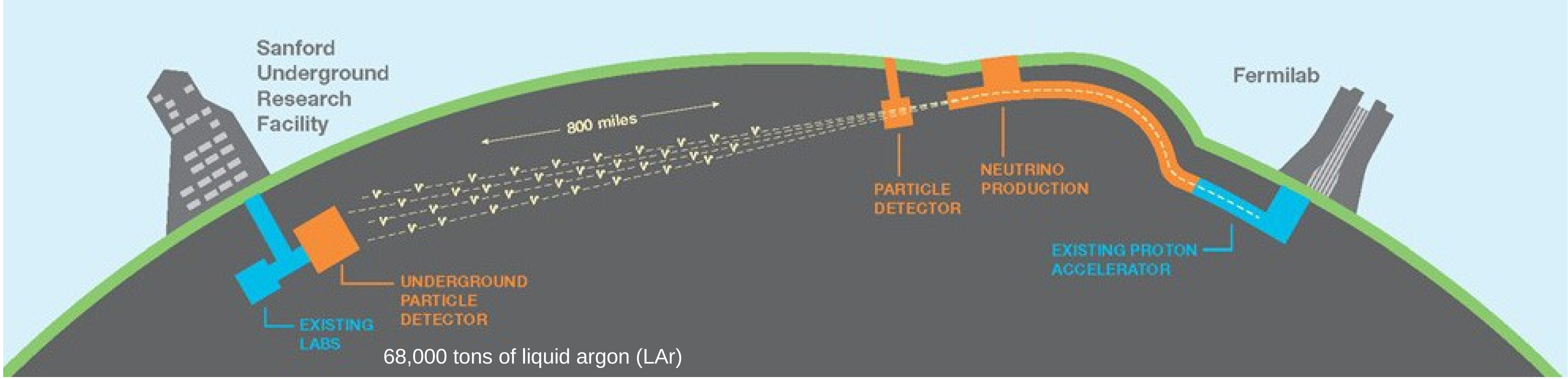
NuSTEC[a] White Paper: Status and Challenges of Neutrino-Nucleus Scattering

L. Alvarez-Ruso,[1] M. Sajjad Athar,[2] M. B. Barbaro,[3] D. Cherdack,[4] M. E. Christy,[5] P. Coloma,[6] T. W. Donnelly,[7] S. Dytman,[8] A. de Gouvêa,[9] R. J. Hill,[10,6] P. Huber,[11] N. Jachowicz,[12] T. Katori,[13] A. S. Kronfeld,[6] K. Mahn,[14] M. Martini,[15] J. G. Morfín,[6] J. Nieves,[1] G. Perdue,[6] R. Petti,[16] D. G. Richards,[17] F. Sánchez,[18] T. Sato,[19,20] J. T. Sobczyk,[21] and G. P. Zeller[6]

1. establish whether nature violates CP in the lepton sector and, if so, measure δ_{CP};
2. improve the accuracy on θ_{23} and, if not maximal, a determination of the octant it belongs to: $\theta_{23} < \pi/4$ vs. $\theta_{23} > \pi/4$;
3. determine the neutrino mass ordering at high confidence level: $m_1 < m_2 < m_3$ vs. $m_3 < m_1 < m_2$.

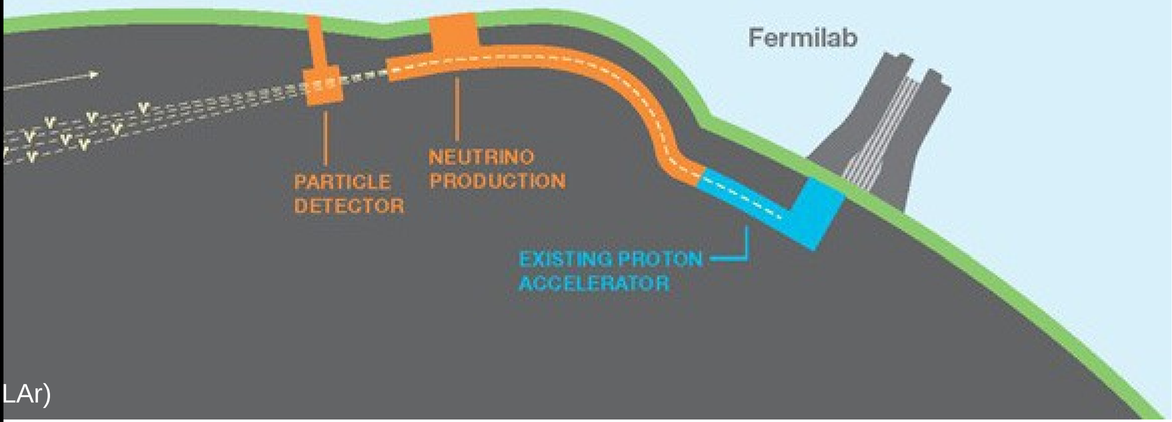
	θ_{12}	θ_{13}	θ_{23}	$\Delta m^2_{21}/10^{-5}$	$\Delta m^2_{3j}/10^{-3}$	δ_{CP}
Normal Ordering	$33.56^{+0.77}_{-0.75}$	$8.46^{+0.15}_{-0.15}$	$41.6^{+1.5}_{-1.2}$	$7.50^{+0.19}_{-0.17}$	$2.524^{+0.039}_{-0.040}$	261^{+51}_{-59}
Inverted Ordering	$33.56^{+0.77}_{-0.75}$	$8.49^{+0.15}_{-0.15}$	$50.0^{+1.1}_{-1.4}$	$7.50^{+0.19}_{-0.17}$	$-2.514^{+0.038}_{-0.041}$	277^{+40}_{-46}

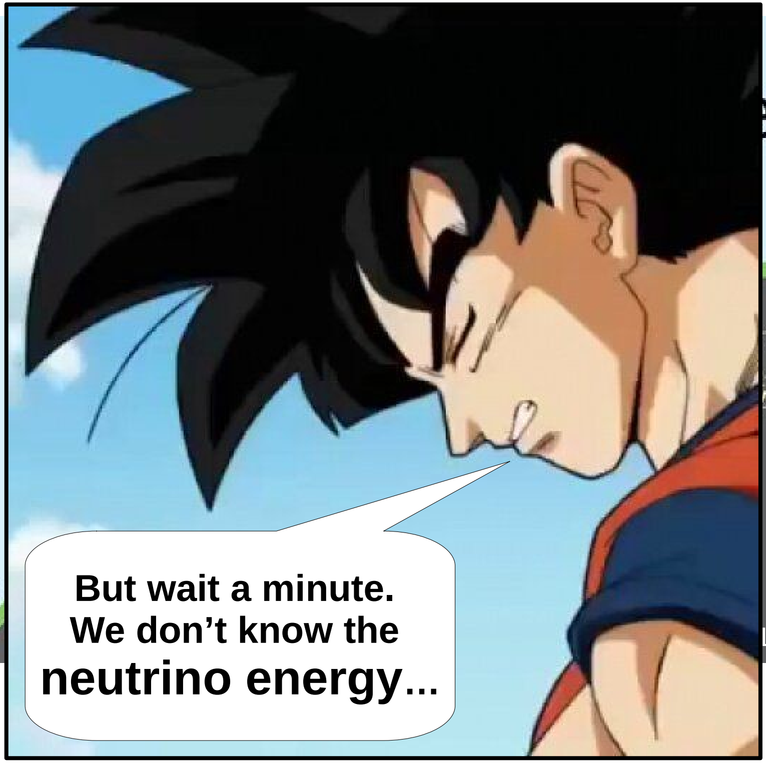
DUNE: Deep Underground Neutrino Experiment



$$P_{a \to b} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\text{eV}^2)L(\text{km})}{E_\nu(\text{GeV})}\right),$$

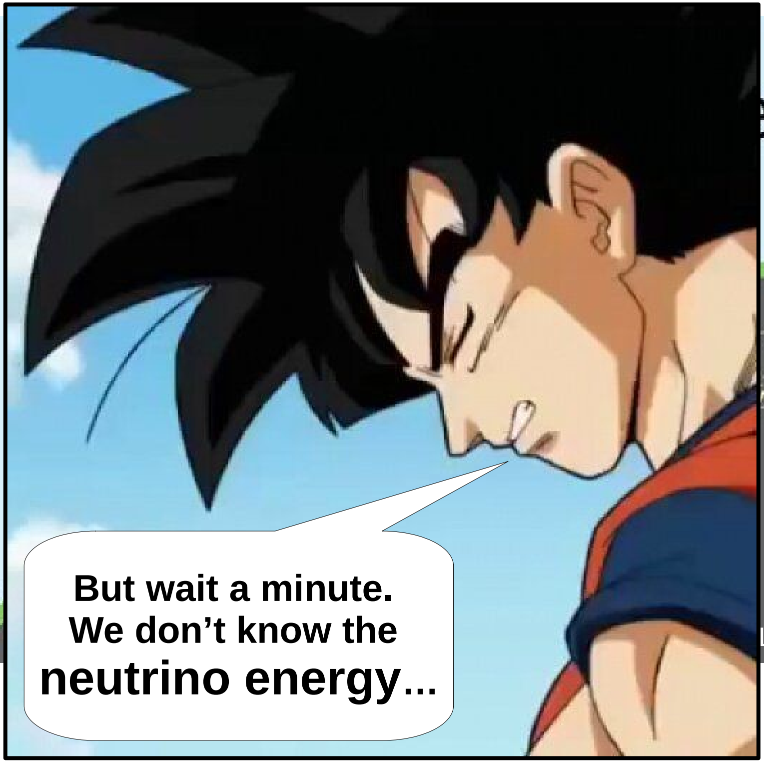
…erground Neutrino Experiment

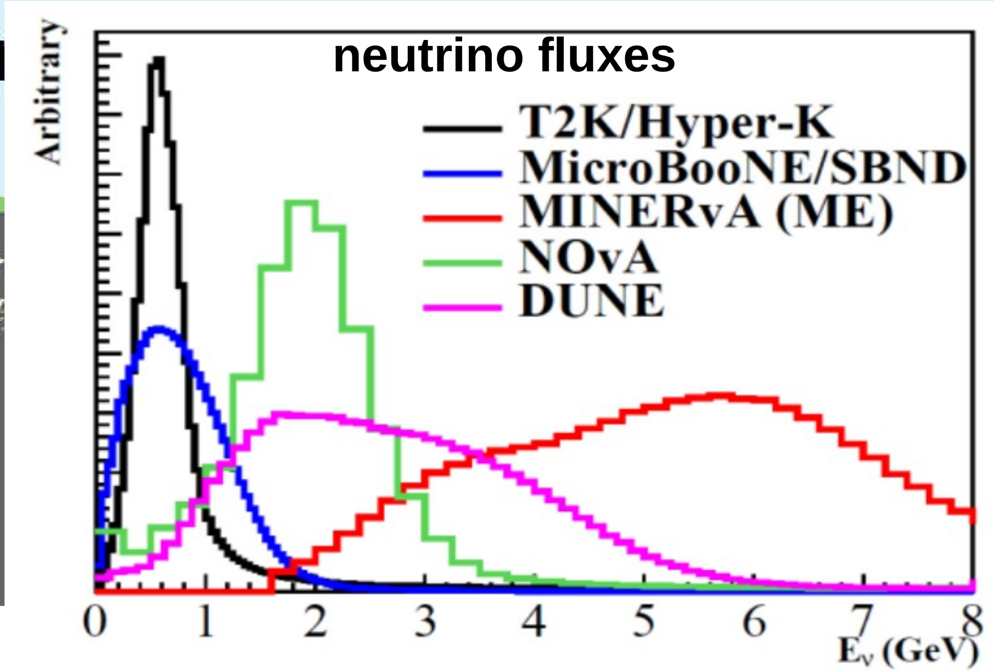




LAr)

$$P_{a\to b} = \sin^2 2\theta \, \sin^2\left(\frac{1.27\Delta m^2(\text{eV}^2)L(\text{km})}{E_\nu(\text{GeV})}\right),$$





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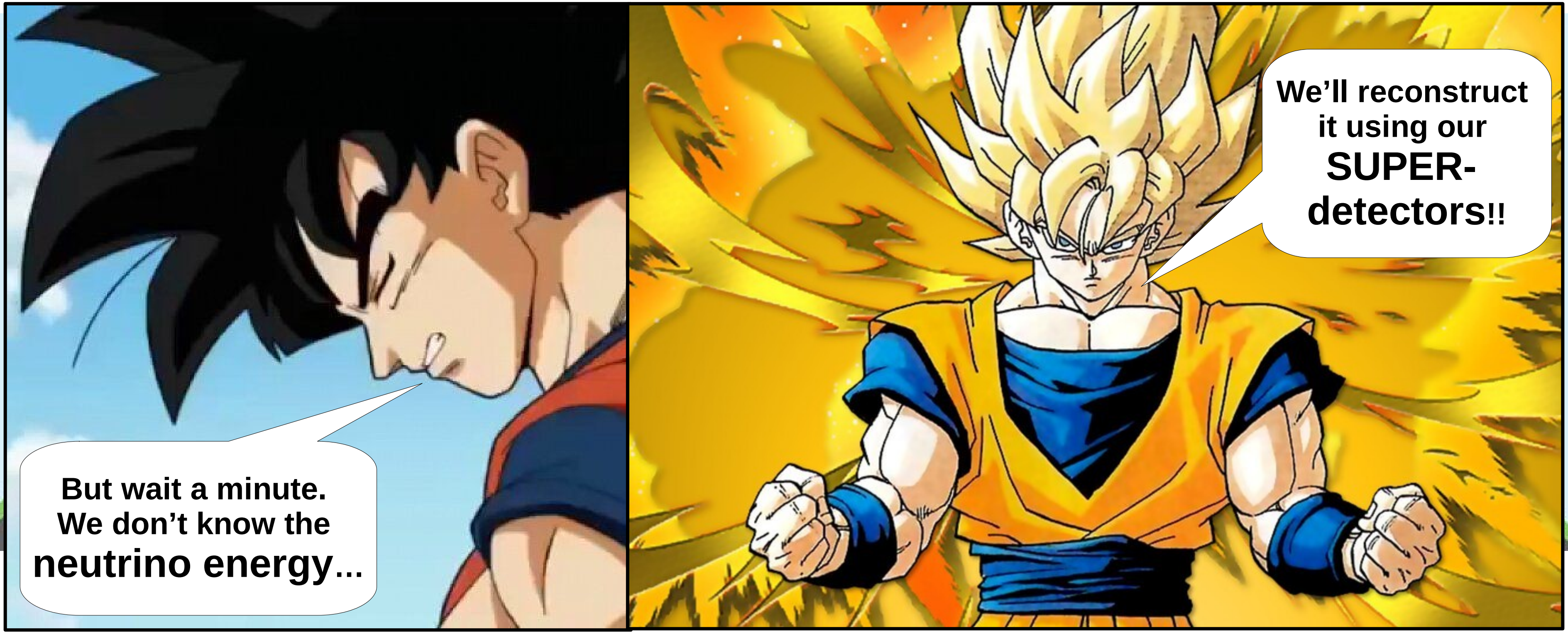

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SLOW
DOWN!


Nuclear Physics

ν-oscillations experiment 101

***STEP 1**: Making a beam*
***STEP 2**: Checking twice*
***STEP 3**: Gonna find out if you've more of one type*

$$N^{\mu\rightarrow e}_{FD}(Er) = \int \phi^{\mu}_{FD}(Et)\, \mathbf{P_{\mu\rightarrow e}(Et)}\,\sigma^{e}(Et)\,\varepsilon^{e}(Et)\,U_{FD}(Et, Er)\,dEt$$

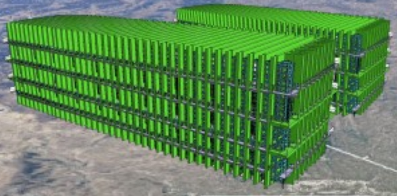
Neutrino Flux

Oscillation Probability

ν_e Cross Section

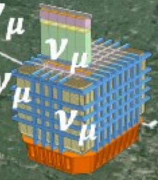
Signal efficiency

Detector Response



Sanford Underground Research Facility

$$N^{\mu}_{ND}(Er) = \int \phi^{\mu}_{ND}(Et)\,\sigma^{\mu}(Et)\,\varepsilon^{\mu}(Et)\,U_{ND}(Et, Er)\,dE$$



Fermilab

Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy… but your **oscillation probability** is a function of the true neutrino energy & it is convoluted with quantities depending on your model: flux, **cross section** and detector response.

slide from Elena Gramellini's talk in NuFact 2023

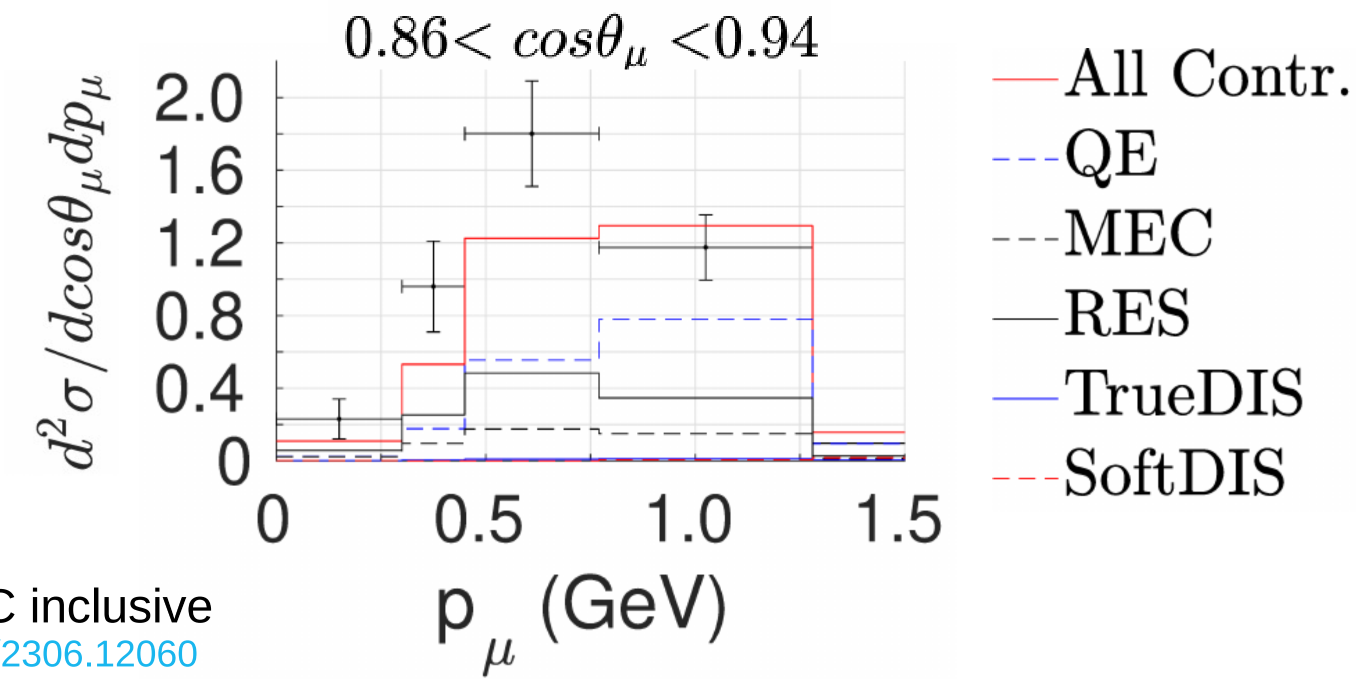
Summarizing,

cross section <u>models</u> are needed, for two reasons:

1) To get $\mathbf{P}_{\alpha\rightarrow\beta}$ from the measured $\mathbf{N}_{\beta}$.

2) To reconstruct the neutrino energy (keep watching).

Different reaction channels but **same event topology**

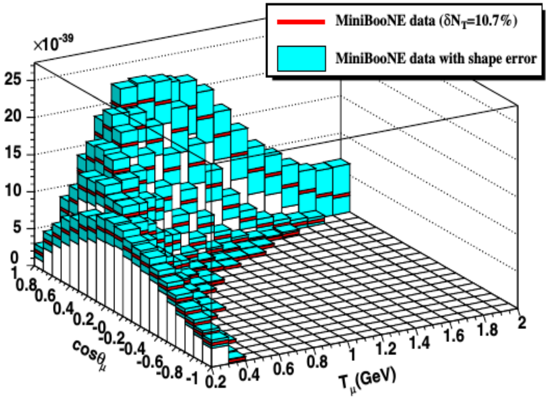


MicroBooNE CC inclusive
https://arxiv.org/abs/2306.12060

How does this affect the reconstruction of the neutrino energy?

Example:

1) **QE-like event** in MiniBooNE: muon and no pions are detected. Scattering angle and energy of the muon.



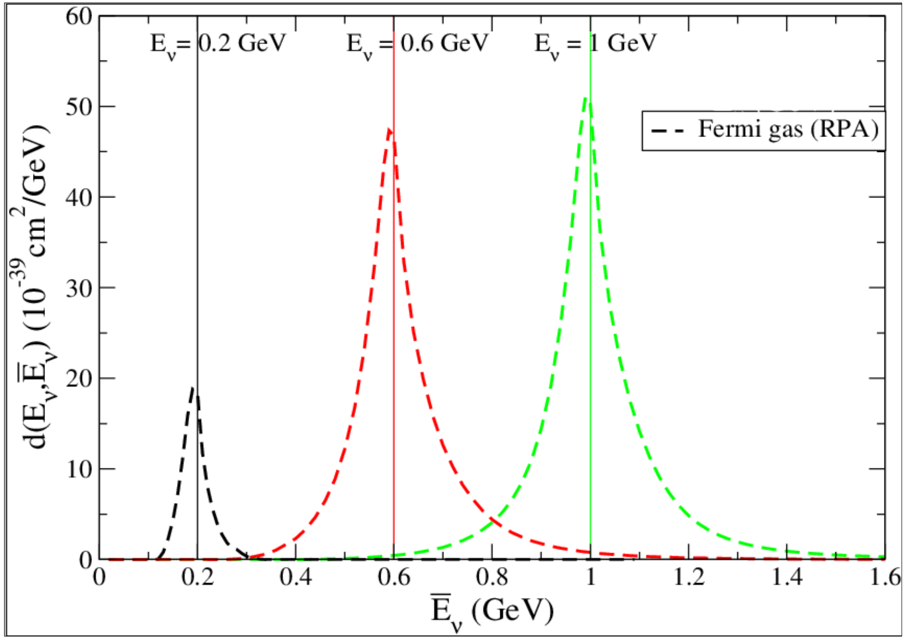
2) Reconstructed energy estimator:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

This formula gives us an estimate of the energy of the neutrino.

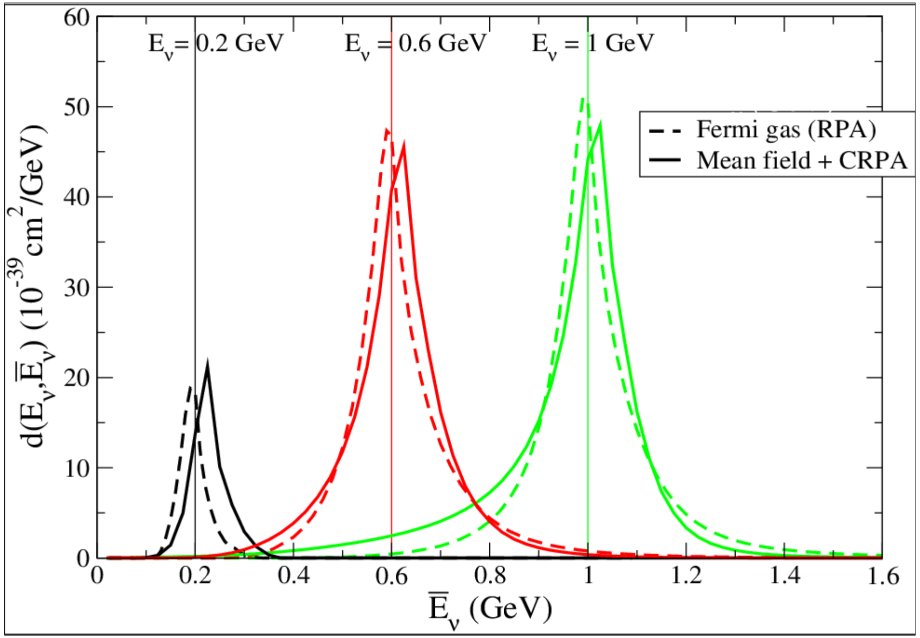
3) One can compute the **probability of the reconstructed energy E^{QE} matching the true energy E: $P(E^{QE}|E)$**

Probability density of the reconstructed energy $\bar{E}$ matching the true energy E



https://doi.org/10.1103/PhysRevC.98.054603

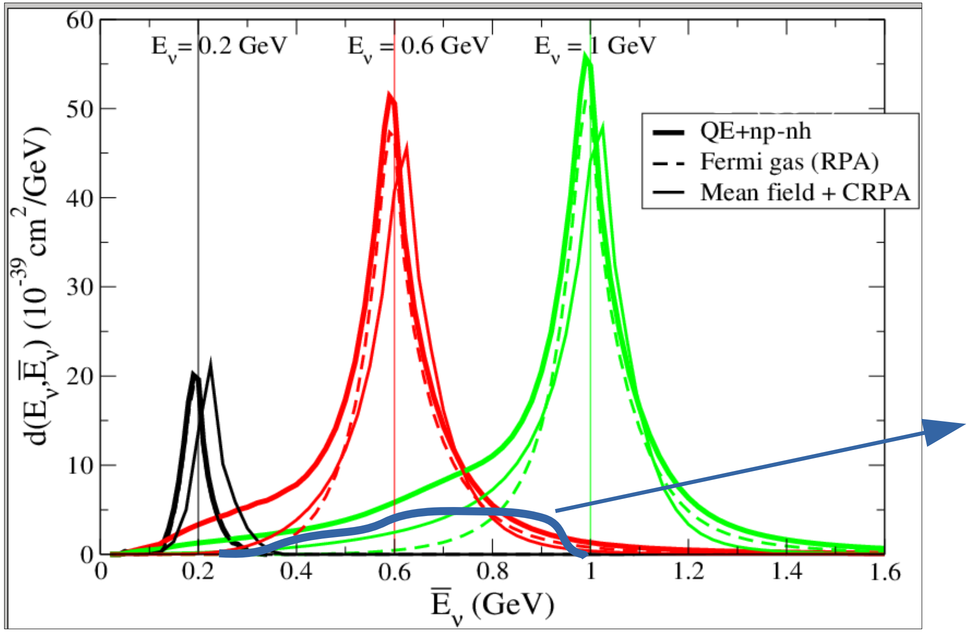
Probability density of the reconstructed energy $\bar{E}$ matching the true energy E



https://doi.org/10.1103/PhysRevC.98.054603

+ The distributions are **model dependent**

Probability density of the reconstructed energy Ē matching the true energy E



https://doi.org/10.1103/PhysRevC.98.054603

+ The distributions are **model dependent**
+ Different reaction channels produce VERY different distributions

Summarizing,

GOOD cross section <u>models</u> are needed, for two reasons:

1) To get $\mathbf{P}_{\alpha\rightarrow\beta}$ from the measured $\mathbf{N}_{\beta}$.

2) To reconstruct the neutrino energy.

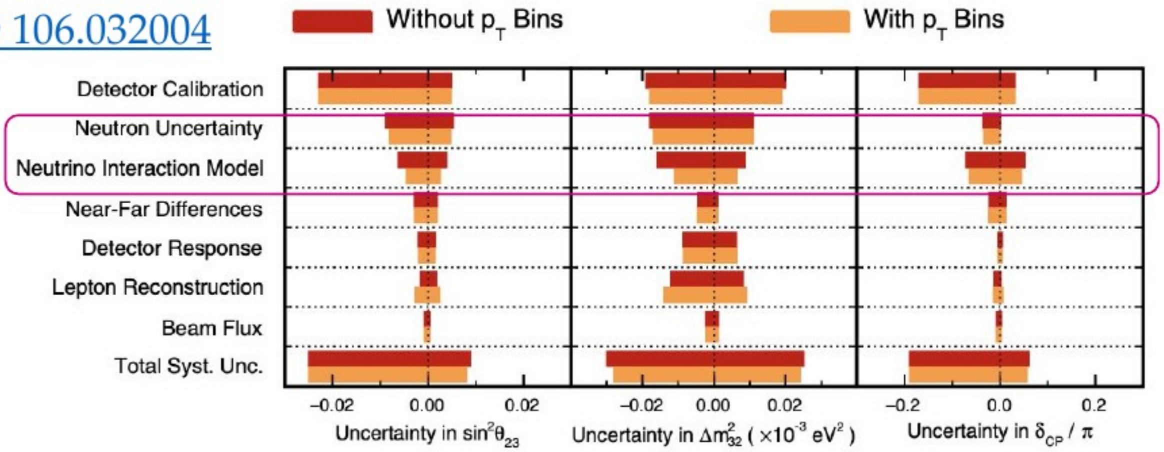
How does this feeds back into neutrino “new” physics? CP Violation @ long baseline

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

T2K, Nature 2020

“uncertainty on the ν_e and $\bar{\nu}_e$ cross-sections… [is] the 2nd largest single source of systematic uncertainty in the CP asymmetry measurement.”

NOνA PRD 106.032004

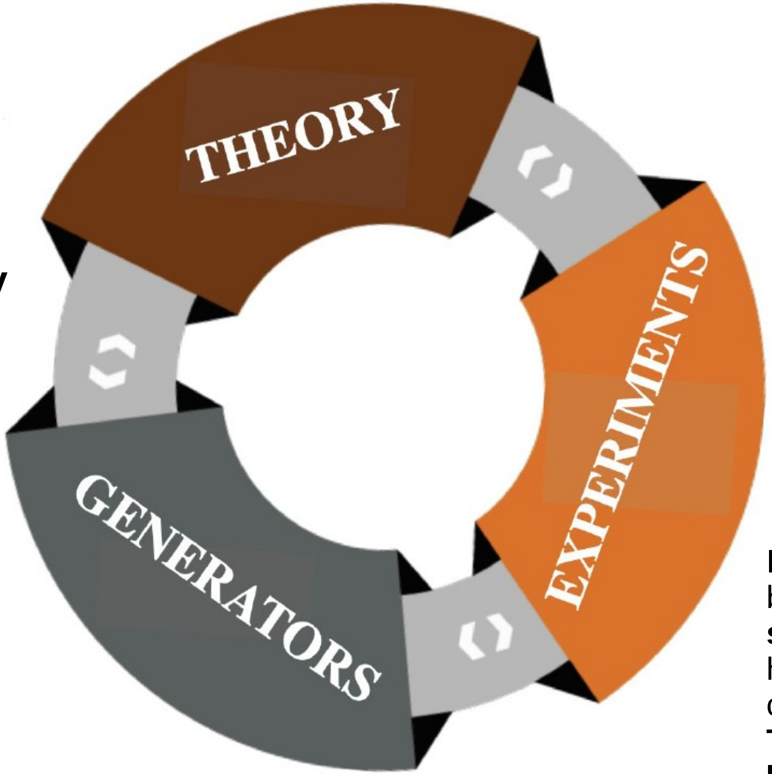


slide from Elena’s talk in NuFact 2023

WG2 Overview:

adapted from Elena's talk in NuFact 2023

Continuous improvement of our understanding of neutrino interactions from the **interplay** between model developments (**theory & implementation**) and **experimental cross section results**



Important **experimental efforts** have been done in the last years aiming at **studying nuclear effects**. Thanks to the high statistics, new sets of differential cross sections have been presented: **Transverse Kinematic Imbalance, Inferred Variables**,…
It definitely helps identify and highlight different nuclear effects.

WG2 Overview:

	Mon	Tue	Wed	Thur	Fri	Sat
8:30-10:00		**2 Plenaries**: Cross sect. theory Cross sect. results				Summary
10:30-12:30			Experiment: current results (5)			
13:45-15:45	Theory (5)	MC generators (5)		Miscellaneous (5)	Miscellaneous (4)	
16:15-18:15	Posters	MC generators & Theory (4)		Experiment: LAr detectors (4)		

WG2 Overview:

Experimental:
→ 10 talks (T2K, MINERvA, NOvA, NINJA, SND@LHC, DUNE, ICARUS, SBND, MicroBooNE, FASER)

Theory:
→ 10 talks (QE, DIS, MEC, SRC, FSI, nucleon form factors,...)

MC Generator:
→ 6 talks (NEUT, GENIE, NuWro, GiBUU, MARLEY, ACHILLES)

Miscellaneous:
→ 5 talks (at the boundary of theory, generator and experiment)

TOTAL: 32 AMAZING talks

Still a long way untill we fully understand what happened here…

Enjoy
NuFact 2024!

Image from https://microboone.fnal.gov/

Questions to be addressed by WG2

1) How can we have more theory-based uncertainties, in particular for neutrino oscillation studies? Give us details!

2) How can we incorporate state-of-the-art nuclear models, providing information on the hadrons, in generators? Give us details!

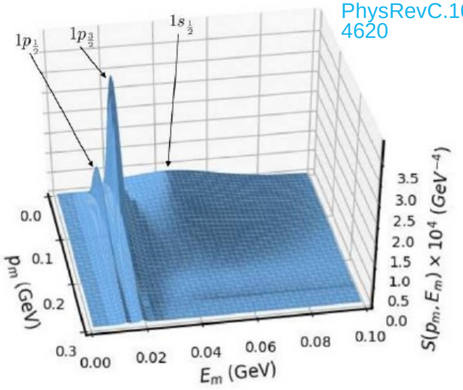
3) How to use the wealth of experimental measurements already available and expected in the coming years to solve key issues in neutrino scatterings?

4) Which kind of experiments are needed to improve the modeling of neutrino-nucleus cross section? Give us details!

5) What are the main reaction channels and, therefore, identify the main systematic uncertainties in oscillation experiments?

6) Can you highlight the unique experimental capabilities of your detector... and how that relates to important observables?

Small list of **nuclear and nucleonic effects** in the cross sections:



PhysRevC.100.044620

+ **Initial state**: binding energy, Fermi motion (or momentum distributions), short- and long-range correlations

+ **Interaction:** nucleon form factors, Pauli blocking, beyond one-body currents

+ **Final state interactions**:
  ++ Distortion effects or elastic FSI
  ++ Inelastic FSI (modeled with intranuclear cascade)

All this, and more, will be discussed in WG2 parallel sessions at NuFact 2024 workshop.