WG2 introduction (Neutrino Scattering Physics)

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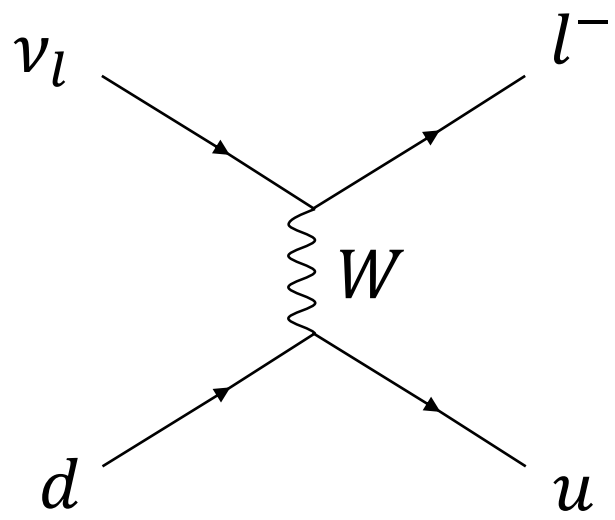
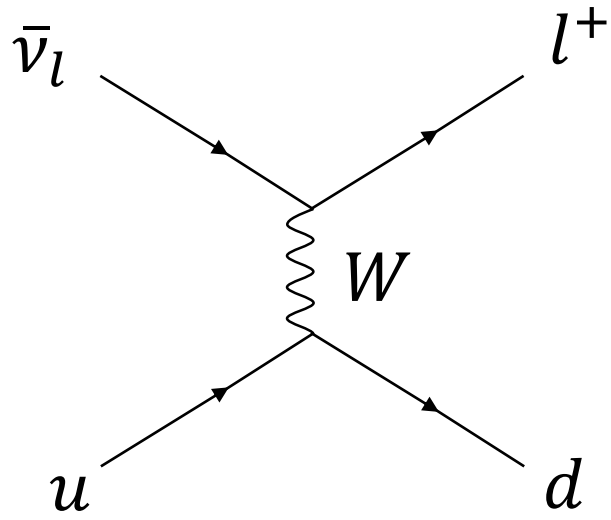
NuFact 2022: The 23rd International Workshop
on Neutrinos from Accelerators @ Salt Lake City
August 1, 2022

Neutrino-quark interaction

- Neutrino interaction with a point particle can be described by the standard model.
  → **Simple and explicit.**





$$\frac{d\sigma}{dy} = \frac{G_F^2 \cos^2\theta_c s}{\pi}$$

$$\frac{d\sigma}{dy} = \frac{G_F^2 \cos^2\theta_c s}{\pi}(1-y)^2$$

Neutrino-nucleon interaction

- Neutrino actually interacts with nucleons which have size and internal structure.
  → **Complicated.**

Llewellyn-Smith formula

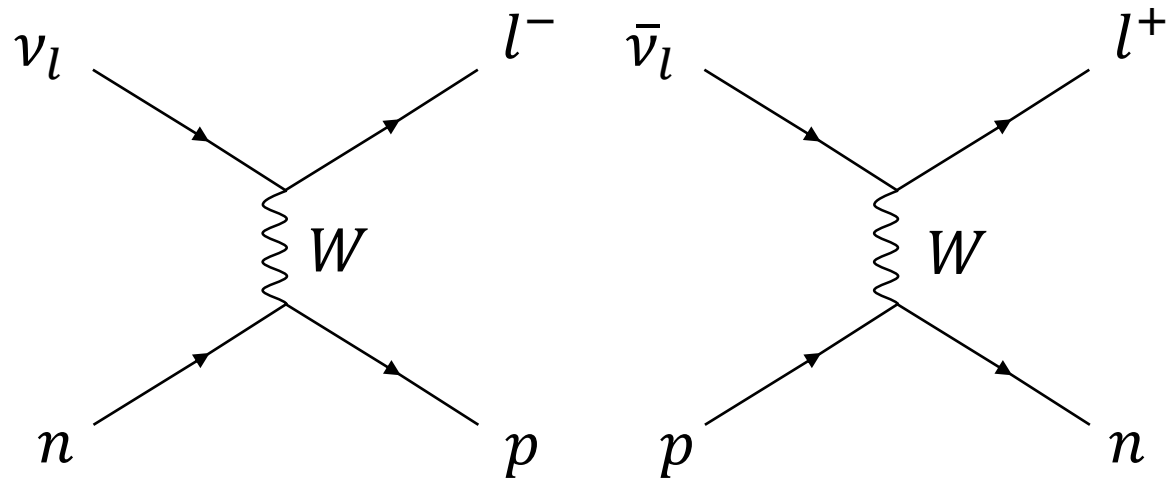
$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 m_N^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{s-u}{m_N^2} + C(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

Dipole form factors

$$F_A(Q^2) = \frac{g_A M_A^2}{M_A^2 + Q^2}$$

$$G_E^V(Q^2) = \frac{M_V^2}{M_V^2 + Q^2}$$

$$G_M^V(Q^2) = \frac{(1+\xi)M_V^2}{M_V^2 + Q^2}$$

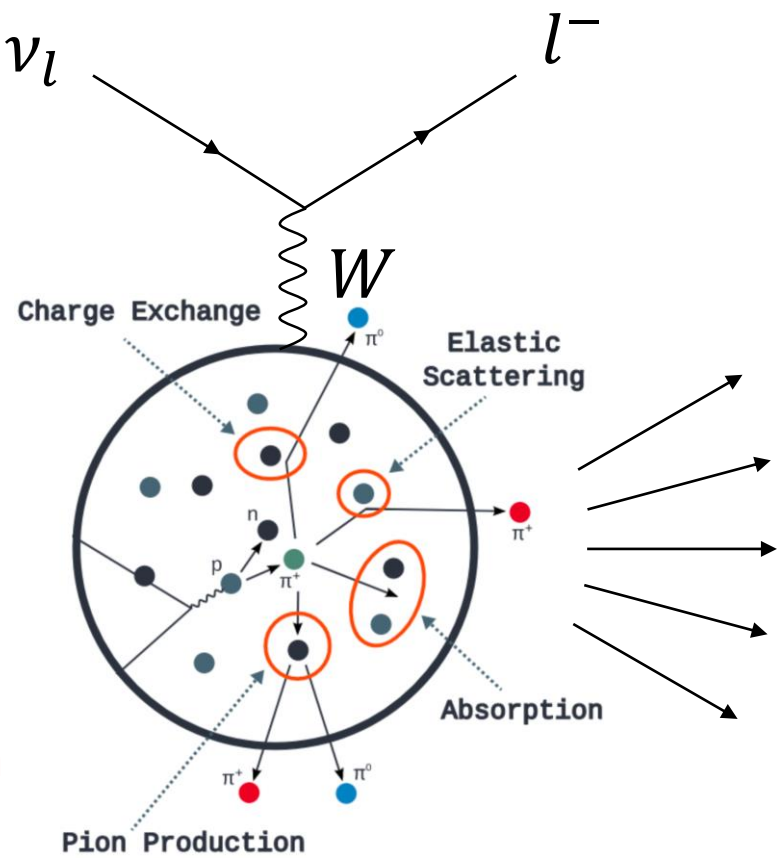


Neutrino-nucleus interaction

- Nucleons are not free but are bounded in nucleus.
- Involving various nuclear effects.
  - Multi-body nucleon correlation
  - Fermi momentum
  - Pauli blocking
  - Intra-nuclear hadronic interaction

$$H = \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 + \sum_{i<j} v\left(\vec{r}_i \vec{p}_i \vec{\sigma}_i, \vec{r}_j \vec{p}_j \vec{\sigma}_j\right)$$

Nucleon-nucleon correlation



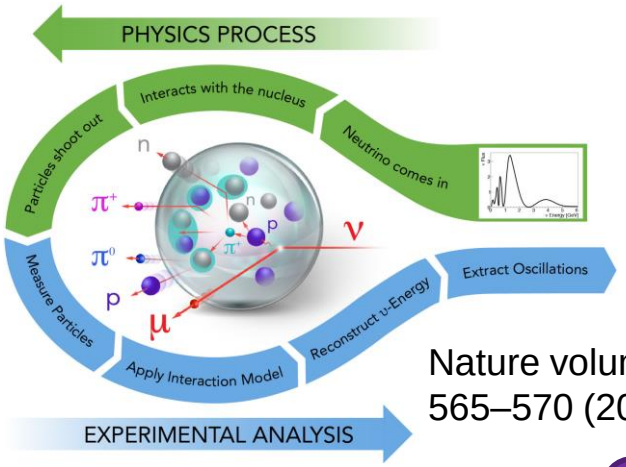
→ **Very complicated and poorly understood.**

Neutrino oscillation measurements

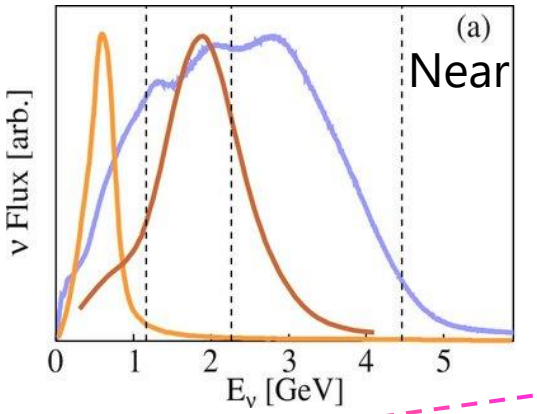
- Neutrino energy spectrum is different between near and far detectors.

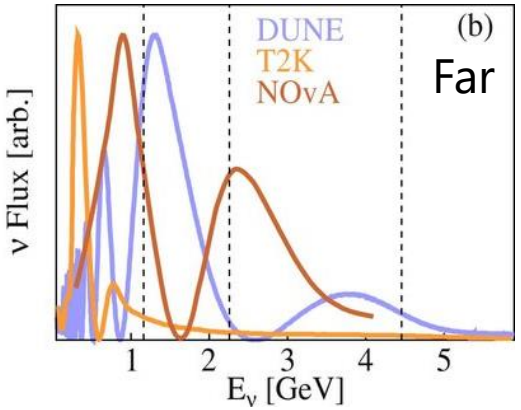
$$\frac{N_{far}}{N_{near}} = \frac{\int \Phi(E_\nu)\sigma(E_\nu)\varepsilon(E_\nu)P_{osc}(E_\nu)dE_\nu}{\int \Phi(E_\nu)\sigma(E_\nu)\varepsilon(E_\nu)\,dE_\nu}$$

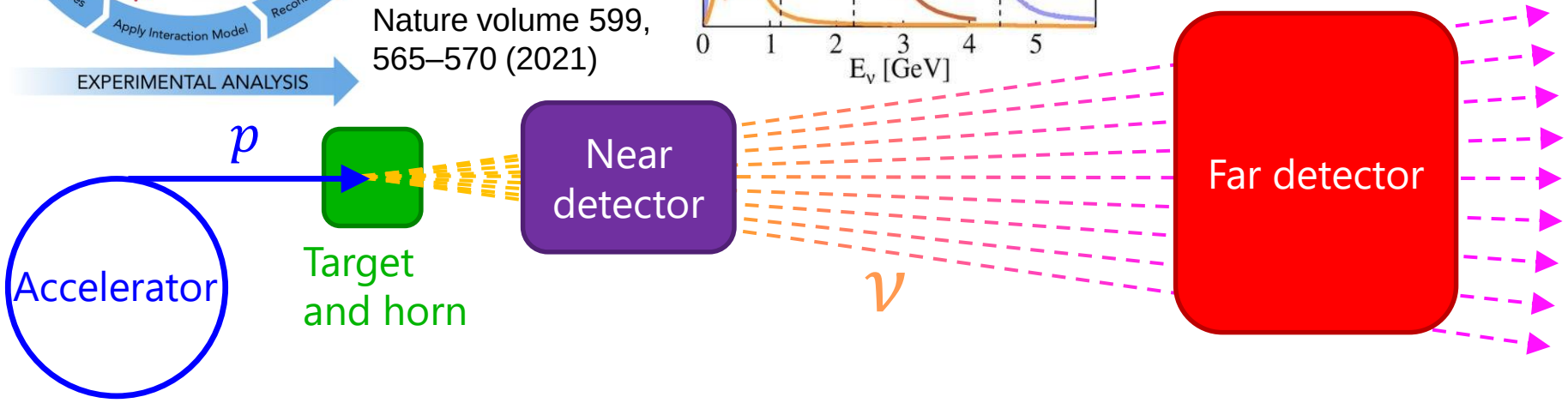
→ **Precise neutrino interaction model and neutrino event generator are essential.**



Nature volume 599, 565–570 (2021)







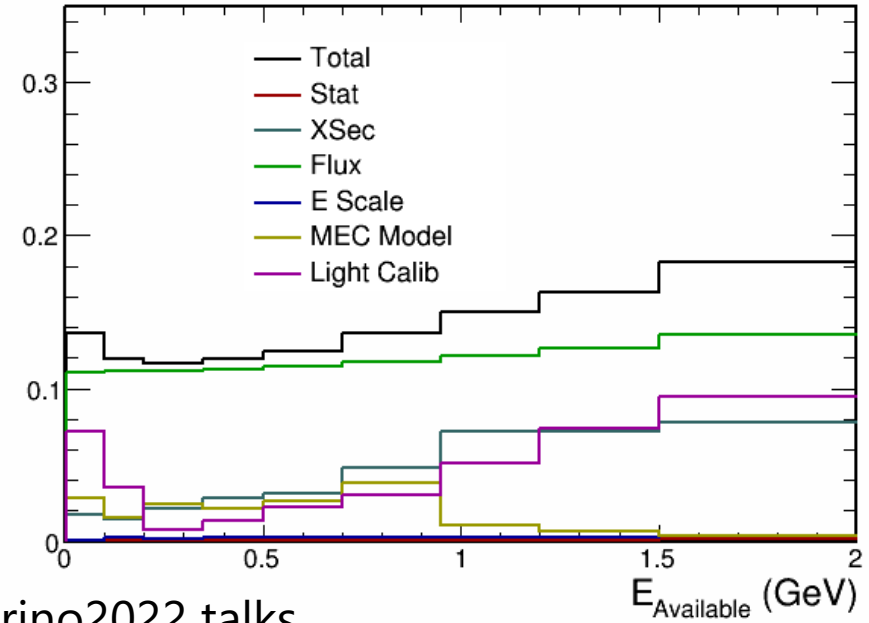
Ongoing neutrino oscillation experiments

- Statistical error is dominant.
- Neutrino interaction uncertainty is source of one of the largest systematic errors.
  → **Better understanding about neutrino interaction improves the precision of neutrino oscillation measurement.**

T2K systematic errors

Error source (units: %)	1Re FHC	1Re RHC	1Re FHC CC1π^+
Flux	2.8	3.0	2.8
Xsec (ND constr)	3.8	3.5	4.1
Flux+Xsec (ND constr)	2.8	2.7	3.4
Xsec (ND unconstr)	2.9	3.3	2.8
SK+SI+PN	3.1	3.8	13.6
Total All	5.2	5.8	14.3

NOvA systematic errors

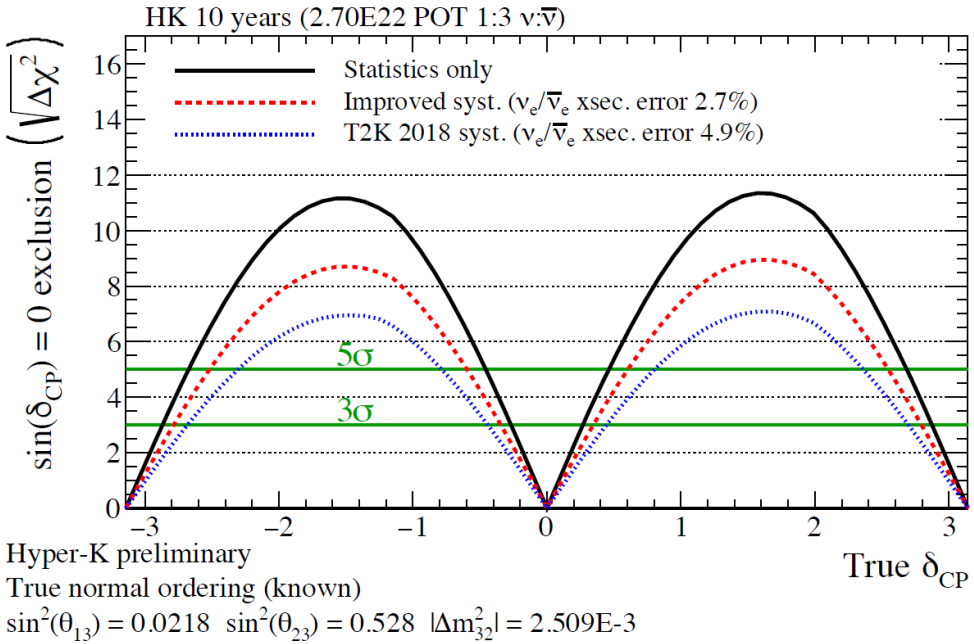


Taken from Neutrino2022 talks

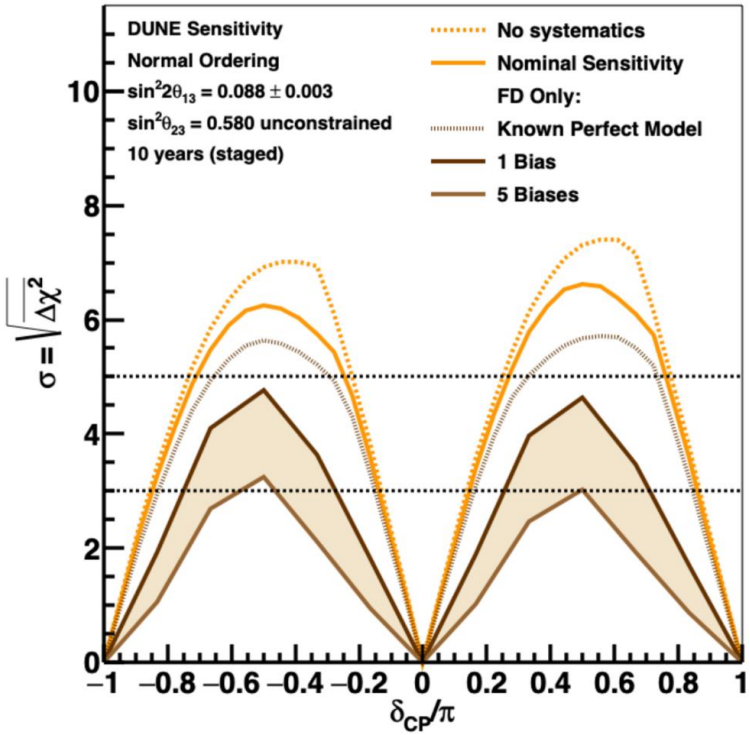
Future neutrino oscillation experiments

- Statistics will significantly increase and effect of neutrino interaction model uncertainty will be dominant.
  → **Precision of neutrino interaction model translates directly into precision of neutrino oscillation measurement.**

Hyper-Kamiokande CPV sensitivity



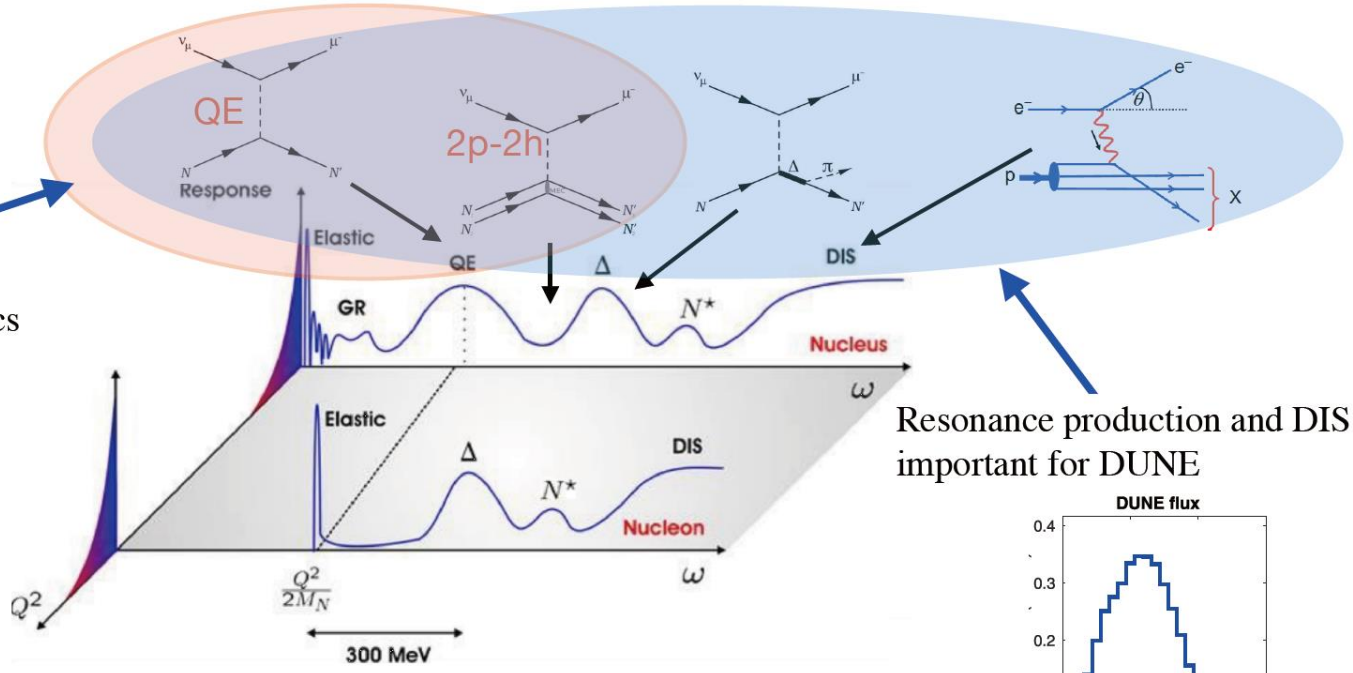
DUNE CPV sensitivity



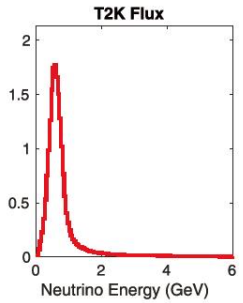
Symmetry 13, 9, 1625 (2021)

Theory

- Neutrino-nucleus interaction is a complex many-body problem.
- Solved approximately using nuclear models.
- Dependent on the dominant primary process (quasi-elastic, 2p2h, resonance production, DIS)



QE and 2p2h dominant at T2K kinematics

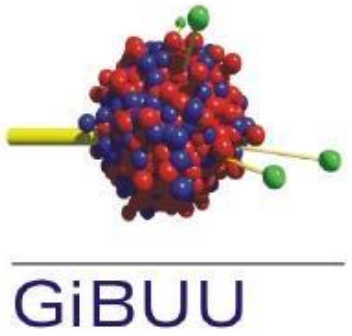


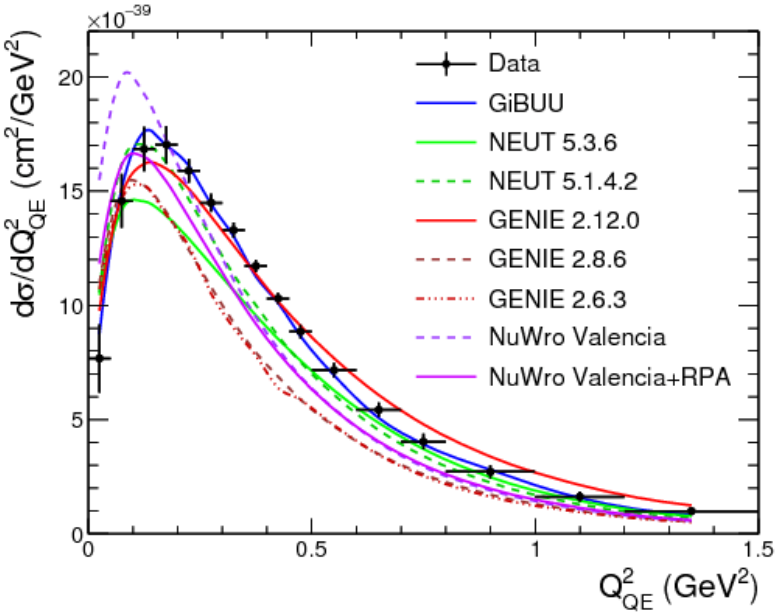
Resonance production and DIS important for DUNE

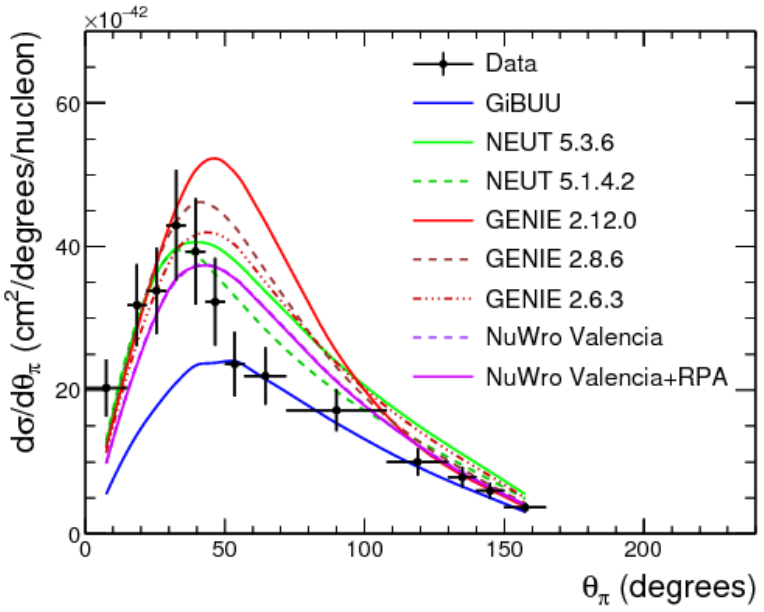
Taken from M. Barbaro's slides on NuFact2021

Neutrino event generators

- Neutrino event generator is needed to estimate the efficiency and backgrounds for neutrino experiments.
- Several neutrino event generators are being developed.
  - GENIE
  - NEUT
  - NuWro
  - GiBUU



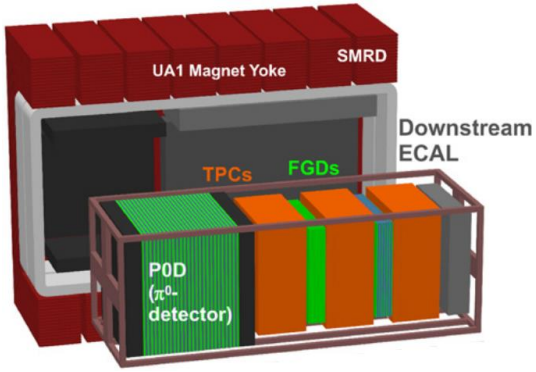




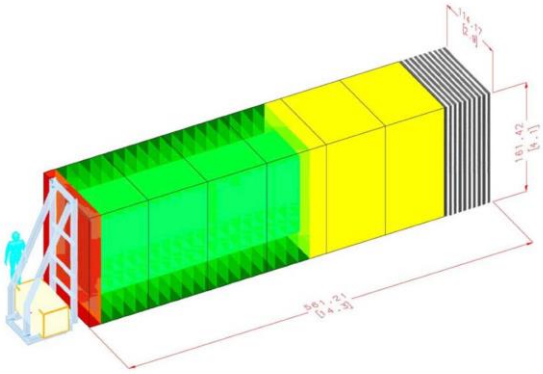
Experiments

- Several experiments are measuring neutrino-nucleus cross sections. (mainly differential cross sections)
- Measurements to improve neutrino interaction models.
  - Electron scattering
  - Improvement of flux prediction

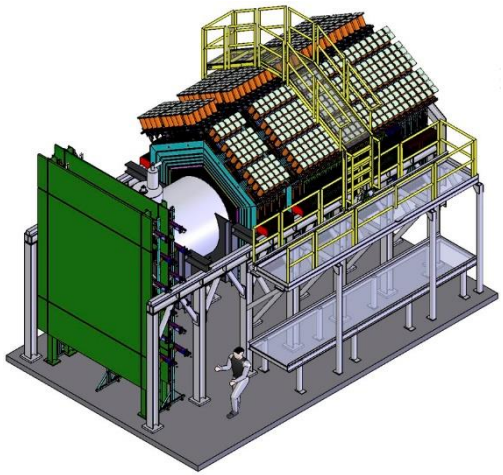
T2K near detector



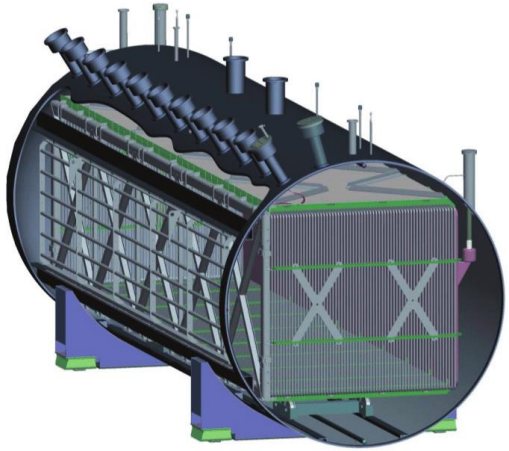
NOvA near detector



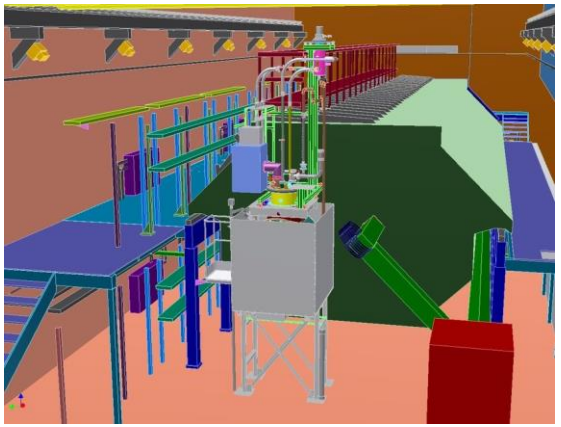
MINERvA detector



MicroBooNE detector

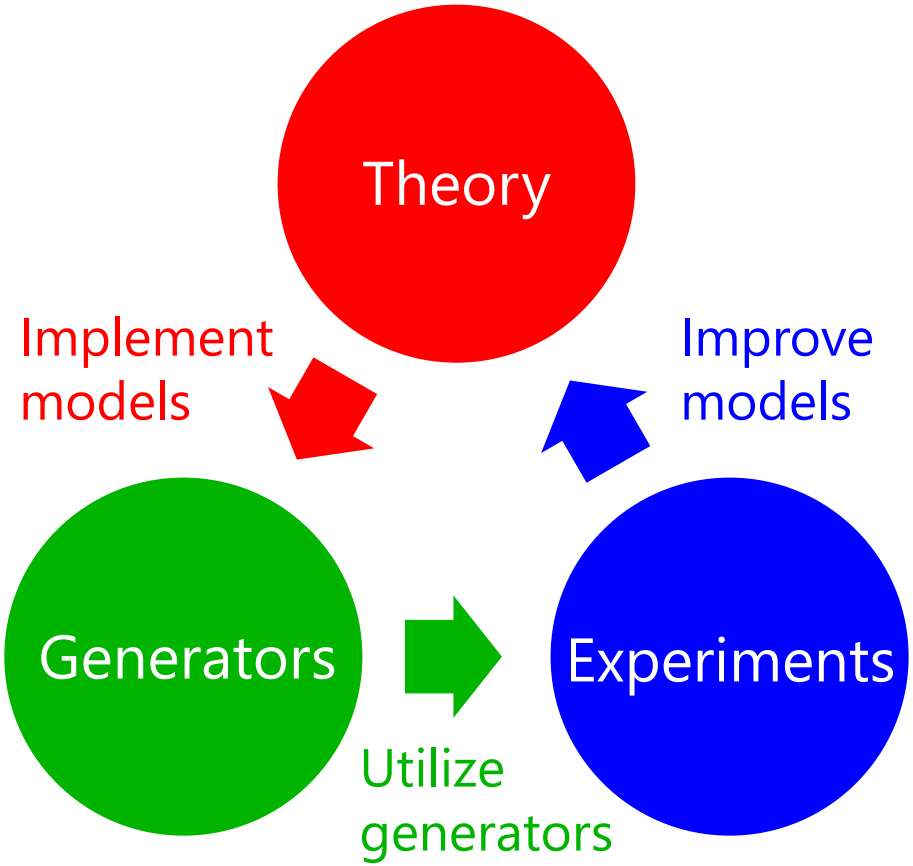


ArgoNeuT detector



WG2 focuses

- Experimental efforts
  - 16 talks (12 on cross section measurement, 2 on electron scattering, 4 on flux prediction)
- Theory inputs
  - 5 talks
- Generator developments
  - 2 talks
- Joint session WG1-WG2: Constraining Xsec systematics / Xsec tuning
  - 4 talks
- Joint session WG1-WG2-WG6: Near detector constraints
  - 5 talks



WG2 parallel sessions

August 2 (Tue), 16:00-17:20, Session focused on constrains on neutrino interaction models

16:00

- The ENUBET monitored neutrino beam for high precision cross section measurements — *Claudia Caterina Delogu* — Wasatch B — 16:00 - 16:20
- Electro-nuclear scattering measurements for neutrinos with LDMX — *Wesley Ketchum* — Wasatch B — 16:20 - 16:40
- Electron-Nucleus Scattering Constraints For Neutrino Interactions And Oscillations — *Afroditi Papadopoulou* — Wasatch B — 16:40 - 17:00

17:00

- EMPHATIC: Table-top Hadron Scattering Measurements for Improved Neutrino Flux Predictions — *Jonathan Paley* — Wasatch B — 17:00 - 17:20

August 4 (Thu), 14:20-15:40 and 16:10-17:10, Sessions focused on theory and event generators

14:00

- Suppression of quasielastic electron scattering cross sections at small q and extraction of the Coulomb Sum Rule — *Arie Bodek*
- Investigation of the MicroBooNE inclusive neutrino cross sections on Argon — *Marco Martini* — Wasatch B — 14:40 - 15:00

15:00

- Benchmarking intra-nuclear cascade models for neutrino scattering with relativistic optical potentials — *Alexis Nikolakopoulos*
- Final state interactions in semi-inclusive neutrino-nucleus scattering: Application to T2K and MINERvA experiments — *Mr Juan Manuel Franco-Patiño*

16:00

- Nuclear PDFs with Neutrino DIS data - a compatibility analysis from nCTEQ — *Richard Ruiz* — Wasatch B — 16:10 - 16:30
- Cross section measurements with MINERvA and prospects of cross section measurements with ICARUS — *Minerba Betancourt*
- Recent developments in the GENIE neutrino event generator — *Steven Gardiner* — Wasatch B — 16:50 - 17:10

17:00

August 5 (Fri), 11:15-12:35, 14:20-15:35 and 16:10-17:30, Sessions focused experimental results

11:00

- Recent MicroBooNE cross-section results: neutrino-induced baryon production — *Afroditi Papadopoulou* — Wasatch B — 11:15 - 11:35
- Recent MicroBooNE cross-section results: inclusive channels and pion production — *Elena Gramellini* — Wasatch B — 11:35 - 11:55

12:00

- Pion-argon inclusive cross-section measurement on ProtoDUNE-SP — *Yinrui Liu* — Wasatch B — 11:55 - 12:15
- The NEUT Neutrino Interaction Simulation — *Stephen Dolan* — Wasatch B — 12:15 - 12:35

14:00

- Detection of high-energy neutrinos at LHC with SND@LHC — *SND@LHC Coll.* — Wasatch B — 14:20 - 14:35
- Overview of physics results with coherent elastic neutrino-nucleus scattering data — *Matteo Cadeddu* — Wasatch B — 14:35 - 14:50

15:00

- NA65(DsTau) experiment at CERN — *DsTau Collaboration* — Wasatch B — 14:50 - 15:05
- The Accelerator Neutrino Neutron Interaction Experiment — *Jingbo Wang* — Wasatch B — 15:05 - 15:20
- CEvNS at CSNS in China — *qian liu* — Wasatch B — 15:20 - 15:35

16:00

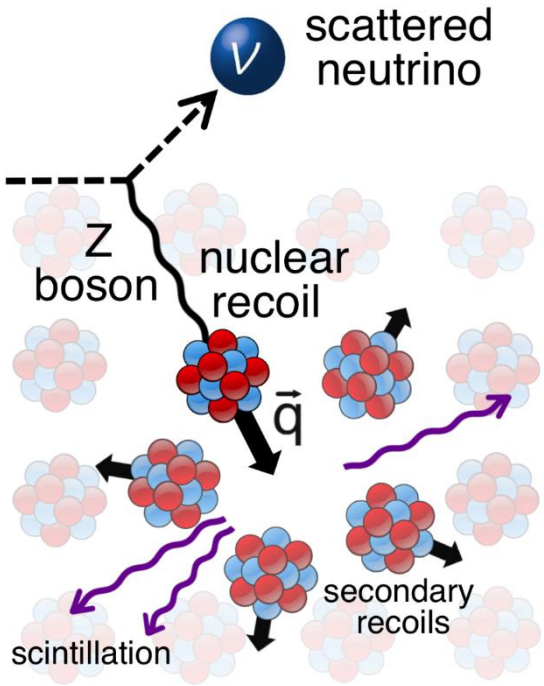
- nuSTORM; Neutrinos from Stored Muons — *Mark Scott* — Wasatch B — 16:10 - 16:30
- Status of the NINJA experiment — *Takahiro Odagawa* — Wasatch B — 16:30 - 16:50

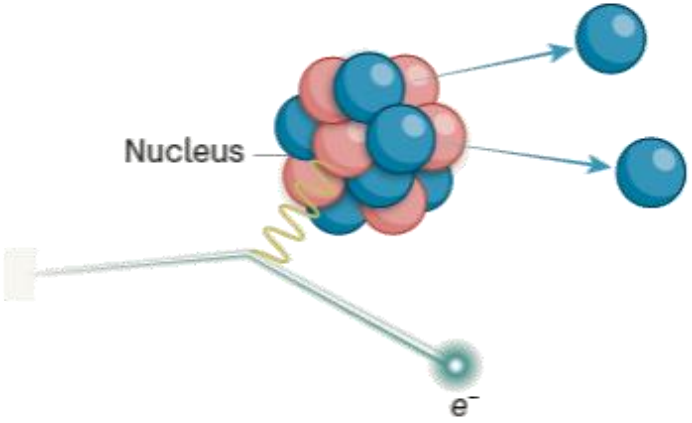
17:00

- T2K latest results on neutrino-nucleus cross sections — *Andrew Cudd* — Wasatch B — 16:50 - 17:10
- Muon antineutrino charged-current neutral pion production differential cross-section measurement in the NOvA near d… — *Fan Gao*

Plenary talks from WG2

- **August 2 (Tue), 9:00-10:30**
- Latest results from COHERENT - Samuel Hedges
- Latest from Models and Generators - Noemi Rocco
- Potential Constraints to Neutrino - Nuclei interaction based on electron scattering data - Vishvas Pandey





Summary

- Neutrino-nucleus interaction is very complicated and poorly understood.
- It's important for the precise measurement of neutrino oscillation.
- Tremendous efforts for better understanding of neutrino interaction models.
  - Theory
  - Generators
  - Experiments
- **Please join us and let's enjoy discussions in WG2.**

Thank you