The influence of cross section uncertainties on oscillation physics

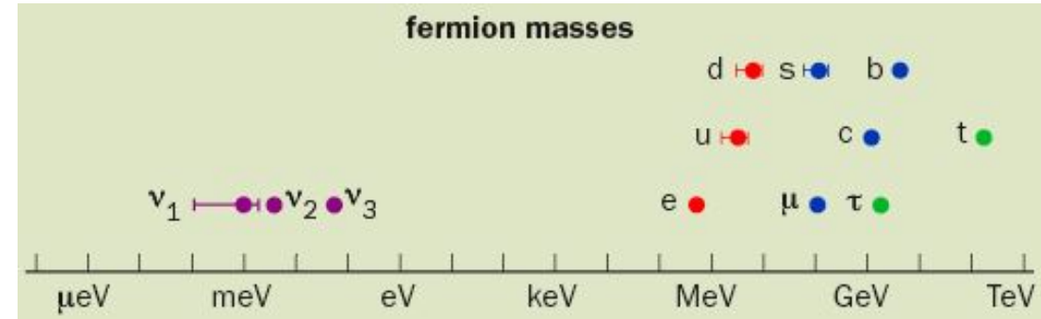
Vishvas Pandey

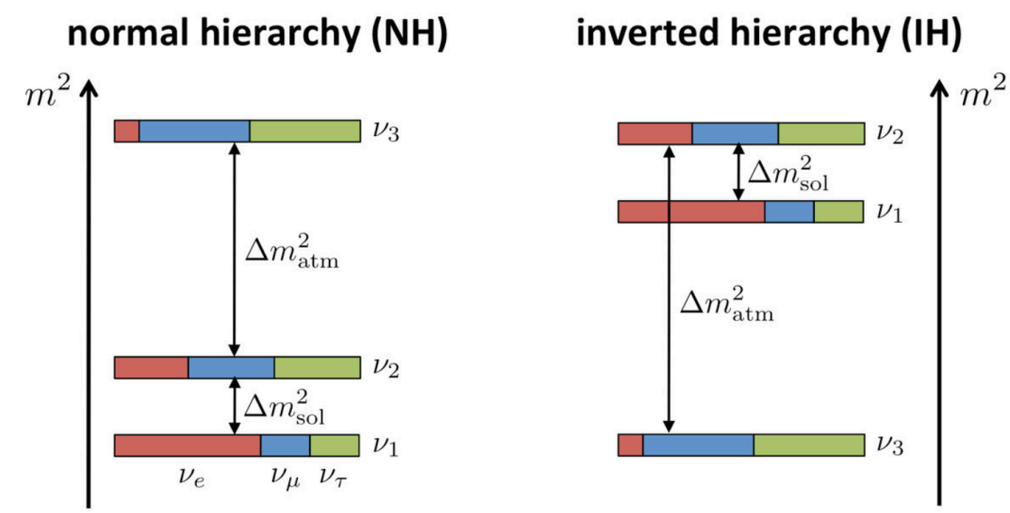
NuFact 2021, September 6 - 11, 2021, Cagliari, Italy

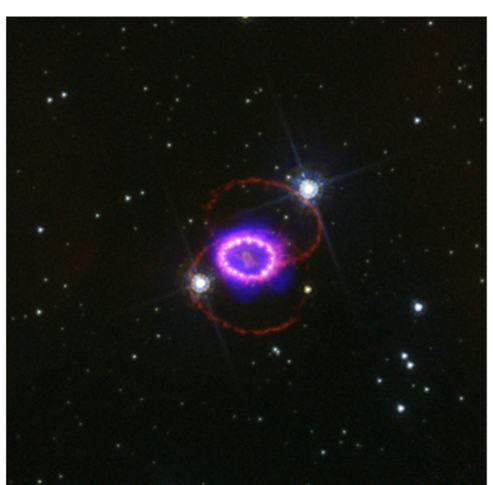
The Brave ν World

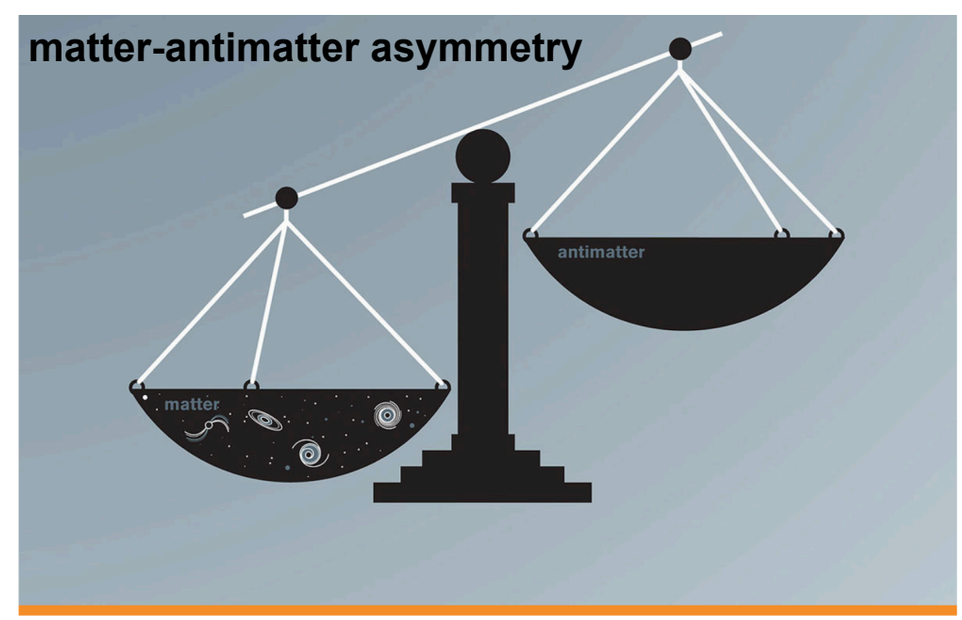
✦ These are extremely exciting times for neutrino physicists. We are building intense neutrino beams and powerful advanced neutrino detectors, to probe:

- Neutrino properties:
  - Determine neutrino masses and hierarchy
  - Determine neutrino mixing parameters
  - Determine CP violation phase
- Use neutrinos as a probe for BSM physics:
  - Additional neutrino flavors (*sterile neutrinos)*
  - Dark matter
  - .....
- Enabling multi-messenger astronomy:
  - Detecting Supernova
  - .....









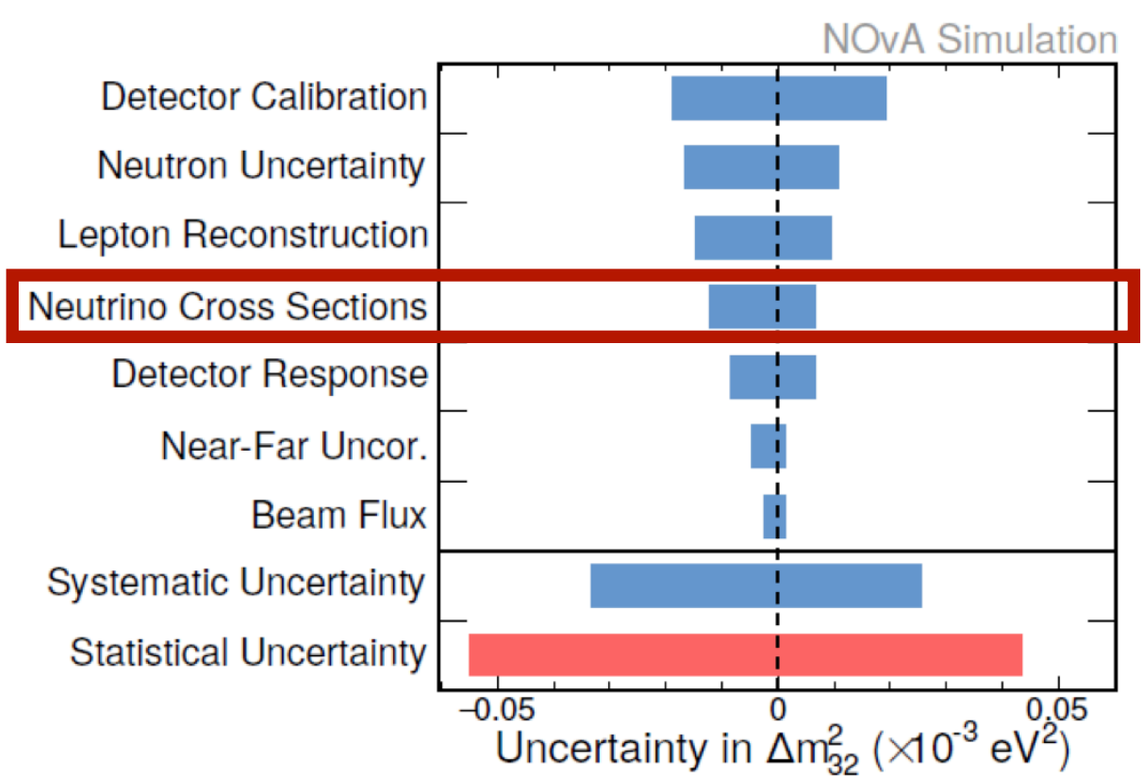
Credit: Symmetry Magazine / Sandbox Studio, Chicago

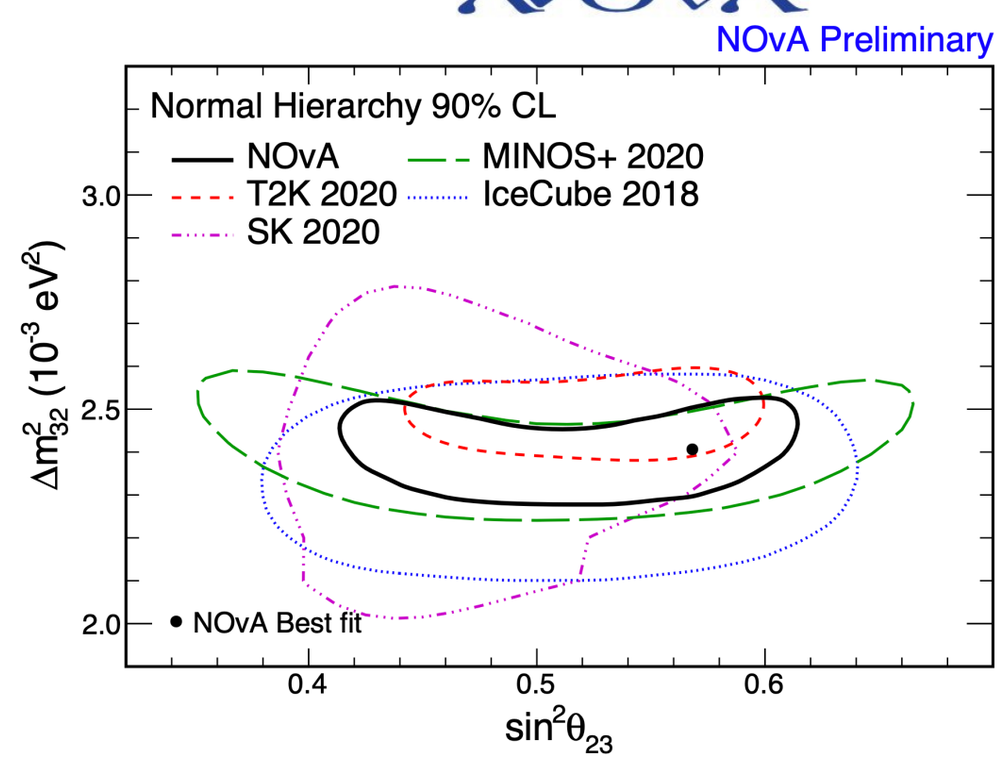
Systematics in Long-Baseline Neutrino Experiments

- Looking at our currently running long-baseline oscillation experiments - one of the largest systematic uncertainties in the oscillation measurement comes from neutrino interactions.
  - Systematic uncertainty on T2K's latest neutrino oscillation results:
    (Ciro Riccio's talk on Monday)

Systematic uncertainties					
Beam mode	**Neutrino**			**Antineutrino**	
SK sample	**1 Ring μ-like**	**1 Ring e-like**	**1 Ring e-like 1de**	**1 Ring μ-like**	**1 Ring e-like**
Flux	5.1%	4.8%	4.9%	4.7%	4.7%
Cross-section	10.1%	10.3%	12.0%	10.1%	11.9%
SK	2.9%	4.4%	13.4%	2.5%	3.3%

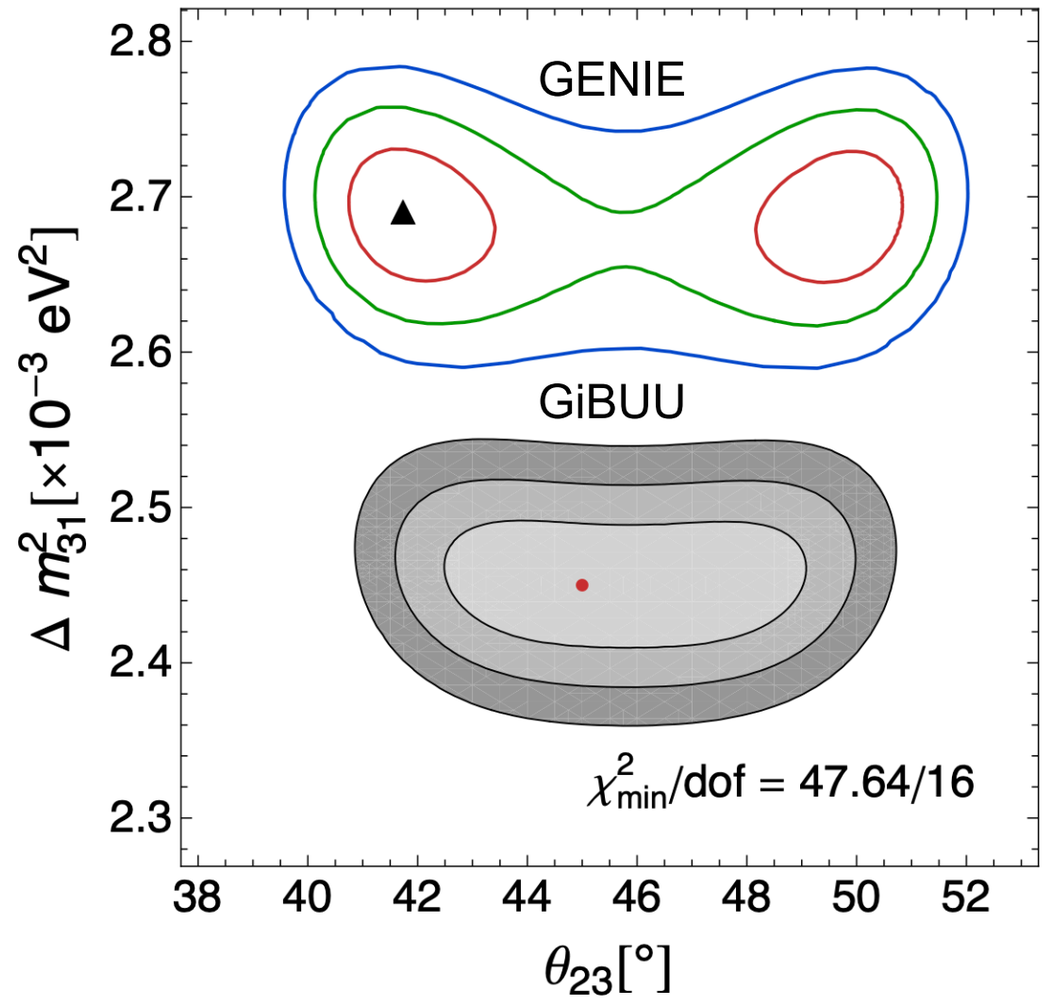
  - Systematic uncertainty on NOvA's latest neutrino oscillation results:
    (Daniel M. Kaplan's talk on Monday)



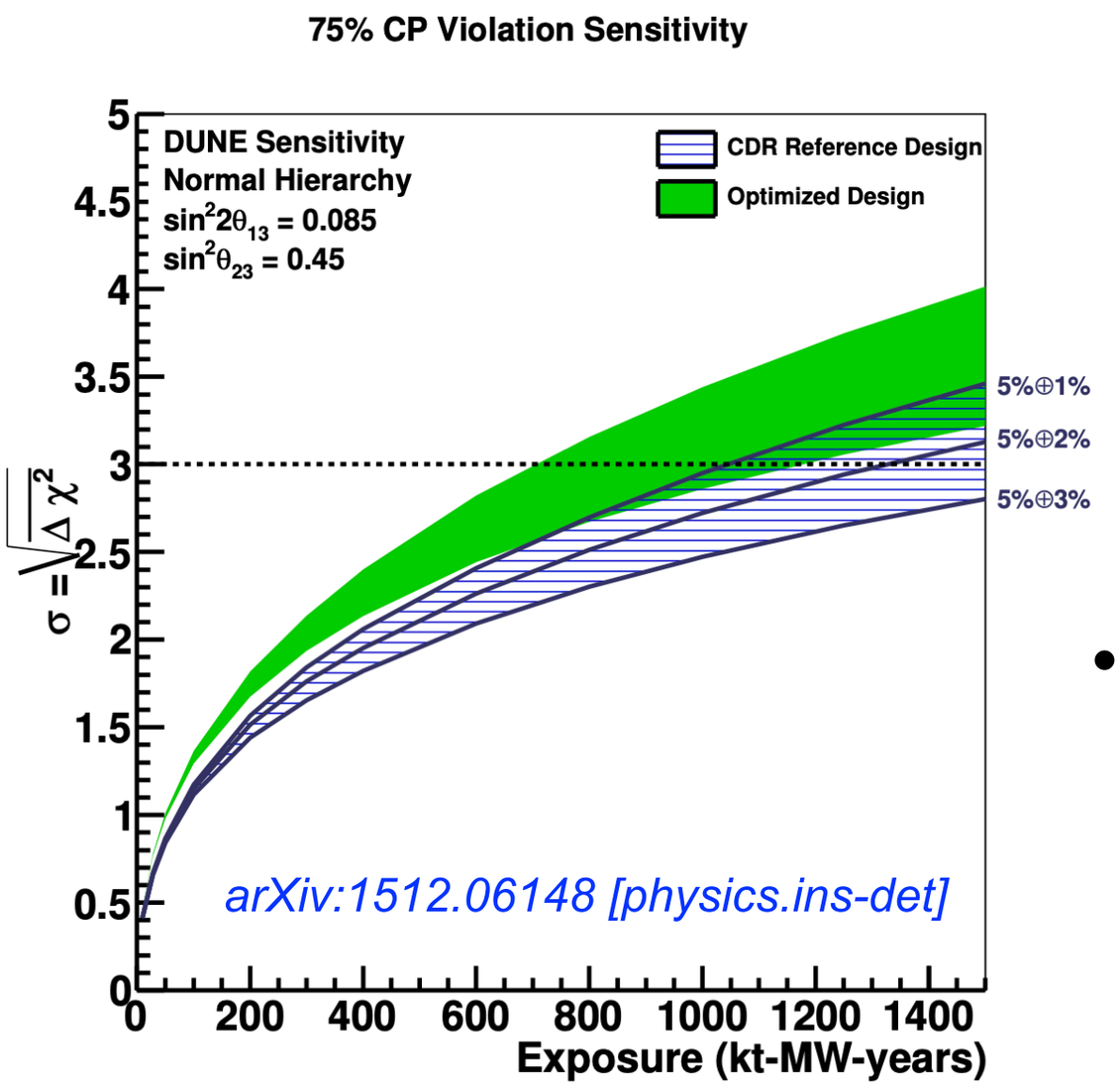


Systematics in Long-Baseline Neutrino Experiments

- Interaction model choice could bias the extraction of oscillation parameter.
- Impact on the oscillation physics if a different generator is used to compute the true and fitted rates in the analysis (events created with GiBUU, reconstruct with GiBUU and with GENIE).



P. Coloma, et al., Phys.Rev. D89, 073015 (2014)

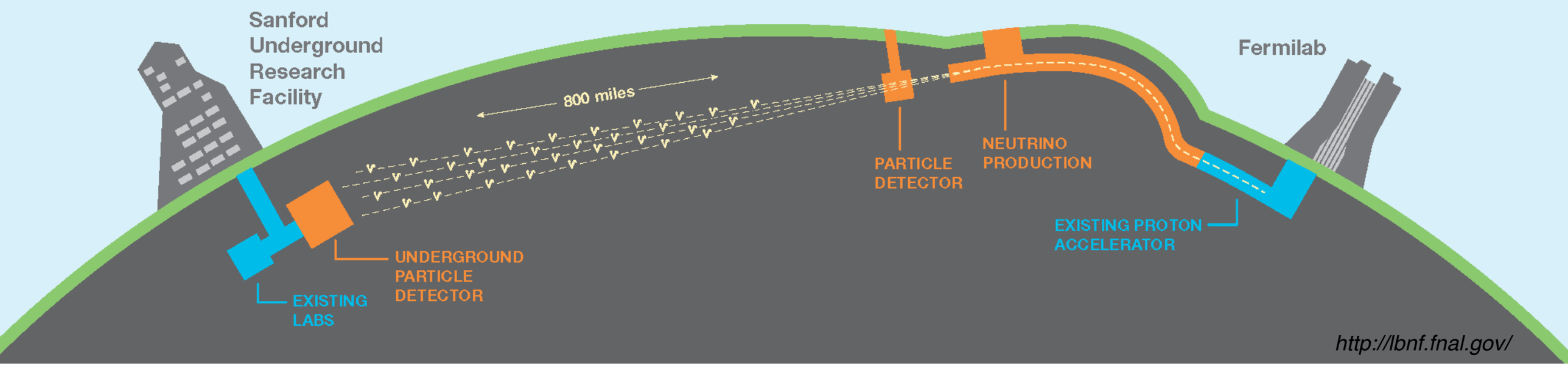


- Lower systematic uncertainty can considerably lower the exposure needed to discover CP violation in DUNE.

Accelerator-Based Neutrino Oscillation Experiment

- **General Oscillation Analysis Strategy**

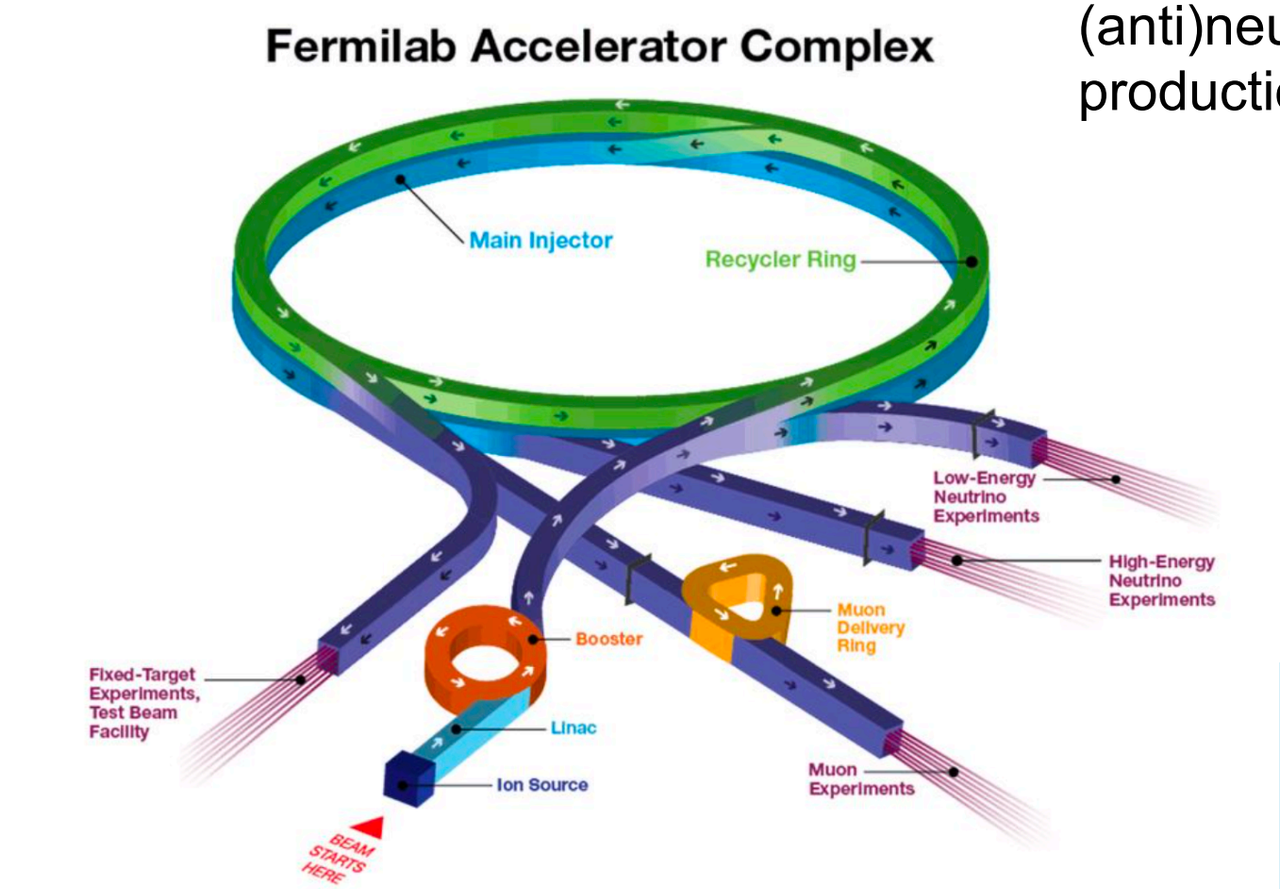
DUNE

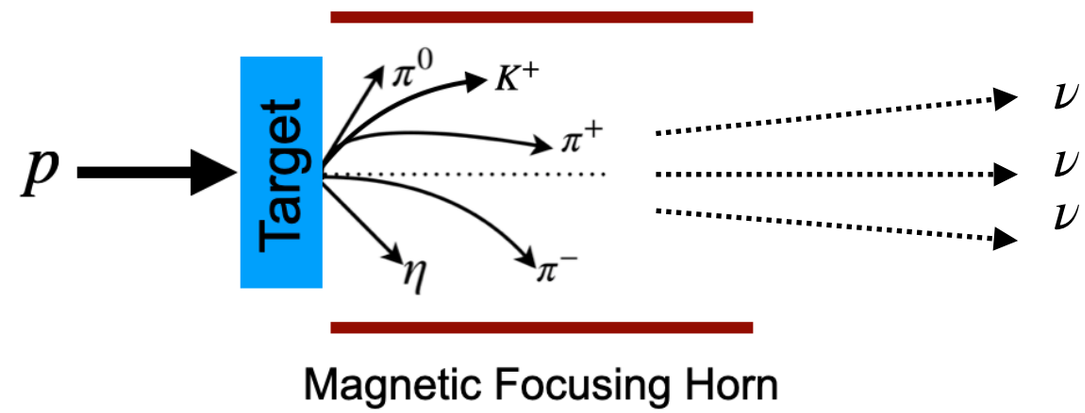


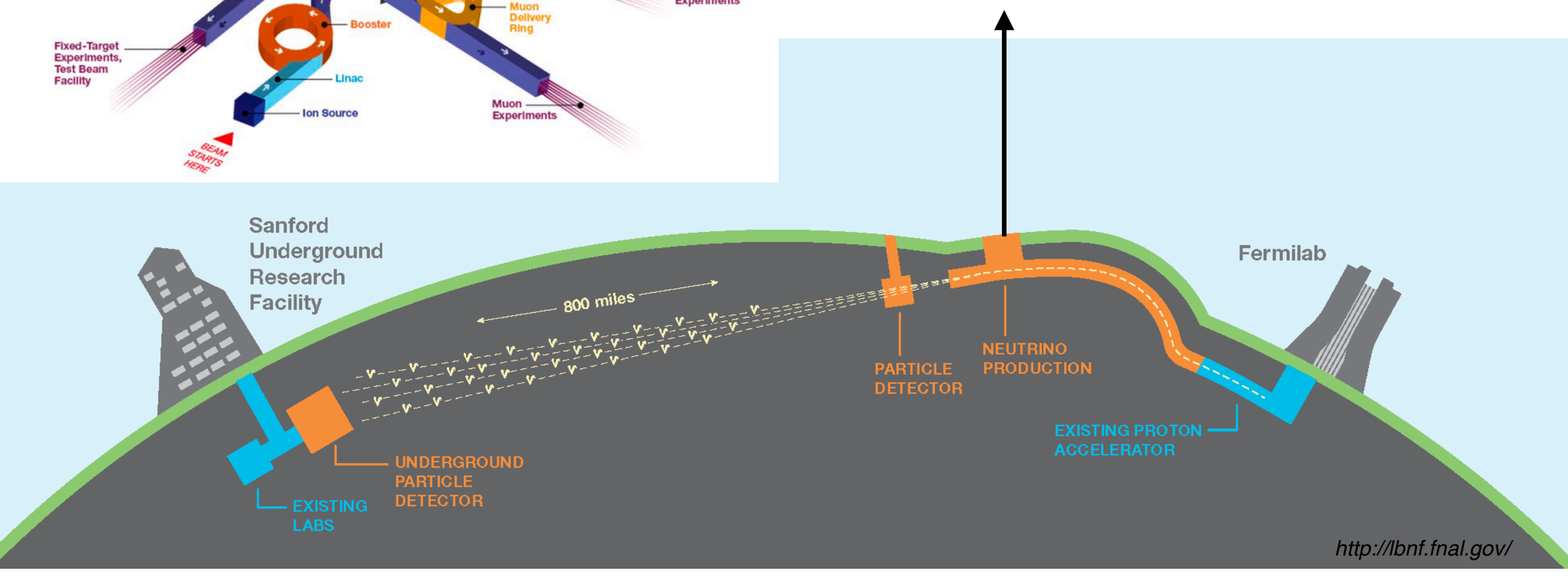
Accelerator-Based Neutrino Oscillation Experiment

General Oscillation Analysis Strategy

- Produce Neutrino Beam: Accelerator produces an intense (anti)neutrino source. Constrained by external hadron production measurement





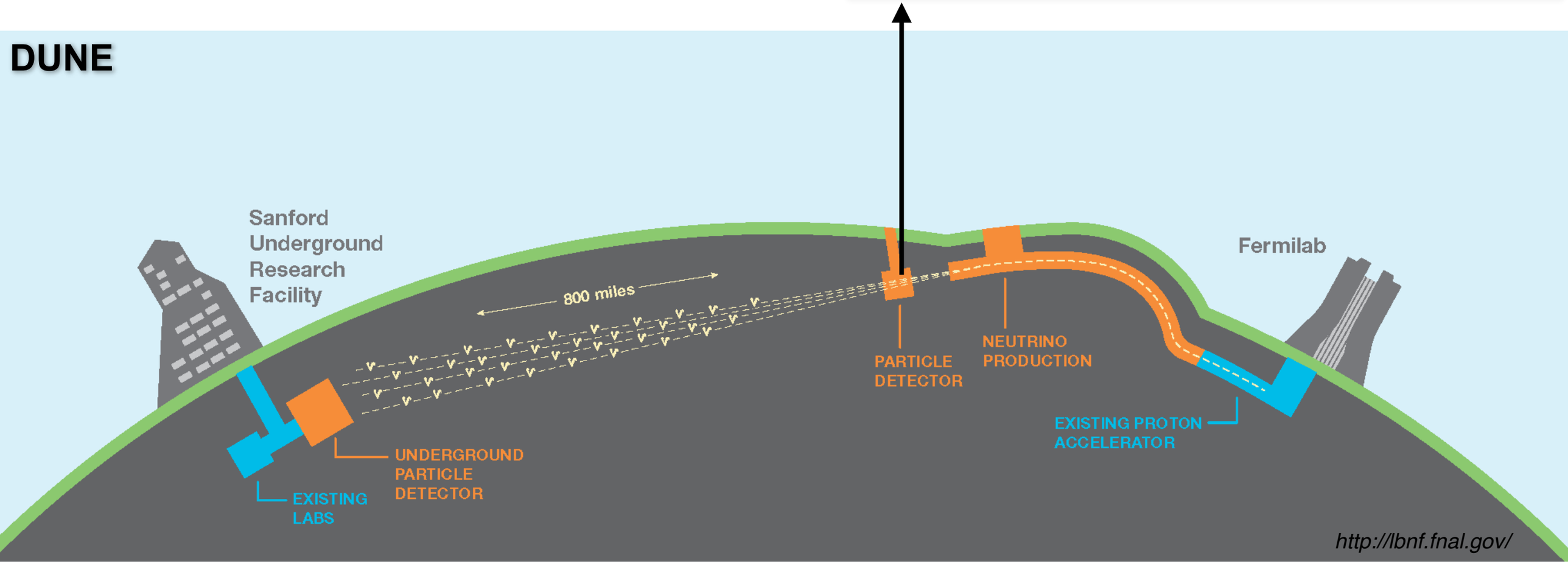


Accelerator-Based Neutrino Oscillation Experiment

General Oscillation Analysis Strategy

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

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



Accelerator-Based Neutrino Oscillation Experiment

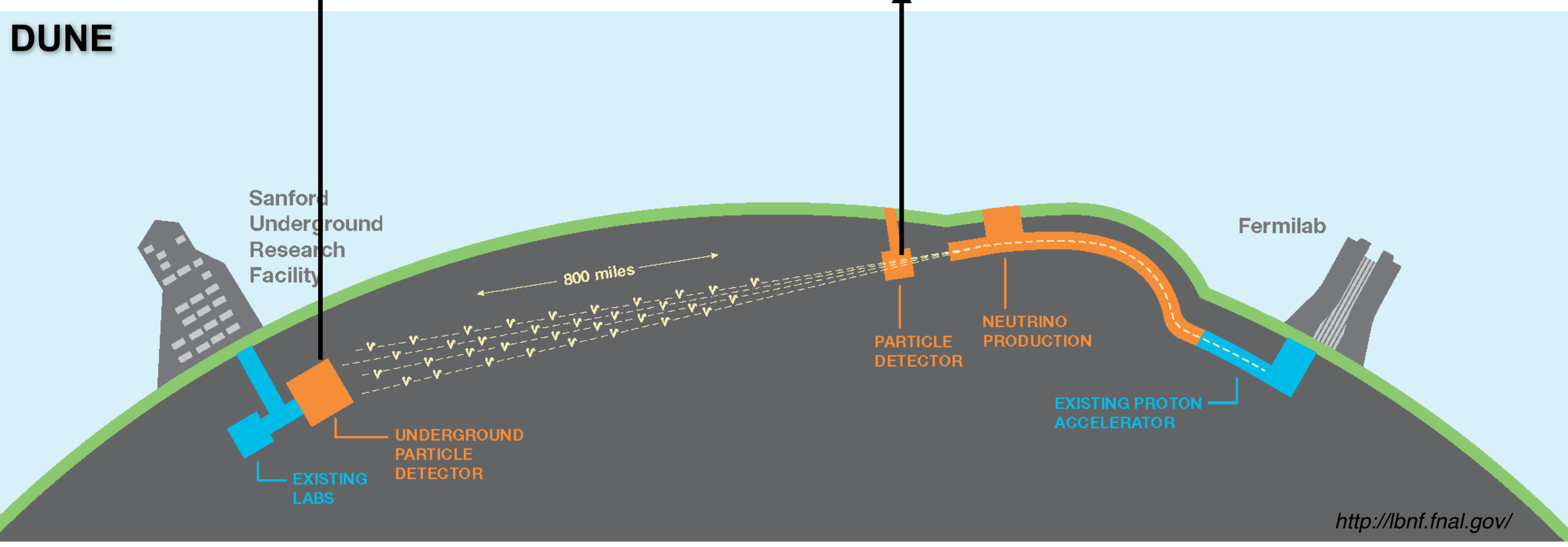
General Oscillation Analysis Strategy

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

$$N_{FD}^{\alpha\to\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\beta^i(E_\nu) \times P(\nu_\alpha \to \nu_\beta) \times \epsilon_\beta(E_\nu, E_{\nu,rec})$$

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

$$N_{ND}^{\alpha}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\alpha^i(E_\nu) \times \epsilon_\alpha(E_\nu, E_{\nu,rec})$$



Accelerator-Based Neutrino Oscillation Experiment

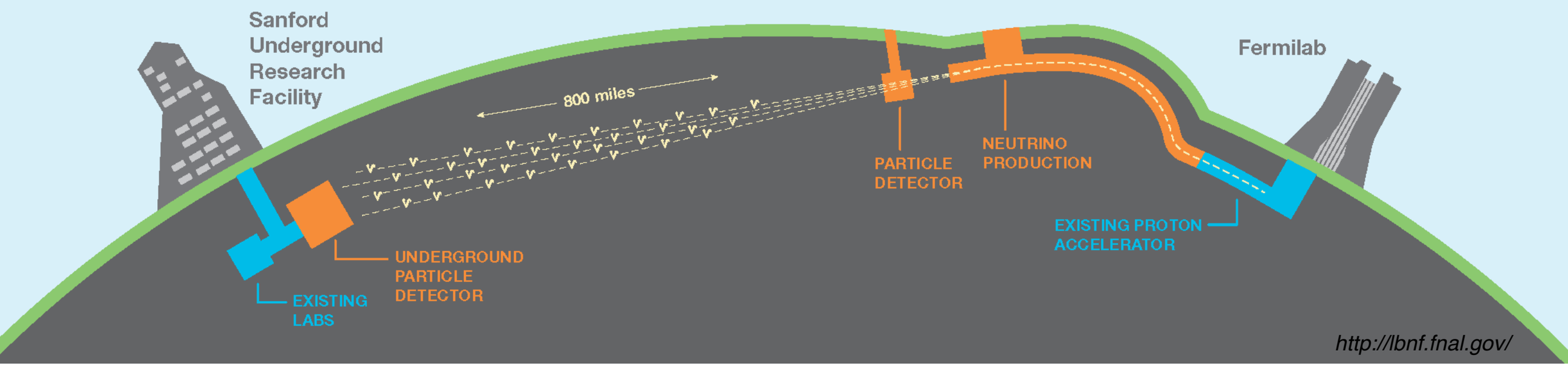
General Oscillation Analysis Strategy

- Extract Oscillation Parameters:

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

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

DUNE



Accelerator-Based Neutrino Oscillation Experiment

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Near to far ratio doesn't fully cancel it out:

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

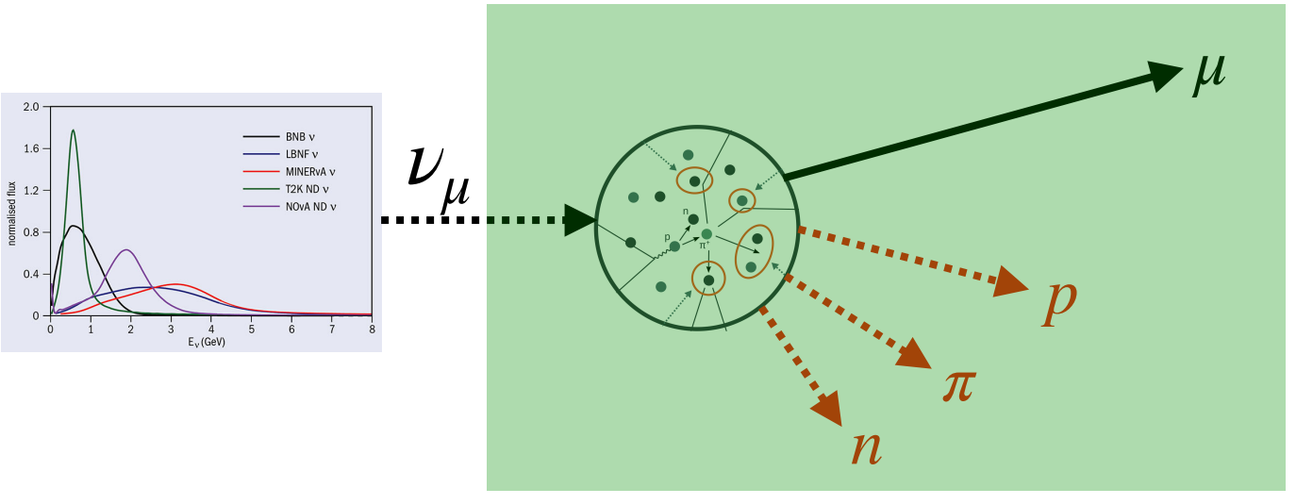
Neutrino Energy and Neutrino-Nucleus Interactions

$$\frac{N_{FD}^{\alpha\to\beta}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\beta^i(E_\nu) \times P(\nu_\alpha \to \nu_\beta) \times \epsilon_\beta(E_\nu, E_{\nu,rec})}{N_{ND}^{\alpha}(E_{\nu,rec}) \propto \sum_i \phi_\alpha(E_\nu) \times \sigma_\alpha^i(E_\nu) \times \epsilon_\alpha(E_\nu, E_{\nu,rec})}$$

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

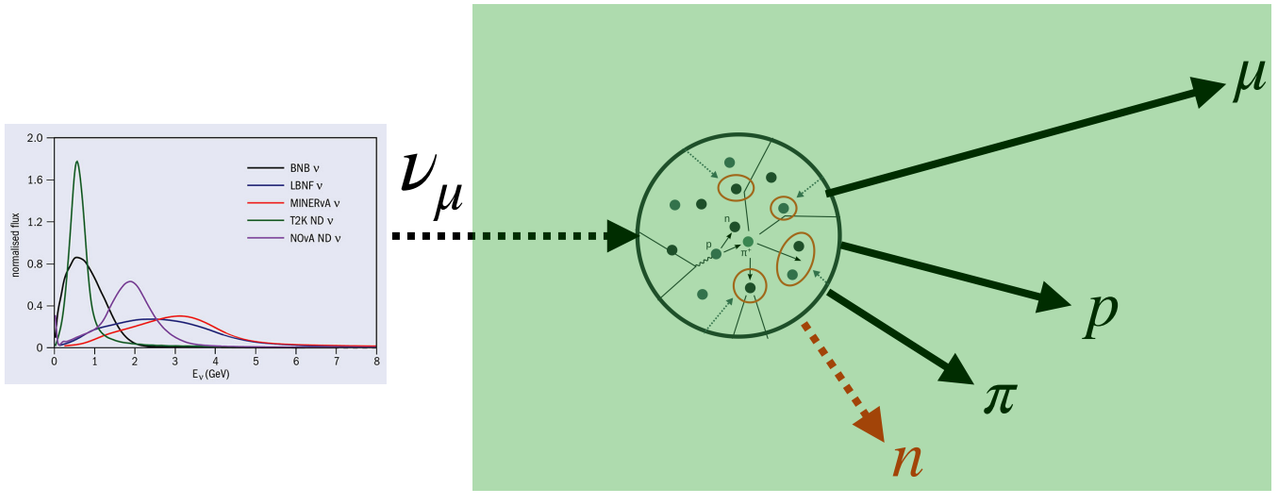
- **Neutrino Energy Reconstruction**:
  - Kinematic Method (T2K/HK):

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



  - Calorimetric Method (NOvA/SBN/DUNE):

$$E_\nu^{Cal} = \sum E_{observed\ particles} + E_{neutrons} + E_{missing}$$

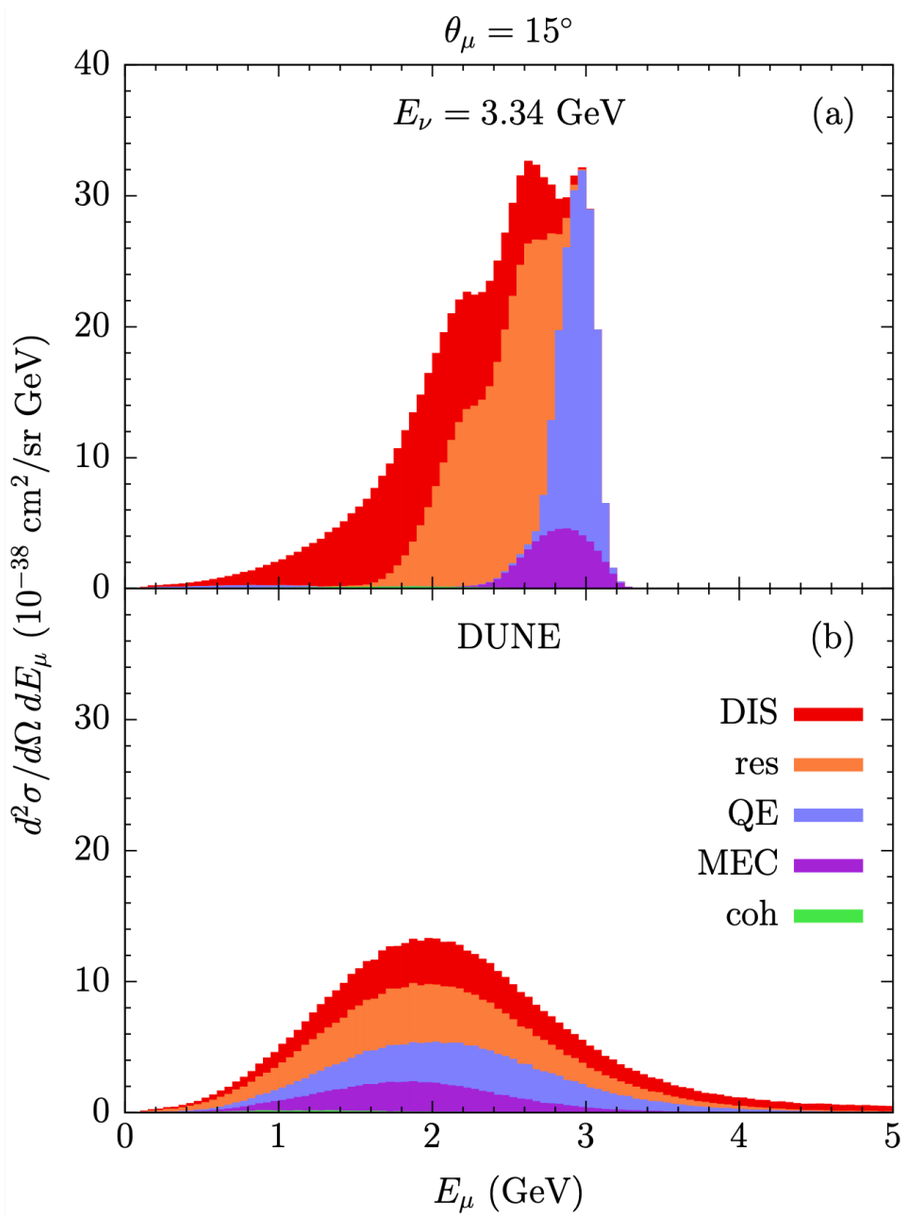


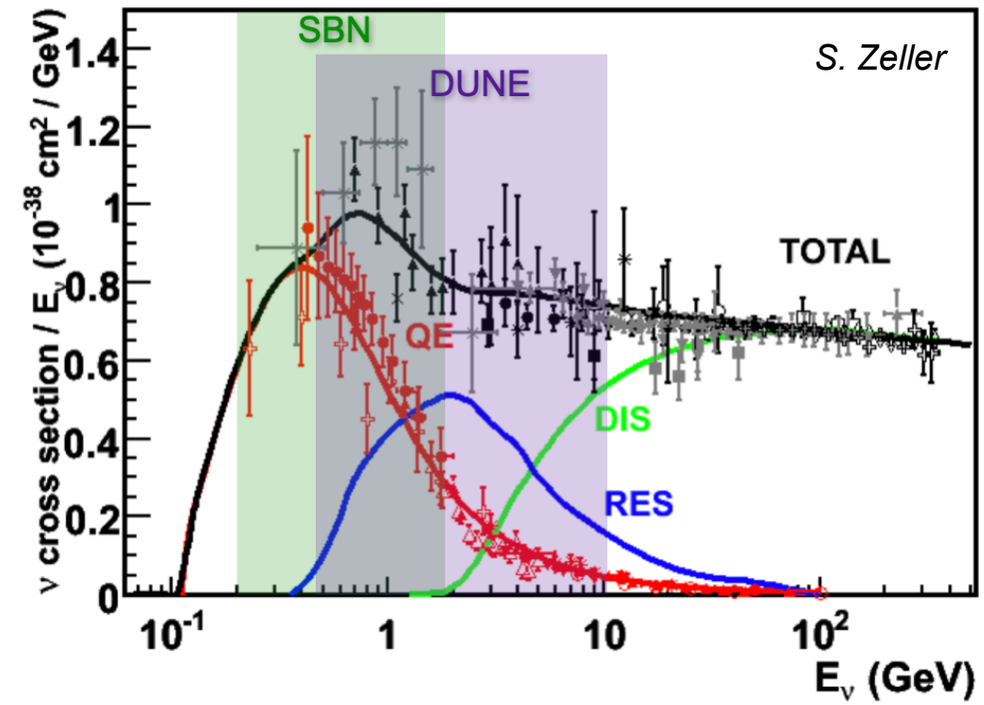
- "CCQE" topology may have contribution from 2p2h, pion absorption, etc.
- Missing energy from neutrons, detector threshold, etc.

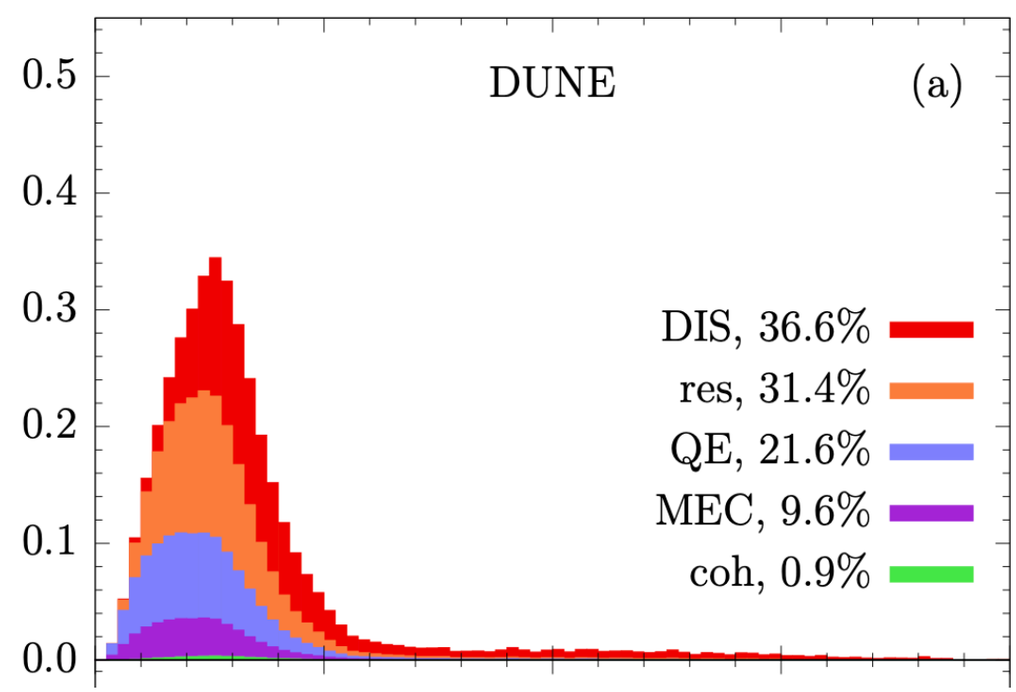
✦ In both cases, neutrino energy reconstruction requires predictions from the interaction model.

Neutrino Energy and Neutrino-Nucleus Interactions

- **Neutrino-Nucleus Interactions**:
  - Neutrino fluxes span over a wide range of energies where a number of complex nuclear reaction mechanisms overlap.
  - Typical target systems are large and complex: water, liquid scintillator, and liquid argon
  - Not possible to separate different processes



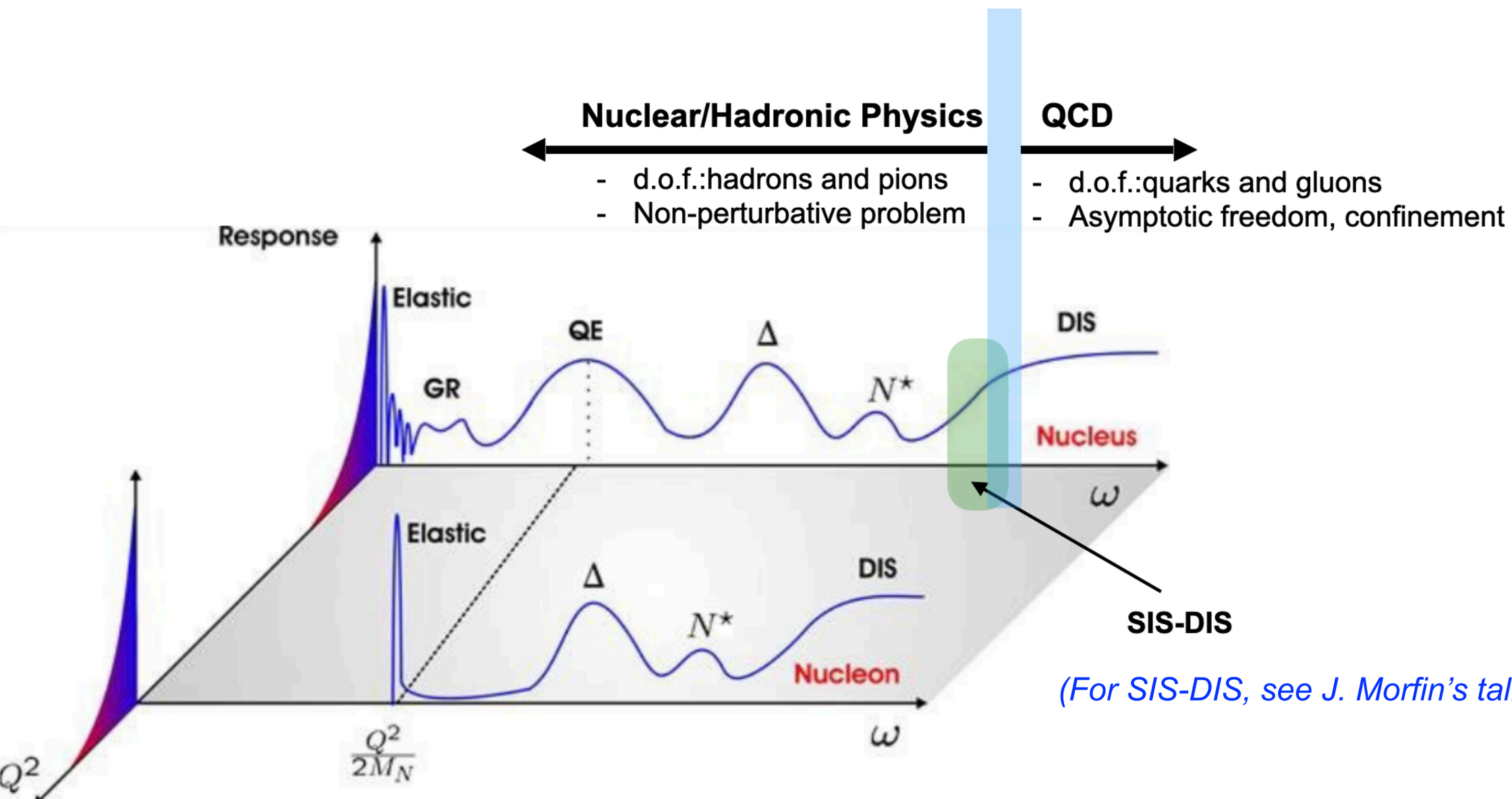




A. M. Ankowski et al., Phys. Rev. D 102, 053001 (2020)

Neutrino Energy and Neutrino-Nucleus Interactions

- **<u>Neutrino-Nucleus Interactions</u>:**
  - Multi-scale, multi-process, many-body, non-perturbative problem subject to complex nuclear structure and dynamics. Includes transition from the hadronic d.o.f. to quark d.o.f.
  - Usually solved with approximate methods using nuclear models.
  - Different model rely on different approximations, which are valid in specific kinematics and for the specific process (quasi-elastic, 2p2h, resonance production, DIS).



(For SIS-DIS, see J. Morfin's talk on Tuesday)

Neutrino-Nucleus Interactions: Wish List

- In an ideal scenario, for an oscillation analysis, experiments need a consistent neutrino interaction models that provide predictions 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*
  - 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.

*Constrain ν_μ to ν_e differences (lepton mass effects, radiative corrections), and constrain ν to $\bar{\nu}$ differences (specially for an isospin asymmetric nuclei, e.g. ^{40}Ar)

Neutrino-Nucleus Interactions: Theory Models

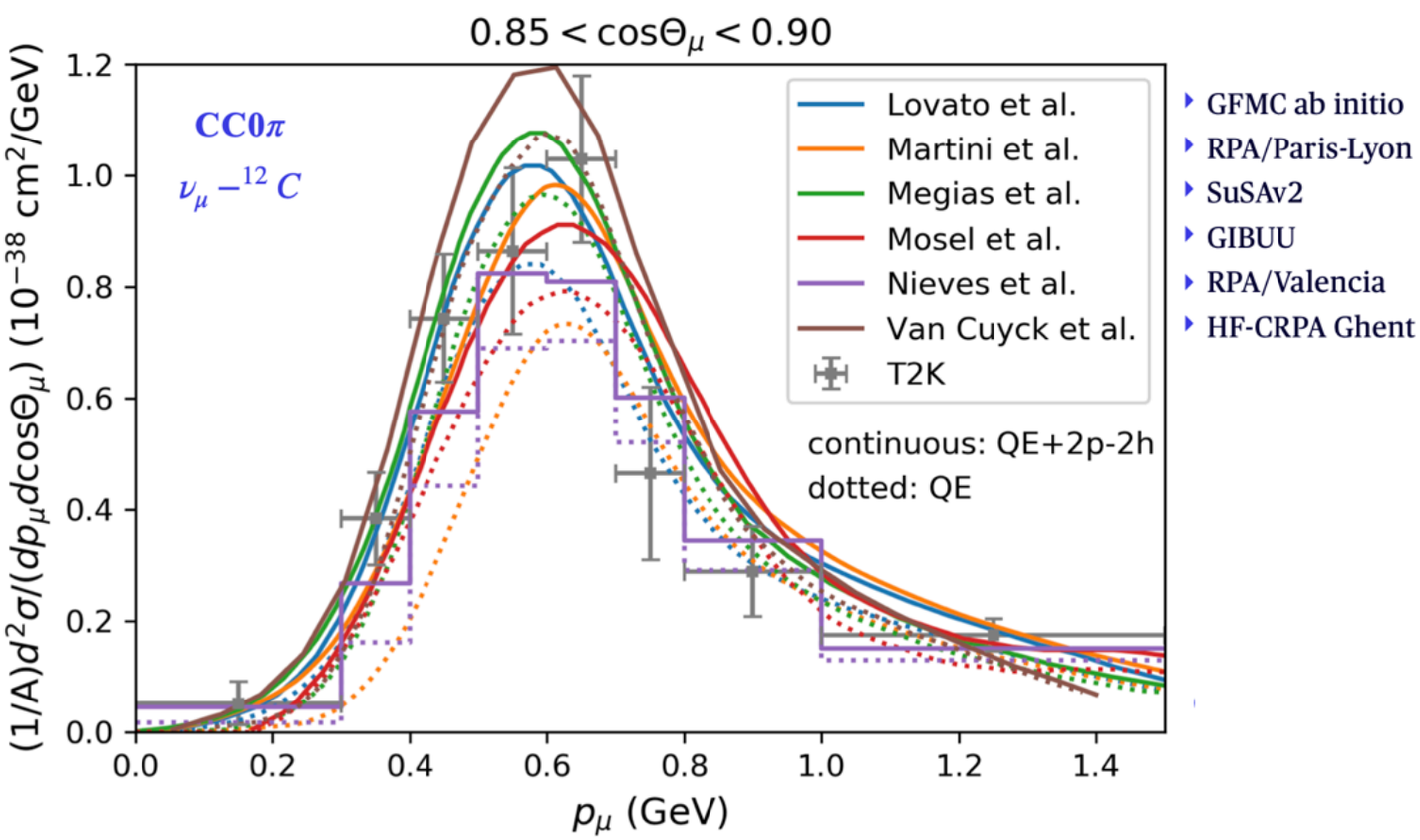
- A lot of theoretical development in last 10-15 years.

  - RPA:Valencia (Nieves and coll.), Lyon/Paris (Martini and coll.)
  - HF-CRPA: Ghent (Jachowicz and coll.)
  - Spectral function approach: Rome (Benhar and coll.)
  - Green's function Monte Carlo "ab initio": Los Alamos (Carlson, Lovato and coll.)
  - GIBUU event generator, transport theory: Giessen (Mosel and coll.)
  - Relativistic Green's function: Pavia (Giusti and coll.)
  - SuSAv2 superscaling/relativistic mean field: Granada, Madrid, MIT, Sevilla, Torino

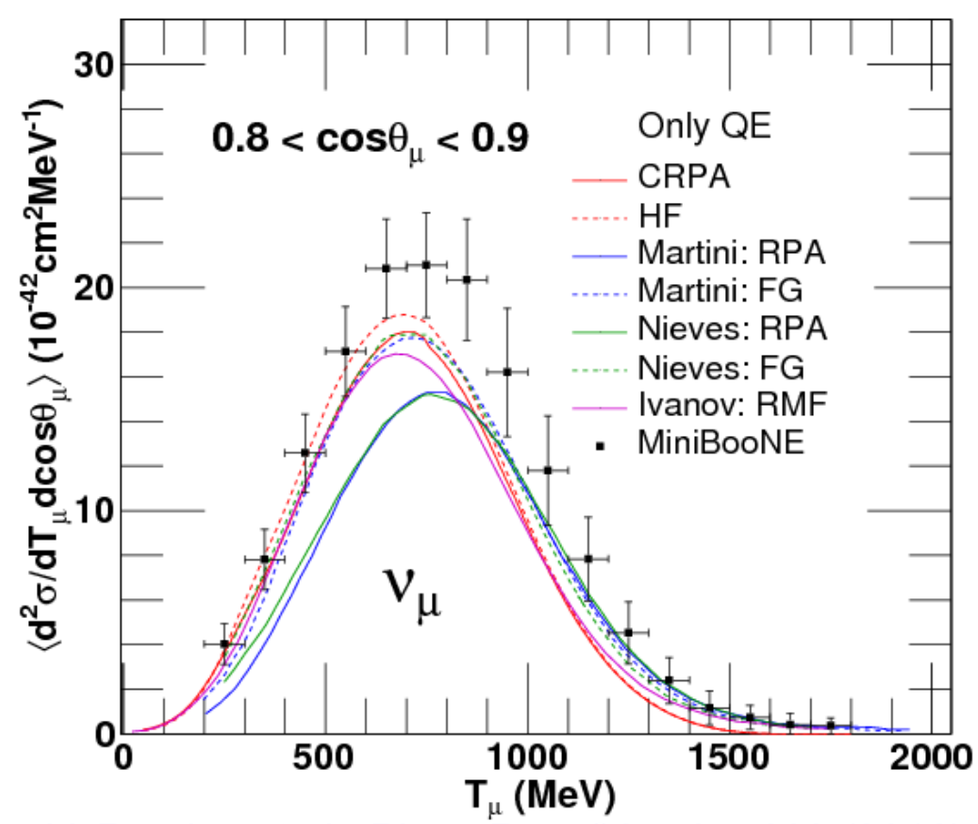
(Maria Barbaro's talk on Monday)

(See N. Rocco, H. Haider, and O. Tomalak's talk)

- Most models up to now have been focussed on inclusive reactions, and show reasonable agreement with neutrino data. Not sufficient measurement precision to discriminate between models.



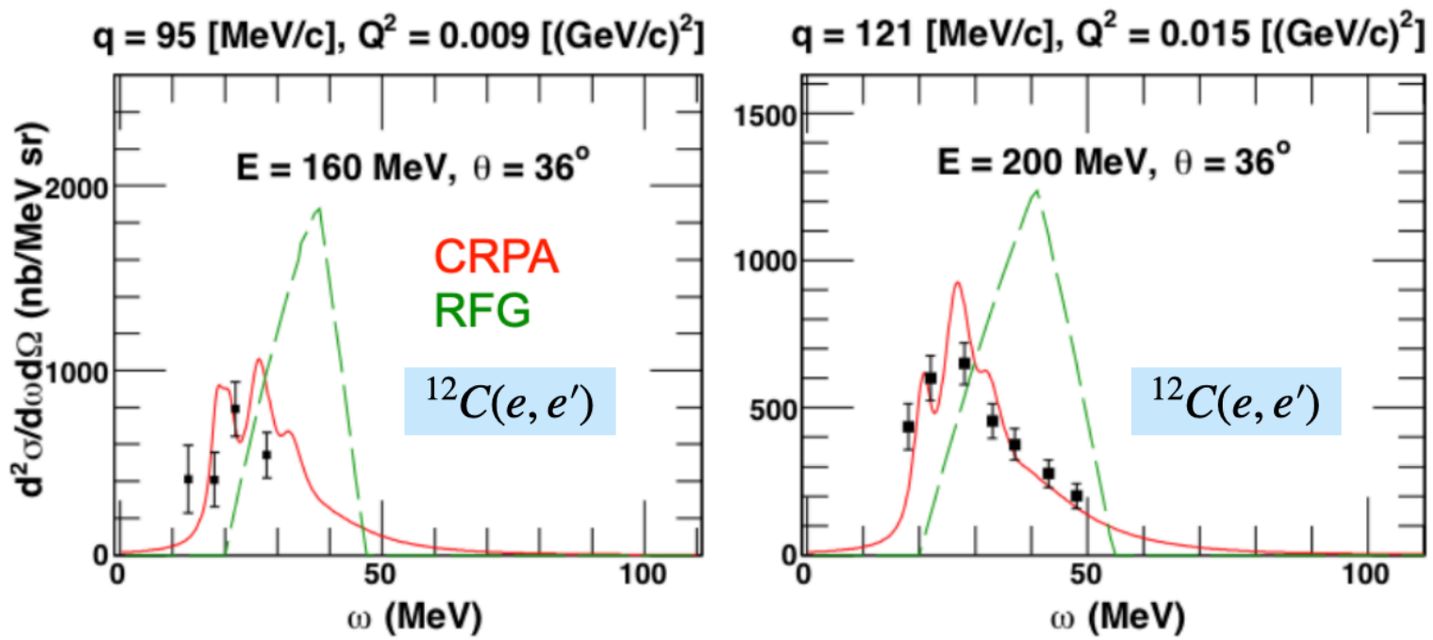
A. Branca, et al., arXiv:2108.12212 [hep-ex]

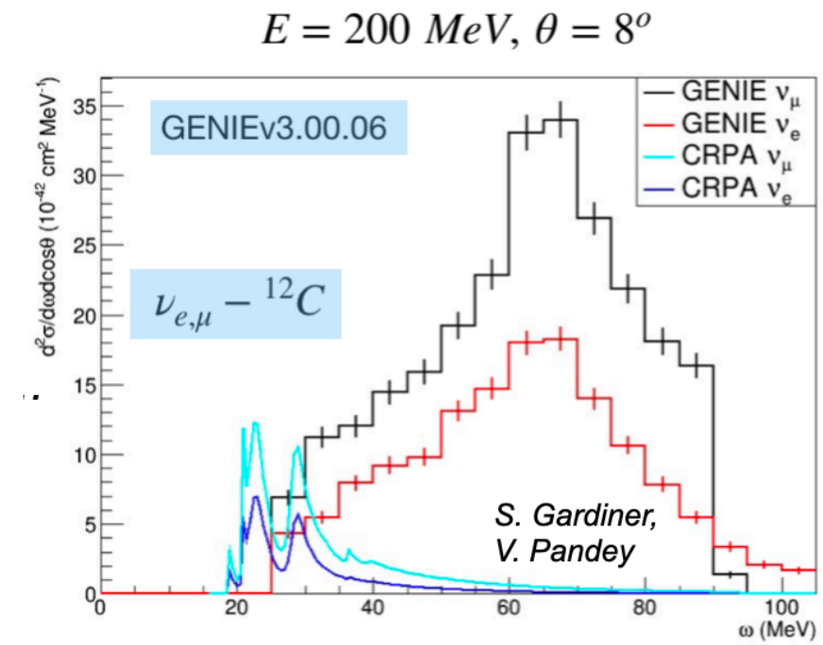


V. Pandey et al., Phys. Rev. C94, 054609 (2016)

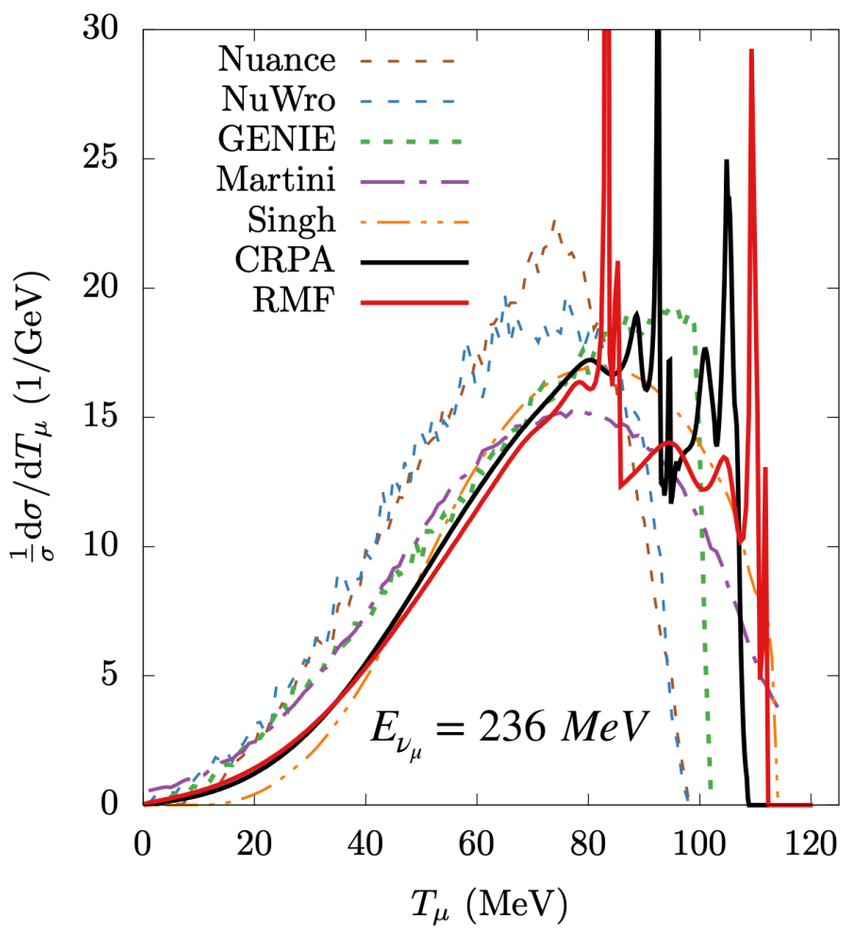
Neutrino-Nucleus Interactions: Theory Models

Lower Energies

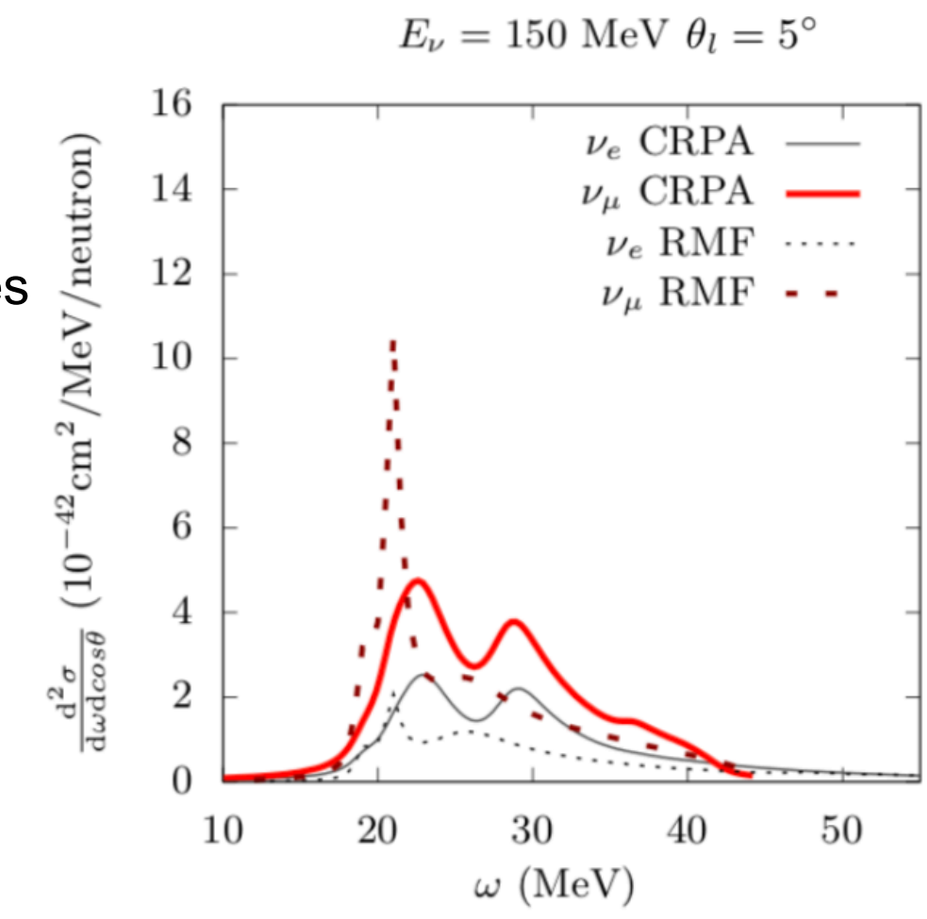




- Mono-energetic kaon decay at rest neutrinos:



- ν_μ, ν_e XS differences

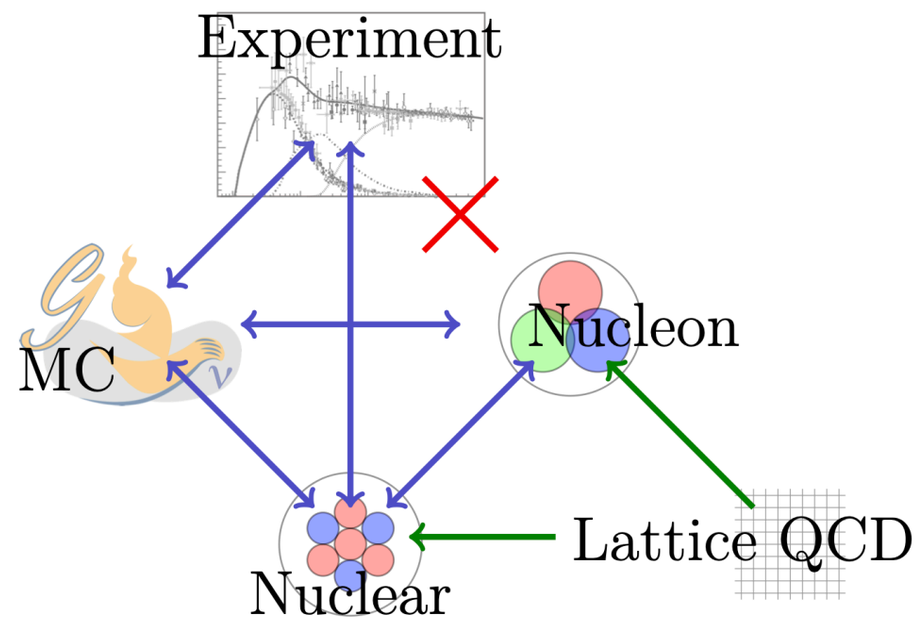


A. Nikolakopoulos et al., Phys.Rev.C 103, 064603 (2021)

A. Nikolakopoulos et al., Phys. Rev. Lett. 123, 052501 (2019)

Neutrino-Nucleus Interactions: Theory Models

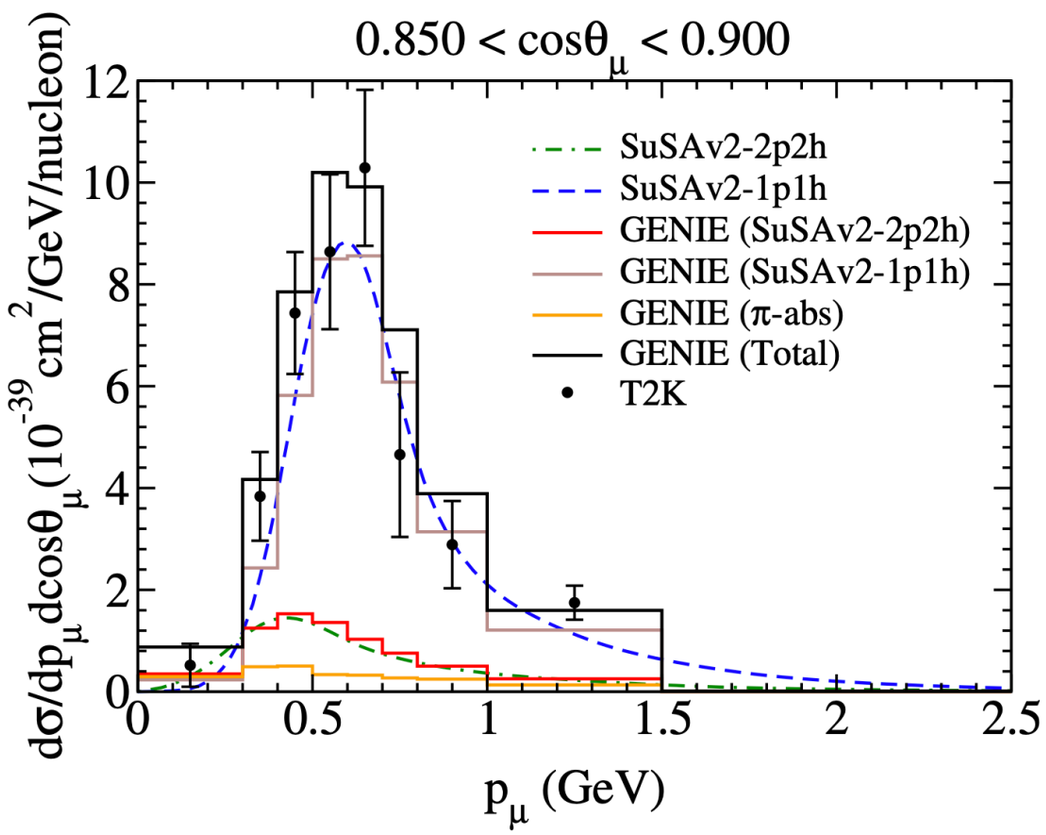
- **Challenges and opportunities:**
  - Most models up to now have been focussed on inclusive reactions, semi-inclusive/exclusive predictions are needed. See Maria Barbaro's talk from Monday.
  - More exclusive processes require more detailed modeling. More response functions enter in the calculations.
  - Further development from LQCD community will also improve the situation: nucleon level robust input from LQCD to nuclear model/EFT



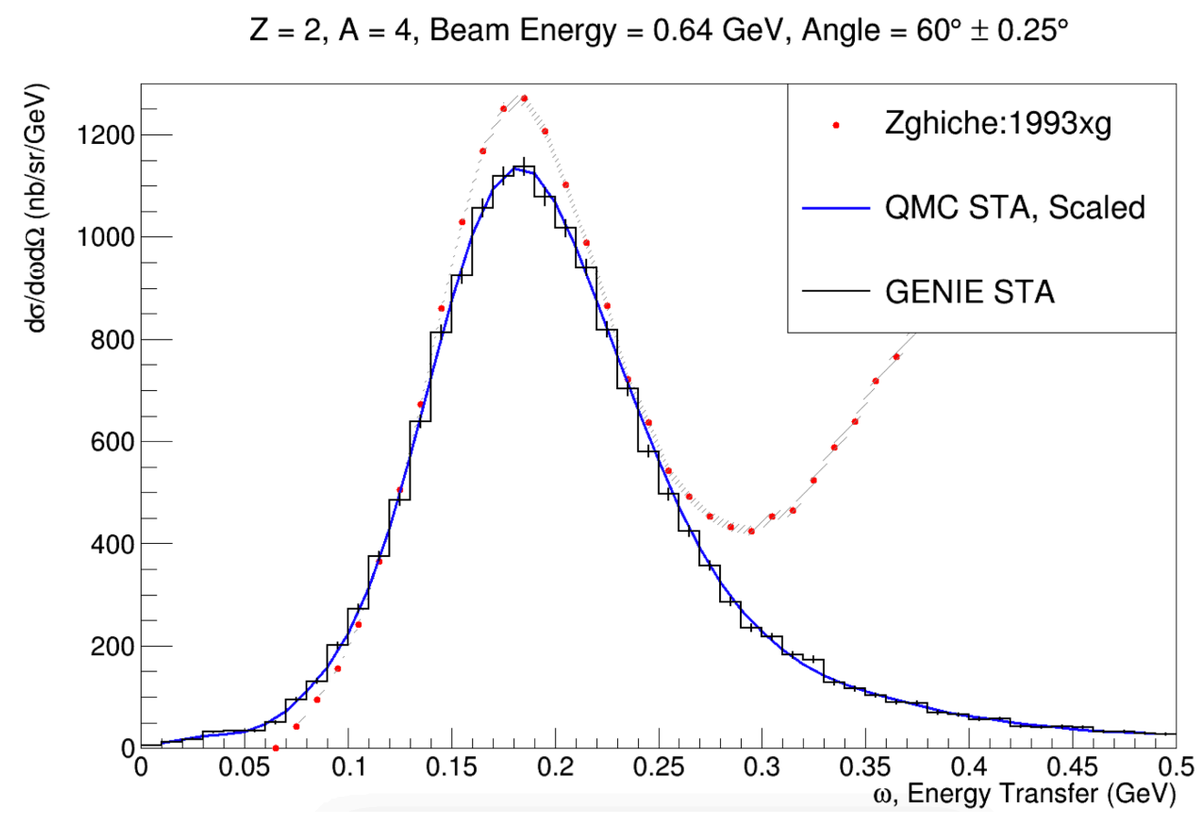
A. S. Meyer at a Snowmass Workshop

Neutrino-Nucleus Interactions: Generators

- Widely used generators, in general, have good description of Flux Drivers, and Target Geometries.
- In recent years, generators made significant improvement in implementing new models that describe electron scattering data.



S. Dolan, G. Megias, S. Bolognesi, Phys.Rev. D 101, 033003 (2020)



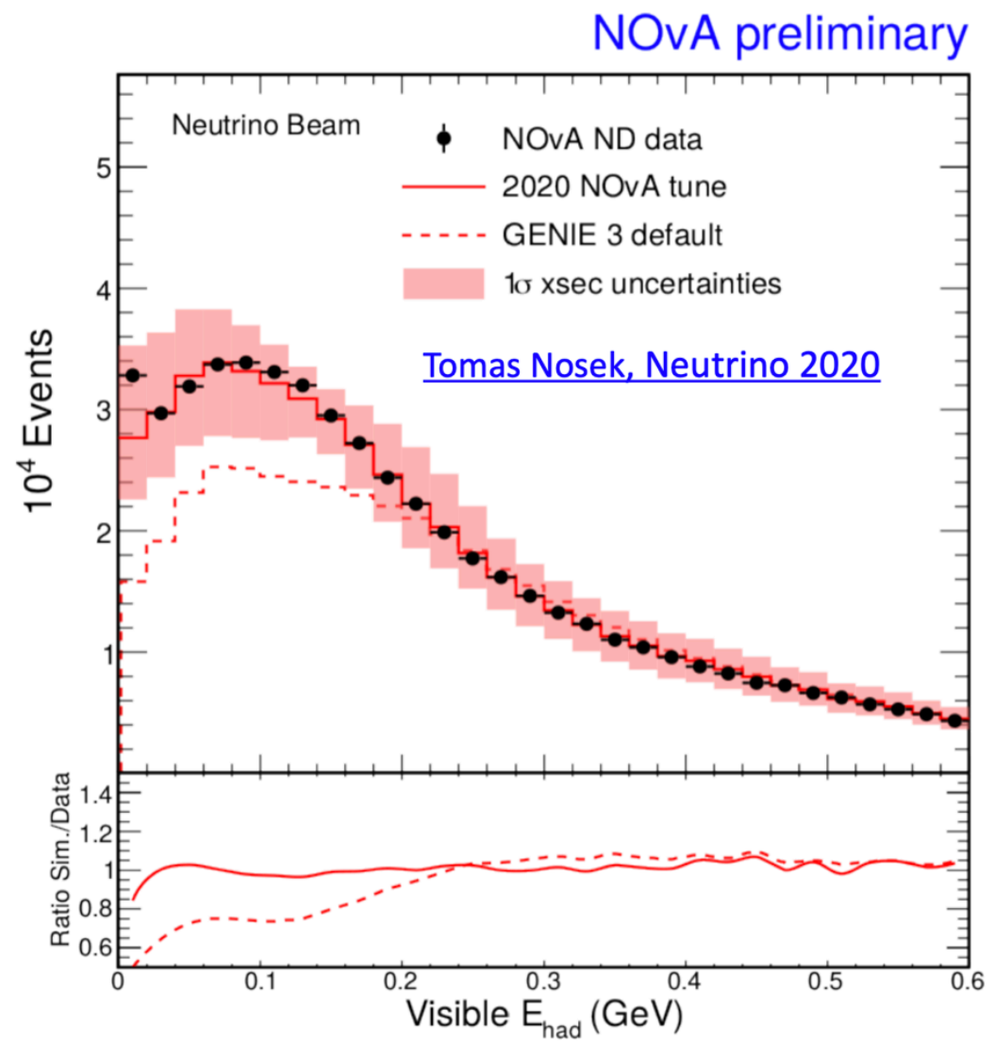
J. Barrow, et al., Phys. Rev. D 103, 052001 (2021)

- e4Nu Collaboration: Phys.Rev.D 103, 113003 (2021)
- GENIE Collaboration: arXiv:2106.09381 [hep-ph], arXiv: 2106.05884 [hep-ph]

- Major developments in NEUT, NuWro. See Wednesday WG2 session.

Neutrino-Nucleus Interactions: Generators

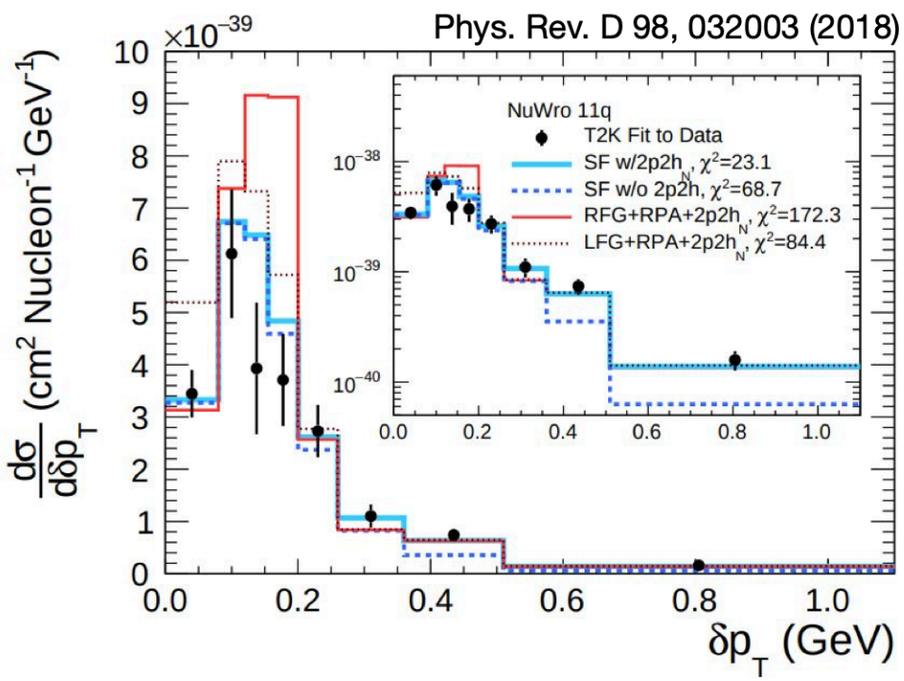
- **Challenges and opportunities:**
  - Models provide inclusive predictions, generators have to produce energy and momentum of all the final state particles using additional schemes, that leads to inconsistencies.
  - Analyzers have to develop experiment-specific interaction model or “tuning”, using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



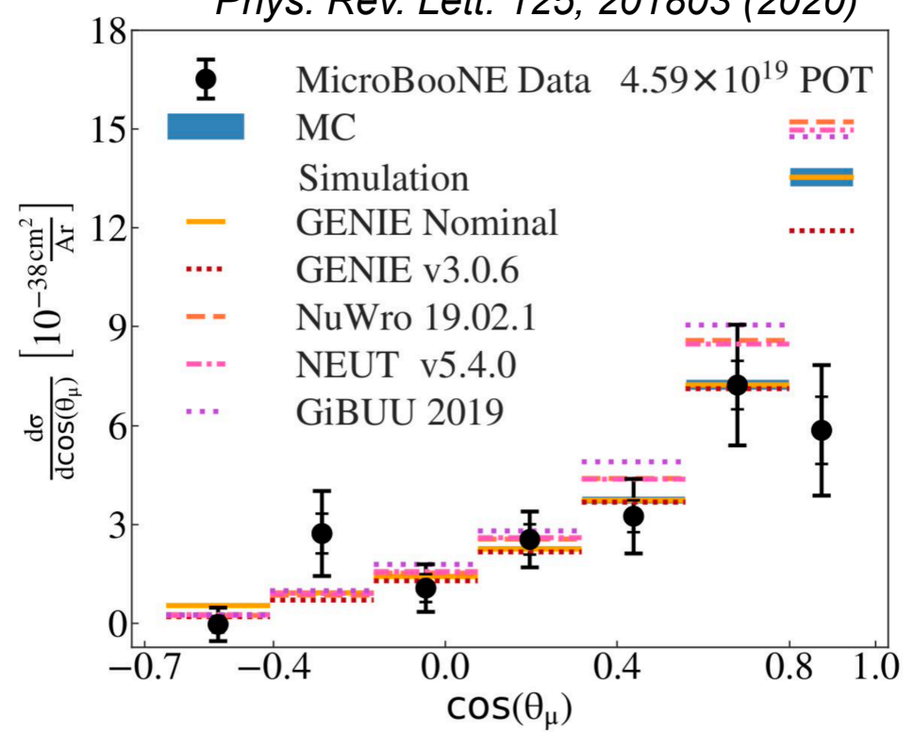
Neutrino-Nucleus Interactions: Measurements

- In recent years, T2K/MINERvA/MicroBooNE/NOvA and others have made a wide range of innovative cross-section measurements. See many experimental talks of WG2.

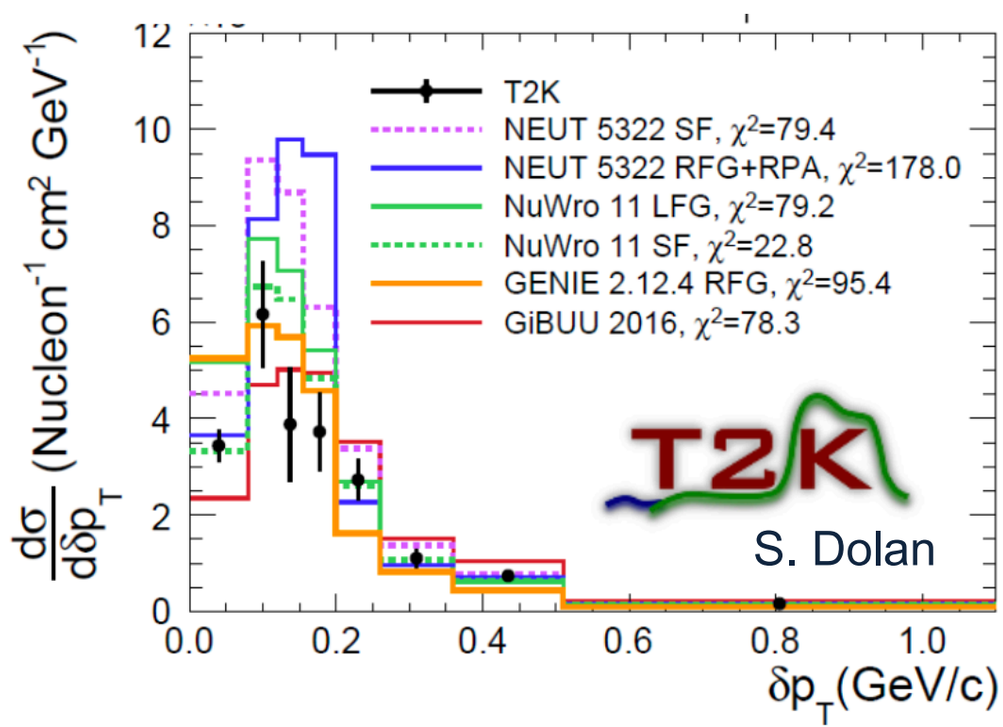
T2K



Phys. Rev. Lett. 125, 201803 (2020)

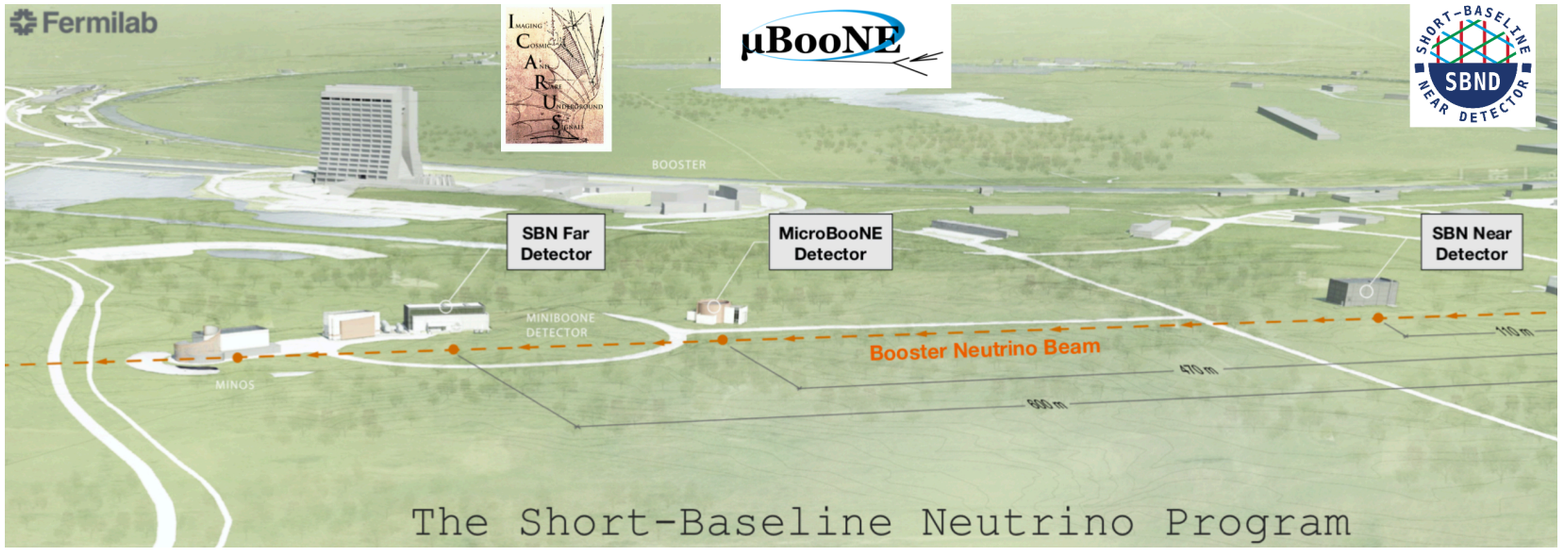


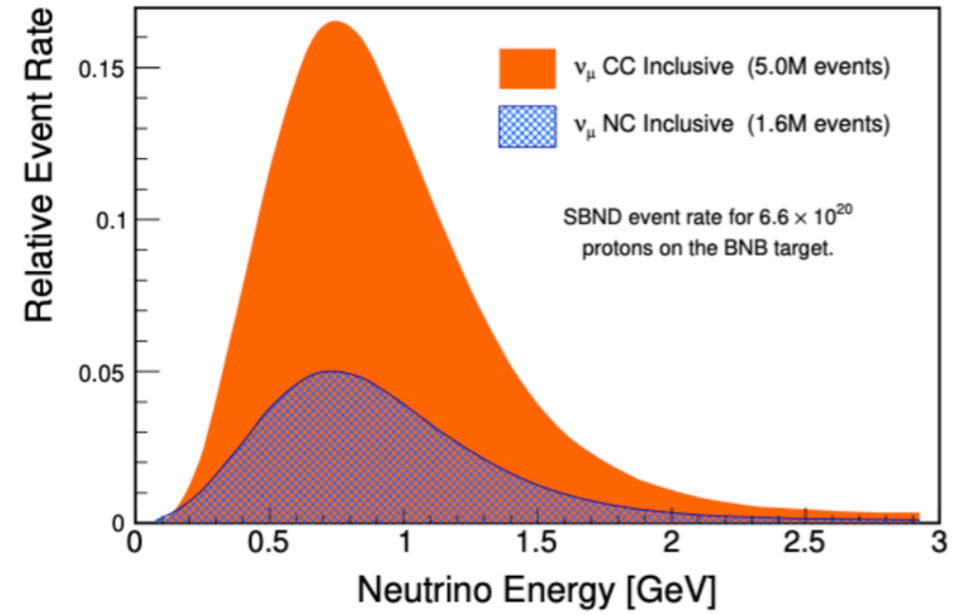
- Current generators, in general are not able to describe anything more than the lepton kinematic distributions.



Neutrino-Nucleus Interactions: Measurements

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





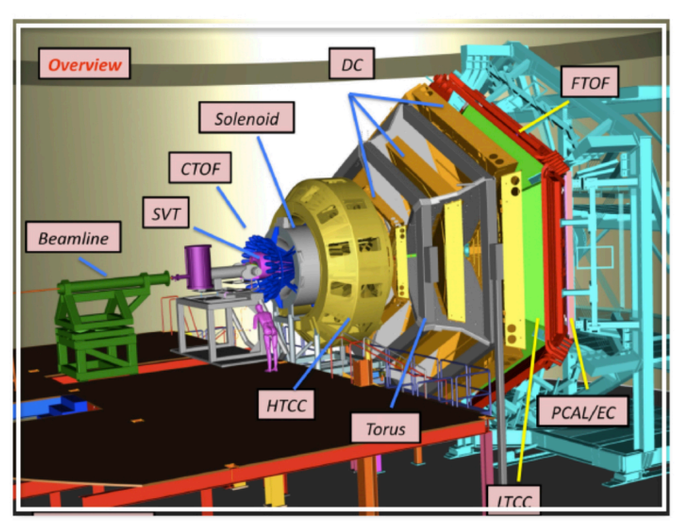
- <u>SBN Program at FNAL (LArTPCs)</u>:
  - MicroBooNE: Already producing interesting measurements
  - ICARUS: Started taking data
  - SBND: SBND will compile data with an unprecedented high event rate

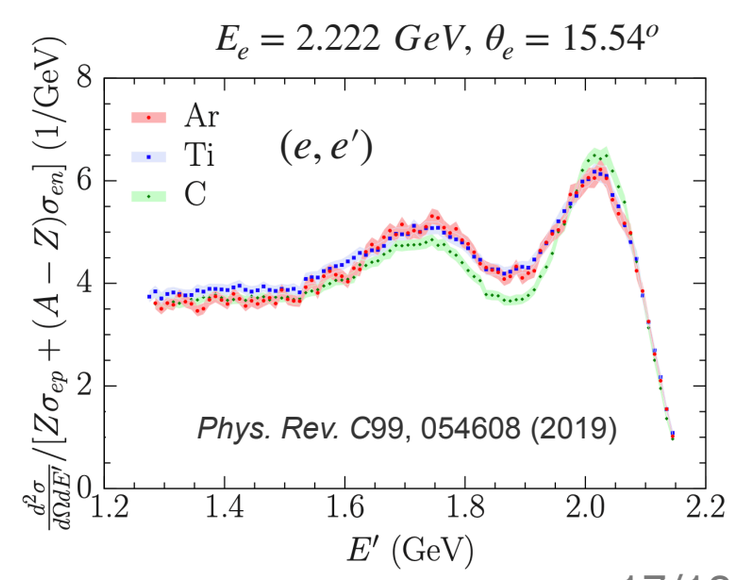
- Lots of exciting measurements to come from T2K, NOvA and MINERvA.

- <u>Electron-scattering data</u>:

  (L. Weinstein's talk on Monday)

  - E12-14-012 at JLab Hall A
  - e4nu collaboration/CLAS
  - LDMX at SLAC





Summary

- Neutrino interaction uncertainties constitute one of the largest source of uncertainty in the accelerator-based neutrino program.

- There has been a lot of theoretical development in the last decade in describing inclusive neutrino-nucleus scattering. Progress towards semi-inclusive/exclusive predictions are needed, they require more detailed modeling and resources.

- In recent years, the 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.