Neutrino Generators

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WCD-2025 - September 18th, 2025

Neutrino Physics & Neutrino-Nucleus Interactions

- Various neutrino physics searches are ongoing.
- Key: Understanding ν-nucleus interactions, the dominant syst. unc.

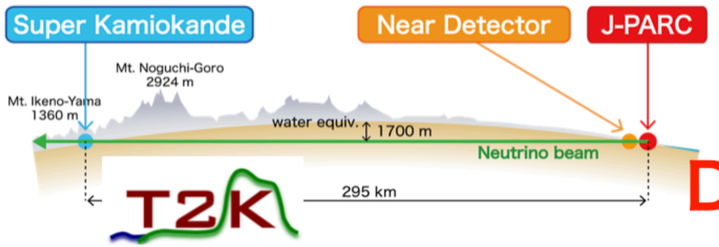
Neutrino CP-violation

Cosmogenesis physics

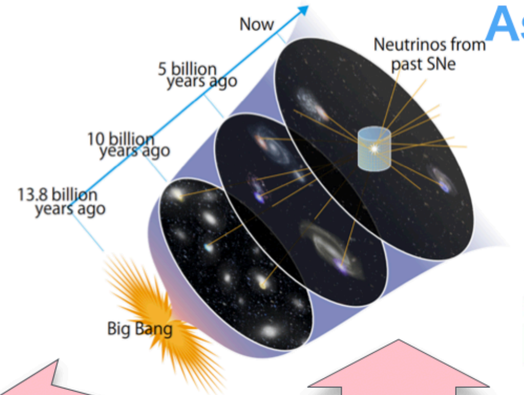
Osc. prob.

$$P(\nu_\mu \to \nu_e) \overset{?}{\neq} P(\bar{\nu}_\mu \to \bar{\nu}_e)$$

δ_{CP}



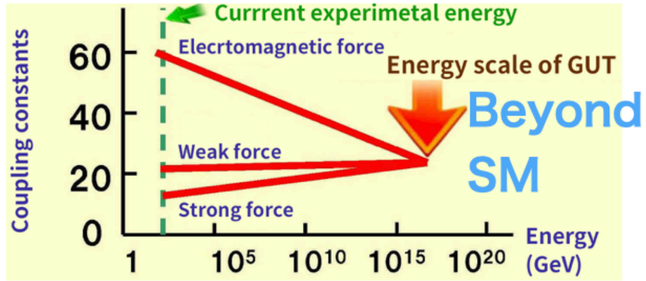
Diffused Supernova ν

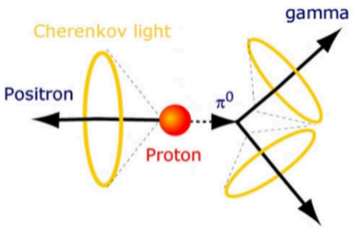


Astrophysics

SUPER-K Gd

Nucleaon Decay

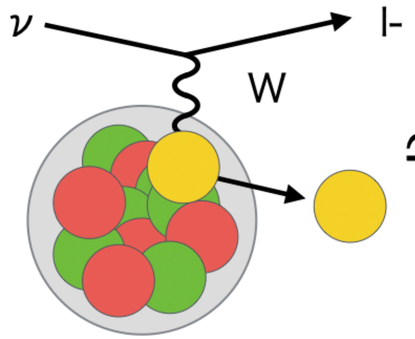




Develop neuturino physics

Understanding signal/BG

Understand ν-nucleus (νN) interactions



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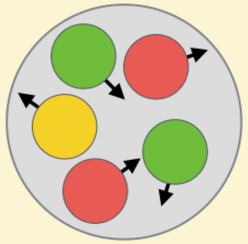
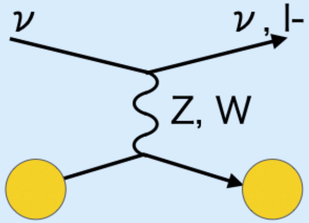
Initial state



Binding energy, momentum

X

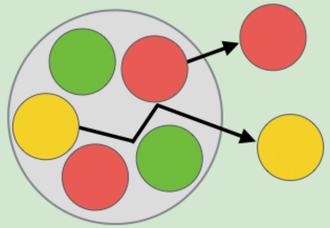
Weak interaction



V-A current

+

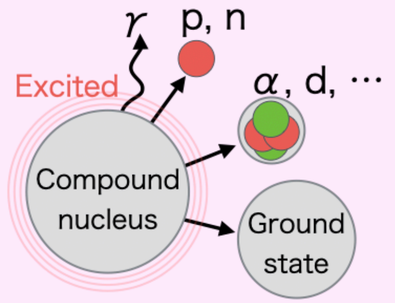
Final state interaction



Intranuclear cascade

+

Deexcitation



Compound process

Contents

- **Role of neutrino generators.**
  - e.g.) in neutrino oscillation experiments

- **Introduction to the neutrino event generator NEUT.**
  - History, overview, recent updates, etc.

Next generation neutrino oscillation

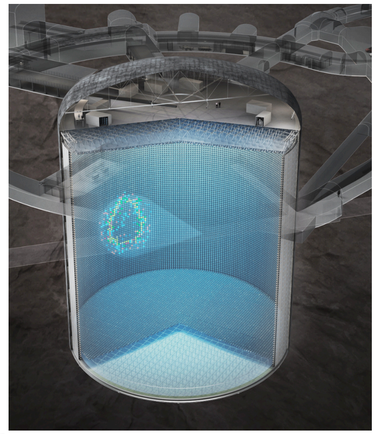
- ν interactions are the dominant systematic uncertainty.
  - Currently dominated by statistical uncertainty.

- In the next-generation experiment, systematic uncertainty will be dominant.

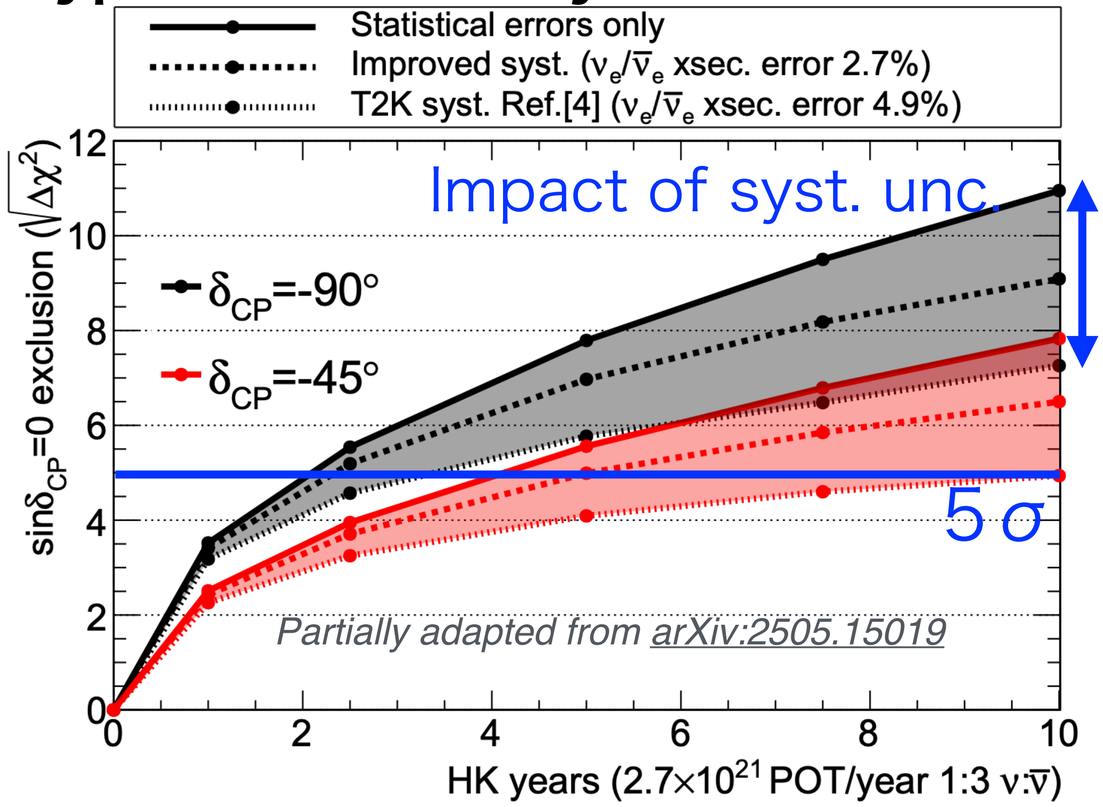
- **Toward HK in the Next Decade: Confronting Neutrino Interaction Systematics.**

Fiducial volume

22.5 kt ×8 190 kt



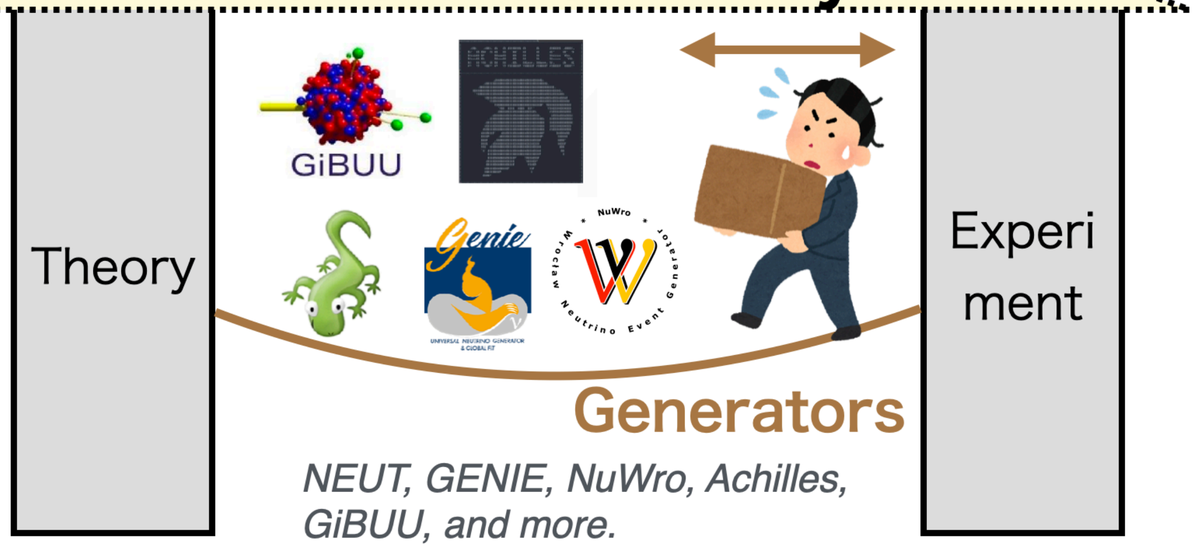
Hyper-K sensitivity on CP-violation



Role of Neutrino Generators

- **A bridge between theory and experiments.**
  - Essential software to conduct analysis.
- **Cover a wide neutrino energies.**
  - ~100 MeV to TeV.

Precise ν-N interaction prediction or oscillation analysis



NEUT, GENIE, NuWro, Achilles, GiBUU, and more.

Accelerator ν

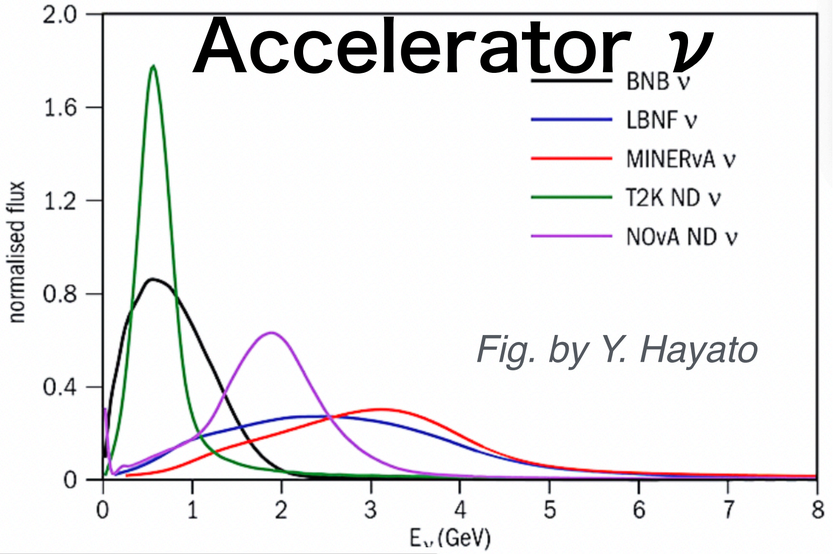
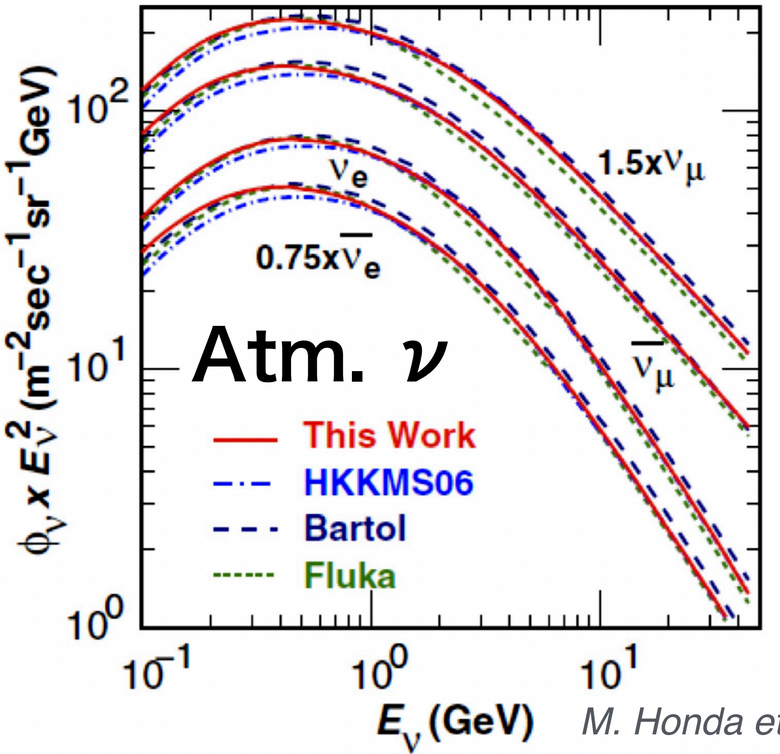


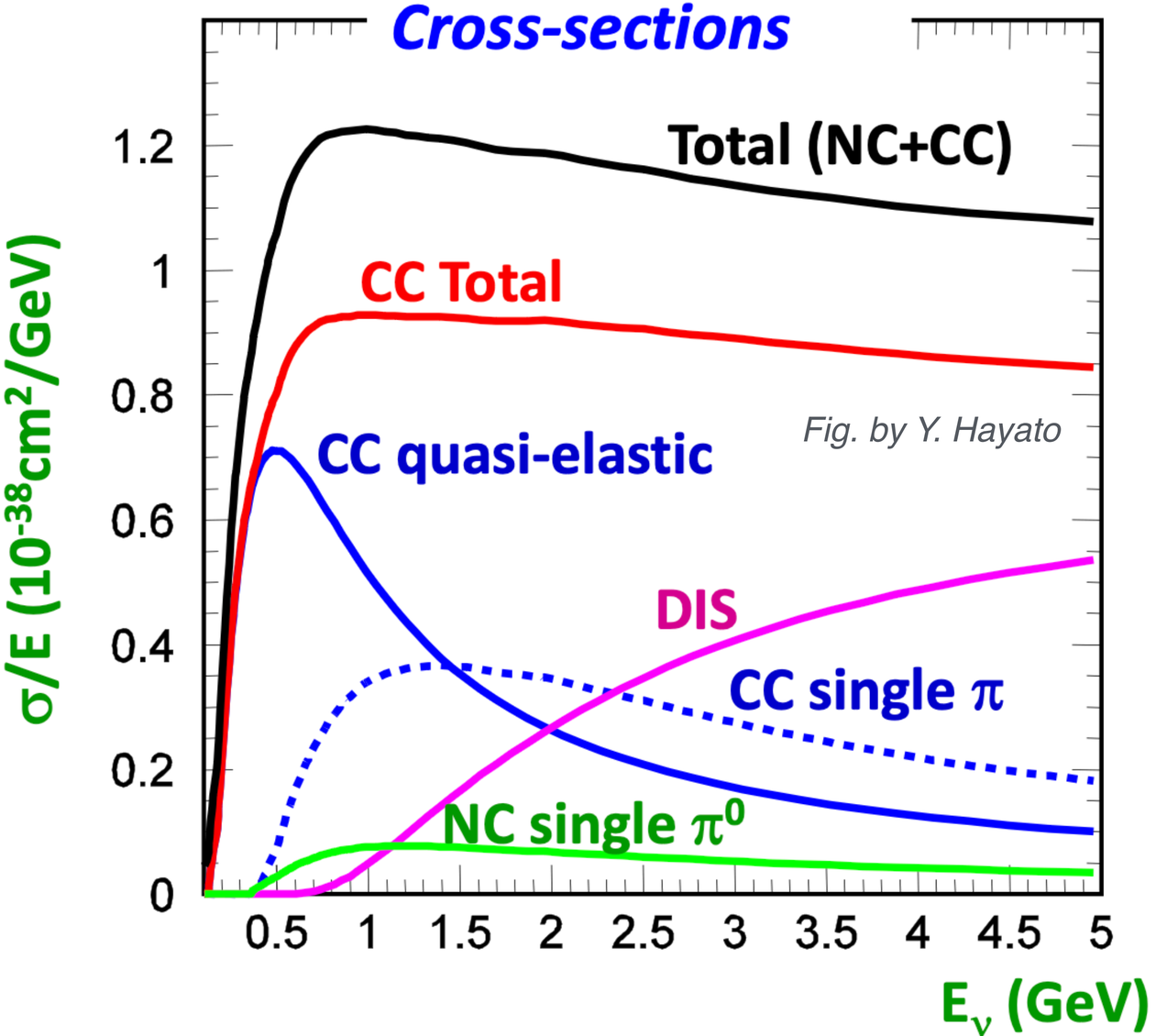
Fig. by Y. Hayato



M. Honda et al., PRD 83, 123001

Variety of interaction channels (e.g. NEUT)

Charged Current (CC)
Neutral Current (NC)



* This is not a perfect list.

CC Quasielastic:

$\nu + n \rightarrow l^- + p$

CC Multi-nucleon:

$\nu + n + N \rightarrow l^- + p + N$

CC single π:

$\nu + N \rightarrow l^- + N' + \pi$

Deep inelastic scattering (DIS):

$\nu + N \rightarrow l^- + N' + m\pi\,(\eta, K, etc.)$

Low
ν energy
High

Neutrino Generators

GENIE:

- Main generator in US experiments.
  - NOvA, MicroBooNE, DUNE, etc.

NuWro:

- Developed by theorists in Wroclaw.
- Frequently used for comparisons.

Achilles:

- Developed by theorists.
- Relatively new project with theoretically important features.

GiBUU:

- Developed by theorists in Giessen.
- Sophisticated FSI model.

- **This talk focuses on NEUT.**
  - Main generator in Japan experiments: Super-Kamiokande and T2K.

Contents

- Role of neutrino generators.
  - e.g.) in neutrino oscillation experiments

- **Introduction to the neutrino event generator NEUT.**
  - History, overview, recent updates, etc.

NEUT

Y. Hayato and L. Pickering, Eur. Phys. J. Special Topics 230, 4469 (2021).

- Born for the Kamiokande experiment in the **1980s**.

```
(Creation Date and Author)
  1983.??.?? ; M.NAKAHATA
  1987.08.?? ; N.SATO    FOR TAU
  1988.08.31 ; T.KAJITA  DATA UPDATE
  1988.09.06 ; T.KAJITA  R1314 IS ADDED
```

- Mainly used in experiments in Japan: **Super-Kamiokande (SK), T2K**
  - The primary target is **water**, but it can be used for carbon, iron, etc.

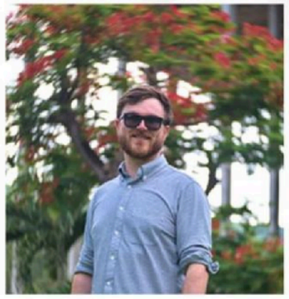
- Not open to the public yet, but distributed upon request.
  - e.g.) KamLAND, JUNO, etc.

- Recently developed by T2K NIWG members, mainly.

  UK: Luke, Kamil, Patrick, Jake
  Japan: Hayato, Abe
  + other contributors

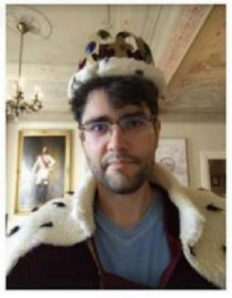
Hayato

T2K NIWG conveners (Neutrino Interaction Working Group)



Luke

Kevin



Kamil

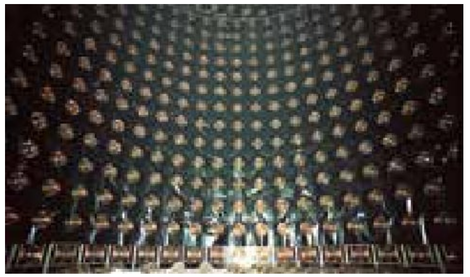
Patrick

Abe

NEUT in transition period

Passed 1983-1996

Kamiokande

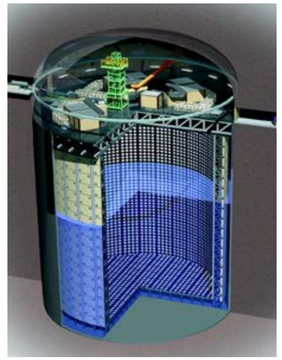


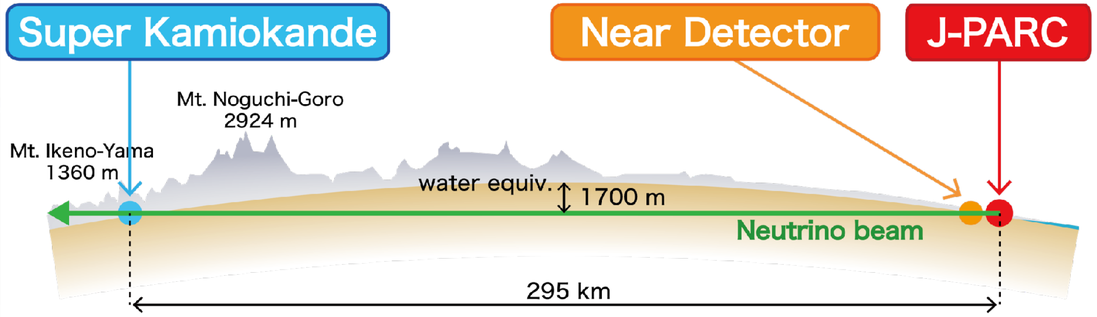
https://www-sk.icrr.u-tokyo.ac.jp/about/history/

Running 1996-

SUPER-K Gd

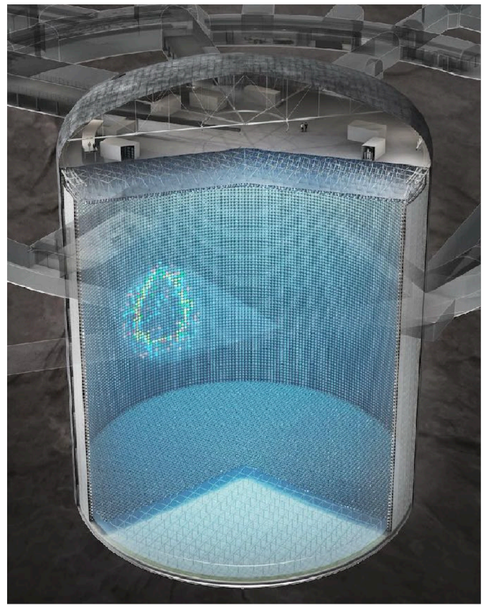
T2K





Coming 2028-

Hyper-K

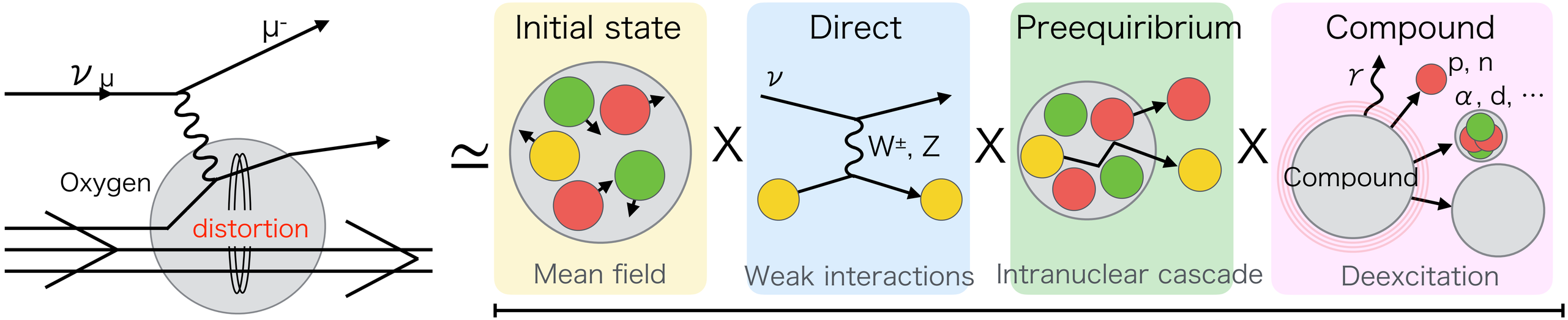


https://www-sk.icrr.u-tokyo.ac.jp/hk/

NEUT is in a transition period!

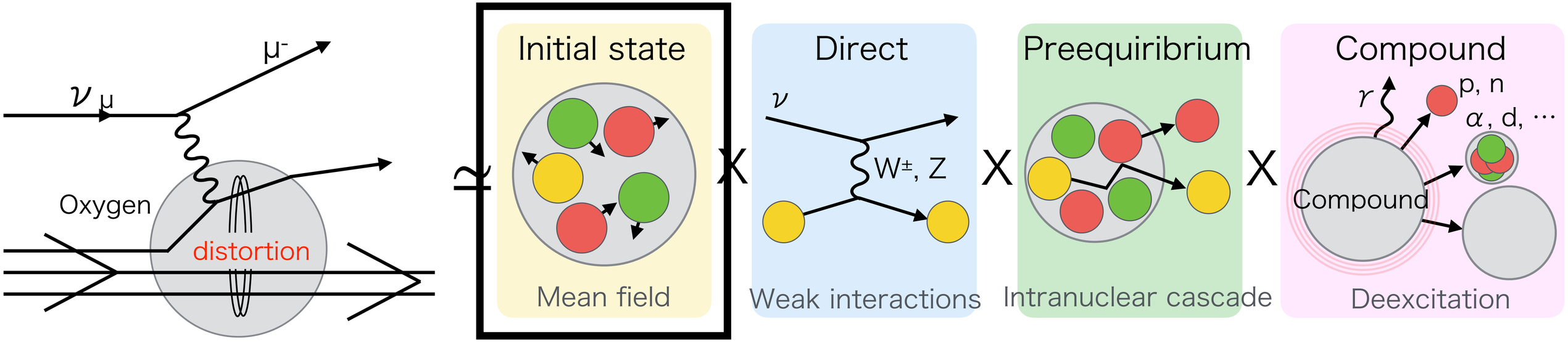
- Keep updating NEUT as well.
- **NEUT6** project:
  - Fortran77 → Fortran90/2008.
  - Minimize dependence on CERNLIB.
  - A global format, “NuHepMC”.
- **v6.0.3 was released!**

Description of ν-nucleus Interactions



- **Based on the impulse approximation (IA):**
  - A complicated many-body process is factorized into 4 processes.
  - The generator variations are produced from the treatment of nuclear effects.

- Based on **"plane" wave IA, neglecting "distortion"**, with a few exceptions.
  - Direct reaction is approximated by scattering with a single nucleon.



Initial state

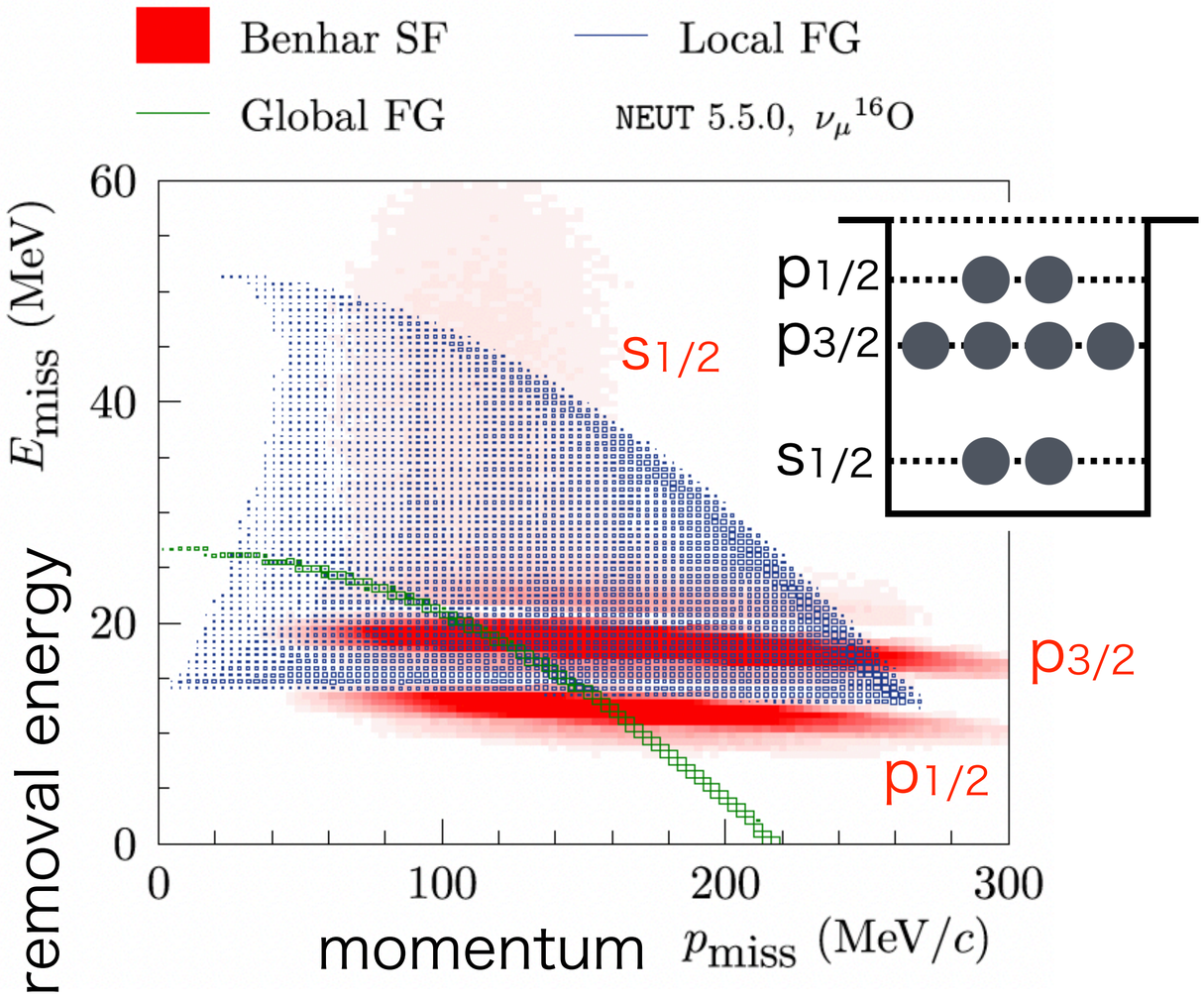
Initial State

- NEUT offers several models to predict the momentum and removal energy of bound nucleons.

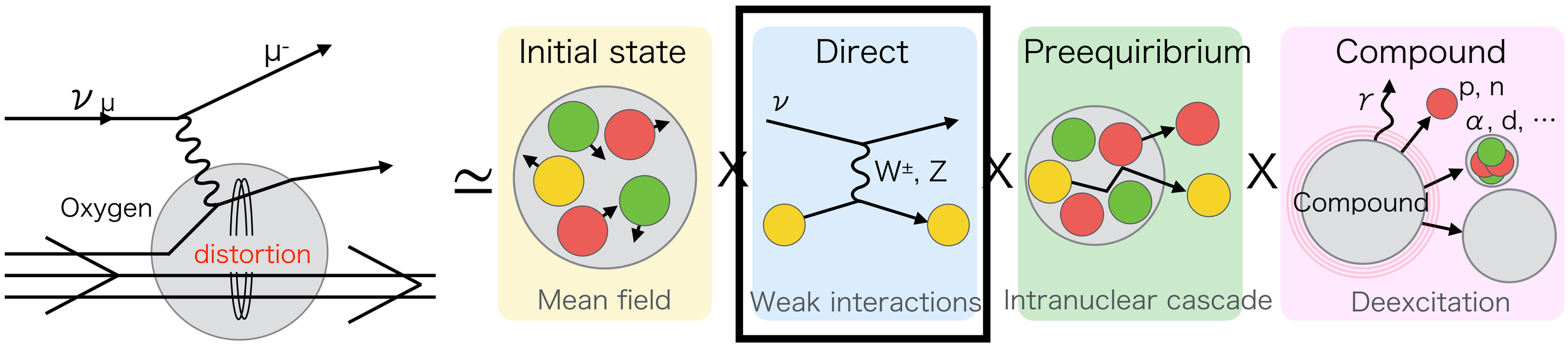
- **FG (Fermi Gas)**
  - **Global:** Without nuclear density.
  - **Local:** With nuclear density.
  - Compatible with various interaction channels and targets.

  "Global" is often referred to as "relativistic".

- **Spectral Function (SF)**
  - Derived from (e,e'p) experiments.
  - Involves shell-level structure.
  - For quasielastic on ^{12}C, ^{16}O, ^{56}Fe



Eur. Phys. J. Special Topics 230, 4469 (2021).



Direct scattering

- Quasielastic
- Multi-nucleon
- Single pion production
- Shallow and deep inelastic scattering

Quasielastic (QE) interaction

Model	Initial state	CC/NC/EM			Form factors		Comments/reference
		CC	NC	EM	Vector	Axial	
Smith-Moniz	Global FG	✔	✔	×	Dipole, **BBBA05**, or BBBA507	**Dipole**, 3-component, or Z-expansion	-
Benhar et al.	SF	✔	✔	✔			*New! S. Abe, PRD 111, 033006 (2025).*
Nieves et al.	Local FG	✔	×	×			*R. Gran et al., PRD 88, 113007 (2013).* *B. Bourguille et al., JHEP 04, 004 (2021).*
ED-RMF	RMF	✔	×	✔	Dipole	Dipole	*New! J. McKean et al, PRD 112, 032009 (2025)*

EM: Electronmagnetic interaction for electron scattering

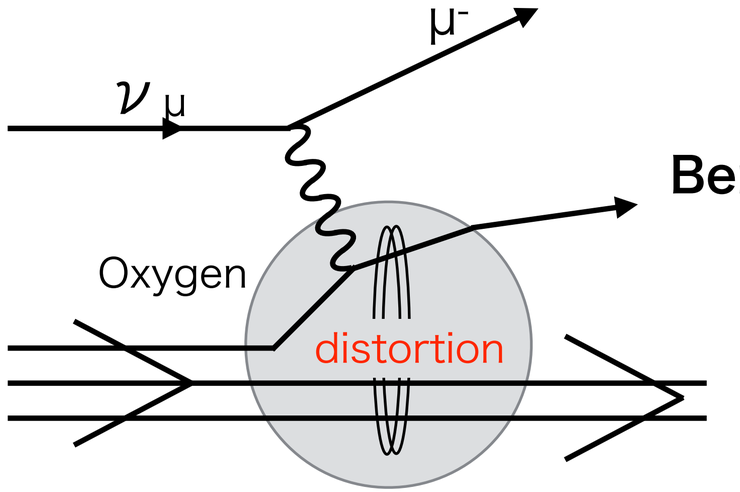
- Various models and form factors are available.
- Recent progress is remarkable!

Quasielastic (QE) interaction

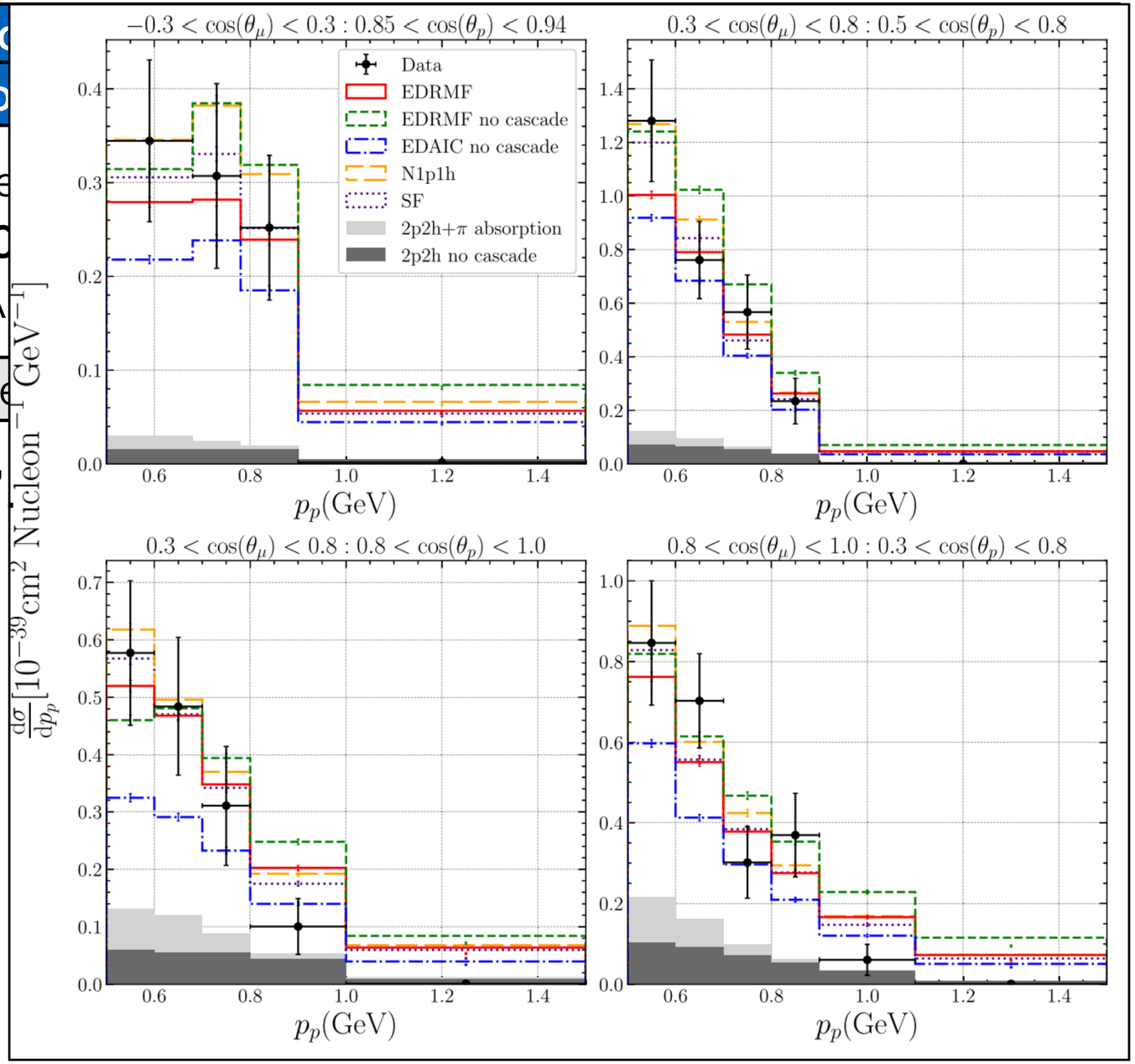
Unique to NEUT!

Model	Initial state	CC/NC/EM			Fo
		CC	NC	EM	Vecto
Smith-Moniz	Global FG	✔	✔	×	Dipole
Benhar et al.	SF	✔	✔	✔	**BBBAC**
Nieves et al.	Local FG	✔	×	×	or BBBA
ED-RMF	RMF	✔	×	✔	Dipole

- Model incorporates nucleon "distortion".
- Consistently combines with the intranuclear cascade.



Benchmark against T2K CC0πNp



J. McKean et al, PRD 112, 032009 (2025)

Quasielastic (QE) interaction

Model	Initial state	CC/NC/EM			Form factors		Comments/reference
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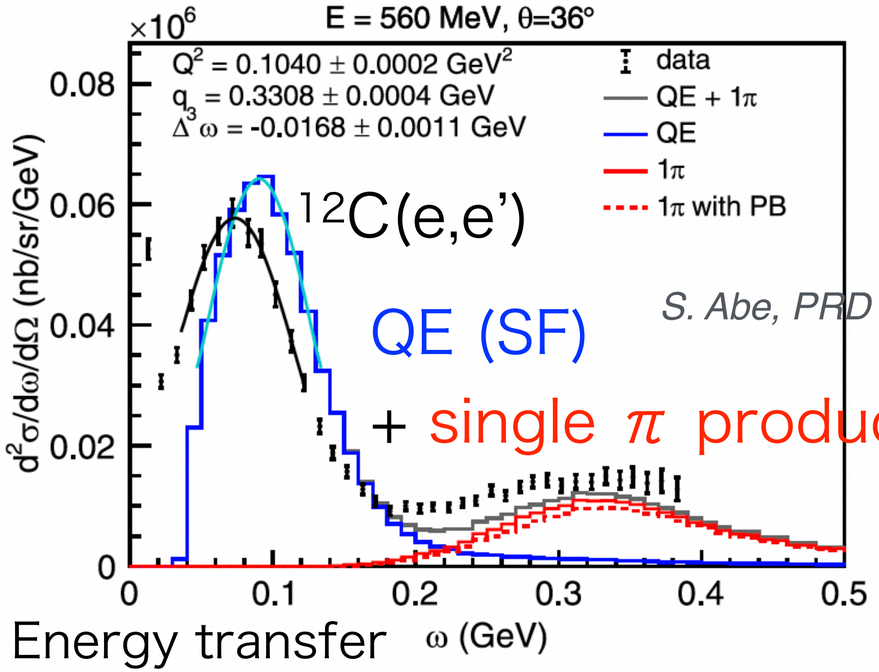
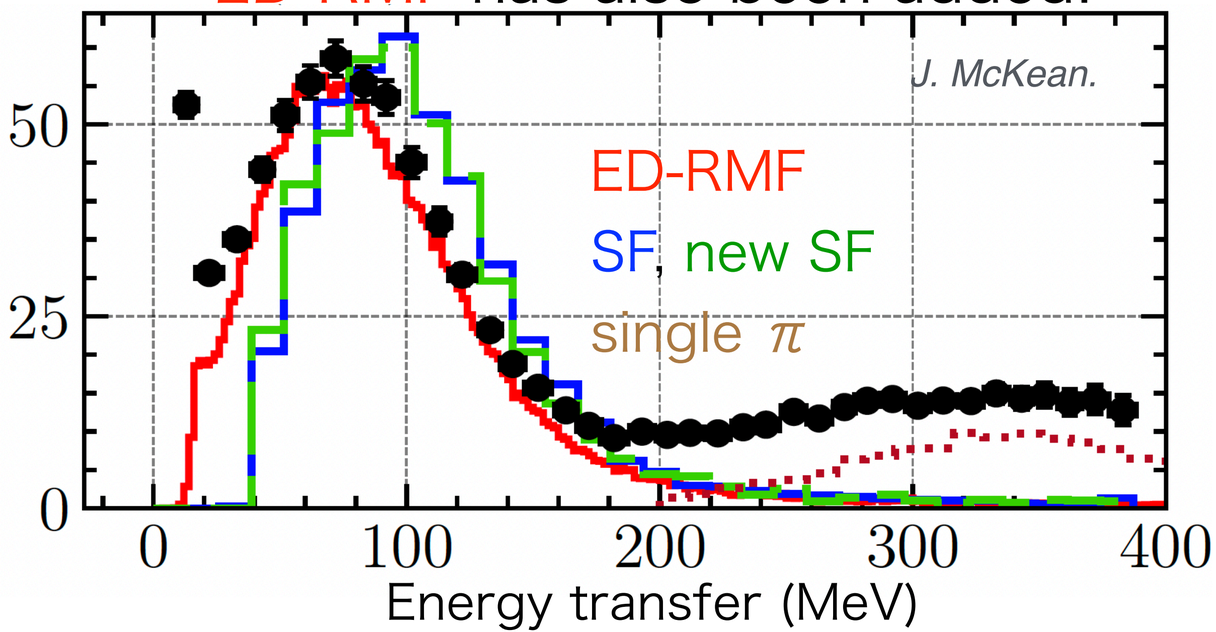
Benhar et al.	SF	✔	✔	✔			*New! S. Abe, PRD 111, 033006 (2025).*
Nieves et al.	Local FG	✔	×	×			*R. Gran et al., PRD 88, 113007 (2013).* *B. Bourguille et al., JHEP 04, 004 (2021).*
ED-RMF	RMF	✔	×	✔	Dipole	Dipole	*New! J. McKean et al, PRD 112, 032009 (2025)*

- **Electron scattering** has been recently implemented into NEUT!



S. Abe, PRD 111, 033006 (2025).

ED-RMF has also been added!

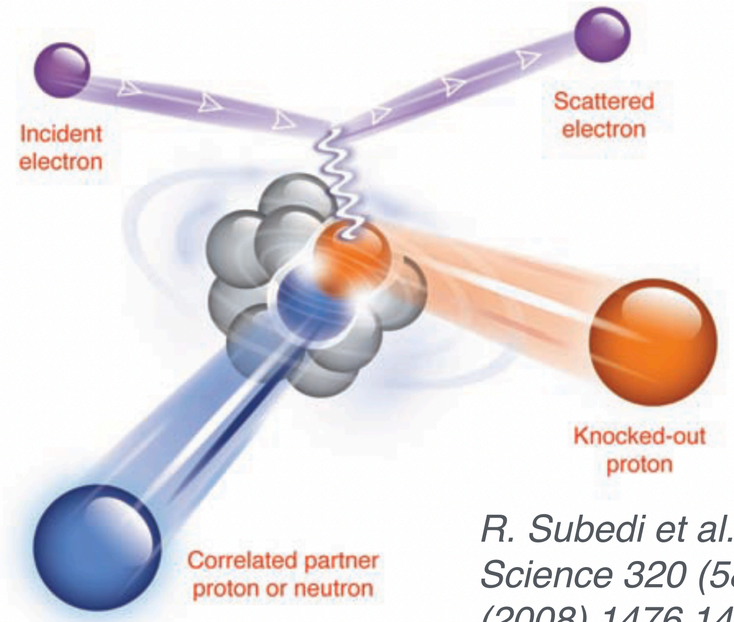


Multi-nucleon interaction

- It accounts for ~20% (depending on models) of QE interaction in electron scattering.

2p2h (2-particle 2-hole)

- **Inclusive** 2p2h: Valencia model by Nieves et al.
  - Two nucleons are emitted isotropically.

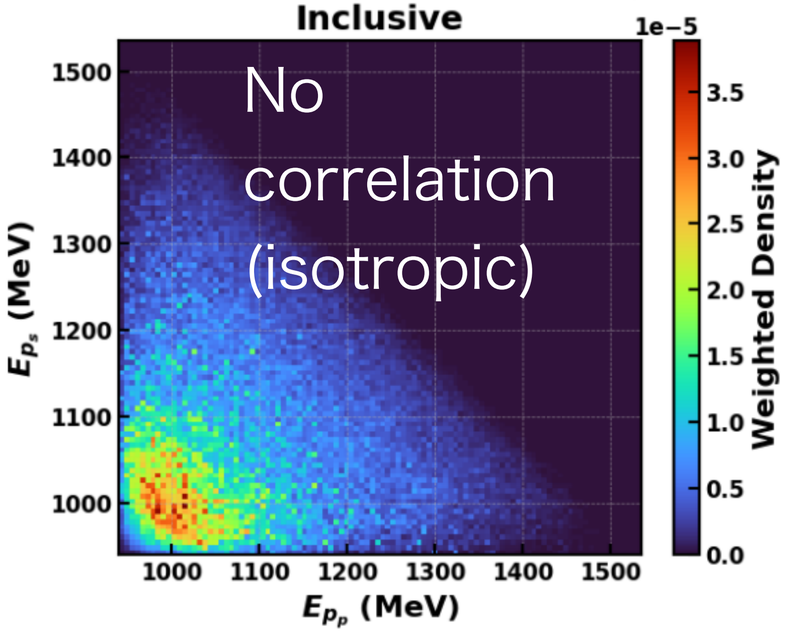


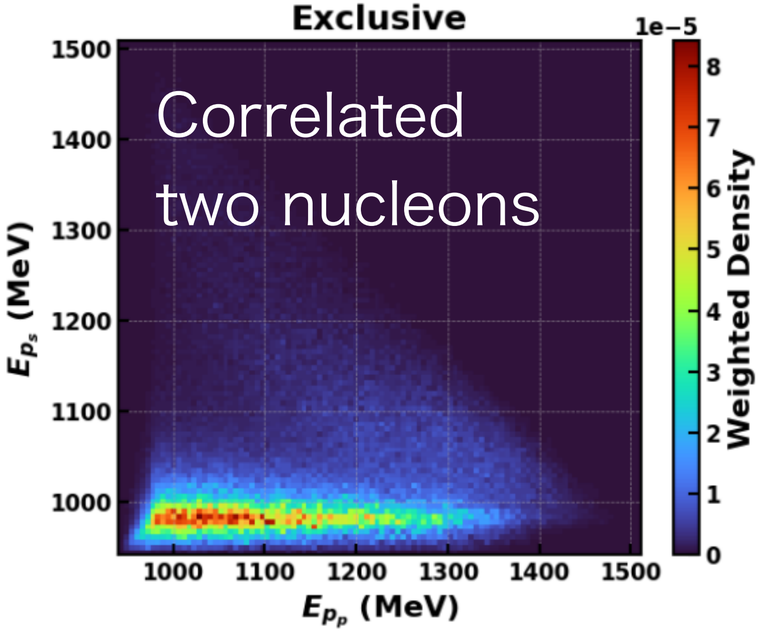
R. Subedi et al., Science 320 (5882) (2008) 1476 1478.

R. Gran et al., PRD 88, 113007 (2013).

J. E. Sobczyk et al., PRC 102, 024601 (2020).
J. E. Sobczyk et al., PRC 111, 025502 (2025).

- **Exclusive** 2p2h is in progress.
  - Correlated two nucleons.
  - Computational cost is a task to be solved.

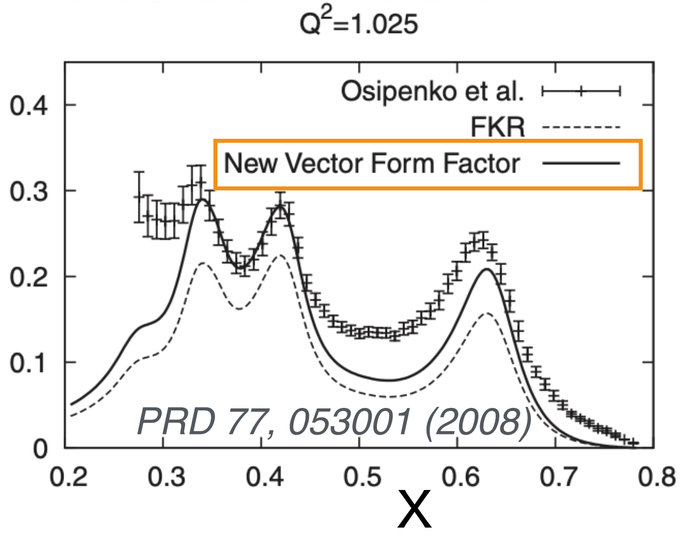




K. V. Srinivas. Work in progress.

Single Pion Production

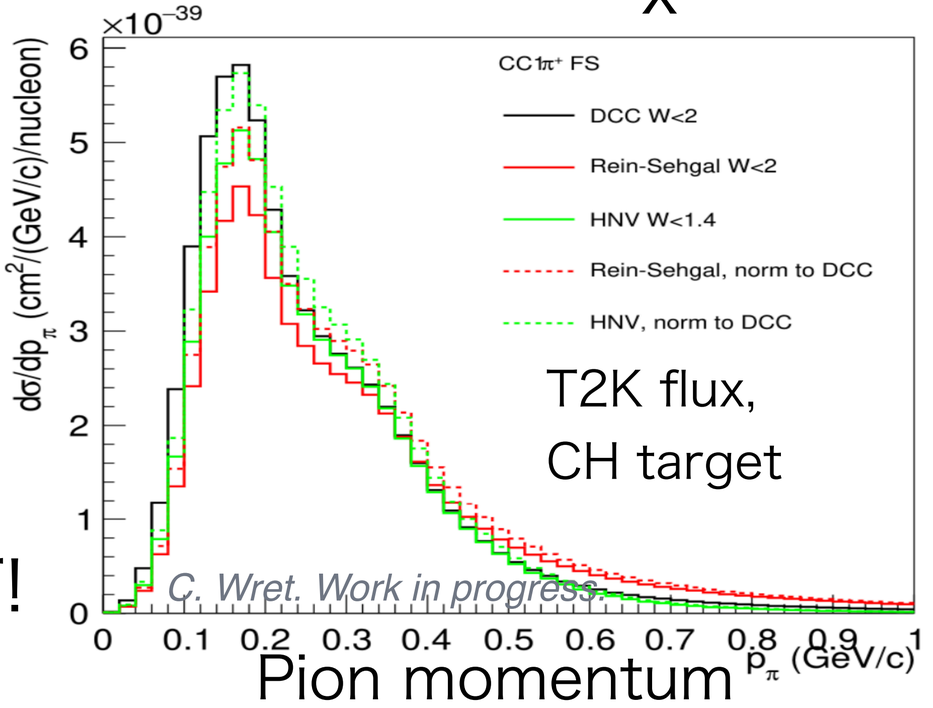
- Rein-Sehgal model w/ Berger-Sehgal lepton mass effect correction.
  - Described by 2 steps:
    - Produce a baryon resonance & decay.
  - Resonances up to W < 2 GeV.
  - Graczyk-Sobczyk form factors. PRD 77, 053003 (2008).
  - Single η, ω, and γ production is also implemented.



X

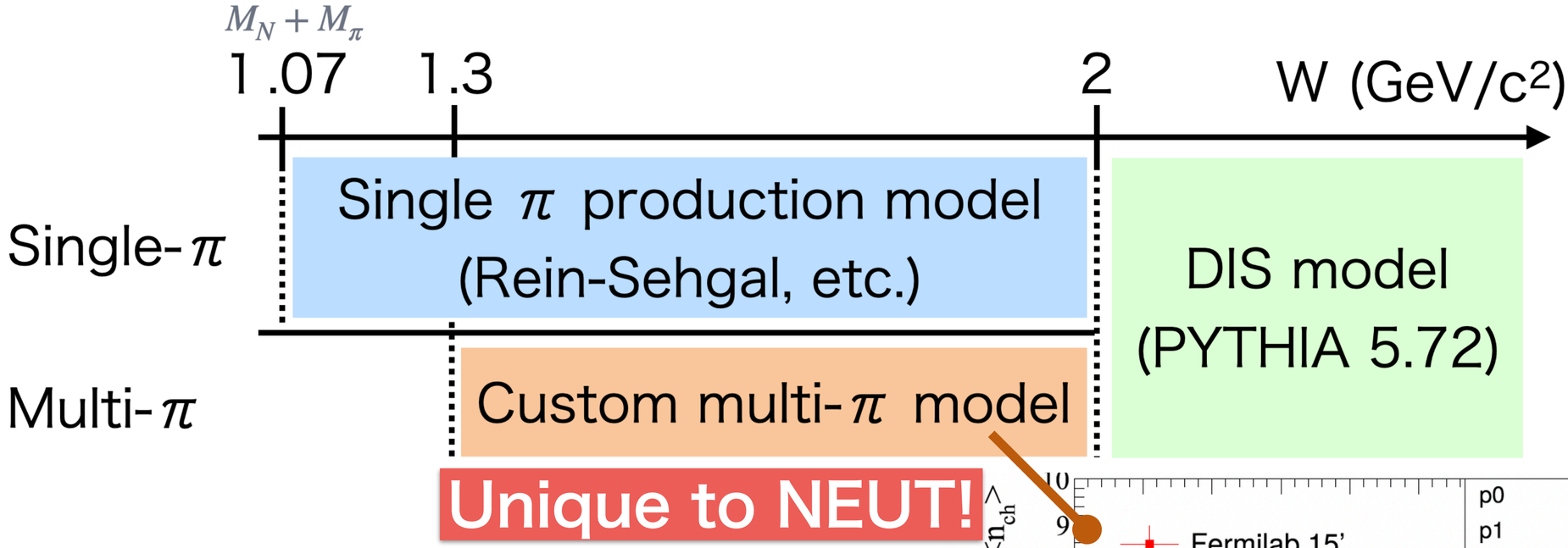
- New 3 models are under implementation:
  - DCC, HNV, and MK.
  - More sophisticated modes.

- Investigating 4 model variations using NEUT!

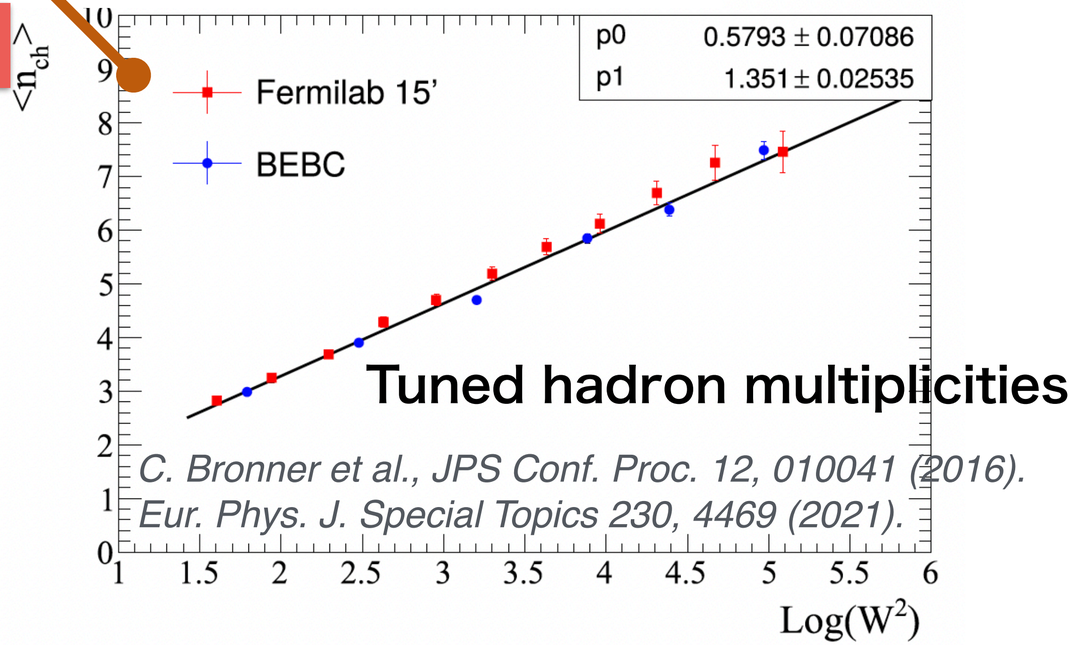


Shallow and Deep Inelastic Scattering SIS, DIS

- Need to avoid double-counting **single-** and **multi-π** channels.

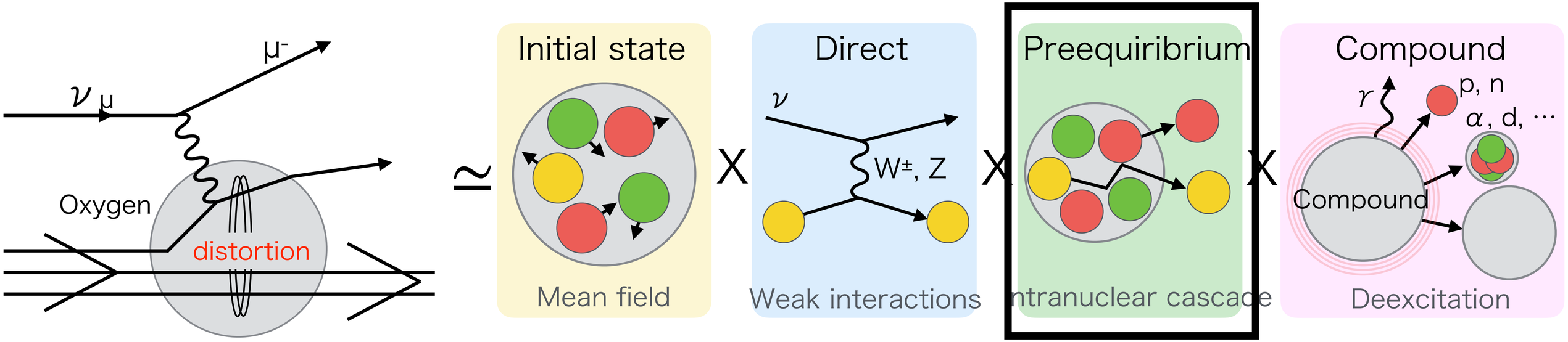


- The same parton distribution functions (PDFs) were used for both SIS and DIS:
  - GRV98 with Bodek Yang correction.



Tuned hadron multiplicities

C. Bronner et al., JPS Conf. Proc. 12, 010041 (2016).
Eur. Phys. J. Special Topics 230, 4469 (2021).



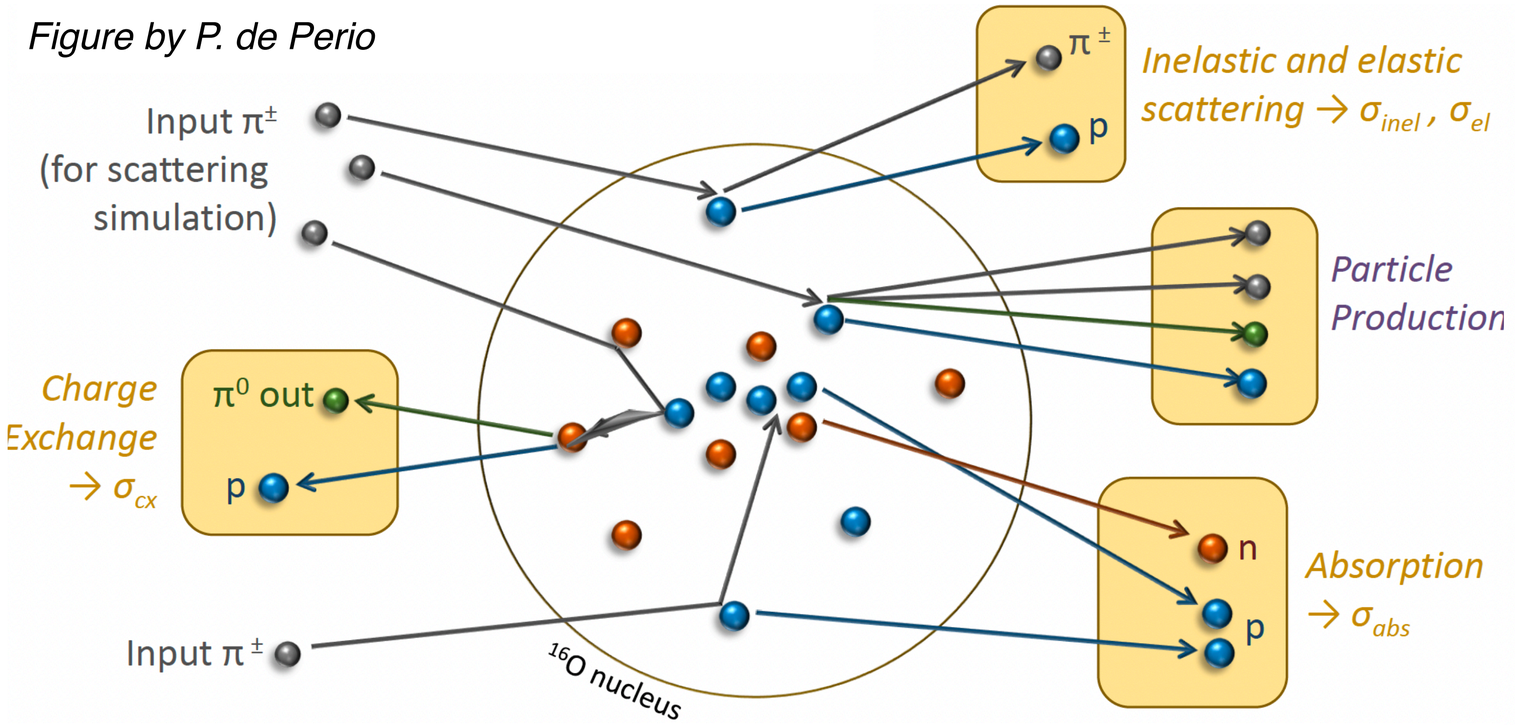
Intranuclear cascade

Intranuclear Cascade (π)

- Particle transportation within a nucleus.
  - The transportation continues until the particle goes out.
- Various interaction channels: Charge exchange, absorption, etc.
- Cross section for each channel were tuned using experimental data.

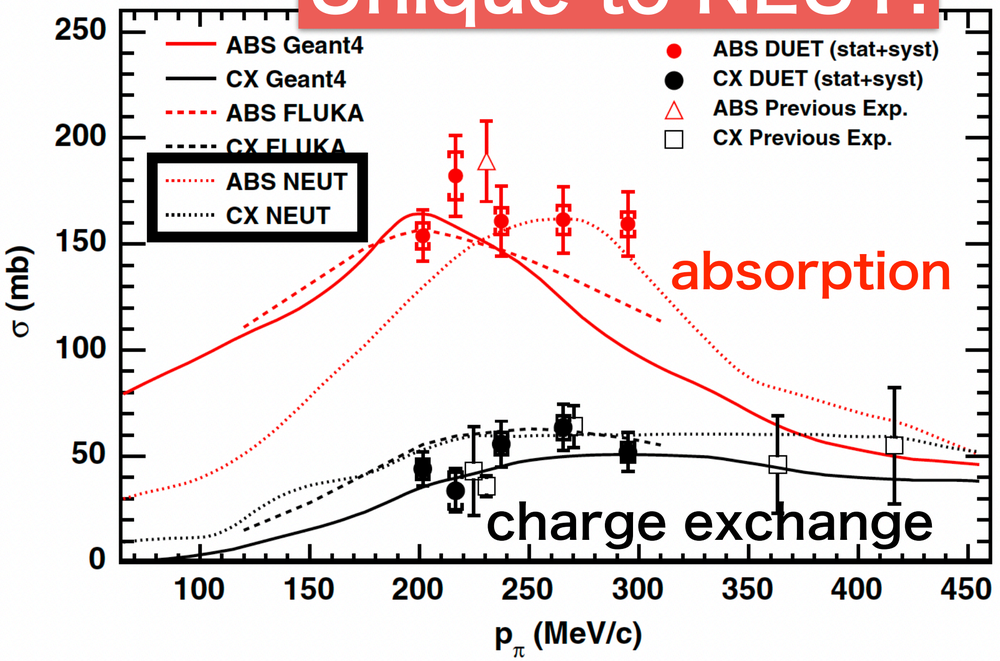
Nucleon: Bertini et al. MECC-7
Interactions of other mesons (K, η, ω) are also considered.

Figure by P. de Perio



Woods-Saxson nucleon density with Local FG.

Unique to NEUT!



E. S. Pinzon Guerra et al., PRD 99, 052007 (2019)

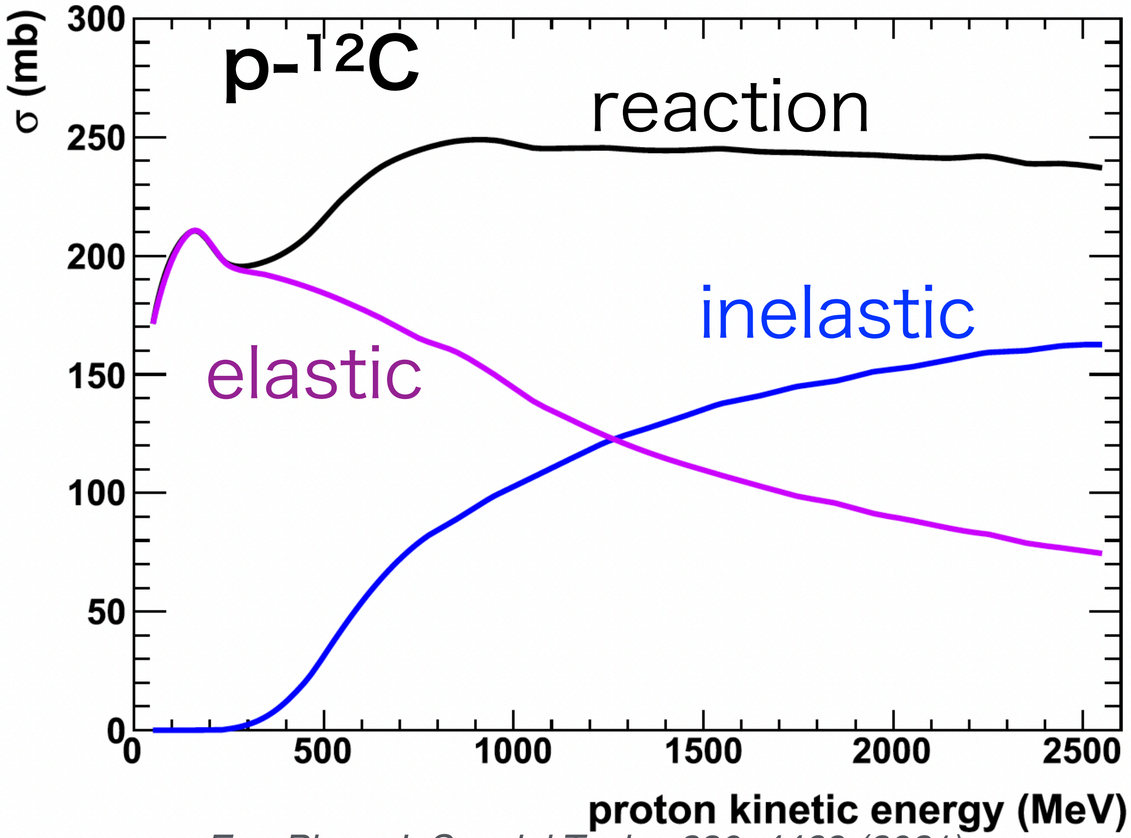
Intranuclear Cascade (nucleon)

- Bertini et al. for MECC-7.

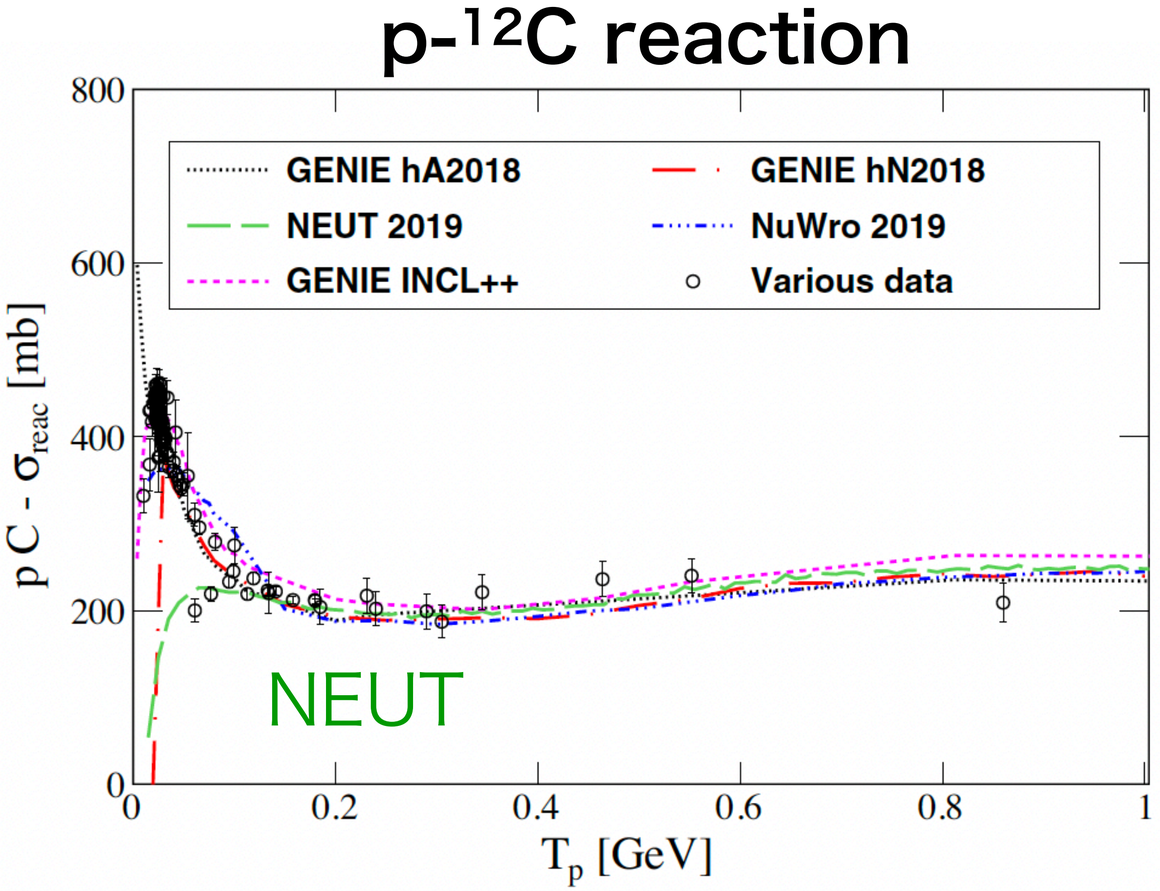
H.W. Bertini, Phys. Rev. C 6, 631 (1972).

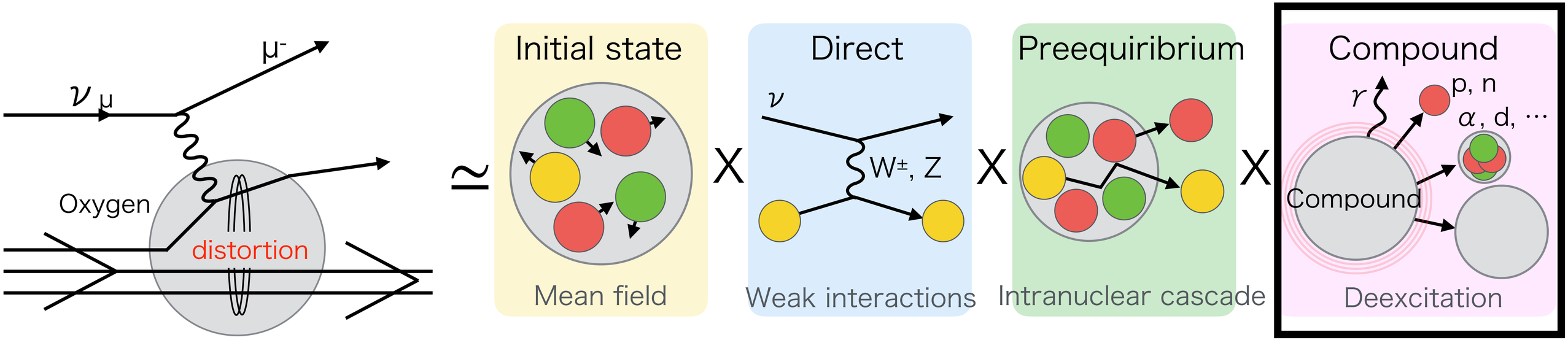
  - Lacks reproducibility in the low-energy region, dominated by elastic.
  - A study to understand this discrepancy is ongoing (Pauli blocking, effective mass)

- Implementations of other cascade models (INCL and GiBUU) are ongoing.



Eur. Phys. J. Special Topics 230, 4469 (2021).





Nuclear deexcitation

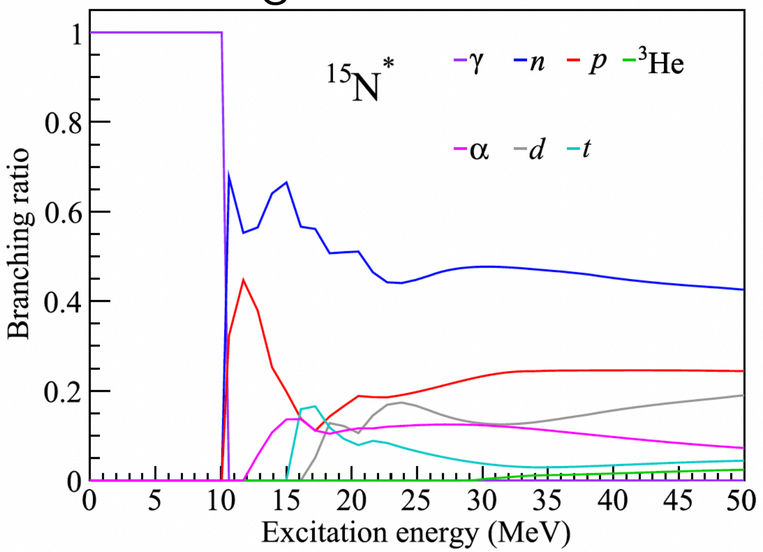
Nuclear Deexcitation

- A data-driven model for ^{16}O.
  - The data was measured in a limited phase space (energy, particle)
  - Various simplifications and assumptions were made.

Unique to NEUT!

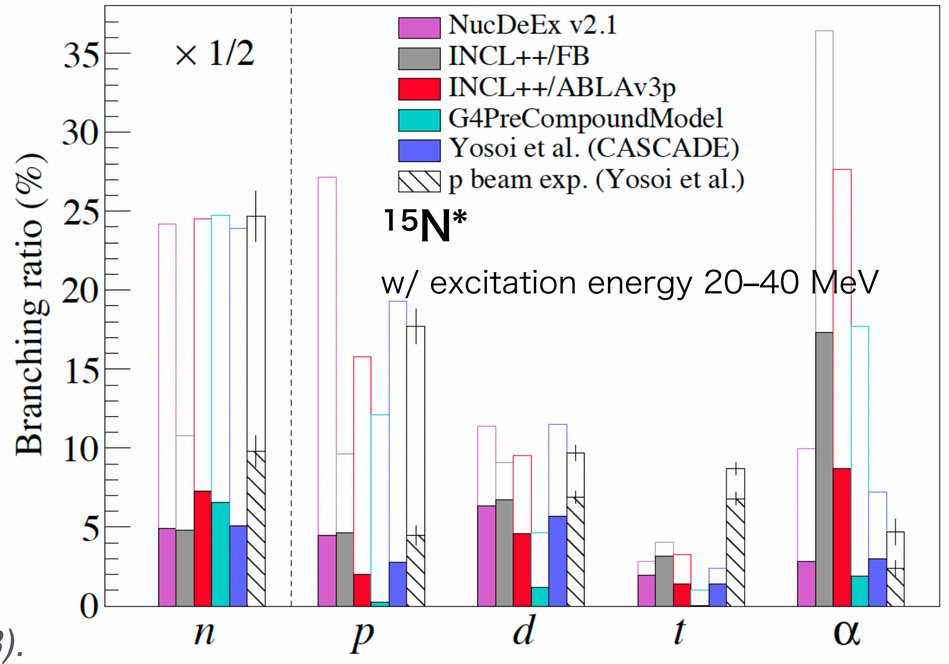
- New deexcitation event generator NucDeEx is now available.
  - It enables theoretical calculation (TALYS).

Branching ratios

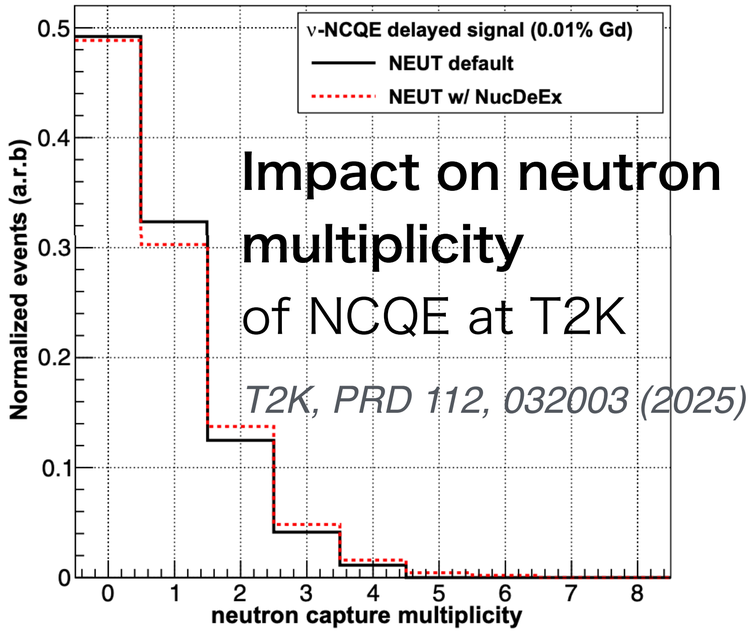


S. Abe, Phys. Rev. D 109, 036009 (2024)
S. Abe, arXiv:2508.04040 (2025)
A. Koning et al., Eur. Phys. J. A 59,131 (2023).

Benchmark existing deex. gen.



NucDeEx vs default in NEUT at T2K



Impact on neutron multiplicity of NCQE at T2K

T2K, PRD 112, 032003 (2025)

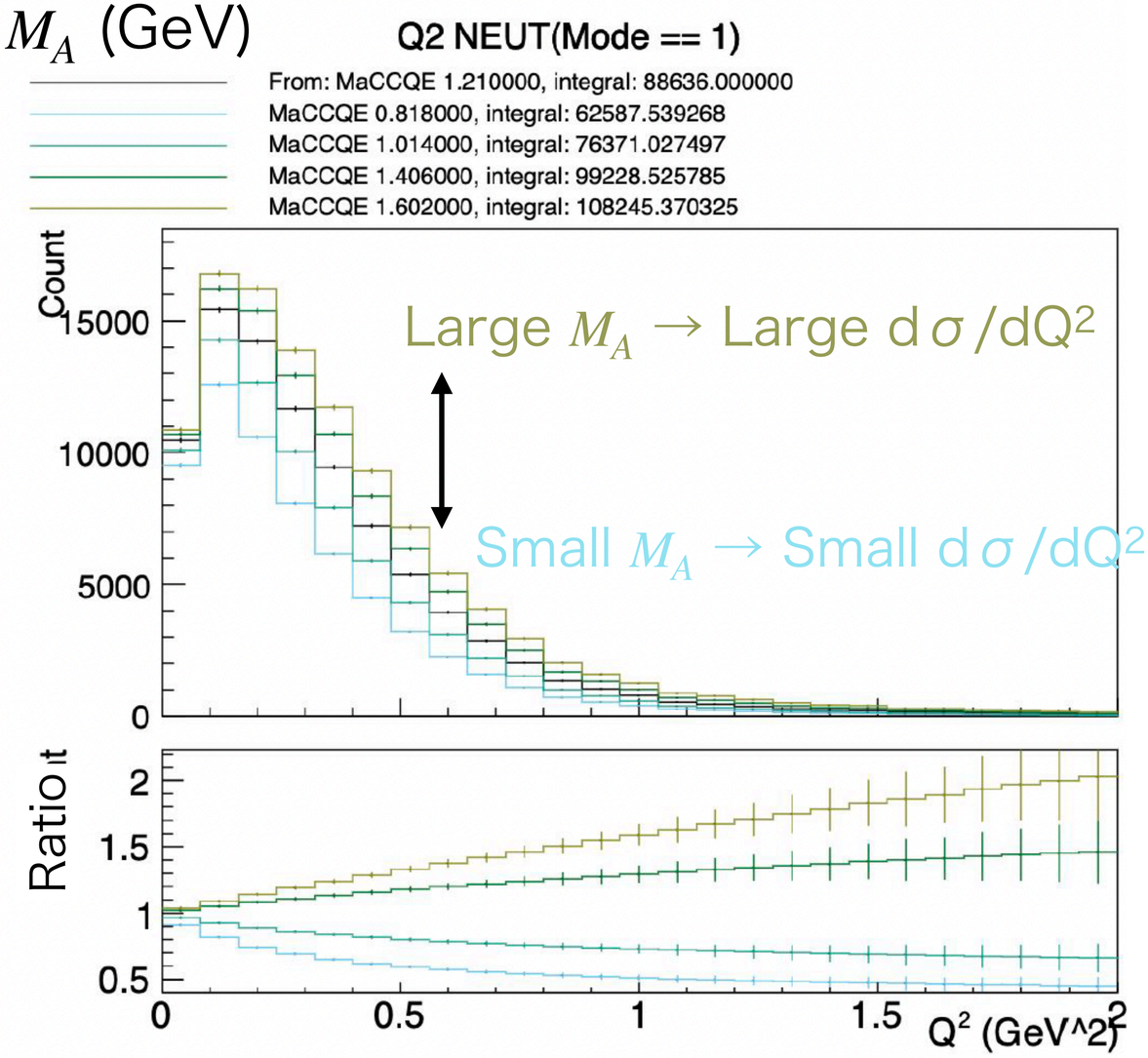
Notable Software: Reweight

- It estimates the impact of changing parameters without regenerating events.

- **A critical tool to estimate model uncertainty in experiments.**
  - It reduces simulation (event generation) costs.
  - Need to meet the experimental needs.

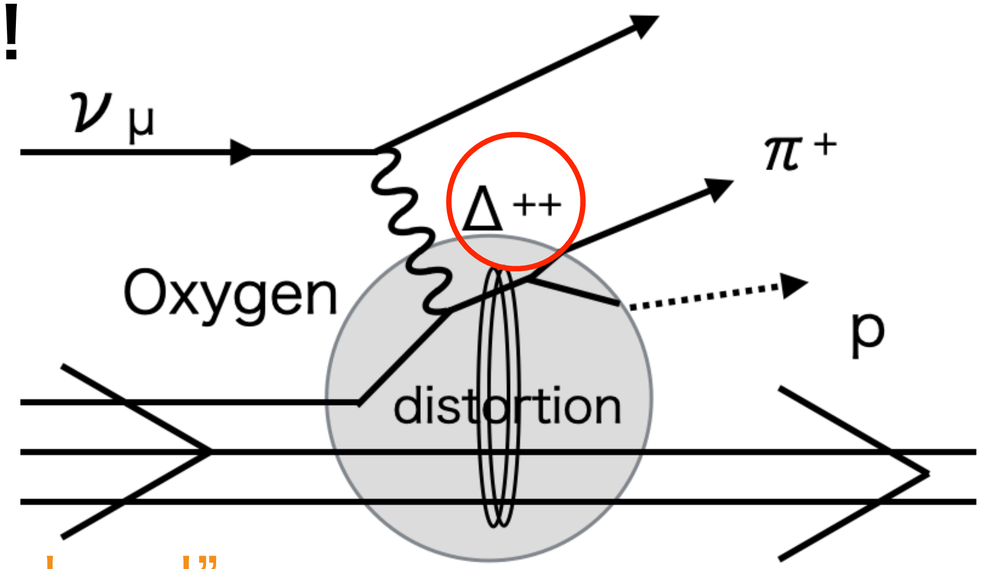
- The reweight package for NEUT is kept updated to catch up on recent model improvements.

Axial mass **CCQE $d\sigma/dQ^2$**



Thinking of HK era, what can we do for NEUT?

- **Modernize software. User-friendliness!**
  - C++? open-source?



- **Single π production:**
  - Nuclear effect of baryon resonance.

  Currently, NEUT simply extends “nucleon-level” calculation to the ν-nucleus.

- **Theoretical consistency btw QE, multinucleon, and single π.**
  - The current model is sometimes referred to as “Franken-model”.
  - Are we avoiding double-counting of the same effects?

Summary

- **Neutrino event generators are an essential tool in various neutrino physics analyses.**

- **NEUT provides a set of models for neutrino interactions.**
  - A long and rich history, mainly in water Cherenkov detectors.
  - Not only maintaining it, but also keep updating for the next generation.

- **Factorisation is necessary, but it misses essential physics in the reaction.**
  - Various challenges are ongoing to deal with this task.

backup

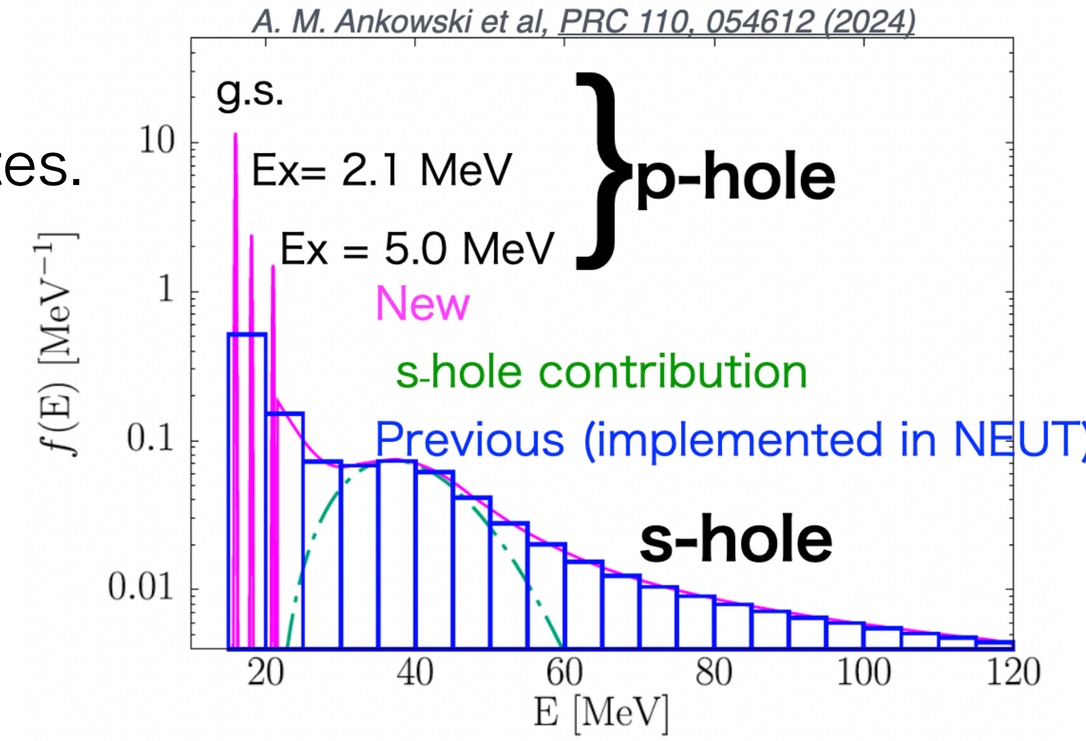
Quasielastic (QE) interaction

Model	Initial state	CC/NC/EM			Form factors		Comments/reference
		CC	NC	EM	Vector	Axial	
Smith-Moniz	Global FG	✔	✔	×	Dipole, **BBBA05**, or BBBA507	**Dipole**, 3-component, or Z-expansion	-
Benhar et al.	SF	✔	✔	✔			*New!* S. Abe, PRD 111, 033006 (2025).
Nieves et al.	Local FG	✔	×	×			*R. Gran et al., PRD 88, 113007 (2013).* *B. Bourguille et al., JHEP 04, 004 (2021).*
ED-RMF	RMF	✔	×	✔	Dipole	Dipole	*New! J. McKean et al, PRD 112, 032009 (2025)*

1. New SF on carbon was implemented.
   - For precise simulation of low-lying excited states.
2. g_A^s was introduced for NC form factors.
   - For precise BG estimation at DSNB.

$$F_A^{\mathrm{NC}} = \frac{1}{2}(\pm g_A + g_A^s)\left(1 + \frac{\tilde{Q}^2}{M_A^2}\right)^{-2},$$

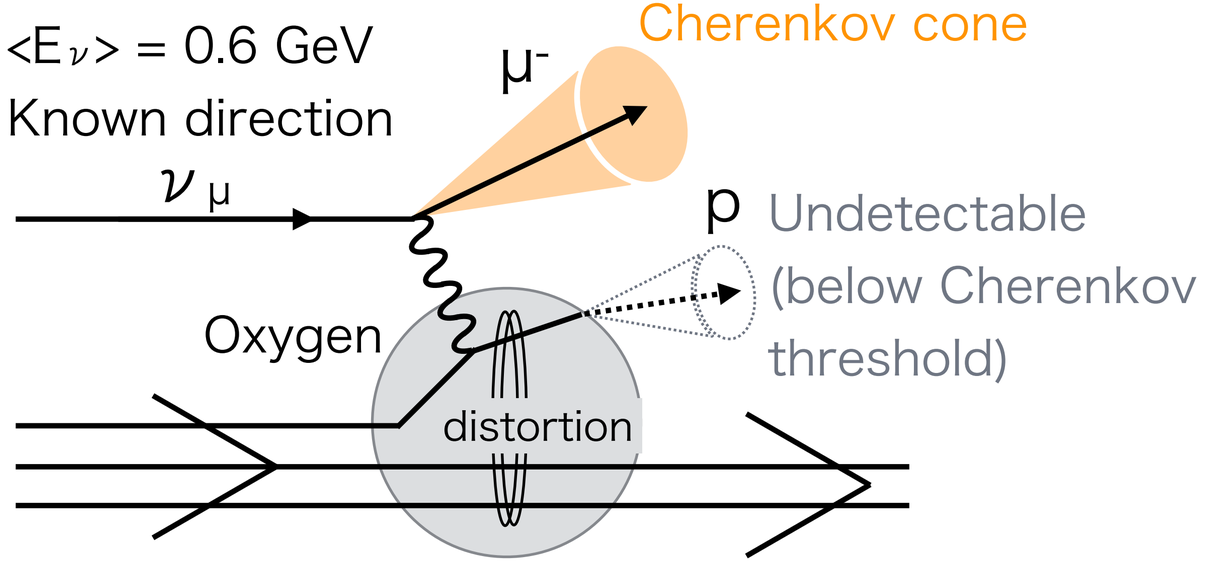
strange quark contribution



Neutrino energy reconstruction (in T2K)

Water Cherenkov detector

CCQE (Charged-Current Quasi Elastic) $\nu A \to l^- p A'$



Key: Nuclear effects "distortion"

Precise modeling of charged lepton response in many-body neutrino-nucleus interactions.

Largest systematic uncertainty

Neutrino energy reconstruction:

$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

$$\tilde{M} = M_i - E_b,$$

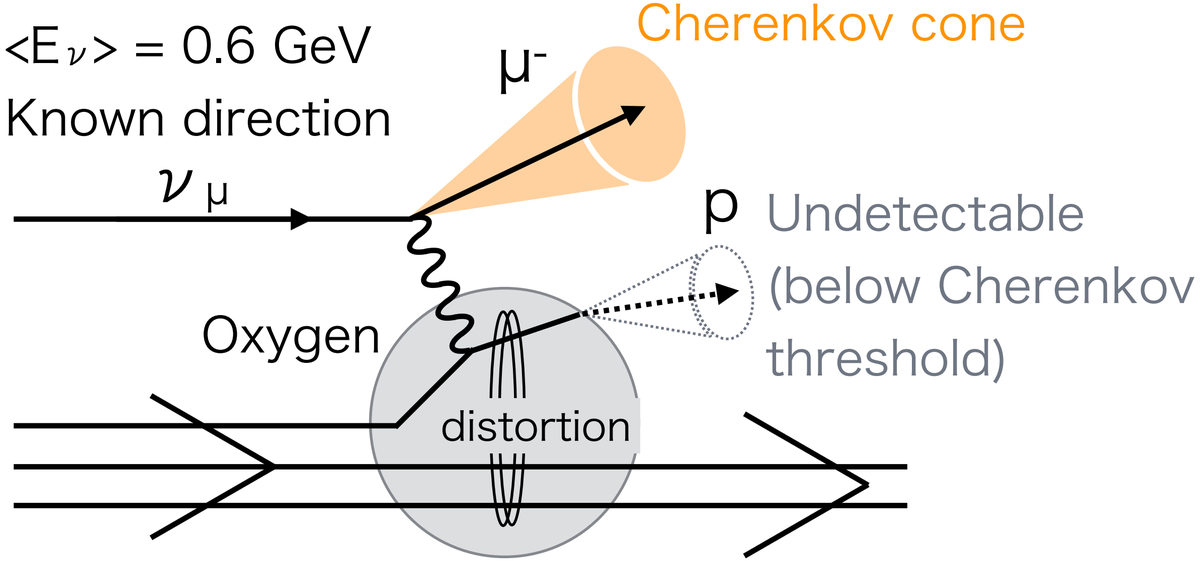
Nucleon mass Binding energy

Charged lepton kinematics

Neutrino energy reconstruction (in T2K)

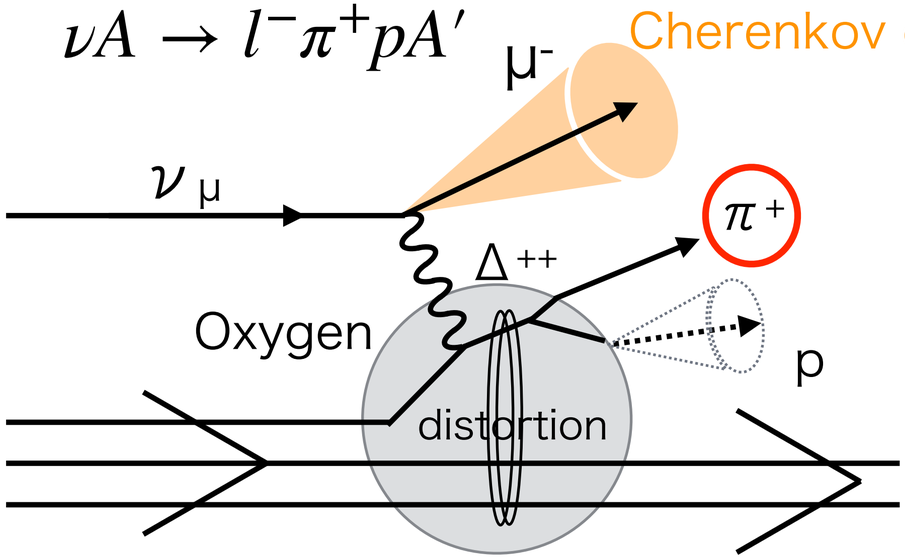
Water Cherenkov detector

CCQE (Charged-Current Quasi Elastic) $\nu A \rightarrow l^- p A'$



CC1π (Charged-Current Single Pion Production)

$\nu A \rightarrow l^- \pi^+ p A'$



- If absorbed in the nucleus, it is misidentified as CCQE.
- It biases the neutrino energy reconstruction.
- Nuclear effects, including pions, are also important.

Neutrino energy reconstruction:

$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

$$\tilde{M} = M_i - E_b,$$

Charged lepton kinematics

Nucleon mass Binding energy

Long-baseline neutrino oscillation experiment

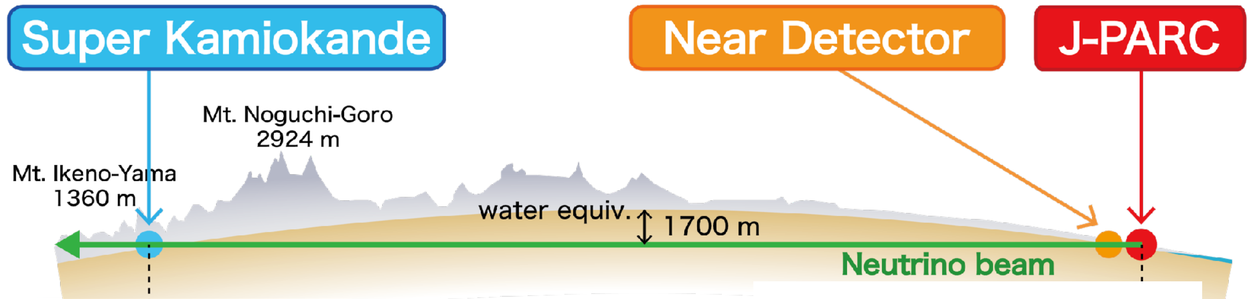
$$P(\nu_\alpha(\bar{\nu}_\alpha) \to \nu_\beta(\bar{\nu}_\beta)) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}) \sin^2\left(\frac{\Delta m^2_{ij}L}{4E_\nu}\right)$$

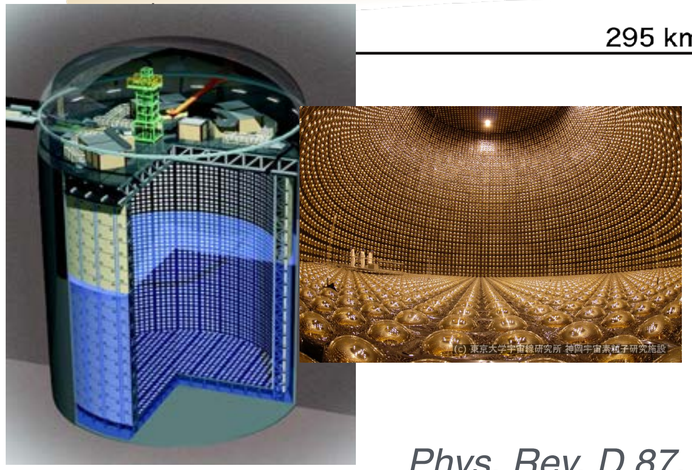
Oscillation probability

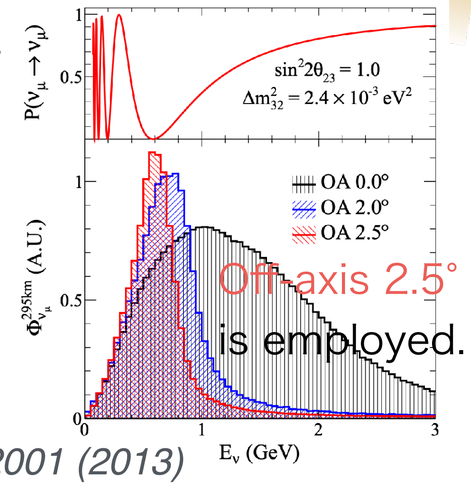
$$\pm 2\sum_{i>j} \mathrm{Im}(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}) \sin\left(\frac{\Delta m^2_{ij}L}{2E_\nu}\right).$$

- L: Baseline (fixed).
- **E_ν: Neutrino energy.**

T2K L = 295 km, <E_ν> = 0.6 GeV



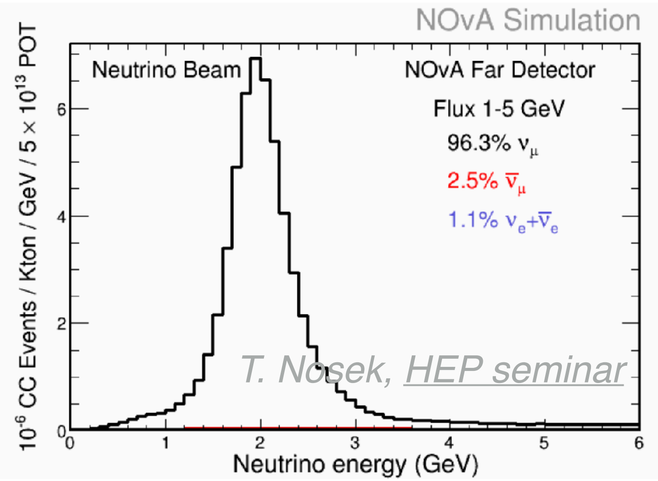




Off-axis 2.5° is employed.

Phys. Rev. D 87, 012001 (2013)

NOvA L = 810 km, <E_ν> = 1.8 GeV



Essential challenge: Neutrino energy reconstruction

* **Broad energy spectra** due to π/K decay in flight.