Neutrino-nucleus cross sections at the upgraded T2K near detector and their impact on T2K Oscillation Analyses

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Réunion de Comité de Suivi Individuel de thèse

Neutrino oscillation experiments

Study the oscillation

$$\nu_\alpha \rightarrow \nu_\beta$$

reconstructed energy — true energy — baseline length — oscillation parameters

$$N_{\nu_\beta}(E_\nu^{rec}) \sim \int \Phi_{\nu_\alpha}(E_\nu^{true})\, P_{\nu_\alpha \rightarrow \nu_\beta}(E_\nu^{true}, L, \Theta)\, \sigma_{\nu_\beta}(E_\nu^{true})\, \epsilon_{\text{det}}\, d(E_\nu^{true}, E_\nu^{rec})\, dE_\nu$$

number of detected events

ν flux

ν oscillation probability

ν cross section

detector efficiency

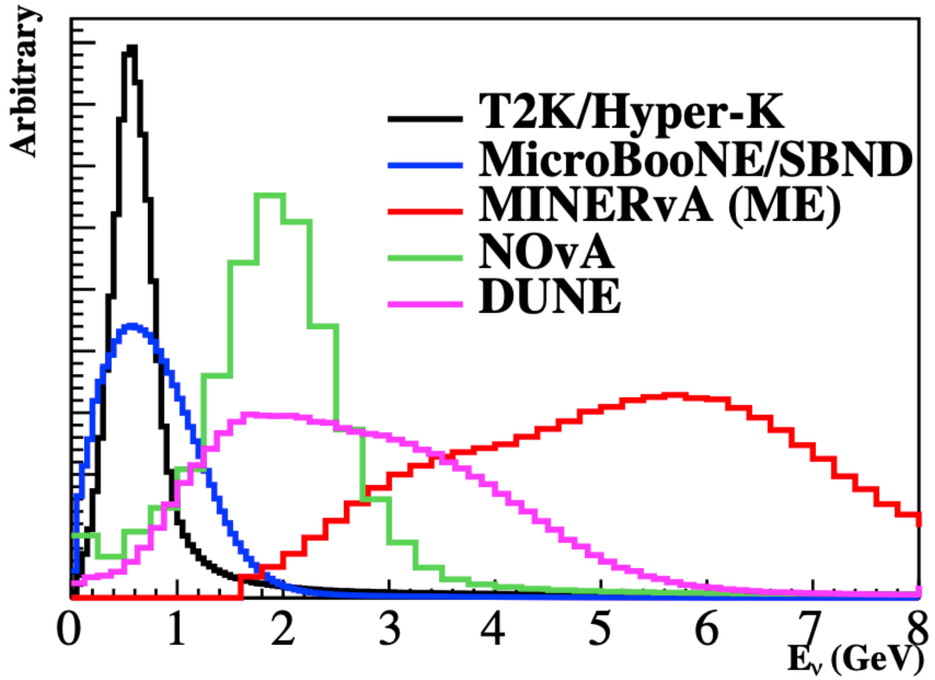
migration matrix

The knowledge of the neutrino-nucleus cross section is crucial

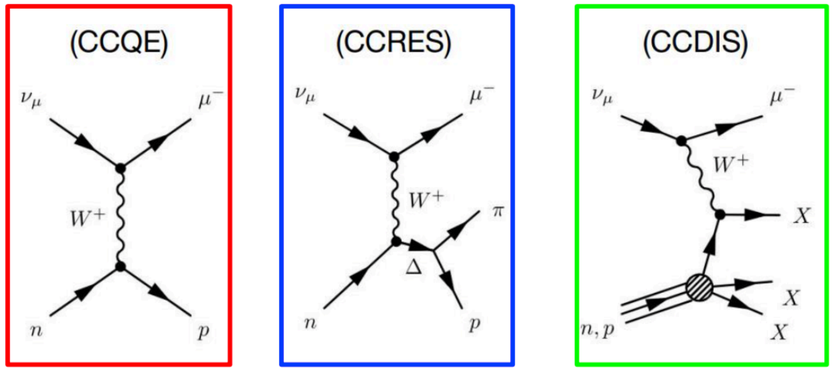
Neutrino oscillation experiments

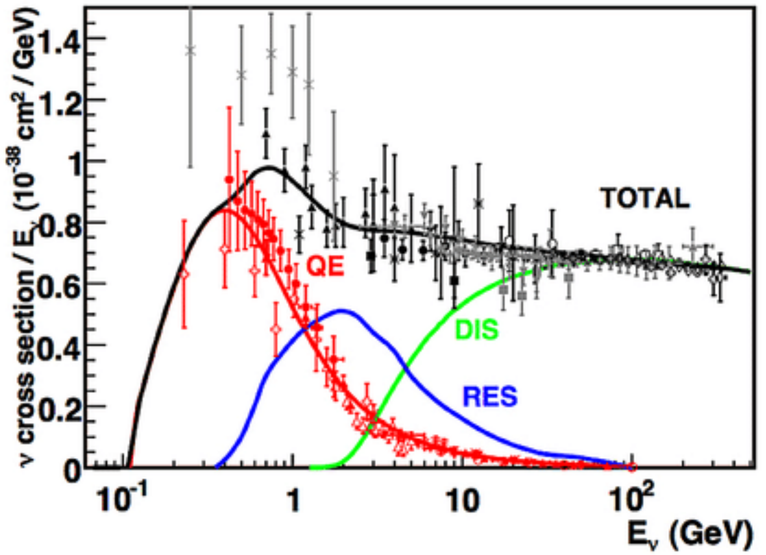
Accelerator based case

1. Neutrino beams are not monochromatic



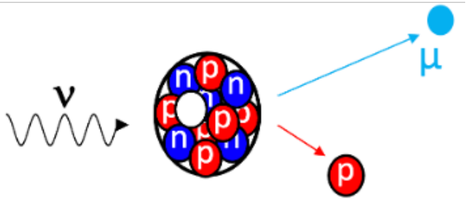
2. Different reaction mechanism contribute



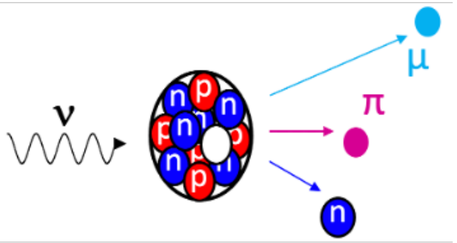


Neutrino - nucleus interactions at $E_\nu \sim \mathcal{O}(1\mathrm{GeV})$

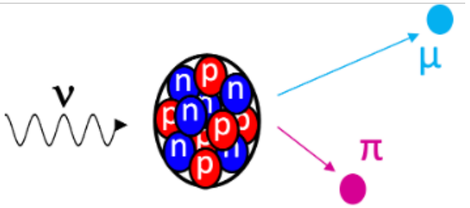
- quasielastic (QE)



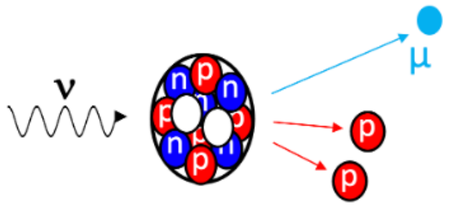
- incoherent π production



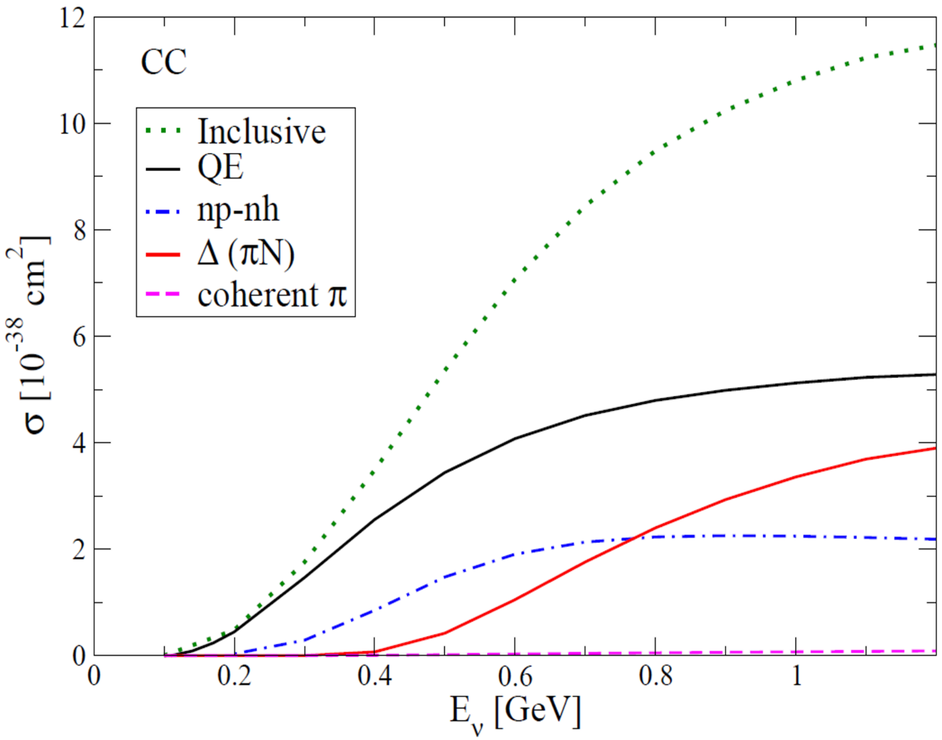
- coherent π production



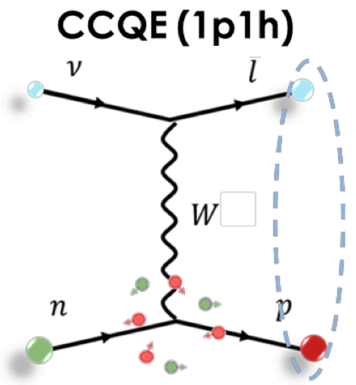
- n nucleons knocked out (npnh)



Martini et al model case



E_ν reconstruction in T2K



- identify the neutrino interactions without any mesons in the final state
- E_ν is reconstructed **assuming** the interaction is **CCQE** on a stationary nucleon with fixed nuclear binding energy

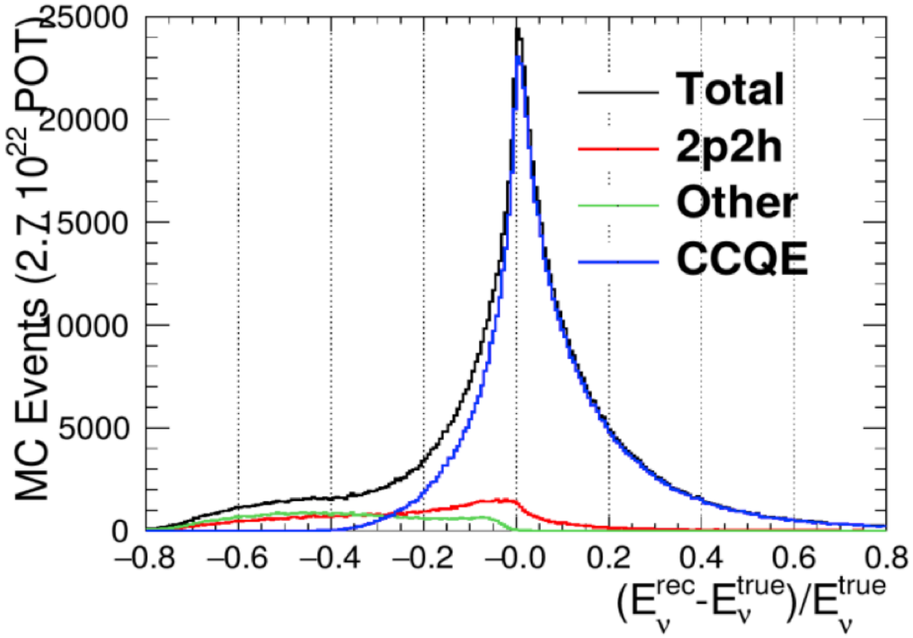
only use lepton kinematics to get $\overline{E}_\nu$!

$$E_\nu^{rec} \equiv E_\nu^{CCQE} = \frac{2\,(m_n - E_B)\,E_l - (E_B^2 - 2m_n E_B^2 + m_l^2 + \Delta M)}{2\left[(m_n - E_B) - E_l + p_l \cos\theta_l\right]}$$

↓

smearing from nuclear effects (e.g. Fermi motion) and **bias** from non CCQE backgrounds

Having a (correct) model that describes the ν - nucleus interaction is crucial !

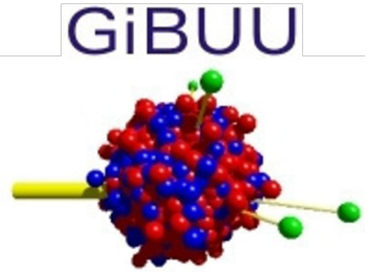


Martini et al model implementation in GENIE

Many models and many MC event generators

- Main models to calculate the nuclear responses and the ν cross sections:
  - **Local Fermi Gas + RPA** (Nieves et al, Martini et al)
  - **Hartree-Fock + (Continuum) RPA**
  - **SuperScaling** (SuSAv2)

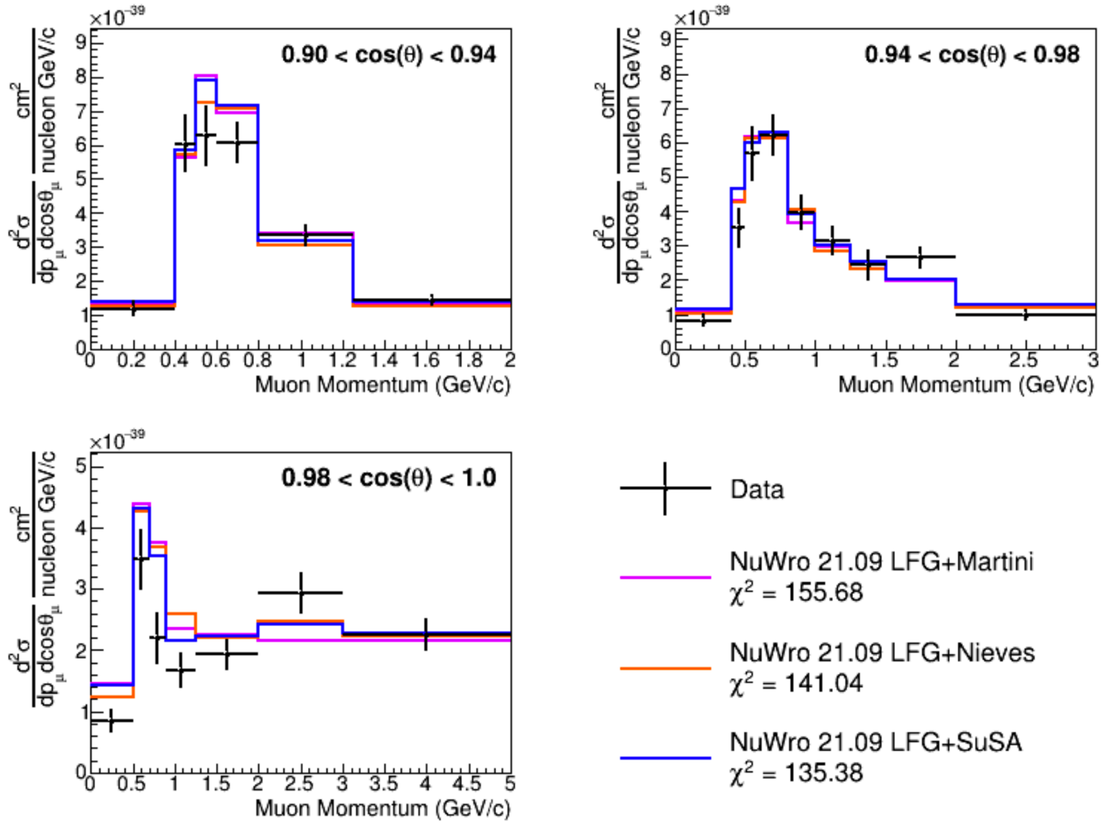
- Main event generators for neutrino interactions:



Comparison between models

$d^2\sigma$ in NuWro MC generator

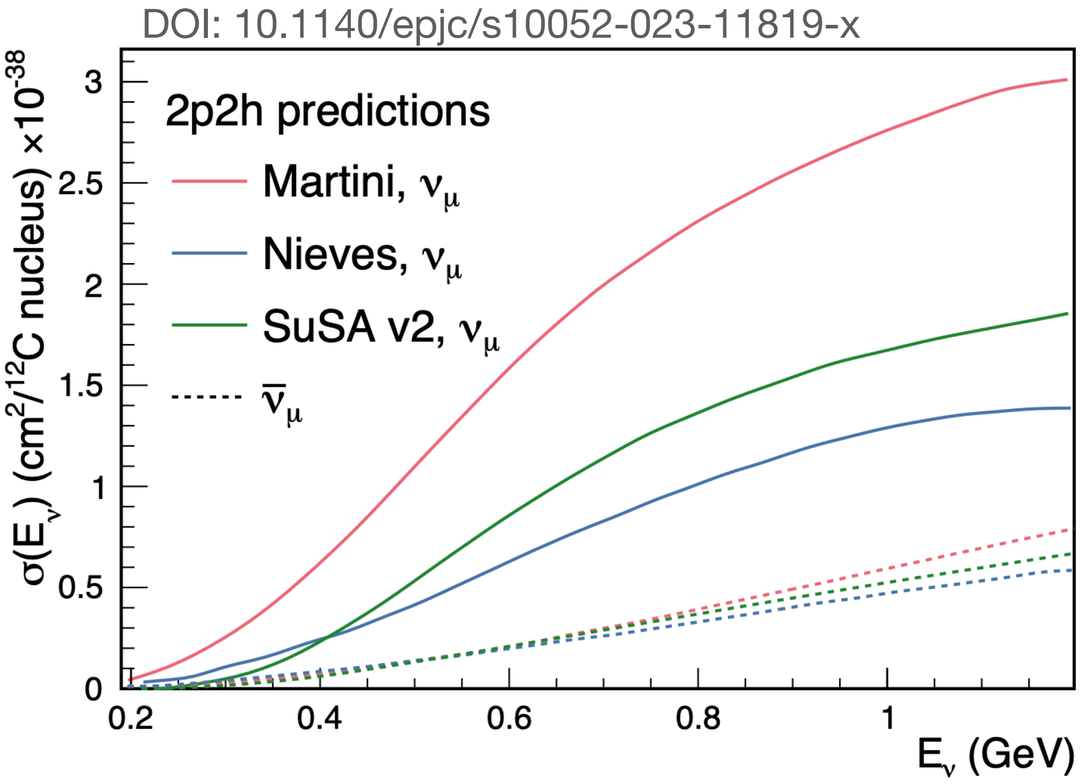
DOI: 10.1103/PhysRevD.108.112009



- Different approximations by different groups lead to different results by each group
- Models are often mixed (LFG + Martini/ Nieves/SuSA) and this can raise problems

Comparison between models

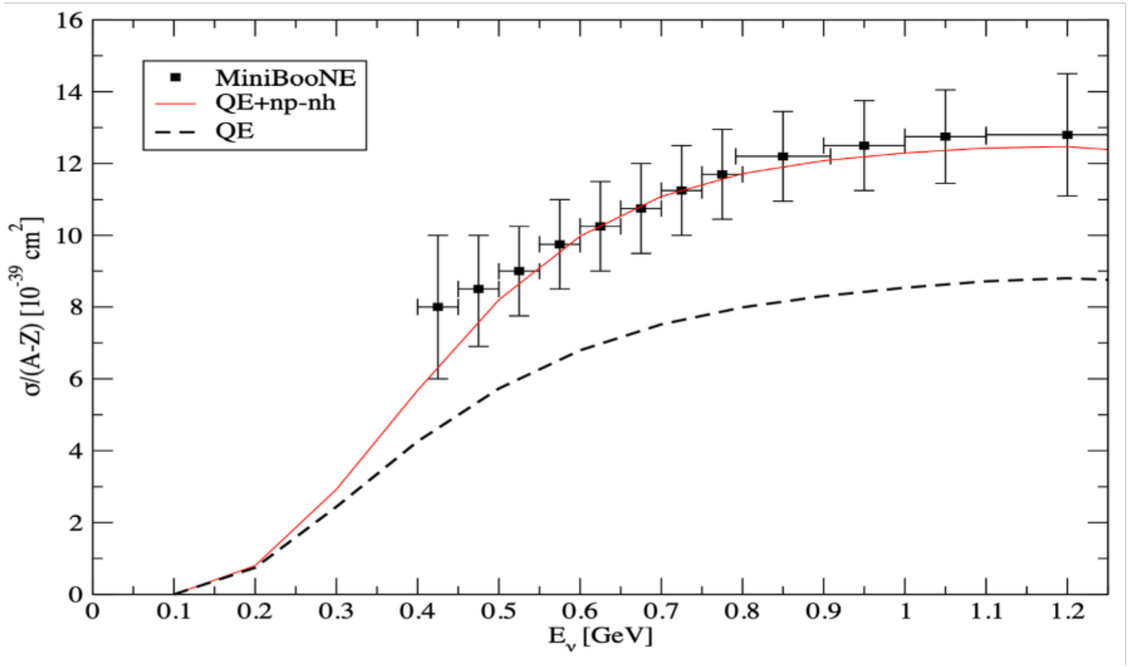
2p2h cross section



The relative role of 2p2h for neutrinos and antineutrinos varies in each approach

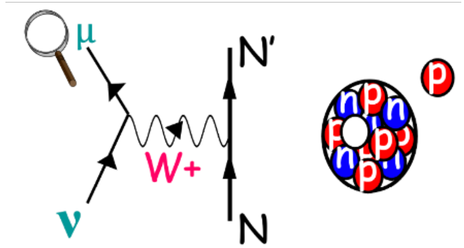
First explanation of the MiniBooNE CCQE-like σ and M_A puzzle

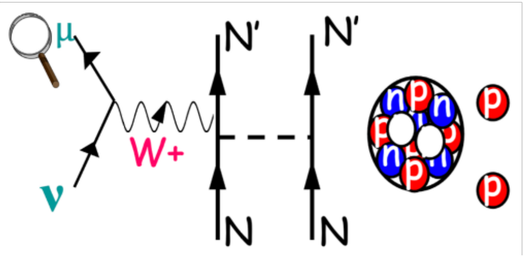
M. Martini, M. Ericson, G. Chanfray, J. Marteau
Phys. Rev. C 80 065501 (2009)



CCQE-like = genuine CCQE + npnh

- genuine CCQE
- npnh





Inclusion of the multinucleon emission channel - **npnh**

→

Agreement with MiniBooNE without increasing M_A

Motivation and strategy

Up to now there is no implementation of Martini et al model in any of the MC generators

Present project: full Martini et al model implementation into GENIE MC generator

Same **strategy**, approach and tools as:

✳ SuSAv2: npnh [2]

PHYSICAL REVIEW D **101,** 033003 (2020)

Implementation of the SuSAv2-meson exchange current 1p1h and 2p2h models in GENIE and analysis of nuclear effects in T2K measurements

S. Dolan,[1,2,3] G. D. Megias,[1,2,4] and S. Bolognesi[2]

✳ CRPA: QE [3]

PHYSICAL REVIEW D **106,** 073001 (2022)

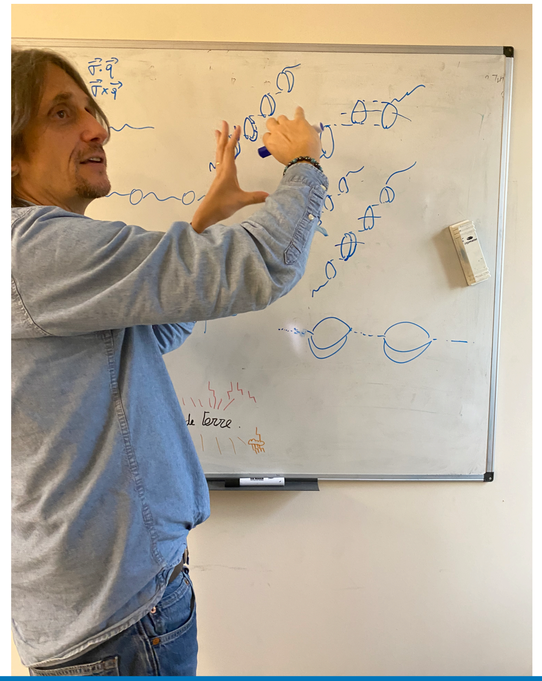
Implementation of the continuum random phase approximation model in the GENIE generator and an analysis of nuclear effects in low-energy transfer neutrino interactions

S. Dolan,[1,*] A. Nikolakopoulos,[2,†] O. Page,[3] S. Gardiner,[2] N. Jachowicz,[4] and V. Pandey[2,5]

Collaborators: Stephen Dolan and Laura Munteanu

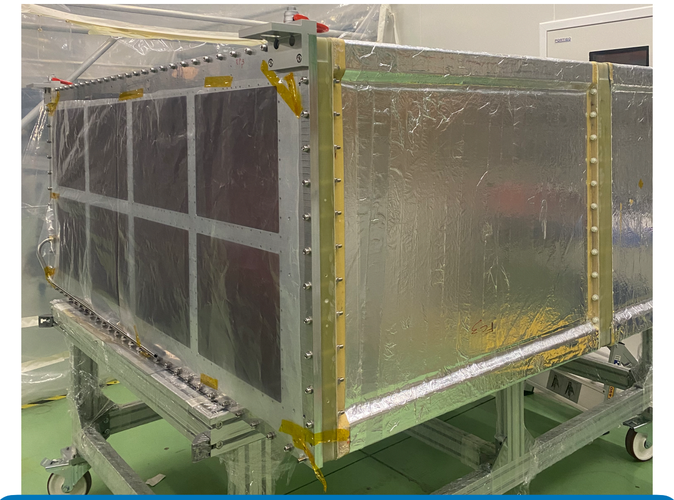
My stay at CERN

13 - 21 February 2024



Marco at the whiteboard

lunch break with Stephen and Laura



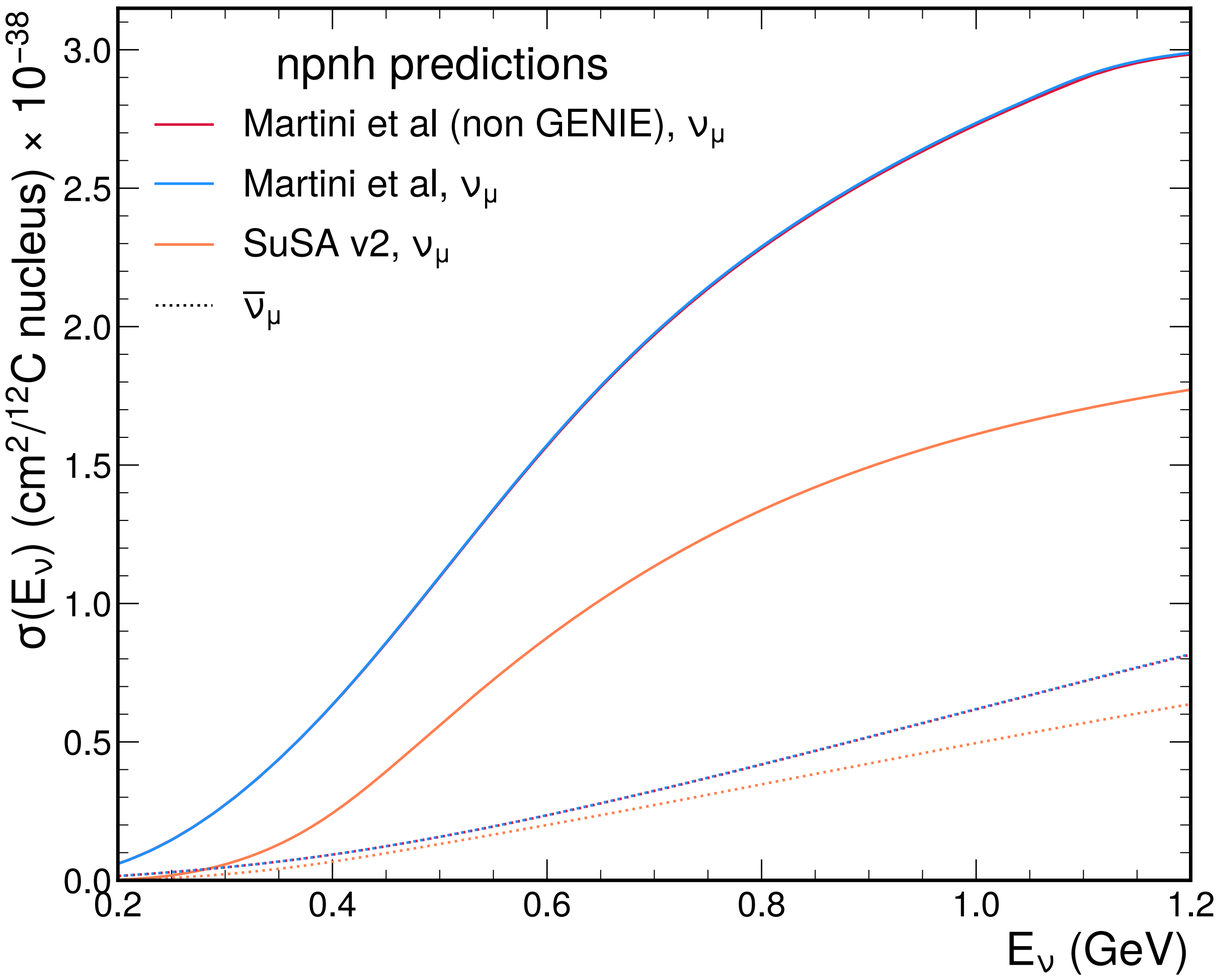
bottom HA-TPC in building 182
before being shipped to Japan

Martini et al model implementation in GENIE

npnh channel implementation

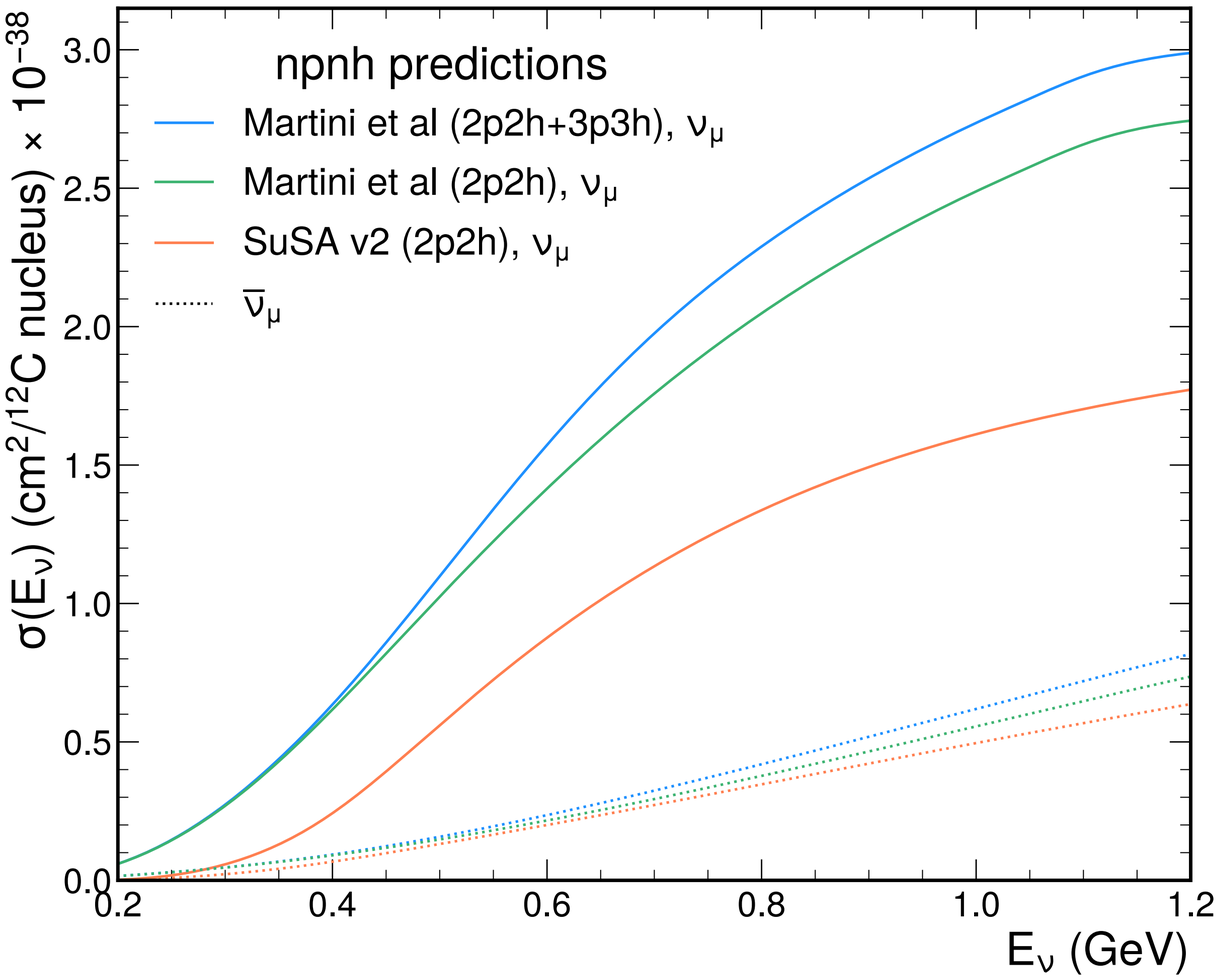
npnh implementation

Step 1



npnh implementation

Step 2



Conclusions and perspectives

Martini et al model implementation

✓ I started Martini et al model implementation into GENIE

✓ npnh channel is correctly implemented

Prospects:

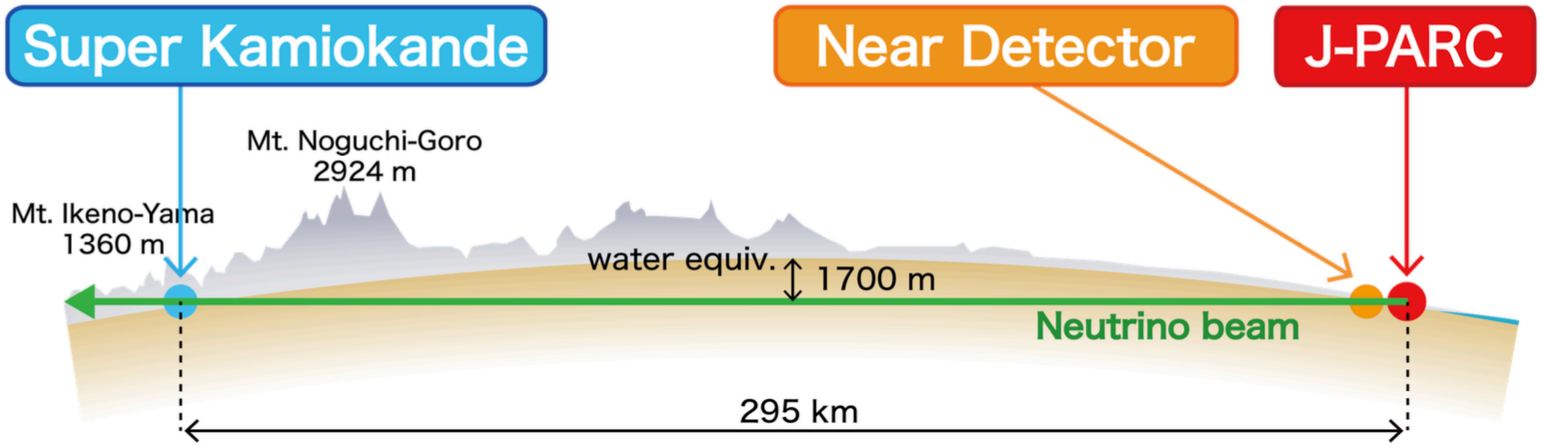
- Finalise the npnh implementation (add ^{16}O and ^{40}Ca targets)
- Implement QE channel
- Write a paper on model-data comparison
- Port the implementation to NEUT

Performances of the HA-TPCs of the T2K upgraded near detector

The T2K experiment and its upgrade

The T2K experiment

2011 - 2022	2022 - 2027
T2K - I	T2K - II



measure Φ and σ after the oscillation

ν_μ , ν_e

characterise Φ and σ before the oscillation

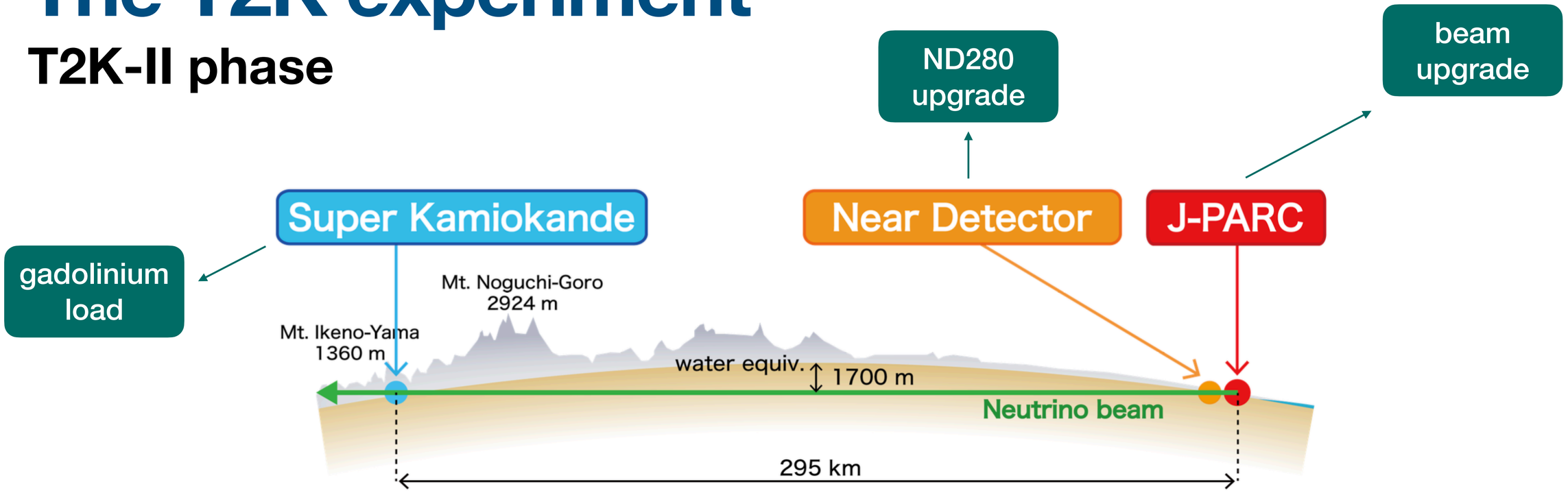
ν_μ

ν_μ beam production

3 2 1

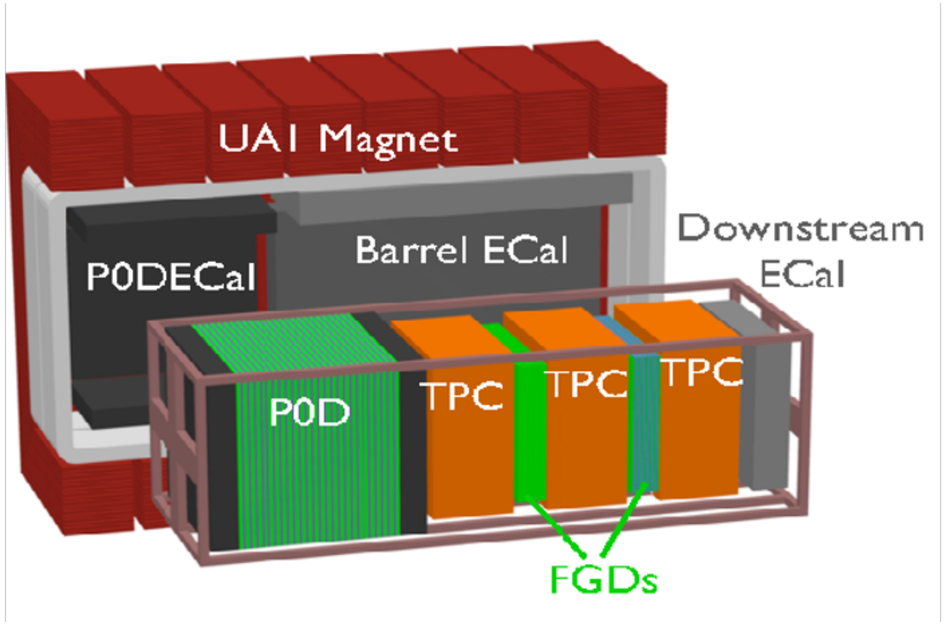
The T2K experiment

T2K-II phase

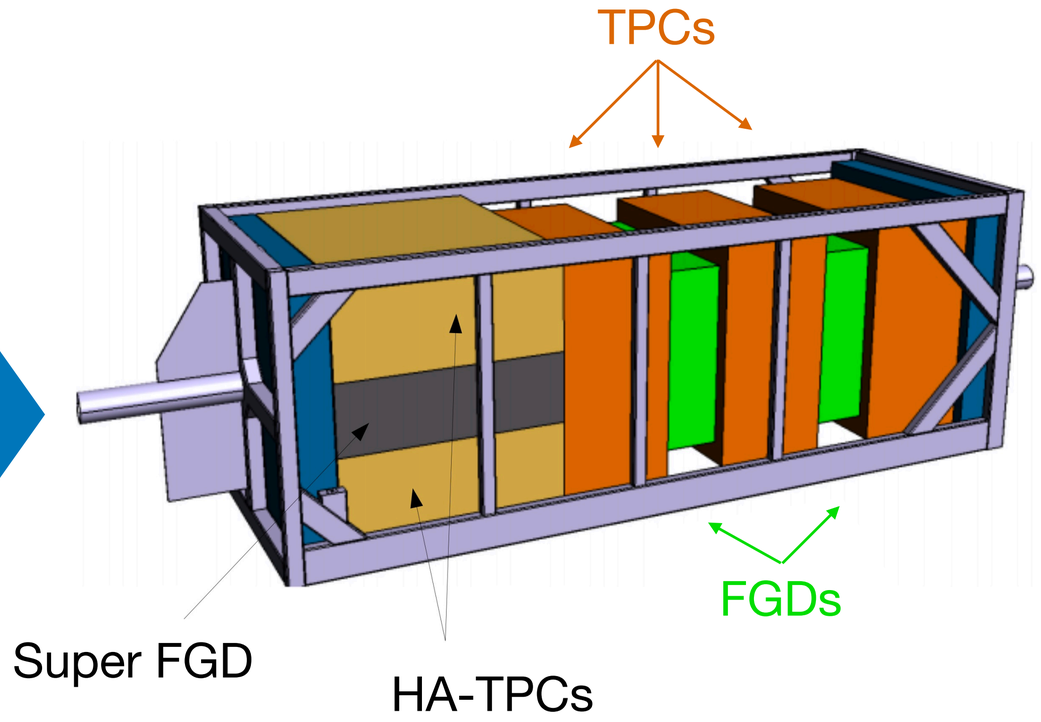


Goal: confirm CP symmetry violation in the leptonic sector with 3σ significance

The ND280 upgrade

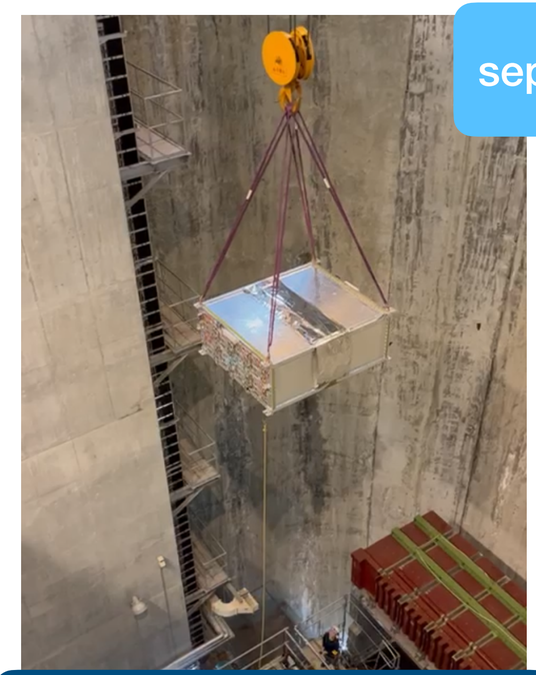


ND280 upgrade



The ND280 upgrade

The ND280 upgrade is finally fully installed !



bottom TPC installation

sept 2023

sFGD and bottom TPC

top TPC arrival

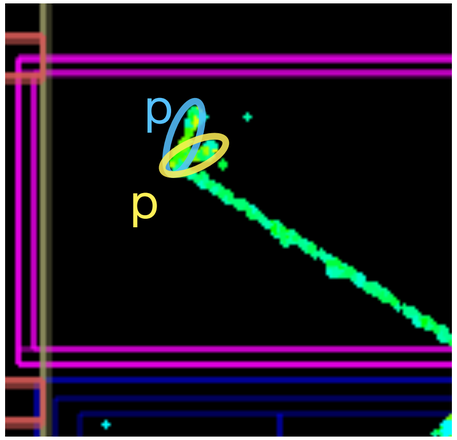
may 2024

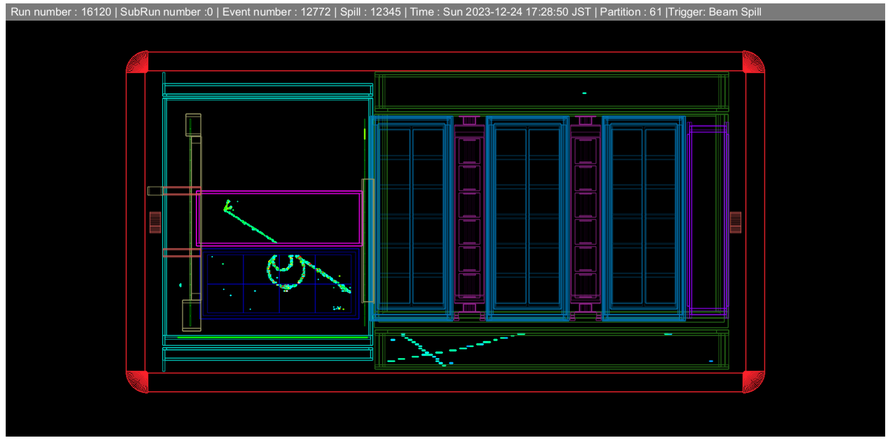
full ND280 upgrade installation

The ND280 upgrade

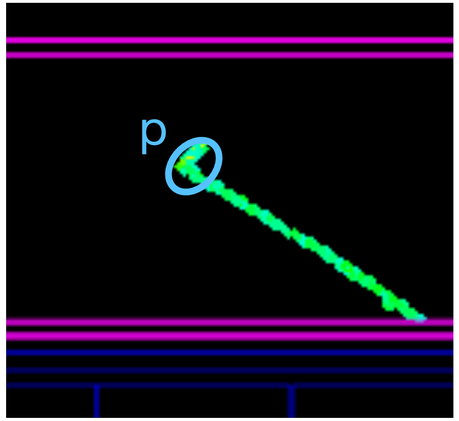
Event displays

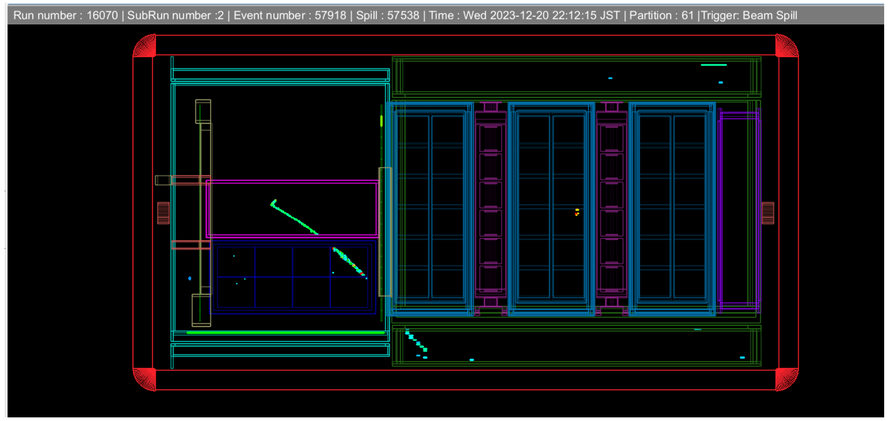
- 2 stopping protons from 2p2h interaction ?





- 1 stopping proton ?

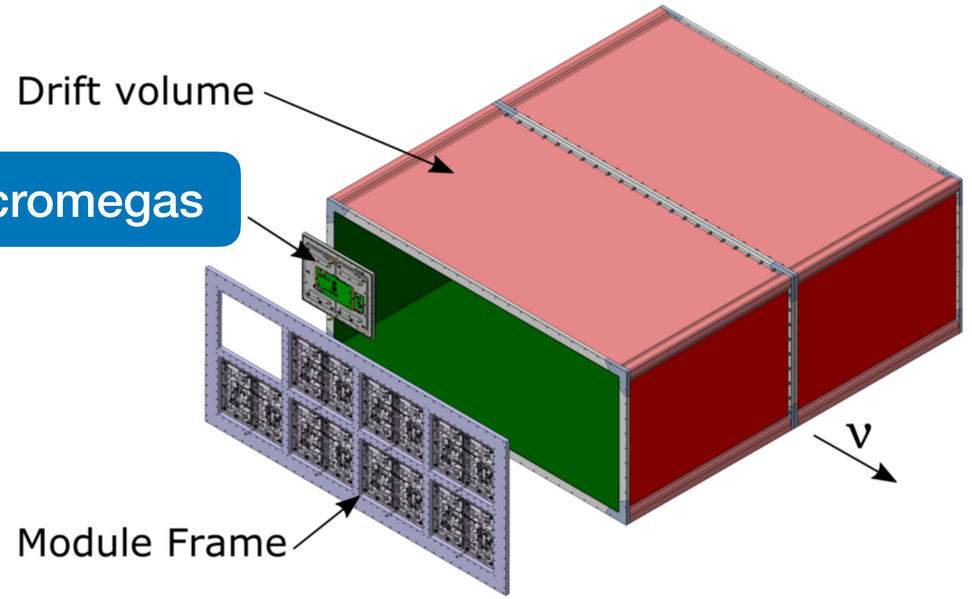




The ND280 upgrade

The HA-TPCs

Encapsulated Resistive Micromegas

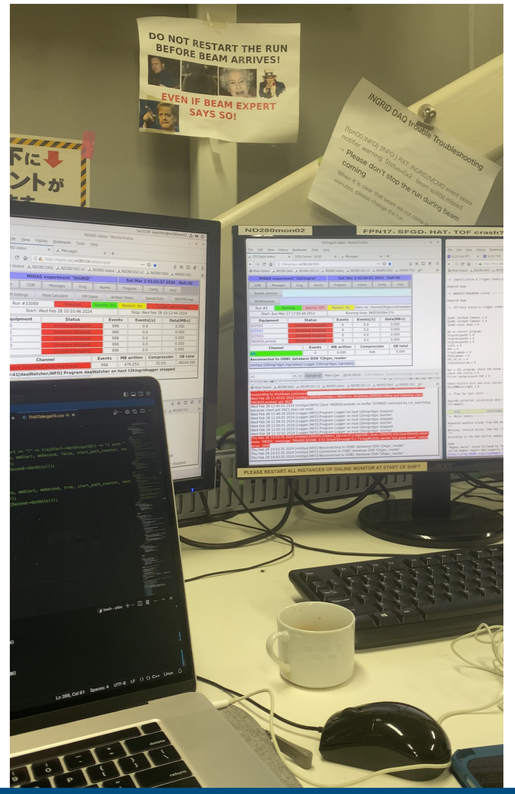


Requirements

- momentum resolution better than 10% at 1 GeV/c ⟶ to reconstruct neutrino energy
- dE/dx resolution better than 10% ⟶ to discriminate between electrons and muons

My stay in Tokai - Japan

27 February - 17 March 2024



first (and last) night shifts

first Collaboration Meeting

2 preliminary talks:

- neutrino interaction working group
- HA-TPC working group

Study of cosmic dE/dx resolution

March 2023 data taking

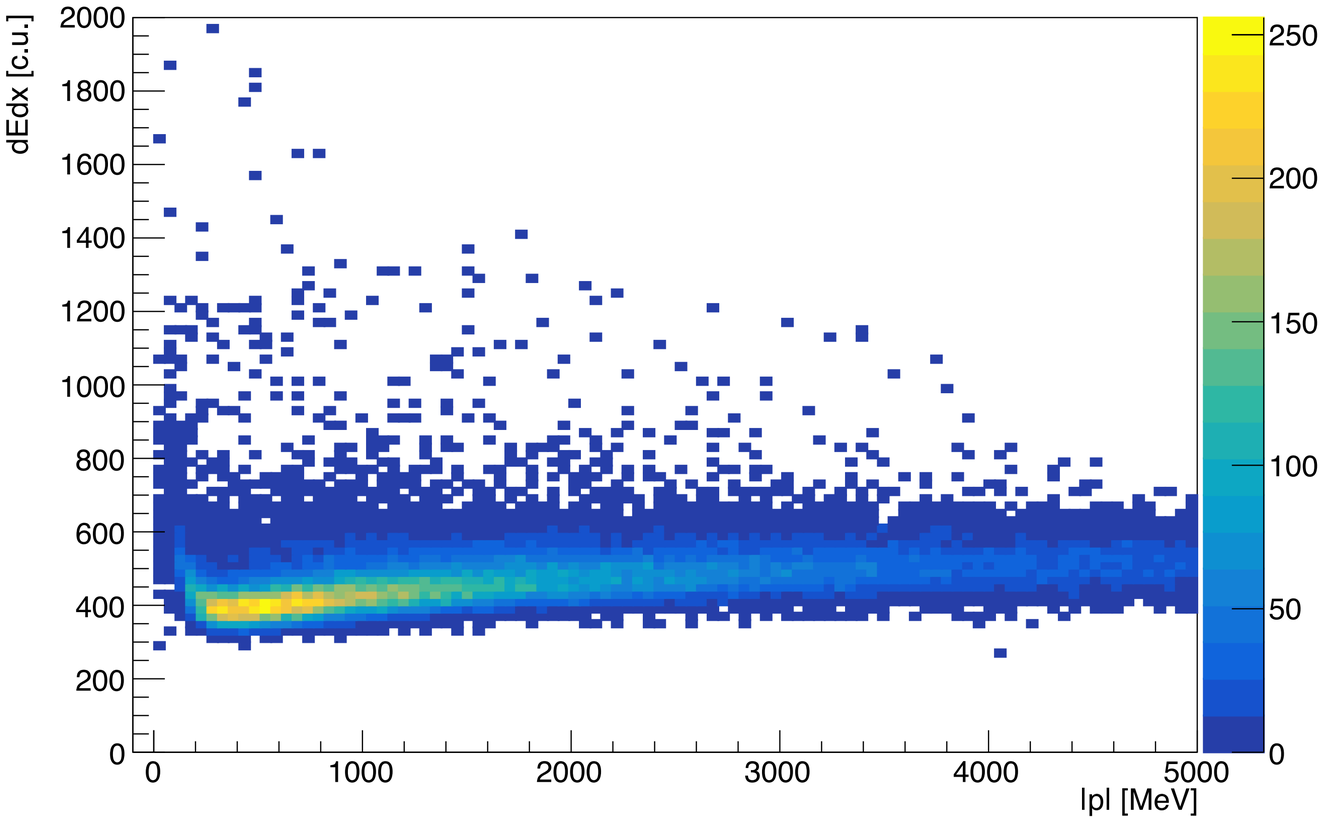
Steps of the analysis

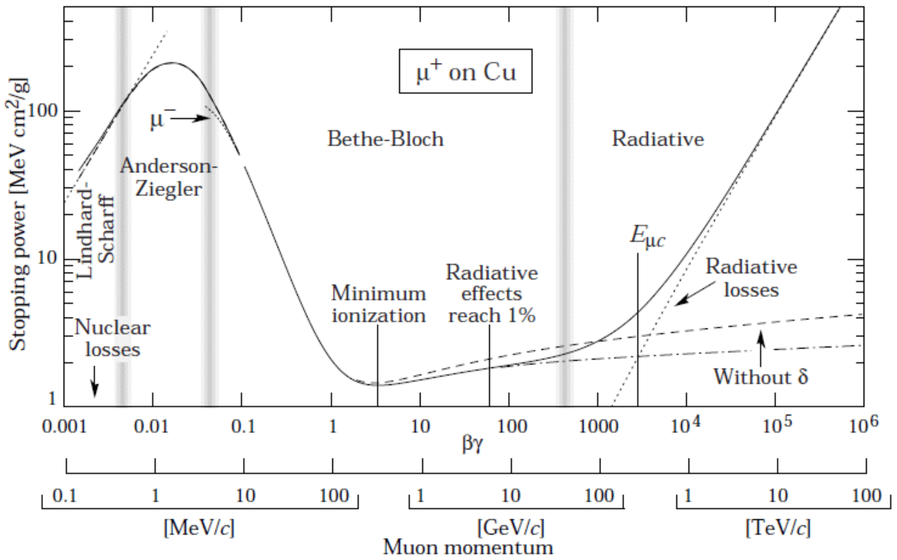
- Analysis of run of cosmic rays taken at J-PARC with magnet ON
- Data are reconstructed with **hatRecon** - official reconstruction software of HA-TPCs
- I look at:

  - **dE/dx** reconstructed by collected charge on ERAM plane
  - **p** reconstructed by B field

- I correct dE/dx by the nominal gain of each pad composing the ERAM modules - **(calibrated dE/dx)**
- I compare data with a MC simulation

dE/dx vs momentum



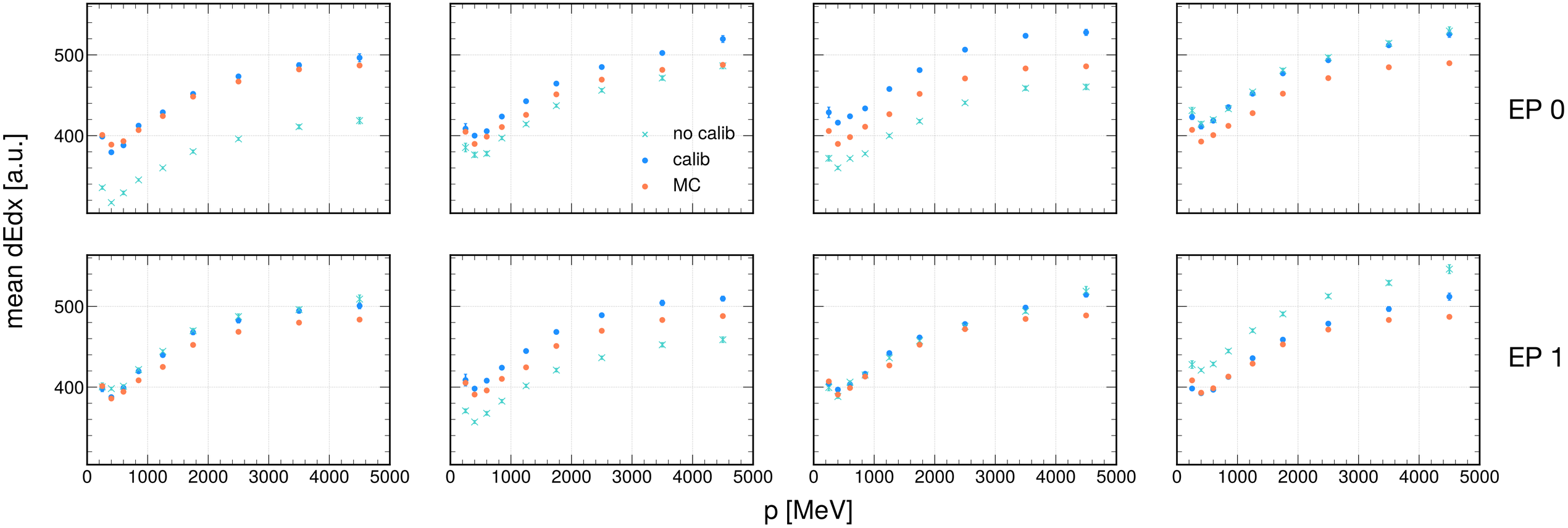


✓consistent with Bethe Bloch curve

Mean dE/dx

separation by module

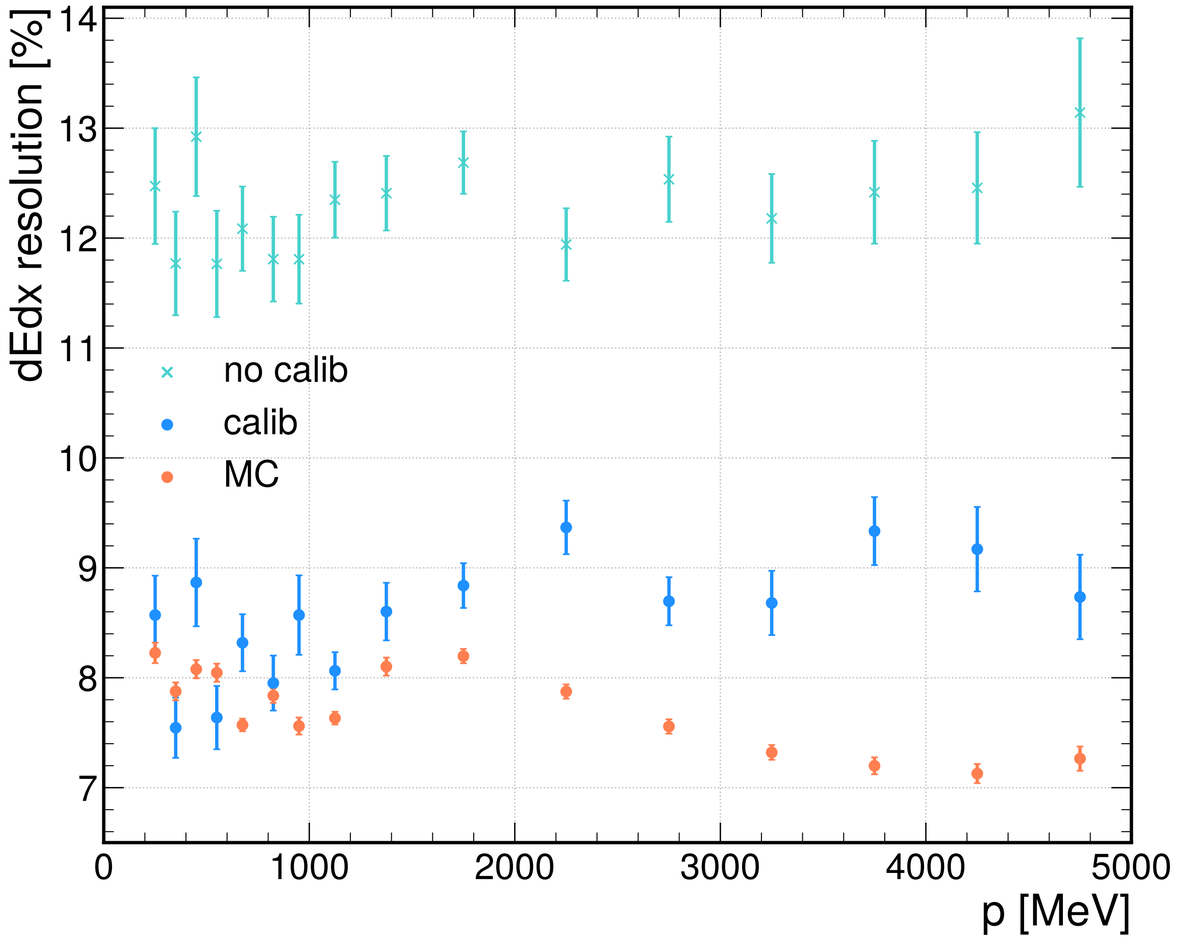
- **no calibration:** data have lots of variation
- **calibration:** more stable trend
- **MC:** no variation



dE/dx resolution

no separation by module

- **calibration:** improves dEdx resolution: it better matches the MC (both below 10%)
- **MC:** better dEdx resolution for high p



Conclusions and perspectives

Performances analysis of HA-TPCs

✓ I work actively on HA-TPCs' official reconstruction software - I am guided by Claudio

✓ So far my contributions are mainly focused on dE/dx resolution (PID)

Prospects:

- Data analysis of first data taking with T2K upgrade ~ June 2024
- Study the systematics in HAT PID and HAT momentum resolution

Conclusions

- I work on 2 different topics:

  - Martini et al model implementation into GENIE (and NEUT)
  - Performances and track reconstruction in HA-TPCs

  that will merge into CC0π cross section analysis - probably focusing on 0 protons and 1 proton samples (profiting of the incoming data taking)

- I plan to **write a paper** about my work with Marco ~ September 2024

1st year conferences and experiences

Done and to be done

	aim	when	contribution
CERN	start Martini's model implementation	13 - 21 February	:)
Tokai, Japan	shifts + CM	27 Feb - 17 Mar	2 preliminary talks
Milano Neutrino 2024	conference	16 - 22 June	poster about Martini model implementation into GENIE
T2K CERN workshop	CM	22 - 27 July	talks

Points de l’école doctorale

Formation	Duration	STEP’ UP points	PIF points
French course	30 h	3/4	?
NUSTEC summer school	June 5 - 13	4 max	?
Statistics course	June/July	?	?
Machine learning course	September	?	?
Teaching	let’s see!	1 per year	?

References

(1) M. Martini et al. “Unified approach for nucleon knock-out and coherent and incoherent pion production in neutrino interactions with nuclei”. In: Physical Review C 80.6 (Dec. 2009). ISSN: 1089-490X. DOI: 10.1103/physrevc.80.065501. URL: http://dx.doi.org/10.1103/PhysRevC.80.065501

(2) S. Dolan, G. D. Megias, and S. Bolognesi. “Implementation of the SuSAv2-meson exchange current 1p1h and 2p2h models in GENIE and analysis of nuclear effects in T2K measurements”. In: Phys. Rev. D 101.3 (2020), p. 033003. DOI: 10.1103/PhysRevD.101.033003. arXiv: 1905.08556 [hep-ex]

(3) S. Dolan et al. “Implementation of the continuum random phase approximation model in the GENIE generator and an analysis of nuclear effects in low-energy transfer neutrino interactions”. In: Phys. Rev. D 106.7 (2022), p. 073001. DOI: 10.1103/PhysRevD.106.073001. arXiv: 2110.14601 [hep-ex]

Backup slides

Neutrino flux integrated $d^2\sigma$

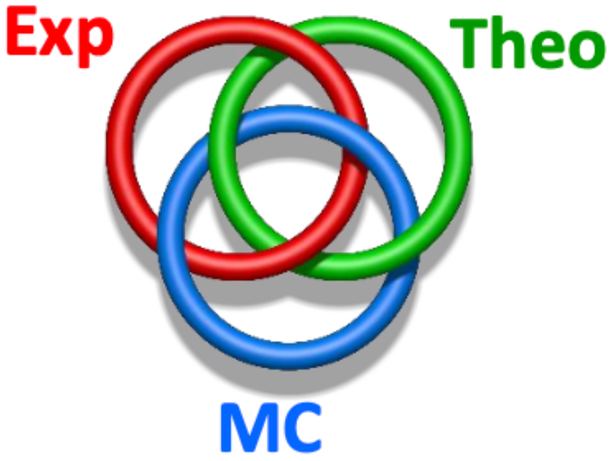
theoretical definition

$$\frac{d^2\sigma}{dT_l\, d\cos\theta} = \frac{1}{\int \Phi(E_\nu)\, dE_\nu} \int dE_\nu \left[\frac{d^2\sigma}{d\omega\, d\cos\theta}\right]_{\omega=E_\nu-E_l} \Phi(E_\nu)$$

experimental definition

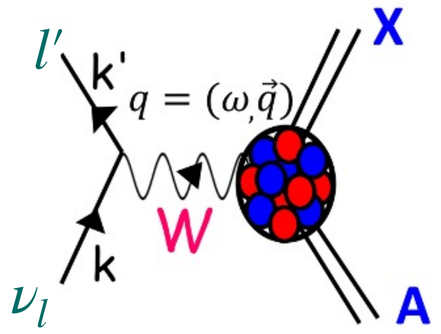
$$\left(\frac{d^2\sigma}{dT_l\, d\cos\theta}\right)_i = \frac{\sum_j U_{ij}\,(d_j - b_j)}{\Phi \cdot T \cdot \epsilon_i \cdot (\Delta T_l, \Delta\cos\theta)_i}$$

- U_{ij}: unfolding matrix to remove detector effects
- d_j: # of detected events
- b_j: background contribution
- Φ: total integrated flux
- T: # of targets
- ϵ_i: efficiency
- $(\Delta T_l, \Delta\cos\theta)_i$: bin widths



Charged current neutrino - nucleus σ

$$\nu_l\ (\bar{\nu}_l) + A \rightarrow l^-\ (l^+) + X$$



$$\frac{d^2\sigma}{d\Omega_{k'}d\omega} = \frac{G_F^2 \cos\theta_C}{4\pi} \frac{|\mathrm{k}'|}{|\mathrm{k}|} L_{\mu\nu} W^{\mu\nu}(\mathrm{q}, \omega)$$

leptonic tensor

- **kinematic variables**

hadronic tensor

- **nucleon properties**: nucleon Electric, Magnetic and Axial form factors
- **nuclear dynamics**: nuclear response function

Difference between generators

Nieves model

DOI: 10.1103/PhysRevD.108.112009