Prospects for physics with the T2K ND280 Upgrade

Capabilities and impact on oscillation measurements

Laura Munteanu (CERN), on behalf of the T2K Collaboration

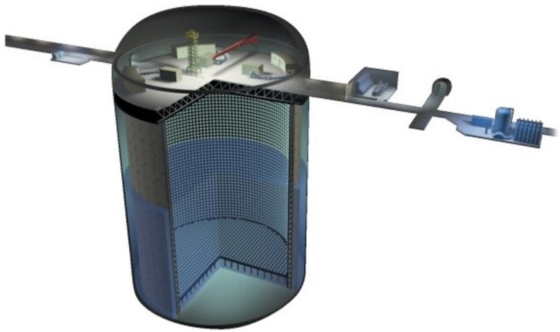
NuFACT 2023, Seoul, South Korea

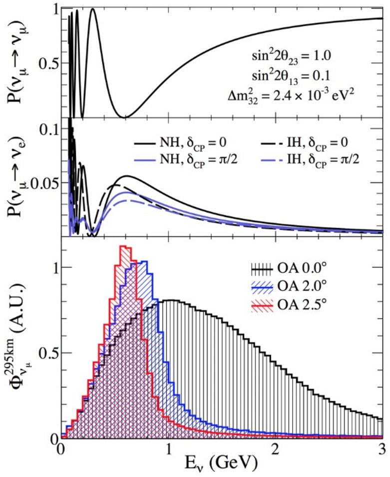
25 August 2023

CERN

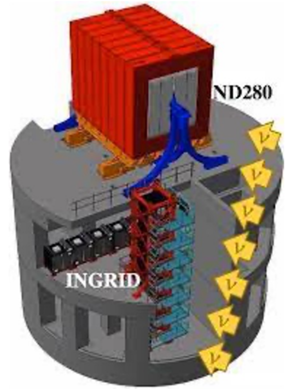
The T2K Experiment

Far detector: Super-Kamiokande

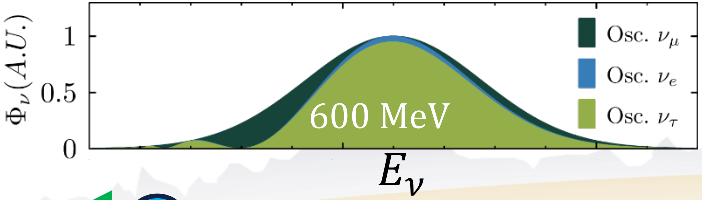




Near detector complex



$$N_{\nu_{\mu/e}}(E_\nu) = P_{\nu_\mu \to \nu_{\mu/e}}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$



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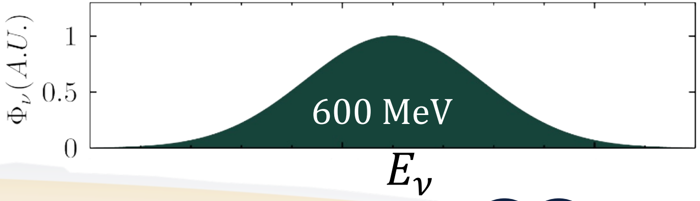
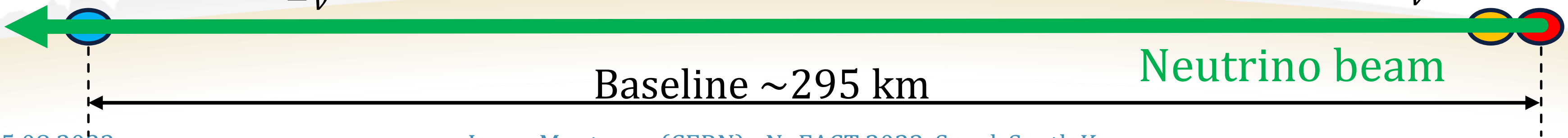
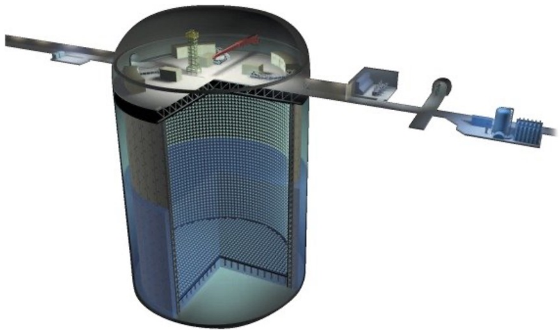
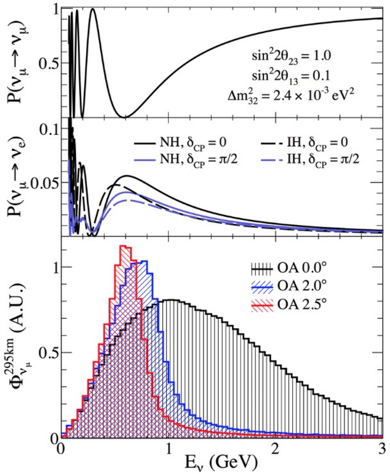




The T2K Experiment

Far detector: Super-Kamiokande





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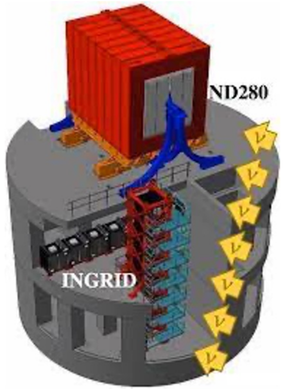

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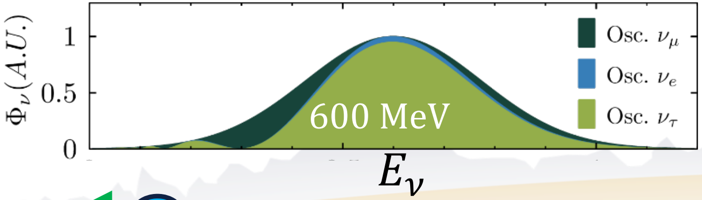

See talks by
M. Friend
Y. Sato
C. Naseby

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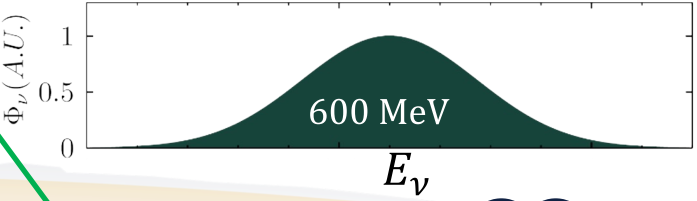


Neutrino beam

Baseline ~295 km

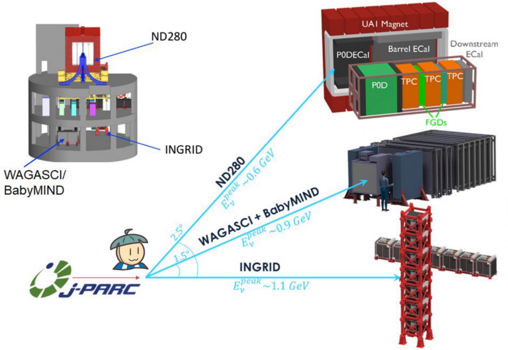
Physics program and recent achievements

Nature 580, 339–344 (2020)

Neutrino oscillations

- Hint of CP-violation in the lepton sector!
- Joint fits with NOvA and SK-atmospherics

See talks by
D. Cherdack
A. Blanchet
T. Doyle



Neutrino cross-sections

- CC0π, CC1π, TKI, CCCoh
- Particular focus on "joint" measurements ($\nu_\mu/\bar{\nu}_\mu, \nu_e/\bar{\nu}_e$, C/O,on/off-axis)

See talk by L. Koch

Exotic searches

- Searches for HNLs

T2K Extended Run

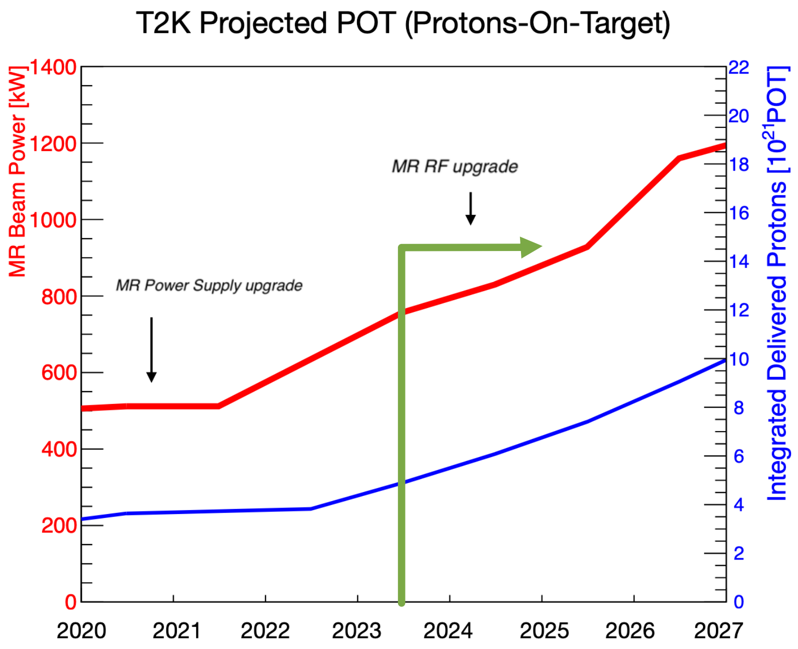
See talks by Y. Sato and C. Naseby

Beamline upgrade

- Increase beam power from 500 kW to 800 kW to 1.3 MW (Hyper-K era)
- Increase horn current from 250 kA to 320 kA (better wrong-sign separation)

Goals of extended run:

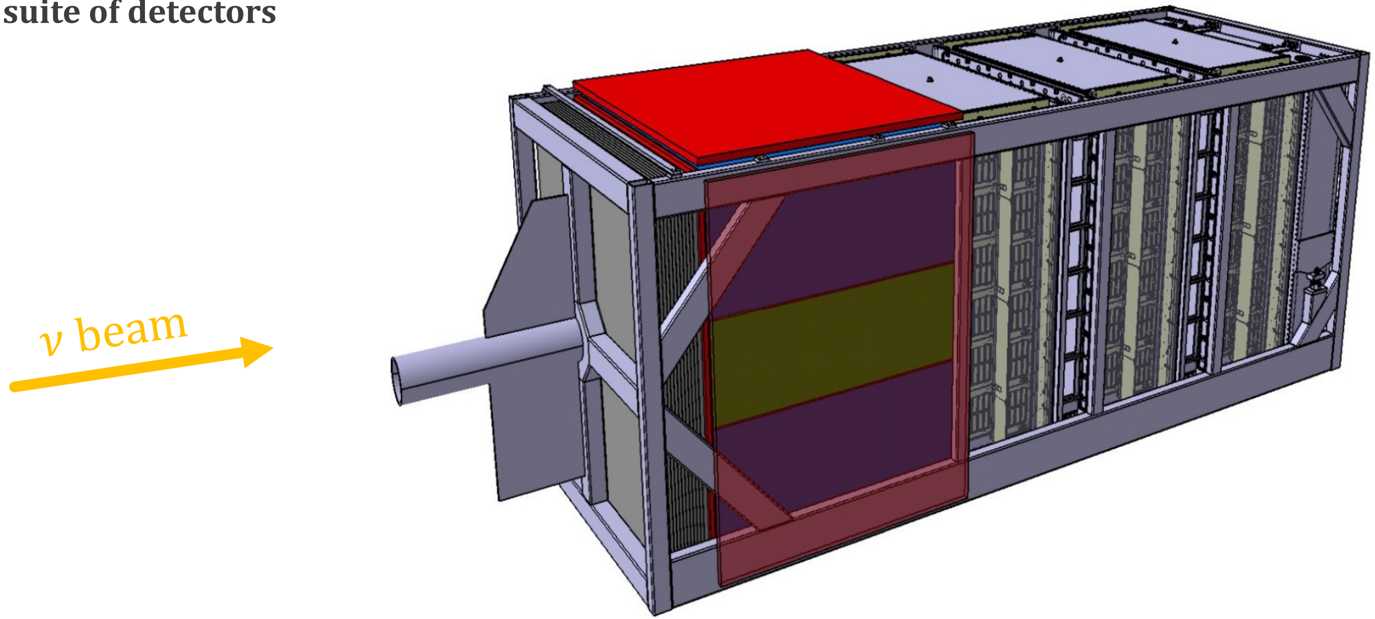
- Improve oscillation parameter measurements
- Perform new cross-section measurements



The T2K ND280 Upgrade project

ND280 Upgrade TDR

Replace P0D by new suite of detectors



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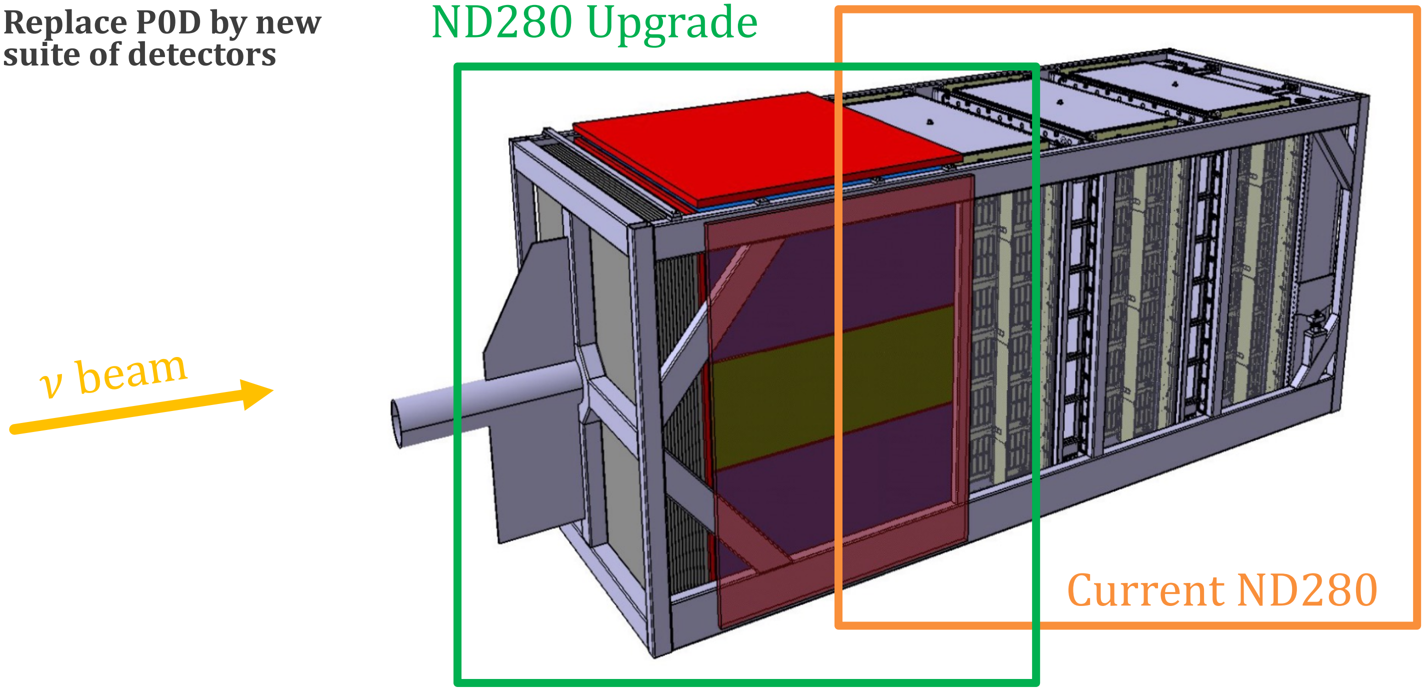

See talks by
D. Nguyen
K. Lachner

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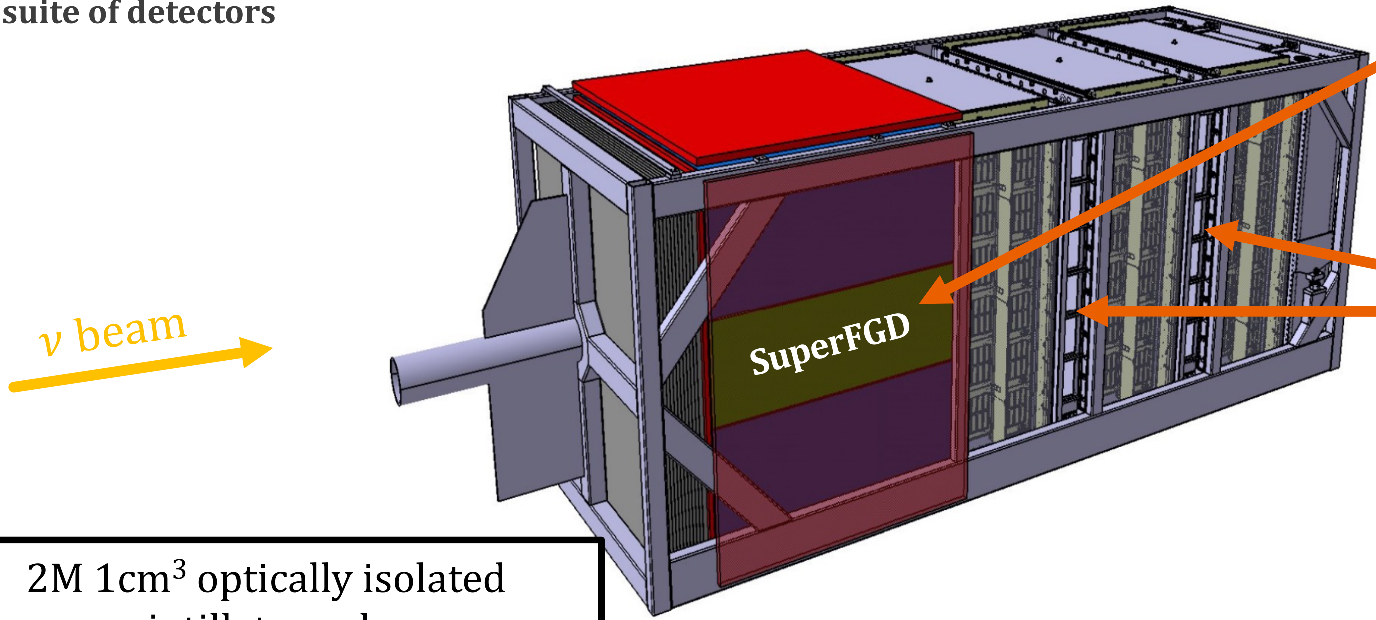

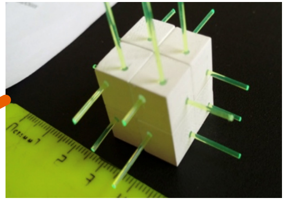

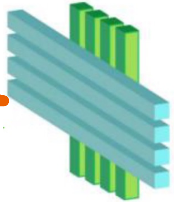

2M 1cm^3 optically isolated scintillator cubes

2x fiducial mass of current FGDs

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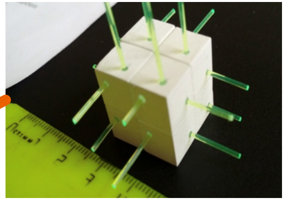
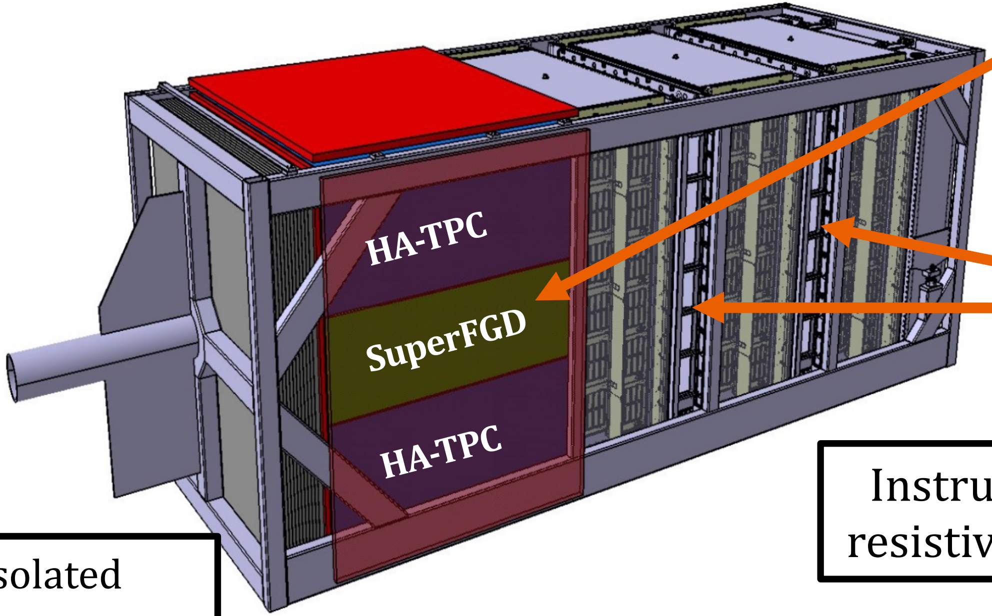
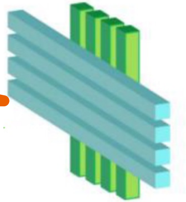


ν beam





Instrumented with resistive Micromegas

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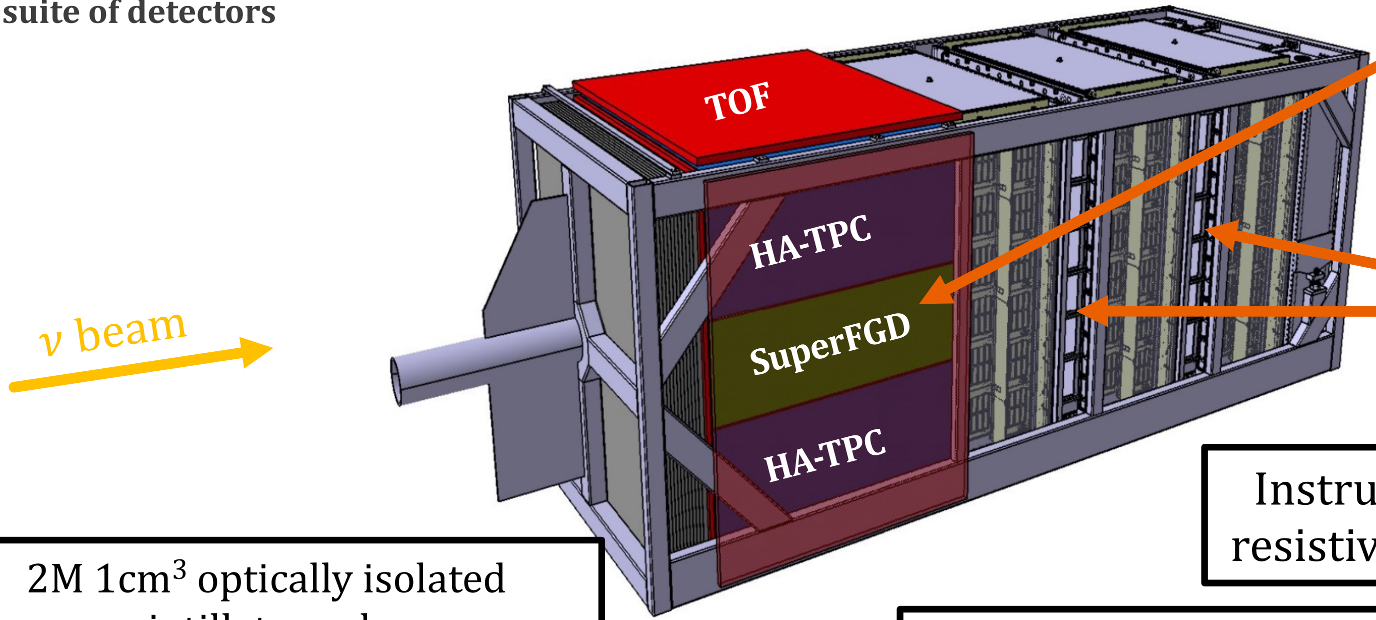

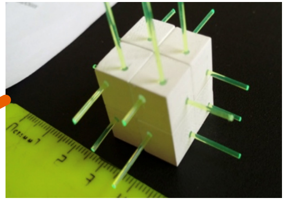

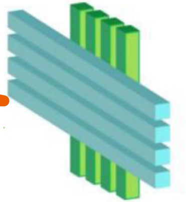

Instrumented with resistive Micromegas

150 ps timing resolution for PID

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The T2K ND280 Upgrade project

ND280 Upgrade TDR

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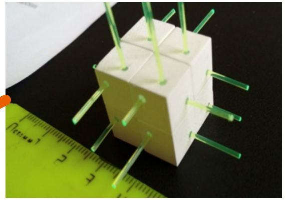

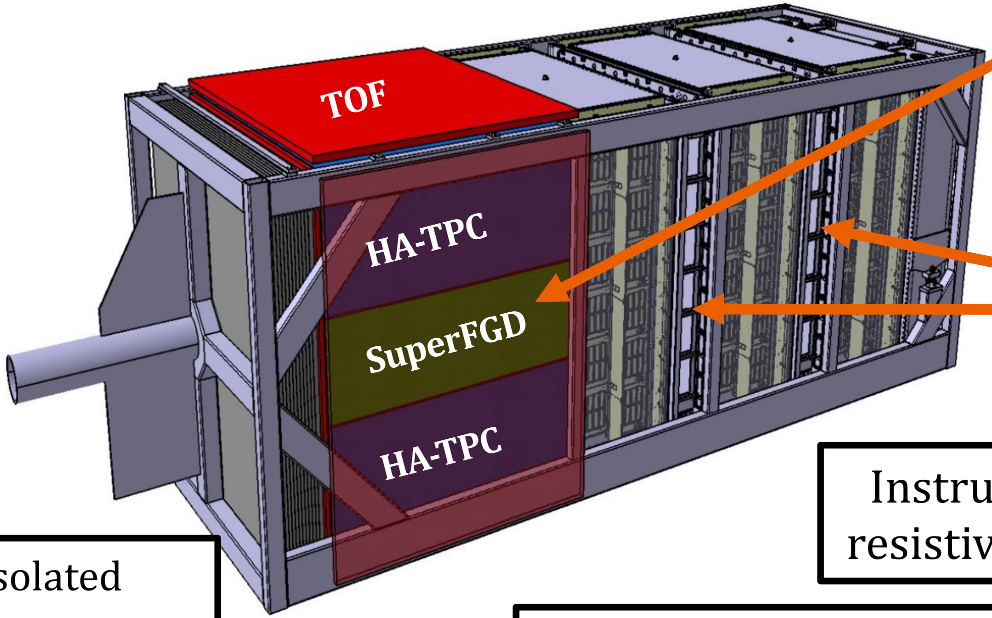

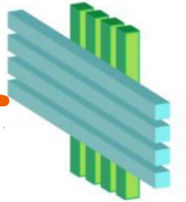

>100 researchers
22 institutes
7 countries

2M 1cm^3 optically isolated scintillator cubes

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The T2K ND280 Upgrade project

ND280 Upgrade TDR

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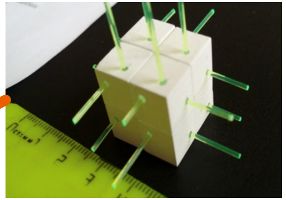

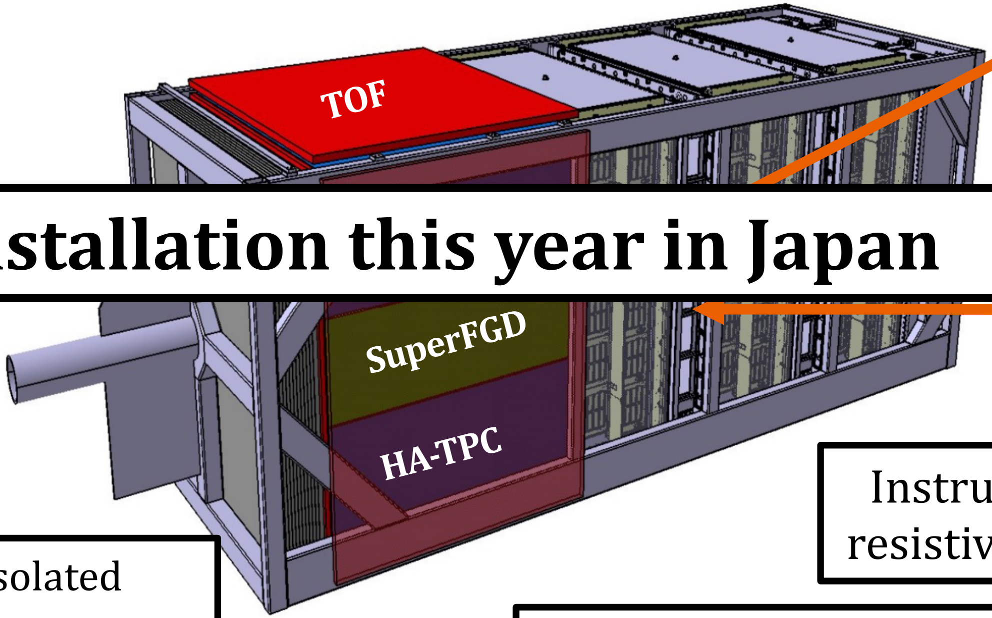

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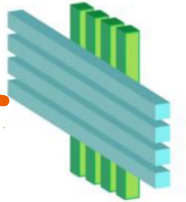
Installation this year in Japan



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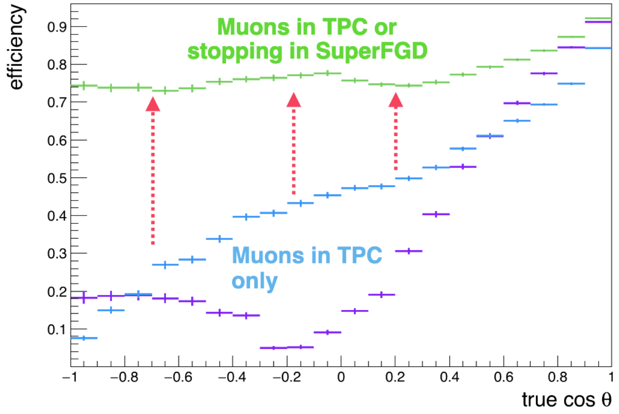
Capabilities of the ND280 Upgrade

- Full 4π angular coverage (same as SK)



Capabilities of the ND280 Upgrade

- Full 4π angular coverage (same as SK)
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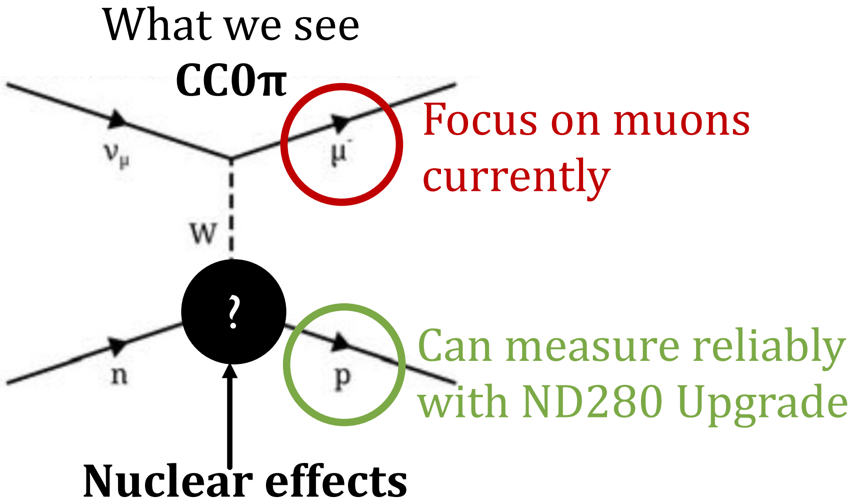
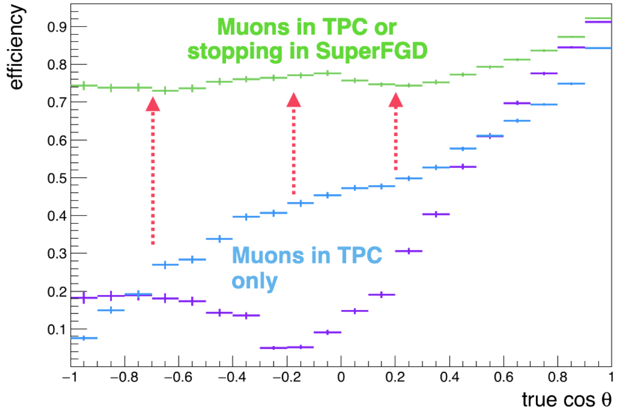
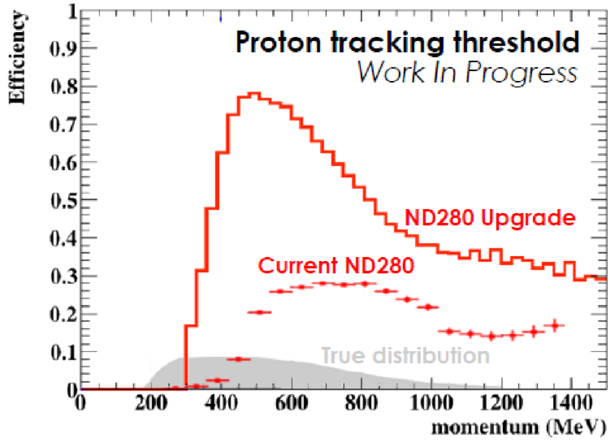
  - Can realiably measure full final state in neutrino interactions!

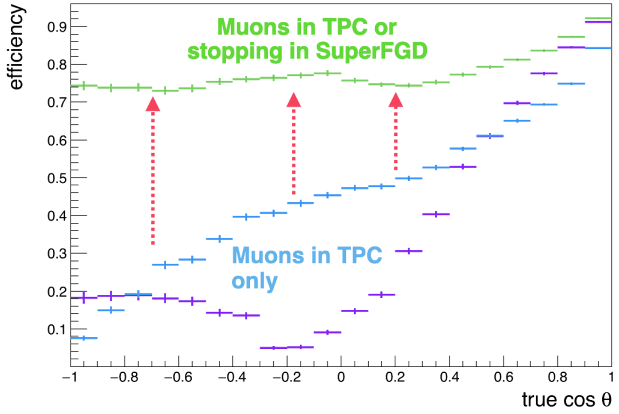


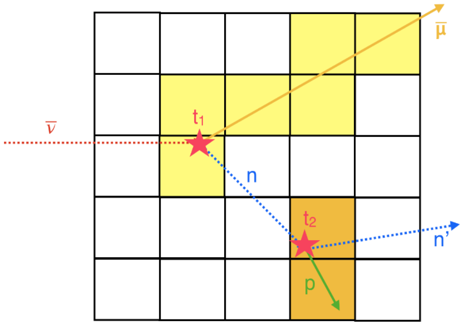




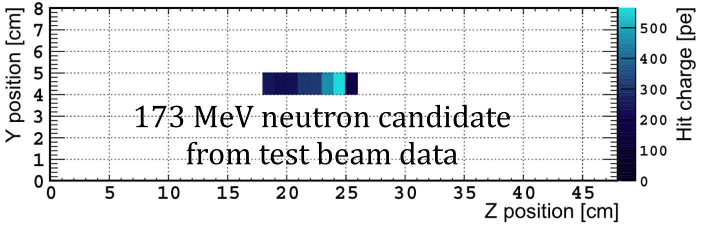
Capabilities of the ND280 Upgrade

- Full 4π angular coverage (same as SK)
- Low momentum thresholds for detecting **protons**
  - Can realiably measure full final state in neutrino interactions!
- Capability to measure (not just tag!) **neutron** kinetic energy
  - **Expect ~30% resolution + ~50% detection efficiency**

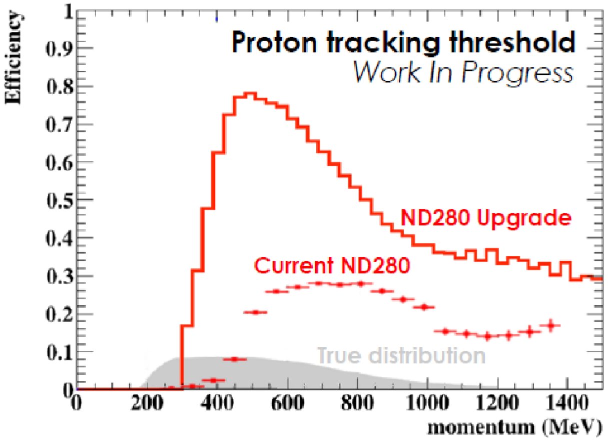




Phys. Rev. D 101, 092003

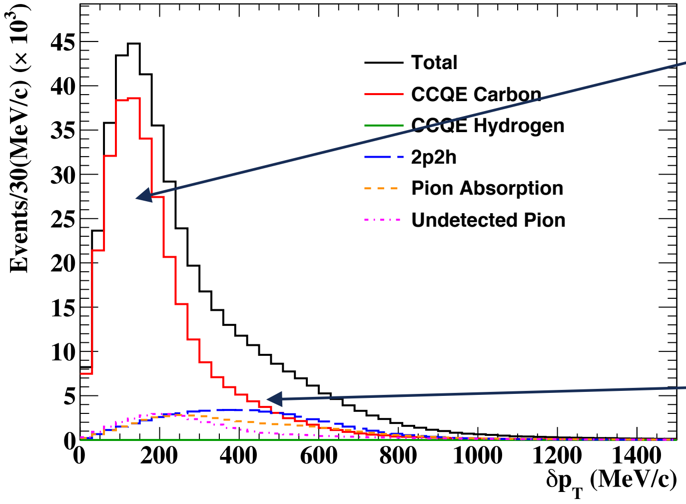


Phys.Lett.B 840 (2023) 137843



What can the ND280 Upgrade do for us?

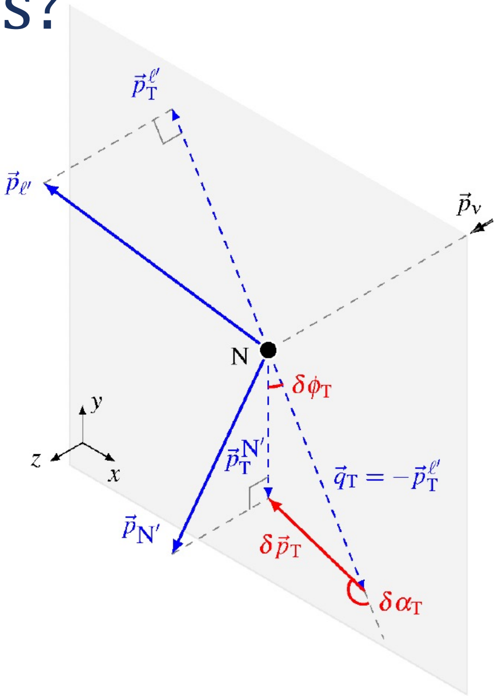
- Access to **exclusive** variables
  - E.g. probe nuclear effects by looking at Transverse Kinematic Imbalance (TKI)



Phys. Rev. D 105, 032010

Bulk dominated by CCQE

Tails dominated by FSI+2p2h



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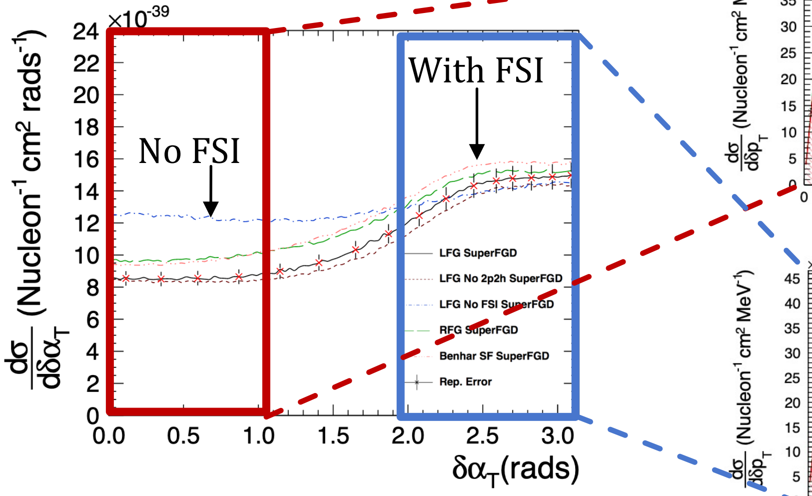
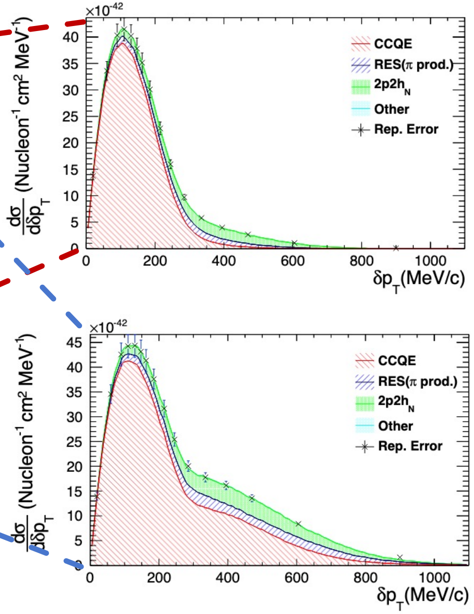
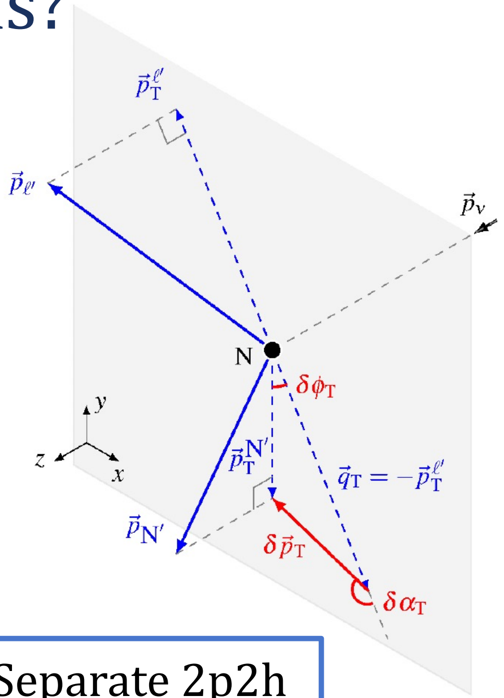


ND280 Upgrade TDR





Separate 2p2h and FSI effects!

What can the ND280 Upgrade do for us?

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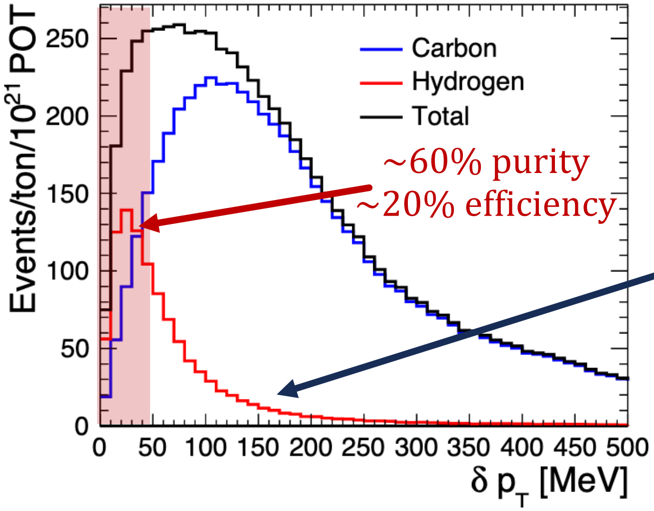
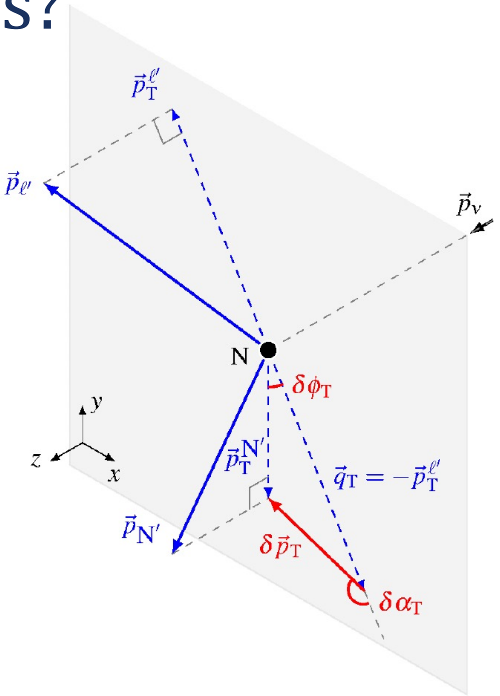


[Phys. Rev. D 101, 092003 (2020)](#)

Antineutrinos:
Peak from interactions on hydrogen

No nuclear effects

Possible thanks to **neutron detection**!



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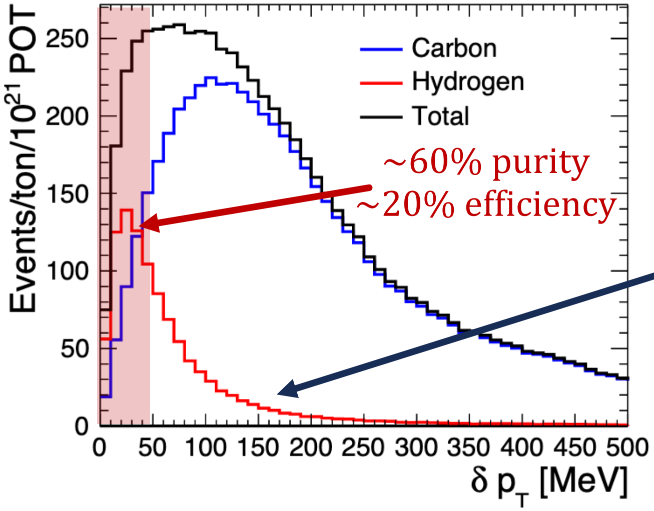
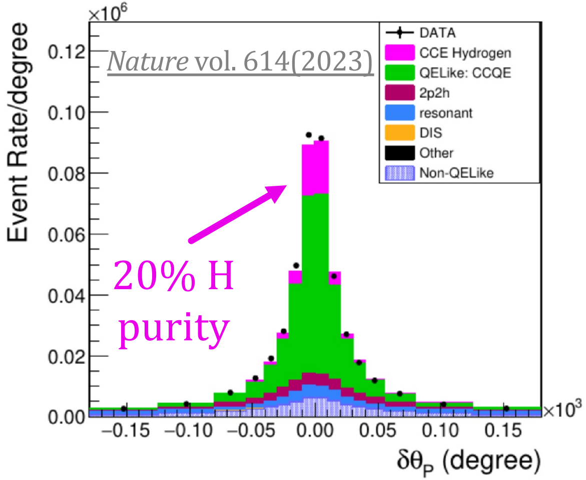


Phys. Rev. D 101, 092003 (2020)

Recent MINERvA measurement



First measurement using similar method

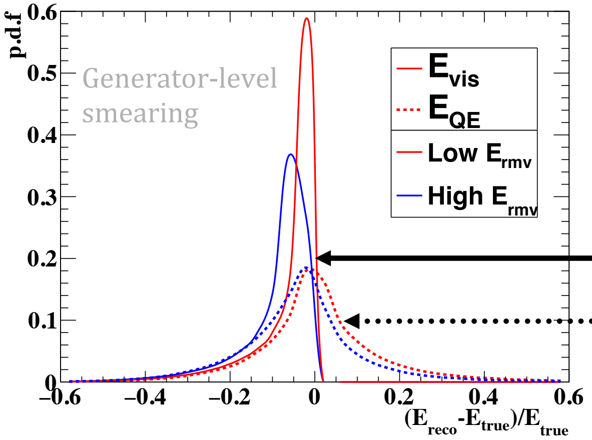
ND280 Upgrade will likely expand on such measurements with improved purities!

What can the ND280 Upgrade do for us?

- Access to **exclusive** variables
  - E.g. probe nuclear effects by looking at Transverse Kinematic Imbalance (TKI)
  - Using calorimetric estimators for neutrino energy

$$E_{vis} = E_{\mu} + T_N$$

Method used by NOvA & DUNE



Phys. Rev. D 105, 032010

Reduced bias in neutrino energy reconstruction

E_{vis} bias dominated by **detector resolution**

E_{QE} dominated by **nuclear effects**

Impact on the oscillation analysis: Sensitivity studies

Samples and model

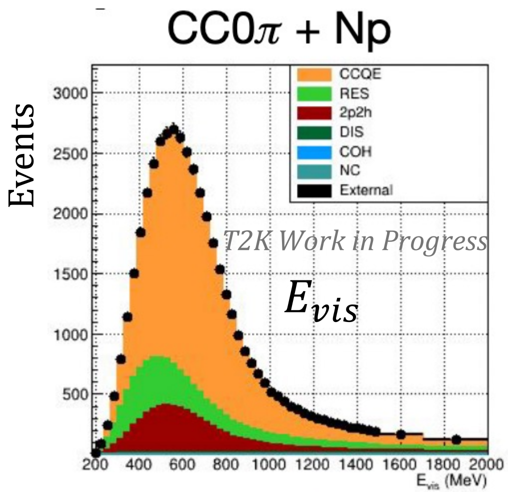
Preliminary impact on sensitivity to constrain systematic parameters using

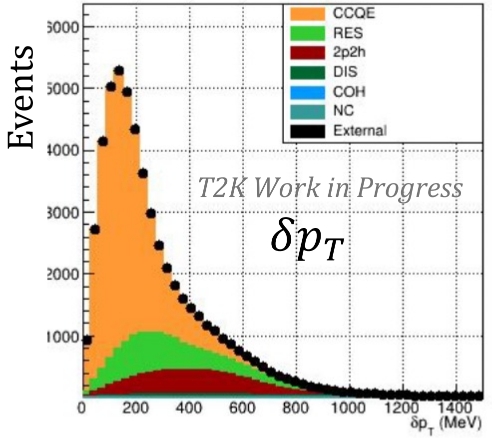
- Latest T2K interaction uncertainty model (arXiv:2308.01838)
- Current ND280 samples binned in lepton kinematics

See talk by T. Doyle

- SuperFGD samples binned in **exclusive variables** ($E_{vis}, \delta p_T$)
- Simplified (conservative) reconstruction effects
- No detector systematics (expected to be sub-leading)

See talk by K. Lachner on details of simulation and reconstruction





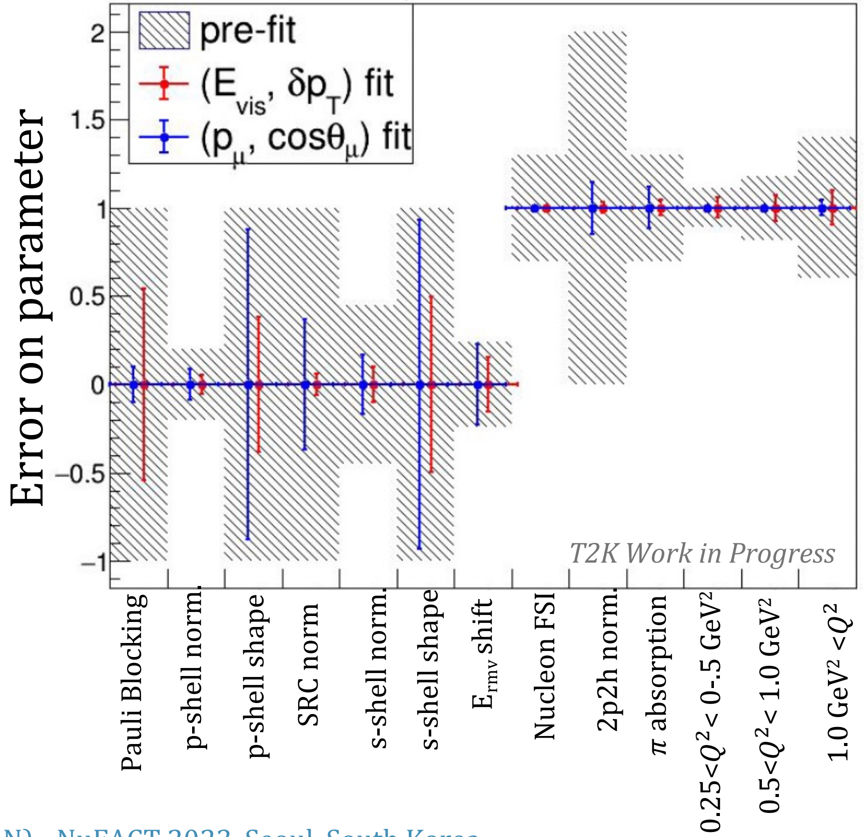
Impact of SuperFGD

Tested the impact of SuperFGD-only samples assuming

- 2D $(p_\mu, \cos\theta_\mu)$ binning – lepton only
- 2D $(E_{vis}, \delta p_T)$ binning – lepton + hadron information

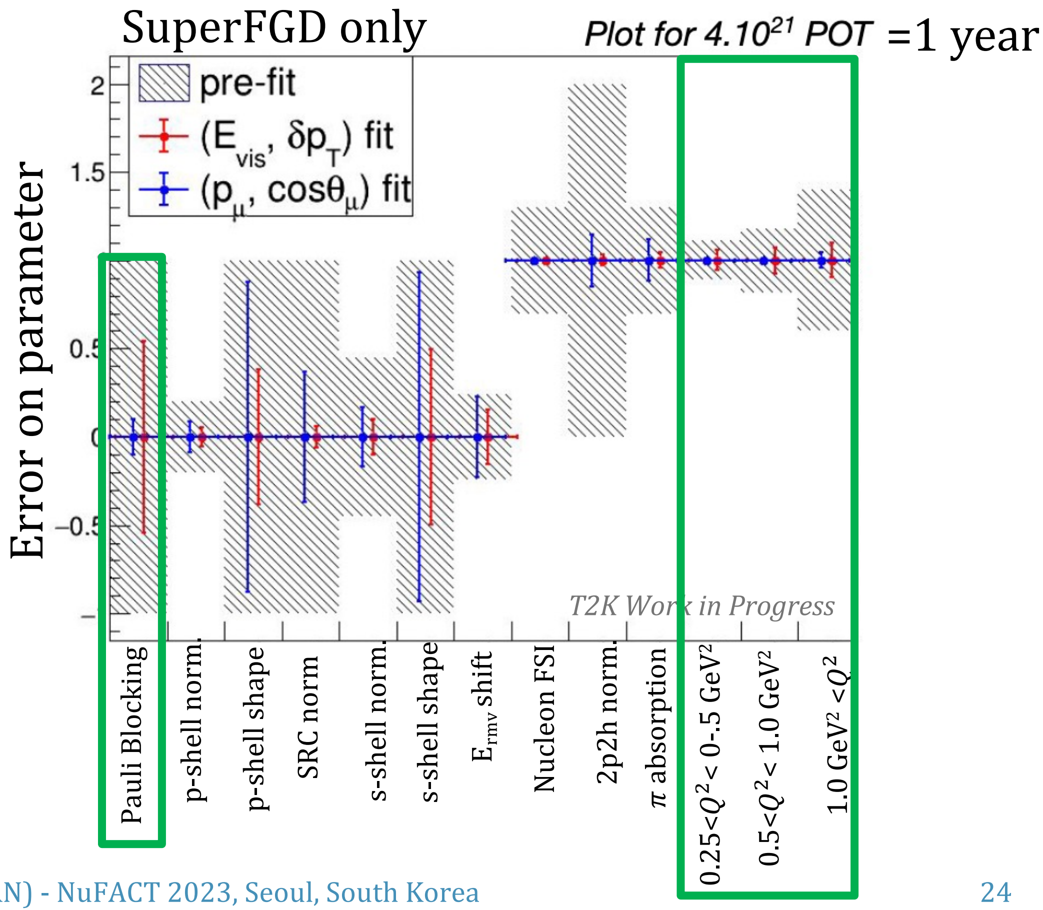
SuperFGD only

Plot for 4.10[21] POT =1 year



Impact of SuperFGD

Effective parameters (high-Q^2 shape freedom and ad-hoc Pauli Blocking) designed for inclusive variables better constrained by lepton binning



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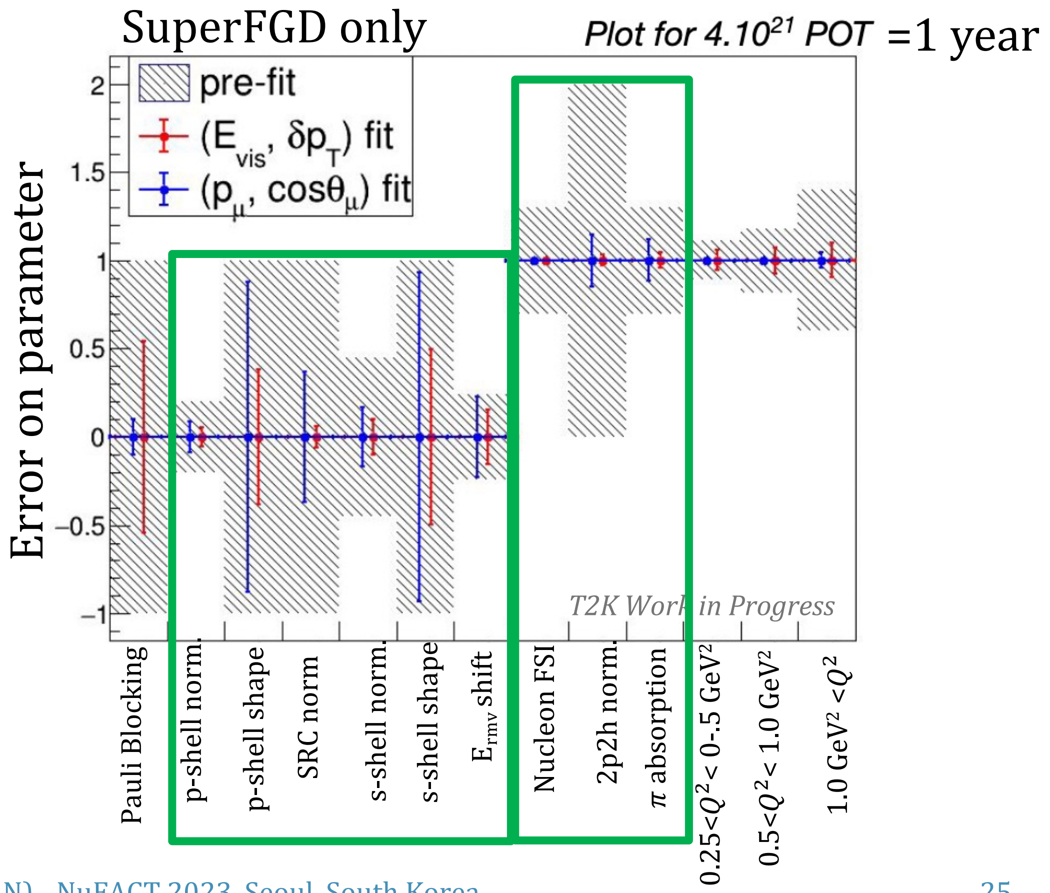
Effective parameters (high-Q^2 shape freedom and ad-hoc Pauli Blocking) designed for inclusive variables better constrained by lepton binning

Spectral Function + 2p2h parameters (direct physical correspondence) better constrained by adding hadronic information!



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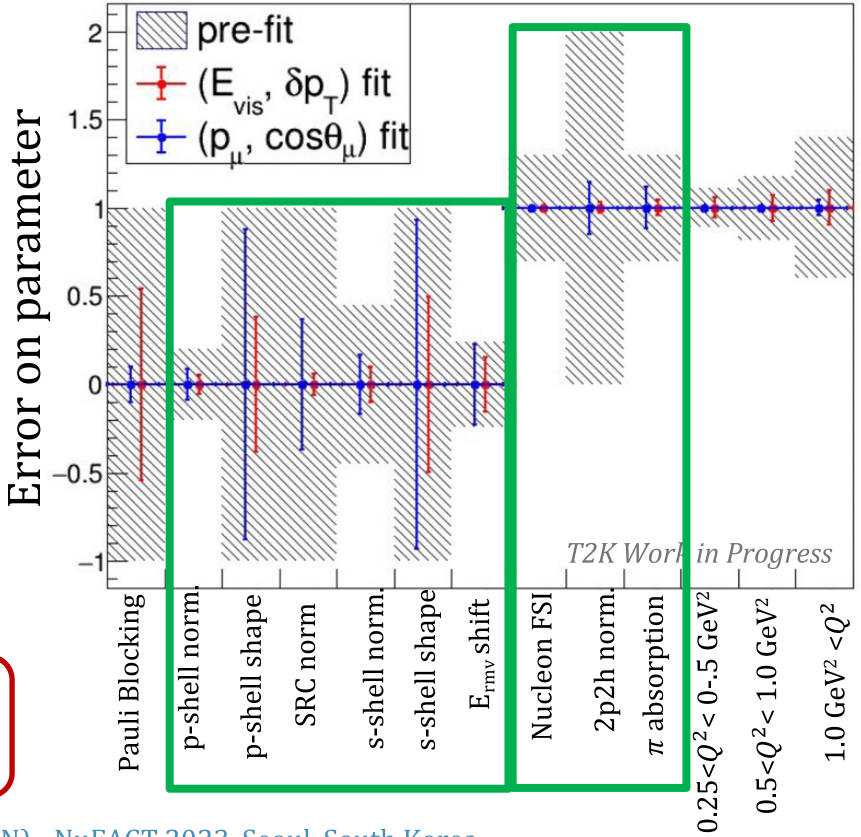
Effective parameters (high-Q^2 shape freedom and ad-hoc Pauli Blocking) designed for inclusive variables better constrained by lepton binning

Spectral Function + 2p2h parameters (direct physical correspondence) better constrained by adding hadronic information!

These are the parameters which drive the resolution on Δm^2_{32} and $\sin\theta_{23}$

SuperFGD only

Plot for 4.10^{21} POT =1 year



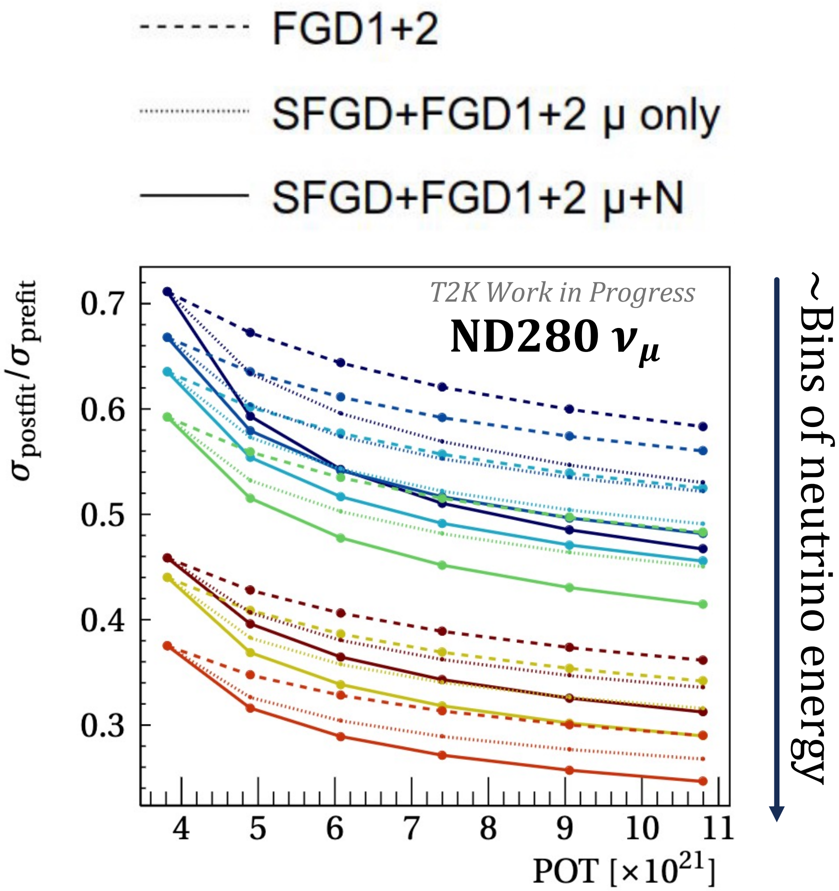
SuperFGD + current FGDs

Assume all T2K ND280 POT to date (3.6×10^{21}POT)
+ $\sim1.13\times10^{21}$ POT/year ($\nu:\bar{\nu}$ ratio 1:1)

- $(p_\mu, \cos\theta_\mu)$ binning for FGD samples
- $(E_{vis}, \delta p_T)$ binning for SuperFGD samples

Flux parameters

E_{vis} is a much more accurate estimator of neutrino energy – improvement in constraint due to SuperFGD samples



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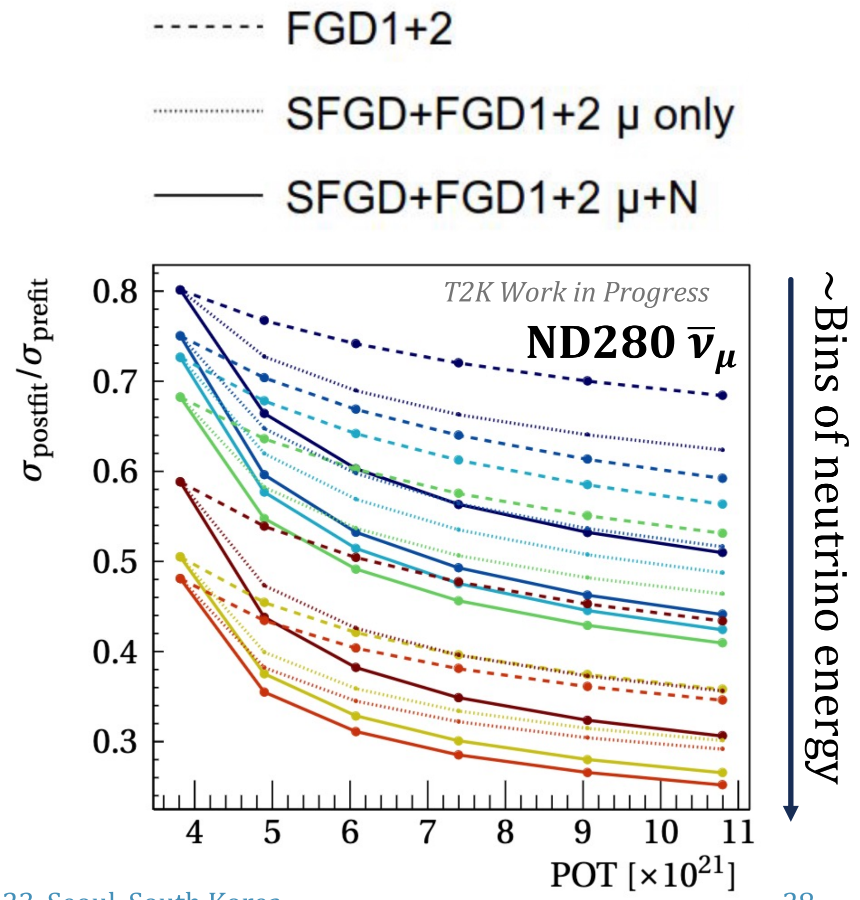
Flux parameters

E_{vis} is a much more accurate estimator of neutrino energy – improvement in constraint due to SuperFGD samples

Larger effect for antineutrinos due to **neutron information!**



SuperFGD + current FGDs

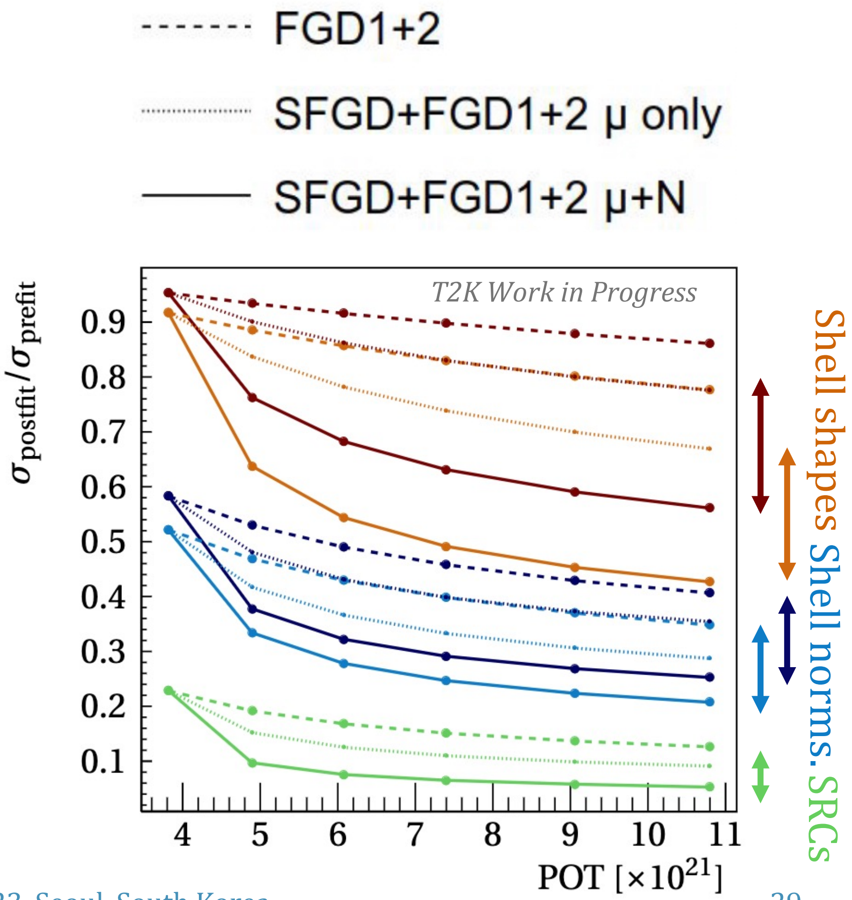
Assume all T2K ND280 POT to date (3.6×10^{21}POT)
+ $\sim1.13\times10^{21}$ POT/year ($\nu:\bar{\nu}$ ratio 1:1)

- $(p_\mu, \cos\theta_\mu)$ binning for FGD samples
- $(E_{vis}, \delta p_T)$ binning for SuperFGD samples

Spectral Function Carbon shell parameters

Dramatic improvement due to addition of hadronic variables

→key shape effects which impact oscillation measurements



Prospects for impact on oscillation measurements

The quantitative impact on oscillation measurements is being studied.

The final impact depends on:

- A **revised error parametrization**
  - Parts of the current uncertainty model adapted for muon-kinematics only fits – additional uncertainties needed for exclusive variables

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- **Understanding ν_e/ν_μ differences**
  - Currently investigating scope to constrain uncertainties on ν_e samples via ND280 Upgrade ν_μ measurements

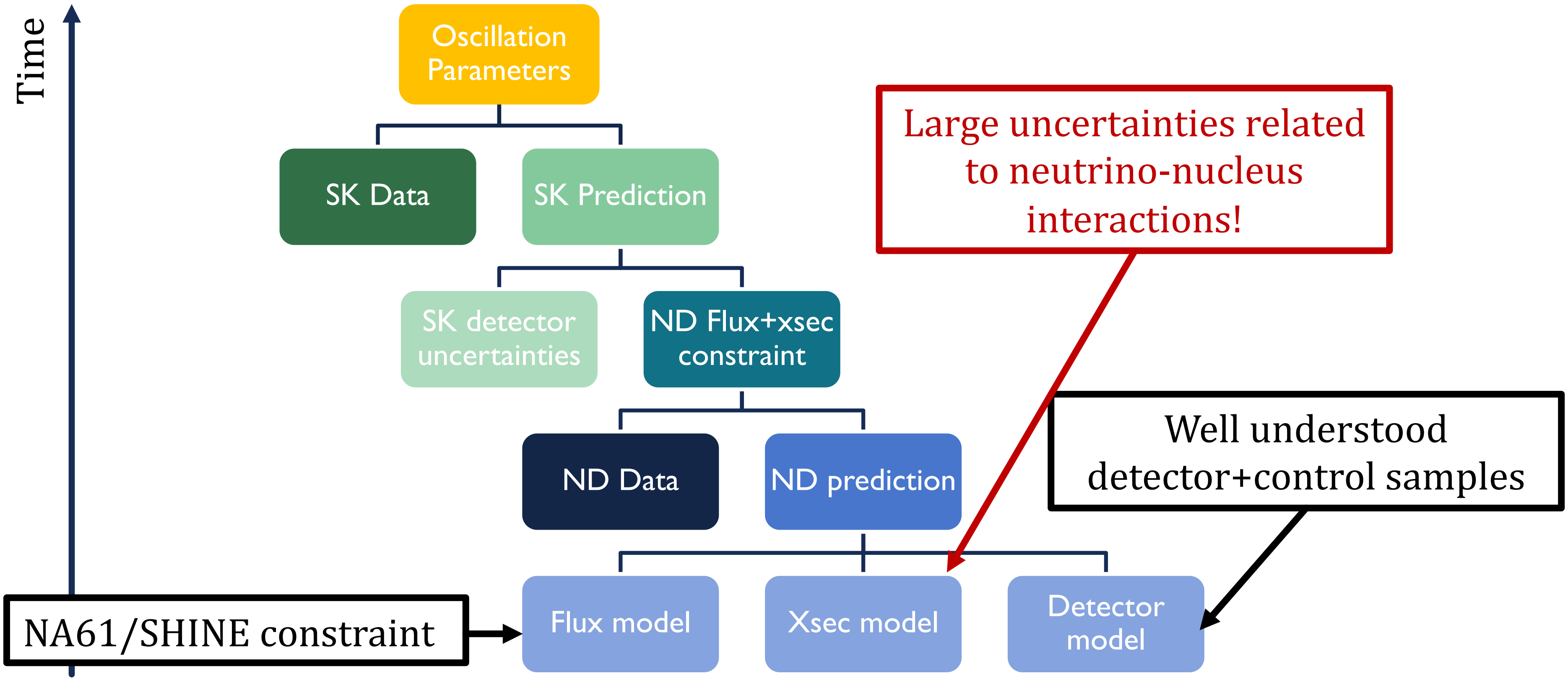
Summary

- T2K will begin a new data-taking phase with an upgraded beamline
- Preparing a comprehensive Upgrade of the ND280 detector
- ND280 Upgrade will enable us to
  - Reach 4π acceptance
  - Detect low momentum hadrons
  - Measure neutrons through secondary interactions
- Combined mass+new capabilities show significant improvements on key systematic uncertainties for oscillation measurements
- Rich physics program which is essential for future oscillation experiments

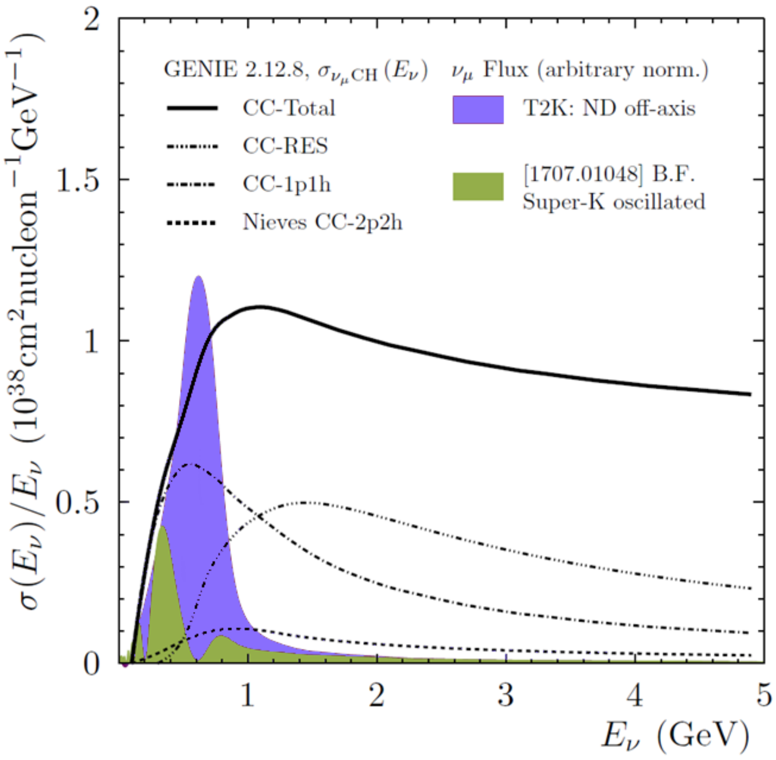
Thank you for your attention!

Supplementary material

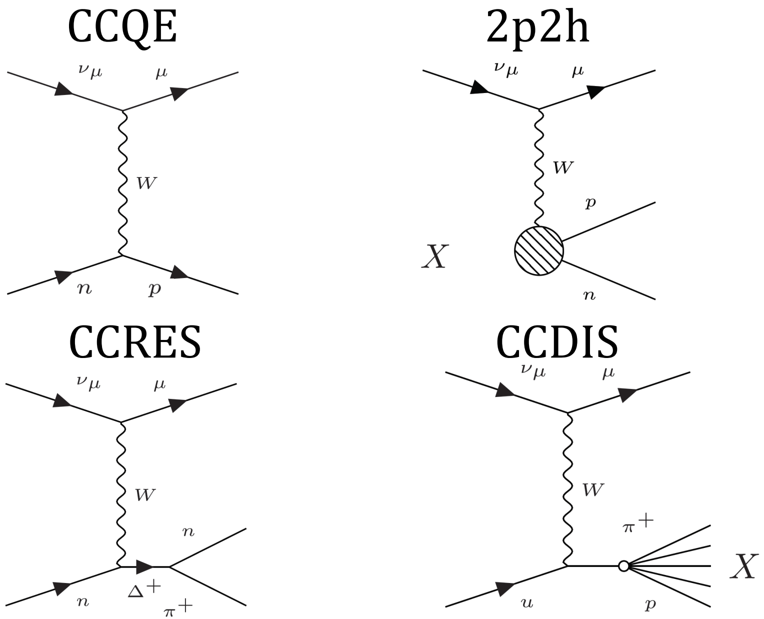
Analysis strategy



Neutrino interactions at T2K energies

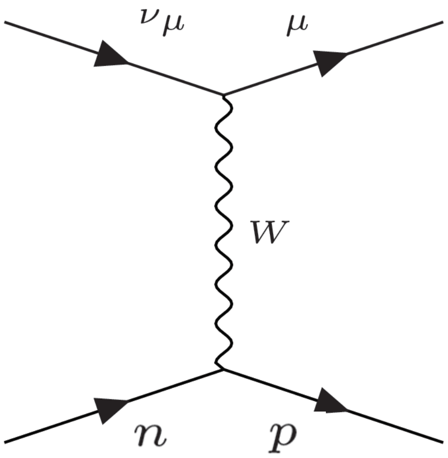


- Dominant channel is charged-current quasi-elastic (**CCQE**)
  - But also multinucleon interactions (**2p2h**) resonant interactions (**CCRES**) and deep inelastic scattering (**CCDIS**)



Neutrino interactions at T2K energies

CCQE

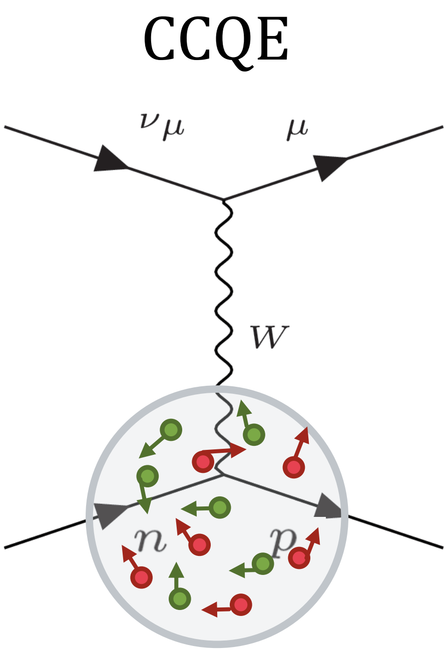


- If initial state nucleon is at rest: two body process → exact energy reconstruction

$$E_{QE} = \frac{m_p^2 - m_\mu^2 - (m_n - E_B)^2 + 2E_\mu(m_n - E_B)}{2(m_n - E_B - E_\mu + p_\mu^z)}$$

- Far detector can only detect charged leptons
  - Optimize near detector to do the same!

Aside - Nuclear effects



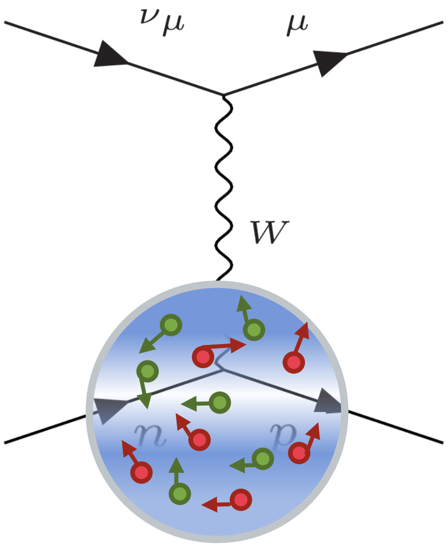
- In reality, the true process is not a simple 2-body scatter
- Nucleons are bound inside complex nuclei

Nuclear effects

- Fermi motion

Aside - Nuclear effects

CCQE



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- Nuclear/optical potential

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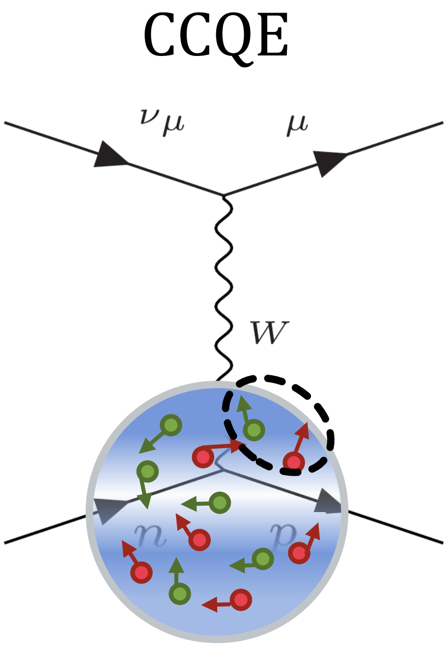

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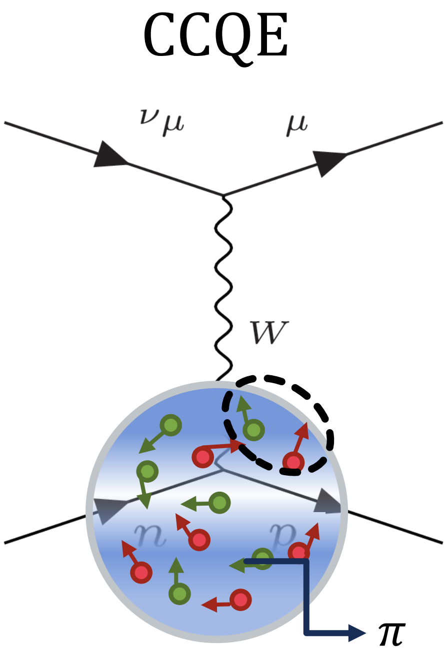

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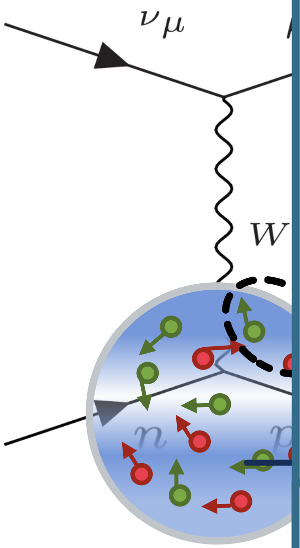
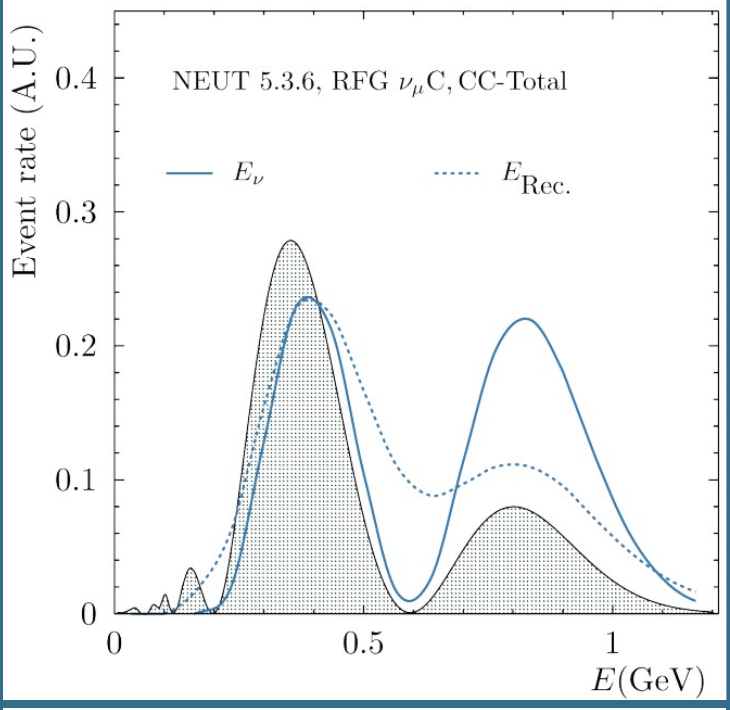
Nuclear effects

- Fermi motion
- Nuclear/optical potential
- Correlations between nucleons
- Interactions with the nuclear medium (Final State Interactions or FSI)

Aside - Nuclear effects

CCQE





Impact of nuclear effects on reconstructed neutrino energy (oscillated spectrum)

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inside complex nuclei

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n nucleons

e nuclear medium (Final FSI)