ND280-Upgrade and the neutrino cross section measurements in T2K

Konosuke Iwamoto

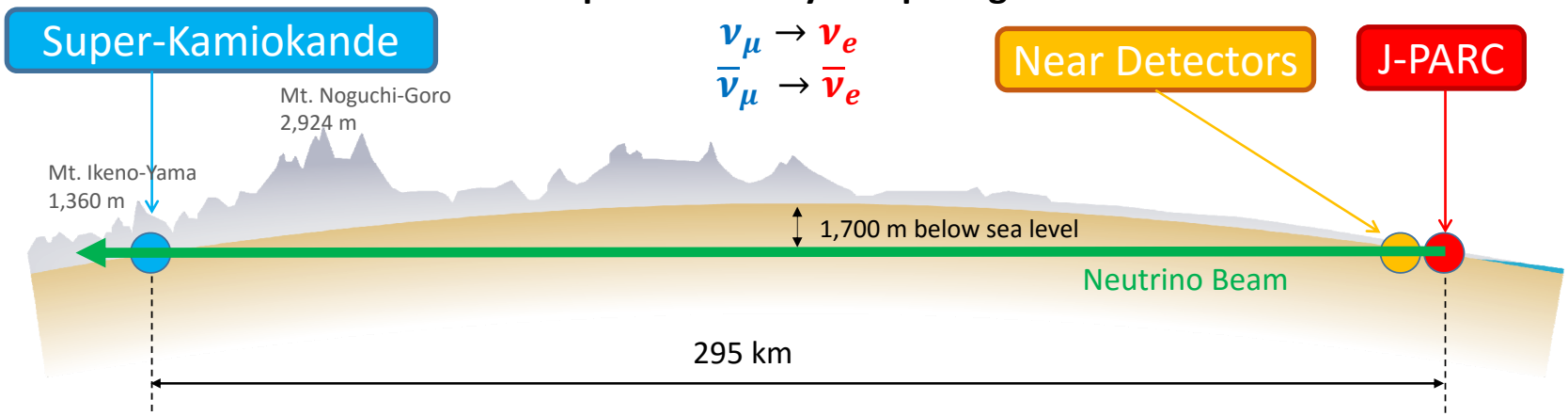
University of Tokyo

2019 Joint workshop of FKPPL and TYL/FJPPL (May 8-10, 2019)

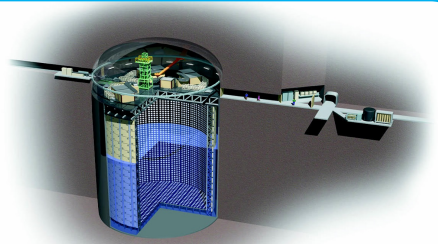
T2K Experiment

T2K Experiment

Goal to discover CP violation in the lepton sector by comparing ν and $\overline{\nu}$ oscillation measurements:

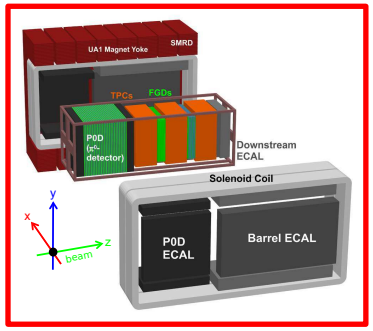


Far Detector

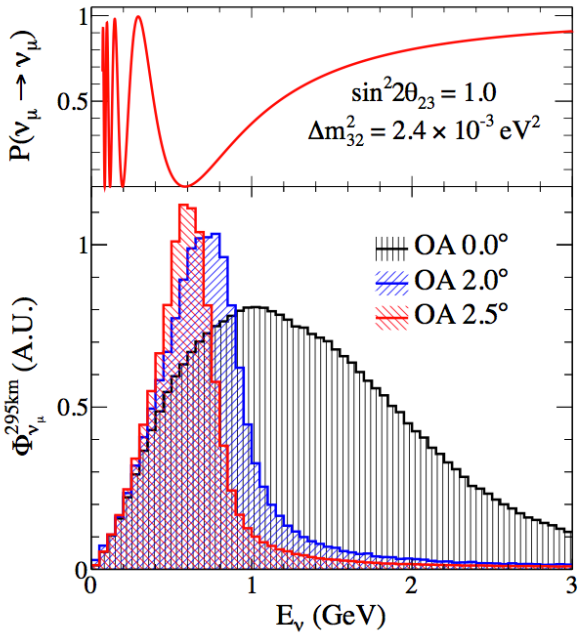


Near Detectors

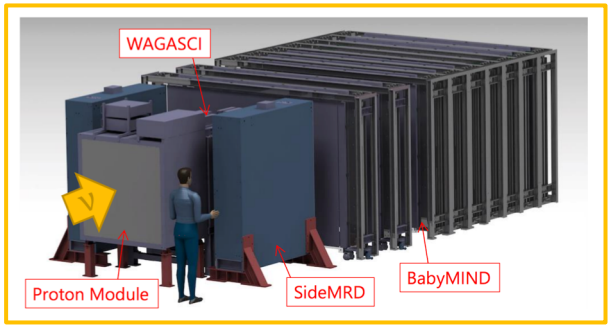
Off-axis ND280



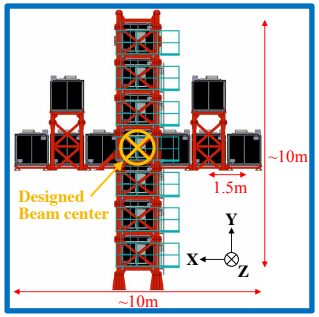
2.5° "off-axis"



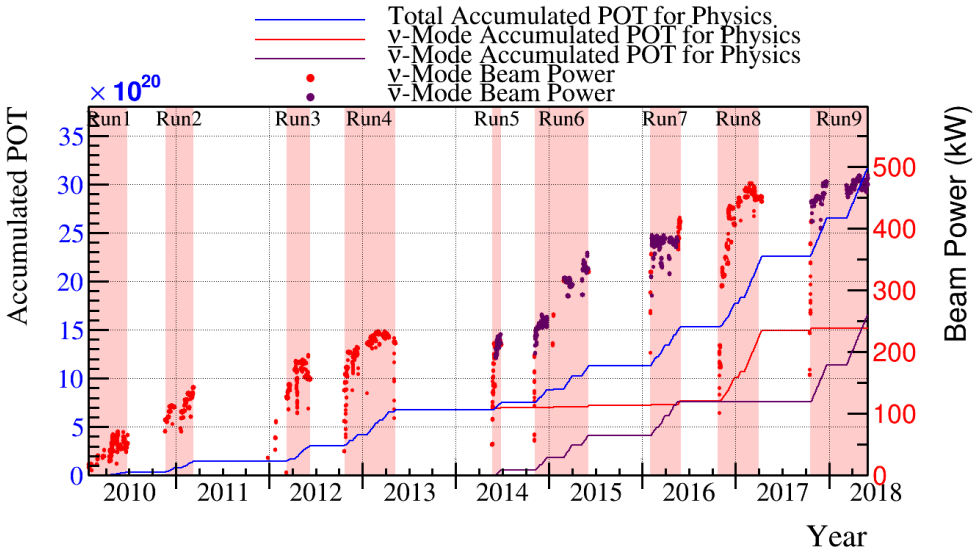
WAGASCI (by Nu05)



On-axis INGRID



T2K Latest Results



23 Jan. 2010 – 31 May 2018
POT total: 3.16 x 10^{21}

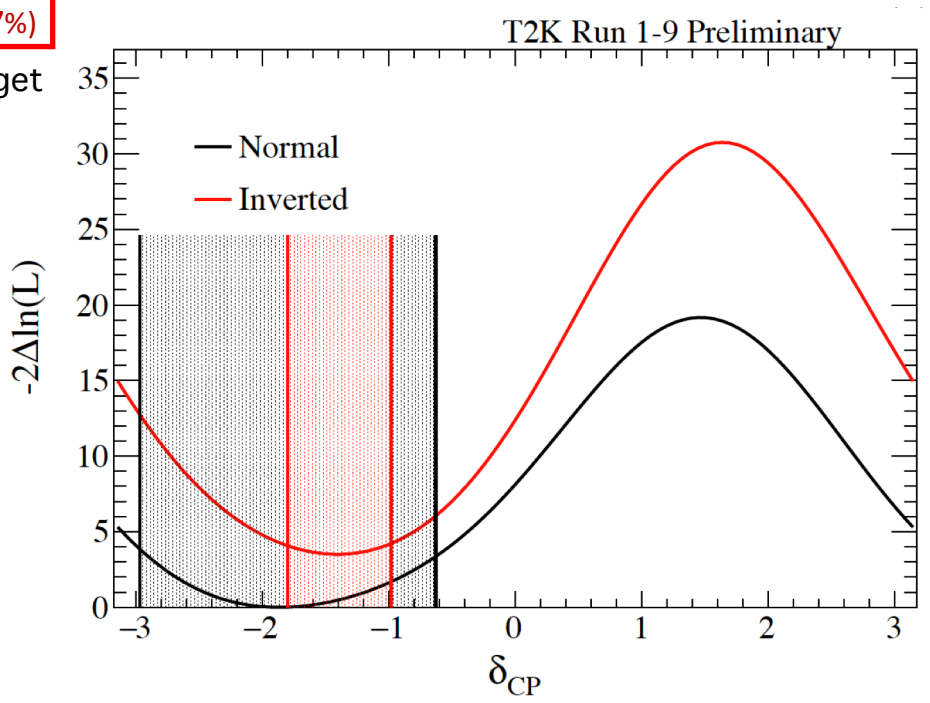
ν-mode 1.51 x 10^{21} (47.83%)
$\bar{\nu}$-mode 1.65 x 10^{21} (52.17%)

*POT: Protons on Target, number of protons collided on the target

- Neutrino statistics has doubled during 2016-2017 run
- Anti-neutrino statistics has doubled during the latest run

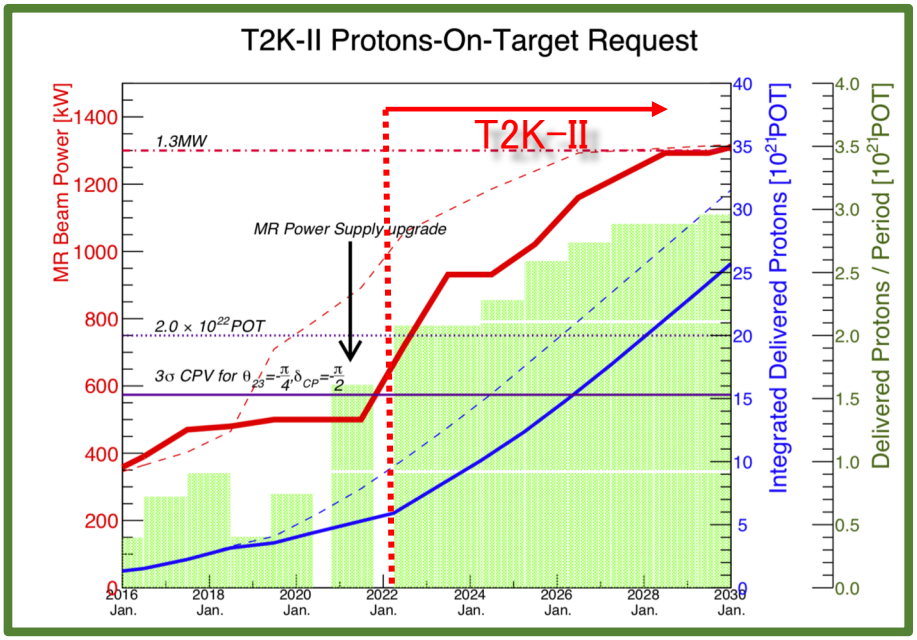
$\delta_{CP} = [-2.966, -0.628]$ (Normal),
$[-1.799, -0.979]$ (Inverted)
at 2σ confidence level (CL)

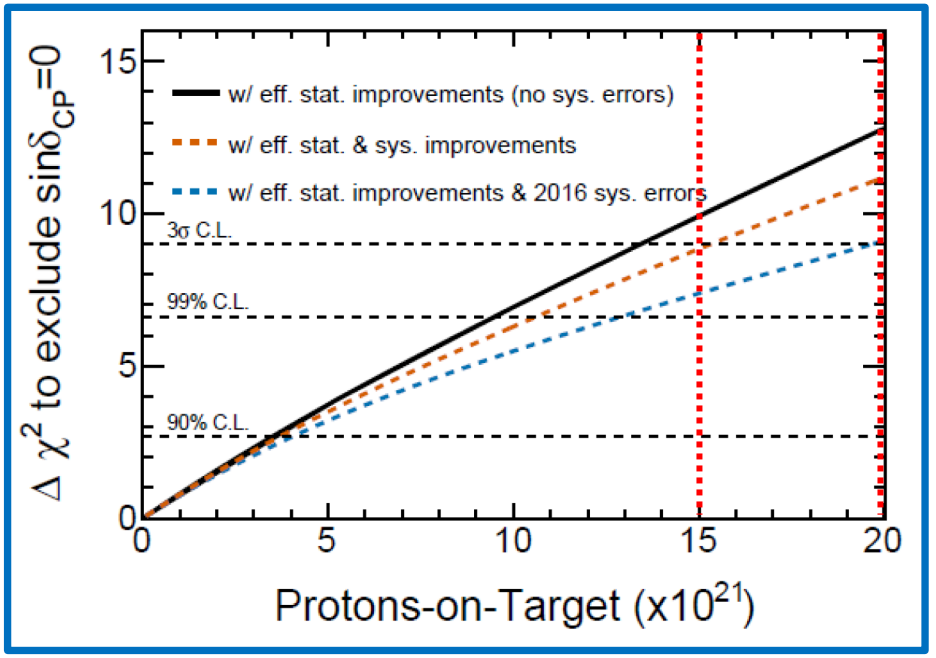
→Rejects CP conservation at 2σ CL



T2K Future Prospects

arXiv:1609.04111





- **Beam power upgrade (485 kW→1.3 MW)**
- **Plan to accumulate 20×10^{21} POT**
- Reaches $> 3\sigma$ sensitivity to CP violation in lepton sector for ~40% of the δ_{CP} values with known mass ordering

Phys. Rev. D ***96****, 092006 (2017)*

Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross section (w/o ND280 constraint)	11.3%	10.8%	16.4%
Flux+cross section (w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI + SI + PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All (w/o ND280 constraint)	12.7%	12.0%	21.9%
All (w/ ND280 constraint)	5.5%	5.1%	14.8%

Improved systematic uncertainties allow to achieve the $> 3\sigma$ sensitivity with less POT

→ Reduction of the neutrino interaction systematics to maximize the T2K sensitivity

FJPPL Project 2019

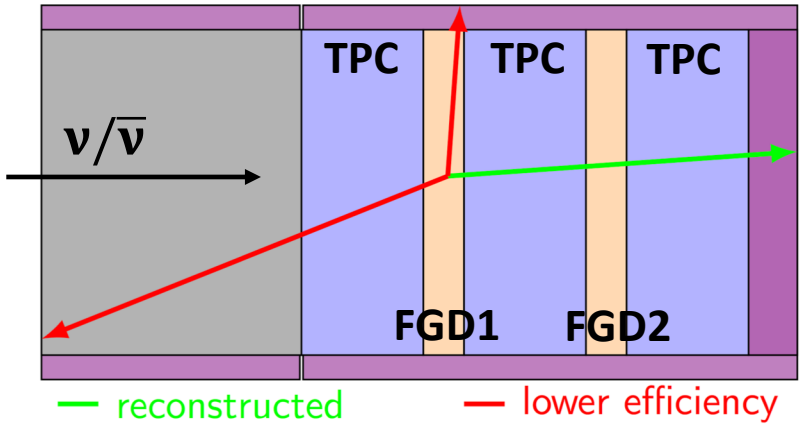
French Group			Japanese Group		
Name	**Title**	**Lab./Organis.[2]**	**Name**	**Title**	**Lab/Organis.[3]**
Margherita BUIZZA AVANZINI	**Dr.**	**IN2P3/LLR**	**Masashi YOKOYAMA**	Associate Professor	Univ. Tokyo
Olivier Drapier	Dr.	LLR/IN2P3	Takashi Kobayashi	Professor	KEK
Michel Gonin	Prof.	LLR/IN2P3	Toshifumi Tsukamoto	Associate Professor	KEK
Thomas Mueller	Dr.	LLR/IN2P3	Takeshi Nakadaira	Associate Professor	KEK
Olivier Volcy	Grad. student	LLR/IN2P3	Tsunayuki Matsubara	Assistant Professor	KEK
Sara Bolognesi	Dr.	IRFU/DPhN CEA Saclay	Yoshinari Hayato	Associate Professor	ICRR, University of Tokyo
Alain Delbart	Dr.	IRFU/DEDIP CEA Saclay	Konosuke Iwamoto	Dr (postdoc)	Univ. of Tokyo
Sandrine Emery	Dr.	IRFU/DPhN CEA Saclay	Tsuyoshi Nakaya	Professor	Kyoto University
Samira Hassani	Dr.	IRFU/DPhN CEA Saclay	Atsuko Ichikawa	Associate Professor	Kyoto University
Laura Munteanu	Grad. student	IRFU/DPhN CEA Saclay	Tatsuya Kikawa	Assistant Professor	Kyoto University
Marco Zito	Dr.	IRFU/DPhN CEA Saclay	Kenji Yasutome	Ph.D student	Kyoto University
Jacques Dumarchez	Dr.	LPNHE/IN2P3	Akihiro Minamino	Associate Professor	Yokohama National Univ.
Claudio Giganti	Dr.	LPNHE/IN2P3	Giorgio Pintaudi	Ph.D student	Yokohama National Univ.
Mathieu Guigue	Dr.	LPNHE/IN2P3, Sorbonne Université	Yoshihiro Seiya	Professor	Osaka City Univ.
Boris Popov	Dr.	LPNHE/IN2P3	Kazuhiro Yamamoto	Associate Professor	Osaka City Univ.

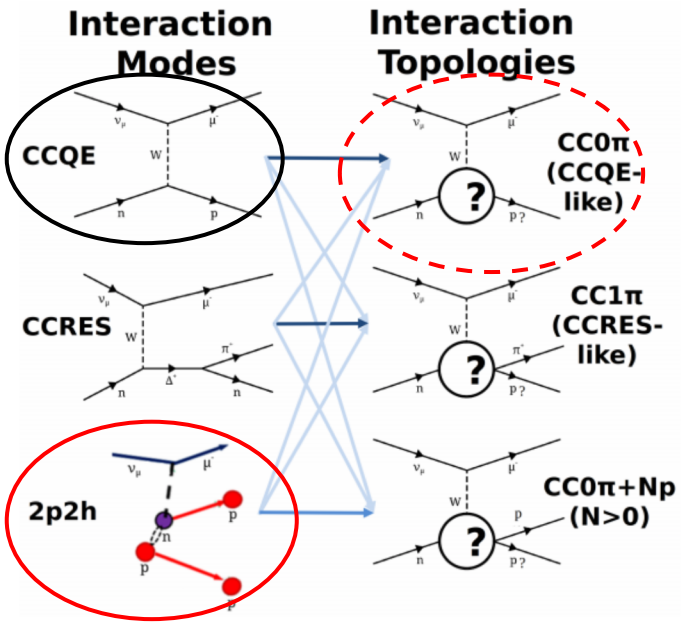
- **Takes over the Nu05 activities; further development of detectors and analyses for T2K**
- **French-Japan working groups leading the project to maximize the T2K sensitivity by:**
  - **Hardware upgrade of the ND280 detector**
  - **ND280+WAGASCI+INGRID neutrino-nucleus cross section measurements**

ND280-Upgrade

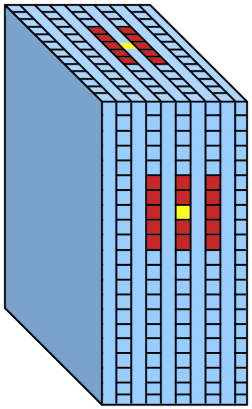
Overview of Current ND280

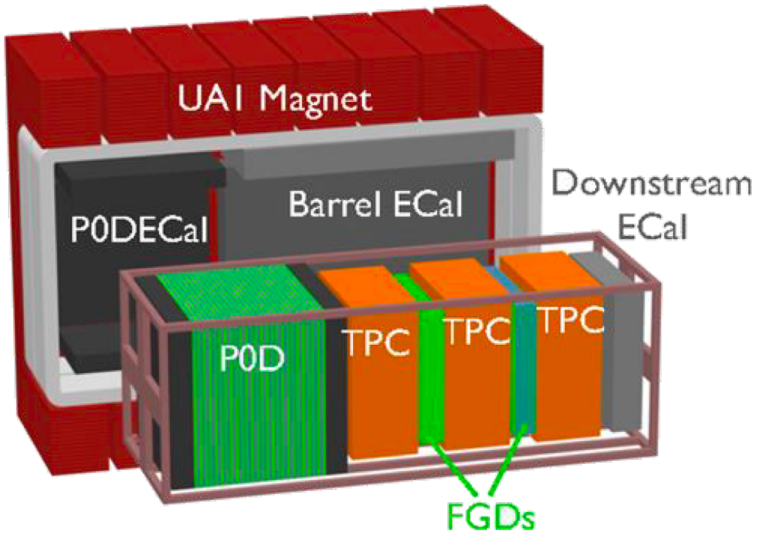
- Measures particles produced by neutrino interactions prior to oscillations by trackers:
  - **3 Time Projection Chambers (TPCs)**
  - **2 Fine-Grained Detectors (FGD1, FGD2 w/ water target)**
- **Excellent forward acceptance but not for wide angle and backward tracks**
- **Limited tracking efficiency near the interaction vertex**
  - Complicates low momentum pions and protons measurements to investigate nuclear effects (e.g. 2p2h)
  - Misidentifies the final state topology of neutrino interactions



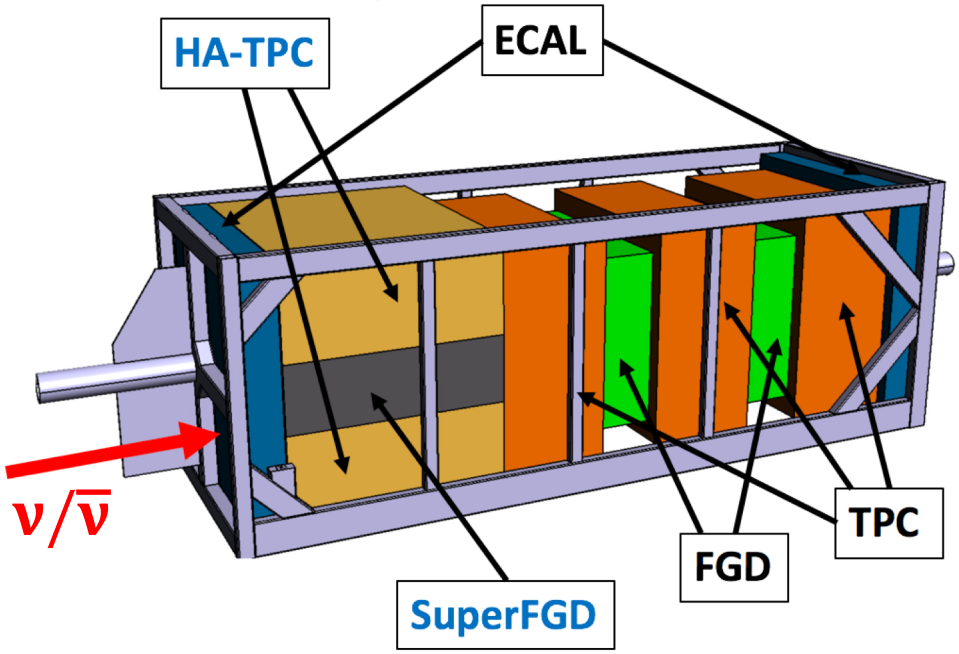


FGD Planes

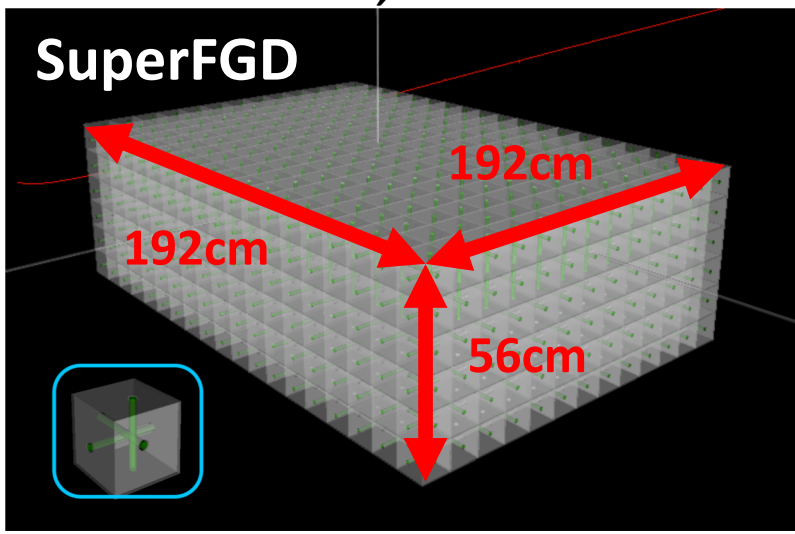




ND280-Upgrade



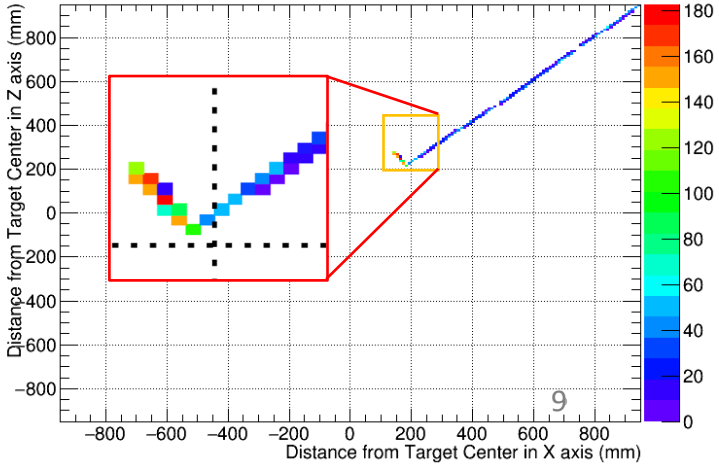
CERN-SPSC-2018-001 ; SPSC-P-357



Total # of cubes: 2,064,384
Total # of MPPC ch: 58,368
Total target mass:
2.2 (FGDs) +2.1 (SuperFGD) = 4.3 tons

- Keep 2 FGDs, 3 TPCs, ECAL
- Implement new upstream trackers:
  - **2 High-Angle TPCs (HA-TPCs)**
  - **1 fine-grained scintillator target (SuperFGD)**
  - **Time-of-Flight (ToF) counters around the new trackers**
- **Sufficiently large mass for high statistics**
- **Uniform angular acceptance for TPCs**
- **Scintillator tracker with reduced momentum threshold**

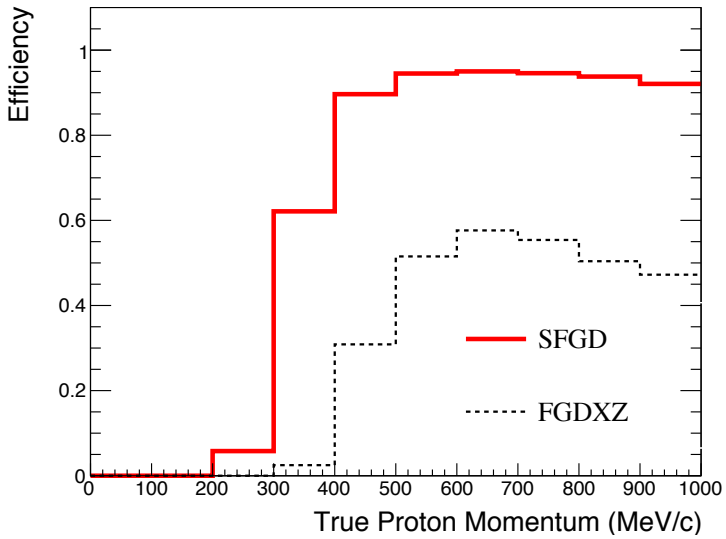
R&D ongoing towards planned installation in 2021



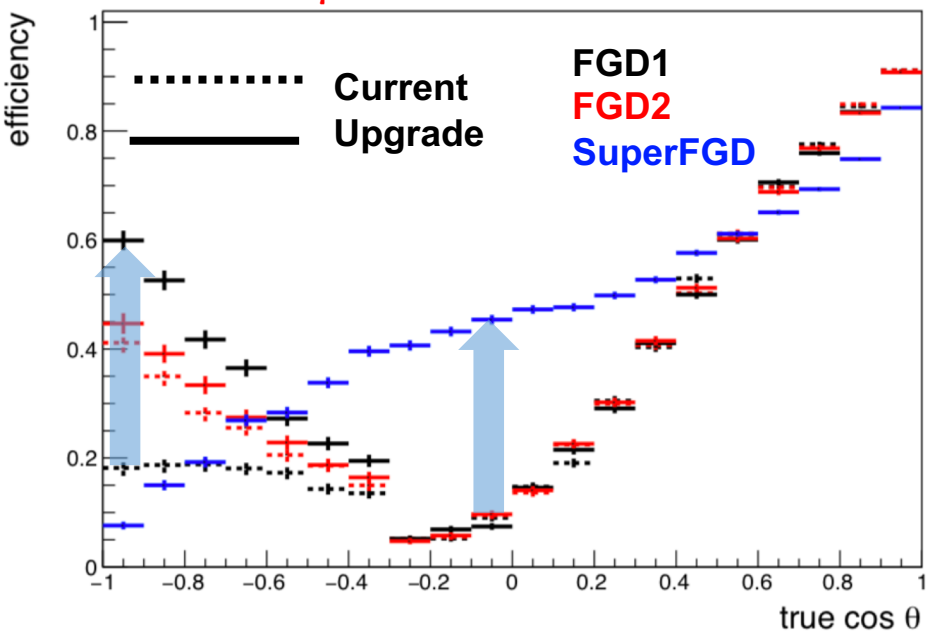
ND280 Upgrade Expected Performance

- Additional Acceptance for high-angle and backward tracks
- Proton momentum threshold down to ~300 MeV/c

Target-stopping proton tracking efficiency



TPC-selected ν_μ charged-current event acceptance

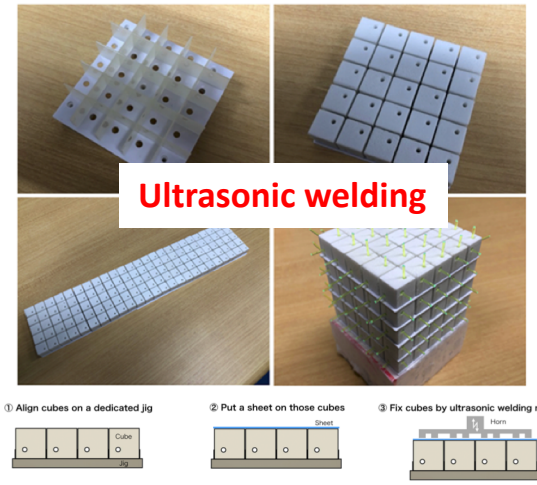


Parameter	Current ND280 (%)	Upgrade ND280 (%)
SK flux normalisation ($0.6 < E_\nu < 0.7$ GeV)	3.1	2.4
MA_{QE} (GeV/c^2)	2.6	1.8
ν_μ 2p2h normalisation	9.5	5.9
2p2h shape on Carbon	15.6	9.4
MA_{RES} (GeV/c^2)	1.8	1.2
Final State Interaction (π absorption)	6.5	3.4

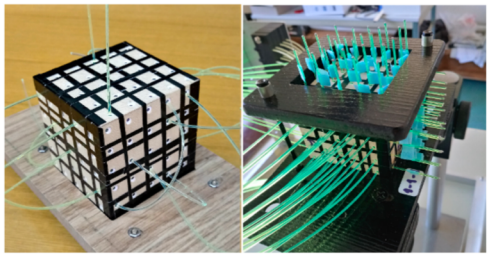
- Impact of the wider phase space on the neutrino flux and cross section parameters evaluated by the Monte-Carlo fit
- **Expected to reduce systematic uncertainties at SK by ~30% than the current ND280**

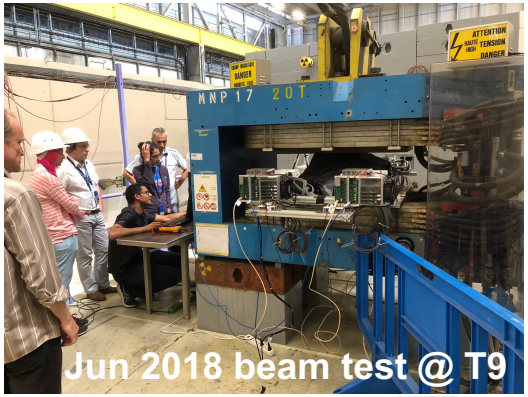
R&D Status: SuperFGD

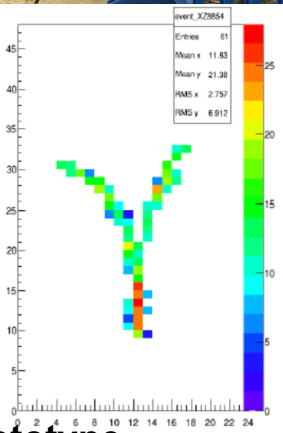
- Three beam tests performed at CERN T9 and T10
  - SuperFGD cube response (light yield/fiber, crosstalk rate)
  - Test with CITIROC-based electronics **(LLR)**
- Two beam test at Tohoku University, Japan
  - Prototype surface mount MPPC-PCB interface **(KEK, Kyoto, Tokyo, Yokohama)**
- Cube assembly method under tests and development
  - Ultrasonic welding method development by **KEK**



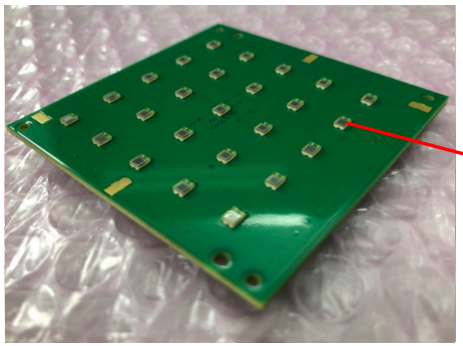
5x5x5 prototype
(Oct 2017 beam test @ T10)
arXiv:1808.08829



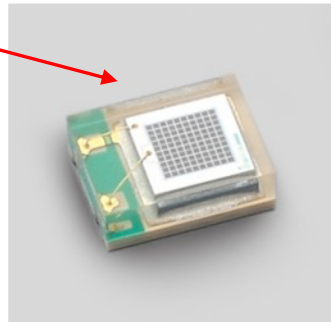


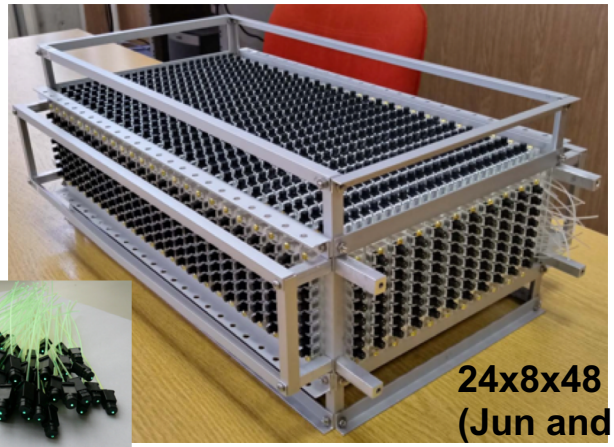


5x5 MPPC-PCB
(Nov 2018 beam test @ Tohoku)



Surface mount MPPC
13360-1325PE

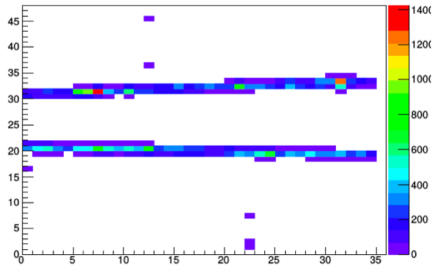


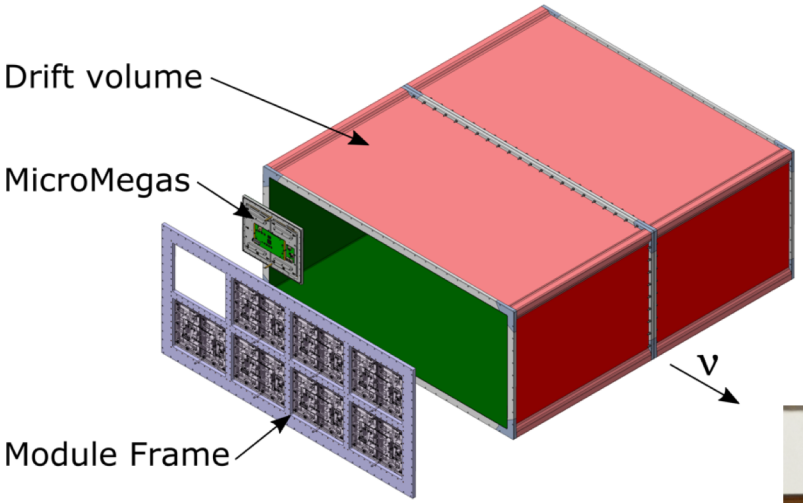


24x8x48 prototype
(Jun and Aug 2018 beam tests @ T9)

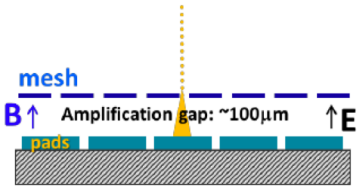
R&D Status: HA-TPC

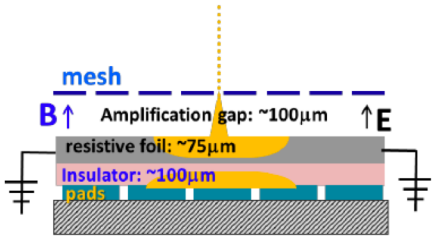
- Based on the current TPCs with two major changes:
  - **Resistive Micromegas (CEA-Saclay, LPNHE)**
    - Pads covered by an insulating layer to achieve high spatial resolution
  - **Thin field cage** wall (~3 cm) design **(CEA-Saclay, LPNHE)**
- Beam test at CERN T9 in summer 2018 with prototype resistive Micromegas
  - Mounted on the ex-HARP TPC field cage
- Test with prototype field cage planned in summer 2019 at DESY

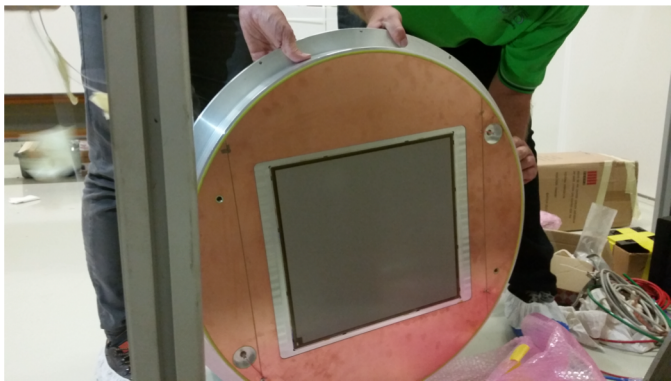




Aug 2018 beam test at CERN T9

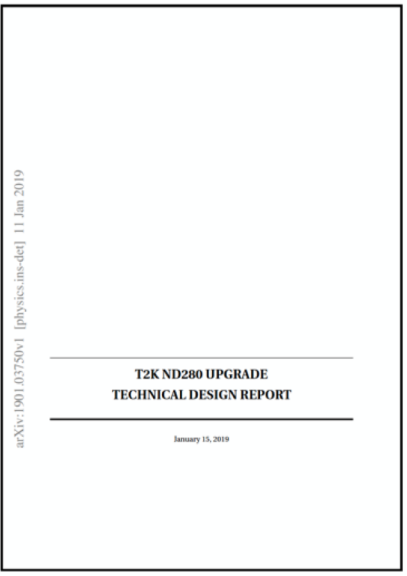






Technical Design Report (TDR)

ND280 upgrade TDR



- Reviewed by a committee formed under IPNS/KEK
- Also sent to CERN-SPSC

arXiv:1901.03750

18

Review committee report @ J-PARC PAC

T.Sumiyoshi, Committee chair

- **Executive Summary**

➢ The goal for the future T2K data taking after the main ring upgrade is to obtain a world-leading result on δ_{cp} establishing CP violation with the highest possible statistical significance. The review committee assesses this goal is reasonable.

➢ The committee recognizes the importance of ND280 upgrade in order to reduce the systematic errors related to the neutrino flux and cross section measurements to achieve the above object. In order to convince the improvement of δ_{cp} sensitivity with this ND280 upgrade plan a breakdown of errors and their propagation related to δ_{cp} in terms of ND280-constrained/unconstrained errors should be addressed hopefully in a written document. (explained at the follow-up session in the review meeting)

➢ The committee recommends KEK and the T2K group to make every effort to accomplish the proposed ND280 upgrade by 2021 in accordance with the main ring intensity upgrade.

2019/1/16 T. Sumiyoshi @J-PARC PAC Jan. 16, 2019 2

- Similar endorsement from J-PARC PAC

19

- **ND280 Upgrade TDR submitted to PAC in November 2018**
- J-PARC PAC on December 8-9, 2018
- CERN-SPSC presentation on January 23, 2019
- **Received positive statements by both committees**
  - **CERN SPSC recognizes that the ND280 Upgrade project to be part of CERN neutrino platform**

Neutrino Cross Section Measurement

T2K Neutrino Cross Section Measurements

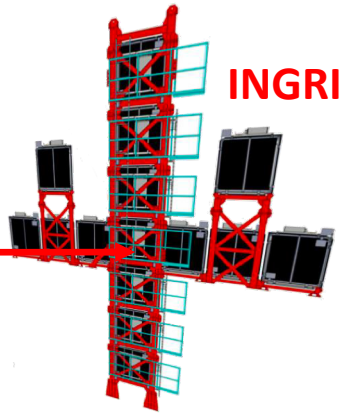
- **Separate cross section analyses with three near detectors**
  - Carbon and oxygen target measurements at different neutrino energies
- **Preparation of the joint analysis framework ongoing**
  - Correlated flux error cancellation, combined measurement

$\nu/\bar{\nu}$

$E_\nu \sim 1.1\ GeV$

1.5^o

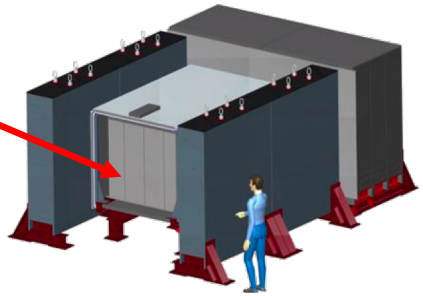
2.5^o



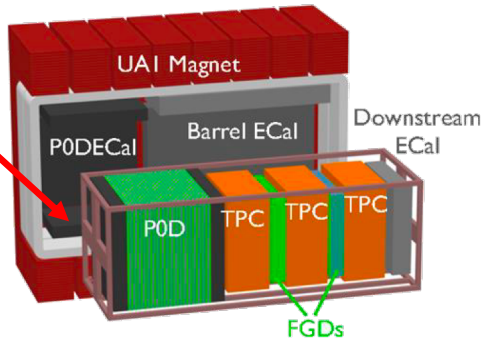
INGRID

$E_\nu \sim 0.9\ GeV$

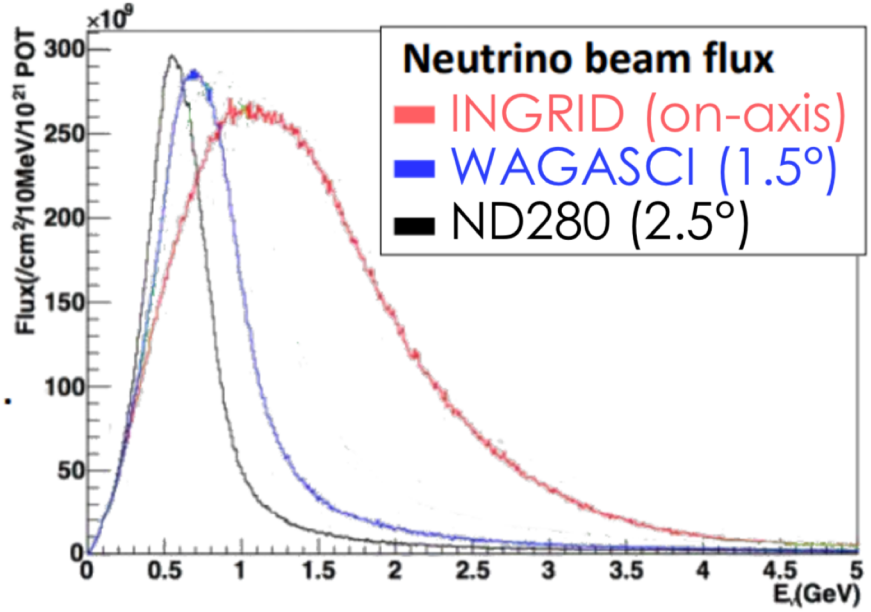
WAGASCI



ND280



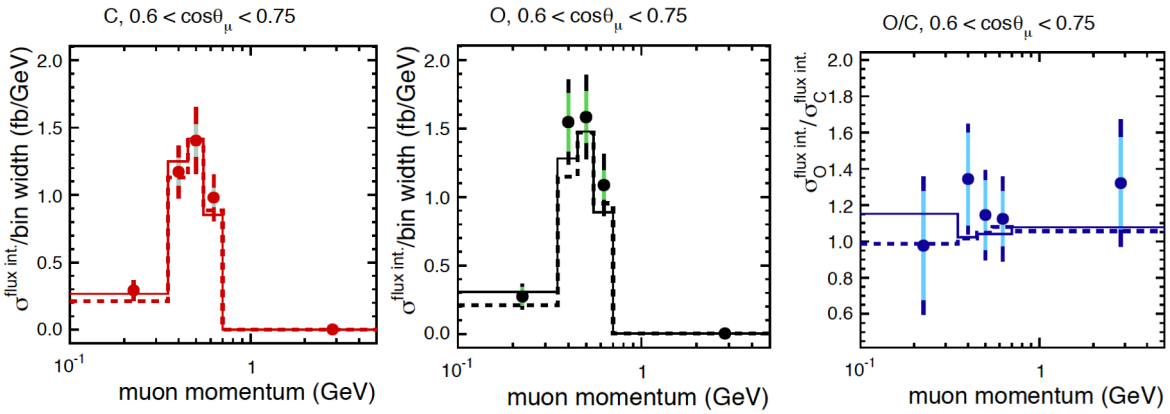
$E_\nu \sim 0.6\ GeV$

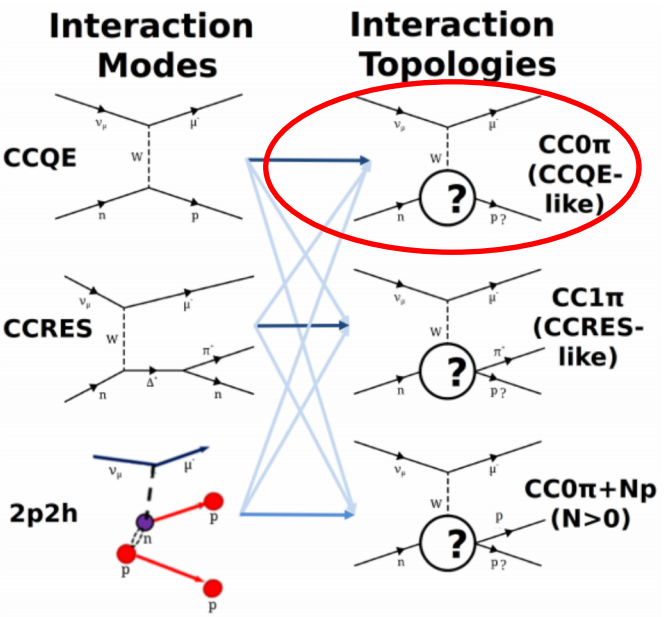


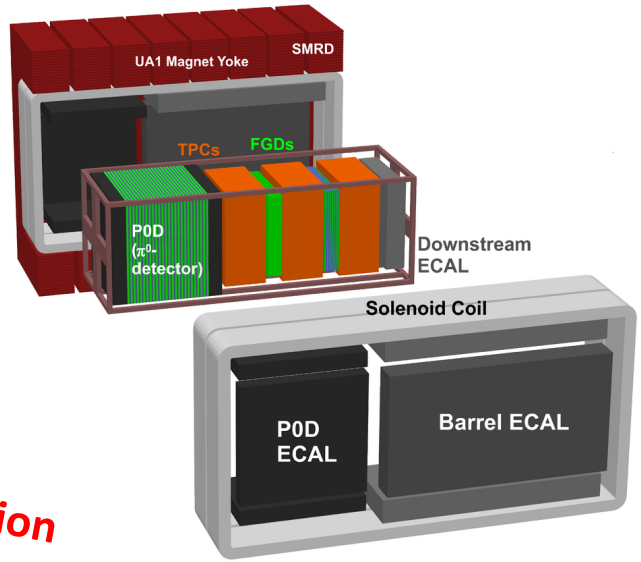
ND280 ν_μ CC0π Cross Section on C/O

By M. Buizza Avanzini (LLR/IN2P3), S. Emery (IRFU/DPhN CEA-Saclay), L. Maret (UniGe)

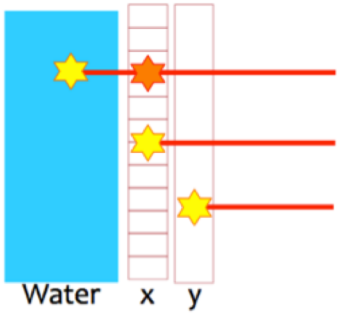
- Joint measurement on CC0π cross section on carbon (C) and water (O) using FGD1 and FGD2
- Simultaneously fit the C- and O-enhanced samples, obtain correlation and covariance between different phase space for C and O







Analysis result is public
Paper is under preparation



CC0π interaction in water: first muon hit in x layer

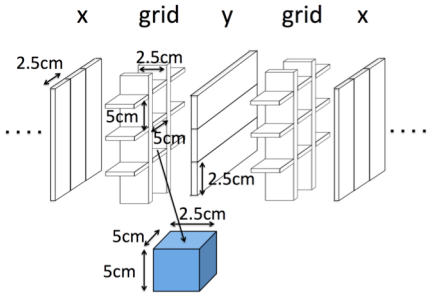
CC0π interaction in x layer

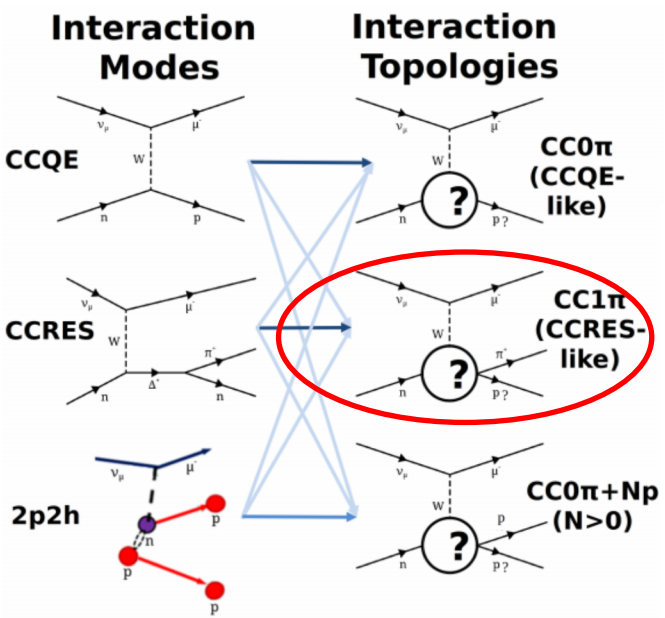
CC0π interaction in y layer

INGRID ν_μ CC1π Cross Section on C/O

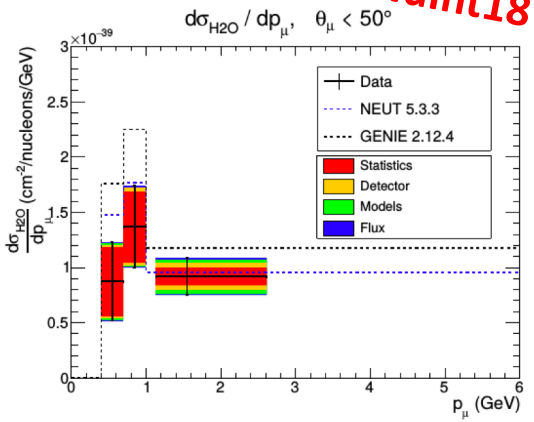
By M. Licciardi (LLR/IN2P3), B. Quilain (Kavli IPMU)

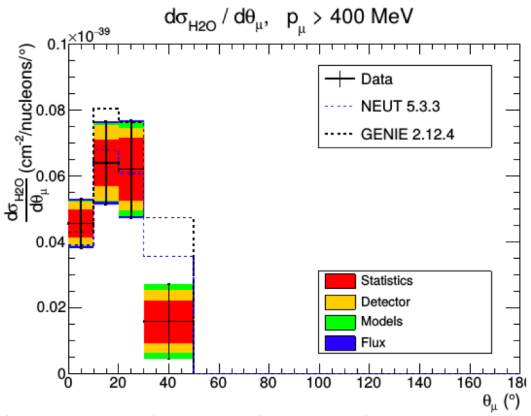
- Measurement on CC1π cross section on C and O using an on-axis target and INGRID
- Proton (PM) and water modules (WM) installed during two different data taking periods
  - **PM**: Plastic scintillator tracker; finer scintillator bars than ones of FGDs
  - **WM**: Grid-like plastic scintillator (~20%) structure to contain water target (~80%)





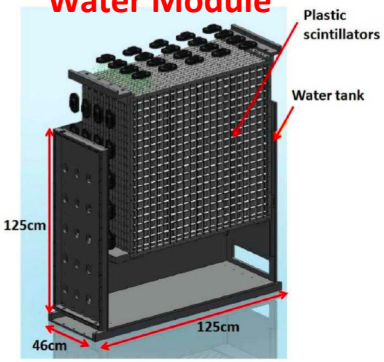
Analysis is public; presented at NuInt18

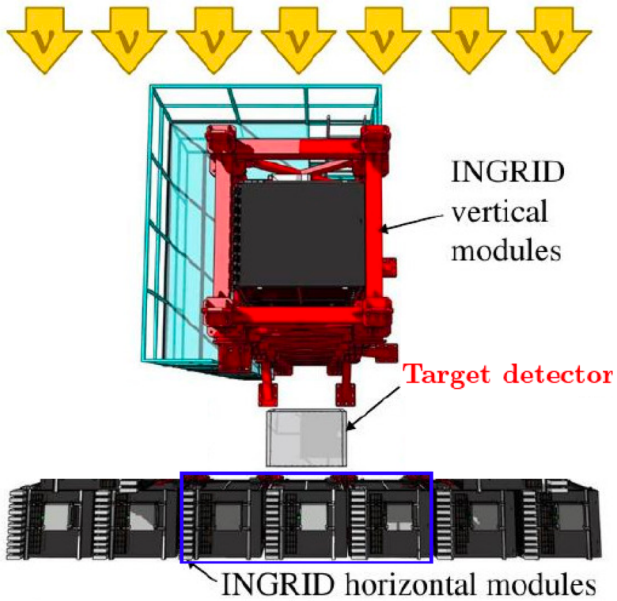




Proton Module

Water Module





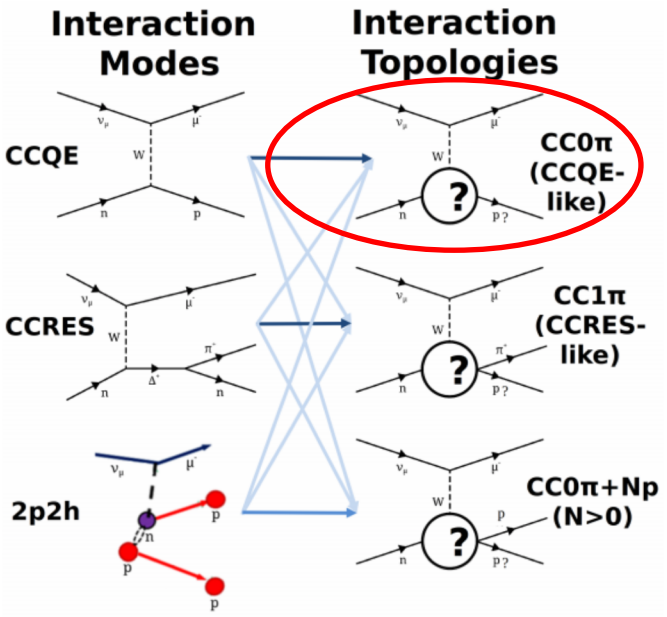
https://indico.cern.ch/event/703880/contributions/3169493/attachments/1737033/2809843/CrossSection_20181008_CC1piOnCarbonAndWater_QuilainLicciardi_v3.pdf

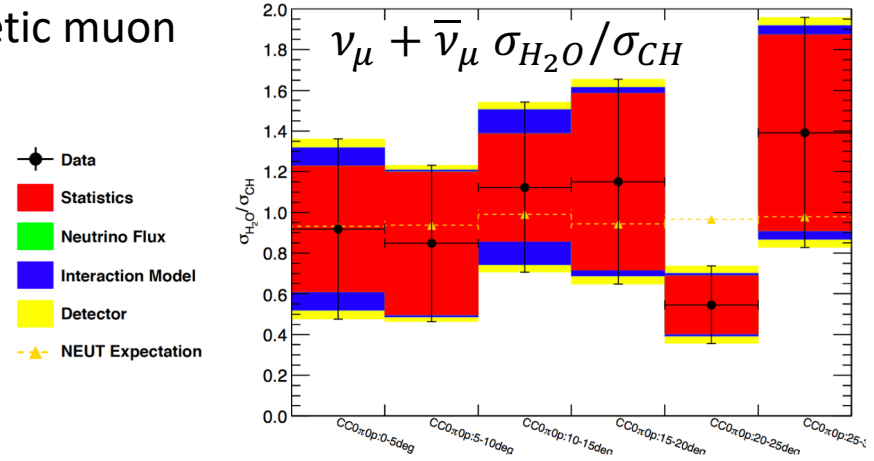
WAGASCI $\bar{\nu}_\mu$ CC0π Cross Section on C/O

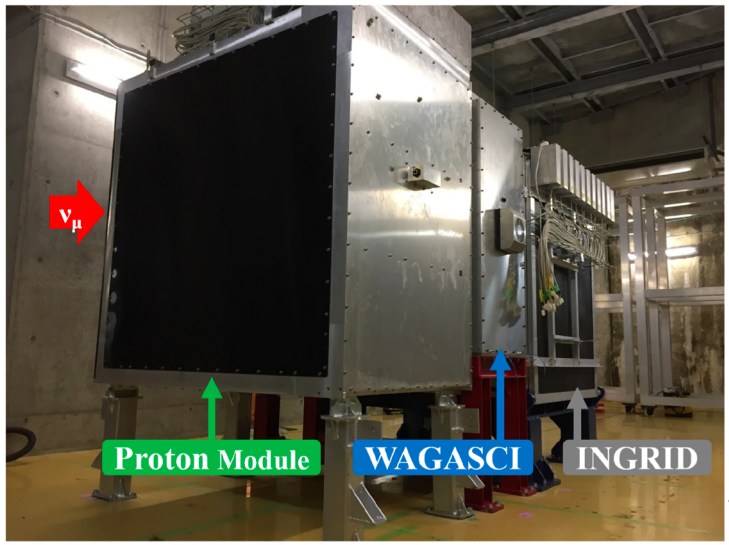
By N. Chikuma (Tokyo), H. Kim (Osaka City Univ.)

- Measurement of $\bar{\nu}_\mu$ CC0π cross section on C and O using WAGASCI water module, proton module and INGRID module as muon detector
- ~1.5^0 off-axis; expected neutrino energy peak at ~900 MeV
- Limited statistics and acceptance; expect to improve in future data collection and configuration with SMRD and Baby MIND magnetic muon spectrometer

Collaboration review is finished; results are public
Paper is under preparation







Expected Common Articles and Summary

Expected Common Articles

- ***Measurement of CC $\bar{\nu}_\mu$ cross section on H_2O and CH with limited acceptance with WAGASCI and Proton Module***, by *N. Chikuma (Tokyo*), H. Kim (Osaka City Univ.*)*

- ***Measurement of flux-integrated cross-section on Oxygen and Oxygen/Carbon ratio of CC0π events in FGD1+FGD2***, by *M. Buizza Avanzini* (LLR/IN2P3*), S. Emery* (IRFU/DPhN CEA–Saclay*), L. Maret (UniGe)*

- ***Measurement of the ν_μ charged-current cross sections on water, hydrocarbon, iron, and their ratios with the T2K on-axis detectors***, by *T. Koga (Tokyo*)*

- ***Differential measurement of the ν_μ-CC1π cross section on H_2O and CH and of the H_2O / CH cross-section ratio using the on-axis detectors***, by *M. Licciardi (LLR/IN2P3*), B. Quilain (Kavli IPMU)*

- ***Beam Test Analysis on the Prototype Time Projection Chamber for ND280 Upgrade***, contribution from *LLR/IN2P3*, IRFU/DPhN CEA–Saclay*, IRFU/DEDIP CEA–Saclay*, LPNHE/IN2P3*, Sorbonne Université**

* FJPPL 2019-2020 members or organizations

Summary

- **T2K Experiment**
  - Doubled the anti-neutrino statistics during the 2018 run
  - Latest neutrino oscillation analysis result rejects CP conservation at 2σ confidence level
  - Neutrino charged current interaction cross section on carbon and oxygen and their ratios measured separately by near detectors at different energy peaks (**ND280**, **INGRID**, and **WAGASCI**)
    - Publications expected for ND280
    - The first WAGASCI measurement is public
    - Preparation of the near detector joint analysis in progress

- **ND280 Upgrade**
  - New detectors to measure ν interactions with wide angular acceptance and low momentum threshold
  - Expected to reduce the systematic uncertainties by ~30%
  - Reviewed by IPNS/KEK committee, J-PARC PAC, and CERN SPSC
    - Received positive statements
  - R&D ongoing towards planned installation and run in 2021

Thank you very much!!

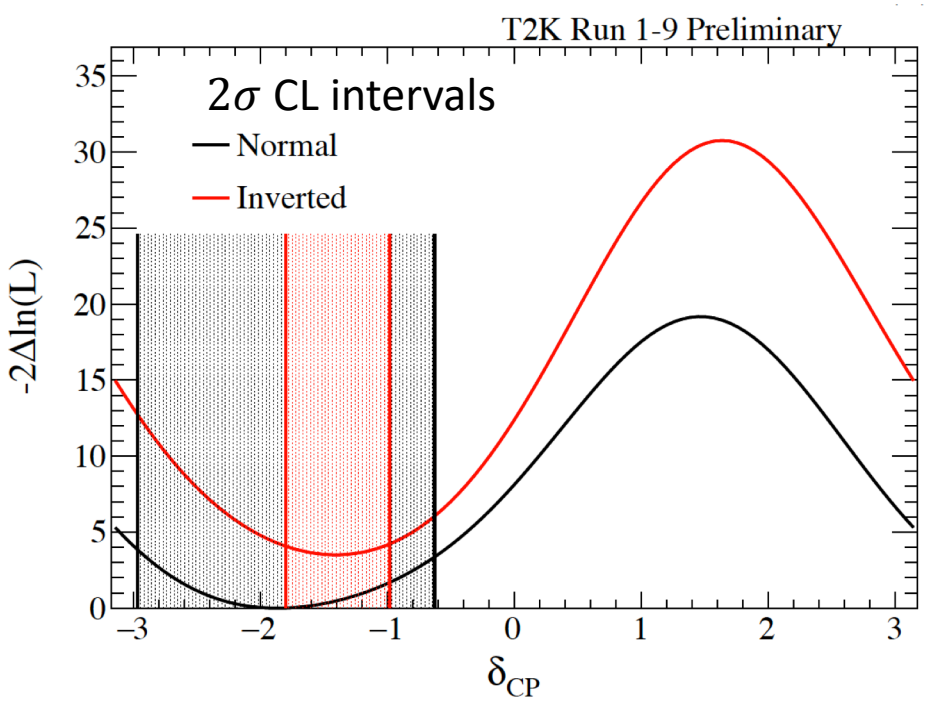
θ_{13} and δ_{CP} Measurements

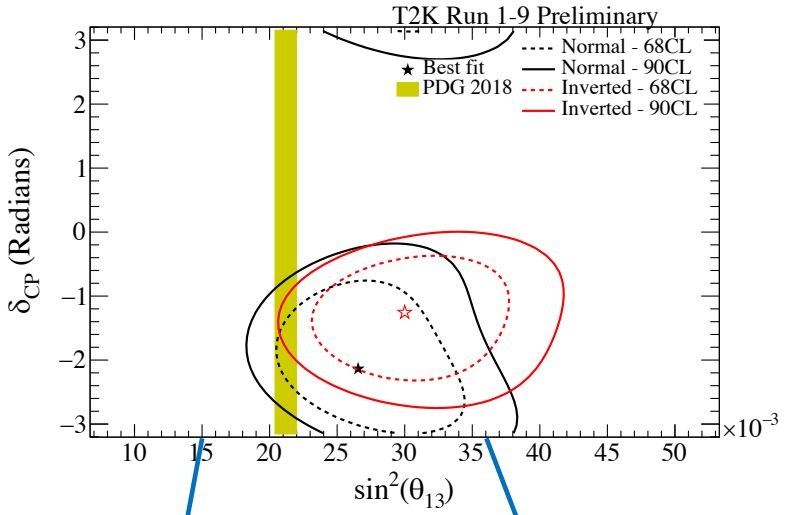
Best Fit: $\sin^2\theta_{13} = 0.0268^{+0.0055}_{-0.0043}$ (Normal)

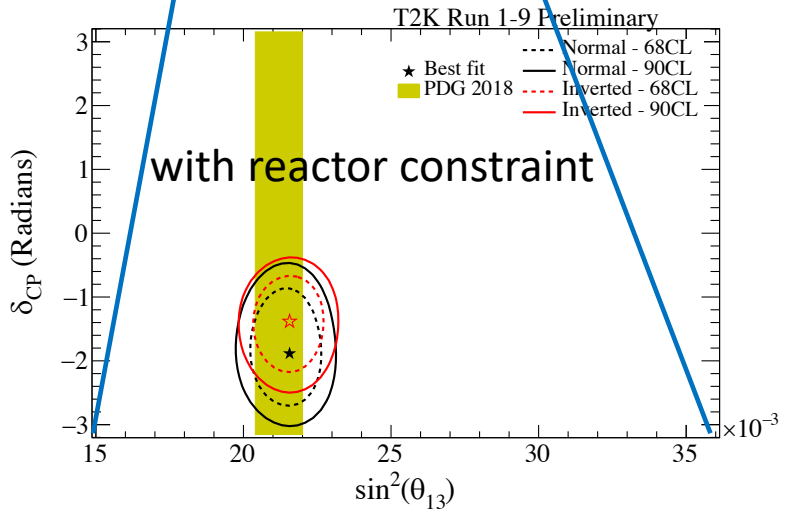
PDG2018: $\sin^2\theta_{13} = 0.0212 \pm 0.0008$

$\delta_{CP} = [-2.966, -0.628]$ (Normal),
$[-1.799, -0.979]$ (Inverted)
at 2σ confidence level (CL)

→Rejects CP conservation at 2σ CL

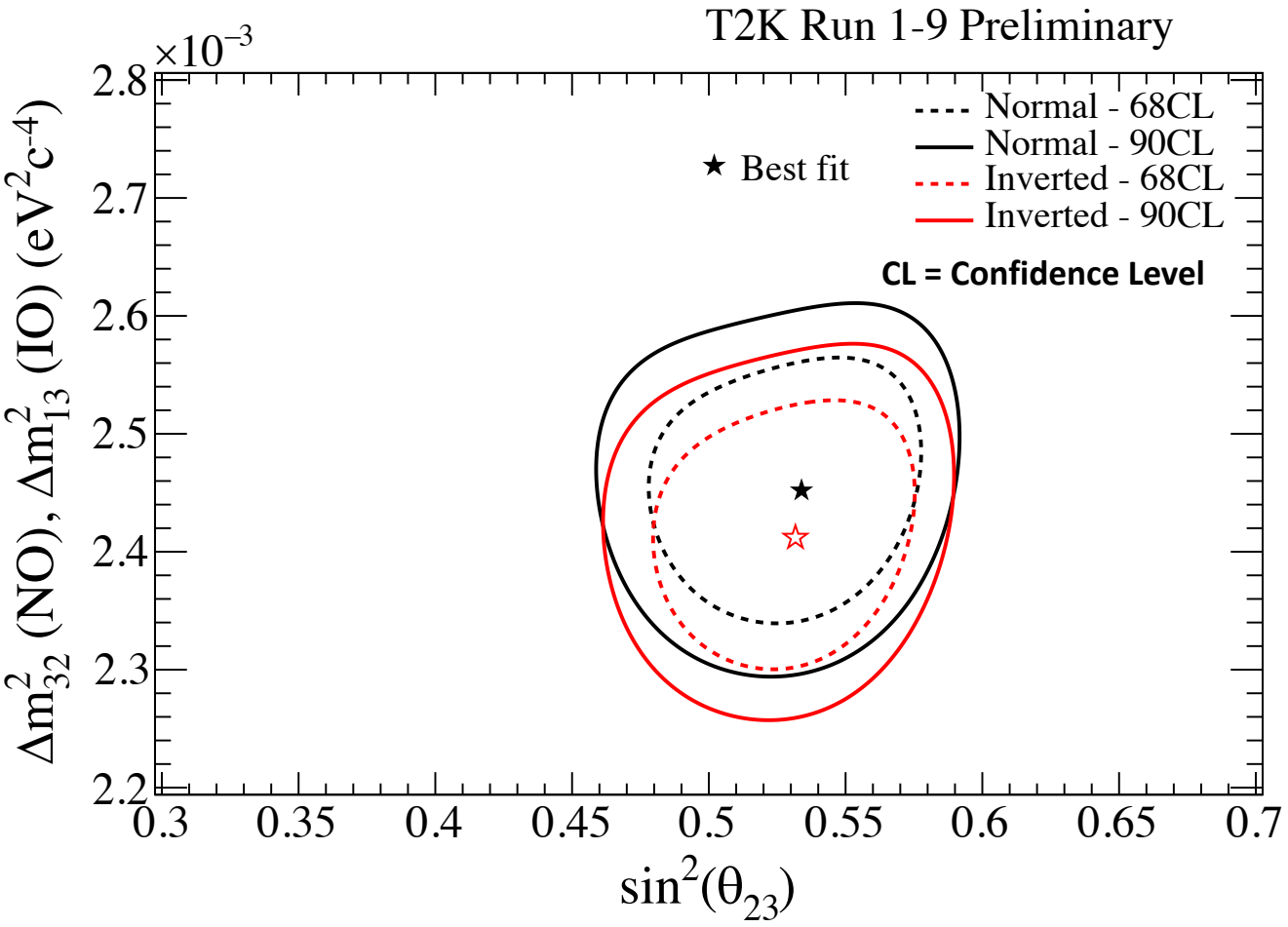






Atmospheric Parameters Measurements

Best fit results for normal and inverted mass ordering hypotheses:



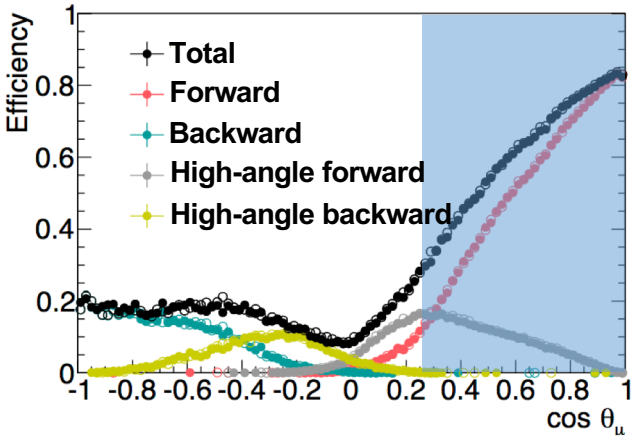
$\mathbf{sin^2\theta_{23}} = 0.532^{+0.030}_{-0.037}$ (Normal), $0.532^{+0.029}_{-0.035}$ (Inverted)

$\mathbf{\Delta m^2} = (2.452^{+0.071}_{-0.070})\times10^{-3}eV^2$ (Normal), $(2.432^{+0.069}_{-0.071})\times10^{-3}eV^2$ (Inverted)

Consistent with maximal mixing ($\sin^2\theta_{23} = 0.5$)

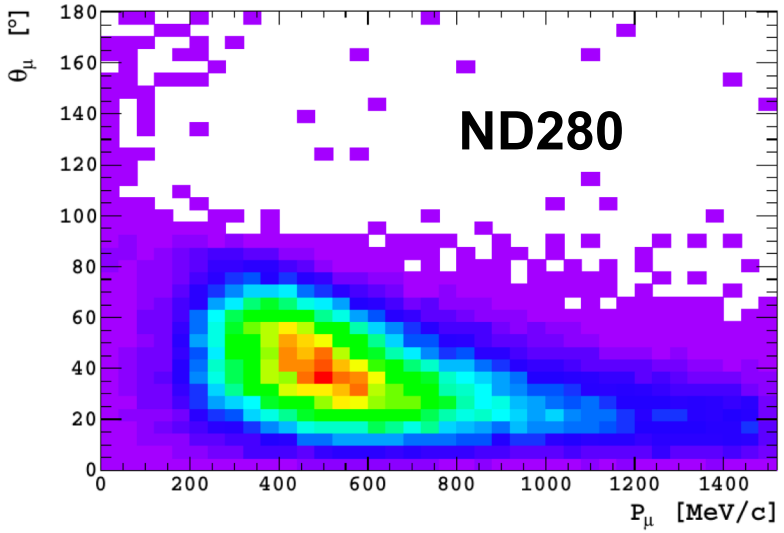
Limitations of Current ND280 (1)

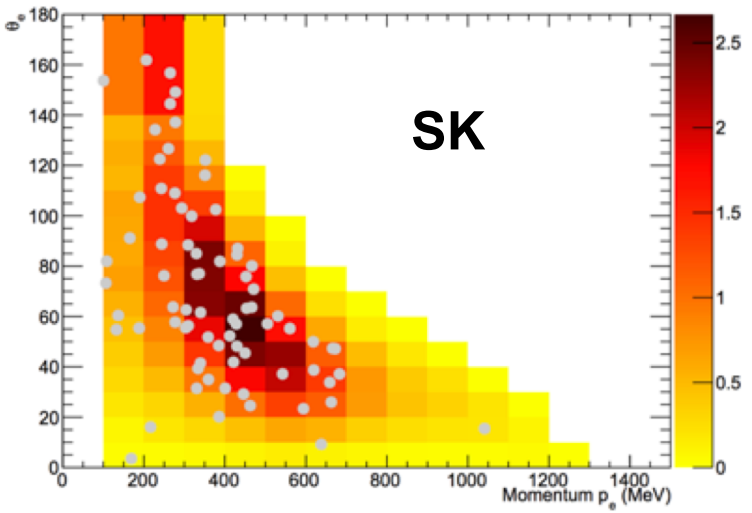
- **Excellent forward acceptance but not for wide angle with respect to the the beam direction**
- ND280 Current (forward) → SK (4π) extrapolation requires cross-section models to explain the Q^2 and/or momentum-angle dependencies



- Angular acceptance improvement by selecting high angle events using time of flight between scintillator detectors (*Phys. Rev. D **98**, 012004 (2018)*)

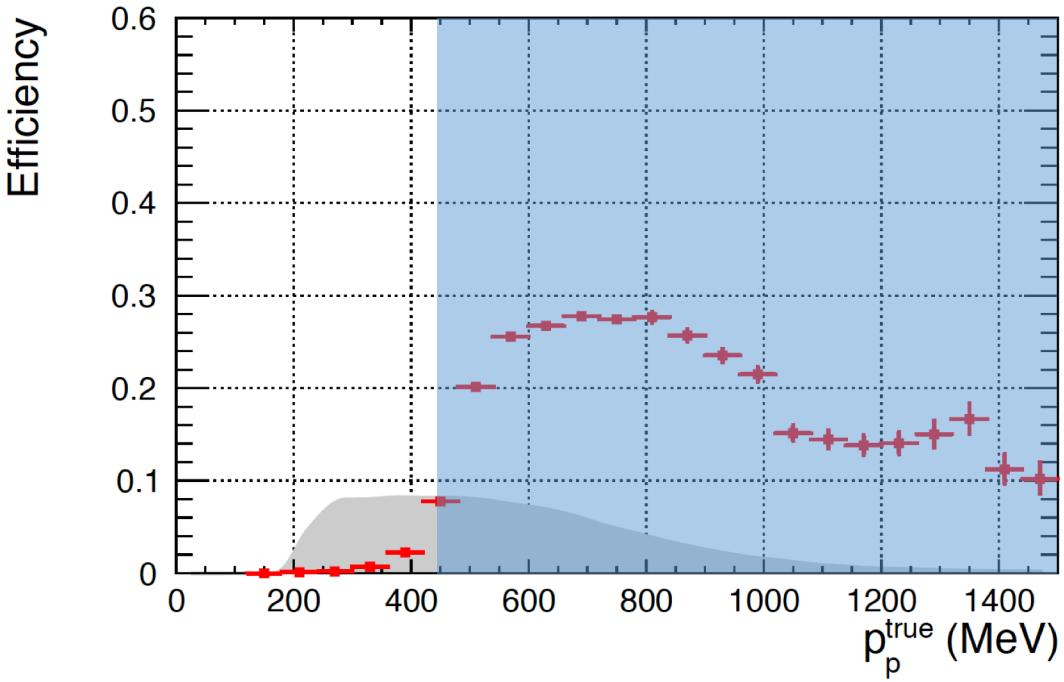
- Wide-backward region ($\cos\theta_\mu < 0.25$) introduces large systematic uncertainties due to poor track matching

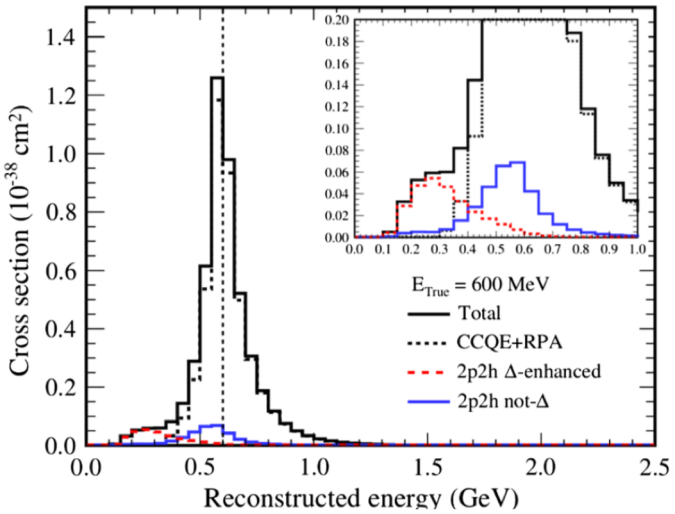


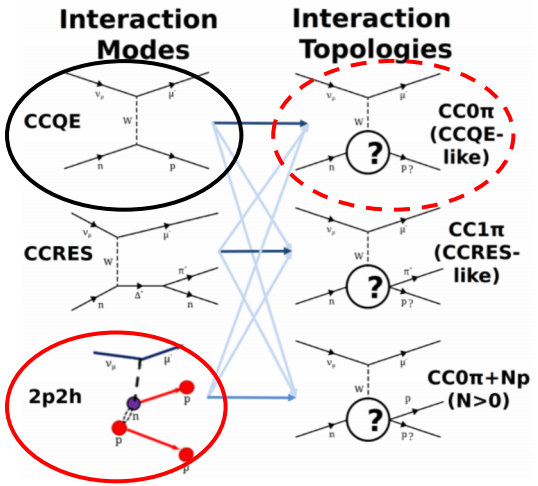


Limitations of Current ND280 (2)

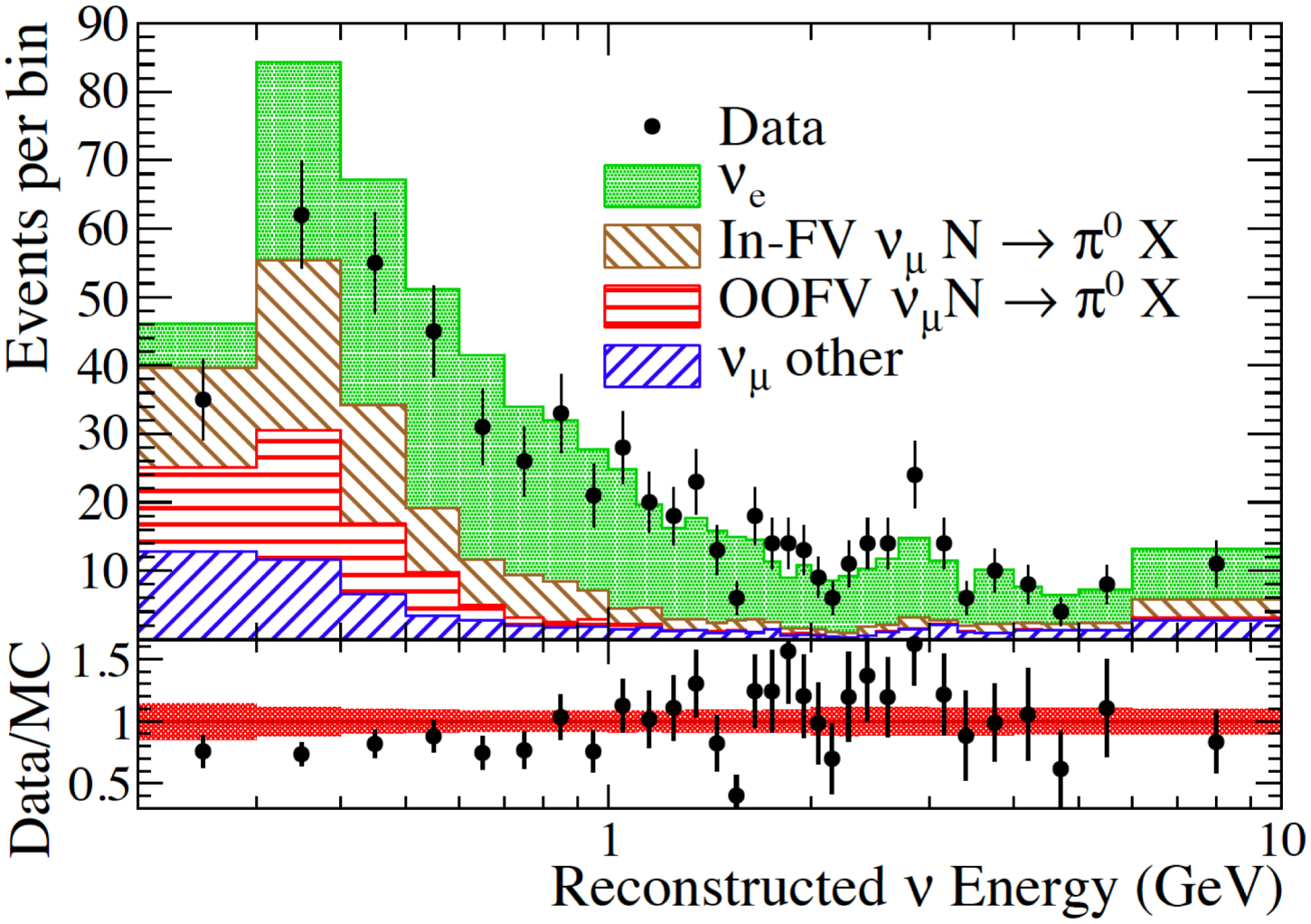
- **Limited tracking efficiency near the interaction vertex**
  - Tracks in the current FGDs can only be reconstructed with light yield measurement from alternating scintillator bar layers
- **Complicates the low momentum pions and protons measurements to investigate nuclear effects (e.g. 2p2h)**
  - Proton momentum threshold at ~450 MeV/c
- **Event selection based on the final state topology**
  - Biases the E_ν reconstruction due to the poor understanding of the neutrino interactions





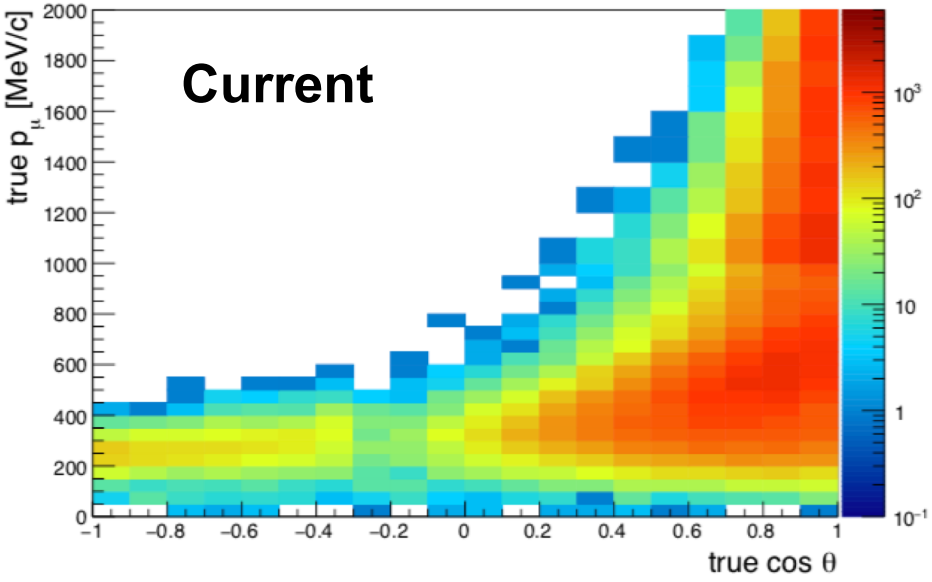


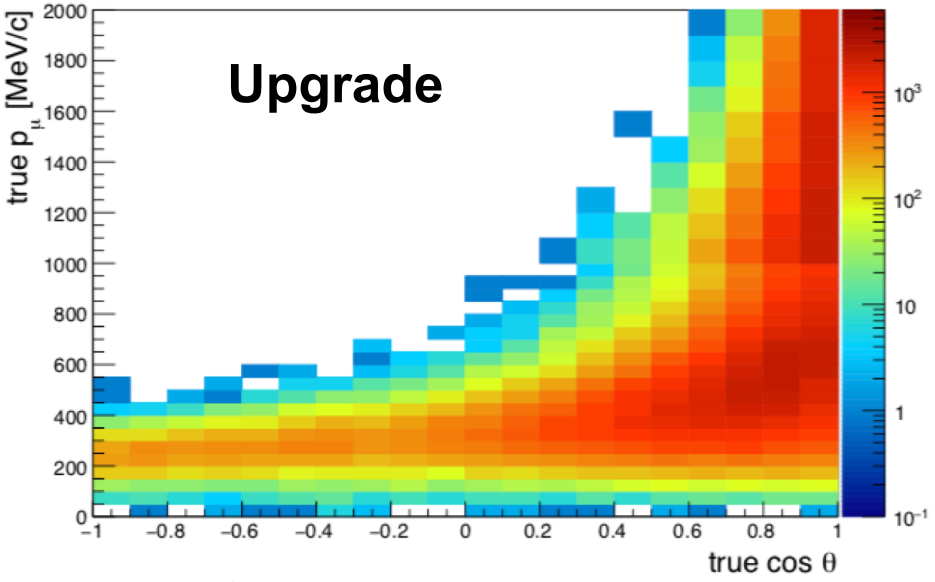
Electron Neutrino Selection in Current ND280



Expected Performance of ND280 Upgrade

- GENIE MC events with T2K FHC ν_μ flux prediction (1×10^{21} POT)
- Detector response modelled by GEANT4
- TPC ν_μ CC event selection comparison between Current and Upgrade configurations



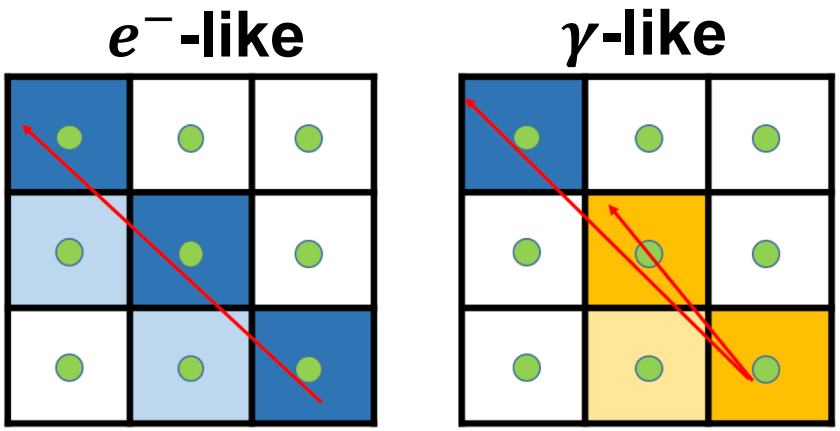


- Selected event distribution (FGD1+FGD2+SuperFGD)
- Double the statistics due to the larger target mass and improved performances

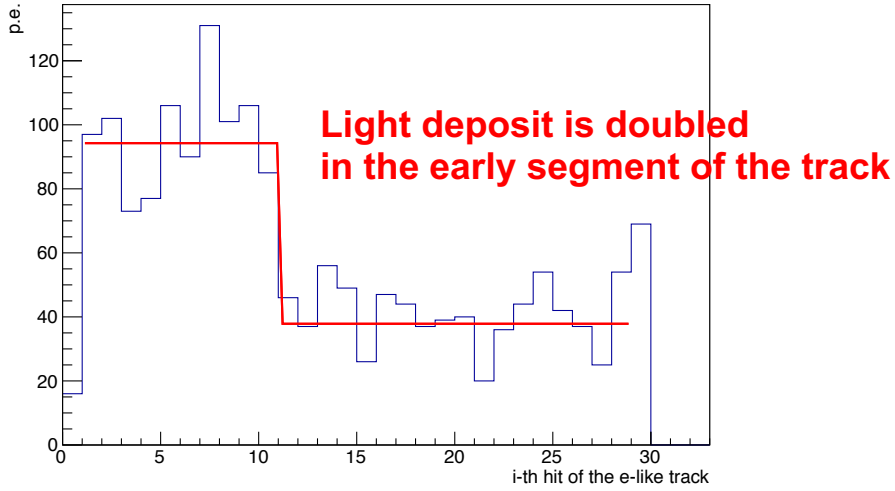
Selection	Current-like	Upgrade-like
ν_μ (ν beam)	100632	199605
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	32671	60763
ν_μ ($\bar{\nu}$ beam)	16537	29593

SuperFGD Electron-Photon Separation

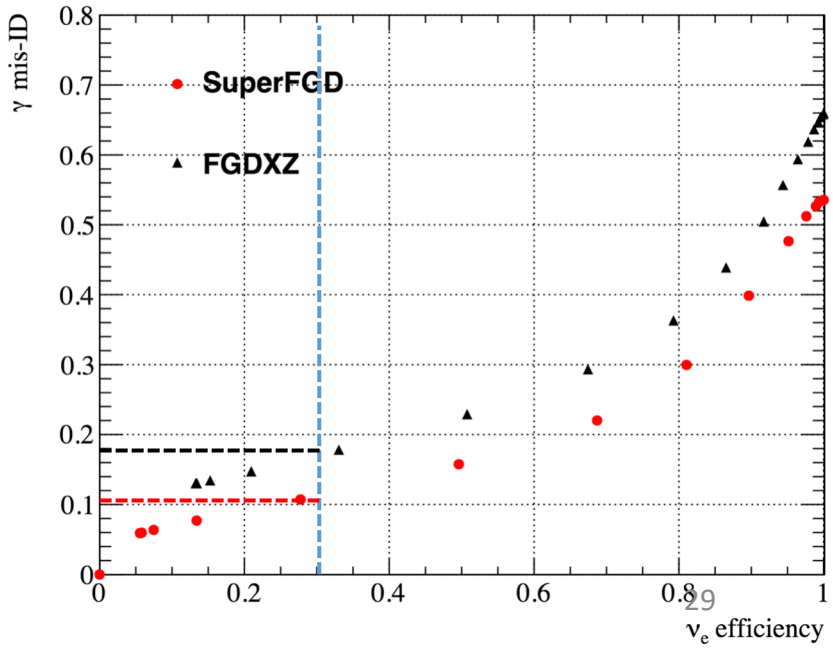
- In ND280 ν_e analysis, $\gamma \rightarrow e^- e^+$ from ν_μ CC/NC π^0 is the major background
  - single-track, low momentum (200 < p < 600 MeV/c)
- Preliminary approach to distinguish e^-- and γ-tracks using the pulse shape of the track



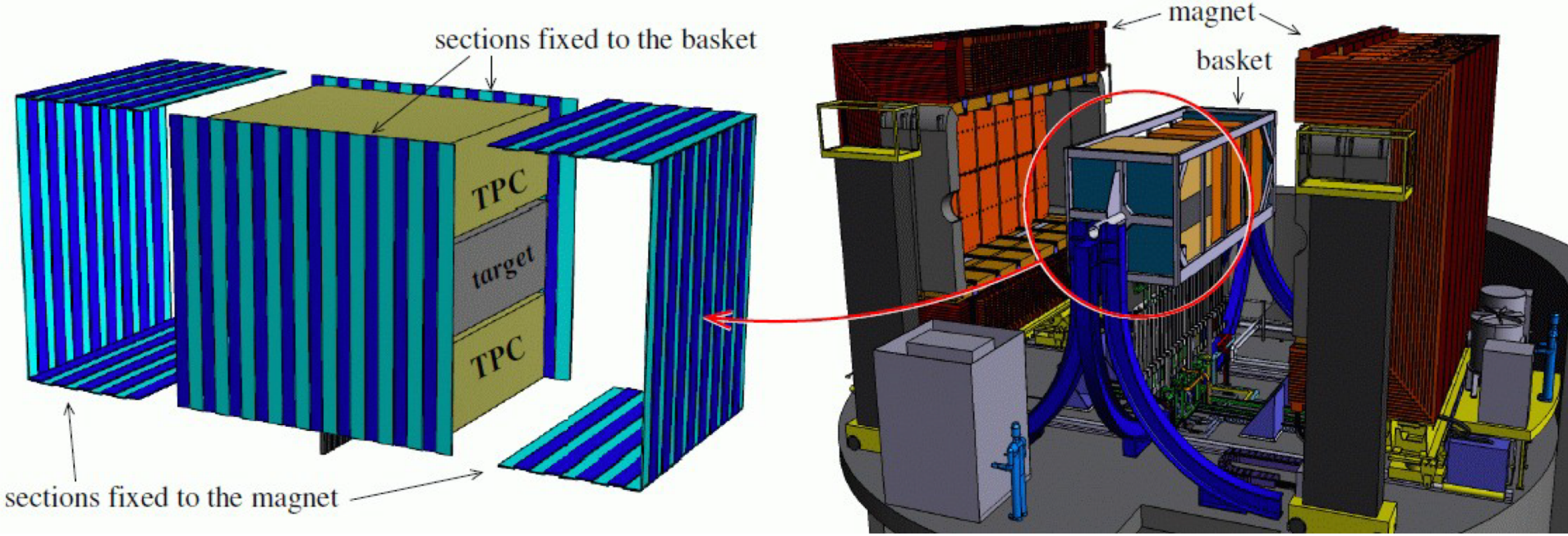
Sequence of light deposit (γ-track)



- The light deposit ratio within the track is used as the gamma PID evaluate ν_e selection efficiency and γ mis-ID probability
- **At ~30% ν_e efficiency (current ND280), approximately a factor of 2 more γ's rejected by SuperFGD**



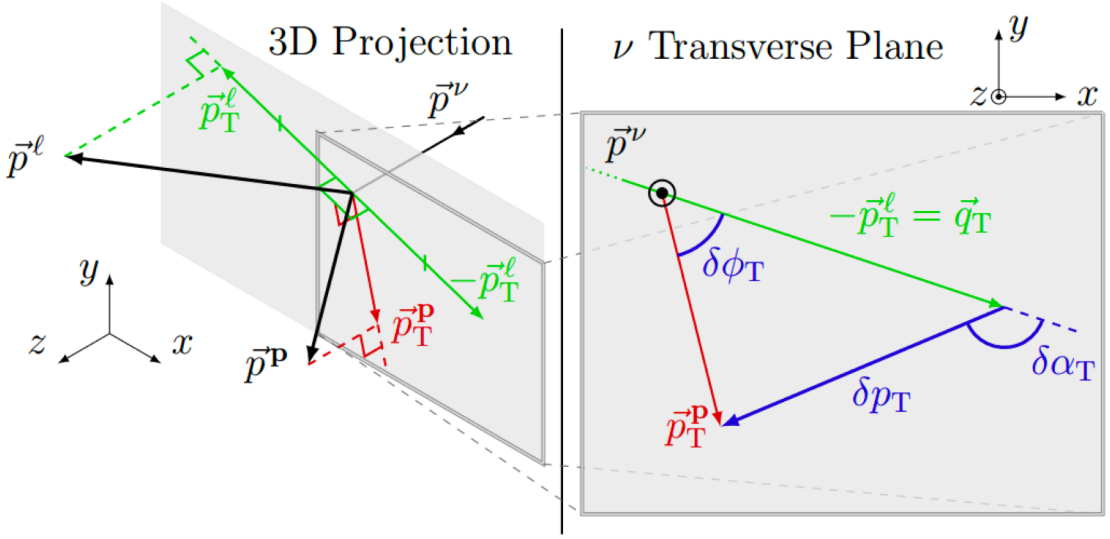
ToF Counter

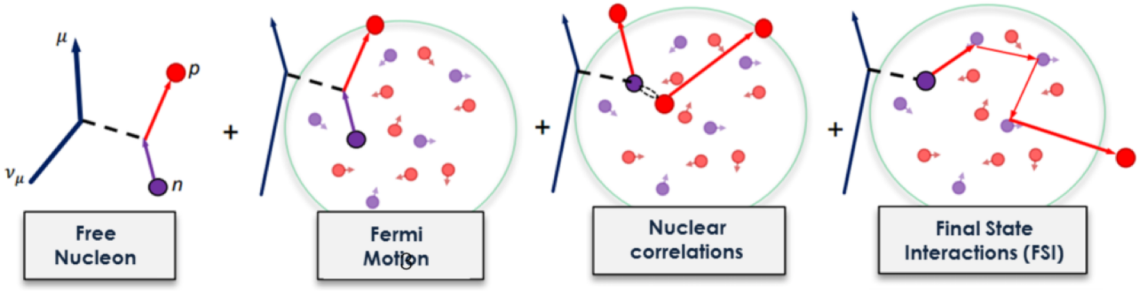


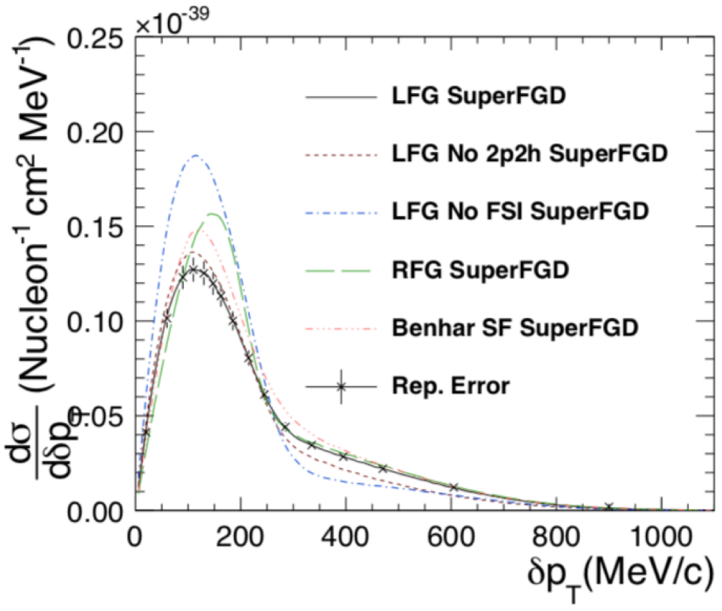
- Consists of six planes of plastic scintillators
  - 8 MPPC arrays ($6 \times 6\ \mathrm{mm}^2$)
  - Timing resolution of 150 ps
- Provides timing information for track reconstruction
- Improved particle identification (p/e^+, electrons/muons)
- Out-of-fiducial-volume event rejection

ND280 Upgrade Single Transverse Variable Studies

- Using deviation of transverse kinematics between the final state leptons and hadrons as a direct probe of nuclear effects (*Phys. Rev. C* ***94****, 015503 (2016)*)
- Low proton momentum threshold and high statistics allow a deeper probe to separate impact of FSI and 2p2h

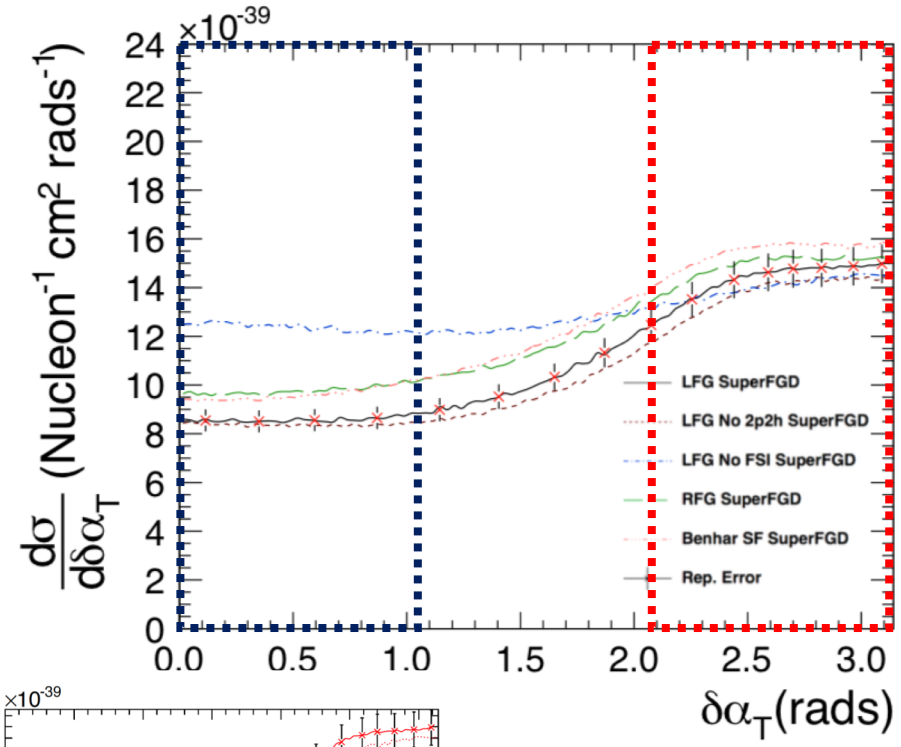


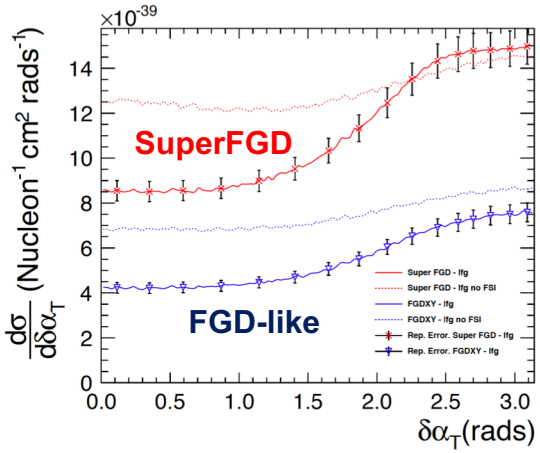




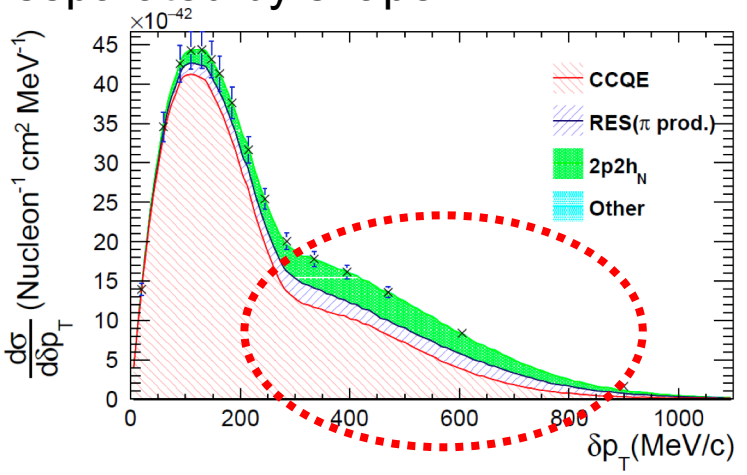
ND280 Upgrade Single Transverse Variable Studies

- Considering $\delta\alpha_T$, direction of $\delta\vec{p}_T$ relative to lepton direction, the δp_T can be studied in the regions where 2p2h and FSI effects are well separated by shape

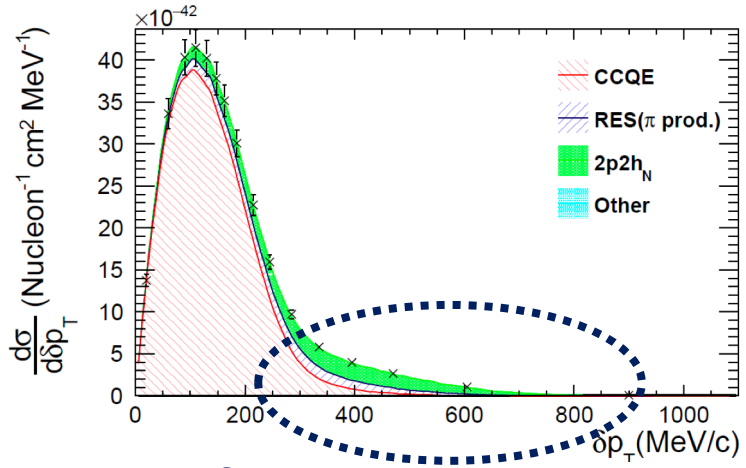




Improved acceptance of SuperFGD allows better sensitivity to FSI effects



δp_T tail dominated by FSI



δp_T tail dominated by 2p2h

WAGASCI $\bar{\nu}_\mu$ CC0π Event Selection Criteria

- Single track μ events selected to perform $\bar{\nu}_\mu$ cross section measurement on C and O
- Requirement on muon, proton, and pion kinematics:
  - Muon with $\mathrm{p}_\mu > 0.4\ \mathrm{GeV}/c$ and $\theta_\mu < 30^o$
  - **No** protons with $p_\mathrm{p} > 0.6\mathrm{GeV}/c$ and $\theta_\mathrm{p} < 70^o$
  - **No** pions with $p_\pi > 0.2\ \mathrm{GeV}/c$ and $\theta_\pi < 70^o$