T2K upgrades: near detector and beam

Lorenzo Magaletti (Politecnico di Bari & INFN Bari)
On behalf of the T2K collaboration

NOW 2024: Neutrino Oscillation Workshop 2024
2-8 September 2024

Big international collaboration of neutrino LBL

Belgium
Ghent U.

Canada
TRIUMF
York U.

CERN

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
Keio U.
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tohoku U.
Tokyo Institute Tech
Tokyo Metropolitan U.
Tokyo U of Science
U. Tokyo
Yokohama National U.
ILANCE

~560 physicists, 74 institutes, 14 countries + CERN

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Imperial C. London
King's College London
Lancaster U.
Oxford U.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
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NCBJ, Warsaw
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Stony Brook U.
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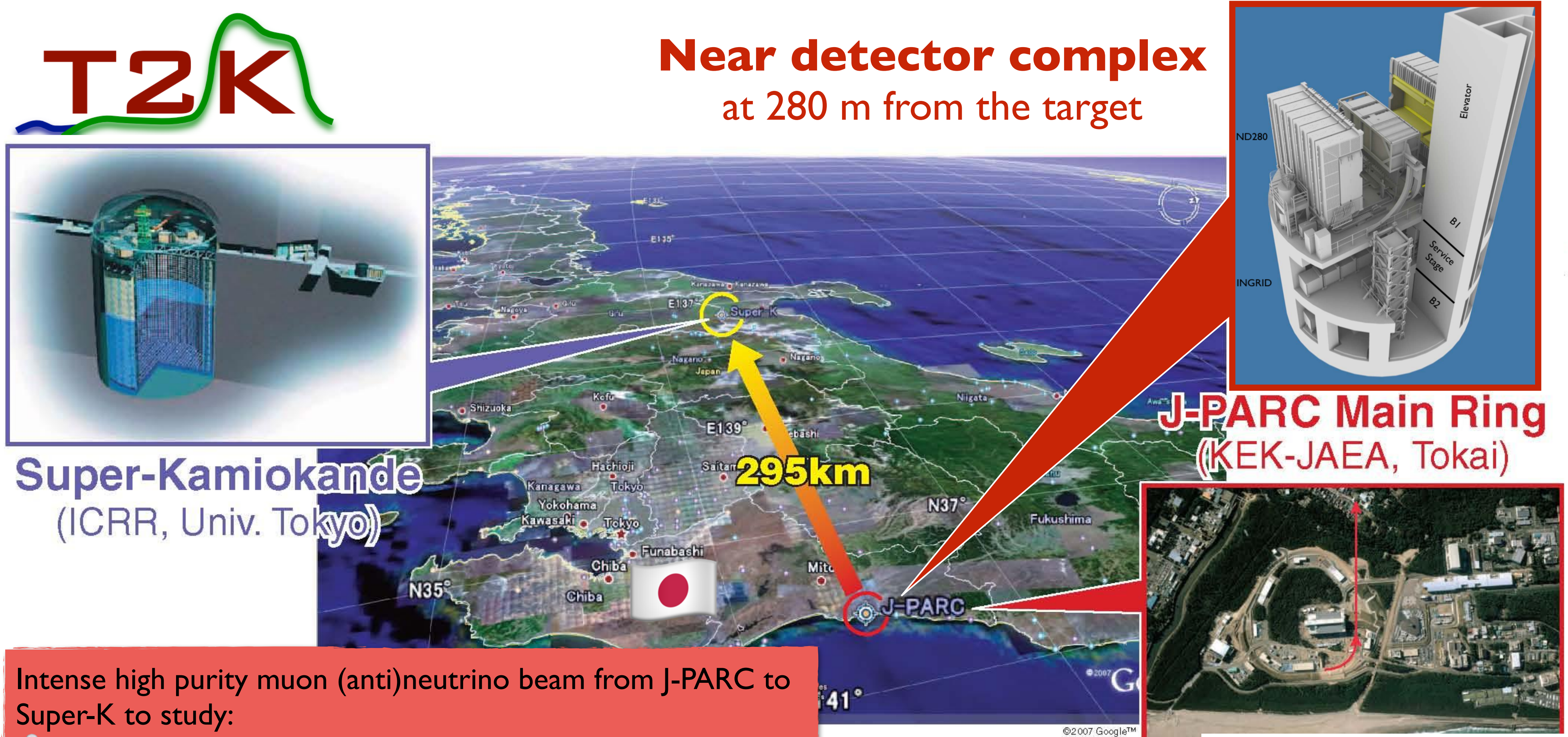
U. C. Boulder
U. Minnesota
U. Pennsylvania
U. Pittsburgh
U. Rochester
U. Washington
SDSMT
LBNL

Near detector complex

at 280 m from the target



Super-Kamiokande
(ICRR, Univ. Tokyo)

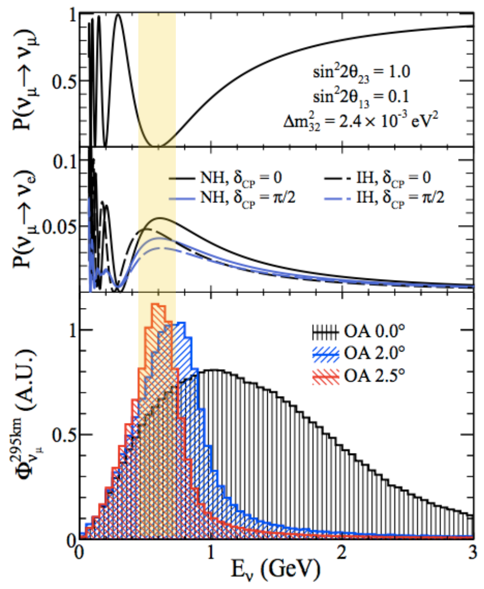
J-PARC Main Ring
(KEK-JAEA, Tokai)

Intense high purity muon (anti)neutrino beam from J-PARC to Super-K to study:

- Muon (anti) neutrino disappearance $\nu_\mu \nrightarrow \nu_\mu$ ($\bar{\nu}_\mu \nrightarrow \bar{\nu}_\mu$)
- Electron (anti) neutrino appearance $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)
- Rich program of:
  - neutrino cross sections studies with near detectors
  - "exotic" physics: sterile neutrinos, etc…

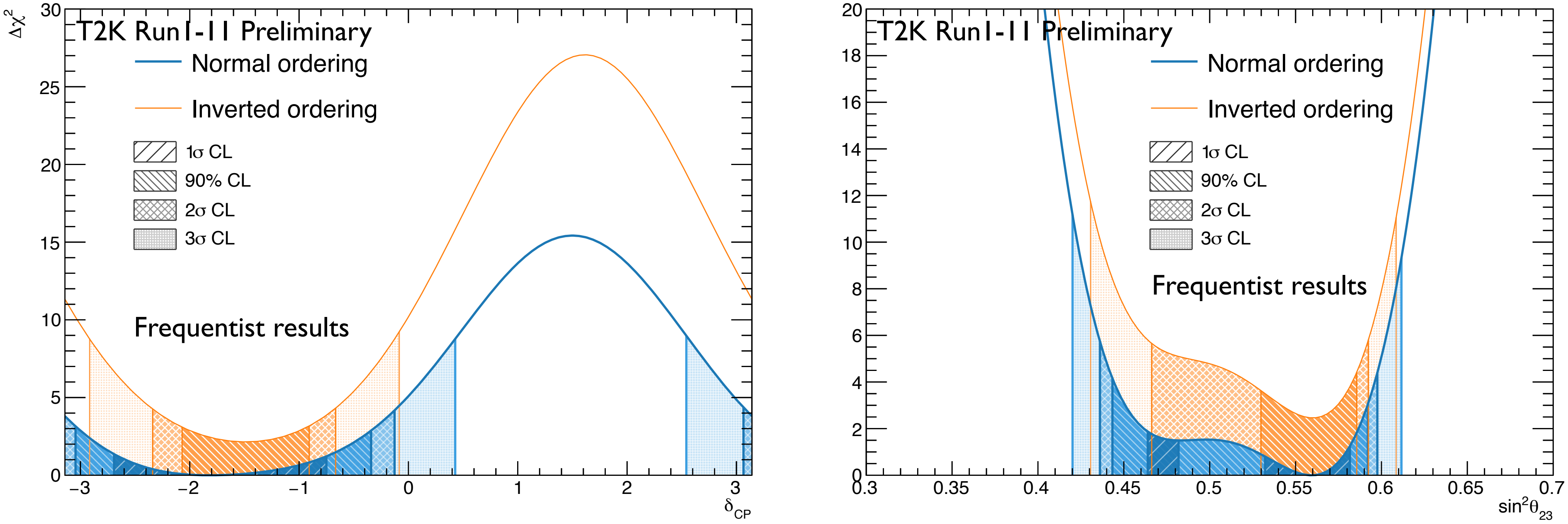
Off-axis beam characteristics:

- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduce background from π^0 interactions
- Changing horn current possible to run in ν and $\bar{\nu}$ beam mode



Latest T2K oscillation results

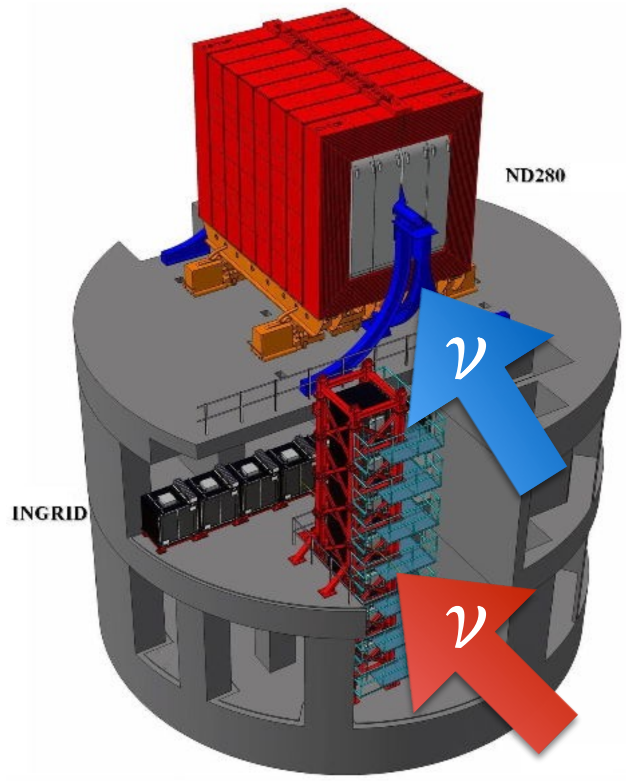
T2K + Reactor θ_{13} ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)

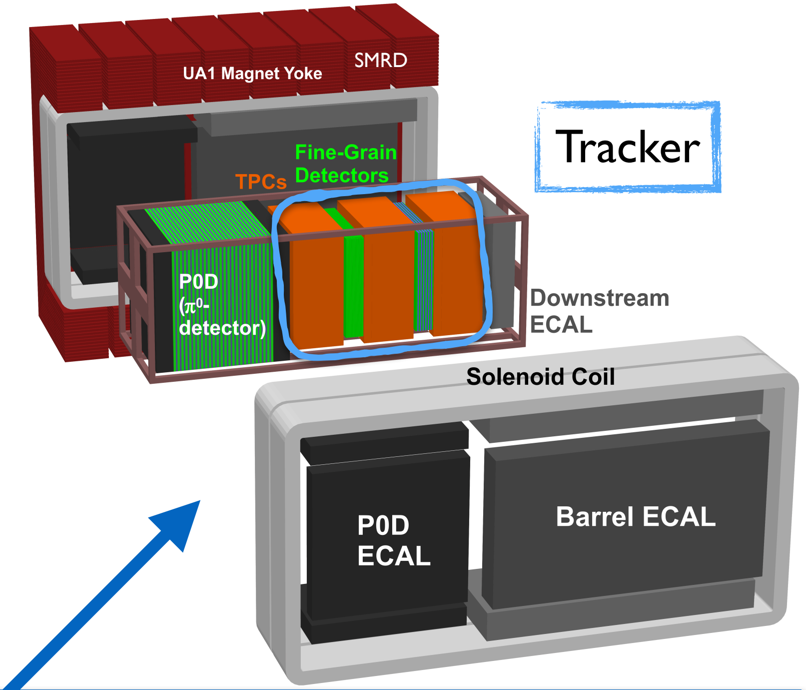


- Best fit value **near maximal CP violation** (-$\pi/2$)
- **CP conserving values excluded at 90% C.L.**
- Slight preference for **normal ordering**
- Best fit in the **upper octant** for θ_{23}
- See Daniel's plenary talk for more details

Confidence level	NO	IO
	$\sin^2\theta_{23}$	
1σ	$[0.464, 0.482] \cup [0.532, 0.582]$	
90%	$[0.443, 0.592]$	$[0.530, 0.586]$
2σ	$[0.436, 0.598]$	$[0.466, 0.592]$
	δ_{CP}	
1σ	$[-2.69, -0.75]$	
90%	$[-3.04, -0.34]$	$[-2.07, -0.91]$
2σ	$[-\pi, -0.13] \cup [3.06, \pi]$	$[-2.34, -0.67]$
3σ	$[-\pi, 0.43] \cup [2.54, \pi]$	$[-2.92, -0.08]$

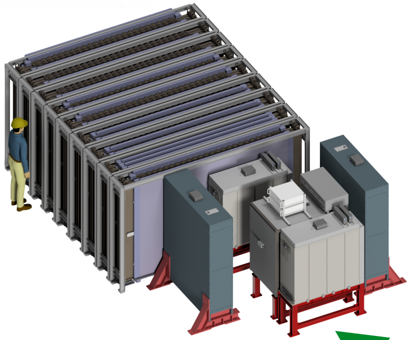
Near Detectors





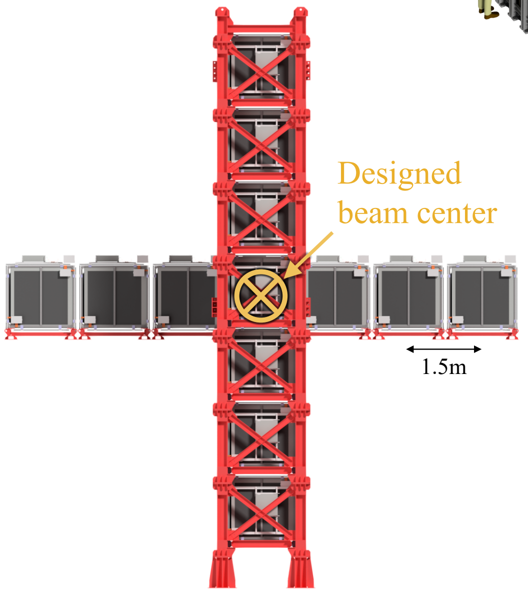
ND280 (off-axis 2.5°)

- **Magnet:** B = 0.2 T
- **TPC:** p measurement + particle-ID with dE/dx
- **FGD:** Fine-grained detectors (2 x 0.8 t) → FGD1 (C), FGD2 (C+H_2O)
- **SMRD:** magnetized muon range detector
- **P0D:** pi-zero detector (Pb/brass-H_2O-scintillator)
- **ECal:** electromagnetic calorimeter



WAGASCI-Baby MIND (off-axis 1.5°)

- **WAGASCI**: plastic scintillator detector filled with water (~ 80%)
- **BabyMIND**: magnetised iron and scintillator (μ charge and range)
- **Not used yet in the oscillation analysis**

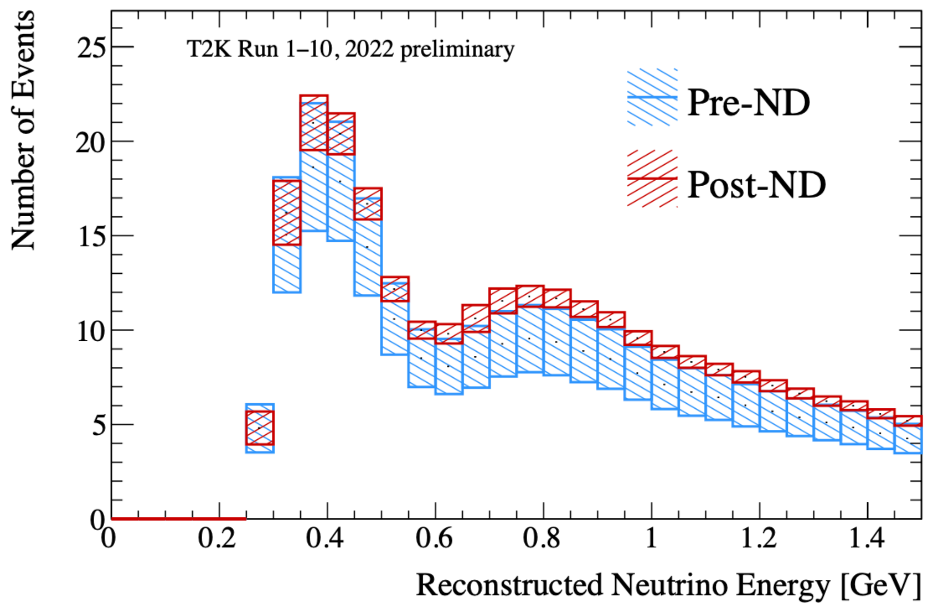


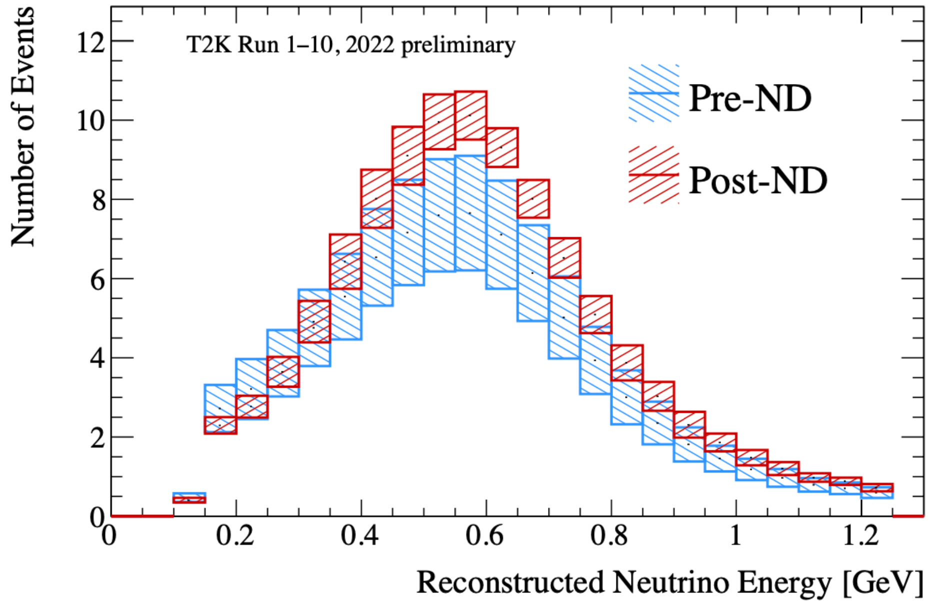
INGRID (on-axis)

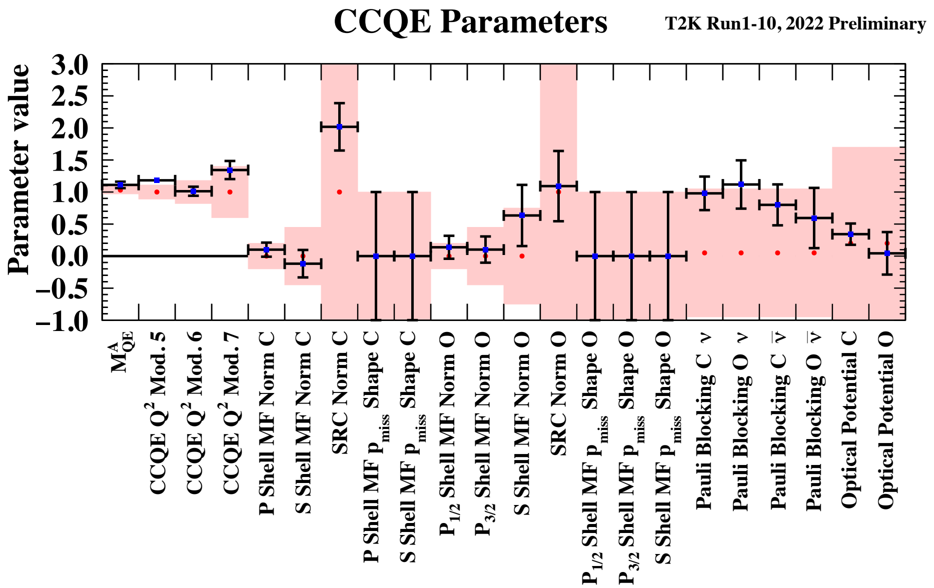
- **ν_μ CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (14 Fe/Scint modules + 1 central one made of scintillator only)

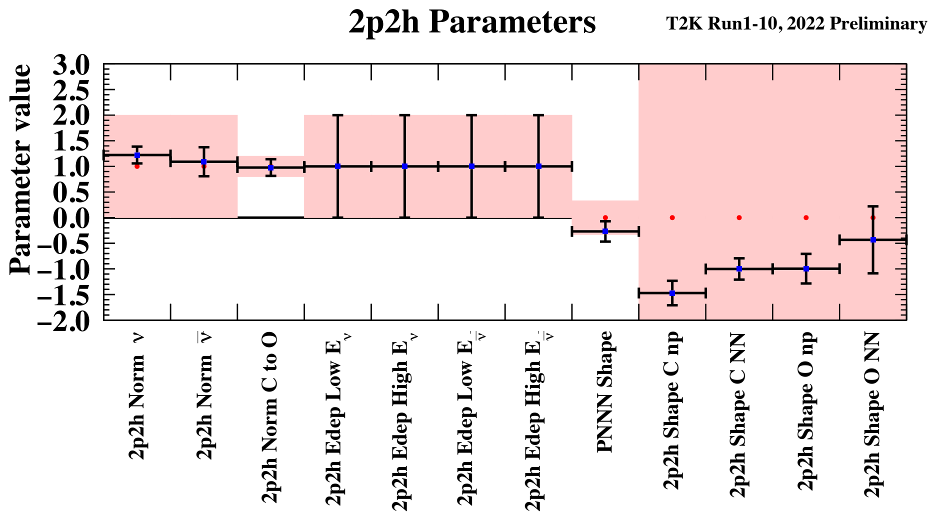
Reduction of systematics thanks to ND280

Thanks to ND280 fit systematics uncertainties on and energy spectra at SK are reduced from 15% to 5% !

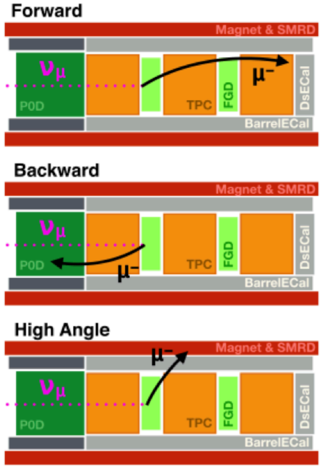


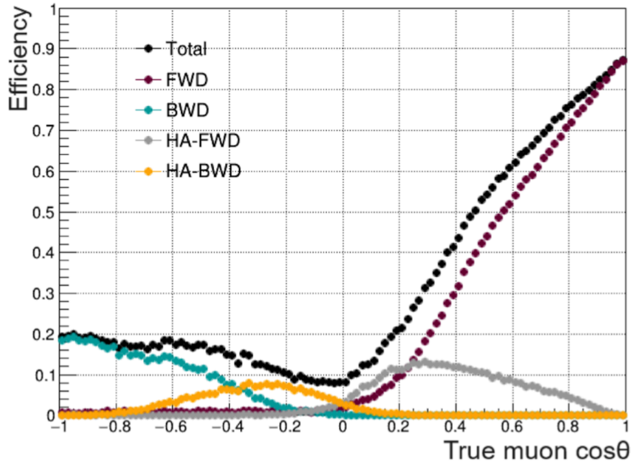




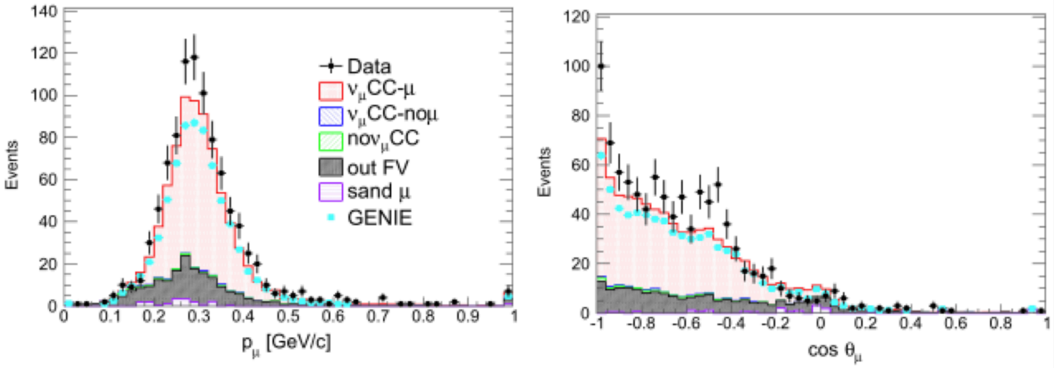


Next iteration of OA (with old ND280 config.) and limitations





Phys. Rev. D 98, 012004 (2018)

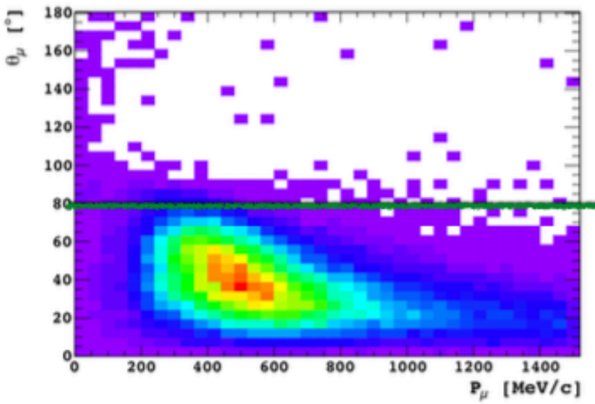


Preliminary Asimov fit → similar systematics

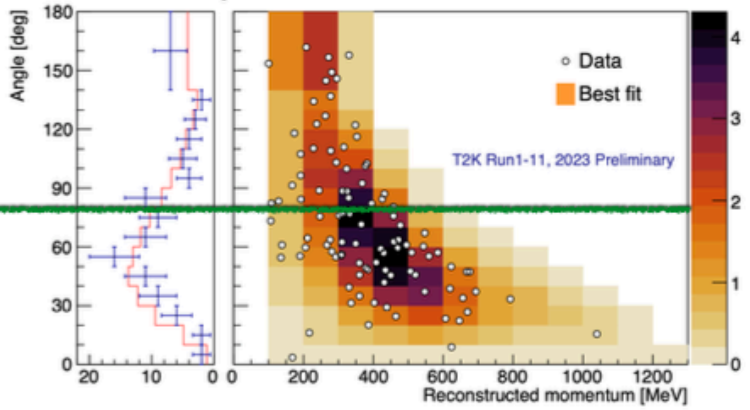
- **New x-sec model** with more freedom and higher x-sec uncertainties
- **Inclusion of high angle and backward going tracks** in ND280 to match SK acceptance
  - Limited efficiency selection ($\sim 20\,\%$) due to the absence of TPCs in the high angle region ⇒ **ND280 upgrade**
  - Low efficiency of low momentum proton reconstruction ⇒ **ND280 upgrade**
- Increase of statistic is needed to exclude CP-conservation at $> 3\sigma$ ⇒ **Beam upgrade**

Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	15.8%	2.6%
ν-mode 1Re	20.8%	4.0%
ν-mode MR	12.1%	2.8%
ν-mode 1Re+d.e.	13.8%	4.7%
$\bar{\nu}$-mode 1Rμ	15.3%	2.7%
$\bar{\nu}$-mode 1Re	15.5%	3.5%

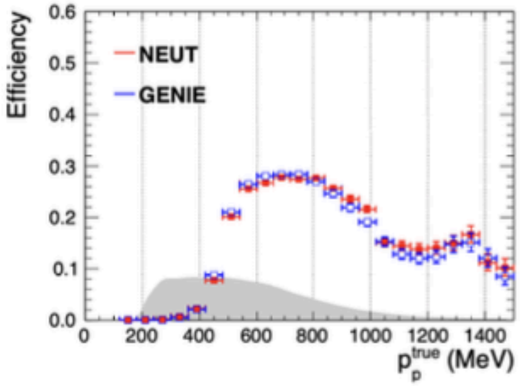
ND280 acceptance



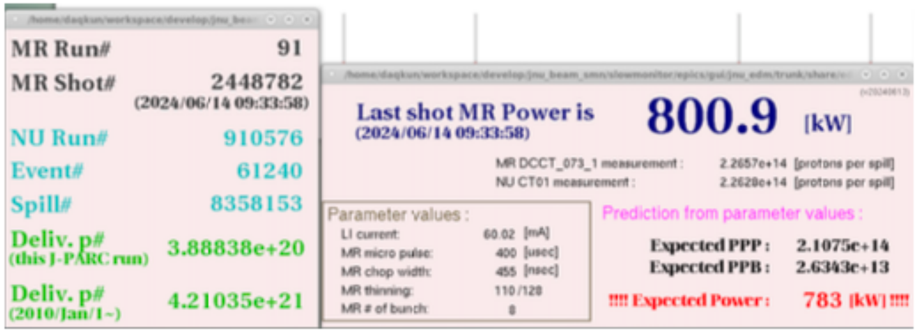
SK acceptance



ND280 Proton reconstruction efficiency

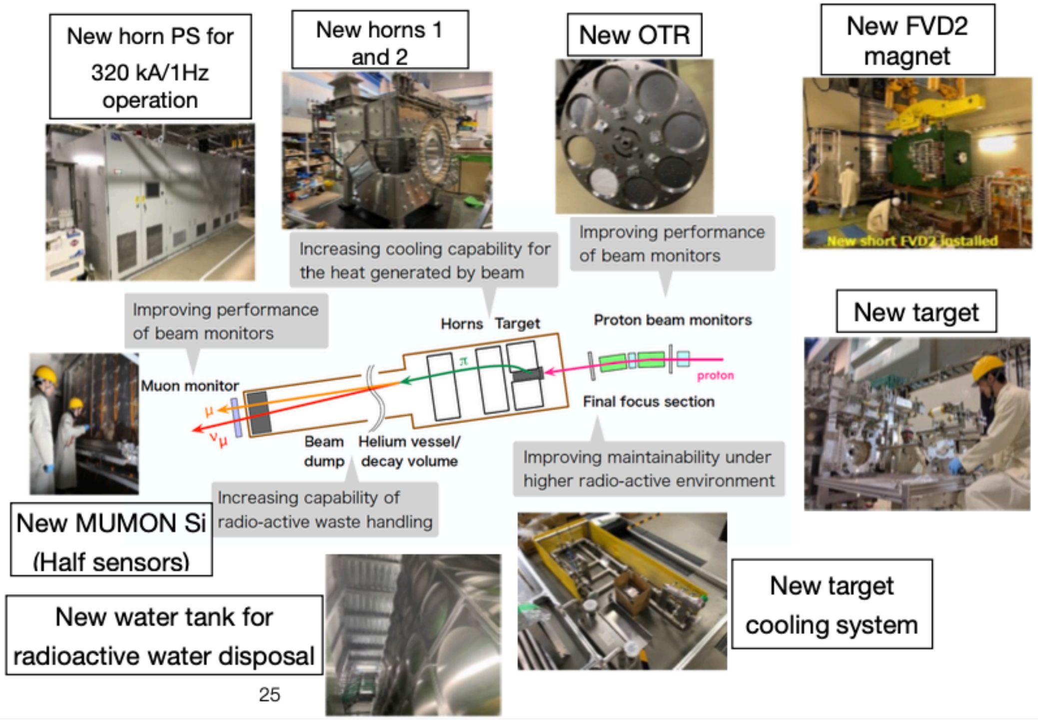


Neutrino beam upgrade

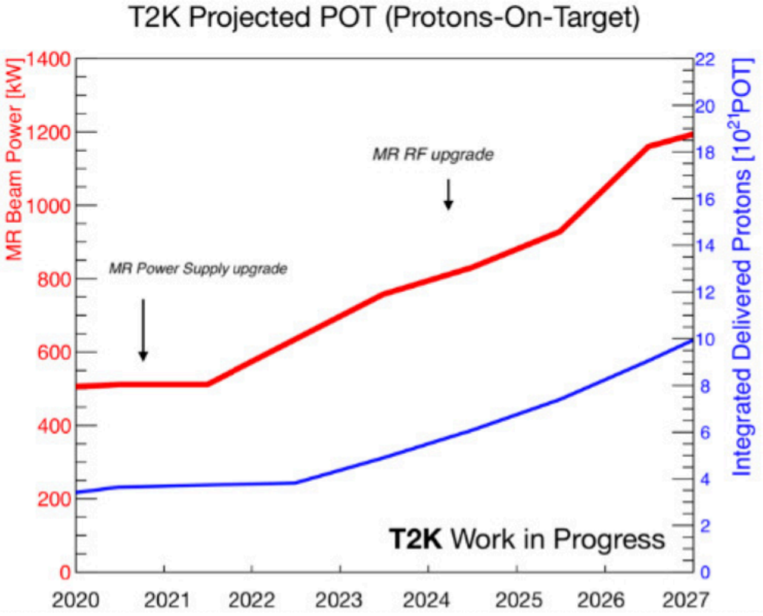


```
MR Run#                    91
MR Shot#              2448782
            (2024/06/14 09:33:58)
NU Run#                910576
Event#                  61240
Spill#                8358153
Deliv. p#
(this J-PARC run)   3.88838e+20
Deliv. p#
(2010/Jan/1~)       4.21035e+21
```

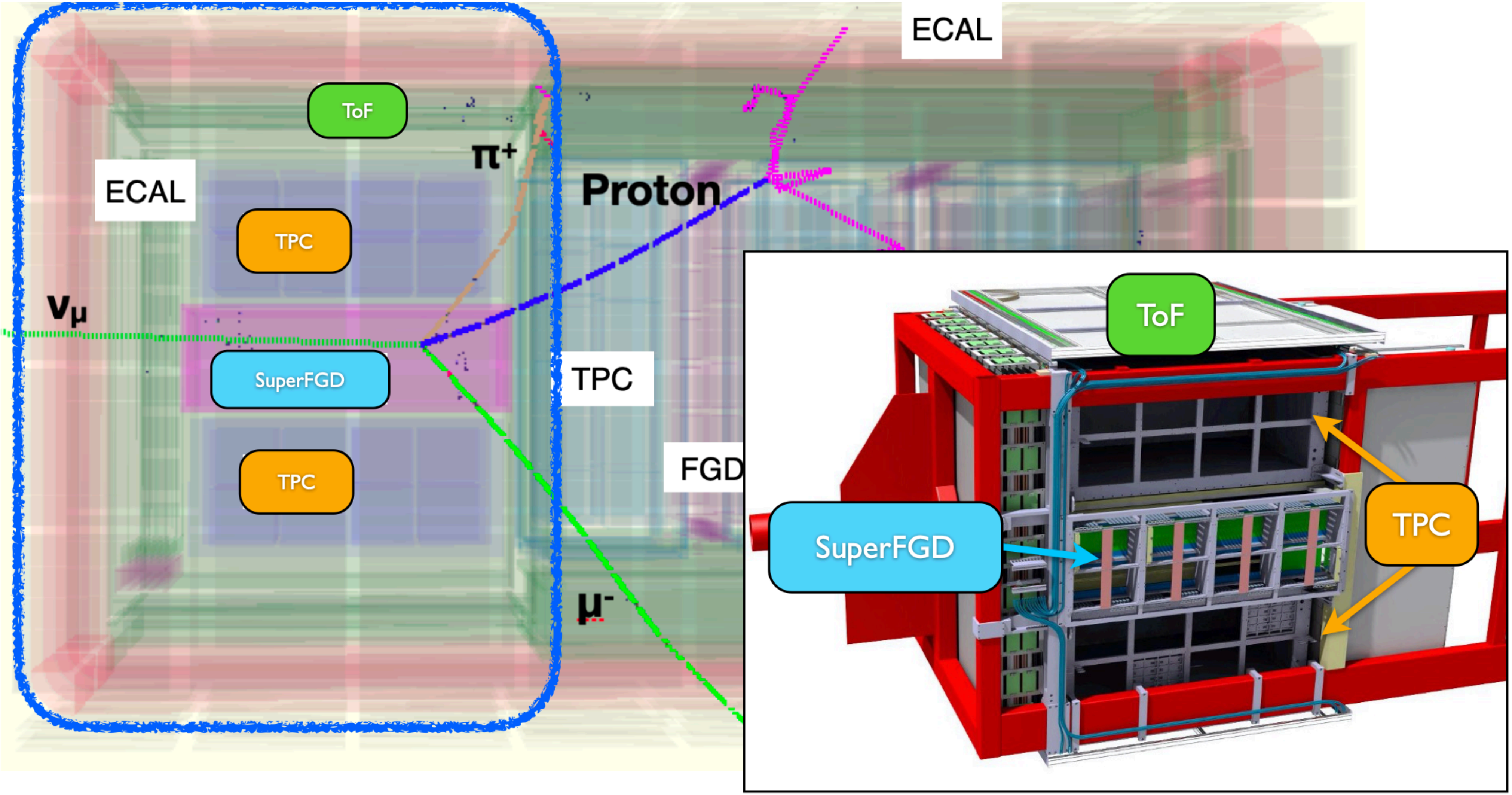
```
Last shot MR Power is                 800.9  [kW]
(2024/06/14 09:33:58)

          MR DCCT_073_1 measurement :   2.2657e+14  [protons per spill]
          NU CT01 measurement :         2.2628e+14  [protons per spill]

Parameter values :                 Prediction from parameter values :
  LI current:          60.02 [mA]
  MR micro pulse:        400 [usec]      Expected PPP :   2.1075e+14
  MR chop width:         455 [nsec]      Expected PPB :   2.6343e+13
  MR thinning:       110 /128
  MR # of bunch:           8         !!!! Expected Power :   783 [kW] !!!!
```



- **Reach design 750kW by increasing T$_{rep}$ (2.48 → 1.3s)**
  - Replace Main Ring Power Supply (MR-PS)
  - Upgrade MR-RF core for higher accelerating gradient
- **Several upgrades done on neutrino beamline in order to achieve higher beam power**
- **Horn current increase (250 kA → 320 kA)**
  - $\sim 10\,\%$ increase in ν flux
- **In December 2023 beam power increased from 500 to 750 kW and up to 800 kW in June!**
- **Steady improvement to reach 1.3 MW by 2027 (factor of 3 more stat in 2027)**
- **Larger statistic needs a reduction of systematic uncertainties**



ND280 upgrade

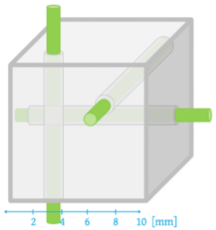


P0D replaced by:

- A new fine grained scintillator target **SFGD** capable to measure low energy protons and neutrons produced in CC interactions
- Two high angle TPCs (**HATPC**) to increase the angular acceptance as SK
- Six super fast **ToF** panels (130 ps) to identify charged particle directions

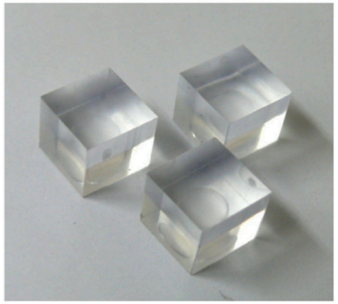
No changes in the remaining part of ND280

Super-FGD



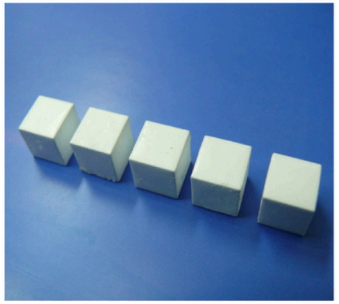
- SFGD ingredients: 2 million optically independent plastic scintillator cubes of 1 cm made of **polystyrene** and doped with **1.5%** of paraterphenyl (**PTP**) and **0.01%** of **POPOP**.
- ~ **40 p.e./MIP/Fiber**
- 3 WLS fiber in each cube (3D recon.)
- ~ 56k channels
- high granularity ⇒ low threshold to reconstruct hadrons

Produce cubes by injection molding



→

Etched in a chemical to deposit a reflective layer



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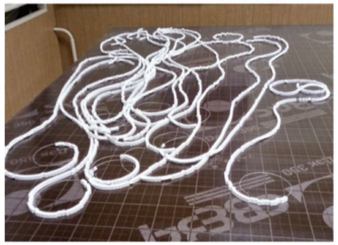
3 orthogonal holes are drilled



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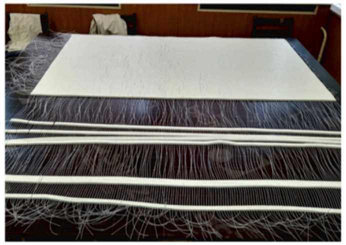

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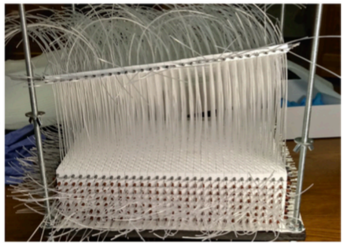
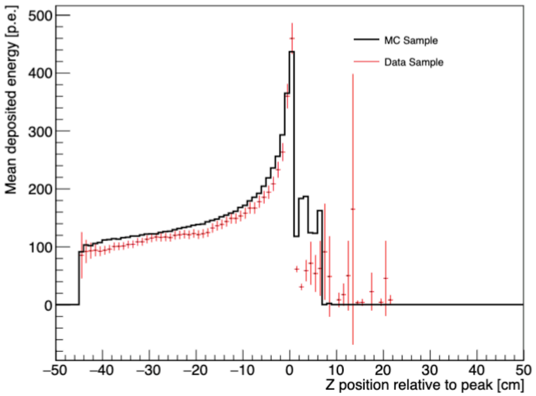


ith fishing lines before shipment to Japan

Proton Bragg peak



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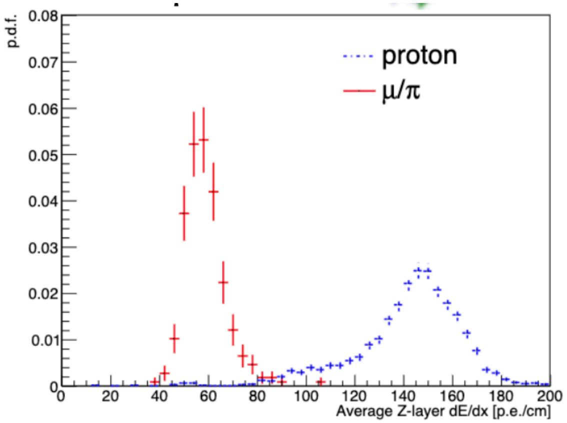

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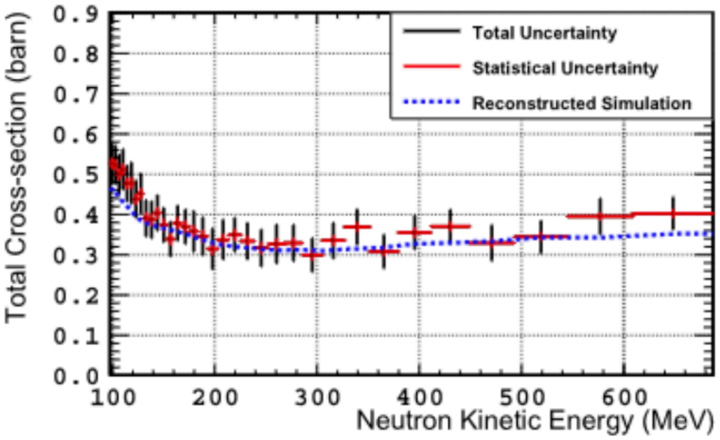
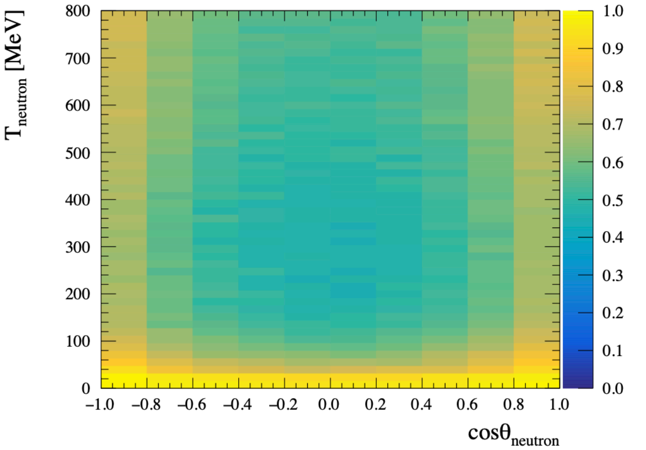


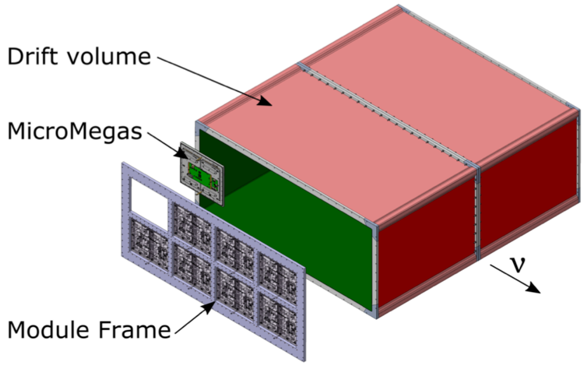
Neutrons now can be measured with the new sFGD!

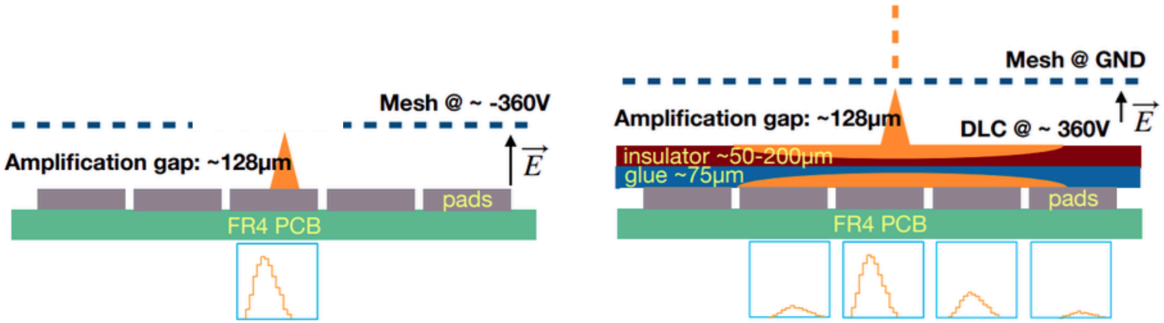
Neutron detection efficiency



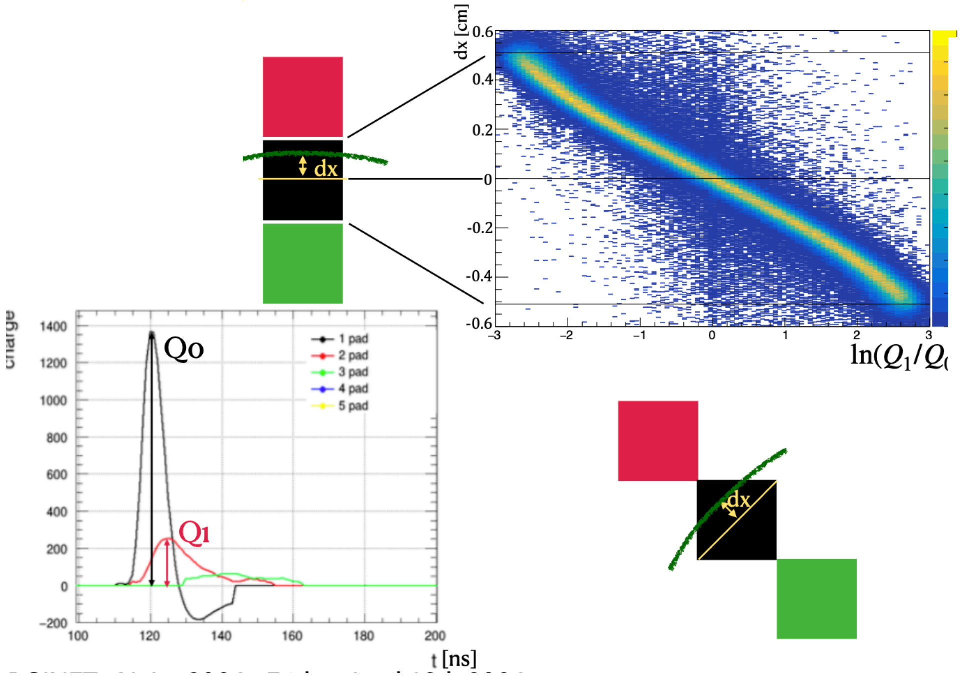
High-Angle TPCs (HAT)

- New TPCs equipped with the resistive anode MicroMegas (**ERAM**) technology
- Contrary to the bulk MicroMegas which equip the vertical TPC, ERAM allow a charge spreading on several pads

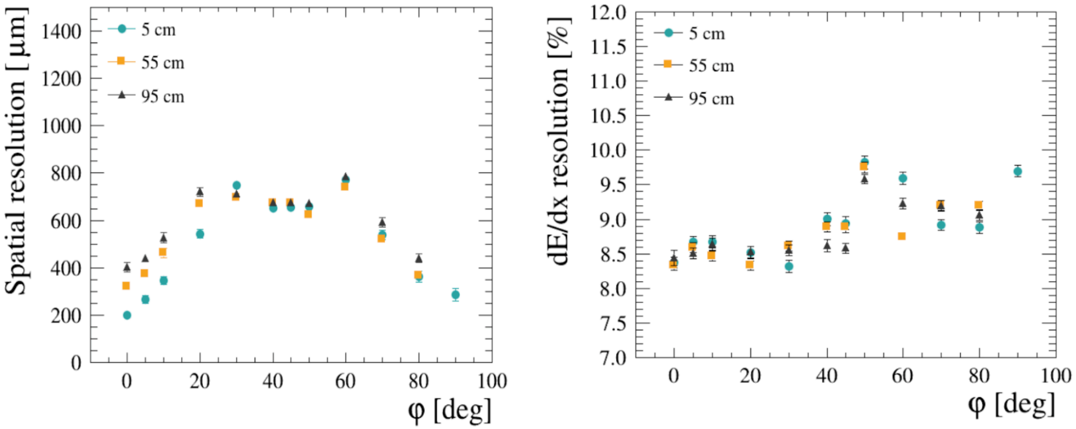




- 200-800 μm is the spatial resolution of new HAT, as opposed to 600-1600 μm for old vertical TPCs



Nucl.Instrum.Meth.A 1052 (2023) 168248

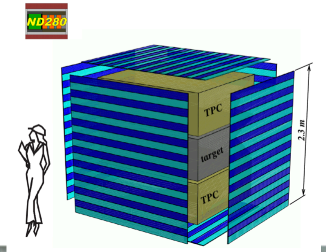


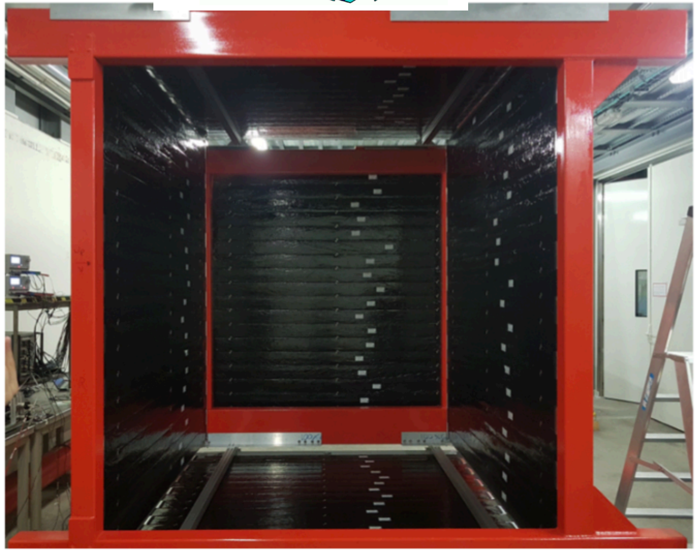
- dE/dx resolution of less than 10% has also been measured in this test beam campaign

- **more precise measure of track position by using leading pad and neighbour pads**

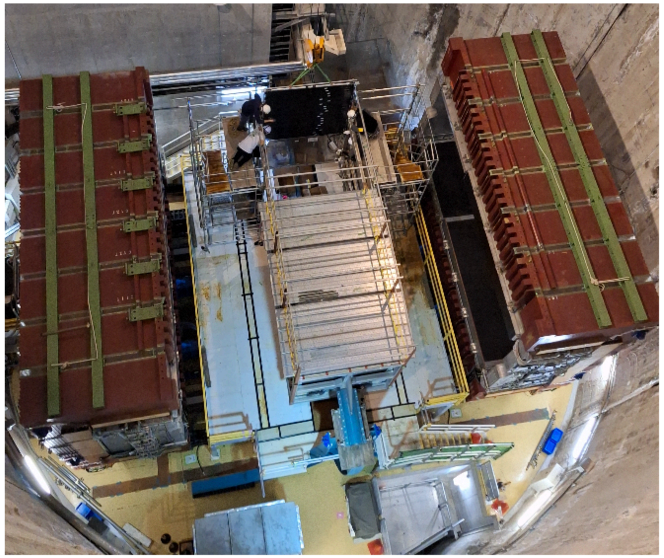
Time of Flight (TOF)

- 6 Plastic scintillator planes forming a cube that surround SFGD and HAT
- Reconstruction of track timing with a resolution between 100 and 130 ps

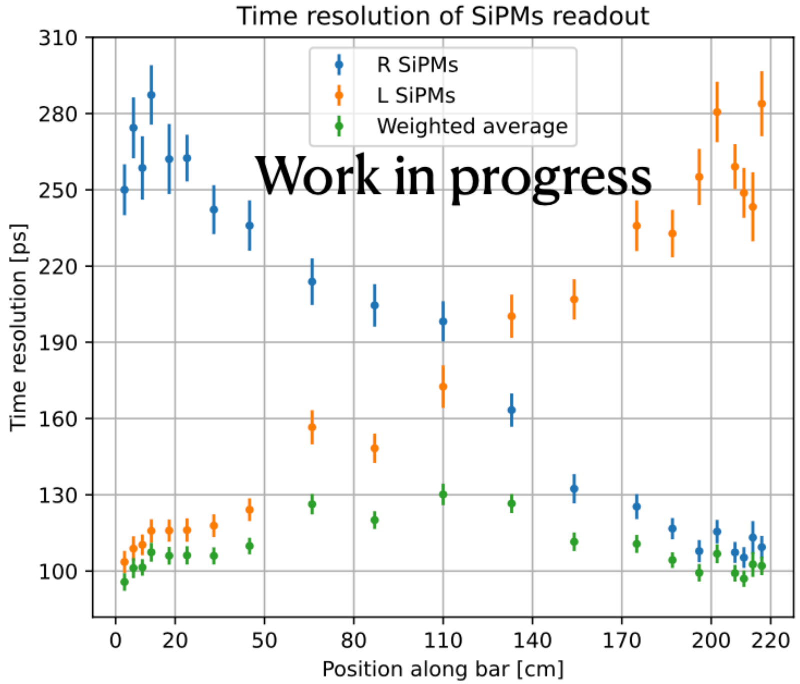


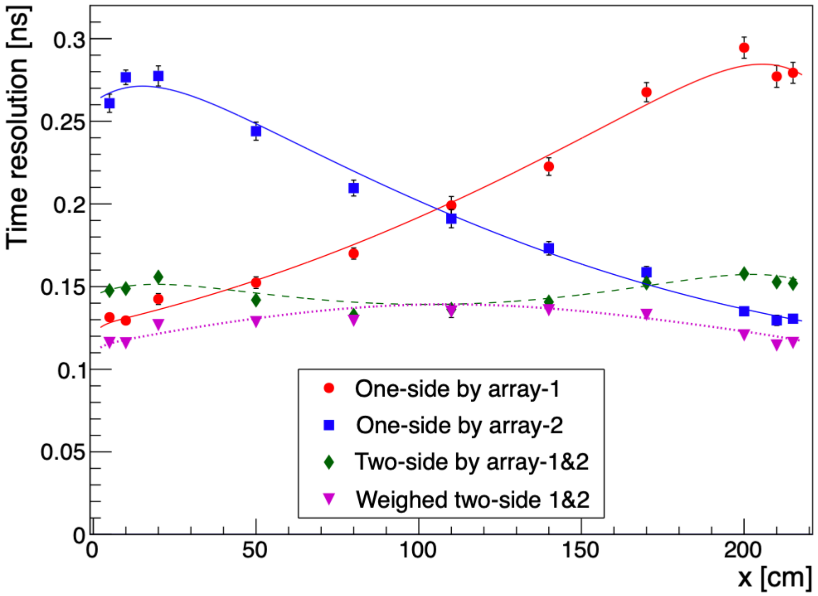


TOF panels assembled in ND280 basket prototype at CERN, June 2022



TOF panel installation in the ND280 pit at J-PARC, July 2023

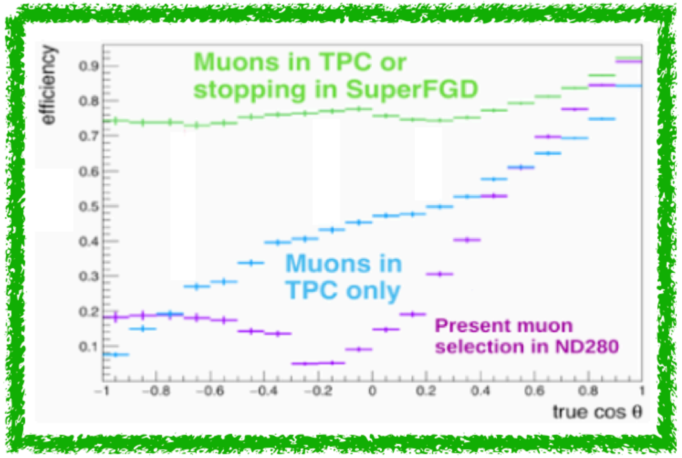




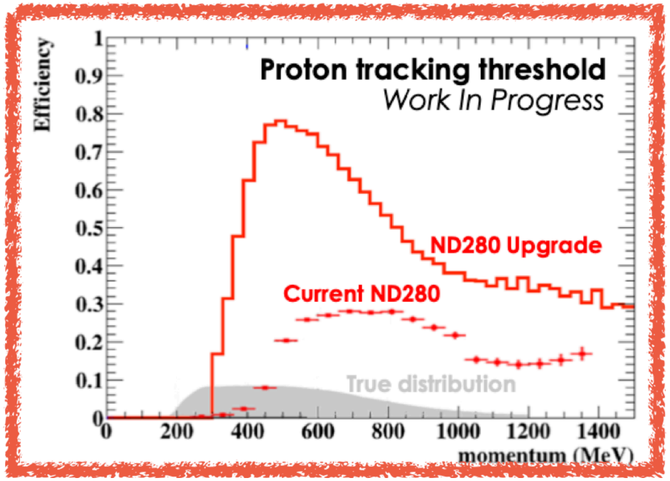
JINST 17 (2022) 01, P01016

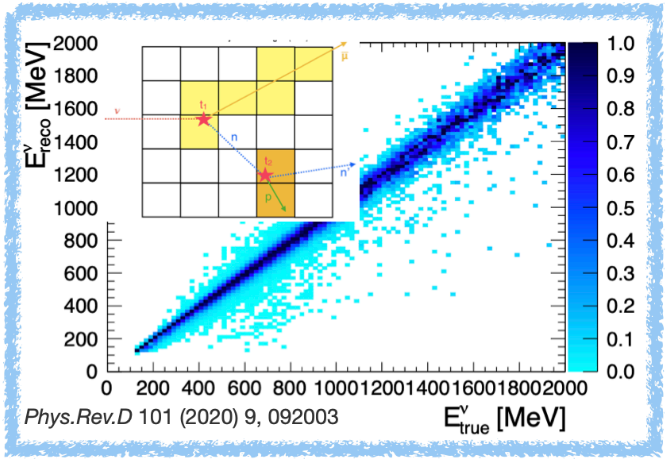
ND280 upgrade improvements

- High Angle TPC (HATPC) allows to reconstruct high angle charged particles with respect to beam direction
- Super-FGD (SFGD) allows to fully reconstruct 3D tracks from ν interactions
  - Improved PID performance with respect to FGD thanks to high granularity and light yield
  - Good performance in neutron reconstruction by using time of flight between $\bar{\nu}$ interaction vertex and neutron re-interaction ($\sim 50\,\%$ tagging efficiency, $\sim 30\,\%$ mom. resolution)
  - Better separation between γ and e from ν_e interactions thanks to sFGD high granularity
- First physics run with full upgrade successfully completed this summer
- Expect to select $\sim 20\text{k}\ \nu_\mu\ CC0\pi$ interactions in SFGD



Protons → threshold down to 300 MeV/c
(>500/c MeV with current ND280)



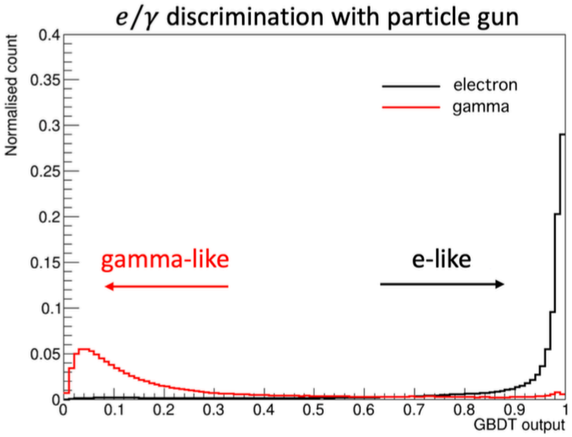


Phys.Rev.D 101 (2020) 9, 092003

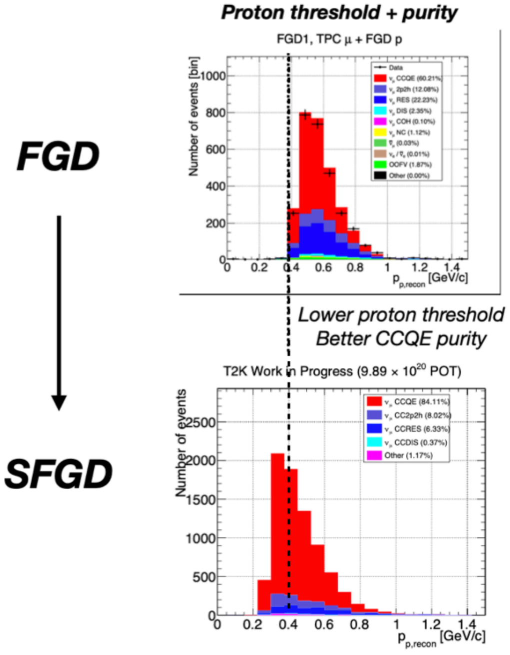
CC0π Event rates

Expect 85%-90% purity for SFGD samples

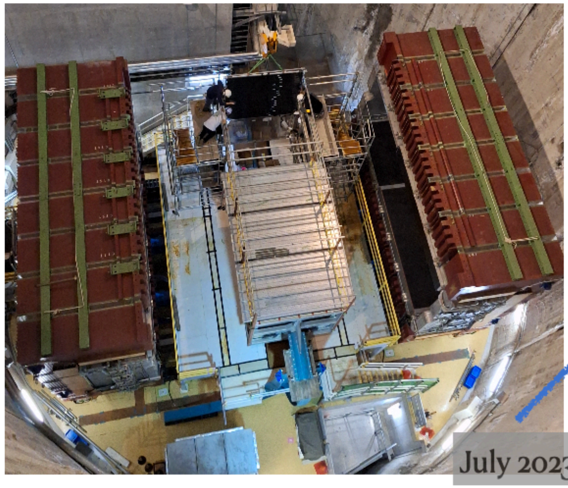
FHC only	1 cycle	3+1 cycles
SFGD total	21.8k	90.0k
SFGD w/nucleon	10.6k	43.9k

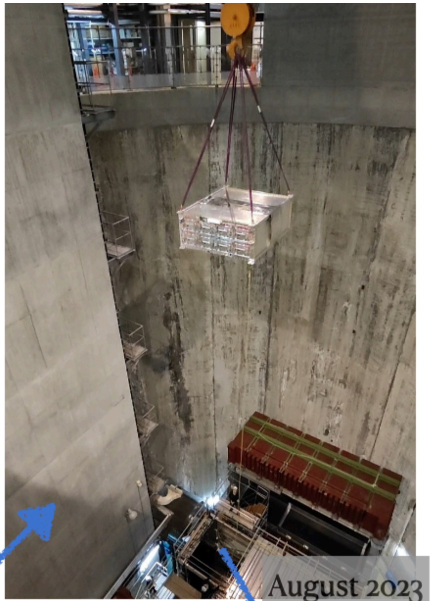


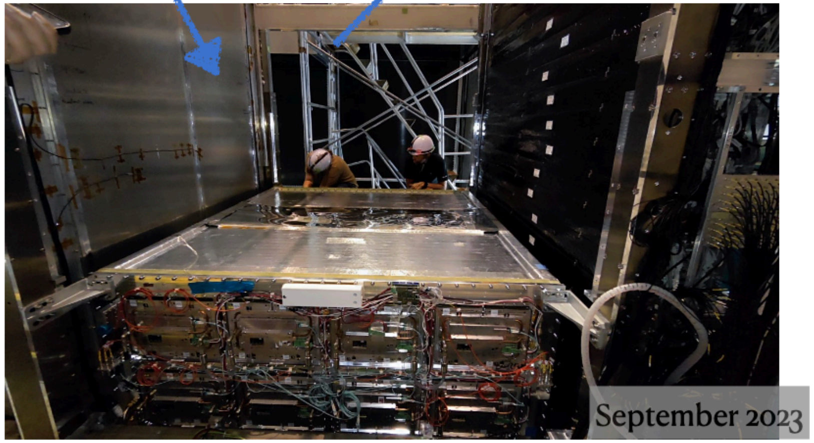
FHC = neutrino mode
1 cycle $\sim 3 \times 10^{20}$ POT
1 cycle ~ 1 month of data taking

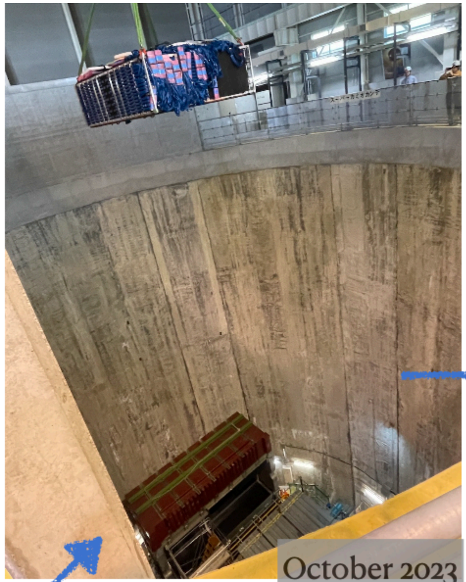


ND280 upgrade installation

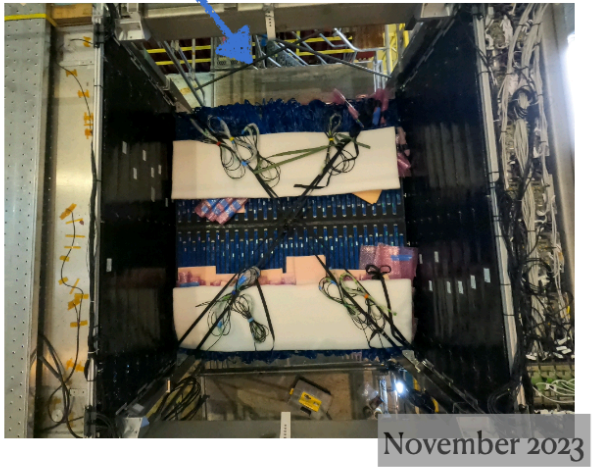

July 2023


August 2023


September 2023

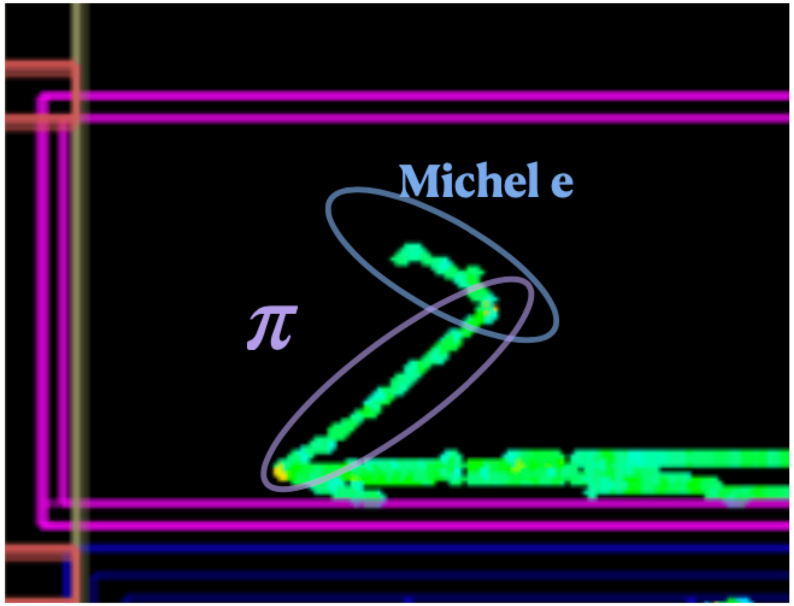

October 2023

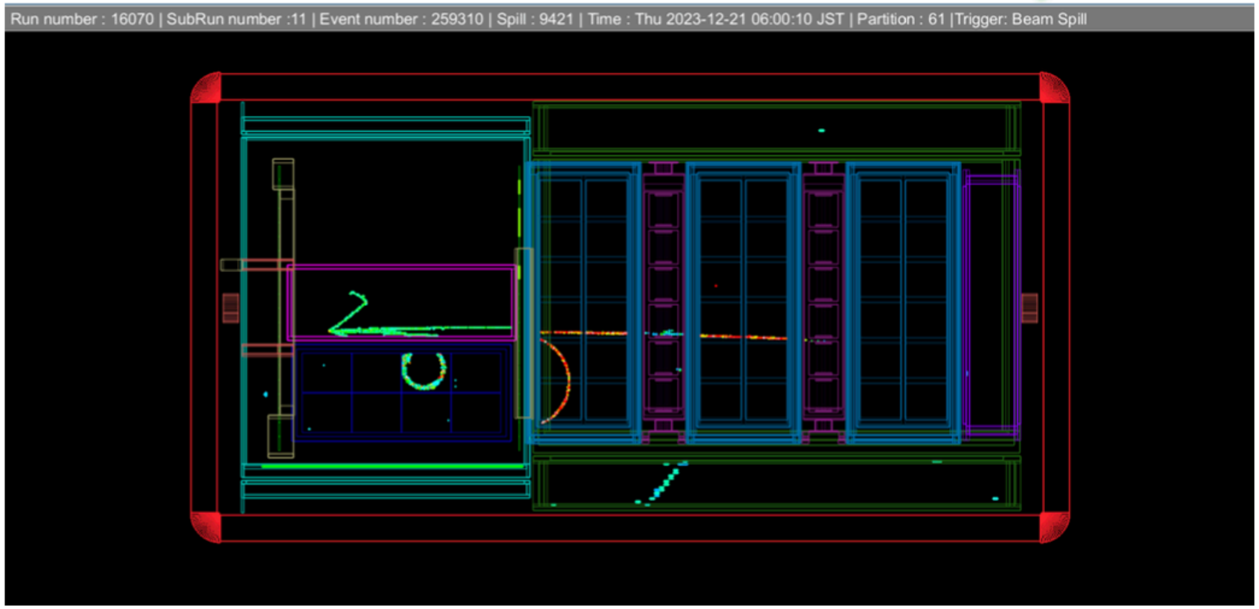

November 2023

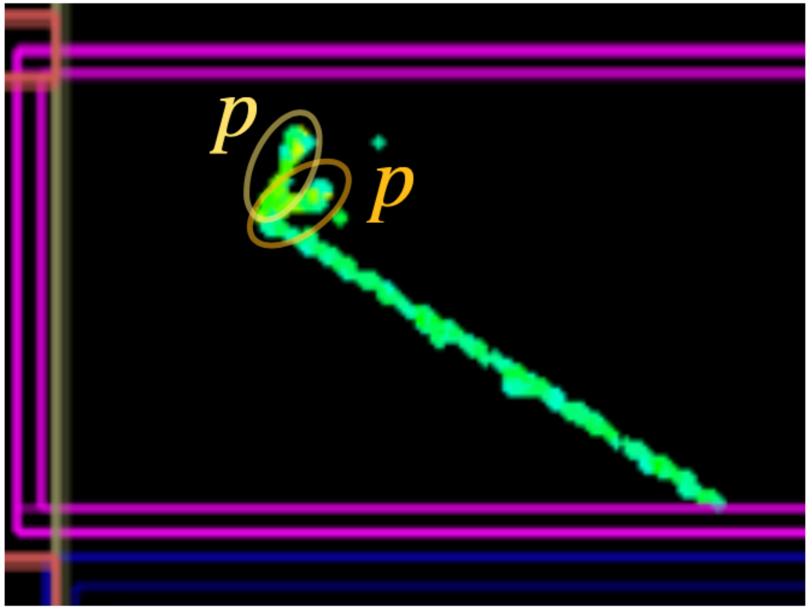

November 2023

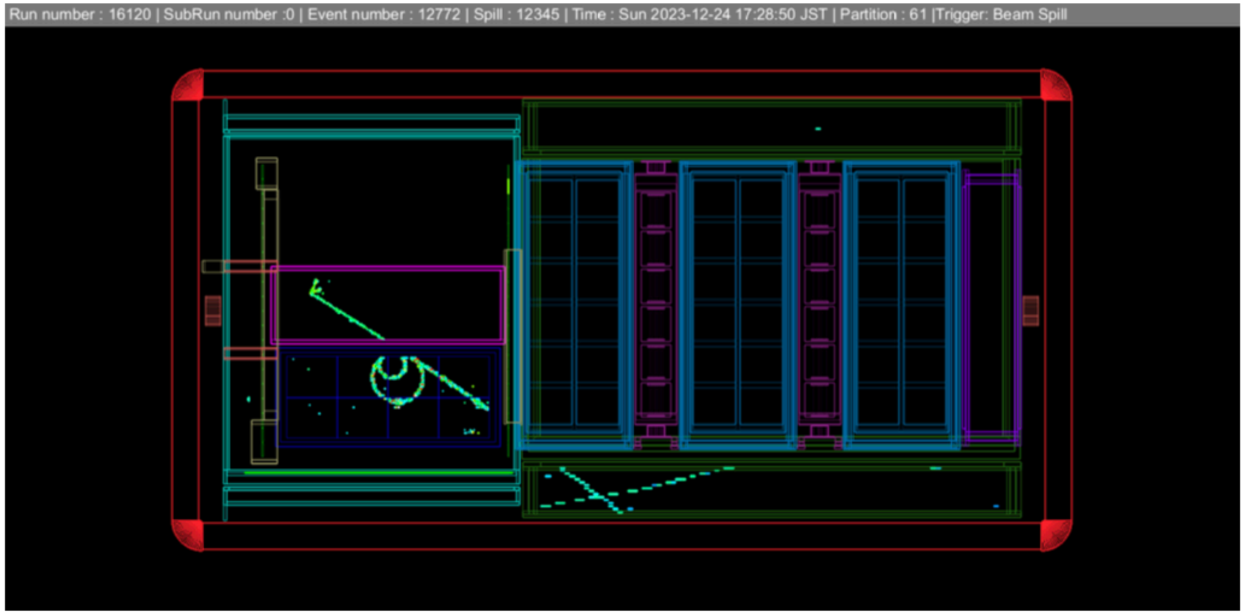
Full upgrade installed successfully last May!

Some nice events from December 2023 without top-HAT

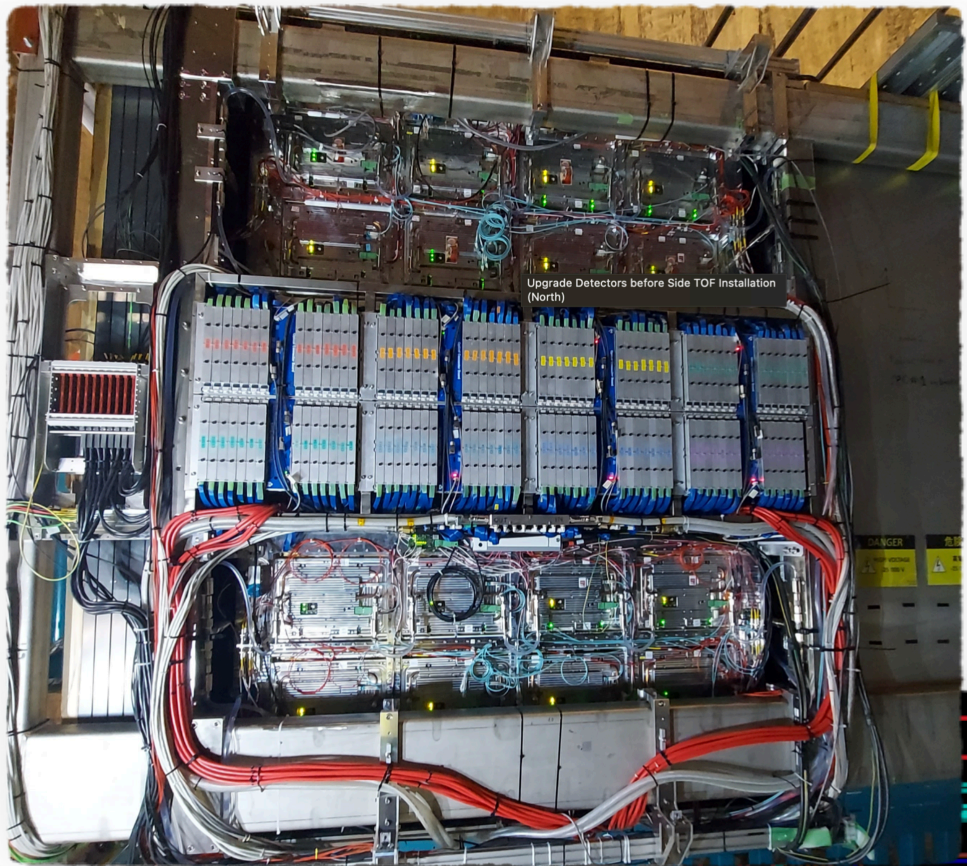


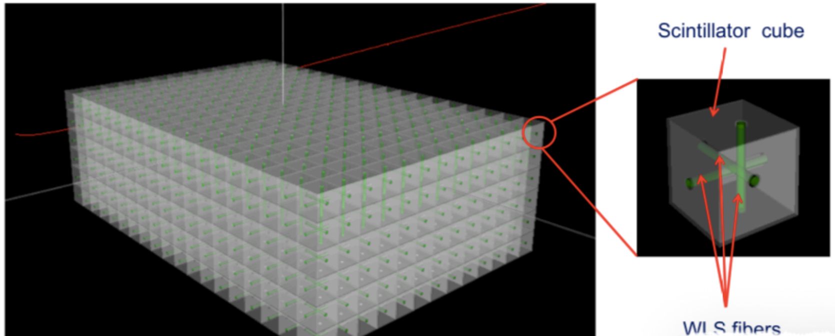

Run number : 16070 | SubRun number :11 | Event number : 259310 | Spill : 9421 | Time : Thu 2023-12-21 06:00:10 JST | Partition : 61 |Trigger: Beam Spill

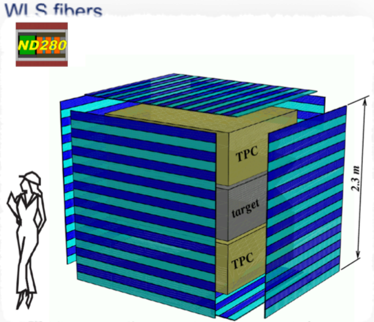


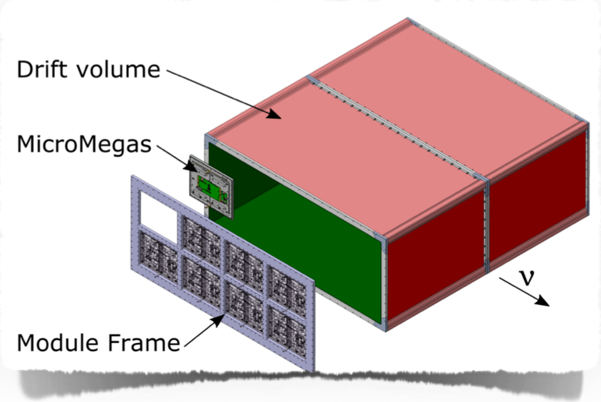

Run number : 16120 | SubRun number :0 | Event number : 12772 | Spill : 12345 | Time : Sun 2023-12-24 17:28:50 JST | Partition : 61 |Trigger: Beam Spill

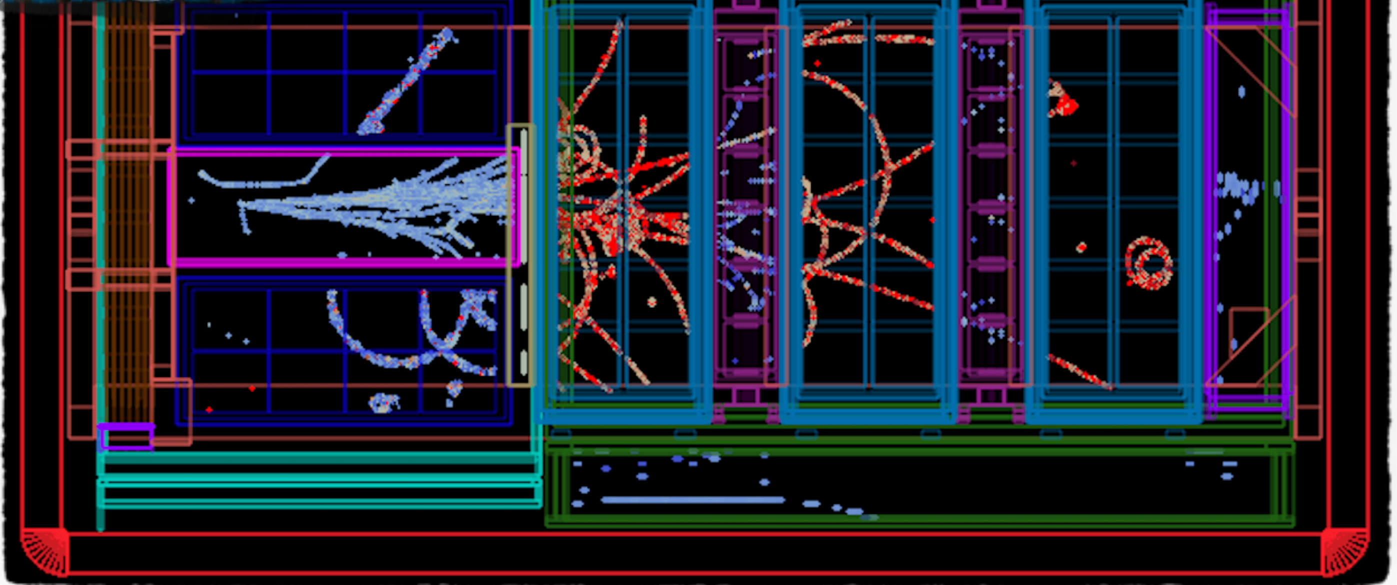
Full ND280 upgrade successfully installed in spring 2024 and running











Conclusions

- The next to next T2K OA will include **new near detector upgraded samples** with a 4π acceptance like in SK
- To achieve the exclusion of δ_{CP} conserving values at $> 3\sigma$ **more statistic is needed**

- **Neutrino beam upgrade**
  - 800 kW reached last June
  - Steady improvement to reach 1.3 MW by 2027 (factor of 3 more stat in 2027)
  - Need to collect 10^{22} POT to almost reach 3σ for CPV measure

- **ND280 upgrade**
  - Improve 4π lepton reconstruction thanks to HATPC
  - Improve low energy nucleon reconstruction thanks to sFGD
  - Better discrimination of OOFV Background thanks to the TOF
  - Better understanding of x-sec modeling leads to an improved OA

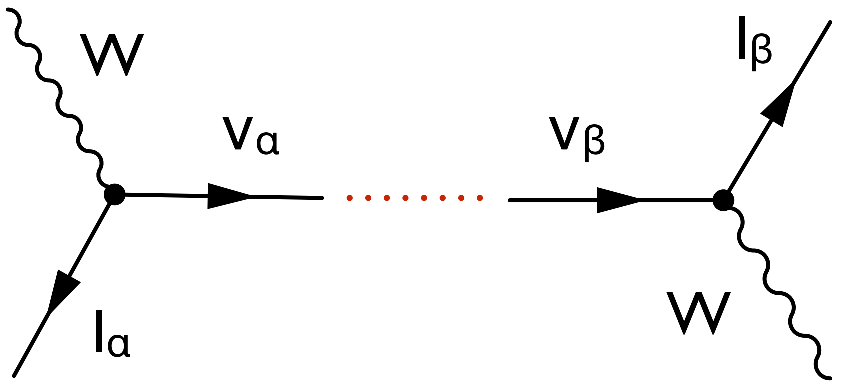
- **Thanks to a lot of work from many people, and thanks to the support of funding agencies, T2K has entered its second phase!**

- **Full upgrade installed last spring**

- **Detectors are working very well**
  - Already observed very nice neutrino interactions
  - Stay tuned for next T2K OA with improved statistic and new near detector upgrade samples!

Backup

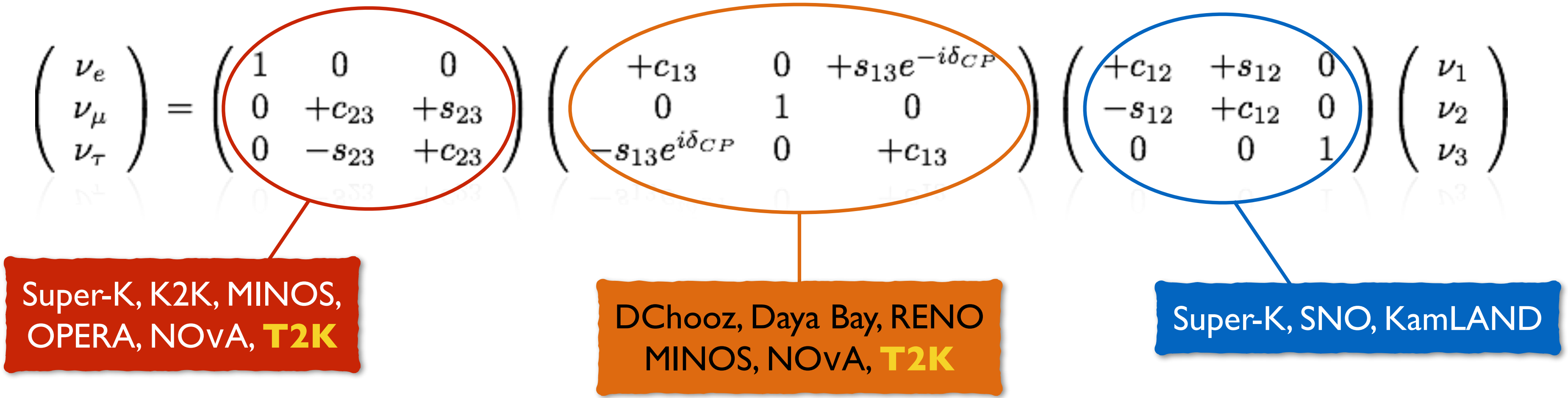
Mixing of three neutrinos



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matrix



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Super-K, K2K, MINOS, OPERA, NOvA, **T2K**

DChooz, Daya Bay, RENO MINOS, NOvA, **T2K**

Super-K, SNO, KamLAND

$c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$
(PMNS Neglecting possible Majorana phases)

Current knowledge:

- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

Open questions:

- CP violation?
- Mass Ordering ($m_{1,2} \gtrless m_3$)?
- Is $\theta_{23} = 45^\circ$?
- Majorana/Dirac? ($0\nu\beta\beta$)

Neutrino appearance and disappearance at T2K

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta m^2_{31}\frac{L}{4E}$$

- Precision measurement of θ_{23} and Δm^2_{31}
- CPT test with anti-neutrino mode ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = \; & 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E_\nu} \times \left[1 \pm \frac{2a}{\Delta m^2_{13}}(1-s^2_{13})\right] \\ & +8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta_{CP} - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E\nu} \\ & \mp 8c^2_{13}c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta_{CP}\sin\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\ & +4s^2_{12}c^2_{13}(c^2_{13}c^2_{23} + s^2_{12}s^2_{23}s^2_{13} - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta_{CP})\sin\frac{\Delta m^2_{12}L}{4E_\nu} \\ & \mp 8c^2_{12}s^2_{13}s^2_{23}\cos\frac{\Delta m^2_{23}L}{4E_\nu}\sin\frac{\Delta m^2_{13}L}{4E_\nu}\frac{aL}{4E_\nu}(1-2s^2_{13}) \end{aligned}$$

θ_{13} driven

CP even

CP odd

Solar driven

Matter effect (CP odd)

Change sign by changing ν with $\bar{\nu}$

B. Richter, SLAC-PUB-8587

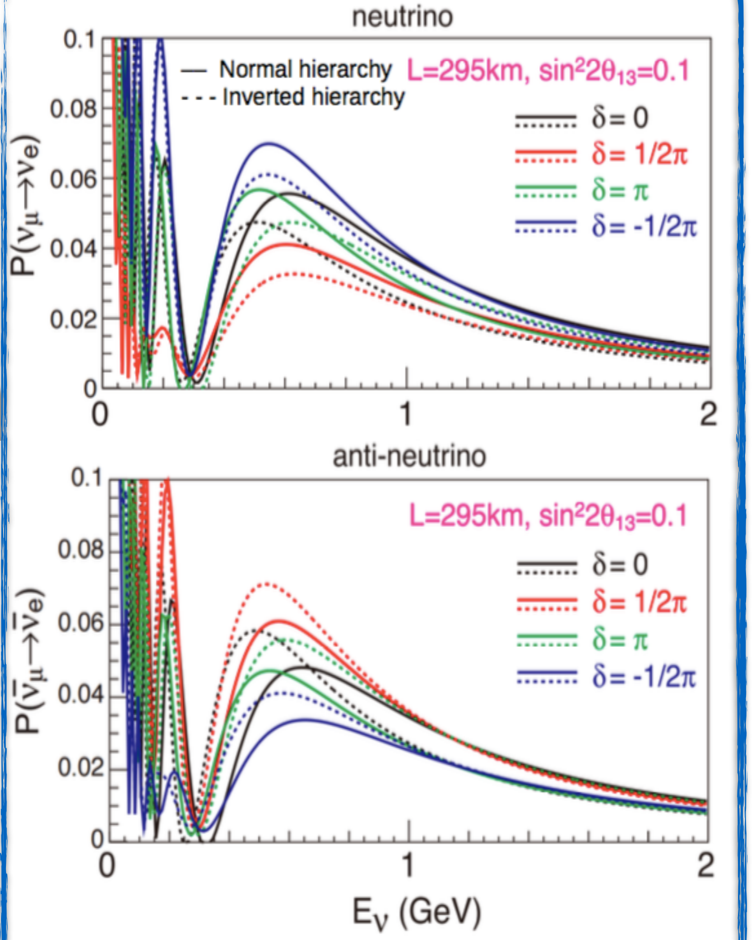
$$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6 \times 10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$$

- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term (θ_{23}=45° or $\theta_{23} \gtrsim 45°$?)
- ➤ **CP violation**: asymmetry of probabilities P($\nu_\mu \rightarrow \nu_e$) ≠ P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) if sinδ≠0
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted) mass ordering

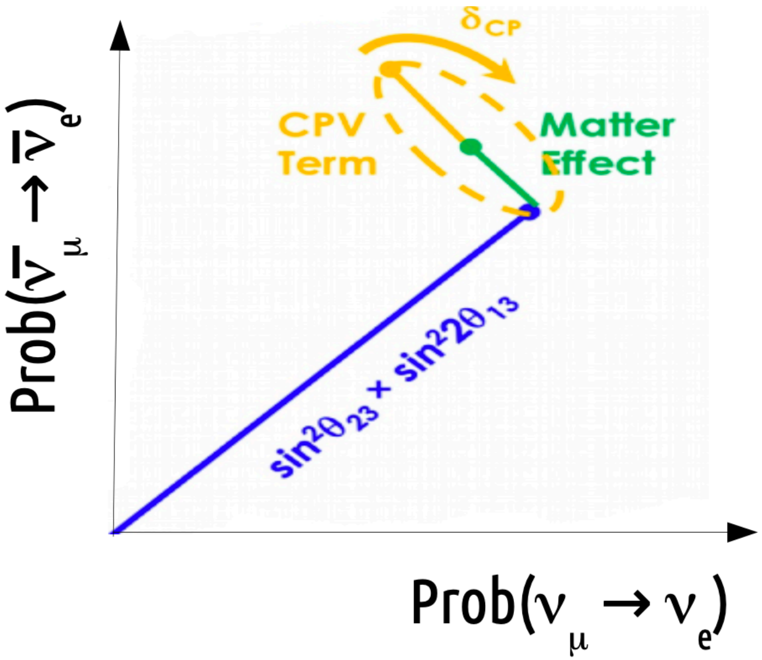
Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ and $\sin^2\theta_{23}$ enhance/suppress both ν_e and $\bar{\nu}_e$ appearance

- CP-violating phase δ_{CP} (**up to ±30% effect at T2K**)
  - **δ_{CP} = 0, π**⇒ no CP violation: $P(\nu_\mu\rightarrow\nu_e) = P(\bar{\nu}_\mu\rightarrow\bar{\nu}_e)$ in vacuum
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu\rightarrow\nu_e$ and suppress $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu\rightarrow\nu_e$ and enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$



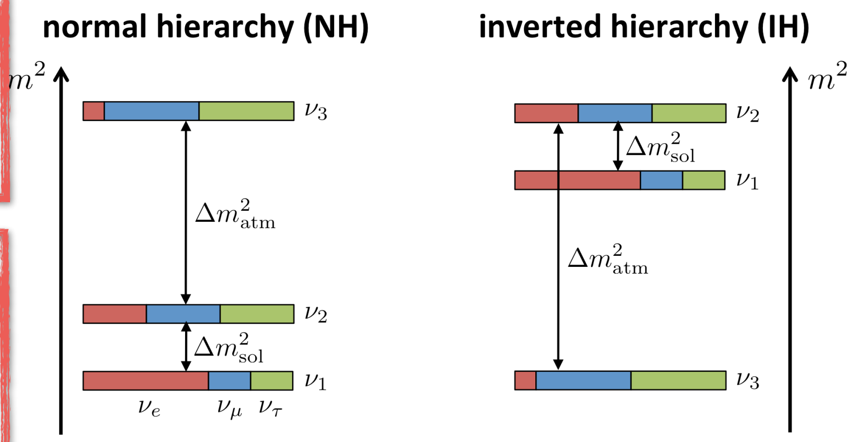
PTEP 2015 (2015) 053C02



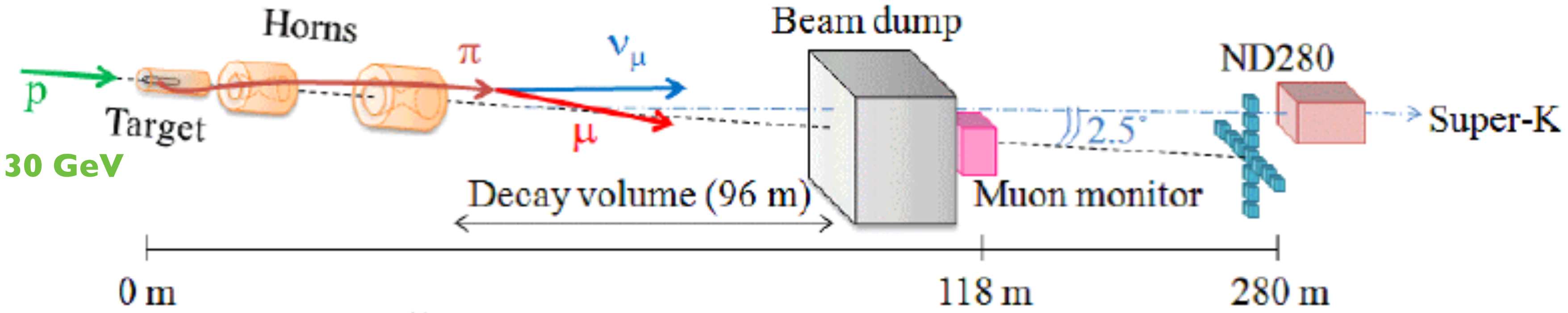
±10% matter effect at T2K

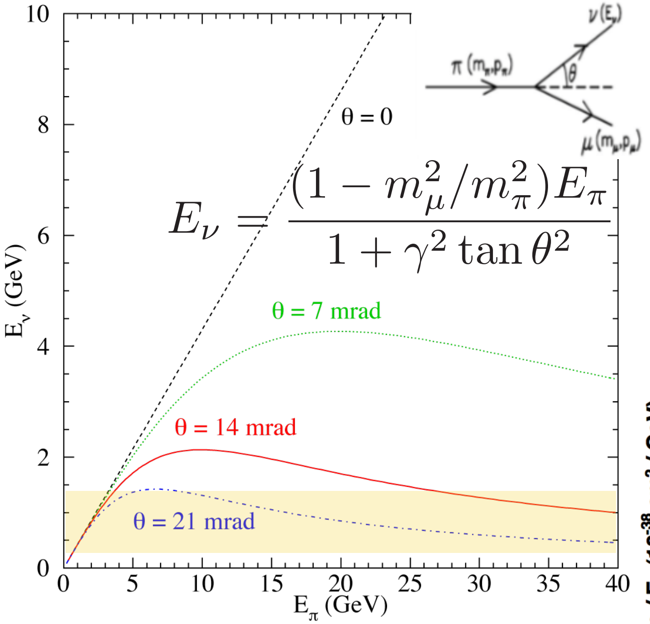
Normal hierarchy
- Enhance $\nu_\mu\rightarrow\nu_e$
- Suppress $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

Inverted hierarchy
- Suppress $\nu_\mu\rightarrow\nu_e$
- Enhance $\bar{\nu}_\mu\rightarrow\bar{\nu}_e$

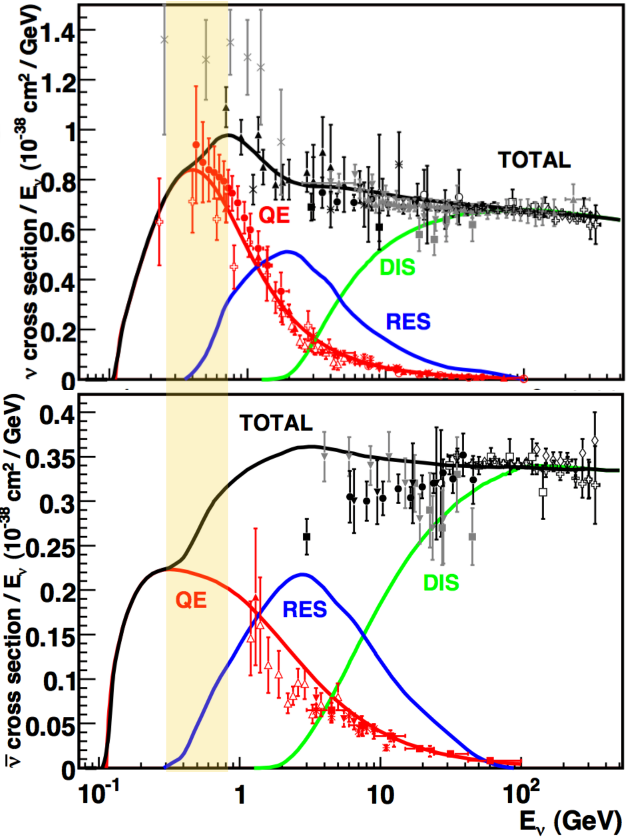


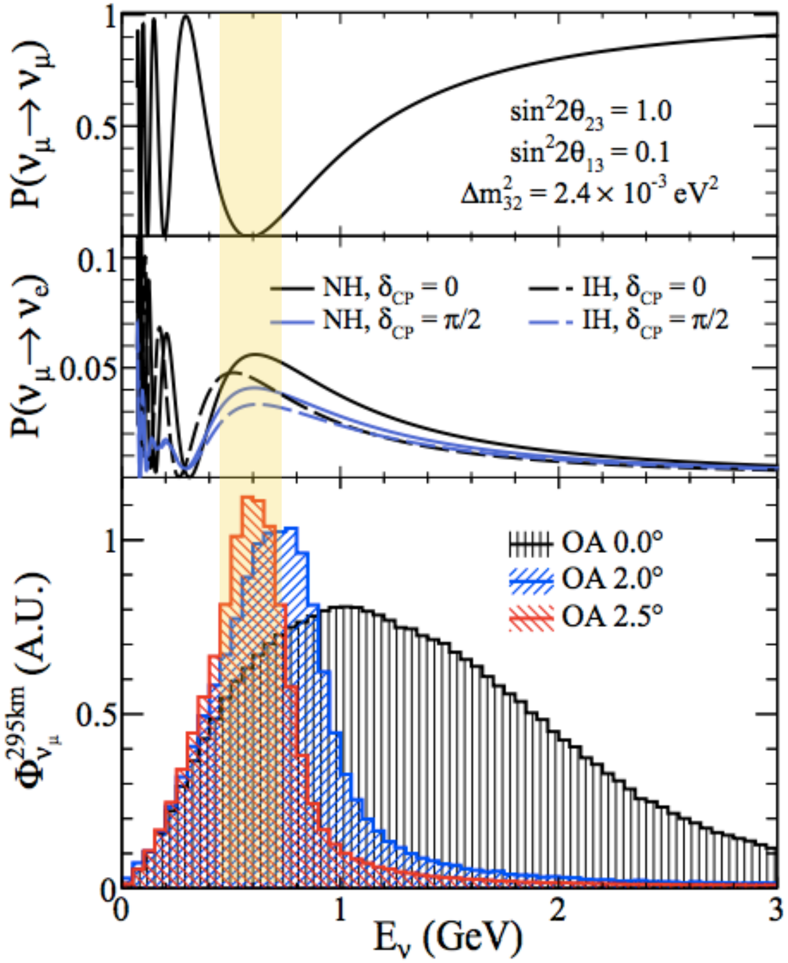
The off-axis neutrino beam





$$E_\nu = \frac{(1-m_\mu^2/m_\pi^2)E_\pi}{1+\gamma^2\tan\theta^2}$$



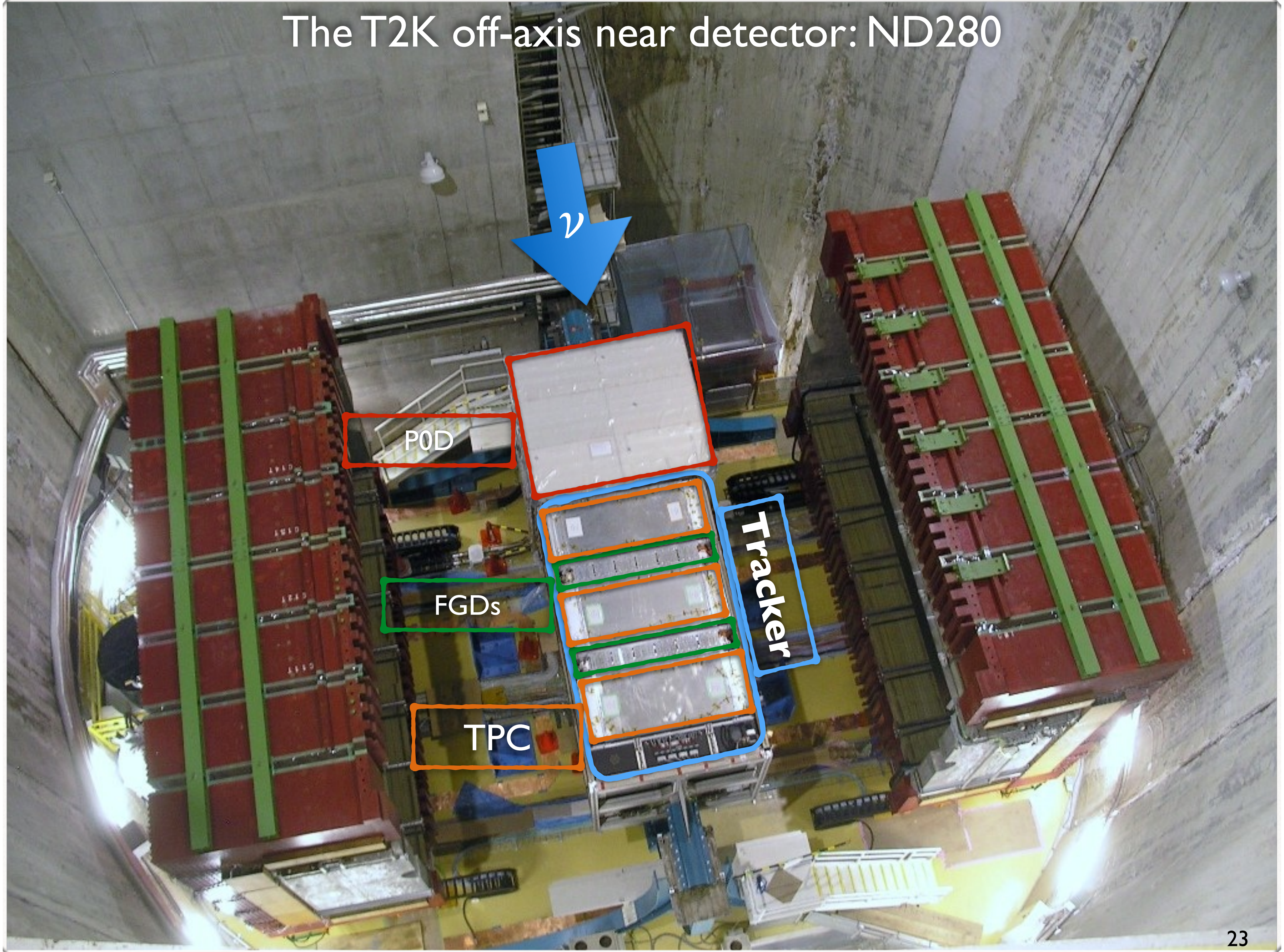


Charged Current Quasi-Elastic (CCQE)

$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

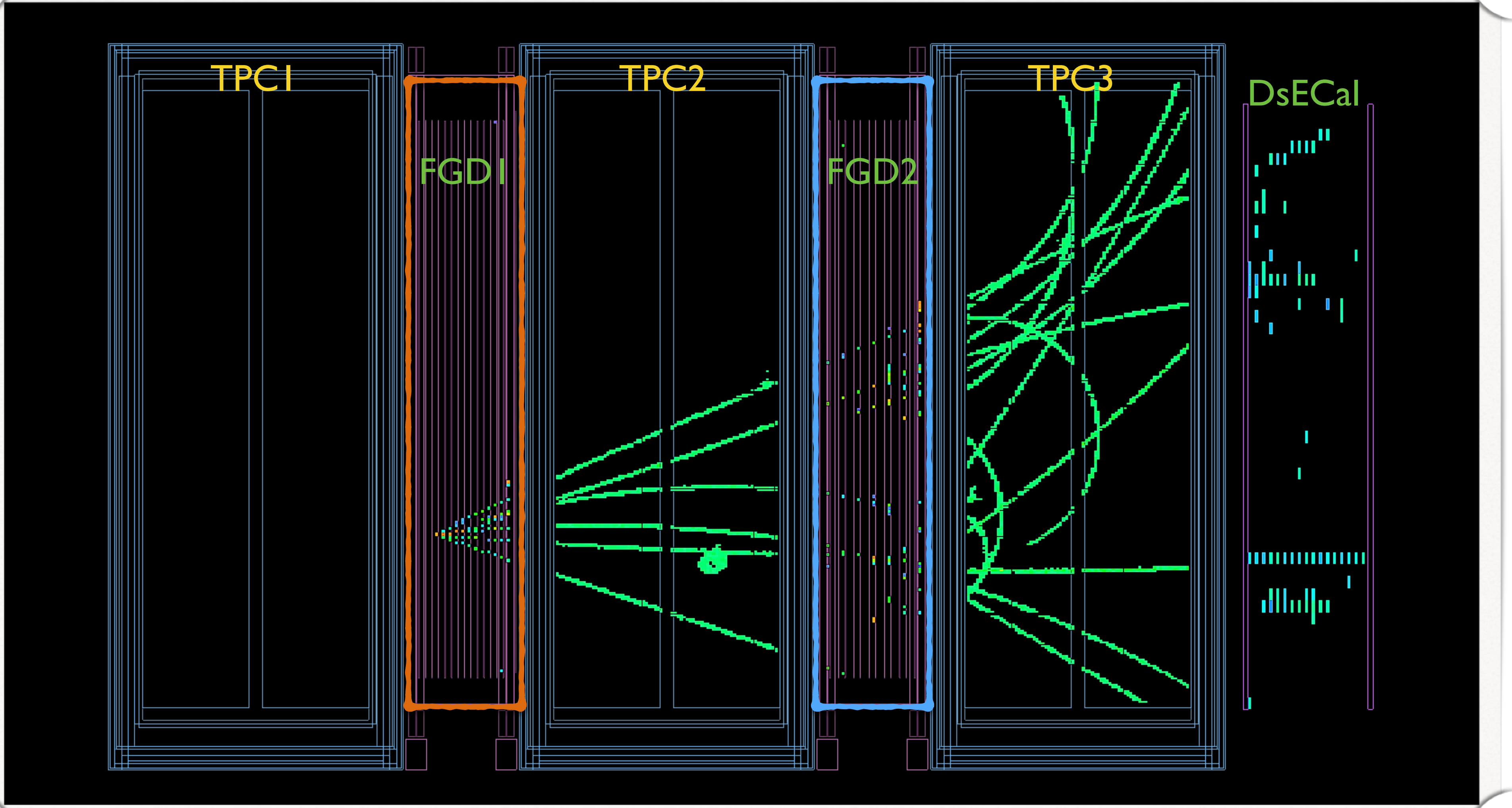
- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduce background from π^0 interactions
- Changing horn current possible to run in ν and $\bar{\nu}$ beam mode

The T2K off-axis near detector: ND280

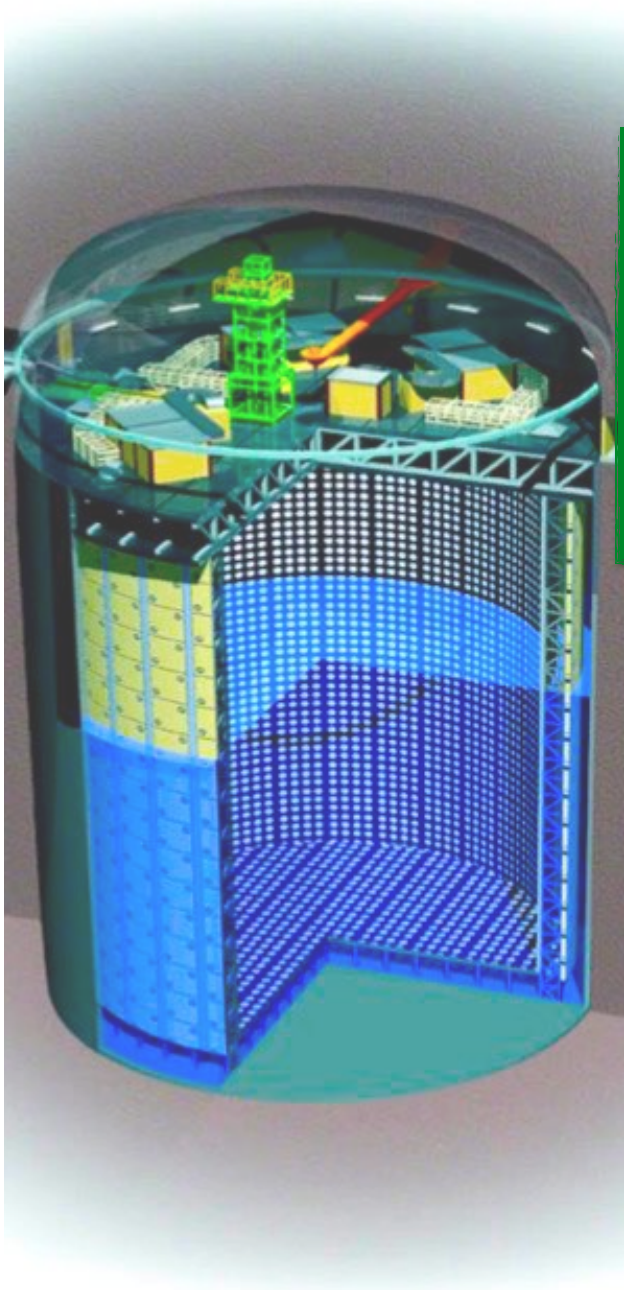


The T2K off-axis near detector: ND280

- ND280 **samples of ν_μ ($\bar{\nu}_\mu$) interactions in Carbon (FGD1) and water (FGD2)** have been employed **in the near detector analysis**.
- Precise measurement of P_μ and θ_μ with TPCs
- Distinguish ν from $\bar{\nu}$ interactions thanks to the **reconstruction of the charged lepton**
- Separate samples based on number of **reconstructed pions** ($CC0\pi$, $CC1\pi$, $CCN\pi$), **protons** and presence of **photons**

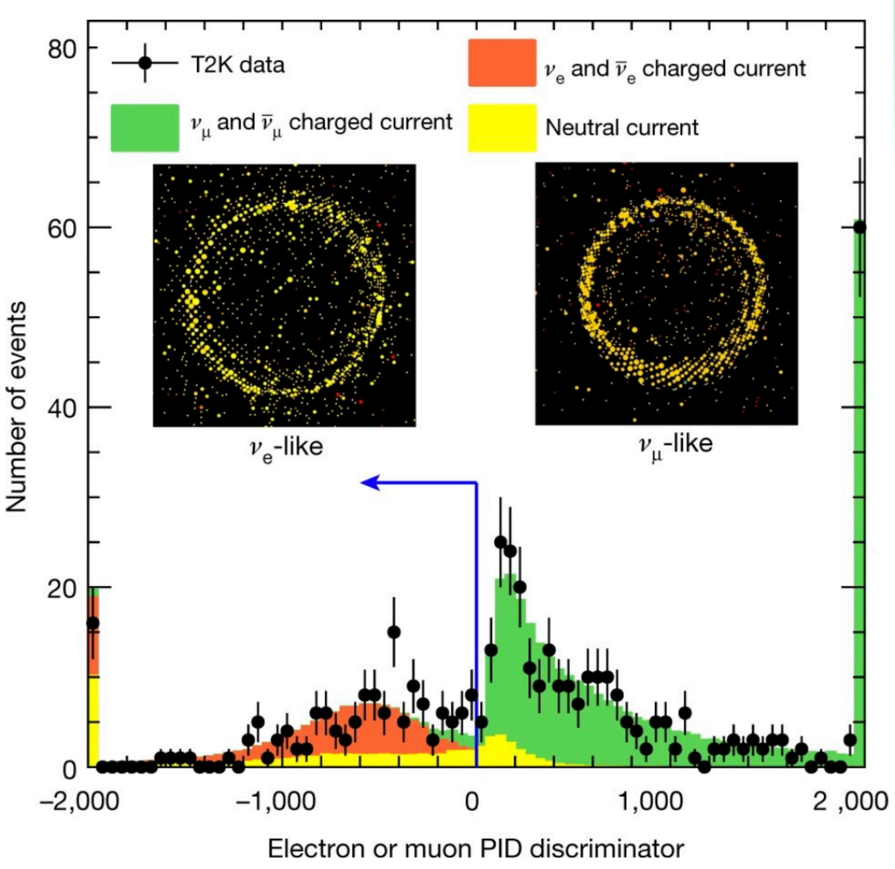


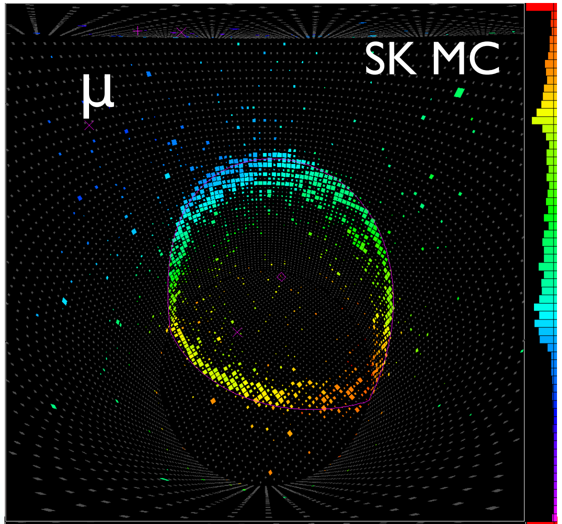
Far detector: Super-Kamiokande

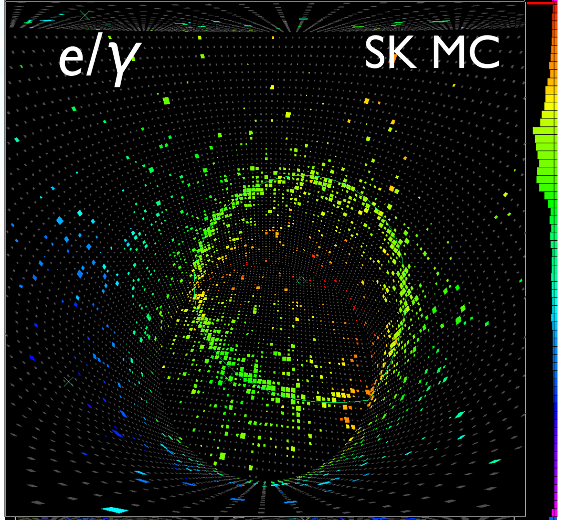


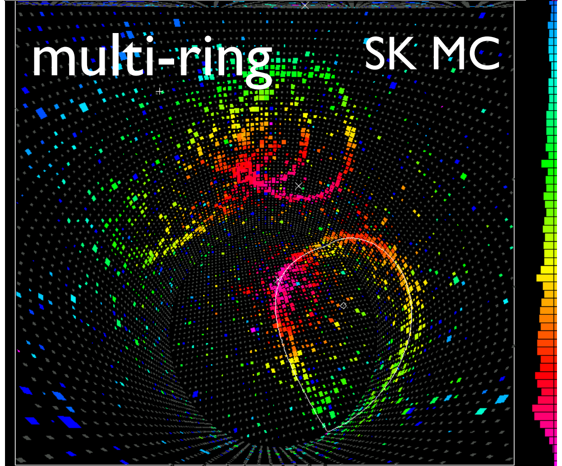
Super-K (2.5° off-axis)

- Water Cherenkov (22.5 kt fiducial volume, > 11k PMT, ~40 m x 40 m)
- Excellent μ/e separation (based on ring profile) and π^0 detection (2 e-like rings)
- <1% mis-PID at 1GeV
- ΔE/E ~10% for Quasi-Elastic (QE) events



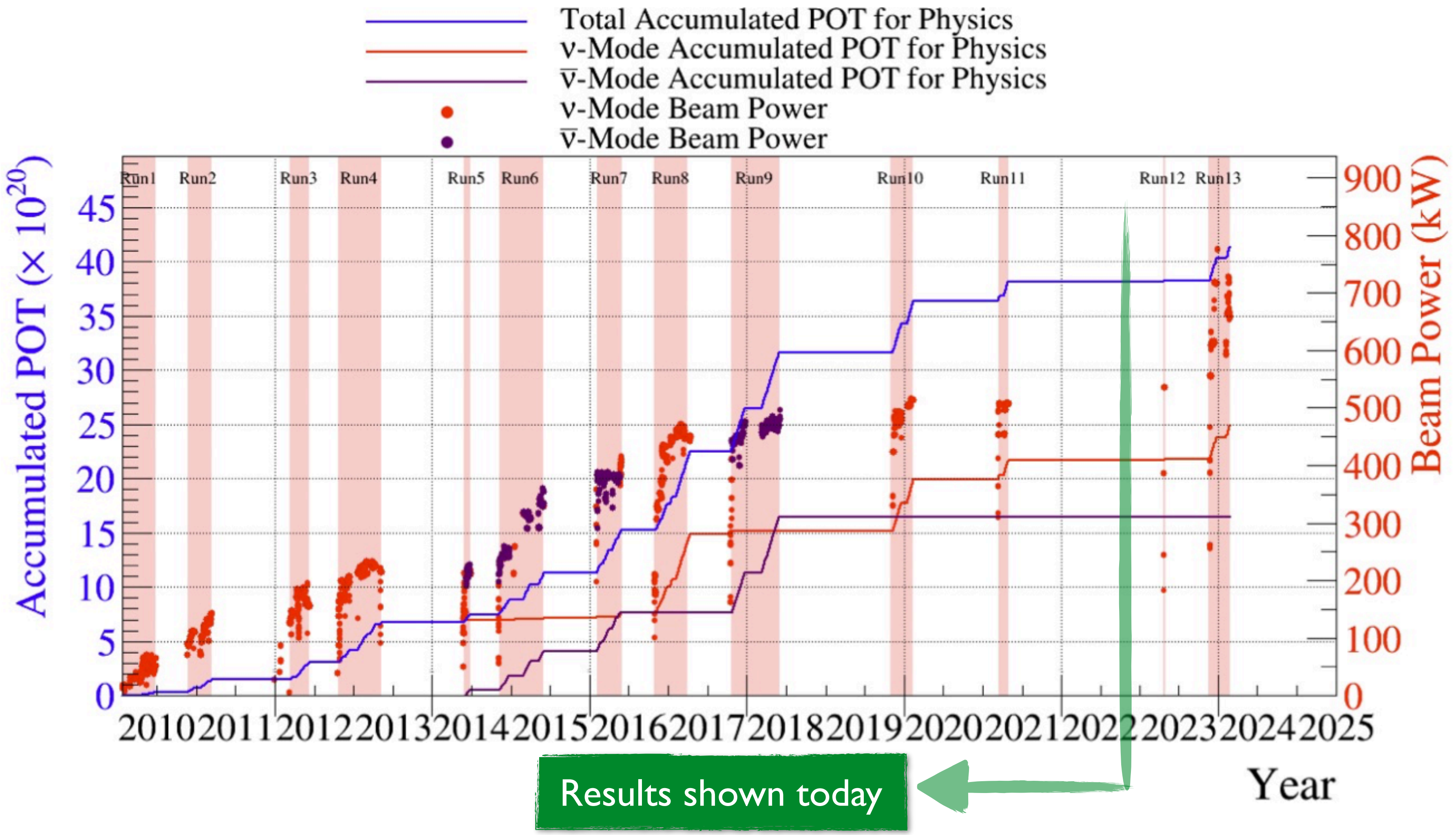






T2K oscillation results

Collected data

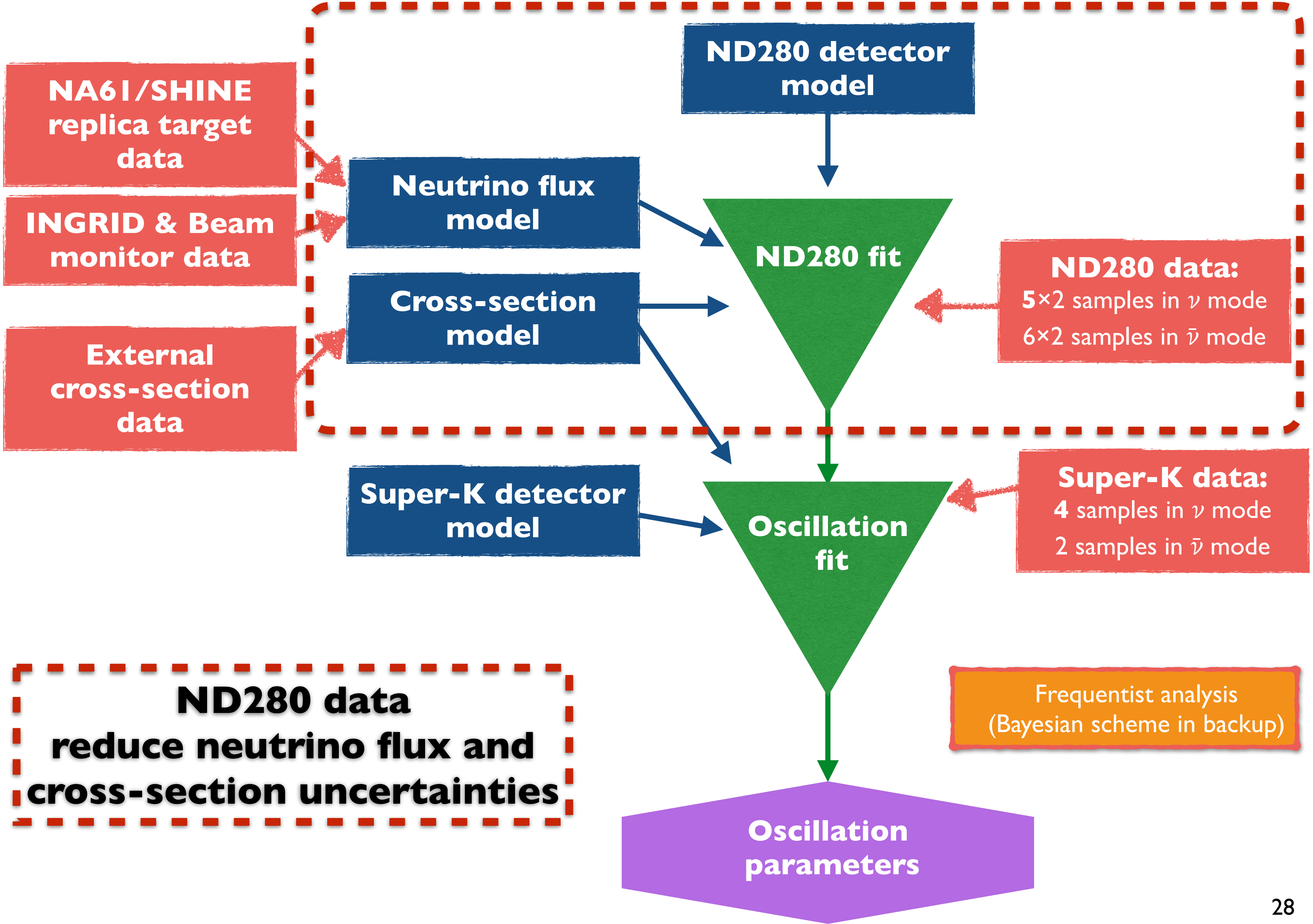


Results shown today

Results shown today with **3.77×10²¹ POT**
Run 11 with 0.01% Gd load added (~9% statistic)

POT	ND		FD	
Beam mode	ν	$\bar{\nu}$	ν	$\bar{\nu}$
This analysis	1.15×10^{21}	0.83×10^{21}	2.14×10^{21}	1.63×10^{21}

Oscillation analysis strategy



NA61/SHINE replica target data

INGRID & Beam monitor data

External cross-section data

Neutrino flux model

Cross-section model

ND280 detector model

ND280 fit

ND280 data:
5×2 samples in ν mode
6×2 samples in $\bar{\nu}$ mode

Super-K detector model

Oscillation fit

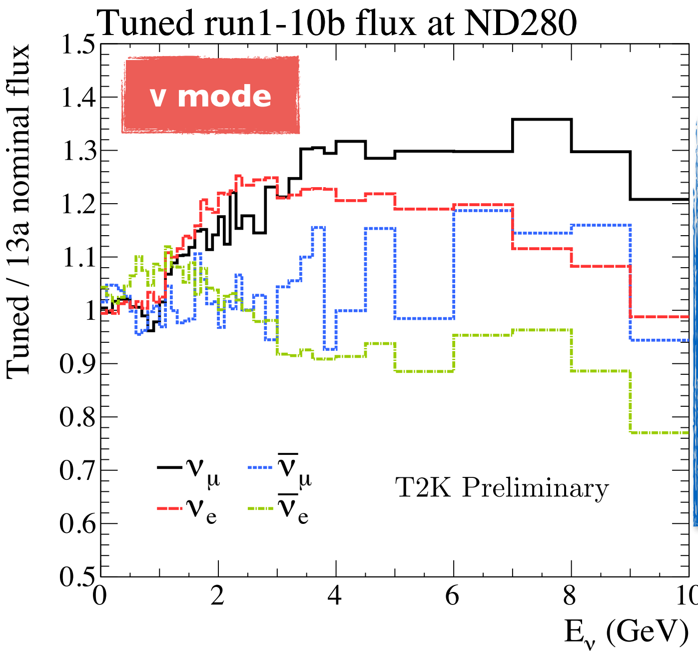
Super-K data:
4 samples in ν mode
2 samples in $\bar{\nu}$ mode

Oscillation parameters

ND280 data reduce neutrino flux and cross-section uncertainties

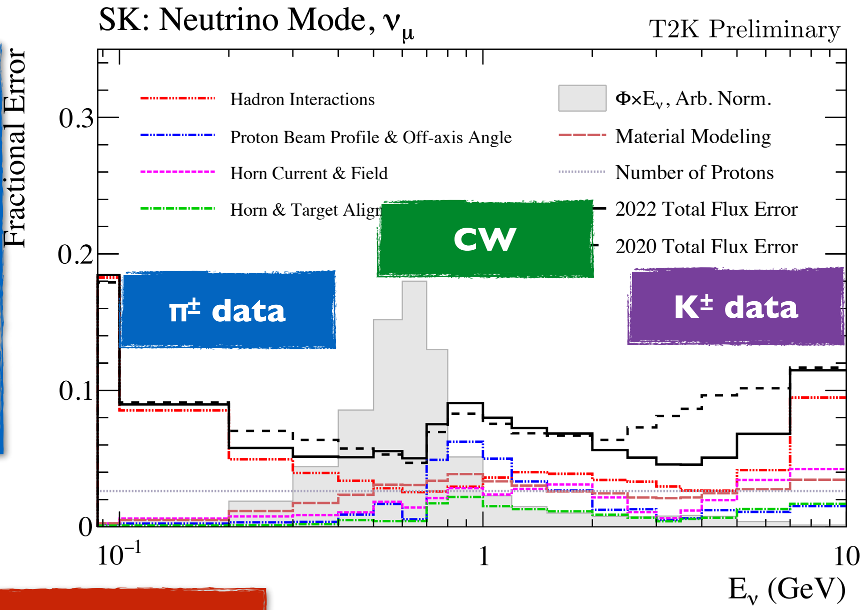
Frequentist analysis
(Bayesian scheme in backup)

ν flux and x-sec @ T2K



New NA61/SHINE Replica Target Data

- Improved (2020→2022) flux uncertainties
  - ↓ $\pi^\pm$ data improvements
  - ↑ Cooling water (CW)
  - ↓ $K^\pm$ data improvements

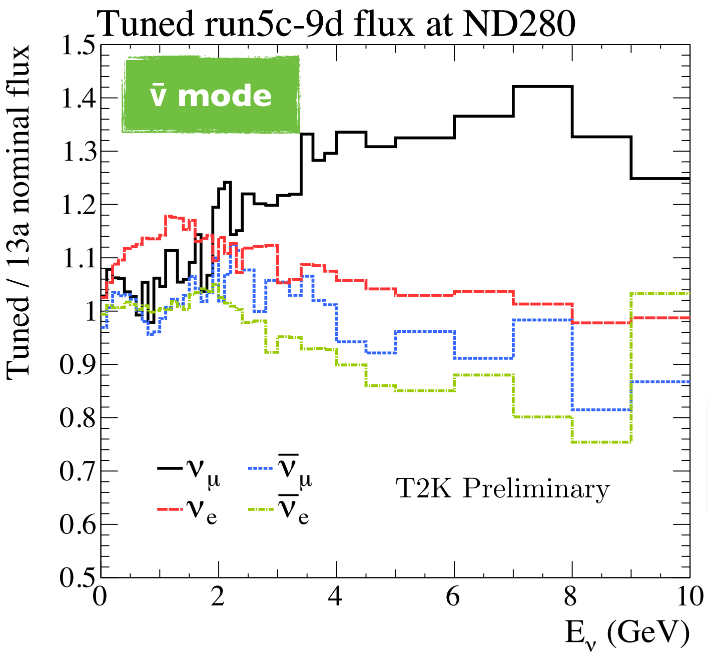


CW

$\pi^\pm$ data

$K^\pm$ data

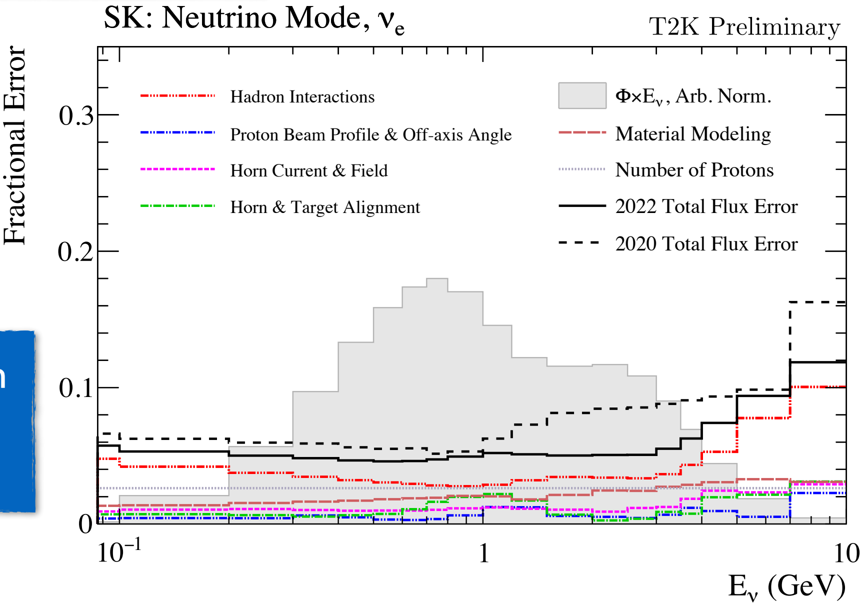
Overall reduction of flux error (by ~6%)



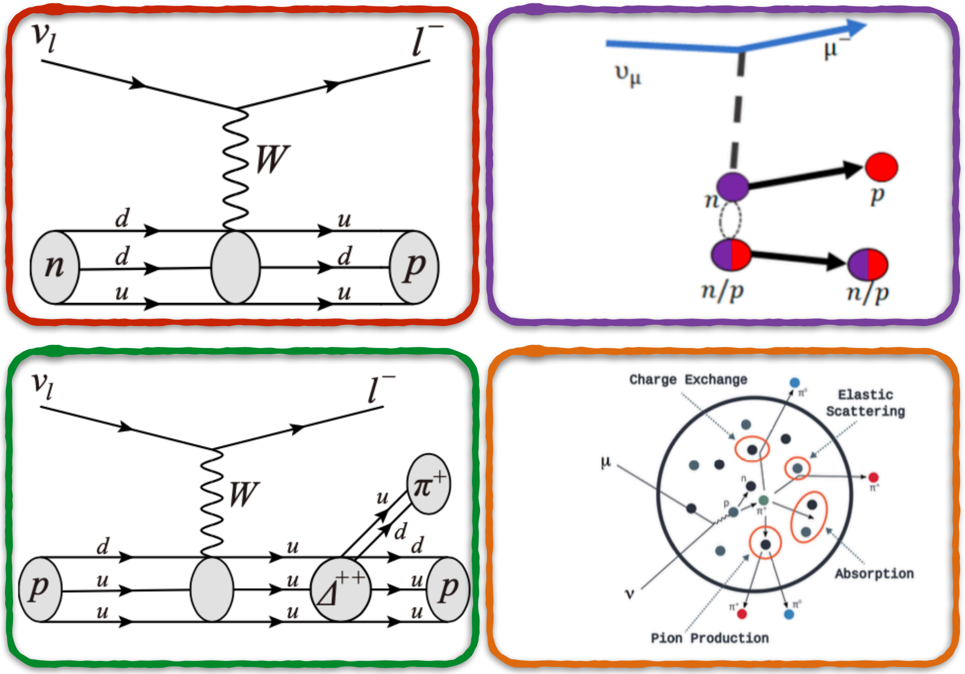
━━ 2022 Total Flux Error

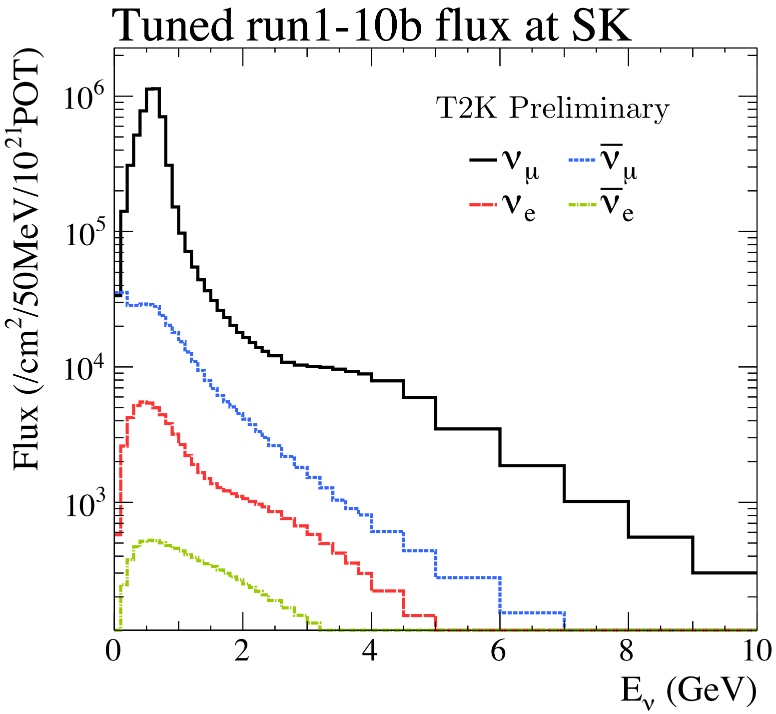
- - - 2020 Total Flux Error

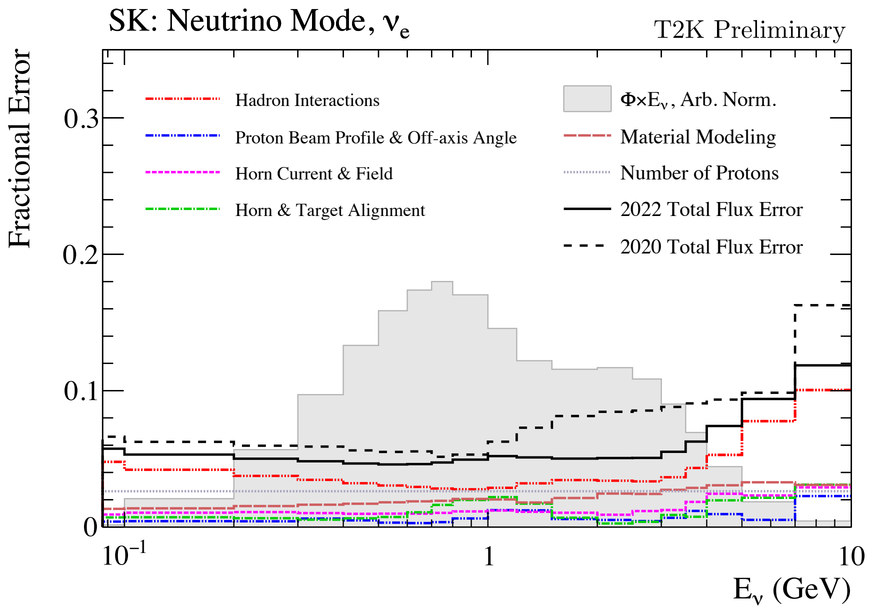
Impact of flux tuning based on **replica target** hadron production data



ν flux and x-sec @ T2K







- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction
  - **Mis-modeling might bias energy reconstruction!**

- Uncertainties on ν and $\bar{\nu}$ fluxes of ~5% thanks to NA61/SHINE measurements of hadron-production

Neutrino cross sections model improvements

- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction

- **Mimic CCQE interactions:**
  - Neutrino scatters on a correlated pair of nucleons (called multi-nucleon or 2 particle-2 hole, **2p-2h**)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion absorbed by the detector

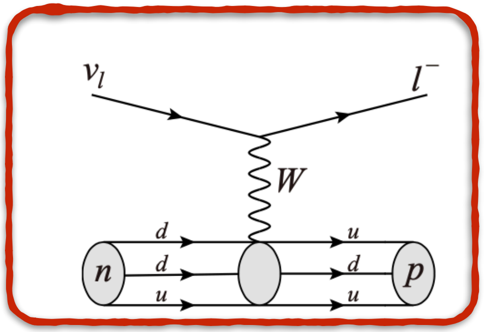
- **CCQE:**
  - Improved uncertainties for the **spectral function** model, specifically normalisation of nuclear shell model and short range correlations.
  - New treatment of **binding energy**.
  - Replaced ad-hoc **Q^2 normalisations** with Pauli blocking

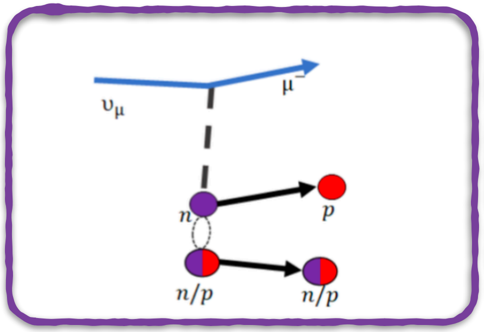
- **2p2h/MEC:**
  - Better descriptions of **2p2h proton-neutron/ neutron-neutron** pair contributions.

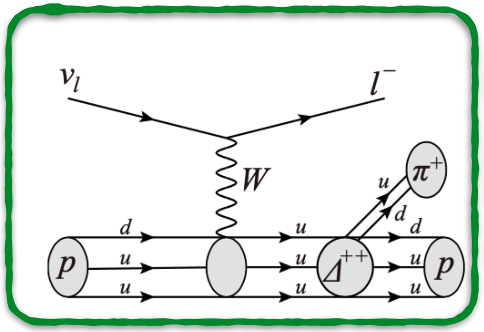
- **CCRes:**
  - New **bubble-chamber tuning of Rein-Sehgal model** parameters.
  - Effective inclusion of **binding energy**.
  - New **Δ resonance decay** uncertainty
  - New uncertainty in **$\pi^\pm$** vs **π^0** production

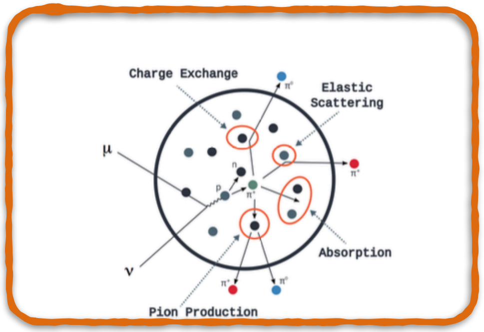
- **FSI:**
  - New nucleon final state interactions (FSI) uncertainty.

[link to NuFACT talk on Neutrino interaction models]

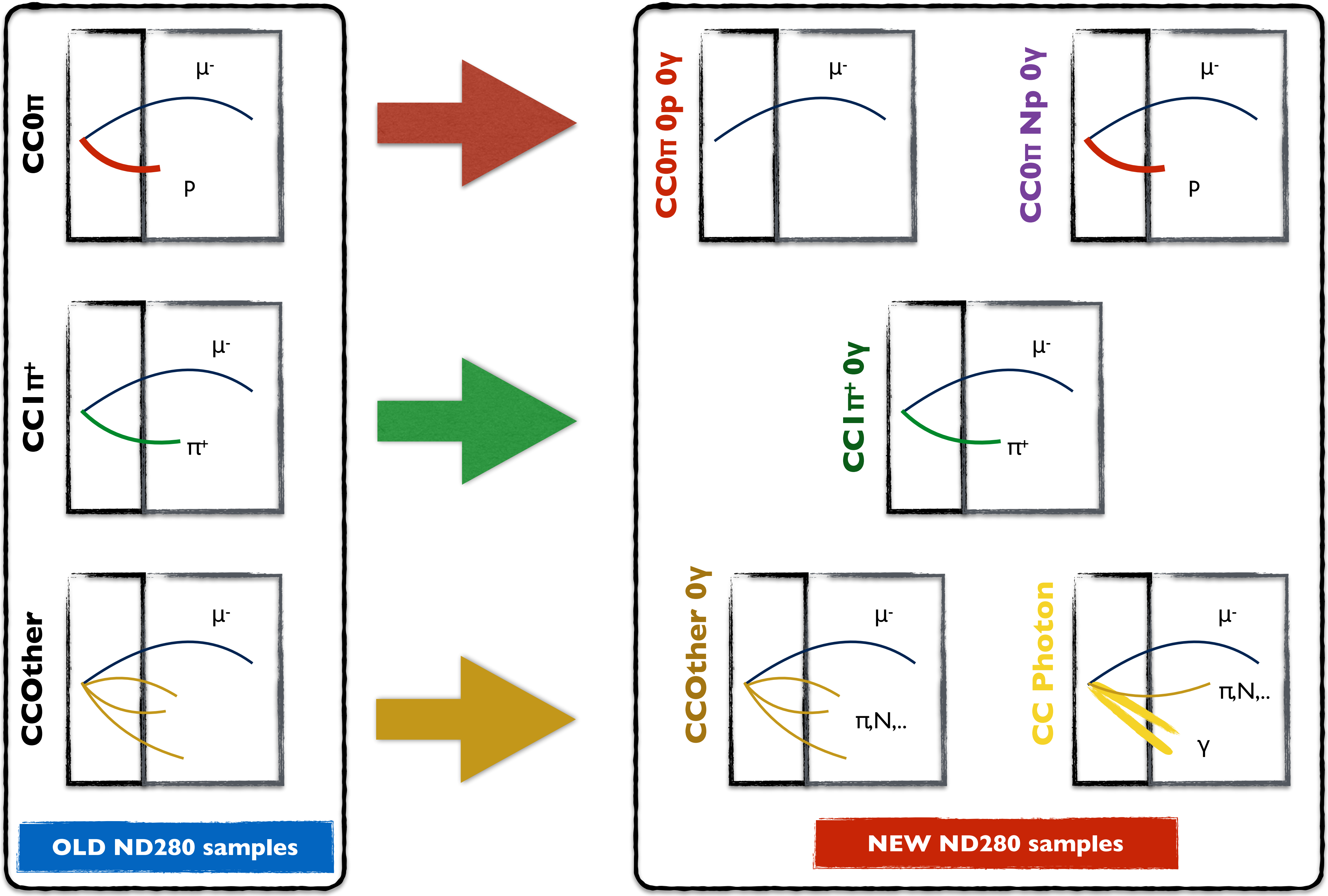








New ND280 samples in neutrino beam mode



CC0π

CC1π+

CCOther

OLD ND280 samples

CC0π 0p 0γ

CC0π Np 0γ

CC1π+ 0γ

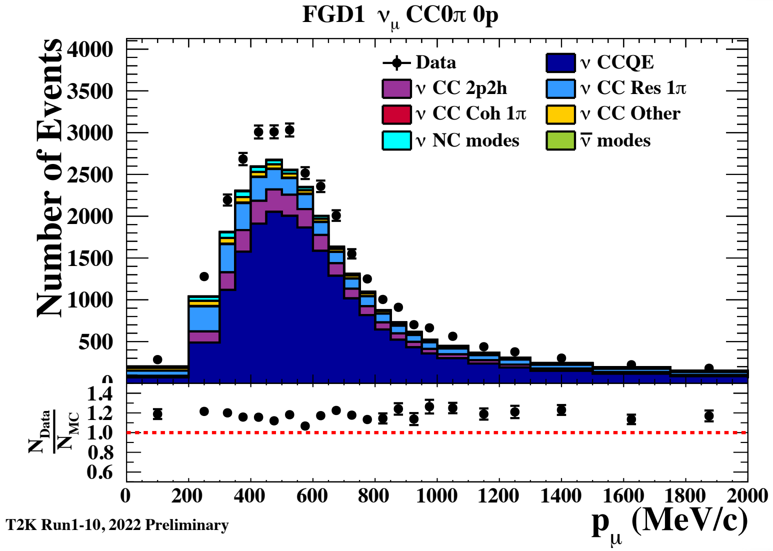
CCOther 0γ

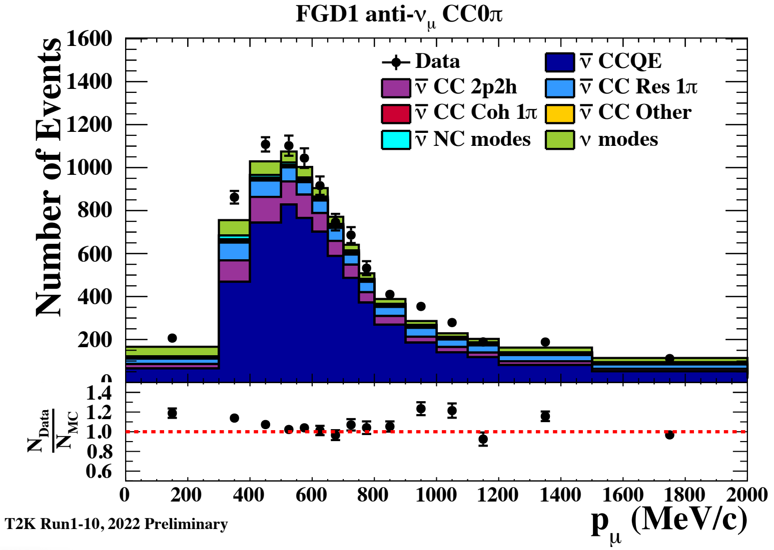
CC Photon

NEW ND280 samples

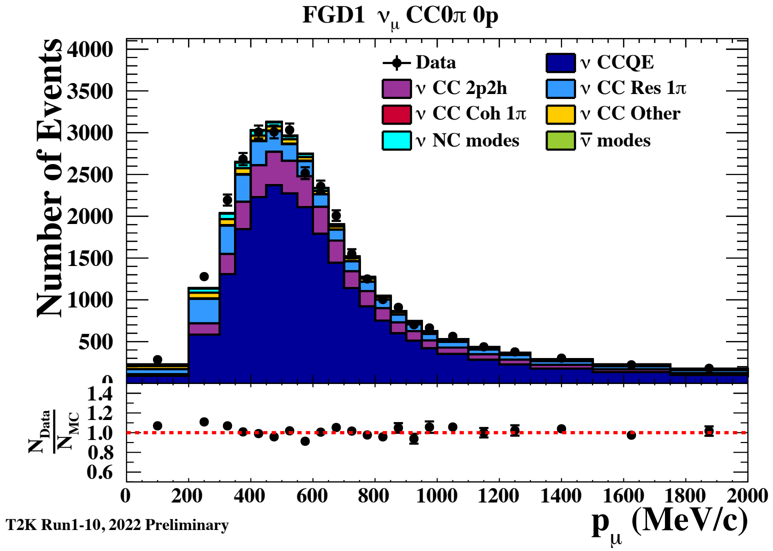
Fitting ND280 samples

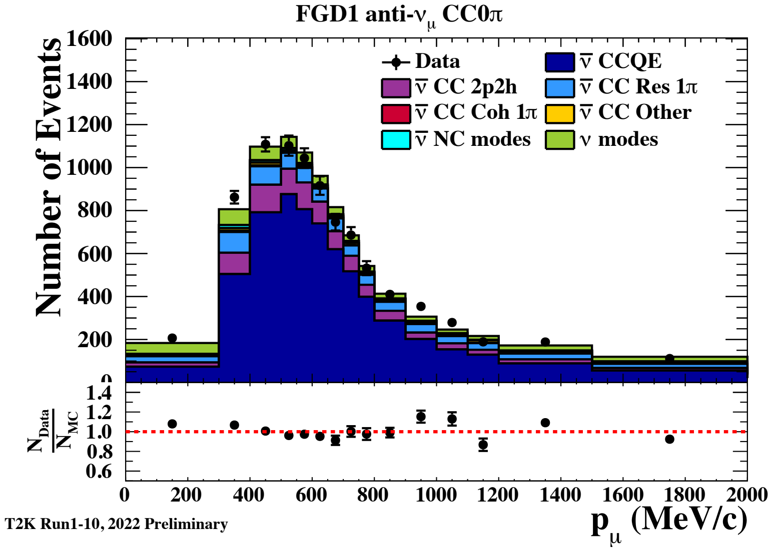
Pre ND280 fit





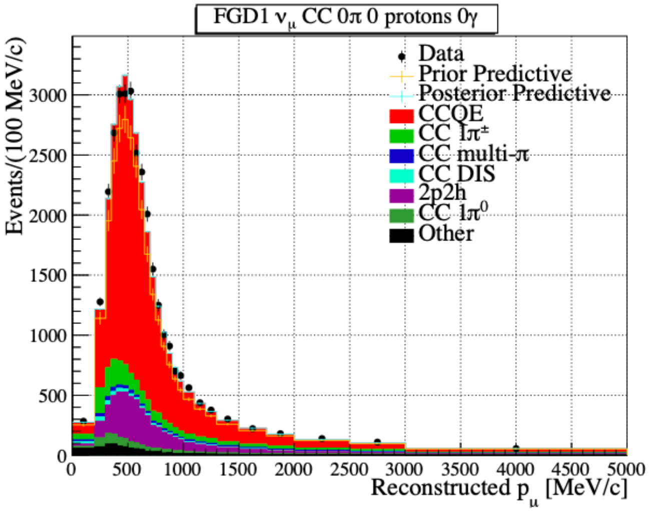
Post ND280 fit

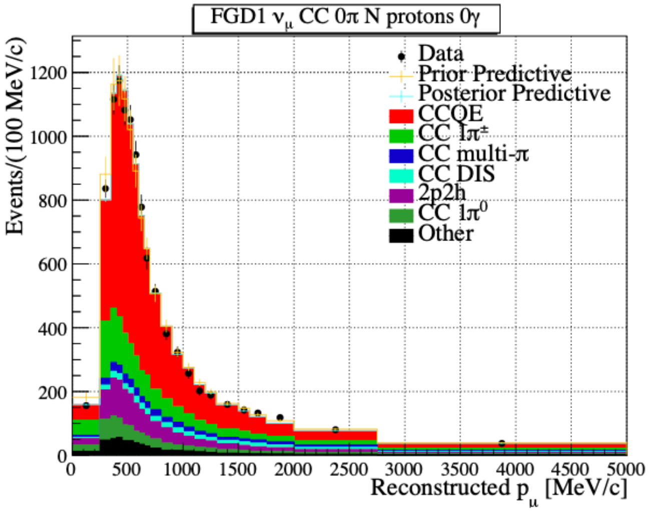


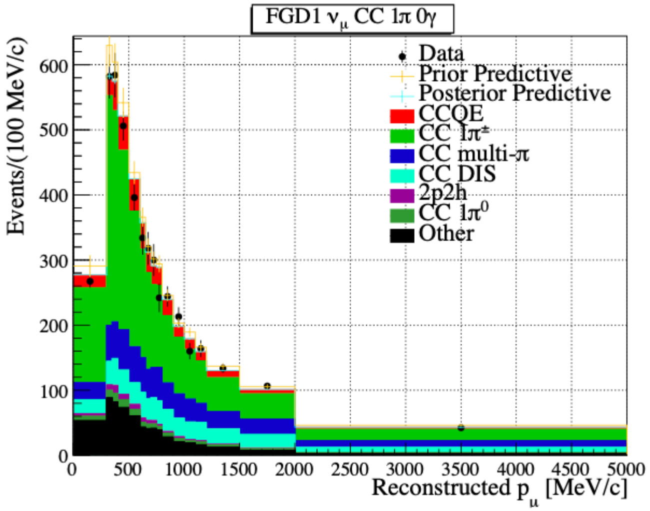


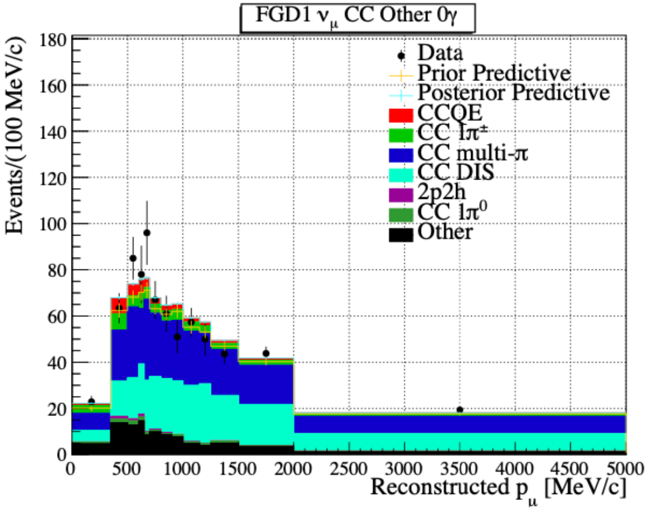
ND280 samples used to constraint on flux and x-sec models

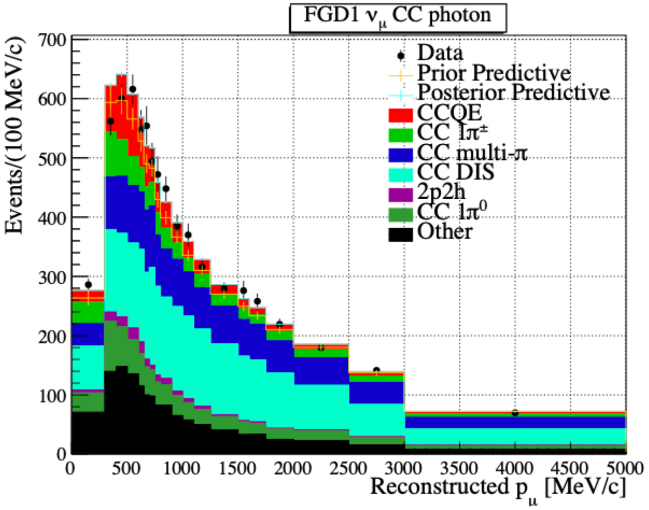
ND280 samples in neutrino beam mode





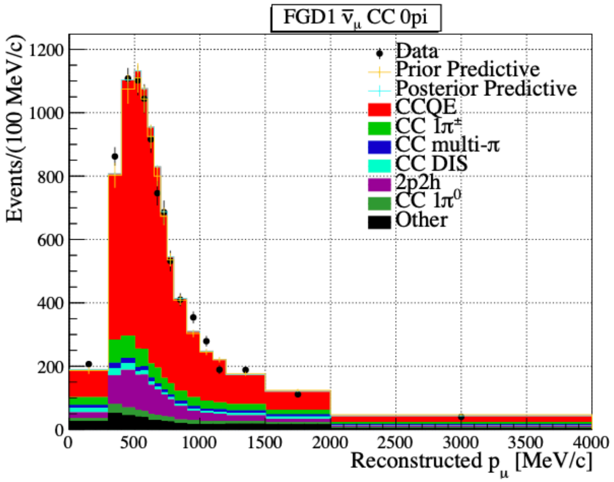


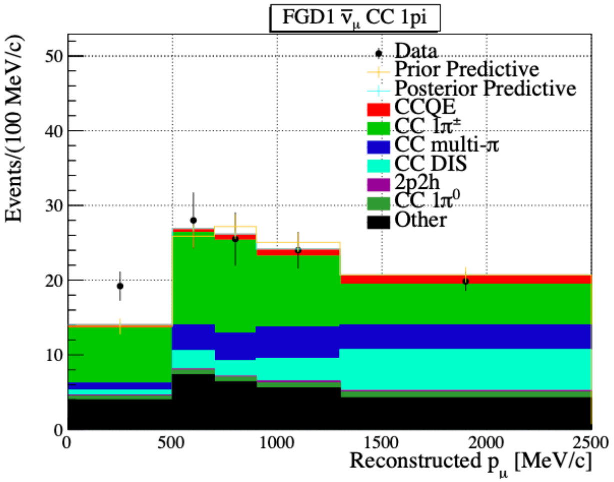


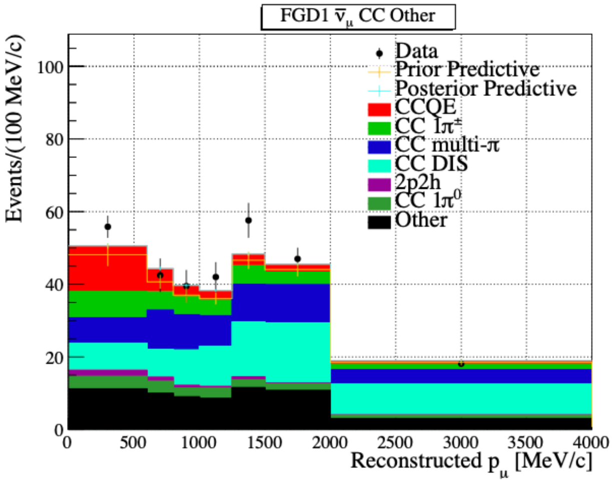


5 × 2 neutrino beam mode ND280 samples used in the oscillation analysis

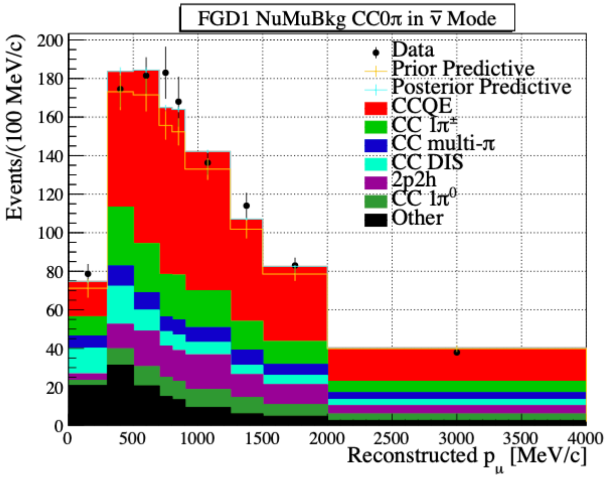
ND280 samples in neutrino beam mode

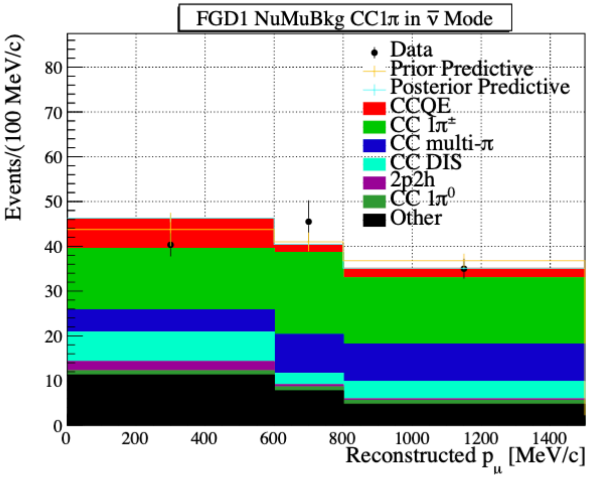


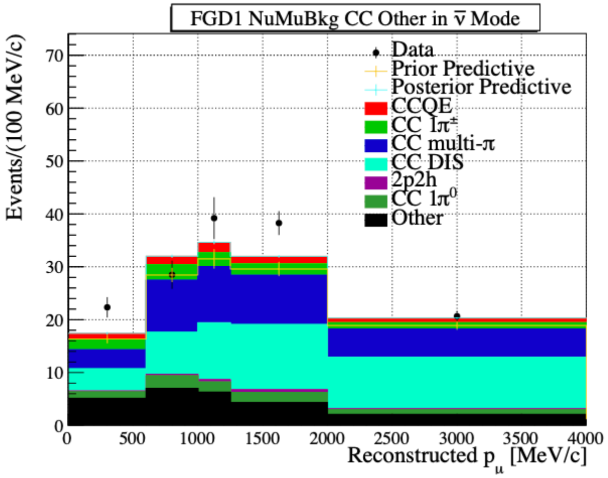




Right sign component





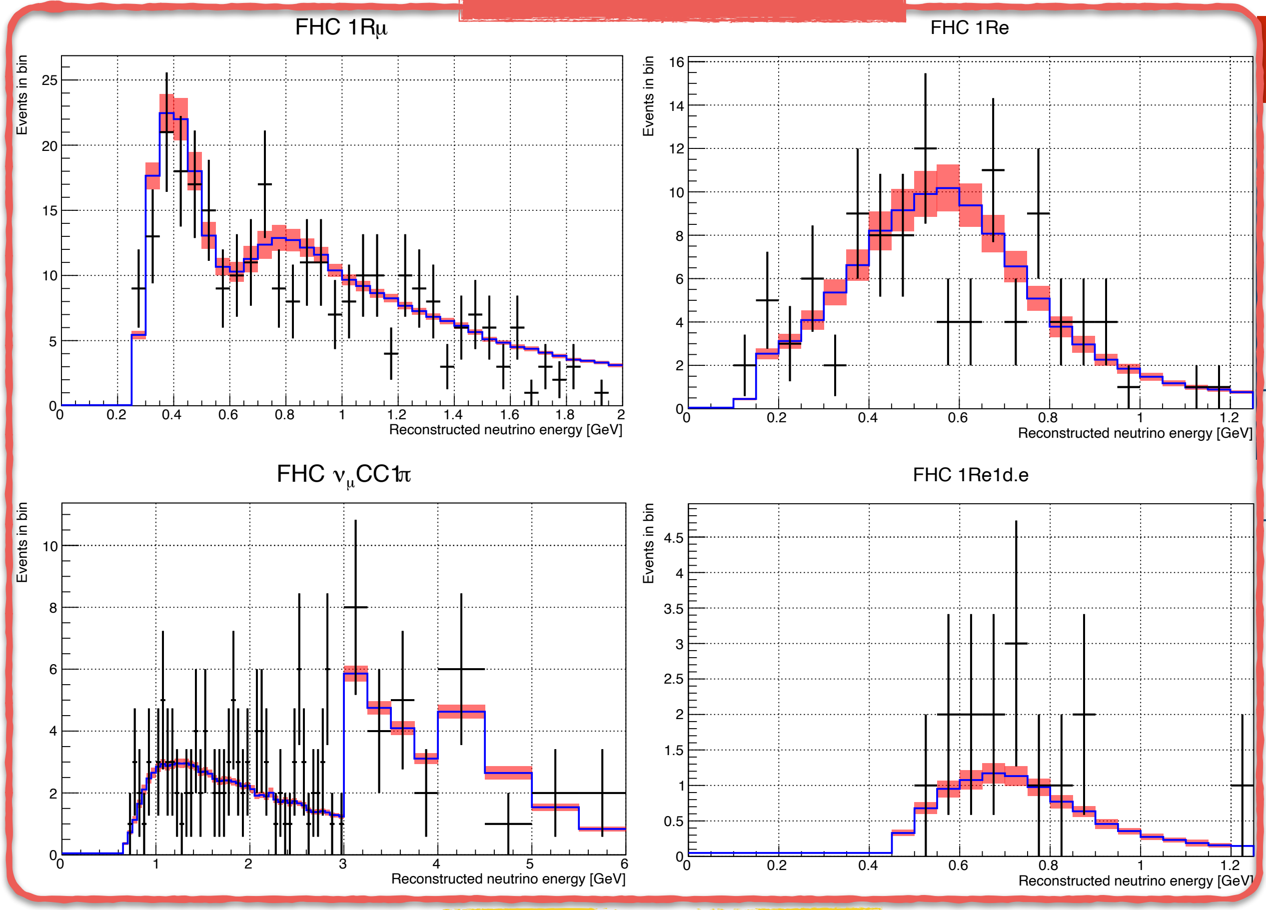


Wrong sign component

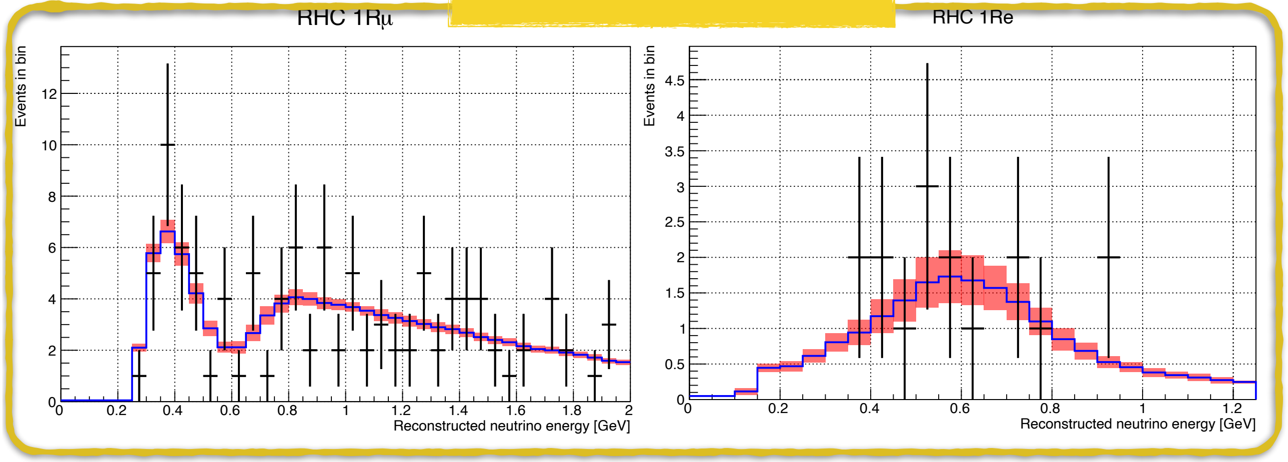
6 × 2 anti-neutrino beam mode ND280 samples used in the oscillation analysis

Super-K samples

ν beam mode

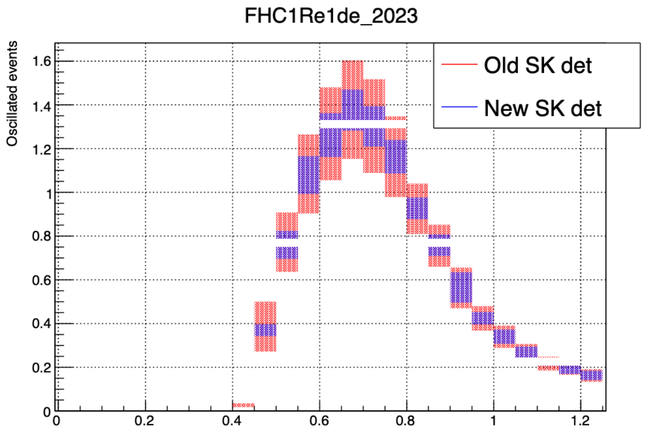


$\bar{\nu}$ beam mode

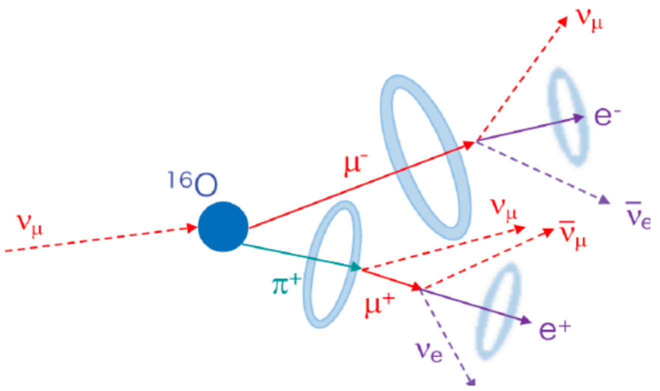


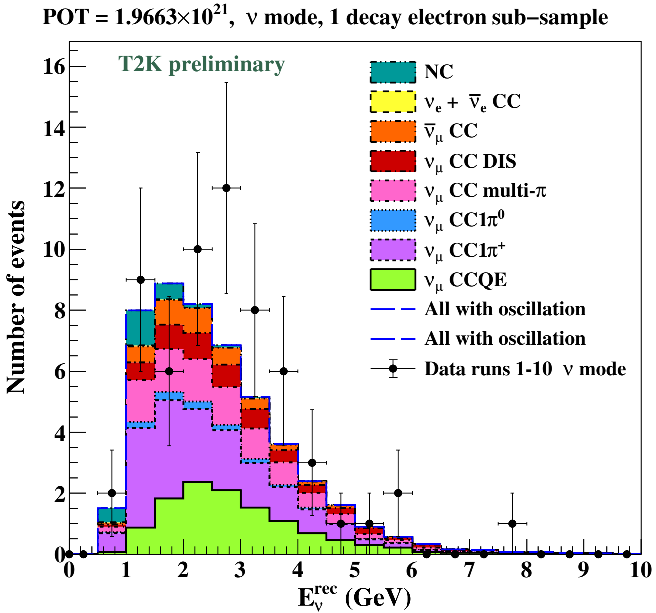
Beam mode	Sample	Description
ν	**1Re**	One e-like ring, 0 decay electrons
	1Re CC1π+	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	**MRμ CC1π+**	One μ-like ring, 2 decay electrons/ μ-like ring + π+-like ring, 1 decay e
$\bar{\nu}$	**1Re**	One e-like ring, 0 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons

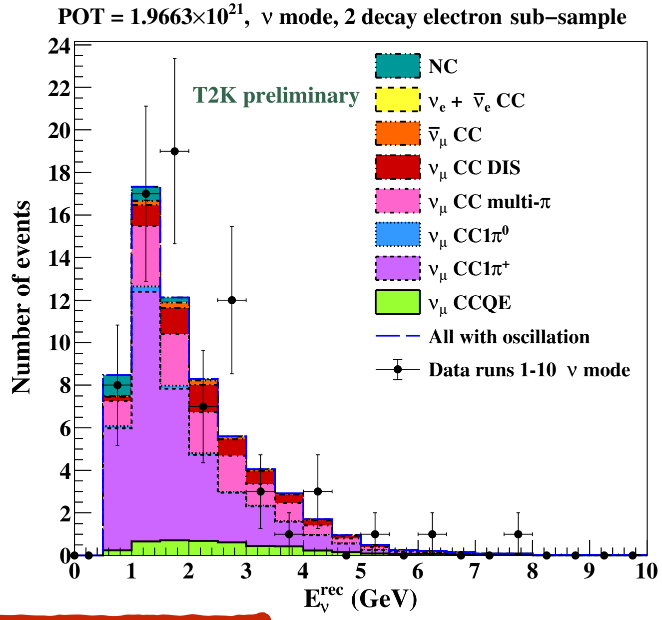
- New SK detector modeling significantly reduce systematics in some of the samples
- Add ~10% statistic in ν mode



Super-K samples





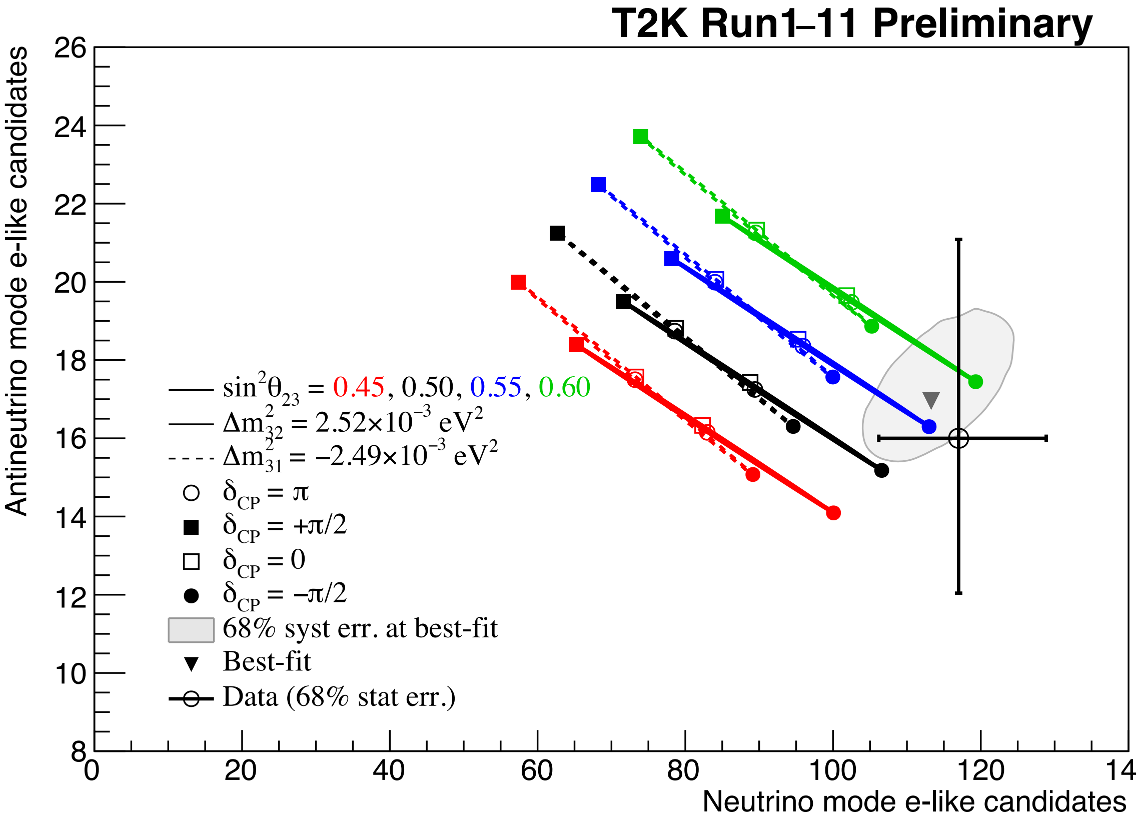


- New "multi-ring" ν_μ CC1π^+ sample
- Increases μ-like statistics by ~30%
- Small sensitivity to oscillation, tests the robustness of our model

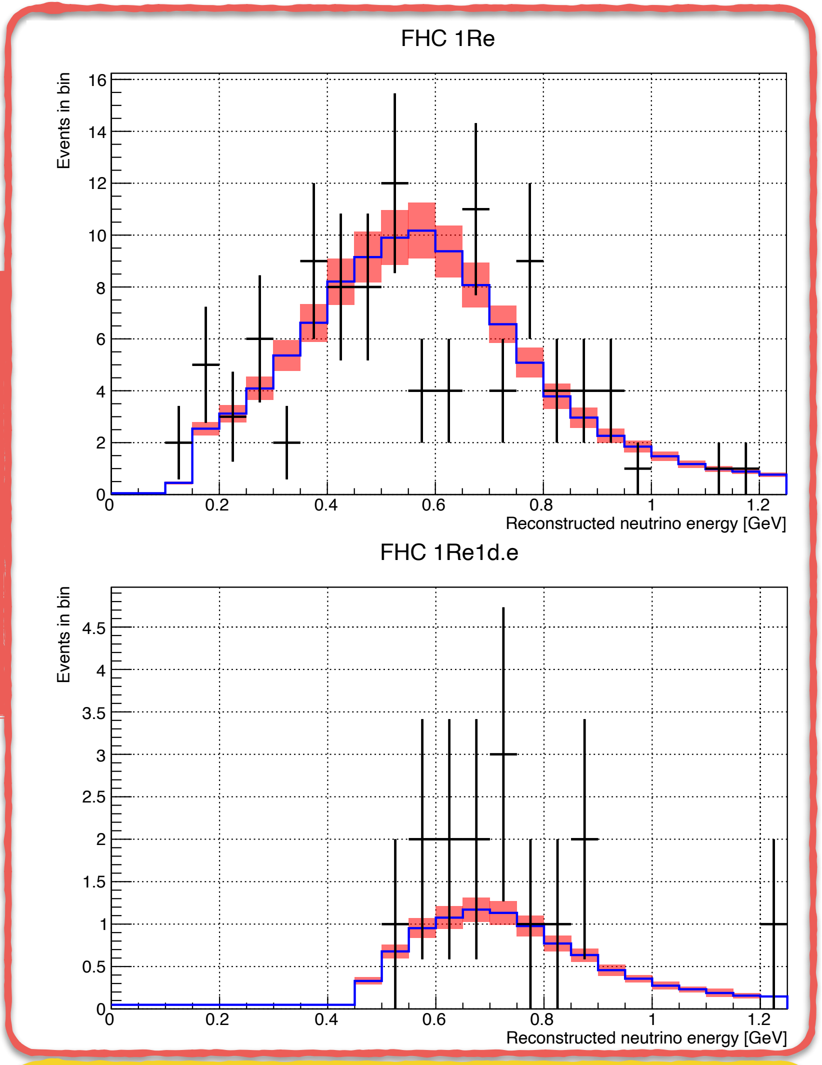
Beam mode	Sample	Description
ν	**1Re**	One e-like ring, 0 decay electrons
	1Re CC1π⁺	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	**MRμ CC1π⁺**	One μ-like ring, 2 decay electrons/ μ-like ring + π^+-like ring, 1 decay e
$\bar{\nu}$	**1Re**	One e-like ring, 0 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons

Latest T2K oscillation results

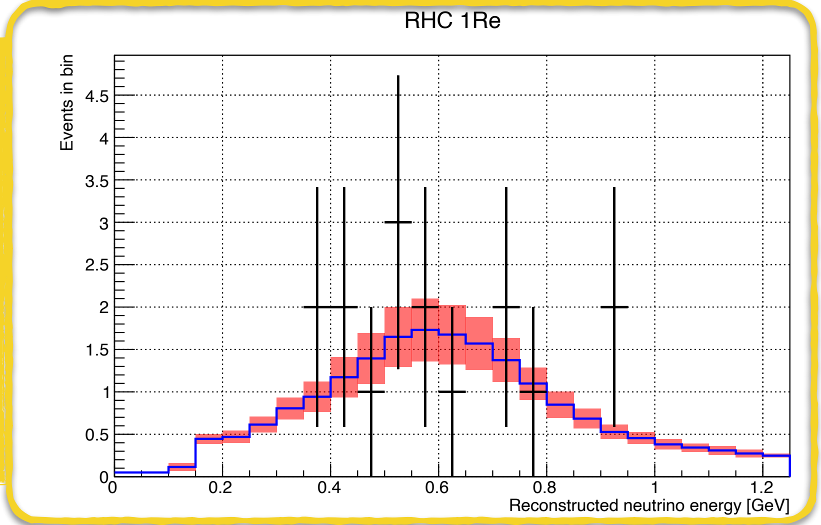
- **Oscillation parameters at the limit**
  - **Maximal mixing in θ_{23}**
  - **Maximal $\nu_e/\bar{\nu}_e$ asymmetry**
- **Consistent w/ PMNS, within stat. +syst. errors**



ν beam mode



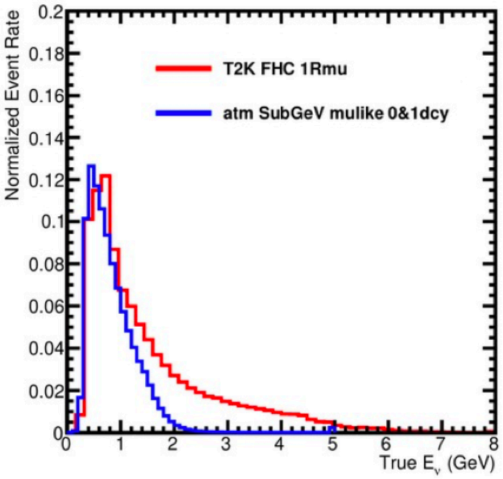
$\bar{\nu}$ beam mode

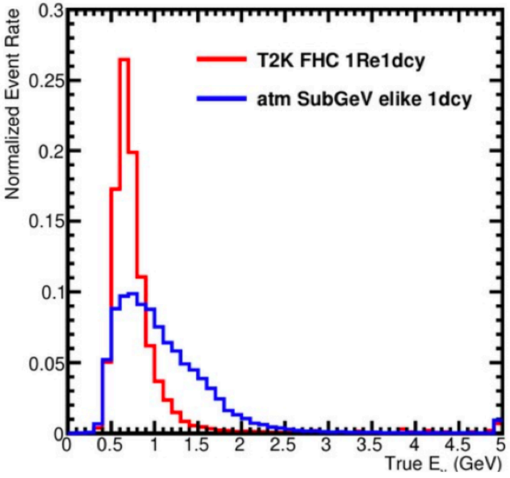


Joint analyses

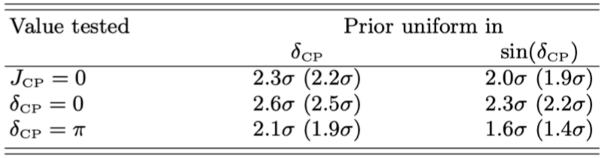
T2K-SK atmospheric joint analysis

- T2K has good sensitivity to δ_{CP} but mild preference for NO
- SK has a good constraint on MO but not on δ_{CP} due to poor energy resolution
  - T2K constraint on $\sin^2\theta_{23}$ reduce degeneracies in SK
- Same far detector SK
  - Same SK detector modeling for the two samples
  - Use ND280 data to constraint x-sec models

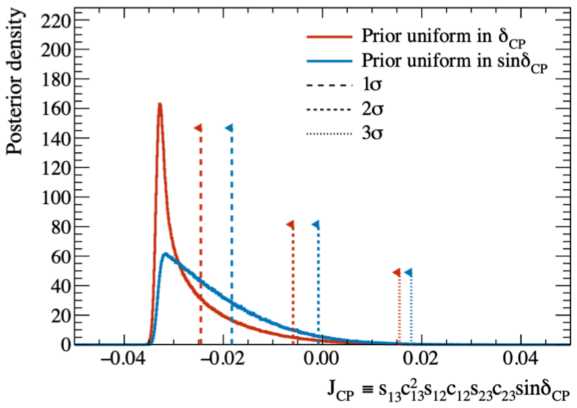


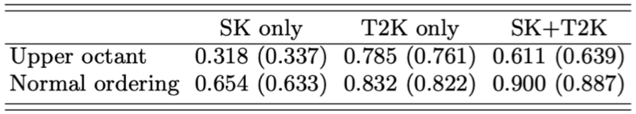


- Both experiments prefer NO and $\delta_{CP} \sim -\pi/2$, T2K prefers higher octant while SK lower octant
- The CP conserving value of the Jarlskog invariant is excluded with a significance varying between 1.9σ and 2.3σ depending on the analysis considered

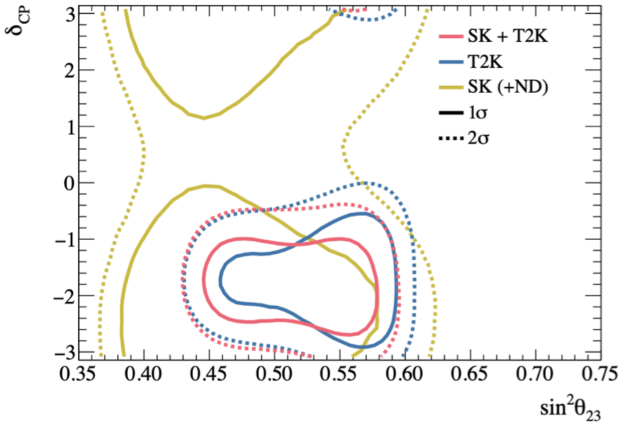


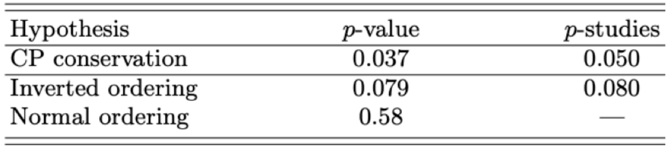
Value tested	Prior uniform in δ_{CP}	Prior uniform in $\sin(\delta_{CP})$
$J_{CP} = 0$	2.3σ (2.2σ)	2.0σ (1.9σ)
$\delta_{CP} = 0$	2.6σ (2.5σ)	2.3σ (2.2σ)
$\delta_{CP} = \pi$	2.1σ (1.9σ)	1.6σ (1.4σ)



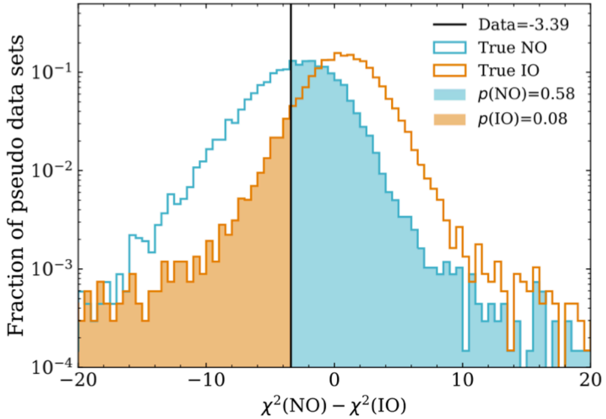


	SK only	T2K only	SK+T2K
Upper octant	0.318 (0.337)	0.785 (0.761)	0.611 (0.639)
Normal ordering	0.654 (0.633)	0.832 (0.822)	0.900 (0.887)

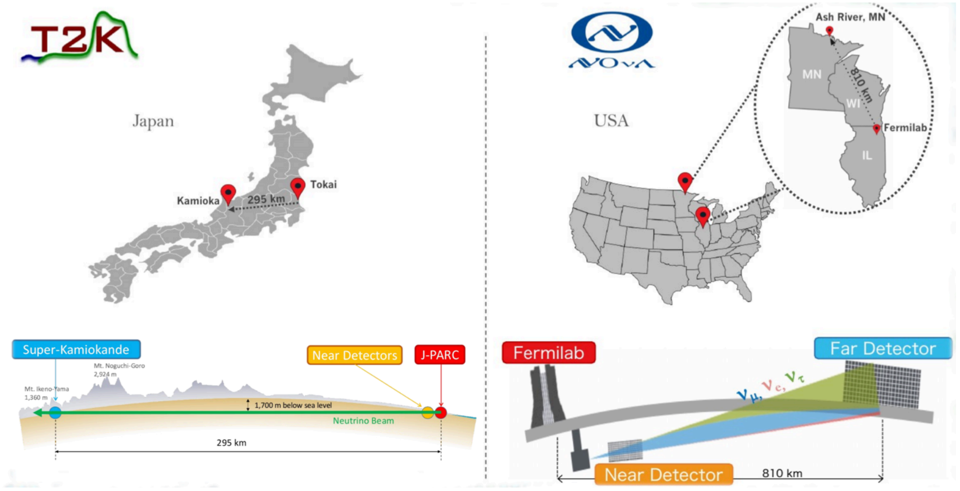




Hypothesis	p-value	p-studies
CP conservation	0.037	0.050
Inverted ordering	0.079	0.080
Normal ordering	0.58	—

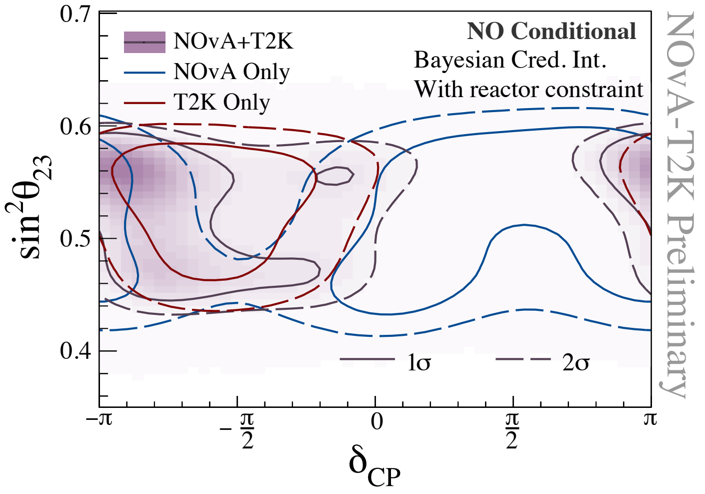


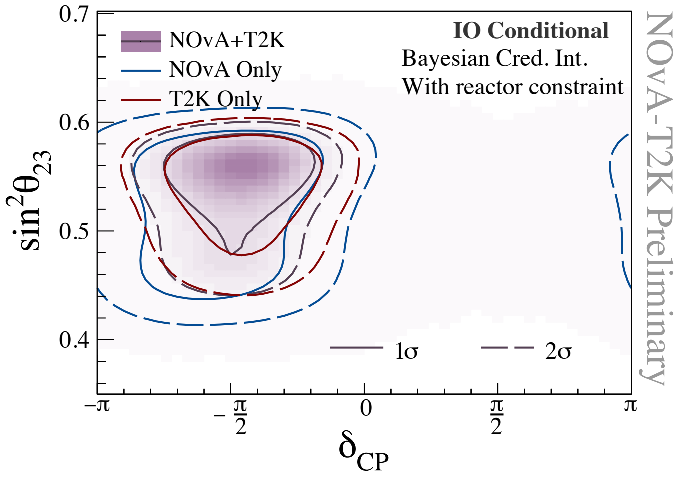
T2K-NOνA joint analysis

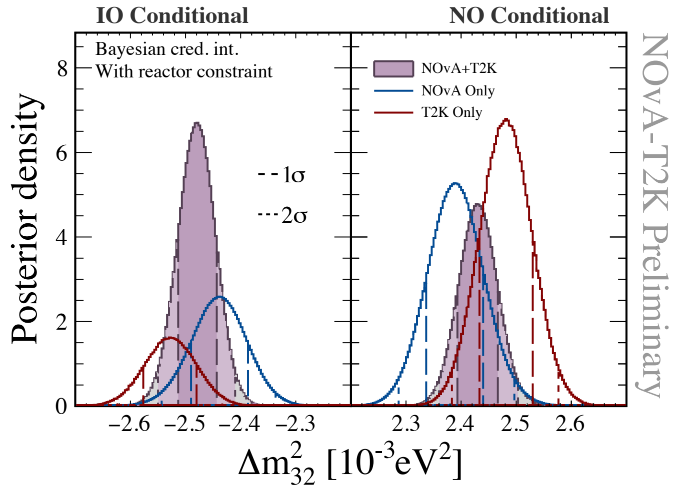


Experimental Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak nu energy	0.6 GeV	2 GeV
Detection tech	Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%

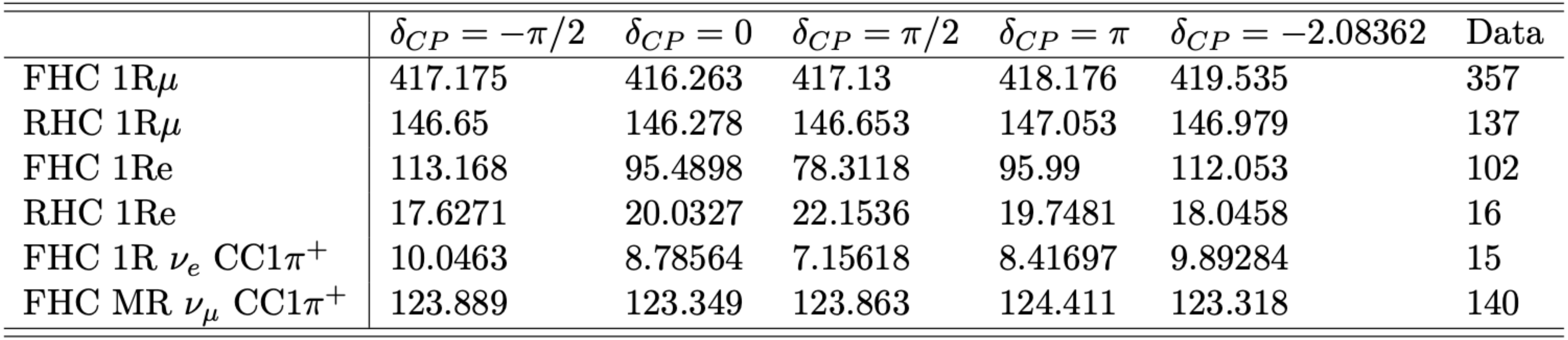
- Current world smallest uncertainty on Δm^2_{32}
- Slight preference for IO masses (better compatibility $\delta_{CP} - \sin^2\theta_{23}$ in IO) and upper octant of θ_{23}
- $\delta_{CP} = -\pi/2$ disfavored at $> 3\sigma$ but wide range of values consistent with data in NO
- If another experiment determines masses are IO, CP-conserving values of δ_{CP} lie outside of 3σ credible intervals and best fit close to maximal CP violation $\delta_{CP} = -\pi/2$





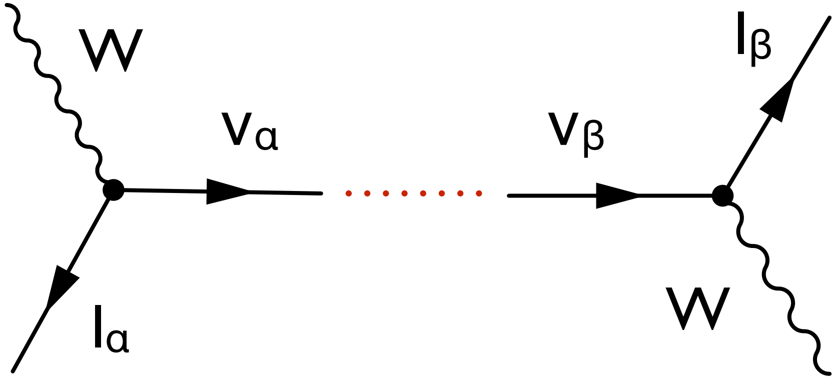


Number of events at SK vs δ_{CP}



	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	$\delta_{CP} = -2.08362$	Data
FHC 1Rμ	417.175	416.263	417.13	418.176	419.535	357
RHC 1Rμ	146.65	146.278	146.653	147.053	146.979	137
FHC 1Re	113.168	95.4898	78.3118	95.99	112.053	102
RHC 1Re	17.6271	20.0327	22.1536	19.7481	18.0458	16
FHC 1R ν_e CC1π^+	10.0463	8.78564	7.15618	8.41697	9.89284	15
FHC MR ν_μ CC1π^+	123.889	123.349	123.863	124.411	123.318	140

Neutrino oscillations



Neutrinos produced in weak processes (ν_α) are linear combinations of mass eigenstates (ν_i)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

where **U** is the **Pontecorvo-Maki-Nakagawa-Sakata (PMNS)** matr

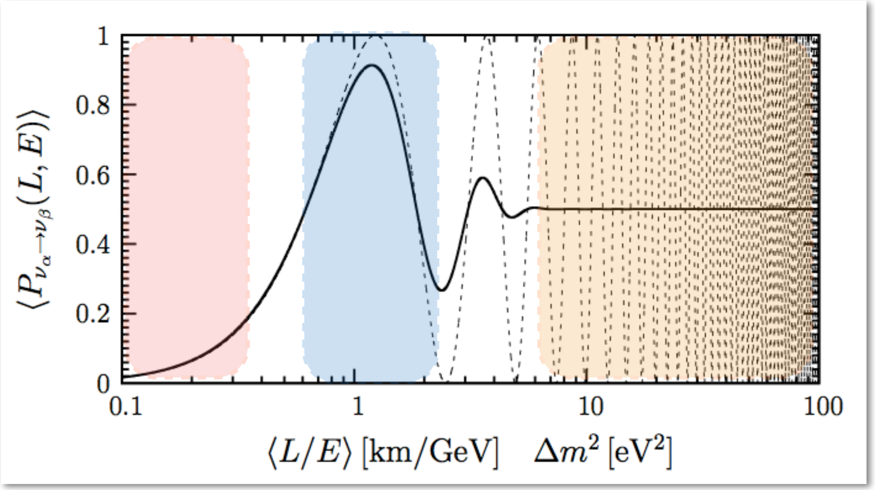
Time evolution: flavor content "oscillates" in L(distance)/E(neutrino)

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \quad & \delta_{\alpha\beta} \\ & -4\sum_{i>j} \Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left[1.27\Delta m^2_{ij}(L/E)\right] \\ & +2\sum_{i>j} \Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left[2.54\Delta m^2_{ij}(L/E)\right] \end{aligned}$$

oscillation amplitude

oscillation frequency

Parameters controlled by experiments



L/E << Δm^2 no time for the oscillation to develop

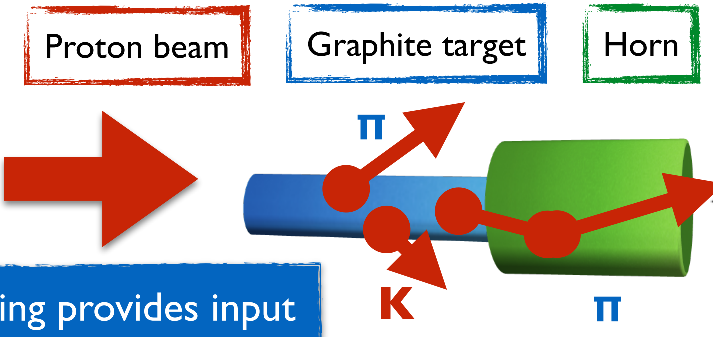
L/E >> Δm^2 only average oscillation probability can be measured

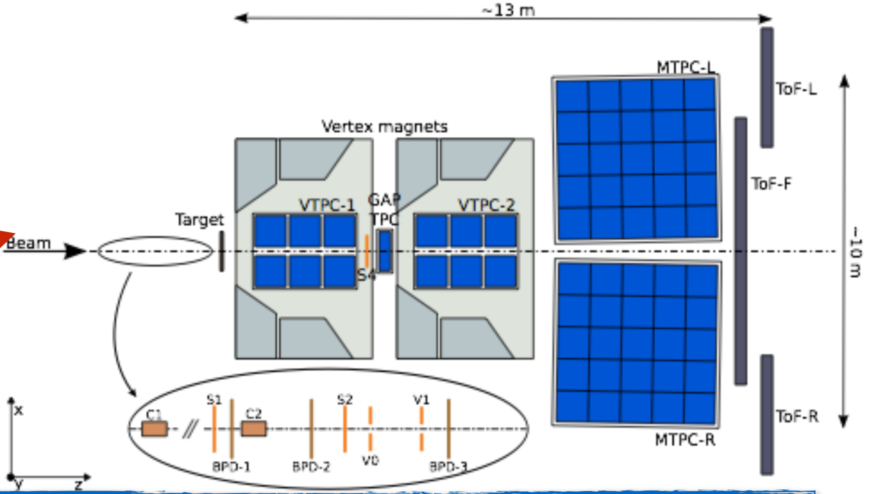
L/E ≈ Δm^2 best sensitivity to oscillation

The neutrino beam: flux predictions

- Fluxes are predicted from a data-driven simulation→**NA61/SHINE experiment** measures hadron production cross sections using a **T2K replica target**

Flux error reduction from ~25% to less than 10%

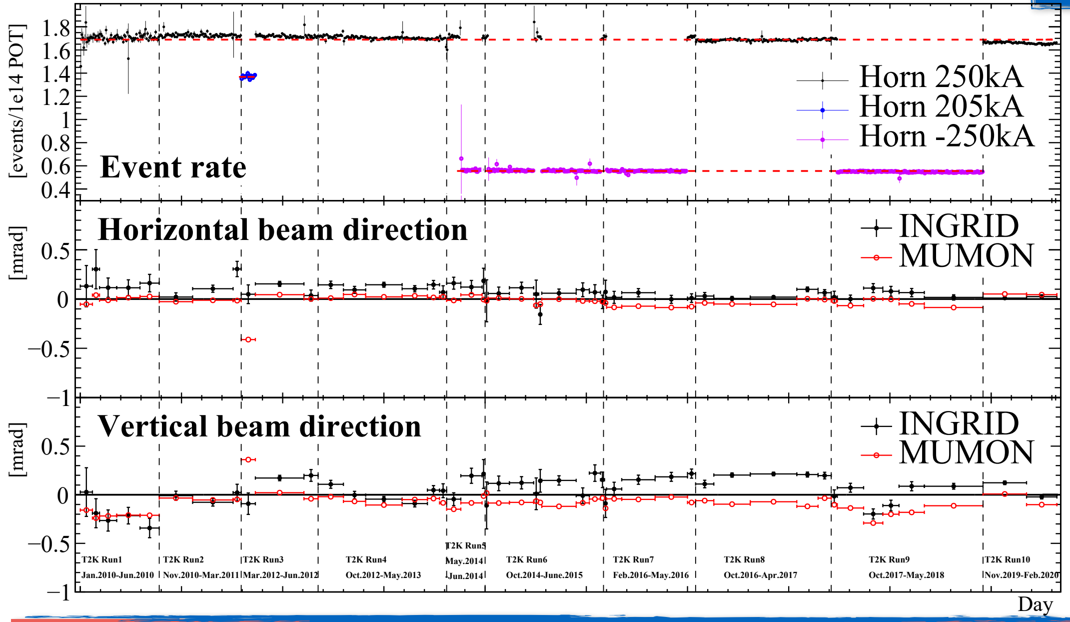


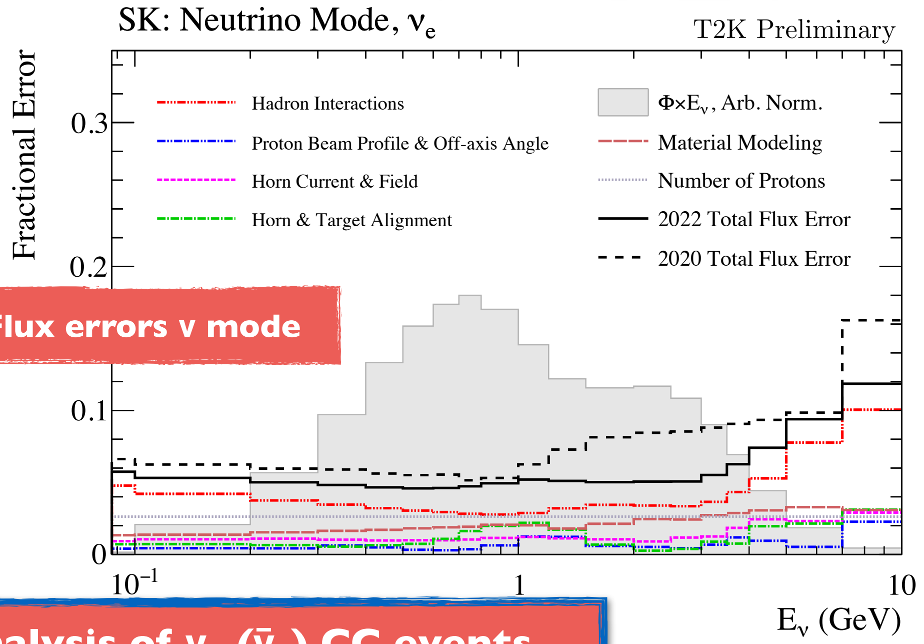


- Beam alignment monitoring provides input to estimations of beam systematics

- INGRID detector provides high-statistics monitoring of the beam intensity, direction, profile and stability

ν daily event rate

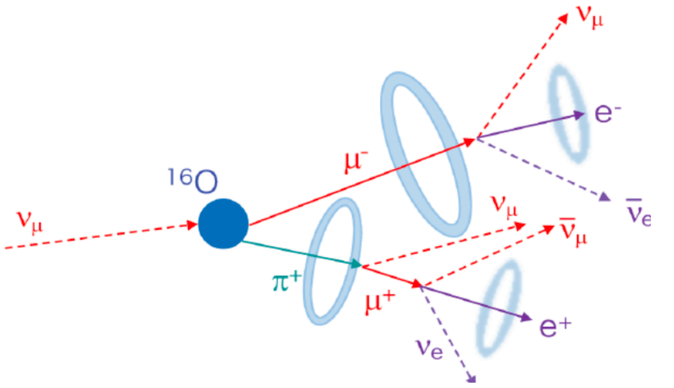


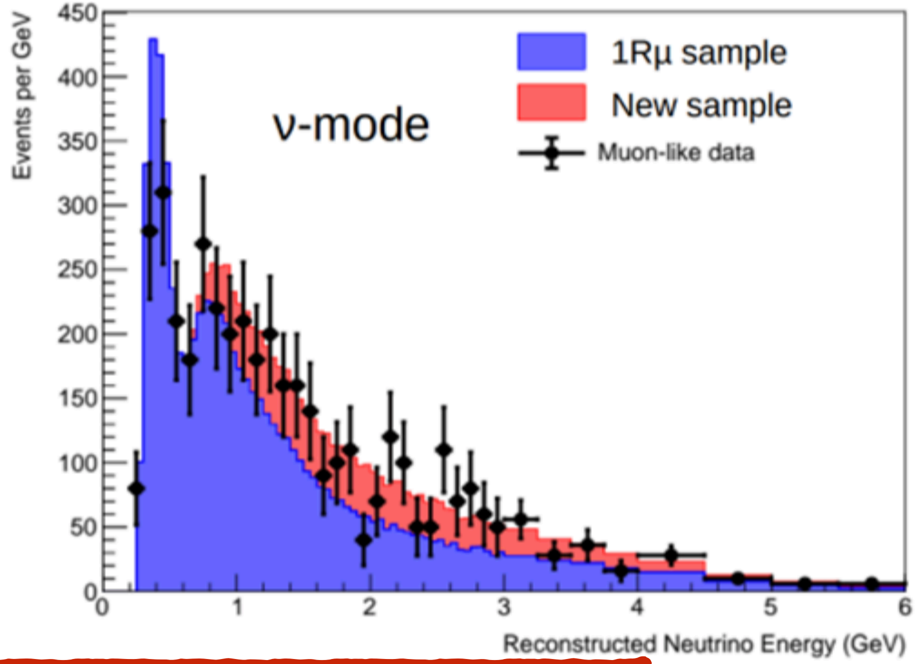


Flux errors ν mode

Flux errors are further constrained with the ND280 analysis of ν_μ ($\bar{\nu}_\mu$) CC events

Super-K samples





- New "multi-ring" ν_μ CC1π^+ sample
- Increases μ-like statistics by ~30%
- Small sensitivity to oscillation, tests the robustness of our model

Beam mode	Sample	Description
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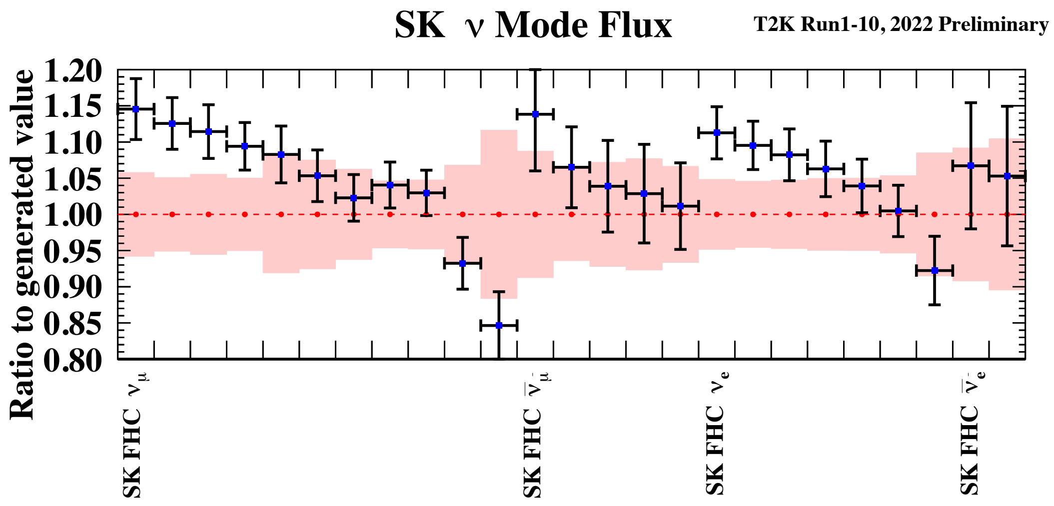
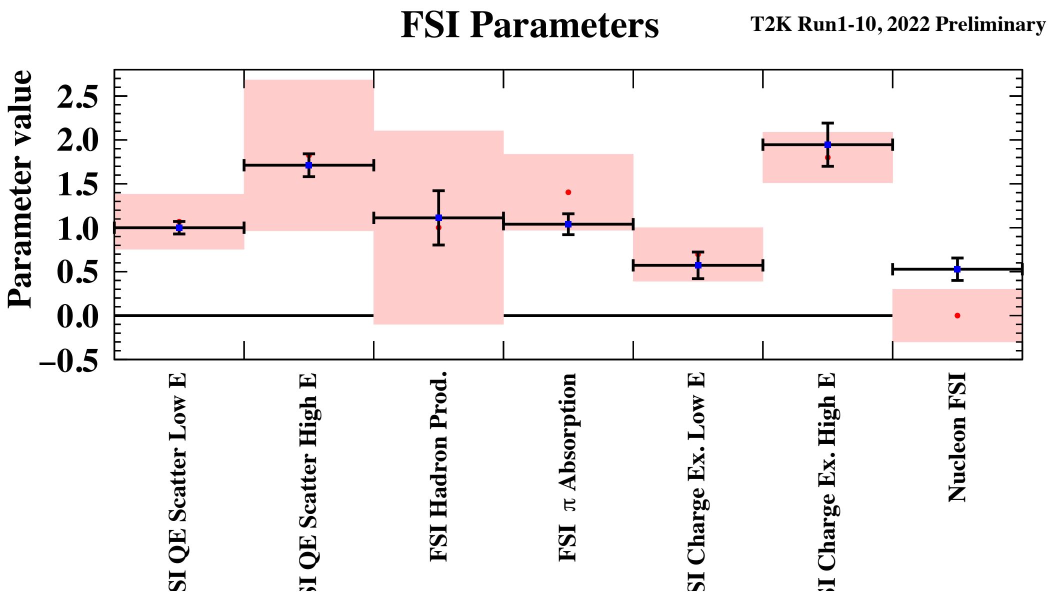
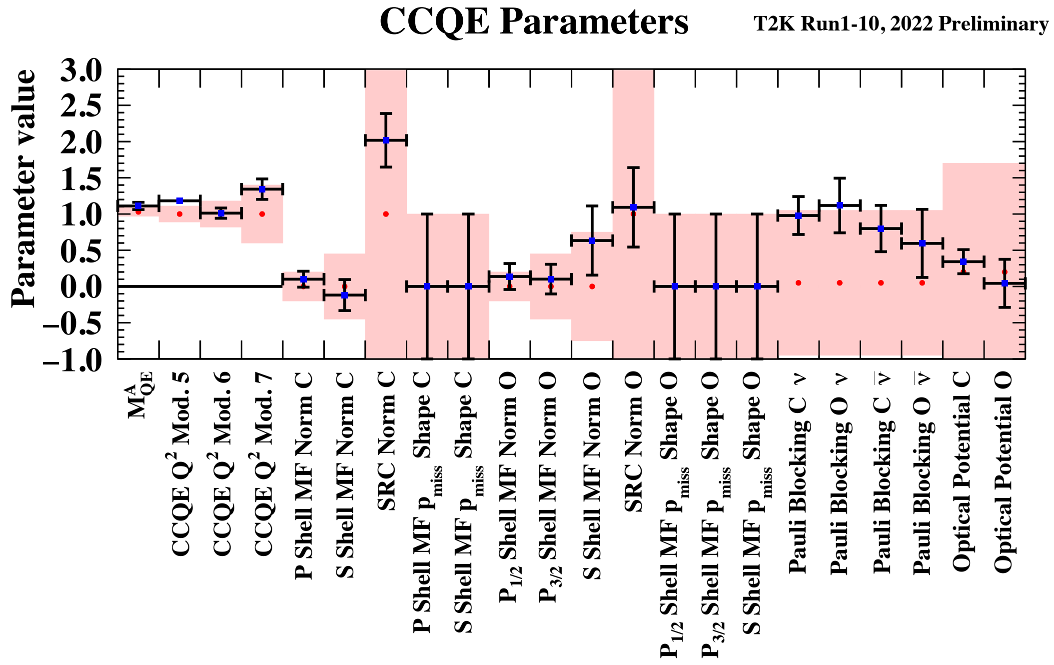
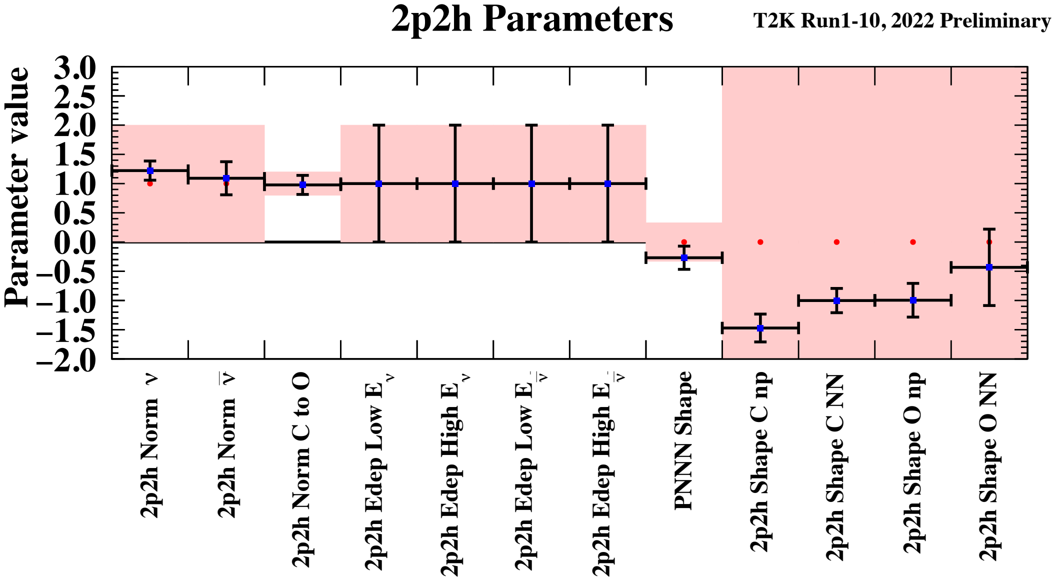
NEW	**MRμ CC1π^+**	One μ-like ring, 2 decay electrons/ μ-like ring + π^+-like ring, 1 decay e
$\bar{\nu}$	**1Re**	One e-like ring, 0 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons

ND280 best fit nuisance parameters

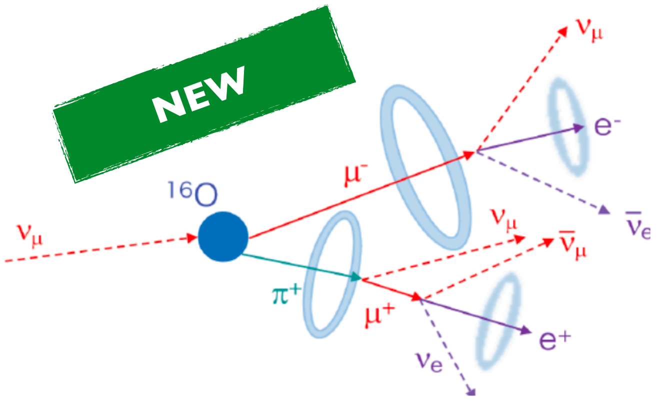


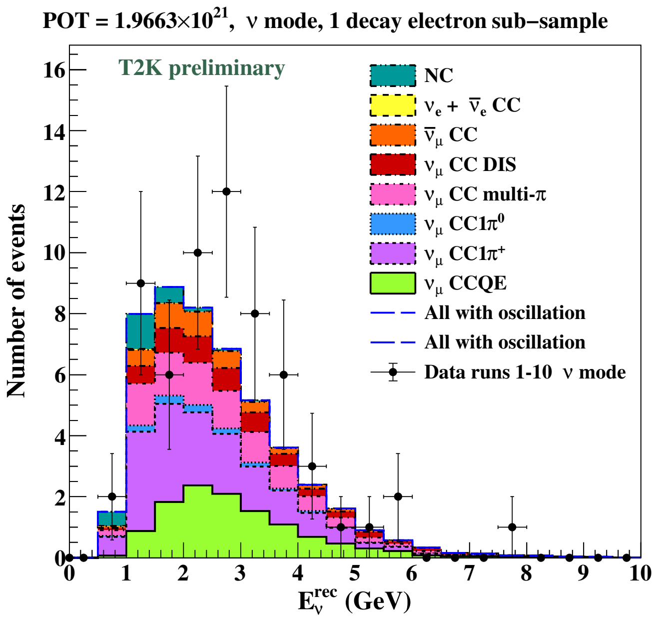


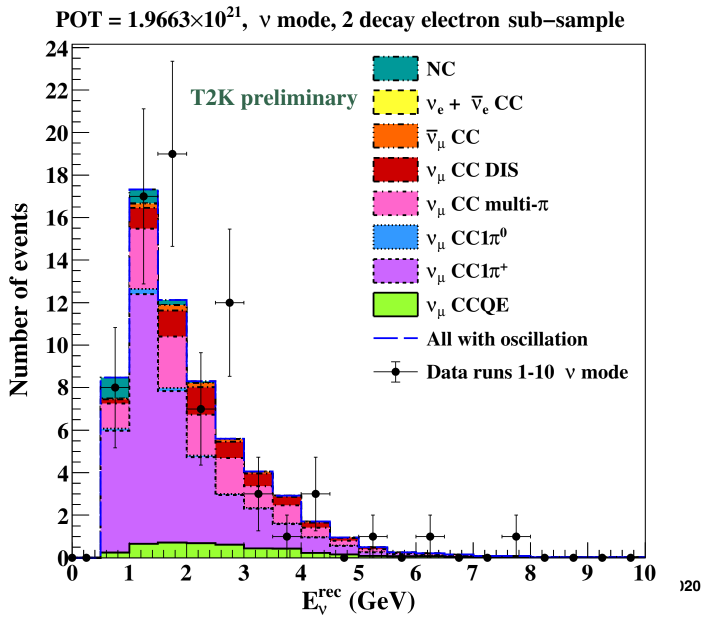


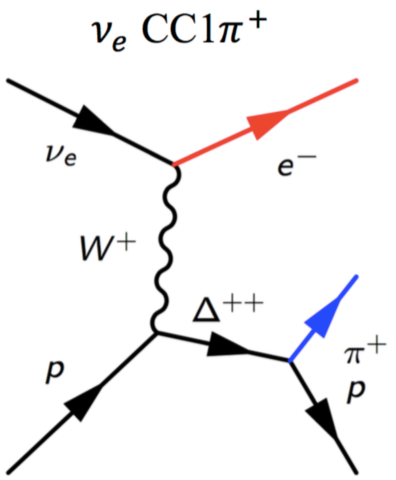


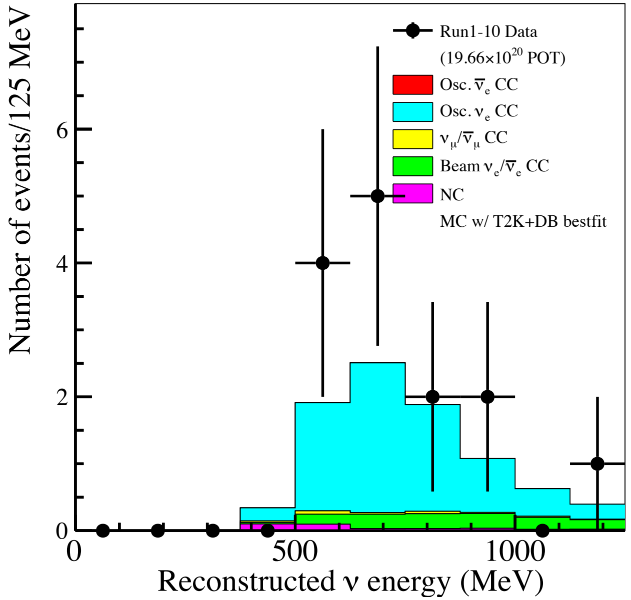
Pion samples @ SK

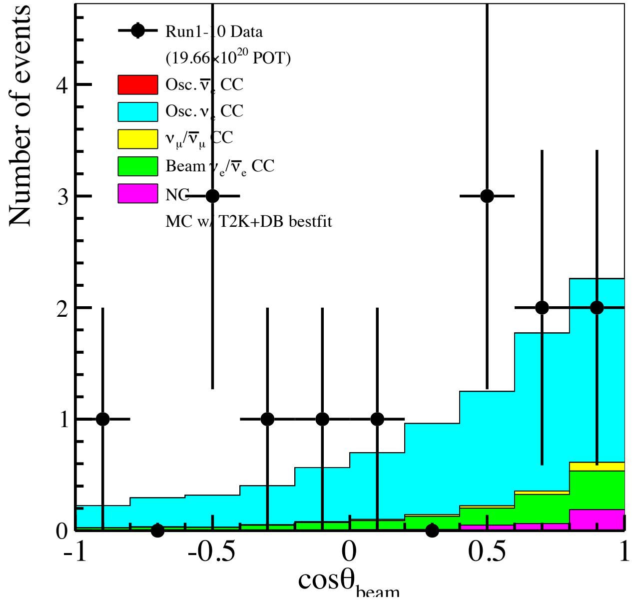






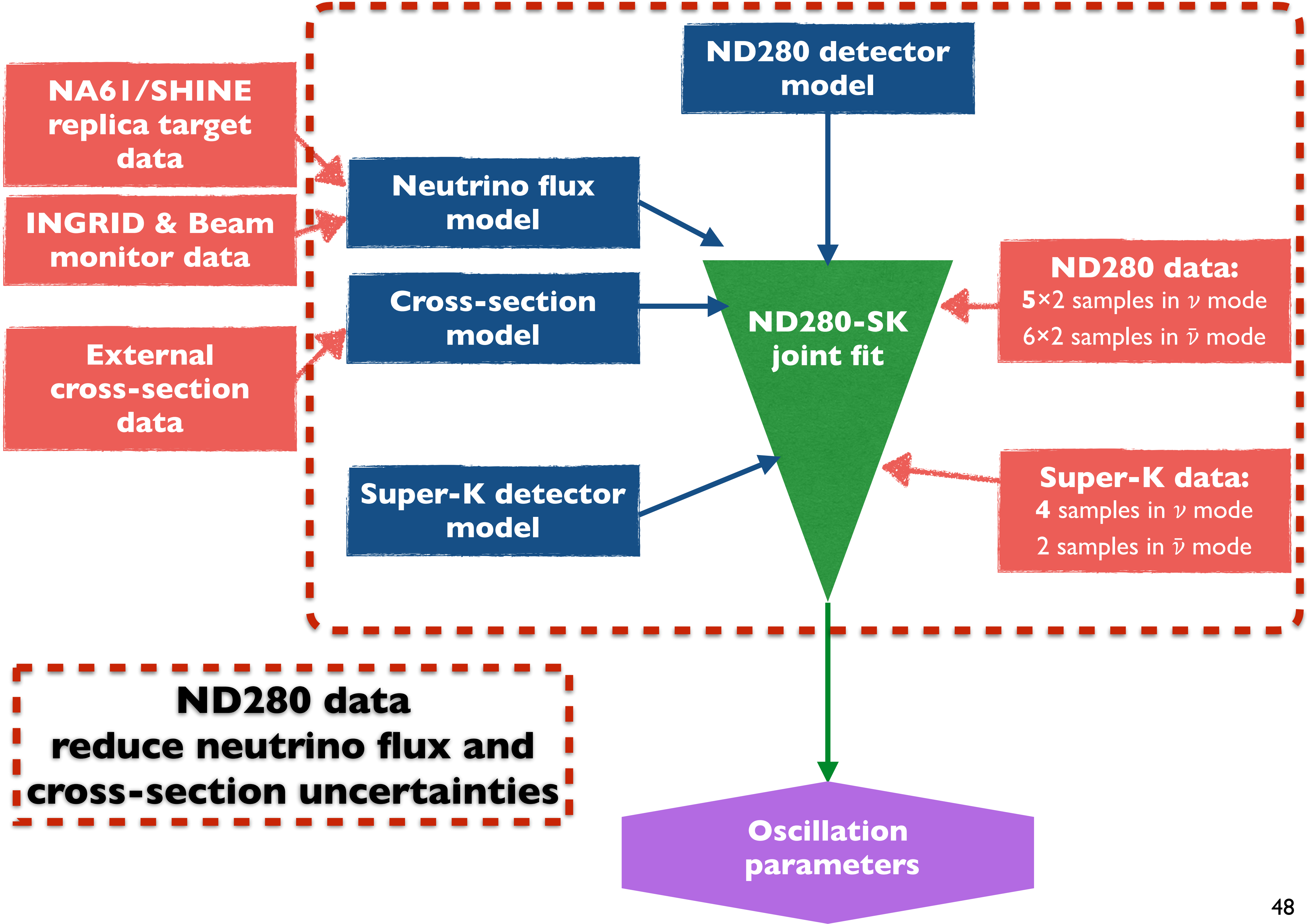






$$E_{rec}^{\nu_\mu\;CC\Delta^{++}} = \frac{2m_pE_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2(m_p - E_\mu + |\mathbf{p}_\mu|\cos\theta_\mu)}$$

Oscillation analysis strategy



NA61/SHINE replica target data

INGRID & Beam monitor data

External cross-section data

ND280 detector model

Neutrino flux model

Cross-section model

Super-K detector model

ND280-SK joint fit

ND280 data:
5×2 samples in ν mode
6×2 samples in $\bar{\nu}$ mode

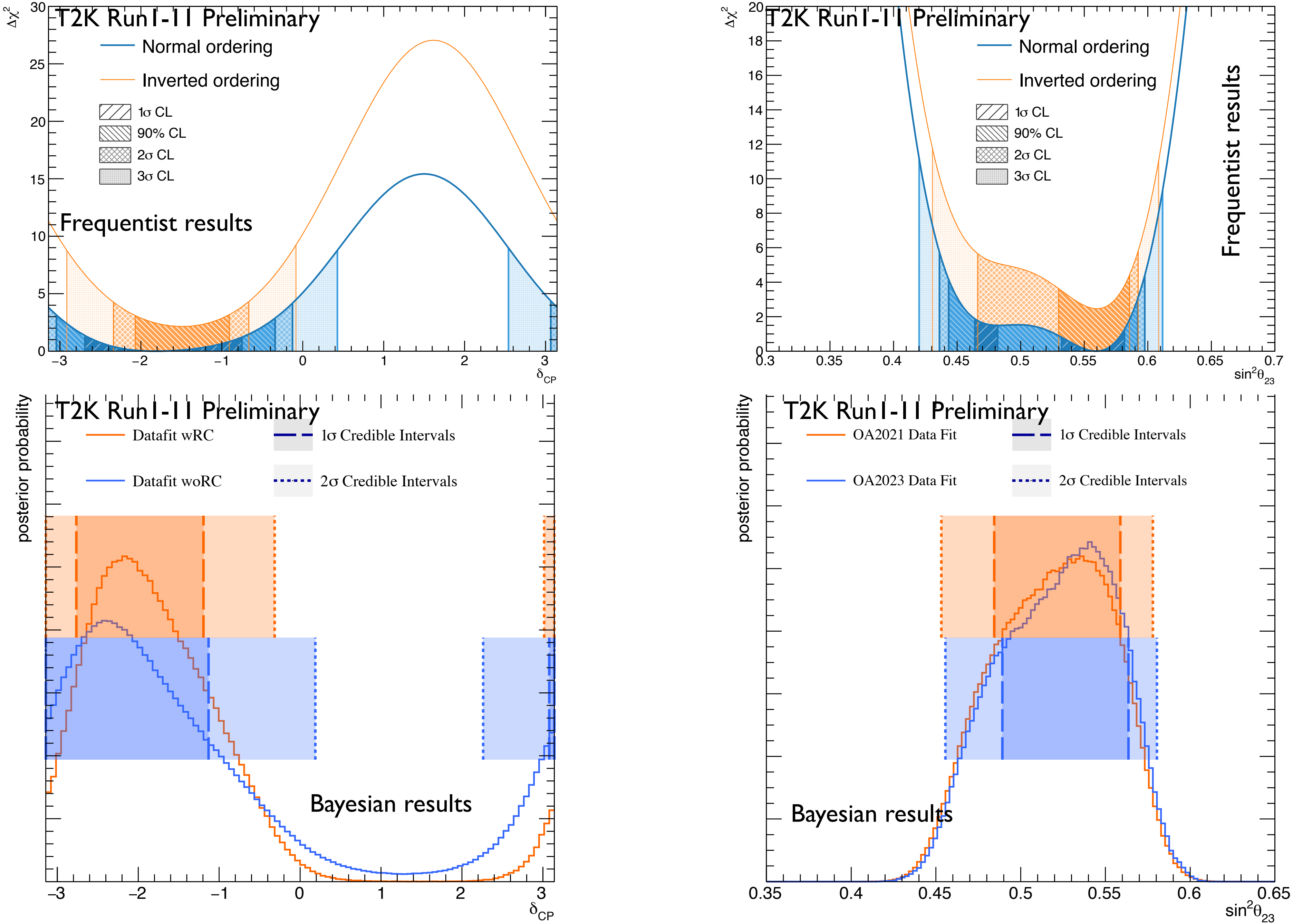
Super-K data:
4 samples in ν mode
2 samples in $\bar{\nu}$ mode

Oscillation parameters

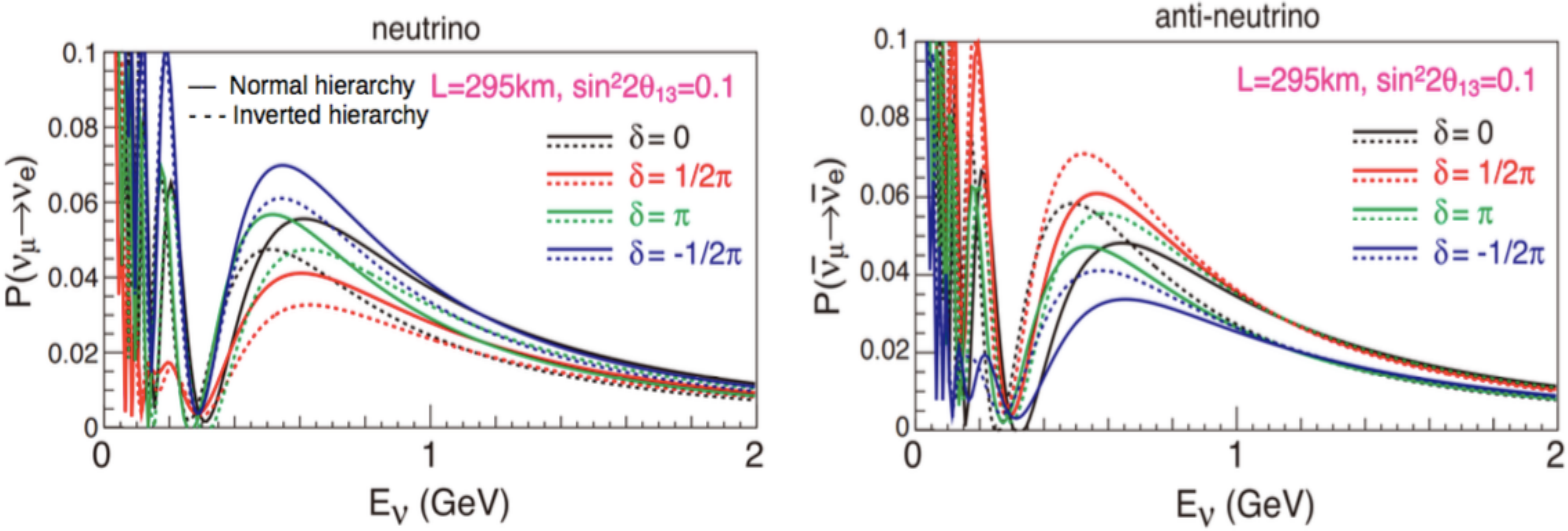
ND280 data reduce neutrino flux and cross-section uncertainties

Frequentist and Bayesian analyses in agreement

T2K + Reactor θ_{13} ($\sin^2 2\theta_{13} = 0.0861 \pm 0.0027$)



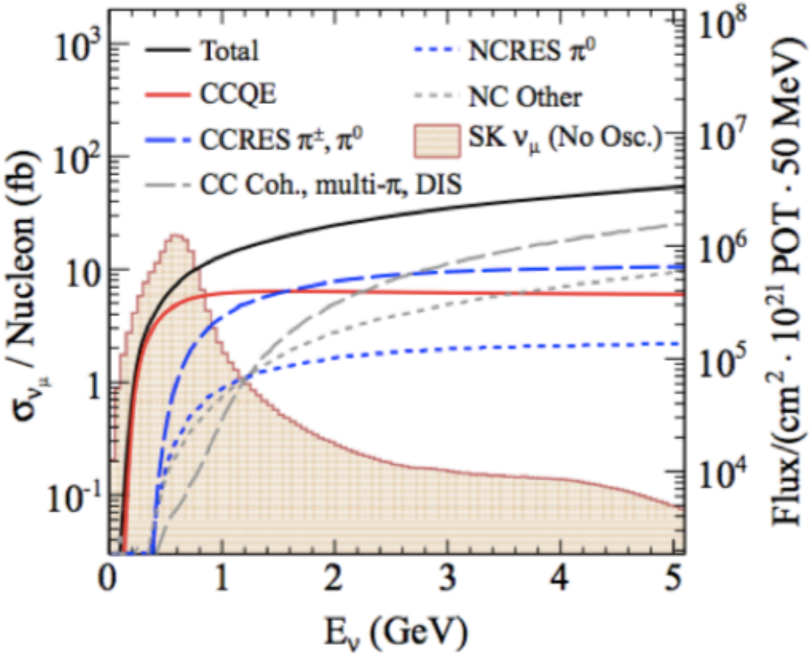
Summary of oscillation results



Neutrino cross sections at T2K energies

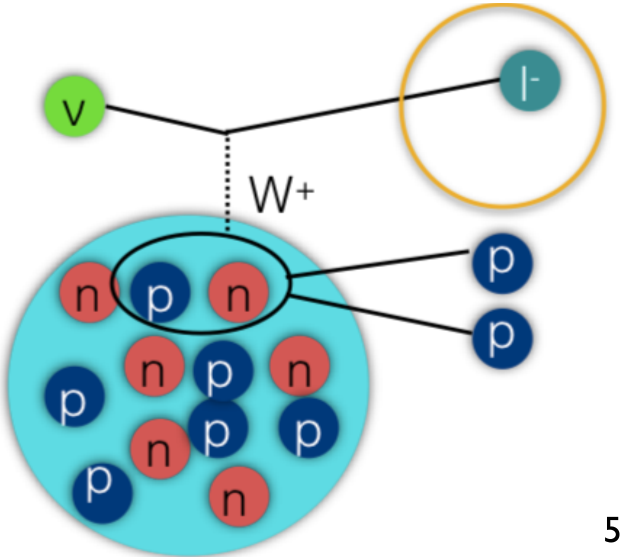
- At T2K energies the favoured interactions are **CCQE**
  - Other neutrino interactions with production of **pions** in the final state are important as well
  - **Nuclear effects** can mimic a CCQE interaction

- **Mimic CCQE interactions:**
  - Neutrino scatters on a correlated pair of nucleons (called multi-nucleon or 2 particle-2 hole, **2p-2h**)
  - Neutrino scatter produces a pion, which is re-absorbed in the nucleus
  - Neutrino scatter produces a pion absorbed by the detector



Improvements of neutrino interaction model in NEUT:

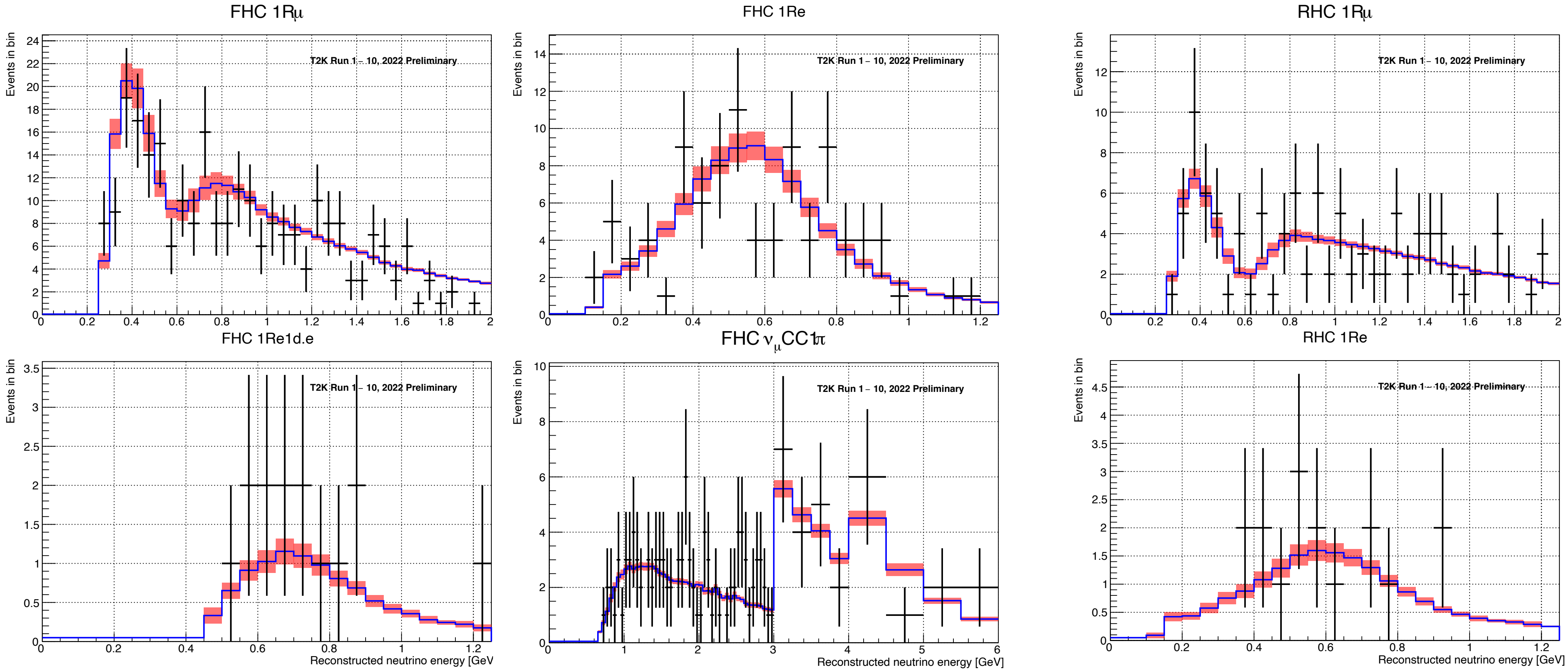
- **Improved pion production model** with tuning to data on hydrogen and deuterium
- **Inclusion of a model for multi-nucleon scattering processes**: Valencia 2p-2h model (Phys. Rev. C83 (2011) 045501)
- Improved the CCQE model by including the effect of **long-range correlations in the nucleus** (calculation technique called random phase approximation, **RPA**)



Fitted spectra at Super-Kamiokande

ν beam mode

ν̄ beam mode



	$\delta_{\rm CP} = -\pi/2$	$\delta_{\rm CP} = 0$	$\delta_{\rm CP} = \pi/2$	$\delta_{\rm CP} = \pi$	$\delta_{\rm CP} = -2.18$	Data
FHC 1Rμ	358.669	358.011	358.63	359.405	359.083	318
RHC 1Rμ	139.427	139.094	139.429	139.788	139.63	137
FHC 1Re	99.0567	83.5624	68.6139	84.1084	96.4746	94
RHC 1Re	17.0154	19.3474	21.4265	19.0946	17.3399	16
FHC 1R ν_e CC1π^+	10.8521	9.44959	7.70161	9.10421	10.4699	14
FHC MR ν_μ CC1π^+	118.527	118.017	118.501	119.02	118.813	134
FHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	217.808	217.493	217.78	218.21	218.029	191
RHC 1Rμ ($E_{\rm rec} < 1.2\,$GeV)	71.9451	71.7674	71.9474	72.1506	72.0591	71

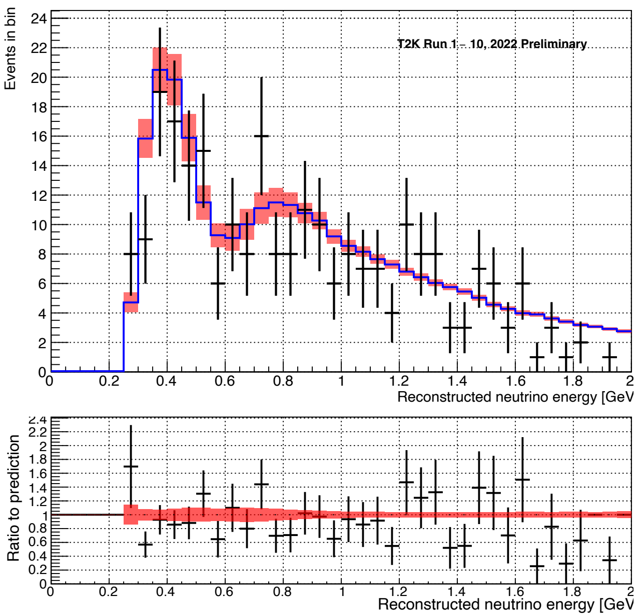
T2K Run 1-10, preliminary

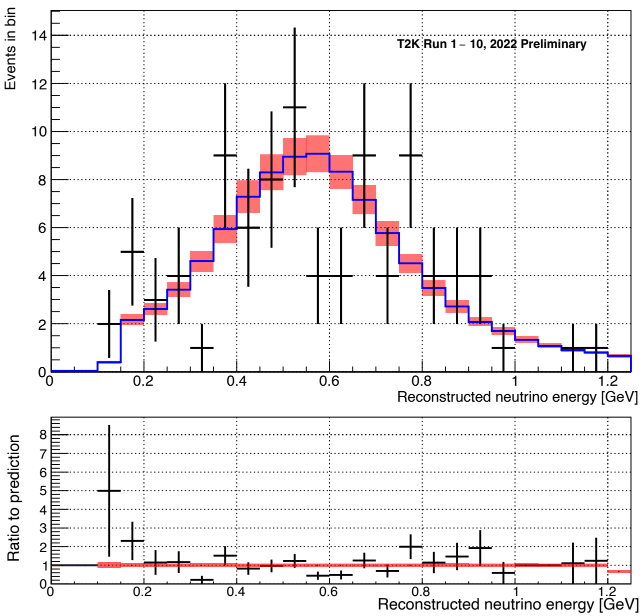
- **Oscillation and systematic parameters are shared between the 6 samples**
- **Fit simultaneously the 6 samples to maximize the sensitivity to the oscillation parameters**

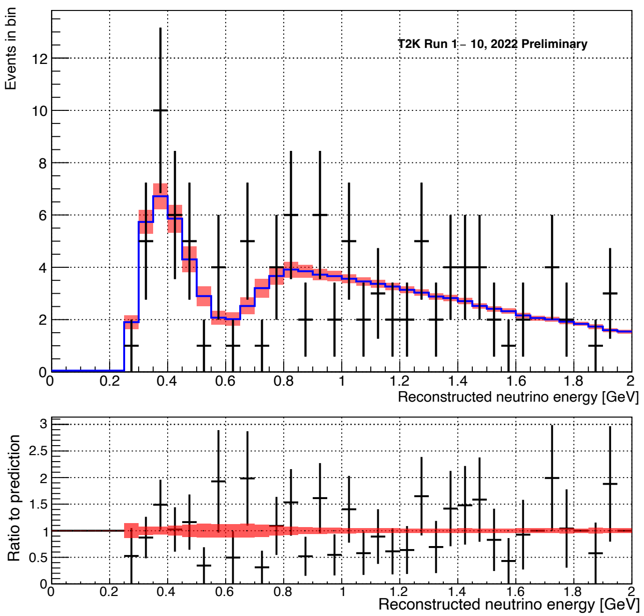
Fitted spectra at Super-Kamiokande

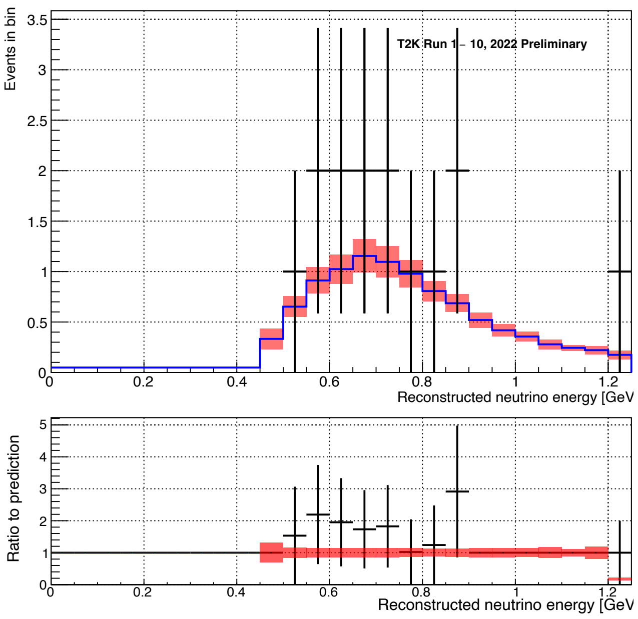
ν beam mode

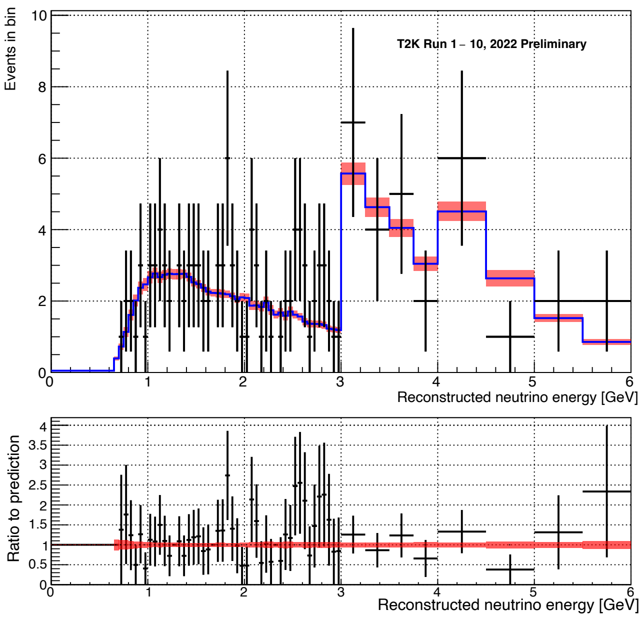
ν̄ beam mode

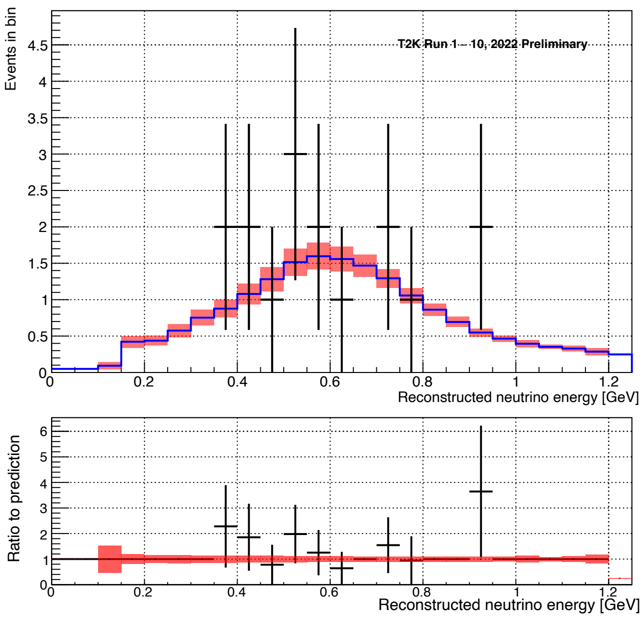

FHC 1Rμ


FHC 1Re


RHC 1Rμ


FHC 1Re1d.e

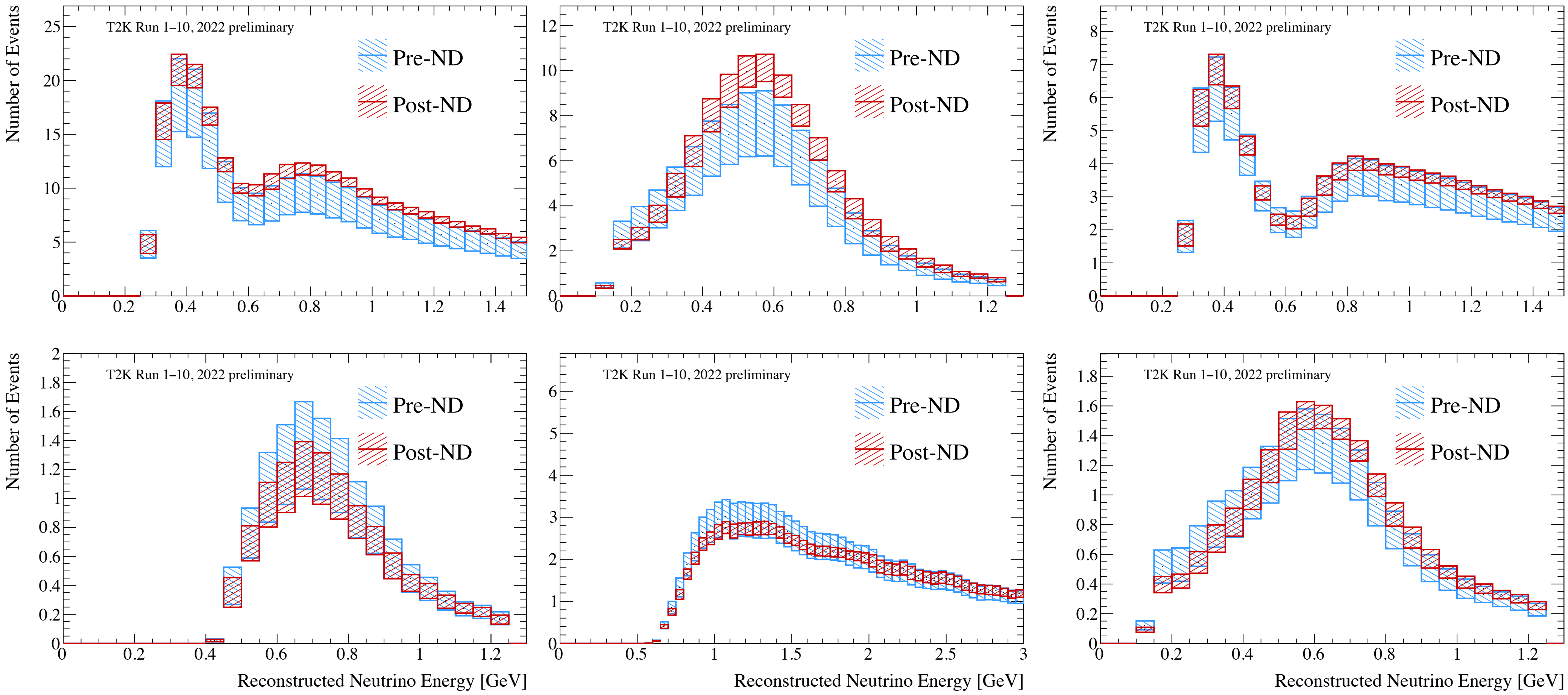

FHC ν_μCC1π


RHC 1Re

ND280 constraints for Super-Kamiokande

ν beam mode

ν̄ beam mode



Before ND280 fit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

T2K Run 1-10, preliminary

After ND280 fit

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

T2K Run 1-10, preliminary

Summary of oscillation results