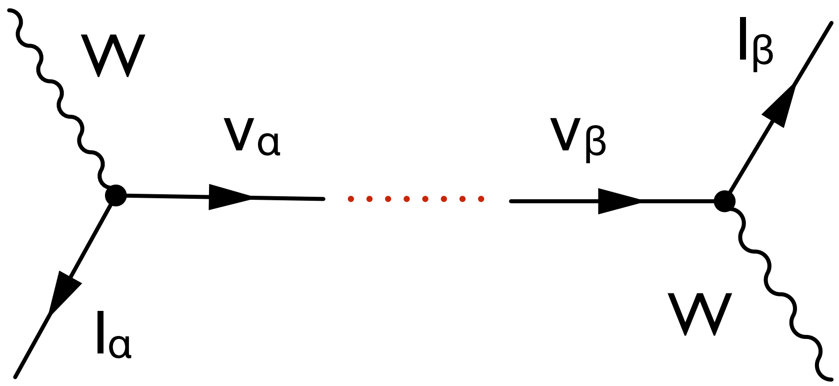
CP violation and mass hierarchy in the neutrino sector: T2K and HK

Lorenzo Magaletti (Politecnico di Bari & INFN Bari)
On behalf of the T2K and Hyper-K collaborations

FPCapri2024: 9th Workshop on Theory, Phenomenology and Experiments in Flavour Physics
19-21 June 2024

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:

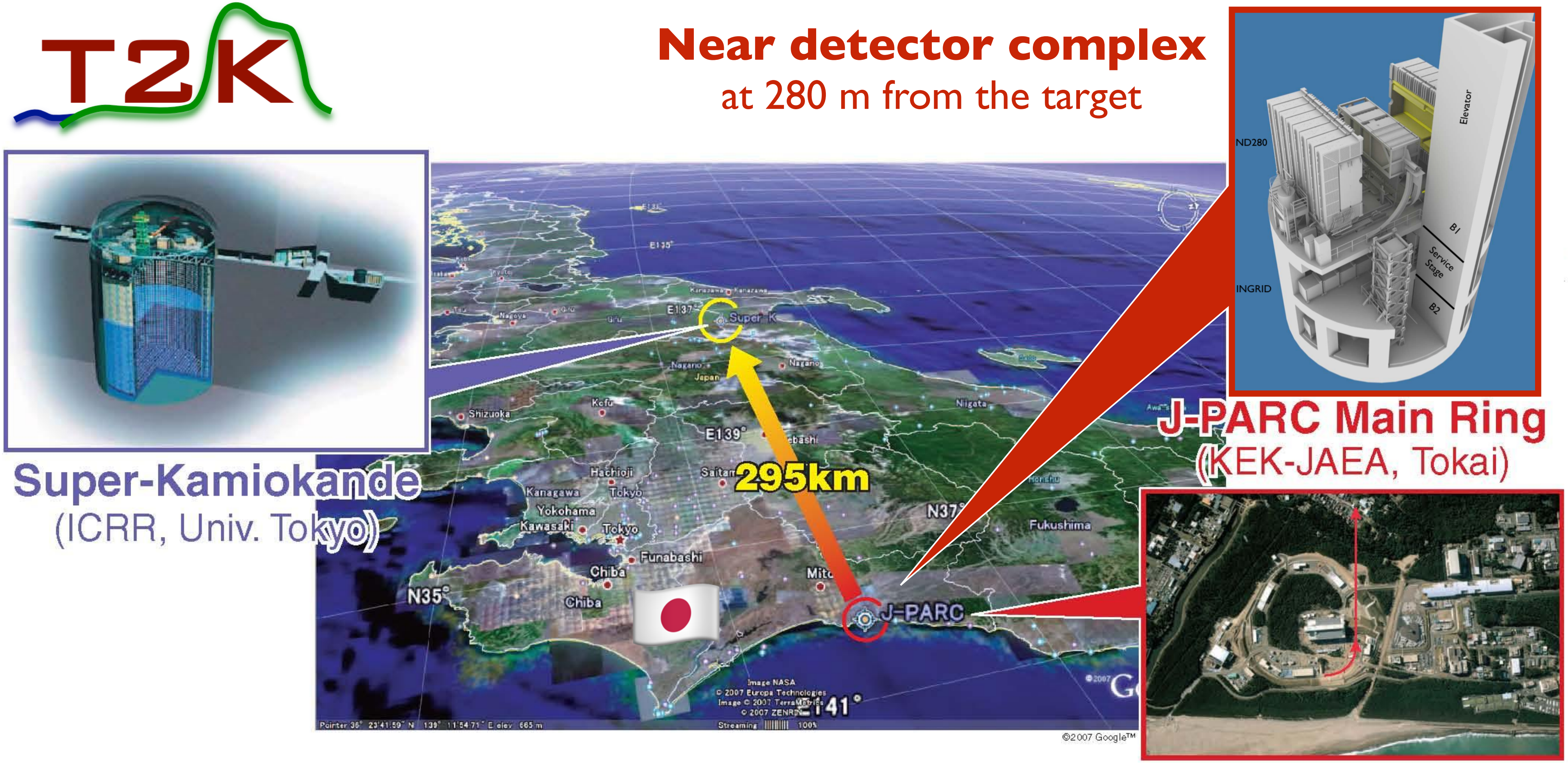
- $\theta_{12} \approx 33^\circ$
- $\theta_{23} \approx 45^\circ$
- $\theta_{13} \approx 9^\circ$
- $\Delta m^2_{21} \approx 7.5 \times 10^{-5}$ eV^2
- $|\Delta m^2_{31}| \approx 2.4 \times 10^{-3}$ eV^2

Open questions:

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

Neutrino oscillations at T2K

Near detector complex
at 280 m from the target



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

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

T2K

Big international collaboration of neutrino LBL

~560 physicists, 74 institutes, 14 countries + CERN

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

United Kingdom
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
U. Warwick

Hungary
Eötvös Loránd U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Spain
IFAE, Barcelona
U. Autonoma Madrid
U. Sevilla

Germany
RWTH Aachen
Universität Mainz

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U.T.
Wrocław U.

Russia
INR
JINR

ITALY
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Switzerland
ETH Zurich
U. Bern
U. Geneva

Vietnam
IFIRSE
Hanoi Univ. Science

USA
Boston U.
Duke U.
U. Houston
Louisiana State U.
Michigan S.U.
SLAC
Stony Brook U.
U. C. Irvine
U. C. Boulder
U. Minnesota
U. Pennsylvania
U. Pittsburgh
U. Rochester
U. Washington
SDSMT
LBNL

Neutrino appearance and disappearance at T2K

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

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

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

θ13 driven

CP even

CP odd

Solar driven

Matter effect (CP odd)

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

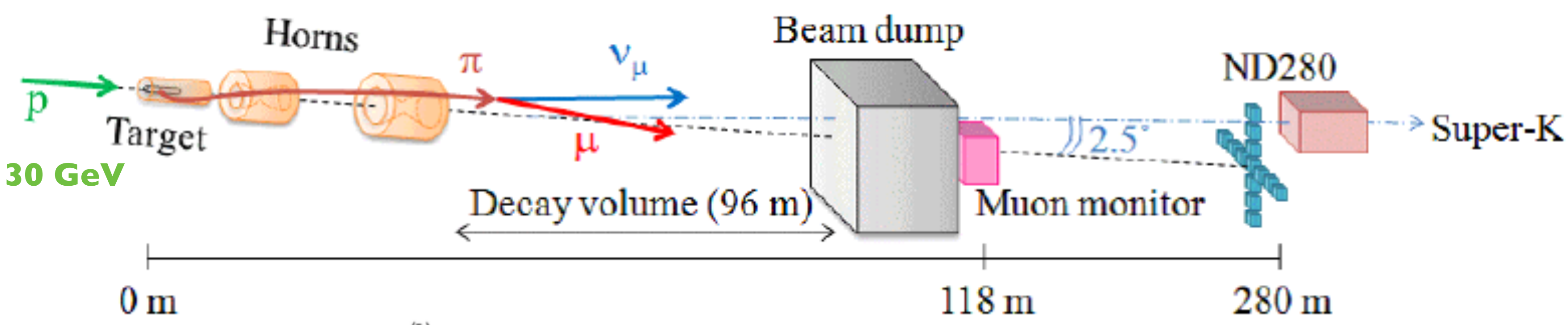
B. Richter, SLAC-PUB-8587

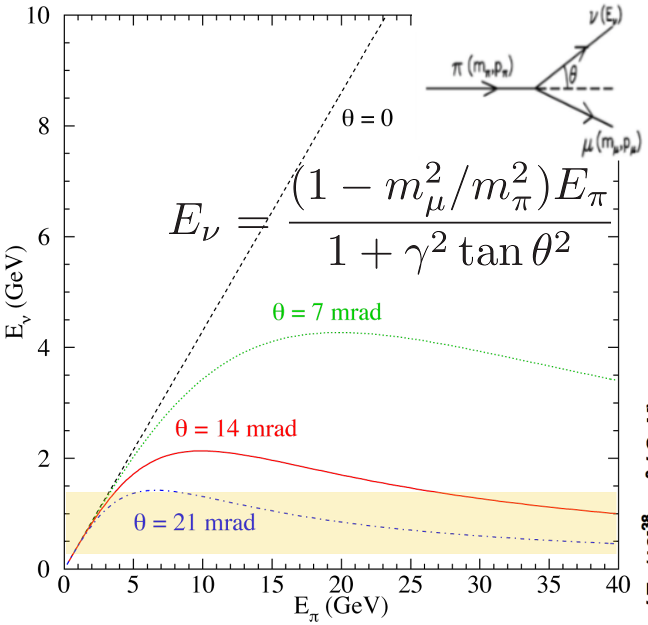
$a[\mathrm{eV}^2] = 2\sqrt{2}G_F n_e E_\nu = 7.6 \times 10^{-5}\rho[\mathrm{g/cm}^2]E_\nu[\mathrm{GeV}]$

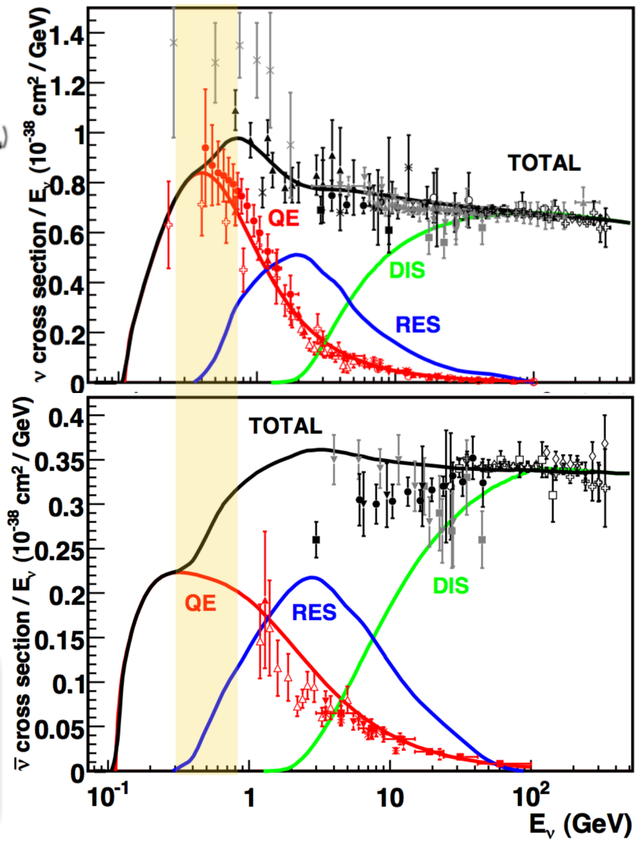
- θ_{13} dependence of the leading term
- θ_{23} dependence of the leading term (θ_{23}=45° or θ_{23}≷45°?)
- ➤ **CP violation**: asymmetry of probabilities P($\nu_\mu \to \nu_e$) ≠ P($\bar{\nu}_\mu \to \bar{\nu}_e$) if sinδ≠0
- Matter effect: ν_e ($\bar{\nu}_e$) appearance enhanced in normal (inverted)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

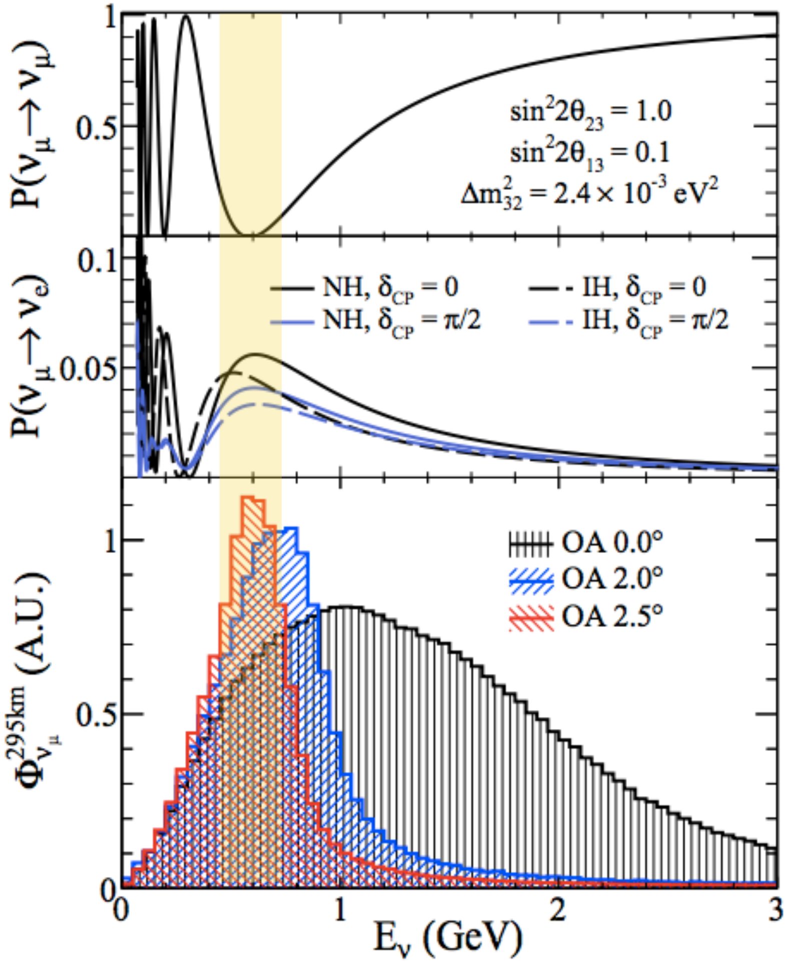
T2K experimental setup

The off-axis neutrino beam







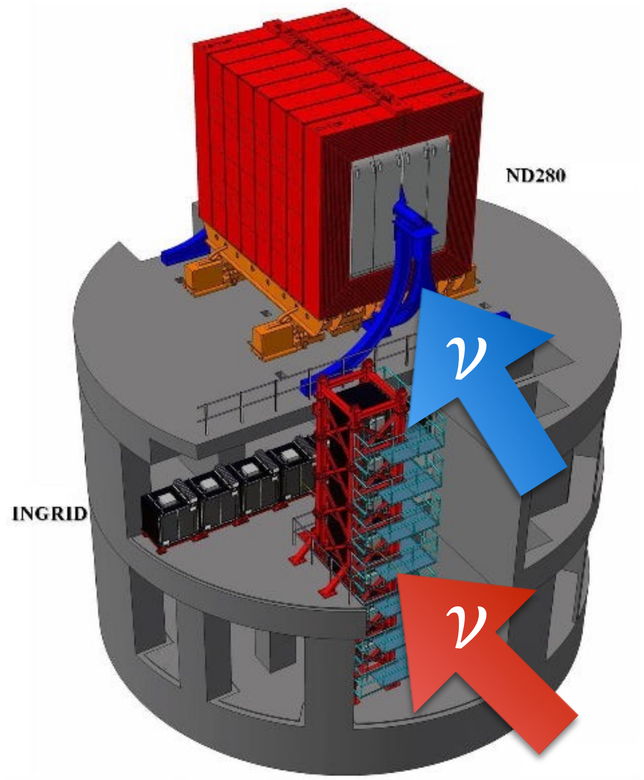


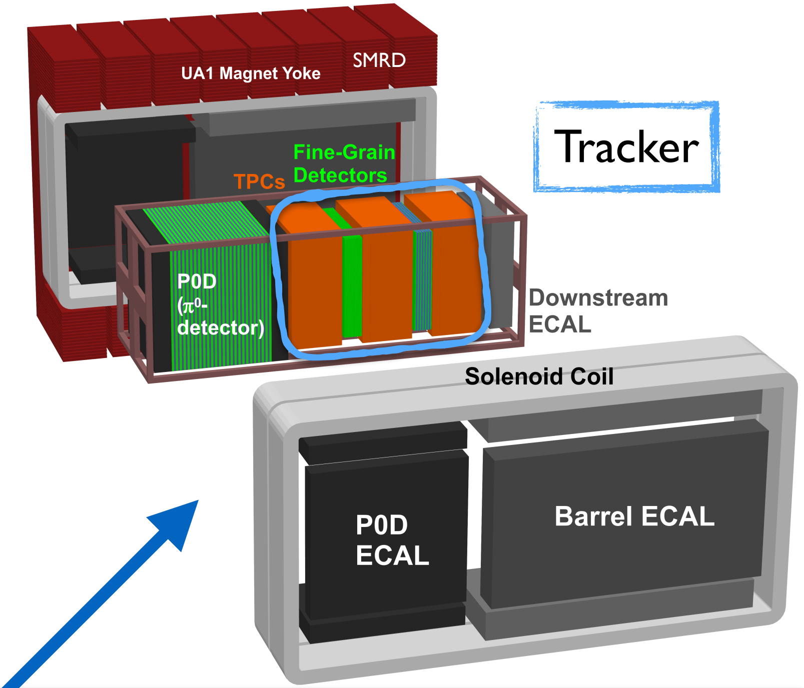
Charged Current Quasi-Elastic (CCQE)

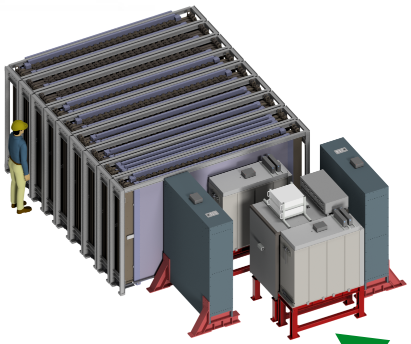
$$\nu_\mu + n \to \mu^- + p$$
$$\bar{\nu}_\mu + p \to \mu^+ + n$$

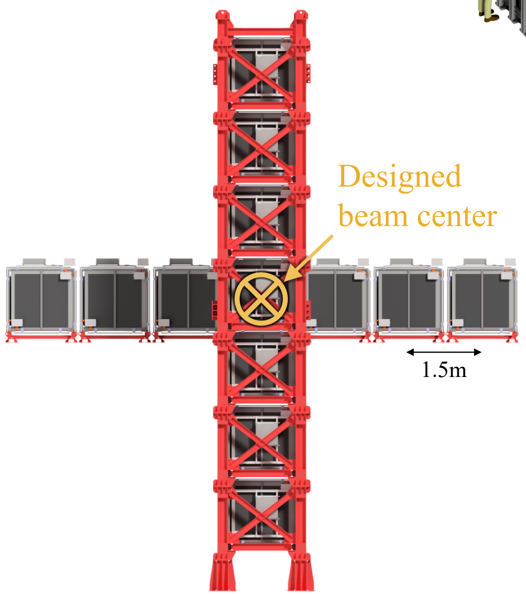
- Enhance neutrino oscillation effects
- Enhance CCQE-like interactions (signal at Super-Kamiokande)
- Reduce background from π^0 interactions
- Changing horn current possible to run in ν and $\bar{\nu}$ beam mode

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°)

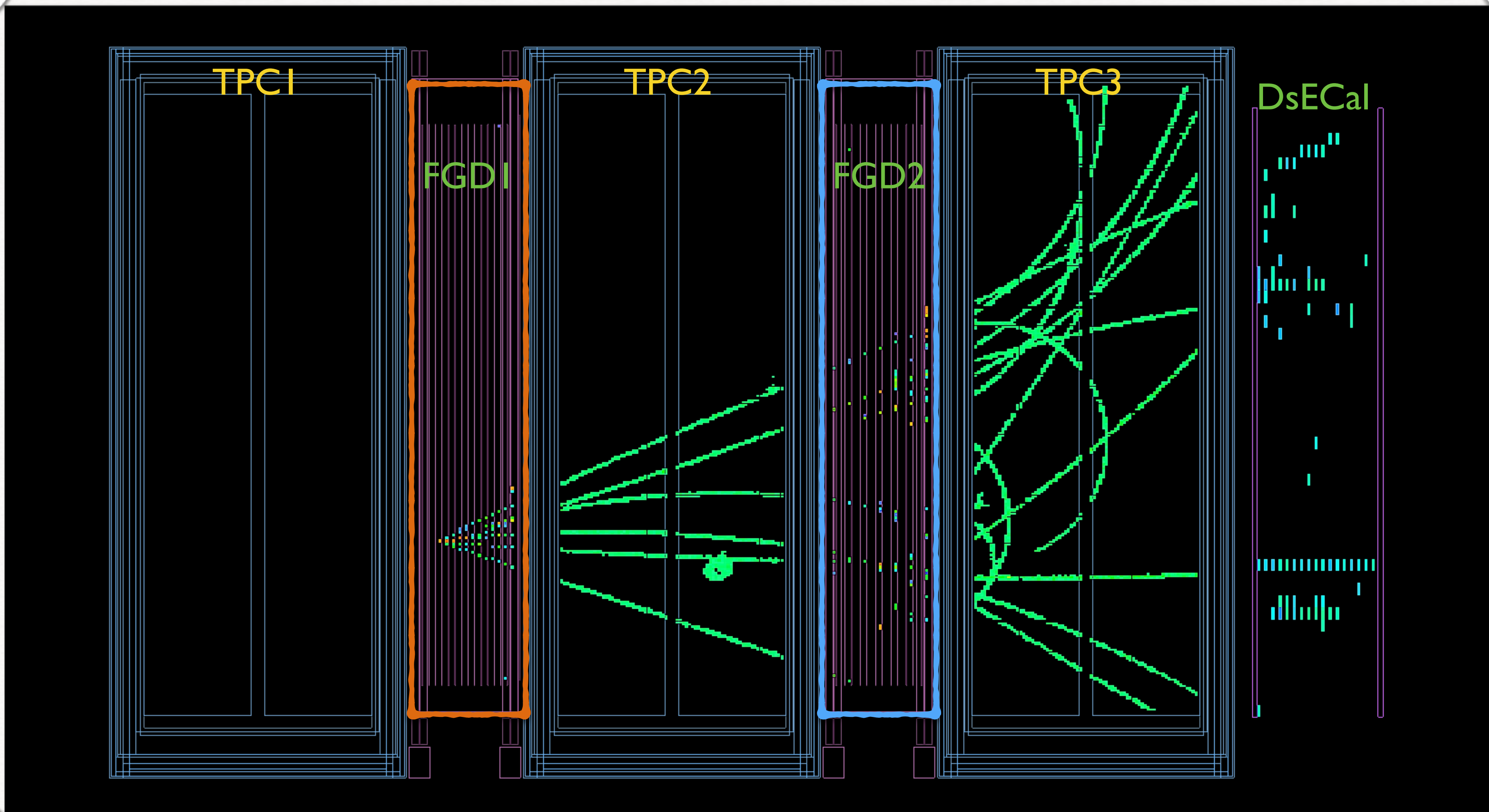
- **WAGASCI**: plastic scintillator detector filled with water (~ 80%)
- **BabyMIND**: magnetised iron and scintillator (μ charge and range)
- **Not used yet in the oscillation analysis**

INGRID (on-axis)

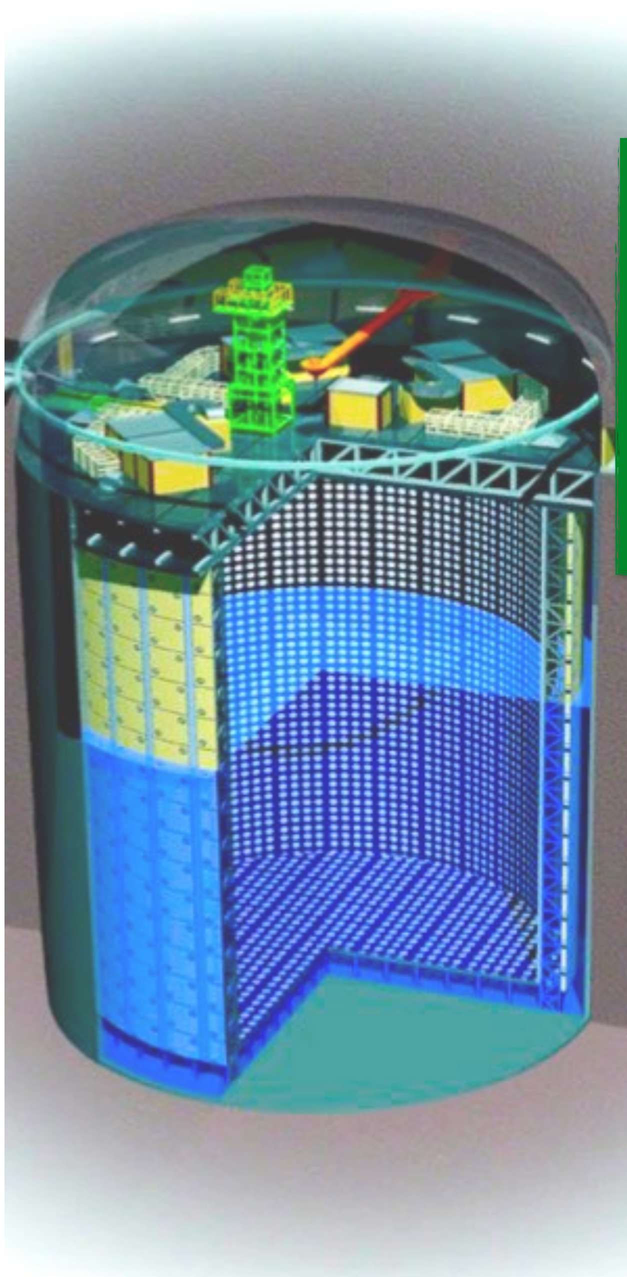
- ν_μ **CC rate → monitor beam profile and stability**
- **Fe/Scintillator tracking calorimeter** (16 Fe/Scint modules + 1 central one made of scintillator only)

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**

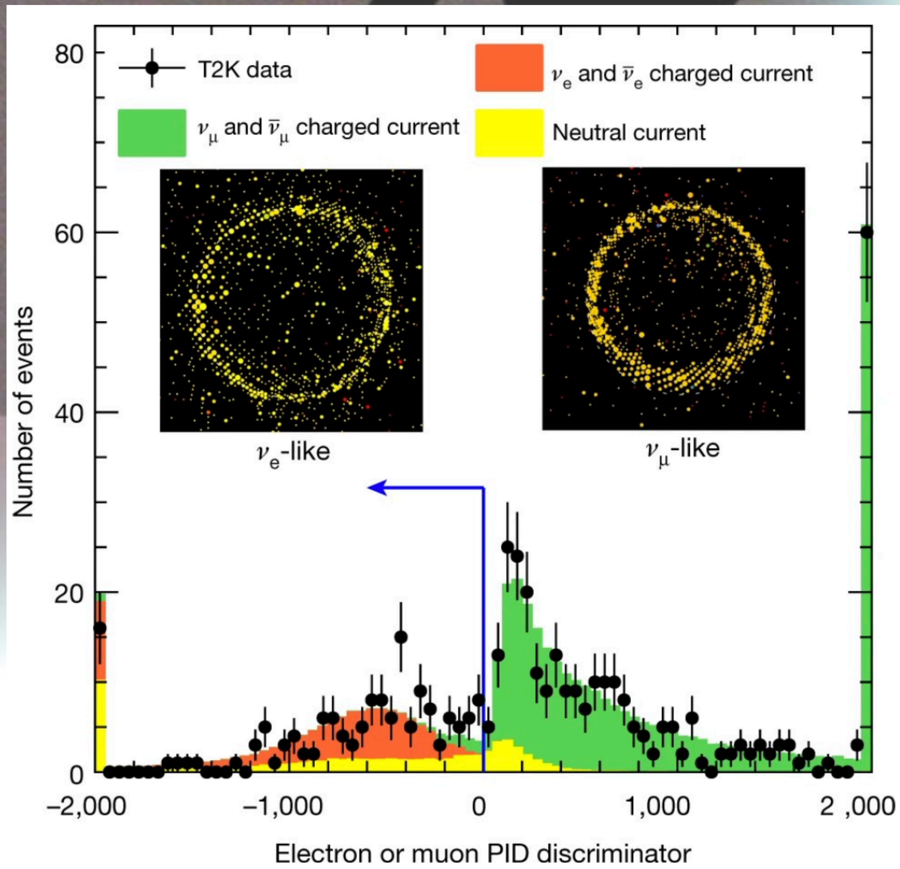


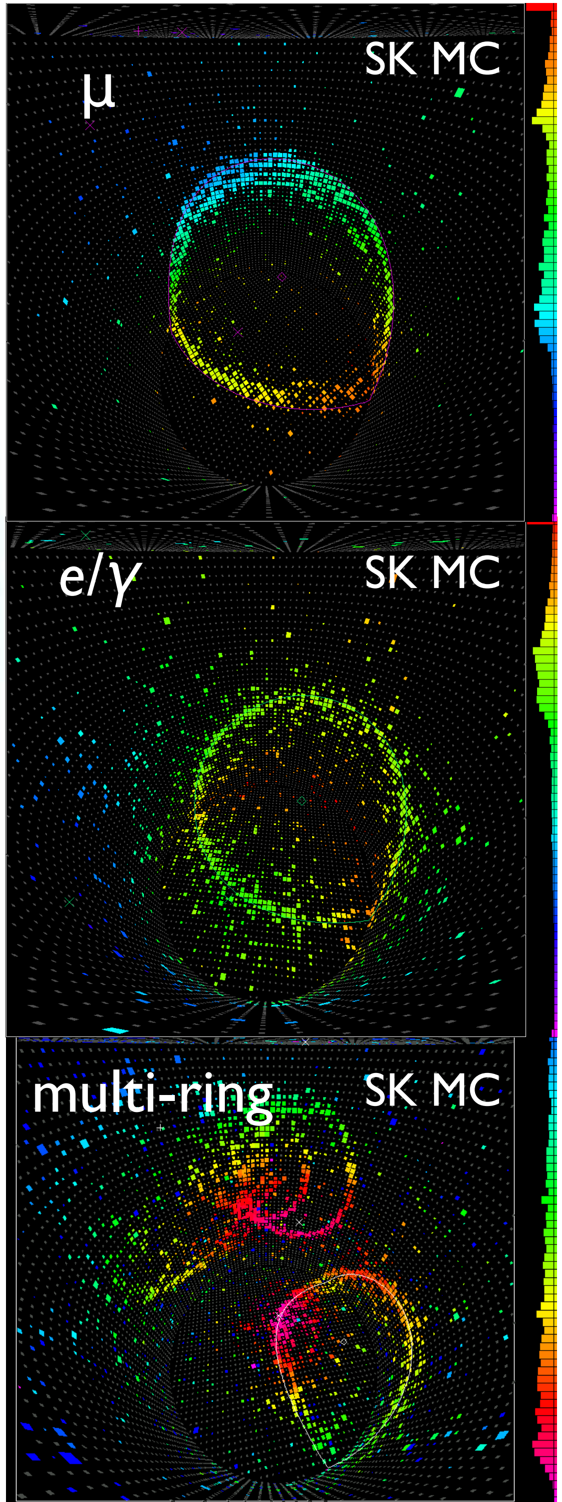
Far detector: Super-Kamiokande



Super-K (2.5° off-axis)

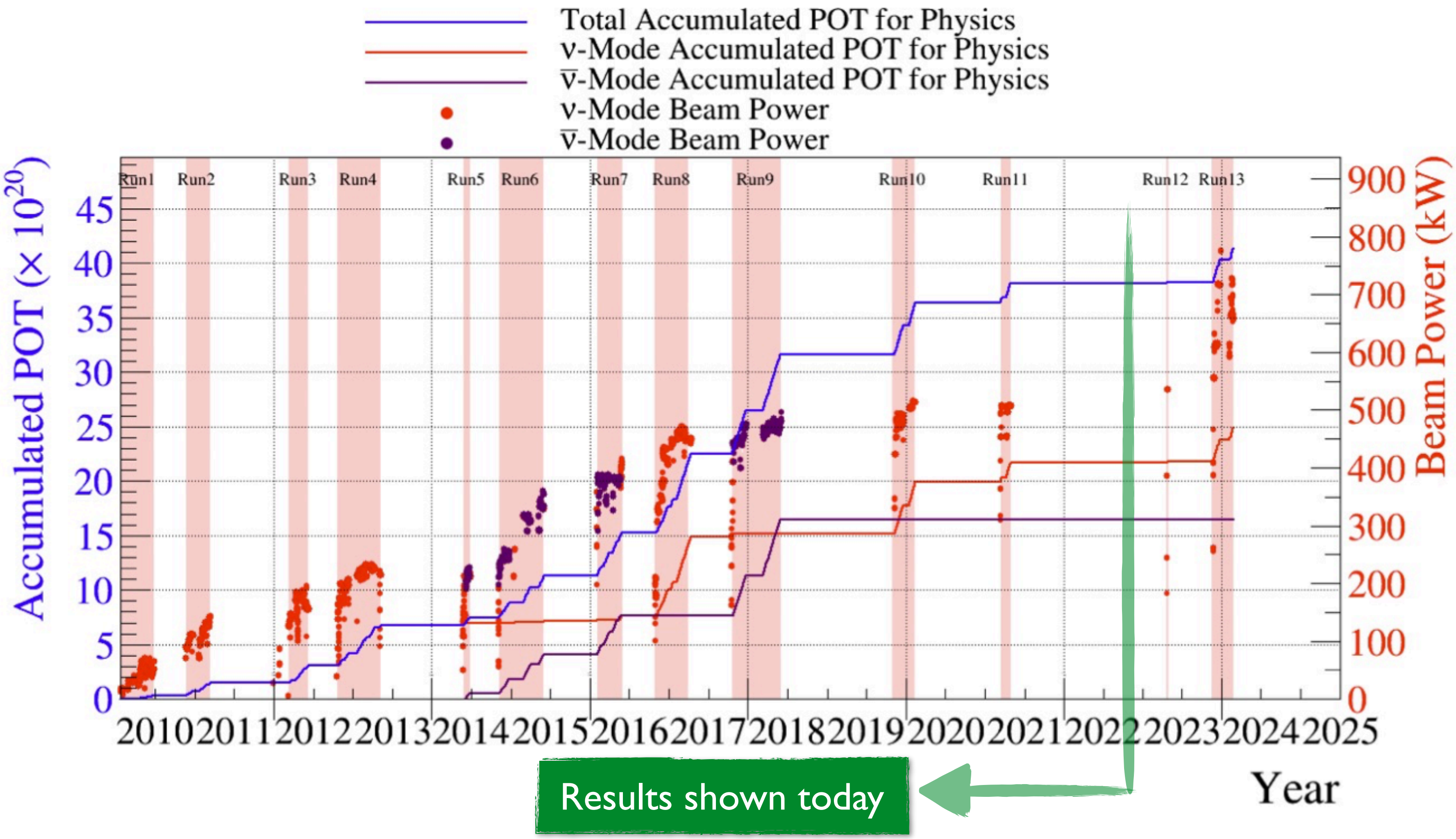
- Water Cherenkov (22.5 kt fiducial volume, > 11k PMT, ~40 m x 40 m)
- Excellent μ/e separation (based on ring profile) and π^0 detection (2 e-like rings)
- <1% mis-PID at 1GeV
- ΔE/E ~10% for Quasi-Elastic (QE) events





T2K oscillation results

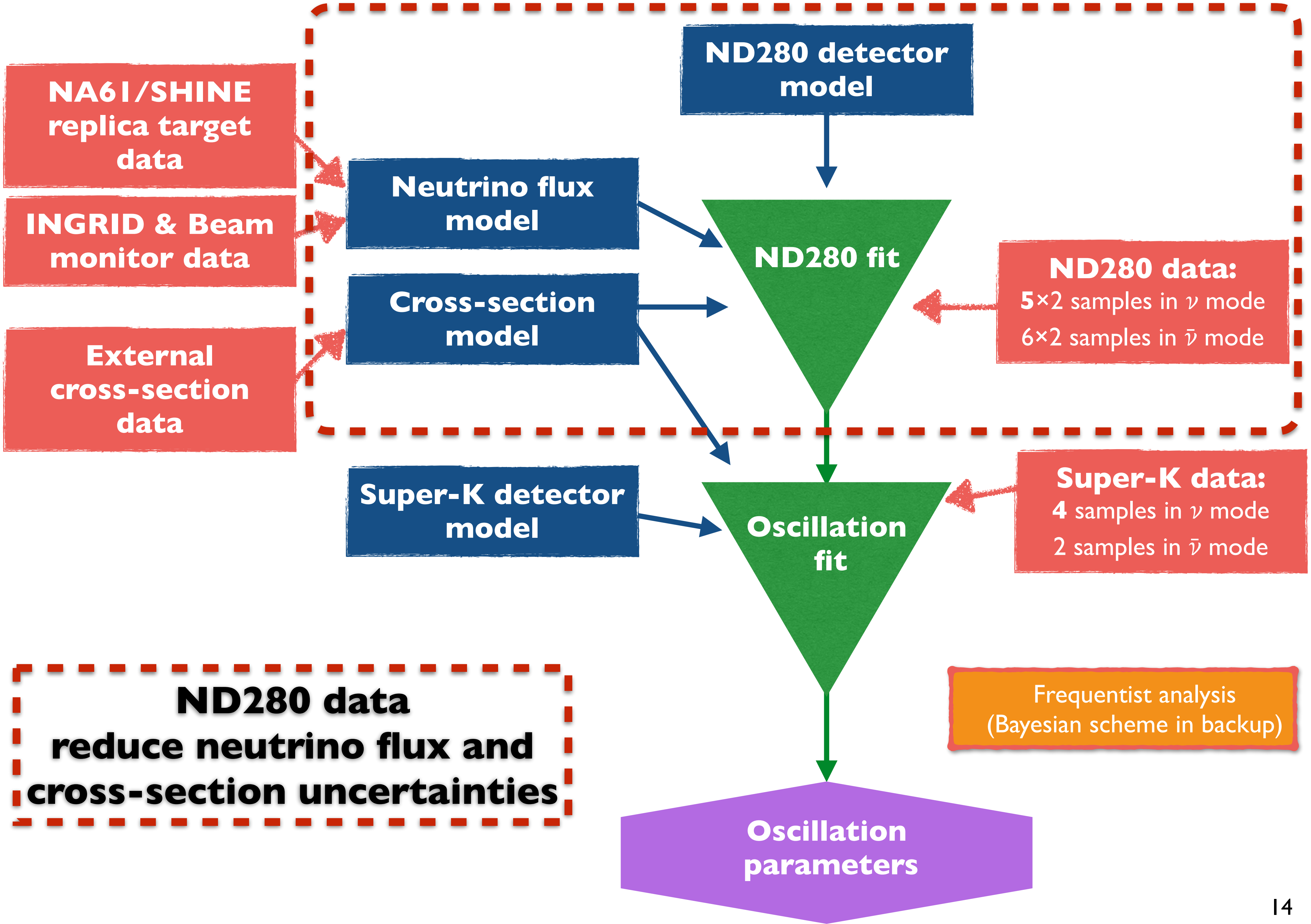
Collected data



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

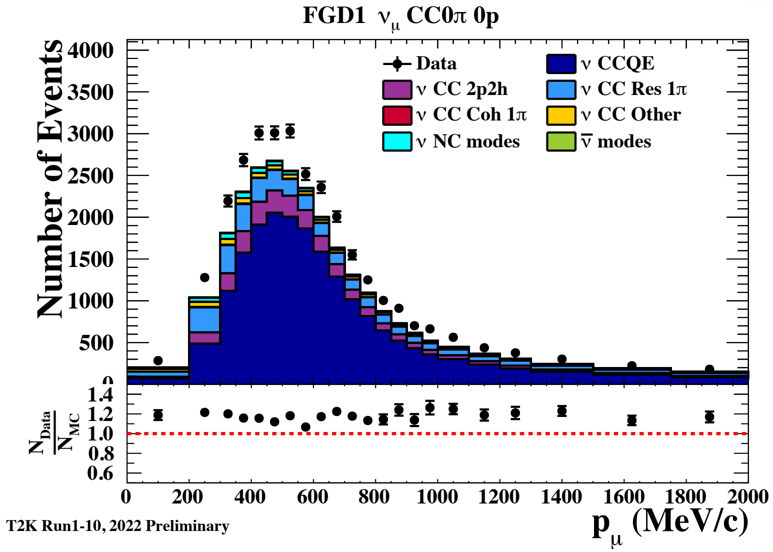
POT	ND		FD	
Beam mode	ν	$\bar{\nu}$	ν	$\bar{\nu}$
This analysis	1.15×10^{21}	0.83×10^{21}	2.14×10^{21}	1.63×10^{21}

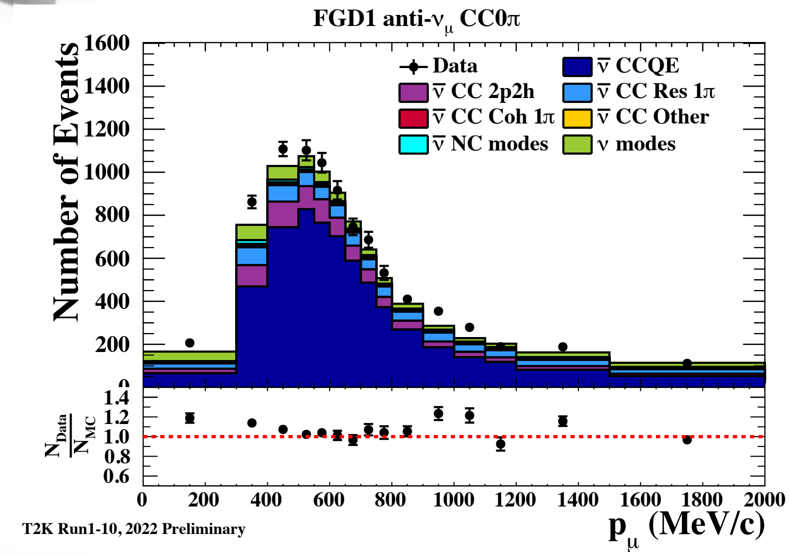
Oscillation analysis strategy



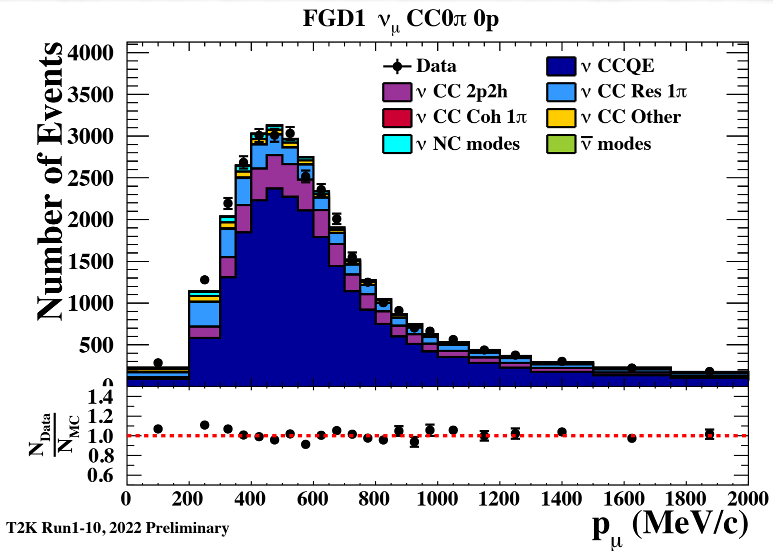
Fitting ND280 samples

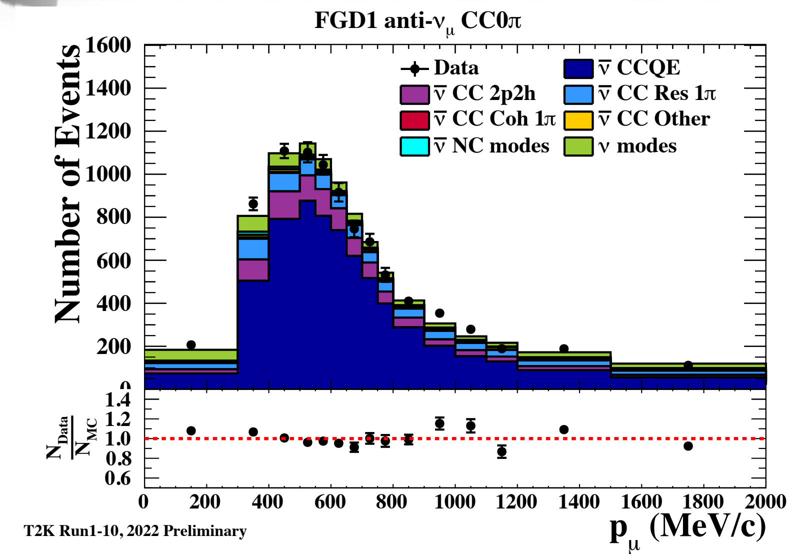
Pre ND280 fit





Post ND280 fit

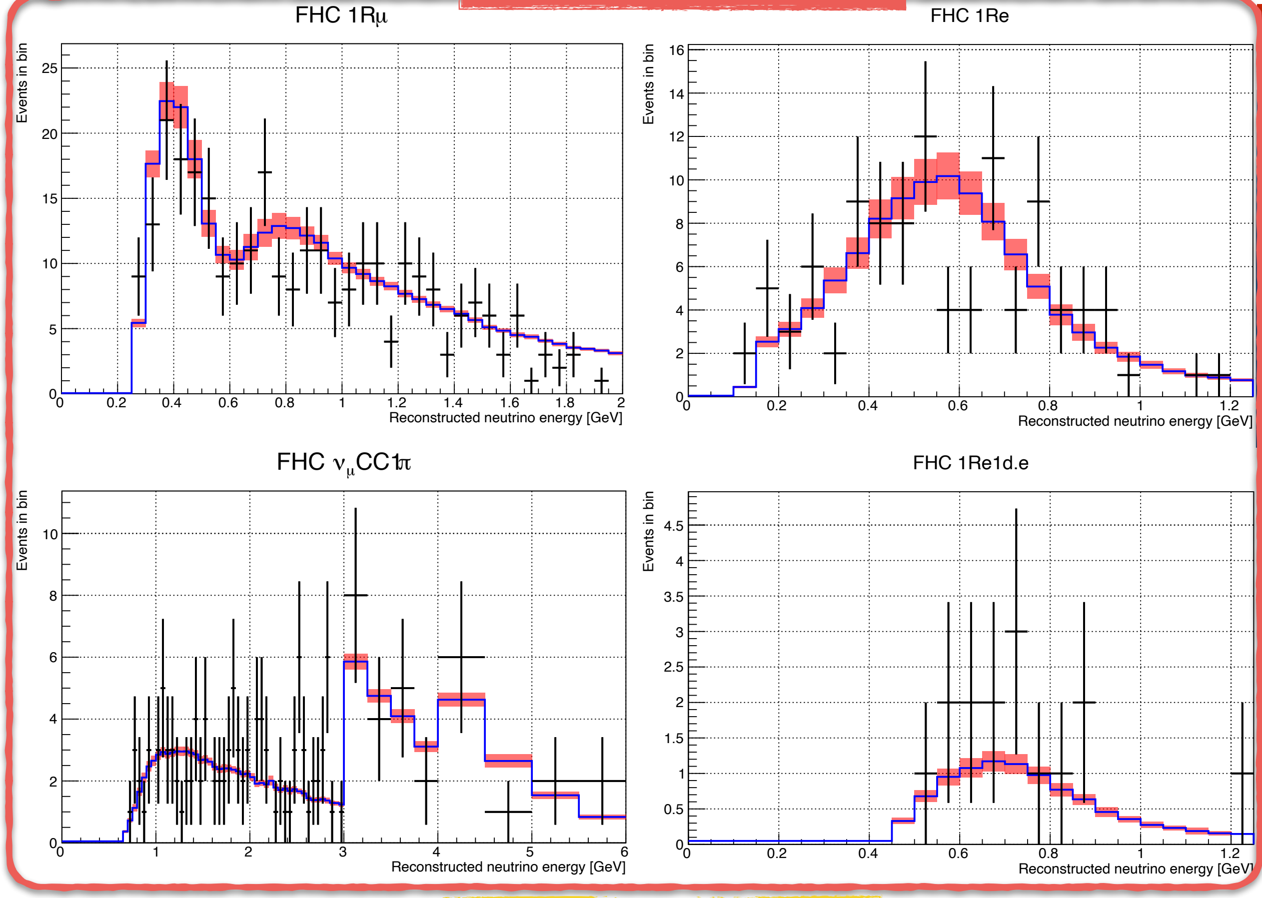




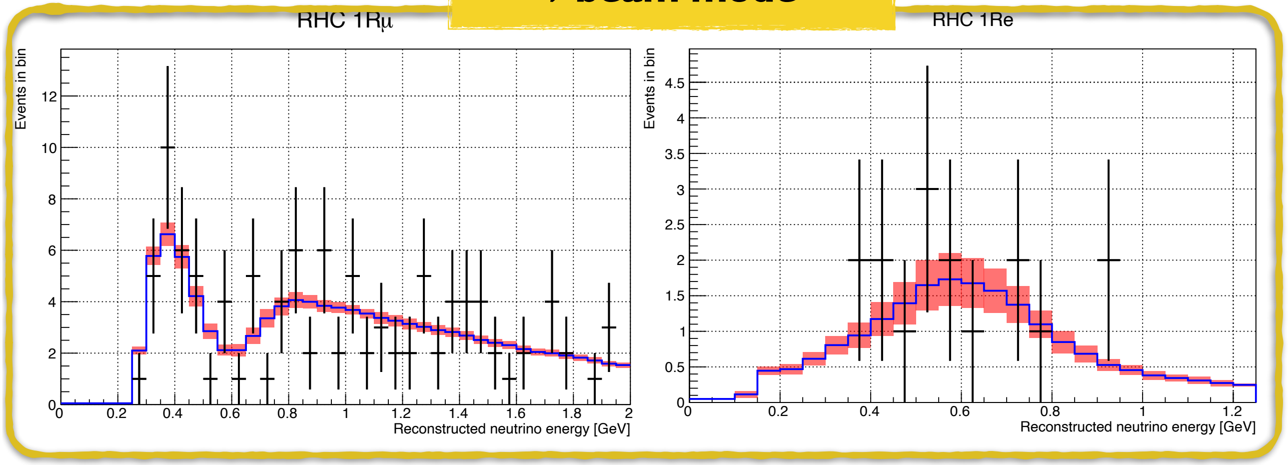
ND280 samples used to constraint on flux and x-sec models

Super-K samples

ν beam mode

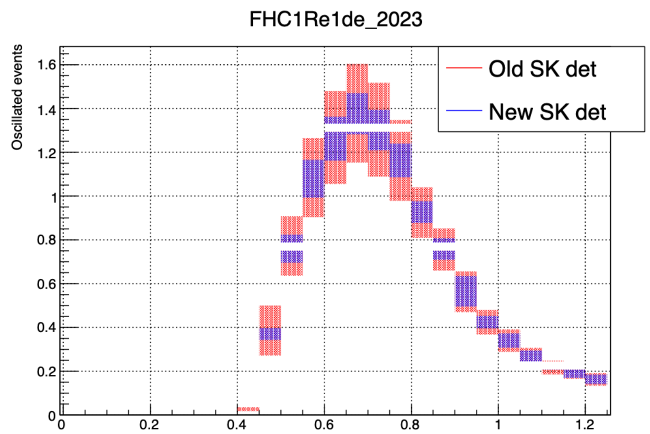


$\bar{\nu}$ beam mode



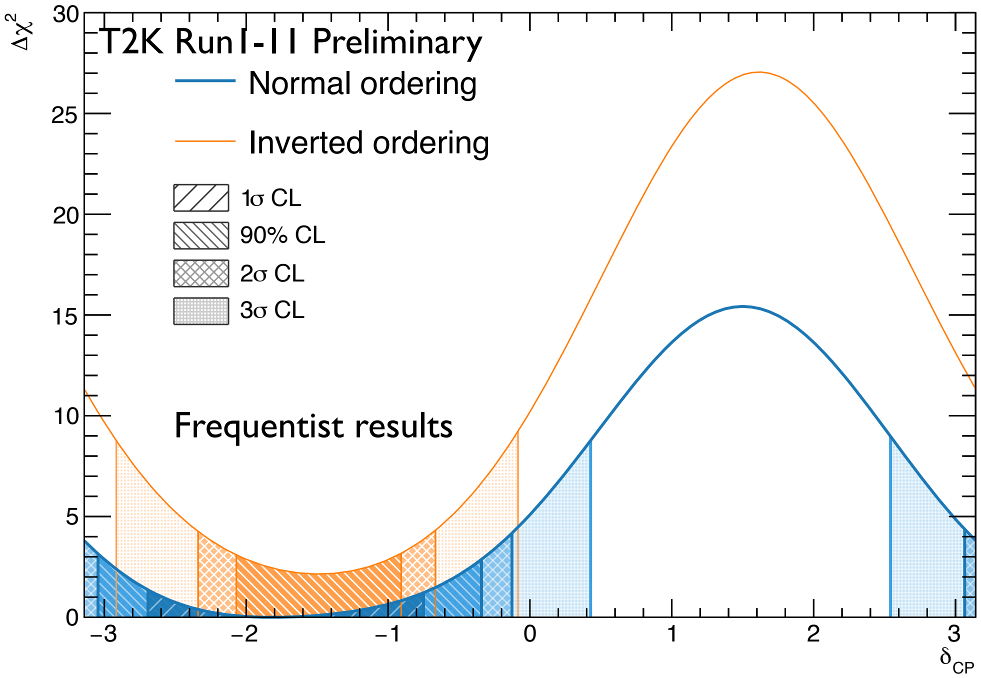
Beam mode	Sample	Description
ν	1Re	One e-like ring, 0 decay electrons
	1Re CC1π+	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	MRμ CC1π+	One μ-like ring, 2 decay electrons/ μ-like ring + π+-like ring, 1 decay e
$\bar{\nu}$	1Re	One e-like ring, 0 decay electrons
	1Rμ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

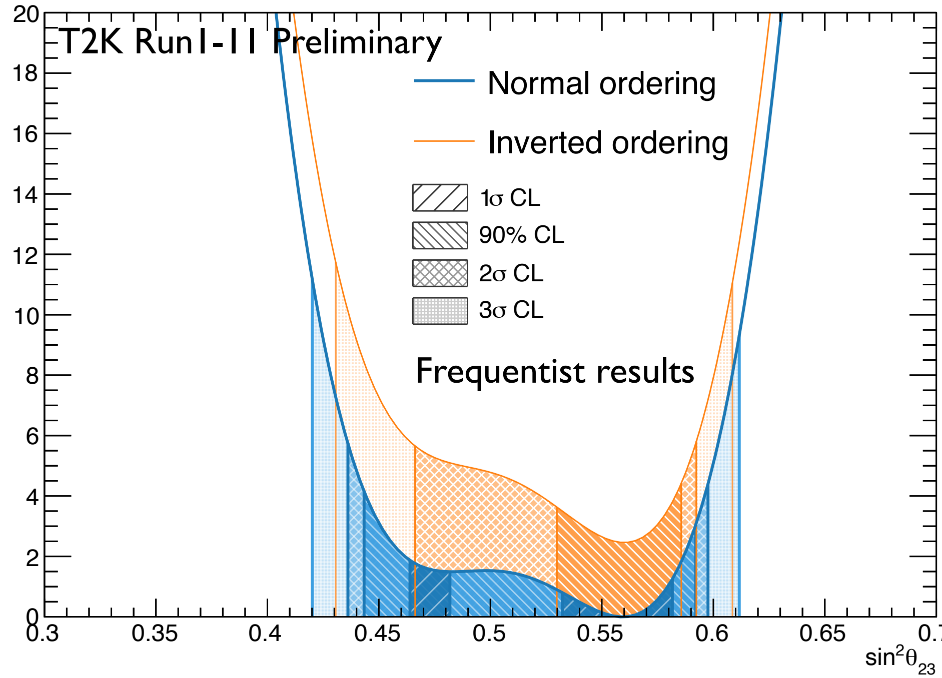
- New SK detector modeling significantly reduce systematics in some of the samples
- Add ~10% statistic in ν mode



Results: δ_{CP} confidence regions

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



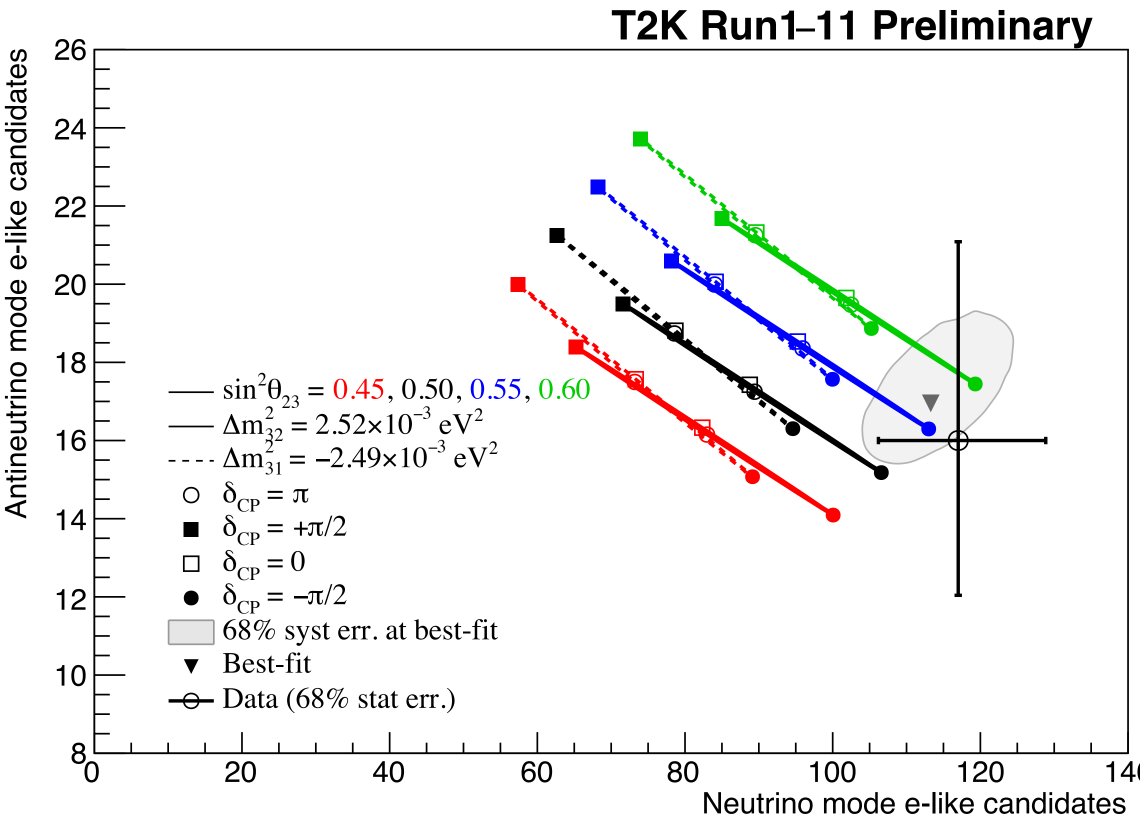


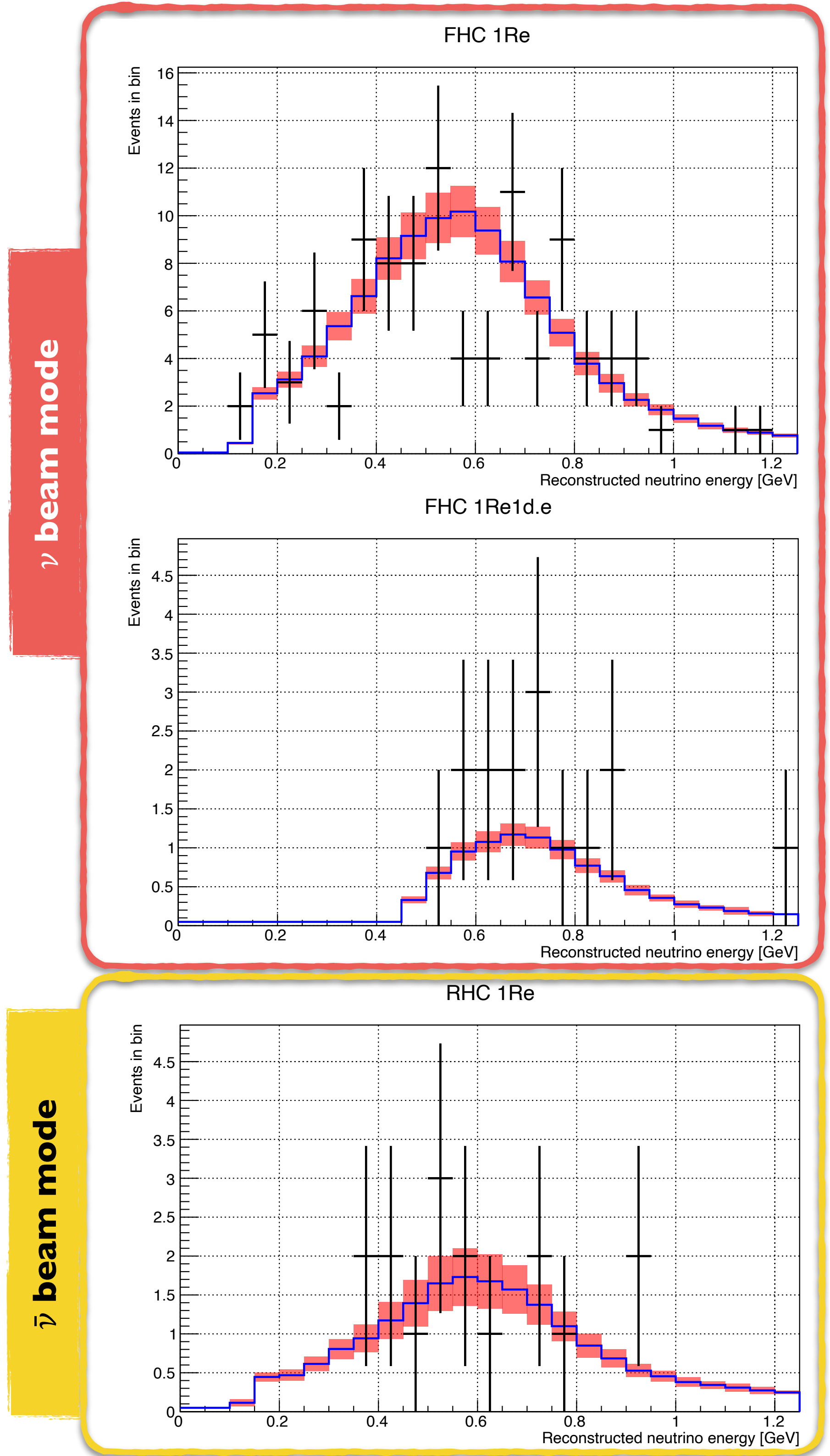
- Best fit value **near maximal CP violation** ($-\pi/2$)
- **CP conserving values excluded at 90% C.L.**
- Slight preference for **normal ordering**
- Best fit in the **upper octant** for θ_{23}

Confidence level	NO	IO
	$\sin^2\theta_{23}$	
1σ	[0.464, 0.482] ∪ [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] ∪ [3.06, π]	[-2.34, -0.67]
3σ	[$-\pi$, 0.43] ∪ [2.54, π]	[-2.92, -0.08]

Summary of 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**

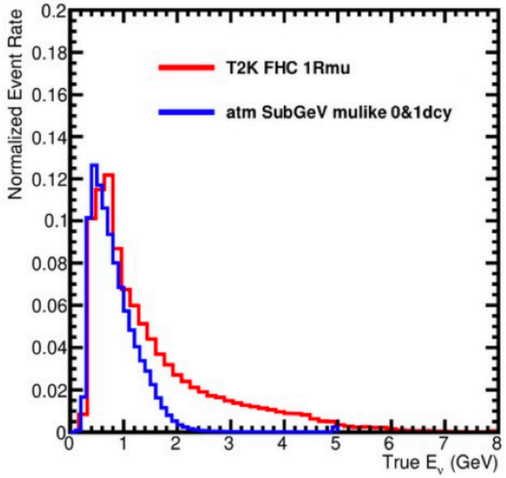


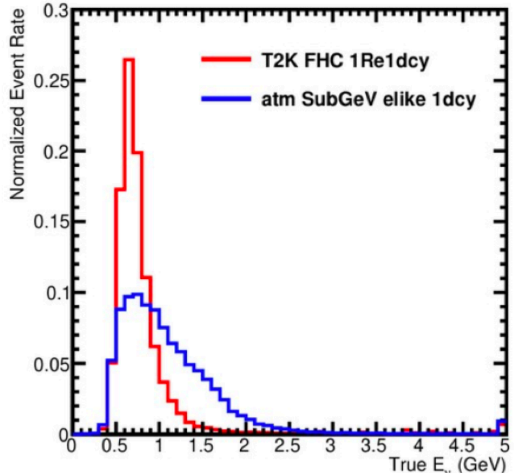


Joint analyses

T2K-SK atmospheric joint analysis

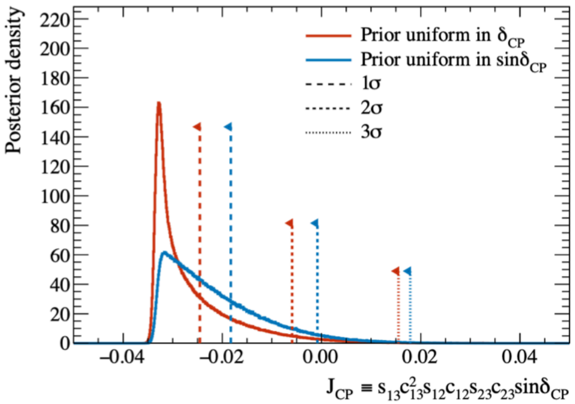
- T2K has good sensitivity to δ_{CP} but mild preference for NO
- SK has a good constraint on MO but not on δ_{CP} due to poor energy resolution
  - T2K constraint on $\sin^2\theta_{23}$ reduce degeneracies in SK
- Same far detector SK
  - Same SK detector modeling for the two samples
  - Use ND280 data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



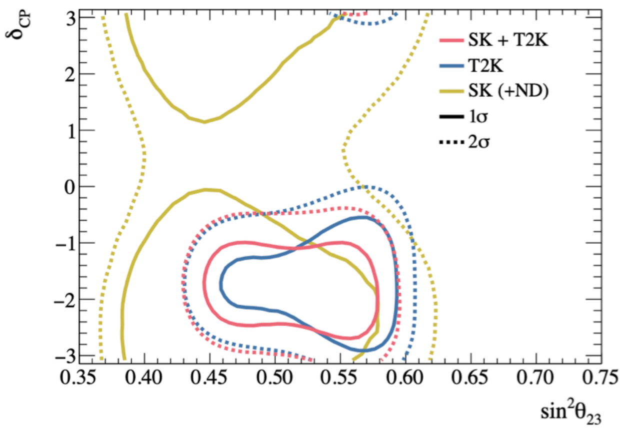


- Both experiments prefer NO and $\delta_{CP} \sim -\pi/2$, T2K prefers higher octant while SK lower octant
- The CP conserving value of the Jarlskog invariant is excluded with a significance varying between 1.9σ and 2.3σ depending on the analysis considered

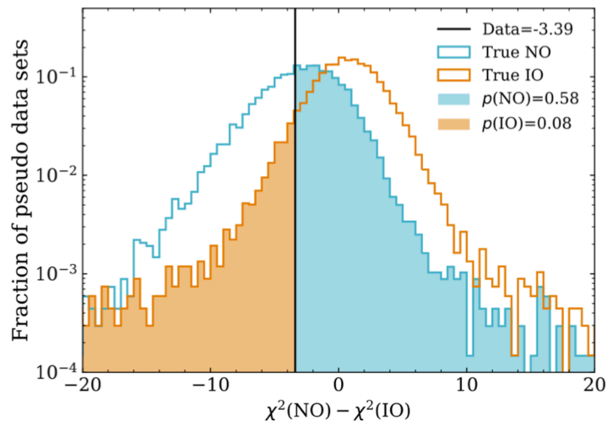
Value tested	Prior uniform in δ_{CP}	Prior uniform in $\sin(\delta_{CP})$
$J_{CP} = 0$	2.3σ (2.2σ)	2.0σ (1.9σ)
$\delta_{CP} = 0$	2.6σ (2.5σ)	2.3σ (2.2σ)
$\delta_{CP} = \pi$	2.1σ (1.9σ)	1.6σ (1.4σ)



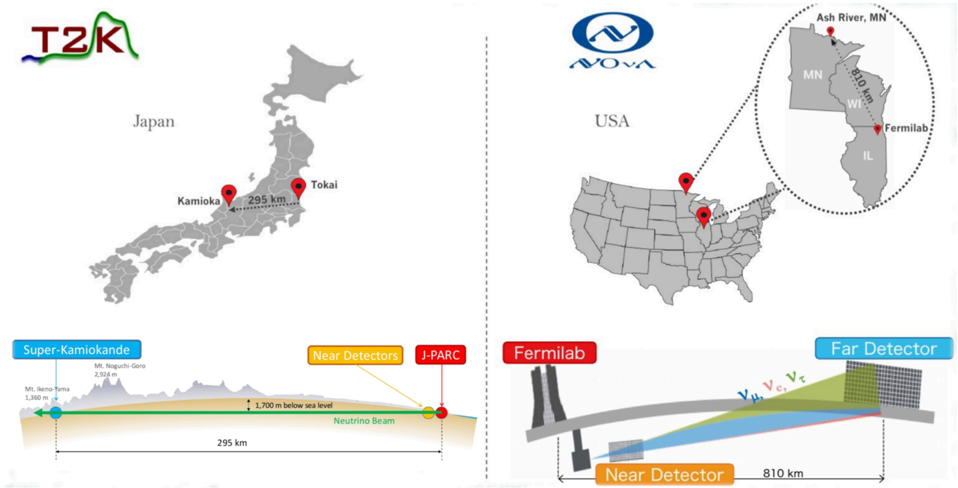
	SK only	T2K only	SK+T2K
Upper octant	0.318 (0.337)	0.785 (0.761)	0.611 (0.639)
Normal ordering	0.654 (0.633)	0.832 (0.822)	0.900 (0.887)



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

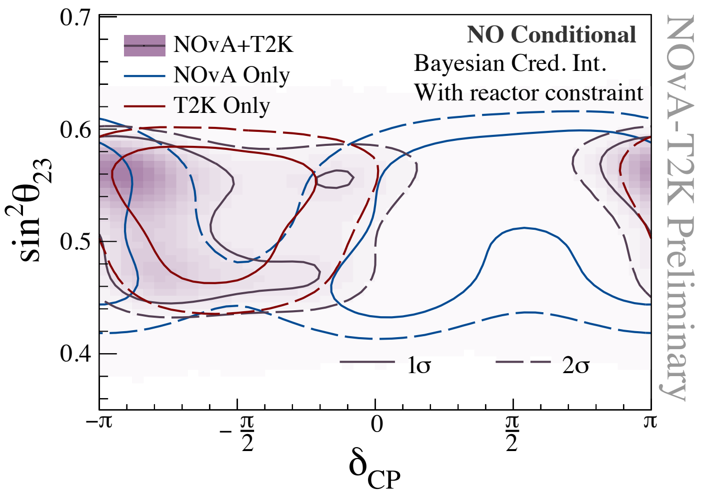


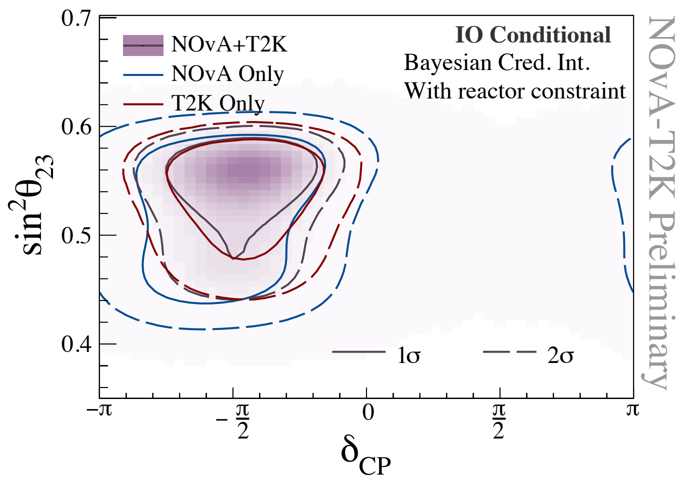
T2K-NOνA joint analysis

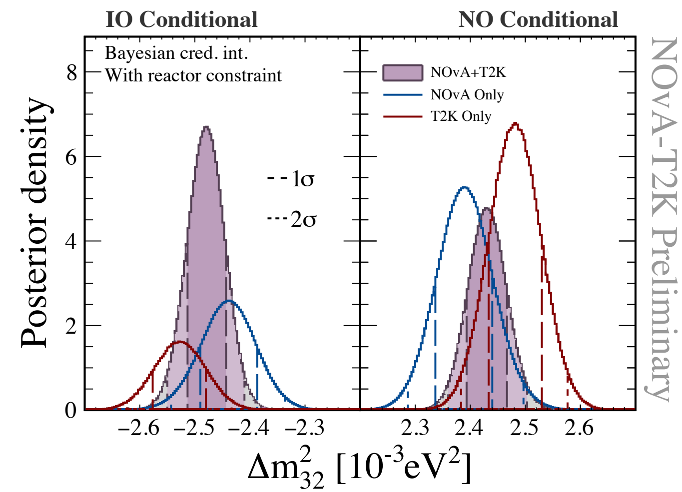


Experimental Property	T2K	NOvA
Proton beam	30 GeV	120 GeV
Baseline	295 km	810 km
Peak nu energy	0.6 GeV	2 GeV
Detection tech	Water Cherenkov	Segmented Liq scin. bars
CP effect	32%	22%
Matter effect	9%	29%

- 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 $\delta_{CP} = -\pi/2$

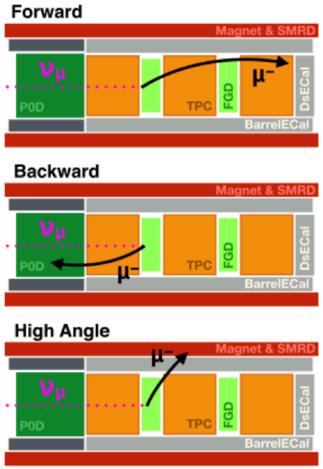


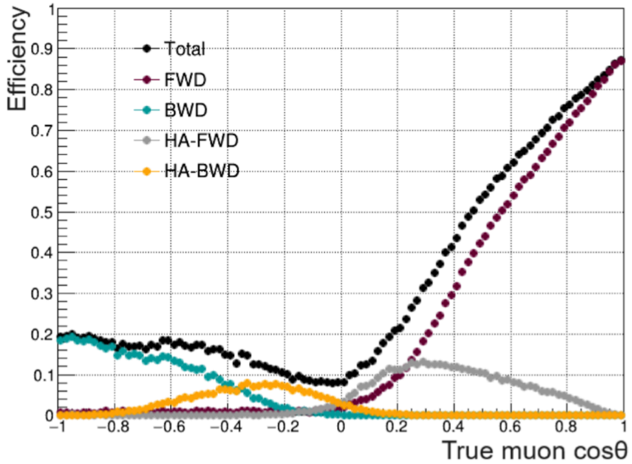




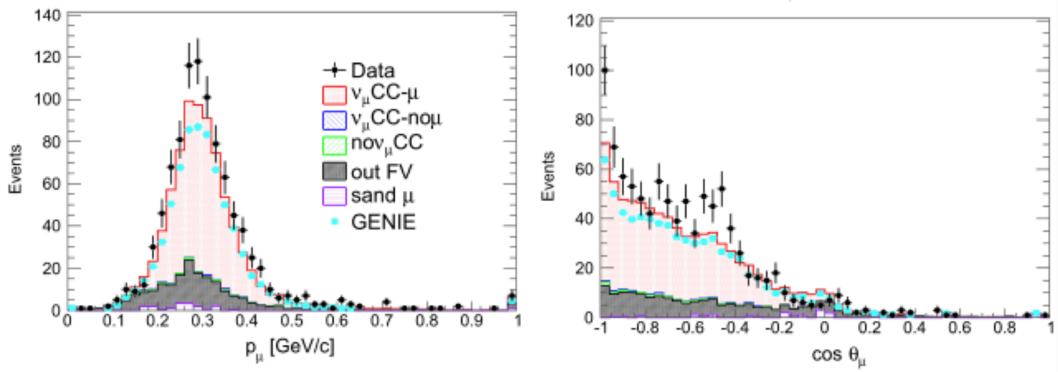
What's next

Next iteration of OA





Phys. Rev. D 98, 012004 (2018)

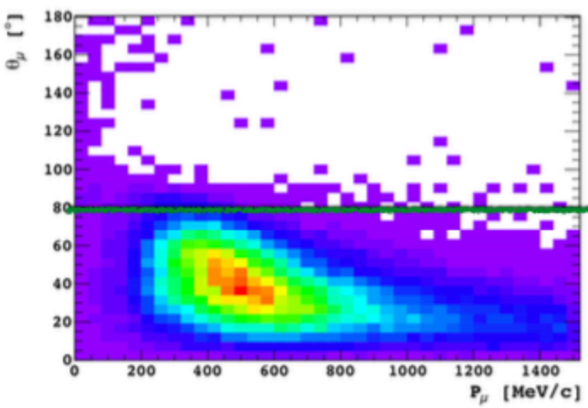


Preliminary Asimov fit → similar systematics

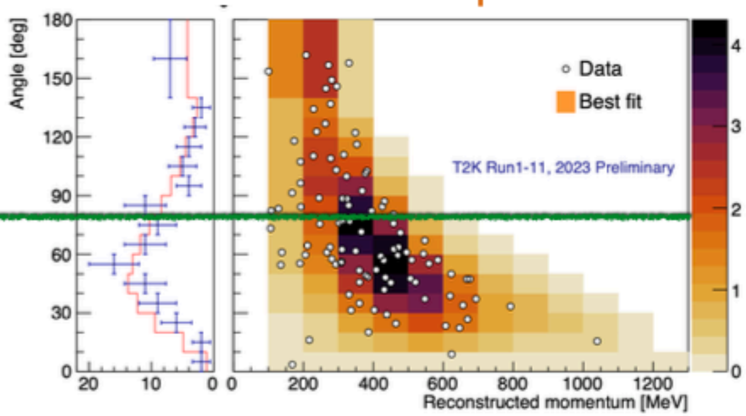
- New x-sec model with more freedom and higher x-sec uncertainties
- Inclusion of high angle and backward going tracks in ND280 to match SK acceptance
  - Limited efficiency selection ($\sim 20\,\%$) due to the absence of TPCs in the high angle region $\Longrightarrow$ **ND280 upgrade**
  - Low efficiency of low momentum proton reconstruction $\Longrightarrow$ **ND280 upgrade**

Sample	Pre-ND fit	Post-ND fit	Previous x-sec model - no 4π
ν-mode 1Rμ	15.8%	2.6%	2.5%
ν-mode 1Re	20.8%	4.0%	3.8%
ν-mode MR	12.1%	2.8%	2.1%
ν-mode 1Re+d.e.	13.8%	4.7%	4.2%
$\bar{\nu}$-mode 1Rμ	15.3%	2.7%	2.4%
$\bar{\nu}$-mode 1Re	15.5%	3.5%	3.5%

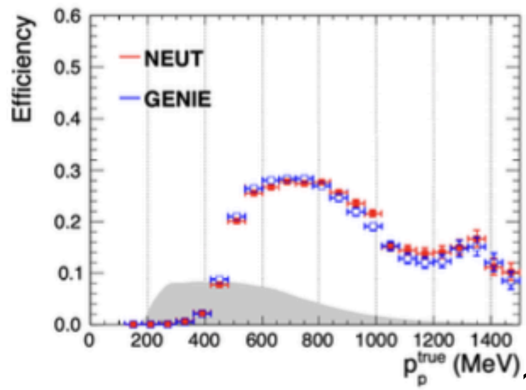
ND280 acceptance



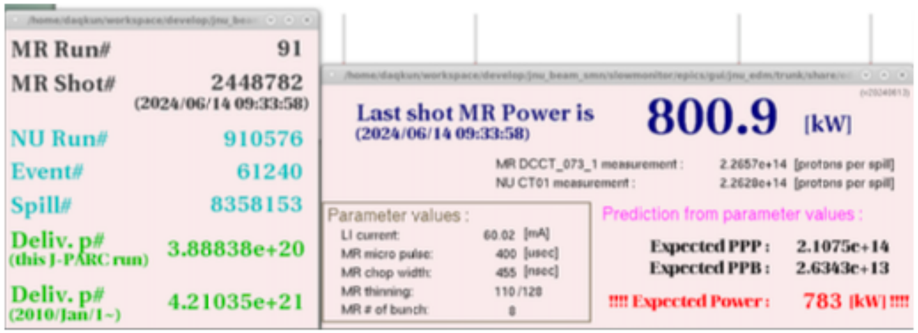
SK acceptance



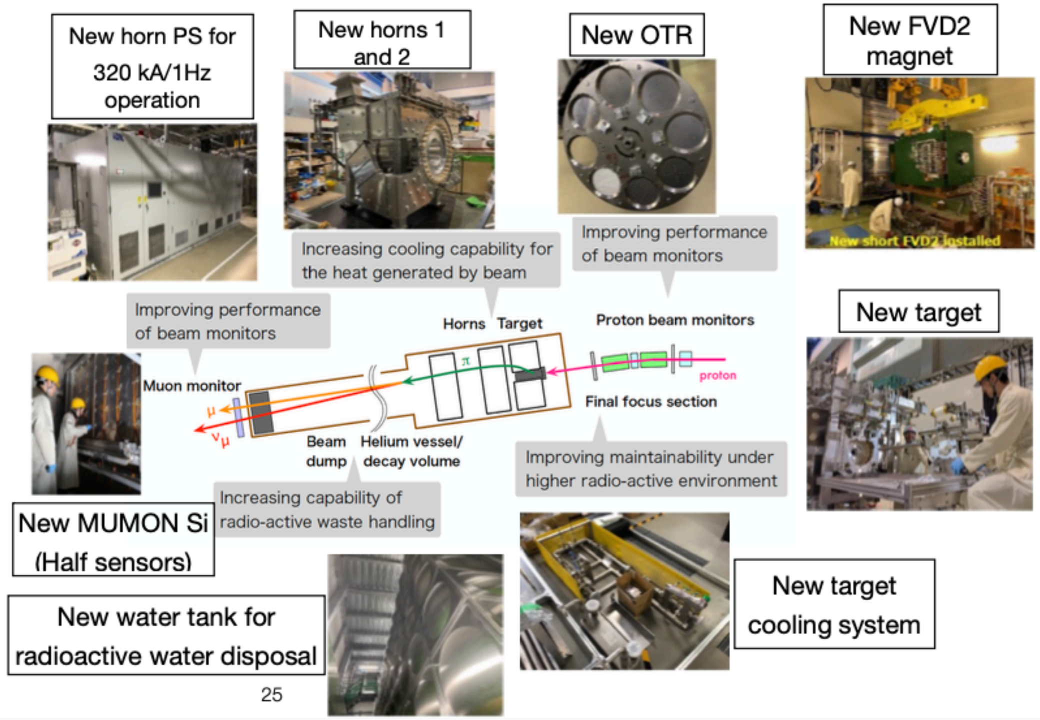
ND280 Proton reconstruction efficiency

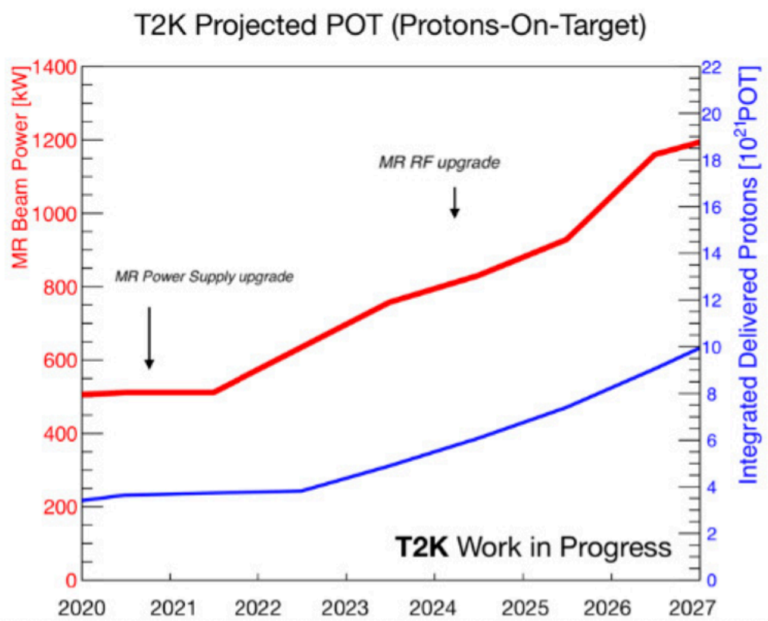


Neutrino beam upgrade

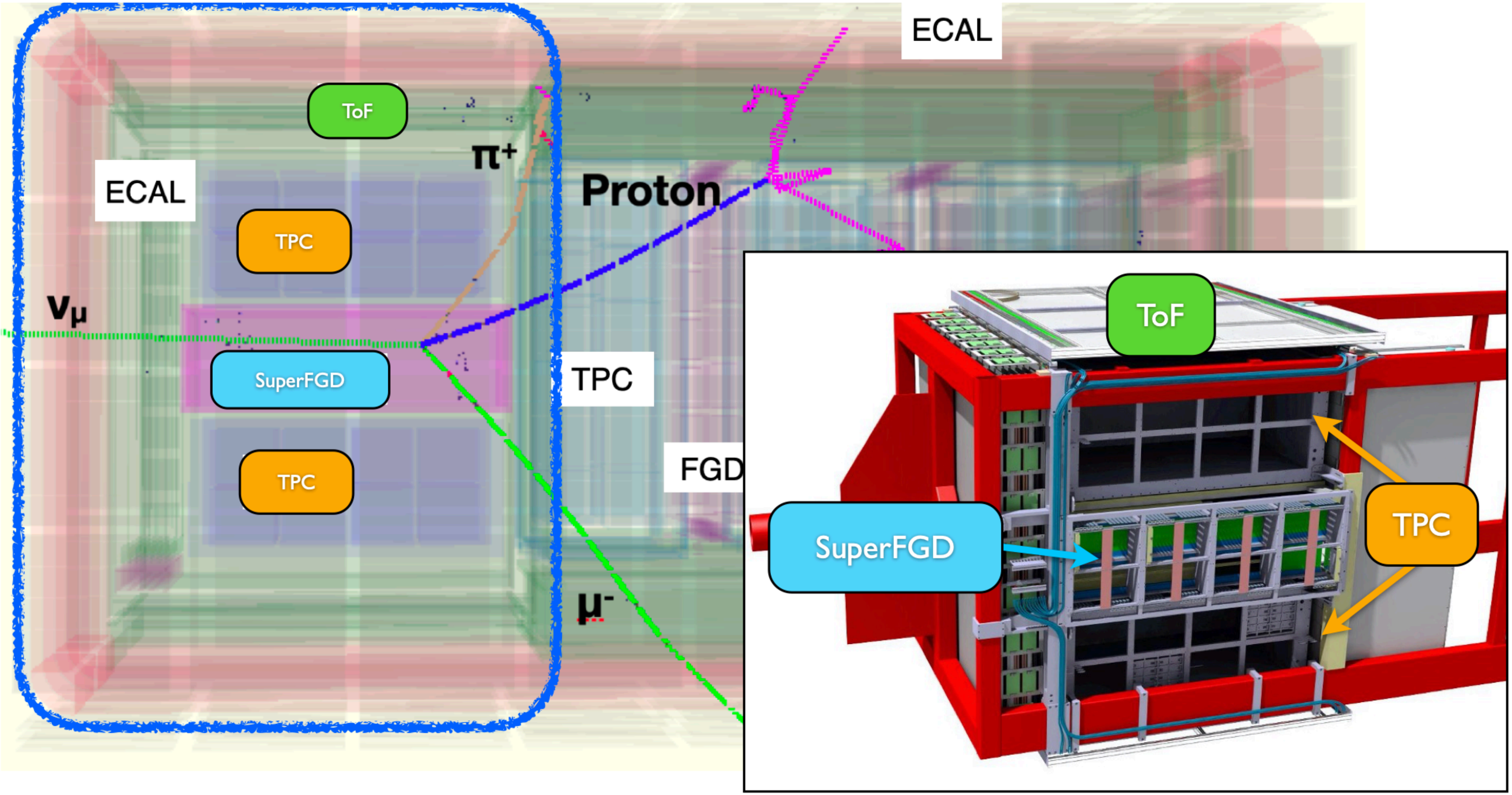


- **Reach design 750kW by increasing T_{rep} (2.48 → 1.3s)**
  - Replace Main Ring Power Supply (MR-PS)
  - Upgrade MR-RF core for higher accelerating gradient
- **Several upgrades done on neutrino beamline in order to achieve higher beam power**
- **Horn current increase (250 kA → 320 kA)**
  - $\sim 10\,\%$ increase in ν flux
- **In December 2023 beam power increased from 500 to 750 kW and 800 kW last week!**
  - T2K is currently taking beam data
- **Steady improvement to reach 1.3 MW by 2027 (factor of 3 more stat in 2027)**
- **Larger statistic needs a reduction of systematic uncertainties**





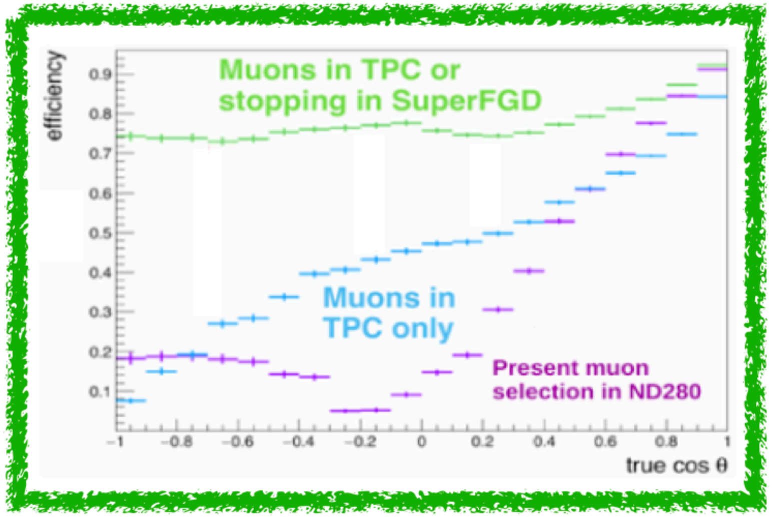
ND280 upgrade



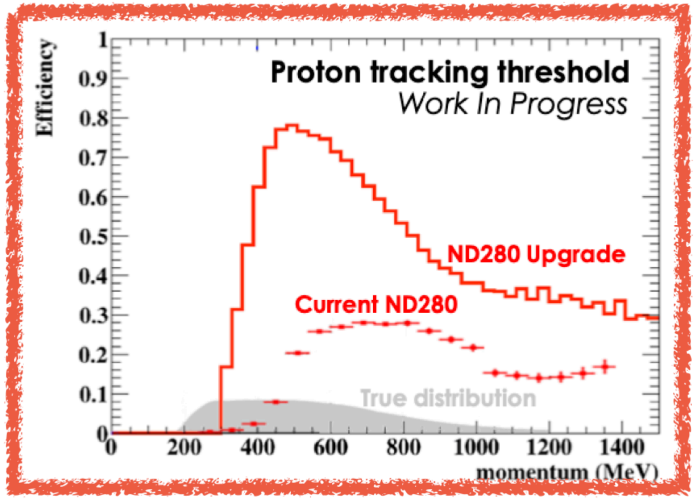
P0D replaced by:

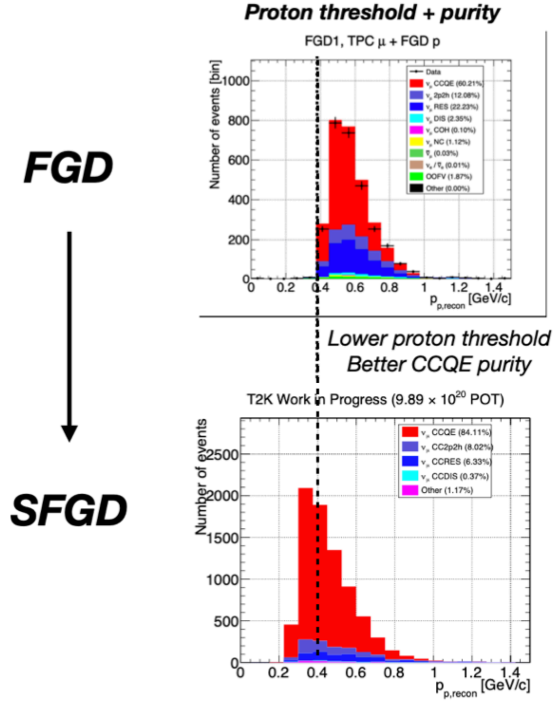
- A new fine grained scintillator target **SFGD** capable to measure low energy protons and neutrons produced in CC interactions
- Two high angle TPCs (**HATPC**) to increase the angular acceptance as SK
- Six super fast **ToF** panels (150 ps) to identify charged particle directions

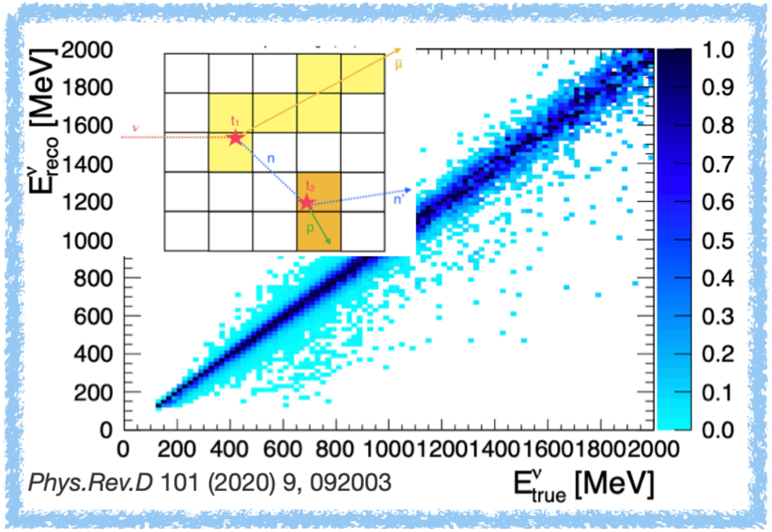
ND280 upgrade improvements



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







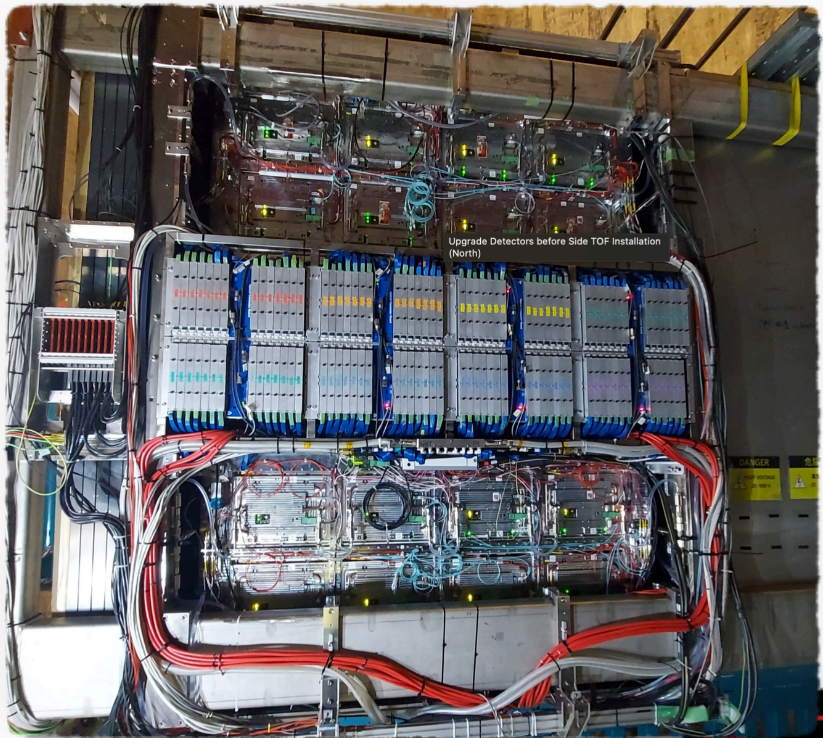
- High Angle TPC (HATPC) allows to reconstruct high angle charged particles with respect to beam direction
- Super-FGD (SFGD) allows to fully reconstruct 3D tracks from ν interactions
  - Improved PID performance with respect to FGD thanks to high granularity and light yield
  - Good performance in neutron reconstruction by using time of flight between $\bar{\nu}$ interaction vertex and neutron re-interaction
- First physics run with full upgrade currently ongoing
- Expect to select 20k ν_μ $CC0\pi$ interactions in SFGD

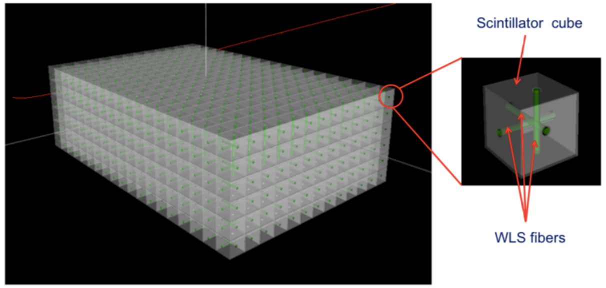
CC0π Event rates

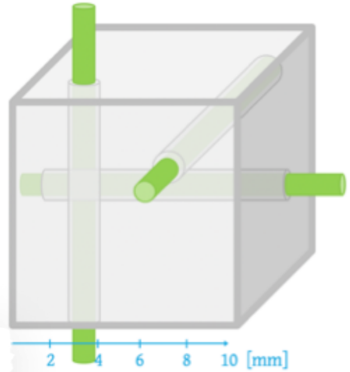
Expect 85%-90% purity for SFGD samples

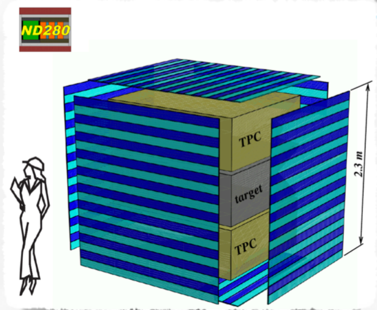
FHC only	1 cycle	3+1 cycles
SFGD total	21.8k	90.0k
SFGD w/nucleon	10.6k	43.9k

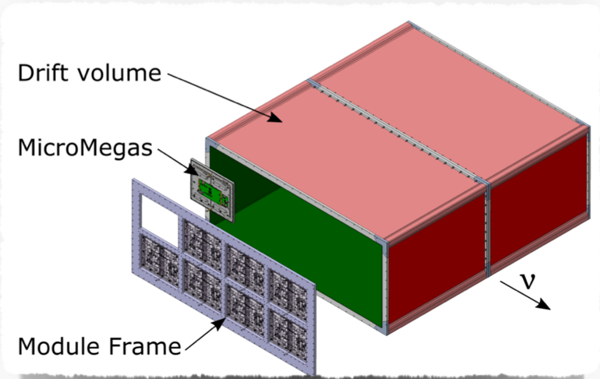
ND280 upgrade in place and taking data!

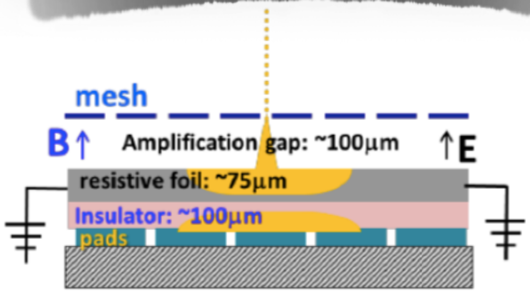


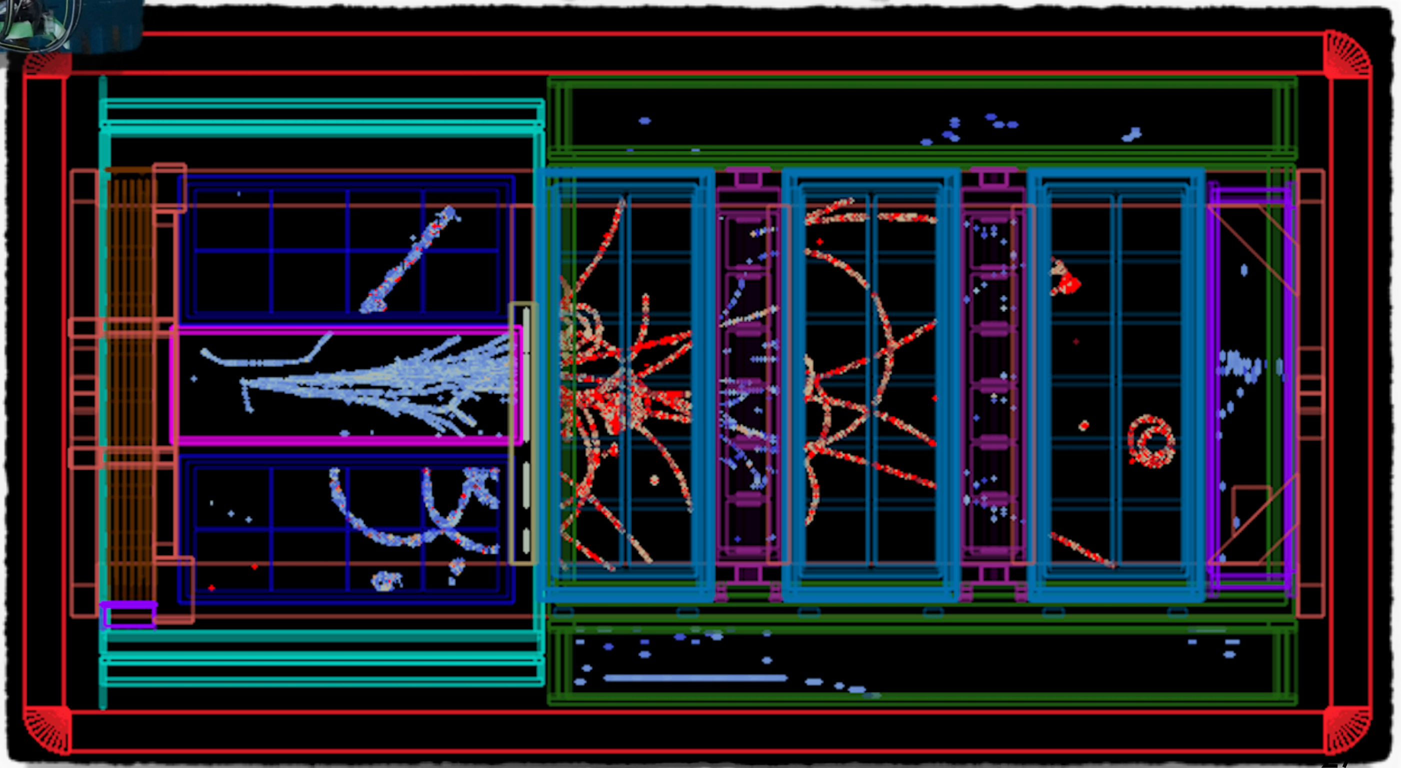




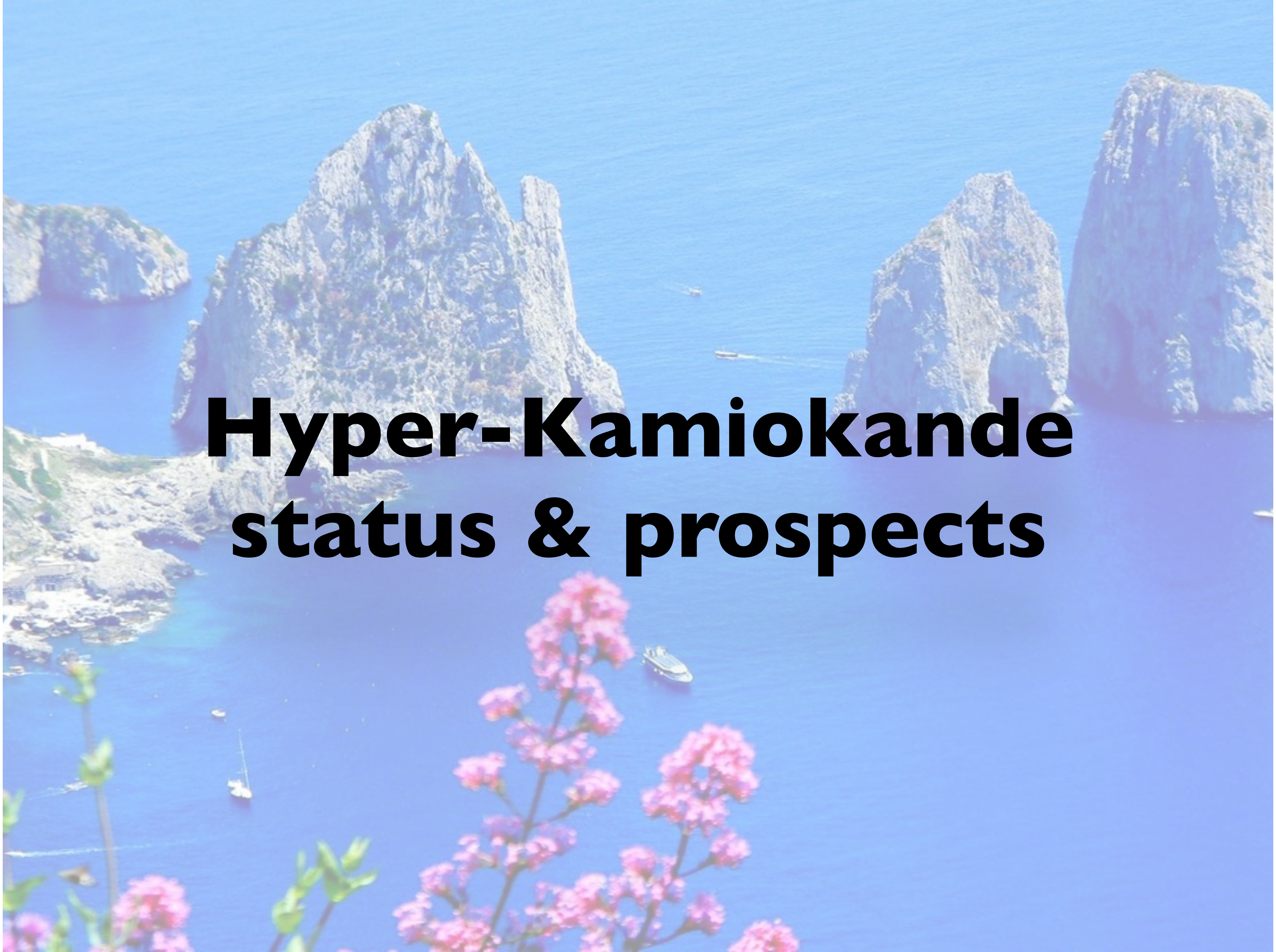








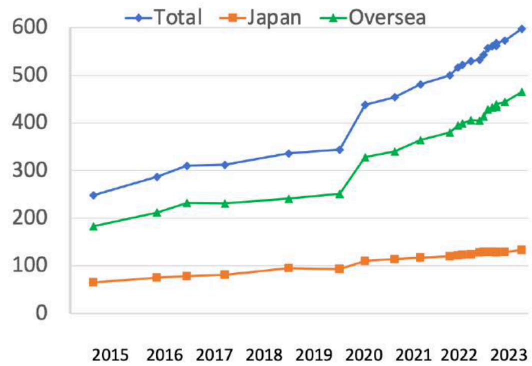
Hyper-Kamiokande status & prospects



The Hyper-Kamiokande project

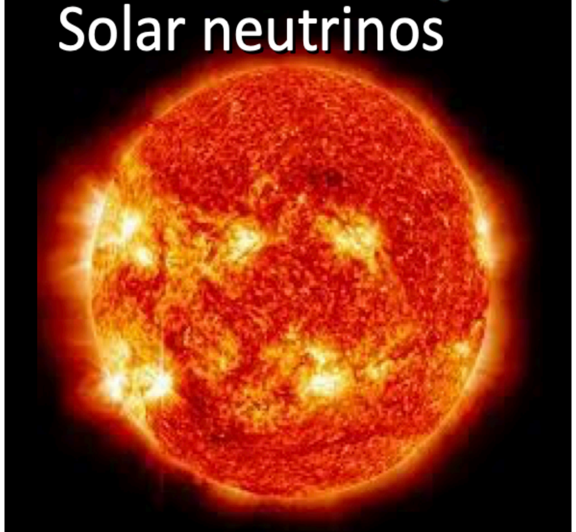
~580 physicists, 104 institutes, 22 countries

still linearly increasing…

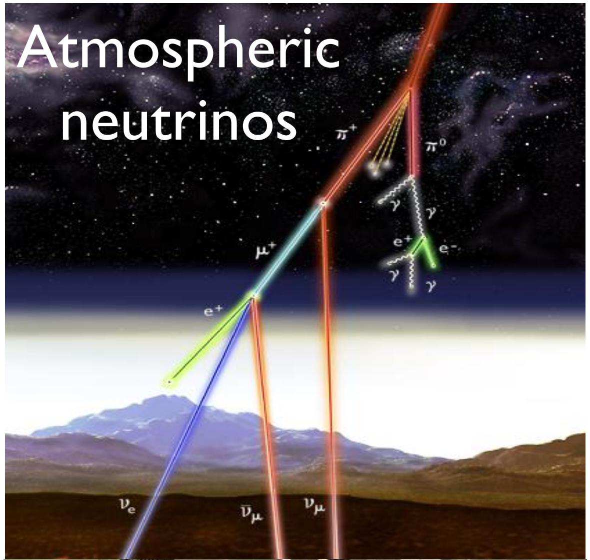


Hyper-K meeting @Kamioka Oct. 2023

Huge physics program and discovery potential



- **Construction started in 2020**
- **Operation will start in 2027**
- **Neutrino oscillations**
  - Atmospheric neutrinos + $\nu/\bar{\nu}$ beam from JPARC
  - CP violation and precise measurements of neutrino oscillations parameters
  - mass ordering determination
- **Search for nucleon decay**
- **Astrophysics** (not covered in this talk)
  - Solar neutrinos
  - Supernovae burst, diffuse Supernovae Background Neutrinos
  - Dark Matter search



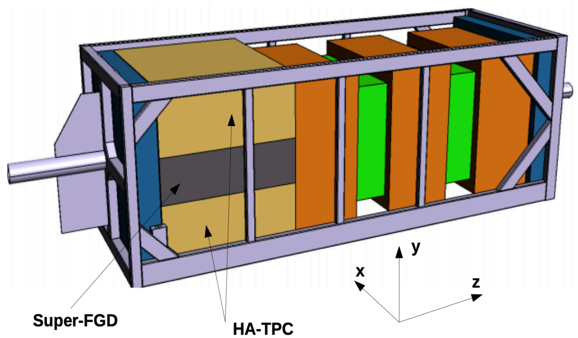
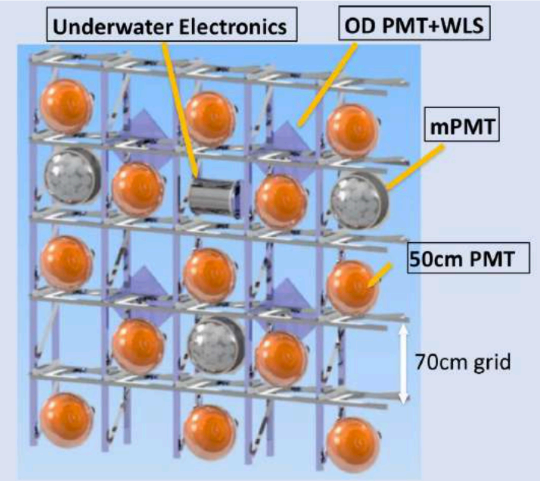
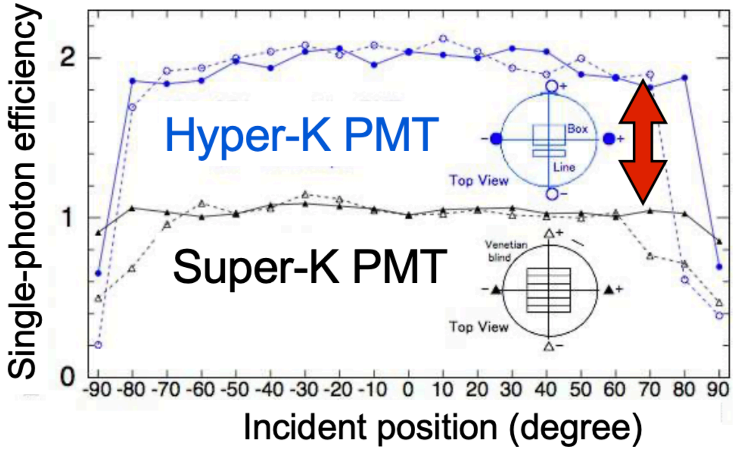


Photo-detection system

Detailed **design of the tank** lining and photosensor support structure **completed**

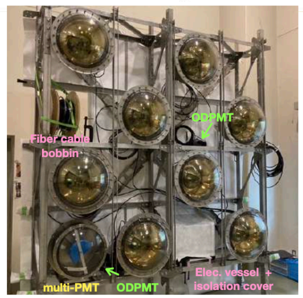




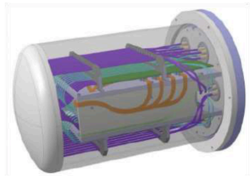
- New features on **50 cm PMT** (B&L-dynode) include:
  - High QE, time resolution, pressure tolerance (x2 better than Super-K)
  - dark rate reduction, low radioactivity, cover development
  - long-term performance evaluation already in Super-K
    - 20 000 of 50 cm PMTs from Japan
- **International contributions**:
  - OD, Photosensors/elec. mockup, electronics, Multi-PMT and PMT cover

Outer detector: PMT+WLS plate

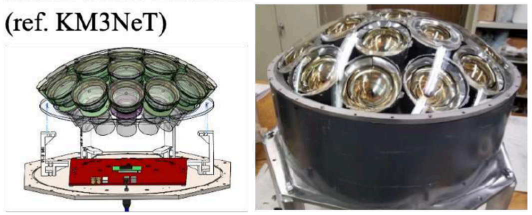
Photosensors/elec. mockup



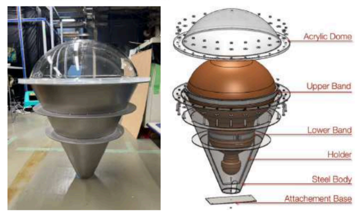
Underwater electronics: Case design and feedthrough



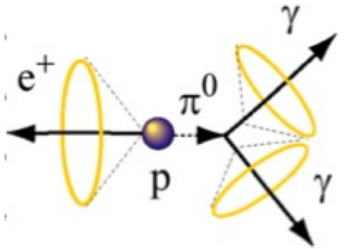
Multi-PMT module: (ref. KM3NeT)



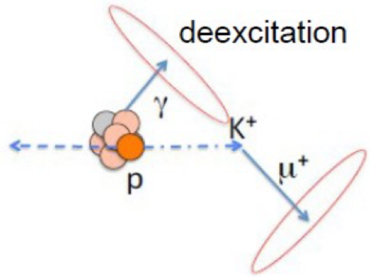
PMT cover

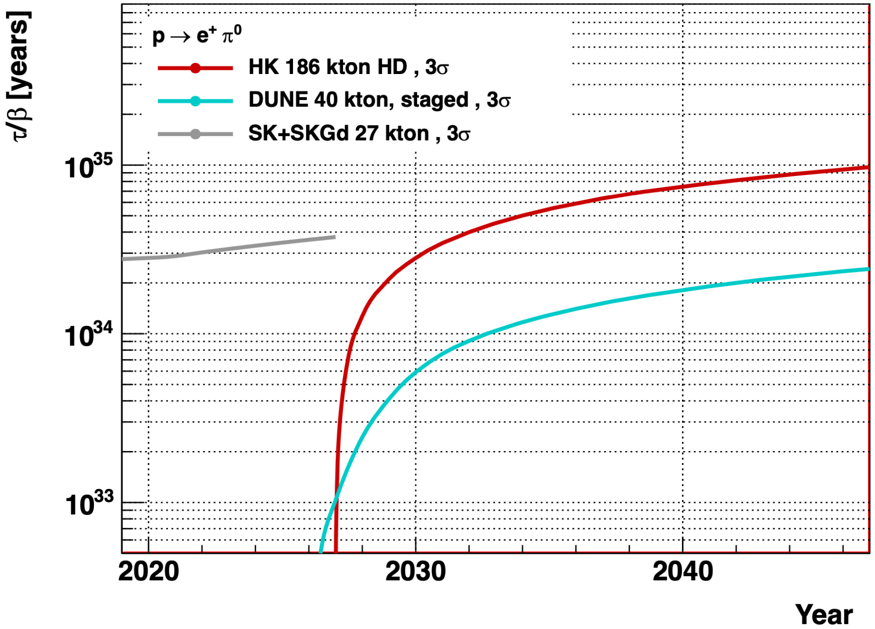


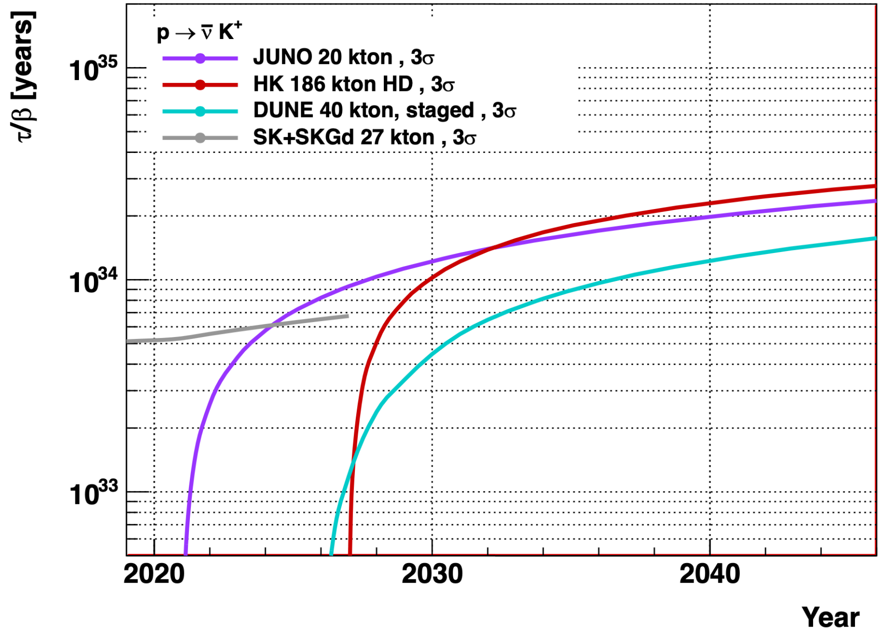
Search for proton decay



Hyper-K will play a leading role in the next-generation proton decay search
(3σ discovery potential)







- Positron and photons are reconstructed as e-like rings
- Background reduction from atmospheric $\bar{\nu}_e$ by detecting neutron capture on water (after ~200 μs), 2.2 MeV γ emitted

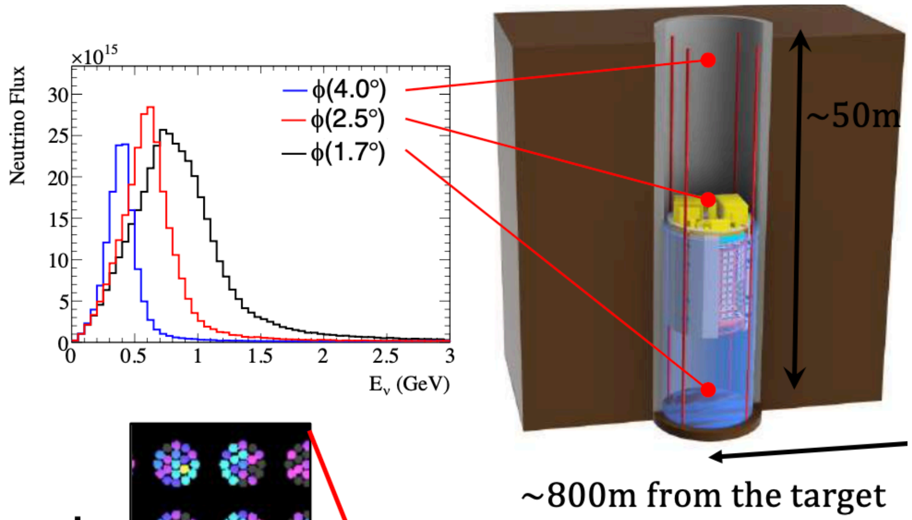
- K^+ is not visible in water Cherenkov detector, but it's reconstructed from its decay products:
  - Monochromatic μ^+ (236 MeV) and prompt photon (6.3 MeV)

Huge water tank containing a lot of protons will allow to extend current limits by one order of magnitude

Intermediate Water Cherenkov Detector (IWCD)

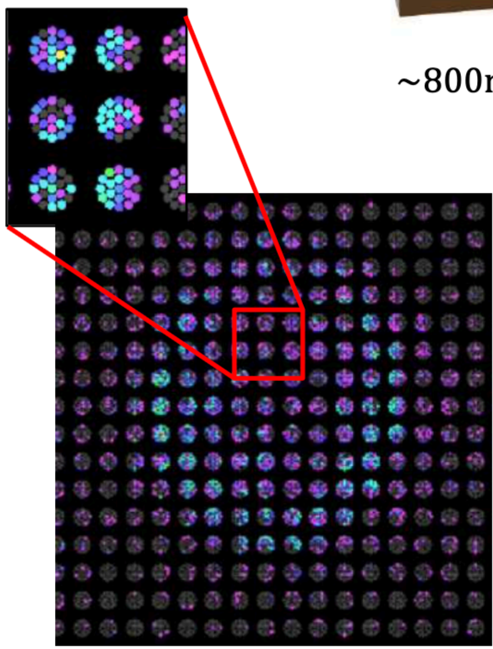
Major purposes of IWCD

- Measuring $\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$
  - 3-4% accuracy at 600 MeV (work in progress)
- Background (beam ν_e, NC) measurement for $\nu_\mu \rightarrow \nu_e$
  - Same flux at 2.5 deg. off axis for Hyper-K
- Measurement of the correlation $(p_l, \theta_l) \leftrightarrow E_\nu$
  - Combination of data with different off axis

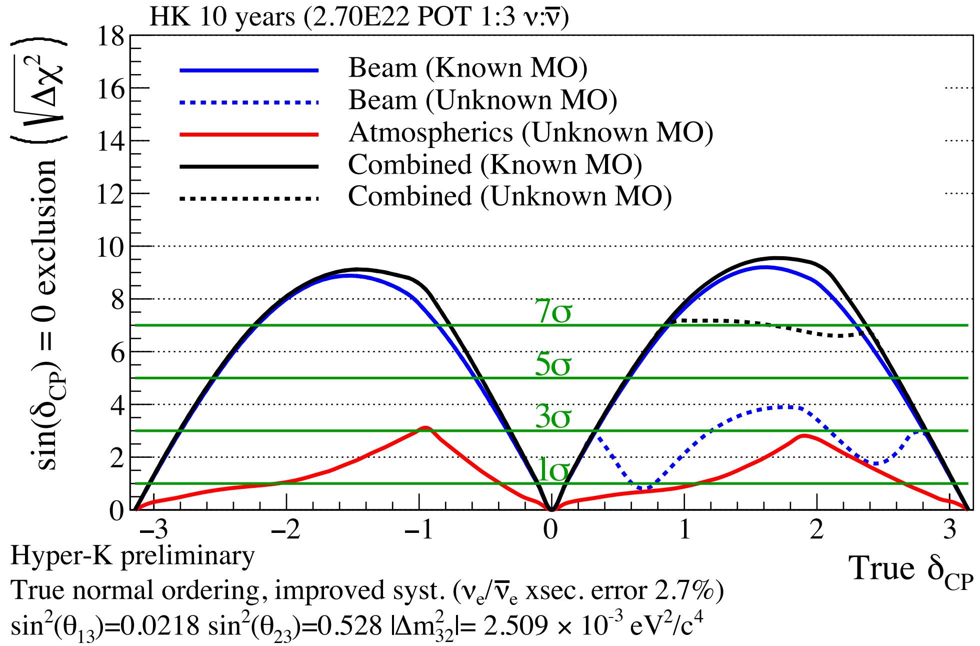


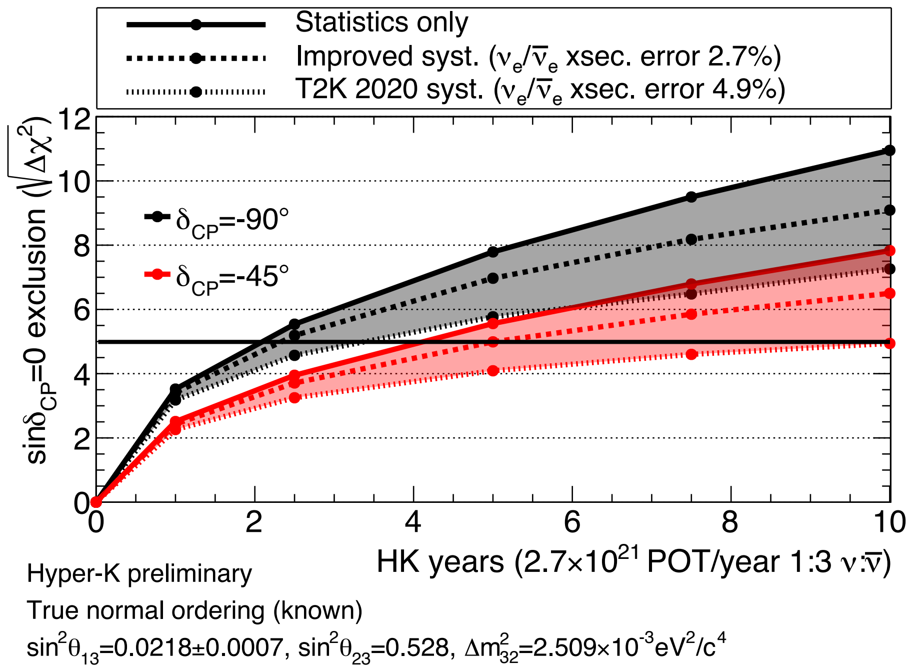
Detector site secured, depth & diameter proposed.

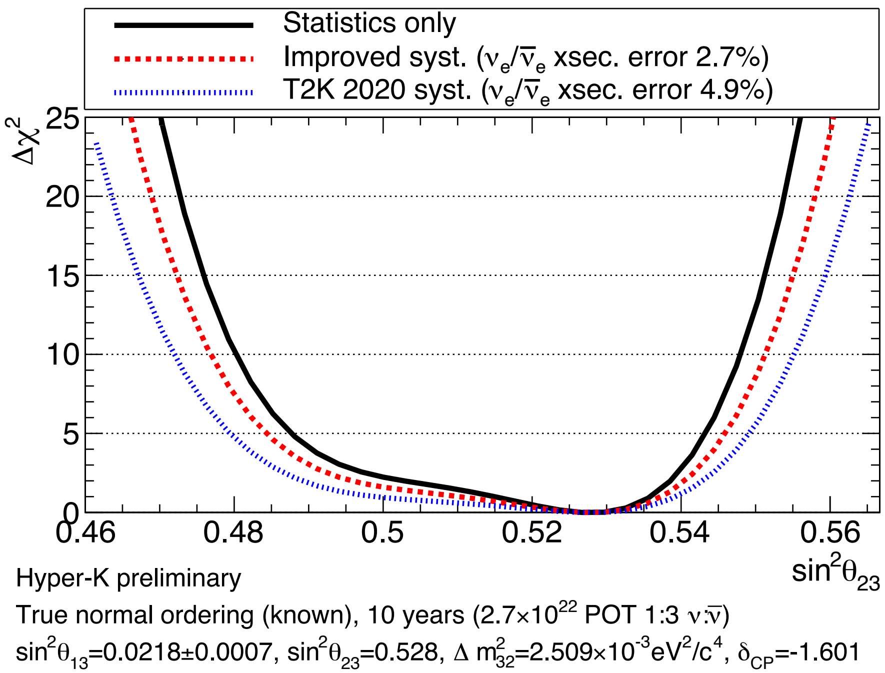
- 8.8 m detector diameter, and 7 m diameter for the inner volume. Entire mass ~ 600 ton.
- Multi-PMTs are useful for resolving vertices close to the wall and accurate particle identifications.
- Basic design is ongoing, and installation procedure is being considered.
- **International contributions welcome!**



Precise measurements of neutrino oscillations parameters







- Discovery of CP violation at > 5σ for >60% of δ_{CP} in 3-5 years (depending on true δ_{CP} and syst. uncertainty)
  - 1σ resolution of δ_{CP} in 10 years
- Reduction of systematic uncertainties has a sizable impact
  - ND280 upgrade + IWCD (1 Ton)
  - Aim to reduce detector error below 1%

Construction status (the largest human made cavern ever build!)

Oct. 3, 2023 Completion of the dome (dia. 69 m, height 21 m, ~1 Super-K)

Cavern excavation ongoing

Excavation of the HK cavern will complete by the end of this year!

Aim to take data in 2027 JFY!

Conclusions

- **Presented the latest T2K results and T2K and HK prospects**
- **Three analyses in parallel**
  - T2K oscillation analysis and prospect of the next iteration
  - T2K-SK joint fit
  - T2K-NOνA joint fit
- **T2K Data continue to prefer maximal θ_{23} mixing, δ_{CP} ~-π/2 and NH**
  - CP conserving values are excluded at 90% C.L.
  - Mild preferences for normal ordering and upper octant
- **T2K-SK joint fit shows similar results but with higher sensitivity to mass ordering**
- **T2K-NOνA joint fit slight prefers IO with CP-conserving values excluded at 3σ**
- **Hyper-K will be ready for data in 2027 JFY**
  - For neutrino oscillations it will take advance from beam and new near detectors
- **Prospects:**
  - New oscillation analyses will include 4π selection at near and far detector
  - New capabilities with upgraded beam and ND280
  - HK project will take advance from the experience gained with T2K with high discovery potential

Backup

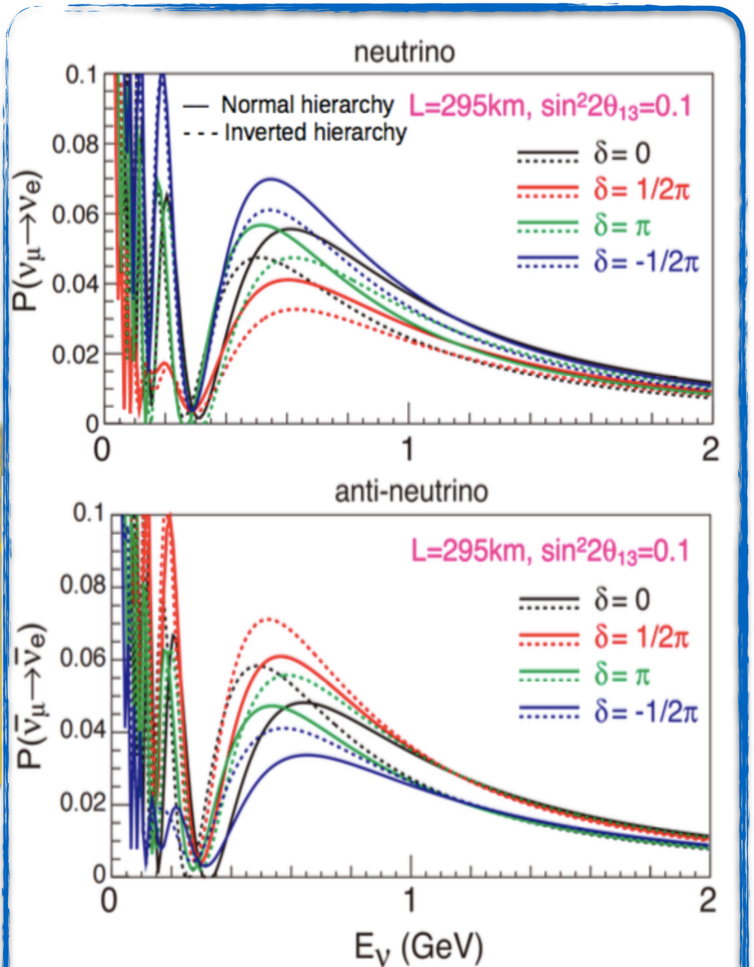
Number of events at SK vs δ_{CP}

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	$\delta_{CP} = -2.08362$	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

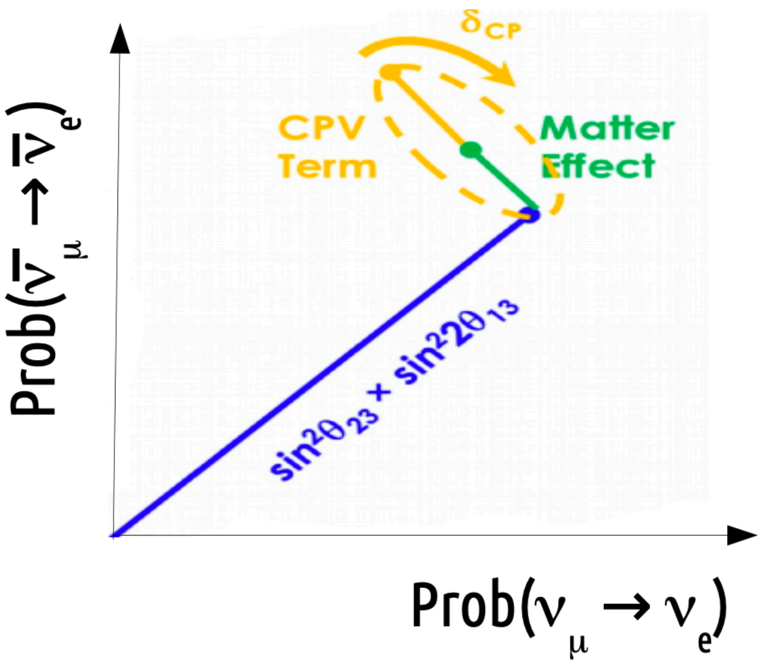
Learning from ν_e ($\bar{\nu}_e$) appearance

- $\sin^2 2\theta_{13}$ 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: $P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$ in vacuum
  - **δ_{CP} ~ -π/2**: enhance $\nu_\mu \to \nu_e$ and suppress $\bar{\nu}_\mu \to \bar{\nu}_e$
  - **δ_{CP} ~ +π/2**: suppress $\nu_\mu \to \nu_e$ and enhance $\bar{\nu}_\mu \to \bar{\nu}_e$



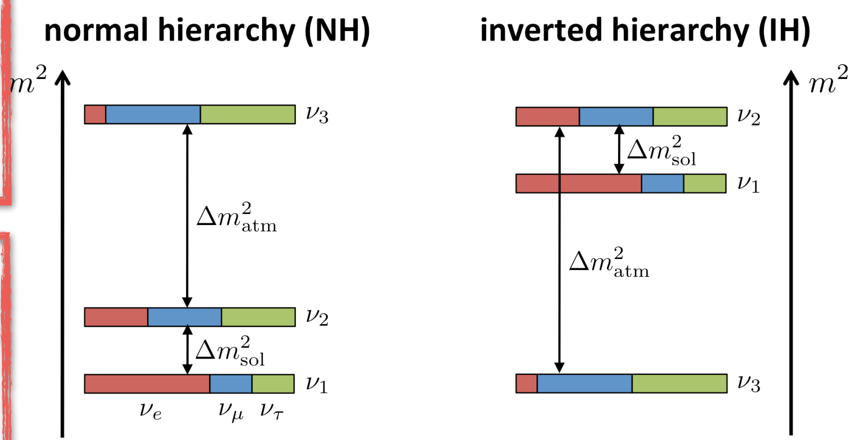
PTEP 2015 (2015) 053C02



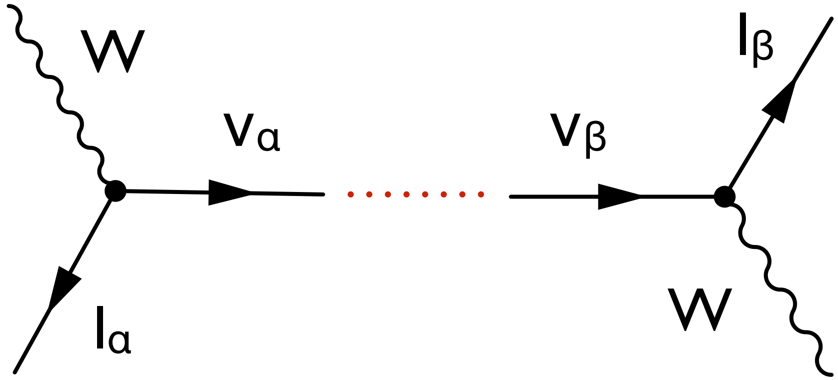
±10% matter effect at T2K

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

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



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

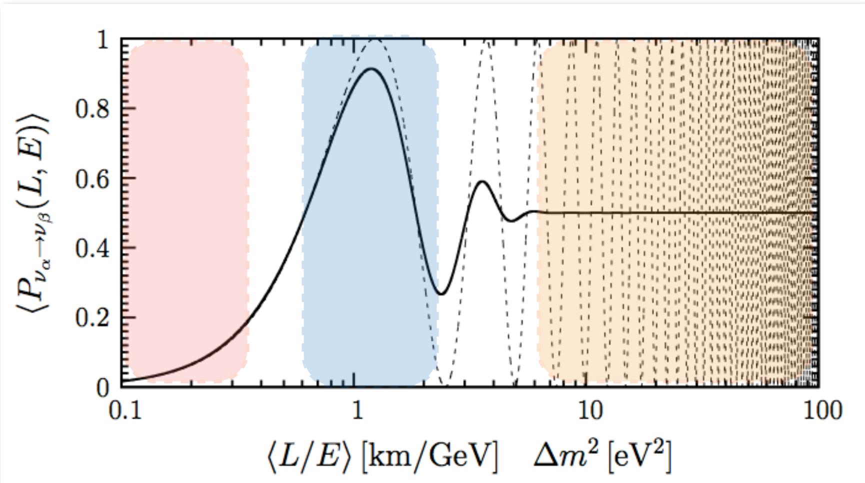
Time evolution: flavor content "oscillates" in L(distance)/E(neutrino)

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

oscillation amplitude

oscillation frequency

Parameters controlled by experiments



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

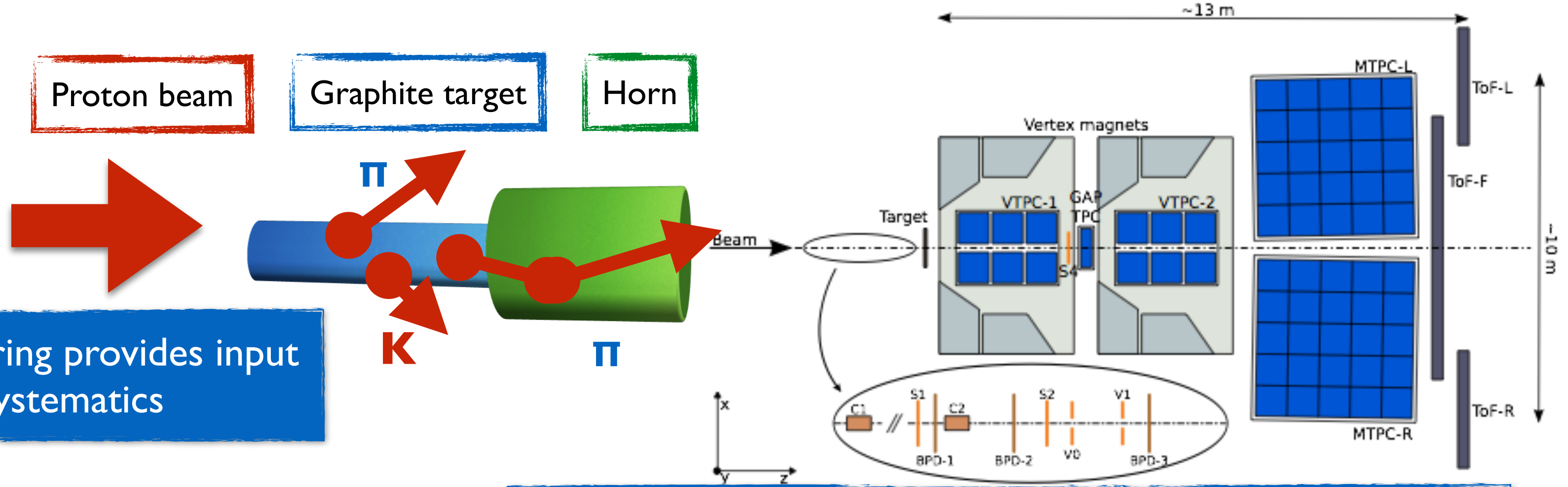
L/E >> Δm^2 only average oscillation probability can be measured

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**

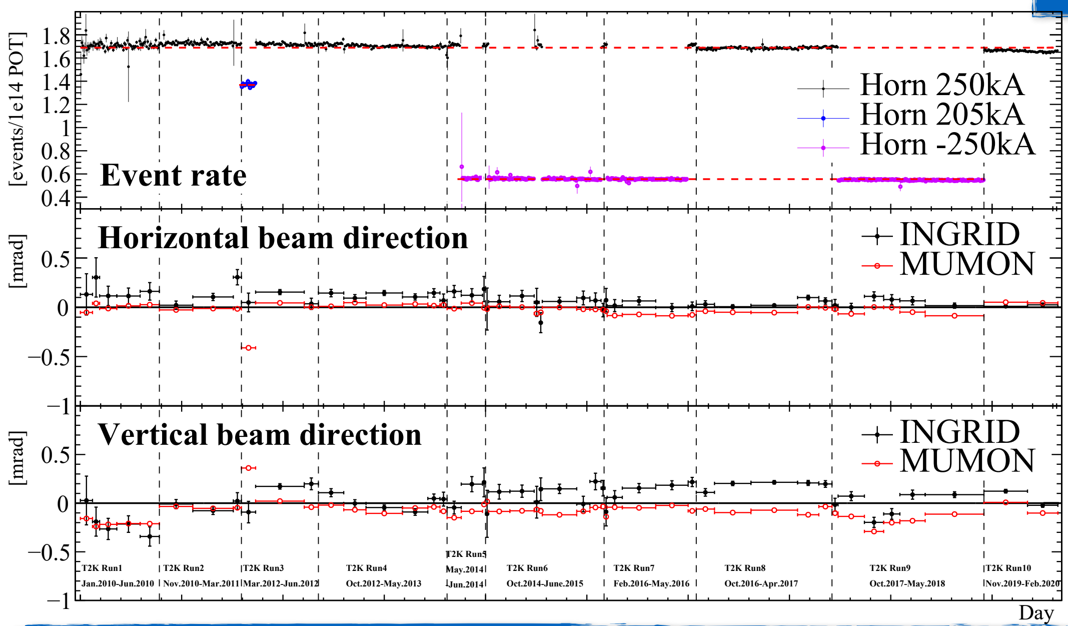
Flux error reduction from ~25% to less than 10%

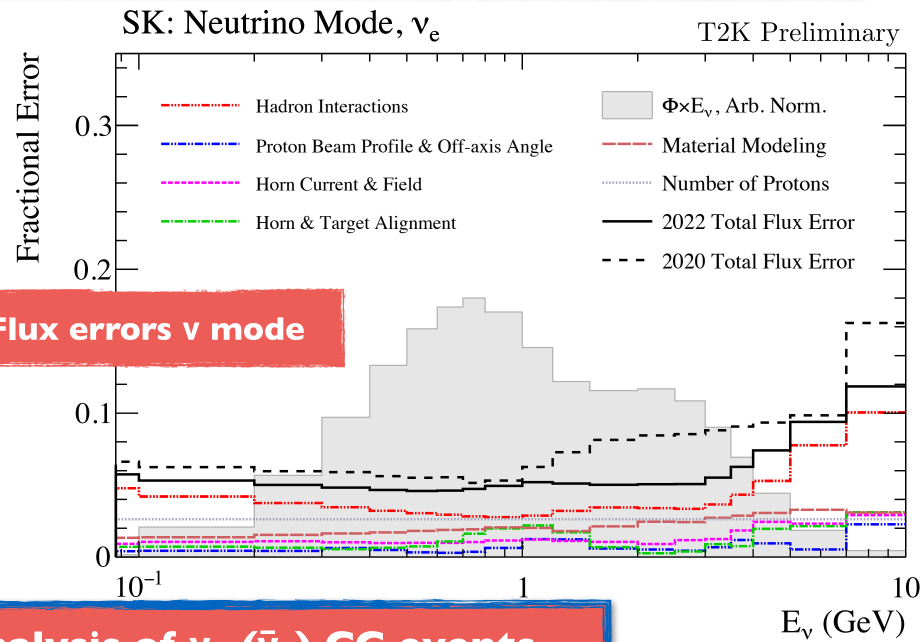


- Beam alignment monitoring provides input to estimations of beam systematics

ν daily event rate

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

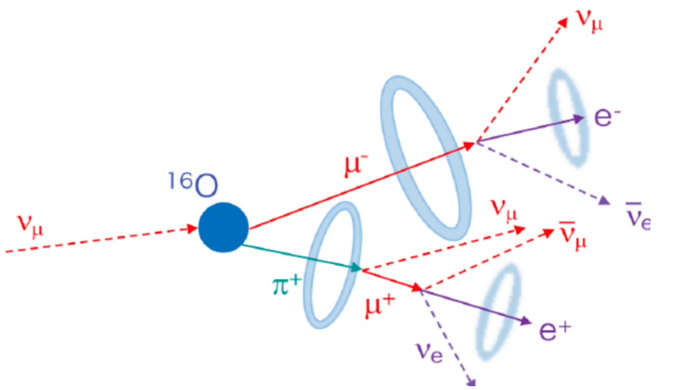


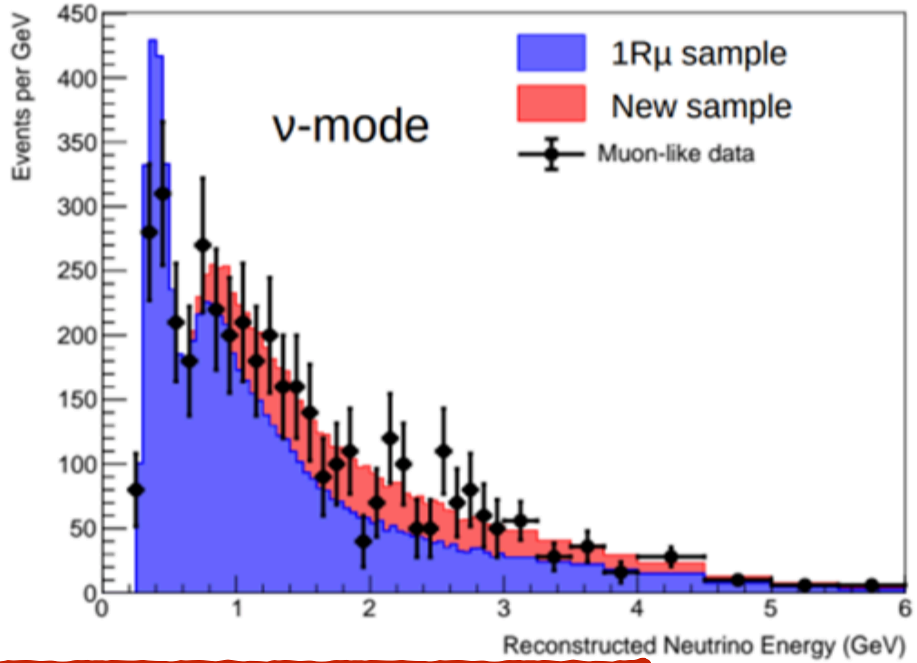


Flux errors ν mode

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

Super-K samples

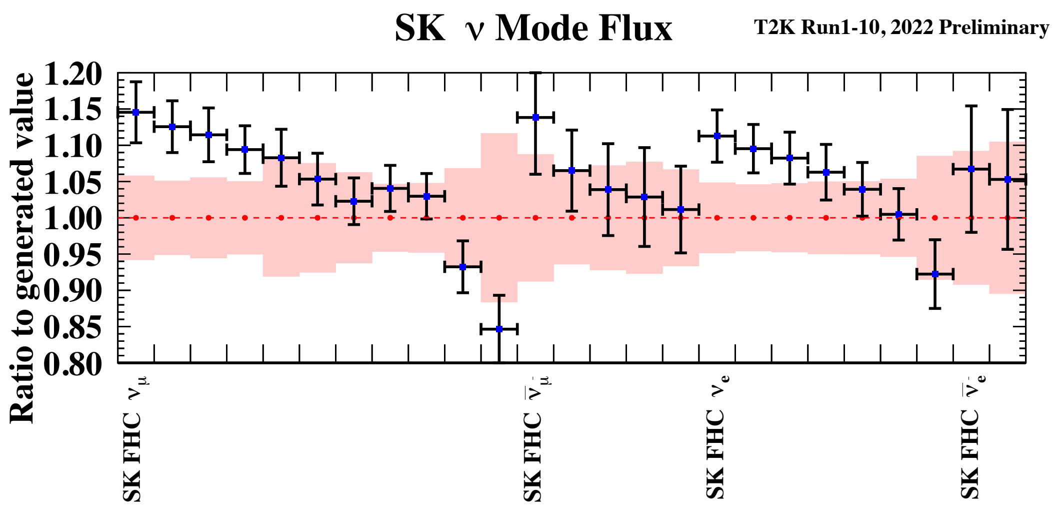


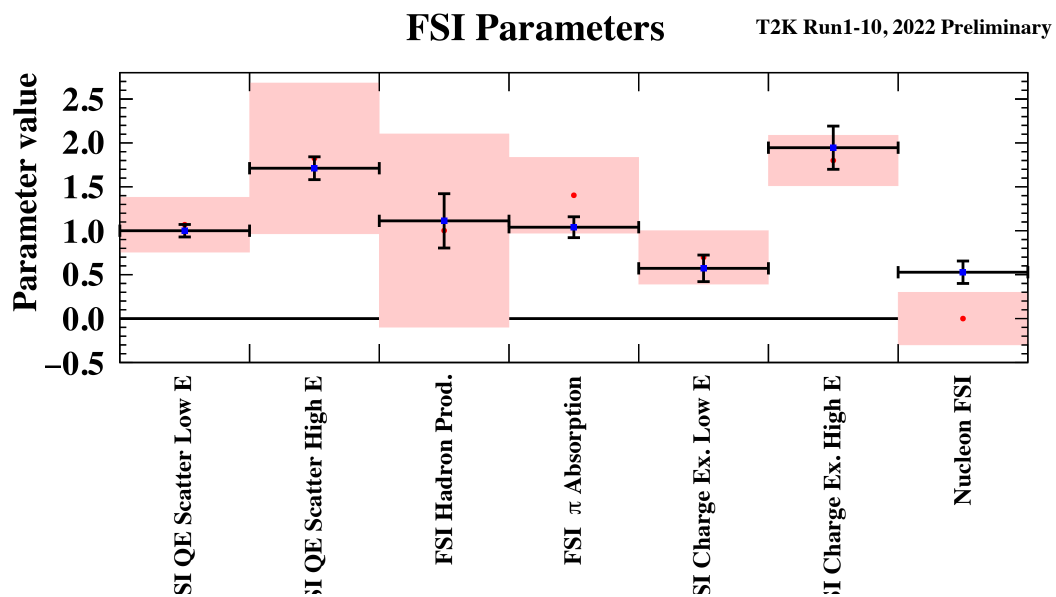


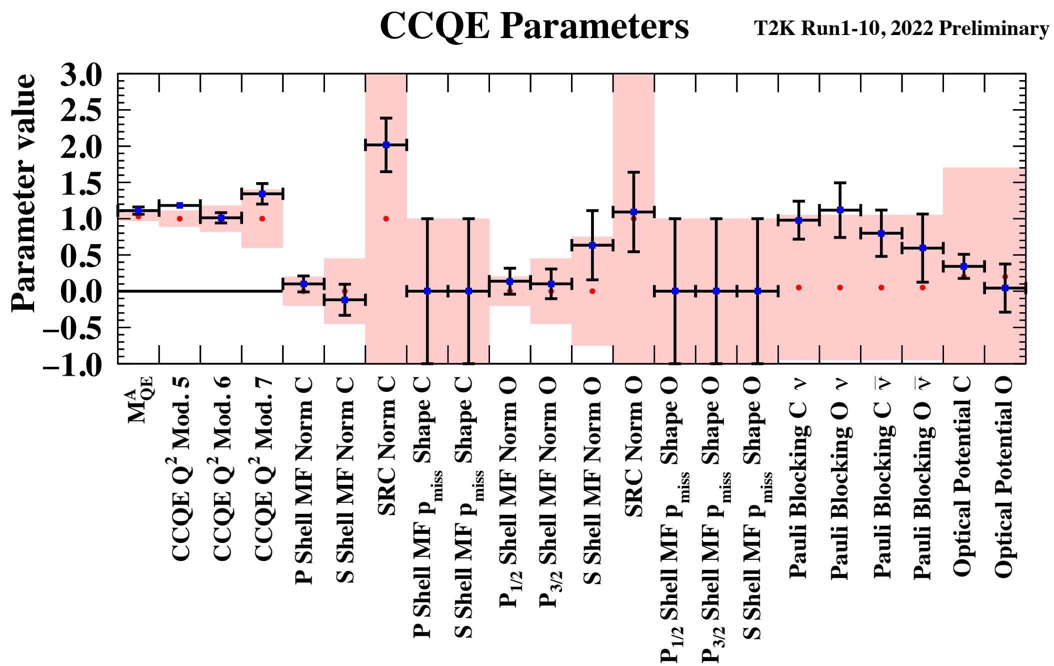
- New "multi-ring" ν_μ CC1π+ sample
- Increases μ-like statistics by ~30%
- Small sensitivity to oscillation, tests the robustness of our model

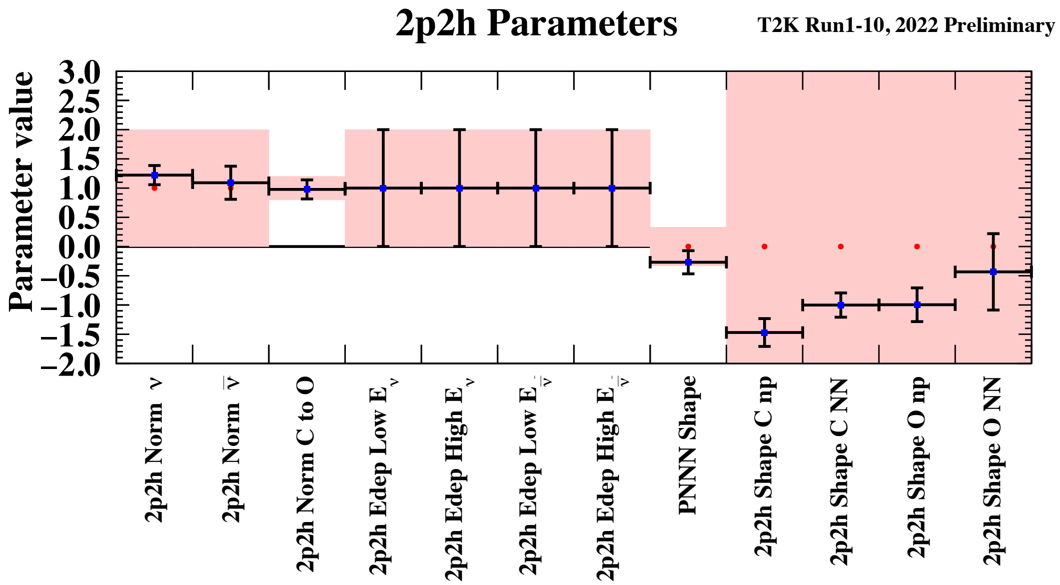
Beam mode	Sample	Description
ν	1Re	One e-like ring, 0 decay electrons
	1Re CC1π+	One e-like ring, 1 decay electrons
	1Rμ	One μ-like ring, 0/1 decay electrons
NEW	MRμ CC1π+	One μ-like ring, 2 decay electrons/ μ-like ring + π+-like ring, 1 decay e
$\bar{\nu}$	1Re	One e-like ring, 0 decay electrons
	1Rμ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

ND280 best fit nuisance parameters

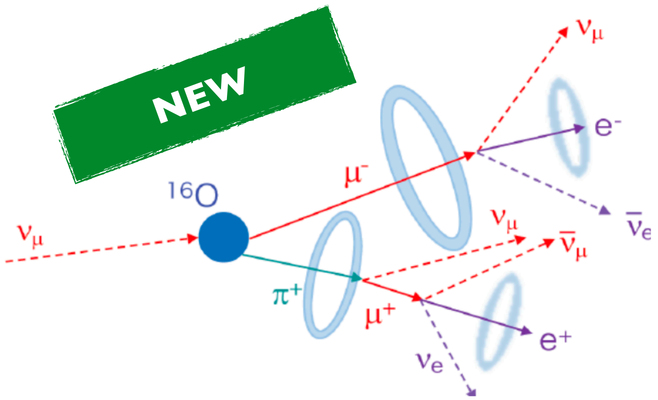


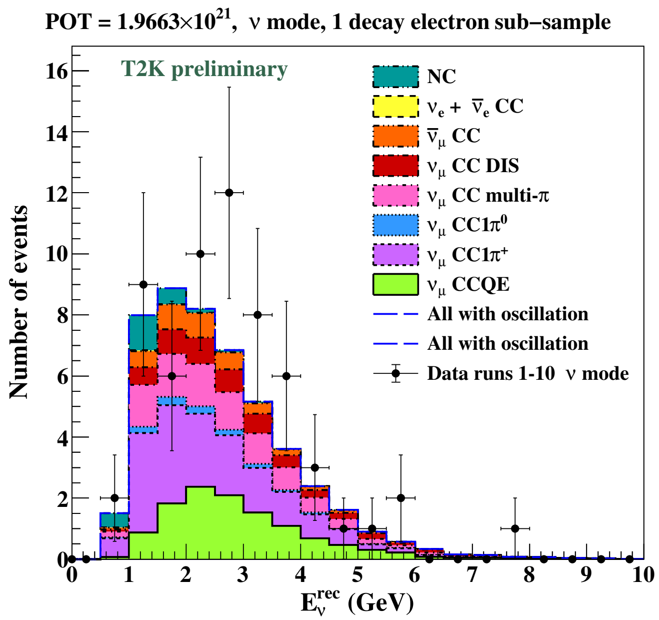


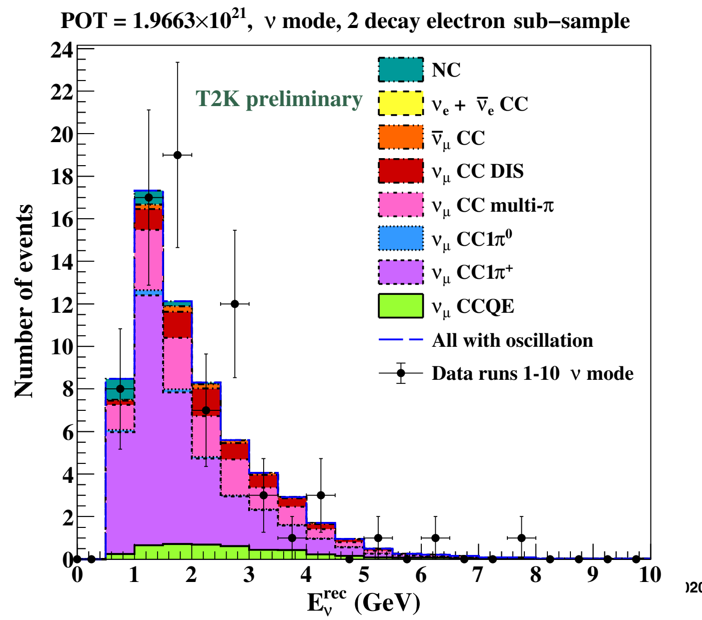


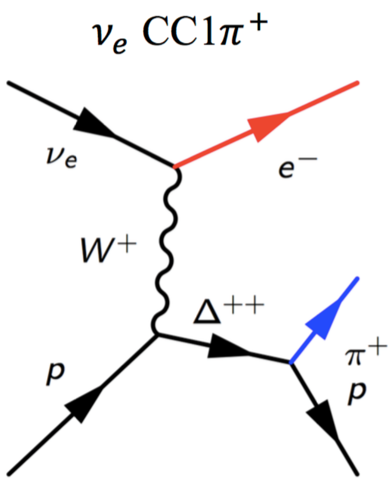


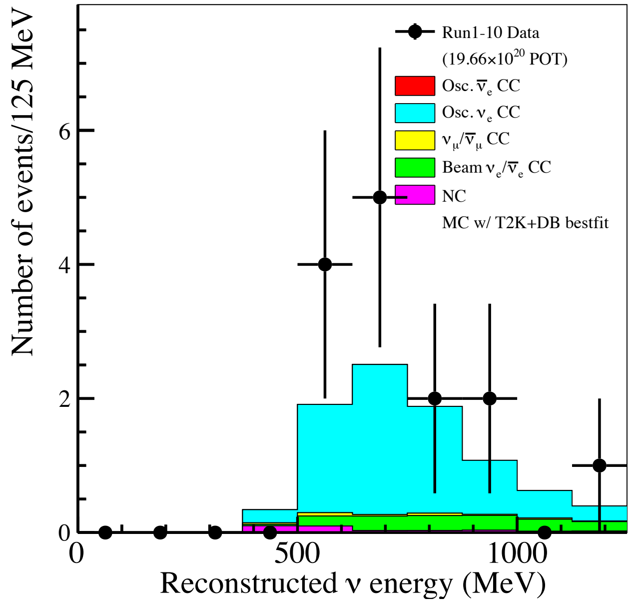
Pion samples @ SK

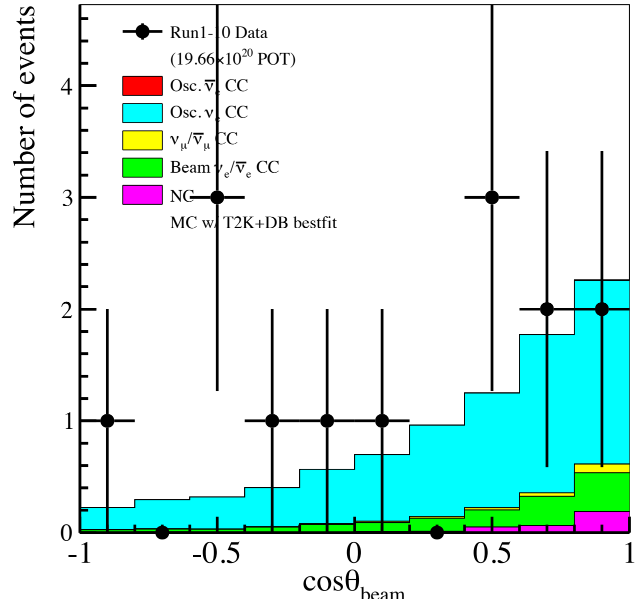






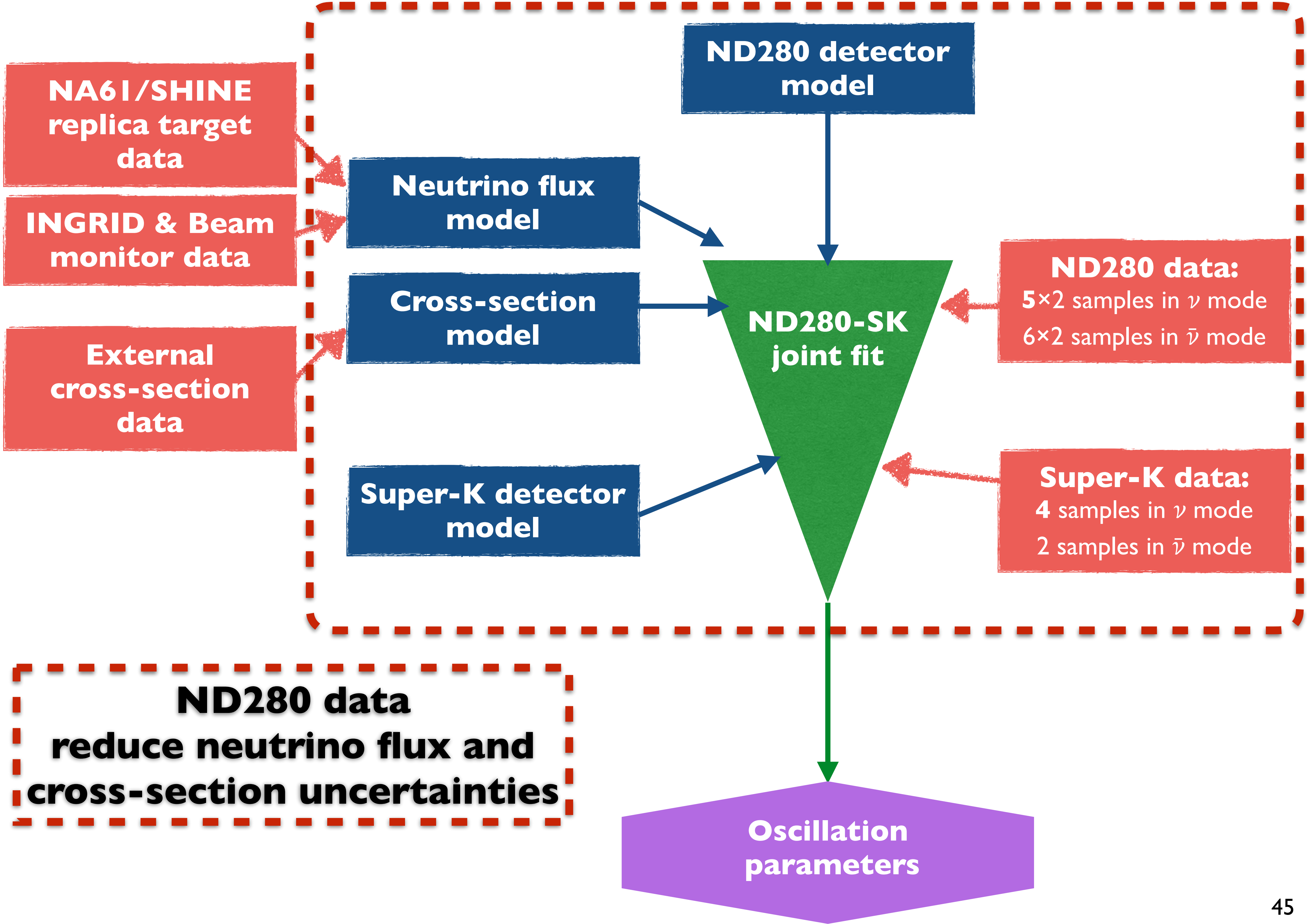






$$E_{rec}^{\nu_\mu\ CC\Delta^{++}} = \frac{2m_p E_\mu + m_{\Delta^{++}}^2 - m_p^2 - m_\mu^2}{2(m_p - E_\mu + |\mathbf{p}_\mu|\cos\theta_\mu)}$$

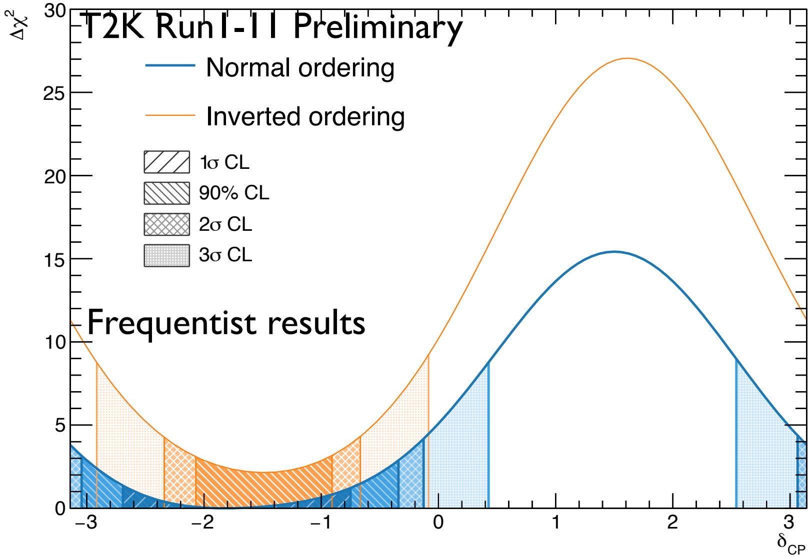
Oscillation analysis strategy

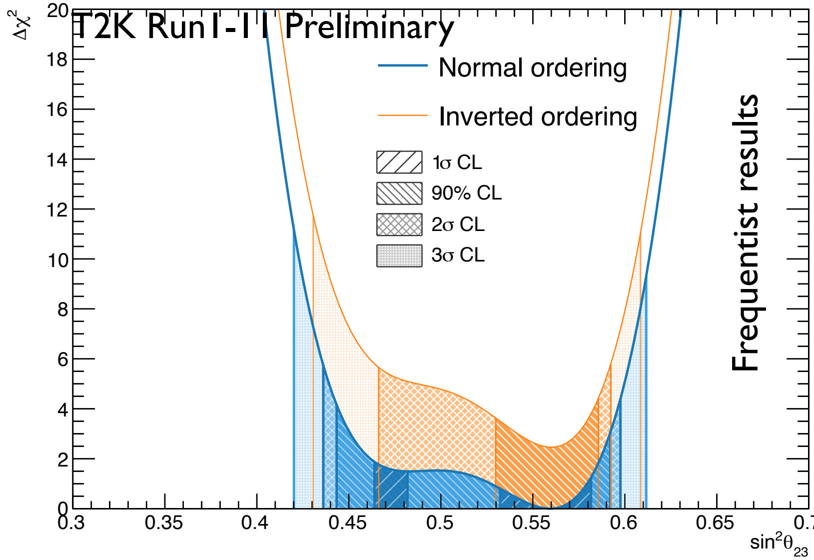


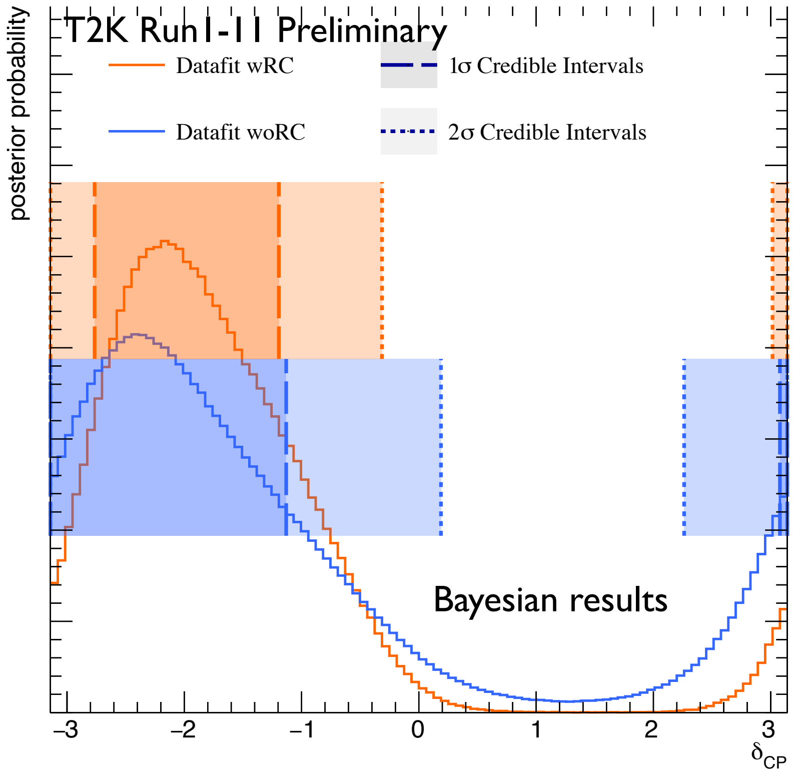
ND280 data reduce neutrino flux and cross-section uncertainties

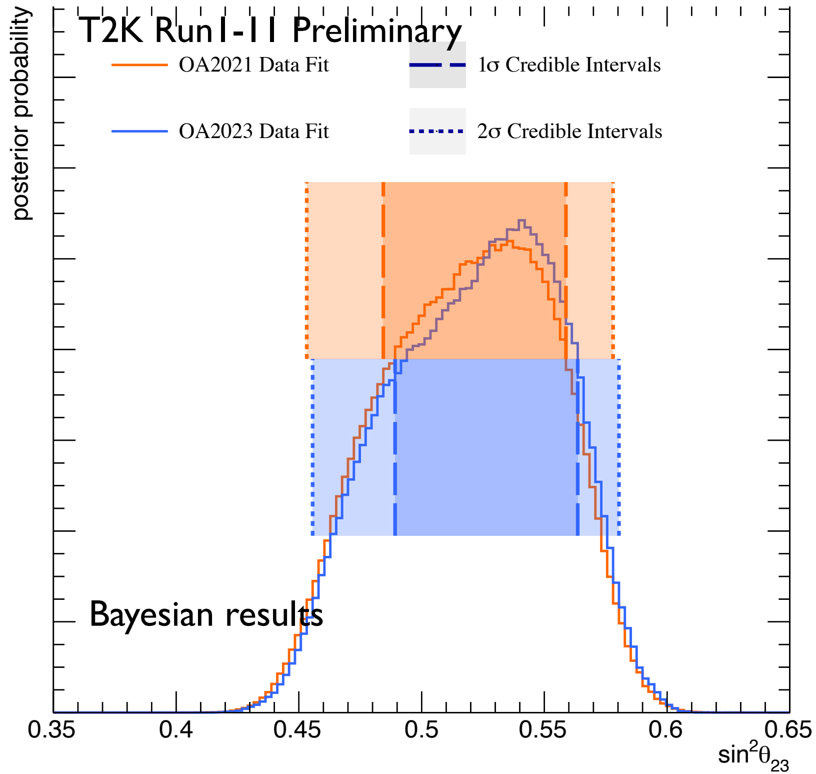
Frequentist and Bayesian analyses in agreement

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









Summary of oscillation results