T2K NEAR DETECTOR UPGRADE

Alexander Izmaylov
Institute for Nuclear Research (INR RAS)

on behalf of the T2K Collaboration

Technology & Instrumentation in Particle Physics (TIPP2023)
4-8 September 2023
CTICC, Cape Town, South Africa

* supported by RSF 22-12-00358

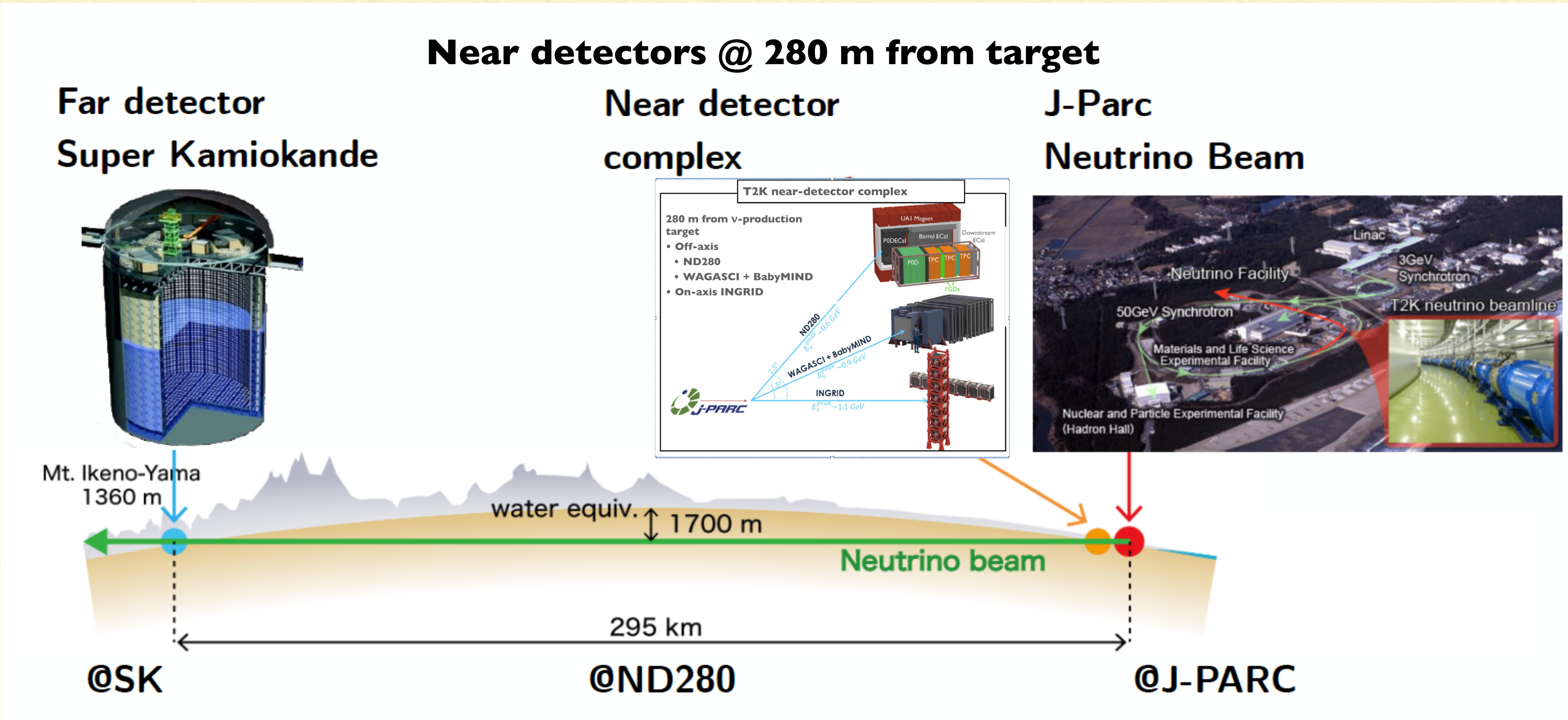
T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

World-leading long-baseline accelerator neutrino project

Hunting neutrinos since 2010

- Discovery of $\theta_{13} > 0$ with accelerator neutrinos
- First hints of CPV in neutrino (lepton) sector, $\delta_{CP} \neq \{0,\pi\}$
- Leading sensitivities to Δm^2_{23}, θ_{23} (octant)
- Rich variety of neutrino cross-section measurements
- BSM studies results

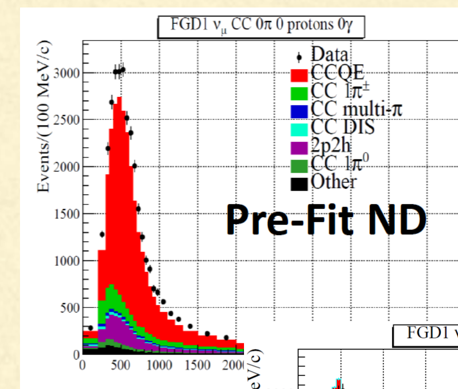
T2K CONCEPT: NEAR DETECTORS

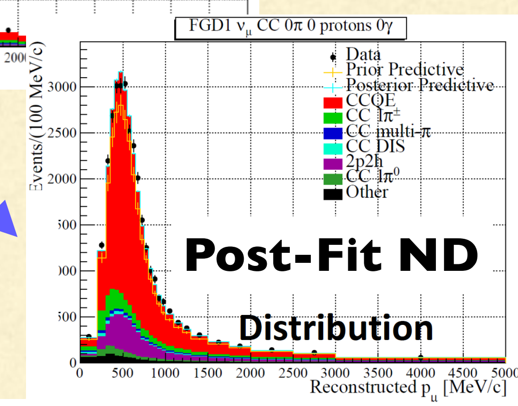


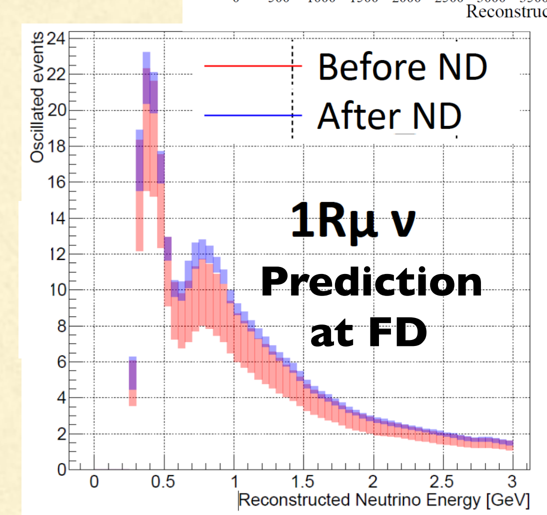
Flux model | Detector model | Neutrino interaction model

$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

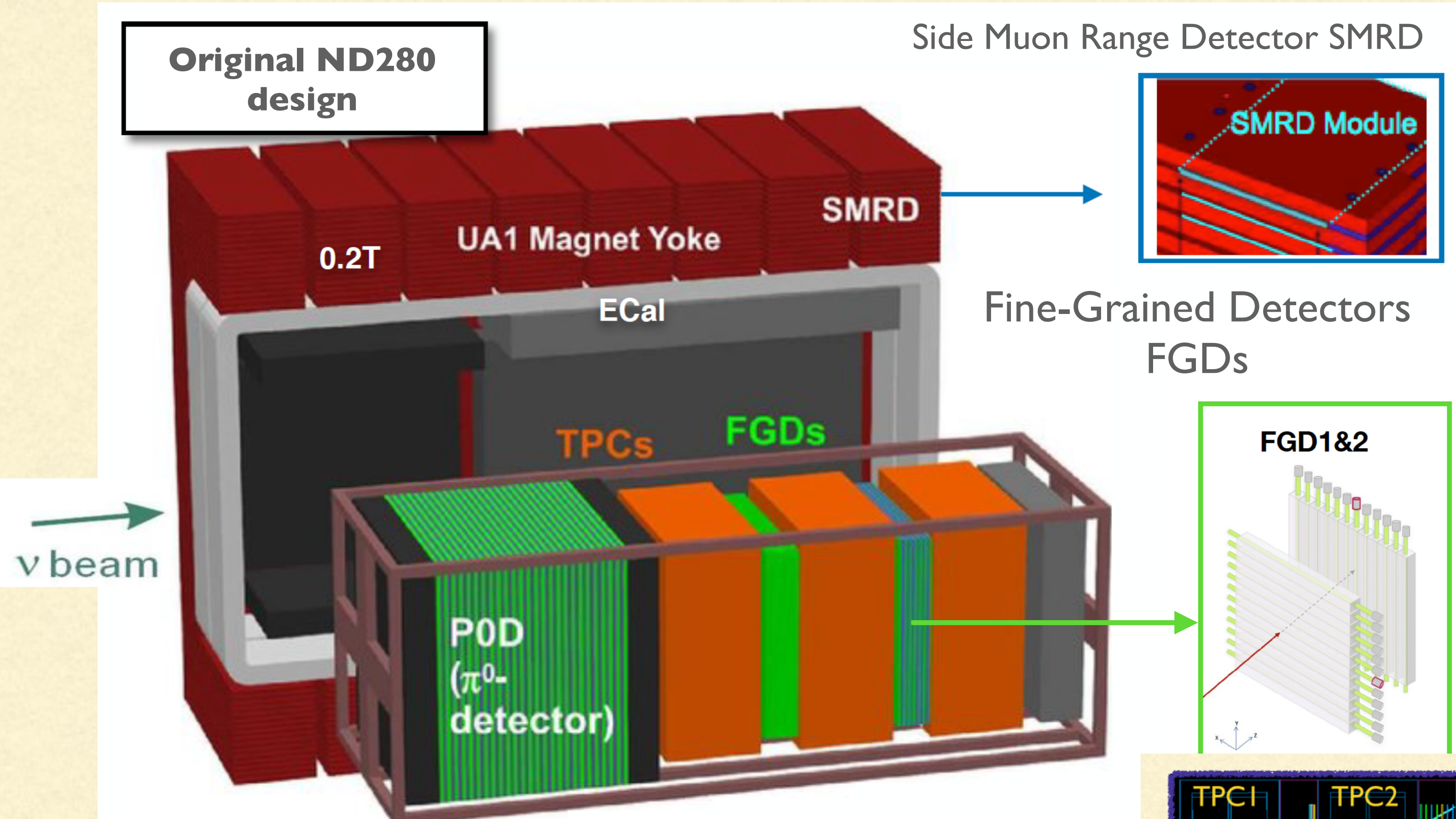


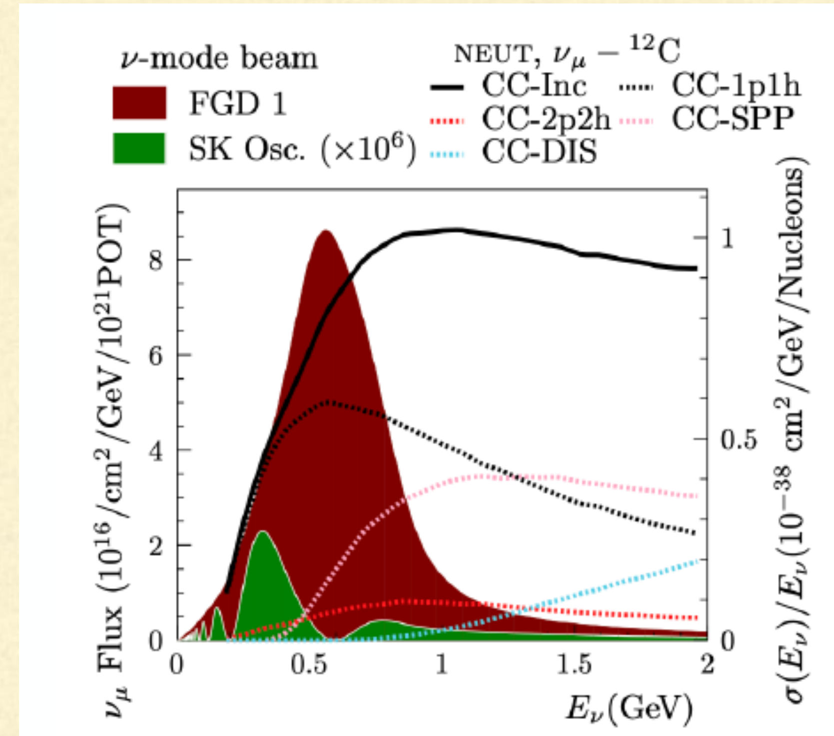


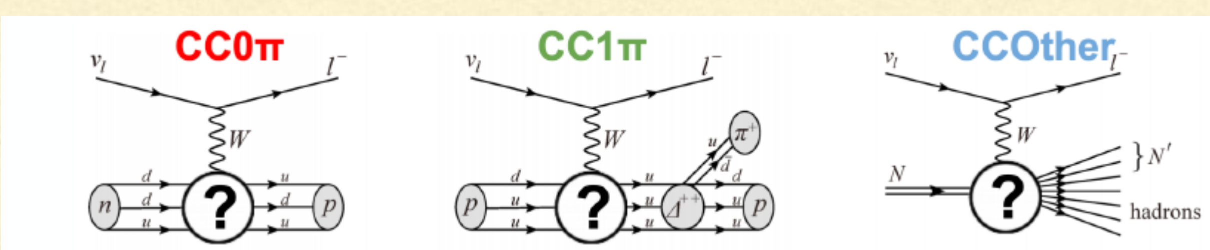


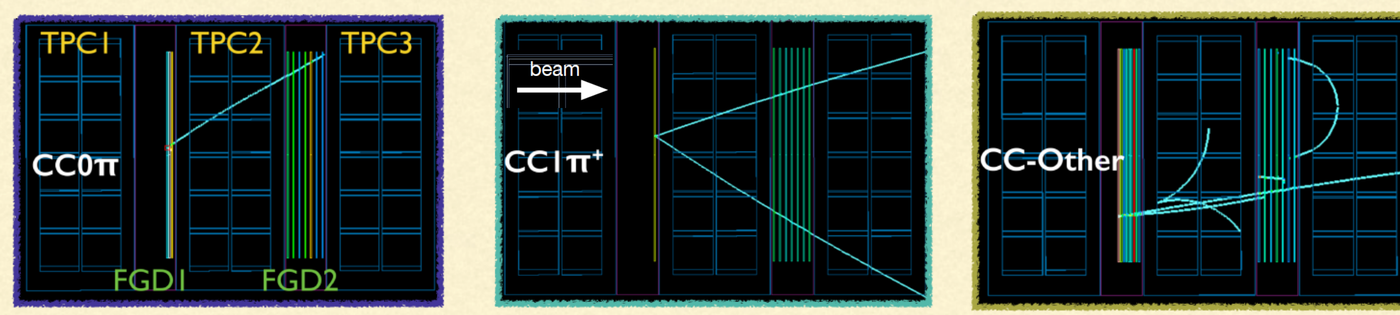
- **ND** measurements constrain **flux and ν-xsec model params** then **propagated to FD**
- Systematic uncertainties do **not fully cancel with Far/Near ratio** concept:
  - Flux model different at ND vs. FD due to geometry and oscillation
  - Different detectors → different acceptance and efficiencies
  - At ND mainly $\nu_\mu(\bar{\nu}_\mu)$ interacting on CH ⟶ use model to infer interactions of $\nu_\mu/\nu_e(\bar{\nu}_\mu/\bar{\nu}_e)$ on water at FD

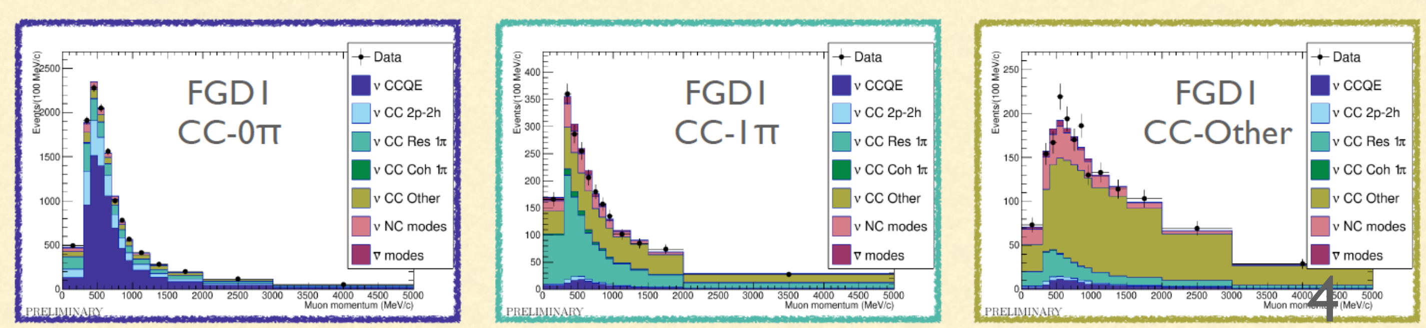
NEAR DETECTOR COMPLEX ND280









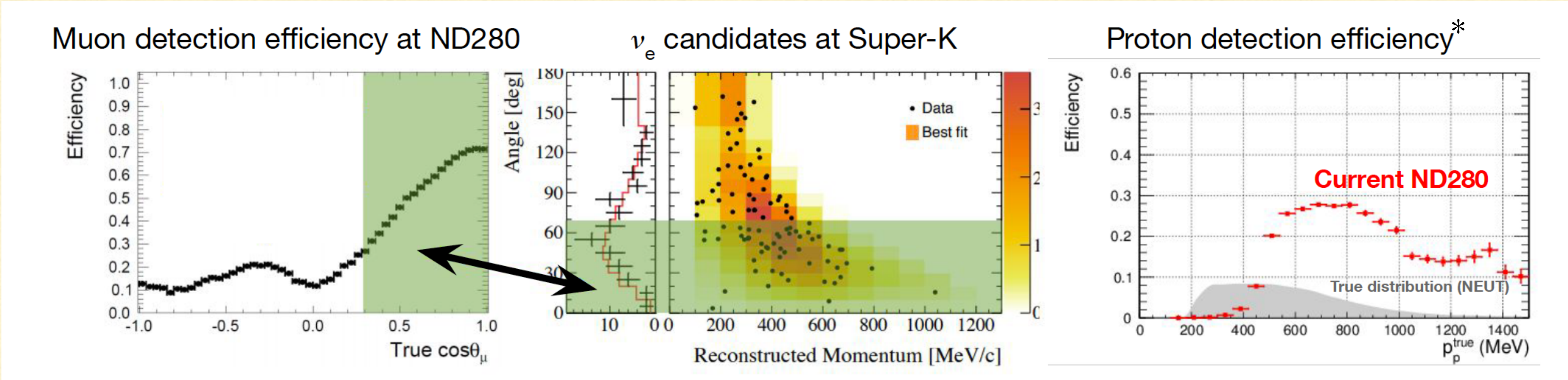


FROM ND280 TO ND280-UPGRADE

Data-taking with T2K-II approved till Hyper-K times, ND280 continues as a part of T2K-HK

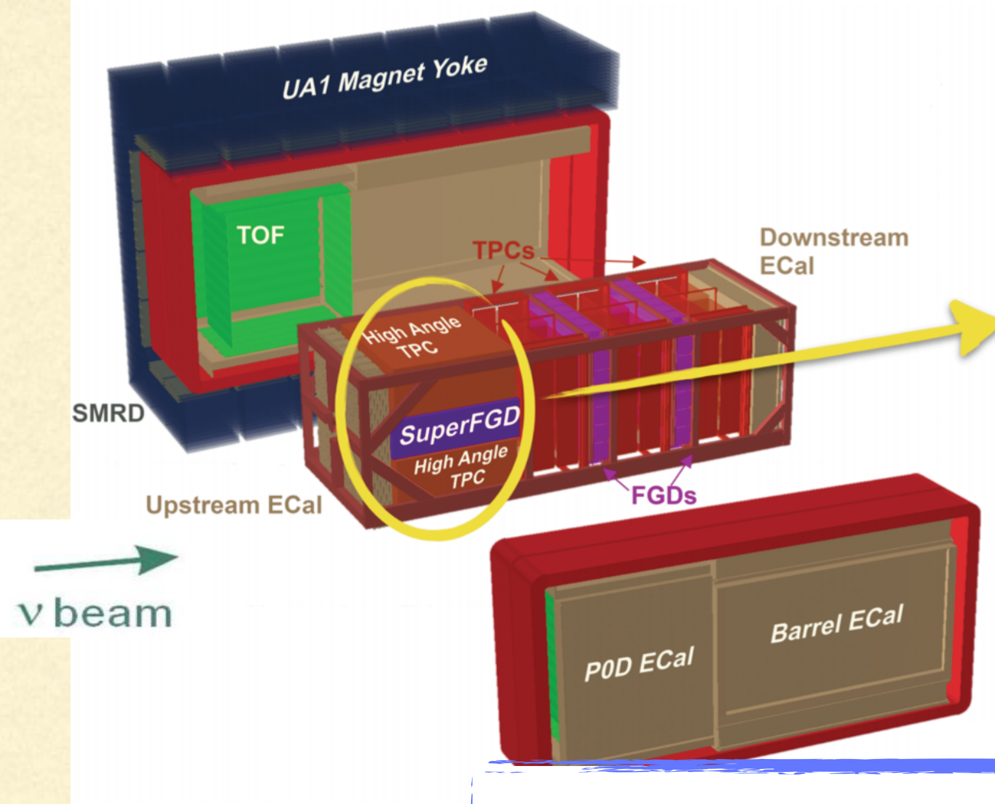
ND280 has supplied T2K physics with **high-quality measurements**, but with the **increasing statistics** its **limitations** on the flux and the ν interaction model uncertainties are **starting to arise** in the analyses

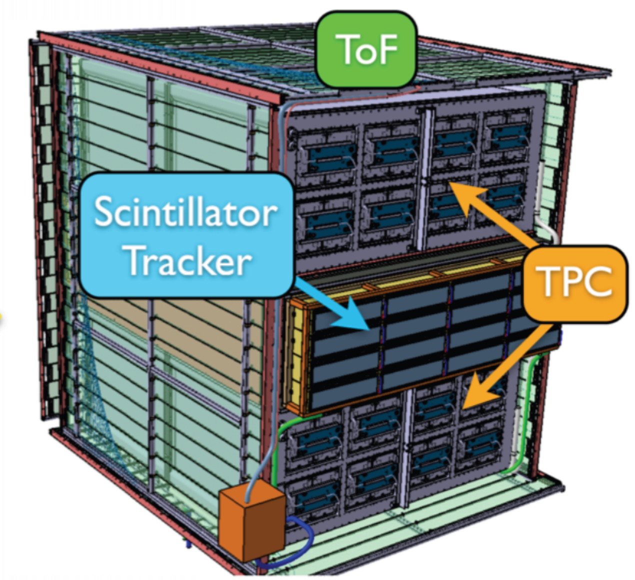
- **Non-isotropic efficiency** (wrt 4π Super-Kamiokande)
- Hadronic information is essential to improve ν-interaction modelling and hence energy reconstruction for OA inputs
  - **Relatively high-momentum threshold for protons** ≃ 450 MeV/c (~100 MeV E_{kin})
  - **No detection of neutrons**



* proton tracking with CC0π selection

ND280-UPGRADE CONCEPT



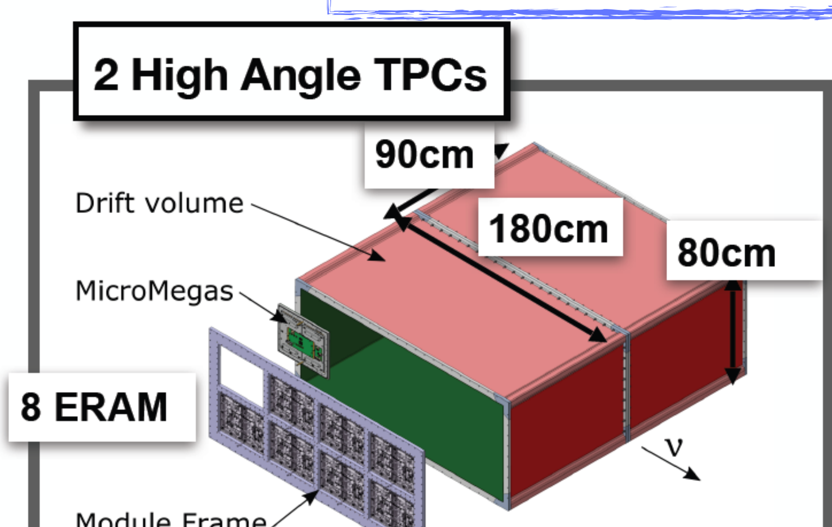


P0D replaced with new detectors

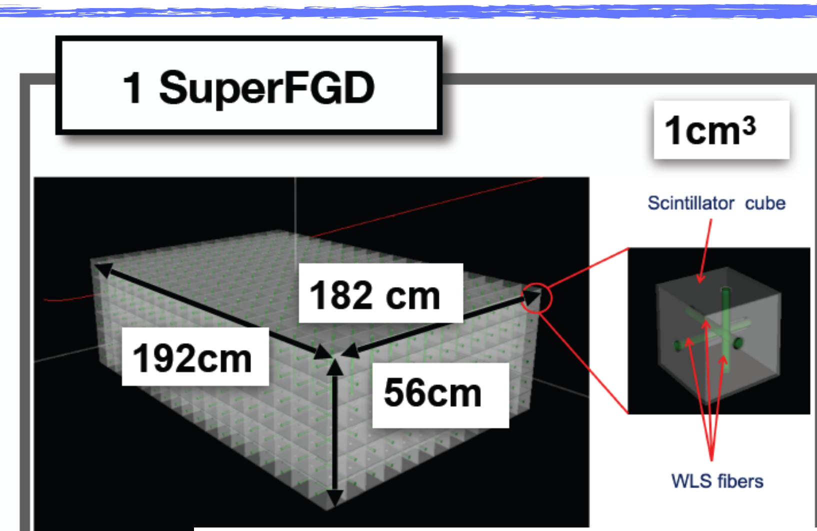
ND280Upgrade design aims for **overall systematics reduction for T2K OA**

- Fully active target
- 4π acceptance for charge products
- Lower proton detection threshold (~300 MeV/c)
- Electron/gamma separation
- Improved veto for backgrounds
- Detection of neutrons

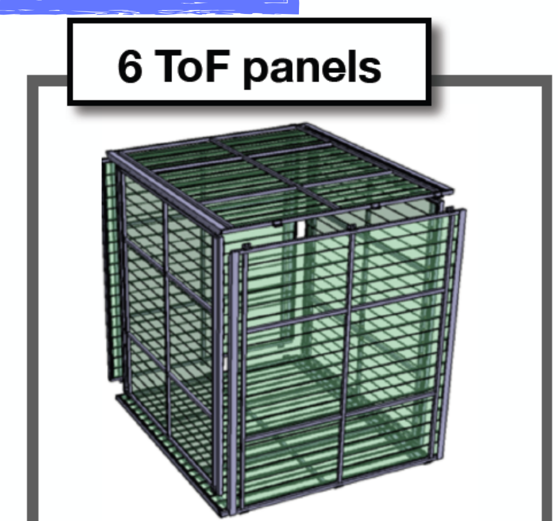
Three novel detector technologies for ND280Upgrade



New readout concept



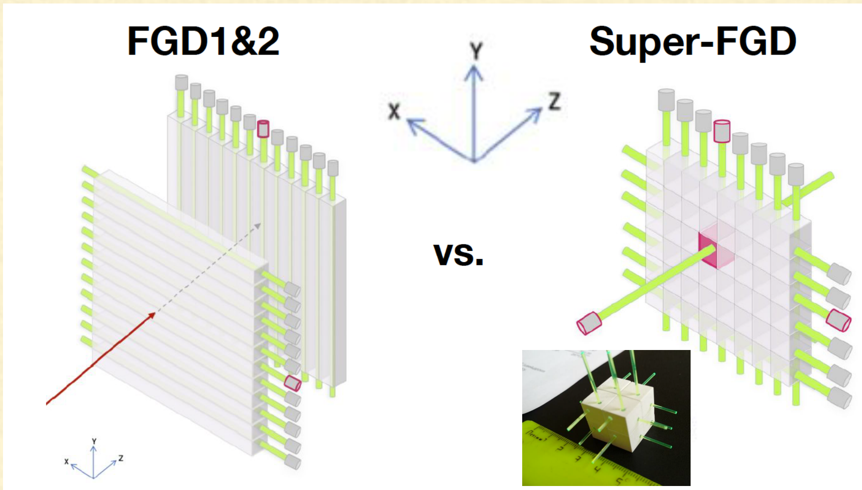
Original detector concept

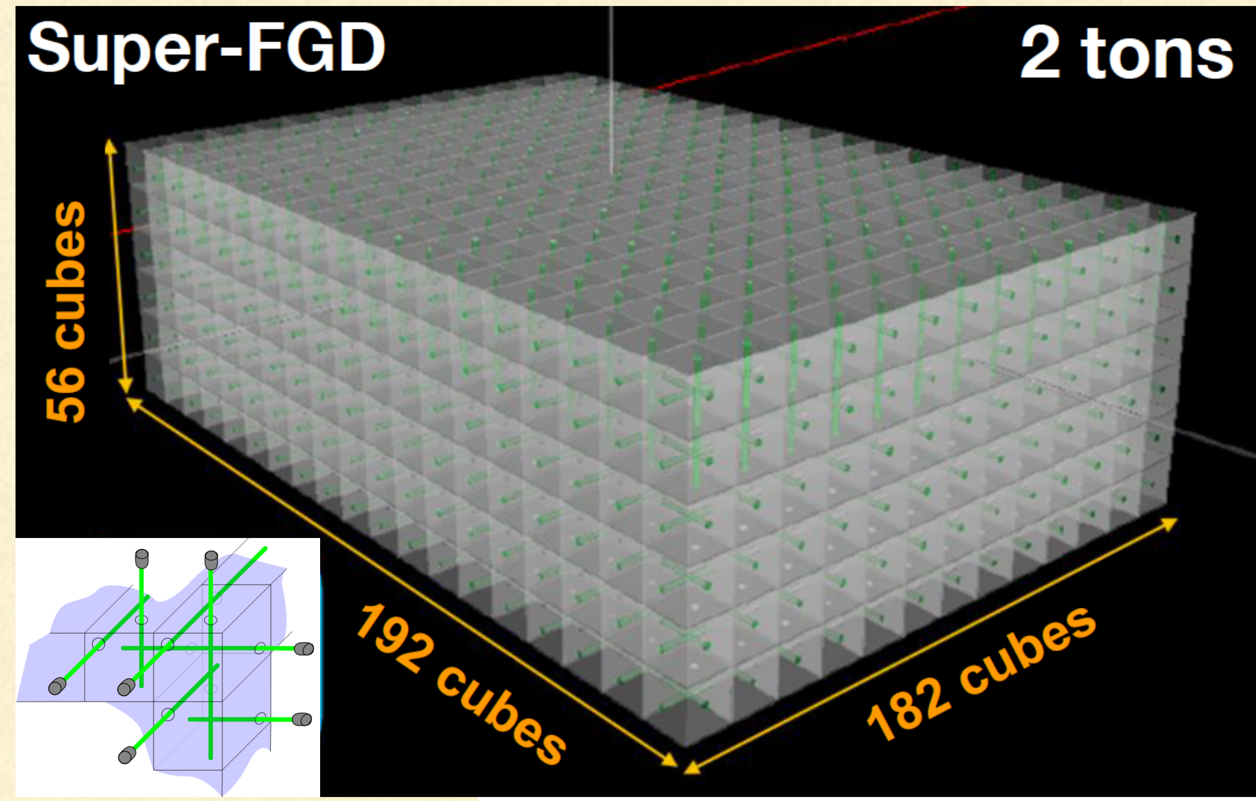


150 ps resolution

3D SUPER-FGD DETECTOR

JINST 13 (2018) 02006





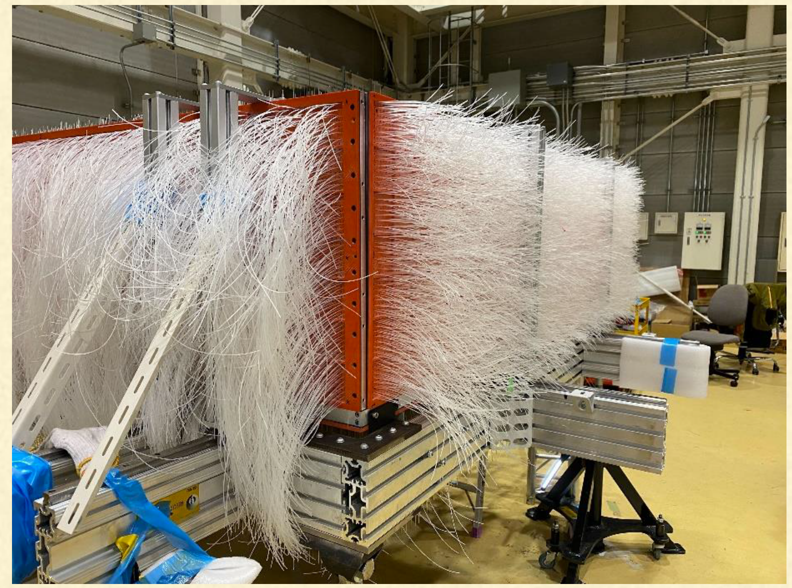
Fully active and highly granular 4π scintillator neutrino detector

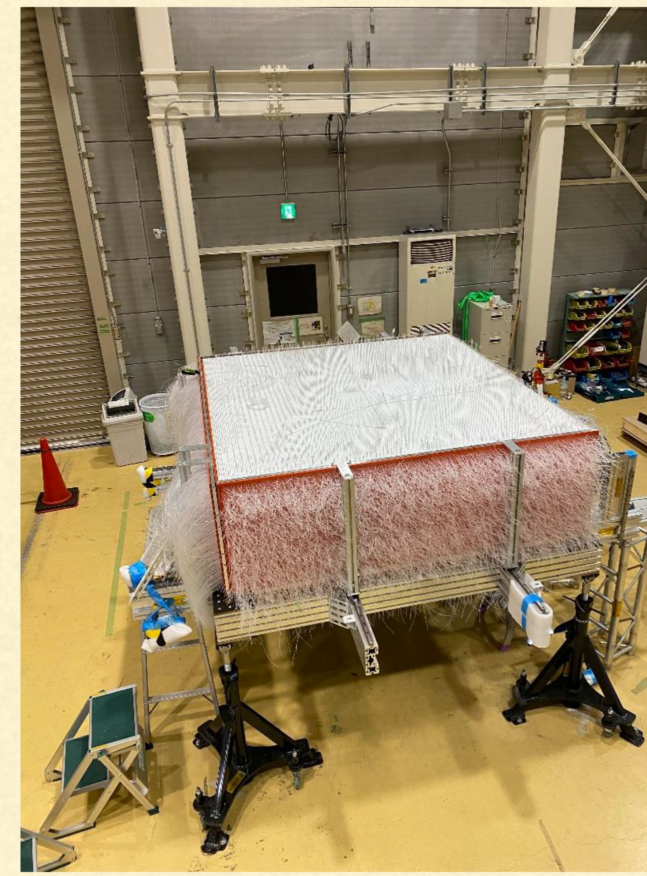
- Total volume ~192 x 182 x 56 cm^3
- $2x10^6$ optically isolated cubes
  - Each cube: 1 x 1 x 1 cm^3
  - Each cube: 3 orthogonal Ø 1.5 mm holes
- Total mass: ~2 tons
- One-end 1mm Y-11(200) MS WLS fibre
  - ~60.000 readout channels*
- S13360-1325CS Hamamatsu MPPCs
  - 1.3.x1.3 mm^2, 2668 pixels, ~1% cross-talk, 70 kHz dark-rate → LED calibration system

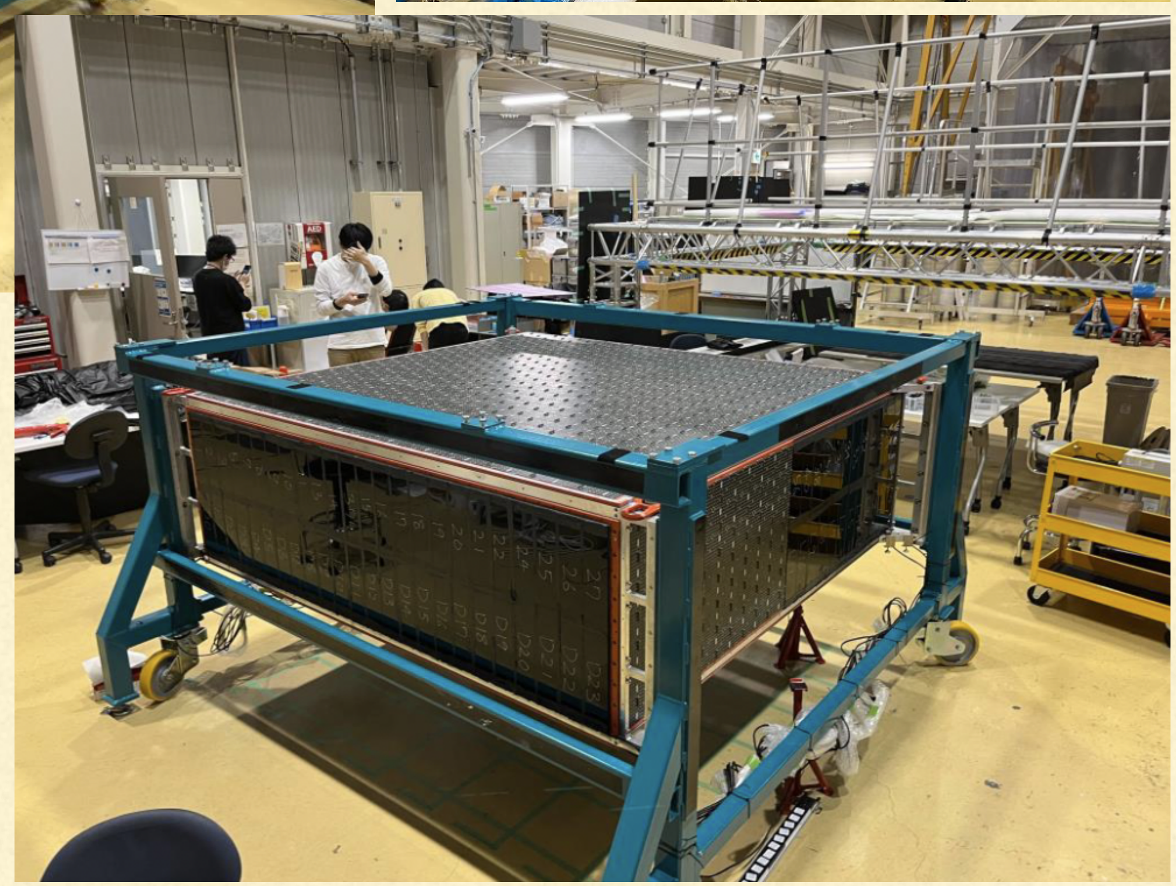
- Polysterene doped with PTP (1.5 %) + POPOP (0.01%)
- Injection moulding @ Uniplast, Vladimir, Russia
- Chemical reflector coating

* Electronics: FEBs based on CITIROC ASIC *JPS Conf. Proc.27(2019) 011011*

3D SUPER-FGD DETECTOR





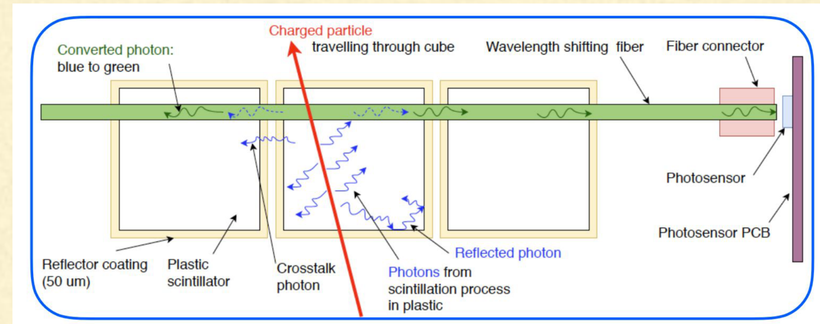


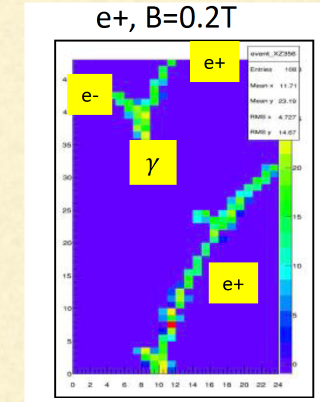
3D SUPER-FGD DETECTOR PROTOTYPES

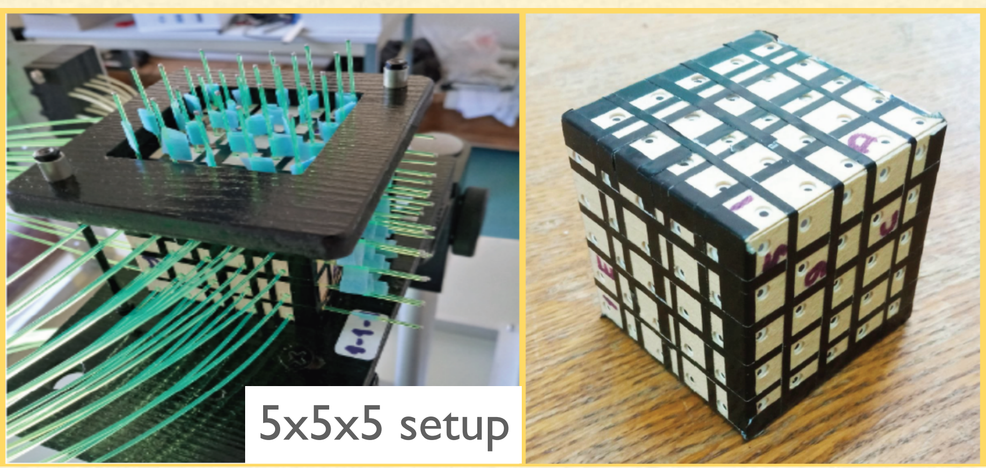
Detailed SFGD talk by A.Dergacheva @ B2 Neutrino Detectors on Tuesday

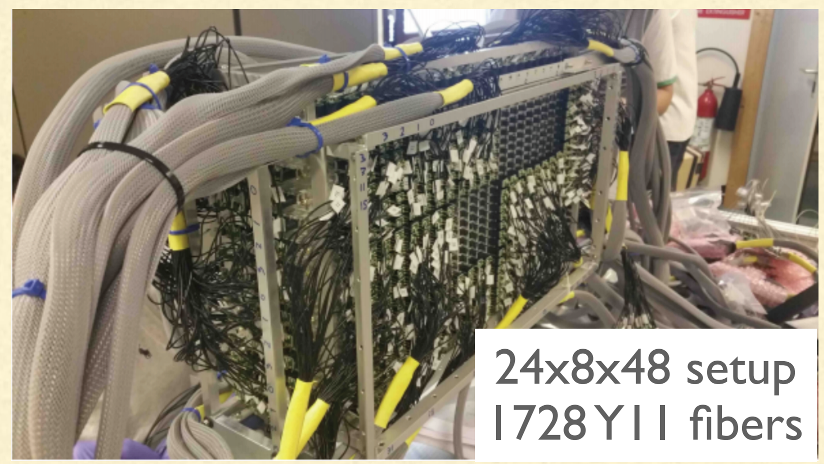
Tests with small prototypes to confirm the SFGD concept

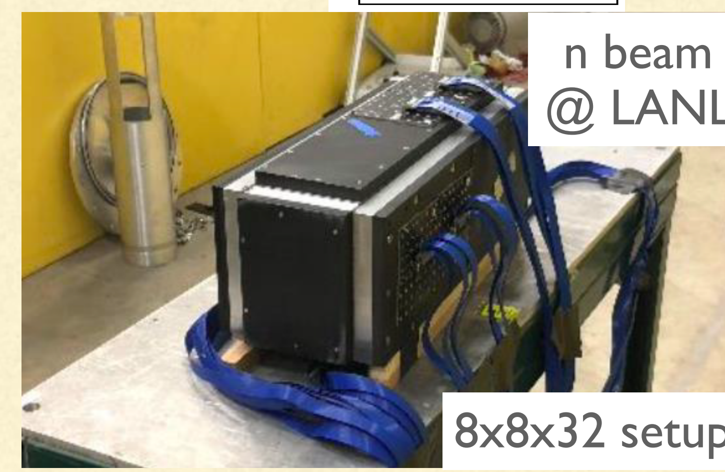
- Check performance: light-yield over detector, inter-cubes cross-talk, timing











2017: mu/e/p beam @ CERN and cosmics

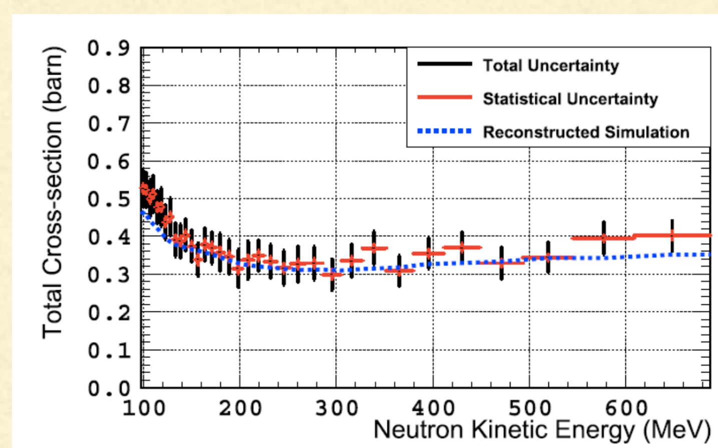
- SFGD concept *JINST 13 (2018) 02006*
- Proof of concept *NIMA 923 (2019) 134-138*

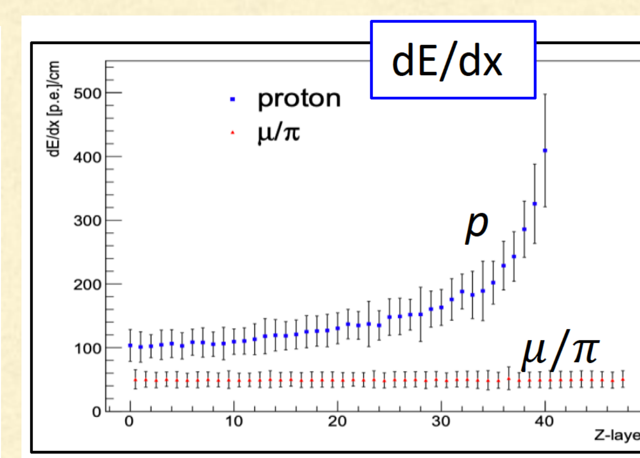
2018: e/μ/π/p beam + 0.2 T field @ CERN

- Characterisation *JINST 15 (2020) 12, P12003*
- Timing studies *JINST* 18 (2023) 01, P01012

2019-2020: neutron beam @ LANL total x-section

- $N(z)=N_0 \cdot exp(-T\sigma_{tot}z)$ *PLB 840 (2023) 137843*

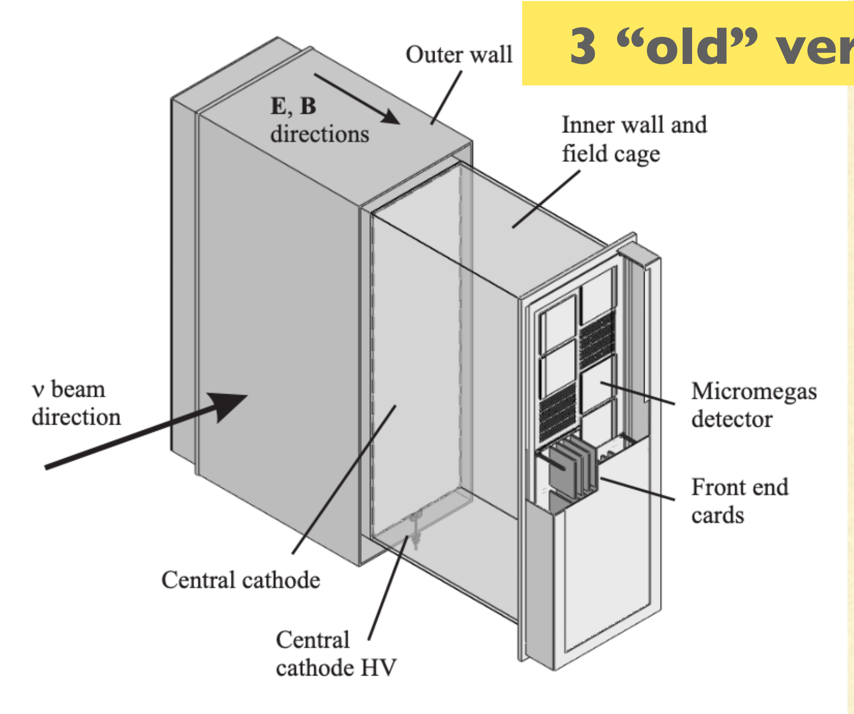


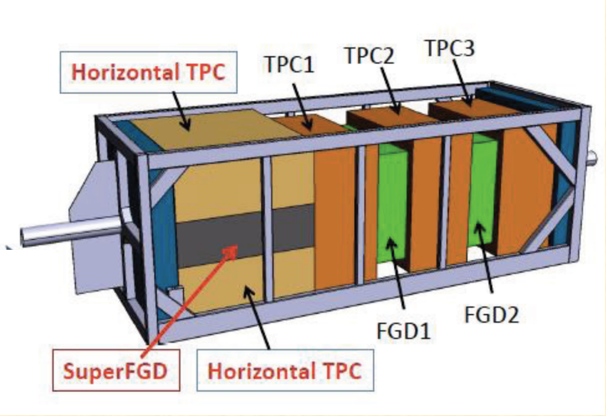


One channel timing < 1ns, further improved with > 1 cubes/fibres

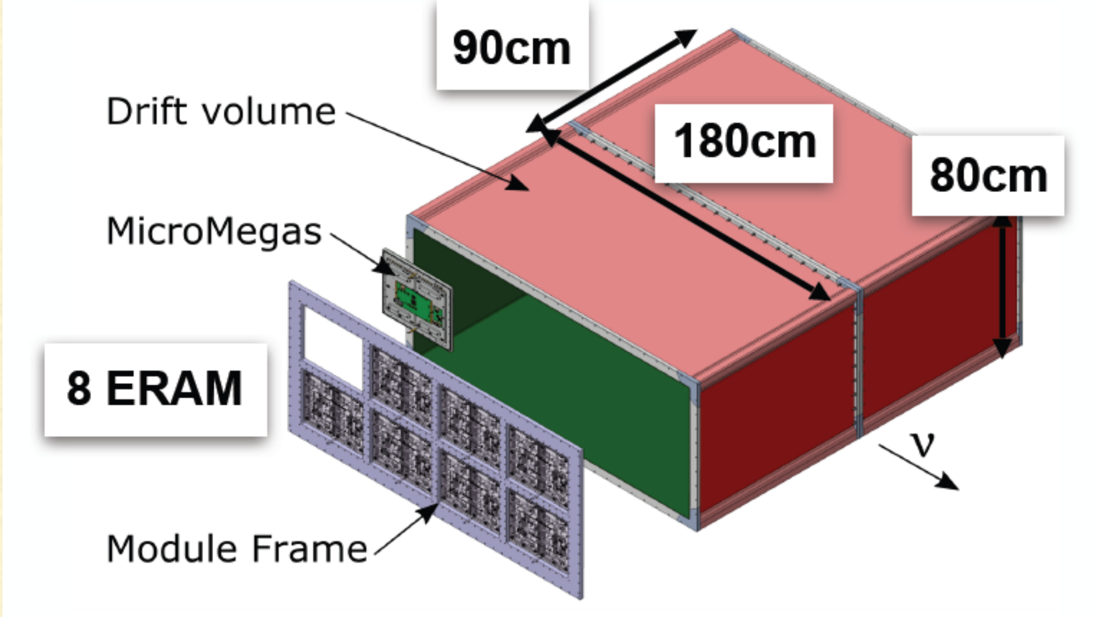
TIME-PROJECTION CHAMBERS

3 "old" vertical TPCs





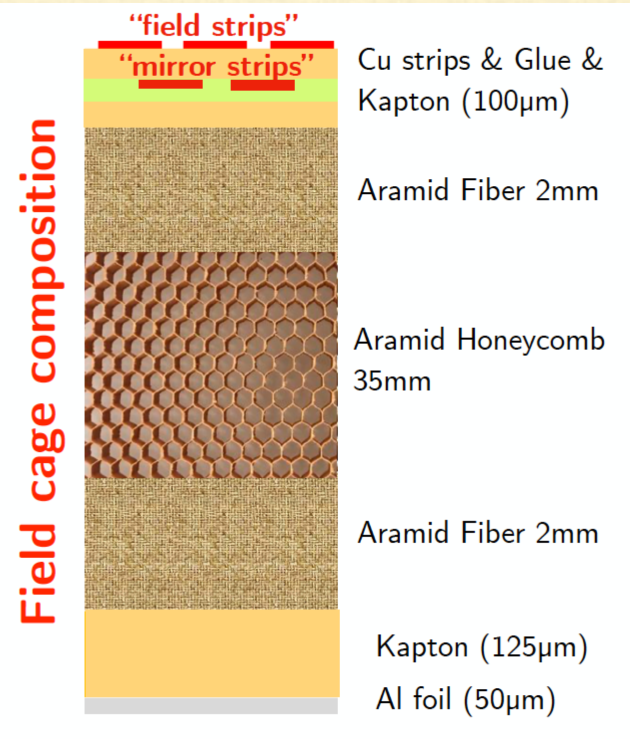
2 new horizontal TPCs



Two new additional "horizontal" TPCs up and down SFGD detector

- High resolution tracking and particle identification. Design requirements
  - $\sigma_p/p < 9\%$ @ 1GeV/c, $\sigma_{dEdX} < 10\%$
  - 3D tracking capability of TPCs → excellent pattern recognition, matching tracks/hits from active targets O(500 μm) space resolution
  - Low material budget walls ~ 5% X_0
- New field cage design to minimize dead space and maximize the tracking volume
  - Aim to gain maximum profit from the space available around SFGD
  - No CO_2 filled outer volume wrt vertical TPCs
- Replace the standard bulk-MicroMegas with a new resistive bulk-MicroMegas

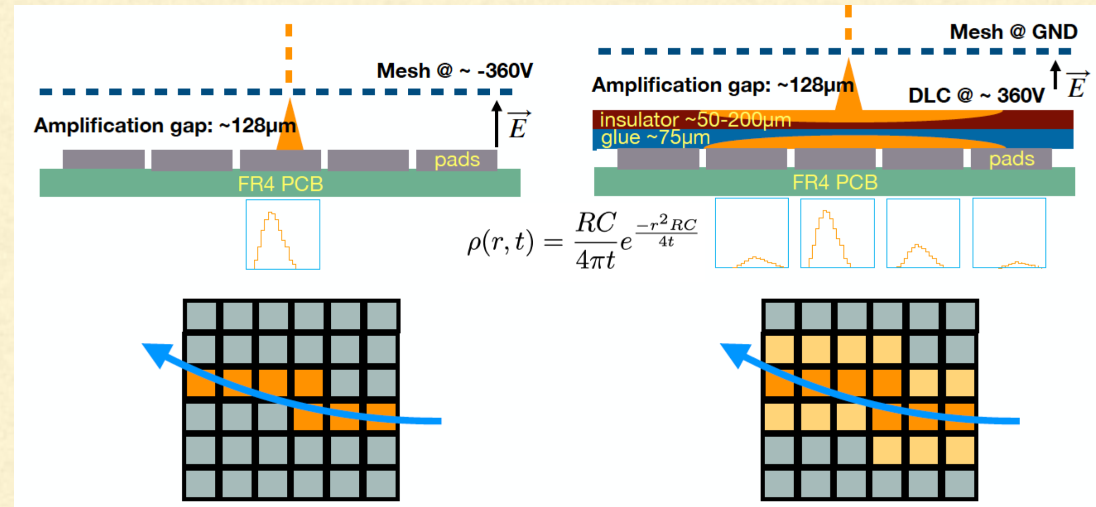
TIME-PROJECTION CHAMBERS



Field cage material budget "original" vertical TPCs: 12 cm — 3.4% X_0

new TPCs: 4 cm — 2% X_0

Electronics (all TPCs): AFTER 72-channel ASIC chip



Parameters	HATPC	vs VTPC
Overall x × y × z (m)	2.0 × 0.8 × 1.8	0.85 x 2.2 x 1.8
Drift distance (cm)	100	90
Magnetic Field (T)	0.2	
Electric field (V/cm)	275	
Gas Ar-CF_4-iC_4H_{10} (%)	95 - 3 - 2	"T2K" gas mix
Drift Velocity $cm/\mu s$	7.8	
Transverse diffusion $(\mu m/\sqrt{cm})$	265	
Micromegas gain	1000	
Micromegas dim. z×y (mm)	340x420	340x360
Pad z × y (mm)	10 × 11	7x10
N pads	36864	124272
el. noise (ENC)	800	
S/N	100	
Sampling frequency (MHz)	25	
N time samples	511	

Encapsulated Resistive Anode Micromegas (ERAM) with grounded mesh, anode at a positive amplification voltage

- Pad plane covered by a resistive layer
  - Spread the charge over several pads → less and larger pads for the same spatial resolution
  - Insulation of the resistive anode from the pads
- Suppress formation of sparks and limit their intensity
- Safe operation by a capacitive coupling readout
- Get rid of the cumbersome anti-spark protection circuitry
- Detection plane is fully equipotential → more uniform field, less track distortions + module flexibility

* field cages by NEXUS company (Barcelona)

TIME-PROJECTION CHAMBERS PROTOTYPES

2018-2023: 4 prototypes + hundreds of validation tests

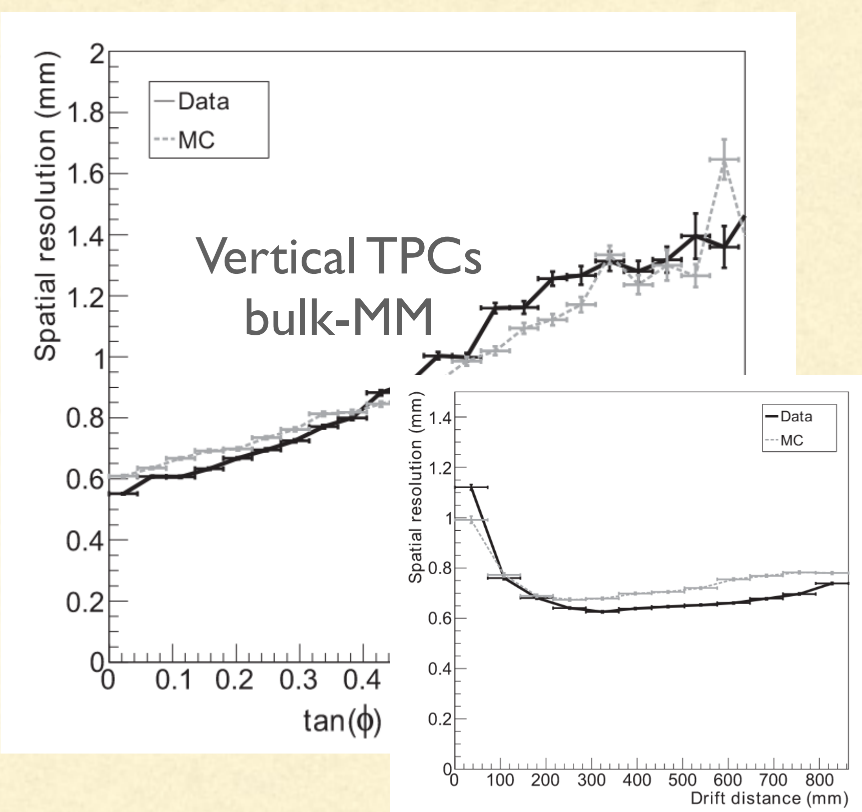
- Production readiness in 2023. Bottom TPC to be installed in fall 2023, top TPC in spring 2024

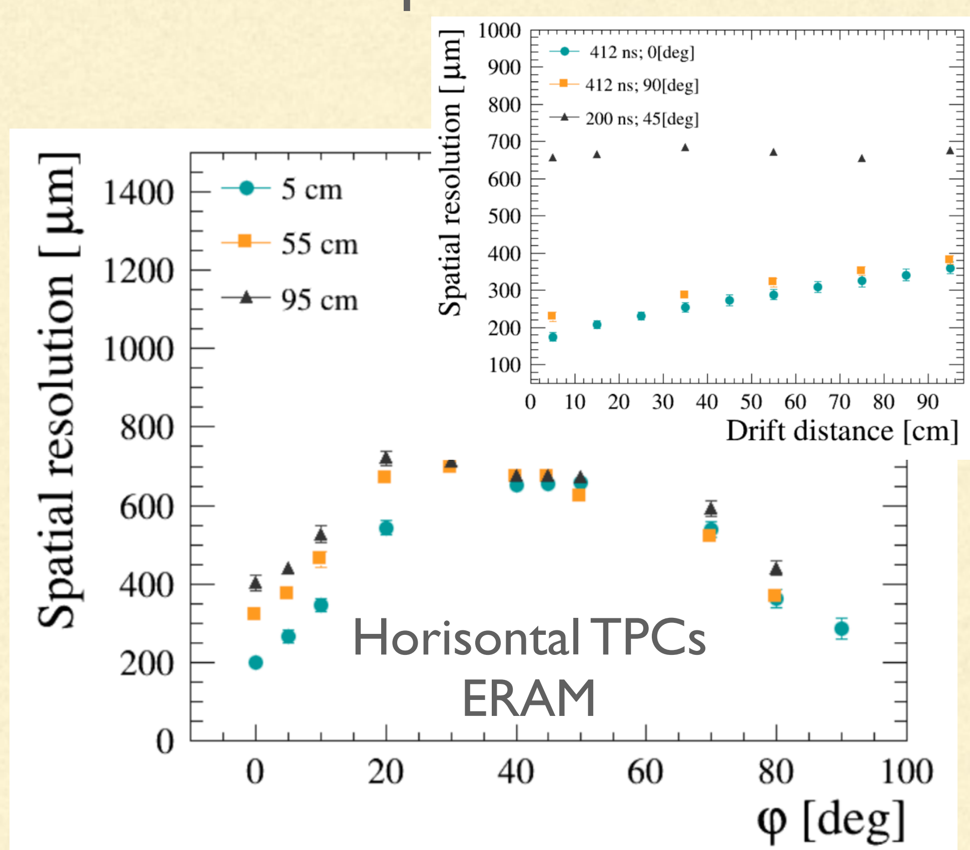
Characterization of charge spreading (RC) and gain of ERAMs using X-ray at CERN

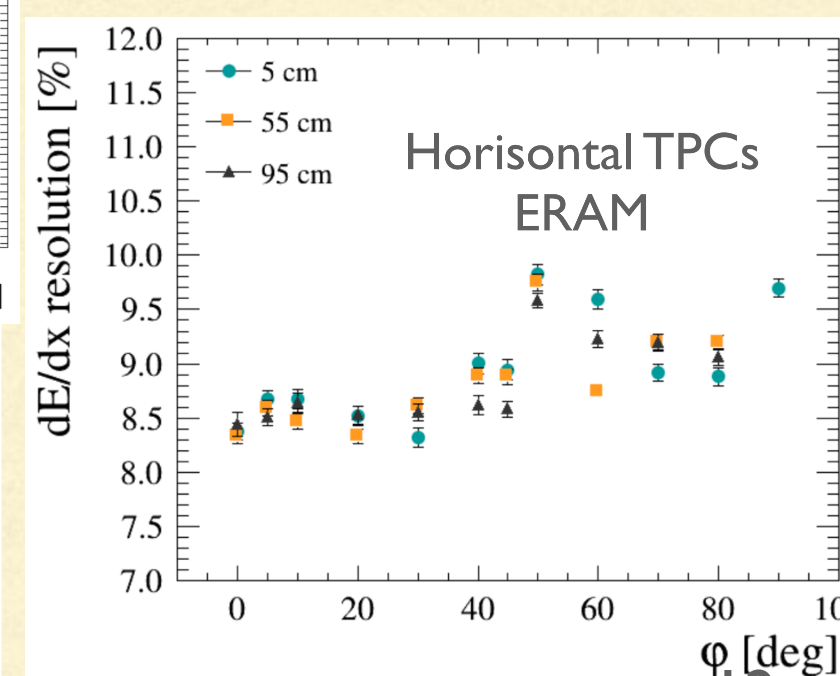
- *NIMA 1052 (2023) 168248*
- Detailed physical model to simultaneously extract gain and RC information of the ERAMs

Measurements of spatial and dEdX resolution via several test beam campaigns at CERN and DESY

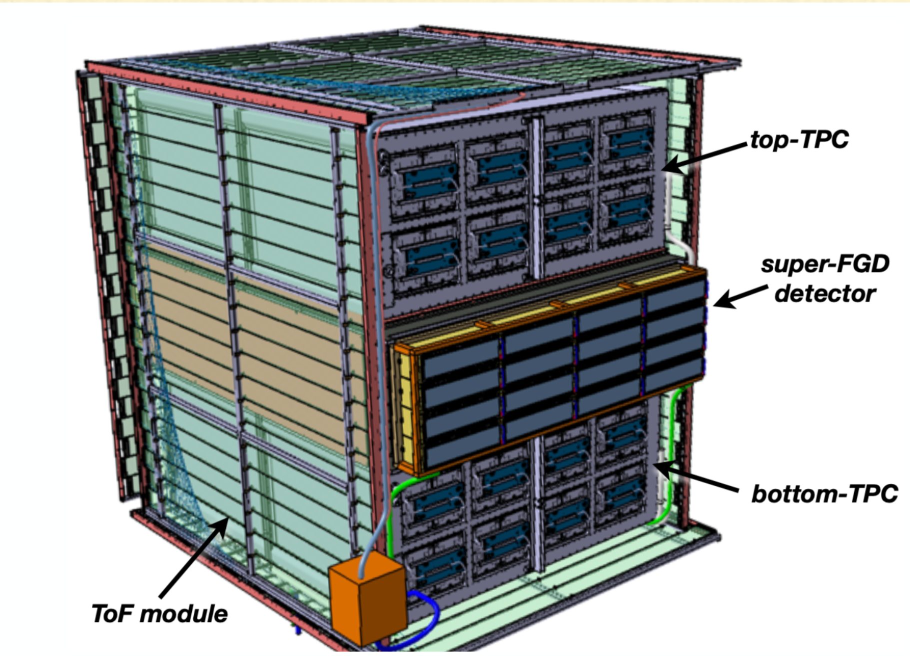
- *NIMA 957 (2020) 163286, NIMA 1025 (2022) 166109, NIMA 1052 (2023) 168248*
- Achieved spatial resolution better than 800 μm and dE/dx resolution better than 10%.

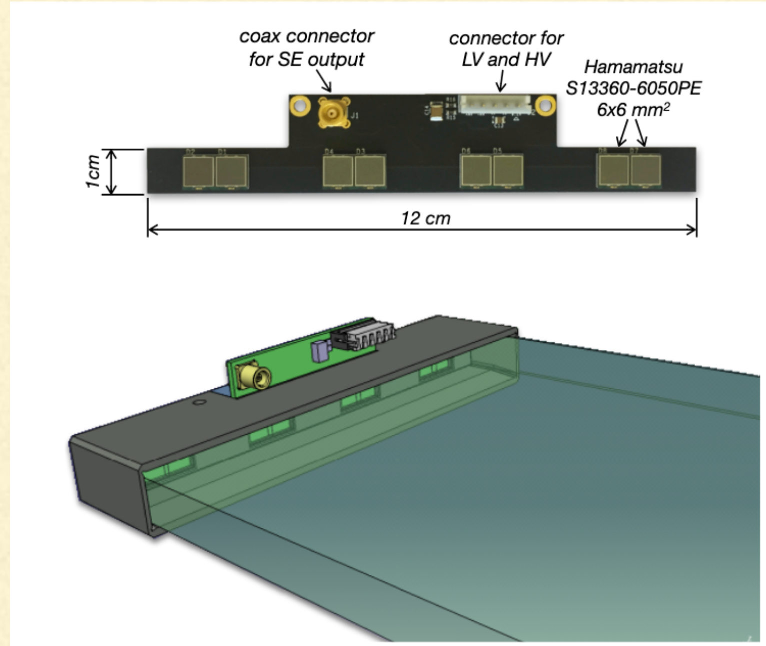


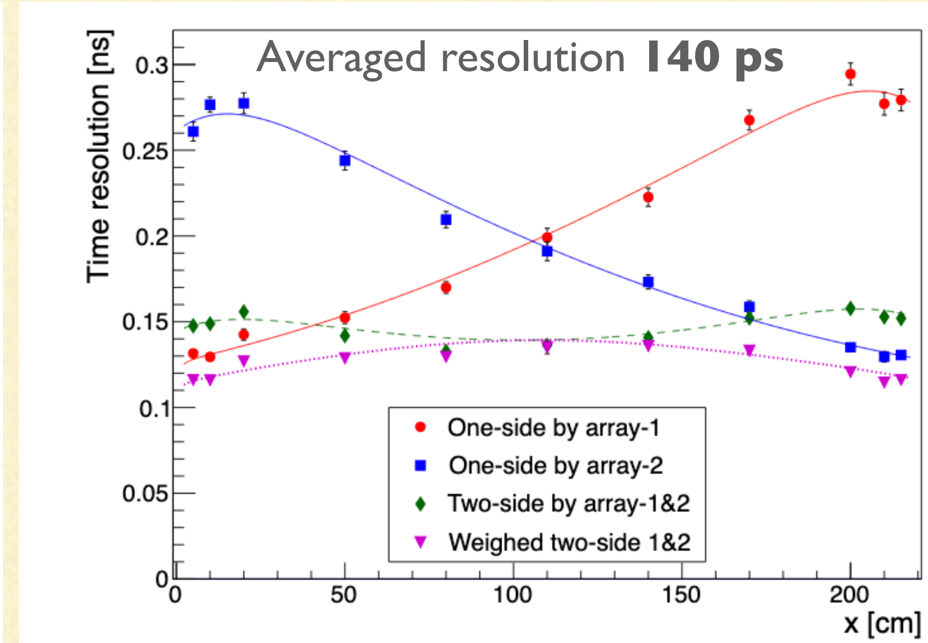




TOF DETECTORS







6 TOF planes fully envelope SFGD&HA-TPCs

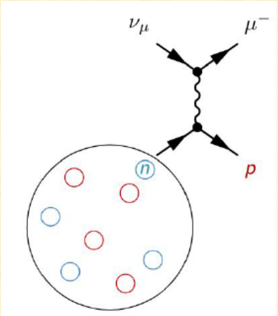
- Measure crossing time of charged particles
  - Aim for < 0.5 ns resolution
- Separate and veto inward going background
- Provide cosmic trigger for SFGD and TPCs
- Improve PID using timing (if reach < 0.2 ns)

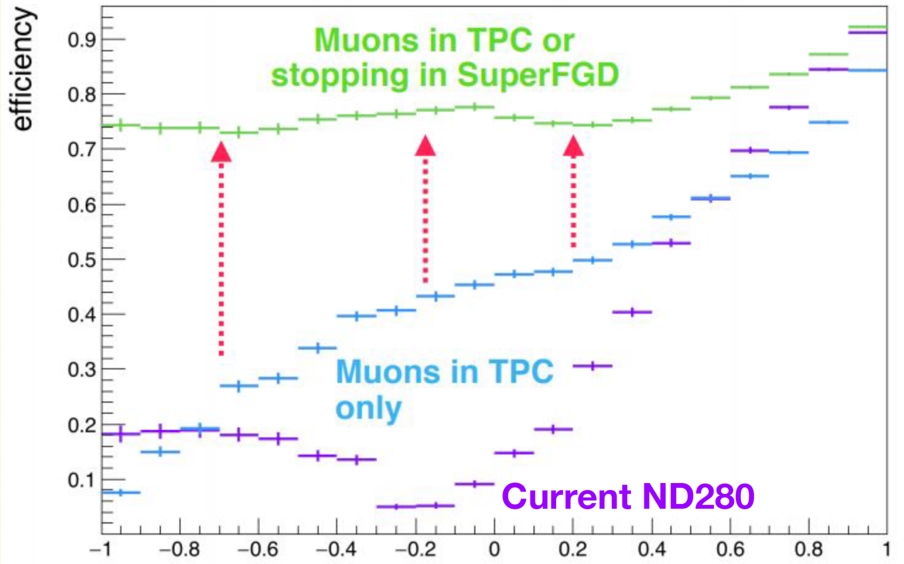
JINST 17 (2022) 01, P01016

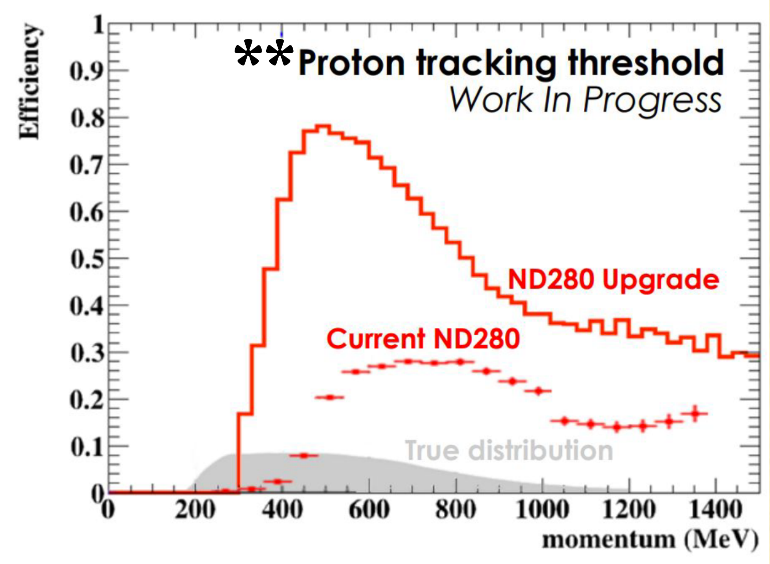
- Cast EJ-200 plastic scintillator
  - 0.9 ns rise, 2.5 ns decay times, 380 cm L_{att}
  - No WLS → would further degrade timing
- 20 (18 in bottom) 12 x 1 x 230 cm^3 bars in each plane
- Large area 6x6 mm^2 SiPM readout from both bar ends
  - Hamamatsu S13360-6050PE (SiPM/MPPC)
  - Array of 8 SiPMs at each side, grouped in 4 pairs
  - Channels` connection and signal processing optimisation to further avoid timing depletion

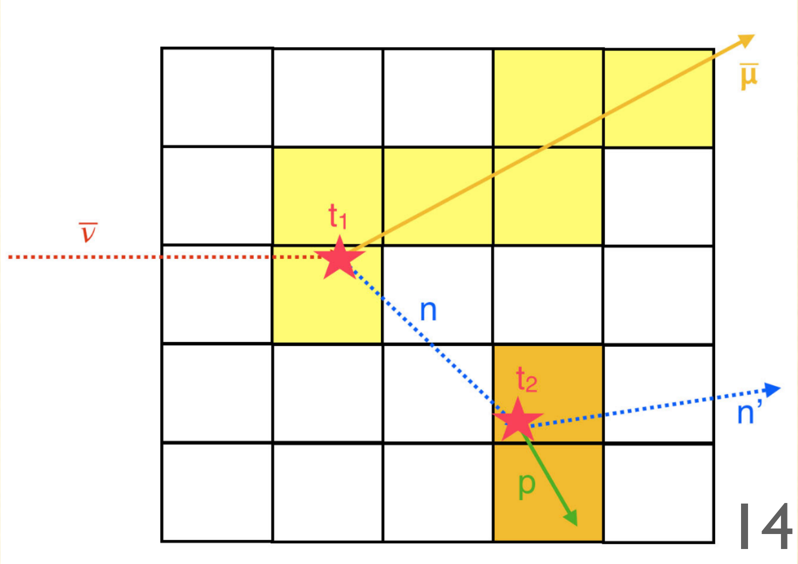
PHYSICS WITH ND280 UPGRADE

- Improved ~4π acceptance → better constraints on the neutrino interaction model
- Better reconstruction of outgoing nucleons → access to new observables
  - Neutron tagging and TOF-based neutron energy reconstruction in anti-ν channel
- Increased target mass (x2 current ND280) → more statistics
- ν interaction measurements beyond p_μ, $\cos\theta_\mu$ → exclusive and multidimensional analyses with nucleon info, transverse kinematics*
- Enhance electron analyses purities
  - e+/e- vs γ separation
  - TOF detectors further suppress external backgrounds





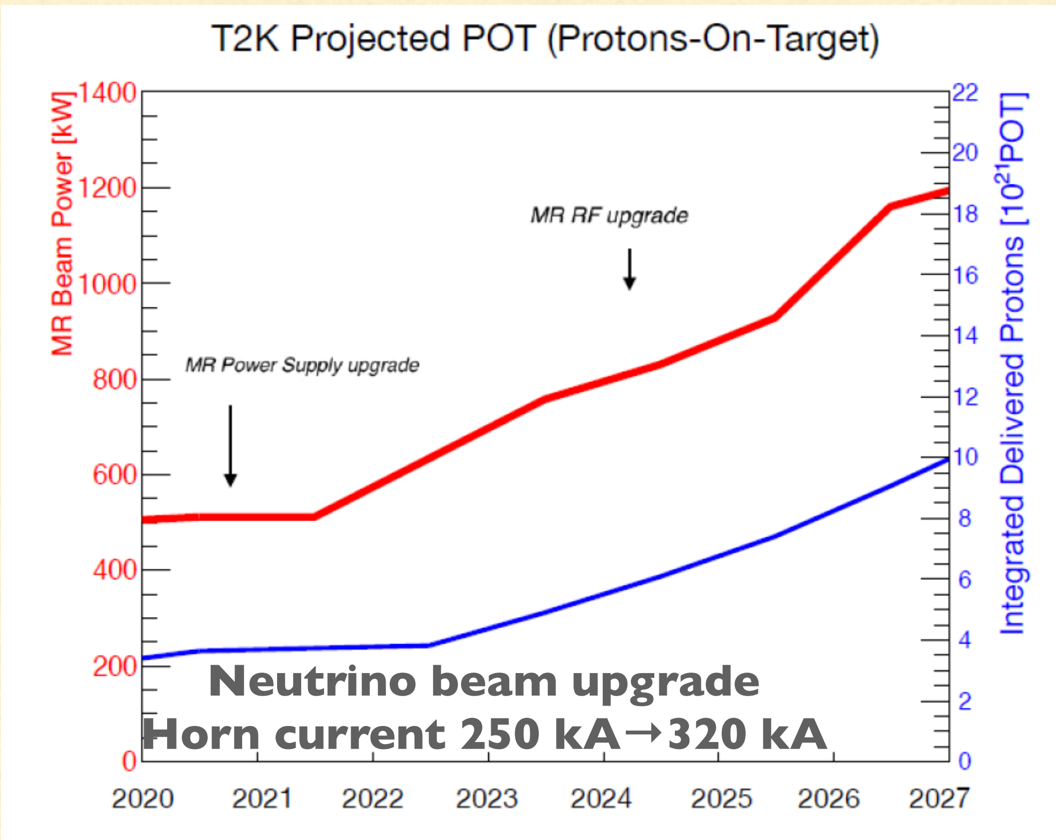




* see Backup Slides for transverse variables details

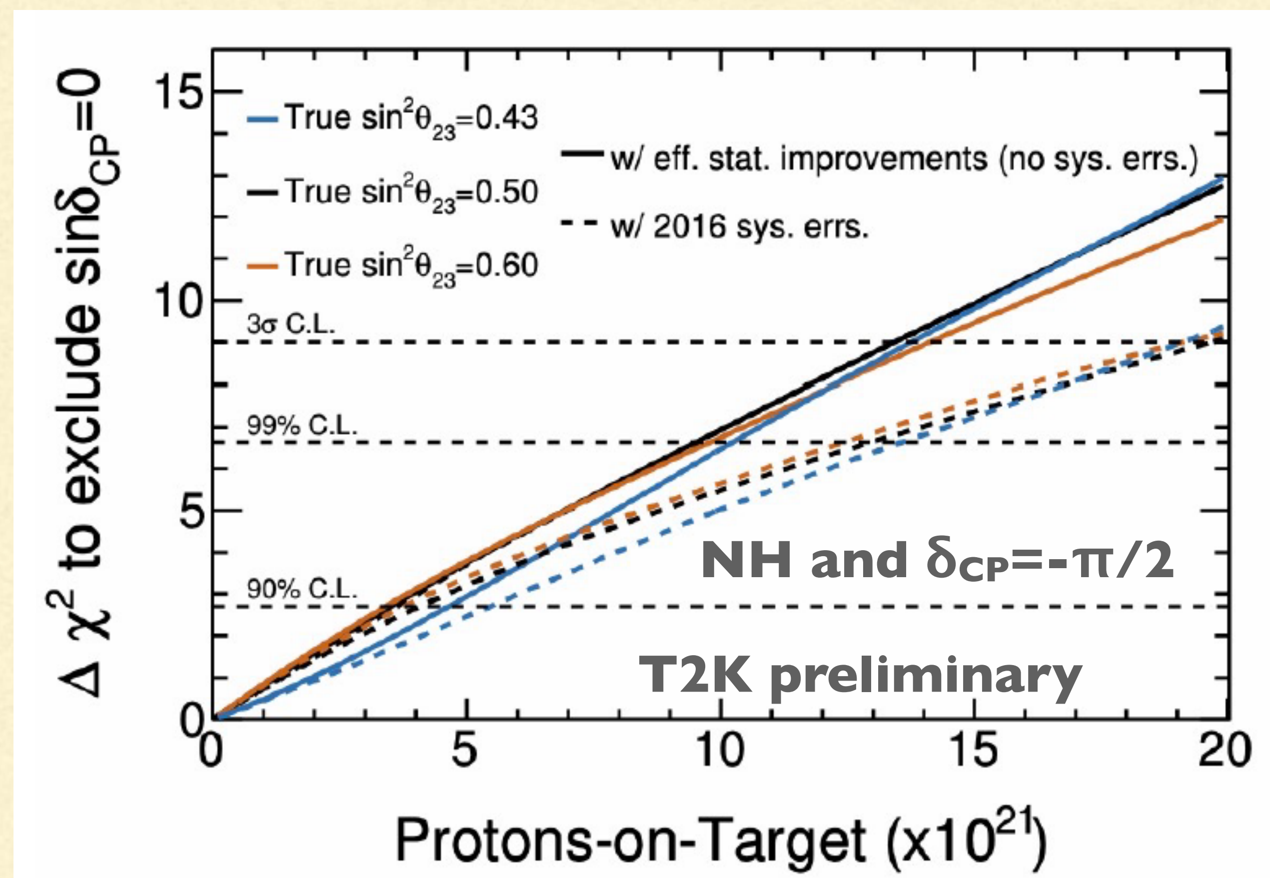
** proton tracking with CC0π selection

PHYSICS WITH T2K & ND280 UPGRADE: OSCILLATION ANALYSIS



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

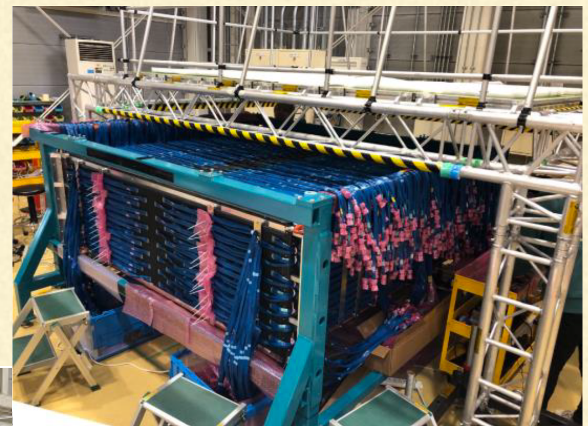
Reduction of systematics uncertainties crucial to enhance T2K-II OA sensitivities

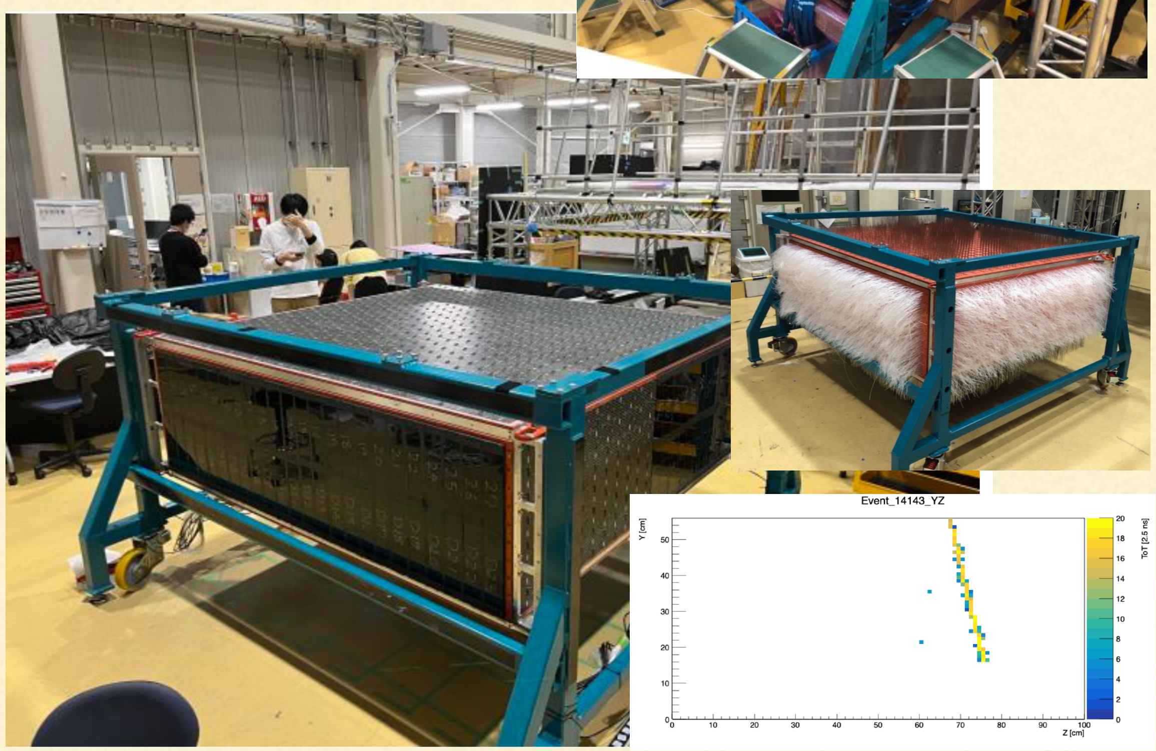


Phys. Rev. D 105,032010 - for sensitivity to ν-xsec nuclear model parameters

STATUS OF ND280 UPGRADE

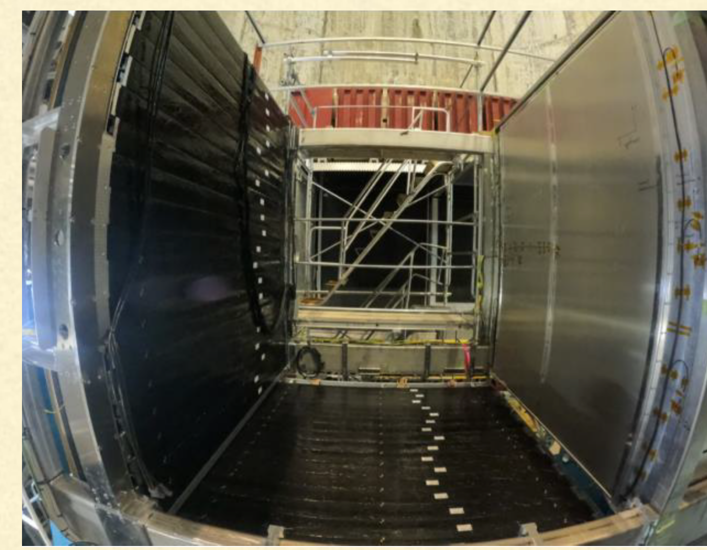
SuperFGD at J-PARC. Electronics installation, calibration, on surface tests with cosmics.





Bottom TPC delivered to J-PARC in August 2023. “On surface” tests. New gas system assembled.

TOF detector at J-PARC. 2 modules installed into the Near Detector pit.



The upgraded ND280 is to begin collecting first neutrino data in November 2023

SUMMARY

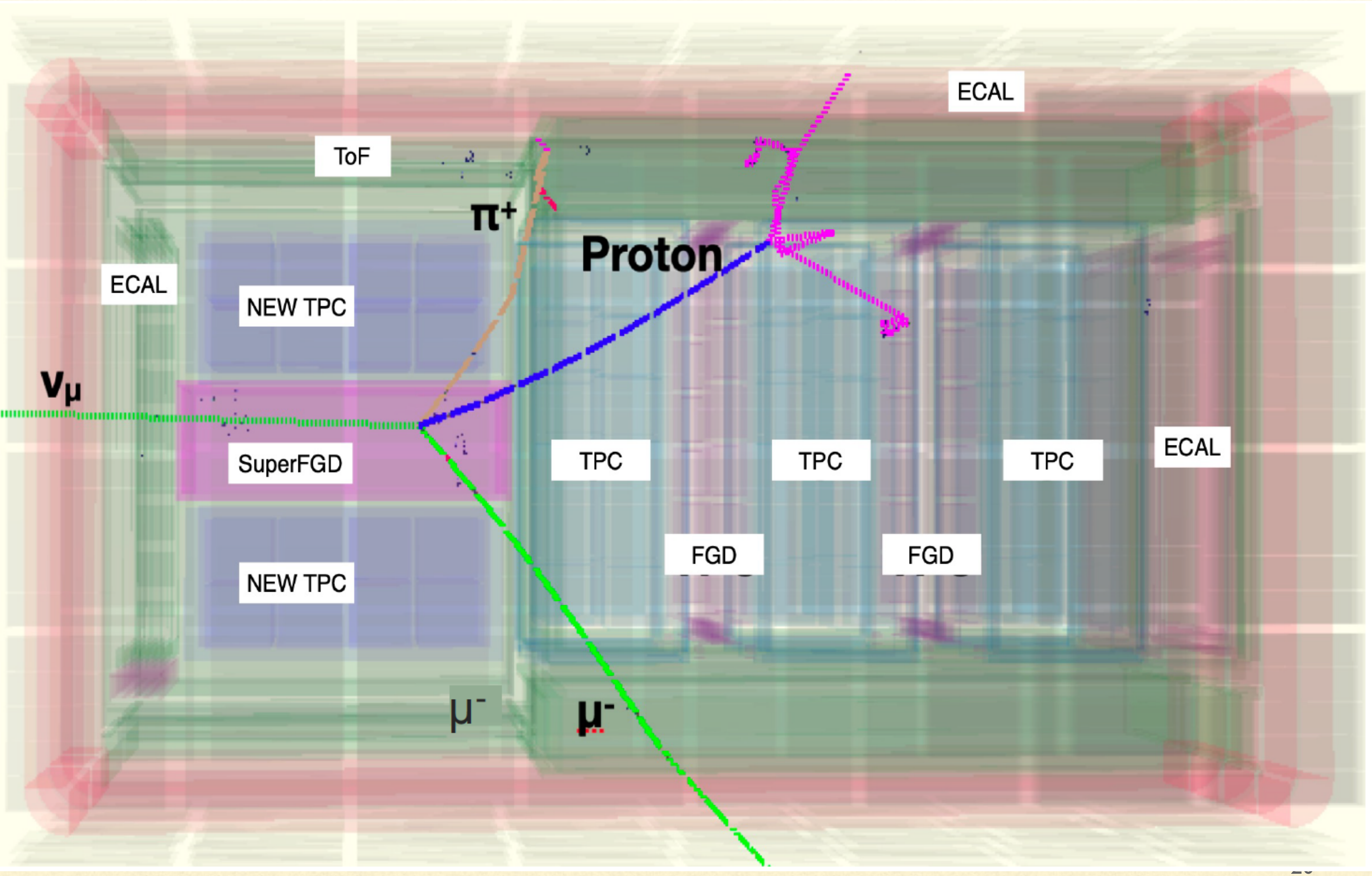
stay tuned
new data beckons

- **T2K is working steadily on its quest on filling neutrino puzzle**
- **T2K Phase-II approved extended run for ~2023-2027 to give smooth transition to Hyper-Kamiokande era**
  - Reach 3σ exclusion of non-CPV for certain δ_{CP} and MH
  - Key element: **near detector upgrade** to further reduce systematic uncertainties + enhance physics capabilities
- **ND280Upgrade features novel detectors**
  - **Super-FGD** with 2M plastic scintillator cubes readout by 3 WLS fibres each → unique tracking capabilities
  - **2 Ar gaseous TPCs** with improved ERAM readout → better spatial resolution with less and larger pads + less affected by sparks
  - **TOF** cast scintillator plates readout by large area SiPMs providing < 150 ps timing
- **First neutrino data with ND280Upgrade in November 2023**

T2K

Thank you for your attention

BACKUP MATERIALS


ECAL
ToF
π+
Proton
ECAL
NEW TPC
νμ
SuperFGD
TPC
TPC
TPC
ECAL
FGD
FGD
NEW TPC
μ-
μ-

PHYSICS WITH ND280 UPGRADE: NEW OBSERVABLES AND ENERGY RECONSTRUCTION

- Neutrino energy can be estimated with lepton kinematics only

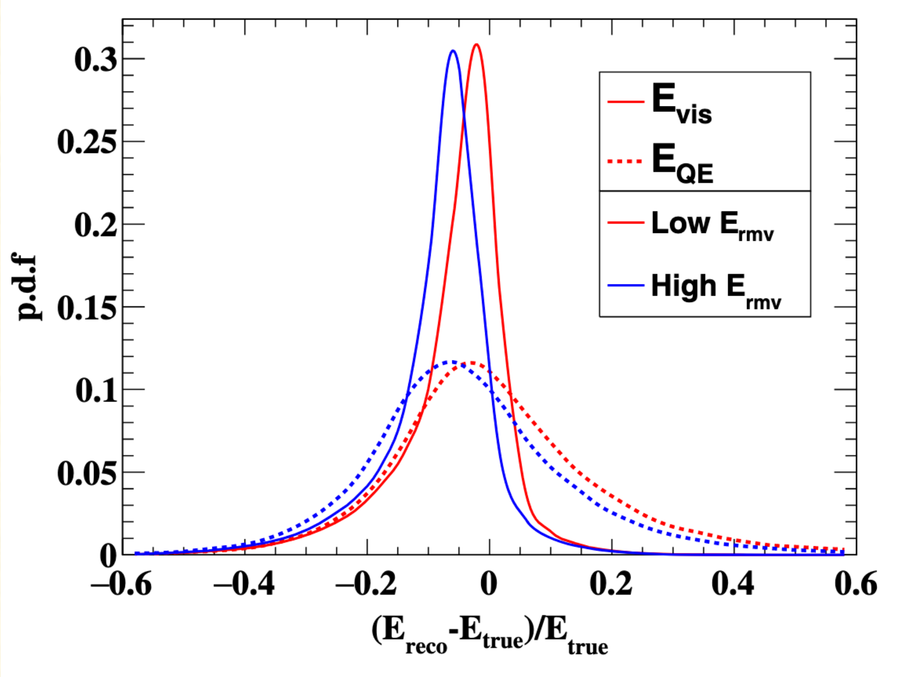
$$E_{\nu}^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

- With a nucleon reconstructed, the visible energy can give a better estimation

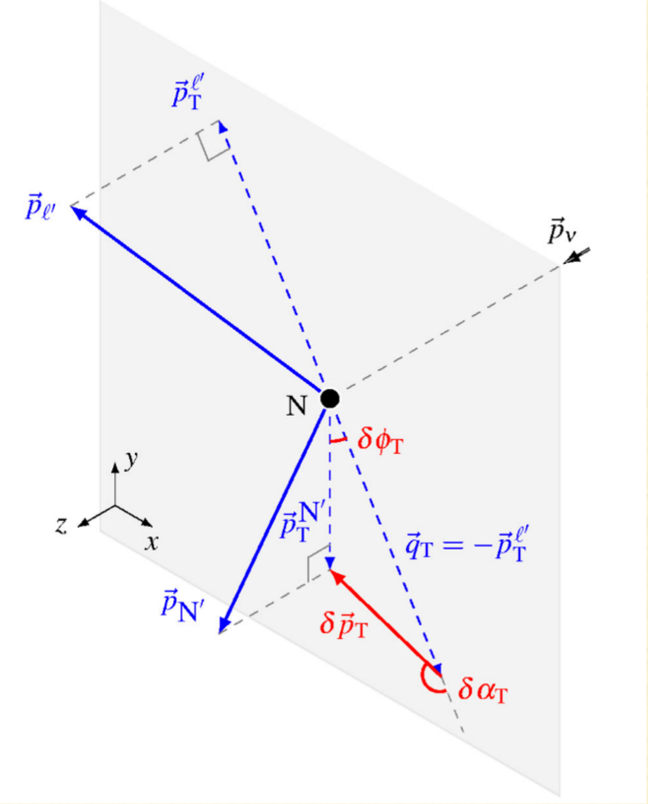
$$E_{\text{vis}} = E_\mu + T_N$$

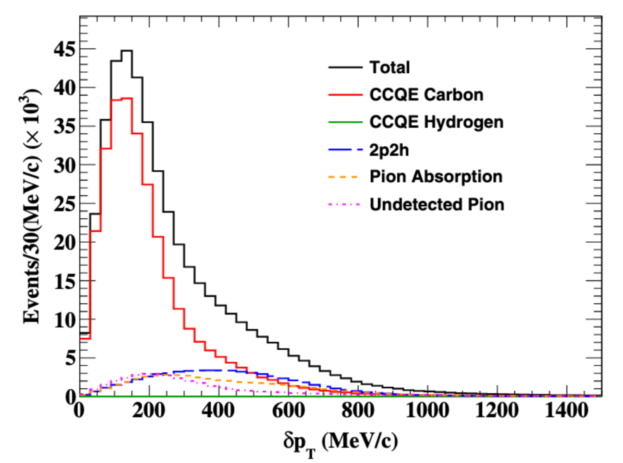
Phys. Rev. D 105,032010

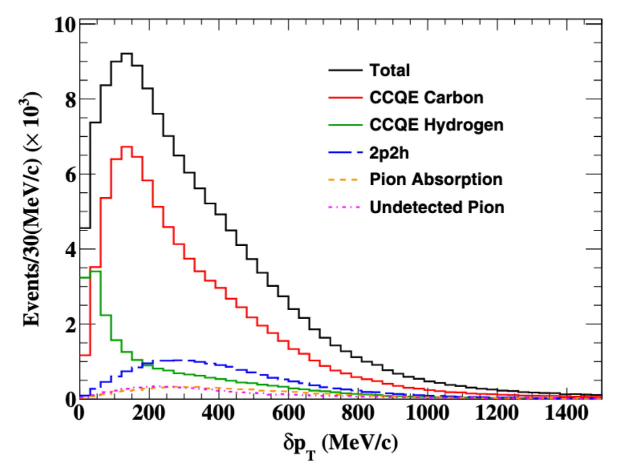
Phys. Pev. D 101,092003

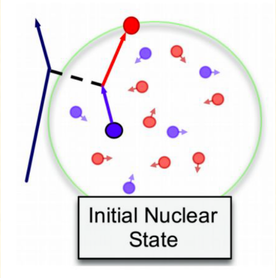


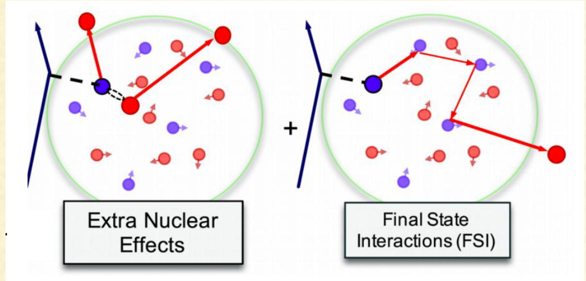
- Transverse kinematic imbalance → probe nuclear effects: Fermi motion, FSI, multi-nucleon processes







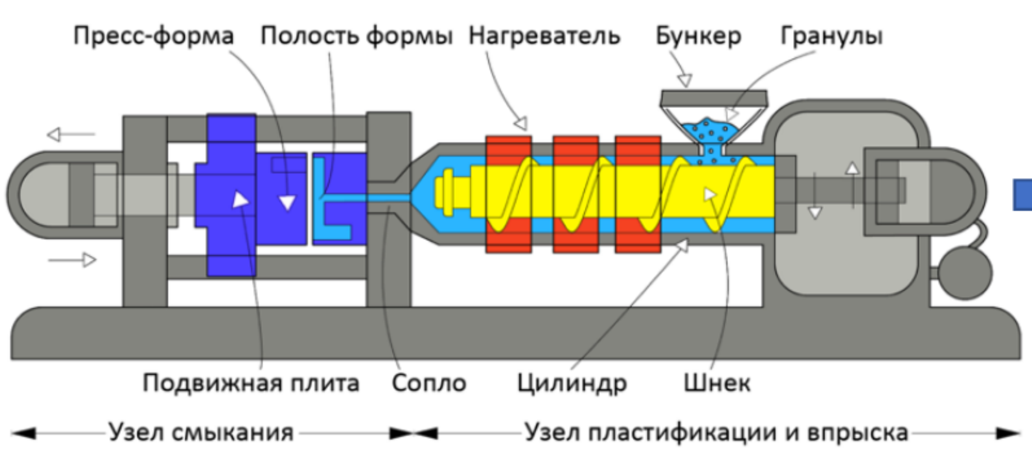




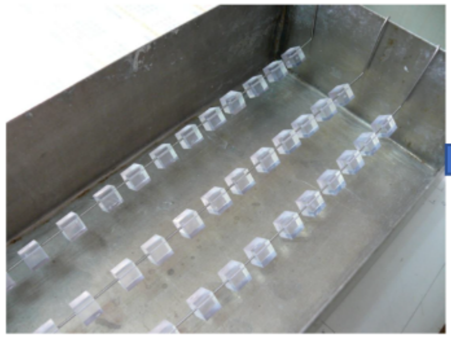
3D SUPER-FGD CUBES MANUFACTURING

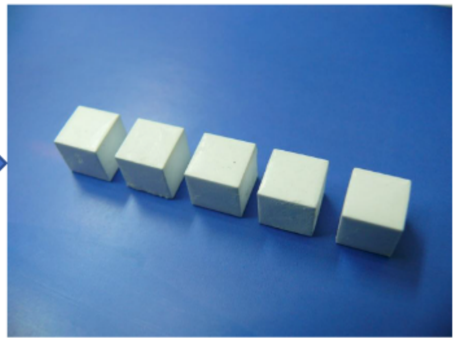
Uniplast Co. (Vladimir city): Cube production

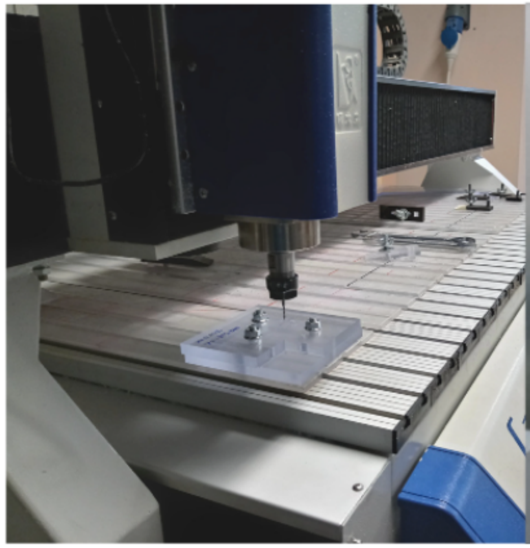
Injection molding



Chemical reflector







Hole drilling

Hole cleaning

NEW TIC GAS SYSTEM

New **simplified** gas system designed to

- serve all 5 TPC's (3 present TPC's + 2 new HA-TPC's)
  → total 18.5 m^3 detector active volume
- mix and closed-loop circulate active volume gas through filters

Main parameters (unchanged wrt present)

- gas mixture unchanged: **Ar-CF_4-iC_4H_{10} (95:3:2)**
- flow rates: up to 1 volume change per 6 hours (~3m^3/h)
  → for keeping O_2 CO_2 H_2O contamination at ppm level
- fresh gas injection: 10% of circulation flow
- flow CO_2 gas through outer volume of present 3 TPC's (~1.2m^3/h)
- maintain **overpressure ΔP~4mbar** wrt **atmospheric** P and
  ΔP~0.1mbar between inner and outer volumes old TPC's

Gas system modules design based on CERN standards

- modules: mixers, closed-loop circulation modules, analyzers, …
- HW PLC control via profibus connection, SW WinCC-OA SCADA2 itf
  → simplified operations and maintenance

→ fully automate system with high degree of reliability

T2K→T2K-II UPGRADES

J-PARC upgrades

- Operation at a higher beam intensity.
- Subsequent upgrade of neutrino beamline to support the beam intensity.
- Horn power supply ramp up for better focusing.
- Expected to be ready for autumn 2023

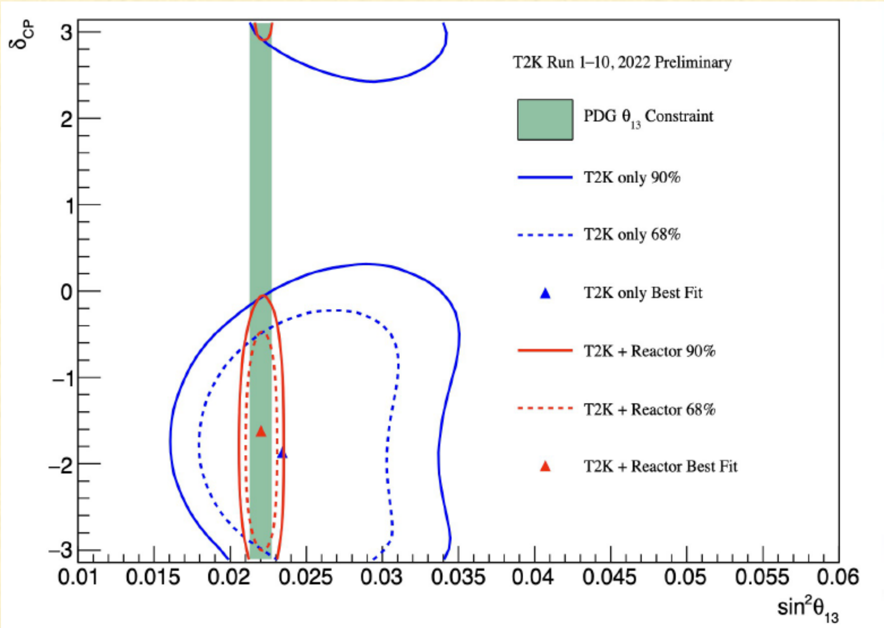
ND upgrades

- New complex detectors to replace the old P0D detector.
- This will improve our constraints on flux and interaction uncertainties, and also paves way for better xsec measurements.
- Expected to start data taking in 2023

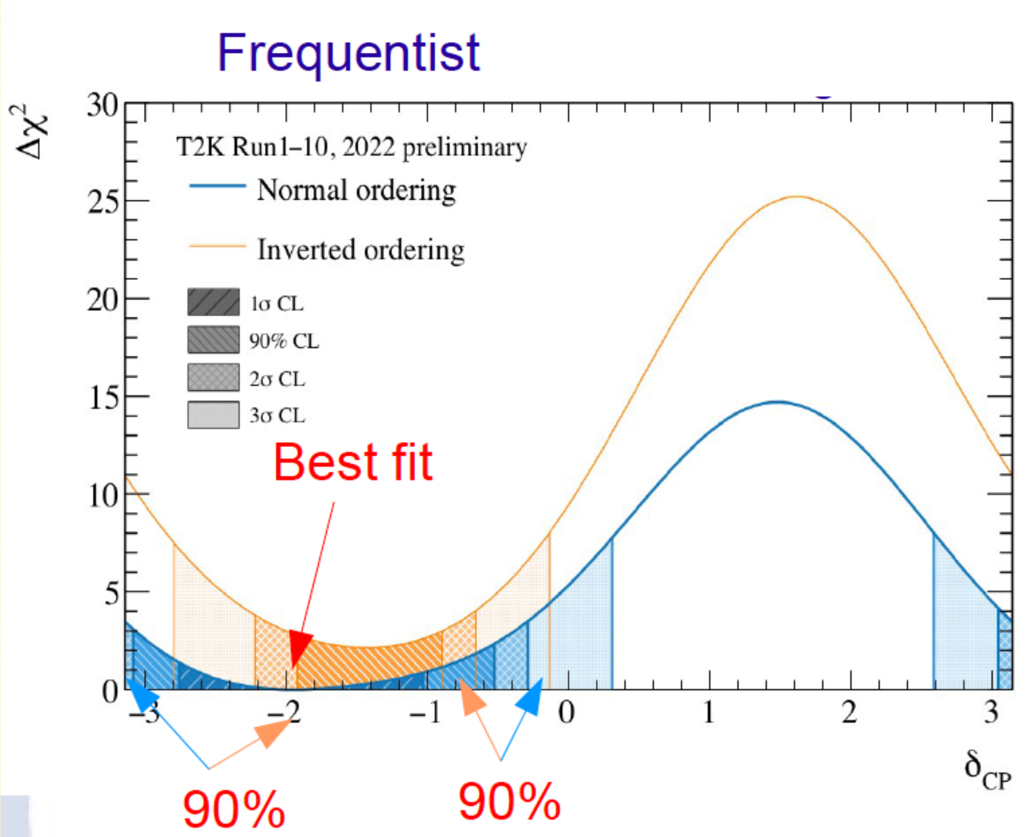
FD upgrades

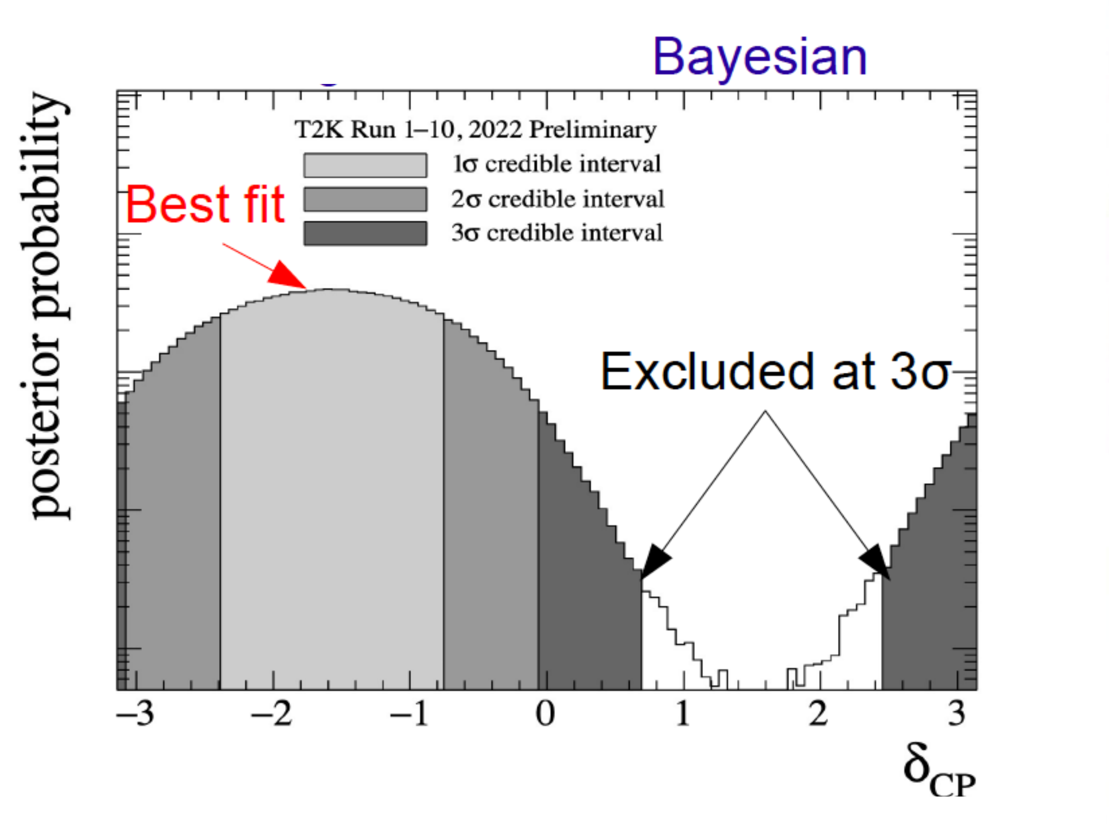
- Gadolinium was loaded into SK in summer 2020 in different stages with different concentration
- This leads to improved neutron tagging and hence better $\nu/\overline{\nu}$ separation.
- T2K took its Run11 data using SK-Gd, although not yet used in the analysis.

ANALYSIS RESULTS: θ_{13} MEASUREMENTS

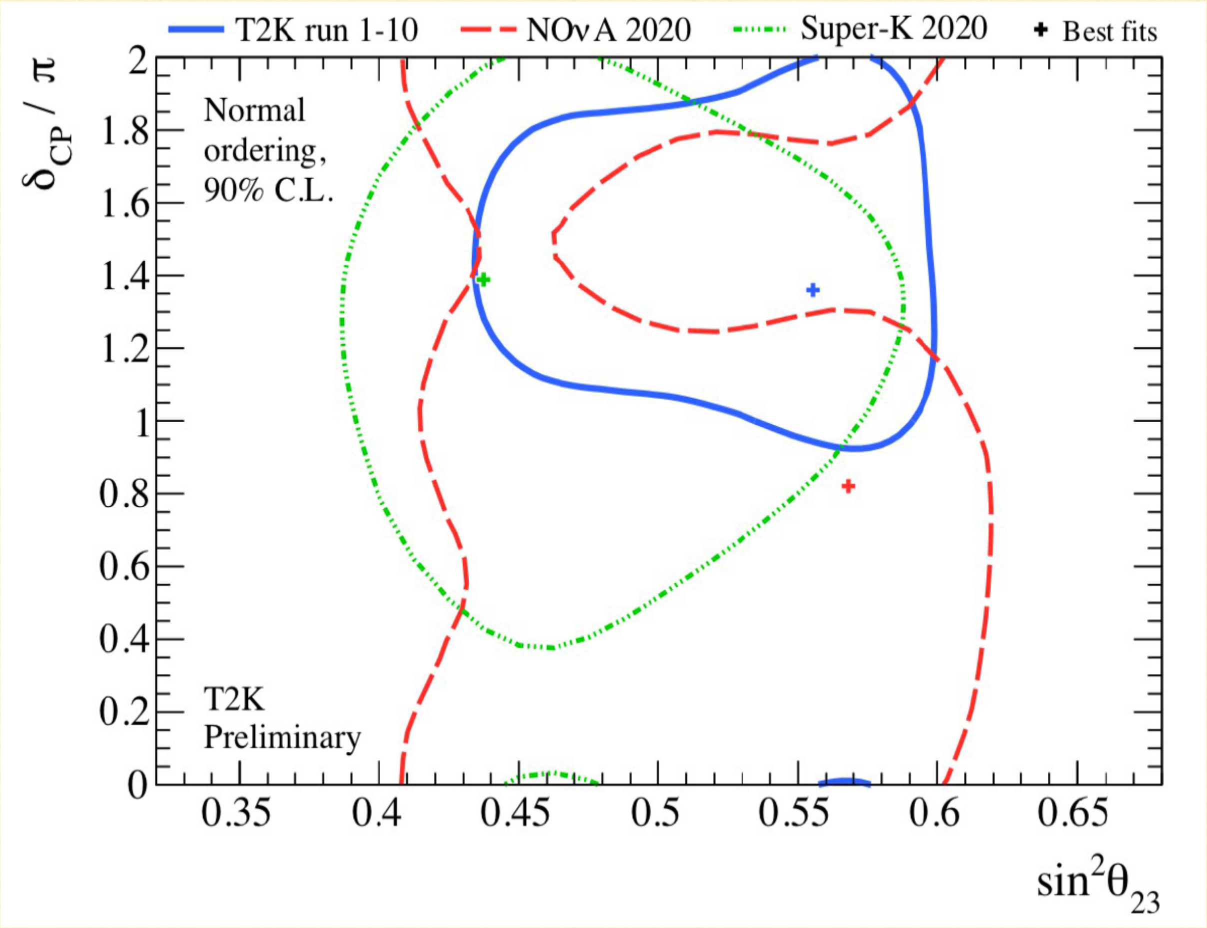


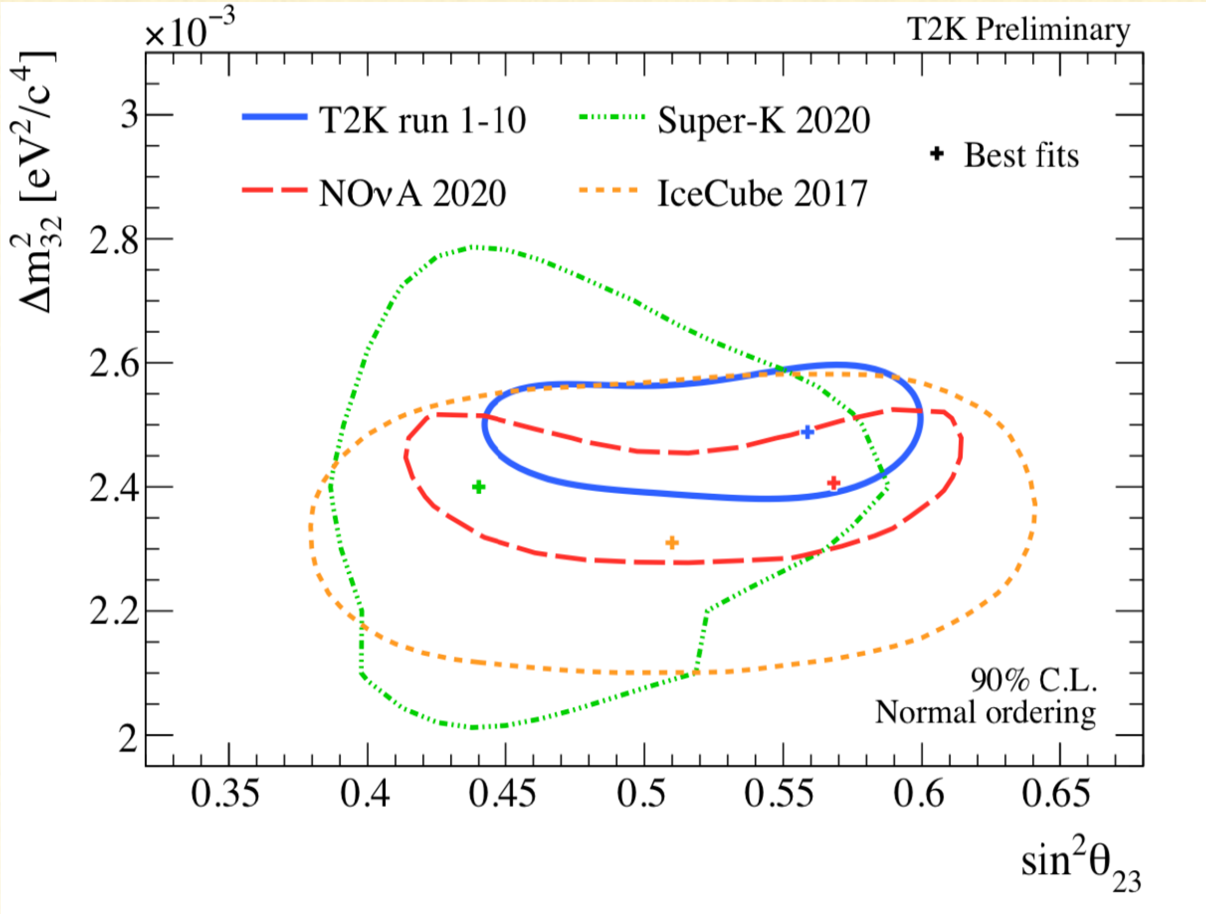
- Good agreement with reactor on θ_{13}
- **Large CPV favoured**
- CP-conserving values of δ_{CP}=0 and δ_{CP}=π both outside of 90% CL intervals





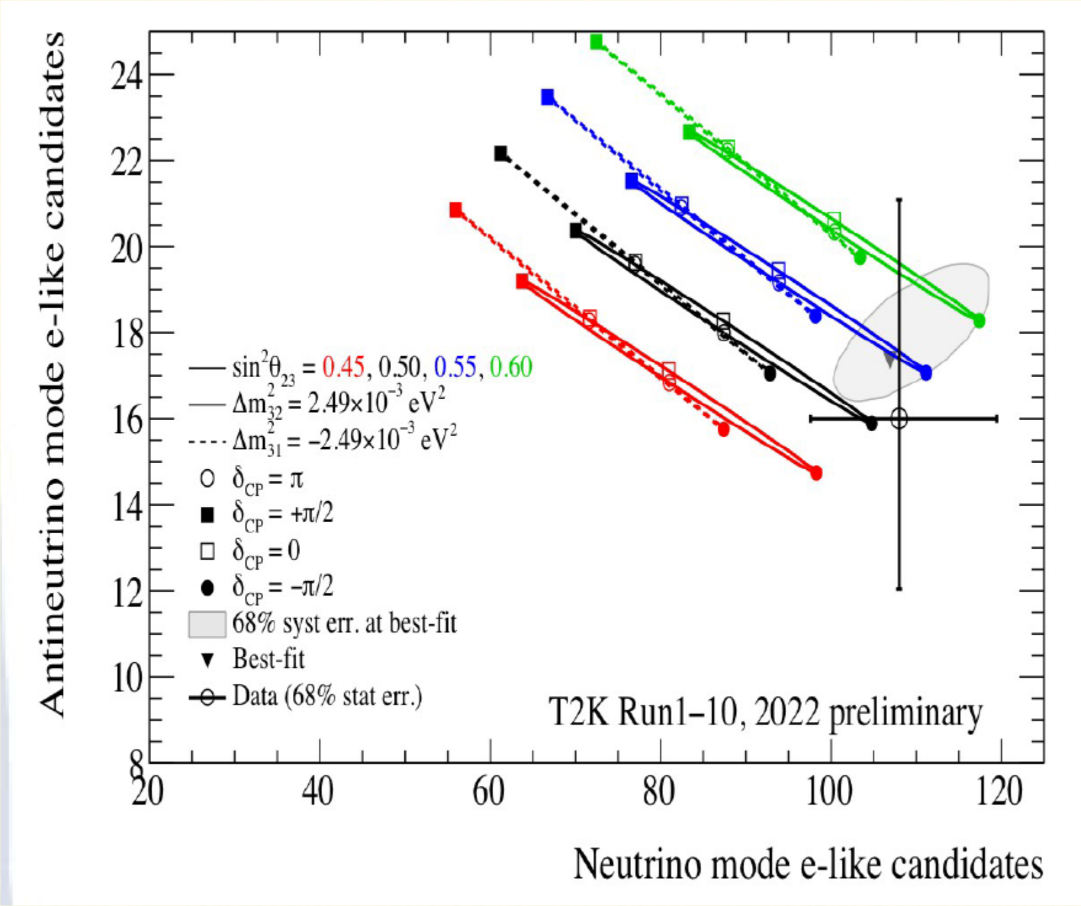
T2K VS OTHER MEASUREMENTS

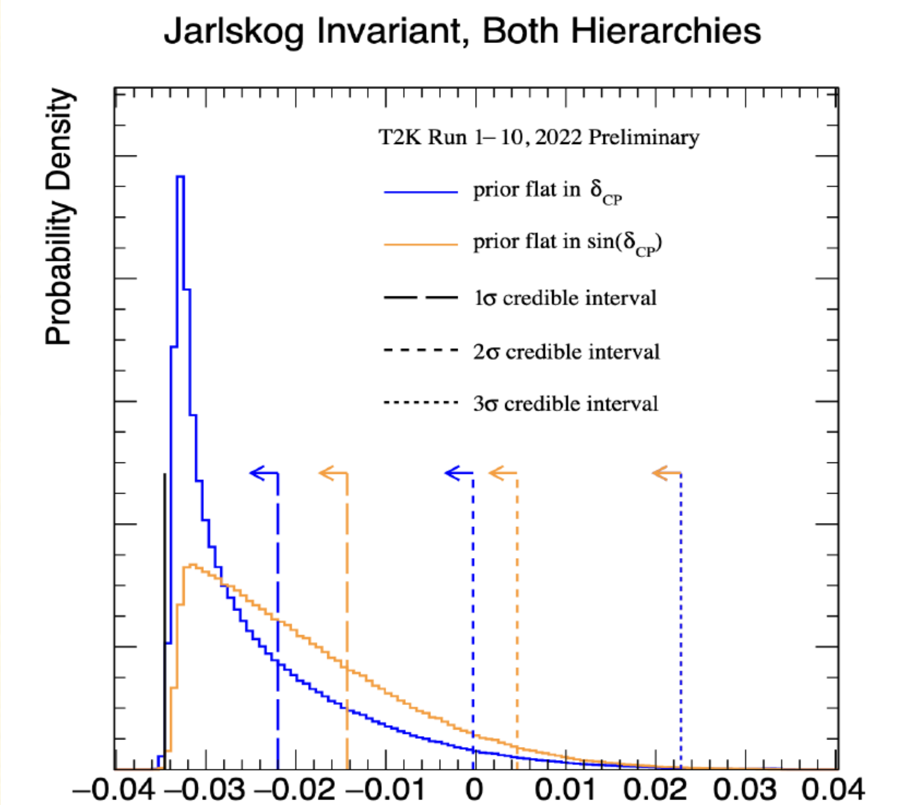




- δ_{CP}-vs-$\sin^2\theta_{23}$: at 90% CL, δ_{CP} T2K, NOνA and Super-K contours overlap. T2K consistent with Super-K best fit, NOνA best fit just outside contour
- Δm^2_{32} -vs-$\sin^2\theta_{23}$: at 90% CL, θ_{23} contours overlap. T2K and NOνA favour upper octant while Super-K prefers lower

MORE T2K OSCILLATIONS RESULTS





$$J_{CP} \approx 0.033 \sin(\delta_{CP})$$

$$J = s_{13} c_{13}^2 s_{12} c_{12} s_{23} c_{23} \sin\delta_{CP}$$

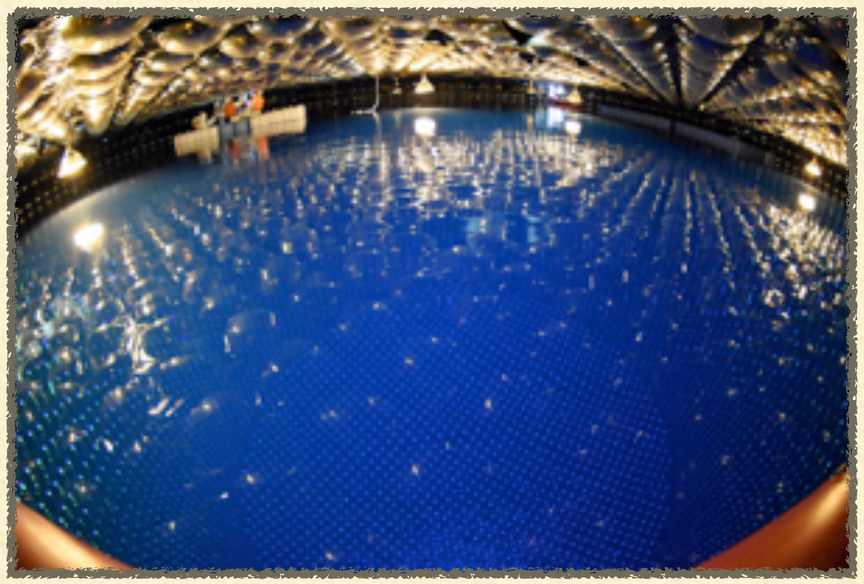
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.19	0.65	0.83
Inverted ordering	0.03	0.14	0.17
Column total	0.21	0.79	1.00

- Bayesian with reactor constraint

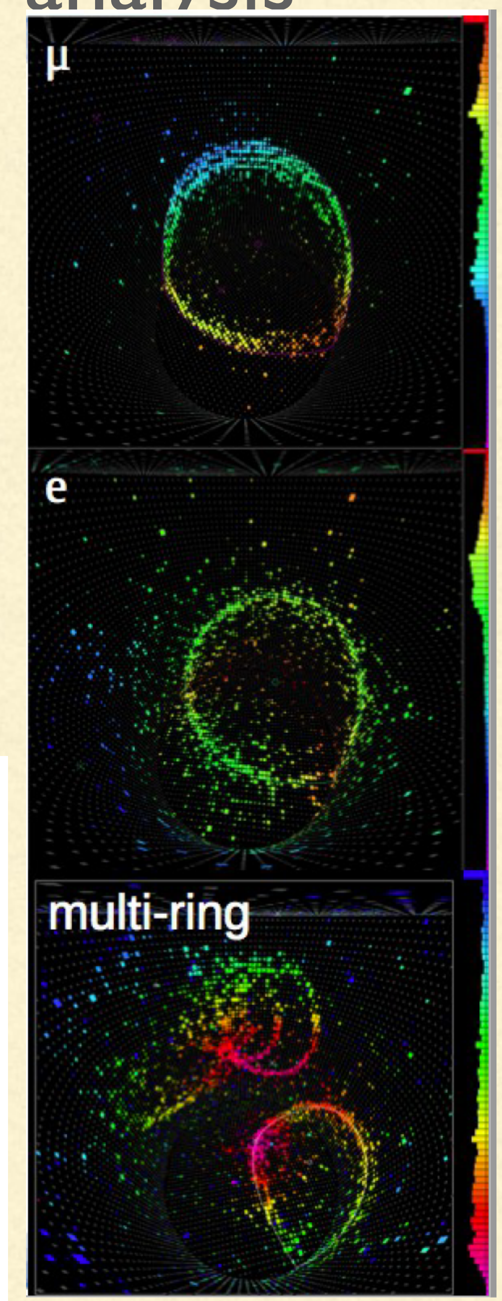
- Independent of PMNS parametrisation
  Stable CPV-preference for different priors

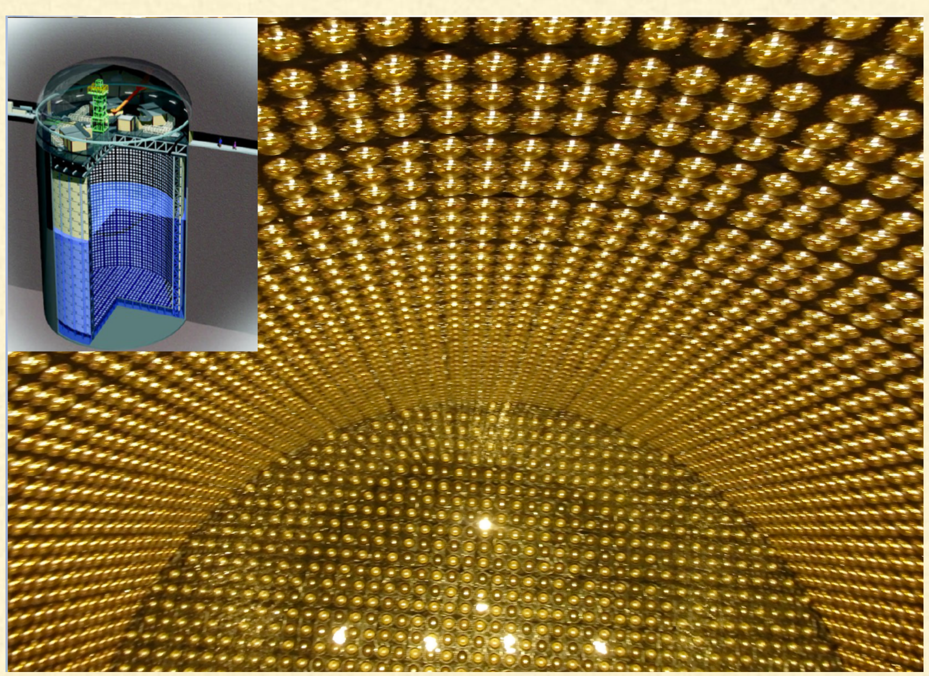
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

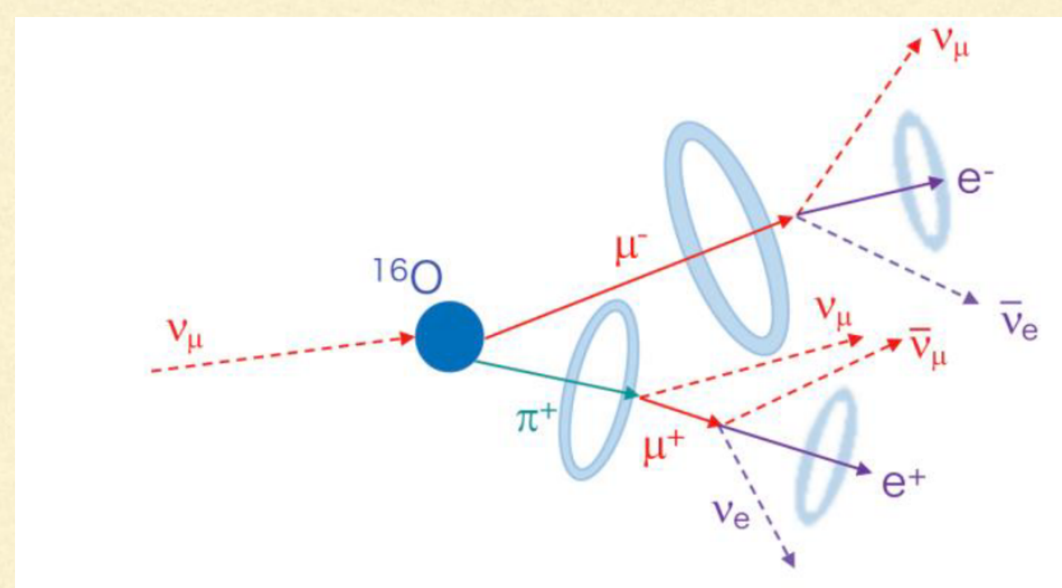
- Total 6 Super-K samples currently used in oscillation analysis



Mode	Sample Name	Description
ν	1Re	One e-like ring in ν mode
	1Re CC1π+	One e-like ring and Michel electron in ν mode
	1Rμ	One μ-like ring in ν mode
	MRμ CC1π+ (Multi-Ring)	Two rings (μ + π) + ME or 1 μ-ring + 2 ME
$\bar{\nu}$	1Re	One e-like ring in $\bar{\nu}$ mode
	1Rμ	One μ-like ring in $\bar{\nu}$ mode



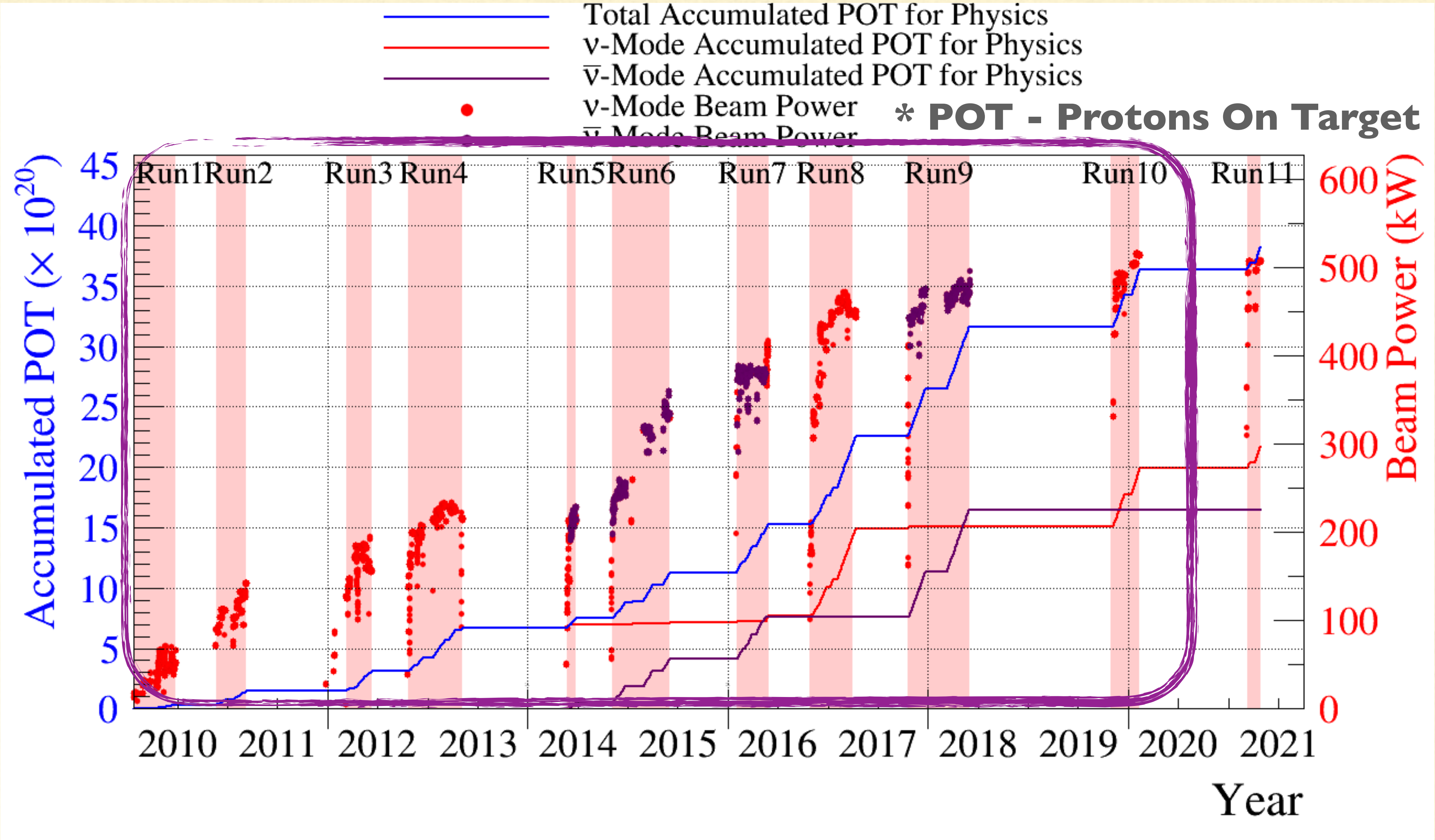




T2K DATA TAKING

2010:
start
operation

FHC
and
RHC
modes



* **POT - Protons On Target**

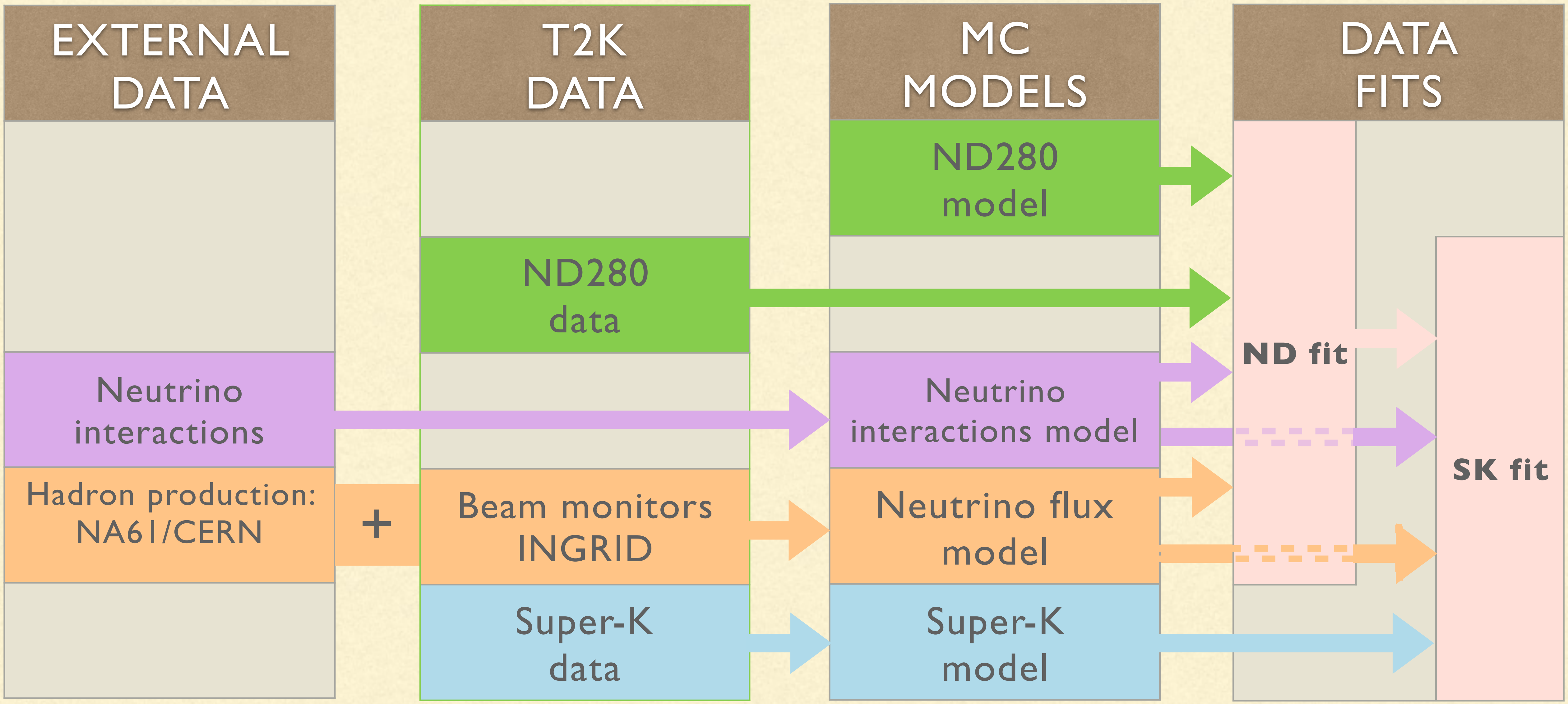
2021:
stable operation at ~500 kW
max 522.6 kW

* **Used for the current results**

23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}

ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

T2K ANALYSIS STRATEGY

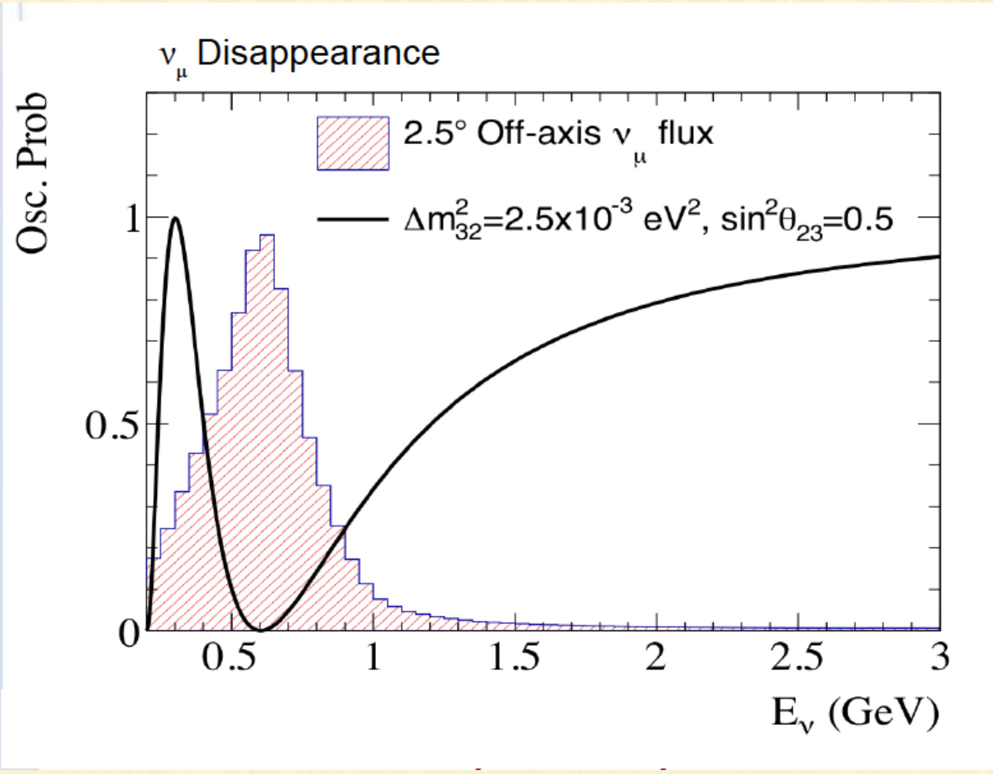


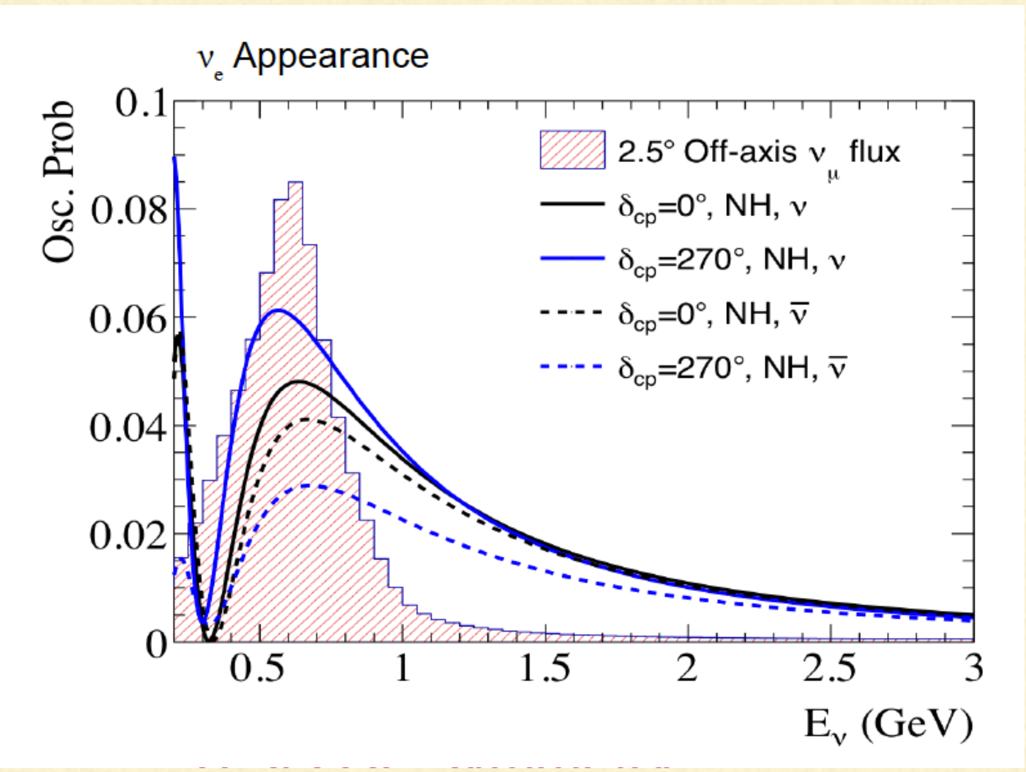
Frequentist lhood fit:
- E_{rec}/ θ_ℓ for (anti)ν_e
- E_{rec} for (anti)ν_μ

Frequentist lhood fit:
- p_ℓ / θ_ℓ for (anti)ν_e
- E_{rec} for (anti)ν_μ

Bayesian with MCMC
- E_{rec} for all samples
- Joint ND and FD fit

NEUTRINO OSCILLATIONS IN T2K





CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

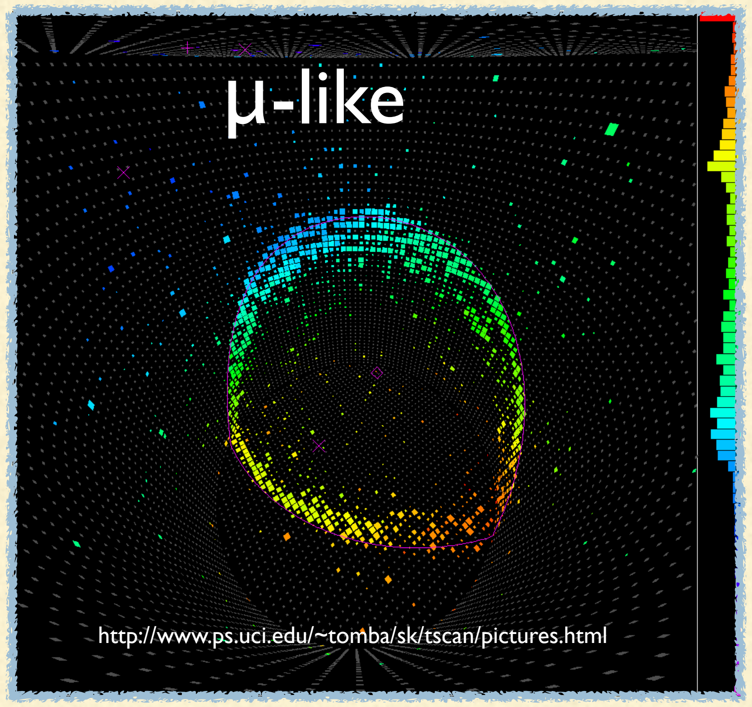
- Test CPT symmetry
- LO dependence on $\sin^2 2\theta_{23}$
    - cannot retrieve octant $\theta_{23}>45°$ vs $\theta_{23}<45°$
- LO dependence on $|\Delta m^2_{23/31}|$
    - not sensitive to mass ordering

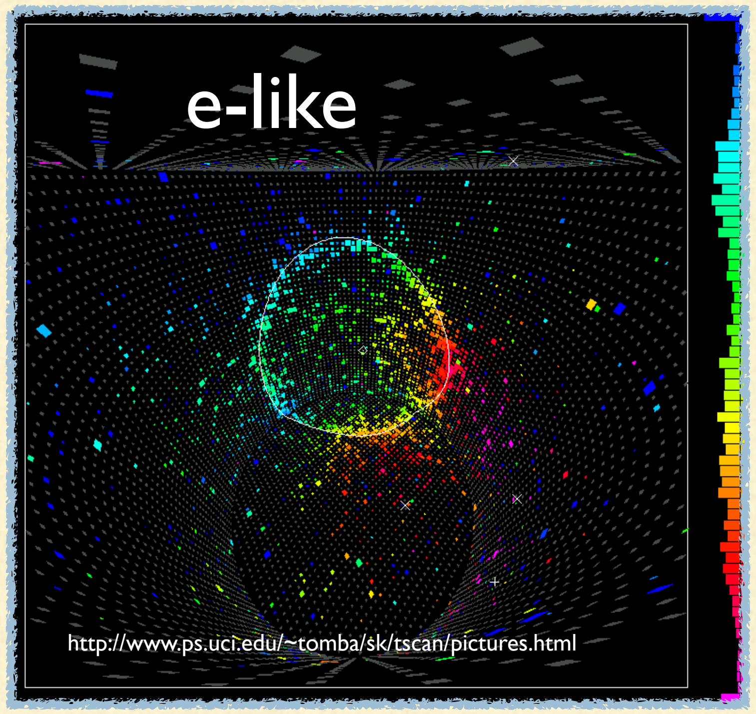
- Test CP symmetry
- LO dependence on $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$
    - can distinguish octant $\theta_{23}>45°$ from $\theta_{23}<45°$
- Sub-leading dependence on $\sin(\delta_{CP})$
    - can probe CPV with ~30% effect
- Sub-leading dependence on $\pm\Delta m^2_{23}$
    - ~10 % matter effect

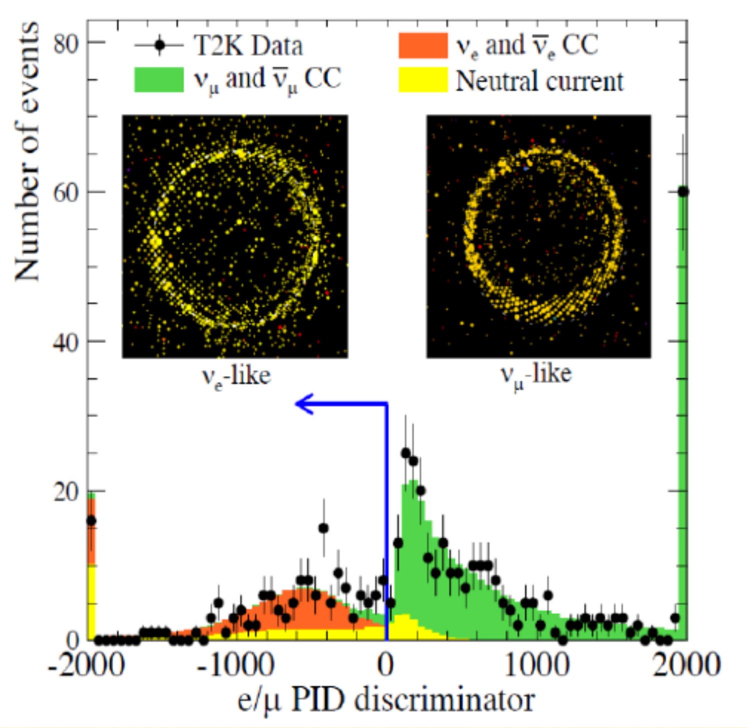
*LO - leading oder

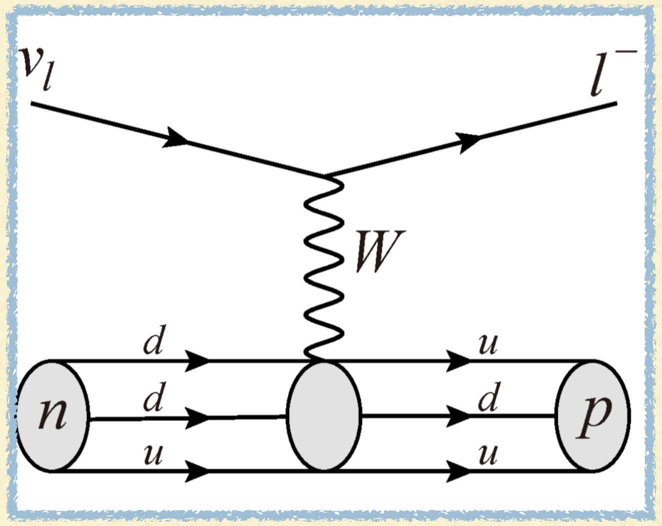
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

- 50 kton water-Cherenkov tank
- Separate e/μ-like rings:
  - <1% misidentified μ as e
- π^0 rejection
- No magnetic field



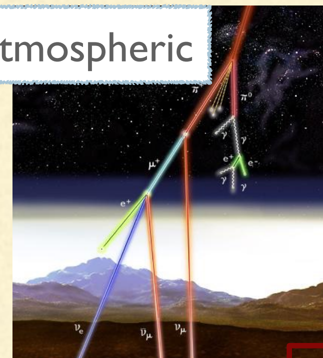


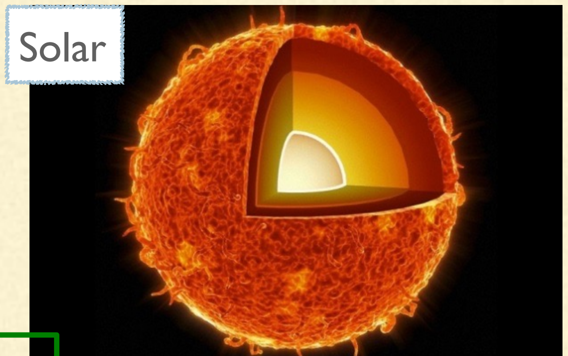




3-FLAVOUR NEUTRINO OSCILLATIONS

Neutrino mixing: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix





$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

$\Delta m^2_{ij} = m^2_i - m^2_j$

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

Oscillations governed by * PDG 2022

- three mixing angles:
  - $\theta_{12} \approx 34^\circ$, $\theta_{13} \approx 9^\circ$, $\theta_{23} \approx 48^\circ$ (41-51 within 3σ)
- two mass squared differences:
  - $\Delta m^2_{21} \approx 7.4 \times 10^{-5}$ eV^2 and $|\Delta m^2_{32}| \approx 2.5 \times 10^{-3}$ eV^2
- source-detector baseline and neutrino energy

Open questions:

- CP-violation in lepton sector? δ_{CP} value?
- Mass hierarchy(MH), "normal" (NH) or "inverted"(IH):
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$?
- Octant of θ_{23}: <, > or = 45°?
- Dirac/Majorana, steriles, Lorentz violation, CPT…

Credit to APS

The Growing Excitement of Neutrino Physics

- ✧ 1930: On-paper appearance as "desperate" remedy by W. Pauli
- ✧ 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- ✧ 1962: ν_μ existence confirmed by Lederman *et al.*
- ✧ 1998: Atmospheric neutrino oscillations discovered by Super-K
- ✧ 2000: ν_τ first evidence reported by DONUT experiment
- ✧ 2001: Solar neutrino oscillations detected by SNO (KamLAND 2002)
- ✧ 2011: $\nu_\mu \to \nu_\tau$ transitions observed by OPERA
- ✧ 2011-13: $\nu_\mu \to \nu_e$ by T2K, $\bar{\nu}_e \to \bar{\nu}_e$ deficit observed by Daya Bay(2012)
- ✧ 2015: Nobel prizes for ν oscillations, Breakthrough prize (2016)

Nobel & Breakthrough for ν oscillations

T2K observe $\nu_\mu \to \nu_e$ appearance

Daya Bay observe theta 13 at 5 sigma

K2K confirms atmospheric oscillations

KamLAND confirms solar oscillations

Nobel Prize for neutrino astroparticle physics!

SNO shows solar oscillation to active flavor

Super K confirms solar deficit and "images" sun

Super K sees evidence of atmospheric neutrino oscillations

Nobel Prize for ν discovery!

LSND sees possible indication of oscillation signal

Nobel Prize for discovery of distinct flavors!

Kamioka II and IMB see supernova neutrinos

Kamioka II and IMB see atmospheric neutrino anomaly

SAGE and Gallex see the solar deficit

LEP shows 3 active flavors

Kamioka II confirms solar deficit

Pauli predicts the Neutrino

Fermi's theory of weak interactions

Reines & Cowan discover (anti)neutrinos

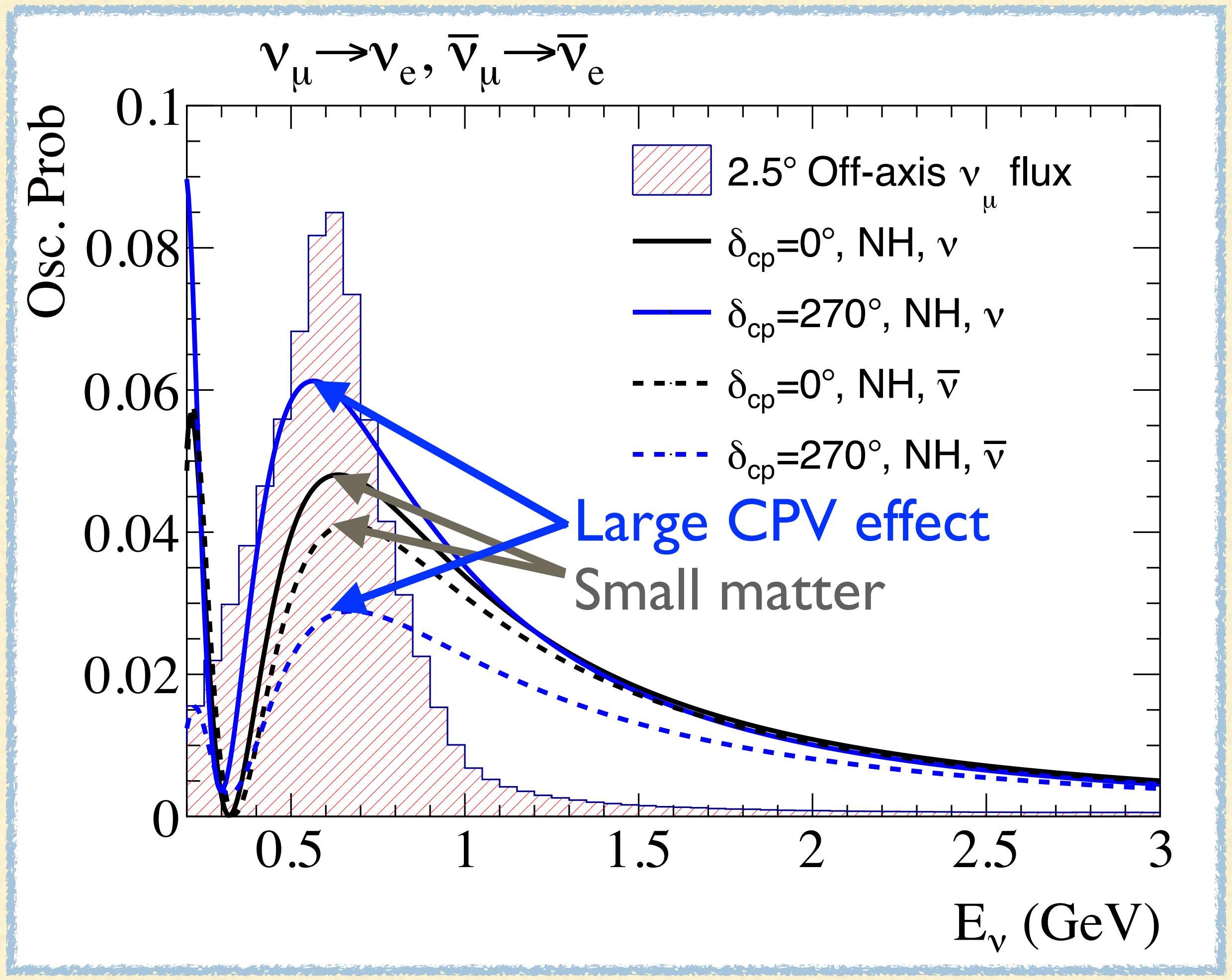
2 distinct flavors identified

Davis discovers the solar deficit

1930 — 1955 — 1980 — **2015**

NEUTRINO OSCILLATIONS IN T2K

δ_{CP} and mass hierarchy (MH) both cause differences in ν and anti-ν oscillations

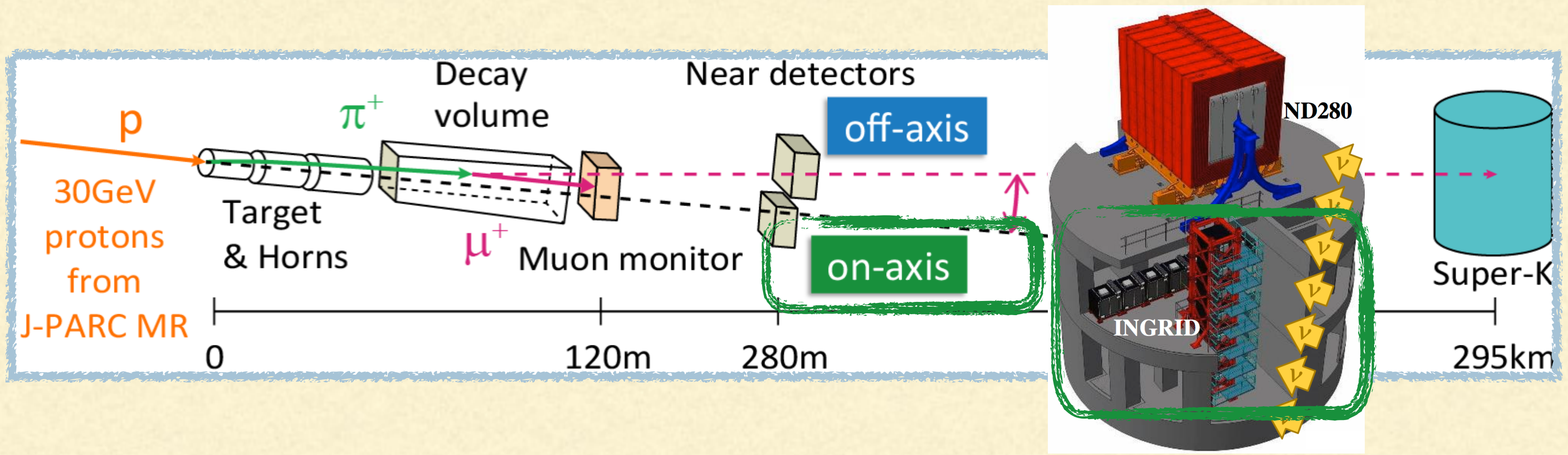


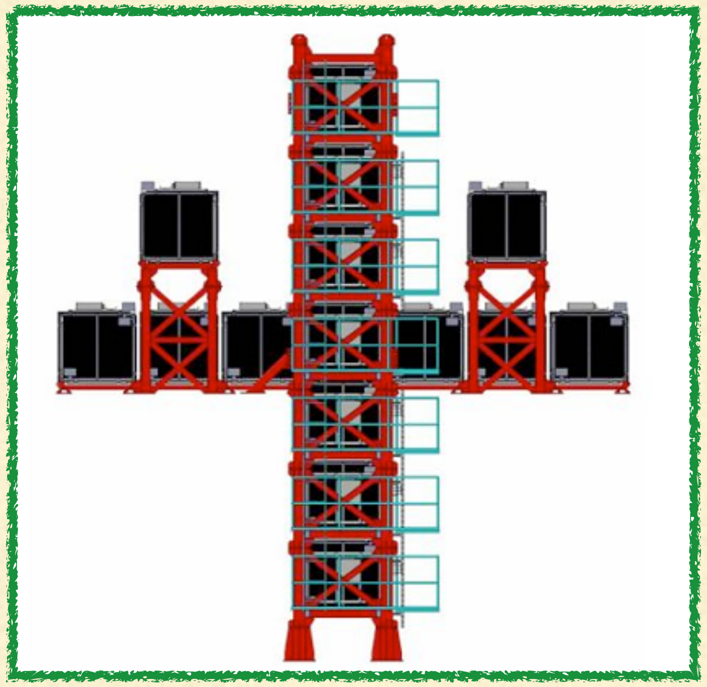
CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

At T2K baseline (L~295km, E~0.6GeV):

- CPV: ≈ ±30% effect
- Mass hierarchy: ≈ ±10% effect

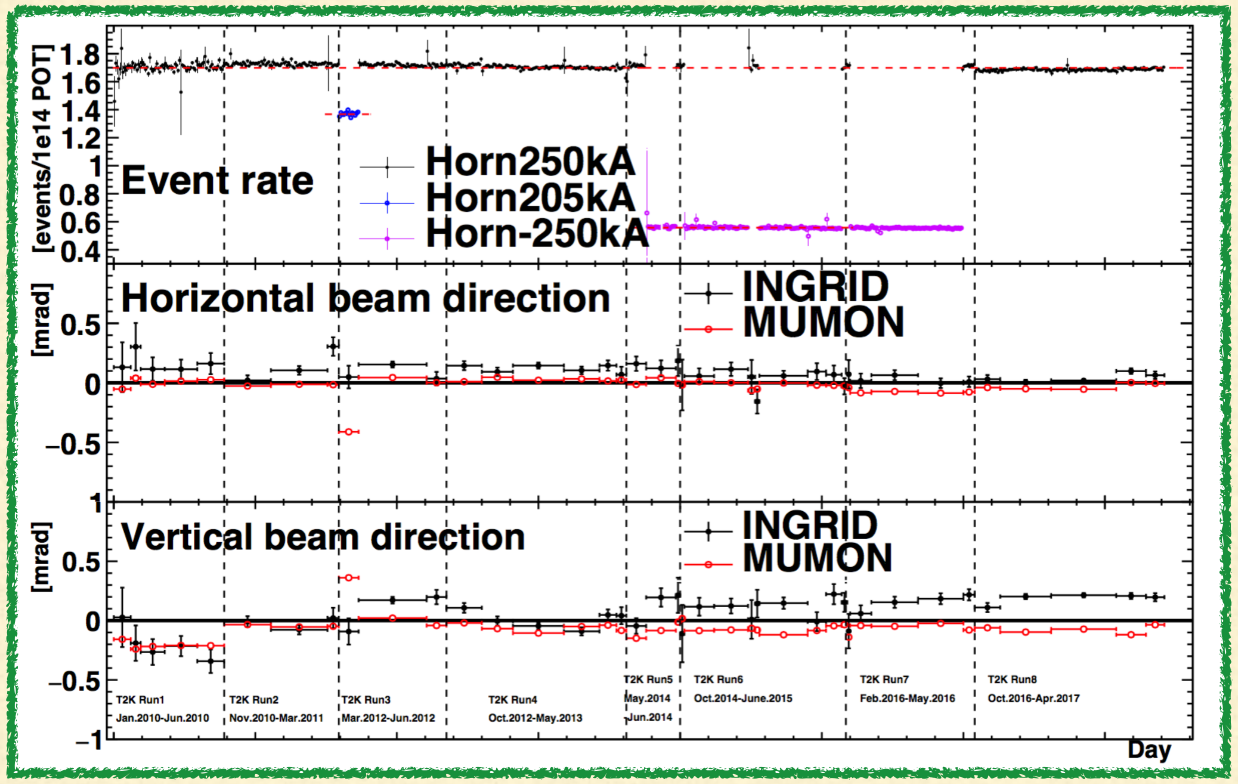
ON-AXIS NEAR DETECTOR INGRID



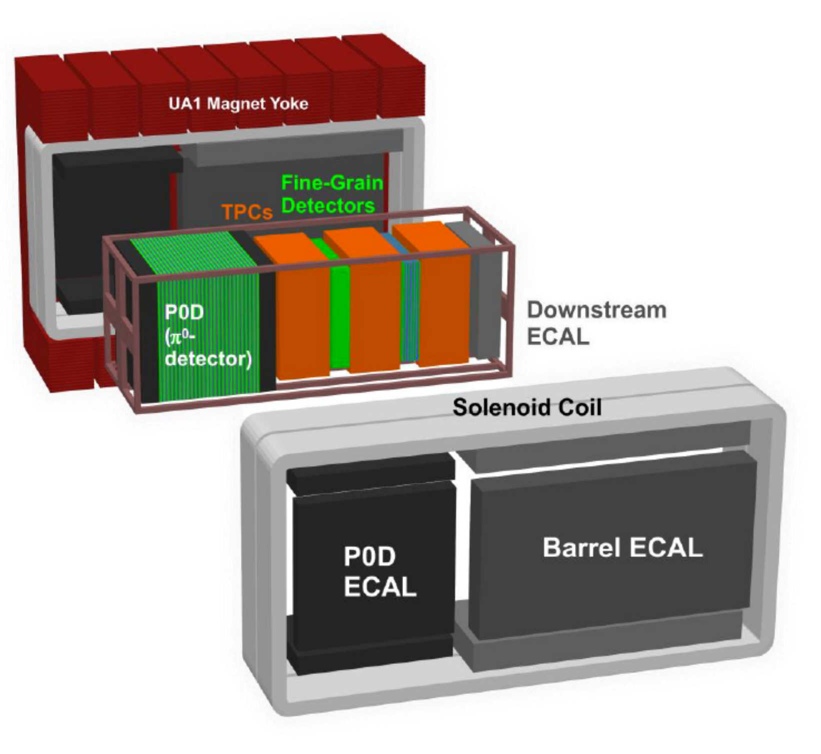


- T2K utilises off-axis neutrino beam:
  - Important to monitor beam intensity and direction

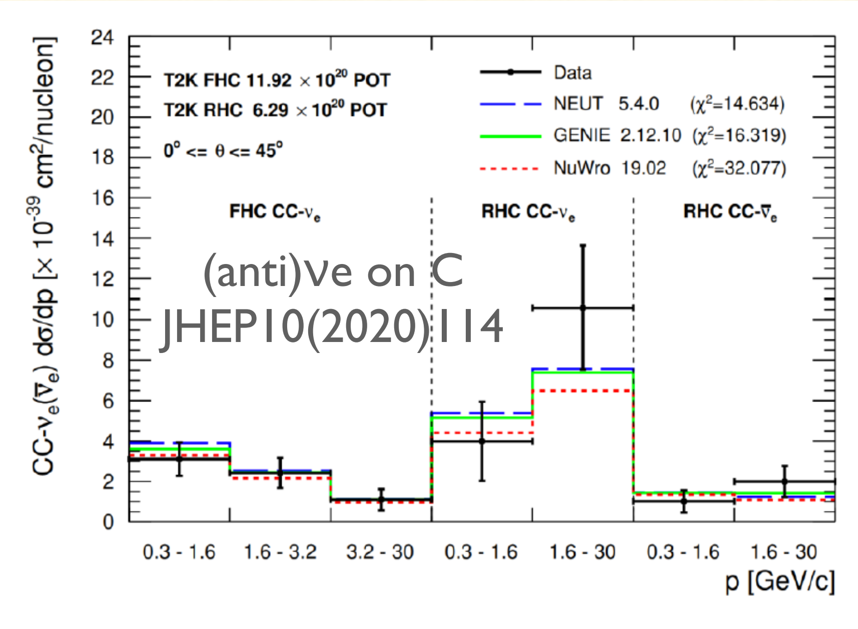
- Iron/scintillator detector to measure beam profile and rate
- Day-by-day monitoring
- Direction stable within 1 mrad (~2% shift in peak energy)

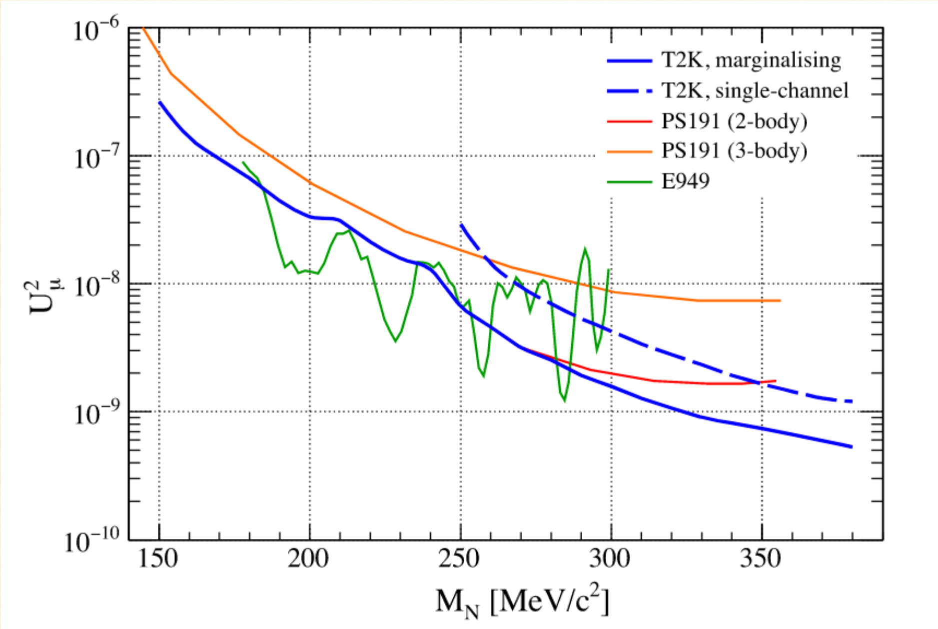


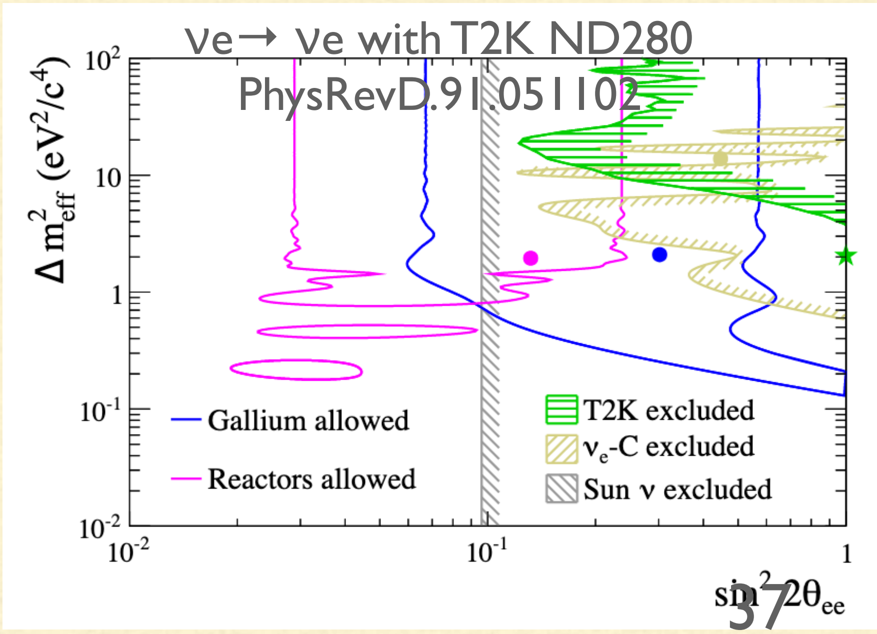
ANALYSES WITH T2K ND280



- Constrain flux and ν interaction model parameters prior to oscillations
- 30 GeV protons on C target, intense ν beam from π/K + complex detector →
- **Rich opportunities for physics** measurements:
  - Neutrino cross-sections
  - New physics signals
    - Light-sterile neutrinos with SBL oscillations
    - Heavy neutral leptons M ~ O(1 GeV)
  - Dark-photon/LDM signals







SYSTEMATIC UNCERTAINTIES

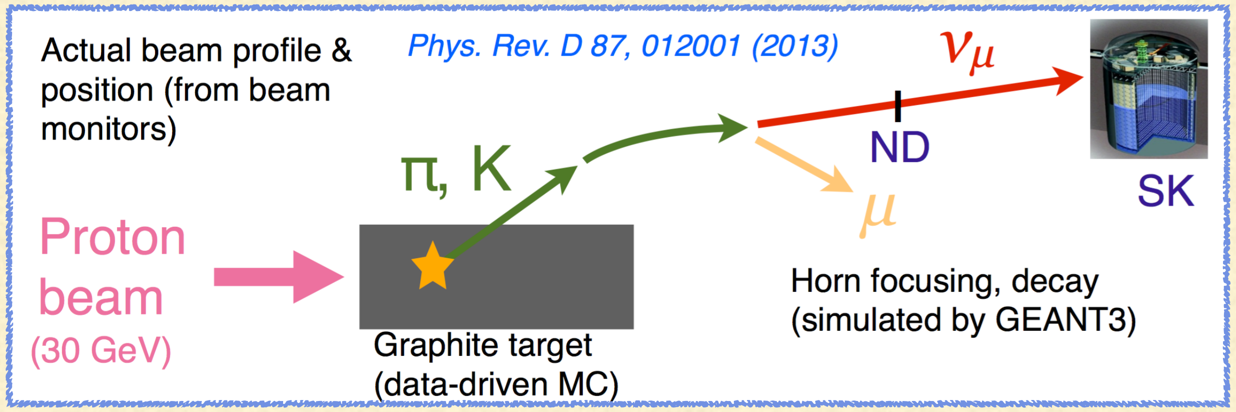
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6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

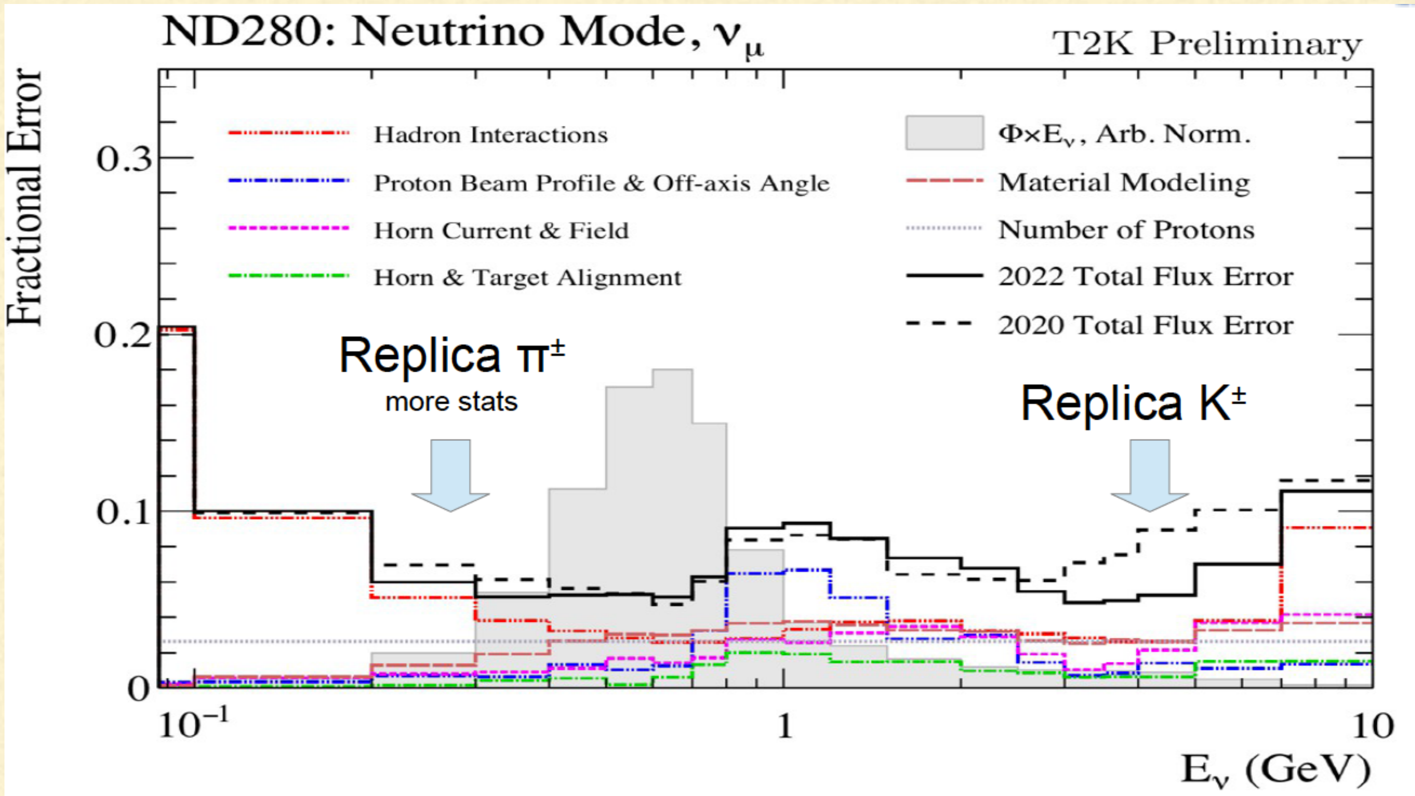
- Numbers quoted are the RMS of the predicted numbers of events in the far detector sample obtained when varying systematic parameters according to their prior distribution
- Some systematic parameters do not have a prior constraint, and can end up having larger effect than estimated with this method in a fit

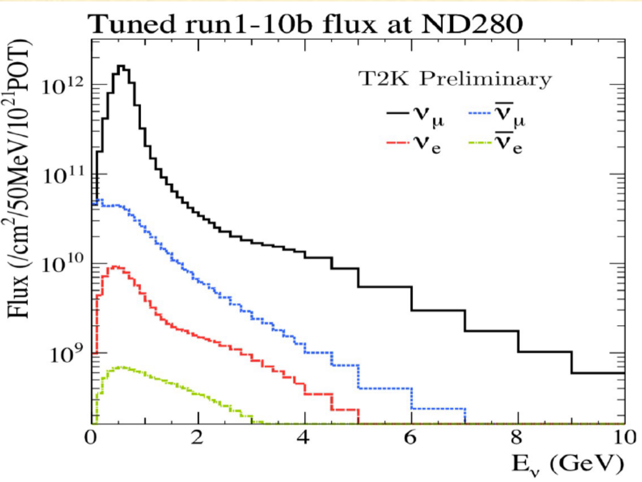
T2K NEUTRINO FLUX PREDICTION AND UNCERTAINTIES

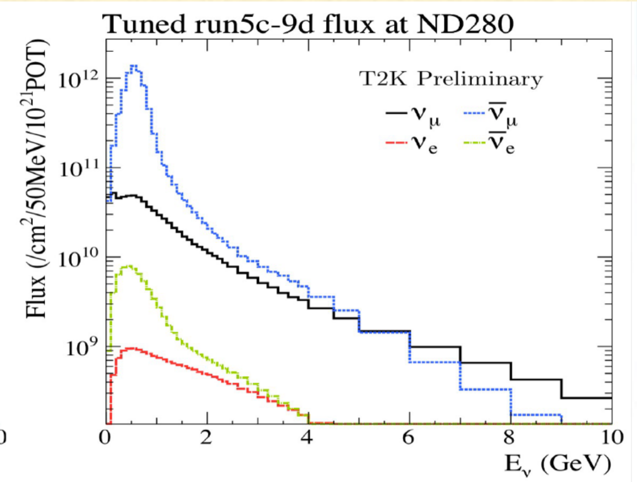
- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
- UPDATE: moved from 2009[1] T2K replica target data to 2010[2] one
  - more statistics for $\pi^{\pm}$ production.
  - adds $K^{\pm}$ and p data.
- Intrinsic ν_e background at ~0.4% level

1 Eur. Phys. J. C76, 617 (2016)
2 Eur. Phys. J. C79, 100 (2019)





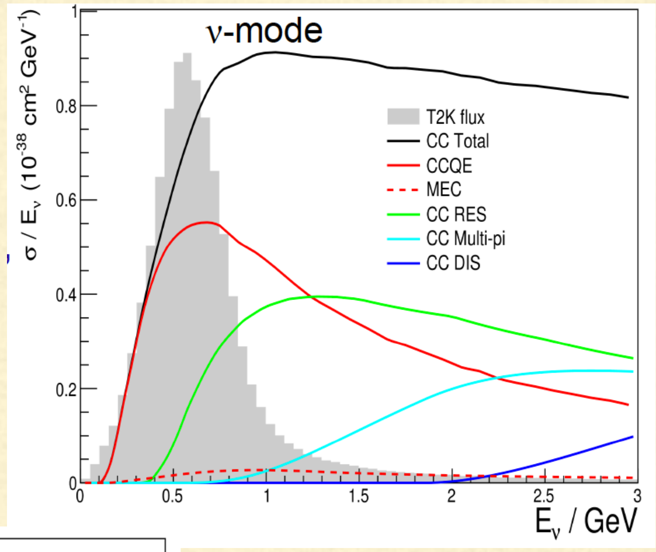


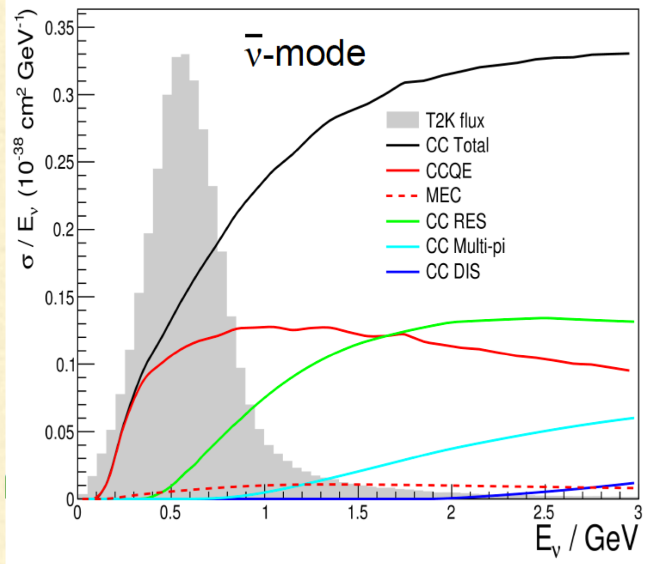


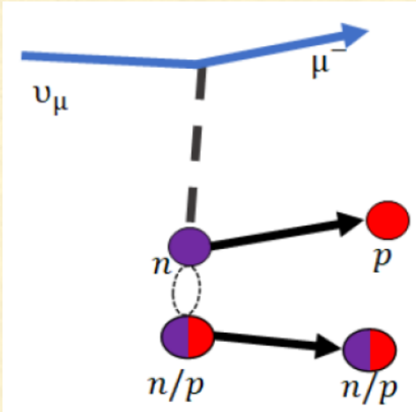
T2K NEUTRINO INTERACTION MODELLING

- **NEUT generator tuned to external data** from MiniBooNE, MINERνA, bubble chambers, etc
- **CCQE dominant @ T2K energies**
- **Updates: Charge Current Quasi Elastic (CCQE)**
  - Expanded parameterization of the spectral function
  - Normalization of each nuclear shell for Mean Field (**MF**)
  - Normalization of Short Range Correlations (**SRC**)
  - Added Pauli Blocking to give more freedom in low Q2 region
- **Updates: 2p2h/MEC**
  - Better description of 2p2h pn/nn pairs contribution
- **Updates: other**
  - New tune of bubble chamber data to resonance model parameters
  - New resonance decay uncertaintiesEffective inclusion of binding energy for Resonant channel
  - New Nucleon Final State Interactions (FSI) uncertainty
  - New multi-π uncertainty varying shape of hadronic mass and π-multiplicity

T2K uses the **NEUT neutrino nucleus interaction simulation** to model this
The European Physical Journal Special Topics **volume 230**, pages 4469–4481 (2021)
See our NuFact 2022 talk on NEUT for details!

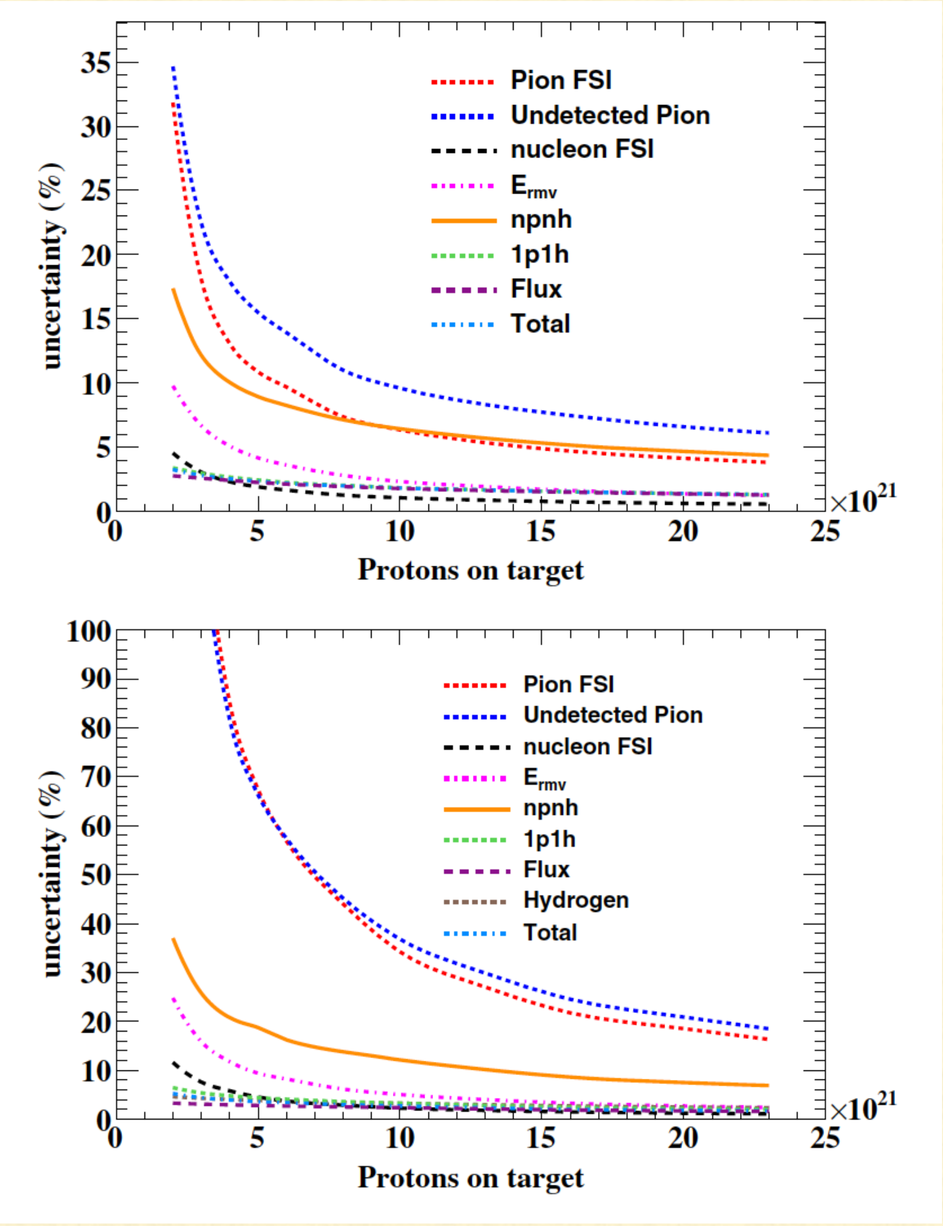


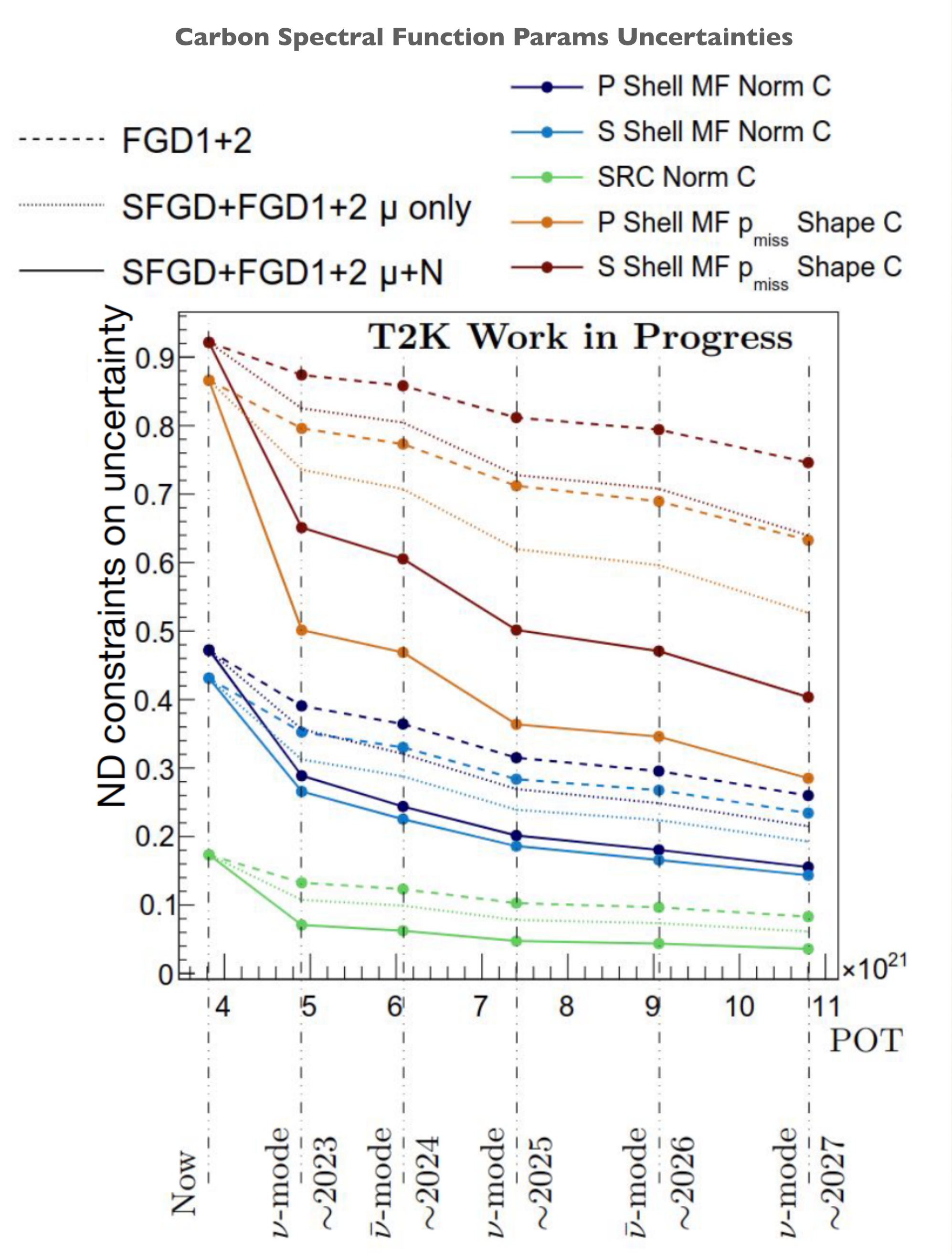




PHYSICS WITH T2K & ND280 UPGRADE: OSCILLATION ANALYSIS

Sensitivity to nuclear model parameters





Phys. Rev. D 105,032010