RECENT RESULTS FROM THE T2K NEUTRINO EXPERIMENT AND FUTURE PERSPECTIVES

T2K

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on behalf of the T2K Collaboration

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Quy Nhon, Vietnam

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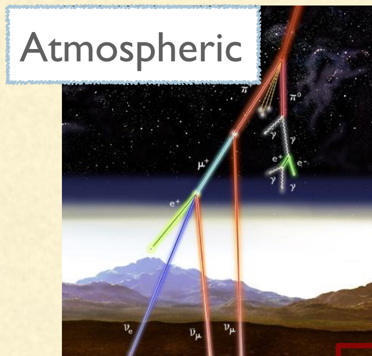
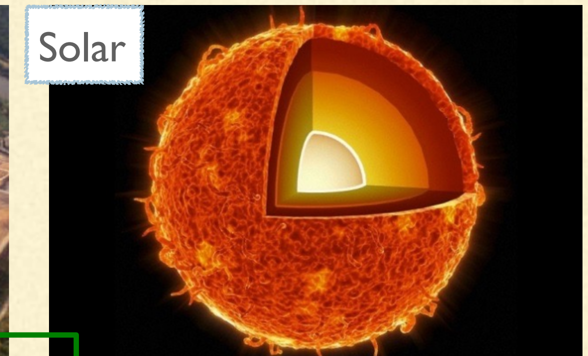
3-FLAVOUR NEUTRINO OSCILLATIONS

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





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

$\Delta m_{ij}^2 = m_i^2 - m_j^2$

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

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 3$\sigma$)
- two mass squared differences:
  - $\Delta m^2_{21}\approx 7.4\mathrm{x}10^{-5}\mathrm{eV}^2$ and $|\Delta m^2_{32}|\approx 2.5\mathrm{x}10^{-3}\ \mathrm{eV}^2$
- 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…

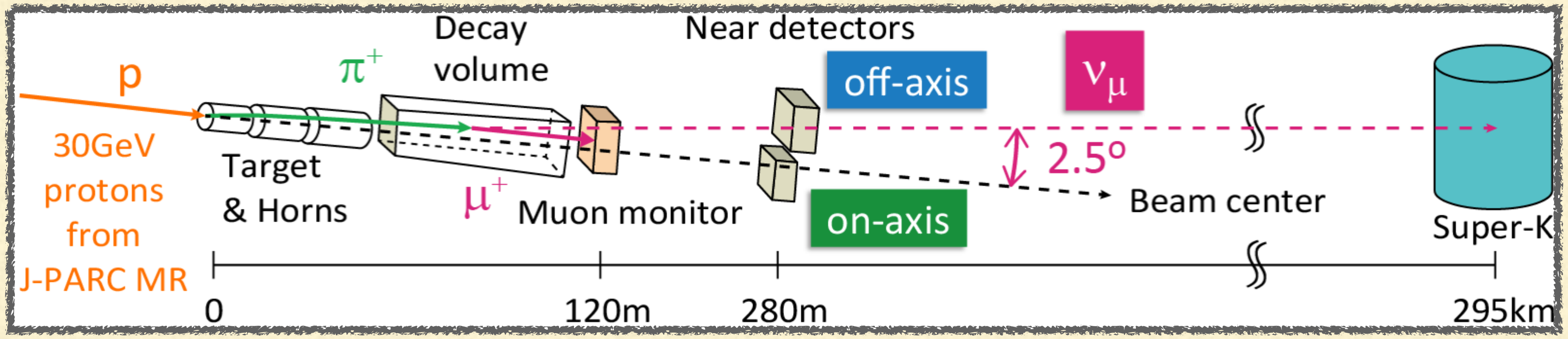
T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

- World-leading neutrino physics project

Taking data since 2010

- T2K — long-baseline neutrino oscillation accelerator experiment in Japan
- International collaboration:
    - ~500 members, 13 countries, 76 institutes

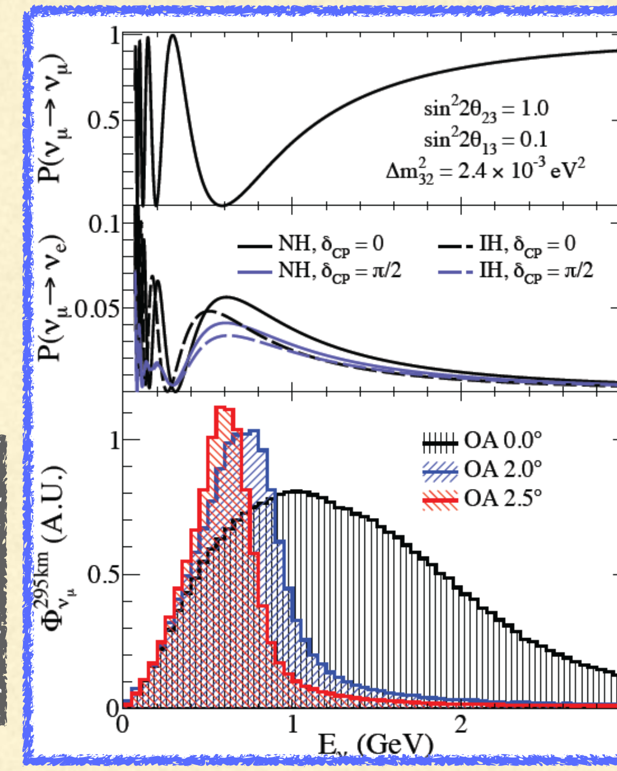
T2K DESIGN



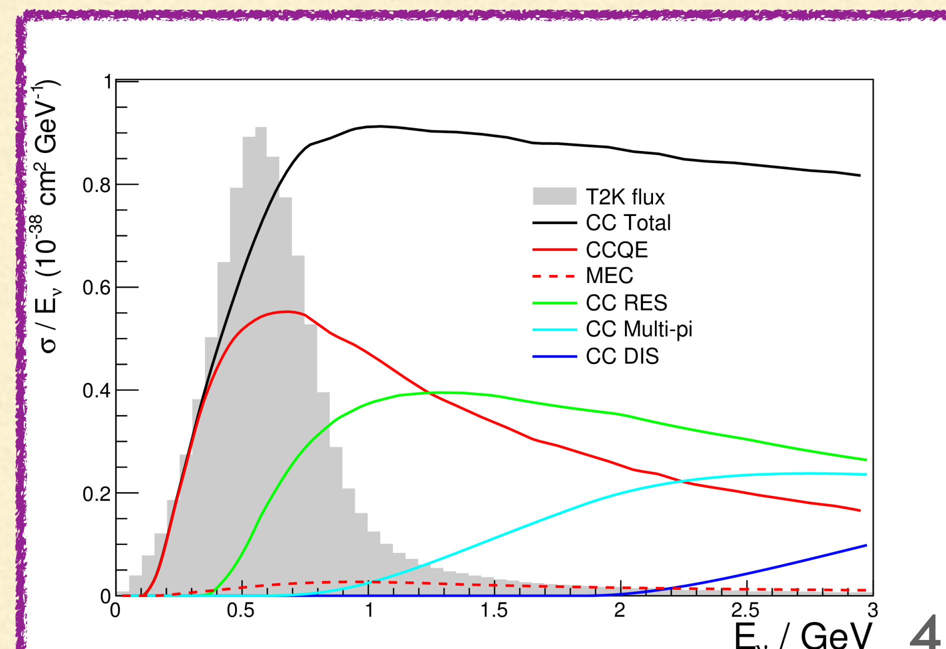
$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

Observable | Flux | Cross section | Detector response

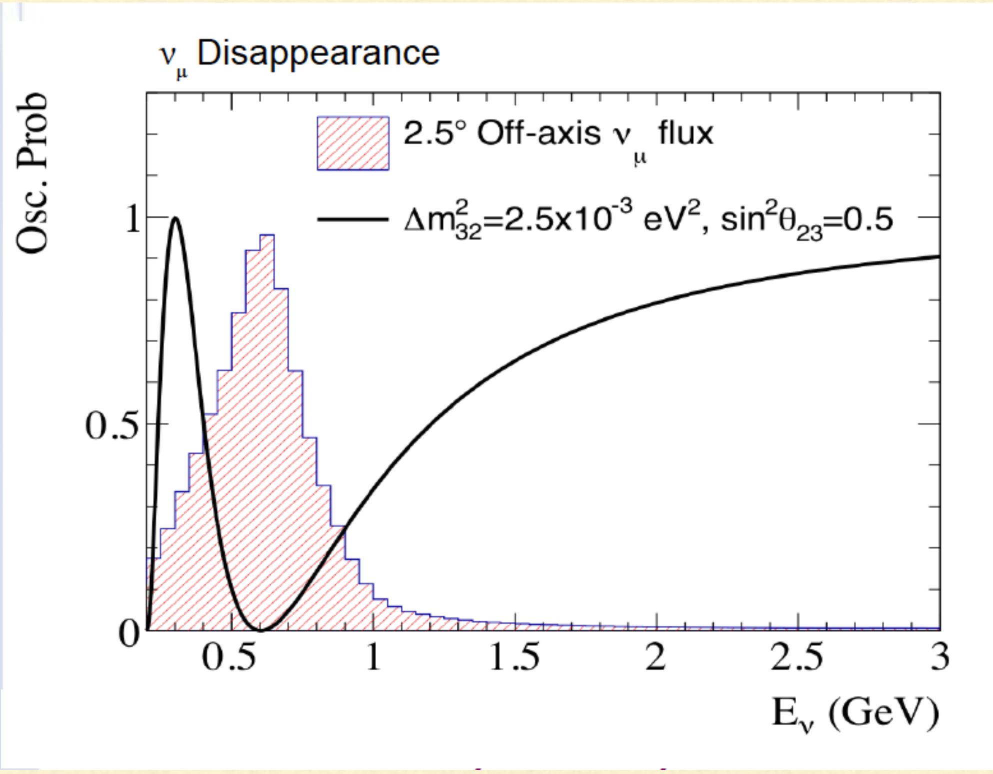
$$N_{FD} \sim \Phi_{FD} \cdot \sigma_{FD} \cdot \epsilon_{FD} \cdot P_{Osc}$$

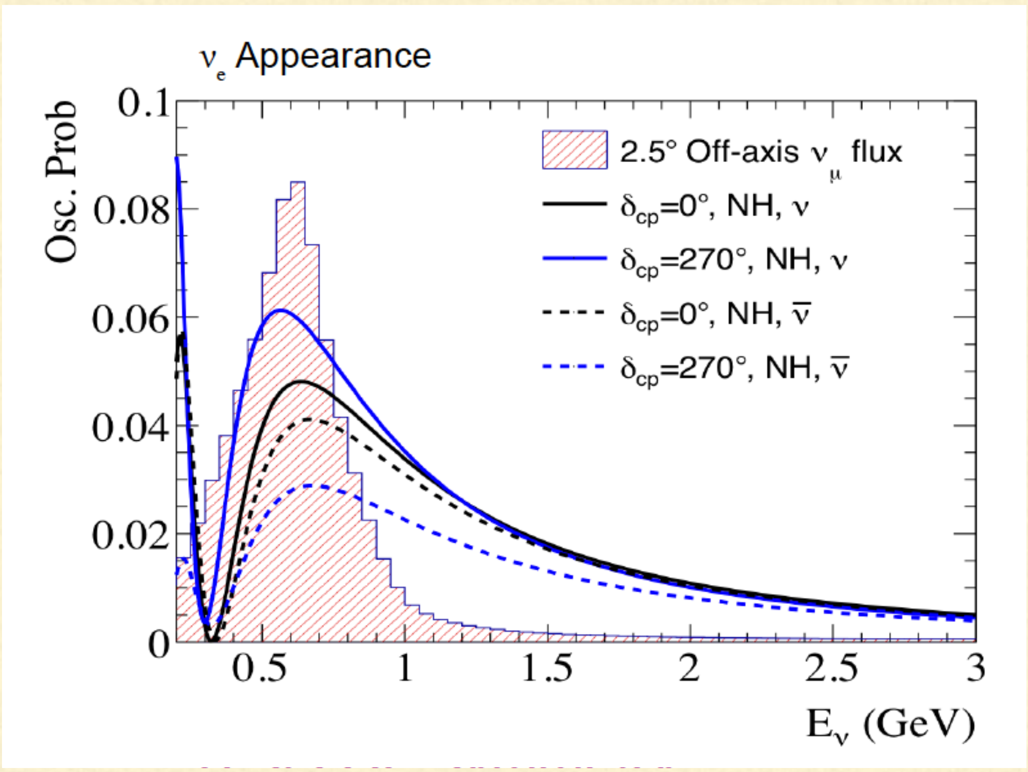


- Near and Far detectors
- **Off-axis (anti)muon-neutrino beam**
- **Energy peaked at oscillation maximum (E~0.6 GeV)**
- ν_μ neutrino and antineutrino enhanced modes via horn polarity switching: Forward and Reversed Horn Currents **FHC** and **RHC** running modes
- Dominant process for ν detection: charged-current quasi-elastic interactions (CCQE)
- **Reduced intrinsic ν_e contamination (≲0.5%)**
- **Reduced backgrounds from high-energy tail**



NEUTRINO OSCILLATIONS IN T2K





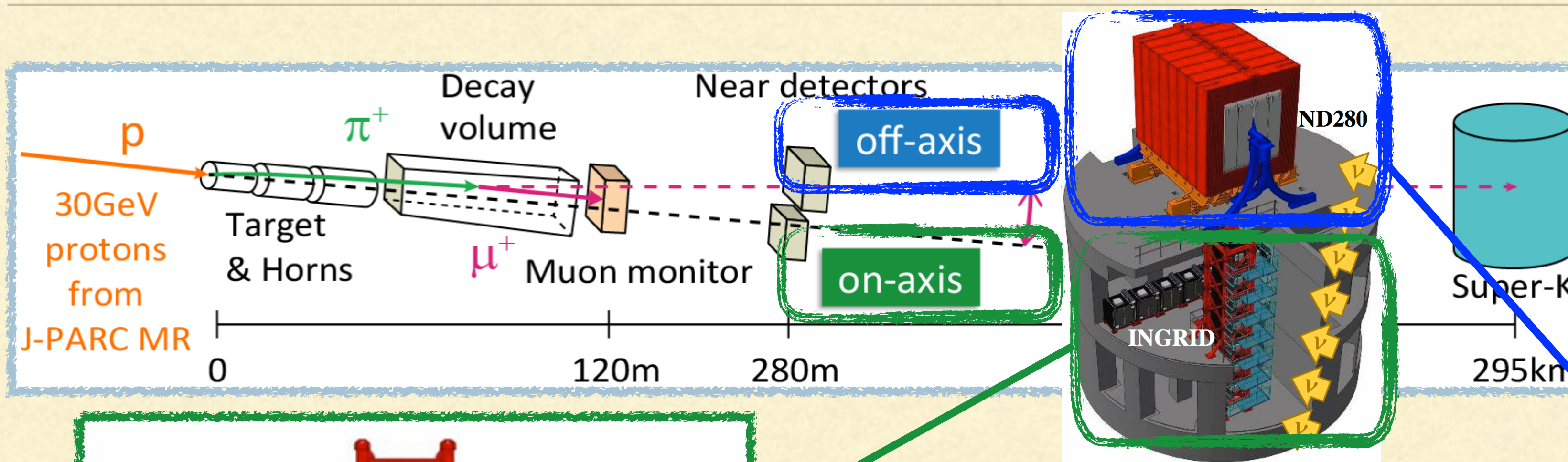
CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

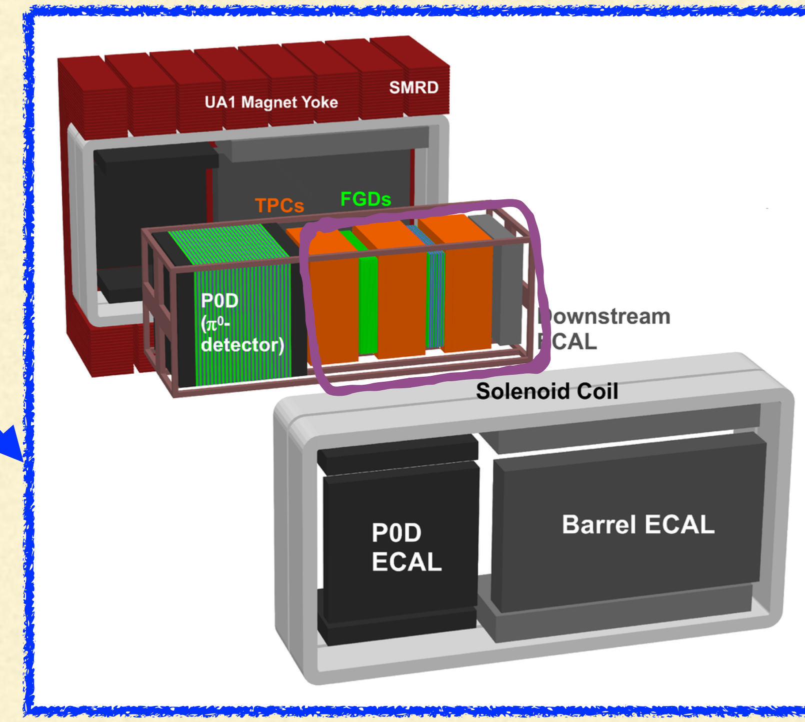
- Test CPT symmetry
- LO dependence on $\sin^2 2\theta_{23}$
  - cannot retrieve octant $\theta_{23}>45°$ vs $\theta_{23}<45°$
- LO dependence on $|\Delta m^2_{23/31}|$
  - not sensitive to mass ordering

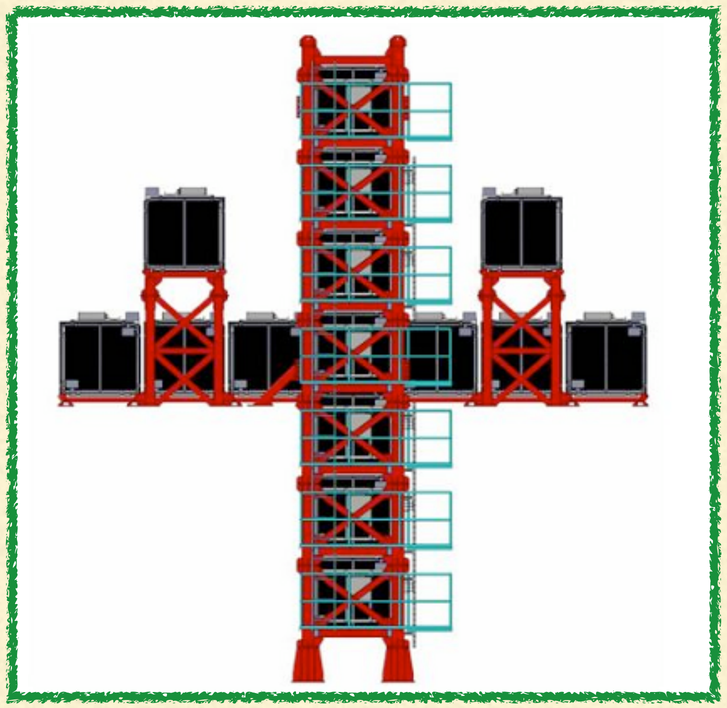
- Test CP symmetry
- LO dependence on $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$
  - can distinguish octant $\theta_{23}>45°$ from $\theta_{23}<45°$
- Sub-leading dependence on $\sin(\delta_{CP})$
  - can probe CPV with ~30% effect
- Sub-leading dependence on $\pm\Delta m^2_{23}$
  - ~10 % matter effect

*LO - leading oder

NEAR DETECTOR COMPLEX

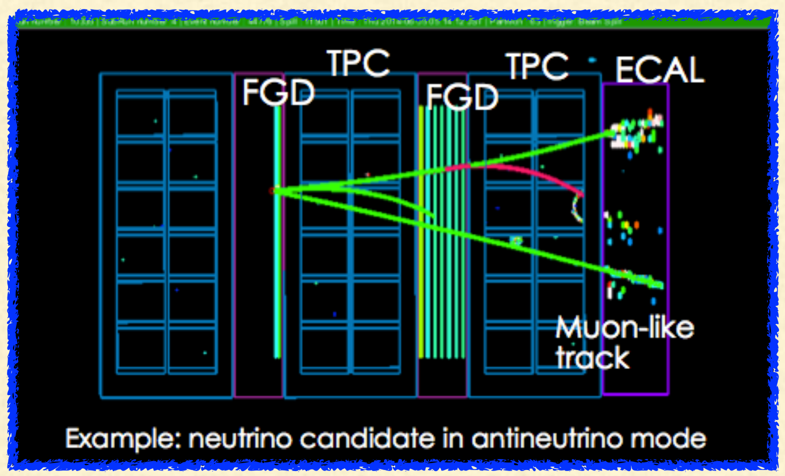


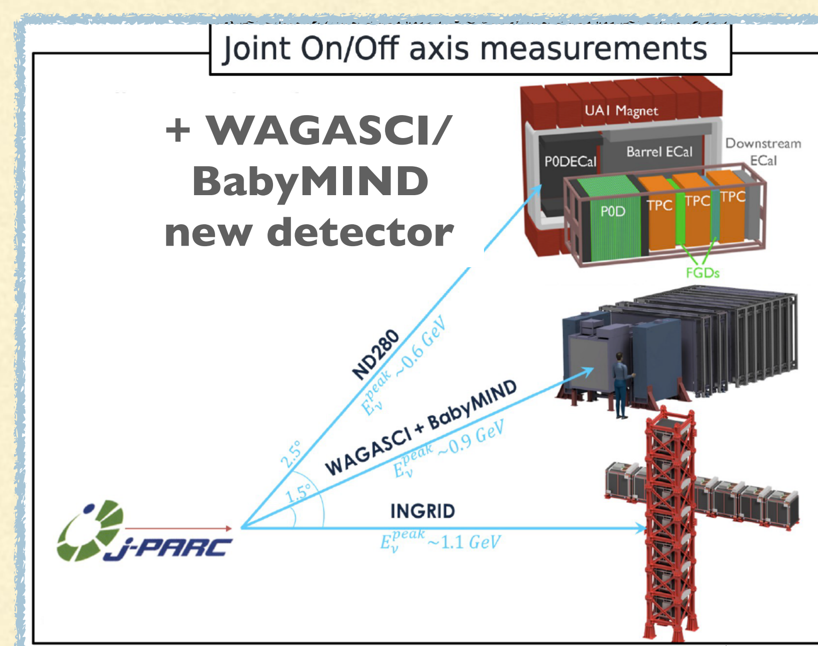




- Off-axis detector ND280
- Detectors in 0.2 T B field
- Tracker:
  - Time projection chambers
  - Scintillator fine-grained detectors

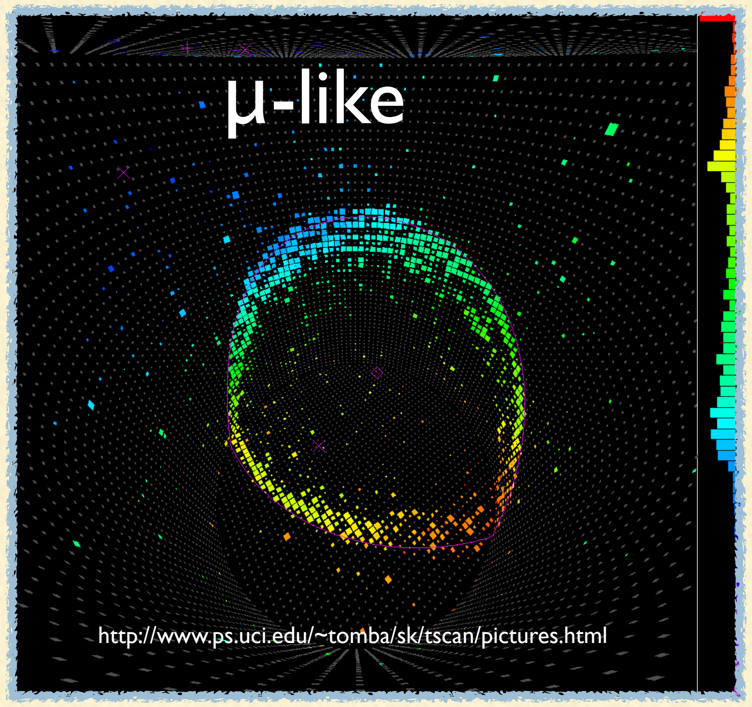
- On-axis detector INGRID
- Iron-scintillator layers
- Day-by-day monitoring of the ν beam position and rate

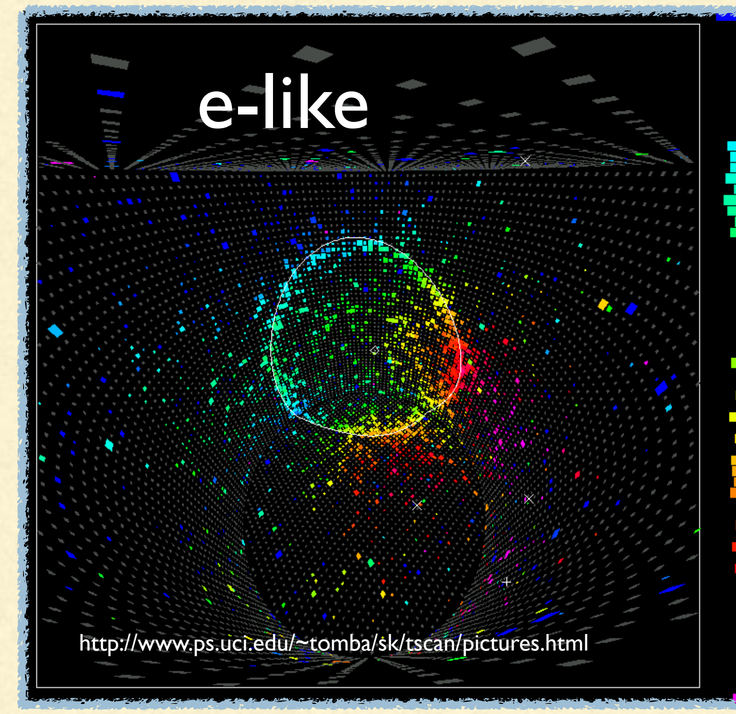


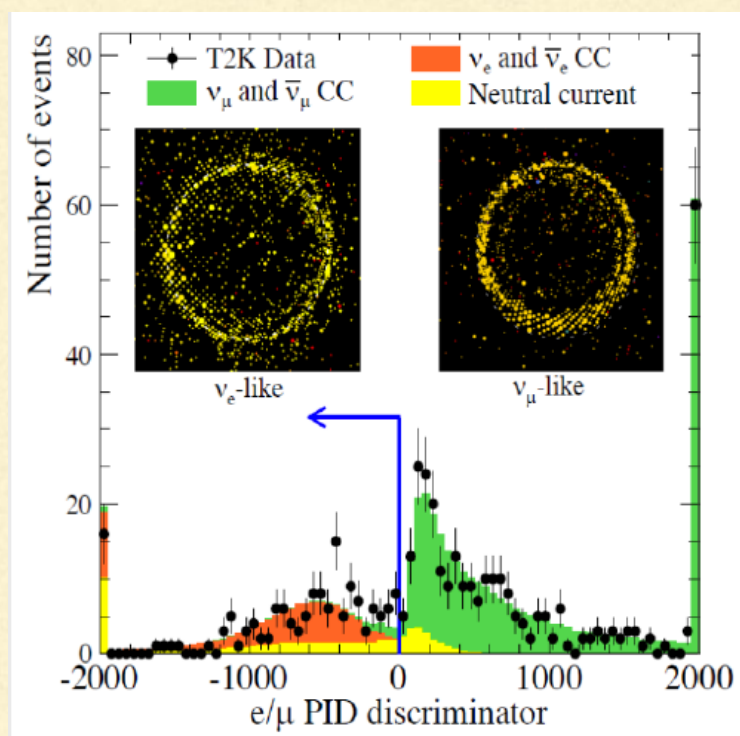


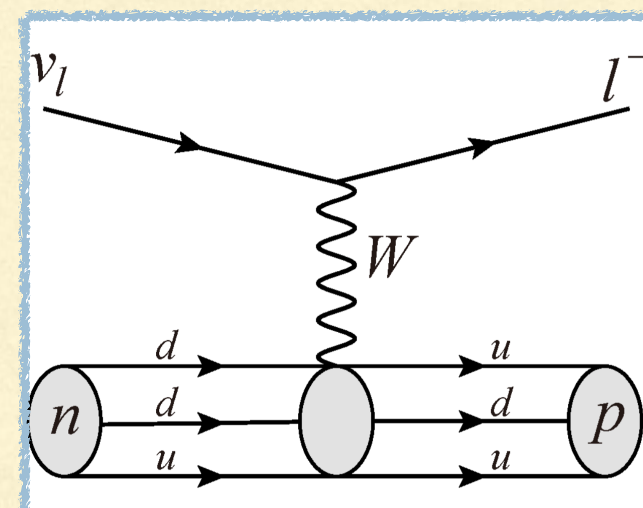
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

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

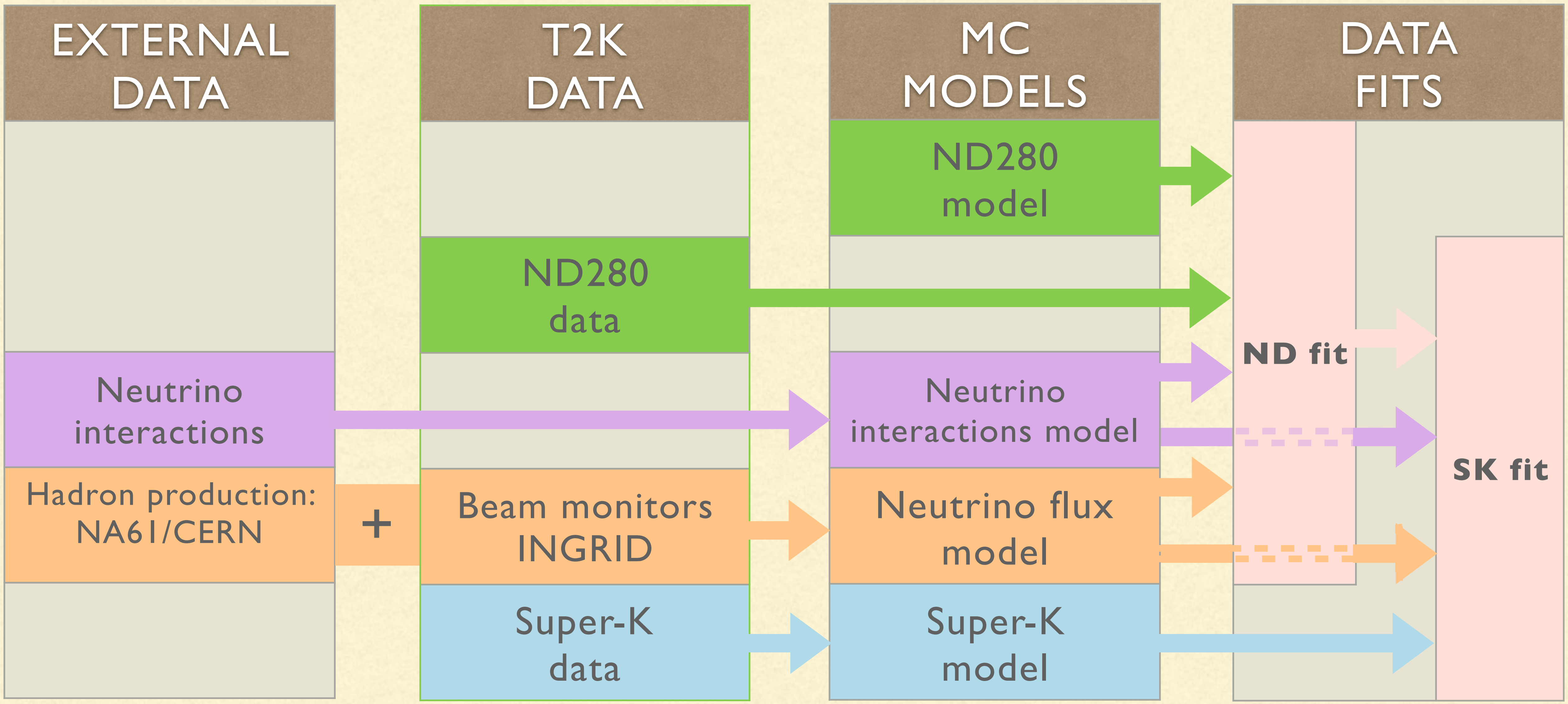








T2K ANALYSIS STRATEGY



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

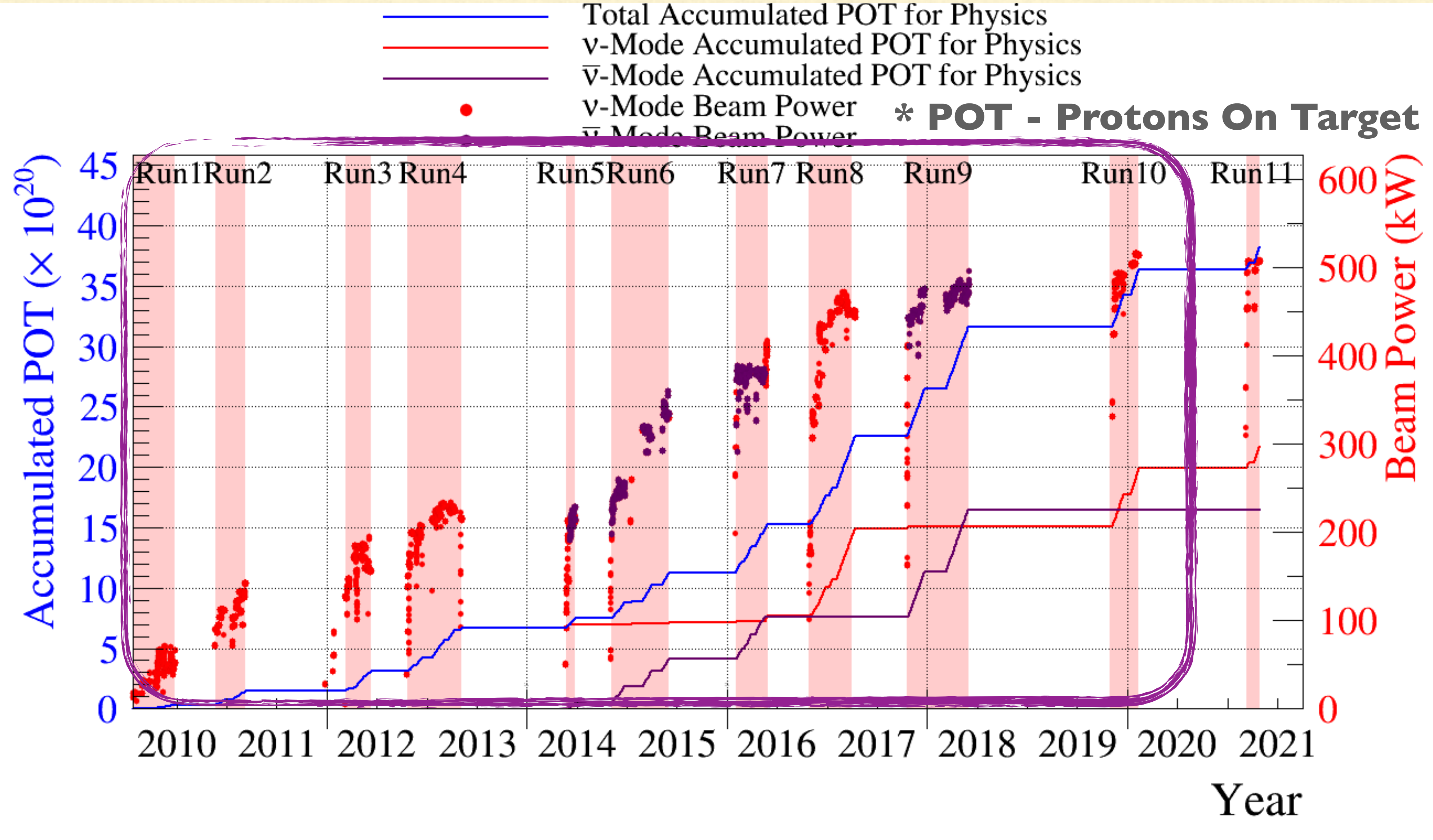
Bayesian with MCMC

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

T2K DATA TAKING

2010: start operation

FHC and RHC modes



*** POT - Protons On Target**

2021: **stable operation at ~500 kW max 522.6 kW**

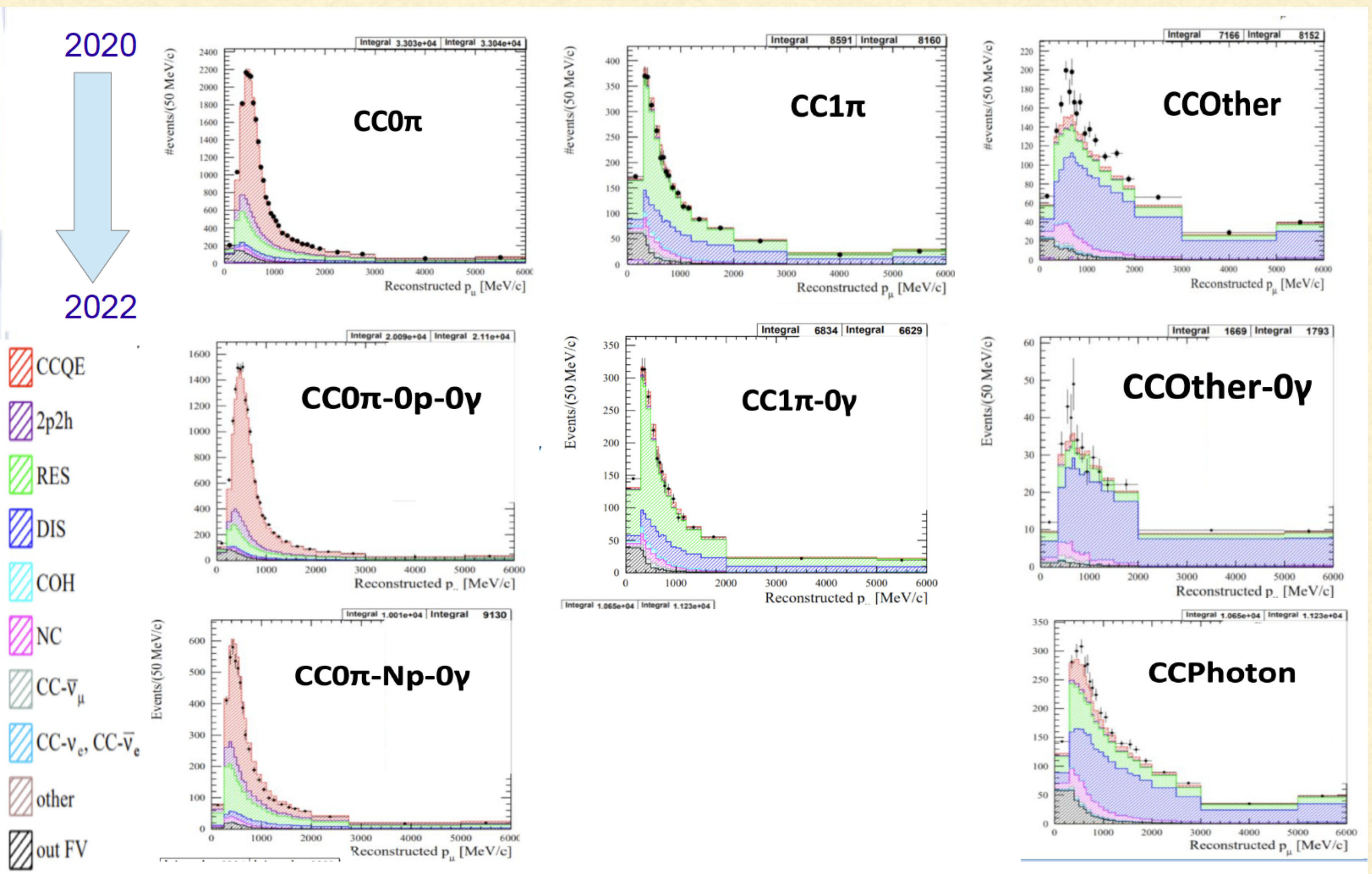
*** Used for the current results**

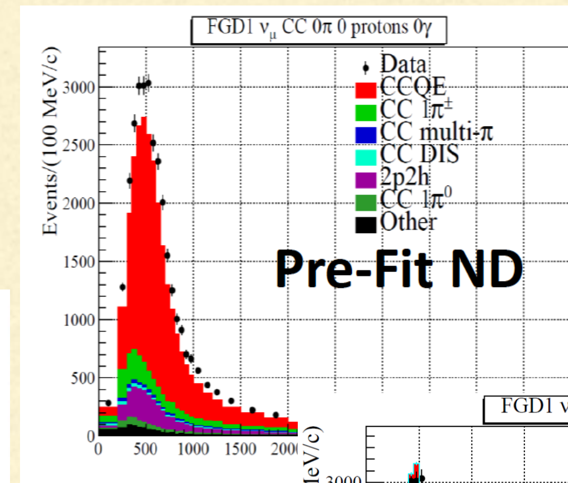
23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}

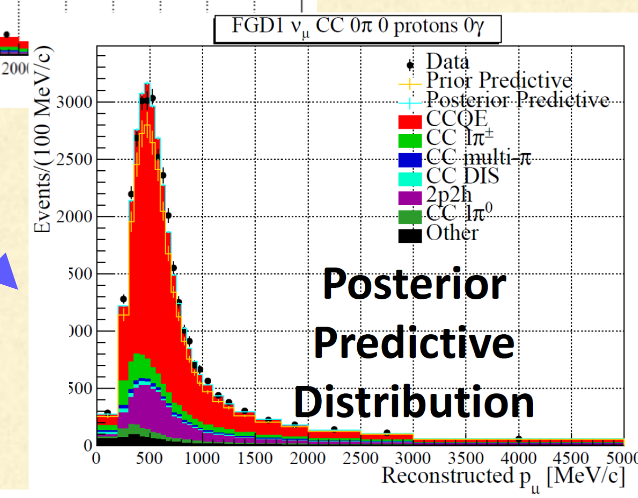
ν-mode: 2.17×10^{21} (56.8%)
$\bar{\nu}$-mode: 1.65×10^{21} (43.2%)

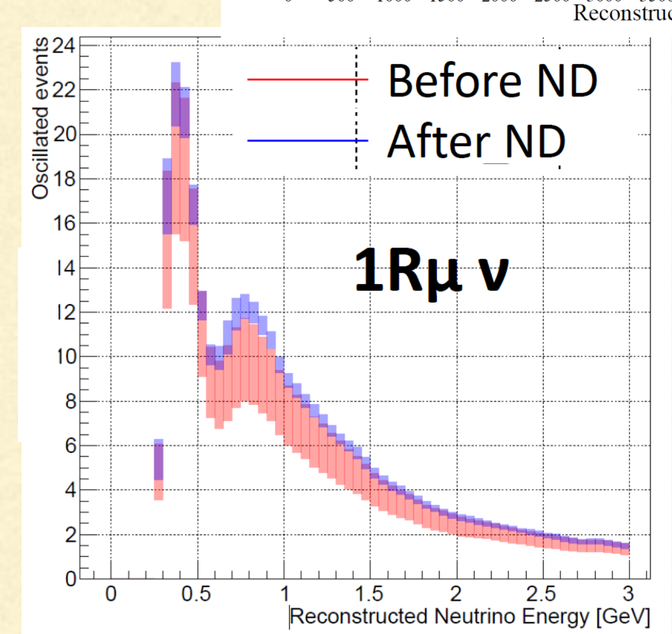
ND280 IN 2022 ANALYSIS

More stats + new selections
→ new samples for OA





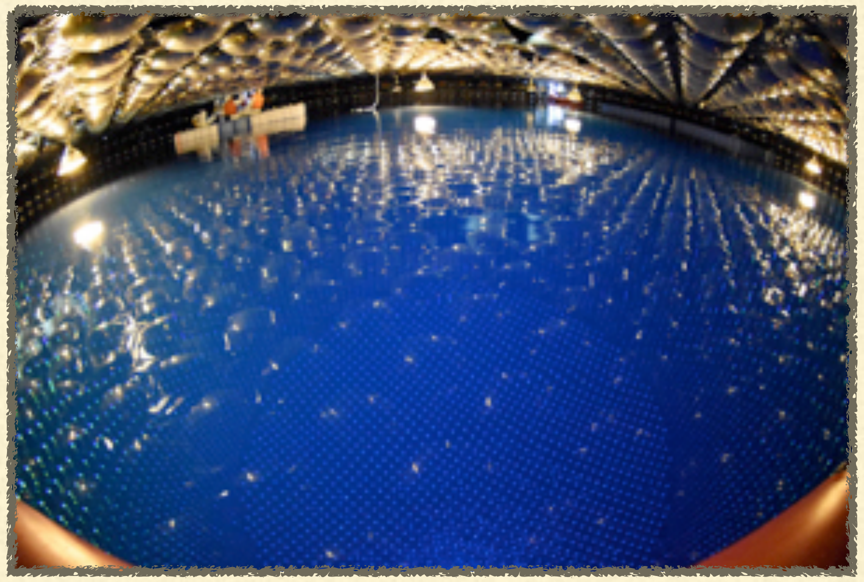




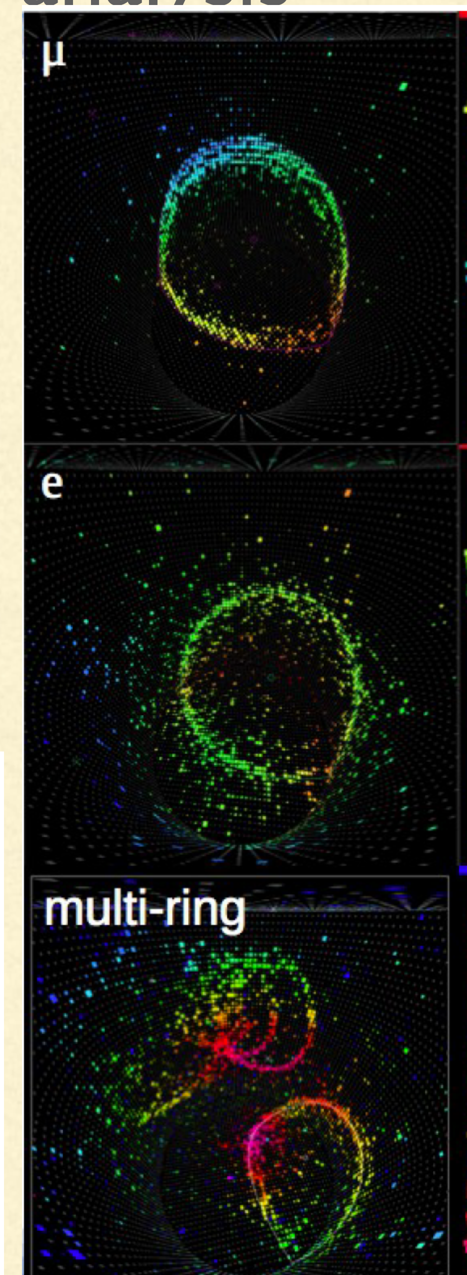
* CC-0π + CC1π+ CC-Other in RHC

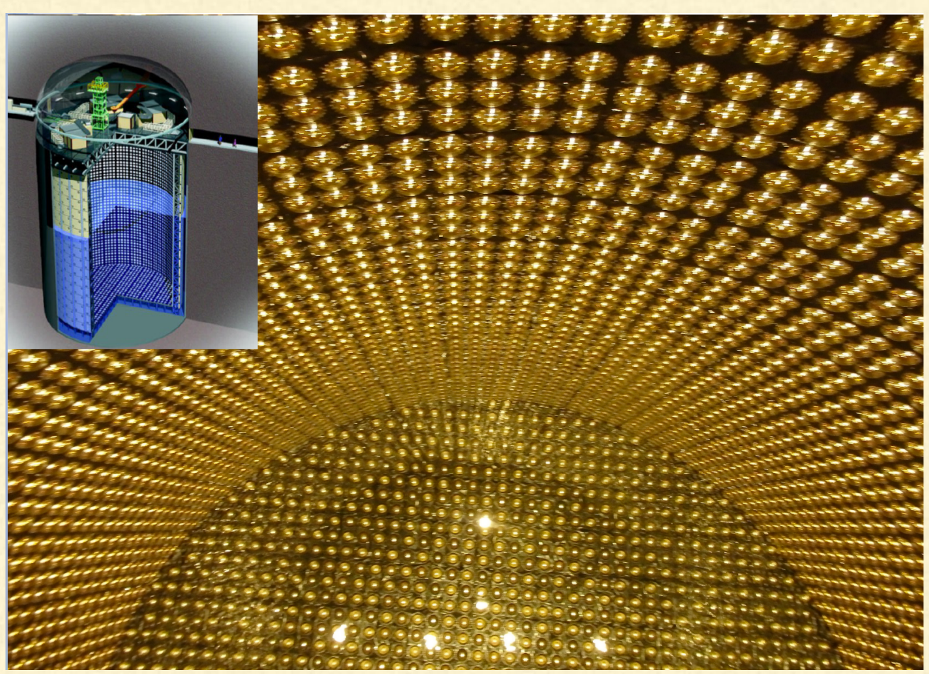
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

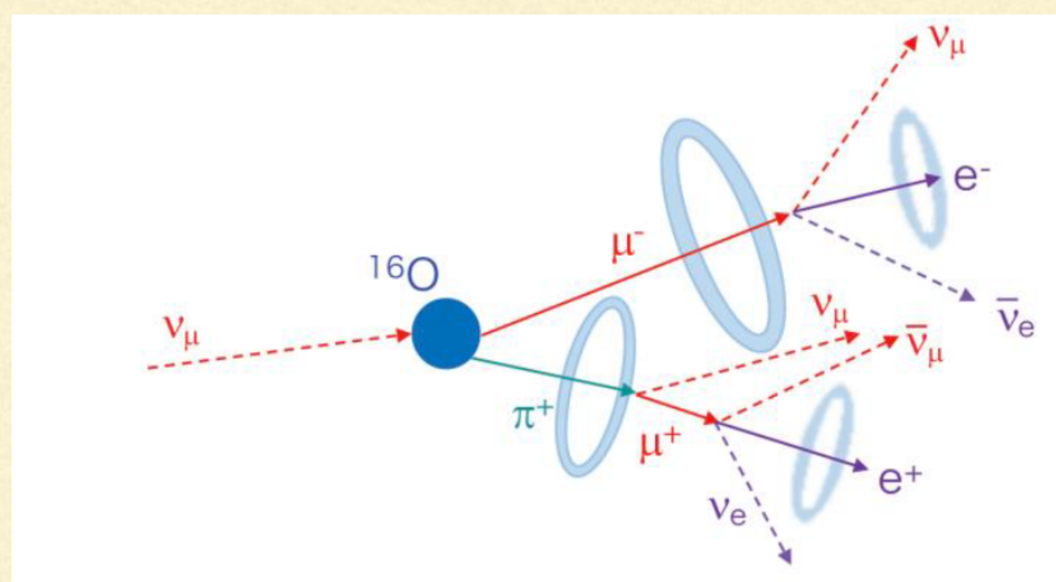
- Total 6 Super-K samples currently used in oscillation analysis



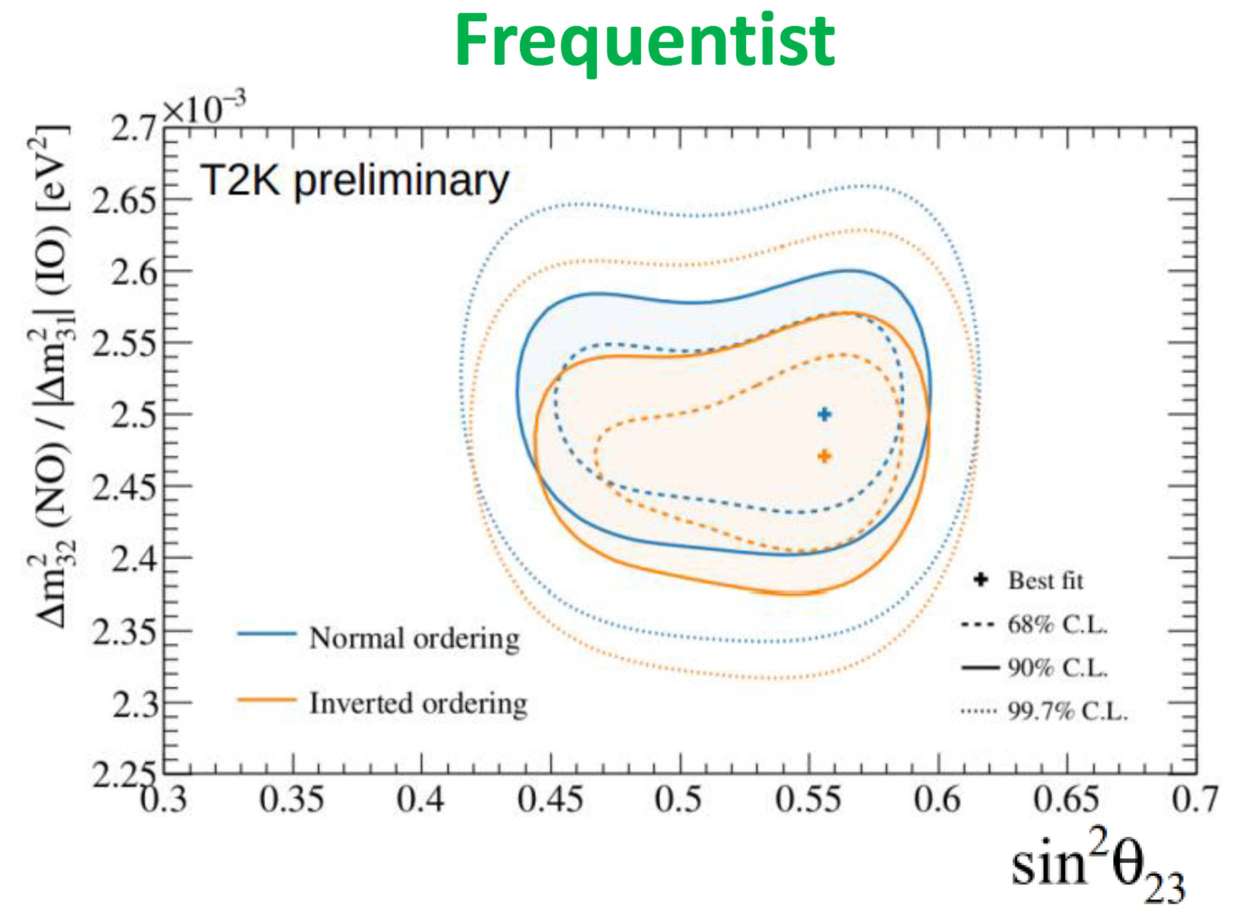
Mode	Sample Name	Description
ν	1Re	One e-like ring in ν mode
	1Re CC1π+	One e-like ring and Michel electron in ν mode
	1Rμ	One μ-like ring in ν mode
	MRμ CC1π+ (Multi-Ring)	Two rings (μ + π) + ME or 1 μ-ring + 2 ME
$\bar{\nu}$	1Re	One e-like ring in $\bar{\nu}$ mode
	1Rμ	One μ-like ring in $\bar{\nu}$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

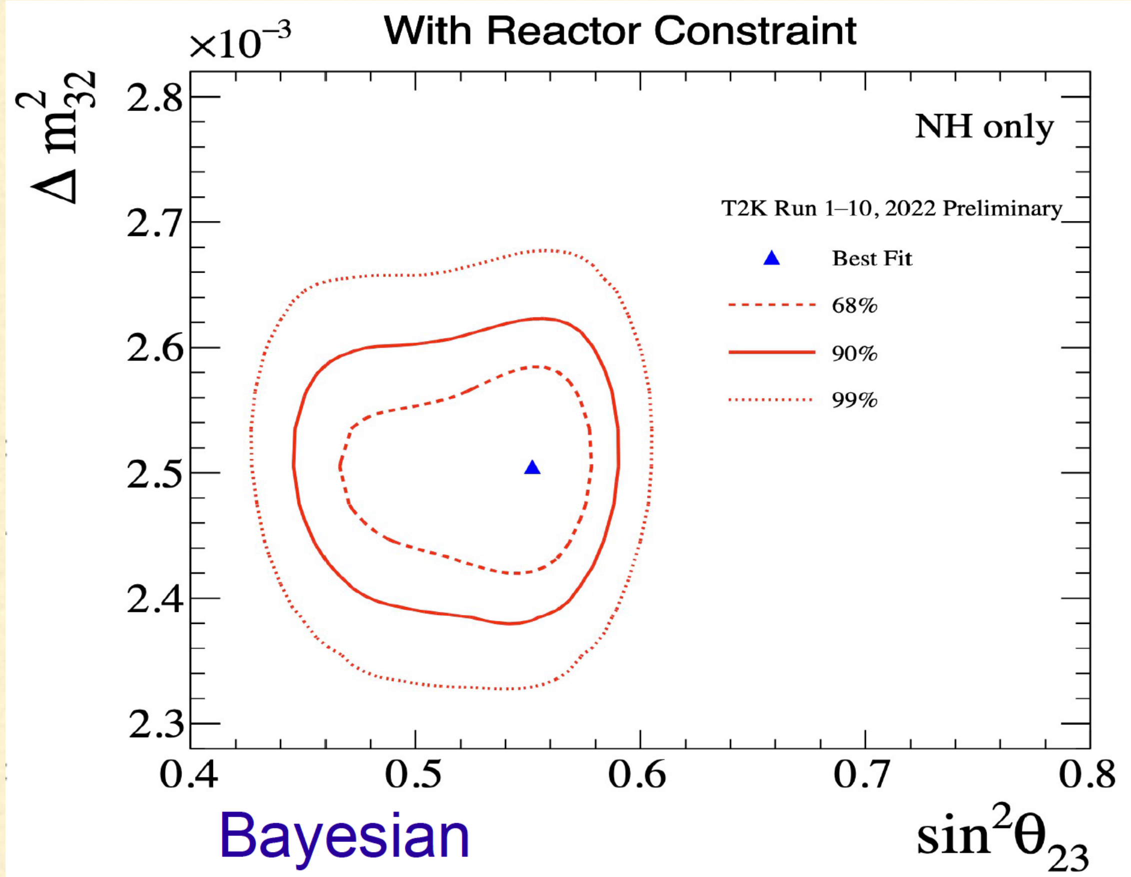






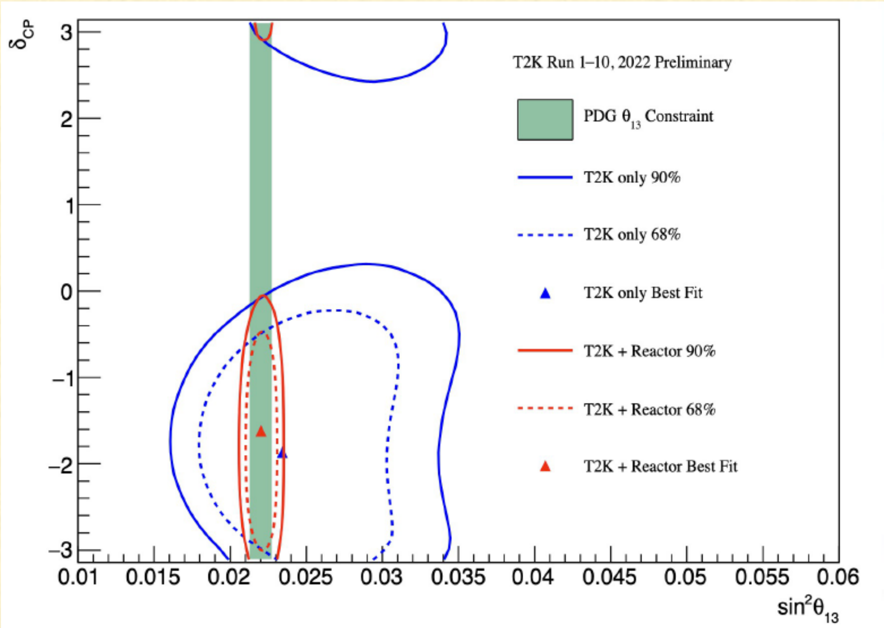
ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS θ_{23} AND Δm^2_{32}



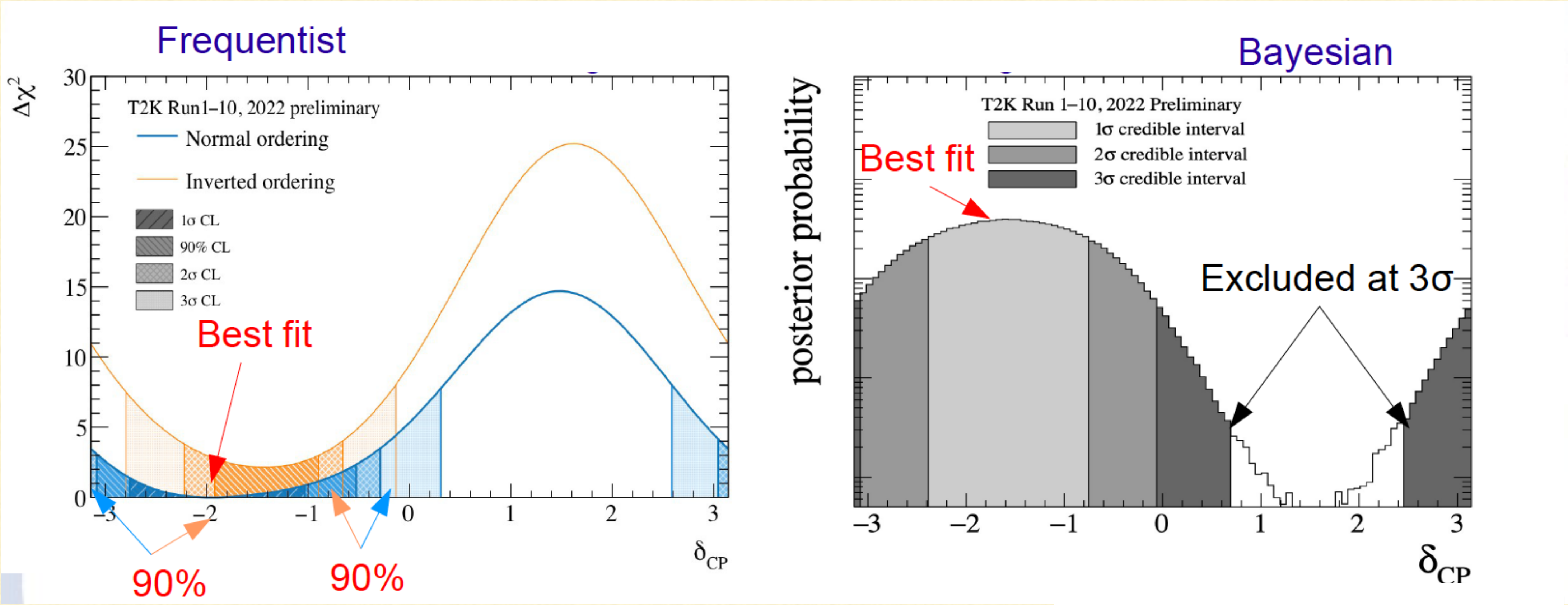


- 2022 analysis: joint fit of 6 Super-K samples with reactor data-driven constraint on θ_{13}
- Best-fit point in the upper octant
- Lower octant still consistent within 68% CL.

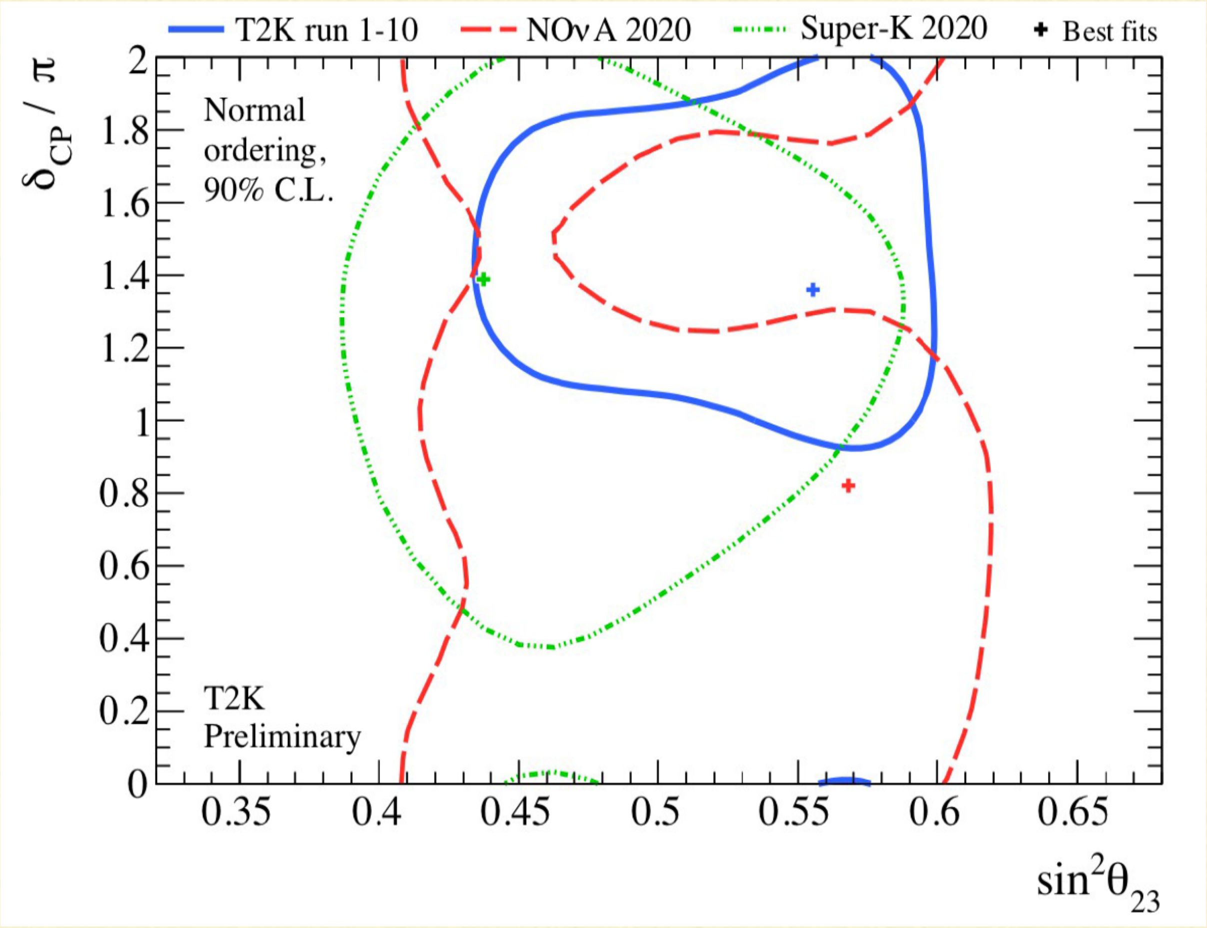
ANALYSIS RESULTS: θ_{13} MEASUREMENTS

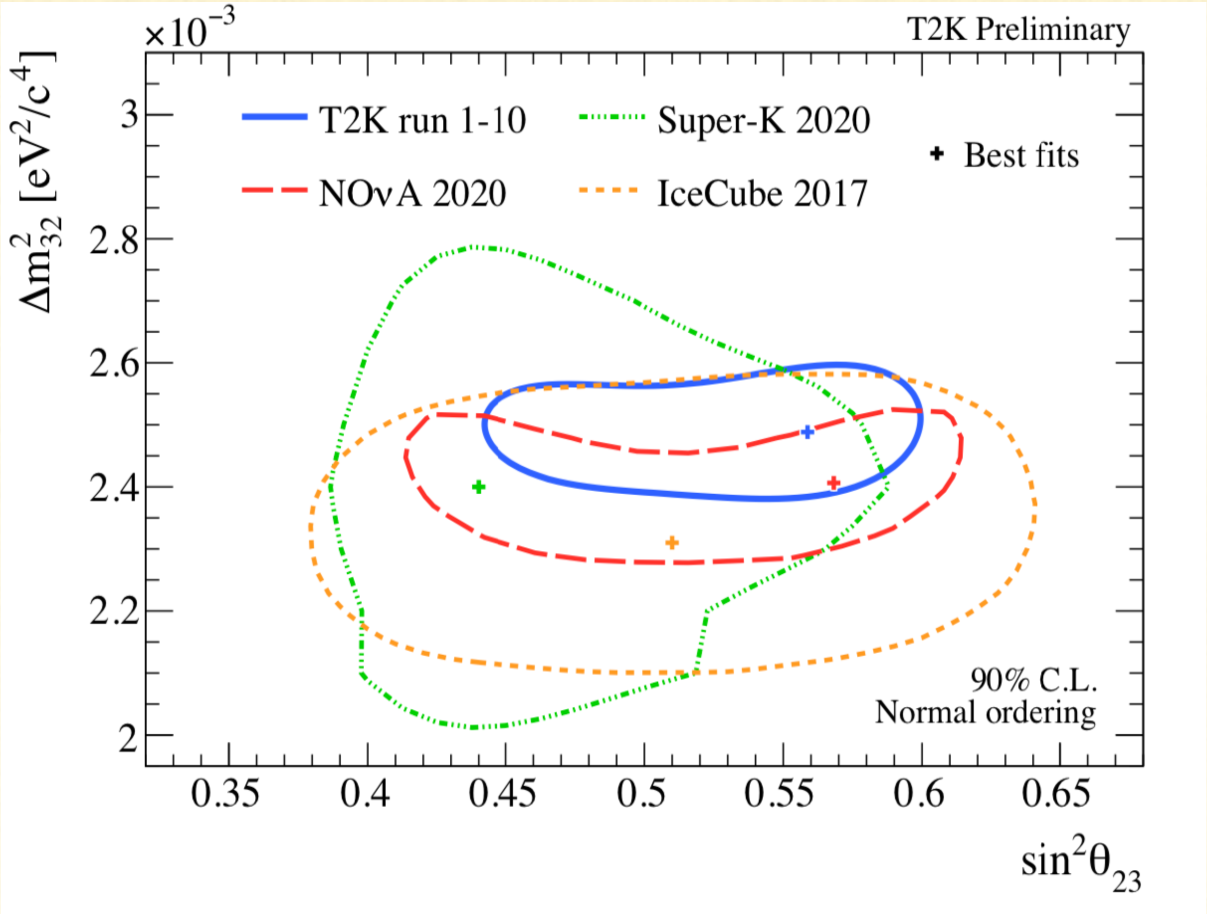


- Good agreement with reactor on θ_{13}
- **Large CPV favoured**
- CP-conserving values of δ_{CP}=0 and δ_{CP}=π both outside of 90% CL intervals



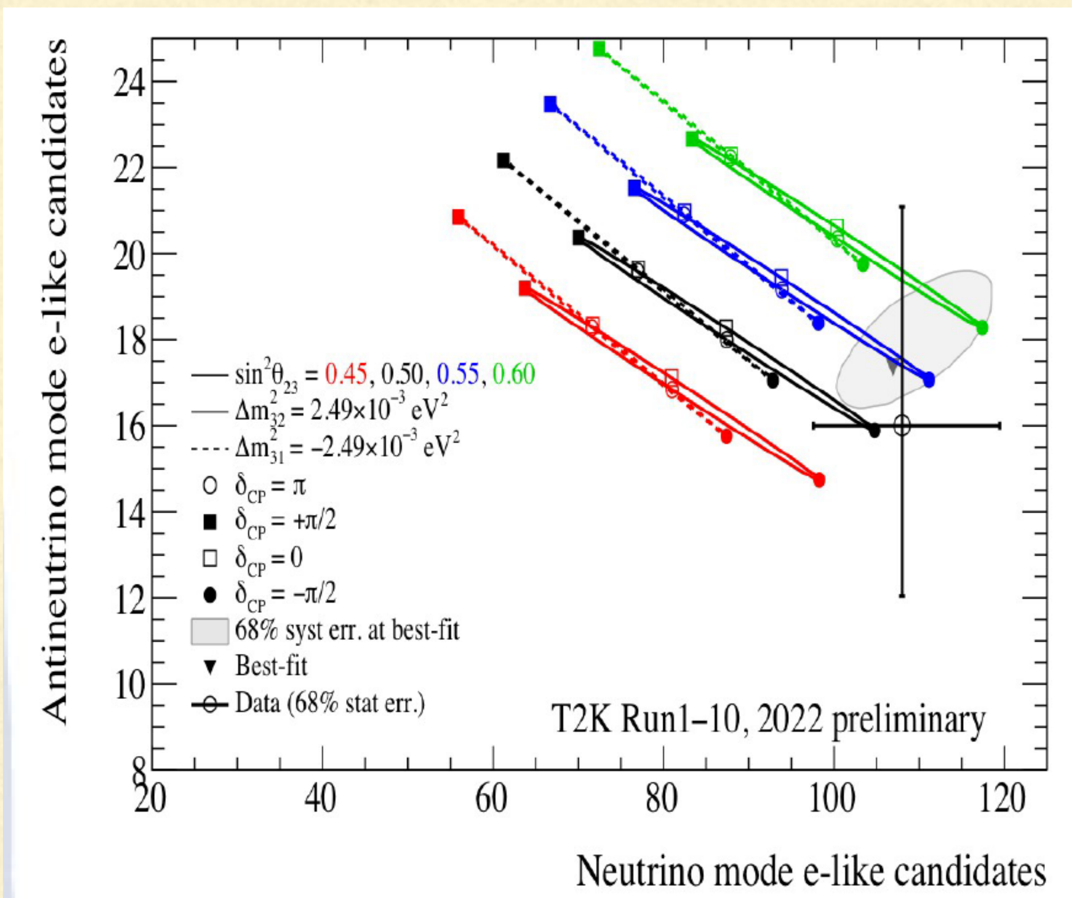
T2K VS OTHER MEASUREMENTS

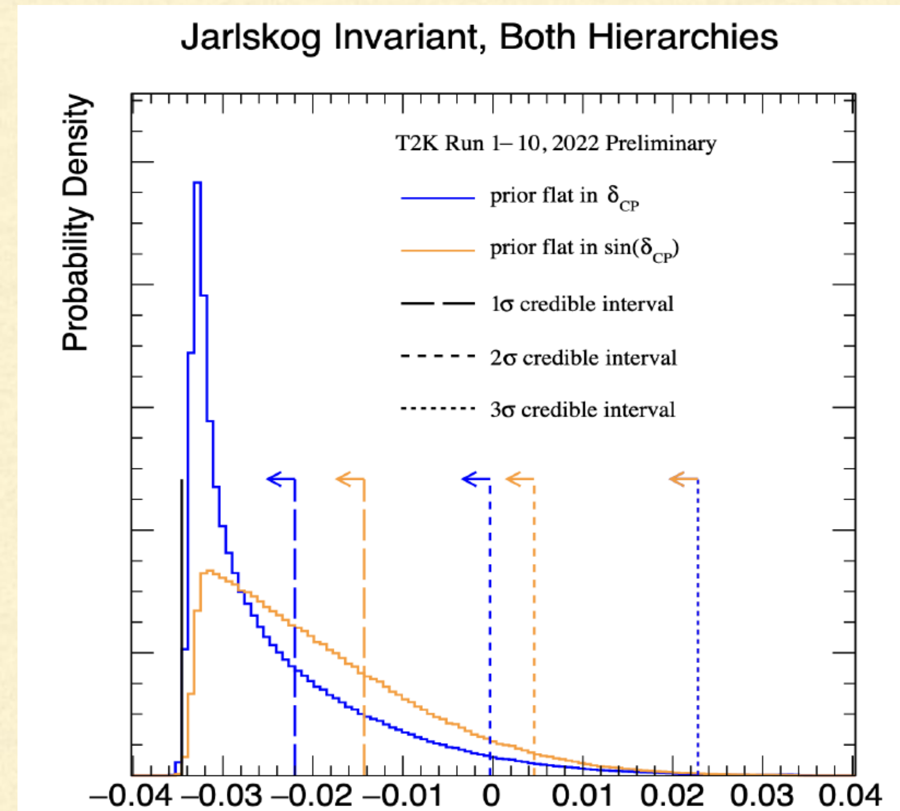




- δ_{CP}-vs-$\sin^2\theta_{23}$: at 90% CL, δ_{CP} T2K, NOνA and Super-K contours overlap. T2K consistent with Super-K best fit, NOνA best fit just outside contour
- Δm^2_{32} -vs-$\sin^2\theta_{23}$: at 90% CL, θ_{23} contours overlap. T2K and NOνA favour upper octant while Super-K prefers lower

MORE T2K OSCILLATIONS RESULTS





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

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

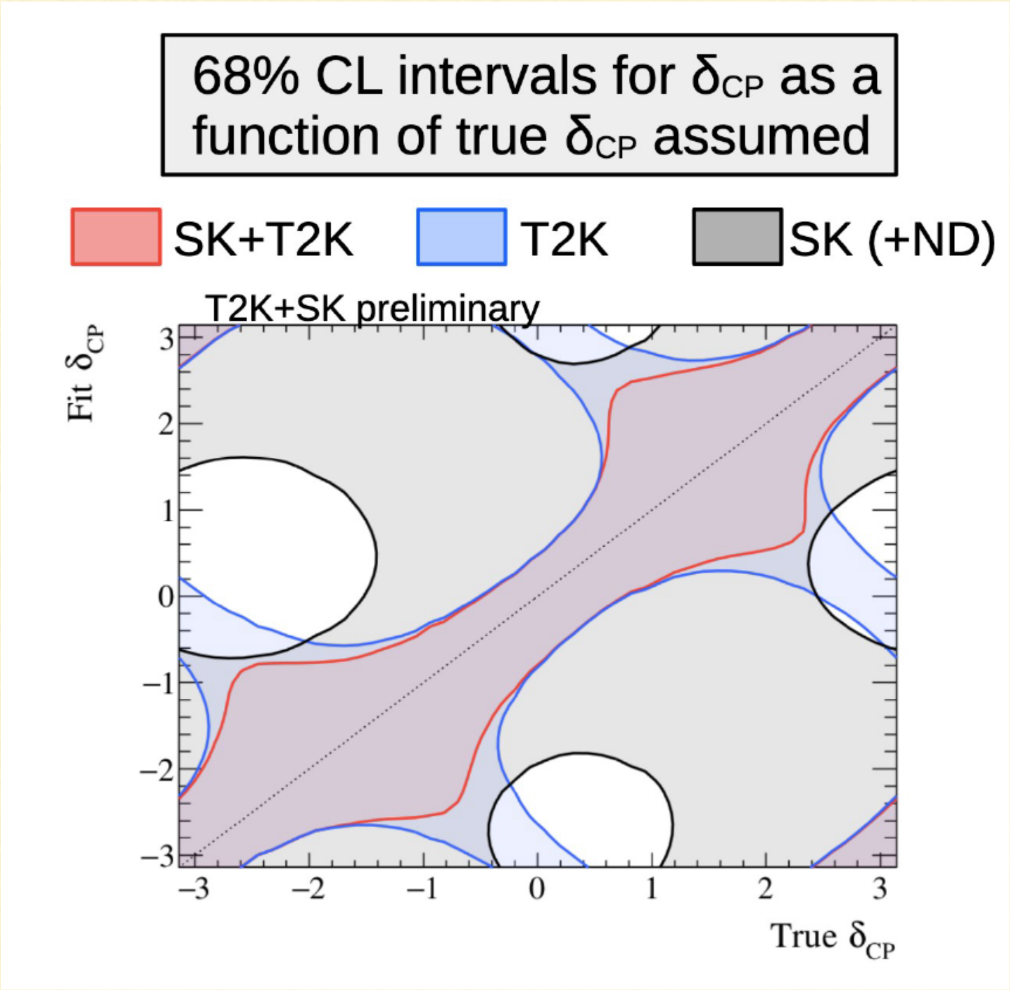
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.19	0.65	0.83
Inverted ordering	0.03	0.14	0.17
Column total	0.21	0.79	1.00

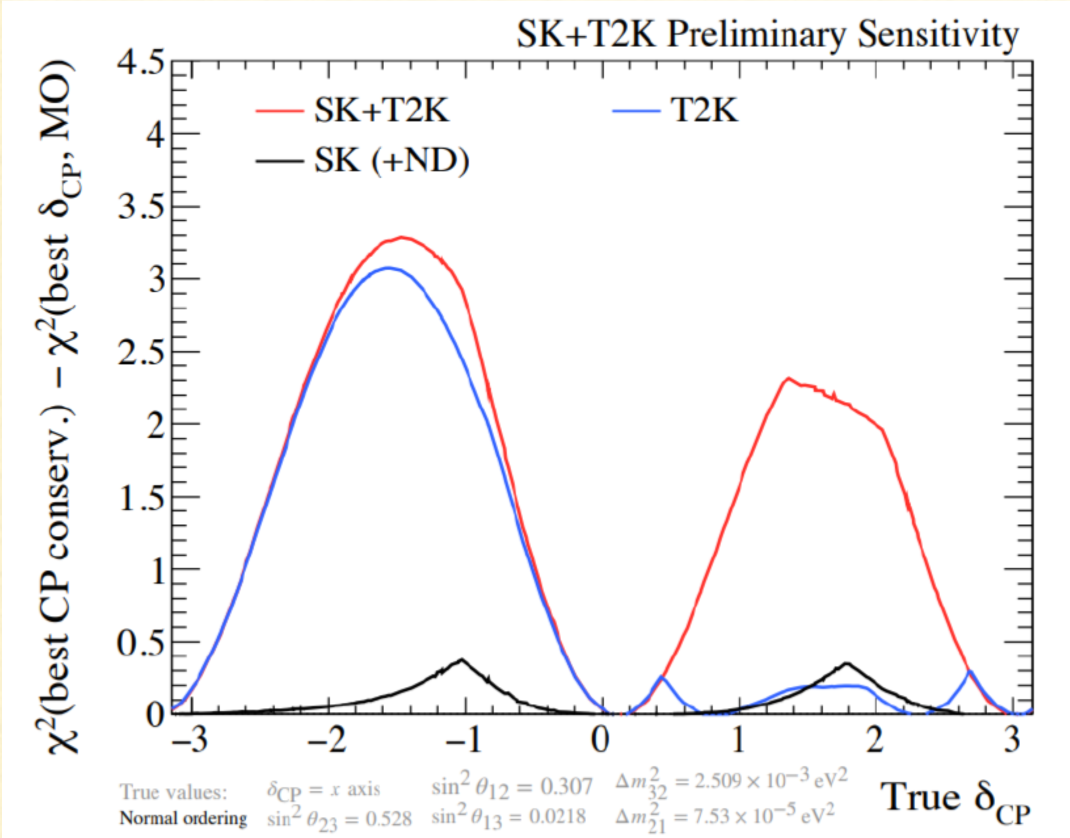
* Bayesian with reactor constraint

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

NEAR FUTURE: JOINT T2K + SUPER-K ATMOSPHERIC ANALYSIS

- Sensitivity to δ_{CP} dominated by T2K ←
- Super-K atmospheric data can contribute to solving degeneracies due to $\cos(\delta_{CP})$ and MO
    - Covers wider range of energies and baseline → sensitivity to MO
    - Ability to reject wrong MO and define θ_{23} quadrant
    - Same detector → detector systematics correlations





SK(+ND) — ND fits used to constrain model params used for low-E Super-K samples

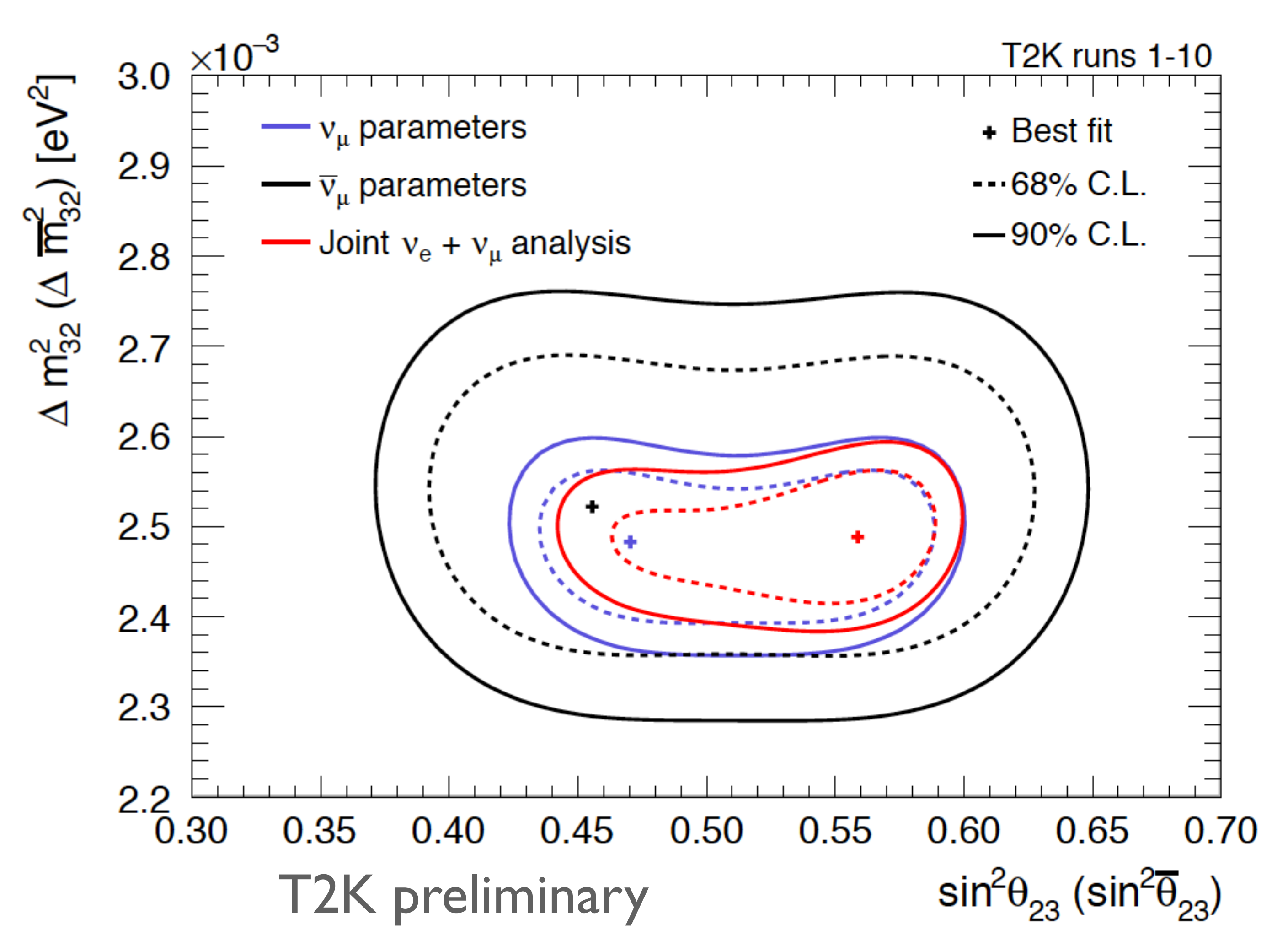
NEAR FUTURE: JOINT T2K + NOVA ANALYSIS

- Two world-leading neutrino accelerator projects currently in operation
- Different baseline, ν mean energy, detector design
  - Liquid-CH filled barrels (NOVA) vs complex ND280 (CH-target) + water Cherenkov Super-K
    - Complementary neutrino oscillations studies: degeneracies in MO and δ_{CP}
    - Challenge to include all local peculiarities and inter-detector correlations into a global fit
- Groups formed and work is on-going

Experimental Property	T2K	NOvA
Proton beam energy	30 GeV	120 GeV
Baseline	295 km	810 km
Peak neutrino energy	0.6 GeV	2 GeV
Detection technology	Water Cherenkov	Segmented liquid scintillator bars
CP effect*	32%	22%
Matter effect	9%	29%
*Minimum difference $\sin(\delta_{CP})=0$ and ±1, between ν and $\bar{\nu}$		

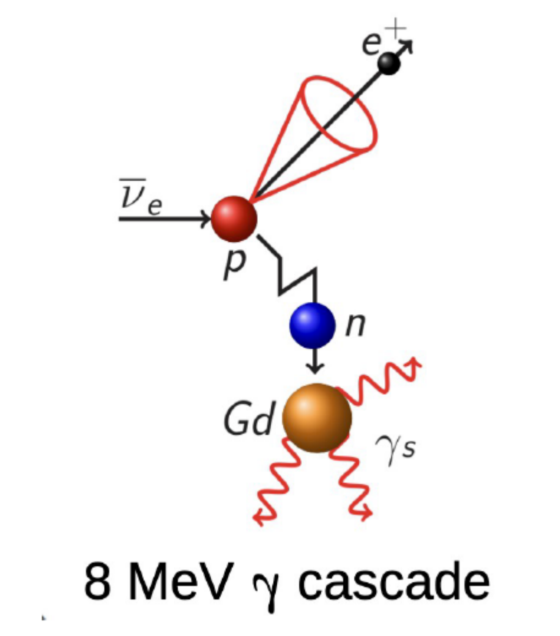
CPT TESTS WITH T2K

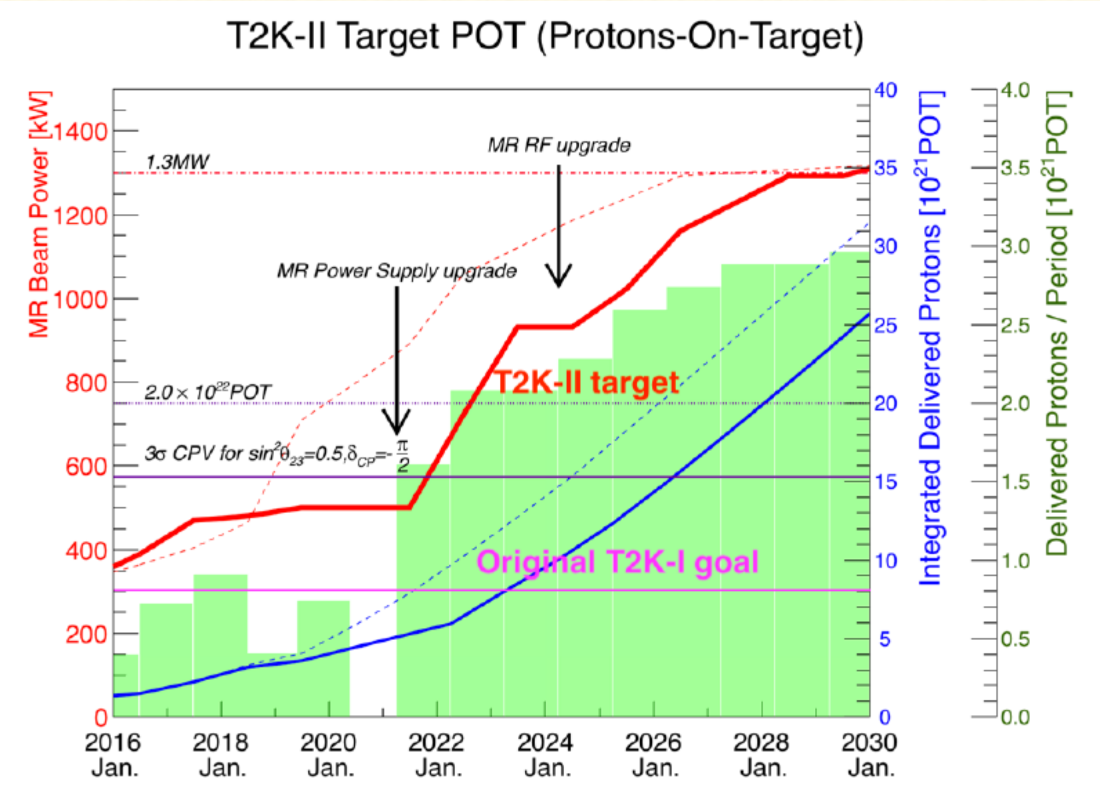
- Study appearance and disappearance channels
  - Use separate fitting params for neutrino and antineutrino: Δm^2_{23} and θ_{23}
  - **Consistent results with no CPT-V**



T2K FUTURE PROSPECTS: T2K-II

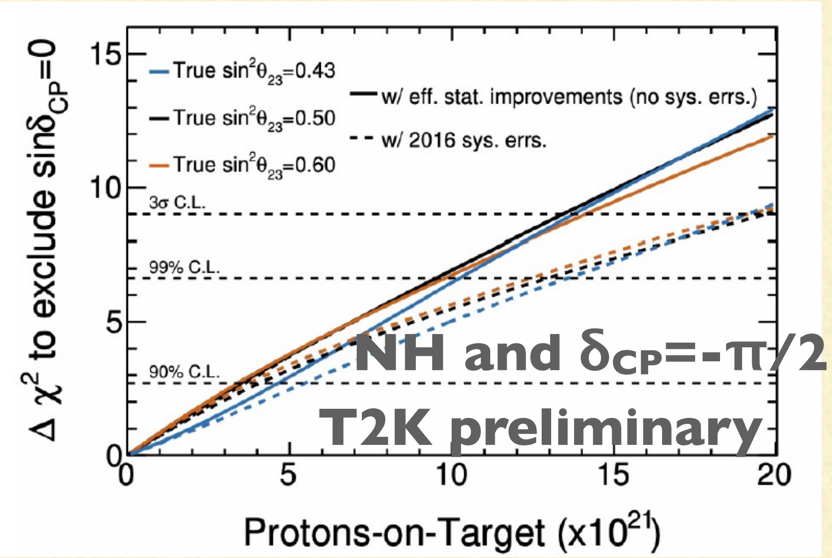
- Gd now added to SK: not yet used in analysis but neutron signal seen
- Significant enhancement in neutron capture: anti-neutrino events tagging
- T2K neutrino beamline upgrade is also on-going
- Accumulate more data
  - Reduce systematics uncertainties
  - Reach 3σ for non-CPV rejection prior to Hyper-Kamiokande era

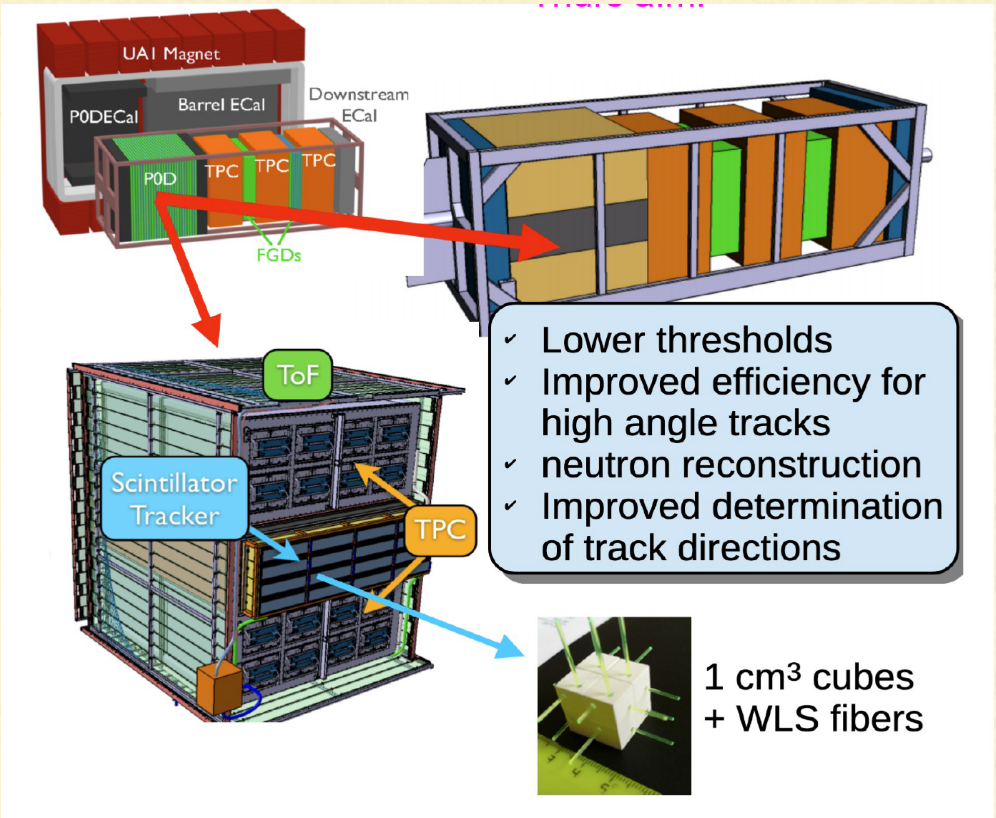


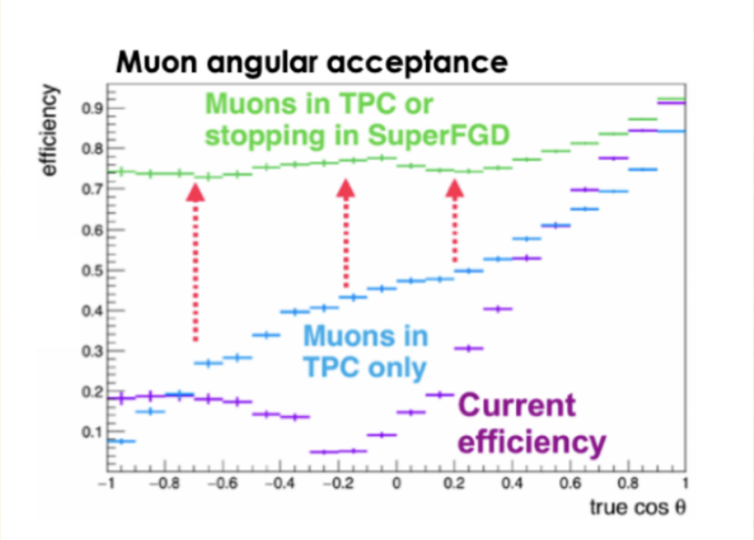


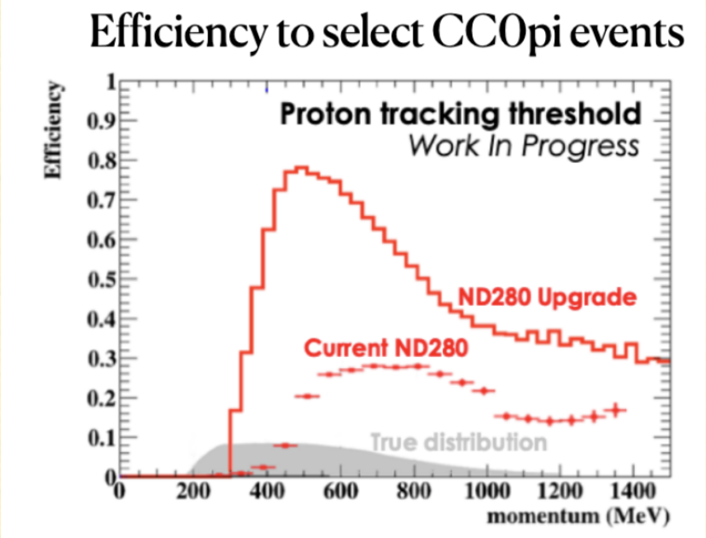
T2K FUTURE PROSPECTS: NEAR DETECTOR UPGRADE

- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 5-7% (2022) → 4%(202X..)
- <u>ND280 measurements play the key role</u>
- Near detector upgrade
  - Key elements → **Super-FGD 3D-cubes** based segmented plastic scintillator active target surrounded by TPCs





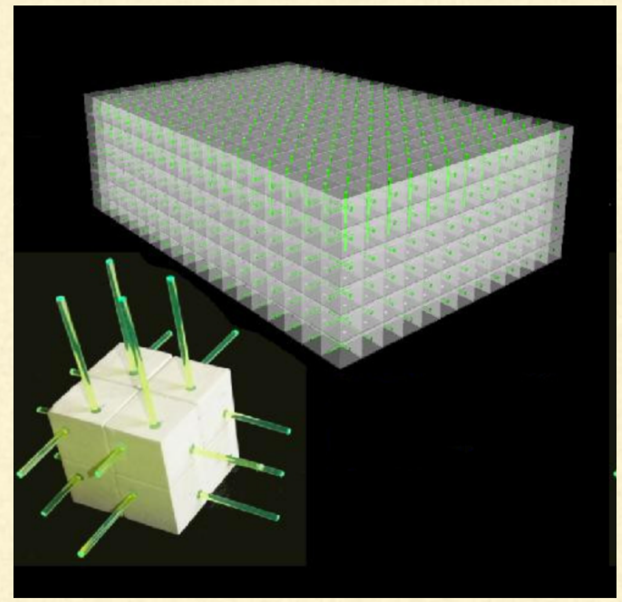


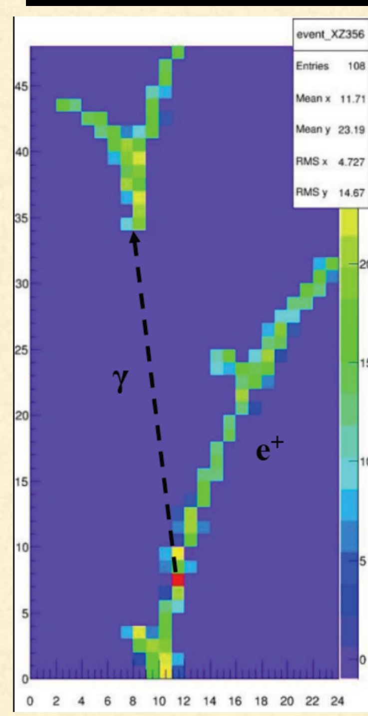


ND280Upgrade to start data taking in 2023

3D-SUPER FGD DETECTOR

- Plastic scintillator detector based on
  - 192×182×56 of 1 cm^3 cubes → 3D-like detector ← ~2 tons active mass
  - polystyrene based with dopes via injection molding followed by chemical etching
  - ~60k readout channels with WLS fibres + Hamamatsu MPPCs
- Active elements designed and manufactured by INR RAS and Uniplast (Russia)
- Small prototypes tested @CERN beam and also with neutrons @ LANL





SuperFGD cubes arrived at J-PARC in summer 2022 and ready for assembling

SUMMARY

Stay tuned
new data beckons

- T2K is working steadily on its quest on filling neutrino puzzle
- New samples in near and far detectors, upgraded neutrino x-sec and flux modelling
- Current T2K data favours strong CP-violation, CP-conservation excluded at 90% C.L.
- Atmospheric mixing elements: T2K favours upper octant for θ_{23}
  - Still consistent with lower octant and maximal mixing
- Slight preference for normal mass hierarchy
- Planned joint analyses: suppress degeneracies with different energies and baselines
  - T2K + Super-K atmospheric data joint fit
  - T2K + NOνA joint analysis
- 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
  - Super-K already loaded with Gd to enhance neutron tagging
  - Near detector upgrade to further reduce systematic uncertainties + enhance physics capabilities with ND280Upgrade
    - Key part SuperFGD cubes already in J-PARC and ready for assembling

Cám ơn vì sự quan tâm của bạn

BACKUP MATERIALS

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

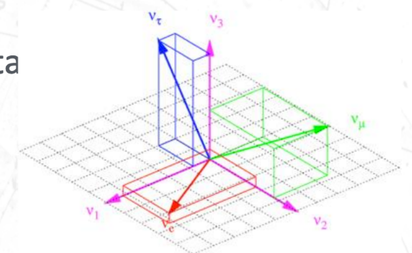
- Neutrino have mass and mixings:

- Neutrino flavour eigenstates are not the same than the neutrino Lorentz eigenstates.
- Eigenstates are related through a rotation matrix.

Flavour eigenstates	Lorentz eigenstates
$(\nu_e, \nu_\mu, \nu_\tau)$	(ν_1, ν_2, ν_3)
state of the neutrino interactions	states of the neutrino propagation in space

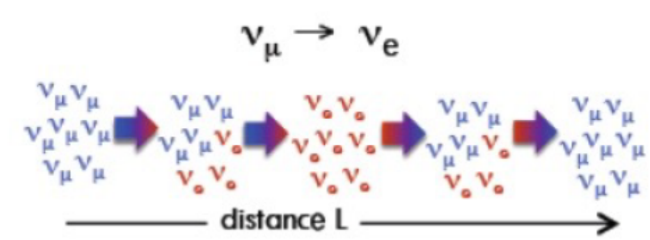
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

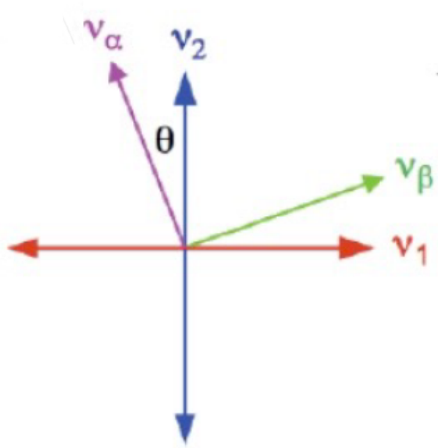
$$(\nu_e \quad \nu_\mu \quad \nu_\tau) = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Neutrino Oscillations imply neutrino mass





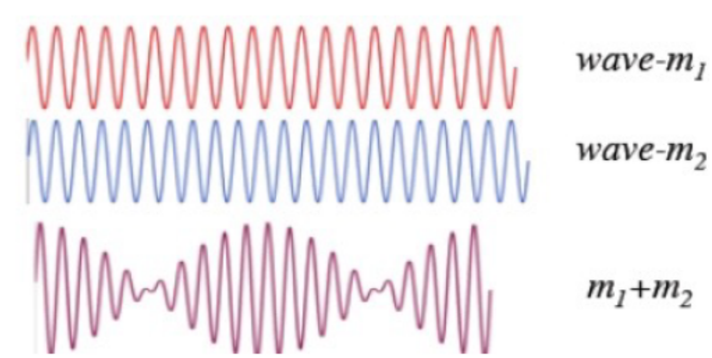
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

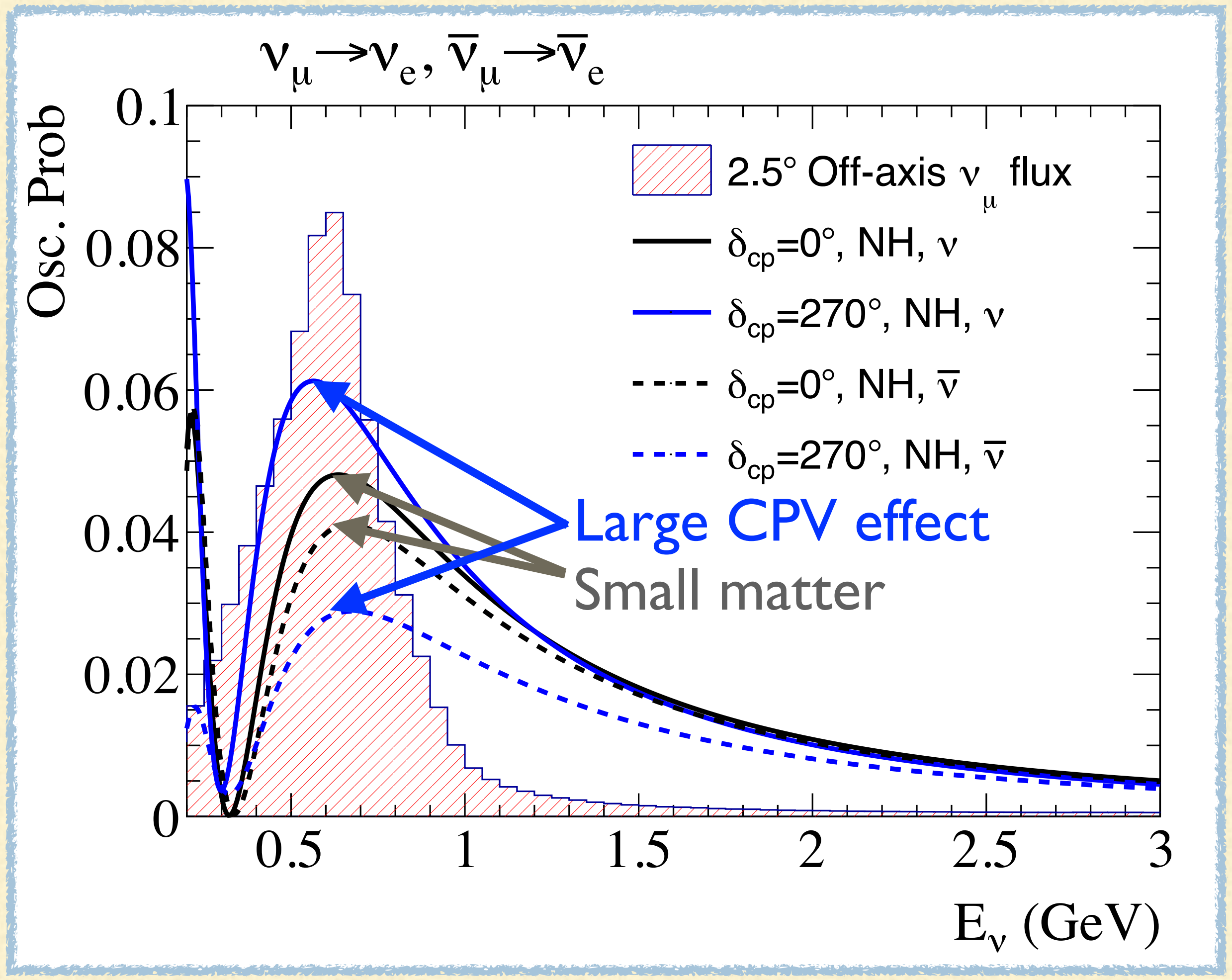
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



T2K

NEUTRINO OSCILLATIONS IN T2K

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

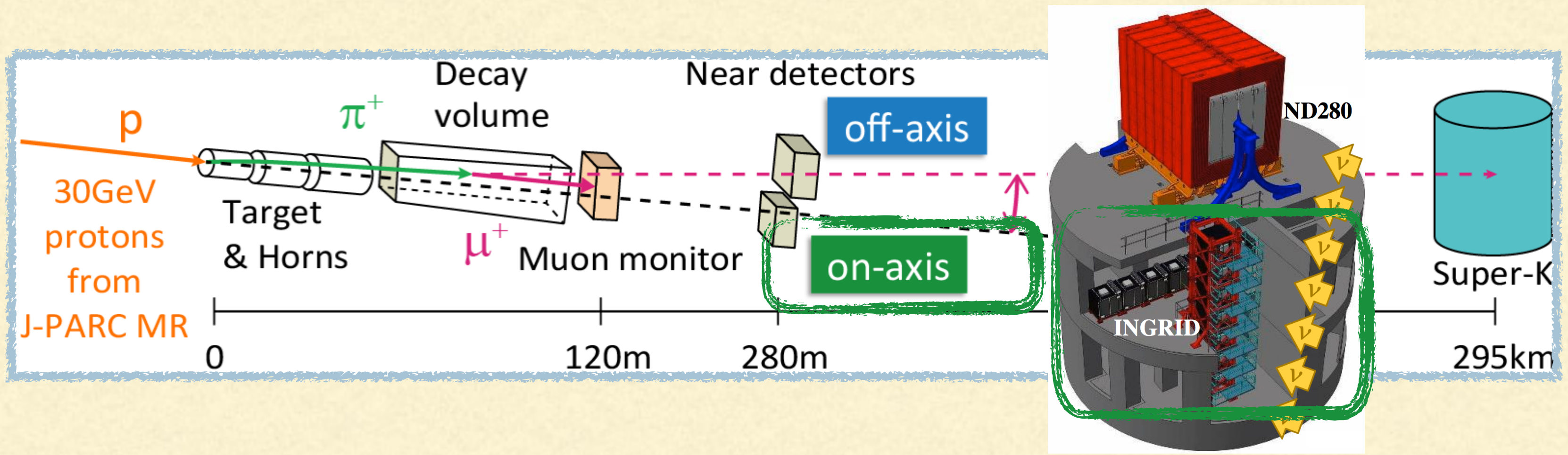


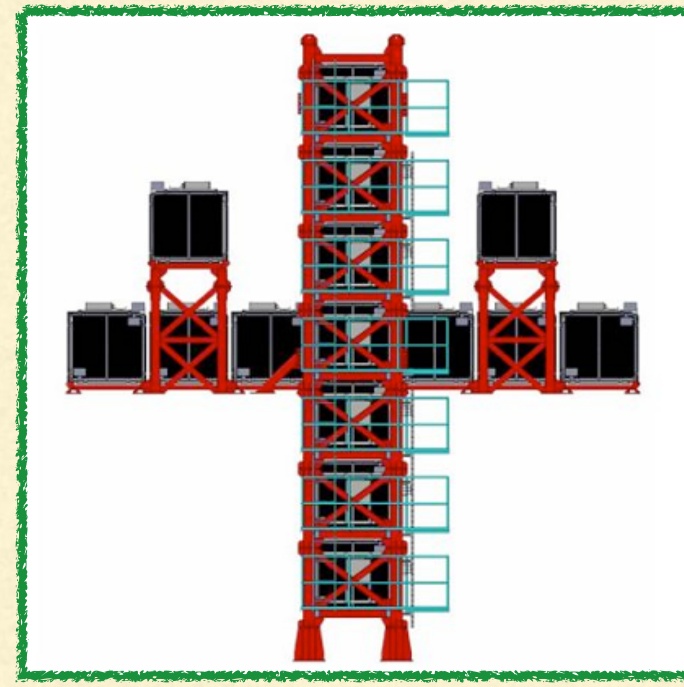
CP PHASE/ CHANNEL	$P(\nu_\mu \to \nu_e)$	$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

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

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

ON-AXIS NEAR DETECTOR INGRID



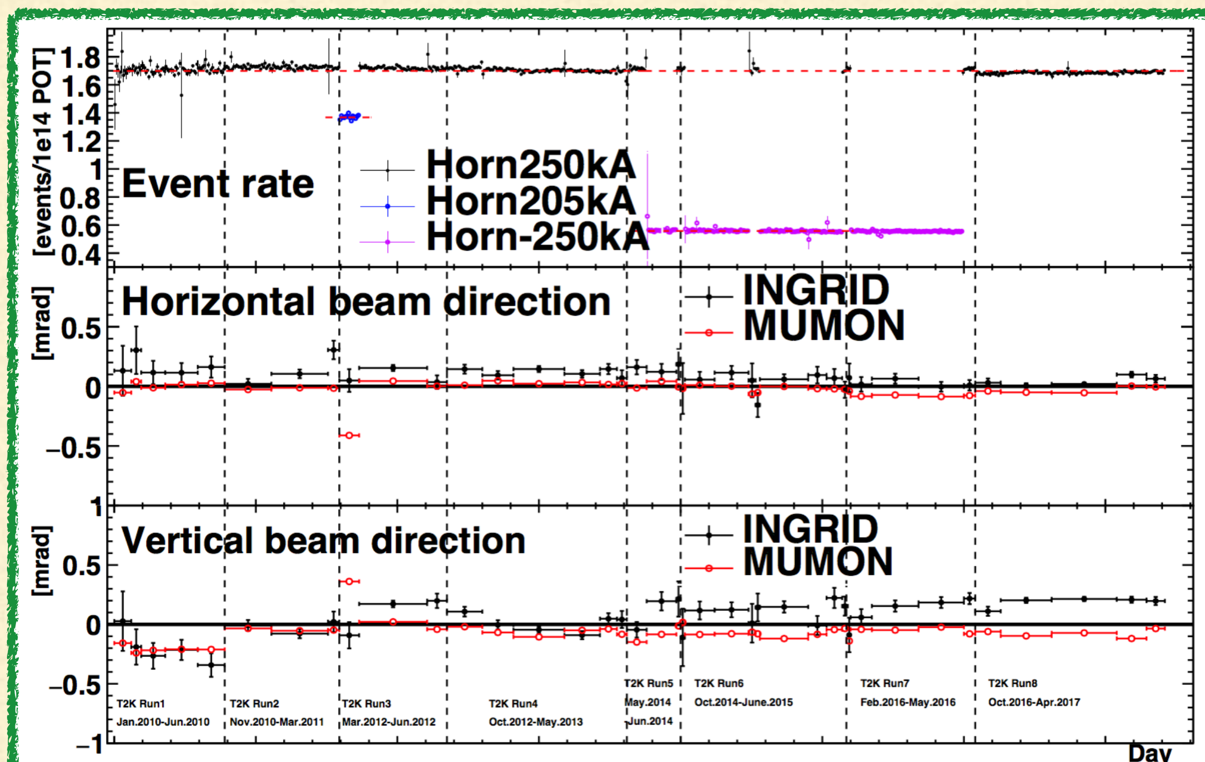


- T2K utilises off-axis neutrino beam:
  - Important to monitor beam intensity and direction

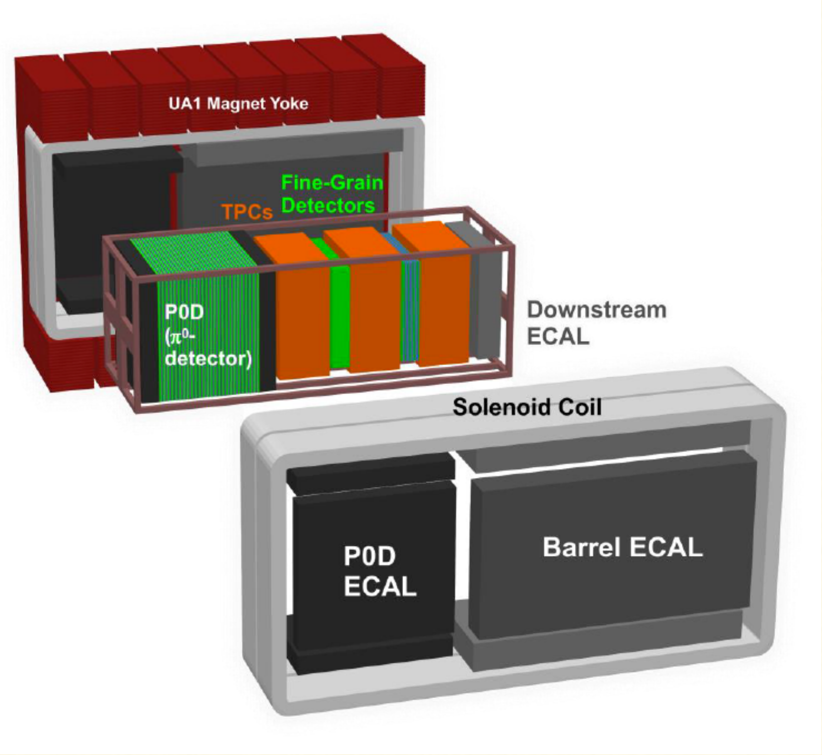
- Iron/scintillator detector to measure beam profile and rate

- Day-by-day monitoring

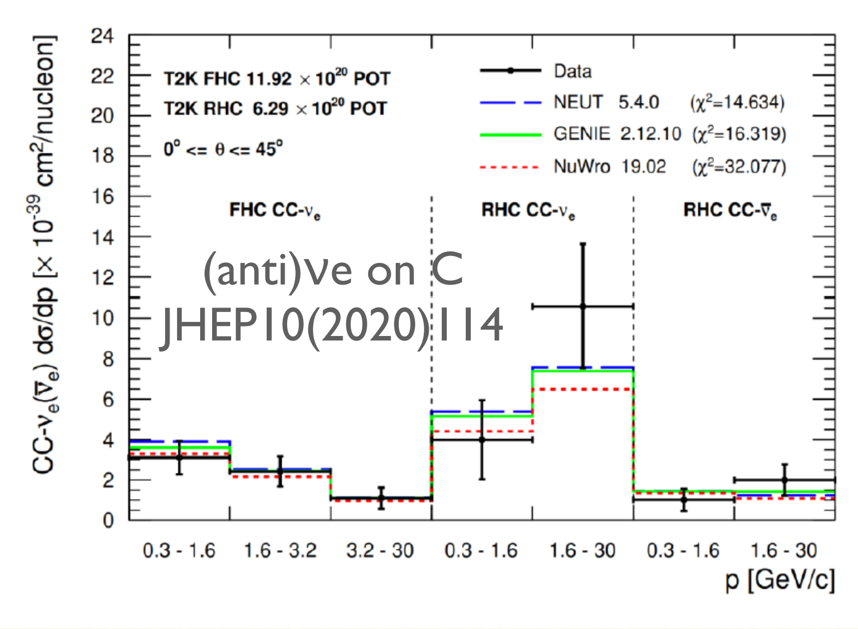
- Direction stable within 1 mrad (~2% shift in peak energy)

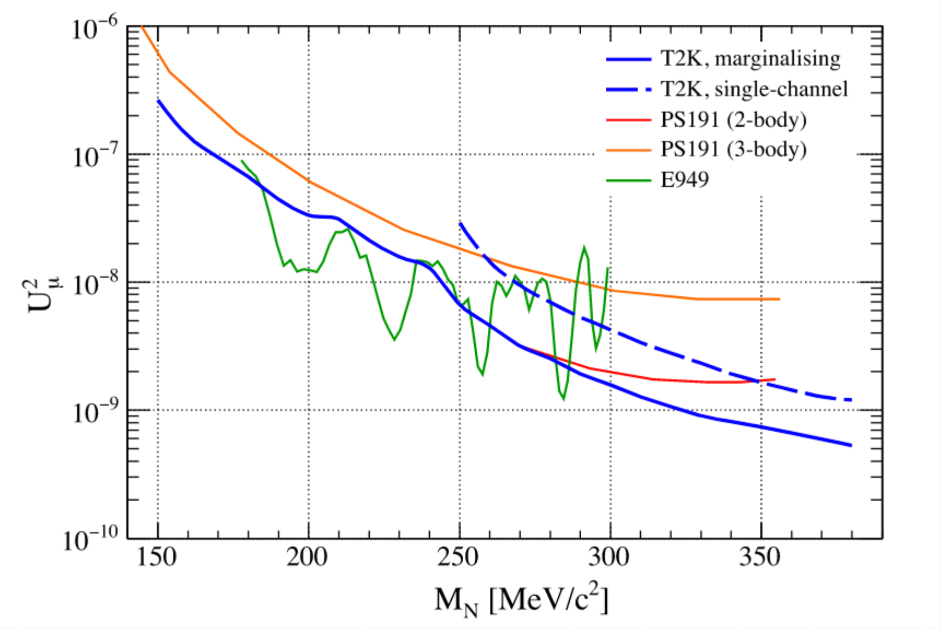


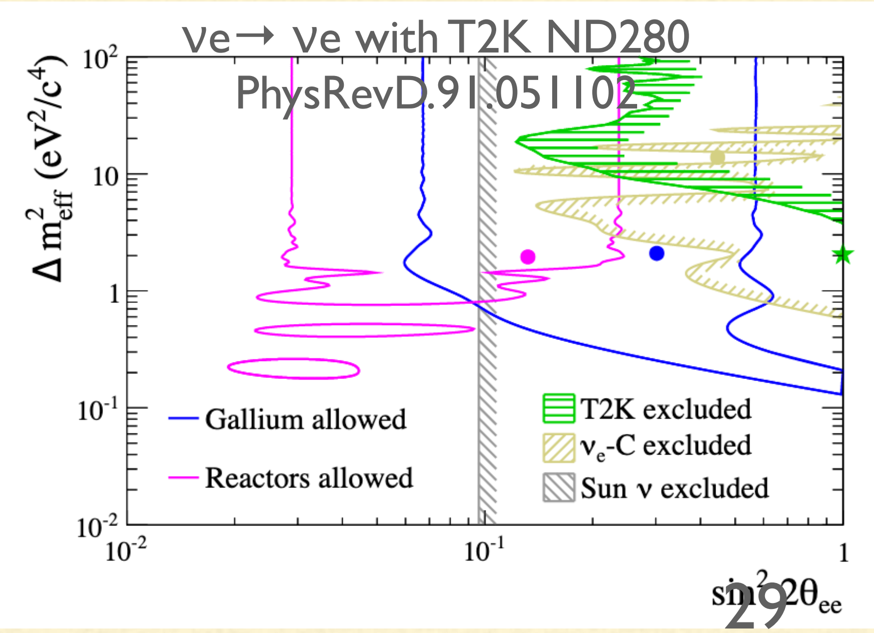
ANALYSES WITH T2K ND280



- 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

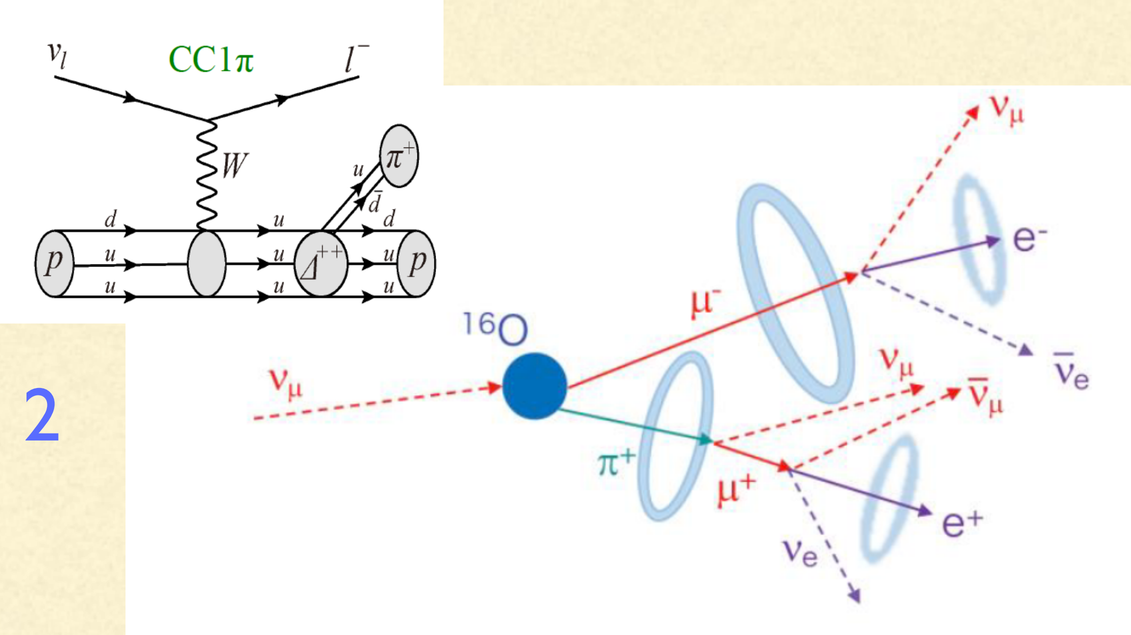


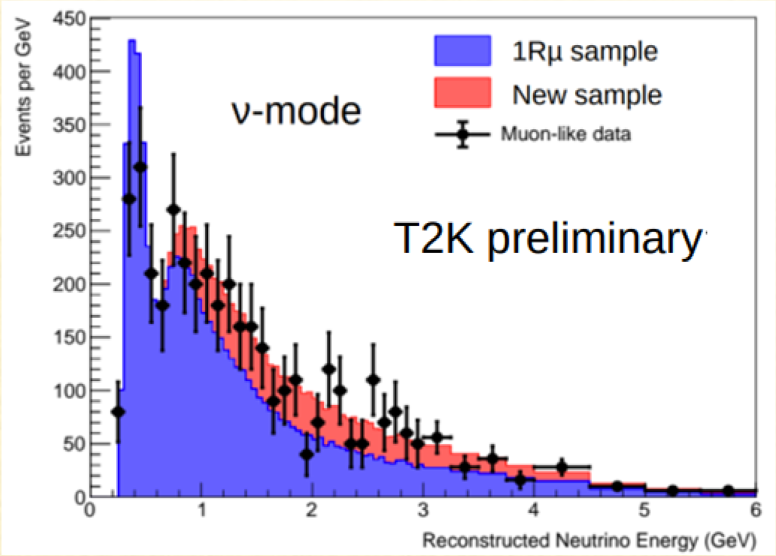


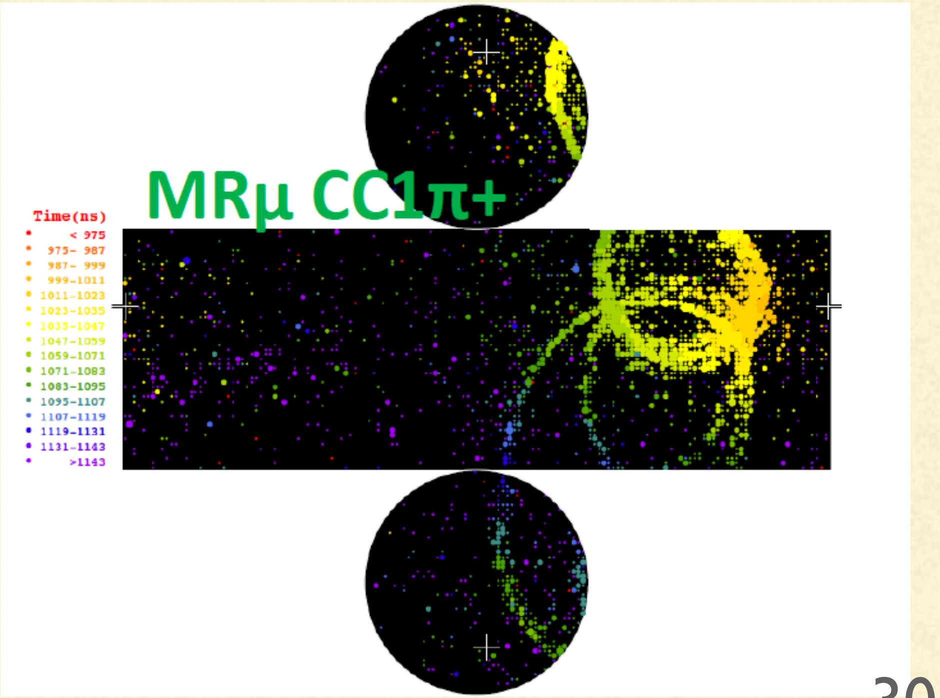


SUPER-K MULTI-RING SAMPLE FOR NUMU

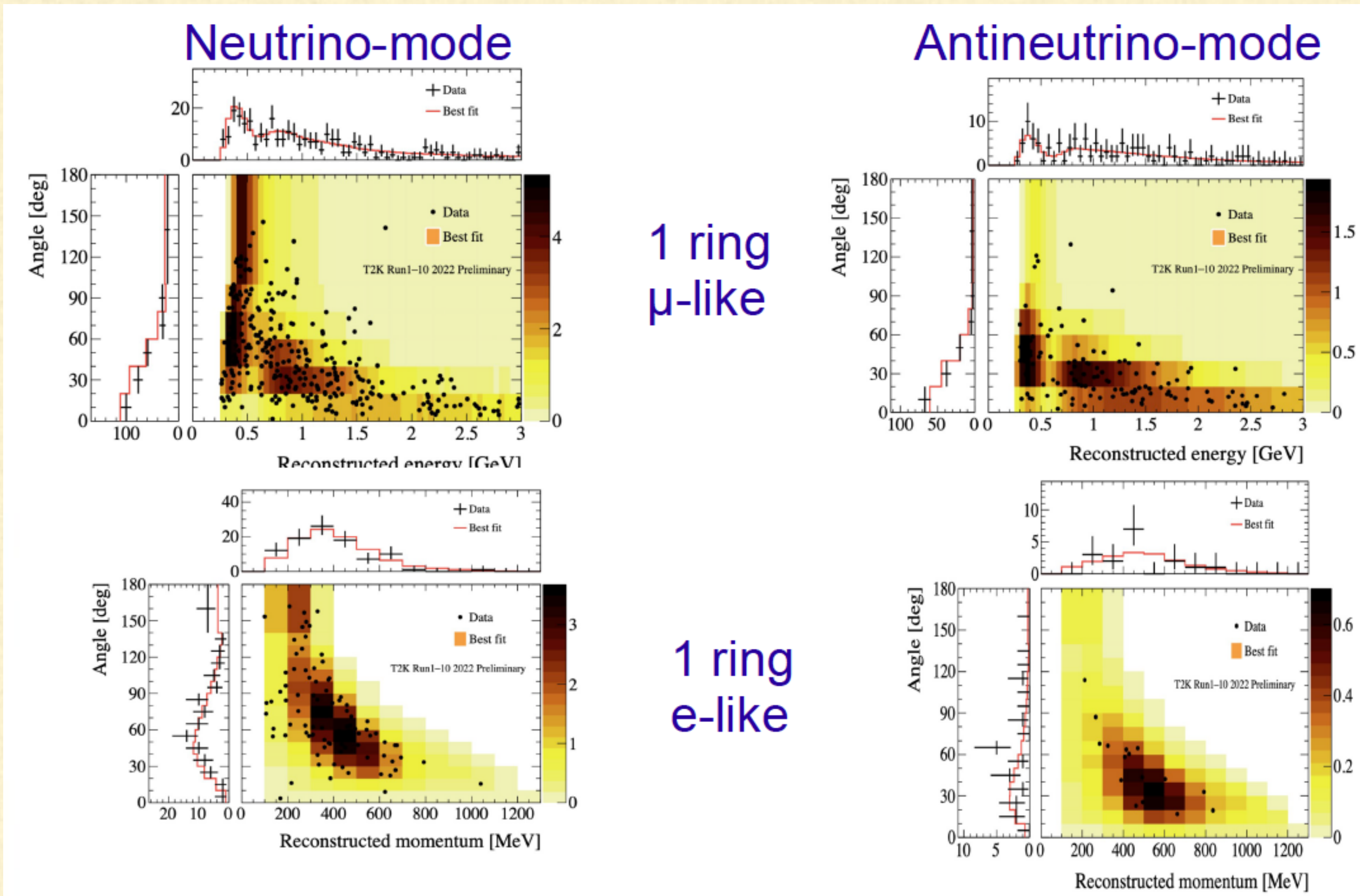
- Multi-ring $\mu CC1\pi^{+}$ sample in FHC mode
  - Two rings from $1\mu^{-}$ and $1\pi^{+}$ and Michel electron
  - One or two rings from $1\mu^{-}$ and $1\pi^{+}$ and 2 Michel electrons
- Increase ν-mode μ-like stats by ~30%
- Higher energy but yet oscillation sensitive → interaction modelling cross-checks

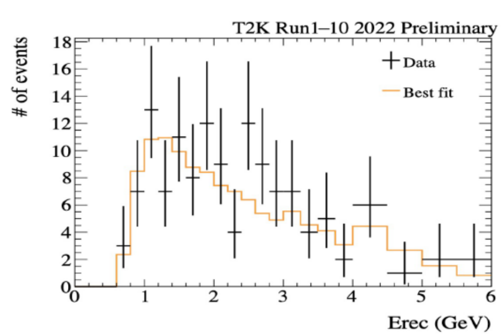




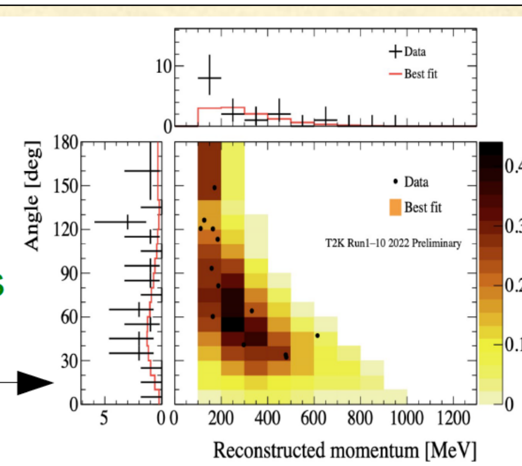


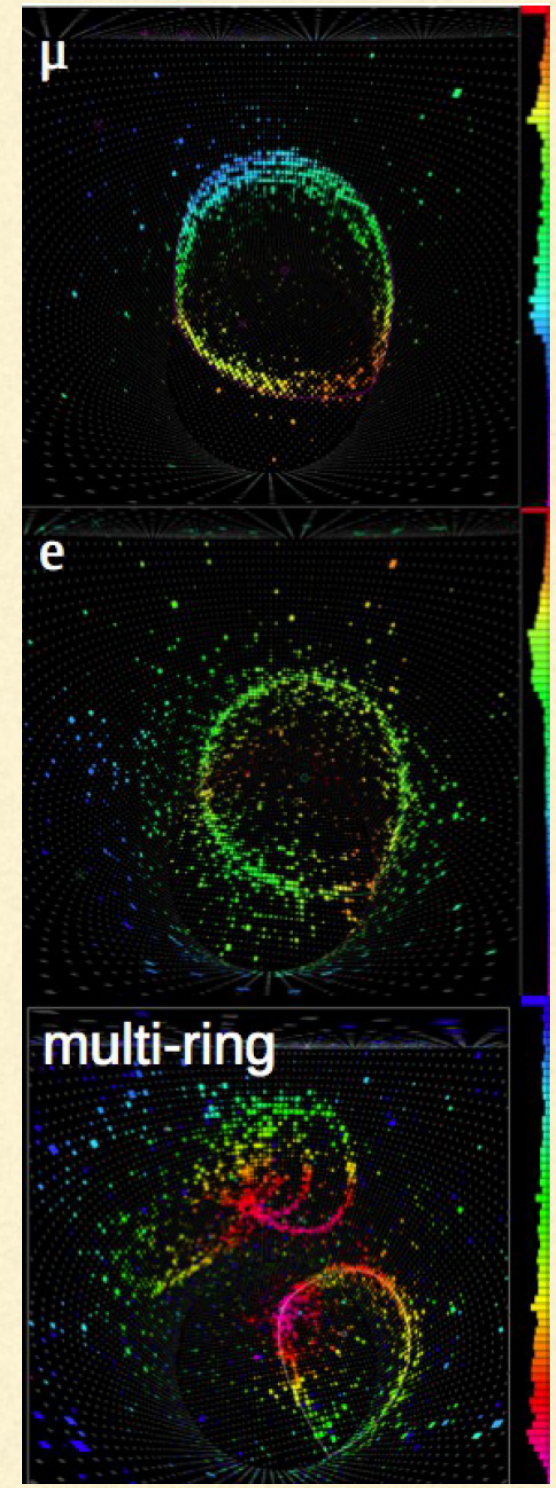
SUPER-K SAMPLES





Update: Neutrino-mode ν_μ CC1π^+, complements existing ν_e CC1π^+





FULL JOINT ANALYSIS OF FHC AND RHC MUON AND ELECTRON EVENTS

Three analysis frameworks

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

	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	$\delta_{CP}=-2.18$ (Best fit)	Data
FHC 1Rμ	373.617	372.977	373.576	374.339	374.023	318
RHC 1Rμ	143.227	142.891	143.229	143.593	143.433	137
FHC 1Re	101.809	85.601	70.123	86.324	99.163	94
RHC 1Re	17.171	19.509	21.610	19.273	17.503	16
FHC 1Re1de	9.970	8.664	7.045	8.451	9.618	14
FHC ν_μ CC1π^+	115.383	114.884	115.357	115.864	115.662	134

ND280-tuned predictions using normal MO, 2021 PDG θ_{13}, $\sin^2\theta_{23}=0.528$

SYSTEMATIC UNCERTAINTIES

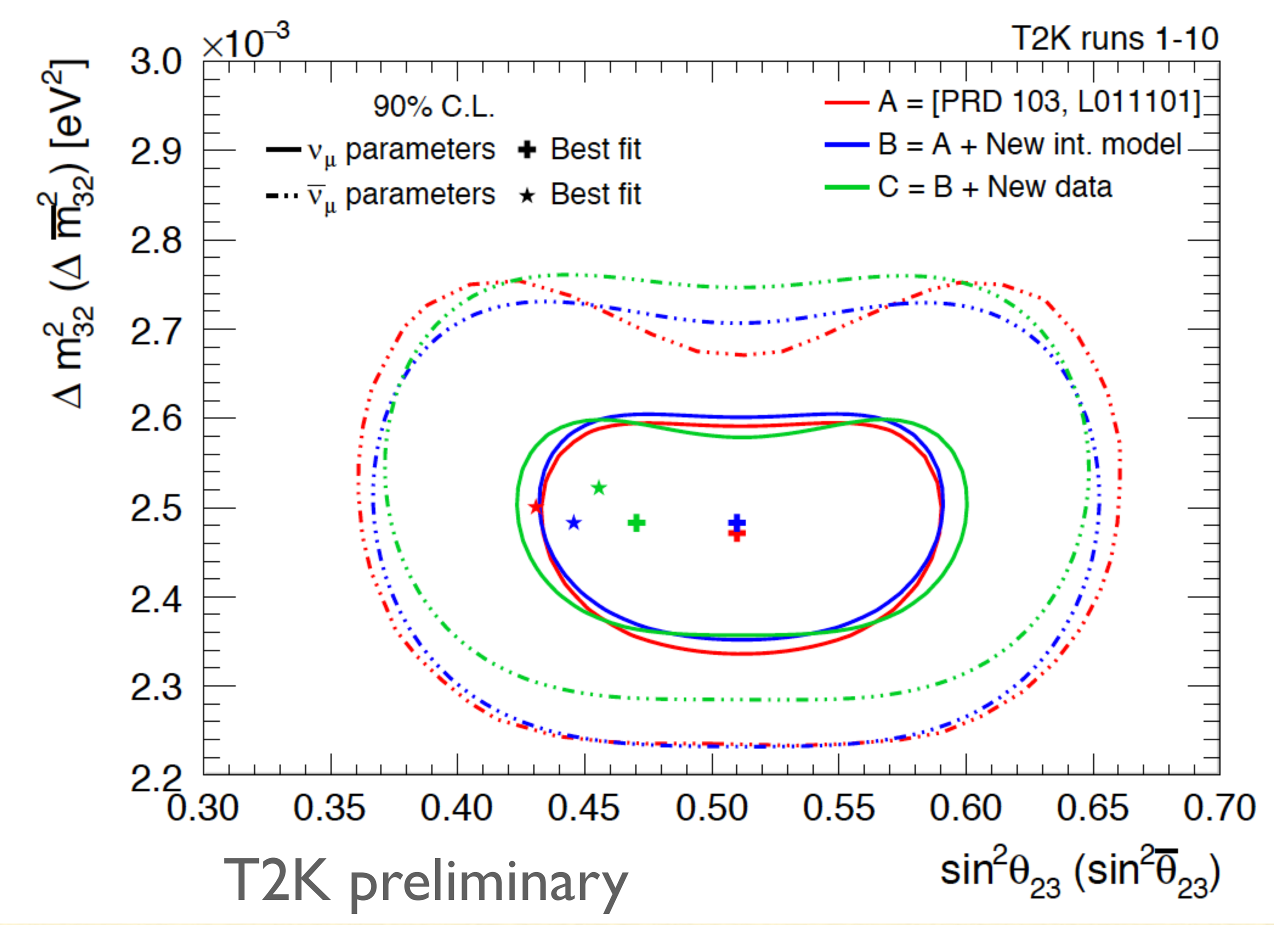
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6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

CPT TESTS WITH T2K

- Study appearance and disappearance channels
  - Use separate fitting params for neutrino and antineutrino: Δm^2_{23} and θ_{23}
  - Also consistent with previous T2K results Phys. Rev. D 103, L011101, tested effects of updated interaction model + new Super-K data



T2K HIGHLIGHTED IN NATURE

The Mirror Crack'd:

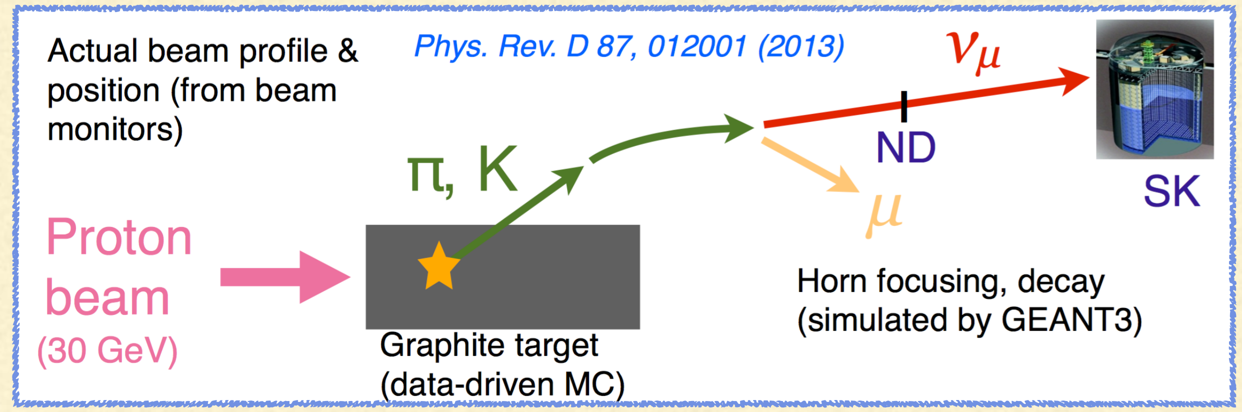
Constraining the matter-antimatter asymmetry with T2K

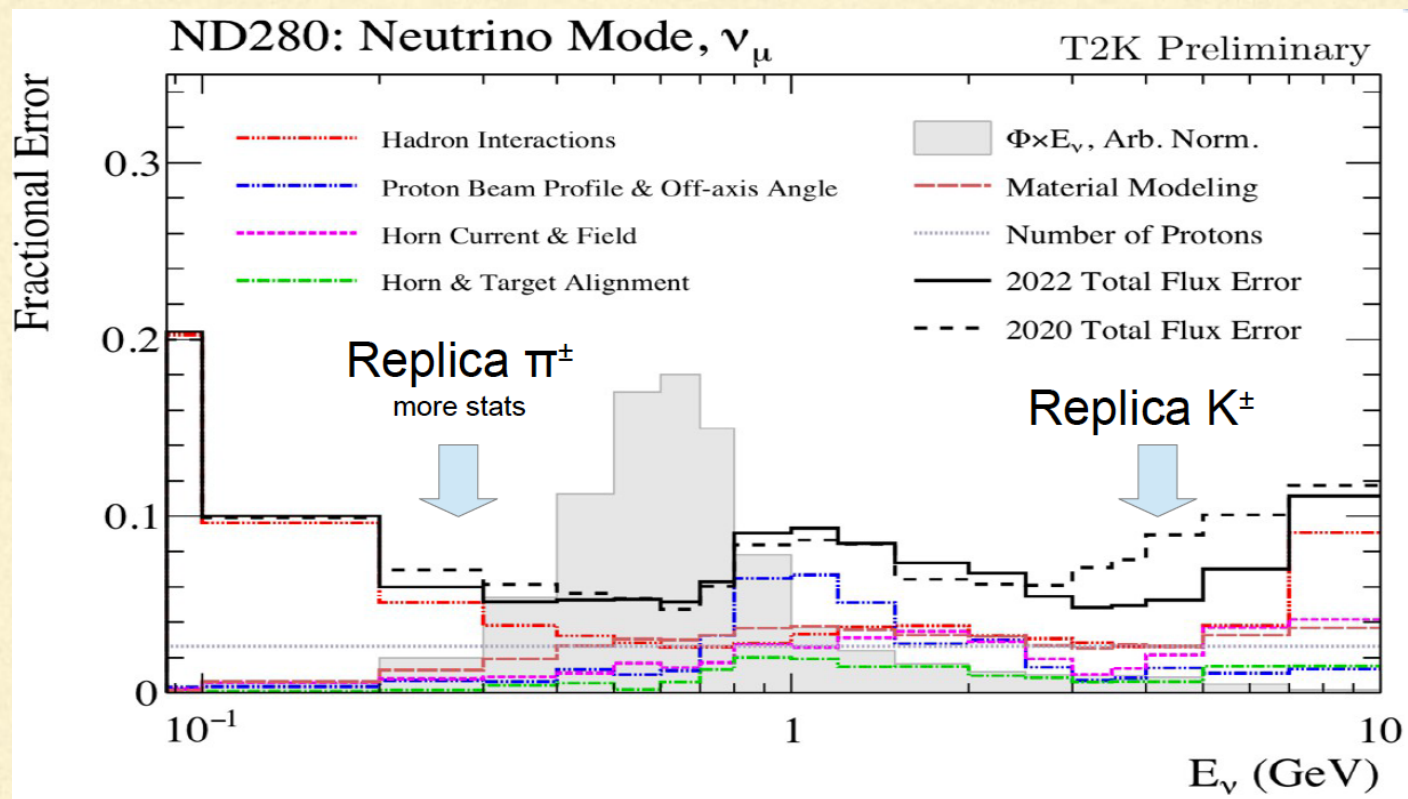
https://doi.org/10.1038/s41586-020-2177-0

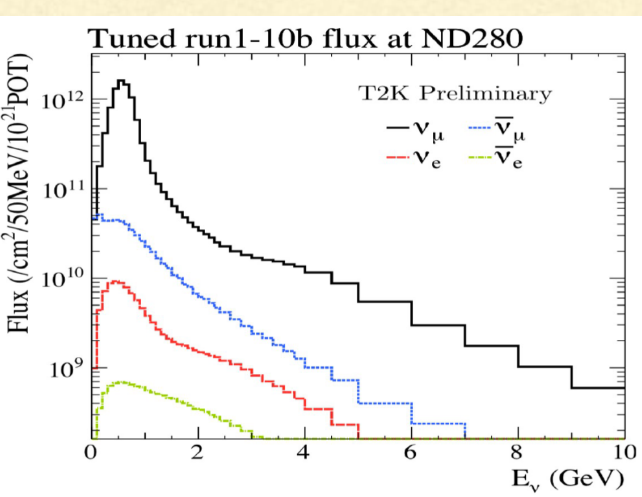
T2K NEUTRINO FLUX PREDICTION AND UNCERTAINTIES

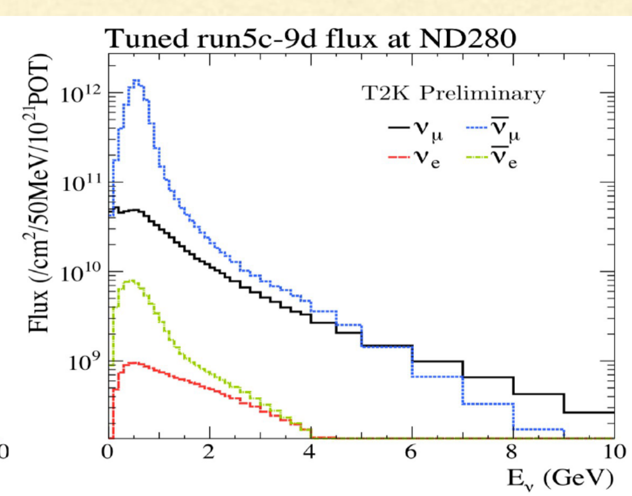
- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
- UPDATE: moved from 2009[1] T2K replica target data to 2010[2] one
  - more statistics for $\pi^{\pm}$ production.
  - adds $K^{\pm}$ and p data.
- Intrinsic ν_e background at ~0.4% level

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!