НЕЙТРИННАЯ ФИЗИКА В ПРОЕКТАХ T2K→T2K-II→HYPER-KAMIOKANDE

T2K

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НЦФМ, МГУ, Саров

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NEUTRINO OSCILLATIONS

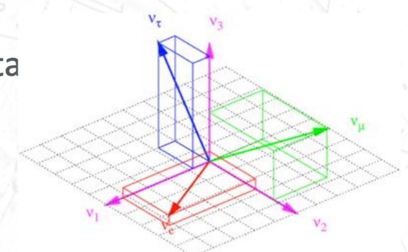
- Neutrino have mass and mixings:

- 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

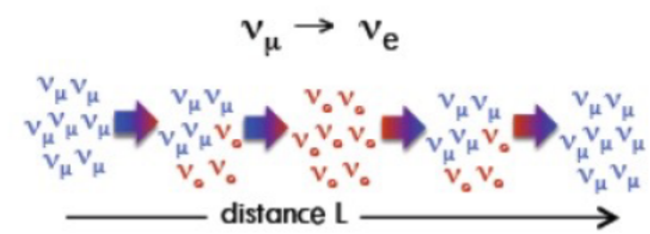
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

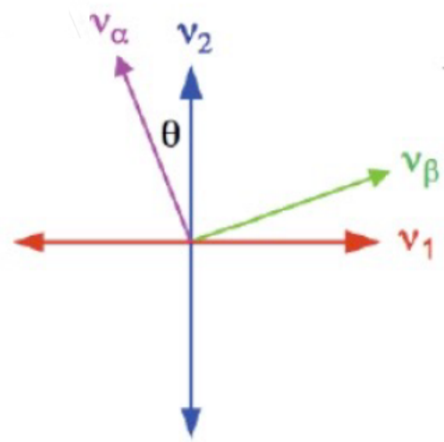
$$(\nu_e \quad \nu_\mu \quad \nu_\tau) = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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

Neutrino Oscillations imply neutrino mass





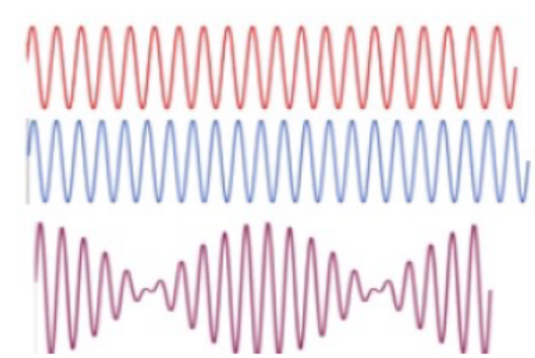
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

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)

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

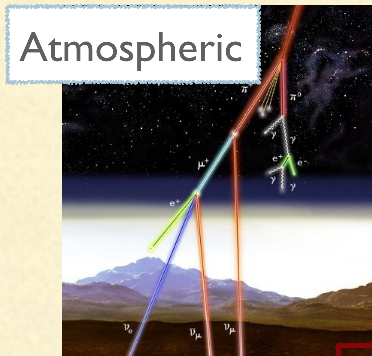
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

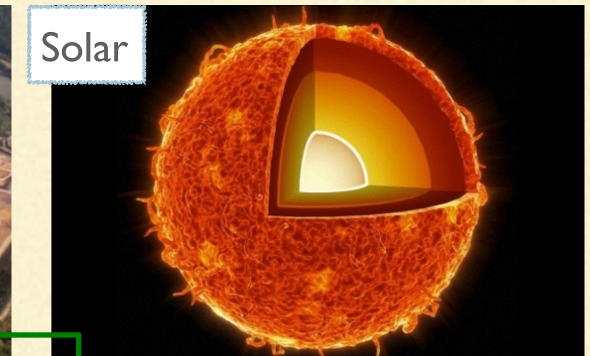


T2K

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 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:

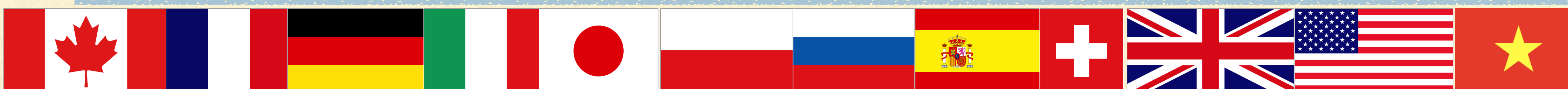
- CP-violation in lepton sector? δ_{CP} value?
- Mass hierarchy(MH), "normal" (NH) or "inverted"(IH):
  - $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$?
- Octant of θ_{23}: <, > or = 45°?
- Dirac/Majorana, steriles, Lorentz violation, CPT…

T2K (TOKAI-TO-KAMIOKA) EXPERIMENT

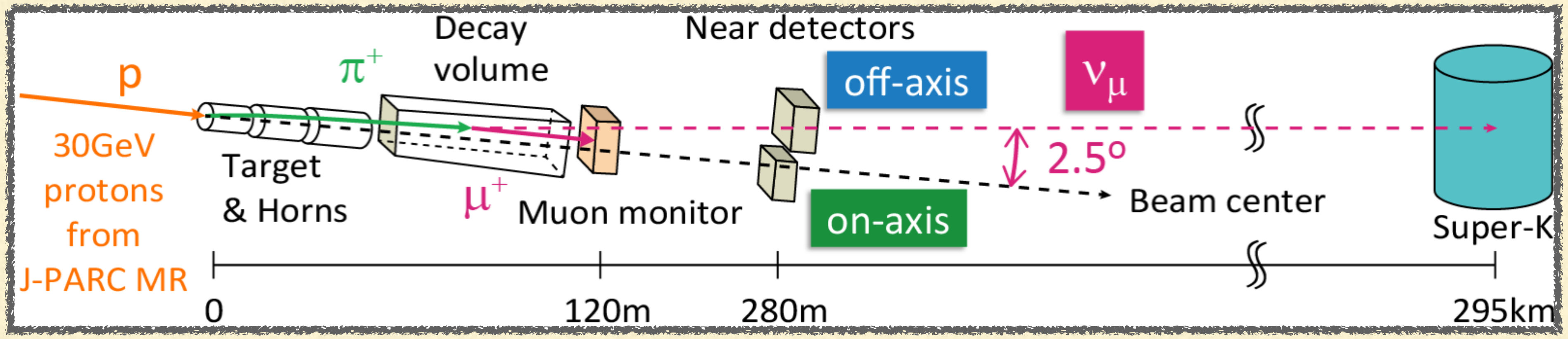
- World-leading neutrino physics project
- T2K — long-baseline neutrino oscillation accelerator experiment in Japan
- International collaboration:
  - ~500 members, 12 countries

Taking data since 2010

Russia: INR RAS and JINR Dubna



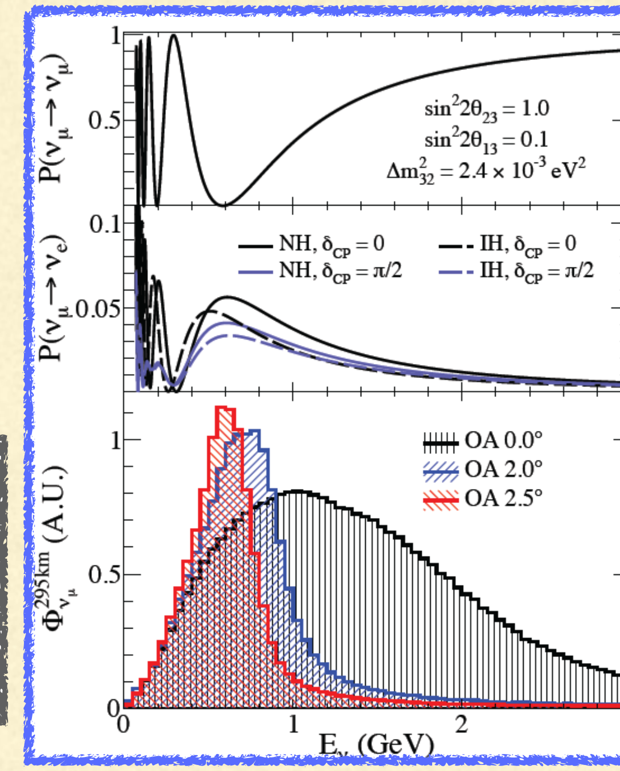
T2K DESIGN



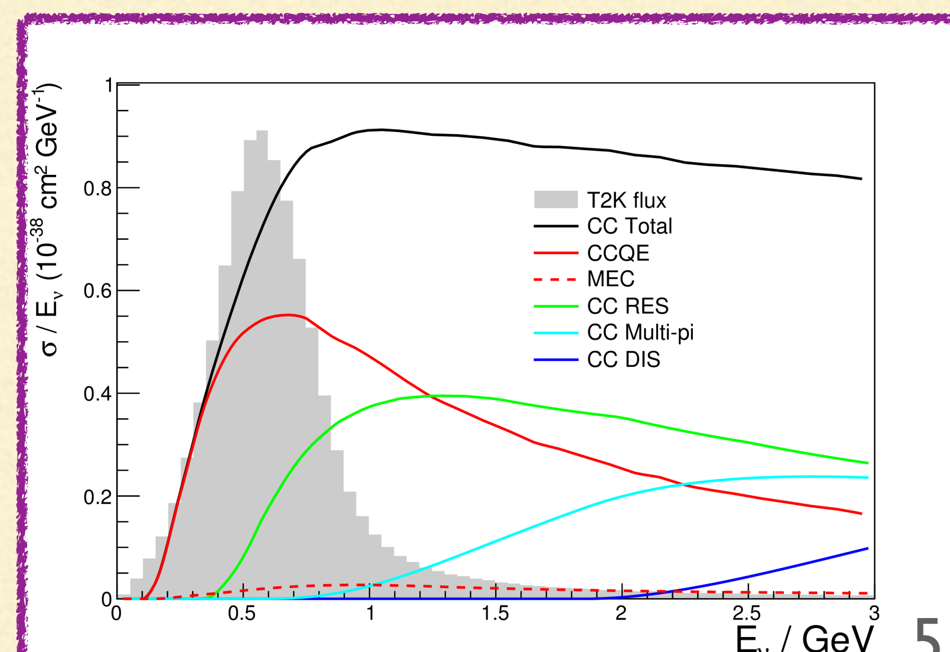
$$N_{ND} \sim \Phi_{ND} \cdot \sigma_{ND} \cdot \epsilon_{ND}$$

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)**
- Neutrino and antineutrino enhanced modes via horn polarity switching
- Dominant process for ν detection: charged-current quasi-elastic interactions (CCQE)
- **Reduced intrinsic ν_e contamination (≲1%)**
- **Reduced backgrounds from high-energy tail**



NEUTRINO OSCILLATIONS IN T2K

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

"Disappearance" channel

- **Precise measurement of "atmospheric" parameters θ_{23} and Δm^2_{32} and CPT test via ν vs anti-ν analysis**

From Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13}\sin^2\theta_{23}\times\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Leading term

CP-violating
"+" sign for anti-ν

$$-\alpha\sin\delta_{CP}\times\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\times\sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP-conserving

$$+\alpha\cos\delta_{CP}\times\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\times\cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

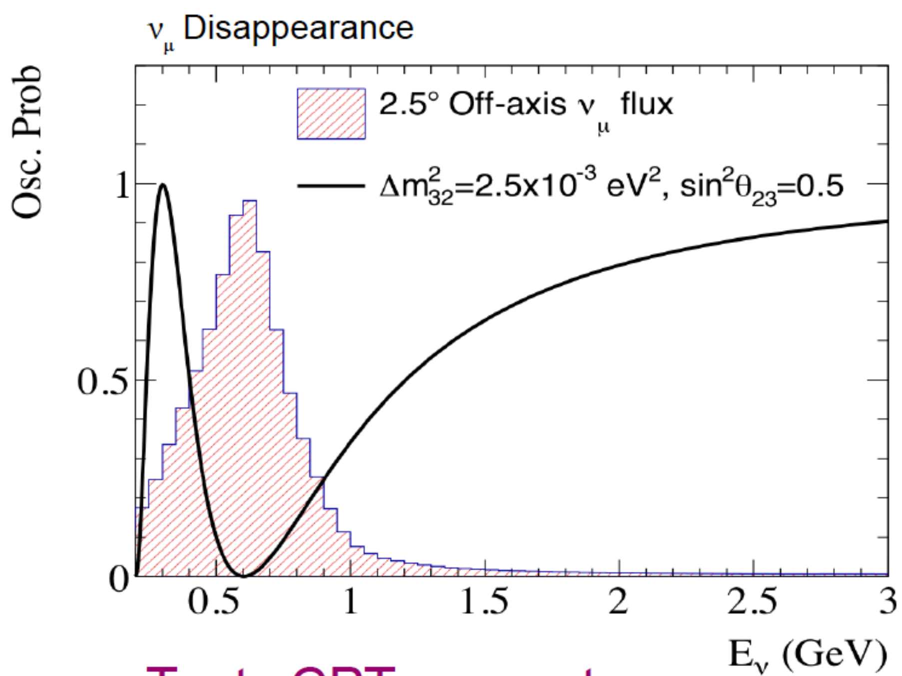
$$+O(\alpha^2) \quad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31}L}{4E} \quad x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

"Appearance" channel: measuring θ_{13} and probing CP-violation (CPV)

- **Leading term defines the octant of θ_{23}: <, > or = 45°**
- **Sub-leading term accounts for CPV: enhanced effect when comparing neutrino and antineutrino data**

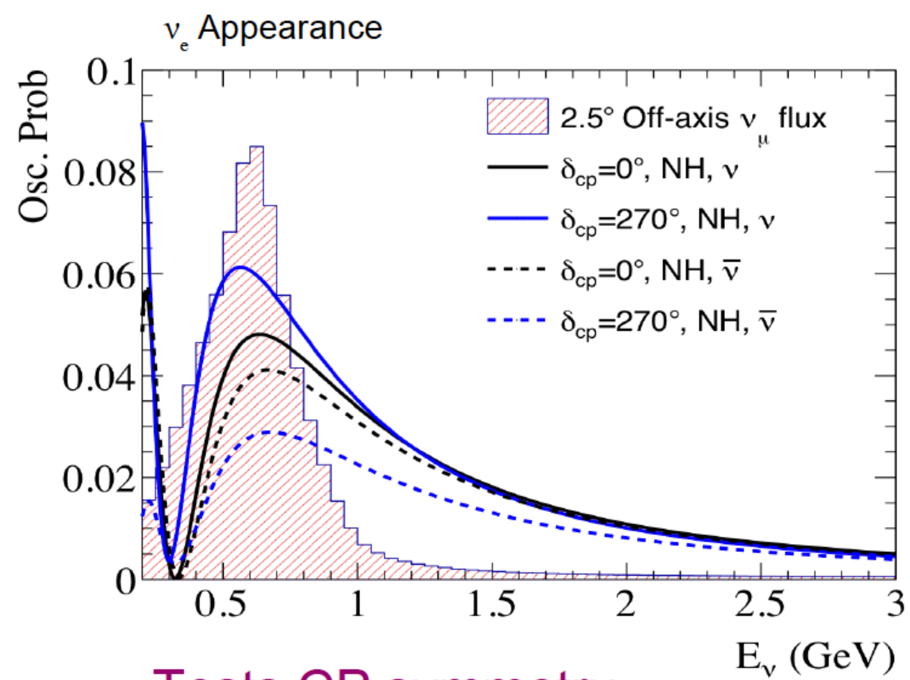
*** T2K leading efforts**

NEUTRINO OSCILLATIONS IN T2K



- Tests CPT symmetry
- LO* dependence on $\sin^2 2\theta_{23}$
  - hard to distinguish θ_{23}>45° from θ_{23}<45°
- LO dependence on $|\Delta m^2_{32}|$
  - doesn't depend on sign of mass splitting

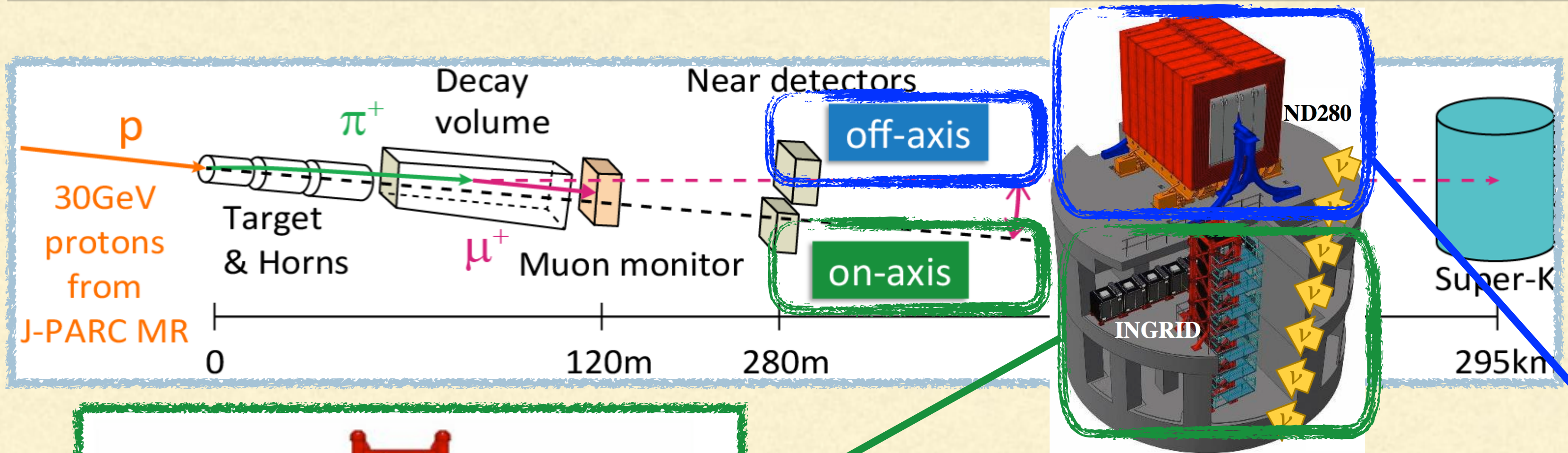
(* Leading Order)

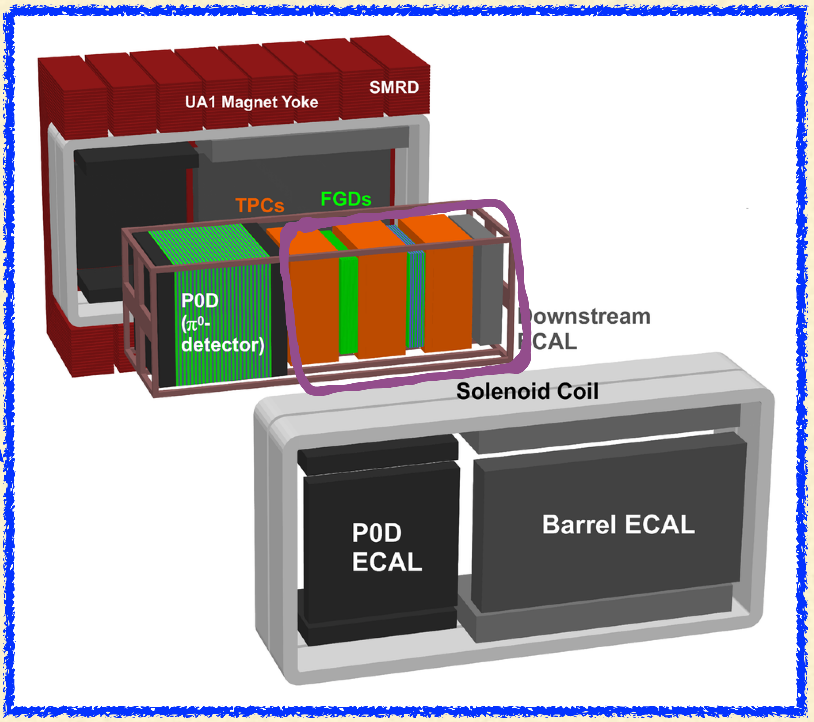


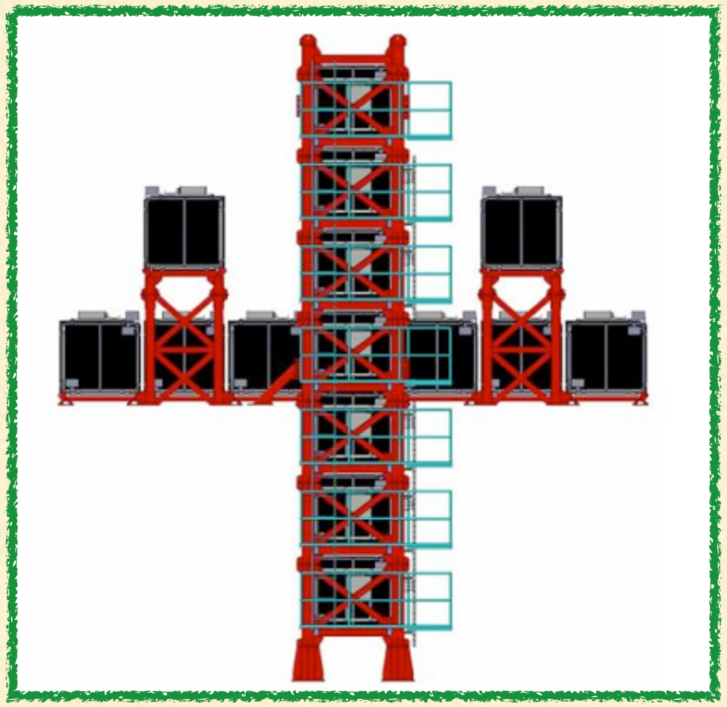
- Tests CP symmetry
- LO dependence on $\sin^2 2\theta_{13}$, $\sin^2 \theta_{23}$
  - can separate θ_{23}>45° from θ_{23}<45°
- Sub-leading dependence on $\sin(\delta_{CP})$
  - can detect CP violation (~27% effect)
- Sub-leading dependence on $\pm\Delta m^2_{32}$
  - ~10% matter effect

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

NEAR DETECTOR COMPLEX

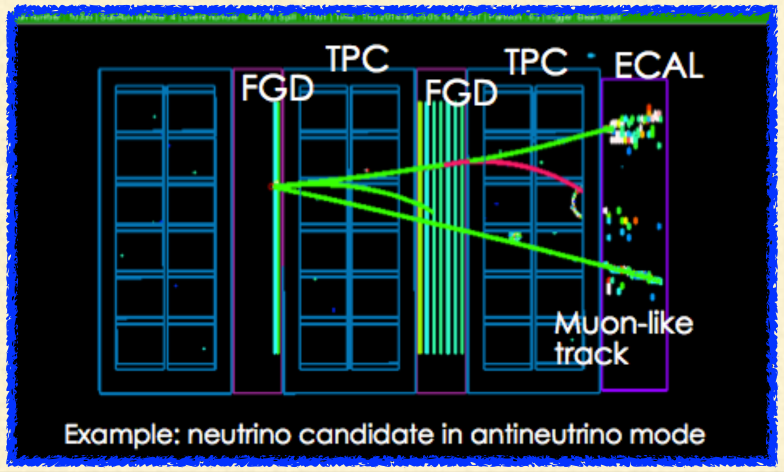


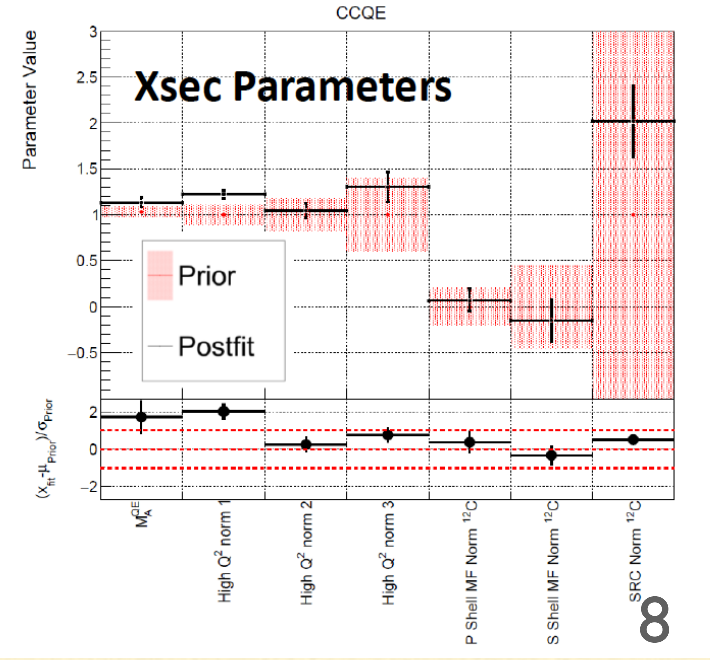




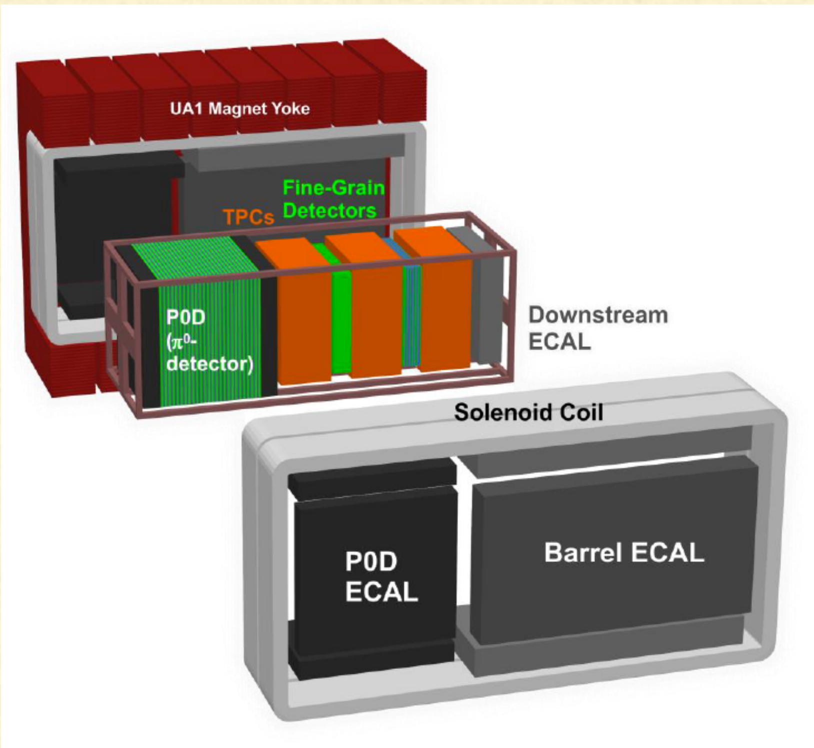
- **Off-axis detector ND280**
- **Detectors in 0.2 T B field**
- **Tracker:**
  - **Time projection chambers**
  - **Scintillator fine-grained detectors**

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



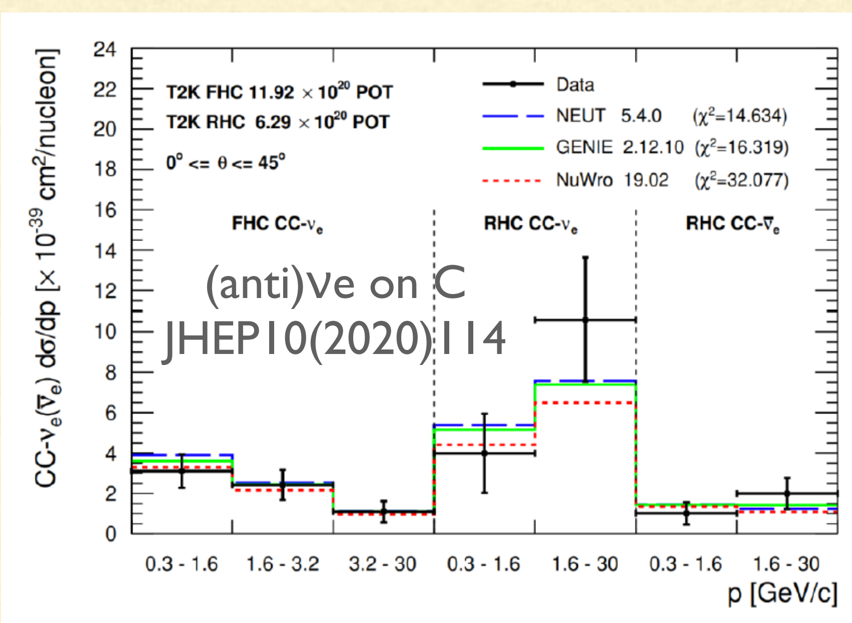


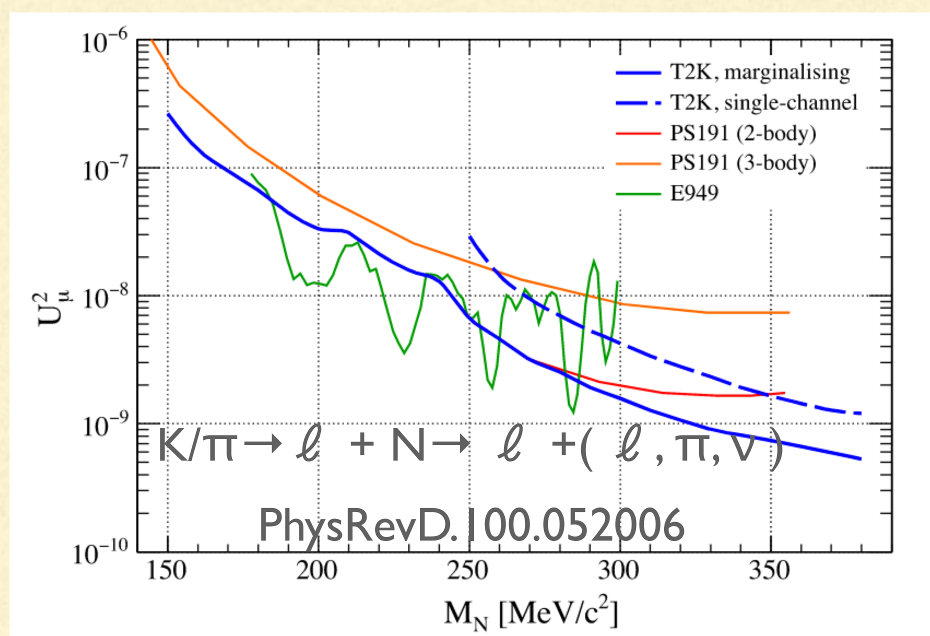
ANALYSES WITH T2K ND280

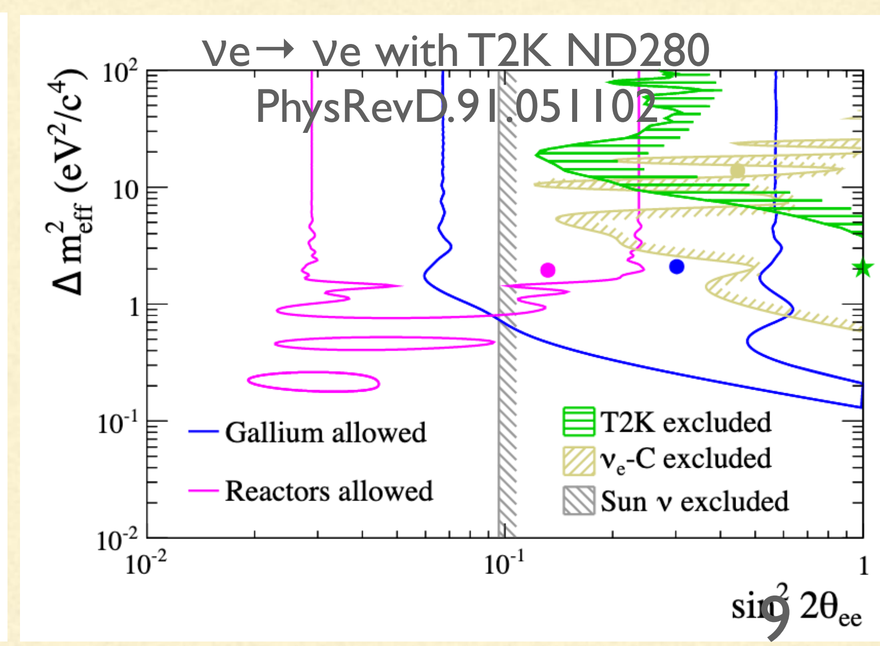


- Constrain flux and ν interaction model parameters prior to oscillations
- 30 GeV protons on C target, intense ν beam from π/K + complex detector →
- **Rich opportunities for physics** measurements:
  - Neutrino cross-sections
  - New physics signals
    - Light-sterile neutrinos with SBL oscillations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

* Доклад А. Горина

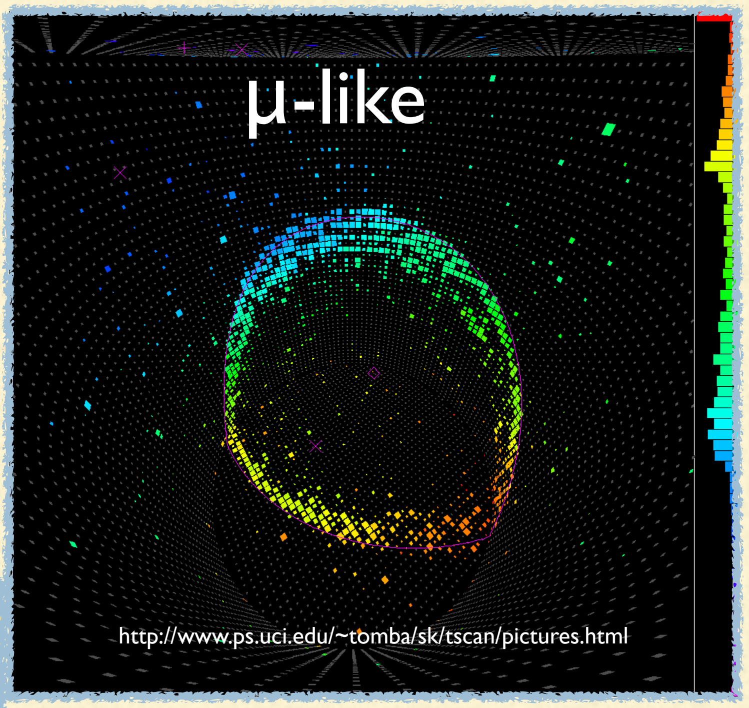


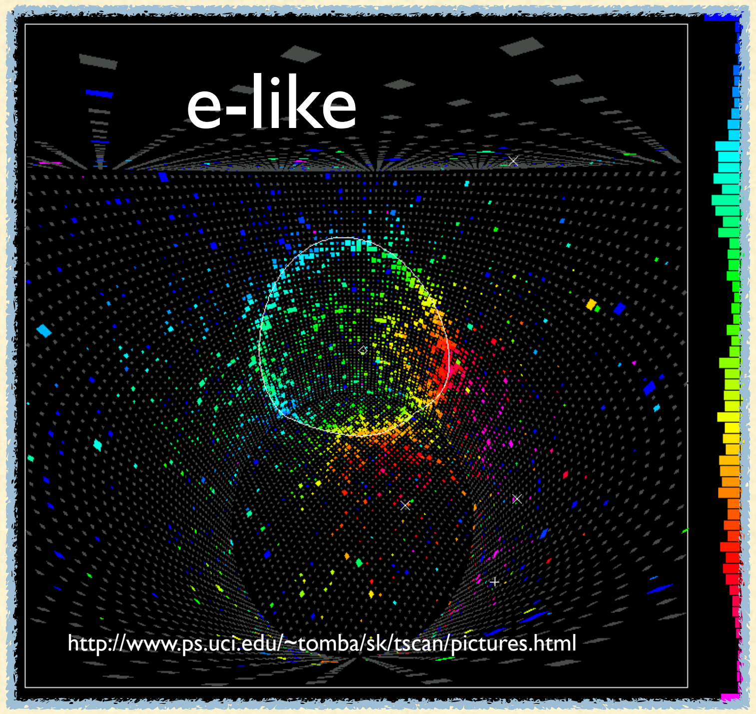


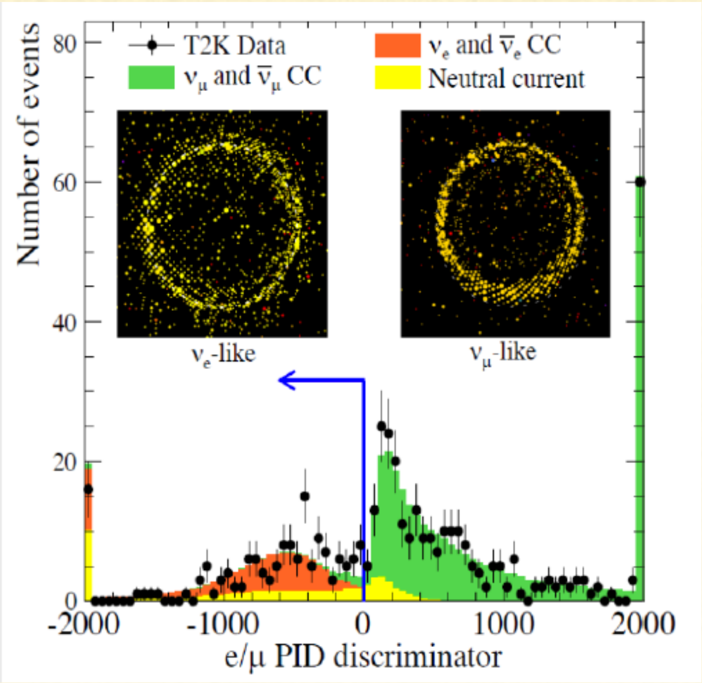


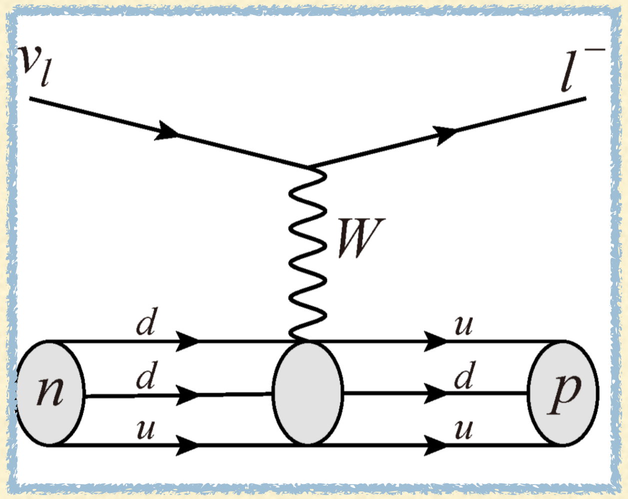
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

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



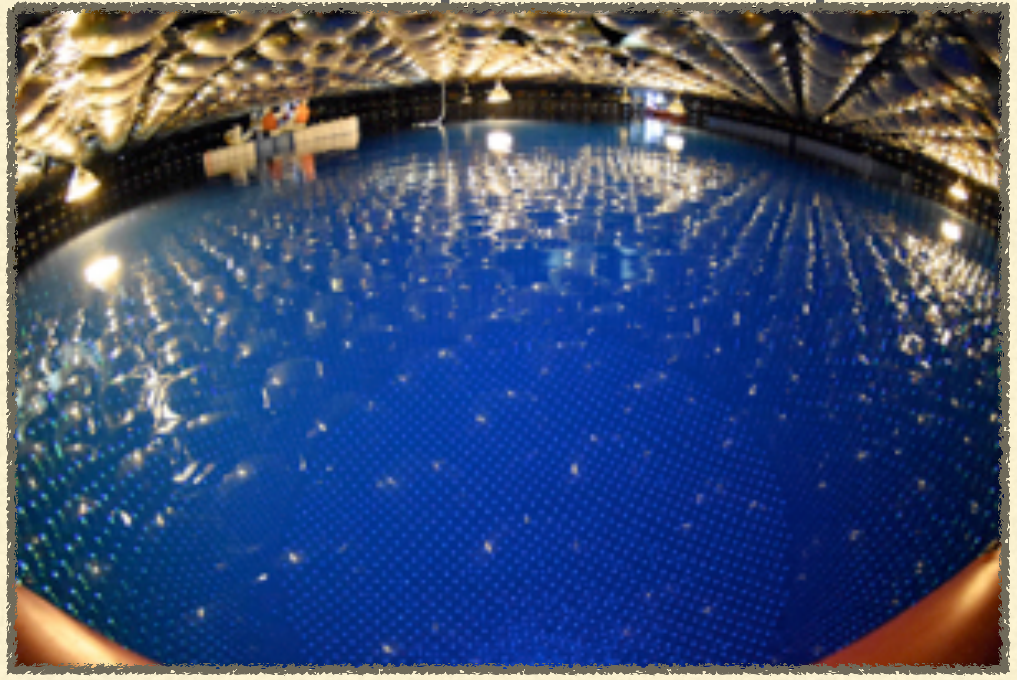




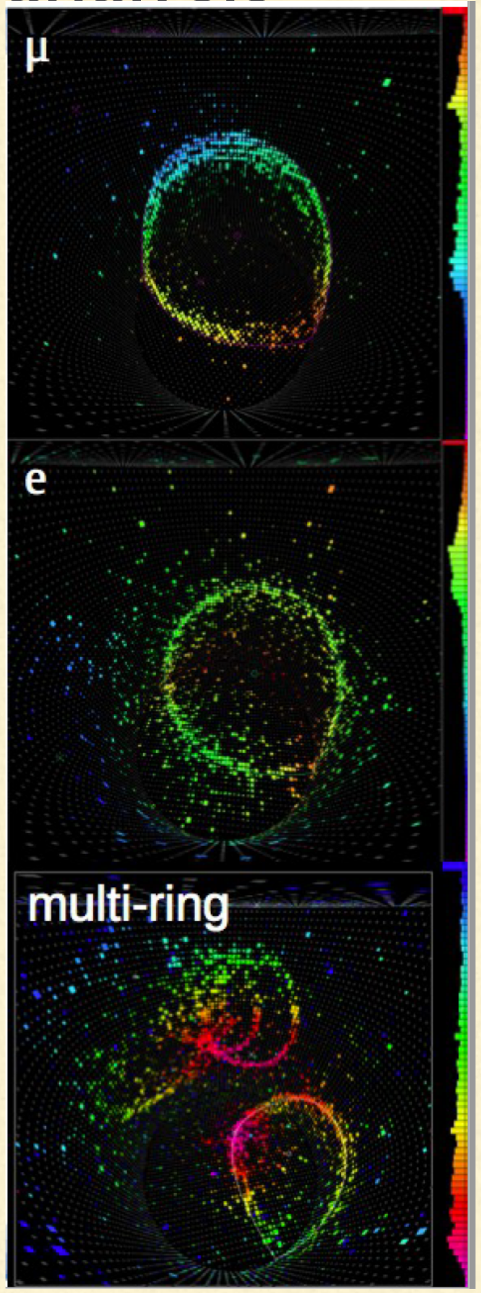


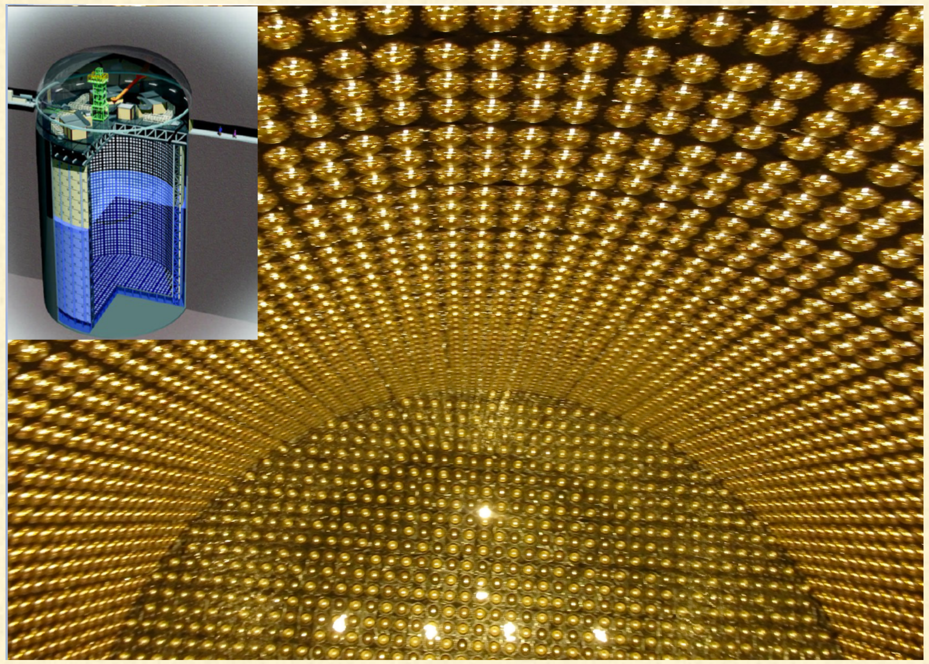
FAR DETECTOR MEASUREMENTS SUPER-KAMIOKANDE (SUPER-K)

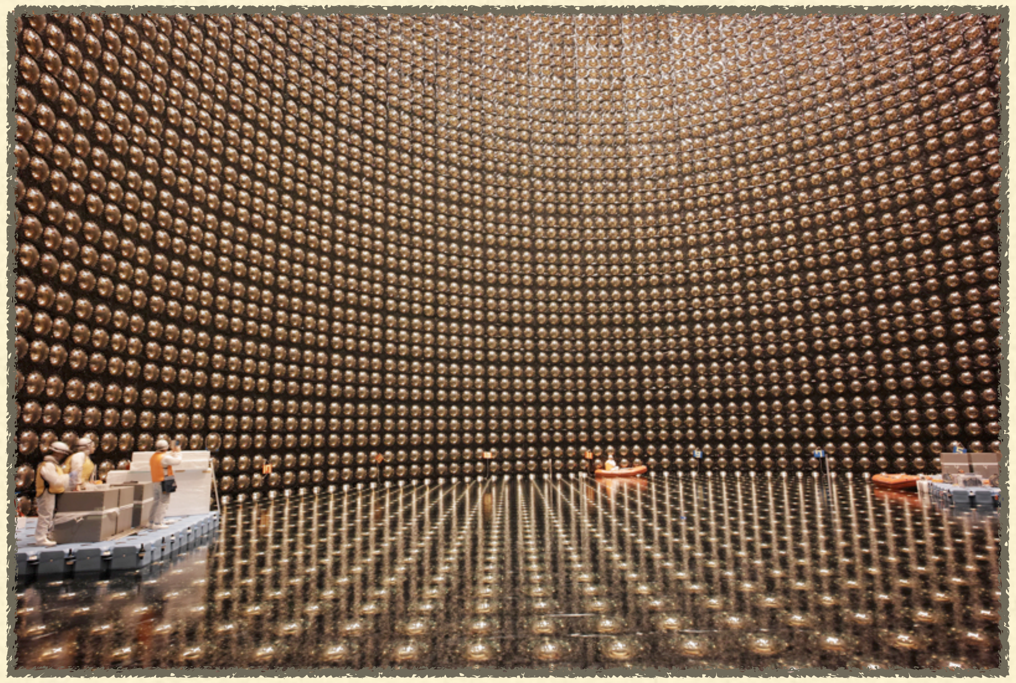
- Total 6 Super-K samples currently used in oscillation analysis



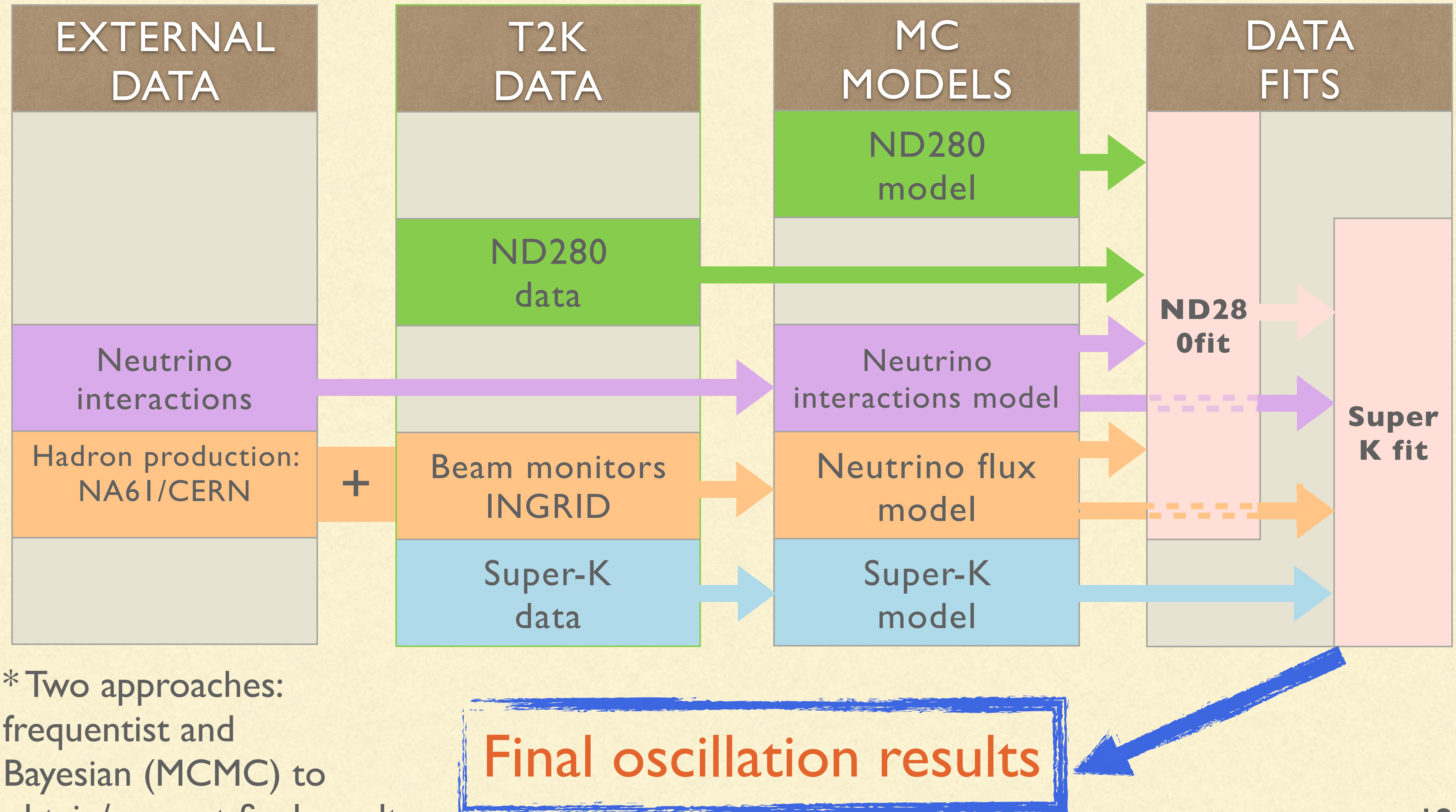
Mode	Sample Name	Description
ν	1Re	One e-like ring in ν mode
	1Re CC1π+	One e-like ring and Michel electron in ν mode
	1Rμ	One μ-like ring in ν mode
	MRμ CC1π+ (Multi-Ring)	Two rings (μ + π) + ME or 1 μ-ring + 2 ME
$\bar{\nu}$	1Re	One e-like ring in $\bar{\nu}$ mode
	1Rμ	One μ-like ring in $\bar{\nu}$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





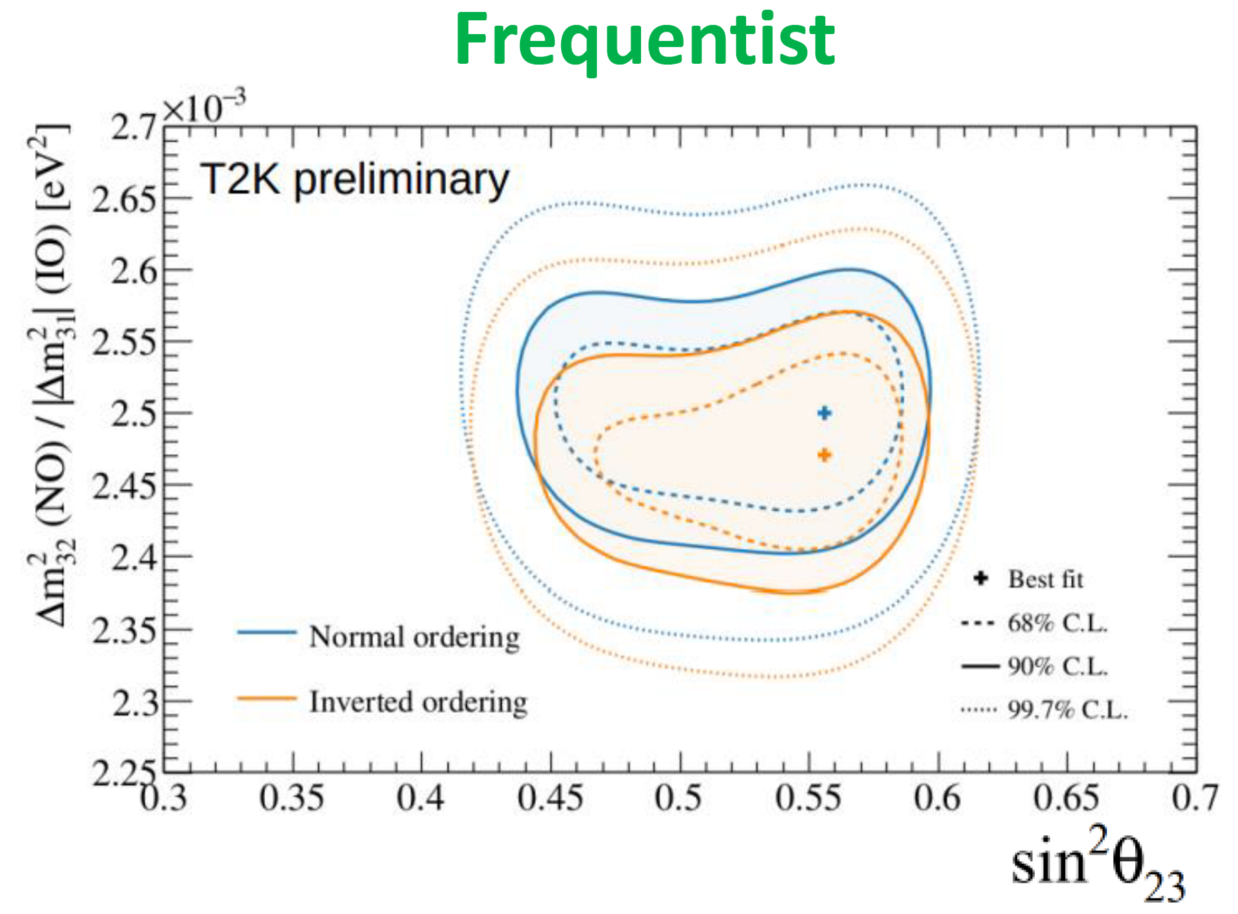


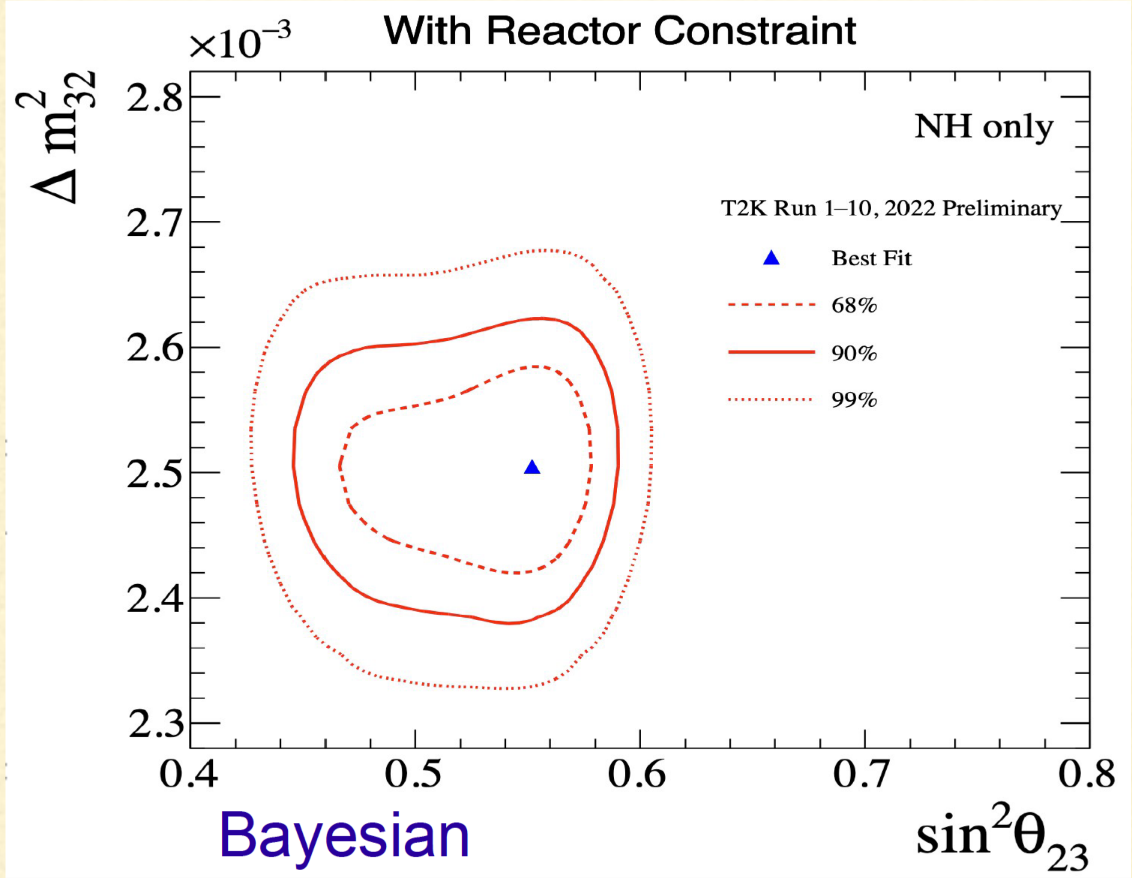
T2K ANALYSIS STRATEGY



* Two approaches: frequentist and Bayesian (MCMC) to obtain/present final results

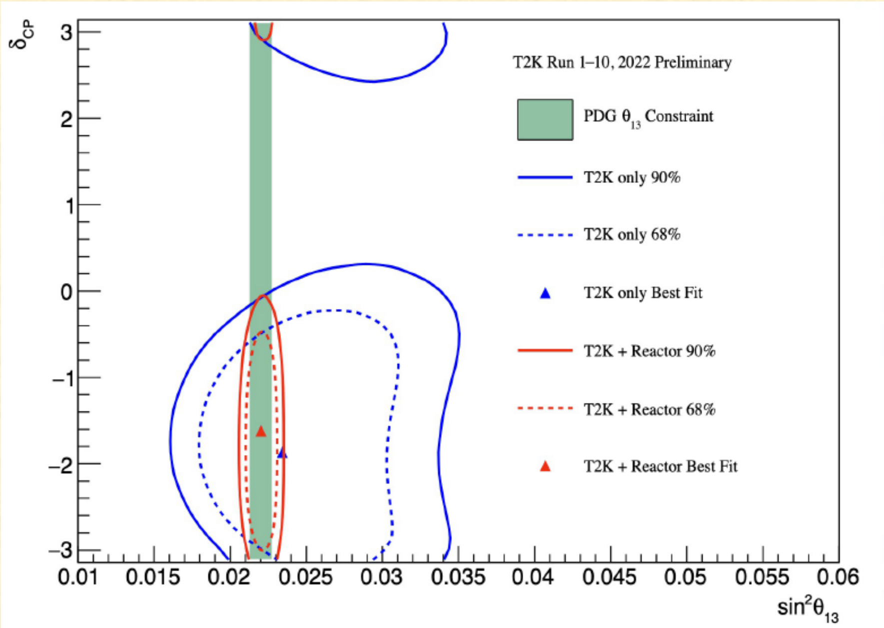
ANALYSIS RESULTS: ATMOSPHERIC PARAMETERS θ_{23} AND Δm^2_{32}



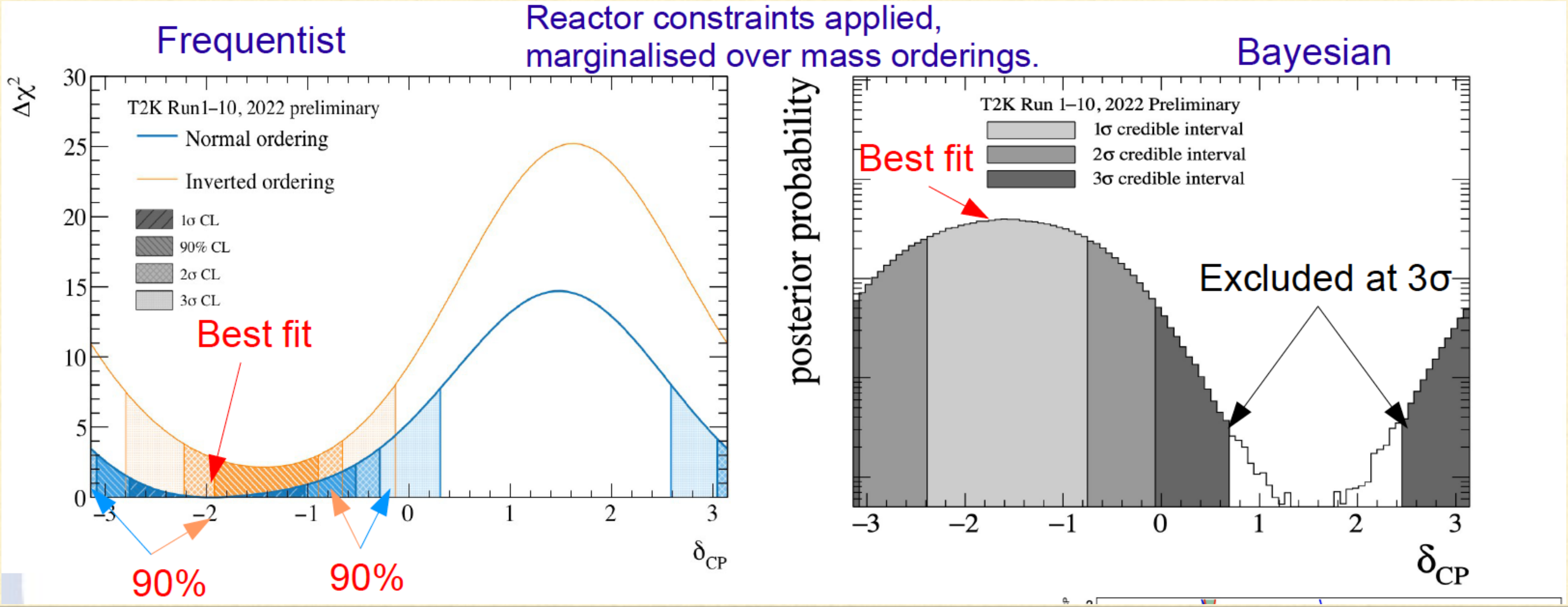


- 2022 analysis: joint fit of 6 Super-K samples with reactor data-driven constraint on θ_{13}
- Best-fit point in the upper octant
- Lower octant still consistent within 68% CL.

ANALYSIS RESULTS: θ_{13} MEASUREMENTS



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



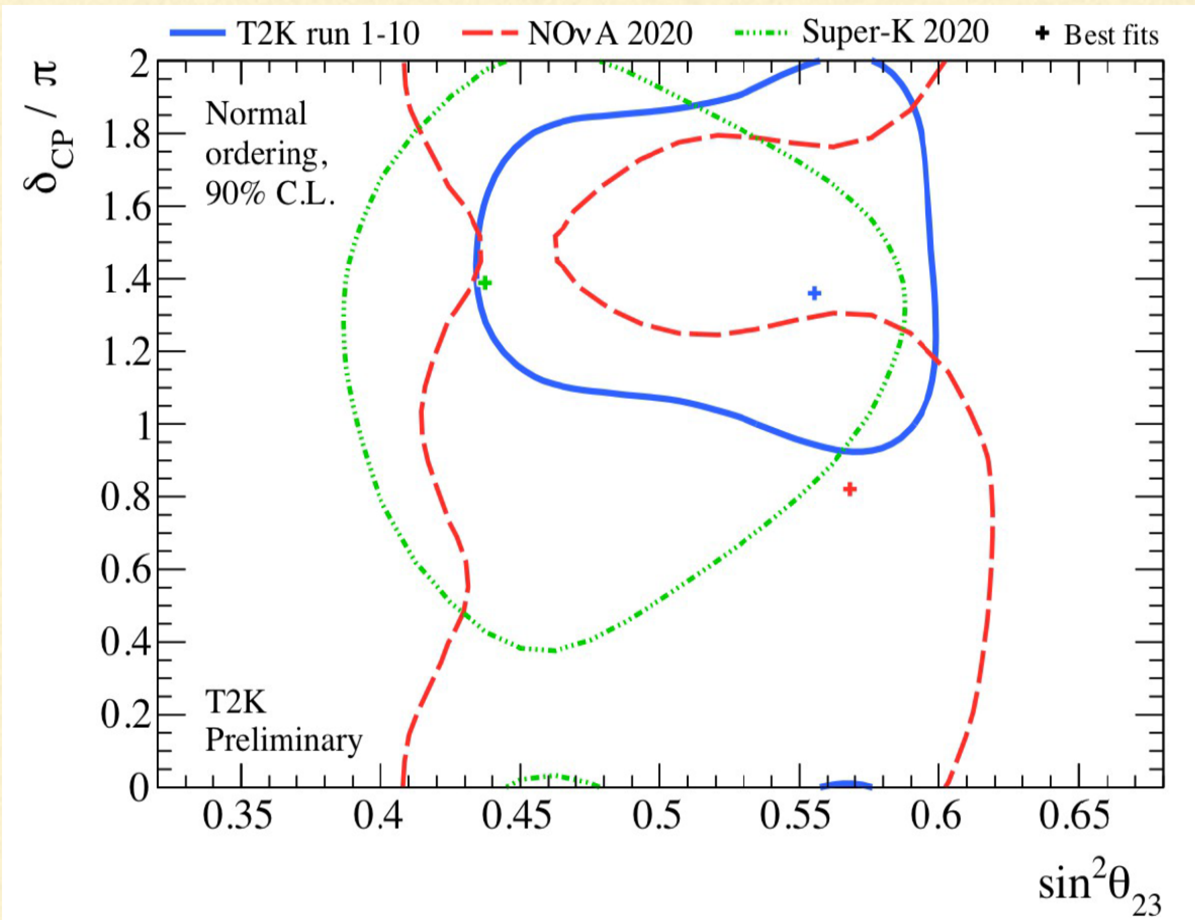
T2K HIGHLIGHTED IN NATURE

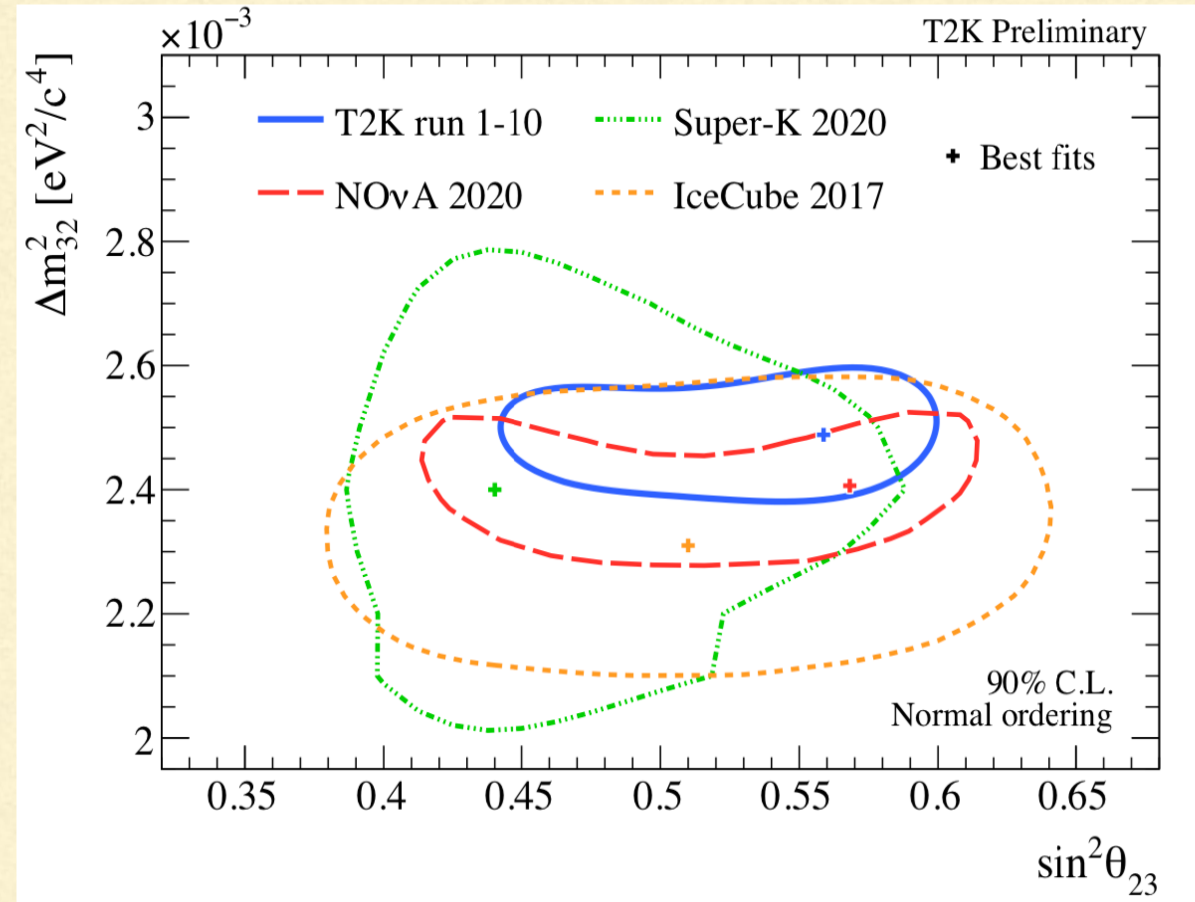
The Mirror Crack’d:

Constraining the matter-antimatter asymmetry with T2K

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

T2K VS OTHER MEASUREMENTS

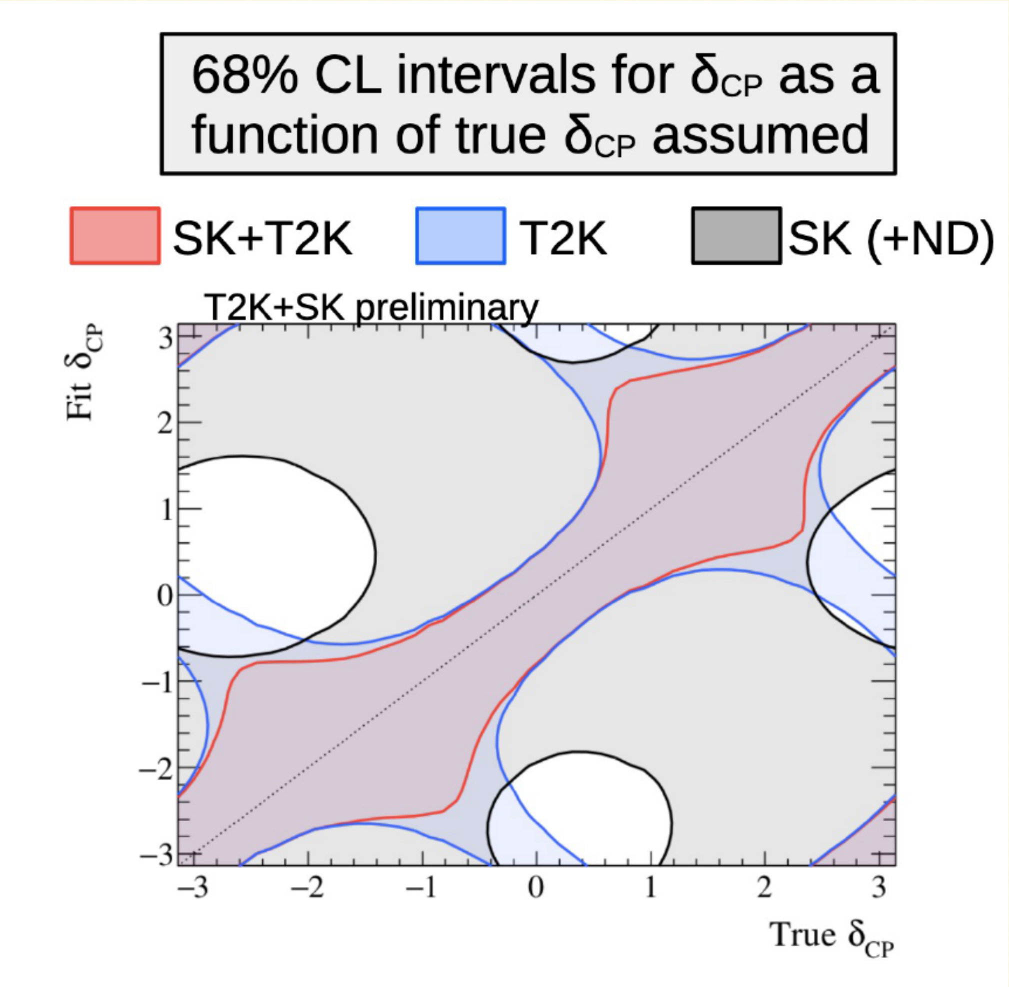


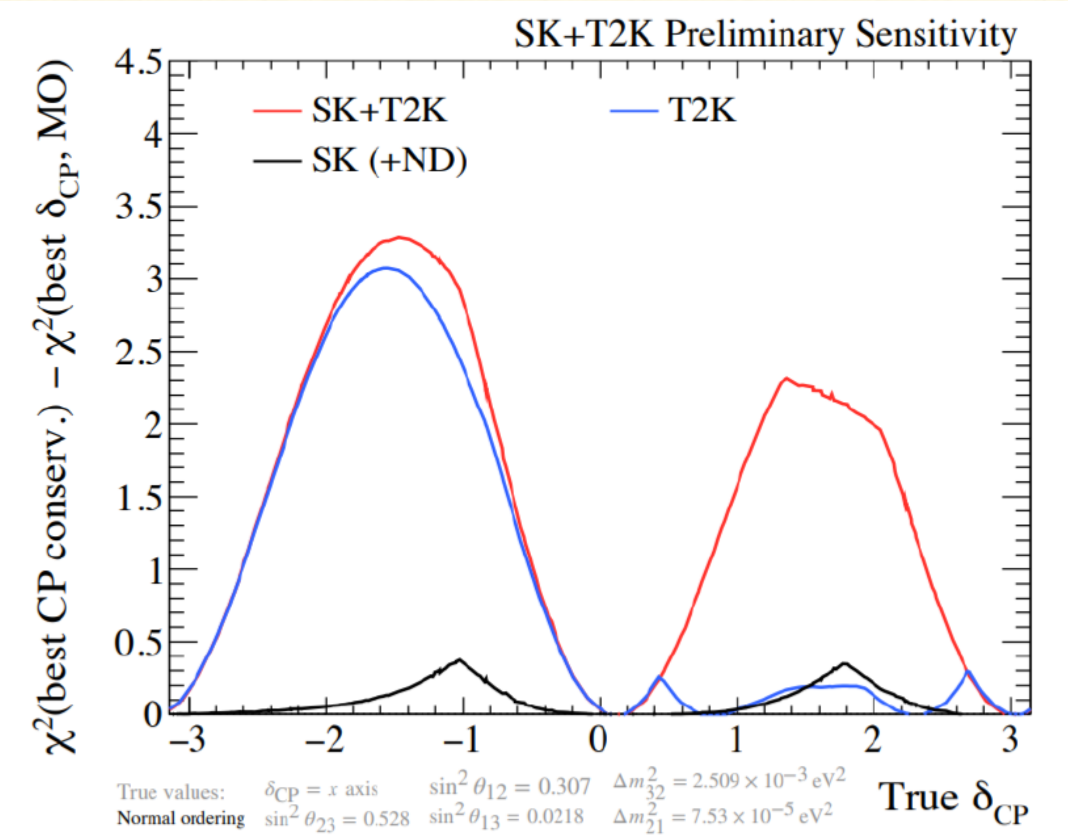


- δ_{CP}-vs-$\sin^2\theta_{23}$: at 90% CL, δ_{CP} T2K, NOνA and Super-K contours overlap. T2K consistent with Super-K best fit, NOνA best fit just outside contour
- δ_{CP}-vs-$\sin^2\theta_{23}$: at 90% CL, θ_{23} contours overlap. T2K and NOνA favour upper octant while Super-K prefers lower

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(δ_{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

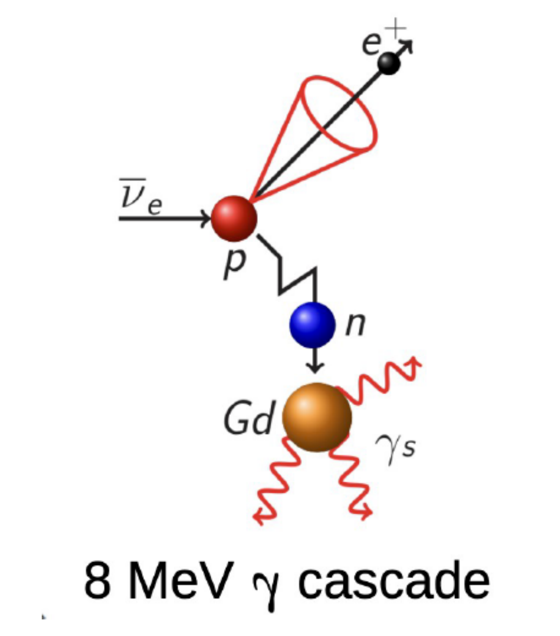


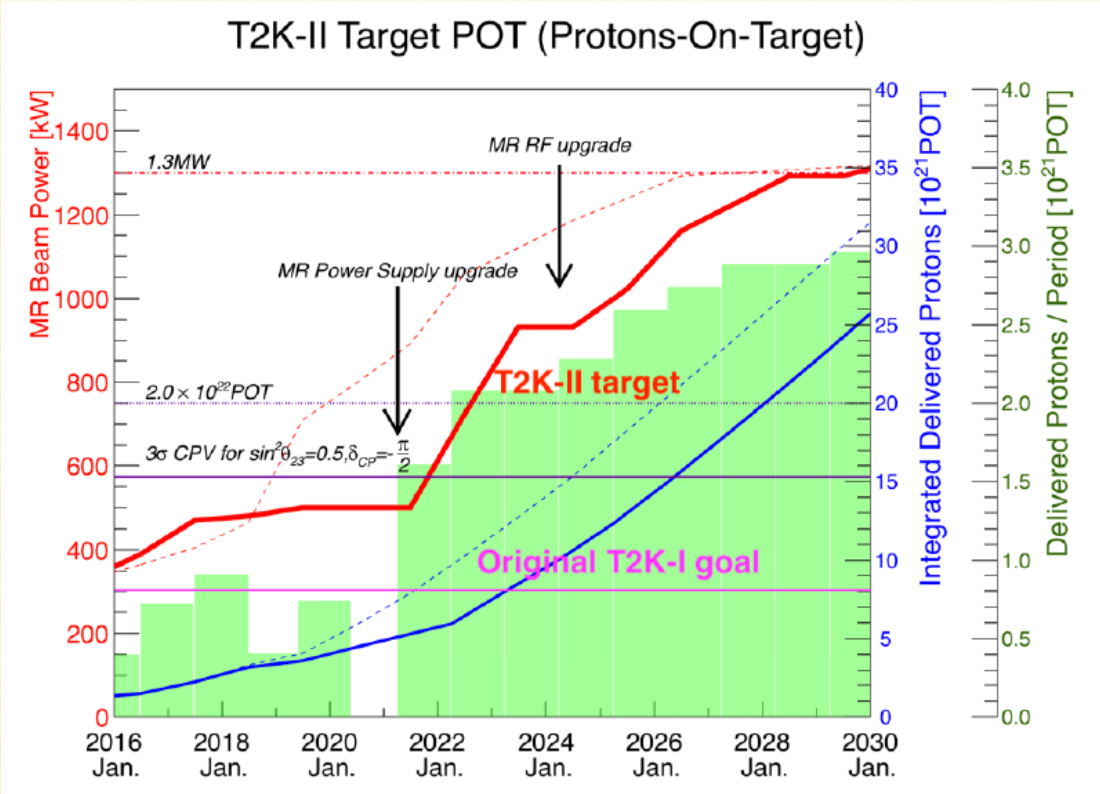


SK(+ND) — ND fits used to constrain model params used for lowE Super-K samples

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

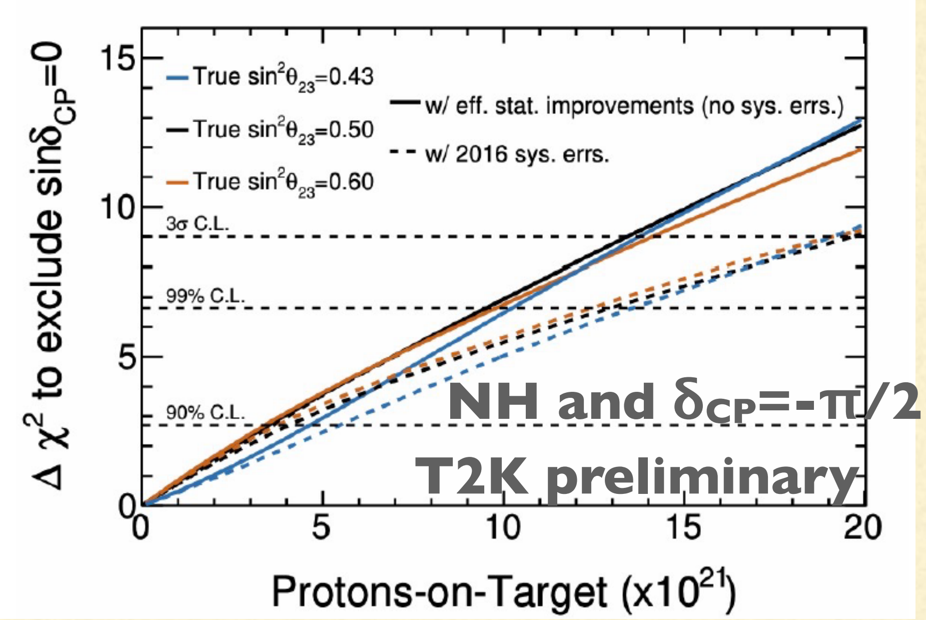


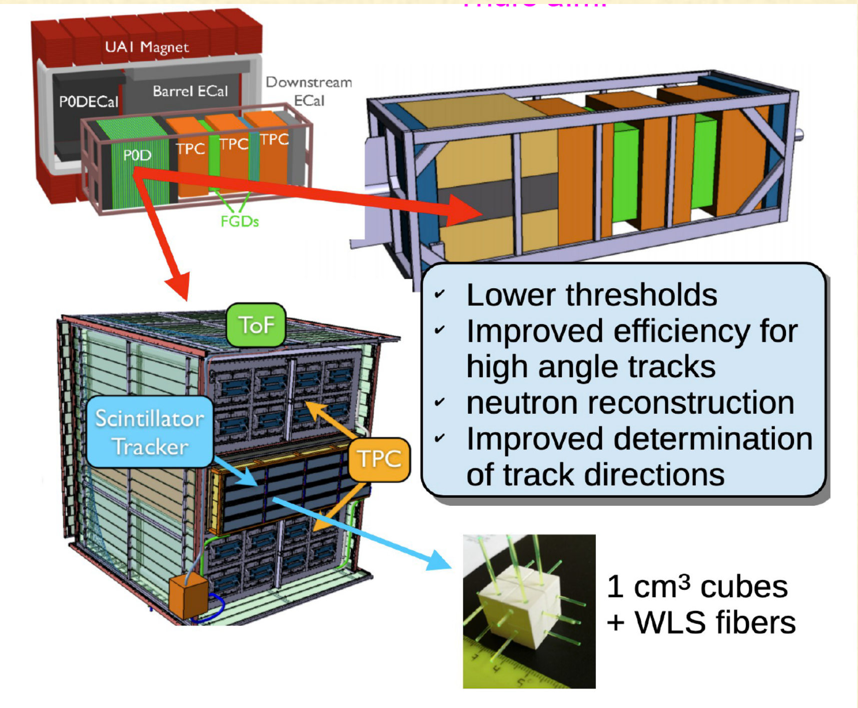


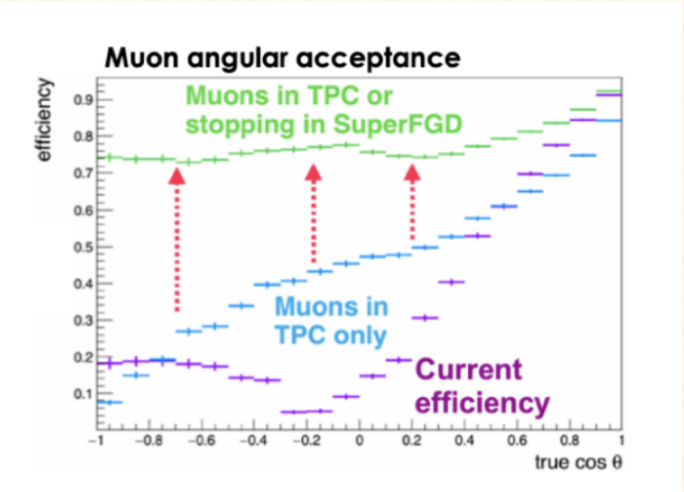
T2K FUTURE PROSPECTS: NEAR DETECTOR UPGRADE

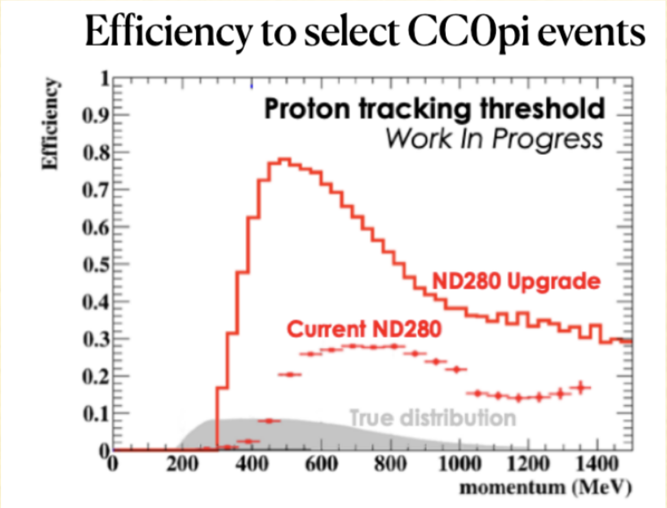
- Reduction of systematic uncertainties is crucial
  - 18% (2011) → 5-7% (2022) → 4%(202X..)
- ND280 measurements are crucial
- Near detector upgrade
  - Increase phase-space available
  - Reduce thresholds for ν products detection
  - Neutron detections for anti-neutrinos
  - Key element → **Super-FGD* 3D-cubes** based segmented plastic scintillator detector ← designed by INR RAS
    - Detector elements arrived in Japan in summer 2022

* Доклад С. Суворова







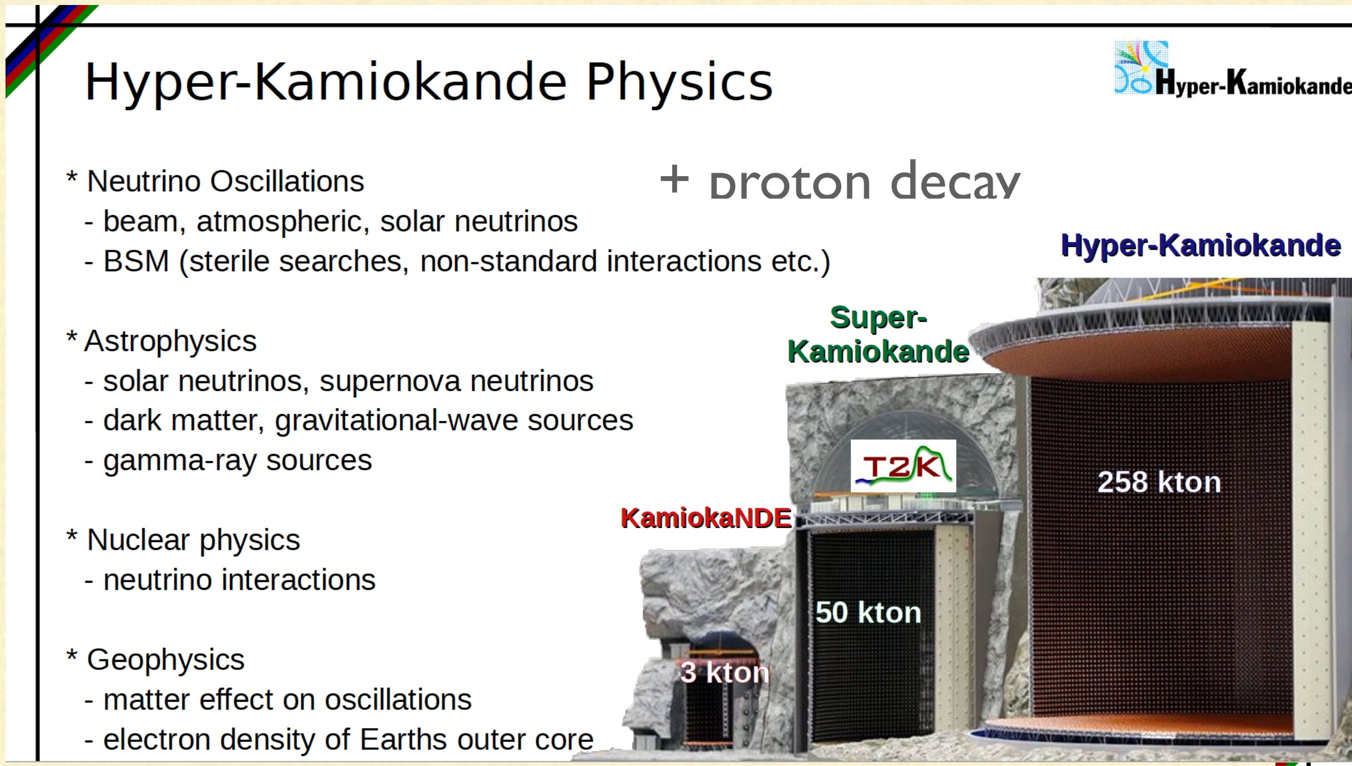


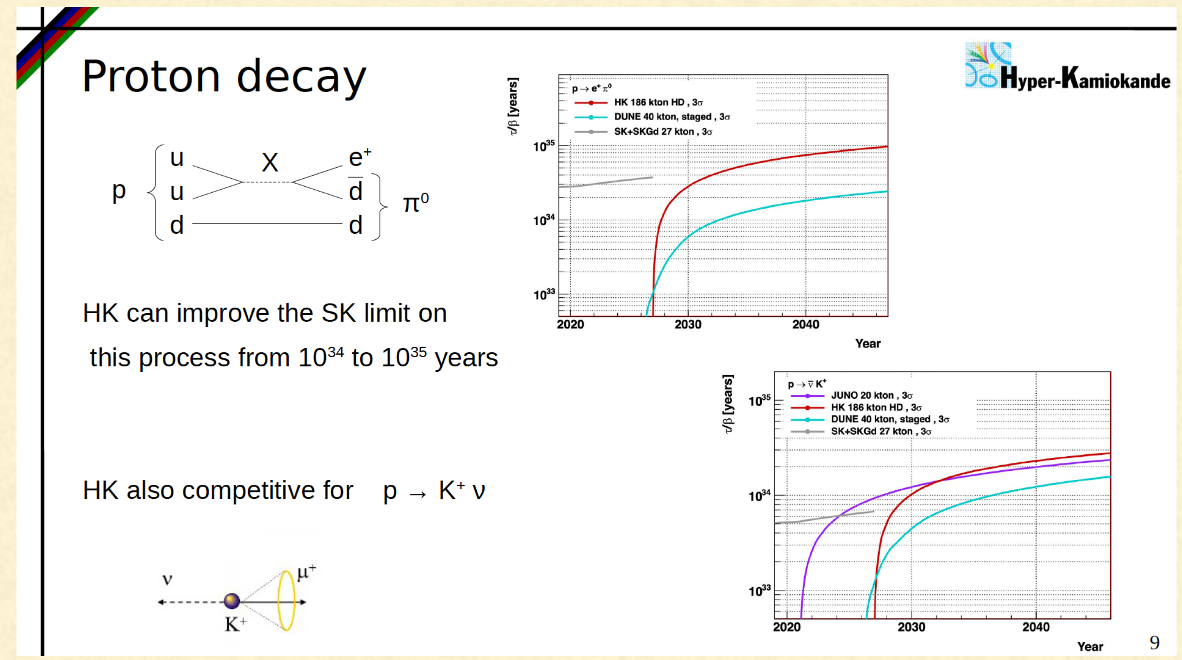
ND280Upgrade to start data taking in 2023

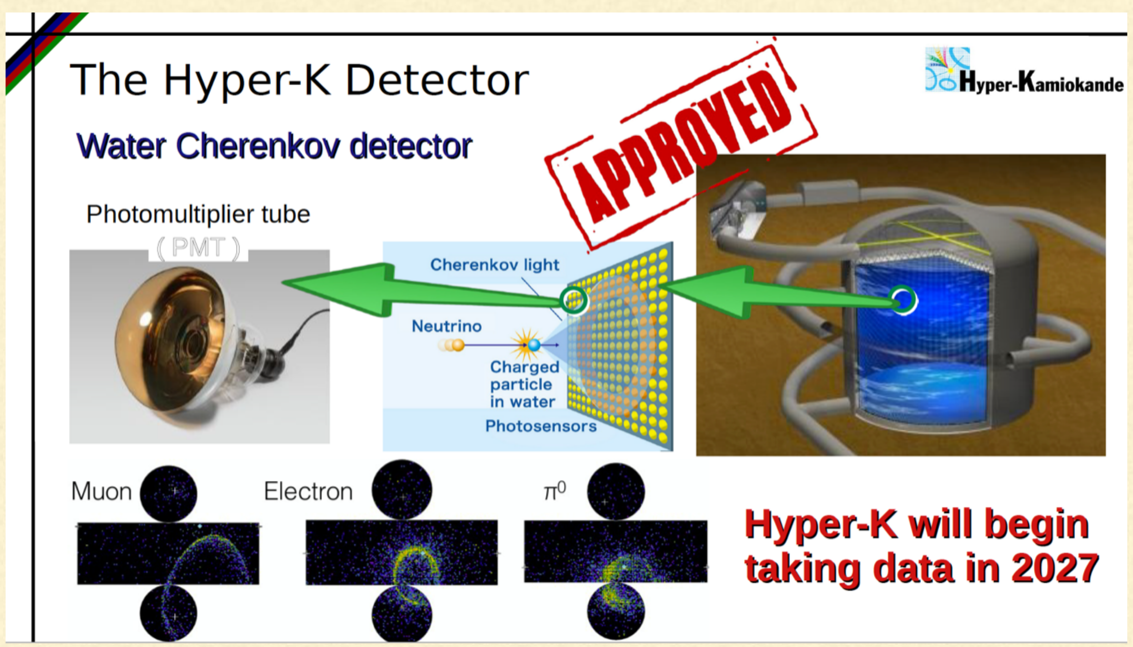
FUTURE OF NEUTRINO OSCILLATIONS

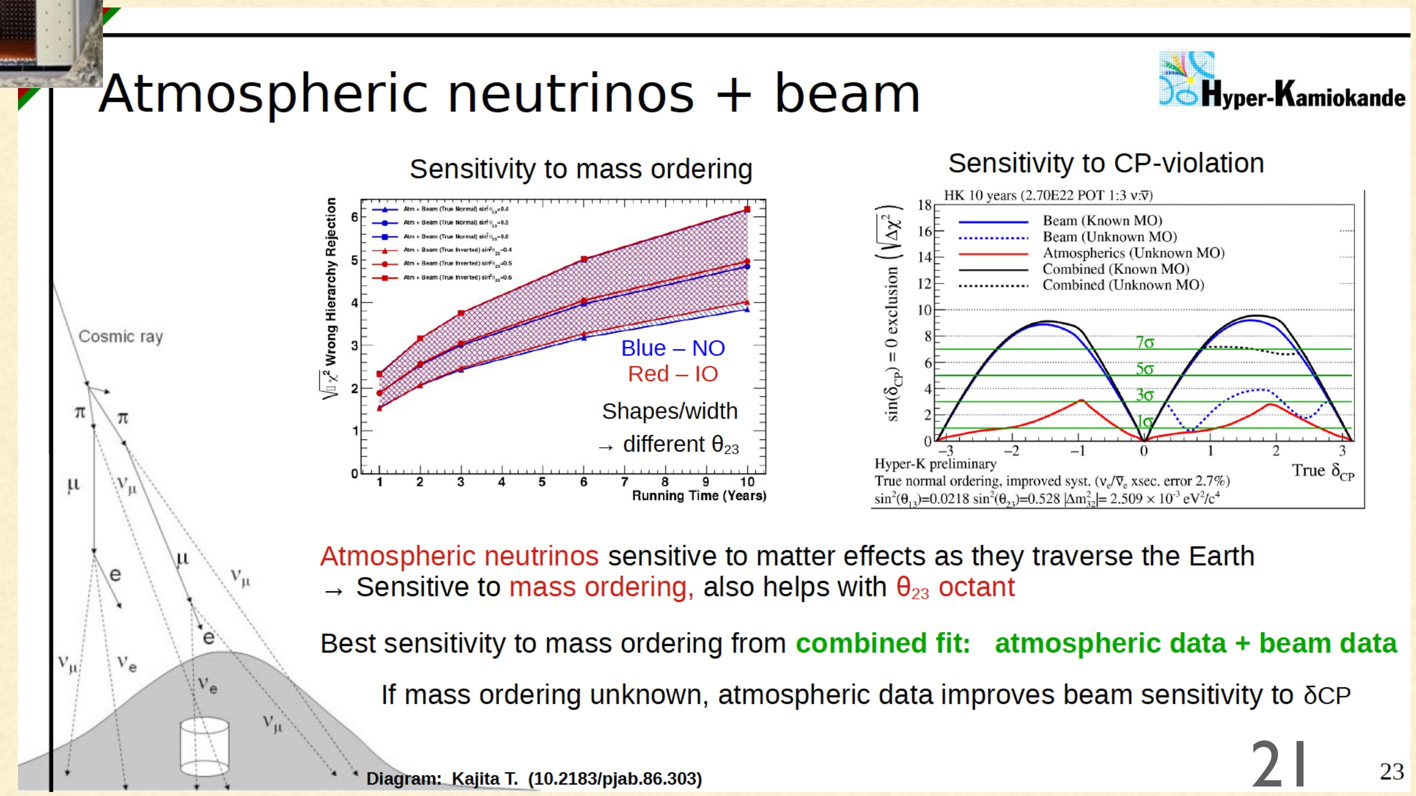
- Need large scale detectors of the next generation to make definitive discoveries in neutrino puzzle
- **Hyper-Kamikande (Japan)** and DUNE (USA) era
- Combined efforts of different projects: solar + reactor + atmospheric + accelerator measurements →
- Define neutrino mass hierarchy + octant + CPV by 2030s

T2K-SUPER-K → T2K-HYPER-K









SUMMARY

- **T2K is working steadily on its quest on filling neutrino puzzle**
  - Neutrino experiments foreseen to play a leading role in particle physics of the next decade
- **Current T2K data favours strong CP-violation in neutrinos and upper octant for θ23**
- **T2K Phase-II** extended run for ~2023-2027 to provide smooth transition to Hyper-Kamiokande era
  - Reach 3σ exclusion of non-CPV for certain δ_{CP} and MH
  - Near detector upgrade to further reduce systematic uncertainties + enhance physics studies capabilities with T2K near detector
  - Super-K already loaded with Gd to enhance neutron tagging
  - Joint T2K + Super-K atmospheric data analysis and T2K + NOνA on-going
- Hyper-Kamikande next generation water Cherenkov detector site under construction → **Hyper-Kamiokande will open a new era of definitive discoveries** in neutrino sector and other physics searches

Спасибо за внимание!

И спасибо за организацию замечательной Школы!

Credit to APS

The Growing Excitement of Neutrino Physics

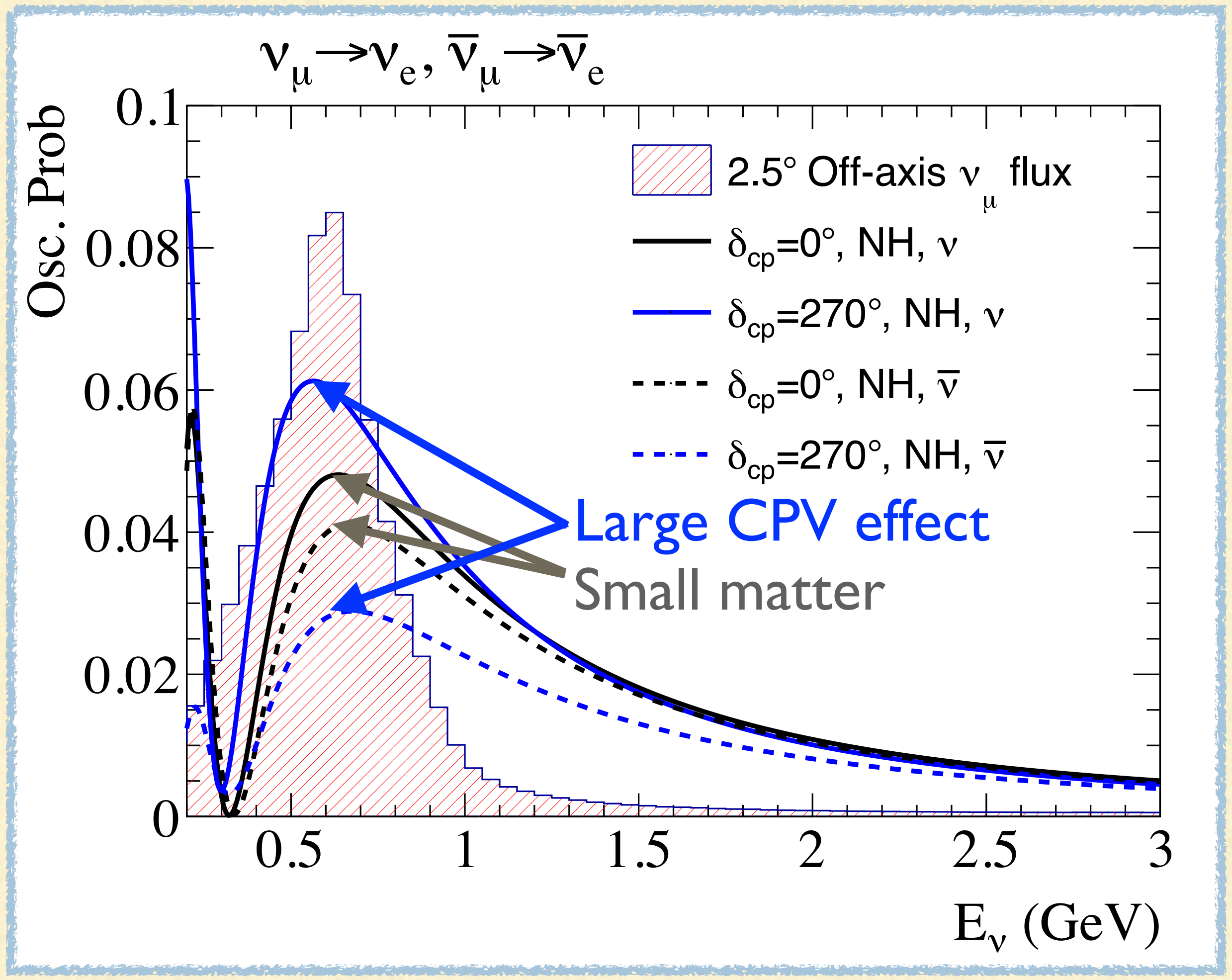
- 1930: On-paper appearance as "desperate" remedy by W. Pauli
- 1956: $\bar{\nu}_e$ first experimentally discovered by Reines and Cowan
- 1962: ν_μ existence confirmed by Lederman *et al.*
- 1998: Atmospheric neutrino oscillations discovered by Super-K
- 2000: ν_τ first evidence reported by DONUT experiment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

Pauli predicts the Neutrino
Fermi's theory of weak interactions
Reines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit
Kamioka II confirms solar deficit
LEP shows 3 active flavors
SAGE and Gallex see the solar deficit
Kamioka II and IMB see atmospheric neutrino anomaly
Kamioka II and IMB see supernova neutrinos
Nobel Prize for discovery of distinct flavors!
LSND sees possible indication of oscillation signal
Nobel Prize for ν discovery!
Super K sees evidence of atmospheric neutrino oscillations
Super K confirms solar deficit and "images" sun
SNO shows solar oscillation to active flavor
Nobel Prize for neutrino astroparticle physics!
KamLAND confirms solar oscillations
K2K confirms atmospheric oscillations
Daya Bay observe theta 13 at 5 sigma
T2K observe $\nu_\mu \rightarrow \nu_e$ appearance
Nobel & Breakthrough for ν oscillations

1930 1955 1980 **2015**

NEUTRINO OSCILLATIONS IN T2K

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

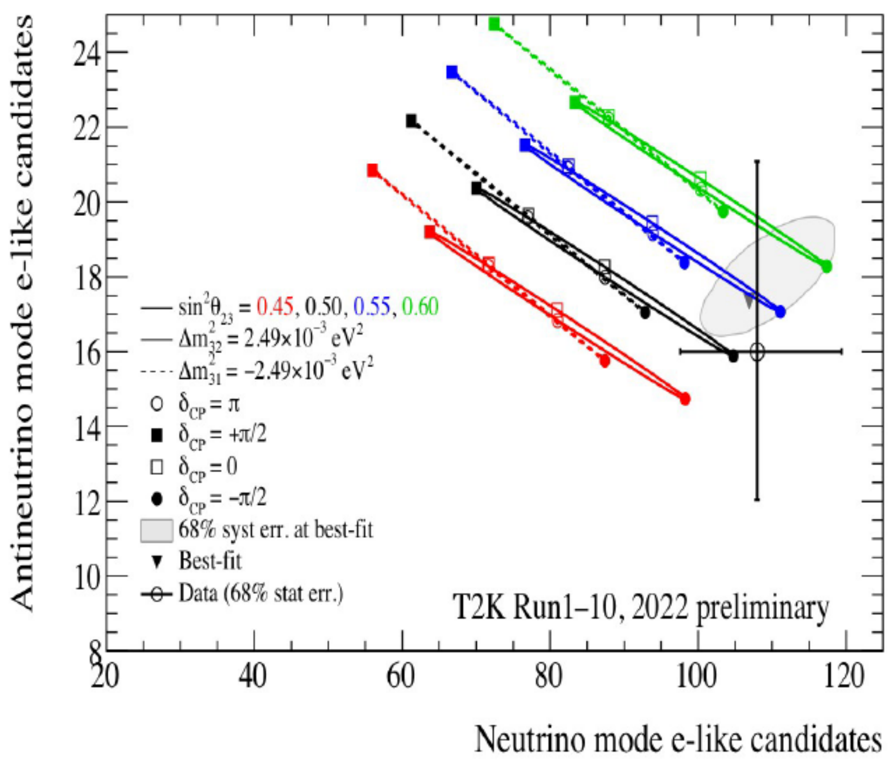


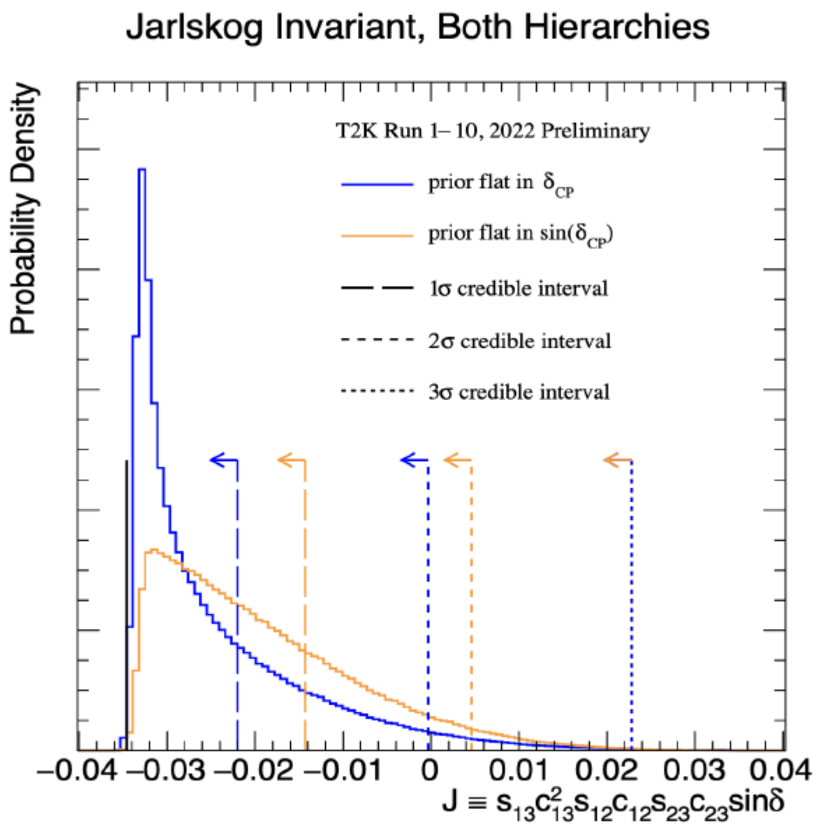
CP PHASE/ CHANNEL	$P(\nu_\mu \rightarrow \nu_e)$	$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
$\delta_{CP}=-\pi/2$	Enhance	Suppress
$\delta_{CP}=\pi/2$	Suppress	Enhance

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

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

MORE T2K OSCILLATIONS RESULTS





Jarlskog Invariant: $J_{CP} = \sin\theta_{13}\cos^2\theta_{13}\sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\delta_{CP}$

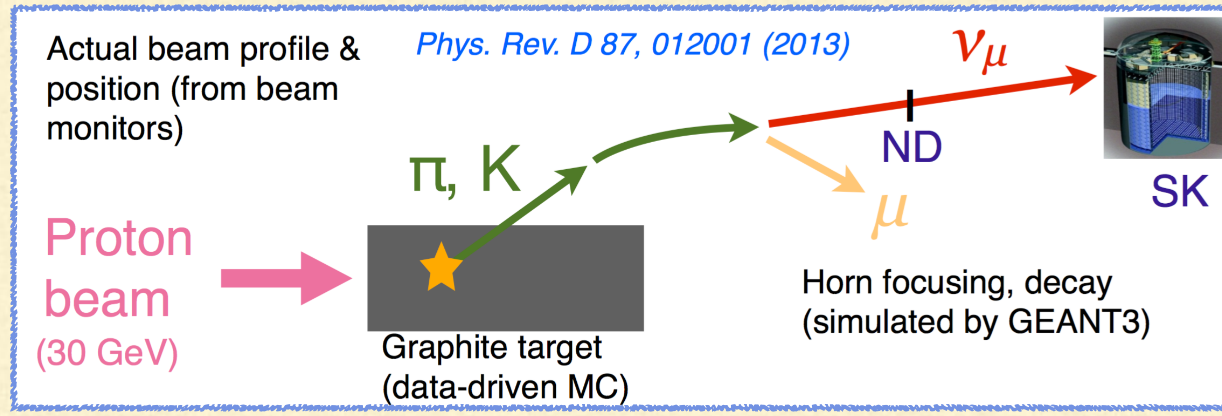
Bayesian posterior probabilities (with reactor constraint)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	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

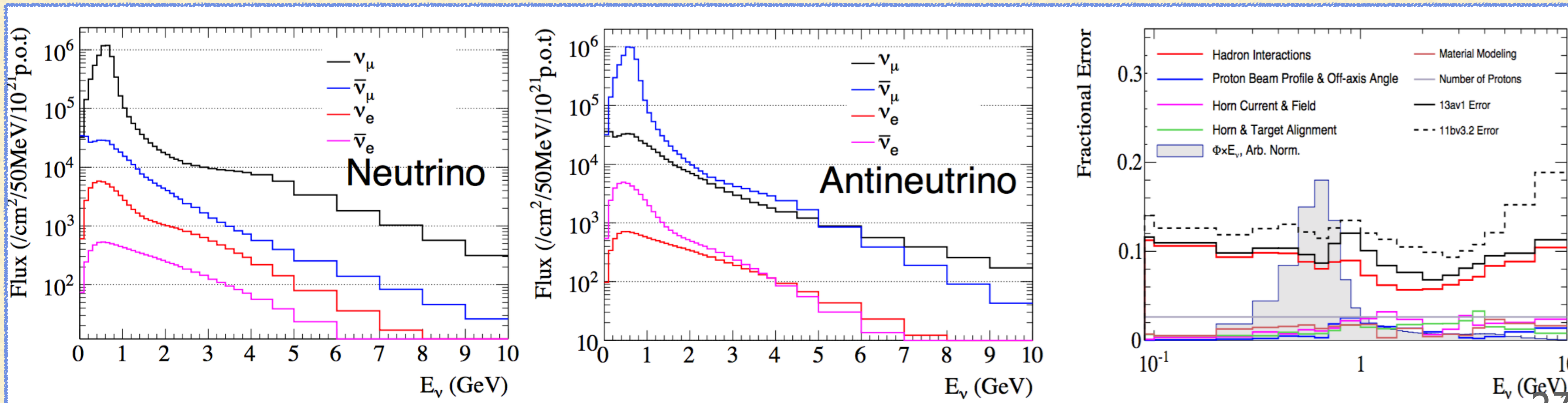
Jarlskog invariant is independent of PMNS parameterization.

T2K NEUTRINO FLUX PREDICTION

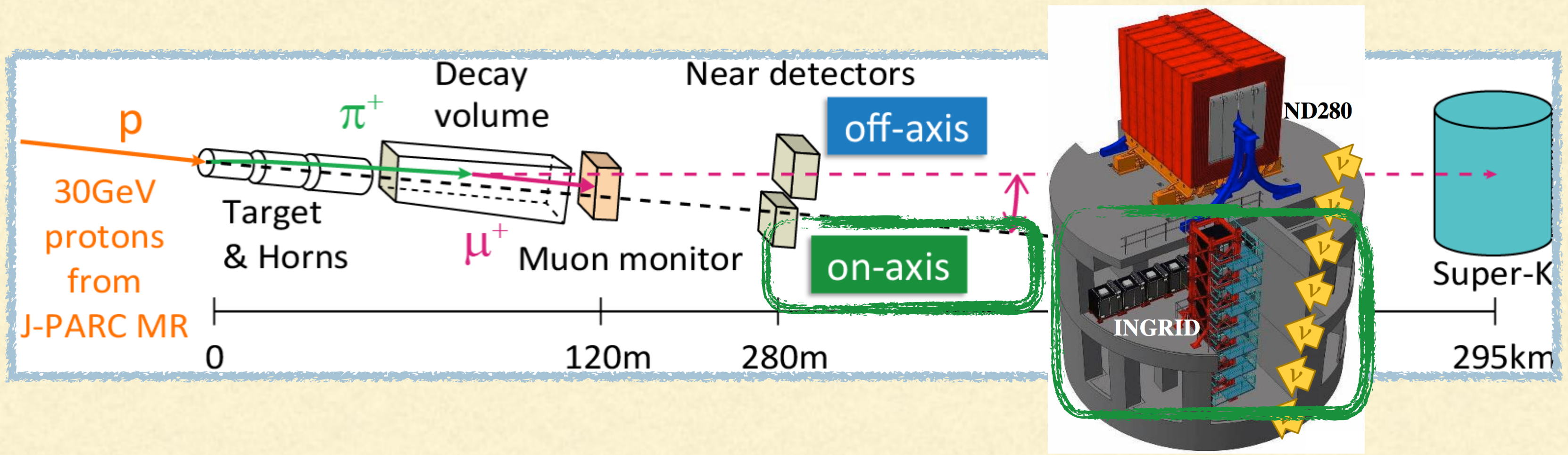
- Simulation: FLUKA, GCALOR and GEANT3
- Tuned to external data: NA61/SHINE (CERN)
  - Measurement of pion/kaon production of 31 GeV/c proton beam with carbon target
  - Thin target (4%λ) and T2K replica target
  - Reduction of uncertainties: ~30% to ~10%
- Intrinsic ν_e background at ~0.5% level

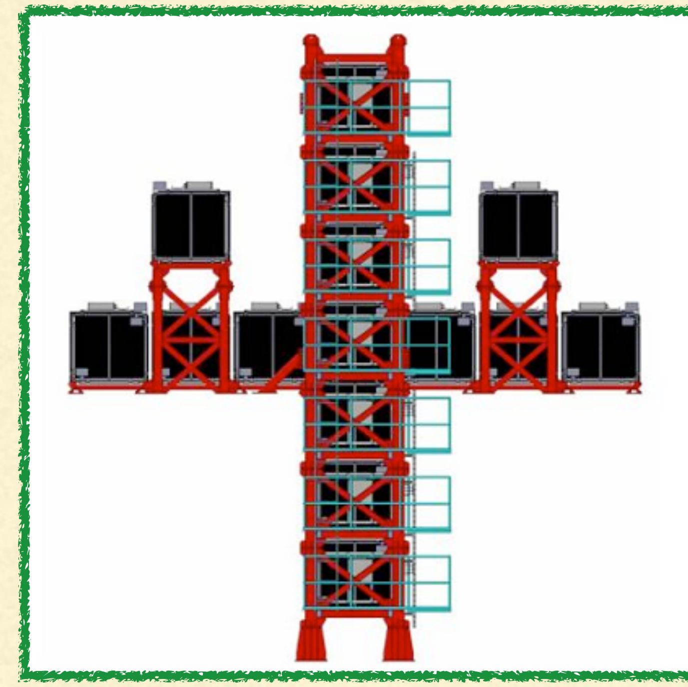


Replica target results are being incorporated into analysis



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)