Neutrino oscillation physics with neutrinos from accelerators

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For the T2K collaboration

Physics in Collisions

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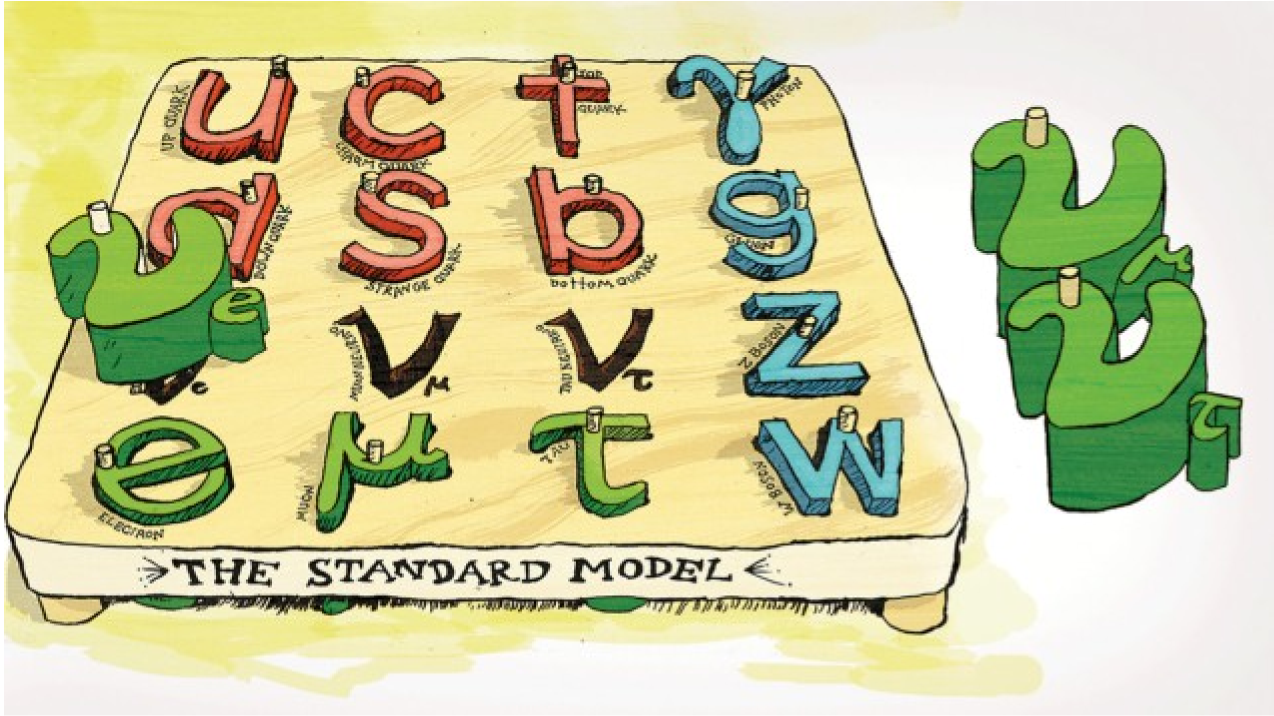
Outline

- Introduction
- T2K experiment
- T2K oscillation analysis and results
- T2K-NOvA combined fit
- T2K-SK combined fit
- Next generation long baseline experiments : HyperKamiokande
- Conclusions

On behalf of the T2K collaboration, and for some results of the T2K-NovA, T2K-SK and HyperKamiokande collaborations

Extraordinary neutrinos

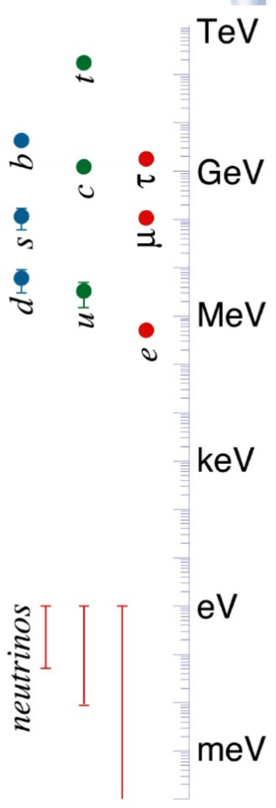


Credit :Symmetry

Extraordinary neutrinos

- « Nonzero neutrino masses are not possible without the existence of new fundamental fields » (A. De Gouvea CERN Courier May 2024, see also PDG Neutrino Masses Mixing and Oscillations,)
- Neutrino masses are at least 6 orders of magnitude below the other fermions
- Large mixing angles

$$V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \qquad V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



- Neutrinos are a crucial link between particle physics and cosmology

The PMNS neutrino mixing matrix

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

Flavor eigenstates

Mass eigenstates

Atmospherics and LBL
θ_{23}~ 45°

$|\Delta m^2_{32}|$ ~ 2.5 10^{-3} eV^2

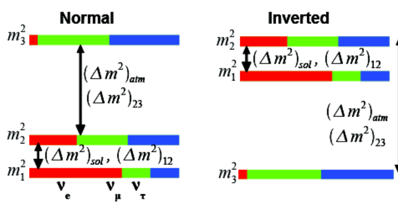
Reactors
θ_{13}~ 10°

LBL θ_{13} δ_{CP}

Solar and reactors
θ_{12}~ 35°

Δm^2_{21} ~7.5 10^{-5} eV^2

- Long baseline (LBL) experiments are sensitive to 5 of the PMNS parameters :
- θ_{23} $|\Delta m^2_{32}|$ most precise measurements by LBL
- θ_{13} Precisely measured by reactor exp.
- δ_{CP} (LBL only) and mass ordering (LBL, atm, JUNO)



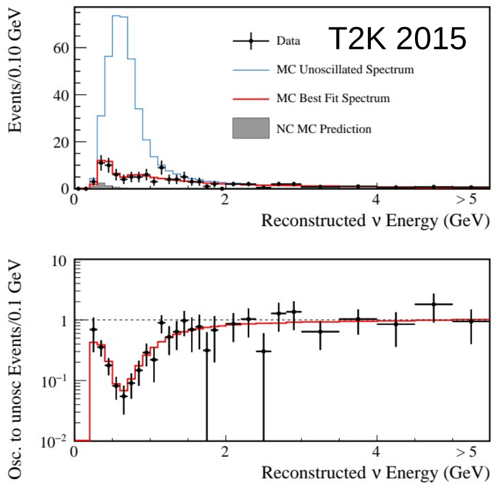
What we measure in long baseline experiments :

$\nu_\mu \to \nu_\mu$ disappearance

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

Leading term

- θ_{23} close to 45° : maximal disappearance
- Easy to observe, but difficult to determine θ_{23} octant, relying mainly on the subleading term



What we measure in long baseline experiments :

$\nu_\mu \to \nu_e$ appearance

$$P(\nu_\mu \rightarrow \nu_e) = 4 c^2_{13} s^2_{13} s^2_{23} \sin^2 \Delta_{31}$$ "Atmospheric" term (leading)

$$+8 c^2_{13} s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) S_{12} S_{13} S_{23} \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CP conserving

$$\mp 8 c^2_{13} c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21}$$ CP violating term

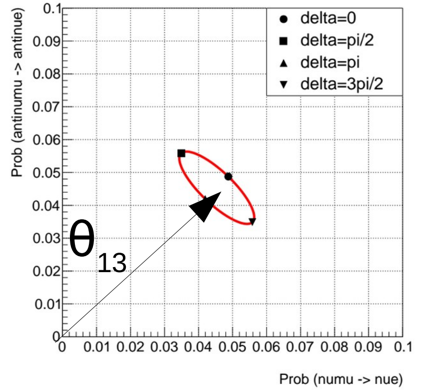
$$+4 s^2_{12} c^2_{13} (c^2_{12} c^2_{23} + s^2_{12} s^2_{23} s^2_{13} - 2 c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2\Delta_{21}$$ "Solar" term

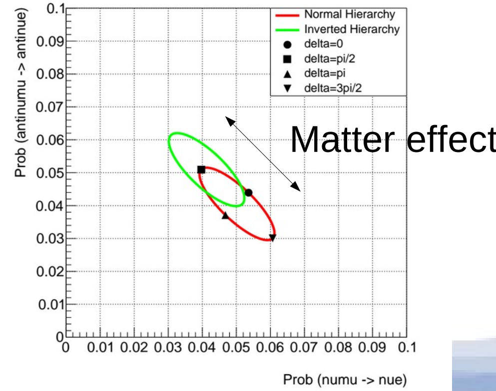
NB in vacuum !

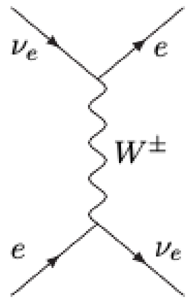
$$c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$\Delta_{ij} = \Delta m^2_{ij} L / 4E$$

- θ_{13} relatively large (precisely measured by reactors exp.)
- CP violation effect : small modulation ~30 %
- Neutrino propagating in the Earth crust : « matter effect », mimicking a CP violation effect. Enhancement or suppression for neutrinos depending on the mass ordering.







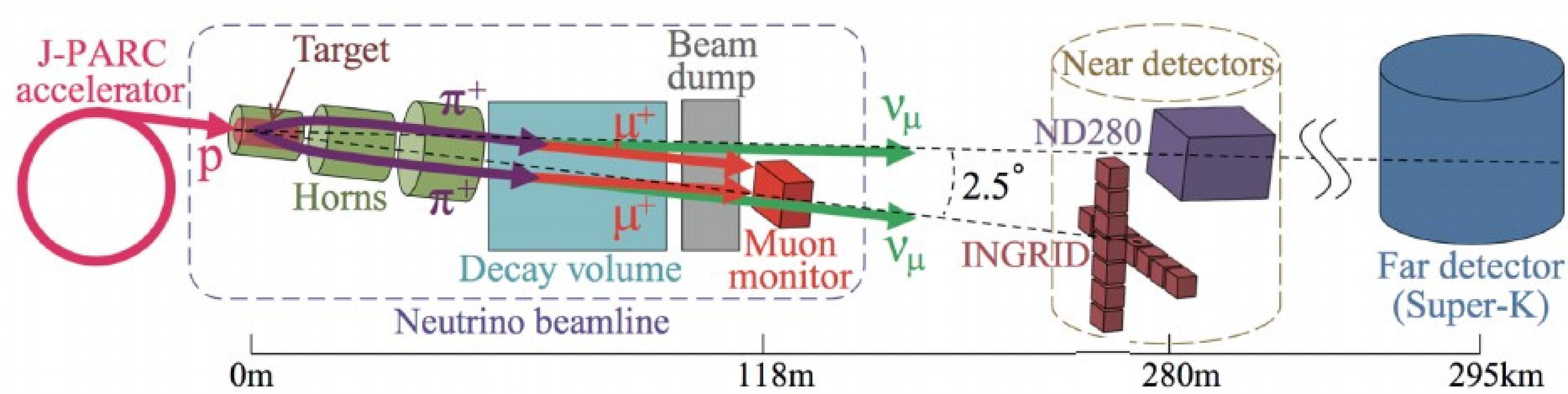
Why accelerator-based experiments ?

- Allow to produce an (almost) pure ν_μ neutrino beam, with tuned and controlled flux
- Allow to choose a beam of neutrinos or antineutrinos by reversing the polarity of the magnetic focussing system (CP measurement!)
- Precisely measure neutrino interactions at the near detectors. Precisely control other neutrino species, (anti)neutrinos with a magnetic spectrometer
- Control of the experimental conditions: precision measurements of parameters (ideally we would like to push precision to the % level like the CKM matrix)
- Underground observatory for other neutrinos : solar, atmospherics, SN etc

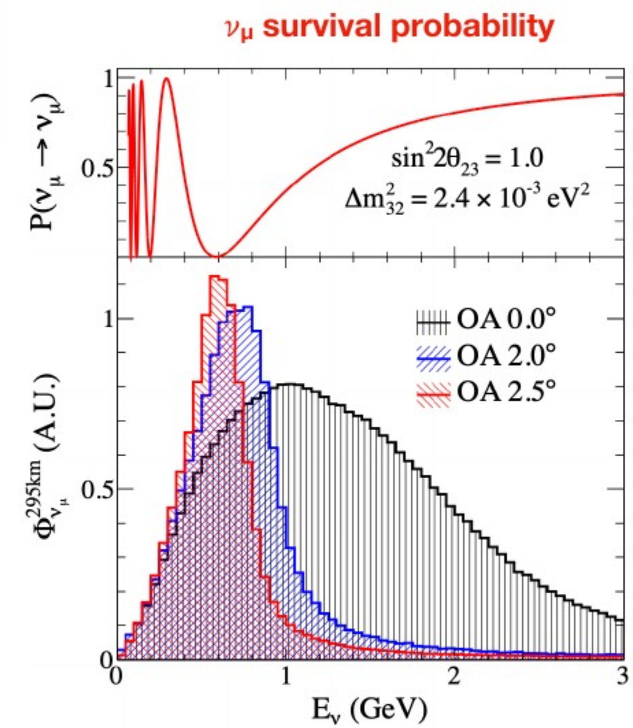
The Tokai to Kamioka (T2K) experiment

- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, 800 kW   Proton On Target >3.8 10^{21}
- SK: 50 kt mass. ~100% livetime

The T2K beamline

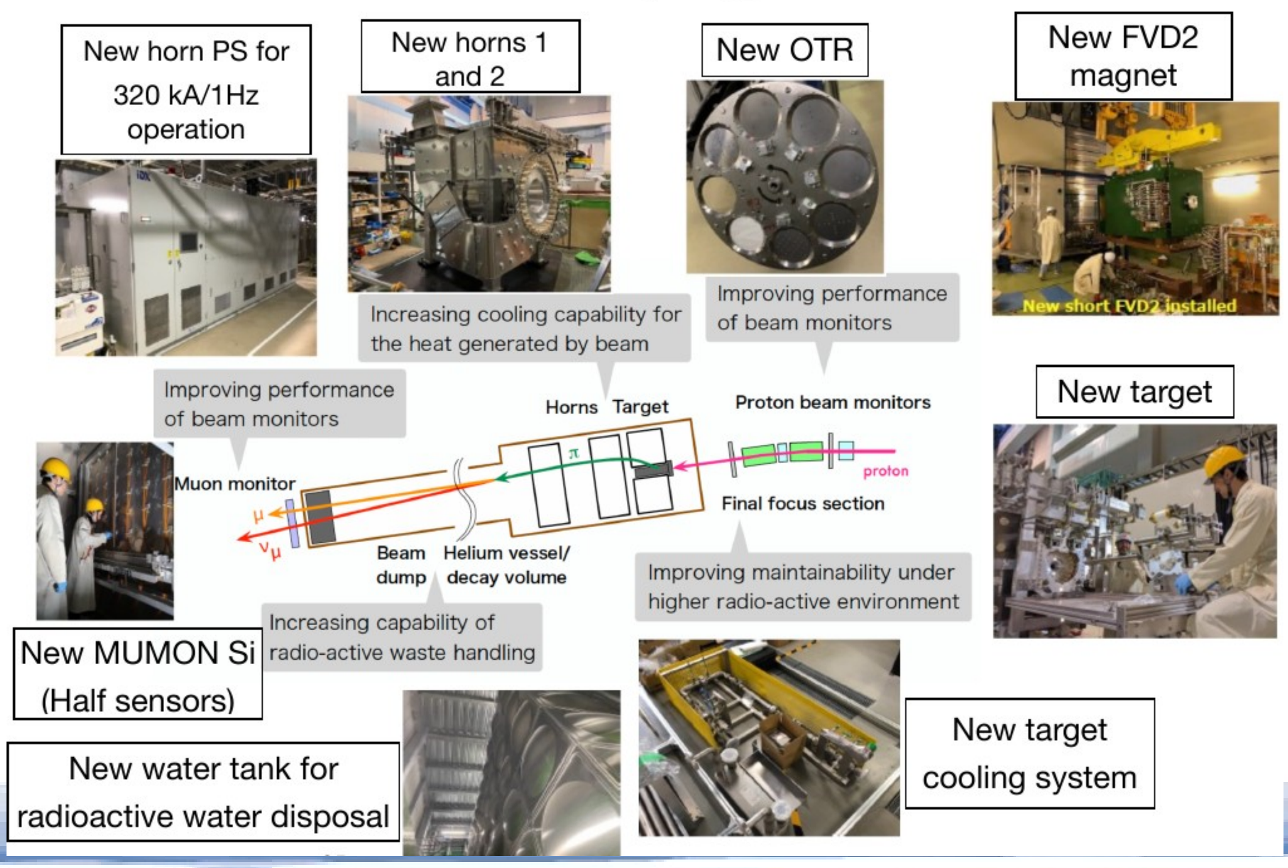


- 30 GeV/c proton beam from J-PARC main ring impinging on a graphite target
- p+C interactions copiously produce pions (and kaons)
- 90m decay volume followed by beam dump and muon monitors
- Off-axis beam (kinematics of pion two-body decay) allow to tune the energy by aiming the beam slightly off (2.5°)
- Charge selected and focused by three magnetic horns : either $\pi^+ \rightarrow \mu^+ \nu_\mu$ or $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$



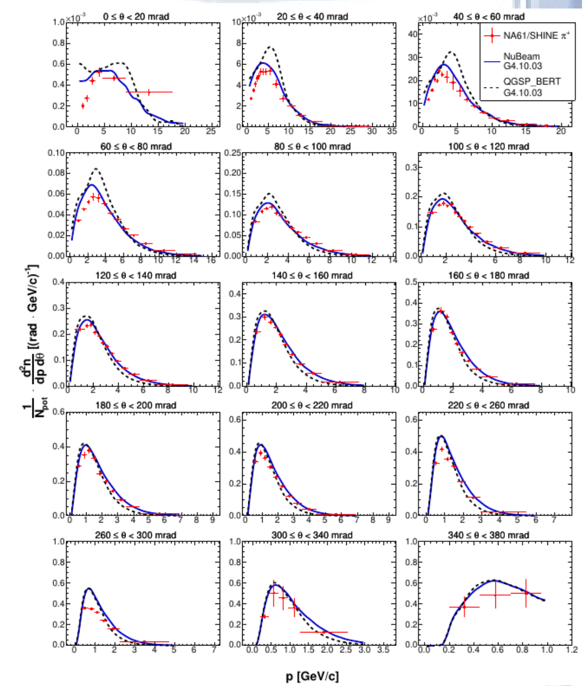
T2K beamline upgrade

- Replacement of the Main Ring Power Supply for higher repetition rate from 2.48 s to 1.36s
- Horns operated at 320 kA (instead of 250 kA) : 10 % increase in ν flux
- A major upgrade preparing for HK period, 800 kW reached in 2024 (1.3 MW by 2027)

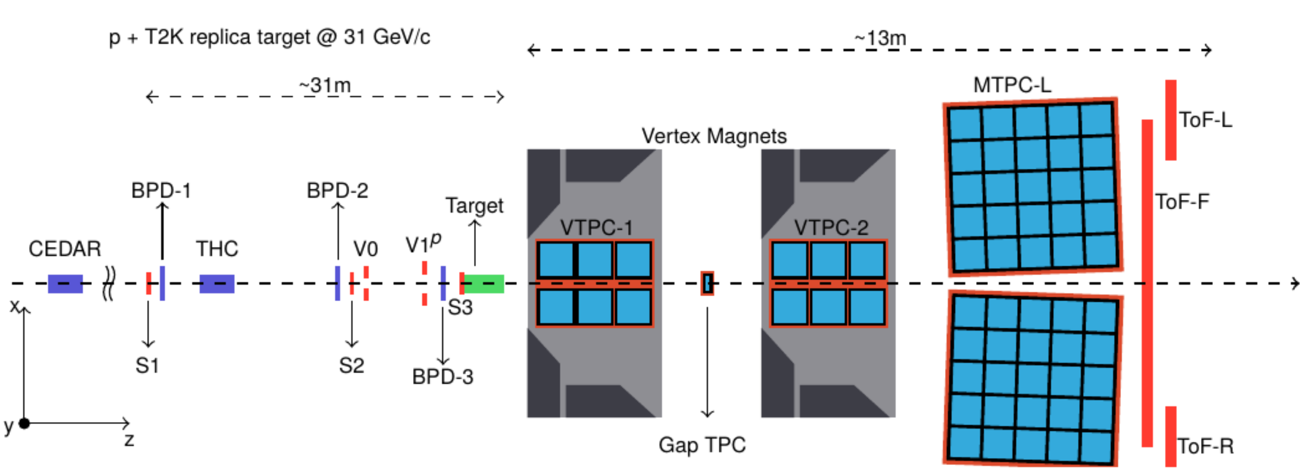


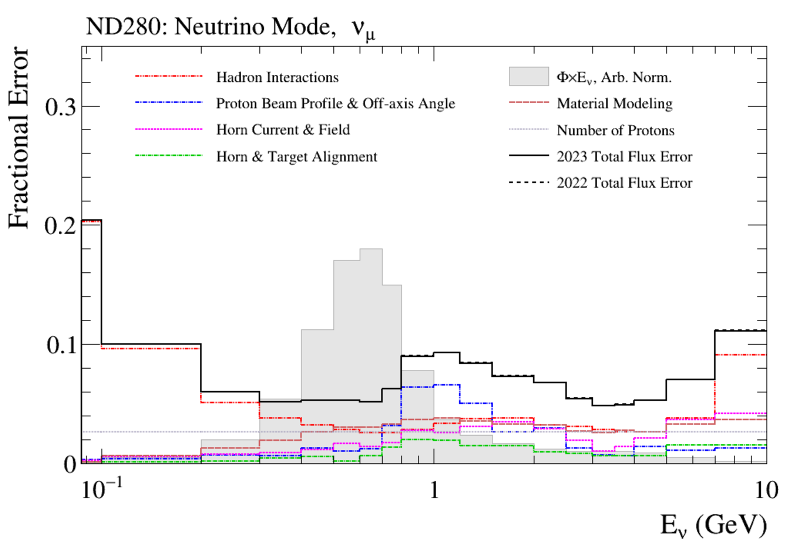
NA61-SHINE

- Hadroproduction experiment at CERN SPS
- Precisely measures pion and kaon cross-section and spectra with a T2K replica target
- Allows to precisely control the neutrino flux (unprecedented 5 % level !)
- Will provide measurements also for NOvA, DUNE

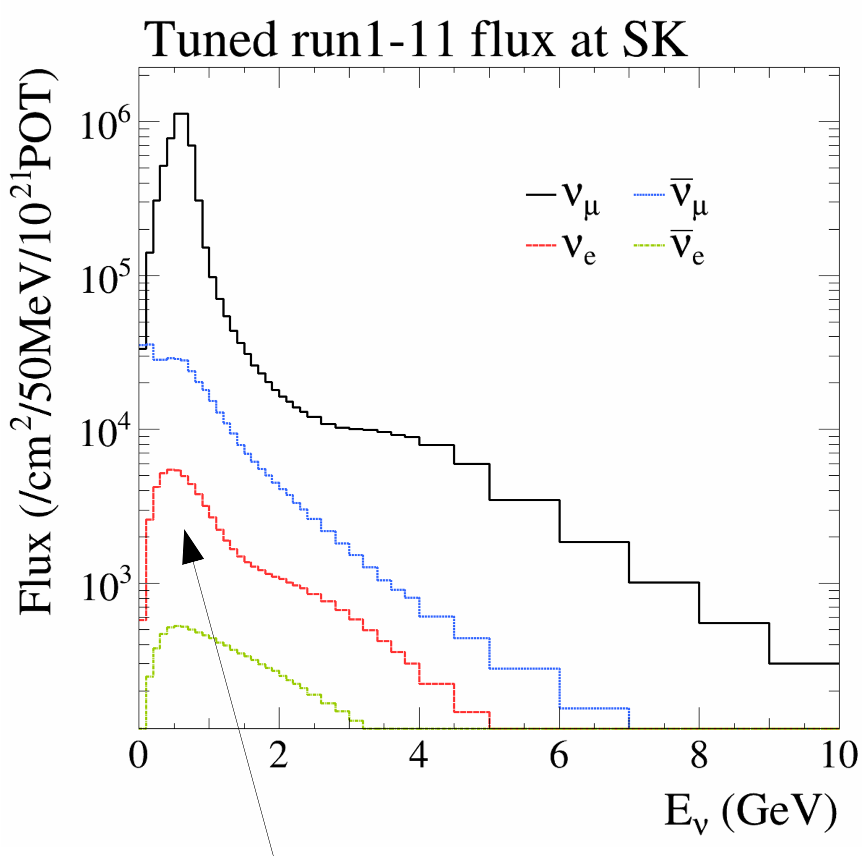


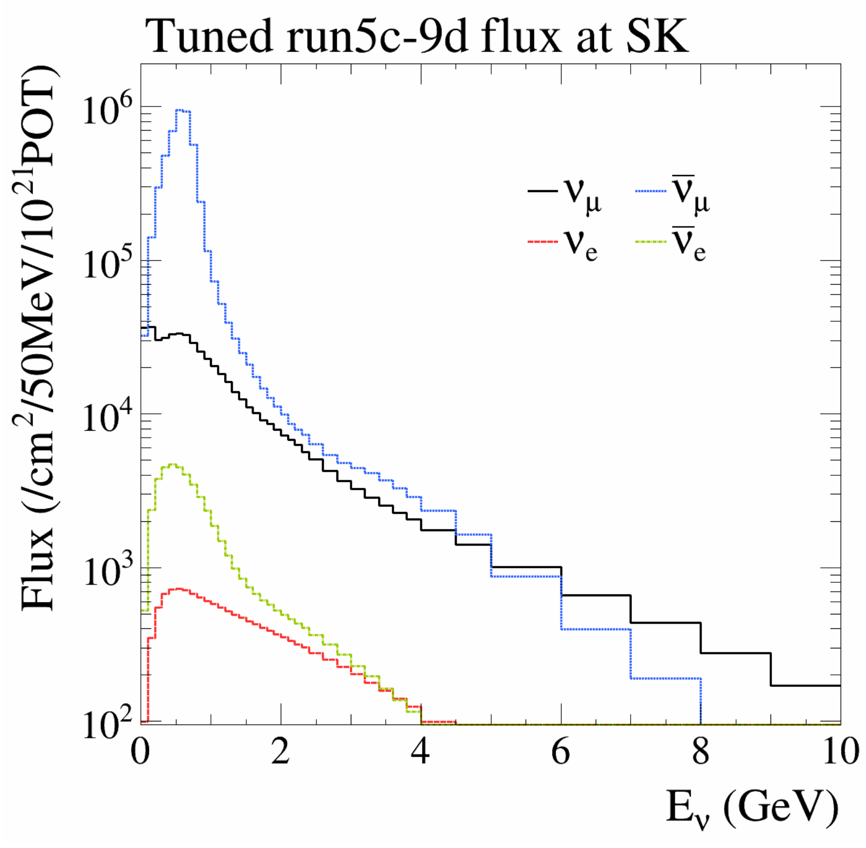
Double differential cross-section
Eur.Phys.J.C 79 (2019) 2, 100





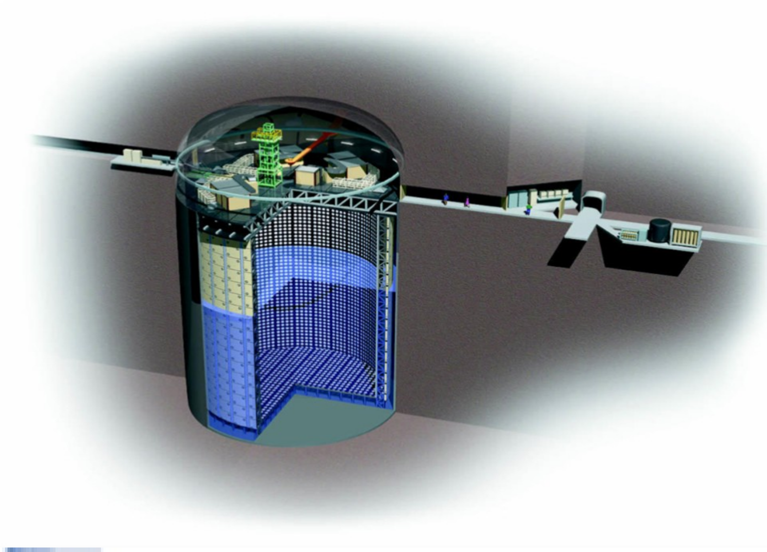
T2K Neutrino flux



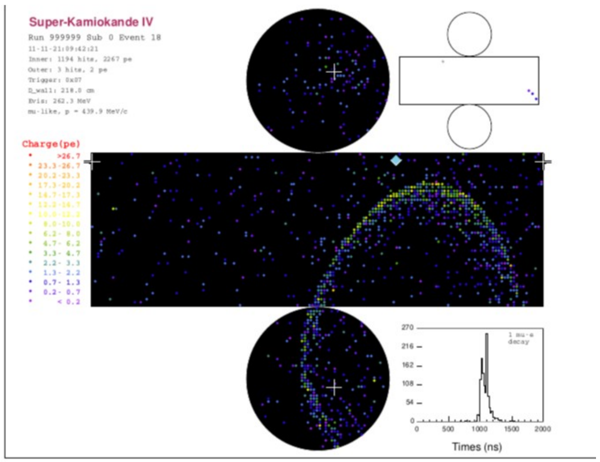


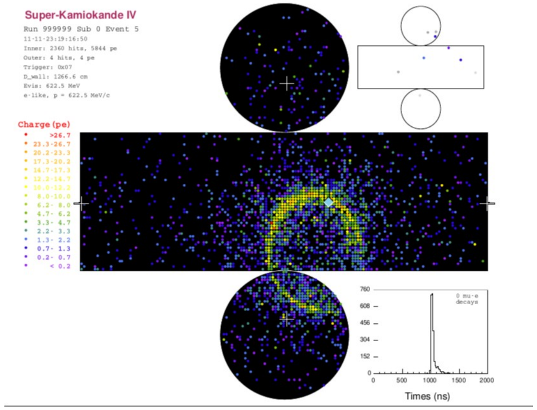
Notice ν_e/ν_μ < 1 % at the peak

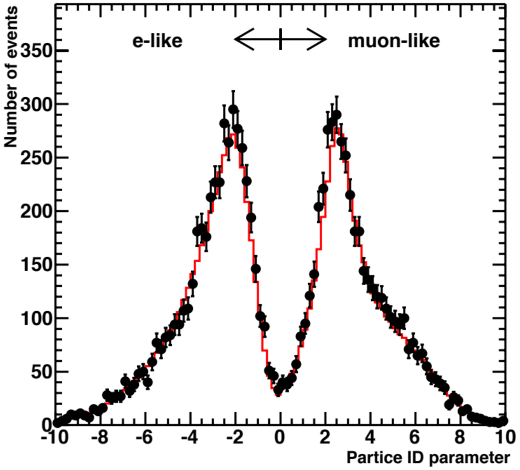
Super-Kamiokande



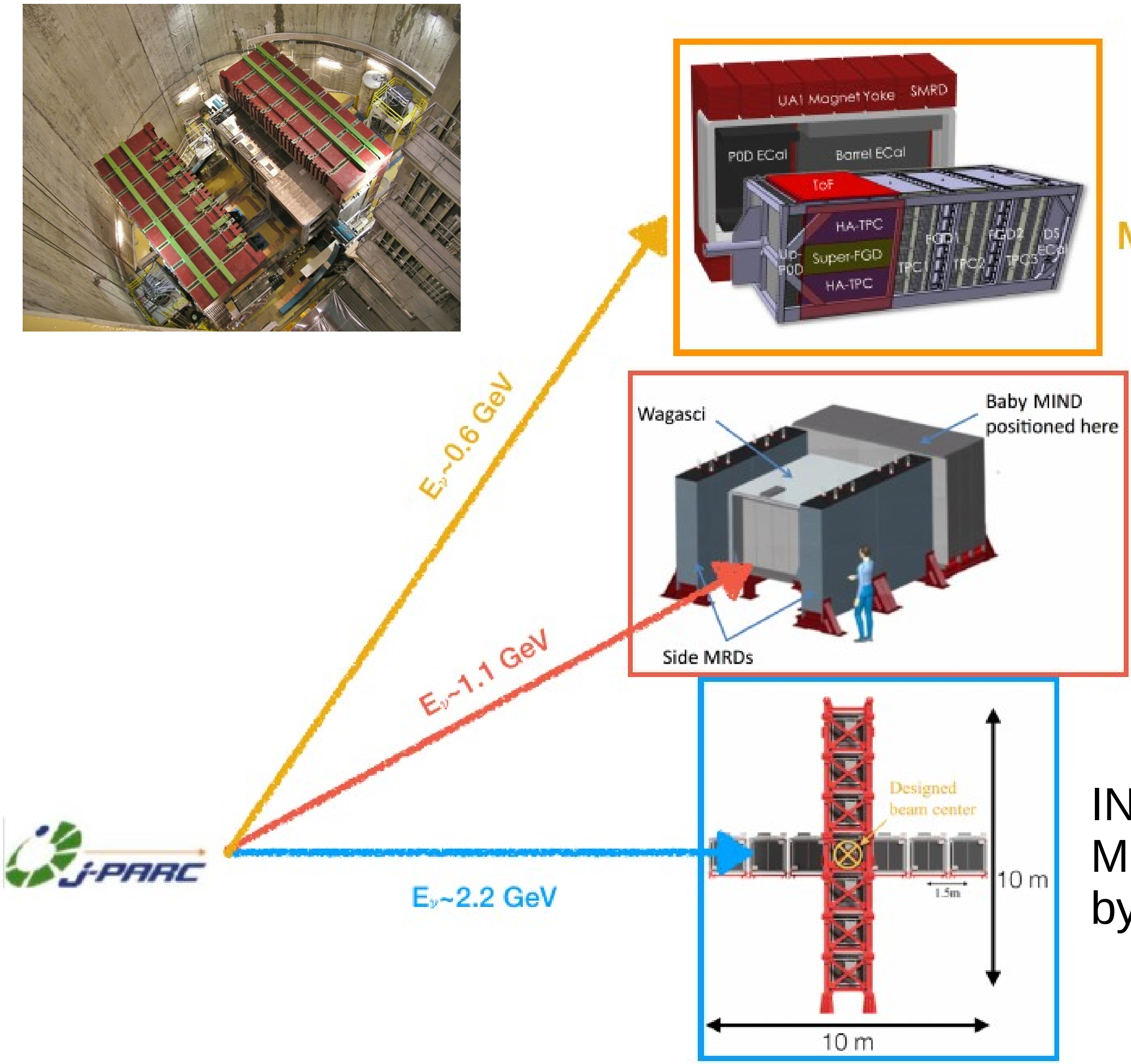
- 50 kton Water Cherenkov detector operated since 1996
- 11146 20'' PMTs inner detector, 1885 8'' PMTs outer detector
- Depth ~1000 m (2700 mwe)
- Particle identification capability e/μ
- Added 0.03 % Gd in 2022 to improve the neutron tagging efficiency
- Reconstruction of the lepton momentum and angle
- Multi-ring fit allows to identify π° decays (suppresses the NC π° background)
- Identification of delayed Michel electrons







Near detector complex at 280 m

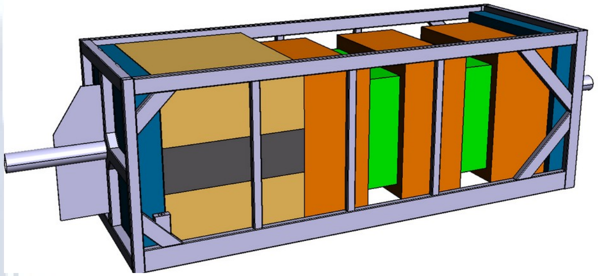


Off-axis ND280 (~beam going to SK)
Constrain (flux).(cross-section) for T2K oscillation analyses
Major upgrade in 2023

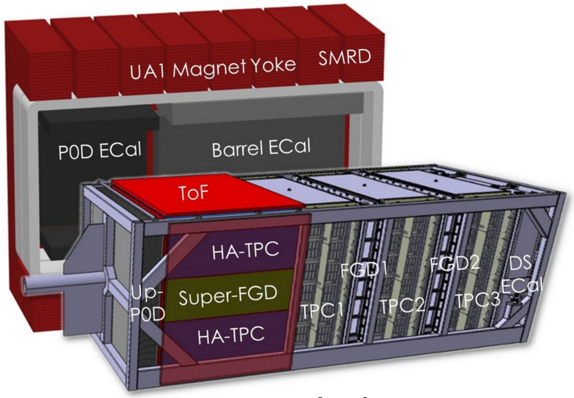
WAGASCI/BabyMIND
Cross-section on water

INGRID on-axis detector
Monitor neutrino beam profile day-by-day

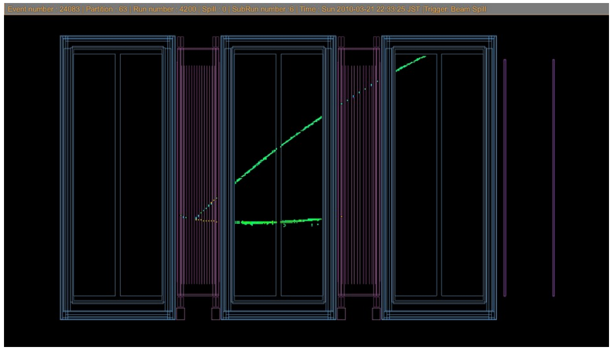
The off-axis near detector ND280



ND280 installed in 2009



ND280 upgrade in 2023



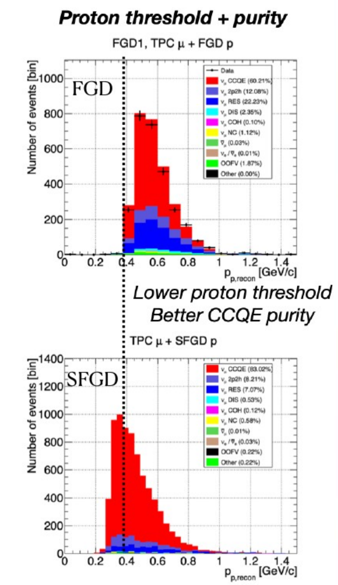
Candidate ν_μ CC1p

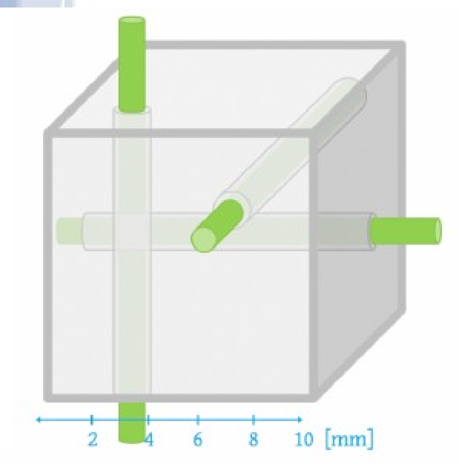
- Installed inside the UA1/NOMAD magnet (0.2 T) donated by CERN
- Active targets (FGD1 pure scintillator ; FGD2 includes also water layers)
- Three large TPCs with MicroMegas detectors : charge and momentum, PID based on dE/dx
- An electromagnetic calorimeter
- A major upgrade with novel detectors was installed in 2023-2024 including TOF all around it

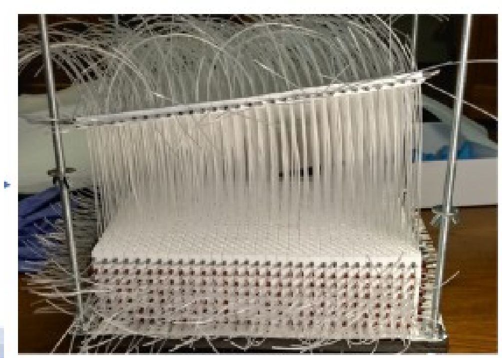
NIM A 1041 (2022) 167219

ND280 Upgrade : Super Fine Grained Detector

- A novel detector to serve as active target for the neutrino interactions
- 2 million optically independent scintillator cubes ($1cm^3$) read out by three orthogonal WLS fibers (60 000 channels, MPPC)
- ~ 40 p.e./MIP/fiber
- High granularity: proton threshold at 300 MeV/c, separation of electron/gamma, 3D-like tracking reconstruction. Reconstruction of neutrons
- Lowering the proton threshold will help modeling neutrino nucleus interactions



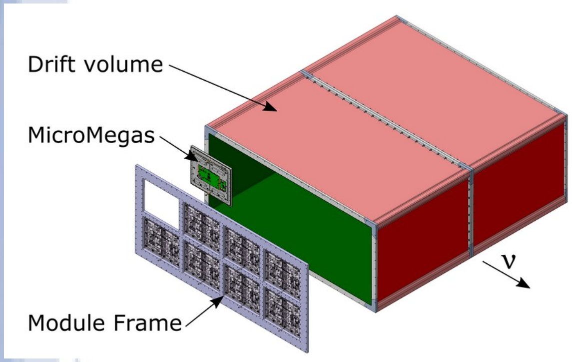


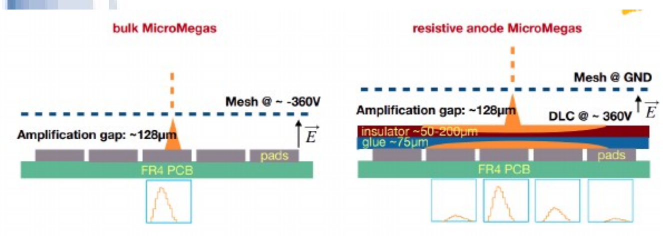


A candidate event of numu interaction with two protons exiting the nucleus

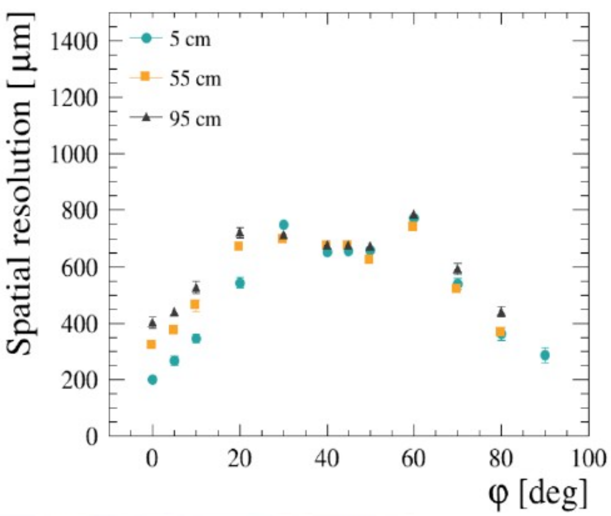
ND280 Upgrade :High Angle TPCs

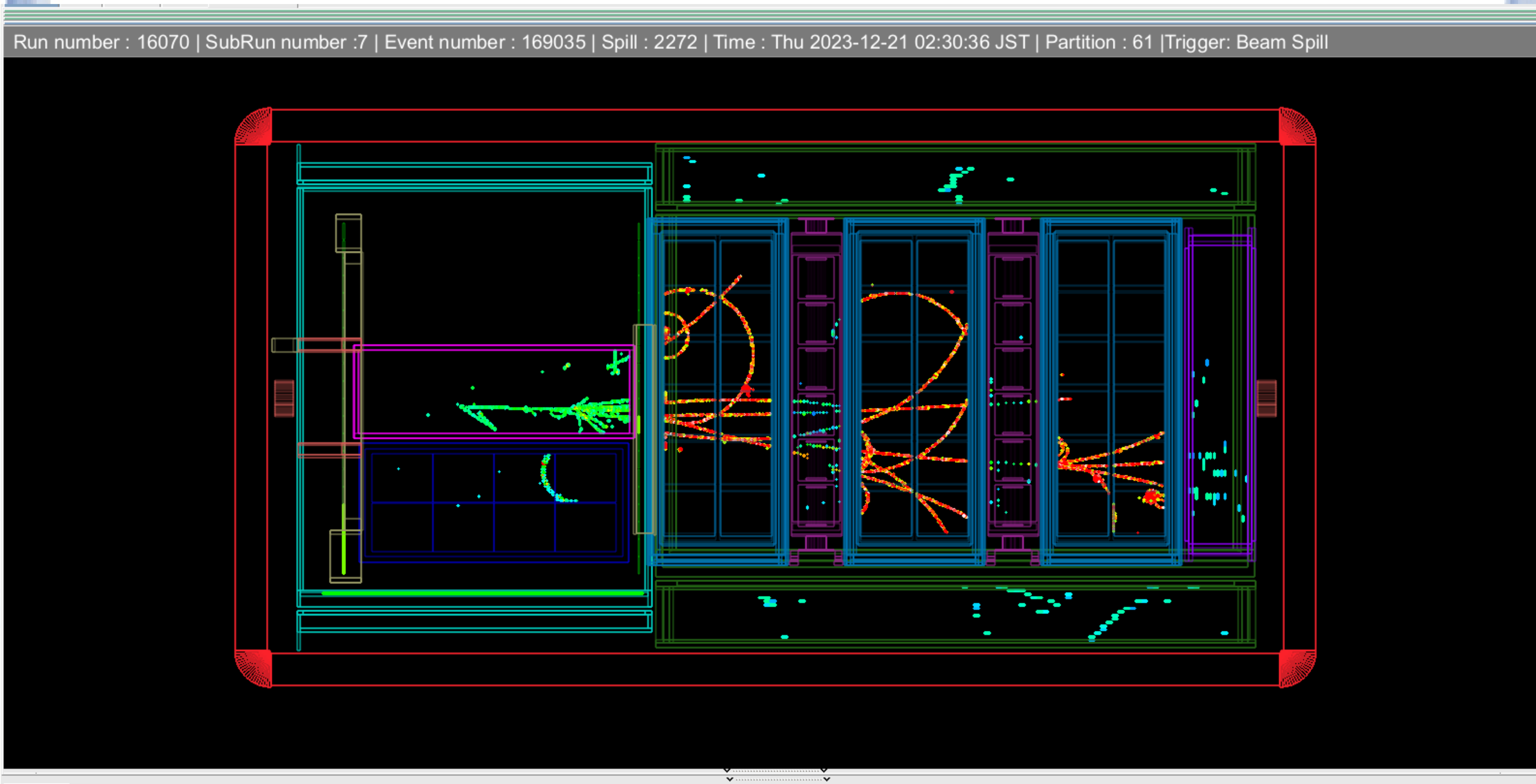
- Two new TPCs equipped with resistive MicroMegas technology (charge spreading)
- Atmospheric pressure : Ar – CF_4 (3%)- iC_4H_{10} (2%)
- Pad size ~1x1 cm², 200 µm space resolution
- dE/dx ~ 7 % for MIP, PID e/µ





NIMA 1052 (2023) 168248

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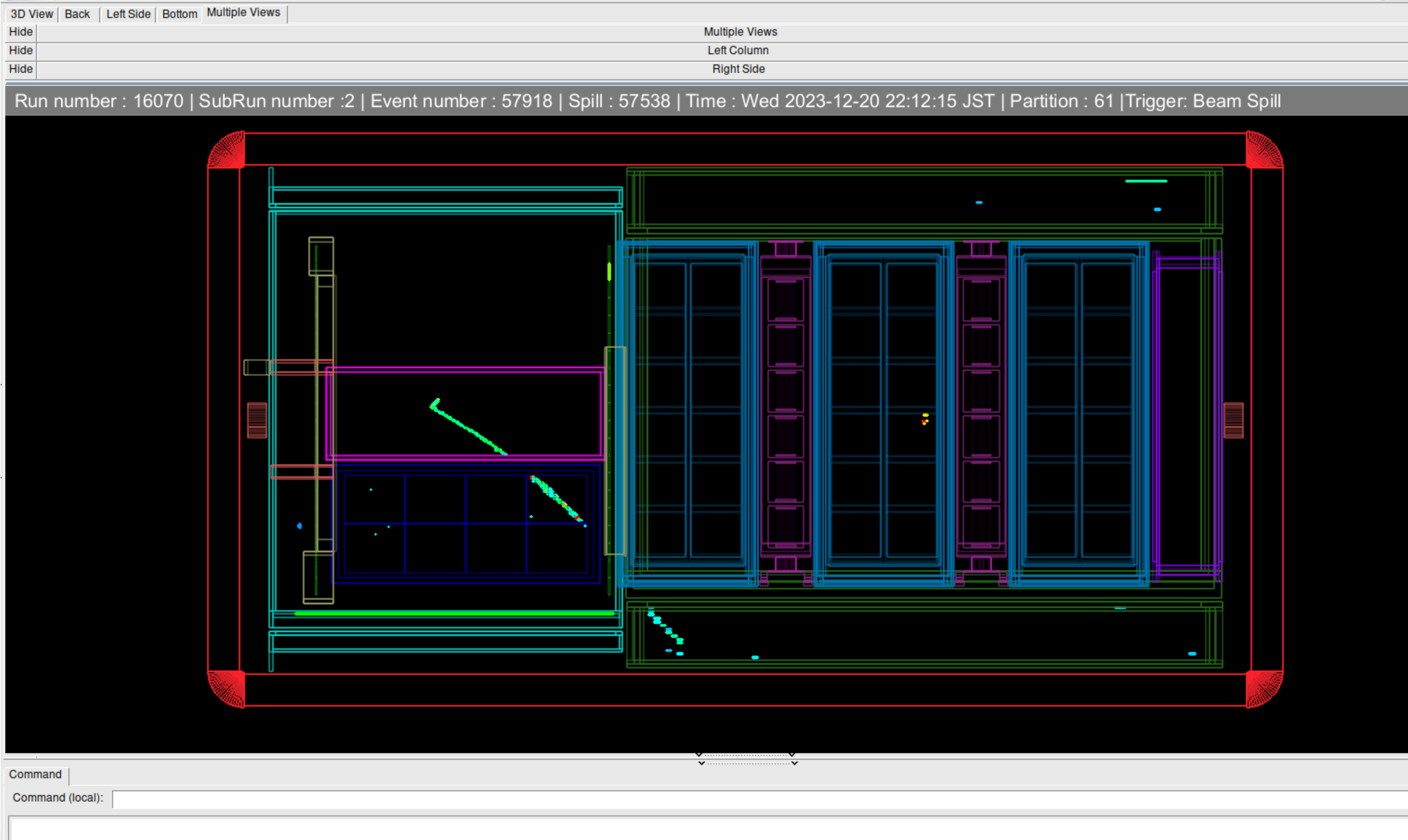
3D View
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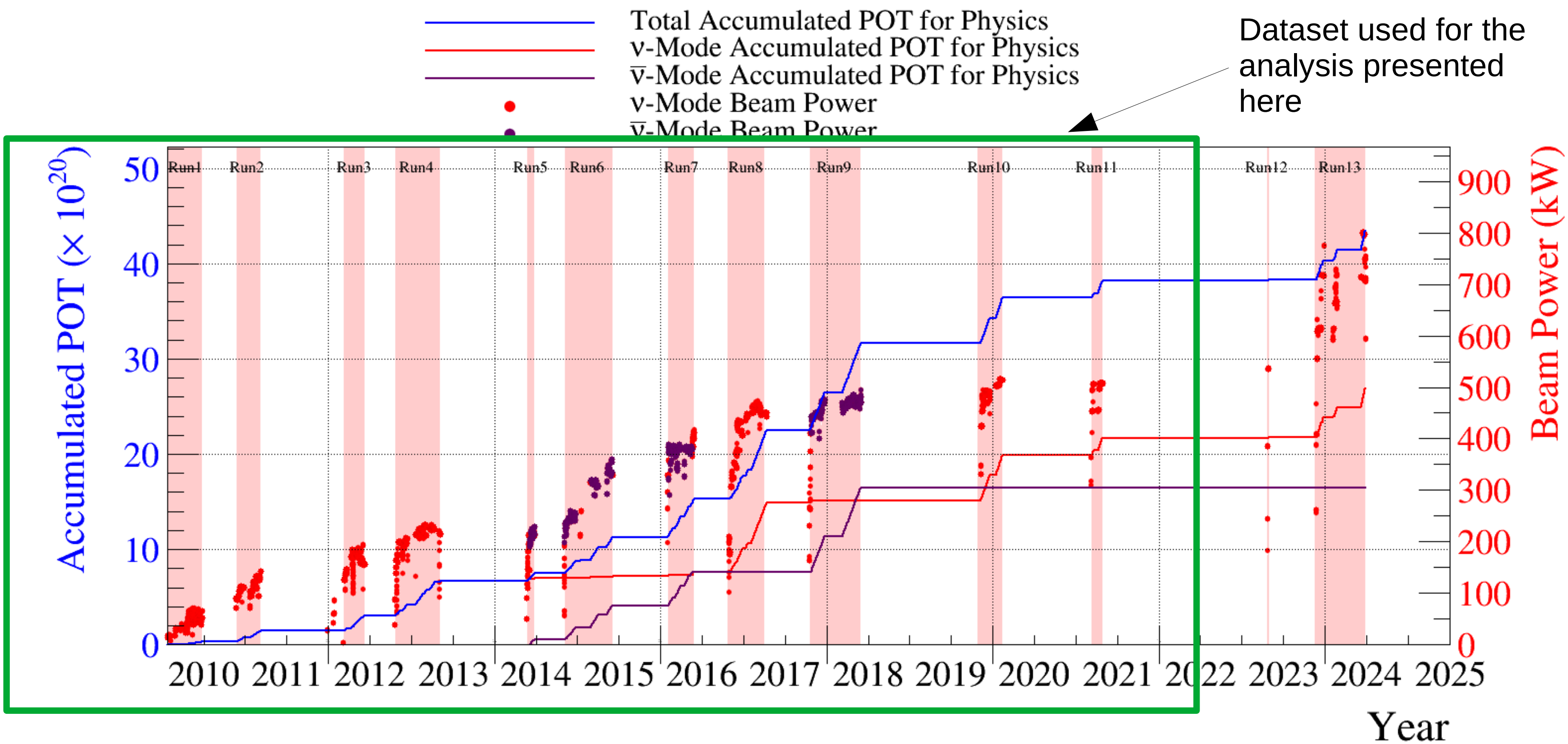
Run number : 16070 | SubRun number :2 | Event number : 57918 | Spill : 57538 | Time : Wed 2023-12-20 22:12:15 JST | Partition : 61 |Trigger: Beam Spill
Command
Command (local):

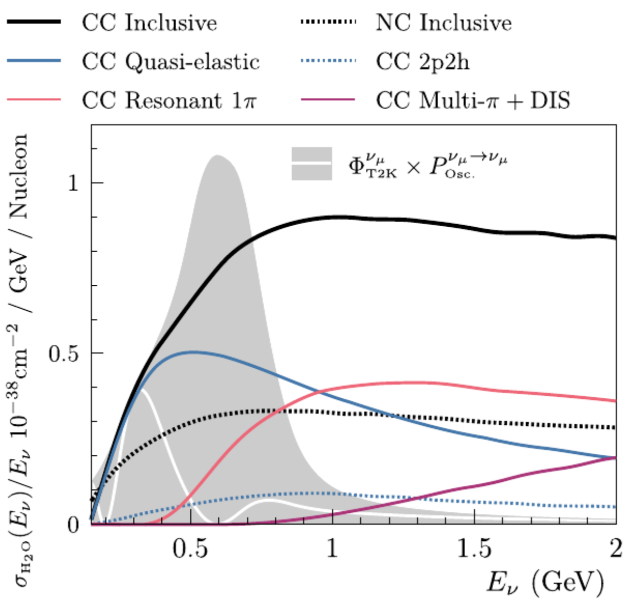
T2K dataset

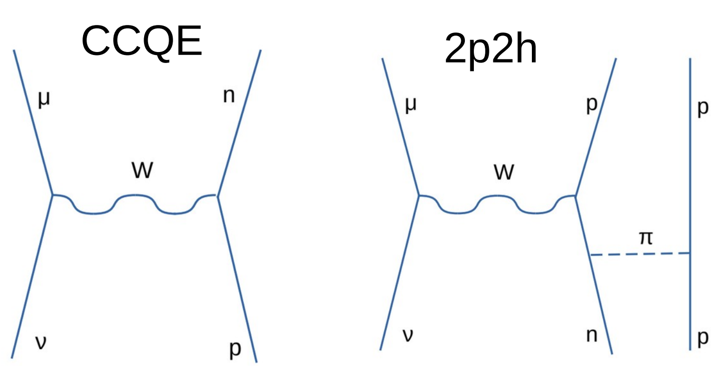


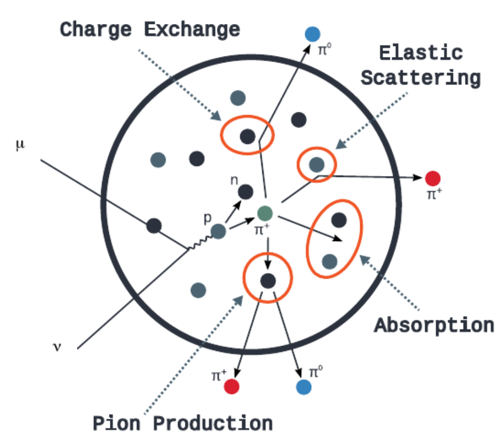
- Added Run 11 First T2K data with SK-Gd
- Total POT 2.14 × 10^{21} POT (neutrino mode) and 1.63 × 10^{21} POT (antineutrino mode)

Neutrino-nucleus cross-section

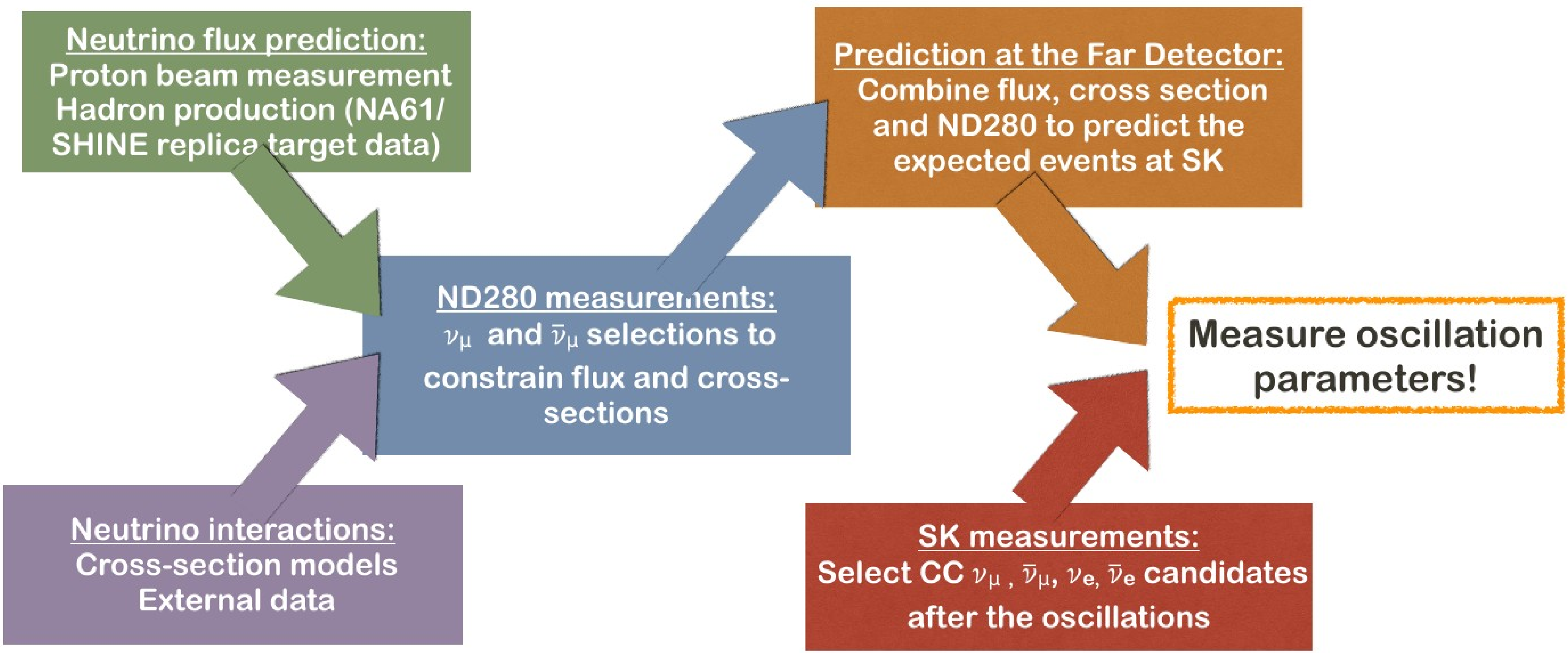
- At T2K energies the Charged Current Quasi-Elastic (CCQE) scattering is dominant
- But significant 2p2h and resonant contribution (CCRES)
- A wrong model for the cross-section might bias the neutrino oscillation results
- Selection of relevant samples at the near detector : CC0pi, CC1pi, CCnpi, topologies related to CCQE, CCRES, DIS





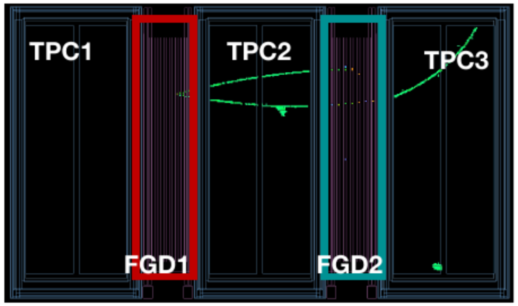


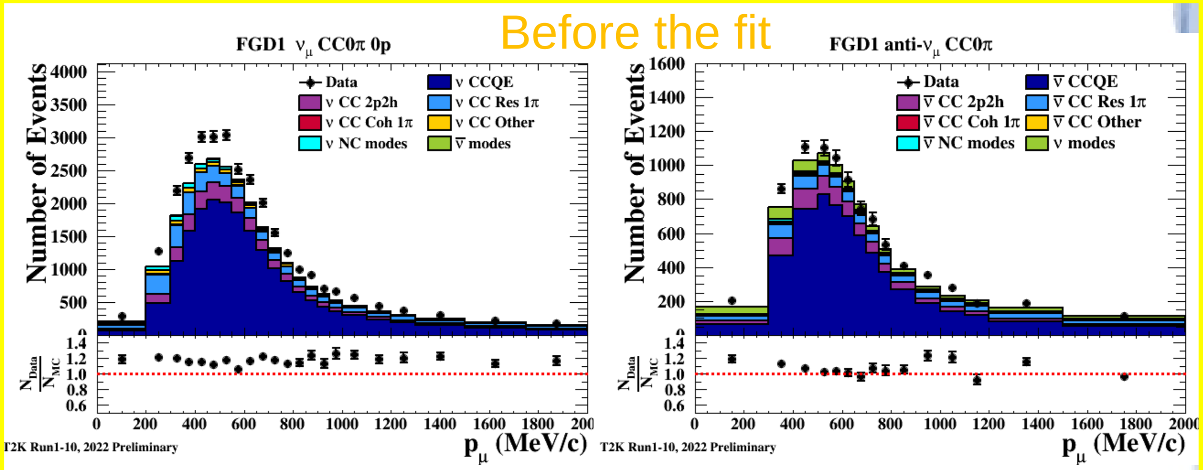
T2K oscillation analysis

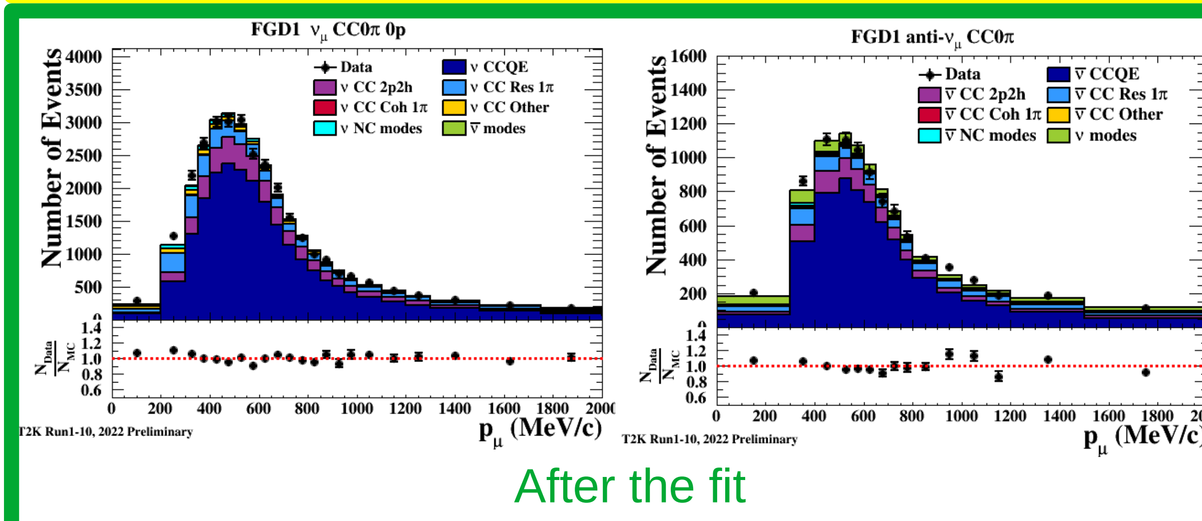


Near and Far detector data are fitted either sequentially or simultaneously depending on the analysis considered

ND280 selections



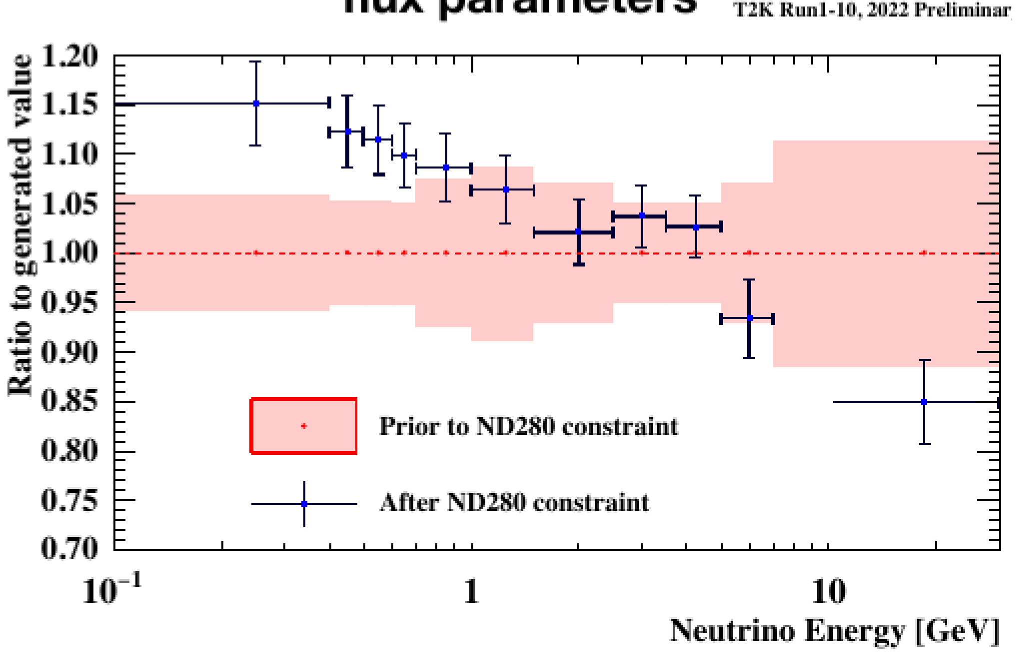




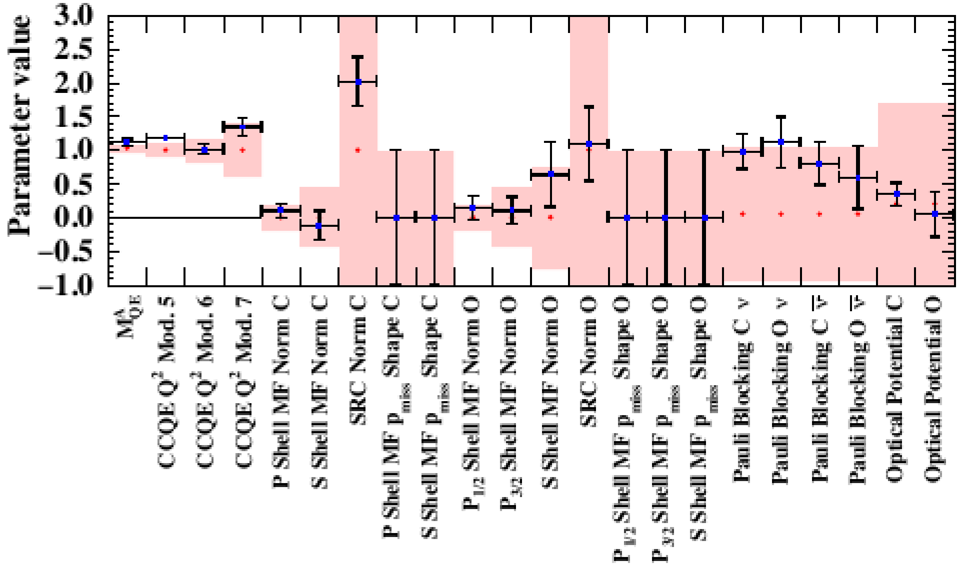
- ND280 is a magnetized detector
- We select interactions on CH (FGD1) and CH/Water (FGD2)
- Precise measurement of p and θ
- We separate nu from antinu interactions on the basis of the charge of the lepton
- Separate samples based on the number of reconstructed pions, protons, photons. 22 samples used in the fit (about 120 k ev)

ND280 Fit

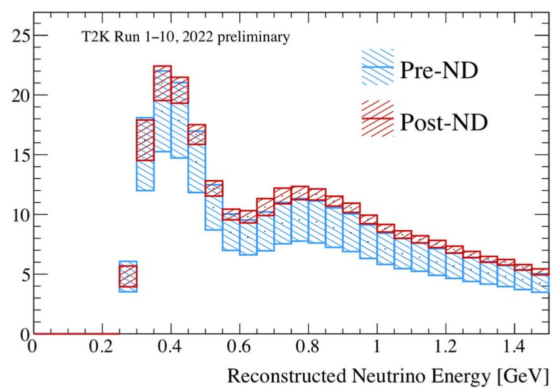
ND280 ν-mode flux parameters

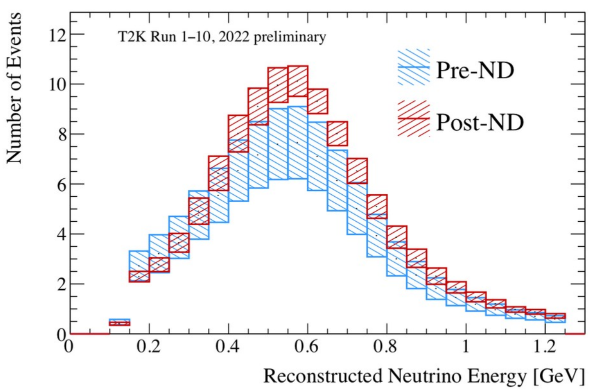


CCQE x-sec parameters

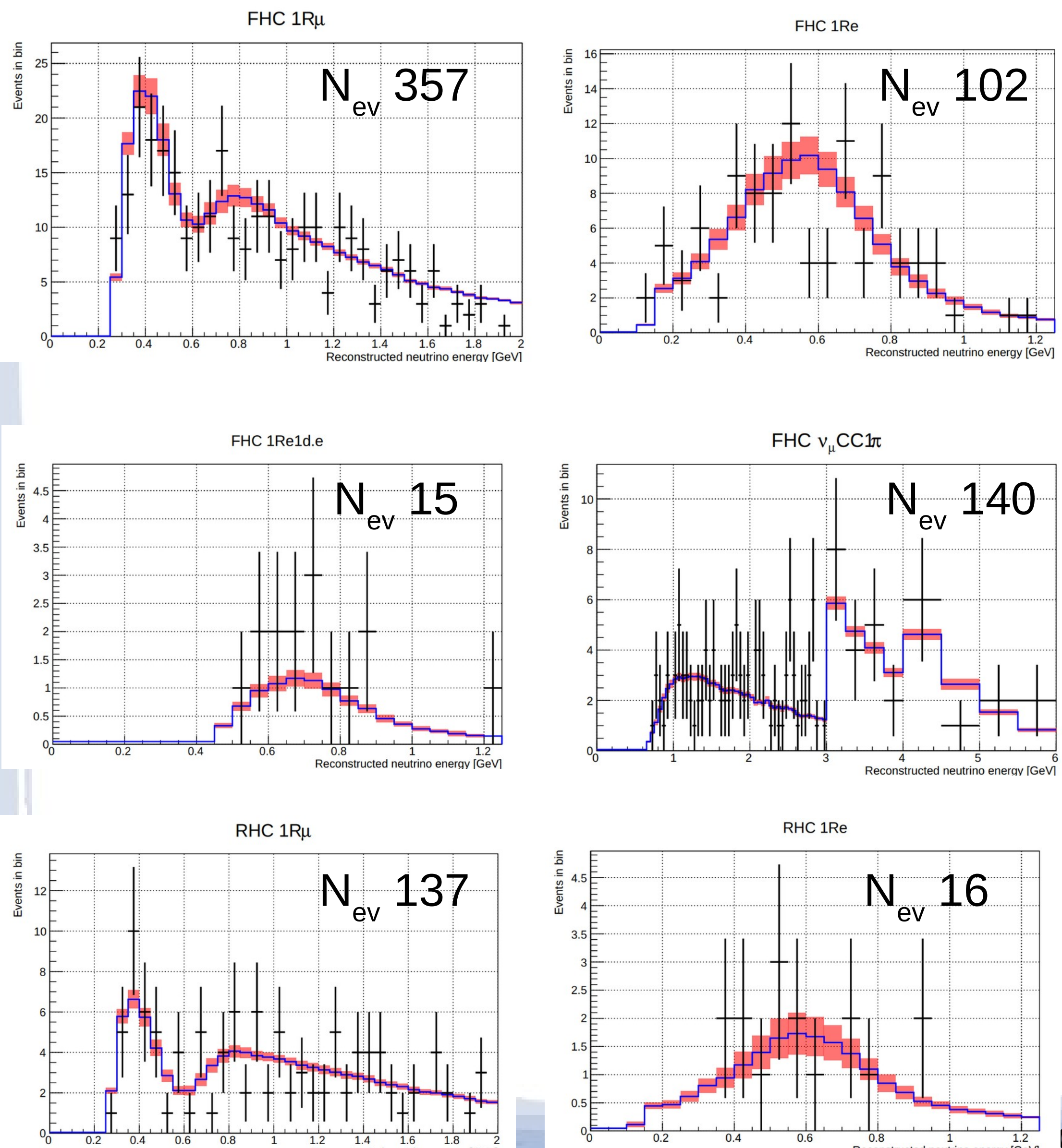


Sample	Pre-ND fit	Post-ND fit
ν-mode 1Rμ	16.7%	3.4%
ν-mode 1Re	17.3%	5.2%
ν-mode MR	12.5%	4.9%
ν-mode 1Re+d.e.	20.9%	14.3%
$\bar{\nu}$-mode 1Rμ	14.6%	3.9%
$\bar{\nu}$-mode 1Re	14.4%	5.8%





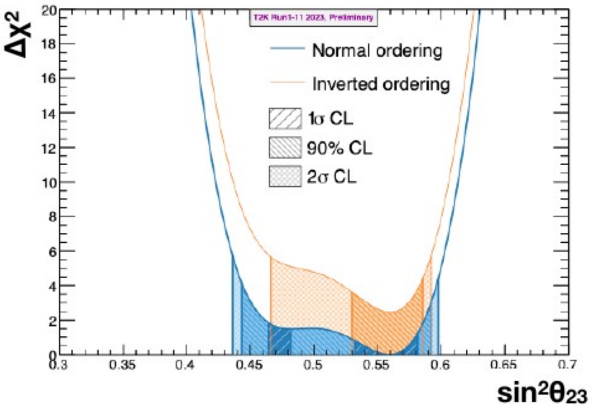
Super-Kamiokande selections

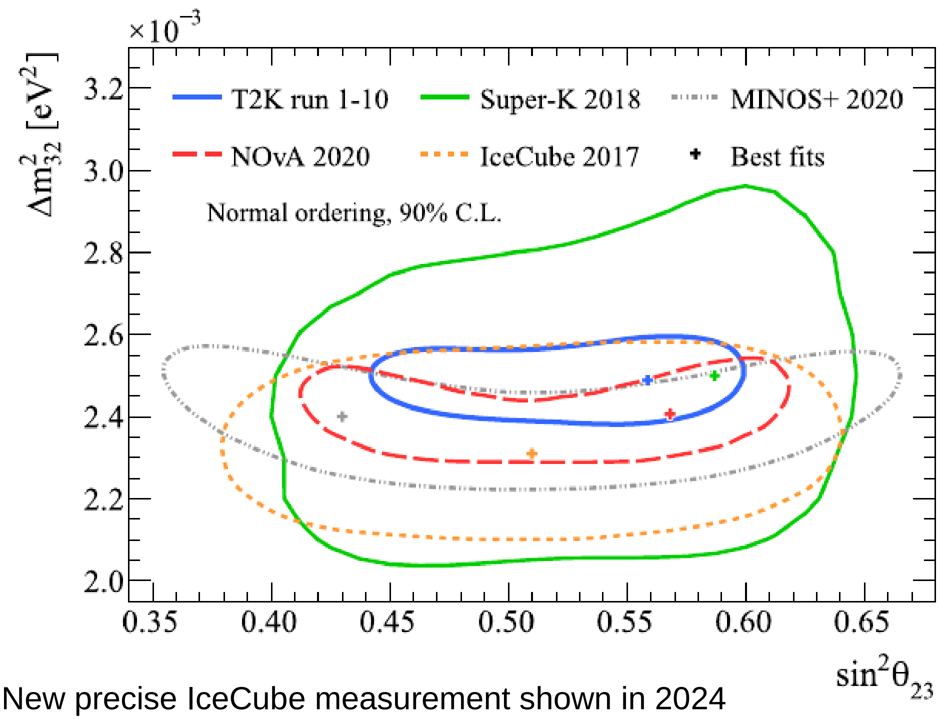


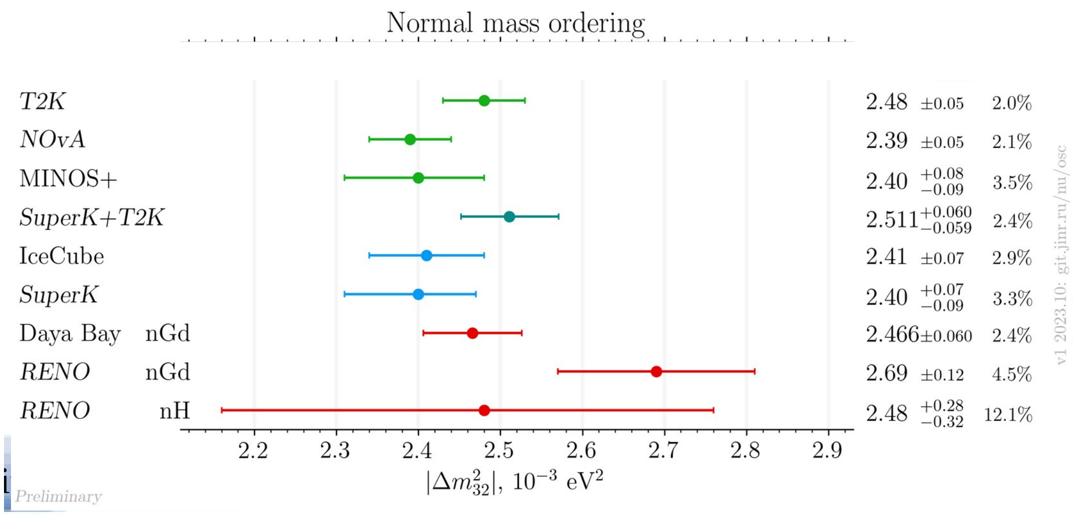
- 6 samples selected at SK
- 1 Ring mu-like or e-like in nu mode (CCQE enhanced)
- 2 Rings (mu-like) or additional decay el. (e-like) (CC1pi enhanced)
- 1 Ring mu-like or e-like in antinu mode (CCQE enhanced)

Oscillation analysis results : θ_{23} and $|\Delta m^2_{32}|$

- Mature and precise measurements (2 % on $|\Delta m^2_{32}|$)
- θ_{23} close to maximal disappearance
- Slight preference for upper octant



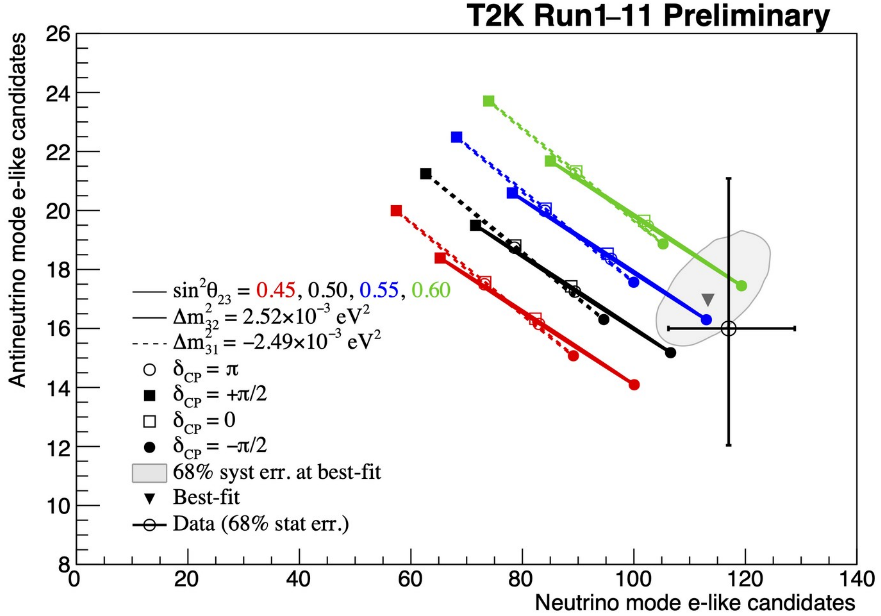




New precise IceCube measurement shown in 2024

Oscillation analysis results : δ_{CP} and mass ordering

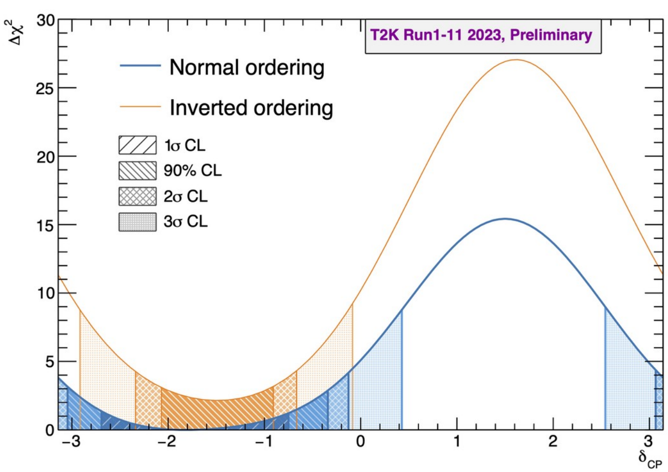
Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
ν-mode 1Rμ	417.2	416.3	417.1	418.2	357
ν-mode MR	123.9	123.3	123.9	124.4	140
$\bar{\nu}$-mode 1Rμ	146.6	146.3	146.6	147.0	137
ν-mode 1Re	113.2	95.5	78.3	96.0	102
$\bar{\nu}$-mode 1Re+d.e.	10.0	8.8	7.2	8.4	15
$\bar{\nu}$-mode 1Re	17.6	20.0	22.2	19.7	16



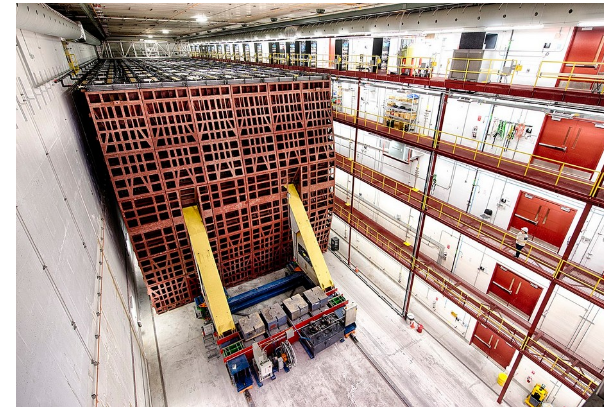
Slight preference for $\delta_{CP} \sim -\pi/2$ but CP conserving value within 2σ

slight preference for normal ordering

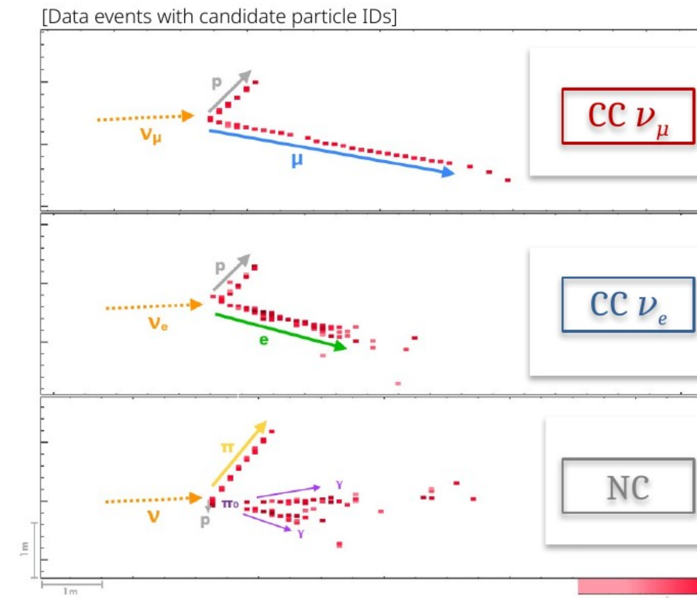
NB this is not a simple counting analysis

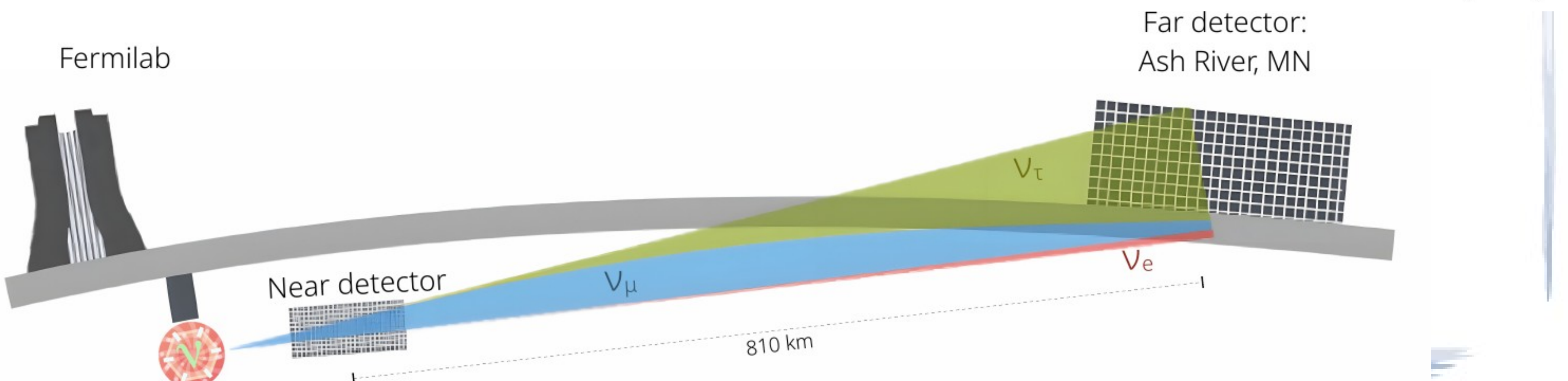


NOVA



- Long baseline neutrino experiments based on the Fermilab NUMi neutrino beam
- E~2 GeV L=810 km
- Similar liquid scintillator calorimeters at near (300 t) and far position (14kt) (Ash River, MN)
- Calorimetric neutrino energy reconstruction

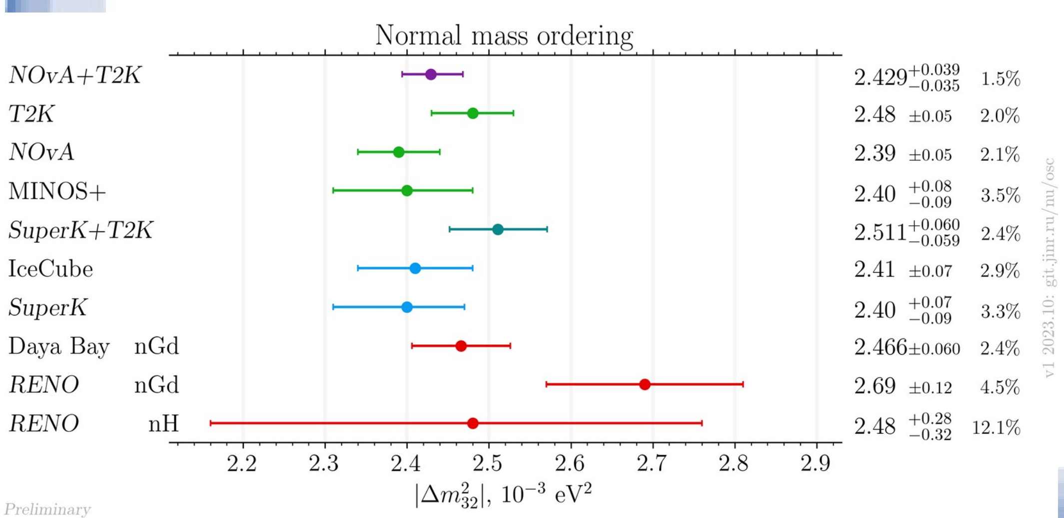


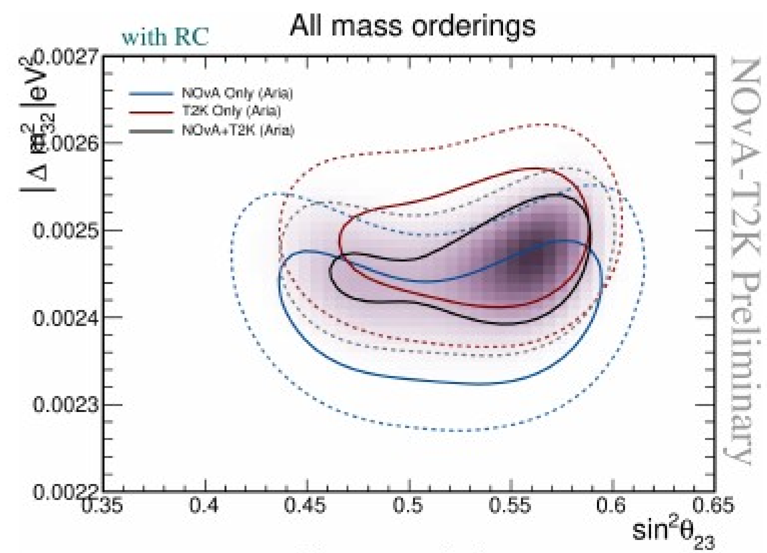


Figures and plots courtesy Nova Collaboration

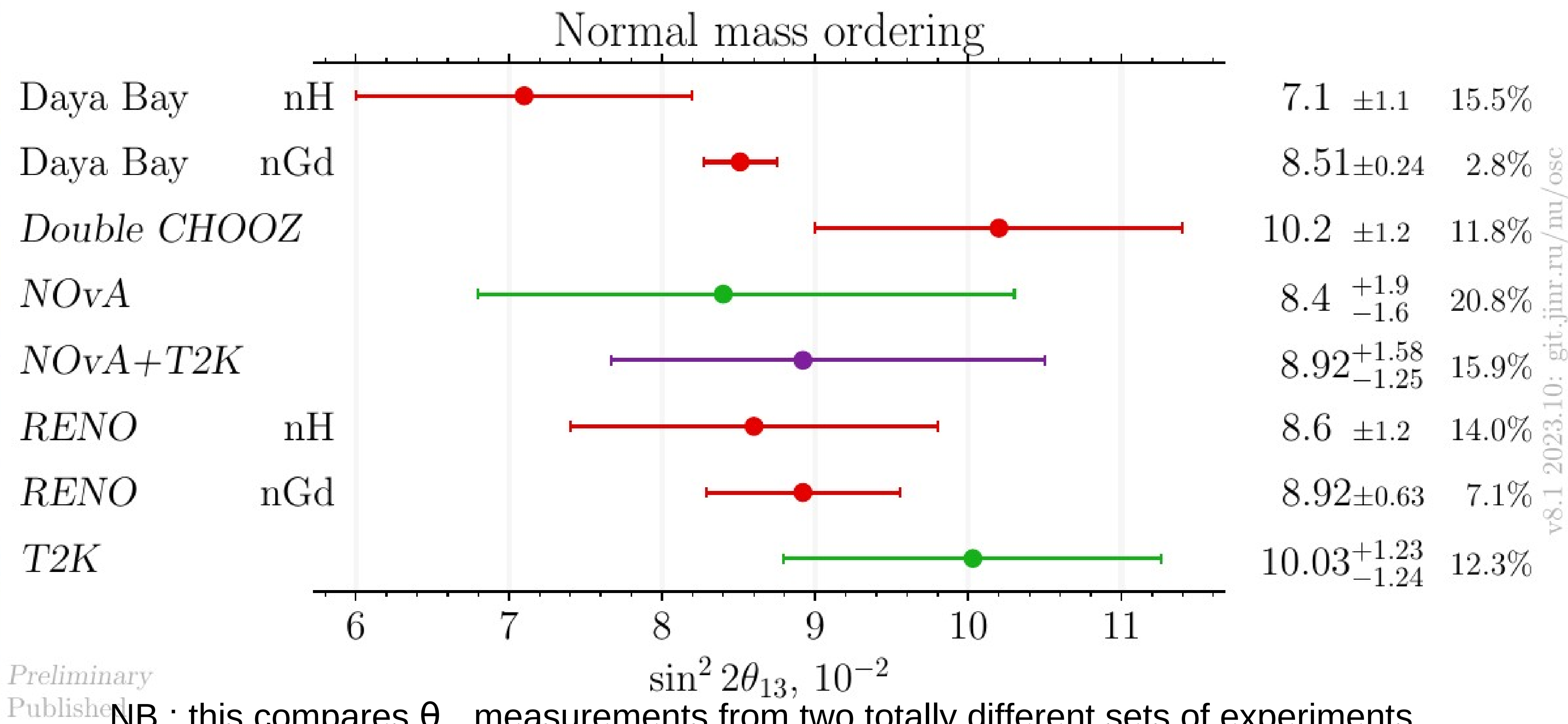
T2K-NovA : θ_{23} and $|\Delta m^2_{32}|$

- The NovA and T2K collaborations have worked very hard on a joint fit
- Full use of multidimensional likelihoods
- Thorough check of correlation between sources of syst. uncertainties
- A lot of checks on the neutrino interaction models used
- The joint fit p-value is greated than 5 %



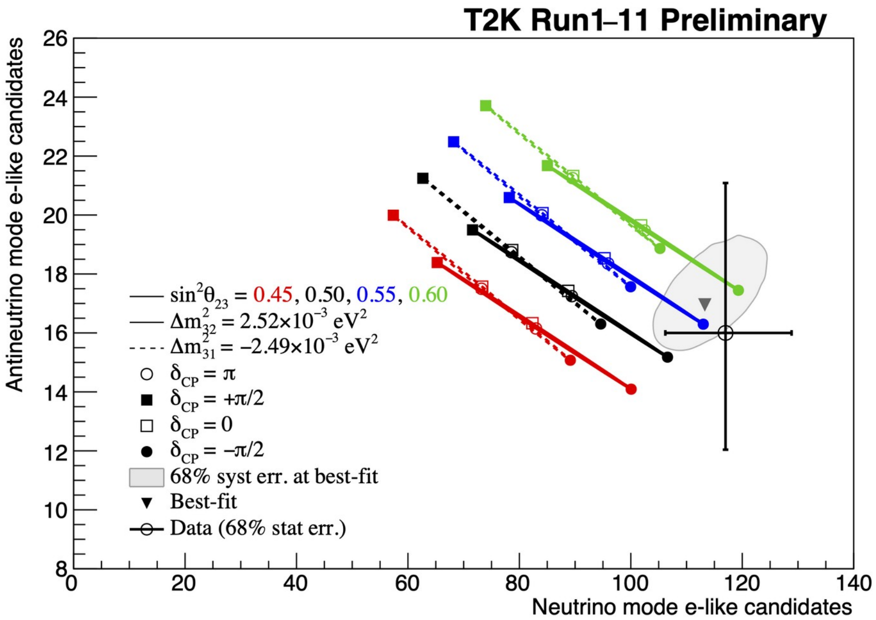


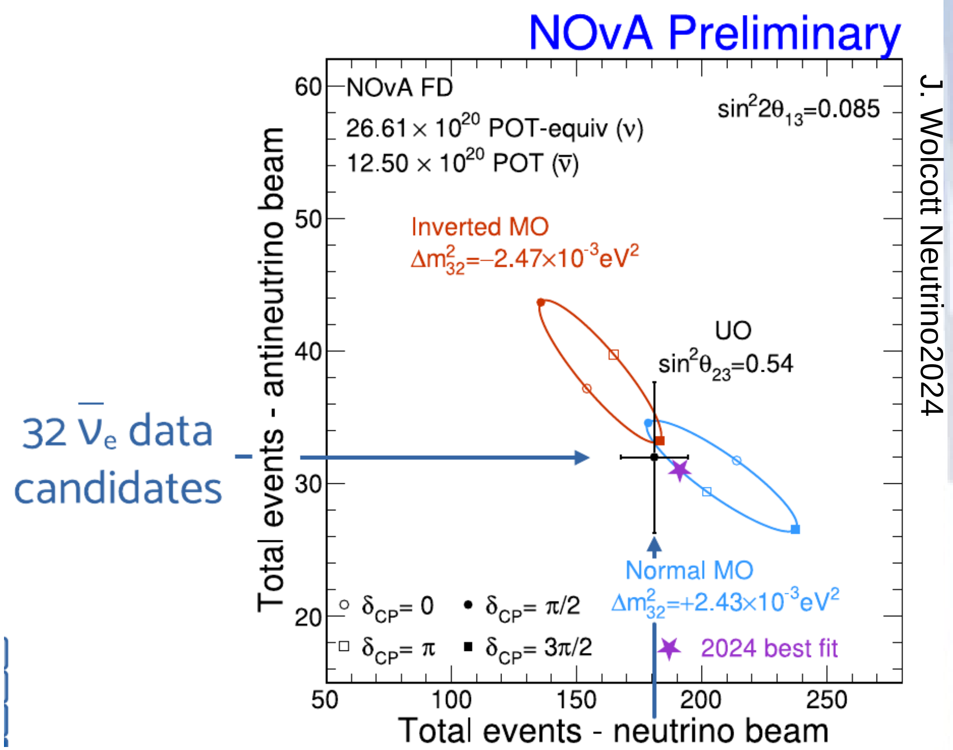
T2K-NovA : θ_{13}



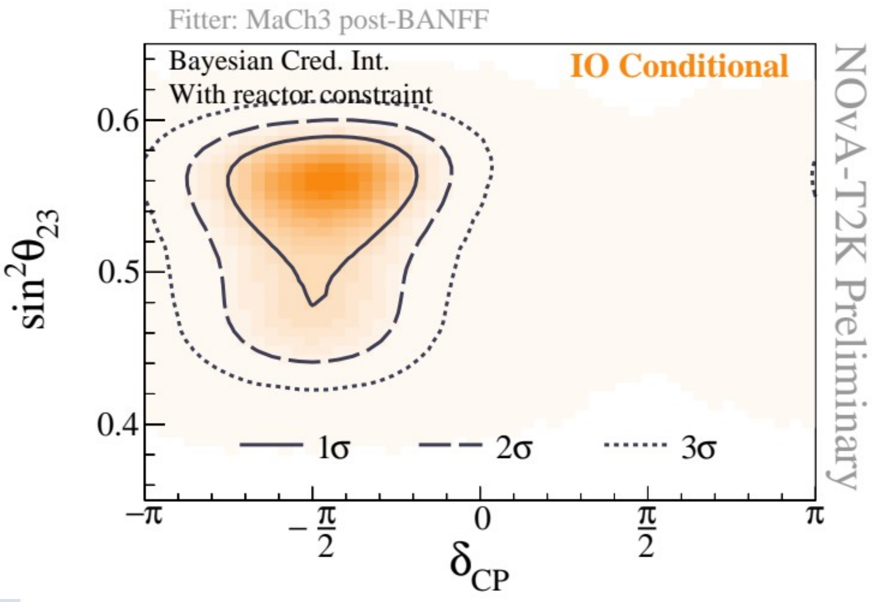
NB : this compares θ_{13} measurements from two totally different sets of experiments. On one side the disappearance measurement of $\overline{\nu}_e$ in reactor neutrinos expt. On the other side the $\nu_\mu \to \nu_e$ appearance in long baseline. It is an important test of the consistency of the 3ν model.

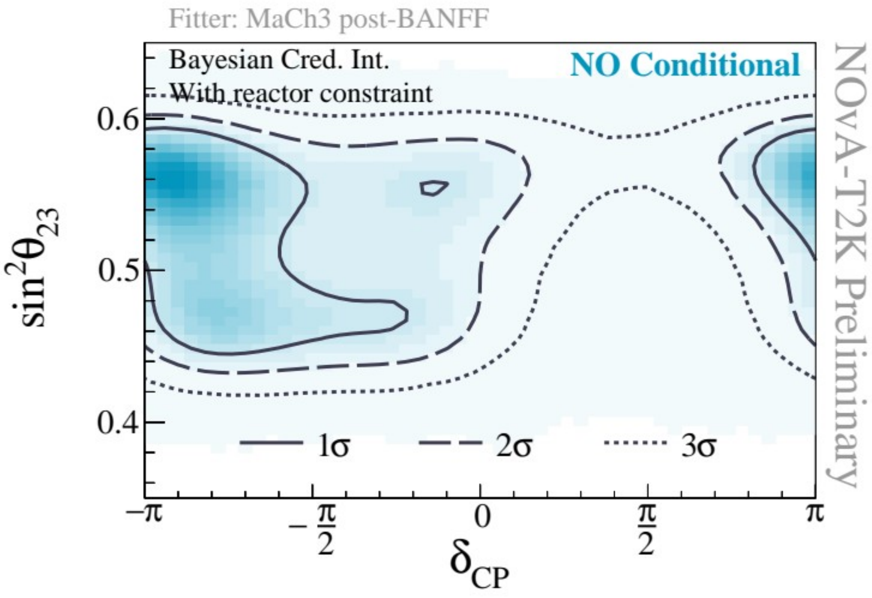
T2K-NovA : ν_e appearance





T2K-NovA δ_{CP}



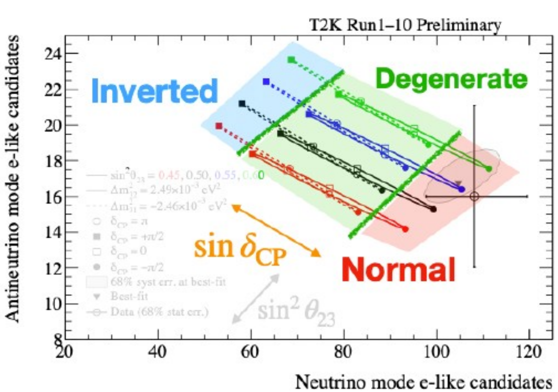


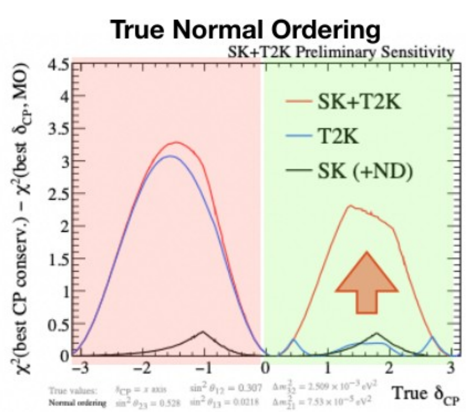
Inverted ordering : δ_{CP} ~ -π/2 preferred. Normal ordering δ_{CP} ~ -π (but very weak constraint).
The mass ordering preference is not statistically significant.

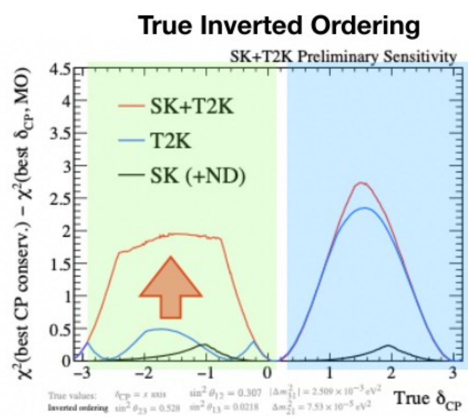
arXiv : 2405.12488

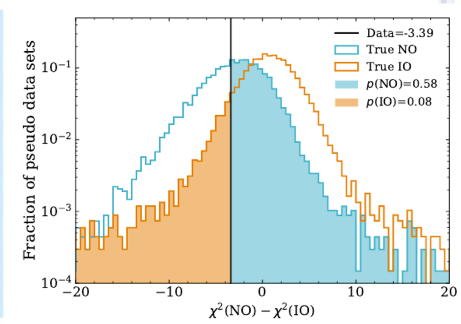
T2K-SK

- T2K has good sensitivity to δ_{CP} but mild sensitivity to mass ordering
- SK has good constraint on mass ordering but not on δ_{CP}
- Adding SK atmospheric sample allows to break the degeneracies between the CP violation parameter δ_{CP} and the mass ordering → boost sensitivity to CP
- Unified interaction model for T2K and SK low-energy samples, and detector systematics
- Normal ordering is preferred, p-value for IO 0.08



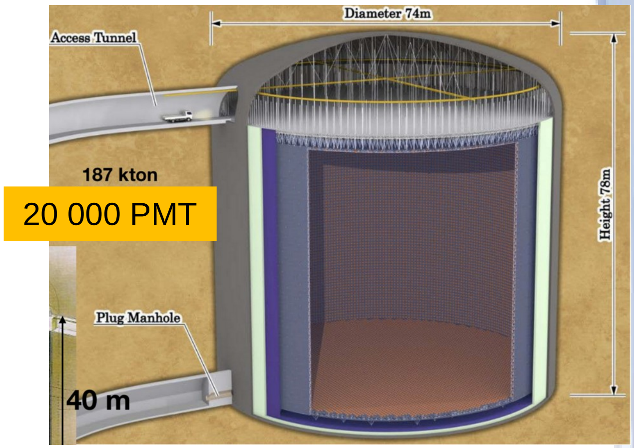


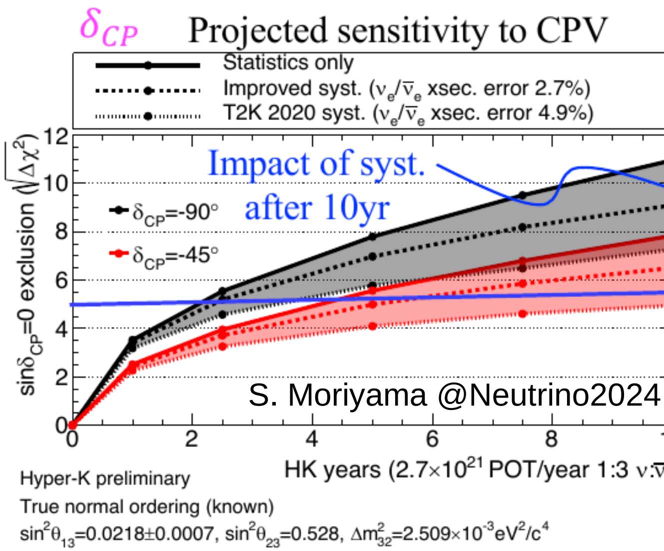




Hyper-Kamiokande

- 187 kt (8 times bigger than SuperKamiokande)
- Same baseline as T2K (295 km)
- Upgraded beam from J-PARC (1.3 MW)
- Instrumented with 20k PMTs and 800 mPMT
- Start operation end of 2027
- **ν_μ -> ν_e** samples larger than 1000 ev
- Mass ordering with atmospherics and beam
- Other topics : solar neutrinos, SN (70k events at 10kpc), SN relics, proton decay

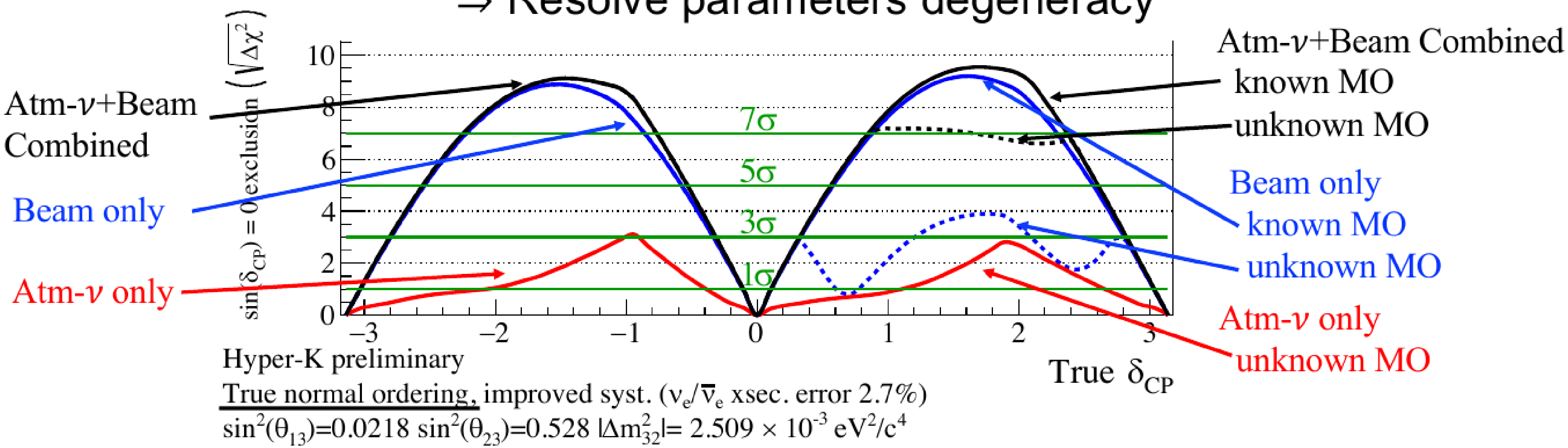




Strategy of oscillation measurement at Hyper-K

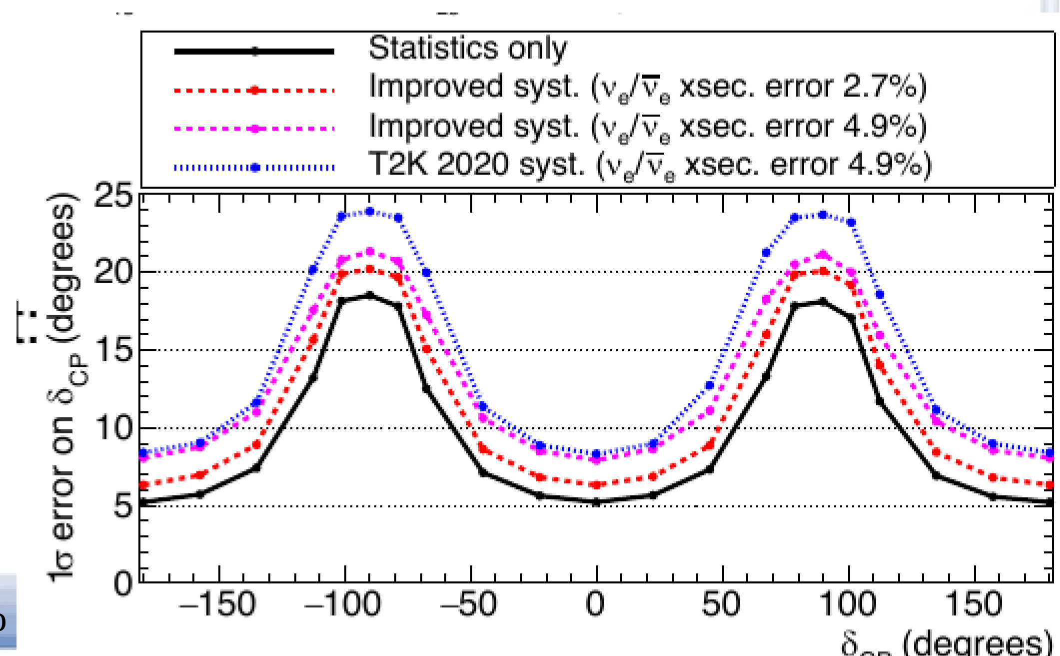
Combination of long-baseline and atm. ν observations

⇒ Resolve parameters degeneracy



	$\sin^2 \theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ →	3.8 σ
	0.60	4.9 σ →	6.2 σ
θ_{23} octant	0.45	2.2 σ →	6.2 σ
	0.55	1.6 σ →	3.6 σ

10 years with 1.3MW, normal mass ordering is assumed



Conclusions

- The present generation of long baseline experiments has contributed to establishing the 3-neutrinos oscillation paradigm (ν_e appearance, precision $|\Delta m^2_{32}|$, θ_{13} in agreement with reactors)
- It has established new methods for modelling neutrino-nucleus interactions, near detector fit etc
- It has unveiled tantalizing hints of (possible) CP violation effects, however these measurements are statistically limited
- A new generation of experiments HyperKamiokande and DUNE is in construction with complementary features. They will bring in precision to solve the remaining questions.

Acknowledgements

Thanks to Claudio Giganti, Shigetaka Moriyama, Jeremy Winscott, for providing slides and plots

Backup

This is a simplified two neutrino scenario

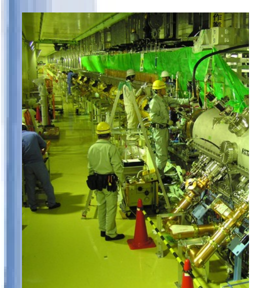
Neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

$\nu_\mu = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2$

If neutrino flavor eigenstates are different from mass eigenstates, propagation induces a phase shift with the appearance of a new flavor

Source



$\text{Prob}(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\,\sin^2(\Delta m^2 L/4E)$

W

ν_μ

μ

Detector

e

ν_e

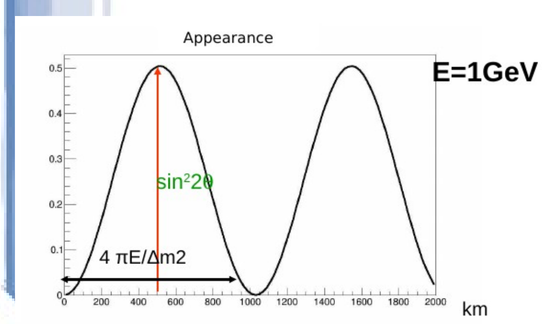
L

$\nu_1 \rightarrow \exp(-ip_1x)\,\nu_1$

$\nu_2 \rightarrow \exp(-ip_2x)\,\nu_2$

$\Delta\varphi = \Delta m^2 L/(4E)$

Propagation



CP violation effects

$\nu_\mu \to \nu_e$: beyond the leading term in vacuum

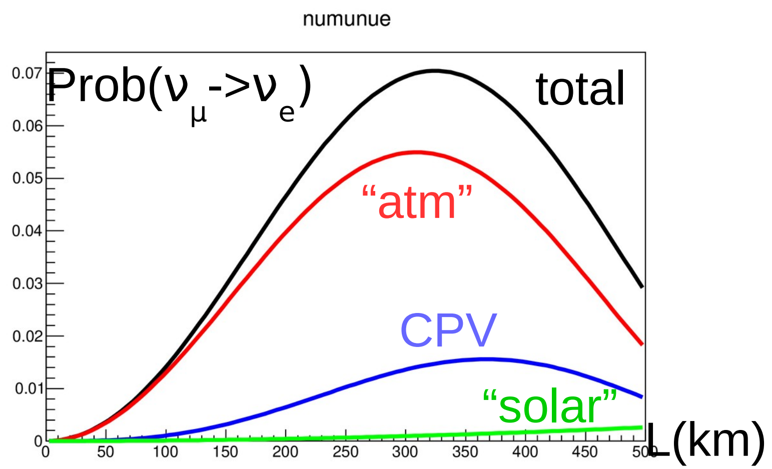
$$P(\nu_\mu \to \nu_e) \approx 4 C^2_{13} S^2_{13} S^2_{23} \sin^2 \Phi_{31}$$ "Atmospheric" term

$$\pm 8 C^2_{13} C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$ CP violating term

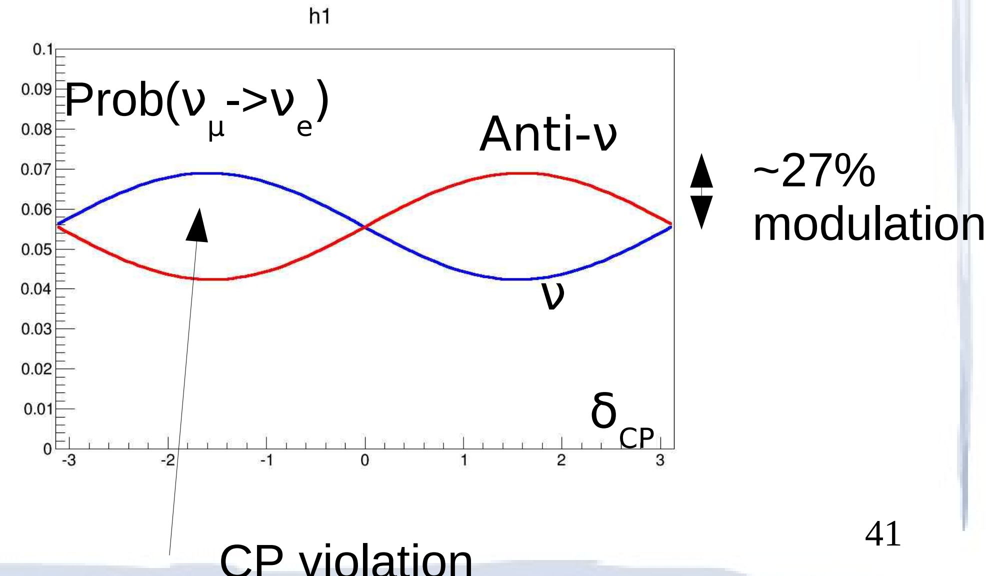
$$+4 S^2_{12} C^2_{13} (C^2_{12} C^2_{23} + S^2_{12} S^2_{23} S^2_{13} - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2 \Phi_{21}$$ "Solar" term

$$C_{ij} = \cos(\theta_{ij})$$
$$\Phi_{ij} = \Delta m^2_{ij} L / 4E$$

Change sign from ν to anti-ν! An accelerator based neutrino beam is ideal to study this, as either neutrinos or antineutrinos can be produced



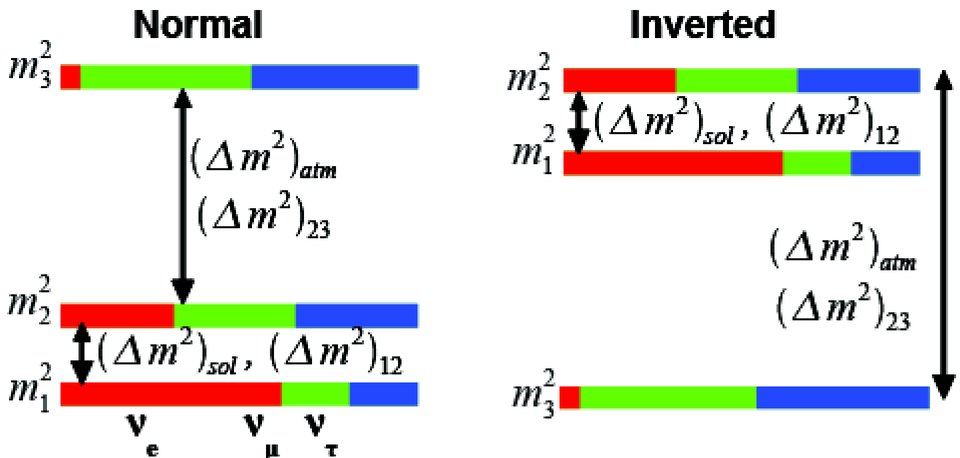
E=0.6 GeV



Neutrino masses and ordering

- Neutrinos have a tiny mass : m < 2 eV from measurement of the β spectrum (Katrin will push this limit to 0.2 eV)
- Since they oscillate, neutrino have masses
- Oscillations have measured two mass splitting: $|\Delta m^2_{atm}|$= 2.4 10^{-3} eV^2 and Δm^2_{sol} = 7.5 10^{-5} eV^2 and vacuum leading order measurements are not sensitive to the absolute mass scale

The lightest solution is: m1~0, m2~7 meV and m3~50 meV

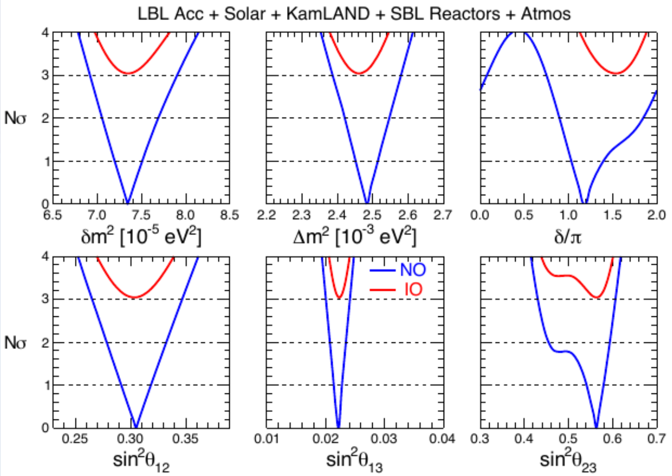


The lightest solution is: m3~0, m1~m2~50 meV

- The measurement of the sign of Δm^2_{atm} has implications for the theoretical understanding of the ν mass mechanism, long baseline CP violation measurements, 0- ν double beta decay, and cosmology

The study of neutrino properties

Today : few % precision on most of the parameters



Oscillation parameter		Best-fit (NO)	Best-fit (IO)	"1σ" error
Δm^2	$/10^{-3}$ eV^2	2.49	2.47	1.3 %
δm^2	$/10^{-5}$ eV^2	7.34	7.34	2.2 %
$\sin^2\theta_{13}$	$/10^{-2}$	2.23	2.24	3.0 %
$\sin^2\theta_{12}$	$/10^{-1}$	3.04	3.03	4.4 %
$\sin^2\theta_{23}$		0.56	0.56	~ 5 %

E. Lisi Granada 2019

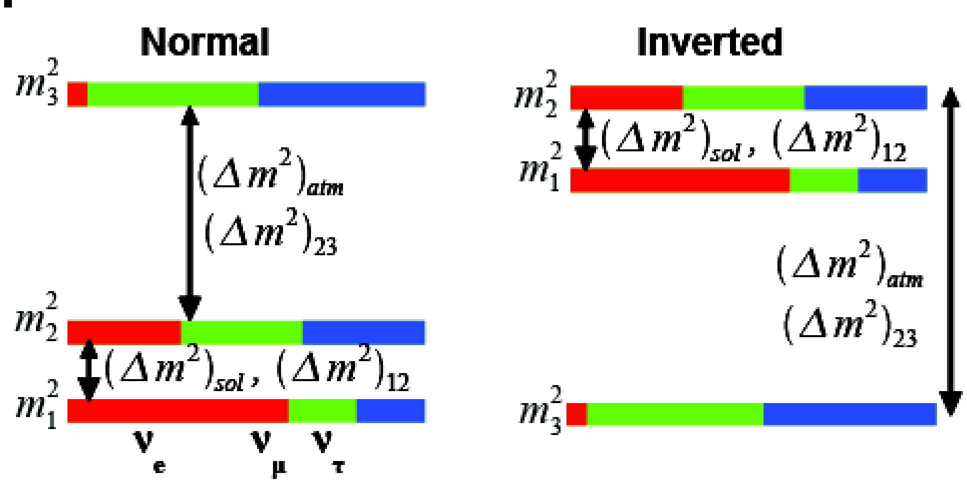
But there are still major unknowns : Dirac or Majorana, CP violation phase δ, mass ordering and θ_{23} octant, absolute mass

Neutrinos : next steps

1) Leptonic CP violation (PMNS parameter δ)
2) Mass ordering (normal or inverse)
3) Is θ_{23} =45°?
4) Precision tests of PMNS (at %, as for CKM)
5) Are there new neutral states ? (steriles, HNL)

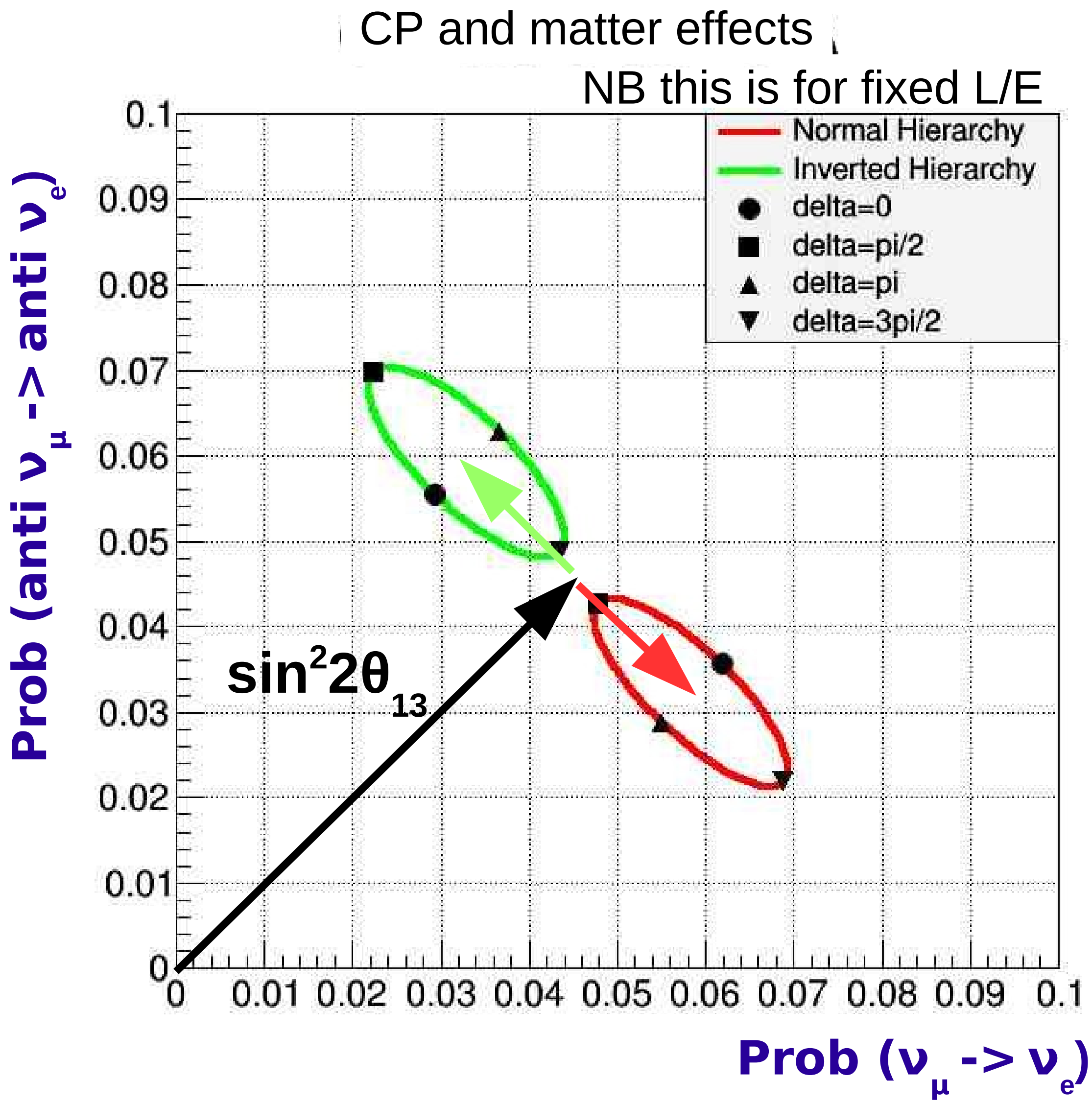
a) What is the nature of neutrinos (Dirac or Majorana) ?
b) What is the absolute mass value of neutrinos ?
c) Discover and measure the cosmological neutrinos
d) Exploration of the Universe with UHE neutrinos

Program of next oscillation experiments

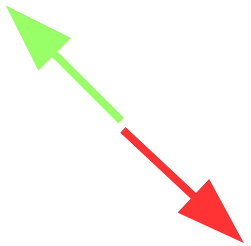


See also Dr. Segarra talk
in today parallel session

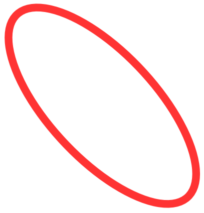
Combined CP and matter effects



Effect of **inverse** or **direct** mass ordering

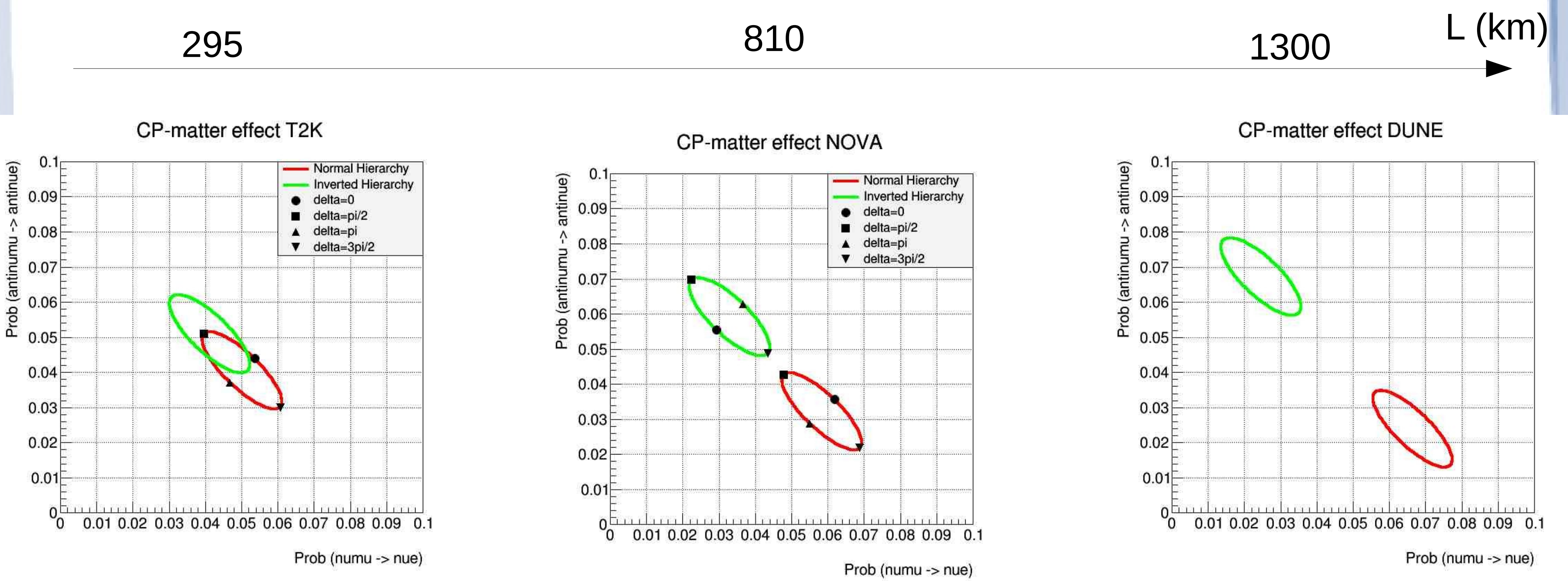


CP violation



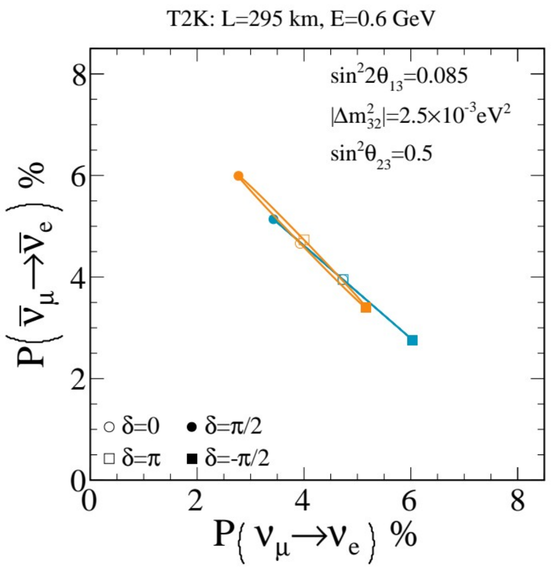
NB A precise measurement in this plane can determine θ_{13}, MO, δ_{CP}, θ_{23} octant

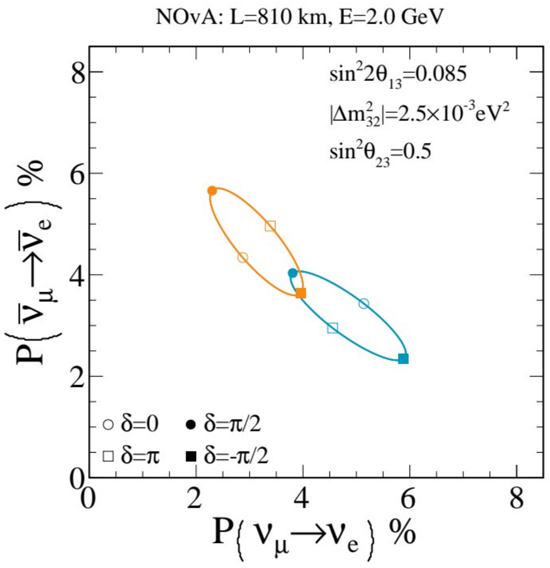
Combined effect of CP and matter



The relative increase of matter effect versus CP effect is due to the fact that these experiments are tuned to the L/E of the first oscillation maximum. The increasing L and therefore E are such that Prob (ν_{μ} -> ν_e) approaches the MSW resonance.

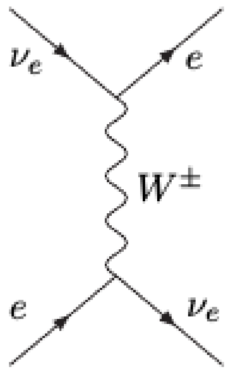
For T2K, CP modulation +-27%, Matter effect ~10%

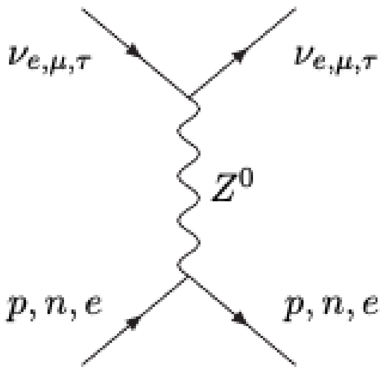

T2K: L=295 km, E=0.6 GeV
sin²2θ13=0.085
|Δm²32|=2.5×10⁻³eV²
sin²θ23=0.5
δ=0
δ=π/2
δ=π
δ=-π/2
P(νμ→νe) %
P(ν̄μ→ν̄e) %

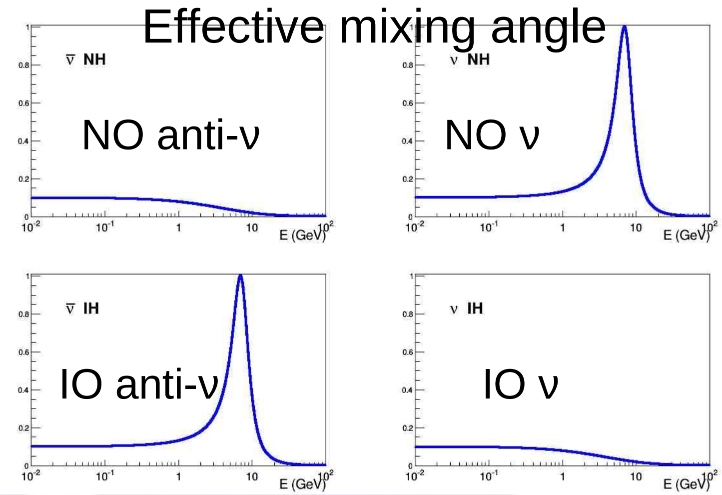

NOvA: L=810 km, E=2.0 GeV
sin²2θ13=0.085
|Δm²32|=2.5×10⁻³eV²
sin²θ23=0.5
δ=0
δ=π/2
δ=π
δ=-π/2
P(νμ→νe) %
P(ν̄μ→ν̄e) %

Neutrino oscillation in matter

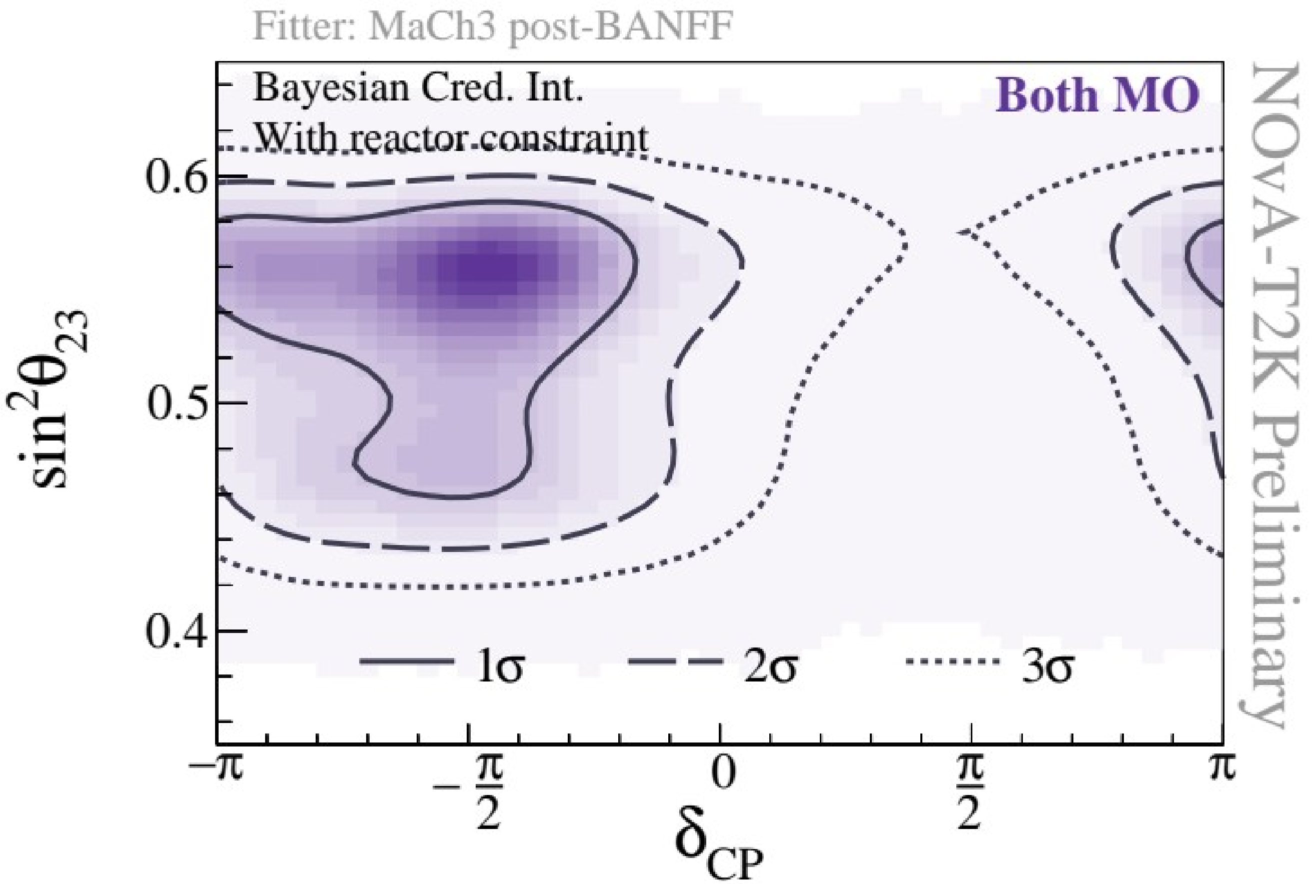
- Neutrino forward scattering on electrons, equivalent to light refraction index, leads to an additional phase for <u>electron neutrinos</u> proportional to $G_F N_e$
- The sign of the potential and therefore the phase depends on neutrino vs antineutrino
- This can be parameterized (for a constant density) as an effective mixing angle exhibiting a MSW resonance (E_{res}~7 GeV for ρ=4.5 g/cm^3) either for neutrinos (NO) or antineutrinos (IO).
- <u>Matter effects can either enhance or suppress **ν_μ -> ν_e** depending on the ordering.</u>







T2K-NOvA



Not conclusive : broad region in deltaCP allowed

ND fit CC0pi parameters

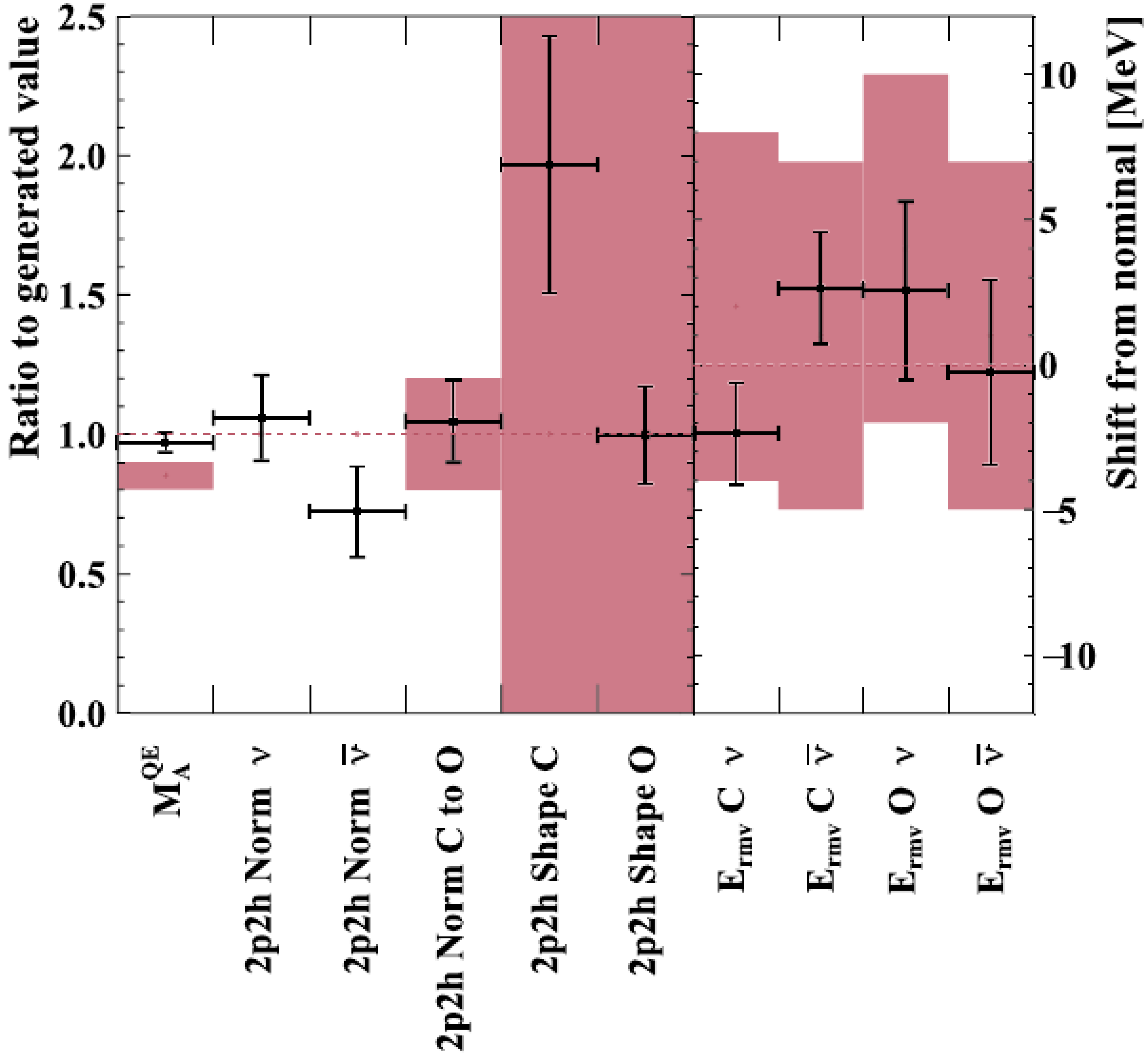


TABLE XIV. Event reduction for the ν_e CC selection at the far detector. The numbers of expected MC events divided into five categories are shown after each selection criterion is applied. The MC expectation is based upon three-neutrino oscillations with the parameters as shown in Table XIII.

		$\nu_\mu + \bar{\nu}_\mu$	$\nu_e + \bar{\nu}_e$	$\nu + \bar{\nu}$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	
ν-beam mode	MC total	CC	CC	NC	CC	CC	Data
Interactions in FV	744.89	364.32	18.55	326.16	0.39	35.47	⋯
FCFV	431.85	279.88	18.09	98.72	0.38	34.78	438
Single ring[a]	223.49	153.40	11.15	28.68	0.32	29.95	220
Electronlike[b]	66.94	6.46	11.06	19.53	0.31	29.57	70
$E_{\mathrm{vis}} > 100$ MeV[c]	61.78	4.59	11.01	16.81	0.31	29.06	66
$N_{\text{Michel-e}} = 0$[d]	50.60	0.97	8.97	14.24	0.31	26.11	51
$E_\nu^{\mathrm{rec}} < 1250$ MeV[e]	40.71	0.25	4.26	10.85	0.22	25.14	46
Not π^0-like[f]	28.55	0.09	3.68	1.35	0.18	23.25	32
$\bar{\nu}$-beam mode							
Interactions in FV	312.38	164.04	9.00	132.75	4.30	2.29	⋯
FCFV	180.48	123.24	8.75	42.05	4.20	2.24	170
Single ring	96.06	73.21	5.51	11.87	3.74	1.73	94
Electronlike	21.55	2.31	5.48	8.36	3.70	1.71	16
$E_{\mathrm{vis}} > 100$ MeV	20.05	1.83	5.46	7.39	3.68	1.69	14
$N_{\text{Michel-e}} = 0$	16.40	0.33	4.71	6.24	3.66	1.46	12
$E_\nu^{\mathrm{rec}} < 1250$ MeV	11.40	0.08	1.89	4.83	3.42	1.19	9
Not π^0-like	6.28	0.02	1.58	0.60	3.04	1.05	4

[a]There is only one reconstructed Cherenkov ring.
[b]The ring is e-like.
[c]The visible energy, E_{vis}, is greater than 100 MeV.
[d]There is no reconstructed Michel electron.
[e]The reconstructed energy, E_ν^{rec}, is less than 1.25 GeV.
[f]The event is not consistent with a π^0 hypothesis.

TABLE XV. Event reduction for the ν_μ CC selection at the far detector. The numbers of expected MC events divided into four categories are shown after each selection criterion is applied. The MC expectation is based upon three-neutrino oscillations with the parameters as shown in Table XIII.

		ν_μ	$\bar{\nu}_\mu$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_e + \bar{\nu}_e$	$\nu + \bar{\nu}$	
ν-beam mode	MC total	CCQE	CCQE	CC nonQE	CC	NC	Data
Interactions in FV	744.89	100.17	6.45	257.70	54.41	326.16	⋯
FCFV	431.85	78.75	4.85	196.28	53.25	98.72	438
Single ring[a]	223.49	73.49	4.70	75.21	41.41	28.68	220
Muonlike[b]	156.56	72.22	4.65	70.06	0.47	9.16	150
$p_\mu > 200$ MeV/c[c]	156.24	72.03	4.65	70.00	0.47	9.08	150
$N_{\text{Michel-e}} \leq 1$[d]	137.76	71.28	4.63	52.61	0.46	8.78	135
$\bar{\nu}$-beam mode							
Interactions in FV	312.38	20.04	30.77	113.23	15.59	132.75	⋯
FCFV	180.48	15.04	24.95	83.26	15.19	42.05	170
Single ring	96.06	13.52	24.28	35.41	10.98	11.87	94
Muonlike	74.52	13.40	23.96	33.56	0.09	3.52	78
$p_\mu > 200$ MeV/c	74.42	13.39	23.92	33.54	0.09	3.48	78
$N_{\text{Michel-e}} \leq 1$	68.26	13.18	23.85	27.79	0.09	3.35	66

[a]There is only one reconstructed Cherenkov ring.
[b]The ring is μ-like.
[c]The reconstructed momentum, p_μ, is greater than 200 MeV/c.
[d]There are less than two reconstructed Michel electrons.

TABLE XVI. Event reduction for the ν_e CC1π^+ selection at the far detector. The numbers of expected MC events divided into five categories are shown after each selection criterion is applied. The MC expectation is based on the parameters of Table XIII.

		$\nu_\mu + \bar{\nu}_\mu$	$\nu_e + \bar{\nu}_e$	$\nu + \bar{\nu}$	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	
ν-beam mode	MC total	CC	CC	NC	CC	CC	Data
Interactions in FV	744.89	364.32	18.55	326.16	0.39	35.47	…
FCFV	431.85	279.88	18.09	98.72	0.38	34.78	438
(1) Single ring[a]	223.49	153.40	11.15	28.68	0.32	29.95	220
(2) Electronlike[b]	66.94	6.46	11.06	19.53	0.31	29.57	70
(3) $E_{\mathrm{vis}} > 100$ MeV[c]	61.78	4.59	11.01	16.81	0.31	29.06	66
(4) $N_{\text{Michel-e}} = 1$[d]	9.36	2.42	1.87	2.14	0.01	2.92	14
(5) $E_\nu^{\mathrm{rec}} < 1250$ MeV[e]	4.66	0.70	0.50	0.78	<0.01	2.66	11
(6) Not π^0-like[f]	3.14	0.29	0.39	0.15	<0.01	2.31	5

[a]There is only one reconstructed Cherenkov ring.
[b]The ring is e-like.
[c]The visible energy, E_{vis}, is greater than 100 MeV.
[d]There is one reconstructed Michel electron.
[e]The reconstructed energy, E_ν^{rec}, is less than 1.25 GeV.
[f]The event is not consistent with a π^0 hypothesis.

TABLE XIX. Effect of 1σ variation of the systematic uncertainties on the predicted event rates of the ν-mode samples.

	ν_e CCQE-like	ν_μ	ν_e CC1π^+
Source of uncertainty	$\delta N/N$	$\delta N/N$	$\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross section			
(w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI + SI + PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All			
(w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%

Table 10 Uncertainties on the number of events in each FD sample broken down by source after (before)the fit to ND data. "FD + SI + PN" combines the uncertainties from the FD detector, secondary particle interactions (SI), and photo-nuclear (PN) effects. "Flux⊗Interaction" denotes the combined effect from the ND constrained flux and interaction parameters, and the unconstrained interaction parameters. The change in the "FD + SI + PN" uncertainties before and after the ND fit is an indirect effect due to the change of interaction mode fractions in the samples after the ND fit

Sample		Uncertainty source (%)			Flux⊗Interaction (%)	Total (%)
		Flux	Interaction	FD + SI + PN		
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\overline{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\overline{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)