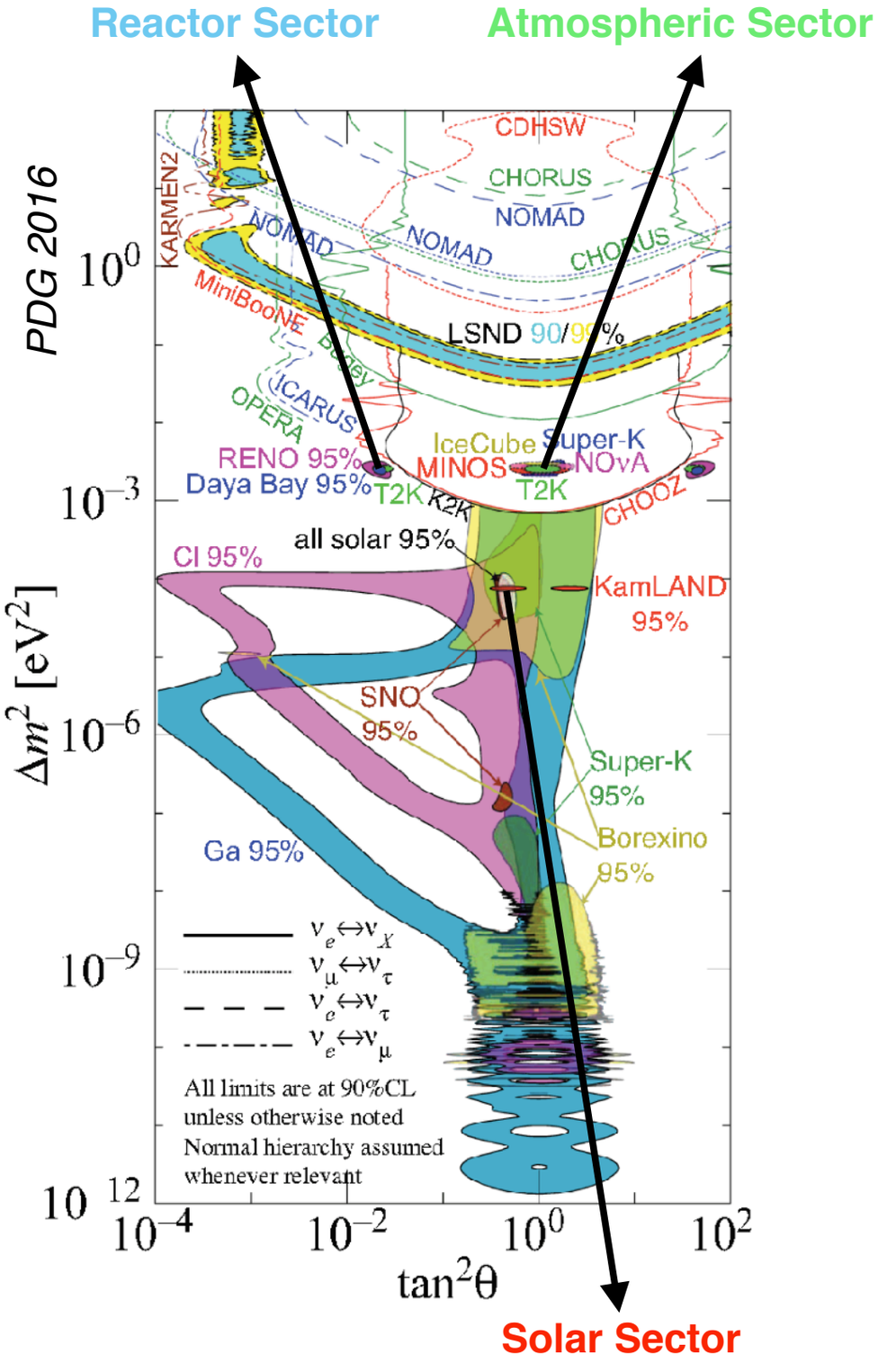
T2K latest oscillation results and SK-T2K joint analysis

Adrien Blanchet
on behalf of the T2K Collaboration

IRN Neutrino meeting

The 2nd of December - 2021

Measuring oscillation parameters



2020's Picture of the PMNS paradigm

arXiv:2006.11237

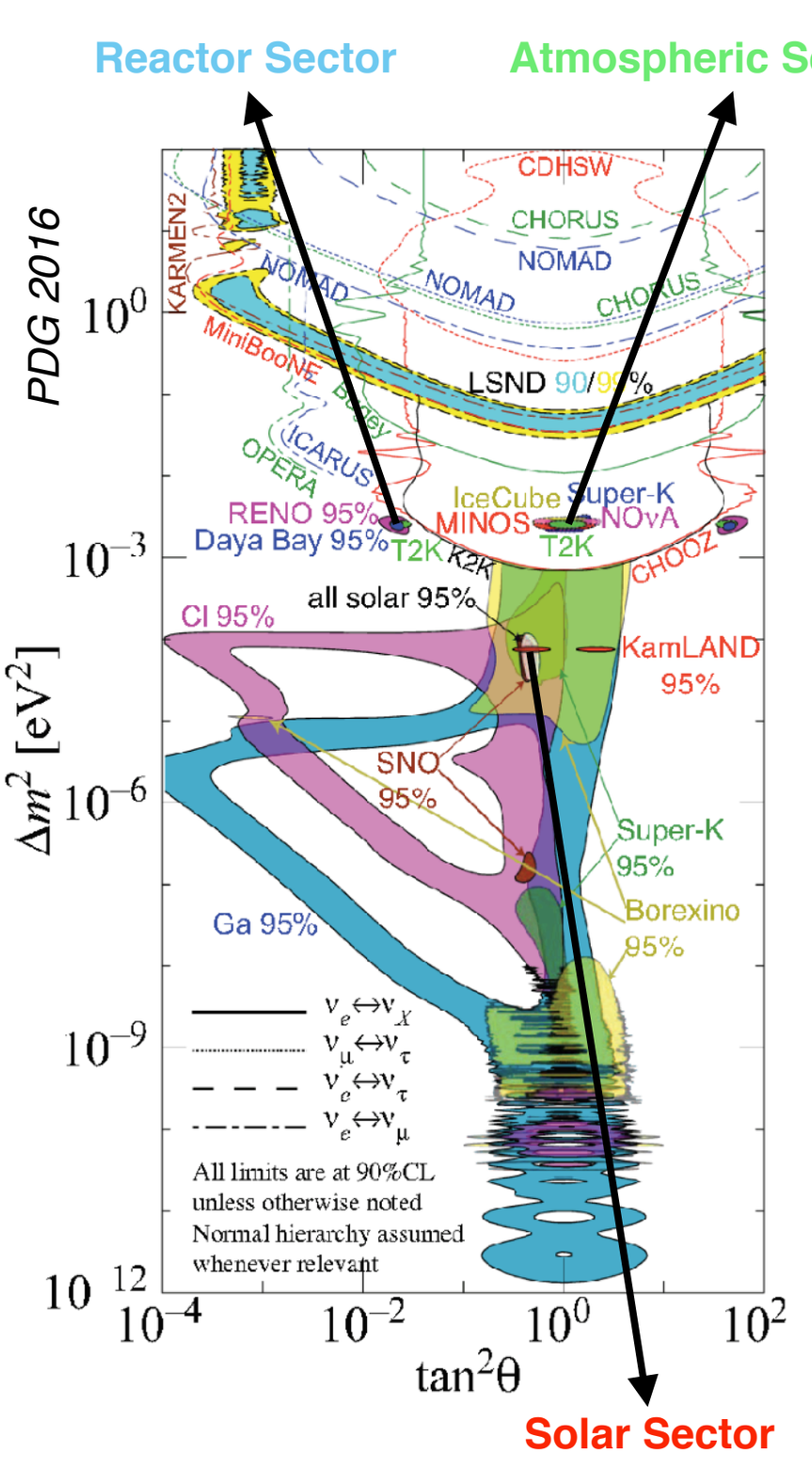
parameter	best fit $\pm 1\sigma$	3σ range	1σ relat.
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	***2.7%***
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	***1.2%***
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.70	***5.2%***
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	***4.9%***
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	***3.0%***
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	
δ/π (NO)	?		
δ/π (IO)			

Most of the parameters measured with < 5% precision

θ_{23} is known with 5% precision

Remaining parameters are δ_{CP} and the mass ordering

Measuring oscillation parameters



2020's Picture of the PMNS paradigm

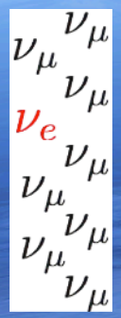
arXiv:2006.11237

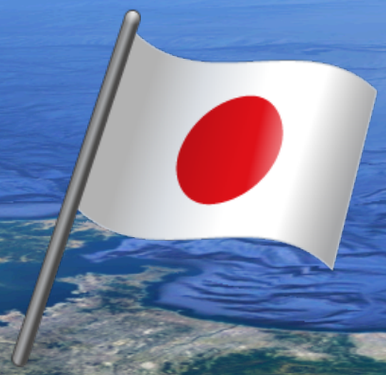
parameter	best fit $\pm 1\sigma$	3σ range	1σ relat.
Δm^2_{21} [10^{-5}eV^2]	$7.50^{+0.22}_{-0.20}$	6.94–8.14	***2.7%***
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	$2.56^{+0.03}_{-0.04}$	2.46–2.65	***1.2%***
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	2.46 ± 0.03	2.37–2.55	
$\sin^2\theta_{12}$ /10^{-1}	3.18 ± 0.16	2.71–3.70	***5.2%***
$\sin^2\theta_{23}$ /10^{-1} (NO)	$5.66^{+0.16}_{-0.22}$	4.41–6.09	***4.9%***
$\sin^2\theta_{23}$ /10^{-1} (IO)	$5.66^{+0.18}_{-0.23}$	4.46–6.09	
$\sin^2\theta_{13}$ /10^{-2} (NO)	$2.225^{+0.055}_{-0.078}$	2.015–2.417	***3.0%***
$\sin^2\theta_{13}$ /10^{-2} (IO)	$2.250^{+0.056}_{-0.076}$	2.039–2.441	
δ/π (NO)	?		
δ/π (IO)			

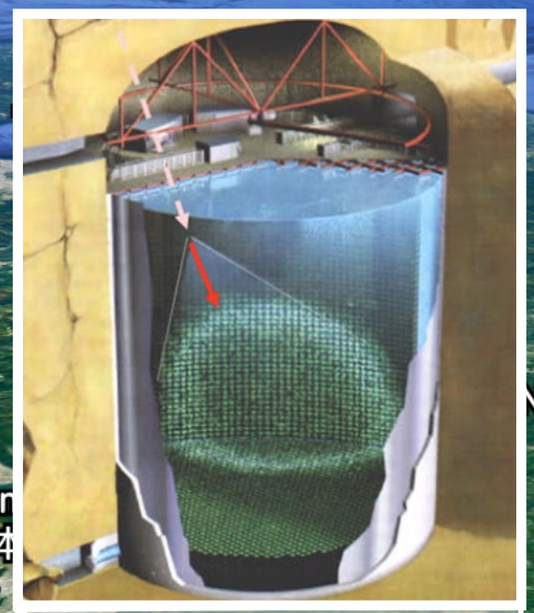
Need to measure oscillation for **both neutrino and antineutrino** to probe the CP violation parameter.

Accessible with T2K

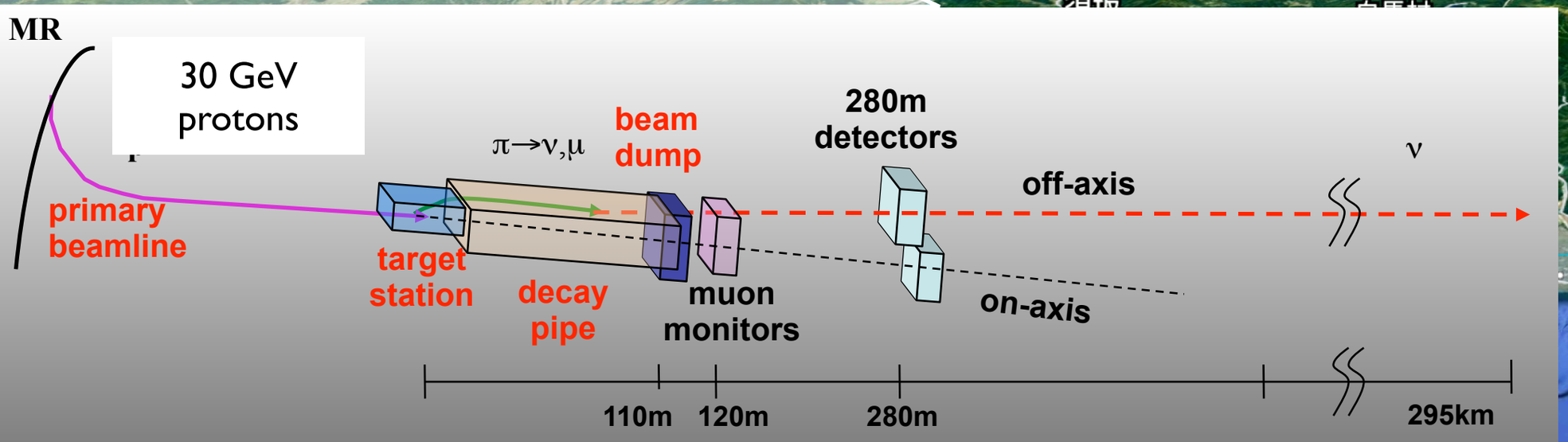
The T2K experiment: Tokai to Kamioka

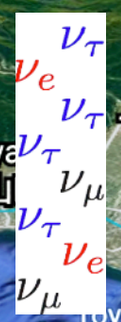






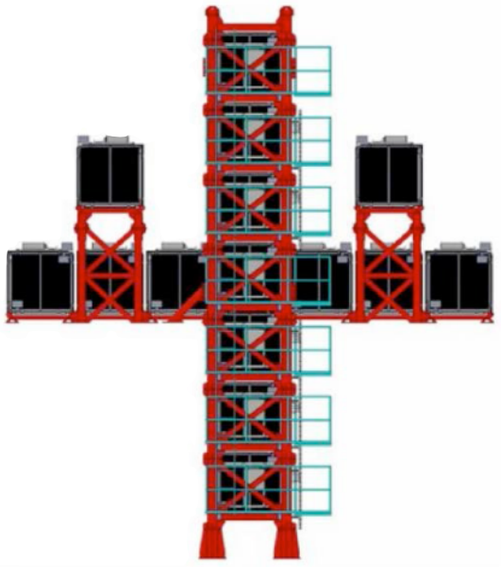
Hitachinaka
たちなか
Tokai
Mito
水戸
Utsunomiya
宇都宮
Nikko
日光
Tsukuba
つくば
Tokyo
東京
Maebashi
前橋
Takasaki
高崎
Karuizawa
軽井沢町
Ueda
上田
Matsumoto
松本
Numazu
沼津
Kofu
甲府
Minamiuonuma
南魚沼
Nozawaonsen
野沢温泉村
Nakano
中野
Nagano
長野
Suzaka
須坂
Hakuba
295 km



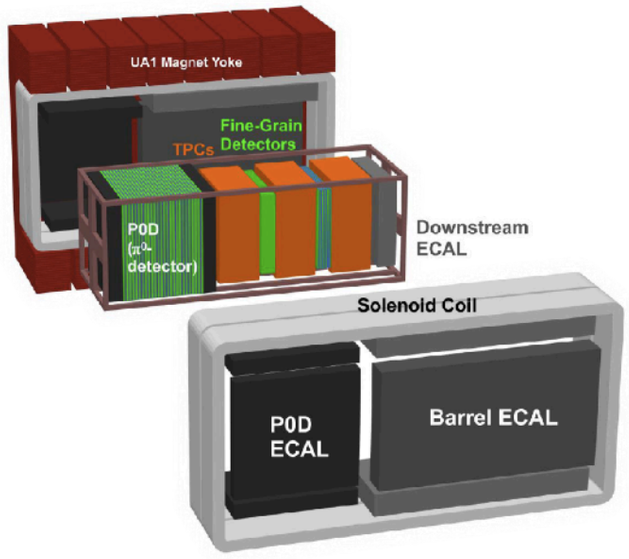


Kurobe
黒部
Tateyama
立山
Toyama
富山
Uozu
魚津
Toyama Bay
富山湾

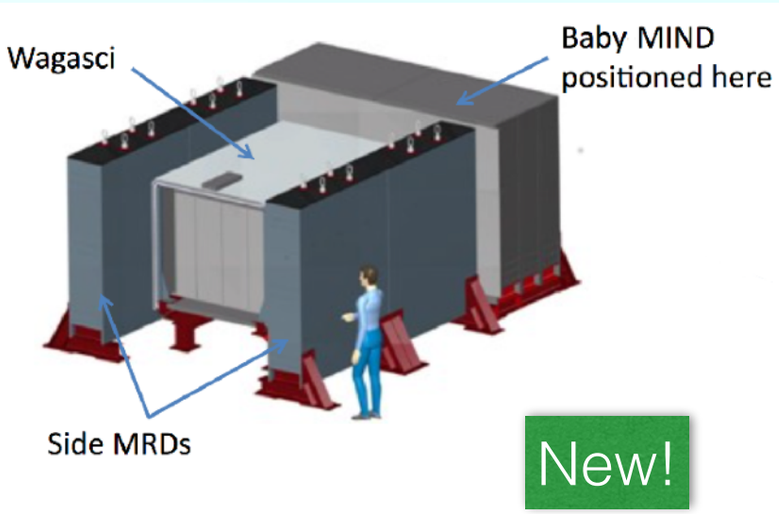
The near detectors



INGRID: On-axis



ND280: Off-axis

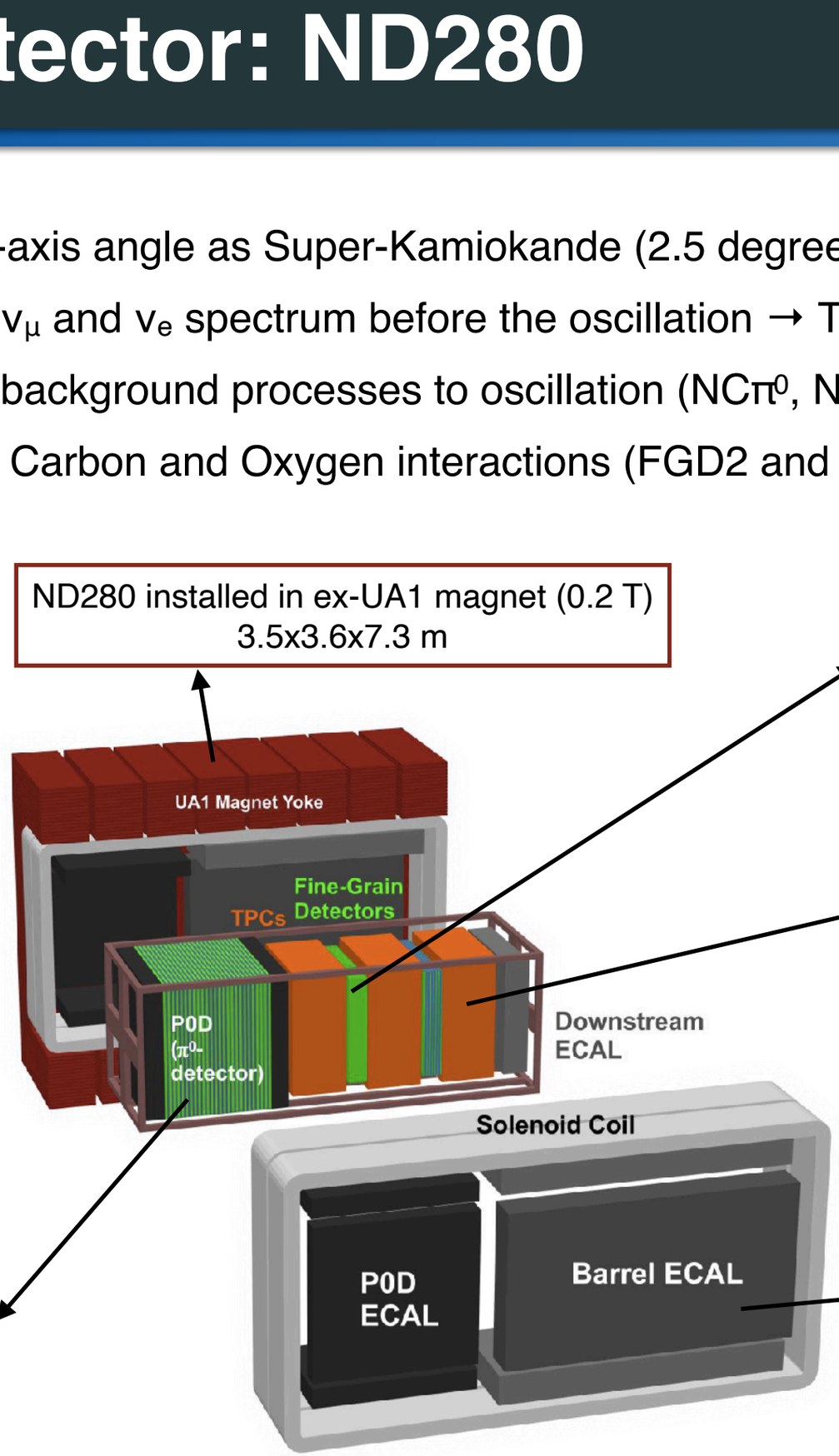


Wagasci/Baby MIND: Off-axis

The near detector: ND280

- Same off-axis angle as Super-Kamiokande (2.5 degrees).
- Measure ν_μ and ν_e spectrum before the oscillation → TPCs + FGDs
- Measure background processes to oscillation (NCπ^0, NC1π, CC1π…)
- Compare Carbon and Oxygen interactions (FGD2 and P0D)

ND280 installed in ex-UA1 magnet (0.2 T)
3.5x3.6x7.3 m



SMRD
(Side Muon Range Detector)
scintillator planes in magnet yokes. Measure high angle muons

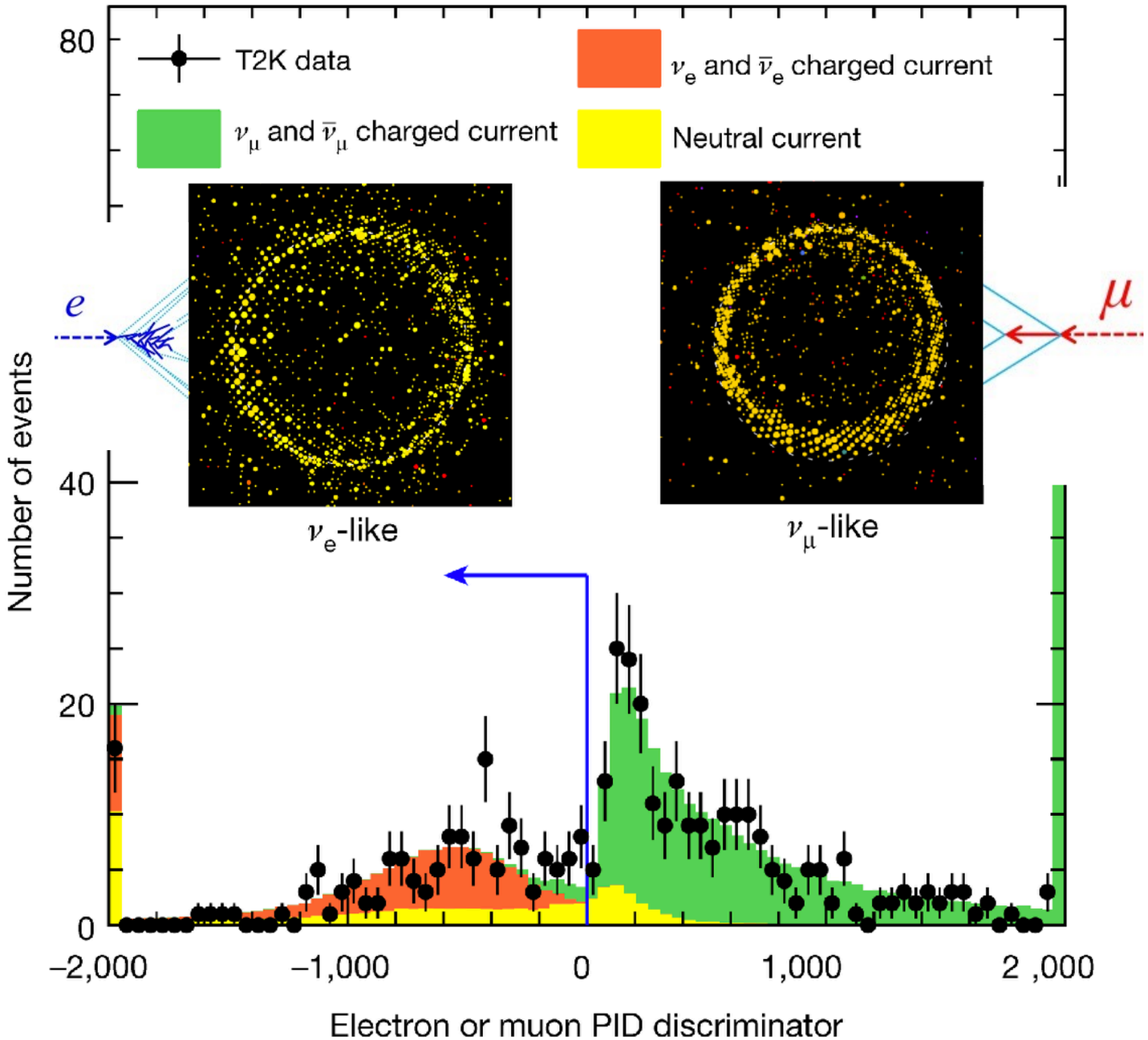
2 FGDs
(Fine Grained Detectors)
active target mass for the tracker, optimized for p/π separation
Carbon+Water target in FGD2

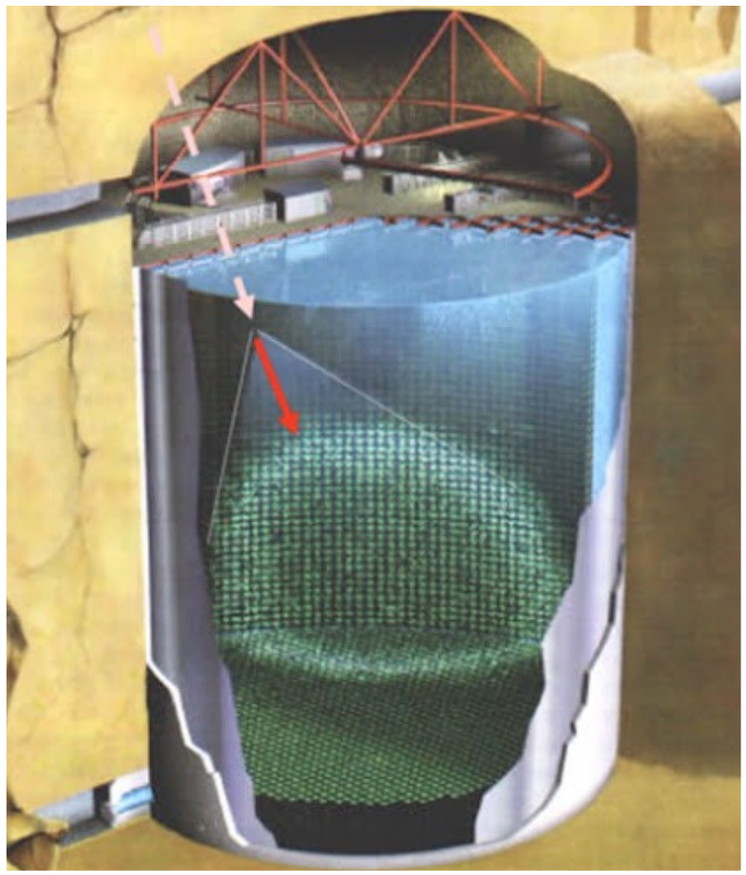
3 TPCs
(Time Projection Chambers)
measure momentum and charge of particles from FGD and P0D, PID capabilities through dE/dx

P0D
(π^0 detector)
scintillator bars interleaved with fillable water target bags and lead and brass sheets.
Optimised for γ detection

P0D, Barrel and Downstream ECAL:
scintillator planes with radiator to measure EM showers

The far detector: Super-Kamiokande





Particle identification

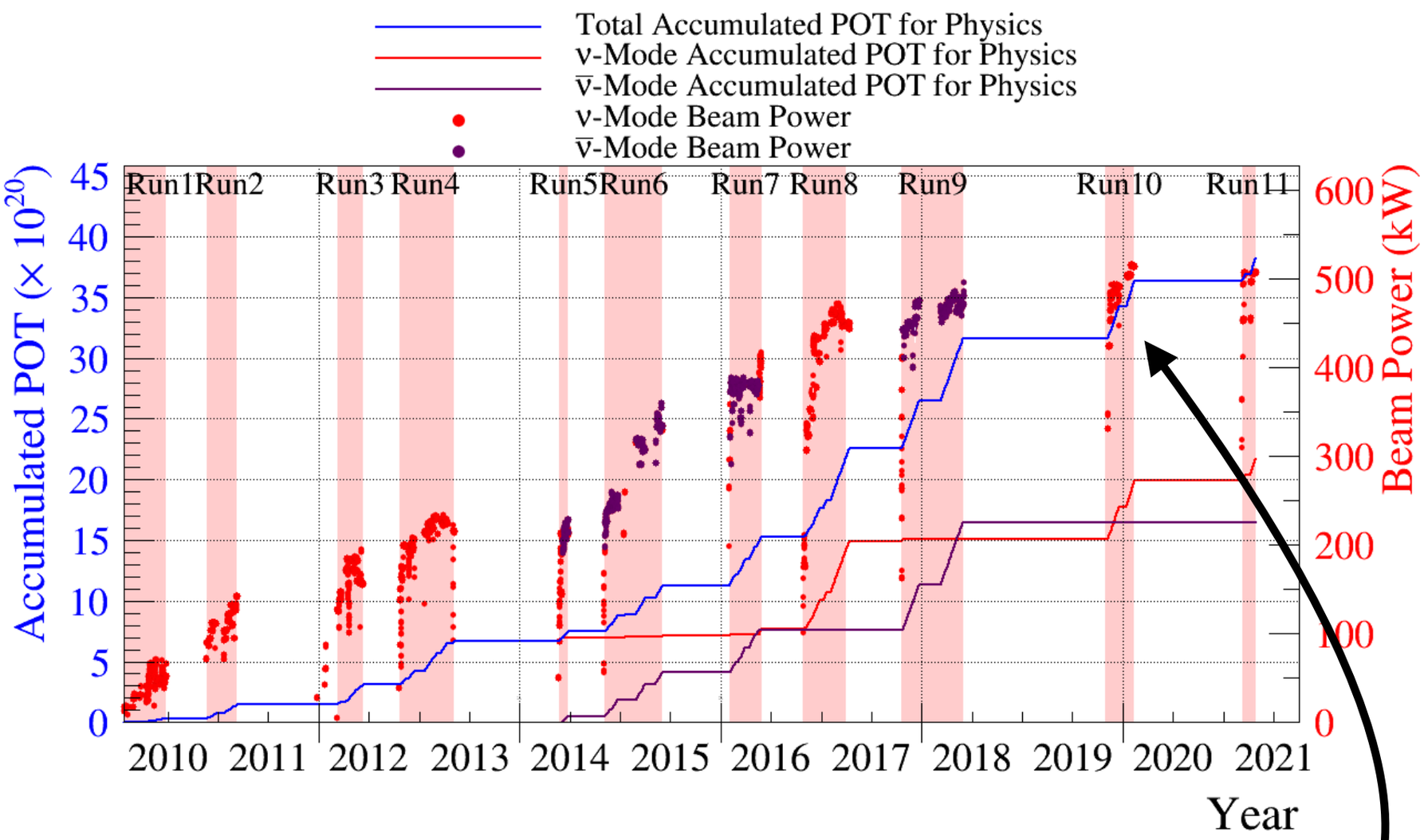
Interaction vertex reconstruction

Track Multiplicity

Particle direction

momentum reconstruction (through range)

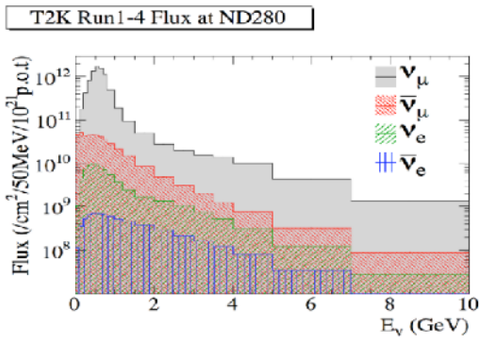
Data taking



- Will present the results with data taken from run 1 to 10.
- Approx. half neutrino - half anti-neutrino.
- **33% of ν-mode for this new analysis 3.6x10^{21} POT.**
- In 2021 we reached the cumulated statistics 3.82x10^{21} POT.

ND280 analysis procedure

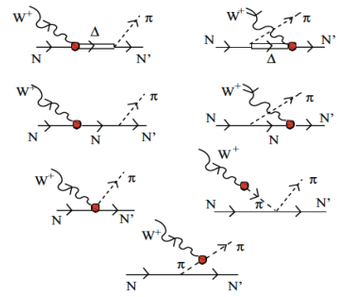
Hadron production flux prediction NA61/Shive + beam monitors



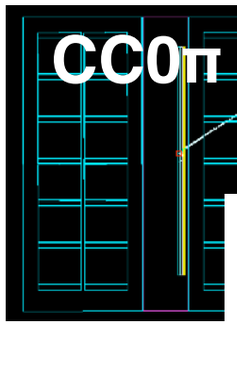
⊕

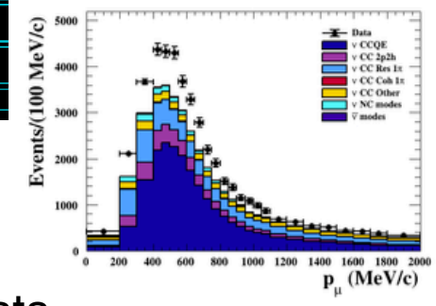
feed back

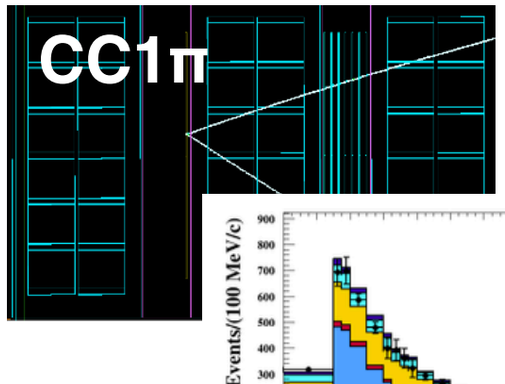
Cross-section model

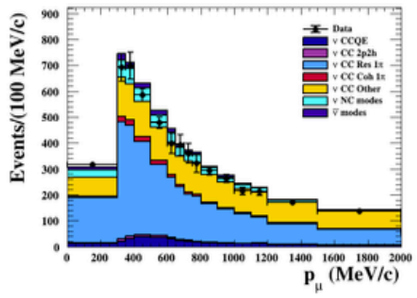


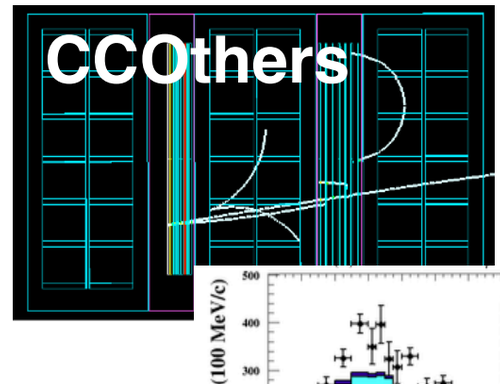
⊕

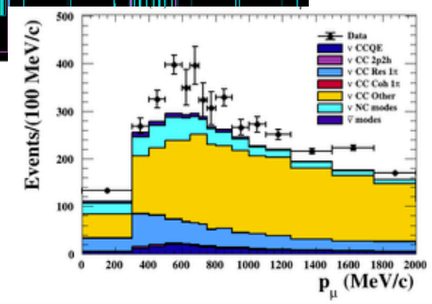








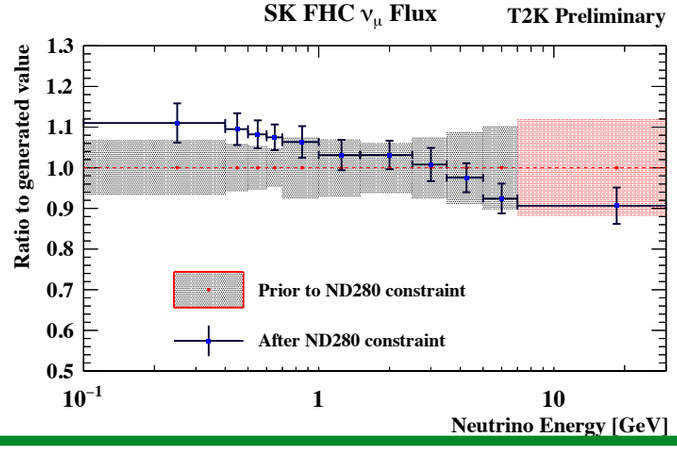




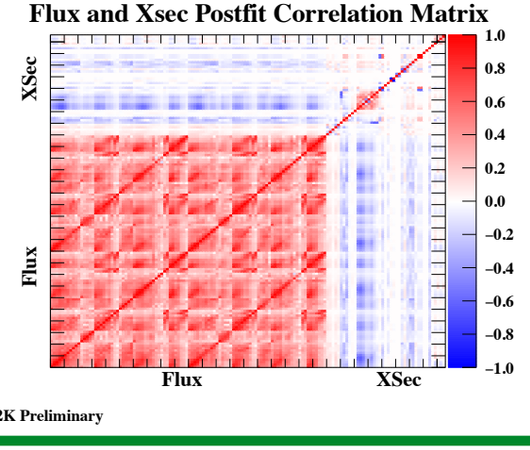
ND280 Data

=

Corrected flux and cross-section model



+ error covariance matrix



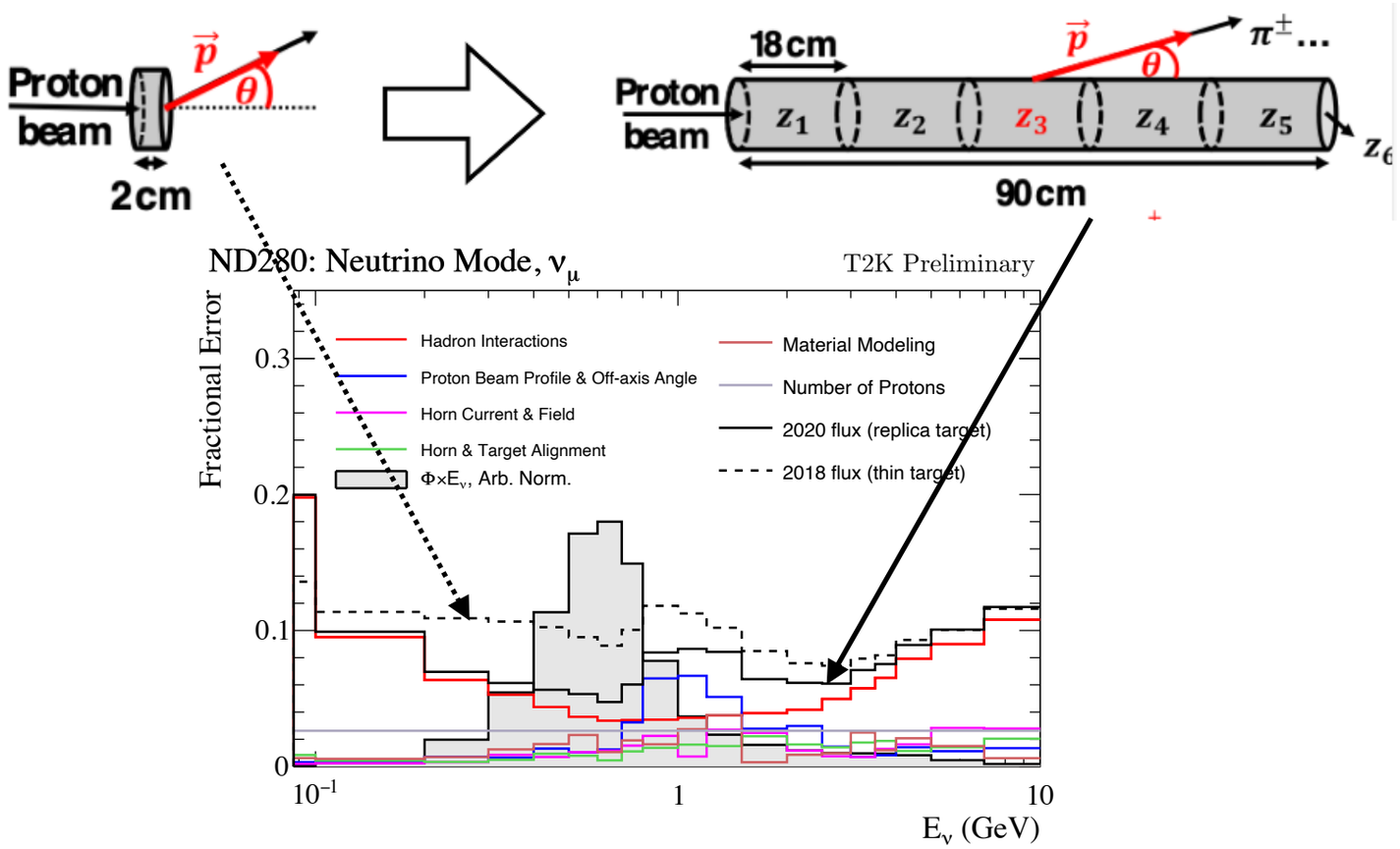
Feeding models for SK oscillation fit.

Flux systematics

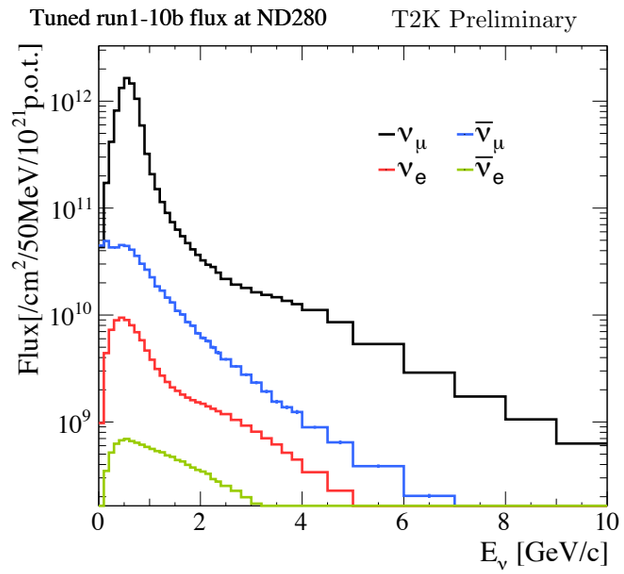
Flux predictions based on **NA61/SHINE measurements + beam monitoring.**

Until 2018, only **thin-target** measurements were used.
Flux uncertainty was > 10%.

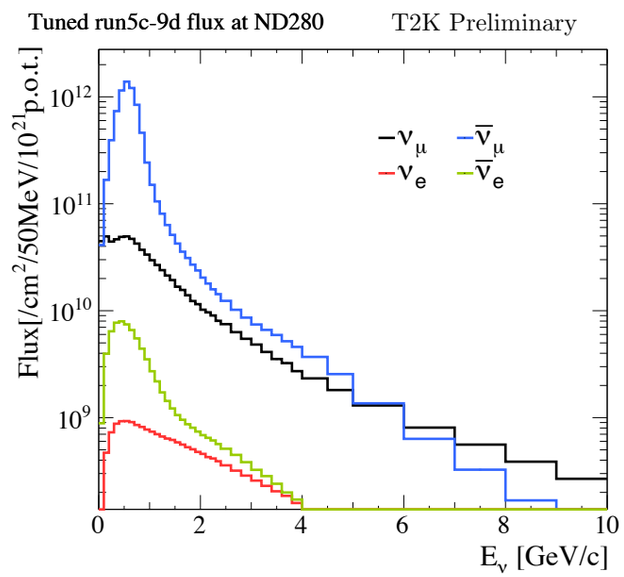
Flux uncertainty were reduced to <5% thanks to the **replica-target** measurements.



*Forward Horn Current (**FHC**)*



*Reverse Horn Current (**RHC**)*



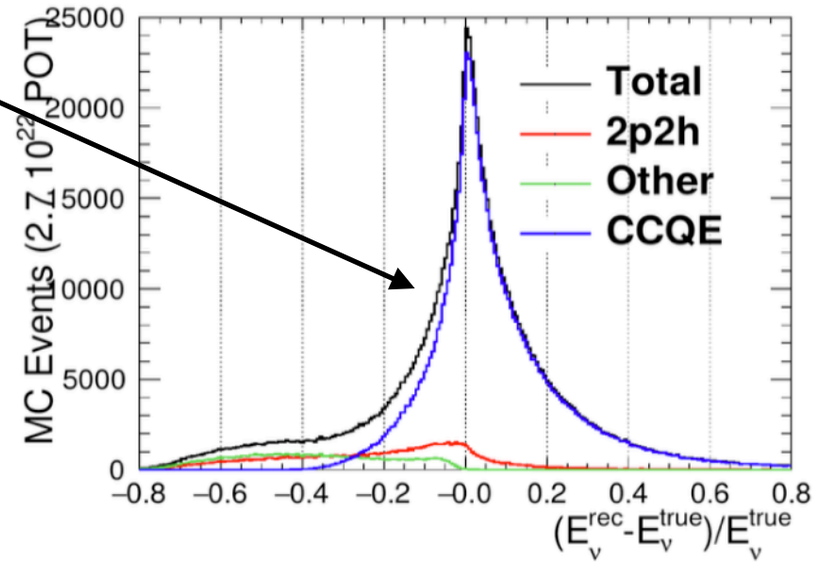
Neutrino-nucleus interaction models

- **Neutrino energy reconstruction formula based on the CCQE reaction (w/ lepton kinematics).** For other interaction modes, this formula is not suited

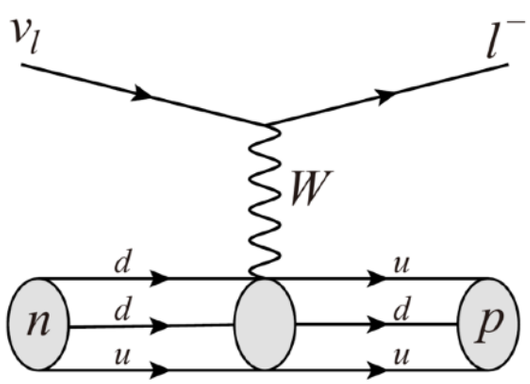
- At T2K energies interaction modes are:
  - CCQE (most dominant type),
  - Multi-nucleon interactions (2p-2h),
  - Resonant pion production (RES) with one pion in final state,
  - Deep Inelastic Scattering (DIS) with other particles in final state.

- NEUT (5.4.0) event generator used for neutrino simulations.

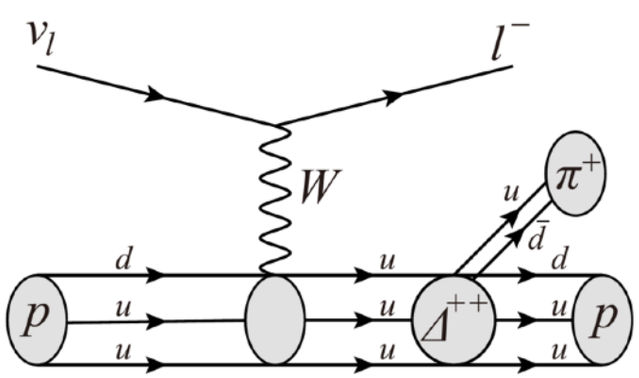
- Cross-section uncertainties are propagated on spectra with nuisance parameters.



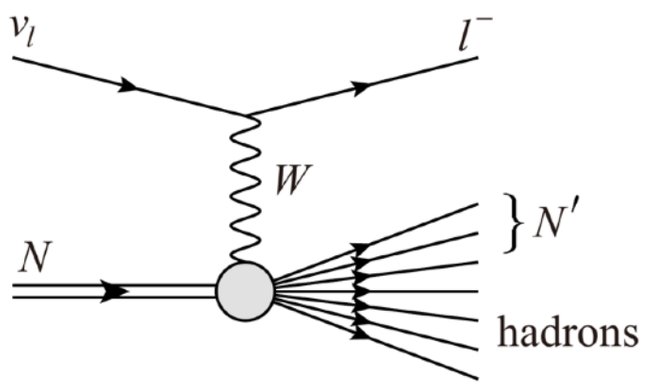
CCQE



CCRES



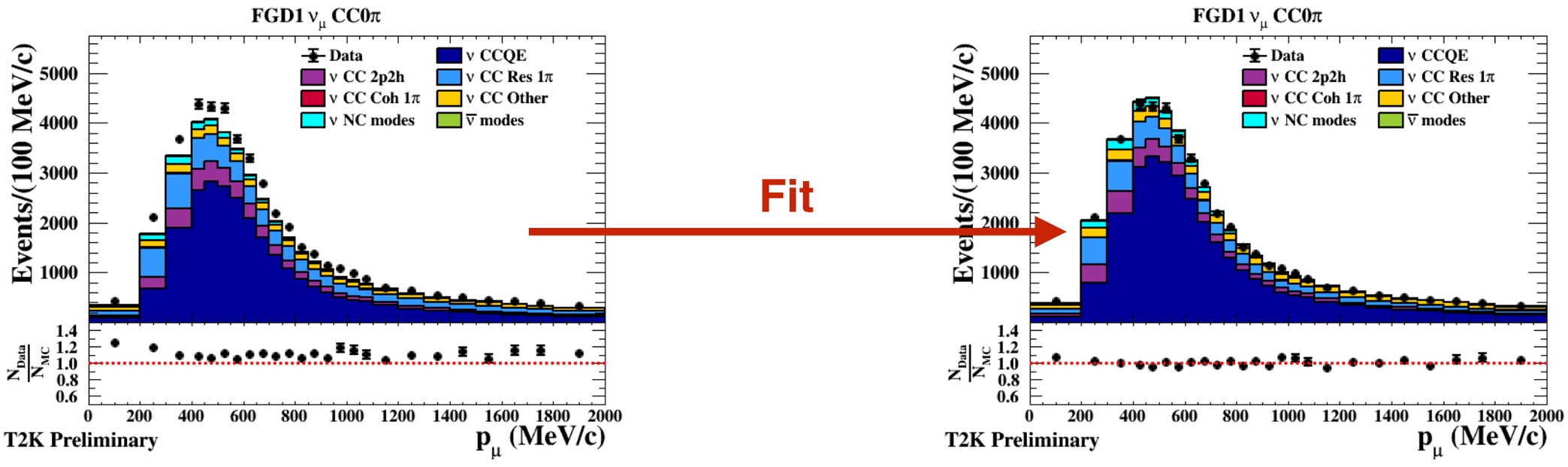
CCDIS



Parameter fit with ND280 data

Neutrino datasets split in 18 samples based on the event topology and beam state:

Beam Mode	Neutrino Target	Topology
FHC / RHC / RHC-neutrino background	**FGD1 / FGD2**	**CC0Pi / CC1Pi / CCOthers**



Systematics on the far detector samples:

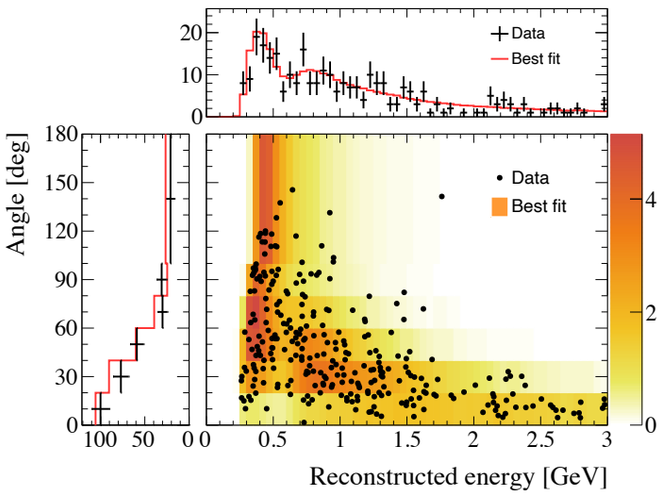
Sample	FHC 1Rμ	RHC 1Rμ	FHC 1Re	RHC 1Re	FHC 1Re1de
Flux+Cross section (before ND)	11.1%	11.3%	13.0%	12.1%	18.7%
Flux+Cross section **(after ND)**	**3.0%**	**4.0%**	**4.7%**	**5.9%**	**14.3%**

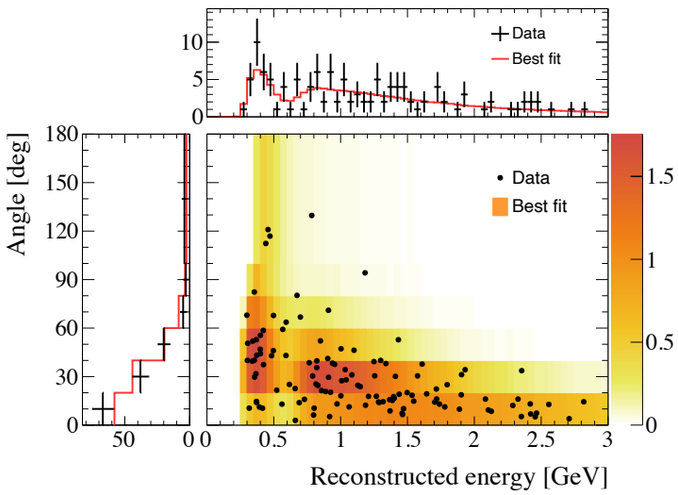
SK data samples

FHC *(neutrino enhanced)*

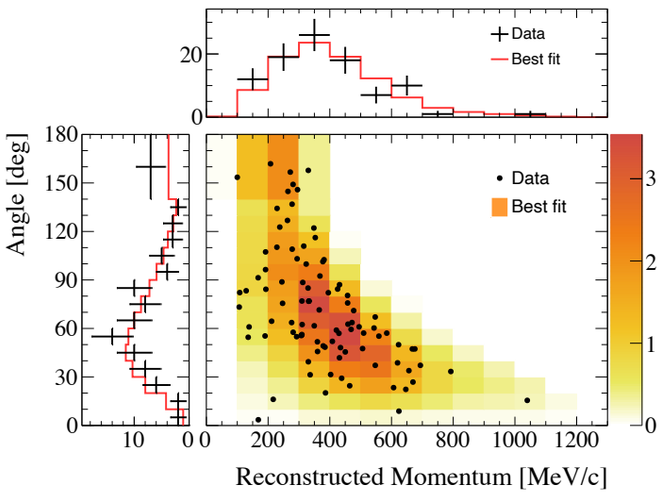
RHC *(anti-neutrino enhanced)*

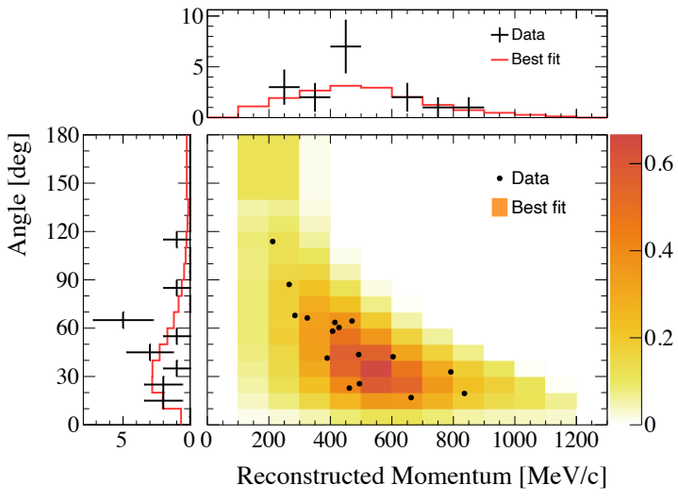
1Rμ



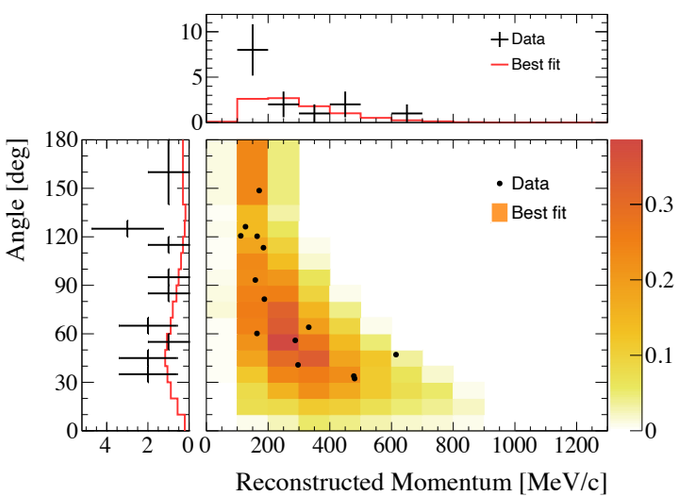


1Re
(CCQE)

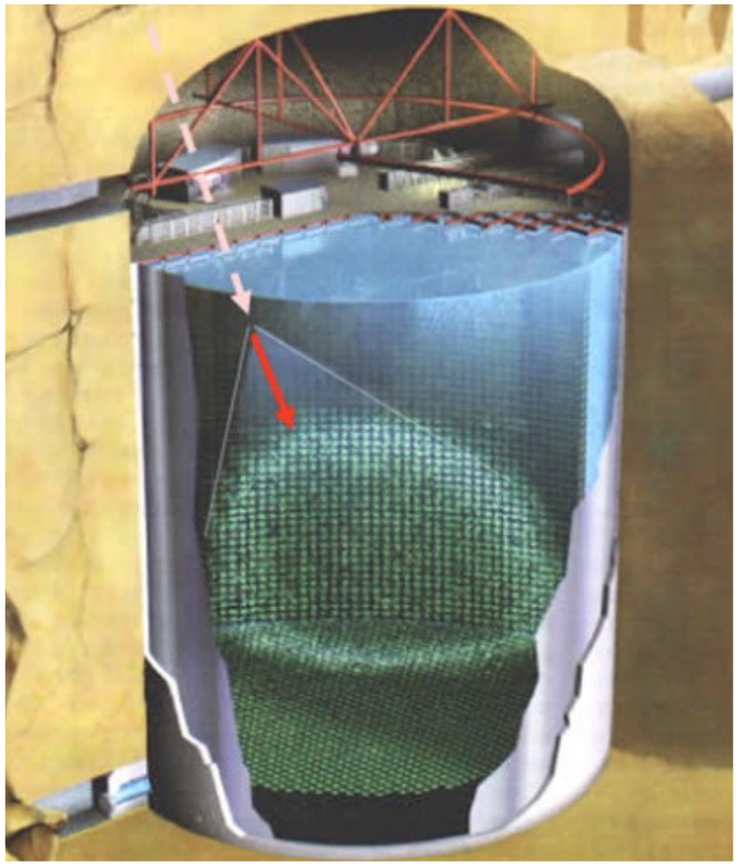




1Re1De
(CC1π)



No CC1π sample in anti-neutrino mode because π^- produced in $\bar{\nu}$ interaction are mostly absorbed before decay.



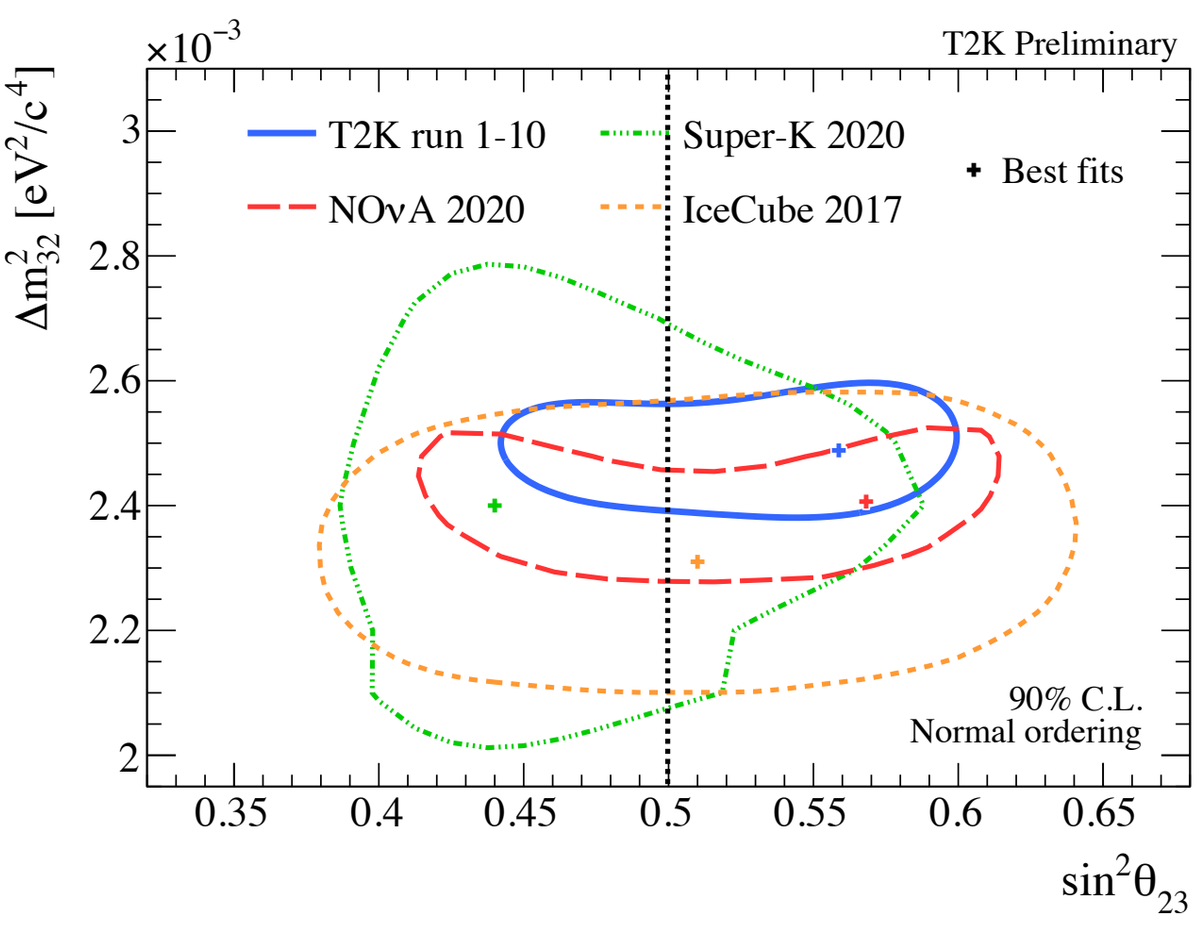
Oscillation results

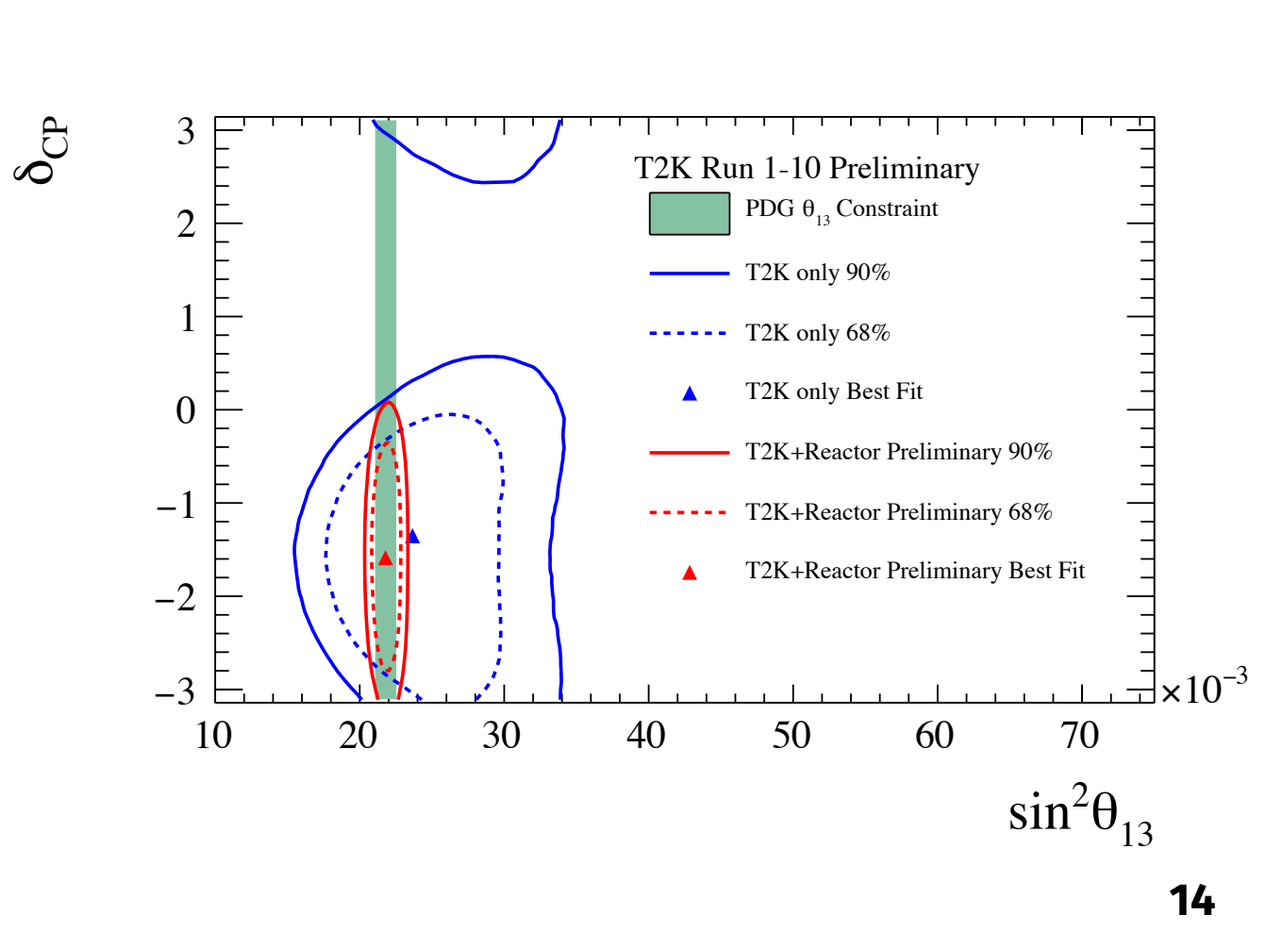
World-leading measurement of atmospheric parameters: compatibility with maximal $\sin^2 2\theta_{atm}$ mixing and slight preference to the upper octant.

Robustness studies performed showed a small bias on Δm^2_{23} which has been added as an additional uncertainty.

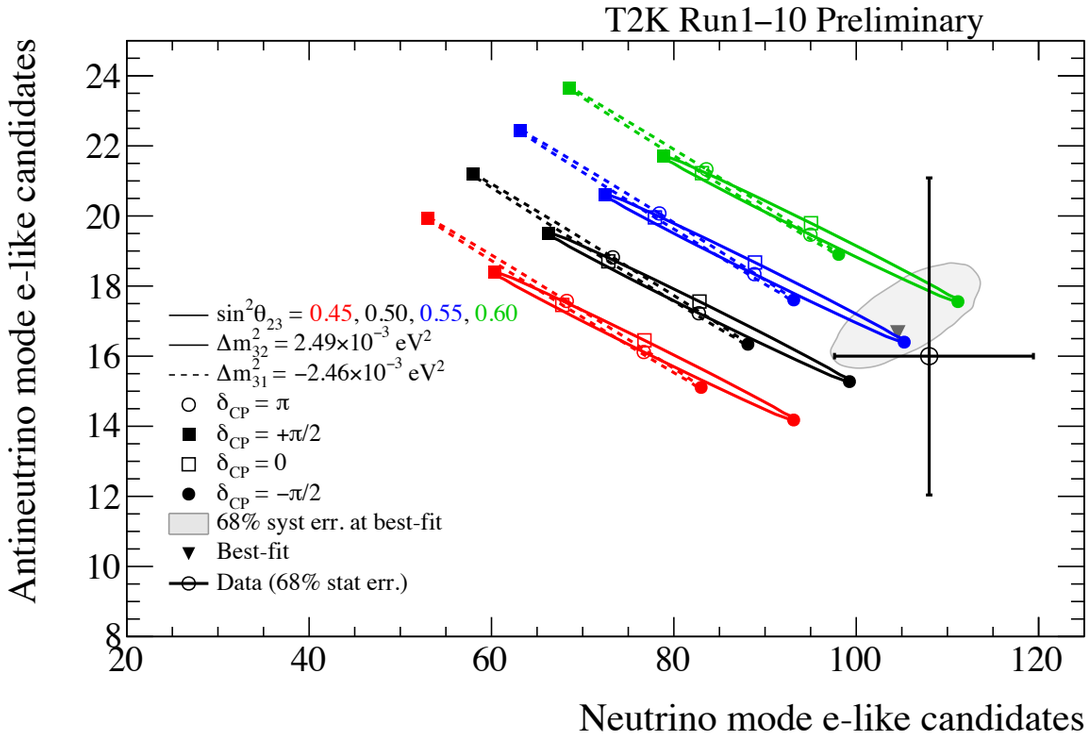
θ_{13} consistent with the constraint from reactor experiments.

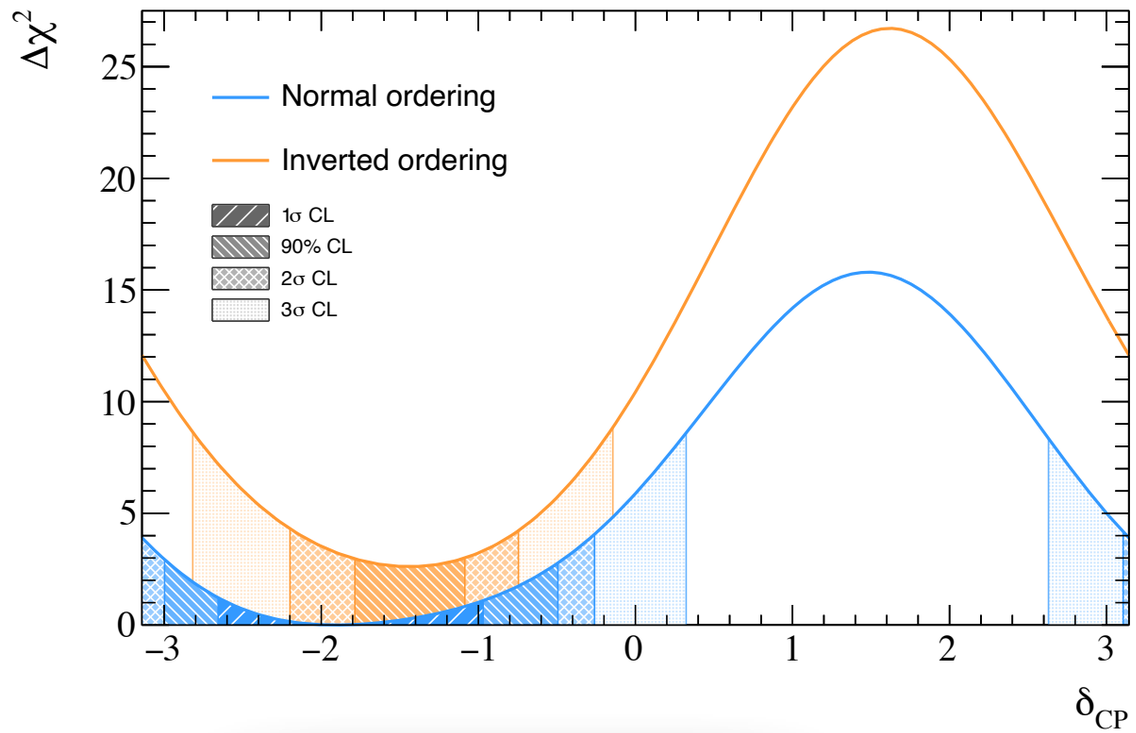
With reactor constrains, results are pointing toward a maximal CP violation.





δ_{CP} measurement





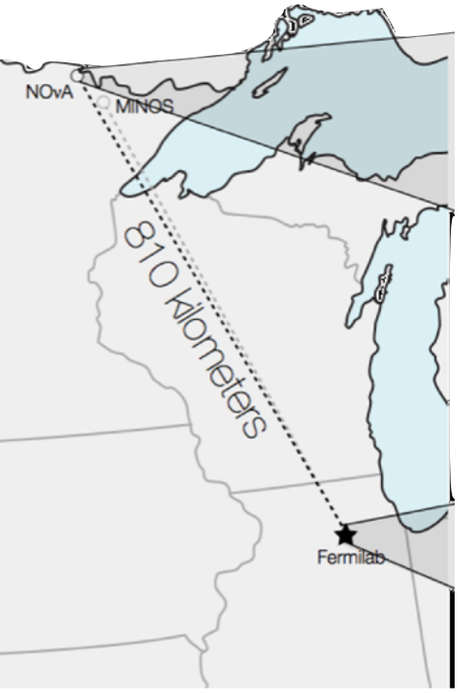
More than $40\,\%$ of δ_{CP} values are excluded at $> 3\sigma$.

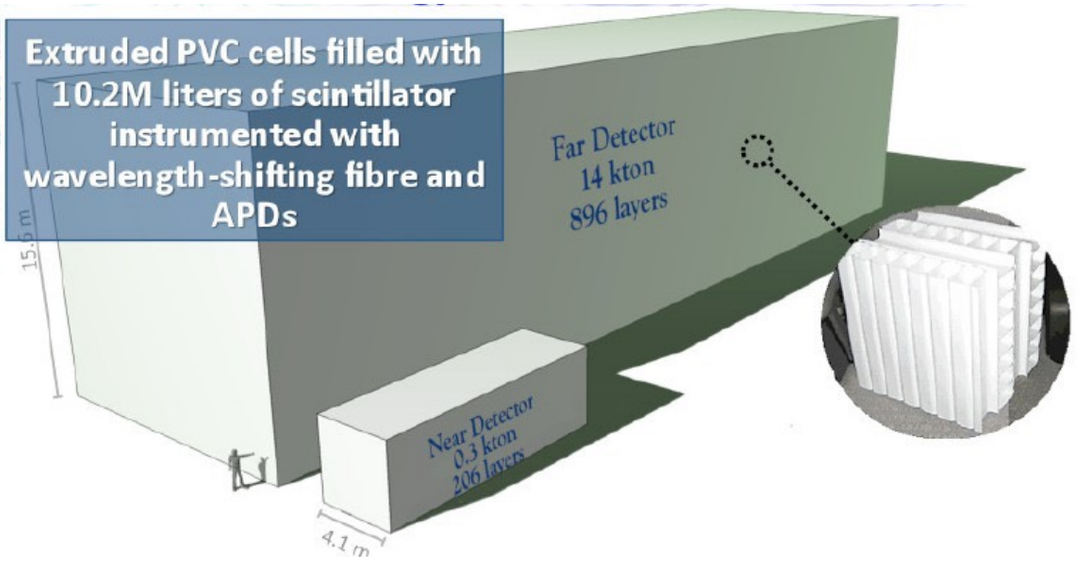
CP conservation scenario (0 and π) excluded at 90% C.L.

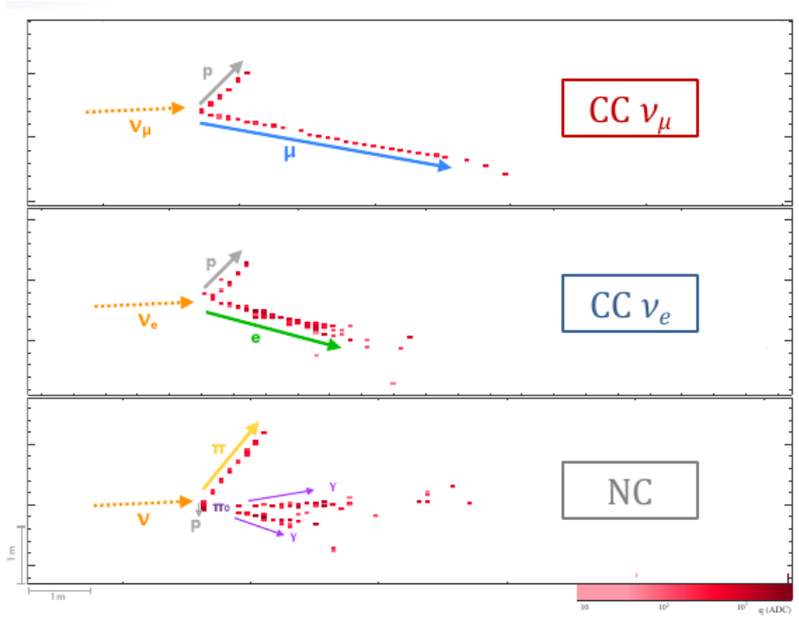
Slight preference for the Normal Ordering (NO).

Last year results from T2K made the cover of Nature! (Including run1 to run9)

Comparing with NOvA





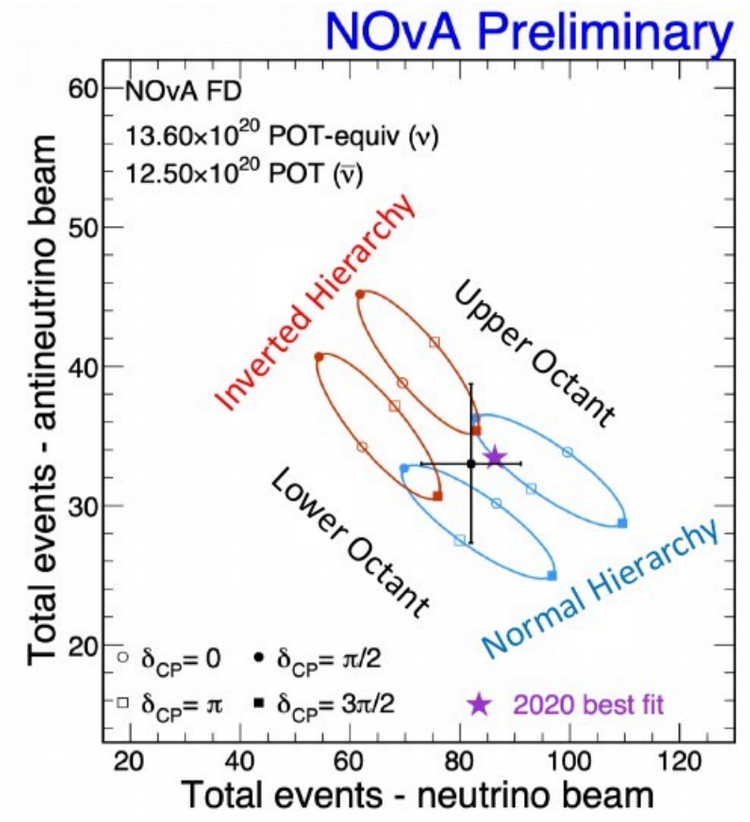


Mass Ordering (MO) sensitivity comes from change of sign in term dominated by matter effects:

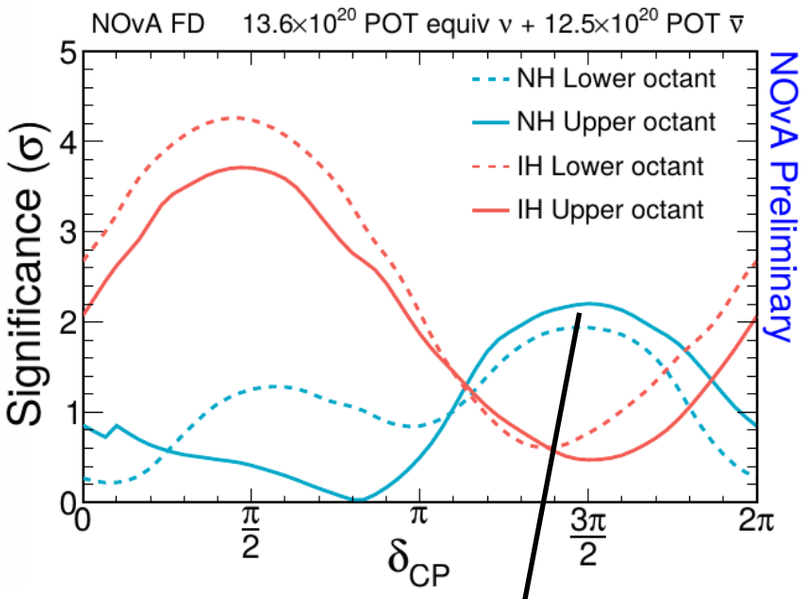
the longer the baseline → the larger the term.

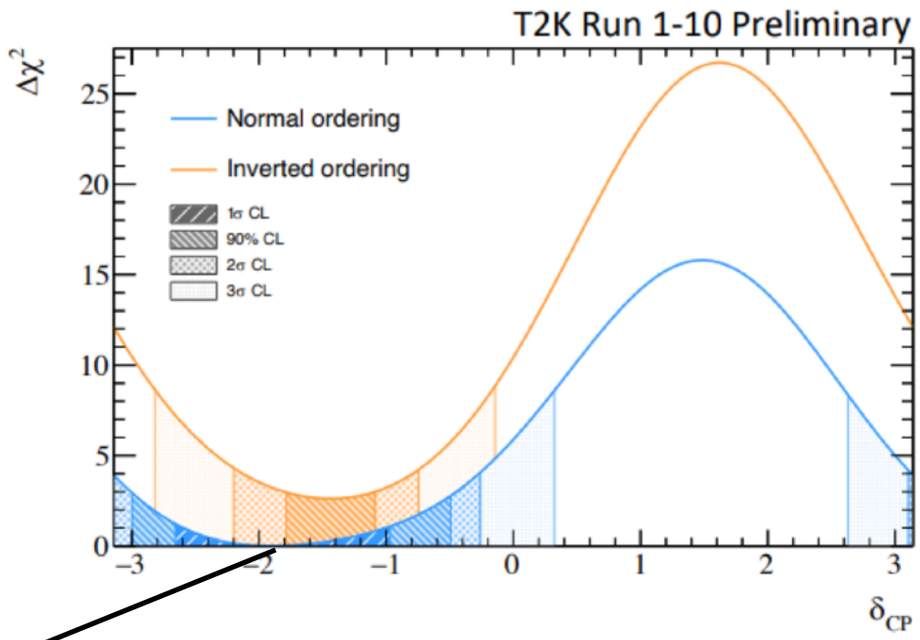
- T2K: clean δ_{CP} measurement with small MO sensitivity.
- NOvA: degenerate δ_{CP} and MO:

$$\{\delta_{CP} = 3\pi/2\} + IO \Leftrightarrow \{\delta_{CP} = \pi/2\} + NO$$

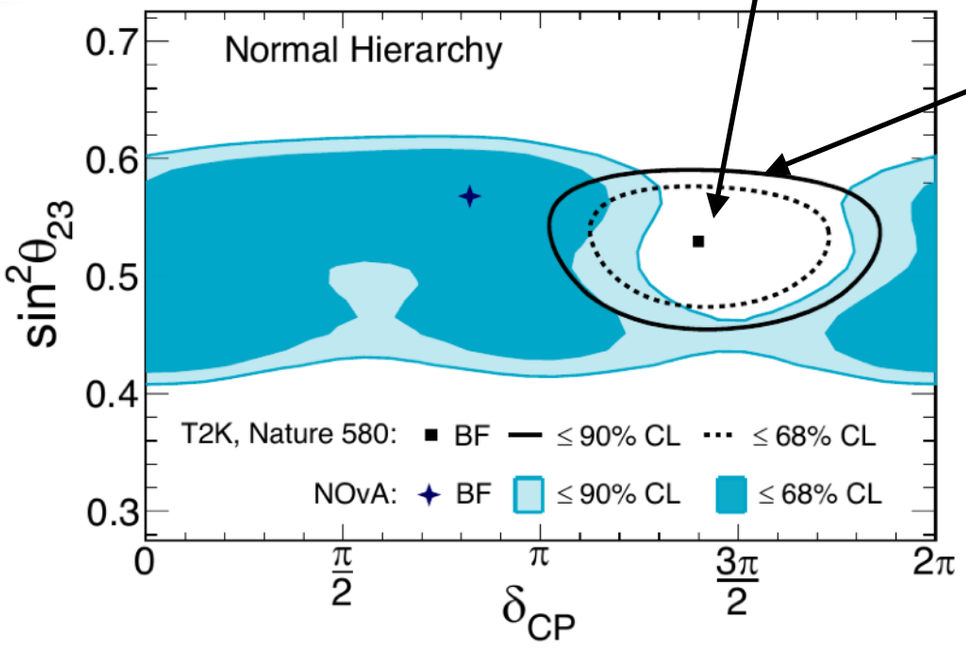


Comparing with NOvA





NOvA Preliminary



No strong MO preference with NOvA

- Also pointing toward $\delta_{CP} = 3\pi/2$, but if IO is assumed…
- But largely compatible with CP conservation if NO

Mild tension between T2K and NOvA

- Both fit still dominated by statistic uncertainties at the far detector
- T2K-NOvA: very different detectors → very different analysis and treatment of systematics

Solving the tension?

- Accumulate more statistics: *T2K-II / LBL program (Hyper Kamiokande, DUNE)*
- **Perform joint-fits**: *combining datasets and analysis methods*

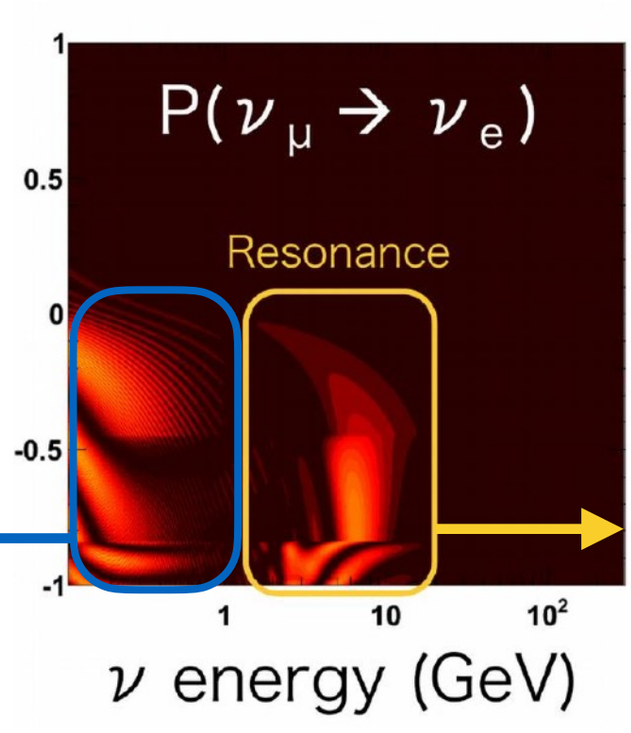
Why making a joint-fit?

Combining constraints from different analysis

- Sensitivity boost expected thanks to the increased statistics and with involved fit parameters
- Same **oscillation parameters** + potentially correlated **cross-section systematics** and **detector systematics**
- Ability to resolve parameter degeneracy with the two datasets → Increase in sensitivity

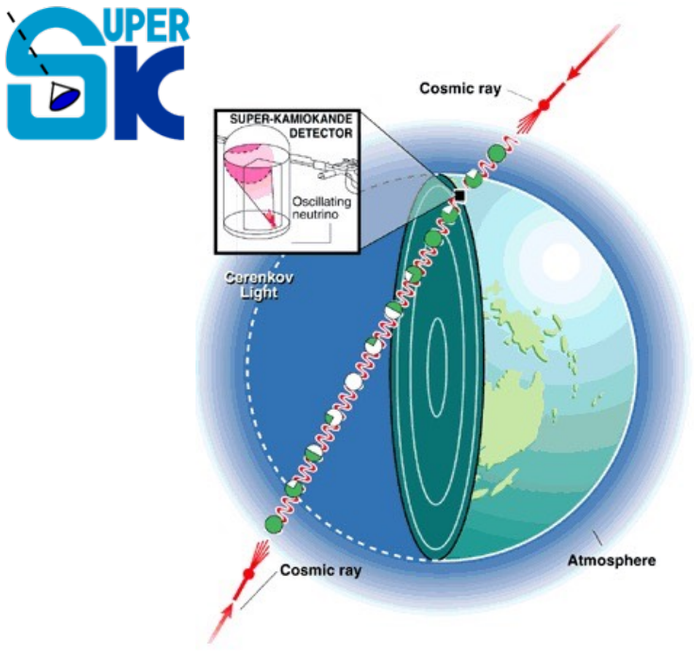
Example with SK atmospheric neutrinos

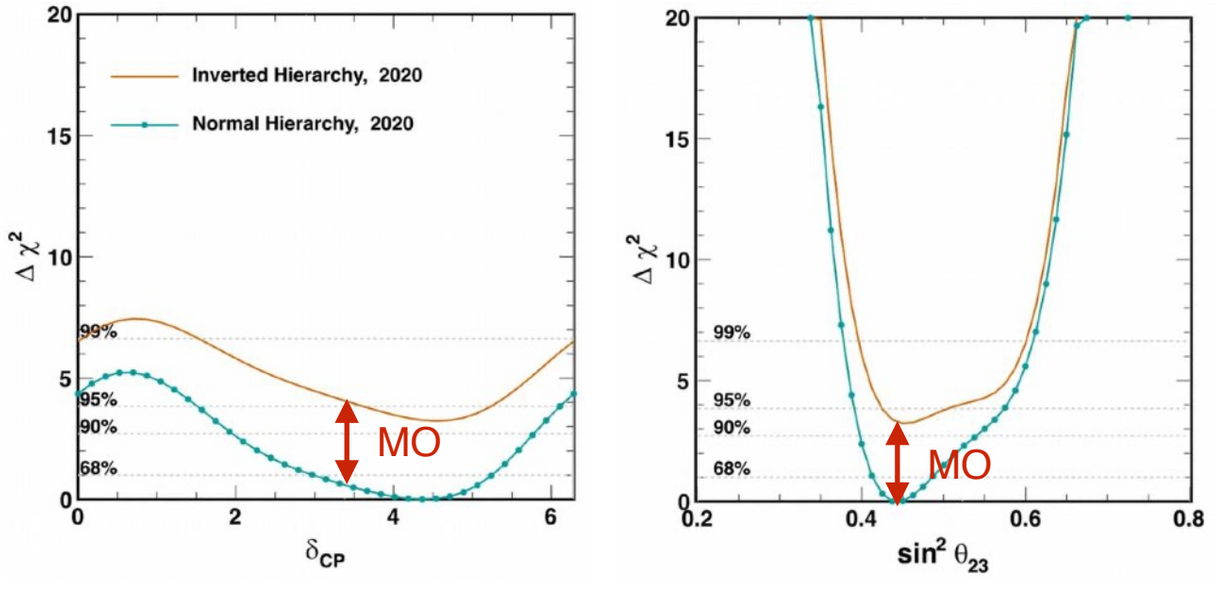
- Use sub-GeV + multi-GeV atmospheric neutrino sample
- Great decoupling between δ_{CP} and Mass Ordering (MO)
- However: **MO highly dependent on** $\sin^2(2\theta_{atm})$**…**
- … for which the world leading measurement is carried by T2K!



Sub-GeV Neutrino
Better sensitivity in δ_{CP}

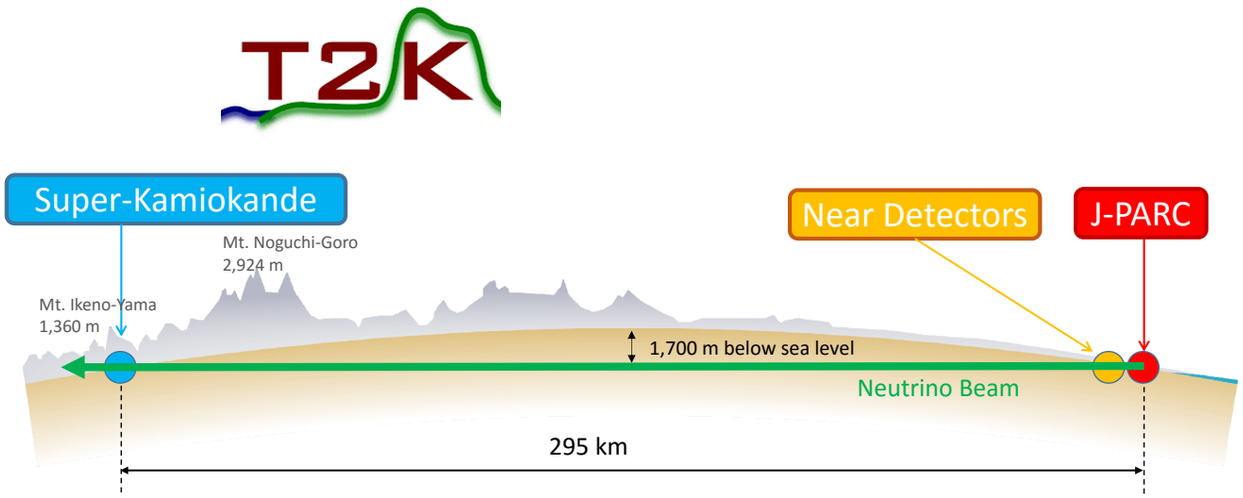
Multi-GeV Neutrino
Better sensitivity in MO



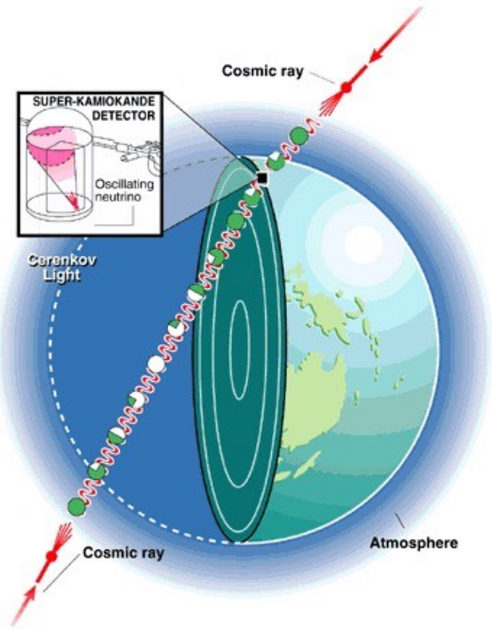


SK + T2K combined analysis

MoU signed in June 2019 between T2K and SK collaborations



+



T2K constraint on θ_{23} → **Improves** → **SK constraint on MO** → **Breaks degeneracy** → **T2K constraint on δ_{CP}**

Improved predictions with the joint analysis:

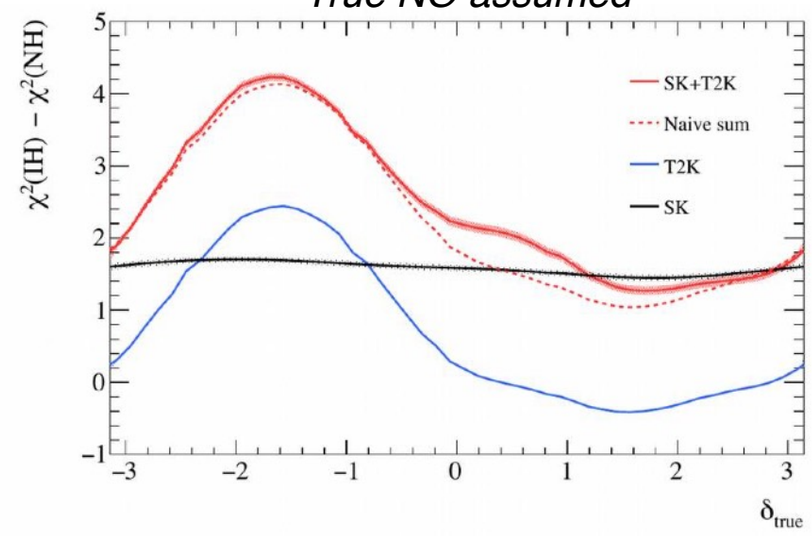
$$\left\{\text{Observed event rate}\right\} = \left\{\nu \text{ Flux models}\right\} \times \left\{\nu \text{ cross-section models}\right\} \times \left\{\text{SK detector model}\right\}$$

- **SK flux prediction:** tuning Honda flux (i.e. BESS&AMS data) + $\mu^{\pm}$ flux measurements with T2K hadronic models
- **ν interaction models partially unified:** same NEUT (MC) + applying ND280 constraints on sub-GeV atmospherics
- **SK detector systematics:** correlate the reconstruction errors in both samples

Preliminary sensitivity studies

T2K constraint on θ_{23} → **Improves** → **SK constraint on MO** → **Breaks degeneracy** → **T2K constraint on δ_{CP}**

True NO assumed



Preliminary improvements

- Marginal difference between naïve sum in sensitivity to $\sin^2(2\theta_{23})$
- Increased sensitivity to MH away from maximal mixing in True NO
- Slight sensitivity increase for joint fit over naïve sum to δ_{CP} while assuming maximal CP violation (close to T2K best-fit)
  - *(remember that data constraints exceed sensitivities in T2K)*

→ Additional correlations are being study

Stay tuned!

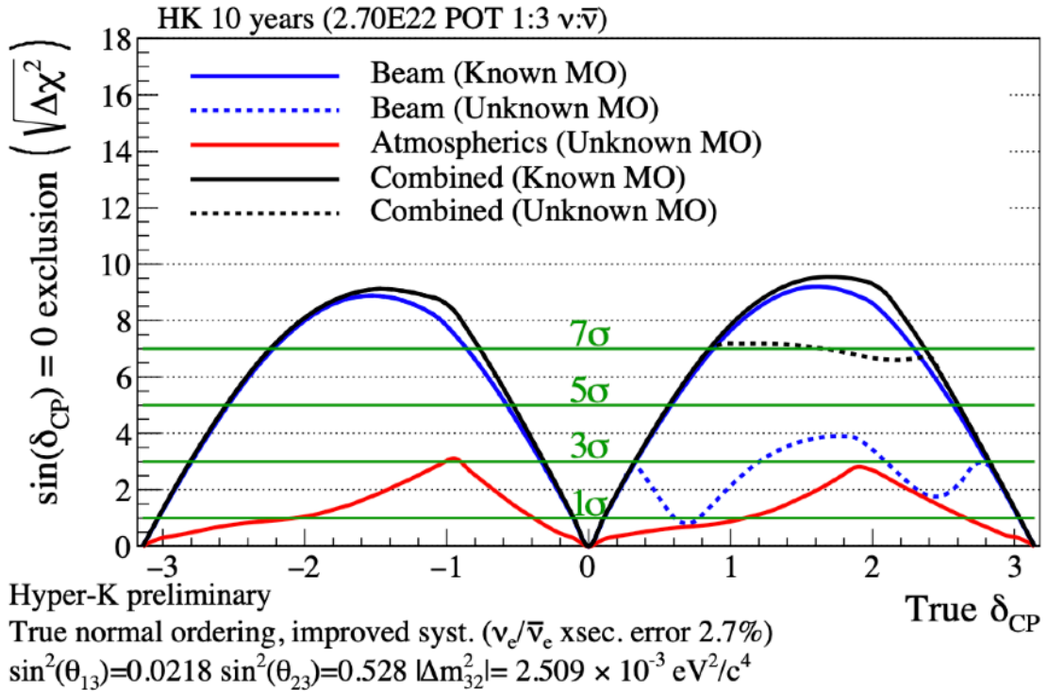
Combined analysis with Hyper Kamiokande

Joint analysis will also be very important for the next generation

- Depending on the θ_{23} octant → sensitivity boost of more than 1σ for MO
- With a known MO, better rejection of the CP-conservation scenario

	$\sin^2\theta_{23}$	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

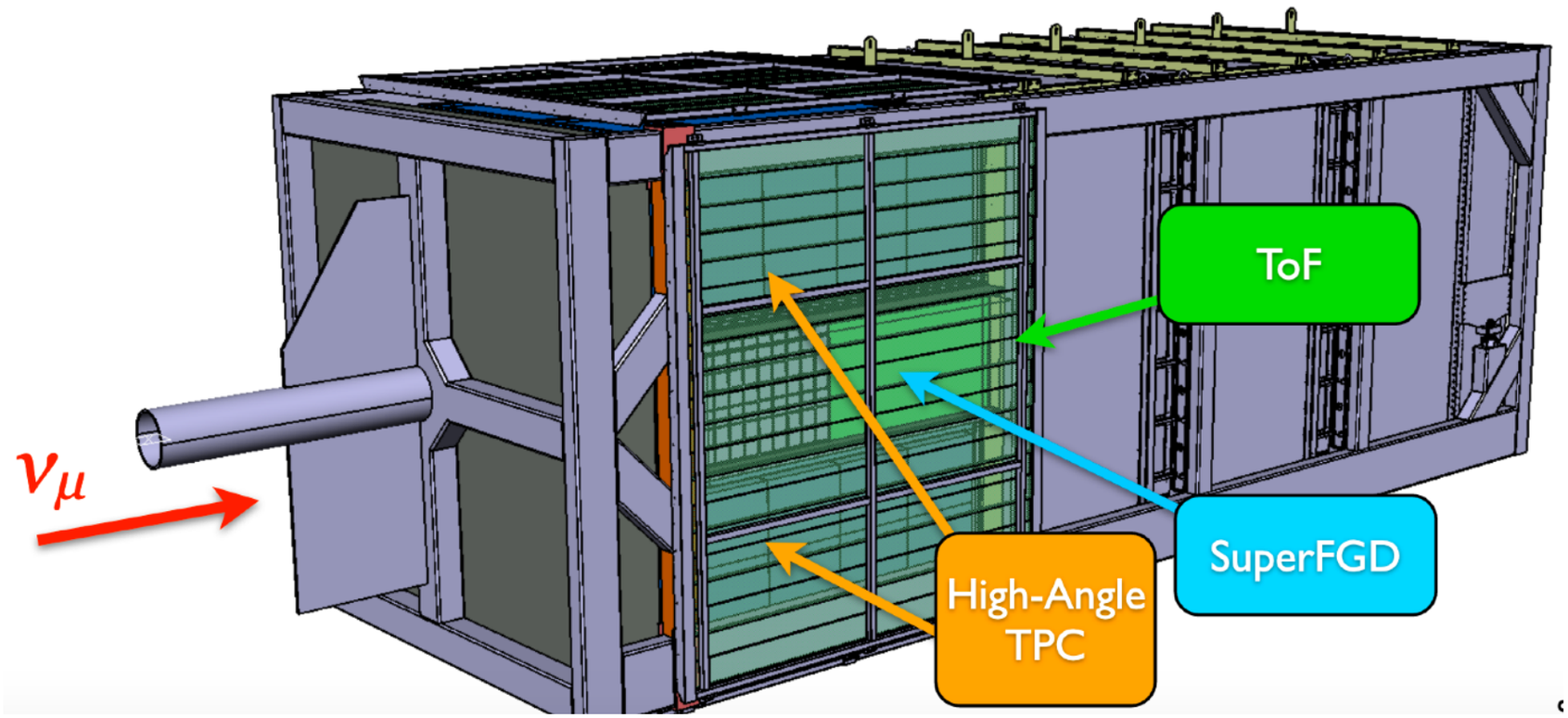


Ongoing plans for T2K

T2K phase II is planned for 2022

→ *see presentation of Sergey Suvorov!*

- Upgraded ND280 with new detectors:
  - A new neutrino target: Super-Fine Grained Detector
  - Two new trackers: High-Angle TPCs
  - Surrounding Time of Flight detector
- Will allow to probe unreached phase-space with the current detectors.
- **Measurement of the transverse kinematic imbalance for unprecedented constrains on cross-section models.**
- Progressive upgrade of the neutrino beam line from 750kW to finally reach 1.3MW.



*T2K measurements are important for **Hyper-Kamiokande, DUNE, NOvA and atmospheric neutrino oscillations**.*

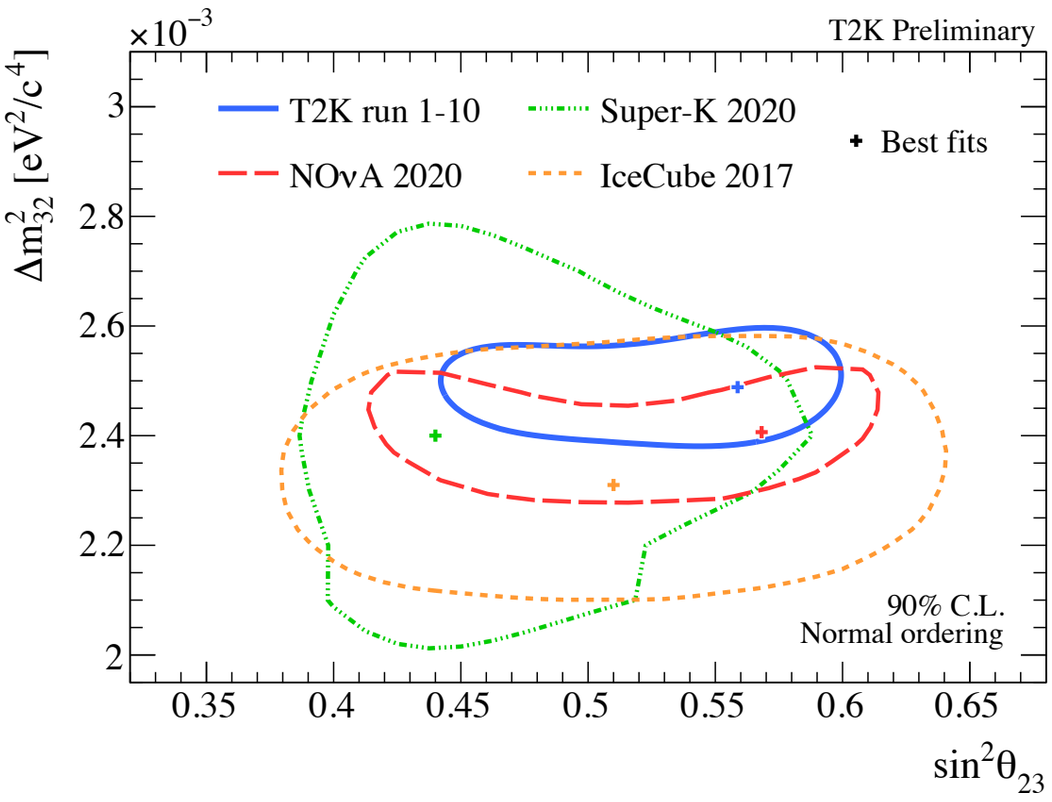
Summary and ongoing plans for T2K

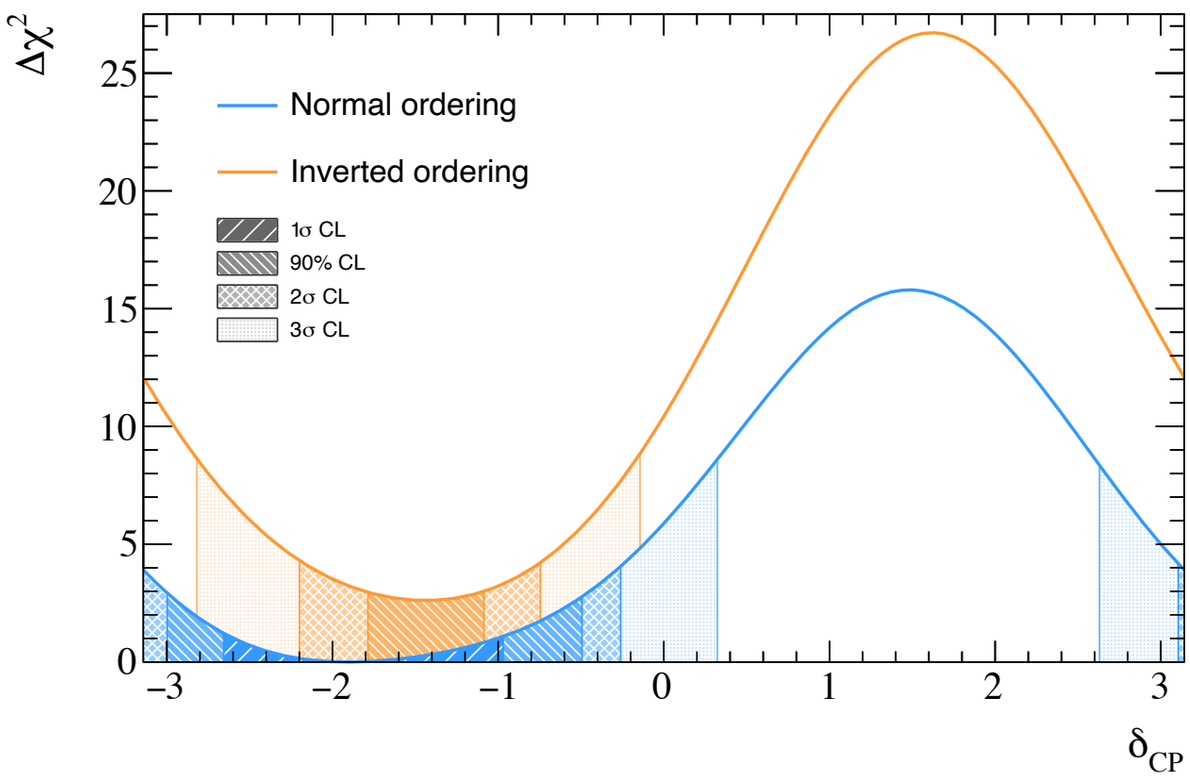
T2K has achieved world-leading measurement of neutrino oscillation parameters

- CP-conservation excluded at 90% C.L.
- Most precise measurement of the atmospheric oscillation parameters.
- Slight preference for normal ordering and upper octant of $\sin^2\theta_{23}$.

Exciting analyses coming from T2K

- Joint-fit with SK atmospheric neutrinos.
- Joint-fit with NovA experiment.
- Improved oscillation analysis with new ND280 samples.
- New cross-section studies across different off-axis angles with WAGASCI and BabyMIND near detectors.





Thank you!