T2K latest results

Matter To The Deepest 2023
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on behalf of the T2K collaboration

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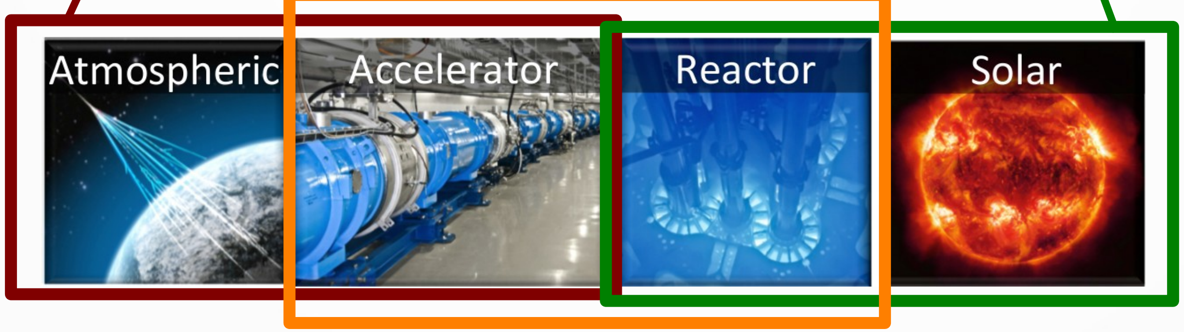
Outline

- Introduction: flavour-mass mixing, neutrino oscillations
- T2K experiment design and analysis strategy
- Updates from 2020 oscillation analysis
- Oscillation analysis results
- Cross section measurements in T2K
- Summary

Flavour-mass mixing

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

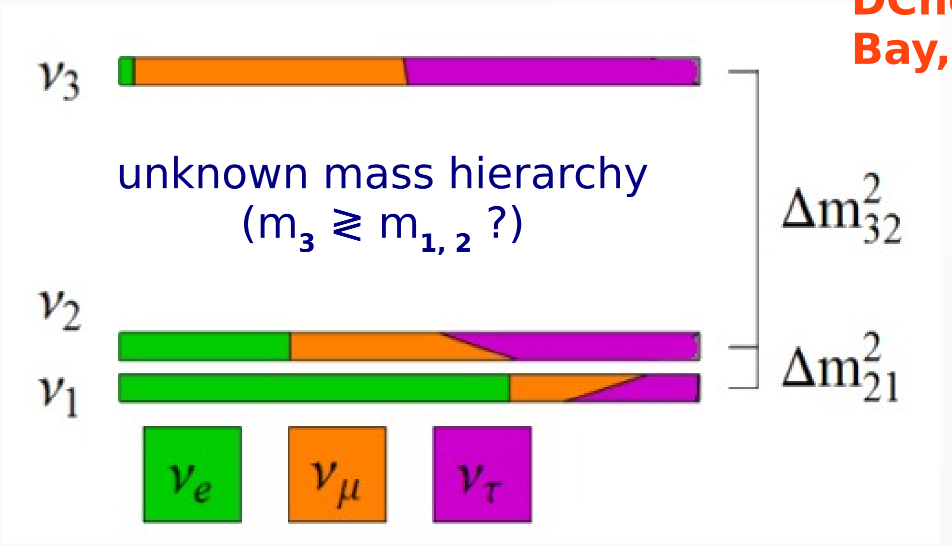
Super-K, K2K, MINOS, OPERA NOνA, T2K



Flavour-mass mixing described with PMNS matrix

Super-K, SNO, KamLAND

DChooz, RENO, Daya Bay, MINOS, NOνA, T2K



c_{ij}, s_{ij} – $\cos\theta_{ij}$, $\sin\theta_{ij}$ (θ_{ij} – mixing angles),
δ_{CP} – CP violation (CPV) phase
α_1, α_2 – Majorana phases
(not relevant for neutrino oscillations)

T2K is sensitive to Δm^2_{32}, θ_{23}, θ_{13} and δ_{CP}.

Oscillation probability in vacuum

Probability that a neutrino produced in ν_α flavour state will interact as neutrino in ν_β state:

Kronecker delta

Elements of PMNS matrix

$$P(\nu_\alpha \to \nu_\beta) = \boxed{\delta_{\alpha\beta}} - 4\sum_{i>j} \mathrm{Re}\left(\boxed{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}}\right) \sin^2\left(\boxed{\Delta m^2_{ij}}\boxed{\frac{L}{4E}}\right)$$

$$\pm 2\sum_{i>j} \mathrm{Im}\left(\boxed{U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}}\right) \sin\left(\boxed{\Delta m^2_{ij}}\boxed{\frac{L}{2E}}\right),$$

Difference of squared masses $\Delta m^2_{ij} = m^2_i - m^2_j$

L – neutrino propagation distance, E – neutrino energy

Matter effects

Presence of electrons modifies the oscillation probabilities as compared to those in vacuum. CC scattering on electrons is possible only for electron (anti-)neutrinos. The probability for (anti-)ν_e appearance with the first order approximation of matter effects is expressed as:

$$\begin{aligned}
P\left(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e\right) &\approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2[(A-1)\Delta_{31}] \\
&\overset{-}{(+)}\,\alpha\frac{J_0\sin\delta_{CP}}{A(1-A)}\sin\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\
&+\alpha\frac{J_0\cos\delta_{CP}}{A(1-A)}\cos\Delta_{31}\sin(A\Delta_{31})\sin[(1-A)\Delta_{31}] \\
&+\alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2(A\Delta_{31})
\end{aligned}$$

where

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

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

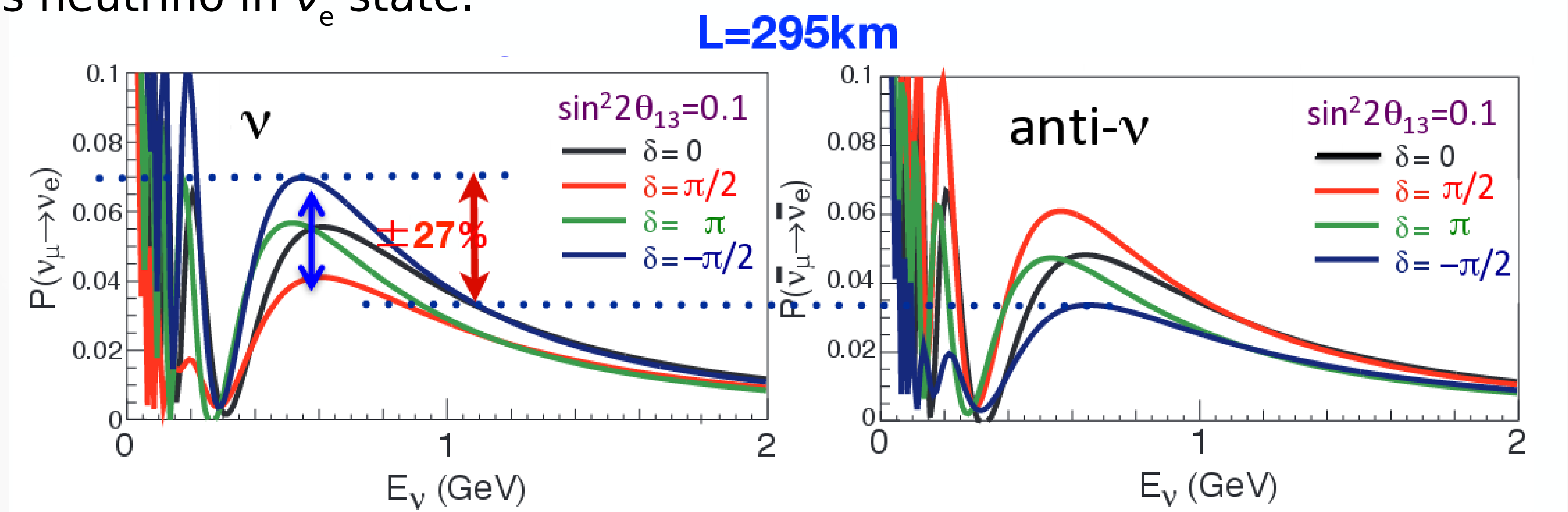
$$\boxed{A = (-)2\sqrt{2}G_F n_e E/\Delta m^2_{31}}$$

$$J_0 = \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\cos\theta_{13}$$

Sign of the matter effects differs for neutrinos and antineutrinos.

Oscillation probability

Example: probability that a neutrino produced in ν_μ flavour state will interact as neutrino in ν_e state.

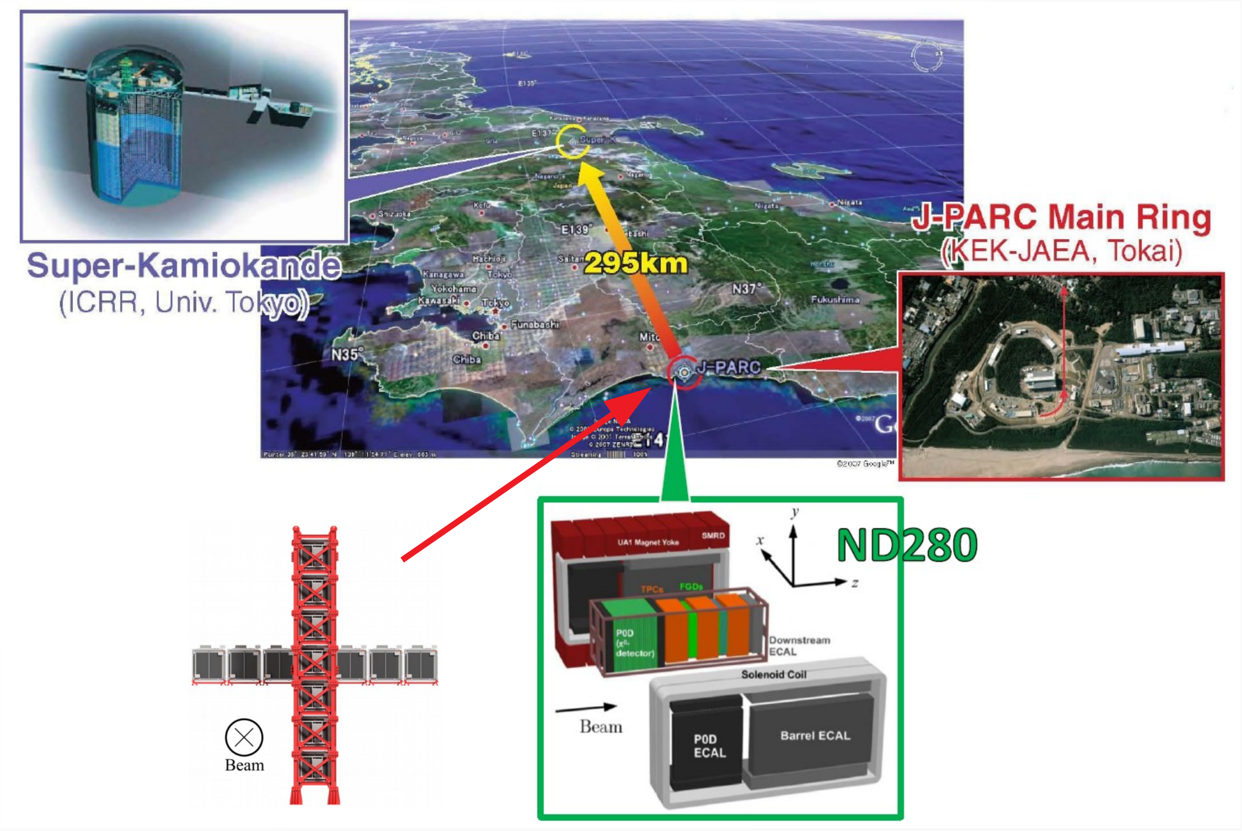


Impact of δ_{CP} violation phase for neutrinos and antineutrinos. Maximal CP violation results in approximately ±27% change of the ν_e appearance probability (wrt. CP conserving values).

Matter effects small compared to CP violation (difference between δ_{CP} = 0, π).

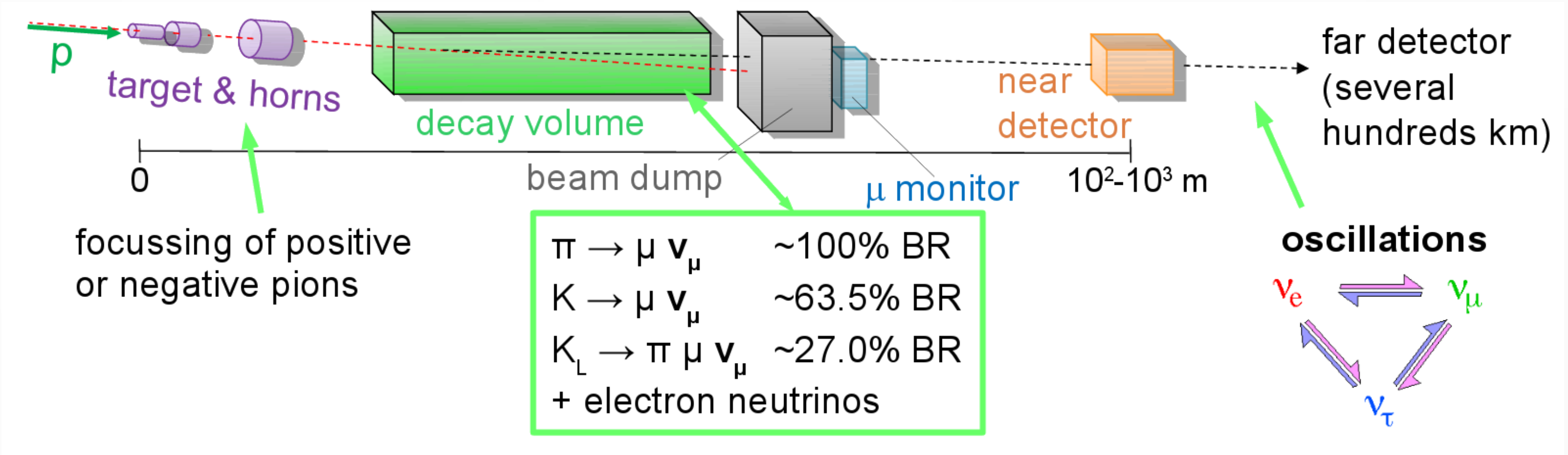
T2K experiment

- T2K is a long-baseline neutrino experiment. Two near detectors (INGRID, ND280) are used to study beam properties ~280 m from the source in J-PARC.
- Super-Kamiokande is used as the far detector.
- Started taking data in 2010, ν_e appearance discovered in 2013.



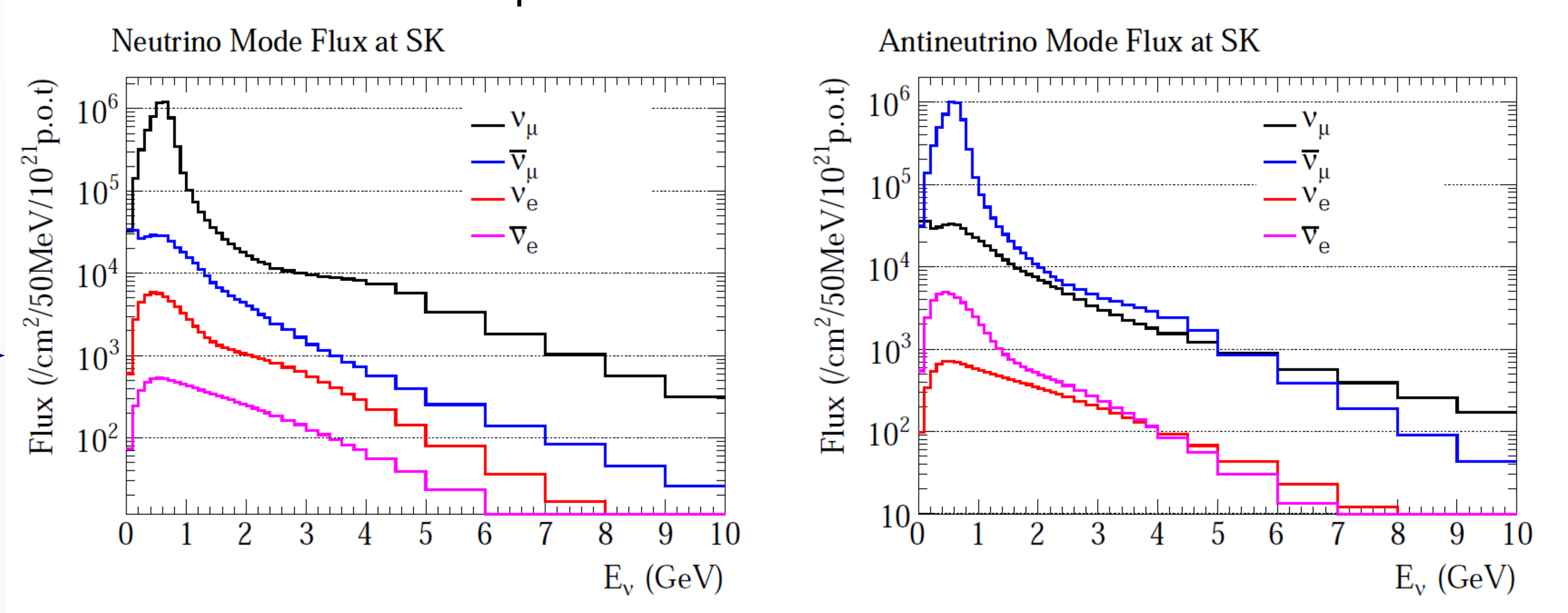
INGRID

T2K beam

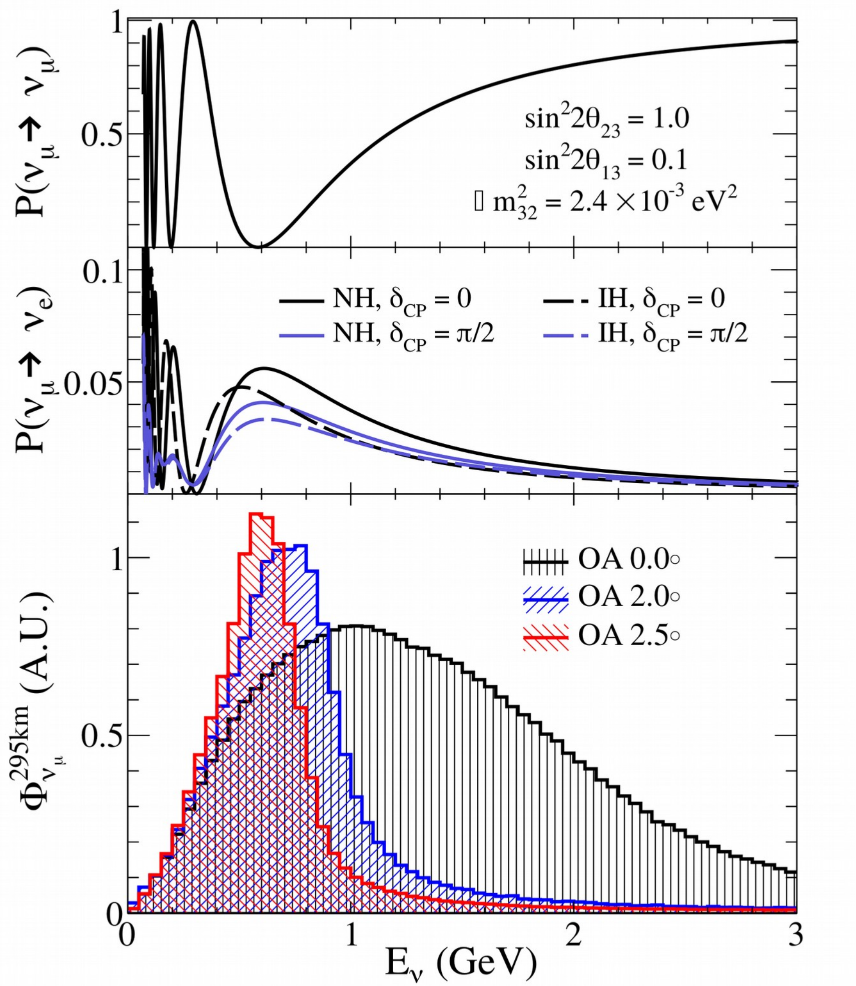


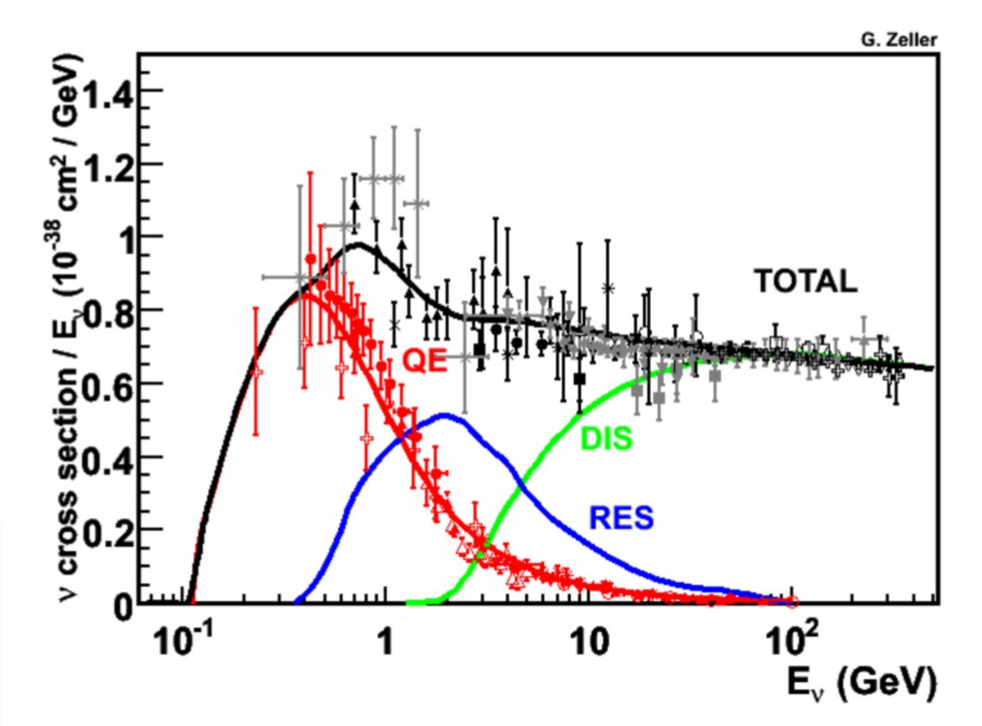
Flux predictions tuned for hadron production results from NA61/SHINE (measurements on T2K target replica)

Beam can operate in neutrino or antineutrino mode.



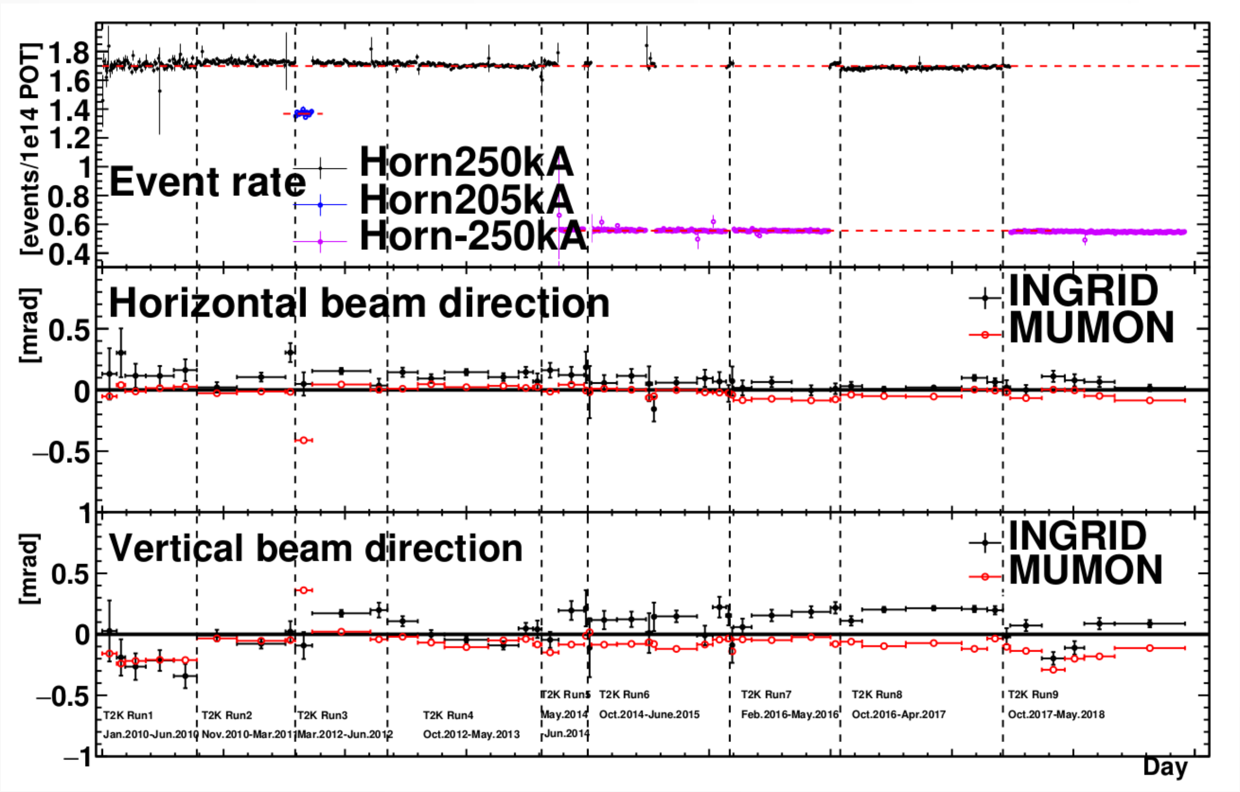
Off-axis strategy

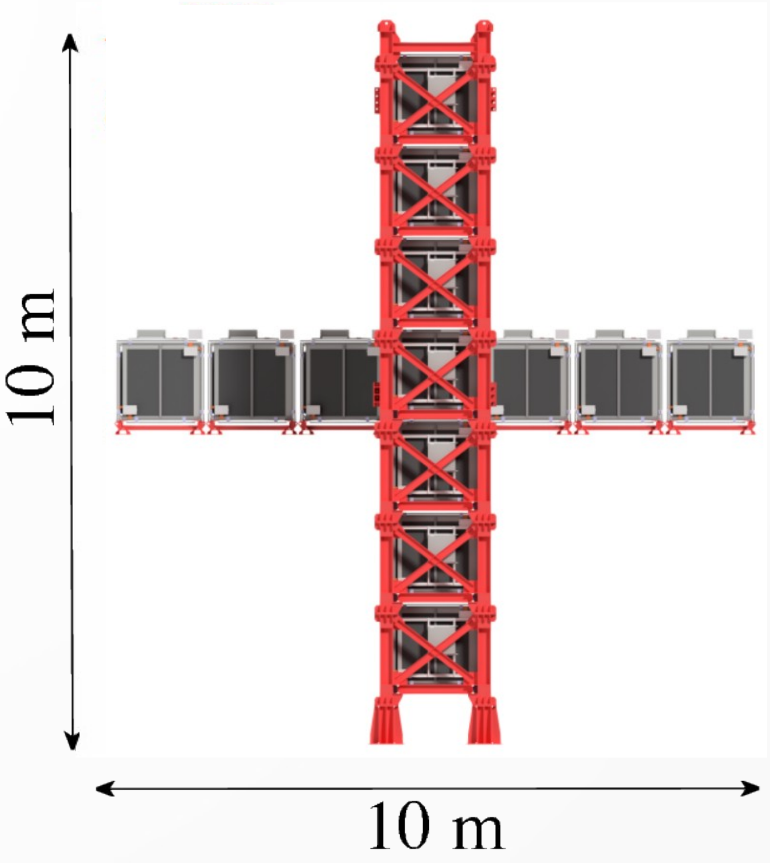




- Off-axis strategy enhances oscillation effect and contribution of CC quasielastic (CCQE) interactions.
- Around T2K beam peak (~600 MeV) mostly CCQE and resonant interactions occur.
- Shift in off-axis angle δOA~1mrad (0.057°) → shift in energy peak δE/E ~2% at far detector

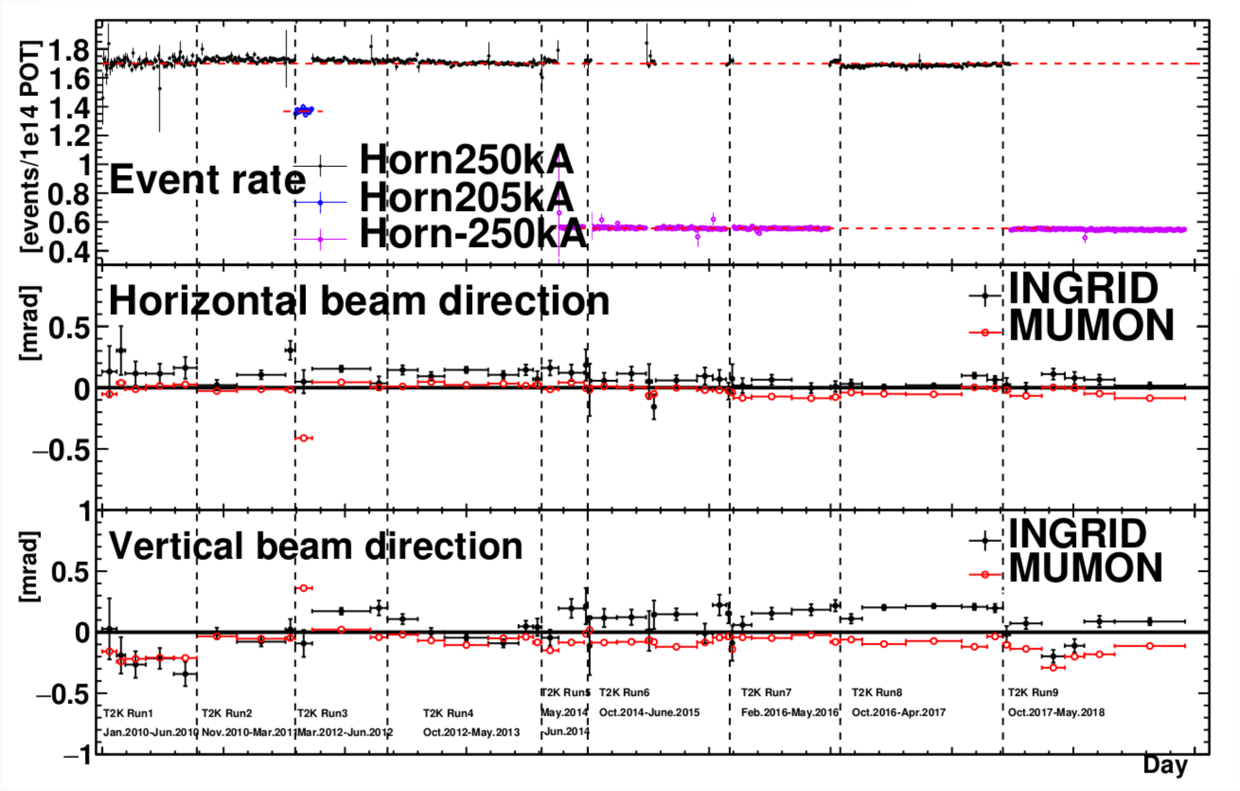
On-axis near detector: INGRID

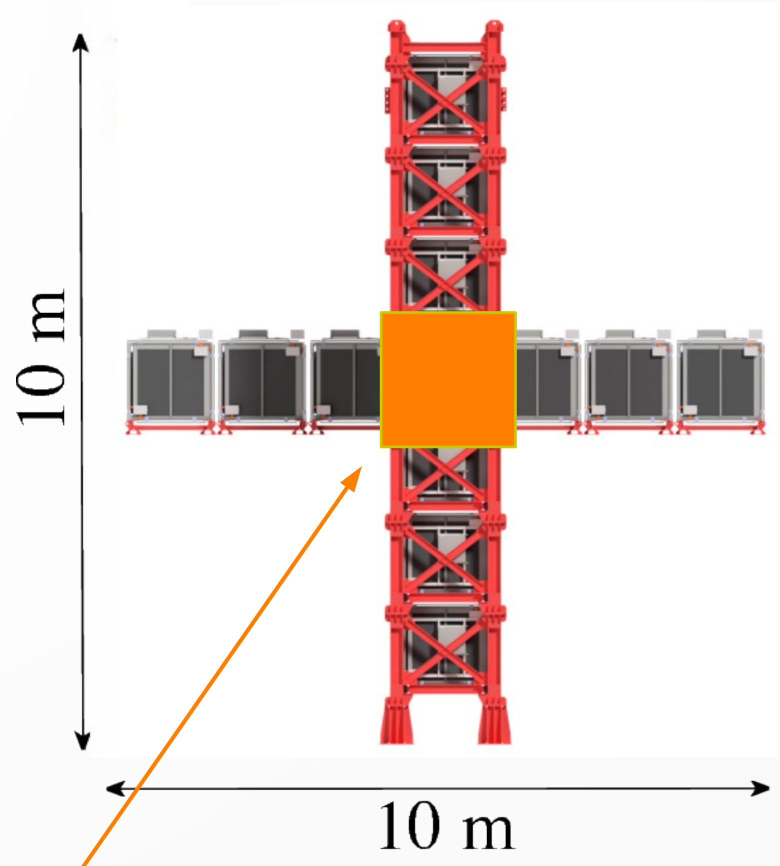




- Cross-shaped detector composed of 14 Fe/scintillator modules.
- Monitors beam's direction, profile and intensity.
- MUMON – muon monitor (for muons exiting decay volume)

On-axis near detector: INGRID





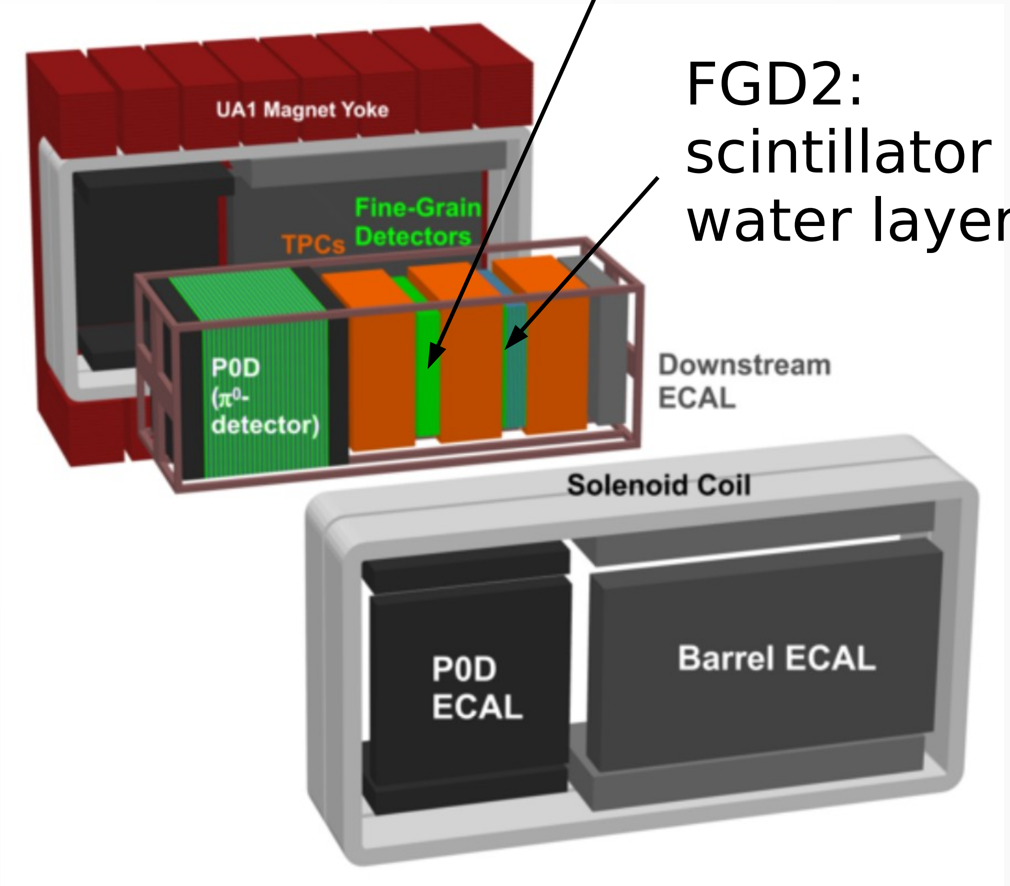
Proton Module (consisting of scintillator material only) installed upstream of INGRID for the cross section measurements.

Off-axis near detector: ND280

- ND280 is a multipurpose detector used to constrain the off-axis flux and neutrino interaction models used in the oscillation analysis.
- CC interactions are studied in the tracker, made of two FGDs (fine grained detectors – scintillators) and three gaseous TPCs.
- FGDs serve as targets and provide good vertex and track resolution.
- Magnetic field allows for charge and momentum measurement.
- Energy loss in the TPCs allows for particle identification.

FGD1: scintillator layers

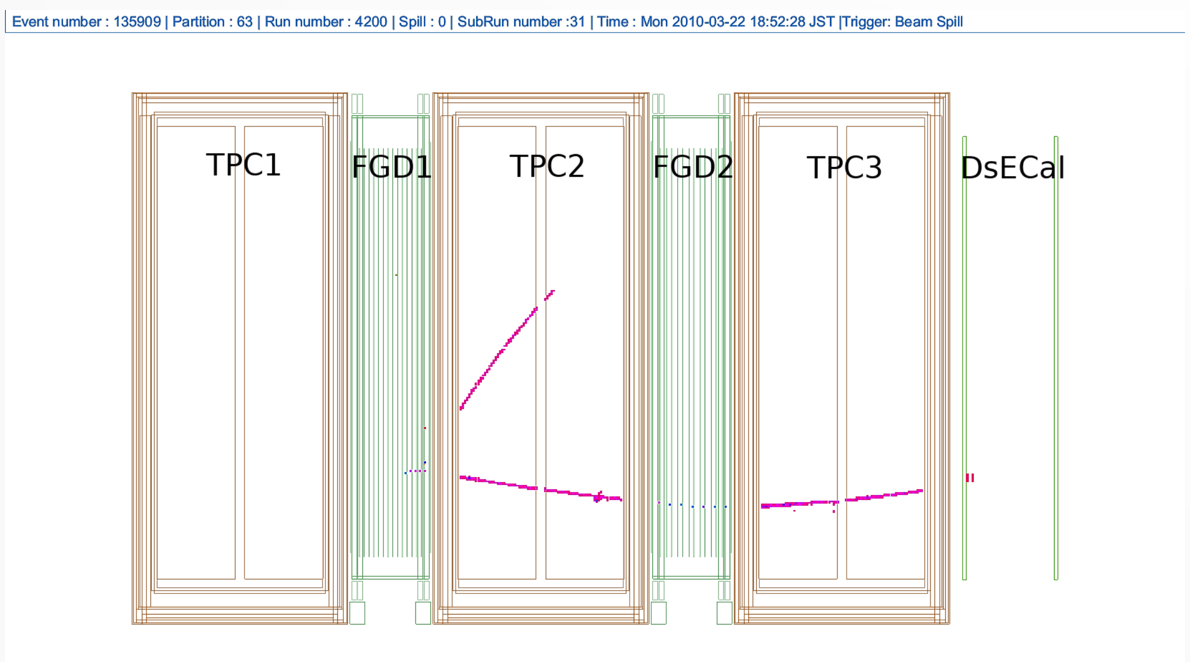
FGD2: scintillator + water layers



Exploded view of ND280

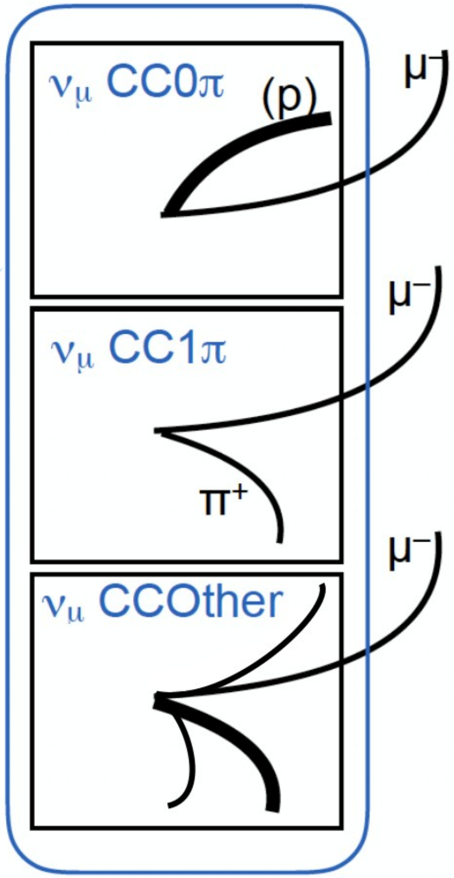
ND280 data samples

- Multiple ND280 samples used in the oscillation analysis:
  - For neutrino and antineutrino beam modes
  - Interaction in FGD1 or FGD2
  - Different signatures with respect to particles multiplicity



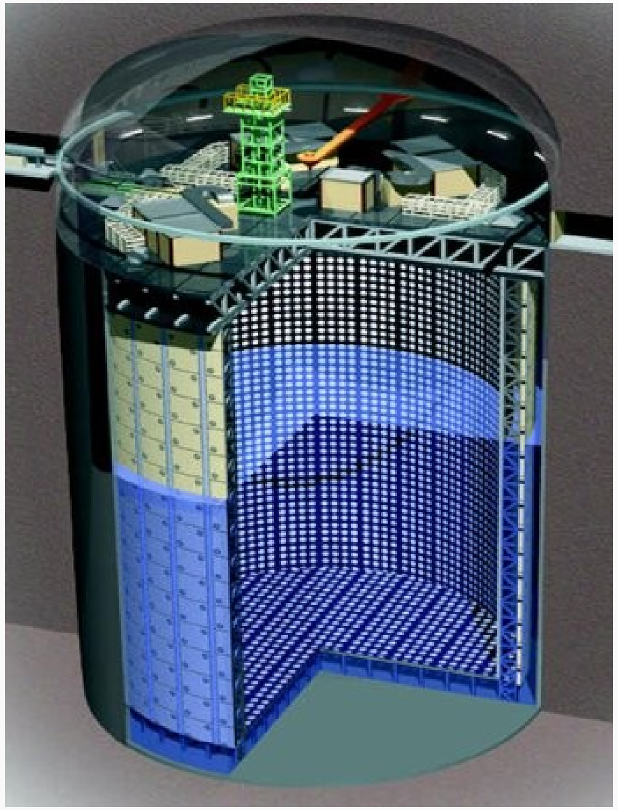
ND280 event display (tracker region)

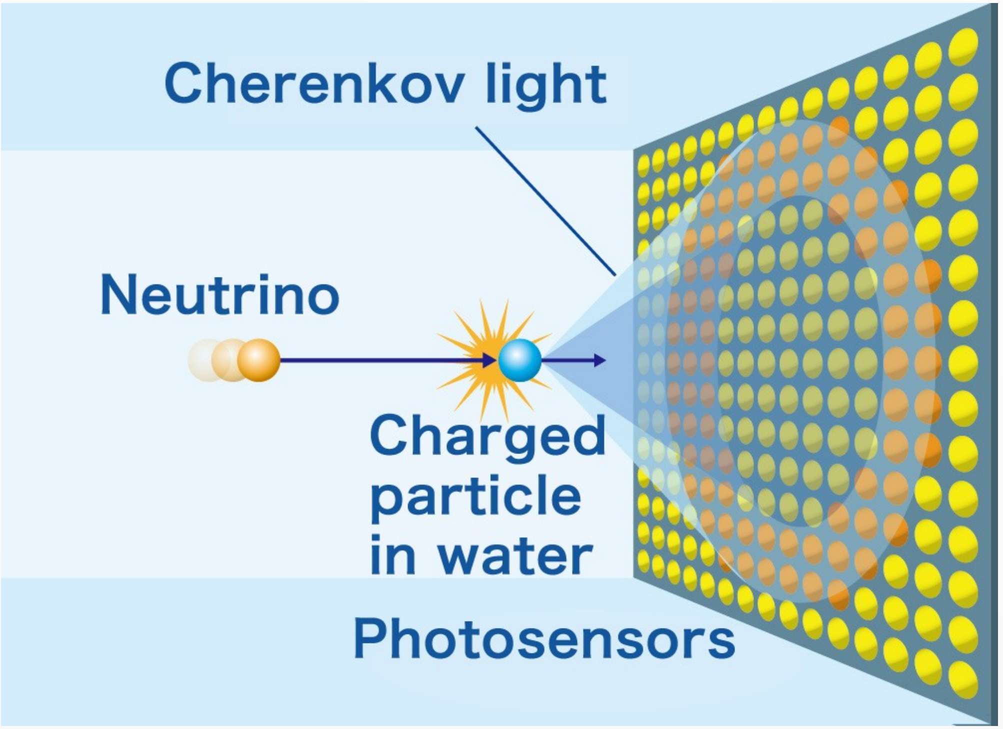
Three basic signatures used for classification. Divided into further subsamples for neutrino beam mode.

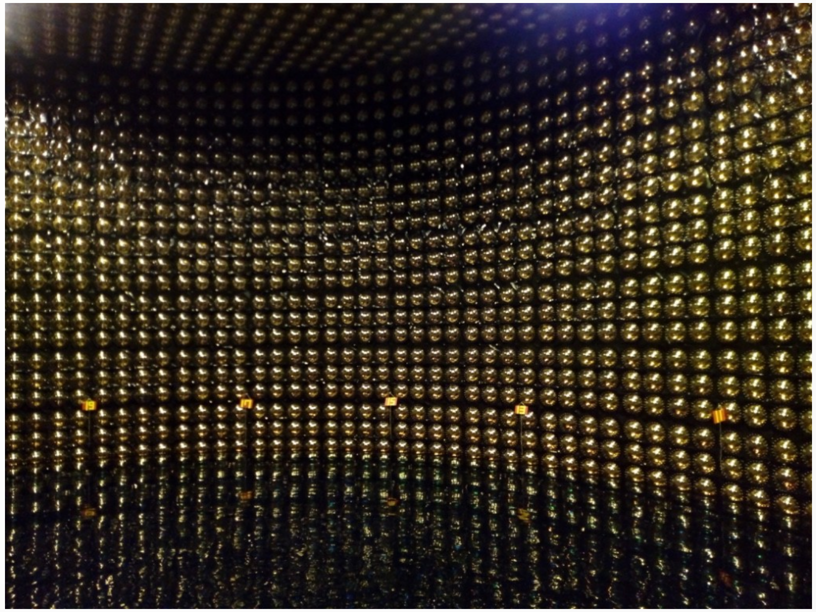


Far detector: Super-Kamiokande

- 50 kton water Cherenkov detector
- Around 11000 PMTs measure the Cherenkov light inside the tank.
- For T2K energy scale most nucleons are under Cherenkov threshold.

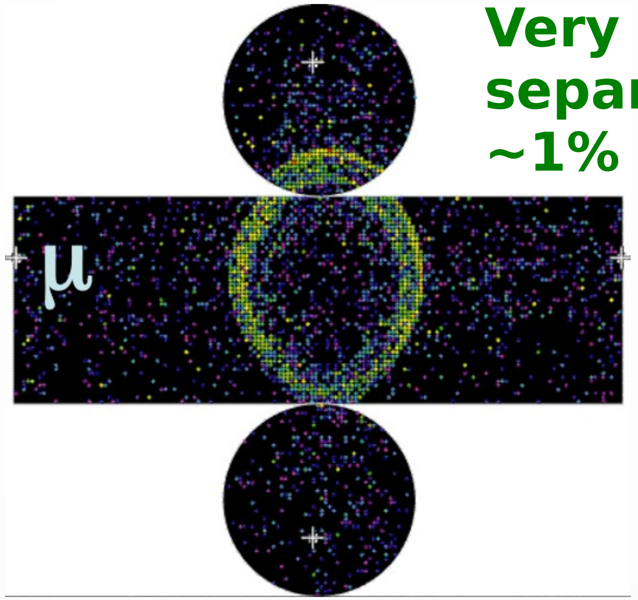




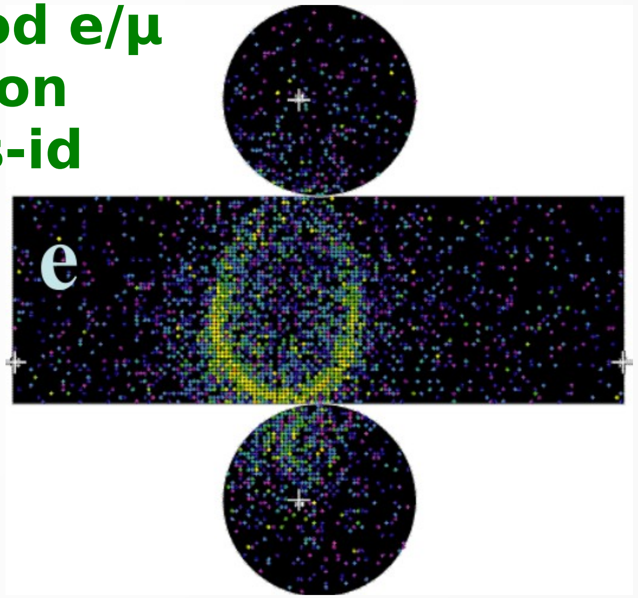


Super-K data samples

- Neutrino energy reconstructed from lepton momentum and angle (assuming 2 body-like interaction).
- Single ring selection targets CCQE events.
- Additional sample targets ν_e CC1π^+ events.

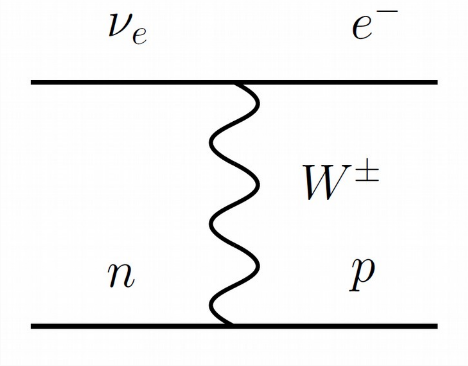


Very good e/μ separation ~1% mis-id

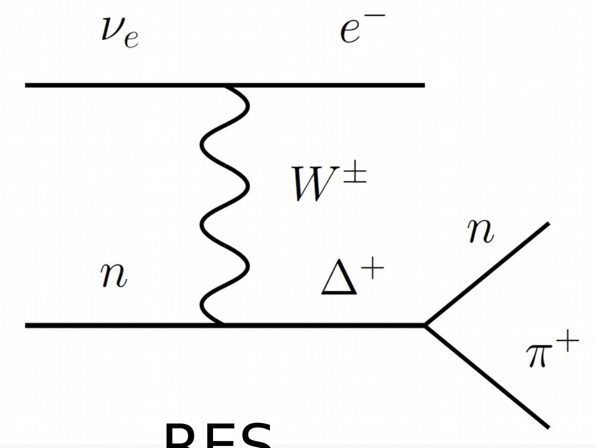


Single ring samples used in the far detector analysis
Re – e-like ring, Rμ – μ-like ring, ME – Michel electron

	e-like	μ-like
ν mode	1Re + 0 ME	1Rμ + 0/1 ME
	1Re + 1 ME	
anti-ν mode	1Re + 0 ME	1Rμ + 0/1 ME



CCQE



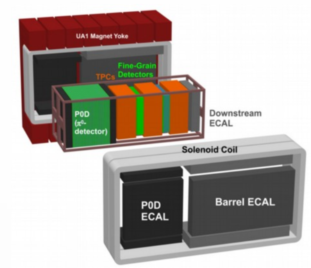
RES

Analysis strategy - Frequentist

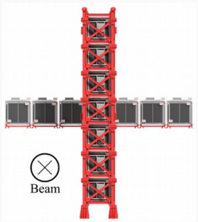
NA61/SHINE external data

ND280 data

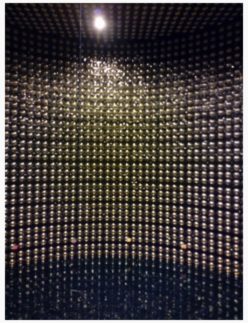
ND280 detector model



INGRID & Beam monitor data → Neutrino flux model → **ND280 Fit** systematics ~2x smaller



Cross-section model



Super-K detector model → **Oscillation Fit** → **Oscillation parameters**

Super-K data

Near detector + Far detector sequential analysis

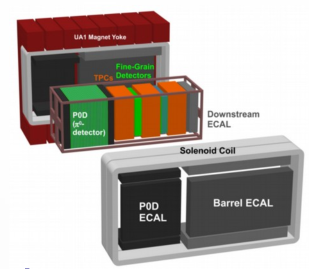
Hybrid Frequentist approach using Poisson likelihood and Gaussian/flat penalty terms for systematic parameters

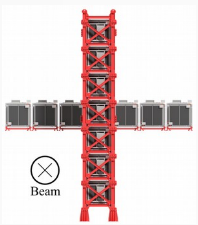
Gradient descent / grid search algorithm

Analysis strategy – Bayesian

NA61/SHINE
external data

ND280 detector
model



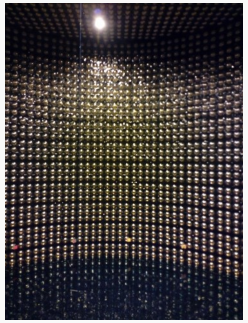


INGRID & Beam
monitor data

Neutrino flux
model

ND280 data

Cross-section model



Super-K
detector
model

Super-K data

Oscillation Fit

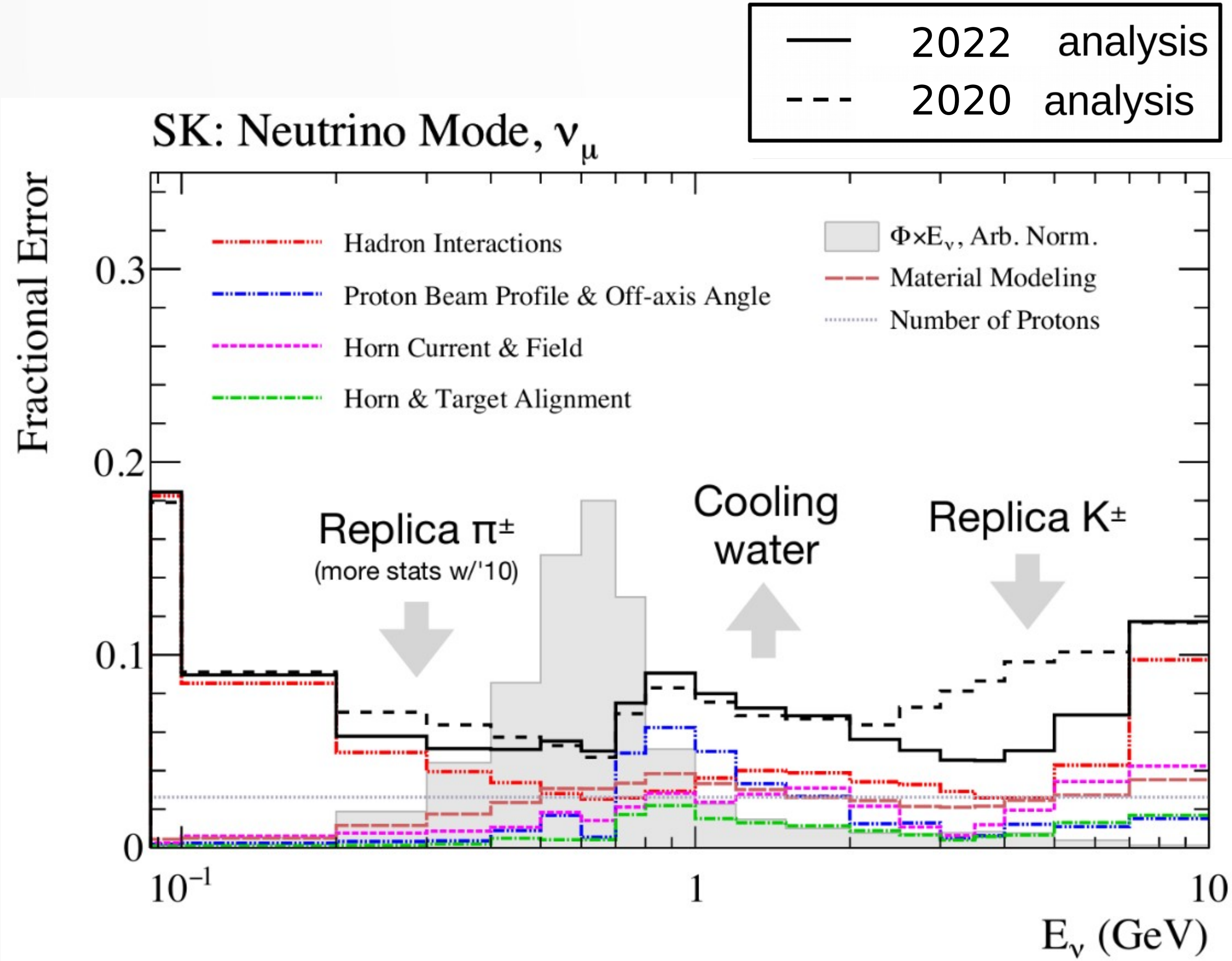
Oscillation parameters

Near detector + Far detector simultaneous fit

Bayesian approach using Poisson likelihood and Gaussian/flat penalty terms for systematic parameters

Markov Chain Monte Carlo with Metropolis Hastings algorithm

Updates from 2020 analysis



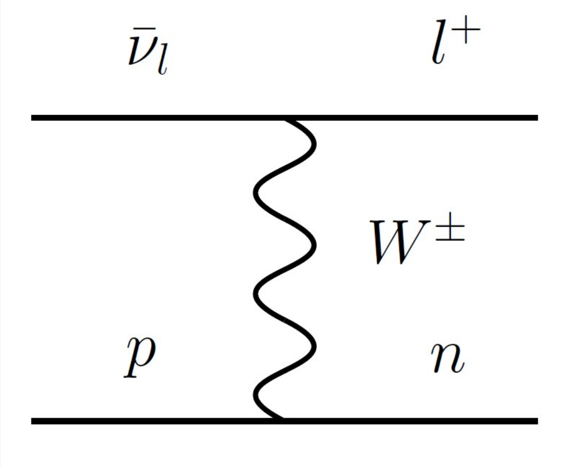
- Major uncertainty in neutrino flux simulation arises from uncertainty of hadron production in proton interactions on graphite target.
- **Improved flux prediction** based on hadron multiplicity measurements by NA61/SHINE.
- Now using 2010 T2K replica target data [Eur. Phys. J.C79, 100 (2019)].

Updates from 2020 analysis

Updated neutrino interaction modeling.
At T2K energy scale CCQE and CC RES interactions are dominant.

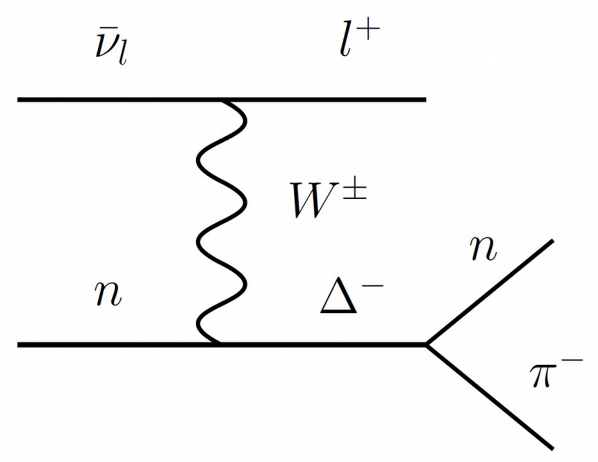
CCQE

- Improved uncertainties for spectral function model by normalization of each nuclear shell for mean field
- Pauli Blocking included



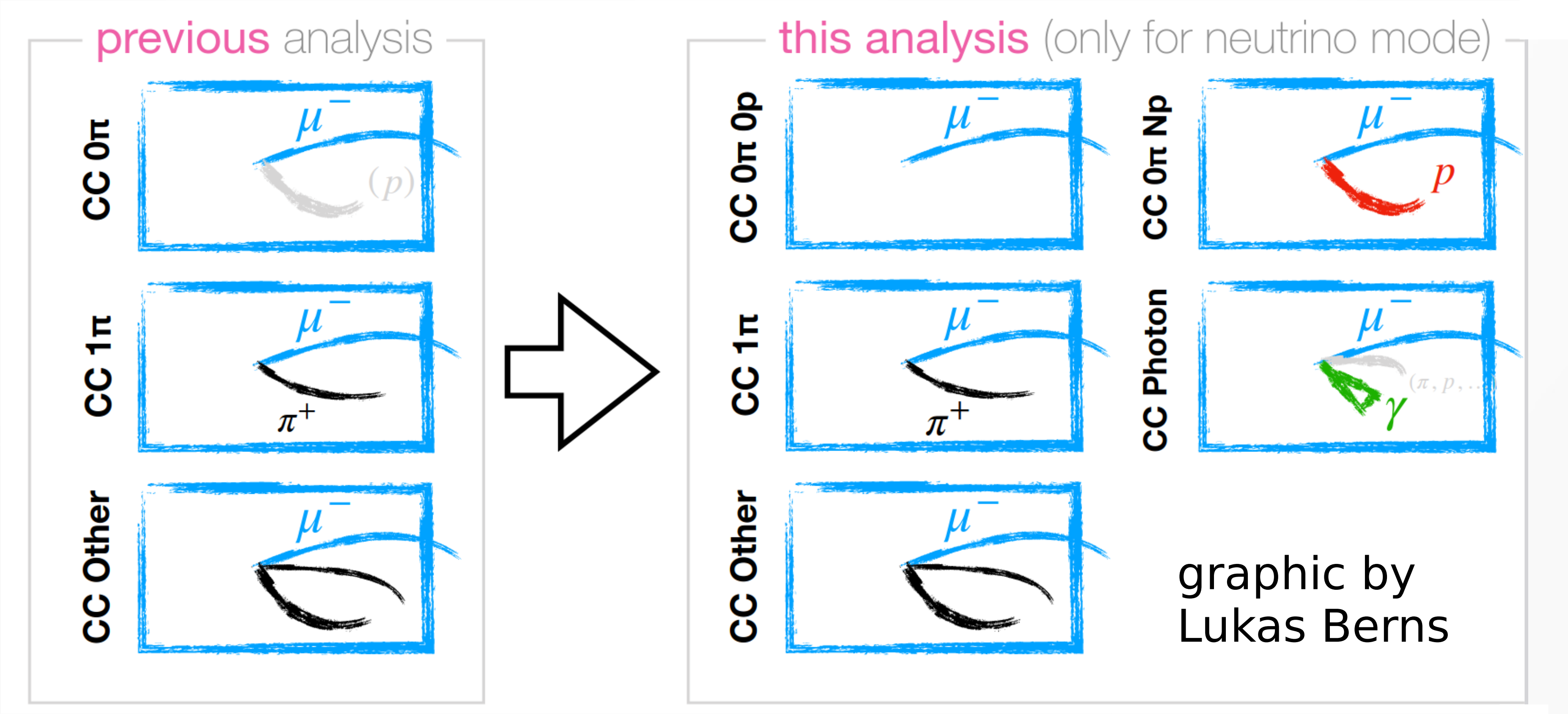
CC Resonant (Rein-Sehgal)

- New tune to bubble chamber data
- New uncertainties on Δ resonance decay and effective binding energy



Updates from 2020 analysis

- **New selection samples in ND** analysis with proton and gamma tagging.
- Altogether 22 ND samples used.

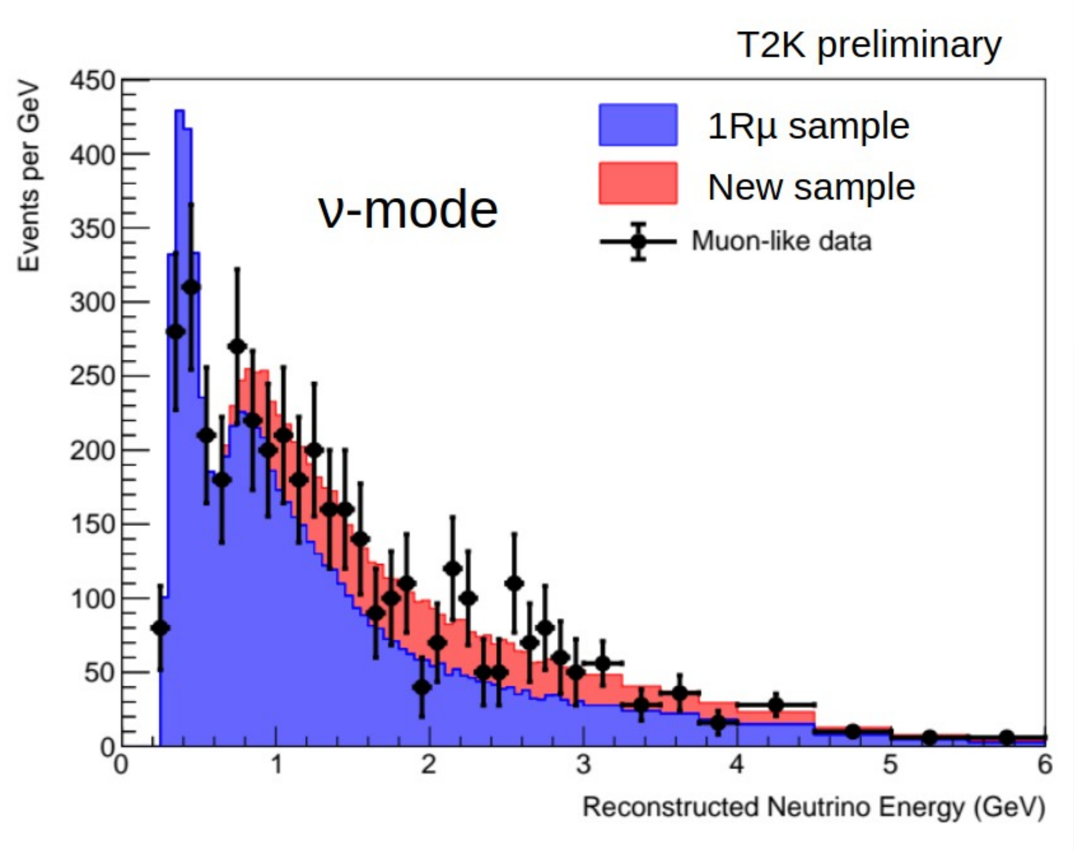


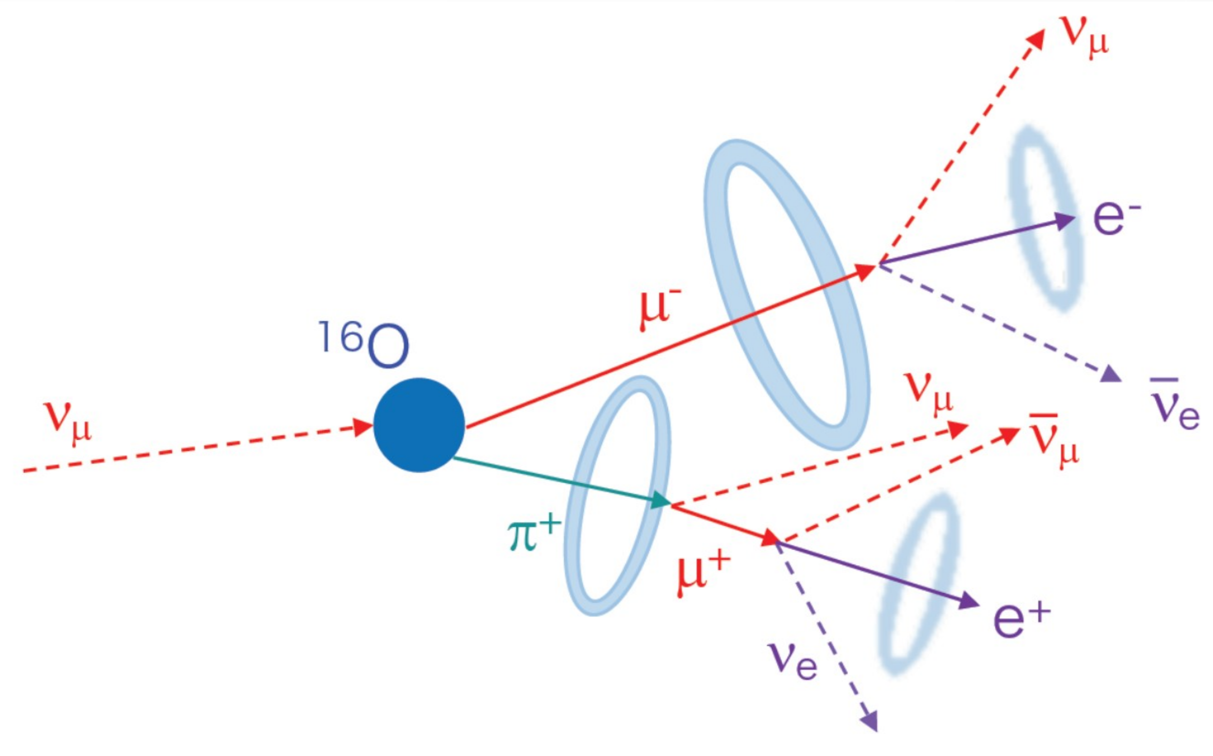
2020

2022

Updates from 2020 analysis

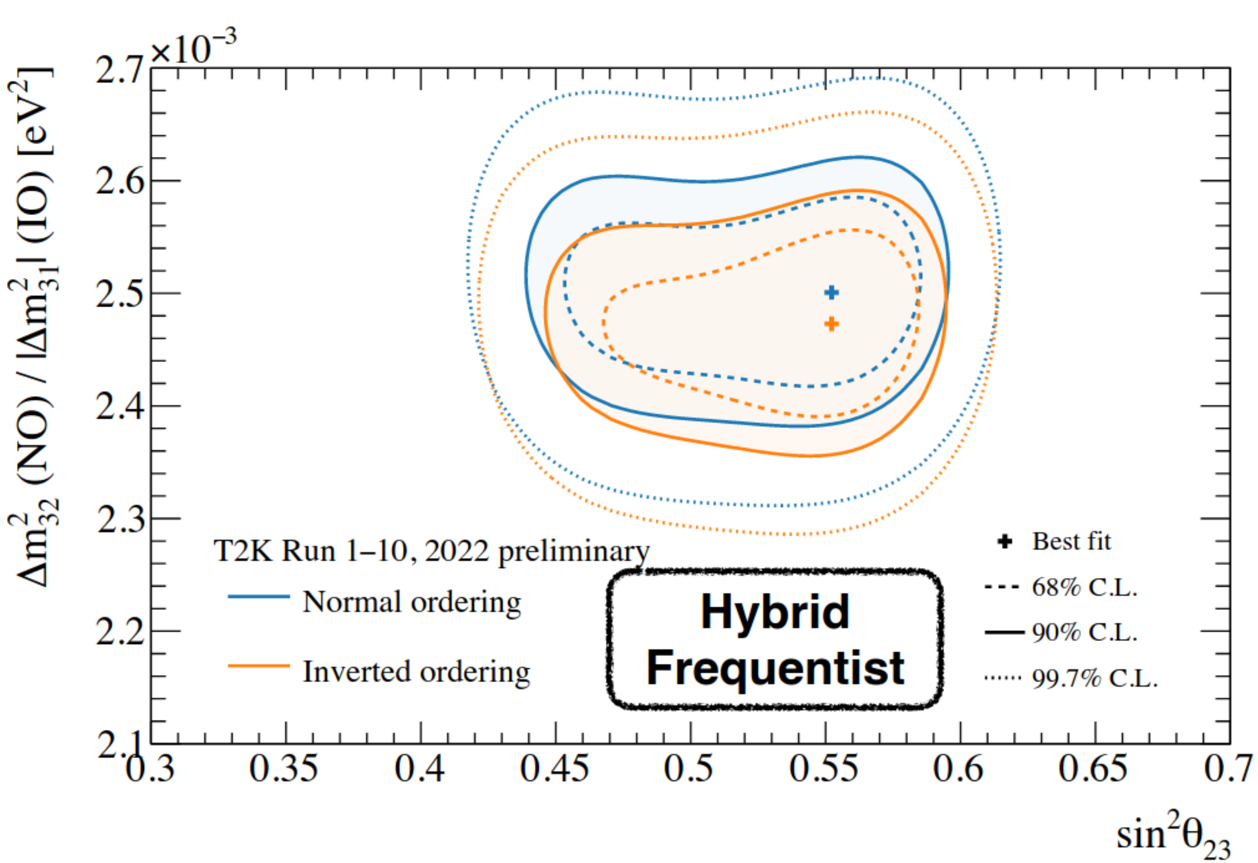
- **New selection sample in FD** – first use of multi-ring events.
- Sample targets ν_μ interactions with single π^+ production.
- ~30% increase in μ-like statistics

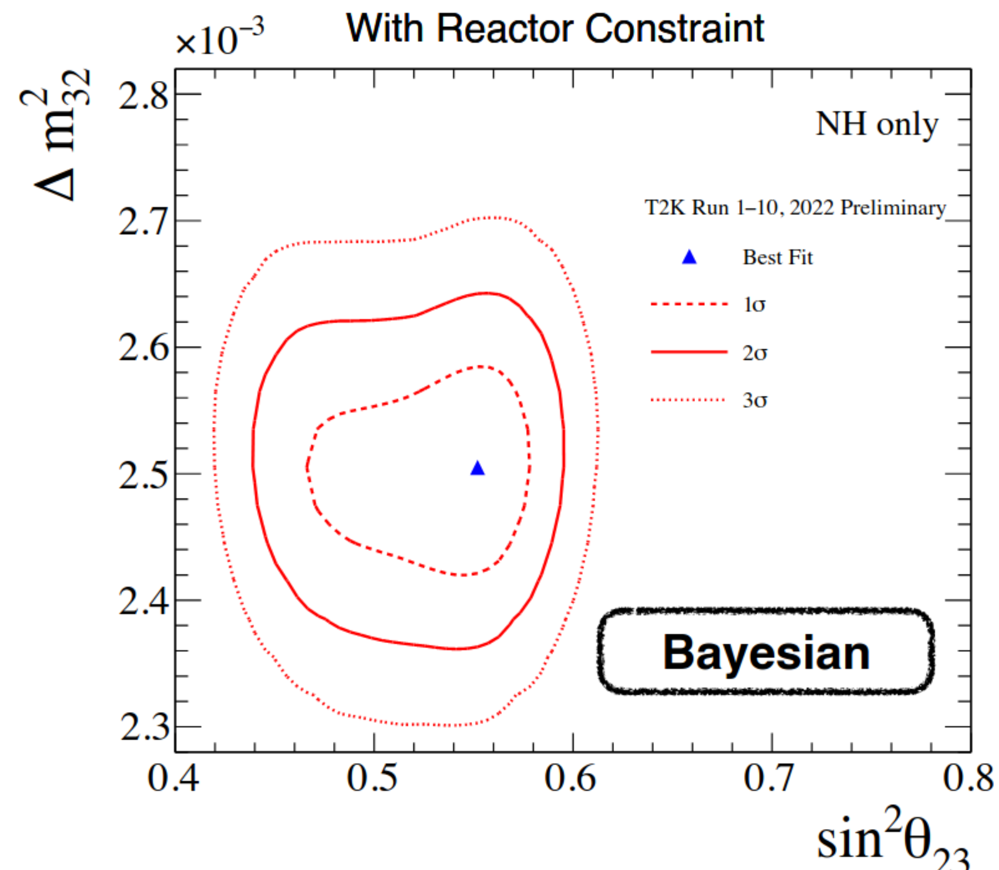




Oscillation analysis results

$\sin^2\theta_{23}$ vs Δm^2_{32}

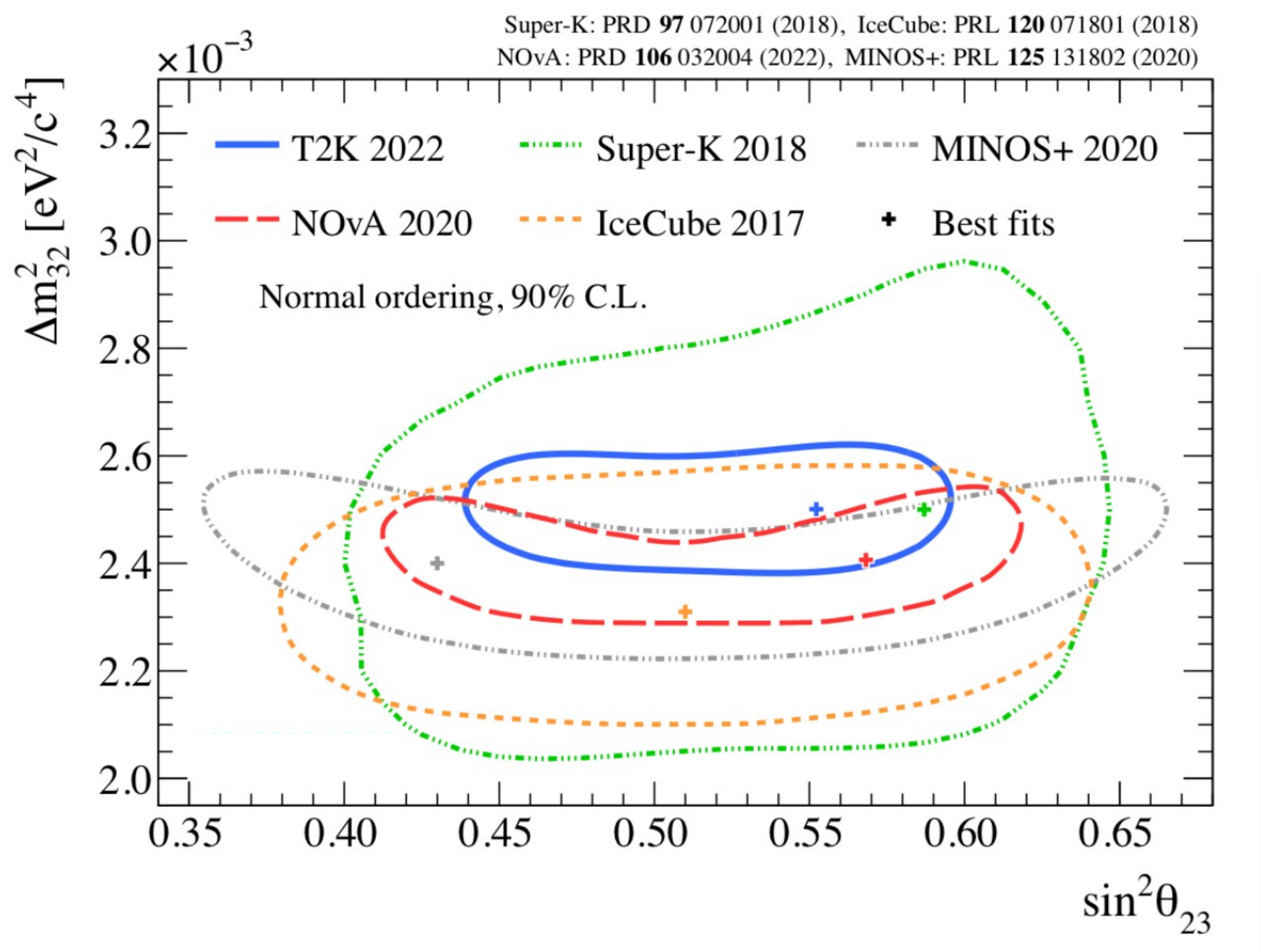




Weak preference for upper octant of θ_{23} ($\theta_{23} > \pi/4$).

Reactor constraint on θ_{13} applied ($\sin^2 2\theta_{13} = 0.0861 \pm 0.027$).

Comparison with other experiments

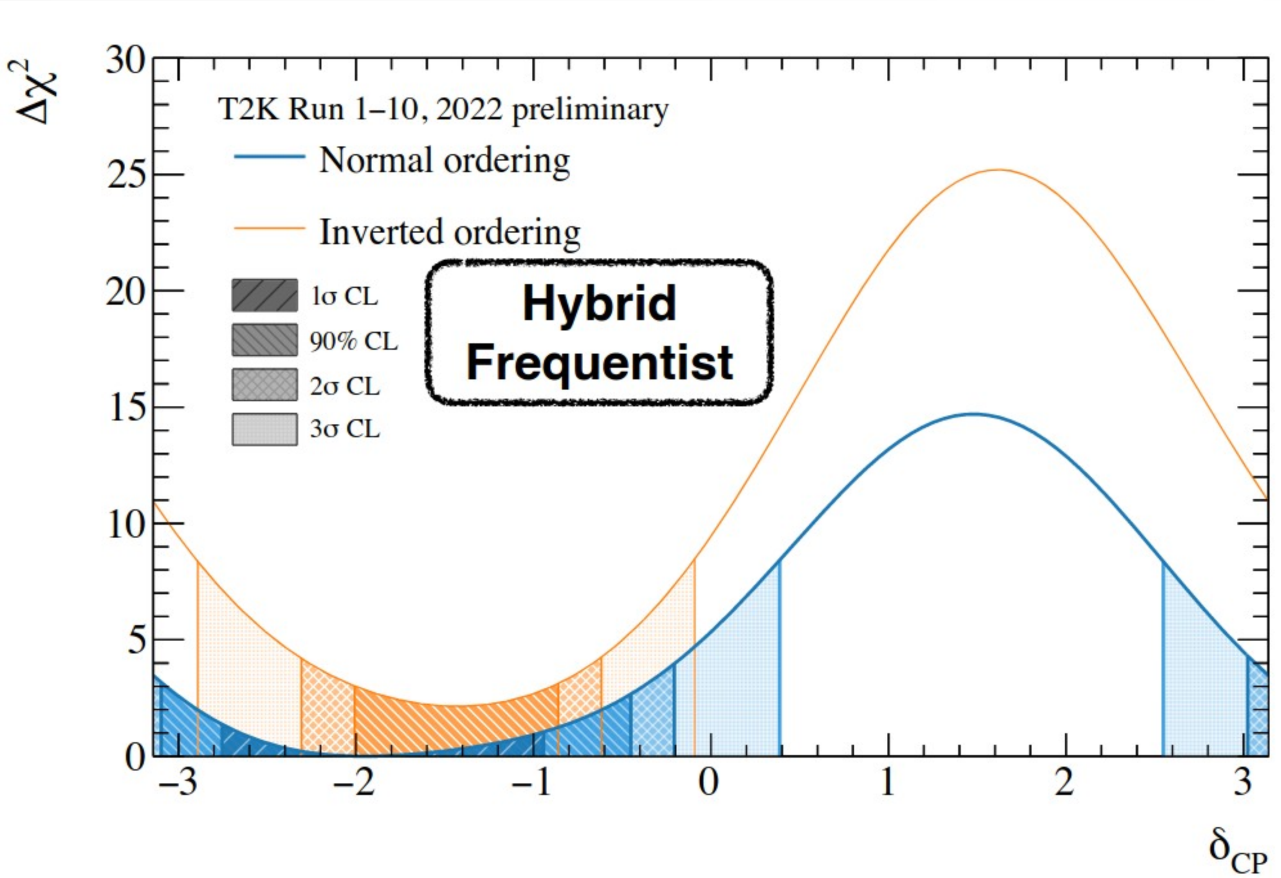


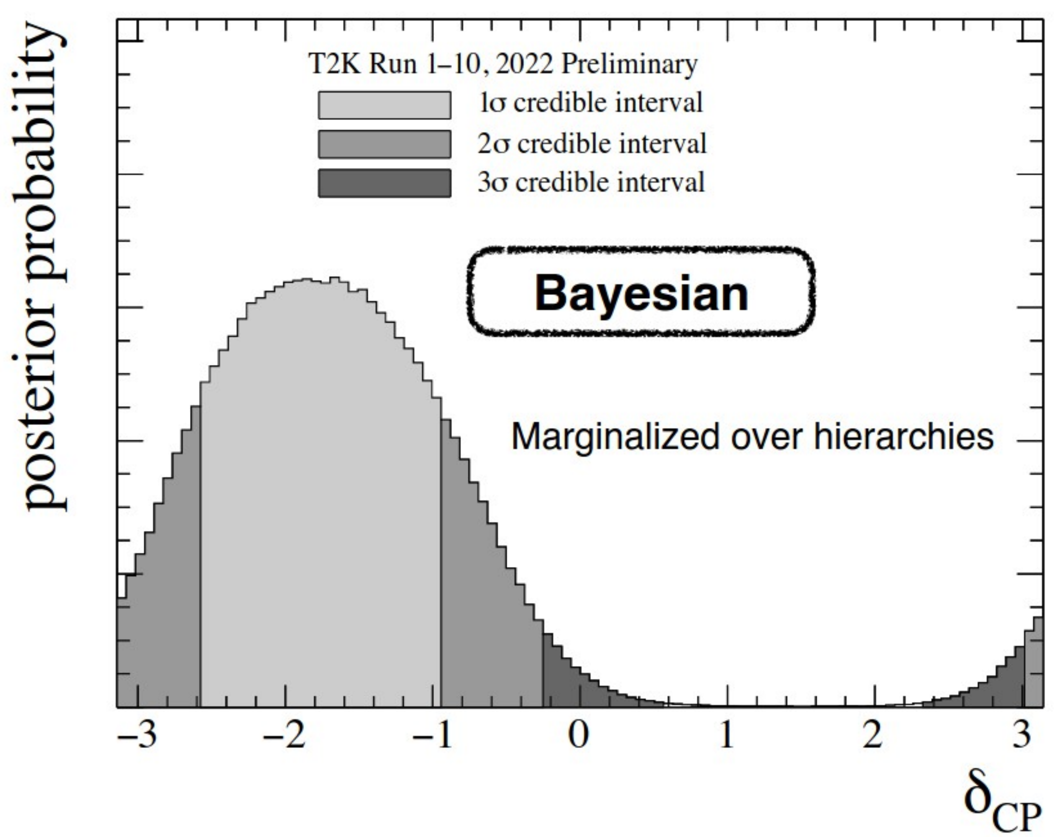
T2K result taken from frequentist analysis. Contour computed with the constant $\Delta\chi^2$ method.

Best fit points for other experiments taken from arXiv:2303.03222

Super-K and IceCube improved their results recently.

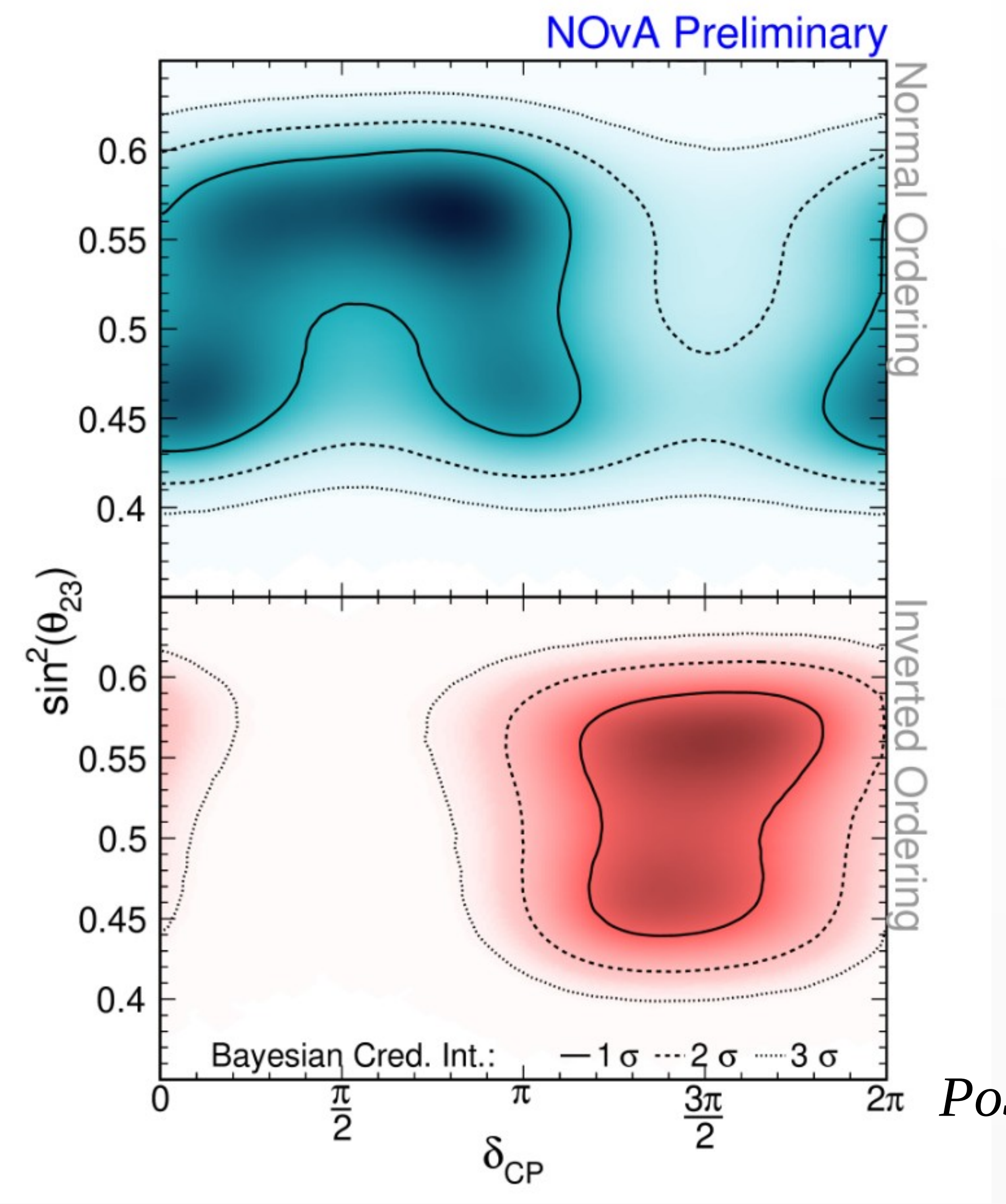
CP violation phase δ_{CP}





CP conserving values (δ_{CP} = 0, ±π) excluded at 90% CL.
Best fit value near maximal CP violation (δ_{CP} = -π/2).

Comparison with NOvA



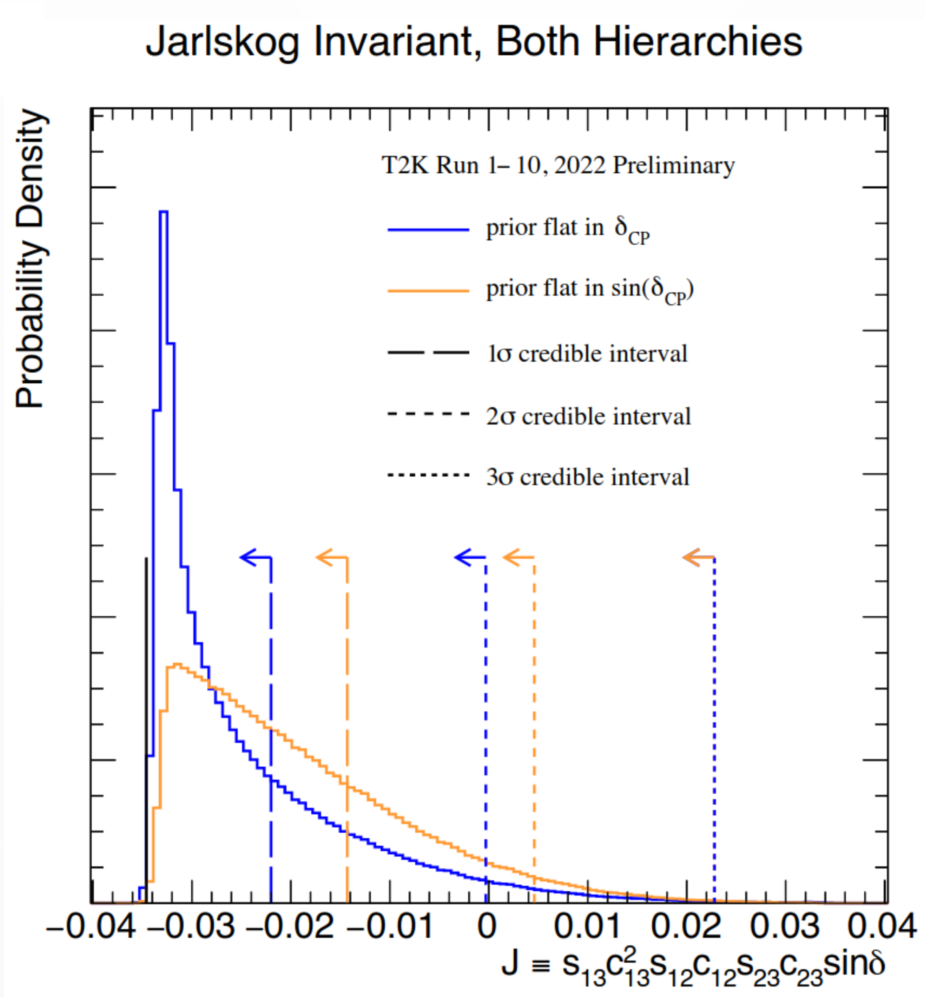
PoS NOW2022 (2023) 015

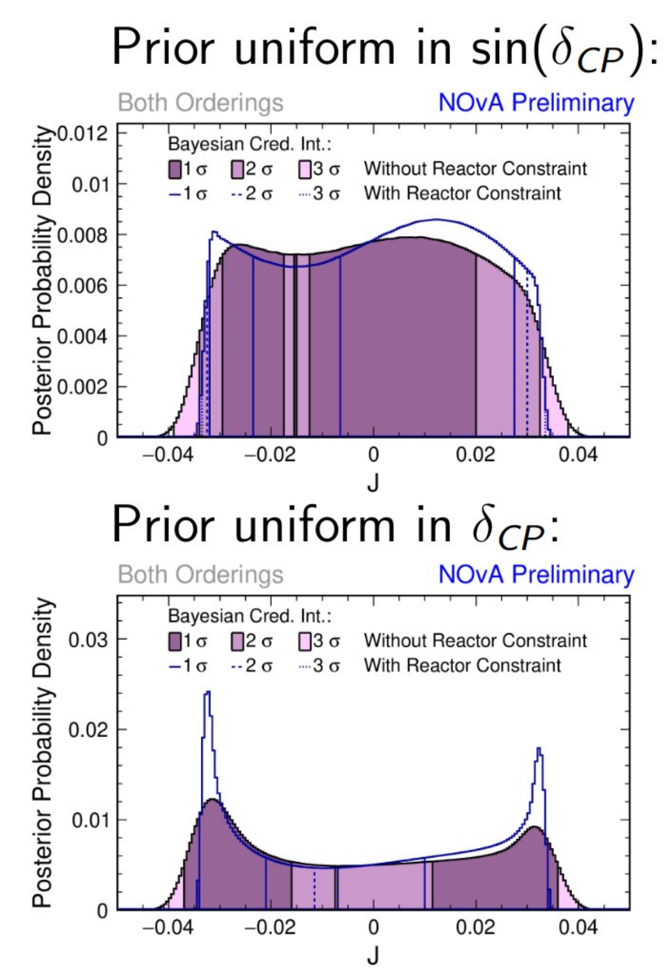
- NOvA results are much more consistent with CP conserving values for normal mass ordering.
- For inverted mass ordering both NOvA and T2K measure δ_{CP} near -π/2 (or 3π/2).
- Slight preference for the normal mass ordering and the upper octant of θ_{23}.

Jarlskog invariant J_{CP}

$$J_{CP} = \frac{1}{8}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\cos\theta_{13}\sin\delta_{CP}$$

- PMNS parametrisation independent
- Requires prior probability density function for Bayesian analysis.
- Results depend on using uniform (flat) prior probability in δ_{CP} or $\sin\delta_{CP}$.
- In both cases T2K excludes J_{CP}=0 (CP conserving value) at 90% CL and prefers maximal CP violation.





Artur Sztuc
Moriond EW 2023

Cross section measurements in T2K

T2K cross section measurements

Multiple targets: hydrocarbon, water, iron, argon

Multiple angles w.r.t. neutrino beam axis – different energies

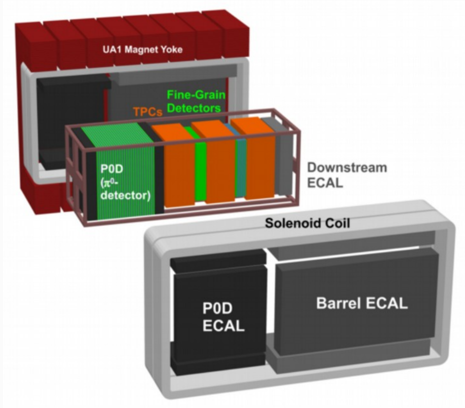
Neutrino and anti-neutrino beam modes

Possibility to study interactions relevant for T2K oscillation analysis (CC0π, CC1π on C, O), explore nuclear effects and measure rare processes.

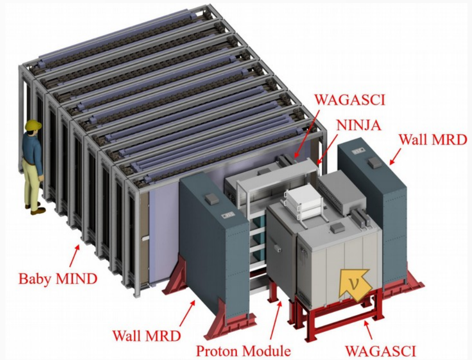
Blind analysis approach, fake data studies

Reducing model dependencies by selection studies, binning optimisation, phase-space reduction, accurate choice of observables.

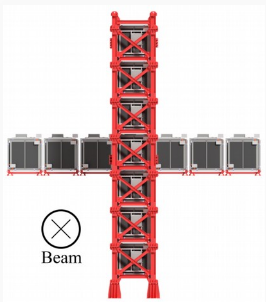
ND280
2.5 deg
off-axis



WAGASCI
1.5 deg
off-axis



INGRID
on-axis



Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module (1)

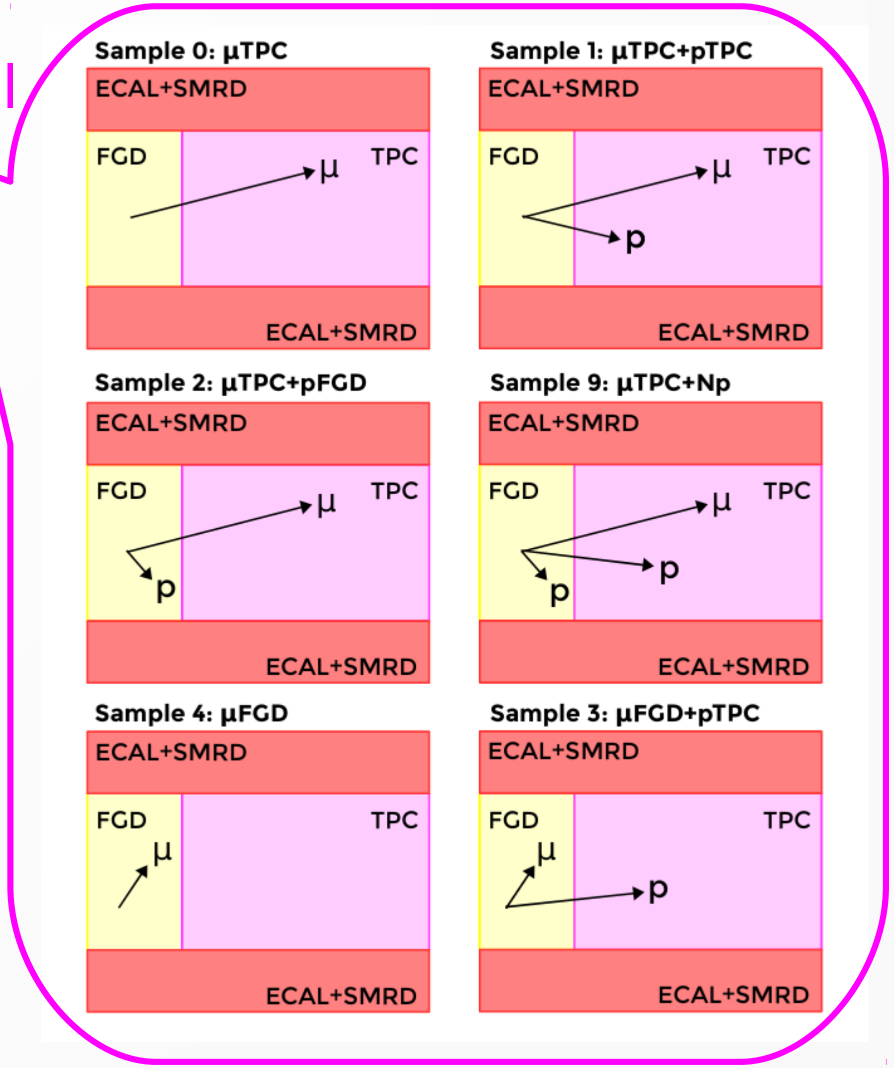
First on-axis/off-axis analysis

Two different flux spectra

Possibility to study energy dependence of neutrino interactions

Flux constraints

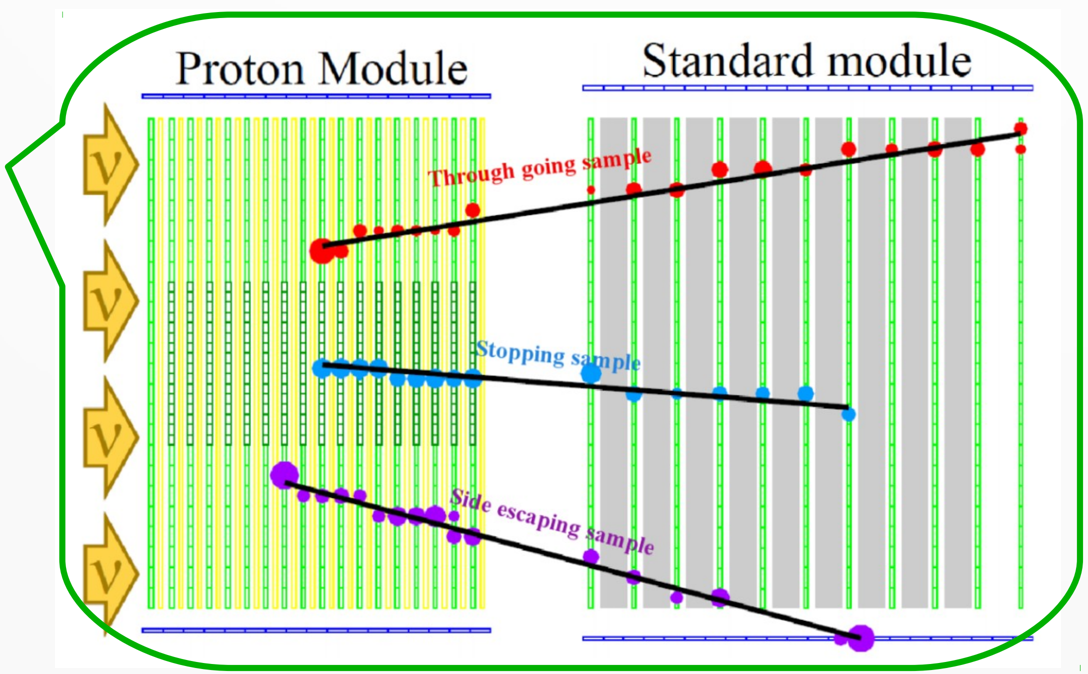
ND280 signal samples



INGRID signal samples

Proton Module: scintillator

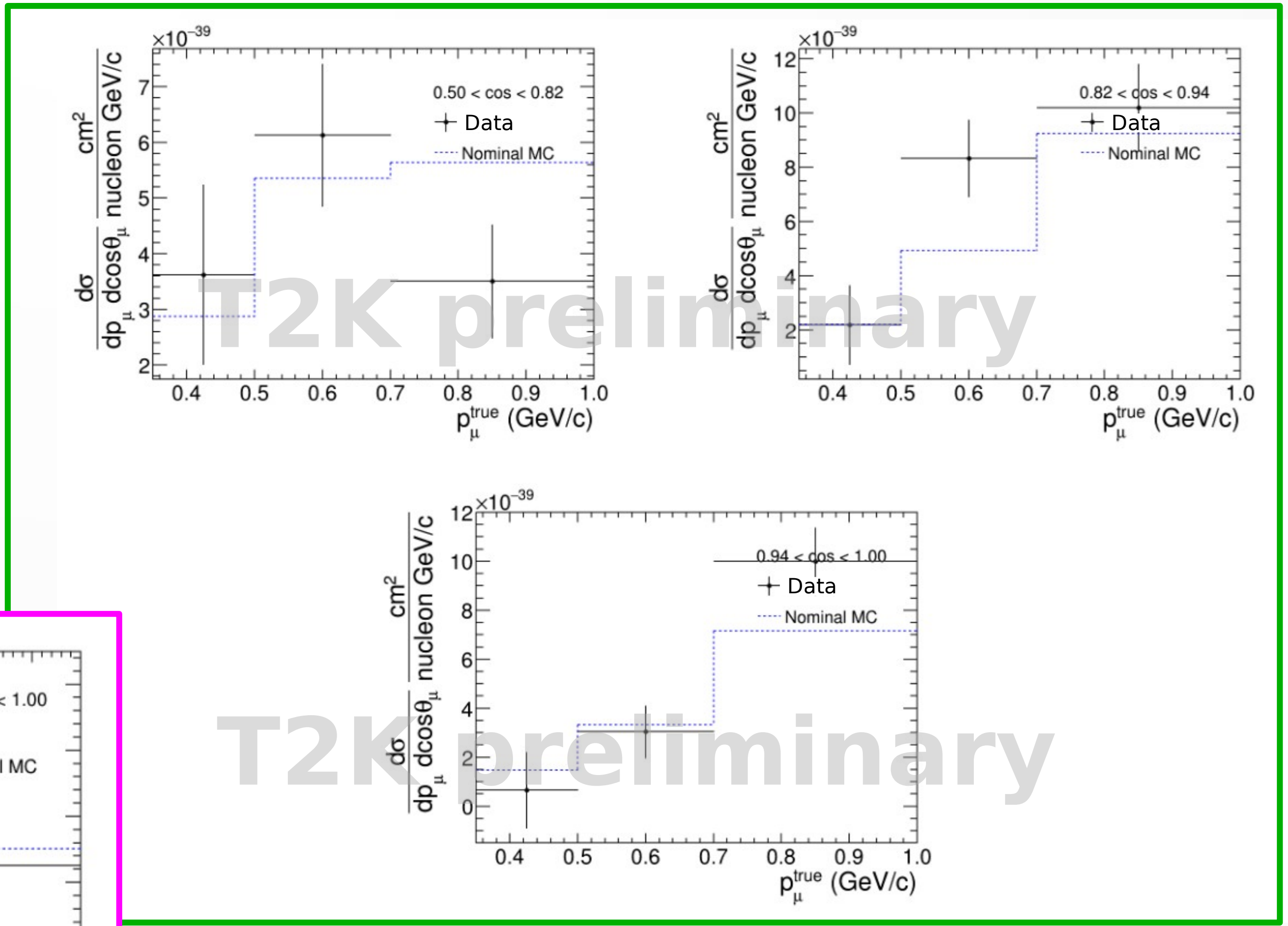
Standard Module: Fe + scintillator



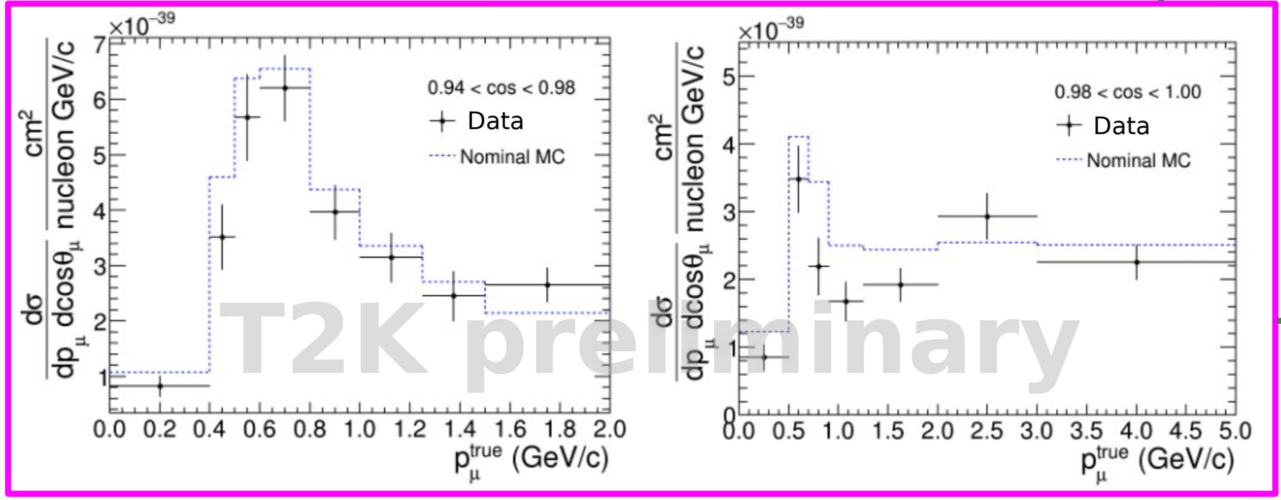
Joint On/Off axis ν_μ CC0π measurement on scintillator with FGD1 and the Proton Module (2)

Cross section is reported as flux integrated for on axis and off axis flux.

Preprint on arXiv:2303.14228



INGRID extracted cross section bins



ND280 extracted cross section bins

Correlations fully available

ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon **(1)**

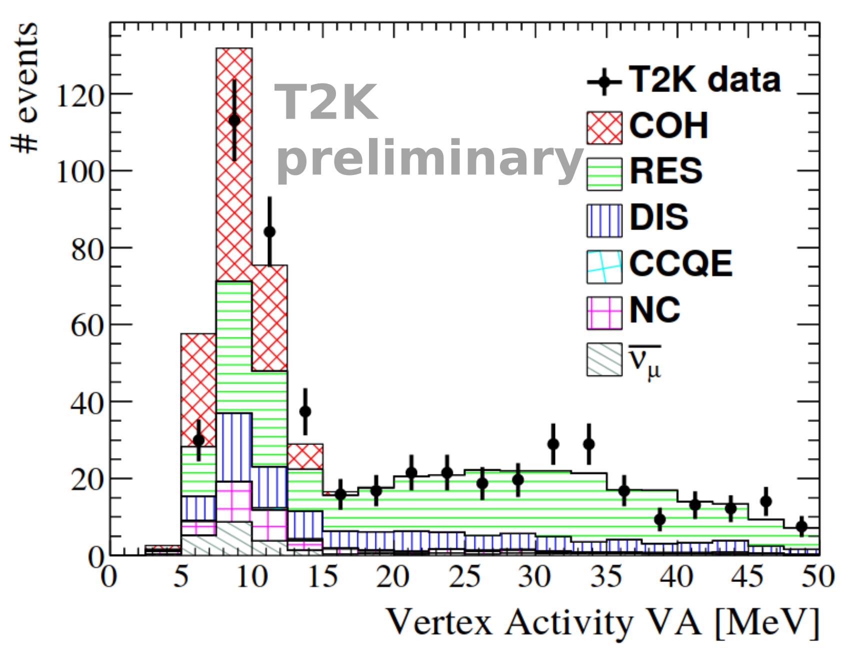
Rare interaction mode that is not well modelled theoretically.

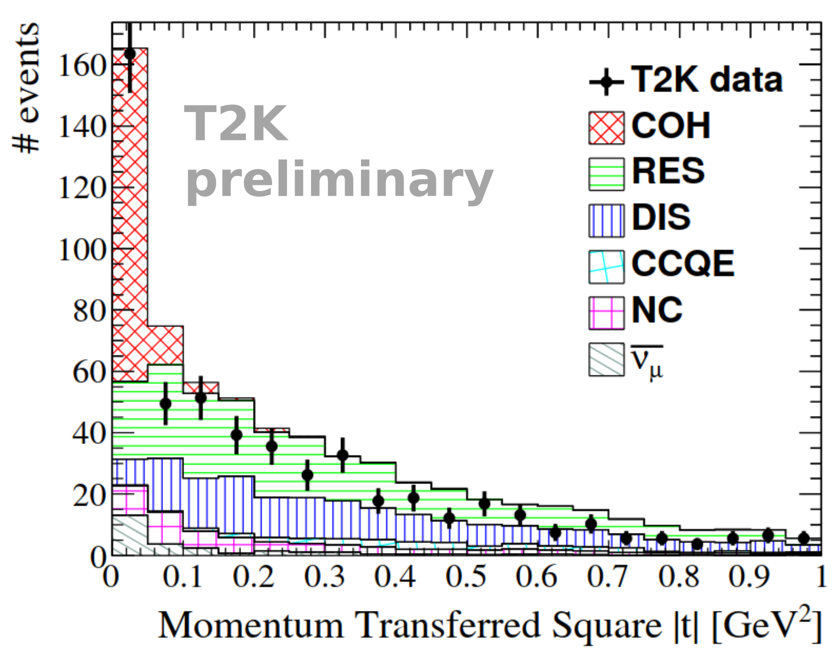
Interactions in ND280's subdetector FGD1. Signal selected as events with exactly two tracks (μ-like and π-like), low energy deposit around vertex (vertex activity) and low momentum transferred squared.

$$\nu_l + N \rightarrow l^- + \pi^+ + N$$

$$\bar{\nu}_l + N \rightarrow l^+ + \pi^- + N$$

Recoiled nucleus remains in the ground state.

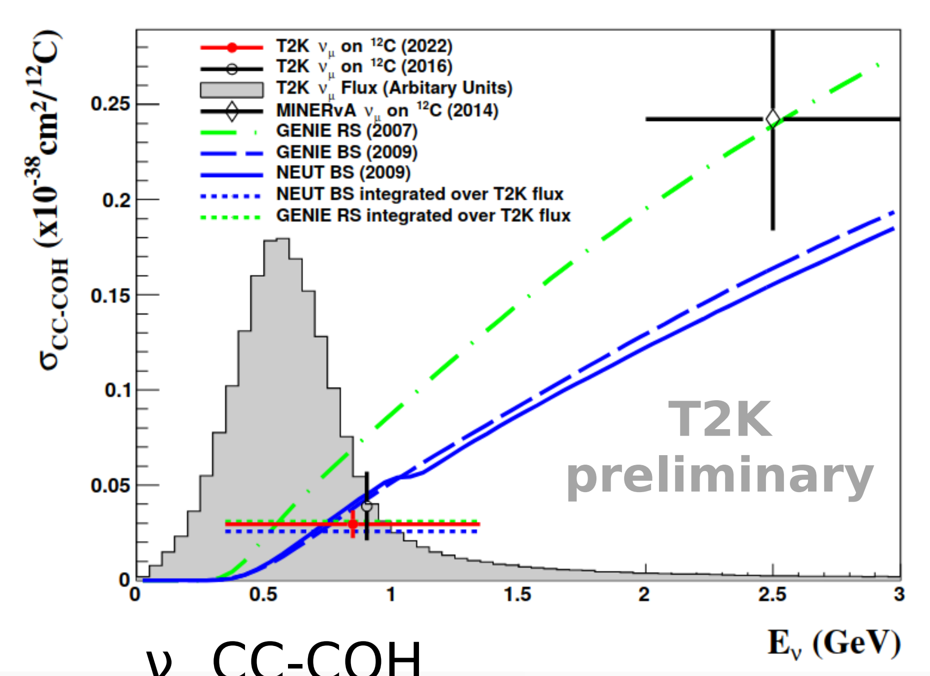




ν_μ and $\bar{\nu}_\mu$ CC coherent pion production on carbon **(2)**

First measurement of antineutrino coherent pion production at sub-GeV energies. Due to statistical limitations the cross section (per nucleus) is reported as a single energy bin.

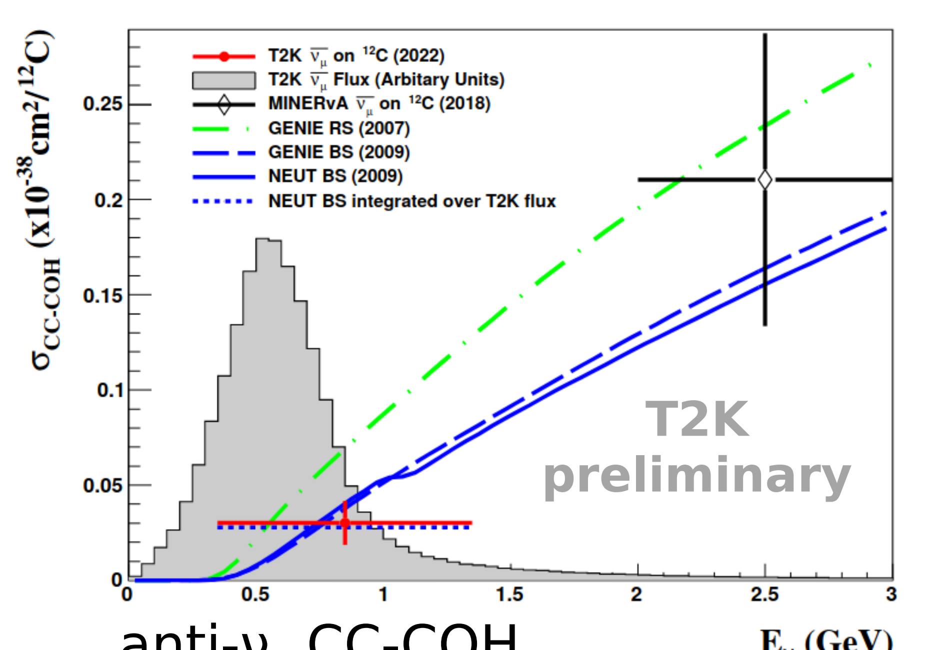
Firstly, the cross section for the entire FGD1 is calculated. Then the result is rescaled based on FGD1 composition and a scaling function F(A) to get cross section on carbon (for the plots below $F(A) = A^{1/3}$). **Preprint on arXiv:2308.16606**



ν_μ CC-COH

flux-averaged cross section on ^{12}C:

$(2.98 \pm 0.37(\mathrm{stat.}) \pm 0.31(\mathrm{syst.})\ ^{+0.49}_{-0.00}\,(Q^2\ \mathrm{model})) \times 10^{-40}\ \mathrm{cm}^2$



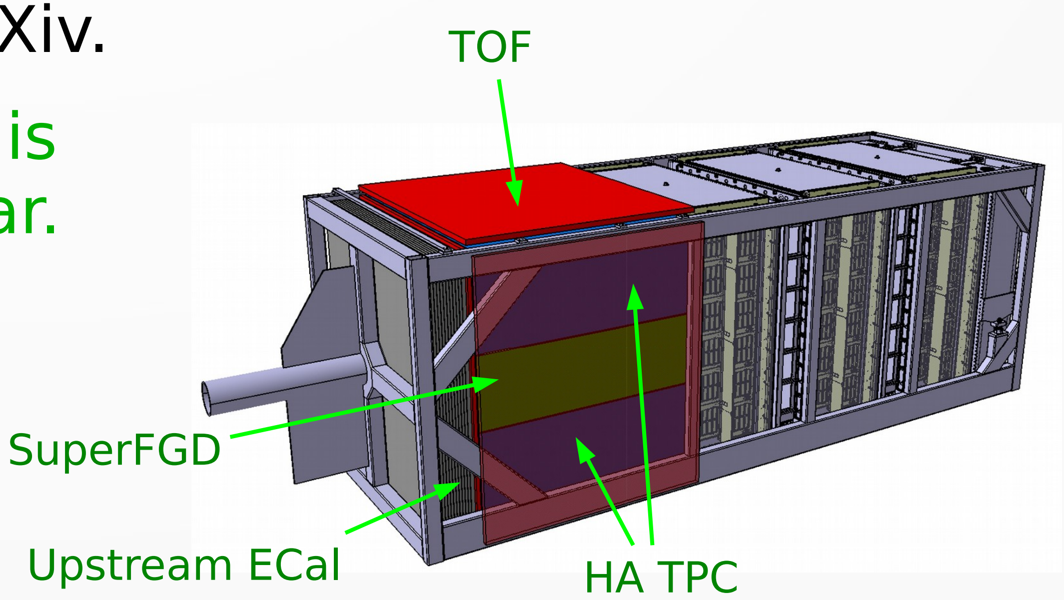
anti-ν_μ CC-COH

flux-averaged cross section on ^{12}C:

$(3.05 \pm 0.71(\mathrm{stat.}) \pm 0.39(\mathrm{syst.})\ ^{+0.74}_{-0.00}\,(Q^2\ \mathrm{model})) \times 10^{-40}\ \mathrm{cm}^2$

Summary and outlook

- T2K collaboration improved the various aspects of the oscillation analysis: new flux prediction, new ND and FD samples, corrections and new uncertainties in modeling the neutrino interactions.
- Current T2K data favors CP violation, while NOvA results are consistent with CP conservation. Both experiments favor normal mass hierarchy and the upper octant of θ_{23}.
- T2K has a broad program of cross section mesurements with new results uploaded this year on arXiv.
- Upgrade of the ND280 detector is expected to be finalised this year. More precise measurements for the oscillation analysis and cross sections!



Backup

Best fit values (Frequentist) with 68.3% credible intervals

$\sin^2\theta_{23}$

	Hierarchy	Most Probable Value	Range
T2K + reactor	Normal	0.555	$[0.492, 0.578]$
	Inverted	0.555	$[0.505, 0.579]$
	Both	0.554	$[0.495, 0.578]$

Δm^2_{32}

	Hierarchy	Most Probable Value	Range
T2K + reactor	Normal	$2.501 \times 10^{-3}\,\mathrm{eV}^2$	$[2.447, 2.554] \times 10^{-3}\,\mathrm{eV}^2$
	Inverted	$2.473 \times 10^{-3}\,\mathrm{eV}^2$	$[2.420, 2.525] \times 10^{-3}\,\mathrm{eV}^2$
	Both	$2.495 \times 10^{-3}\,\mathrm{eV}^2$	$[2.440, 2.548] \times 10^{-3}\,\mathrm{eV}^2$

$\sin^2\theta_{13}$

	Hierarchy	Most Probable Value	Range
T2K + reactor	Normal	22.5×10^{-3}	$[21.8, 23.2] \times 10^{-3}$
	Inverted	22.6×10^{-3}	$[21.9, 23.3] \times 10^{-3}$
	Both	22.8×10^{-3}	$[22.1, 23.5] \times 10^{-3}$

δ_{CP}

	Hierarchy	Most Probable Value	Range
T2K + reactor	Normal	-1.95	$[-2.60, -1.03]$
	Inverted	-1.43	$[-2.02, -0.87]$
	Both	-1.72	$[-2.45, -0.96]$

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Model comparison probabilities (Frequentist)

Table 33: Posterior probabilities for different hypotheses from T2K run 1–10 data and the results of the reactor experiments.

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Line total
Normal ordering	0.236	0.540	0.776
Inverted ordering	0.049	0.174	0.224
Column total	0.285	0.715	1.000

preliminary

T2K
technical note
430

Best Fit values (Bayesian)

	$\sin^2\theta_{23}$	$\Delta m^2_{32}(\times 10^{-3})\mathrm{eV}^2$
2D best fit	0.531	2.51
68% C.I. (1σ) range	0.489 – 0.560	-2.56 – -2.53 $\cup$ 2.42 – 2.58

Table 15: Best-fit values and 1D 68% credible interval ranges for the disappearance parameters from the T2K + reactor constraint data fit. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{23} - \Delta m^2_{32}$.

	$\sin^2\theta_{13}$	δ_{CP}
2D best fit	0.0221	-1.84
68% C.I. (1σ) range	0.0214 – 0.0227	-2.58 – -1.01

Table 16: Best-fit values and 1D 68% credible interval ranges for the appearance parameters from the T2K + reactor constraint data fit. The 2D best-fit values are taken from the mode of the 2D marginal posterior distributions in $\sin^2\theta_{13} - \delta_{CP}$.

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Model comparison probabilities (Bayesian)

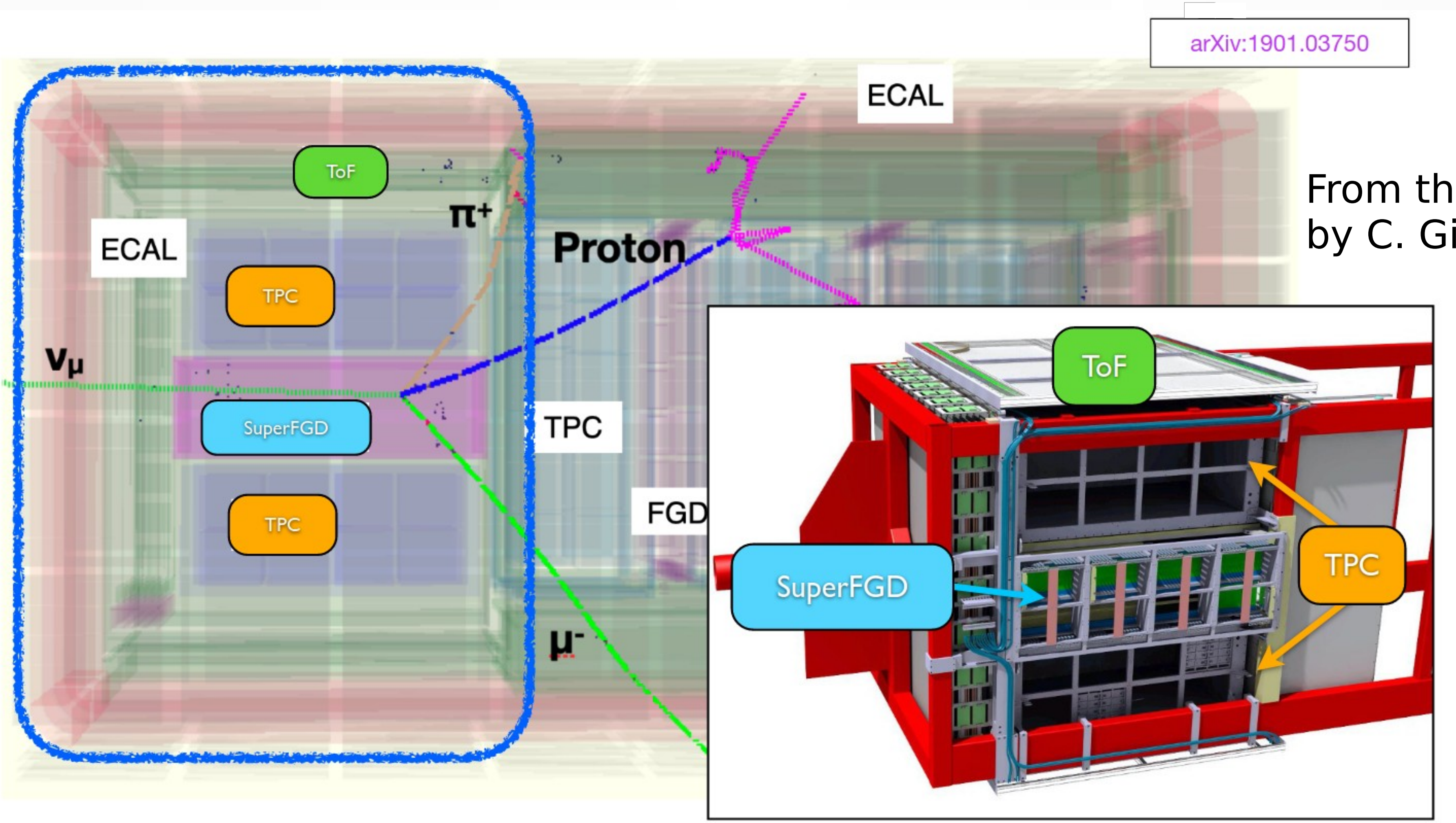
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.24	0.49	0.73
IH ($\Delta m^2_{32} < 0$)	0.07	0.20	0.27
Sum	0.31	0.69	1.00

Table 14: Model comparison probabilities for normal and inverted hierarchies, as well as upper and lower octants, extracted from a T2K + reactor constraint data fit.

preliminary

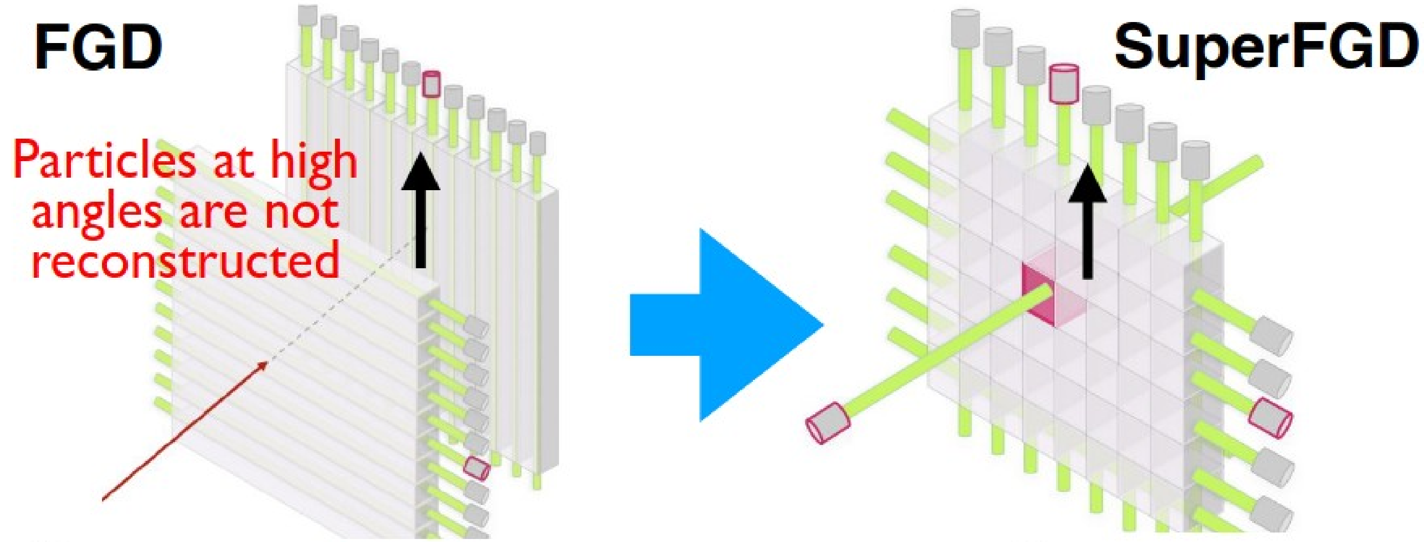
T2K technical note 429

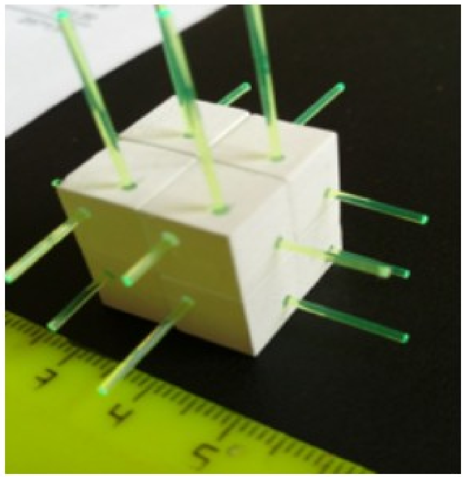
ND280 Upgrade

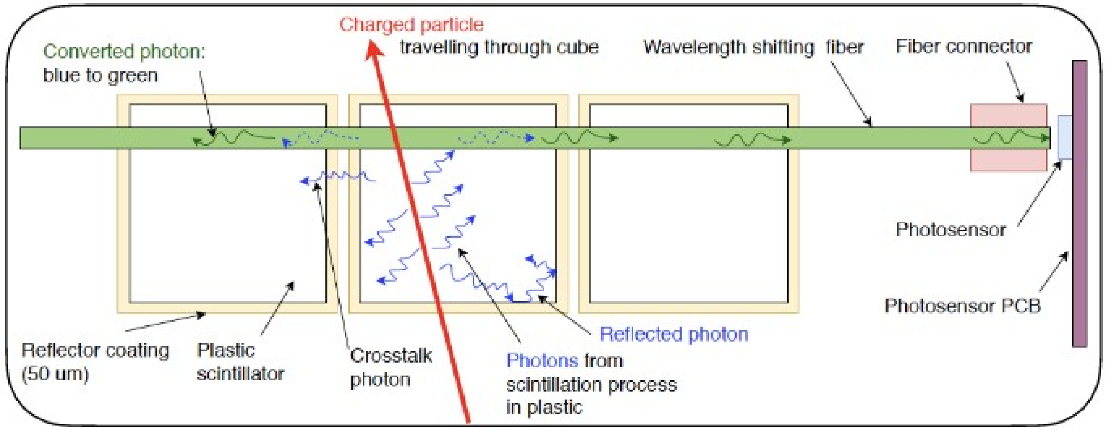


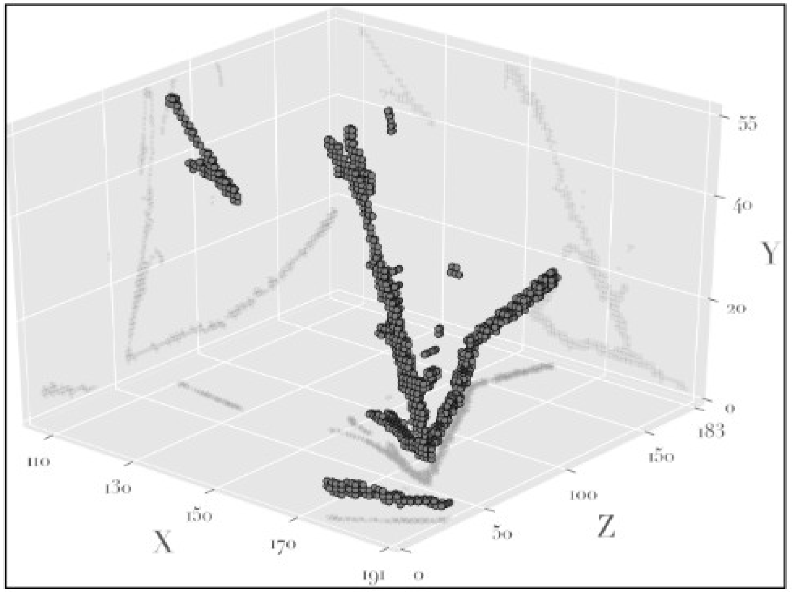
From the presentation by C. Giganti

Replace part of the P0D detector (measured NC π^0 production) with a new scintillator target (SuperFGD), two TPCs and a ToF detector









✓Three projections ⇒ isotropic

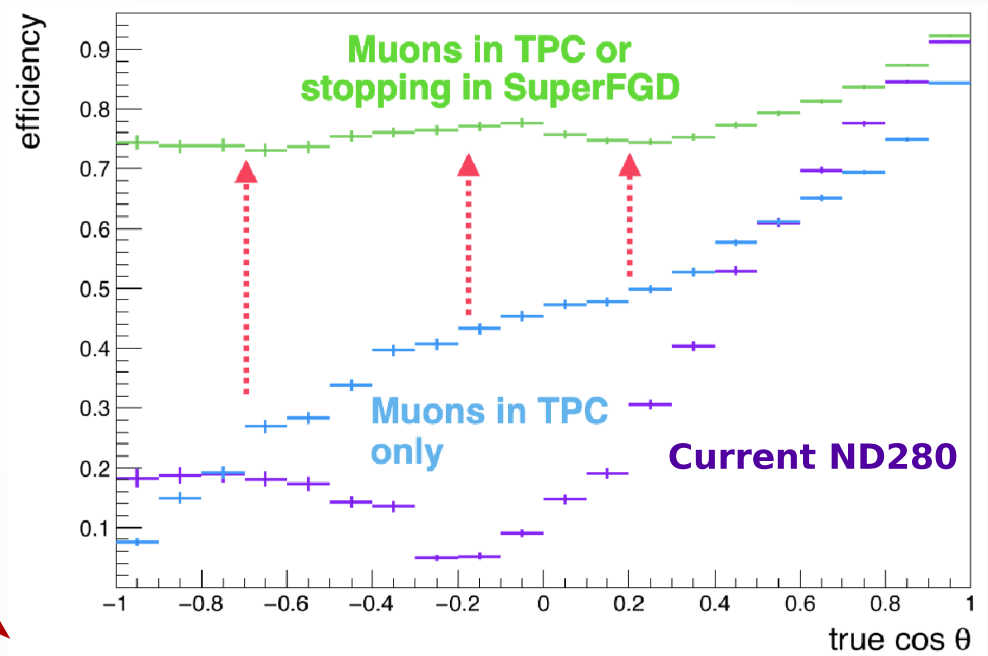
✓3D fine granularity ⇒ short tracks

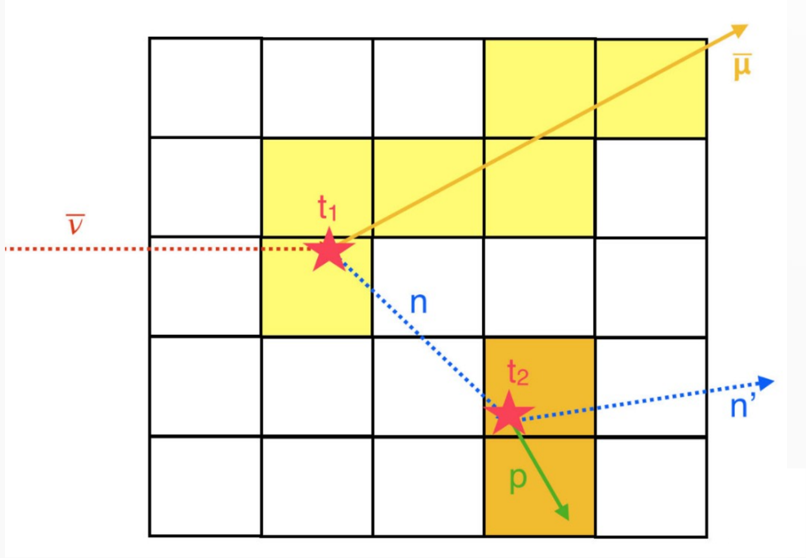
✓0.6 ns time resolution ⇒ neutron energy

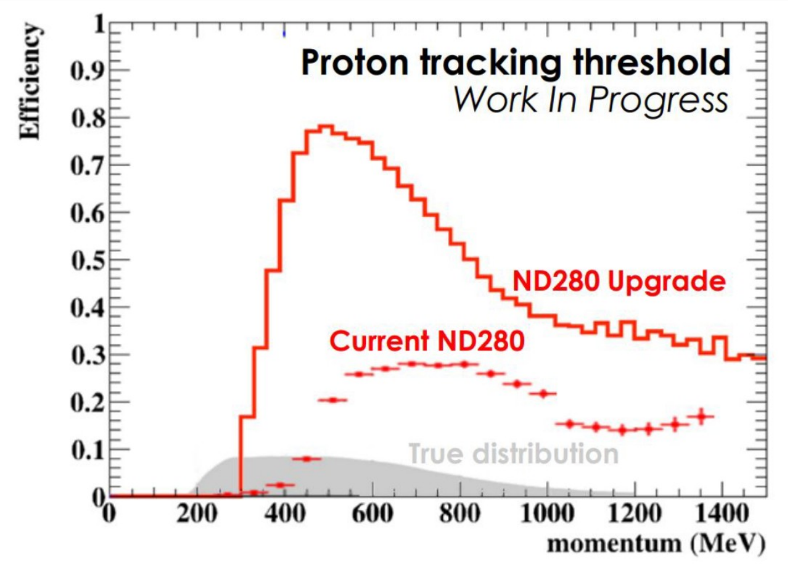
From the presentation
by C. Giganti

Upgraded ND280 performance

- Improved muon angular acceptance
- Lower threshold for proton tracking
- Neutron detection via proton recoil. Neutron energy estimation with time-of-flight.







Upgrade impact on the CPV search