Recent results from T2K

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on behalf of the T2K collaboration

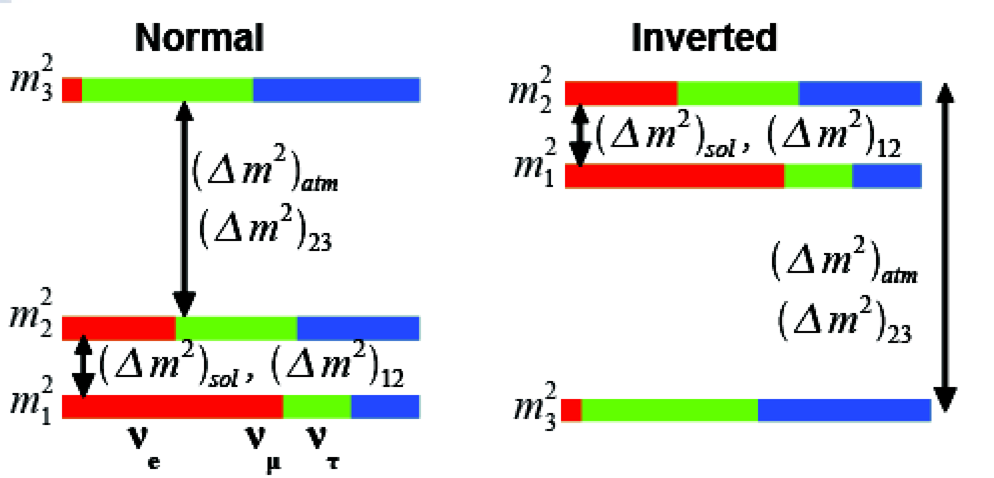
10th Symposium LTPC - Paris
December 16th, 2021

The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- The oscillation phenomena have been observed using solar, atmospheric, reactor and accelerator neutrinos, establishing the three neutrino SM paradigm with a high precision for the parameters (%)
- Next steps for oscillation exp. : mass ordering, CP violation, (θ_{23} octant)



Zito

Review by E. Lisi at this conference

Parameter	Value	Precision (%)
Δm^2_{21}	$7.4\ 10^{-5}$ eV^2	2.3
θ_{12}	34°	4.5
Δm^2_{32}	$2.5\ 10^{-3}$ eV^2	1.1
θ_{23}	42°	7
θ_{13}	9°	3

Capozzi et al.
ArXiv:2107.00532

Neutrino oscillation: $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$

$$P(\nu_\mu \to \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} - \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

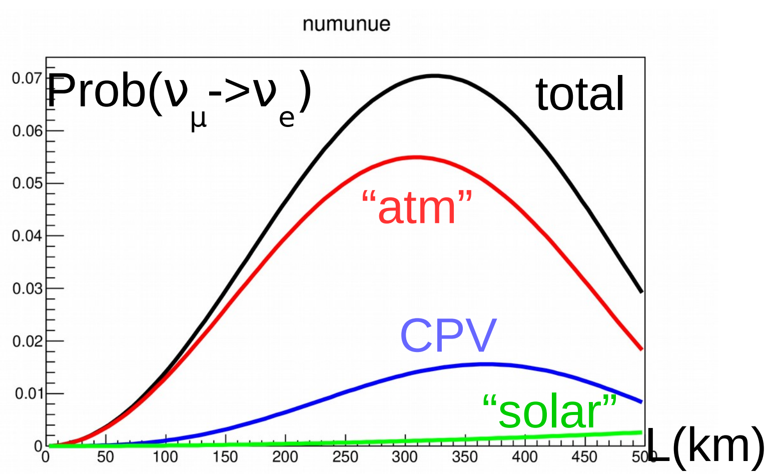
$$P(\nu_\mu \to \nu_e) \approx 4C^2_{13}S^2_{13}S^2_{23}\sin^2\Phi_{31}$$ "Atmospheric" term

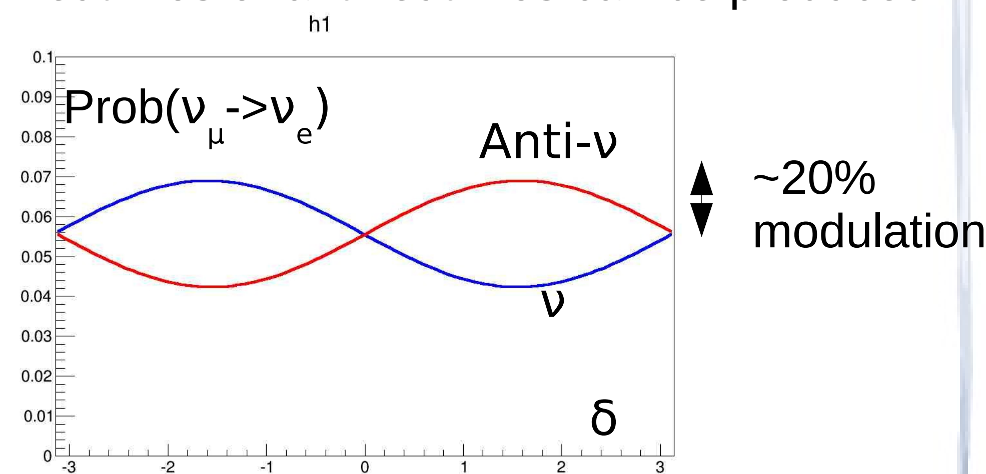
$$\mp 8C^2_{13}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CP violating term

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

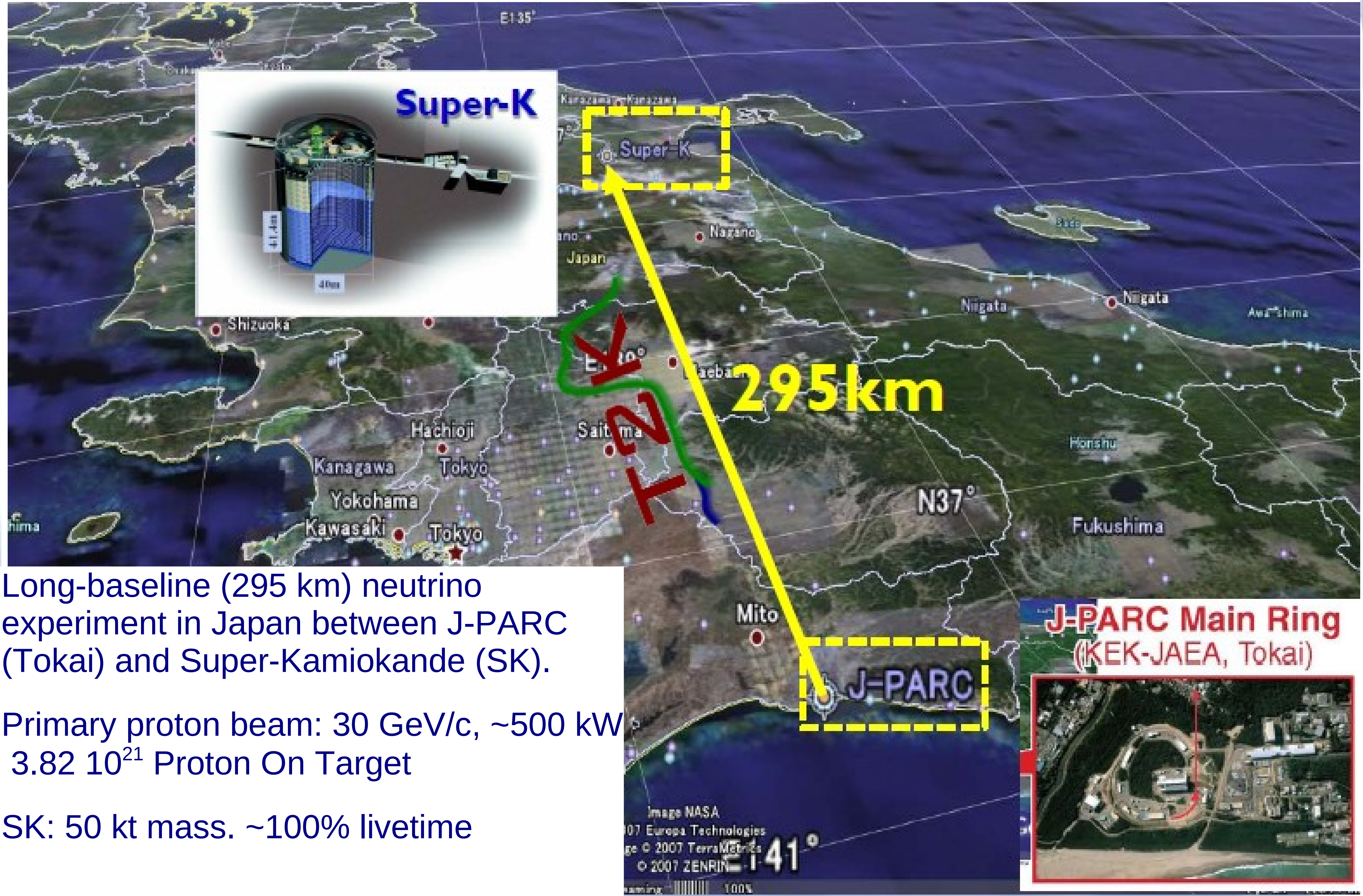




Indicative plots !!

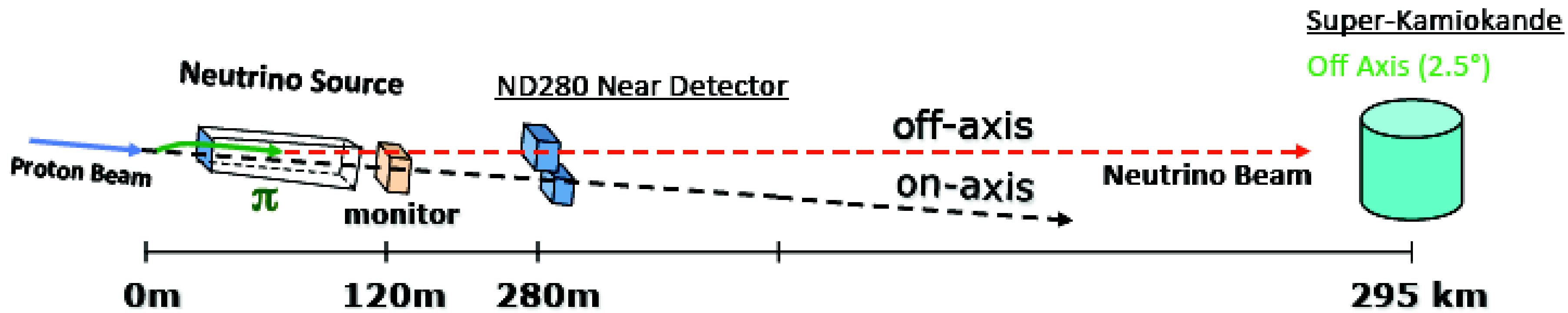
E=0.6 GeV

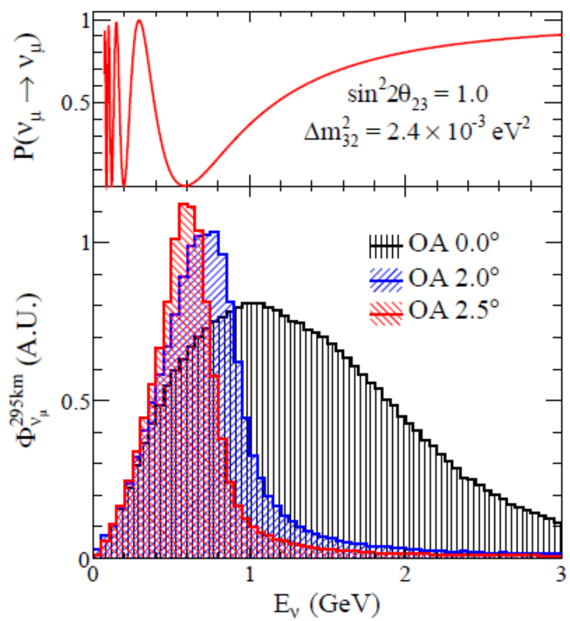
The Tokai to Kamioka (T2K) experiment



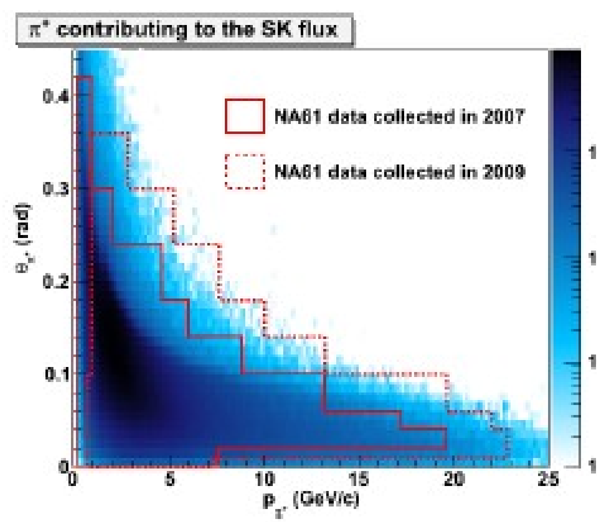
- Long-baseline (295 km) neutrino experiment in Japan between J-PARC (Tokai) and Super-Kamiokande (SK).
- Primary proton beam: 30 GeV/c, ~500 kW
  3.82 10^{21} Proton On Target
- SK: 50 kt mass. ~100% livetime

T2K: Main Experimental Features

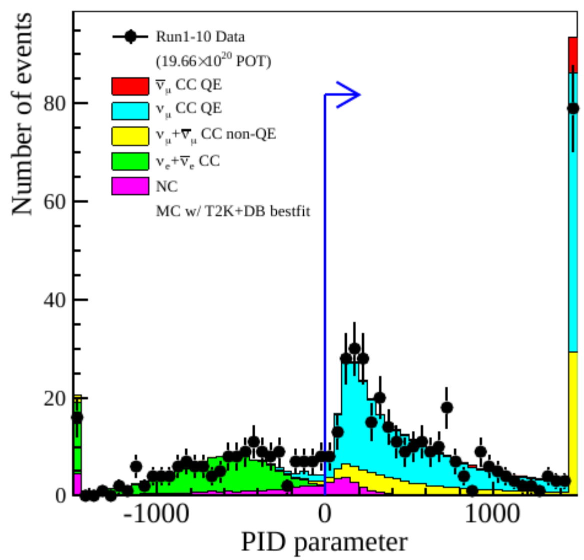




Off-axis beam.
Flux has a narrow peak tuned for the first oscillation maximum

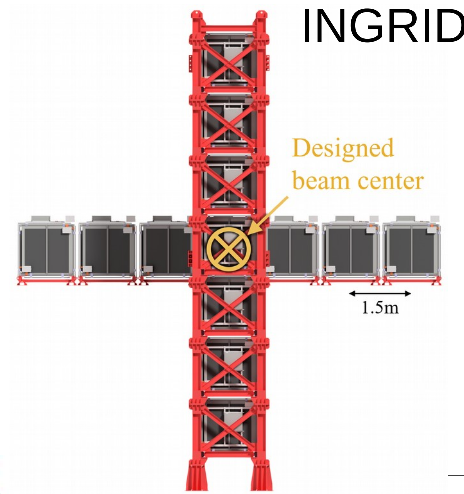


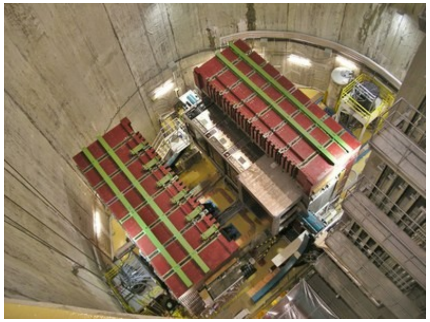
Pion and kaon production measured by the NA61/SHINE exp. at CERN

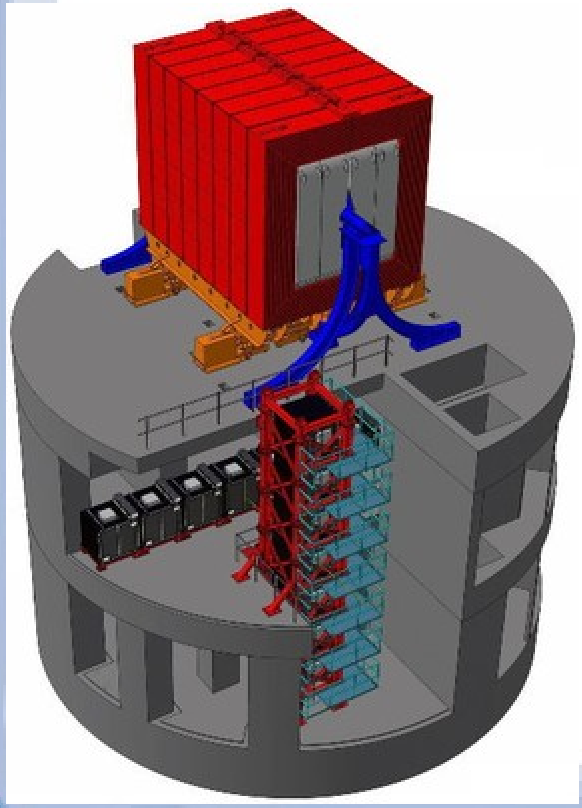


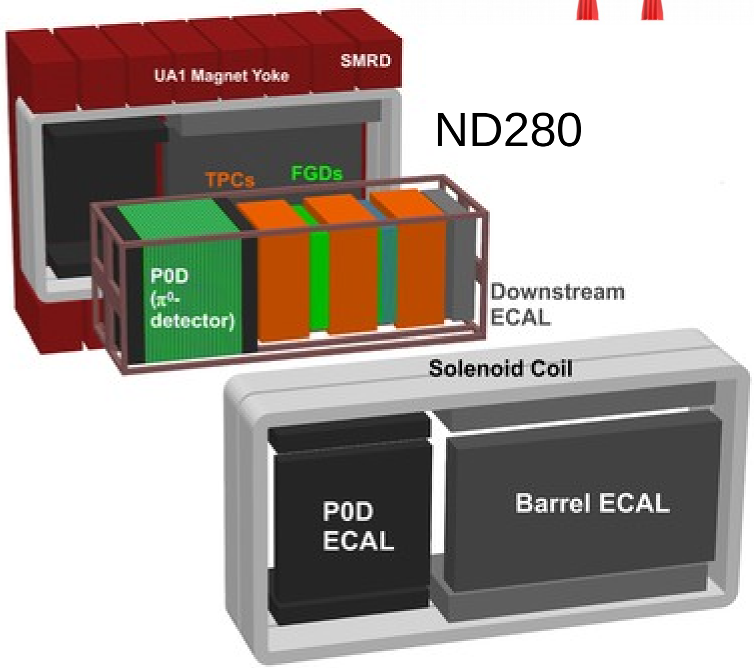
Excellent particle identification capabilities in SK (misid <1%)

The T2K Near Detector suite



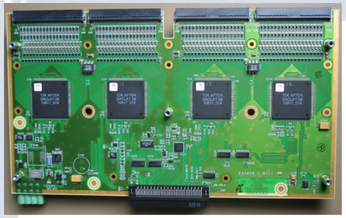




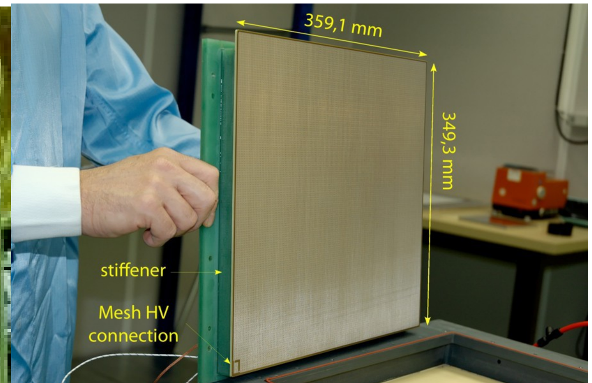


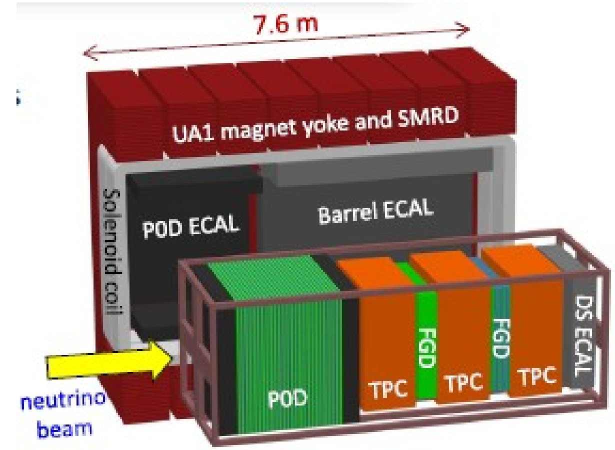
- A complete near detector suite in a pit at 280 m from the proton target.
- An on-axis detector (INGRID) for the beam direction and stability.
- ND280 is a magnetised near detector (using the UA1 magnet)
- New detectors added ! WAGASCI, BabyMind, Ninja...

NIM A 637 2011 25

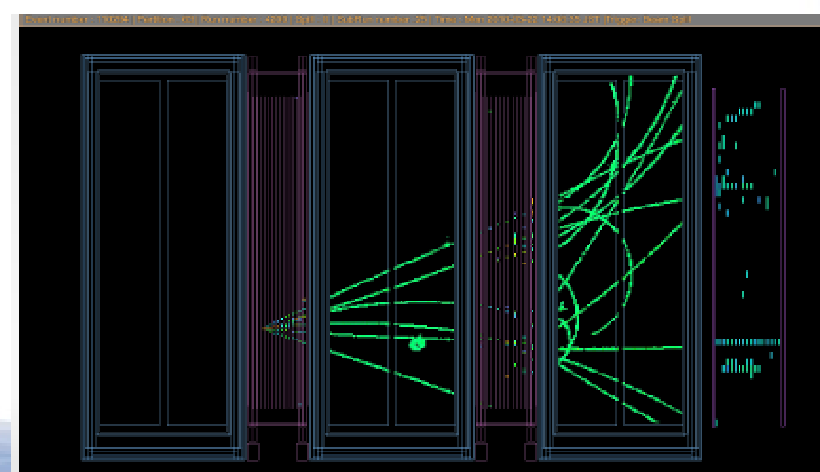


The T2K near detector TPC





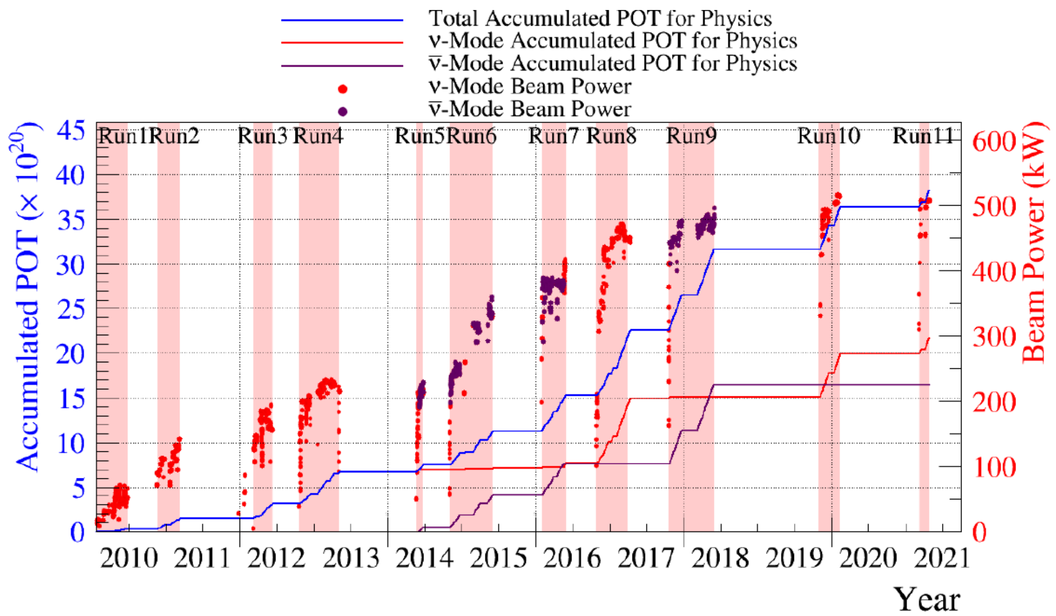
- Three large TPC for the T2K near detector
- The first large TPC using MPGD
- ~9 m**2 equipped with bulk Micromegas detectors
- Playing a key role in the study of the neutrino flux and interactions (charge, momentum and dE/dx PID)
- Space resolution : 0.6 mm
- Momentum res. 9% at 1 GeV
- dE/dx: 7.8 % (MIP)



72 Micromegas and 120k channels functioning flawlessly since 2009 (dead channels 144/124272)

T2K Data analysis flow

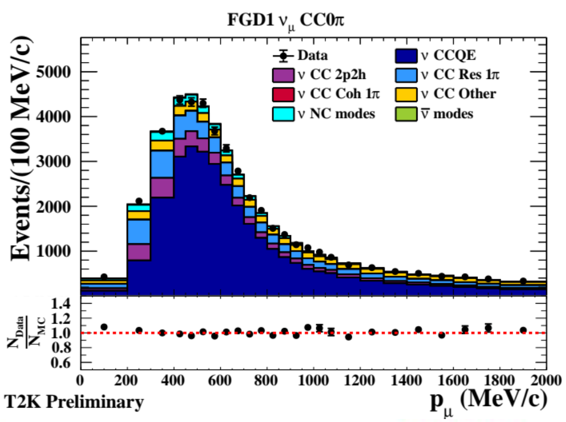
- Define the good stable runs (neutrino intensity, direction, data quality at ND280, SK, …)
- Select neutrino interaction events in ND280 (muon no pions, muon and pions, multi pions) to constrain the neutrino cross-section x flux
- Select neutrino interaction events in SK : single ring muon like, single ring e-like, e-like and one decay-electron ring

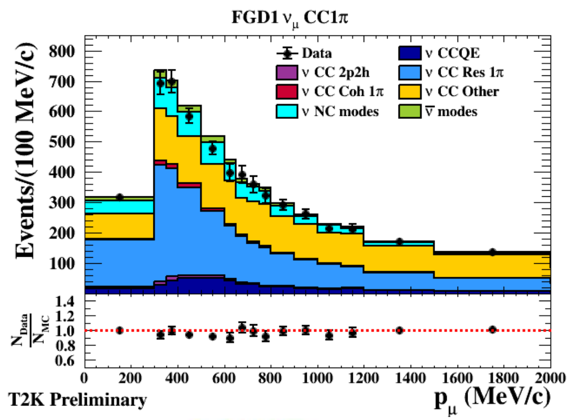


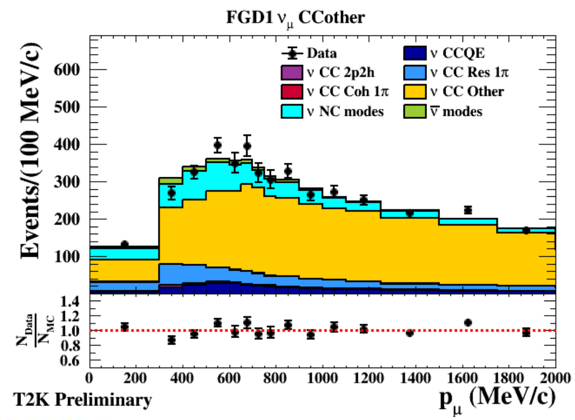
23 Jan 2010 – 27 Apr 2021
POT Total: 3.82×10^{21}
(maximum power 522.6 kW)

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

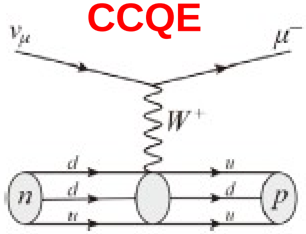
T2K Near detector constraint



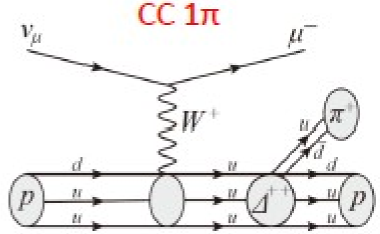




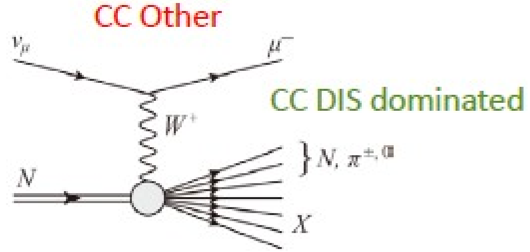
CCQE



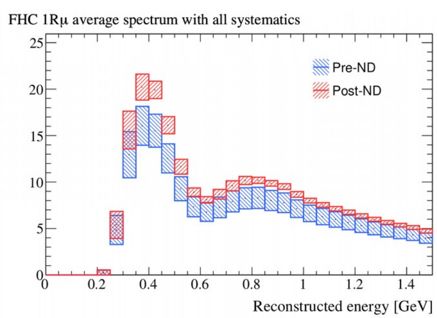
CC 1π

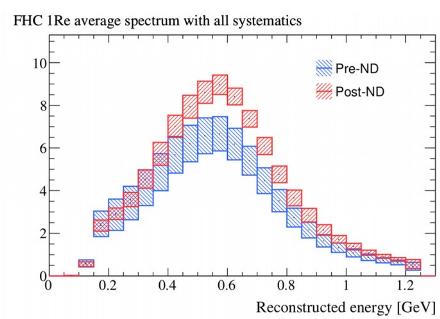


CC Other



Flux and cross-section systematic uncertainty on N_{SK} significantly reduced

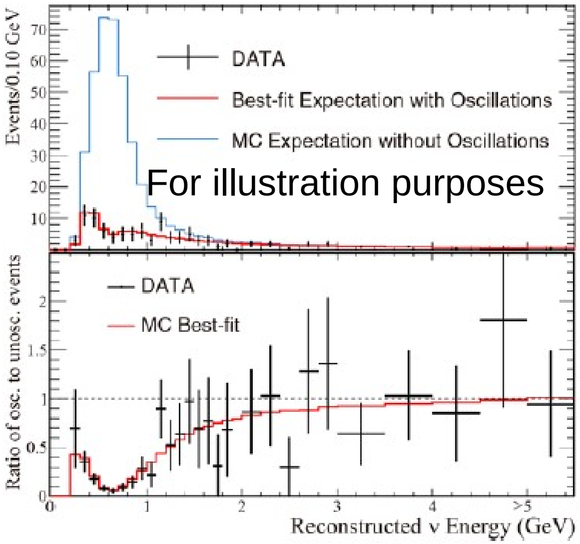


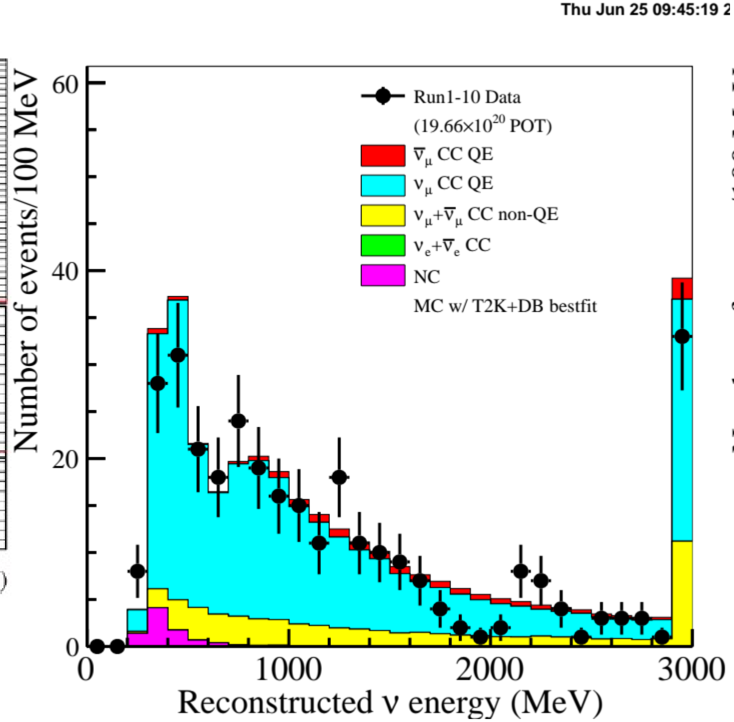


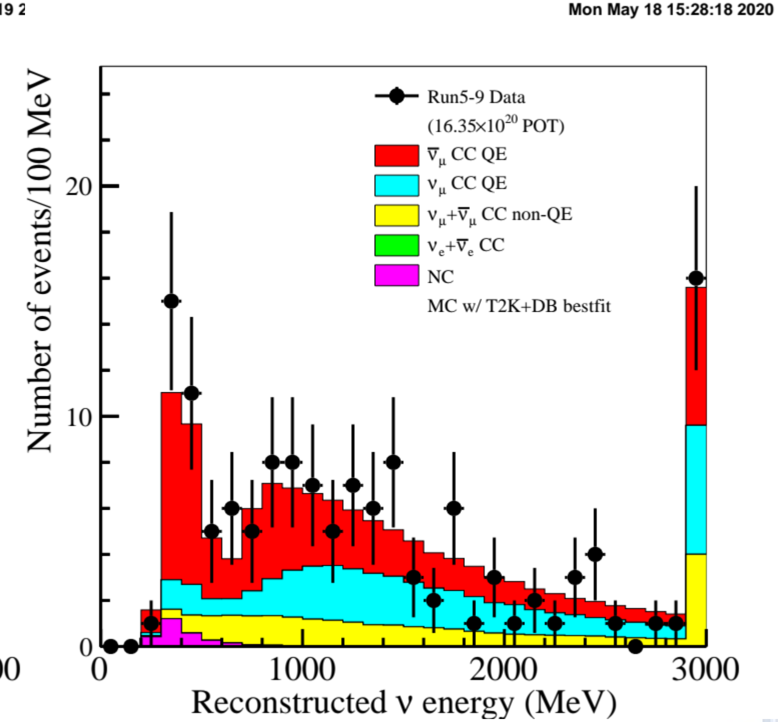
Systematic uncertainties					
Beam mode	Neutrino			Antineutrino	
SK sample	1 Ring μ-like	1 Ring e-like	1 Ring e-like 1de	1 Ring μ-like	1 Ring e-like
Before ND280 fit	11.1%	13.0%	18.7%	11.3%	12.1%
After ND280 fit	3.0%	4.7%	14.3%	4.0%	5.9%

$\nu_\mu \rightarrow \nu_\mu$

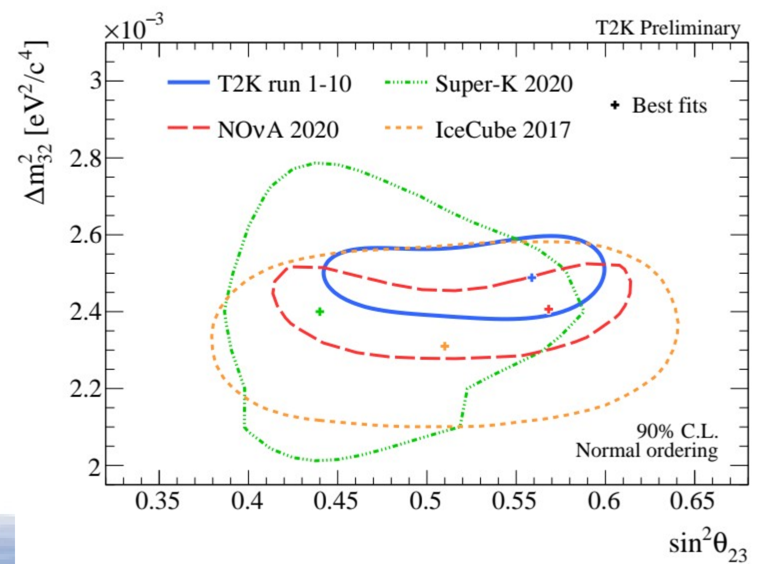
T2K ν_μ disappearance measurement







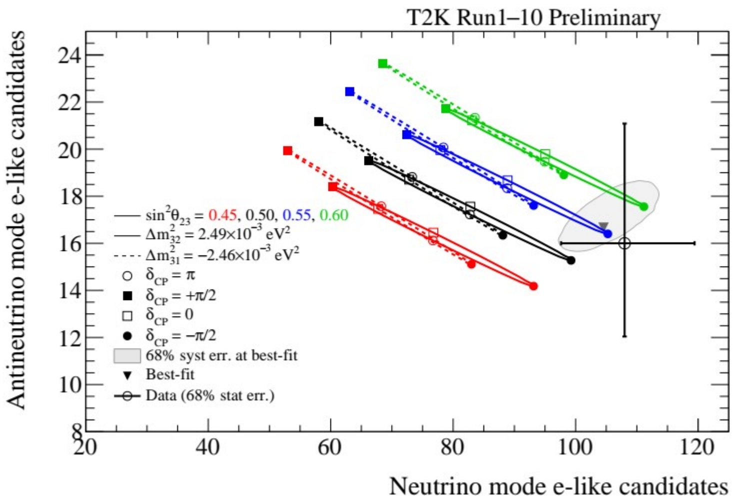
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	Data
FHC 1Rμ	356.48	355.76	356.44	357.27	318
RHC 1Rμ	138.34	137.98	138.34	138.73	137
FHC 1Re	97.62	82.44	67.56	82.74	94
RHC 1Re	16.69	18.96	20.90	18.63	16
FHC 1R ν_e CC1π^+	9.20	8.01	6.51	7.71	14
FHC 1Rμ ($E_{rec} < 1.2\,$GeV)	213.40	213.06	213.36	213.81	191
RHC 1Rμ ($E_{rec} < 1.2\,$GeV)	68.53	68.34	68.53	68.74	71

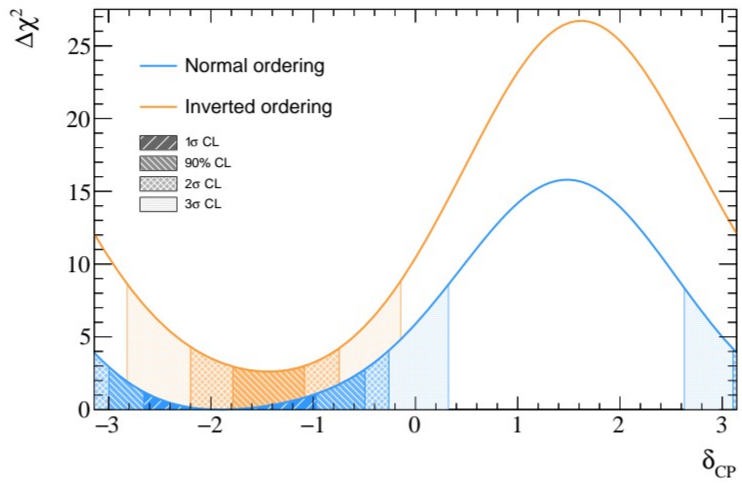


)

$\nu_\mu \rightarrow \nu_e$

T2K constraints on δ_{CP}





- Comparing the e-like events in T2K (θ_{13} measured at reactor experiments) provides constraints on δ_{CP}

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Data
FHC 1Rμ	356.48	355.76	356.44	357.27	318
RHC 1Rμ	138.34	137.98	138.34	138.73	137
FHC 1Re	97.62	82.44	67.56	82.74	94
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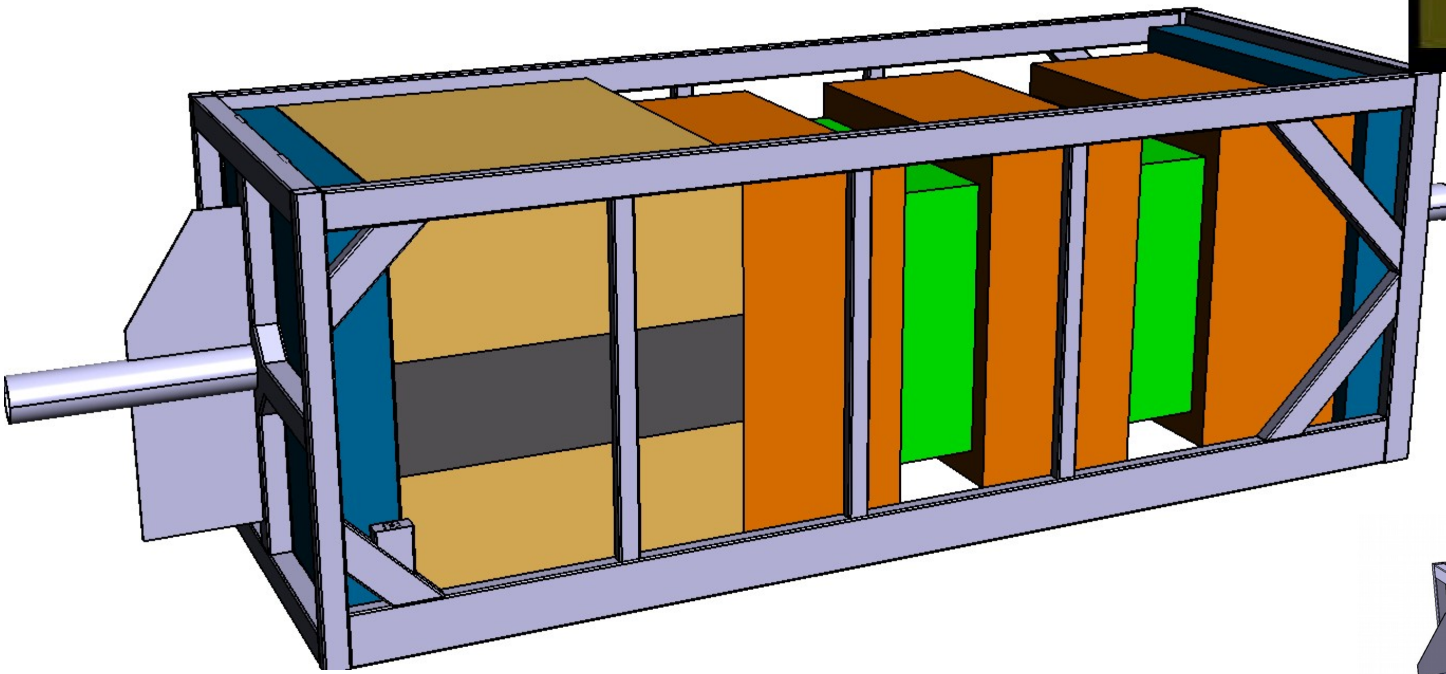
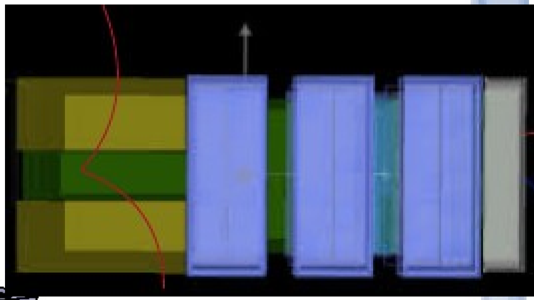
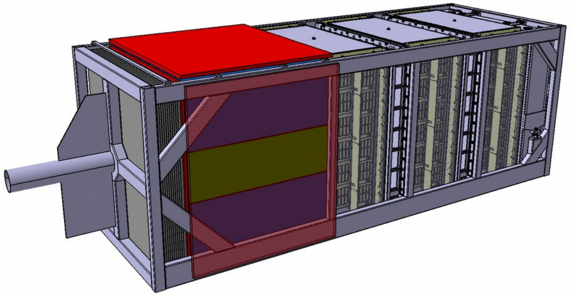
Nature 580, 339–344 (2020)

The upgrade of the ND280 detector

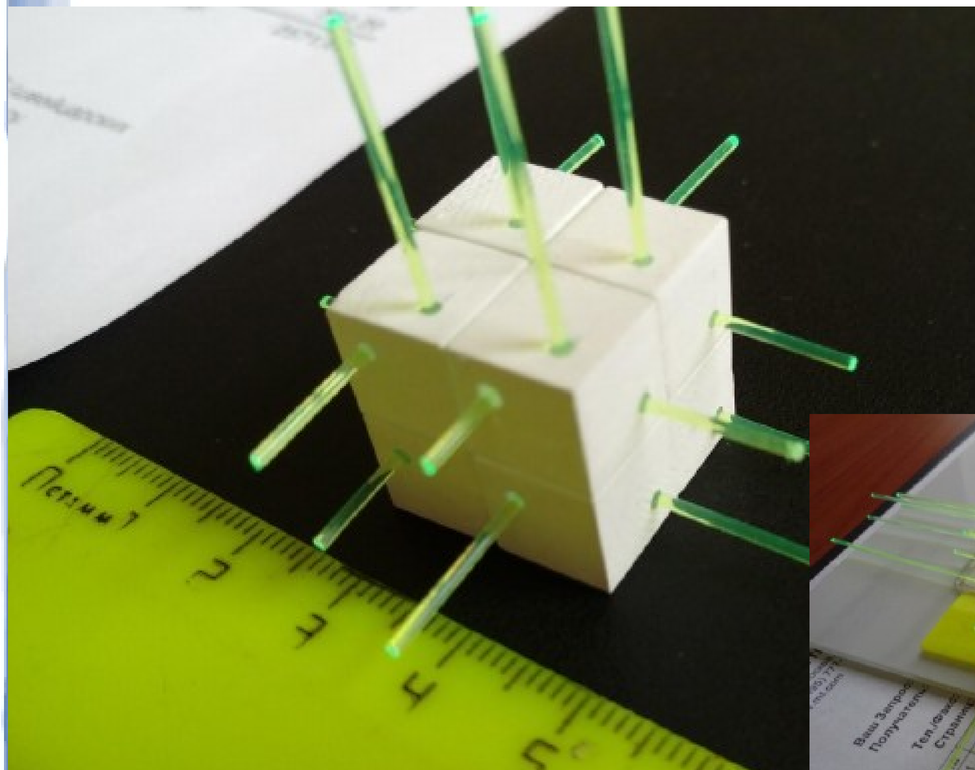
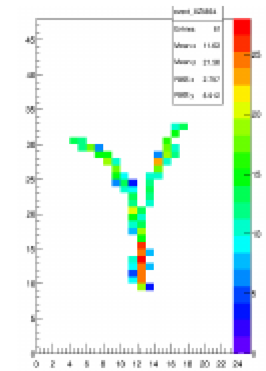


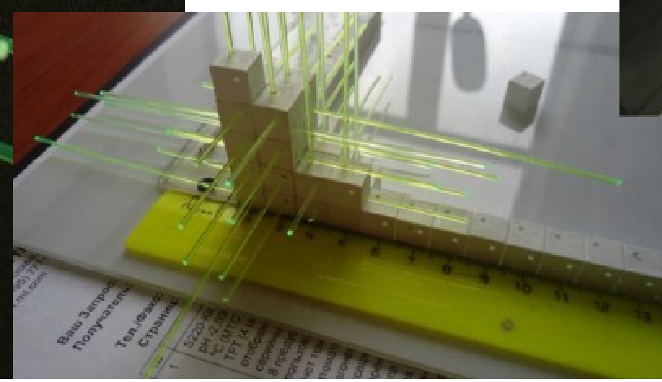
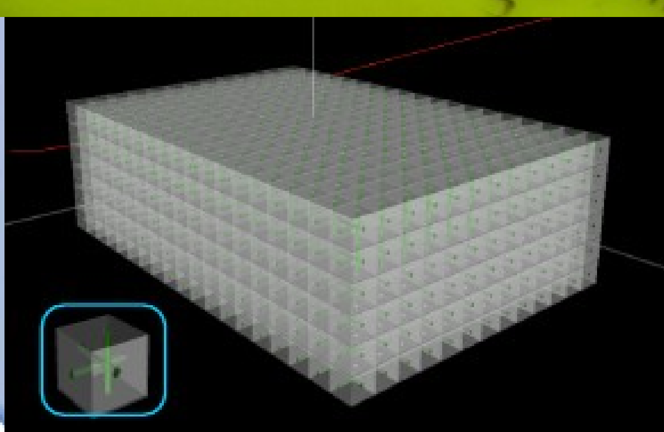




Two new High-Angle TPCs
A highly segmented Scintillator Detector (SuperFGD)
TOF planes all around
No changes to the other detectors
Will be installed in JPARC in 2022

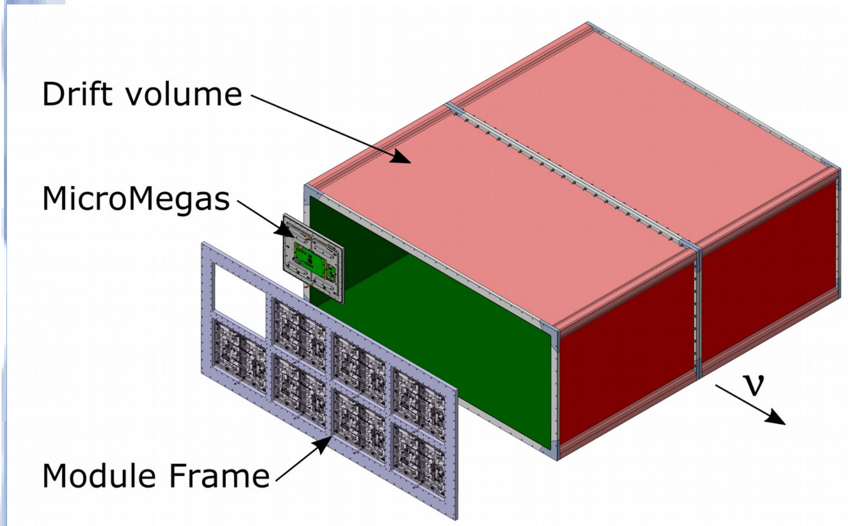
Super-Fine Grained Detector

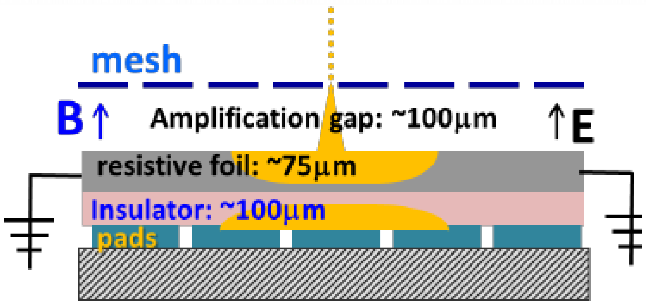



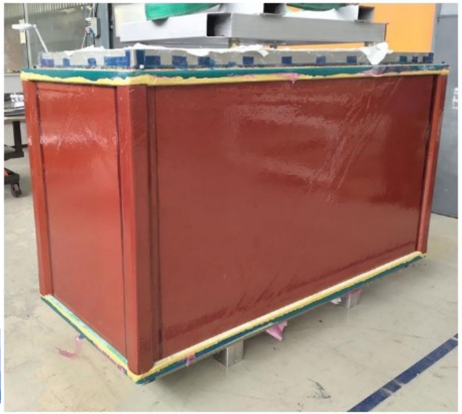
1x1x1 cm^3 plastic scintillator cubes with 3 fibers readout along x, y, z
Detailed (3 2-D projections) and highly segmented view of the interaction
Successful tests of prototypes
Good light yield (50 pe per channel), tracking, PID, timing (1ns)
Scintillator cubes are fully produced
A new fully active detector (~2t) for neutrino interaction

ND280 Upgrade :High Angle-TPCs





- Atmospheric pressure TPC using Ar-CF_4-C_4H_{10} (95-3-2)
- Resistive Micromegas (ERAM*)
- Benefiting from ILC TPC developments and RD51
- Resistive Micromegas production at CERN ongoing
- Succesful beam test with prototypes
- First field cage to arrive at CERN by January

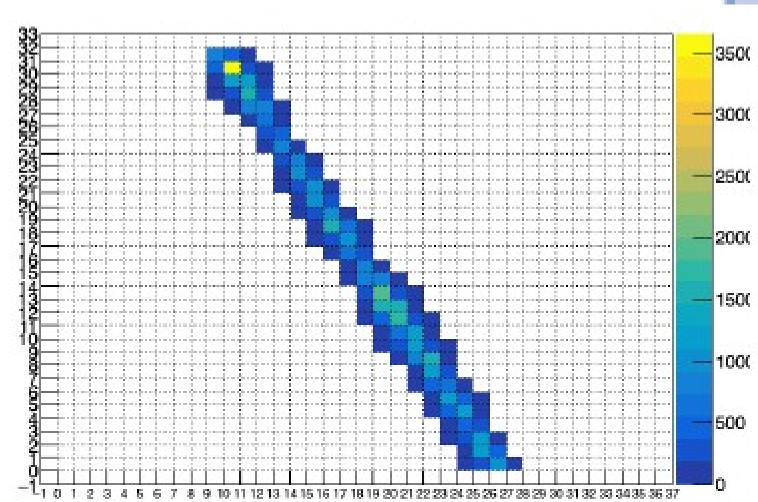


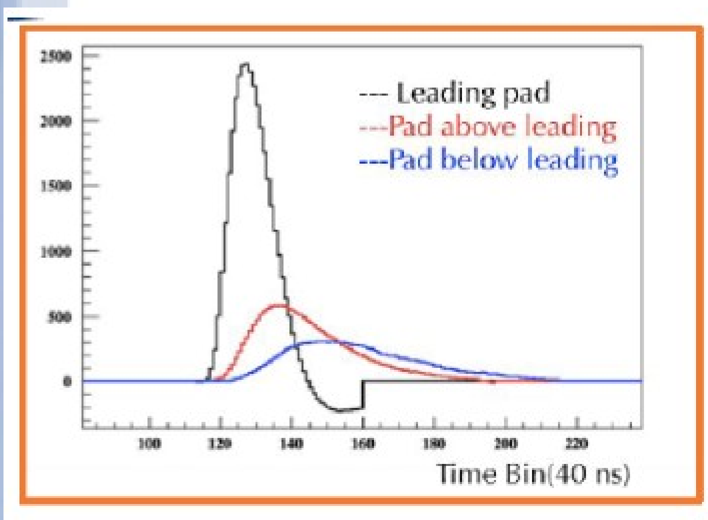
*ERAM : Encapsulated Resistive Anode Micromegas

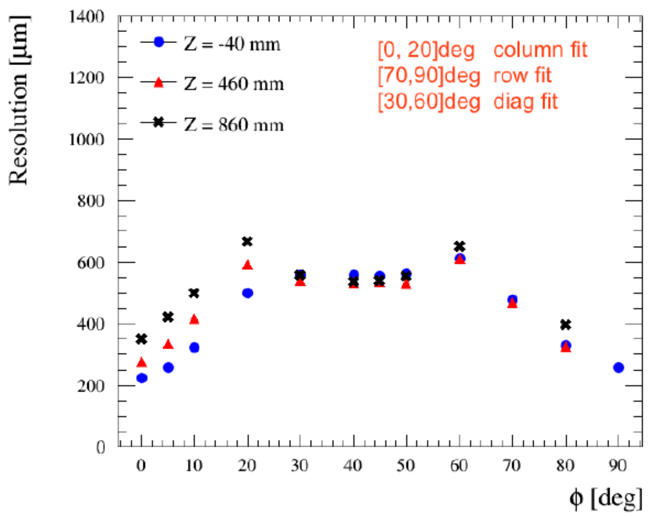
Results from TPC test beams

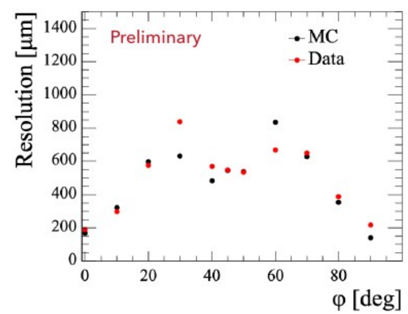
Thanks to CERN and DESY for excellent beams and test facilities !

- The resistive layer works very well as expected
- New methods developed to reconstruct the track position for inclined tracks
- 160 µm resolution at 0 drift (for a 1cm² pad)
- Better than 700 µm at all angles
- MC simulation fully developed with good match to data
- Still improving the track fitting method !







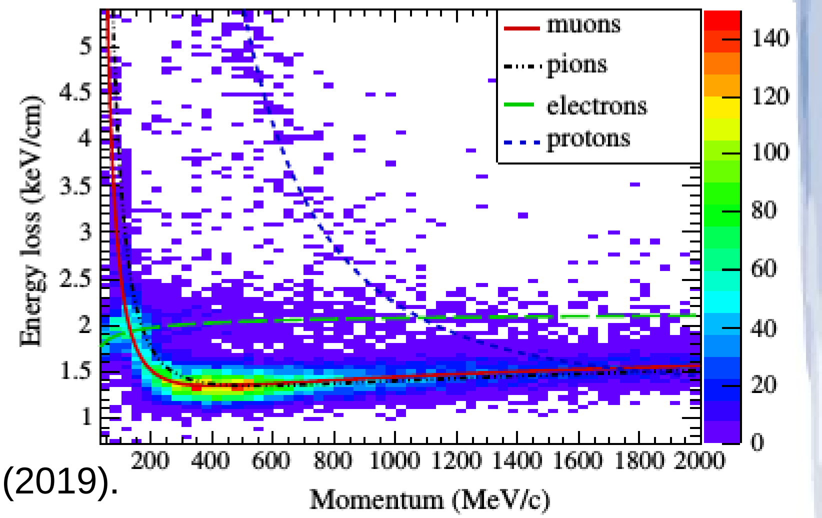


TPC in neutrino near detectors

- CP violation search : need to control neutrinos vs antineutrinos → magnetic field (DUNE and HK will have magnetized near detectors, HPTPC in DUNE ND talk)
- TPC very well adapted to tracking ~100 MeV/c momentum tracks
- dE/dx to separate e from μ/pions enables ν_e analysis (crucial for $\nu_\mu \rightarrow \nu_e$ appearance)
- *Pad partout* TPC have excellent pattern capabilities : separation of electrons from gamma conversion
- Possibility to search for decay vertex in very low density medium (exotic neutrino decays)

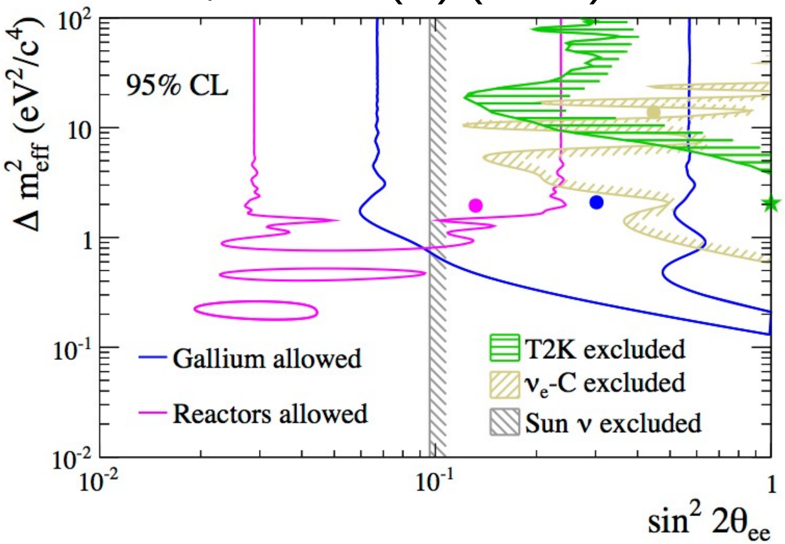
Physics with the T2K ND280 TPC

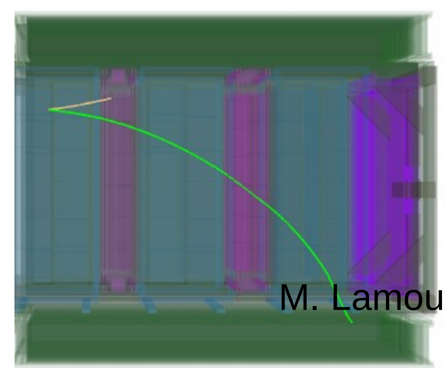
- Neutrino interactions in the near detector : flux and cross-section constraint
- ν_e flux and cross-sections
- Search for short baseline nu osc.
- Search for Heavy Neutral Leptons



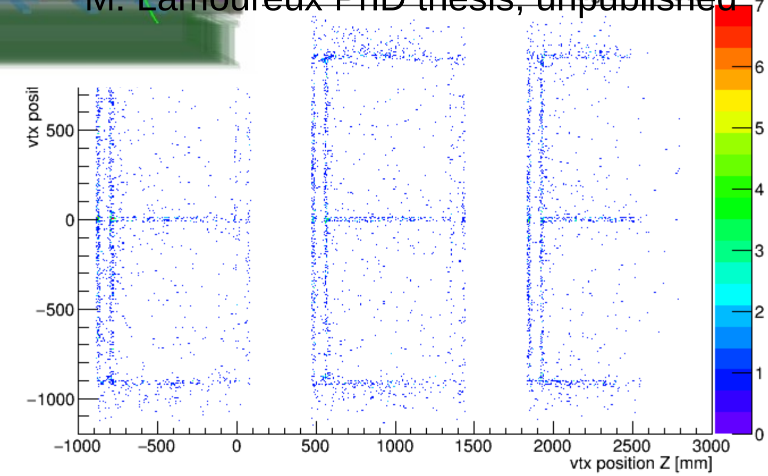
Phys. Rev. D100, 052006 (2019).

PRD 91, 051102(R) (2015)





M. Lamoureux PhD thesis, unpublished



Conclusions

- The study of neutrino oscillations has provided many surprising discoveries in the last 15 years, establishing the three neutrino mixing paradigm, implying physics beyond the SM
- The field is approaching the few % precision era due to dedicated experimental efforts. This requires a matching precision in the control of the beam flux, composition and neutrino cross-sections
- The experiments start to be sensitive to CP violation. T2K will provide improved precision in the next 5 years,
- The TPCs of the Near Detector had a major role in the T2K analysis (both for long baseline oscillation and other studies). More TPCs in the ND280 Upgrade to come soon !
- HyperKamiokande and DUNE (now both in construction) will be able to observe CP violation

Backup

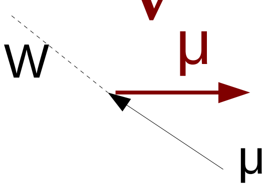
Neutrino oscillations

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

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

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

Source



Propagation

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

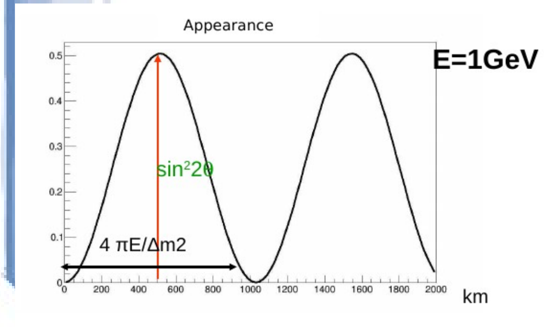
$\nu_2 \rightarrow \exp(-ip_2x)\, \nu_2$

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

ν_e e

Detector

L



E=1GeV

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

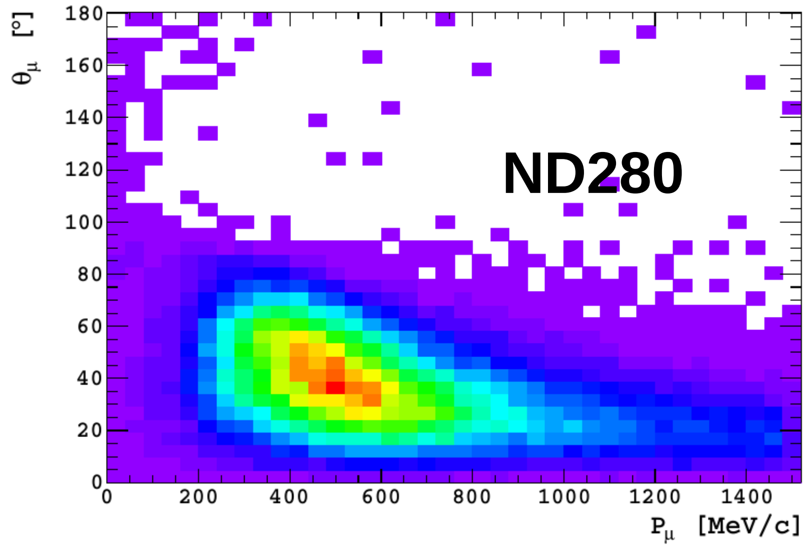
This is a simplified two neutrino scenario

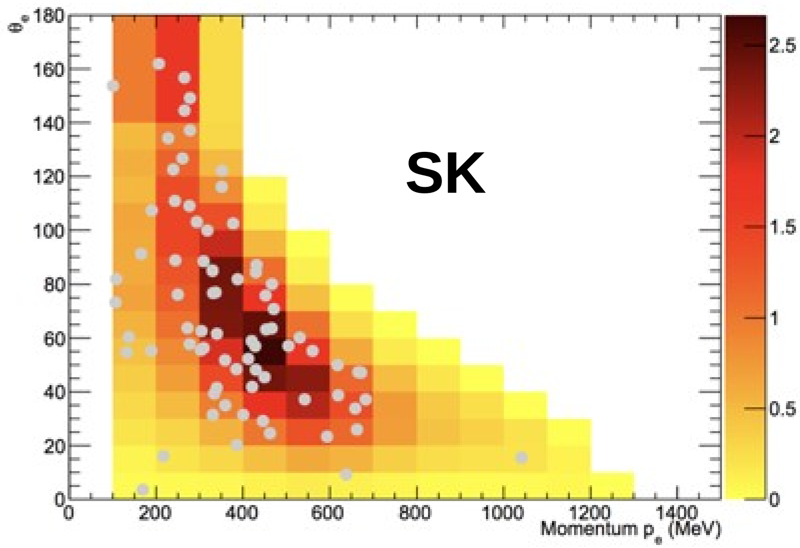
T2K systematic uncertainties

Systematic Source	Relative Uncertainty in # of ν_e Candidates (%)	Relative Uncertainty in # of ν_μ Candidates (%)
Flux + cross section (ND280 constrained)	3.1	2.7
Cross section (ND280-independent)	4.7	5.0
π Hadronic Interactions	2.3	3.5
SK Detector	2.9	3.6
Total	**6.8**	**7.6**

A limitation of the present ND280

- ND280 provides mainly acceptance for tracks in the forward direction, while SuperKamiokande has 4π acceptance
- The near to far prediction relies on a cross-section model
- The neutrino nucleus interaction is not well known, introducing model dependence





T2K, SK and NOvA