Is there CP violation in the neutrino sector?

Agnieszka Zalewska

„Białasówka" seminar

22.05.2020

K.Abe et al. (T2K Collaboration)
Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations

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

Outline

The basics of neutrino oscillations

T2K experiment: apparatus and analysis methods

T2K measurements of the oscillation parameters θ_{23}, $|\Delta m^2_{23}|$ and constraits on δ_{CP}

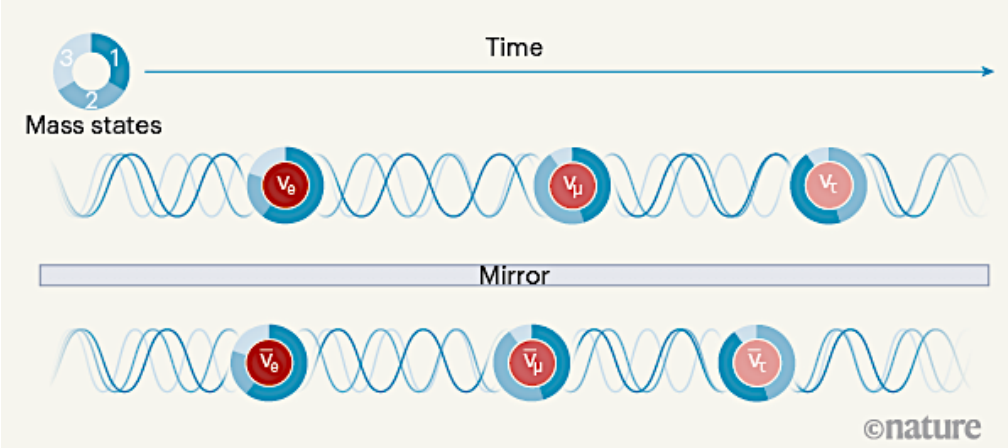
Future measurements of δ_{CP}

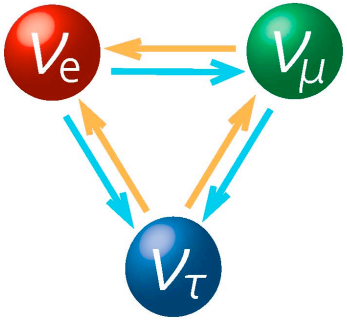
The basics of neutrino oscillations

Neutrino oscillations

Neutrino flavour states are not identical with neutrino mass states, but are their linear combinatons.

Neutrinos are born and interact with matter through the weak interactions (flavour states ν_e, ν_μ. ν_τ), but propagate in space as mass states (ν_1, ν_2, ν_3) at different speeds (mass) keeping the coherence.





1957 – B.Pontecorvo postulates neutrino and antineutrino oscillations

1962 – Maki, Nakagawa, Sakata postulate oscillations of muon and electron neutinos

Now – formalism with 3 flavour states and 3 mass states is commonly applied (PMNS mixing matrix)

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

Oscillations for three neutrino flavours

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

$\theta_{23} = (45\pm3)°$
$|\Delta m^2_{32}| = (2.52\pm0.04)\text{x}10^{-3}\ \text{eV}^2$

$\theta_{13} = (8.5\pm0.15)°$
$|\Delta m^2_{31}| = (2.52\pm0.04)\text{x}10^{-3}\ \text{eV}^2$

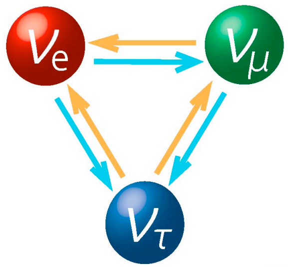
$\theta_{12} = (33.6\pm0.8)°$
$\Delta m^2_{21} = (7.50\pm0.18)\text{x}10^{-5}\ \text{eV}^2$

$$\Delta m^2_{ji} = m^2_j - m^2_i \quad c_{ij} = \cos\theta_{ij} \quad s_{ij} = \sin\theta_{ij}$$

$$P(\nu_\alpha \to \nu_\beta) = P(E, L, \Delta m^2_{ji}, \theta_{ij})$$

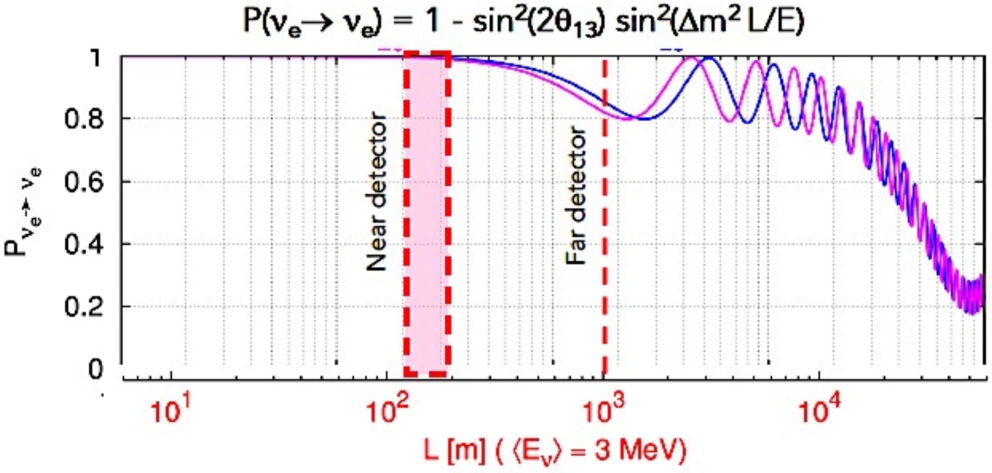
Neutrino oscillations in vacuum are described by 6 theoretical parameters: three mixing angles, two Δm^2 and δ_{CP} phase. For the propagation through matter, eg. from the Sun interior to its face, in addition the so called matter effects have to be taken into account (MSW model with LMA solution). Lenght of the baseline L and neutrino energy E are chosen experimentally to optimise the detrmination of the oscillation parameters.

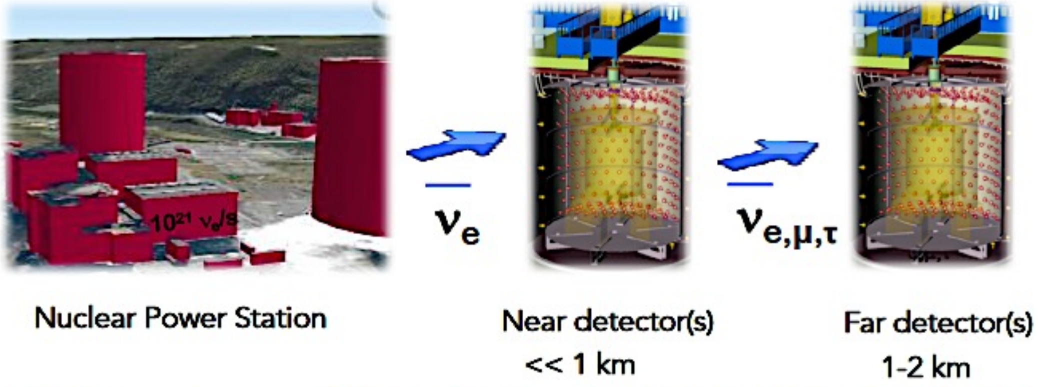
Oscillation parameters in PDG 2018



	Parameter	best-fit	3σ
~4%	Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
~3%	$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~11%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
~15%	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
~7%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
~31%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

Determination of θ_{13}
– the best measurement in the Daya Bay reactor experiment





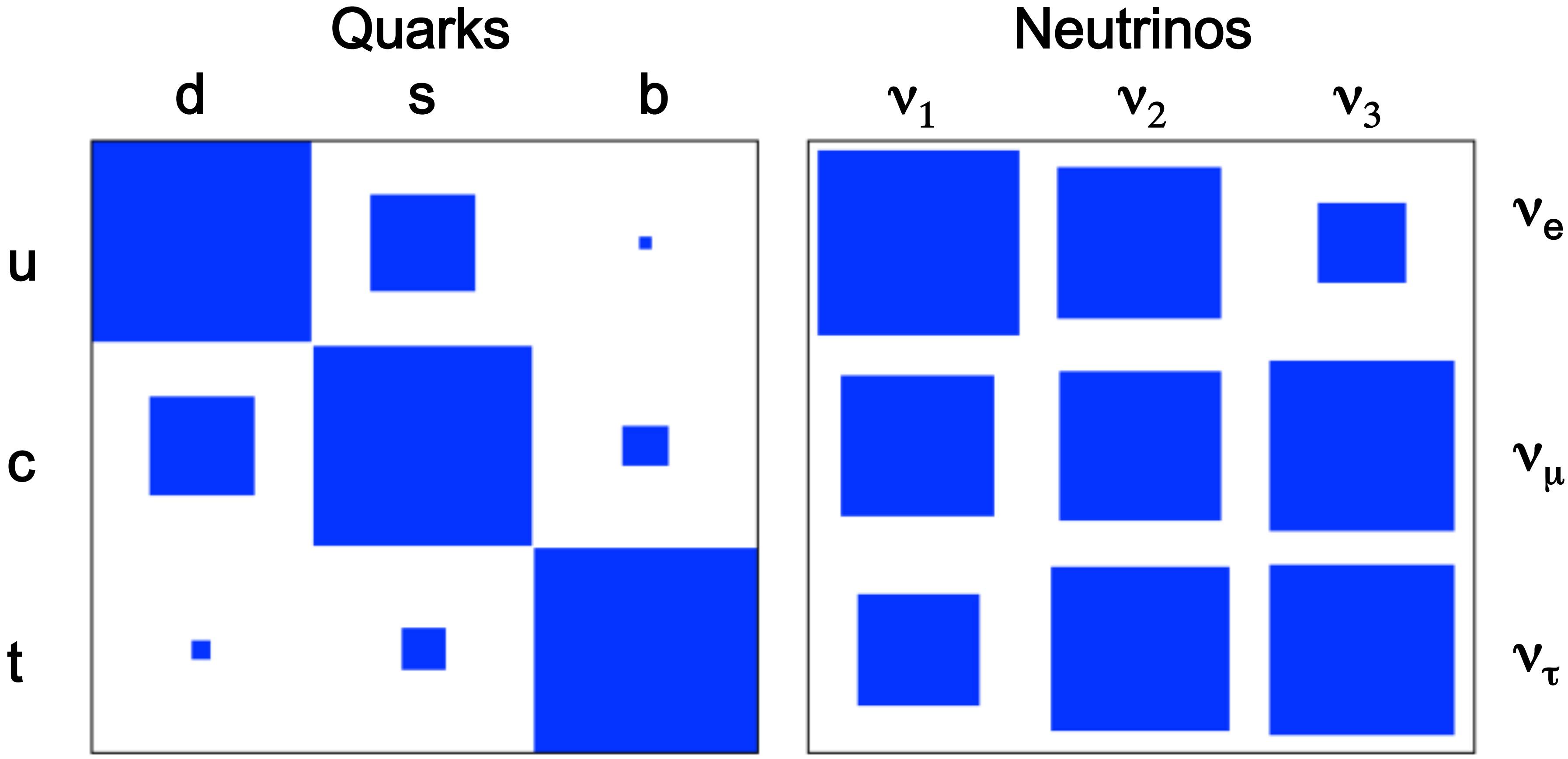
$\sin^2(2\theta_{13}) = 0.0841 \pm 0.0033$ (stat + sys)

$|\Delta m_{ee}^2| = 2.50 \pm 0.06$ (stat.) ± 0.06 (syst.)

22.05.2020

PRD 95, 072006 (2017)

CKM and PNMS mixing matrices

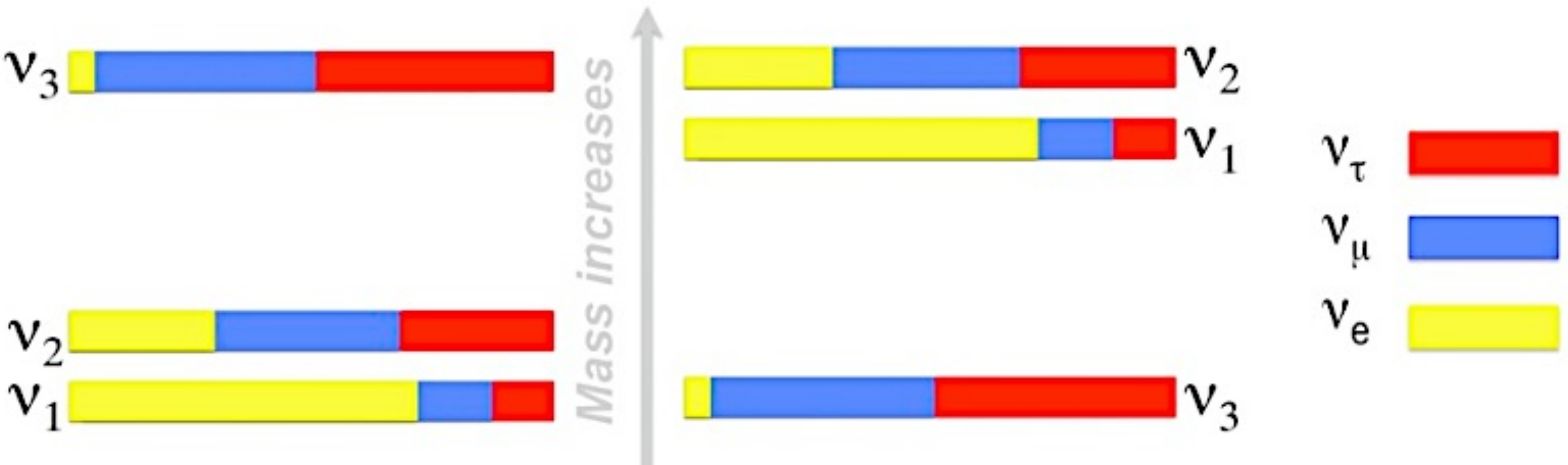


Is something hidden behind this difference of patterns?

Neutrino oscillations – still to be measured

Value of δ_{CP} → CPV for neutrinos?

Sign of Δm^2_{23} → which is the neutrino mass hierarchy?



Normal hierarchy (NH)

m1<m2<m3

Inverted hierarchy (IH)

m3<m1<m2

$$A_{CP} = \frac{P(\nu_\mu \leftrightarrow \nu_e) - P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e)}{P(\nu_\mu \leftrightarrow \nu_e) + P(\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e)}$$

Measurements of θ_{13}, δ_{CP} and mass hierarchy in LBL accelerator experiments

Appearance

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \times \left(1 \pm \frac{2a}{\Delta m_{31}^2}(1-s_{13}^2)\right)$$ Leading term

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

$$\mp 8c_{13}^2 s_{13}^2 s_{23}^2 \cos\Delta_{32}\sin\Delta_{31}\frac{aL}{4E}(1-2s_{13}^2)$$ Matter effect

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

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

ν vs. $\bar{\nu}$ sign change

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$ $\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$ $a = 2\sqrt{2}G_F n_e E$

Disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - (\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\cdot\sin^2\theta_{23})\cdot\sin^2\frac{\Delta m_{32}^2 \cdot L}{4E_\nu}$$

T2K experiment: apparatus and analysis methods

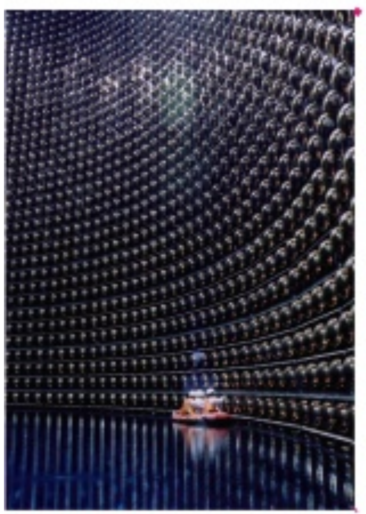
T2K experiment (Tokai to Kamioka)

With a strong participation of Polish groups from six institutions

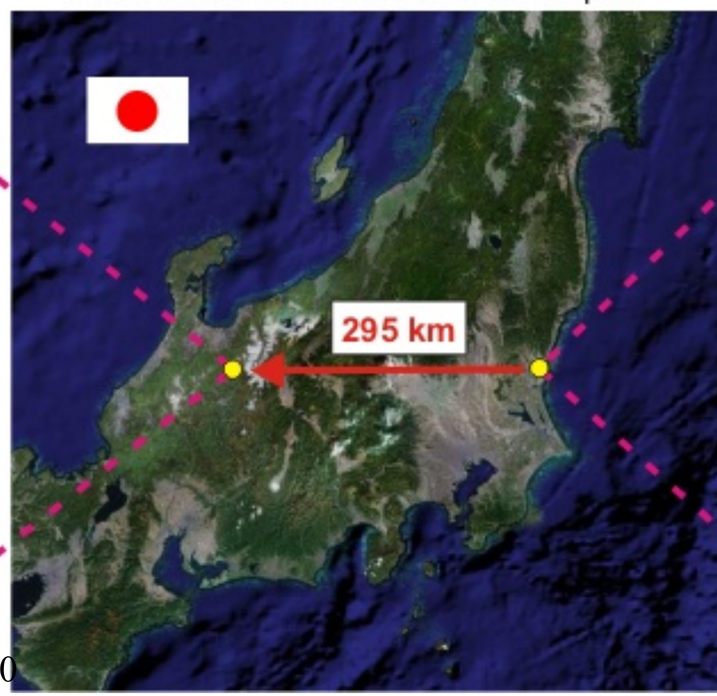
T2K experiment: intensive muon neutrino and antineutrino beams produced at JPARC, near detectors (INGRID and ND280)at JPARC and far detector (SuperK) at Kamioka.

Achievements: world leading measurement of $\theta_{23,}$ direct observation of the transition $\nu_\mu \rightarrow \nu_e$, hint for the CP violation in the neutrino sector.

Super Kamiokande
50,000 tons of water
10,000 phototubes

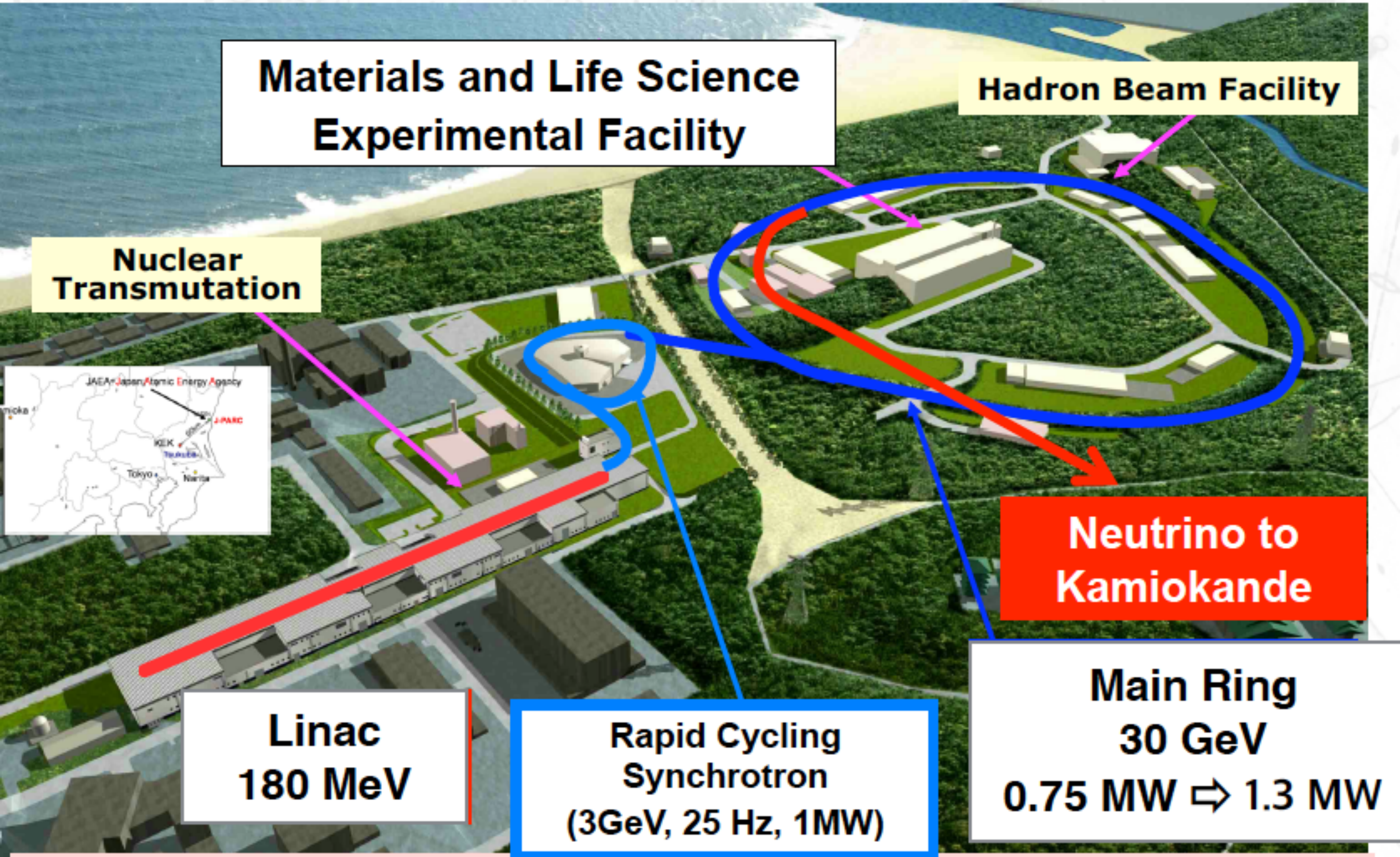


Neutrino beam directed across Japan



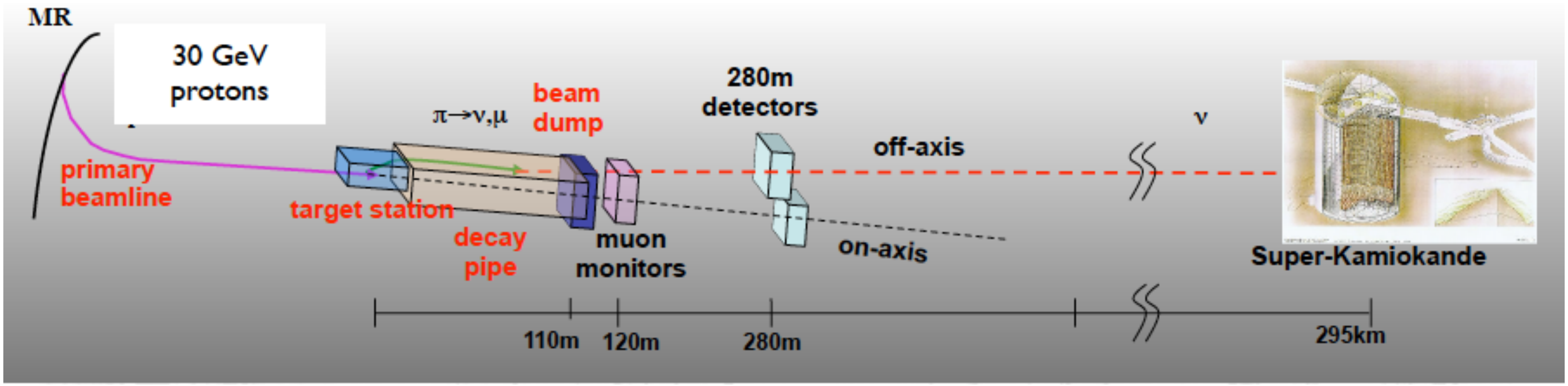
Tokai accelerator complex and
location of near detector (ND280)

JPARC
Japan Proton Accelerator Research Complex

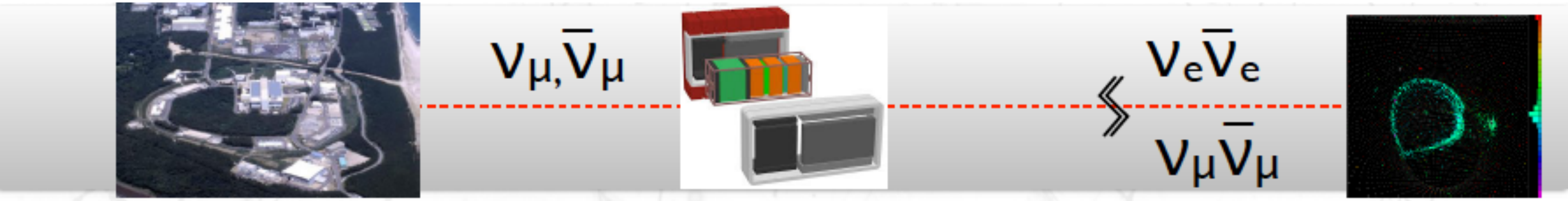


T2K experiment

„Kinematical focusing” with off-axis detectors



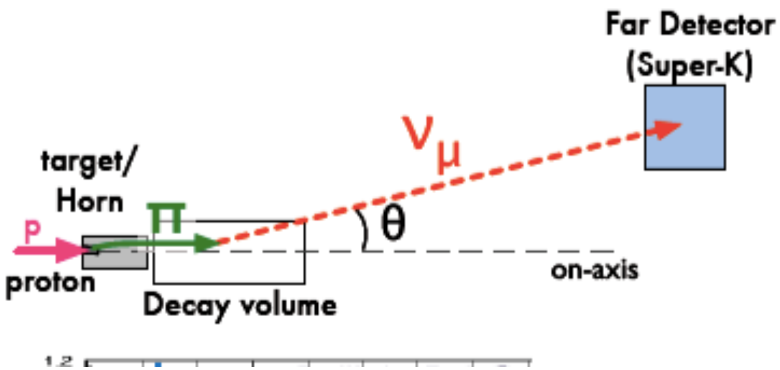
Studies of ν_μ (anti-ν_μ) disapperance and ν_e (anti-ν_e) apperance

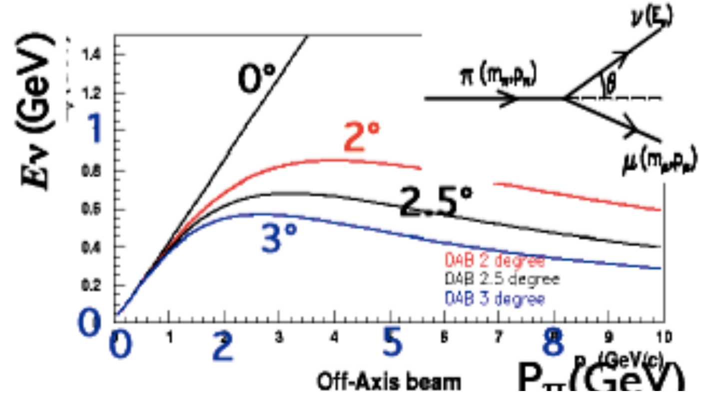


280 m

295 km

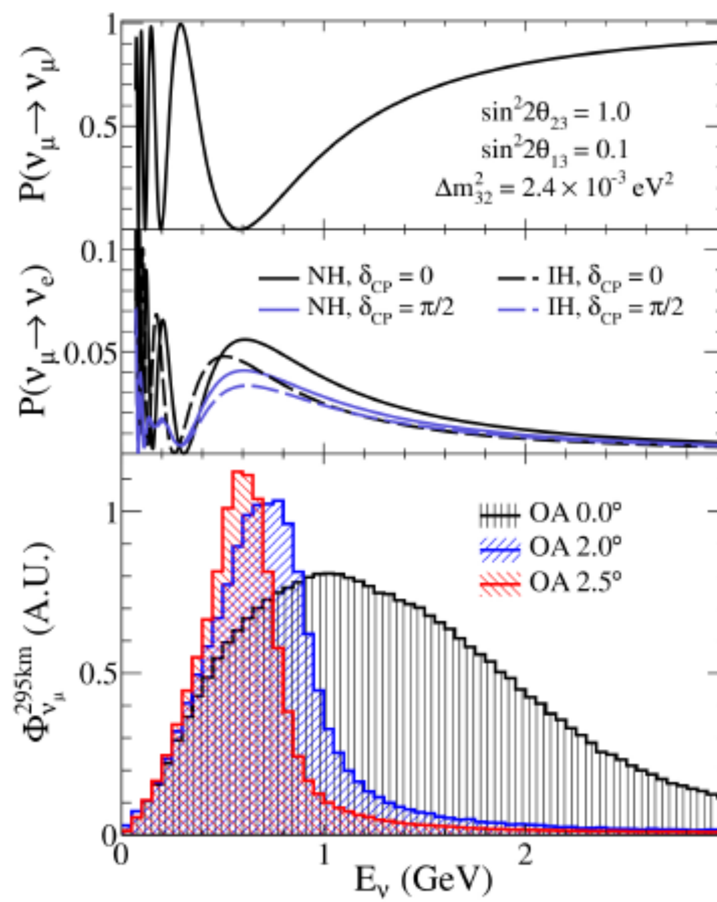
22.05.2020





Kinematical focusing

- Optimises the flux at the maximum of the oscillation
- Narrow beam less dependent on beam uncertaintes, but more on beam pointing
- Lower energies achieved



LBL experiments – measurement principle

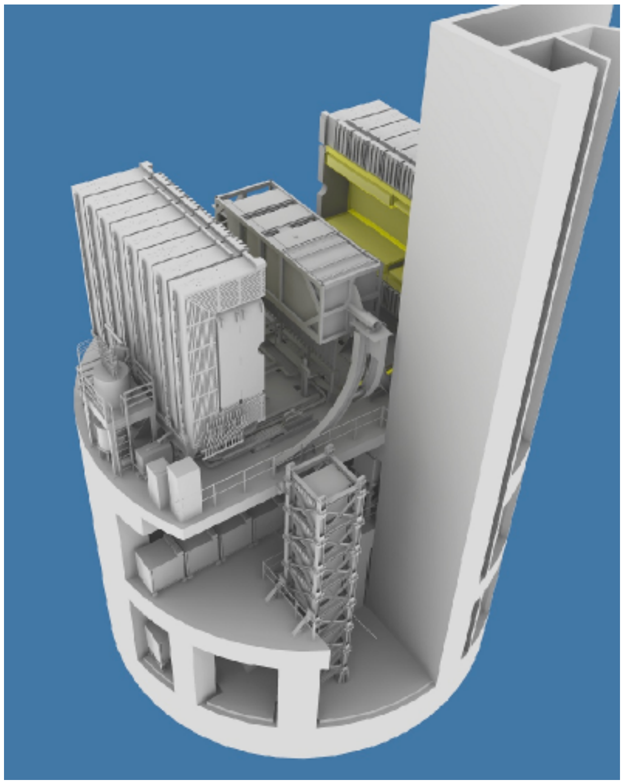
Measurement of the neutrino flux and energy spectrum in the near detector before oscillations

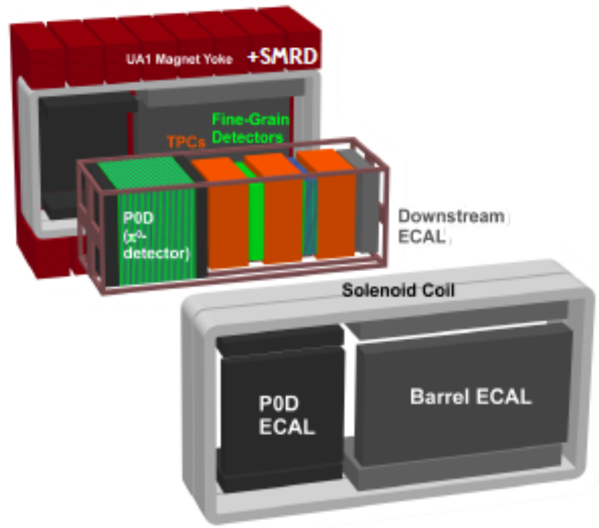
Extrapolation of the flux and energy spectrum to the far detector, assuming no oscillations

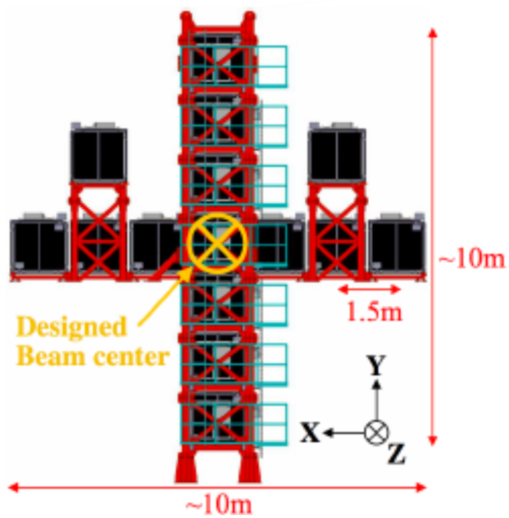
Measurement of the neutrino flux and energy spectrum in the far detector

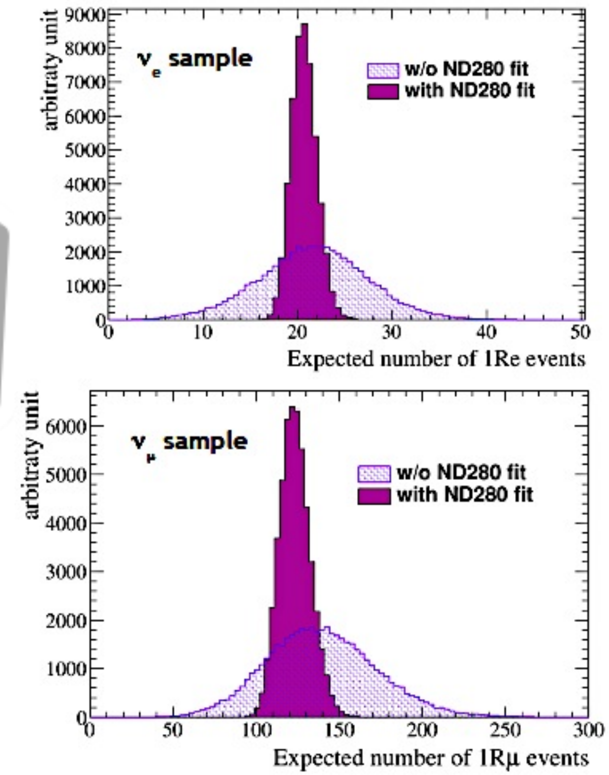
-> conclusions concerning the oscillations based on the reduction of neutrino flux and modification of the neutrino energy spectrum

T2K – near detectors



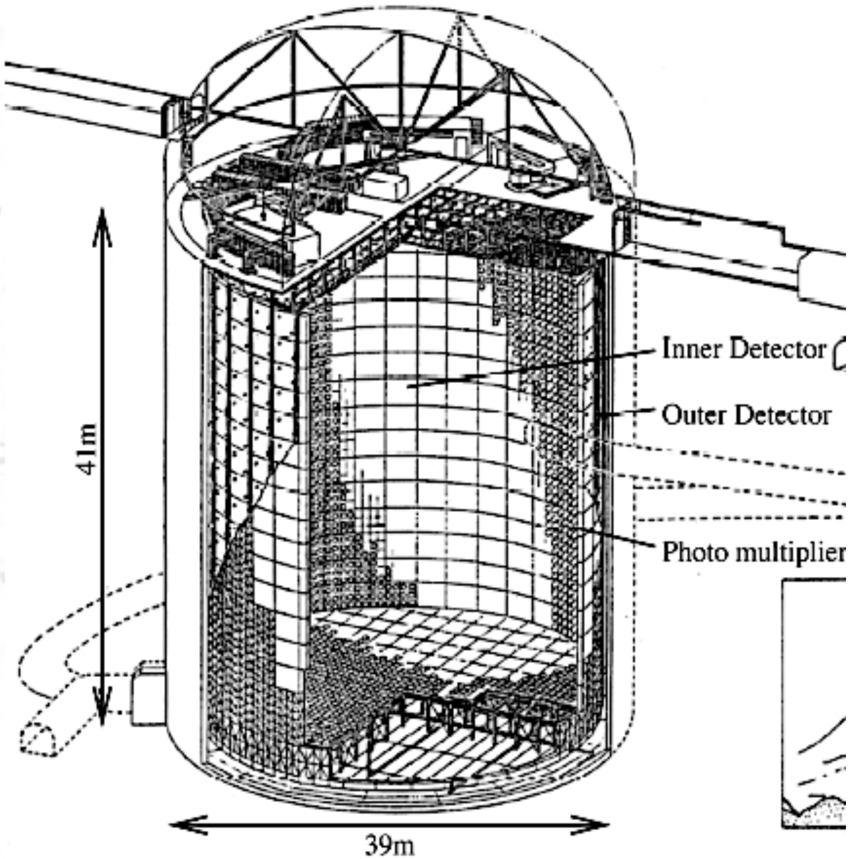


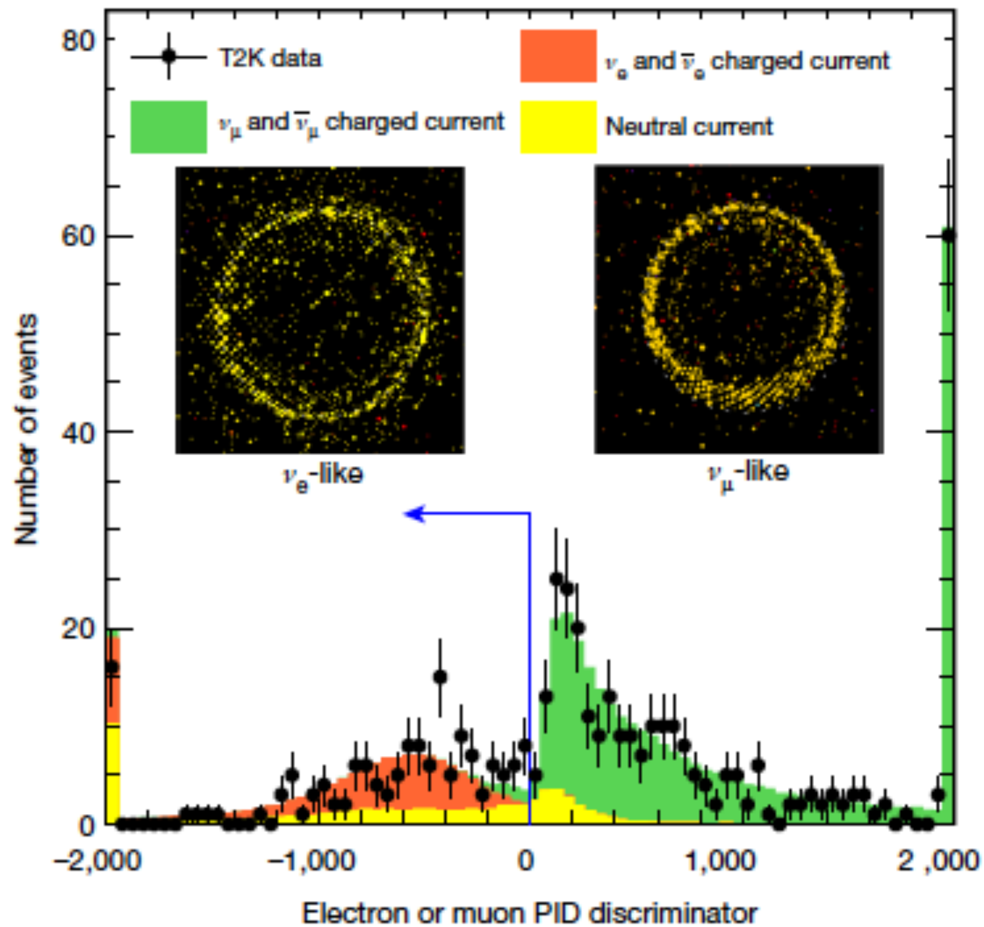


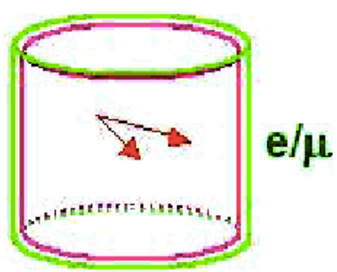


Reduction of the systematic uncertainties by a factor 3 - 4

T2K – far detector







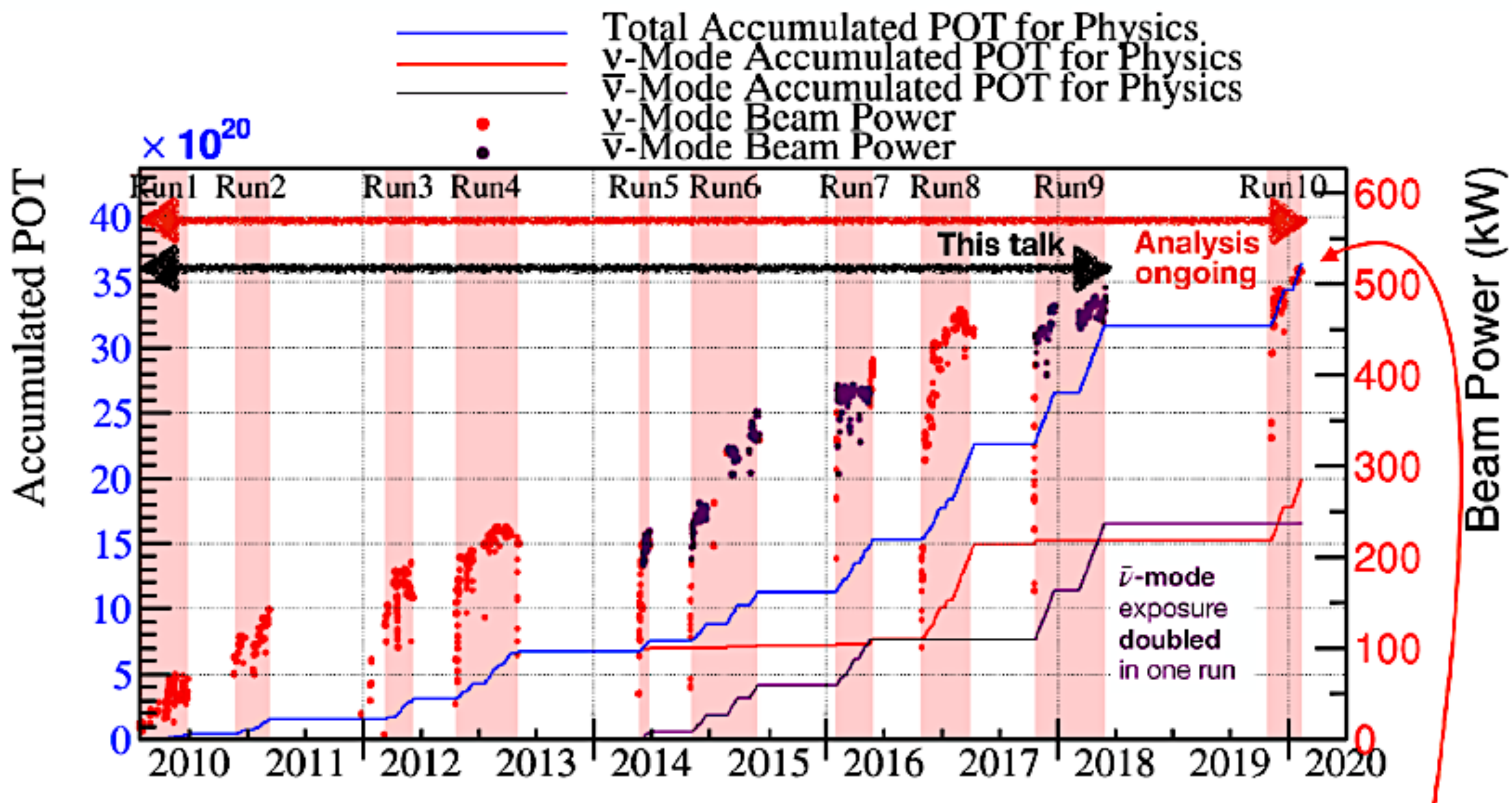
22.05.2020

T2K measurements

of the oscillation parameters θ_{23}, $|\Delta m^2_{23}|$, θ_{13}

and constraits on δ_{CP}

Collected data

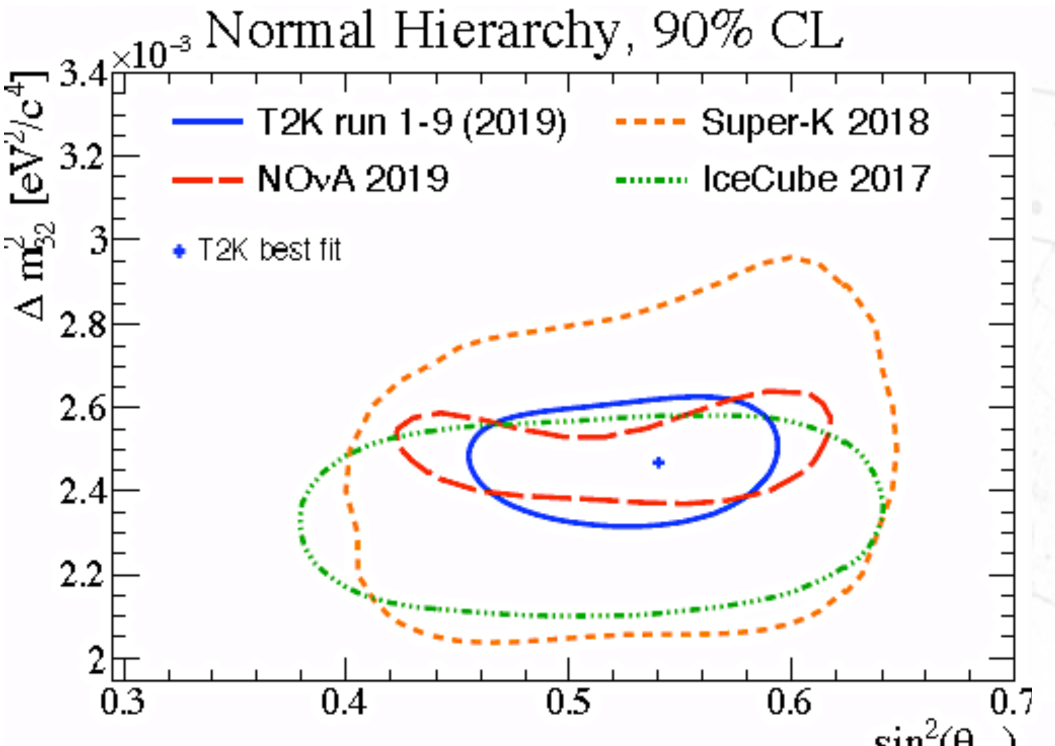


Analyzed: 3.1×10^{21} protons on target (POT)

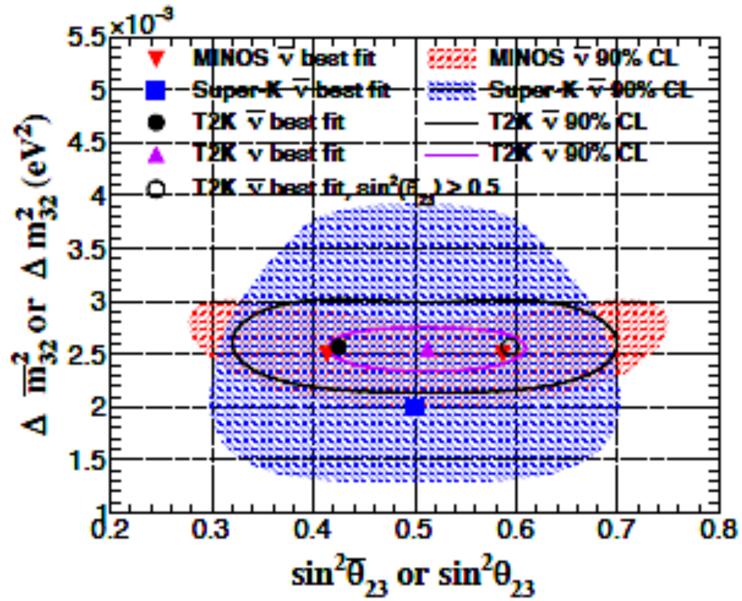
515 kW operation in 2019

50% of ν_μ and 50% of anti-ν_μ

T2K – ν_μ and anti-ν_μ disapperance



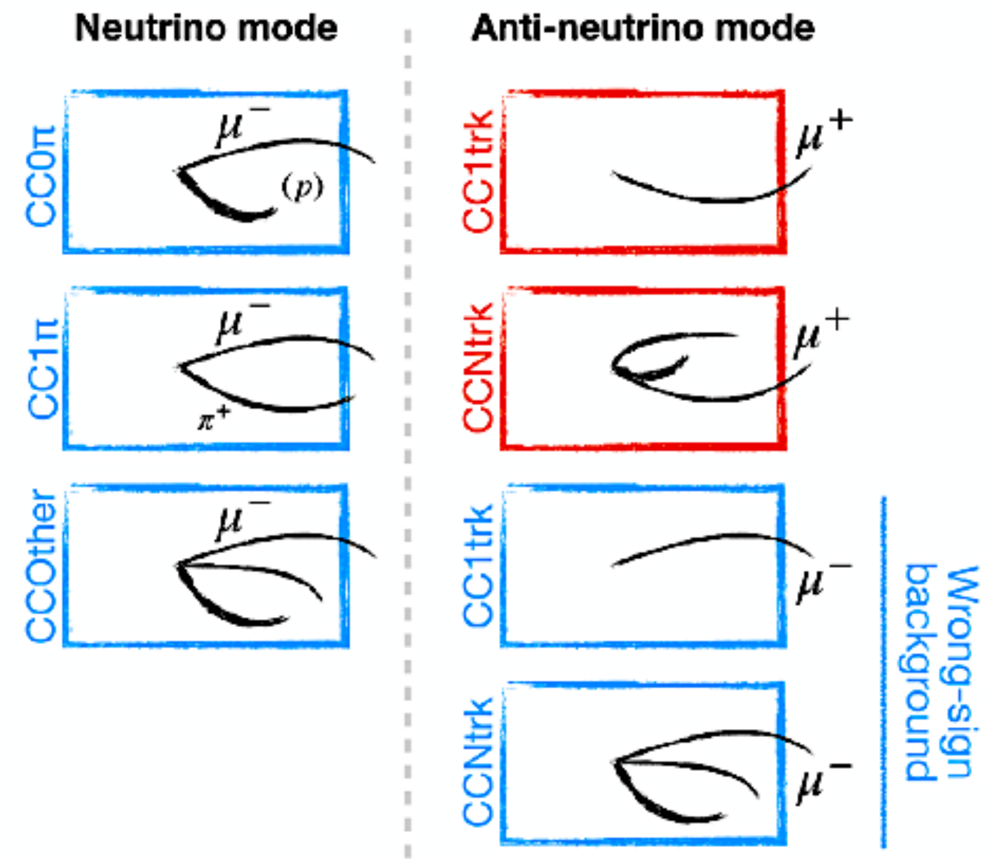
World leading result



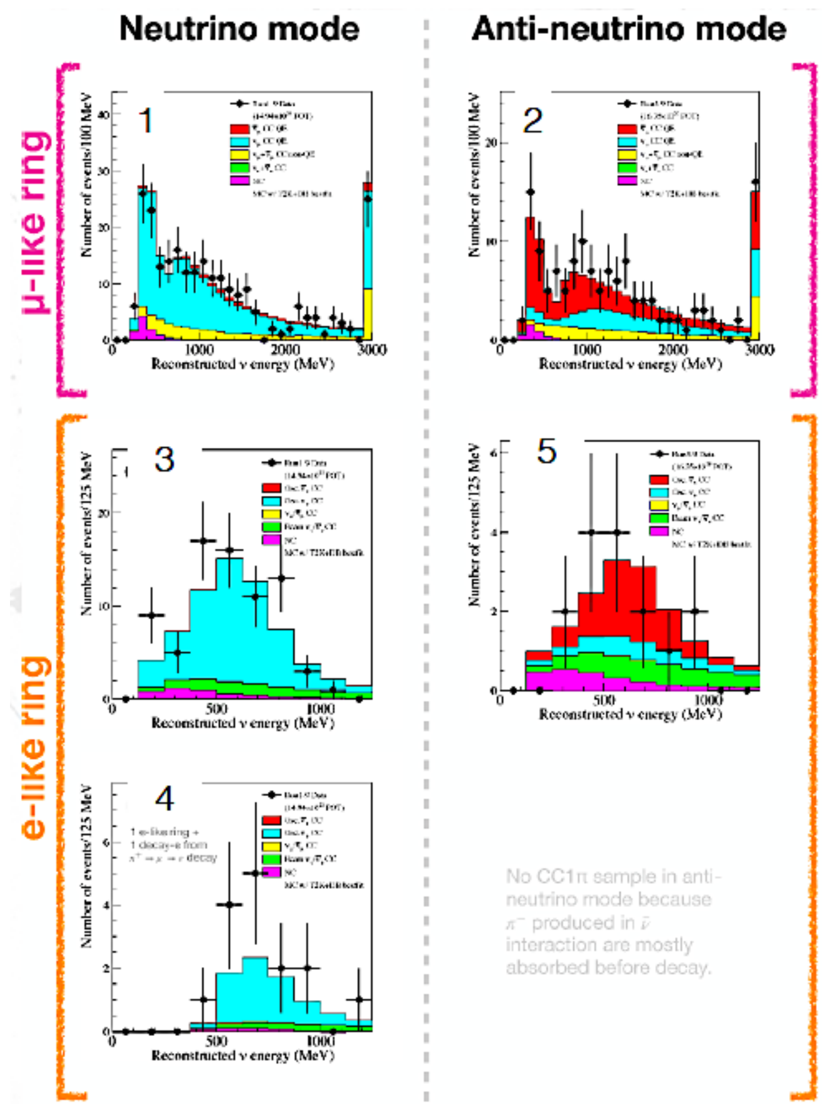
2017 result

Data samples used for δ_{CP} measurement

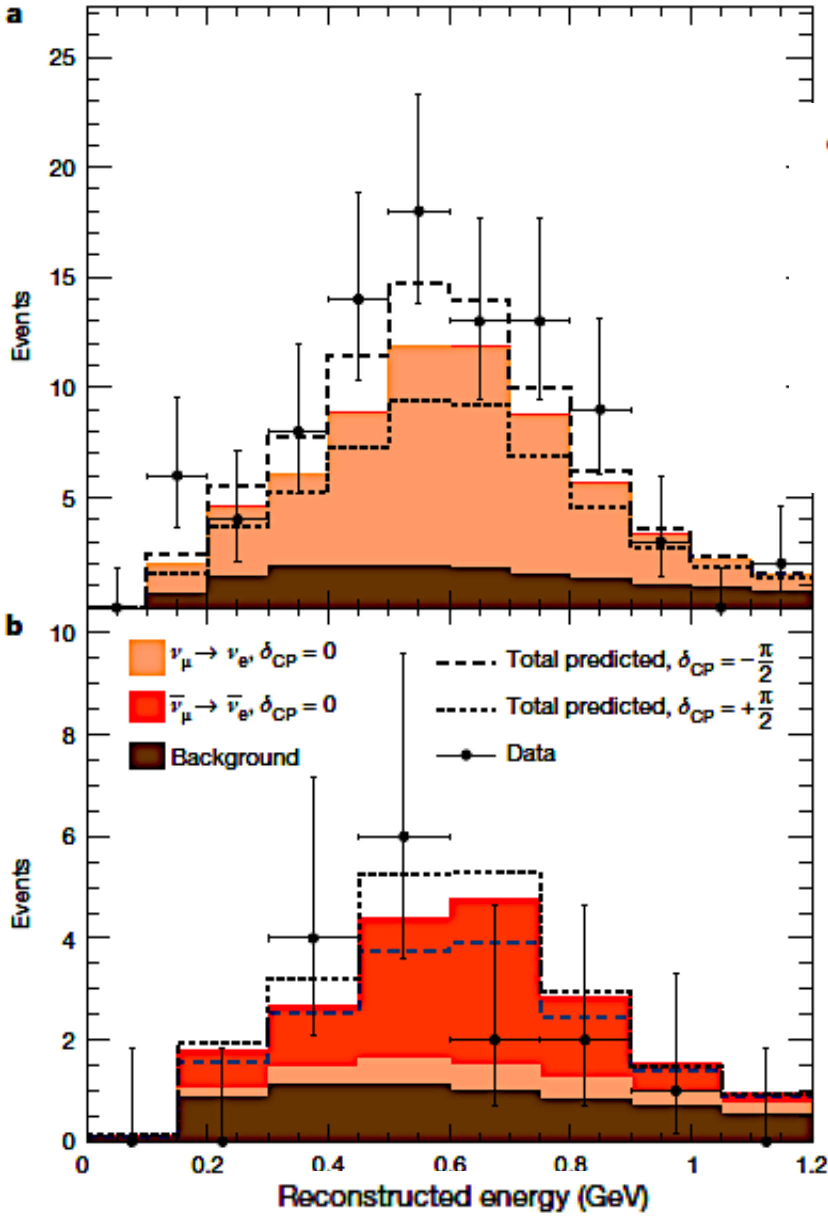
ND280 near detector



SuperK far detector



CP violation phase



c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

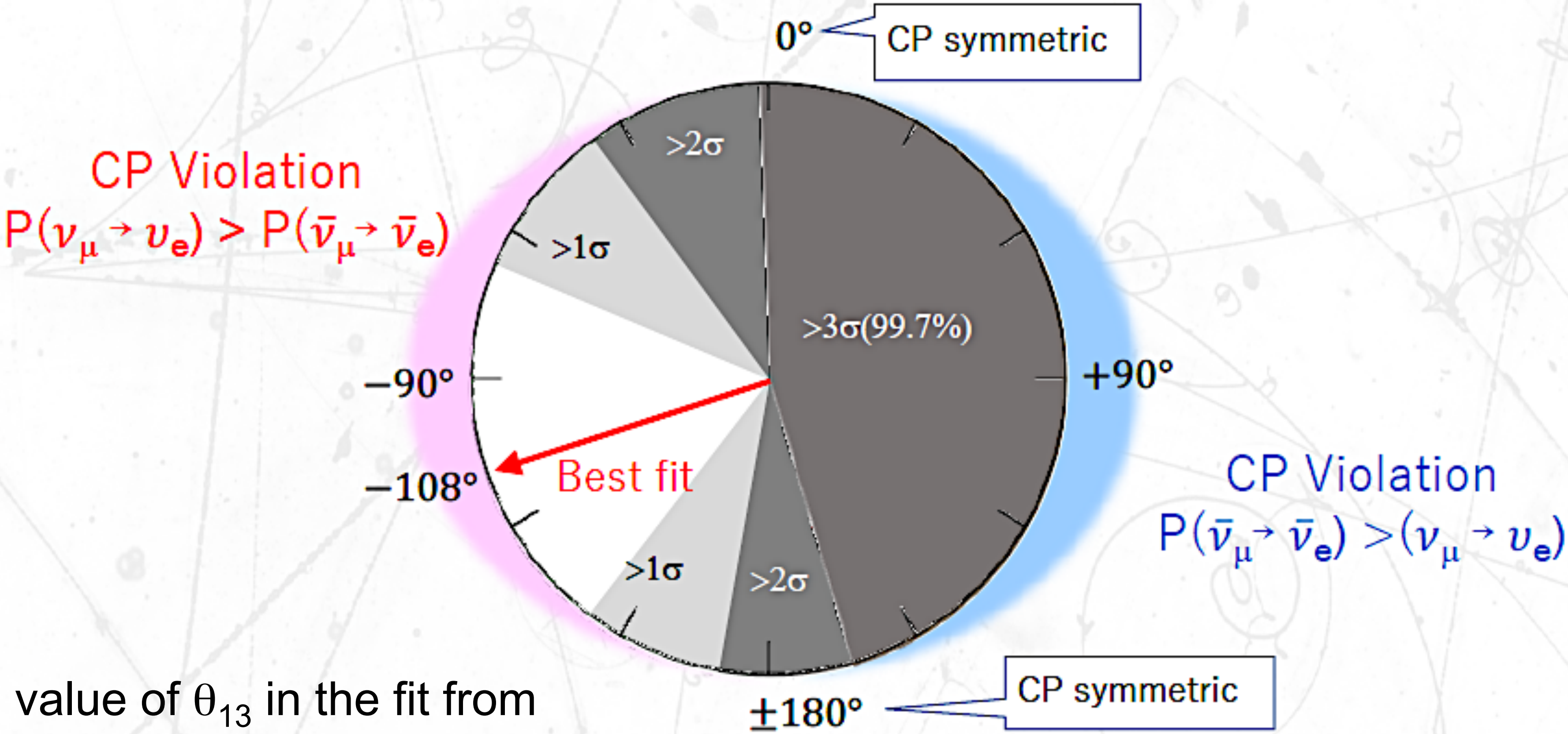
$\nu_e/\bar{\nu}_e$ Systematic Uncertainty

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (
Super-K Detector Model	1.5 %
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0 %

δ_{CP} measurement

T2K result excludes most of the $\delta_{CP}>0$ values @ 99.7% CL

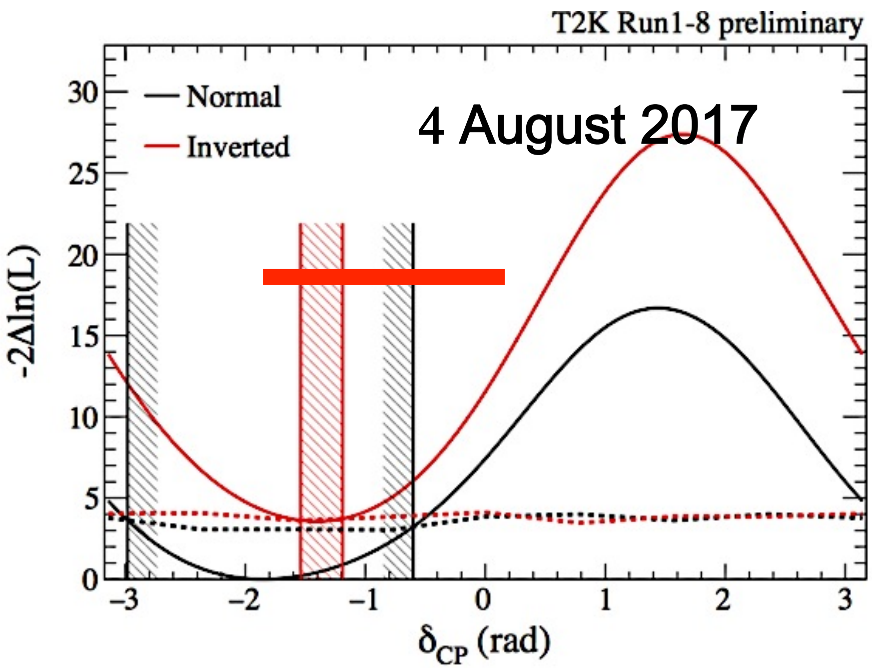
CP phase



value of θ_{13} in the fit from reactor experiments

Plot by the T2K Spokes-Person A.Ichikawa

T2K – early hints of CP violation

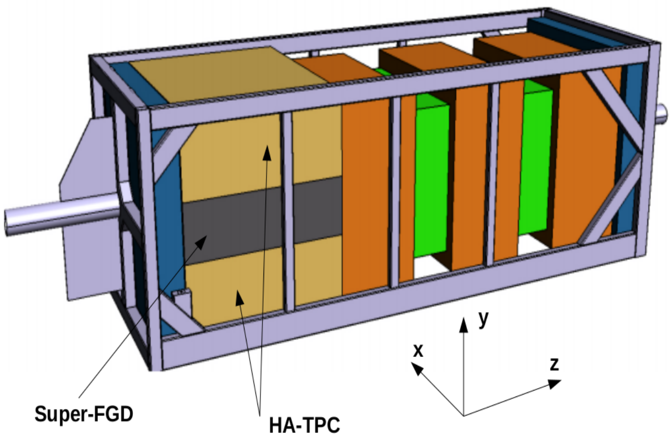


T2K data exclude CP conservation at the 95% confidence (2σ) level. The 95% CL allowed region for the CP violating phase, δ_{CP}, is [–167°; –34°] ([–88°; –68°]) for the normal (inverted) hierarchy, with the best fit point being –105° (–79°).

Future measurements of δ_{CP}

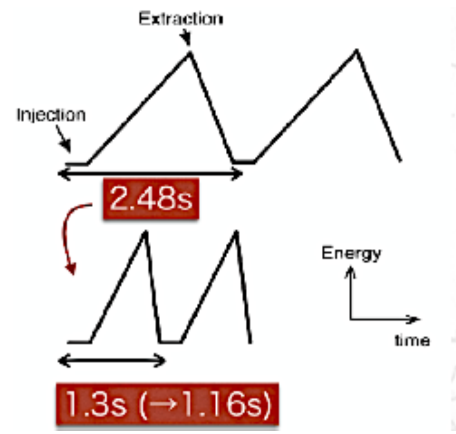
Upgrades of the T2K experiment

ND280 upgrade



Improved acceptance
Twice in statistics for equal pot
ToF for background reduction

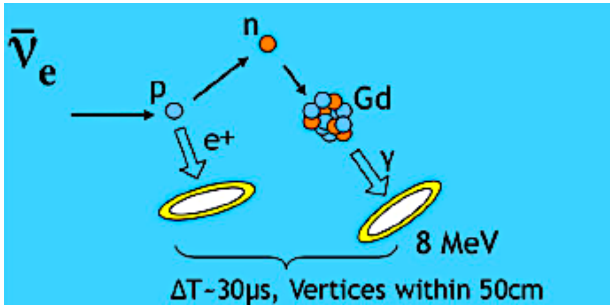
Beam upgrade



Increasing frequency and ppp:
515 kW in 2019, 800 kW by 2023
1.3 MW for T2HK

SK Gadolinium project (delayed by Covid-19)

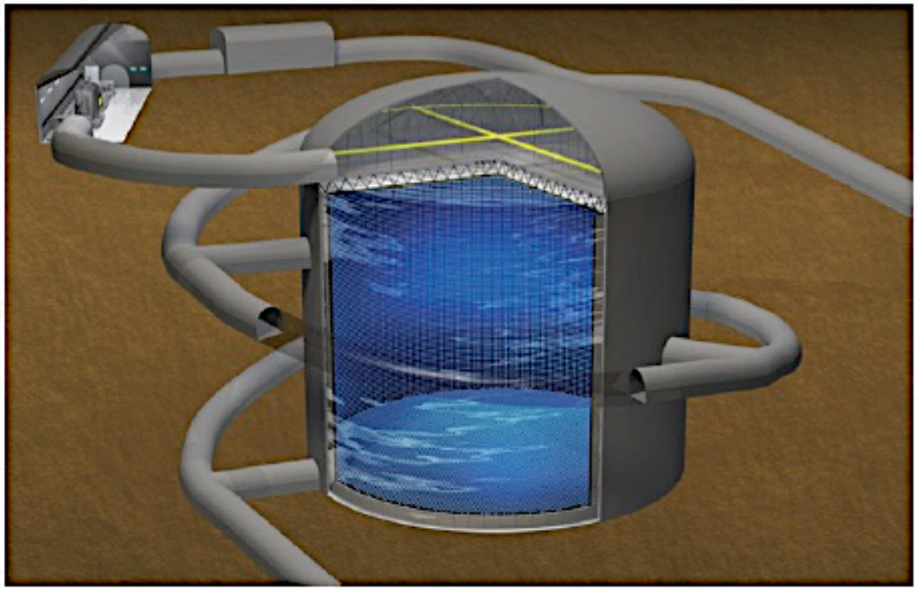
May provide wrong-sign background constraint in anti-ν_e



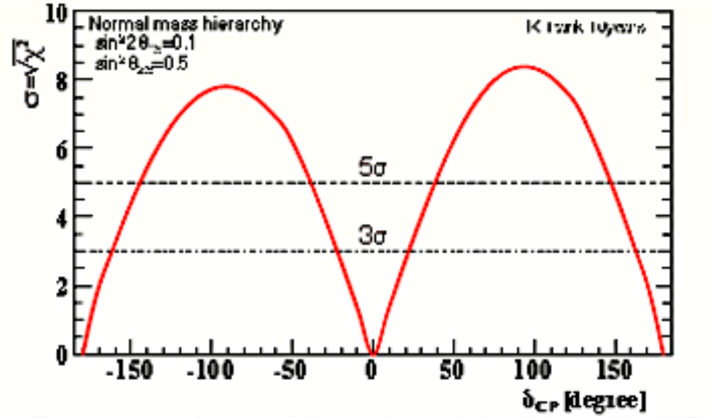
HyperKamiokande

Approved early 2020

- 1000-2000 $\nu_e + \bar{\nu}_e$ events.
  - 115 in T2K
- > 5σ discovery of CP violation.
- Precise measurement of θ_{23}



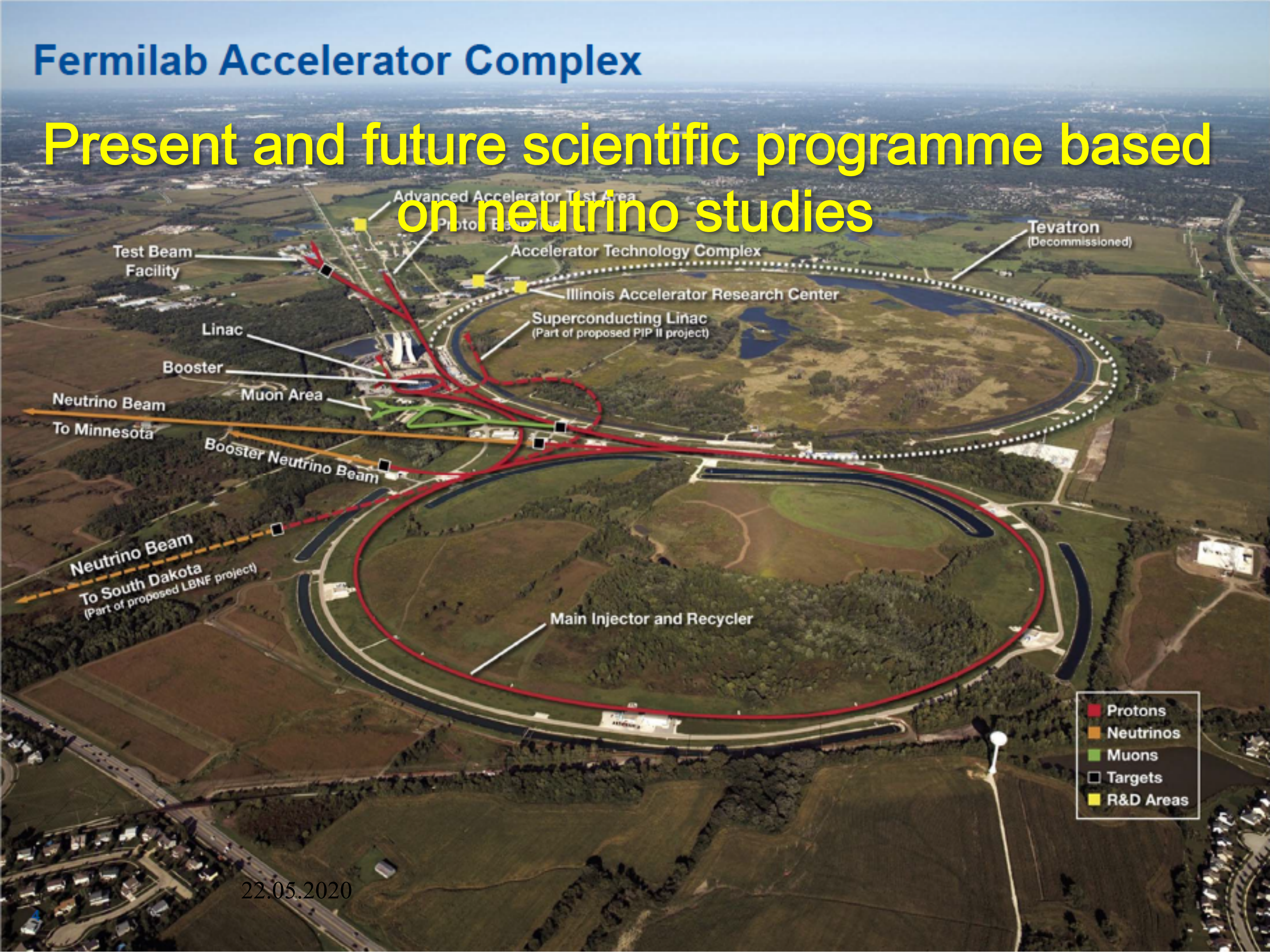
Same neutrino spectrum as T2K.
Same ND280 as in T2K
T2K results in x-sect and oscillation fosters future HK results.



	SK	HK
Site depth	Mozumi (1000m)	Tochibora (650m)
# PMT	11,129	40,000
Photo-coverage	40 %	40% (x2 QE)
Mass Fiducial mass	50 ktons 22.5 ktons	260 kkons 188 ktons

F. Sanchez talk at CERN, 4.05.2020

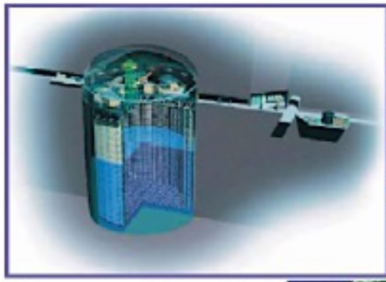
Present and future scientific programme based on neutrino studies



22.05.2020

Combined analysis of T2K and NOvA

T2K



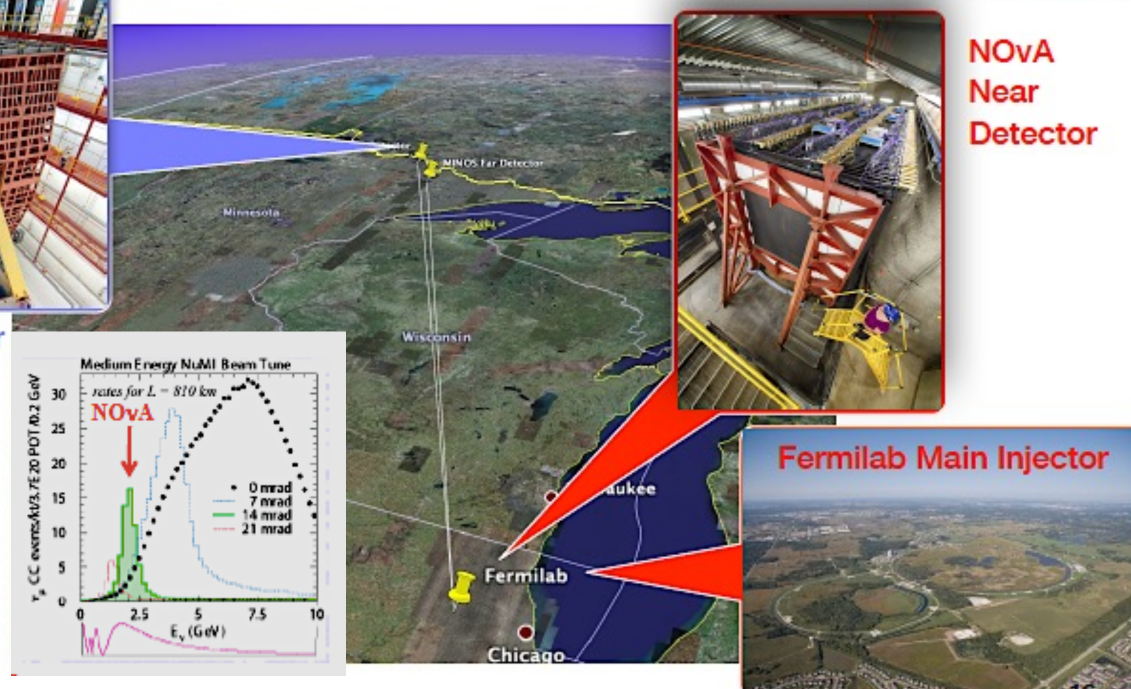
Super-Kamiokande
(ICRR, Univ. Tokyo)

$E_\nu \simeq 0.7$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 295 \text{ km}}{0.7 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA

NOvA Far Detector

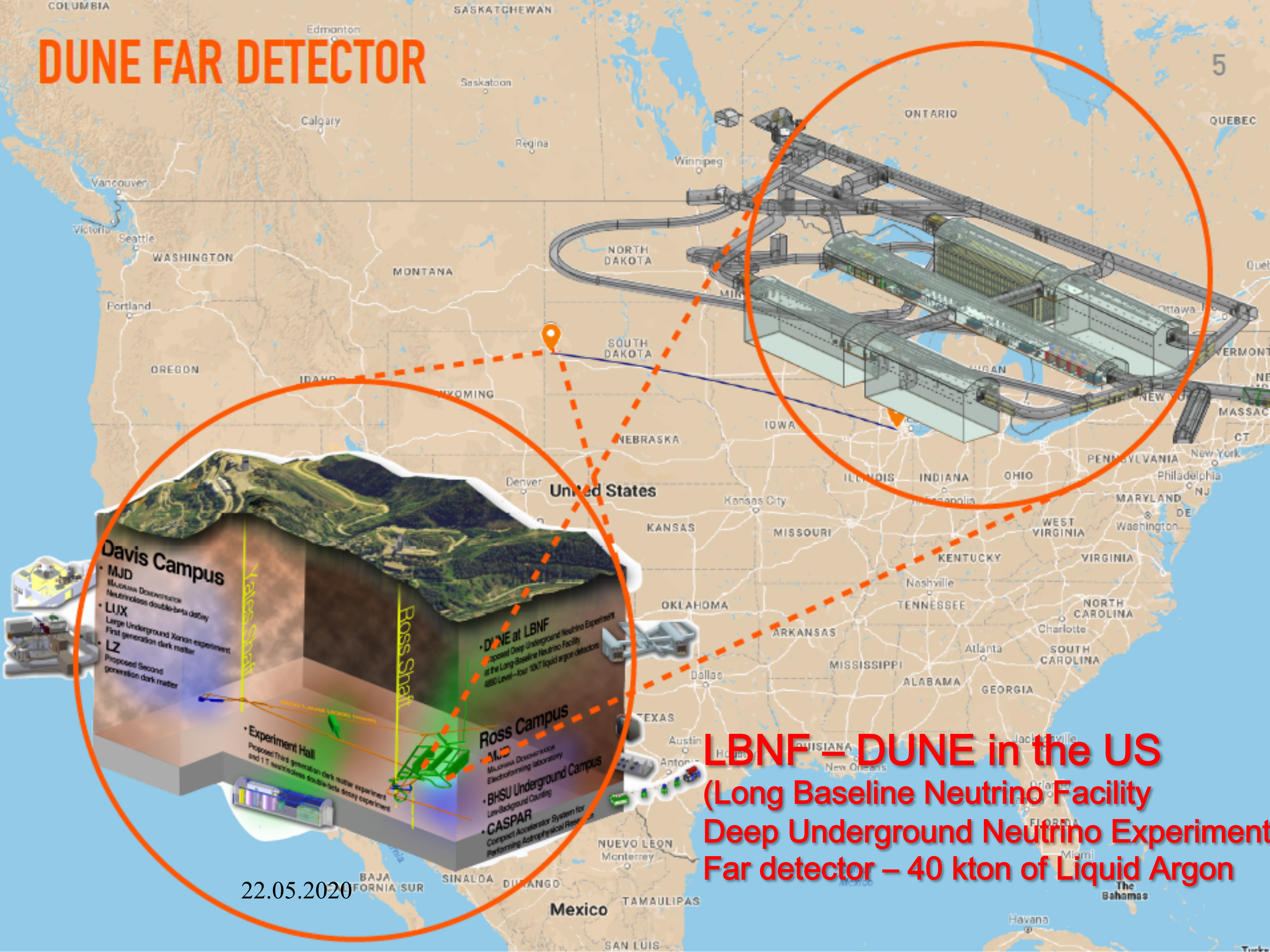


$E_\nu \simeq 2$ GeV,

$$\Delta \equiv \frac{1.27 \cdot 0.0025 \text{ eV}^2 \cdot 810 \text{ km}}{2 \text{ GeV}} \simeq \frac{\pi}{2}$$

NOvA: Indication of the normal hierarchy at the 1.9 σ level

DUNE FAR DETECTOR



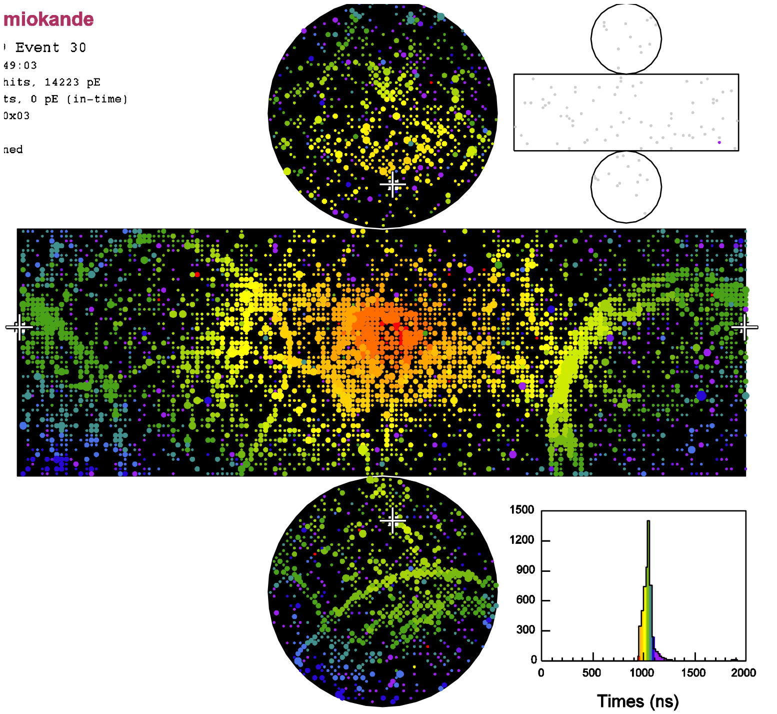
LBNF – DUNE in the US

(Long Baseline Neutrino Facility

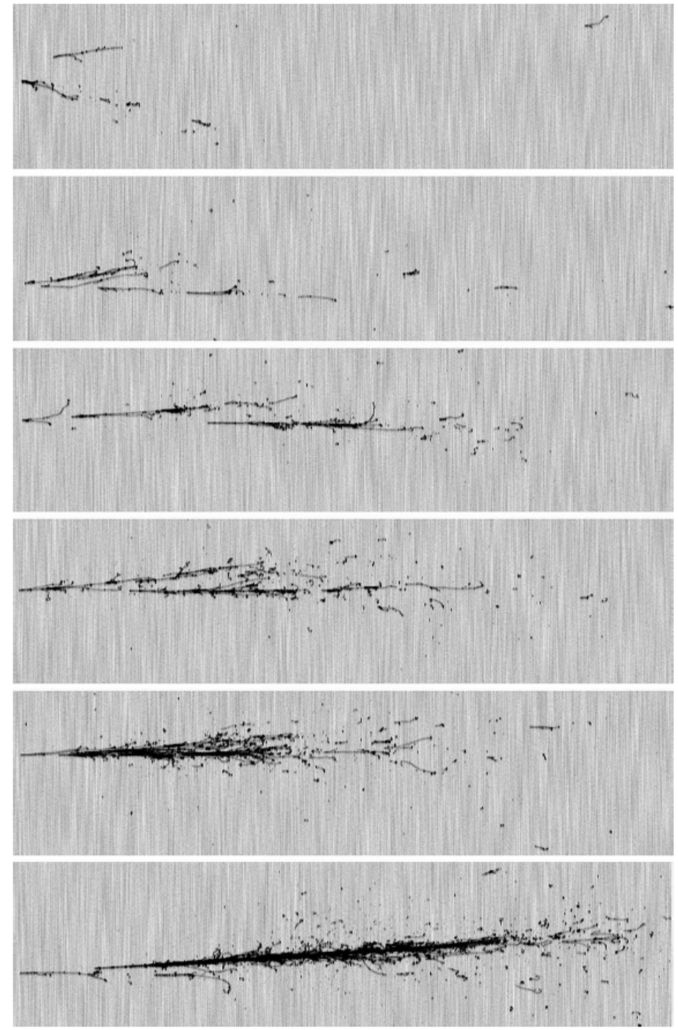
Deep Underground Neutrino Experiment

Far detector – 40 kton of Liquid Argon

Why Liquid Argon?



Water Cherenkov detector is impractical for higher neutrino energies with many particles in the final state.



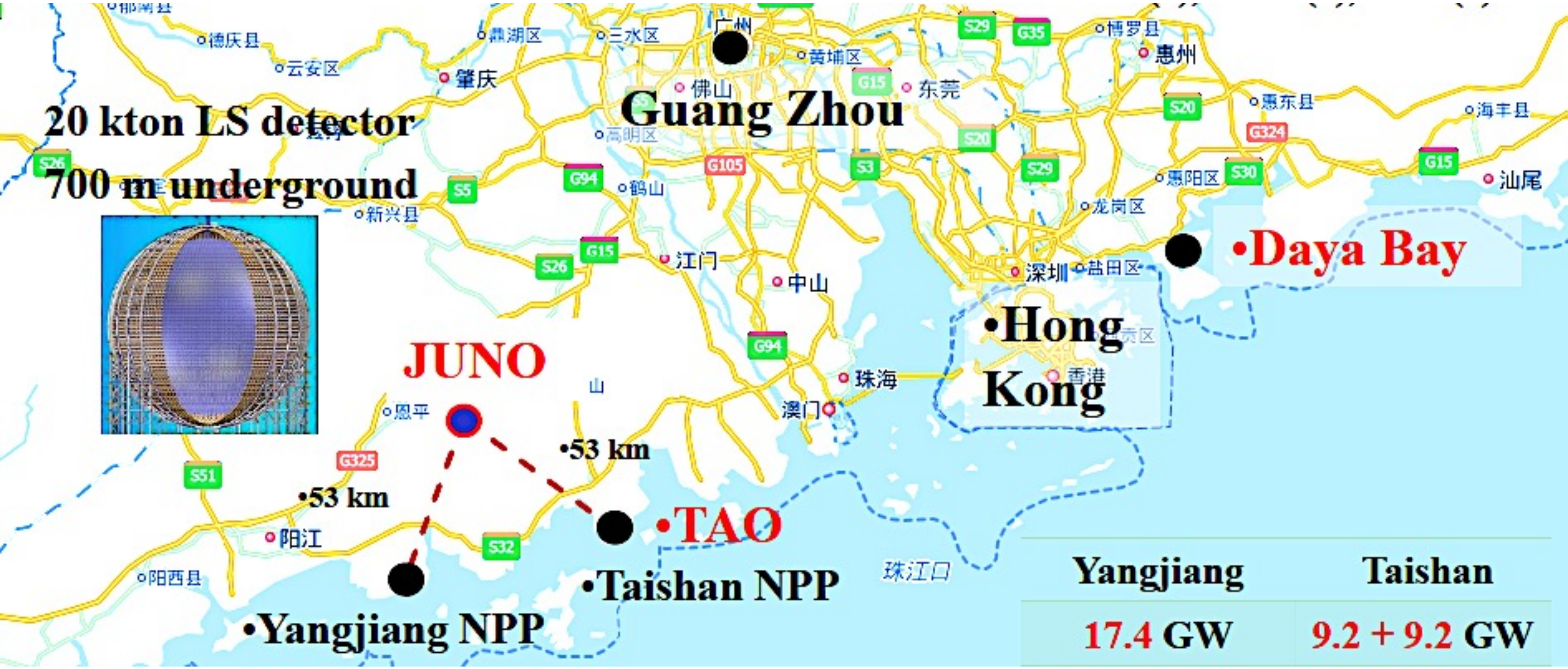
π^0's with momentum
0.5, 1, 2, 3, 5, 10 GeV
in the ICARUS LAr detector

Why Liquid Argon?

Very good energy reconstruction of neutrino interaction products hence detectors can be placed on-axis and profit from:

- High flux → big number of neutrino interactions
- Possible optimisation for both neutrino mass hierarchy and δ_{CP} measurements in the same experiment
- Neutrino energy range may be sufficient to cover two oscillation maxima at the same distance L

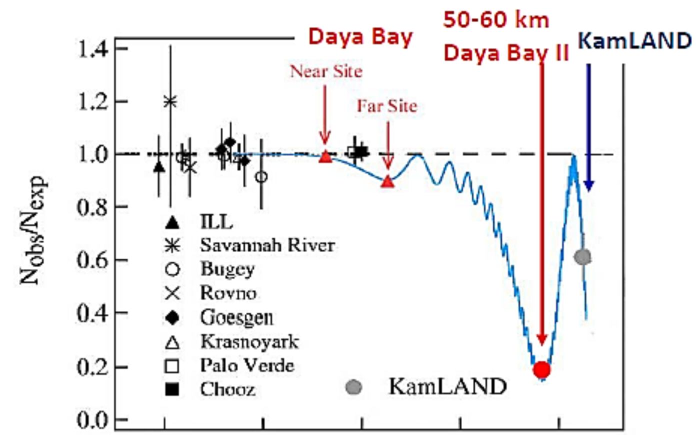
Reactor experiment JUNO:
very precise measurements of θ_{12} and Δm^2_{12} and attempt to determine mass hierarchy



22.05.2020

JUNO – mass hierarchy

- 20 kton LS detector
- 2-3 % energy resolution

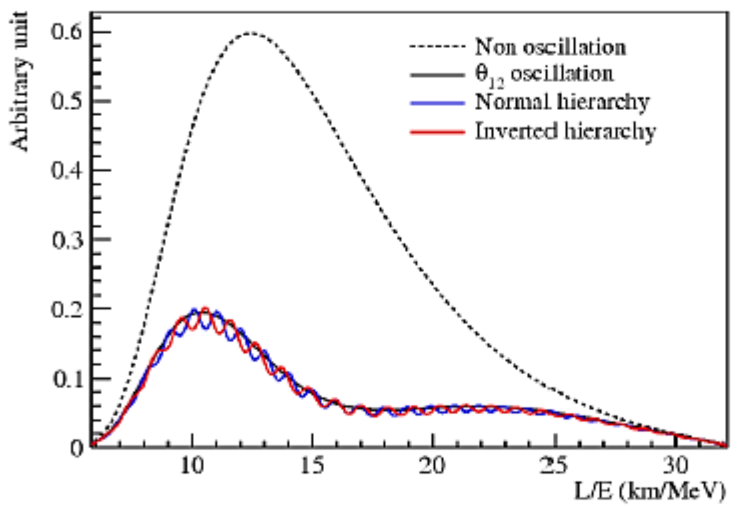


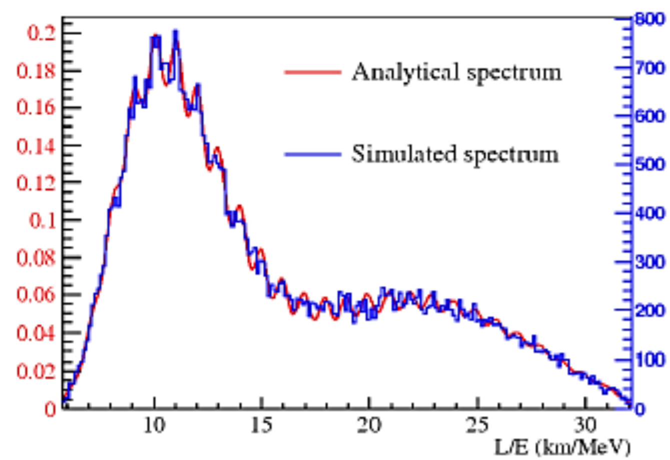
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., hep-ex/0612022 L.

$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\mathrm{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\mathrm{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$

Zhan, Y. Wang, J. Cao, L. Wen,
PRD78:111103, 2008
PRD79:073007, 2009





50000 events

Summary

The T2K recent result opens the era of δ_{CP} measurements

Additional data from T2K with upgraded near detector and beam together with combined analysis with NOvA should lead to a full exclusion of CP conseration and mass hierarchy determination at 3 sigma level

T2HK in Japan, LBNF in the USA and JUNO in China will bring up determination of δ_{CP} and mass hierarchy at >5 sigma level

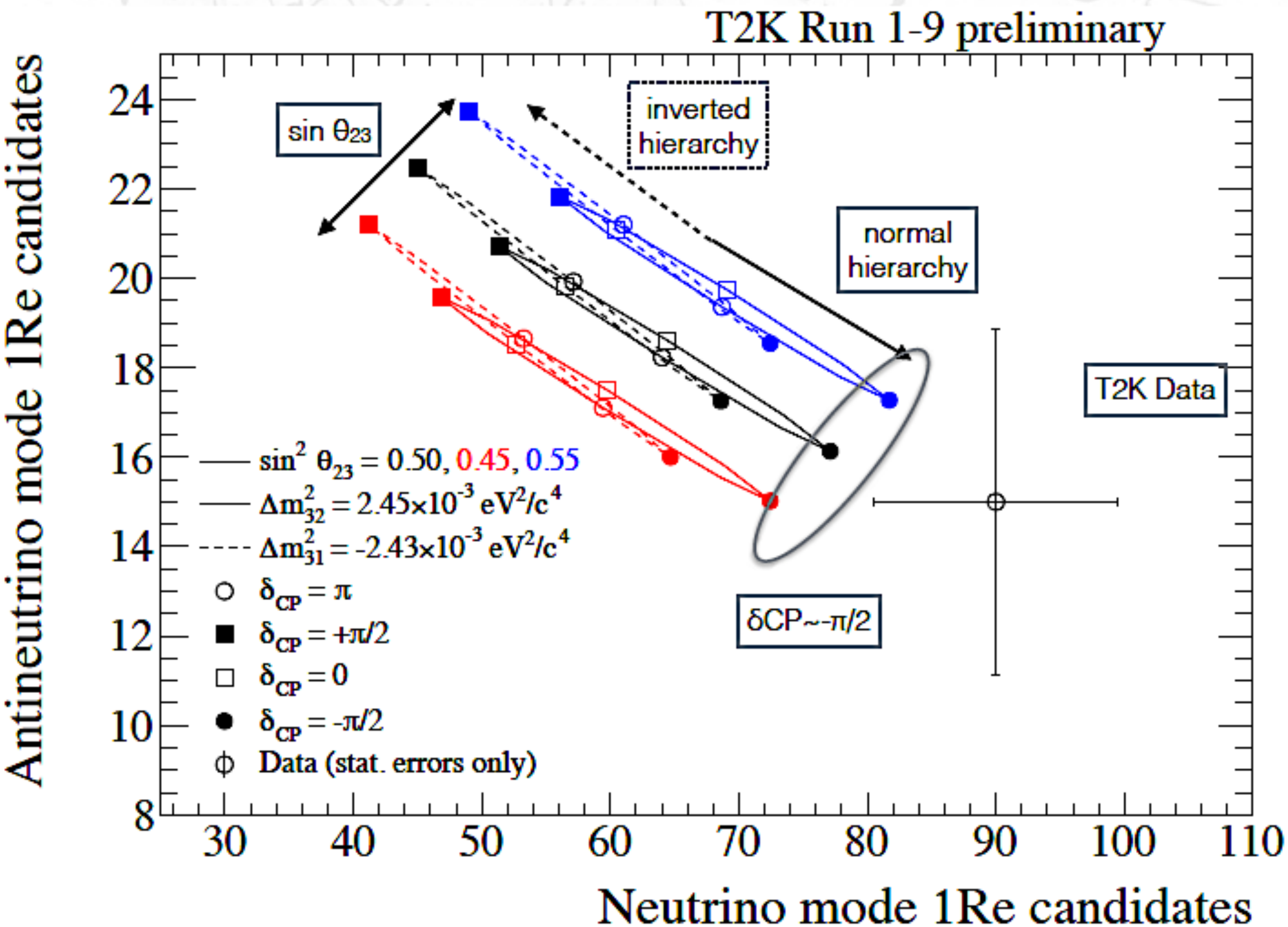
CP violation in the neutrino sector vs matter-antimatter asymmetry in the Universe

Review: C.Hagedorn, R.N. Mohapatra, E.Molinaro, C.C.Nisji, S.T.Petcov, *CP violation in the lepton sector and implications for leptogenesis*, Int. J. Mod. Phys. A33, 1842006 (2018)

Presented various models of leptogenesis, some of them requiring large negative values of δ_{CP} – like indicated by T2K

Theoretical talk on that?

CP violation phase



ν energy dependency is not reflected in this plot

Oscillations for two neutrino flavours

For two flavour states α and β and two mass states 1 and 2, probability that after a distance L in vacuum a neutrino with energy E and initial flavour α will become a neutrino with flavour β equals:

$$P = \sin^2 2\theta \cdot \sin^2 \left[\frac{1.27 \Delta m^2 [\mathrm{eV}^2] \cdot L[\mathrm{km}]}{E_\nu [\mathrm{GeV}]} \right]$$

Δm^2 (difference of mass squares of states 1 and 2) and θ (mixing angle between states 1 and 2) are theoretical parameters; L (baseline) and E (neutrino energy) are experimental parameters.