LONG-BASELINE NEUTRINO EXPERIMENTS

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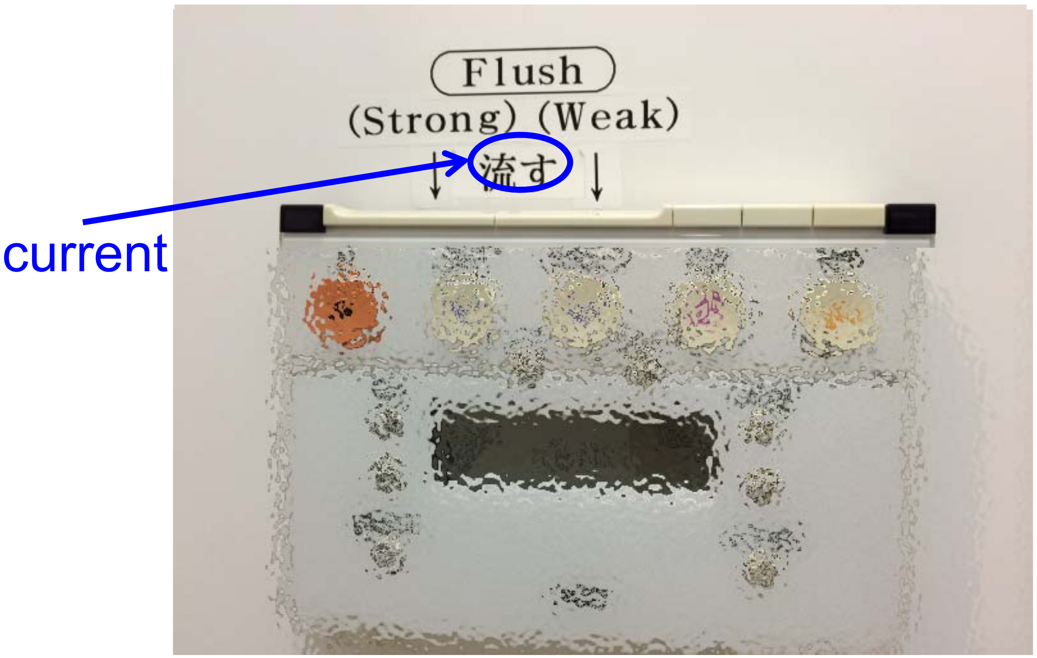
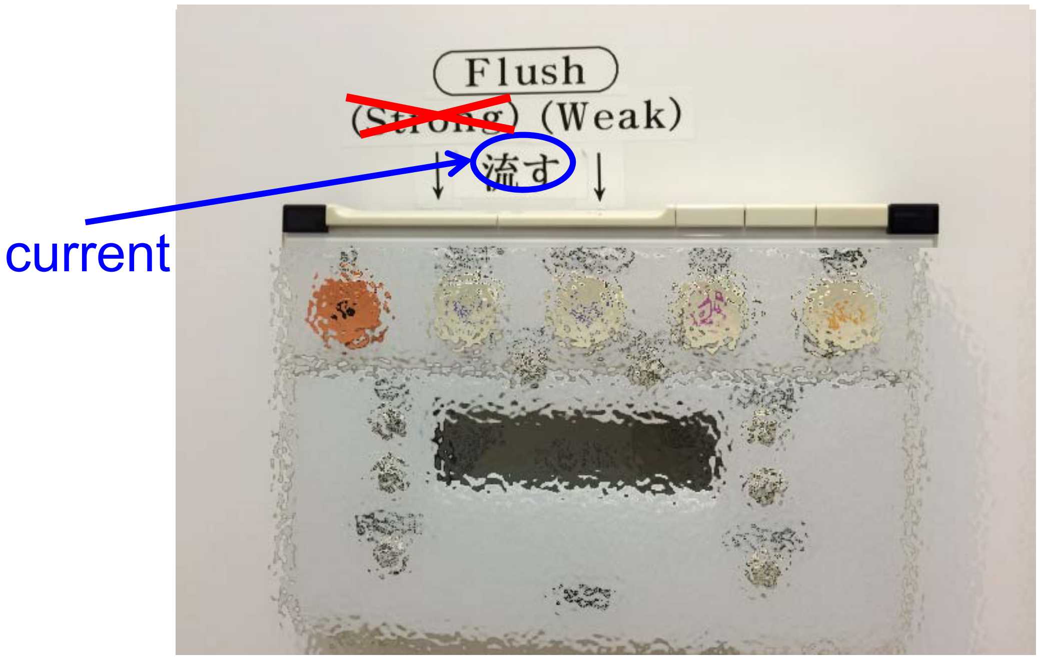
Quark vs. Neutrino

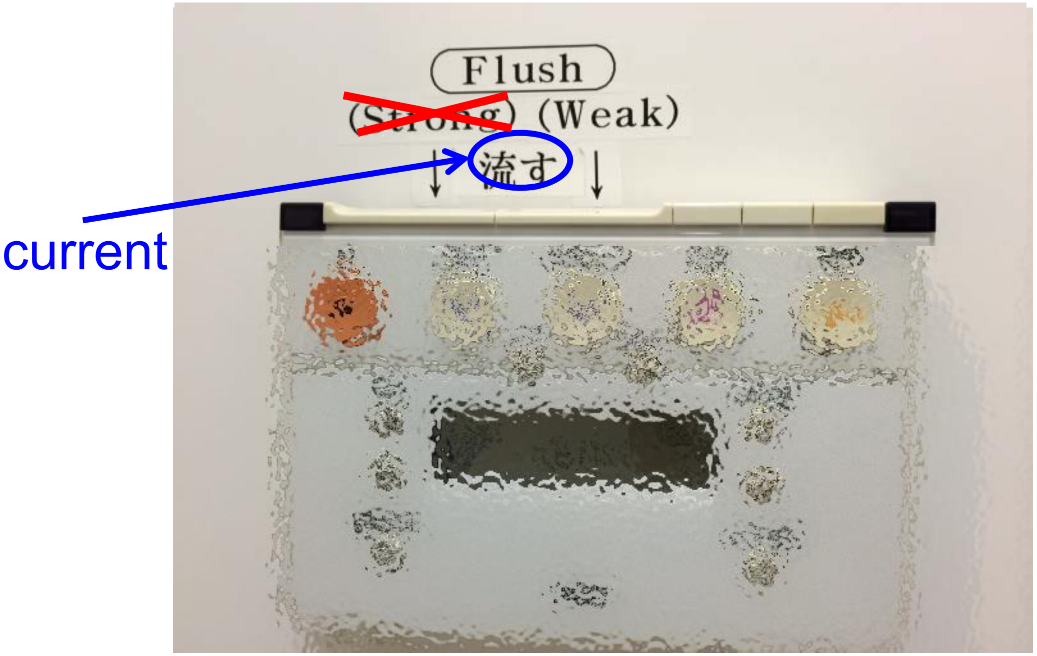
Quark vs. Neutrino



Quark vs. Neutrino



Quark vs. Neutrino



Interaction length of neutrinos from typical sources for ρ~1g/cm^3 material

- ☐ Atmospheric or accelerator neutrinos (~1GeV) : 10^8km ~ 1 AU
- ☐ Solar or reactor neutrinos (~MeV) : 10^{14}km ~ 100 light-year

Quark vs. Neutrino – Oscillation-

time evolution of mass eigenstate: m_i

$$e^{-i(Et-px)}$$

quark

"rest flame" approximation

$$e^{-i(Et-px)} \cong e^{-im_i t}$$

modulation frequency = Δm

⇒ O(nano~pico-sec.)

neutrino

ultra-relativistic approximation

$$e^{-i(Et-px)} \cong e^{-i\left\{EL-\left(E-\frac{m_i^2}{2E^2}\right)L\right\}}$$

$$= e^{-i\frac{m_i^2}{2E}L}$$

modulation frequency = Δm^2

⟹ O(mili-scond)~O(100km)

$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu_\alpha \rangle\right|^2 = \sin^2 2\theta \sin^2(\Delta m^2 \frac{L}{4E})$$

One Page Summary

Mixing matrix of leptons

CP phase
KEY to understand the origin of matter dominant universe

Unknown

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

$\theta_{12} = 33° \pm 1°$

$\theta_{23} =$ How close to 45° ?

$\theta_{13} = 8.9° \pm 0.4°$

Unknown Mass ordering

normal: $m_1 < m_2 \ll m_3$

inverted: $m_3 \ll m_1 < m_2$

$\Delta m^2_{21} = 7.5 \pm 0.2 \times 10^{-5}$ eV²

$|\Delta m^2_{32}| = 2.44 \pm 0.06 \times 10^{-3}$ eV²

Big Impact
on 0ν double-β decay search
(hence on Majorana ν confirmation)
normal → 1 ton detector
inverted → > 100 ton detector
* ν_e mostly couple with m_1 and m_2
so mass is too small in case of normal ordering

Neutrino oscillations

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

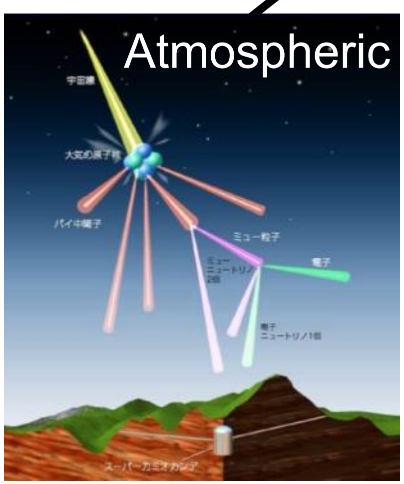
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

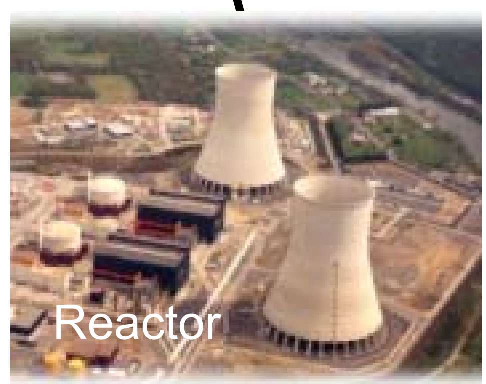
$\theta_{23,} |\Delta m^2_{32}|$

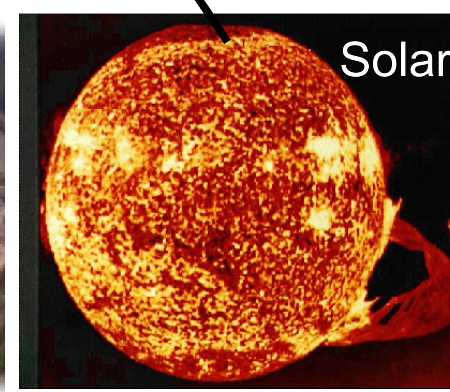
$\theta_{13,} \delta_{CP}$(, MO)

$\theta_{13,} |\Delta m^2_{32}|$(,MO)

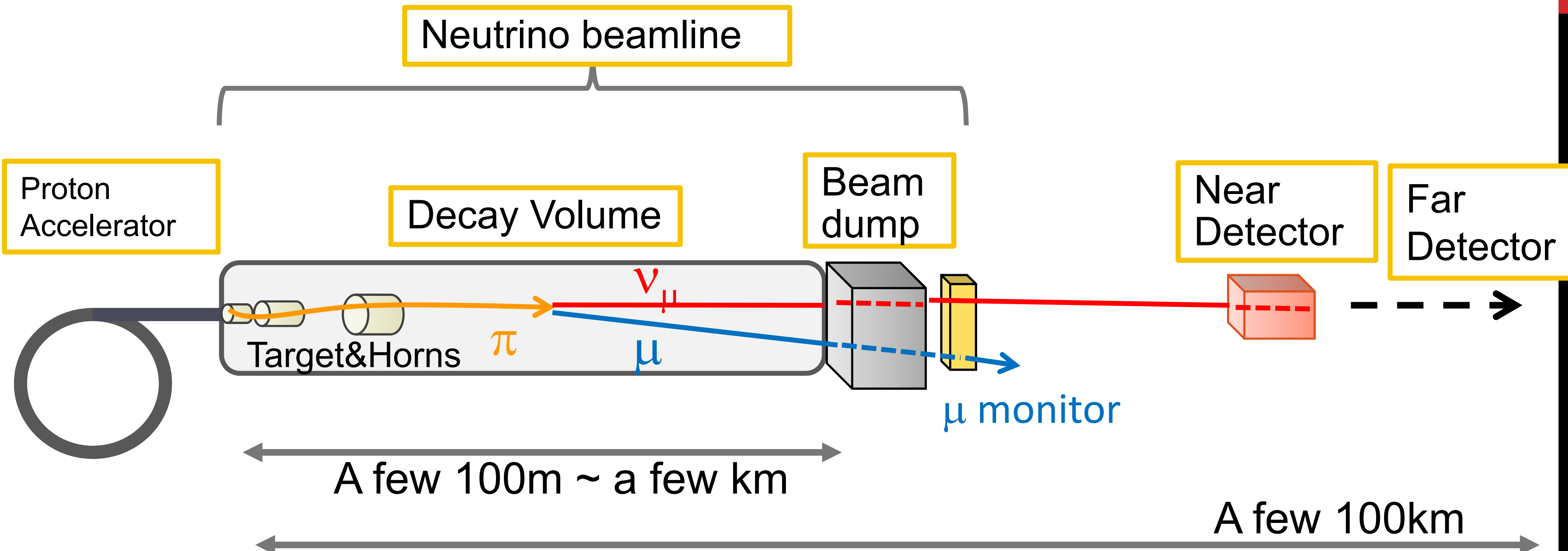
$\theta_{12,} \Delta m^2_{21}$







Components of the Long Baseline Neutrino Experiment



Toroidal magnetic field by `horn' focuses

$\pi^+ \rightarrow \nu_\mu$ beam

or

$\pi^- \rightarrow \bar{\nu}_\mu$ beam

Example:

~1ν/cm²/s at T2K Far detector(295km away)

(@750kW proton beam power)

Oscillations at the Long baseline Accelerator experiments

Δm_{21}^2 terms are small.

$\Delta m_{32}^2 (\sim \Delta m_{31}^2)$ terms are dominant → Can be simplified.

Leading Term

➢ θ_{23} : ν_μ disappearance

$$P(\nu_\mu \to \nu_x) \approx 1 - \underbrace{\sin^2 2\theta_{23}}_{\sim 1} \cdot \sin^2 (\Delta m^2 L / 4E_\nu)$$

$\Delta m^2 \approx \Delta m_{32}^2 \approx \Delta m_{31}^2$

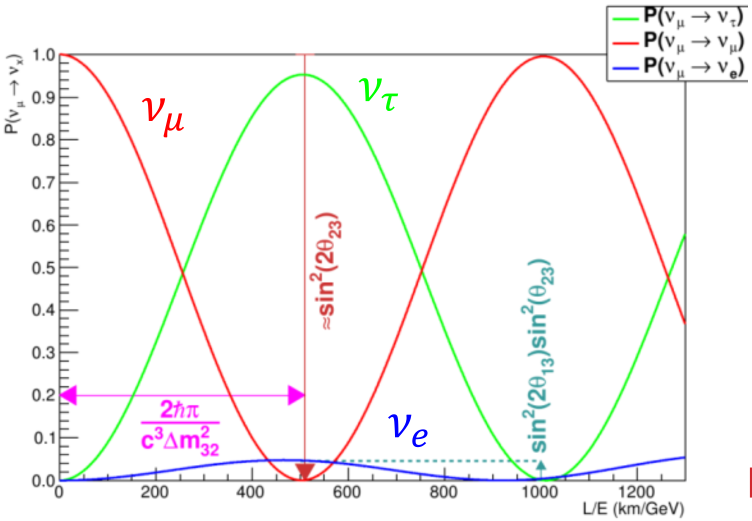
common baseline

➢ θ_{13} : ν_e appearance

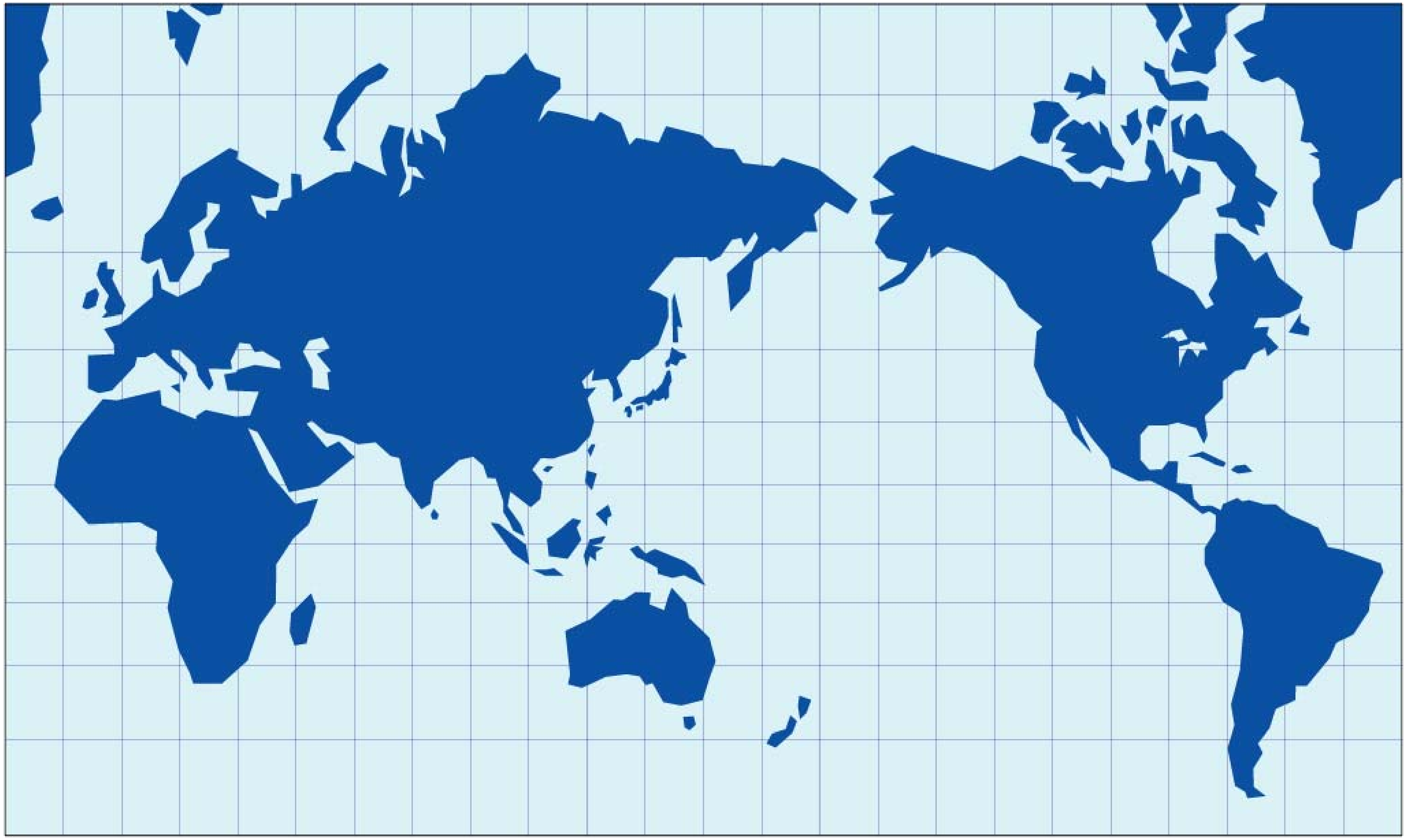
$$P(\nu_\mu \to \nu_e) \approx \underbrace{\sin^2 \theta_{23}}_{\sim 0.5} \underbrace{\cdot \sin^2 2\theta_{13}}_{\sim 0.1} \cdot \sin^2 (\Delta m^2 L / 4E_\nu)$$

➢ ν_τ appearance

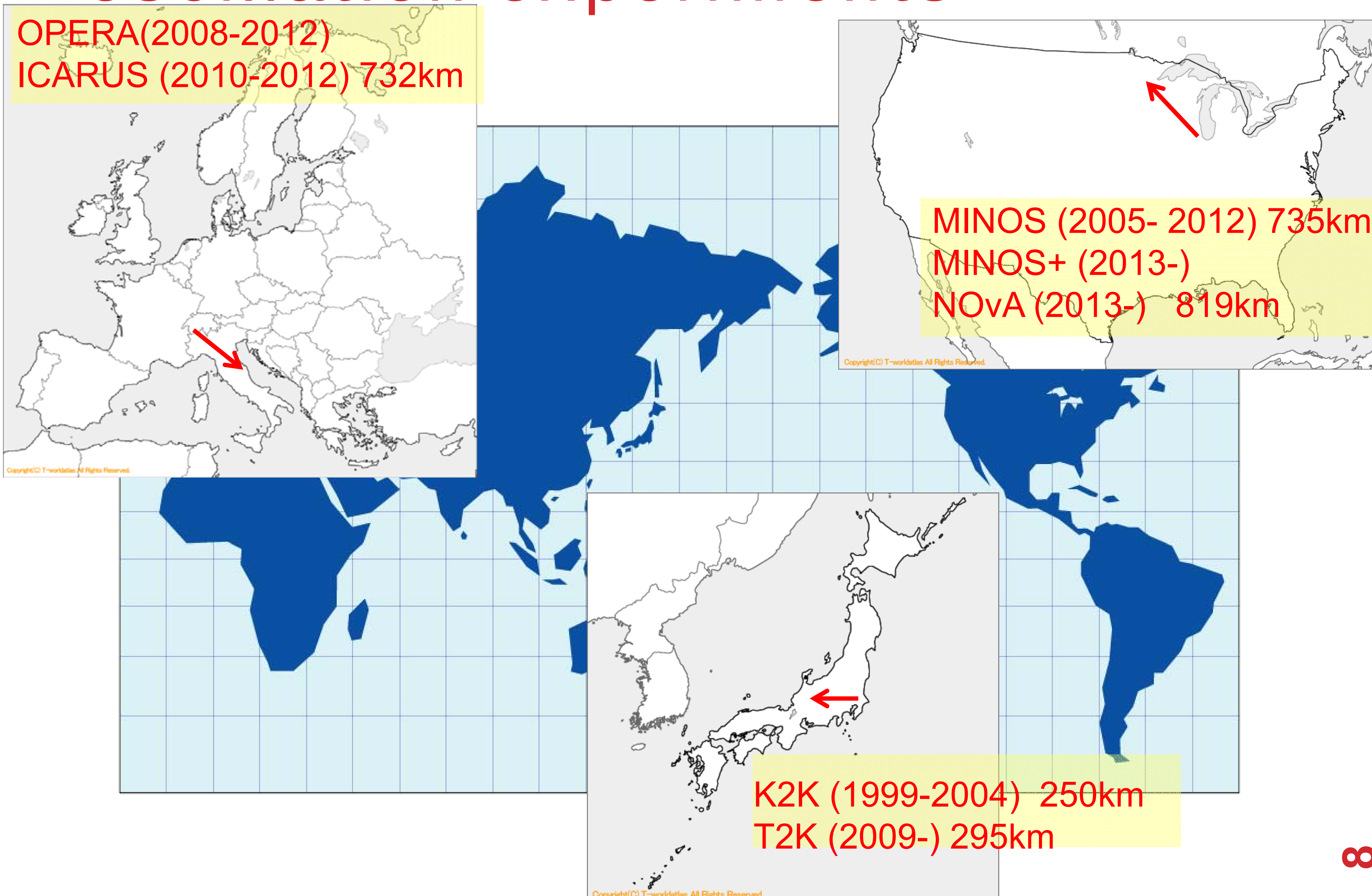
if energy is above τ production threshold (~3.5 GeV)



World Long baseline ν oscillation experiments

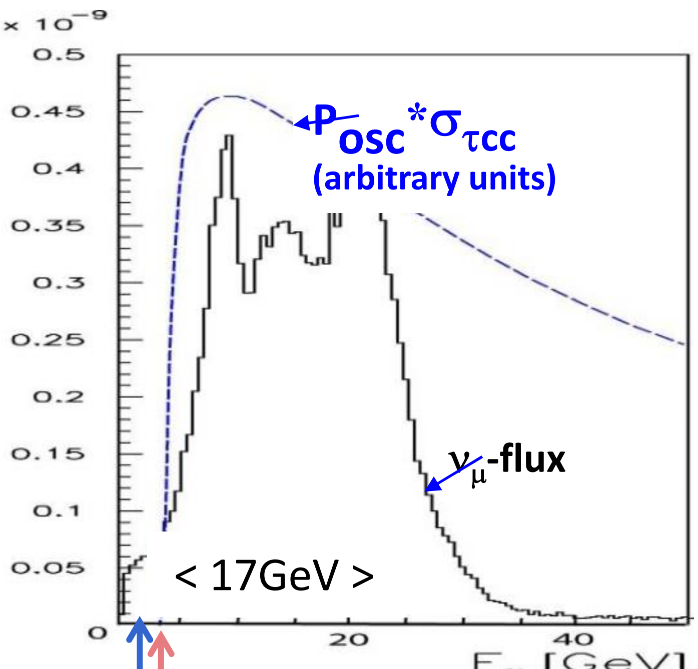


World Long baseline ν oscillation experiments



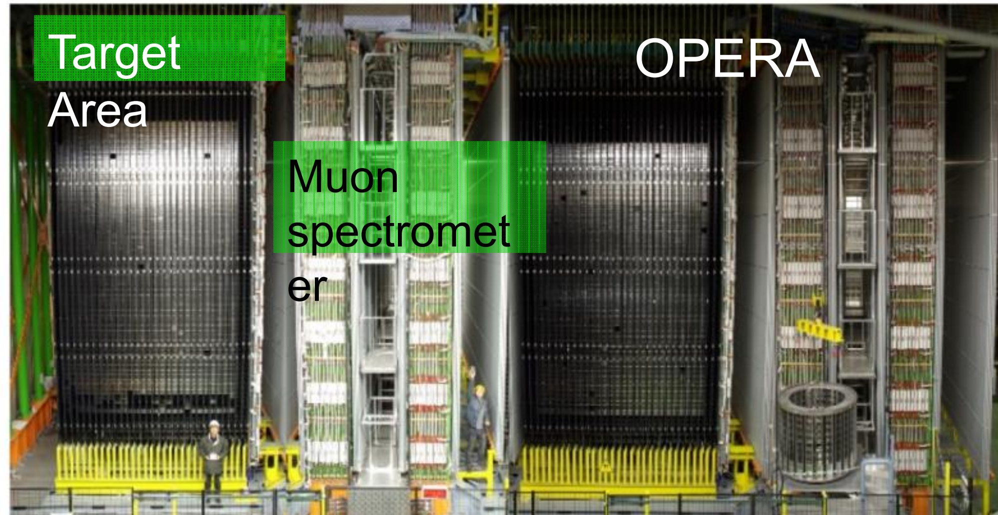
OPERA/ICARUS

neutrino beam x cross section

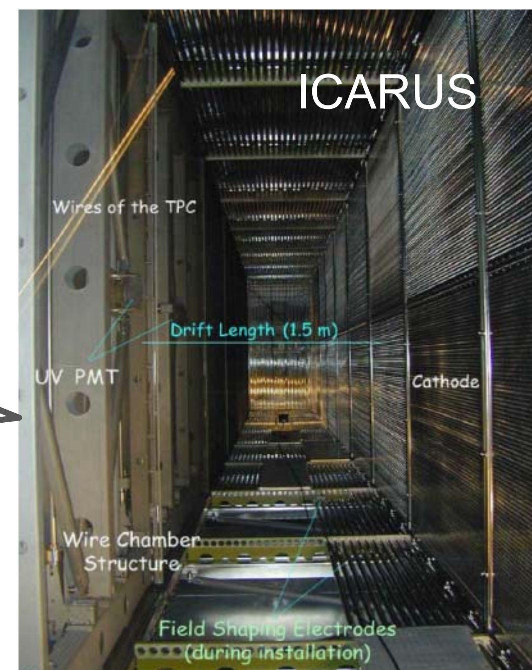


τ production threshold (~3.5 GeV)

Oscillation maximum (~1.4 GeV)

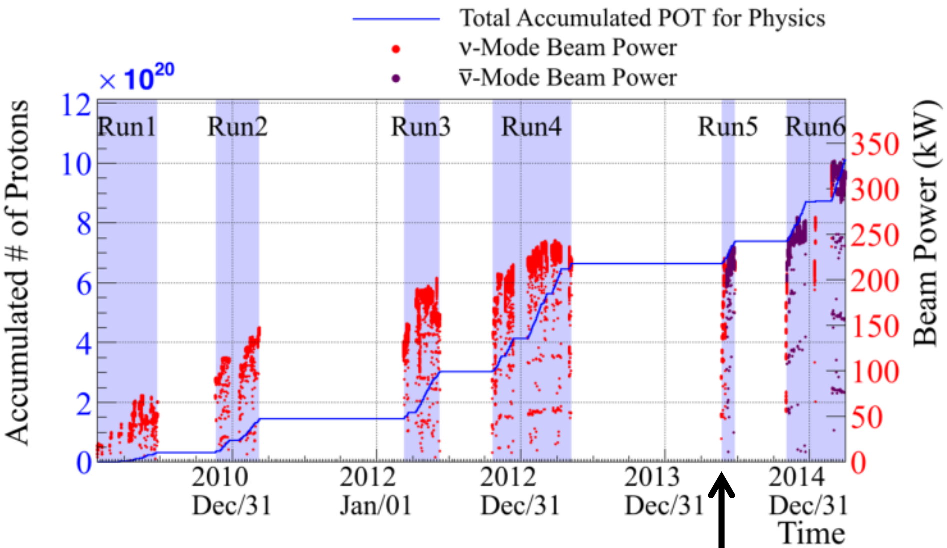


Nuclear emulsion to tag τ decay

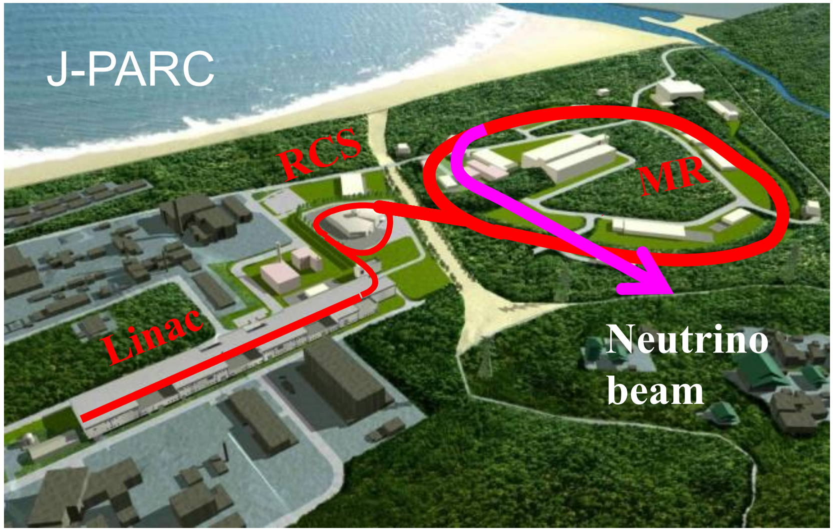


300 ton x 2 Liquid Ar

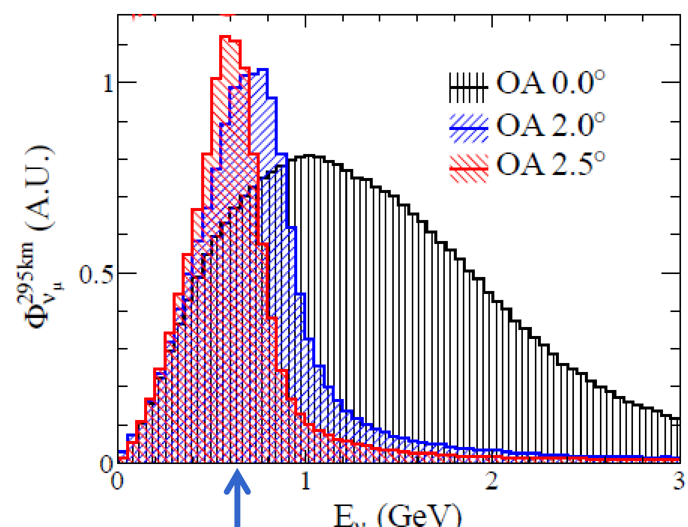
T2K -beam-



$\bar{\nu}$-mode



neutrino beam

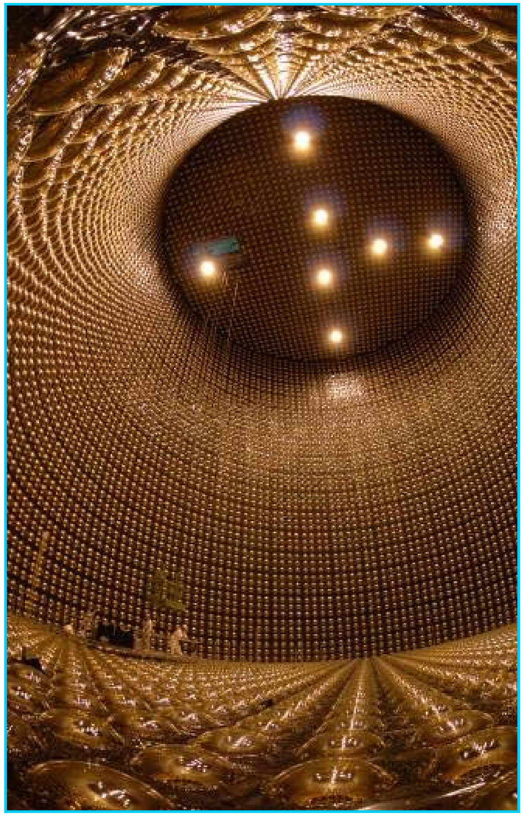


- Maximum beam power achieved
  345kW (goal 750kW)
- Integrated protons-on-target
  7.0×10^{20}(ν beam) + 3.1×10^{20}($\bar{\nu}$ beam)
  (goal 78×10^{20} in total)

running at OA2.5˚

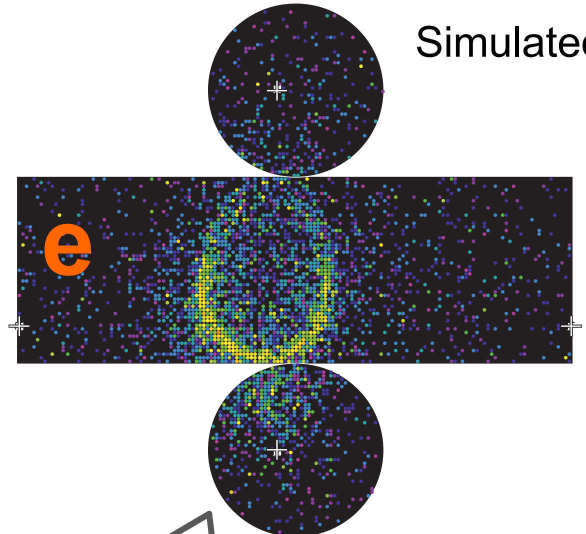
Oscillation maximum (~0.6 GeV)

T2K - Far detector -

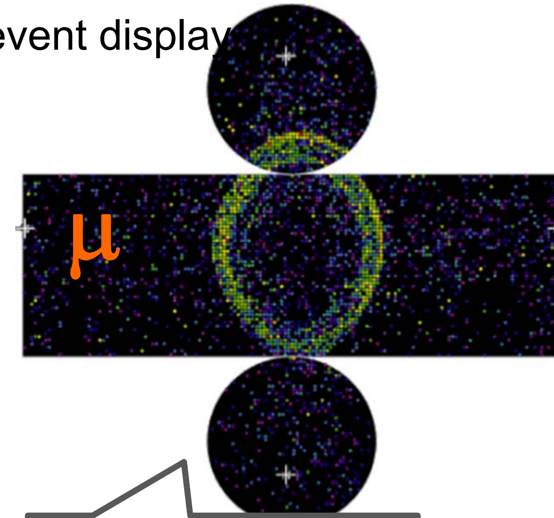


Water Cherenkov Detector

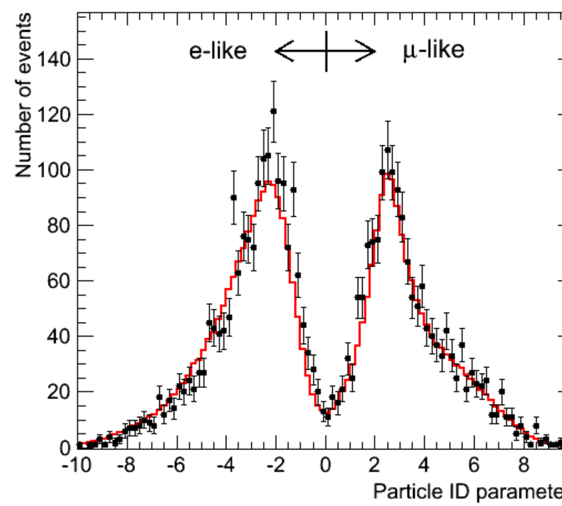
Simulated event display



Signal for ν_e appearance

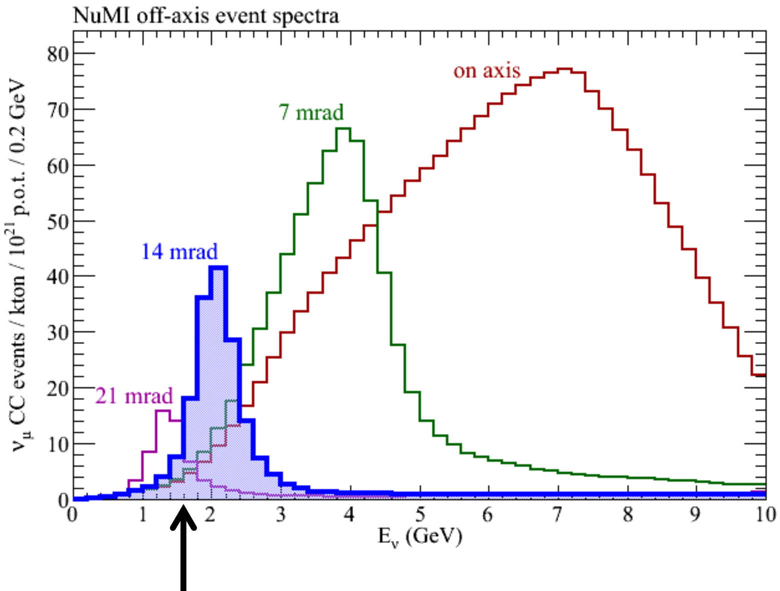


Signal for ν_μ disappearance

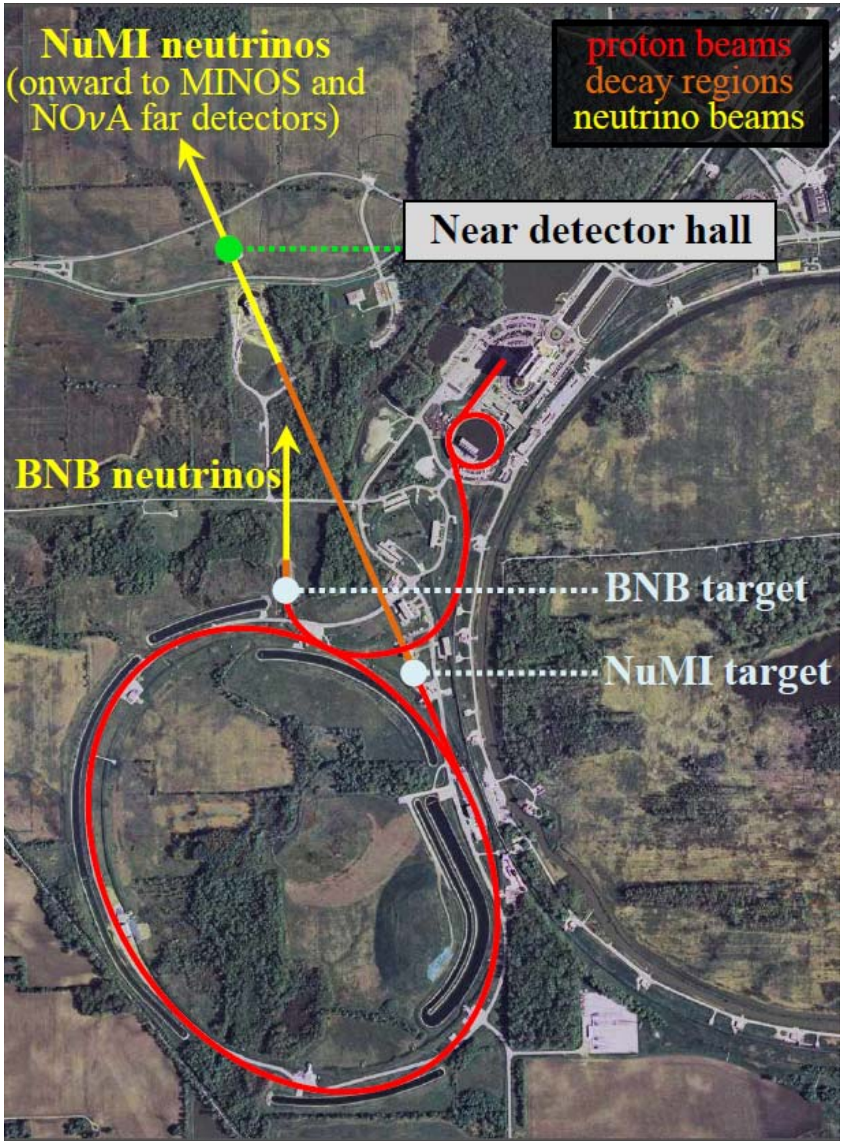


Very good PID for sub-GeV particles
mis-identification ~1%

NOνA –beam-



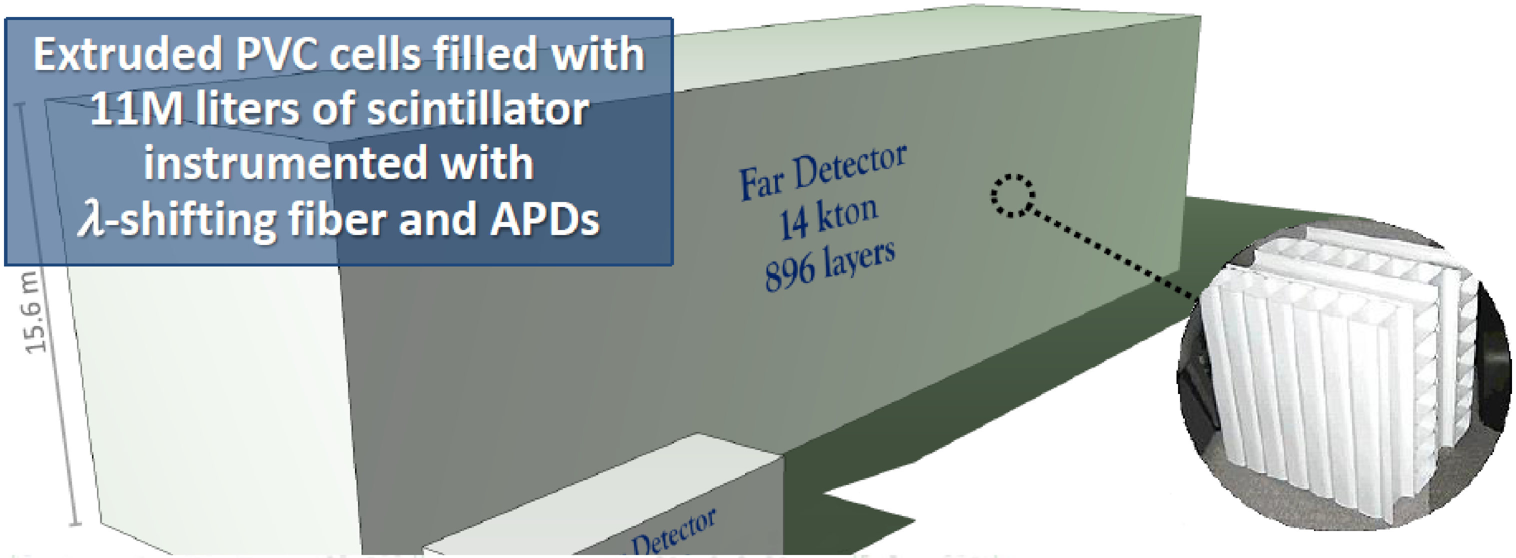
Oscillation maximum (~1.6 GeV)

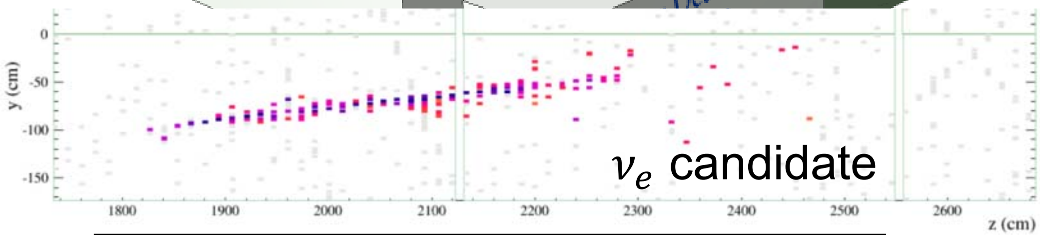


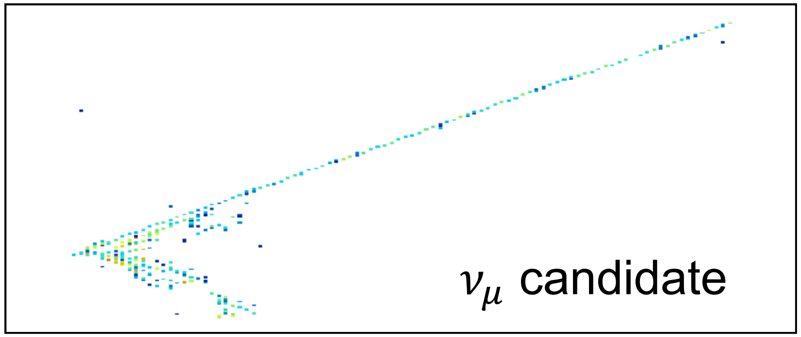
start in 2013.
Now running at 420kW (goal:700kW)

NOνA detectors

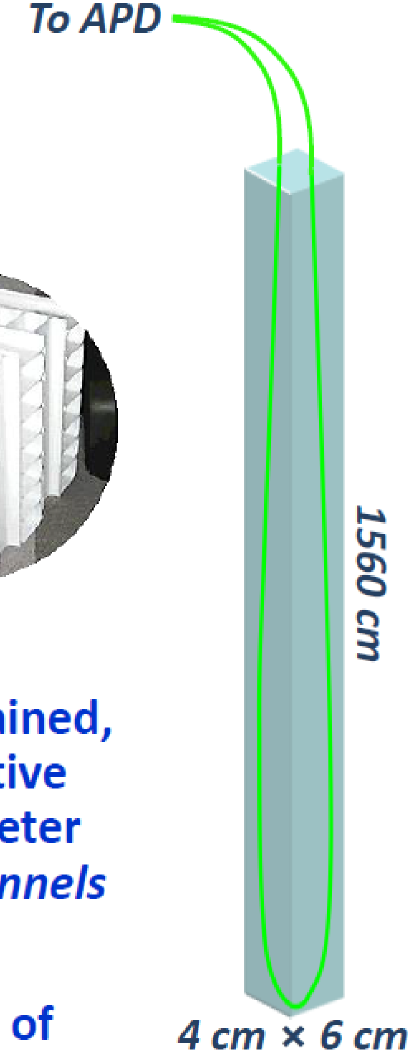
Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs







A NOνA cell



Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter

→ *344,000 channels*

Near detector:

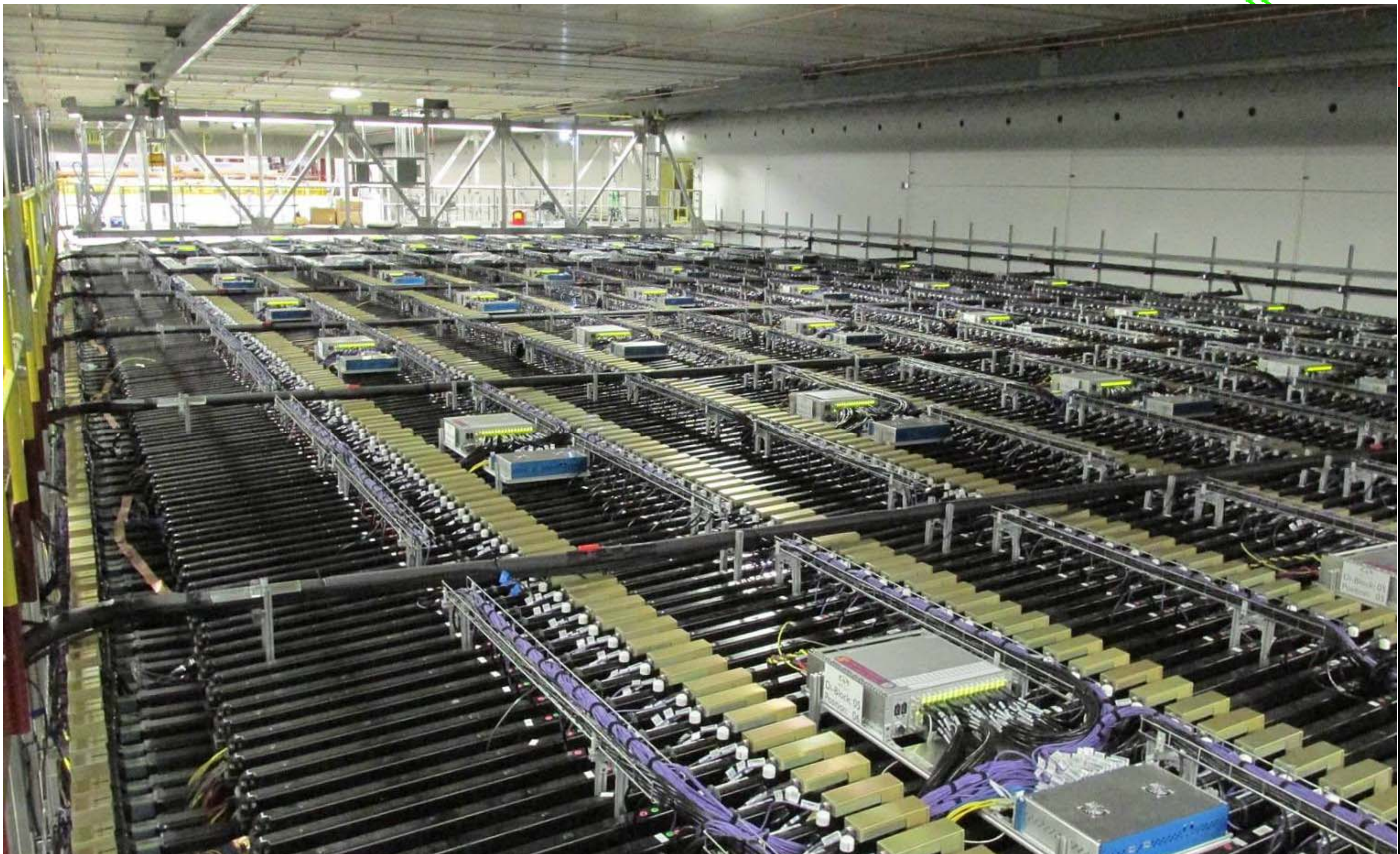
0.3-kton version of the same

→ *18,000 channels*

NOνA detectors

A NOνA cell

To APD

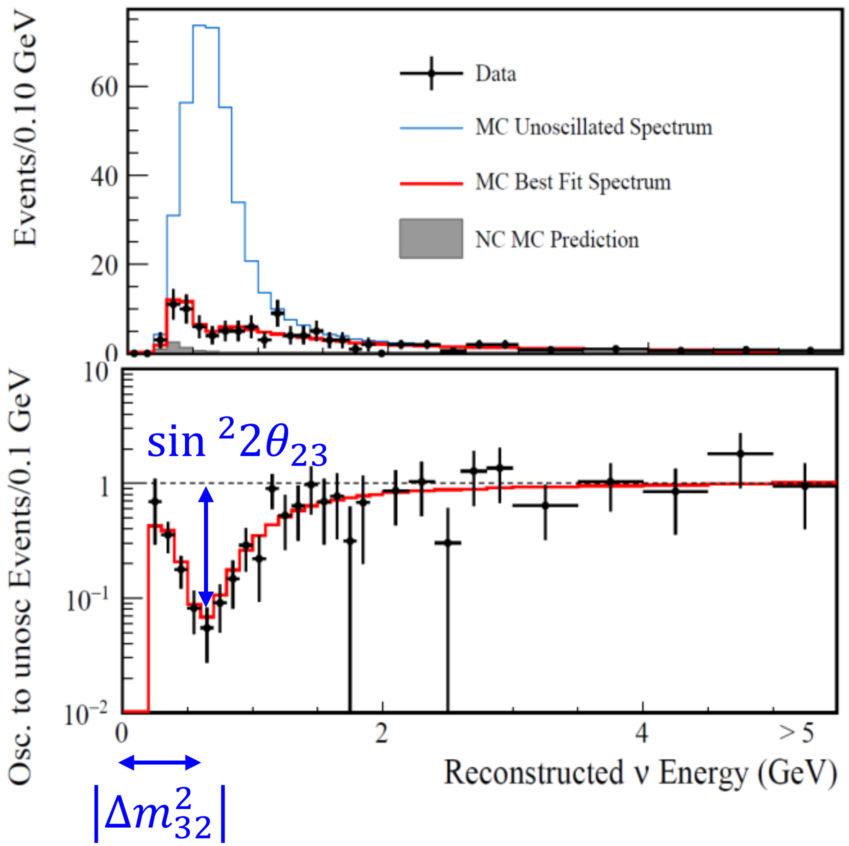


World Long baseline ν oscillation experiments

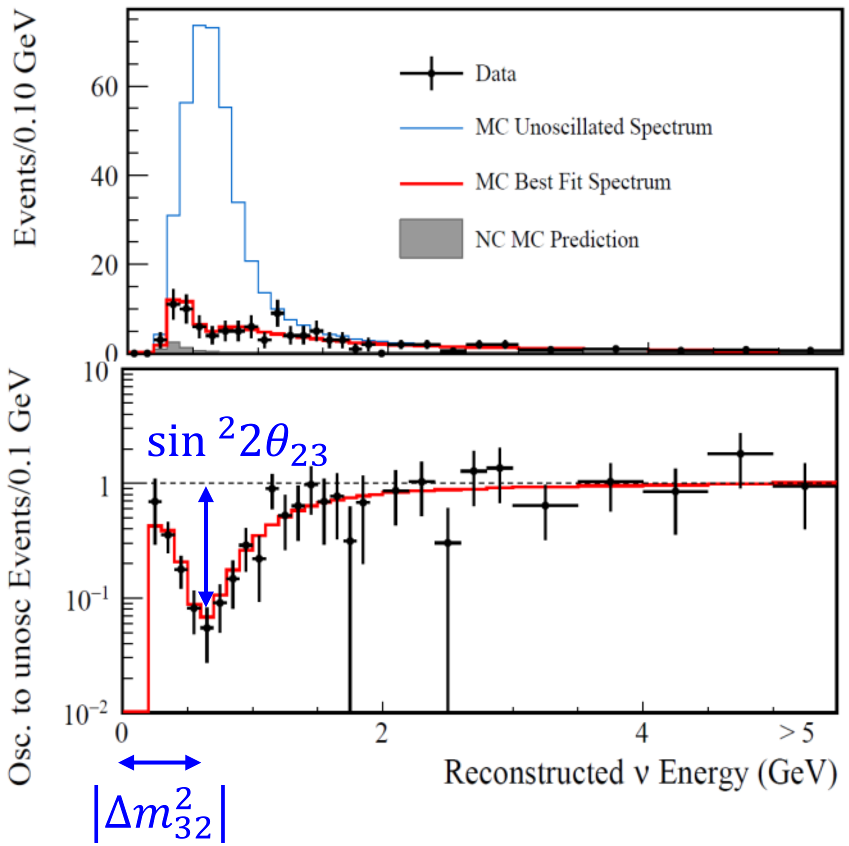
	Accelerator		Detector
	Energy	Power(Planned)	
K2K	12 GeV	7kW	50kt
MINOS	120 GeV	400 kW	5.4kt
OPERA/ICARUS	400 GeV/c	500kW	1.2kt/0.6kt
T2K	30 GeV	350kW (750kW)	50kt
NOvA	120 GeV	420kW (700kW)	14kt

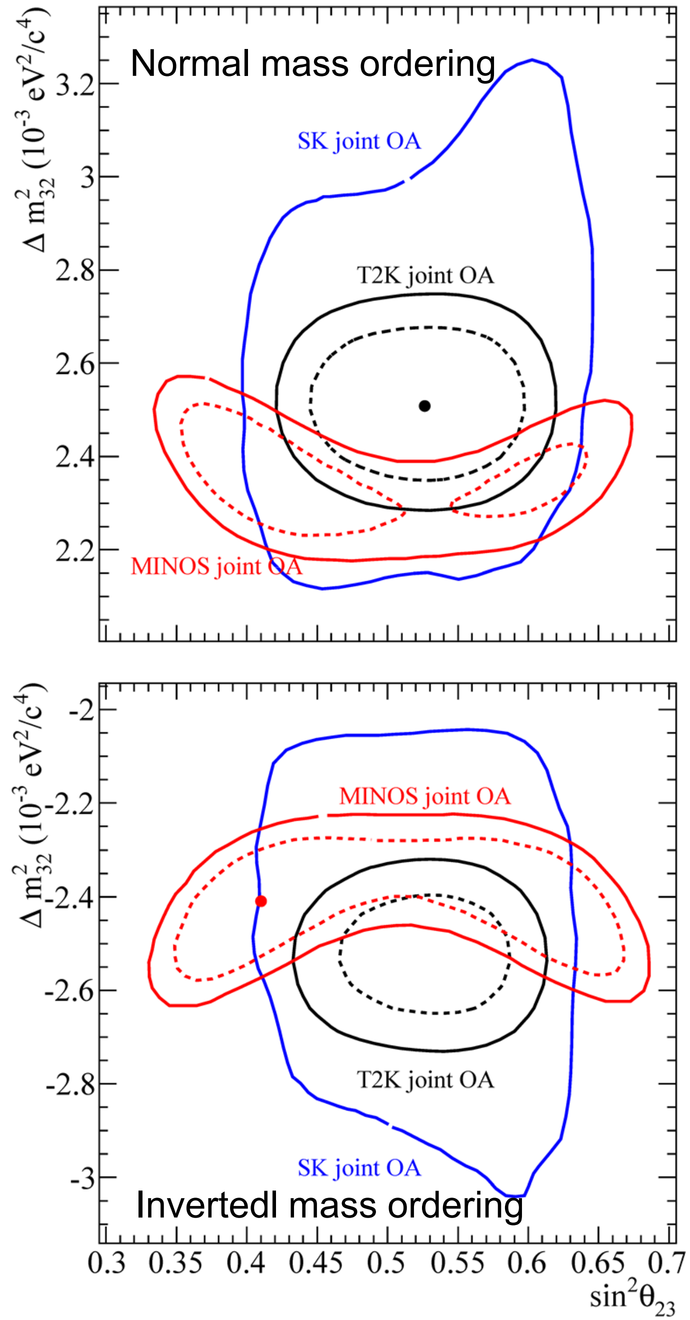
ν_μ disappearance
- Is θ_{23} 45° ? -

T2K w/ data till 2013 May



T2K w/ data till 2013 May





$46° \pm 3°$

T2K

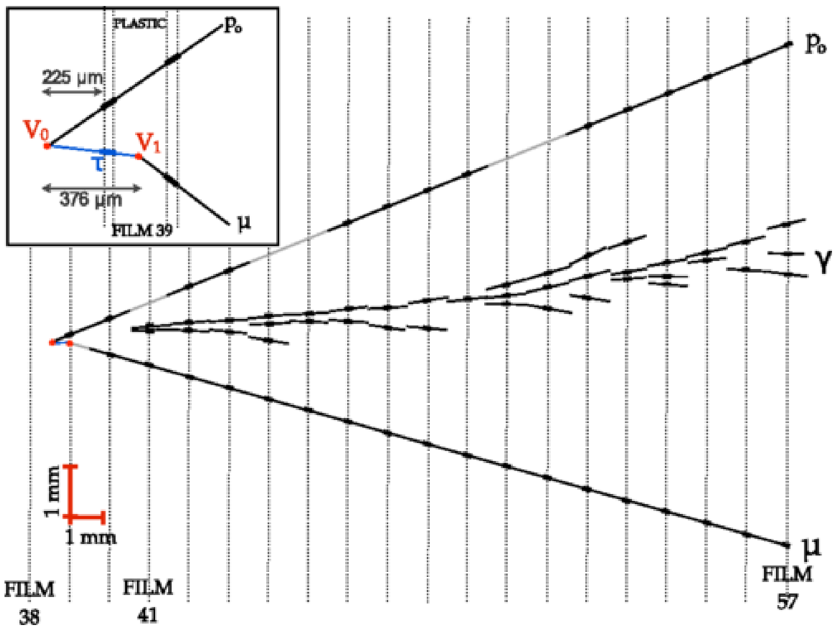
Phys. Rev. D 91, 072010 (2015)

$\boldsymbol{\nu_\tau}$ appearance

- Did disappeared ν_μ really changes to ν_τ? -

OPERA

3.8σ ν_τ appearance by Super-K atmospheric data *(Abe et al., PRL 110, 181802 (2013))* from a sample of enhanced τ-like events.
OPERA identifies τ production in event-by-event basis.



$\tau^- \to \mu^-$ decay, Phys. Rev. D 89, 051102(R) (2014)

4 ν_τ candidates

Decay channel	Expected signal	Observed	background
$\tau \to 1h$	0.41 ± 0.08	2	0.033 ± 0.006
$\tau \to 3h$	0.57 ± 0.11	1	0.155 ± 0.030
$\tau \to \mu$	0.52 ± 0.10	1	0.018 ± 0.007
$\tau \to e$	0.62 ± 0.12	0	0.027 ± 0.005
Total	2.11 ± 0.42	4	0.233 ± 0.041

Prog. Theor. Exp. Phys. **2014**, 101C01

$\nu_\mu \to \nu_\tau$ oscillation is confirmed by 4.2σ significance

ν_e appearance

- Golden mode for CP phase and mass ordering-mixing matrix (PMNS)

$\nu_\alpha \to \nu_\beta$ oscillation

$$|\nu_\alpha(L)\rangle = U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}$$

$$\therefore \langle \nu_\beta | \nu_\alpha(L) \rangle = U_{\beta i}^* U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}$$

if $\beta = \alpha$

$$\langle \nu_\alpha | \nu_\alpha(L) \rangle = |U_{\alpha i}|^2 e^{-i\frac{m_i^2}{2E}L}$$

Imaginary part vanishes!

Appearance is necessary to see CP violation

ν_e appearance (complete version in vacuum)

Leading term

$$P(\nu_\mu \to \nu_e) = 4C_{13}^{\ 2}S_{13}^{\ 2}S_{23}^{\ 2}\sin^2\Phi_{31}$$ θ_{13}

$$+8C_{13}^{\ 2}S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPC

$$-8C_{13}^{\ 2}C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPV

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

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}$$

$$\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

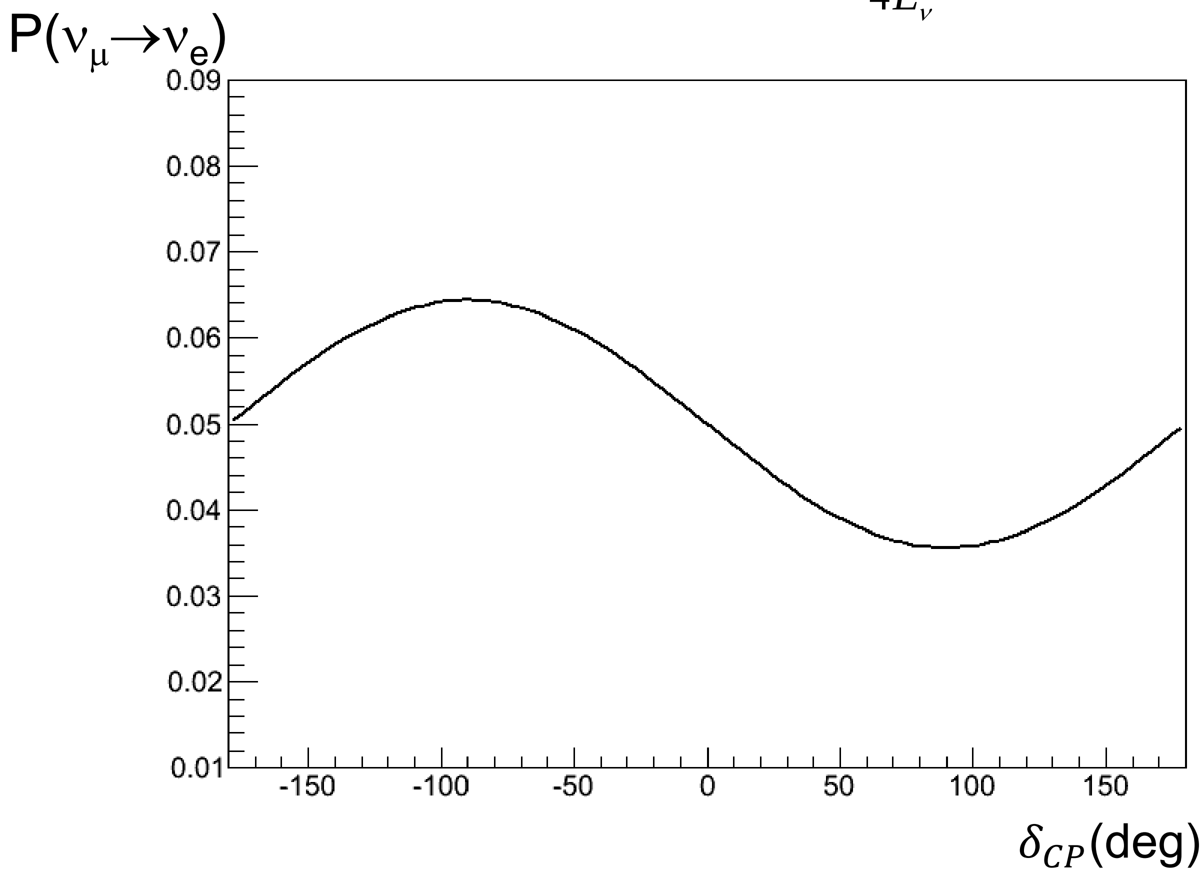
$\delta \to -\delta$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

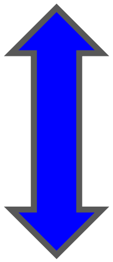
CP violating term introduced by interference btw. θ_{13} and θ_{12}

ν_e appearance at oscillation maximum

$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \qquad -8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin\delta$$

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$





±27% effect
for $\theta_{23} = 45°$

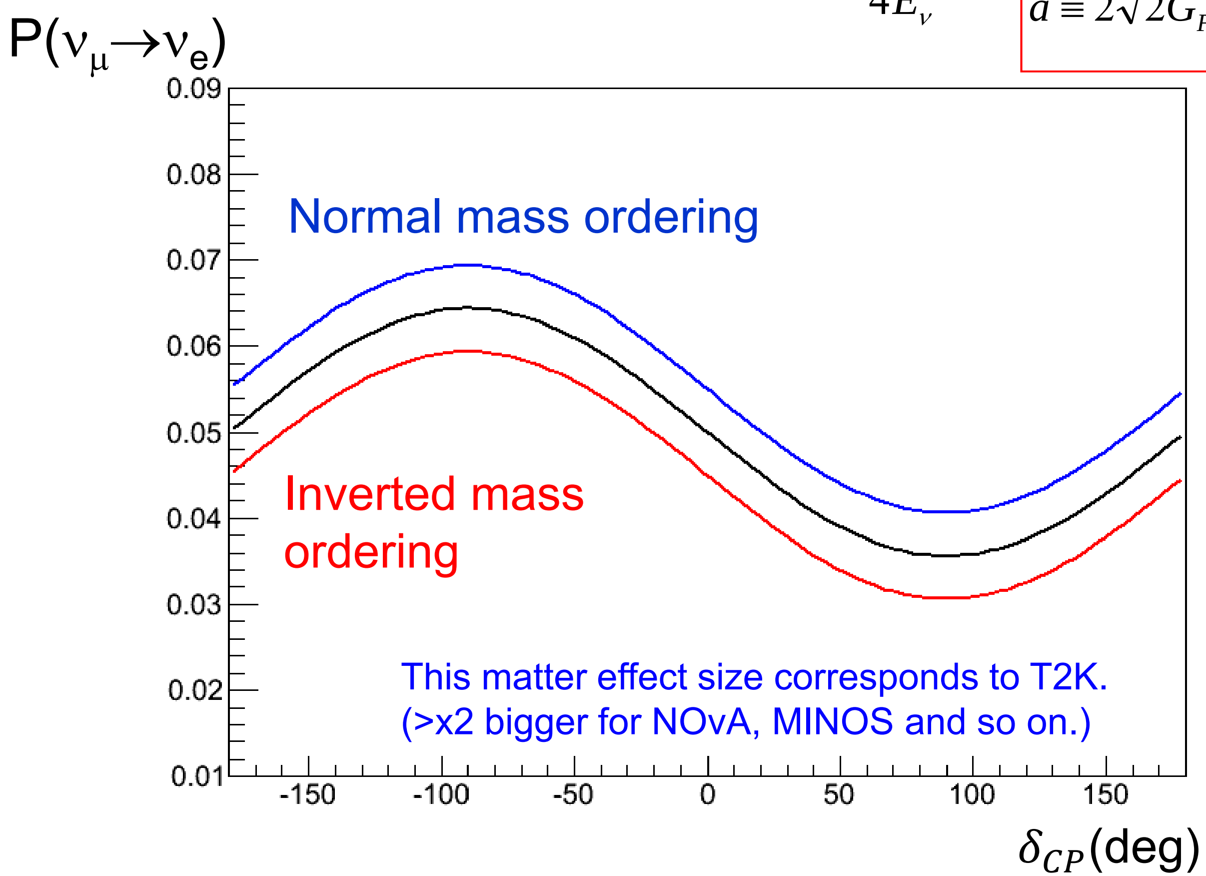
ν_e appearance at oscillation maximum

$$P(\nu_\mu \to \nu_e) \cong 4C_{13}^{\ 2}S_{13}^{\ 2}S_{23}^{\ 2}\left(1+\frac{2a}{\Delta m_{31}^2}\right) - 8C_{13}^{\ 2}C_{12}C_{23}S_{12}S_{13}S_{23}\Phi_{21}\sin\delta$$

Matter effect

$$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij}, \qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\mathrm{eV}^2 \frac{\rho}{g\mathrm{cm}^{-3}}\frac{E}{GeV}$$



ν_e feels different potential than ν_μ and ν_τ in earth.

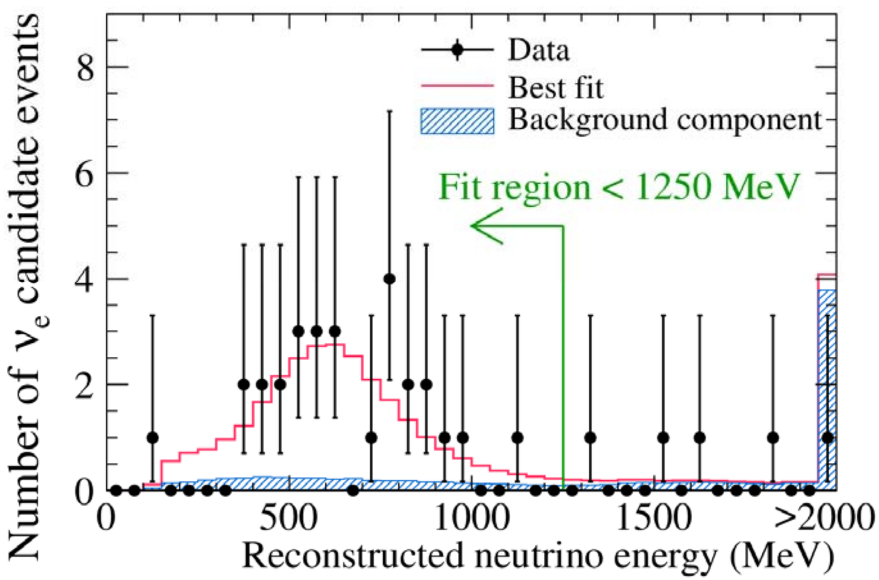
$\pm$27% effect for $\theta_{23} = 45°$

$\delta \to -\delta$, $a \to -a$ for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

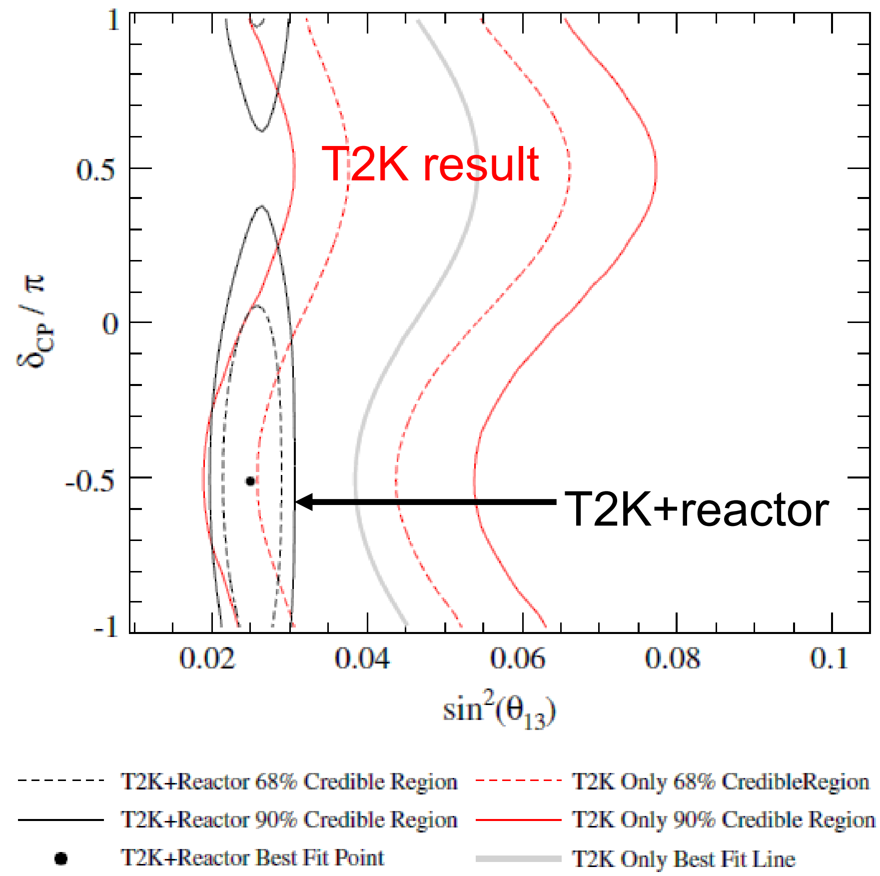
ν_e appearance by T2K

released in August 2013 w/ data till May 2013

Phys. Rev D.91, 072010(2015)

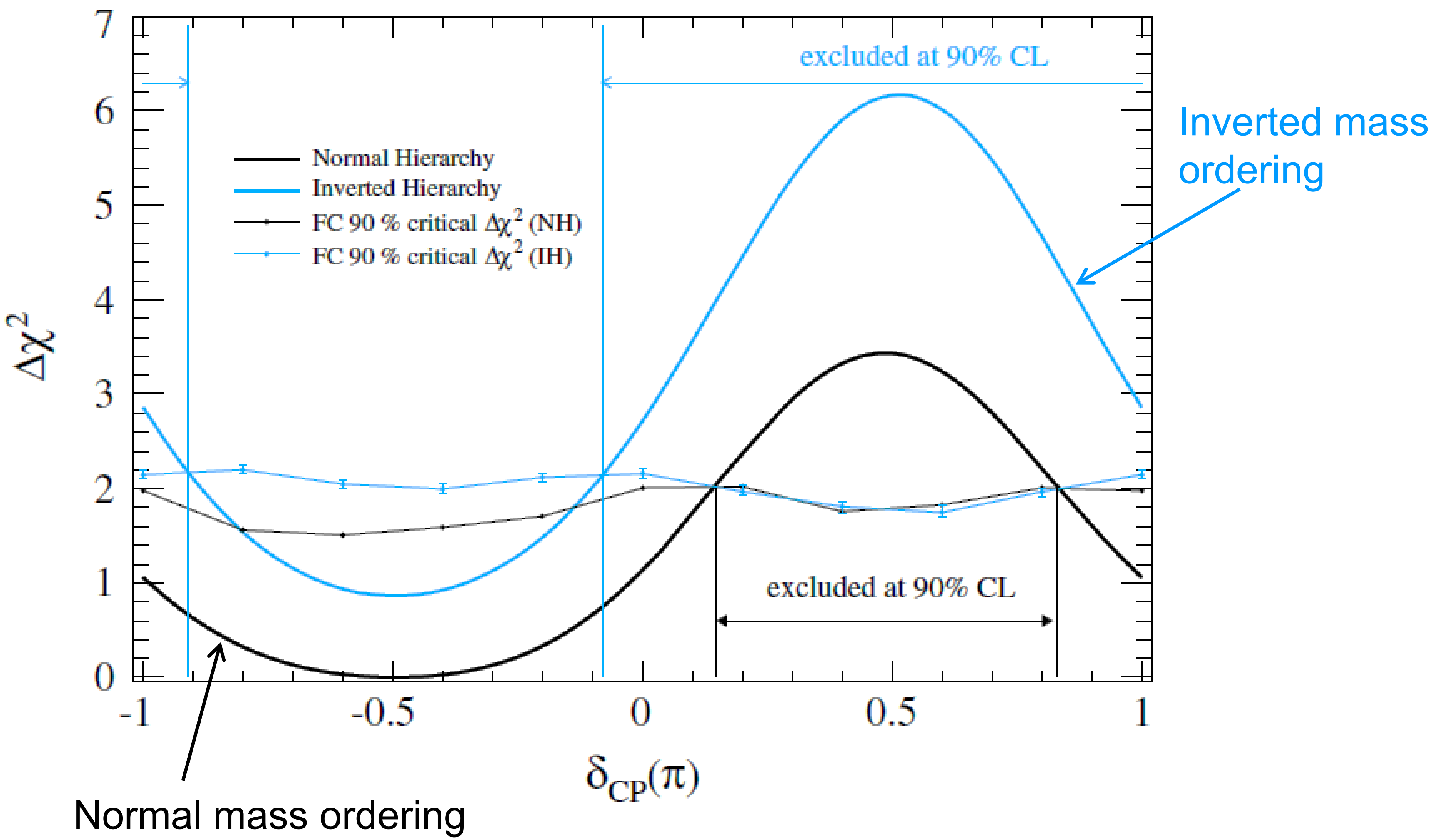


PhysRevLett.112.061802 (2014)



28 events observed over 4.92$\pm$0.55 bkgs $\rightarrow$ 7.3σ excess
First Confirmation of 'Appearance phenomenon' w/ > 5σ significance.

First constraint on δ_{CP} by T2K



Phys. Rev D.91, 072010(2015)

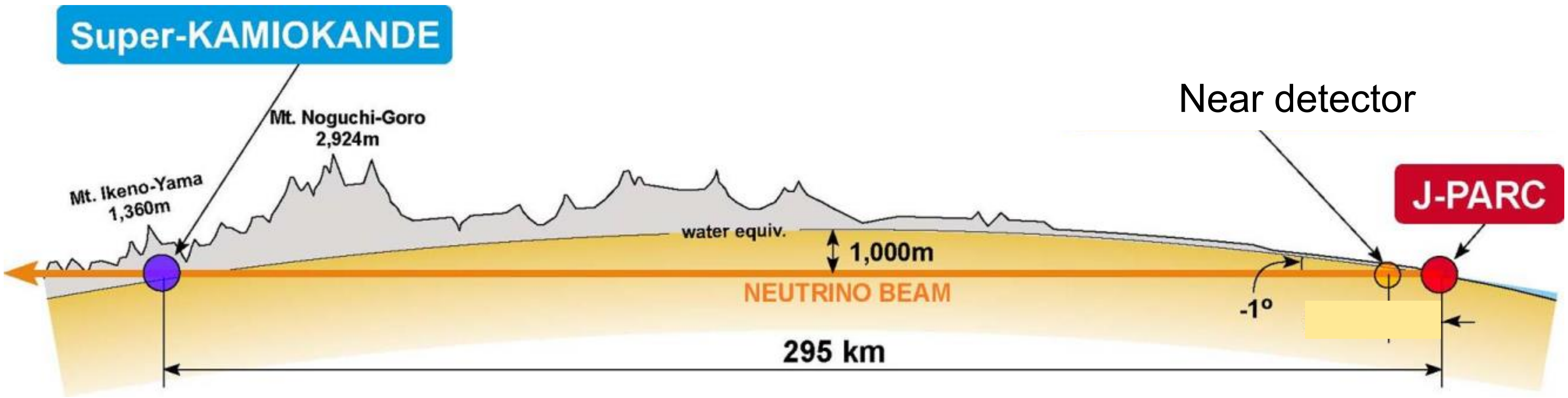
Measurements with antineutrino

An important step towards CPV measurement

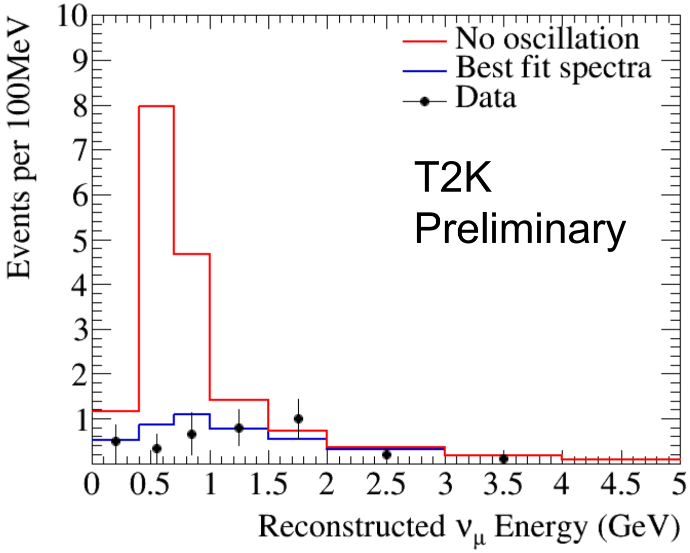
Unique test of new physics

$\bar{\nu}_\mu$ disappearance

- **CPT theorem** $\Rightarrow P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
- $\nu_\mu/\bar{\nu}_\mu$ **disappearance is insensitive to matter effect.**
- **If we observe** $P(\nu_\mu \to \nu_\mu) \neq P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$**, it may be due to CPT violation or non-standard interaction with matter.**

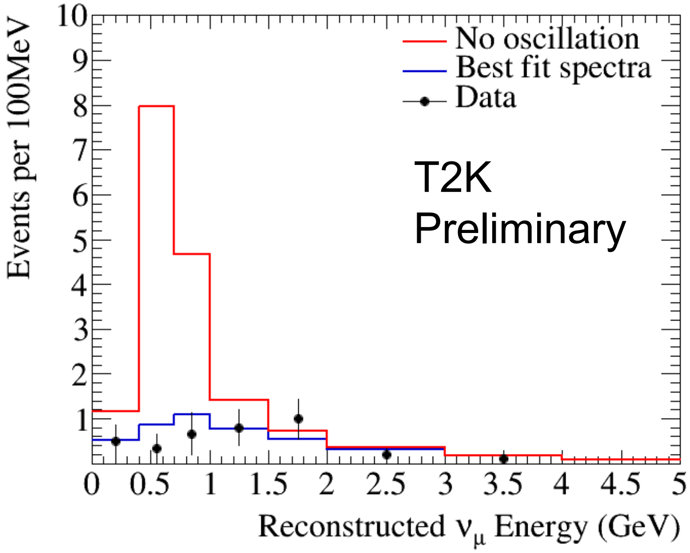


T2K w/ $\bar{\nu}$ beam data till Mar 12 2015 (2.3x10^{20}POT)

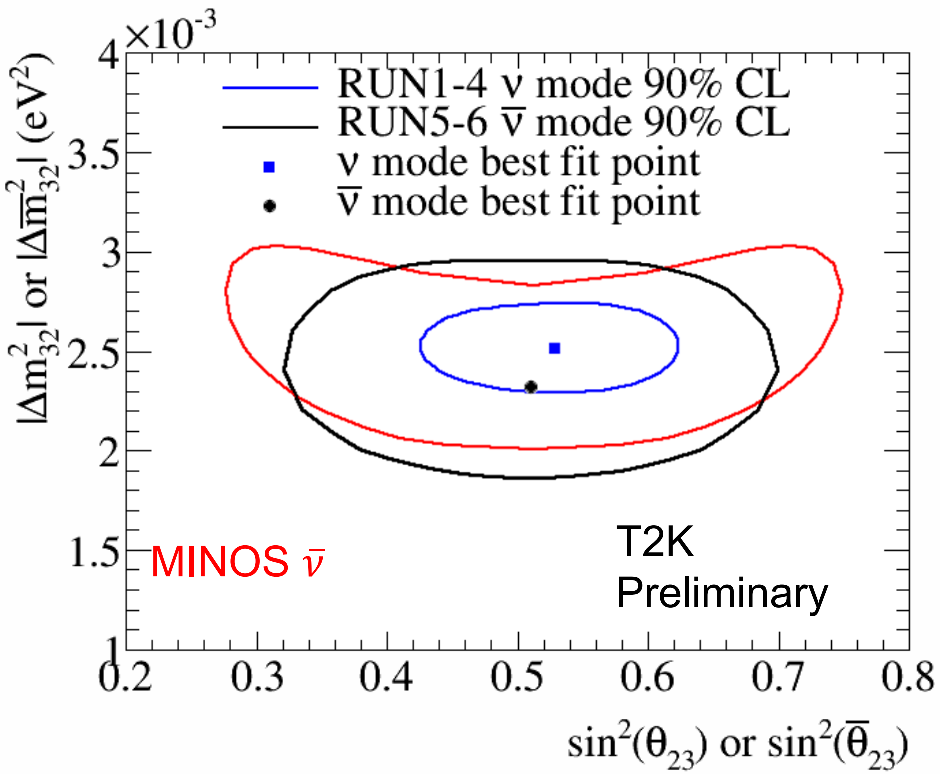


Released on 18 May 2015

T2K w/ $\bar{\nu}$ beam data till Mar 12 2015 (2.3×10^{20}POT)



Released on 18 May 2015



Consistent with ν_μ disappearance

(Near future) Prospects

T2K and NOνA is accumulating data.

T2K : 13% so far

NOνA : 5%?

Do they have a sensitivity to CPV and mass ordering with full statistics?

Expected # of events w/ typical assumptions (*)

T2K : 106 ν_e, 24 $\bar{\nu}_e$

NOνA : 68 ν_e, 32 $\bar{\nu}_e$

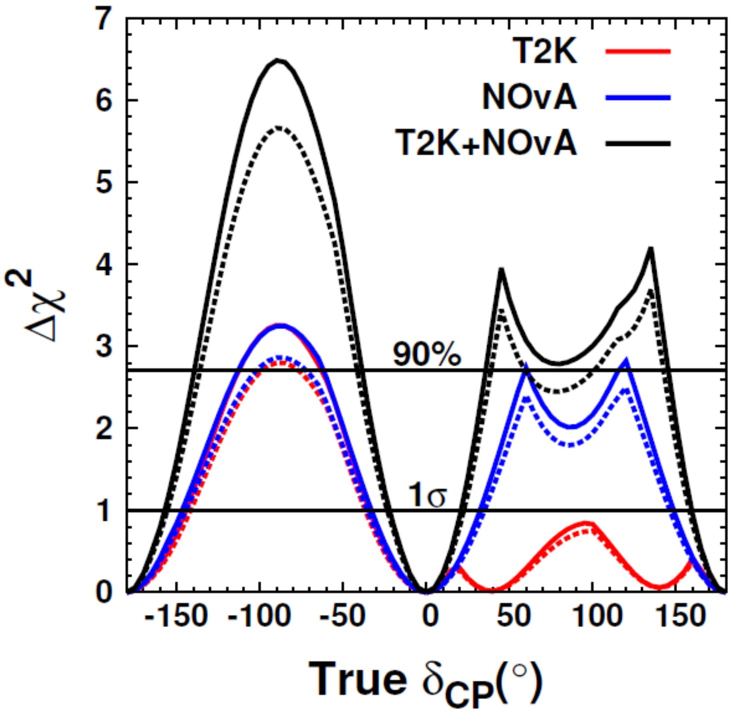
, while CPV effect is 27% at maximum and NOνA matter effect is 30%

(*) Not the latest number

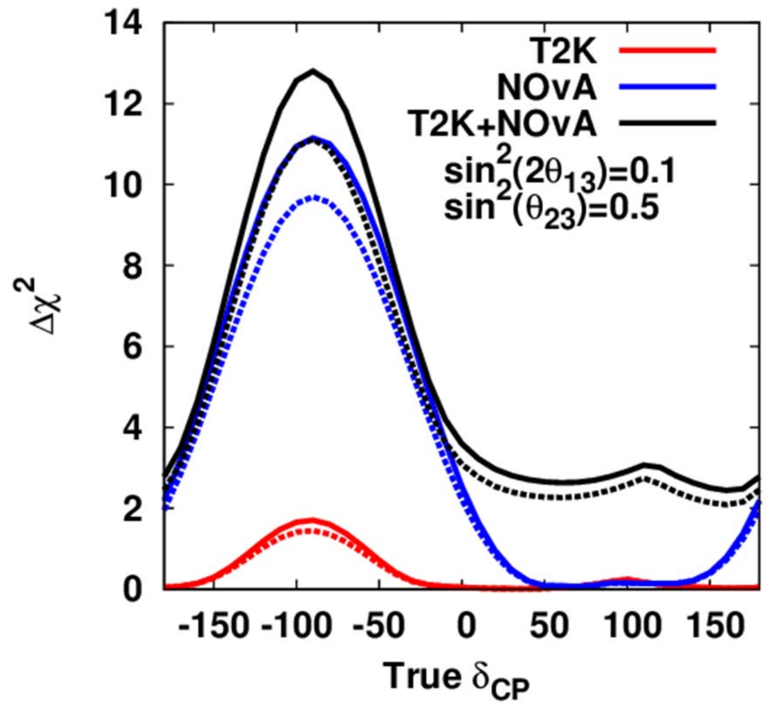
T2K and NOνA combined sensitivity at full statistics

Shown is Normal mass ordering case.

CP violation



Mass Ordering



Big enhancement of sensitivity by combining two experiments having different baseline length

solid: stat. only
dashed: assuming 5% normalization uncertainty on signal and 10% normalization uncertainty on background

Prog. Theor. Exp. Phys. (2015) 043C01 by T2K collaboration

Summary

- **In these 20 years, the skeleton of lepton flavor-mass mixing become significantly clear!**
- **Missings are δ_{CP}, maximal or non-maximal θ_{23} and mas ordering**
  - In a few years, we may see answers with T2K and NOνA
  - Future projects (Hyper-Kamiokande and DUNE) will thoroughly explore these targets.
- **Neutrino has always produced 'surprising'. New physics may appear**
  - oscillation not explained by PMNS framework?
    - Sterile neutrino?
  - Non-standard interaction with matter
  - Lorentz violation at the Plank scale?
  - Precise measurements by both disappearance and appearance and using both CC and NC interactions are desired.
- **$\bar{\nu}_\mu$ disappearance by T2K just released.**
- **In this summer, new results from T2K and NOνA are expected!**