Prospects in Neutrino Physics

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FKPPL/FJPPL(TYL) workshop
Jeju Island, 9 May 2019

Disclaimers

1) Due to limited time, mainly focus on:
FJPPL(TYL)-related projects T2K, Hyper-K, SK
and Korea-related T2HKK
Not covering natural-source neutrino studies
(atmospheric ν, solar-ν, supernova-ν)
and reactor experiments (e.g. RENO, JUNO)

2) Quoted slides from recent workshop
"Prospects of Neutrino Physics"
8-12 April 2019, Kavli IPMU, Japan
https://indico.ipmu.jp/indico/event/236/

Why study neutrinos?

1) 2nd ubiquitous particle in Universe (than photon)
→ should have played crucial role in early Universe

2) Very small mass: (but not zero!)
$m(\nu) < \sim 1\text{eV}$ ($m_e = 0.511$ MeV) → Natural to think different mass mechanism than Higgs

3) Neutral lepton: Very weak interaction with matter
(mean free path of E ~ 1 MeV ν in water:
~ 10^{15} km = 100 light-years)
→ experiments would be exciting and fun!

What to study about ν's?

1) Oscillation phenomena (mixing matrix - see next)

→ 3 mixing angles and CP violation phase

(main topics covered in this talk)

2) Neutrino masses:

Mass^2 differences and ordering: from osc. expt's

Absolute mass: $0\nu2\beta$, direct β and cosmology

(not covered)

3) Other properties: (not covered)

Are there more than 3 ν's? → Sterile ν search

Magnetic moment, EDM, ⋯

Neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix
(Pontecorvo-Maki-
Nakagawa-Sakata)

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \bigcirc{e^{i\delta}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{23} = \cos\theta_{23}$, etc.

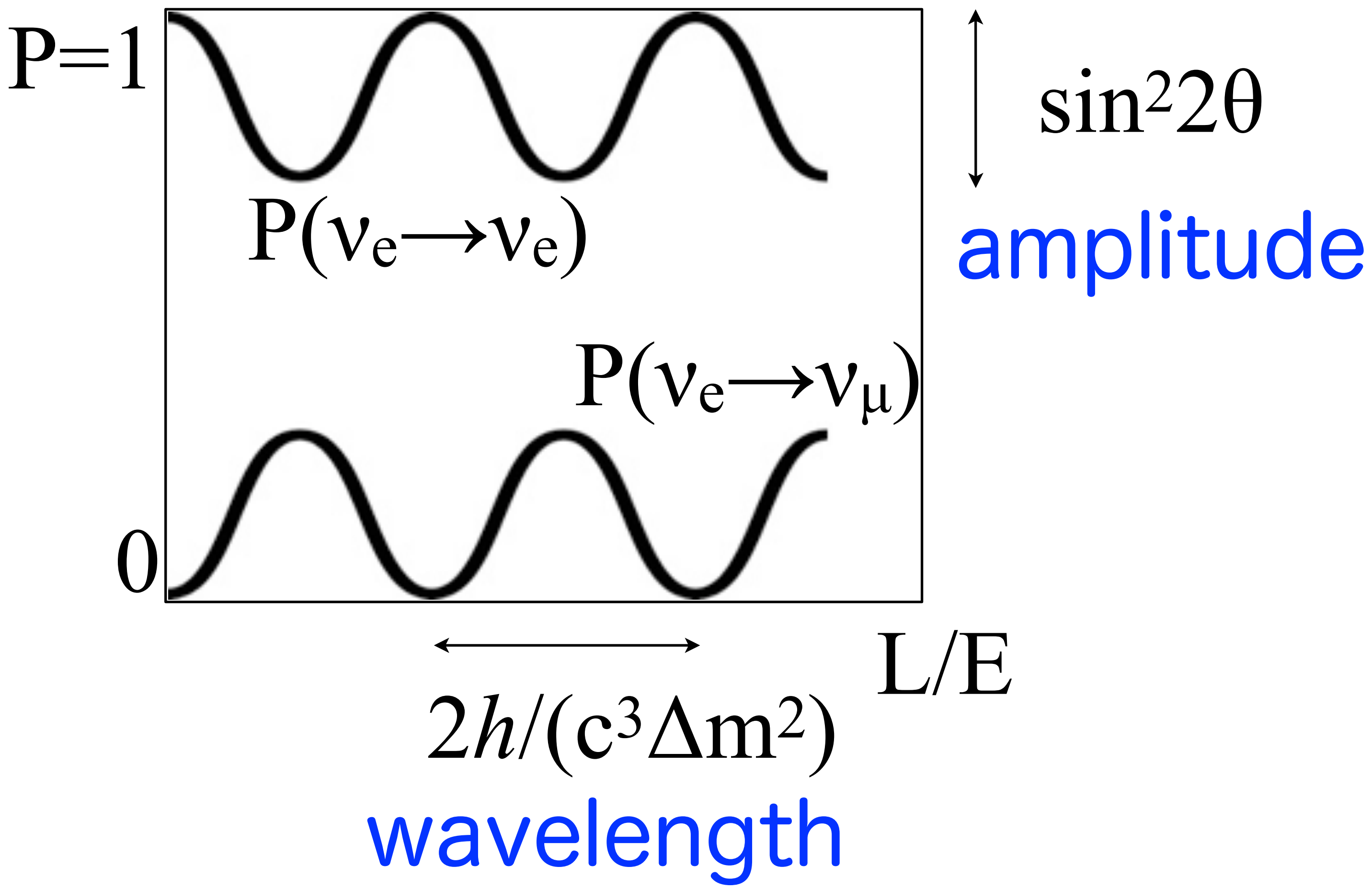
3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 complex phase (δ) ←CP violation

Neutrino oscillation

IF $\theta \neq 0$ AND $\Delta m^2 \neq 0$, flavor transmutation occurs.

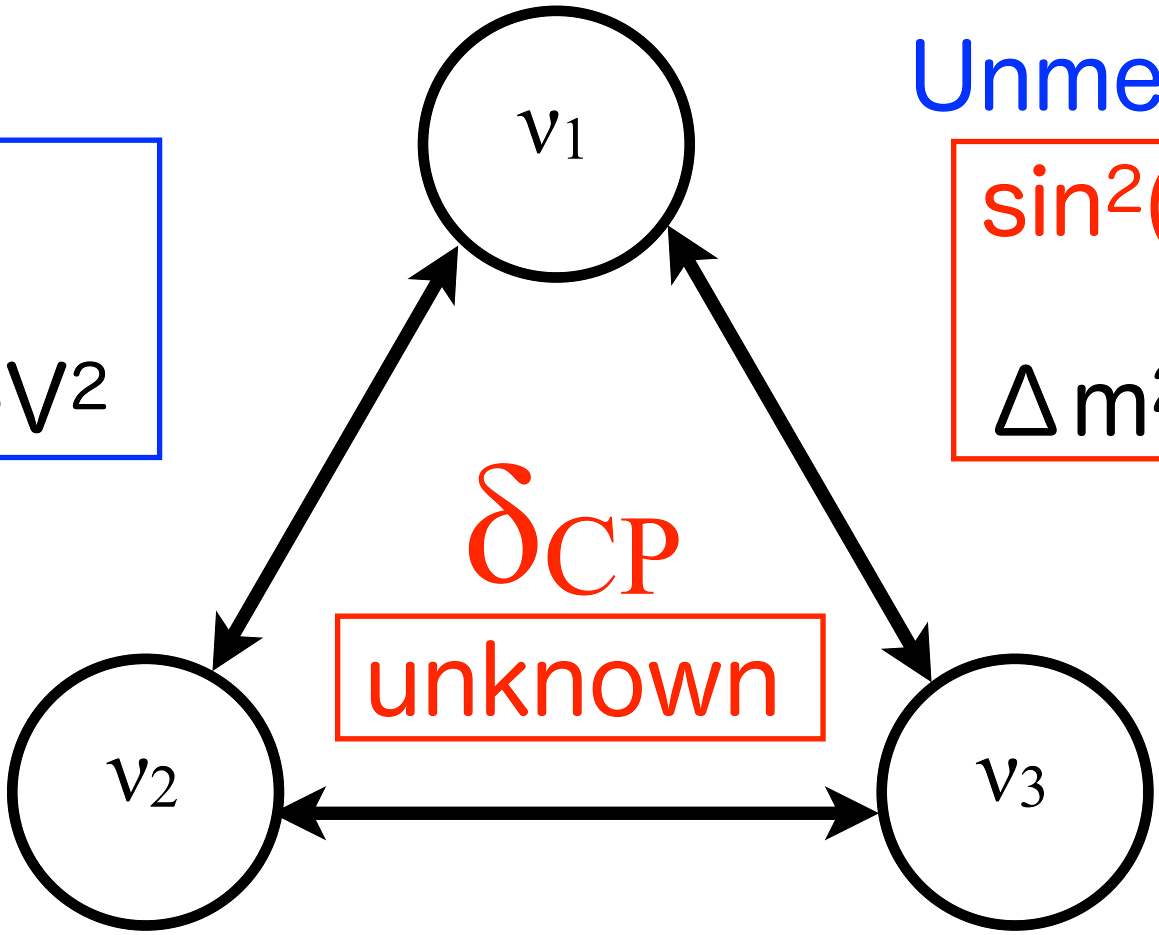
$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \times \sin^2(1.27 \Delta m^2 L/E)$ (2 flavor approx.)

Δm^2 in (eV^2), L/E in (km/GeV or m/MeV)



- 3 mixing angles
  θ_{12}, θ_{23}, θ_{13}
- 2 (independent) mass^2 differences
  $\Delta m^2_{32} = m_3^2 - m_2^2$
  $\Delta m^2_{21} = m_2^2 - m_1^2$
  $(\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21})$
- 1 complex phase (CPV) δ

What we know now



δ_{CP}

unknown

$\sin^2(2\theta_{12}) \sim 0.8$

$\Delta m^2_{21} \sim 8\times10^{-5} eV^2$

Solar-ν

Reactor-ν

Unmeasured <2011

$\sin^2(2\theta_{13}) \sim 0.1$

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Reactor-ν

Acc-ν

Atm-ν

Acc-ν

$\sin^2(2\theta_{23}) \sim 1.0$

$|\Delta m^2_{32}| \sim 2.5\times10^{-3} eV^2$

unknown

mass ordering:

$m_3 >> m_2 > m_1$ or

$m_2 > m_1 >> m_3$

- $\theta_{12} \sim 33°$, $\theta_{23} \sim 45°$, but $\theta_{13} \sim 9°$
- $|\Delta m^2_{32}| >> |\Delta m^2_{21}|$ (by factor ~30)

Where to place detectors?

$1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})/E(\mathrm{GeV})=(2n+1)\pi/2$

1st osc. maximum at $L \sim E/\Delta m^2$ (×1.57/1.27)

- For $\Delta m^2_{32(31)} \sim 2.5\times10^{-3}\ \mathrm{eV}^2$ and $E \sim 1$ GeV,
  → L ~ O(400km): accelerator long-baseline experiments
  (T2K, MINOS, NOvA)

- For $\Delta m^2_{32(31)} \sim 2.5\times10^{-3}\ \mathrm{eV}^2$ and $E \sim 4$ MeV,
  → L ~ O(1.5km): reactor mid-baseline experiments
  (Daya Bay, Double Chooz, RENO)

- For $\Delta m^2_{21} \sim 0.8\times10^{-4}\ \mathrm{eV}^2$ and $E \sim 4$ MeV,
  → L ~ O(50km): reactor long-baseline exp’t (JUNO, KL)

Fascinating quantum physics!

- ν oscillation is quantum-interference phenomenon observable in earth-scale distances
  - Normally, quantum effects are observed only in atomic scale → Why is the scale so large?
- Osc. λ: $L \sim 2hE/m^2c^3 = (2h/mc)(E/mc^2)$ $m=\sqrt{(\Delta m^2)}$

  =50 meV for m_{32}
- Compton WL $\lambda = h/mc$ (2.4 pm for electron)
  - ν mass is so small（10^{-7} times electron）24μm
- Lorentz boost $E/mc^2 \sim 2\times10^{10}$ L~1000km (E=1GeV)

Outstanding issues in neutrino physics

- PMNS matrix:

  All 3 mixing angles θ_{ij} are measured.

  Octant of θ_{23} not yet known (> 45° or < 45°)

  CP violation phase δ_{CP} is unknown.

- Neutrino masses:

  Both mass^2 differences Δm^2_{32} and Δm^2_{21} measured.

  Sign(Δm^2_{32}) still unknown - Mass Ordering (Mass Hierarchy)

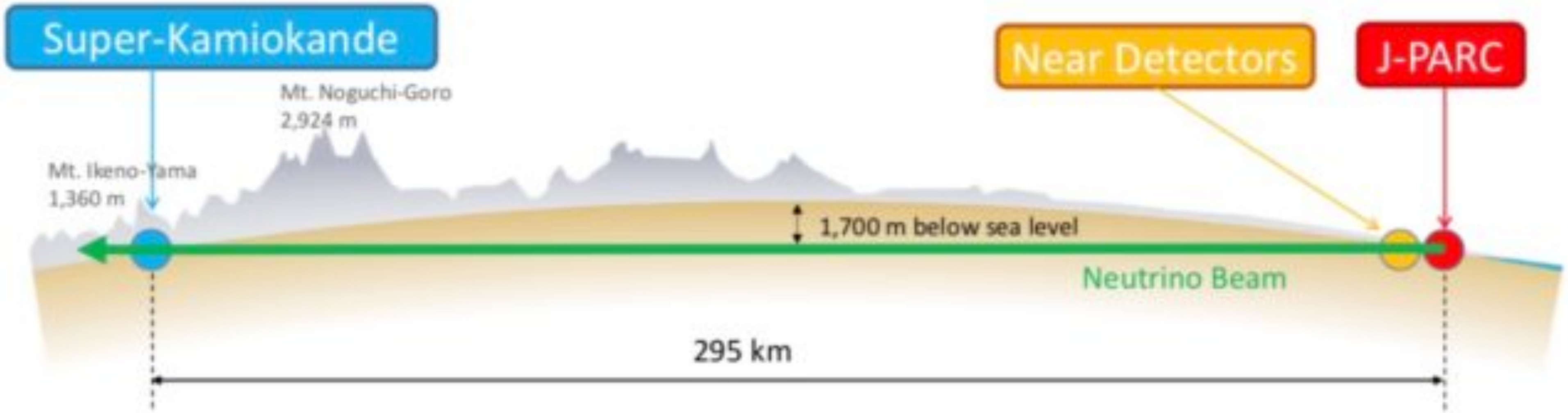
  $m_3 >> m_2 > m_1$ (normal) or $m_2 > m_1 >> m_3$ (inverted)

  Absolute m_ν not measurable with ν oscillation

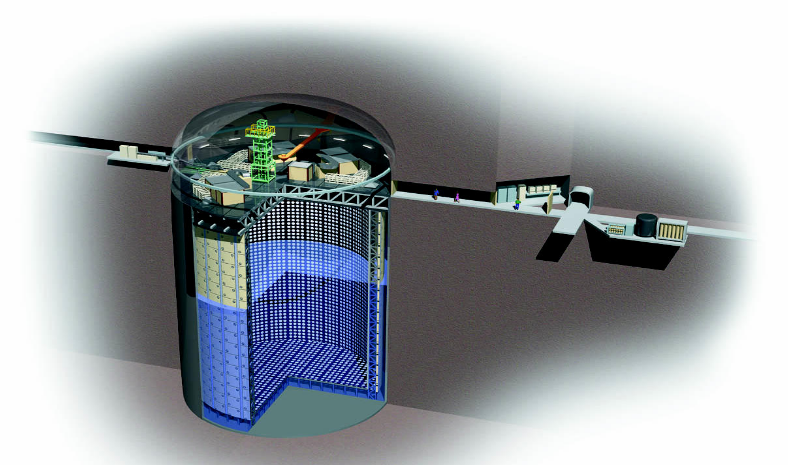
  → $0\nu2\beta$ (if Majorana)／direct β measurement (KATRIN) and cosmological constraints on Σm_ν (ν osc.→ $\Sigma m_\nu > 0.05$ eV)

T2K experiment in Japan

- Tokai (J-PARC) to Kamioka (SK)
  Long-BaseLine accelerator ν exp.



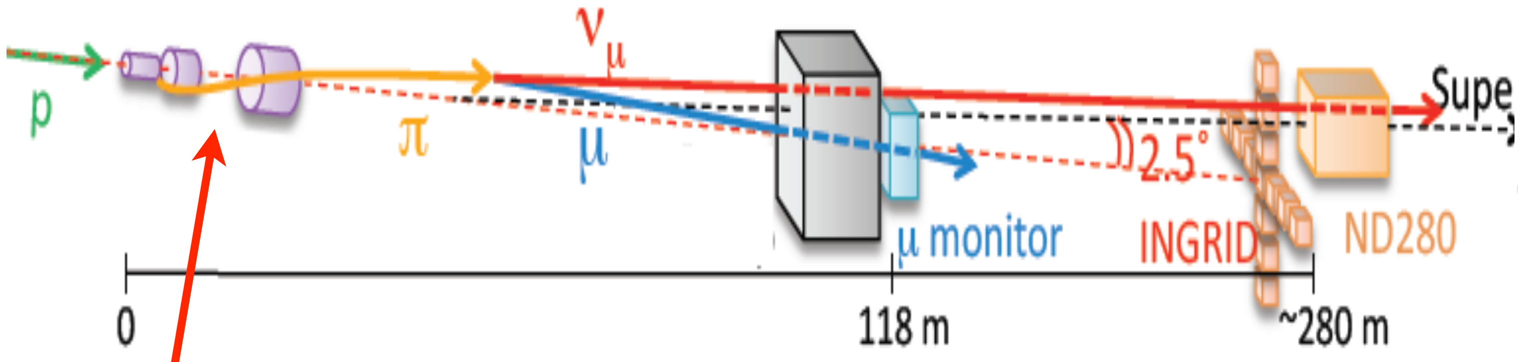
Super-K@Kamioka



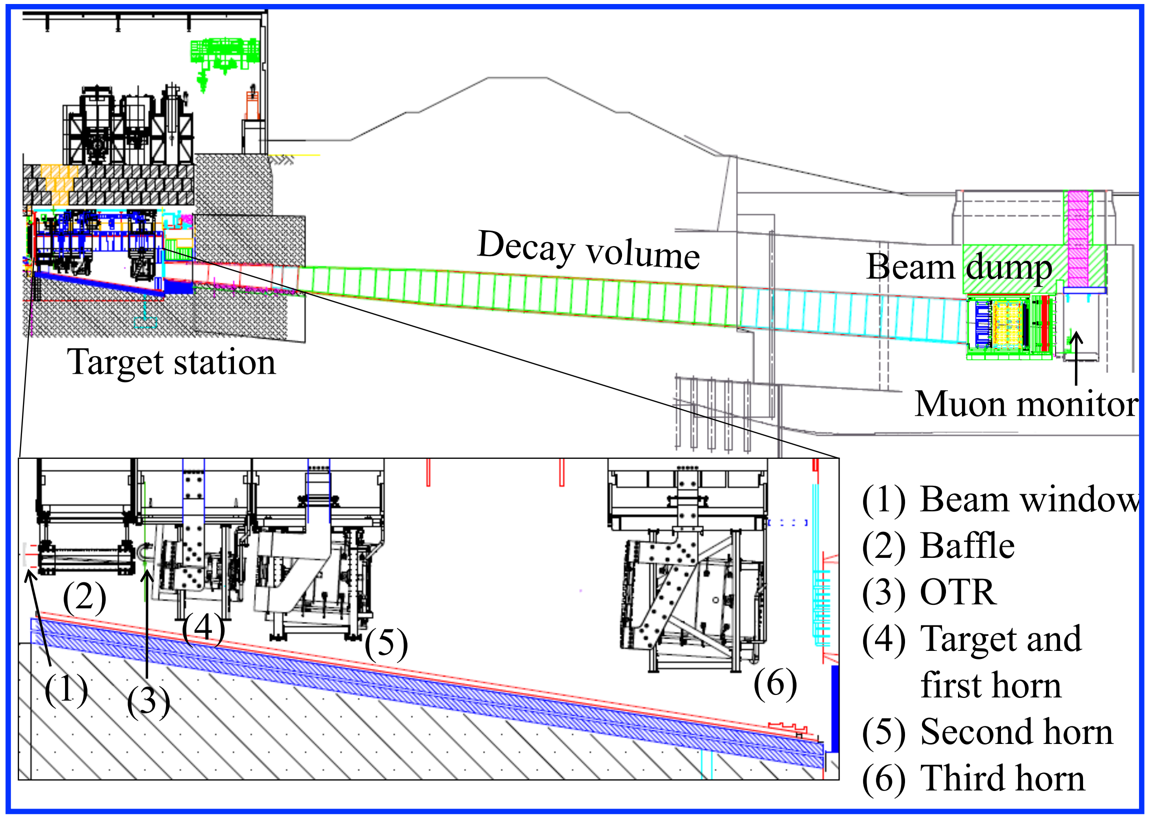
ND280 @Tokai

Off-Axis ν_μ beam

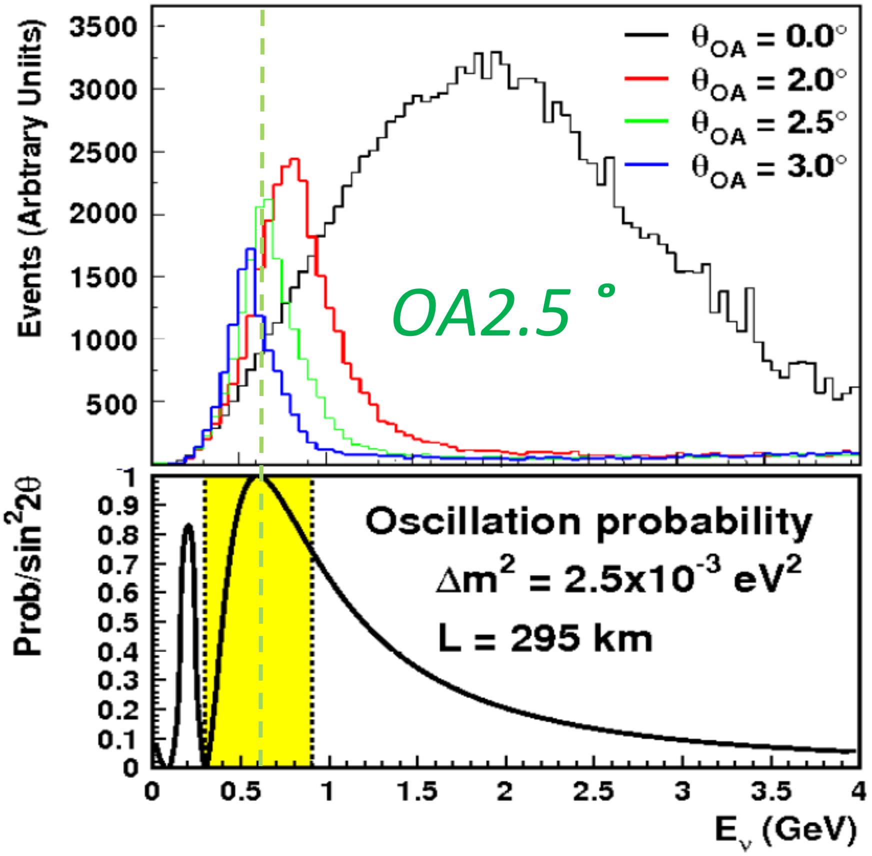
- Narrow-band beam, peak at 0.6 GeV (Δm^2_{32} 1st osc. max.)
- Reduce BG from high-E tail

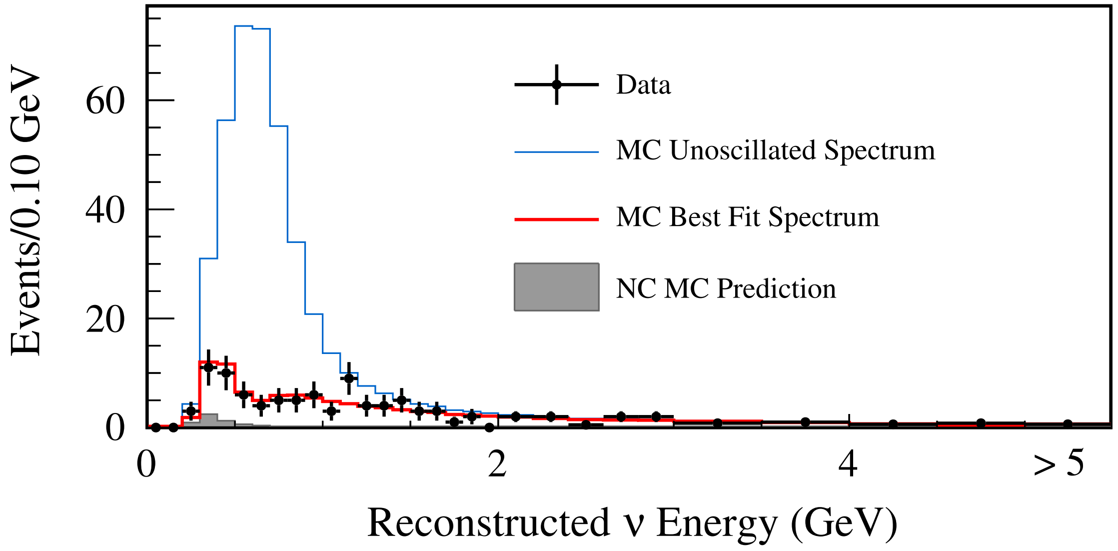


Horns



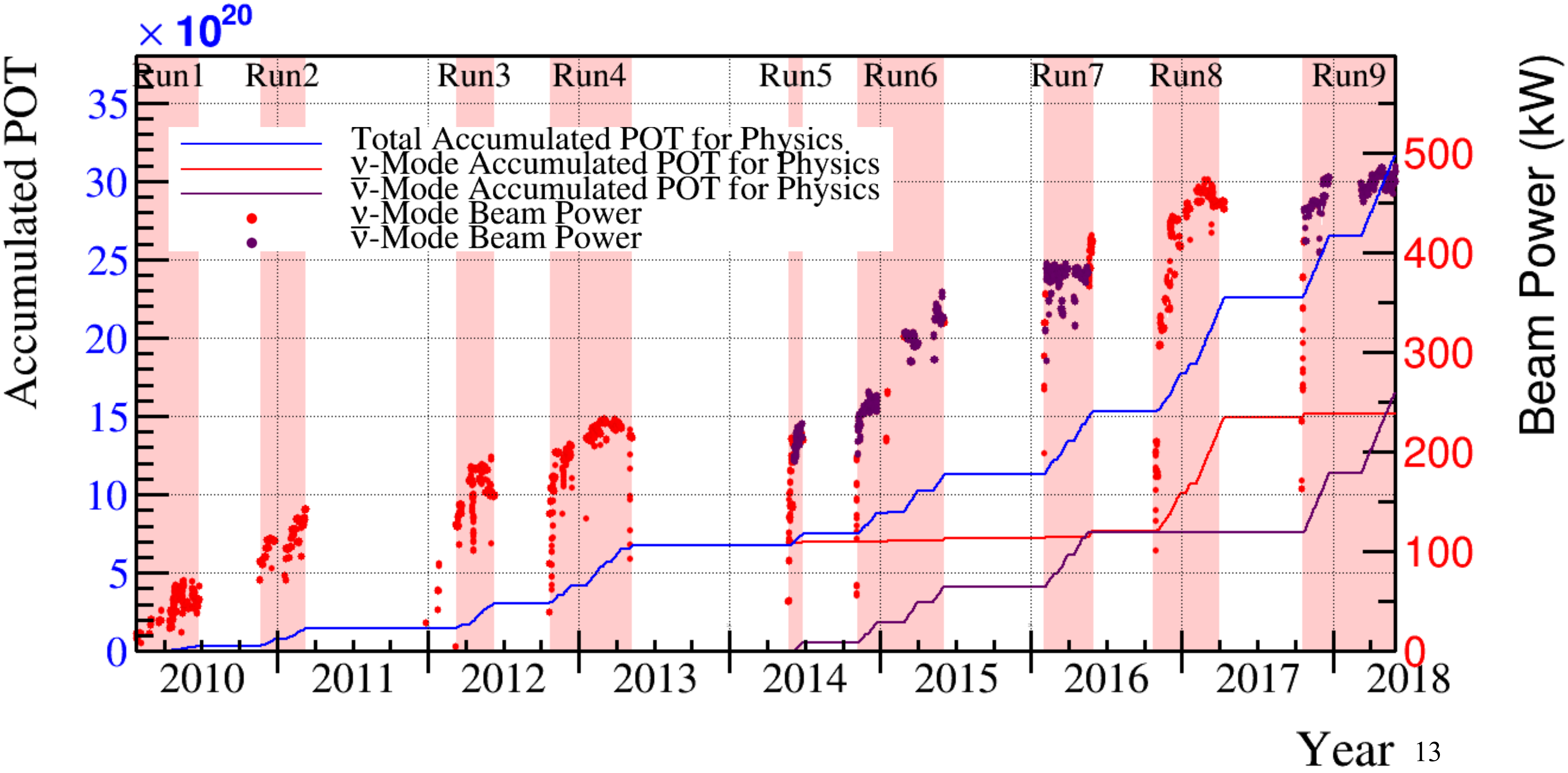
(1) Beam window
(2) Baffle
(3) OTR
(4) Target and first horn
(5) Second horn
(6) Third horn



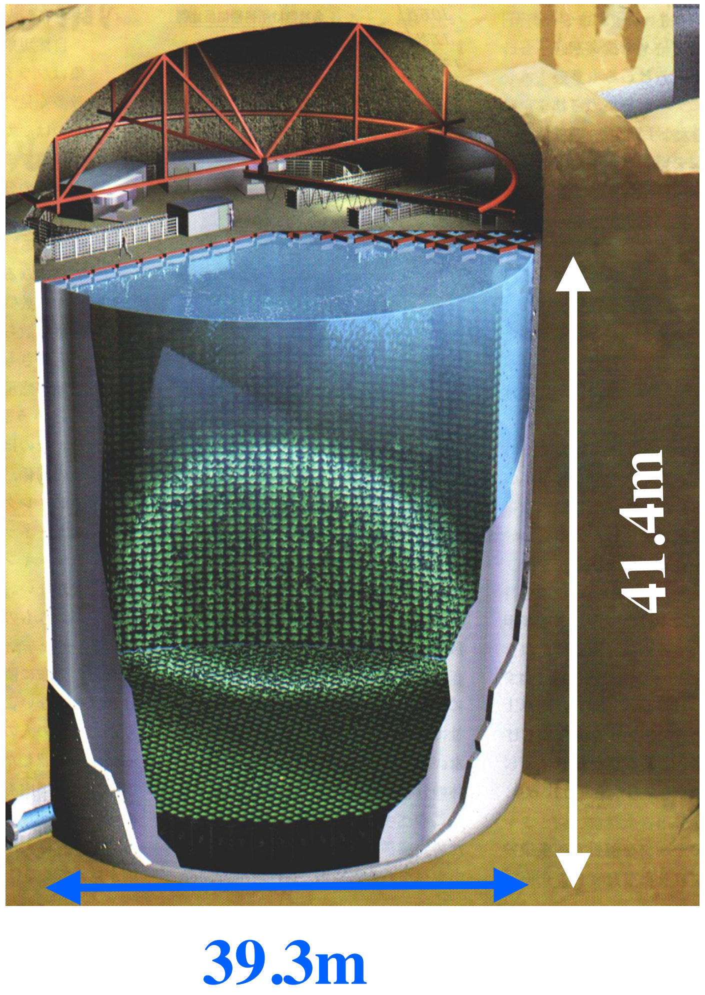


Protons On Target (POT)

- 15.1×10^{20} for ν mode (Forward Horn Current)
- 16.5×10^{20} for anti-ν mode (Reverse Horn Current)
- Beam power ~485kW now



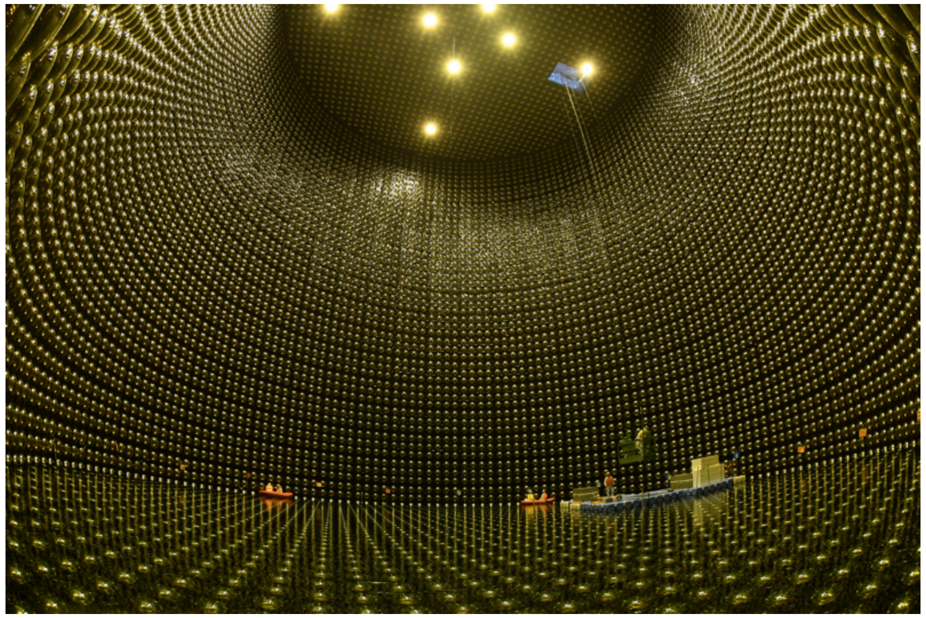
Super-Kamiokande (since 1996)



- 50kt Water Cherenkov Detector
- Under 1km rock (2700m.w.e.)
- 11129 20-inch PMTs (+outer veto det.)
- e/μ separation with Cherenkov ring
- GPS timing for T2K beam coincidence: no accidental b.g.

(Not only as) Far detector of T2K

- Atmospheric-ν
- Solar-ν
- Supernova-ν
- Nucleon decay!



← Refurbishment work in 2018 finished (for future SK-Gd), running since Jan. 2019 as SK-V phase

Observed events at SK

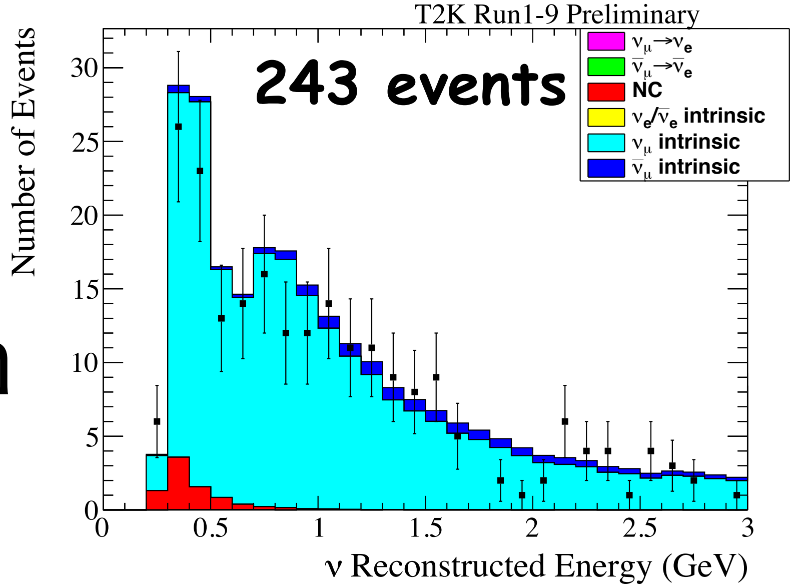
K. Sakashita

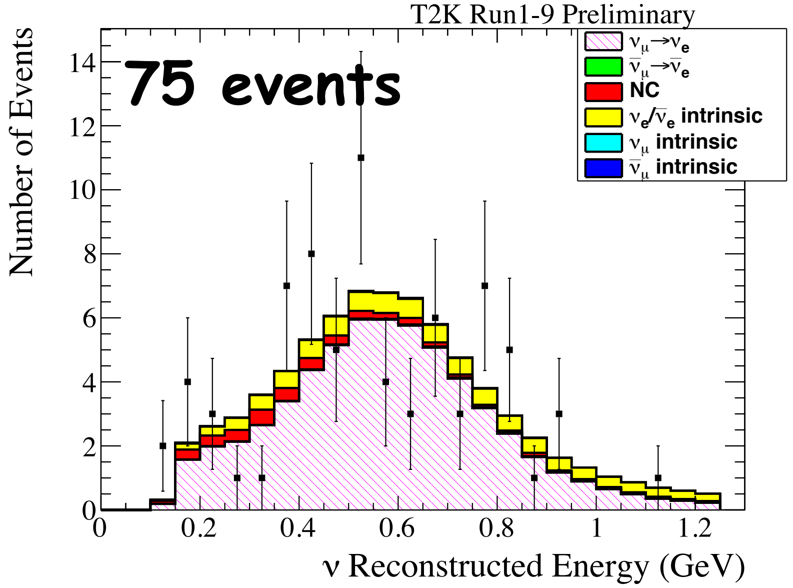
CCQE μ-like

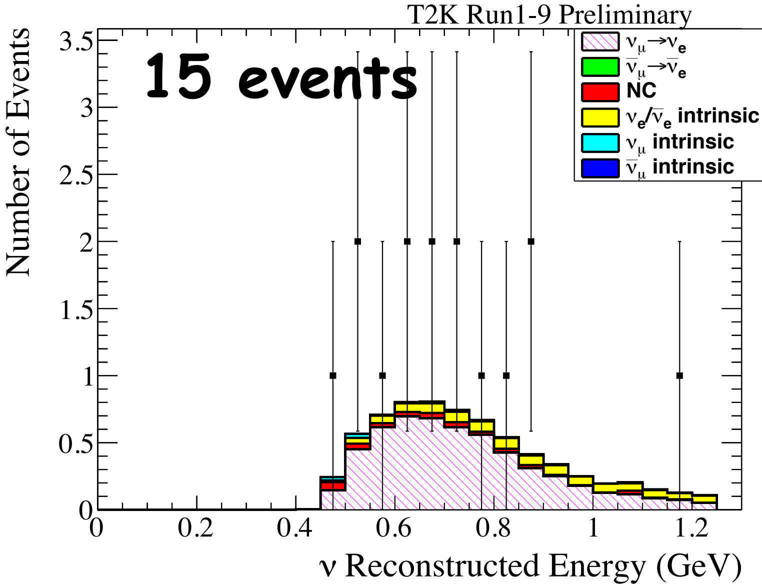
CCQE e-like

CC1π e-like

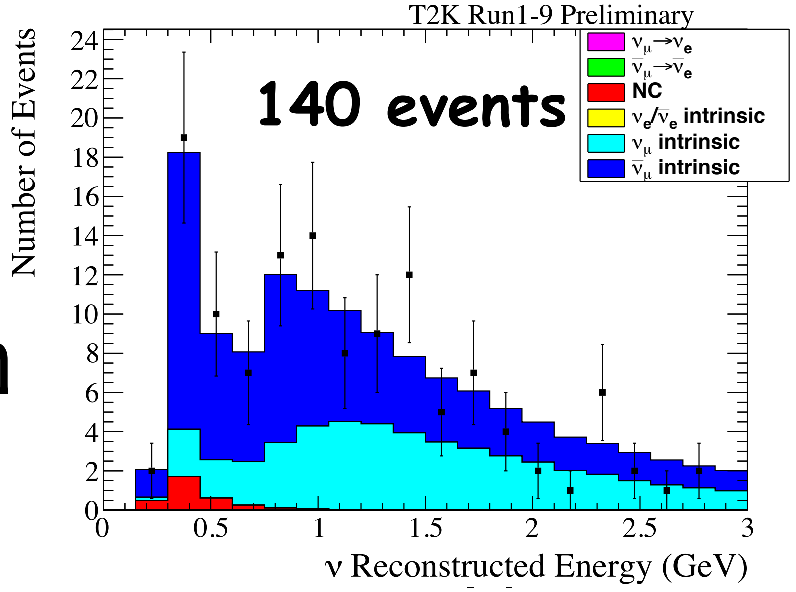
ν beam

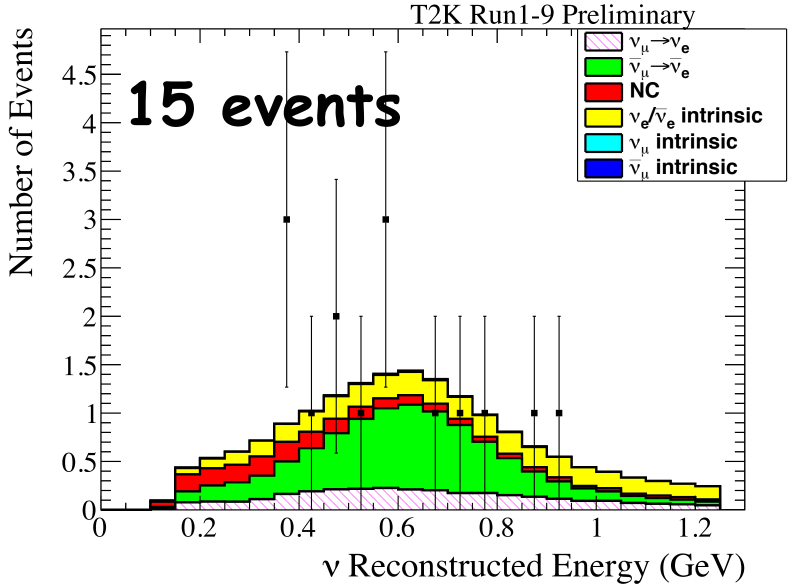






$\overline{\nu}$ beam





MC assumption :

$\delta_{CP} = -\pi/2$

Normal Hierarchy

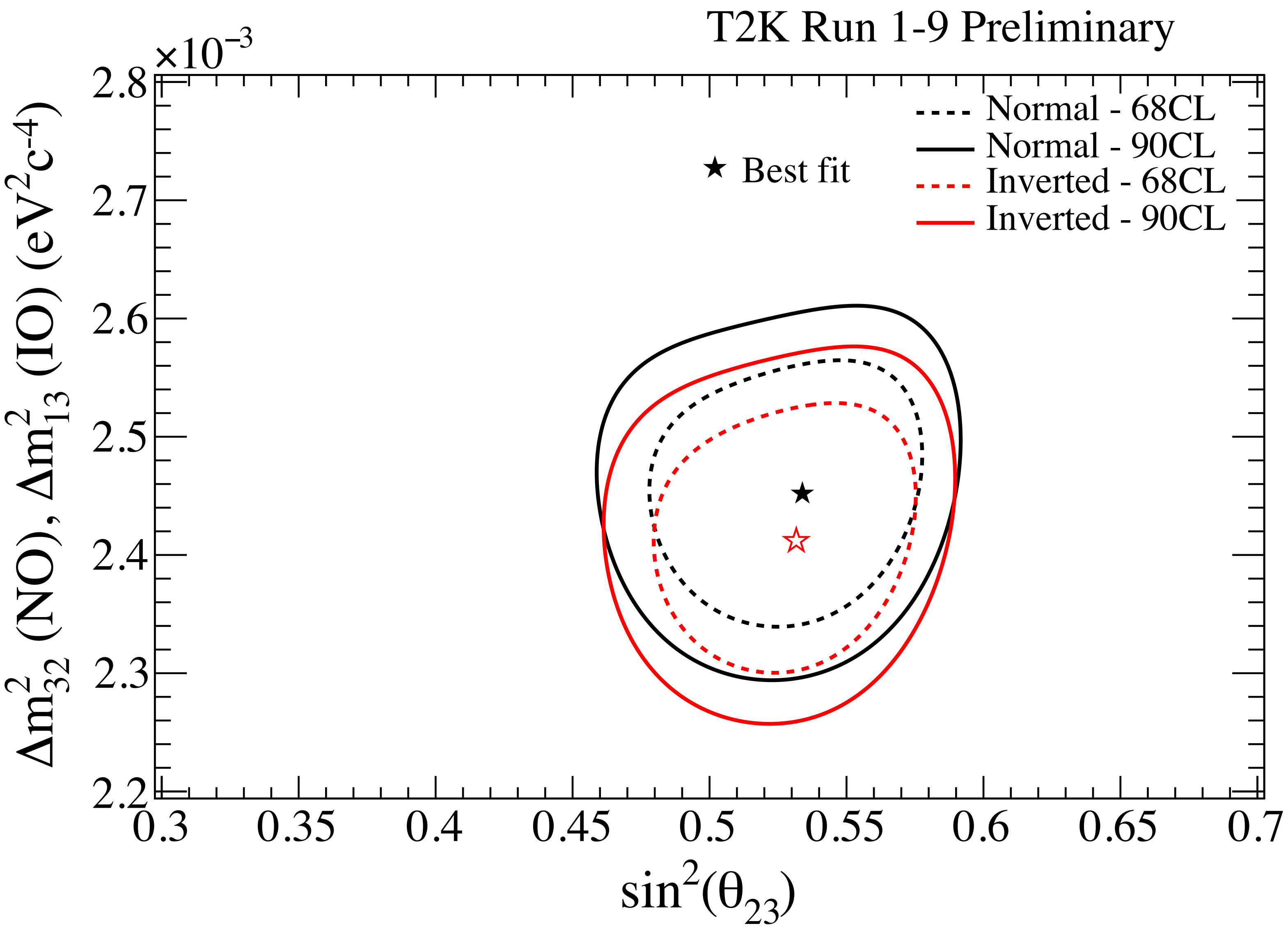
$\sin^2\theta_{23} = 0.528$

$\sin^2\theta_{13} = 0.0212$

ν-mode :14.9x10^{20} POT , $\overline{\nu}$-mode : 16.3x10^{20} POT

ν_μ disappearance

K. Sakashita



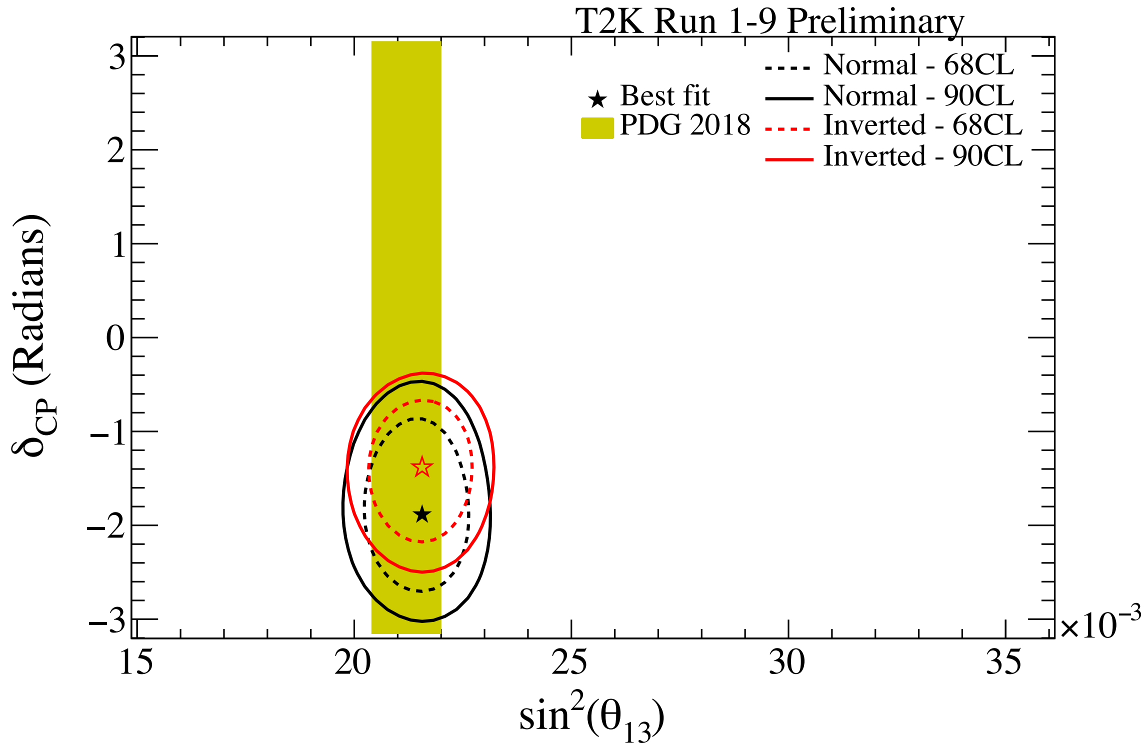
- Contours for ν_μ disappearance parameters $\sin^2\theta_{23}$, Δm^2_{32} (w/ reactor constraint on $\sin^2\theta_{13}$)
- Consistent with maximal mixing
- Data prefers normal mass ordering

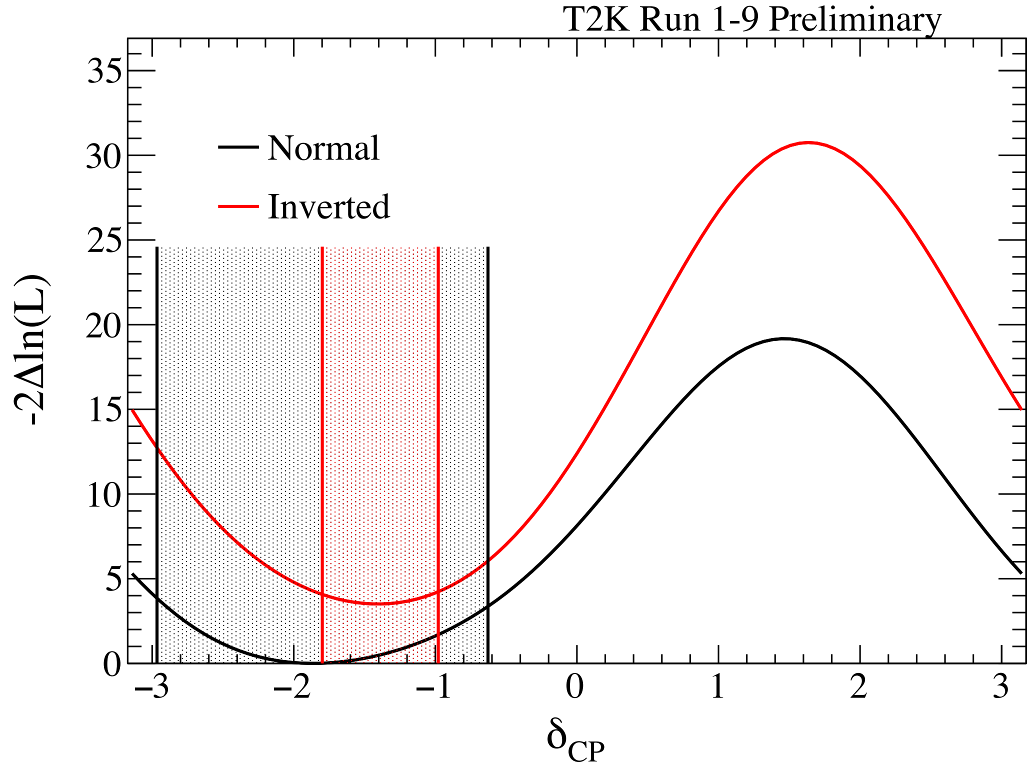
posterior probability

	$\sin^2\theta_{23}<0.5$	$\sin^2\theta_{23}>0.5$	Sum
Normal	0.184	0.705	0.889
Inverted	0.021	0.090	0.111
Sum	0.205	0.795	1

T2K results on δ_{CP}

- Compare $\nu_\mu \to \nu_e$ appearance between ν and anti-ν
- Using reactor θ_{13}, CP conservation excluded at 2σ





K. Sakashita

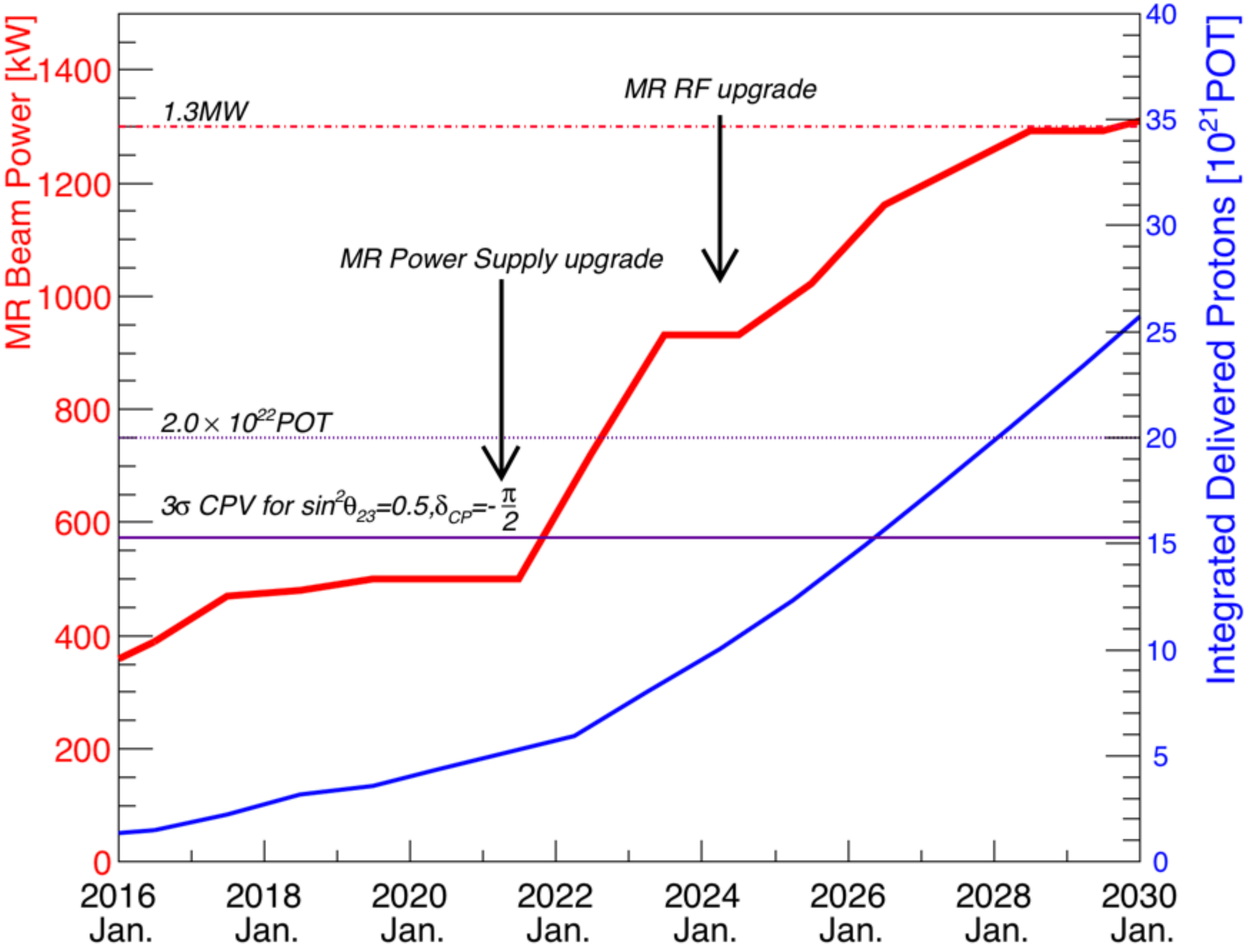
	Obs.
$\nu_\mu \to \nu_e$ candidates	**90**
$\bar{\nu}_\mu \to \bar{\nu}_e$ candidates	**15**

Expectation			
δ=-$\pi/2$	$\delta=\pi$	$\delta=\pi/2$	δ=0
81.4	68.6	55.5	68.3
17.1	19.3	21.7	19.4
CPV	CPC	CPV	CPC

T2K-II proposal

- T2K was proposed with 7.8E21 POT → So far accumulated 3E21
- T2K-II (~2027) to collect 20E21 → MR power upgrade to 1.3 MW
- Aim: 3σ evidence of CPV

	Achieved	Target
Beam power [MW]	0.5	1.3
# of protons per pulse	2.6 x 10^{14}	3.2 x 10^{14}
Rep. Time [sec]	2.48	1.16



T2K-II Target POT (Protons-On-Target)

T2K-II physics prospects

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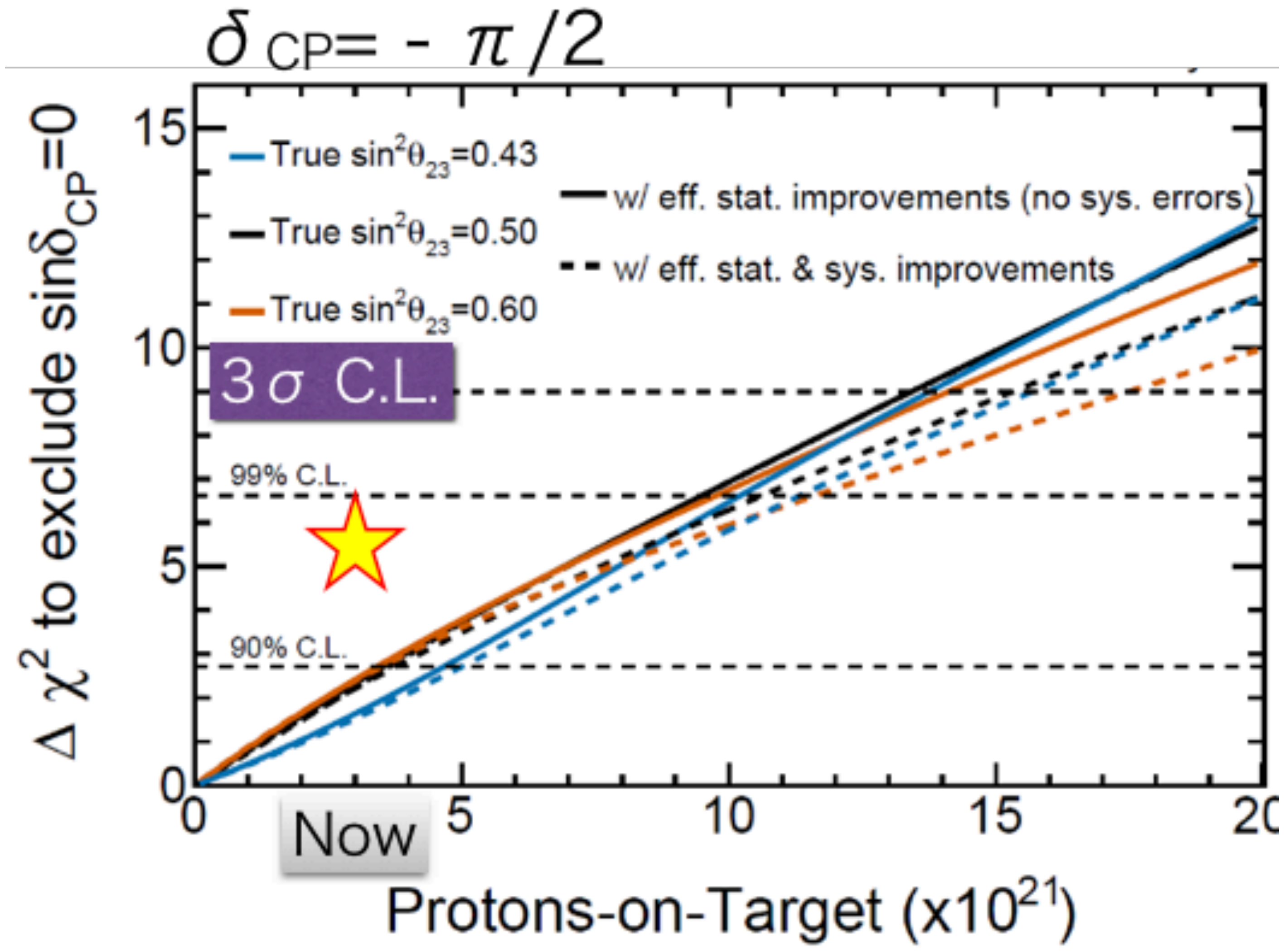
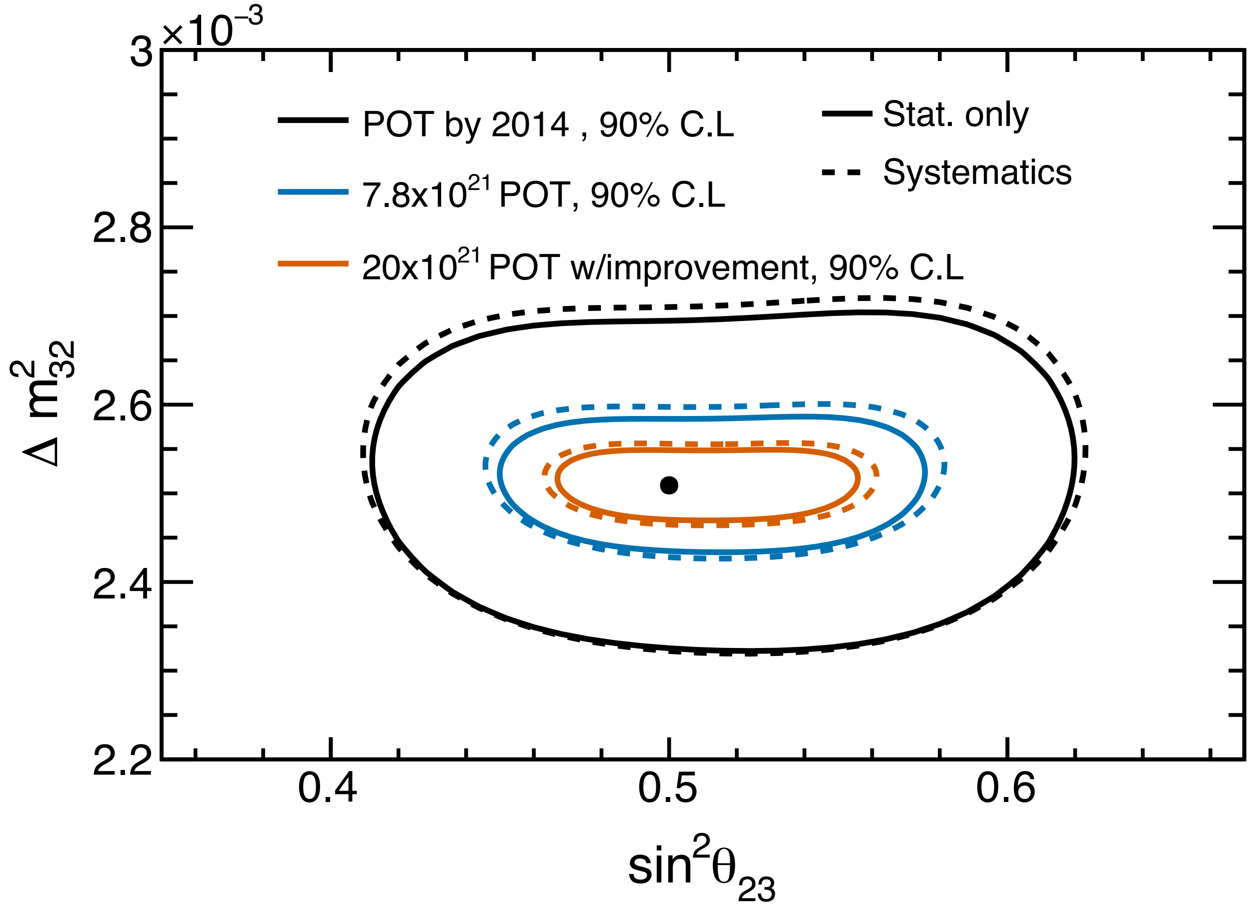
Sensitivity to exclude sinδ_{CP}=0

δ_{CP}= - π/2



>3σ CPV sensitivity

Sensitivity of $\sin^2\theta_{23}$, Δm^2_{32}

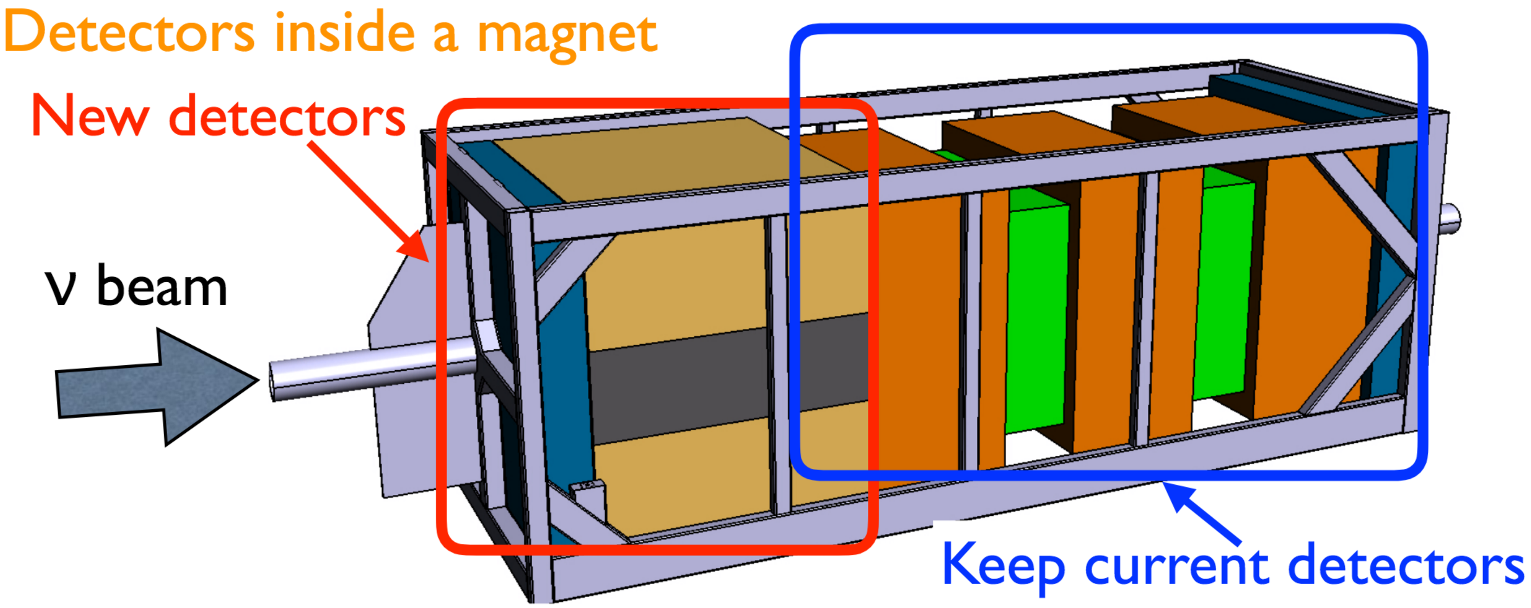


~1% precision of Δm², 0.5°-1.7° precision of θ_{23} (depends on true value)

ND280 upgrade

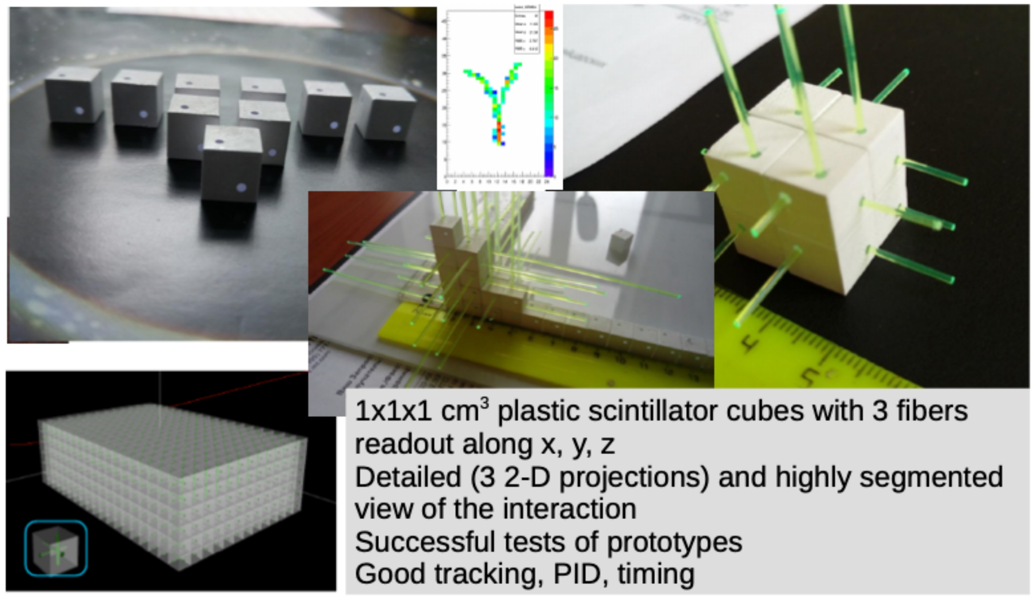
K. Sakashita

Replacing part of ND280 with new detectors to enhance capability



Super-FGD

arXiv:1707.01785

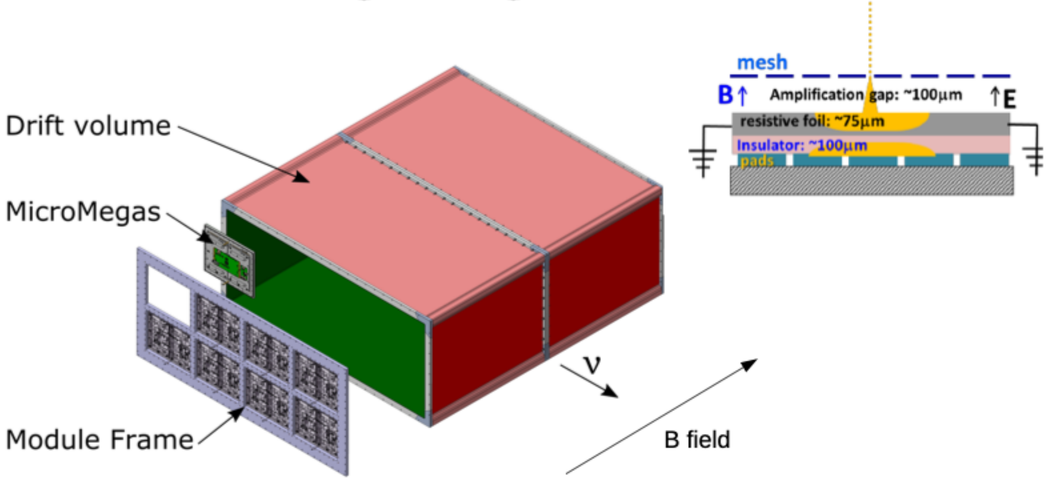


1x1x1 cm^3 plastic scintillator cubes with 3 fibers readout along x, y, z
Detailed (3 2-D projections) and highly segmented view of the interaction
Successful tests of prototypes
Good tracking, PID, timing

- *TDR submitted to PAC and reviewed (J-PARC & CERN)*
- *Strong collaboration of experts from Europe (incl. CERN), Japan and USA*
- *will be approved as CERN NP06*

Aiming installation in 2021

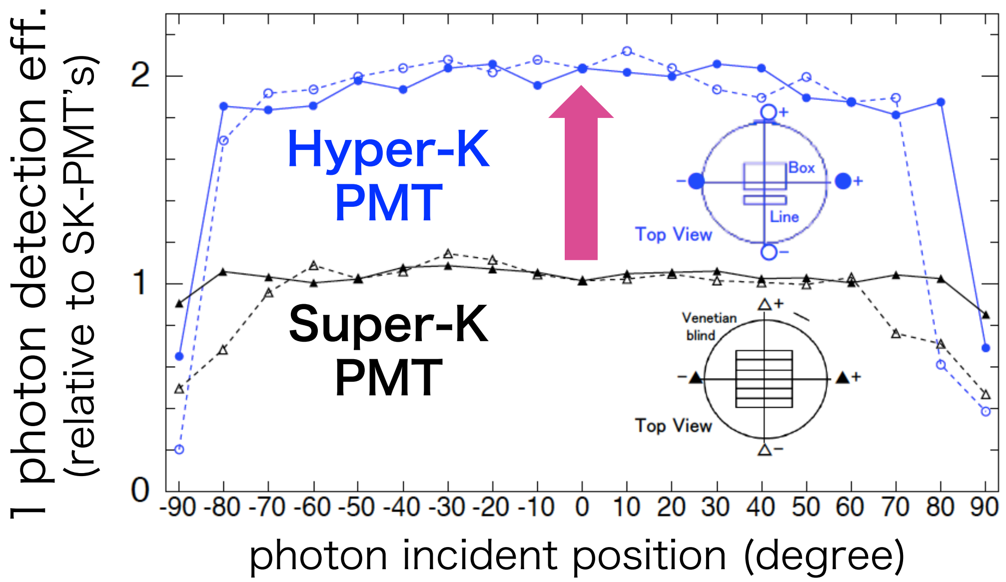
High Angle-TPCs

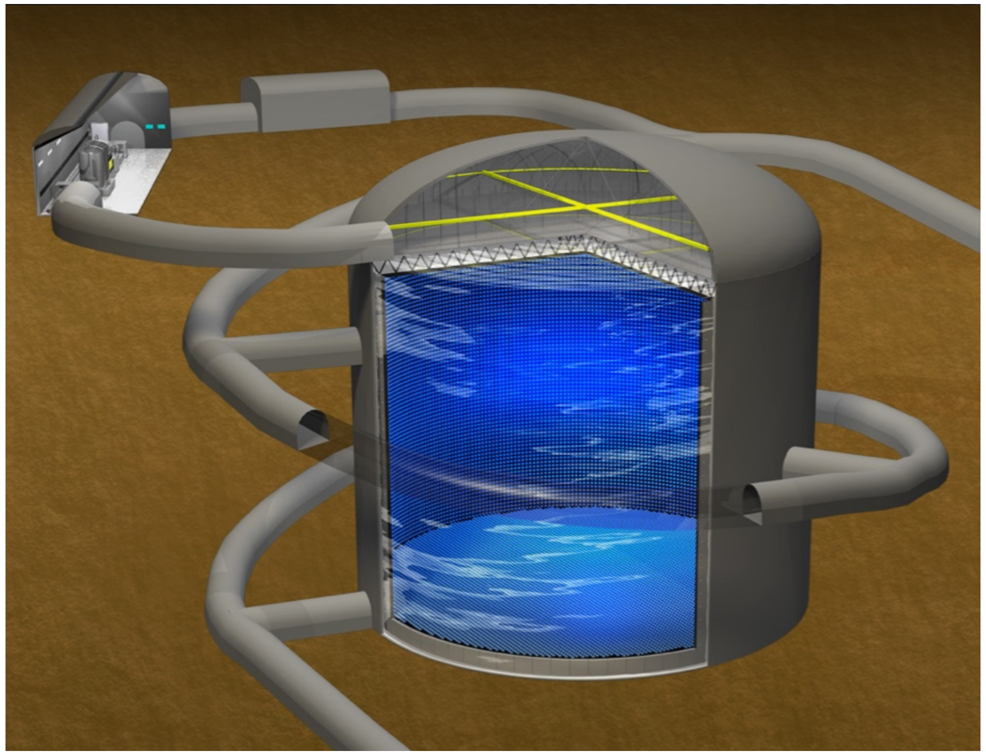


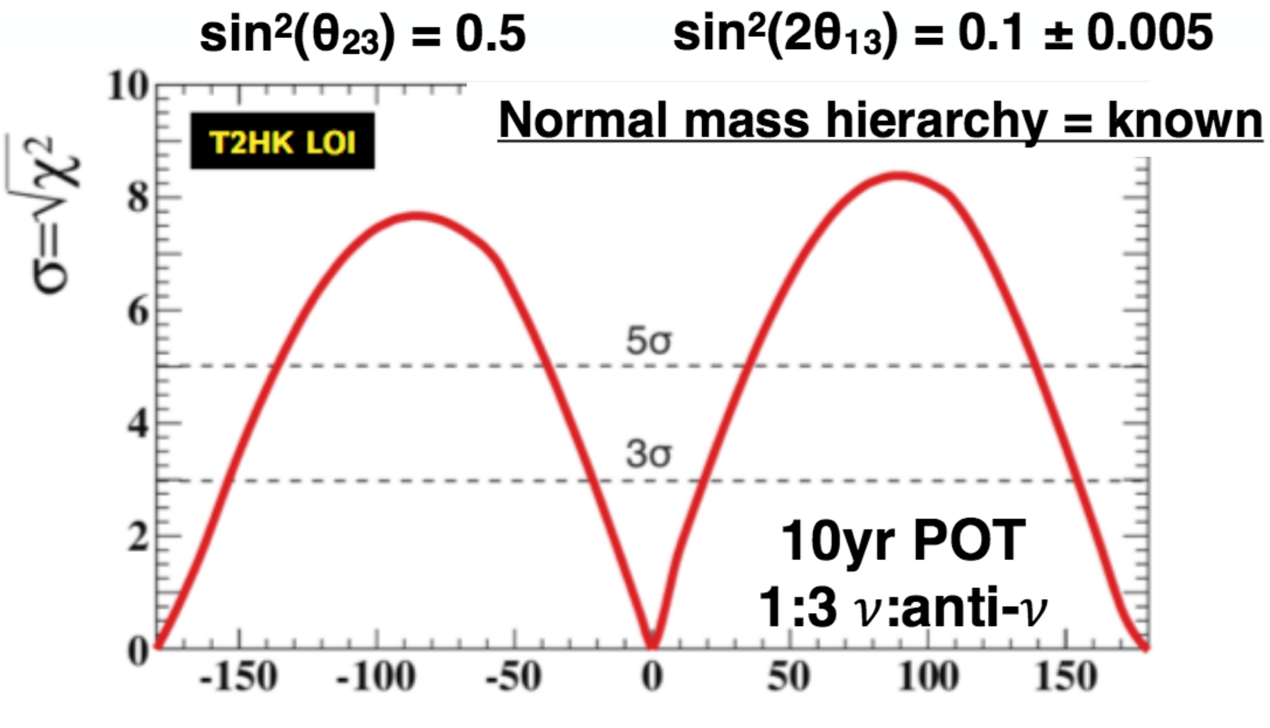
- Atmospheric pressure TPC using the same gas mixture as the present TPC
- Main difference with the existing TPC: thin field cage, resistive Micromegas
- Large overlap with the TPC group
- Benefiting from ILC TPC developments and RD51

Hyper-Kamiokande

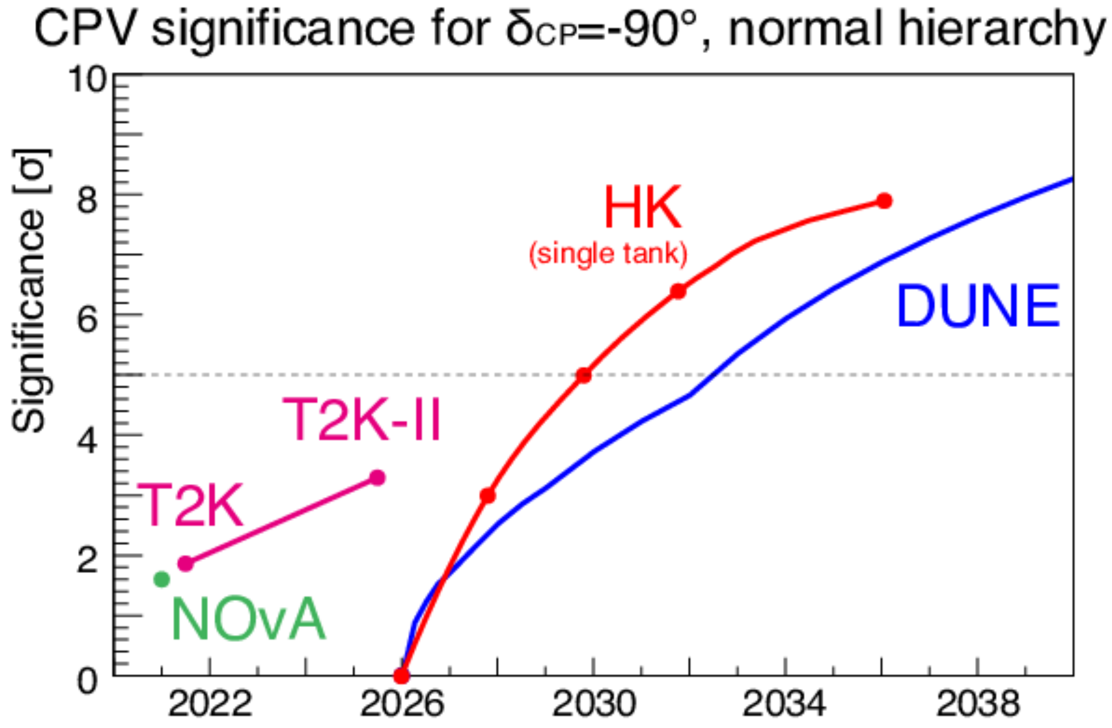
- 260 kton tank (D74m×H60m)
- 190 kton fiducial mass (~×10 of Super-K)
- 40,000 PMTs with 2x eff.
- >5 σ discovery in wide δ_{CP} range







58% of δcp space at 5σ and 76% at 3σ

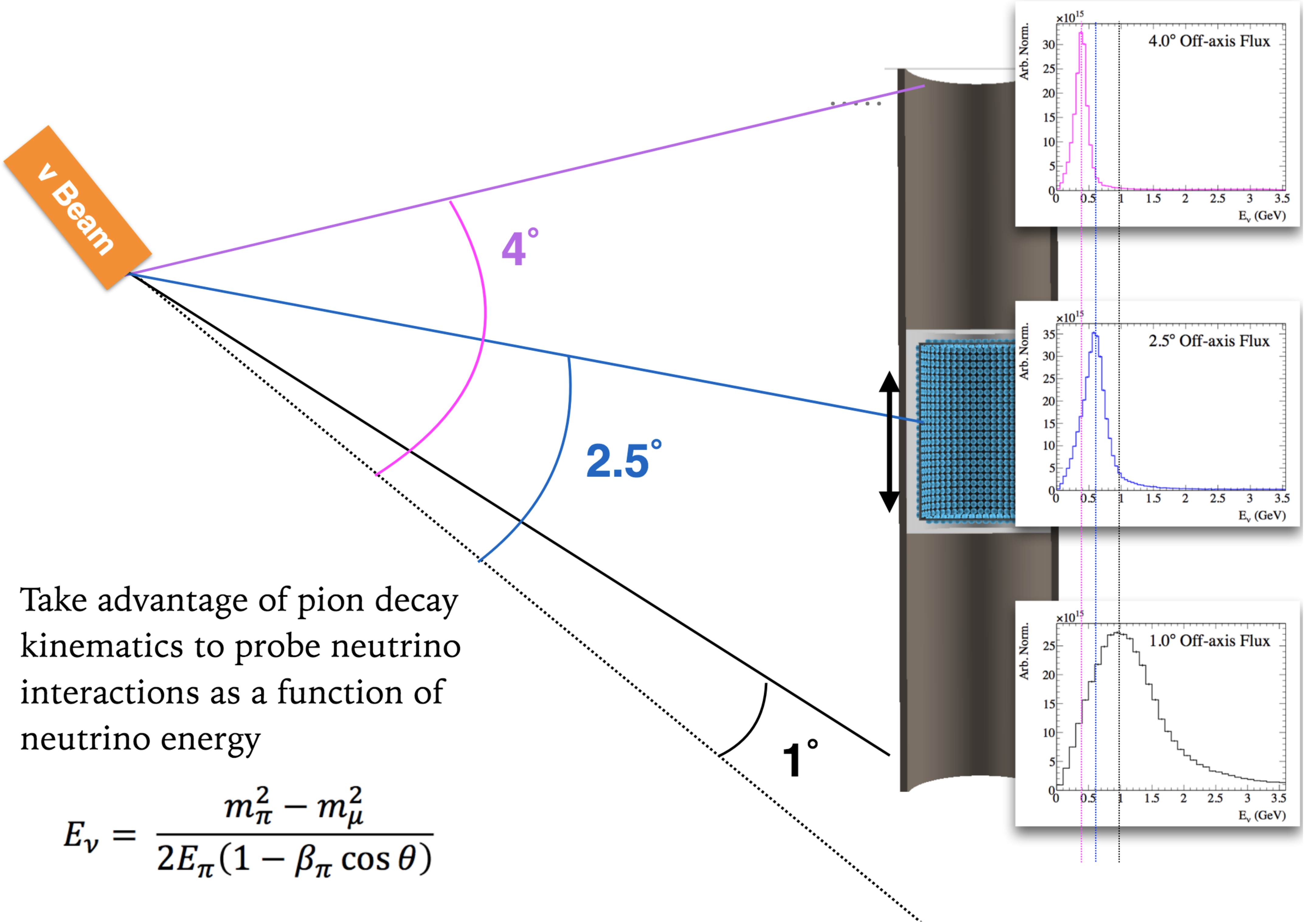


NuPRISM @~1km as HK IWCD

M. Friend

Intermediate Water Cherenkov Detector

Off-Axis Angle Range

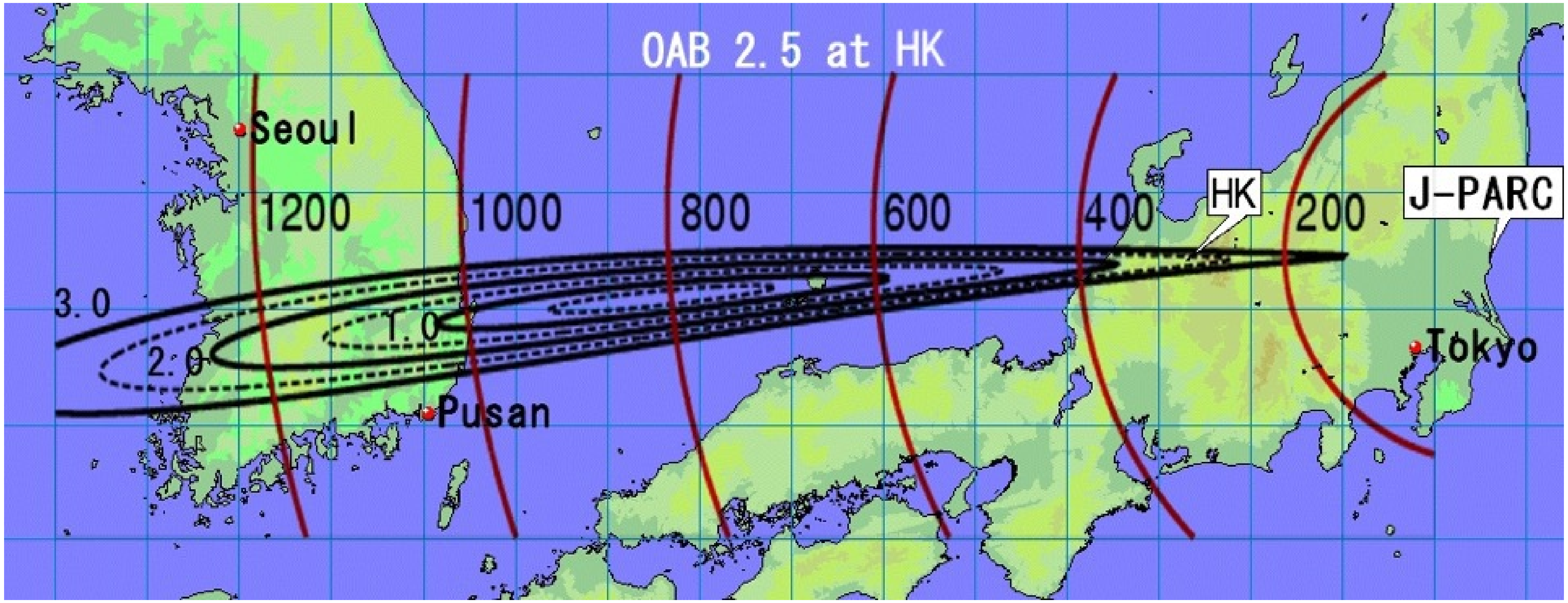


Take advantage of pion decay kinematics to probe neutrino interactions as a function of neutrino energy

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2E_\pi(1 - \beta_\pi \cos\theta)}$$

T2HKK (Tokai to HK & Korea)

- Idea for a 2nd tank in Korea: “Korean Neutrino Observatory” (“lower” Off-Axis beam reaches Earth surface in Korea)
- L~1100km → large matter effect → measure Mass Ordering (same beam energy is around the 2nd osc. max at this L)
- $> 5\sigma$ M.O. determination for any δ_{CP} value
- Also better δ_{CP} precision, sensitivity to exotic interactions
- Non-beam physics benefits from x2 volume (less cosmics than HK)



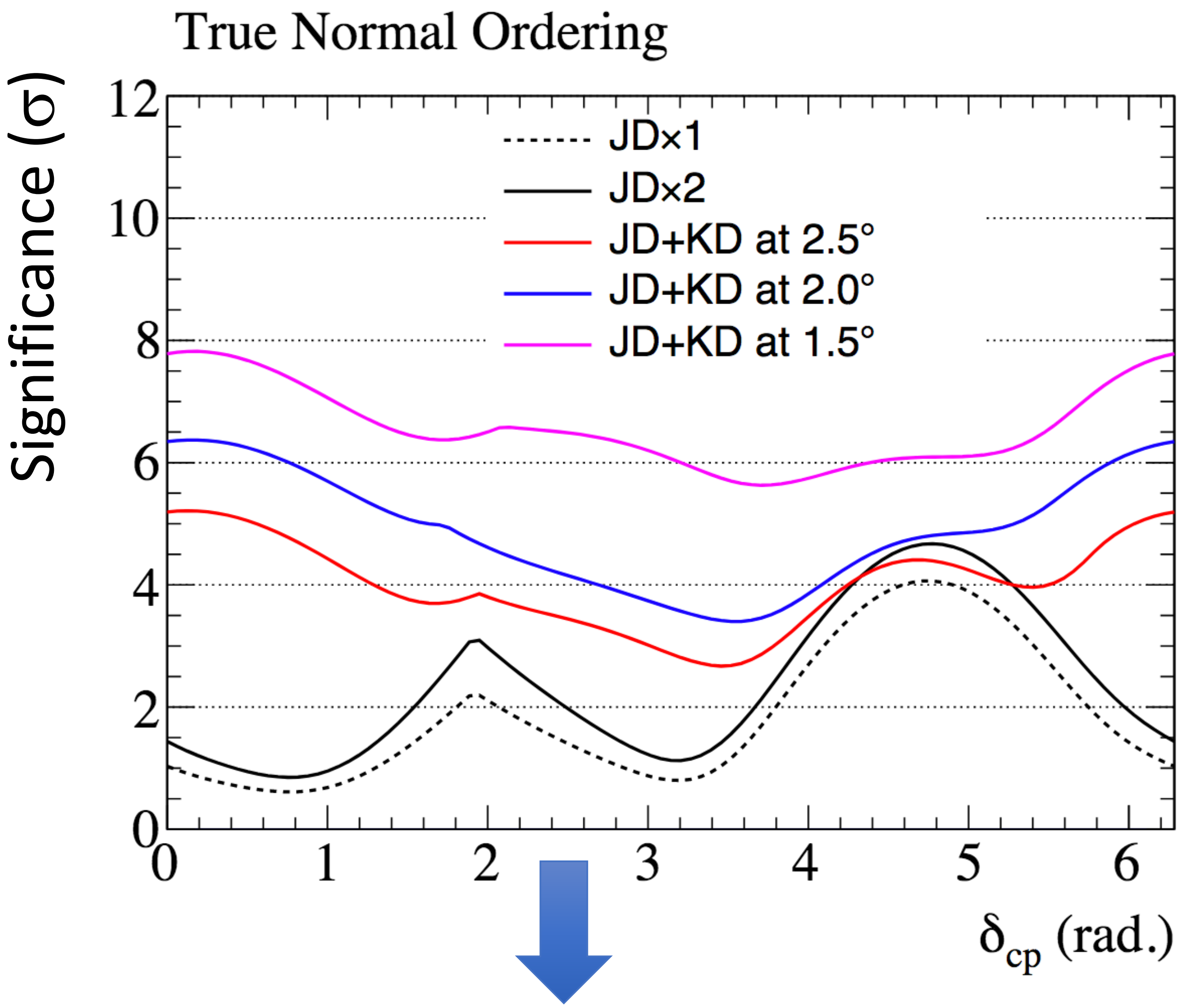
PLB 637(2006)266
PRD 76(2007)093002

Mass Ordering Sensitivities (Beam ν)

S. Seo

PTEP 2018,6, 1-56

Normal

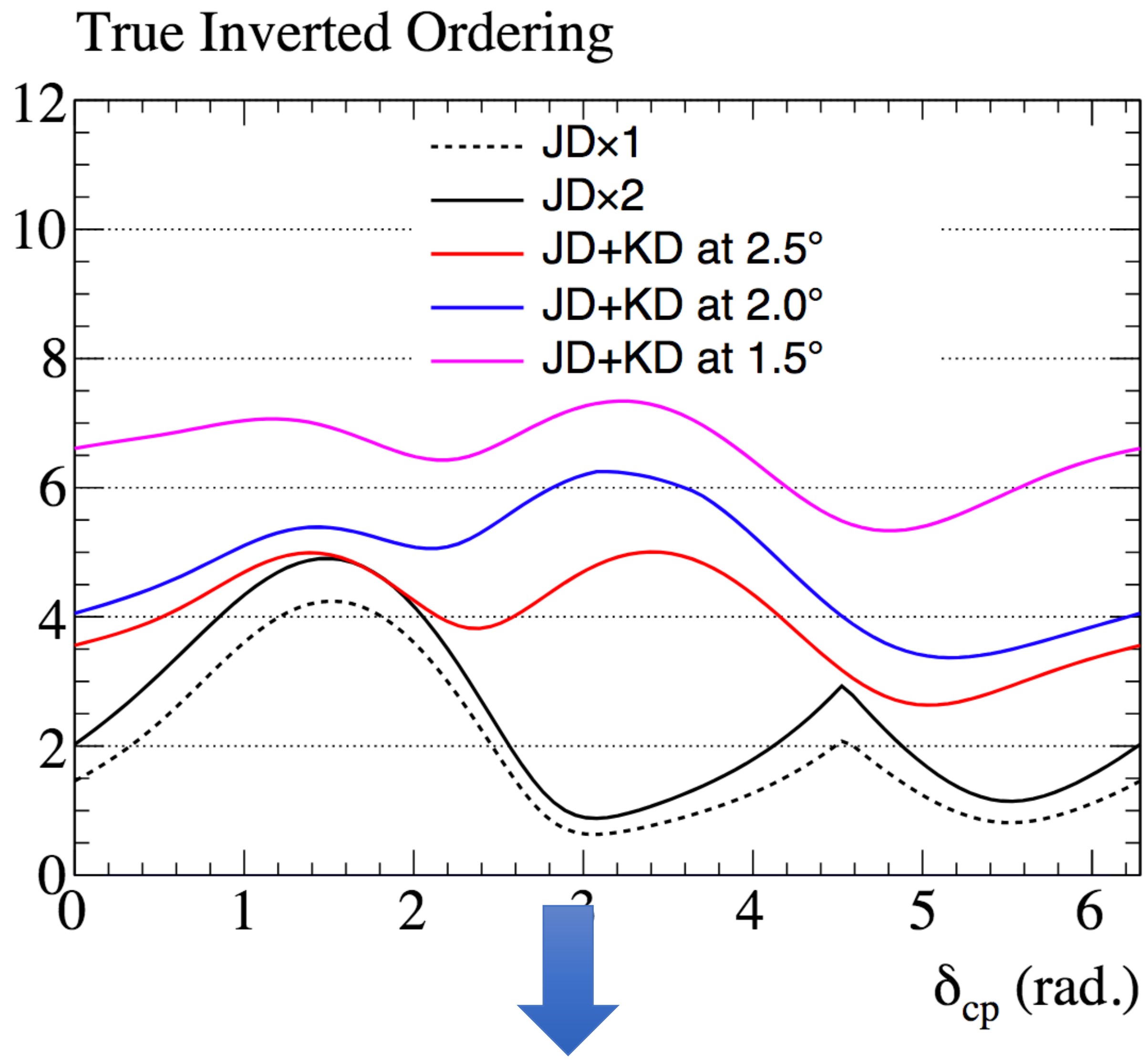


JD+KD 1.5°: 6 ~ 8 σ for all δ_{CP}

JD x2 : 1 ~ 4.5 σ for all δ_{CP}

(< 3 σ for most cases)

Inverted



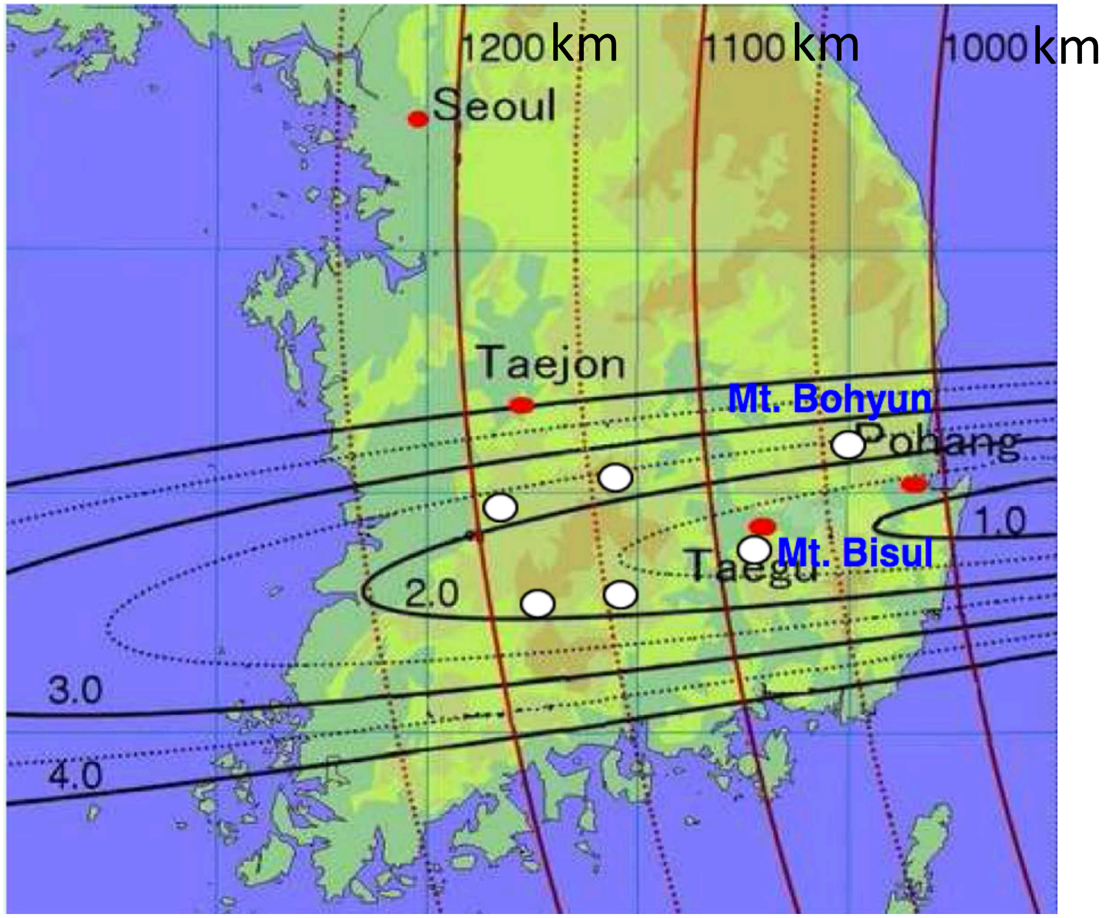
JD+KD 1.5°: 5.5 ~ 7 σ for all δ_{CP}

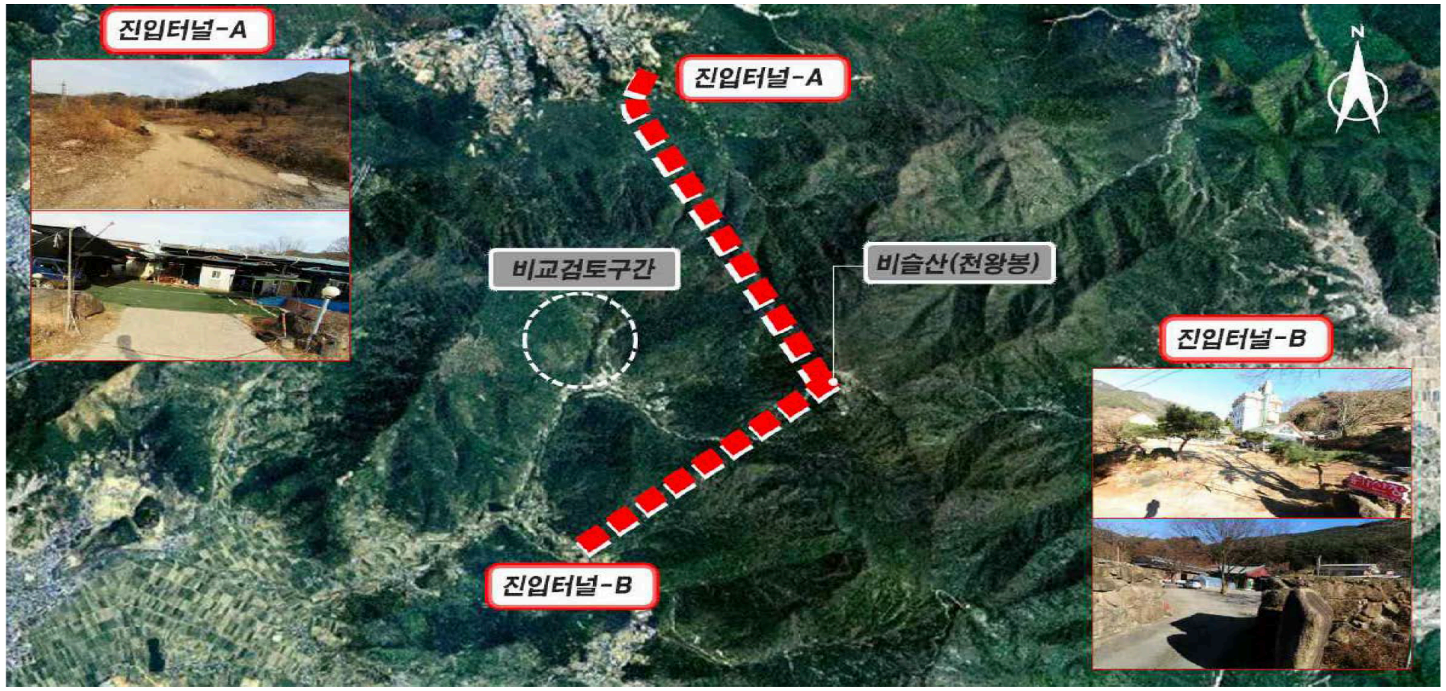
JD x2 : 1 ~ 5 σ for all δ_{CP}

(< 3 σ for most cases)

Mt. Bisul Site

S. Seo





Summary

- Study of neutrino is an important step towards understanding the Universe, complementary to high-energy collider searches and flavor factories.
- ν oscillation is Earth-scale quantum phenomenon.
- Exciting findings in the past and now, next target being CP violation phase, mass ordering and θ_{23} octant.
- Good chance for T2K-II to establish CPV evidence at 3σ.
- Hyper-K proposed to observe CPV at >5σ and many other interesting physics.
- 2nd detector in Korea (T2HKK) will greatly strengthen the physics cases, especially in MO determination.