New experimental results on CPV in the lepton sector

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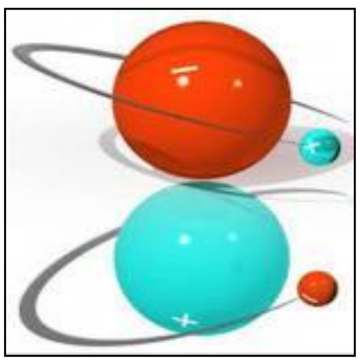
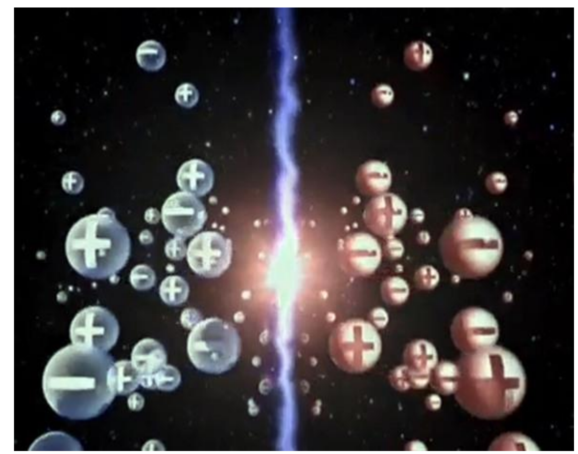
CP violation in the leptonic sector?

Recent results on **neutrino oscillations**

new window to studies of charge-parity (CP) violation in leptonic sector



Is the CP violation in neutrinos in early universe the reason for the matter-antimatter asymmetry?



The new era of precision measurements of neutrino oscillations begins!

Neutrino Oscillations

Neutrinos have non-zero mass and mixing angles

The bulk of the existing data currently is very well described by the oscillation of three active neutrinos

Many open questions:

- What is the neutrino mass hierarchy?
  - Is Δm^2 positive or negative?

    Mass hierarchy (MH) → sign of Δm^2_{32} , Δm^2_{31}

    Normal (NH): $m_3 > m_2 > m_1$

    Inverted (IH): $m_2 > m_1 > m_3$
- Is there CP violation in the lepton sector?
  - CP symmetry is violated if $\delta_{CP} \neq 0, \pi$
- Is the θ_{23} mixing angle maximal?
  - If not, which quadrant?
- What are the precise values of the mixing angles θ_{ij}?
- Majorana or Dirac?

Oscillation parameters: mixing matrix

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

$c_{ij} = \cos\theta_{ij}$

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

$$U_{PMNS} \sim \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \quad U_{CKM} \sim \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

δ_{CP} unknown

$\delta_{CP} = 70^{o}$

CP symmetry is violated in lepton sector if $\delta_{CP} \neq 0, \pi$

Neutrino oscillations

ν_μ survival probability:

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

Sensitive to θ_{23} and Δm^2_{32}

Comparing neutrino and anti-neutrino disappearance: test of CPT symmetry

ν_e appearance probability:

Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Leading term

CP violating $\quad -\alpha\sin\delta_{CP} \times \sin^2 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$

"+" for antineutrino

CP conserving $\quad \alpha\cos\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$

$$+\,O(\alpha^2) \qquad x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \quad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31}L}{4E}$$

For anti-neutrinos, replace δ and x with $-\delta$ and $-x$

- Leading term depends on θ_{13} and θ_{23},
- CP-violating phase δ => $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$,
- Matter effect gives sensitivity to mass hierarchy: sign of x.

Neutrino oscillation search

$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_x)$: deficit on the number of events (disappearance)

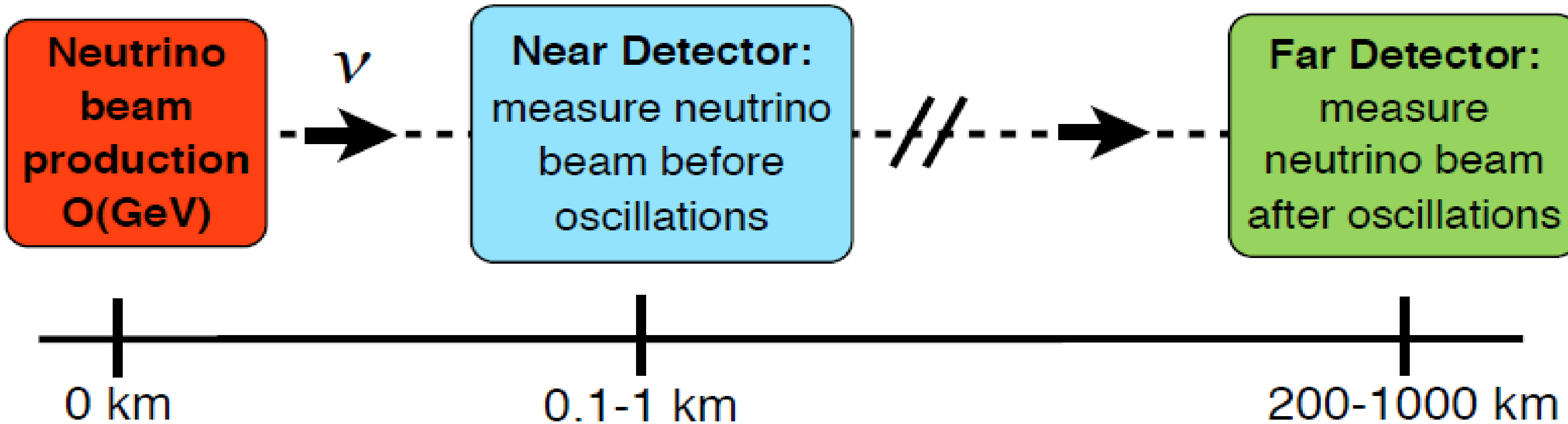
$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e)$: excess of events (appearance)

CP-asymmetry searched for in long base-line experiments looking for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$

Neutrinos (and anti-neutrinos) travel through matter not antimatter: electron density causes asymmetry
It is necessary to disentangle true CP-V effects due to the δ phase from the ones induced by matter

- Keep L small (~200 km): so that matter effects are insignificant
- Make L large (>1000 km): measure the matter effects; unfold CPV from matter effects through E dependence

Long-baseline experiments concept



Near Detector: $N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$

Flux | Cross Section | Detector Efficiency | Oscillation probability

Far Detector: $N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P_{osc}(E_\nu)$

Long-Baseline Experiments

Experiment	Run	Peak E_n	Baseline	Detector
K2K	1999 - 2004	1 GeV	250 km	Water Č
MINOS(+)	2005 - 2015	3 GeV	730 km	Iron/Scint
CNGS/Opera	2008 - 2012	17 GeV	730 km	Emulsion
T2K	2010 -	0.6 GeV	295 km	Water Č
NOνA	2014 -	2 GeV	810 km	Liq.Scint.
DUNE*	2026 -	3 GeV	1300 km	Liq. Argon
Hyper-K**	2026 -	0.6 GeV	295 km	Water Č

K2K: confirm atmospheric neutrino oscillations
MINOS: precise measurement of $|\Delta m_{32}|^2$ and θ_{23}
Opera: observe tau appearance in $\nu_\mu \leftrightarrow \nu_\tau$ oscillations
T2K: observe $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\mu \leftrightarrow \nu_\mu$ oscillations, measure θ_{13}, first results in the search for CP violation
NOνA: $\nu_\mu \leftrightarrow \nu_e$ at a longer baseline for mass hierarchy, CP violation, ….

*DUNE construction approval in 2016; **Hyper-K will be seeking approval in 2017/2018

The T2K experiment

Intense Off-Axis muon (anti)neutrino beam from J-PARC to Super-Kamiokande (295 km from target production): measure oscillated neutrino flux

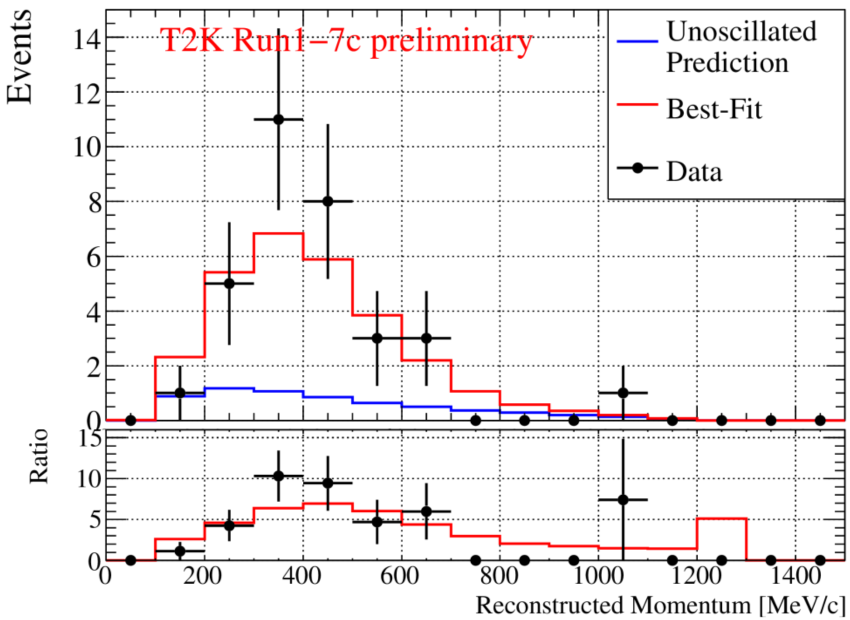
- Unoscillated neutrino flux is measured at the near detector (~280m)
- Two production modes:Neutrino and anti-neutrino
- Precise measurements of

- muon (anti)neutrino disappearance
- electron (anti)neutrino appearance

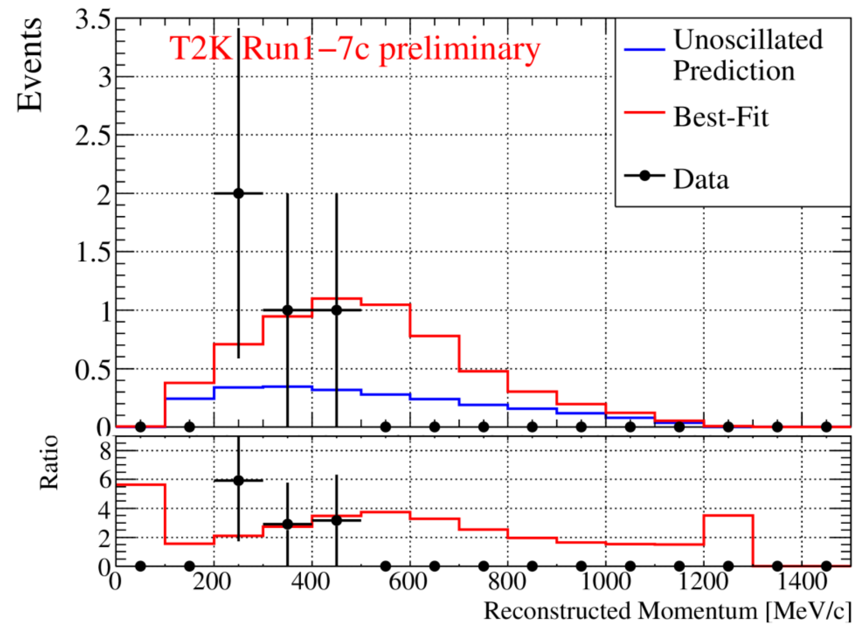
Near detector complex

ν_e and $\bar{\nu}_e$ appearance

Neutrino mode



Anti-neutrino mode



Beam mode	Sample	Exp. Not Osc	Exp. $\delta_{CP} = 0$ (NH)	Observed
neutrino	*e*-like	6.1	24.2	32
antineutrino	*e*-like	2.3	6.9	4

Predictions:

ν_e: 19.6 evts (NH, $\delta_{CP}=\pi/2$) to 28.7 evts (NH, $\delta_{CP}=-\pi/2$)
$\bar{\nu}_e$: 7.7 evts (NH, $\delta_{CP}=\pi/2$) to 6.0 evts (NH, $\delta_{CP}=-\pi/2$)

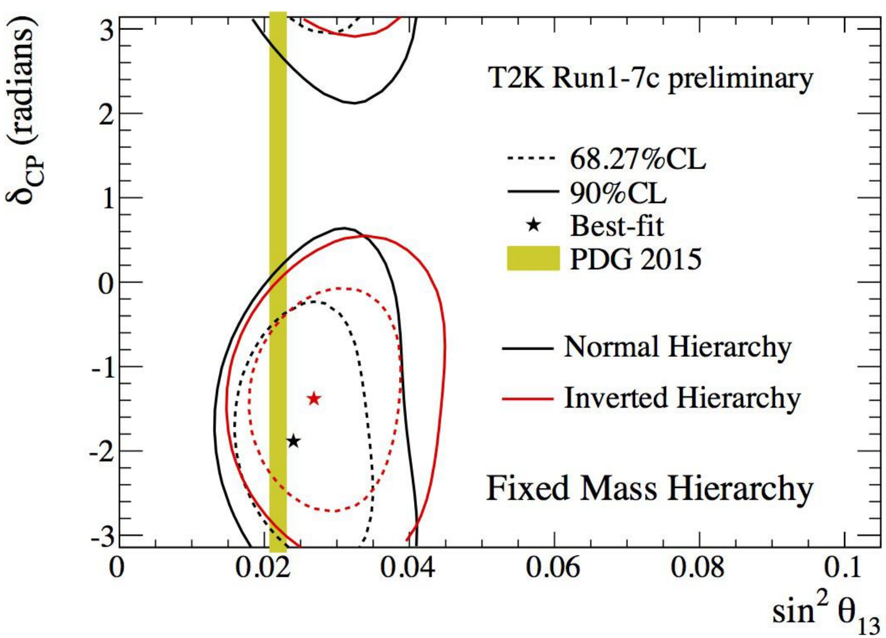
Clear appearance signal for ν_e
More statistics needed for $\bar{\nu}_e$

Constraints on θ_{13} and δ_{CP}

Number of ν_e and ν_e candidates compared with predictions :

- Number of observed events shows larger asymmetry than expected for δ_{CP} = $-\pi/2$ and NH

T2K-only data fit



Reactor experiment constraint from PDG2015 ($\sin^2 2\theta_{13}$= 0.085 —0.005) shown

θ_{13} in agreement with reactor experiments

- T2K begins to probe δ_{CP}
- $\delta_{CP} \sim -\pi/2$ and NH preferred
- T2K disfavors region of $\delta_{CP} = +\pi/2$

Phys.Rev.Lett. 118 (2017) no.15, 151801

Similar (but less significant) effects seen in NOνA and SuperK

Constraints on δ_{CP}

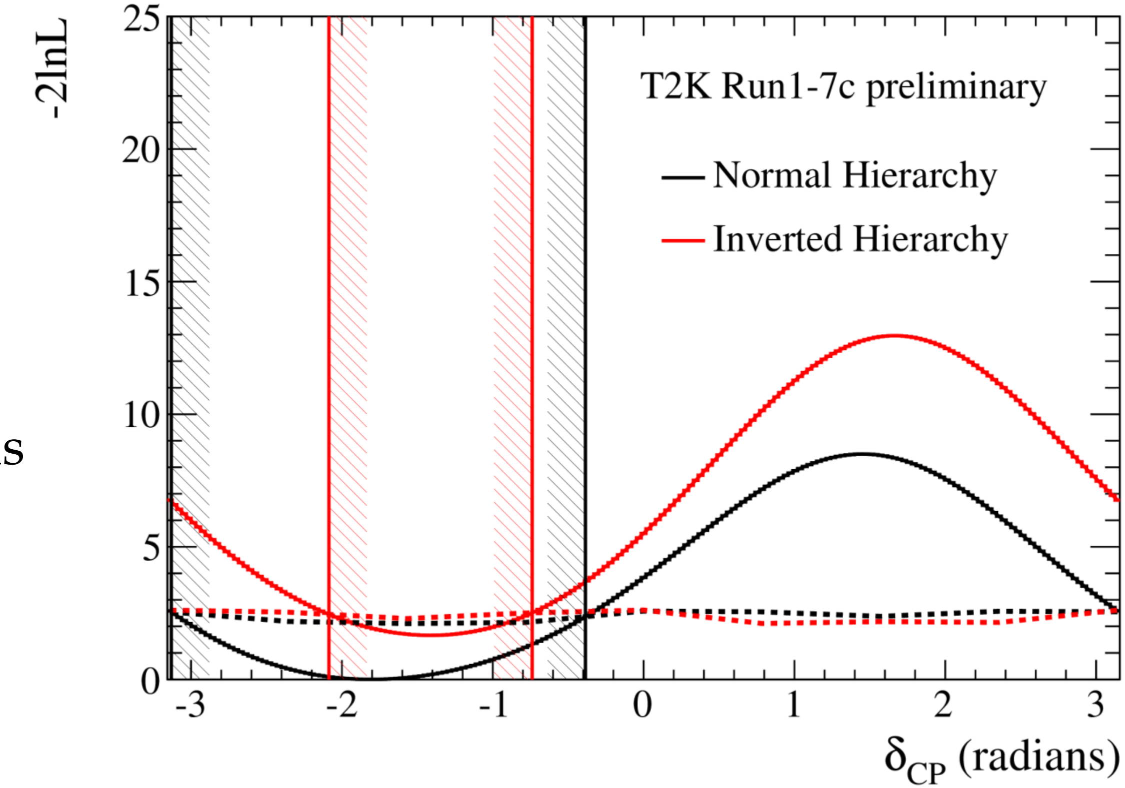
90% CL constraints on δ_{CP} from Feldman-Cousins method
Reactor constraint:
$\sin^2 2\theta_{13} = 0.085 \pm 0.005$ (PDG 2015)

Best fit gives $\boldsymbol{\delta_{CP} = -1.791}$**,**
Normal Hierarchy

- The allowed 90% CL intervals are:

$-3.13 < \delta_{CP} < -0.39$ (NH)
and
$-2.09 < \delta_{CP} < -0.74$ (IH)

- CP conserving values **$\delta_{CP} = 0$** excluded at 90% C.L.



vertical lines show the corresponding allowed 90% confidence intervals, calculated using the Feldman-Cousins method.

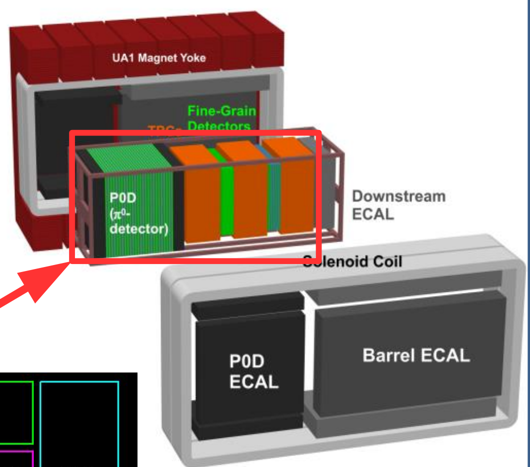
CP conservation hypothesis excluded at 90% CL

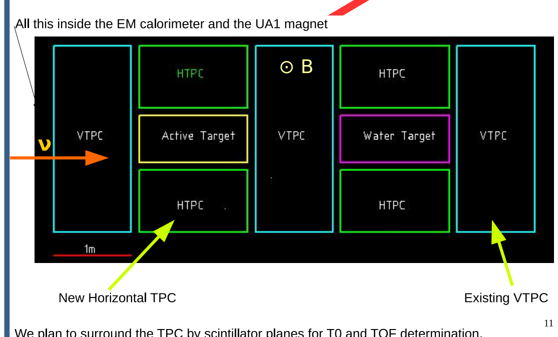
T2K-II

J-PARC neutrino beam upgrade

	Now (achieved)	2020	~2025
p/spill	2.4×10^{14}	2.2×10^{14}	3.2×10^{14}
cycle	2.48s	1.3s	1.16s
power	470kW	800kW	1.3MW

Near Detector upgrade





Intermediate Detectors

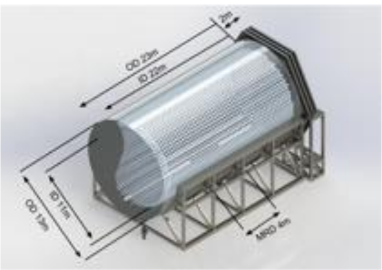
- Water Cherenkov detector at ~1-2 km
- Same technology as the far detector
- Far/Near errors cancelation

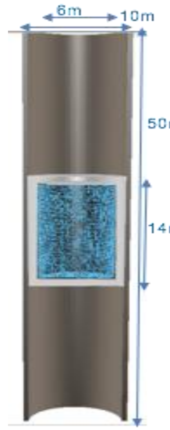
Two proposals: TITUS/nuPRISM

Off-axis angle spanning orientation.

Gd loading, magnetized μ range detector.

Will merge in unique detector

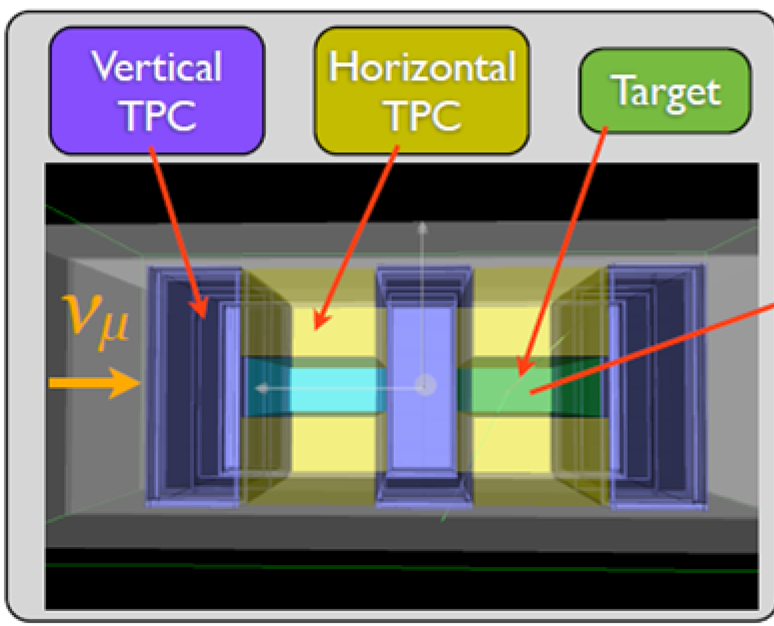


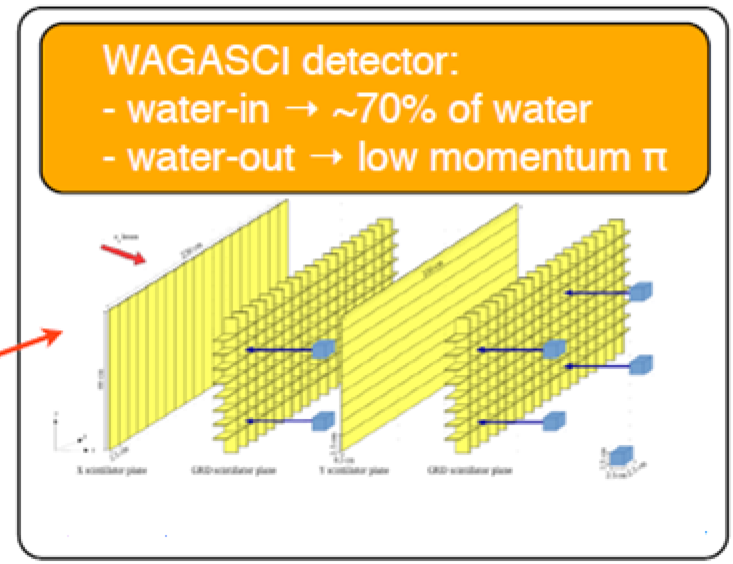


Construction 2020-2023 (?)

T2K-II: Near Detector Upgrade

- Goal is to reduce the cross section systematics
- Need more precise measurements at Near Detector
  - better efficiency for low momenta π and p
  - 4π acceptance





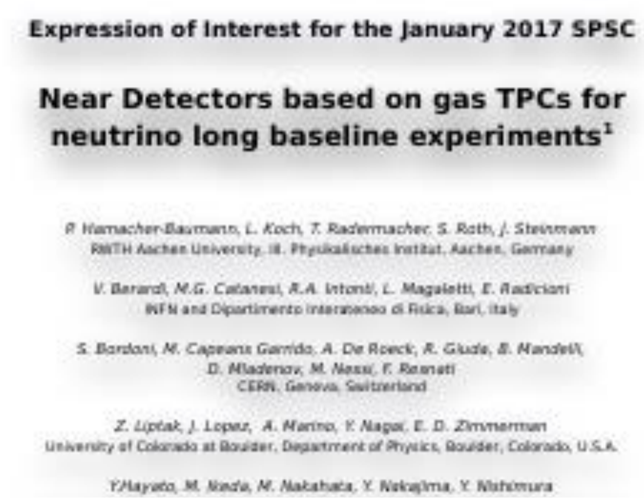
Workshop on "Neutrino ND based on gas TPCs
@CERN: https://indico.cern.ch/event/568177/
https://indico.cern.ch/event/61307/

Alternative configurations to the reference design under study

T2K-II: Near Detector Upgrade

Expression of Interest (EOI) EOI-15 @ Neutrino Platform (CERN): T2K Near Detector upgrade looking forward (HyperK/Dune)

- Signed by 190 people (including a CERN group)
- Submitted to SPSC early January
- First contact with referees and questions received


Expression of Interest for the January 2017 SPSC

Near Detectors based on gas TPCs for neutrino long baseline experiments[1]

P. Hamacher-Baumann, L. Koch, T. Radermacher, S. Roth, J. Steinmann
RWTH Aachen University, III. Physikalisches Institut, Aachen, Germany

V. Berardi, M.G. Catanesi, R.A. Intonti, L. Magaletti, E. Radicioni
INFN and Dipartimento Interateneo di Fisica, Bari, Italy

S. Bordoni, M. Capeans Garrido, A. De Roeck, R. Giuda, B. Mandelli, D. Mladenov, M. Nessi, F. Resnati
CERN, Geneva, Switzerland

Z. Liptak, J. Lopez, A. Marino, Y. Nagai, E. D. Zimmerman
University of Colorado at Boulder, Department of Physics, Boulder, Colorado, U.S.A.

Y.Hayato, M. Ikeda, M. Nakahata, Y. Nakajima, Y. Nishimura

One project, two goals

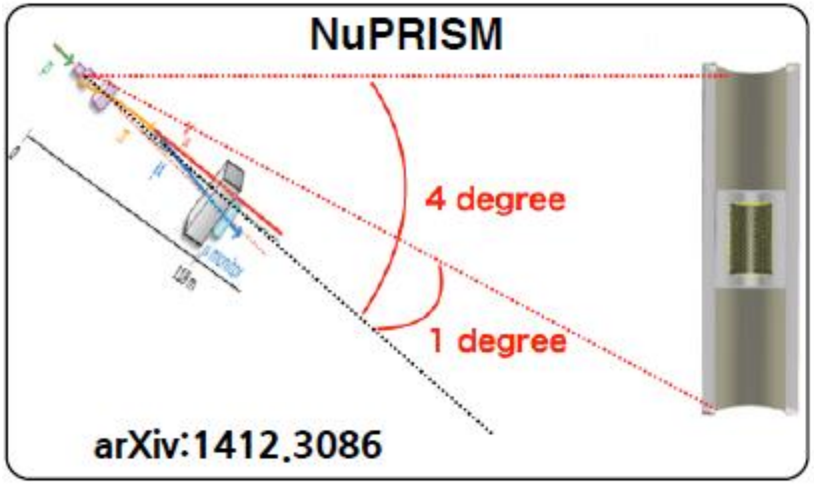
- Study, optimize, design and build an upgrade of the ND280 near detector capable of improved and model-independent precision below ~4% in line with T2K-II physics needs
- Study, optimize, design a High Pressure TPC that could serve as base for a detector aimed at exploring the details of neutrino interactions. Demonstrate the concept with prototypes on a test beam.

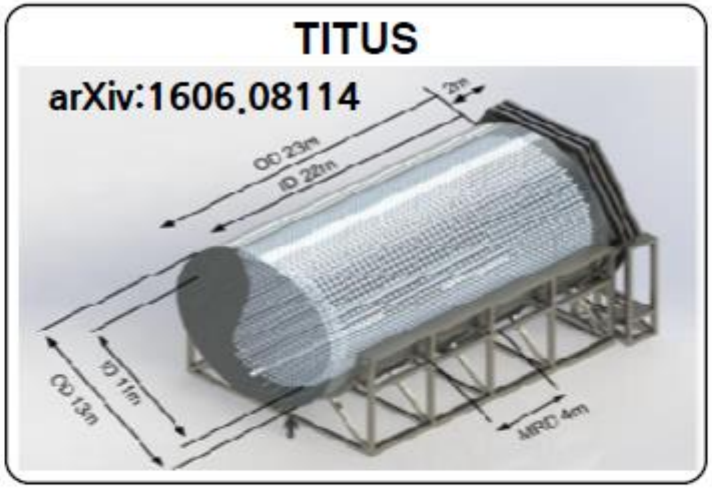
We identified synergies and strong overlaps in the interests expressed by the participating groups. Associating the two projects will strengthen the collaboration.

- ➢ R&D Program based at CERN (Neutrino Platform) to develop both TPC and HPTPC for neutrino experiments
- ➢ Side subjects as Dark Matter searches or Double Beta Decay can be accommodated in case of common developments

T2K-II: Intermediate Detector

- Water Cherenkov detector at intermediate distance (>1 km from target) with a high-intensity neutrino beam
- Same neutrino cross section as at the far detector
- Complementary to the upgrade of Near Detector (magnetized)





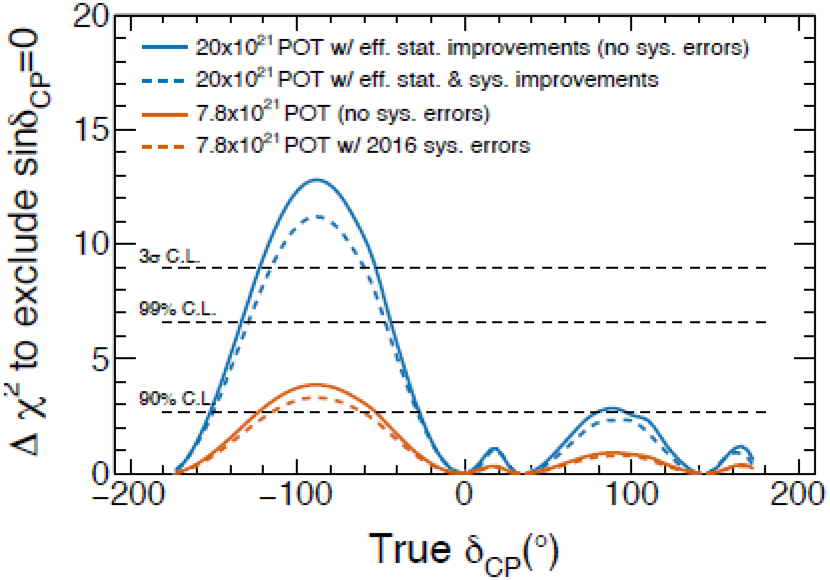
- Spans off-axis 1°/4°
- Mono-chromatic neutrino beam
- Study energy dependence to neutrino interactions

- 2.5° off-axis detector with 1.27 kton FV
- Long geometry to contain high-momentum muons
- Gd loading for neutron detection
- Magnetized muon range detector

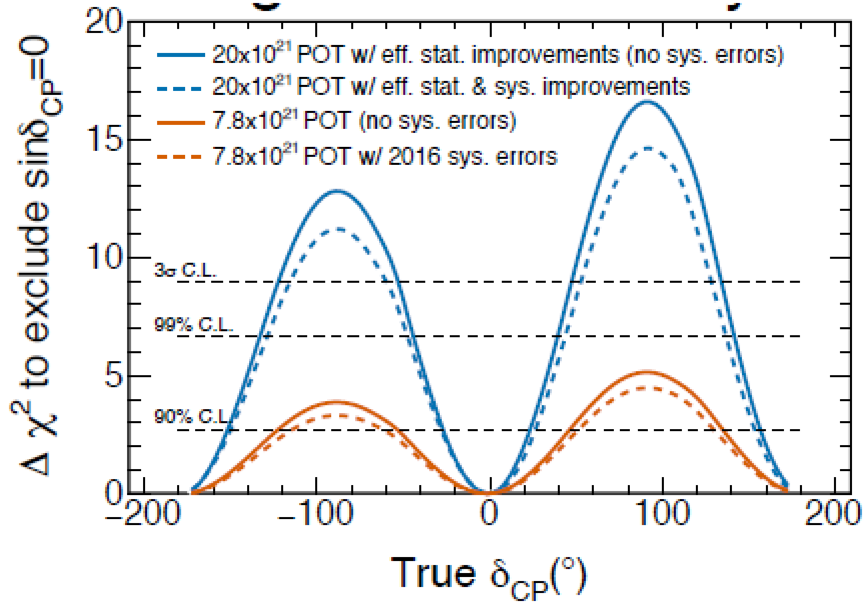
Process for merging the two proposals into a single detector design

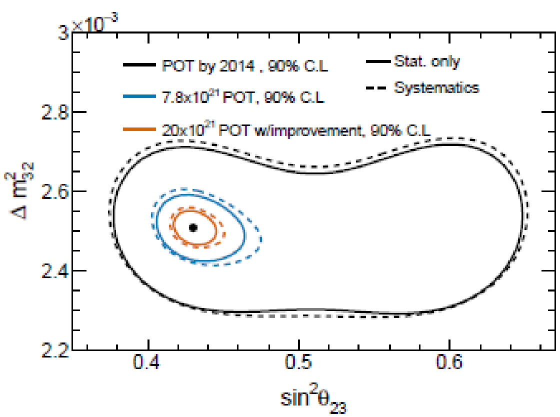
Physics Potential of T2K-II

Unknown Mass Hierarchy



Mass Hierarchy Known





Sensitivity for $\sin^2\theta_{23}$=0.43

With full T2K-II statistics able to:

- Exclude CP conservation hypothesis at more than 3σ if δ_{CP} ~-π/2
- Measure θ_{23} with resolution ~1.7°

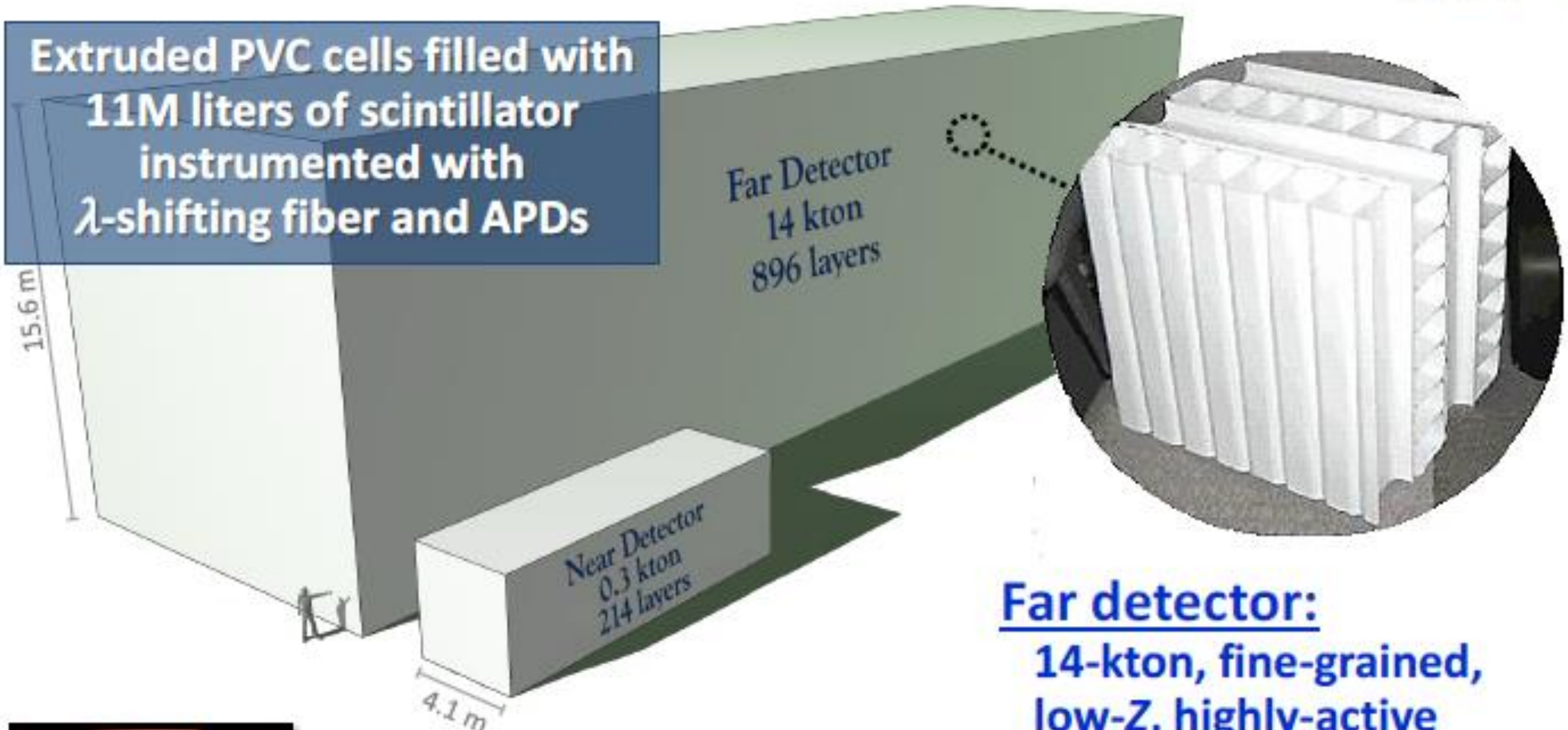
The NOνA experiment

- "Conventional" beam
- Two-detector experiment:
  - Near detector
    – beam composition
    – energy spectrum
  - Far detector
    – measure oscillations and search for new physics

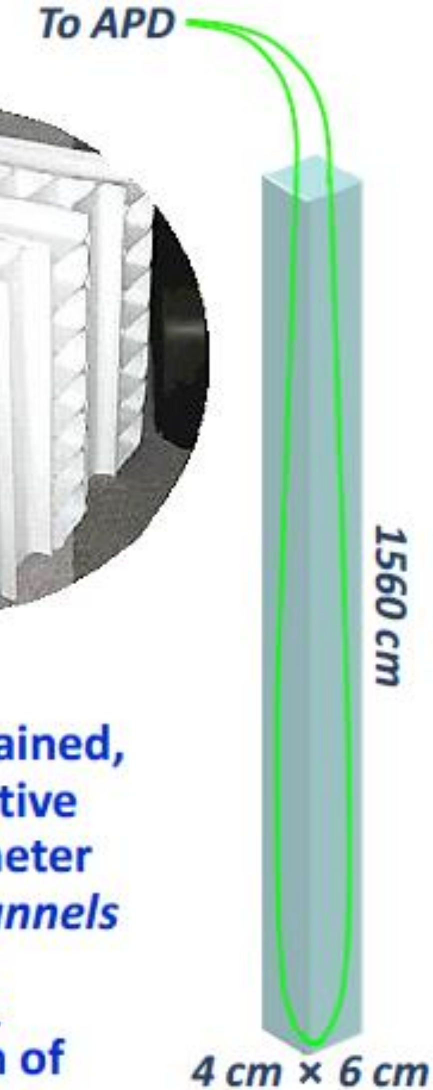
Significant complementarity, with different baselines and different near and far detectors
-- NOνA more sensitive to Mass Ordering
-- T2K directly sensitive to CP violation
Both experiments benefit from off-axis geometry

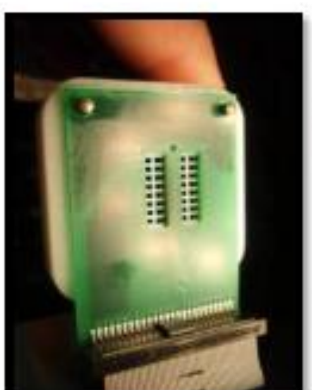
NOνA detectors

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



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

Far detector:

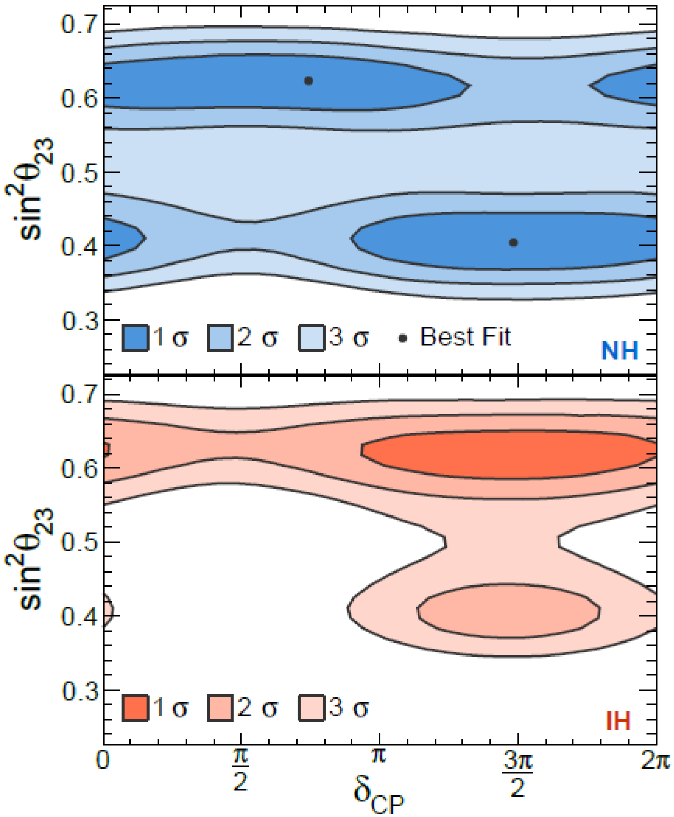
14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:

0.3-kton version of the same
→ *20,000 channels*

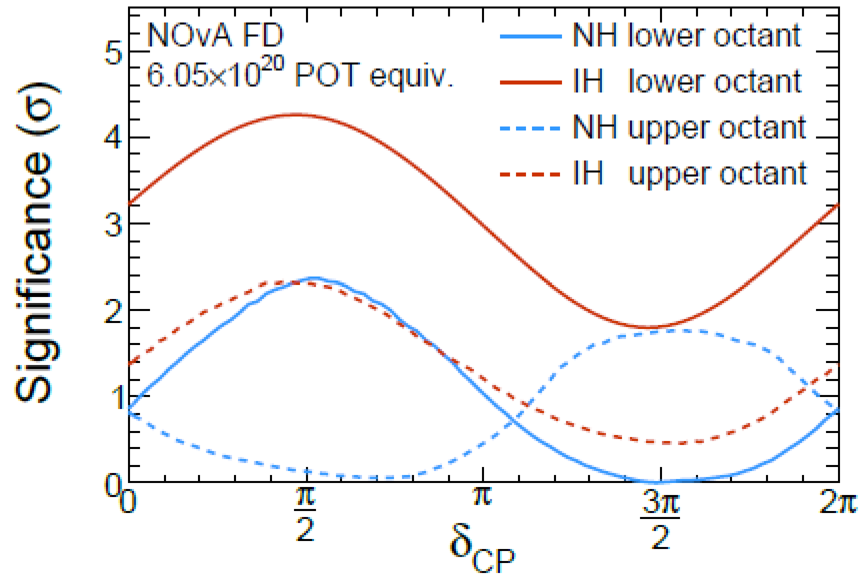
NOνA results

Combined fit of the NOνA ν_e appearance and ν_μ disappearance data



Regions of δ_{CP} vs. $\sin^2\theta_{23}$ parameter space consistent with the observed spectrum of ν_e candidates and the ν_μ disappearance data.

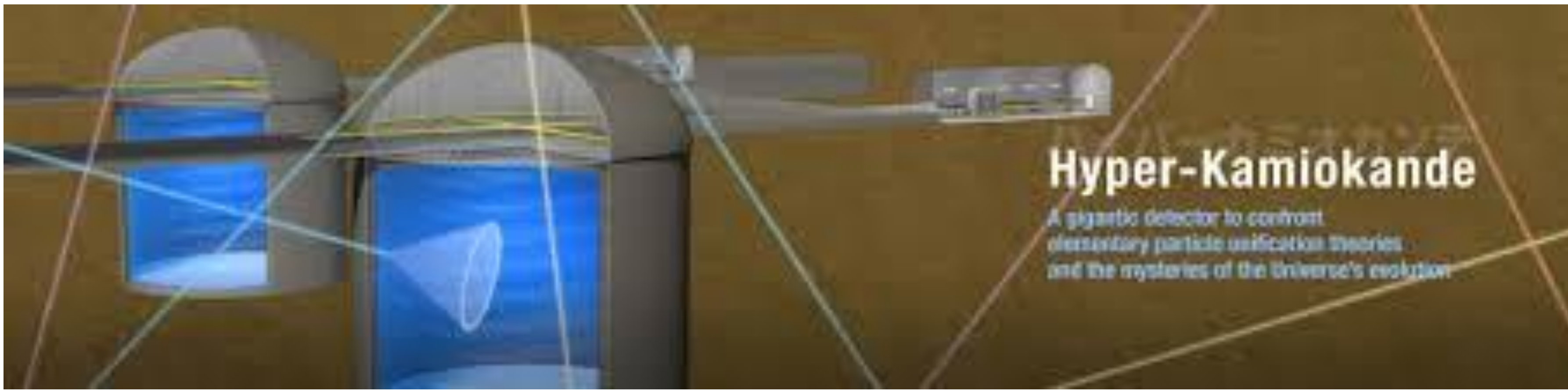
- inverted mass hierarchy disfavored

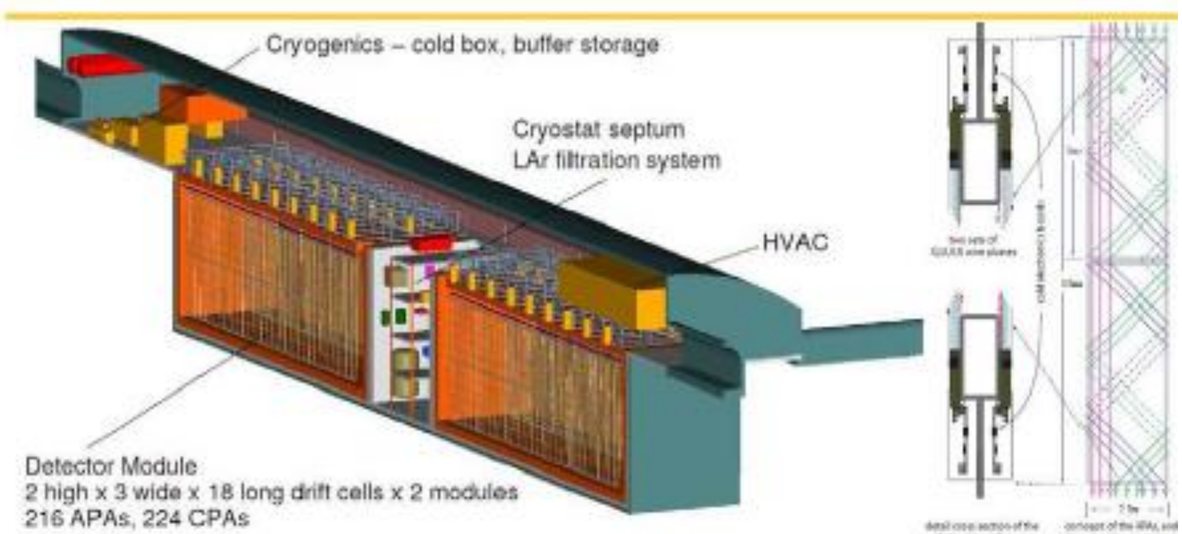


Significance at which each value of δ_{CP} is disfavored for each of the four possible combinations of mass hierarchy

Future data-taking in antineutrino to resolve degeneracies

Future project: DUNE and Hyper-Kamiokande





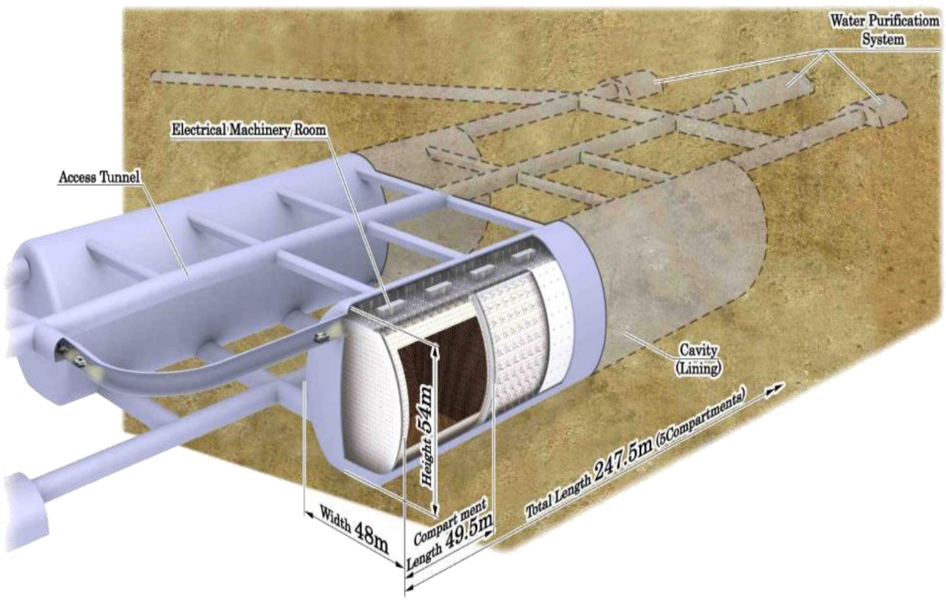
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Two complementary approaches

Hyper-K:
- Short baseline → no matter effects: pure CP but reduced MH
- Off axis → reduced intrinsic ν_e contamination, reduced NC backgrounds

DUNE:
- Long baseline → sensitive to matter effects: exelent performances in MH
- On axis: second oscillation maximum and sensitive to ν_τ appearance (tiny effects at 1300 km)
- On axis: extended lever arm for measurement of oscillation parameters

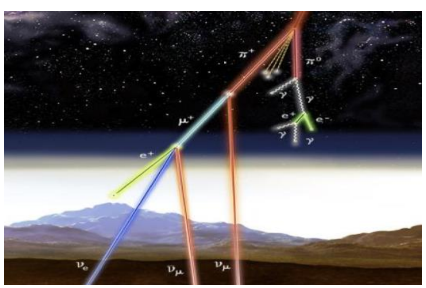
Hyper-Kamiokande: overview

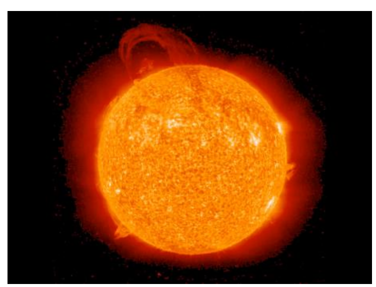


Hyper-Kamiokande is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

- ✧ Neutrino oscillations (atmospheric, accelerator and solar);
- ✧ Neutrino astrophysics;
- ✧ Proton decay;
- ✧ Non-standard physics.

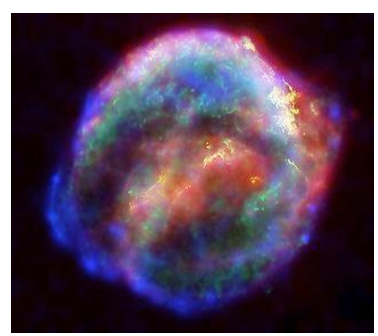
Atmospheric ν





Solar ν

Supernova ν

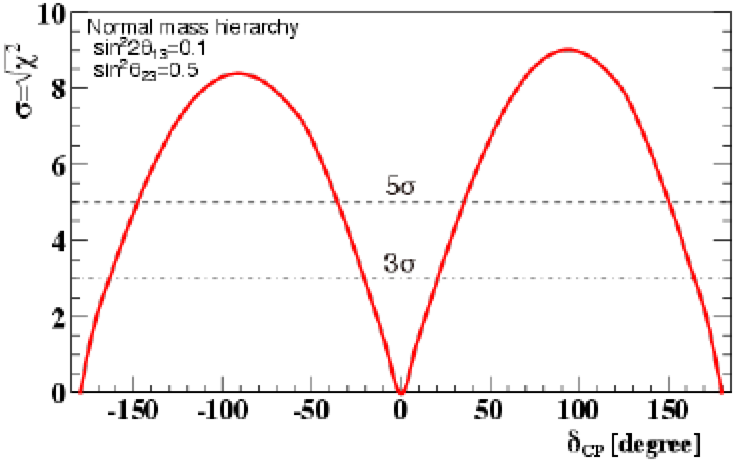


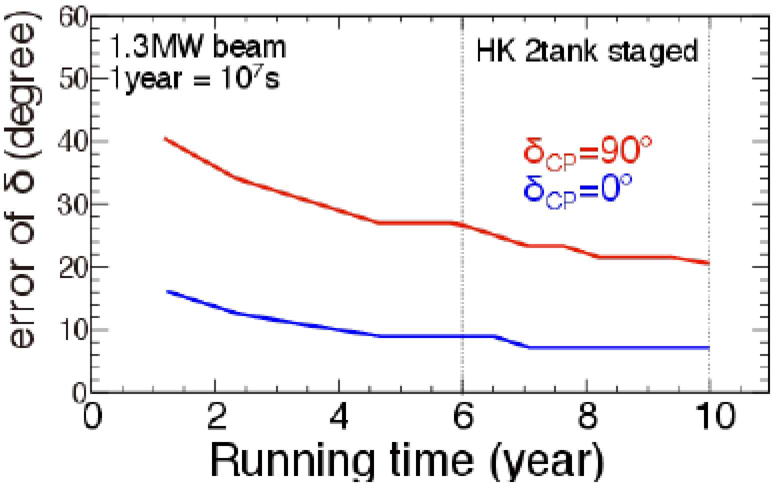
Accelerator ν

Hyper-K CP Sensitivity

CPV sensitivity based on:

6 years with one tank + 4 years with two
Assume MH is already known





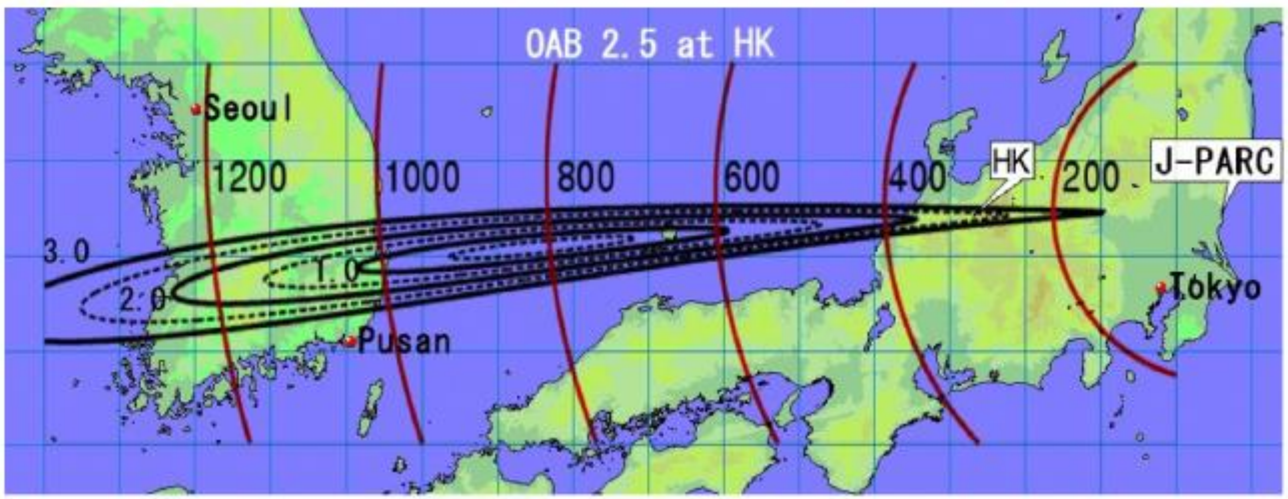
CPV coverage:

78% at 3σ
62% at 5σ

CP violation can be detected with more than 3σ (5σ) significance for 78% (62%) of values of δ_{CP}

Hyper-K: 2° detector in Korea

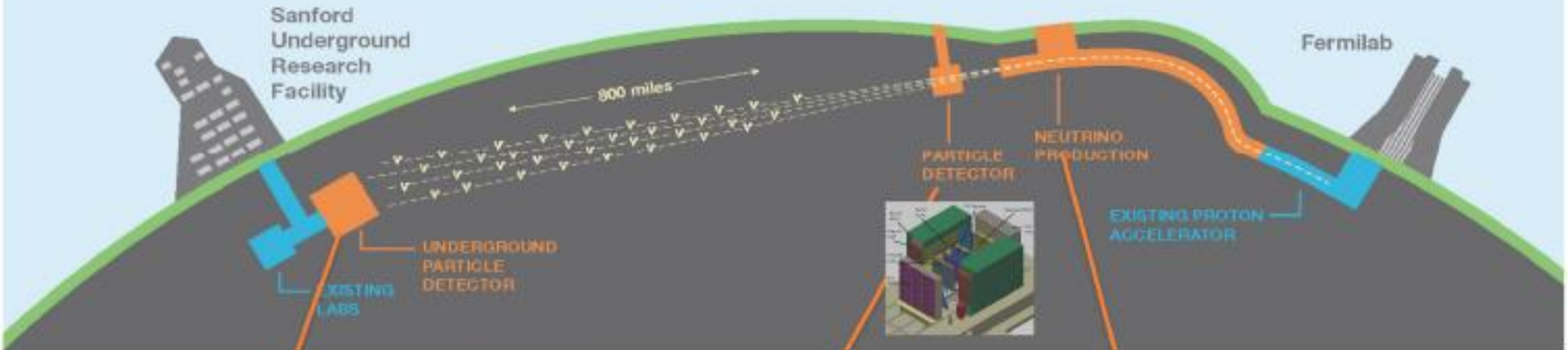
Recently Hyper-K protocollaboration revisited the option of the second tank being in Korea
Off-axis at a baseline of ~1100 km

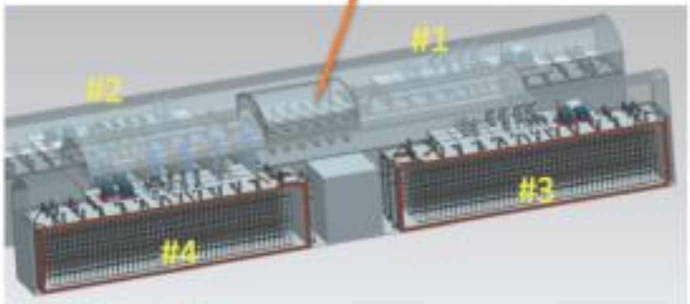


Longer baseline: mass hierarchy sensitivity
+ some benefit to CP sensitivity

DUNE: overview

"Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF" (arXiv:1512.06148)





high precision near detector complex

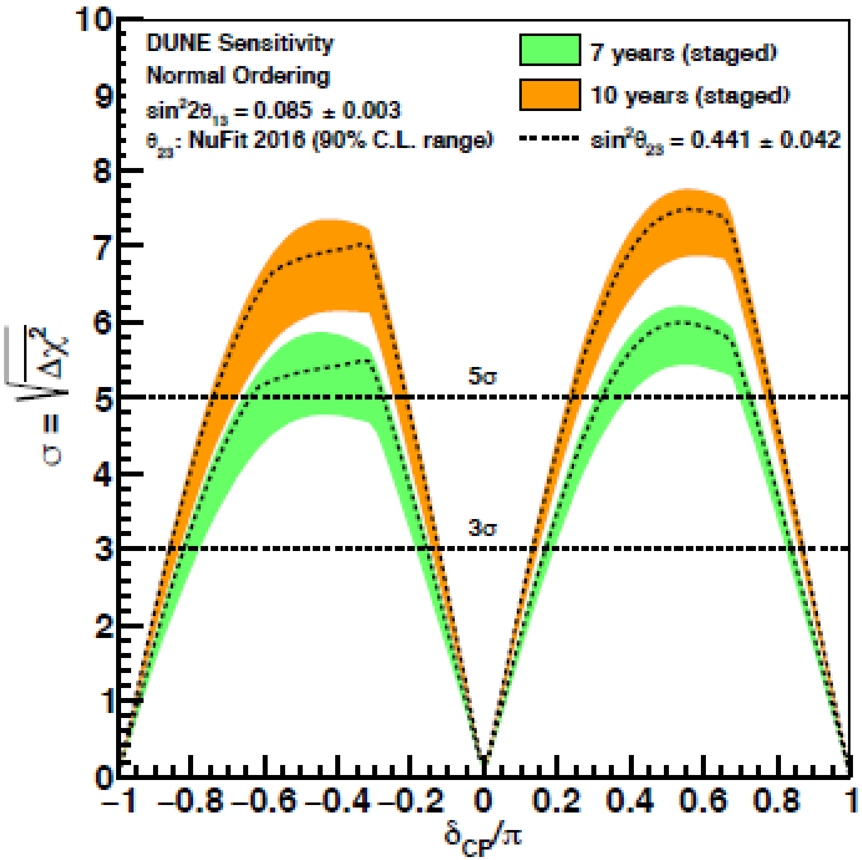
Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

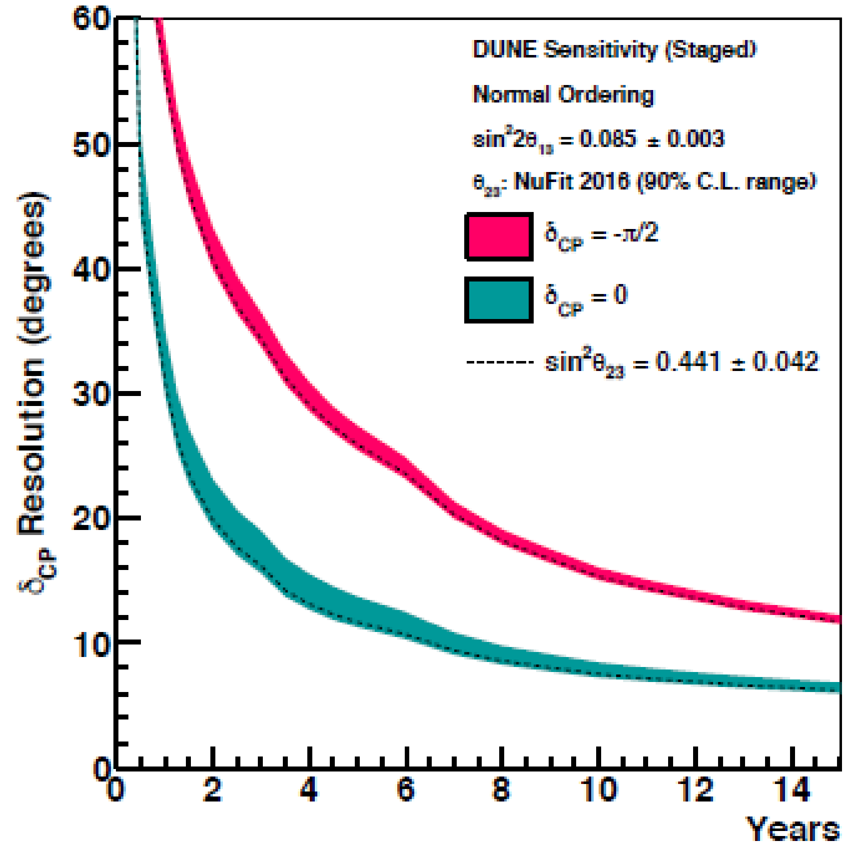
- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and double-phase readout under consideration

"Conceptual Design Report Volume 4: The DUNE Detectors at LBNF" (arXiv:1601.02984)

DUNE CP Sensitivity

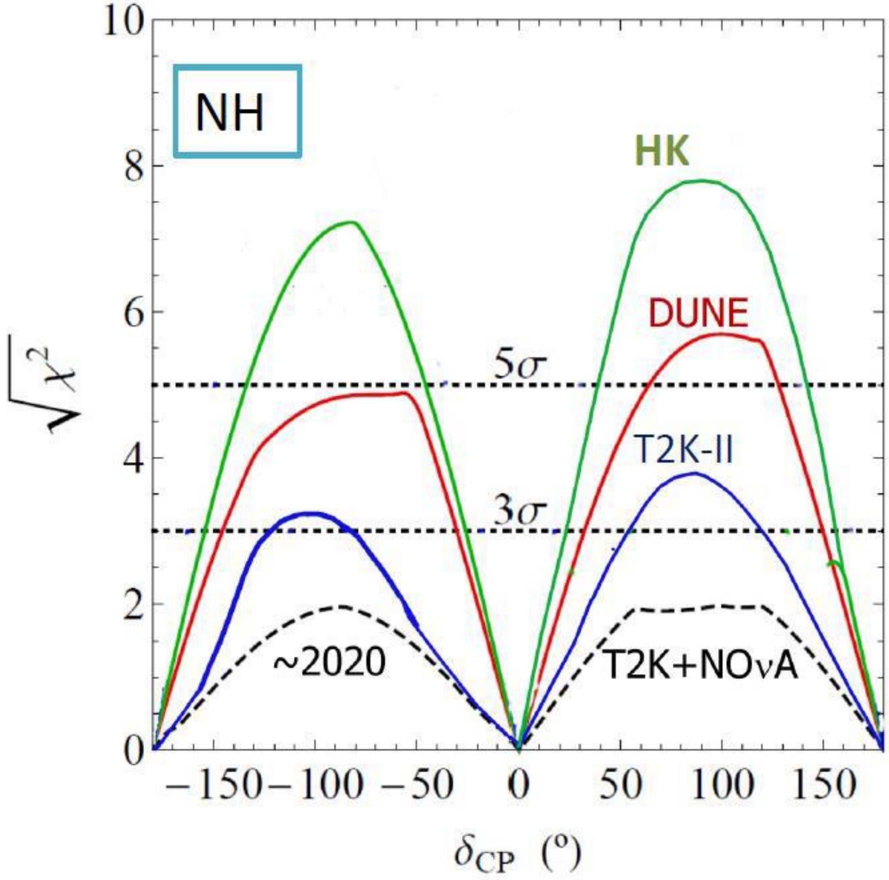
CPV Discovery → **δ_{CP} Measurement**





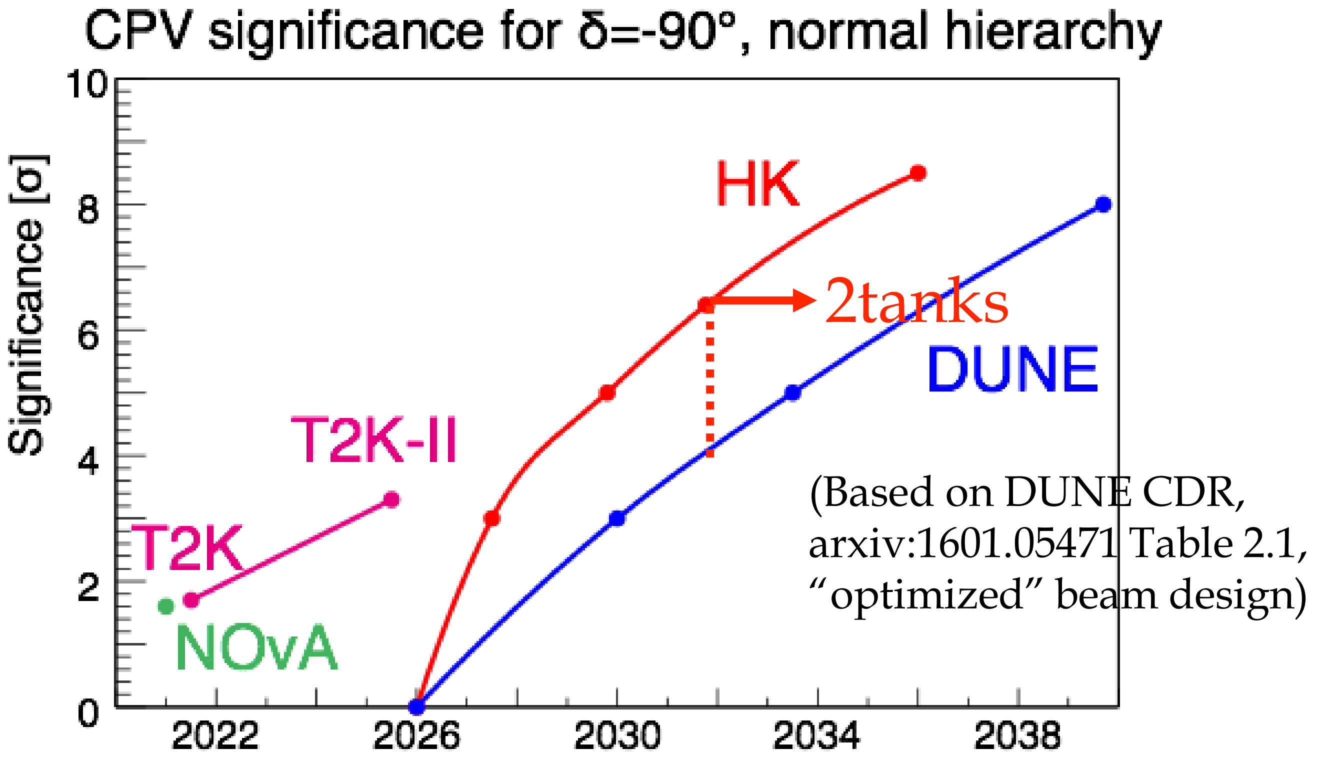
Credits M.Thomson IMFP17

Towards leptonic CP asymmetry



Mezzetto , Neutrino 2016

Towards leptonic CP asymmetry



~3σ indication with T2K→T2K-II,
>5σ discovery and measurement with HK/DUNE

Note: "exact" comparison sometimes difficult due to different assumptions

Conclusions

Long-baseline ν oscillation experiments have played a major part in our current understanding of the neutrino

The question of CP violation in the leptonic sector is a priority of the future neutrino program

DUNE and Hyper-K will tackle fundamental questions:
CP Violation
Mass Hierarchy
Testing the Standard Model of νs
Proton Decay
Supernova neutrinos

> the current hint for maximal leptonic CP violation can be either due to maximal leptonic CP violation or CP conservation in the presence of New Physics

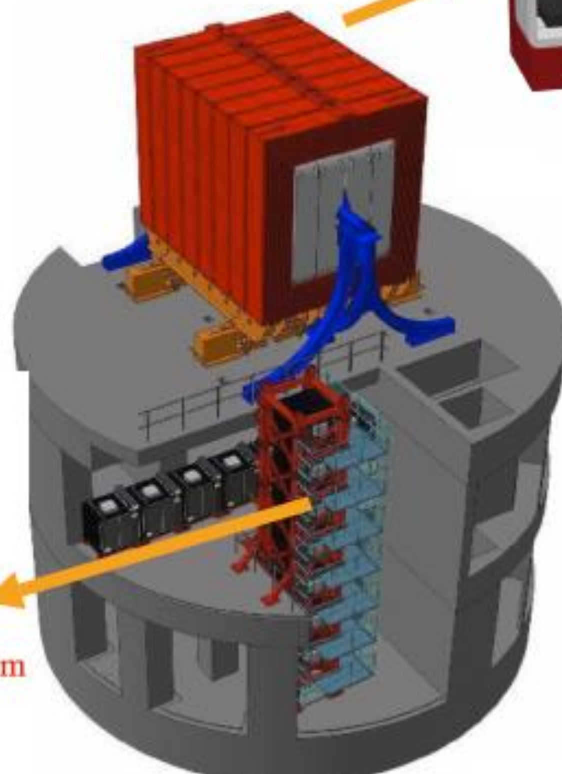
Maybe even more surprises in neutrinos!

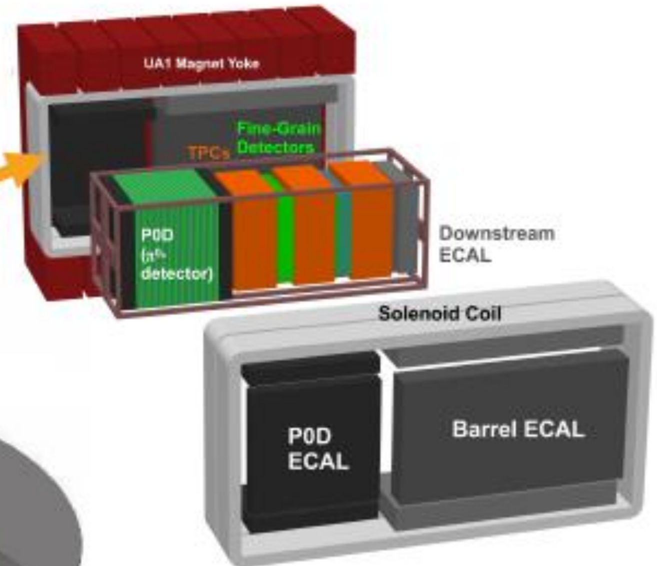
Backup

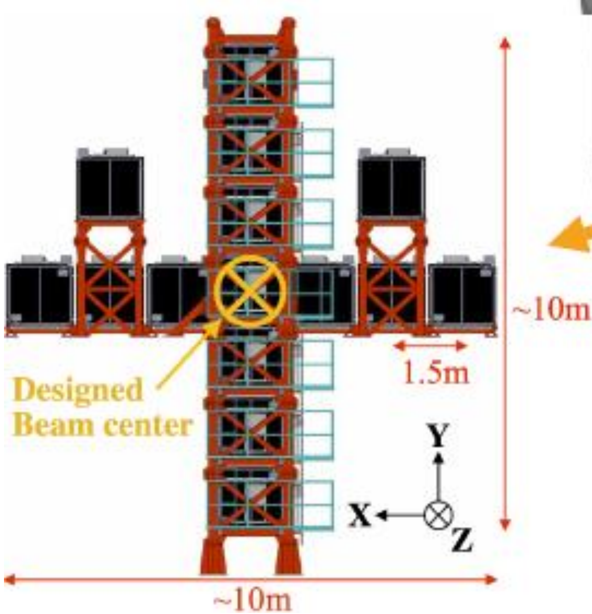
T2K near detector complex

INGRID

- On-axis detector
- 7+7 (+2) identical modules
- Iron and scintillator tracking calorimeter
- Beam direction and stability monitoring





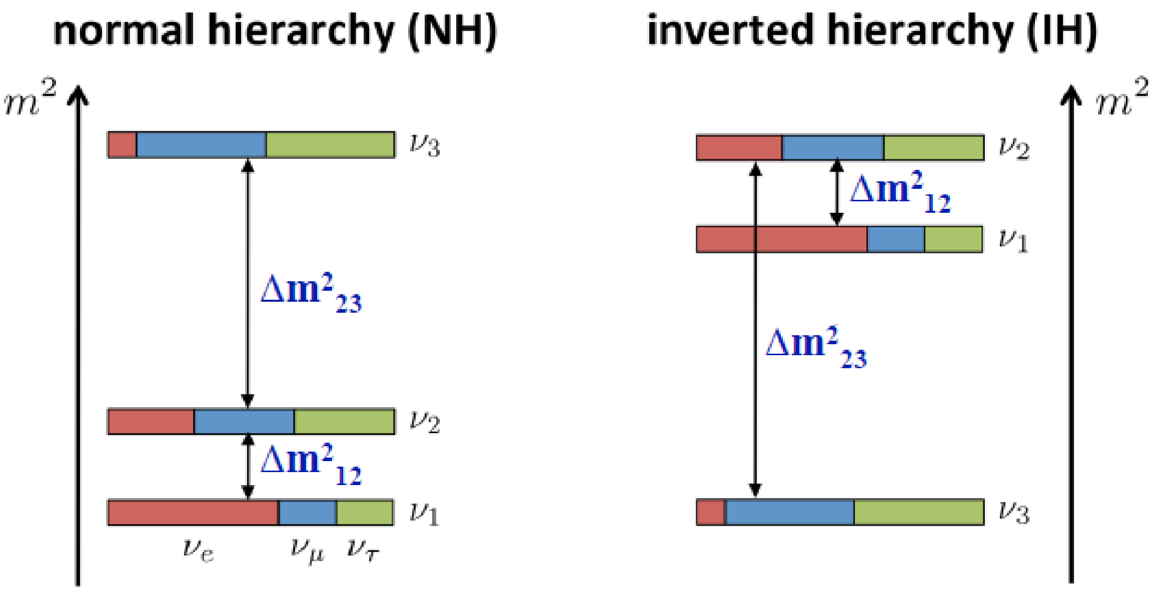


ND280

- Off-axis detector
- Magnet 0.2 T
- Trackers, calorimeters and muon range detectors
- Active (scintillator) and passive (water) targets

Oscillation parameters:

Mass squared difference Δm^2



Solar, Reactors
Accelerators, Atmospheric

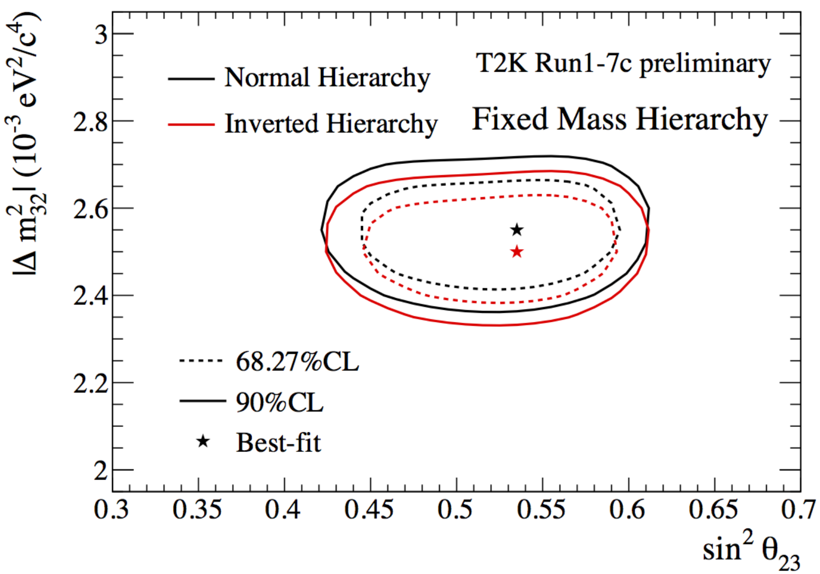
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

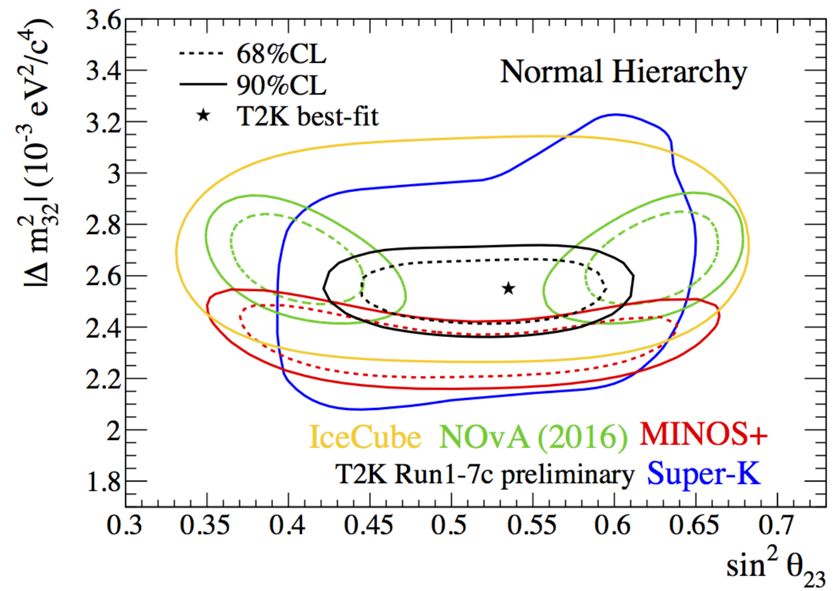
Mass hierarchy is not yet known

Mass hierarchy (MH) → sign of Δm^2_{32}
Normal (NH): $m_3 > m_2 > m_1$
Inverted (IH): $m_2 > m_1 > m_3$

Several projects to improve sensitivity to mass ordering ……

Constraints on θ_{23} and $\Delta m^2{}_{32}$



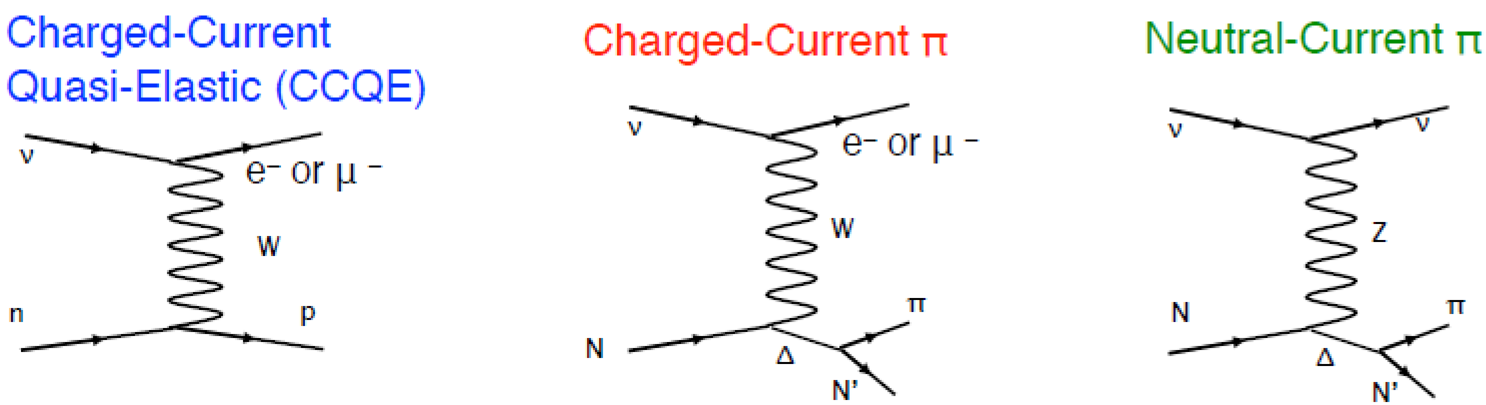


	Normal Hierarchy		Inverted Hierarchy	
Parameter	Best fit	$\pm 1\sigma$	Best fit	$\pm 1\sigma$
$\sin^2\theta_{23}$	0.532	[0.464; 0.578]	0.534	[0.468; 0.577]
$\Delta m^2_{32}(10^{-3} eV^2)$	2.545	[2.461; 2.626]	2.510	[2.427; 2.591]

(Anti)Neutrino interactions at T2K

The dominant neutrino interaction mode is Charge-Current Quasi-Elastic

Neutrino energy from lepton momentum and angle in CCQE hypothesis:
- 2 body kinematics
- assume target nucleon at rest

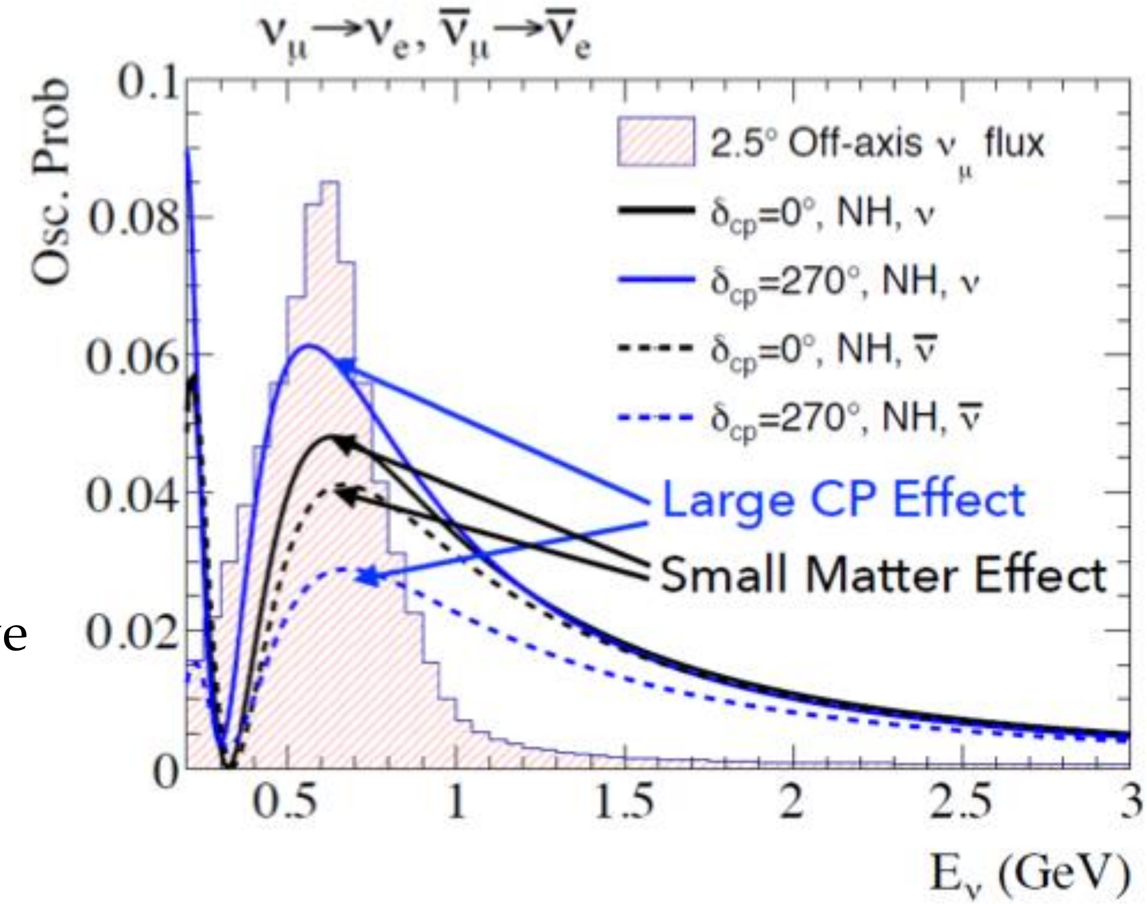


Other cross-section components
- CCQE-like multinucleon interaction (2 nucleons in the final state)
- Charged-current single-pion production (CCπ)
- Neutral-current single-pion production (NCπ)

Effect of CP violation at T2K

- Asymmetric effect on $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$:

- $\delta_{CP} = -\pi/2 \rightarrow$ maximizes $P(\nu_\mu \rightarrow \nu_e)$ and minimizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- $\delta_{CP} = +\delta/2 \rightarrow$ minimizes $P(\nu_\mu \rightarrow \nu_e)$ and maximizes $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



- δ_{CP} and Mass Hierarchy have similar effects

- Effect of δ_{CP} on $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ is about ±20-30%

- Effect of Mass Hierarchy is about ±10%

T2K joint neutrino and antineutrino analysis

The oscillation parameters $\sin^2\theta_{23}$, Δm^2_{32}, $\sin^2\theta_{13}$, and δ_{CP} are estimated by performing a joint maximum-likelihood fit of the four far-detector samples.
The oscillation probabilities are calculated using the full three-flavor oscillation formulas
Matter effects are included with an Earth density of $\rho = 2.6\ g/cm^3$

TABLE I. Number of ν_e and $\bar{\nu}_e$ events expected for various values of δ_{CP} and both mass orderings compared to the observed numbers.

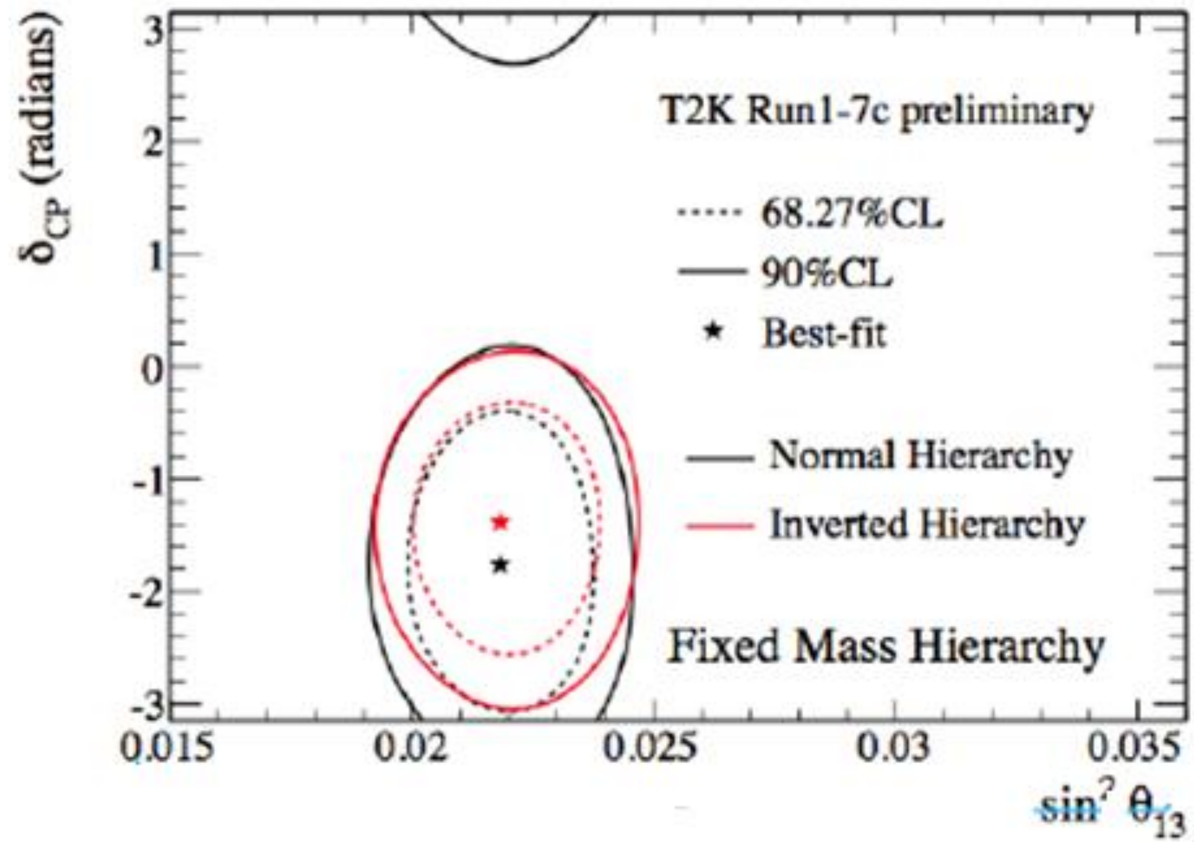
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4
Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\bar{\nu}_e$	6.5	7.4	8.4	7.4	4

The different mass orderings induce a variation of the expected events of ~10%

Matter effects are negligible for the ν_μ and $\bar{\nu}_\mu$ candidate samples, while they affect the number of events in the ν_e and $\bar{\nu}_\mu$ candidate samples by about 6% and 4%, respectively, for maximal CP violation.

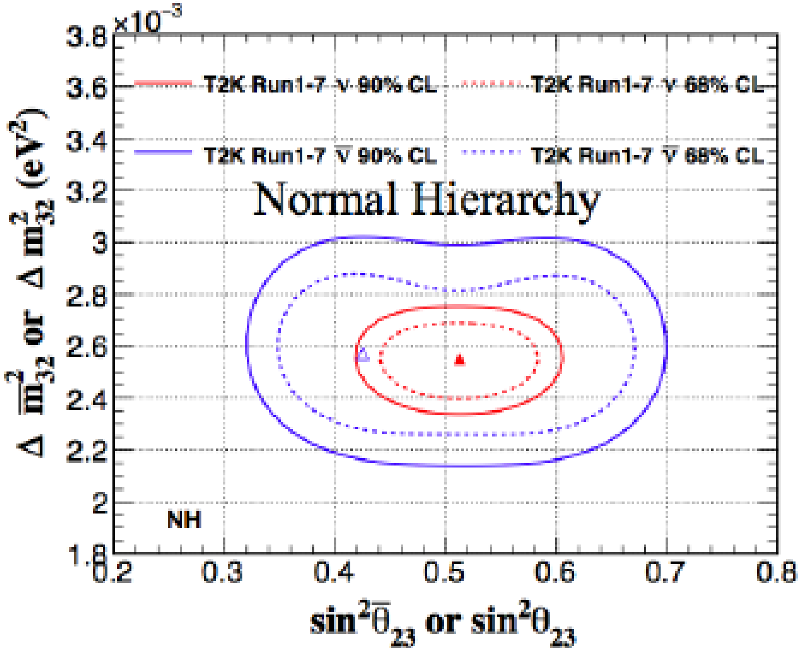
T2K Constraints on δ_{CP}

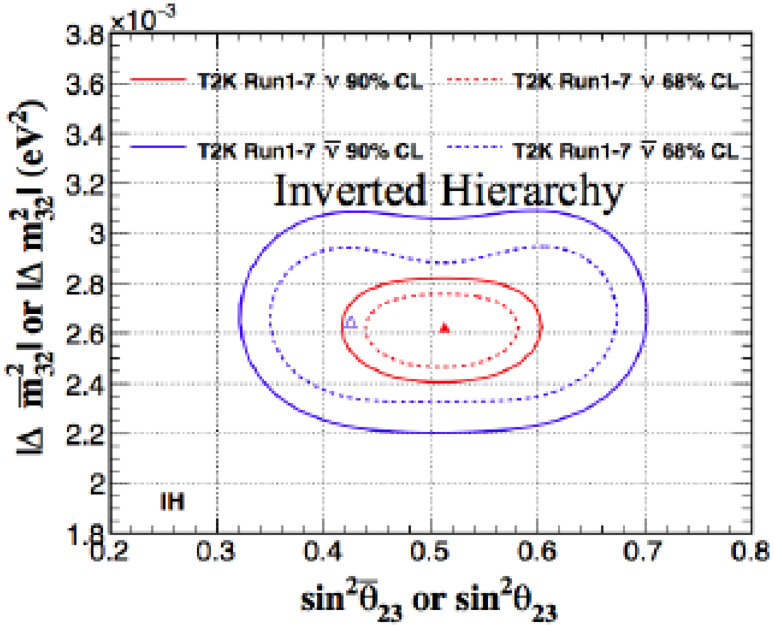
T2K with reactor constrain



Reactor experiment constraint from PDG2015
($\sin^2 2\theta_{13}$= 0.085 —0.005) shown

ν_μ / $\bar{\nu}_\mu$ DISAPPEARANCE – θ_{23} AND Δm^2_{32}





Δm^2_{32} = [2.16, 3.02] x 10^{-3} eV^2 (NH) at 90% CL

$\sin^2\theta_{23}$ = [0.32, 0.70] (NH) at **90%** CL

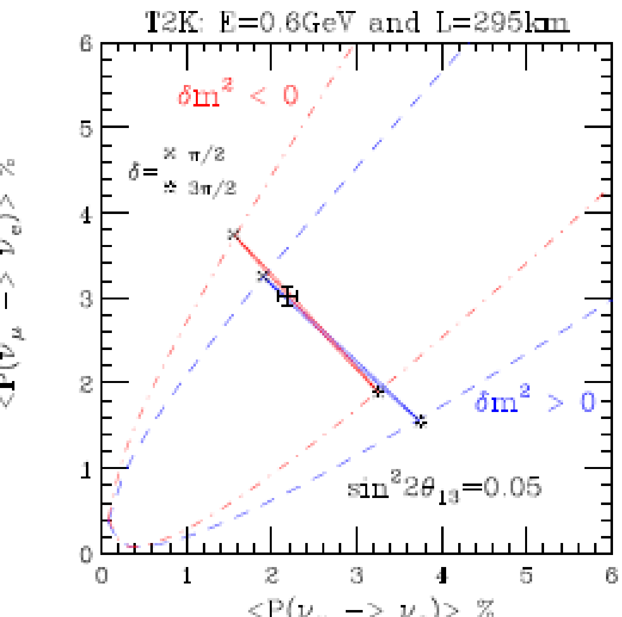
Δm^2_{32} = **[2.34, 2.75]** x **10^{-3}** eV^2 (NH) at 90% CL

$\sin^2\theta_{23}$ = [0.42, 0.61] (NH) at 90% CL

No hint of CPT violation

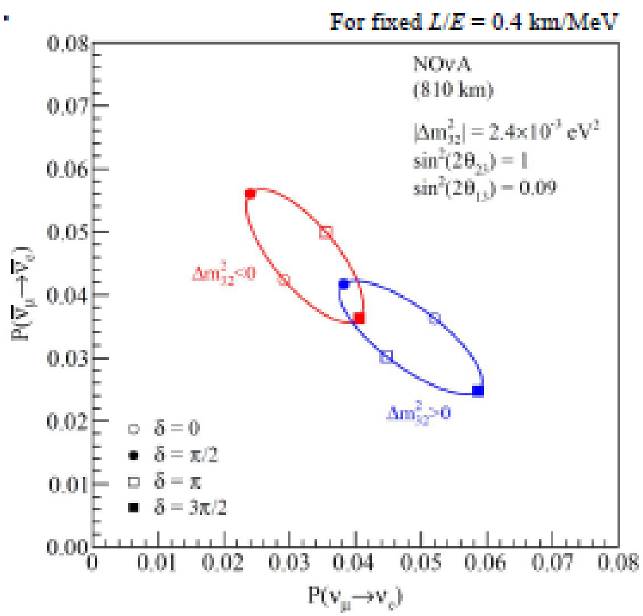
Effect of increasing energy

T2K



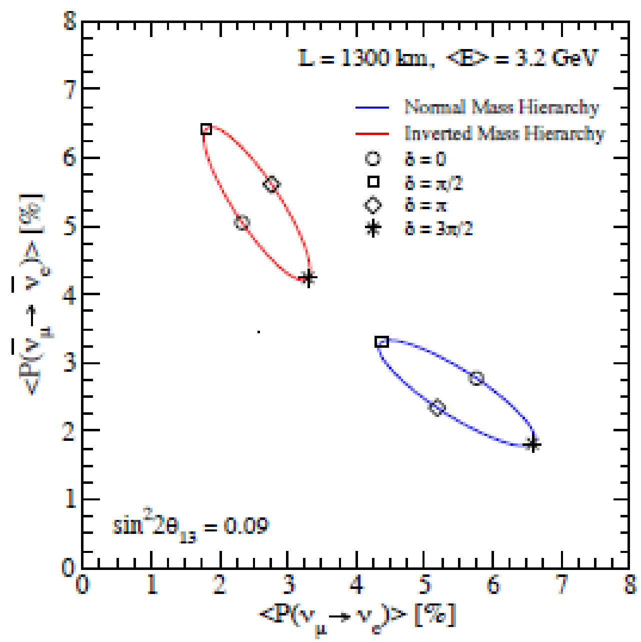
0.6 GeV

NOvA



2 GeV

DUNE



3 GeV

Increasing Energy

[→ bigger matter effect and hence bigger fake CP violation]

LBL ν experiments

DUNE $E_p = 2.5$ GeV, $L = 1300$ km Runtime (yr) = 5 ν + 5 $\bar{\nu}$ 35 kton, LArTPC $\varepsilon_{app} = 80\%$, $\varepsilon_{dis} = 85\%$ $R_\mu = 0.20/\sqrt{E}$, $R_e = 0.15/\sqrt{E}$ $E \in [0.5 - 10.0]$ GeV, Bin width = 250 MeV	**T2K** $E_p = 0.6$ GeV, $L = 295$ km Runtime (yr) = 3 ν + 3 $\bar{\nu}$ 22.5 kton, WC $\varepsilon_{app} = 50\%$, $\varepsilon_{dis} = 90\%$ $R_\mu = 0.085/\sqrt{E}$, $R_e = 0.085/\sqrt{E}$ $E \in [0.4 - 1.2]$ GeV, Bin width = 40 MeV
NOvA $E_p = 1.6$ GeV, $L = 810$ km Runtime (yr) = 3 ν + 3 $\bar{\nu}$ 14 kton, TASD $\varepsilon_{app} = 55\%$, $\varepsilon_{dis} = 85\%$ $R_\mu = 0.06/\sqrt{E}$, $R_e = 0.085/\sqrt{E}$ $E \in [0.5 - 4.0]$ GeV, Bin width = 125 MeV	**T2HK** $E_p = 0.6$ GeV, $L = 295$ km Runtime (yr) = 1 ν + 3 $\bar{\nu}$ 560 kton, WC $\varepsilon_{app} = 50\%$, $\varepsilon_{dis} = 90\%$ $R_\mu = 0.085/\sqrt{E}$, $R_e = 0.085/\sqrt{E}$ $E \in [0.4 - 1.2]$ GeV, Bin width = 40 MeV

Table 4: Detector configuration, efficiencies, resolutions and relevant energy ranges for DUNE, NOvA, T2K, T2HK.

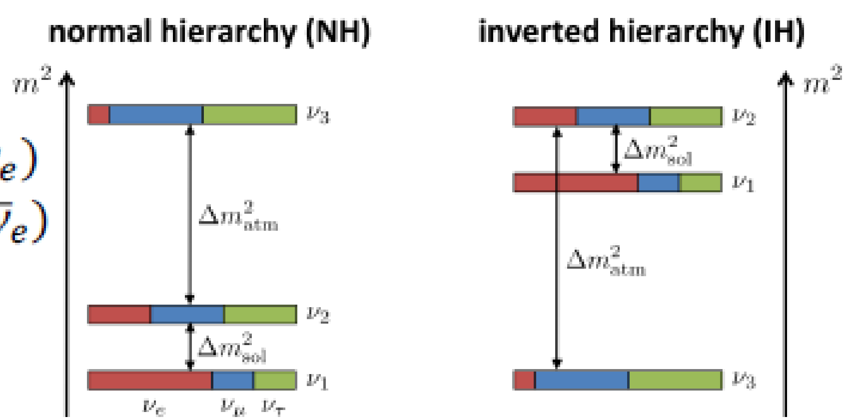
Next questions

- θ_{23} octant ? → sensitivity to $\sin^2\theta_{23}$ (same for ν and $\bar{\nu}$)

- CP violation ?
  - $\delta_{CP}=0,\pi$ → no CP violation
  - $\delta_{CP}=-\pi/2$ → enhance $(\nu_\mu -> \nu_e)$, suppress $(\bar{\nu}_\mu -> \bar{\nu}_e)$
  - $\delta_{CP}=\pi/2$ → suppress $(\nu_\mu -> \nu_e)$, enhance $(\bar{\nu}_\mu -> \bar{\nu}_e)$

  (27% effect at maximum)

- Mass hierarchy (10% effect)



NH:
- enhance $(\nu_\mu -> \nu_e)$
- suppress $(\bar{\nu}_\mu -> \bar{\nu}_e)$

IH:
- enhance $(\bar{\nu}_\mu -> \bar{\nu}_e)$
- suppress $(\nu_\mu -> \nu_e)$

Measuring CP-V: Majorana phases

Neutrinoless double beta experiments

Decay experiments: $(A,Z) \rightarrow (A,Z+2) + 2e^{-}$.

The half-life time, $T_{1/2}$ depends on m_j, the masses of the massive neutrinos ν_j, α_{21} and α_{31} the CP-violating phases

The two Majorana CPV phases α_{21} and α_{31} are physical only if neutrinos are Majorana particles
CP conserved: $\alpha_{21}, \alpha_{31} = 0$ (equal CP-parities) or $\alpha_{21}, \alpha_{31} = \pm\pi$ (opposite CP-parities)

…CUORE, GENIUS, Majorana, SuperNEMO, EXO, GERDA, COBRA…..