Long-baseline neutrino experiments: status and outlook

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ICRR, University of Tokyo

FPCP 2018 at Hyderabad, July 18, 2018

Outline

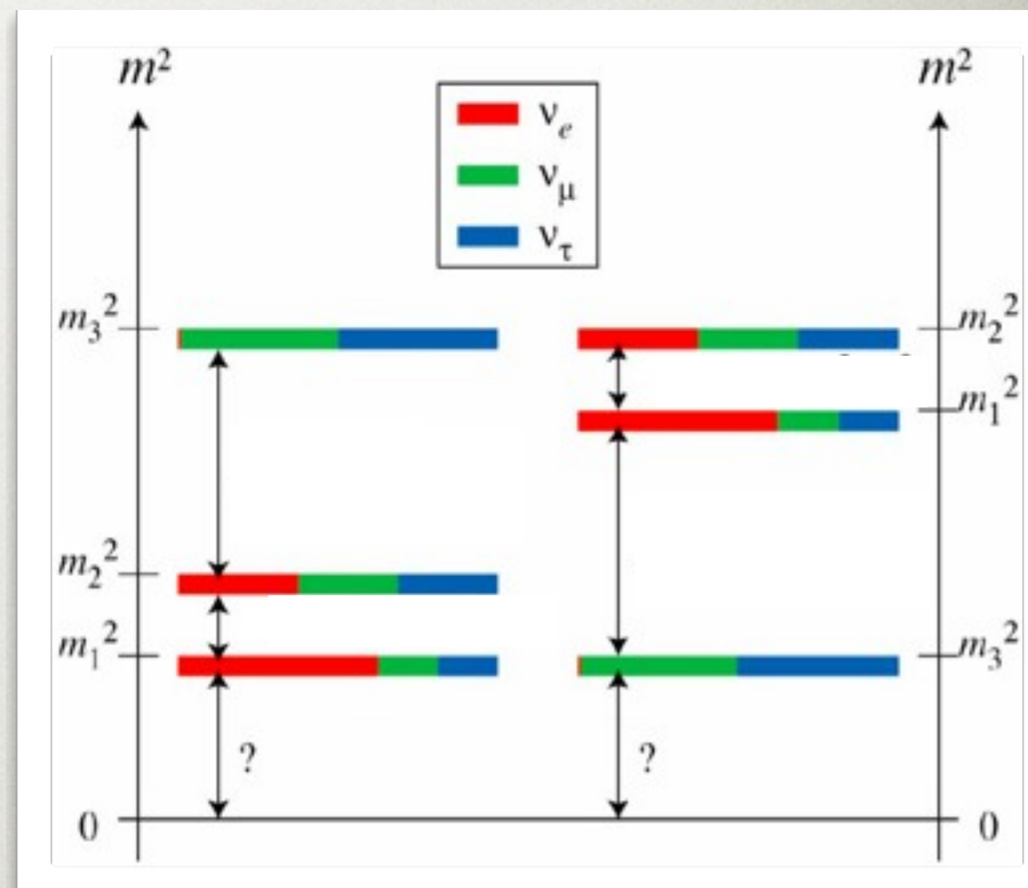
- Status of neutrino oscillation measurements
- Latest results
  - (Largely overlap with T2K and NOvA talks yesterday...)
- Next generation experiments
  - Hyper-K and DUNE
- Caveat
  - This talk focuses on *accelerator-based* long-baseline expts
  - This talk may be highly biased by my personal view and apologies if your experiment is not covered in this talk

Status of ν oscillations

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

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$

- Mixing between all three neutrino flavors has been observed
  - $\theta_{12} \sim 34°$
  - $\theta_{13} \sim 9°$
  - $\theta_{23} \sim 45°$ (maximal?)
- Two mass differences
  - $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2
  - $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2 (hierarchy?)
- CP phase δ_{CP} remains unknown
- Also need to test "standard" 3-flavor neutrino oscillation paradigm



Normal hierarchy ($\Delta m^2_{32}>0$)

Inverted hierarchy ($\Delta m^2_{32}<0$)

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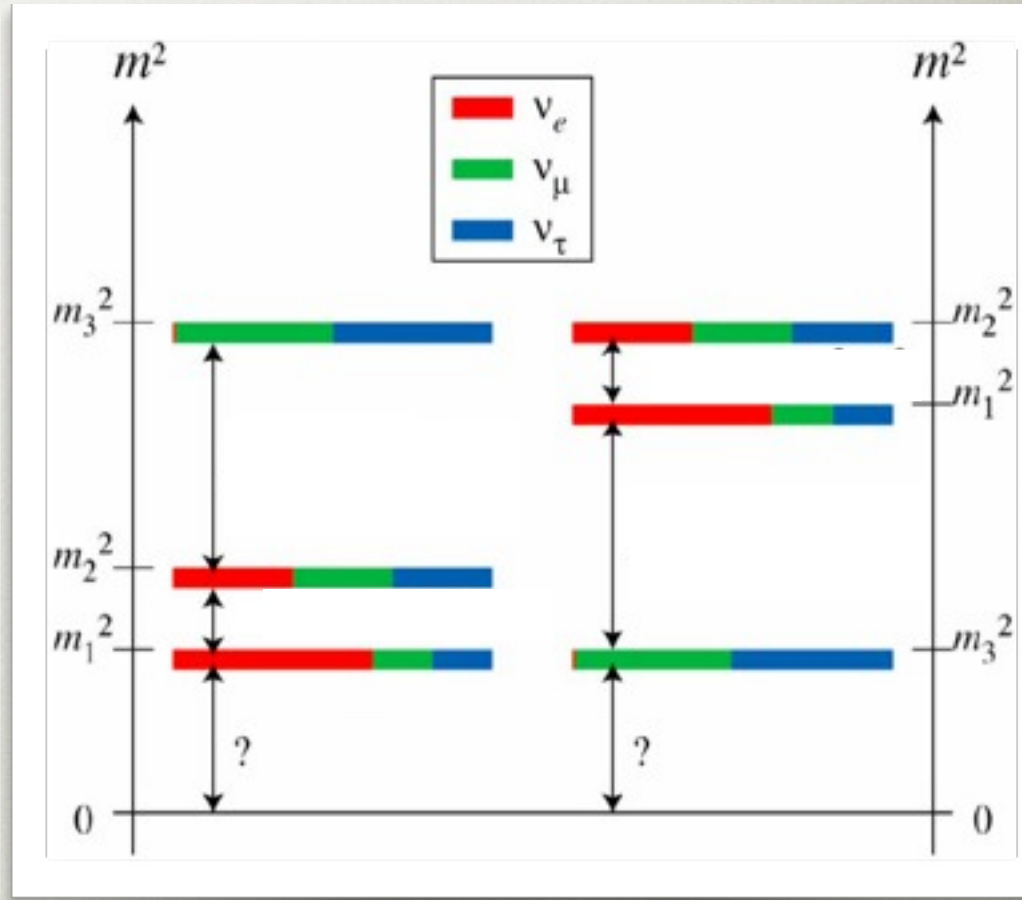

Normal hierarchy ($\Delta m^2_{32}>0$)

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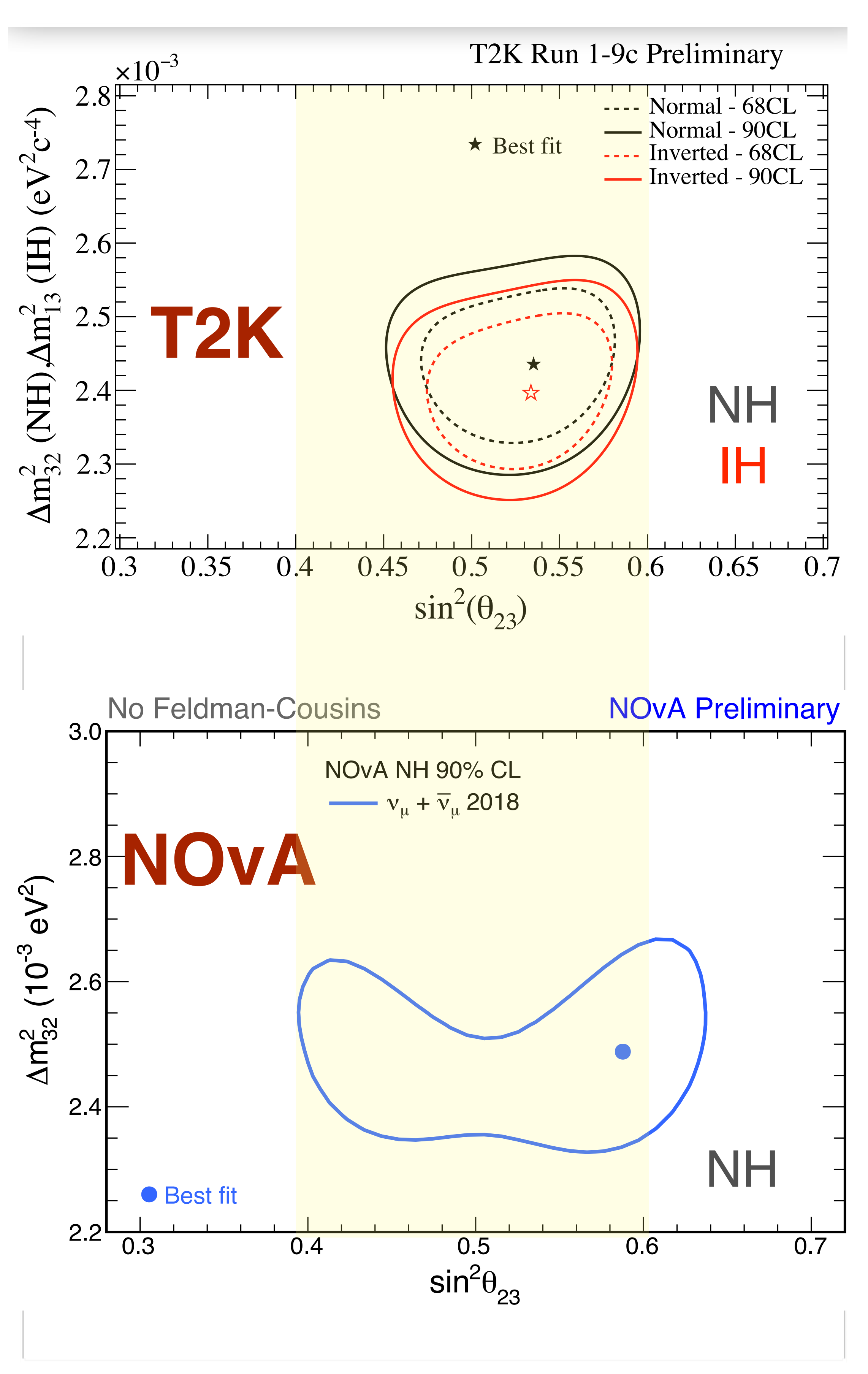
The latest results

From Neutrino 2018 conference

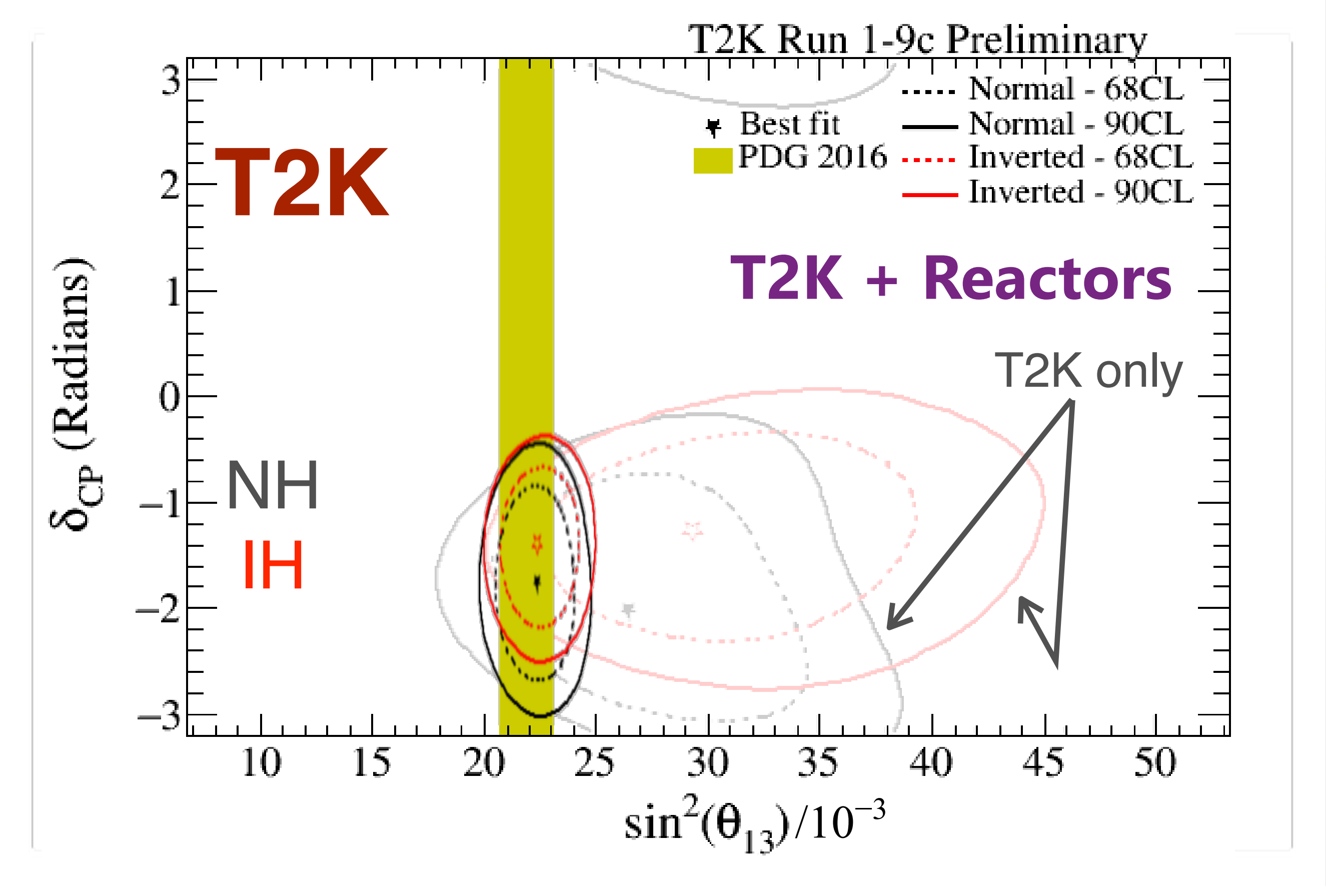
T2K results: M. Wascko's slides at Neutrino 2018
NOvA results: M. Sanchez's slides at Neutrino 2018

Latest results: θ_{23}

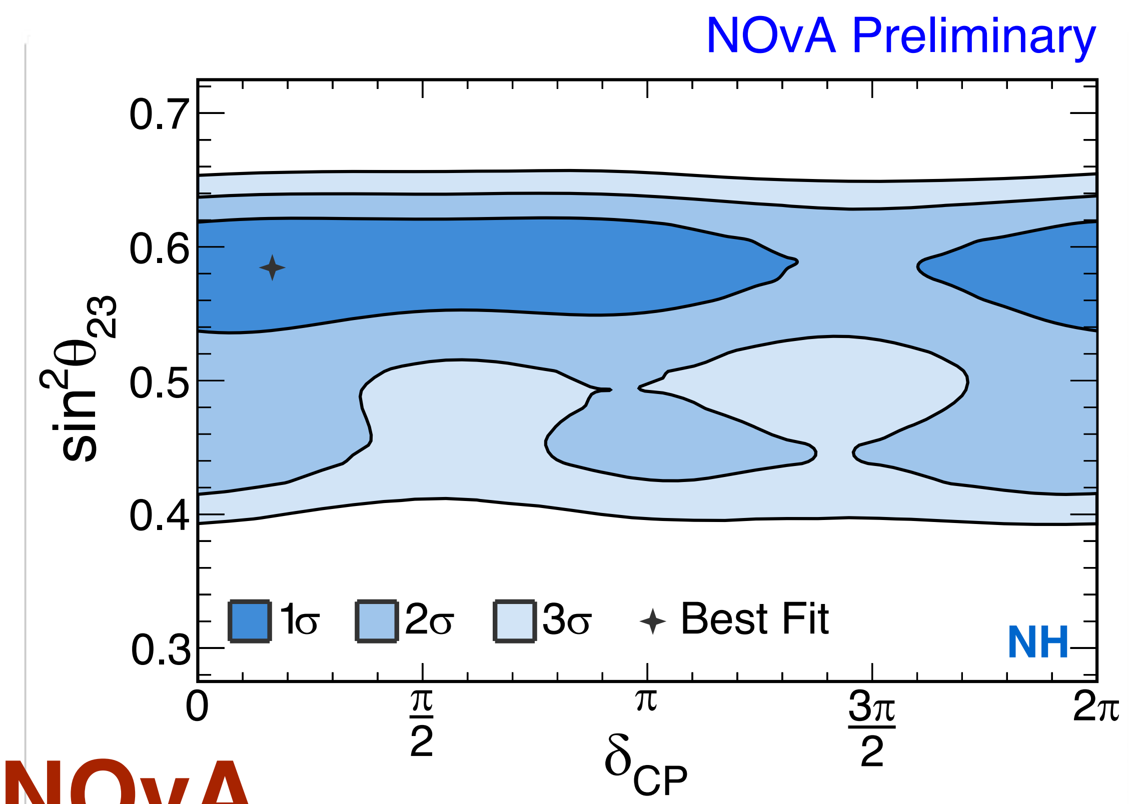


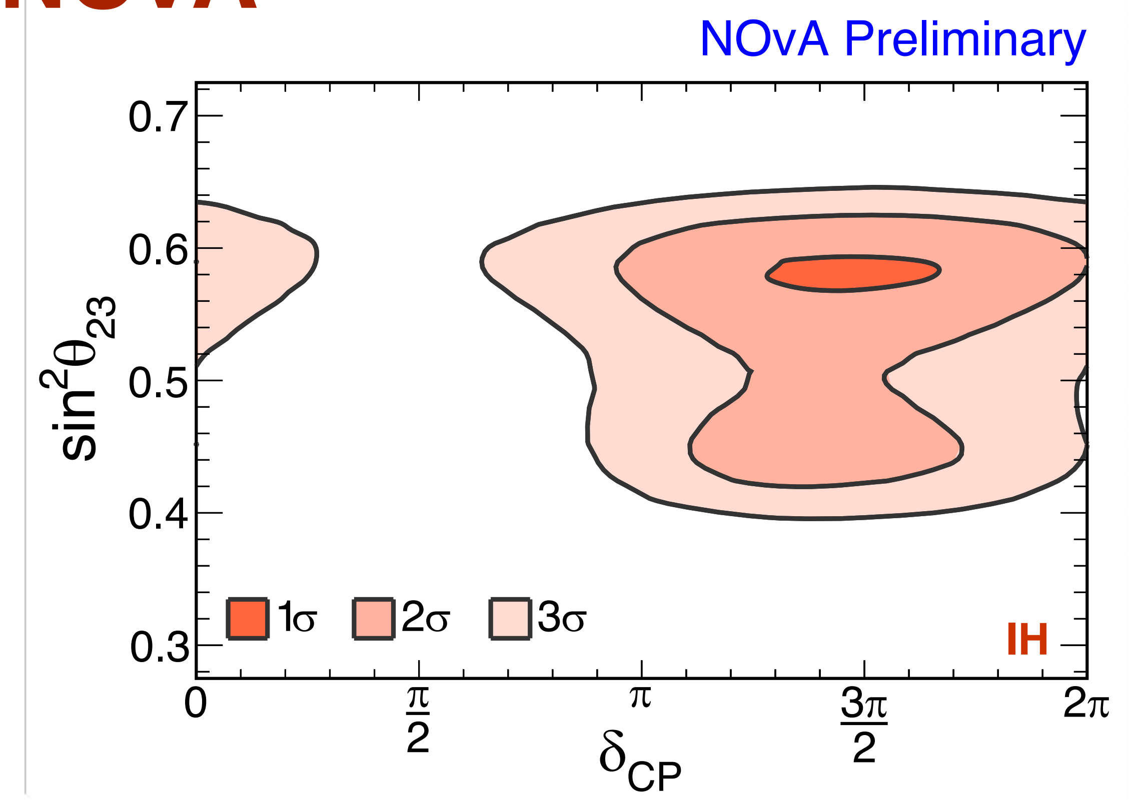
- Results from T2K and NOvA experiments consistent each other
- $0.4 \lesssim \sin^2\theta_{23} \lesssim 0.6$
- Best fit at upper octant
- θ_{23}=45° (maximal mixing) in 90% C.L. allowed region

Latest results: δ_{CP}



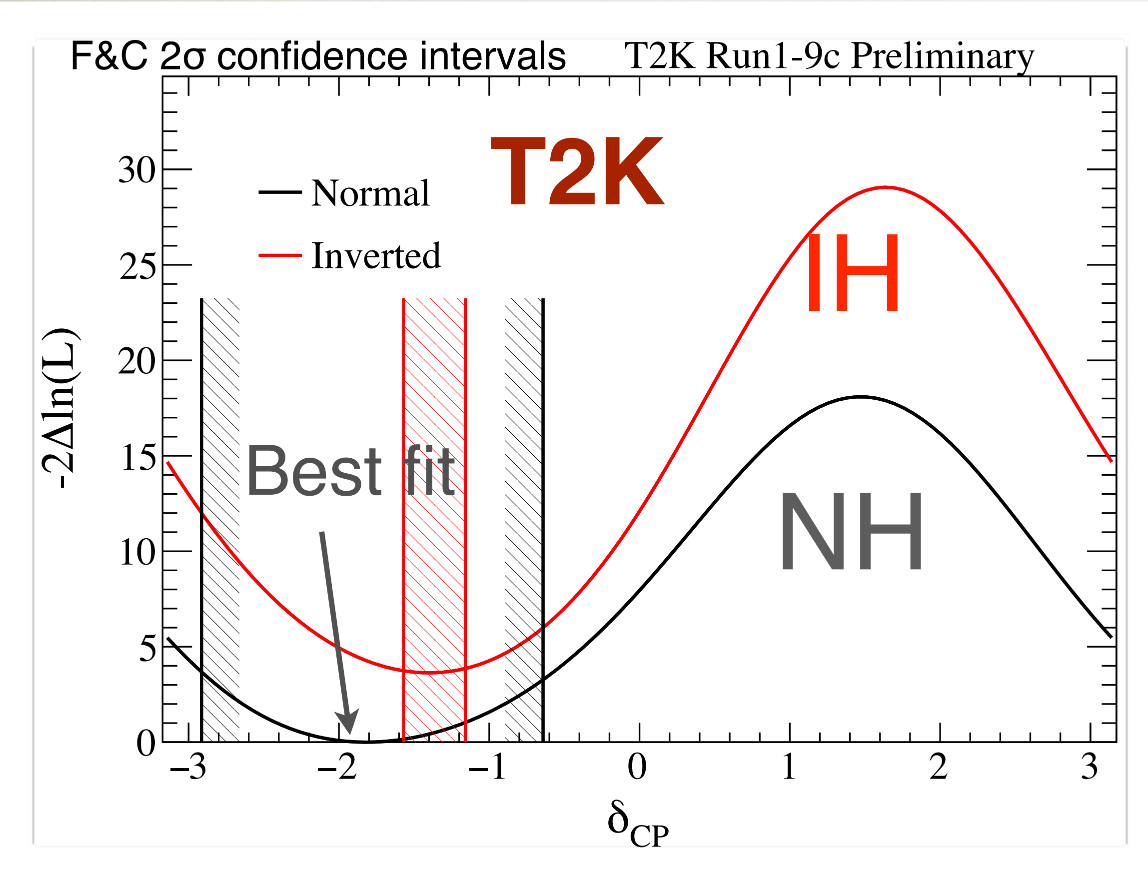
NOvA

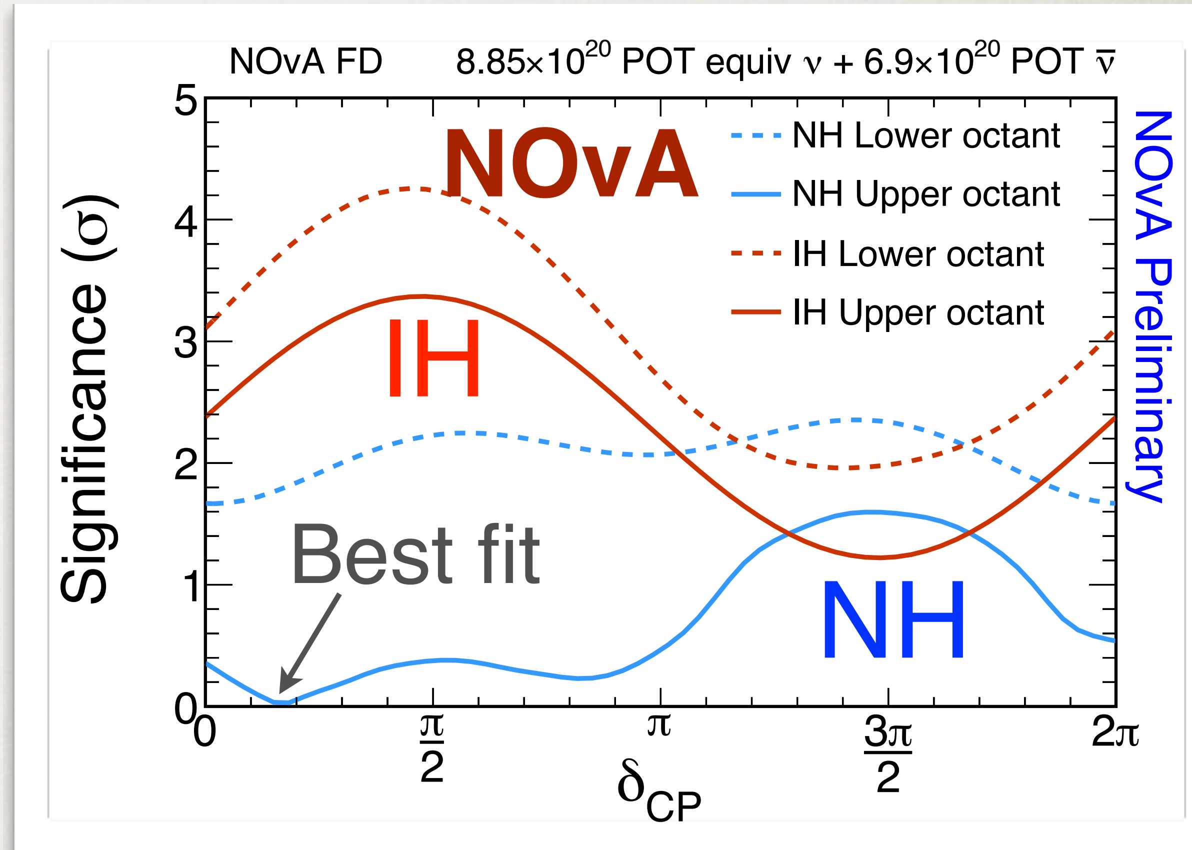




- T2K results:
  - Exclude $\delta_{CP}=0$ with >2σ C.L.
    - Stronger constraint than sensitivity
  - Best fit at $\delta_{CP}\sim-\pi/2$
- NOvA results:
  - Exclude $\delta_{CP}=+\pi/2$ with >3σ (IH)
  - Best fit at $\delta_{CP}=0.17\pi$ (NH)

Latest results: MH





T2K

Bayesian approach to extract posterior probability for mass hierarchy and octant

	$\sin^2\theta_{23}\leq0.5$	$\sin^2\theta_{23}>0.5$	SUM
NH ($\Delta m^2_{32}>0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31}<0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

- T2K and NOvA both results prefer (< 2σ):
  - Normal hierarchy
  - Upper octant
- cf. Super-K atmospheric ν results prefer NH (~2σ)
  - PRD 97, 072001 (2018)

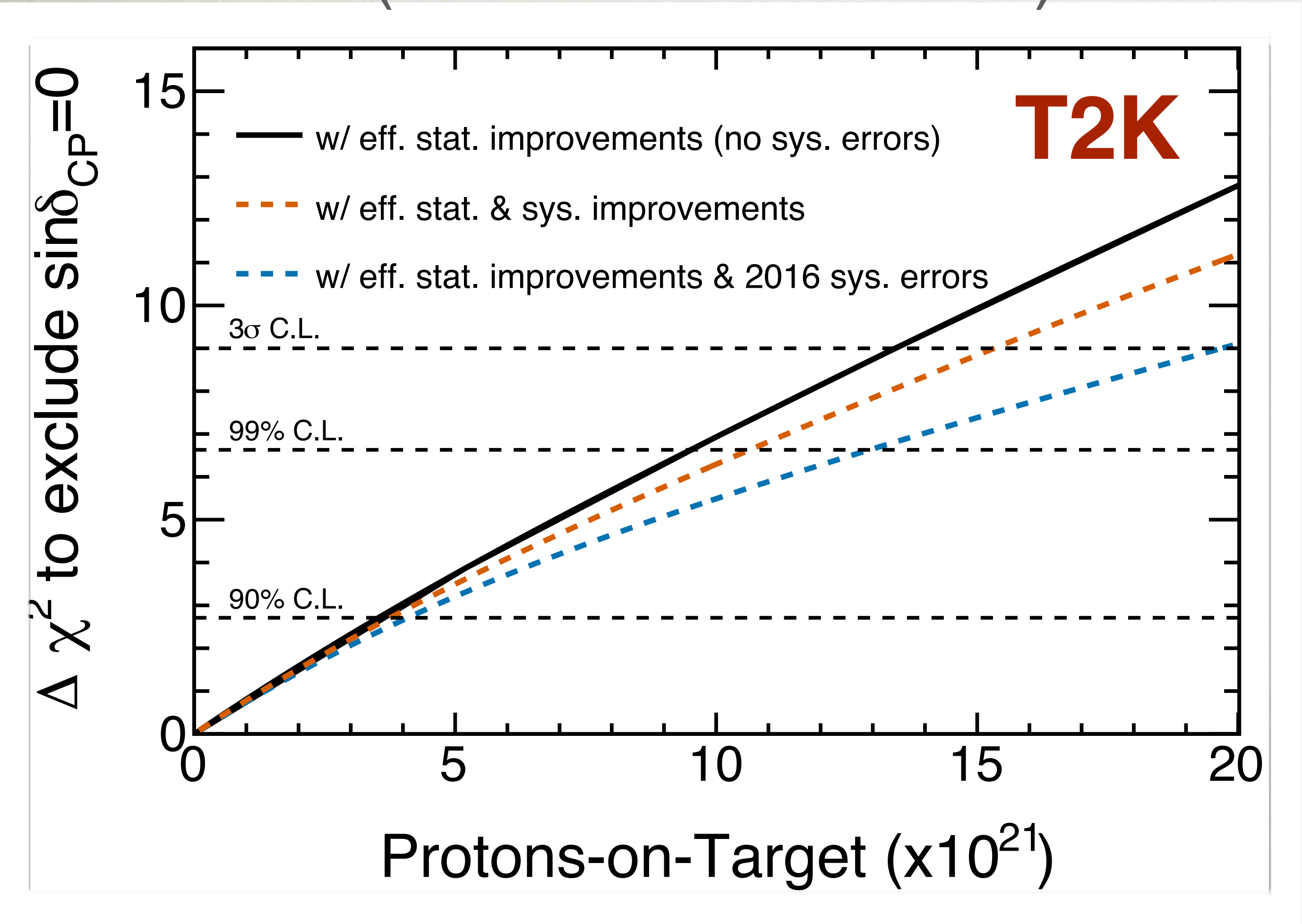
Near Future...

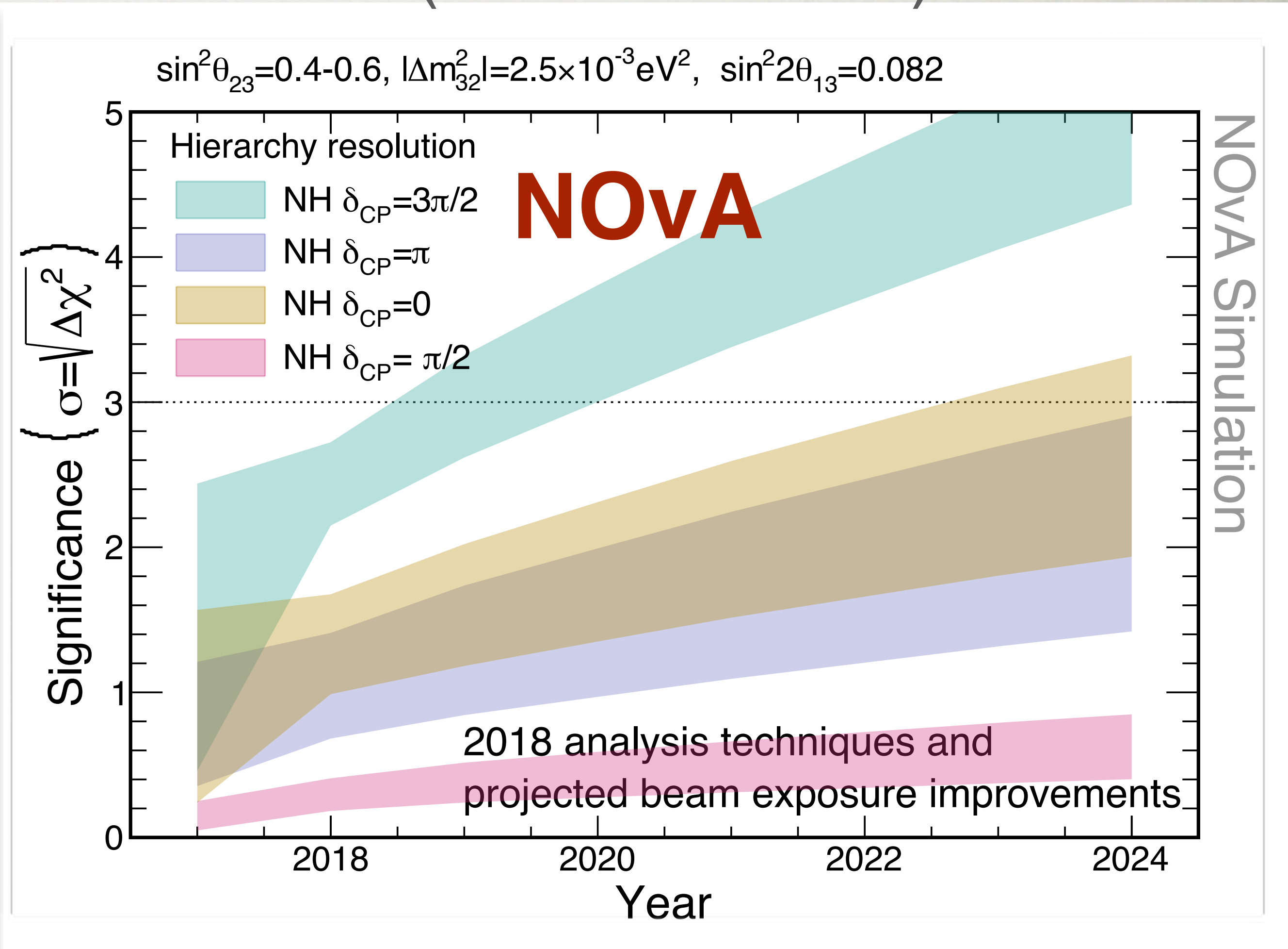
- T2K and NOvA experiments both propose to extend their data taking up around 2024~2026
- $\sin\delta_{CP}=0$ can be excluded with 3σ C.L. (T2K)
- MH can be determined with >3σ C.L. (NOvA)

[Assume true Mass Hierarchy is 'Normal' and $\delta_{CP}=-\pi/2$]

T2K: $\sin\delta_{CP}=0$ exclusion sensitivity (arXiv:1609.04111v1)

NOvA: Mass Hierarchy sensitivity (Neutrino 2018)





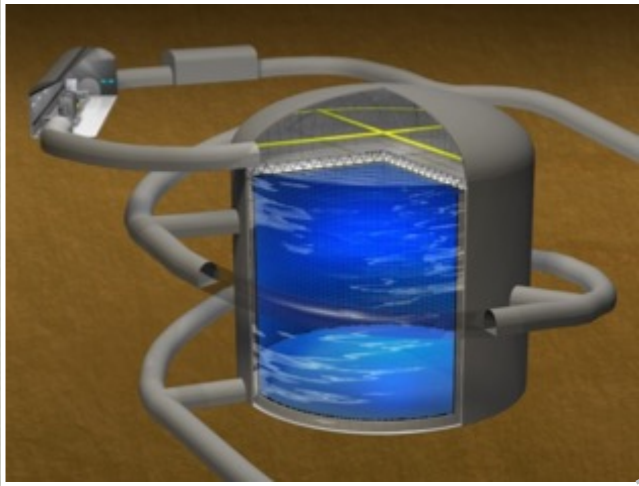
次世代実験

The Next Generation

Experimental Strategy

- Next generation LBL experiments target CP violation (CPV) and Mass Hierarchy
- **Hyper-Kamiokande**
  - **Shorter baseline (295km):**
    Earth matter effect insignificant → Focus on CPV
  - ν beam: Flux peak at 1st oscillation maximum
  - **➜ Off-axis narrow band beam**
  - Mass Hierarchy can be determined with atmospheric ν
- **DUNE/LBNF**
  - **Longer baseline (1300km):**
    Measure matter effect (MH) → Unfold CPV from Earth matter effect through ν spectrum shape
  - ν beam: Cover wide energy range (1st and 2nd maxima)
  - **➜ On-axis wide band beam**

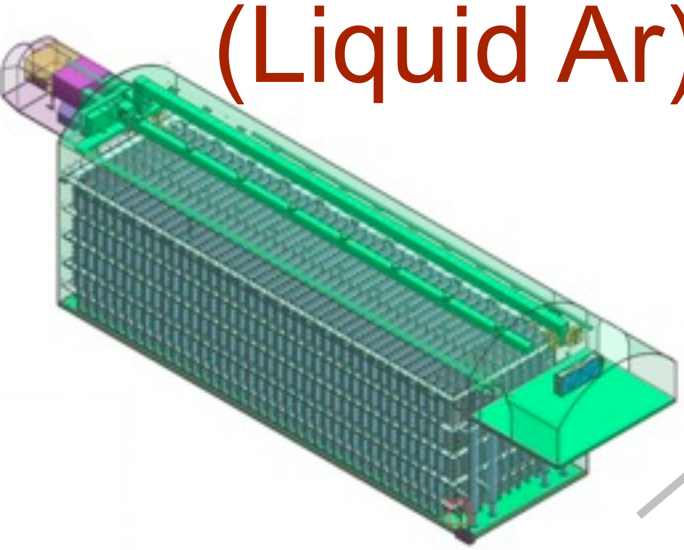
Next Generation LBL expts



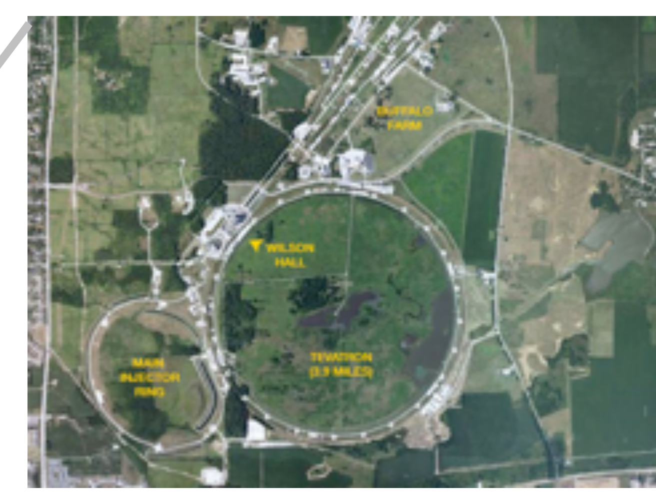
Hyper-K
(Water Č)

J-PARC
Accelerator Complex

DUNE
(Liquid Ar)



Fermilab
LBNF



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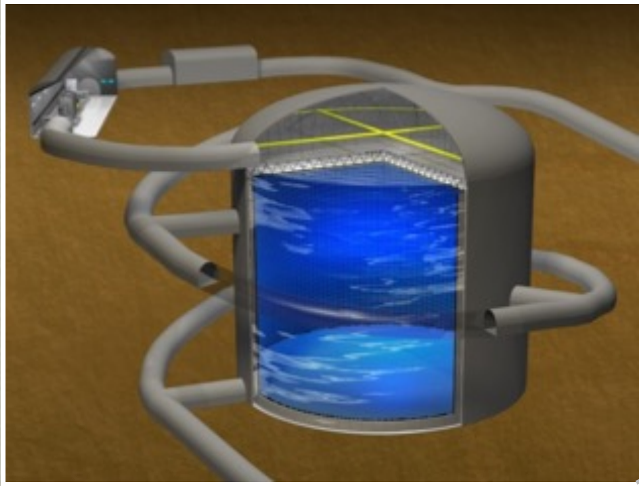

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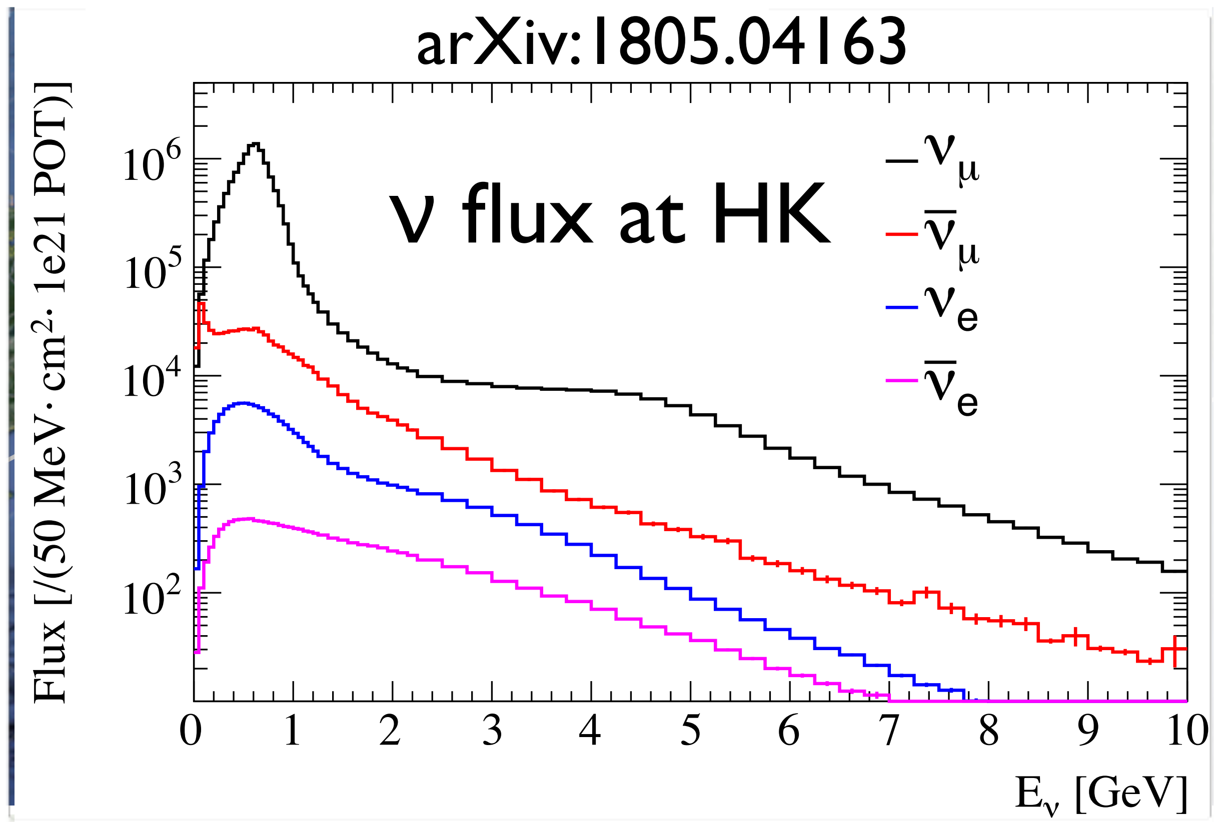

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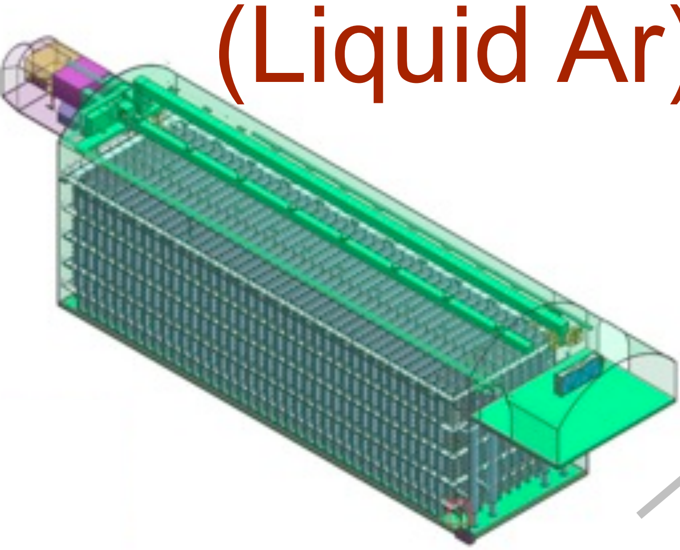
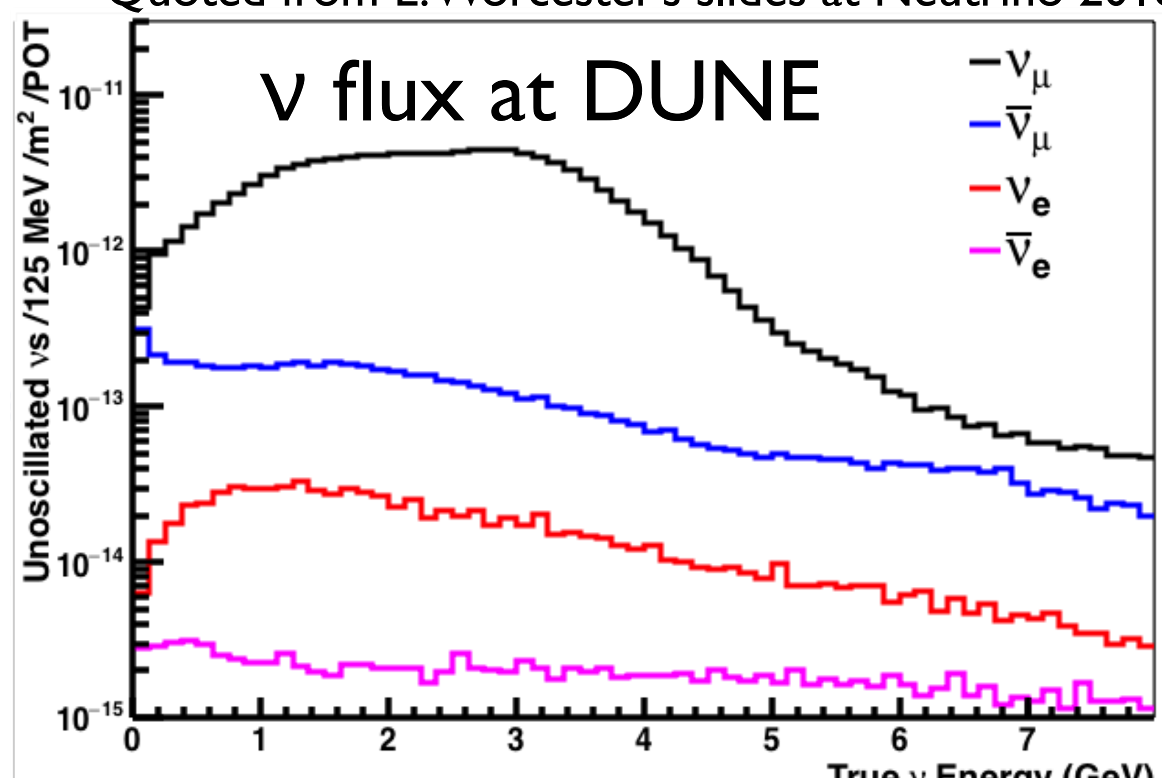


Quoted from E.Worcester's slides at Neutrino 2018



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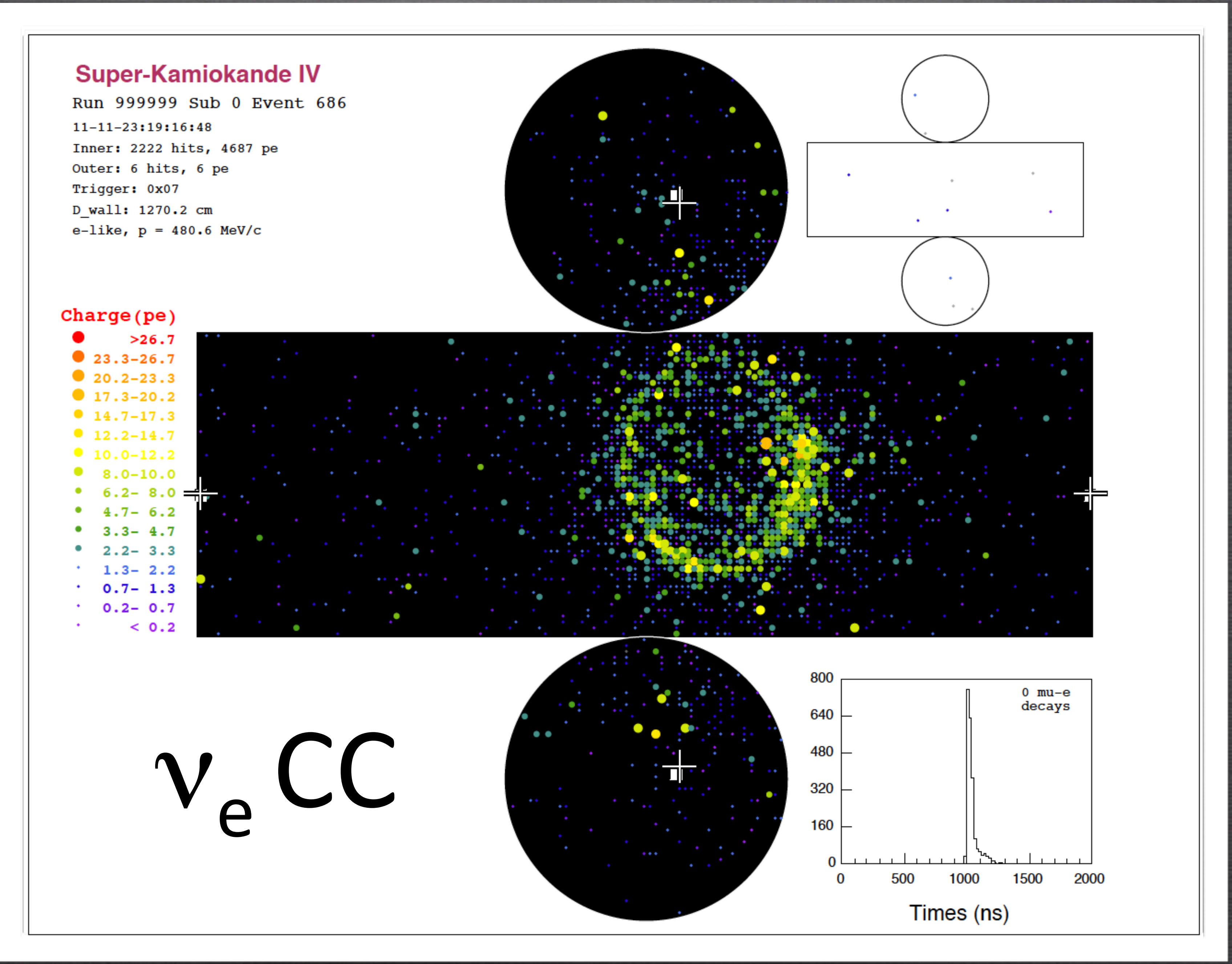
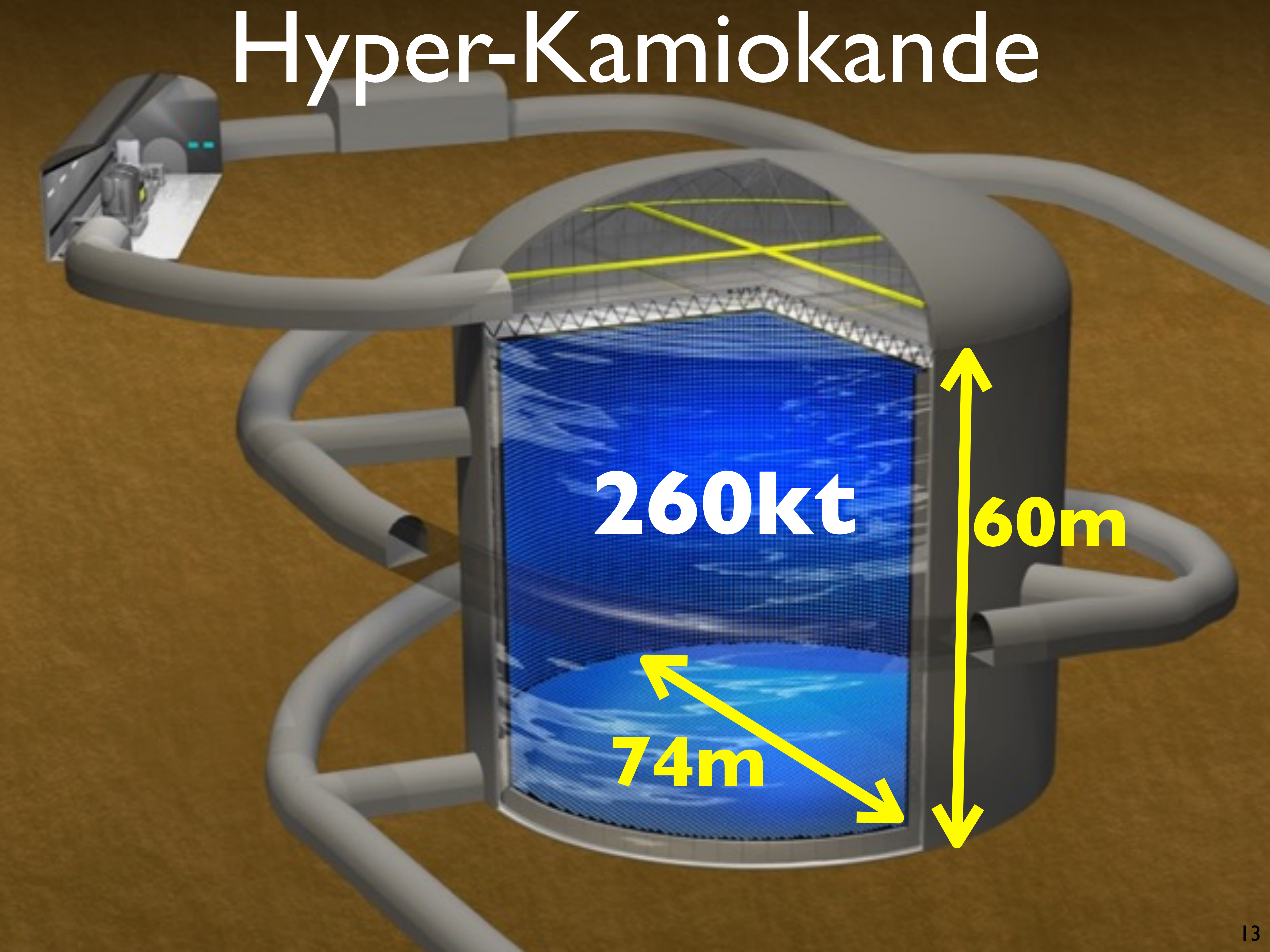


HYPER-KAMIOKANDE

Hyper-K Design Report
arXiv:1805.04163

Hyper-Kamiokande

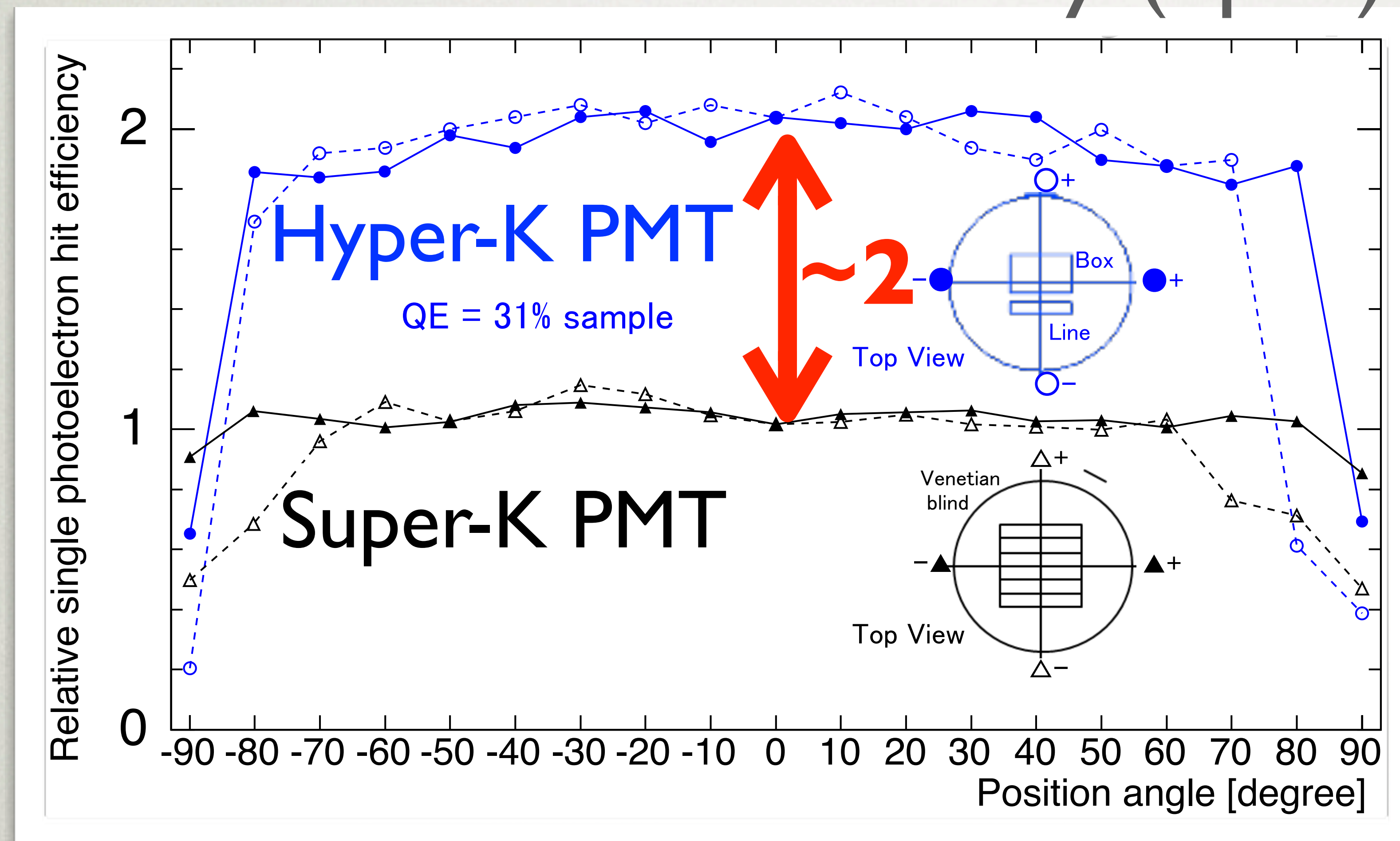


Hyper-Kamiokande

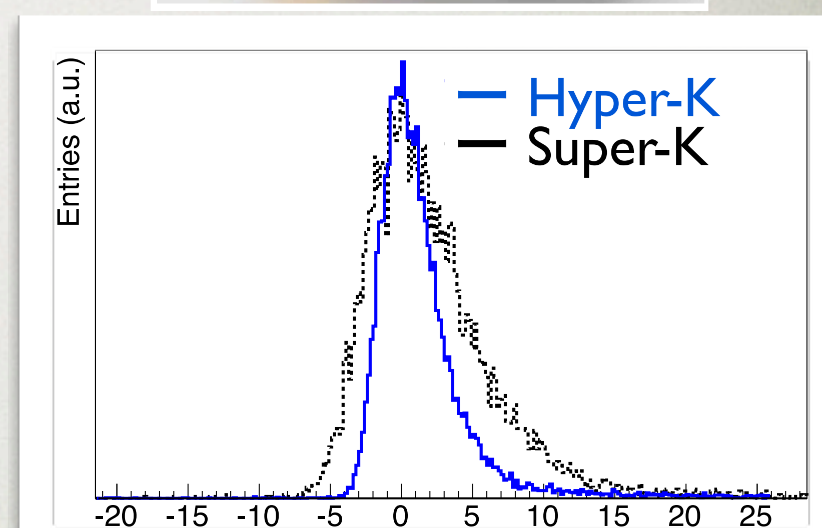
- **Next generation water Cherenkov detector**
  - Construct two detectors in stage
  - Realize the first detector as soon as possible
  - An option of second detector in Korea (PTEP 2018, 6, 1-56)
- The first detector (1 tank)
  - Filled with 260kton of ultra-pure water
    - 60m tall x 74 diameter water tank
  - **Fiducial mass: 190kton**
    - **~10 x Super-K**
  - **Photo-coverage: 40%** (Inner Detector)
    - 40,000 of **new 50cmϕ PMTs**
      - **x2 higher photon sensitivity than SK PMT**
- All physics sensitivities of Hyer-K shown in this talk assumes 1 tank

New 50cmϕ PMT for Hyper-K

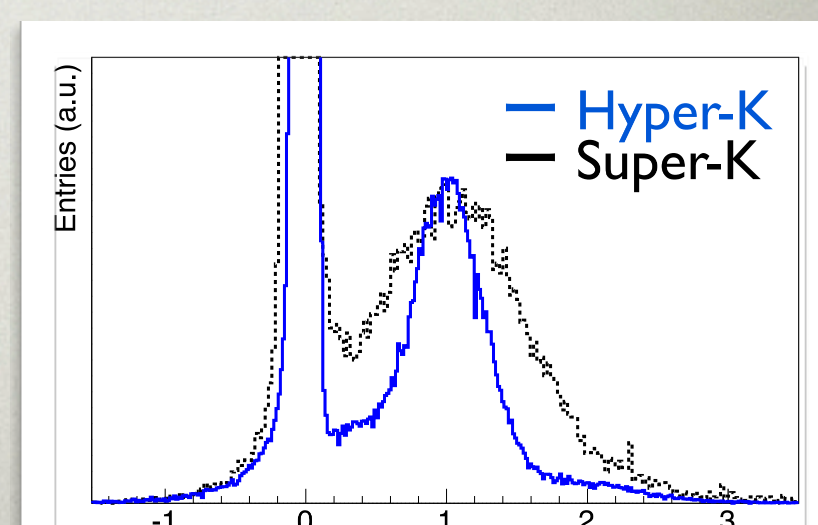
Photo-detection efficiency (1p.e.)



Box & line dynode PMT



Transit time (ns)

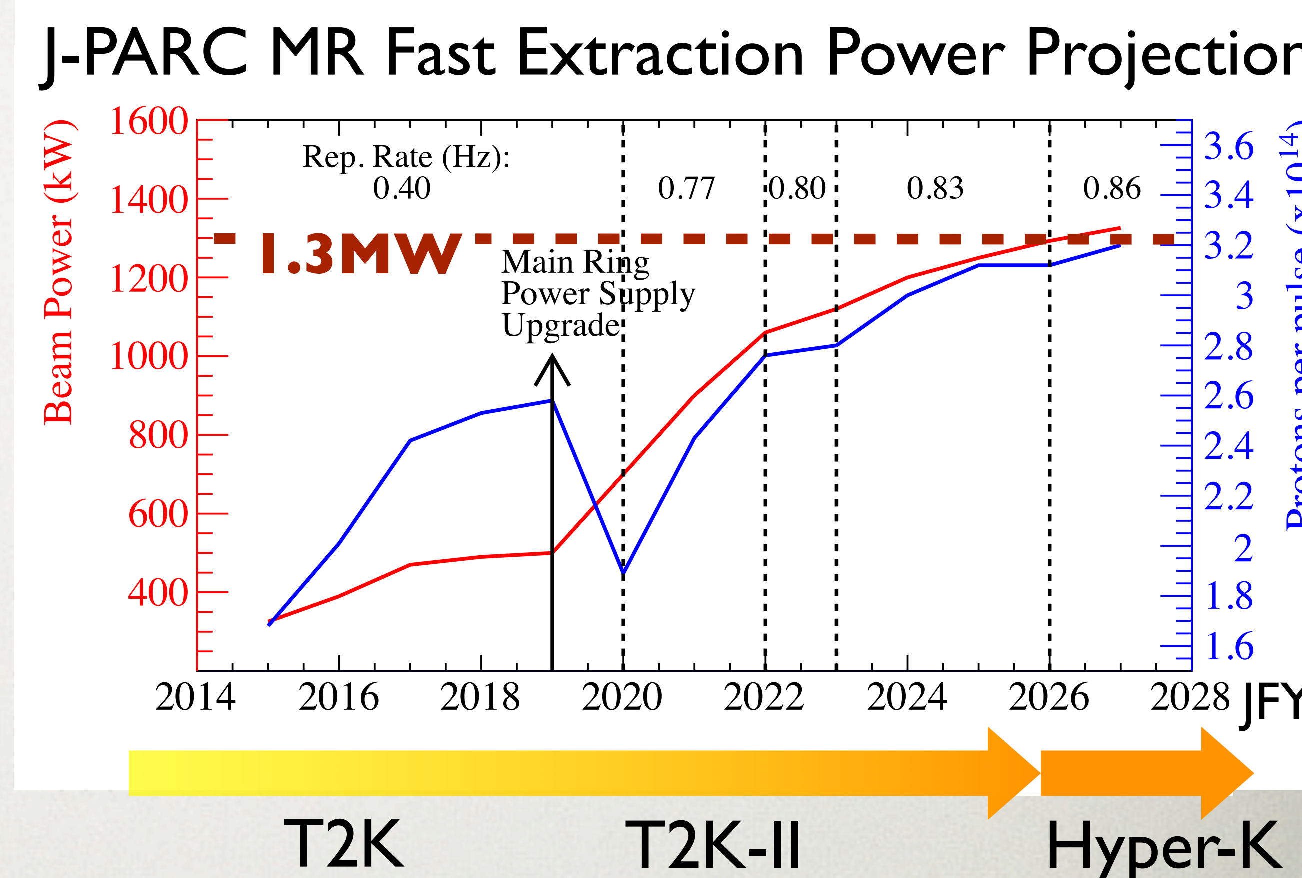


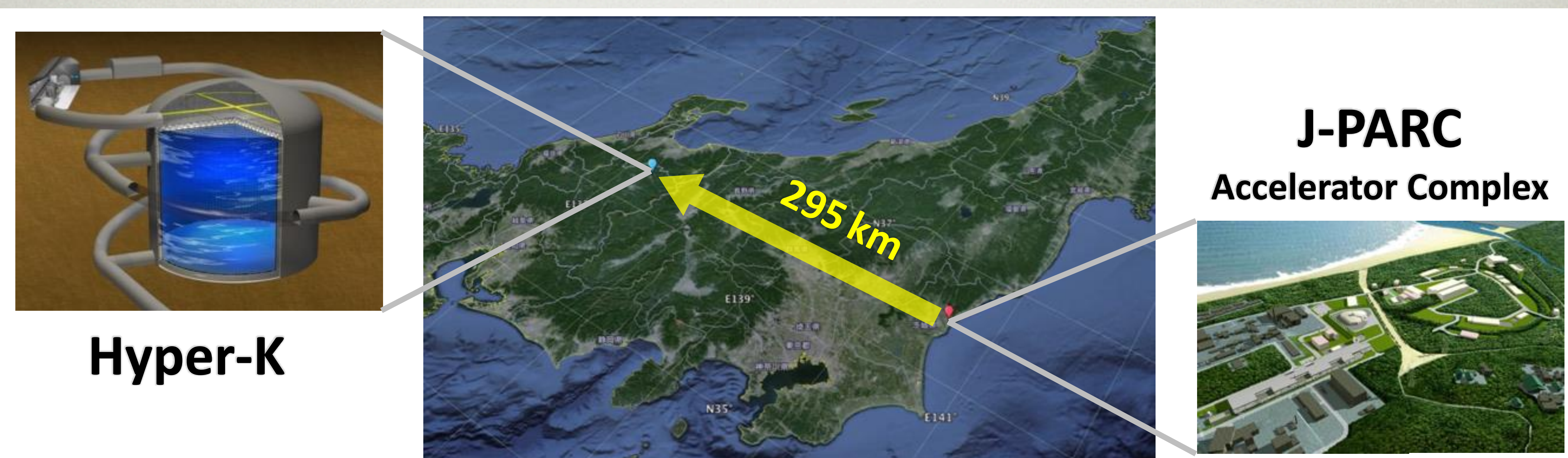
Charge (p.e.)

- Twice better photo-detection efficiency than SK PMTs
- Timing resolution (TTS): 1.1ns
  - cf. SK PMT: 2.1ns
- Higher pressure tolerance: >80m

ν Beam for Hyper-K

- High quality & high intensity neutrino beam
- 2.5 deg. off-axis narrow band neutrino beam (same as T2K)
- Beam power: 1.3MW (before Hyper-K begins)
  - KEK Project Implementation Plan: top priority on ‘J-PARC upgrade for Hyper-K’
  - cf. Reached ~500kW for T2K





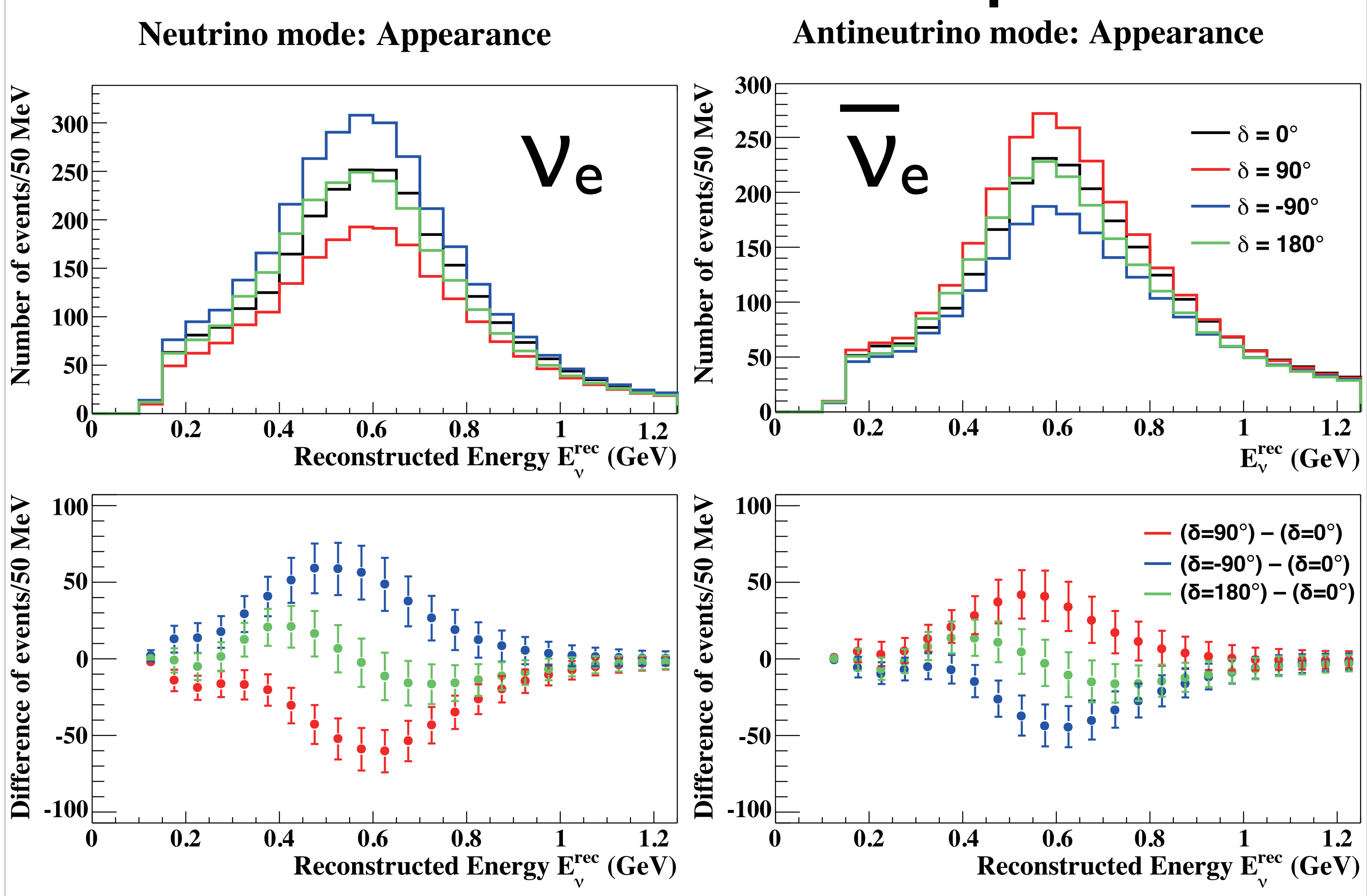
Expected events in HK for CPV

Expected # of events in $\nu_e/\bar{\nu}_e$ appearance
(after applying ν_e selection criteria)

for $\delta_{CP}=0$	Signal $\nu_\mu \to \nu_e$ CC	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	Beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	1,643	15	7	259	134
$\bar{\nu}$ beam	1,183	206	4	317	196

1.3MW x 10 years (10^8 sec), $\nu:\bar{\nu}$=1:3

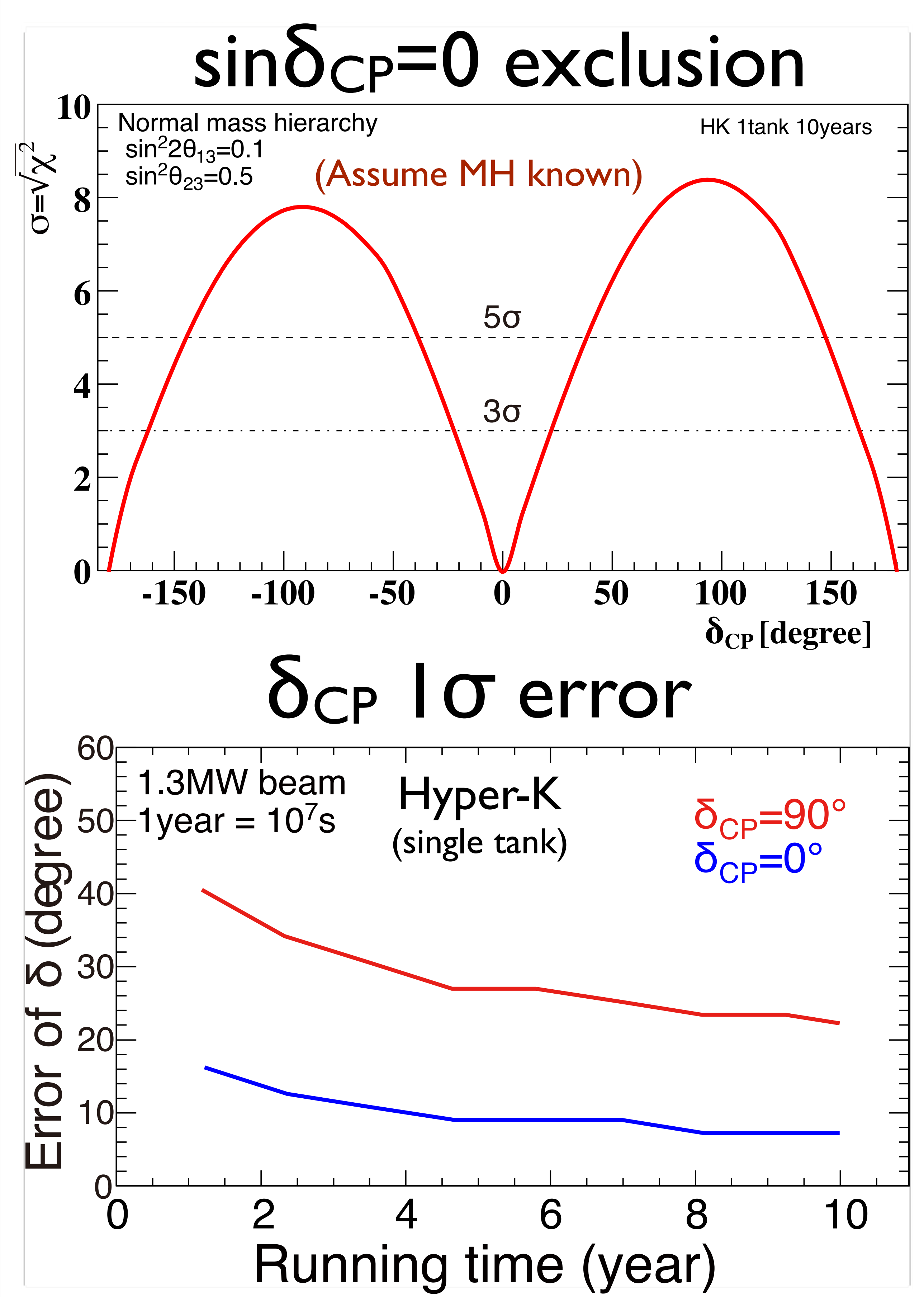
Reconstructed E$_\nu$ spectra



Also sensitive to New Physics
(ex. if any additional phase)

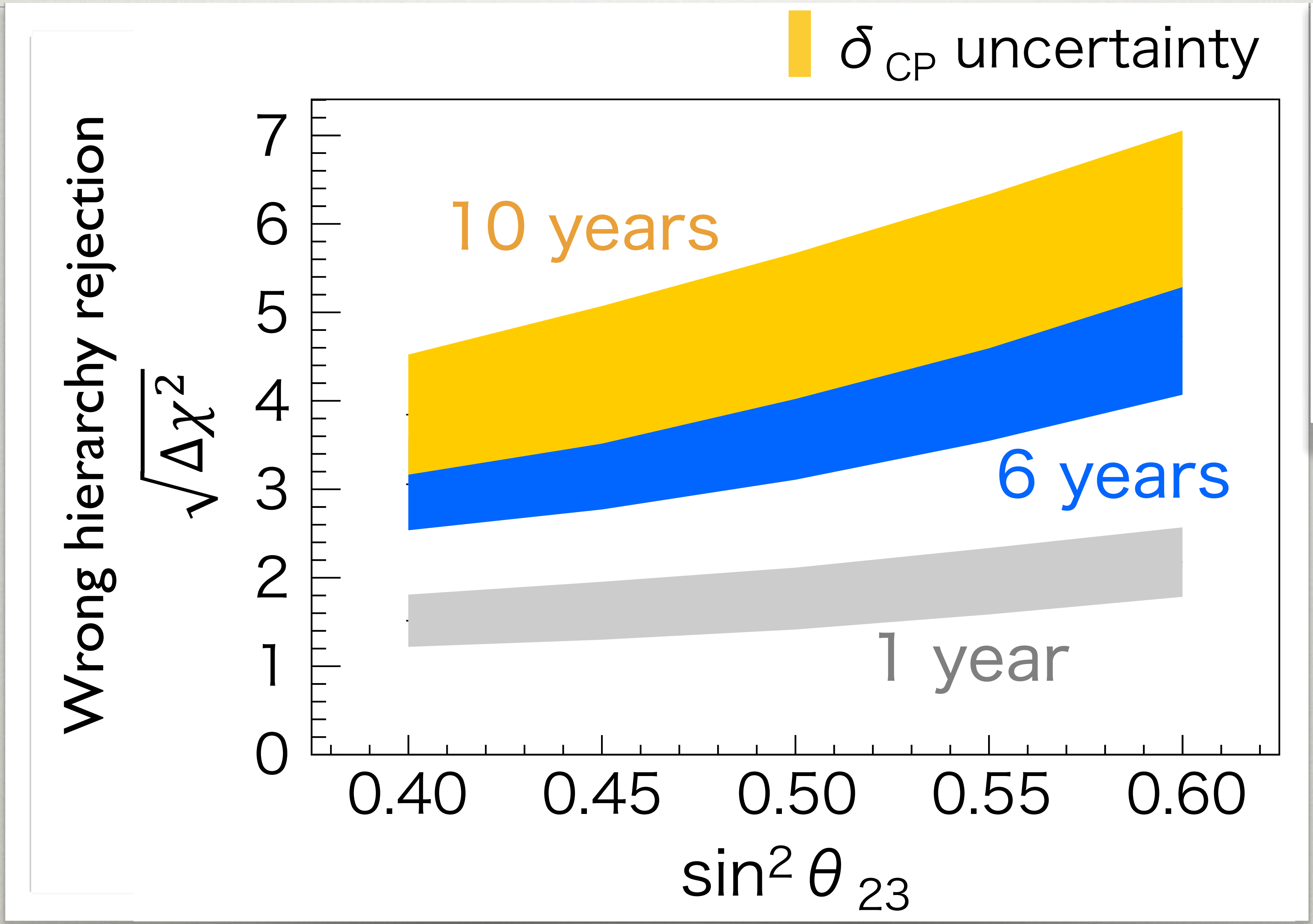
$\sin^2 2\theta_{13}=0.1$
Normal Hierarchy

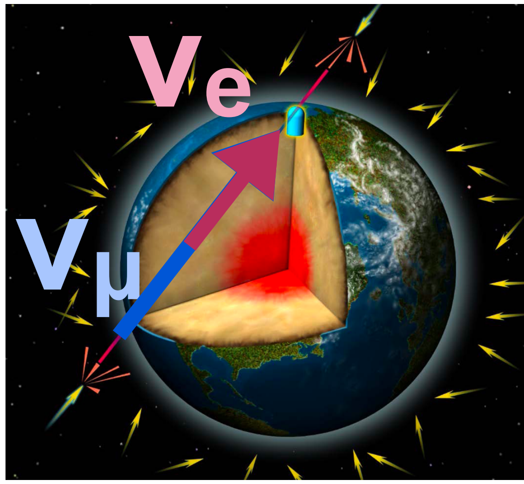
Hyper-K sensitivity for CPV



- $\sin\delta_{CP}$=0 exclusion:
  - ~8σ for δ_{CP}=-90° (T2K best fit)
  - ~80% coverage of δ_{CP} parameter space with >3σ
- δ_{CP} resolution:
  - 22° at δ_{CP}=±90°
  - 7° at δ_{CP}=0°, 180°
- Sensitivity studies adopt analysis techniques and systematic uncertainties used in T2K
  - Realistic systematic uncertainties plus expected reduction of error
  - 3~4% syst. err (cf. 6~7% in T2K)

Mass Hierarchy sensitivity in HK

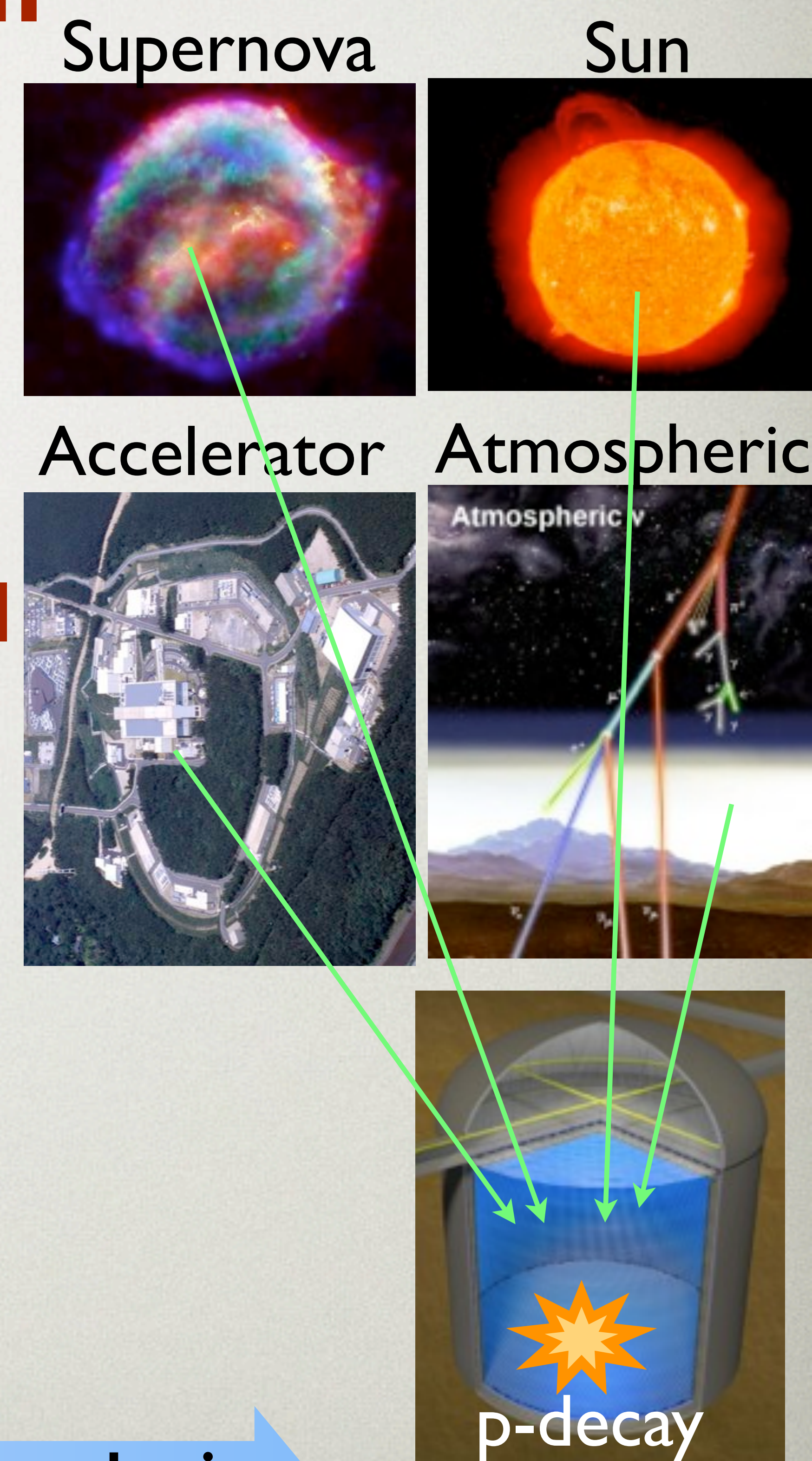




- Hyper-K can determine Mass Hierarchy in ~5 years ($\sin^2\theta_{23}=0.5$) using atmospheric ν's, even if MH not determined before Hyper-K era
    - cf. Super-K suggests Normal Hierarchy with ~2σ
        - Phy. Rev. D97, 072001 (2018)

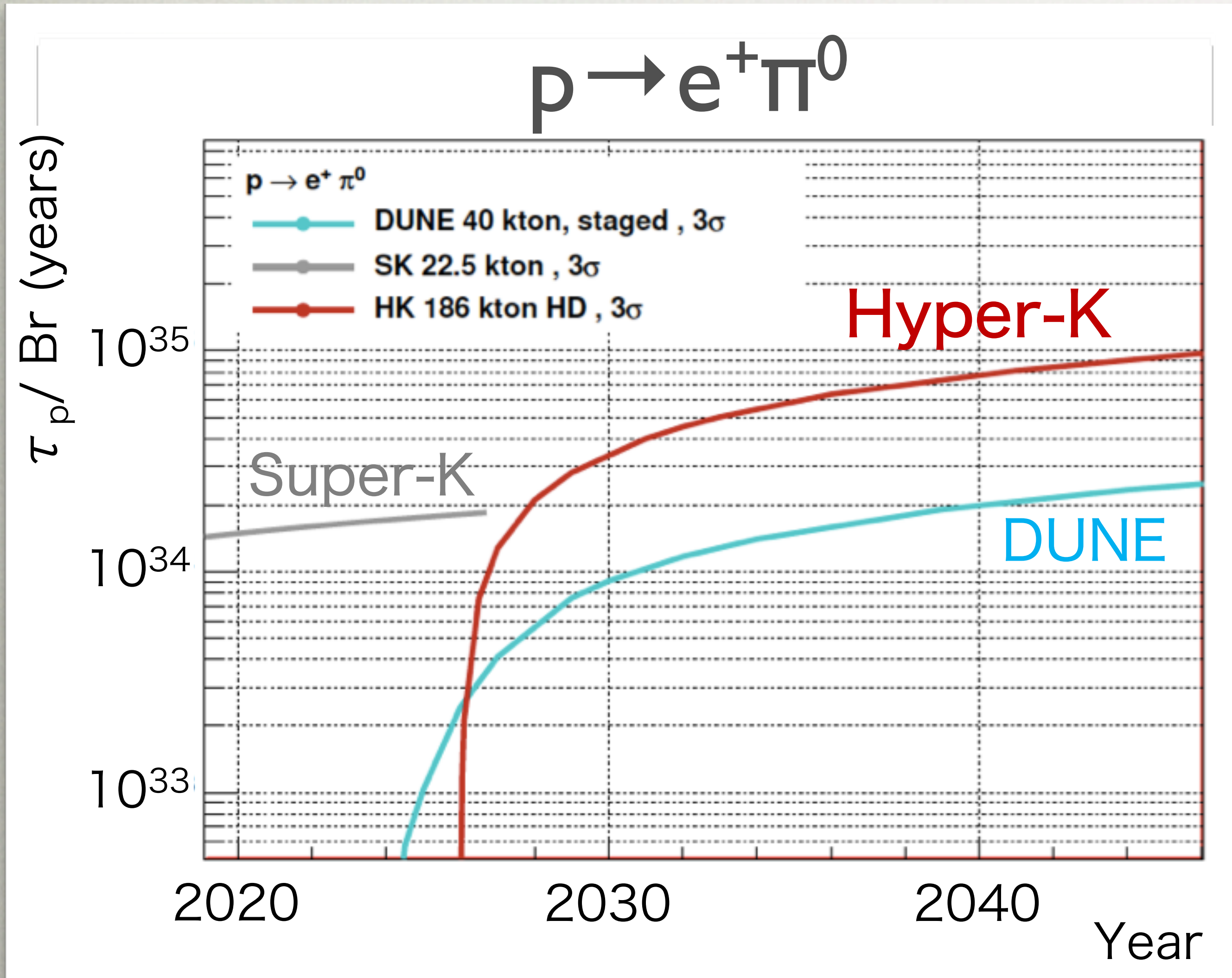
Hyper-K: multi-purpose detector

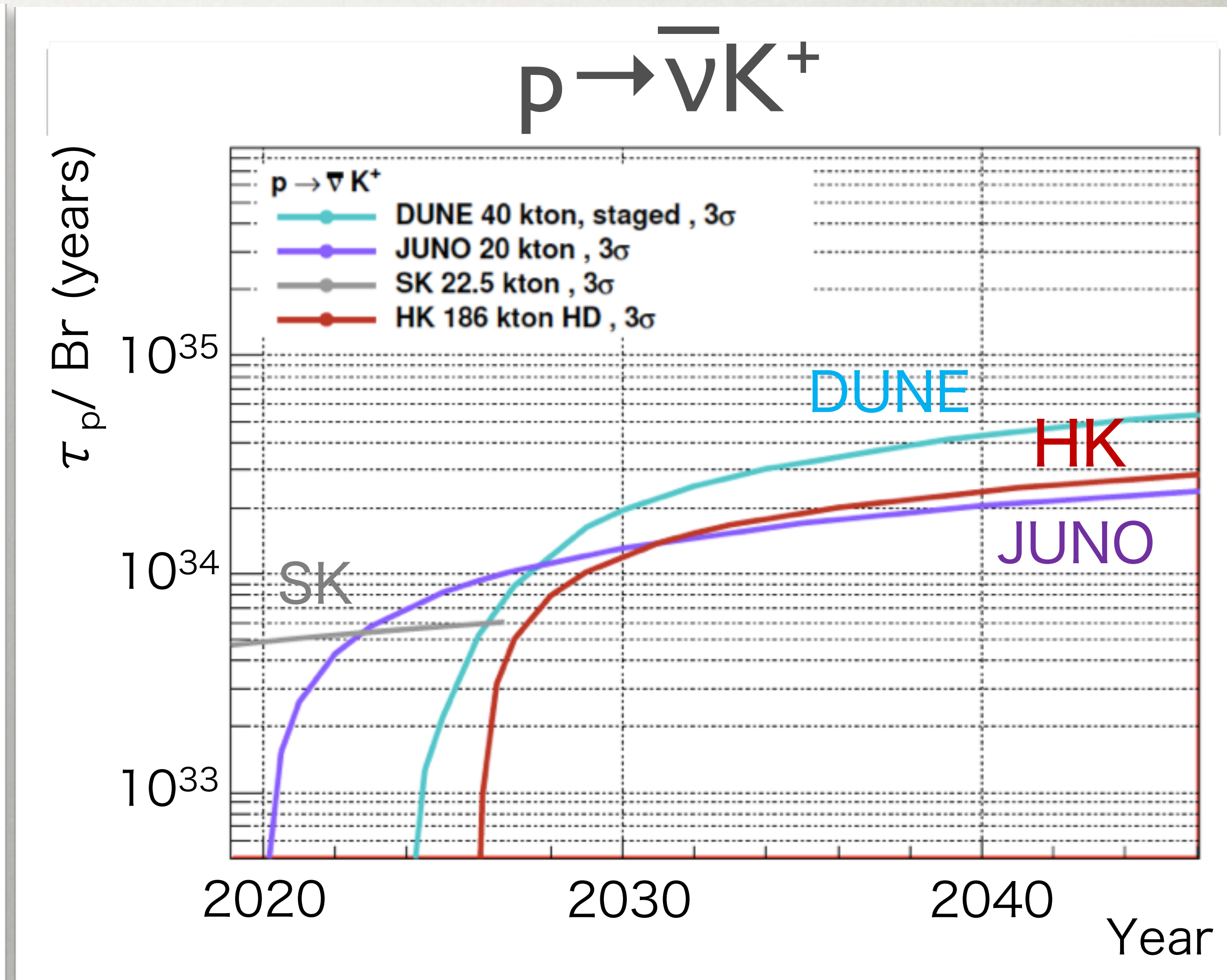
- **Comprehensive study of ν oscillation**
  - CPV: 76% of δ space w/ 3σ, <22° precision
  - MH determination for all δ with J-PARC/Atm ν
  - θ_{23} octant determination at $|\theta_{23}$-45°|>2°
  - <1% precision of Δm^2_{32}
  - Test standard ν oscillation scenario w/ acc/atm ν
- **Proton decay 3σ discovery potential**
  - 1×10^{35} years for $p\rightarrow e^+\pi^0$
  - 3×10^{34} years for $p\rightarrow \nu K^+$
- **Astrophysical neutrino**
  - Solar ν: test standard matter effect (MSW) model
  - Supernova ν, supernova relic-ν
  - Dark matter neutrinos from Sun, Galaxy, Earth



Search for Proton Decay

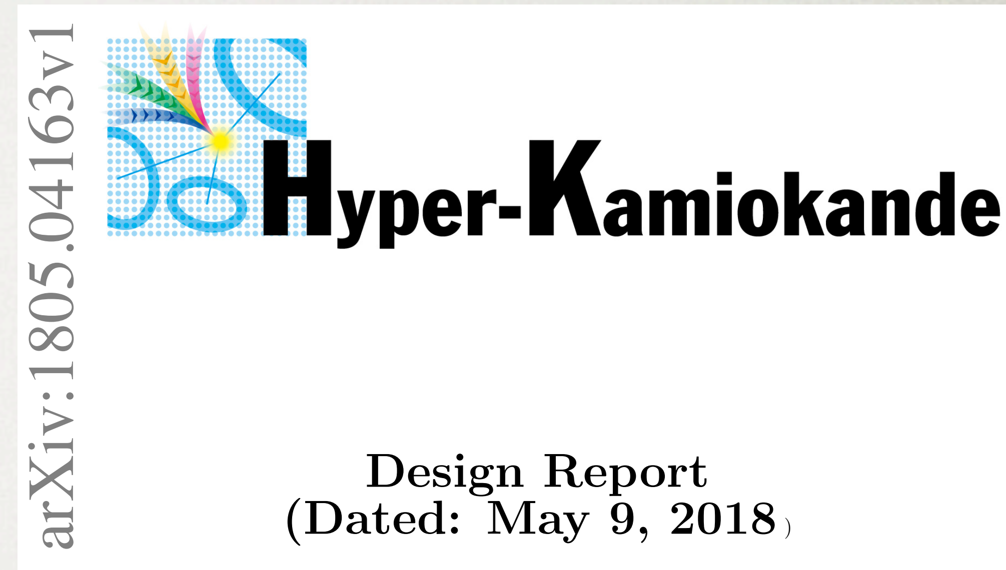
3σ discovery sensitivity





- Hyper-K will explore 10 times longer proton-lifetime than current running experiment
  - ex. $p \to e^+\pi^0$, $p \to \bar{\nu}K^+$
- Many other decay modes can also be searched with an order of magnitude better sensitivity

Status of Hyper-K


arXiv:1805.04163v1

Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

Inaugural Symposium (MoU), Jan. 2015

NNSO Inaugural Ceremony, Oct. 2017

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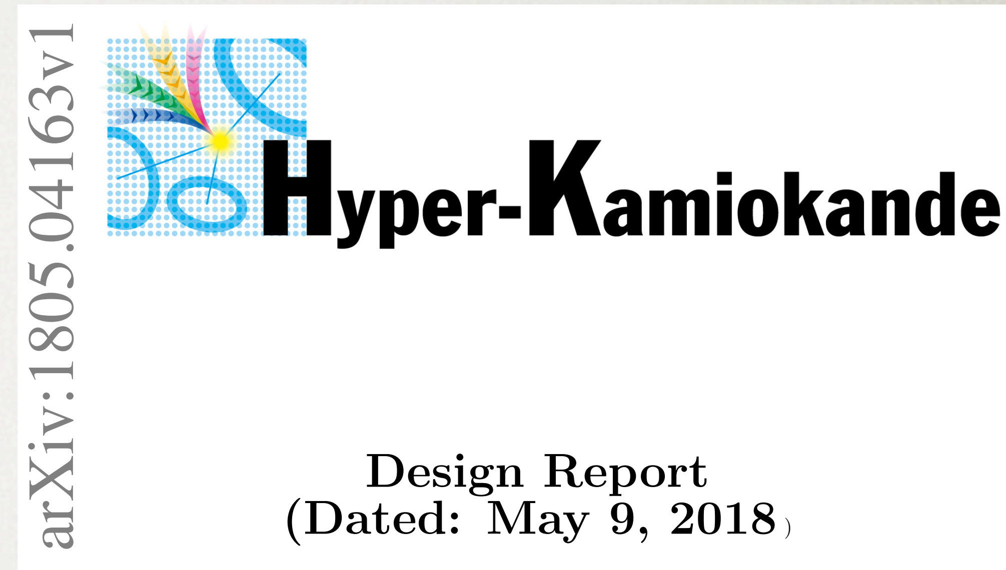
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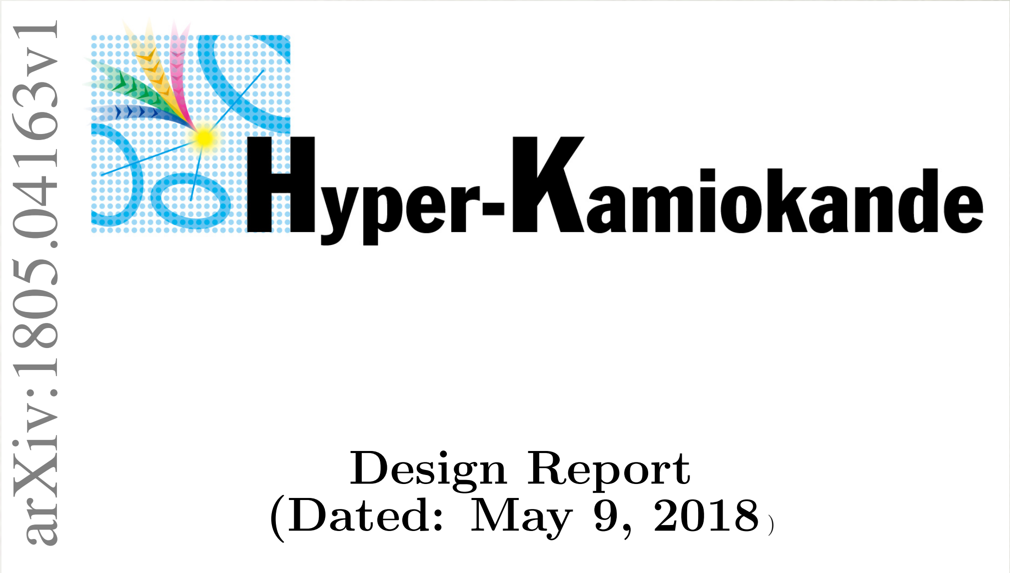

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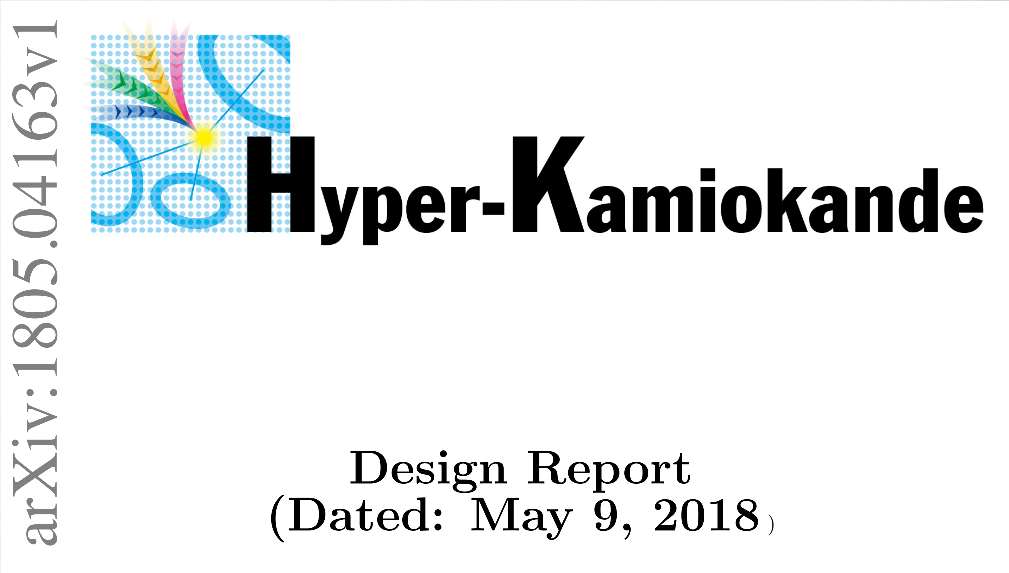
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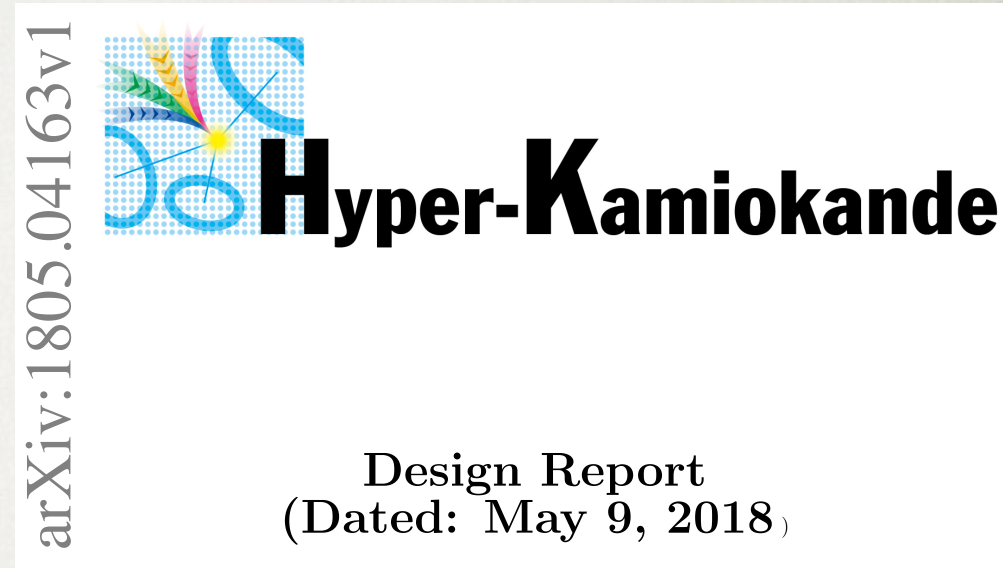

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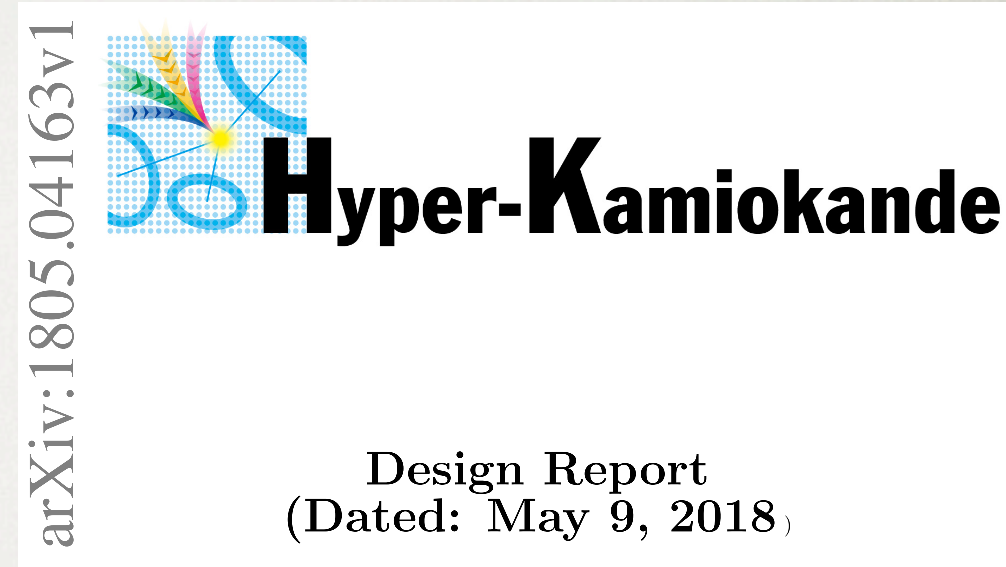

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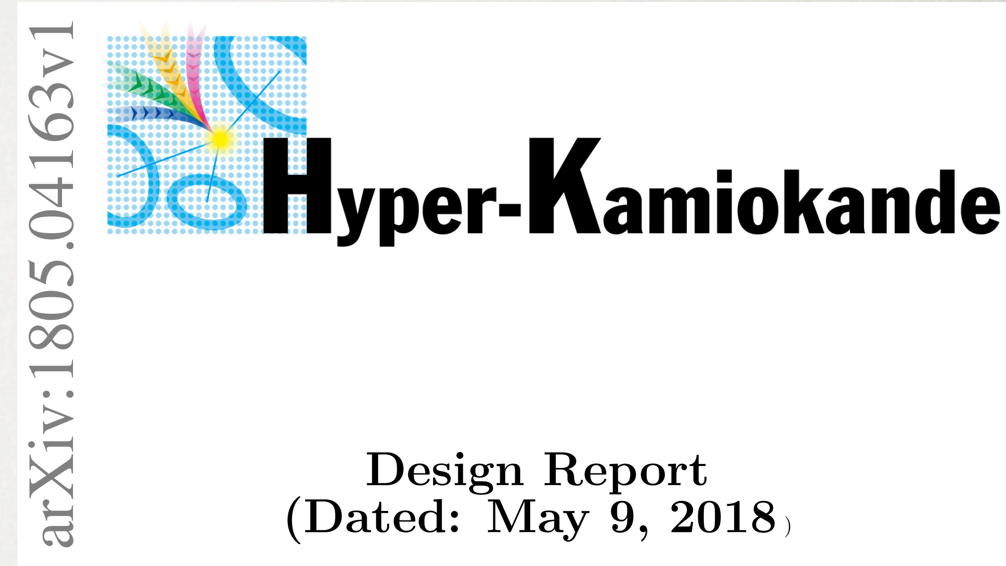
- U.Tokyo making all efforts to get Hyper-K funded, aiming to begin the detector construction in JFY2019 and begin the operation in JFY2026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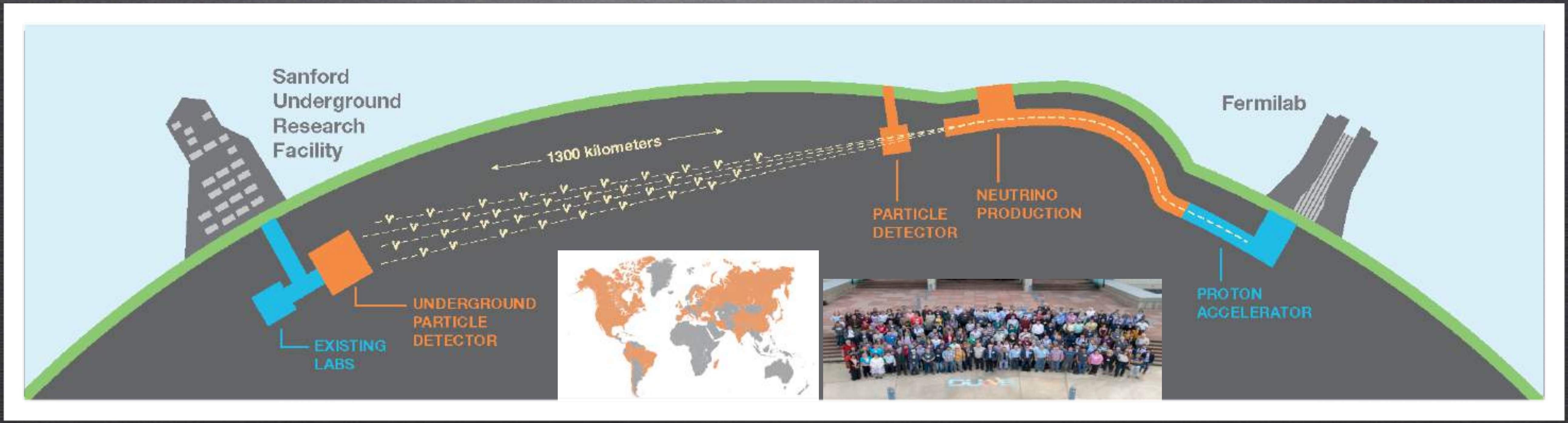
Hyper-K proto-collaboration

- ~300 collaborators
- 73 institutions from 15 countries
- ~75% of collaborators from abroad

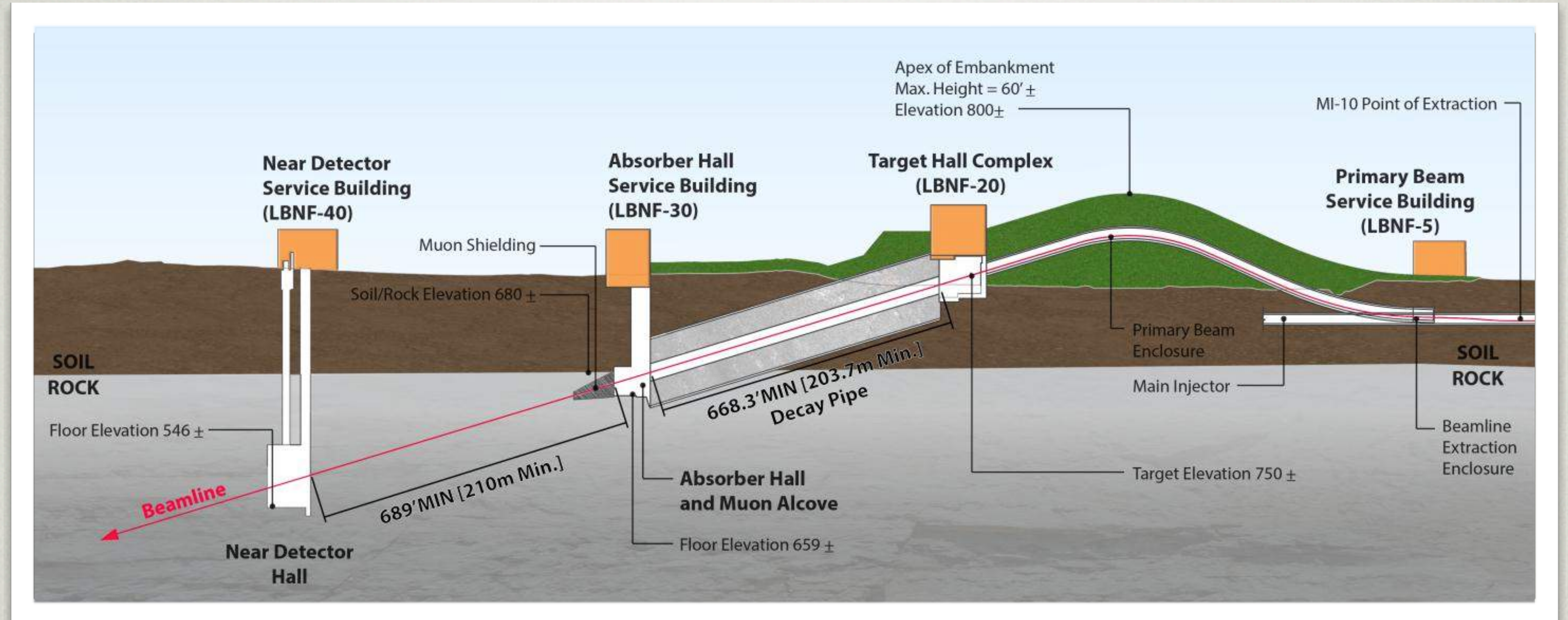
Open for new collaborators



DUNE/LBNF

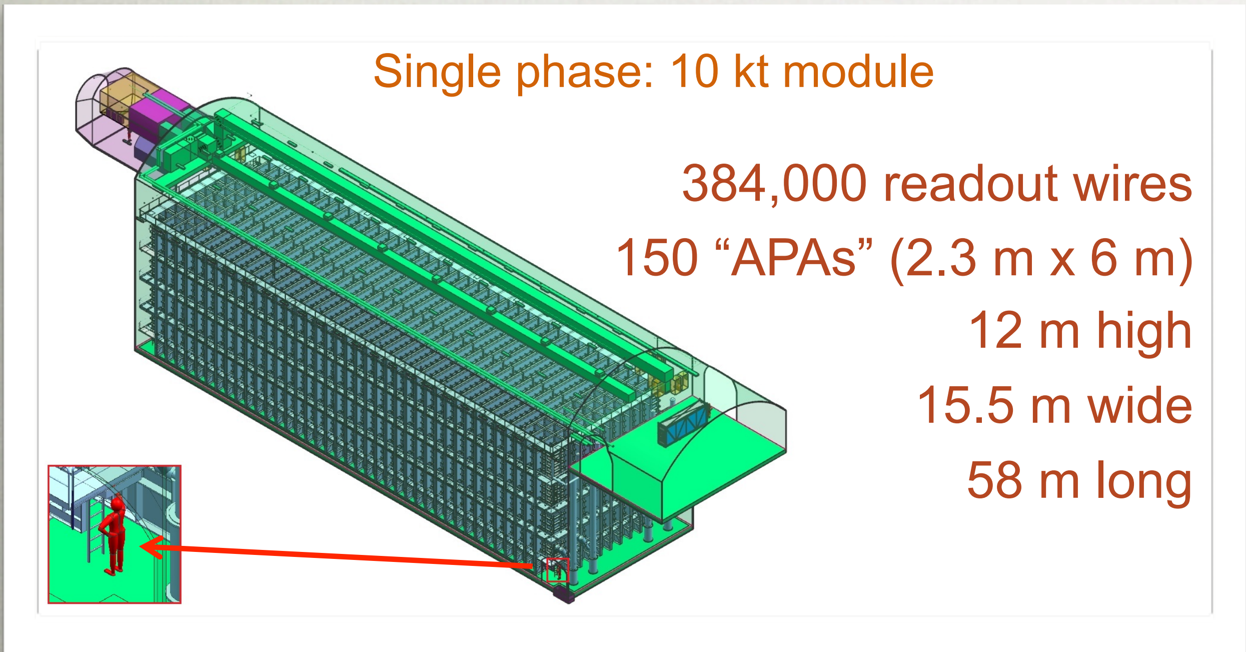
E. Worcester's slides at Neutrino 2018
J. Bian's slides at ICHEP 2018

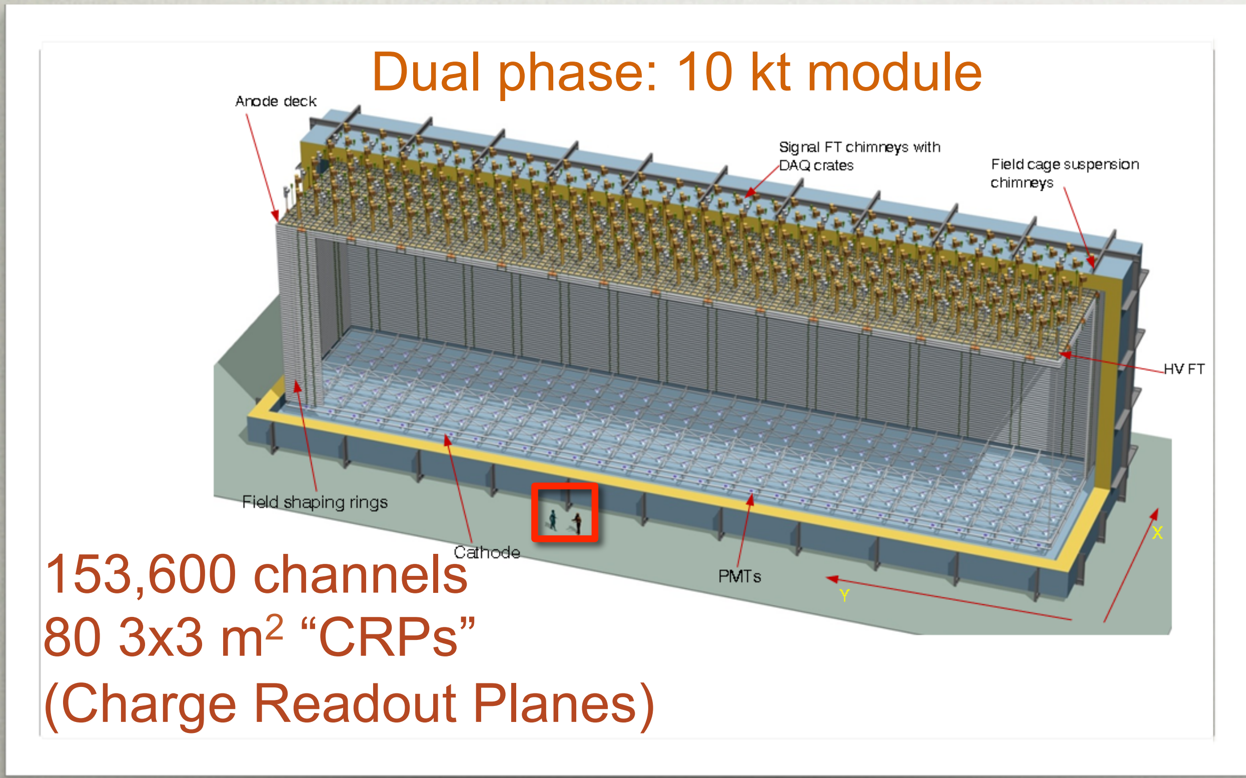
LBNF BEAM



- 60-120 GeV proton beam
- 1.2 MW proton beam power @80GeV
  - cf. NuMI achieved 700kW for NOvA
  - Upgradeable to 2.4 MW
  - DUNE sensitivity studies adopt the beam power upgrade
- Reference design similar to NuMI, optimized to improve sensitivity to oscillation measurement

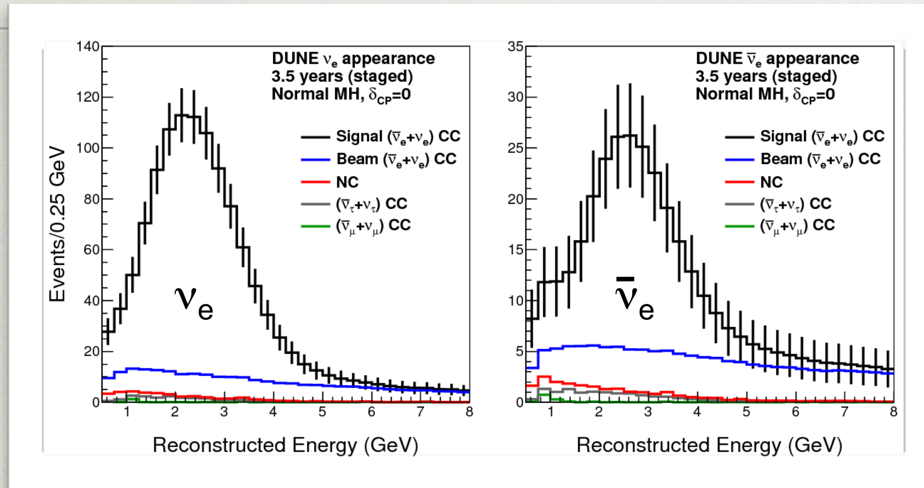
DUNE DETECTOR





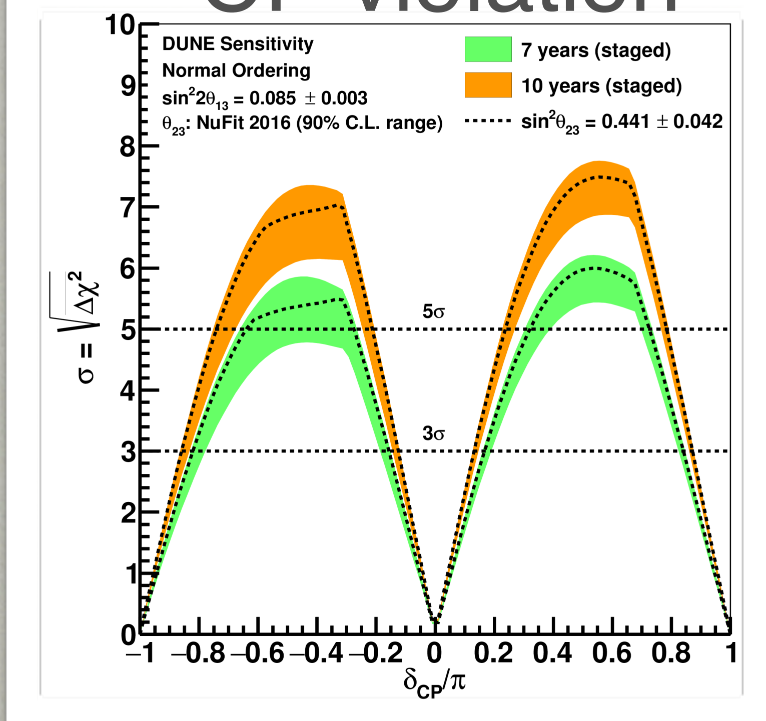
- Large underground Liquid Argon (LAr) Time Projection Chamber
  - Single- and dual-phase LAr TPC
  - Total fiducial mass of 40 kton
    - 10 kton × 4 modules
- Detector modules installed in stages
  - Start with 20kton (FV) and add other 20kton in 4 years
  - 1st modules single-phase
- Two prototype TPCs under construction for a test-beam at CERN (770ton LAr each)

DUNE sensitivity for CPV and MH

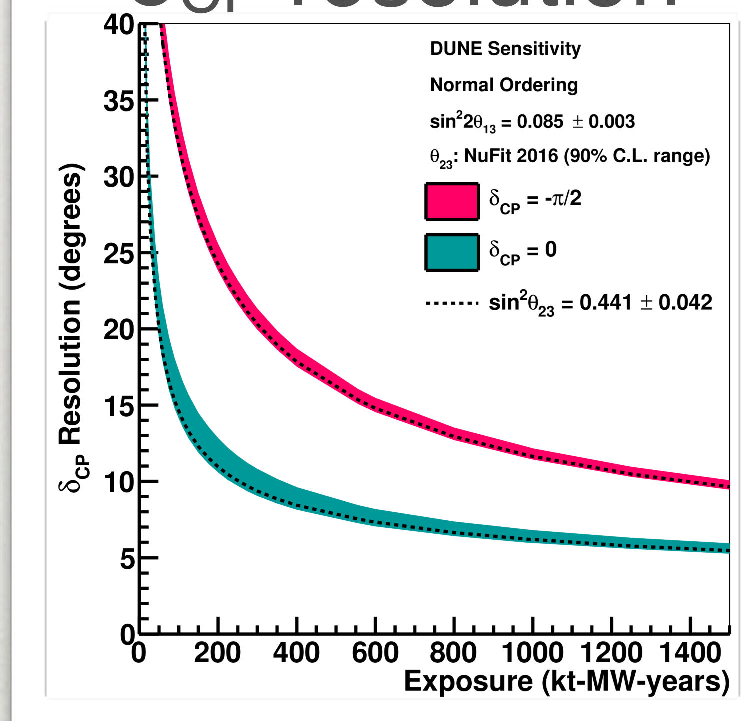


Order 1000 ν_e appearance events in ~10years of equal running in ν and $\bar{\nu}$ mode

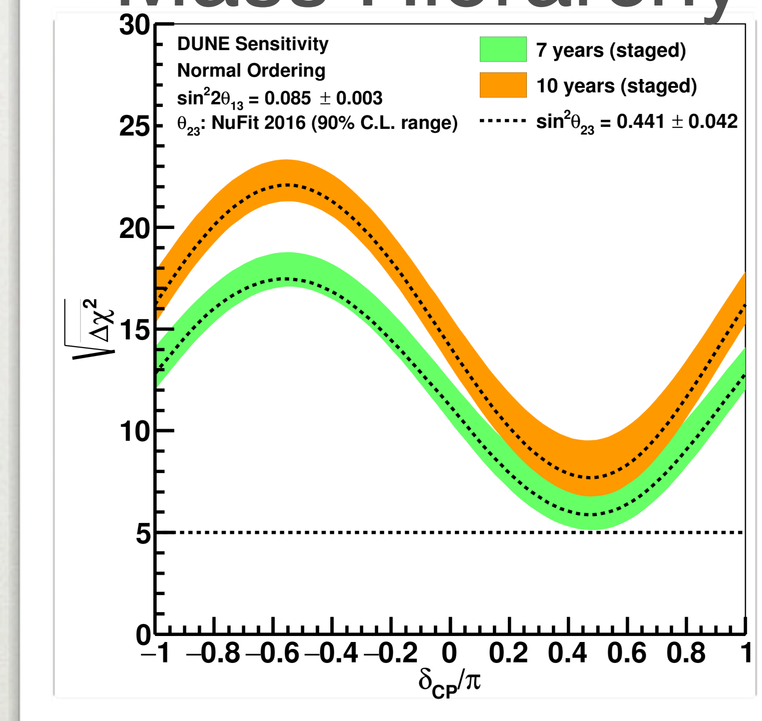
CP violation



δ_{CP} resolution



Mass Hierarchy



- Mass Hierarchy determination at >5σ
- 75% coverage for 3σ CPV discovery
- 7°~15° δ_{CP} resolution

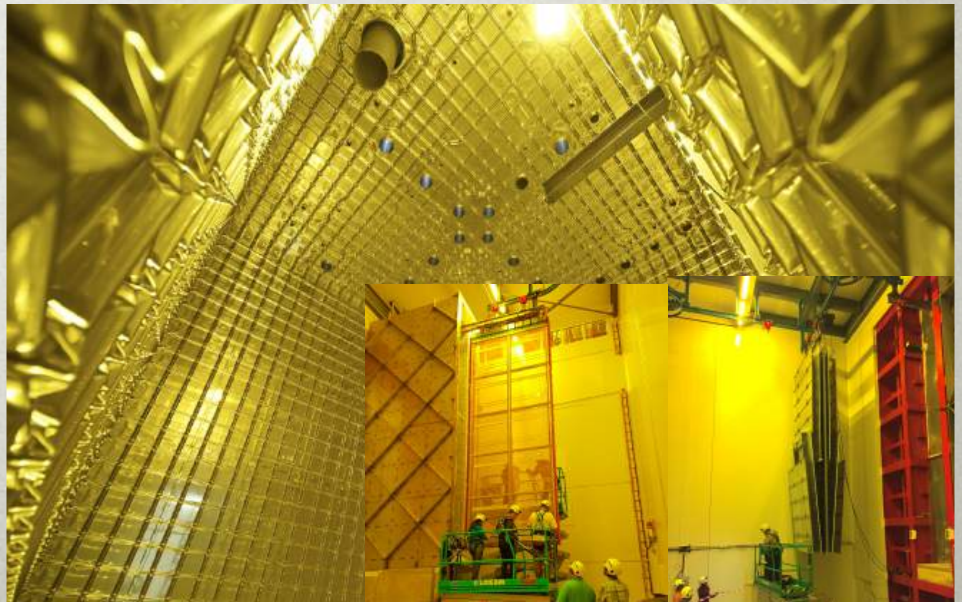
✳ Efficiency tuned using hand scan results

✳ Syst. uncertainties approximated using normalization uncertainties

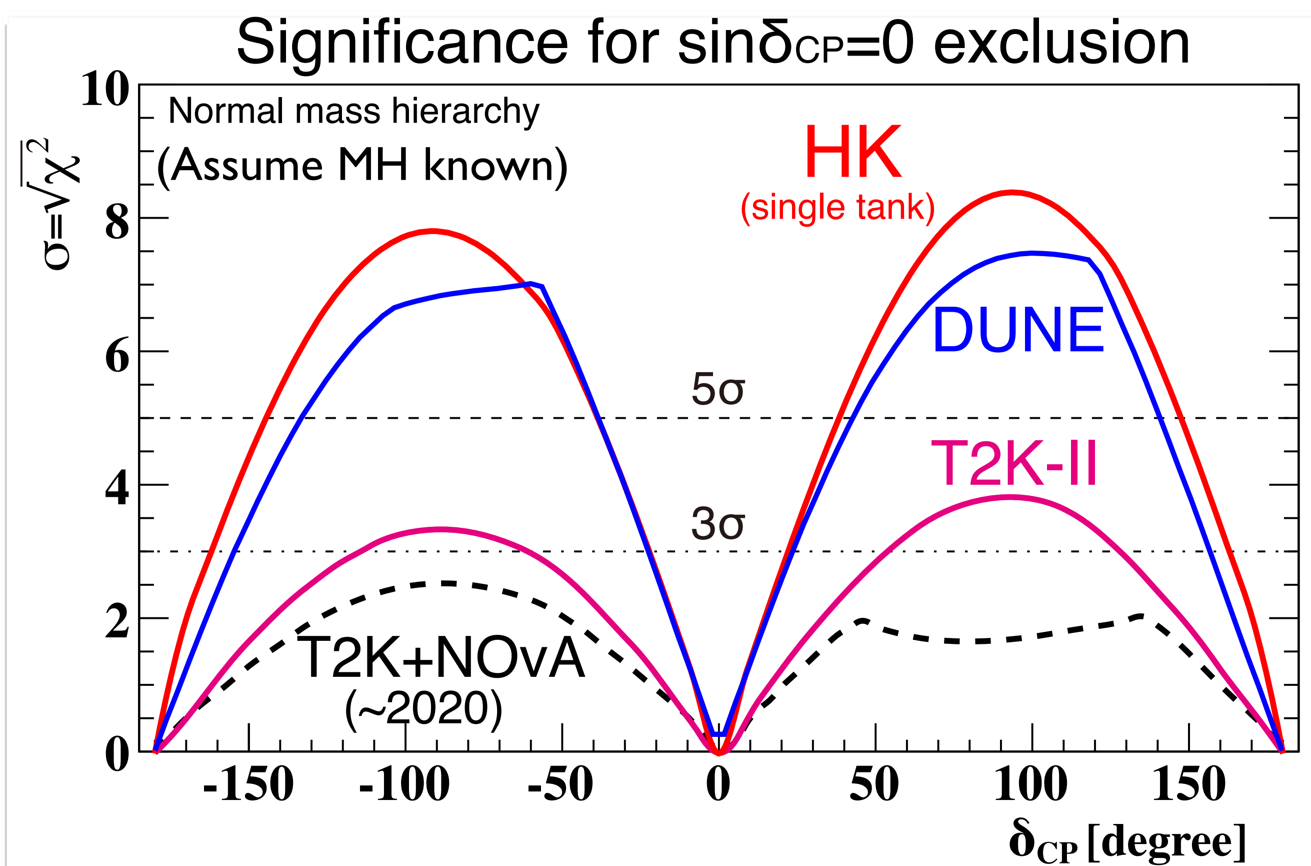
Status/plan of DUNE

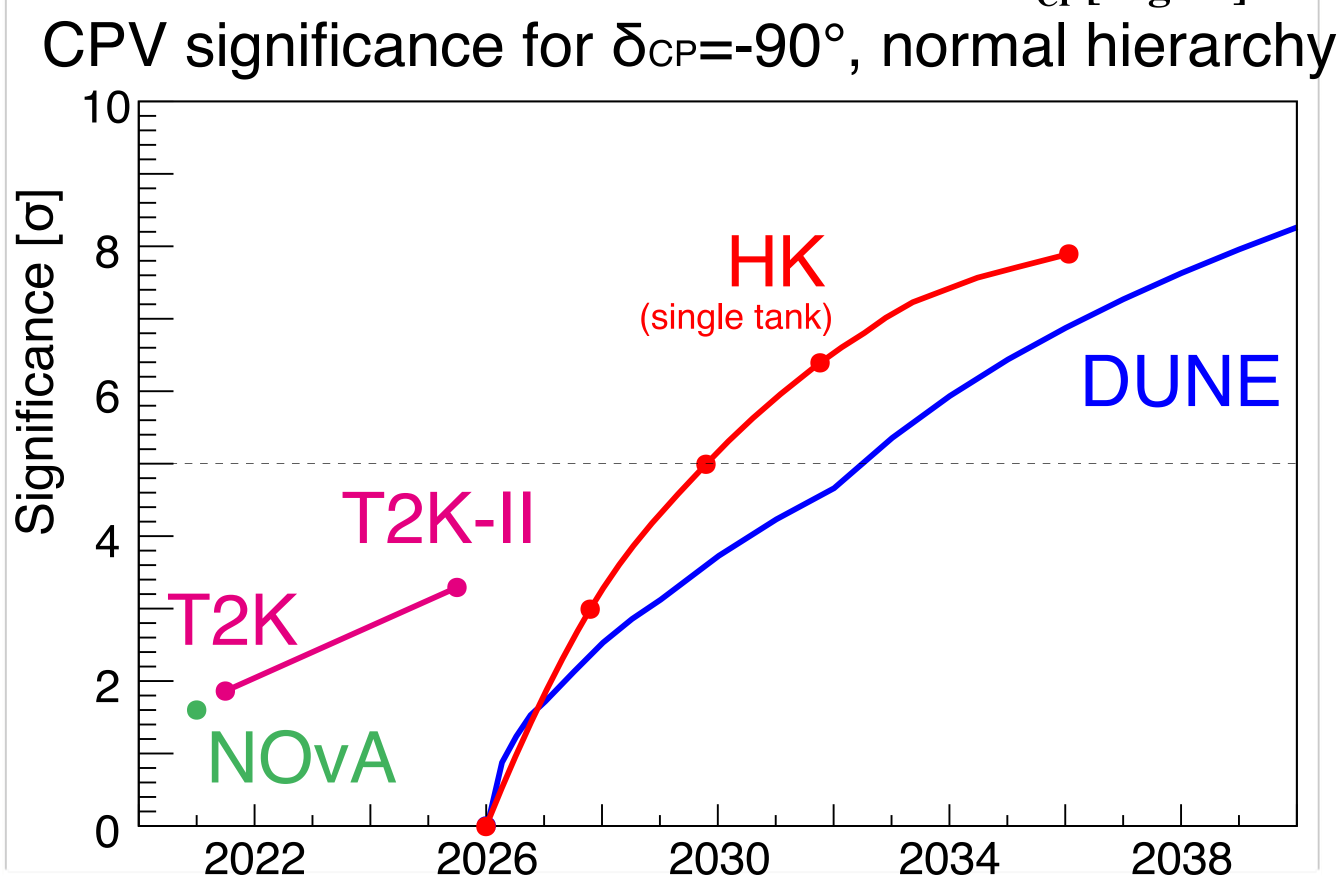
Quoted from J. Bian's slides at ICHEP 2018

- 2017: Far site construction begins
- 2018: Start to operate full-scale protoDUNE at CERN
- 2019: DUNE Technical Design Report ready for funding agencies
- 2019: Main Cavern Excavation
- 2020: Far Detector fabrication facilities ready
- 2022: Start to install FD modules
- 2024: Two FD modules (20kton) operational
- 2026: Beam on with two FD modules



Summary of CPV sensitivity





- Significance for sinδ=0 exclusion
- Hyper-K and DUNE both 5σ sensitivity near δ=-90° after 10ys operation
- Next generation expts have way better sensitivity than current running expts

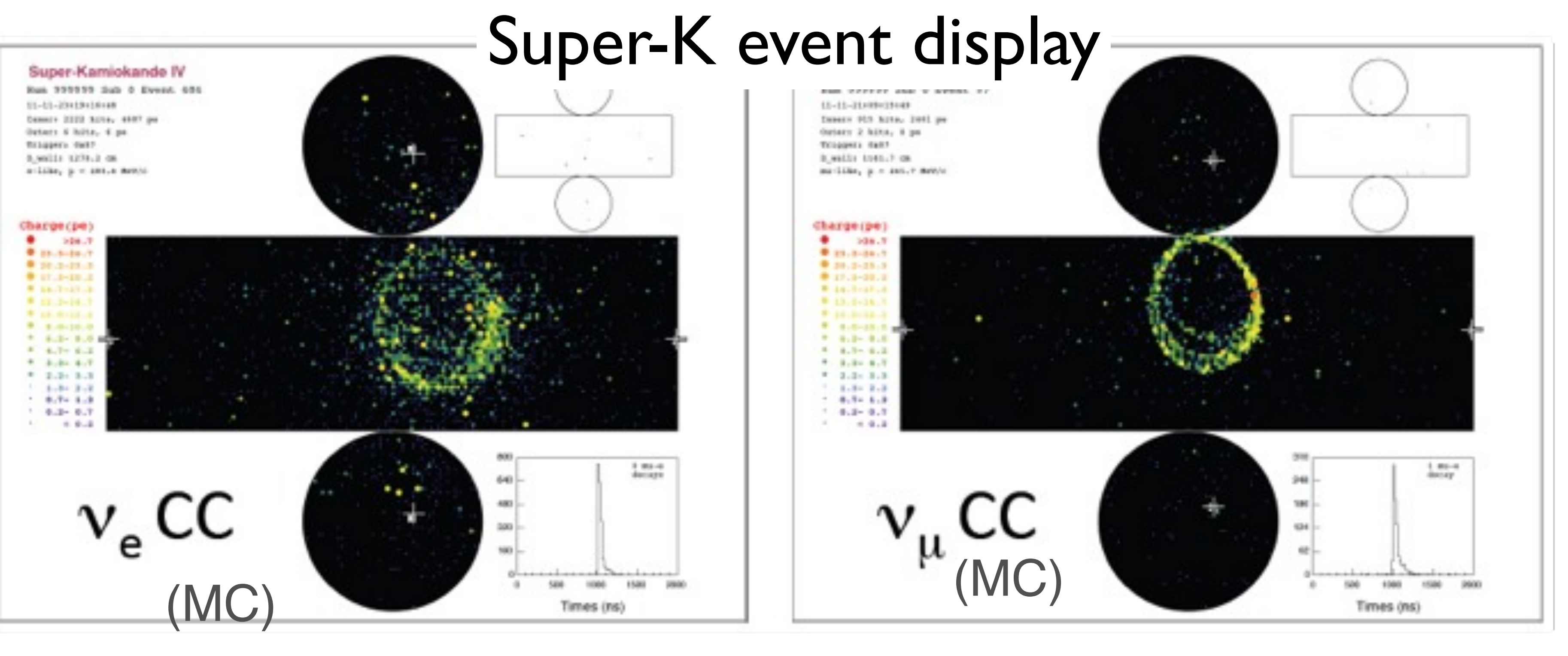
- Hyper-K DR: arXiv1805.04163
- DUNE CDR: arXiv:1512.06148

Summary

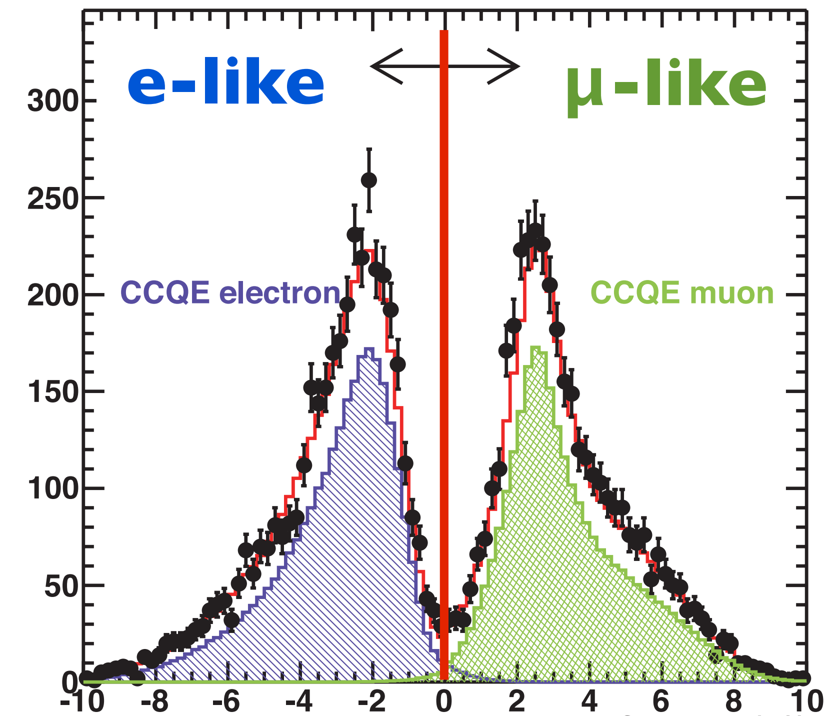
- Current running LBL experiments (T2K, NOvA) playing a major role to improve our understanding of neutrino oscillation
  - Maybe, T2K and NOvA are finding a hint of neutrino CP violation and Mass Hierarchy?
  - Non-accelerator-based experiments (Super-K, IceCUBE, ORCA, JUNO, INO, ...) also have a great potential for Mass Hierarchy determination
- Next generation LBL experiments, Hyper-K and DUNE, aim to reveal a full picture of ν oscillation
  - Primary targets: CPV and Mass Hierarchy
  - Aim to start data taking with ν beam in 2026
  - Significant complimentarily
- Wide physics topics, many discovery potential
  - Proton decay, astrophysical neutrino, ...

Back up

Detector performance



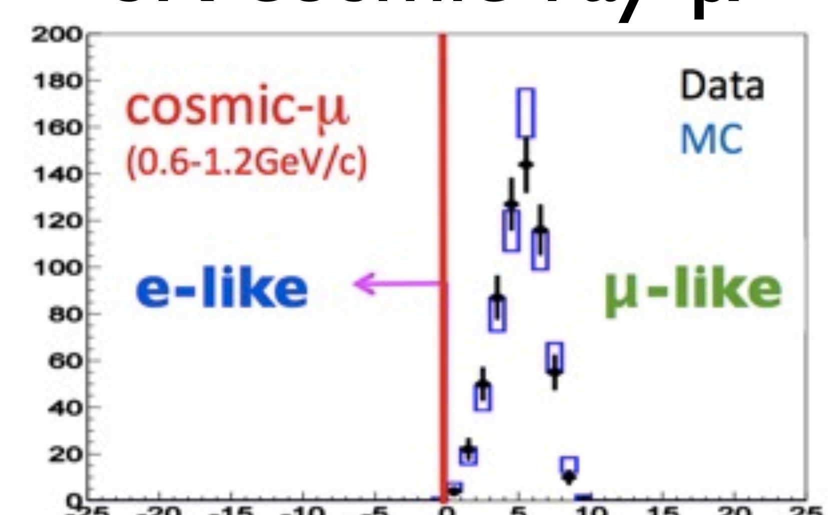
SK atmospheric ν



PID likelihood

- Large mass (~10 x Super-K FV)
  - Statistics is always critical
- Excellent particle ID (e/μ)
  - Mis-identification <1%
- Energy resolution e/μ ~3%
- Quasi-elastic is dominant (sub-GeV)
  - → Clean one-ring event

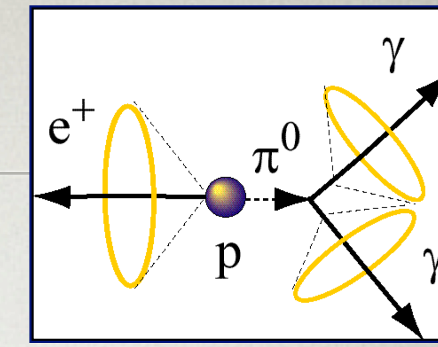
SK cosmic-ray μ



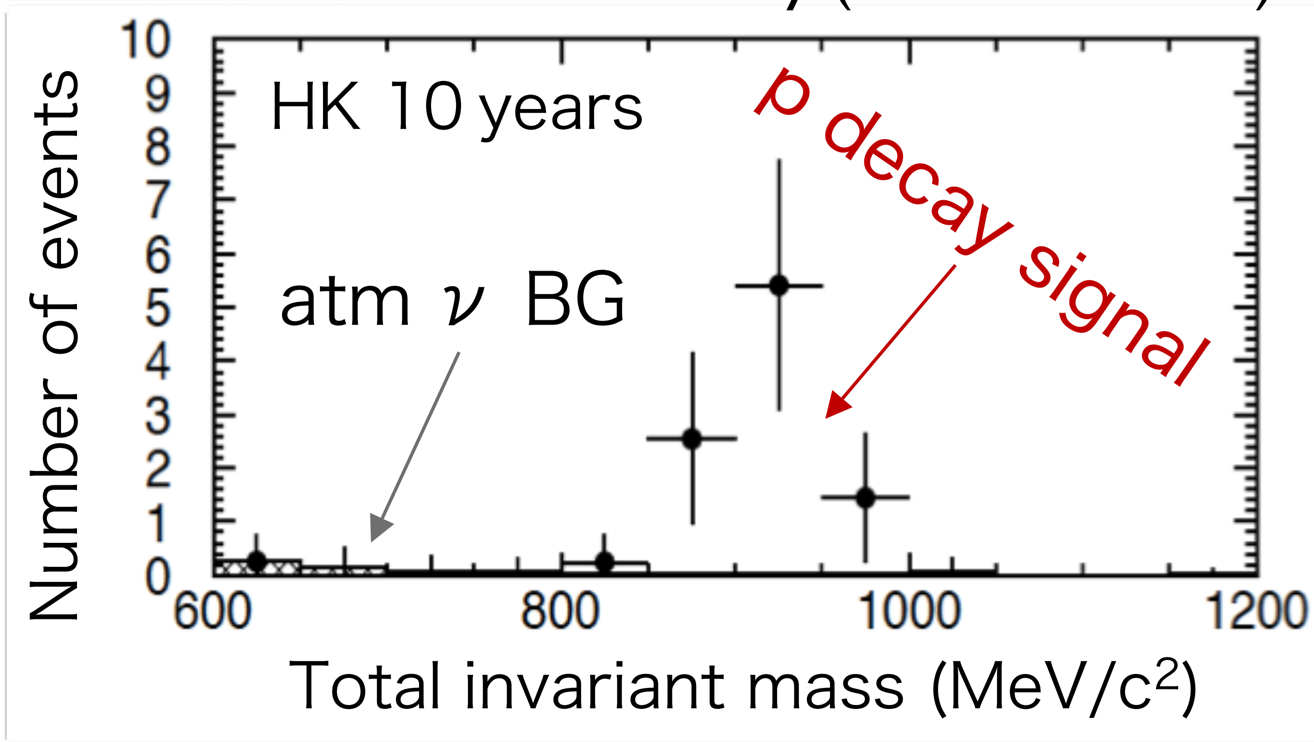
PID likelihood

mis-PID:
Data: 0.00±0.16(stat.)%
MC : 0.10±0.10(stat.)%

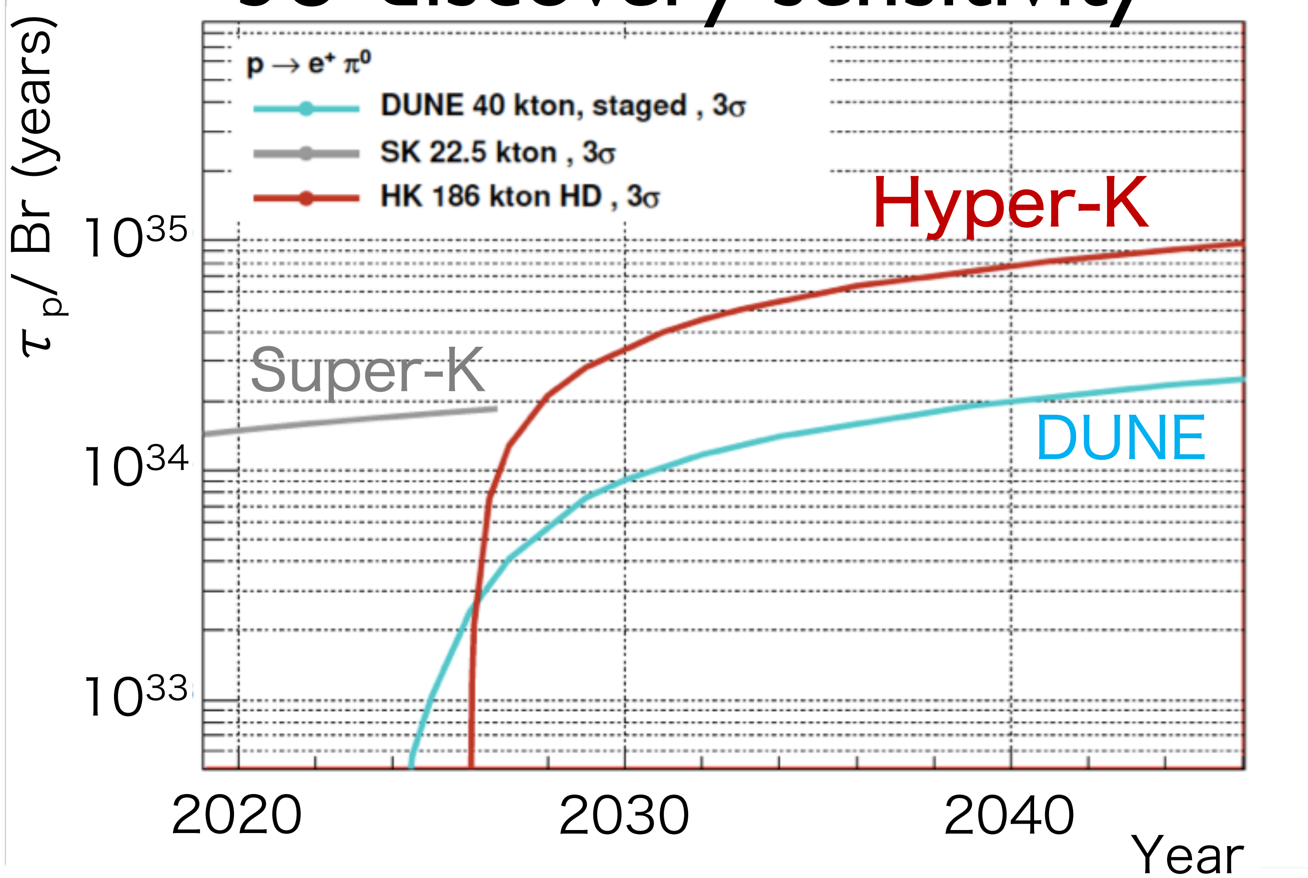
$p \rightarrow e^+\pi^0$ search in Hyper-K



Assume τ/Br=1.7x10^{34}y (SK 90%CL limit)

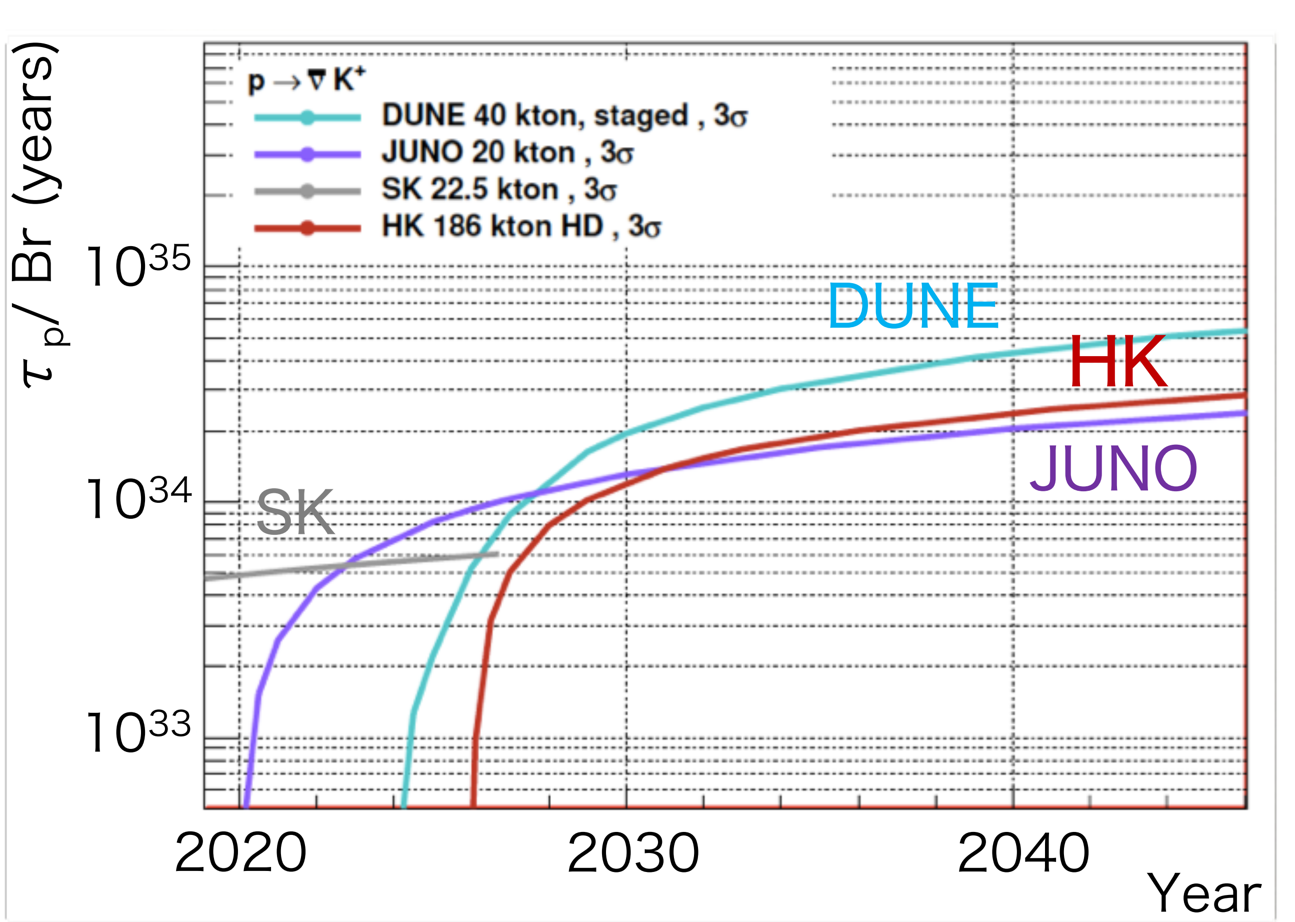


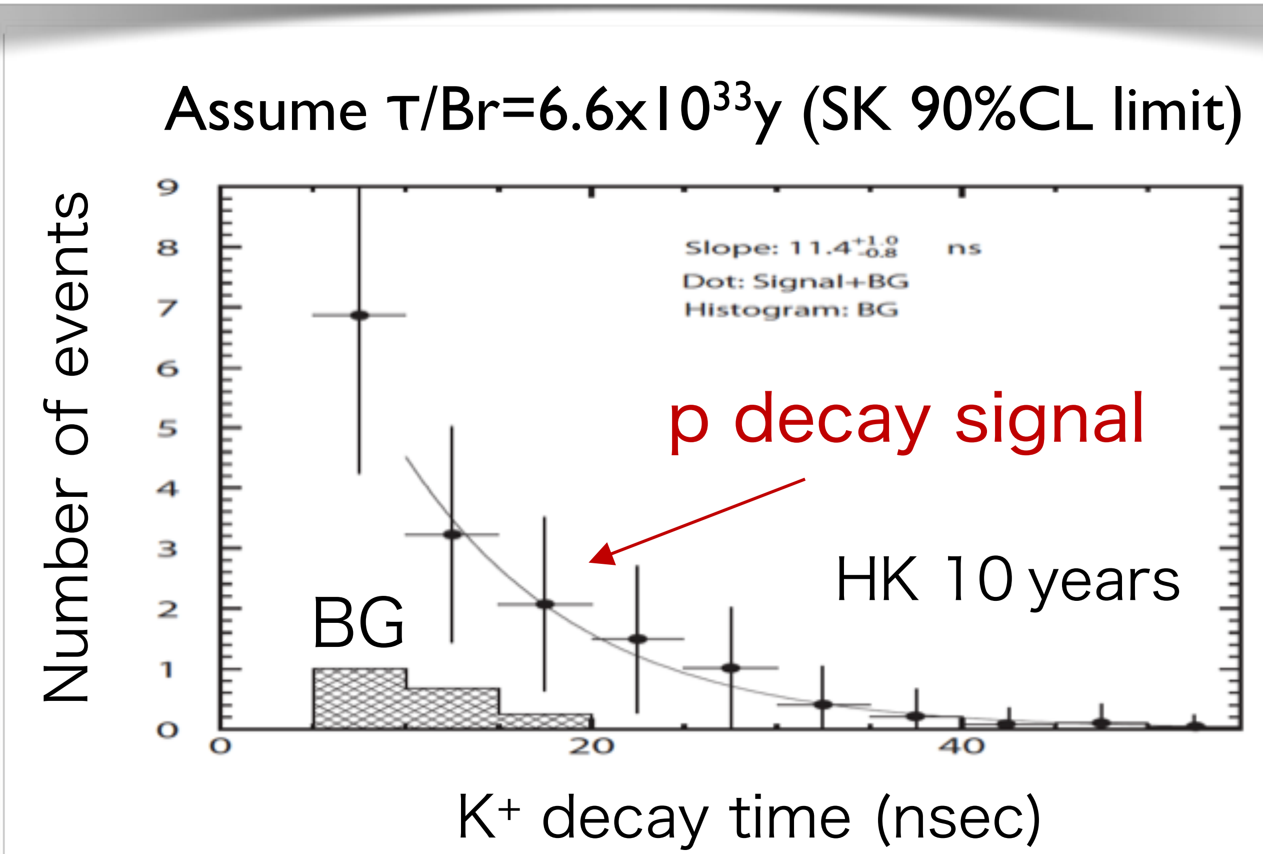
3σ discovery sensitivity



- "Background free" meas. of proton decay
  - 0.06 Bkg events / Mt・year
  - Bkg atm-ν events are largely reduced by 'neutron-tag': eff.~70% with new PMT
    - n+p→d+γ (2.2MeV)
- Great discovery potential
- 3σ discovery sensitivity reaches τ_p/Br=10^{35} years

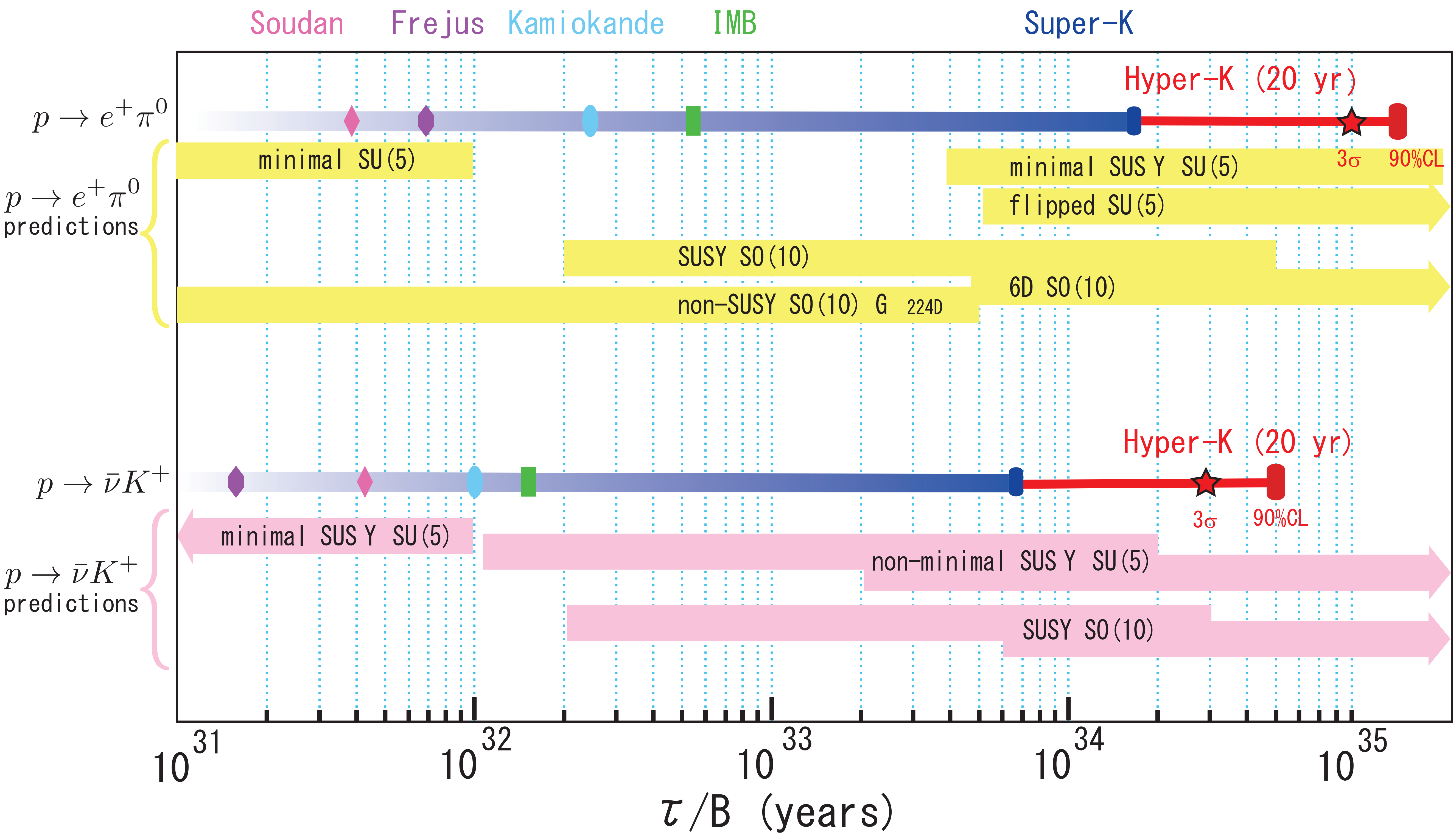
p→$\bar{\nu}$K⁺ search in Hyper-K



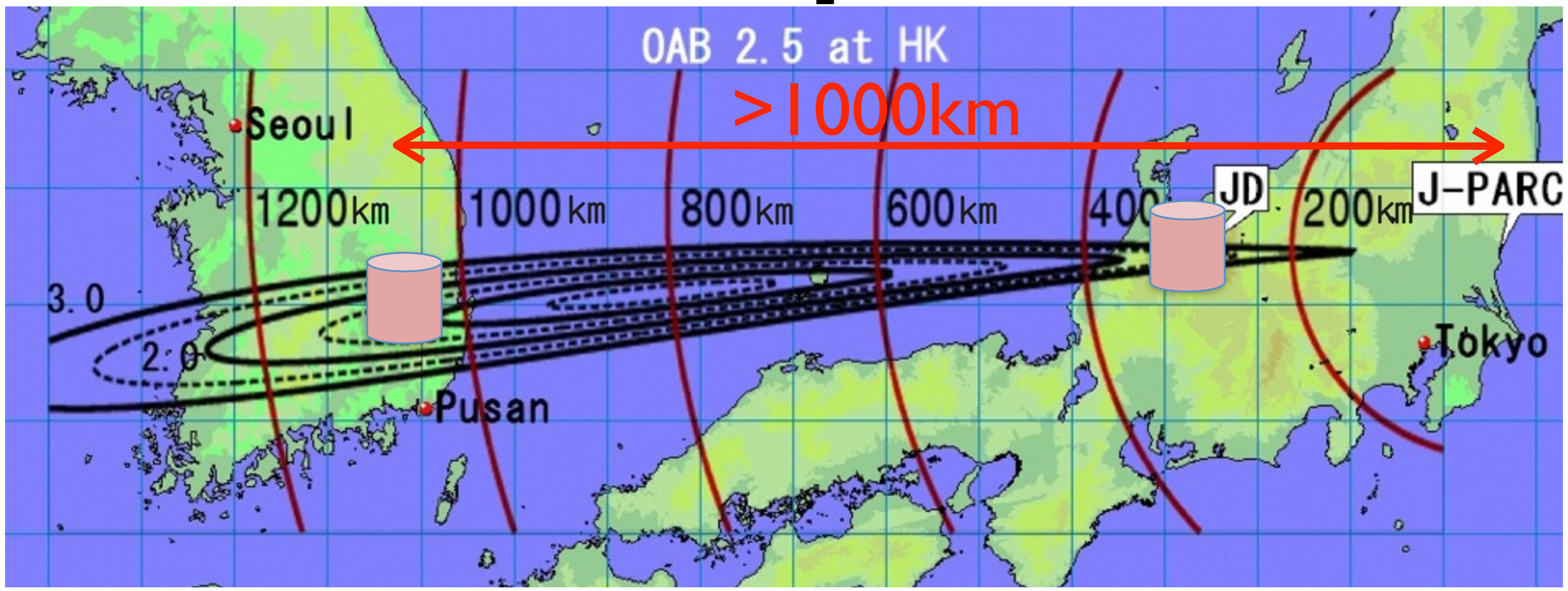


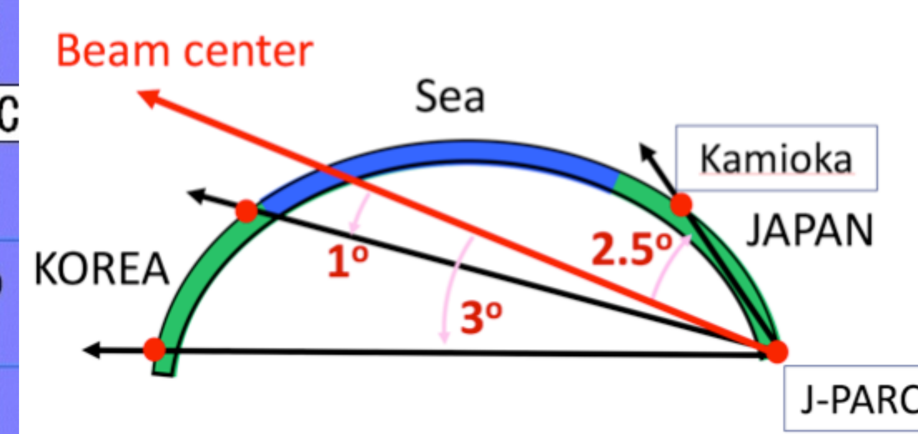
- Identify K^+ by its decaying products
- $K^+ \rightarrow \mu+\nu$ (Br: 64%)
  - 236MeV/c μ^+
  - de-excitation γ from $^{15}O^*$ (6MeV γ)
- $K^+ \rightarrow \pi^+\pi^0$ (Br: 21%)
  - 205MeV/c π^0 & π^+ back-to-back
- New PMT improves signal and background efficiencies
- Other decay modes, l+ω, ρ, η, x10 improved than SK

Predictions & experiments for p-decay

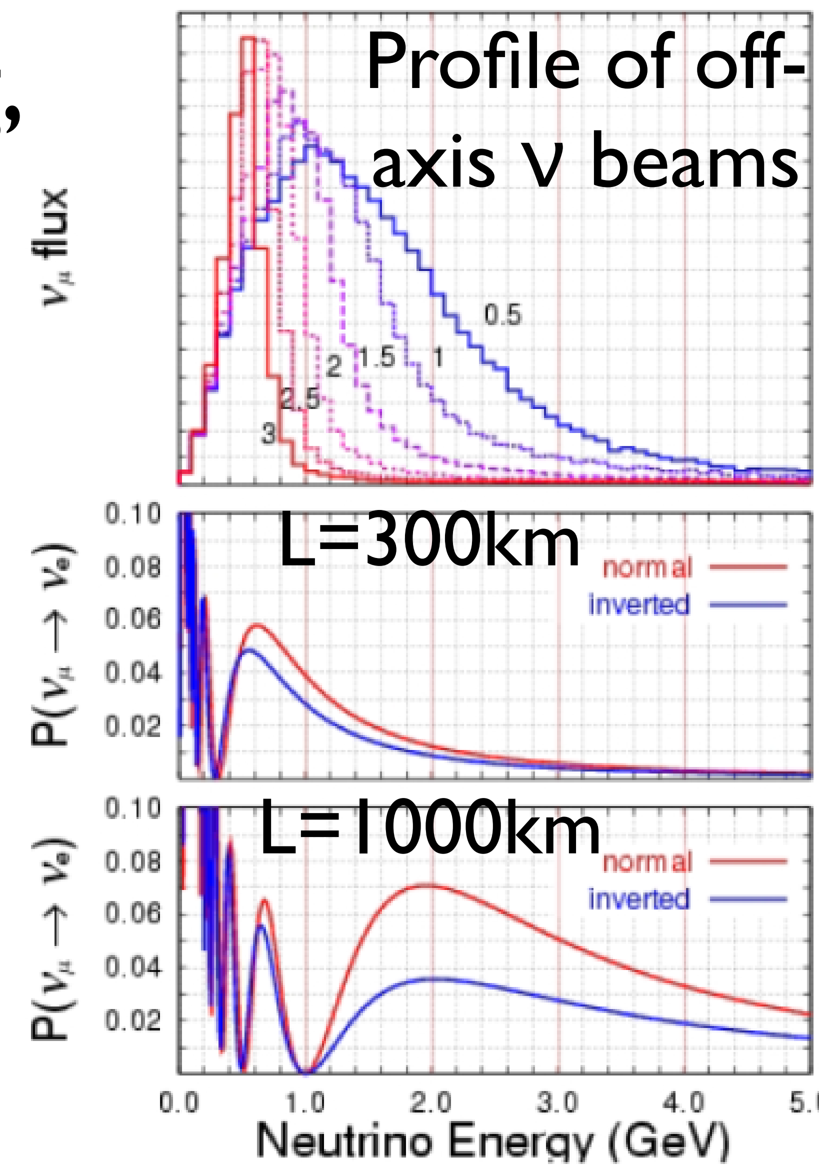


Korean option for 2nd tank



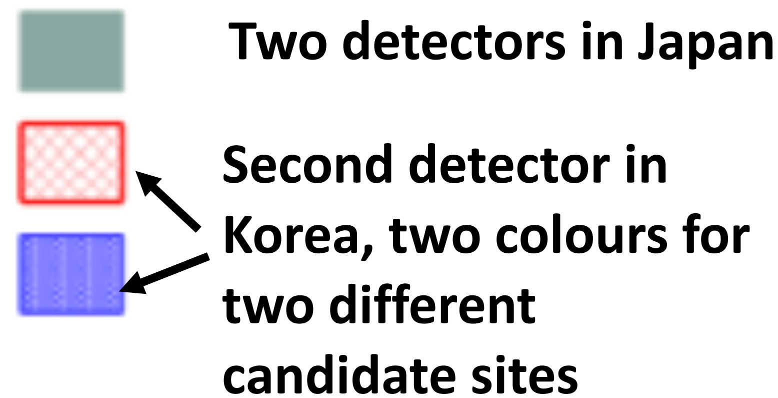


- Given the two tank design with staging, may benefit from building the second tank at a different baseline
- Option for second tank in Korea is being considered
- Advantage of 2nd detector in Korea:
  - CP effect at second oscillation maximum
  - Mass-hierarchy sensitivity to complement the measurement with atmospheric ν

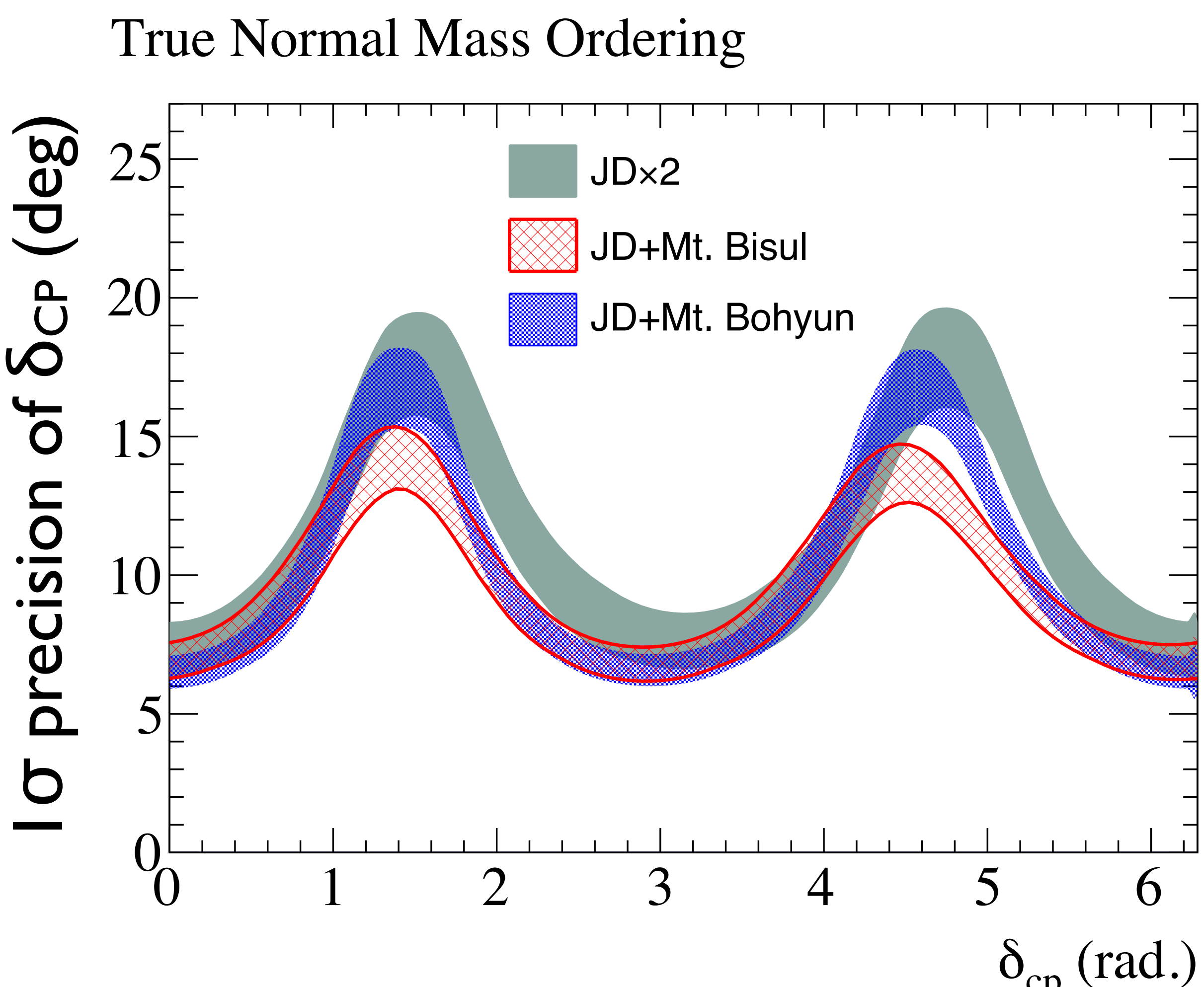


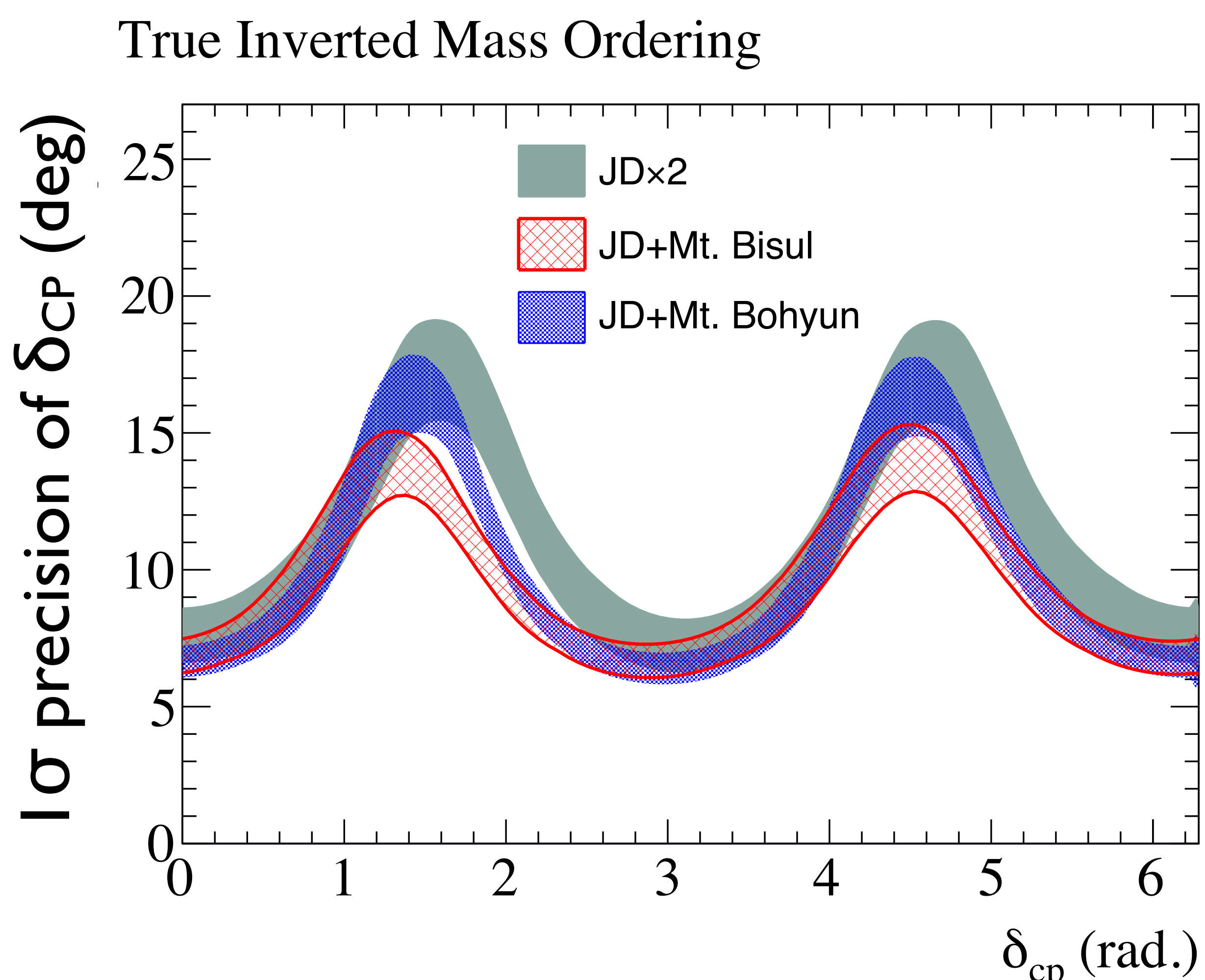
T2HKK: δ_{CP} resolution

arXiv:1611.06118



Band indicates range $0.4<\sin^2\theta_{23}<0.6$





The second detector in Korea allows us to better measure the CP-phase, compared with both detectors in Japan

Intermediate Water Č detector

- Intermediate water Č detector proposed
  - Locate 1~2km downstream of J-PARC neutrino beam
  - J-PARC E61 (NuPRISM)
- Off-axis spanning (1°~4°) to probe neutrino energy vs. final state kinematics relationship
- Increase ν_e purity at higher angles: larger contribution from Kaon
  →Electron neutrino cross-section
  - Aim to $\sigma(\nu_e)/\sigma(\nu_\mu)$ cross-section ratio error down to 2~3%