UK HEP FORUM: THE SPICE OF FLAVOUR

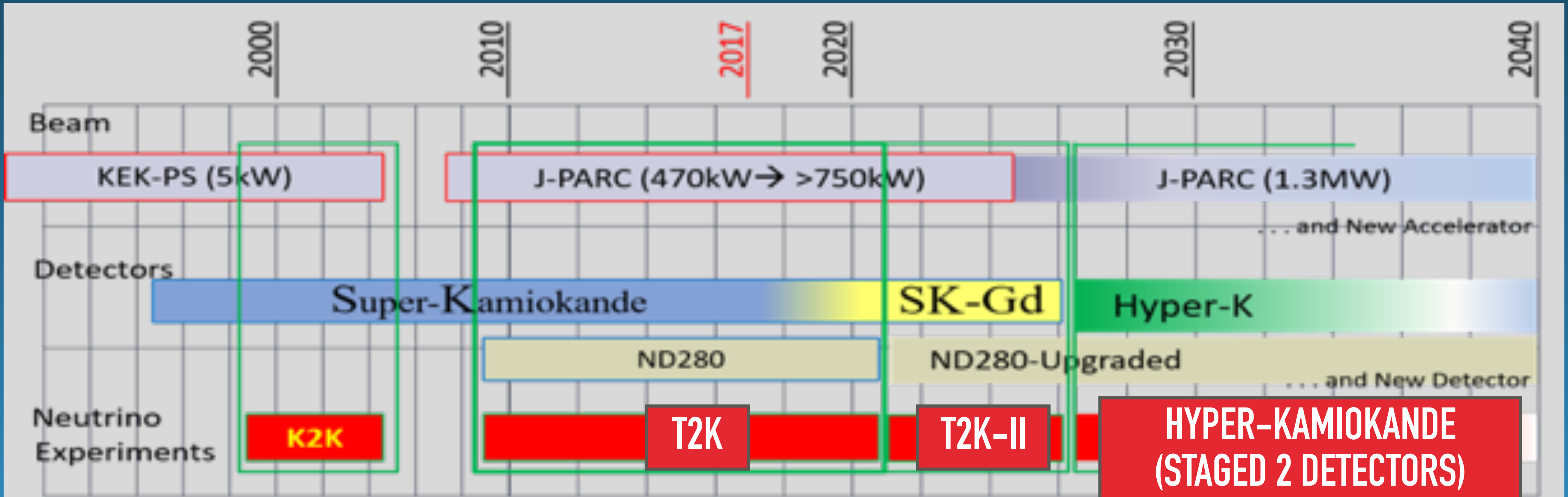
COSENER'S HOUSE, NOVEMBER 27-28 2018

FRANCESCA DI LODOVICO (QMUL)

LONG BASELINE NEUTRINO EXPERIMENTS: T2K, T2K-II, HYPER-KAMIOKANDE (JAPAN, AND JAPAN+KOREA FAR DETECTORS)

INTRODUCTION

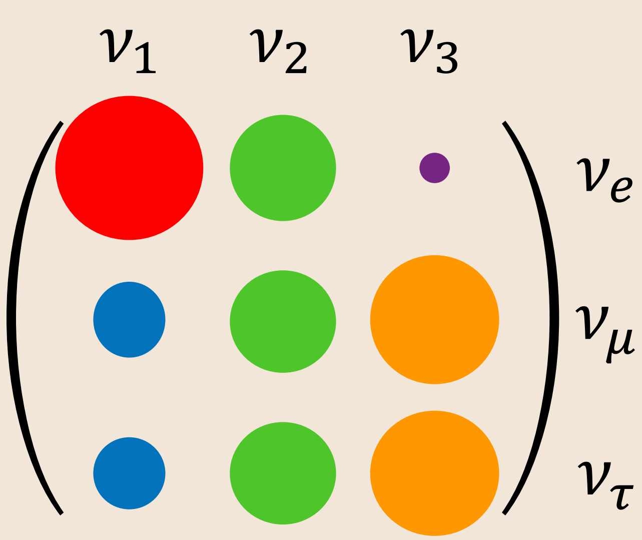
- **The T2K, T2K-II and Hyper-Kamiokande (T2HK and T2HKK) experiments provide a continuous period of data-taking in Japan from ~2010 for the next decades.**
- They address crucial open questions in particle physics.
- Increase in powerful detectors and high powered beams.
- There is a strong track-record in neutrino experiments in Japan.
- Proven technology but very challenging: largest cavern and WC detector in the world
- Short baseline, high statistics, main interaction CC quasi-elastic, simple topology.



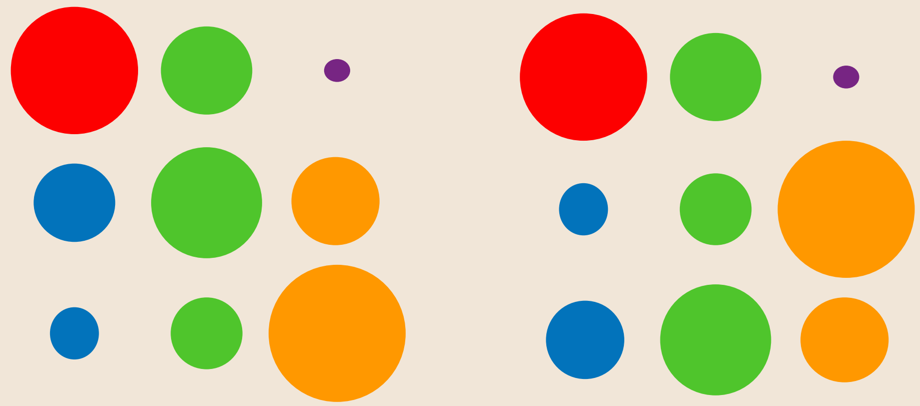
OPEN QUESTIONS

- Neutrino flavours are a mix of mass eigenstates: $|\nu_\alpha\rangle = U_{PMNS}\,|\nu_i\rangle$
- **Main Open Questions to be answered: what is the value of δ^{CP}? what is the mass ordering? what is the value of θ_{23}?**

$|U_{\mathrm{PMNS}}|^2 \simeq$

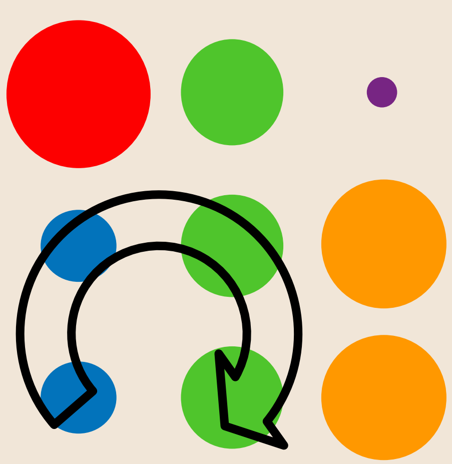


Octant degeneracy



Lower ($\theta_{23} < 45°$) Upper ($\theta_{23} > 45°$)

CP Violation

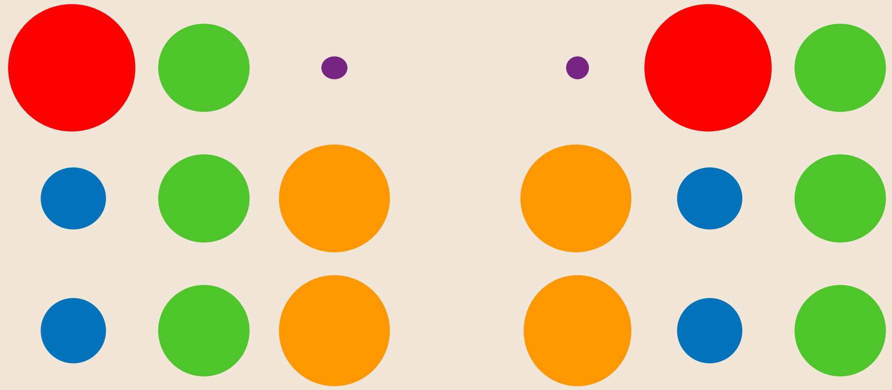


Complex mixing of these 4 elements causes

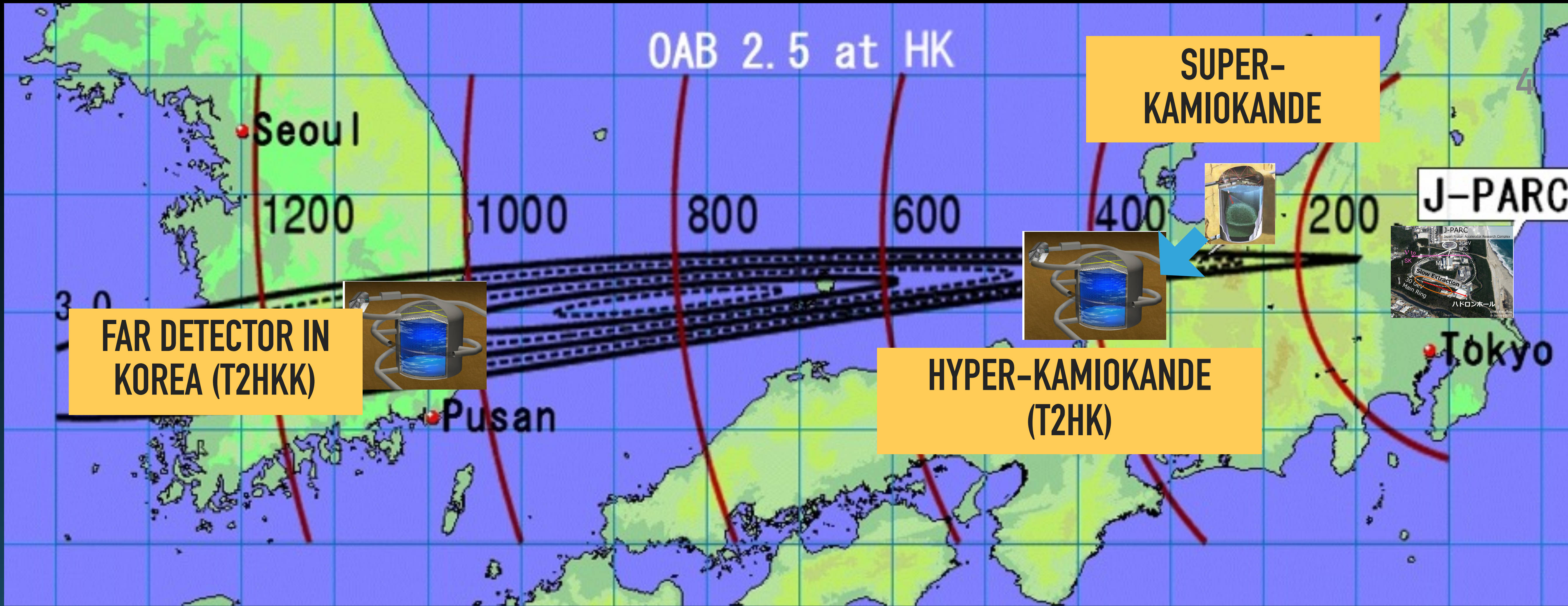
$$P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$$

Key parameter: $\boldsymbol{\delta_{CP}}$

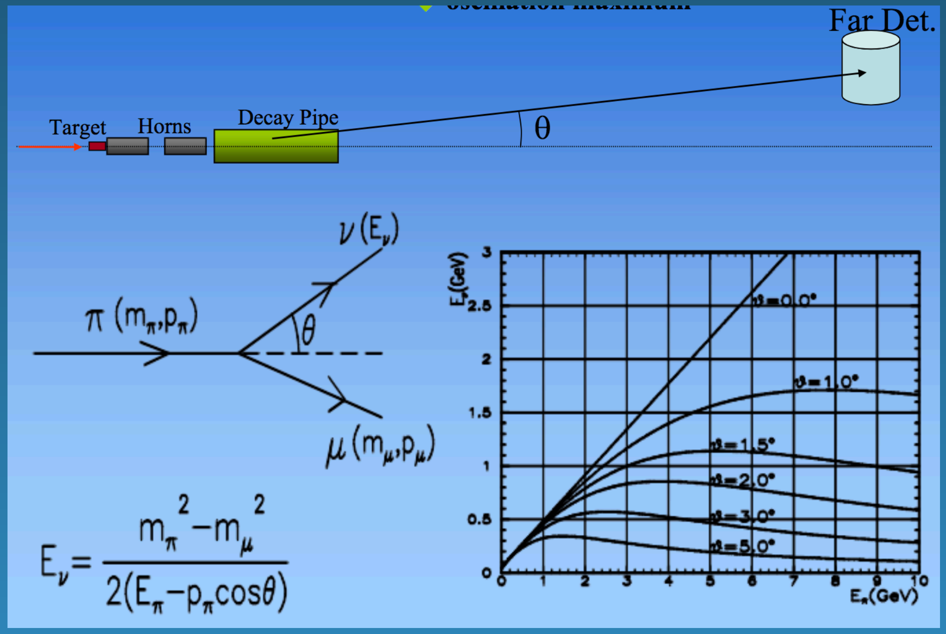
Mass Ordering (Hierarchy)

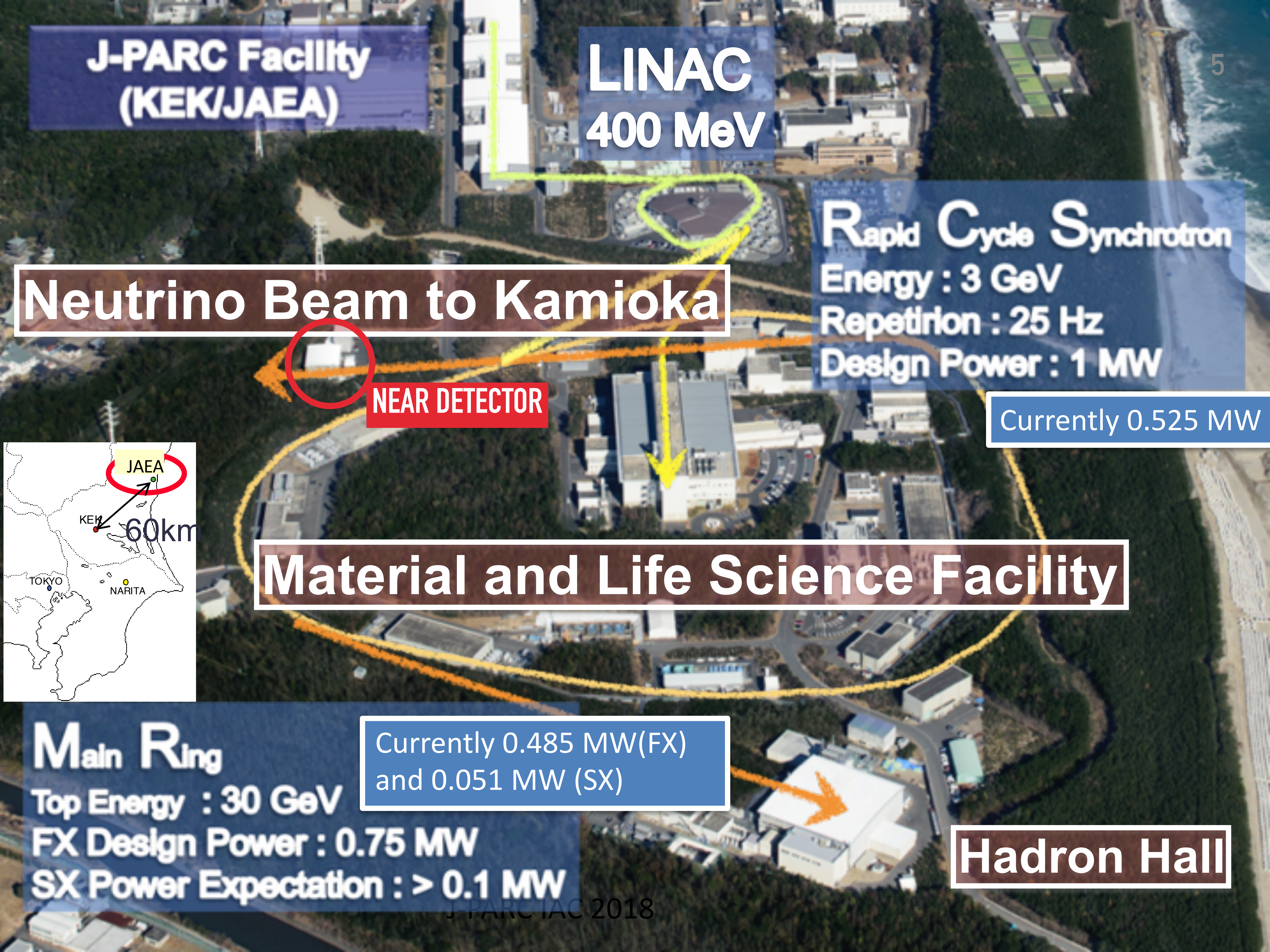


Normal (NO) Inverted (IO)

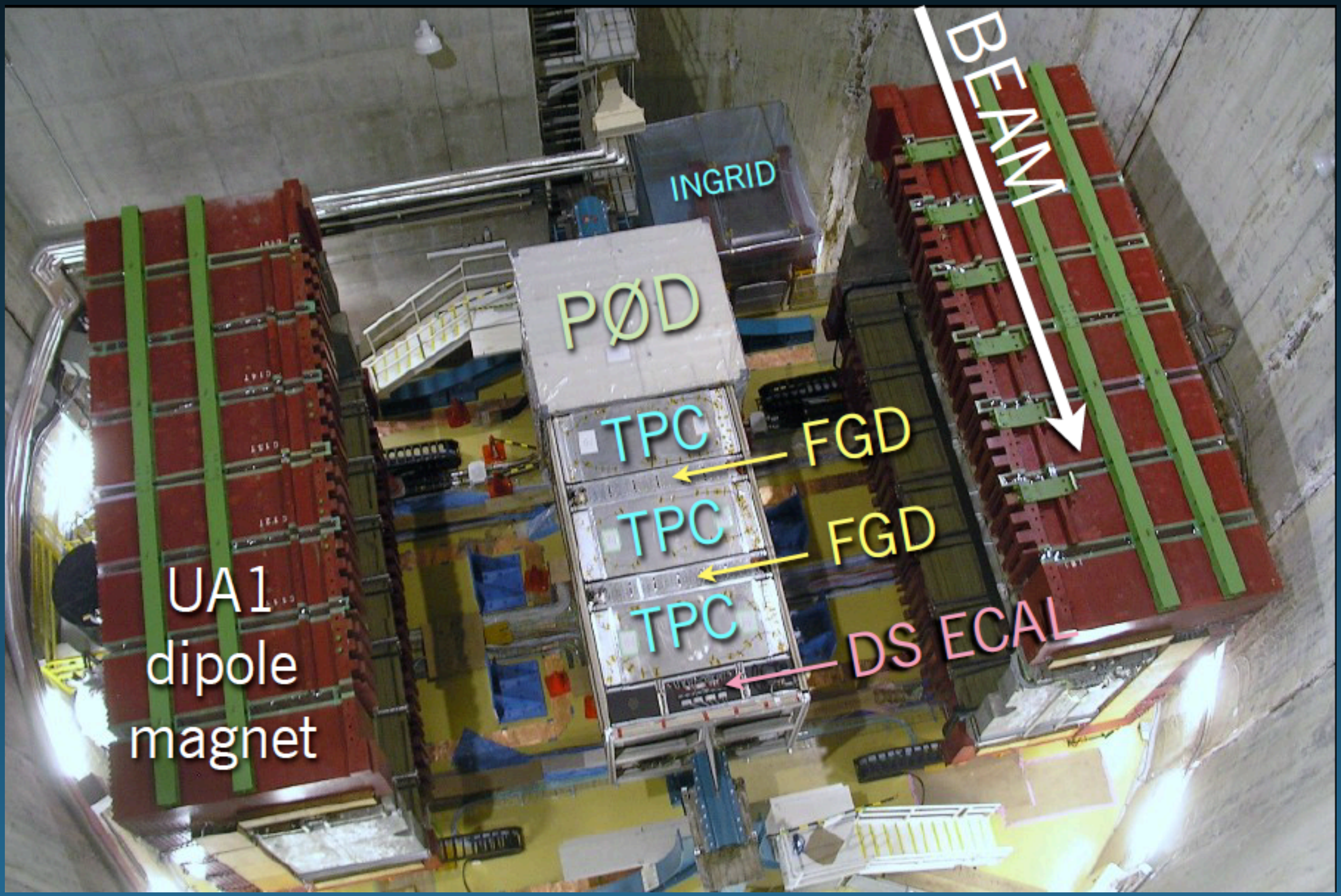


- Long baseline neutrino experiments
  - Baseline in Japan: ~295km
  - Baseline in Korea: ~1000km
- Beam from J-PARC
  - 2.5deg off-axis beam with peak energy around 0.6GeV
- Near detectors:
  - ND280 (T2K)
  - ND280 upgraded (T2K-II)
  - ND280 upgraded and WC intermediate detector (Hyper-K)
- Far detector:
  - Super-K (T2K and T2K-II)
  - Hyper-K (T2HK)
  - Hyper-K and Korean detector (T2HKK)




J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetirion : 25 Hz
Design Power : 1 MW
Currently 0.525 MW
Neutrino Beam to Kamioka
NEAR DETECTOR
JAEA
KEK
60km
TOKYO
NARITA
Material and Life Science Facility
Main Ring
Top Energy : 30 GeV
FX Design Power : 0.75 MW
SX Power Expectation : > 0.1 MW
Currently 0.485 MW(FX)
and 0.051 MW (SX)
Hadron Hall

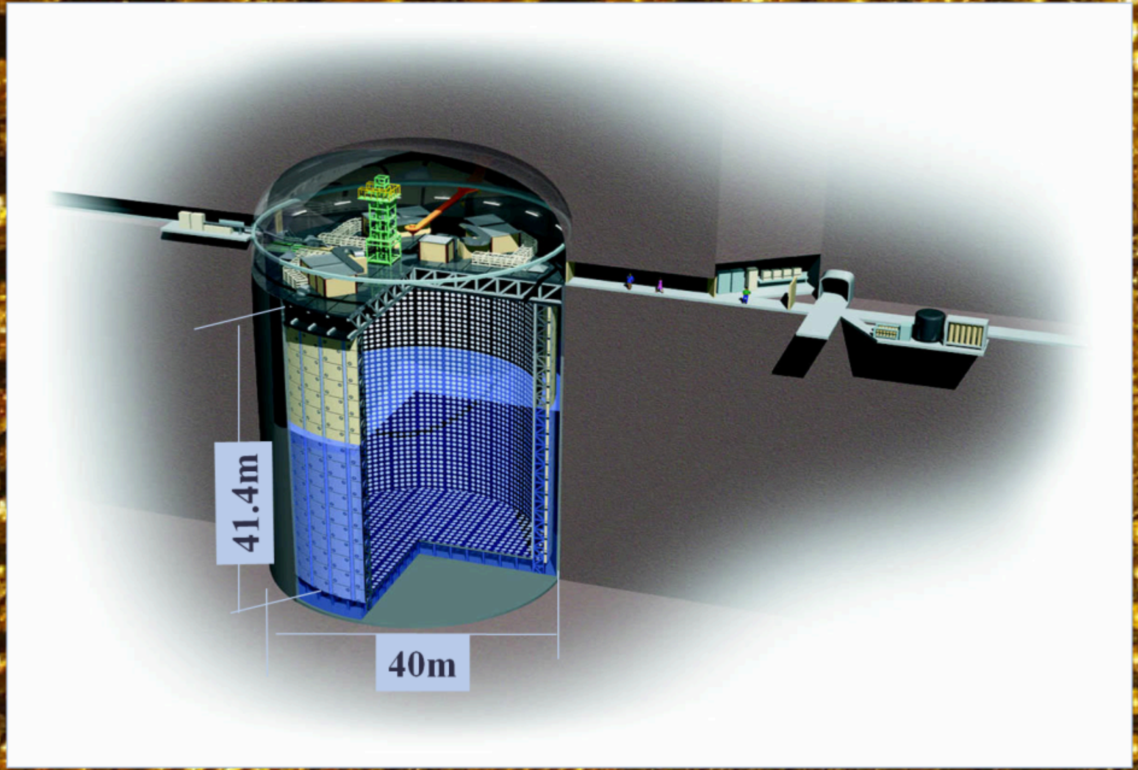
OFF-AXIS NEAR DETECTOR ND280



- PiØ Detector (PØD): optimized for π^0 detection, includes H2O target
- Tracker: 2 Fine-Grained Detectors (FGD), H2O target, 3 TPCs: measure fluxes before oscillation
- ECAL: surrounding PØD and Tracker, measure EM activity
- Side Muon Range Detector: in the magnet yokes, identify muons

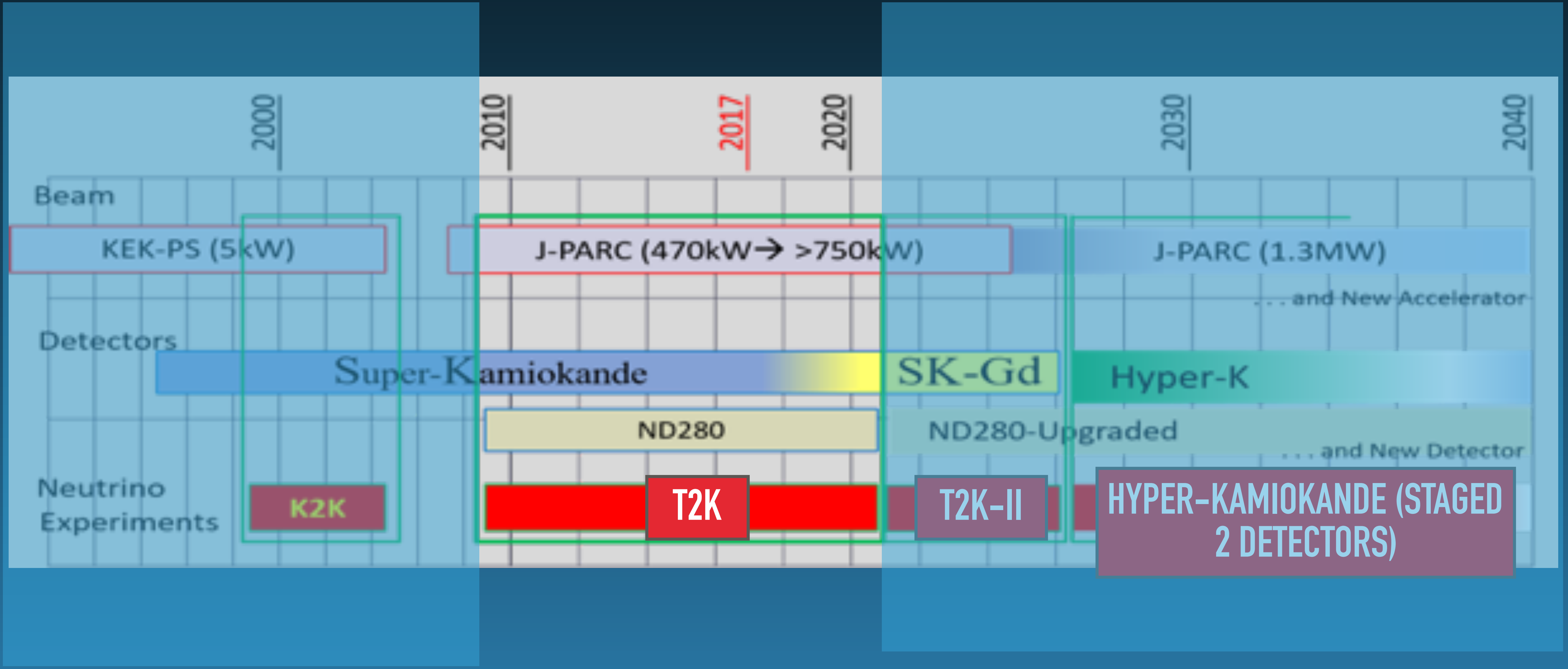
SUPER-KAMIOKANDE

50 KT WATER CHERENKOV
• 11129 20-INCH PMTS IN INNER DETECTOR; 1885 8-INCH PMTS IN OUTER VETO DETECTOR



ORIGINALLY COMMISSIONED 1997
UNDERGOING REFURBISHMENT NOW (TANK IS OPEN)
RECOMMISSIONING AROUND END OF 2018
GADOLINIUM DOPING TO BEGIN NEXT YEAR

TOKAI-TO-KAMIOKA (T2K)



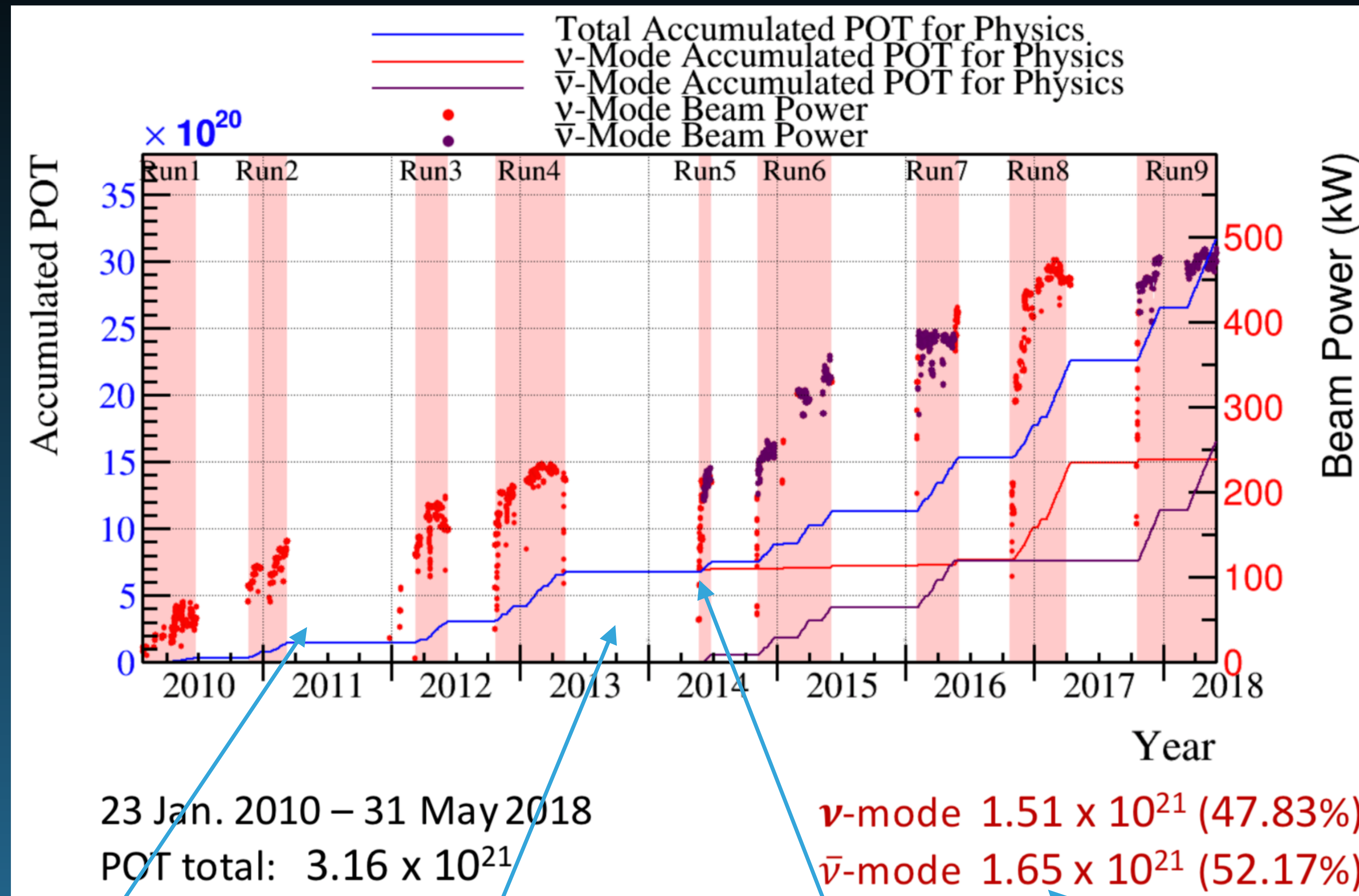
NEUTRINO PHYSICS RUNS

Beam delivery since 2010

3.16×10^{21} protons on target so far

Steadily increasing beam power:

- Have exceeded 500 kW
- Steady running now at 485 kW



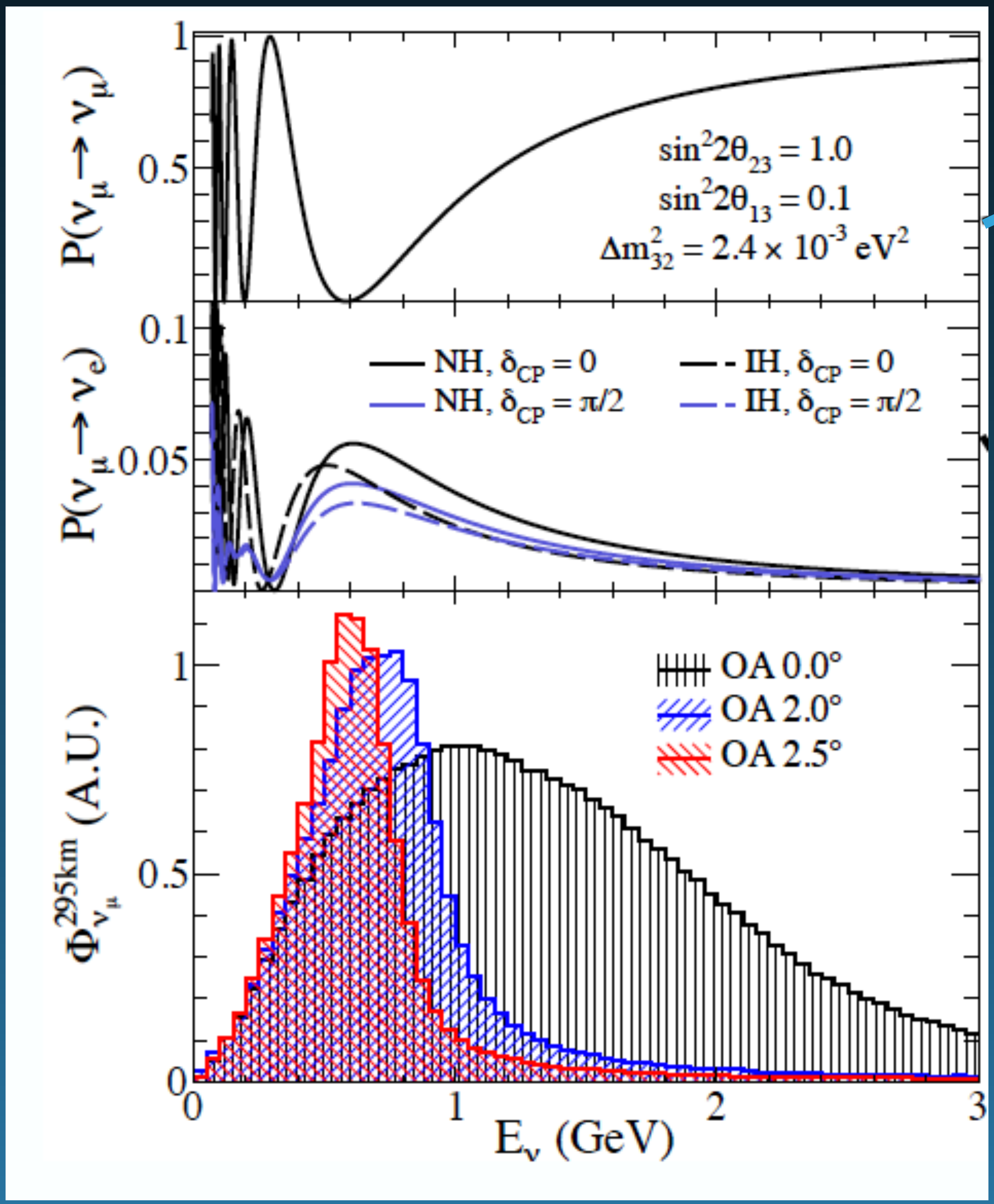
March 2011: Great East Japan Earthquake

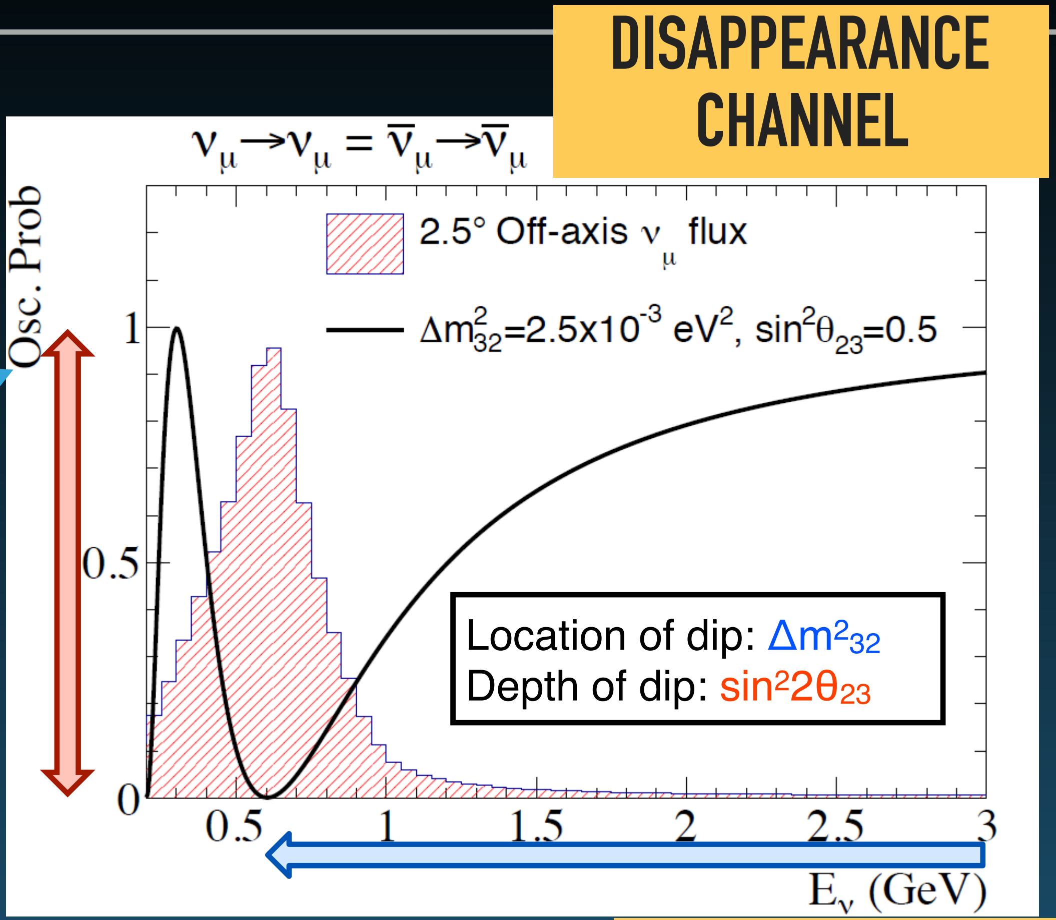
May 2013: Hadron Hall Radiation Accident

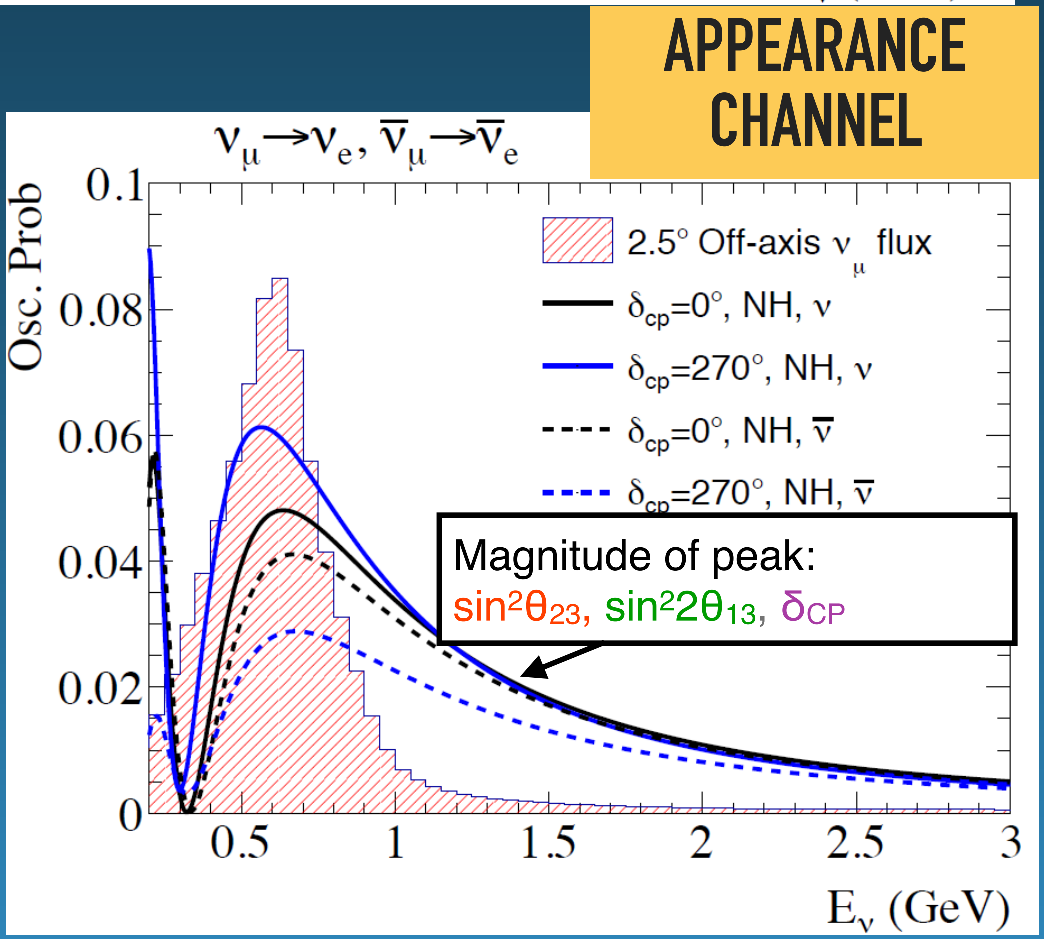
Analysed 1.12×20^{21} POT

JUNE 2014: FIRST ANTINEUTRINO DATA

T2K MEASUREMENTS

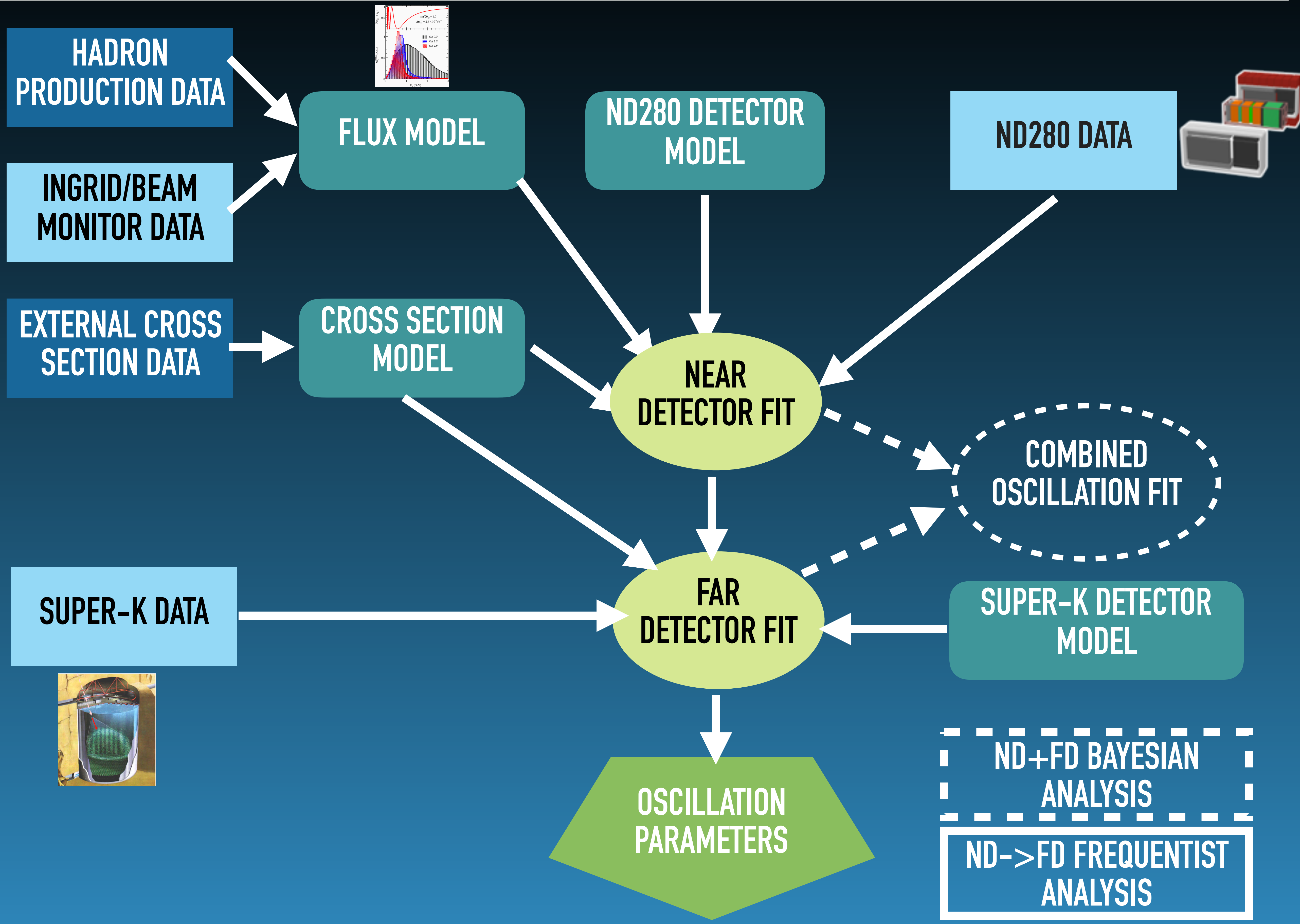






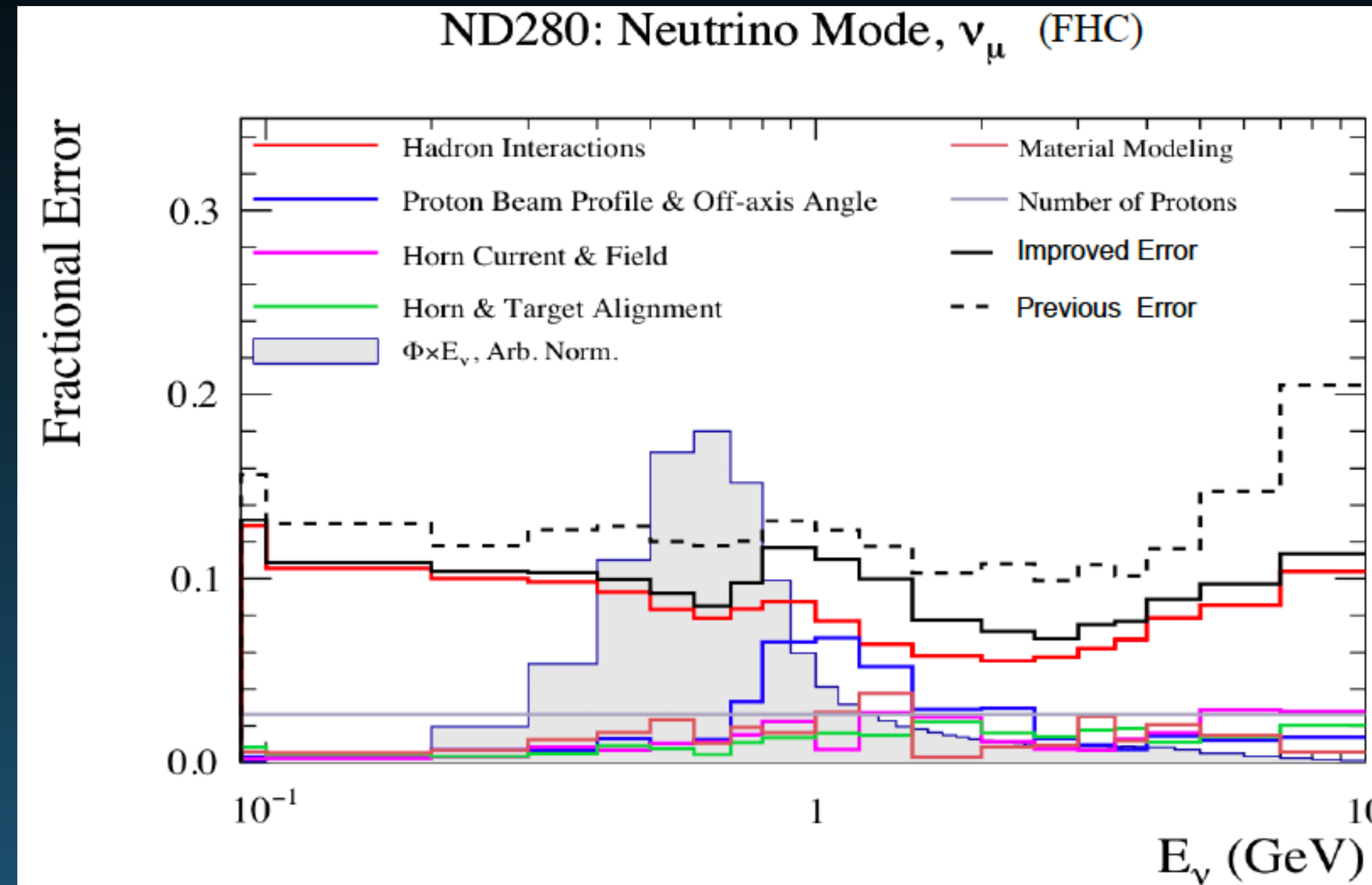
- Enhanced for ν if $-\pi < \delta_{CP} < 0$
- NO/NH also enhances ν

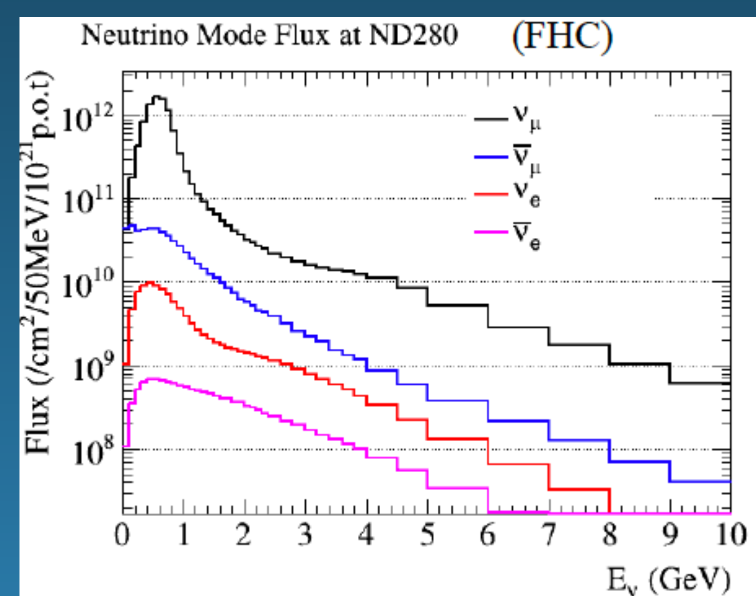
OSCILLATION ANALYSIS MODELS

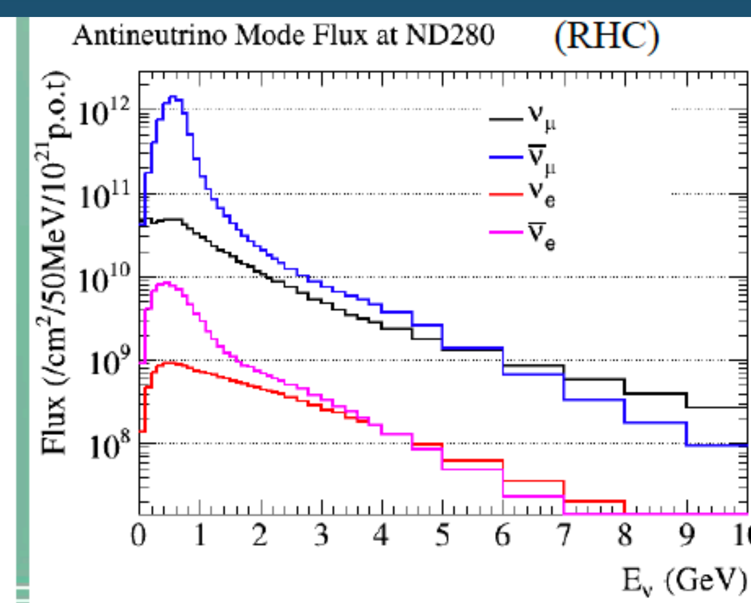


NEUTRINO BEAM FLUX PREDICTION

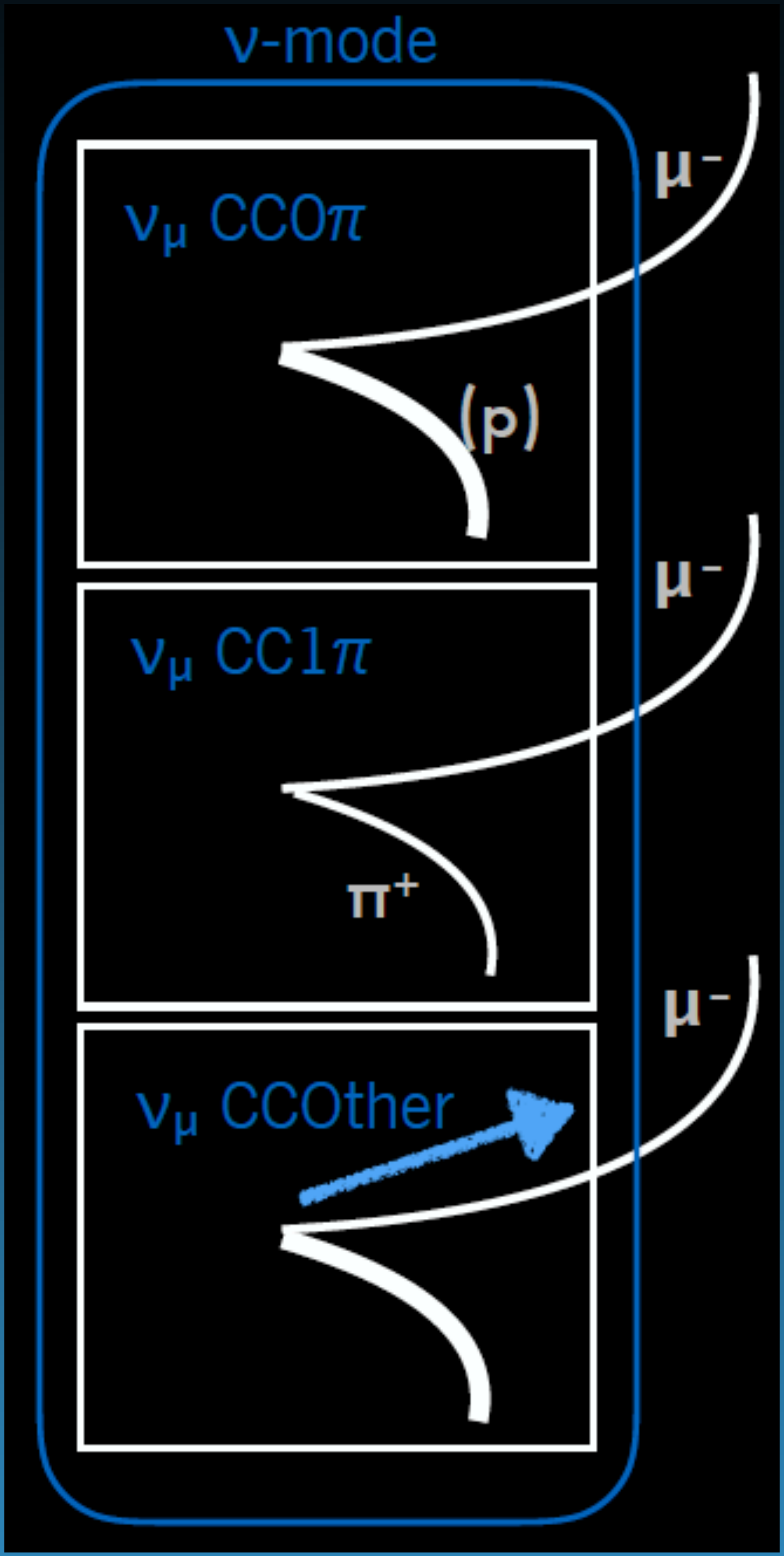
- A priori prediction of unoscillated flux at Super-Kamiokande
- Uses hadron production data from NA61/SHINE
- Hadron production uncertainties still dominate — but new NA61 replica target data will improve this soon
- Absolute flux errors are <10% over most neutrino energies
- Use near detector constraint to improve event rate prediction at SK further



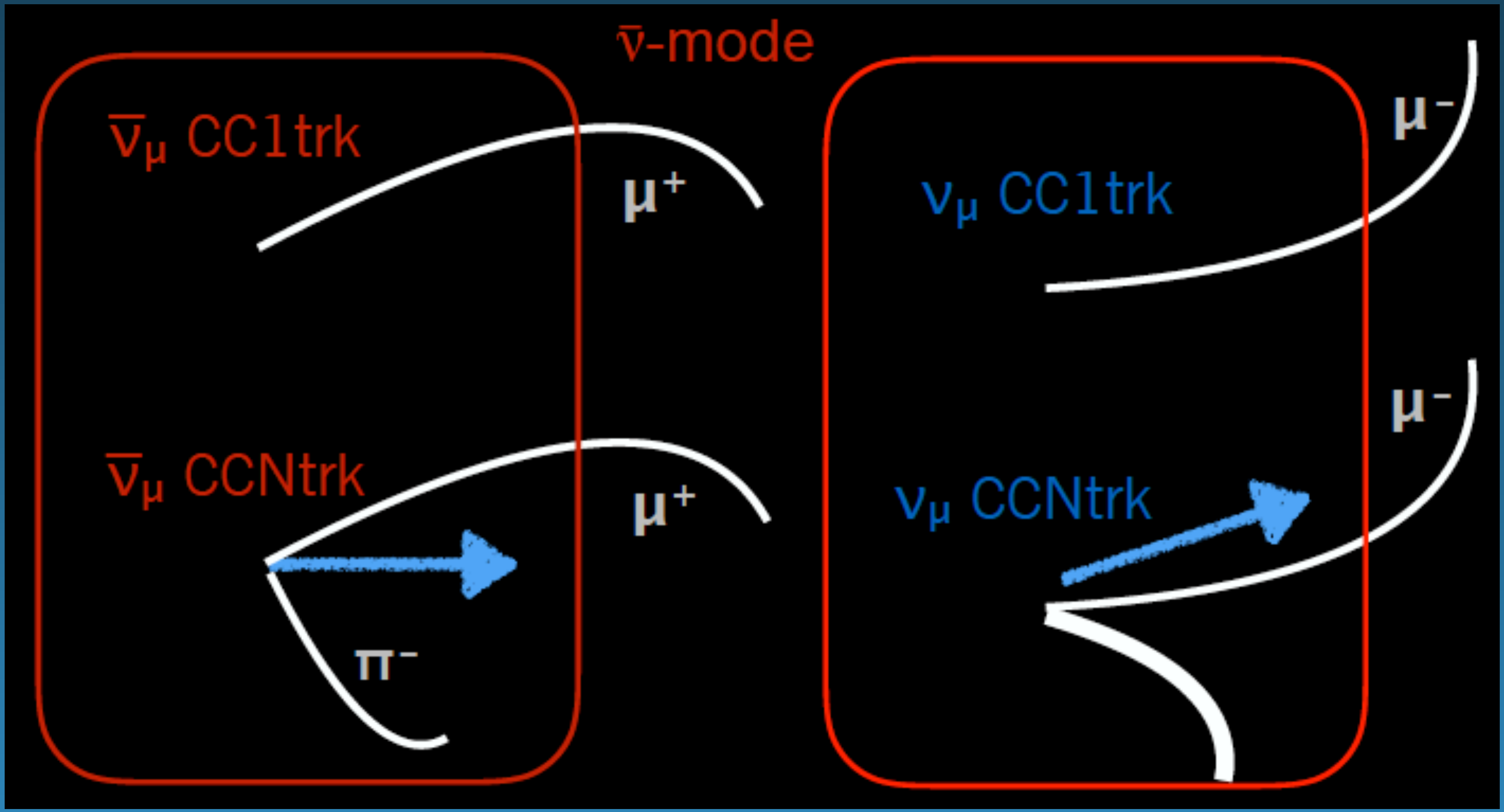




NEAR DETECTOR SAMPLES USED IN OSCILLATION FIT

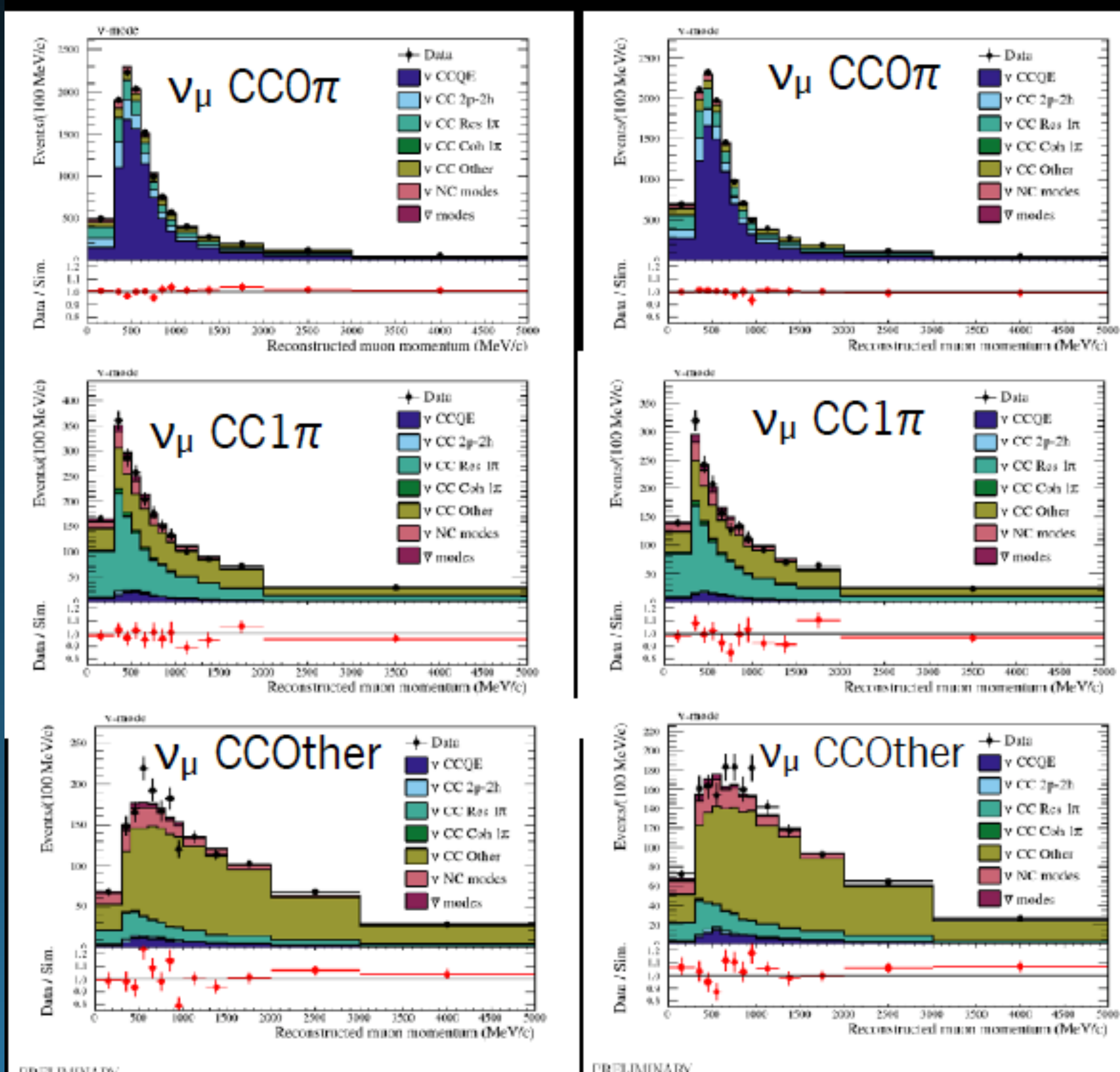


- 14 total samples
- Neutrino mode: sort by pion multiplicity; Carbon and Oxygen fine-grained detectors
- Antineutrino mode: sort by muon charge and number of tracks; C and O fine-grained detectors
- Wrong-sign backgrounds constrained with ND280 magnetic field



ND280 DATA USED FOR OSCILLATION FIT

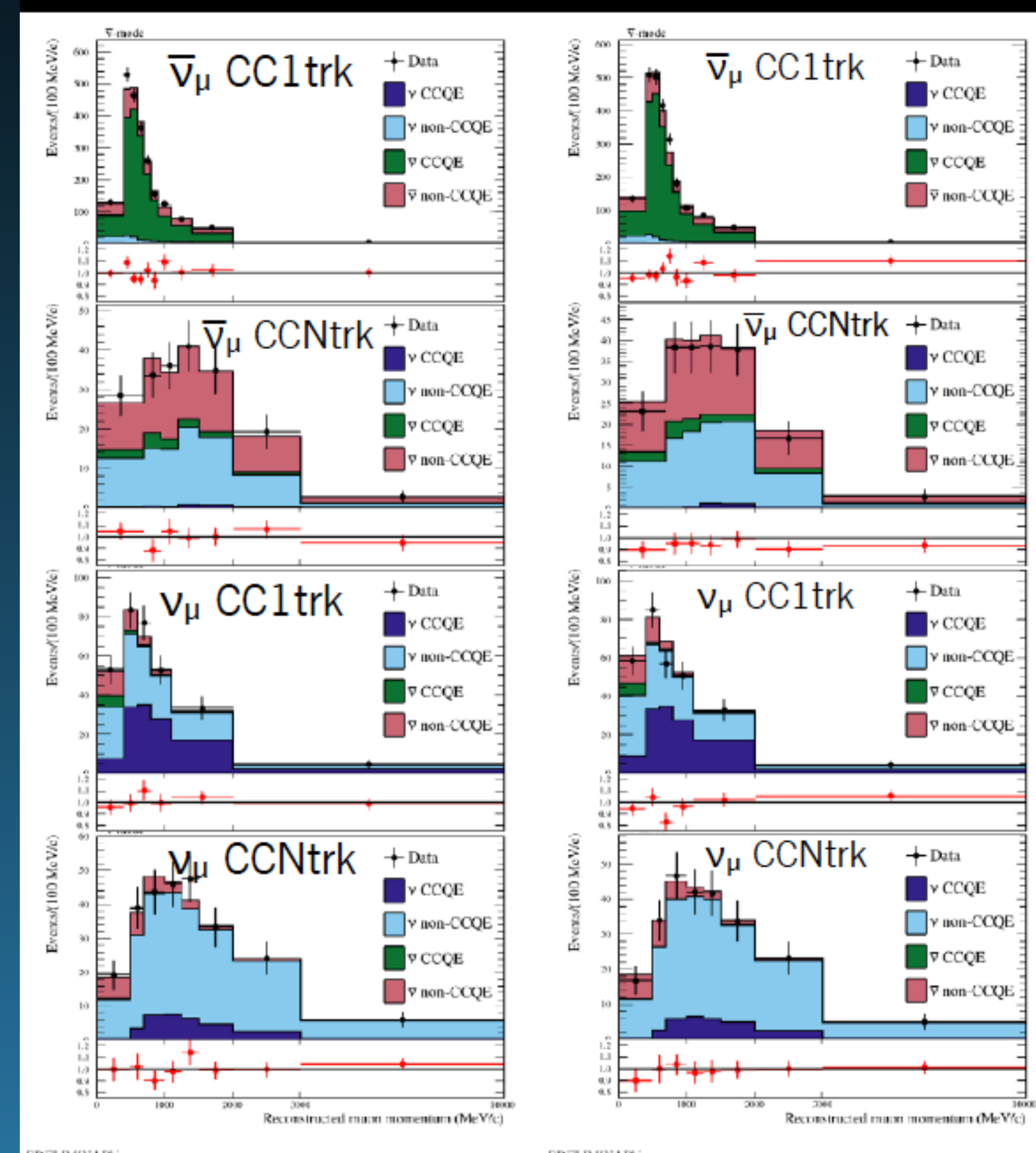
ν-mode



FGD1
(carbon)

FGD2
(carbon & oxygen)

ν̄-mode

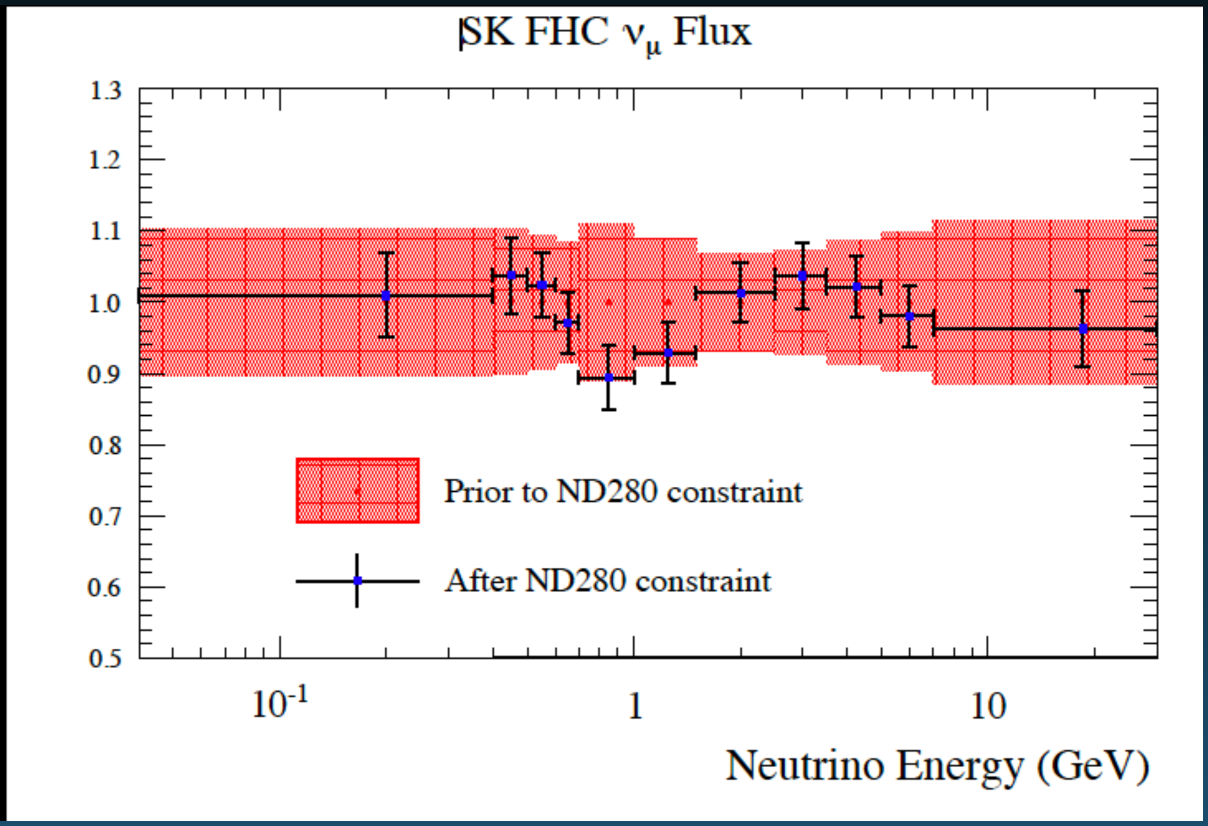


FGD1
(carbon)

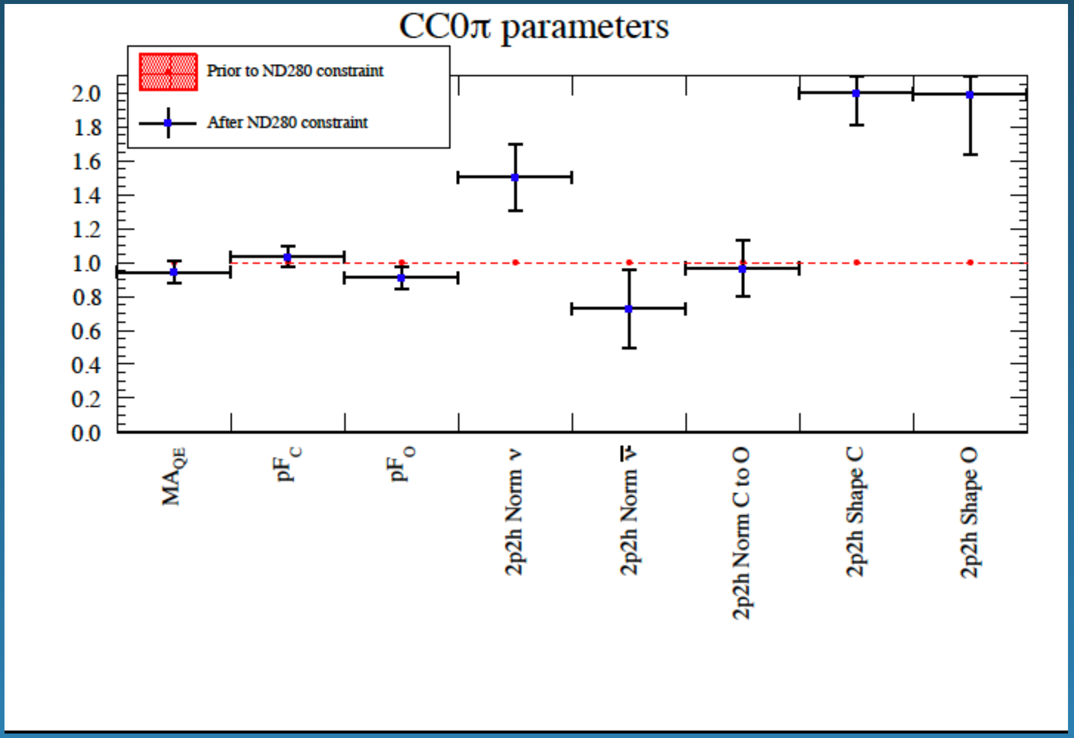
FGD2
(carbon & oxygen)

FITTING THE ND280 DATA

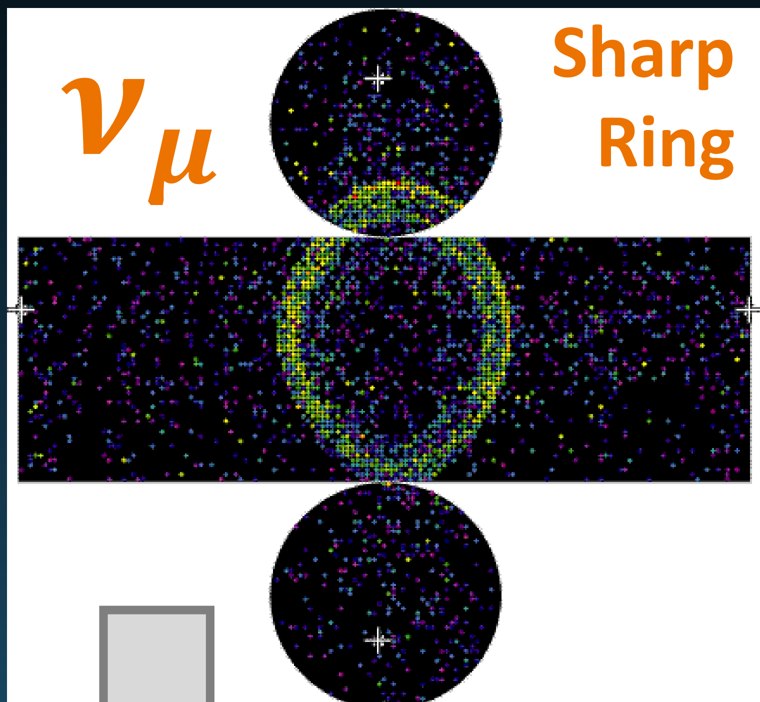
- Fitted flux and cross-section parameters vs. pre-fit (shown for one sample and channel only: ν_μ CC0π)
- Note improvement in flux error; higher 2p2h (scattering off correlated nucleon pairs) vs raw model by Nieves et al
- Data fit result reduces error on SK event rate predictions to about 5-9% depending on channel

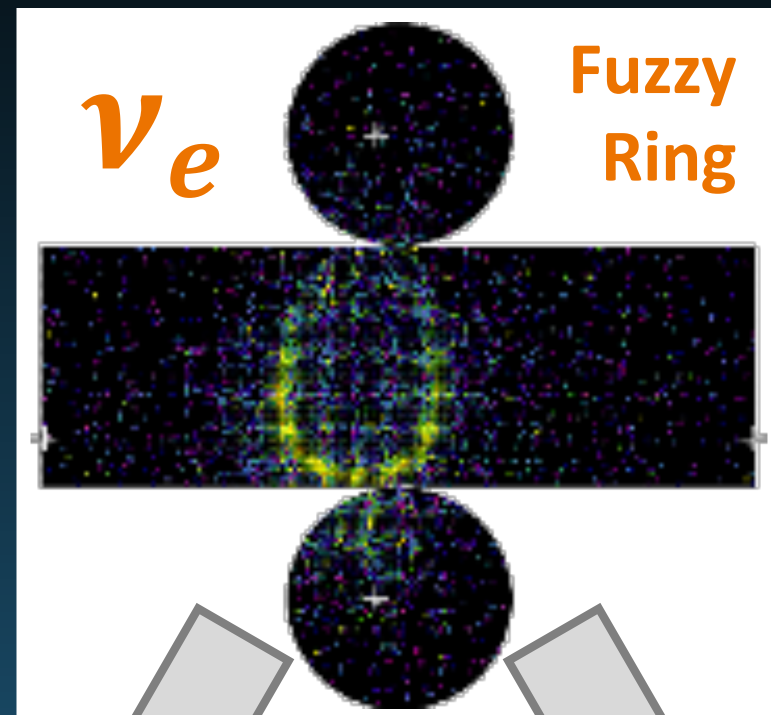


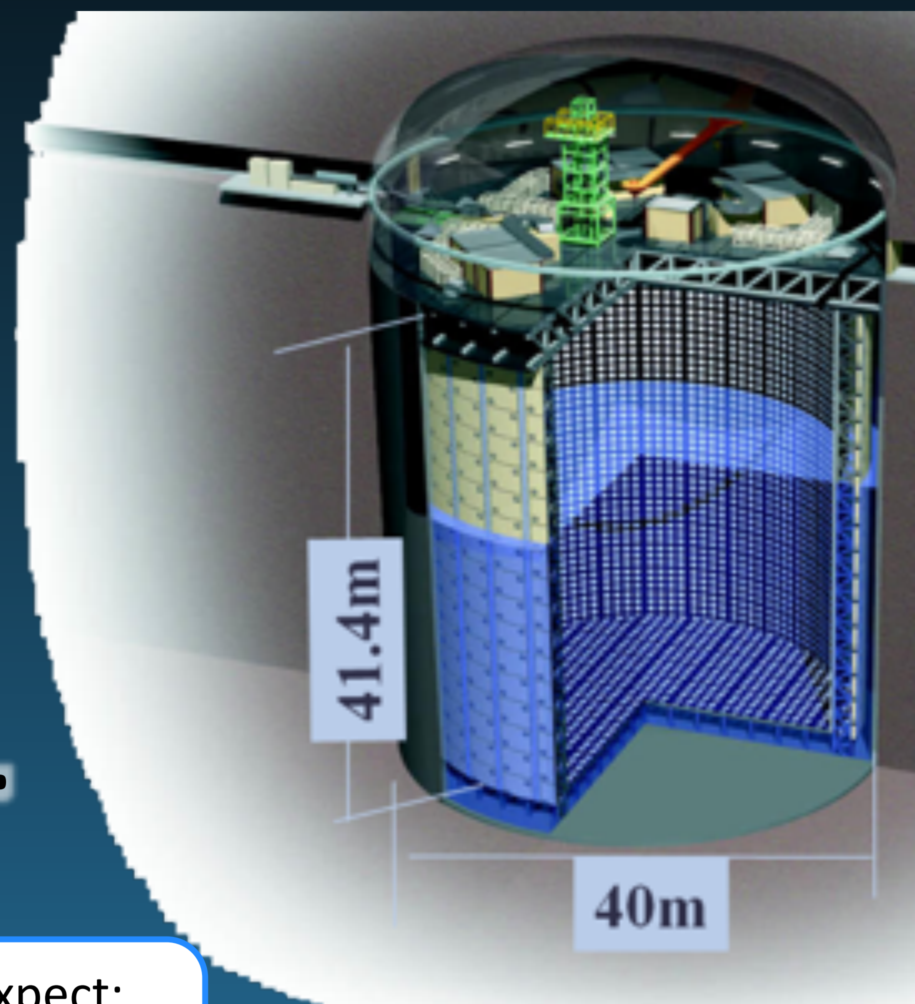
Error source	1-ring μ-like		1-ring e-like			
	ν-mode	ν̄-mode	ν-mode	ν̄-mode	ν-mode CC1π	$\nu_e/\bar{\nu}_e$
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\nu_\mu)$	0	0	2.63	1.46	2.62	3.03
NC1γ	0	0	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93



SUPER-KAMIOKANDE SAMPLES







1R-μ

FHC sample, expect:
$94\%+6\%\ \nu_\mu + \bar{\nu}_\mu$

RHC sample, expect:
$60\%+40\%\ \bar{\nu}_\mu + \nu_\mu$

1R-e

FHC sample, expect:
$81\%\ (\nu_\mu \to)\nu_e$,
18% beam $\nu_e + \nu_\mu$

RHC sample, expect:
$45\%\ (\bar{\nu}_\mu \to)\ \bar{\nu}_e$,
$10\%\ (\nu_\mu \to)\ \nu_e$

1R-e + d.e.

FHC sample, expect:
$79\%\ (\nu_\mu \to)\nu_e$,
21% beam $\nu_e + \nu_\mu$

New! Sample added with delayed-coincidence Michel electron (tags low momentum pion in FHC)

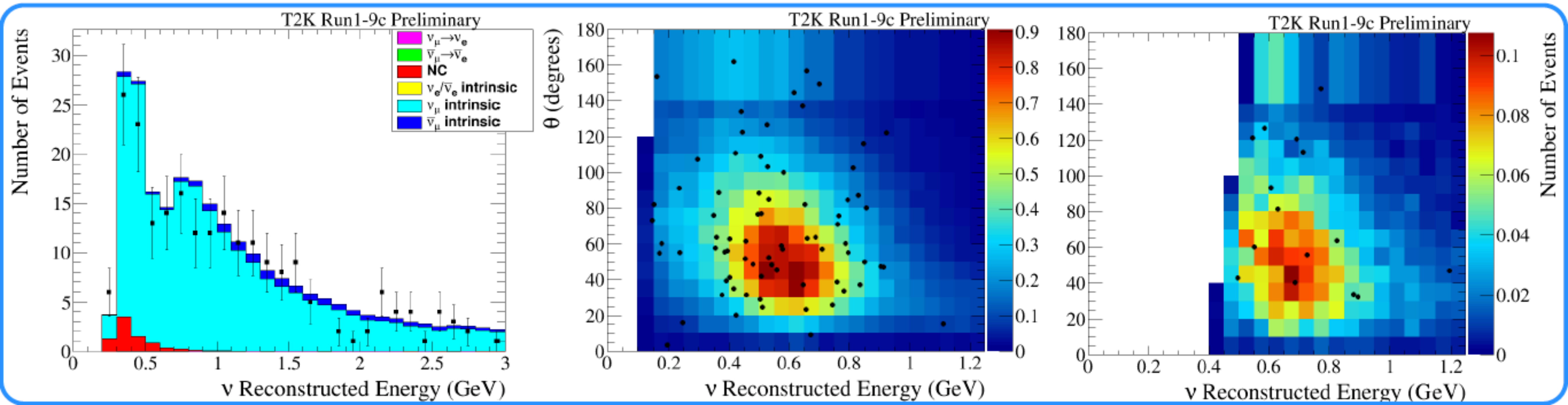
Pion collection & focussing depends on Horn Current

Forward Horn Current (FHC): $\pi^+ \to \mu^+ + \nu_\mu$

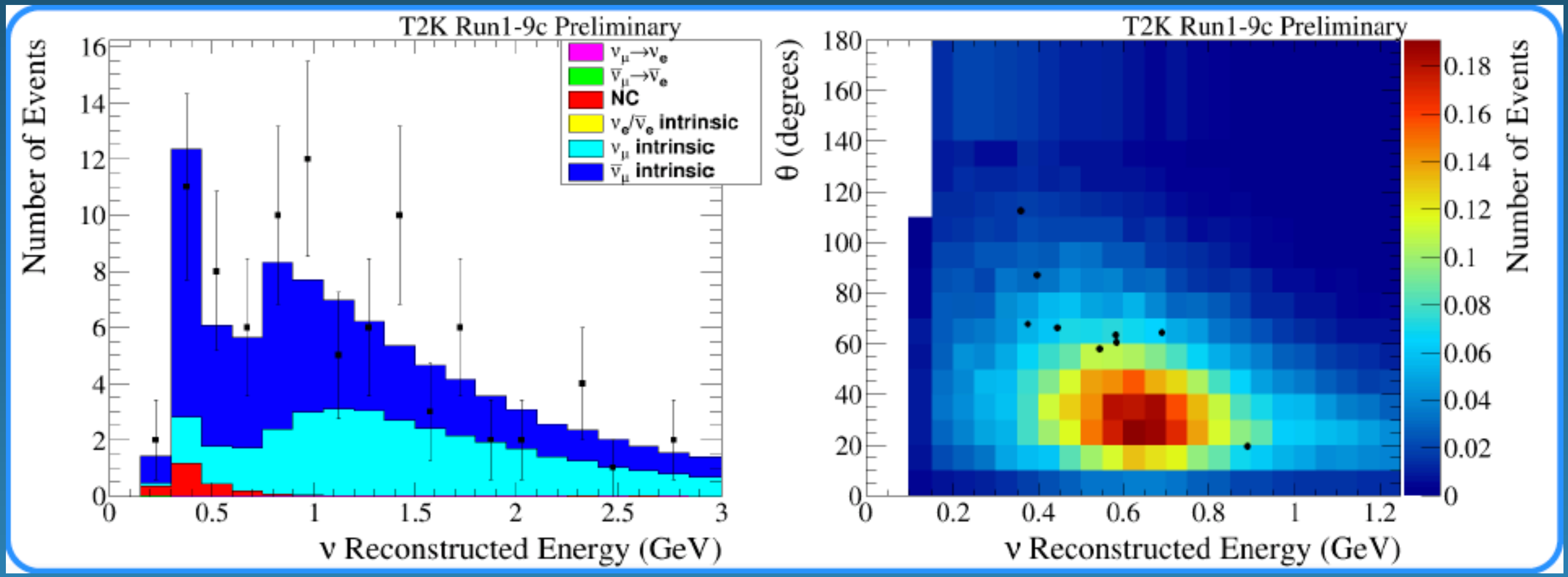
Reverse Horn Current (RHC): $\pi^- \to \mu^- + \bar{\nu}$

SUPER-KAMIOKANDE EVENT DISTRIBUTION

FHC 1R(ing)-μ 1R-e 1Re+ decay e+



RHC 1R-μ 1R-e;



SUMMER 2018 RESULTS – EVENTS RATES

Sample	Expectation, $\sin^2\theta_{23} = 0.528$, $\delta =$ $-\pi/2$	0	π	$+\pi/2$	Observed
FHC 1R-μ	268.5	268.2	268.9	268.9	**243**
RHC 1R-μ	95.5	95.3	95.8	95.5	**102**
Sum of 1R-μ	*364.0*	*363.5*	*364.7*	*364.5*	***345***
FHC 1R-e	73.8	61.6	62.2	50.0	**75**
FHC 1R$-e$ +d.e.	6.9	6.0	5.8	4.9	**15**
RHC 1R-e	11.8	13.4	13.2	14.9	**9**

See fewer ν_μ like events than expected,
⇒ fit will prefer maximal disappearance

See more ν_e and fewer $\bar{\nu}_e$ than expected, even for $\delta = -{}^{\pi}/_{2}$
⇒ fit will have a strong preference for CP-violation that enhances neutrino rates

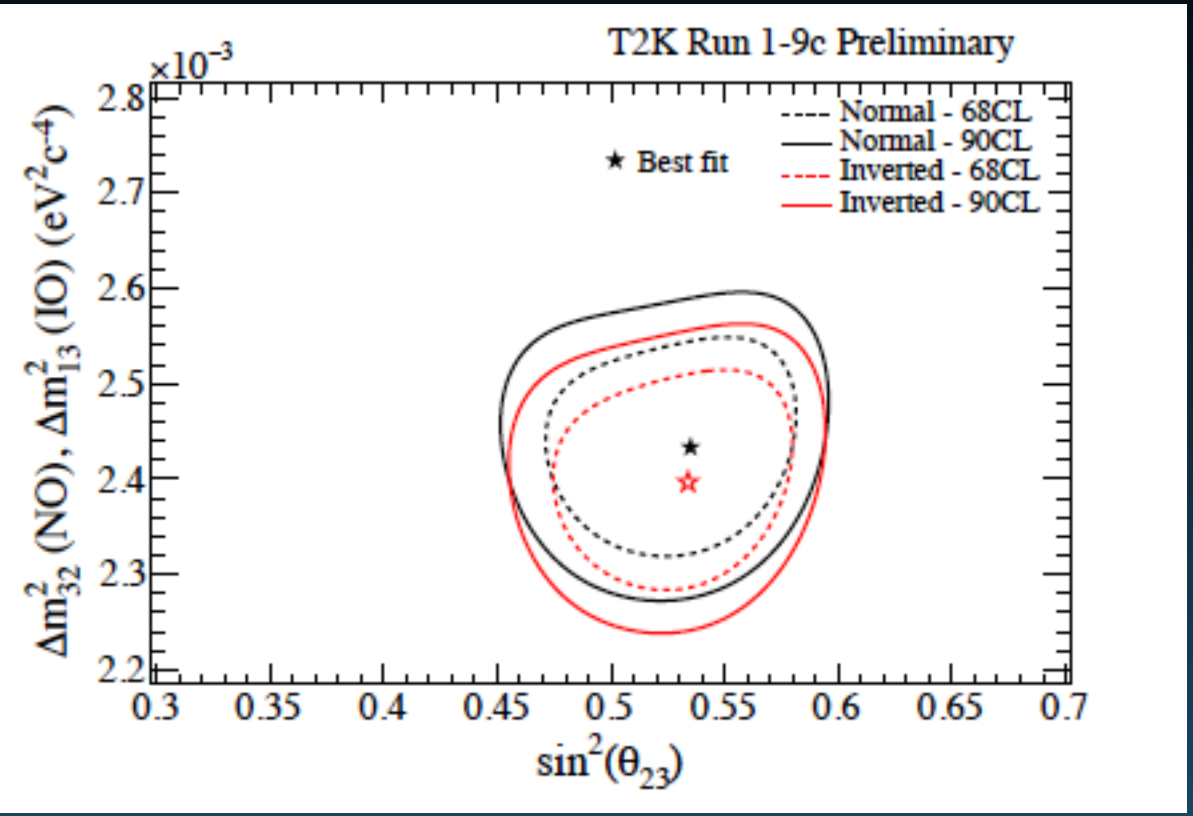
- Excess in d.e. sample has p~1%, but does not have big impact on fit

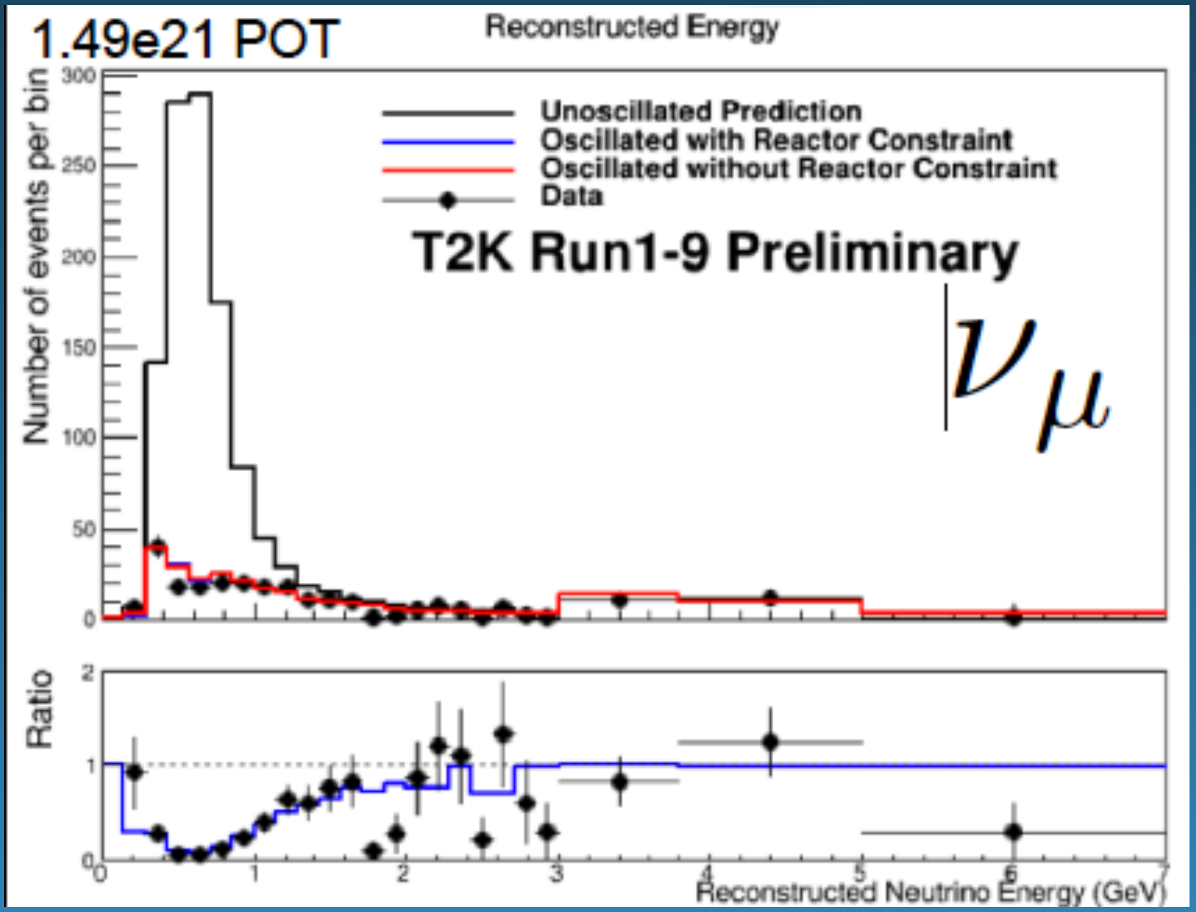
SUMMER 2018 RESULTS: θ_{23} AND ΔM^2_{32} MEASUREMENT

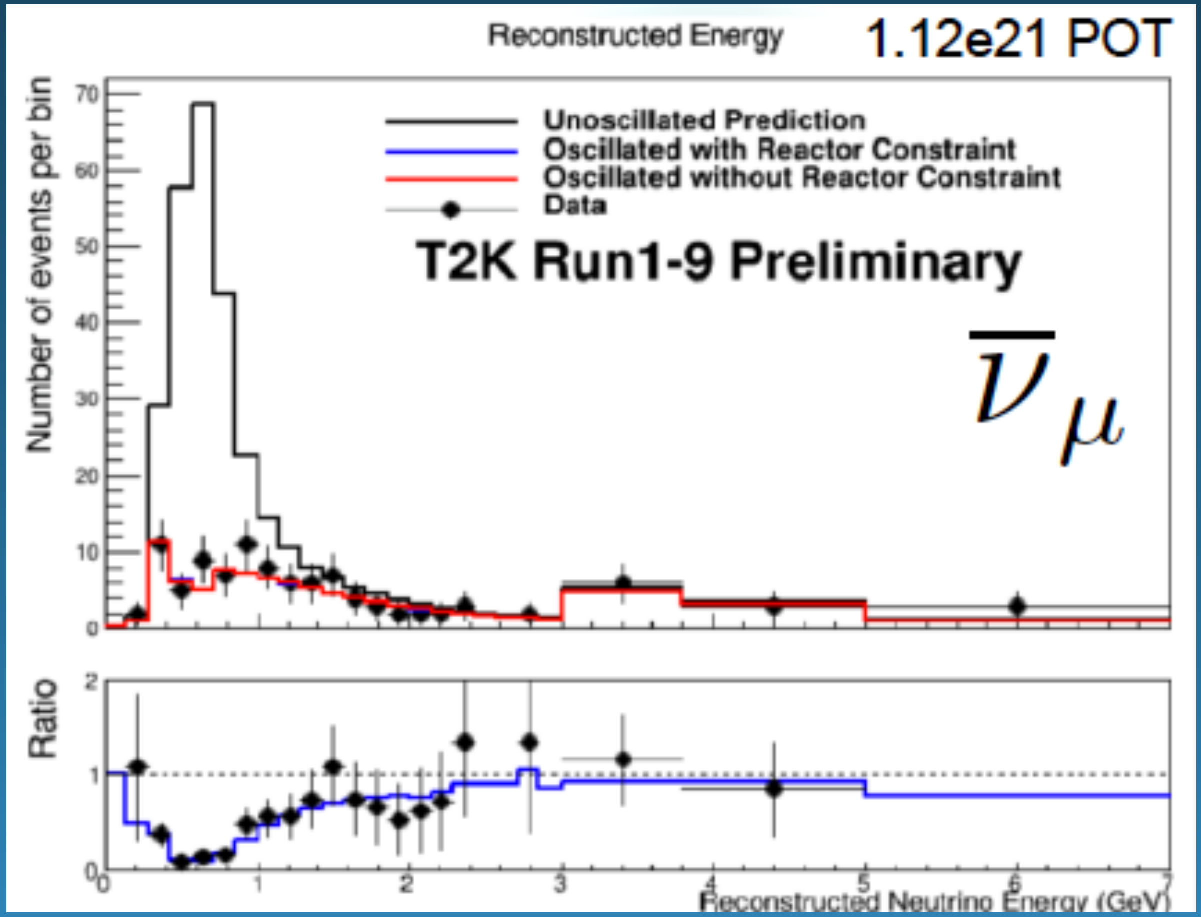
Parameter fit with reactor constraint

Consistent with maximal mixing (θ=45°)

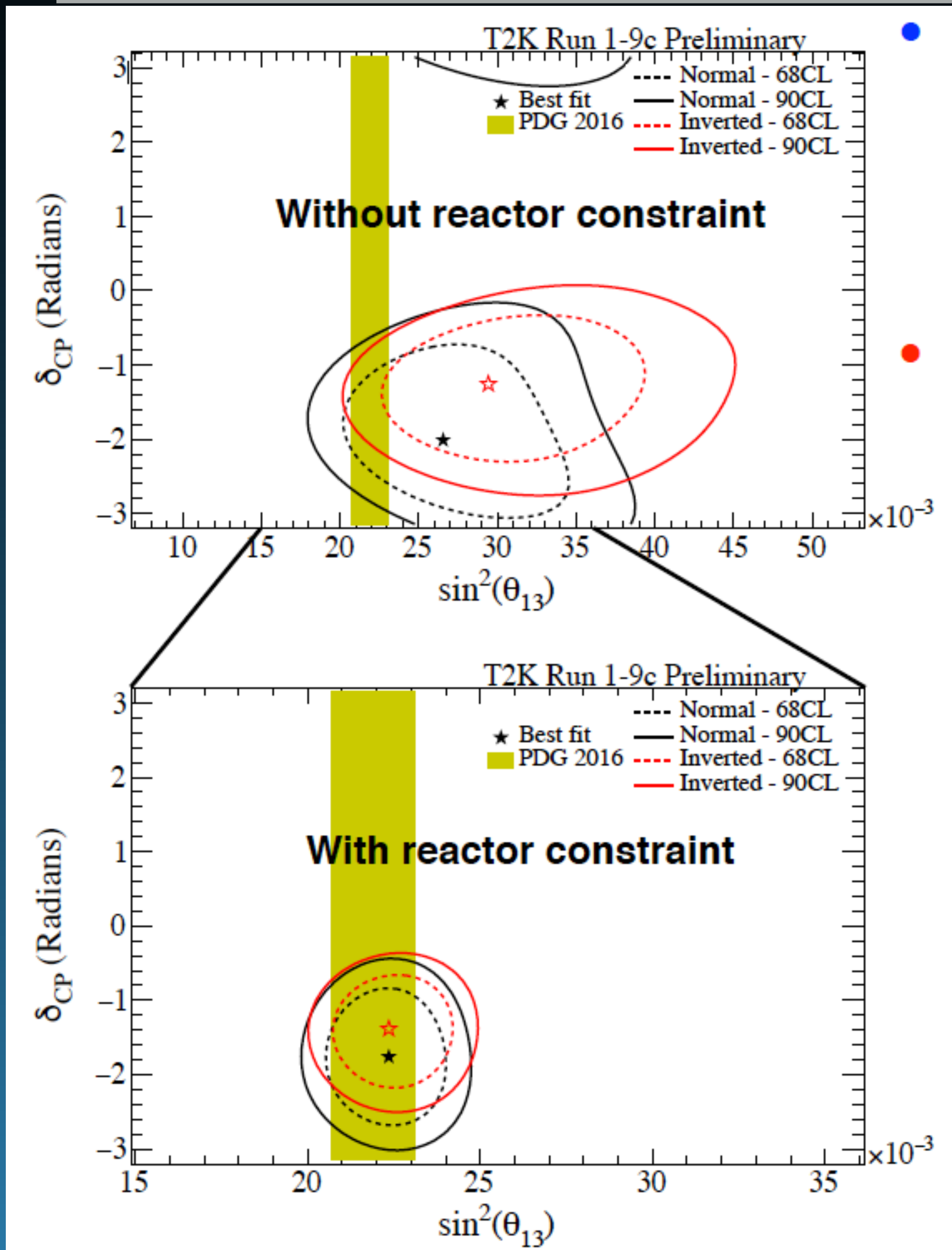
	NH ($\Delta m^2_{32}>0$)	IH ($\Delta m^2_{32}<0$)
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2_{32}\rvert$ (10^{-3} eV^2/c^4)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

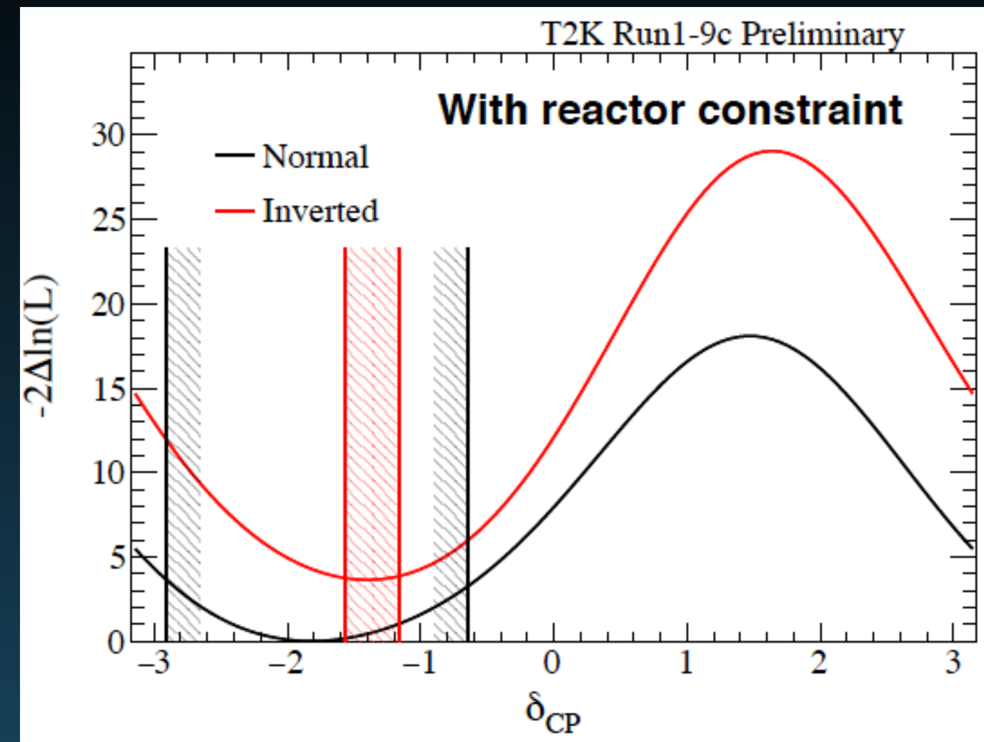






SUMMER 2018 RESULTS: CONSTRAINT ON δ_{CP}

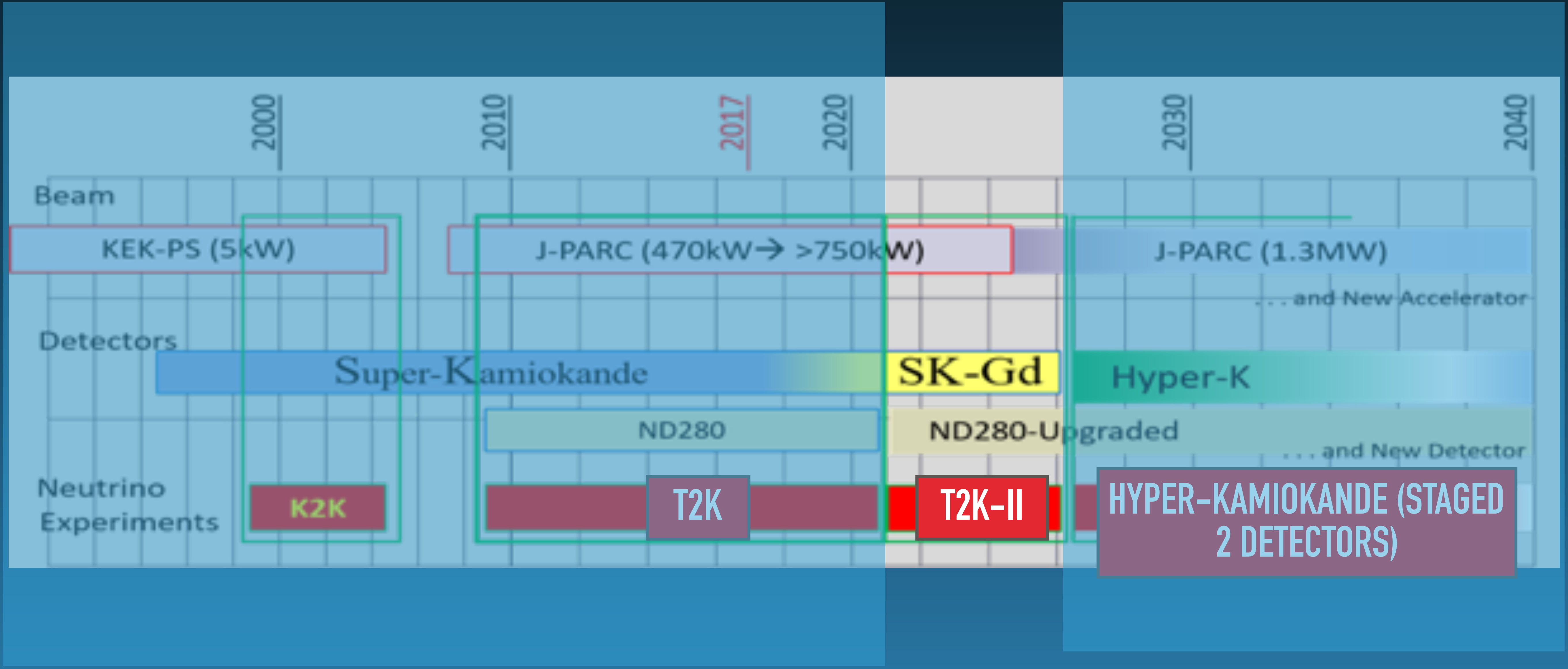




- **Binned-likelihood oscillation fits to all far-detector samples simultaneously.**
- Two oscillation fits: 1) T2K-only 2)T2K+2016 PDG reactor data as constraint
- 2σ interval calculated w/ Feldman&Cousins
- **CP conserving values (0, ±π) outside of 2σ region for both hierarchies**

Mass ordering	Best fit δ_{CP}	2σ interval
Normal	-1.82 (-0.58π)	$[-2.91,\ -0.64]$
Inverted	-1.38 (-0.44π)	$[-1.57,\ -1.16]$

T2K-II


2000
2010
2017
2020
2030
2040
Beam
KEK-PS (5kW)
J-PARC (470kW→ >750kW)
J-PARC (1.3MW)
. . . and New Accelerator
Detectors
Super-Kamiokande
SK-Gd
Hyper-K
ND280
ND280-Upgraded
. . . and New Detector
Neutrino Experiments
K2K
T2K
T2K-II
HYPER-KAMIOKANDE (STAGED 2 DETECTORS)

SECOND PHASE OF T2K (T2K-II)

T2K-II aims to reach a >3σ sensitivity for CP violation if near current best fit

Extension of T2K run (approved 7.8x10^{21} POT) to 20 x 10^{21} POT

T2K upgrade details:

- Beamline upgrade toward 1.3 MW beam power
- Near Detector upgrade to achieve a systematic error improvement 6% → 4%
- Analysis improvement (enlarging fiducial volume and ν_e CC1π sample)

BEAM UPGRADE FOR T2K-II

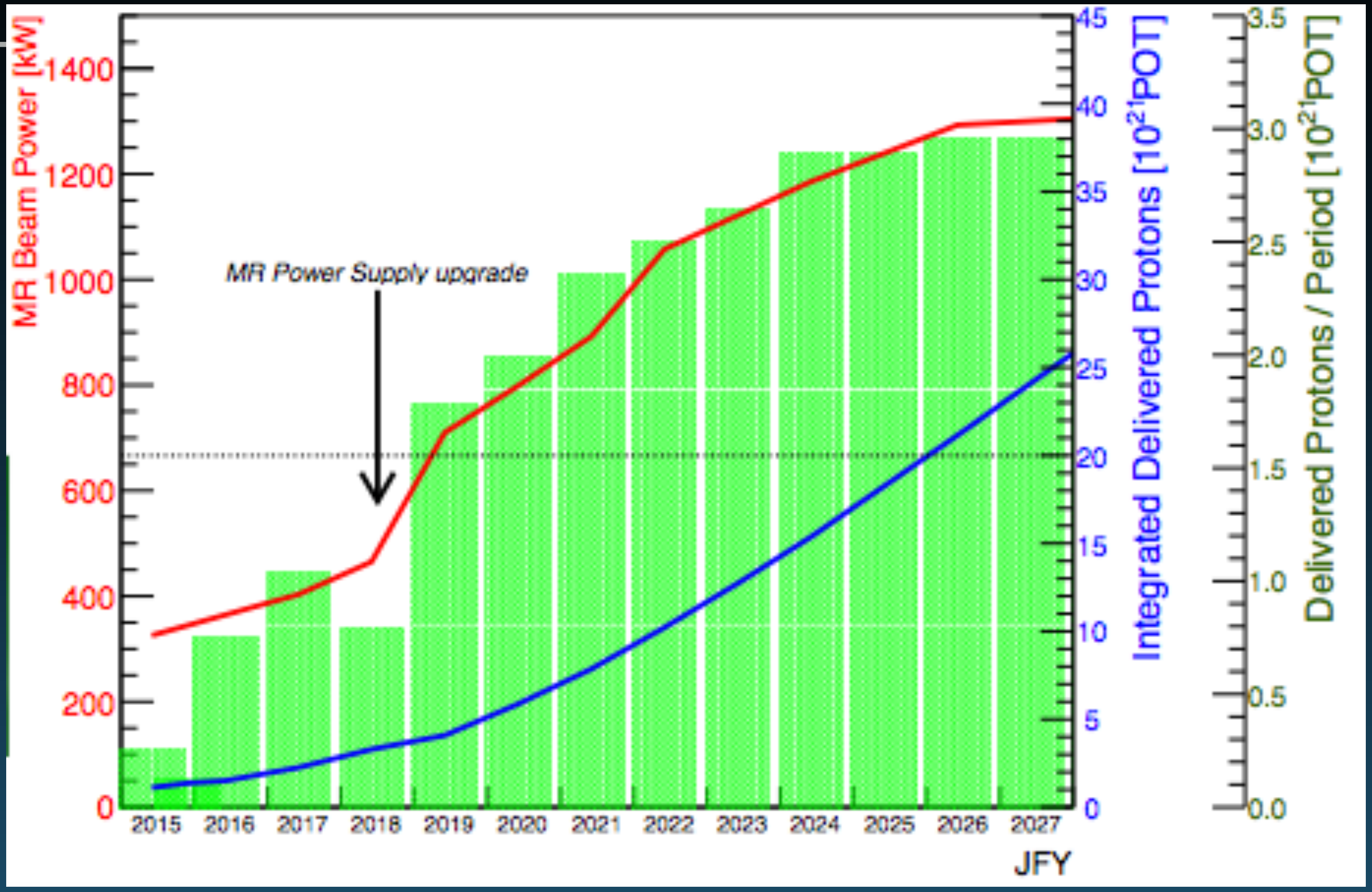
- **Beam power to reach 1.3 MW**
- Strategy

Beam Power (kW)	485 (Achieved)	(940)	1,300 (Goal for T2K-II)
#p/p(10^{12})	250	250	320
Rep T (s)	2.48	1.28	1.16

+25%

Funding started

-10%



Method:

Higher rep rate:

- MR magnet power supply upgrade
- MR RF upgrade (High grad/PS)
- MR Fast Extraction Kicker upgrade

Higher #p/p:

- MR RF upgrade (PS)

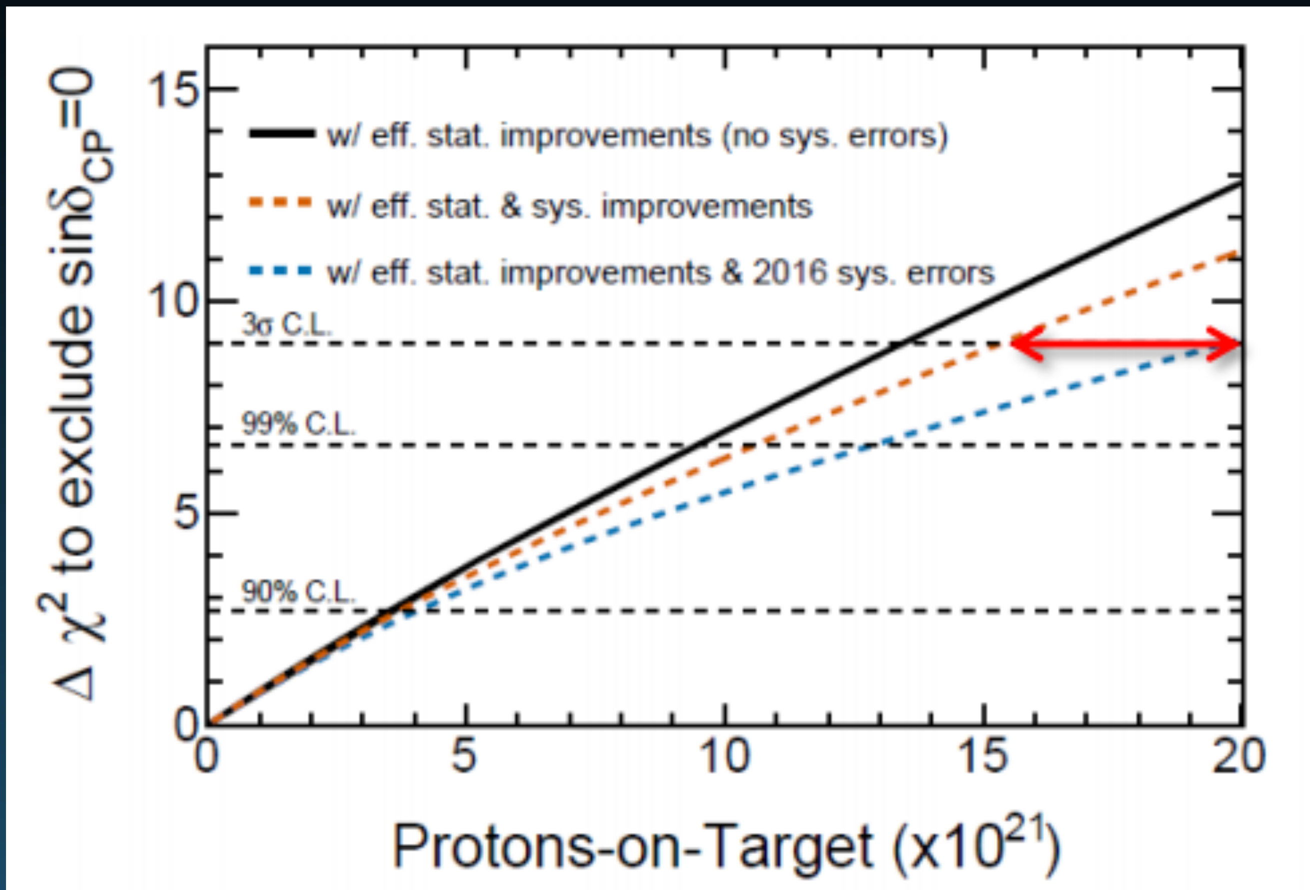
J-PARC plan to upgrade to 750kW and then 1.3MW

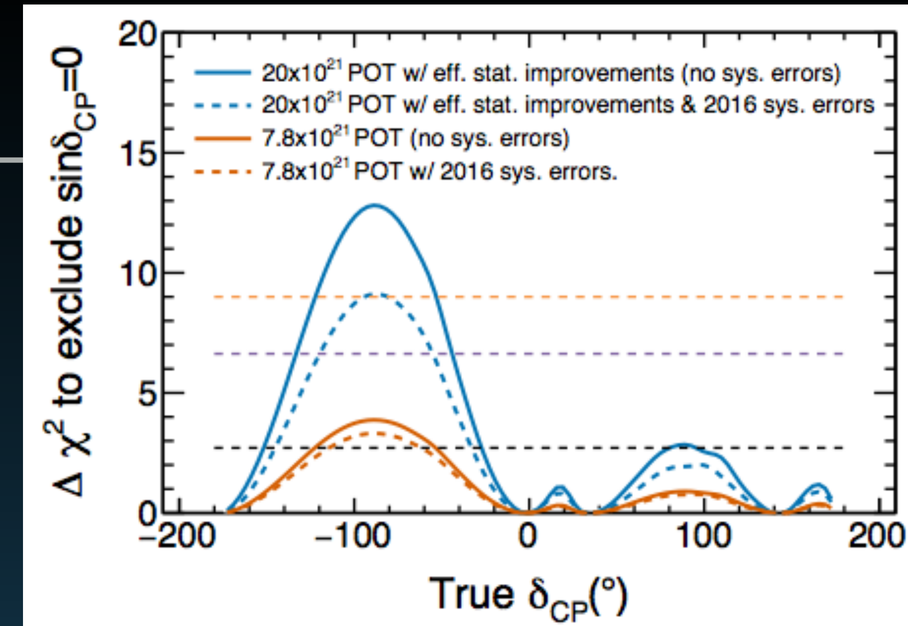
- Funding for 750kW is started (FY2016-)
- Modest upgrade and budget from 750kW to 1.3MW

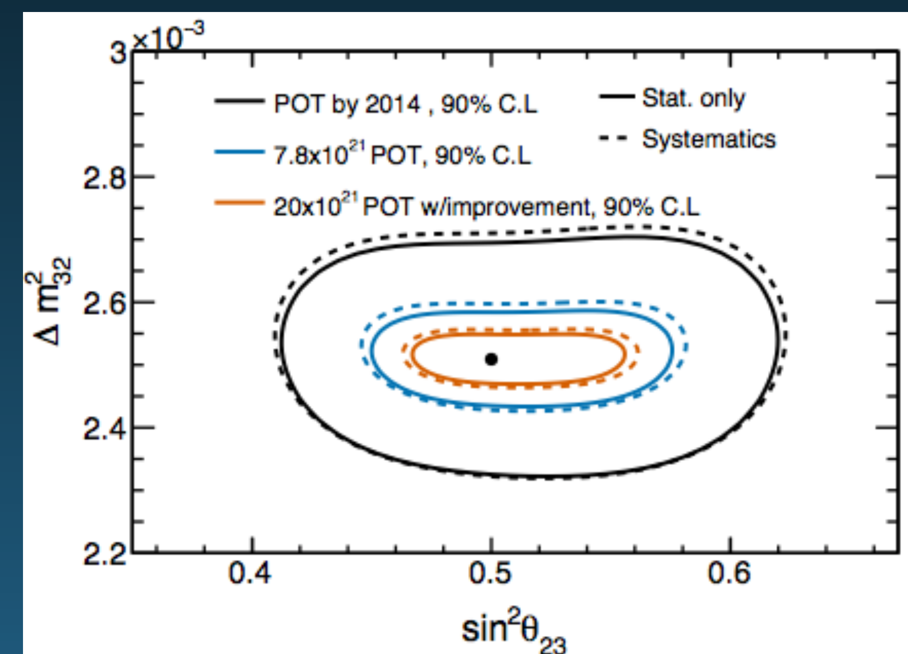
Highest priority project in KEK-PIP

Higher beam power should also be pursued

SECOND PHASE OF T2K (T2K-II)

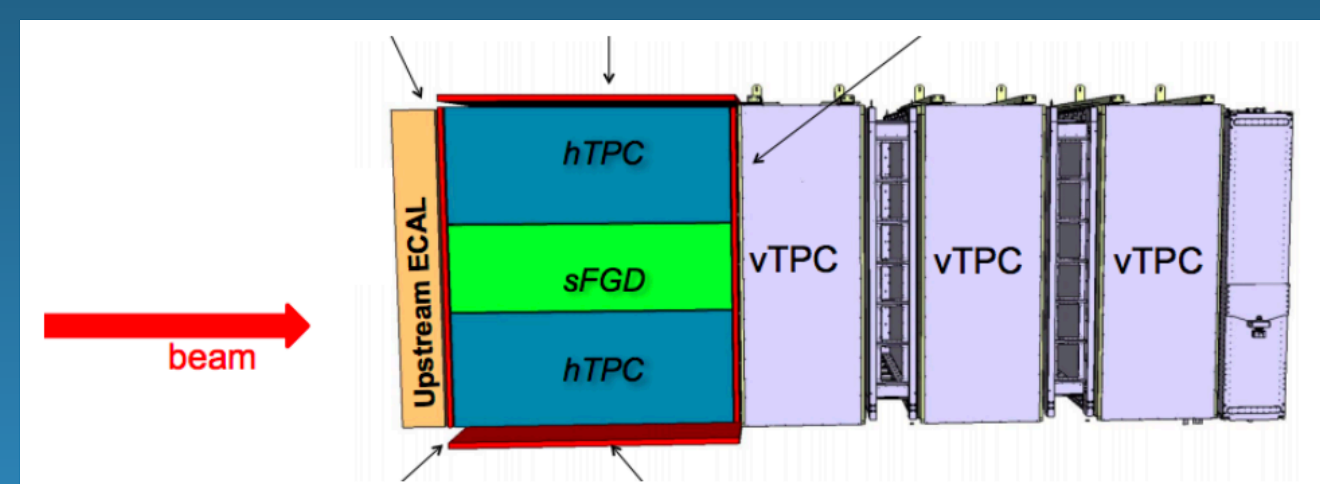






arXiv:1609.04111

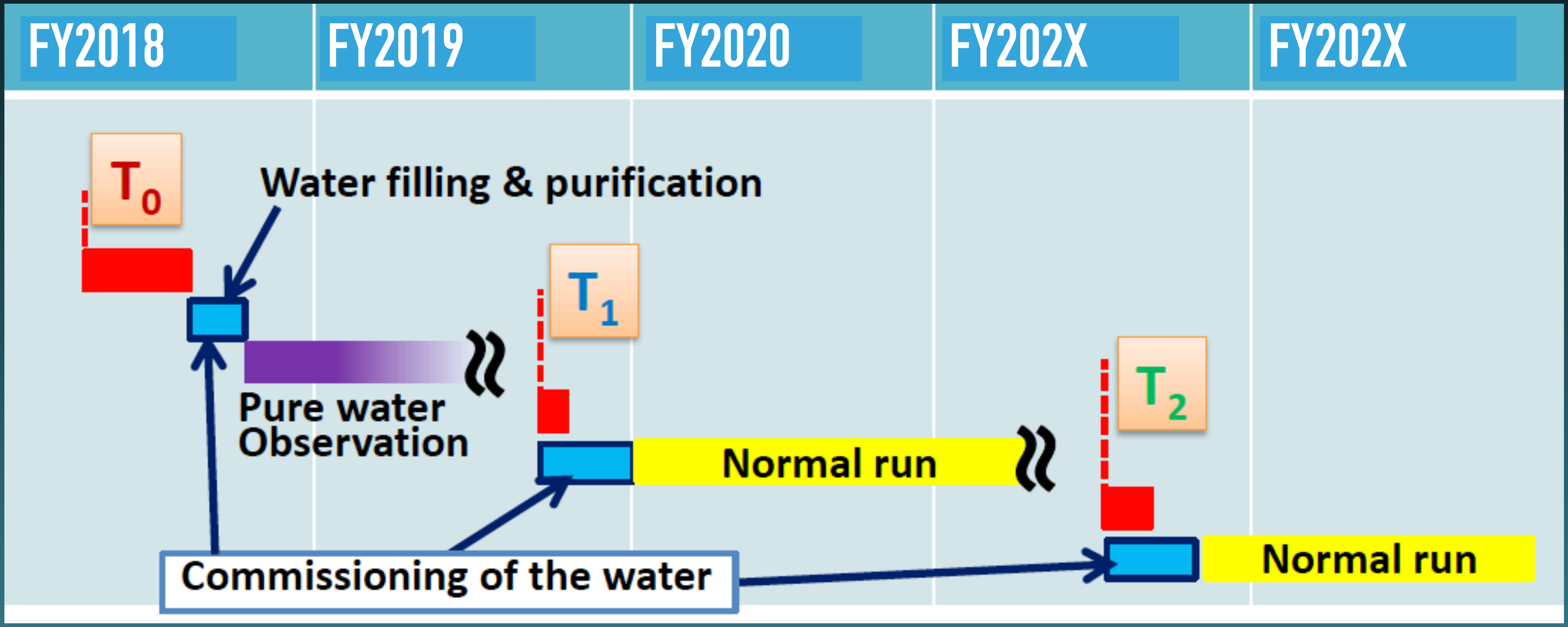
- **T2K-II goal: reduce detector systematics to ~4%** -> improve acceptance, timing, efficiency for short tracks.
- Re-design of the upstream part of ND280
- Down-stream tracker (FGD+TPCs) unchanged



SK-GD

SK-Gd phase:

Add gadolinium (Gd) to enhance neutron tagging efficiency of the SK detector.



T0: Start SK detector refurbishment (**May 31, 2018**)

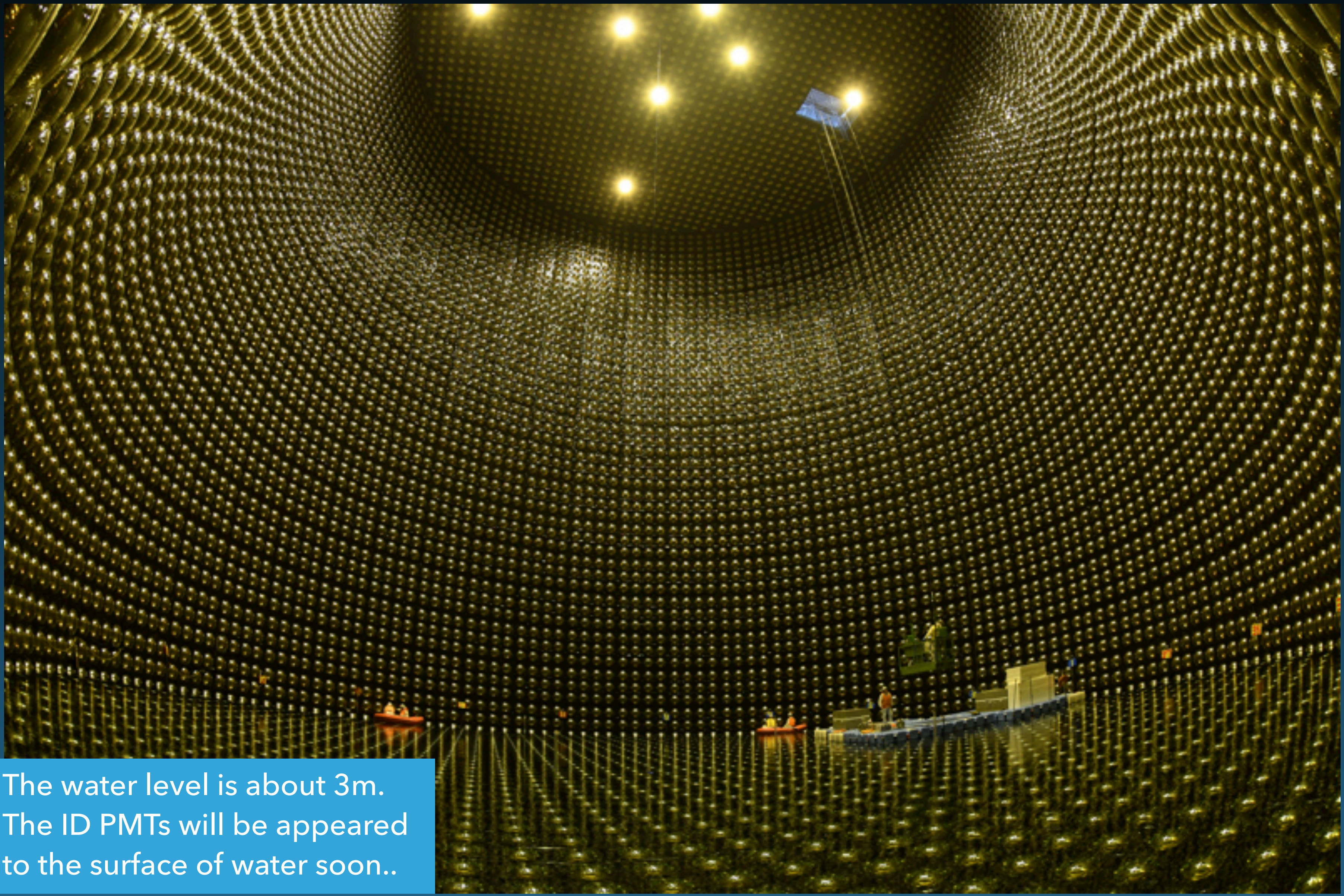
- Jun. ~ Dec. 2018: refurbishment & water filling
- Jan. 2019 ~: pure water run

T1: Load first 10 ton $Gd_2(SO_4)_3$ [0.01% Gd, 50% eff.]

- **First possible T1 is ~2019/2020** (will be decided with T2K/J-PARC ν beam)

T2: Load additional 90 ton $Gd_2(SO_4)_3$[0.1% Gd, 90% eff.]

SK-GD REFURBISHMENT



The water level is about 3m. The ID PMTs will be appeared to the surface of water soon..

Replacement work of inner detector PMTs.

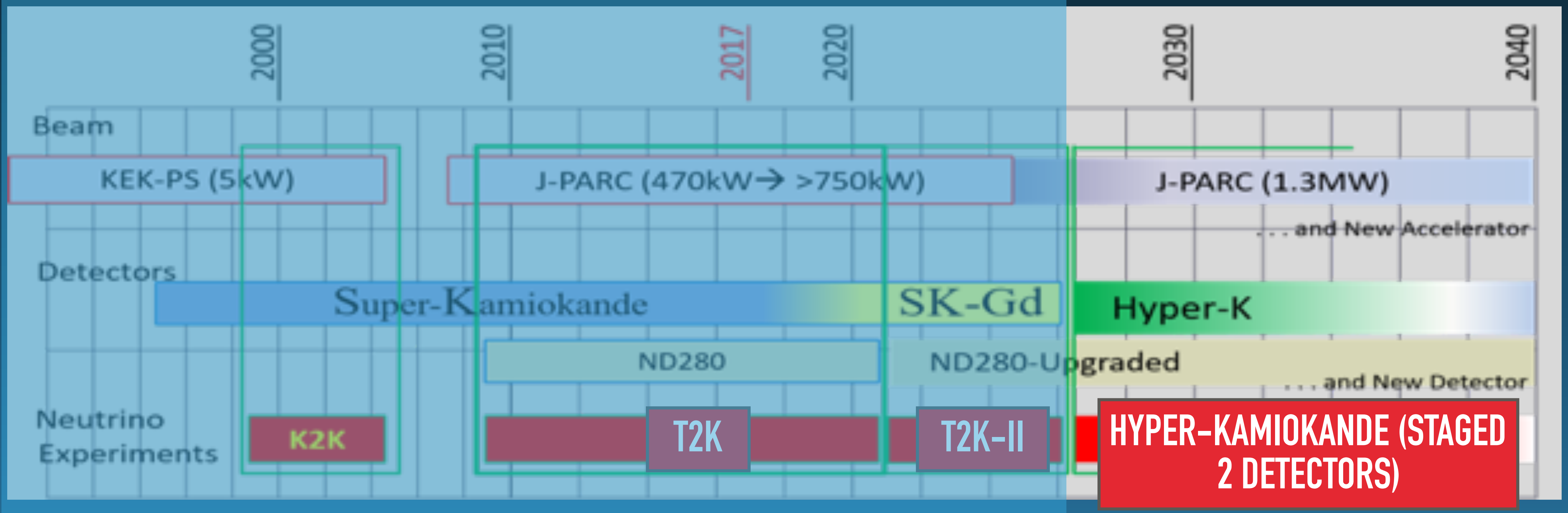
The gondola lift in the inner detector

Measurement of magnetic field in the inner detector.

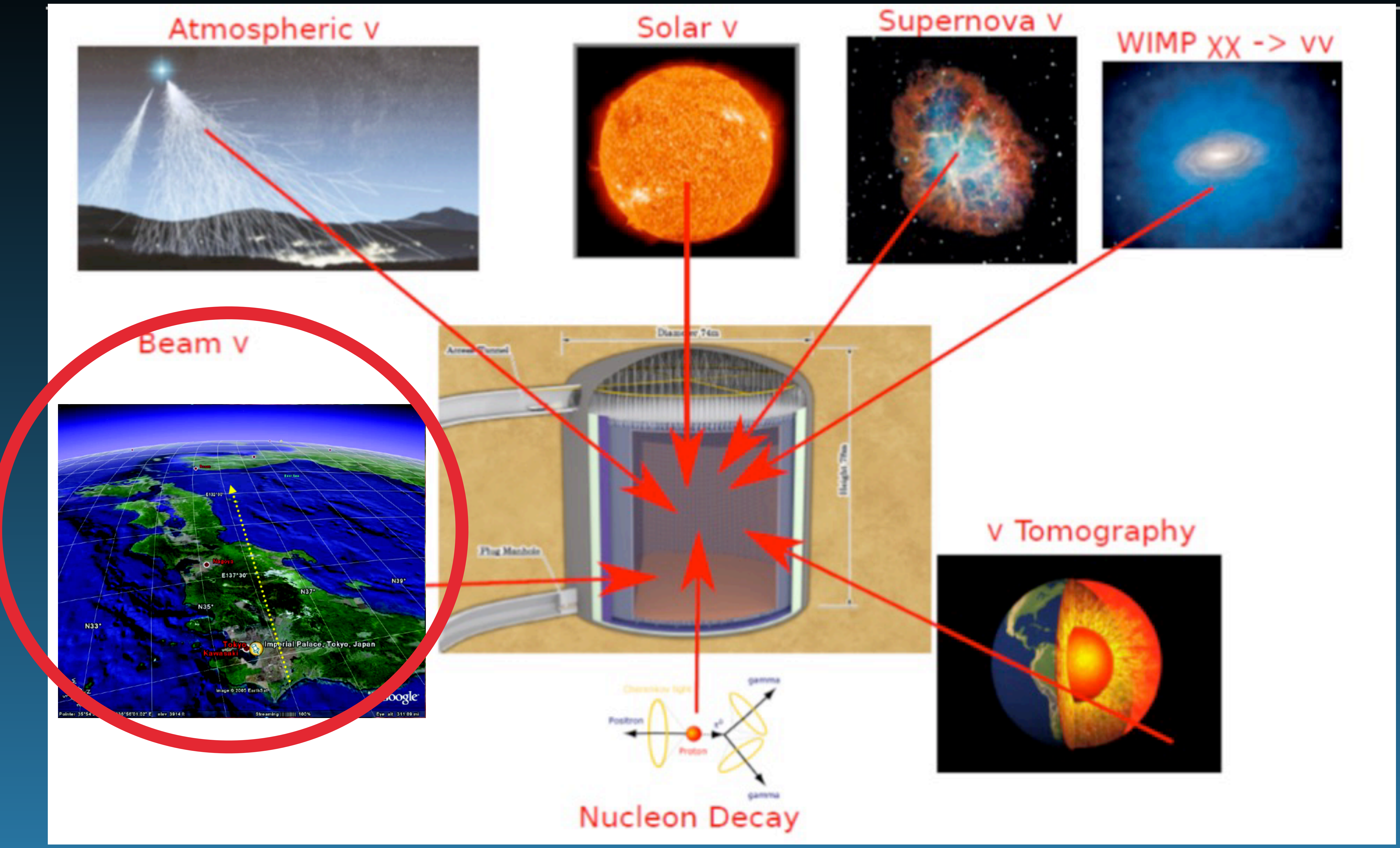
Works in the outer detector. The outer detector is about 2m wide..

All the water of the tank is drained

HYPER-KAMIOKANDE

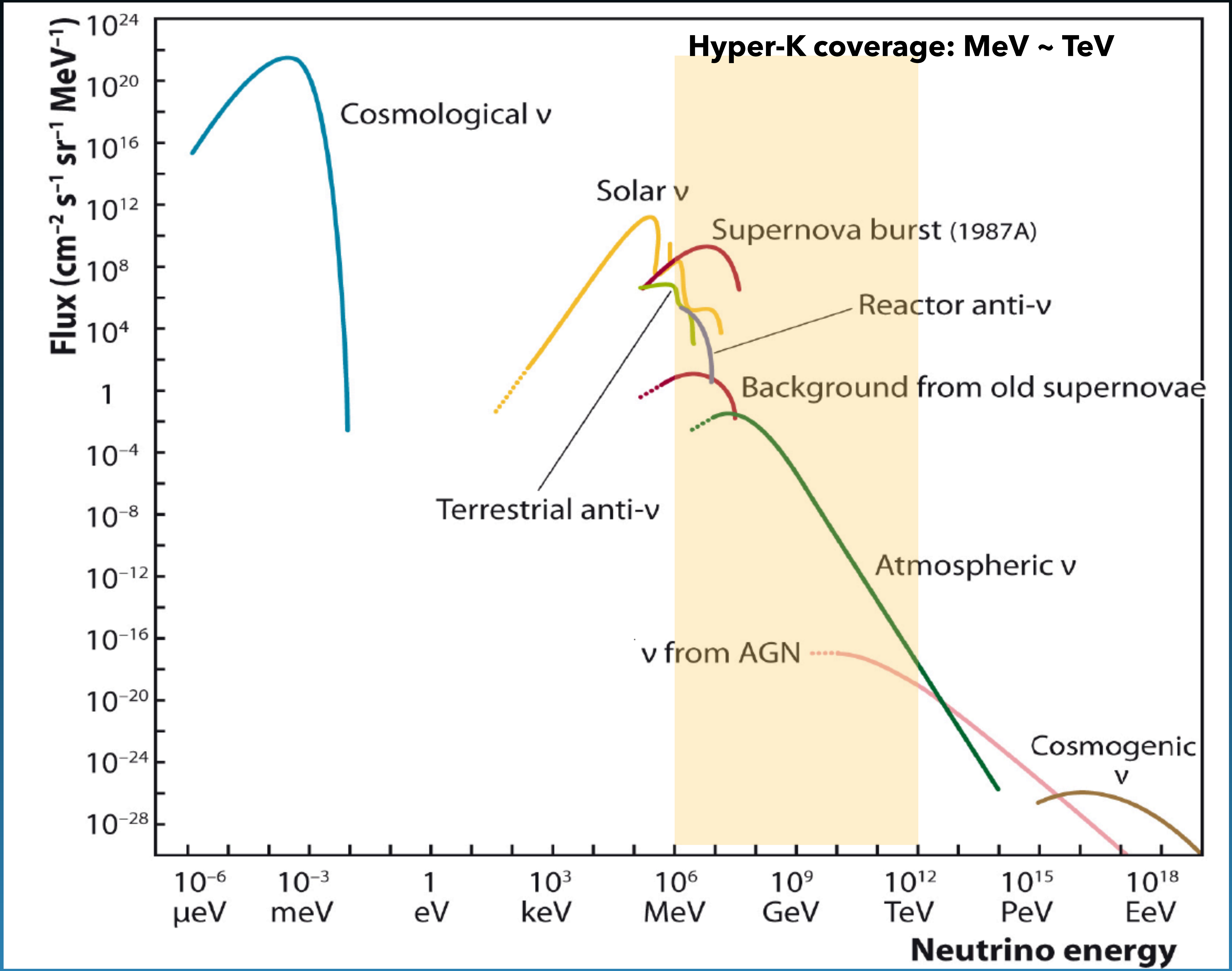


HYPER-KAMIOKANDE: A MULTIPURPOSE EXPERIMENT



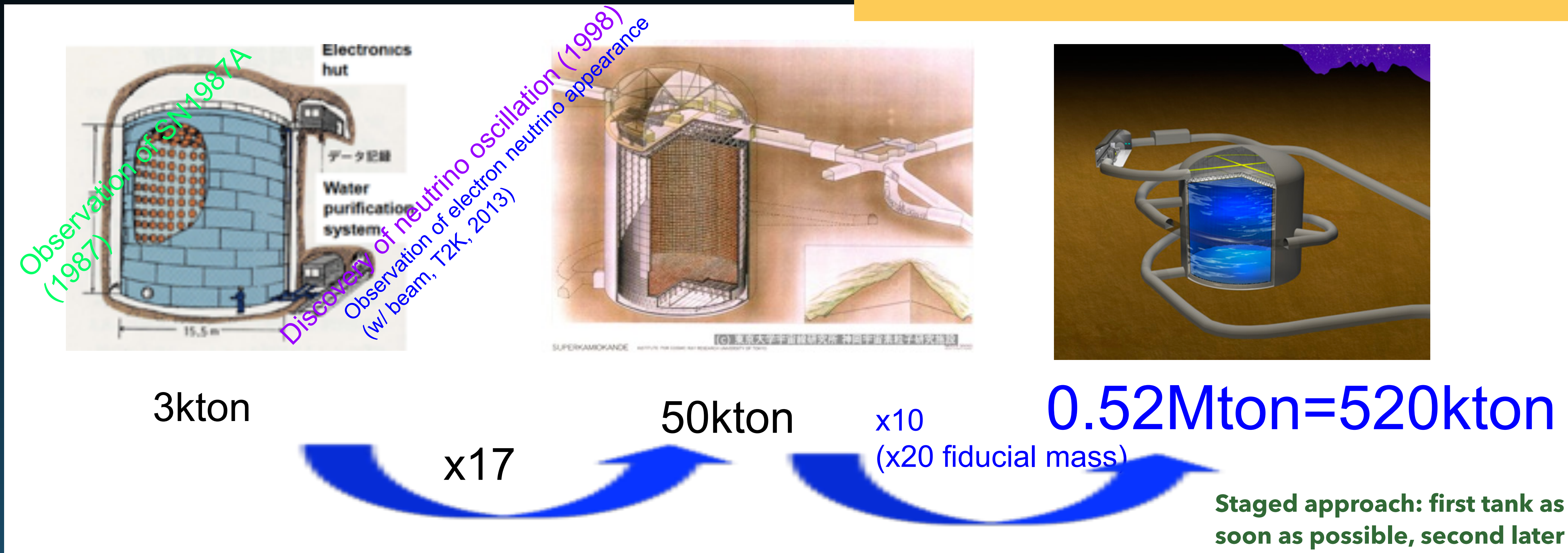
- Excellent capability for a broad area of science.
- Proven technology but very challenging: largest cavern and WC detector in the world
- Full picture of neutrino oscillation with precise measurement of CP and mixing parameters

NEUTRINO SOURCES AND FLUXES



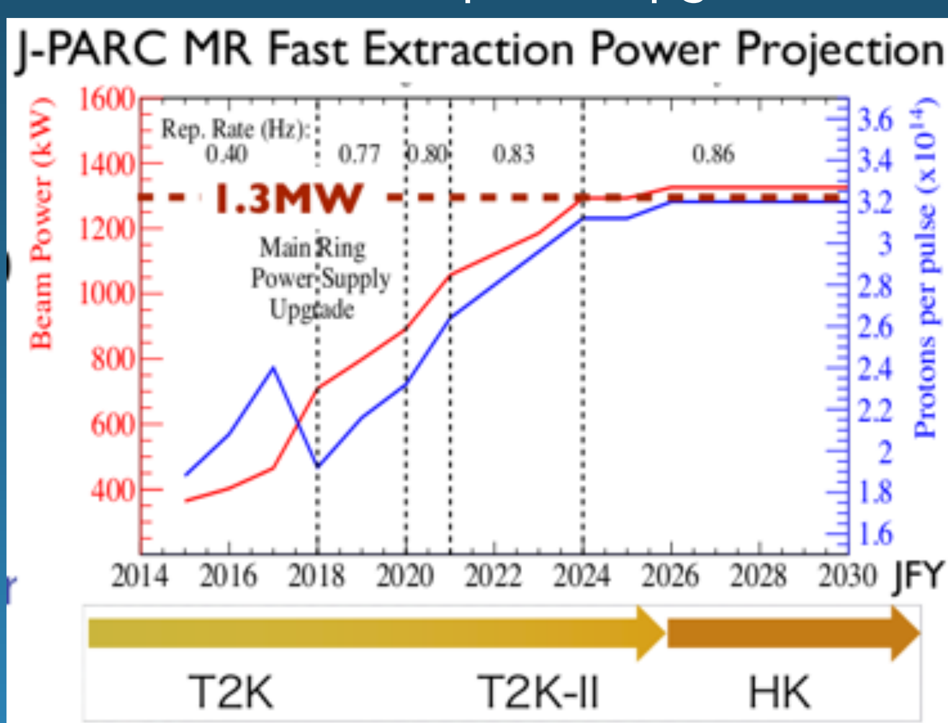
HYPER-KAMIOKANDE

APPROVED EXCAVATION OF THE CAVERN TO START IN 2020

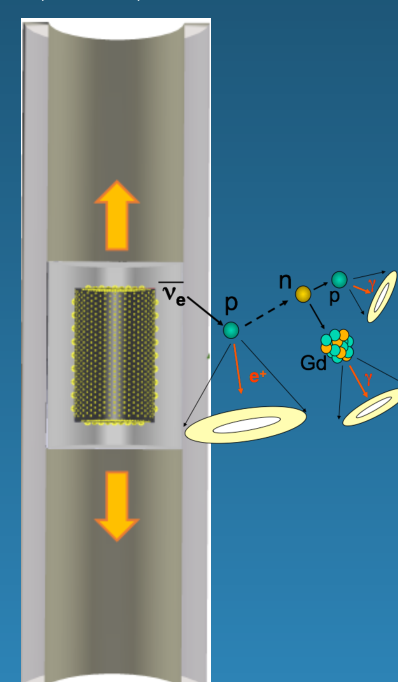


Staged approach: first tank as soon as possible, second later

1.3MW beam power upgrade



Intermediate (~1km) WC detector (E61)



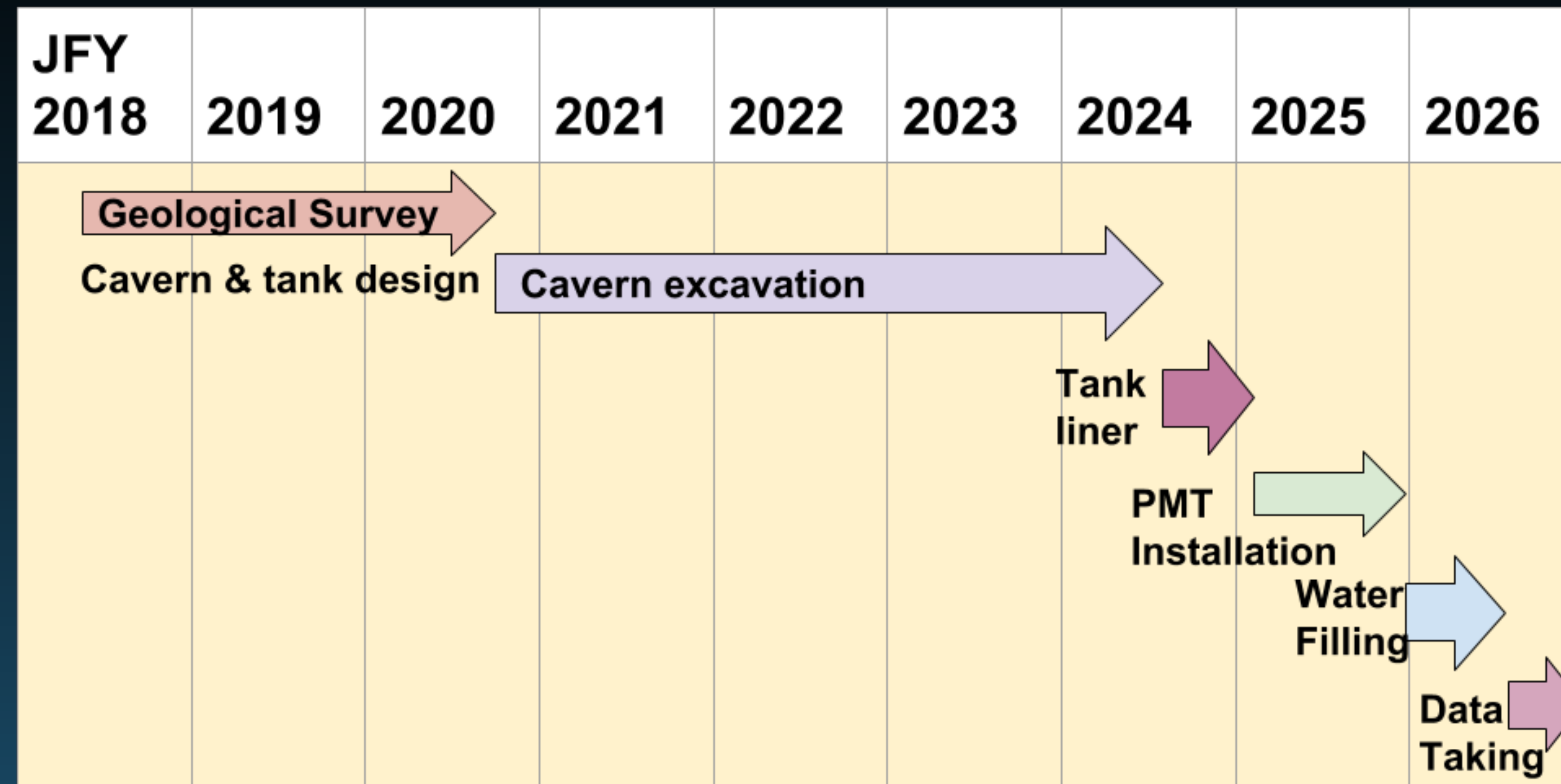
From T2K-II to Hyper-Kamiokande:

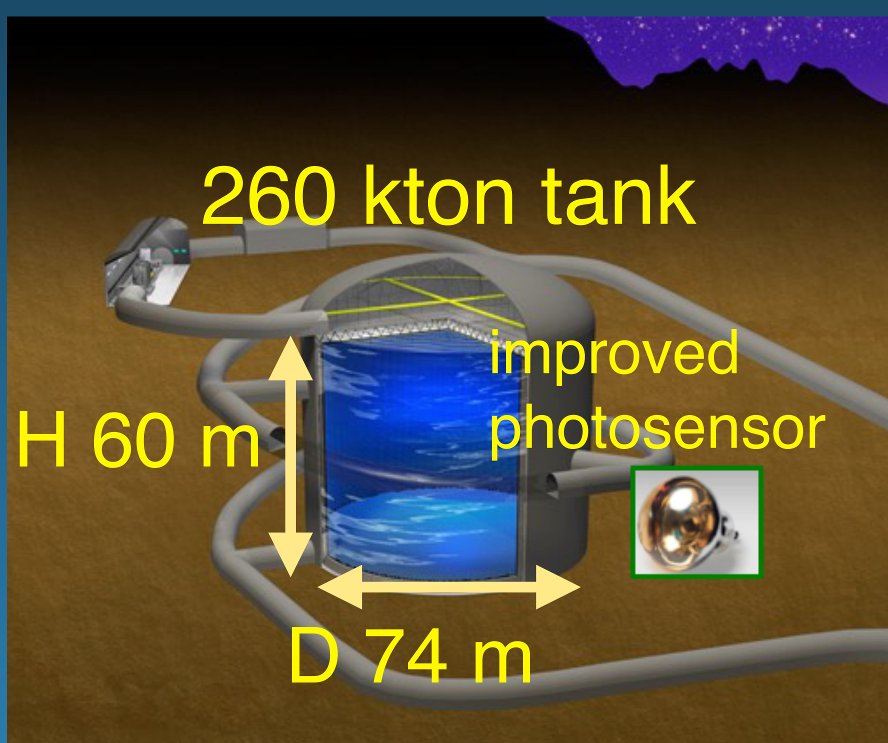
- 1tank: 10 times larger than SK
- 1.3MW beam power
- near detector (possible) upgrade
- new intermediate (~1km) Water Cherenkov detector (see M. Scott's talk)
- staged second far detector

HYPER-KAMIOKANDE

NEXT GENERATION WATER CHERENKOV DETECTOR

- **Construct two detectors in stage**
- Build the **first detector as soon as possible**
- An **option** of **second detector in Korea**

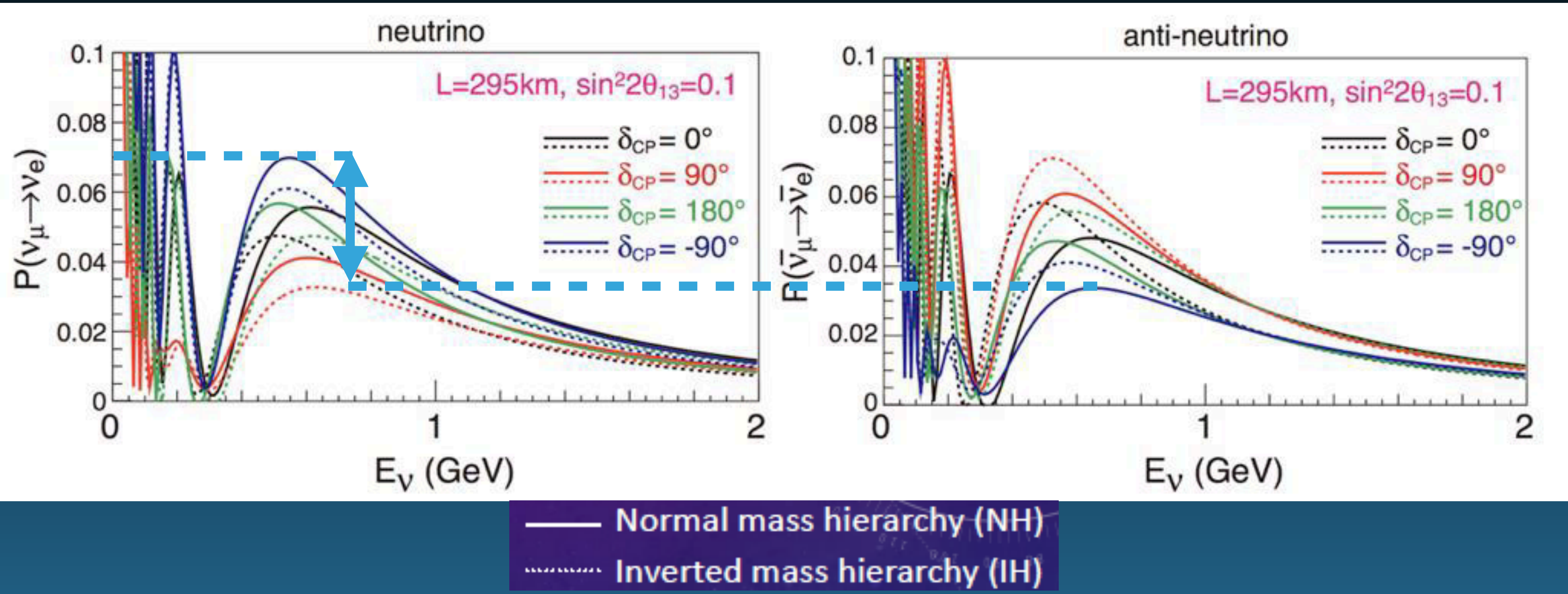




FIRST DETECTOR (JAPAN)

Φ74m x H60m
260 kton total mass
190 kton fiducial volume
~10 x Super-K fiducial mass
40% Photo coverage (ID)
40,000 x new 20” PMTs
x2 higher photon detection efficiency

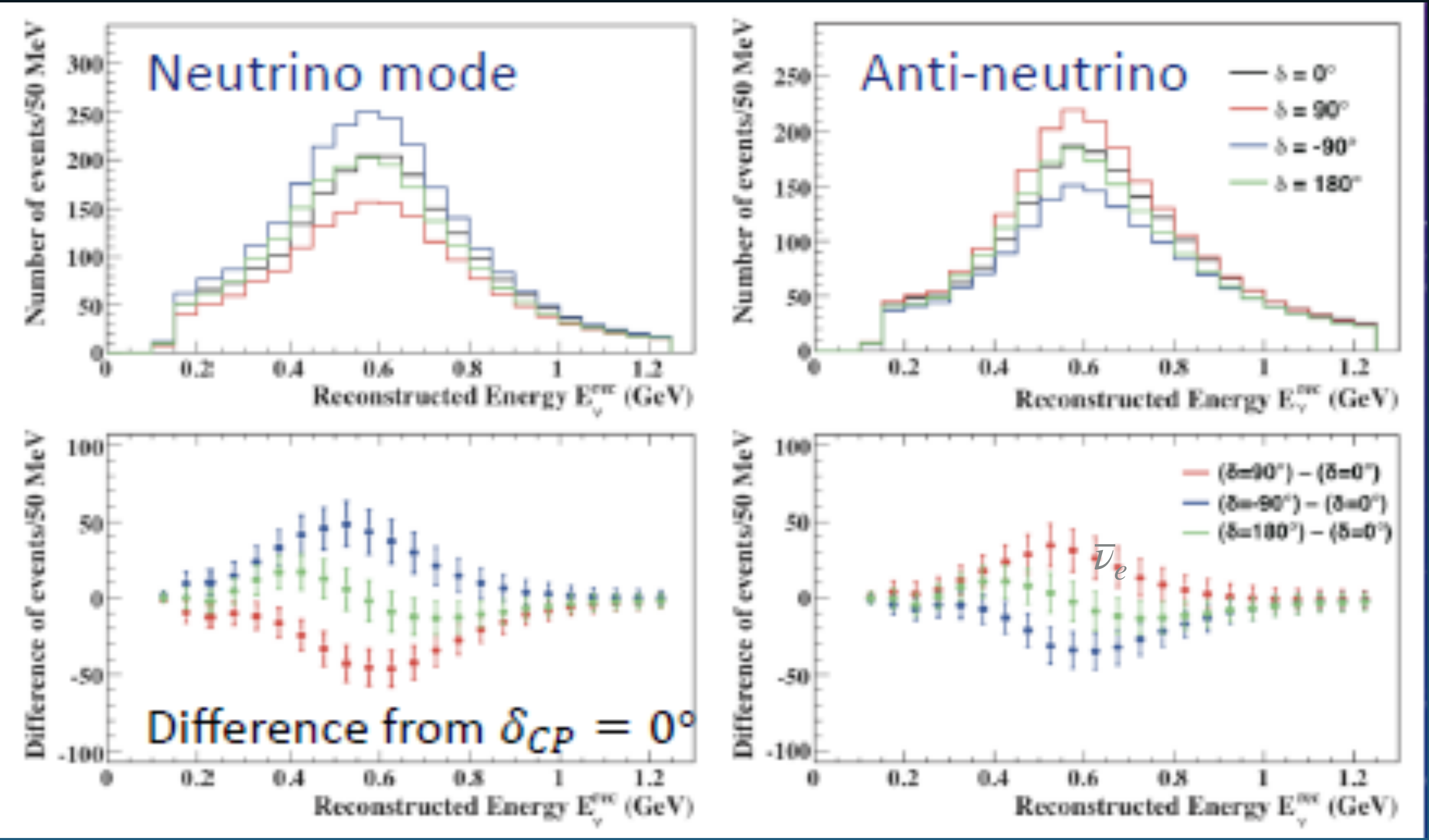
MEASUREMENT OF CP ASYMMETRY



- Comparison between the probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Up to ~±30 % variation at δ_{CP} = -90°in NH (or 90°in IH) wrt $\sin\delta_{CP}$=0

EXPECTED EVENTS IN HYPER-KAMIOKANDE LBN PROJECT

Expected # of events in $\nu_e/\bar{\nu}_e$ appearance



Assumption

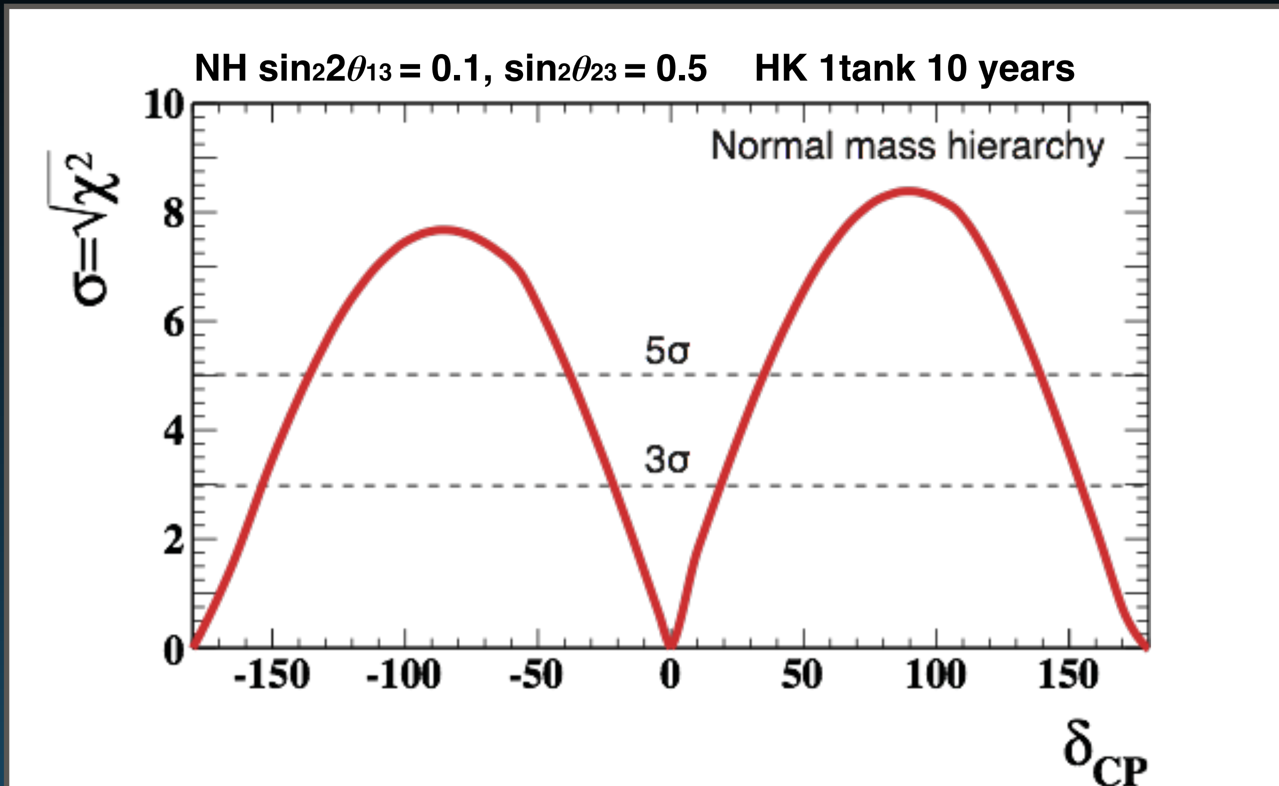
- 1.3MW x 10years (10^8 s)
- $\nu : \bar{\nu}$= 1:3
- $\sin^2 2\theta_{13}$=0.1
- Normal hierarchy

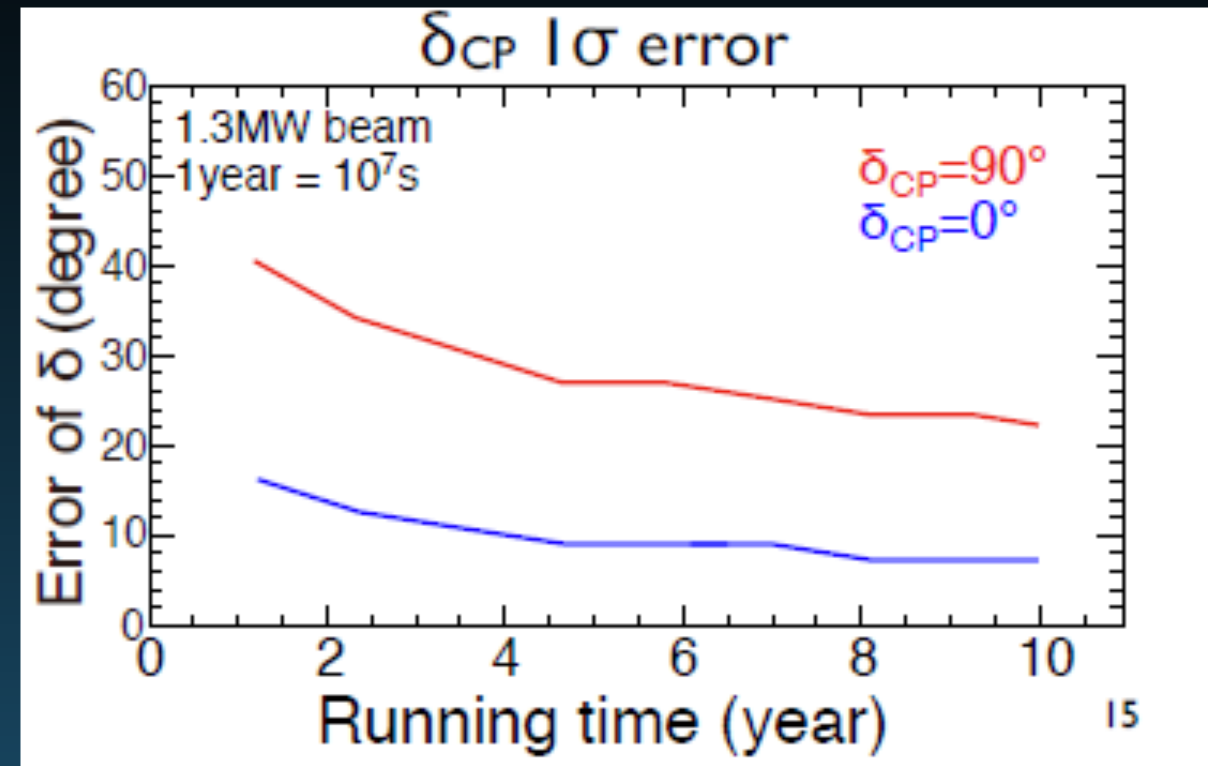
A few % stat. uncertainties on $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ signals

For δ=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

The results are from the HK Design Report (arXiv:1805.04163 [physics.ins-det])

CP VIOLATION SENSITIVITY



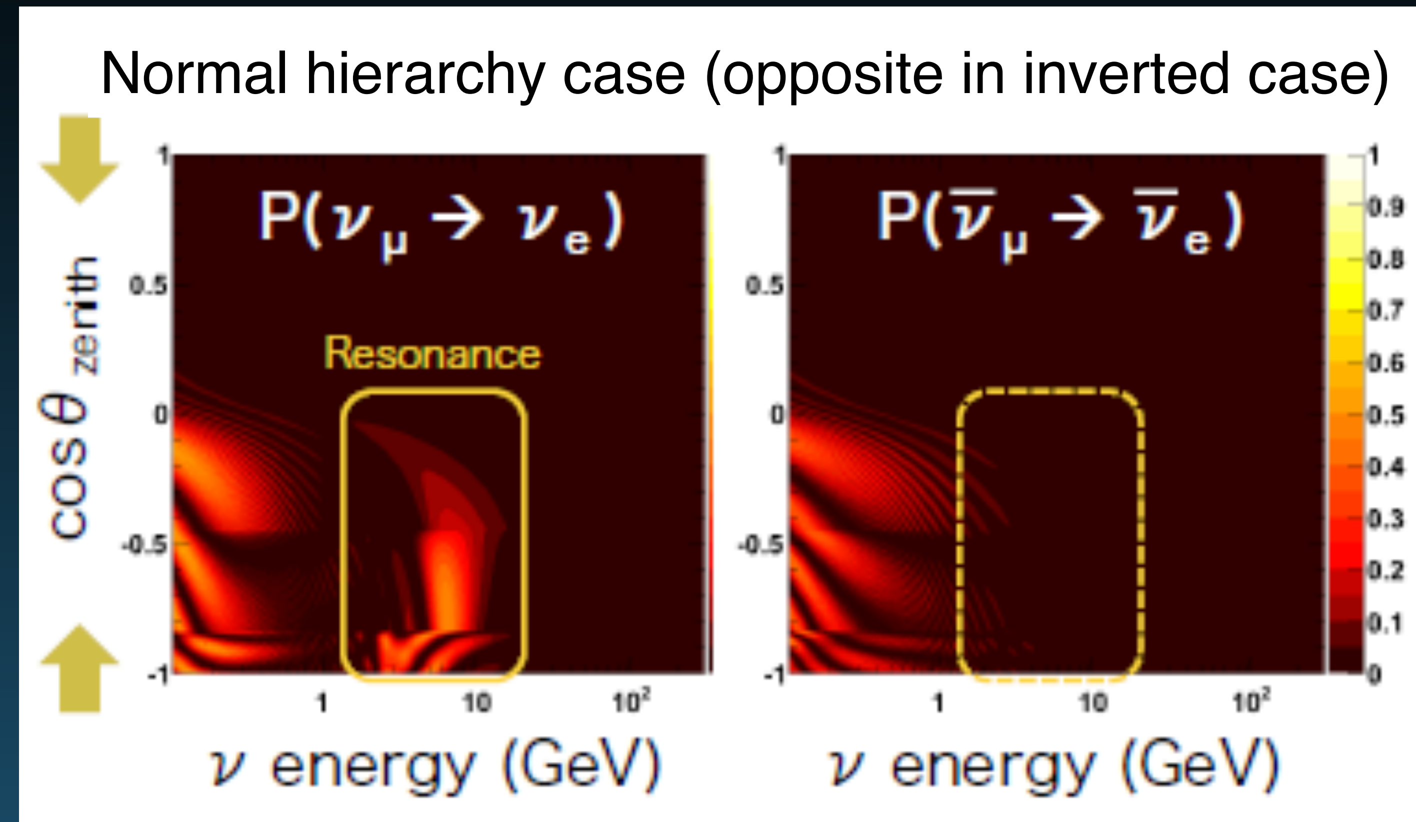


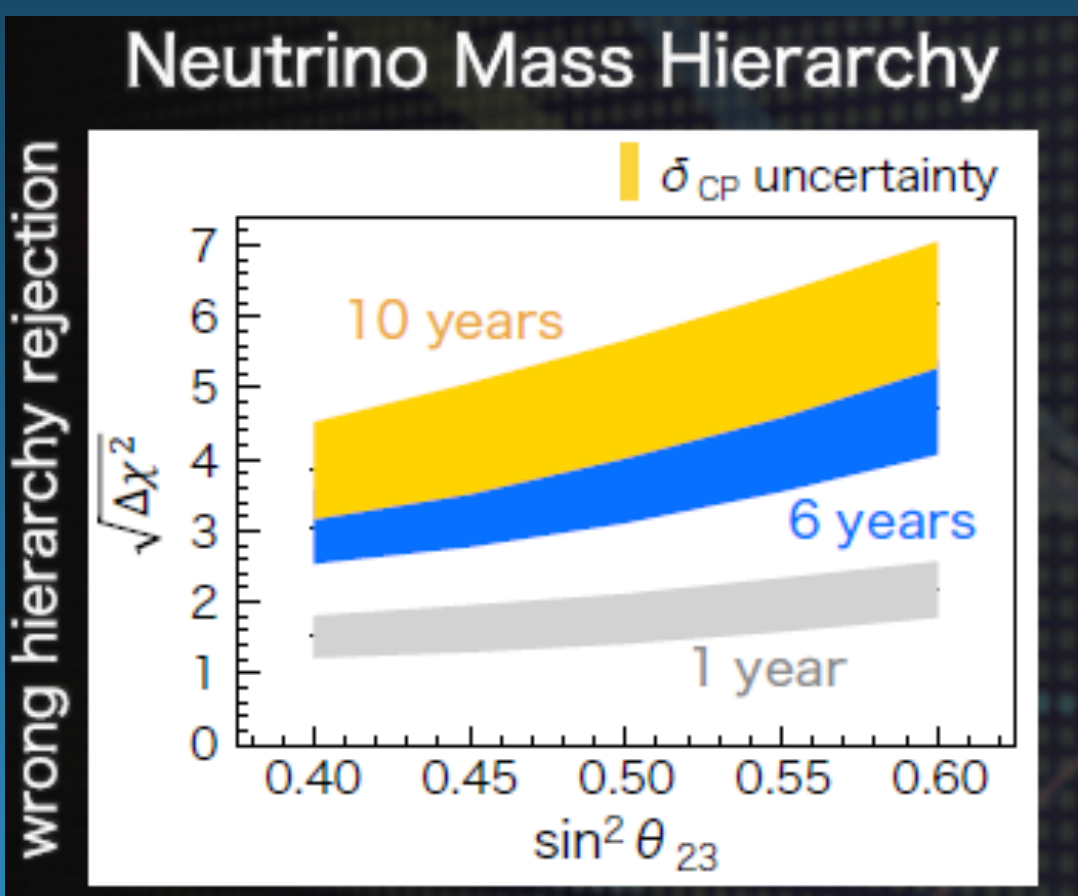
- **Exclusion of $\sin\delta_{CP} = 0$**
  - 8σ for δ = -90°(T2K best fit)
  - 80 % of coverage of δ parameter space for CPV discovery > 3σ
- After 10 years of running, HK will be able to measure ~50% of the δ_{CP} space to better than 5σ

- **δ_{CP} precision measurement**
  - 22°for δ = -90°
  - 7°for δ = 0°

Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K
- Realistic systematic uncertainties plus expected reduction of errors
- 3~4% syst. Error (6~7% in T2K)

MASS HIERARCHY SENSITIVITY



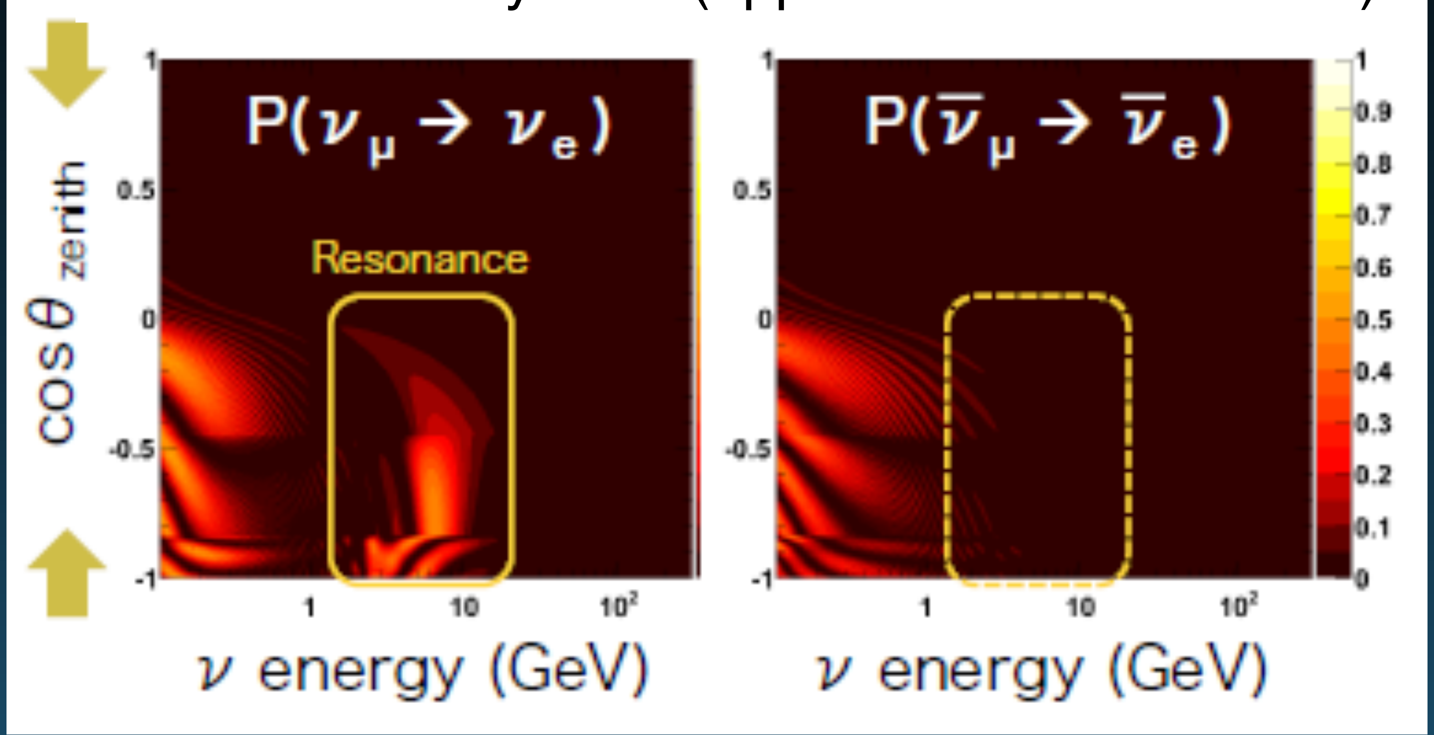


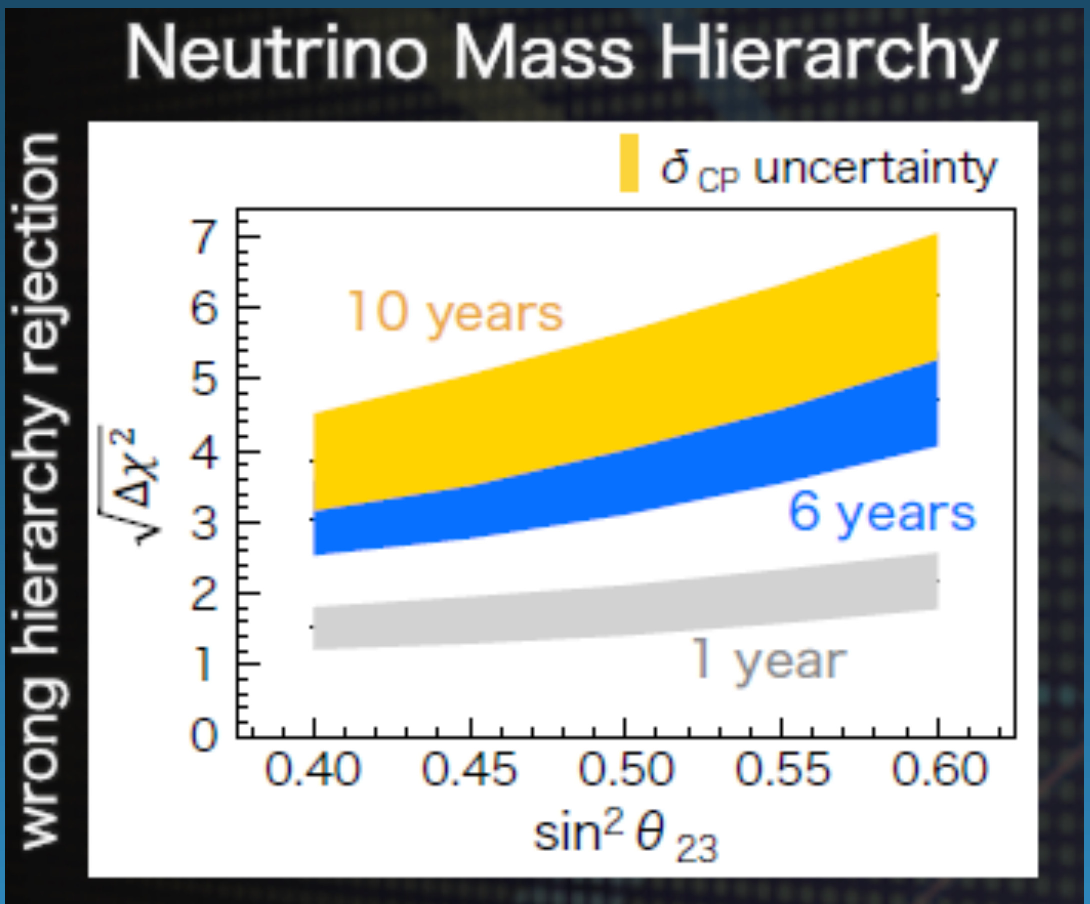
Earth matter effect in upward-going multi-GeV ve sensitive to mass hierarchy

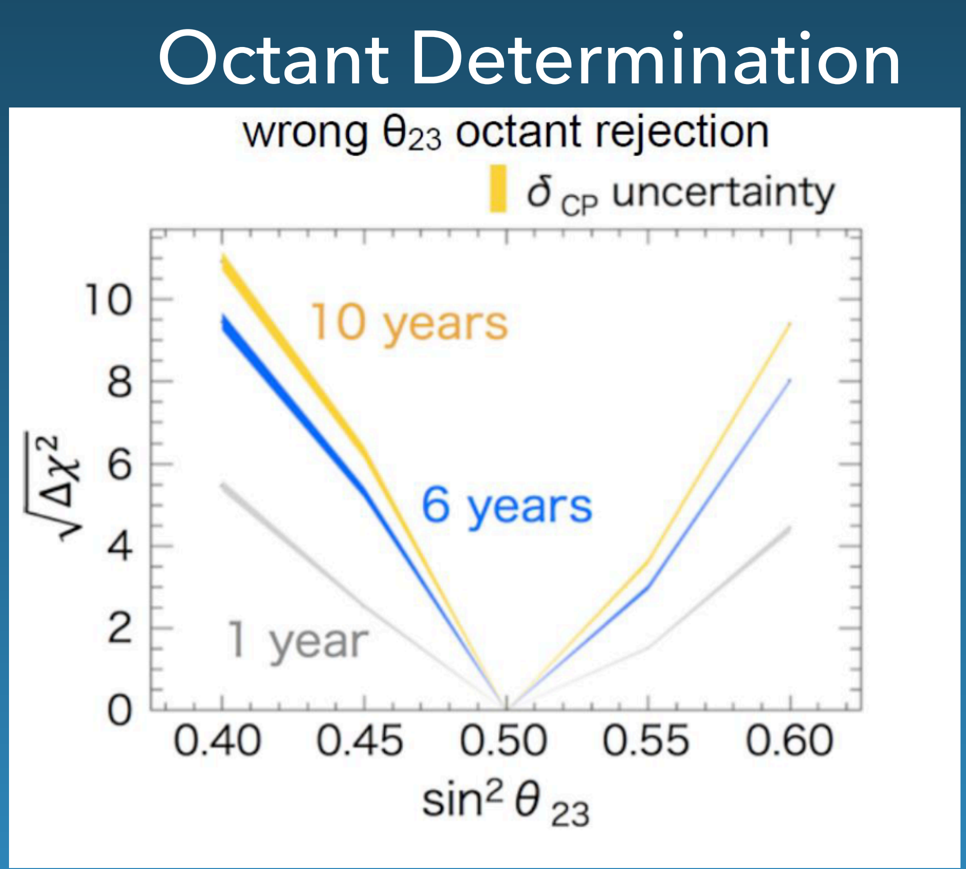
- “Resonance” pattern appears in $\nu_e(\overline{\nu}_e)$ appearance for NH (IH)
- **Combination of atmospheric and beam to determine mass hierarchy**
- Determination possible within ~5 years ($\sin^2\theta_{23}$=0.5) at HK even if MH not determined before HK era.

MASS HIERARCHY SENSITIVITY

Normal hierarchy case (opposite in inverted case)







HYPER-KAMIOKANDE SENSITIVITIES

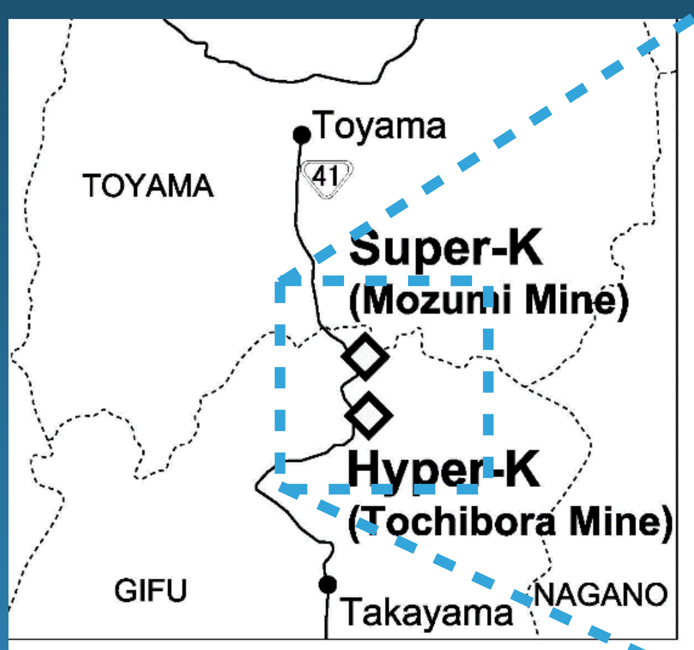
Physics Target	Sensitivity	Conditions
Neutrino study w/ J-PARC ν		$1.3\,\mathrm{MW} \times 10^8$ sec
– CP phase precision	$< 23°$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– CPV discovery coverage	76% ($3\,\sigma$), 57% ($5\,\sigma$)	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
– $\sin^2\theta_{23}$	± 0.017	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric neutrino study		10 years observation
– MH determination	$> 2.2\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\lvert\theta_{23} - 45°\rvert > 4°$
Atmospheric and Beam Combination		10 years observation
– MH determination	$> 3.8\,\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
– θ_{23} octant determination	$> 3\,\sigma$ CL	@ $\lvert\theta_{23} - 45°\rvert > 2.3°$
Nucleon Decay Searches		1.9 Mton·year exposure
– $p \to e^+ + \pi^0$	7.8×10^{34} yrs (90% CL UL)	
	6.3×10^{34} yrs ($3\,\sigma$ discovery)	
– $p \to \bar{\nu} + K^+$	3.2×10^{34} yrs (90% CL UL)	
	2.0×10^{34} yrs ($3\,\sigma$ discovery)	
Astrophysical neutrino sources		
– ^{8}B ν from Sun	130 ν's / day	4.5 MeV threshold (visible energy) w/ osc.
– Supernova burst ν	52,000–79,000 ν's	@ Galactic center (10 kpc)
	$\sim$10 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	70 ν's / 10 years	10–30 MeV, 4.2σ non-zero significance
– WIMP annihilation in the Earth		10 years observation
(σ_{SD}: WIMP-proton spin	$\sigma_{SD} = 10^{-40}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 10\,\mathrm{GeV}$, $\chi\chi \to b\bar{b}$ dominant
dependent cross section)	$\sigma_{SD} = 10^{-44}\mathrm{cm}^2$	@ $M_{\mathrm{WIMP}} = 50\,\mathrm{GeV}$, $\chi\chi \to \tau^+\tau^-$ dominant

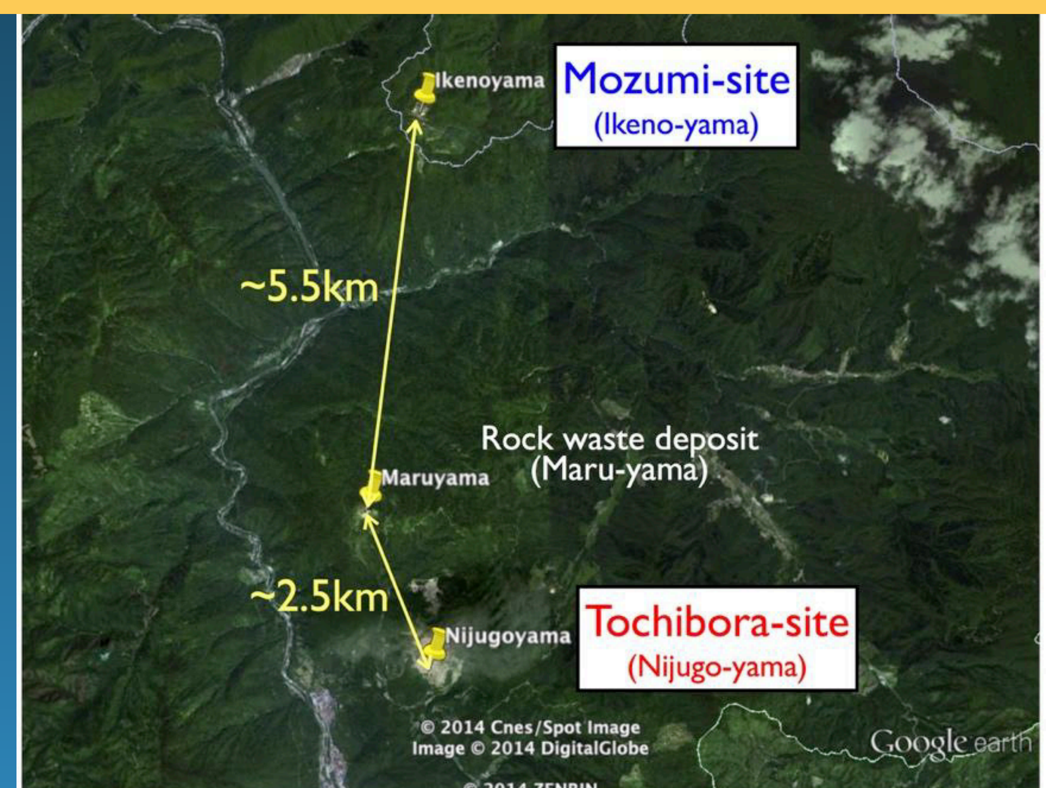
FAR DETECTOR SITE

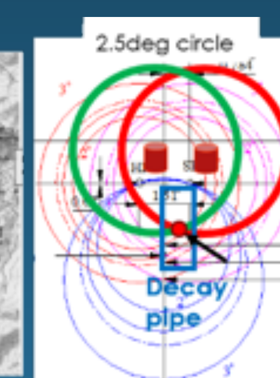
- Tochibora mine in Kamioka
- ~8km south from Super-K
- Identical baseline (295km) and off-axis angle (2.5°) to Super-K for J-PARC beam
- Overburden ~650m (~1755m.w.e.) cf. SK ~2700m.w.e.
- The detector site surrounded by faults
  - Identified during the mining in the past
- Confirmed the geological condition (rock quality) good for a large cavern excavation
- Identified the best location for cavern excavation, where has good rock quality and no faults or fracture zone

Hyper-K cavern will be the world largest underground cavern

APPROVED EXCAVATION OF THE CAVERN TO START IN 2020



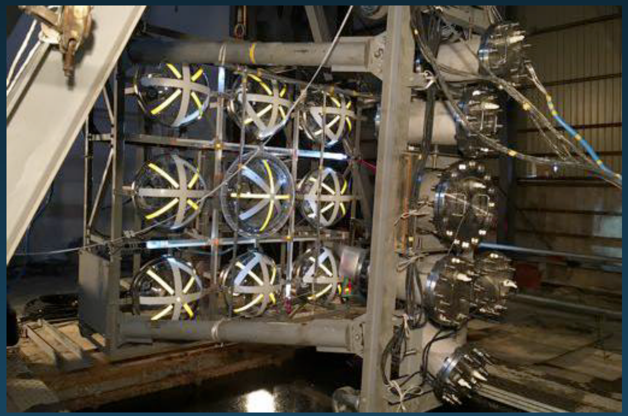


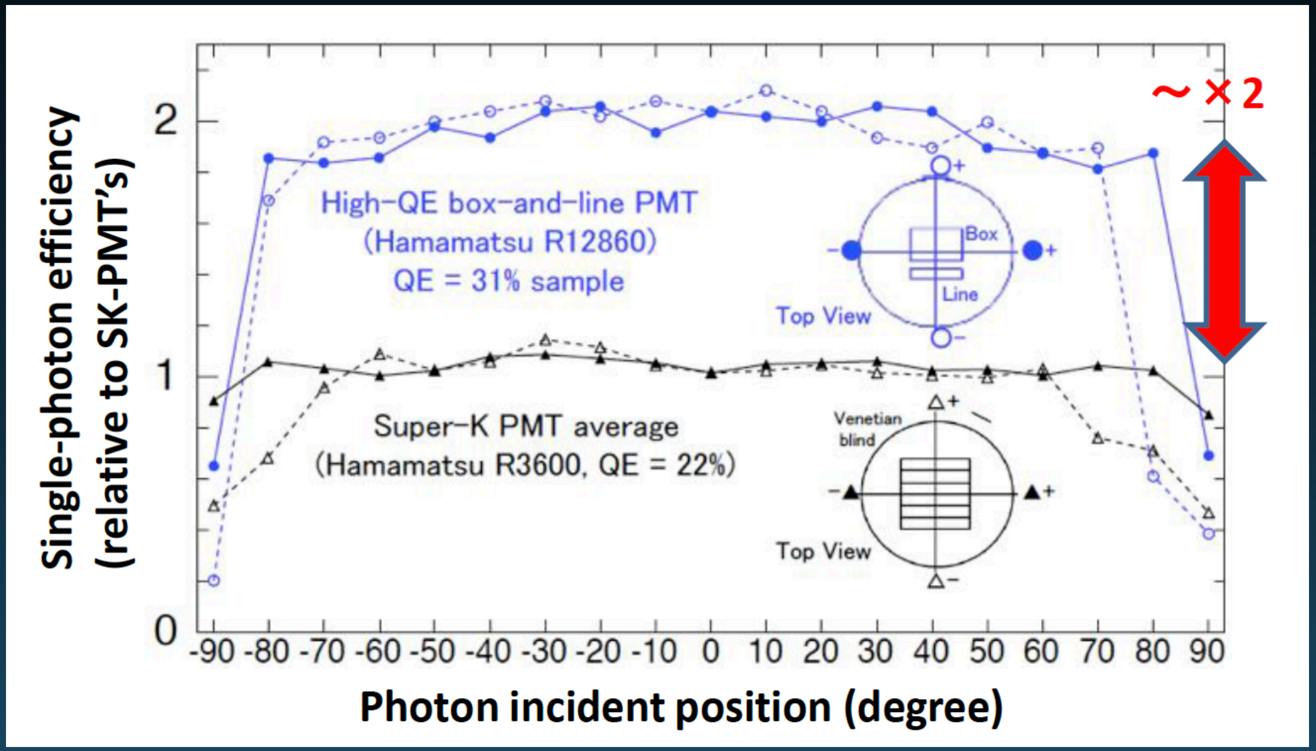


PHOTOSENSORS R&D

- **Sensitivity: 2×SK**
- **Time resolution: ½×SK**
- **Pressure tolerance: 2×SK**

Cover test @ Kamisunagwa, Hokkaido





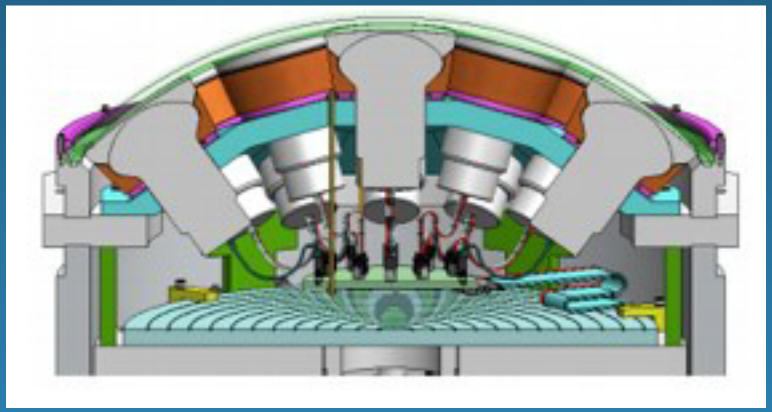
Continuous effort for improvements. Noise reduction, cover design, light concentrator, etc. under study

New 20-inch photo-sensors: higher performance

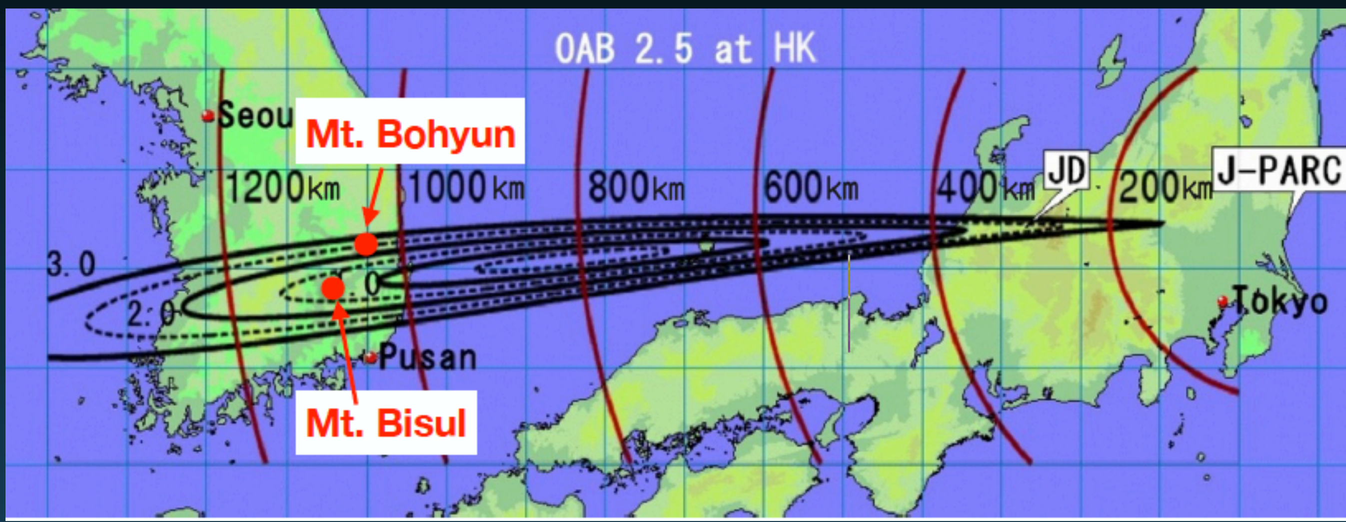
- Single-photon efficiency: x2
- 1 p.e. timing resolution: 2ns → 1ns
- 1 p.e. charge resolution: 53% → 35%
- Large impact on detector performance/physics sensitivity

140 new PMT's installed in Super-K during tank opening.

Single-sided mPMT module being investigates as option for inner detector (20"PMT + mPMTs)



SECOND FAR DETECTOR IN KOREA



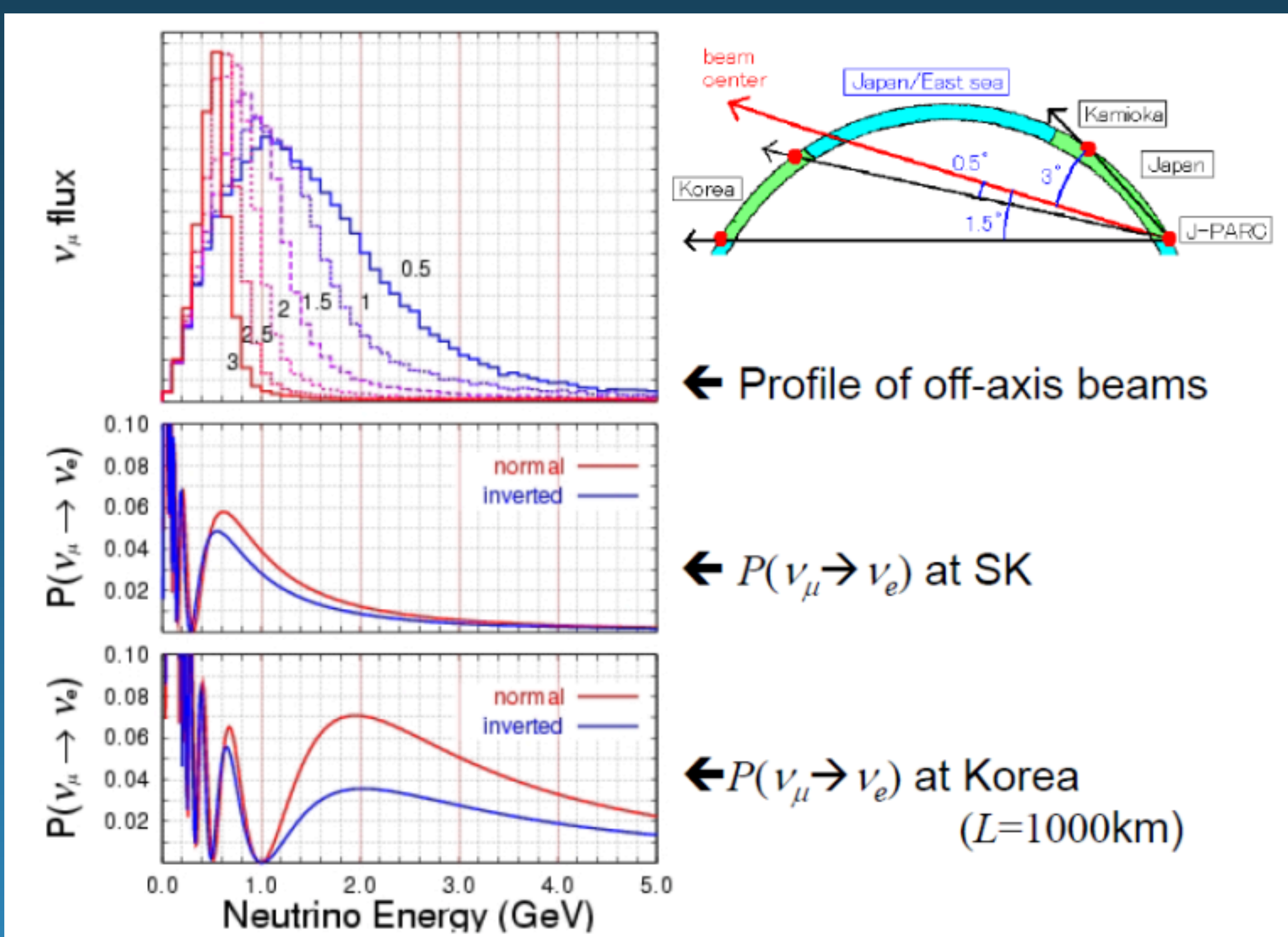
Second tank option in Korea is being considered (PTEP 2018, 063C01)

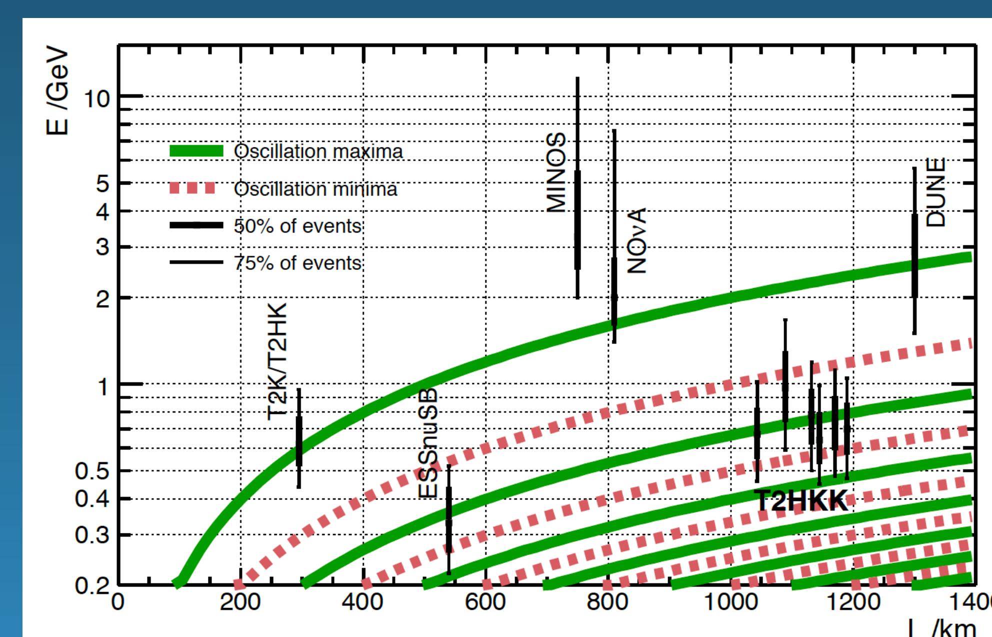
Advantages:

- Large CP effect at second oscillation maximum
- Higher mass hierarchy sensitivity with longer baseline

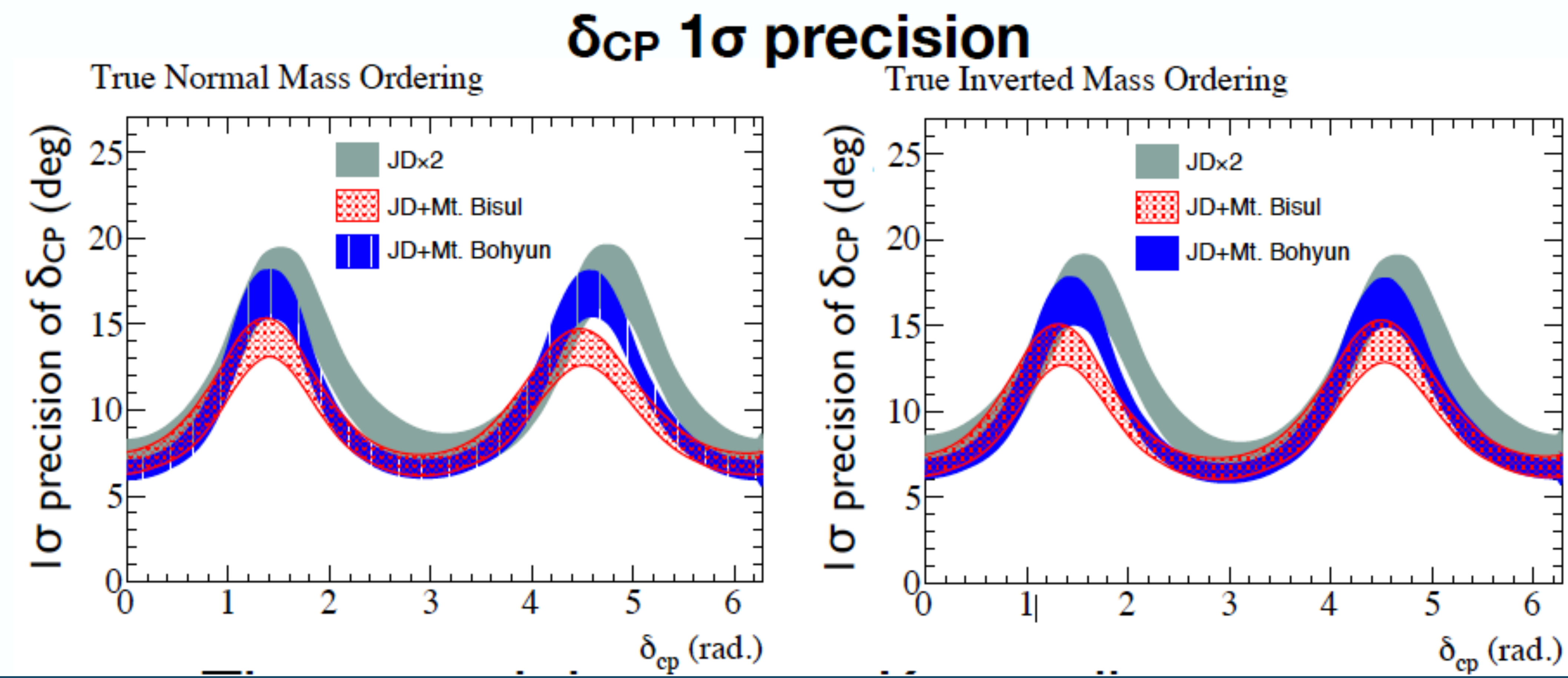
Possible site:

- Mt. Bisul at L=1,088km, OA=1.3°
- Mt. Bohyun at L=1,043km, OA=2.3°





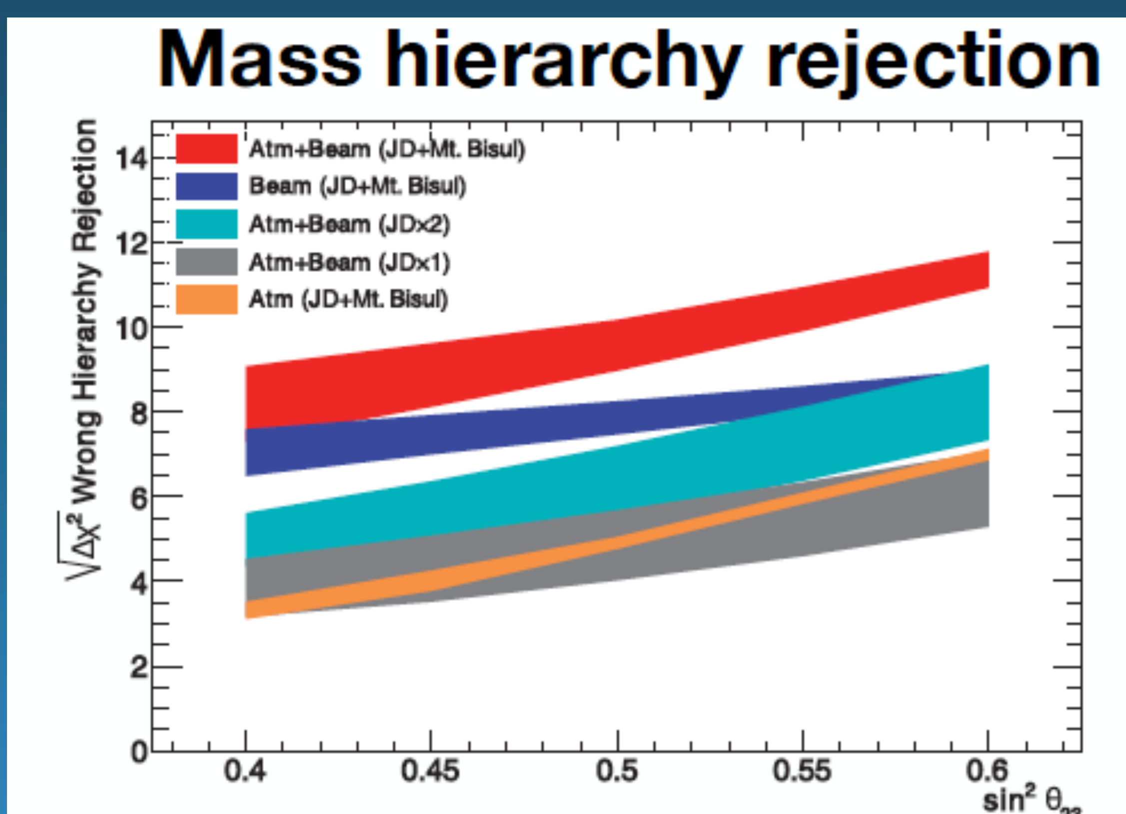
PHYSICS SENSITIVITY WITH KOREAN DETECTOR



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

JD = Japanese detector

Mt Bisul/Bohyun = Korean detector



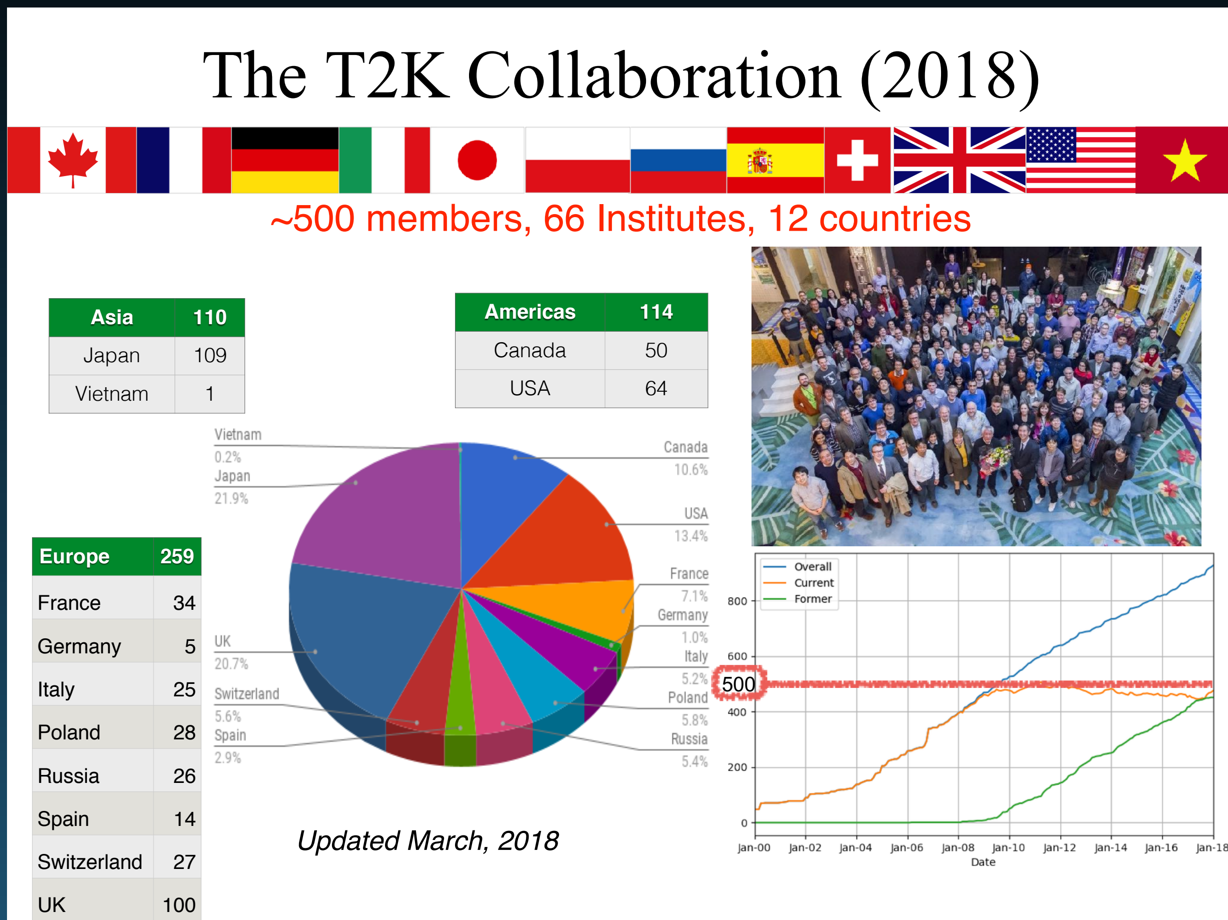
An additional far detector in Korea will allow to have:

- improved δ_{CP} measurement precision $22° \rightarrow <15°$ at $\delta_{CP}=-90°$
- a higher mass hierarchy sensitivity $4.5\sigma \rightarrow 9\sigma$ at $\sin^2\theta_{23}=0.5$l

THE INTERNATIONAL ORGANISATION

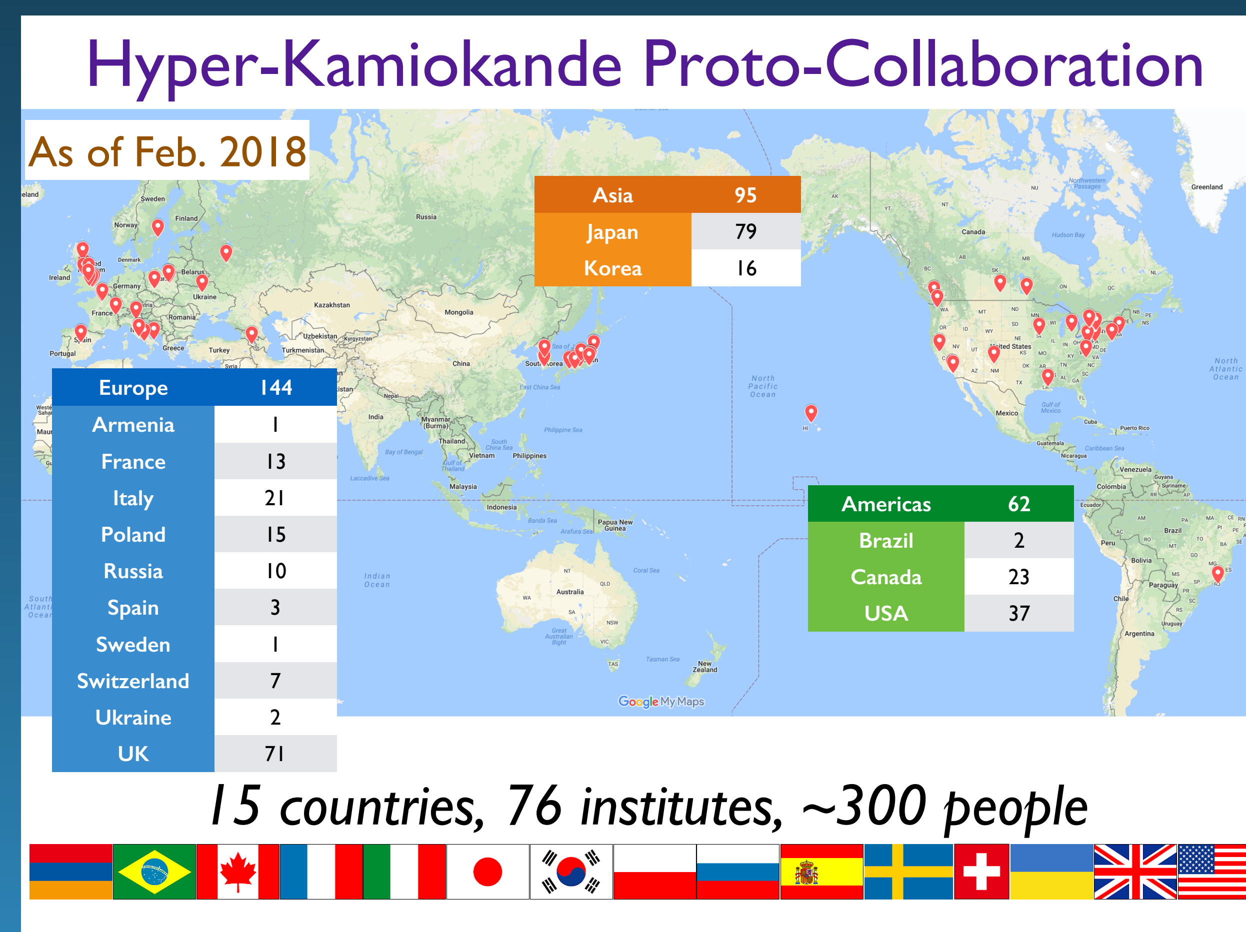
- **International Hyper-K proto-collaboration**
  - 15 countries, 73 institutes, ~300 members, ~75% from abroad
  - International project leaders, steering members, WG conveners
- **2 host institutes**: UTokyo/ICRR and KEK/IPNS (MoU of cooperation for HK)
- UTokyo launched a institute for HK construction: **Next Generation Neutrino Science Organization (NNSO)**
- External review by **International Advisory Committee (HKAC)**

STRONG EUROPEAN CONTRIBUTION TO LBN J-PARC BASED

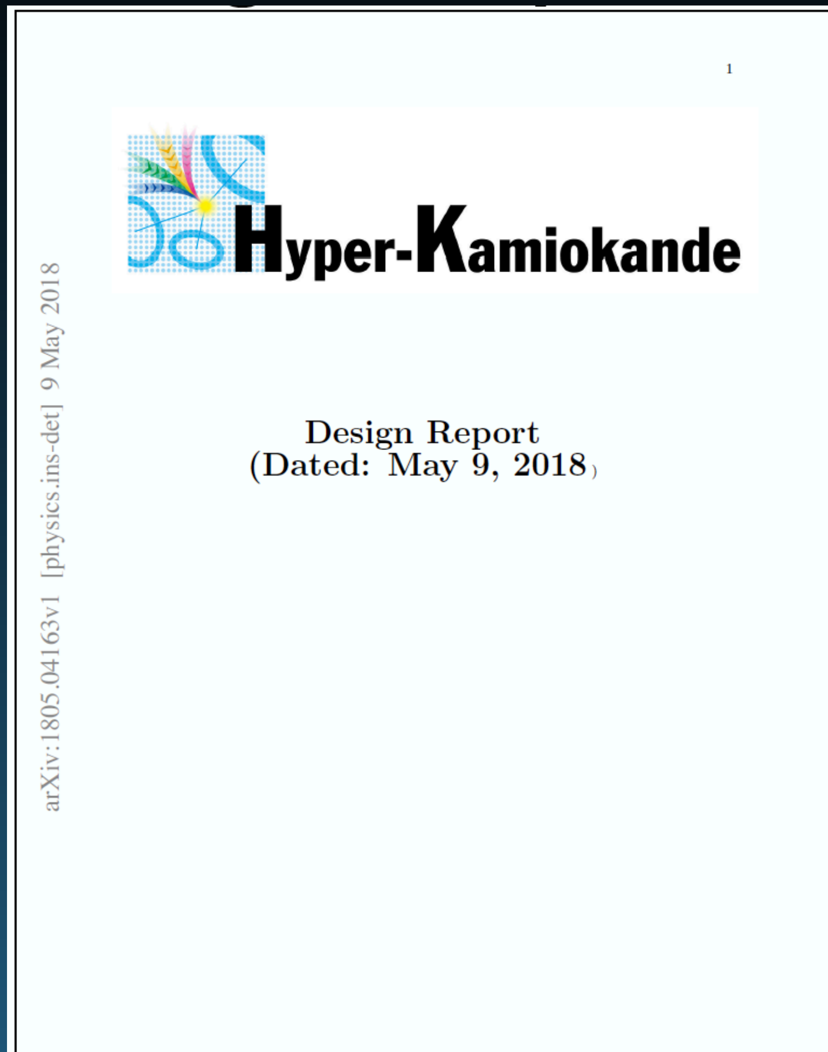


- There is a strong UK contribution in the LBN J-PARC-based LBN experiments.

- Several UK leaderships and crucial positions in the collaborations.



DESIGN REPORT HAS BEEN RELEASED



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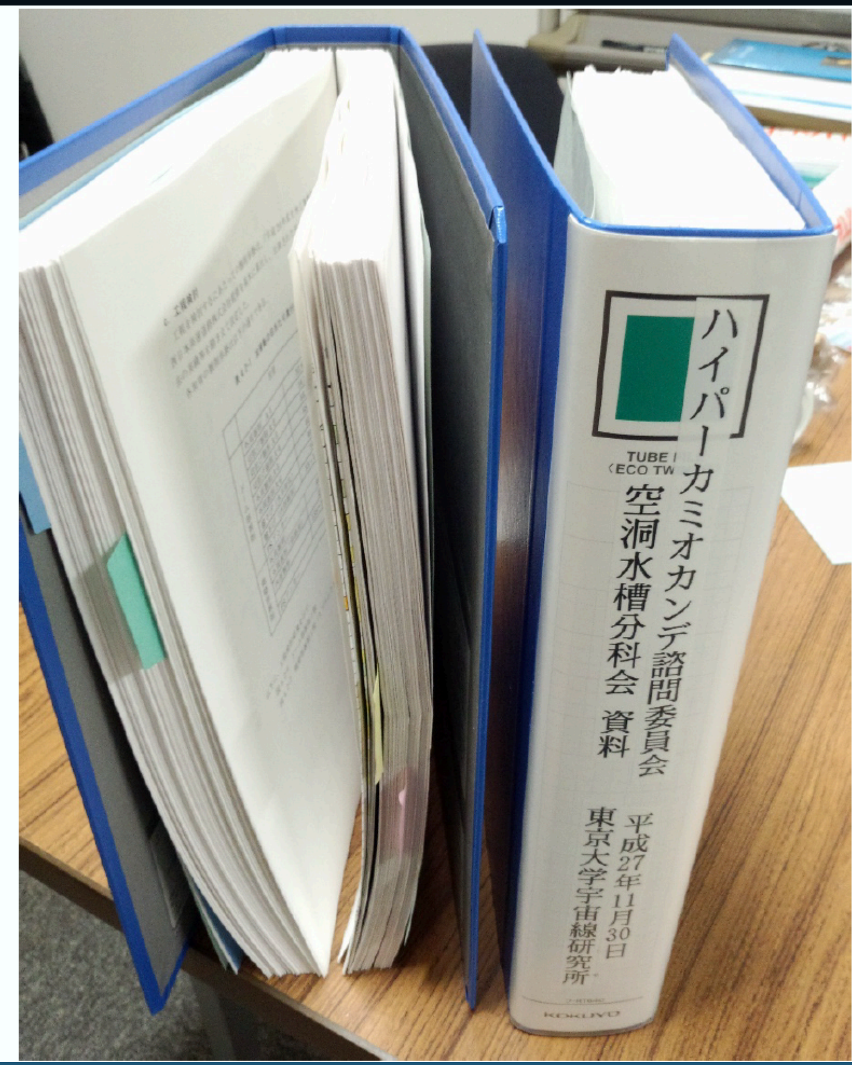
Hyper-Kamiokande

Design Report
(Dated: May 9, 2018)

arXiv:1805.04163v1 [physics.ins-det] 9 May 2018



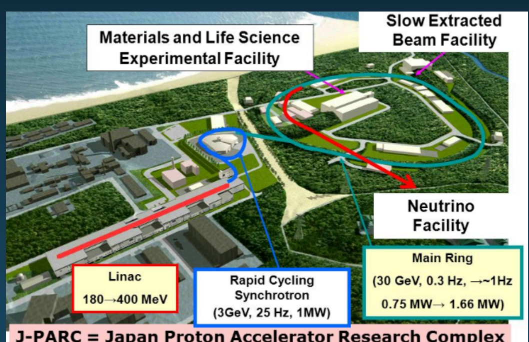
- **"Hyper-Kamiokande Design Report", arXiv:1805.04163** May 9, 2018. 333 pp.
- **"Hyper-Kamiokande Technical Report" is being internally reviewed** - timescale for completion 2019
- Other recent references:
  - **Physics potentials with the second Hyper-Kamiokande detector in Korea** PTEP 2018 (2018) no.6, 063C01

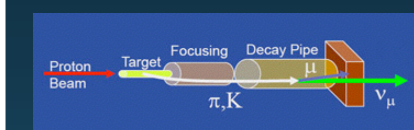
CONCLUSIONS

- **The long baseline experiment T2K, T2K-II and Hyper-Kamiokande (with one and two far detectors) provide a continuous excellent physics from 2010 with J-PARC up to the next decades.**
- Proven track record of experiments in Japan
- Major open questions are being addressed
  - CP violation search
  - Mixing parameters
  - Mass hierarchy
- T2K is searching for CP violation and measuring the other parameters
- Beam Power is being increased up to 1.3MW (during T2K-II and before Hyper-K)
- Near (and intermediate) T2K/T2K-II/Hyper-K detectors are being constructed (or planned)
- Super-Kamiokande was just refurbished and Gd will be added
- Hyper-Kamiokande will start cavern construction in 2020. It has a large physics potential and will determine CP violation. Open to new collaborators!

ADDITIONAL SLIDES

LONG BASELINE EXPERIMENTS IN A NUTSHELL





ν beam

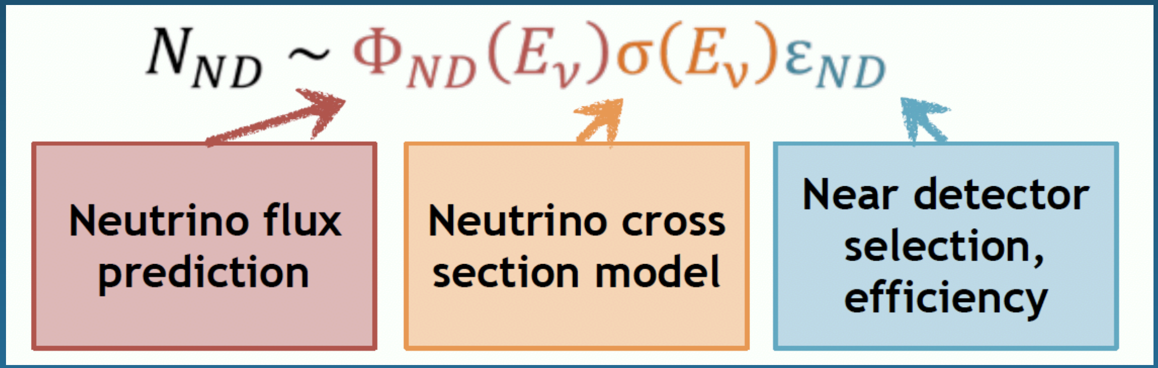
NEAR DETECTOR

ν beam

FAR DETECTOR

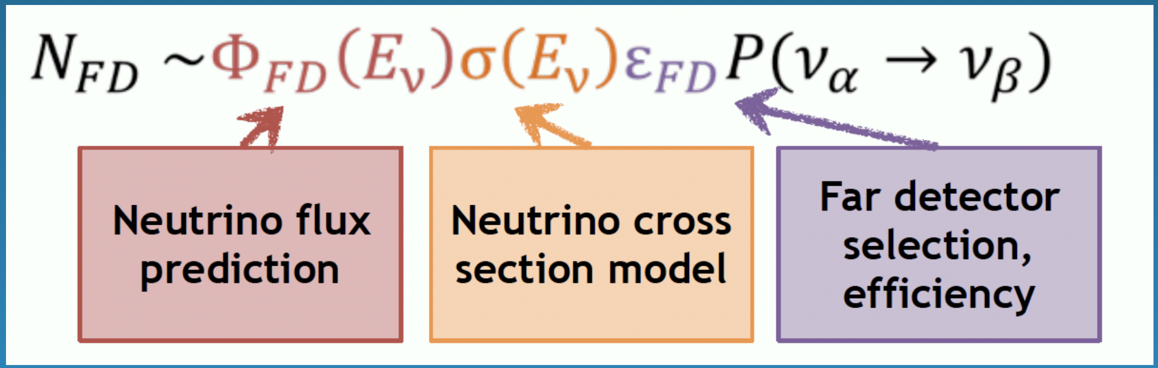
~100 m

~100-1000 km

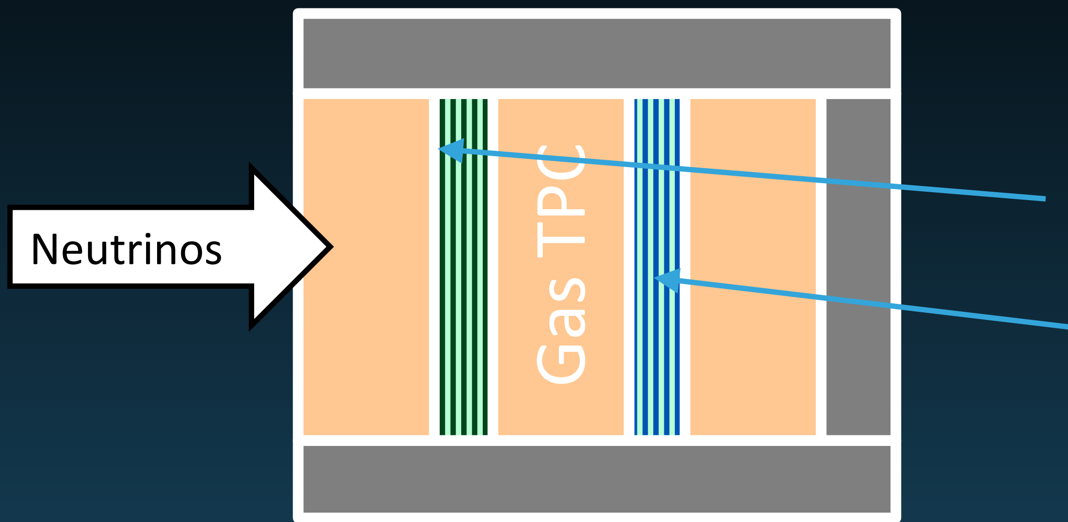


- Predicted events in the Near Detector.

- Predicted events in the Far Detector.



CONSTRAINTS USING ND280

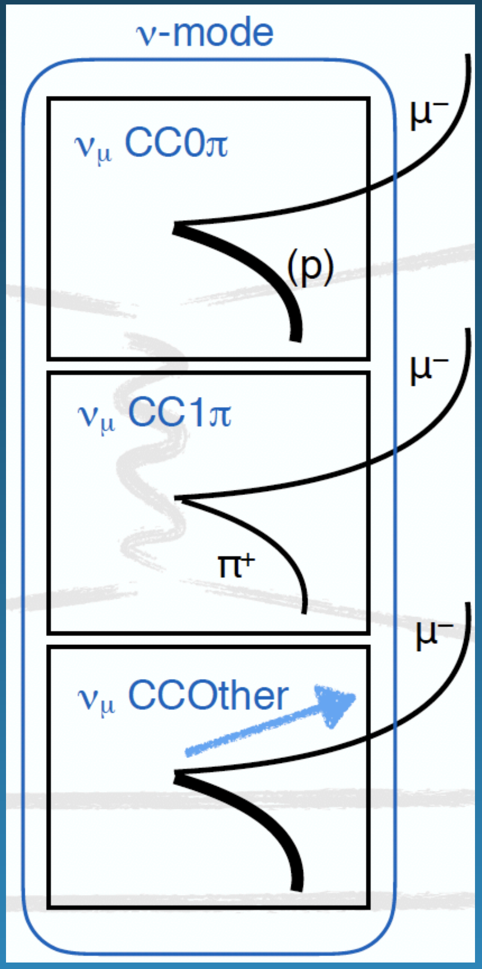


Analysis uses pairs of samples from 2 active target volumes

Pure scintillator: **Carbon** (+H)

Water+ scint.: **Oxygen** (+C, H)

Allows separate constraints for C vs O nuclear effects



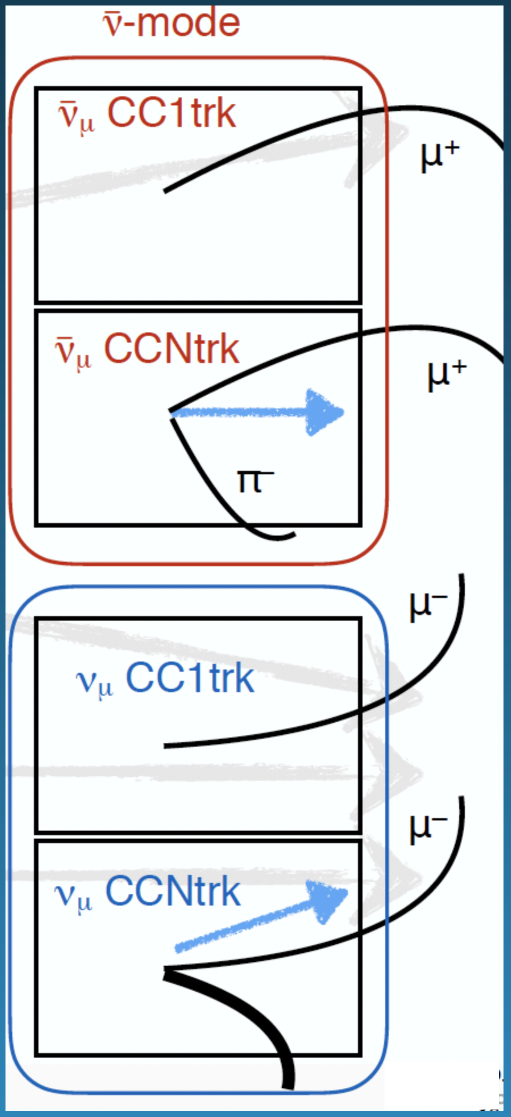
Neutrino beam

- Require 1 muon-like track
- Sub-samples with {0,1,..,*n*} pion-like tracks

Antineutrino beam

- Require 1 muon-like track
- Sub-samples based on muon charge and {0, *n*} extra tracks

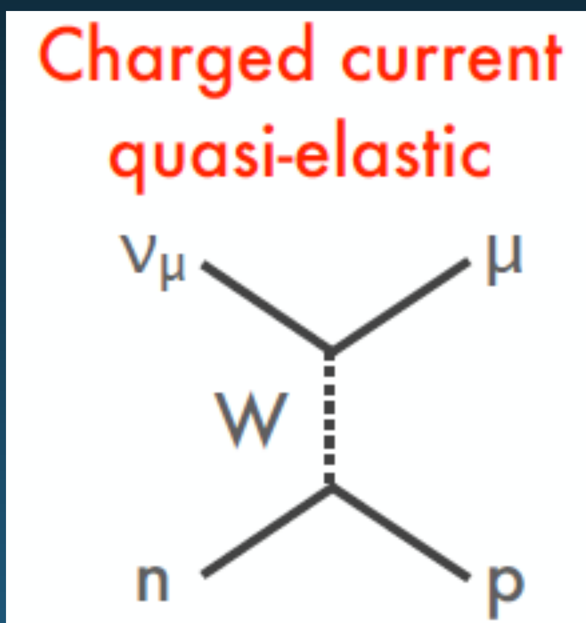
(Larger 'wrong-sign' B/G in RHC mode)

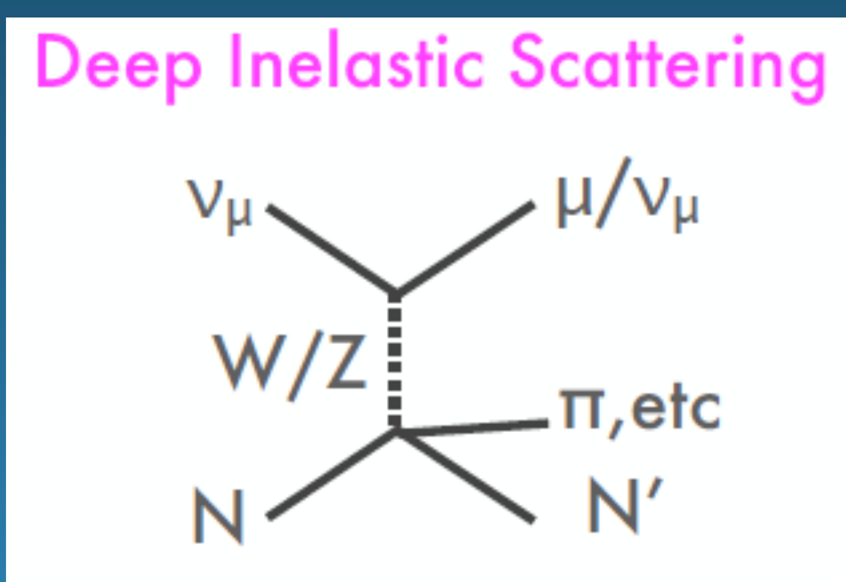


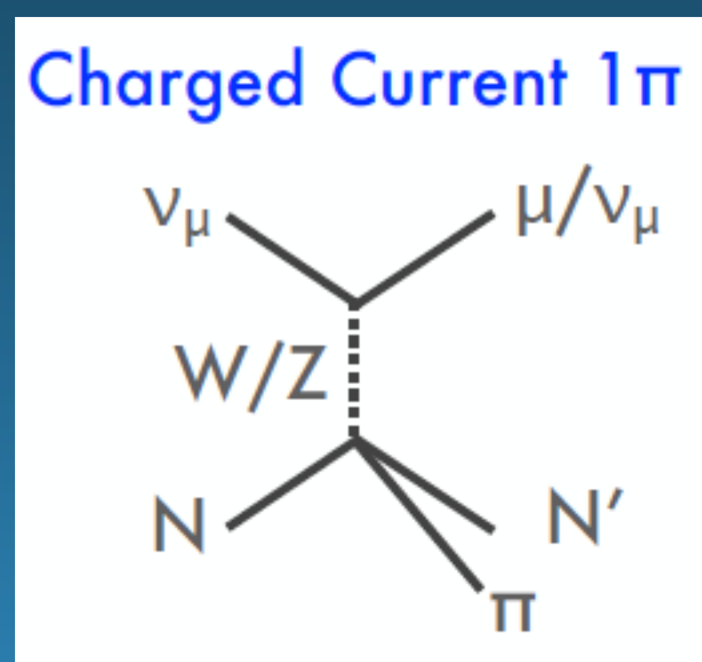
CROSS SECTION MODEL

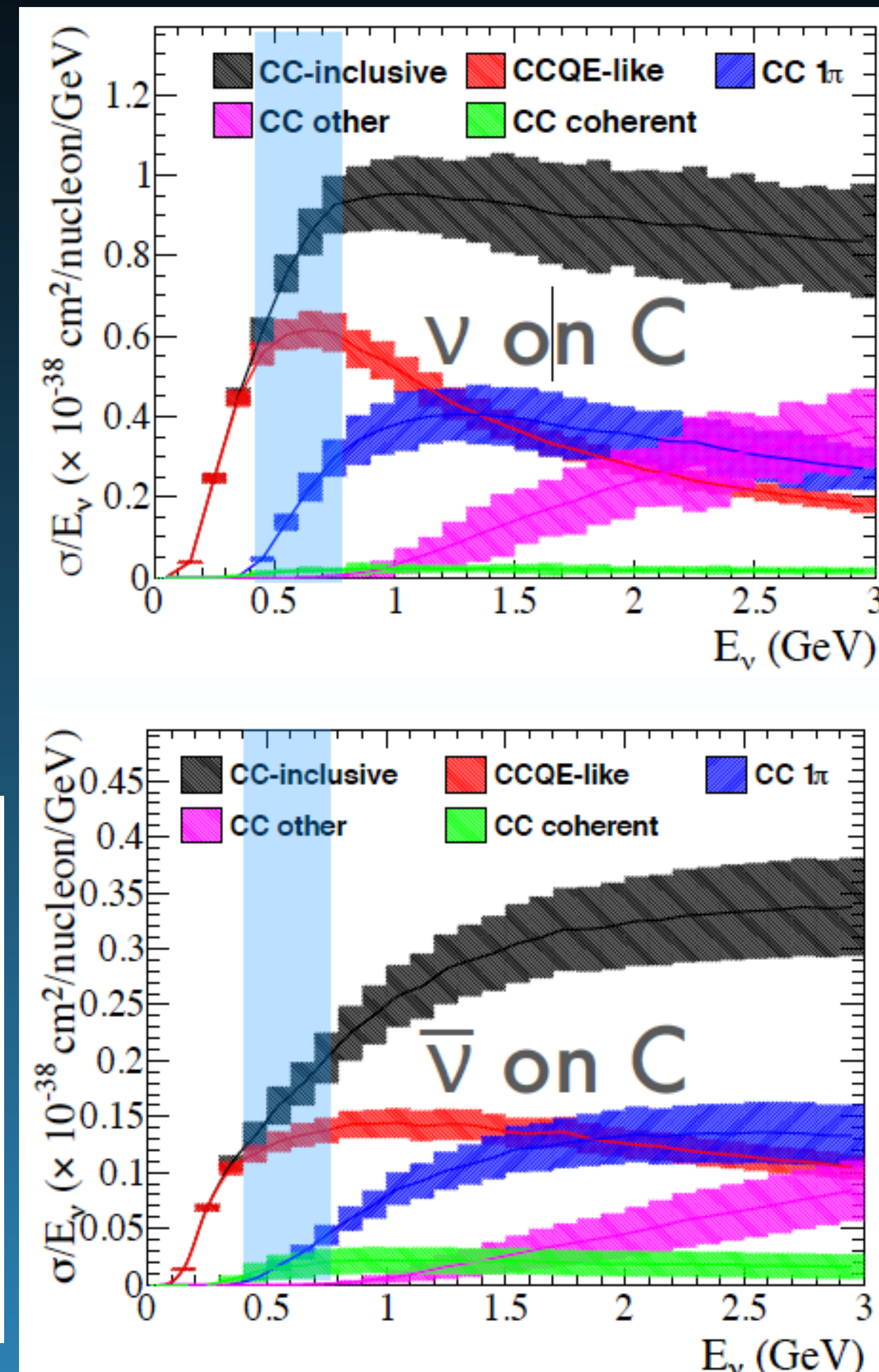
Uncertainties come from underlying model parameters and normalisations

- M_A^{QE}
- M_A^{RES}
- Fermi Momentum
- Binding Energy
- FSI
- 2p2h
- ….









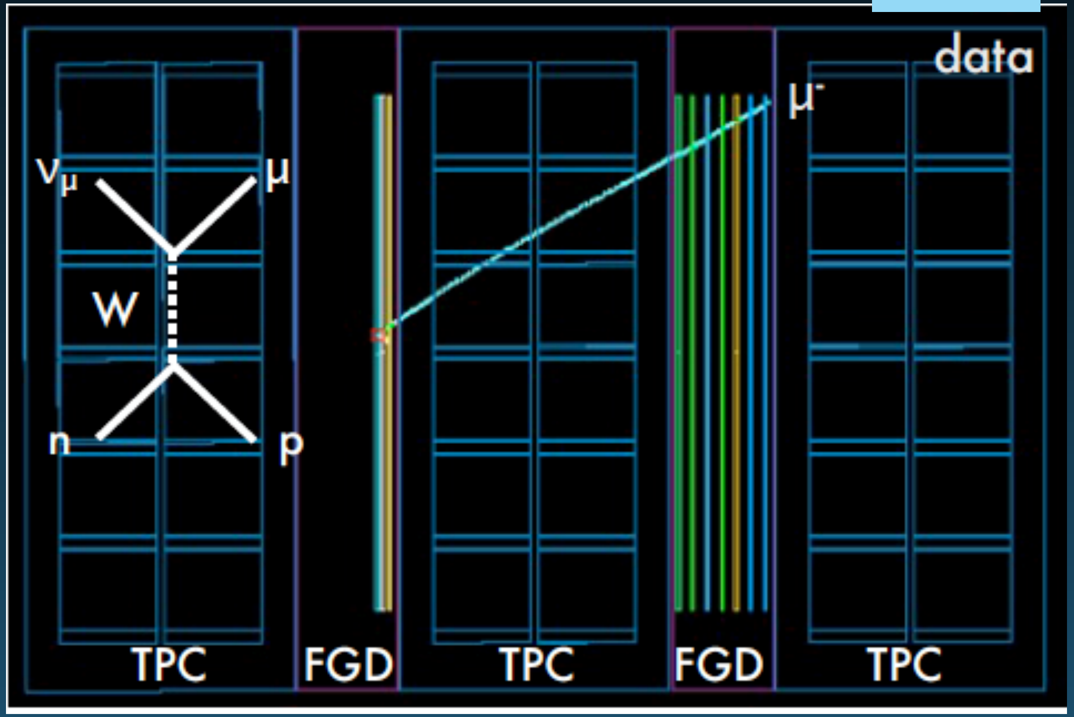
ND280 EVENT DISPLAYS PER FINAL STATE INTERACTION

Separate samples according to topologies:

- CC0π: CC interactions w/ 0 pions in the final state
- CC1π: CC interactions w/ 1 pion in the final state
- CC Other: anything else

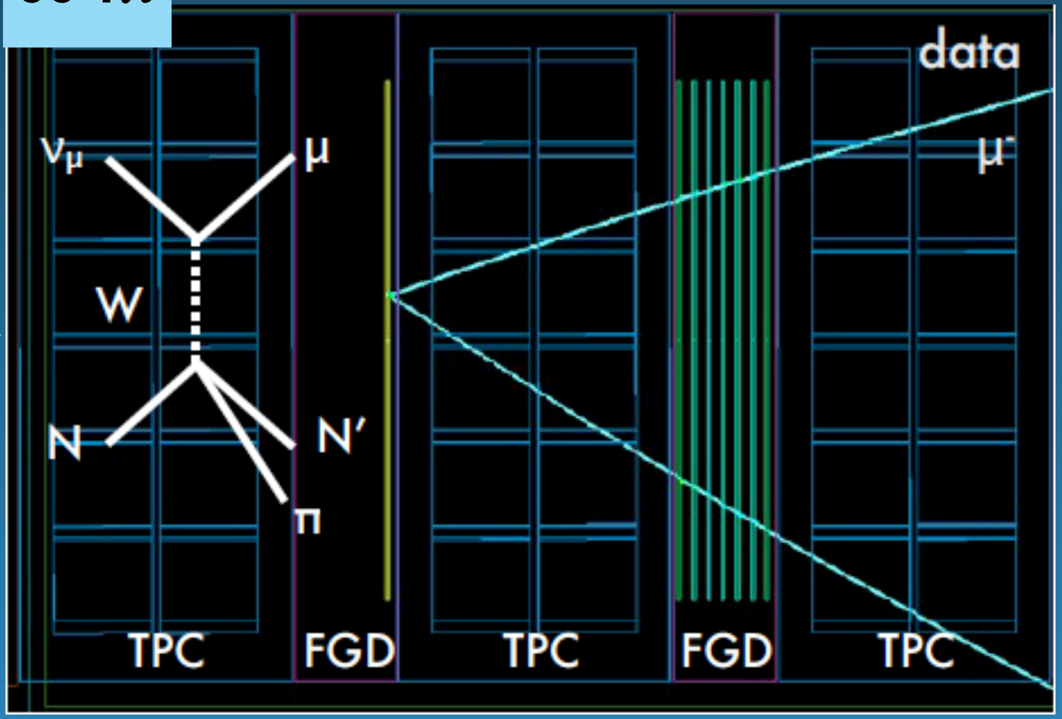
CC 0π

ν beam



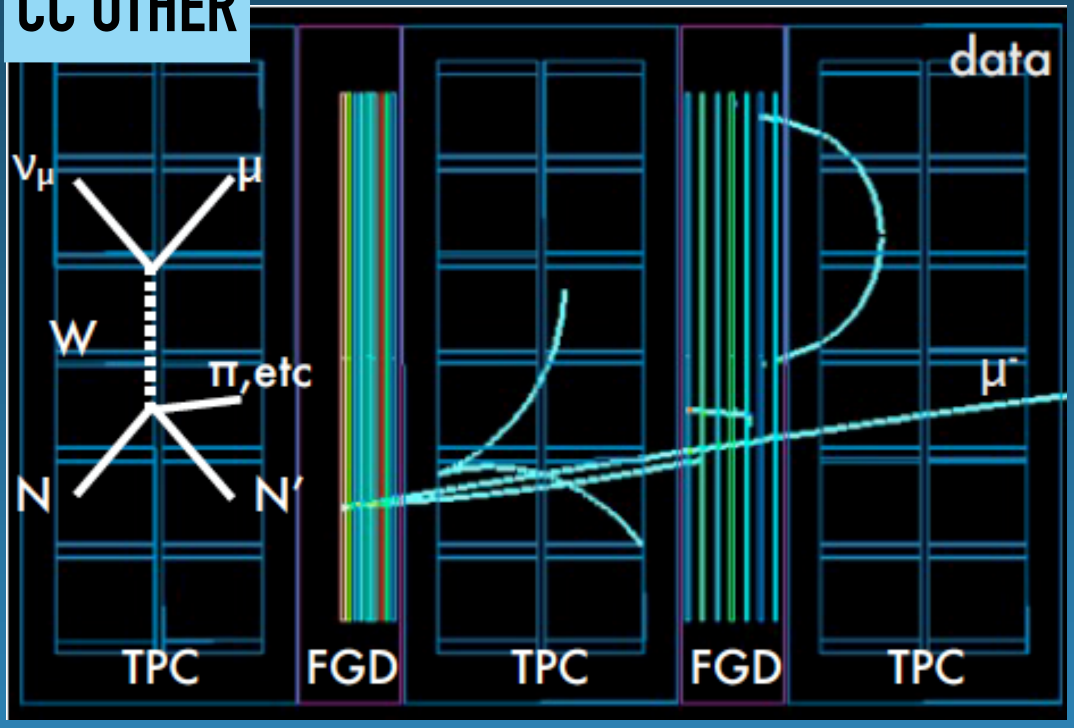
CC 1π

ν beam

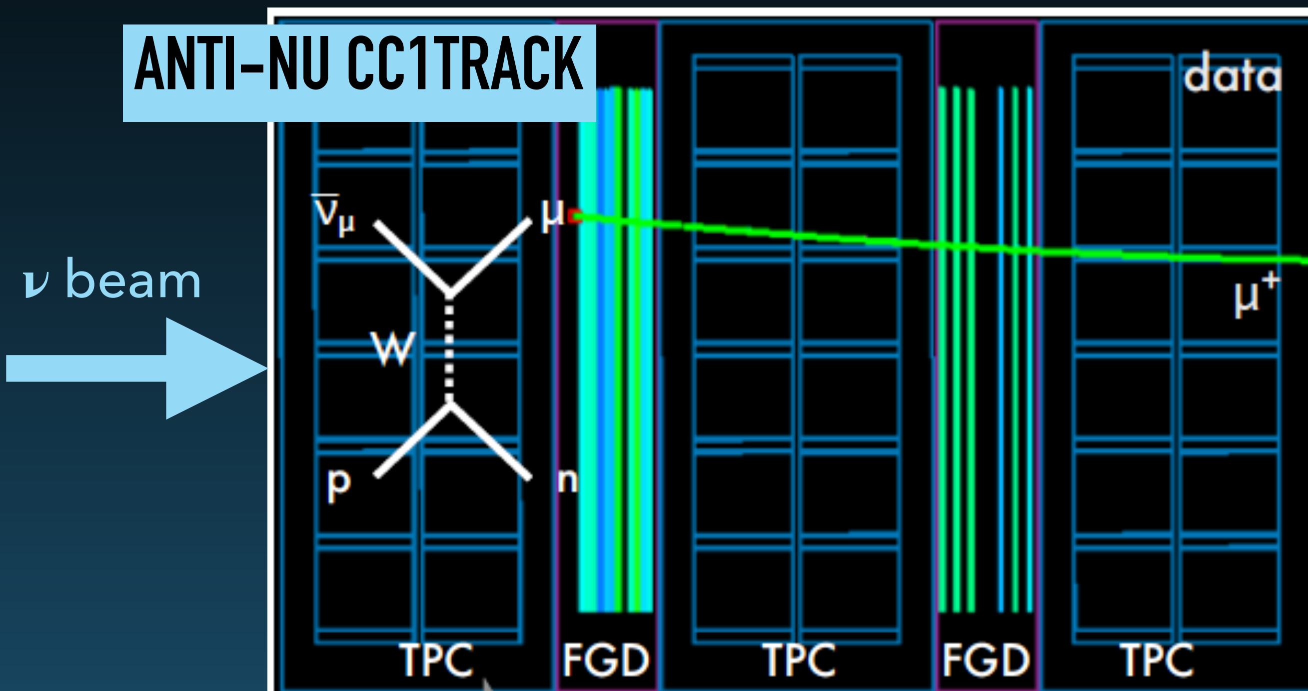


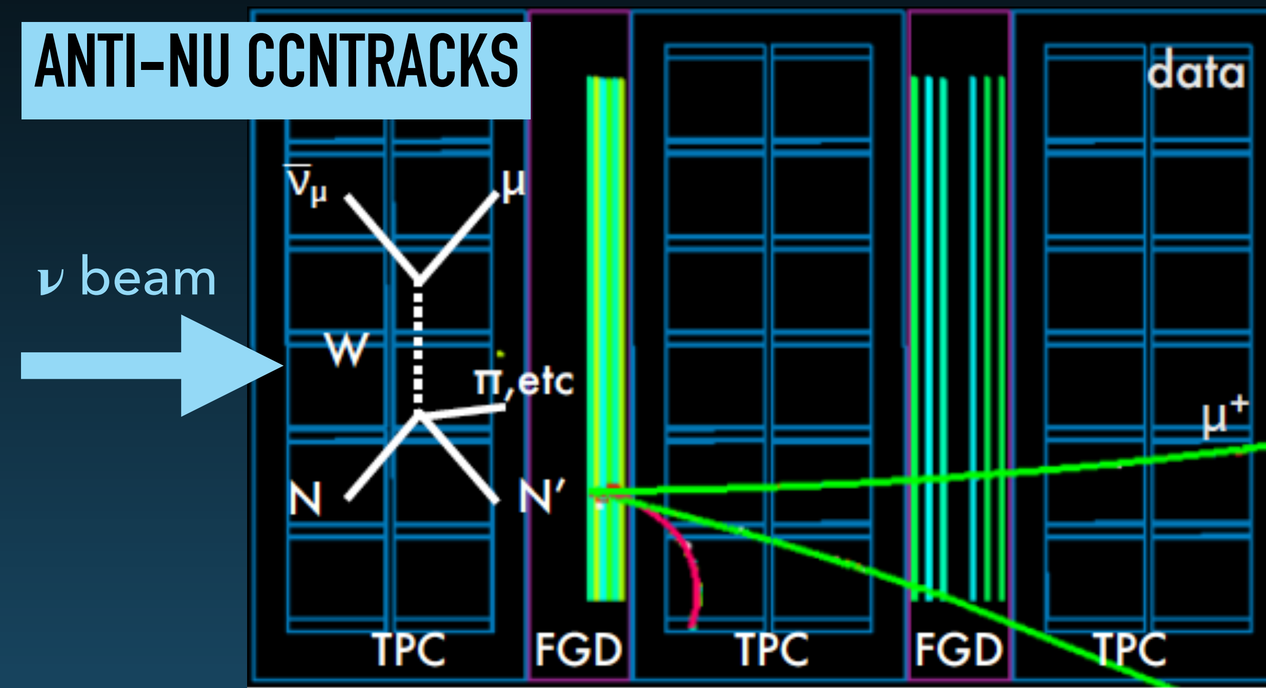
CC OTHER

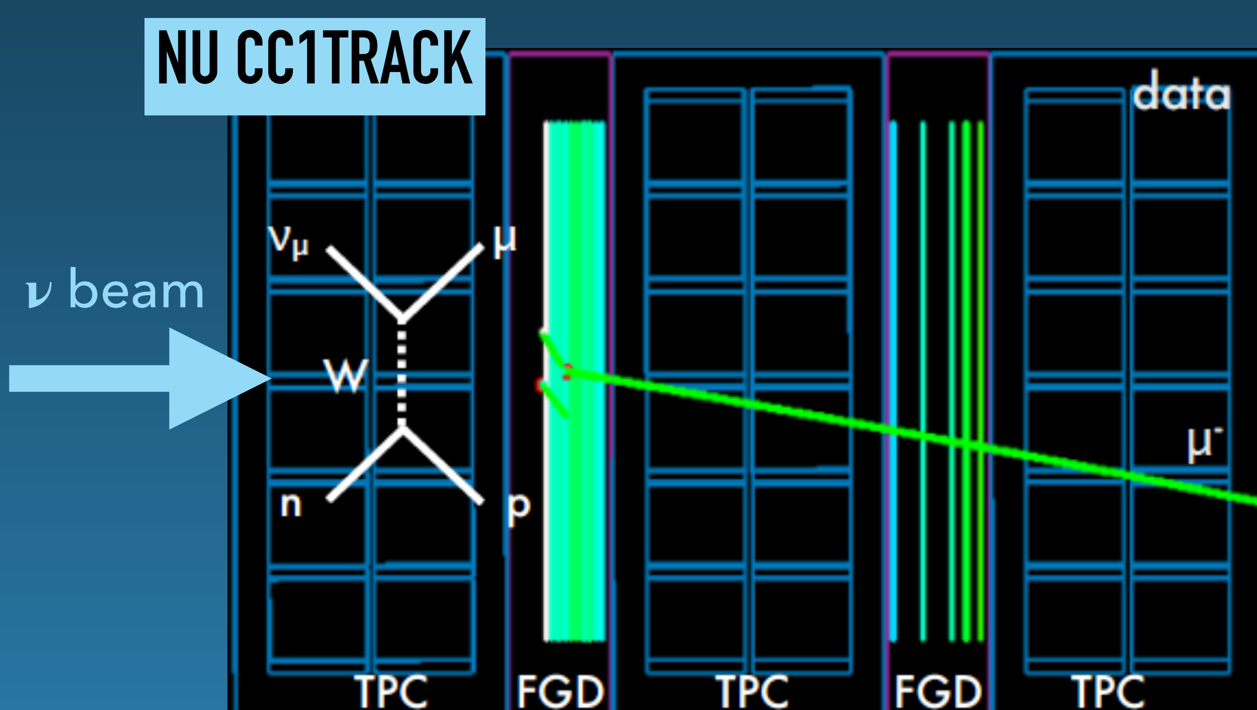
ν beam

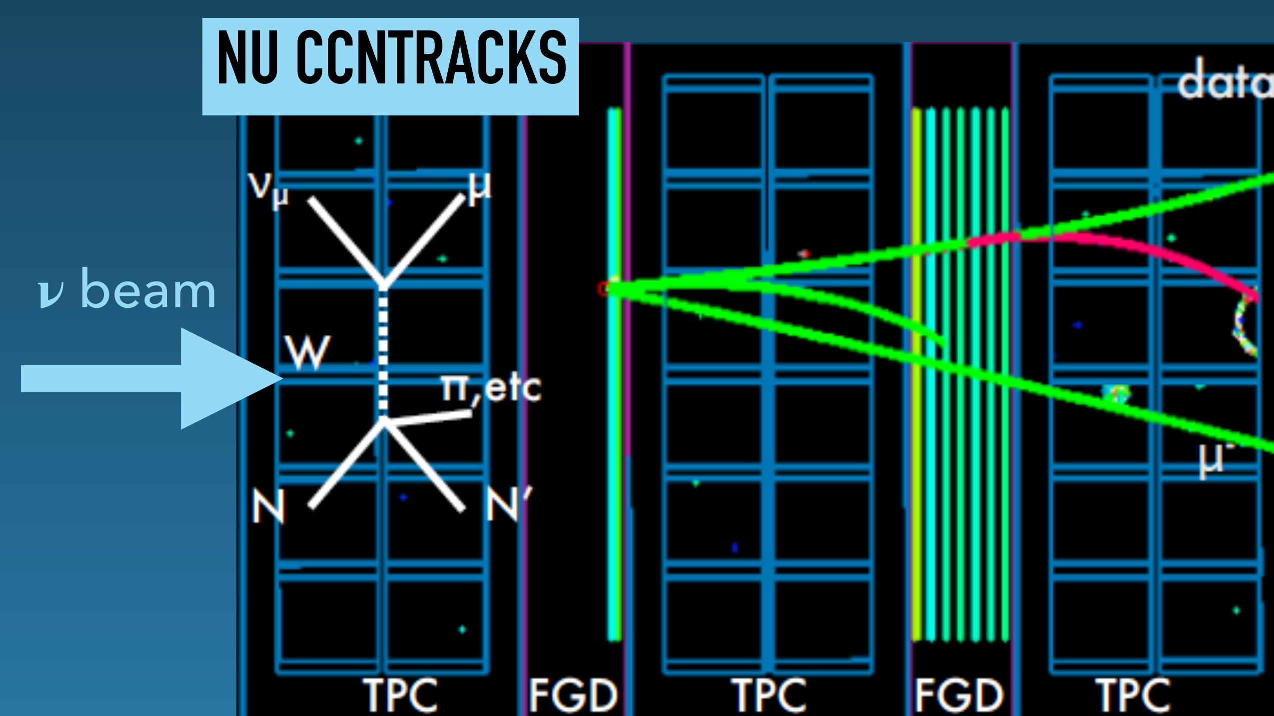


ANTINEUTRINO EVENT DISPLAYS AND BACKGROUNDS





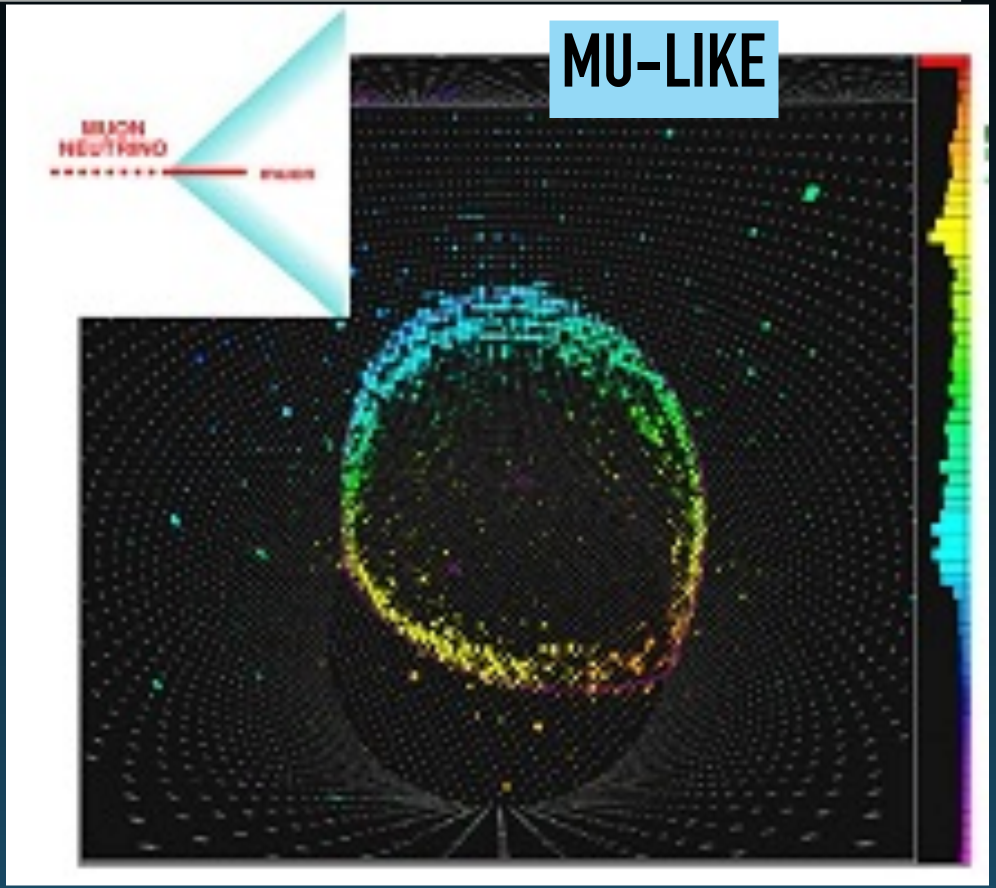


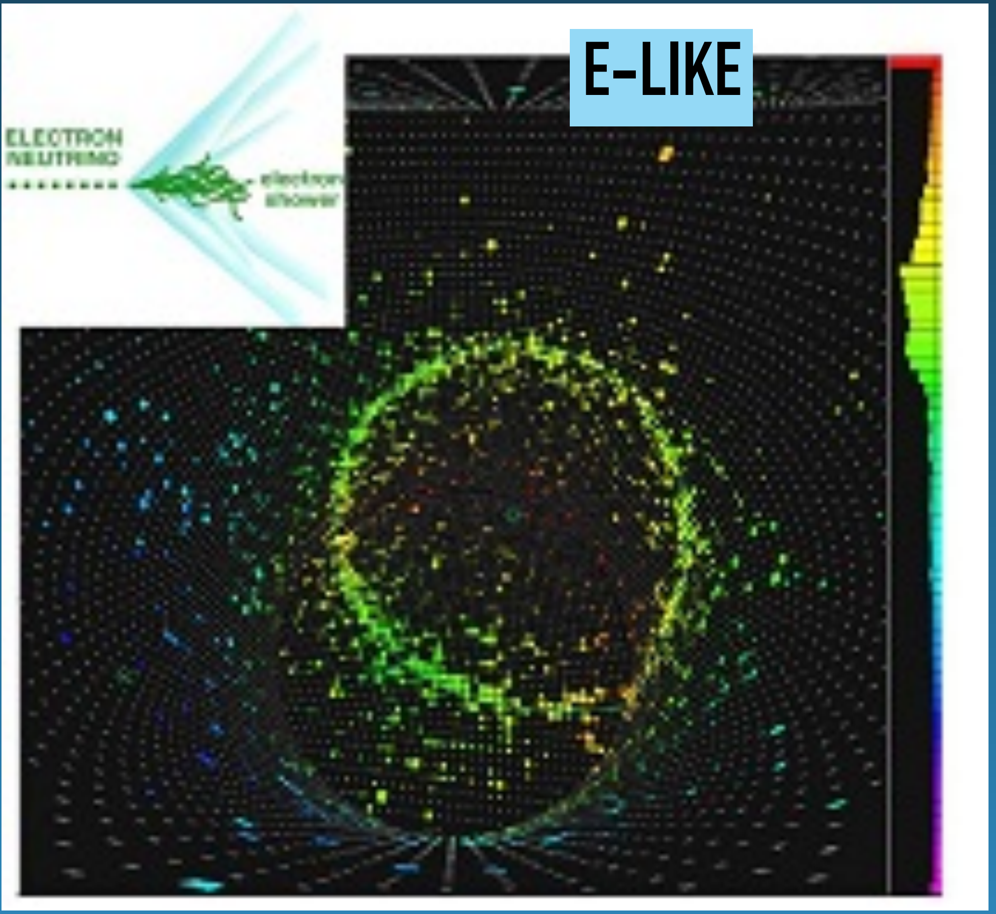


- Examples of antineutrino signal and background events

SUPER-KAMIOKANDE EVENT SELECTION

- Selection categories in Super-Kamiokande: e-like, μ-like events
- New this year:
  - an e-like 1-Michel electron sample in ν-dominated beam—this sample is dominated by resonant pion events
  - A new reconstruction algorithm that improves both efficiency and purity for all samples
- 66% of the data is ν-dominated beam; 34% $\bar{\nu}$-dominated beam





T2K OSCILLATION ANALYSIS

T2K analysis oscillation fit

To fit use:

- Flux predictions from MC and external data
- Near-detector fits to constrain flux and interaction model
- Data fit result reduces error on SK event rate predictions to about 5-9% depending on channel
- Event predictions at SK
- Event reconstruction and selection at SK
- Obtain combined fit of all oscillation parameters using all data channels

Neutrino Interaction Model

- Relativistic Fermi Gas (RFG) with dipole form factor
- 1p1h (scattering off single nucleon) uses Random Phase Approximation parameters from Valencia group, applied to our RFG model
- 2p2h (scattering off correlated nucleon pairs) model also from Valencia group (Nieves et al.).
- Single- and multi-pion uses models by Rein and Sehgal normalized to match D_2 bubble chamber (resonant, non-resonant) and MINERvA (coherent) data
- Deep Inelastic Scattering through PYTHIA 5.9
- FSI via Salcedo Oset and Bertini cascade models, tuned to external pion nucleon scattering data
- We fit parameters for all these models (and flux model) to the ND280 data

SYSTEMATICS

	FHC 1R-μ	RHC 1R-μ	FHC 1R-e	FHC 1R$-e$ +d.e.	RHC 1R-e	FHC / RHC
ND prediction	2.9%	2.7%	3.0%	2.9%	3.8%	2.3%
Unconstrained	0.3%	0.3%	2.8%	3.0%	2.9%	3.4%
Binding Energy	3.4%	1.7%	7.3%	3.7%	3.0%	2.3%
SK Detector	3.3%	2.8%	4.1%	4.4%	17.4%	2.1%
Total	**4.9%**	**4.3%**	**8.8%**	**7.0%**	**18.3%**	**5.9%**
Stat $\sqrt{N}$ $\delta = \pi/2$ $\delta = -\pi/2$	6.1%	10.2%	11.6 ~ 14.1%	38.0 ~ 45.1%	29.1 ~ 25.9%	—

Indicative errors on the total rate —actual analysis doe not use these!

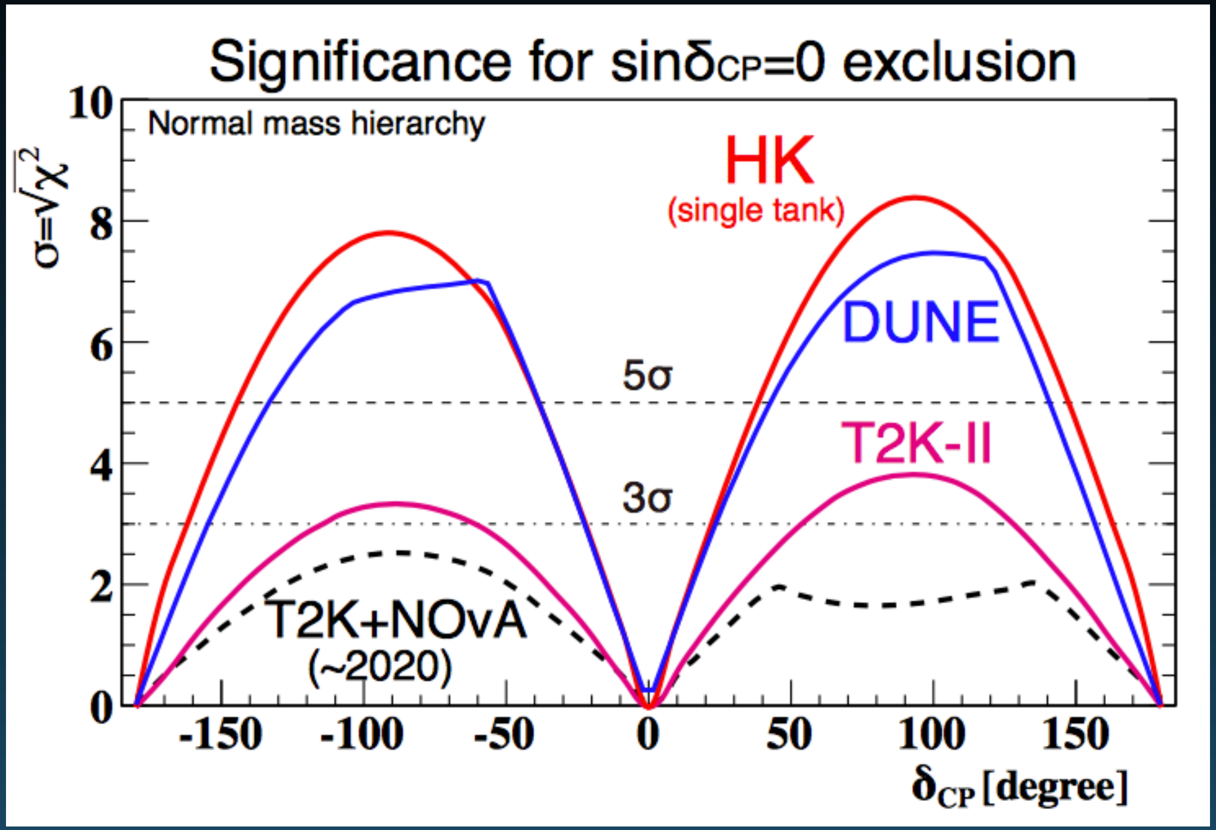
ND prediction: Extrapolated flux and constrained interaction effects

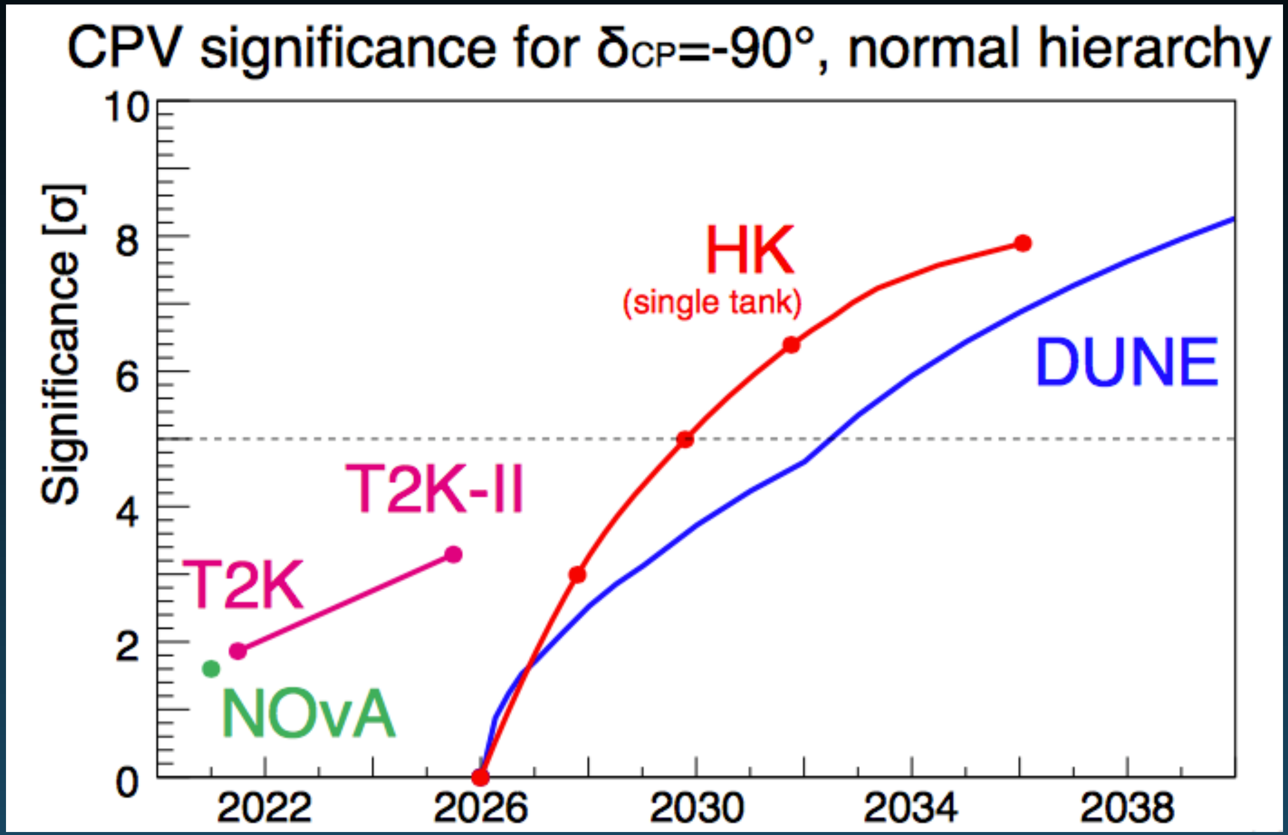
Unconstrained: Cross-sections not constrained by ND280 [Naïve sum]

Binding Energy: Parameterised residual of effect after ND280 prediction

SK Detector: Reconstruction and re-interactions

CP VIOLATION SENSITIVITY

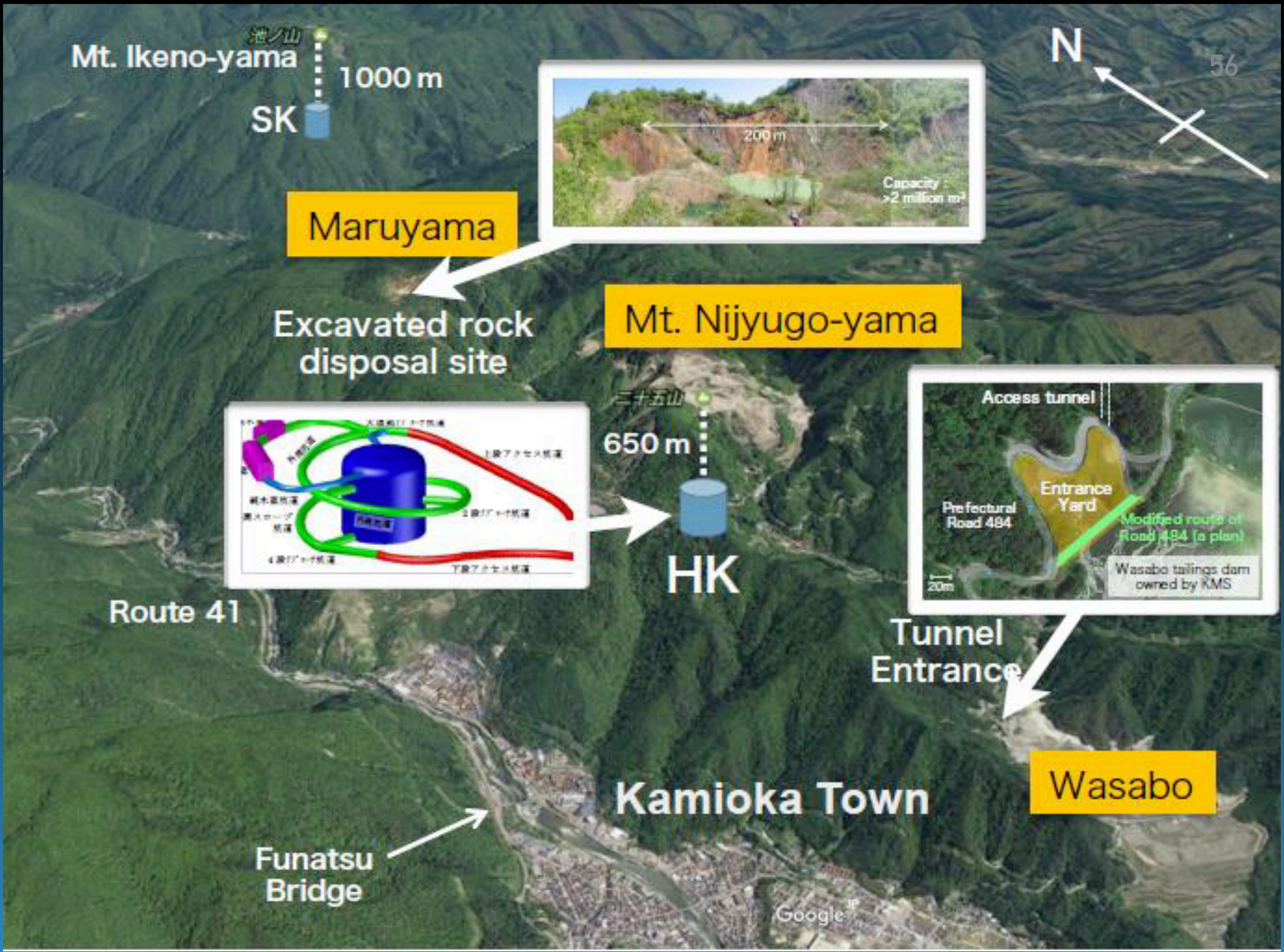




- Exclusion of sinδ_{CP} = 0
  - 8σ for δ = -90°(T2K best fit)
  - 80 % of coverage of δ parameter space for CPV discovery > 3σ
- After 10 years of running, HK will be able to measure ~50% of the δ_{CP} space to better than 5σ

- δ_{CP} precision measurement
  - 22°for δ = -90°
  - 7°for δ = 0°

Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K
- Realistic systematic uncertainties plus expected reduction of errors
- 3~4% syst. Error (6~7% in T2K)


Mt. Ikeno-yama
1000 m
SK
200 m
Capacity :
>2 million m³
N
Maruyama
Excavated rock
disposal site
Mt. Nijyugo-yama
650 m
HK
Access tunnel
Entrance
Yard
Prefectural
Road 484
Modified route of
Road 484 (a plan)
Wasabo tailings dam
owned by KMS
20m
Route 41
Tunnel
Entrance
Wasabo
Kamioka Town
Funatsu
Bridge
Google

SURVEY AND CAVERN DESIGN

- Seismic tomography and reflection imaging were conducted for $(400\ m)^3$ wide area
- An excellent site was identified