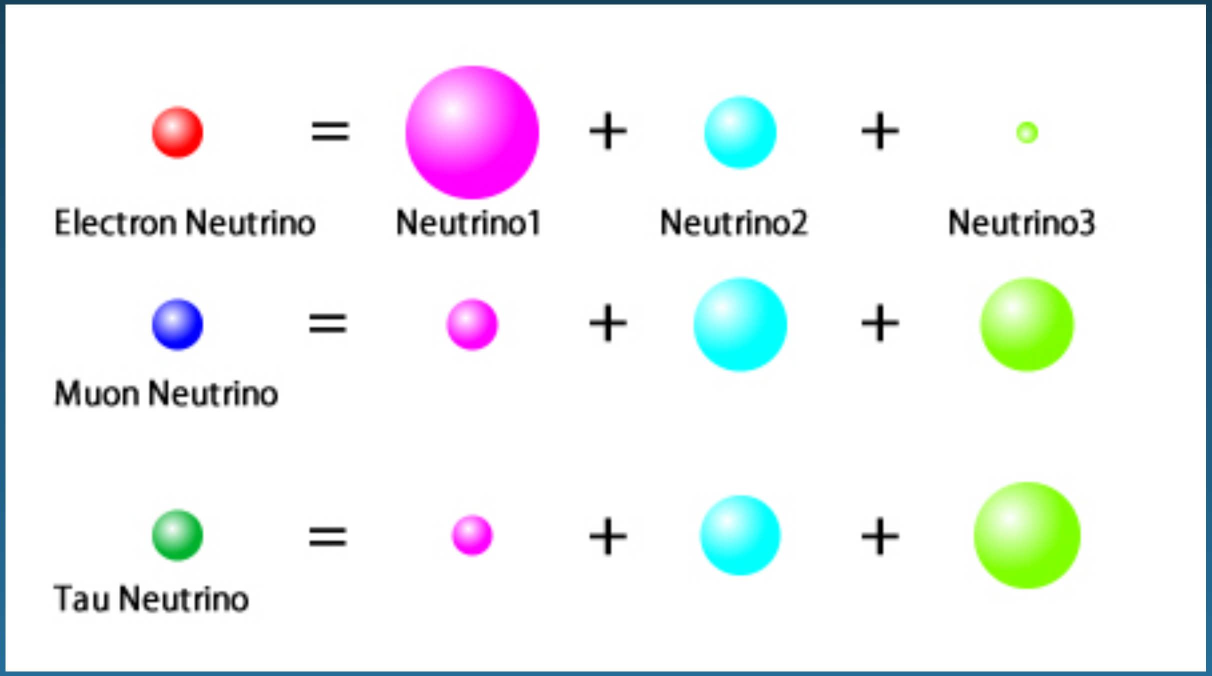
KMI 2019
International Symposium

FRANCESCA DI LODOVICO
QMUL

STATUS AND PROSPECT OF NEUTRINO CP VIOLATION AND BARYON NUMBER VIOLATION

NEUTRINO OSCILLATIONS

- Create in one flavour detect in another.
- Each flavour state is a superposition of different mass states.



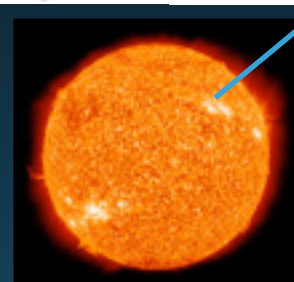
- The relationship between these mass/flavour states is given by the PMNS (Pontecorvo, Maki, Nakagawa, Sakata) matrix.

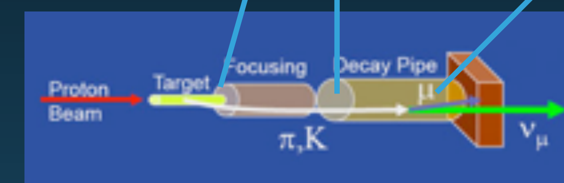
PMNS MATRIX

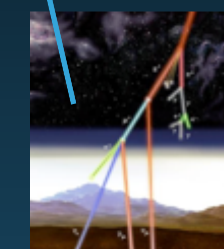
$c_{ij}=\cos\theta_{ij} \quad s_{ij}=\sin\theta_{ij}$

"Solar" "Reactors"/Long baseline "Atmospherics"

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$







- Free parameters usually written in terms of three rotation angles and 1 complex phase: θ_{12}, θ_{23}, θ_{13}, δ_{CP}
- In the two-flavour approximation: $$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(1.27\Delta m^2[eV^2]\frac{L[km]}{E[GeV]}\right)$$

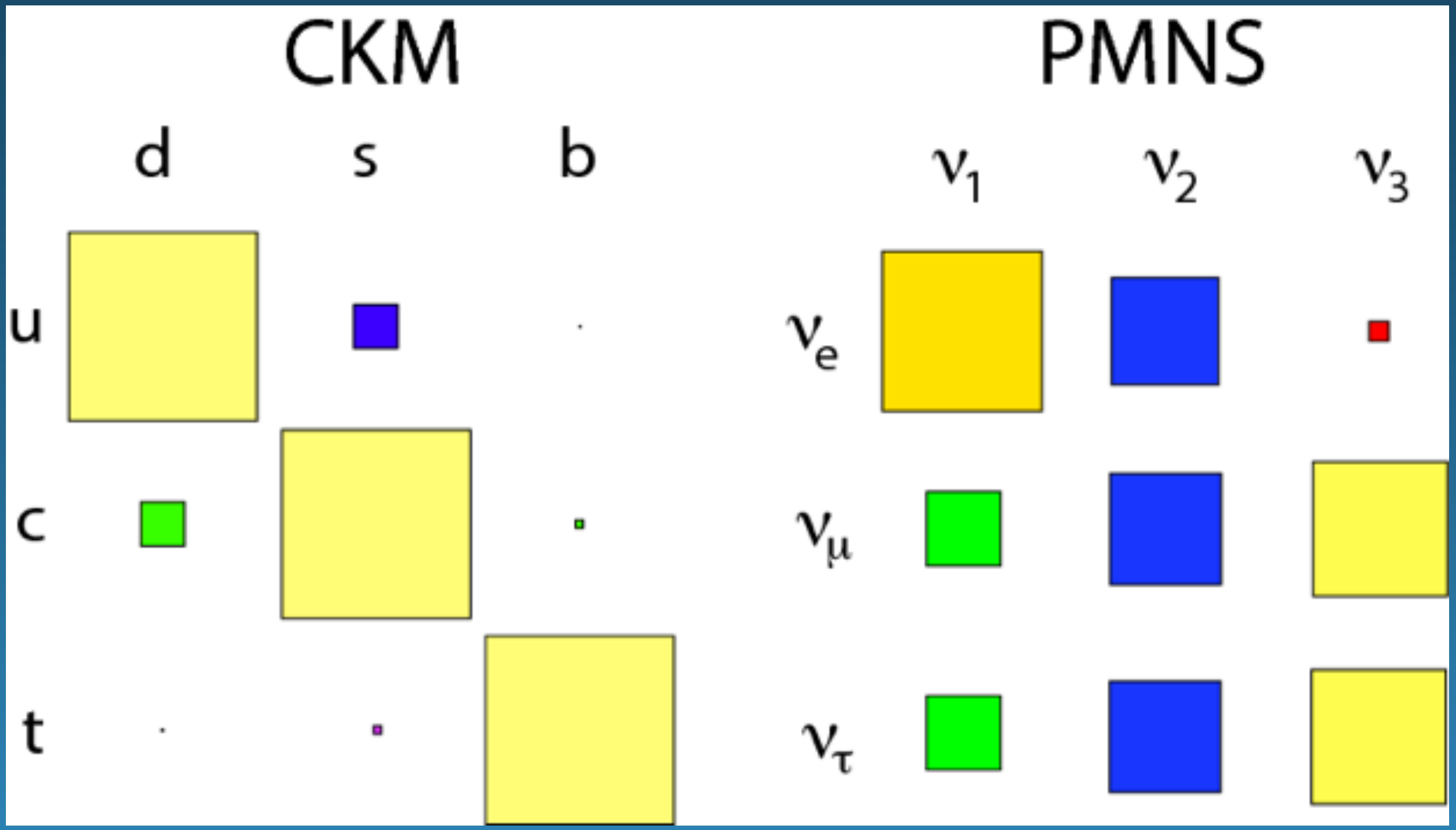
$\lvert\Delta m^2_{32}\rvert \equiv \lvert m^2_3 - m^2_2\rvert \approx 2\times10^{-3}\,eV^2$ $\nu_\mu \rightarrow \nu_\mu$ $\nu_\mu \rightarrow \nu_\tau$ Atmospherics and long baselines	$\lvert\Delta m^2_{31}\rvert \approx \lvert\Delta m^2_{32}\rvert$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_\mu \rightarrow \nu_e$ Reactor and long baselines	$\lvert\Delta m^2_{21}\rvert \approx 8\times10^{-5}\,eV^2$ $\bar{\nu}_e \rightarrow \bar{\nu}_e$ $\nu_e \rightarrow \nu_\mu + \nu_\tau$ Reactor and solar

- $\Delta m^2 = \lvert m^2{}_1 - m^2{}_2\rvert\ [eV^2]$
- L=distance to source
- E=neutrino energy

MEASURED PARAMETERS

The six parameters measurable in neutrino oscillations:

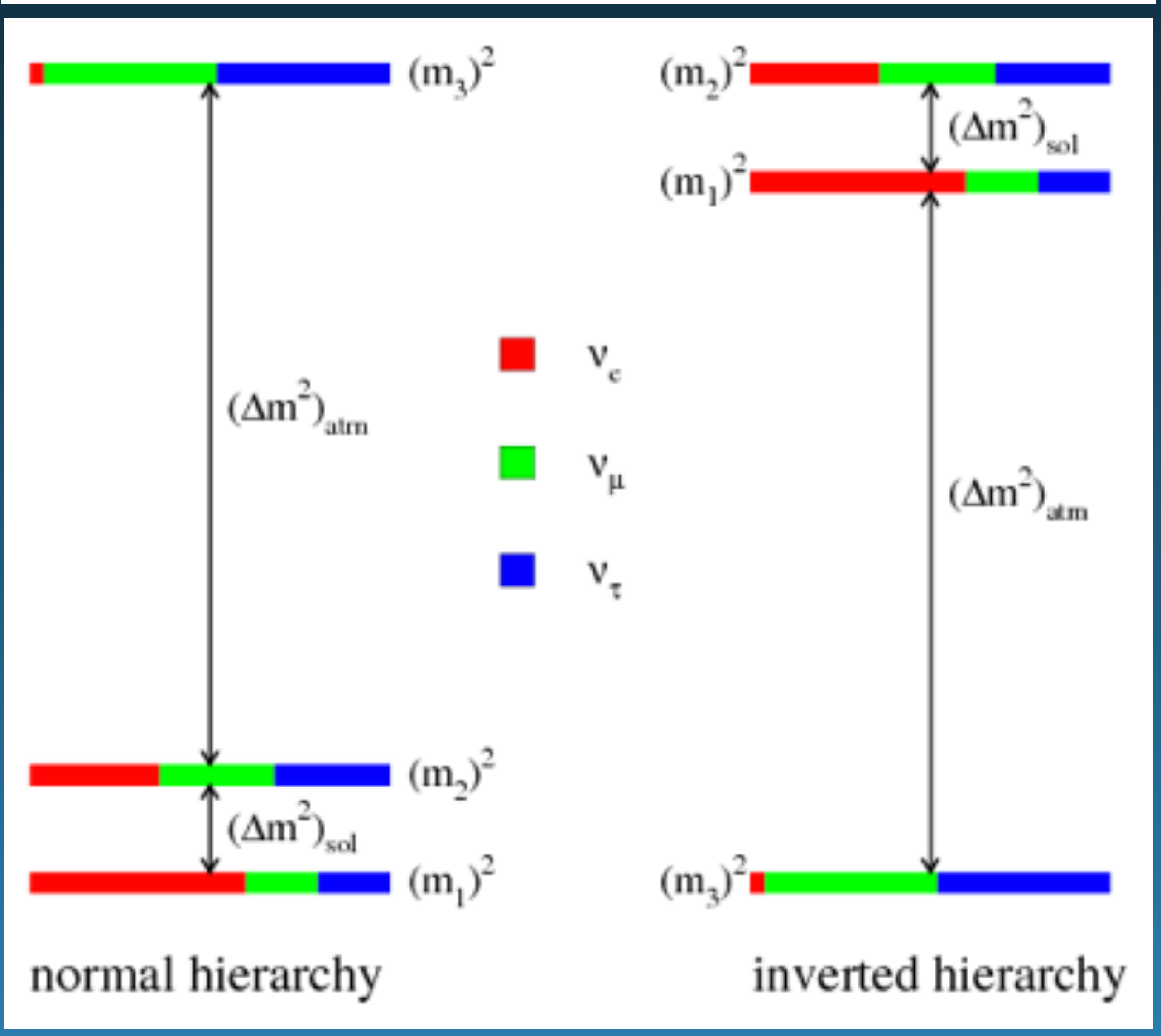
- The atmospheric mass square difference Δm^2_{23}
- The solar mass square difference $\Delta m^2_{12} = m^2_2 - m^2_1$
- The atmospheric angle θ_{23}
- The solar angle θ_{12}
- The reactor angle θ_{13}
- The CP violating phase δ_{CP}

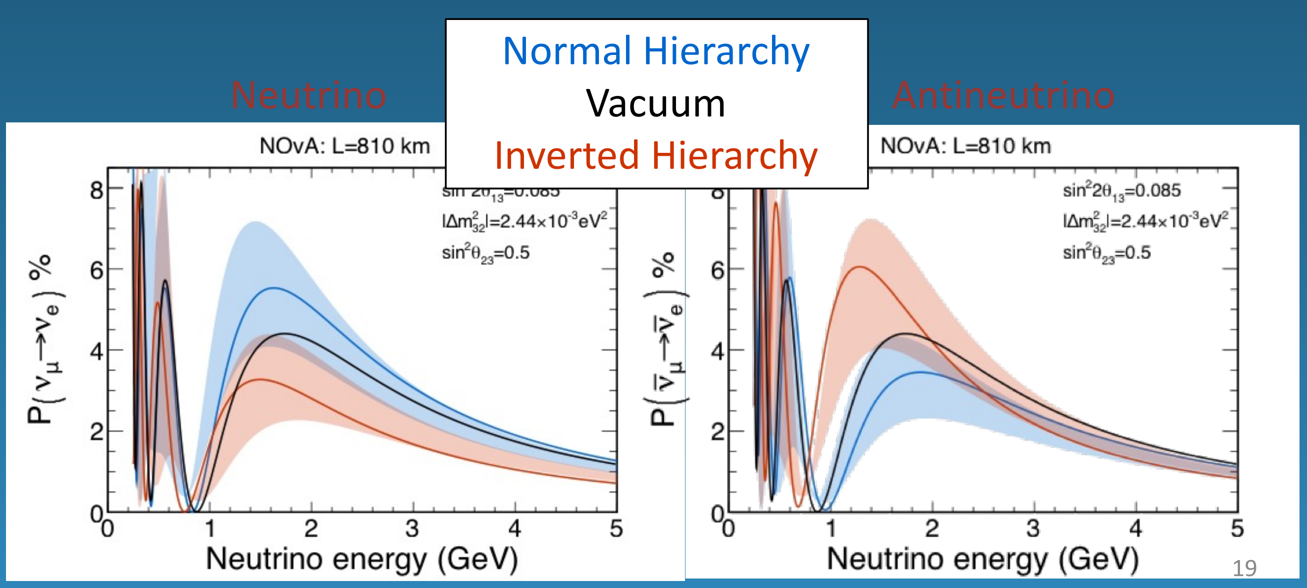


OPEN QUESTIONS

- What is the mass hierarchy?
- There are two possible mass splitting:
  - $|\Delta m^2_{32}|$ = measured in atmospheric and LBN experiments. <u>The sign is unknown.</u>
  - Δm^2_{12} = measured in solar and reactor experiments
- There are two possible mass hierarchies:
  - Normal Hierarchy ($m_1<m_2<m_3$)
  - Inverted Hierarchy ($m_3<m_1<m_2$)
- Enhancement or suppression depending on hierarchy.

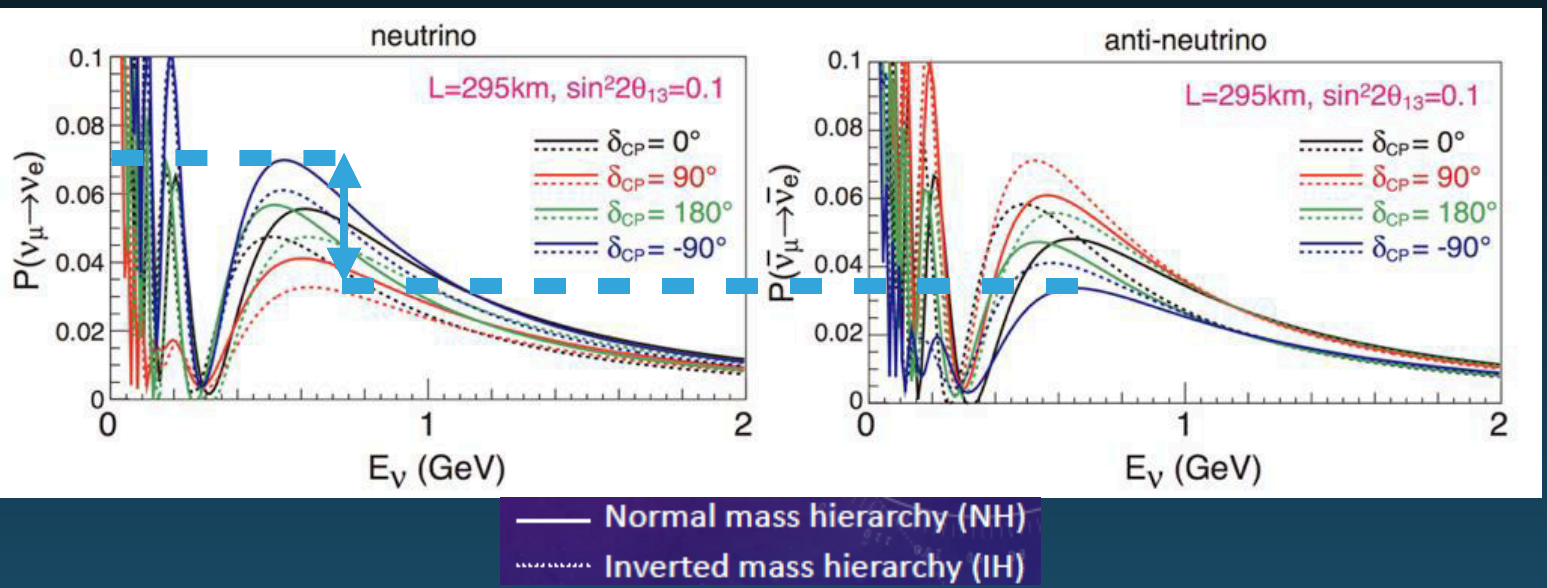
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$





OPEN QUESTIONS

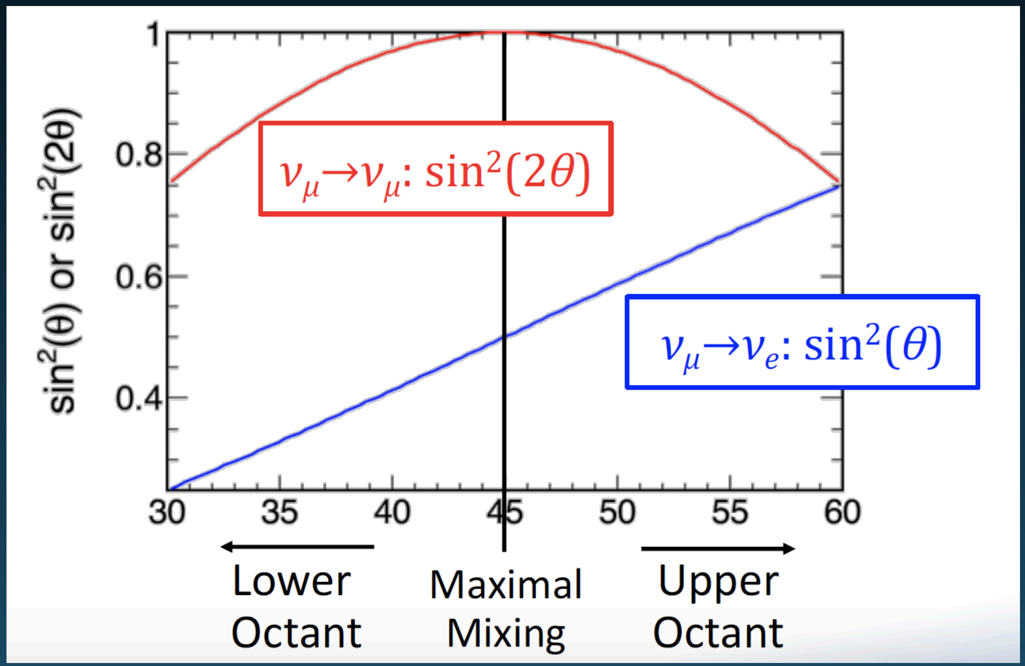
Do neutrino oscillations violate CP symmetry?



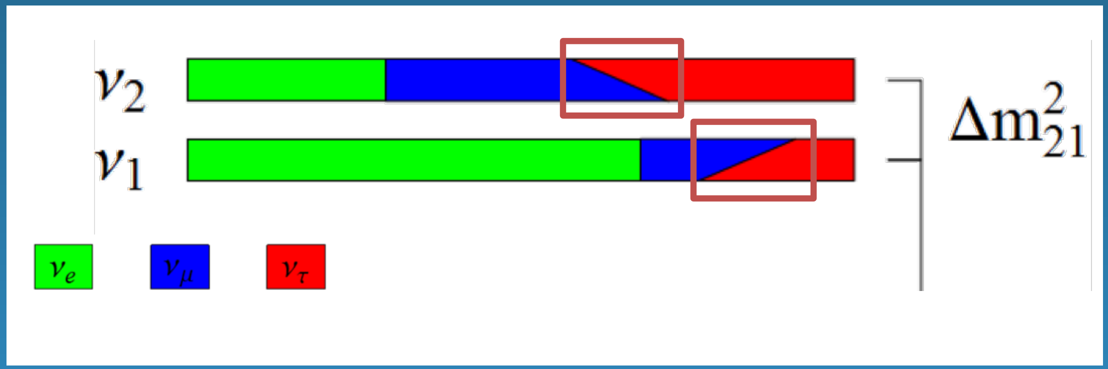
- Only in an *appearance* measurement since *CPT* requires the disappearance probabilities to be the same

  $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- Possibly relevant for understanding origin of matter-dominated Universe (Leptogenesis)

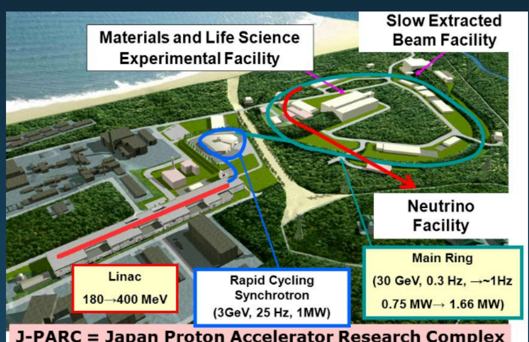
θ_{23} degeneracy (how close to 45°?)

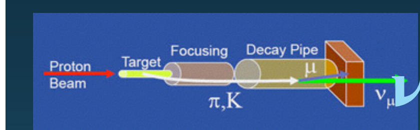


- What is the "octant" of θ_{23}?
- What is the balance ν_μ and ν_τ?
- Or is the mixing "maximal" (e.g. even split)?



LONG BASELINE NEUTRINO EXPERIMENTS





~100 m

ν beam

NEAR DETECTOR

~100-1000 km

ν beam

FAR DETECTOR

$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$$

Neutrino flux prediction | Neutrino cross section model | Near detector selection, efficiency

- Predicted events in the Near Detector.

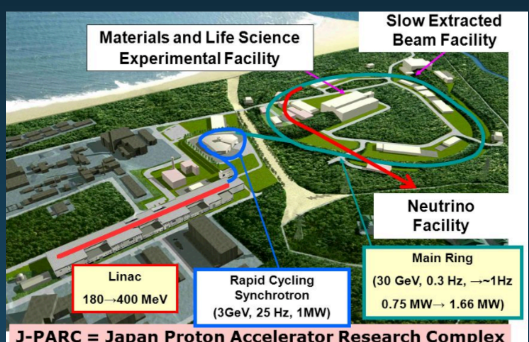
- Predicted events in the Far Detector.

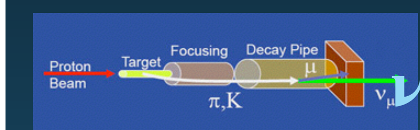
$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD}P(\nu_\alpha \to \nu_\beta)$$

Neutrino flux prediction | Neutrino cross section model | Far detector selection, efficiency

LONG BASELINE NEUTRINO EXPERIMENTS

- Running LBN: T2K & NOvA
  - A joint analysis working group has just started.
  - Joint results will be available in the future.
- Planned LBN: Hyper-Kamiokande & DUNE (+ others)





~100 m

~100-1000 km

ν beam

NEAR DETECTOR

ν beam

FAR DETECTOR

$$N_{ND} \sim \Phi_{ND}(E_\nu)\sigma(E_\nu)\varepsilon_{ND}$$

Neutrino flux prediction | Neutrino cross section model | Near detector selection, efficiency

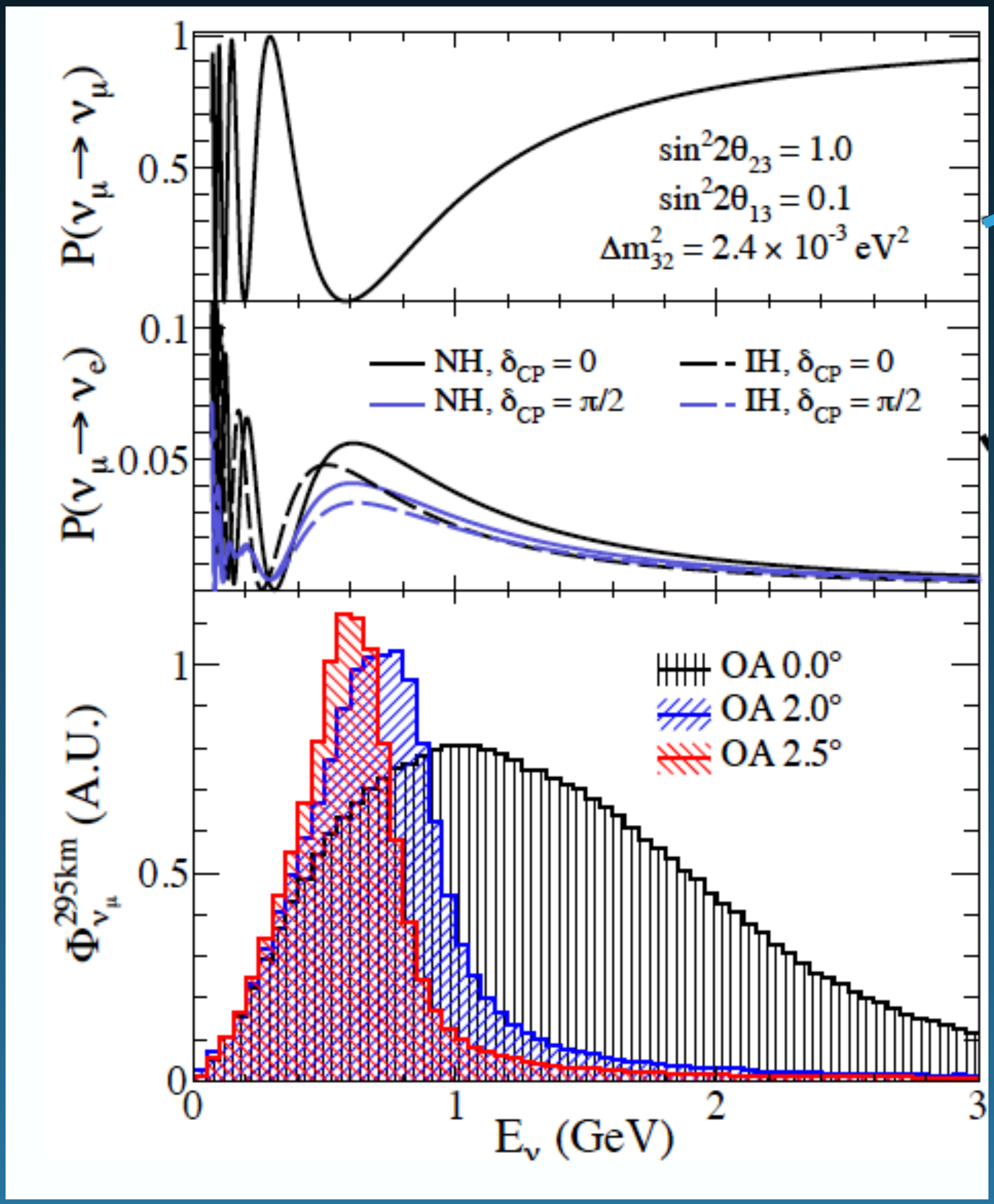
- Predicted events in the Near Detector.

- Predicted events in the Far Detector.

$$N_{FD} \sim \Phi_{FD}(E_\nu)\sigma(E_\nu)\varepsilon_{FD} P(\nu_\alpha \rightarrow \nu_\beta)$$

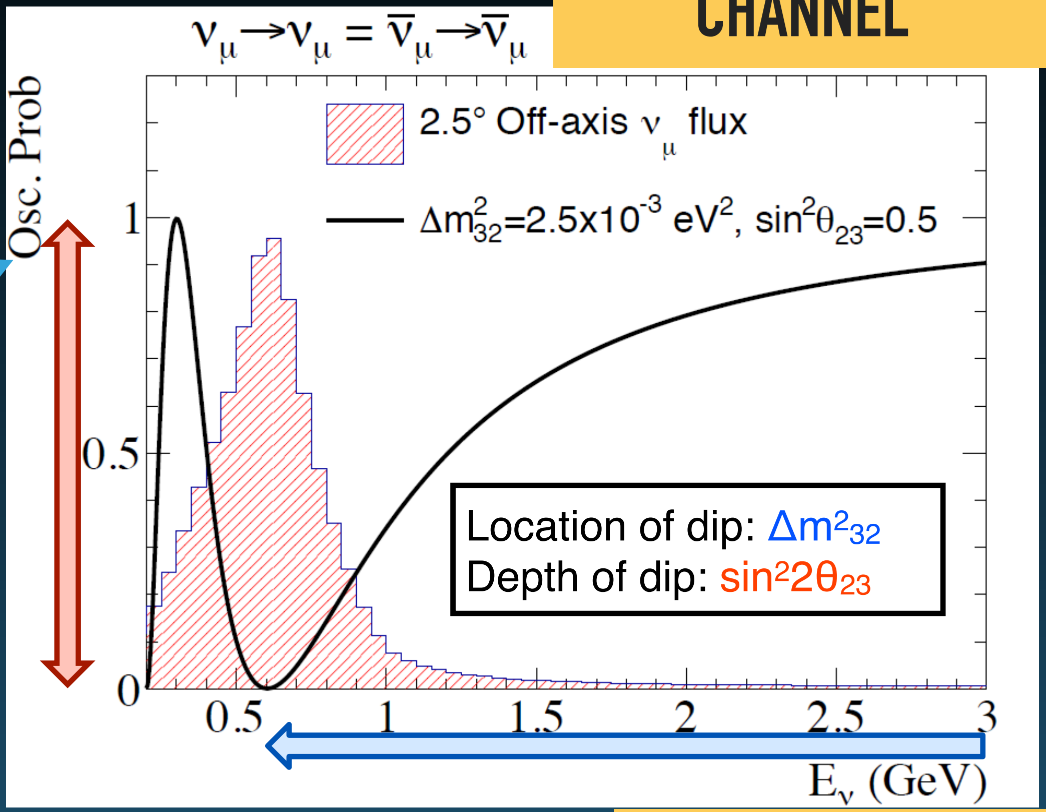
Neutrino flux prediction | Neutrino cross section model | Far detector selection, efficiency

APPEARANCE AND DISAPPEARANCE MEASUREMENTS

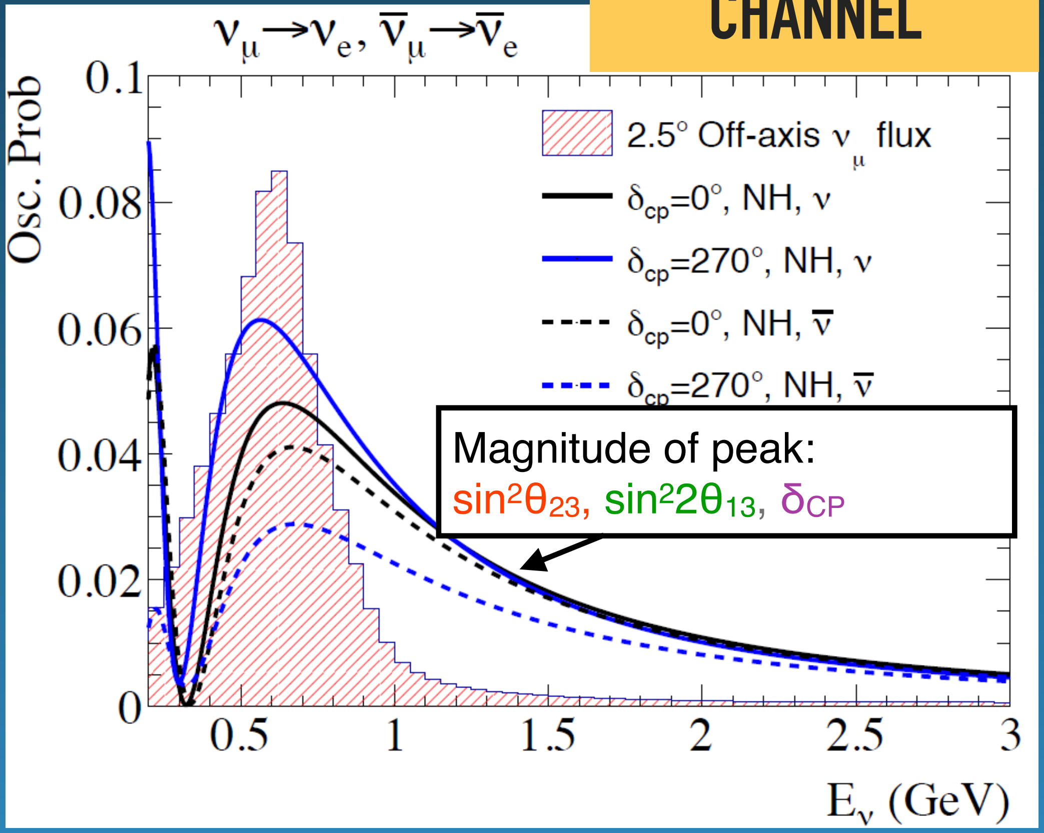


A.U. = Arbitrary Units

DISAPPEARANCE CHANNEL



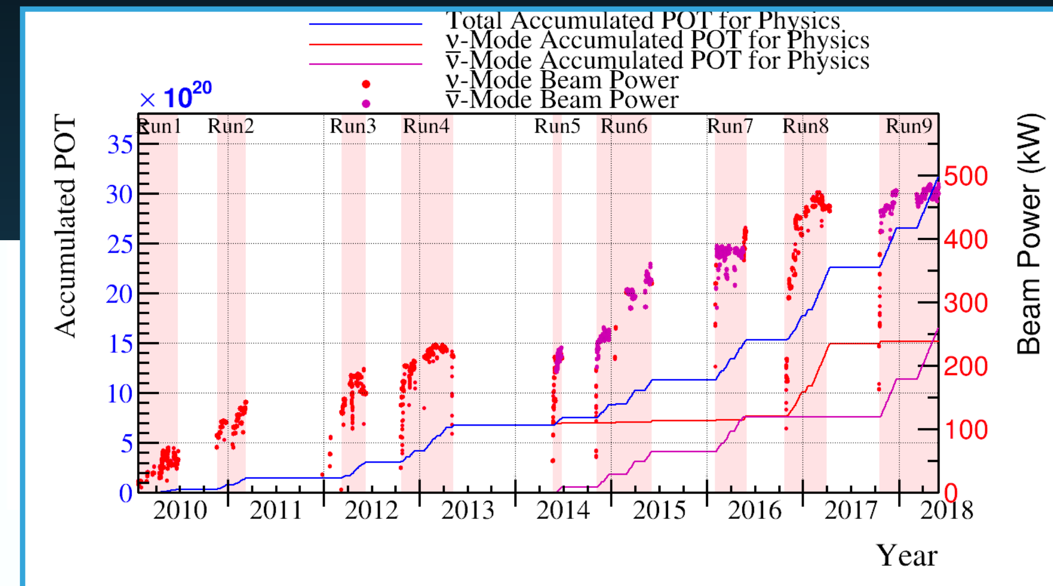
APPEARANCE CHANNEL

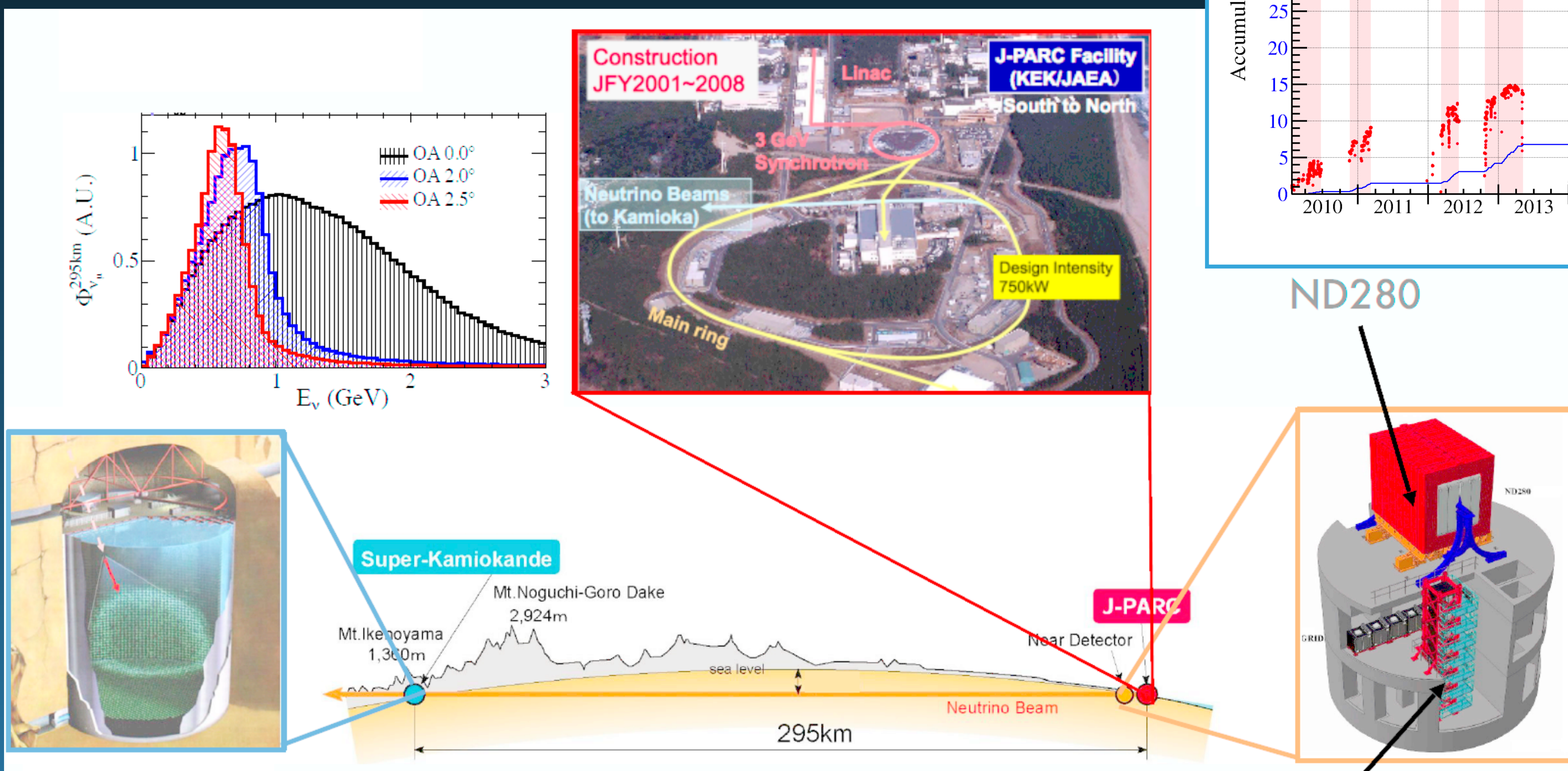


- Enhanced for ν if $-\pi<\delta_{CP}<0$
- NO/NH also enhances ν

T2K OVERVIEW

- Jan. 20 2010 ~ May 31 2018 3.16 x10^{21} Protons On Target (POT) so far
  - 1.51 x10^{21} POT ν-Mode + 1.65x10^{21} POT $\bar{\nu}$-Mode

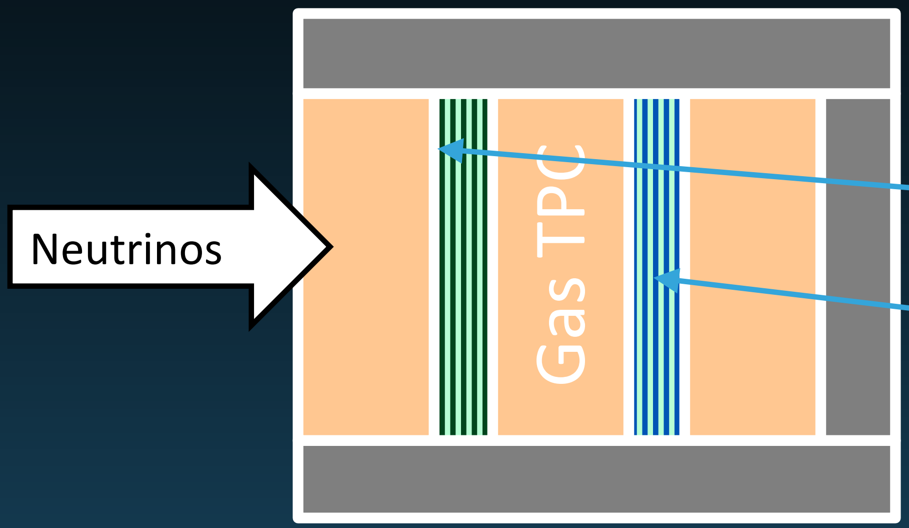




INGRID

- Latest oscillation results based on:
  - 3.13x10^{21} = ~1.49 x10^{21} ν + ~1.63x10^{21} $\bar{\nu}$ POT
  - 40% of the total approved T2K statistics

CONSTRAINTS USING ND280



Analysis uses pairs of samples from 2 active target volumes

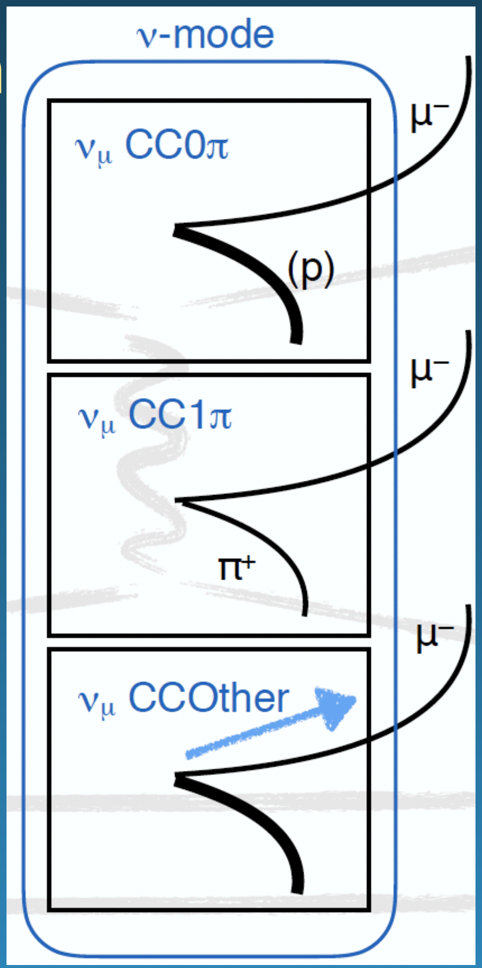
Pure scintillator: **Carbon** (+H)

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

Allows separate constraints for C vs O nuclear effects

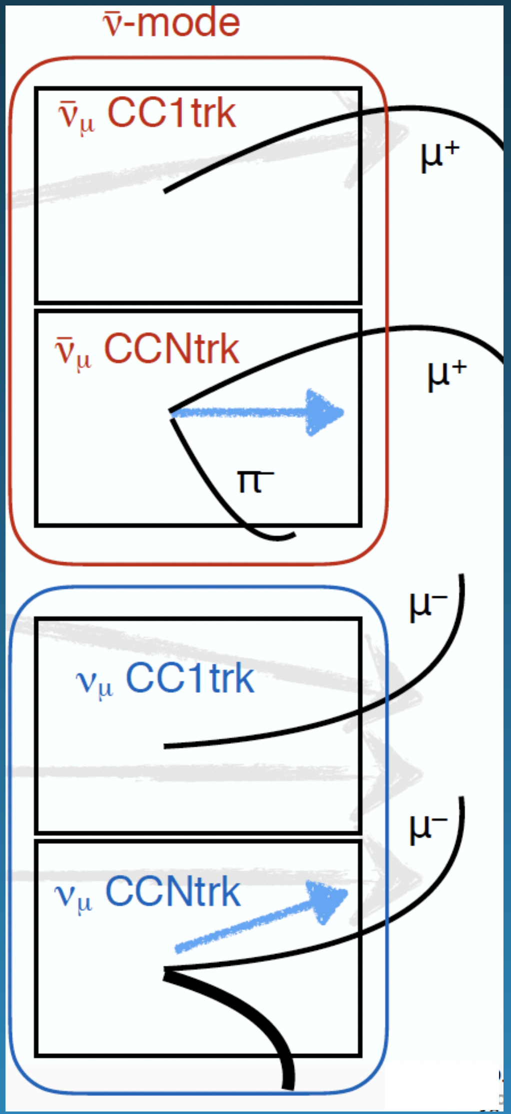
Neutrino beam

- 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)

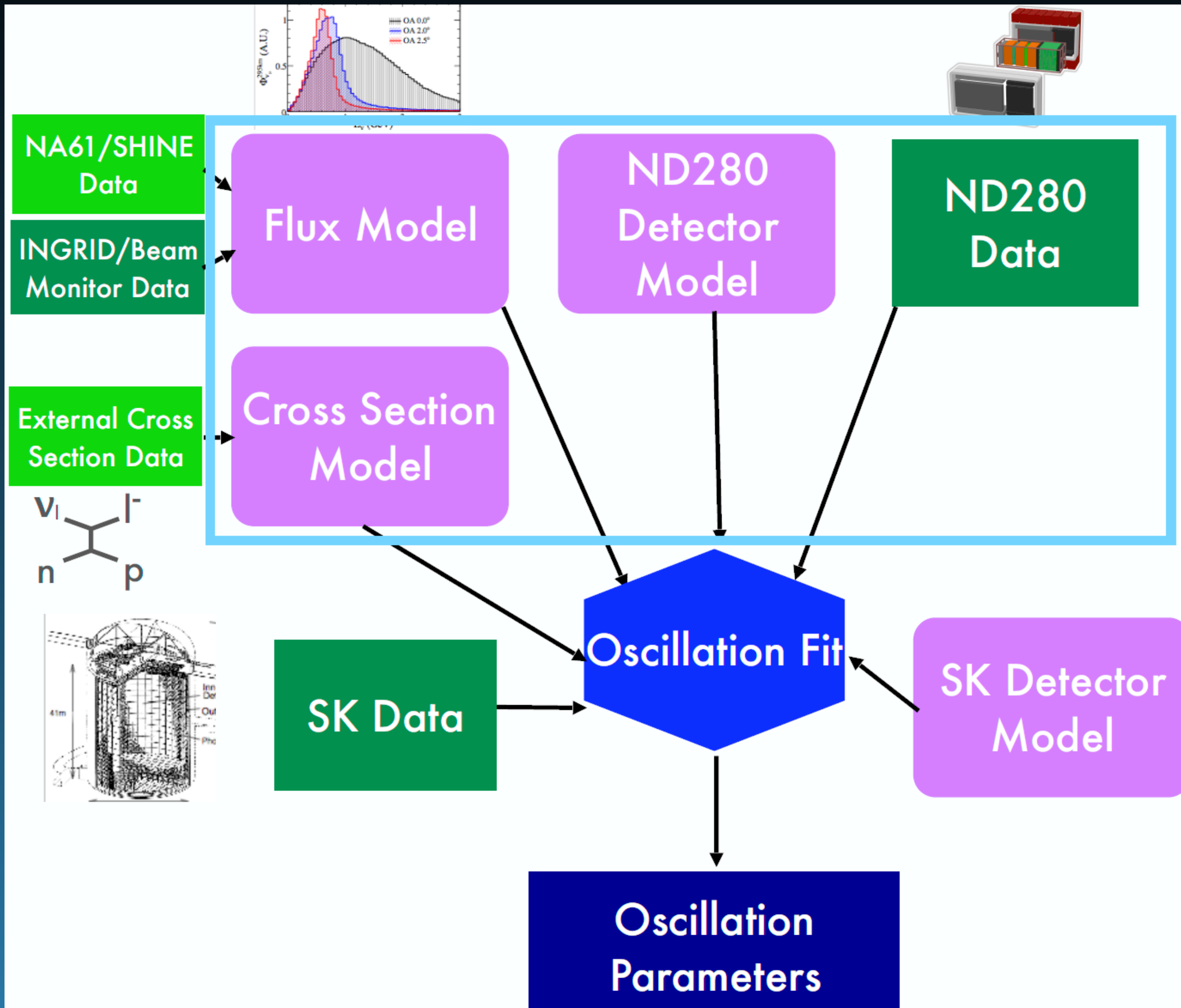


Pion collection & focussing depends on Horn Current

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

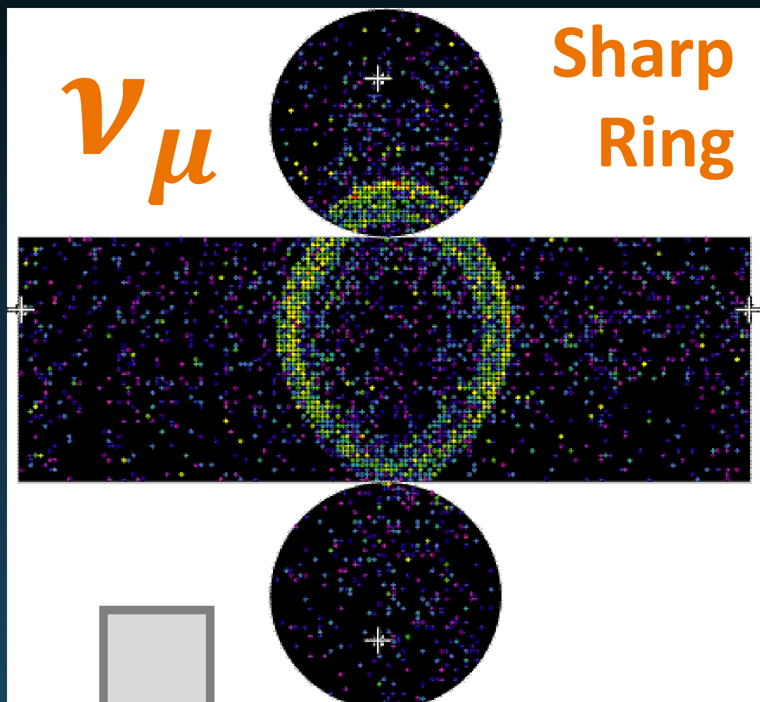
Reverse Horn Current (RH): $\pi^- \to \mu^- + \bar{\nu}$

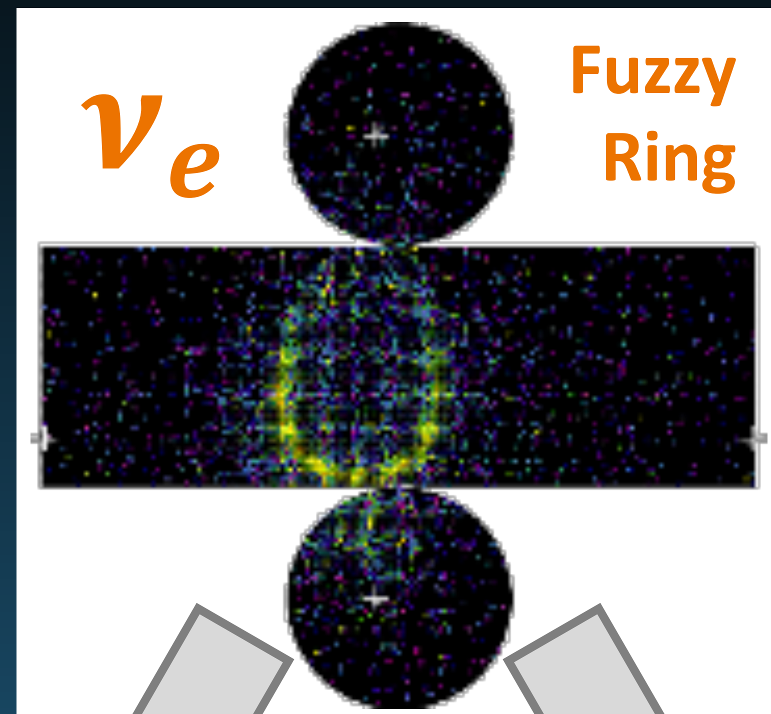
ANALYSIS FLOW

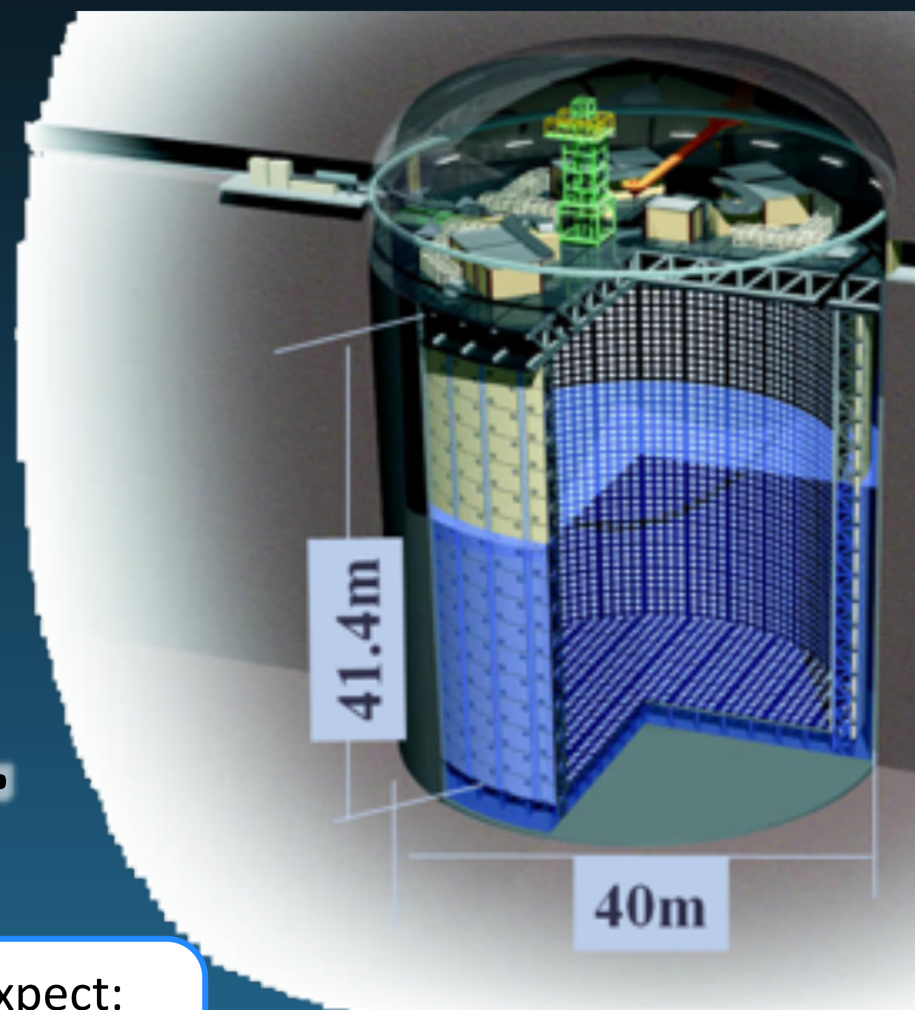


Near Detector data primarily constrains flux and cross section uncertainties

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:
$81\%\ (\nu_\mu \rightarrow)\nu_e$,
18% beam $\nu_e + \nu_\mu$

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

1R-e + d.e.

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

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

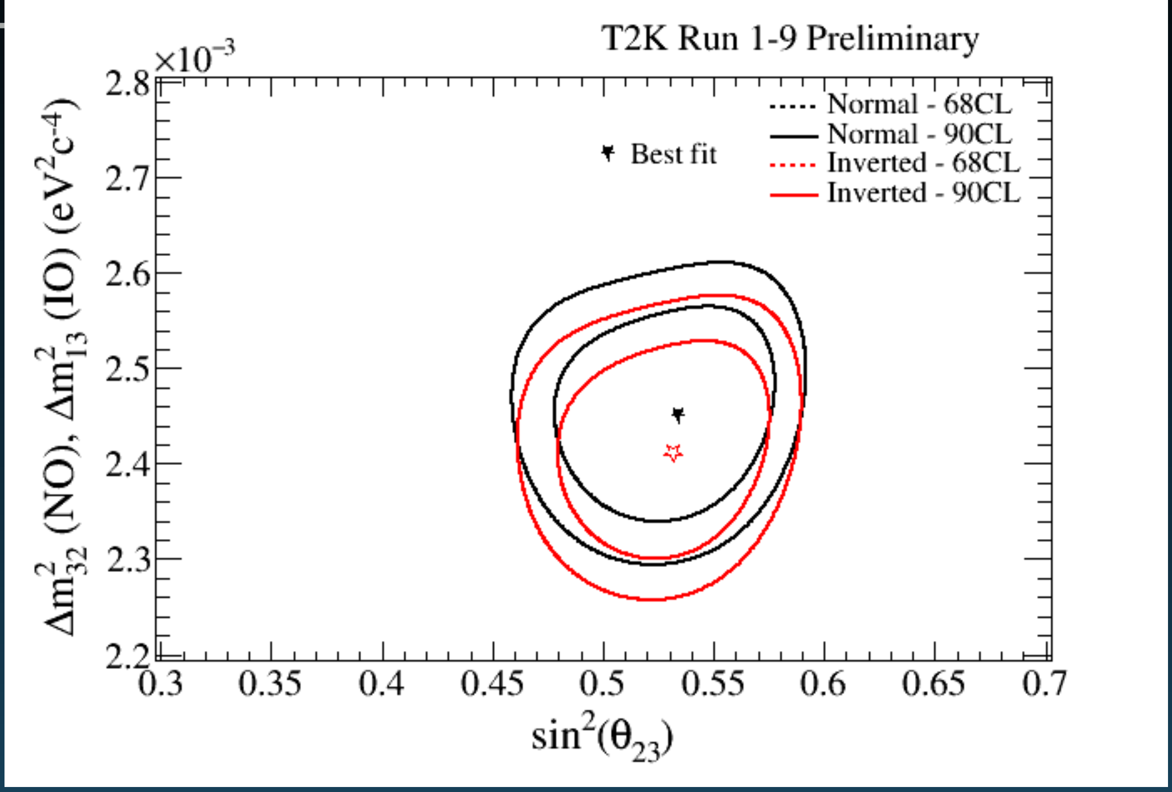
Pion collection & focussing depends on Horn Current

Forward Horn Current (FH): $\pi^+ \rightarrow \mu^+ + \nu_\mu$

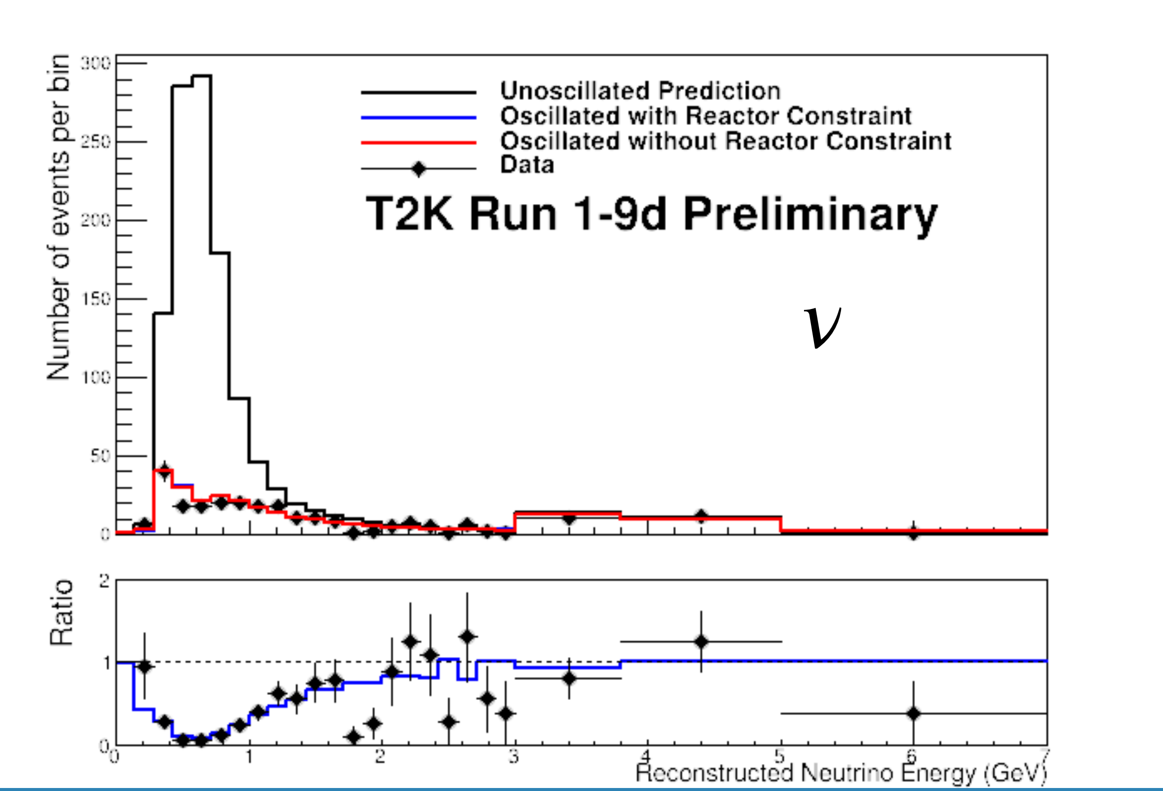
Reverse Horn Current (RH): $\pi^- \rightarrow \mu^- + \bar{\nu}$

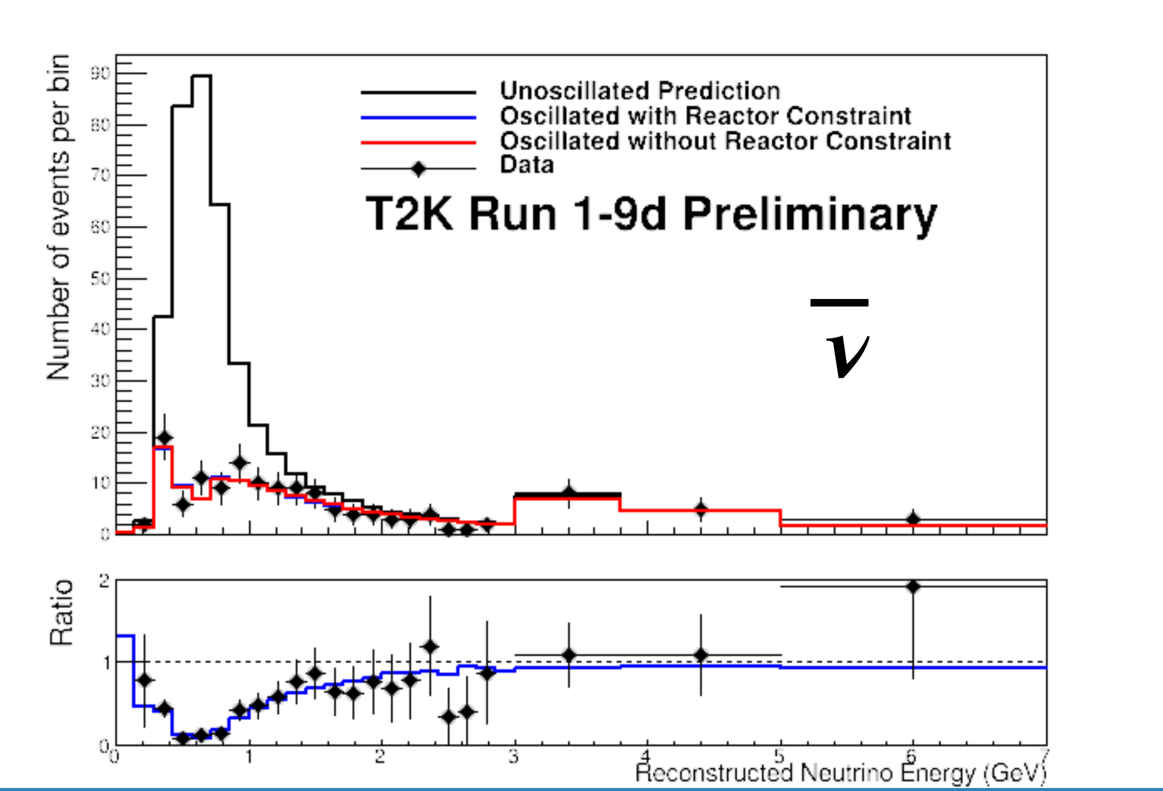
θ_{23} AND Δm^2_{32} MEASUREMENT

- CL contours for $\nu_\mu \to \nu_\mu$ disappearance parameters, including reactor constraint on $\sin^2\theta_{13}$
- Best fit points:
  - $\sin^2\theta_{23} = 0.532$
  - $\Delta m^2_{23} = 2.452 \times 10^{-3}$ eV^2

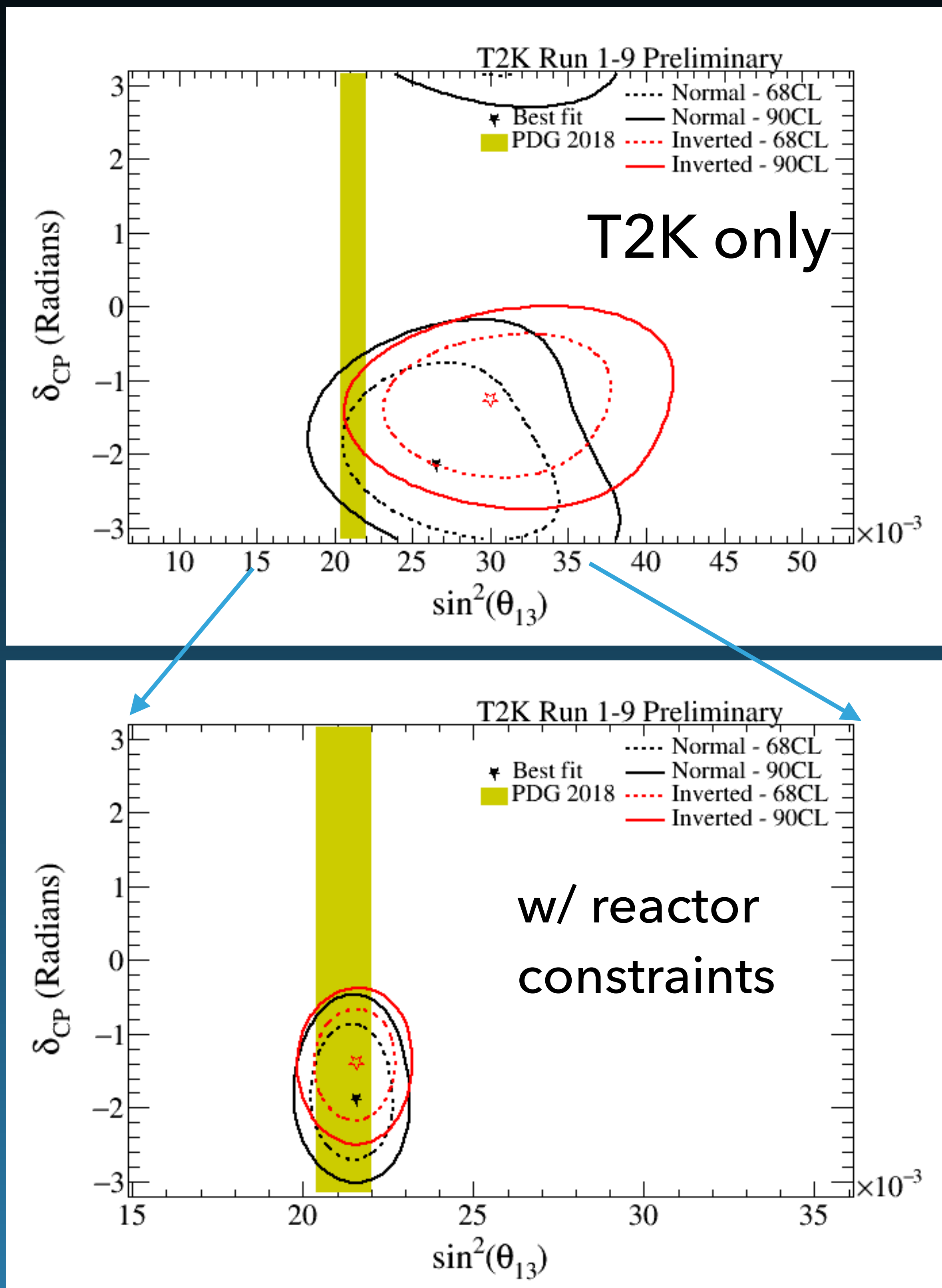


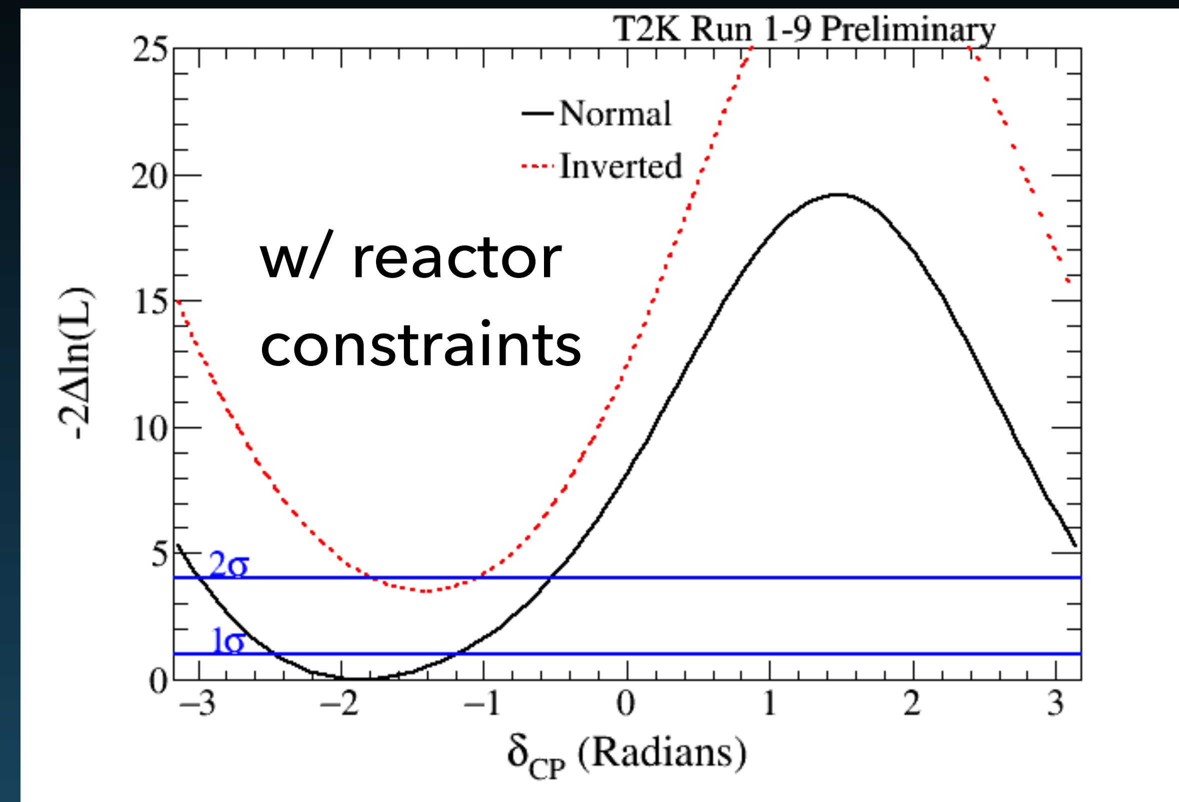
- T2K data compatible with maximal mixing





CONSTRAINT ON δ_{CP}

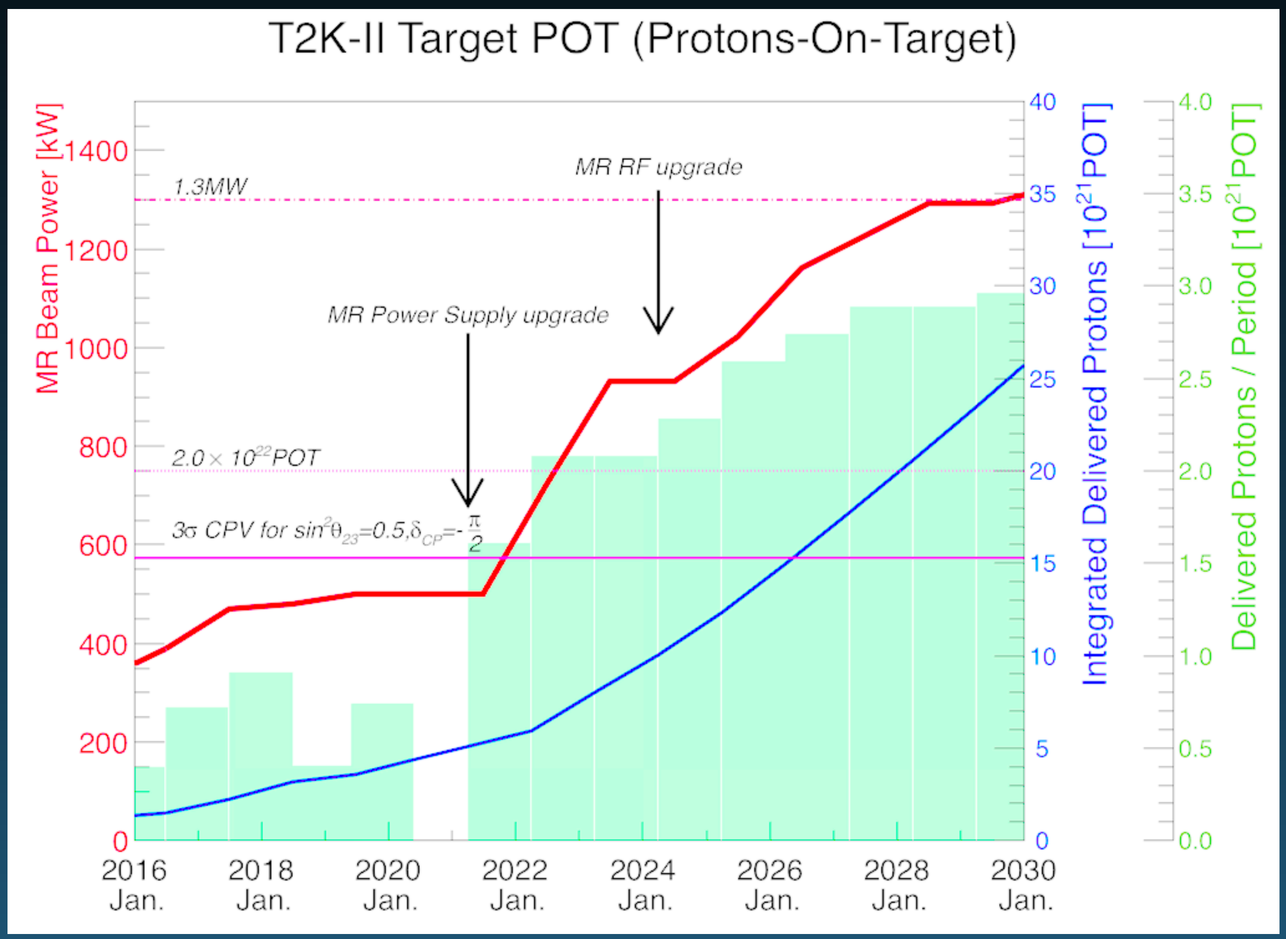




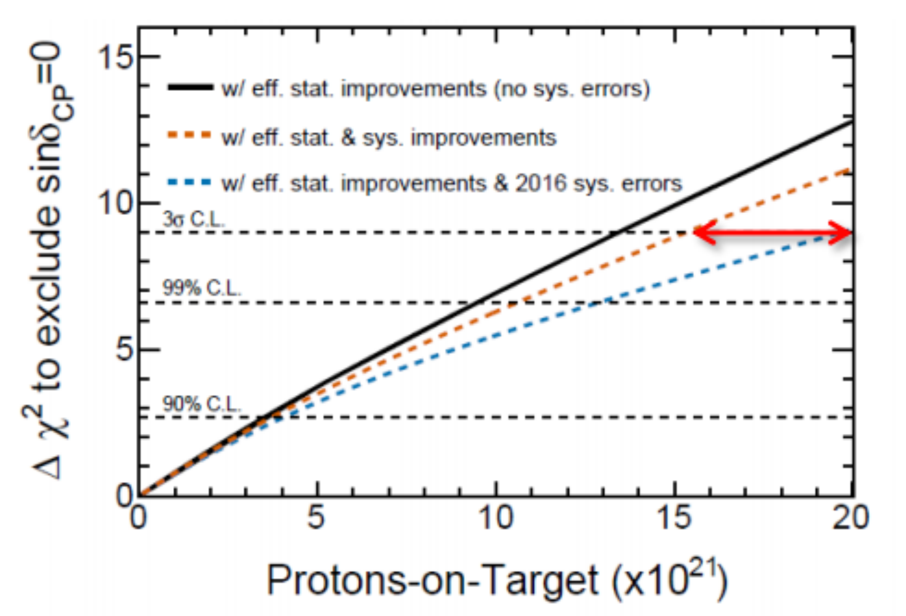
- Preferred value around $\delta_{CP}=-\pi/2$ with the best fit point of $\delta_{CP}=-1.885$
- δ_{CP} 2σ intervals:
  - Normal Hierarchy [-2.966, -0.628] rad
  - Inverted Hierarchy [-1.799, -0979] rad
- CP conserving values ($\delta_{CP}=0$ or π) disfavored at 2σ level
- Need more data to reach 3σ result

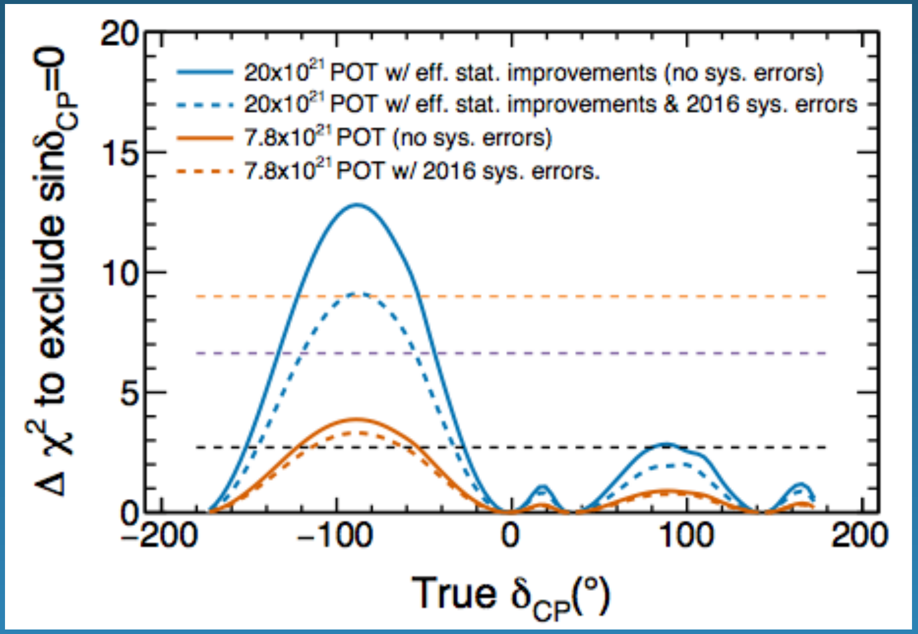
FUTURE SENSITIVITIES

Upgraded Accelerator for higher beam power

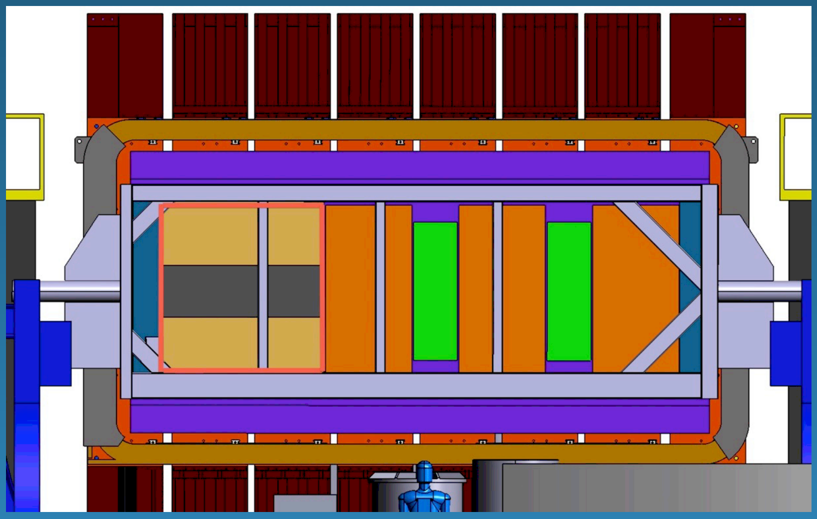


- Proposal for extension of T2K :
  - May have 3σ sensitivity to $\delta_{CP}\neq0$ by around 2026
  - 20 $\times10^{21}$ POT by 2027~2028
  - Target beam power: 1.3 MW
  - Increase effective statistics
    - More new SK event samples
    - 320kA horn current
  - Reduce sys. error ~9% → ~4%
- KEK/J-PARC Stage-1 status





Upgraded near detector ND2



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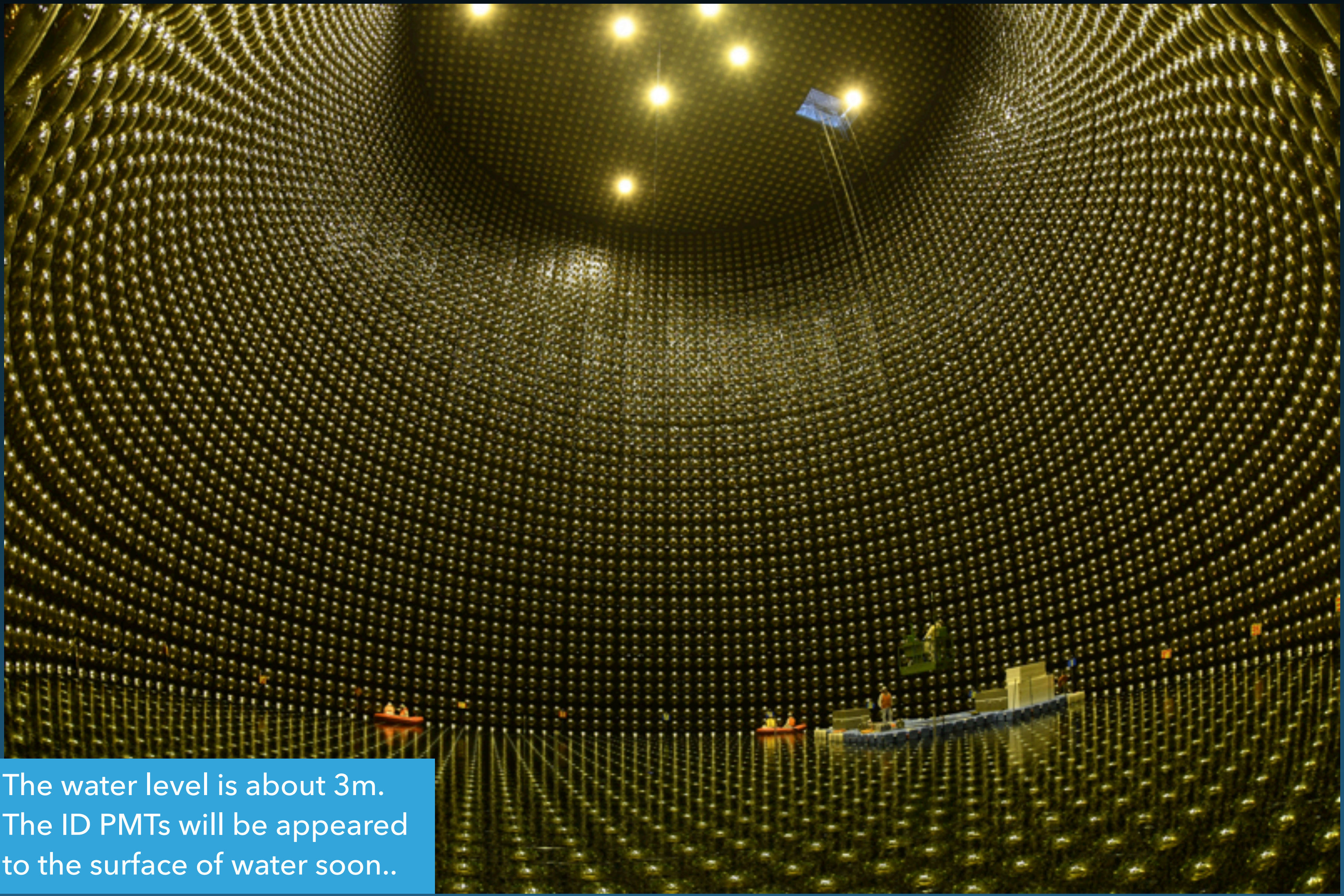
SK-GD REFURBISHMENT



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

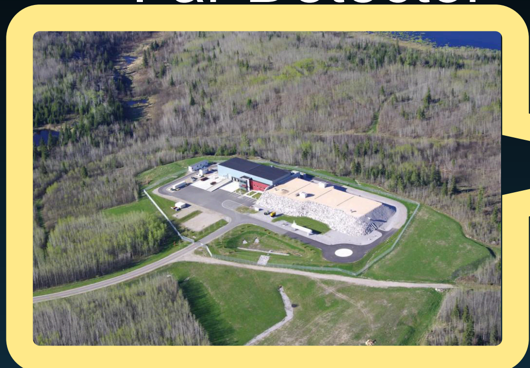
Measurement of magnetic field in the inner detector.

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

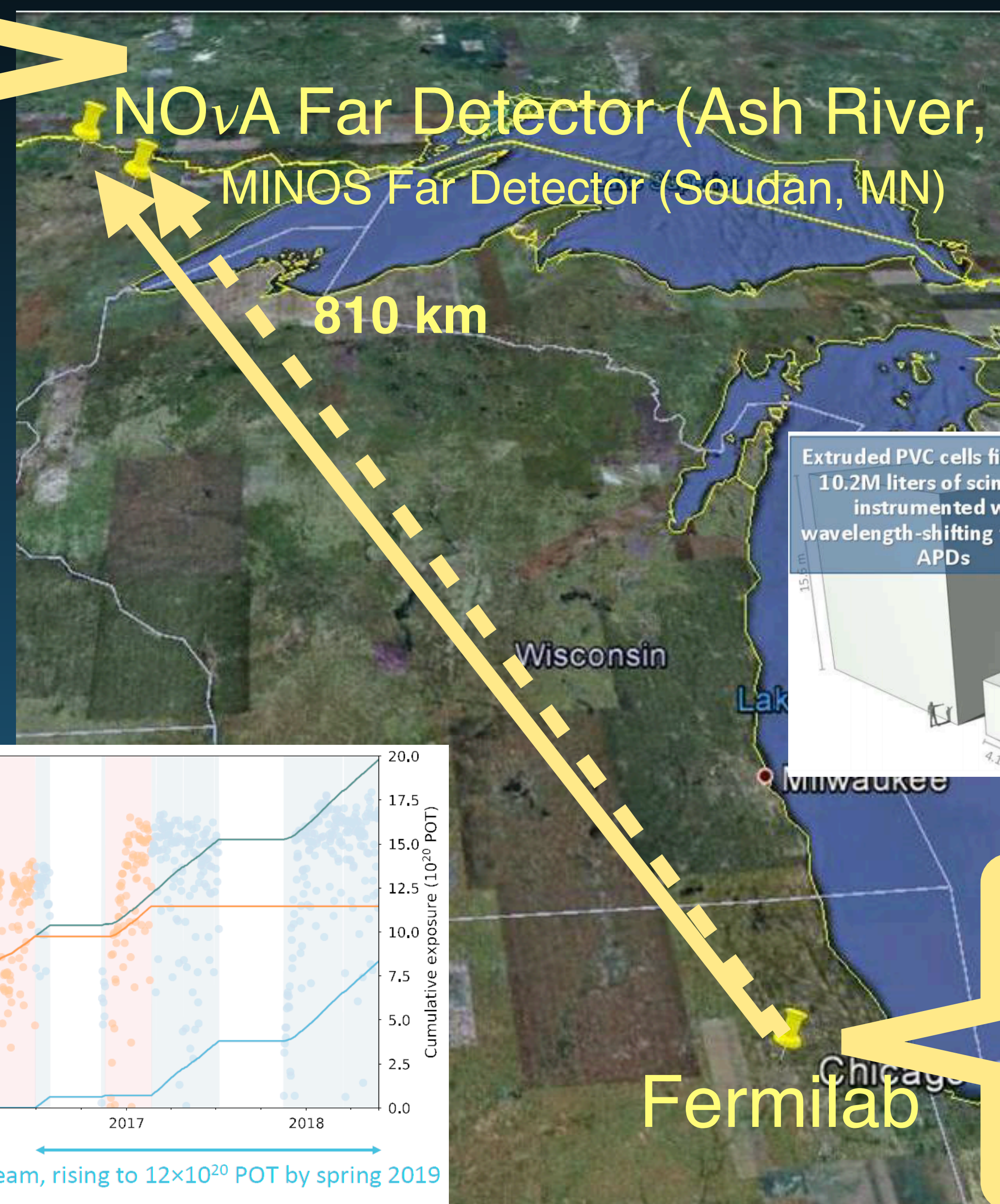
All the water of the tank is drained

NOVA OVERVIEW

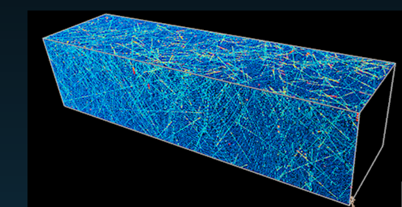
Far Detector



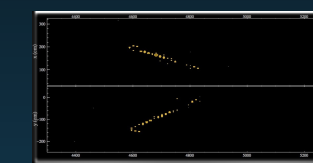
14mrad off-axis

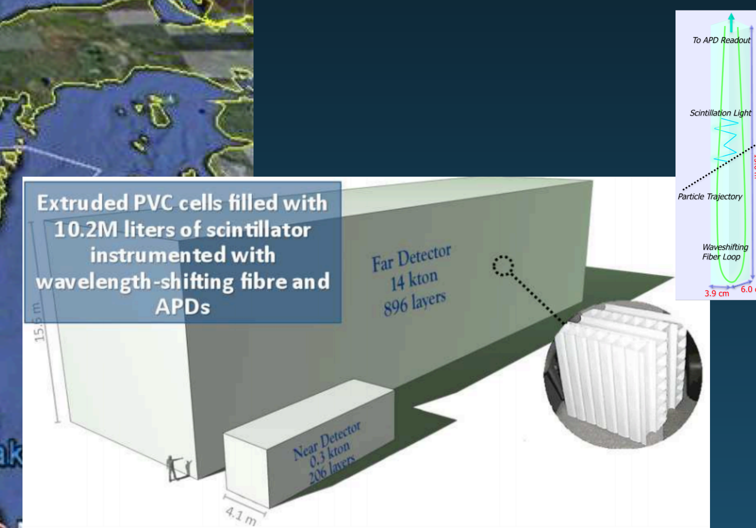


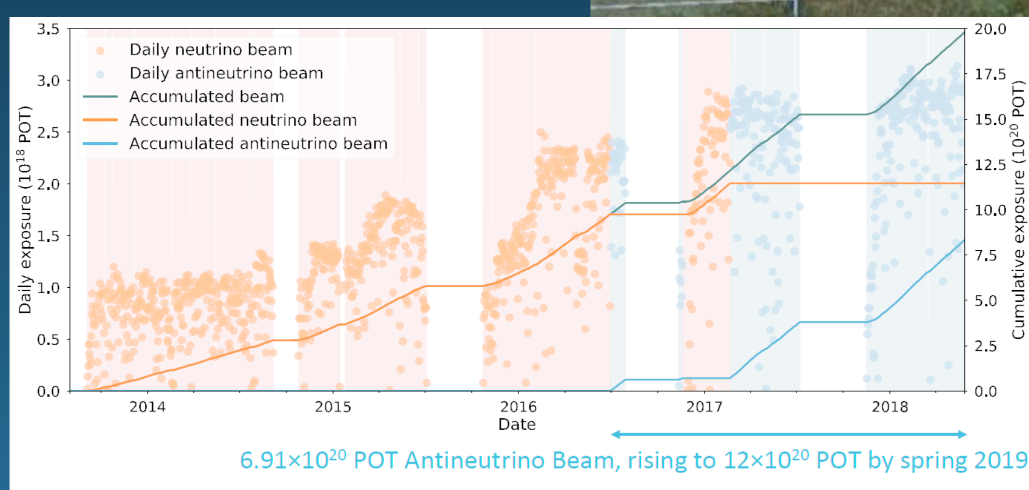
FD: surface detector



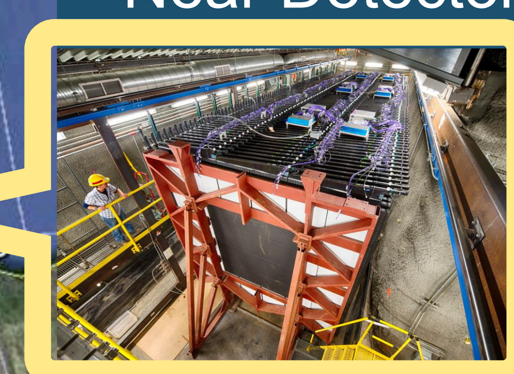
FD: ν_e candidate







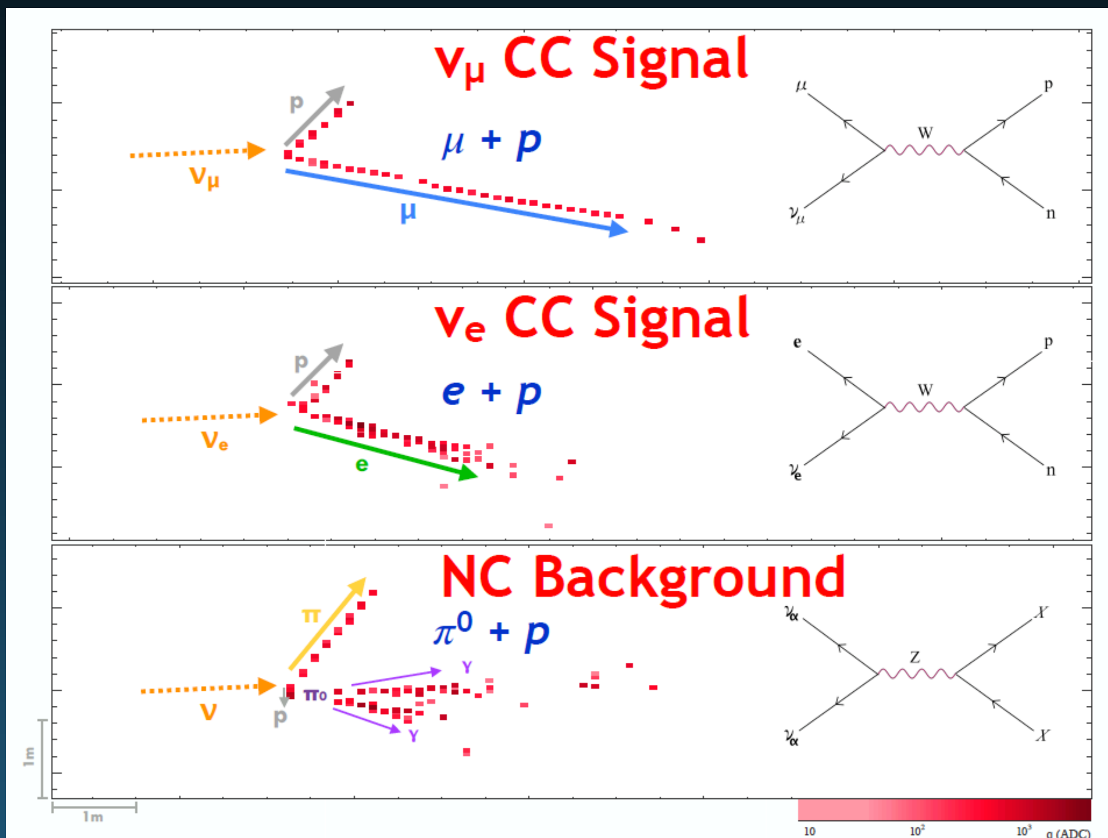
Near Detector



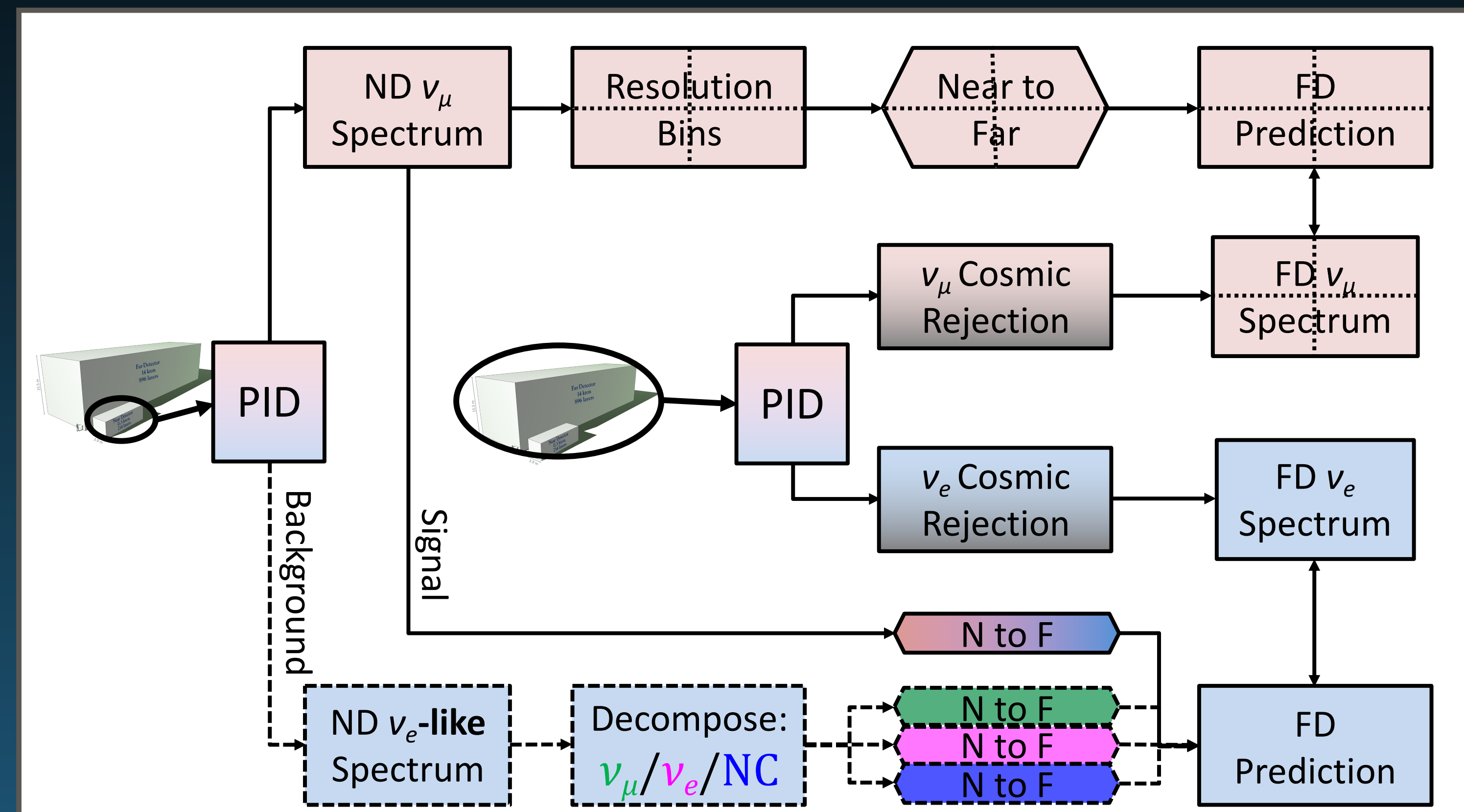
- NuMI beam running at 700 kW design power since January 2017 (> 18 x 10^{18} protons per week). Collected so far:
  - 8.85 x10^{20} POT ν-Mode
  - 6.9x10^{20} POT $\bar{\nu}$-Mode (expected 12x10^{20} POT $\bar{\nu}$ Spring2019)

NOVA EVENT SELECTION

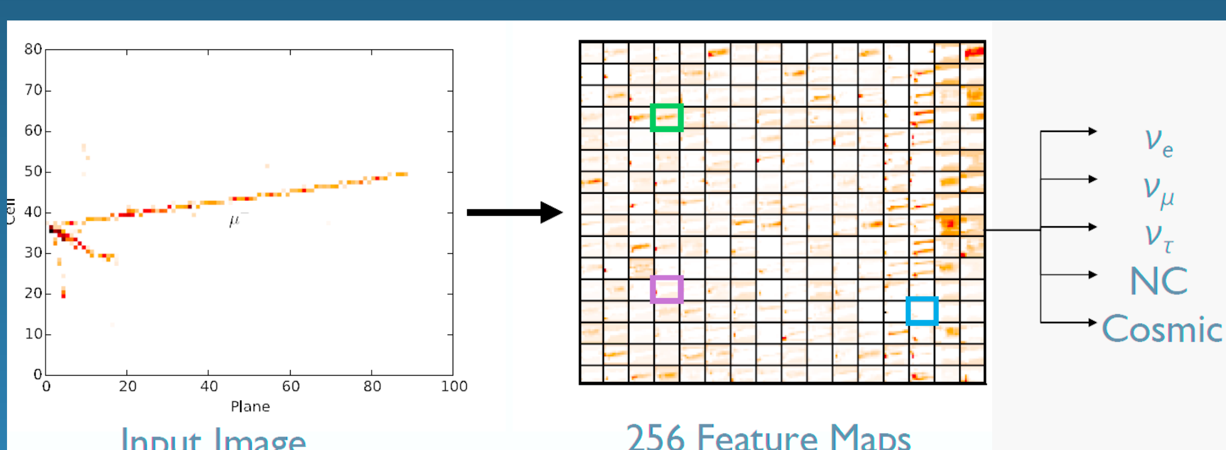
Neutrino Interaction Topologies



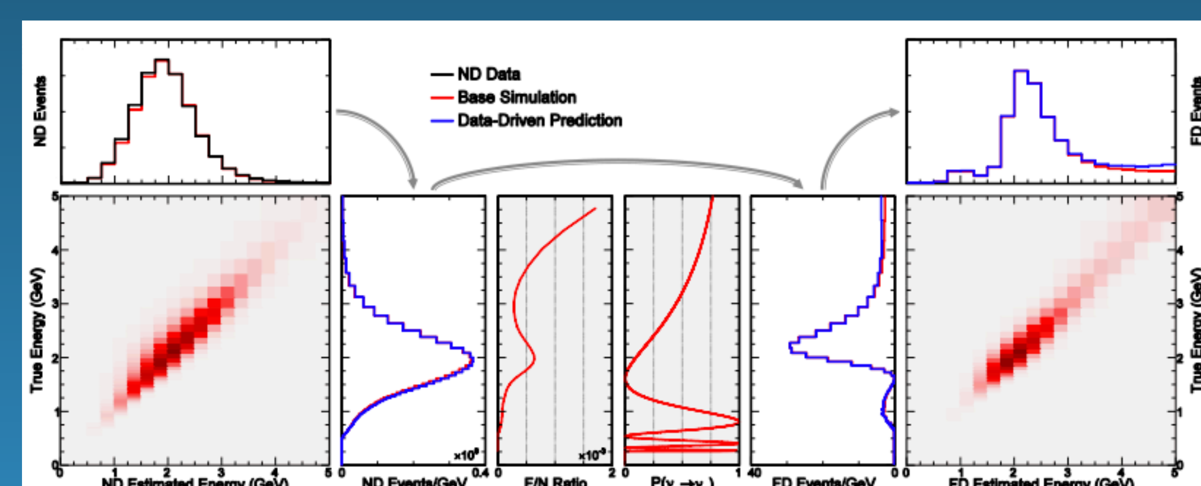
NOvA Analysis Strategy



Deep-learning based Particle identification for ν_e and ν_μ analyses

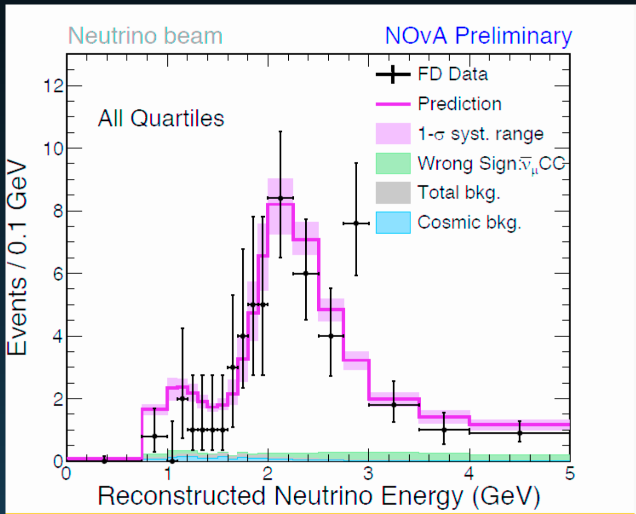


Near-to-Far extrapolation

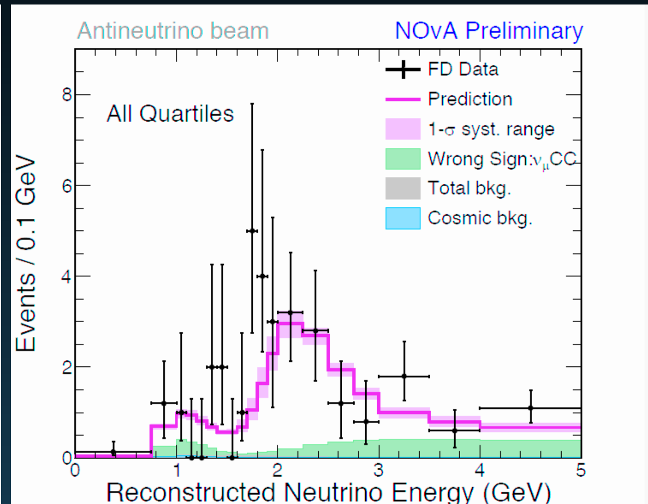


NOVA RESULTS

Disappearance Analysis

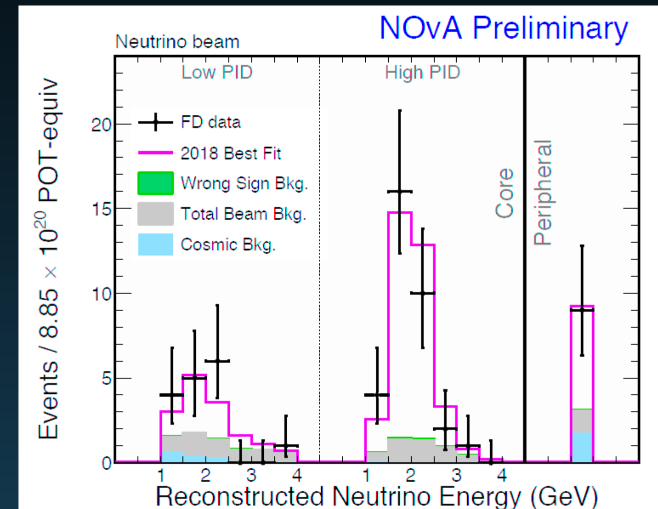


Observed	113
Best Fit Integral	121
Cosmic Background	2.1
Beam Background	1.2
Un-oscillated Prediction	730

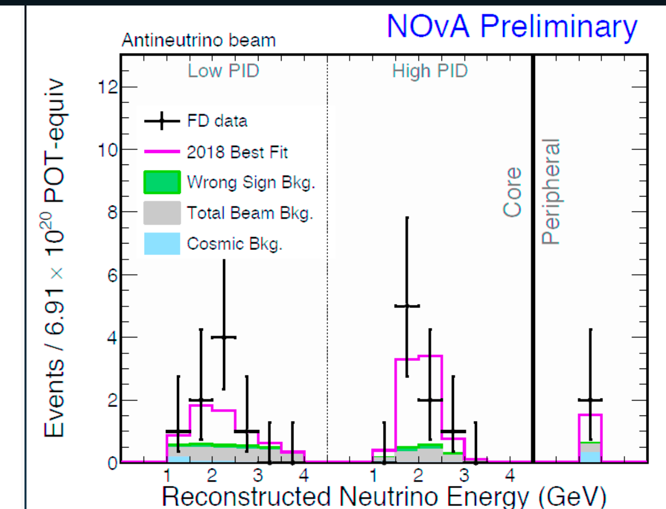


Observed	65
Best Fit Integral	50
Cosmic Background	0.5
Beam Background	0.6
Un-oscillated Prediction	266

Appearance Analysis



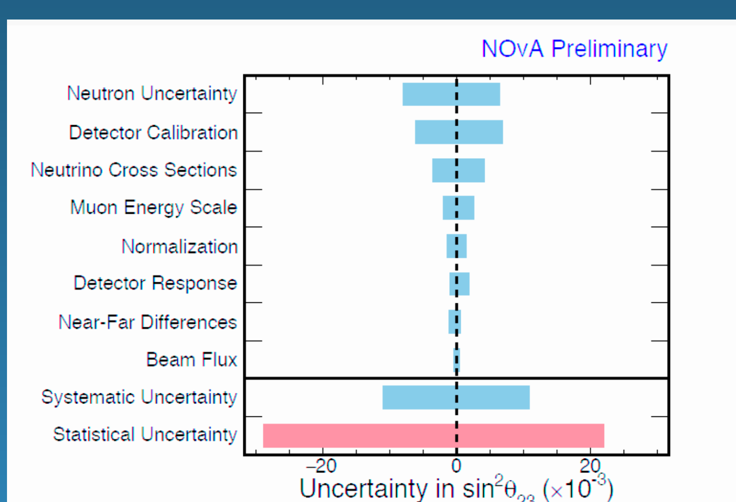
Observed	58
Best Fit Prediction	59
Cosmic Background	3.3
Beam Background	11.1
Wrong Sign Background	0.7

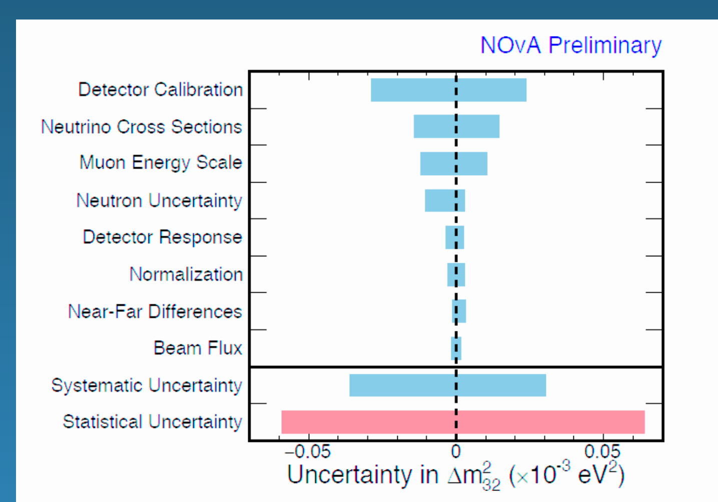


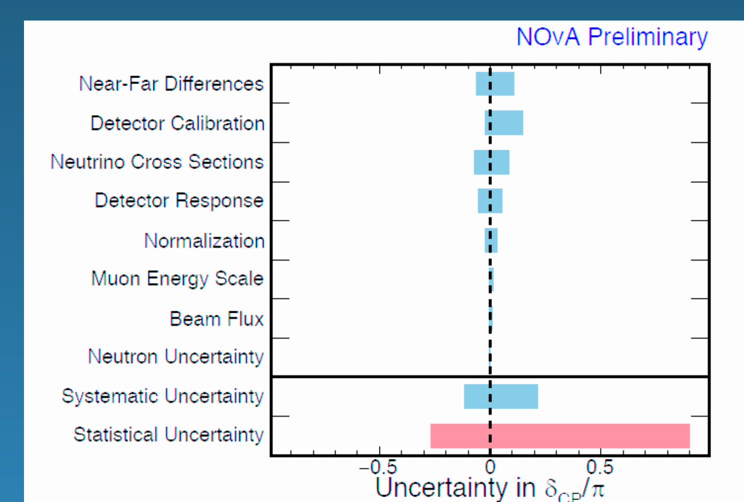
Observed	18
Best Fit Prediction	15.9
Cosmic Background	0.7
Beam Background	3.5
Wrong Sign Background	1.1

Systematic errors: Measurements still statistically limited.

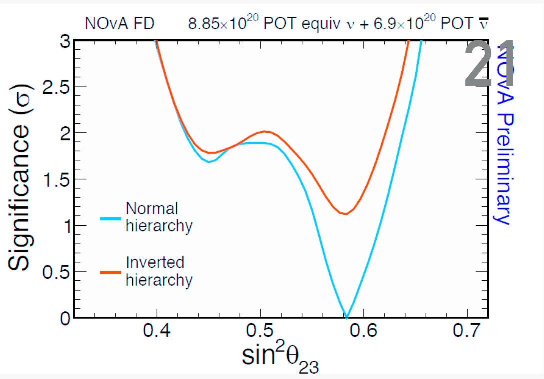
The upcoming test beam program will improve the calibration and detector response systematics.





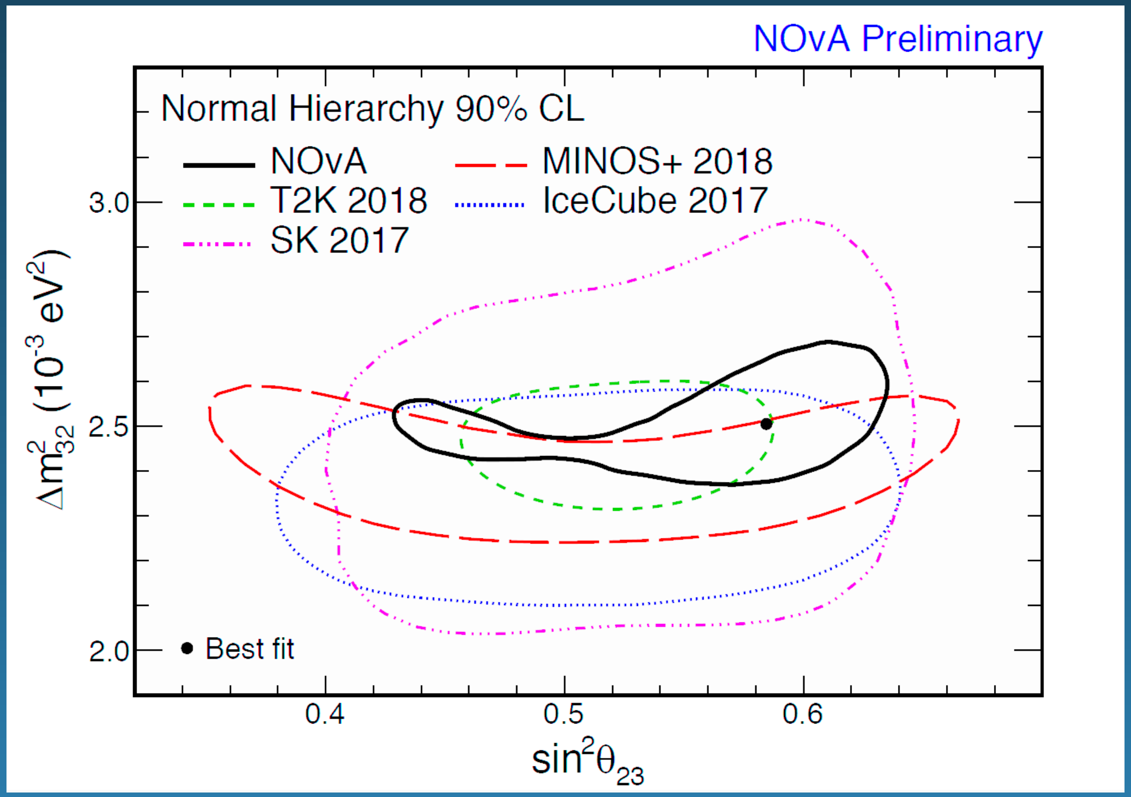


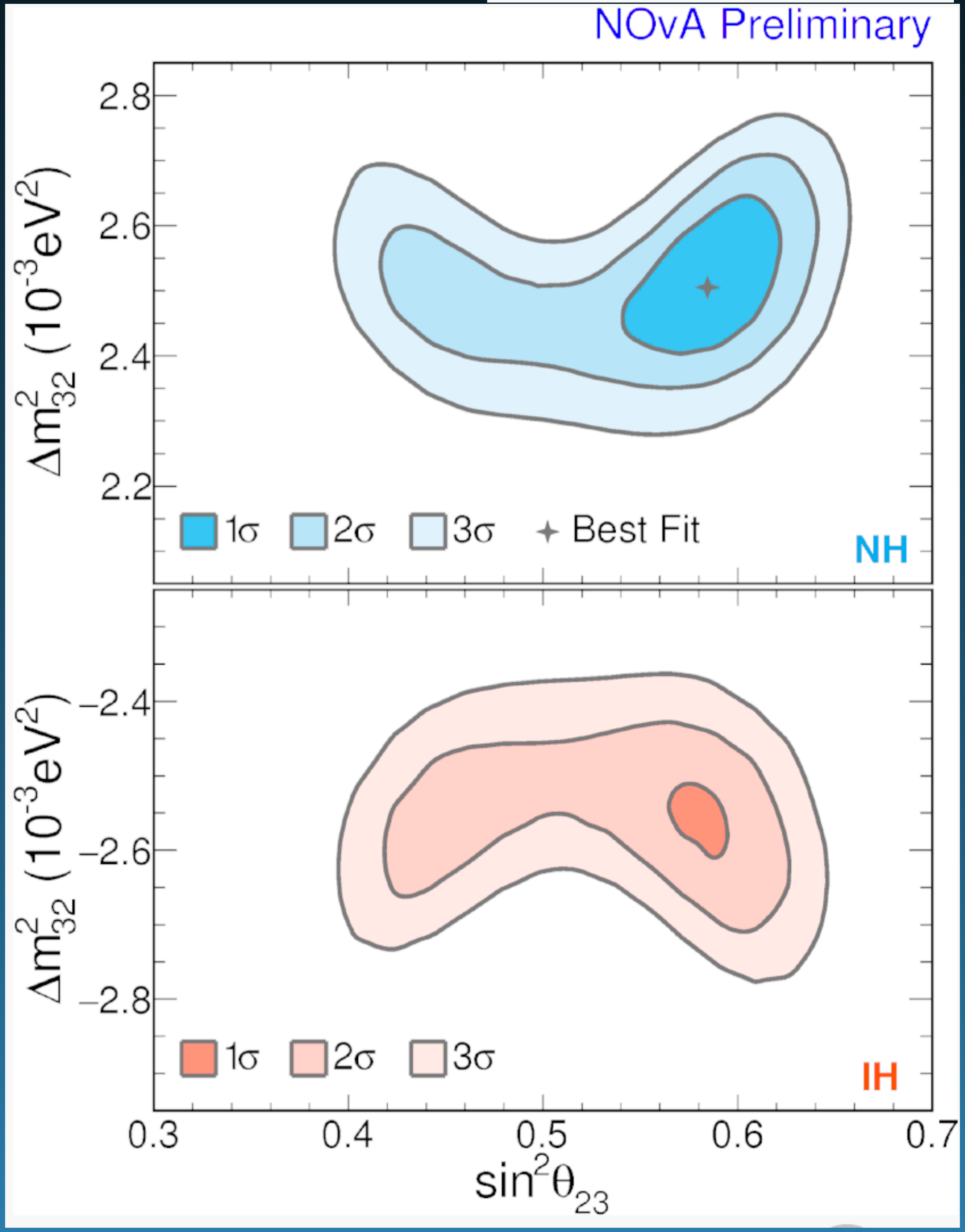
JOINT APPEARANCE AND DISAPPEARANCE



- Prefers non maximal mixing at 1.8σ
- Favours upper octant at a similar level
- Best fit:
  - Normal Hierancy
  - Δm^2_{23} =(2.52+0.13/-0.18)10^{-3} eV^2 (NH)
  - $\sin^2\theta_{23}$=0.58 +/- 0.03 (UO)

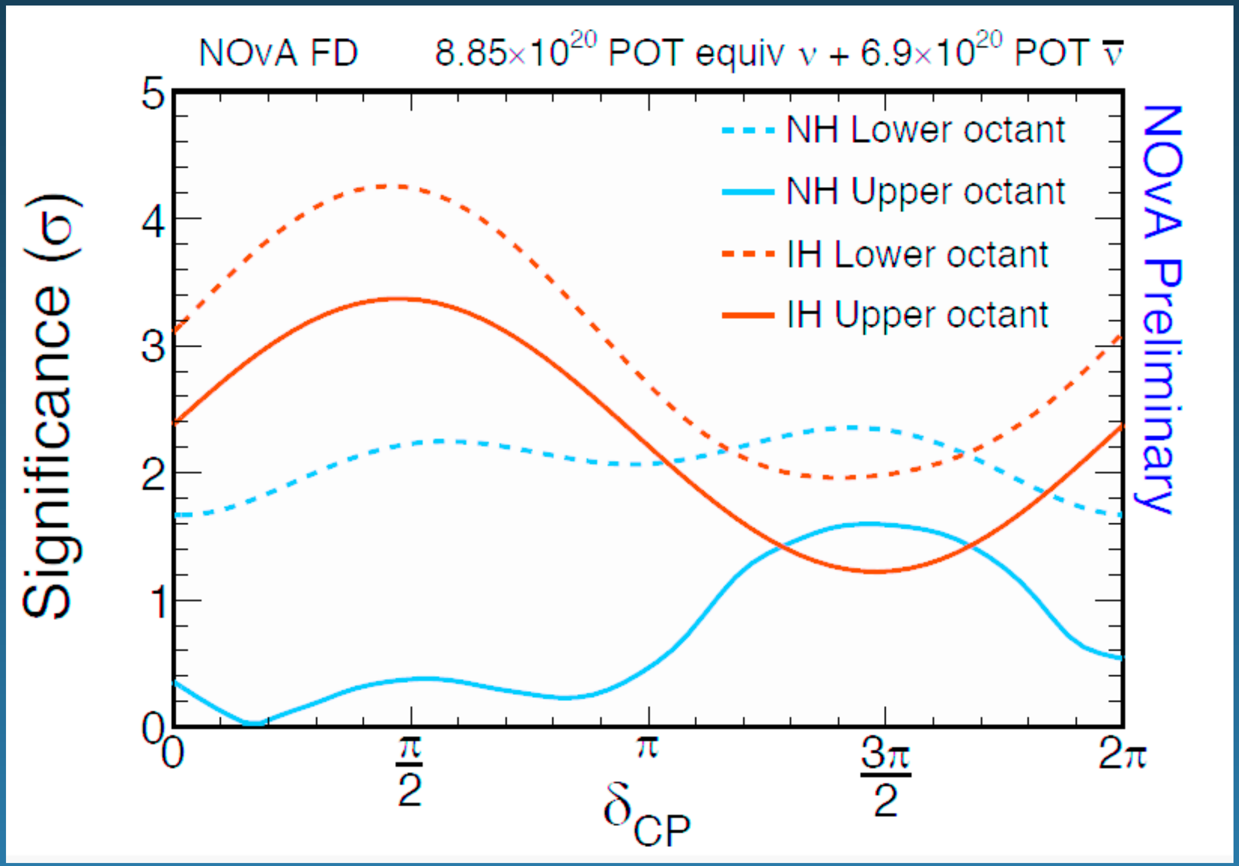
- NOvA is consistent with other long baseline and atmospheric neutrino experiments.

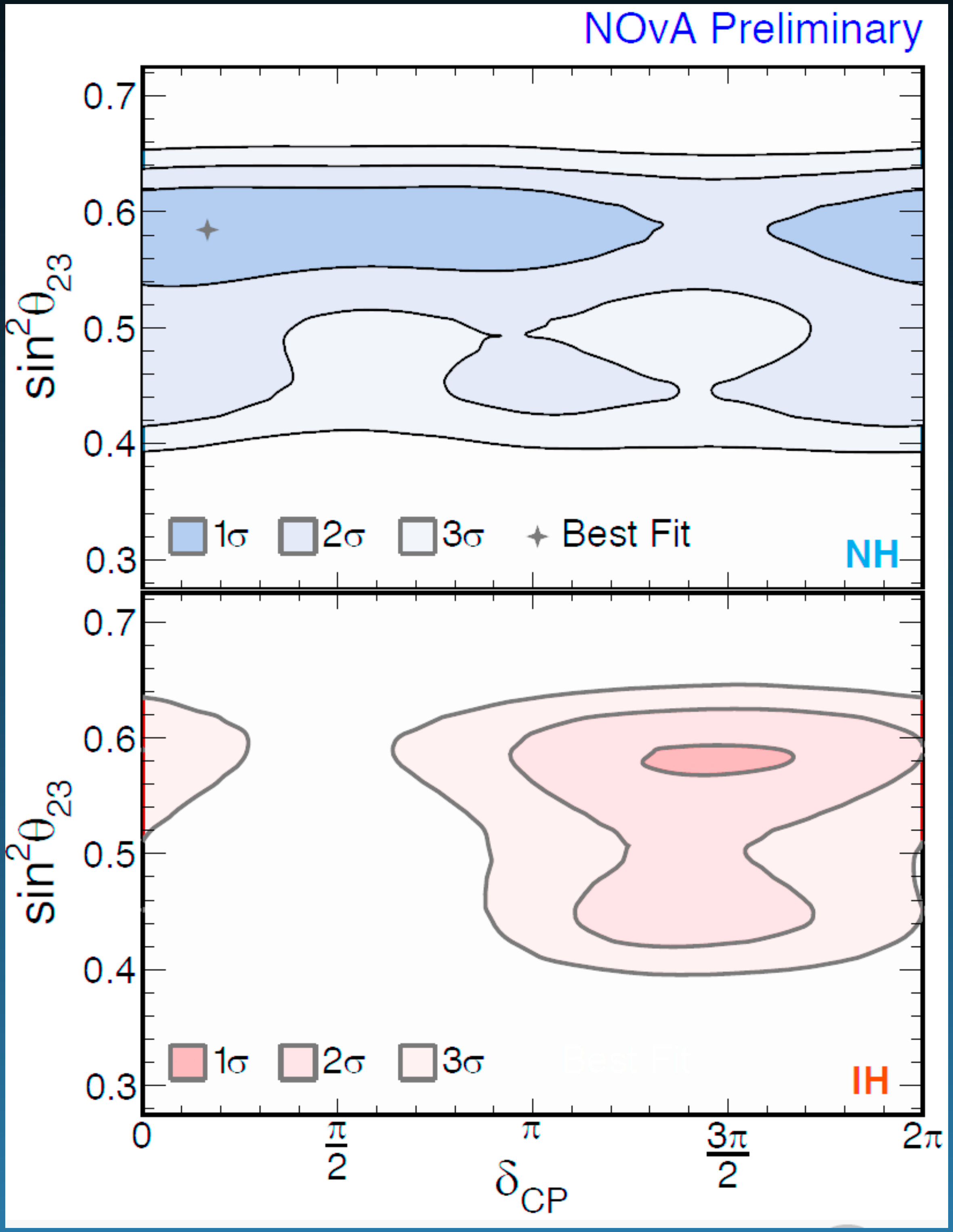




JOINT APPEARANCE AND DISAPPEARANCE

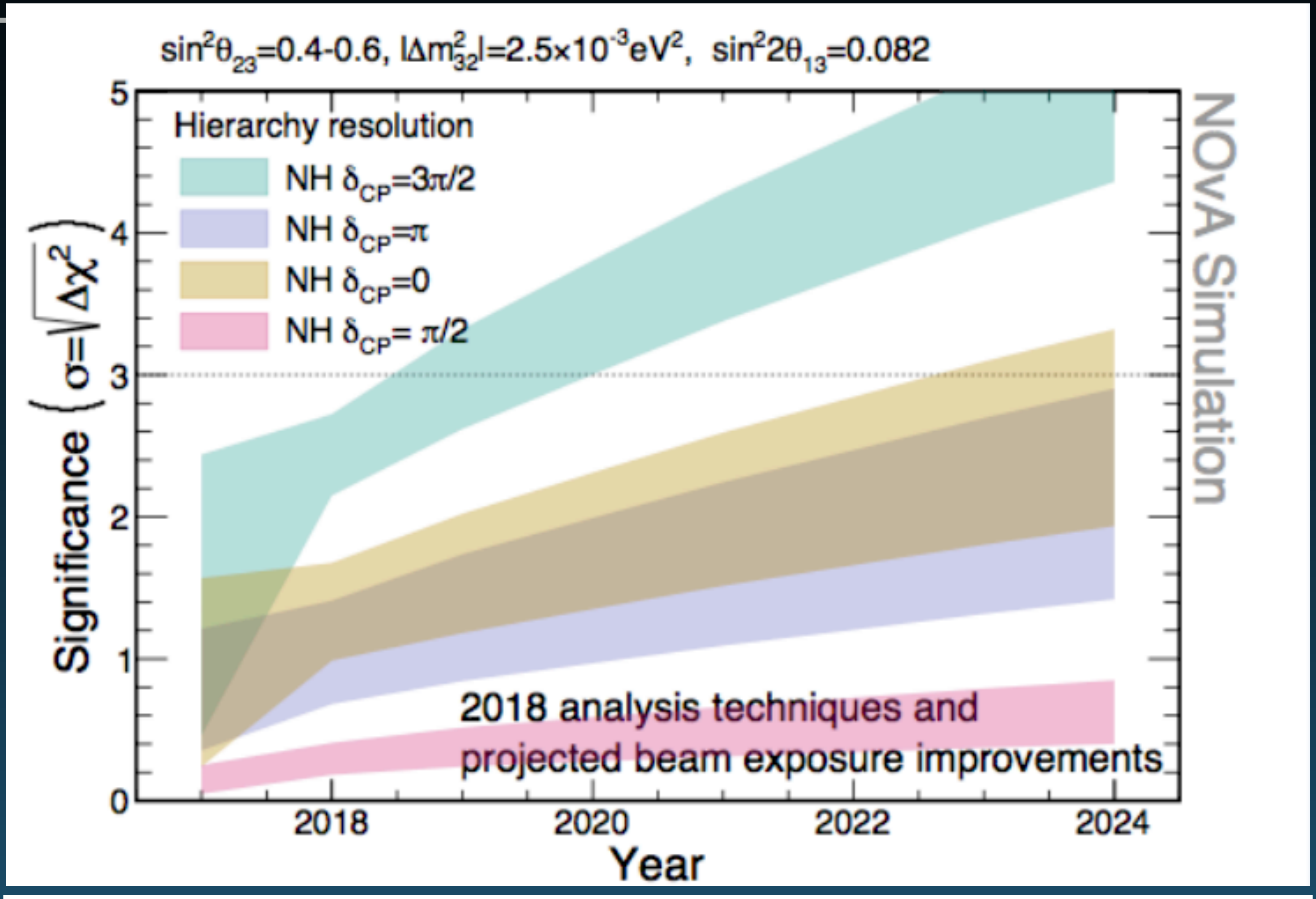
- Excludes $\delta_{CP} = \pi/2$ for IH at > 3σ
- Consistent with all δ_{CP} value at > 1.6σ
- Prefers NH at 1.8 σ
- Best fit:
  - $\delta_{CP} = 0.17\pi$
  - Δm^2_{23} =(2.52+0.13/-0.18)10^{-3} eV^2 (NH)
  - $\sin^2\theta_{23}$=0.58 +/- 0.03 (UO)

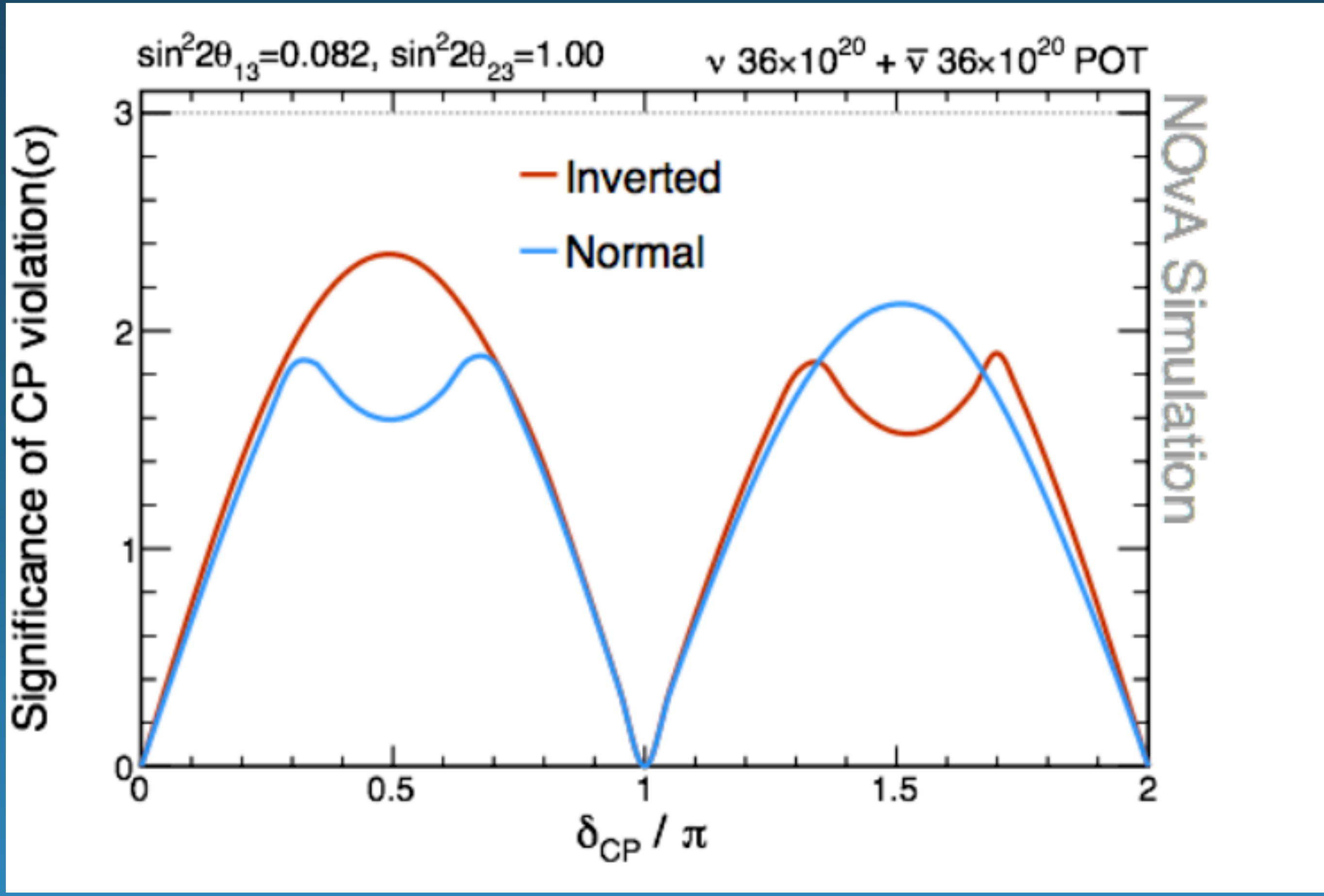




FUTURE PROSPECTS

- Run 50% ν, 50% $\bar{\nu}$ after 2018.
- Extended running through 2024
- Proposed accelerator improvement projects and test beam program.
- Sensitivities:
  - 3σ sensitivity to hierarchy (if NH and $\delta_{CP} = 3\pi/2$) for allowed range of θ_{23} by 2020.
  - 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.
  - 2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024.





NOVA TEST BEAM PROGRAMME

- The test beam program will facilitate numerous analysis improvements, including reduced systematics and simulation improvements.
- Installation and commissioning has happened last summer.
- Beam in the first half of 2019, planning on 2 million particles.

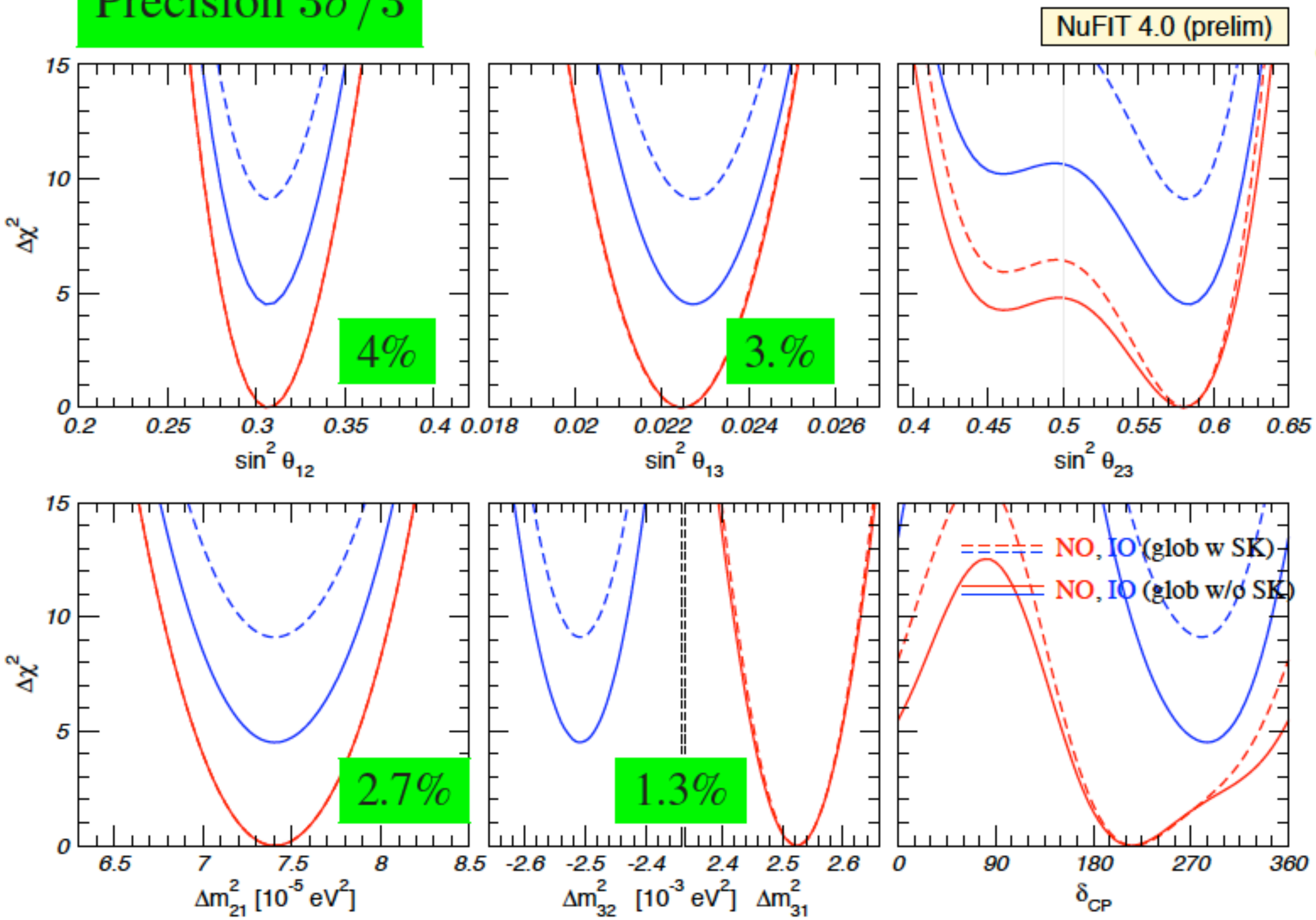
Concha Gonzalez-Garcia

3 ν Flavour Parameters: Status OCT 2018

Global 6-parameter fit http://www.nu-fit.org

Esteban, Hernandez-Cabezudo,Maltoni, Schwetz, MCG-G PRELIMINARY

Precision $3\sigma/3$



- Best determined:

$$\theta_{12},\ \theta_{13}, \Delta m^2_{21},\ |\Delta m^2_{3l}|$$

$$[\Delta m^2_{3l} = \Delta m^2_{31} > 0 \text{ (NO)}$$

$$\Delta m^2_{3l} = \Delta m^2_{32} < 0 \text{ (IO)}]$$

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3 ν Flavour Parameters: Status OCT 2018

Global 6-parameter fit http://www.nu-fit.org

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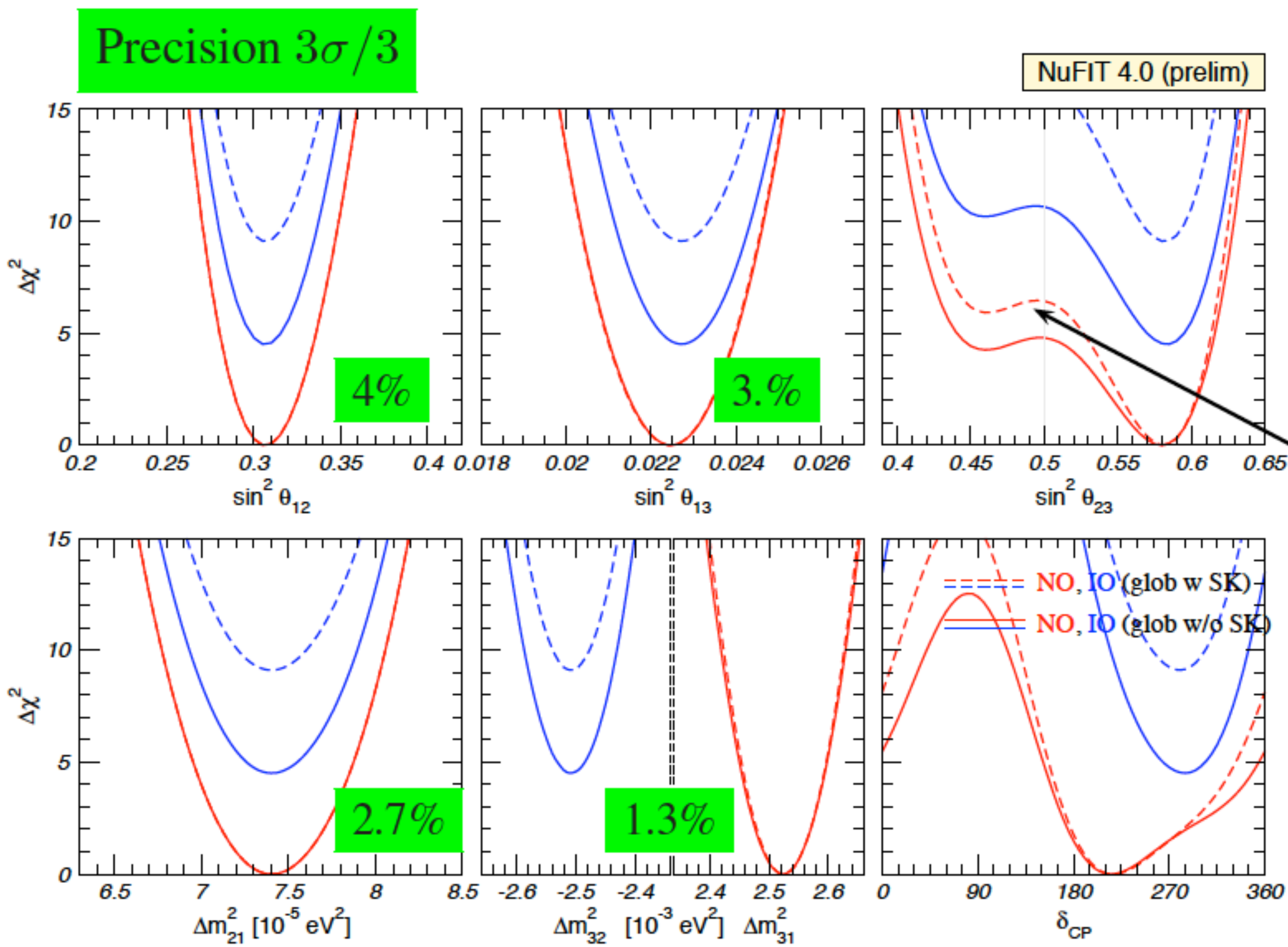

- Best determined:

  θ_{12}, θ_{13},Δm^2_{21}, $|\Delta m^2_{3l}|$

  [$\Delta m^2_{3l} = \Delta m^2_{31} > 0$ (NO)

  $\Delta m^2_{3l} = \Delta m^2_{32} < 0$ (IO)]

- Pending issues:

  * θ_{23}: Maximality/Octant

Concha Gonzalez-Garcia

3 ν Flavour Parameters: Status OCT 2018

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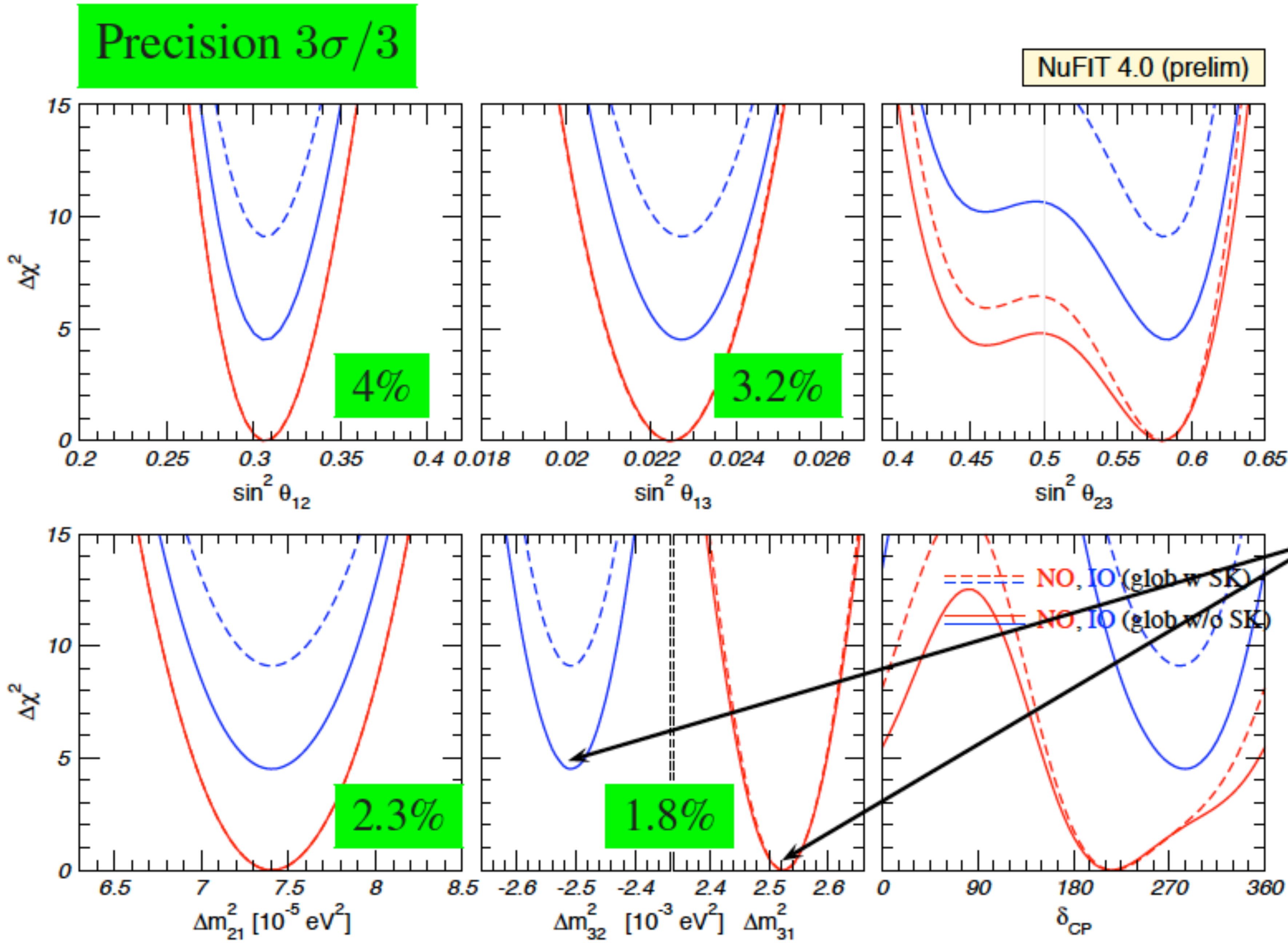
Esteban, Hernandez-Cabezudo,Maltoni, Schwetz, MCG-G PRELIMINARY



- Best determined:

  θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3l}|$

  [$\Delta m^2_{3l} = \Delta m^2_{31} > 0$ (NO)

  $\Delta m^2_{3l} = \Delta m^2_{32} < 0$ (IO)]

- Pending issues:

  ∗ θ_{23}: Maximality/Octant

  ∗ Mass Ordering

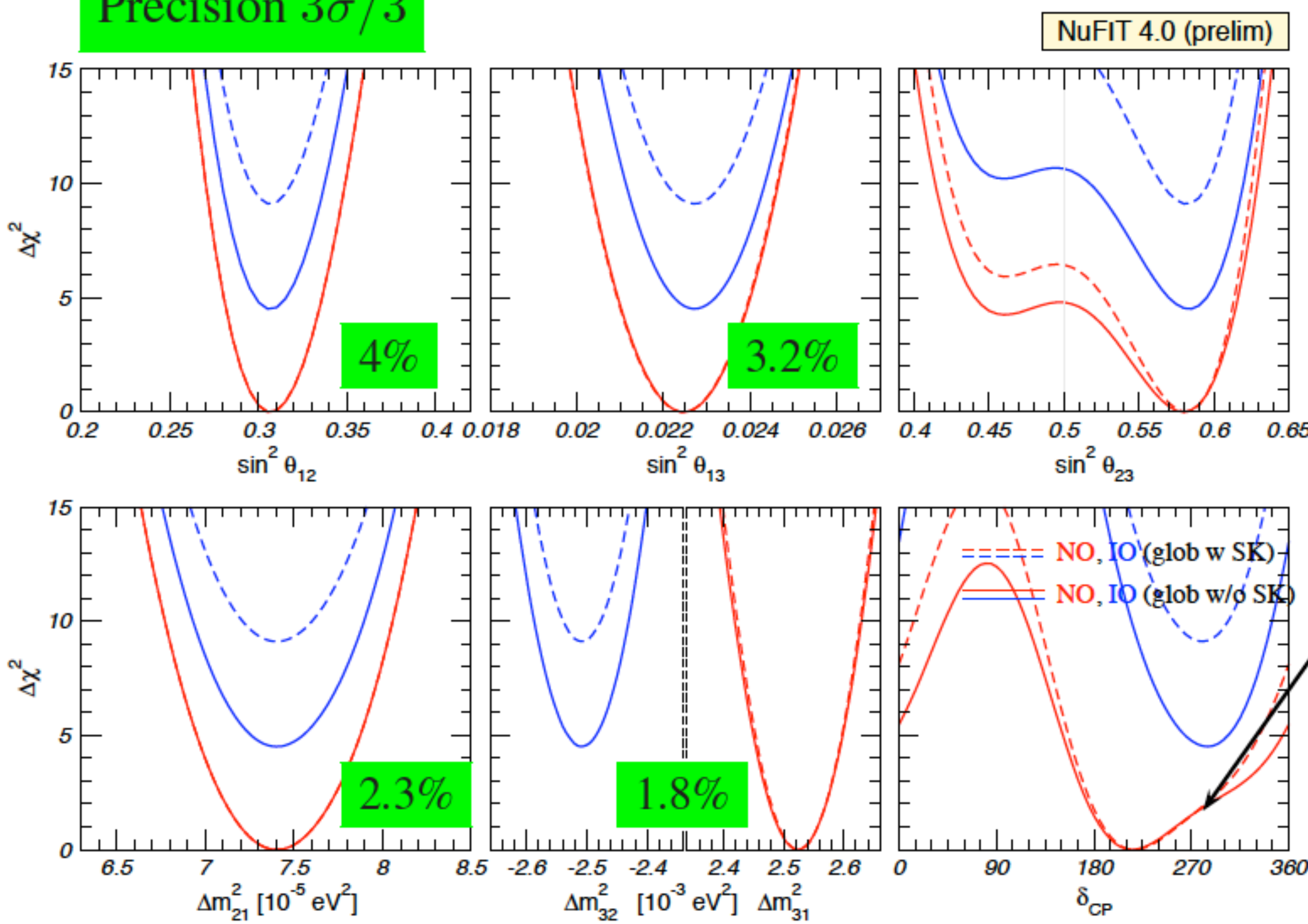
Concha Gonzalez-Garcia

3 ν Flavour Parameters: Status OCT 2018

Global 6-parameter fit http://www.nu-fit.org

Esteban, Hernandez-Cabezudo,Maltoni, Schwetz, MCG-G PRELIMINARY

Precision $3\sigma/3$



- Best determined:

  $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3l}|$

  $[\Delta m^2_{3l} = \Delta m^2_{31} > 0$ (NO)

  $\Delta m^2_{3l} = \Delta m^2_{32} < 0$ (IO)$]$

- Pending issues:

  $*$ θ_{23}: Maximality/Octant

  $*$ Mass Ordering

  $*$ CP phase: $> \pi$?

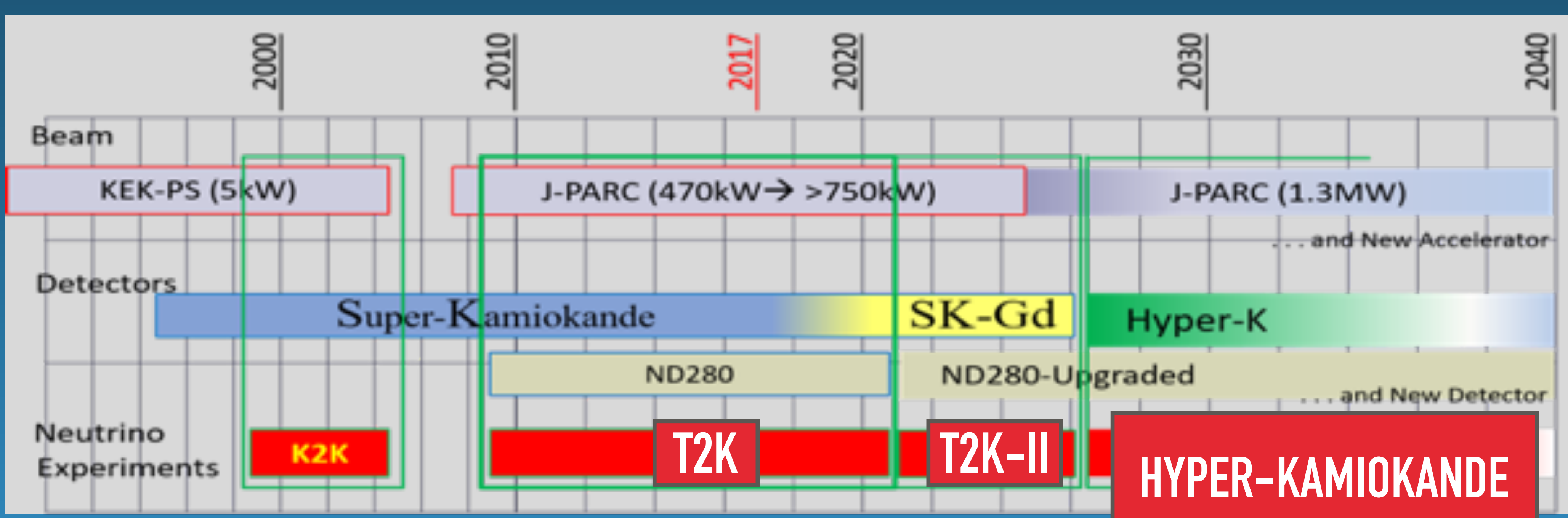
PROGRAMME TOWARDS HYPER-KAMIOKANDE

Super-K, 22kton Fid. mass → **SK-Gd(201X~)**

J-PARC 470kW beam (T2K) → **J-PARC >750kW (T2K-II)**

→ **Hyper-Kamiokande**
2027~, 190kton mass, >1.3MW beam

- Seamless program to get timely results
- Rich physics, enormous discovery potential

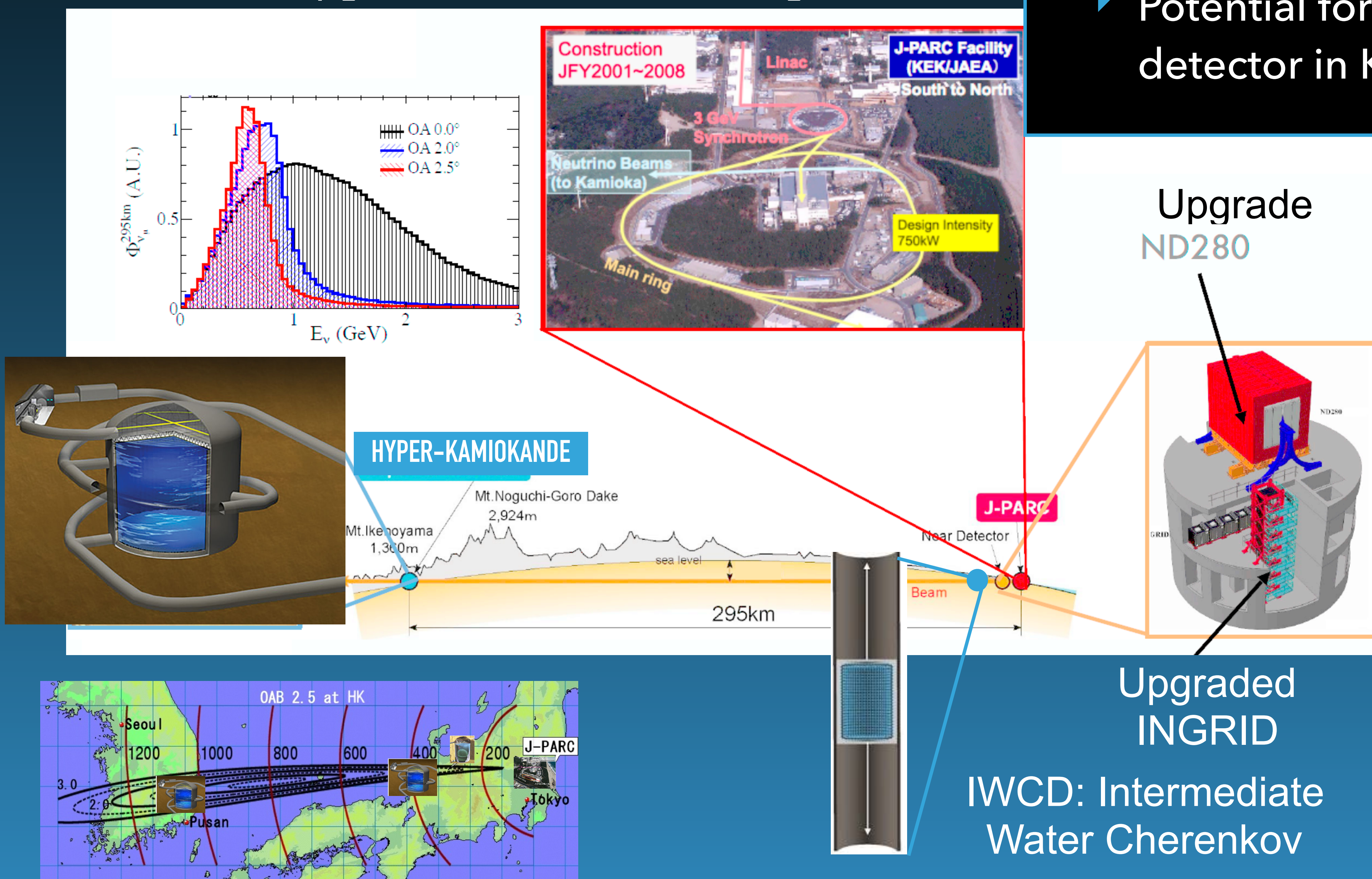


HYPER-KAMIOKANDE OVERVIEW

Same baseline as T2K but:

- 10 times larger far detector
- Higher beam power 1.3MW
- Improved near detectors
- Additional Water Cherenkod near detector
- Potential for second far detector in Korea

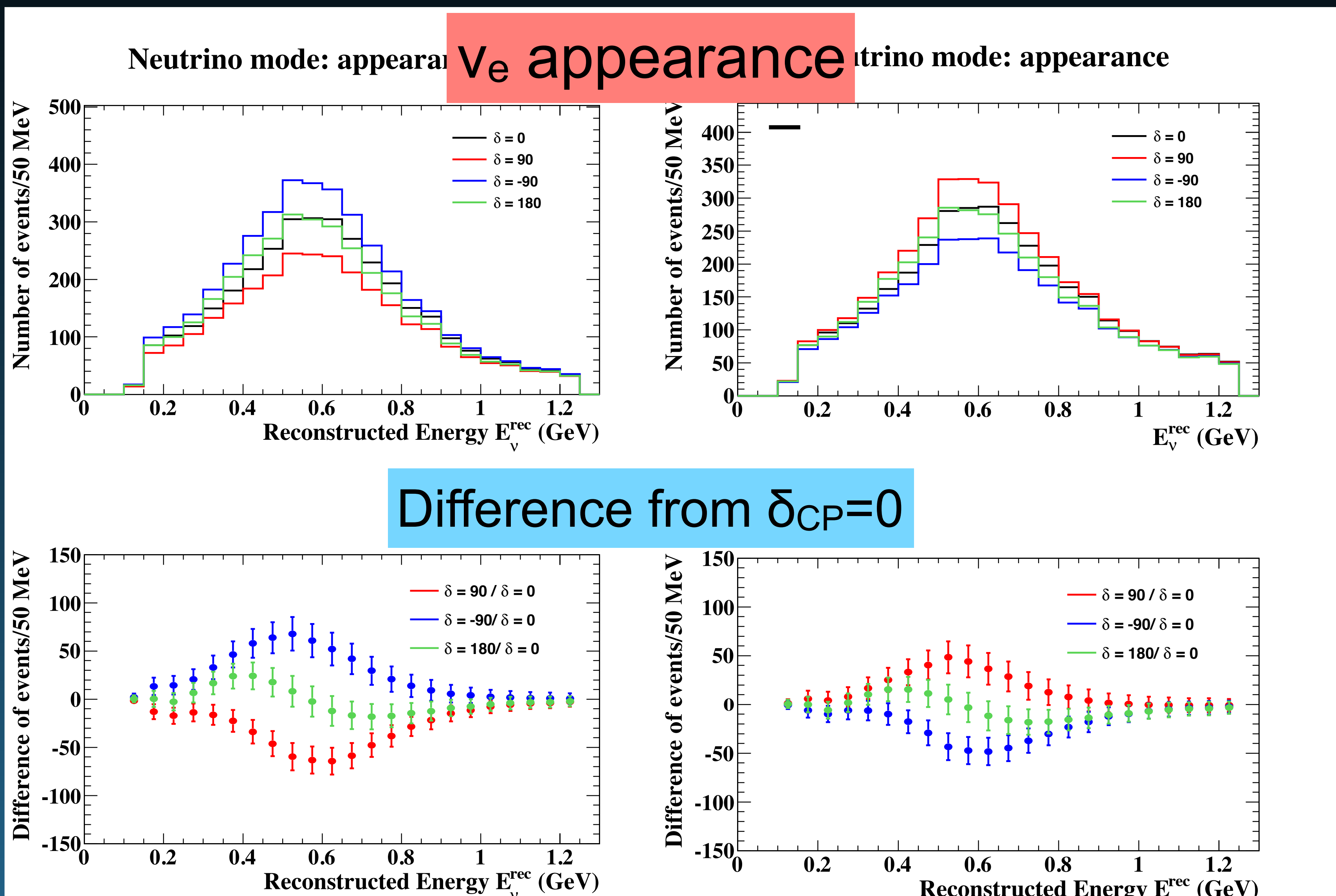
Upgraded Accelerator for higher beam

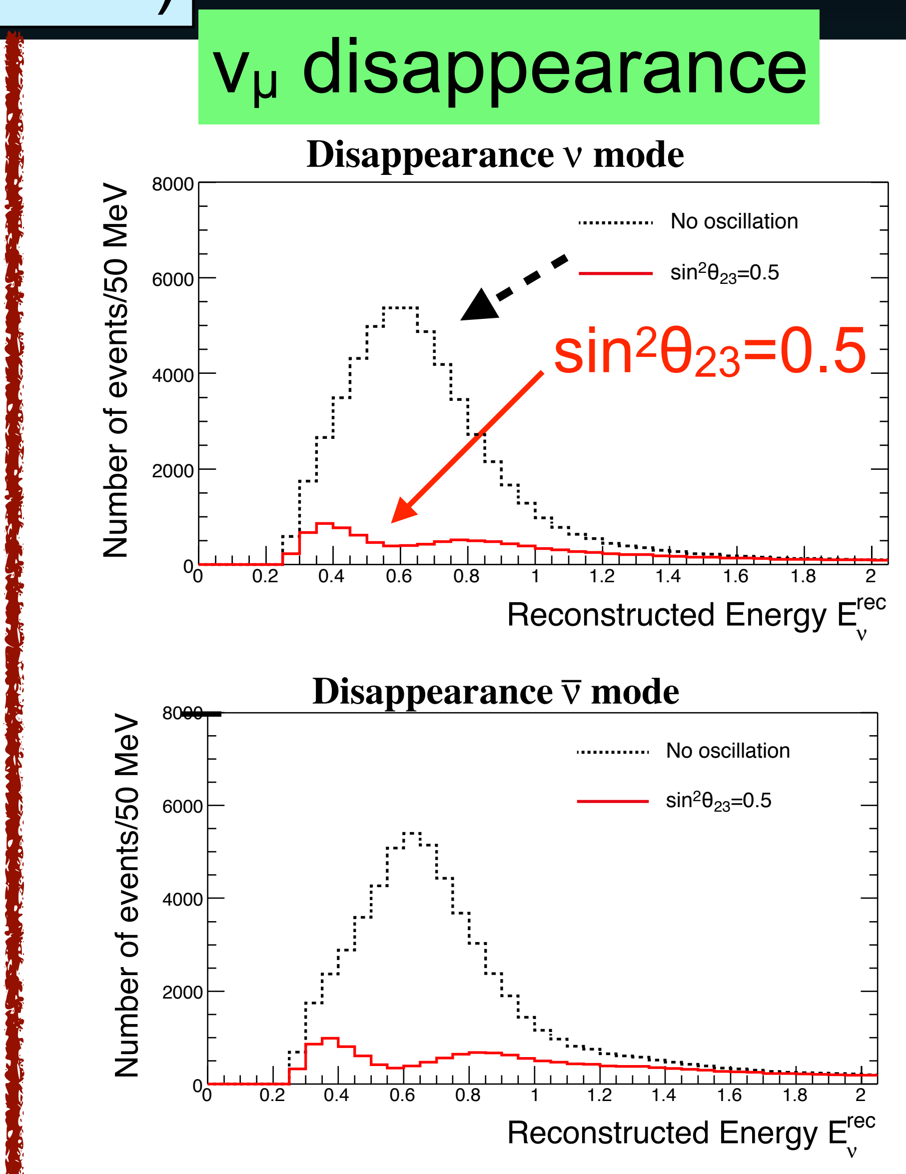


EXPECTED EVENTS

10 years (1.3MW beam power)

arXiv:1805.0416

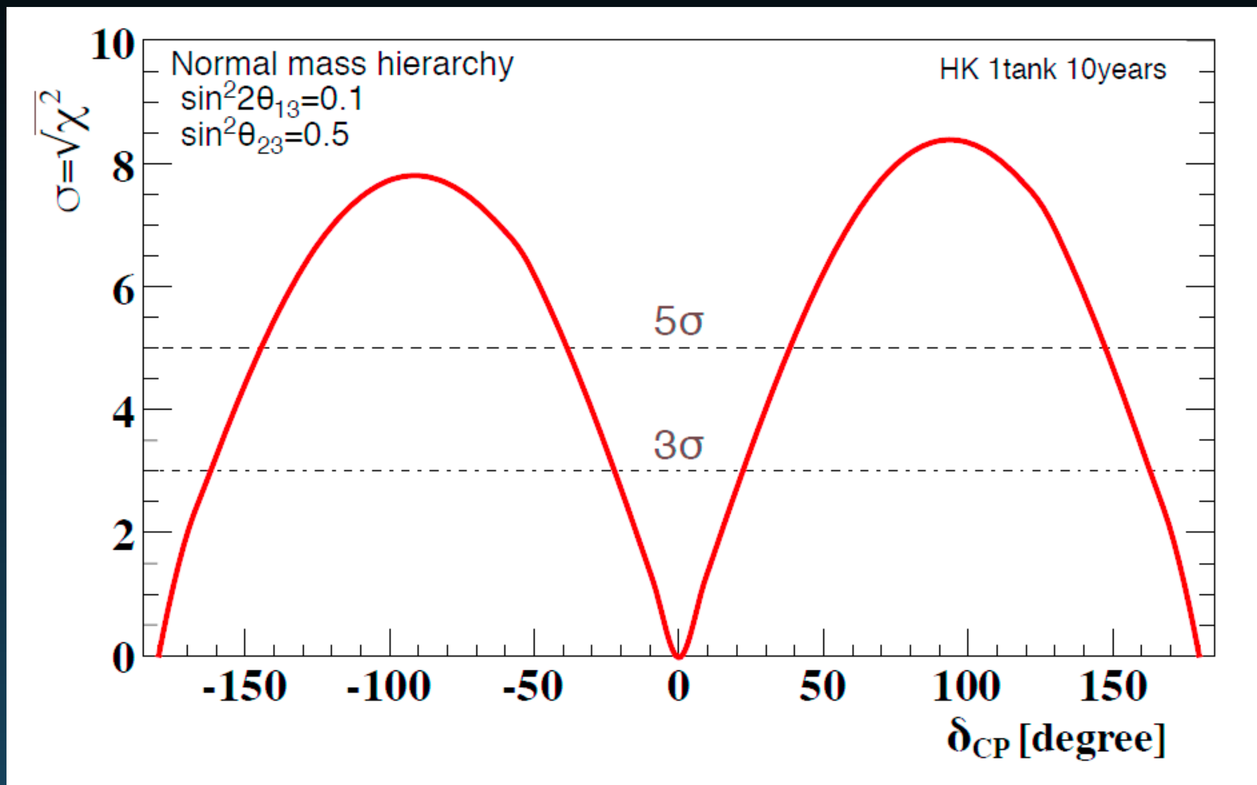


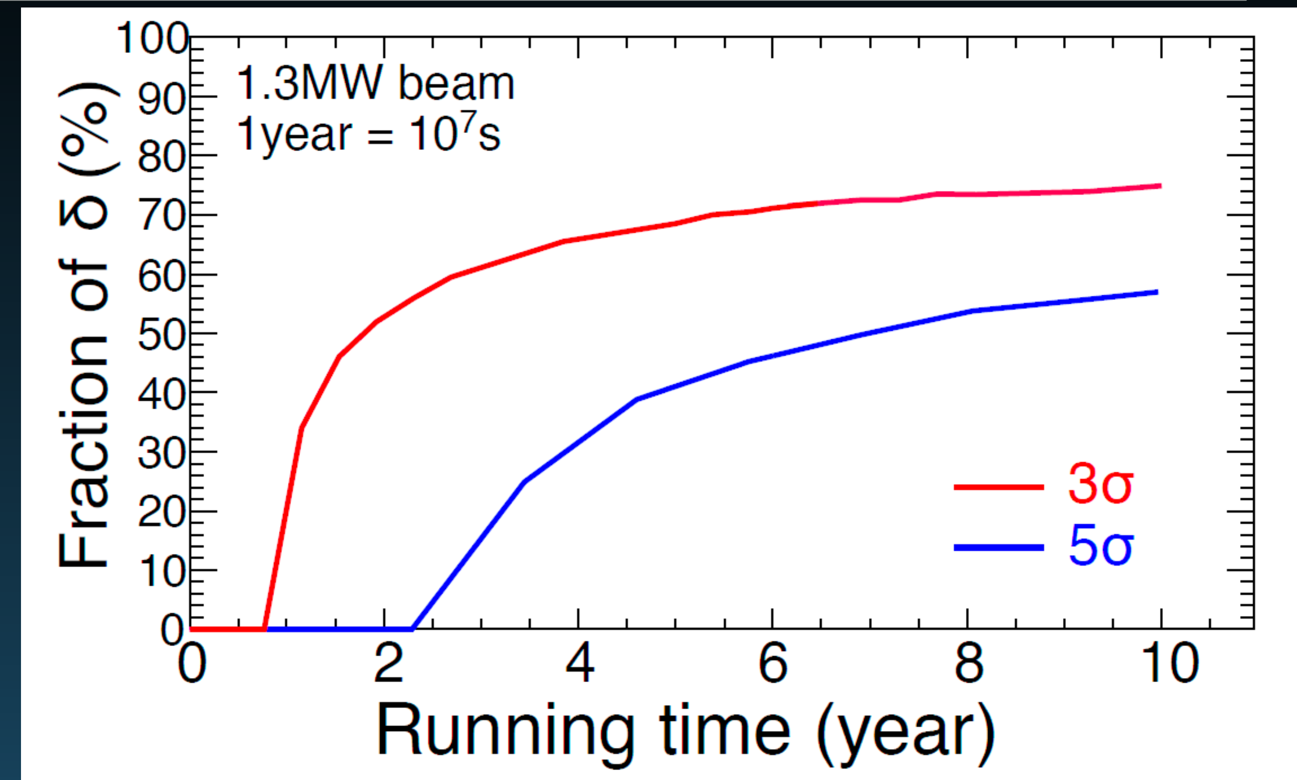


for δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

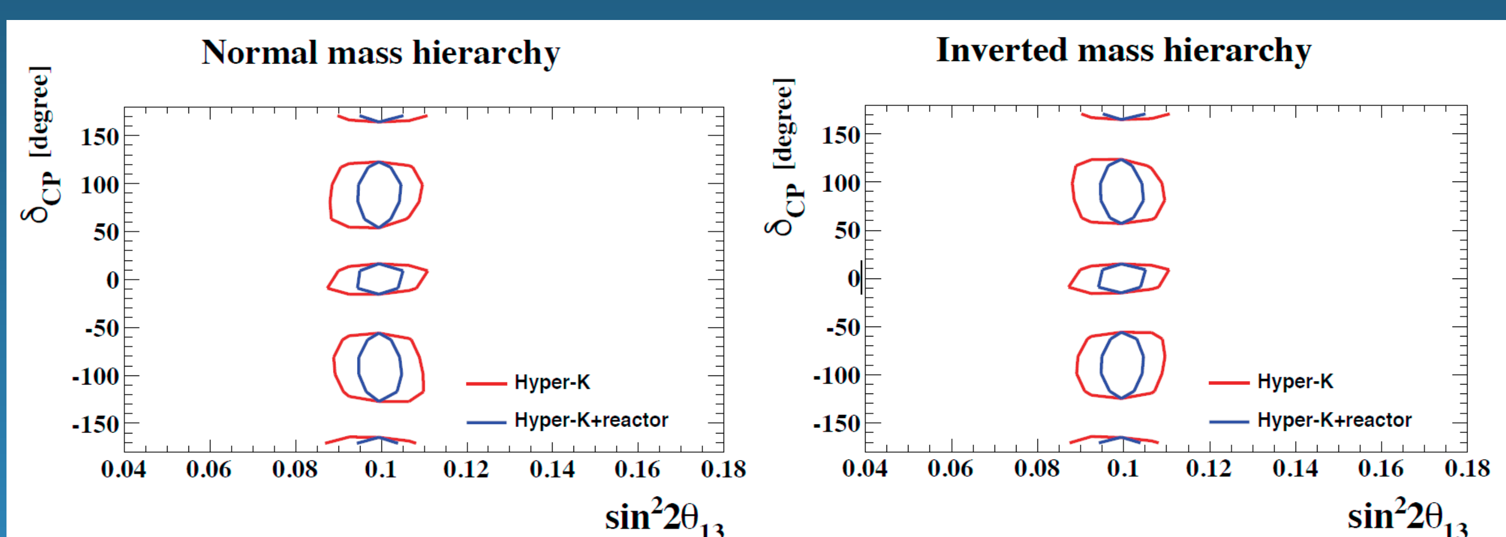
	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	8,947	4444	721
$\bar{\nu}$ beam	12317	6040	859

CP VIOLATION SENSITIVITY



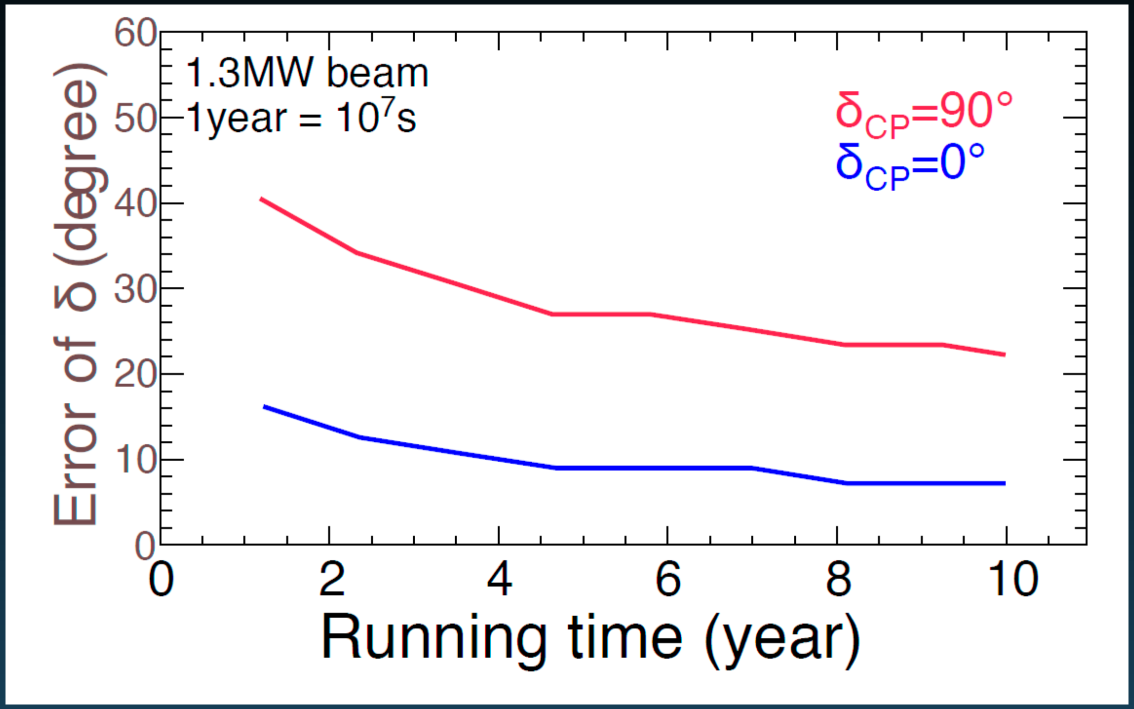


- **Exclusion of sinδ_{CP} = 0**
  - 8σ for δ_{CP} = -90°(T2K best fit)
  - 76% of coverage of δ_{CP} parameter space for CPV discovery > 3σ
- After 10 years of running, HK will be able to measure 58% of the δ_{CP} space to better than 5σ



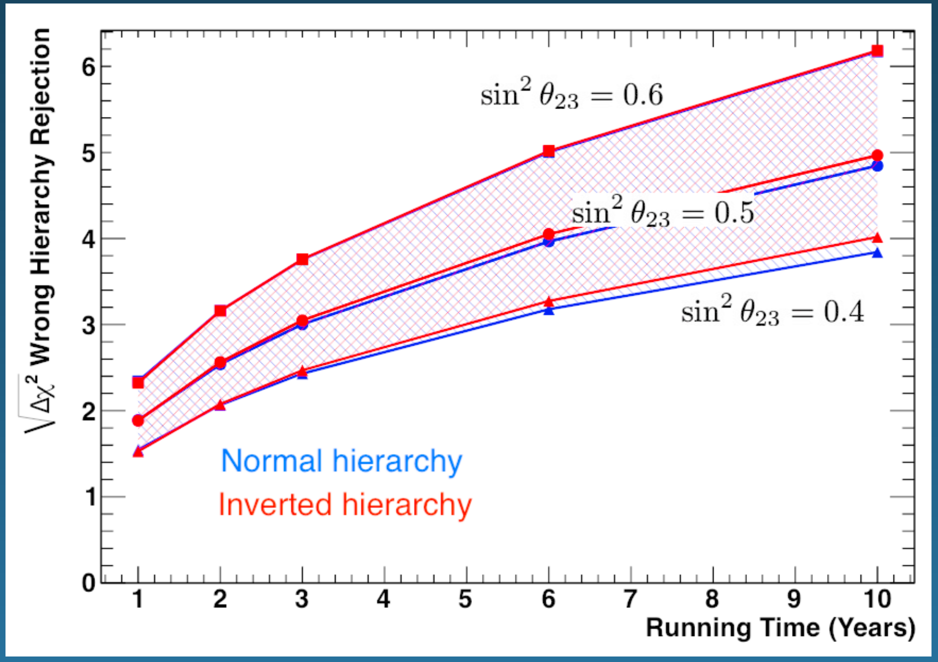
- The expected 90% CL allowed regions in the $\sin^2 2\theta_{13}$-δ_{CP} plane.

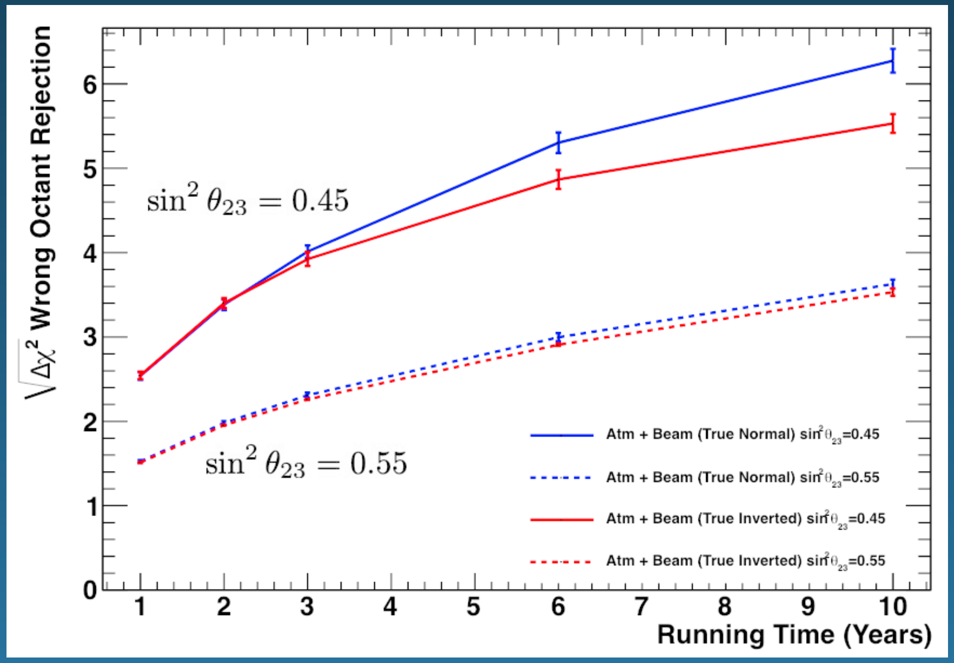
FURTHER RESULTS



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

Atmospheric + beam neutrino sensitivities



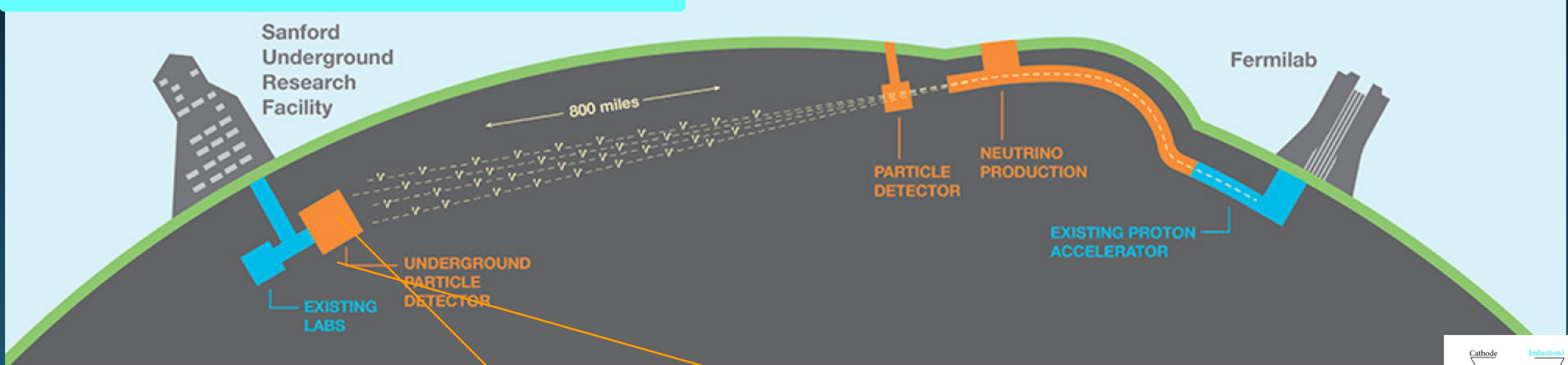


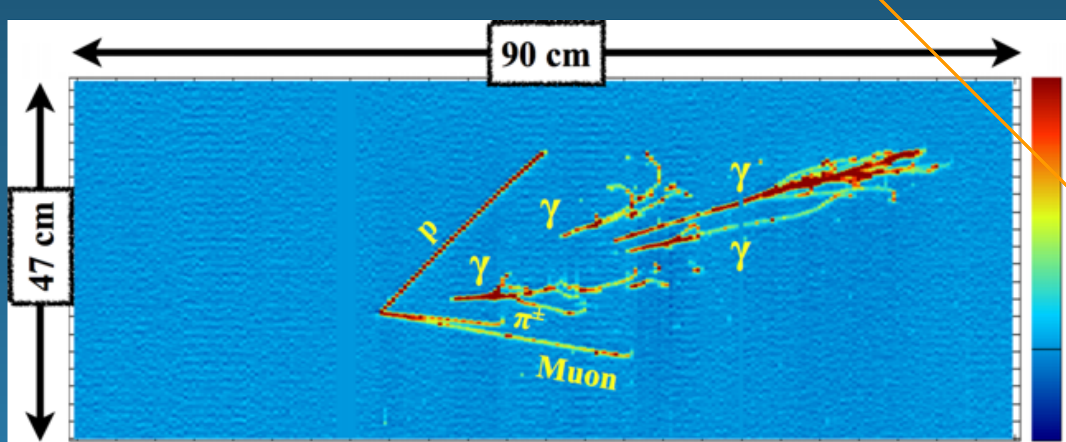
- Wrong mass hierarchy rejection @ 3σ for all possible values of θ_{23}
- Wrong octant rejection @ 3σ for $|\theta_{23} - 45°| \geq 2.3°$

DUNE

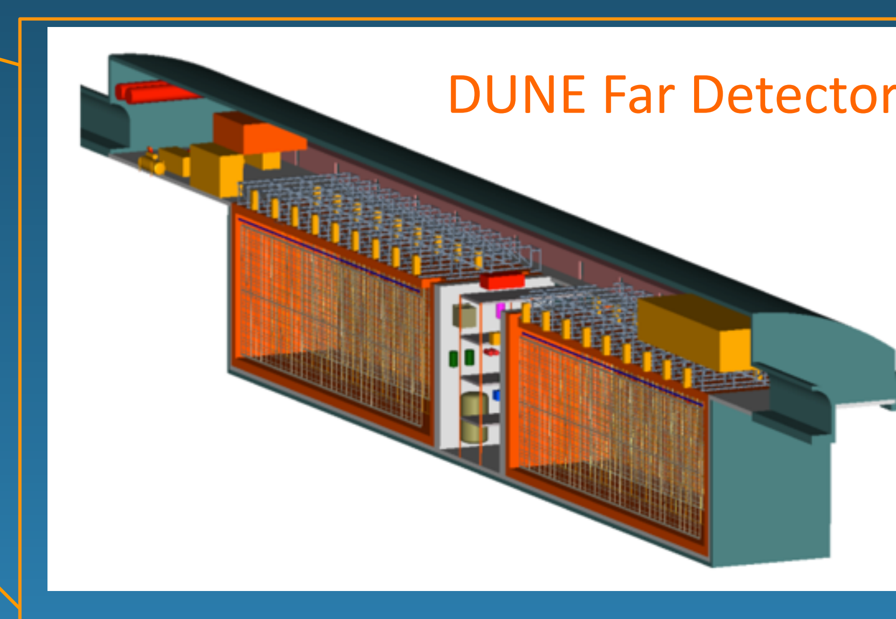
DUNE:
40 kt LAr-TPC Far Detector
(1300 km baseline)
- Near Detector systems
- Science collaboration

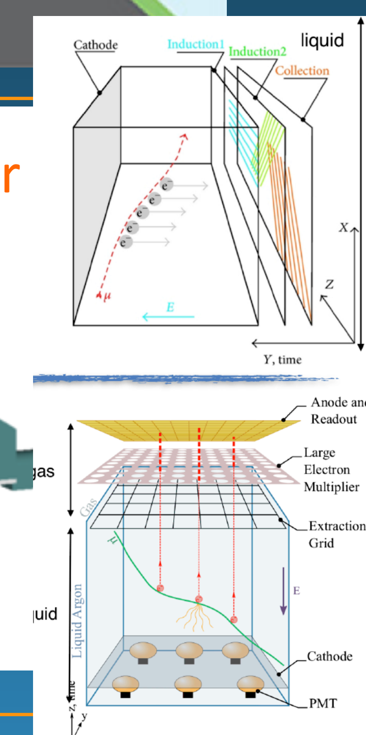
LBNF (Long-baseline Neutrino Facility)
- 1.2 MW wide-band ν beam, upgradable to 2.4 MW
- Conventional facilities at Fermilab and SURF
- Cryostats and cryogenic systems at SURF





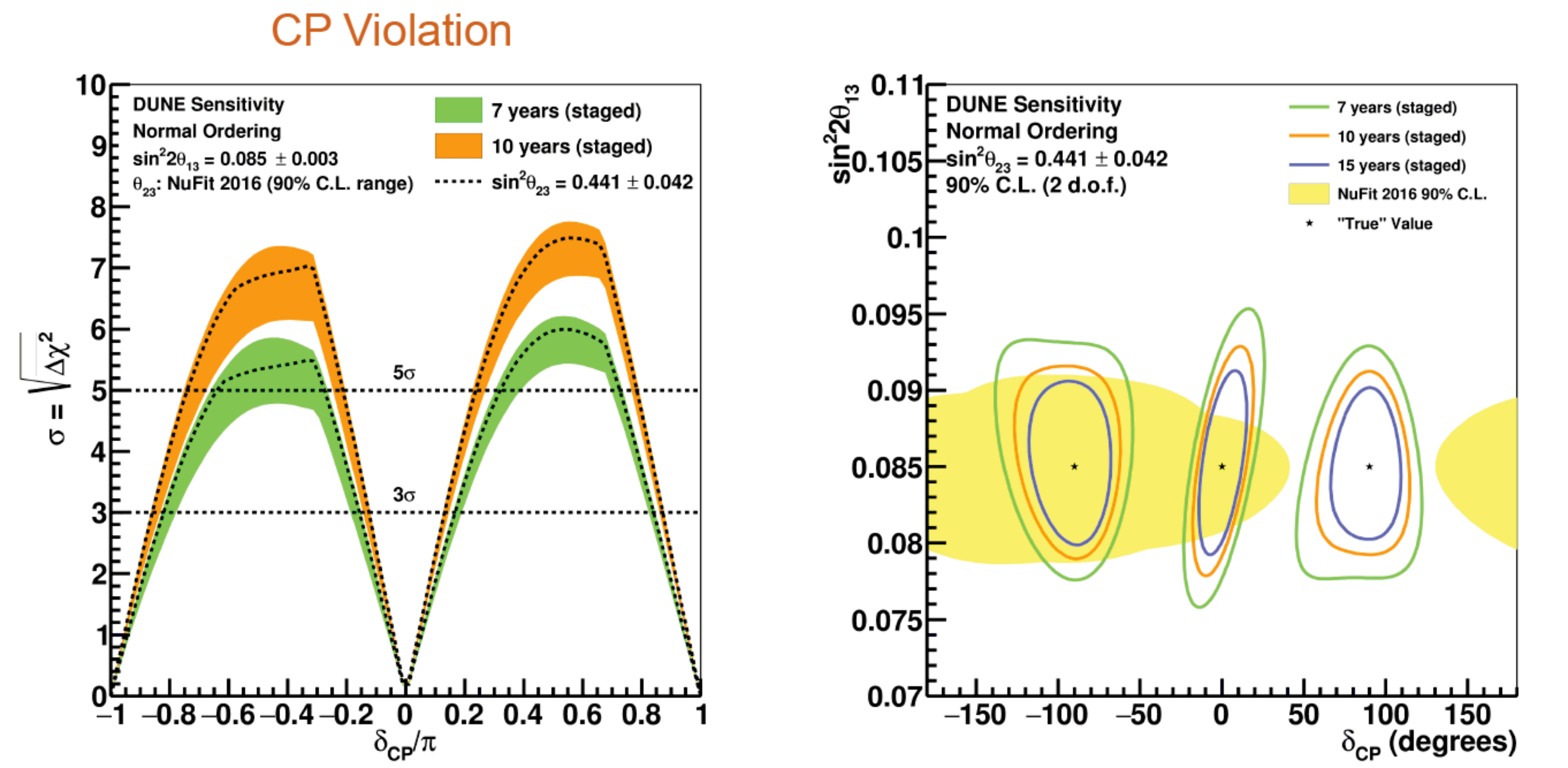
Example DIS event
(courtesy of ArgoNeuT collaboration)





CP VIOLATION SENSITIVITIES

- Over 1k ν_e appearance events in ~7 years assuming 1:1 $\nu:\overline{\nu}$
- Simultaneous fit of four spectra
- Systematics approximated as normalisation uncertainties

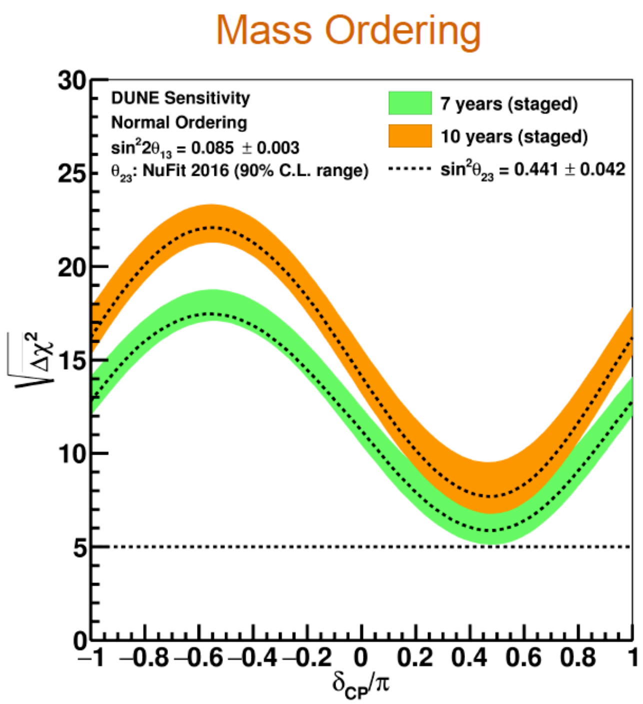


Width of band indicates variation in possible central values of θ_{23}

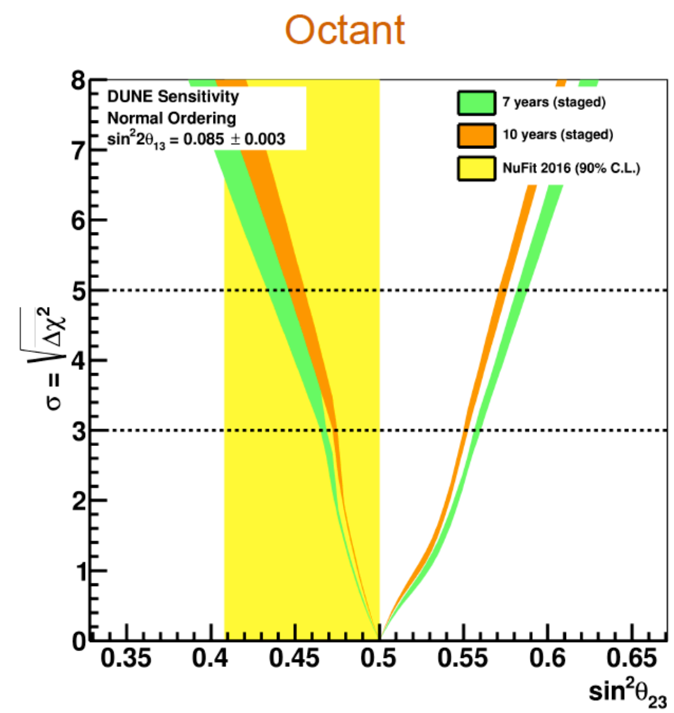
Simultaneous measurement of neutrino mixing angles and δ_{CP}

- 5σ sensitivity after 300 kt·MW·yr exposure (7 yr), for any δ_{CP}
- From DUNE Conceptual Design Report (CDR) arXiv:1512.06148

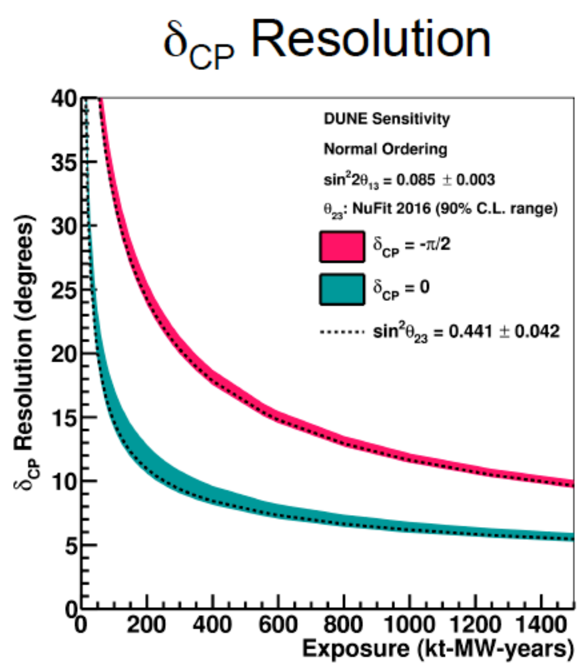
OTHER OSCILLATION PHYSICS AND SENSITIVITIES

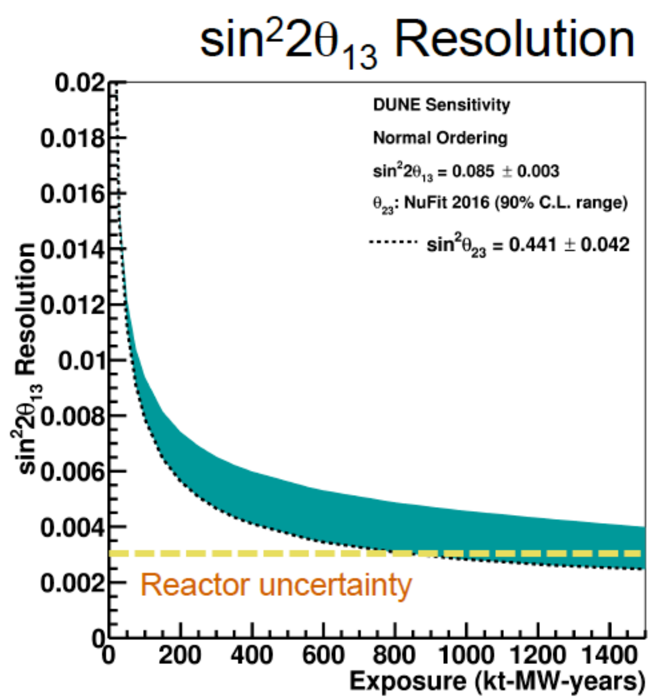


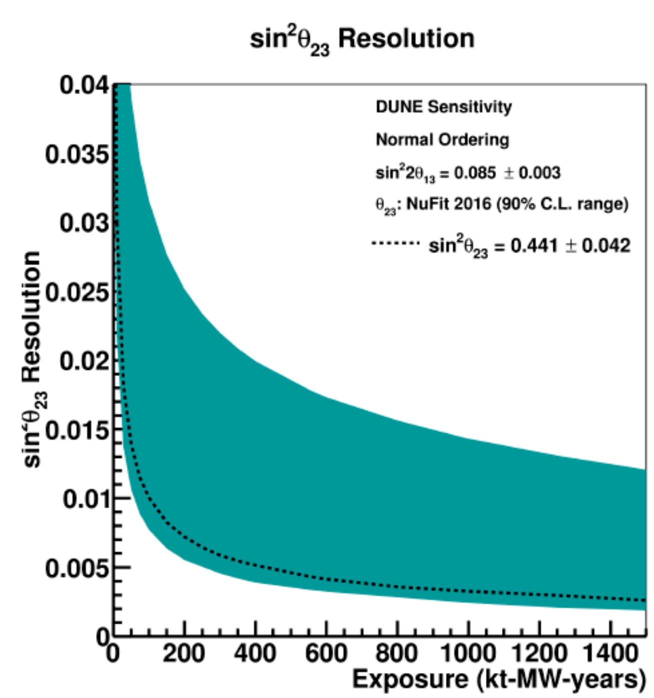
Width of band indicates variation in possible central values of θ_{23}



Width of band indicates variation in possible true value of δ_{CP}







- Normal ordering
- The bands represent the range of sensitivities for the NuFit 2016 90% CL allowed regions for $\sin^2\theta_{23}$

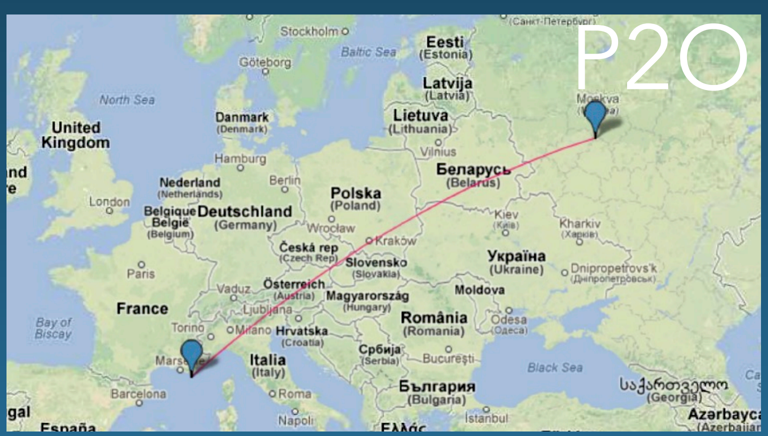
R&D: DUNE PROTOTYPES AT CERN

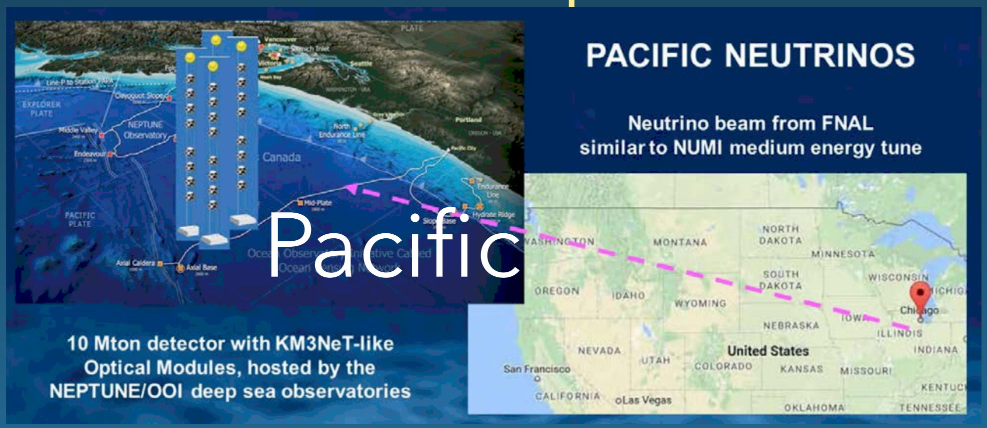
- The DUNE FD LArTPCs will be by far the largest ever built
- ProtoDUNEs are a crucial step in the R&D path for the DUNE FD:
  - validate construction procedures and operational performance, and use full-size components identical to those planned for DUNE FD
- Two ProtoDUNEs, to test the two designs (single and dual phase),of ~800 tons each - largest LArTPCs to date!

EHN1 Extension

OTHER FUTURE OPTIONS

- DUNE and Hyper-K are the first priority for the future of accelerator neutrino physics and must be pursued with the maximum support
- Possibility of optimization should also be studied with great attention
- Other topics in neutrino physics exist that require different accelerator experiments to be addressed
- It is important that the R&D is kept alive and first stage experiments are welcome. In a nutshell:
  - Alternative configurations for LBL experiments: P2O, Pacific, Chips

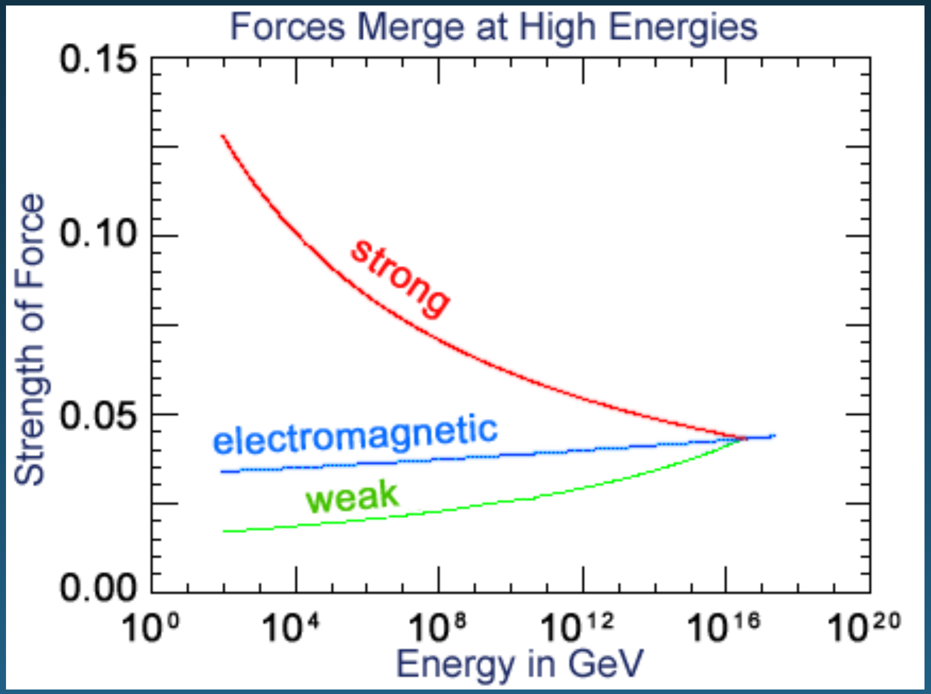




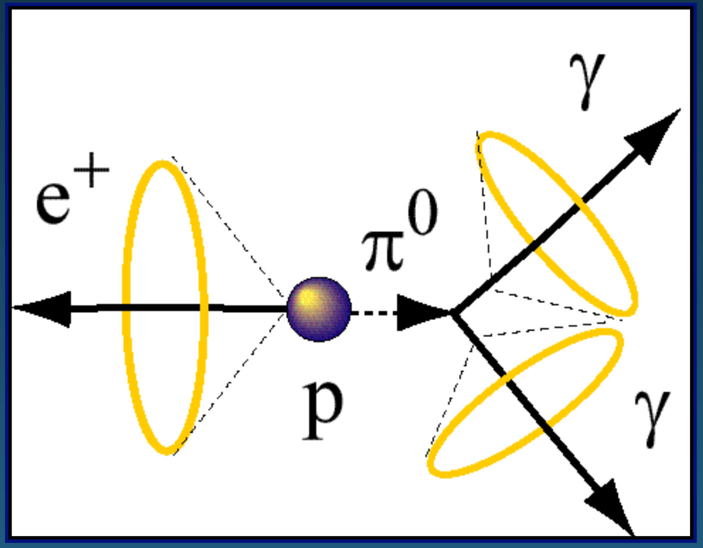
- Ancillary setups for LBL experiments: Enubet, NuStorm.
- New concepts for neutrino beams (and their first stages): ESSnuBeam, DAEδALUS (IsoDAR), Nufact (nuSTORM), Moment (EMuS)

MOTIVATION OF PROTON DECAY SEARCHES

- Proton decay observation would be a strong evidence of the Grand Unified Theories.



- Neutrino mass/mixings/CPV and proton decays could be related to each other at very high energy physics (GUTs).

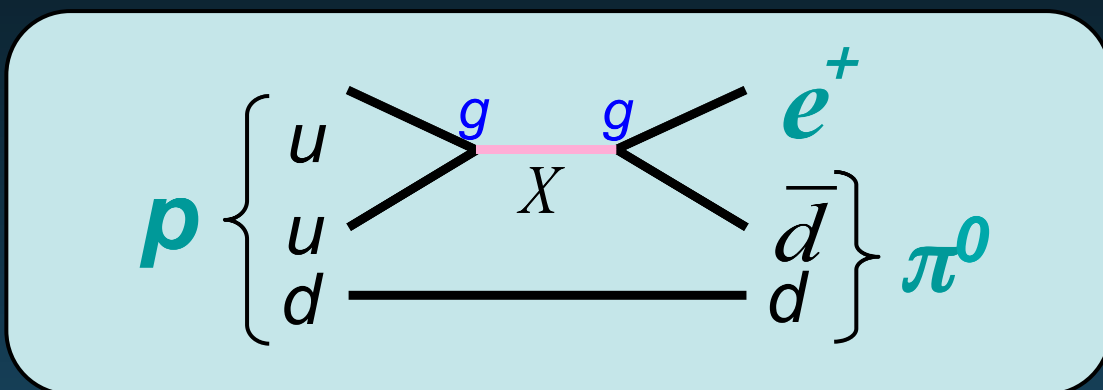


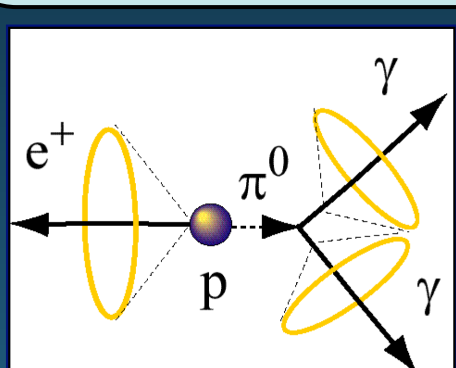
We are in an exciting era because large neutrino detectors (JUNO, DUNE, Hyper-K) are planned to start operation near future. They are also good proton decay detectors!

P-DECAY SEARCHES TO PROVE GUT

- Two major modes predicted by many models

MEDIATED BY GAUGE BOSONS

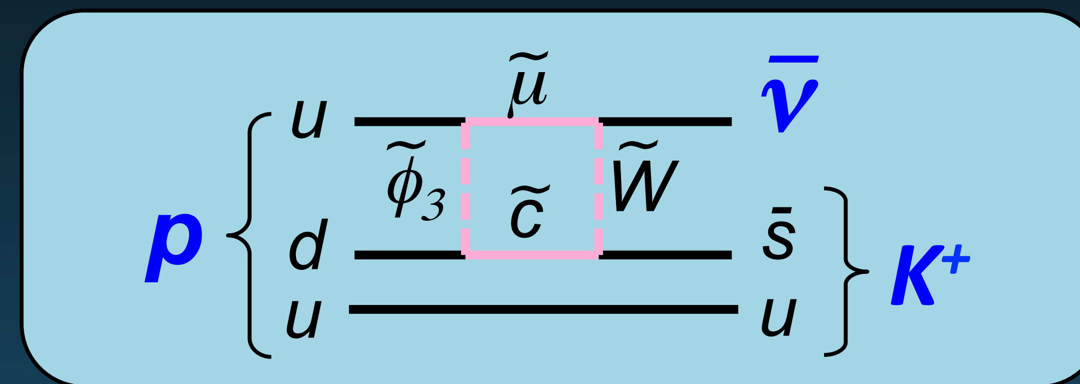


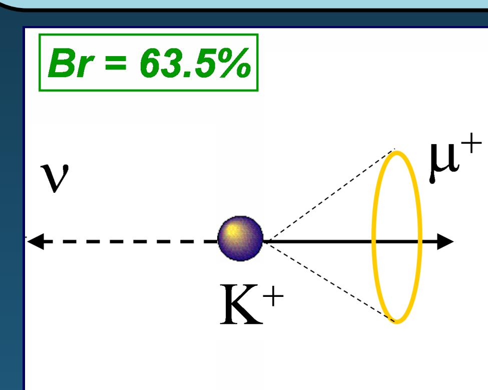


$p \to e^+\pi^0$

$$\Gamma(p \to e^+\pi^0) \sim \frac{g^4 m_p^5}{M_X^4}$$

SUSY MEDIATED





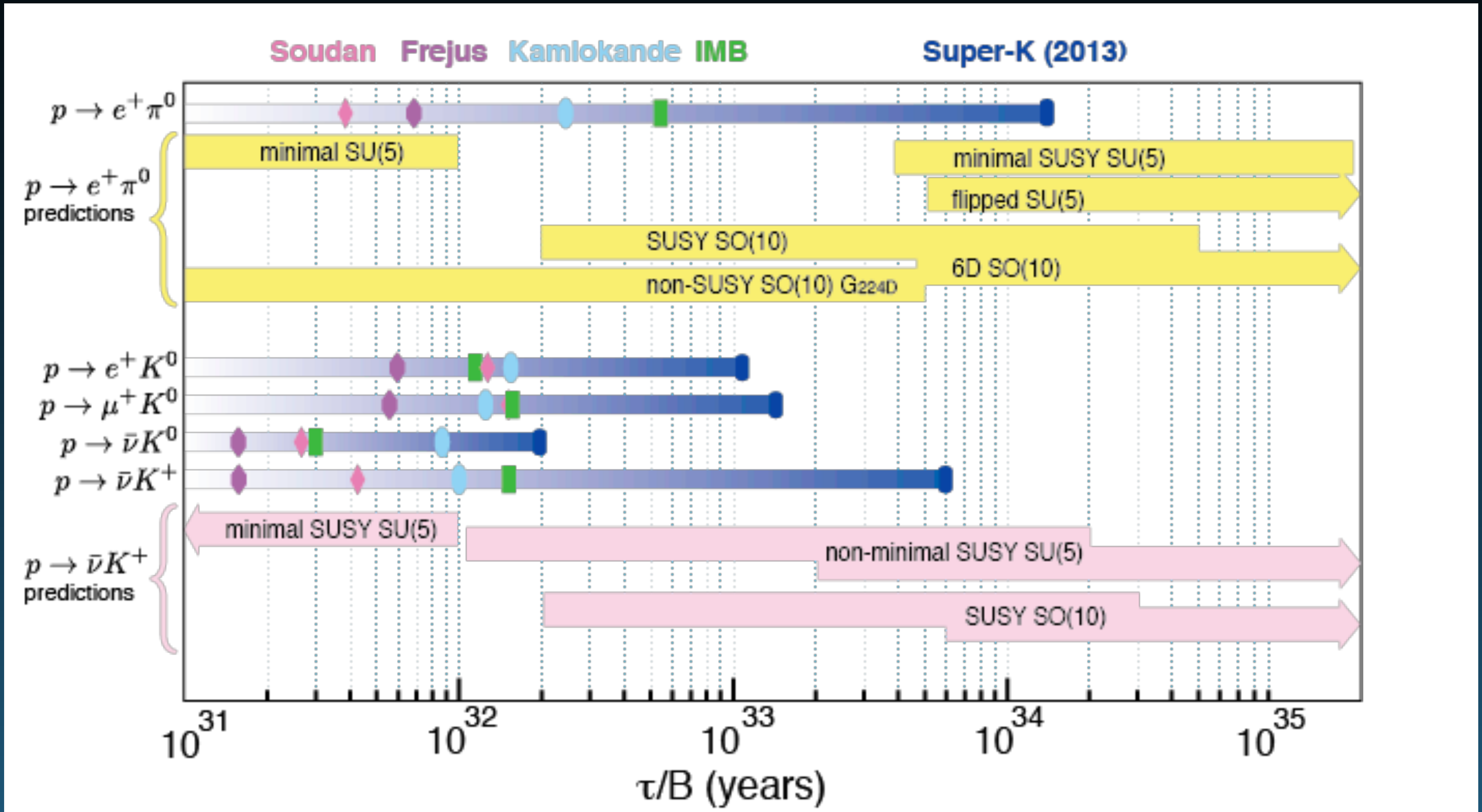
$p \to \nu K^+$

$$\Gamma(p \to \bar{\nu} K^+) \sim \frac{\tan^2\beta \times m_p^5}{M_{\tilde{q}}^2 \times M_3^2}$$

- Variety of predictions and no SUSY in LHC

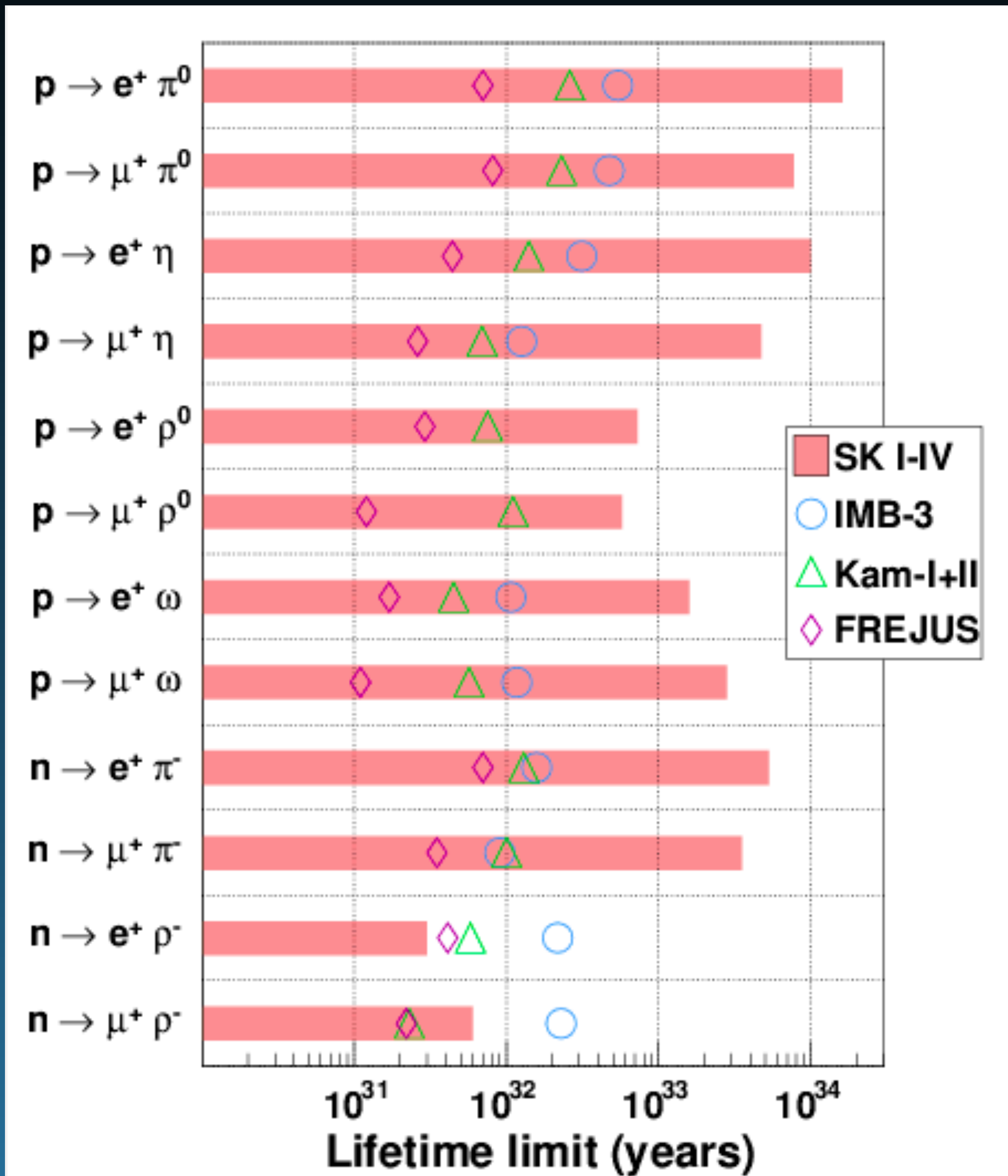
→ We must pursue both these and other decay modes for discovery

EXPERIMENTAL LIMITS AND MODEL



- Super-K provides world stringent limits on the proton lifetime
  - $\tau/B(p \to e^+\pi^0) > 1.6 \times 10^{34}$ years (90%C.L.) PRD95, 012004 (2017)
  - $\tau/B(p \to \bar{\nu}K^+) > 5.9 \times 10^{33}$ years (90%C.L.) PRD90, 072005 (2014)
- Already constrain the construction of many GUT models
- Many models predict $\tau/B = O(10^{34\text{-}35})$ years
  - Discovery could be around corner!

CHARGED LEPTON + MESON DECAY



Modes		Eff.(%) SK-I	SK-II	BG (SK-I+II) NEUT	(NUANCE)	Candidates SK-I+II
$p \to e^+\pi^0$		44.6	43.5	0.31	(0.27)	0
$p \to \mu^+\pi^0$		35.5	34.7	0.34	(0.27)	0
$p \to e^+\eta$	(2γ)	18.8	18.2	0.28	(0.29)	0
	$(3\pi^0)$	8.1	7.6	0.16	(0.32)	0
$p \to \mu^+\eta$	(2γ)	12.4	11.7	0.04	(0.04)	0
	$(3\pi^0)$	6.1	5.4	0.45	(0.44)	2
$p \to e^+\rho^0$		4.9	4.2	0.35	(0.34)	0
$p \to \mu^+\rho^0$		1.8	1.5	0.42	(0.46)	1
$p \to e^+\omega$	$(\pi^0\gamma)$	2.4	2.2	0.14	(0.29)	0
	(3π)	2.5	2.3	0.39	(0.30)	1
$p \to \mu^+\omega$	$(\pi^0\gamma)$	2.8	2.8	0.31	(0.37)	0
	(3π)	2.7	2.4	0.17	(0.05)	0
$n \to e^+\pi^-$		19.4	19.3	0.27	(0.37)	0
$n \to \mu^+\pi^-$		16.7	15.6	0.43	(0.44)	1
$n \to e^+\rho^-$		1.8	1.6	0.38	(0.44)	1
$n \to \mu^+\rho^-$		1.1	0.94	0.29	(0.69)	0

TABLE V. Summary of the nucleon decay searches.

PRD 96, 012003 (2017)

- No evidence is found in Super-K

OTHER SEARCHES

- Test of excess in e/μ spectrum

PRL113,101801(2014)

Mode	SK I-IV Sensitivity (years)	SK I-IV Limit (years)	PDG Limit (years)
$p \rightarrow e^+\nu\nu$	$2.7 \cdot 10^{32}$	$1.7 \cdot 10^{32}$	$1.7 \cdot 10^{31}$
$p \rightarrow \mu^+\nu\nu$	$2.5 \cdot 10^{32}$	$2.2 \cdot 10^{32}$	$2.1 \cdot 10^{31}$

Mode	SK I-IV Sensitivity (years)	SK I-IV Limit (years)	PDG Limit (years)
$p \rightarrow e^+X$	$7.9 \cdot 10^{32}$	$7.9 \cdot 10^{32}$	–
$p \rightarrow \mu^+X$	$7.7 \cdot 10^{32}$	$4.1 \cdot 10^{32}$	–
$n \rightarrow \nu\gamma$	$5.8 \cdot 10^{32}$	$5.5 \cdot 10^{32}$	$2.8 \cdot 10^{31}$
$np \rightarrow e^+\nu$	$9.9 \cdot 10^{31}$	$2.6 \cdot 10^{32}$	$2.8 \cdot 10^{30}$
$np \rightarrow \mu^+\nu$	$1.1 \cdot 10^{32}$	$2.2 \cdot 10^{32}$	$1.6 \cdot 10^{30}$
$np \rightarrow \tau^+\nu$	$1.1 \cdot 10^{31}$	$2.9 \cdot 10^{31}$	–

Preliminary

- $p \rightarrow \nu\pi^0$, $\tau/B_{\pi 0} > 1.1 \times 10^{33}$ years at 90%CL
- $p \rightarrow \nu\pi^+$, $\tau/B_{\pi +} > 3.9 \times 10^{32}$ years at 90%CL

PRL 113, 121802 (2014)

- $\Delta B = 2$, n-$\bar{n}$ oscillations
  - $\tau/B_{n\text{-}\bar{n}}(^{16}O) > 1.9 \times 10^{32}$ years @ 90%C.L.
    - $\tau/B_{n\text{-}\bar{n}}$(free)$>2.7 \times 10^{8}$ sec

PRD91,072006(2015)

- $\Delta B=2$ dinucleon decays:
  - $\tau/B(^{16}O(pp) \rightarrow {}^{14}CK^+K^+) > 1.7 \times 10^{32}$ years @ 90%C.L.
  - Super-K also searched for $pp \rightarrow \pi^+\pi^+$, $pn \rightarrow \pi^+\pi^0$, $n \rightarrow \pi^0\pi^0$

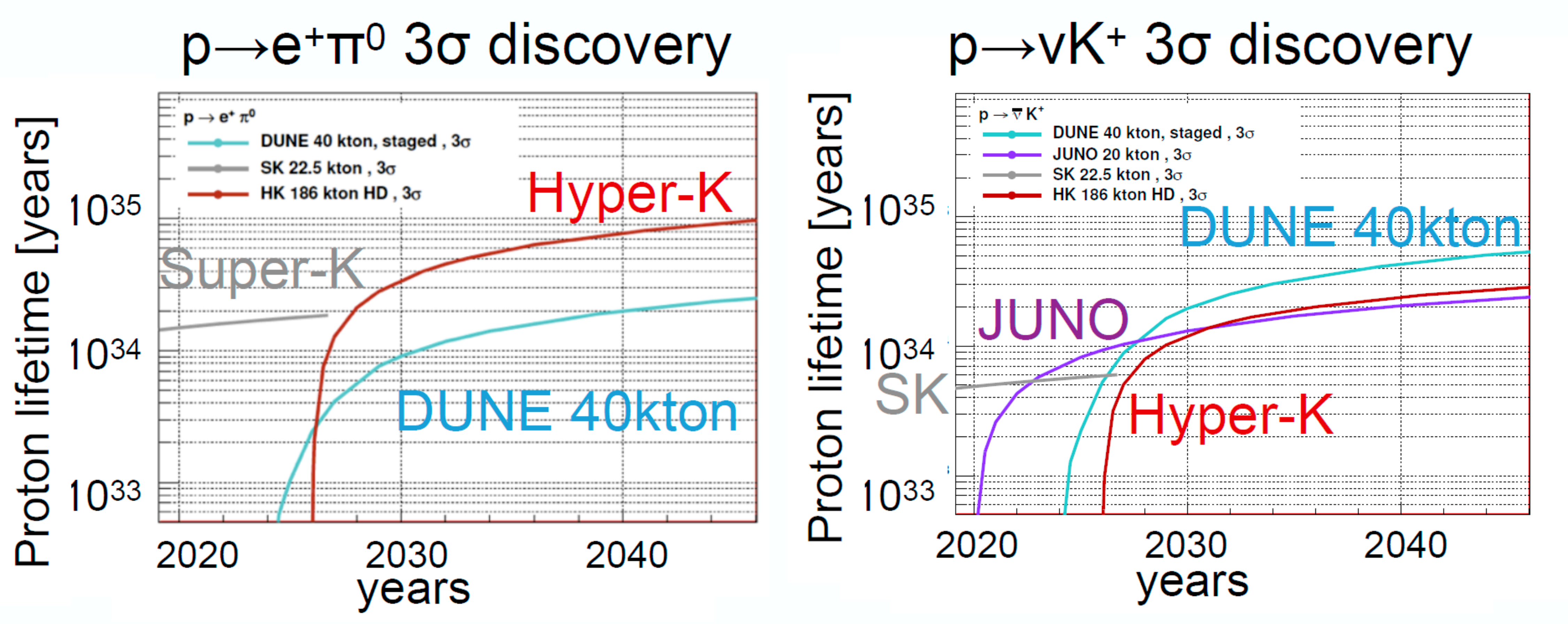
PRL112,131803(2014)

SENSITIVITIES OF FUTURE EXPERIMENTS

	Hyper-K 190 kton		DUNE 40 kton		JUNO 20 ton	
	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)	Eff. (%)	BG (/Mt y)
$e^+\pi^0$	40	0.7	45	1	-	-
$\bar{\nu}K^+$	24	1.6	97	1	64	2.5
	arXiv:1805.04163		JHEP0704(2007)041; arXiv:1512.06148		arXiv:1507.05613	

- For modes with Kaons, DUNE and JUNO can benefit from K identification and expected to have better S/N than water.
- For modes of "charged lepton plus mesons" like $p \to e^+\pi^0$, Hyper-K sensitivities are better by high mass.

PROTON LIFETIME SENSITIVITIES



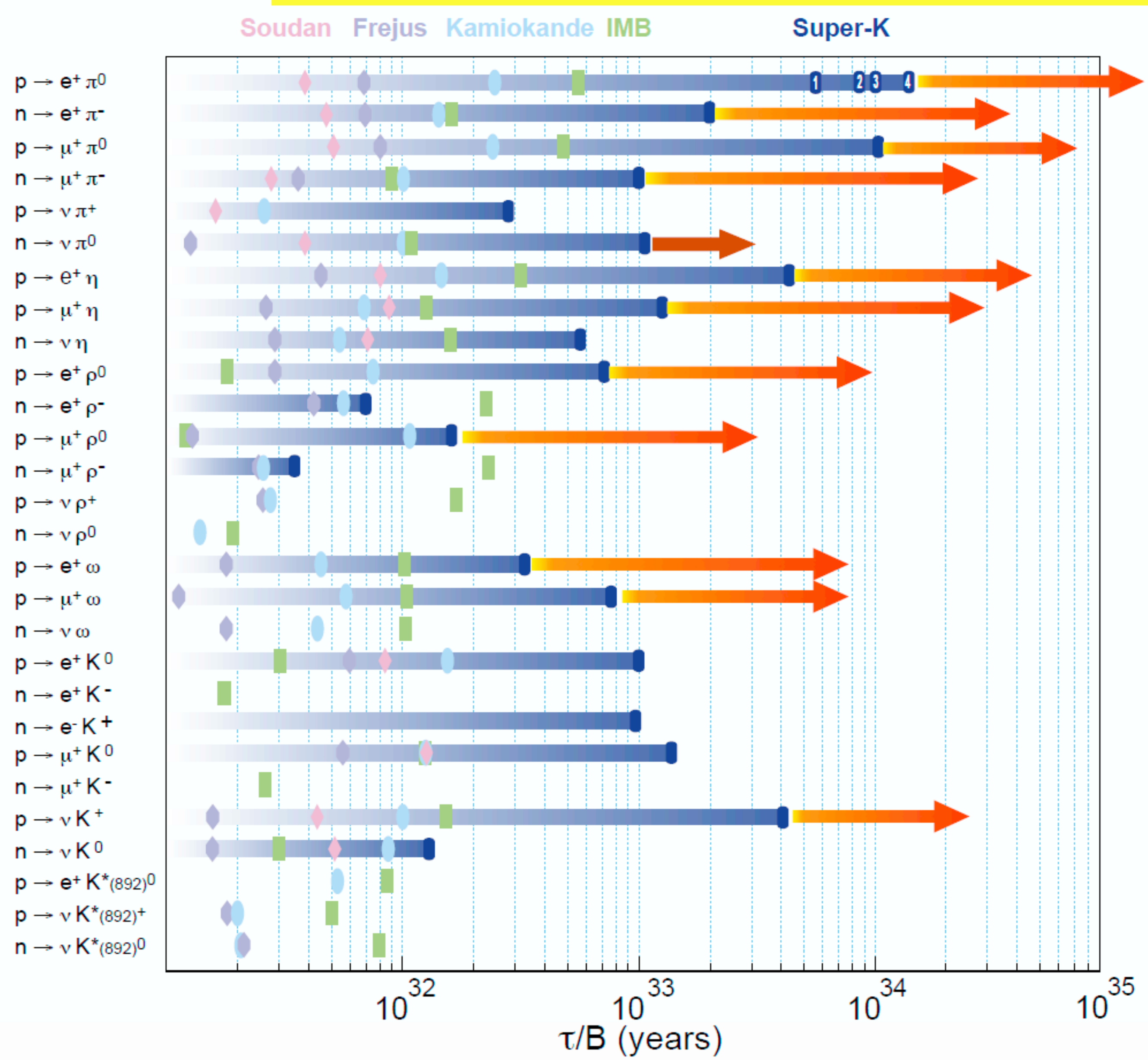
(Lines for DUNE and JUNO experiment have been generated based on numbers in the literature.)

3σ discovery potential will reach:

- 1×10^{35} years for $p \to e^{+}\pi^{0}$
- 5×10^{34} years for $p \to \bar{\nu} K^{+}$

HYPER-K SENSITIVITIES

- Improvements in many modes by a factor ~10
- Large number of decay modes will be investigates, including $p \to e^+\pi^0$, $p \to \bar{\nu}K^+$
- Good chance for discovery!



- $p \to e^+ + \pi^0$
  - $\tau_{proton}/Br > 1\times10^{35}$ years @90%CL
  - 5Mton×years (9 Hyper-K years)
- $p,n \to (e^+,\mu^+) + (\pi,\rho,\omega,\eta)$
  - $O(10^{34\sim35})$years
- *SUSY favored* $p \to \nu + K^+$
  - 3×10^{34} years
- K^0 modes, $\nu\pi^0$, $\nu\pi^+$ possible
- Others
  - (B-L) violated modes
  - radiative decays $p \to e^+\gamma$, $\mu^+\gamma$
  - neutron-antineutron oscillations ($|\Delta B|=2$)
  - di-nucleon decays ($|\Delta B|=2$)
    - $pp \to XX\ldots$, $nn \to XX\ldots$

CONCLUSIONS

- Major quest for CP violation in the lepton sector is being addressed by two running experiments T2K and NoVA.
- Current results
  - Exclude CP = 0 or π at 2σ
  - Prefer normal hierarchy
- Experiments are continuing to run, more data and lower systematics will be achieved.
- Future experiments, chiefly Hyper-K and DUNE, currently being built, will definitely be able to measure CP violation in the lepton sector.
- Proton and neutron decays have been challenged by Super-K. Much higher sensitivity will be provided by Hyper-K, DUNE and JUNO.

ADDITIONAL SLIDES

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**

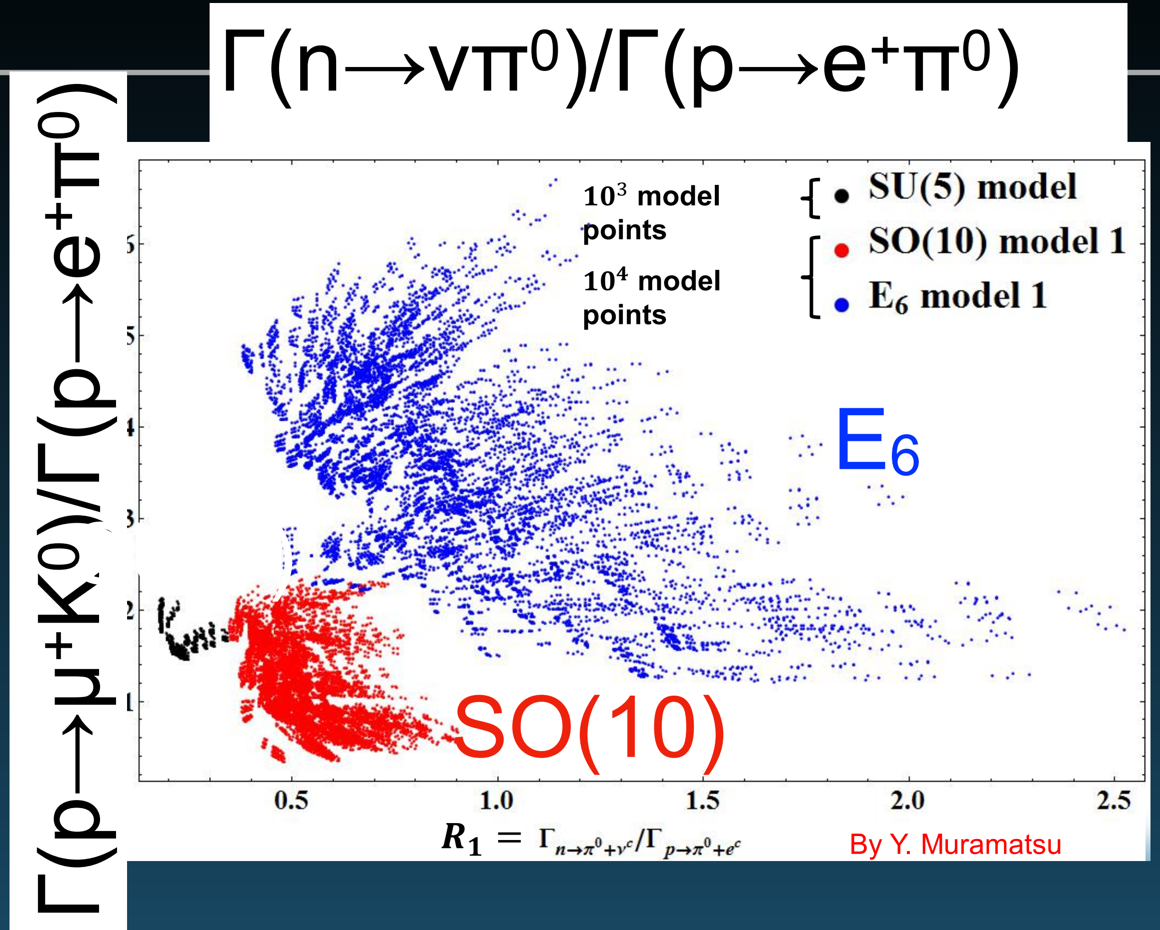
See fewer ν_μ like events than expected,
$\Rightarrow$ fit will prefer maximal disappearance

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

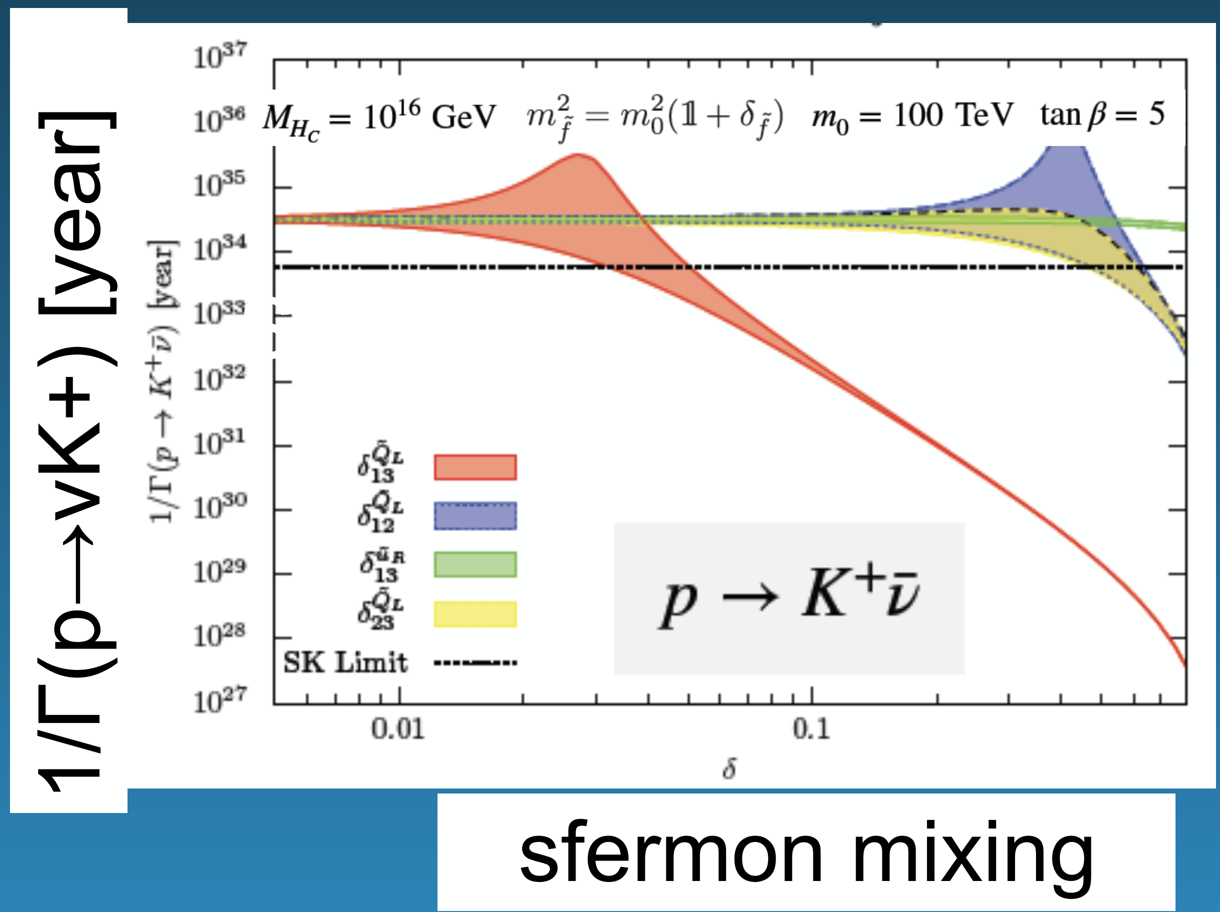
- Excess in d.e. sample has p~1%, but does not have big impact on fit

STRONG CASES

- We could identify details of unification picture, e.g. gauge group and other symmetries
  - $\Gamma(n\rightarrow \nu\pi^0)/\Gamma(p\rightarrow e^+\pi^0)$ depends on SU(5), SO(10), E_6 (Y. Muramatsu)



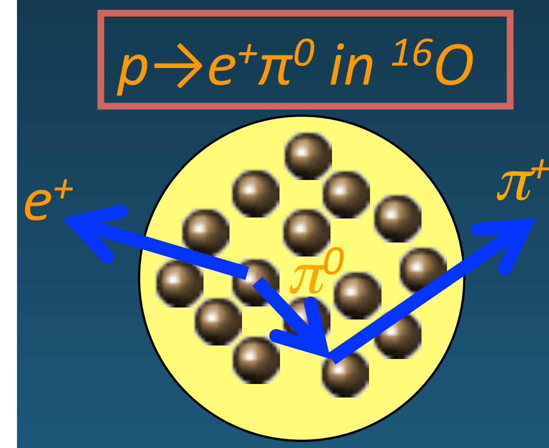
- P-decay Br. ratio could tell us flavor structure of SUSY particles.
  - Decay branches depends on the size of sfermion mixing. (N.Nagata and S.Shirai, JHEP 1403, 049 (2014))



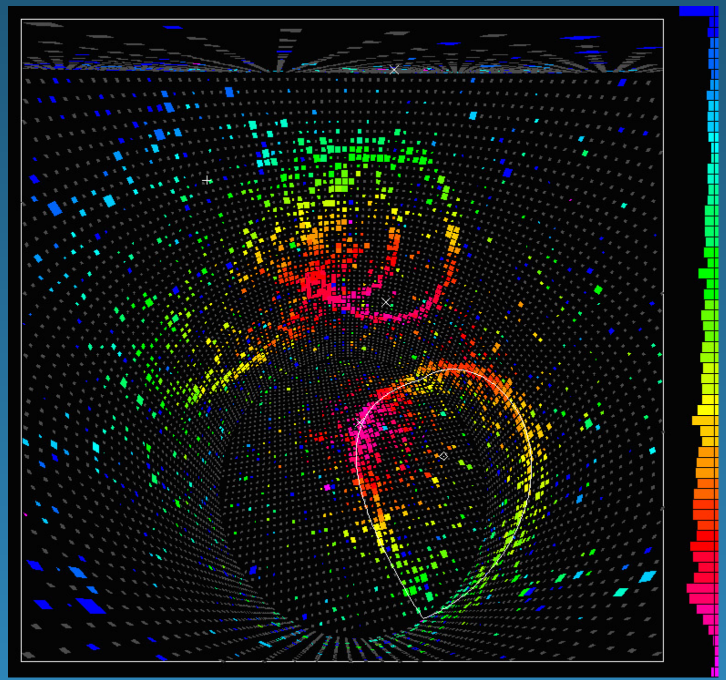
P-DECAY SEARCH BY WATER CHERENKOV

- **High mass** **(190kton for HK)**
    - To advance **$p \to e^+\pi^0$(>10^{35} years), νK^+(>3×10^{34} years),** and others beyond Super-K
- **Free-p (^{1}H) available**
    - No Fermi motion, nuclear effect
    - High efficiency & good S/N separation
- **Excellent & well-proven detector performance**
    - Good ring-imaging capability at sub-GeV
    - Excellent particle ID (e or μ) capability > 99% (single-ring)
    - Energy resolution

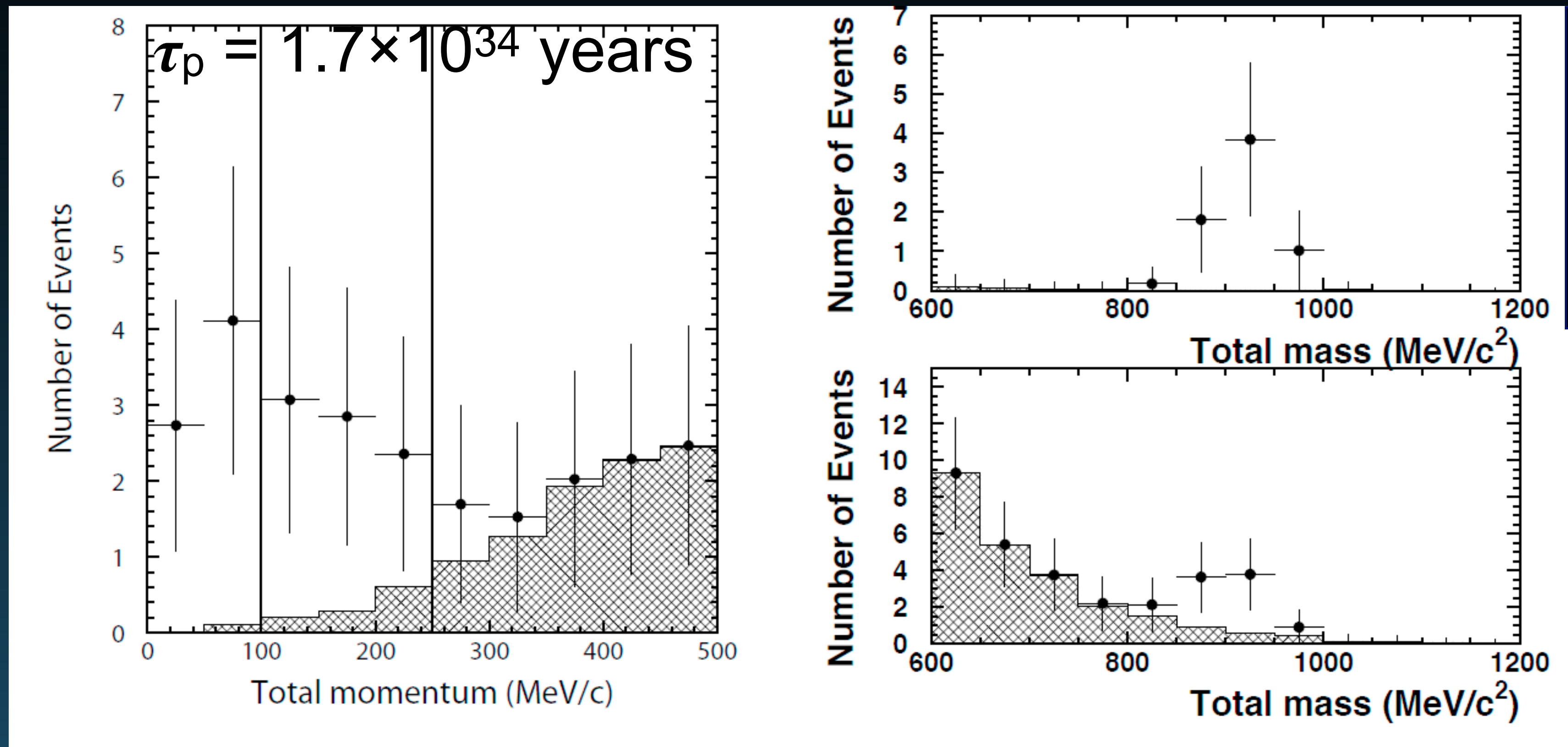
	material	Fiducial Mass (kton)
Super-K	Water	22
Hyper-K	Water	**190**
Dune	Argon	40
JUNO	Liq. Scinti	20

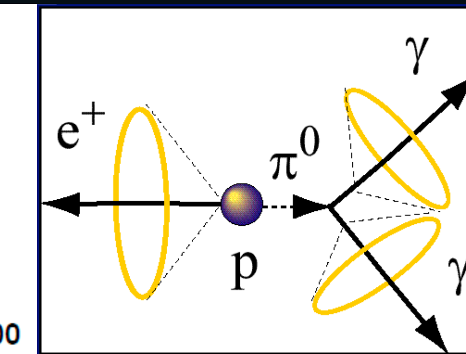


- No Fermi motio
- No π's re-scatt



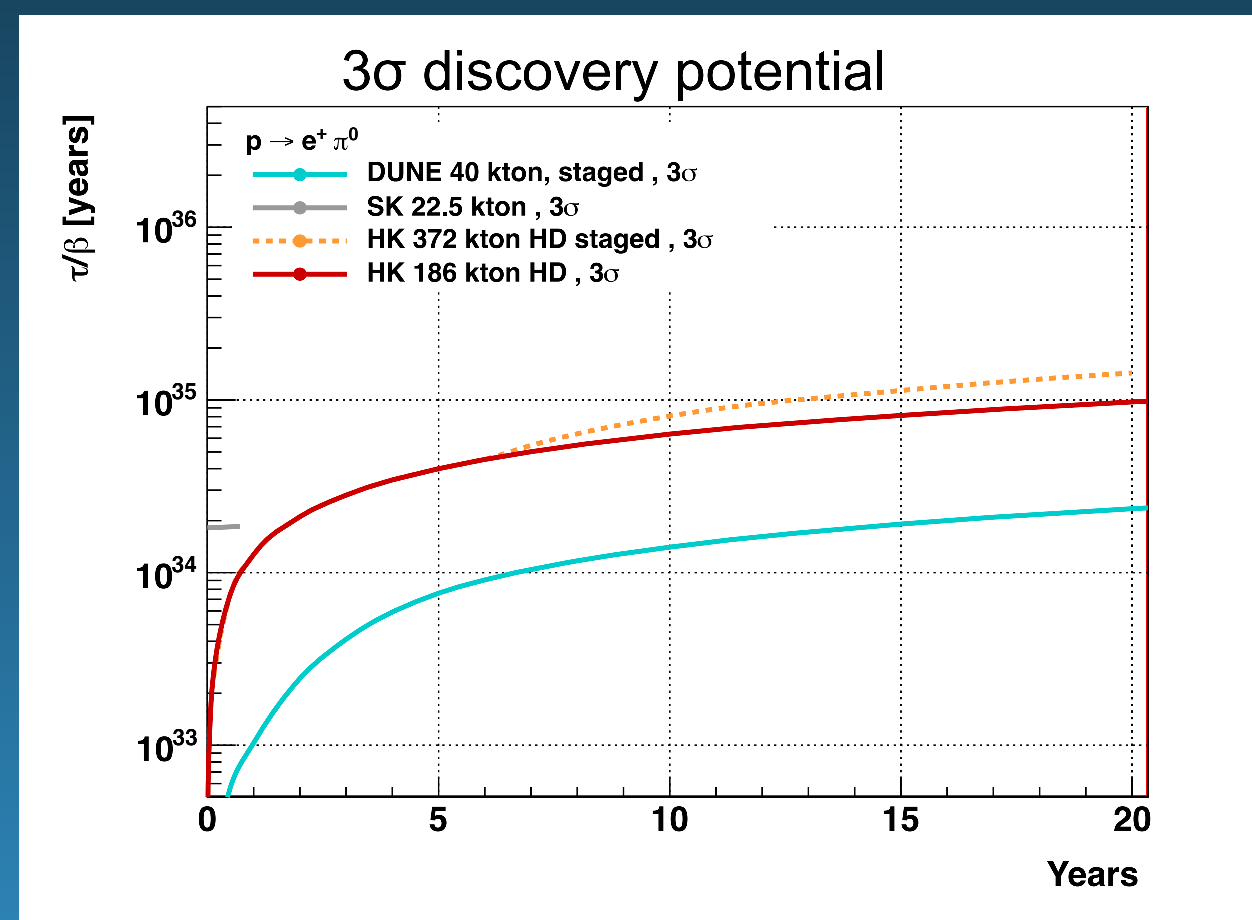
HYPER-KAMIOKANDE P→E+Π⁰





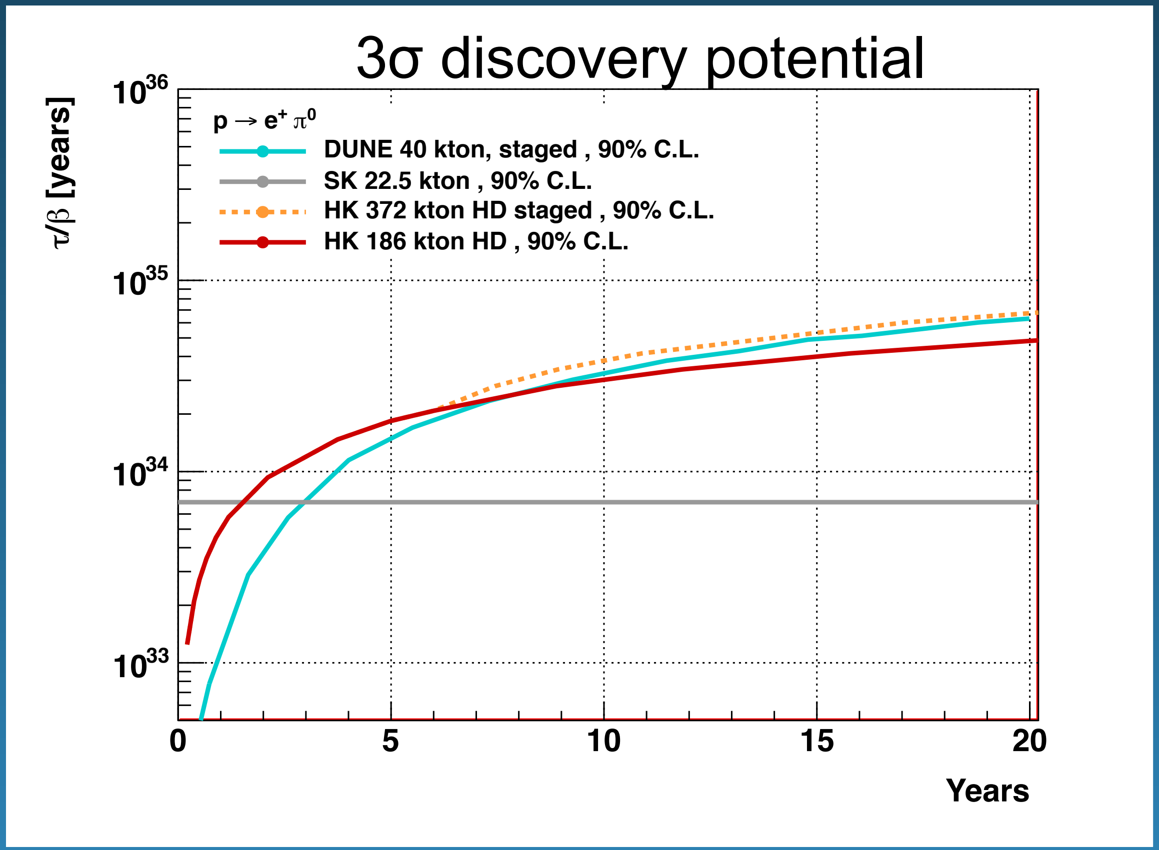
ass (MeV/c²)

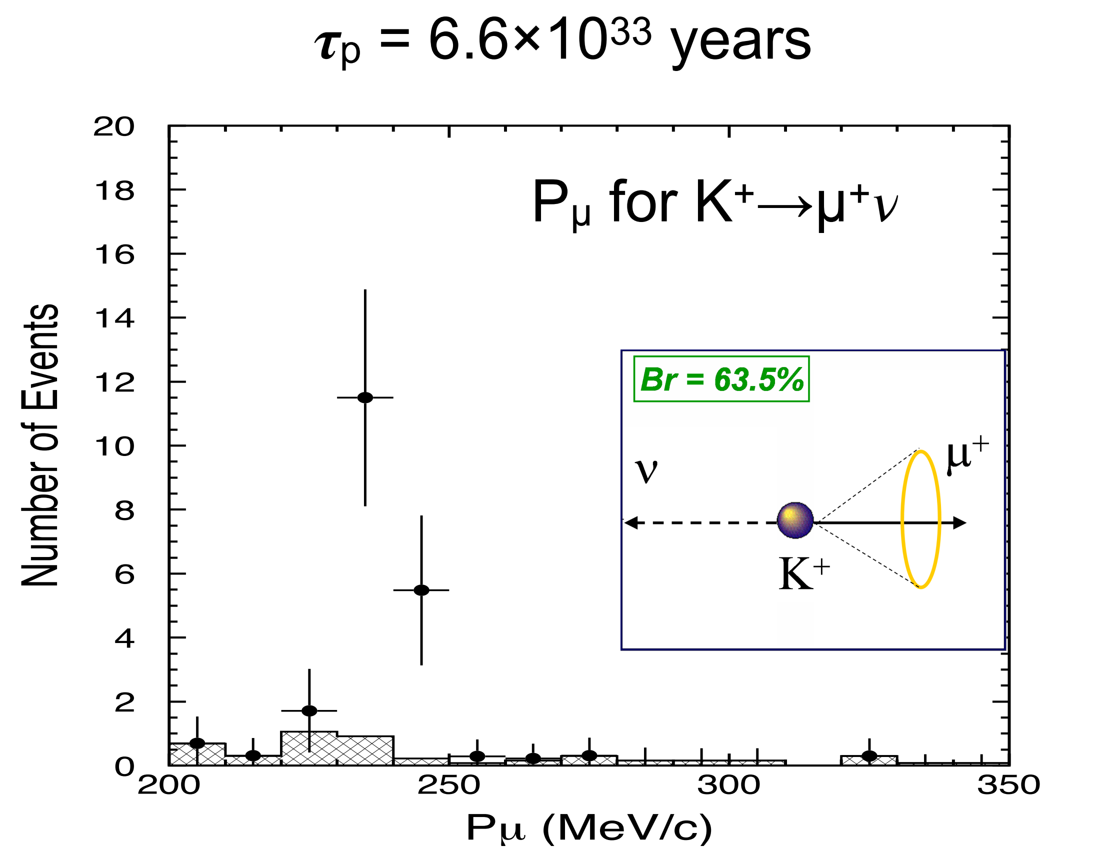
- Background (BG) free search possible (0.06 BG/Mton·year)
  - Free proton (¹H) – no nuclear effect
  - Well proven performance and understood BG
- Discovery potential extends to 10^{35} years

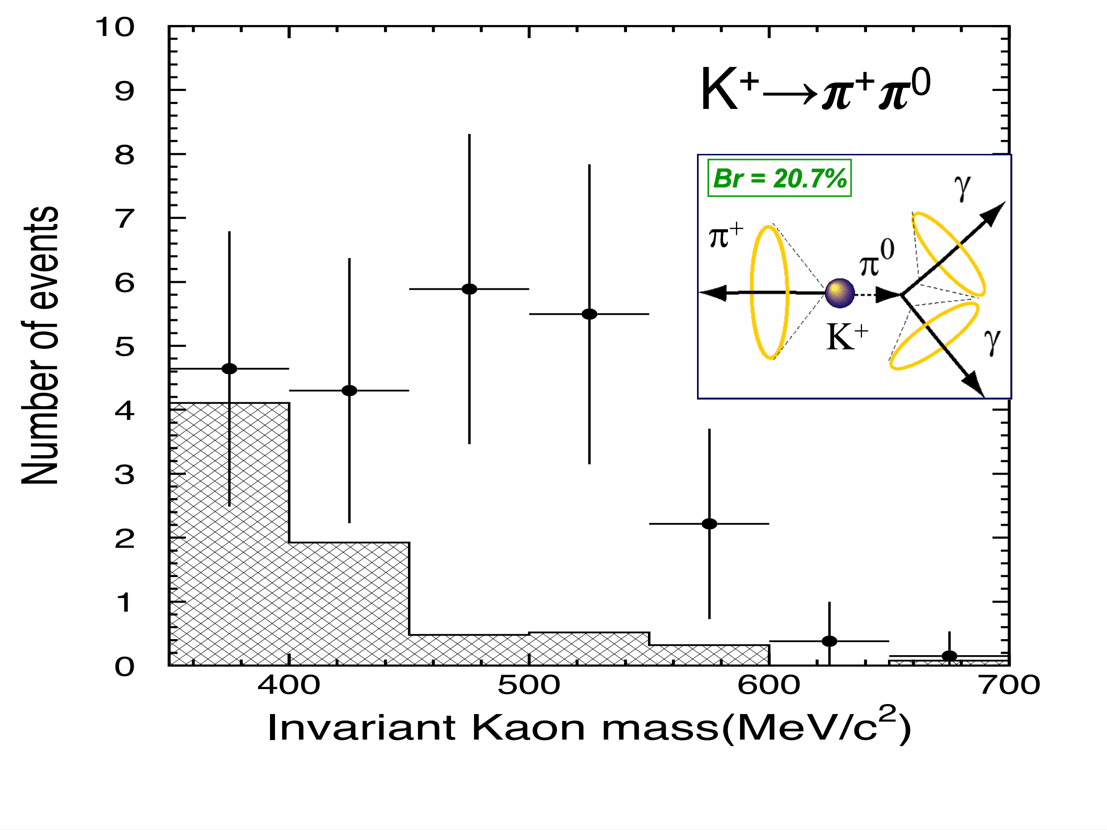


$P \rightarrow \bar{\nu} K^+$ DISCOVERY POTENTIAL

- K is below Cherenkov threshold, identified by daughter particles (established by SK)
- Signatures are:
  - Monochromatic muon ($K^+ \rightarrow \mu^+\nu$)
  - $K^+ \rightarrow \pi^+\pi^0$
- Enhanced sensitivity thanks to improved photosensors (photon efficiency and timing)
- Discovery reach $>3\times10^{34}$ years

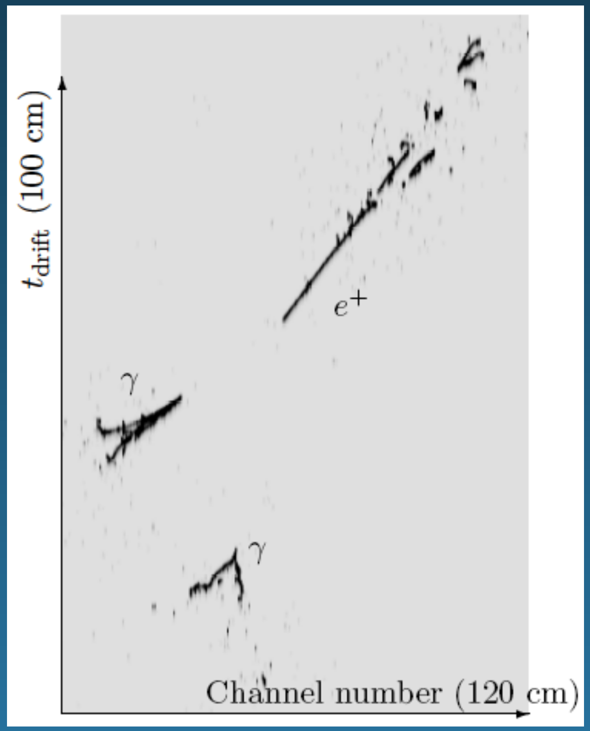




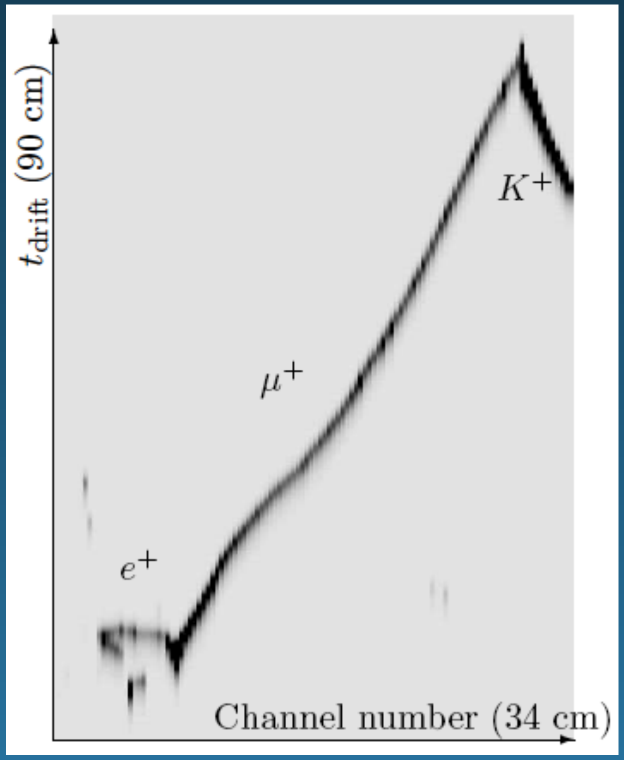


DUNE SENSITIVITY POTENTIAL

- LArTPC could identify the K^+ track by higher ionization density with high efficiency.
- Single-event discovery could be possible.
- In addition, potential clean search for neutron-antineutron oscillation ($\Delta B=2$) and other modes for which significant BG for water Cherenkov detectors

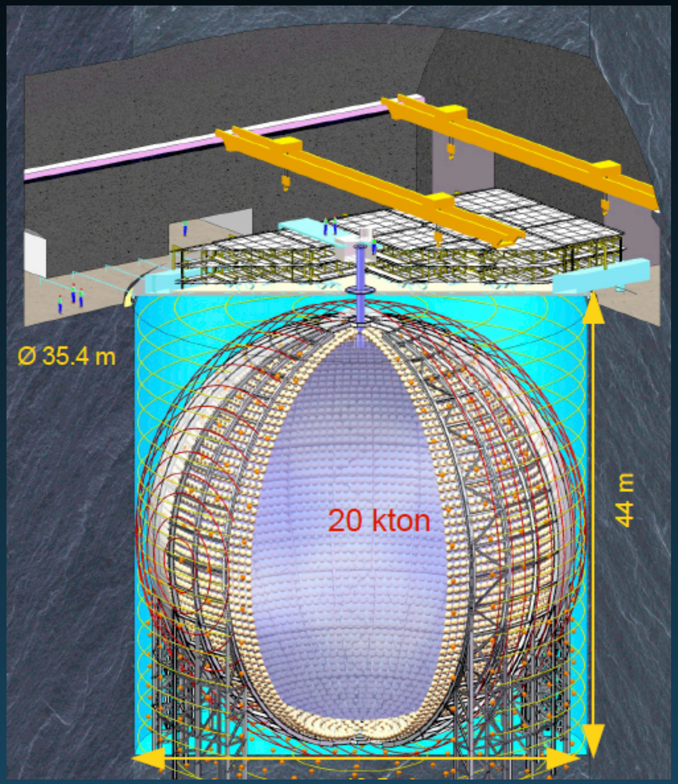


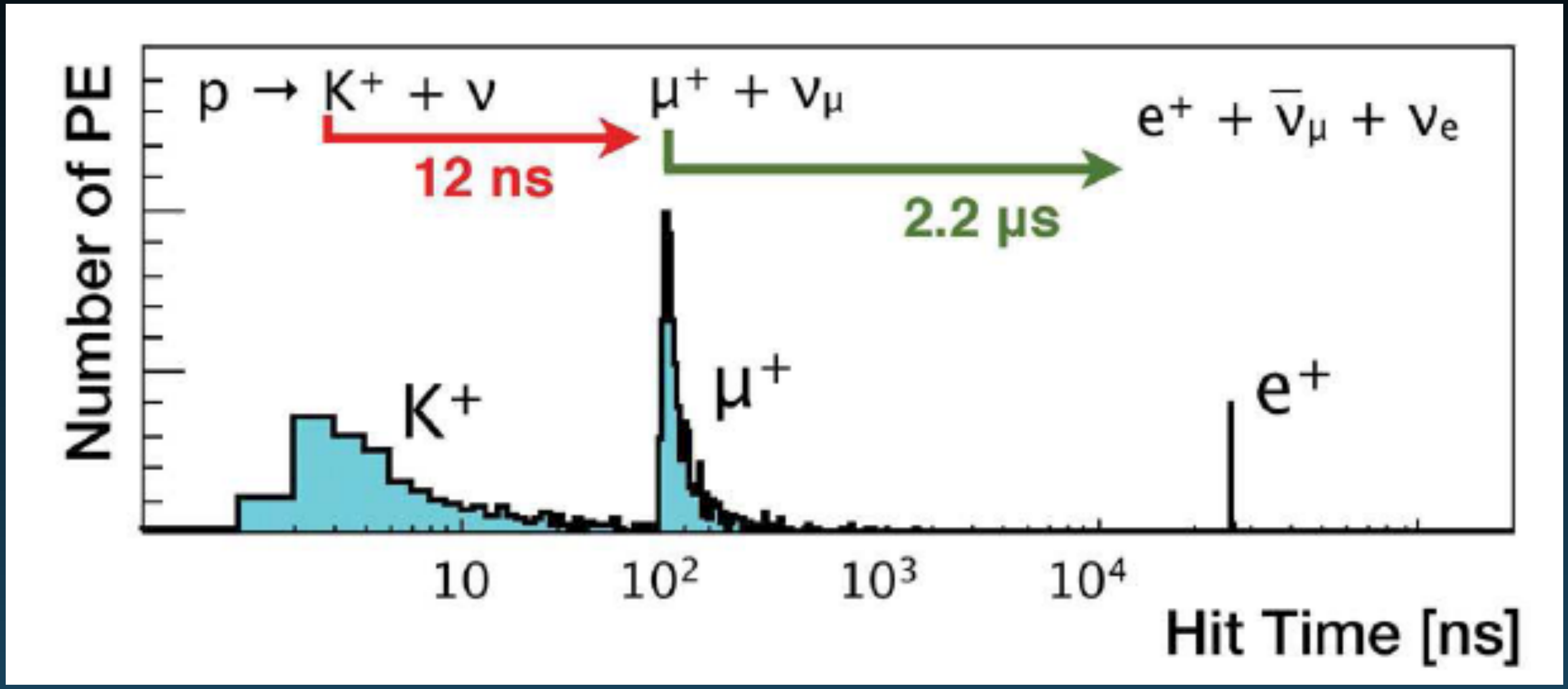
$p \rightarrow e^+ \pi^0$
- efficiency = 45%, 1BG/Mtyr



$p \rightarrow \bar{\nu} K^+$
- efficiency = 97%, 1BG/Mtyr

JUNO SENSITIVITY POTENTIAL



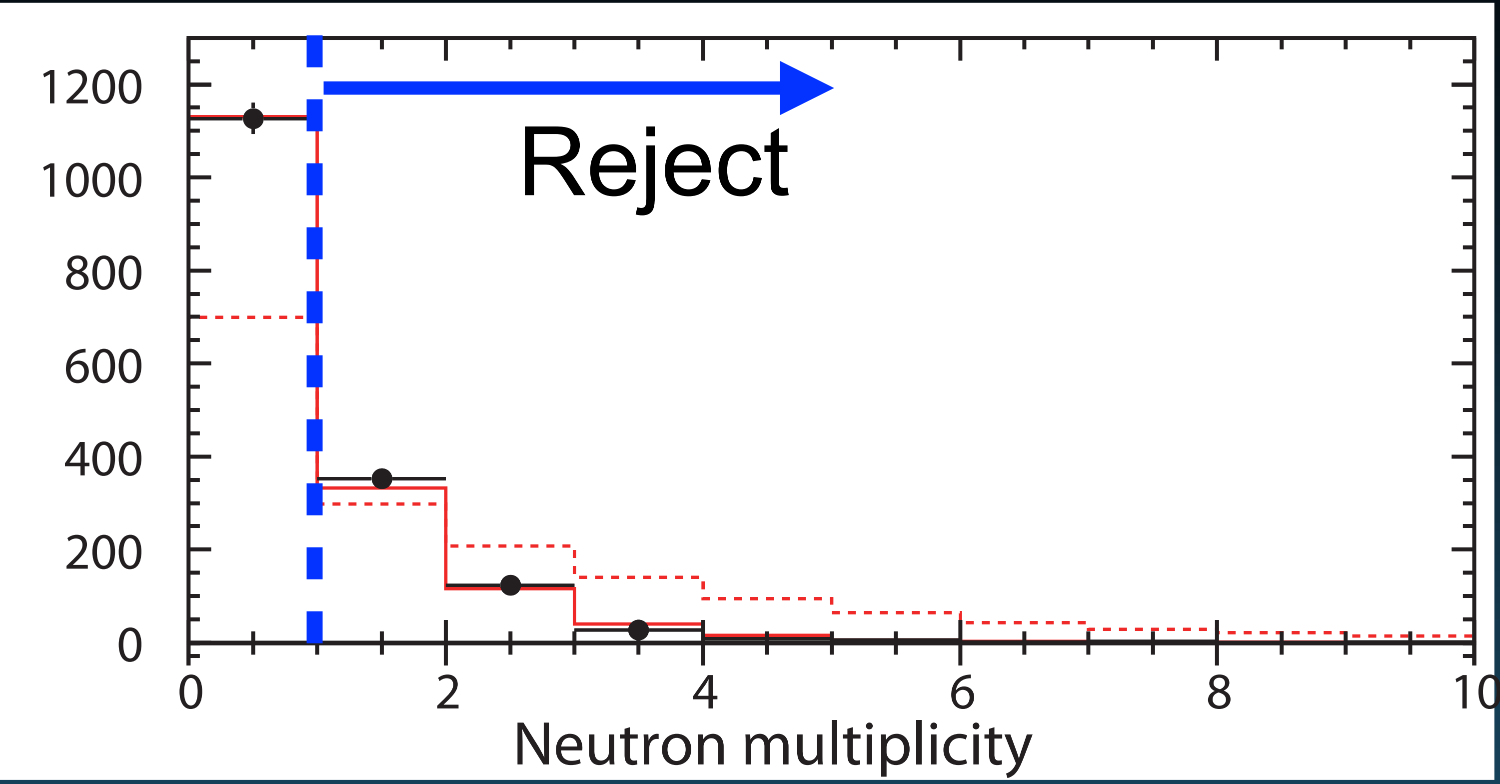


- 20 kiloton liquid scintillator
- Starting data taking in 2021
- Triple coincidence of $K^+ \rightarrow \mu^+ \rightarrow e^+$ w/ well-defined time constant (12nsec, 2.2μsec) and particle energies
- Signal efficiency = 64% (pulse shape cut+energy cut+decay. positron cut)
- Estimated backgrounds = 0.5 evt./ 10 years
- $\tau_{proton}(p \rightarrow \bar{\nu} K^+) = 1.9 \times 10^{34}$ years assuming zero candidates

BG REDUCTION BY NEUTRON-TAG & TIGHTER P_{TOT} CUT

- Shiozawa@NNN00 workshop
- PRD95, 012004 (2017)

- SK-IV w/ new electronics can tag neutrons by $n+p \rightarrow d+2.2\text{MeV}\gamma$
- Atmospheric neutrino BG is reduced by 40%



- Two regions of P_{tot} to enhance discovery reach
  - P_{tot} < 100MeV/c for free proton decays
  - P_{tot} < 250 MeV/c for ^{16}O

p_{tot}<100MeV/c		100<p_{tot}<250MeV/c	
Sig. ε(%)	Bkg (/Mtyr)	Sig. ε(%)	Bkg (/Mtyr)
18.7	0.06	19.4	0.62