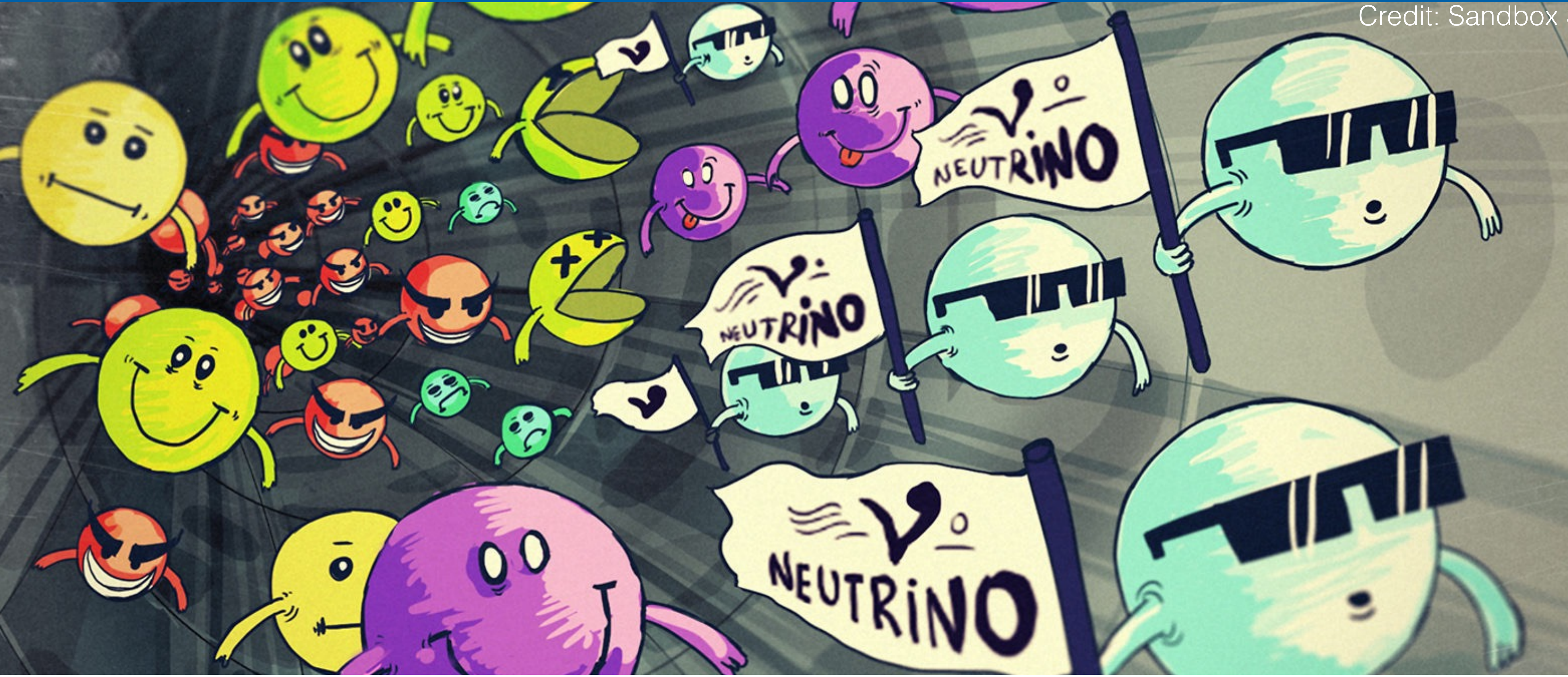


Credit: Sandbox

Neutrino experiment results and prospects for CP violation

Louise Suter, Fermilab

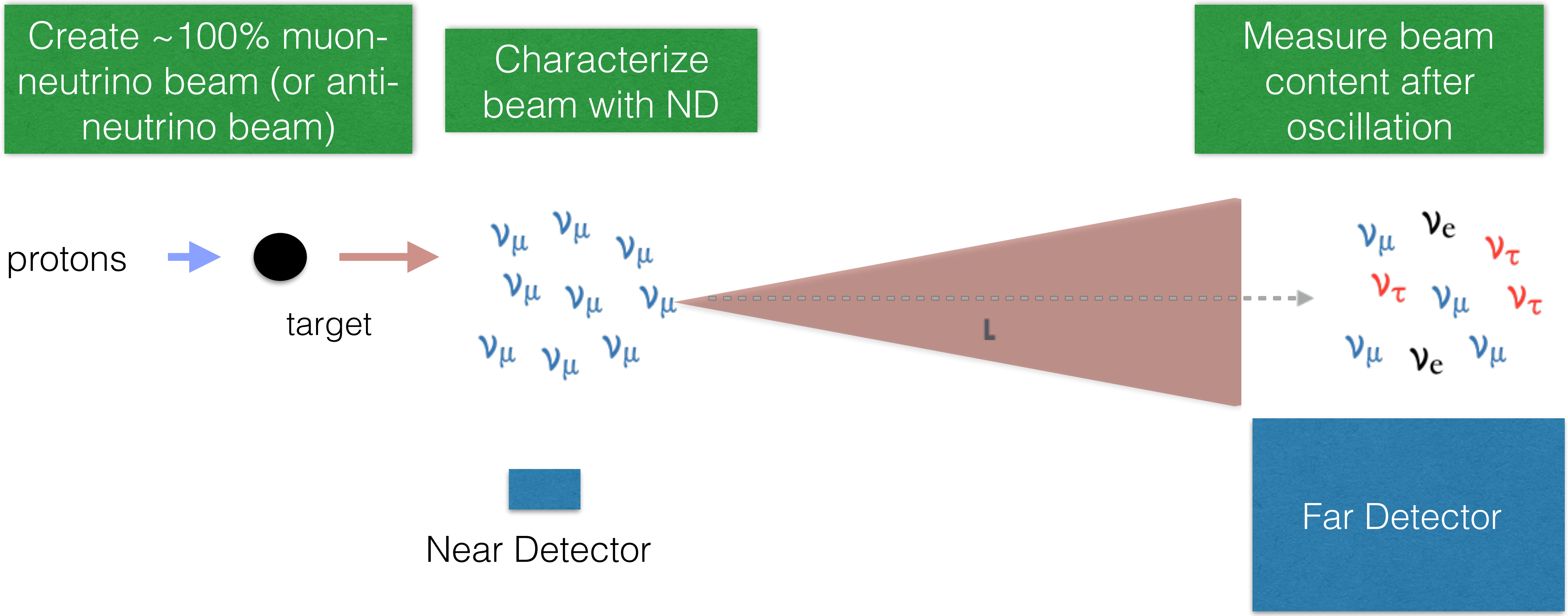
IPA 2018

8th October 2018

Long-baseline neutrino oscillation basics

- Using a accelerator based neutrino beam, which can run as either a beam neutrinos or anti-neutrinos

- Designed measure four samples
  - ν_e appearance ($\nu_\mu \longrightarrow \nu_e$)
  - ν_μ surval ($\nu_\mu \longrightarrow \nu_\mu$)
  - and the anti-neutrino versions of the same



Neutrino mass mixing matrix factorizes into three terms

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

$$\Delta m^2_{32} \simeq 2 \times 10^{-3} \mathrm{eV}^2$$
$$L/E = 500 \text{ km/GeV}$$

$$\nu_\mu \to \nu_\mu$$
$$\nu_\mu \to \nu_\tau$$

atmospheric and long baseline

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

$$\nu_e \to \nu_e$$
$$\nu_\mu \to \nu_e$$

reactor and long baseline

$$\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2$$
$$L/E = 15,000 \text{ km/GeV}$$

$$\nu_e \to \nu_e$$
$$\nu_e \to \nu_\mu + \nu_\tau$$

solar and reactor

$$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$$

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

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reactor and long baseline

$$\nu_e \to \nu_e$$
$$\nu_e \to \nu_\mu + \nu_\tau$$

solar and reactor

LBL experiments can probe

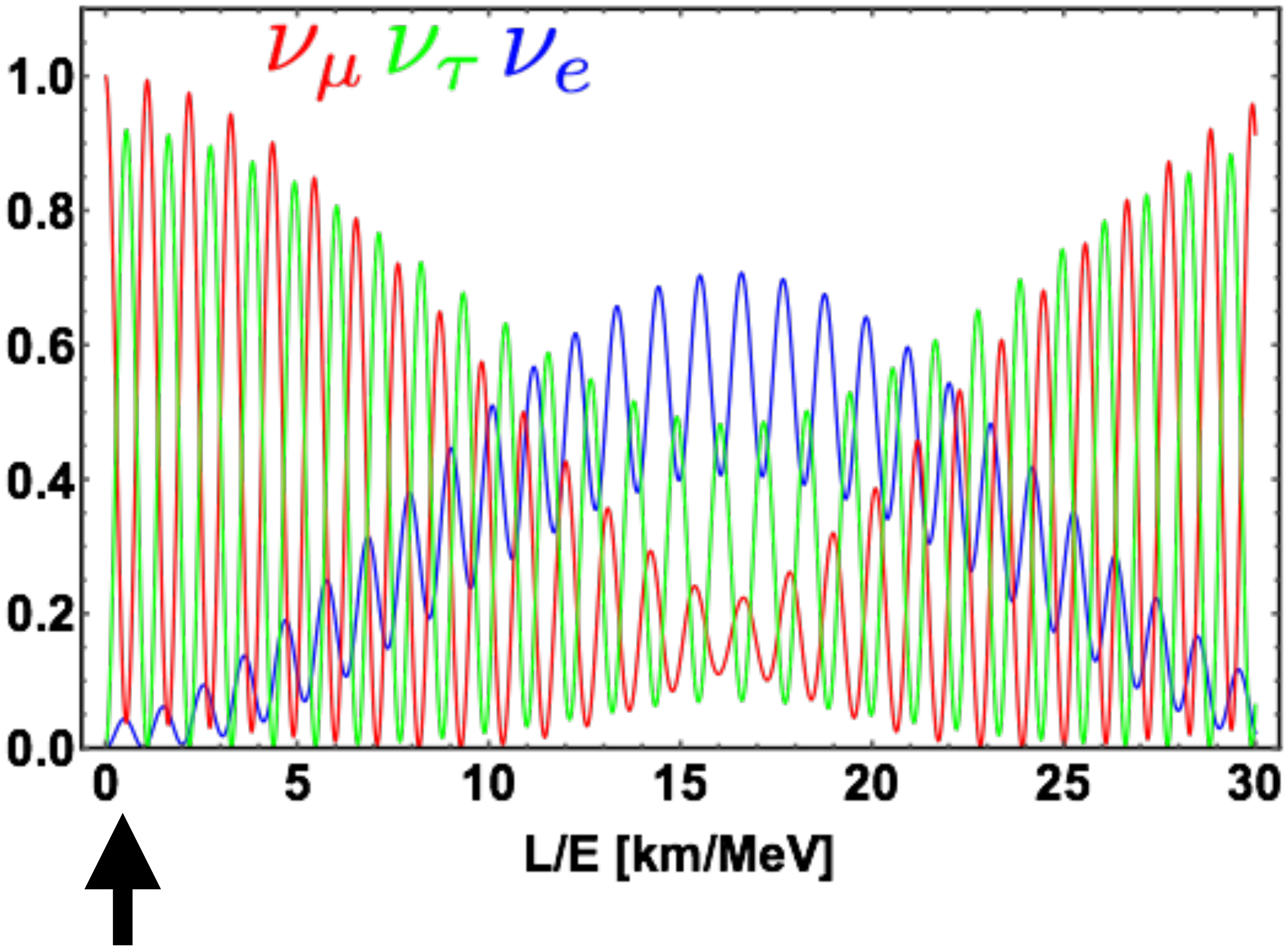
At L/E probed can be approximated by 2-flavor oscillation in a vacuum

$$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$$

$\nu_\mu \rightarrow \nu_\mu, \nu_\mu$ disappearance in a ν_μ beam

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27 \Delta m^2_{32}[\mathrm{eV}^2] L_\nu[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Can make precision measurements of the amplitude, atmospheric mixing angle, $\sin^2(2\theta_{23})$, and frequency, mass difference, Δm^2_{32}



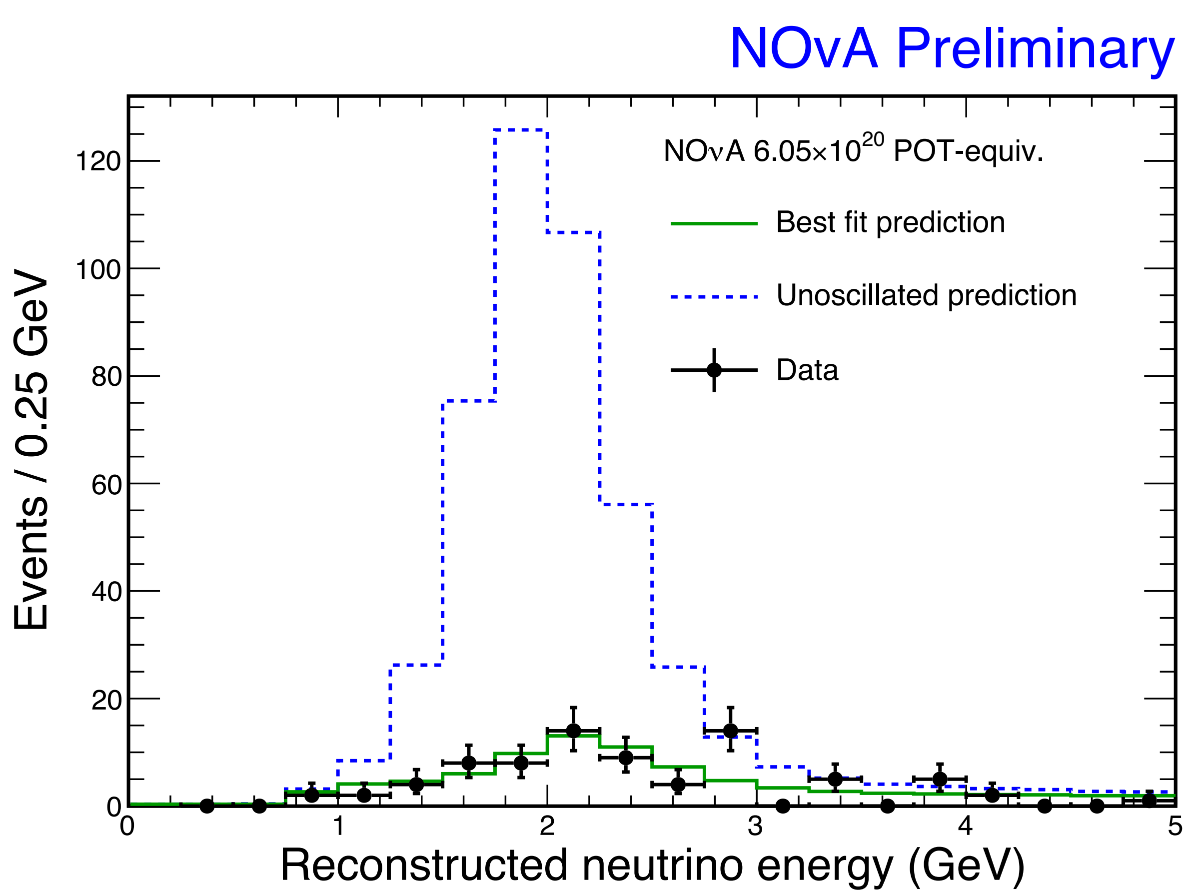
Detector placed where muon-neutrinos maximally oscillated into tau-neutrinos and electron-neutrinos

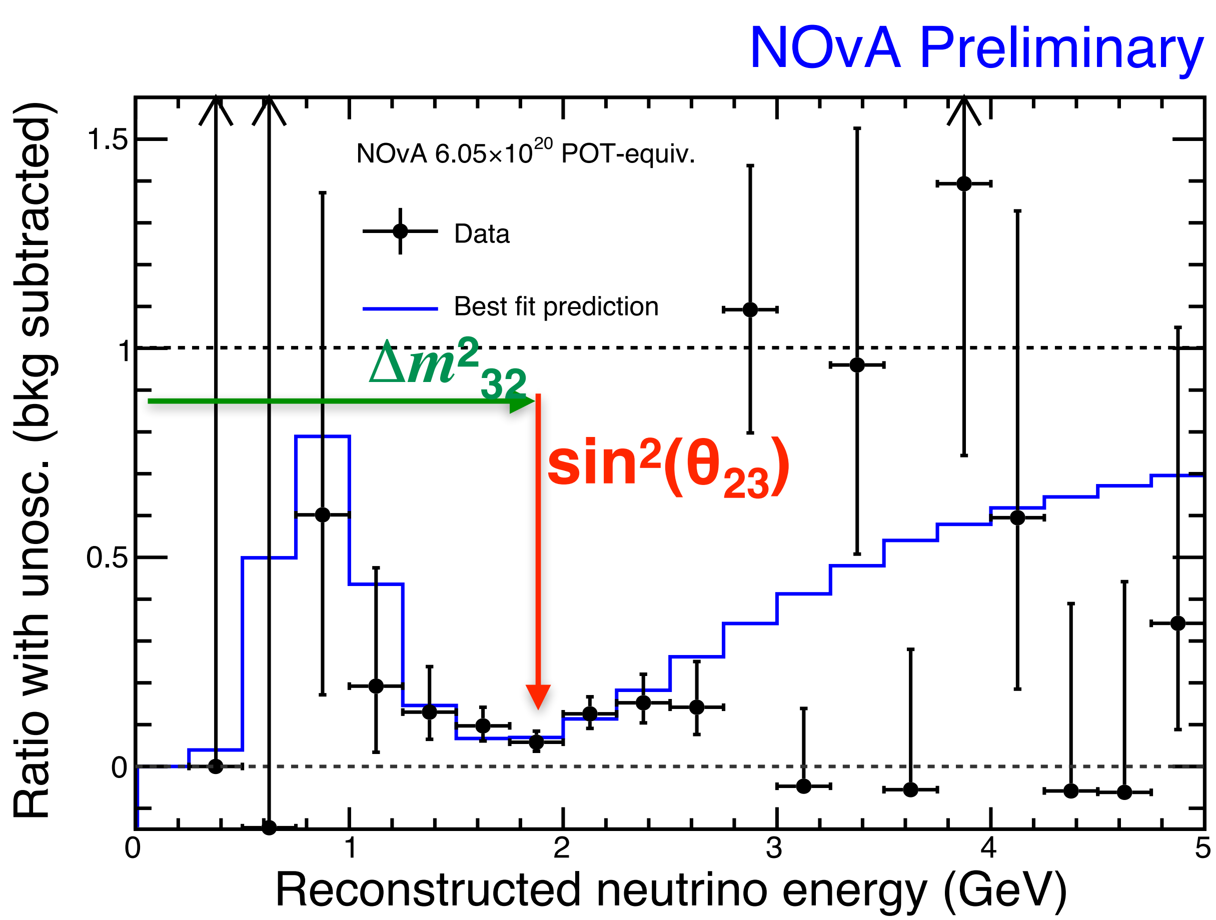
→ First maxima, location of most LBL neutrino experiments

$\nu_\mu \rightarrow \nu_\mu$, ν_μ disappearance in a ν_μ beam

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{32}[\mathrm{eV}^2]L_\nu[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Can make precision measurements of the amplitude, atmospheric mixing angle, **$\sin^2(2\theta_{23})$**, and frequency, mass difference, **Δm^2_{32}**





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

$$\Delta m^2_{32} \simeq 2\times 10^{-3}\text{eV}^2 \quad L/E = 500\ \text{km/GeV}$$

$$\nu_\mu \to \nu_\mu \quad \nu_\mu \to \nu_\tau$$

atmospheric and long baseline

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

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reactor and long baseline

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$$\nu_e \to \nu_e \quad \nu_e \to \nu_\mu + \nu_\tau$$

solar and reactor

LBL experiments can also probe

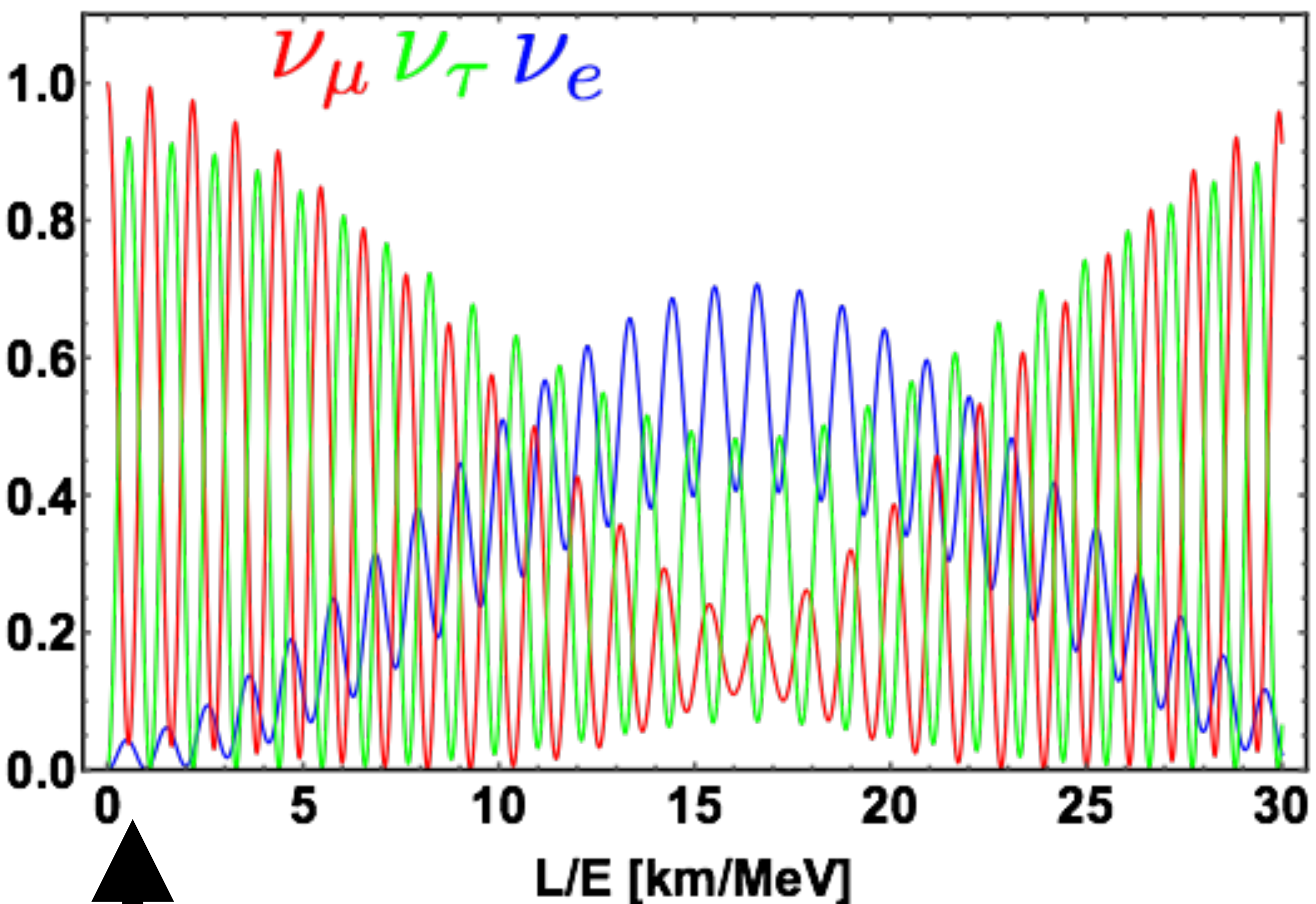
$$c_{\alpha\beta} = \cos_{\alpha\beta} \quad s_{\alpha\beta} = \sin_{\alpha\beta}$$

$\nu_\mu \rightarrow \nu_e$, ν_e appearance in a ν_μ beam

To describe ν_e appearance must use full 3-flavor description and include effects of interaction of neutrinos with matter

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2}$$
$$+\alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)}$$
$$+\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$
$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{13}$$
$$\Delta = \Delta m^2_{31}L_\nu/4E_\nu$$
$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$



Has sensitivity to some of the biggest questions in the field

First maxima, location of most LBL neutrino experiments

Neutrino Mass Hierarchy

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2}$$
$$+\alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)}$$
$$+\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

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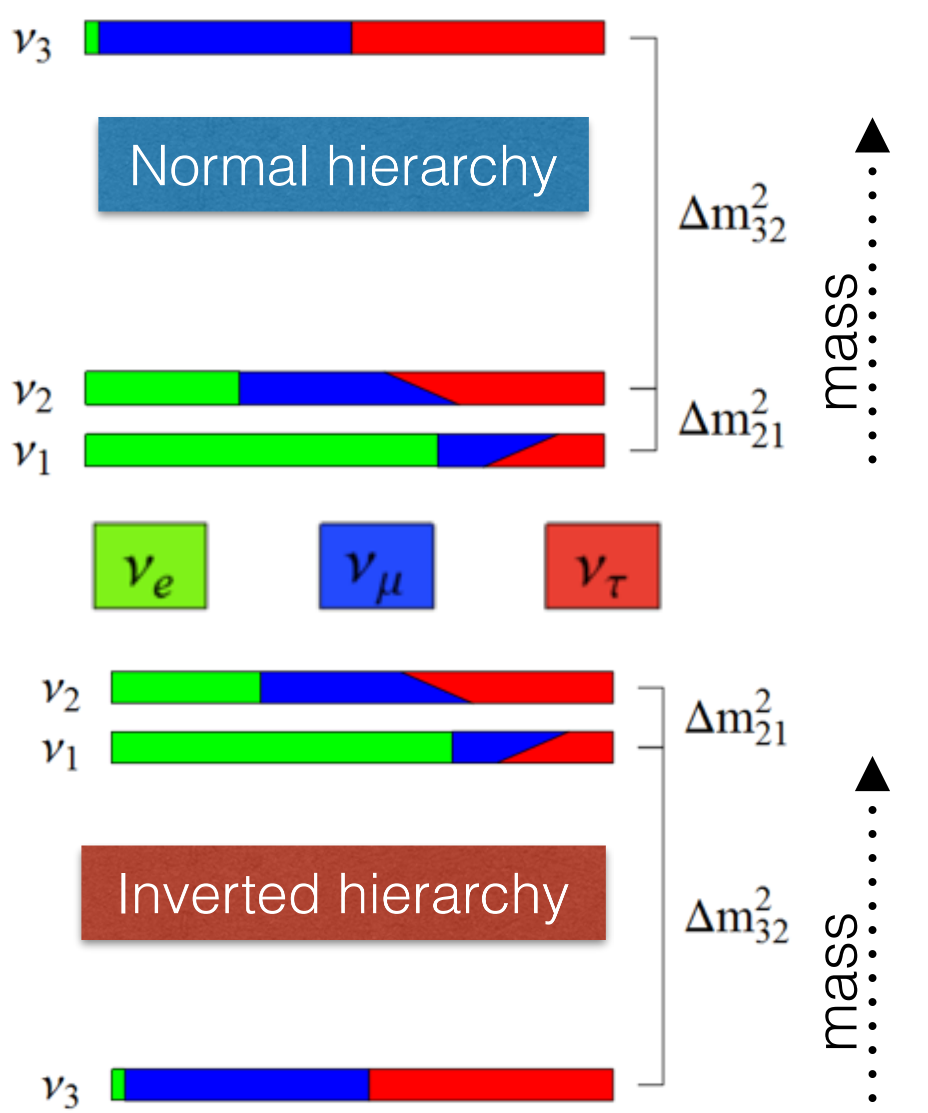

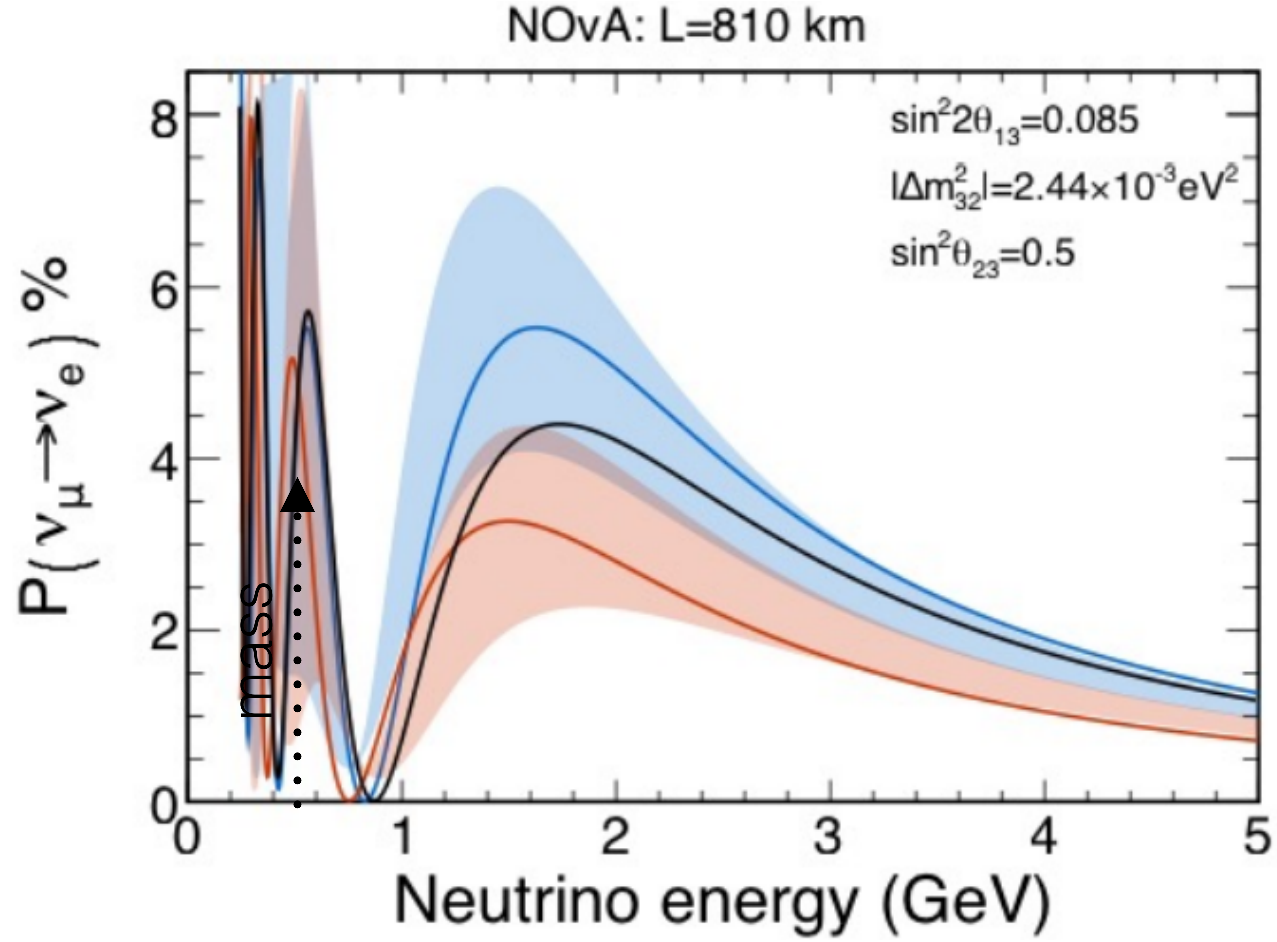

Matter effect: Electron neutrinos experience additional integration with electrons in the earth

Charge Parity violation, δ_{cp}

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2}$$
$$+\alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)}$$
$$+\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$
$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{13}$$
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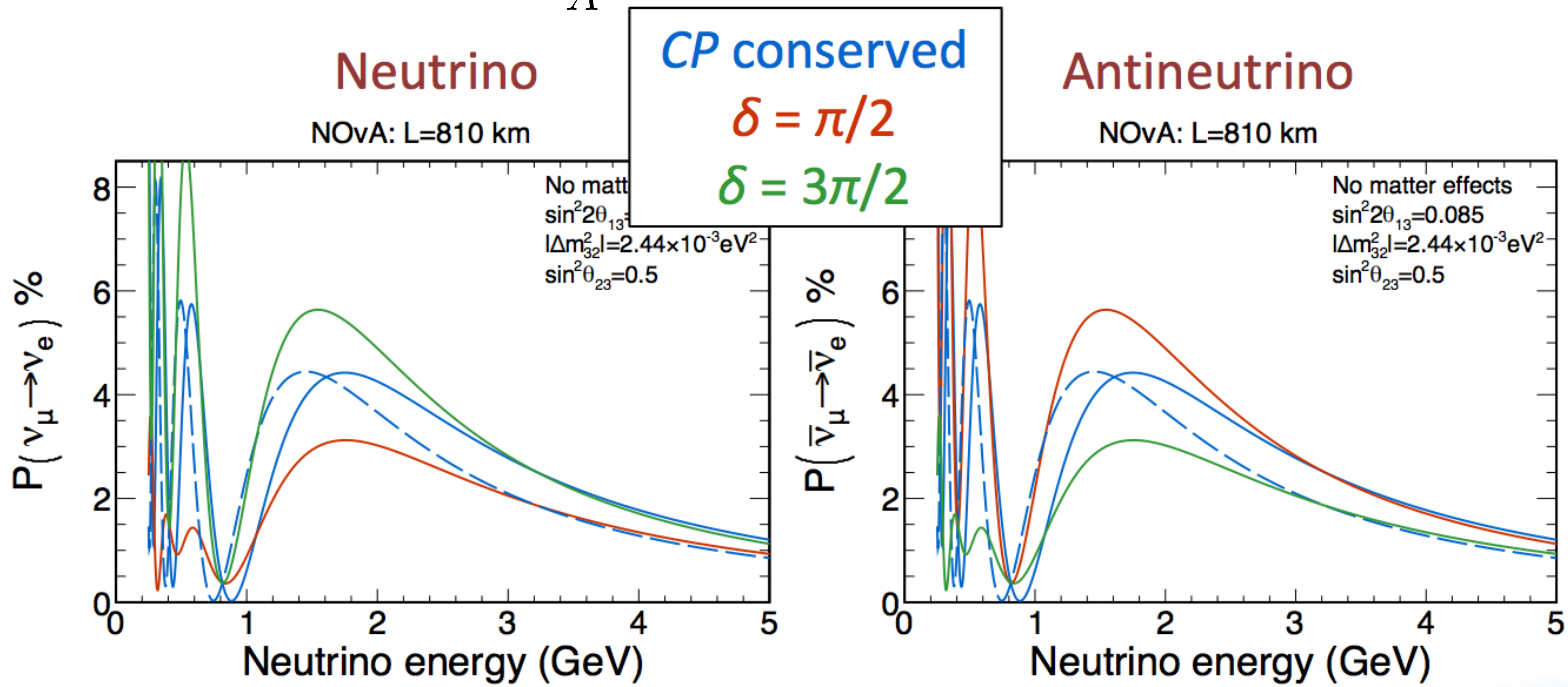
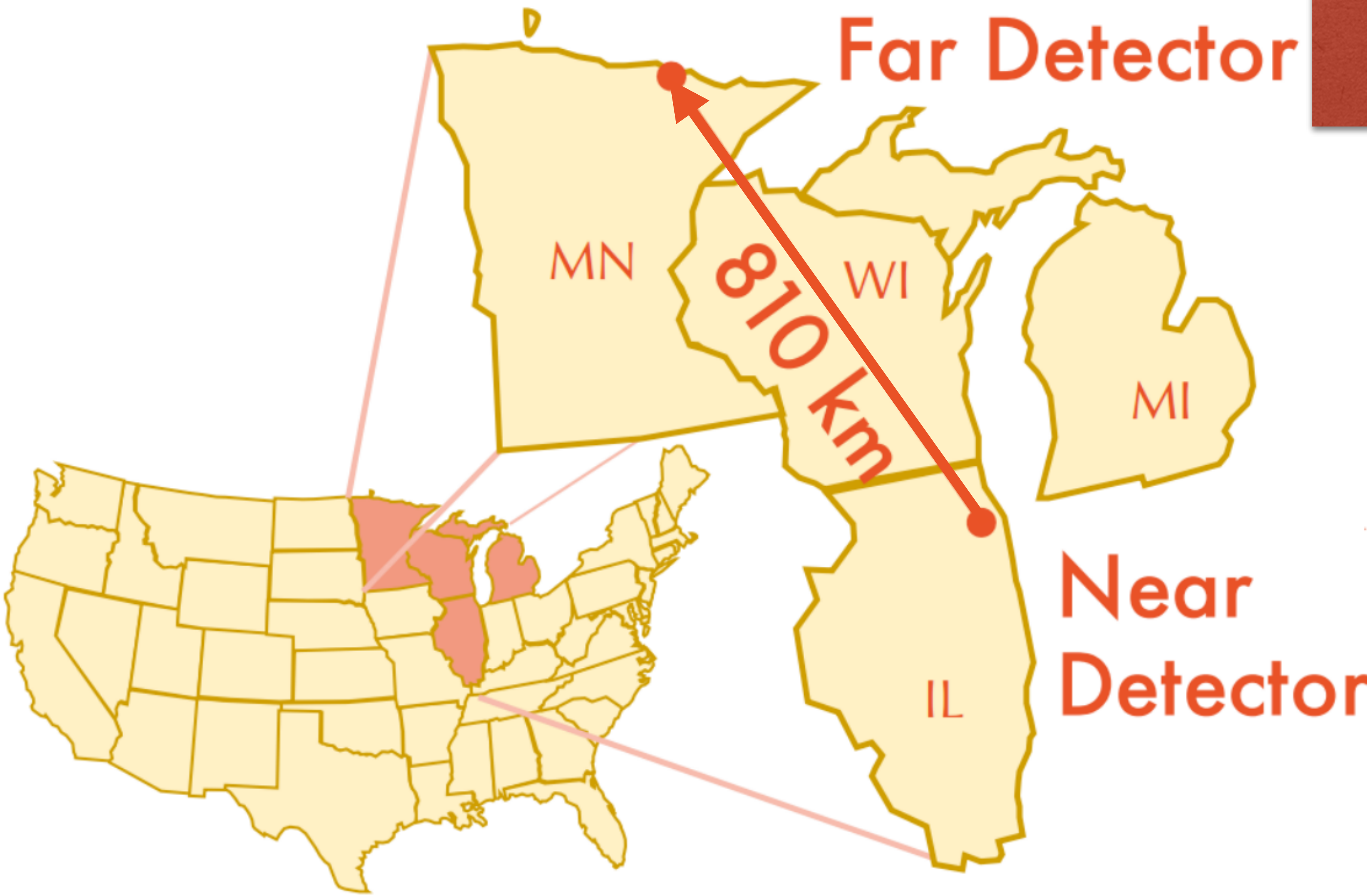


Do neutrinos conserve Charge-Parity?
Could provide insides into the matter anti-matter difference in the universe


NOvA
Far Detector
Credit: Reidar Hahn/Fermilab

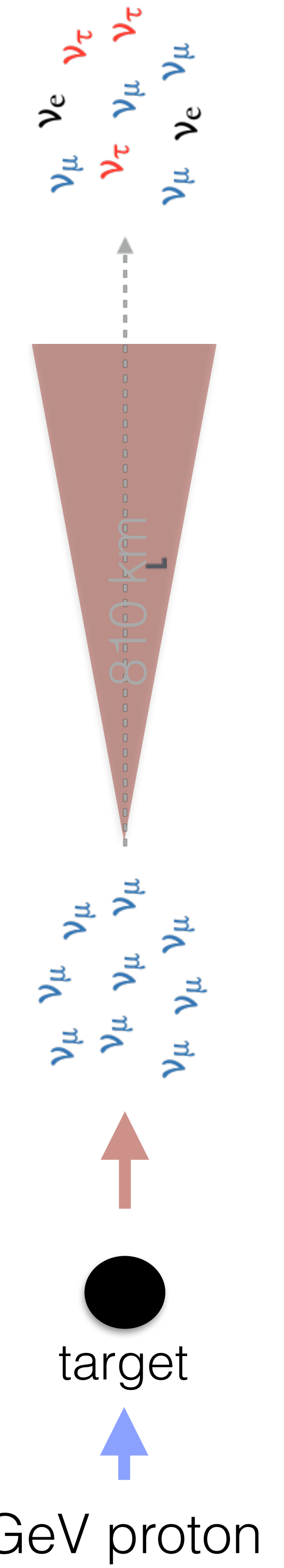
NOvA: Off-axis long-baseline neutrino oscillation experiment



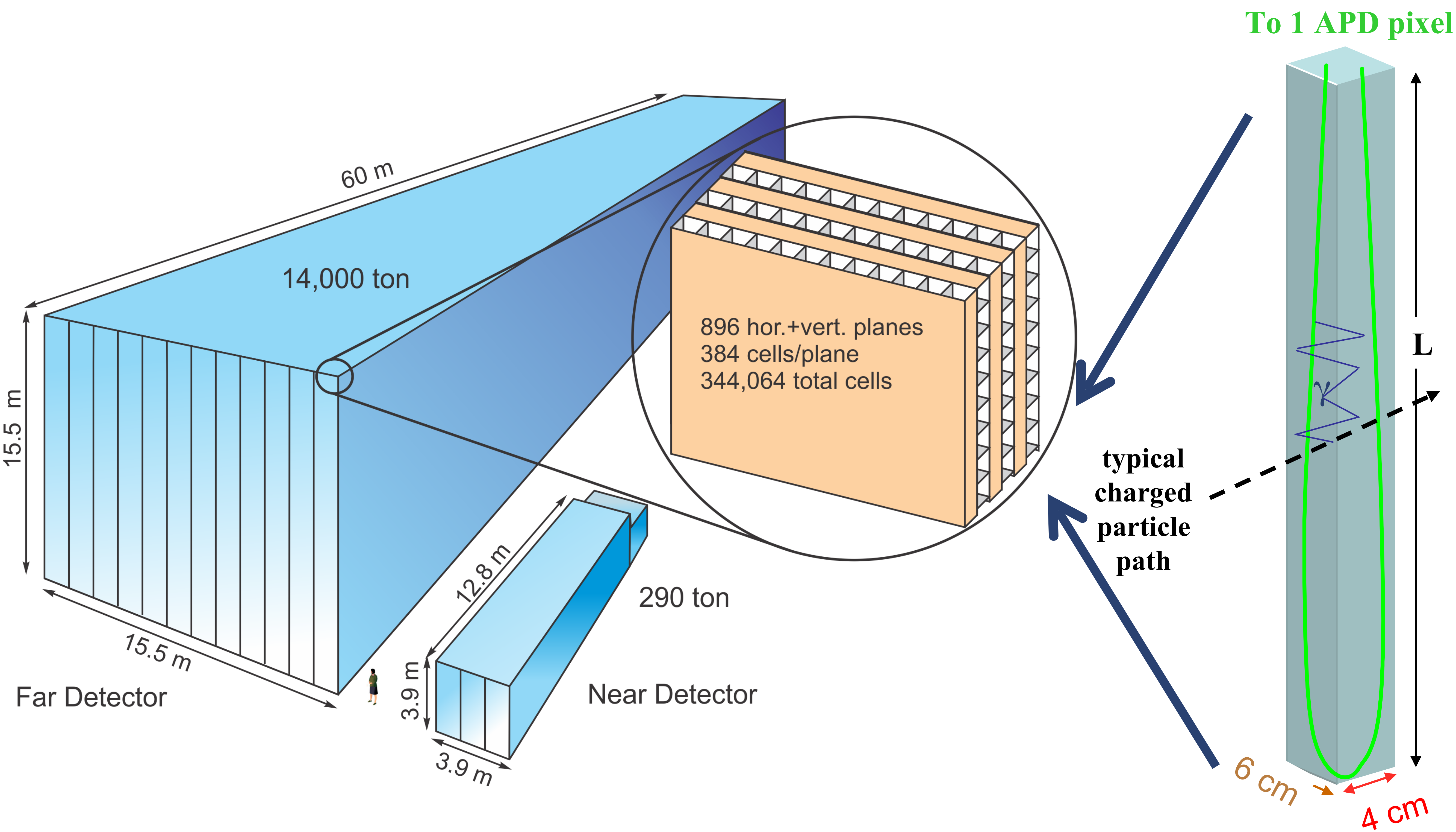
Measure beam content after oscillation

Characterize muon-neutrino beam with ND

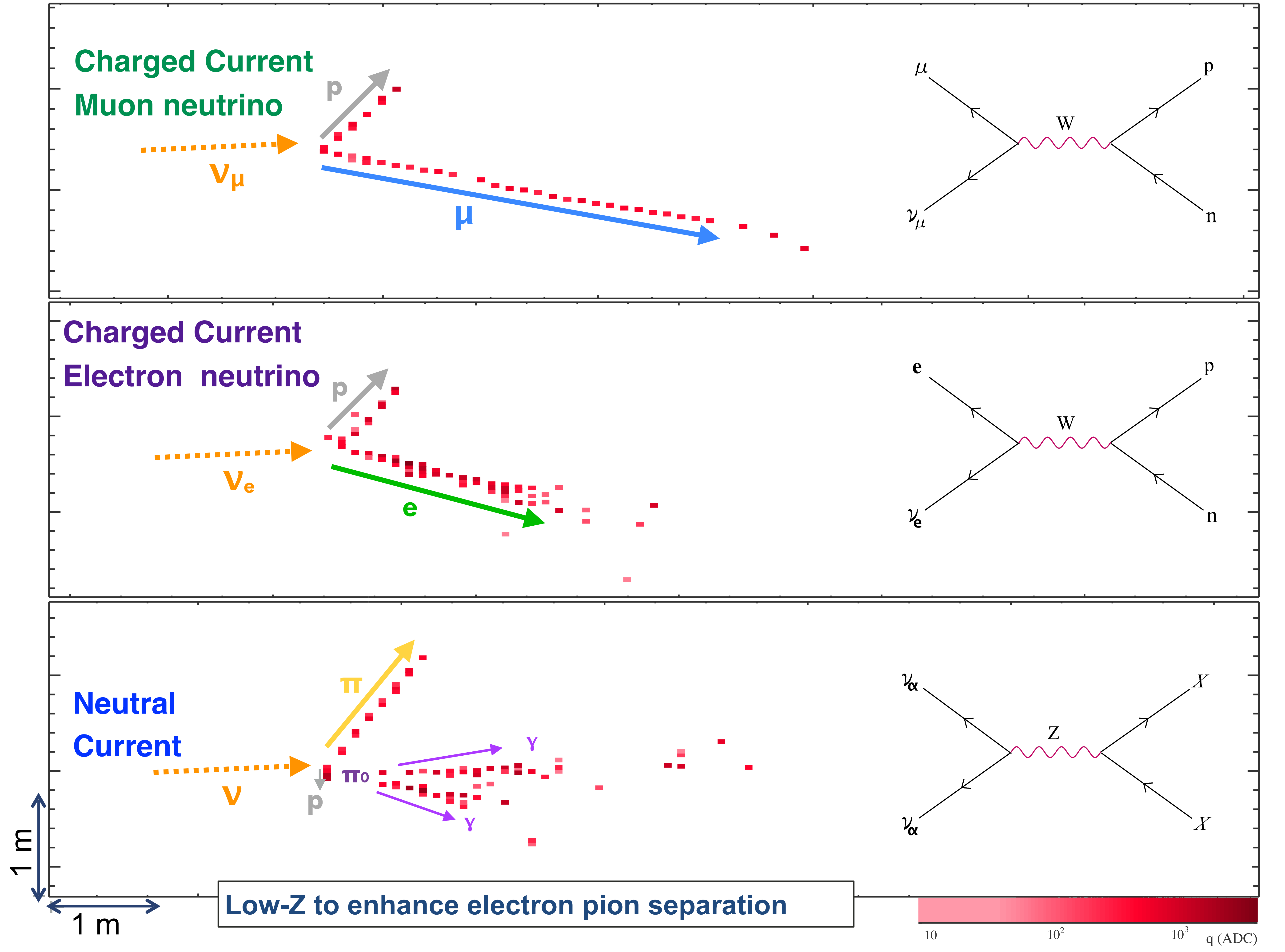
Create ~100% muon-neutrino beam (or anti-neutrino beam)



Huge, low-Z, 65% active, liquid scintillator tracking calorimeter

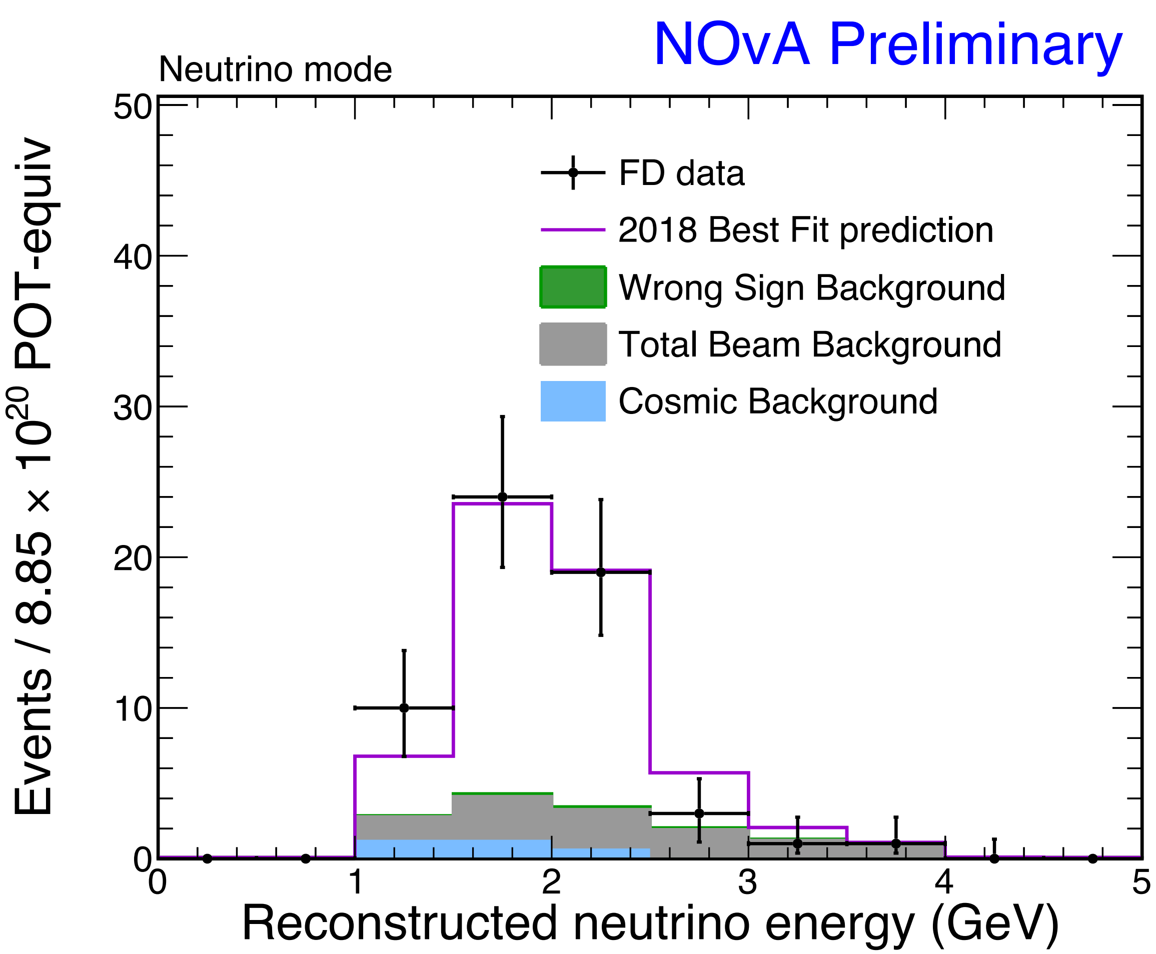


Designed to maximize electron neutrino selection efficiency

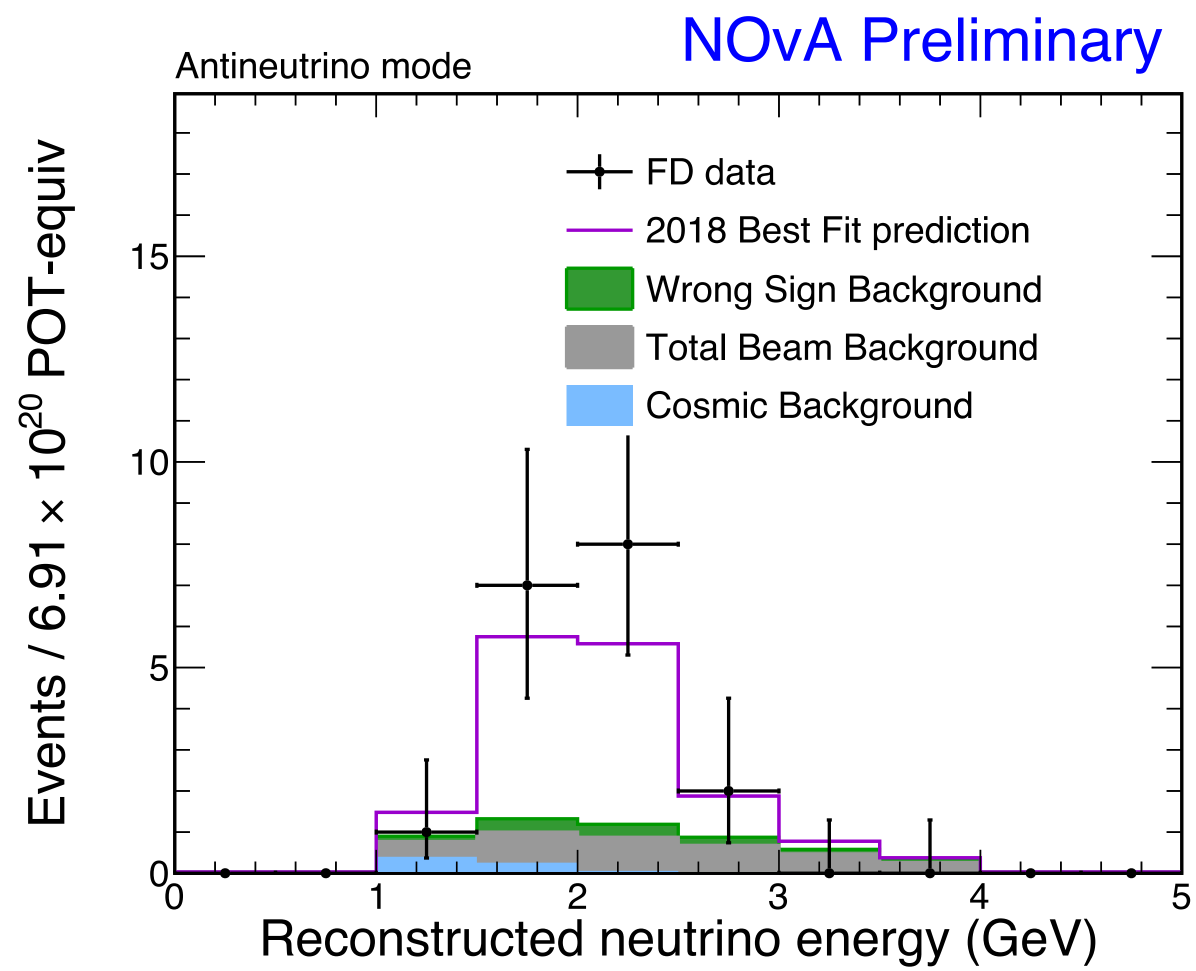

Charged Current
Muon neutrino
p
ν_μ
μ
μ
p
W
ν_μ
n
Charged Current
Electron neutrino
p
ν_e
e
e
p
W
ν_e
n
Neutral
Current
π
γ
ν
p
π0
γ
ν_α
X
Z
ν_α
X
1 m
1 m
Low-Z to enhance electron pion separation
10
10^2
10^3
q (ADC)

Experiment will run until 2024, results shown here represents about 20% of the total data to be collected

Neutrinos:
8.85e20 Protons-on-target



Antineutrinos:
6.9e20 Protons-on-target



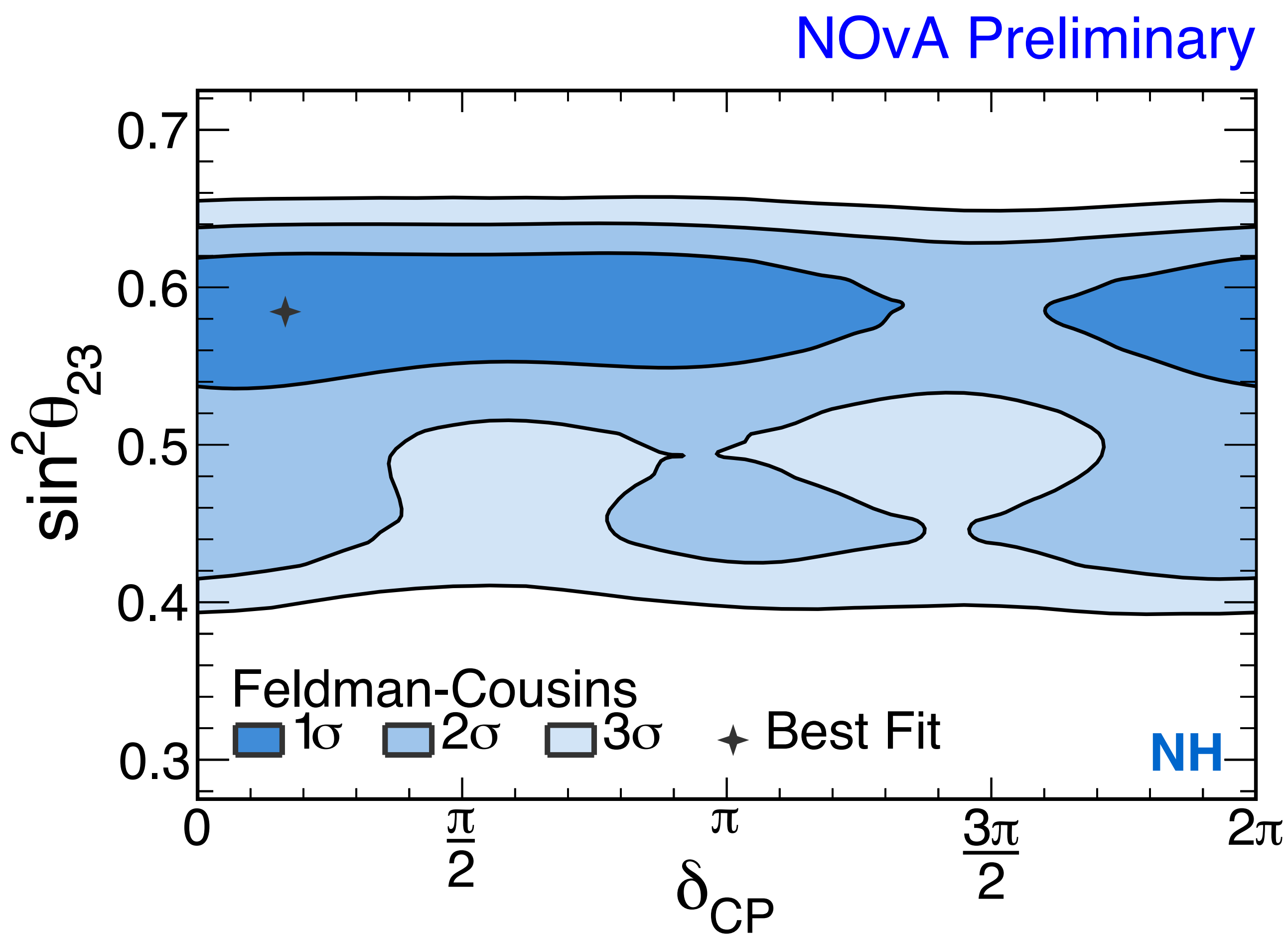
- Measure 58 events in the neutrino beam with a predicted background of 15 events
- Measure 18 events in the antineutrino beam with a predicted background of 5.3 events

Greater than 4σ evidence of electron antineutrino appearance in long-baseline beam

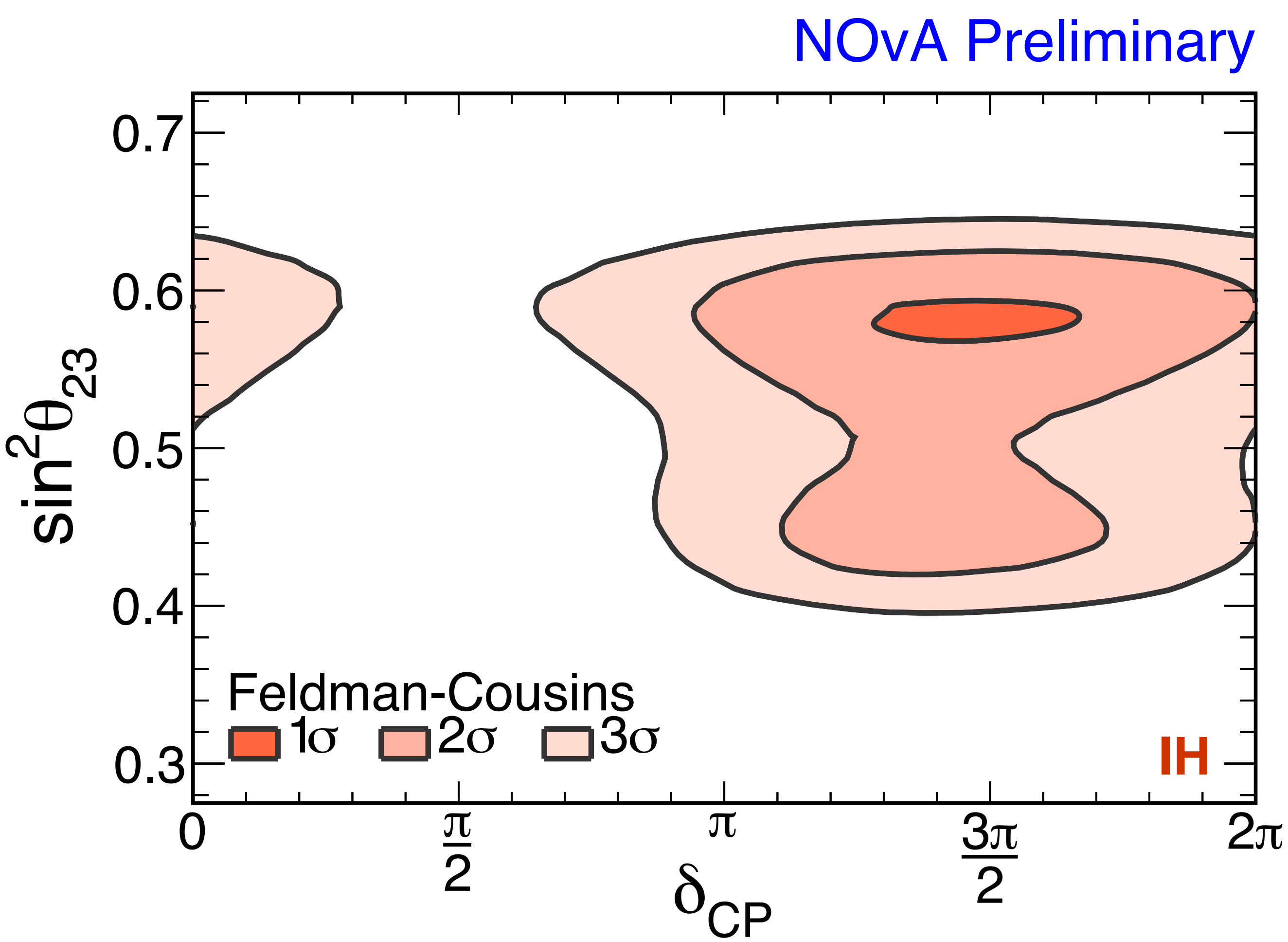
Charge-parity phase, δ_{CP}, at NOvA

Full joint fit all systematics, oscillation pull terms shared. Feldman-Cousins corrections applied, θ_{23} is the least well constrained of the mixing angles

Normal Hierarchy

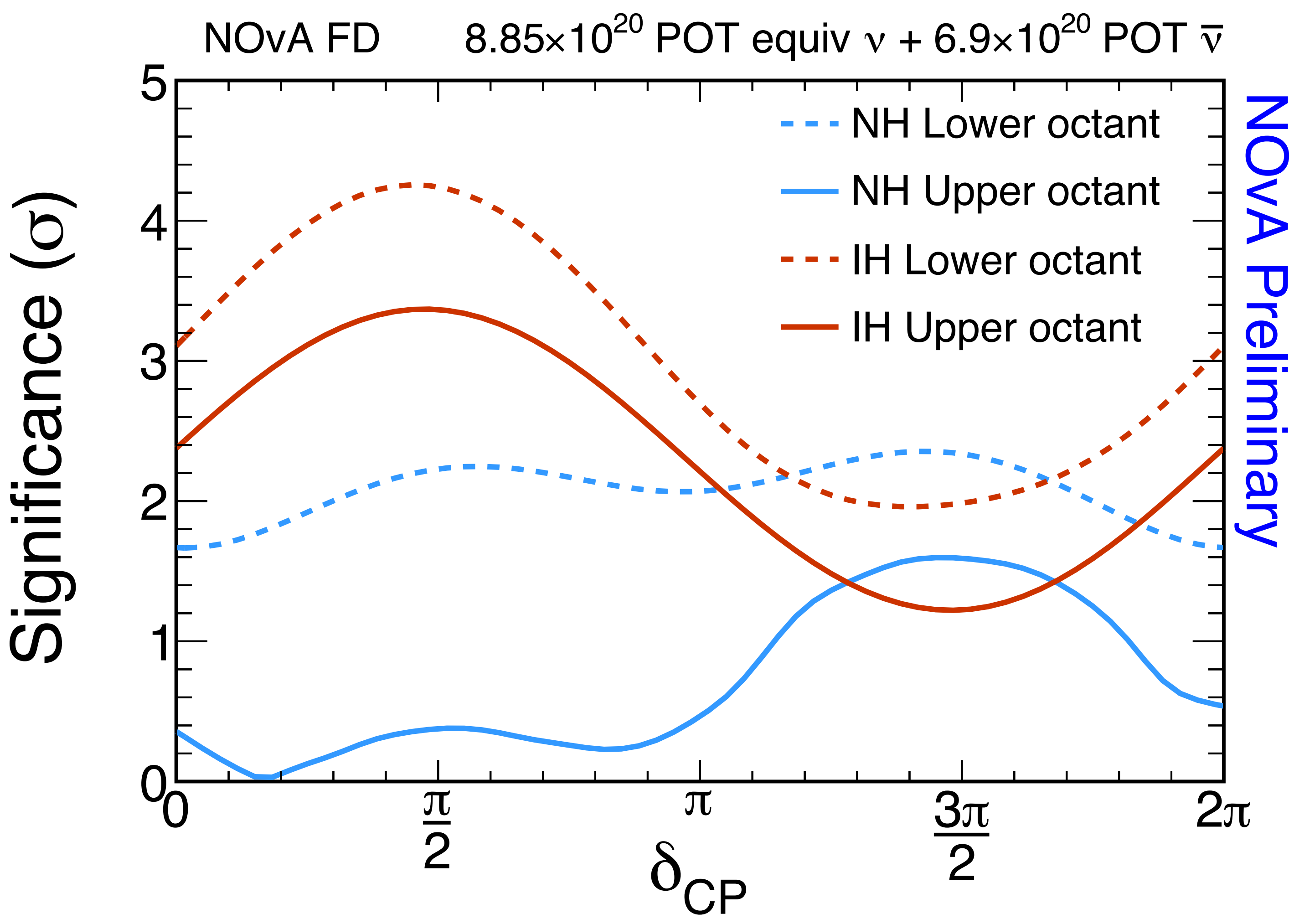


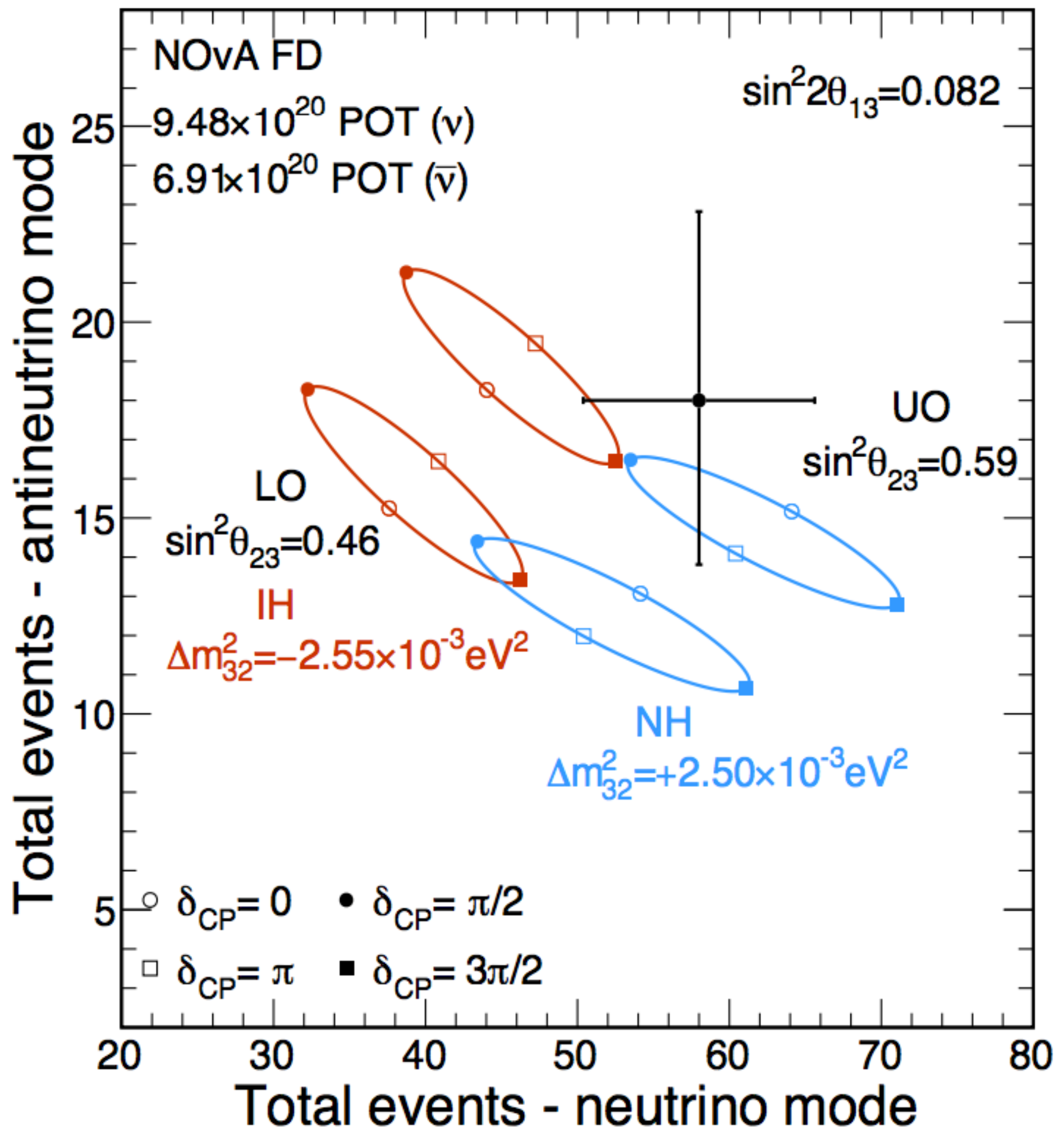
Inverted Hierarchy



θ_{13} using world average from PDG

Charge-parity phase, δ_{CP}, at NOvA

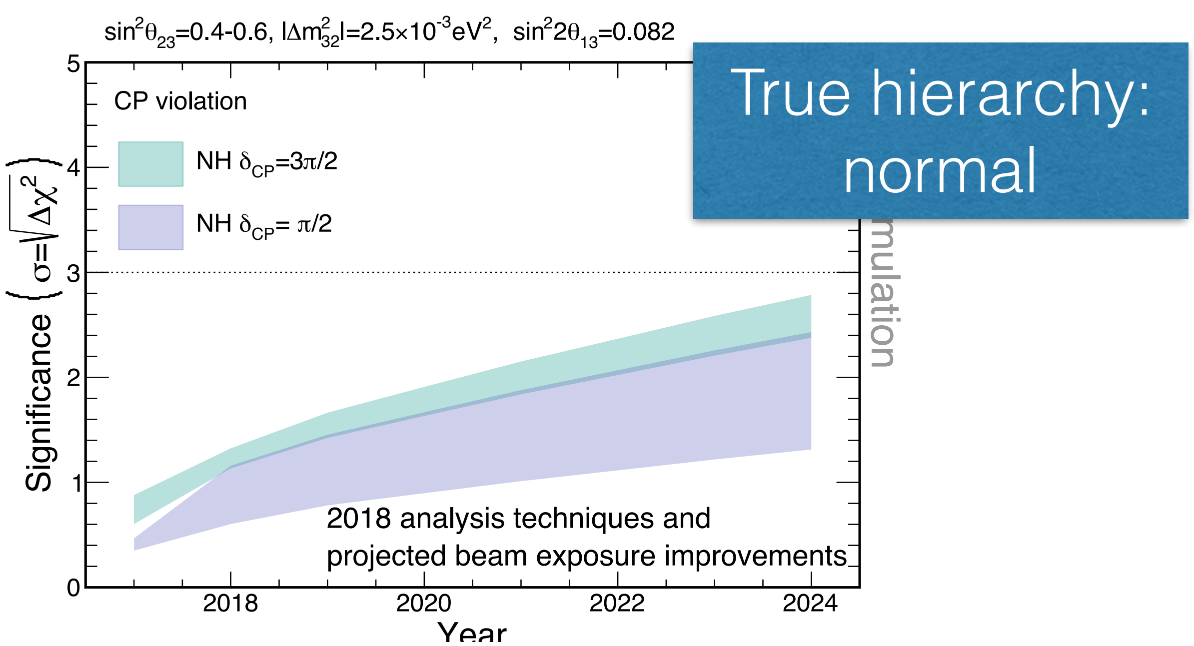


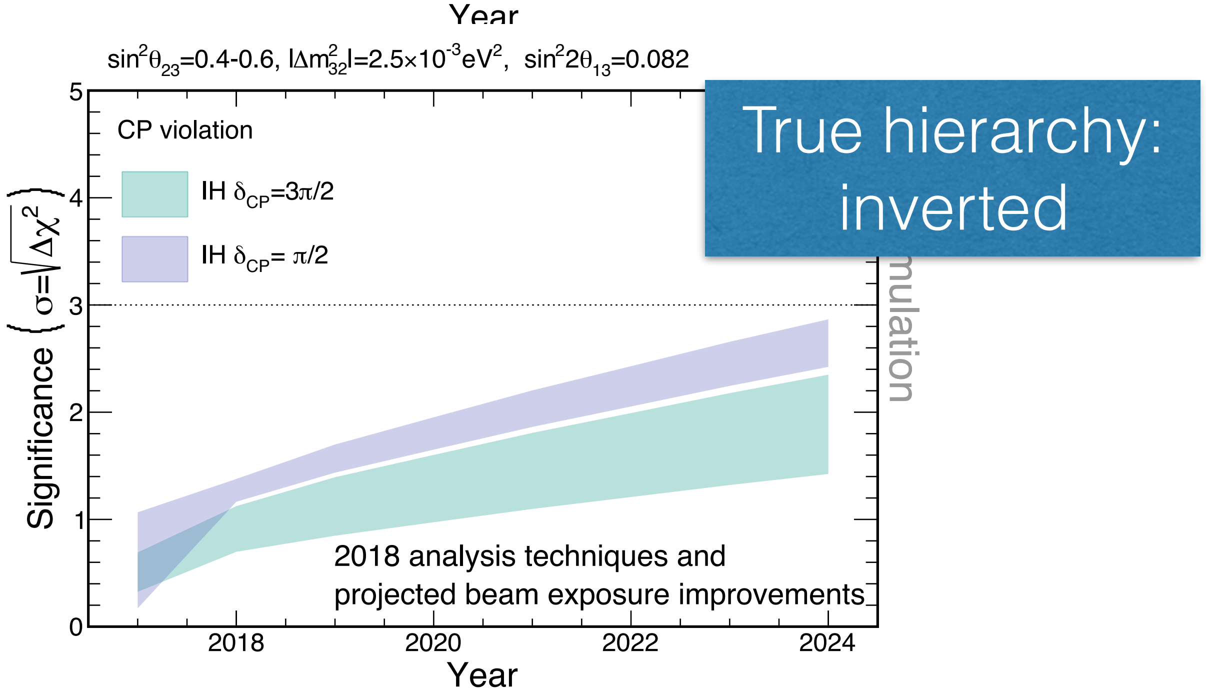


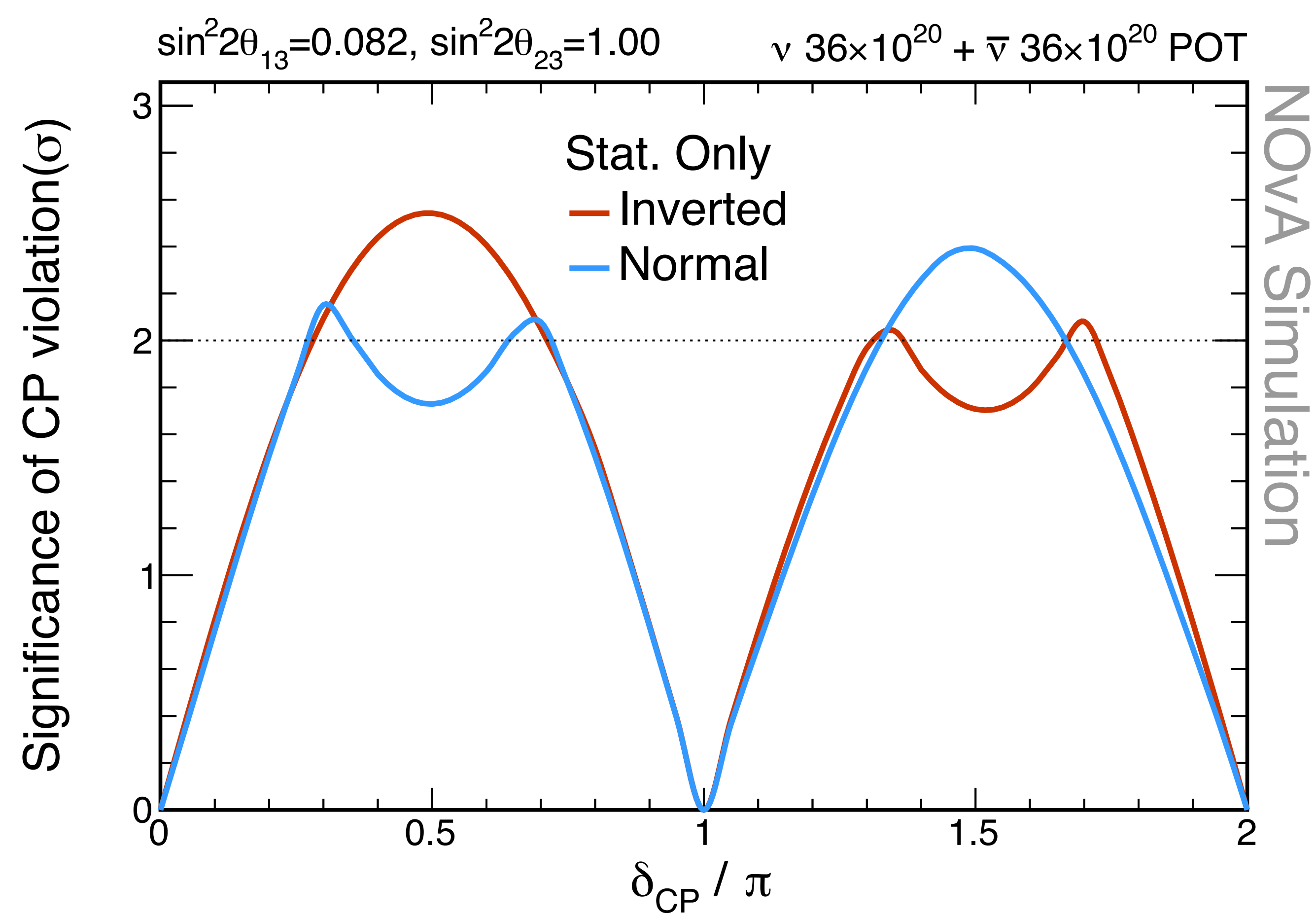
Approaching 2σ exclusion of CP conservation for all of inverted hierarchy

NOvA looking forward

- NOvA will continue take data until ~2024
- Plan to run 50% neutrino, 50% anti-neutrino after 2018
- Proposed accelerator improvement projects, enable beam up to ~1 MW, and test beam program reduce uncertainties enhancing NOvA's ultimate reach



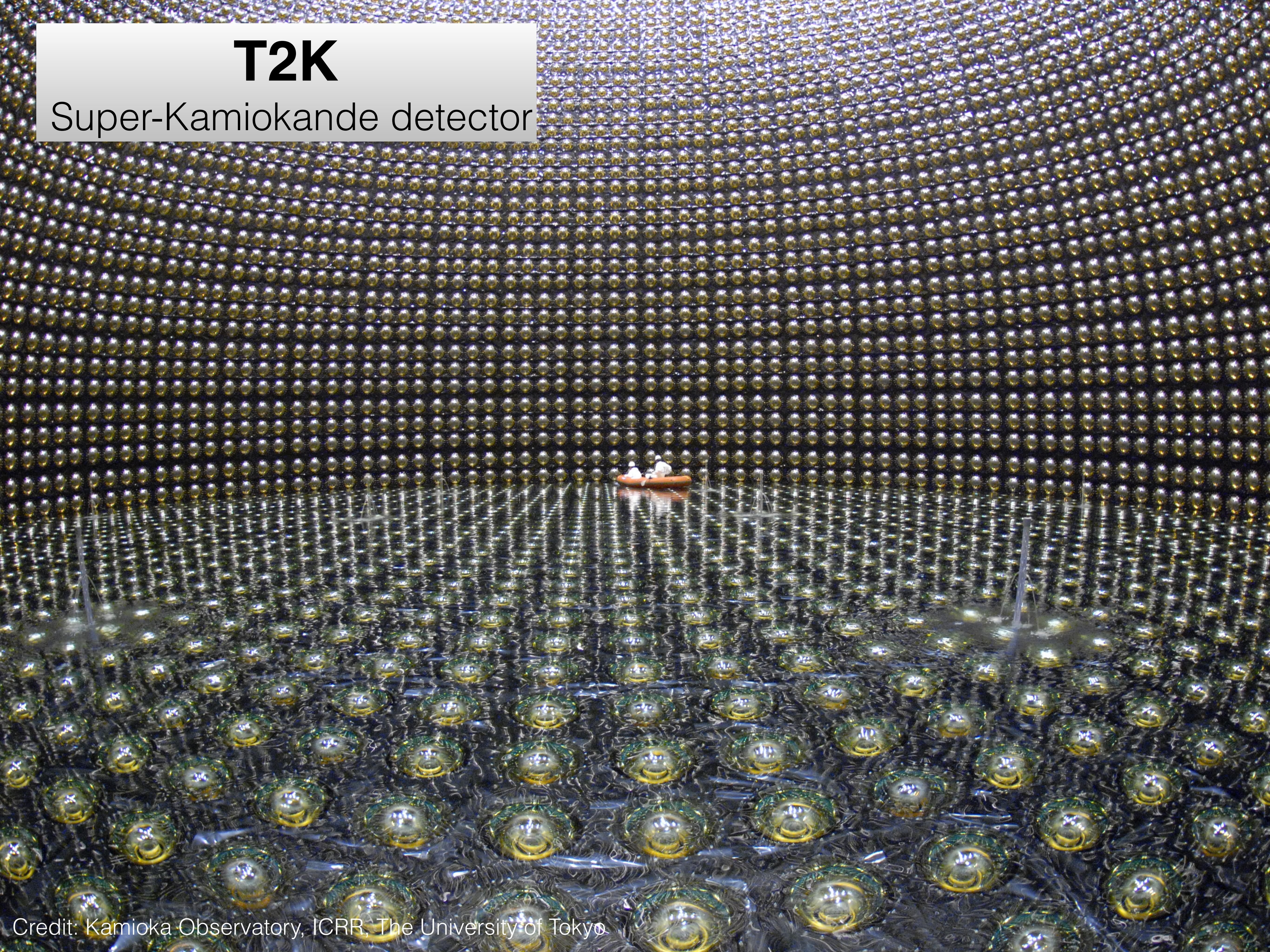




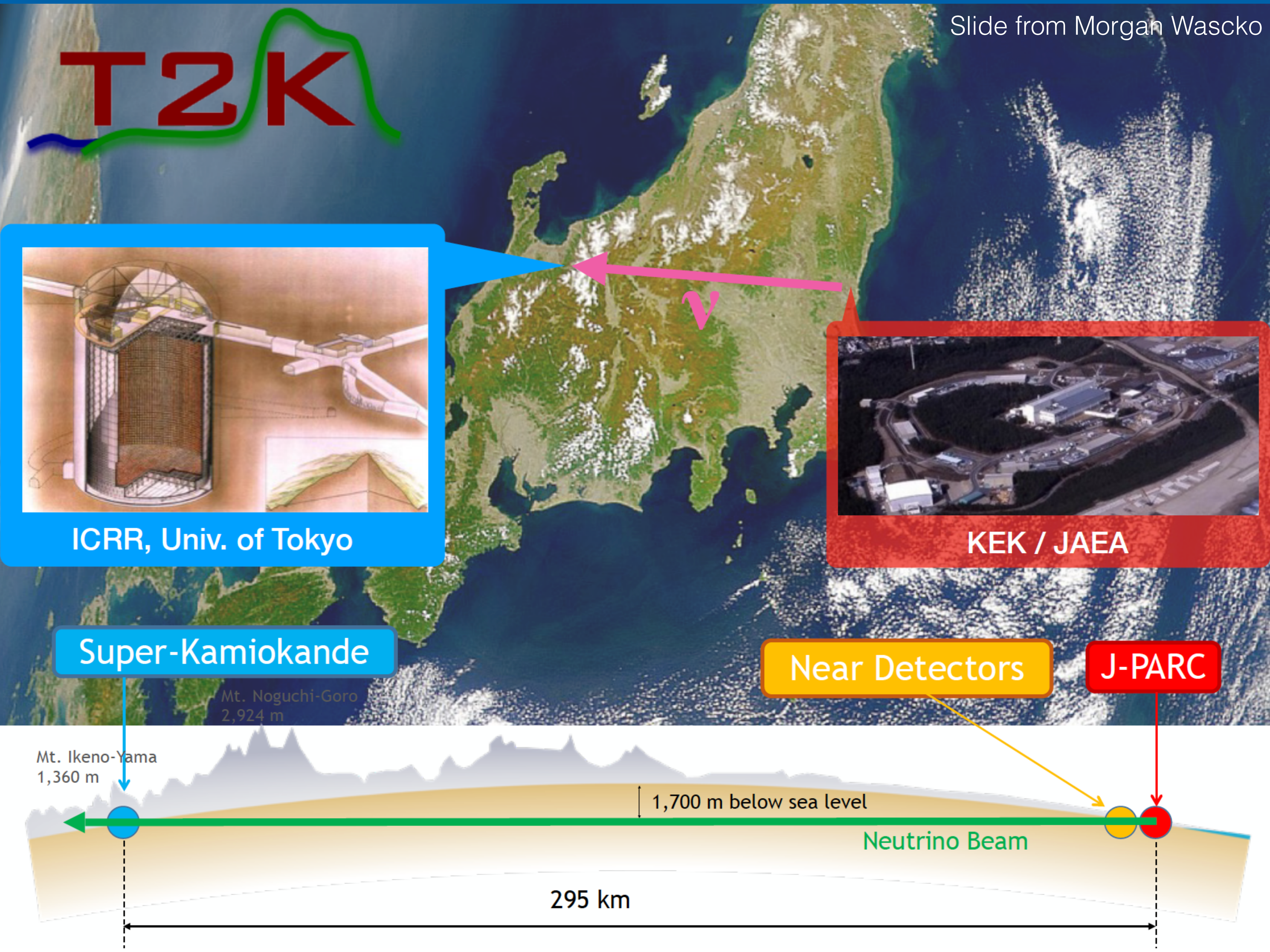
2+ σ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024

T2K

Super-Kamiokande detector



Credit: Kamioka Observatory, ICRR, The University of Tokyo

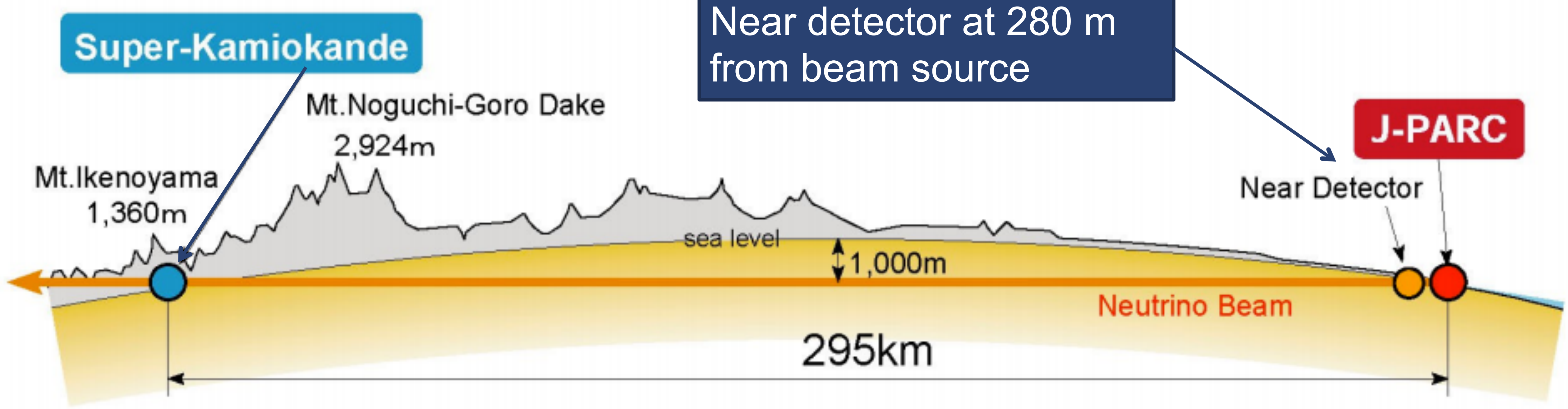

Slide from Morgan Wascko
T2K
ICRR, Univ. of Tokyo
ν
KEK / JAEA
Super-Kamiokande
Near Detectors
J-PARC
Mt. Noguchi-Goro
2,924 m
Mt. Ikeno-Yama
1,360 m
1,700 m below sea level
Neutrino Beam
295 km

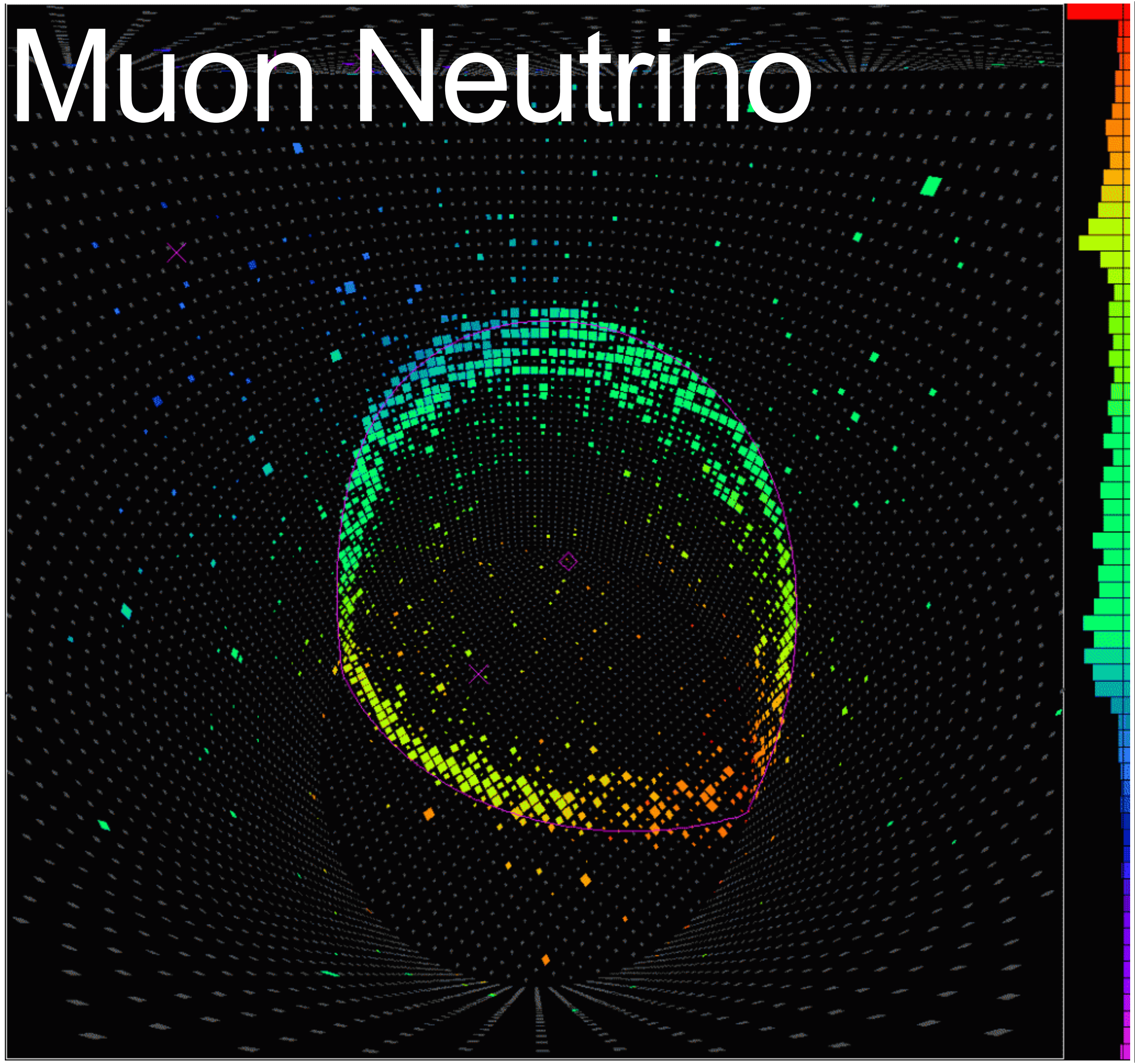
T2K

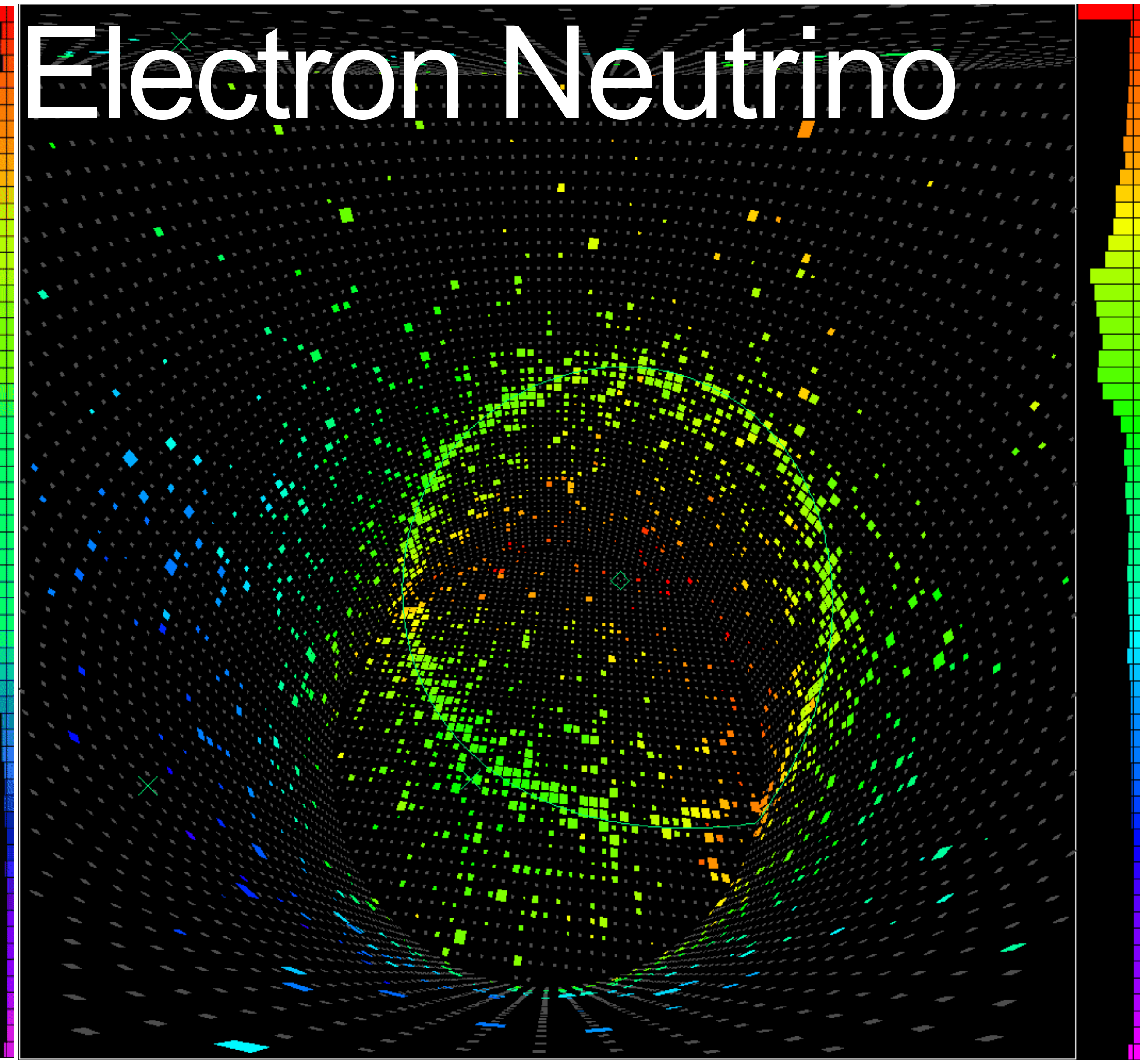
- ~500 members, 67 Institutes, 12 countries
- T2K is a long-baseline neutrino experiment with a 600 MeV narrow band muon neutrino beam
- Steadily increasing beam power, steady running now at 485 kW
- Detectors 2.5° off axis from neutrino beam
- Neutrino energy spectrum tuned to hit oscillation maximum at far detector

Far detector, Super-Kamiokande 295 km from source

Near detector at 280 m from beam source







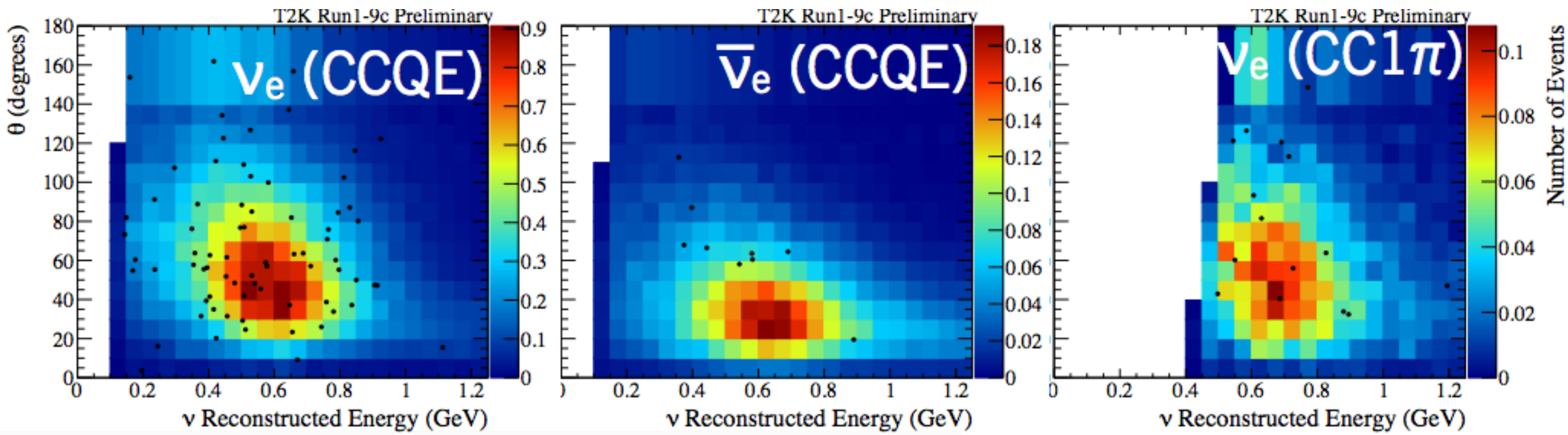
- Far Detector is liquid Cherenkov detector
- Stainless-steel tank, 39.3m diameter and 41.4m tall
- Filled with 50,000 tons of ultra pure water - currently being dropped with Gd
- 13,000 sensitive photo-multipliers

Analysis results presented today:
$1.49e10^{21}$ POT ν-mode
$1.12e10^{21}$ POT $\bar{\nu}$-mode

Electron (anti)neutrino appearance

sample	δ = - π /2	δ = 0	δ = + π /2	δ = π	Data
neutrino μ CCQE	268.5	268.2	268.5	268.9	243
anti neutrino μ CCQE	95.5	95.3	95.5	95.8	102
neutrino e CCQE	73.8	61.6	50.0	62.2	75
neutrino e CC1 π+	6.9	6.0	4.9	5.8	15
anti-neutrino e CCQE	11.8	13.4	14.9	13.2	9

Observed events at Super-K. predictions assuming NH, 2016 PDG θ_{13}, and θ_{23}=45°



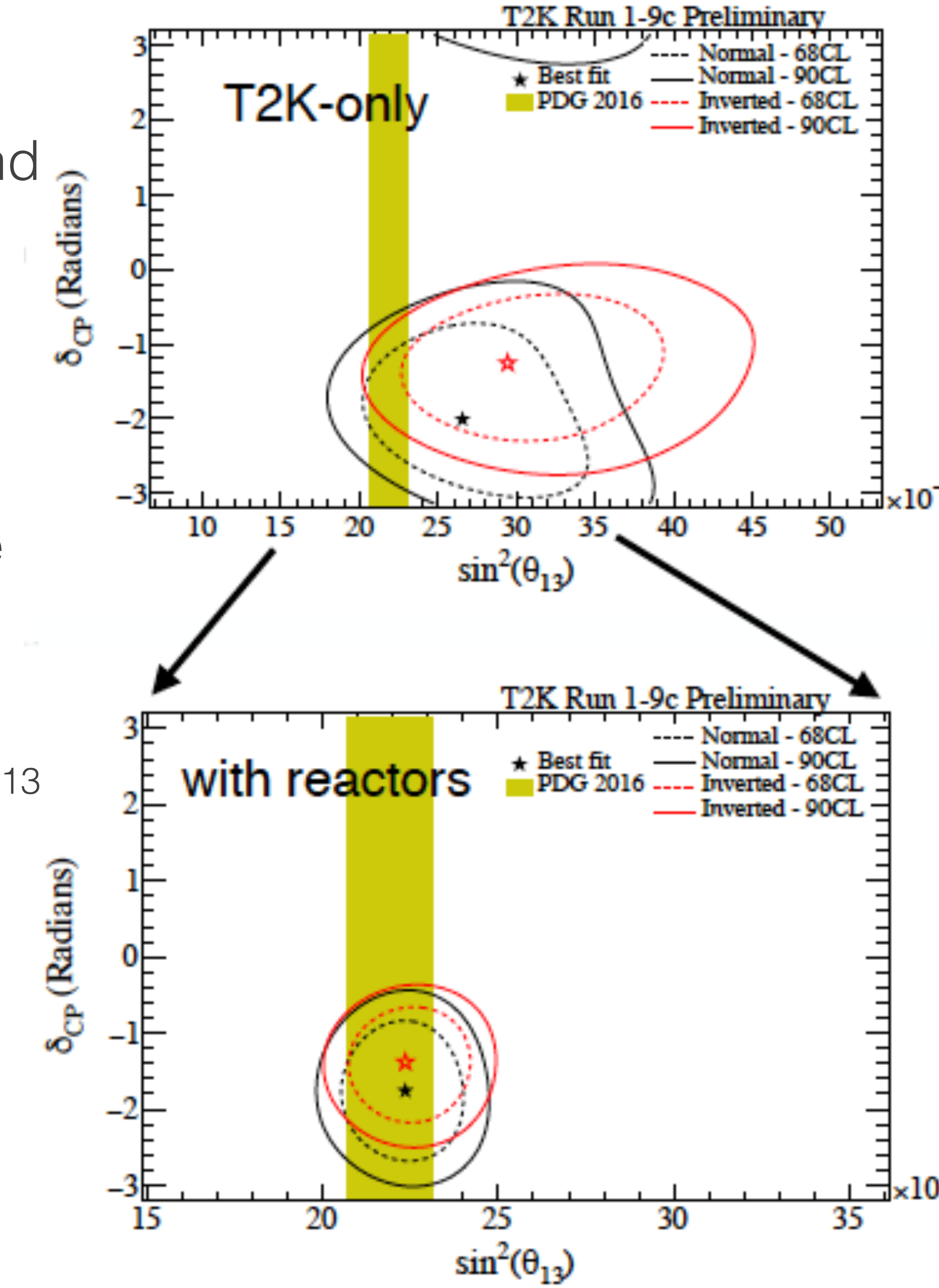
Antineutrino results

- Test hypothesis of appearance (expect 11.8 events) and no-appearance (expect 6.5 events)
- Observe 9 events
- No strong statistical statement yet

HYPOTHESIS	P-VALUE
NO appearance	p=0.233
PMNS appearance	p=0.0867

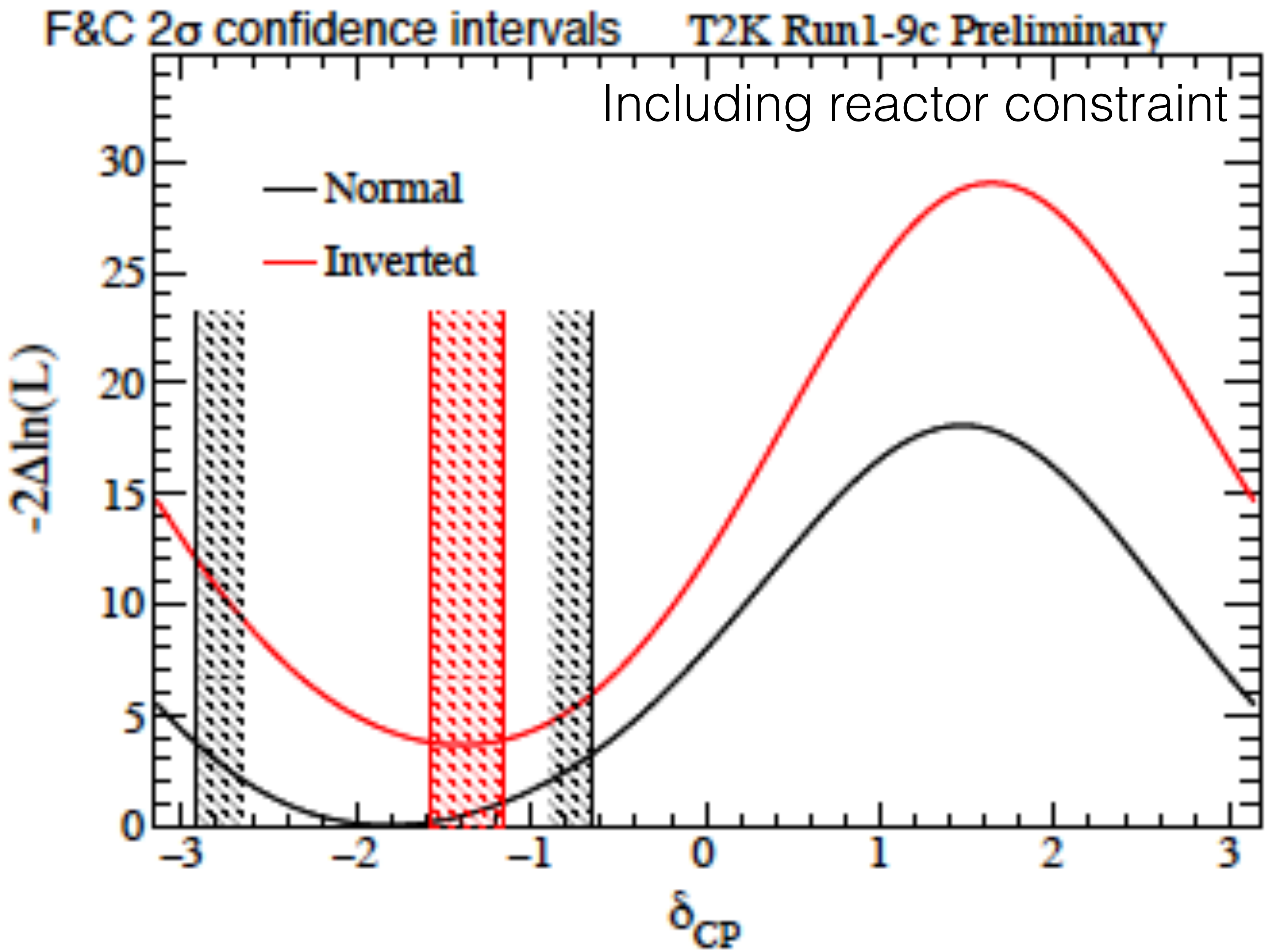
Charge-parity phase, δ_{CP}, at T2K

- Binned-likelihood oscillation fits to all far-detector samples simultaneously (muon and electron)
- Marginalize over all nuisance parameters
- Two oscillation fits:
  - Fit for θ_{13} using T2K data
  - Use 2016 (reactor data only) PDG value as a constraint



- Consistent with reactor measurements of θ_{13}
- CP-conserving values outside of 2σ region for both hierarchies
- Slight preference for normal hierarchy
- Data fit stronger than sensitivity

Charge-parity phase, δ_{CP}, at T2K



δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

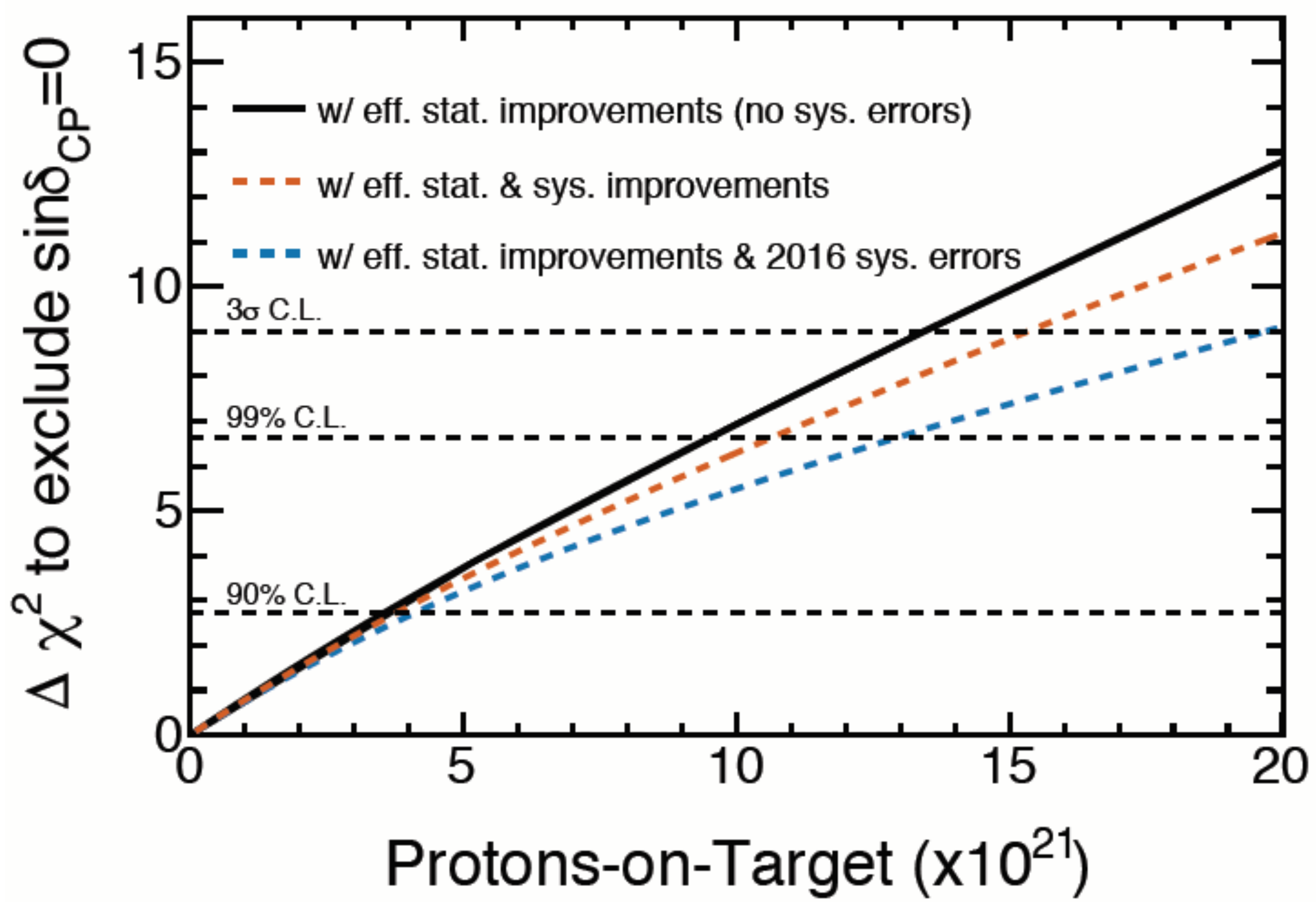
- CP conserving values outside of 2σ region for both hierarchies
- 19% of toys exclude CP conservation at 2σ CL (both $\delta_{CP}=0$ & $\delta_{CP}=\pi$)

T2K looking forward

- Super-K undergoing Gd doping this summer, improves neutron detection capability and may provide wrong sign background constraint in T2K anti-electron data
- In 2016, T2K phase 2 run extension given Stage-1 status by KEK/J-PARC.
- Proposal to collect 8x more data by 2027, 20e10^{21} POT, arXiv:1609.04111 [hep-ex]
- Approved beam upgrades allow 750 kW operation, with eventual upgrades to 1.3 MW (2021)
- T2K initiated Near Detector upgrade project in January 2016 in collaboration with CERN

Enables T2K to have up to 3σ (median) CPV sensitivity

Sensitivity improves beyond 3σ with reduced systematic errors



Combing T2K and NOvA

T2K | Home | News | About T2K | About Neutrinos | Photos | Videos | Contact

T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

The NOvA and T2K Collaborations are working towards the formation of a joint working group to enhance the measurements of neutrino oscillation parameters made by each Collaboration individually. The projected timescale of the NOvA-T2K working group is for production of a full joint neutrino oscillation analysis by 2021.

Preparing for a joint working group: three workshops held so far.

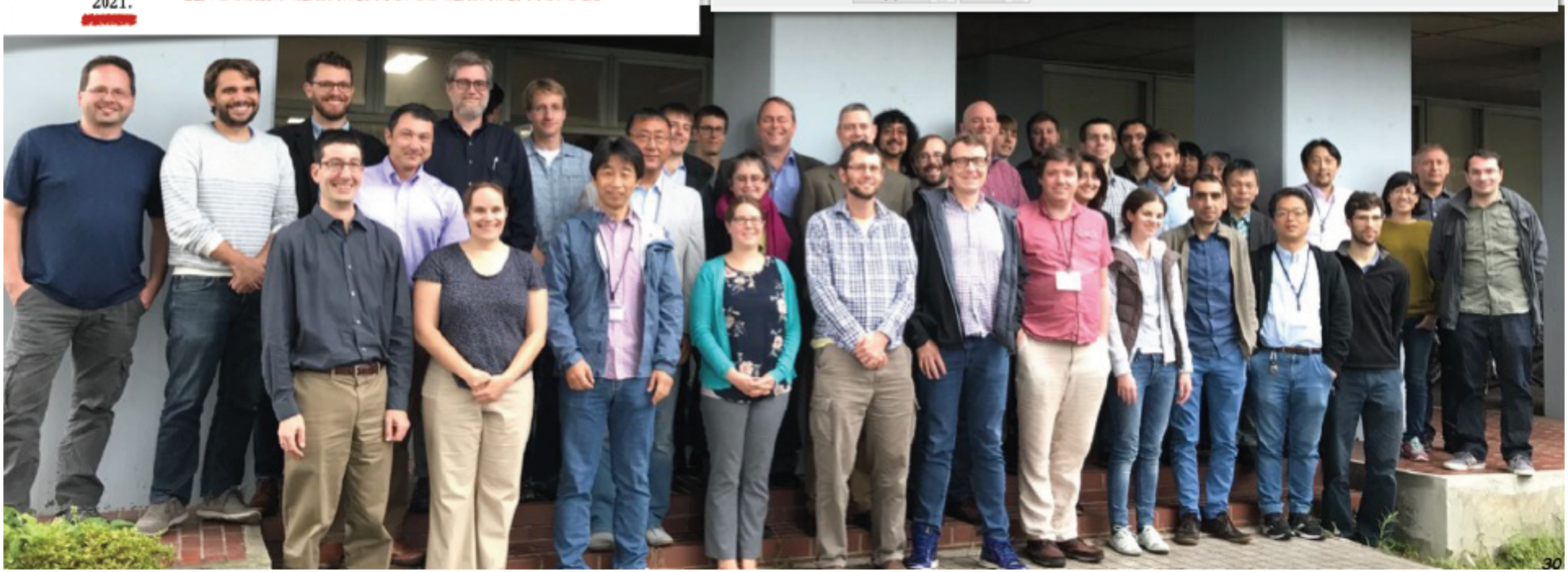
NOvA-T2K Joint Workshop on Neutrino Interaction Uncertainties in Oscillation Measurements

chaired by Tsuyoshi Nakaya (Kyoto), Morgan Wascko (Imperial College London), Peter Shanahan (Fermilab), Mark Messier (Indiana)

from Sunday, October 15, 2017 at **09:00** to Tuesday, October 17, 2017 at **12:00** (Asia/Tokyo)
at **KEK Tokai-1 (Room 116)**
2-4 Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

Description Experts from NOvA and T2K collaboration will discuss
- Status and future projections
- Details of our respective cross-section tunes
- Details on underlying correspondence between GENIE and NEUT models
- Details of the oscillation measurements and the role of uncertainties, and starting work to map out cross-section correlations between the two experiments
- Summaries and plans for ongoing work

Material: Group photo | Slides



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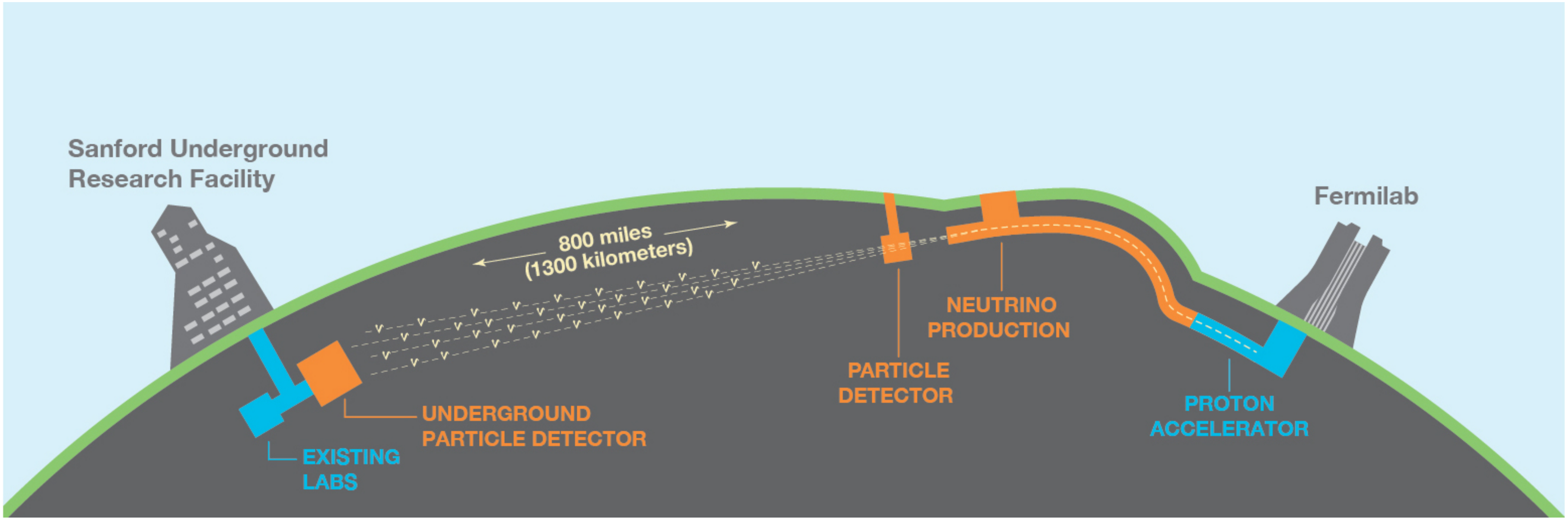
Slide from Morgan Wascko

DEEP UNDERGROUND NEUTRINO EXPERIMENT

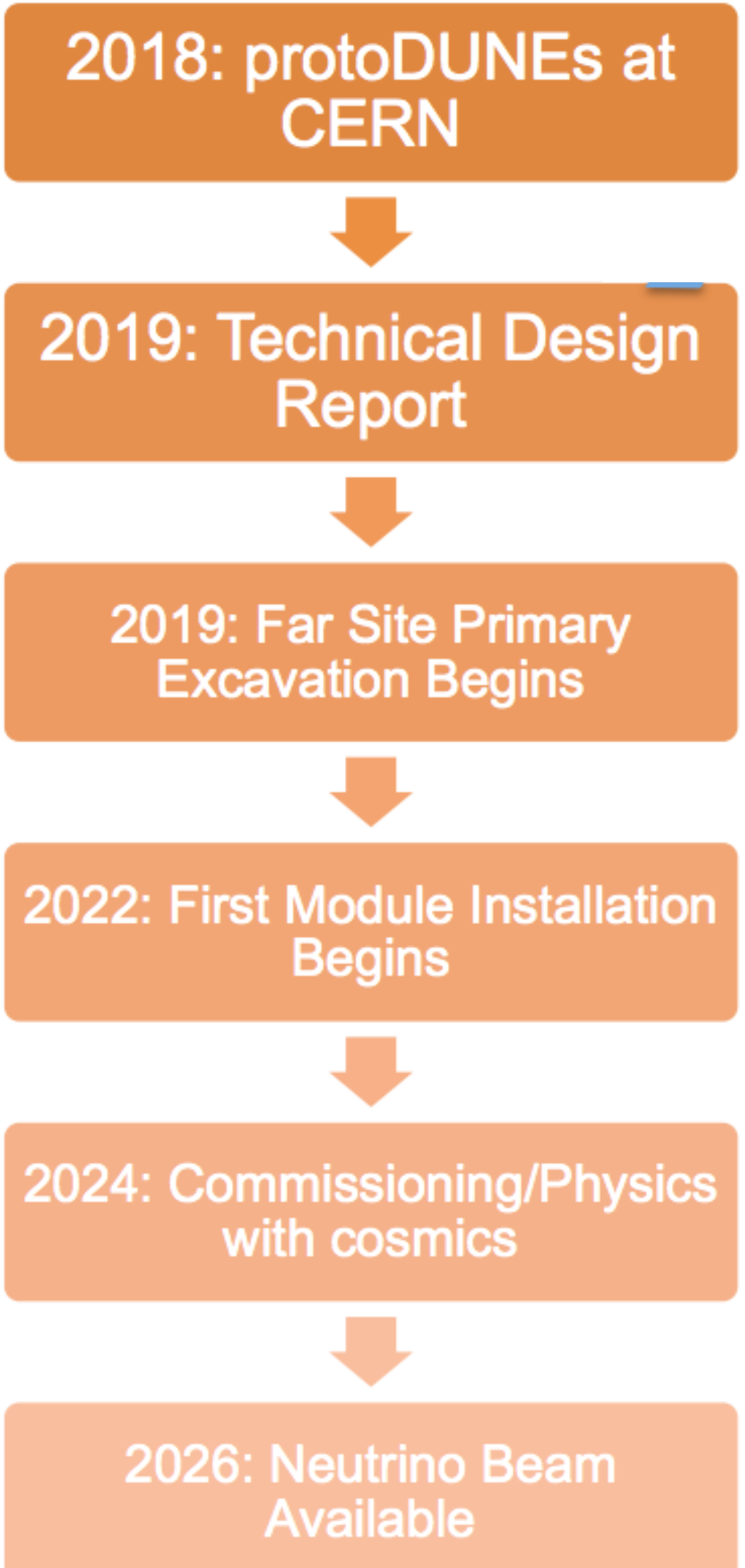


The DUNE collaboration is currently made up of over 1000 collaborators from 175 institutions in 32 countries plus CERN

DUNE – Overview

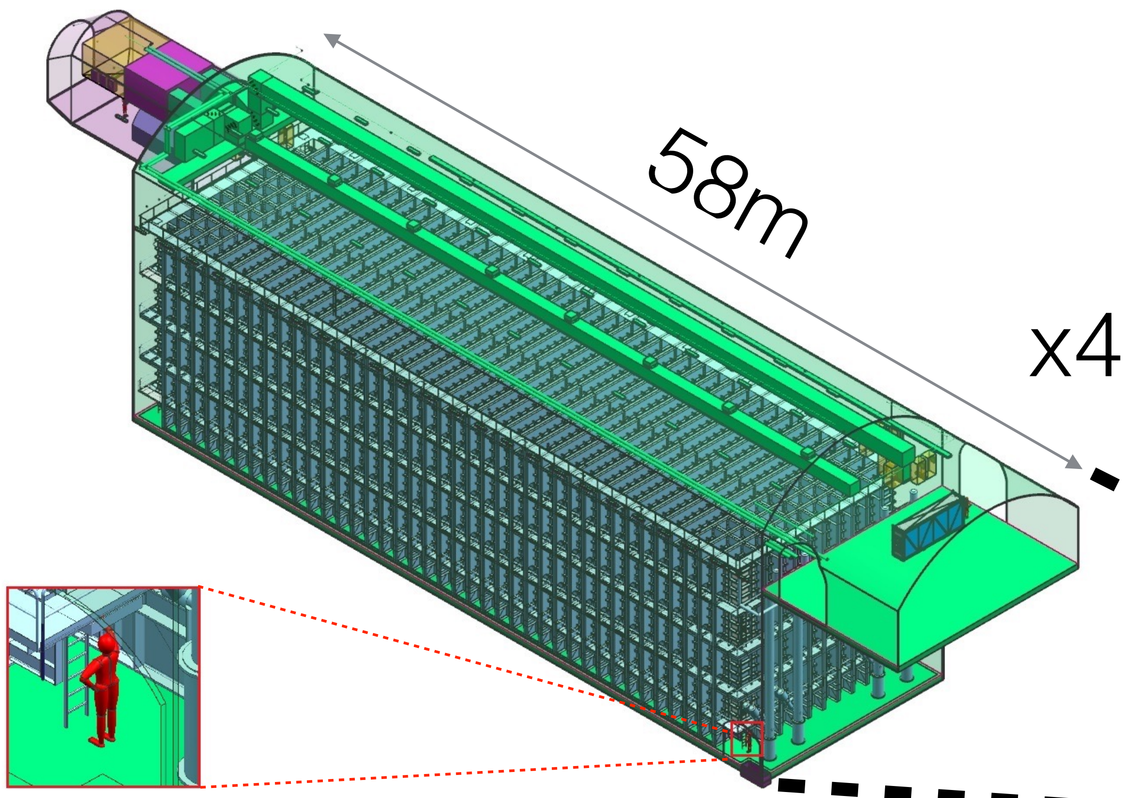
- Located at SURF's 1478 m level
- Wide-band (~Gev range) 1.2 MW neutrino beam, upgradeable to 2.4 MW
- Four 10kt of fiducial mass Liquid Argon Time projection Chambers, Single and dual-phase detector designs
- Near Detector located ~600 m from neutrino source, final design still under discussion

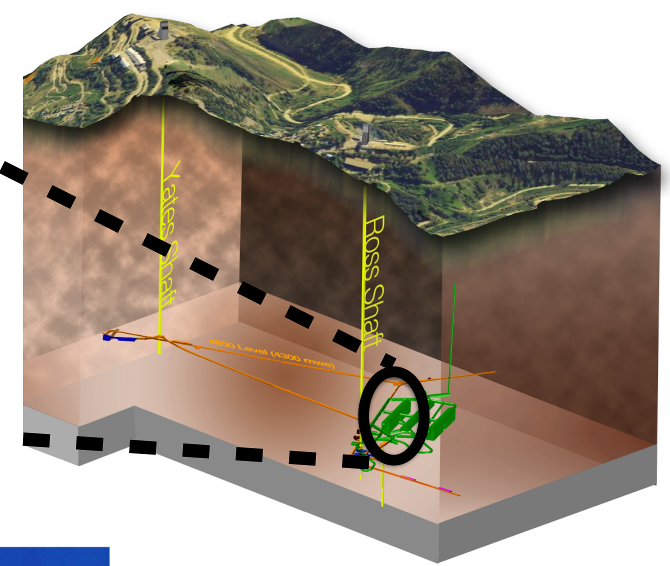
- DUNE's primary physics goals include
  - Measure CP phase
  - Supernova and proton decay
  - Measure mass hierarchy



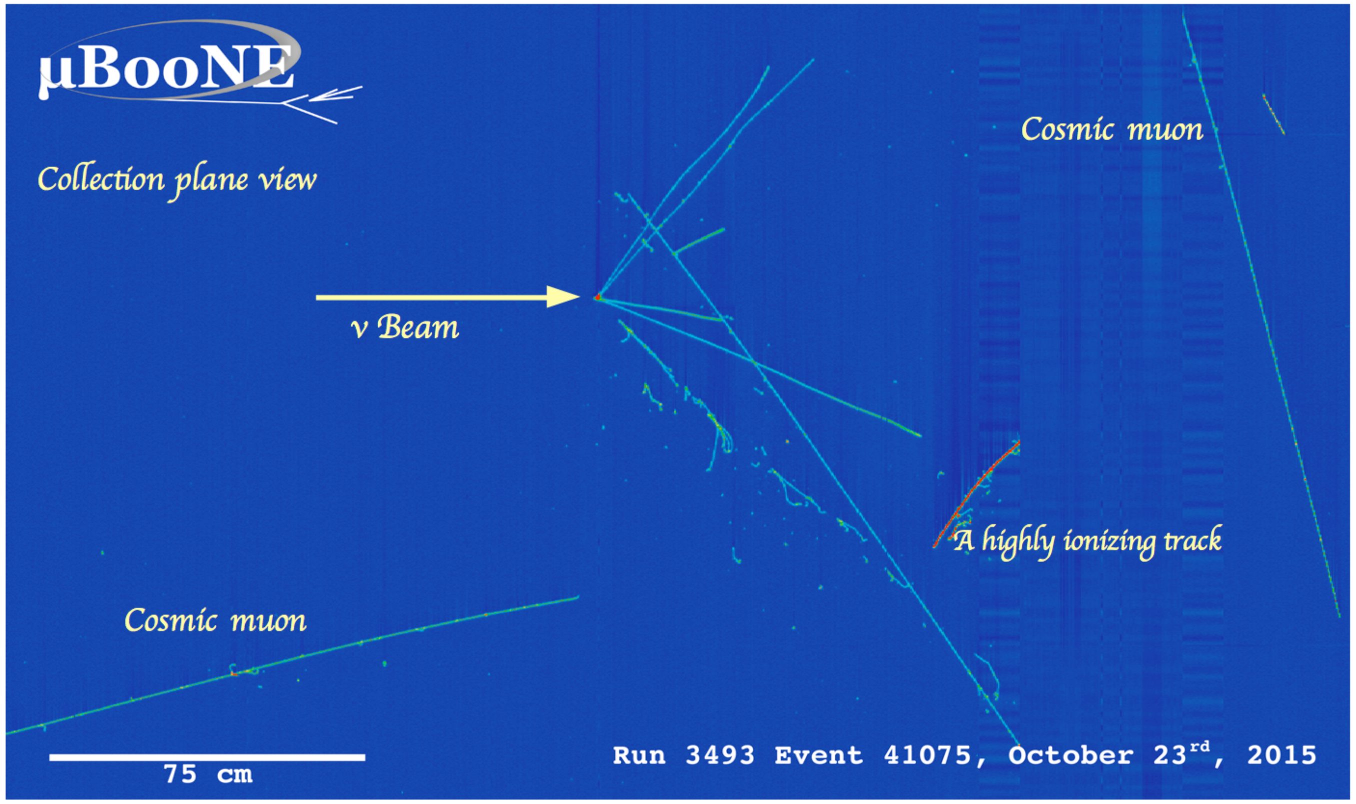
conceptual drawing of detector and location underground

Detectors: Liquid Argon Time Projection Chambers





4 giant detectors, each about 1/2 the size of a football field, containing **70 thousand tons** of liquid argon kept at **minos 186°C**

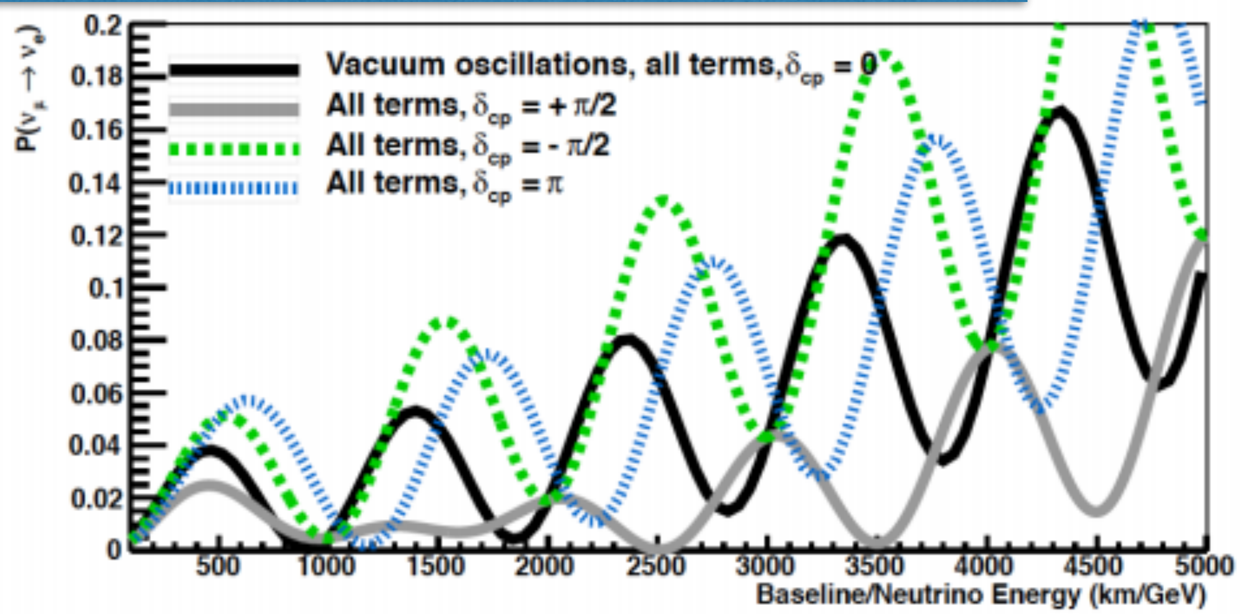


LArTPC features:

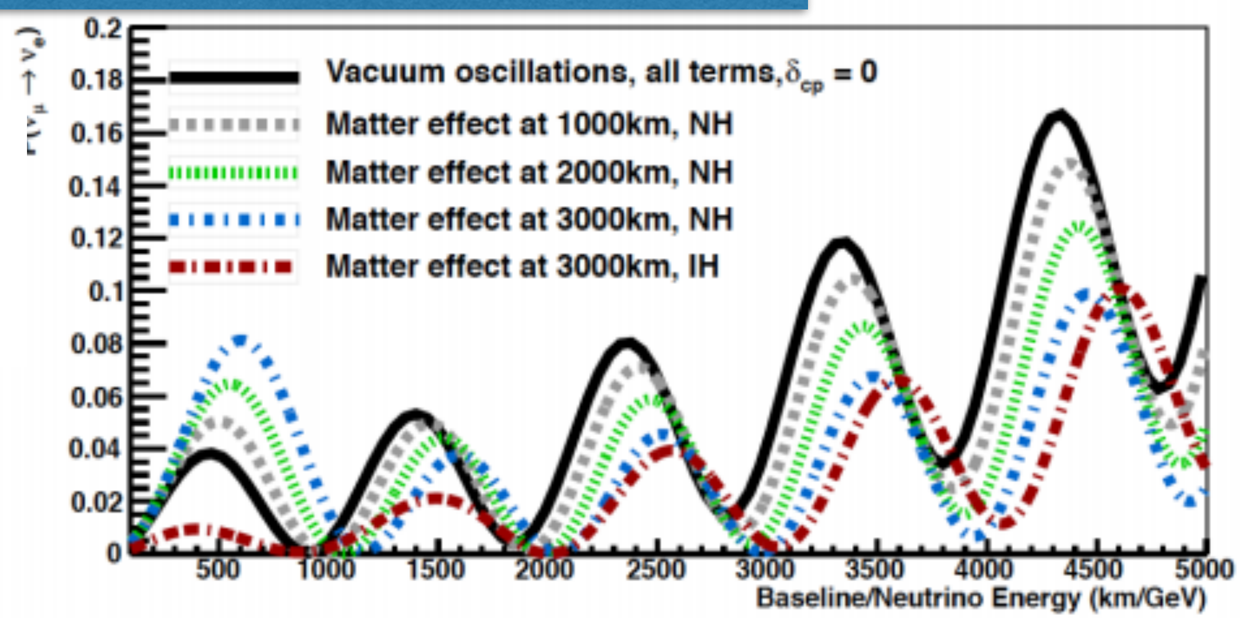
- Precision 3D imaging from mm-scale resolution
- Accurate calorimetry from fully active volume and large ionization signal
- PID from dE/dx, event topology
- Unique e/ɣ separation

Breaking the degeneracy

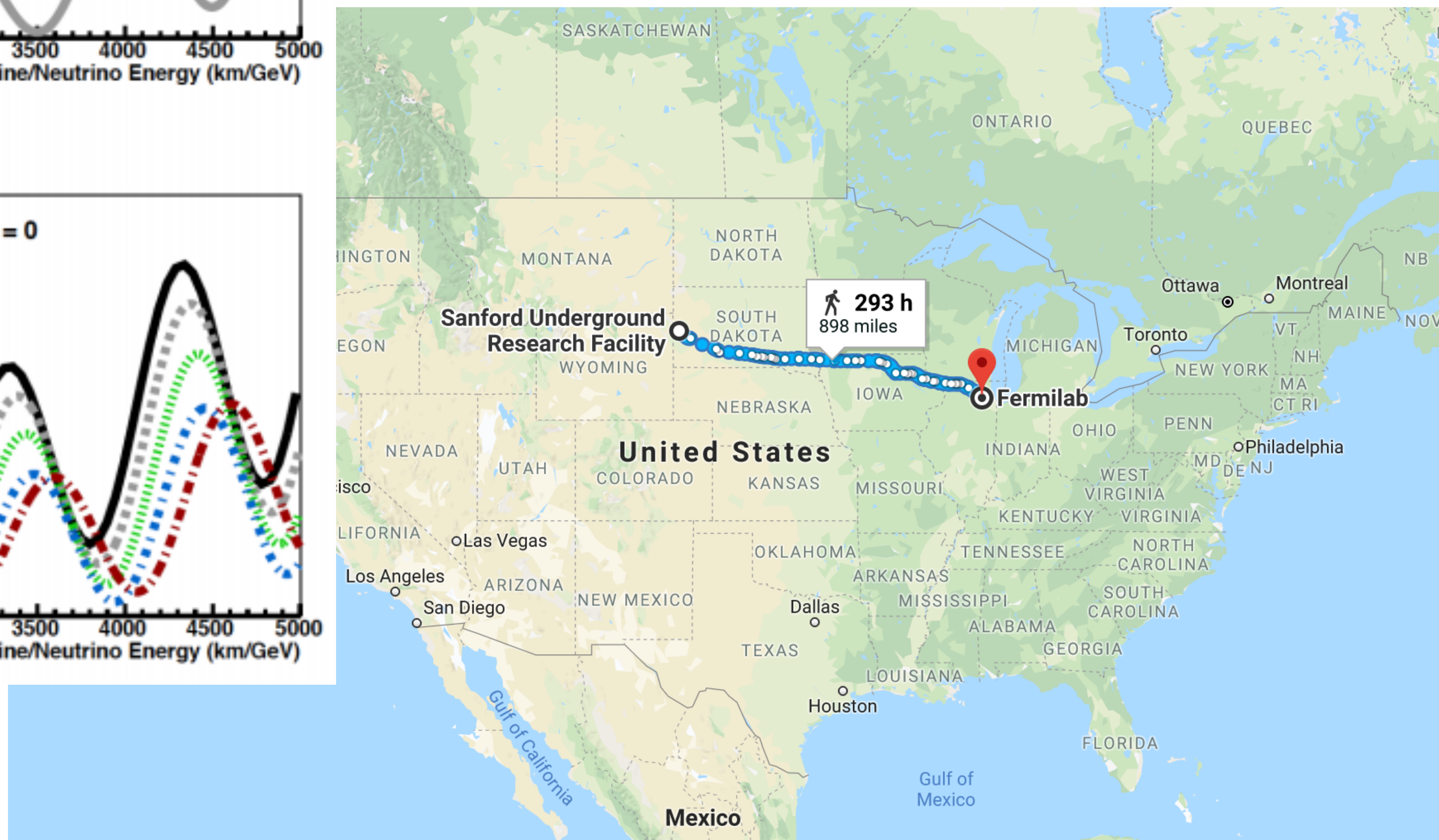
Normal mass hierarchy, different δ_{CP}



δ_{CP}=0, different length values

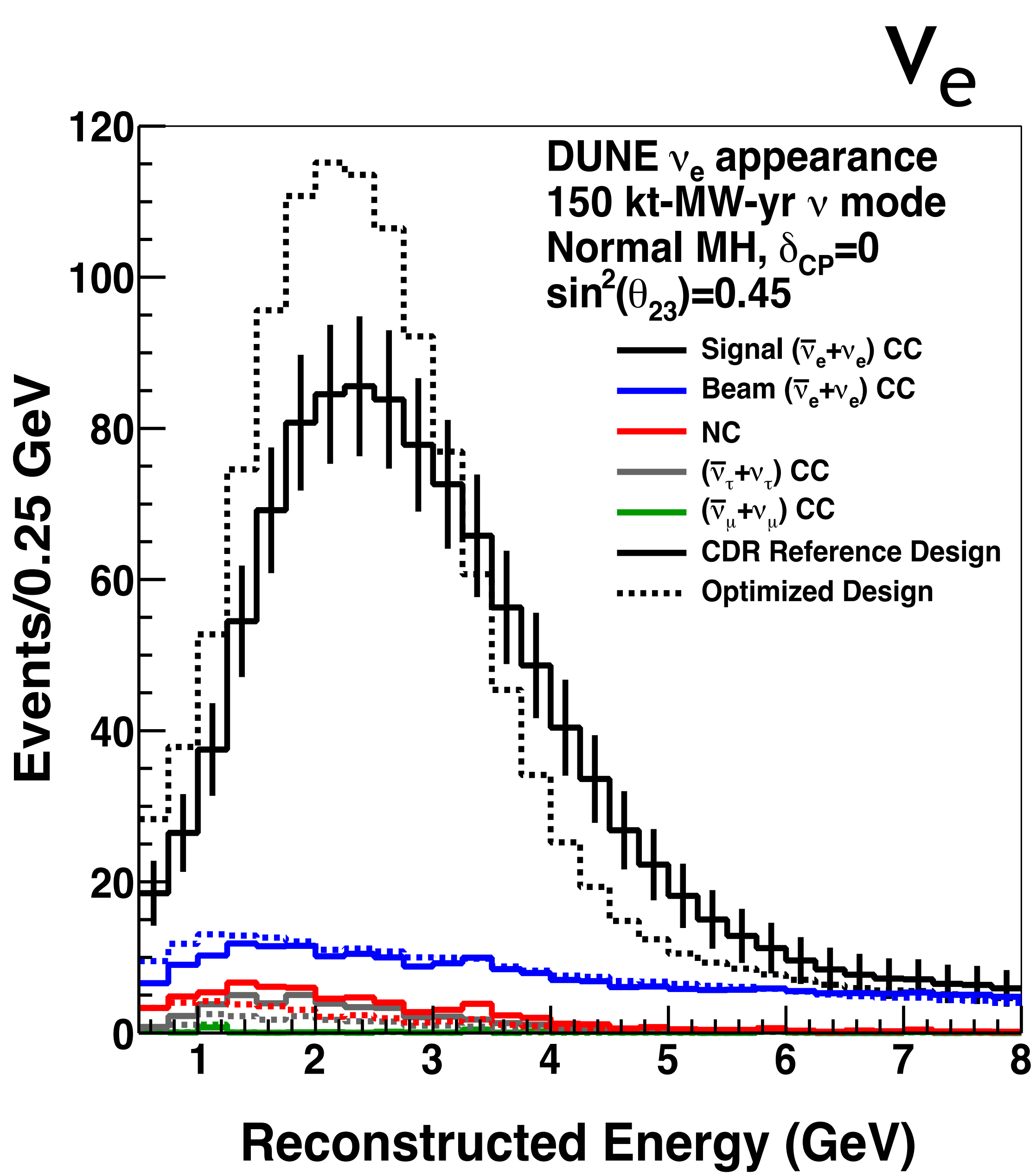


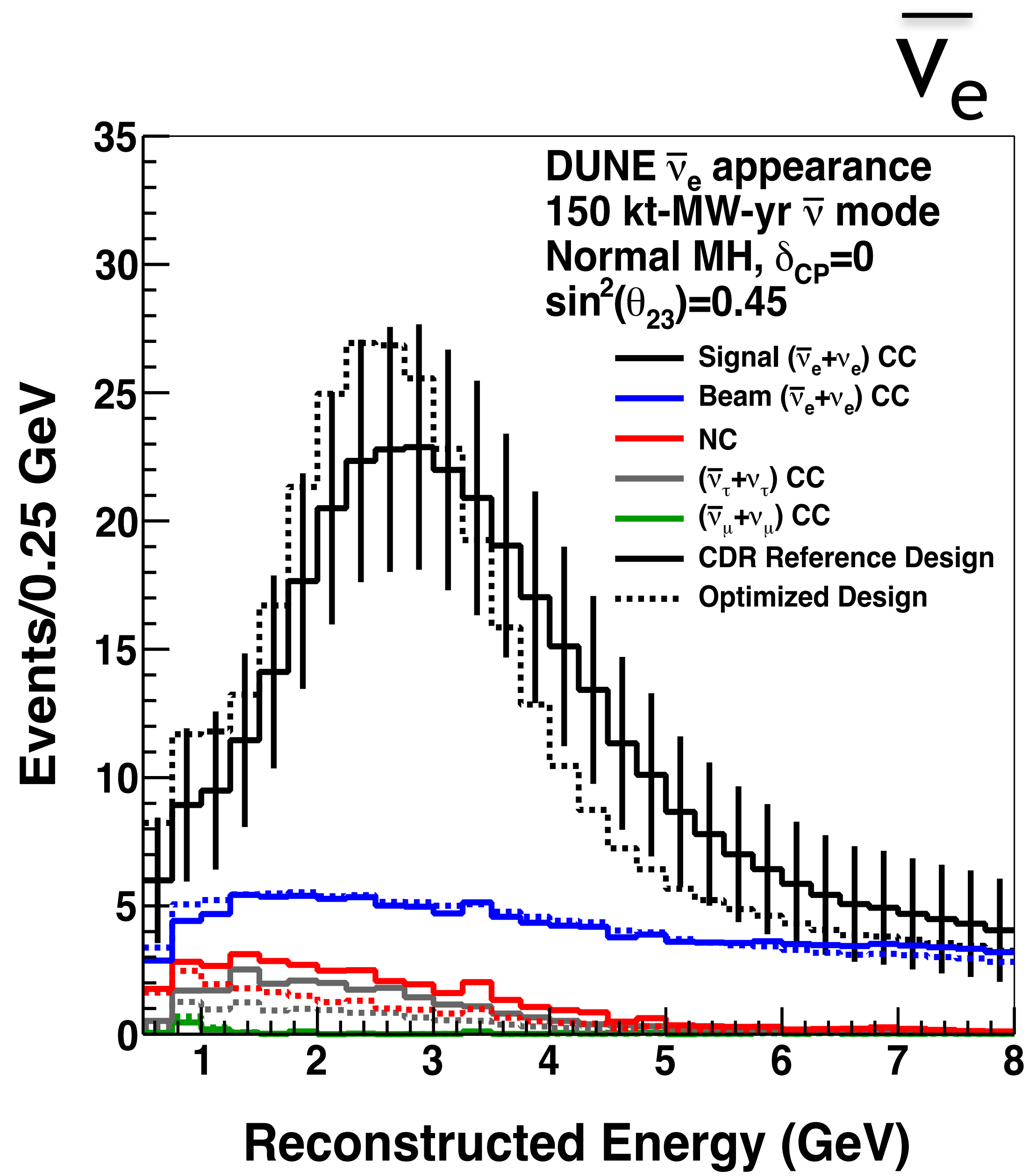
- Both mass hierarchy and δ_{CP} change the height of the peak
- Each shifts the peak differently in L/E — use shape to disentangle
- DUNE will see first and second oscillation maximums



DUNE electron-neutrino appearance

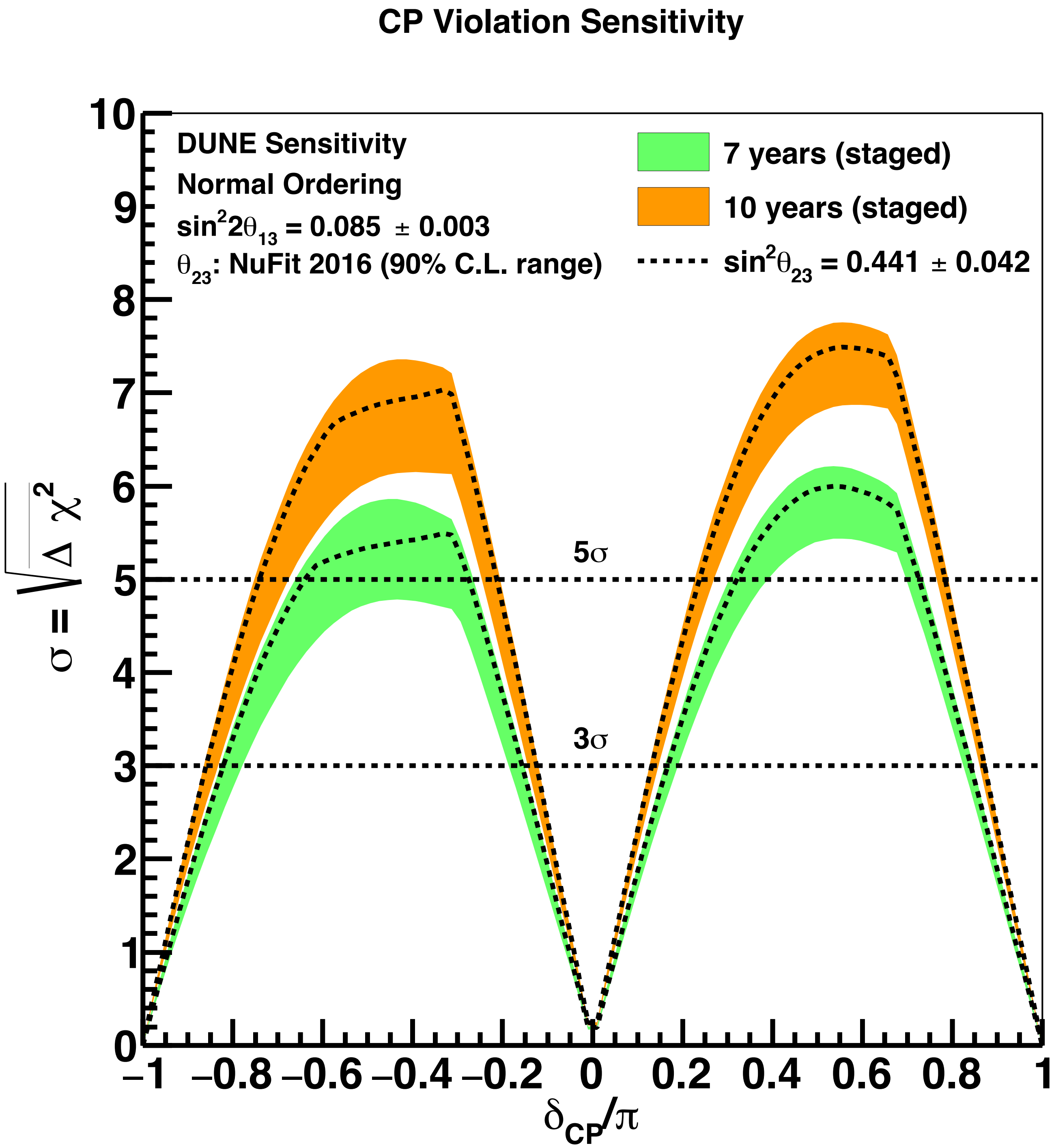
- Measure ν_e appearance and ν_μ disappearance over range of energies
- Disentangle mass ordering and CP violation effects

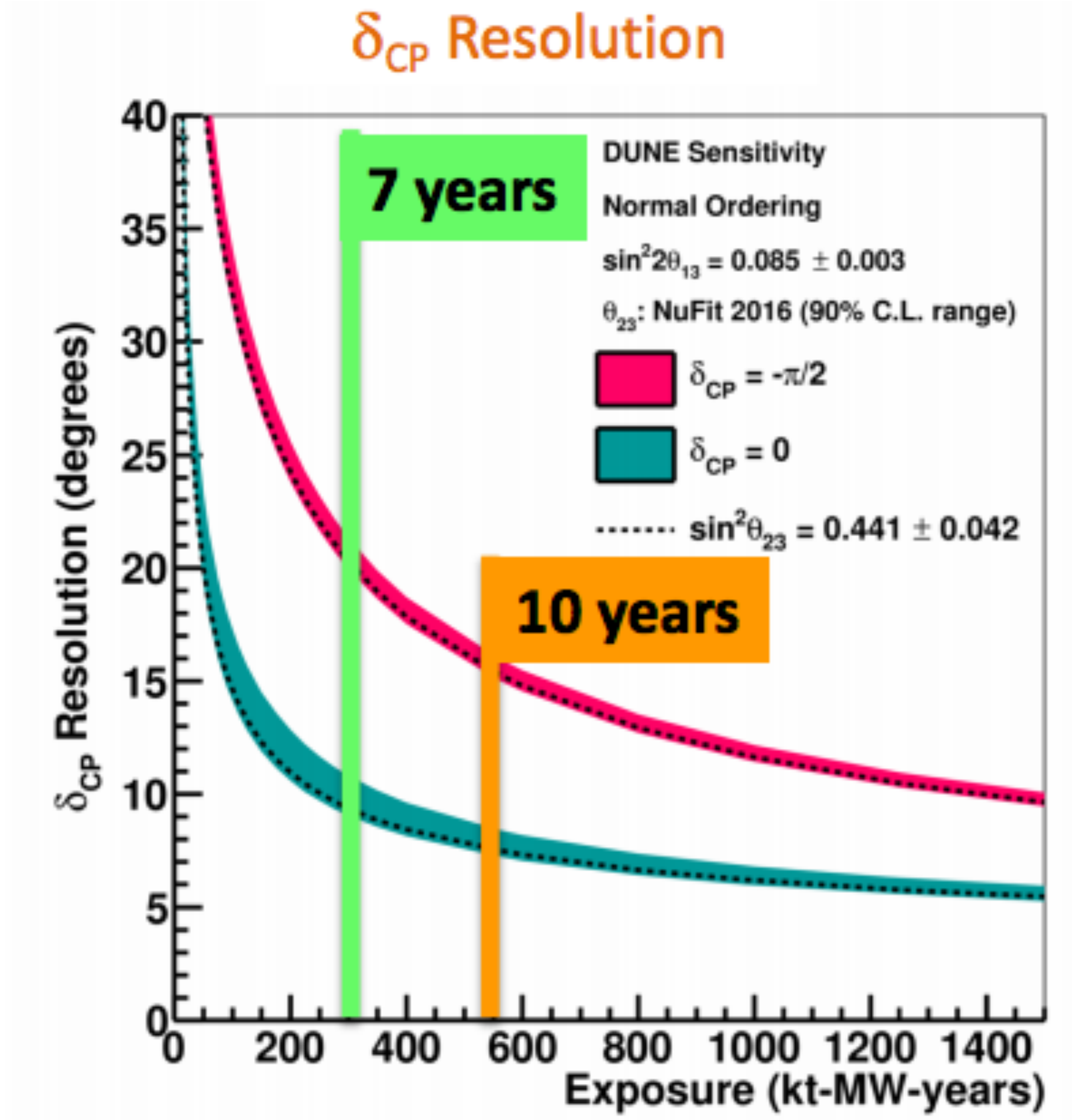




7 years of data

DUNE CP sensitivity





Width of band indicates variation in possible central values of t23 based on NuFit 2016 values

Staging:
- 2026: 20 kt far detector with 1.2 MW beam
- 2027: 30 kt far detector
- 2029: 40 kt far detector
- 2032: Upgrade to 2.4 MW beam

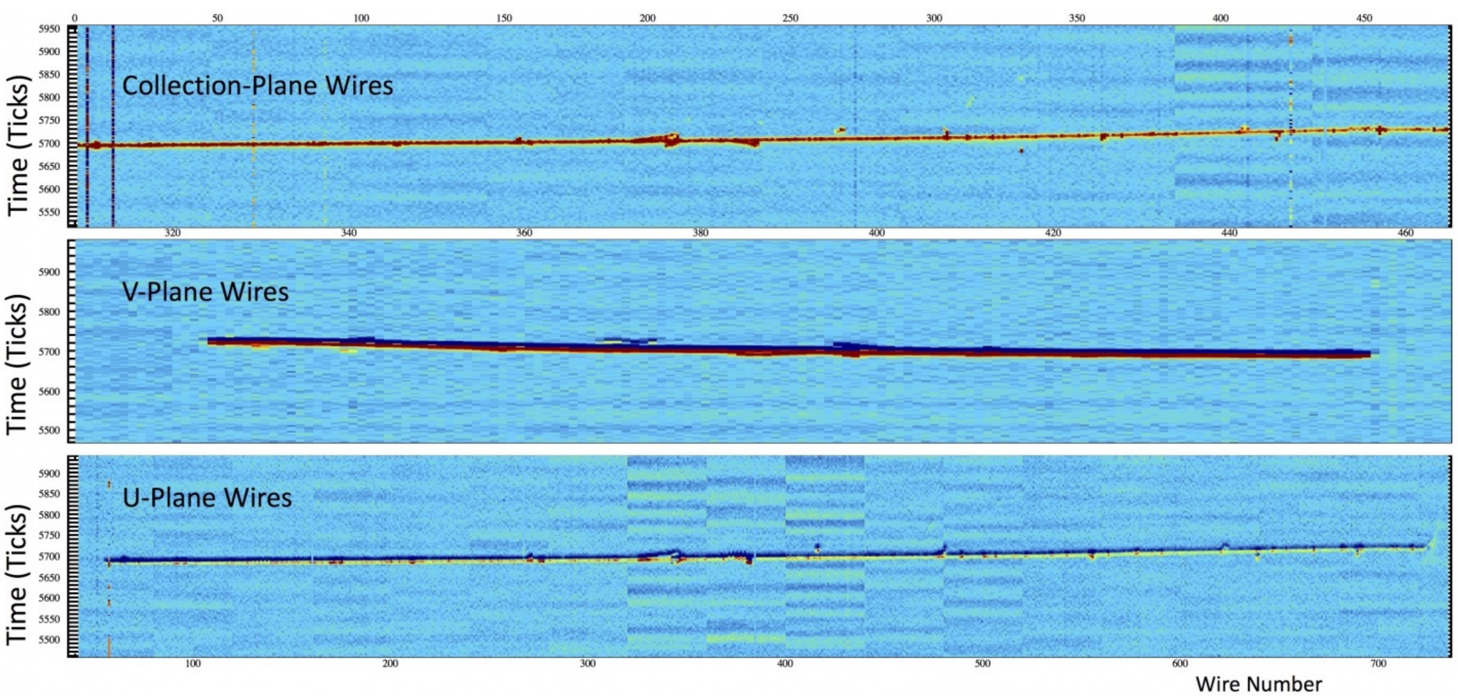
ProtoDUNEs

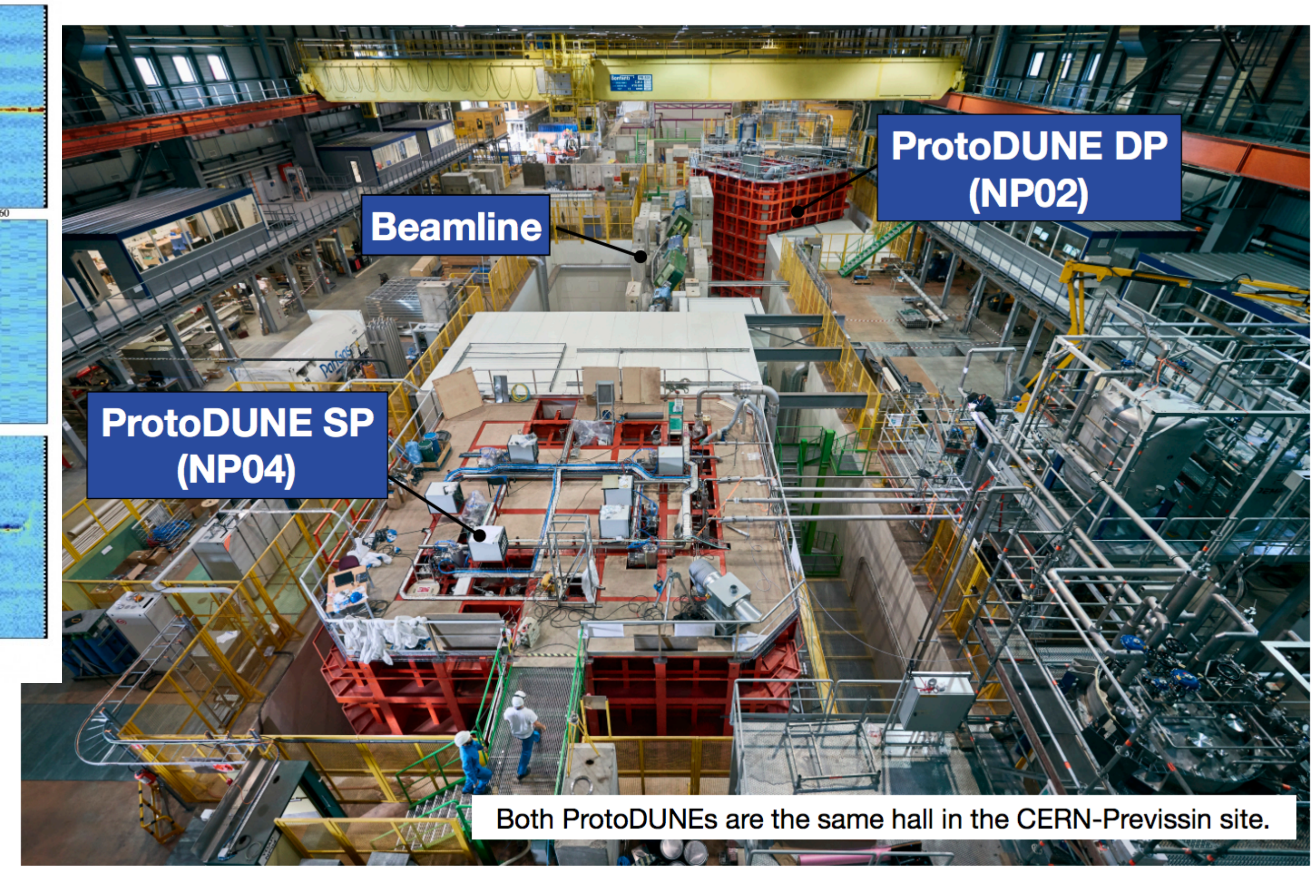
- Currently two (single and duel phase) prototypes being built at CERN
- First tracks seen just a few weeks ago, continuing to take test beam data
- Working to validate the technology going into the first two far detector models

First particle tracks seen in prototype for international neutrino experiment

September 18, 2018

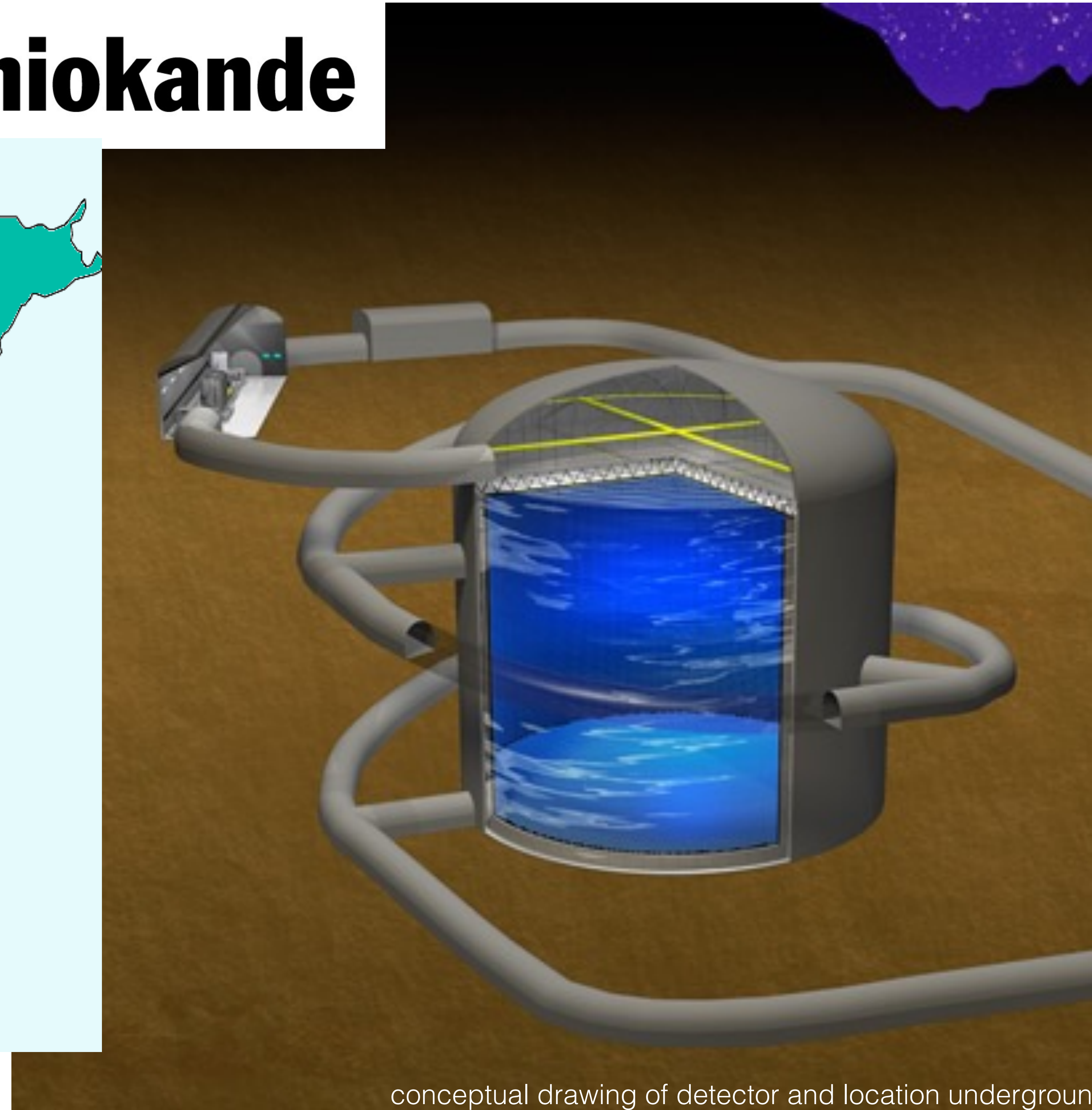
Share Tweet G+ Email





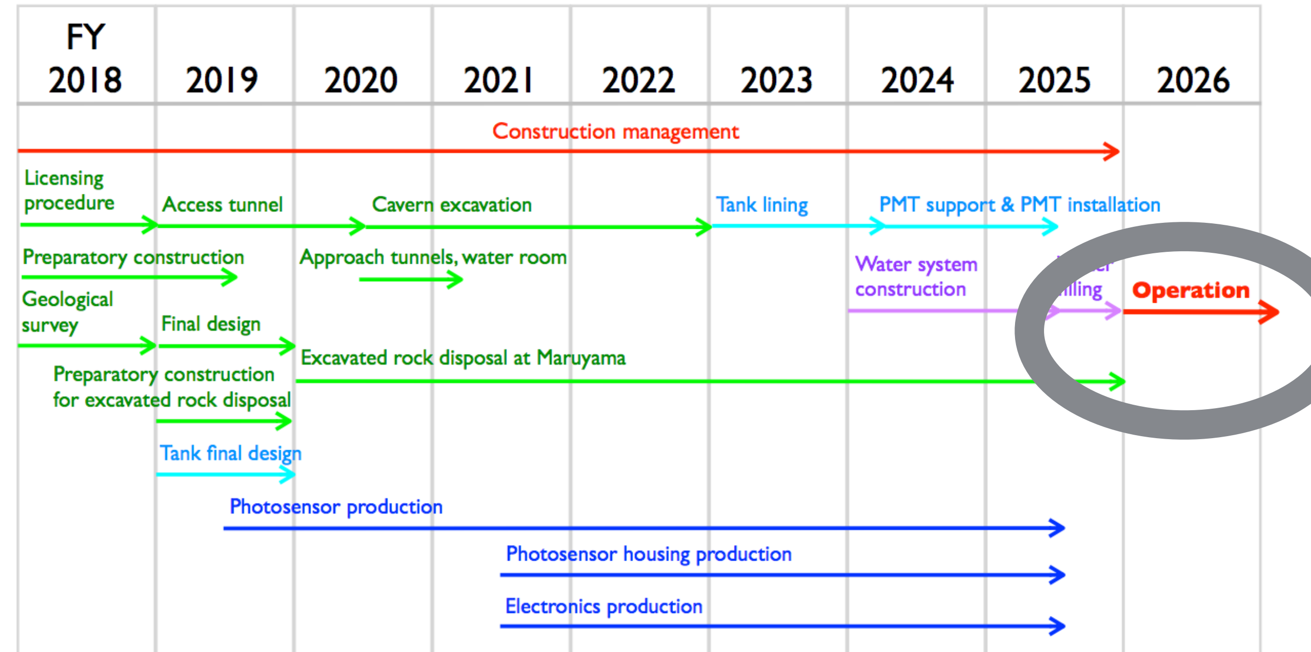
Both ProtoDUNEs are the same hall in the CERN-Previssin site.

Hyper-Kamiokande

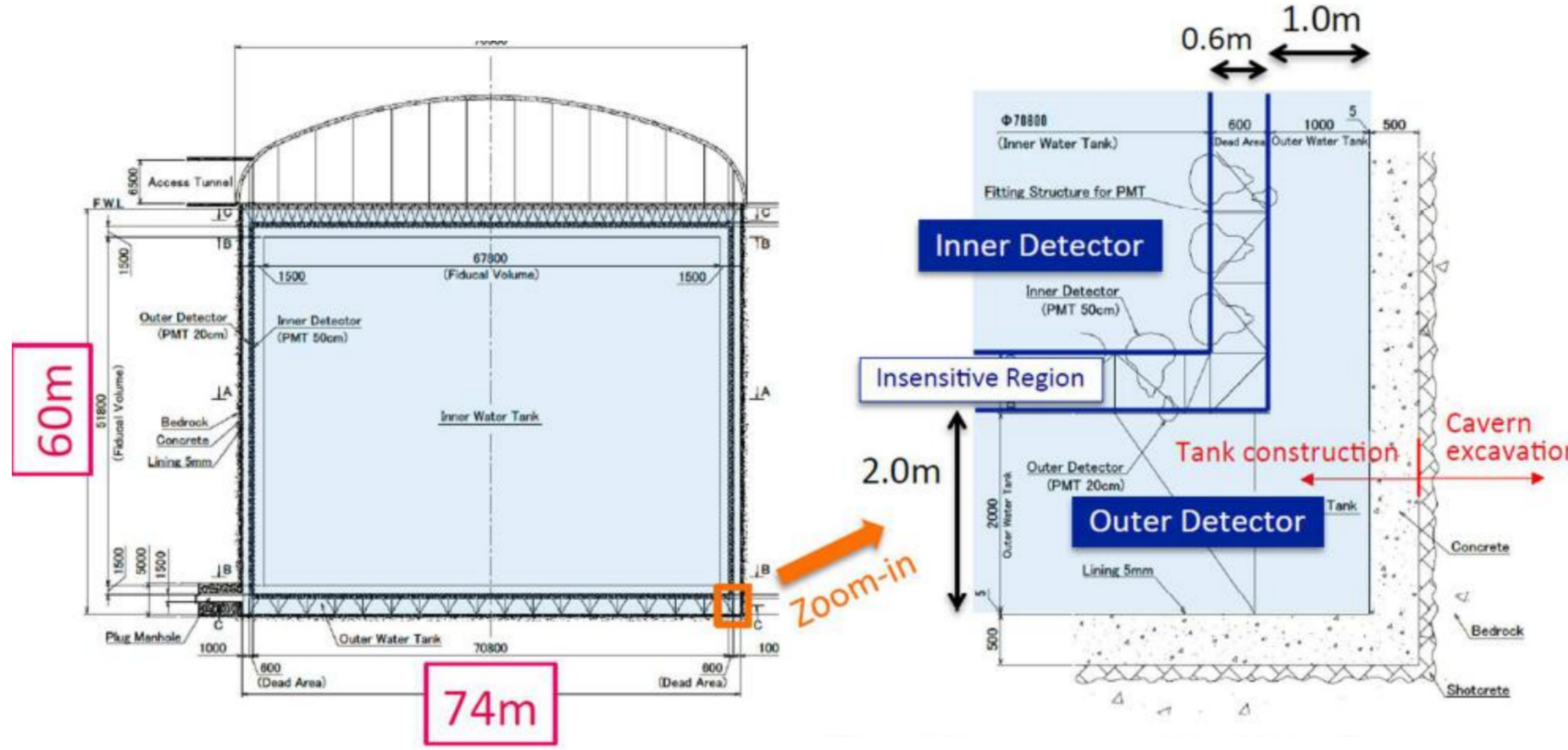


conceptual drawing of detector and location undergroun

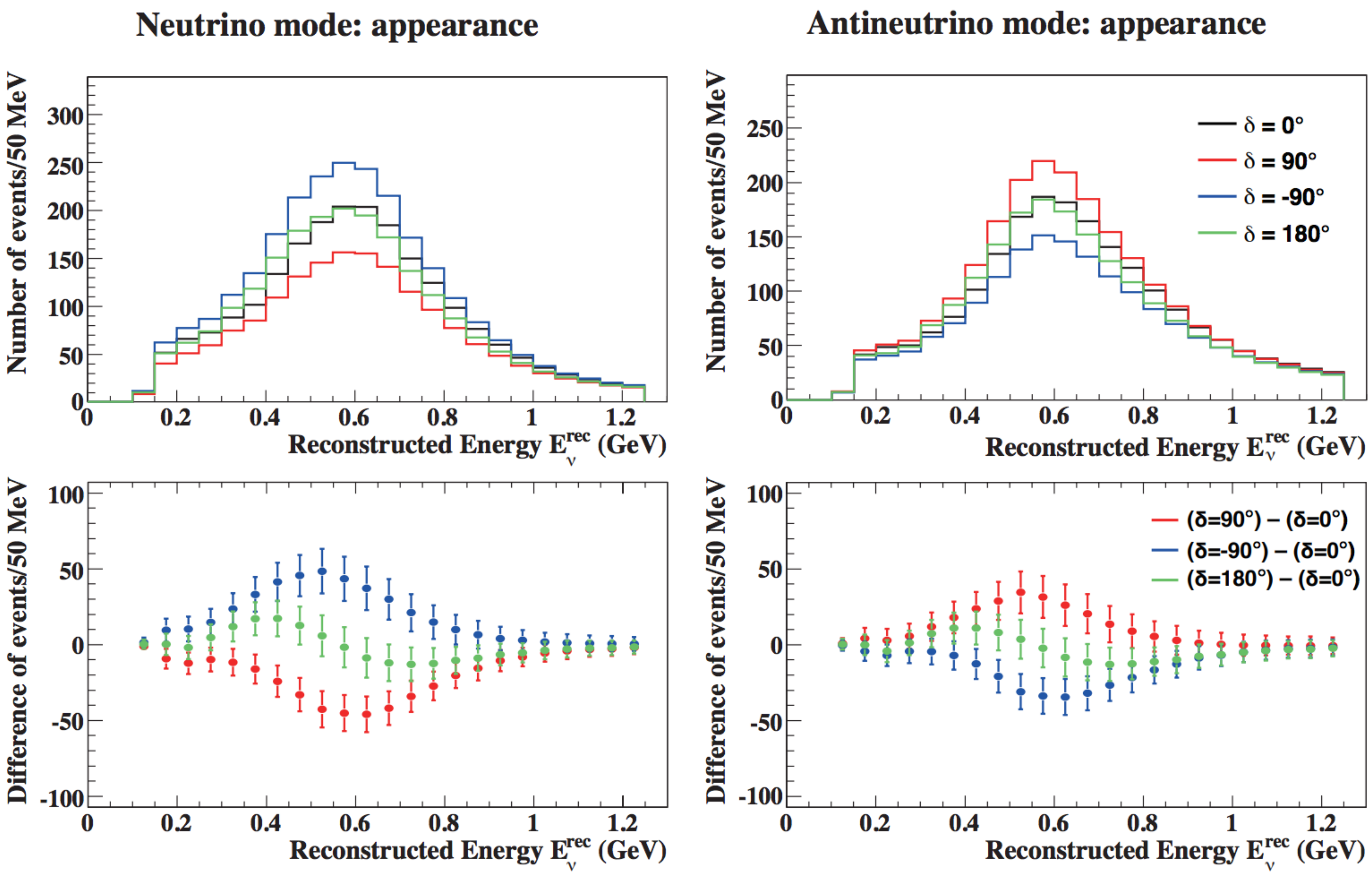
Hyper-K details



- Collaboration is growing 15 countries, 73 institutes, ~300 members
- Far Detector is similar in design to Super-K but much larger
  - Hyper-K: 60 m x 74 m volume 260 kton, per module
  - Super-K: 41 m x 39 m volume 50 kton
- Beam upgraded to 1.3MW
- Main goals:
  - Search for CP violation
  - Proton decay and Neutrino astrophysics



Hyper-K Electron-Neutrino appearance



L is much shorter, effect of matter effects much reduced

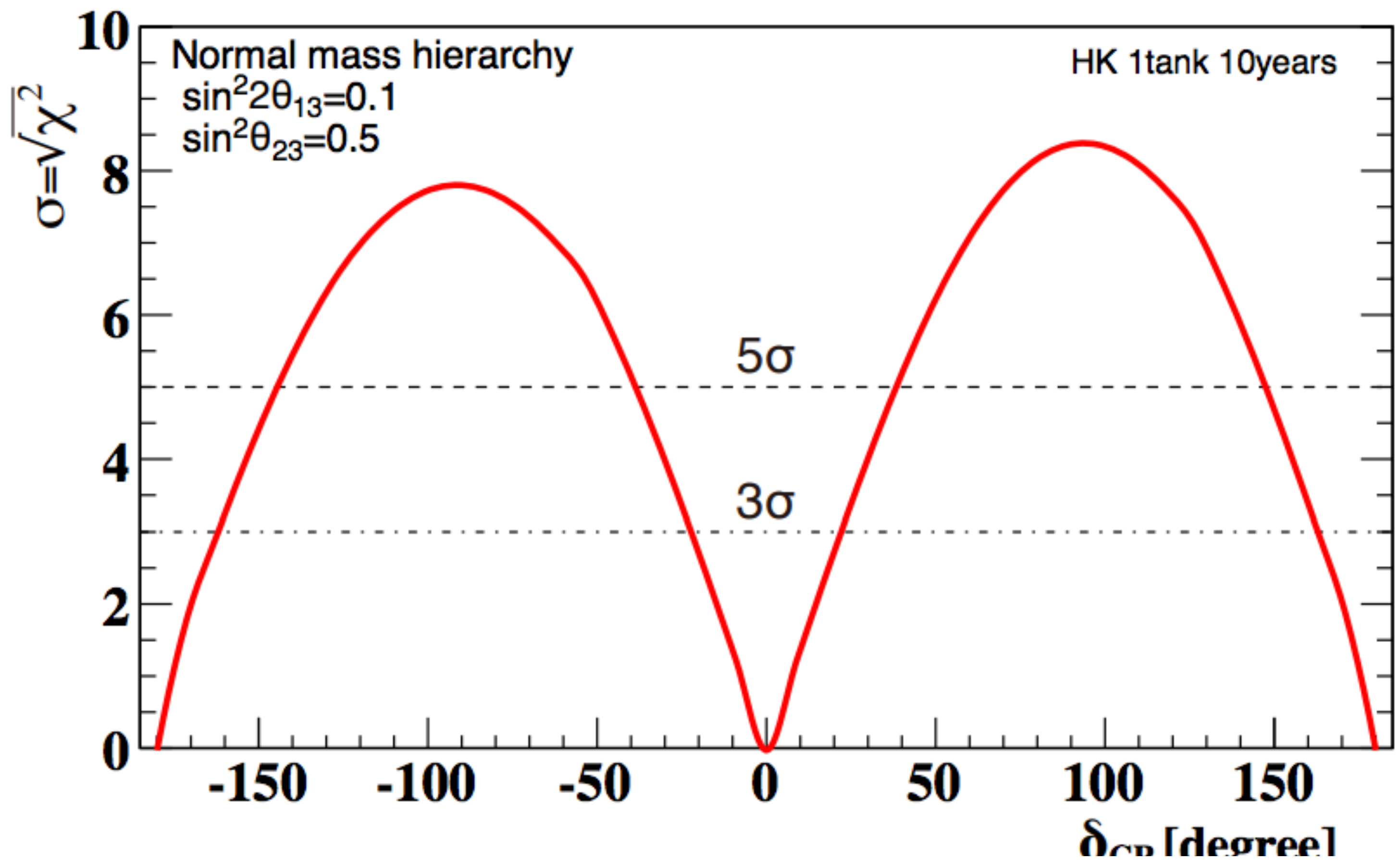
δ = 0 deg	Appearance signal	Wrong sign	Beam ν_e background	NC background
ν mode	1643	15	259	134
anti-ν mode	1183	206	317	196

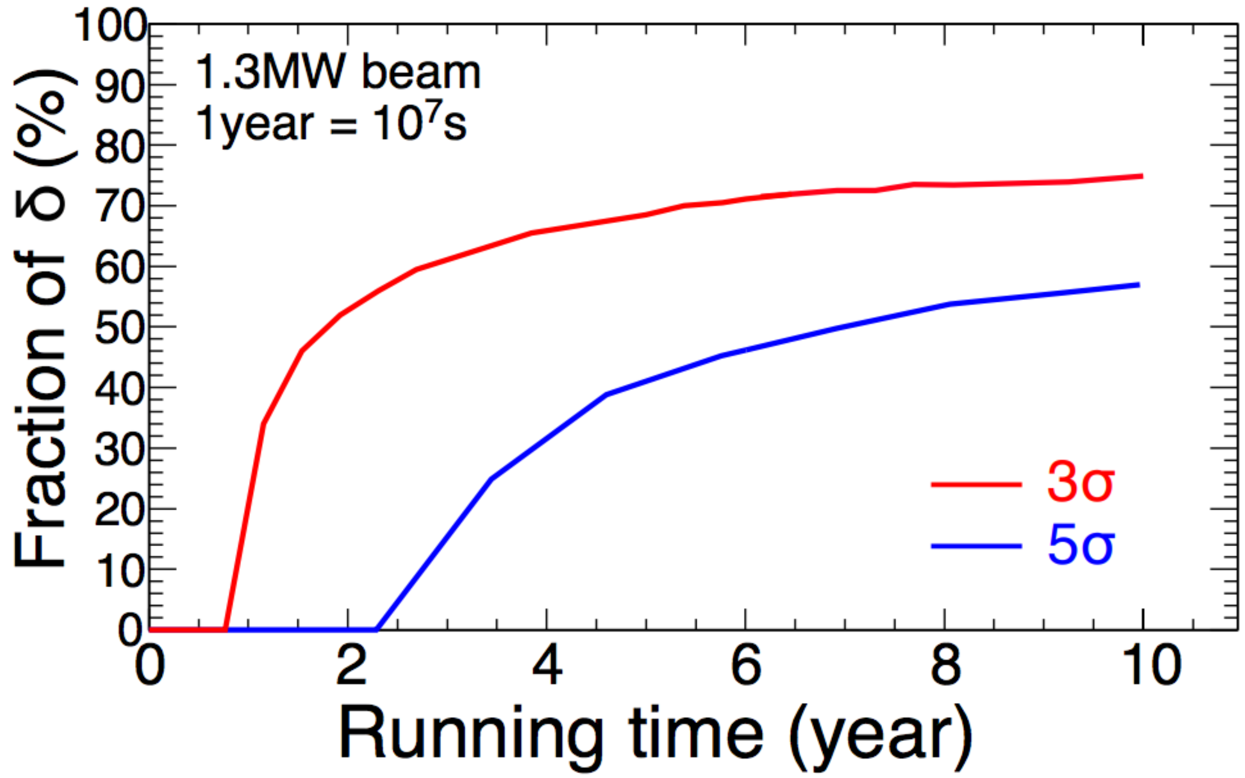
Numbers assuming:
1 Hyper-K tank, 1.3 MW beam and 1:3 ratio anti-nu of beam.
10×10^7 sec, $\sin^2 2\theta_{13} = 0.1$, $\delta = 0$

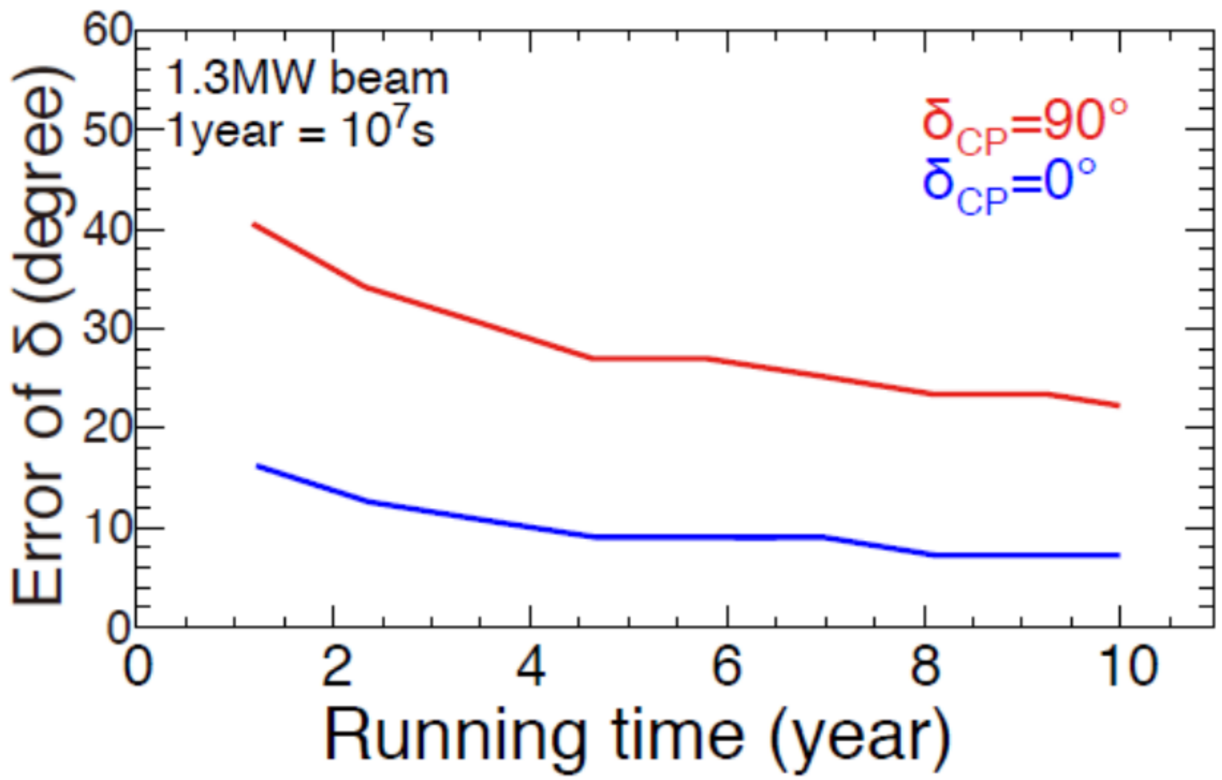
systematic uncertainties 3-4 %

Exclusion of δ = 0 at 8σ (for δ = -π/2)

5σ (3σ) significance for 57(80)% of possible delta values







Sensitivity comparisons from Hyper-K

Hyper-K

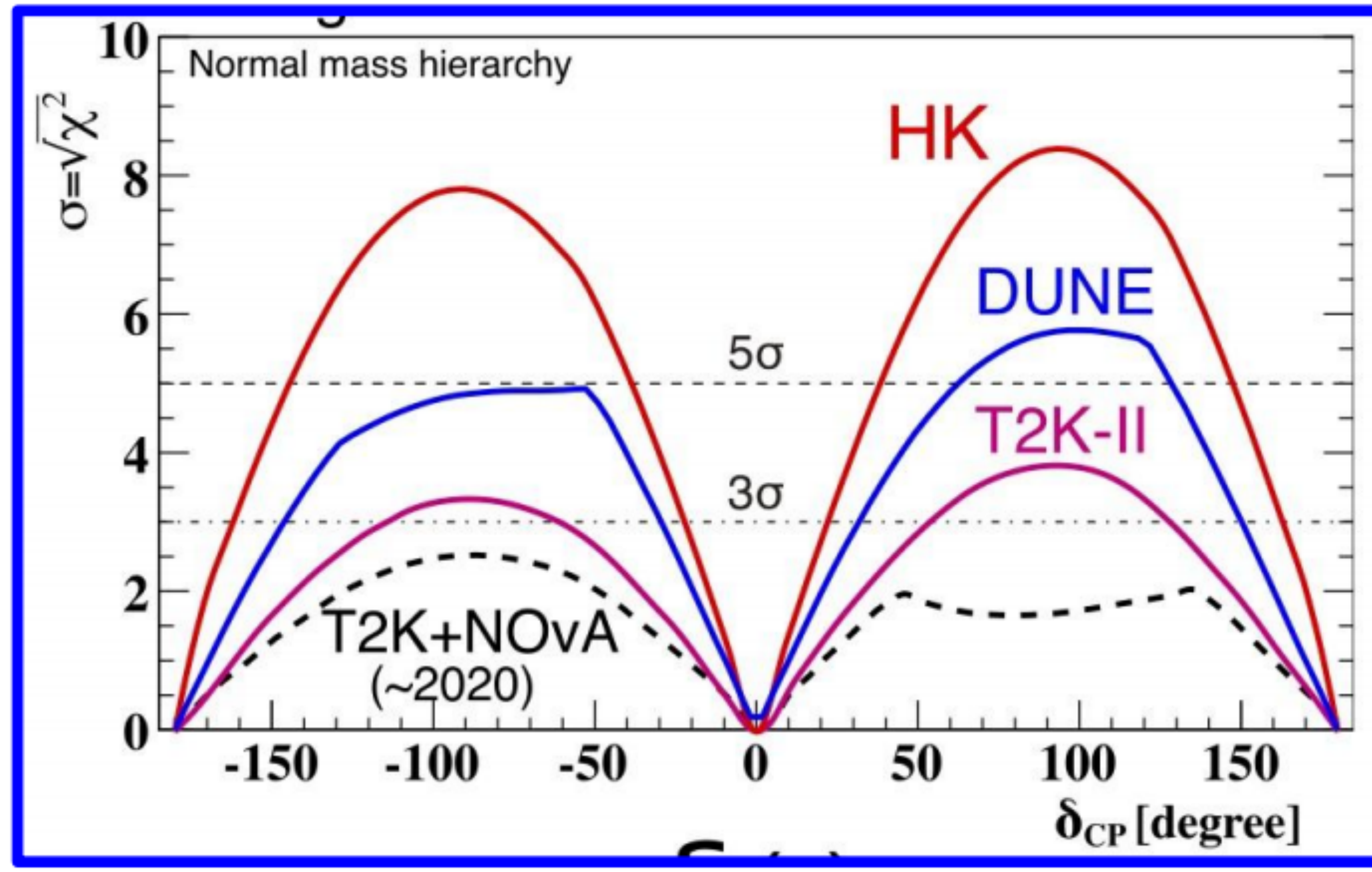
- Single tank
- Normal hierarchy
- Systematics 3-4%
- ratio neutrino/anti 1:3
- CPV (δ = -90 deg, 5σ)
- 1.3MW x 4 years

DUNE

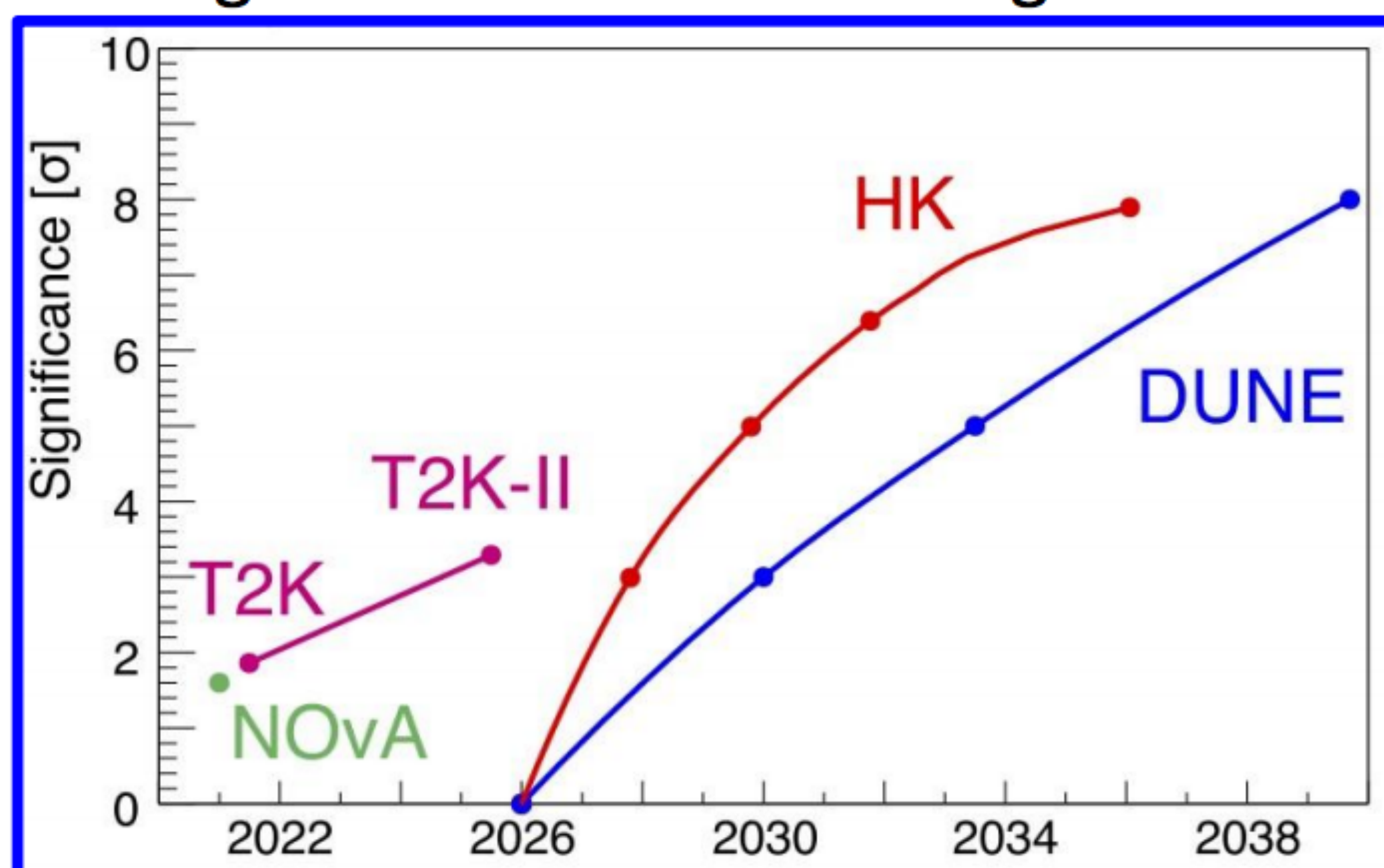
- Staging plan
- Normal hierarchy
- CPV (δ = -90 deg, 5σ)
- 253 kt MW year
- 6.5 years

Combination T2K-II and NOvA can reach 4.5σ for δ= -90 deg by 2026

Significance for δ = 0 exclusion



Significance for δ = -90 deg



Hyper-Kamiokande Experiment to Begin Construction in April 2020

19 September 2018 - Kavli Institute for the Physics and Mathematics of the Universe

Last week at the 7th Hyper-Kamiokande proto-collaboration meeting, a statement was issued by the University of Tokyo recognizing the significant scientific discoveries which the planned Hyper-Kamiokande experiment would enable.

It states that, based on these exciting prospects, the University of Tokyo will ensure that construction of the experiment will begin in 2020. Hyper-Kamiokande now moves from planning to a real experiment.

The Hyper-Kamiokande proto-collaboration welcomes this exciting endorsement of the project and the boost it will give to increasing even further the international contributions and participation in the experiment. Introducing the statement, Professor Takaaki Kajita, Director of the Institute for Cosmic Ray Research at the University of Tokyo and 2015 Nobel Laureate in Physics, pointed out that the Japanese funding agency MEXT has included seed funding for Hyper-Kamiokande in its JFY 2019 budget request. He illustrated with many examples that it is standard in Japan for large projects to begin with a year of seed funding, and said that in any case the University of Tokyo commitment meant that Hyper-Kamiokande construction will begin in April 2020.

The Hyper-Kamiokande Proto-Collaboration will now work to finalize designs, and is very open to more international partners to join in this far-reaching new experiment.

Conclusions

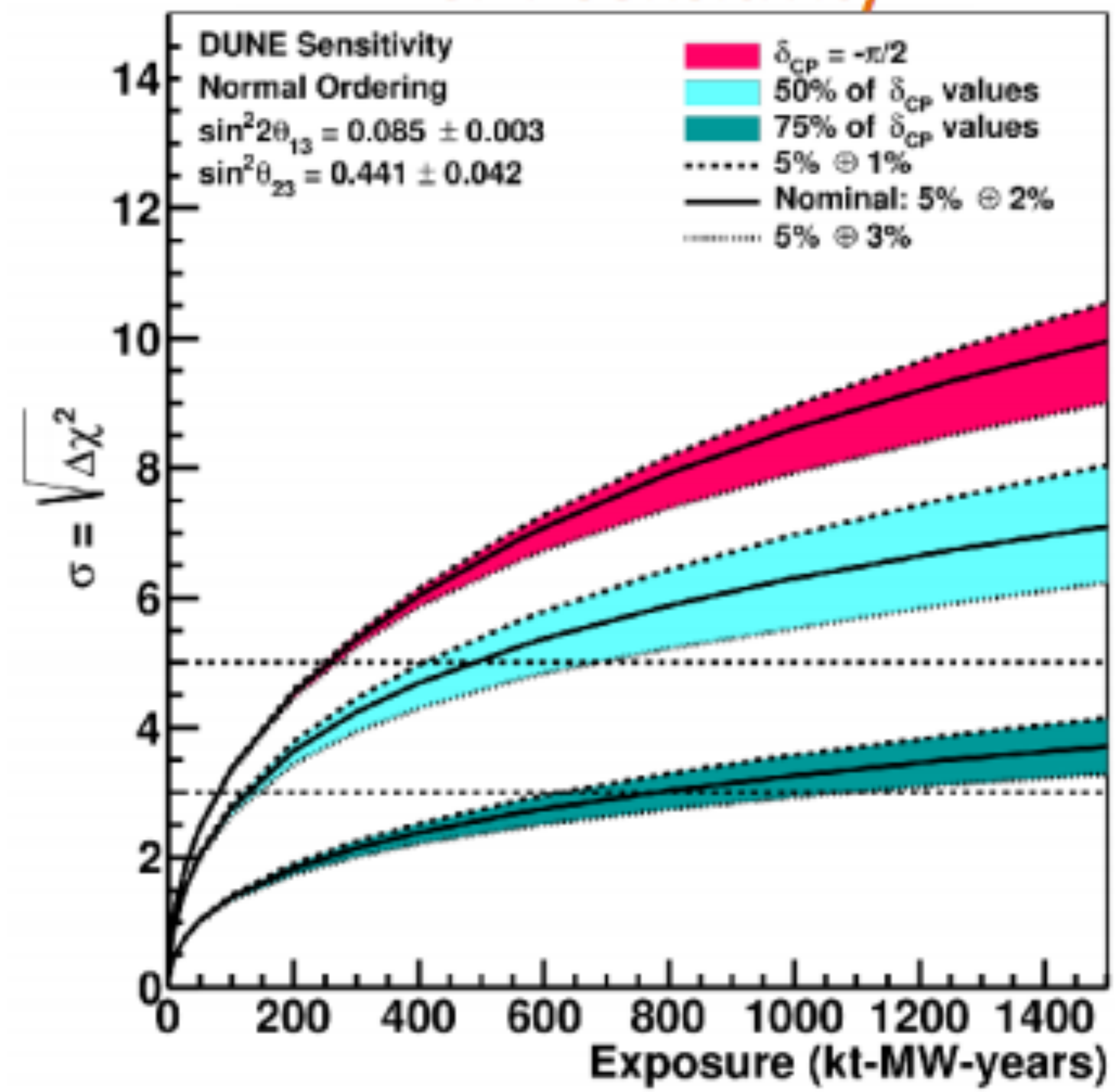
- On-going experiments
  - NOvA and T2K both showed new results this summer
  - Both experiments continue to show conserving values outside of 2σ region for both hierarchies
  - Slight preference for normal heiarchy
  - NOvA showed its first anti-neutrino results summer 2018, with 4 sigma evidence for electron-anti neutrino appearance

- Looking forward
  - DUNE: First of four detectors online in 2024 and beam in 2026
  - Hyper-K initial approval for construction in 2020 and operations to being in 2026

Thanks for all the people I took slides from, including Mayly Sanchez, Yury Kudenko, Morgan Wascko and others

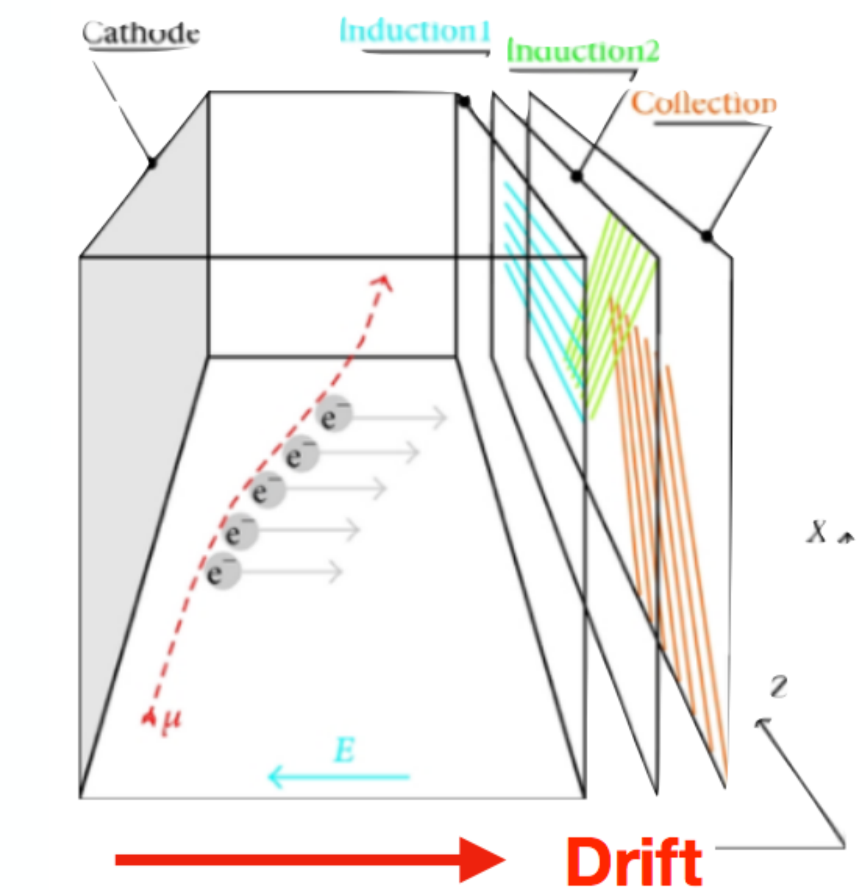
Dune systematics

CPV sensitivity



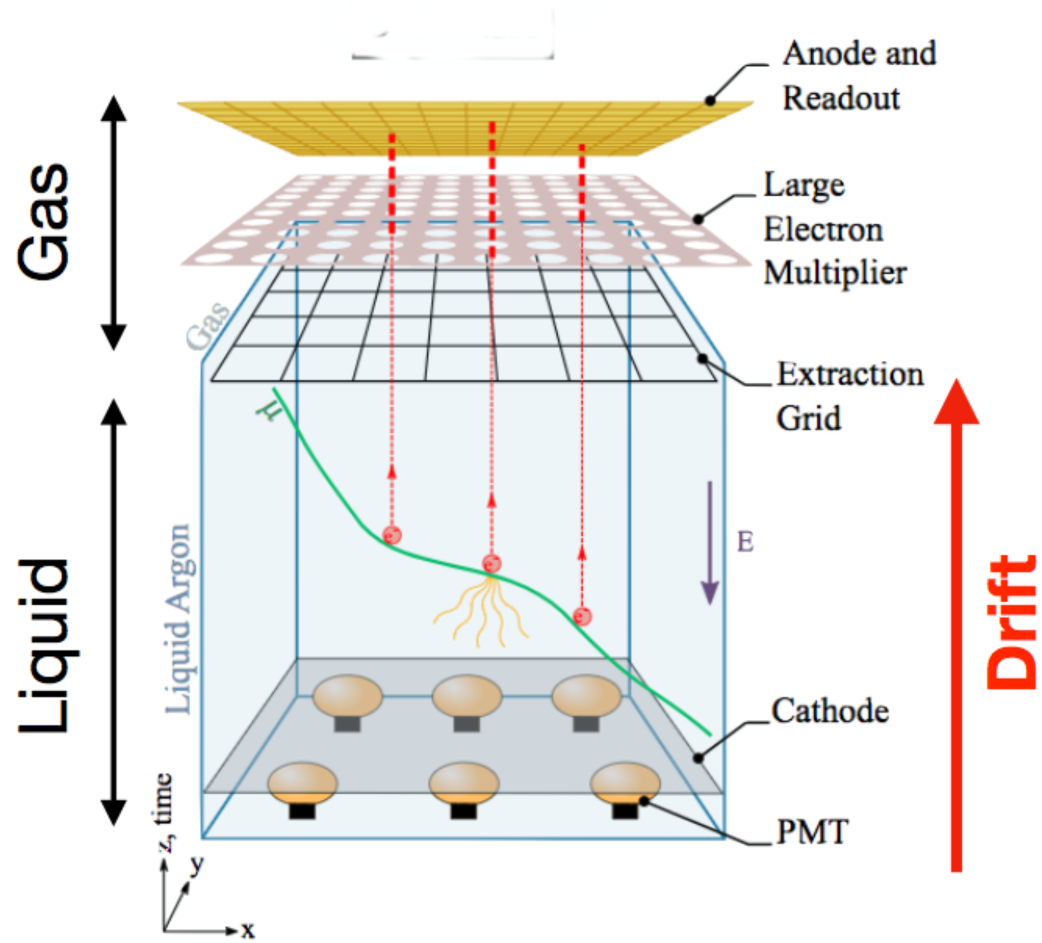
Single phase (SP)

- Only liquid Ar
- Horizontal drift
- No amplification
- 2 Induction and 1 collection plane

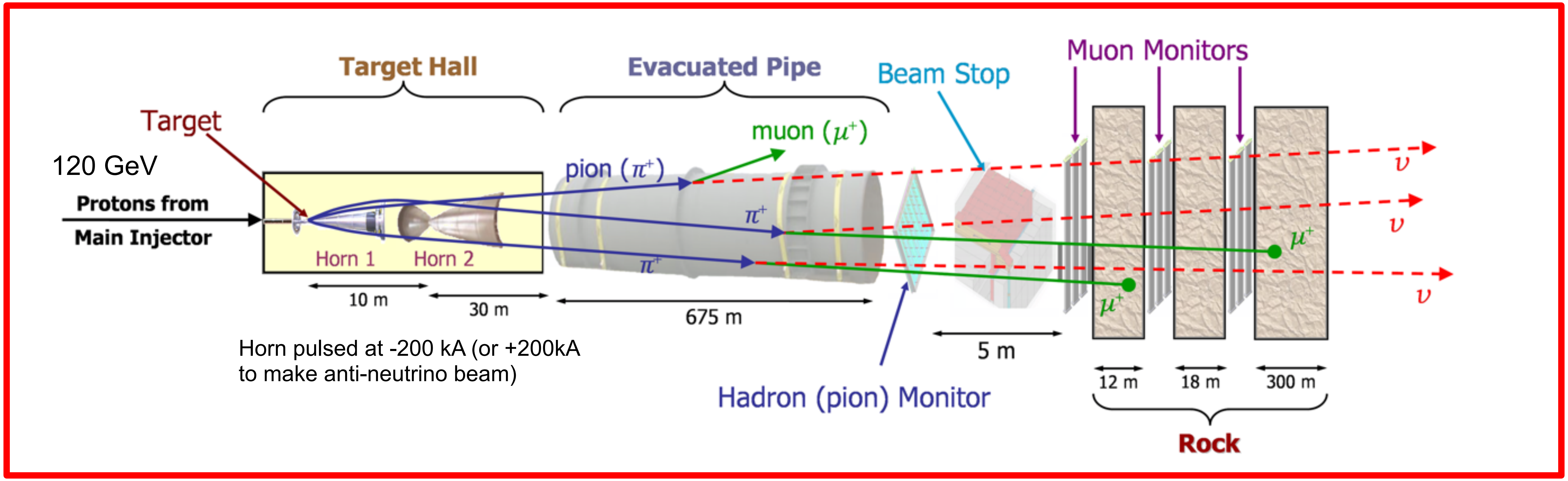


Dual phase (DP)

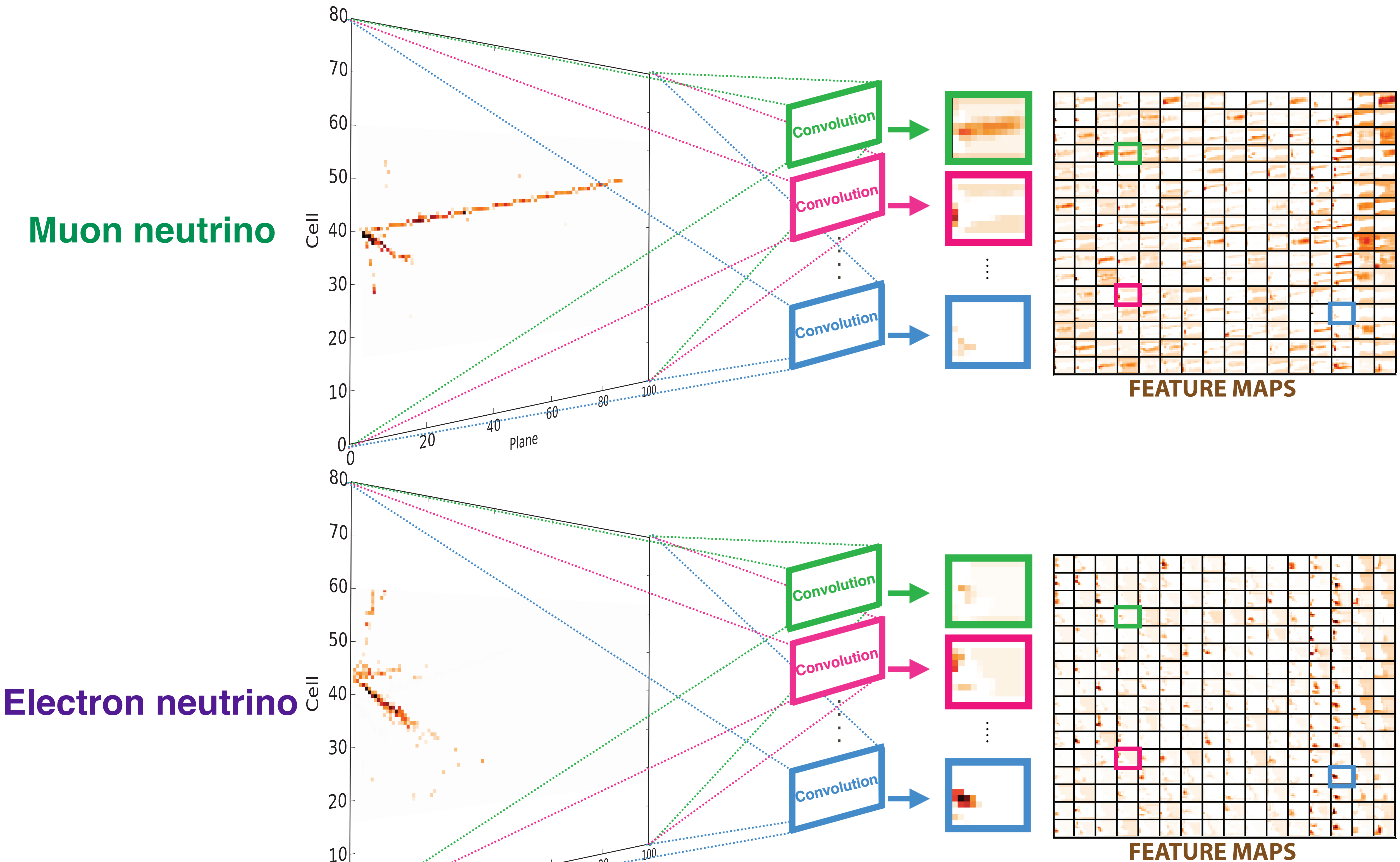
- Liquid and Gas Argon
- Vertical drift
- Amplification in gas
- 2 collection views



Courtesy of L. Zambelli: http://vietnam.in2p3.fr/2017/neutrinos/transparencies/5_friday/2_afternoon/4_zambelli.pdf


Target Hall
Evacuated Pipe
Beam Stop
Muon Monitors
Target
120 GeV
Protons from
Main Injector
muon (μ^+)
pion (π^+)
π^+
π^+
Horn 1
Horn 2
ν
ν
ν
μ^+
μ^+
10 m
30 m
675 m
5 m
12 m
18 m
300 m
Horn pulsed at -200 kA (or +200kA
to make anti-neutrino beam)
Hadron (pion) Monitor
Rock

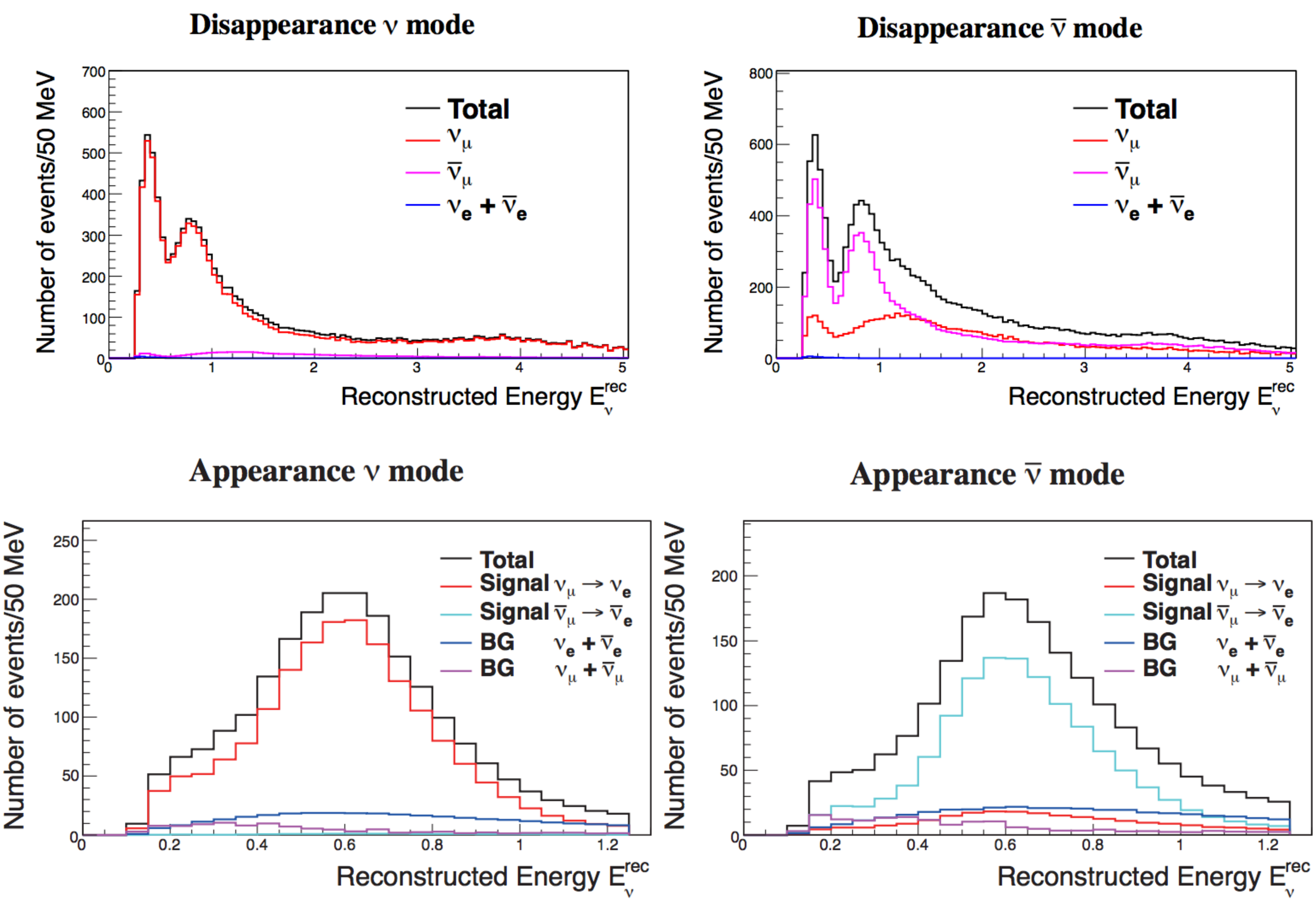
Current version classifies, events in NC, ν_μ CC, ν_e CC, ν_t CC and cosmic



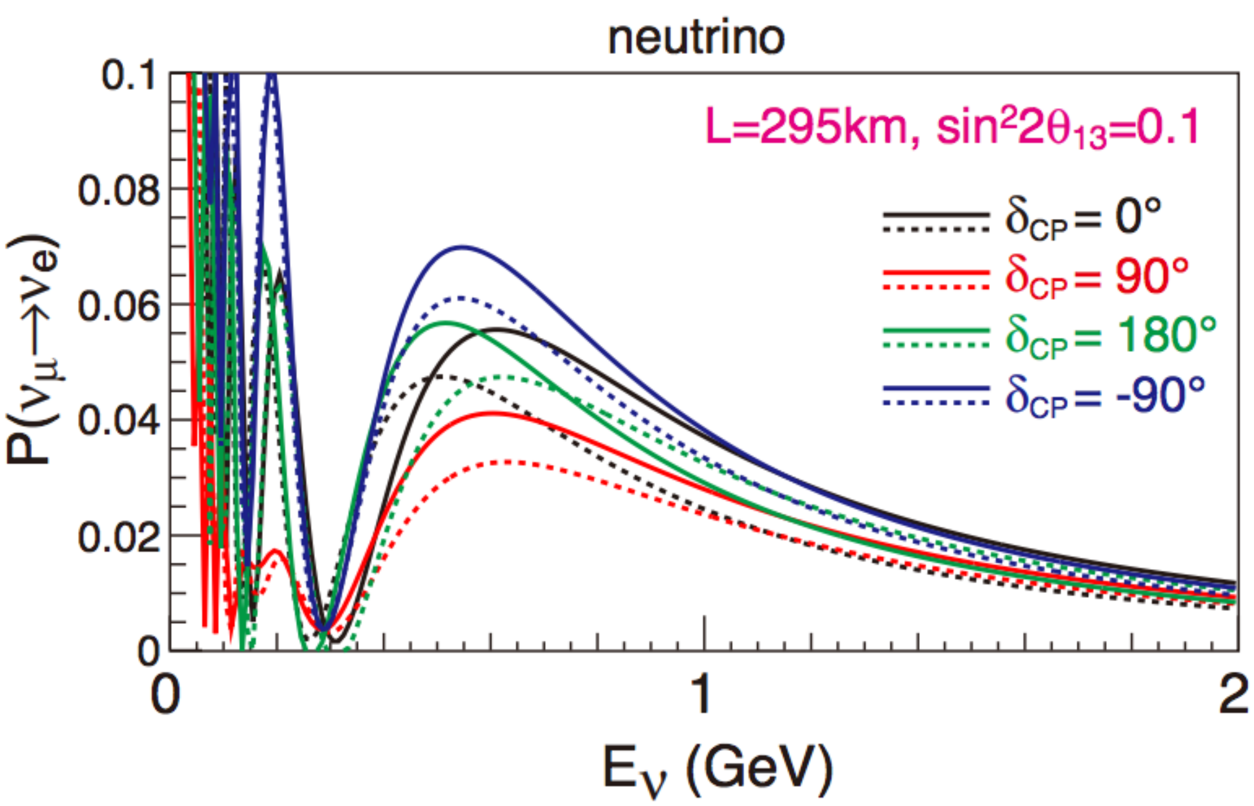
Input is calibrated hit maps, after clustering

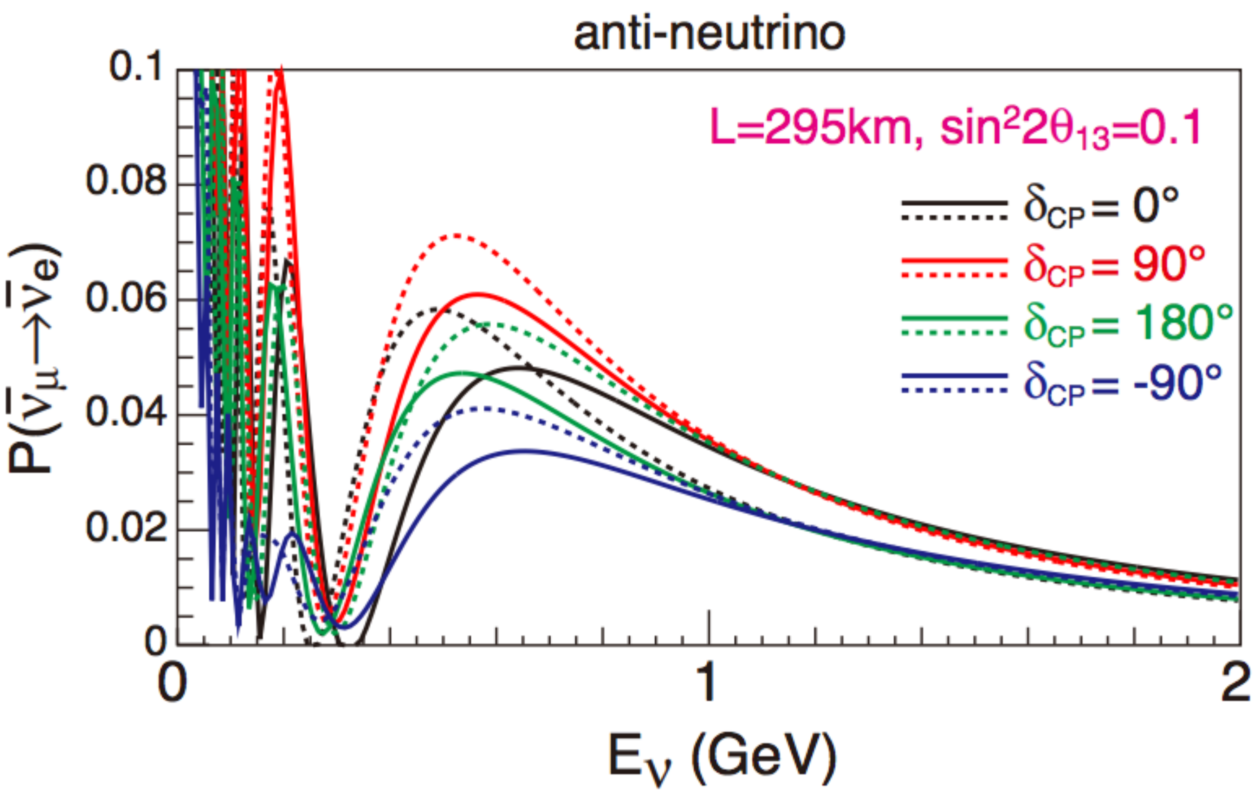
Extracted features used as inputs to neural network

Hyper-K rates



Hyper-K oscillation probabilities

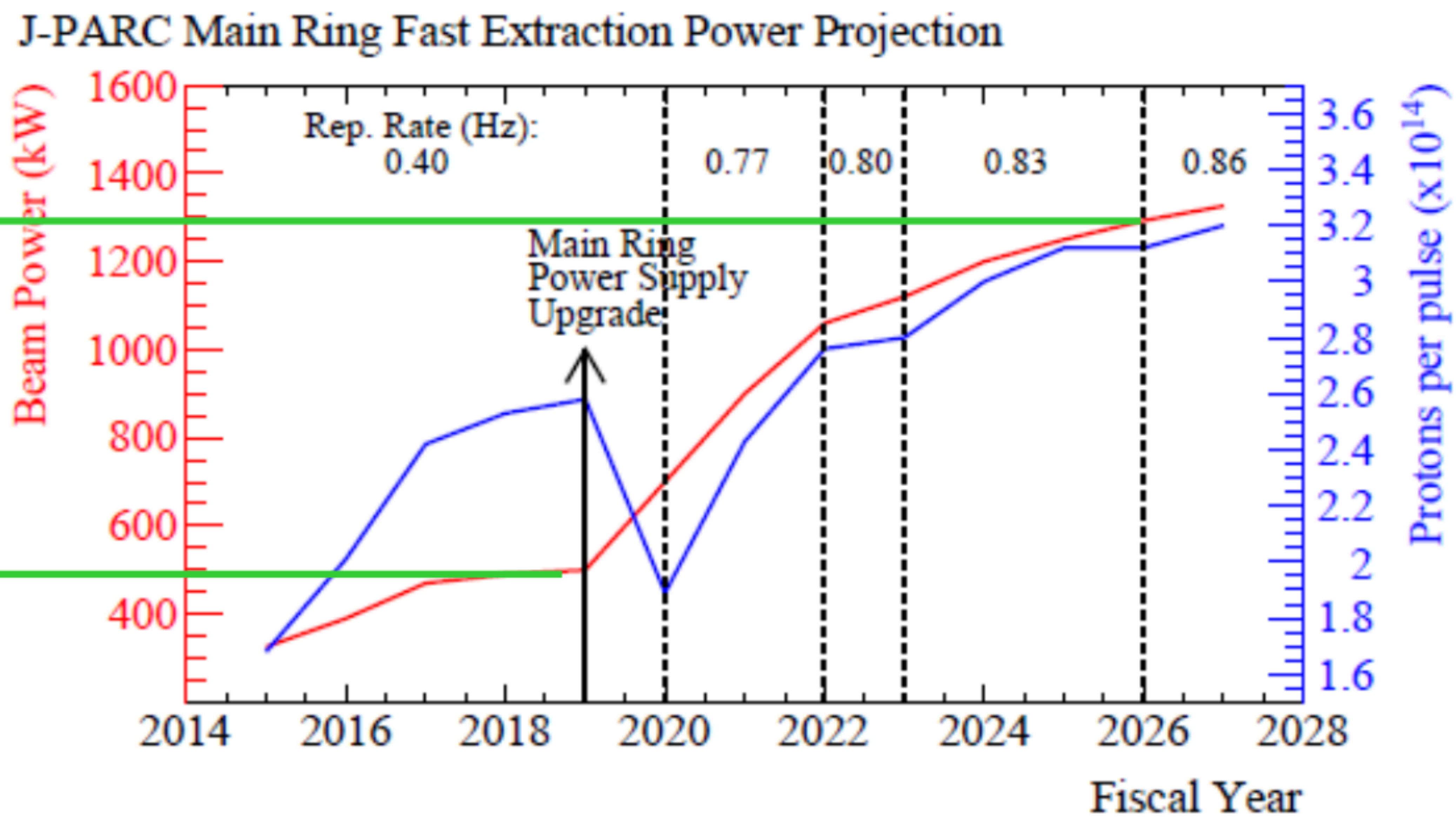




J-Park up grade

1.3MW by Hyper-K

485 kW achieved



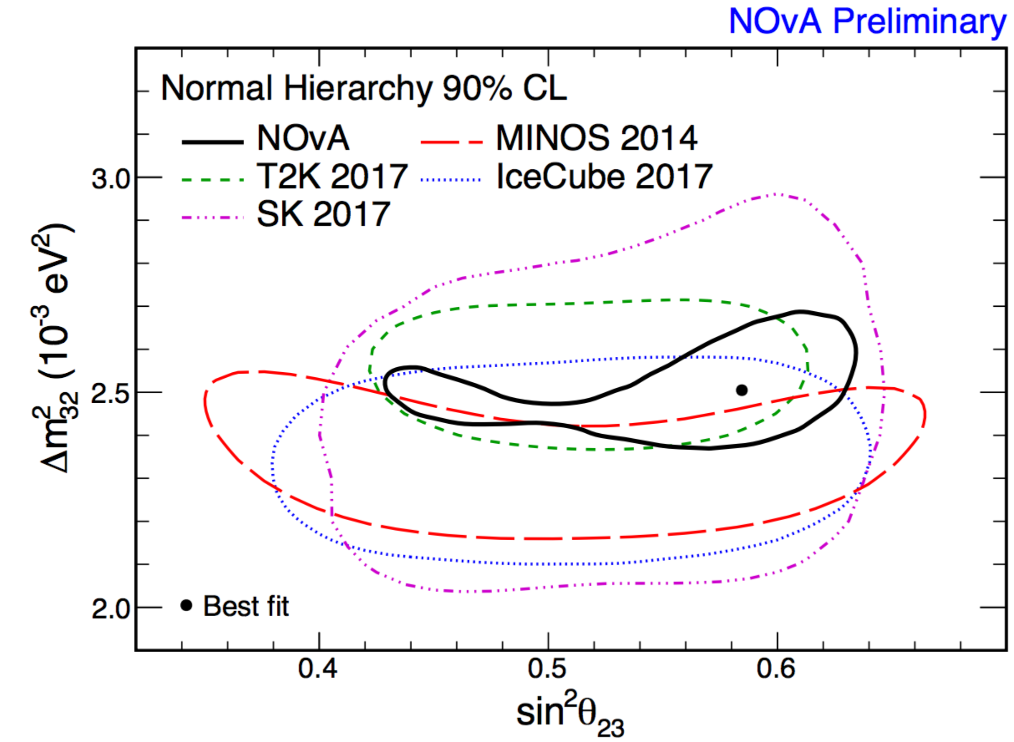
J-PARC 30 GeV main ring

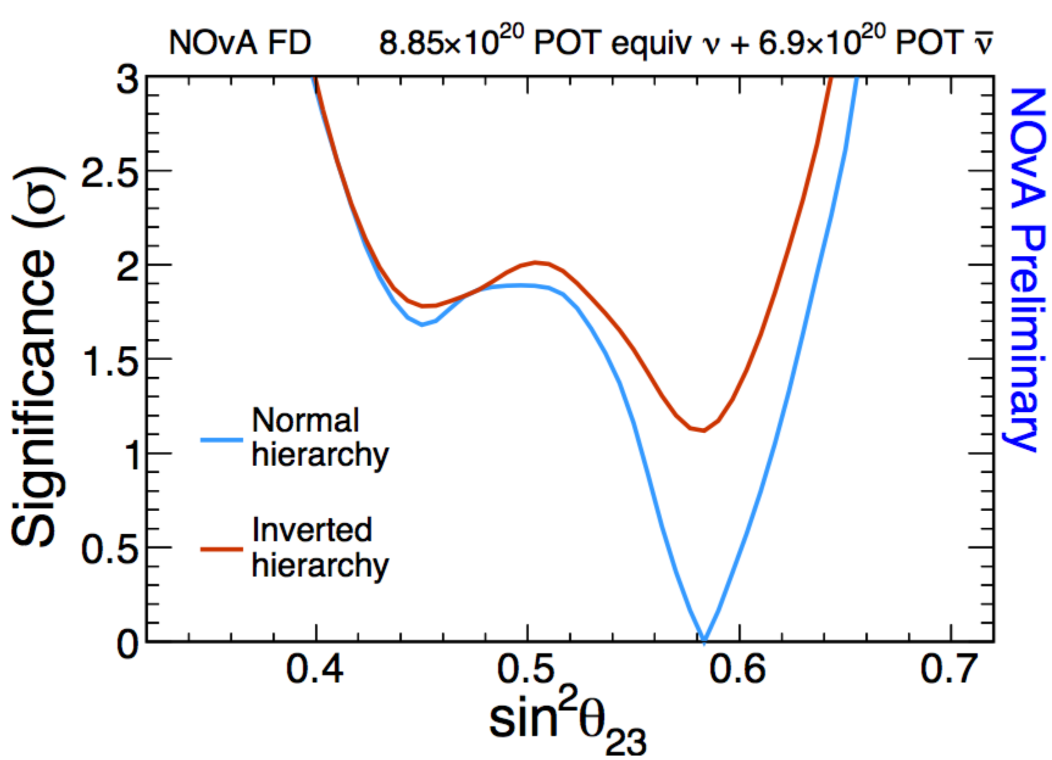
→ 750 kW (cycle 1.3 s) - 2020

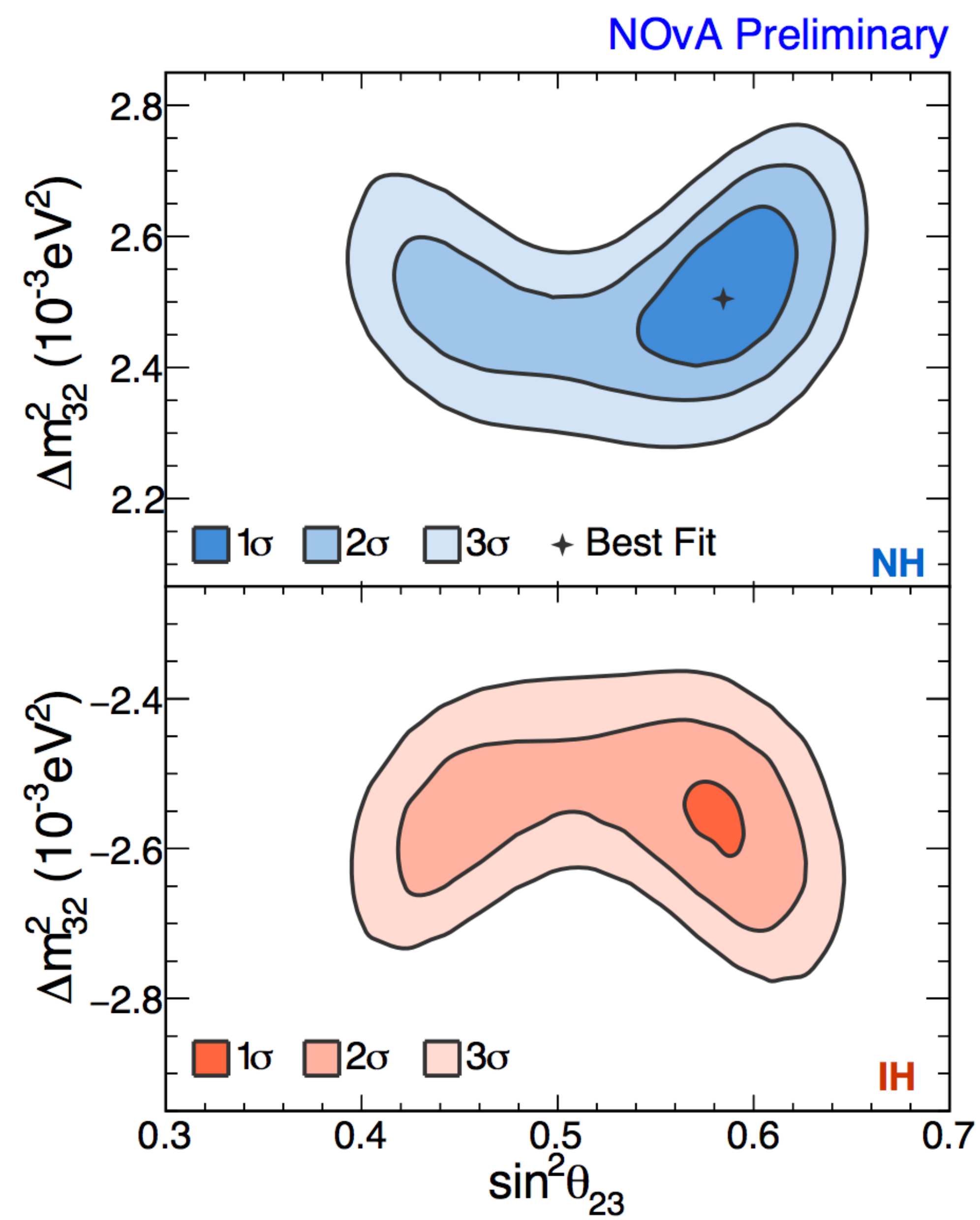
→ 1.3 MW (cycle 1.16 s) - 2026

Narrow-band neutrino beam, peak energy 600 MeV

NOvA Atmospheric mixing angle limits, θ_{23}



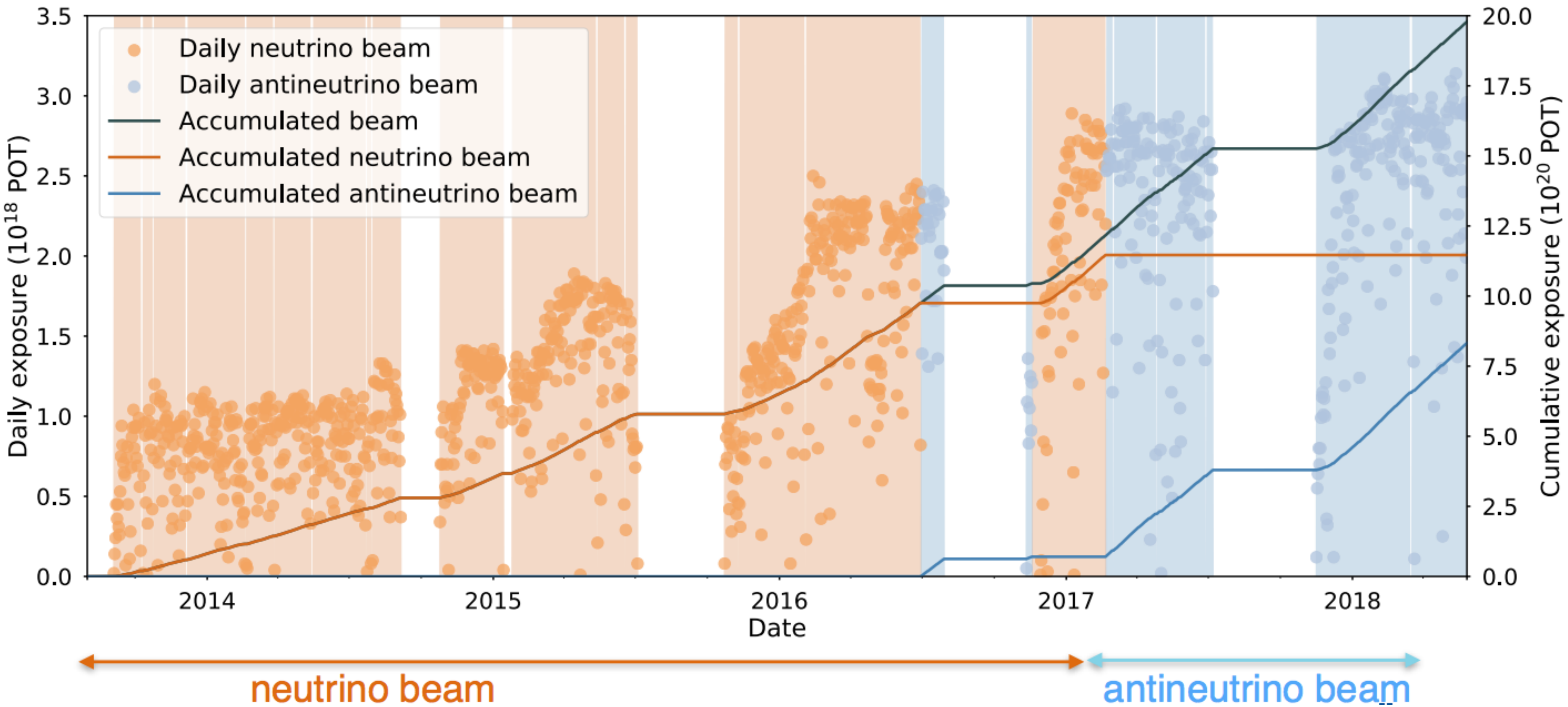




Prefer non-maximal at 1.8σ
and NH at similar level

Best fit:
Normal Hierarchy
$\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}$ eV^2

- Running at 700 kW design power since January 2017, the highest power beam in the world
- Analysis of 8.85x1020 protons-on-target in neutrino beam configuration
- First 6.9x1020 POT of antineutrino beam recorded February 2017 to April 2018



Total Observed	58	Range
Total Prediction	59.0	30-75
Wrong-sign	0.7	0.3-1.0
Beam Bkgd.	11.1	
Cosmic Bkgd.	3.3	
Total Bkgd.	15.1	14.7-15.4

Total Observed	18	Range
Total Prediction	15.9	10-22
Wrong-sign	1.1	0.5-1.5
Beam Bkgd.	3.5	
Cosmic Bkgd.	0.7	
Total Bkgd.	5.3	4.7-5.7