CURRENT & FUTURE NEUTRINO OSCILLATION EXPERIMENTS

Elizabeth Worcester(BNL)

NPC Neutrino Summer Lecture Series

August 25, 2016

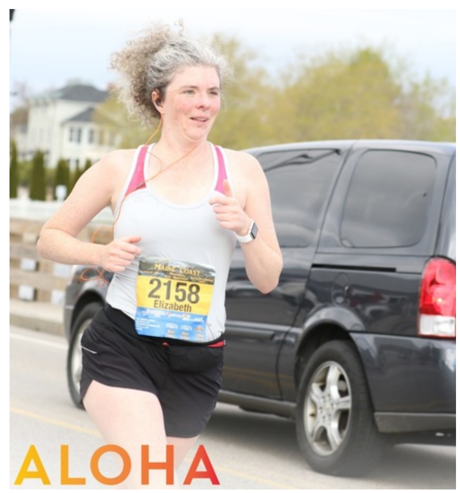
Overview

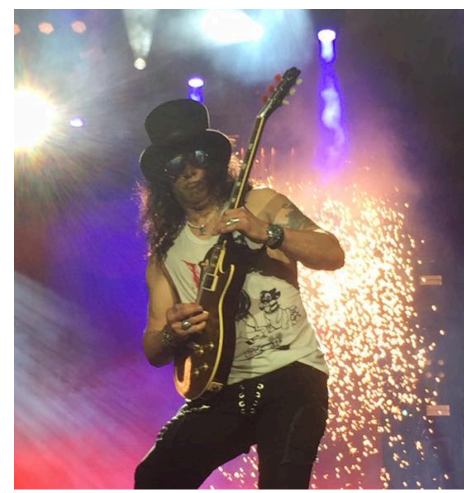
- Introduction to the speaker
- Introduction to neutrino oscillation
- Current global fit
- Short-baseline reactor experiments
- Atmospheric neutrino experiments
- Short-baseline accelerator experiments
- Long-baseline accelerator experiments

Note: Many borrowed slides – thanks to all for their nice presentations which were invaluable in preparing this lecture!

Intro to the speaker

- BS Physics: Georgia Tech 1997
- MS Physics: UCLA 1998
- PhD Physics: U. of Chicago 2007
  - CP/CPT in KTeV
- Stay-at-home mom: 2007-2010
- BNL postdoc: 2011-2013
  - Daya Bay, LBNE, WbLS R&D
- BNL scientist: 2013-present
  - SBN, DUNE
- Primary physics activities:
  - Cold electronics development for LArTPCs (SBND, protoDUNE)
  - Simulation/reconstruction/analysis for LArTPCs (SBND, protoDUNE)
  - Long-baseline physics sensitivity for LBNF/DUNE
- Non-physics interests: marathon running, Slash





Discovery of Neutrino Oscillation

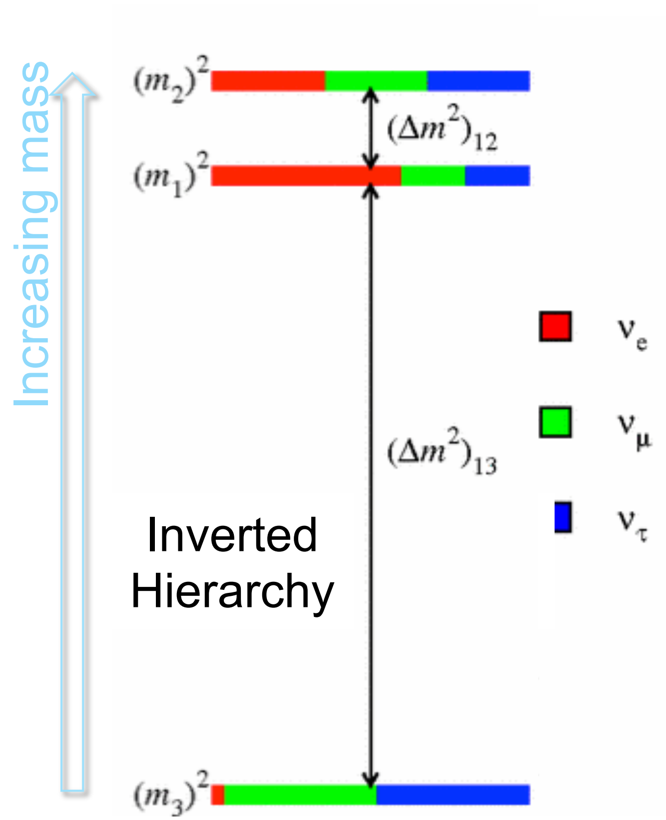
- Ray Davis experiment at Homestake Mine (1960s-1980s)
  - Detect solar neutrinos using capture on chlorine: $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^+$
    - Sensitive only to ν_e
  - Observed ~1/3 of ν_e rate expected from calculation of solar neutrino flux (Bahcall)
- Observation of neutrino oscillation at SNO and SuperK
  - SNO observed oscillation of solar ν_e to ν_μ and ν_τ
  - SK observed oscillation of atmospheric ν_μ to ν_τ
  - Nobel Prize in 2015!

Neutrino Oscillation

- $|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$
- Flavor composition of neutrinos change as they propagate
- Two-neutrino case:

$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \sin^2\left(\Delta m^2 \frac{L}{4E}\right)$$

Amplitude depends on θ.
Oscillation frequency depends on Δm^2, baseline, and energy.



Mass hierarchy (sign Δm^2_{21}) is unknown!

3-Neutrino Model: PMNS Matrix

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle \Rightarrow U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

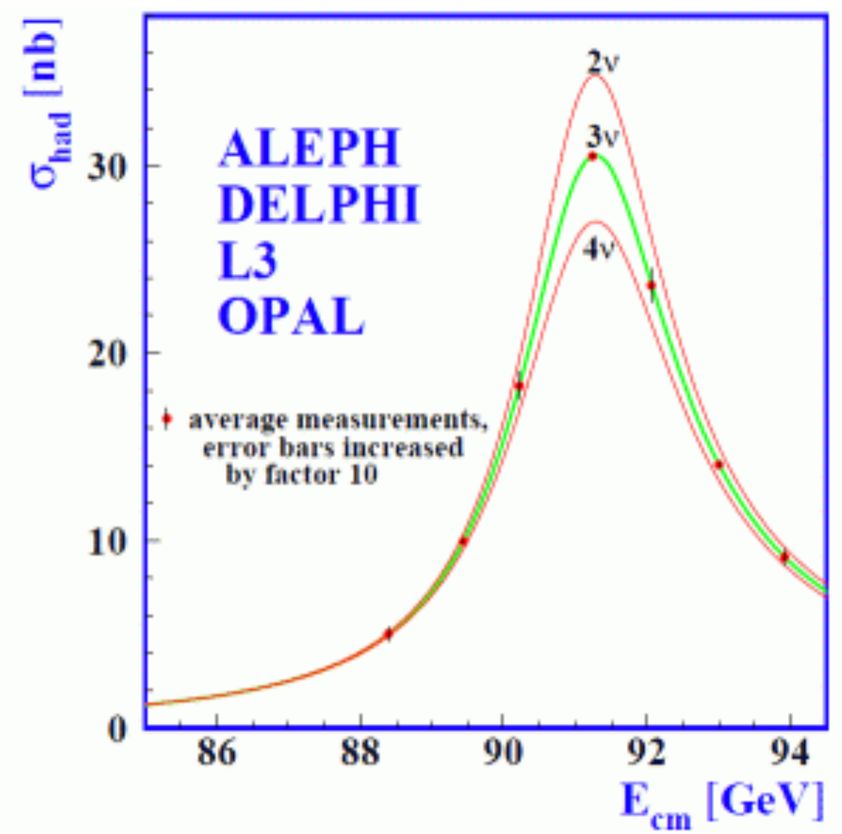
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- $\theta_{23} \approx 45°$
- Atmospheric, Accelerator
- Octant unknown

- $\theta_{13} \approx 10°$
- Short-Baseline Reactor, Accelerator
- δ_{CP} unknown

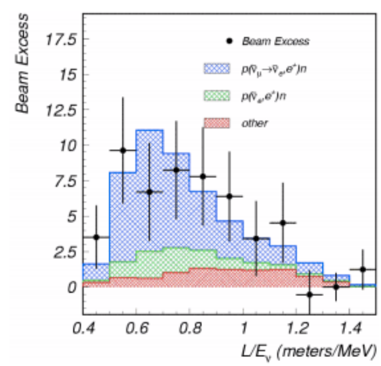
- $\theta_{12} \approx 35°$
- Solar, Long-Baseline Reactor

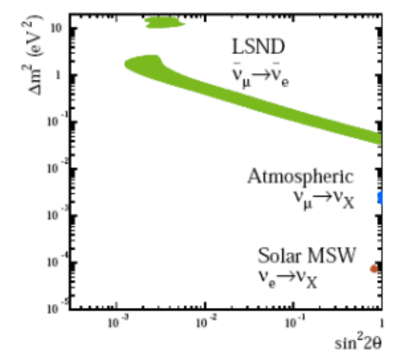
Sterile Neutrino (?)



Z-width measurement at LEP determined the number of active neutrinos

- Sterile ν theoretically well motivated
- Experimental evidence from LSND (1990s)

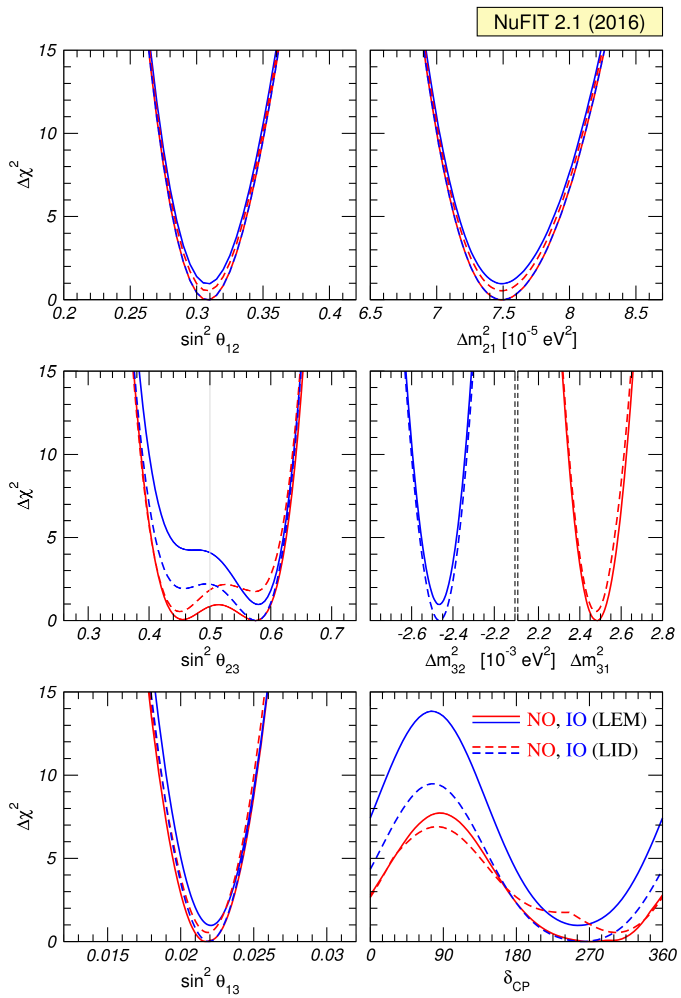




- Significant tension between LSND result and disappearance experiments

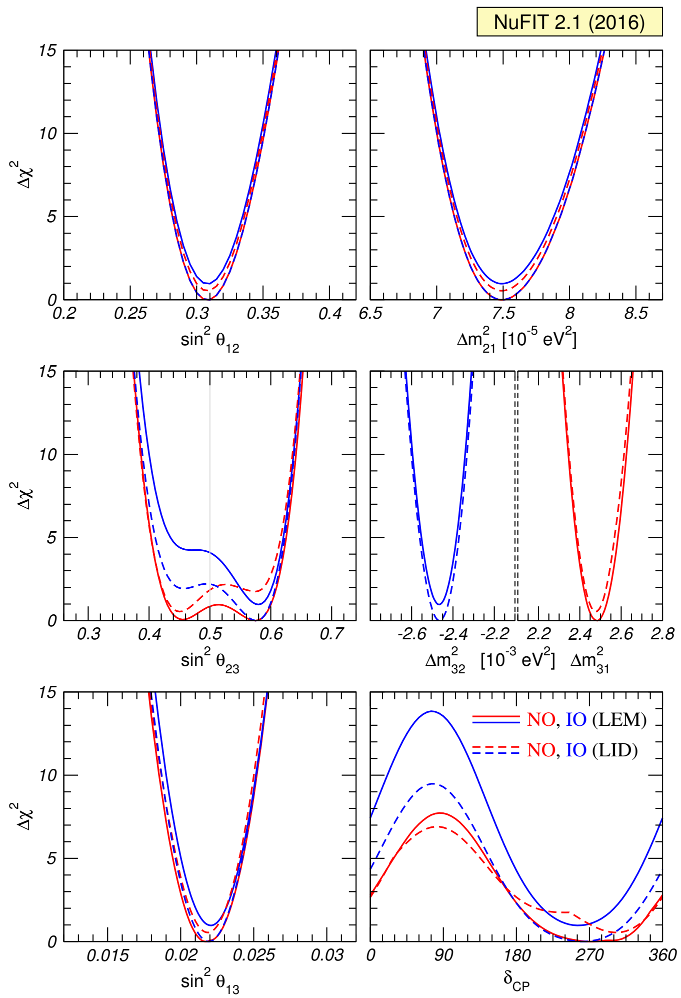
Current (3ν) Global Fit

NuFit: May 2016



- Includes data from:
  - Solar neutrino experiments: Chlorine, Gallex/GNO, SAGE, SK, SNO, Borexino
  - Atmospheric neutrino experiments: SK, ICECUBE
  - Reactor neutrino experiments: KamLAND, CHOOZ, Palo-Verde, Double-Chooz, Daya Bay, RENO
  - Accelerator neutrino experiments: MINOS, T2K, NOvA

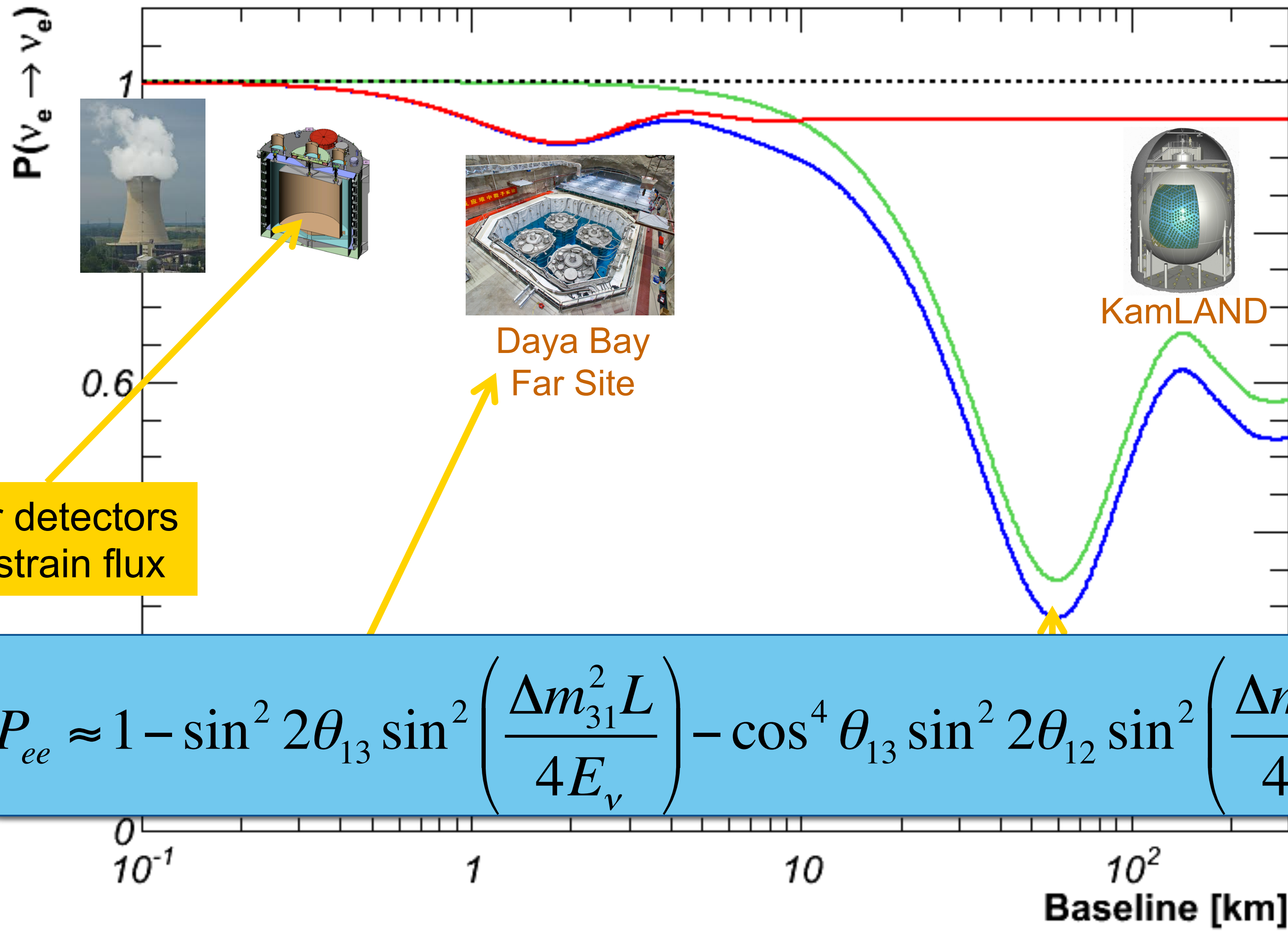
NuFit: May 2016



- Most mixing angles and mass splittings known to ~3%
- Least known mixing angle is θ_{23} (octant unknown)
- No significant preference of neutrino mass ordering
- Some preference for δ_{CP} ~$3\pi/2$ (= $-\pi/2$)

Short-baseline Reactor Experiments

Reactor Antineutrinos



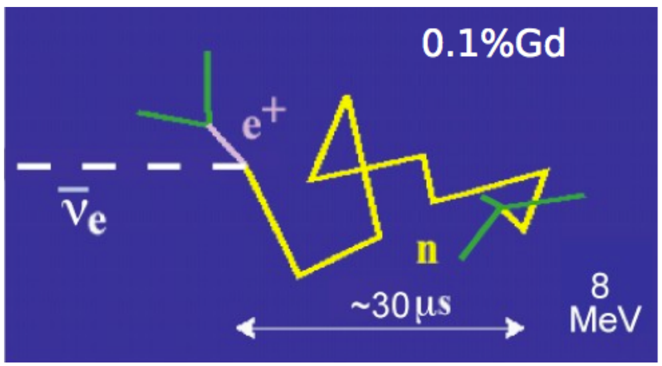
Near detectors constrain flux

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

Detecting Reactor Antineutrinos

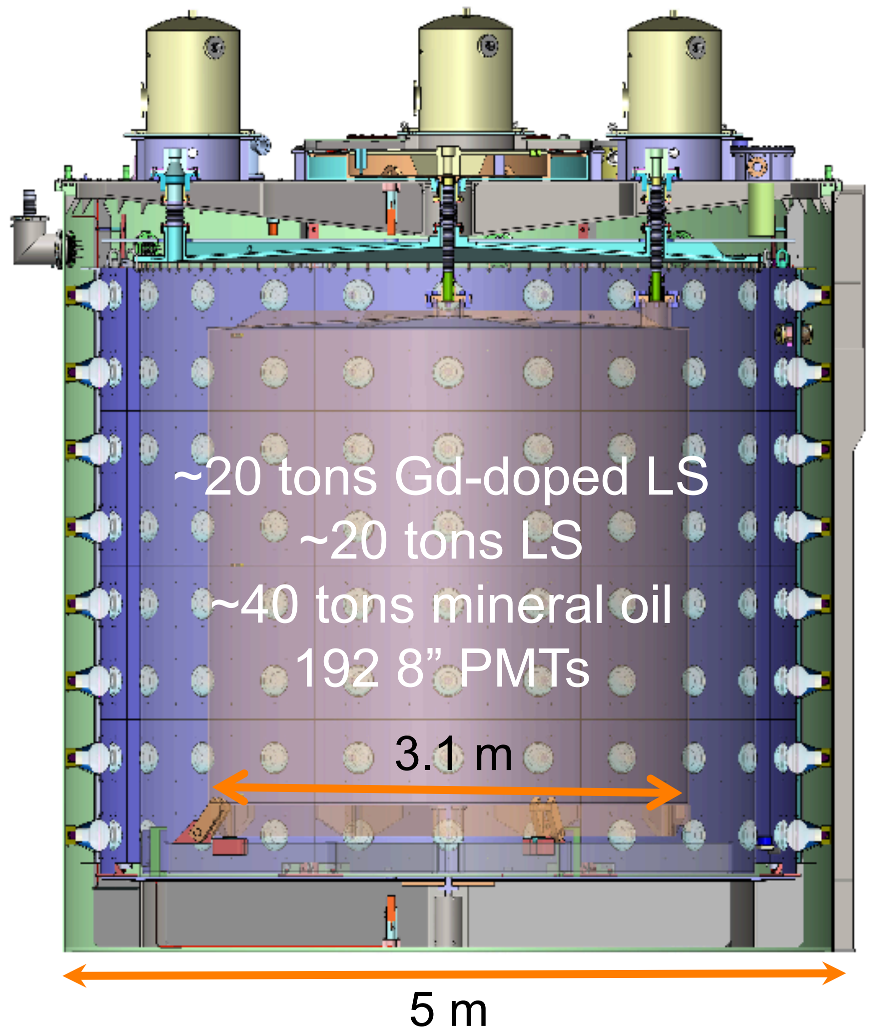
Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$



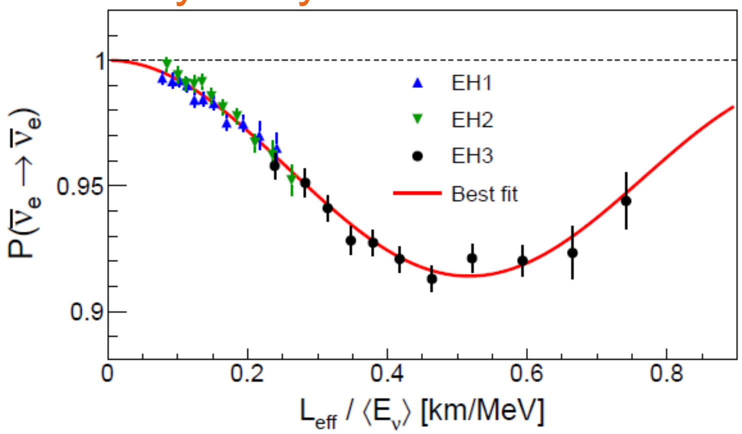
Prompt positron:
Carries antineutrino energy
$E_{e+} \approx E_\nu - 0.8$ MeV
Delayed neutron capture:
Prompt + delayed signature efficiently tags antineutrino signal

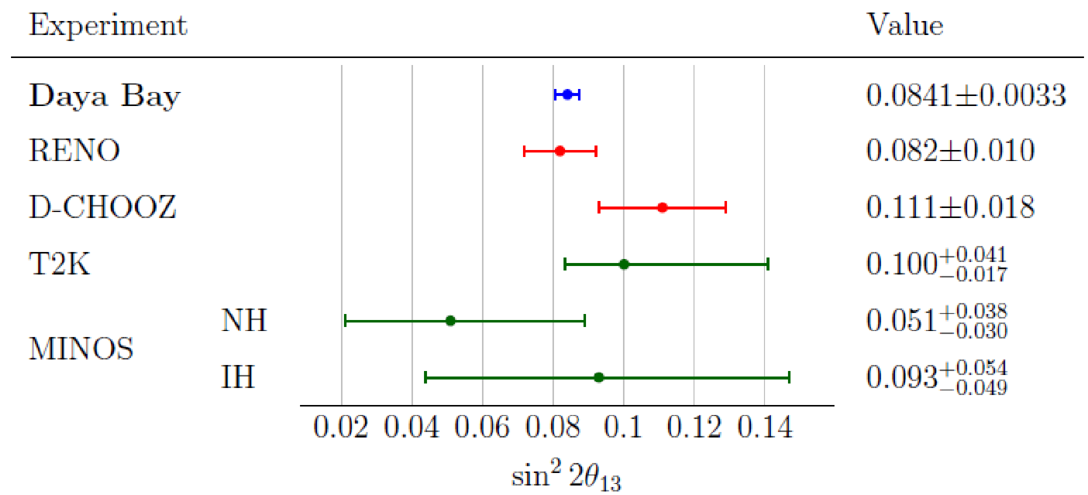
Daya Bay Antineutrino Detector:

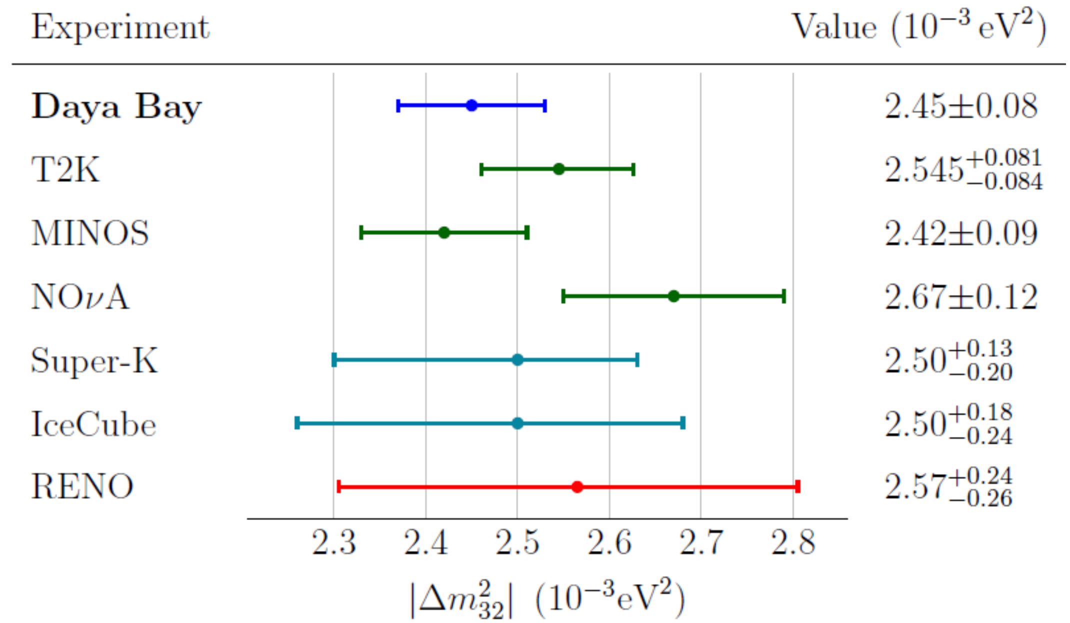


Reactor Results: Oscillation Parameters

Daya Bay:



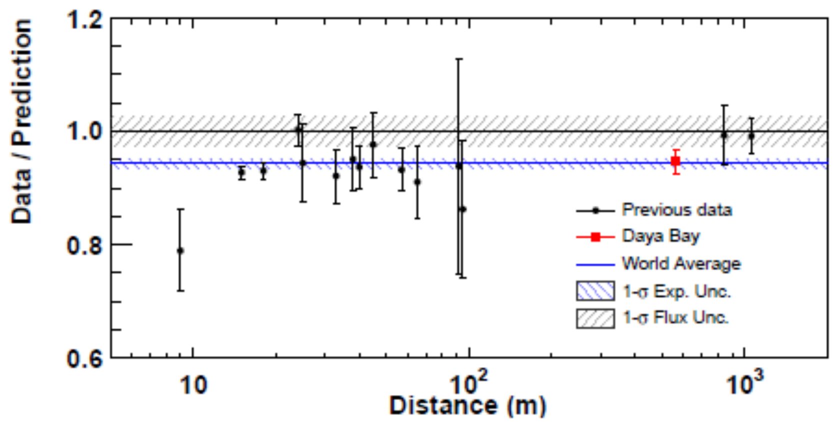




Precise measurements of $\sin^2 2\theta_{13}$ and Δm^2_{32}

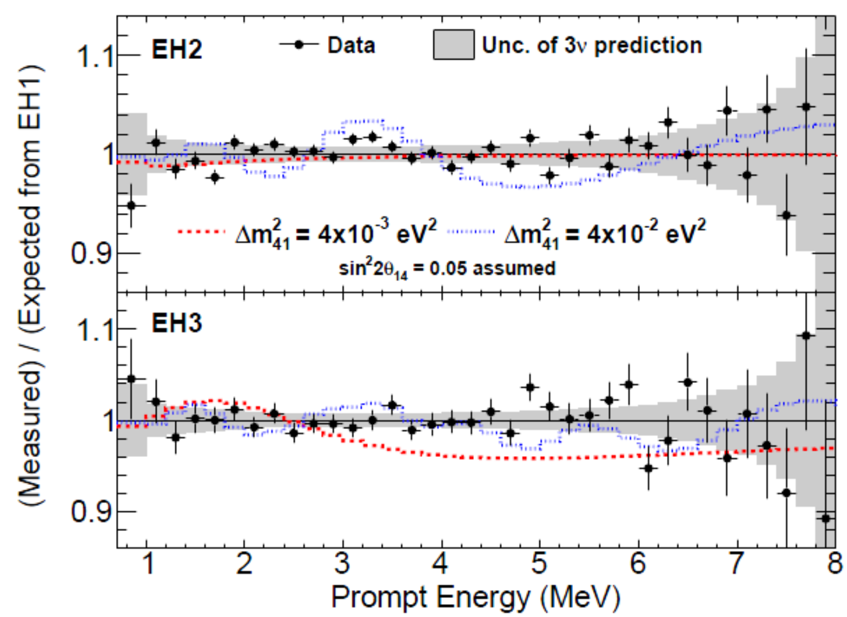
Reactor Results: Flux & Sterile Search

"Reactor anomaly"



Could indicate issues with reactor flux prediction (non-trivial nuclear physics). Could be evidence for a new oscillation mode.

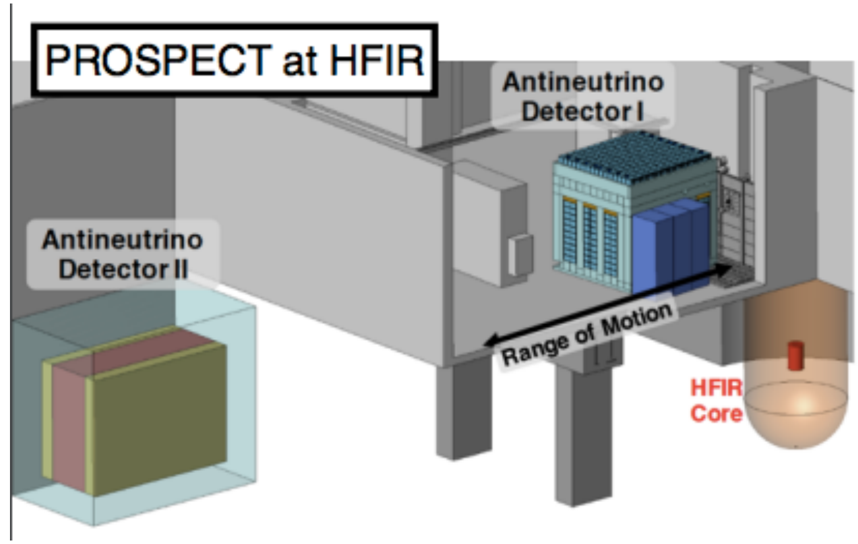
Sterile neutrino search:

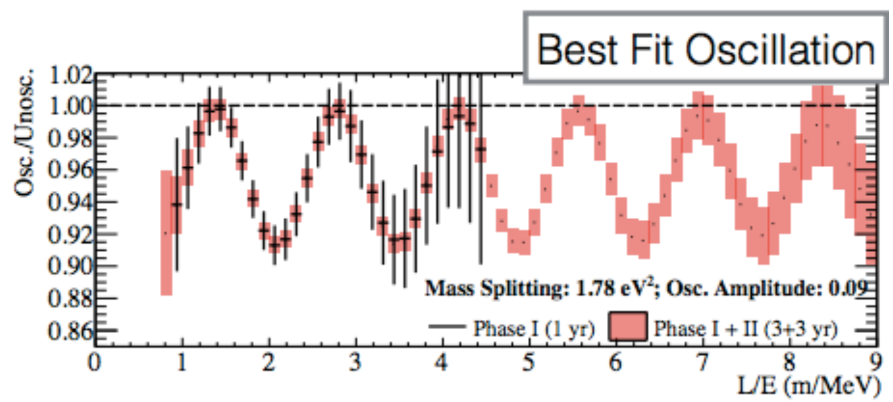


Sensitive to sterile neutrino with mass splitting in the region of 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2. No evidence for oscillation to sterile ν observed.

Very-short Baseline Reactor Experiments

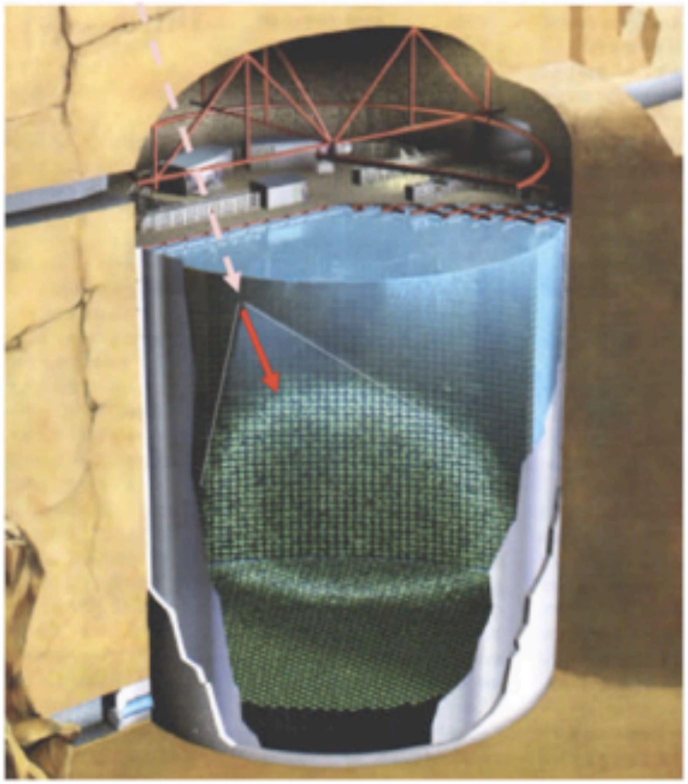
- Search for sterile neutrinos in region suggested by “reactor anomaly”
- Precisely measure reactor neutrino flux
- Utilize small research reactors
  - Allow close (very-short baseline) access
  - Small core size
  - High background environment
- Many current and planned experiments, including:
  - PROSPECT
  - SoLid
  - NEOS





Atmospheric Neutrino Experiments

Super-Kamiokande



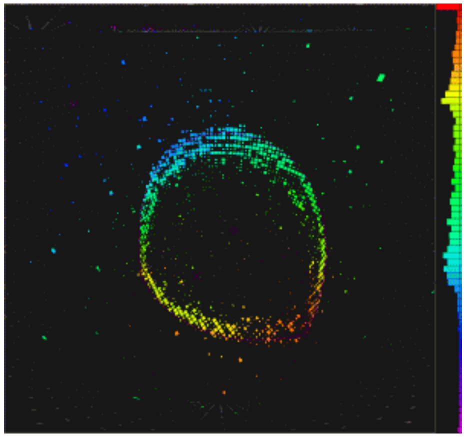
Four Run Periods:
SK-I (1996-2001) SK-II (2003-2005)
SK-III(2005-2008) SK-IV(2008-Present)

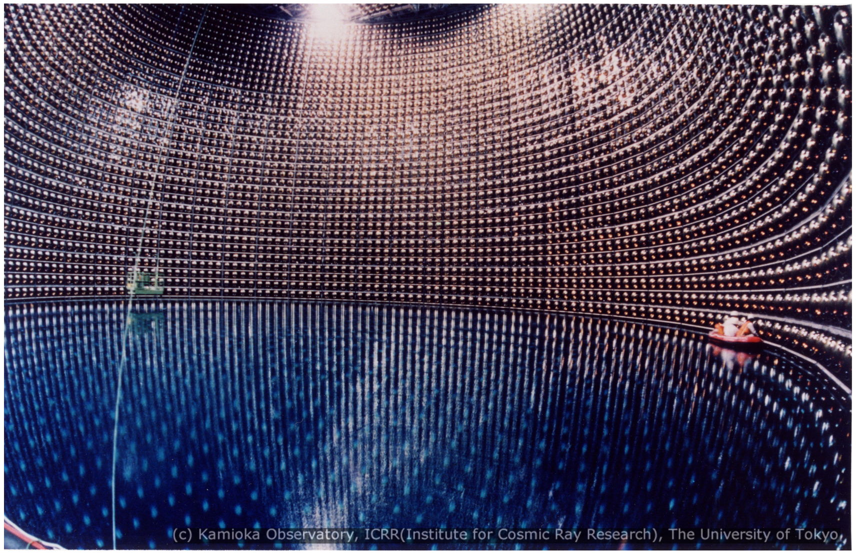
- Super-K is a 50 kton water Cherenkov detector with 22.5 kton of fiducial volume at 2,700 m.w.e underground.
- The detector is optically separated into ID and OD.
- Excellent in detection of atmospheric neutrinos.
- 20 years since the start of data taking in 1996, >47,000 atmospheric neutrino events.
- A Nobel prize winning experiment!

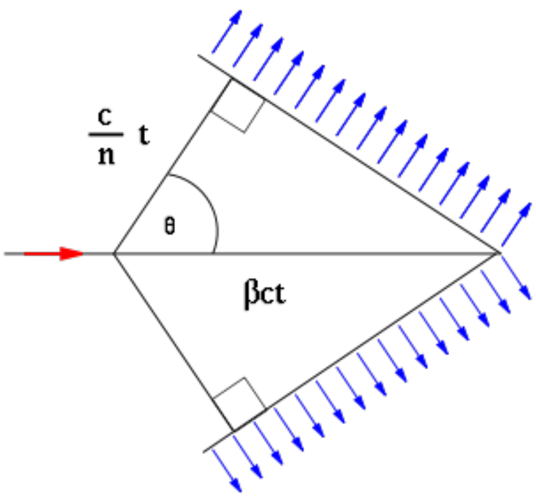
ICHEP 2016

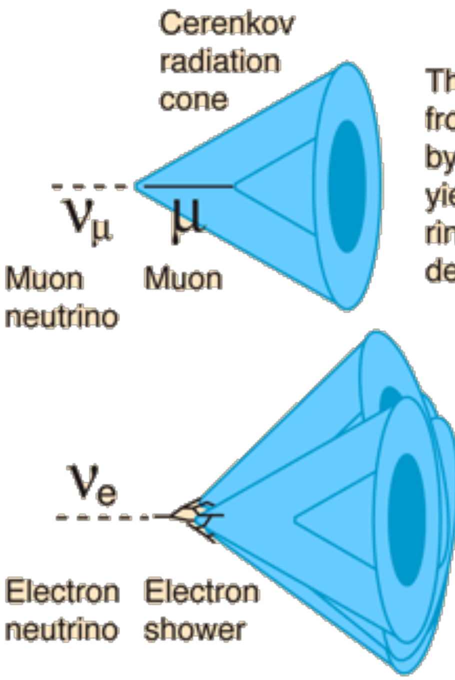
Z. Li

SuperK Detector





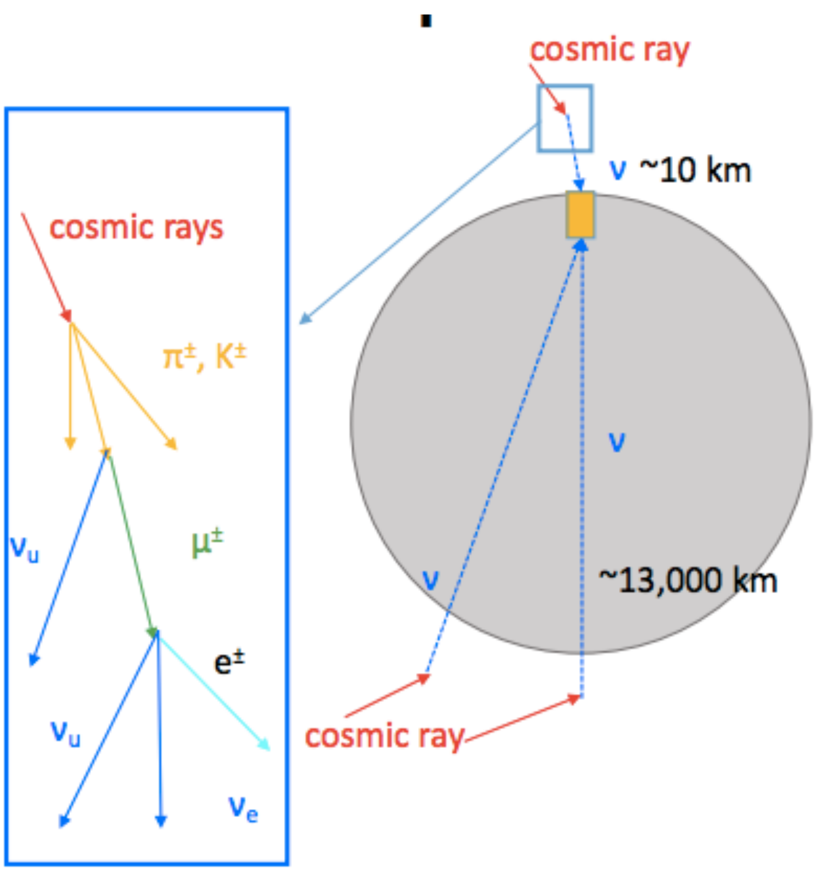




The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

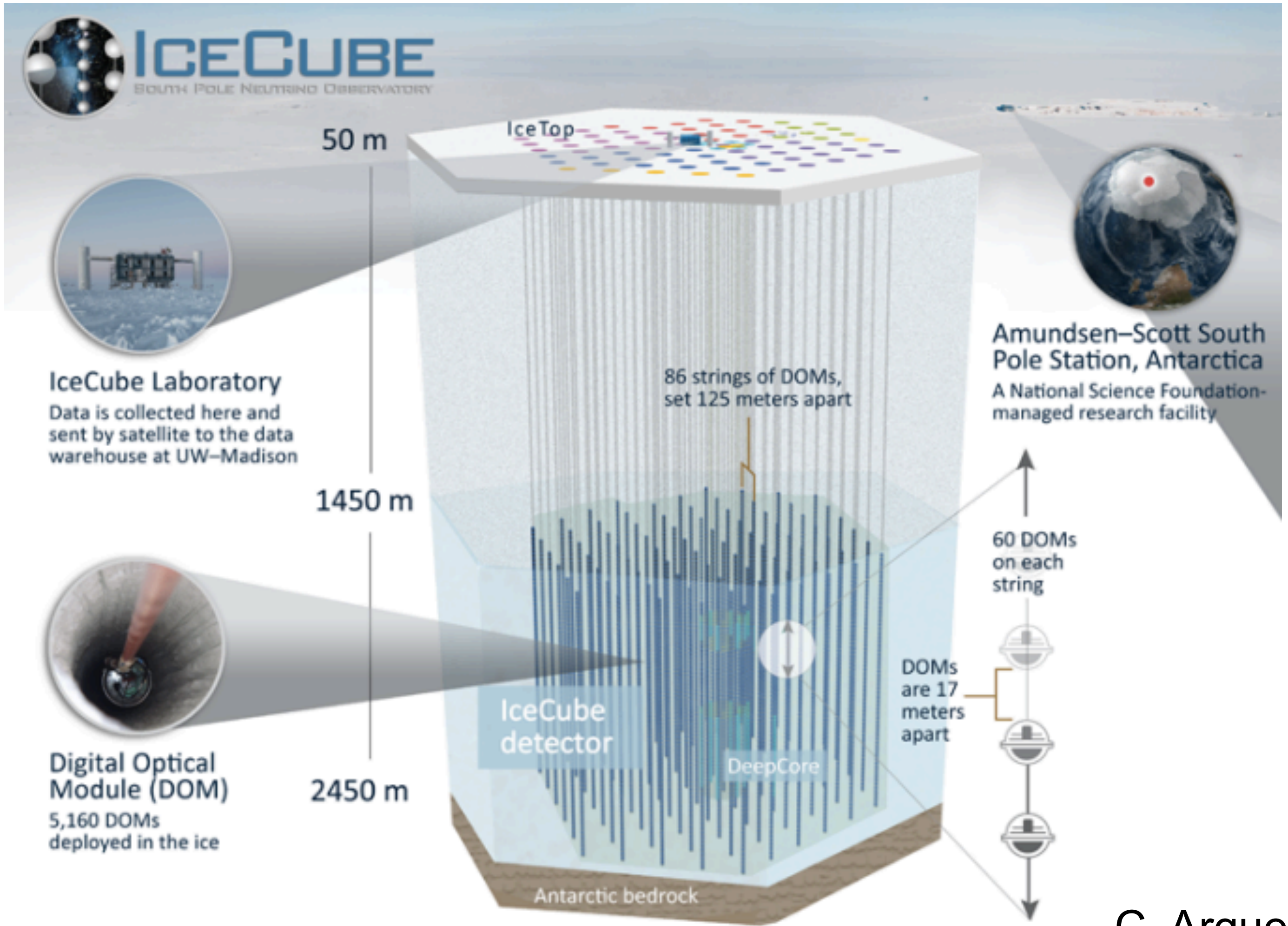
The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

Atmospheric Neutrino Studies



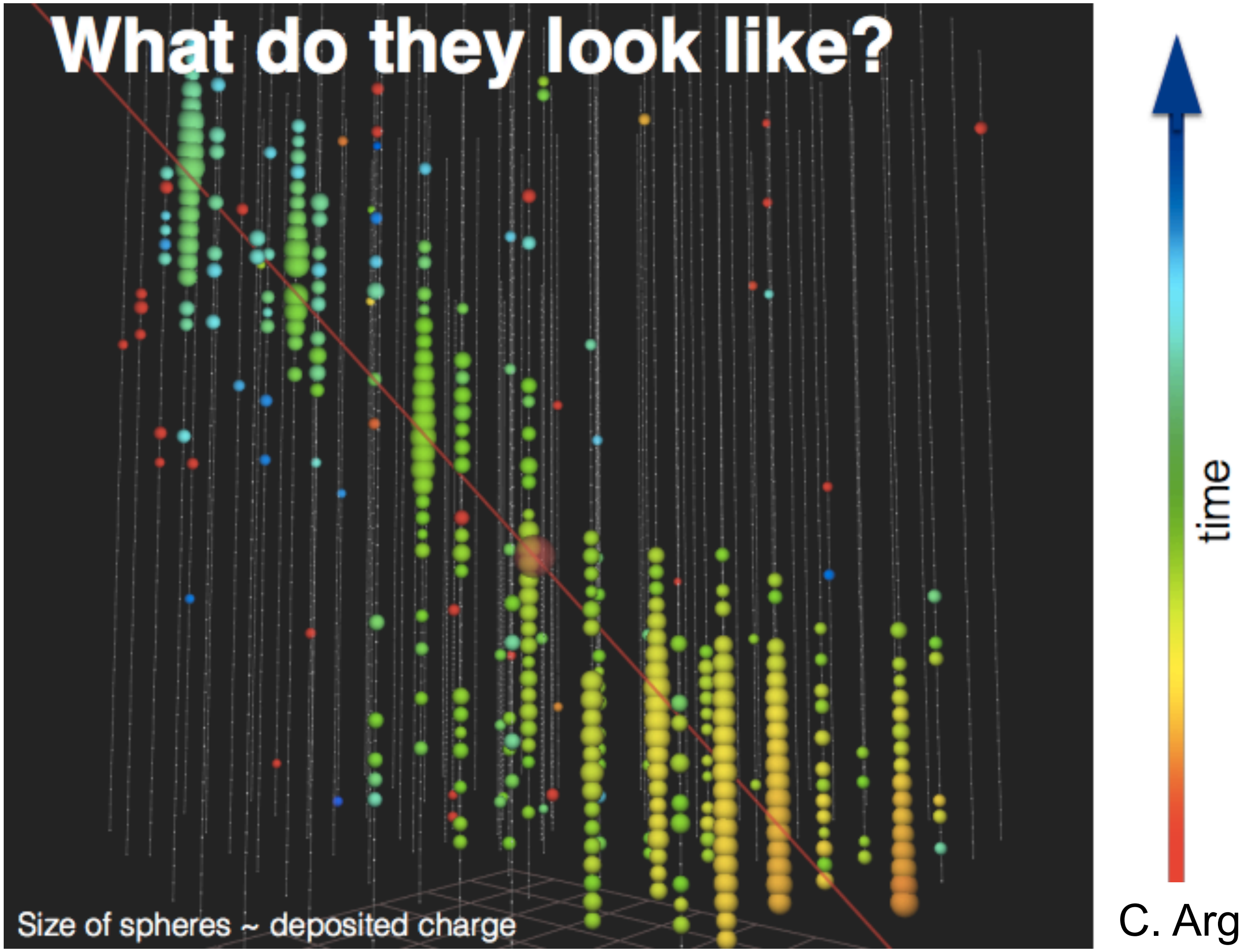
- Played important role in discovery of neutrino oscillation
- Precise measurement of $\sin^2 2\theta_{23}$, Δm^2_{32} in ν_μ disappearance
- Still producing new results including:
  - Atmospheric flux measurements
  - Tau neutrino appearance
  - 3-flavor measurements of oscillation parameters $\sin^2\theta_{23}$, Δm^2_{32}, δ_{CP}, and neutrino mass hierarchy

ICECUBE



C. Arguelles, ICHEP 2016

ICECUBE



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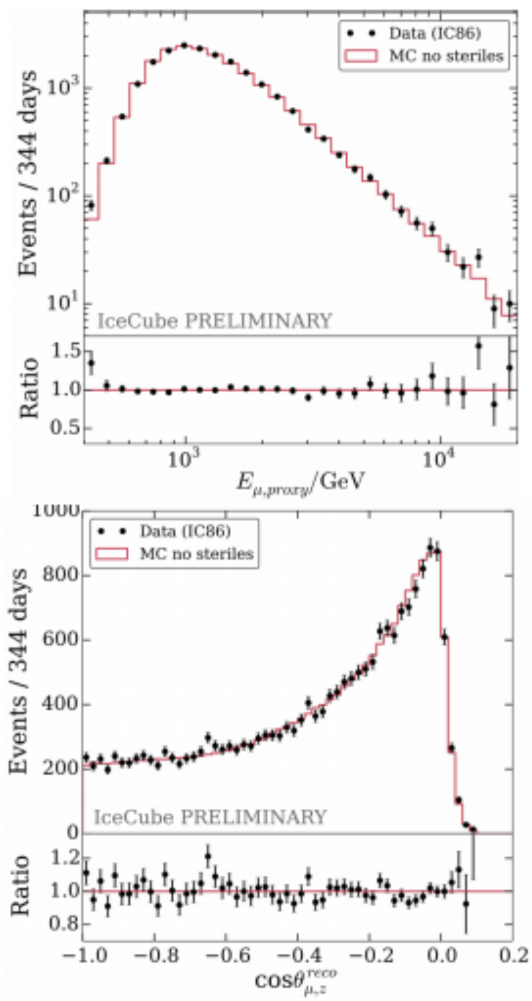
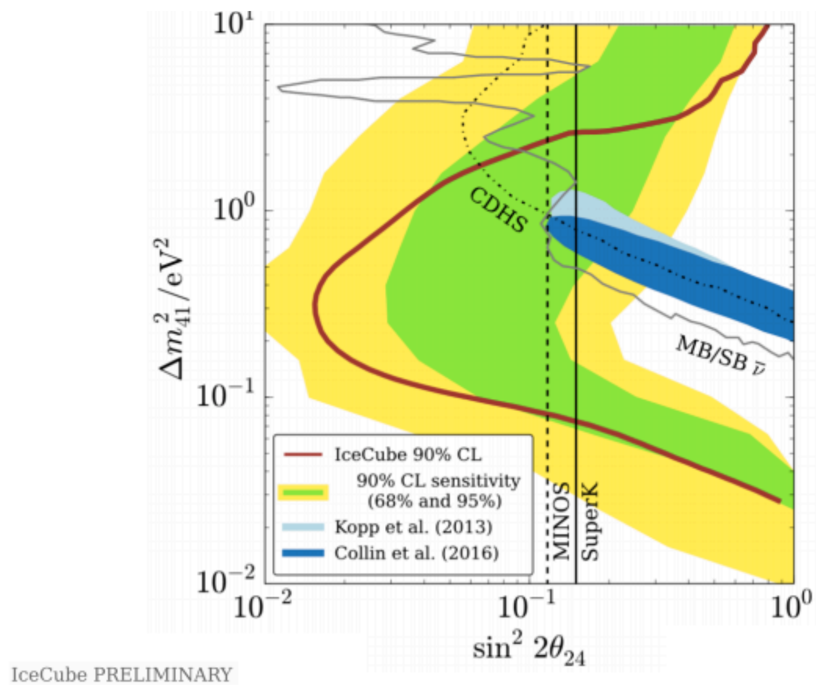
ICECUBE: Sterile Neutrino Search



- No evidence for sterile neutrino oscillation



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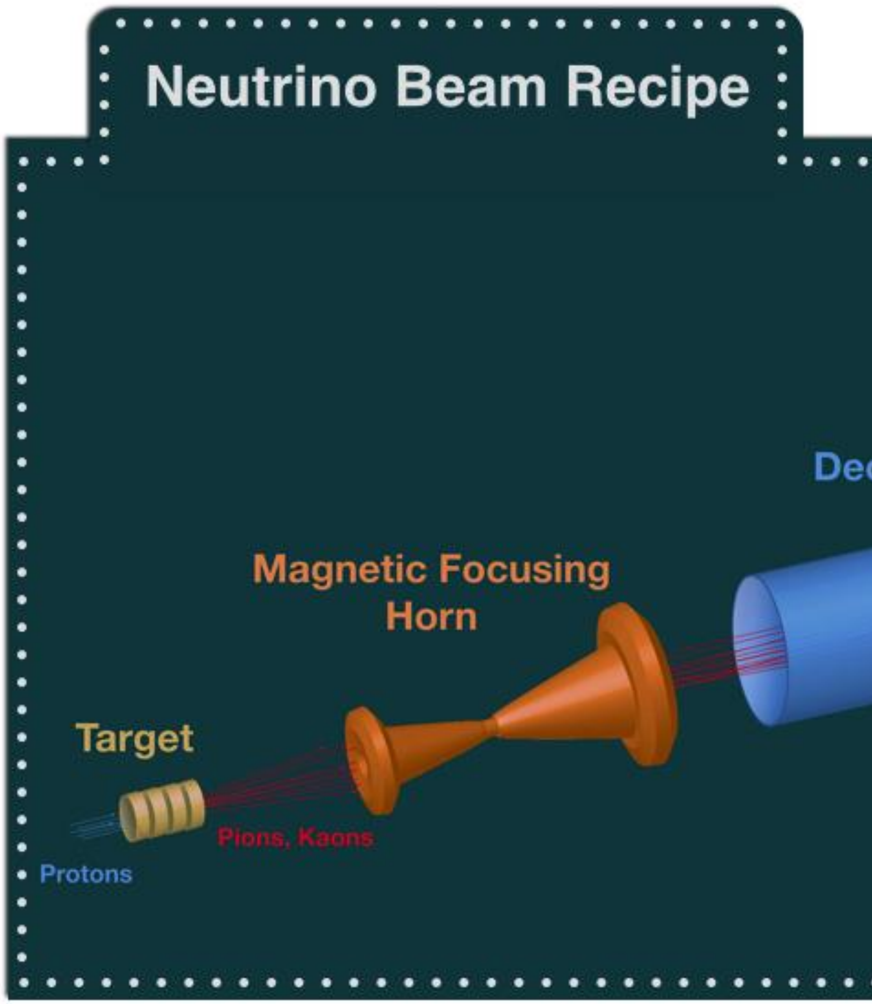
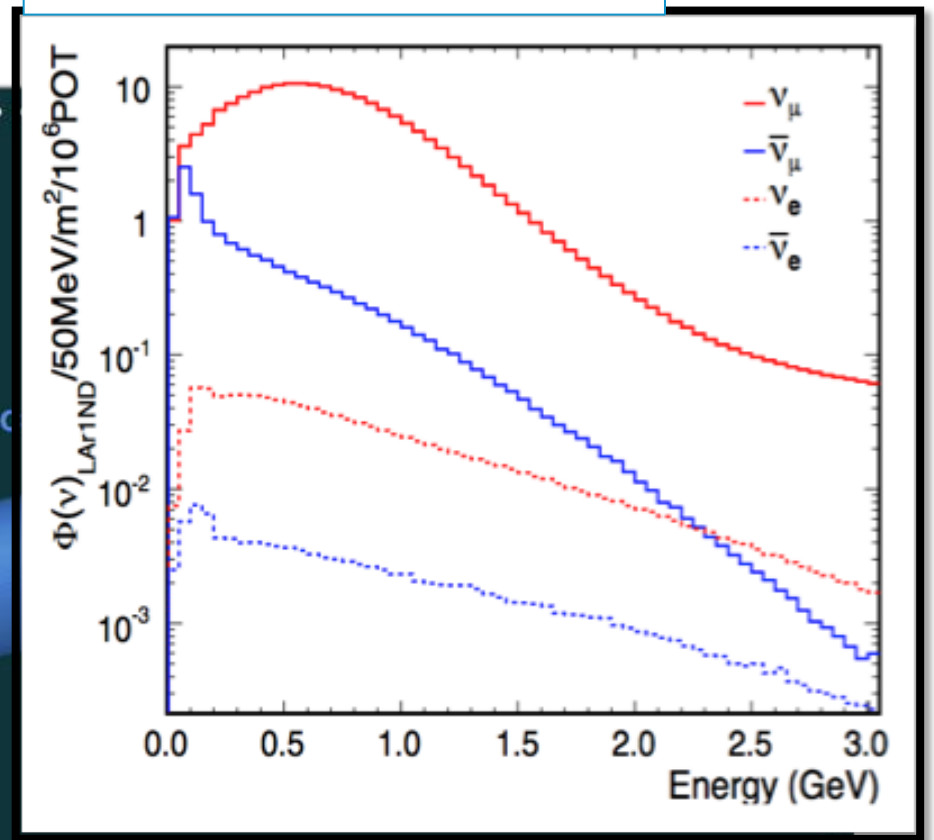
Short-baseline Accelerator Experiments

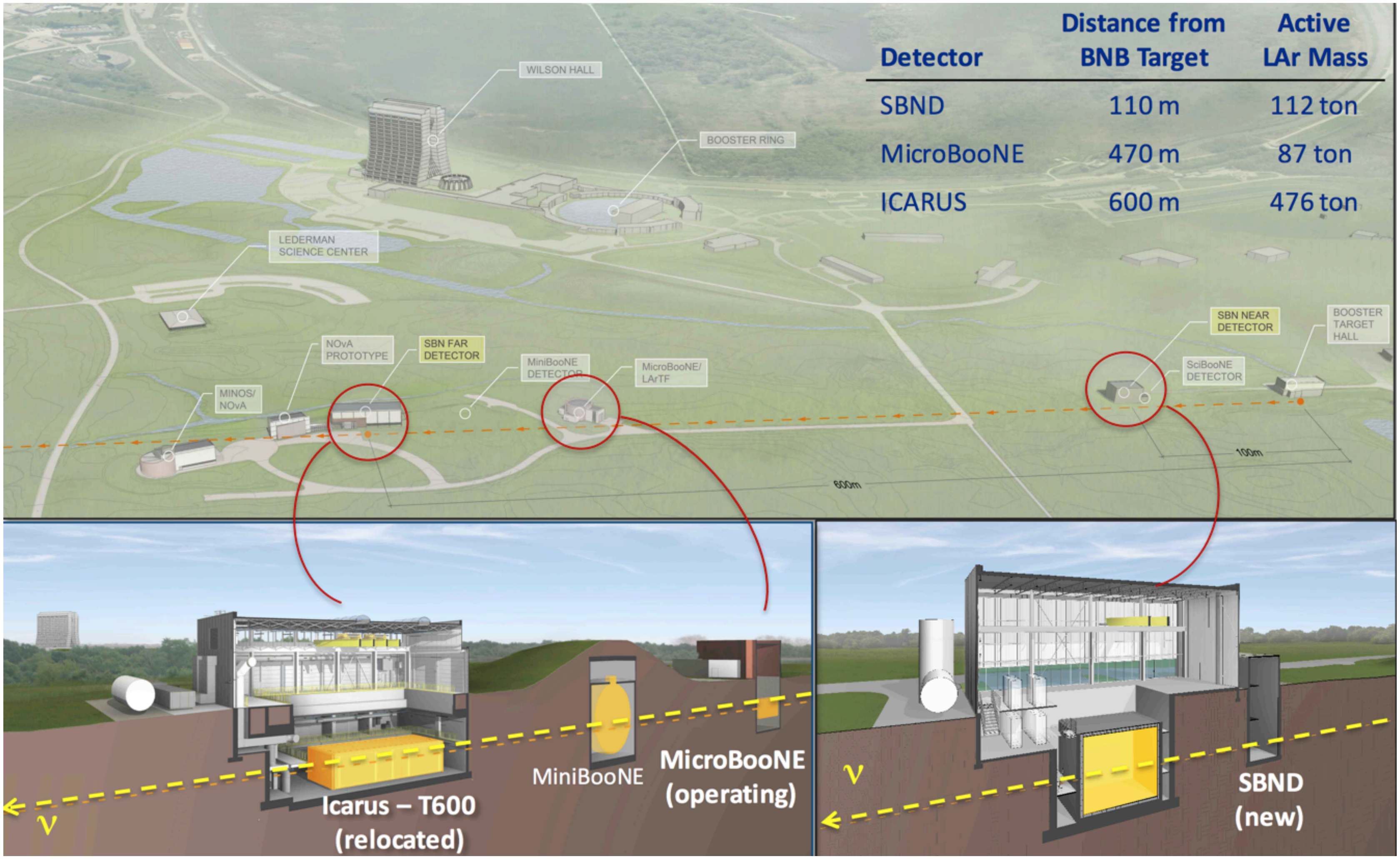
Producing a Neutrino Beam



Booster Neutrino Beam:

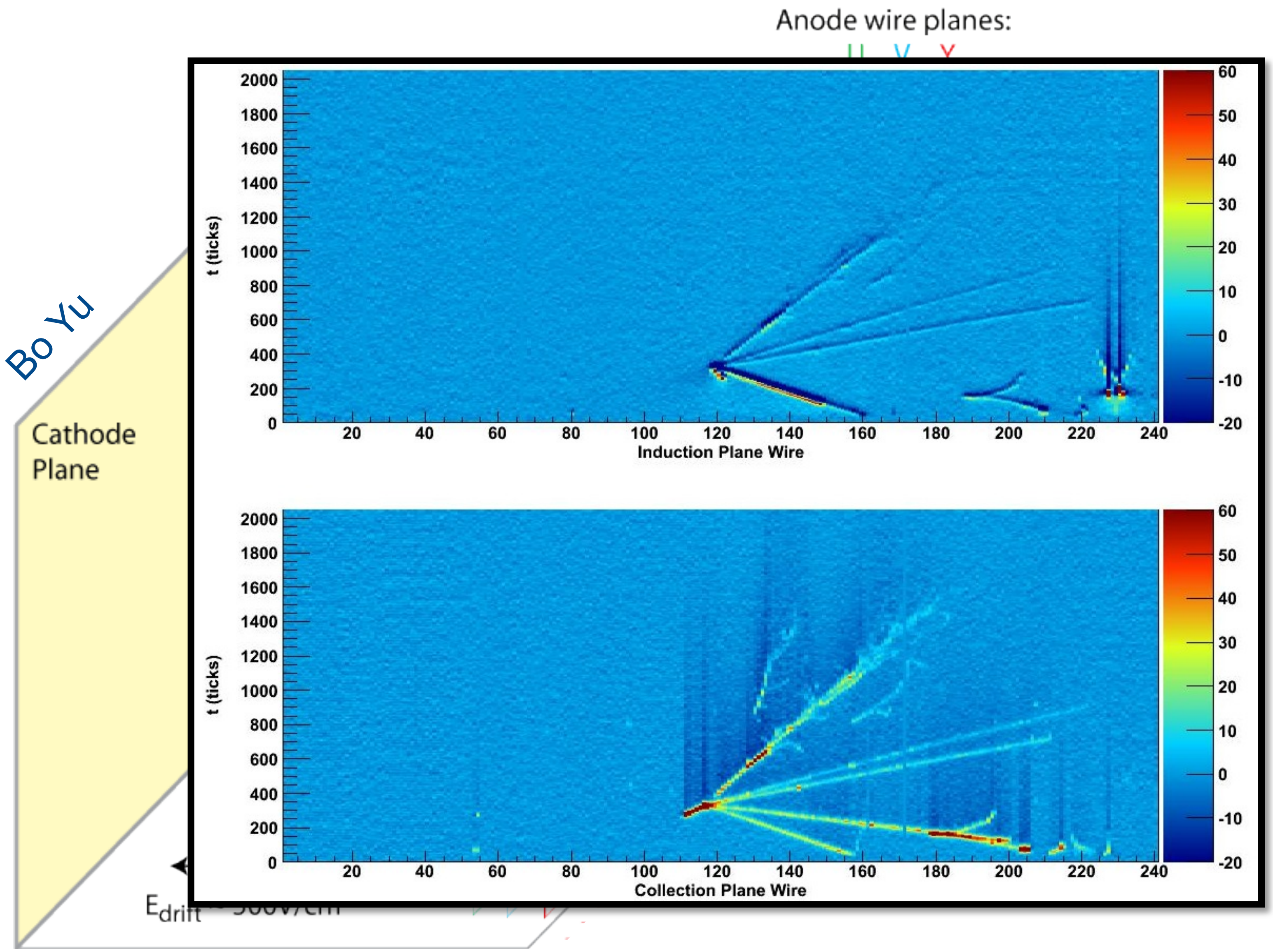


Short Baseline Neutrino Program

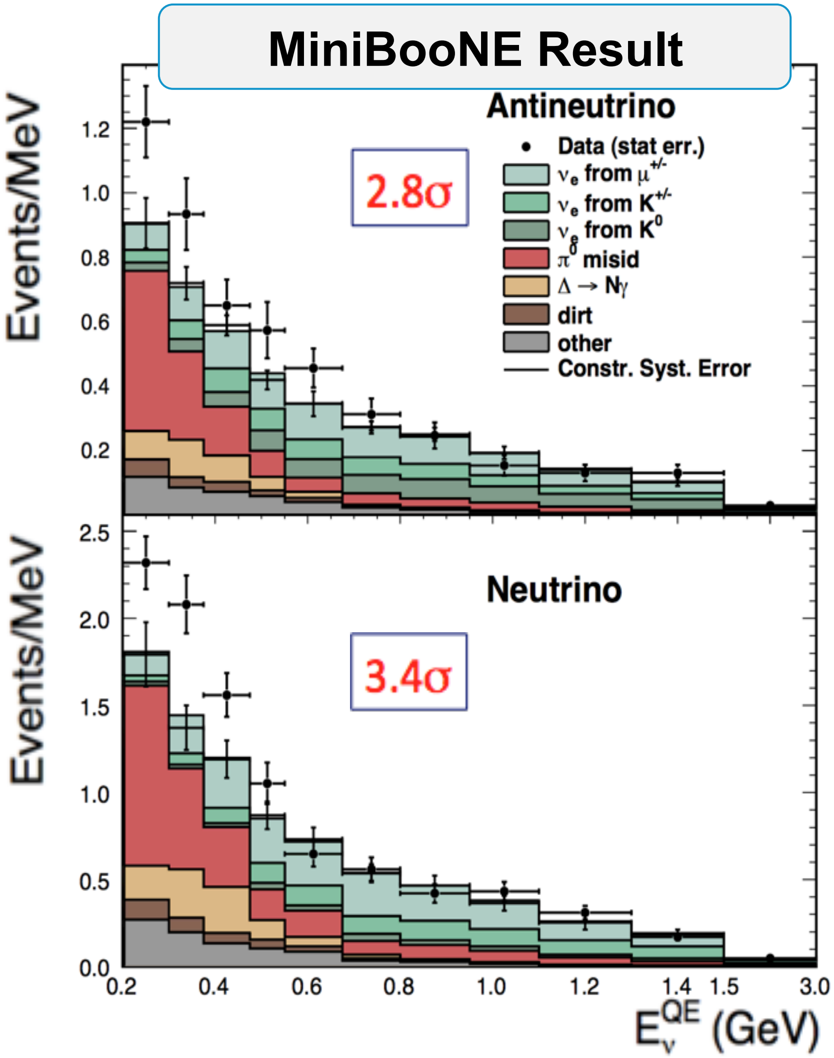


Detector	Distance from BNB Target	Active LAr Mass
SBND	110 m	112 ton
MicroBooNE	470 m	87 ton
ICARUS	600 m	476 ton

Liquid Argon Time Projection Chamber



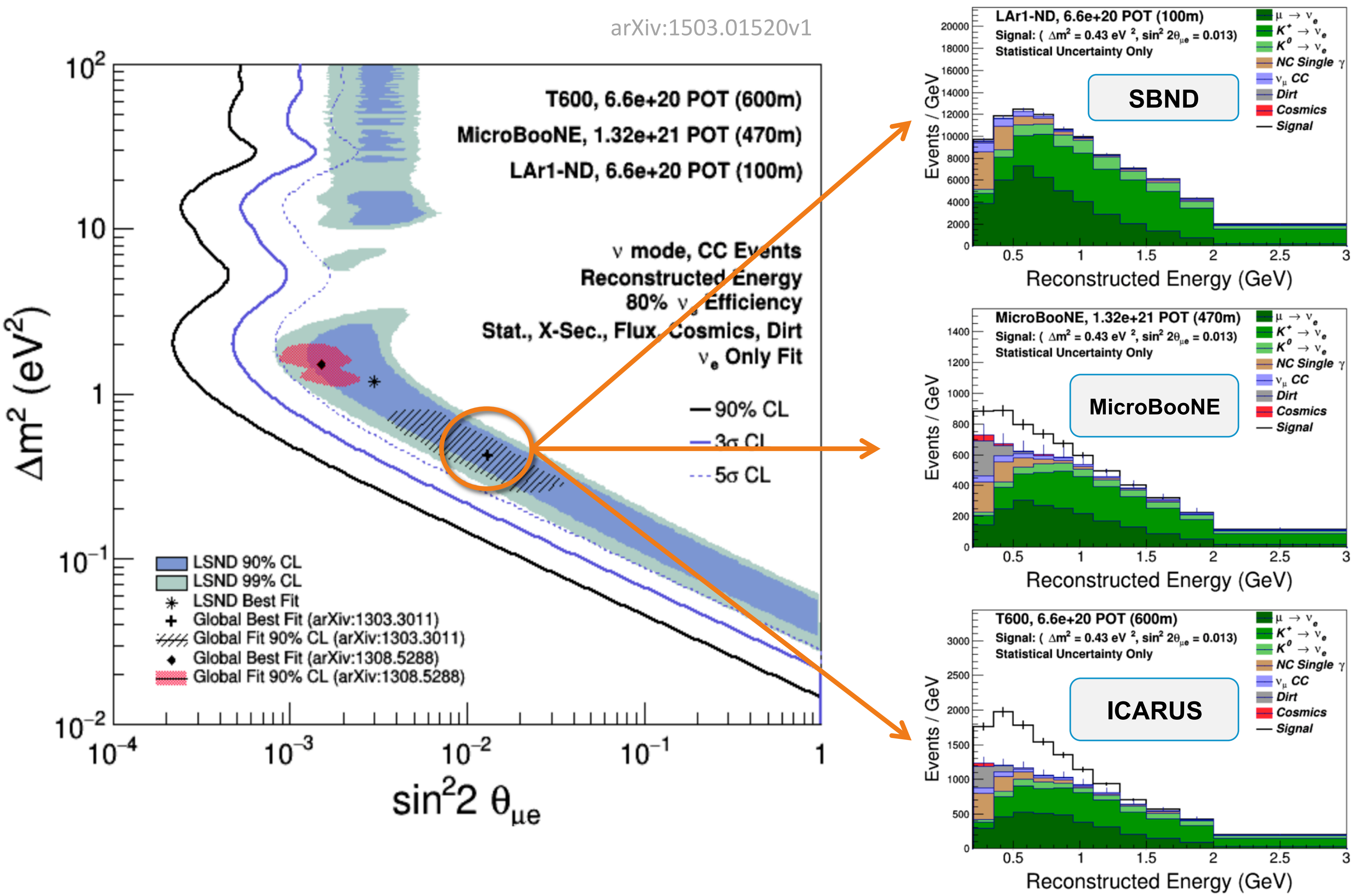
Physics Goals: MiniBooNE Follow-up



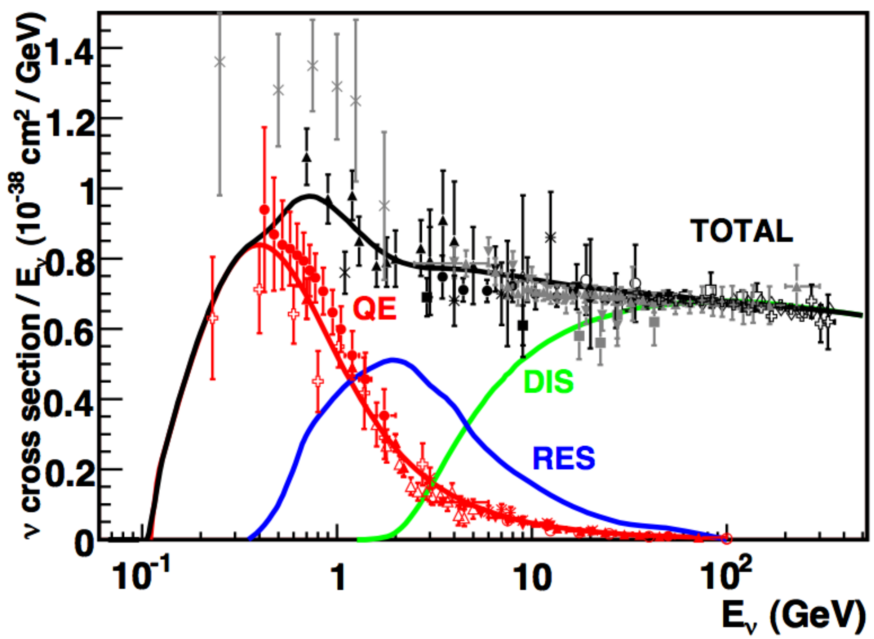
- MiniBooNE:
  - Excess of ν_e like events at low energy
    - Not consistent with other searches for oscillation to sterile neutrinos
    - New physics or misunderstood (photon) background?
  - SBN detectors are liquid argon TPCs, which can distinguish between electrons and photons

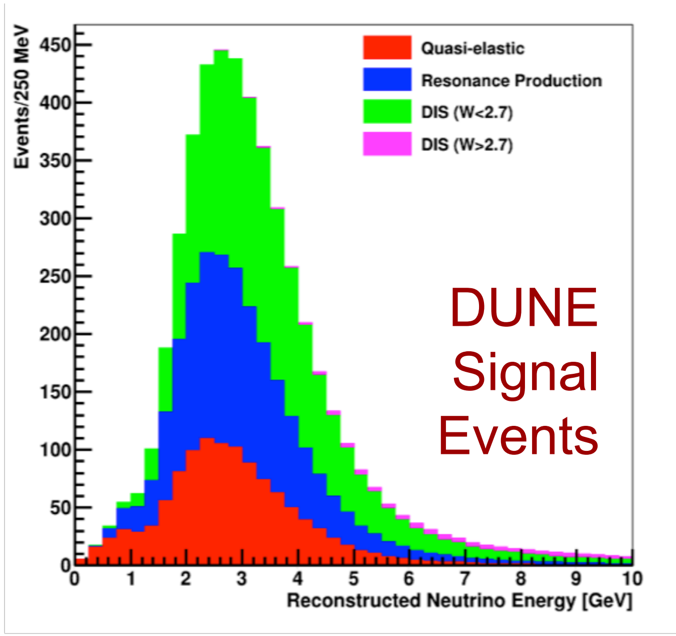
Physics Goals: Sterile Neutrino Search

arXiv:1503.01520v1



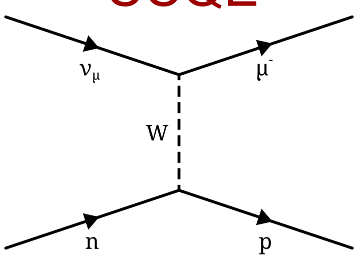
Neutrino Interaction Measurements



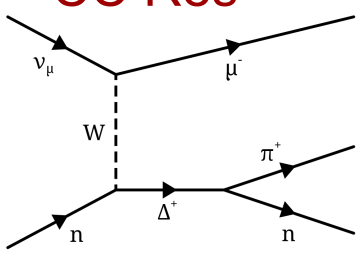


- ν_μ CC Interactions:
  - QE: $\nu_\mu n \to \mu^- p$
  - RES: $\nu_\mu N \to \mu^- N^*$, $N^* \to \pi N'$
  - DIS: $\nu_\mu N \to \mu^- X$

CCQE



CC Res



SBN Status

- SBND detector being built; installation planned for 2018
- MicroBooNE running since 2015
- ICARUS refurbishment at CERN ongoing; installation planned for 2017

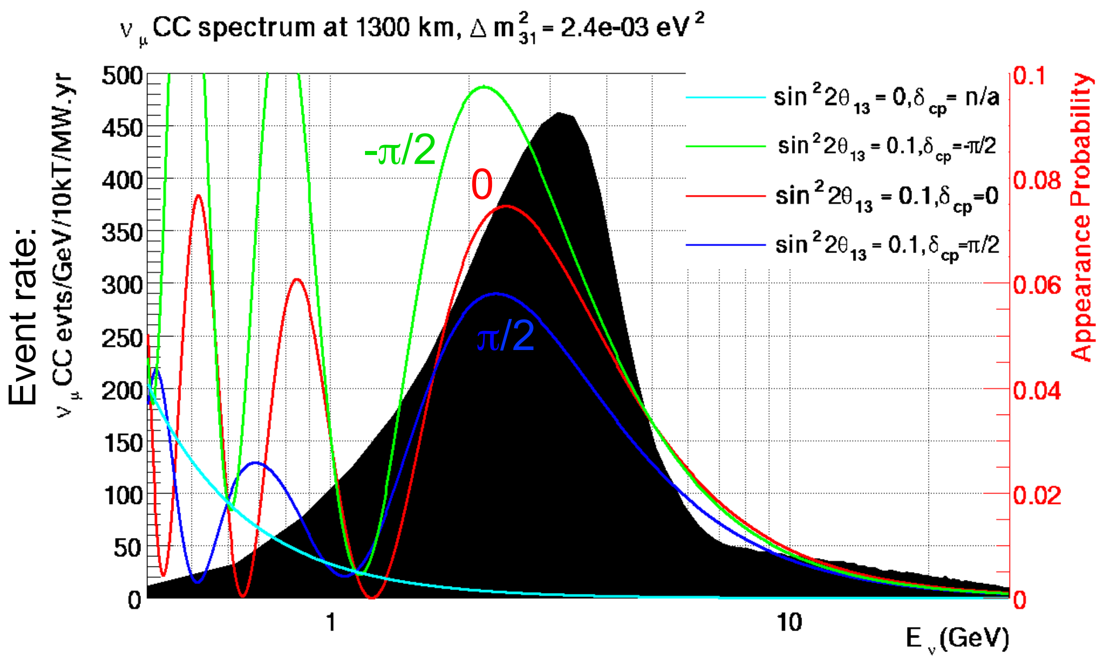
Long-baseline Accelerator Experiments

ν_e Appearance

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$



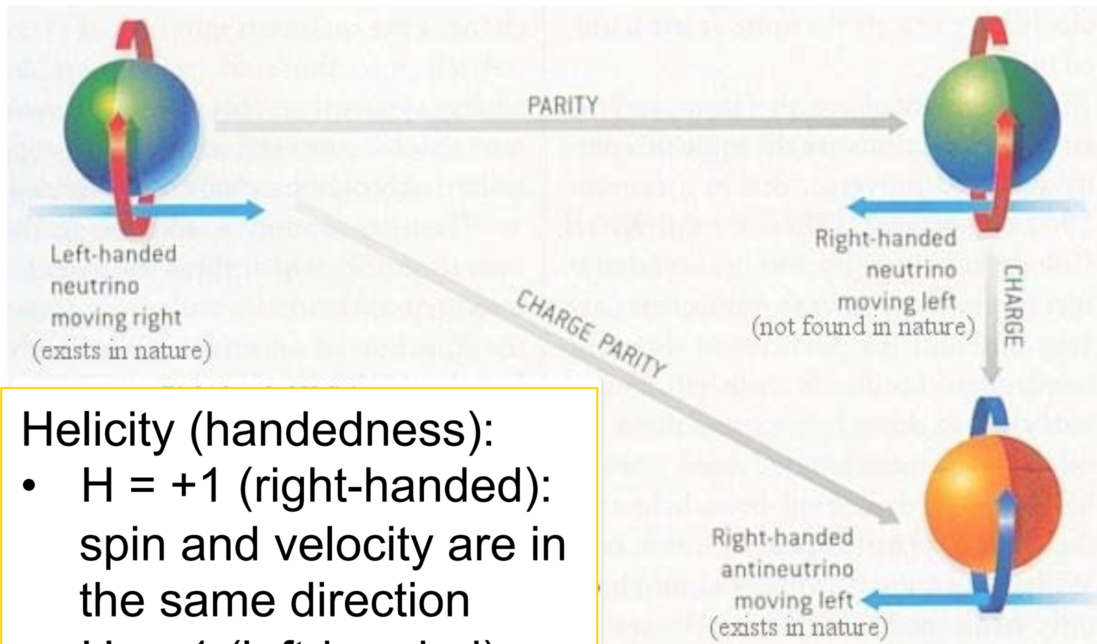
- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

CP Violation

- Three discrete symmetries:
  - C (“charge conjugation”) changes a particle to its antiparticle
  - P (“parity inversion”) inverts space: (x,y,z)→(-x,-y,-z)
  - T (“time reversal) reverses time: t → -t
  - Individually conserved by EM and strong interactions
- Parity found to be violated by the weak interaction in 1957 (Wu, et. al)
- CP found to be violated by the weak interaction in 1964 (Christenson, et. al)
  - Existence of CP violation in kaon decay required the existence of the 3rd quark generation before experimental observation of bottom and top

CP Violation in Neutrinos

- In neutrinos
  - Parity inversion changes left-handed to right-handed
  - Charge conjugation changes neutrino to antineutrino
  - CP changes a left-handed neutrino to a right-handed antineutrino

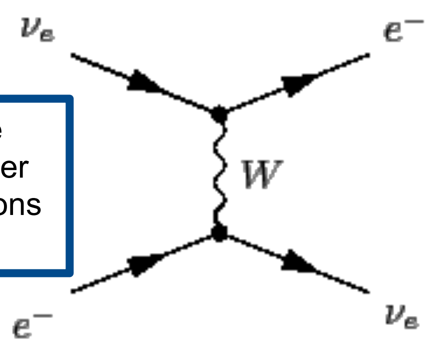


Helicity (handedness):
- H = +1 (right-handed): spin and velocity are in the same direction
- H = -1 (left-handed): spin and velocity are in opposite directions

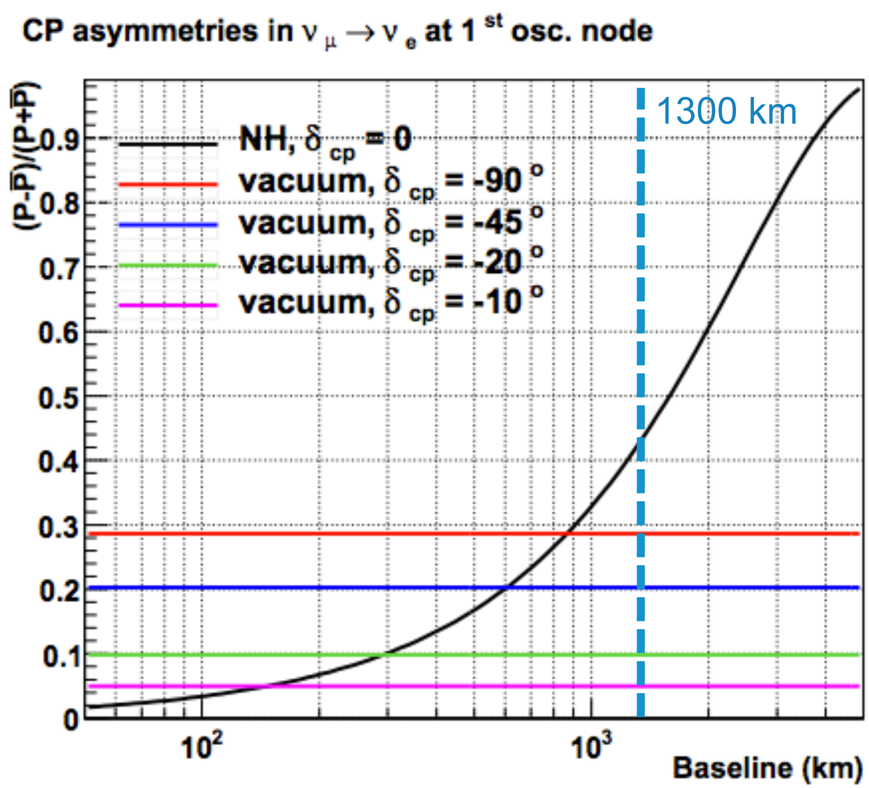
Matter Asymmetry

Charged-current coherent forward scattering on electrons:

Electrons are present in matter while other leptons are not.

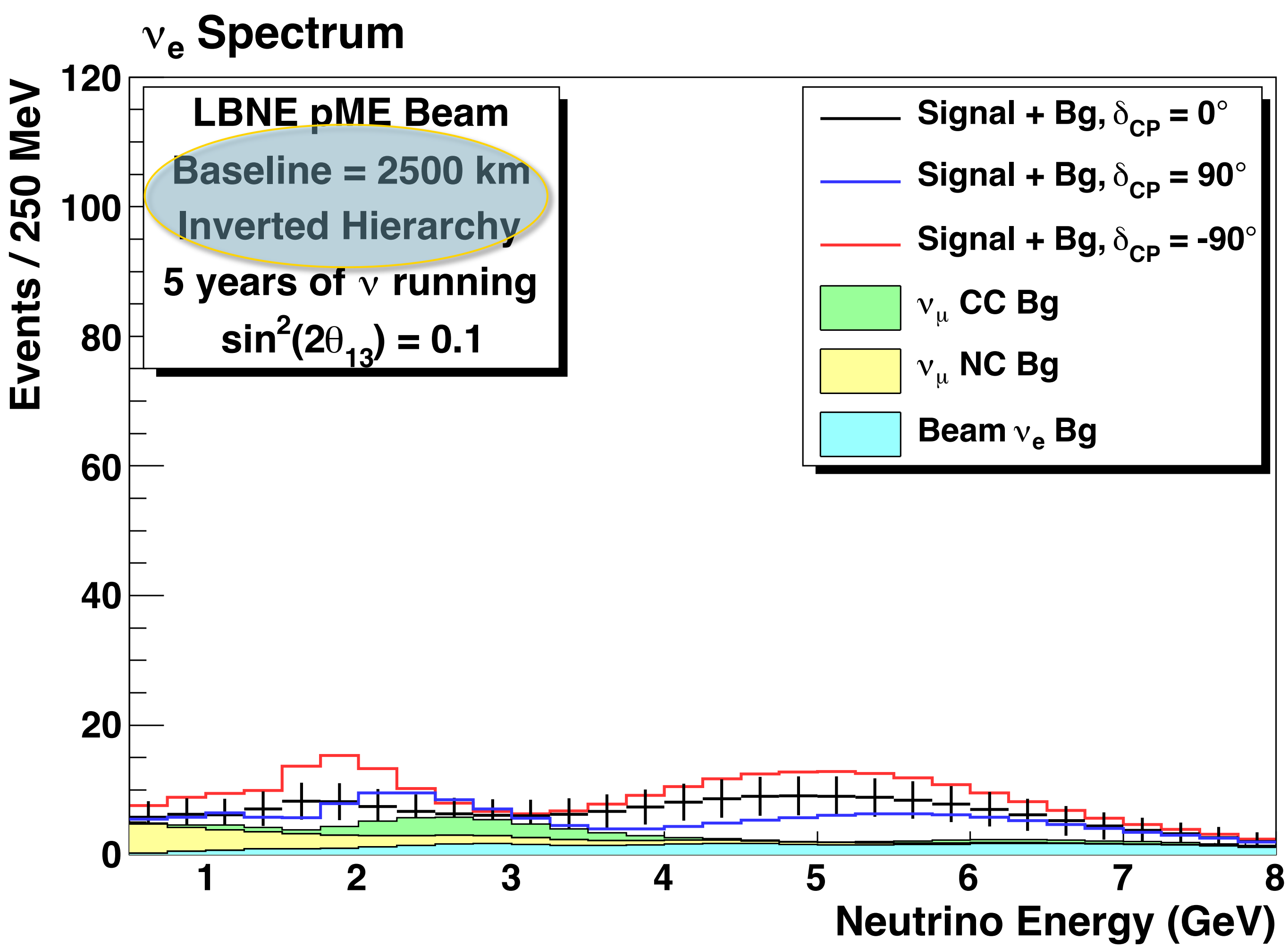


- CC process occurs for electron neutrinos only; muon and tau have only NC interactions with electrons
- Normal hierarchy: matter effect enhances appearance probability for neutrinos and suppresses it for antineutrinos (opposite for IH)

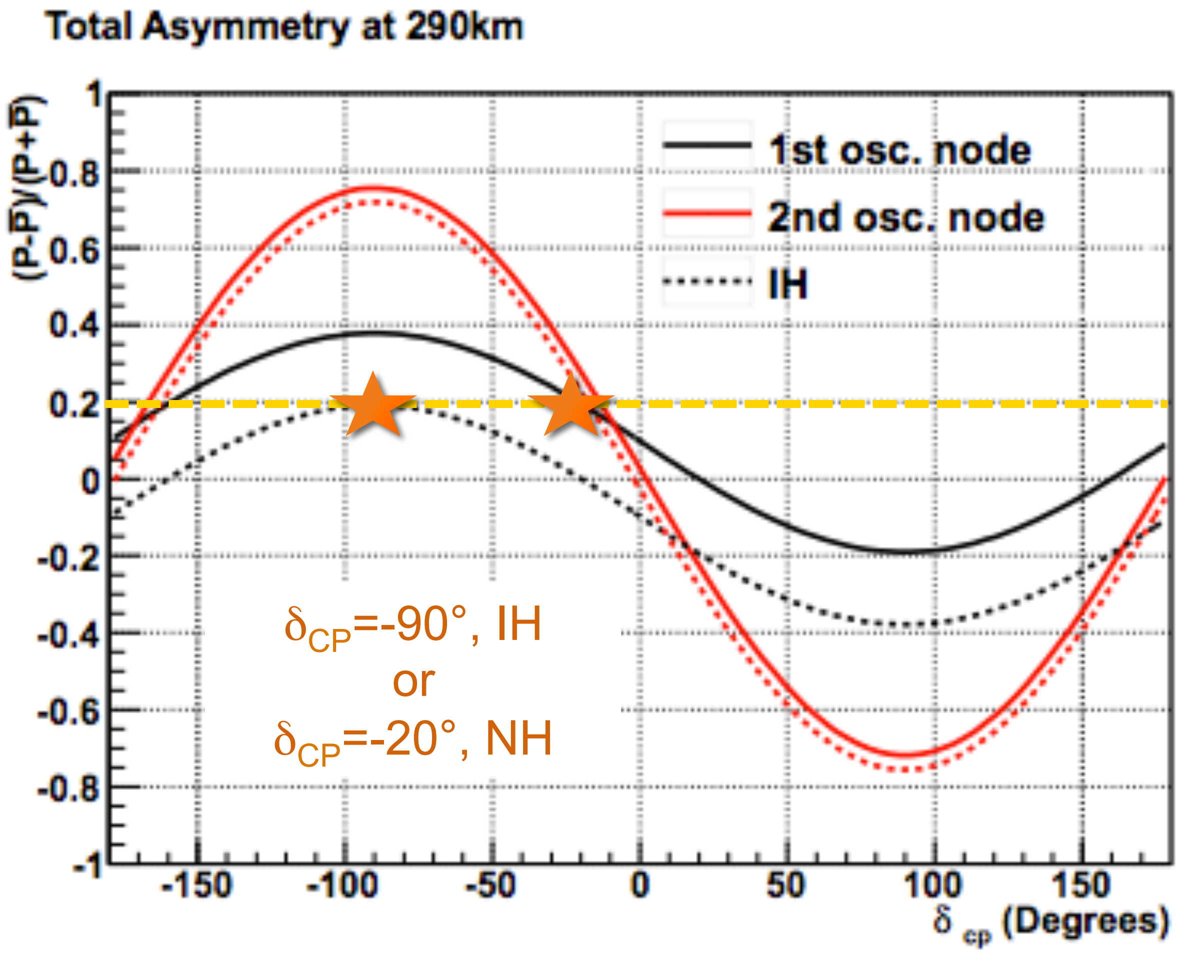


Matter asymmetry very important for long-baseline experiments!

Matter Asymmetry

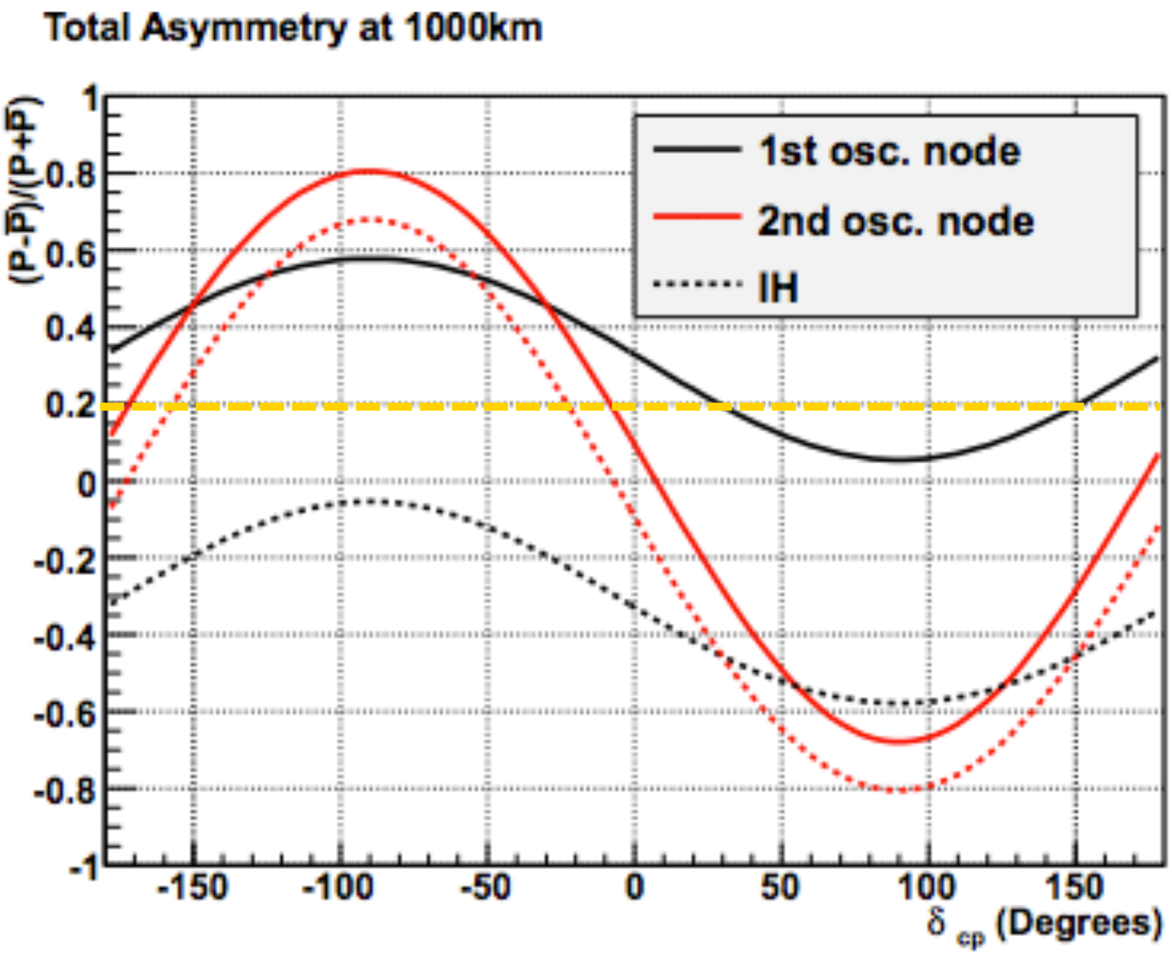


Matter and CP Asymmetry



Degeneracy between CP and matter asymmetry for 1st oscillation node at short baseline

Matter and CP Asymmetry

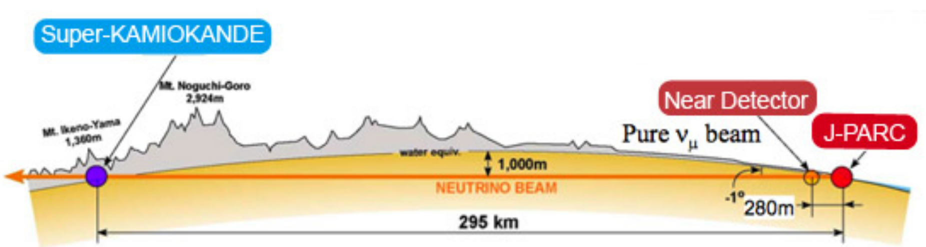


Longer baseline breaks degeneracy between CP and matter asymmetry – 1300 km is a near optimal baseline for these measurements

Current Experiments

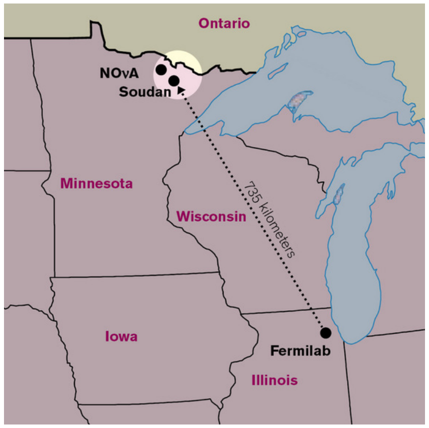
T2K: Tokai to Kamioka

- Beam: J-PARC
- Far detector: SuperK
  - WCD (50 kt)
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV

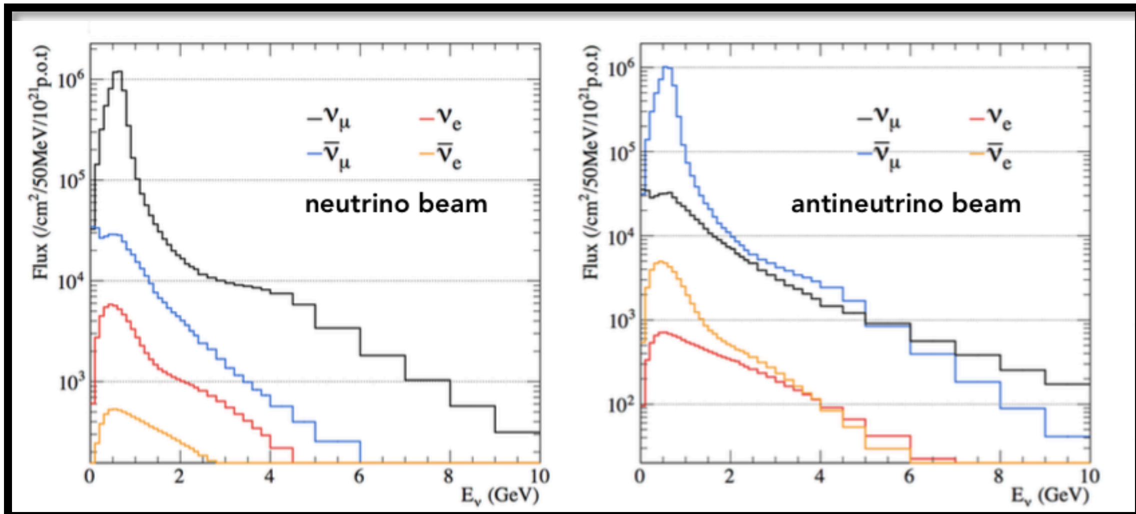


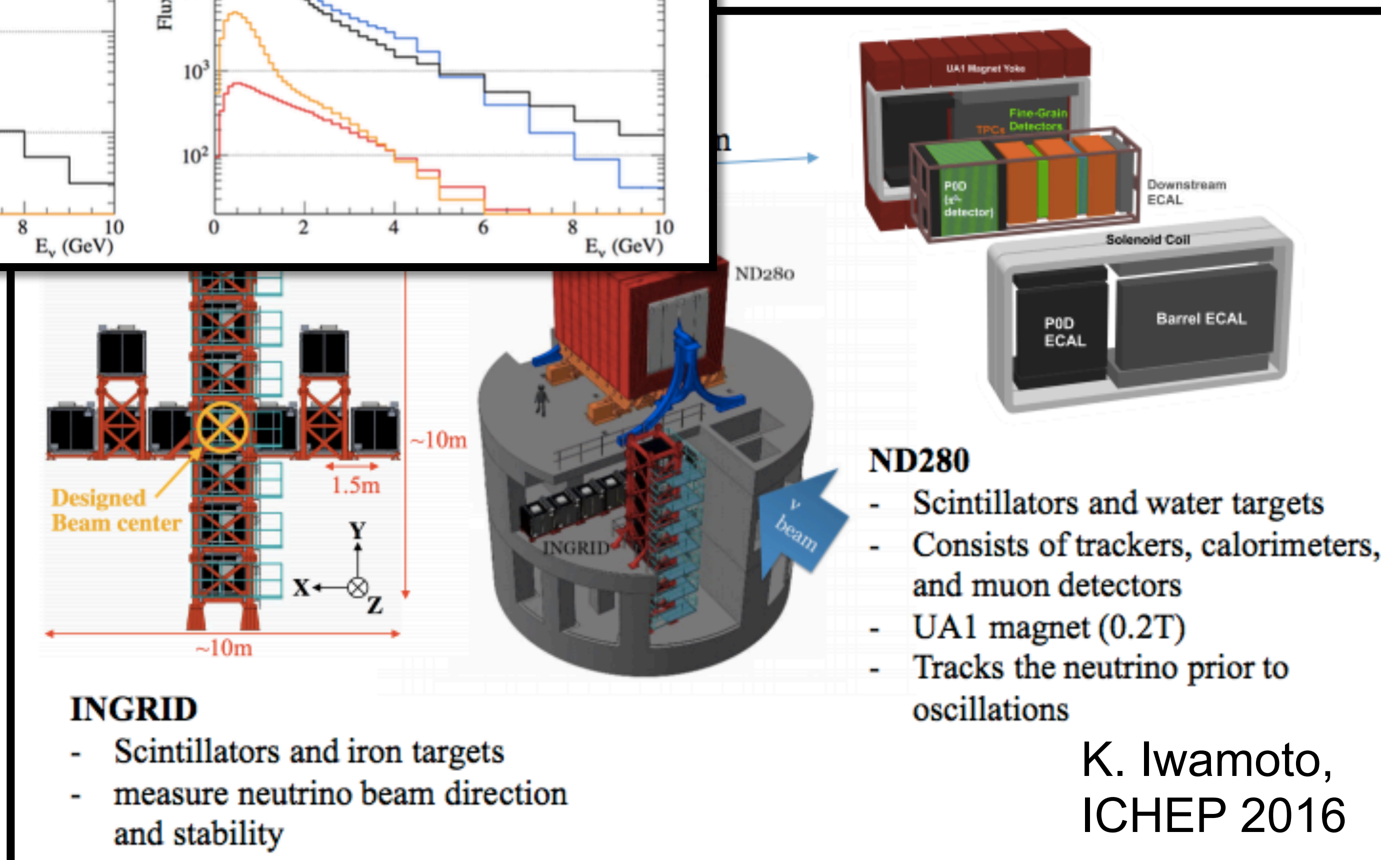
NOvA: FNAL to Ash River

- Beam: NuMI (FNAL)
- Far detector: segmented liquid scintillator detector (14 kt)
- Baseline: 810 km
- Far detector located off-axis such that observed ν flux is peaked at ~2 GeV



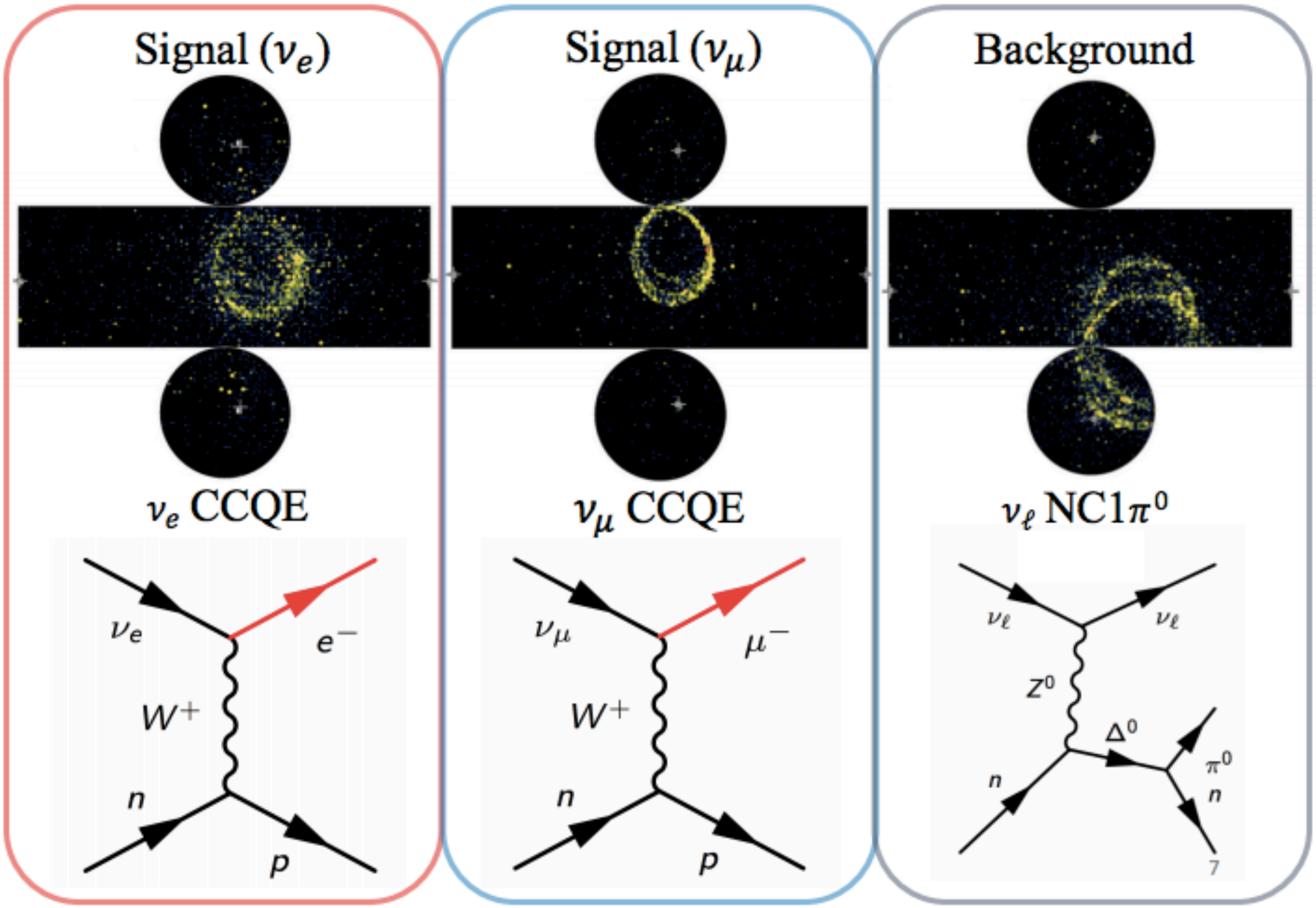
T2K Near Detectors and Flux





K. Iwamoto, ICHEP 2016

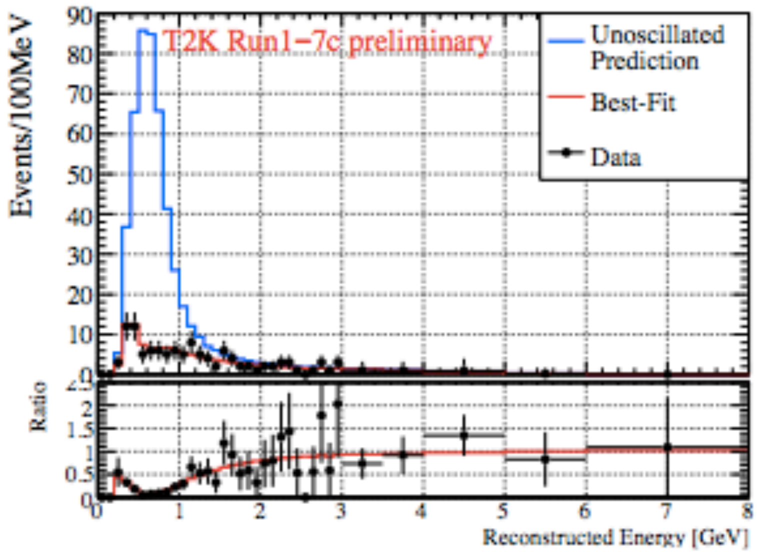
Neutrino Detection at SK Far Detector



K. Iwamoto, ICHEP 2016

T2K Results: ν_μ Disappearance

ν_μ

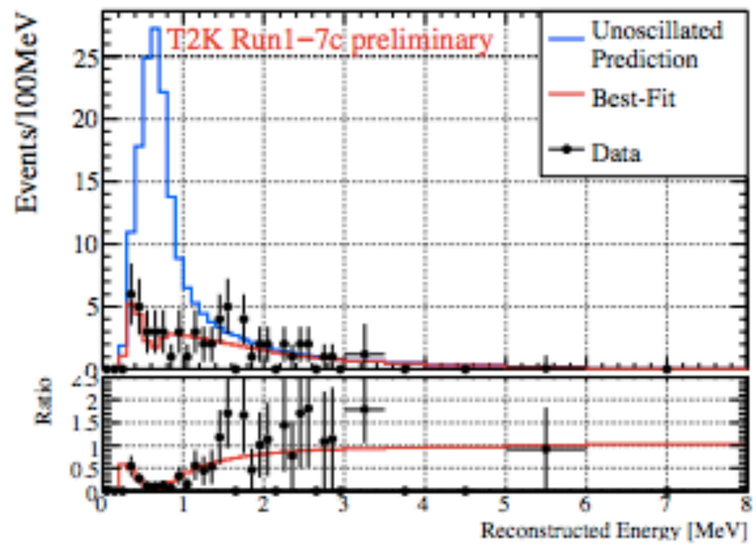


135 events observed

(+10 events since Neutrino 2016)

(135.8 events expected)

$\bar{\nu}_\mu$



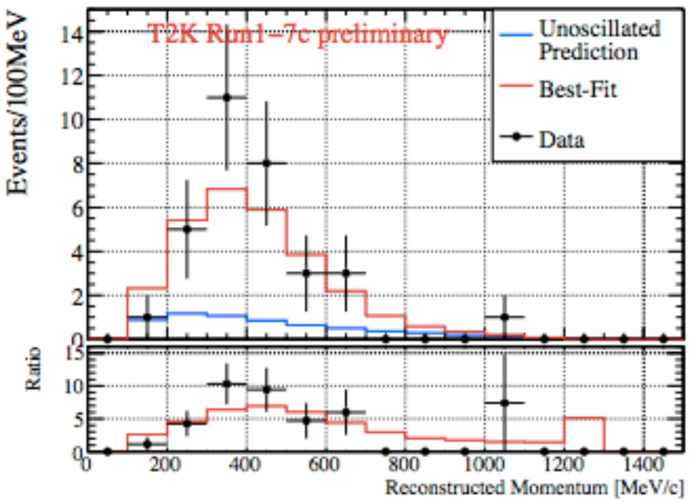
66 events observed

(64.2 events expected)

K. Iwamoto, ICHEP 2016

T2K Results: ν_e Appearance

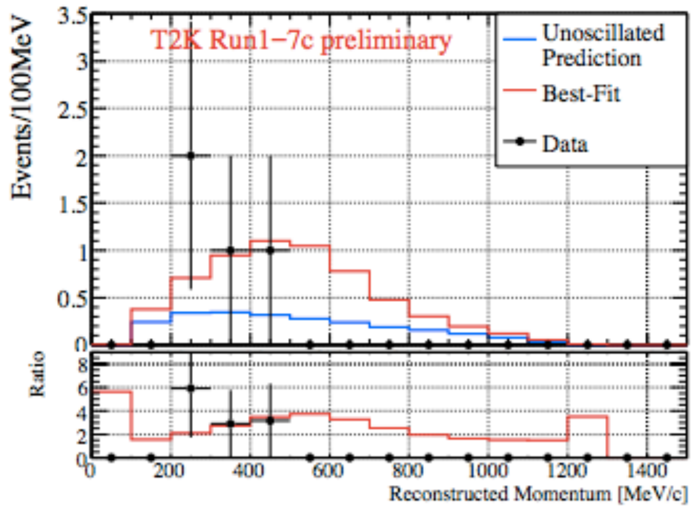
ν_e



32 events observed

(+0 events since Neutrino 2016)

$\bar{\nu}_e$

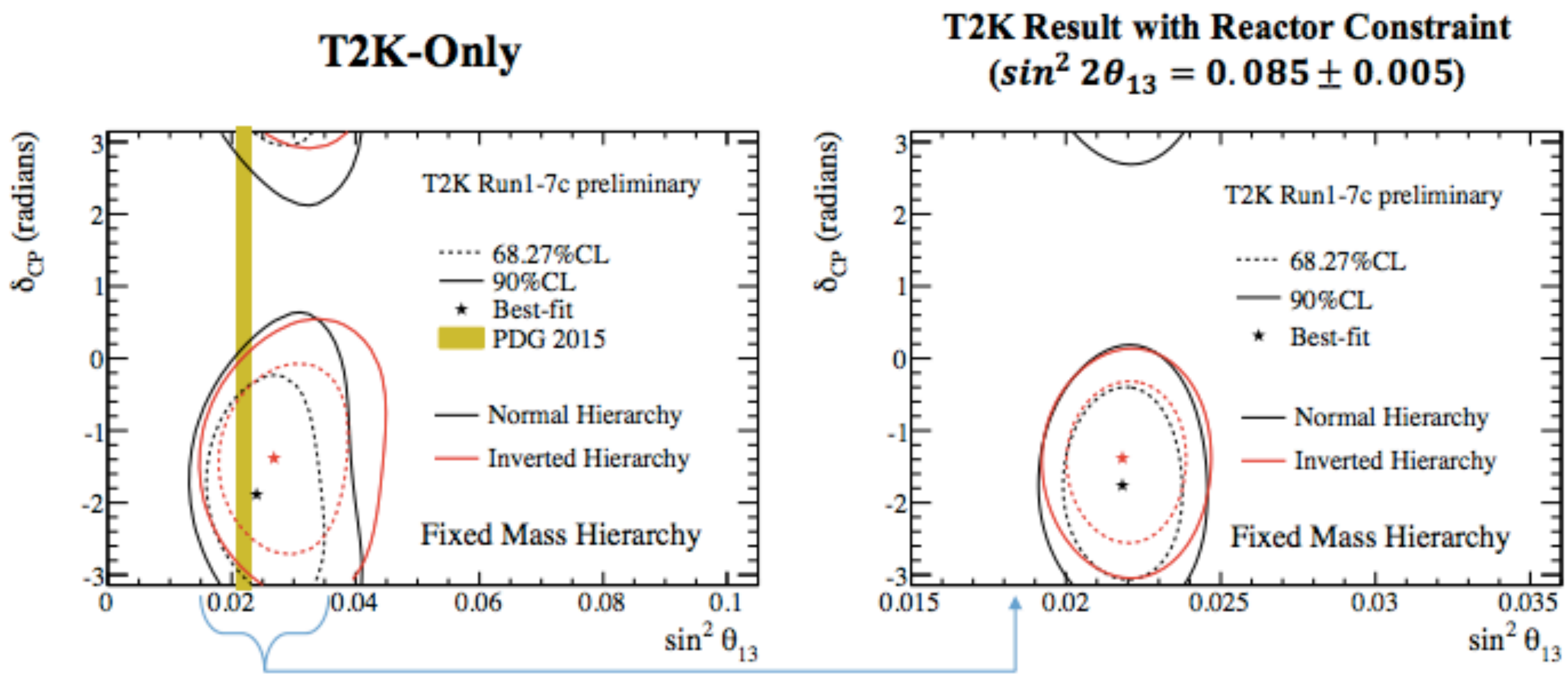


4 events observed

	$\delta_{cp} = -\pi/2$ (NH)	$\delta_{cp} = 0$ (NH)	$\delta_{cp} = +\pi/2$ (NH)	$\delta_{cp} = \pi$ (NH)	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

K. Iwamoto, ICHEP 2016

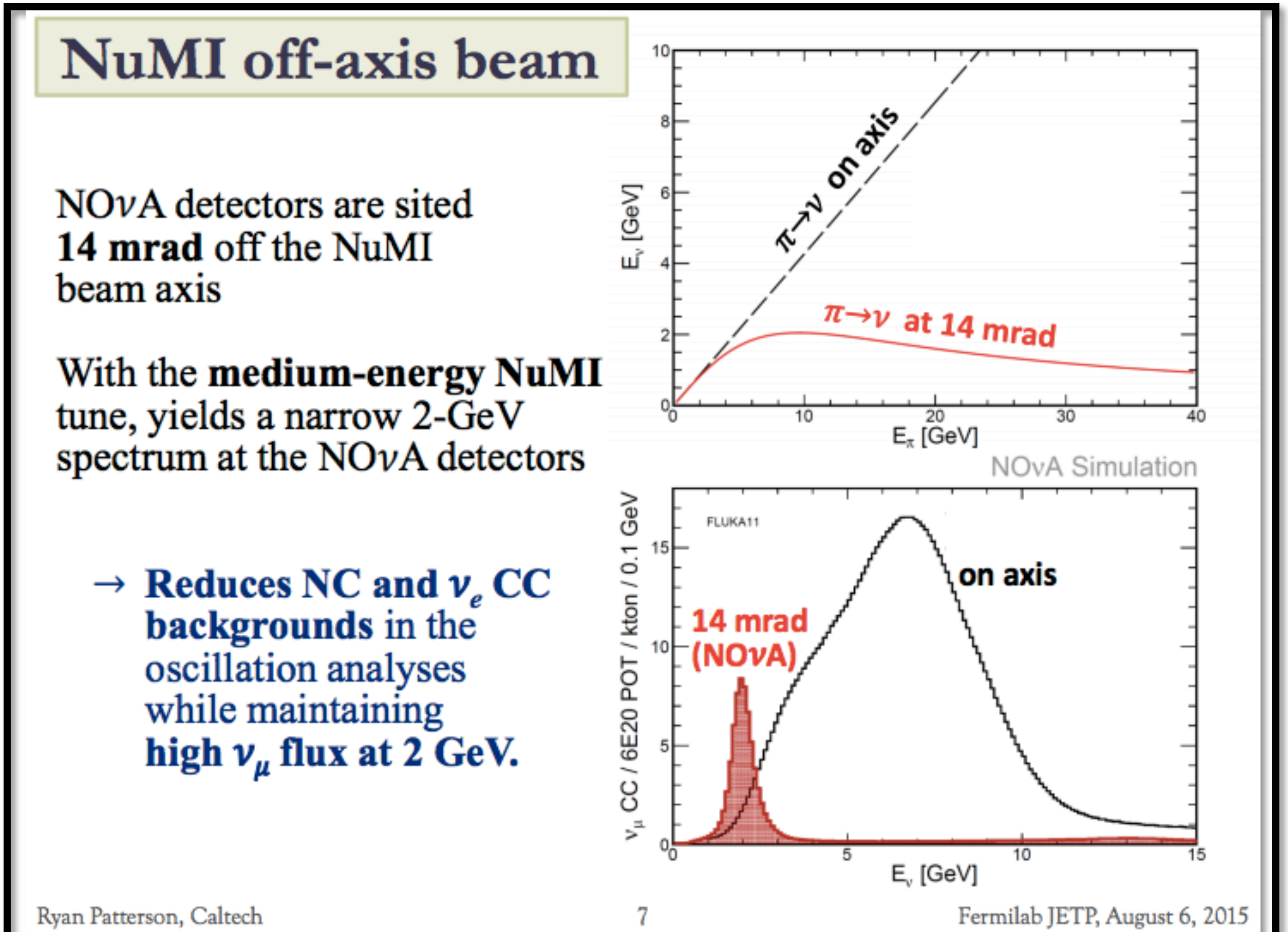
T2K Results: Hint of CPV?



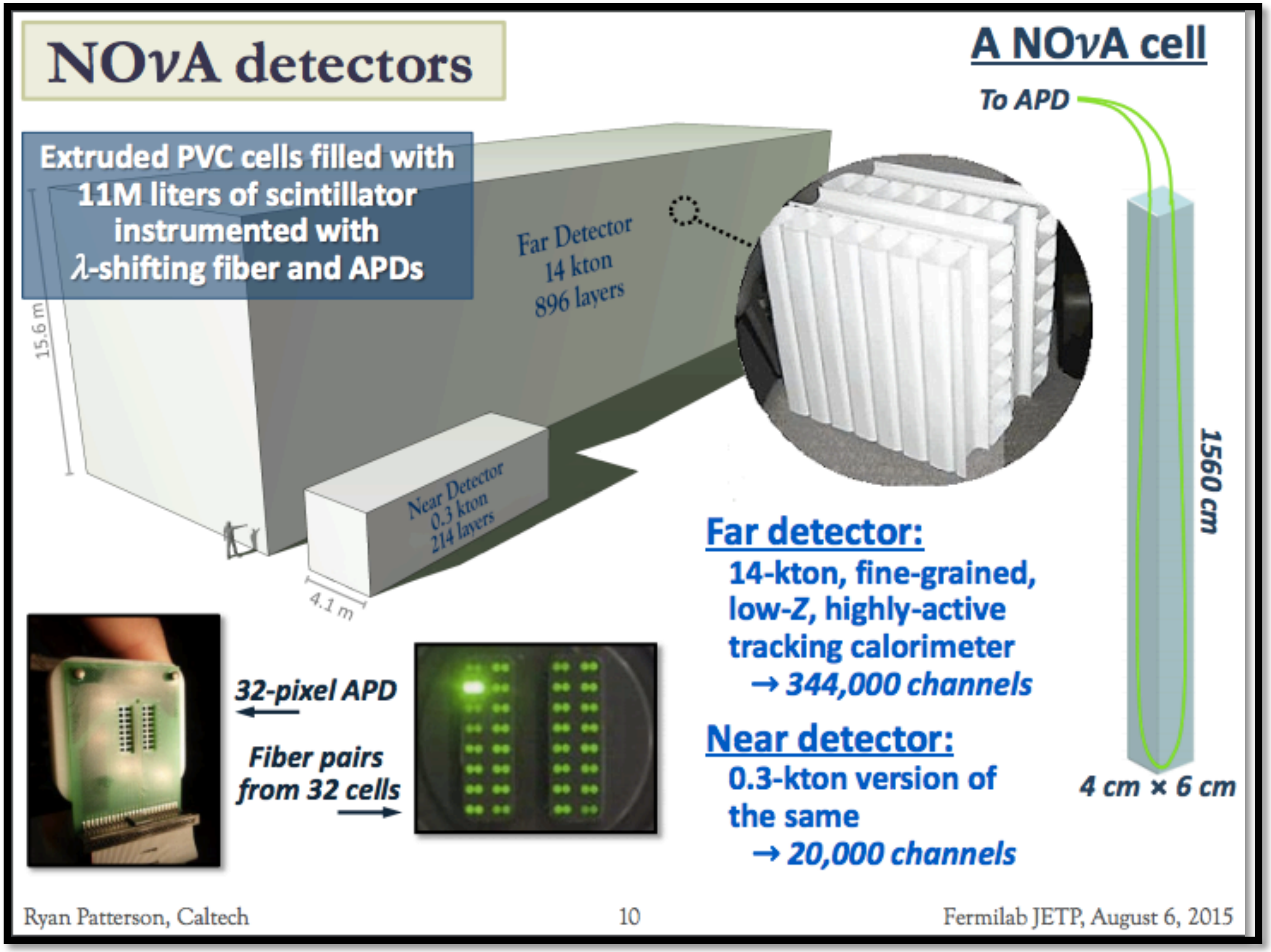
- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region

K. Iwamoto, ICHEP 2016

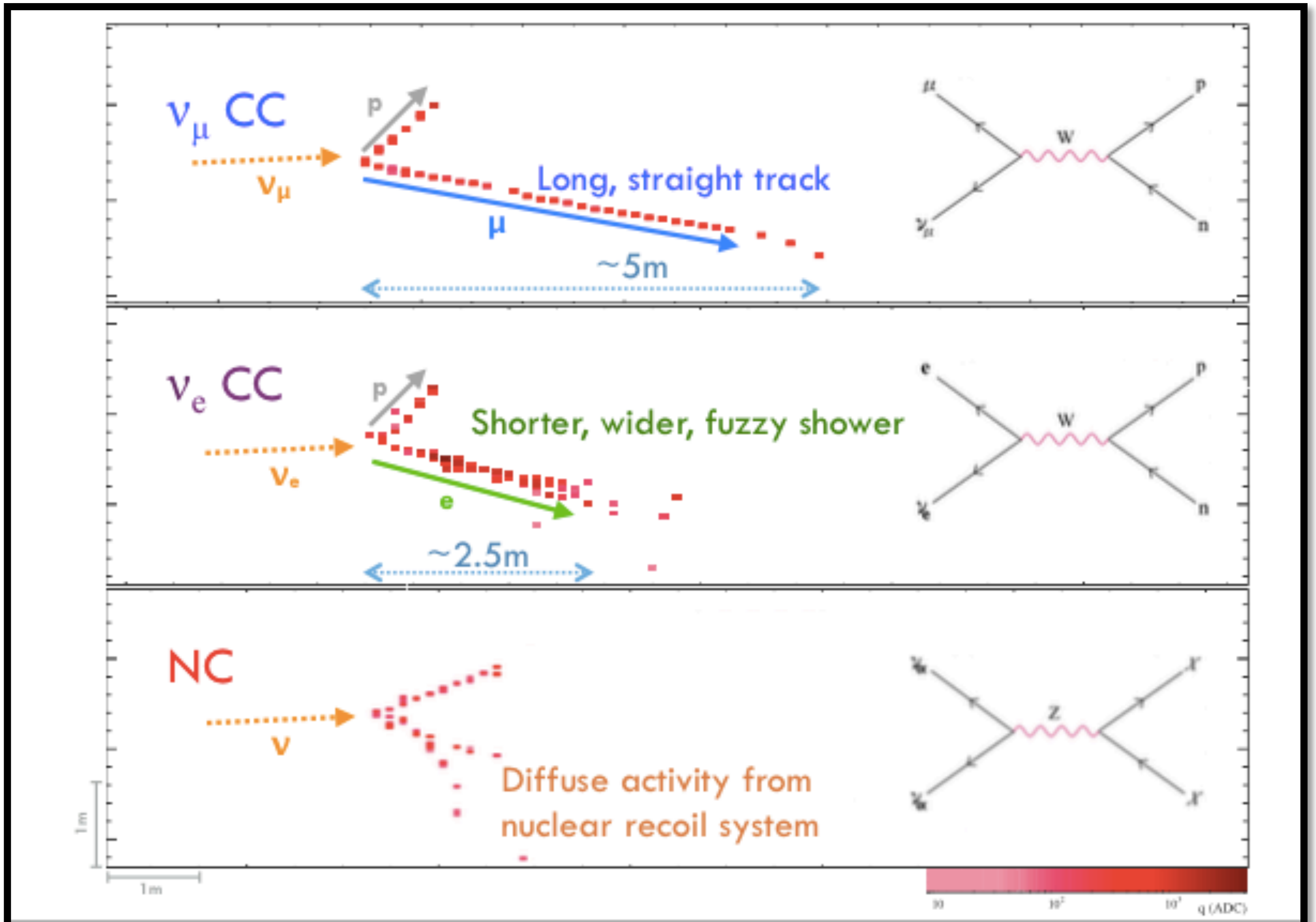
NOvA Beam


NuMI off-axis beam
NOνA detectors are sited **14 mrad** off the NuMI beam axis
With the **medium-energy NuMI** tune, yields a narrow 2-GeV spectrum at the NOνA detectors
→ **Reduces NC and ν_e CC backgrounds** in the oscillation analyses while maintaining **high ν_μ flux at 2 GeV.**
π→ν on axis
π→ν at 14 mrad
E_ν [GeV]
E_π [GeV]
NOνA Simulation
FLUKA11
on axis
14 mrad (NOνA)
ν_μ CC / 6E20 POT / kton / 0.1 GeV
E_ν [GeV]
Ryan Patterson, Caltech
7
Fermilab JETP, August 6, 2015

NOvA Detectors



Neutrino Detection in NOvA

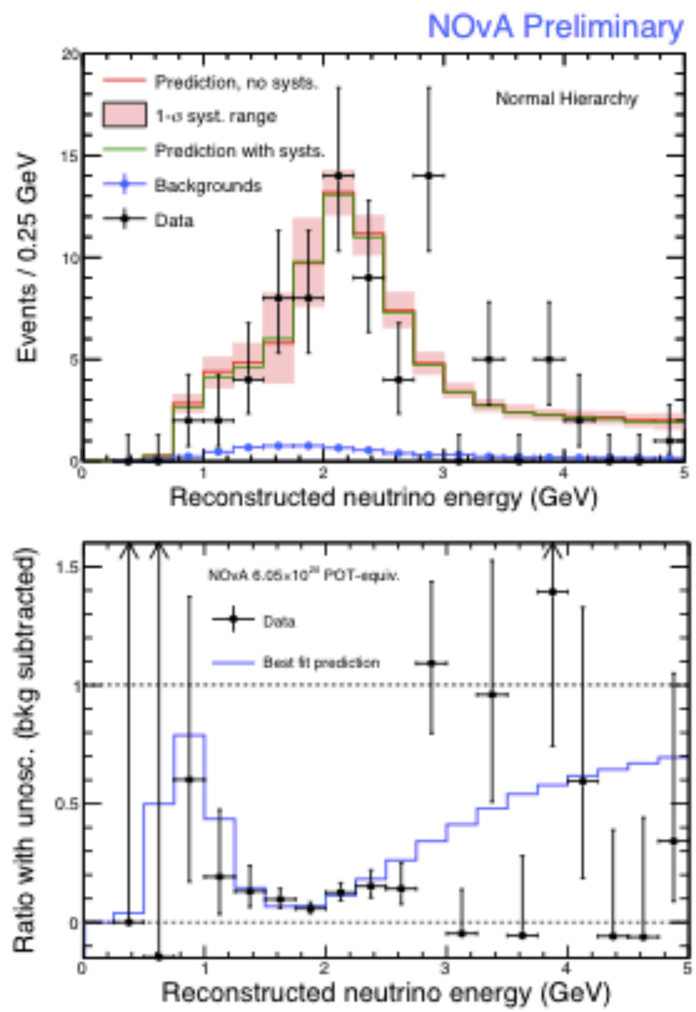


P. Vahle, Neutrino 2016

NOvA Results: ν_μ Disappearance

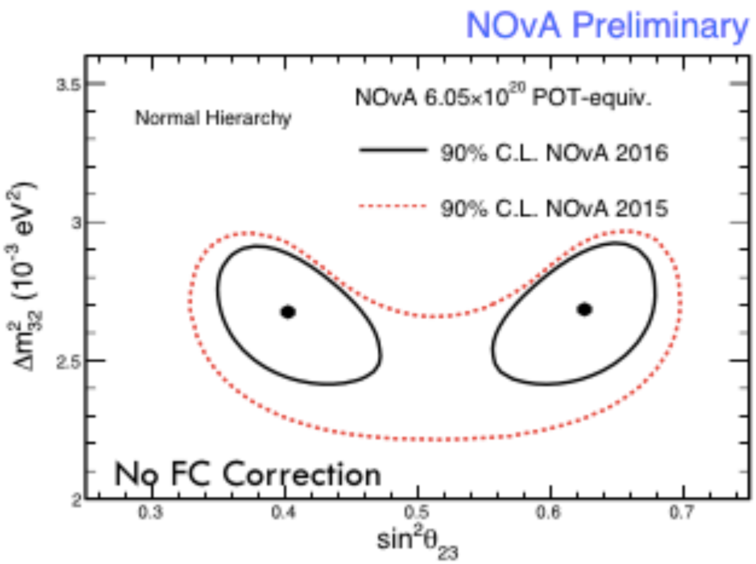
- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

χ^2/NDF=41.6/17
Driven by fluctuations in tail,
no pull in oscillation fit



P. Vahle, Neutrino 2016

Hint of non-maximal mixing?



- Fit for Δm^2 and $\sin^2\theta_{23}$
- Dominant systematic effects included in fit:
  - Normalization
  - NC background
  - Flux
  - Muon and hadronic energy scales
  - Cross section
  - Detector response and noise

Best Fit (in NH):

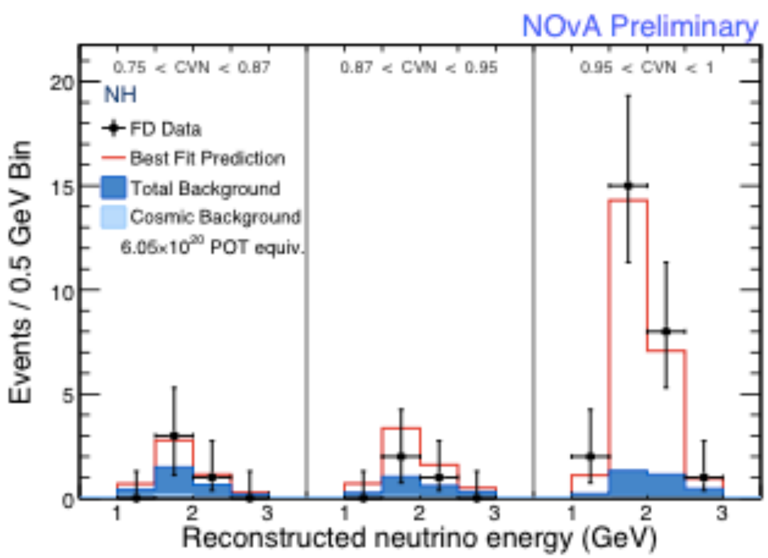
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

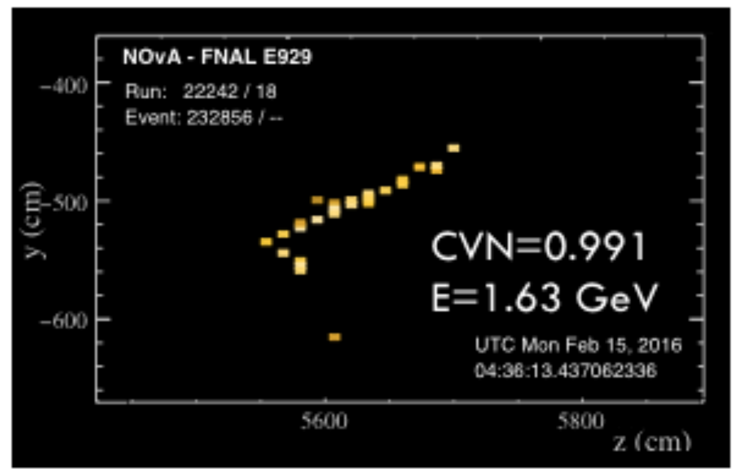
P. Vahle, Neutrino 2016

NOvA Results: ν_e Appearance

>8σ electron neutrino appearance signal



- Observe 33 events in FD
  - background 8.2±0.8



P. Vahle, Neutrino 2016

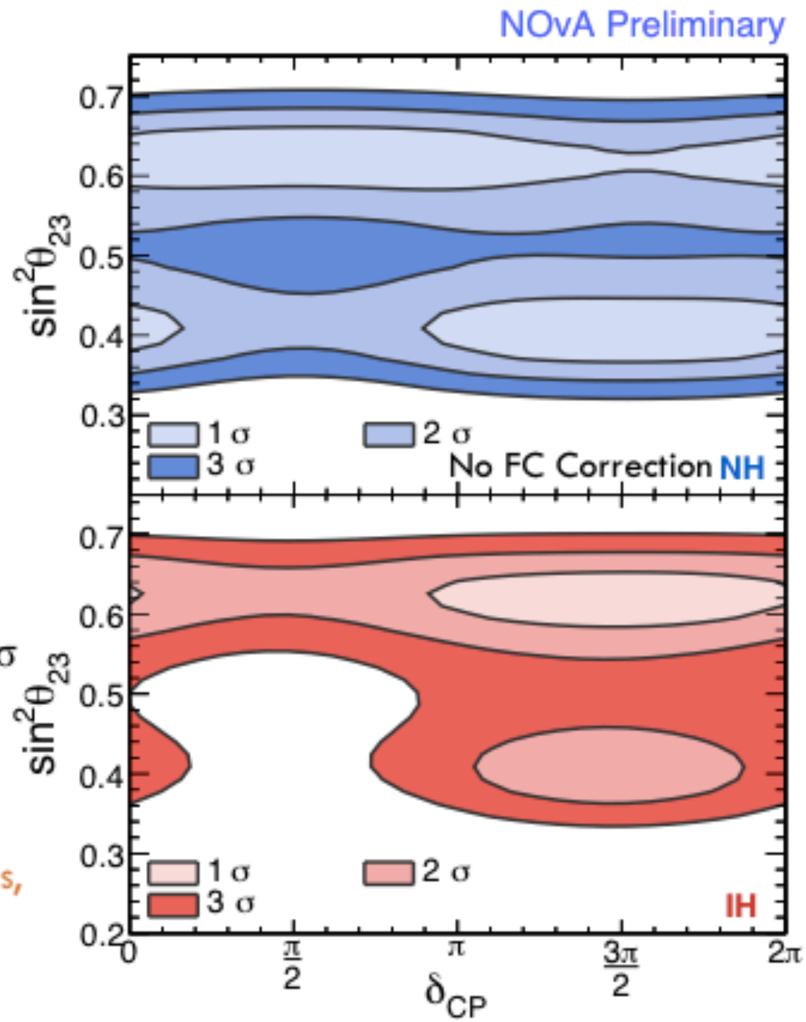
NOvA Results: ν_e Appearance

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$

Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017



P. Vahle, Neutrino 2016

Future Experiments

T2HK: Tokai to HyperK

- Beam: J-PARC
- Far detector: HyperK
  - WCD (~500 kt)
- Baseline: 295 km
- Far detector located off-axis such that observed ν flux is peaked at ~600 MeV

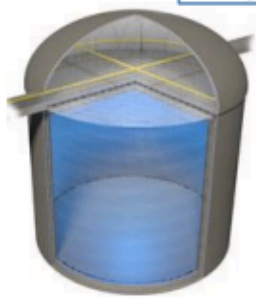
DUNE: FNAL to SURF

- Beam: LBNF (FNAL)
- Far detector: LArTPC (~40 kt fiducial)
- Baseline: 1300 km
- Far detector located on-axis such that observed ν flux is a broadband spectrum covering 1^{st} and some of 2^{nd} oscillation maximum

Both nominally start operations with beam in 2026

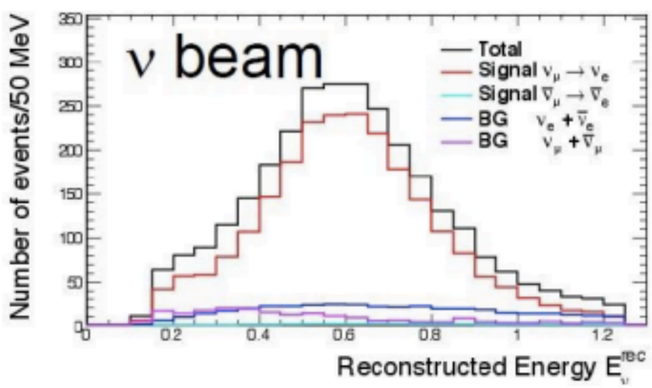
HyperK

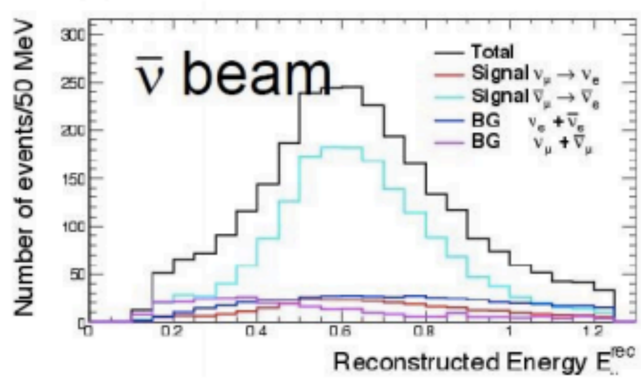
Physics performance for oscillation studies



Assuming
- 10 years of running
- 1.3 MW for JPARC proton beam
- 1 tank then 2 tanks
- ~ 40% PMT coverage in HK
- 3-4% systematic uncertainties

Electron-neutrino appearance

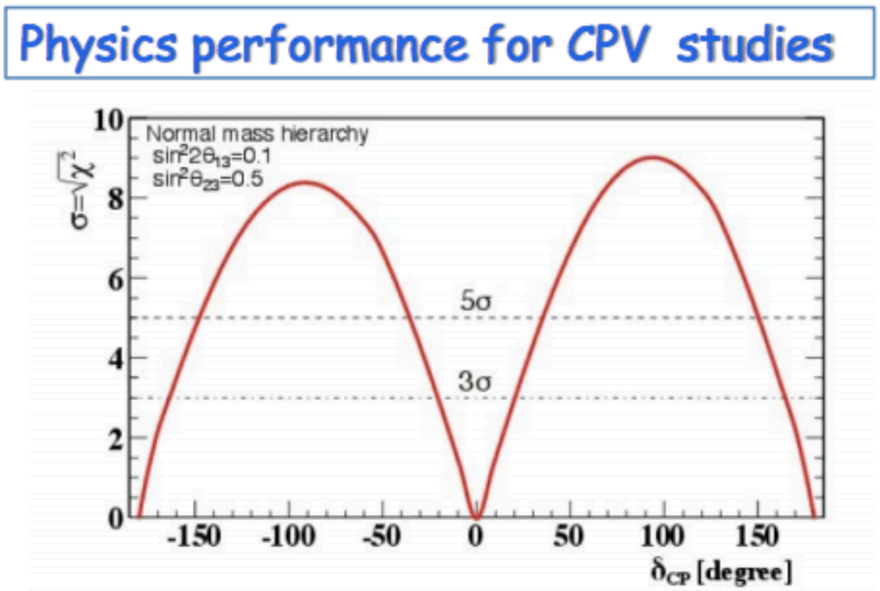




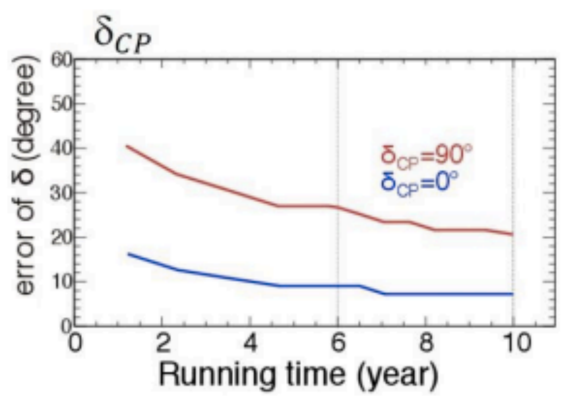
δ=0	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu, \bar{\nu}_\mu$ CC	Beam $\nu_e, \bar{\nu}_e$ contamination	NC
ν beam	2300	21	10	362	188
$\bar{\nu}$ beam	1656	289	6	444	274

M. Gonin, ICHEP 2016

HyperK

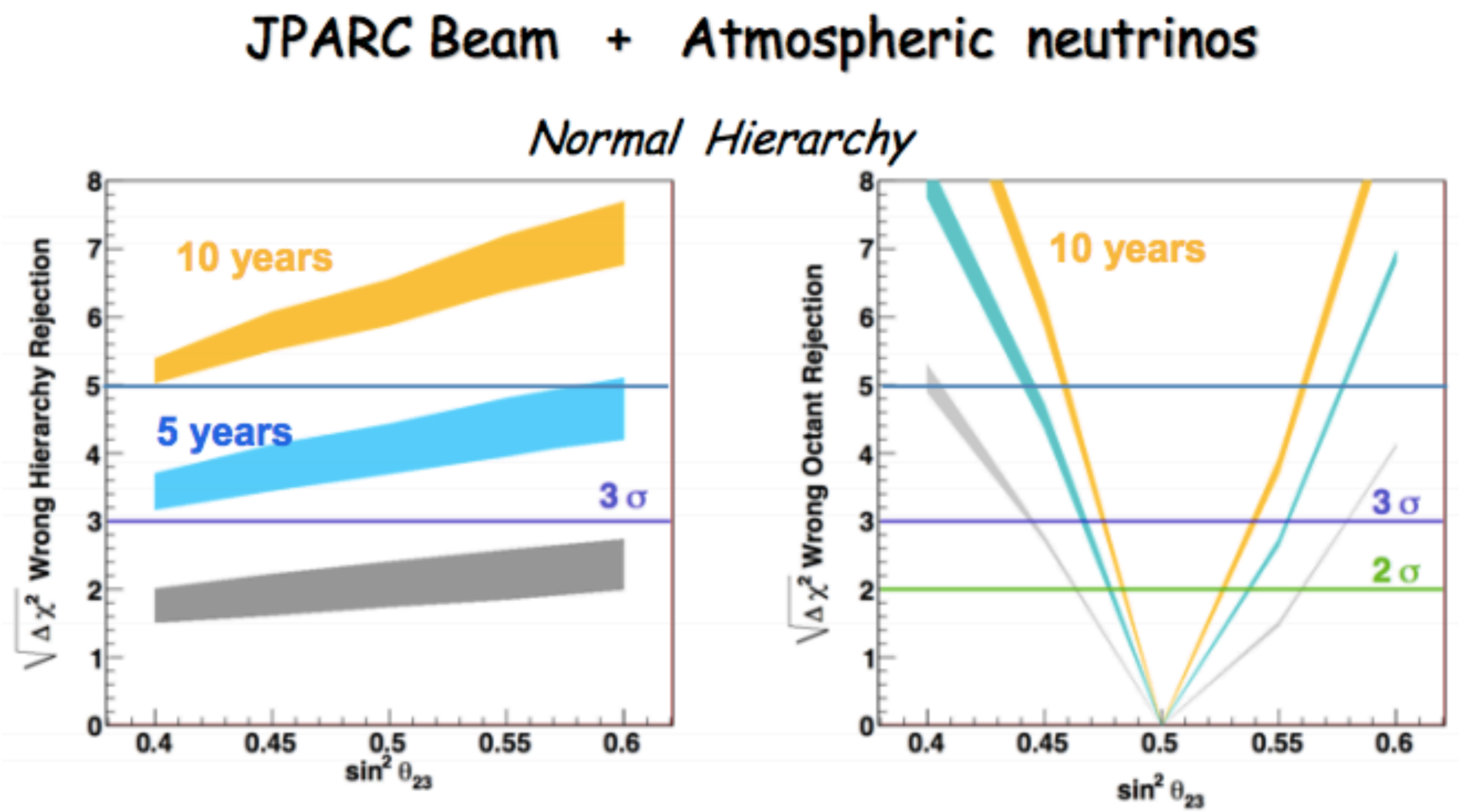


- Exclusion of sinδ_{CP}=0
  - 8σ for δ=-90°
  - 80% coverage of δ parameter space for CPV discovery w/ >3σ
- δ_{CP} precision measurement
  - 20° for δ=-90°
  - 7° for δ=0°



M. Gonin, ICHEP 2016

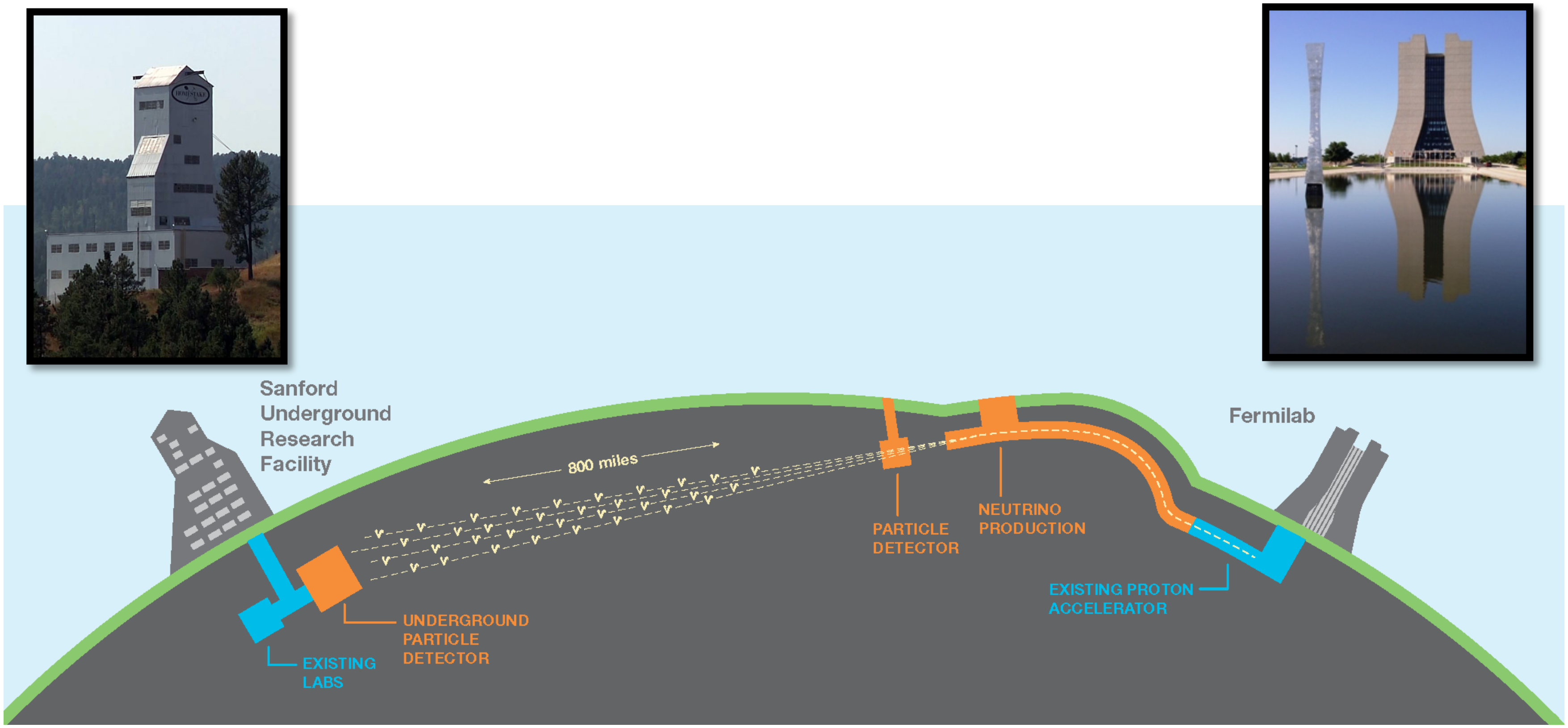
HyperK



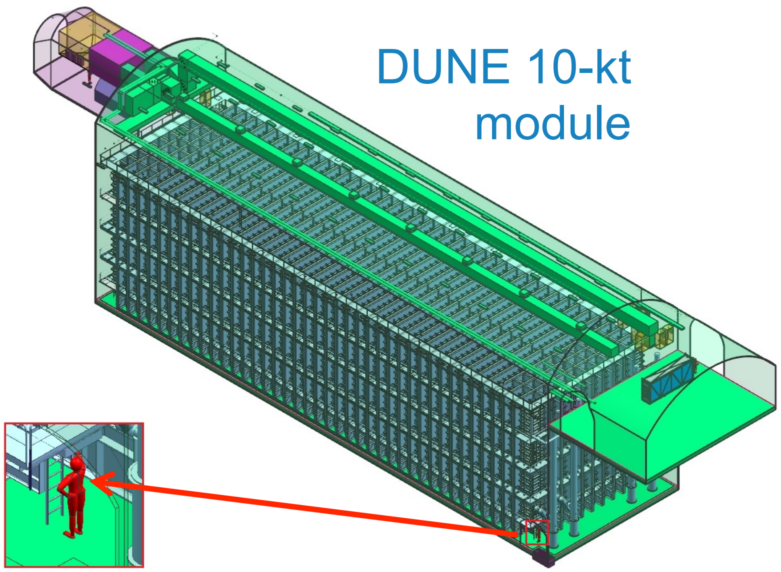
M. Gonin, ICHEP 2016

DUNE

Measure ν_e appearance and ν_μ disappearance in a wideband neutrino beam at 1300 km to measure MH, CPV, and neutrino mixing parameters in a single experiment. Large detector, deep underground provides sensitivity to nucleon decay and supernova burst neutrinos.



DUNE Far Detector

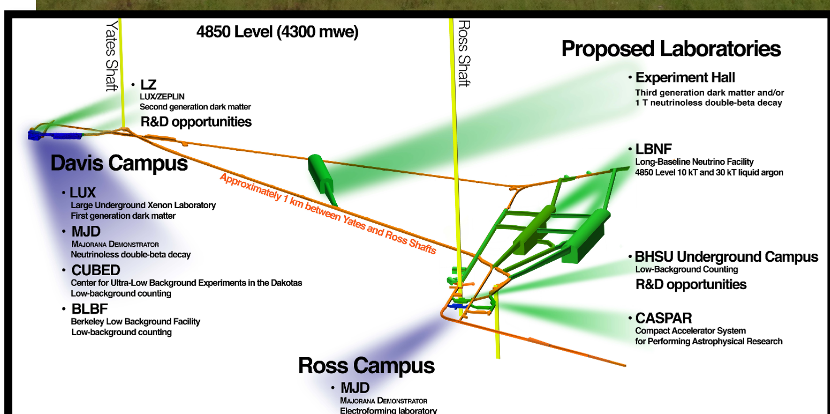


- One 10-kt module (active):
- 12 m high
- 15.5 m wide
- 58 m long
- 150 “APAs” (2.3 m x 6 m)
- 384,000 readout wires

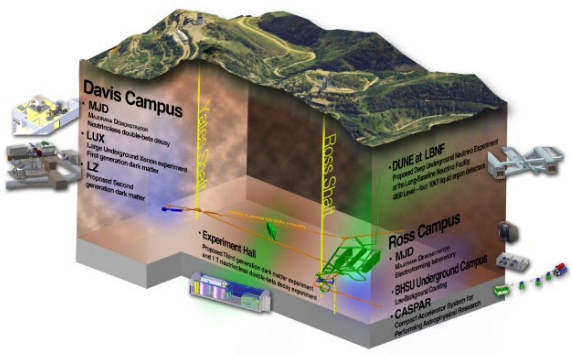
- 40-kt (fiducial) liquid argon TPC at 4850L of SURF
  - Four 10-kt (fiducial) modules
- First module will be a single phase LArTPC
- Modules installed in stages; modules probably will not be identical

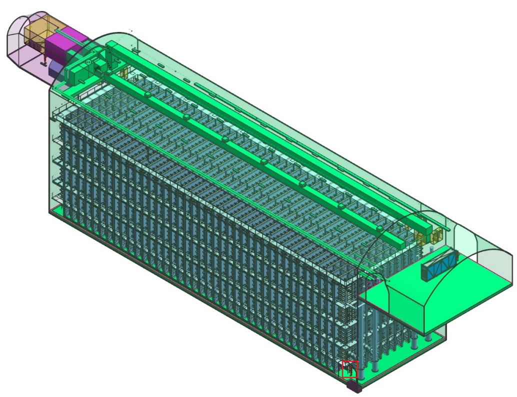
Sanford Underground Research Facility

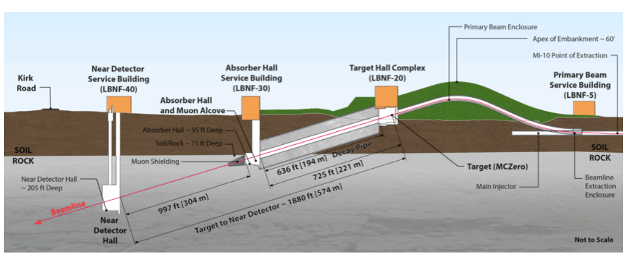
- Located in Lead, SD in the Homestake Mine
- Operated by the state of South Dakota
- Clean, modern experimental area
- Home to LUX and Majorana Demonstrator; planned site of LZ and DUNE far detector



DUNE Timeline







2017: Far Site Construction Begins

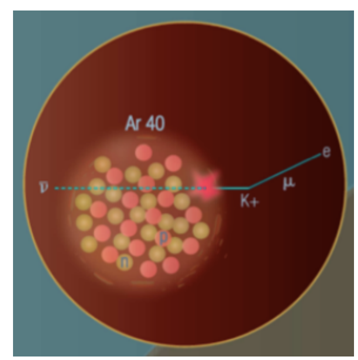
2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

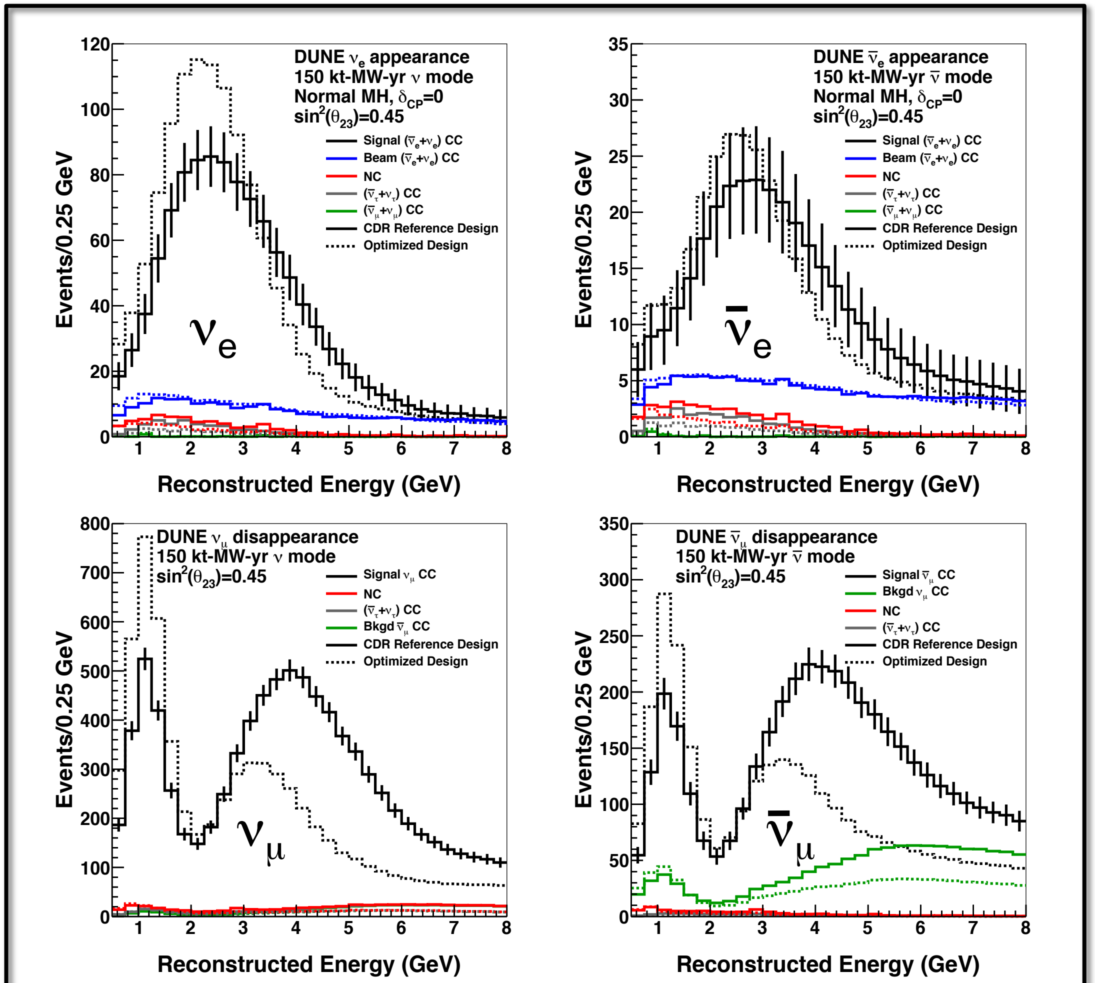
2026: Neutrino Beam Available

The CERN Neutrino Platform



Oscillation Sensitivity Calculations

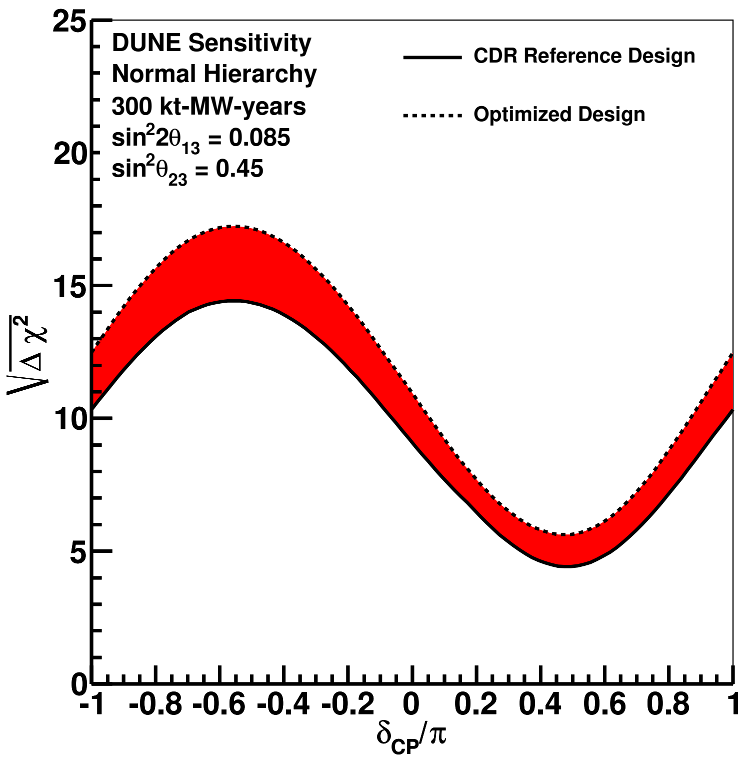
DUNE CDR:



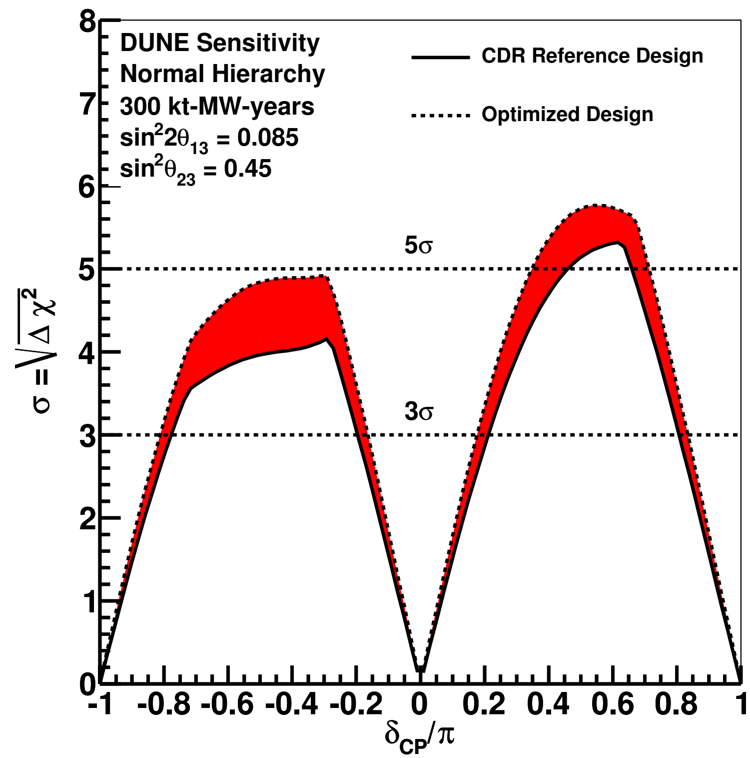
- GLoBES-based fit to four FD samples
- Two neutrino beam line designs shown: optimization of beam design is ongoing
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Order 1000 ν_e appearance events in ~7 years of equal running in neutrino and antineutrino mode
- Simple systematics treatment
- GLoBES configurations arXiv:1606.09550

MH & CPV Sensitivity

DUNE CDR: Mass Hierarchy



CP Violation

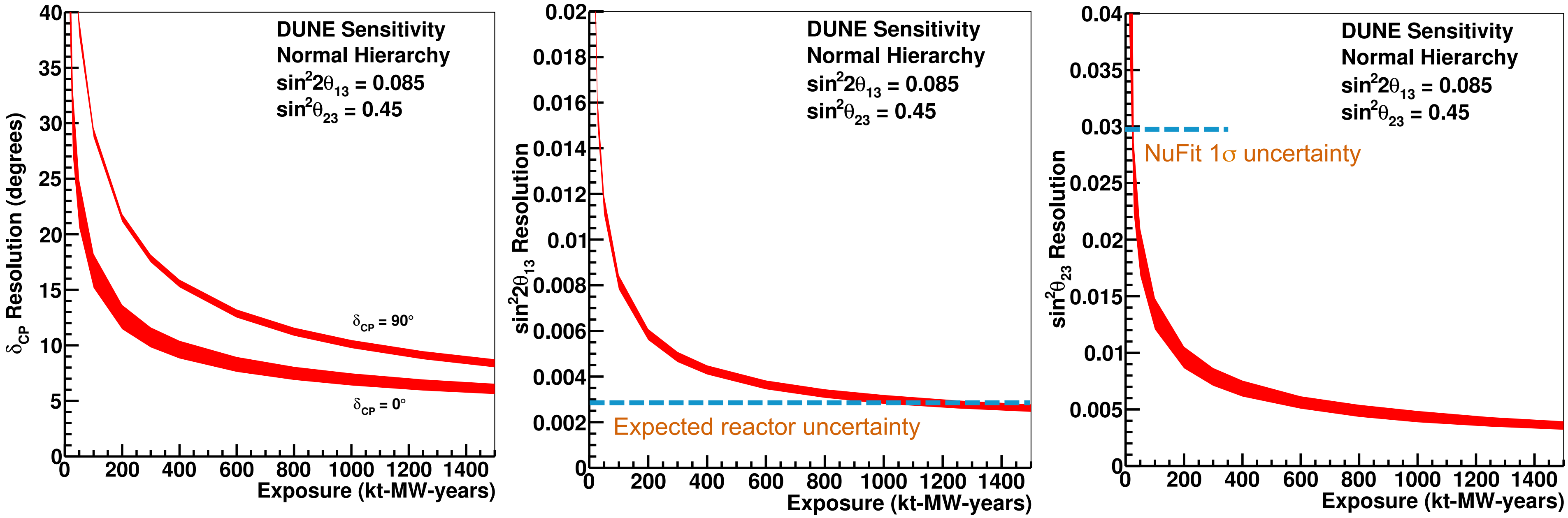


Width of band indicates variation among differing neutrino beam designs.
Exposure is 300 kt-MW-yr = 40 kt x 1.07 MW x ($3.5\nu + 3.5\bar{\nu}$) years.
Includes simple normalization systematics and oscillation parameter variations.

Oscillation Parameter Sensitivity

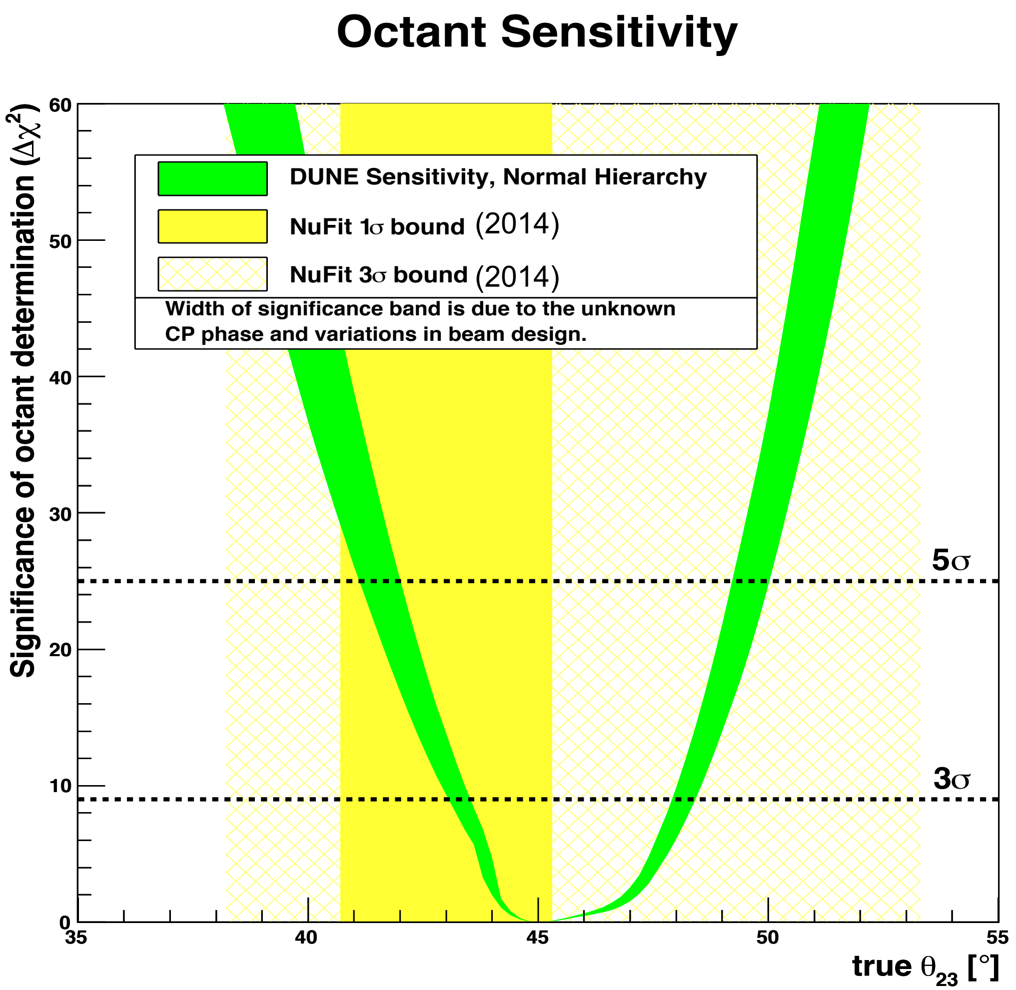
DUNE CDR:

δ_{CP} Resolution | $\sin^2 2\theta_{13}$ Resolution | $\sin^2\theta_{23}$ Resolution



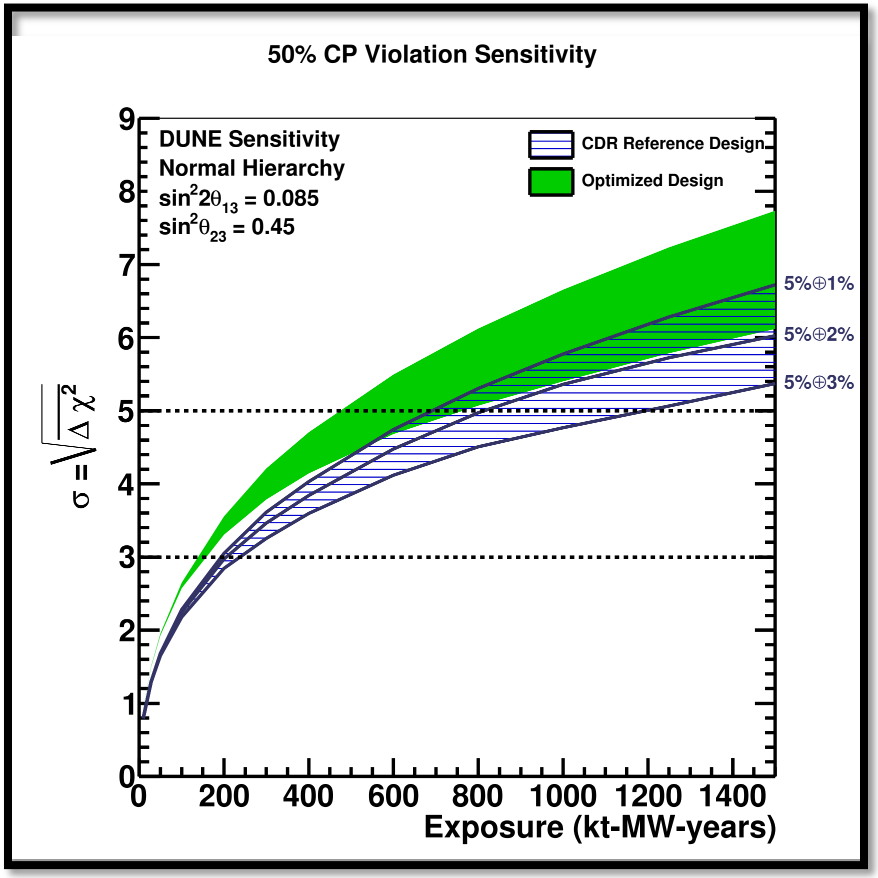
Octant Sensitivity

DUNE CDR:



Systematic Uncertainty

DUNE CDR:



- Next generation long-baseline experiments require precise control of systematic uncertainty ("the precision era of neutrino oscillation")
- Systematic uncertainty arises from uncertainty in:
  - Neutrino flux (beam)
  - Neutrino interactions
  - Detector reconstruction and event selection
- Rely partially on cancellation of uncertainty between appearance/disappearance and neutrino/antineutrino samples

When?

Now: Reactor, SuperK, ICECUBE, MicroBooNE, T2K, NOvA

↓

Near future: VSBL reactor, SBND, ICARUS, protoDUNEs

↓

Future: HyperK, DUNE, ?

Summary

- Neutrino oscillation experiments use a large variety of detector technologies, covering energies from the MeV to multi-GeV scale
- “Anomalous” results hint at sterile oscillations while ever-stronger constraints applied by other results
- May be seeing initial hints of non-maximal θ_{23}, CP violation?
- Next-generation long-baseline experiments provide a huge step forward in ν_e appearance statistics
- It’s a very busy time for the field of neutrino oscillation!