University of Sussex

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Fermilab Neutrino Programme

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Science & Technology Facilities Council

European Research Council
Established by the European Commission

PPAP Meeting, RAL

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Introduction

- Long and short baseline experiments

- NOvA
- DUNE
- SBND, MicroBooNE (and Icarus)
- MINOS+

- UK involvement

Programme spans present and future

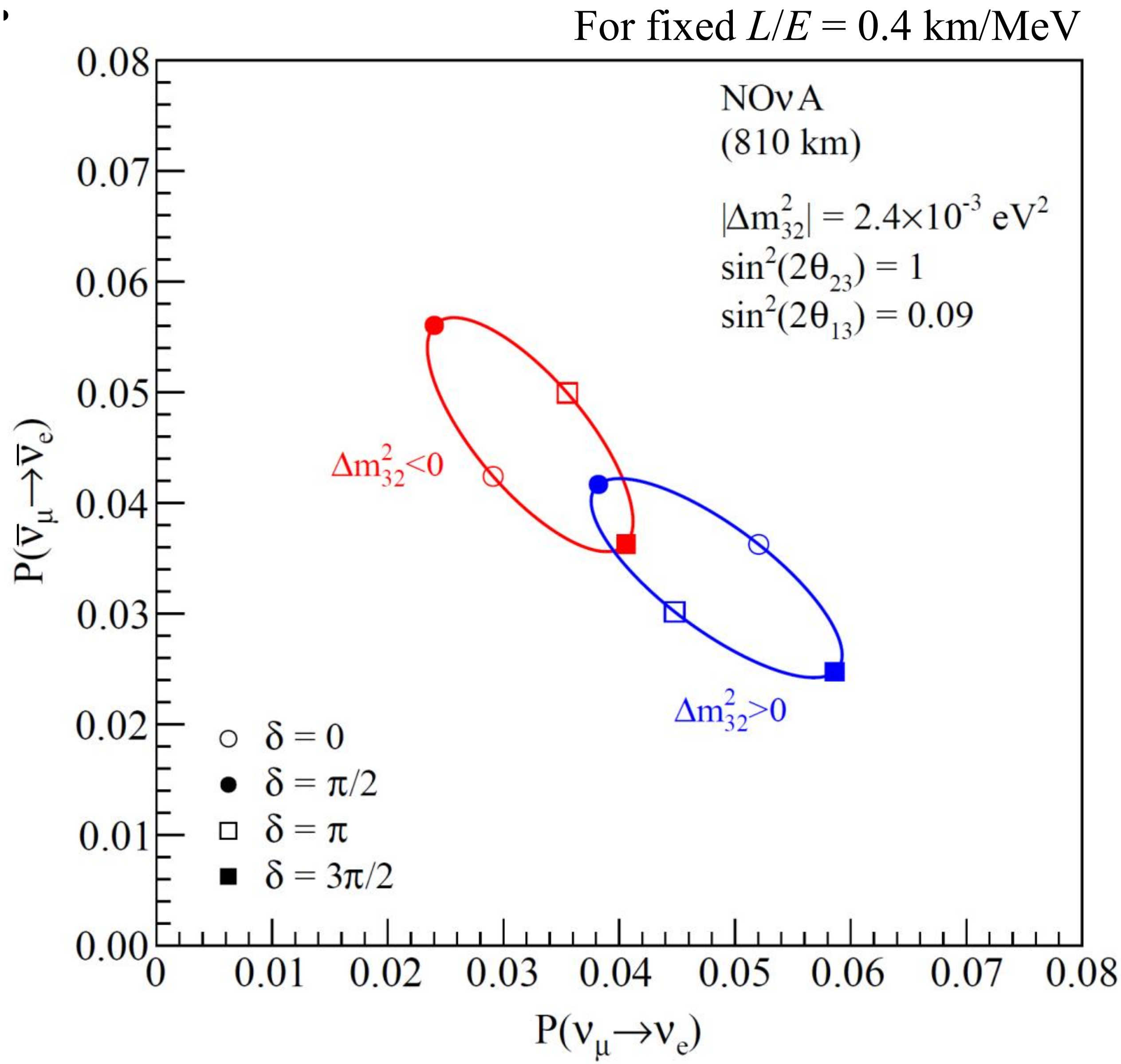
- Present:
  - MINOS+ (final analysis phase, data taking complete)
  - NOvA (early publications, much data and physics to come)

  - MicroBooNE (data taking, first physics results soon)
  - SBND and Icarus (data taking starts in 1-2 years)

- Next generation:
  - DUNE (approved and under construction)

Long-baseline Key Measurement

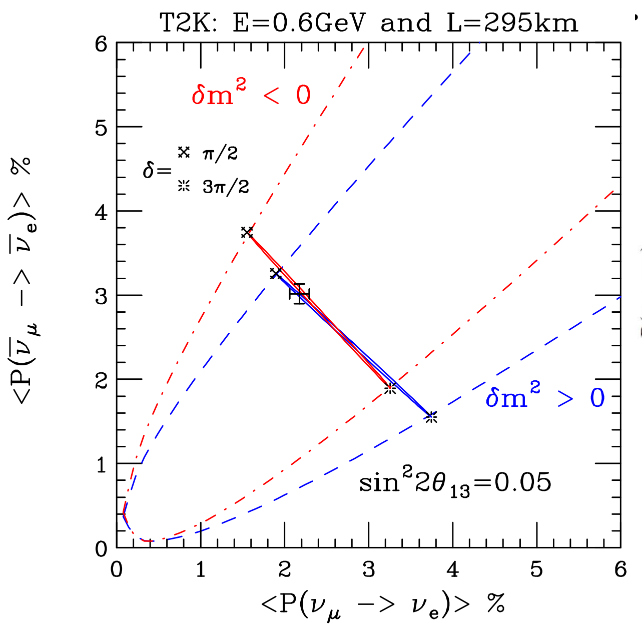
Electron (anti)neutrino Appearance



Effect of Increasing Energy

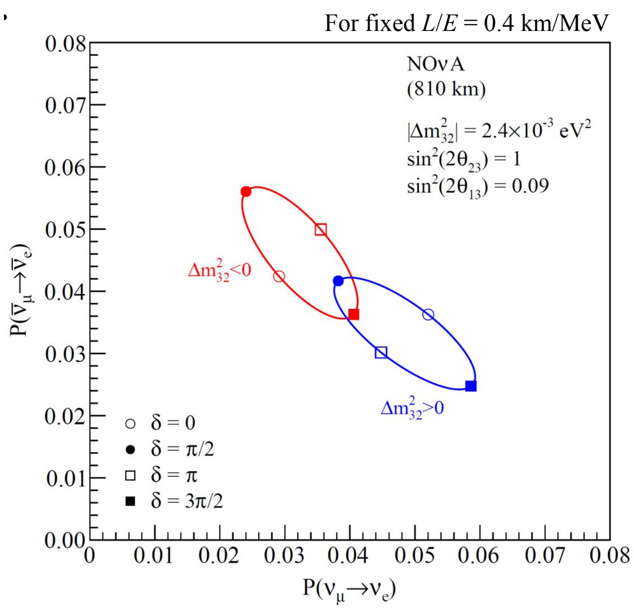
(which requires a longer baseline for oscillations to occur)

T2K (HK)



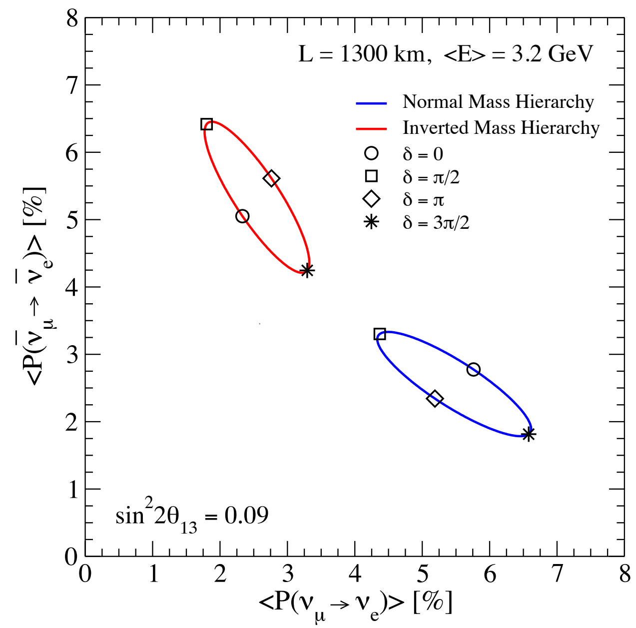
0.6 GeV

NOvA



2 GeV

DUNE



3 GeV

Increasing Energy

[→ bigger matter effect and hence bigger fake CP violation]

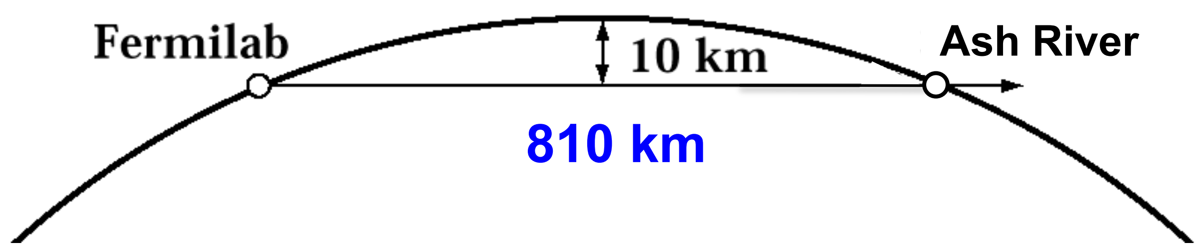
NOvA

NOvA Overview

- "Conventional" beam
- Two-detector experiment:

- Near detector
  - measure beam composition
  - energy spectrum

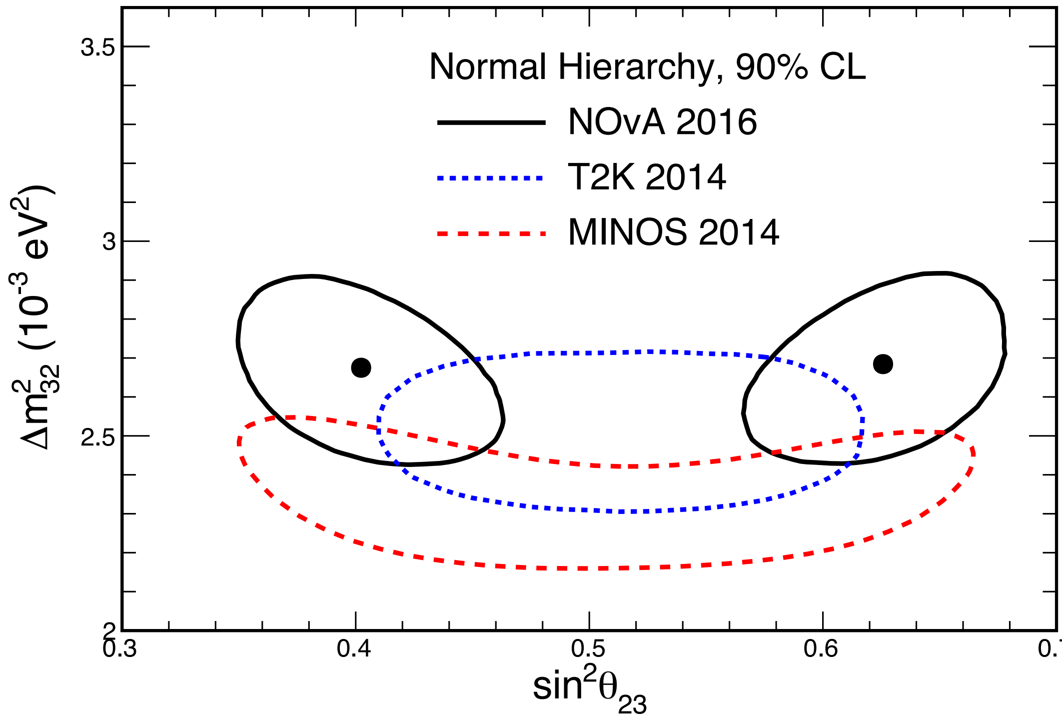
- Far detector
  - measure oscillations and search for new physics



Muon neutrino disappearance

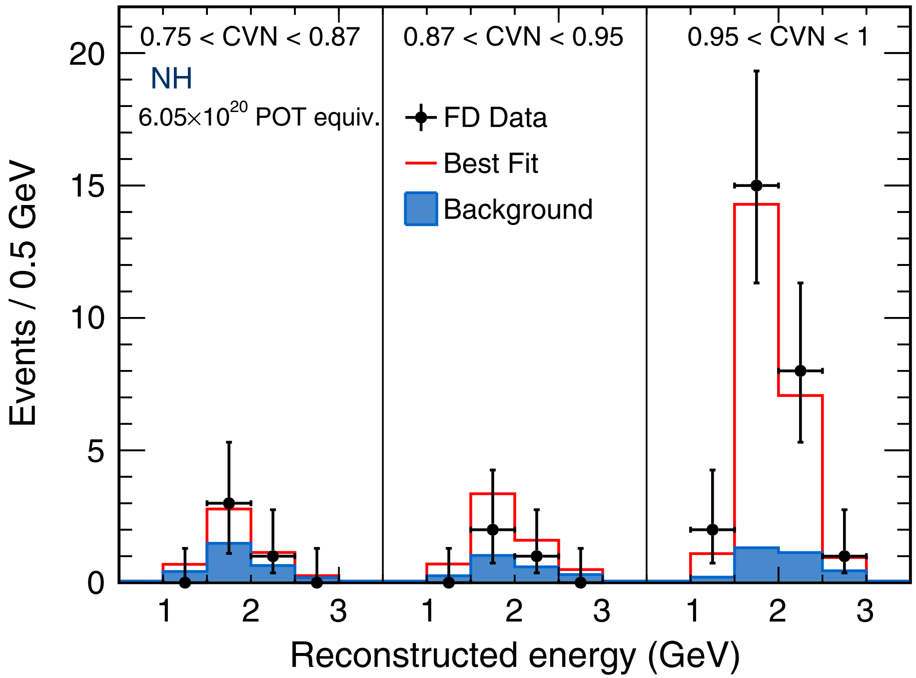
Key question: is there a mu-tau symmetry with $\theta_{23}=\pi/4$?

Phys. Rev. Lett. 118, 151802

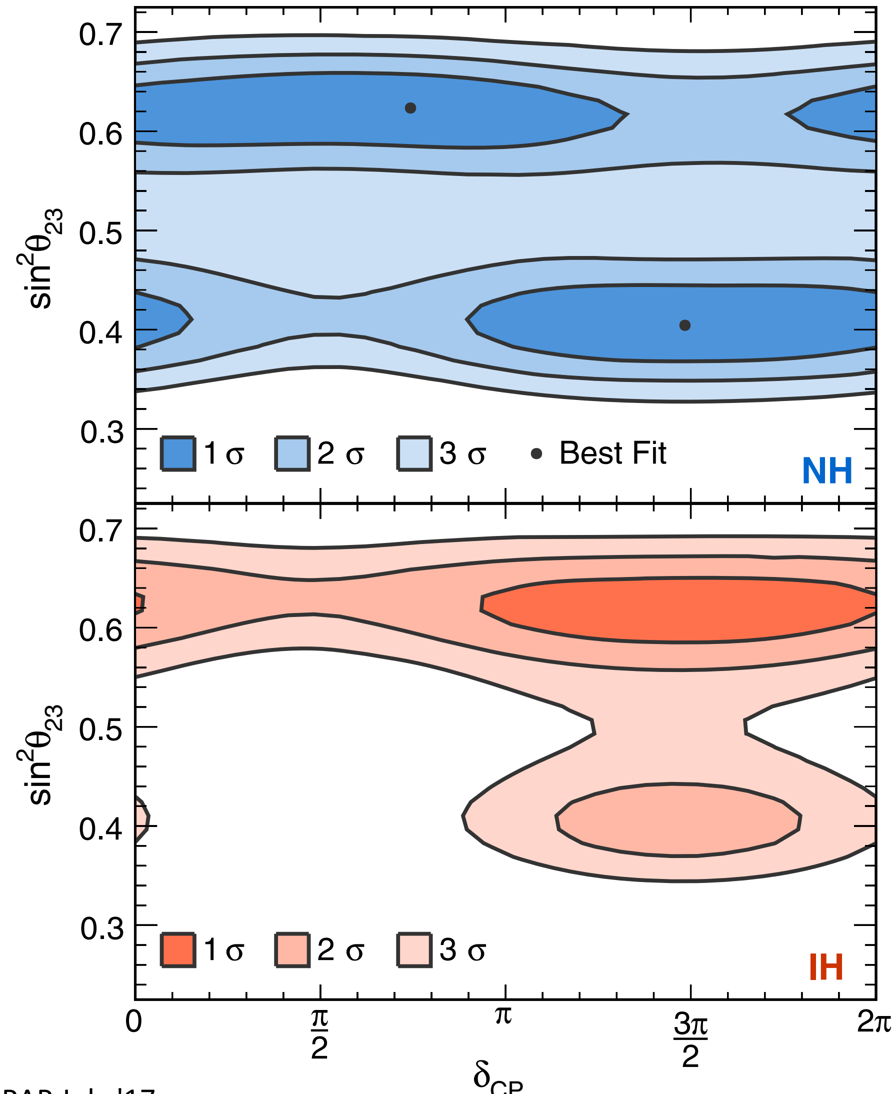


Maximal mixing excluded at 2.6σ

Electron neutrino appearance
(Combined with ν_μ disappearance)



Phys. Rev. Lett. 118, 231801

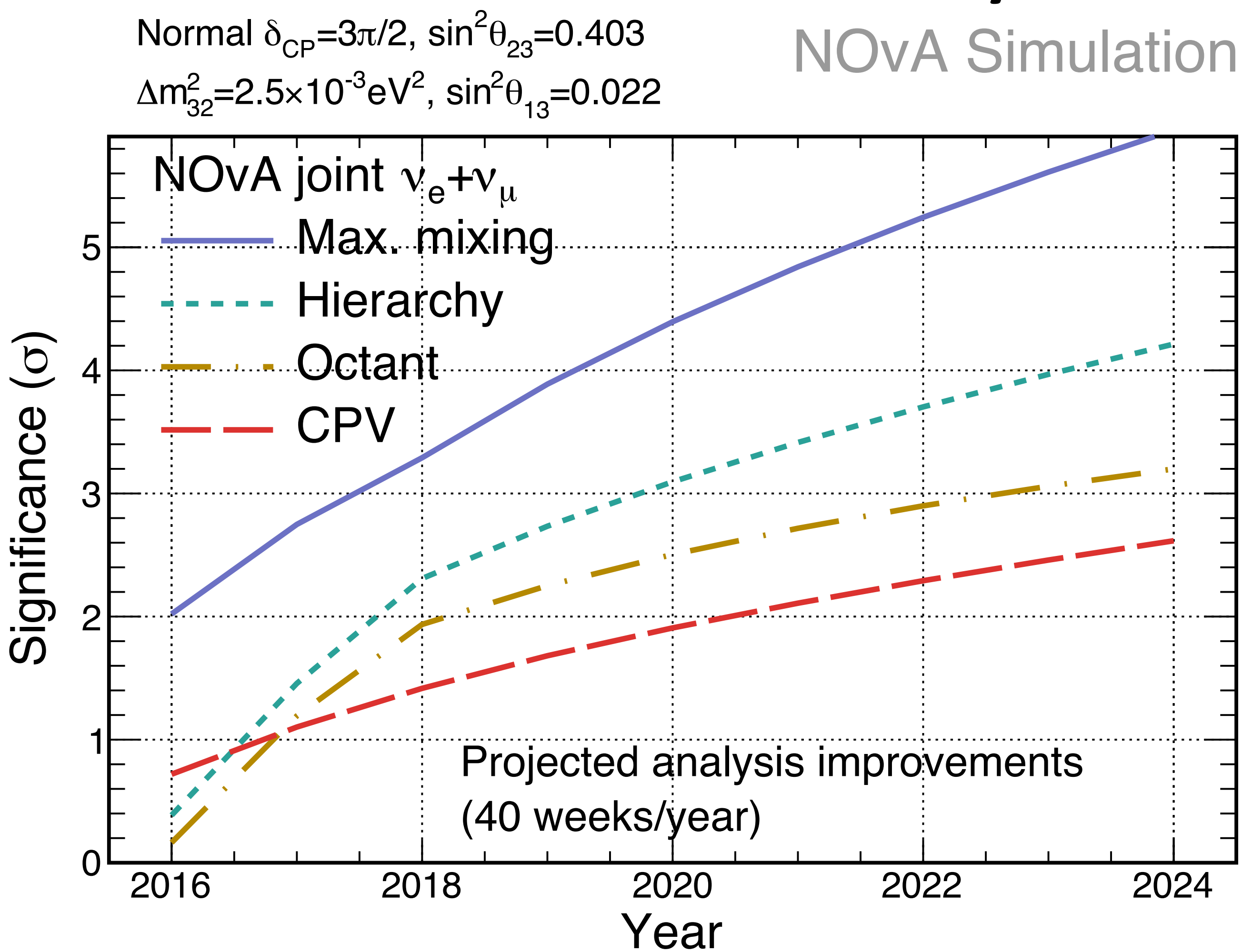


New information on 3 unknowns: mass hierarchy, δ_{CP} and θ_{23} octant.

UK involvement

- Chair of the Institutional Board and Executive Committee member: J. Hartnell (Susx)
- Co-convenors of the two primary analyses
  - Nue Appearance: C. Backhouse (UCL from Oct.)
  - NuMu Disappearance: J. Hartnell (Susx)
- Both Calibration co-convenors: R. Nichol (UCL) and B. Zamorano (Susx)
- Co-convenor of analysis fitting framework (FNEX): S. Germani (UCL)

Future Sensitivity

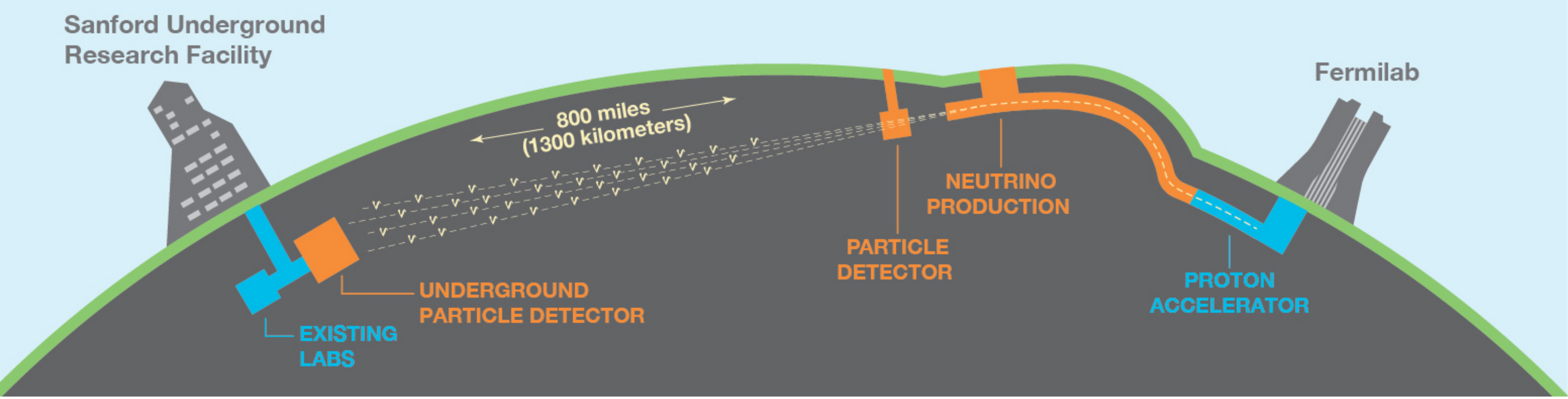


Great complementarity with T2K phase-II due to NOvA's longer baseline and higher energy beam. UK has strong groups on both experiments for the combined analysis to resolve potential degeneracies.

DUNE

DUNE Overview

- Approved expt., under construction ($50M in FY17)
  - Ground-breaking ceremony tomorrow in South Dakota
  - Continued strong support from new administration
- Due to take beam data in 2026 with
  - new MW-scale neutrino beamline (LBNF)
  - 4x10-kilotonne (fiducial) liquid argon far detector
  - high-resolution, high-rate near detector
- CERN providing cryostat for first 1x10kt

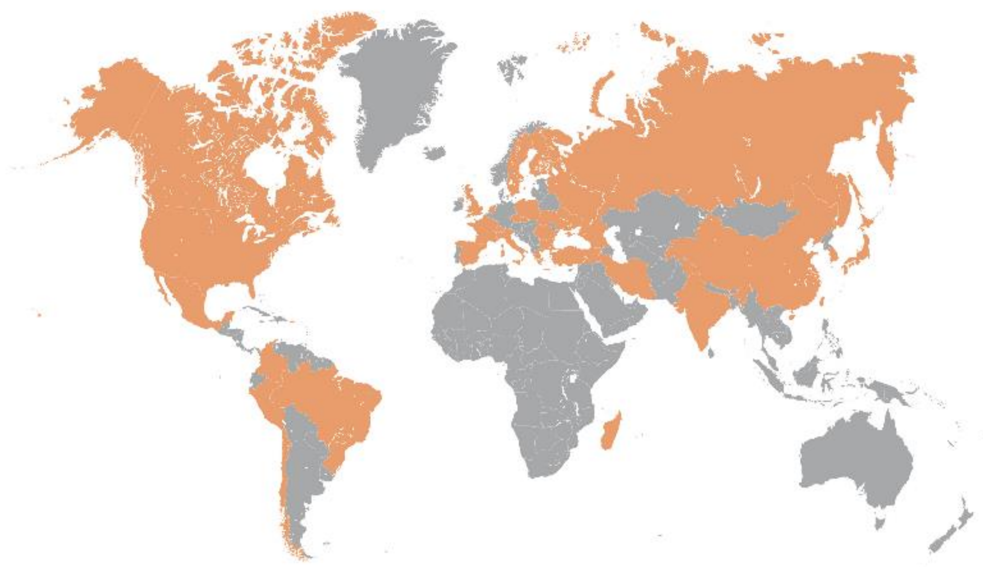


The DUNE Collaboration

60 % non-US

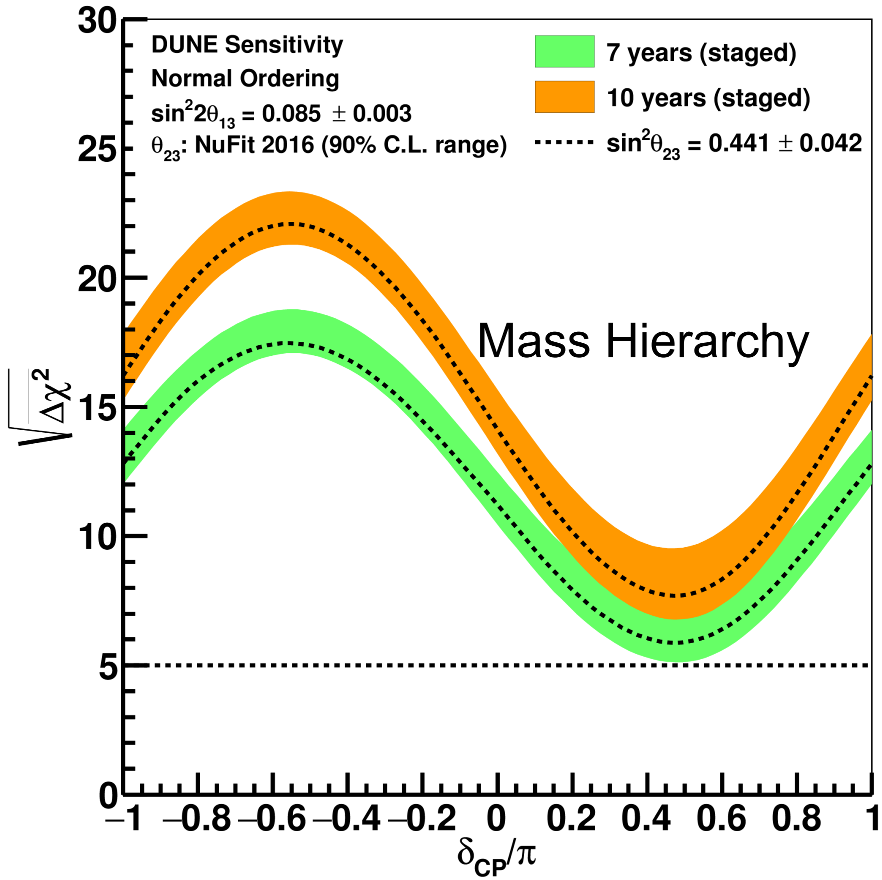
951 collaborators from 164 institutions in 31 nations

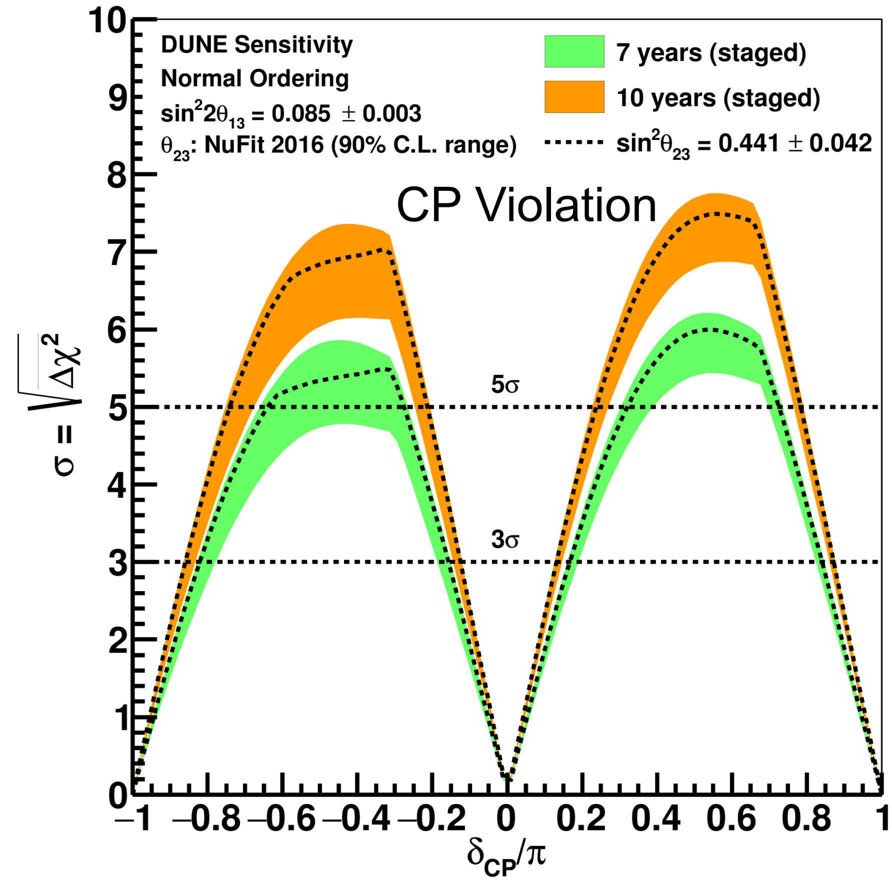
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Peru, Poland, Romania, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, UK, Ukraine, USA



DUNE has broad international support and is growing

DUNE Sensitivity





Wide-band and higher energy beam: => CP, MH, BSM physics in a single expt.

Furthermore, huge, deep, high precision detectors provide abundant non-accelerator physics: proton-decay, supernova neutrinos, ...

ProtoDUNE-SP

- CERN Neutrino Platform
- Large-scale prototyping/ calibration
- UK building 3 (of 6) anode wire planes
  - 6 m tall x 2.3 m wide
- Data taking next year

DUNE UK Involvement

- DUNE Co-spokesperson: M. Thomson (Cam)
- Executive Committee member: S. Soldner-Rembold (Mcr)
- ND Design Study co-convenor: A. Weber (Ox)
- ProtoDUNE-SP Co-coordinator: C. Touramanis (Liv)
- Co-convenor roles in a number of groups

DUNE UK Long-term Objectives

- **To be a leading partner in DUNE far detector construction**
  - ~15% UK core contribution to DUNE
  - TPC readout wire planes (APAs) and the DAQ
- **Construction phase objectives**
  - Construction of 150 of the 300 APAs for the first for 1st 2x10kt
  - UK leadership of the FD DAQ, with UK providing the majority of the back-end DAQ for 1st 2x10kt
  - Continued UK leadership in software/reconstruction
  - Cement leading UK role in preparation for physics exploitation
- **Would secure long-term UK leadership in DUNE**
  - Ionization collection → data readout → reconstruction → physics

DUNE UK Timeline

- Pursuing a clear path towards our long-term goals
  - Developing capabilities/expertise
  - Building the strong team needed for the construction phase

Oct 2014 – Sep 2017

Preparatory Phase
Physics
Reconstruction development
DAQ development
TPC Prototypes

Oct 2017 – Sep 2019

Pre-construction Phase
Physics
Reconstruction for prototypes
DAQ prototyping
Prototype commissioning
APA pre-construction

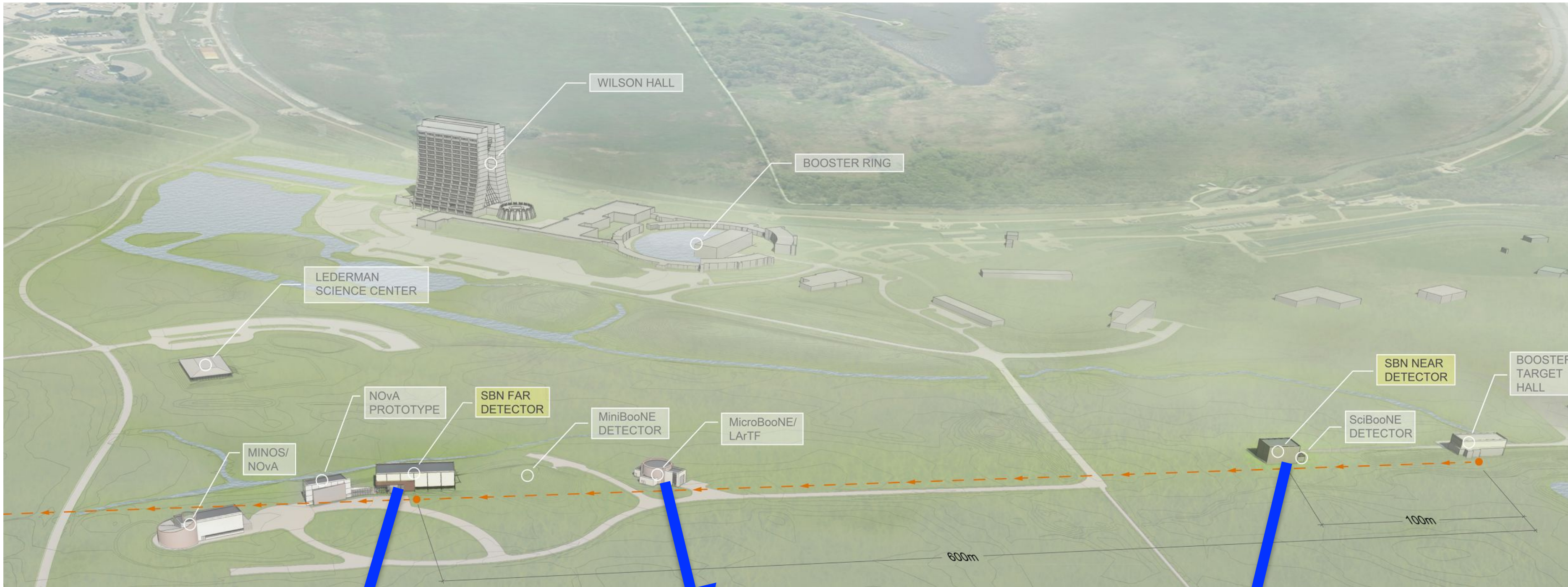
Oct 2019 – Mar 2026

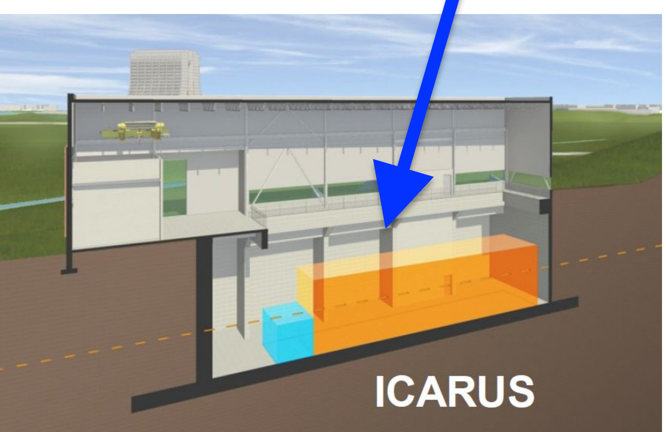
Construction Phase
Physics
Production reconstruction
DAQ construction
APA construction
Computing

Short-Baseline Neutrino Programme

Short-Baseline Neutrino Programme

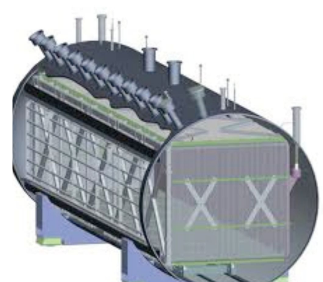
Three liquid argon time projection chamber (LArTPC) detectors in the Booster Neutrino Beam (BNB) at Fermilab



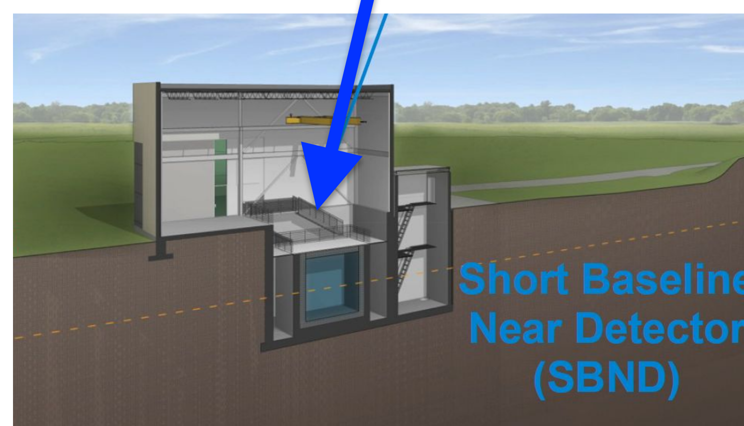


600 m / 476 tons

MicroBooNE



470 m / 89 tons



110 m / 112 tons

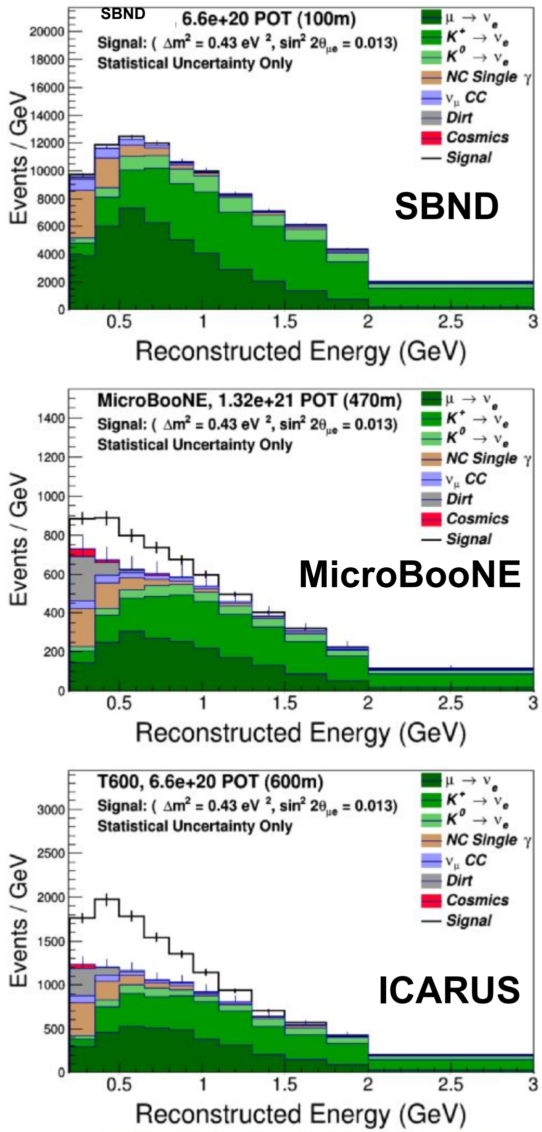
[S. Tufanli, EPS2017]

SBN Programme Goals

- Sterile neutrinos: study the baseline dependence of the MiniBooNE low energy event excess and cover the full LSND allowed parameter space with 5σ
- Make a high precision measurement on nu-Ar cross sections
  - High stats coupled with excellent imaging capabilities
    - e.g. SBND: 1.5M numu-CC / year & 12k nue-CC / year
- Develop LArTPC technology for future large neutrino experiments like DUNE

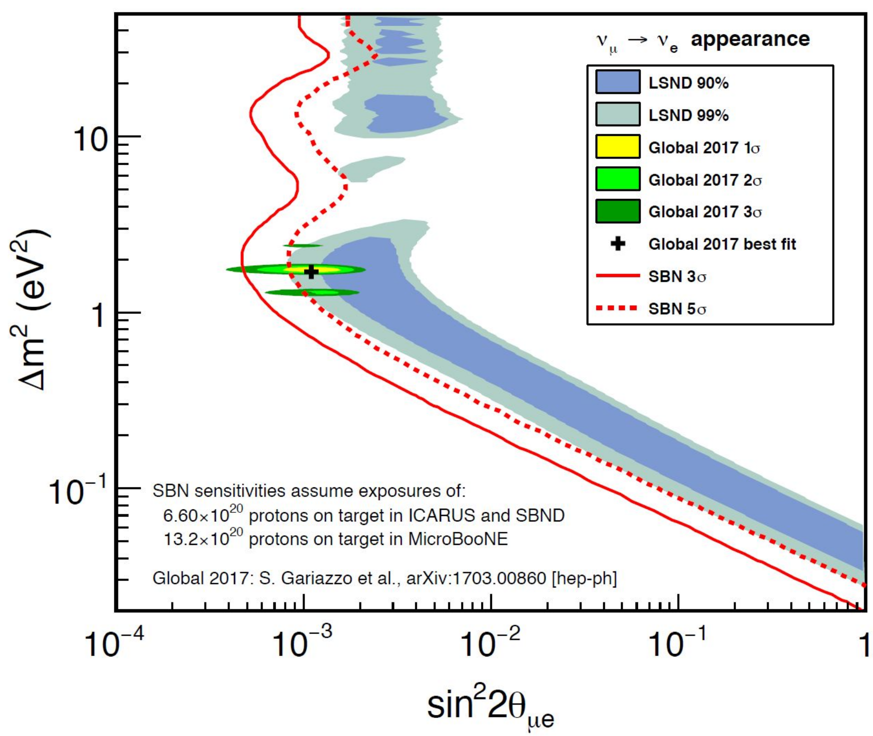
- Run plan
  - SBND: data taking starts 2019
  - MicroBooNE: **taking data since 2015**
  - Icarus: data taking starts 2018

Search for sterile neutrinos: $\nu_{\mu} \twoheadrightarrow \nu_{e}$ appearance



http://arxiv.org/abs/1503.01520

- A large mass far detector and a near detector of the same technology reduces both statistical and systematic uncertainties
- SBN detectors enable 5σ coverage the 99% C.L. allowed region of the LSND signal and global best fit values

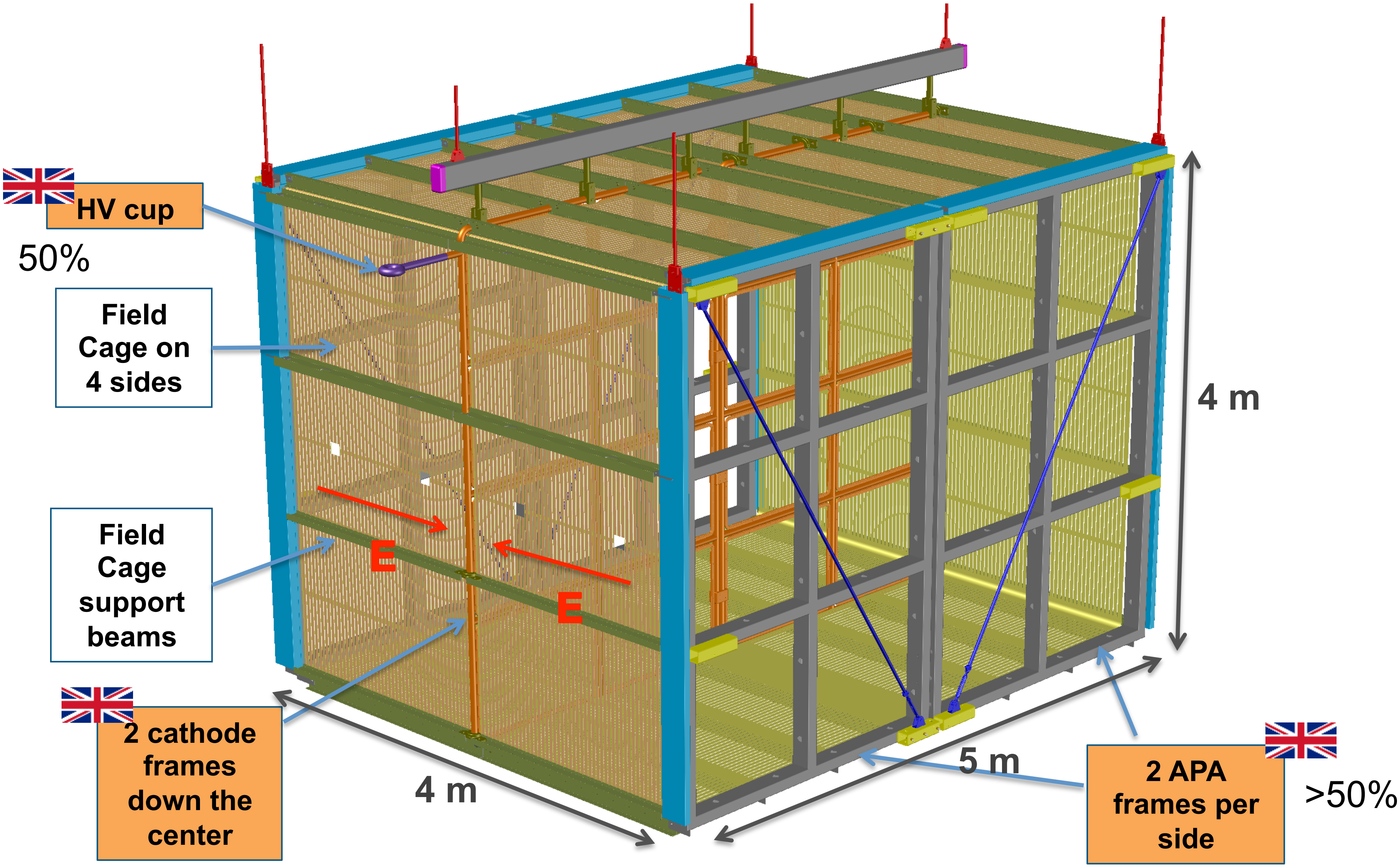


UK Involvement

- SBND
  - UK is building ½ TPC wire planes, the cathode planes and HV components (Mcr/Liv/Shef/Lanc/Dares/UCL)
  - TPC L2 Manager: K. Mavrokoridis (Liv)
  - Both single-detector Physics co-coordinators: C. Andreopoulos (Liv/RAL) and A. Szelc (Mcr)

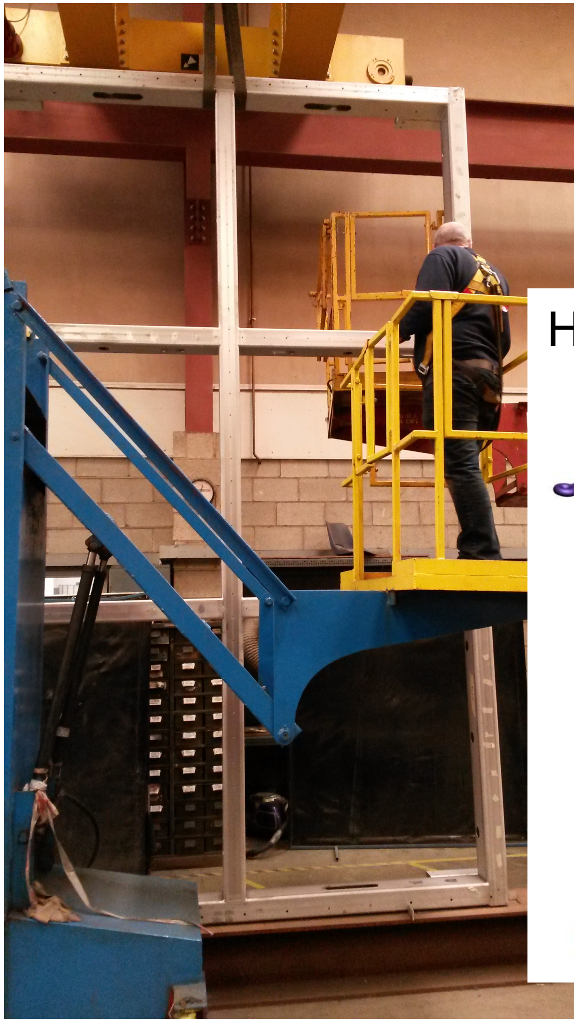
- MicroBooNE (Mcr/Cam/Lanc/Ox)
  - Xsec Physics co-convenor: A. Furmanski (Mcr)
    - (previously a run coordinator)
  - Technical Board member: A. Szelc (Mcr)

SBND TPC

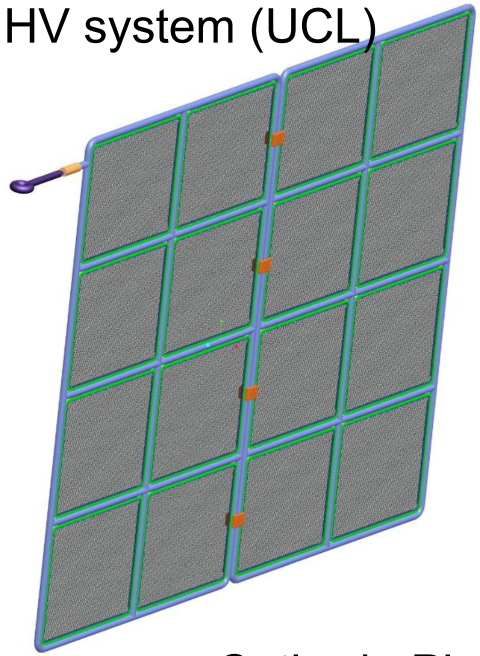


HV cup
50%
Field Cage on 4 sides
Field Cage support beams
2 cathode frames down the center
E
E
4 m
4 m
5 m
2 APA frames per side
>50%

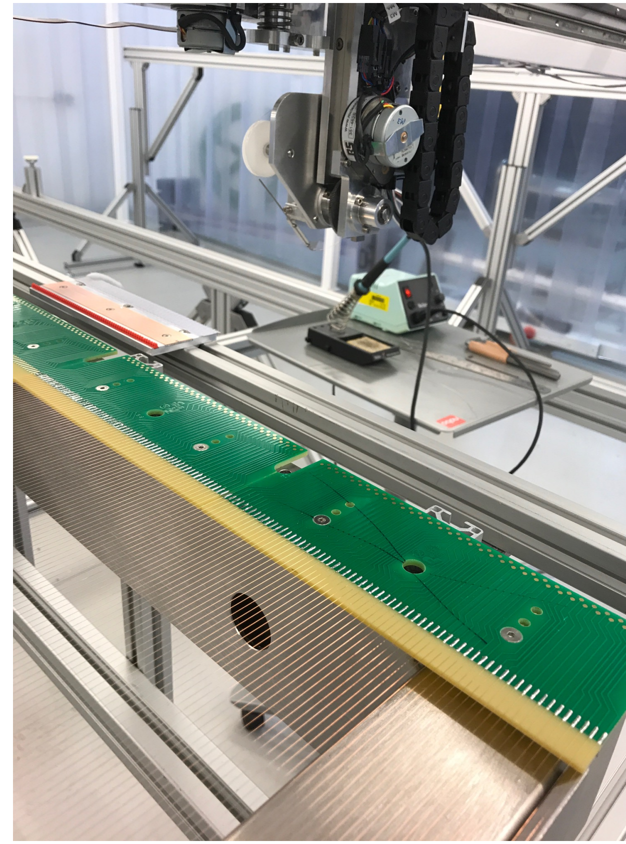
All 4 APA frames designed by
Sheffield and built by Portobello (UK)



HV system (UCL)



Cathode Planes
(Liverpool)

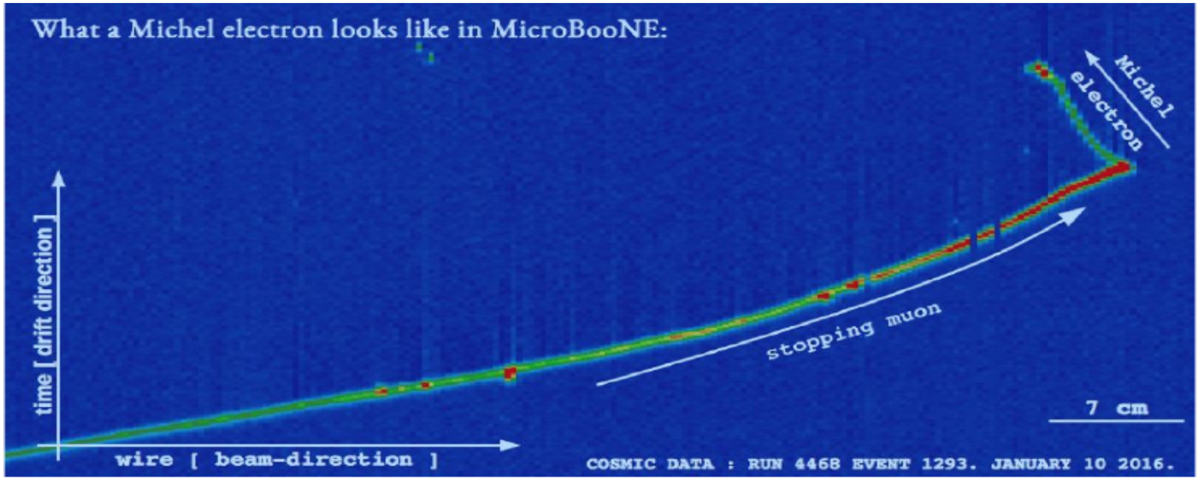


APA Wiring robot (Manchester)

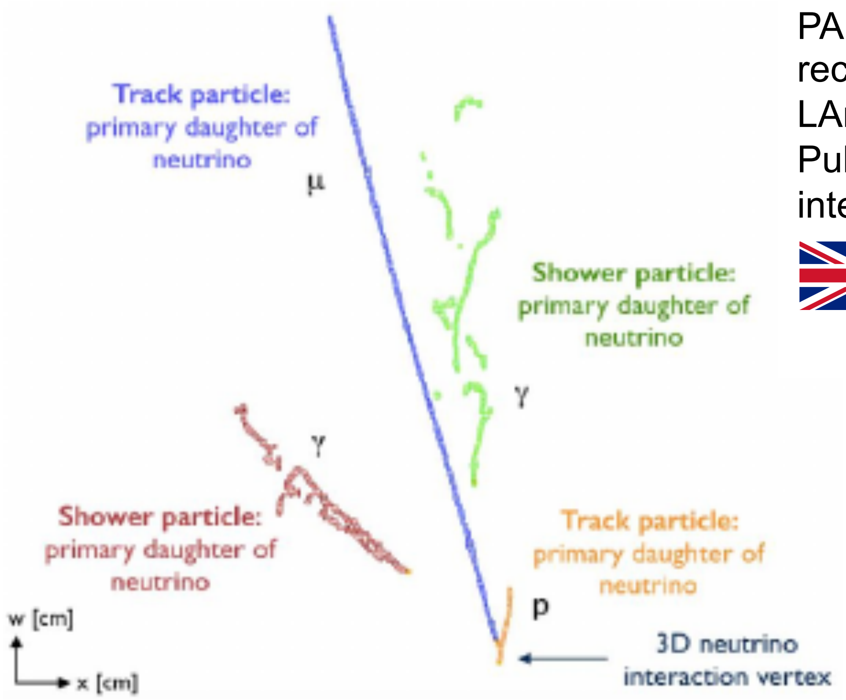
Cryostat for cool-down test
(Lancaster)

Final assembly in Daresbury.

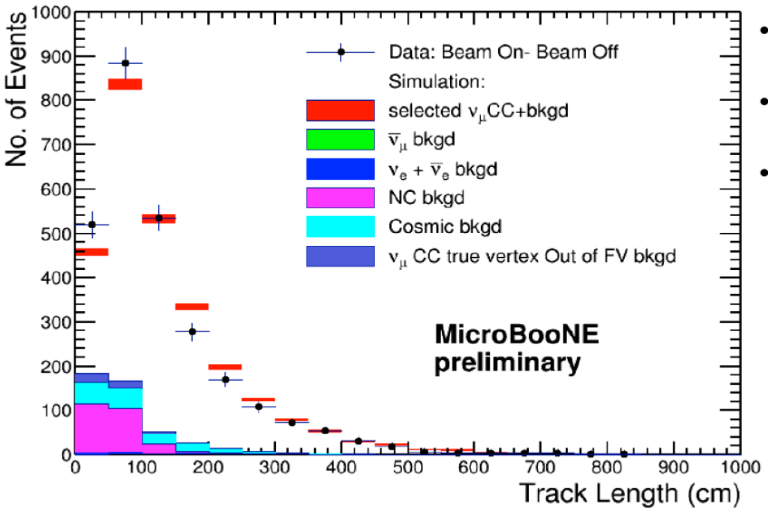
MicroBooNE



Reconstruction of Michel electrons (MeV energy scale) arxiv:1704.02927



PANDORA reconstruction of LArTPC tracks Publication in internal review.

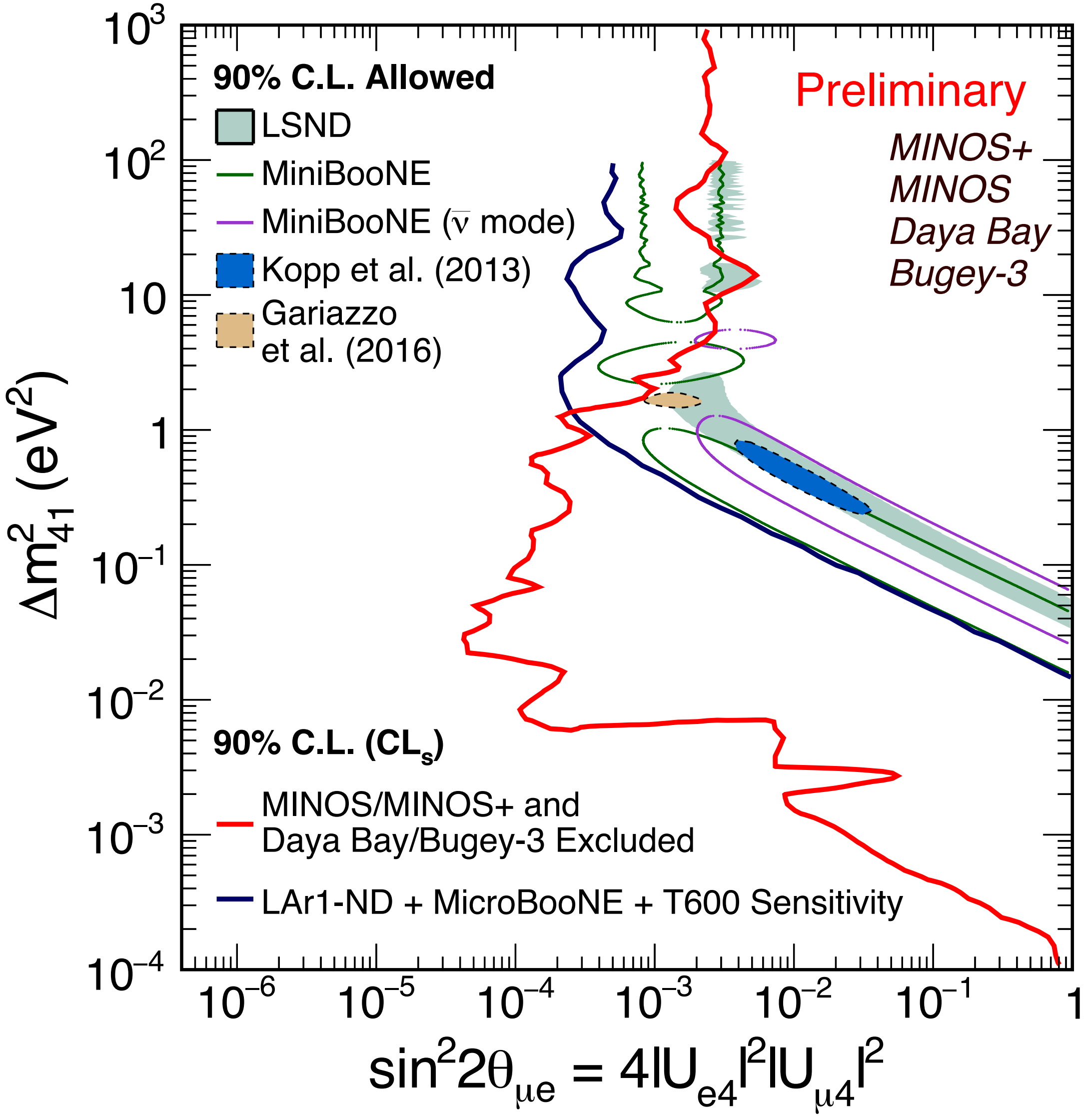


Proceeding towards ν_μ CC cross-section measurement.

MINOS+

MINOS+

- Best limits on sterile neutrinos at $\Delta m^2_{41} < 1$ eV^2
  - now 50% more data
  - UK co-led
- UK involvement:
  - Co-spokesperson: J. Thomas (UCL)
  - & other convenors



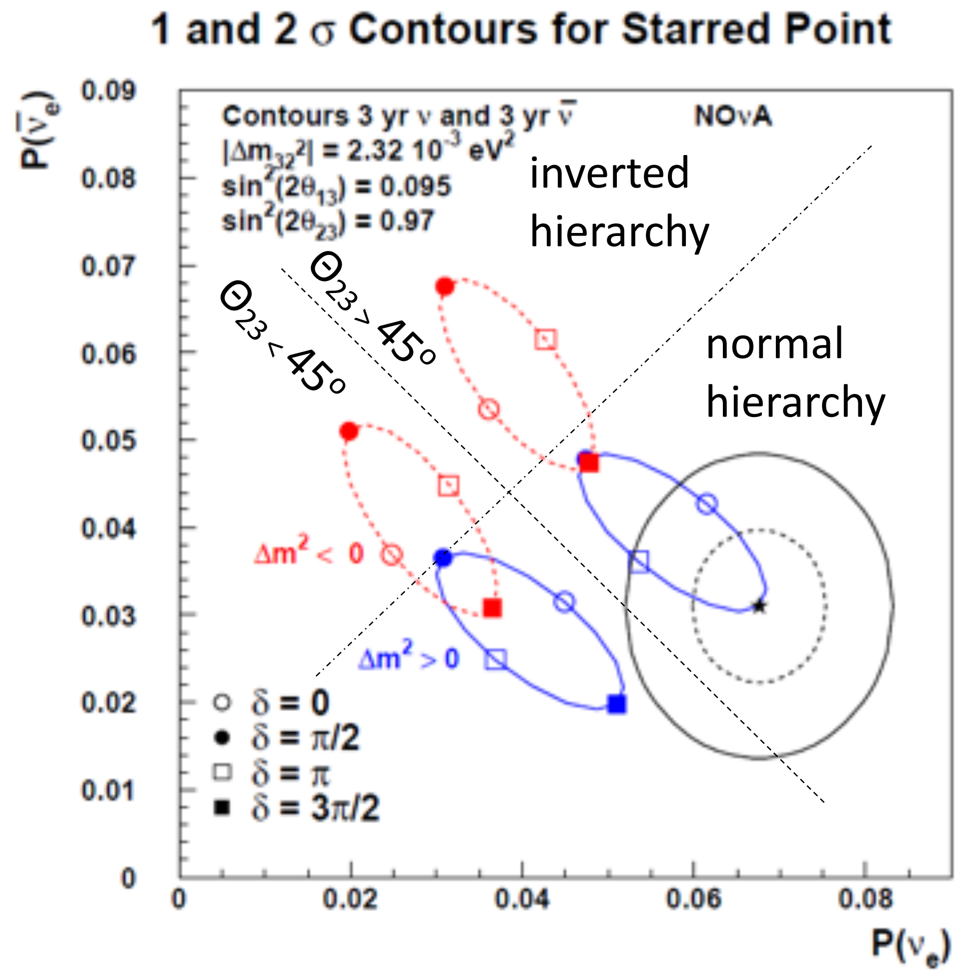
Conclusions

- **Strong UK leadership across the whole Fermilab neutrino programme**
- NOvA
  - Exciting new measurements, **complementary with T2K**
  - Will shed new light on 3 remaining unknowns
- DUNE
  - Under construction, strong CERN involvement
  - Discovery potential across large range of osc. space
  - **Complementary with HK**
- SBND, MicroBooNE
  - Probe sterile neutrinos at short-baselines
  - Test-bed for DUNE (TPC technology, nu-argon interactions)

Backup

Non-maximal mixing scenario

- If θ_{23} non-maximal then effect of octant is important
- Big effect, +/- 20%



$\nu_\mu \rightarrow \nu_e$ appearance probability

[PDG, 2014]

$$P_m^{3\nu\ man}(\nu_\mu \rightarrow \nu_e) \cong P_0 + P_{\sin\delta} + P_{\cos\delta} + P_3 \,.$$

Here

$$P_0 = \sin^2\theta_{23}\ \frac{\sin^2 2\theta_{13}}{(A-1)^2}\ \sin^2[(A-1)\Delta]$$

$$P_3 = \alpha^2\ \cos^2\theta_{23}\,\frac{\sin^2 2\theta_{12}}{A^2}\ \sin^2(A\Delta)\,,$$

$$P_{\sin\delta} = -\,\alpha\ \frac{8\,J_{CP}}{A(1-A)}\,(\sin\Delta)\,(\sin A\Delta)\ (\sin[(1-A)\Delta])\ ,$$

$$P_{\cos\delta} = \alpha\ \frac{8\,J_{CP}\ \cot\delta}{A(1-A)}\,(\cos\Delta)\,(\sin A\Delta)\ (\sin[(1-A)\Delta])\ ,$$

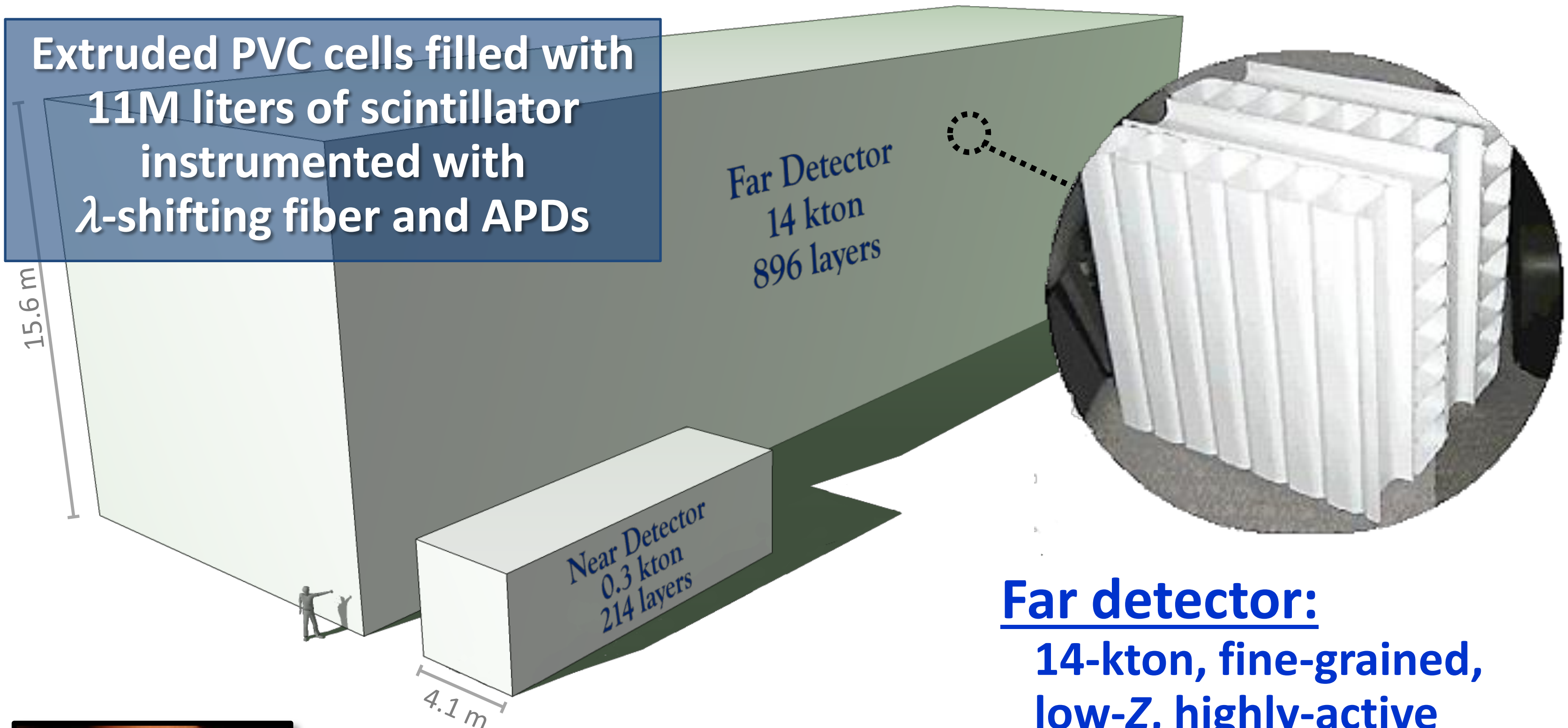
where

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\,,\ \ \Delta = \frac{\Delta m^2_{31}\,L}{4E}\,,\ \ A = \sqrt{2}G_{\mathrm{F}}N_e^{man}\frac{2E}{\Delta m^2_{31}}\,,$$

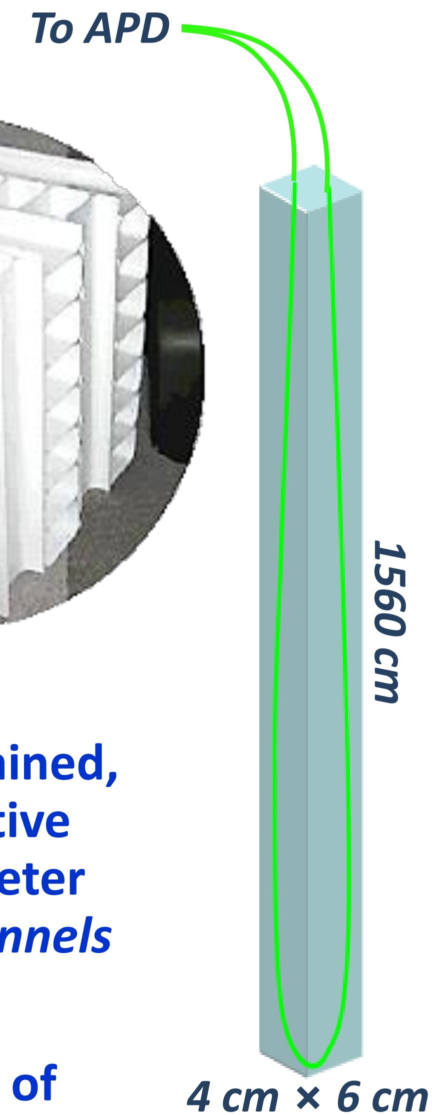
and $\cot\delta\ =\ J_{CP}^{-1}\mathrm{Re}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2}),\ \ J_{CP}\ =\ \mathrm{Im}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$.

NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell

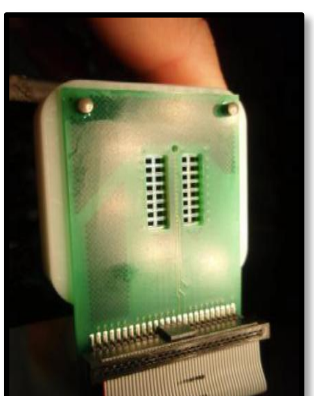


Far detector:

14-kton, fine-grained, low-Z, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:

0.3-kton version of the same
→ *20,000 channels*



32-pixel APD ←

Fiber pairs from 32 cells →