Neutrino Experiments in the USA

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University of Sussex

UK HEP Forum “The spice of flavour”, Cosener’s House

27th November 2018

Introduction

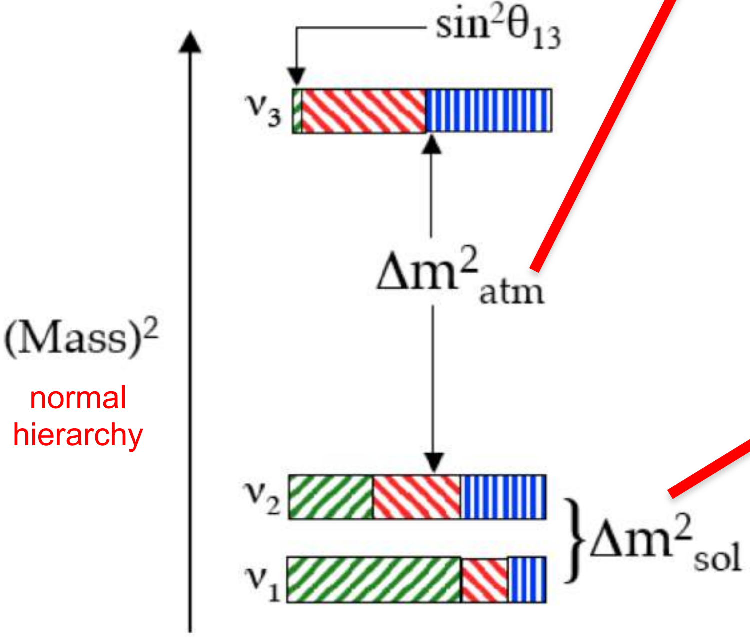
- Brief overview of neutrino oscillations
- What we know and don’t know
- What we measure
- Three flavour oscillations:
  - NOvA
  - DUNE
- Searches for sterile neutrinos:
  - MINOS+
  - Short-baseline neutrino (SBN) programme

Theory Overview

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Subdominant term



normal hierarchy

$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

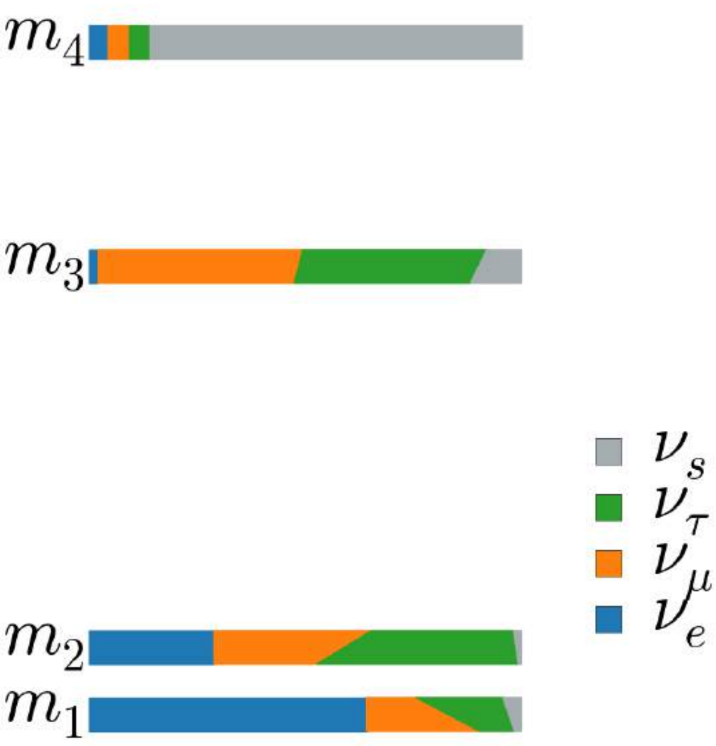
$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

[A. Aurisano, Nu2018]

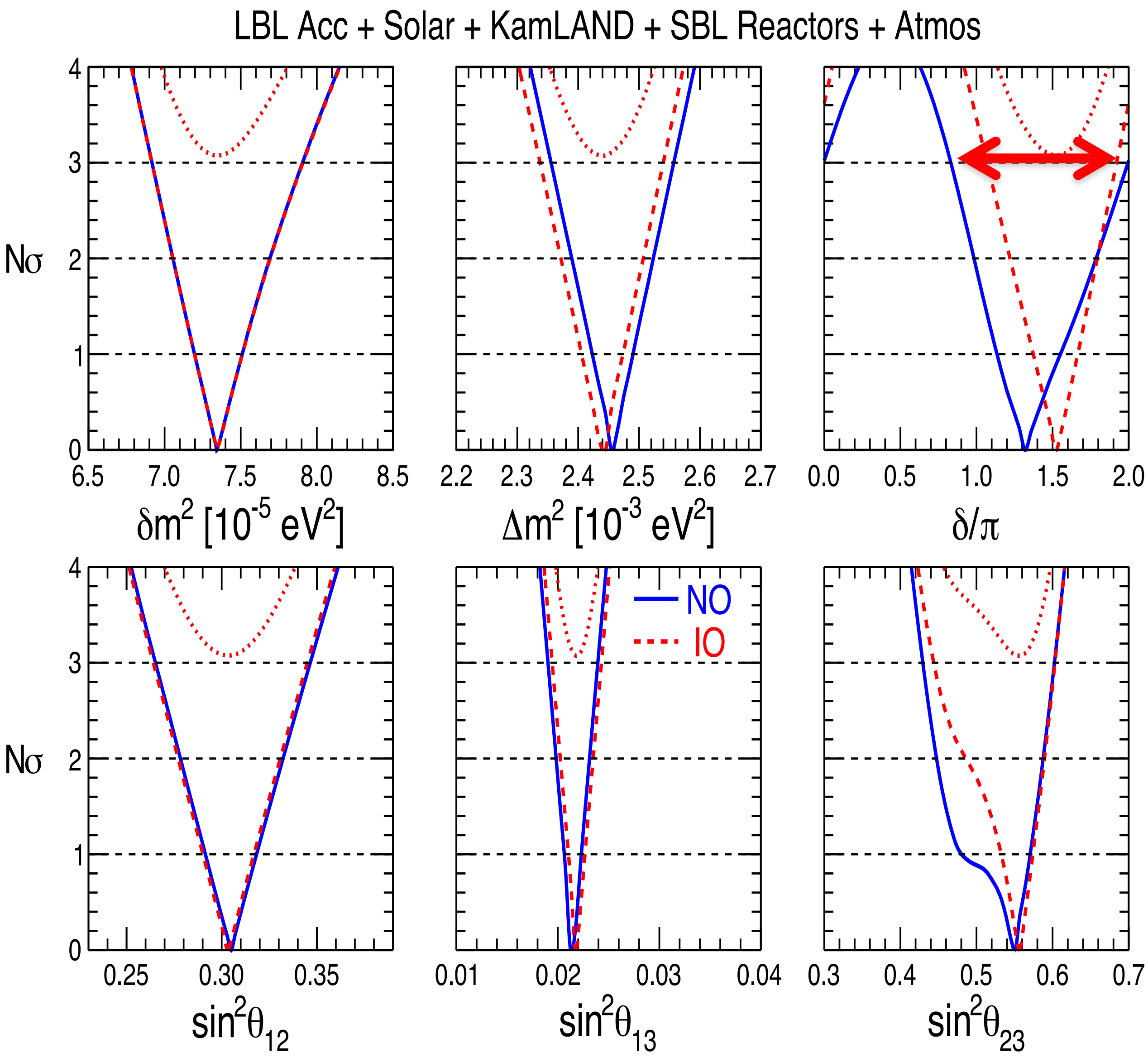
Sterile Neutrinos

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Anomalous short-baseline results consistent with new mass state and new sterile flavor
- Expand PMNS matrix from 3x3 ⟶ 4x4
- 6 new parameters
  - One mass scale (Δm^2_{41})
  - Three mixing angles (θ_{14}, θ_{24}, θ_{34})
  - Two CP-violating phases (δ_{14}, δ_{24})



What we know and don't know



Three "Unknowns"

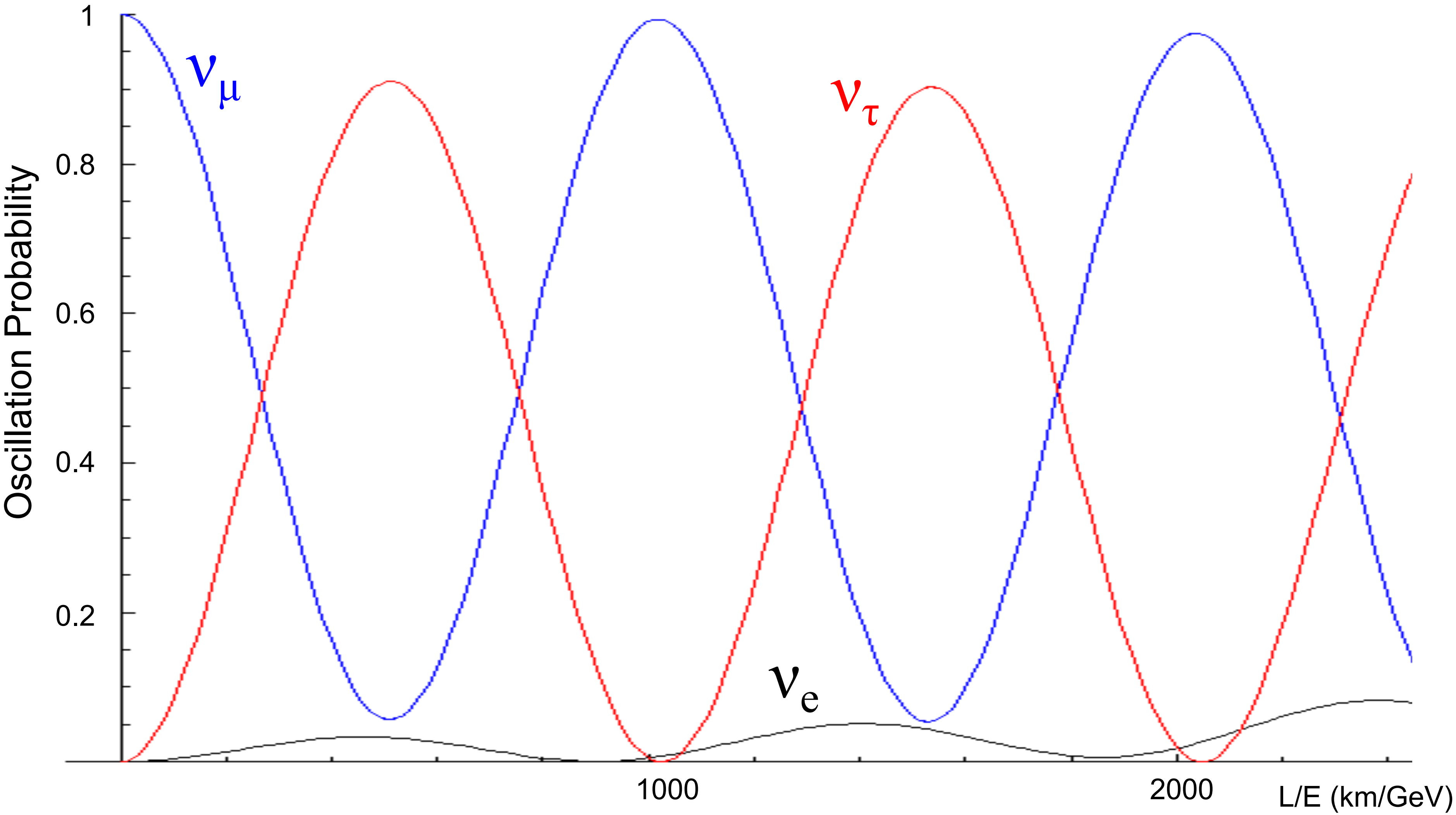
Third of $\boldsymbol{\delta_{CP}}$ values disfavoured (~2 sigma for CPv) (1)

Preference for **NH** (~3 sigma level) (2)

Non-maximal $\boldsymbol{\theta_{23}}$ mixing a possibility. Octant largely unknown. (3)

[arXiv:1804.09678]

Starting with ν_μ



δ_{CP} changes ratio of ν_e to ν_τ appearance (vs anti-ν_e to anti-ν_τ)

θ_{23} affects the fraction of ν_μ disappearing (upper octant means more ν_e vs. ν_τ)

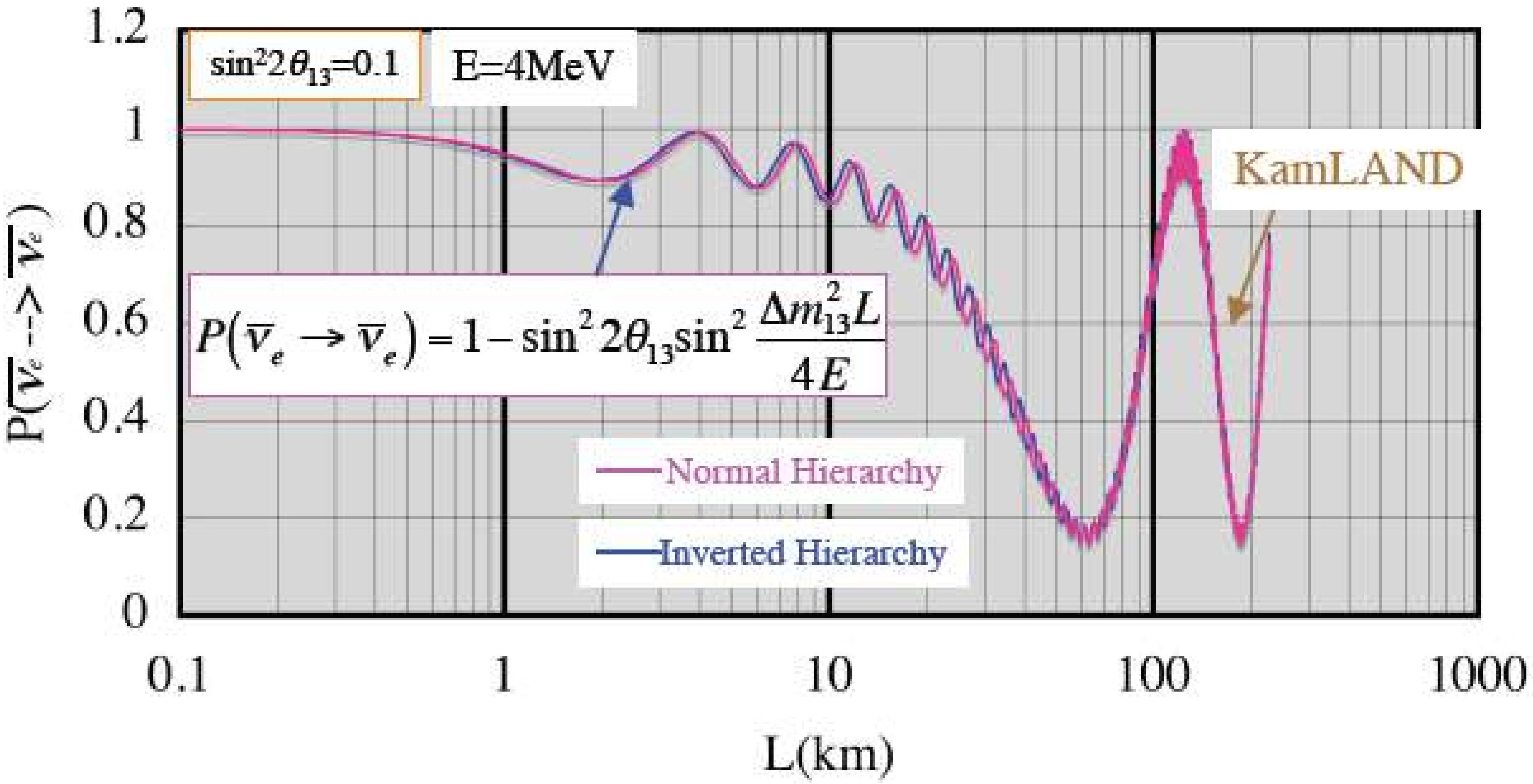
How does the mass hierarchy come into play?

Two ways:

1.) MSW matter effect

2.) Small (3%) difference in Δm^2_{31} and Δm^2_{32}

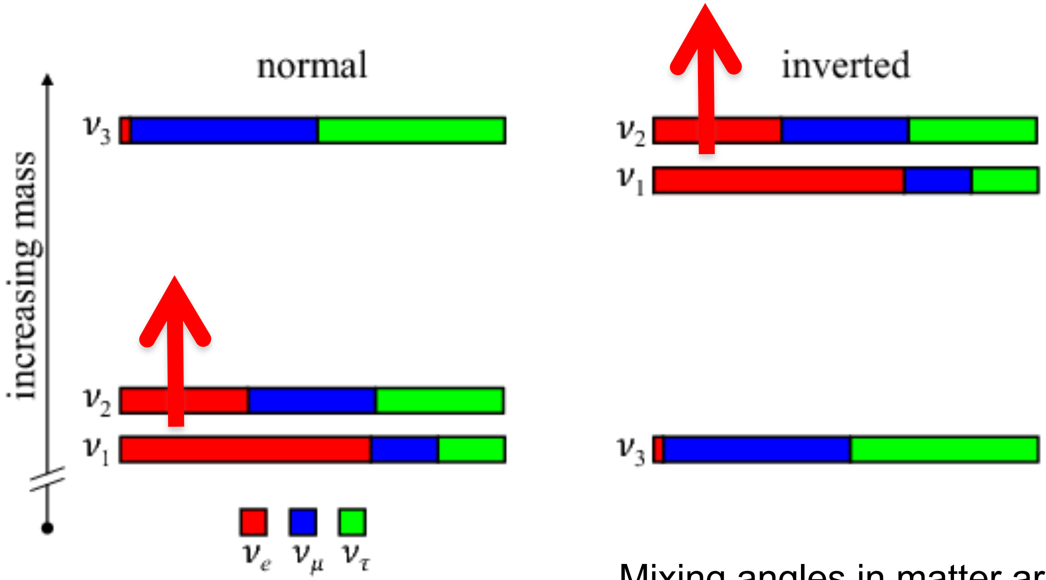
Starting with ν_e



Modulation frequency is slightly different for two hierarchies (due to small (3%) difference in Δm^2_{31} and Δm^2_{32})

Matter Effect & Mass Hierarchy

- Neutrinos (and antineutrinos) travel through matter not antimatter
  - – electron density causes asymmetry (fake CPv!)
    - via specifically **CC** coherent forward elastic scattering
  - – different Feynman diagrams for ν_e and $\bar{\nu}_e$ interactions with electrons so different amplitudes



Arrows flip for antineutrinos

Mixing angles in matter are affected by the mass squared splitting in matter

Now consider the effect of the three unknowns on electron (anti)neutrino appearance in a long-baseline beam

Long-baseline $\nu_\mu \rightarrow \nu_e$

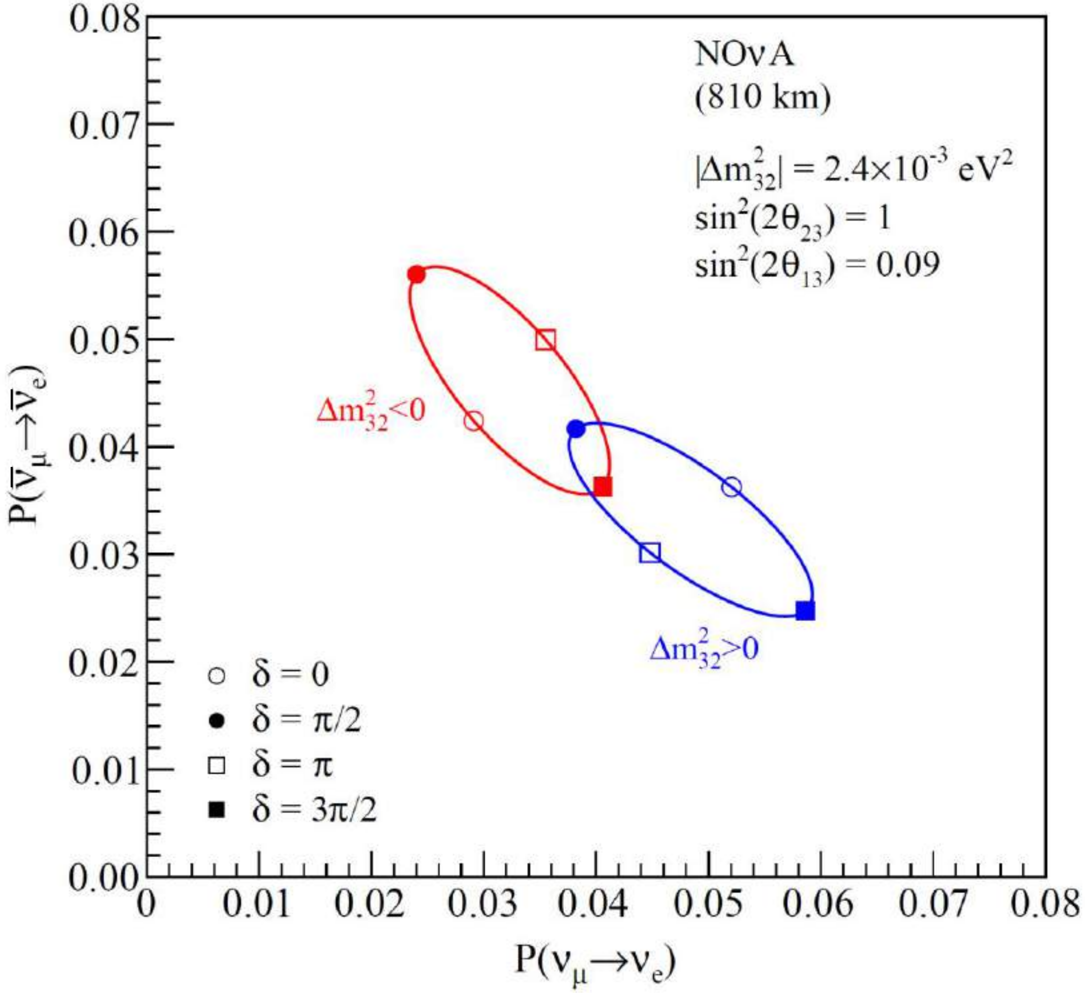
A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$

plotted for a single neutrino energy and baseline

For fixed L/E = 0.4 km/MeV



Long-baseline $\nu_\mu \to \nu_e$

A more quantitative sketch…

At right:

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P(\nu_\mu \to \nu_e)$

plotted for a single neutrino energy and baseline

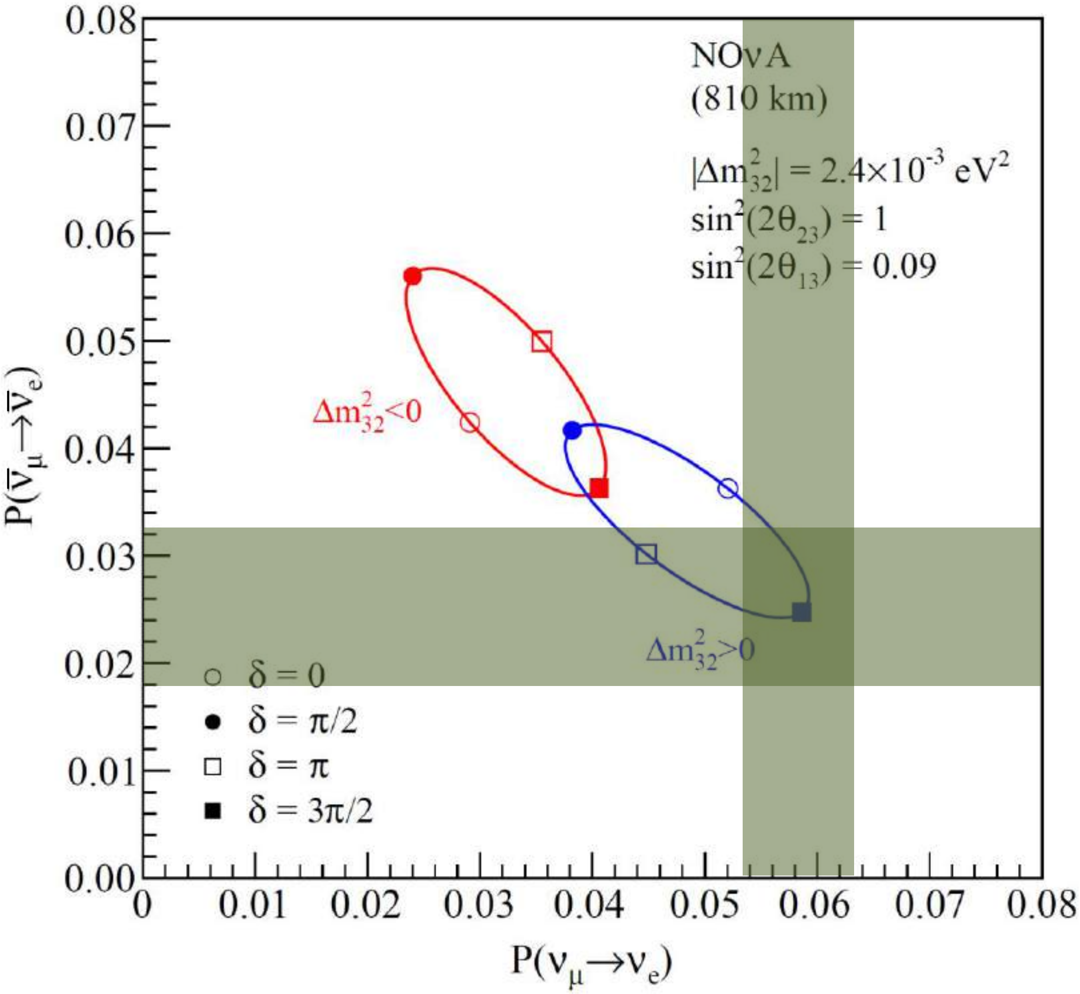
Measure these probabilities

(an example measurement of each shown)

Also:

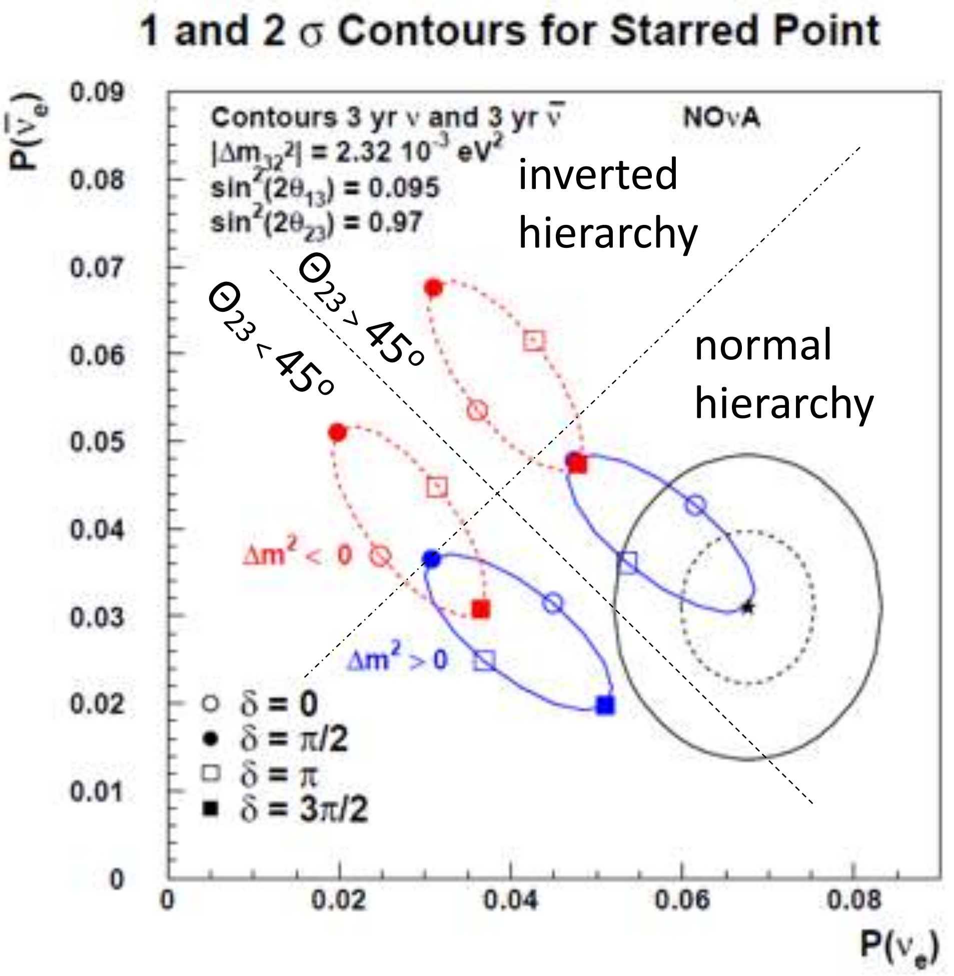
Both probabilities $\propto \sin^2\theta_{23}$

For fixed *L*/*E* = 0.4 km/MeV



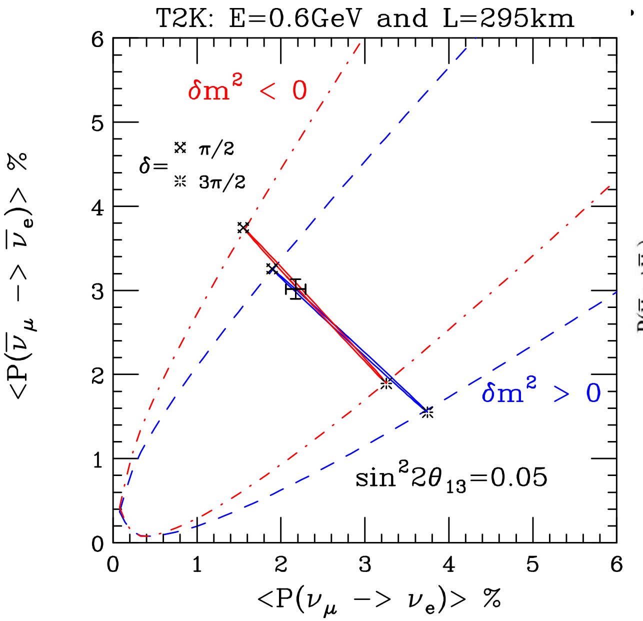
Non-maximal mixing scenario

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



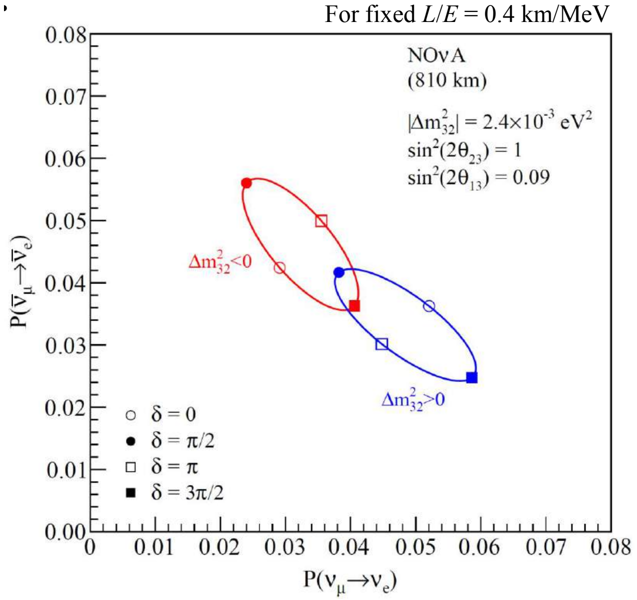
Effect of Increasing Energy

T2K



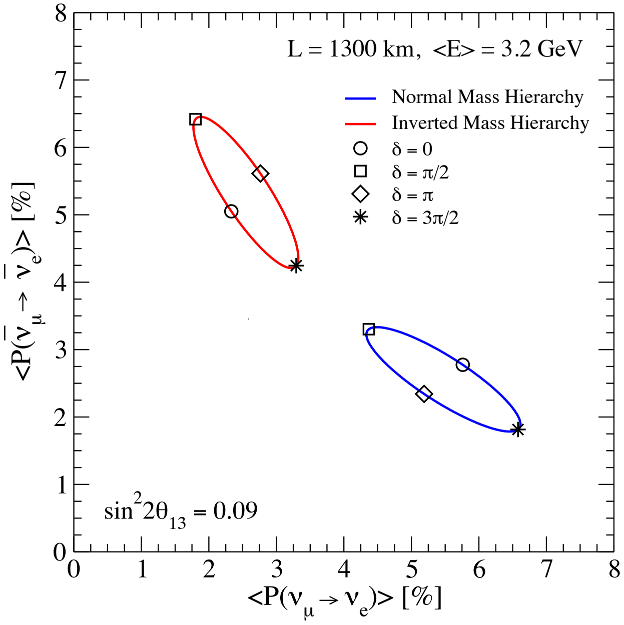
0.6 GeV

NOvA



2 GeV

DUNE



3 GeV

Increasing Energy

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

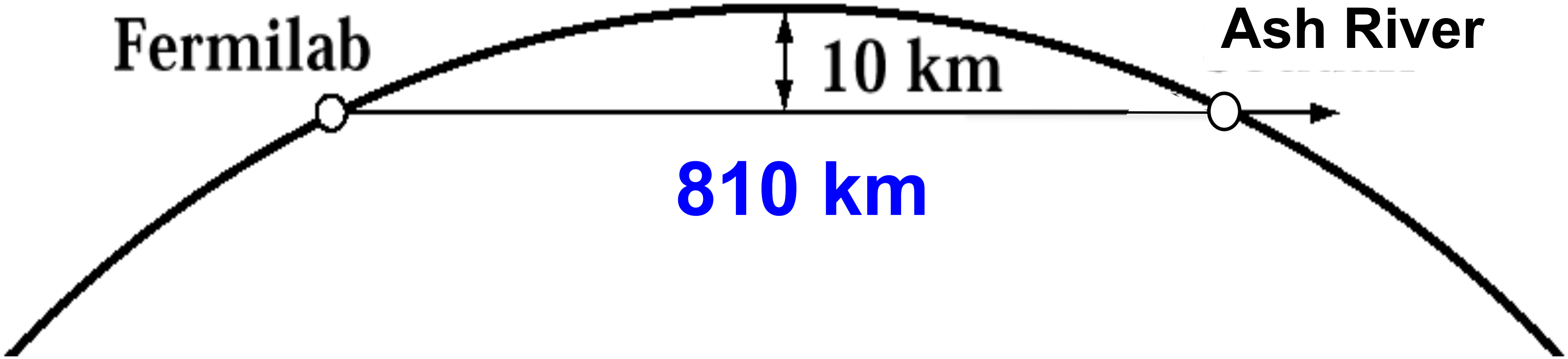
The Experiments

Experimental Concept

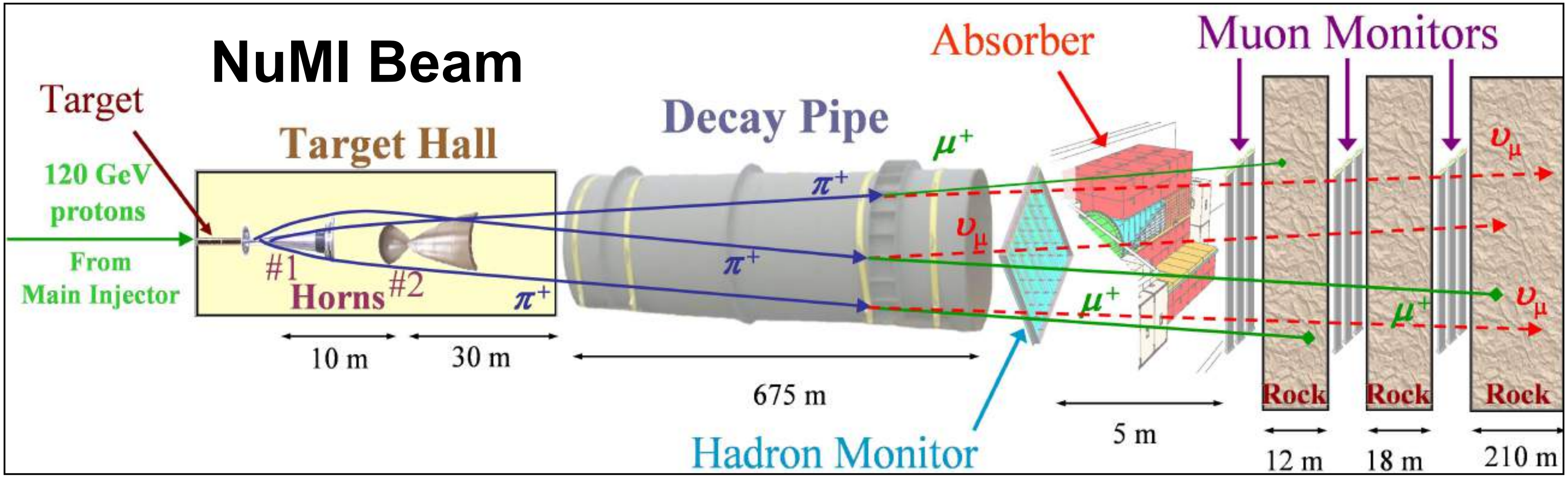
- "Conventional" beam
- Two-detector experiment:

- Near detector
  - measure beam composition
  - energy spectrum

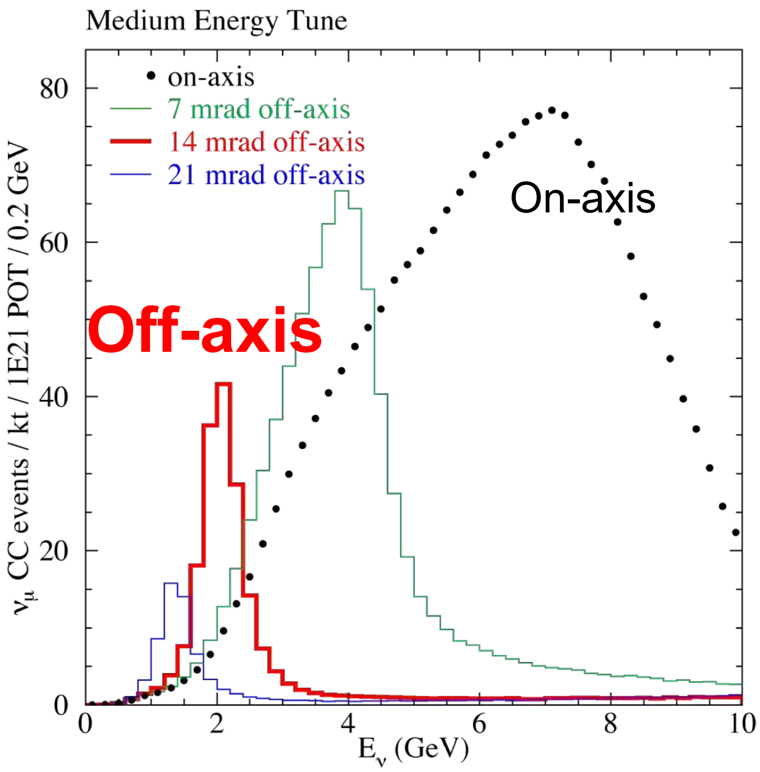
Far detector
  - measure oscillations and search for new physics



NuMI Beam

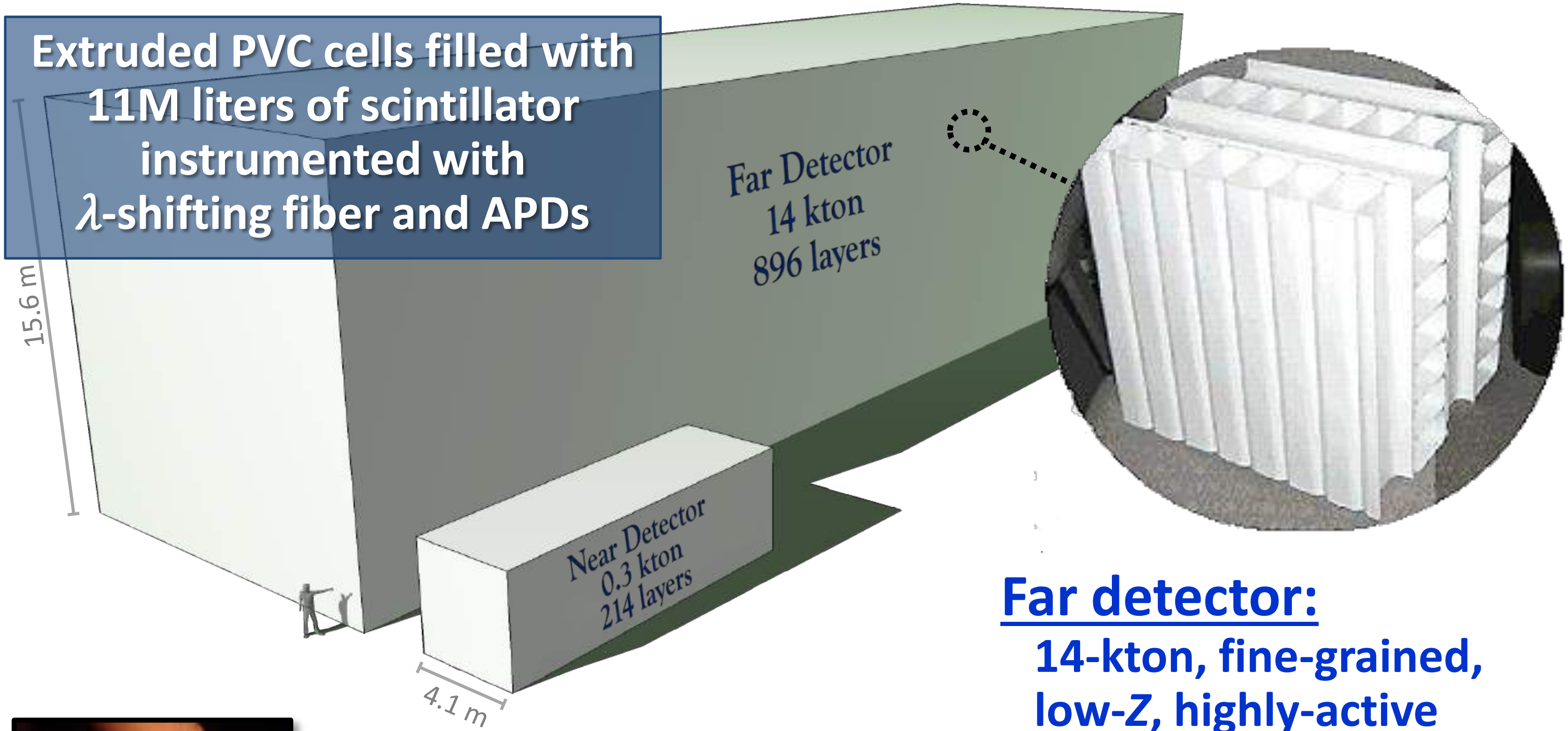


Neutrino
or
antineutrino
beam

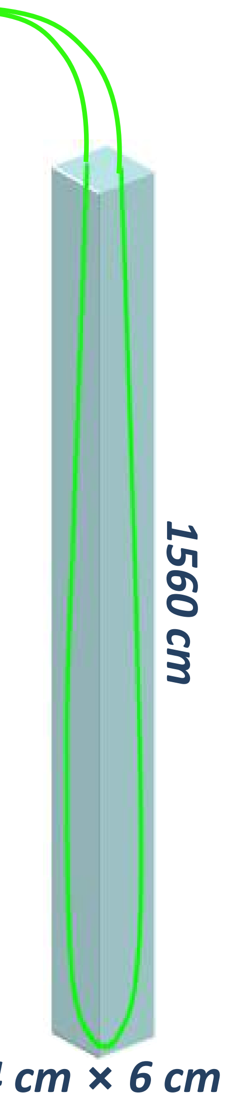


NOνA detectors

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



A NOνA cell



Far detector:

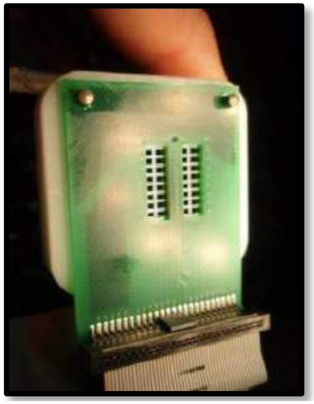
14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter

→ 344,000 channels

Near detector:

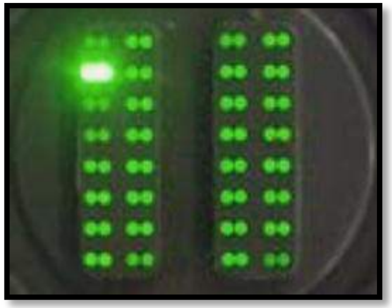
0.3-kton version of the same

→ 20,000 channels



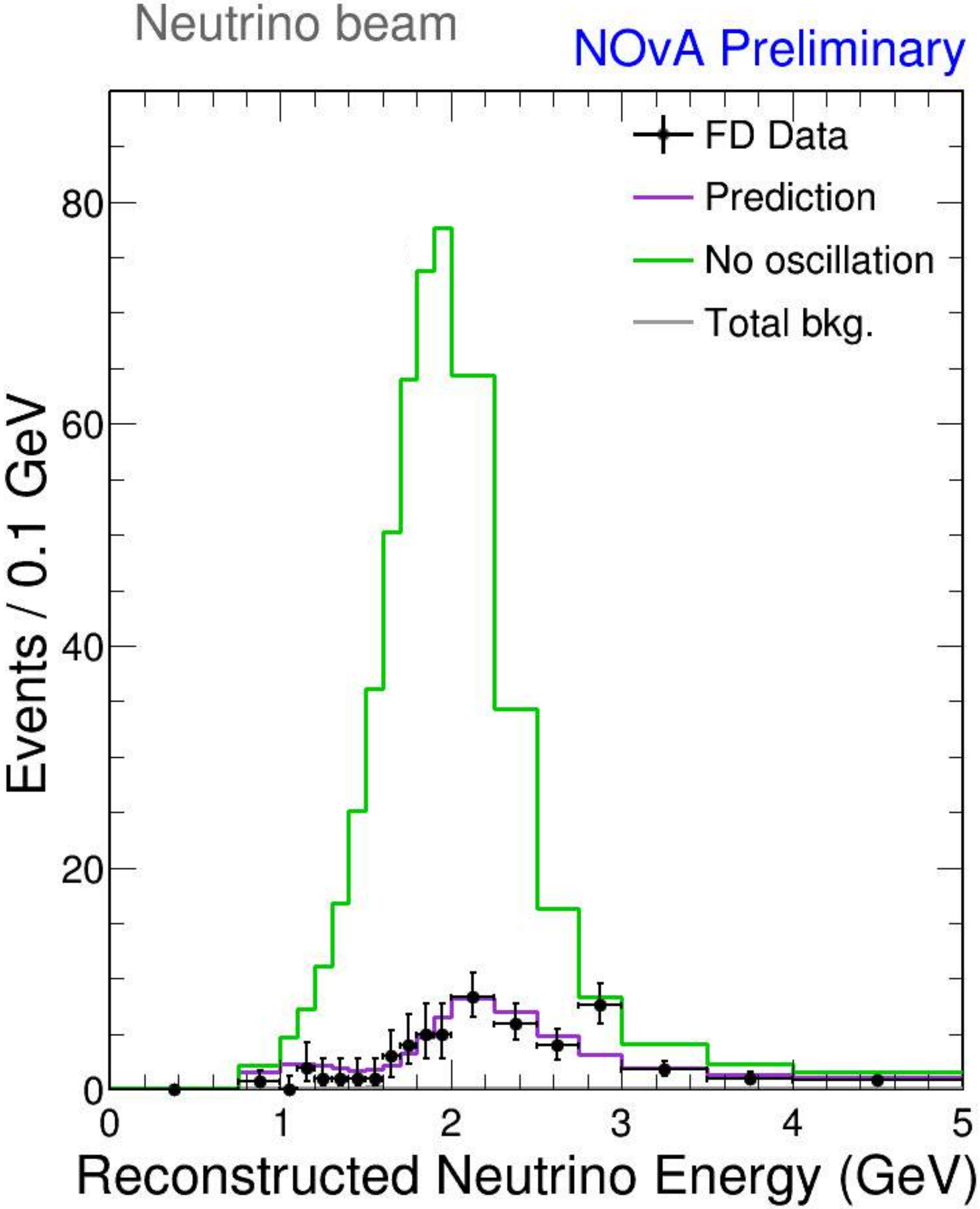
32-pixel APD ←

Fiber pairs from 32 cells →

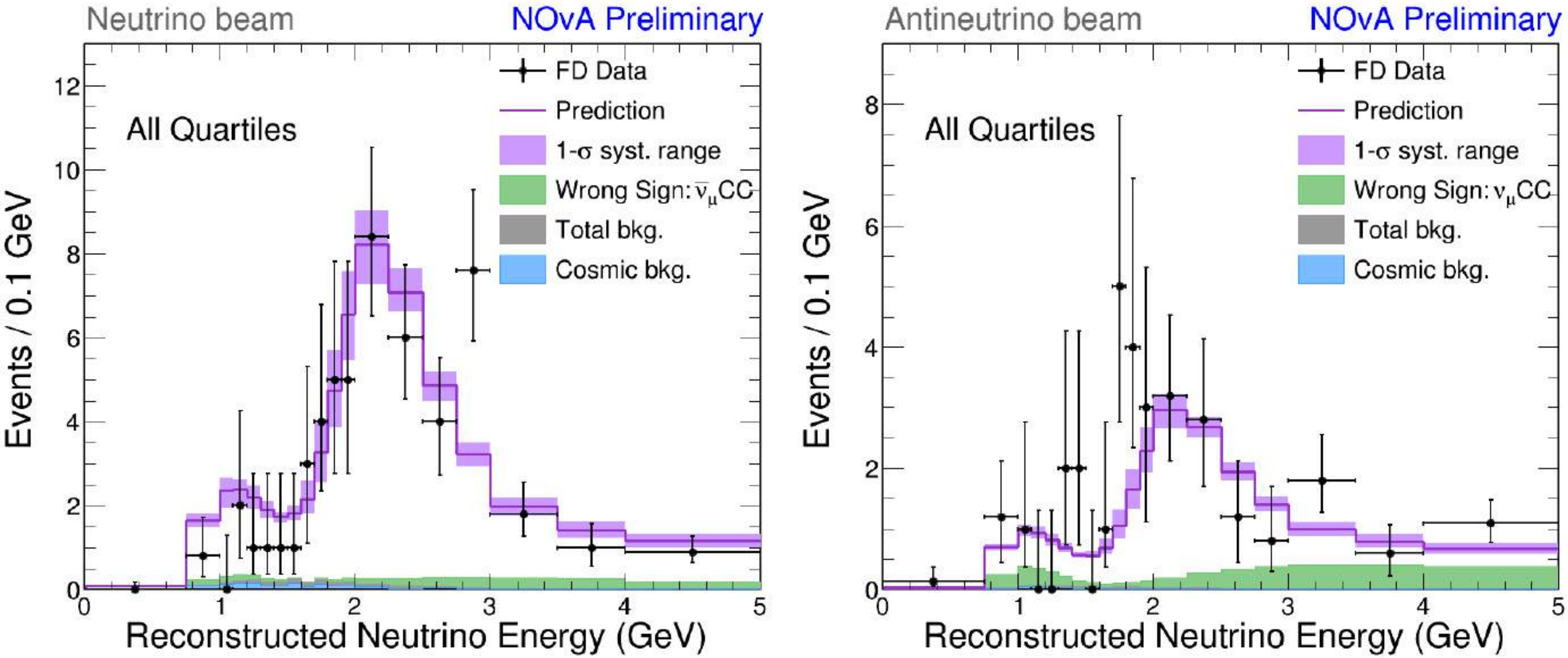


ν_μ

Huge (85%) disappearance effect



ν_μ Disappearance



113 events in neutrino mode

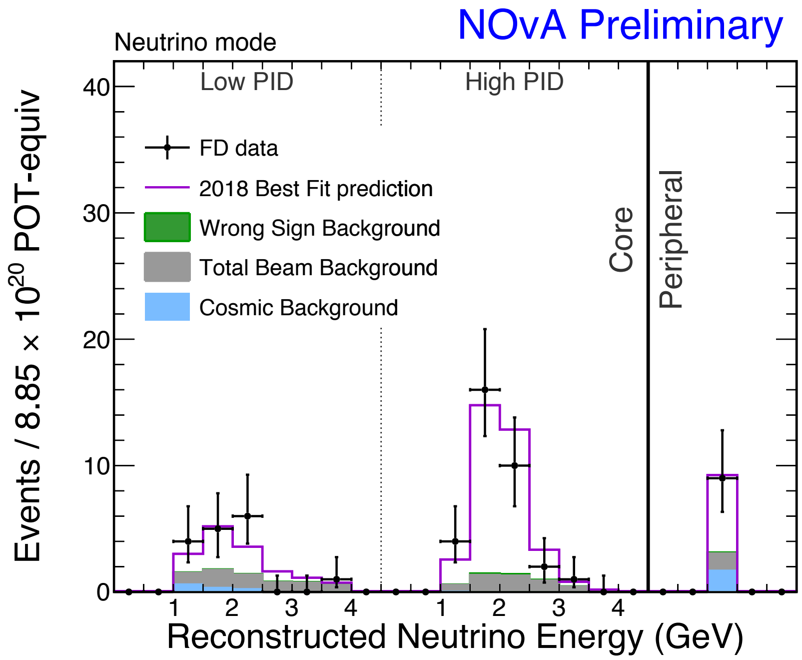
expect 730 +38/-49(syst.)
w/o oscillations

65 events in **antineutrino** mode

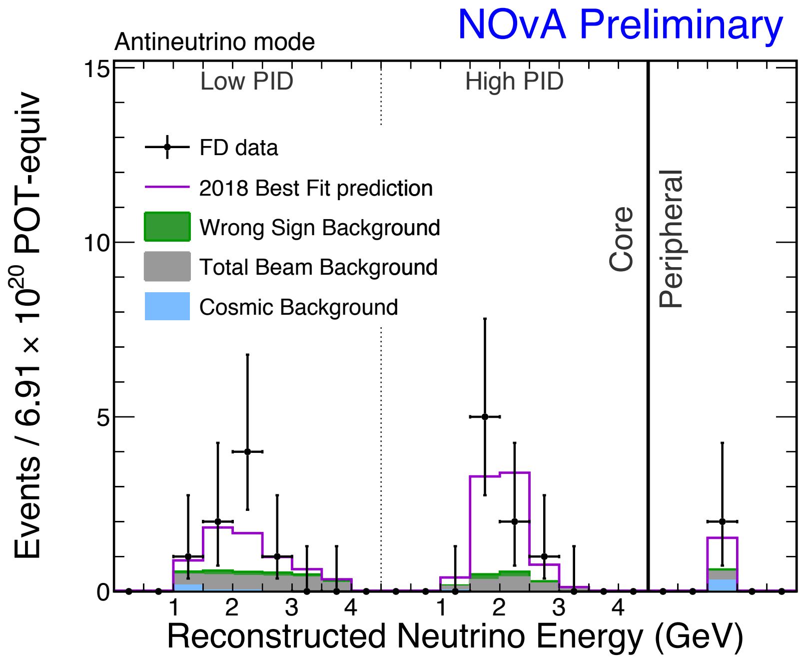
expect 266 +12/-14(syst.)
w/o oscillations

ν_e Appearance

- Observe 58 ν_e candidates
  - ➢ background 15



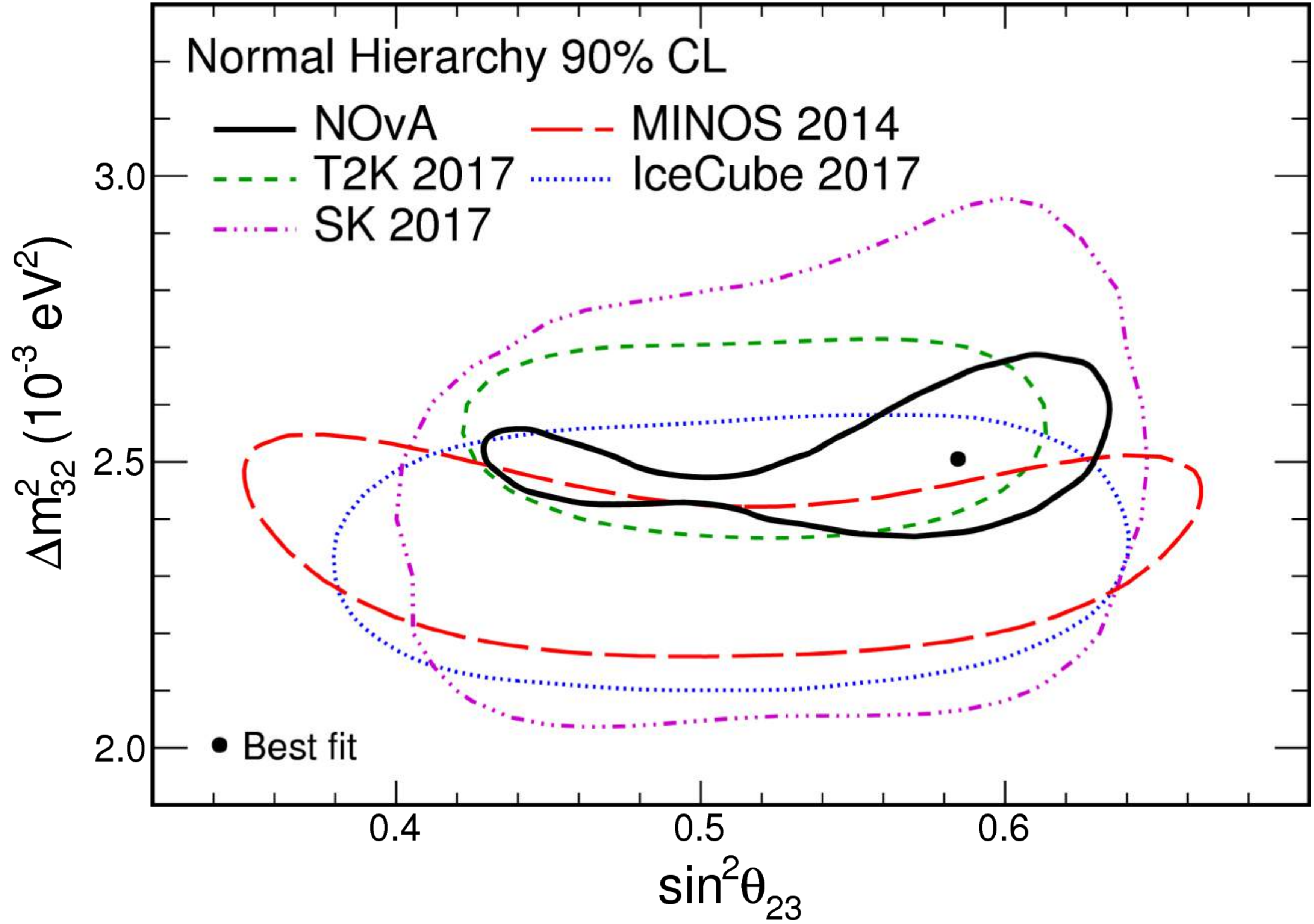
- Observe 18 $\bar{\nu}_e$ candidates
  - ➢ background 5.3



>4σ electron antineutrino appearance signal

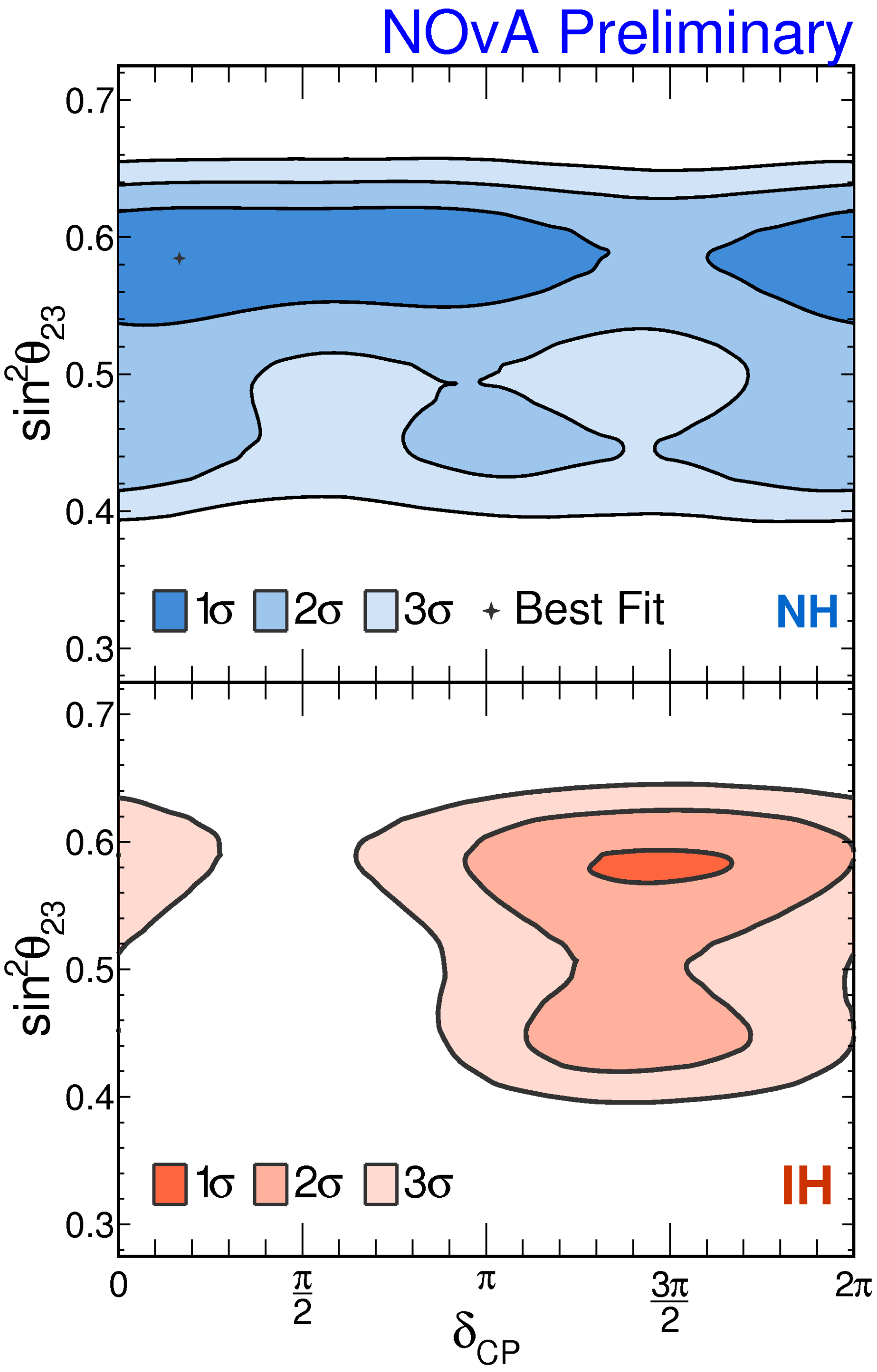
A world first!

NOvA Preliminary



Constraints on "unknowns"

- Prefer Normal Hierarchy at 1.8 σ
- Exclude δ_{CP}= π/2 in Inverted Hierarchy at > 3 σ
- Disfavour maximal mixing at 1.8 σ and lower octant at a similar level

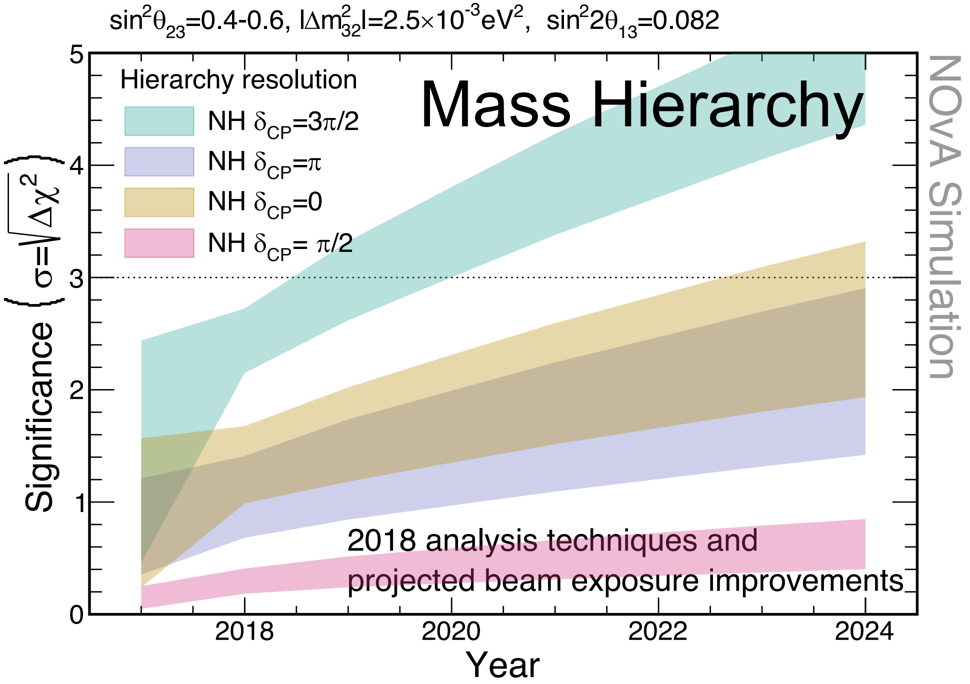


Near Term Future Sensitivity

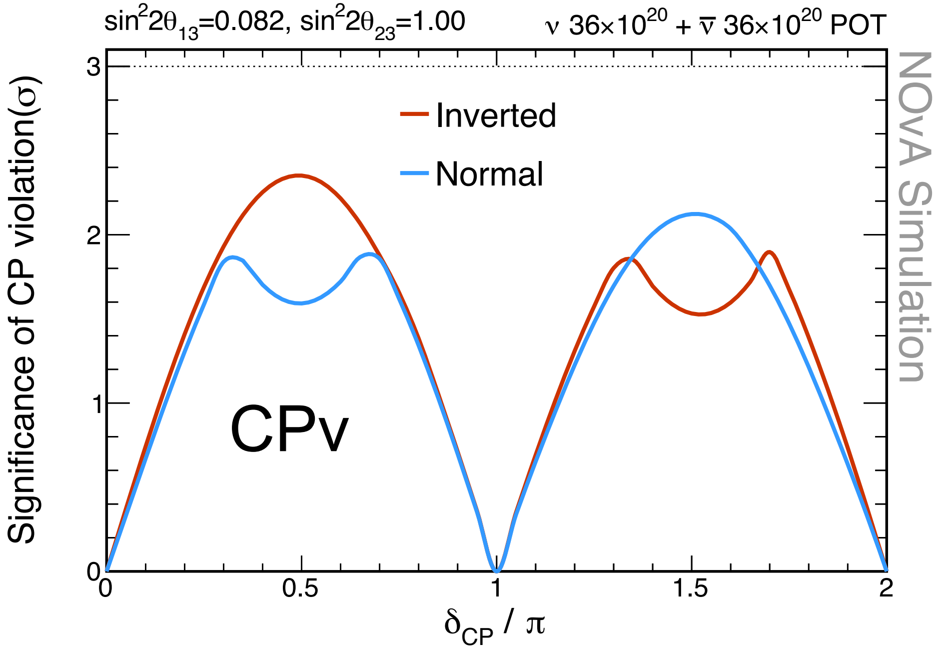
- Currently running antineutrinos
  - Plan 50:50 for future
- Extended running until 2024
  - Beam improvement projects (bring forward DUNE work)

Great complementarity with T2K phase-II due to different baselines and beam energy.

Combined analysis to resolve potential degeneracies in 2021.



2018 analysis techniques and projected beam exposure improvements



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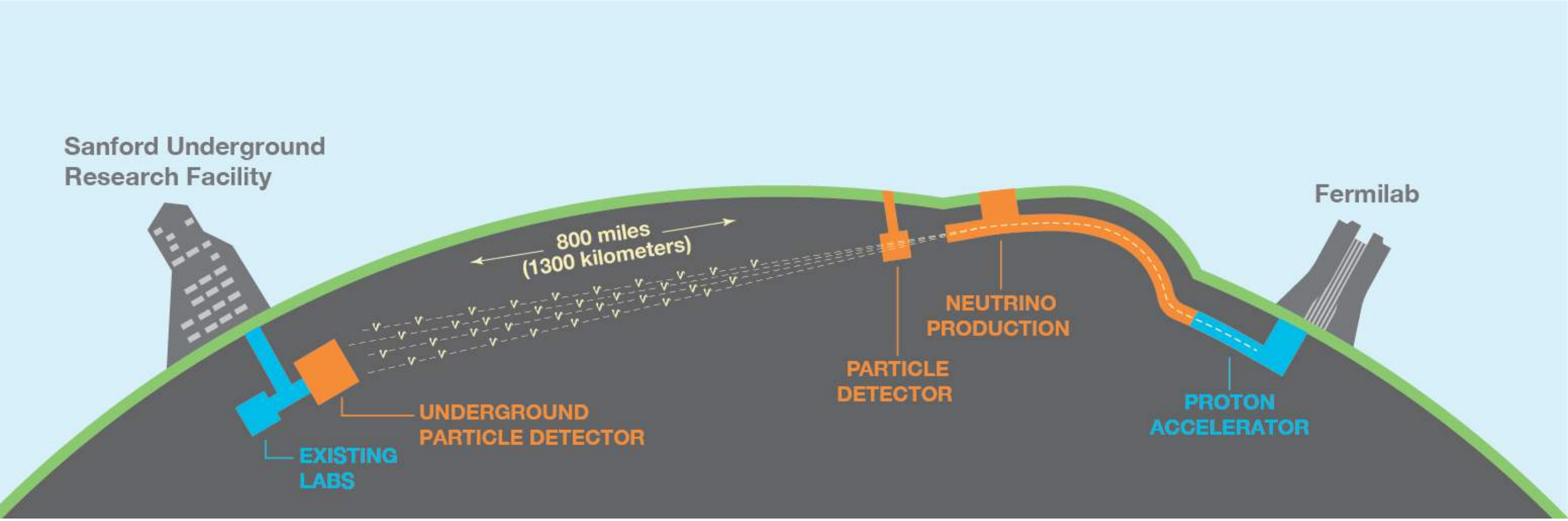
DUNE Overview

- Approved expt., under construction
- 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



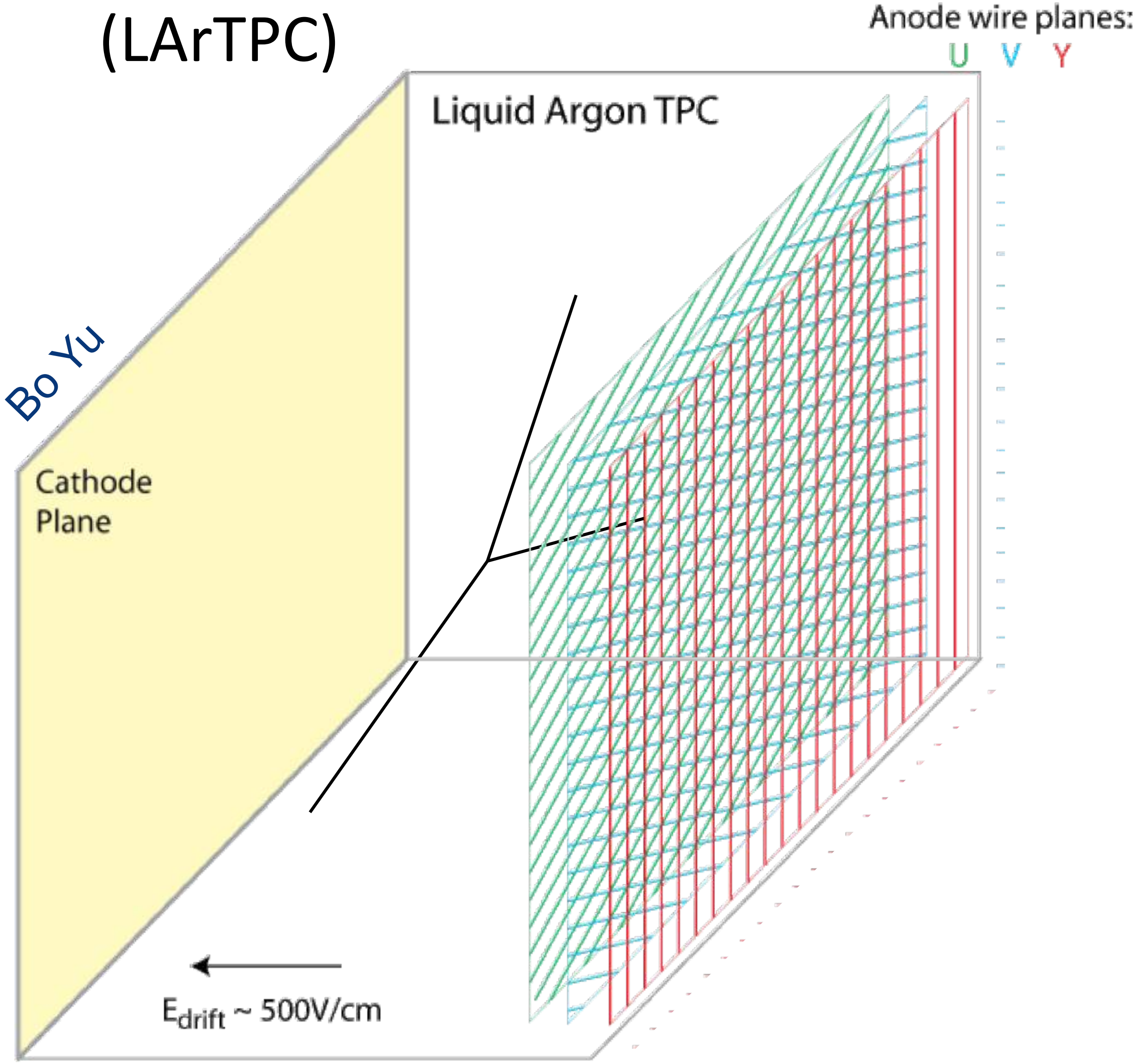
DUNE – a truly global collaboration

- 1144 collaborators from 178 institutions in 32 countries
- 622 faculty/scientists, 191 postdocs, 106 engineers, 5 computing professionals, 220 PhD students
- Growing at a rate of about 100 collaborators/year

Armenia (3), Brazil (29), Bulgaria (1), Canada (1), CERN (32), Chile (3), China (5), Colombia (13), Czech Republic (11), Spain (34), Finland (4), France (23), Greece (4), India (45), Iran (2), Italy (63), Japan (7), Madagascar (8), Mexico (8), The Netherlands (4), Paraguay (4), Peru (8), Poland (6), Portugal (7), Romania (7), Russia (10), South Korea (4), Sweden (1), Switzerland (35), Turkey (2), UK (136), Ukraine (4), USA (621)

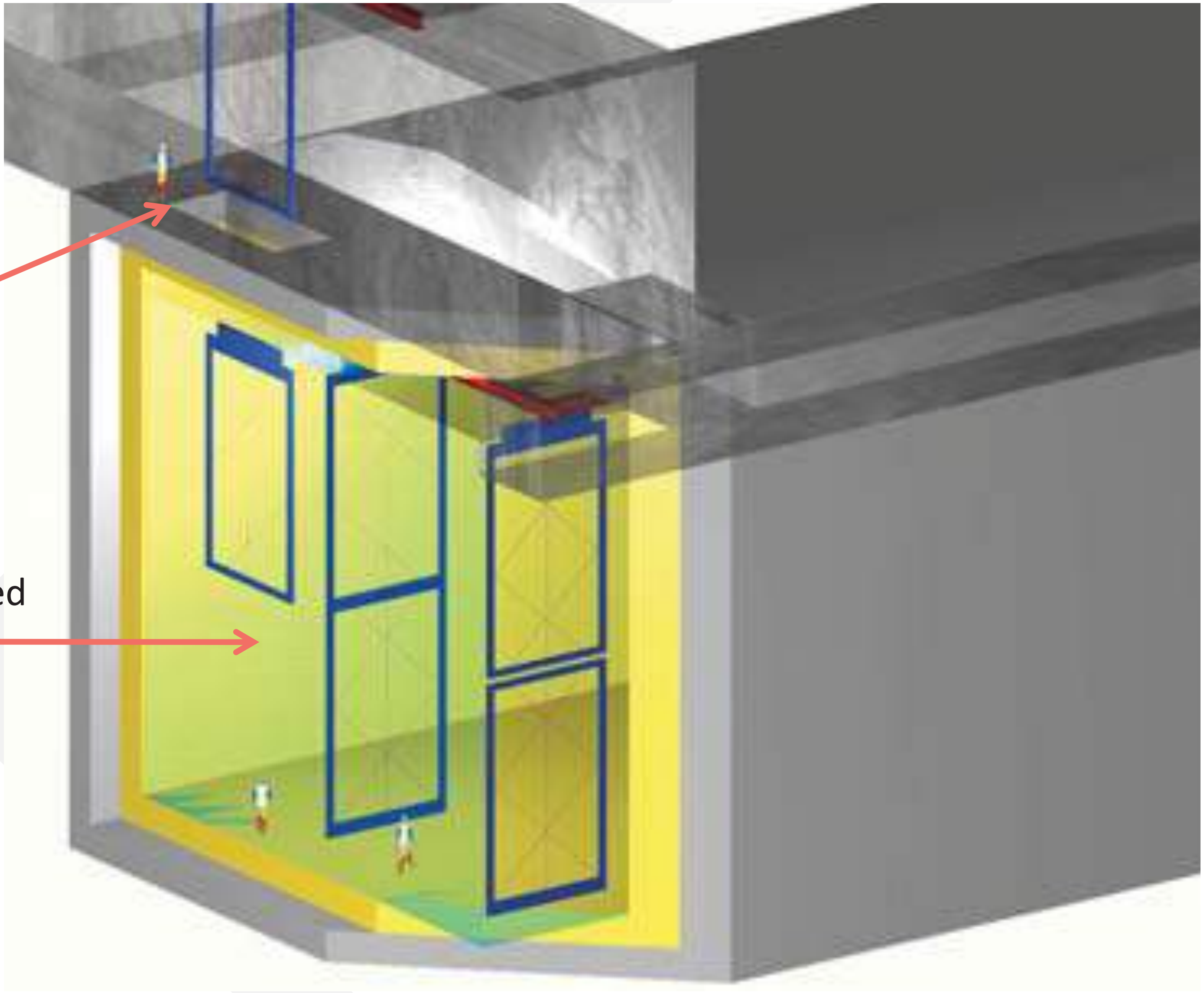
Liquid Argon Time Projection Chamber (LArTPC)

Single Phase



Detector schematic

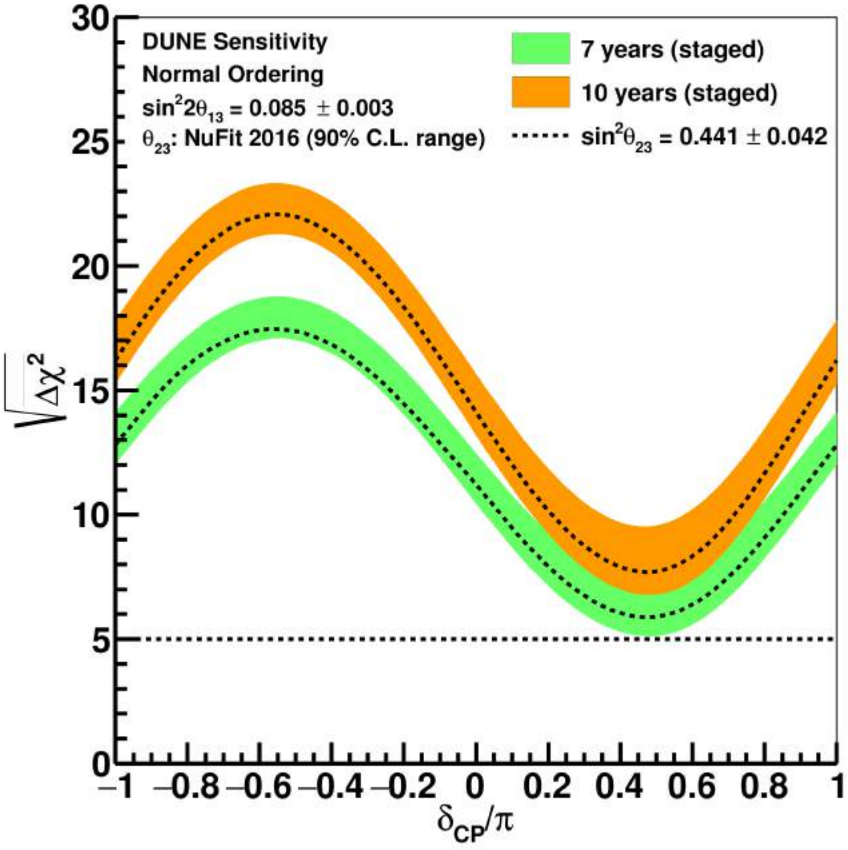
(Single phase module)

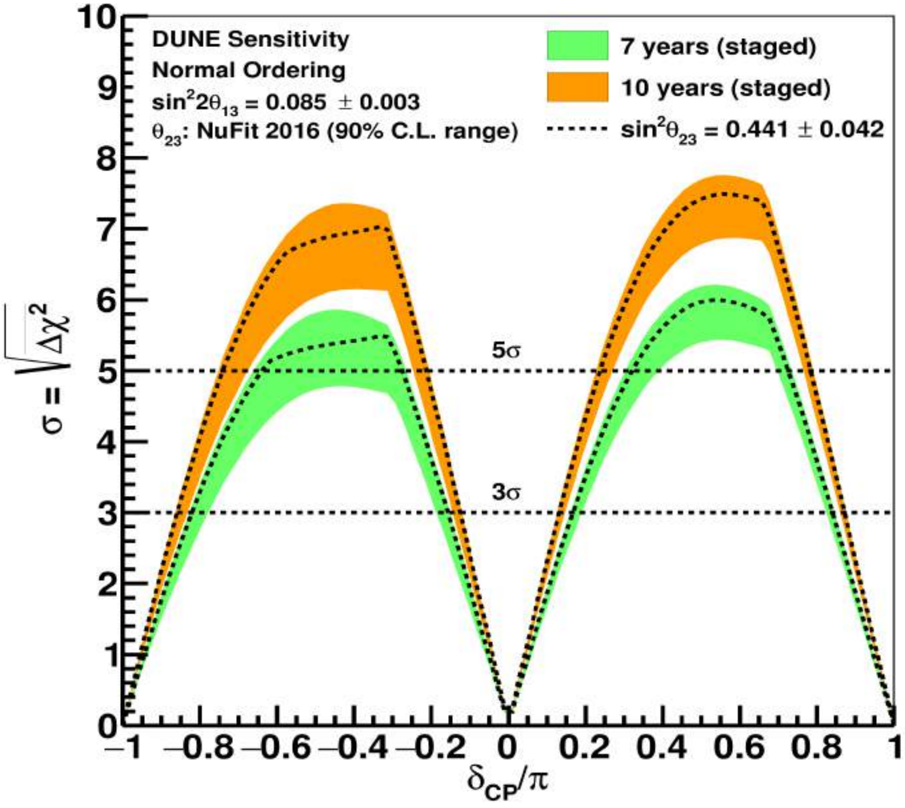


Cryostat access hatch,
plugged when cryostat is filled

Wire and Cathode frames are transported in halves which are joined in cryostat

DUNE Future Sensitivity





Measure the Mass Hierarchy in all scenarios

CP violation sensitivity depends on the true value

ProtoDUNE(s)

- CERN Neutrino Platform
- Large-scale prototyping/calibration

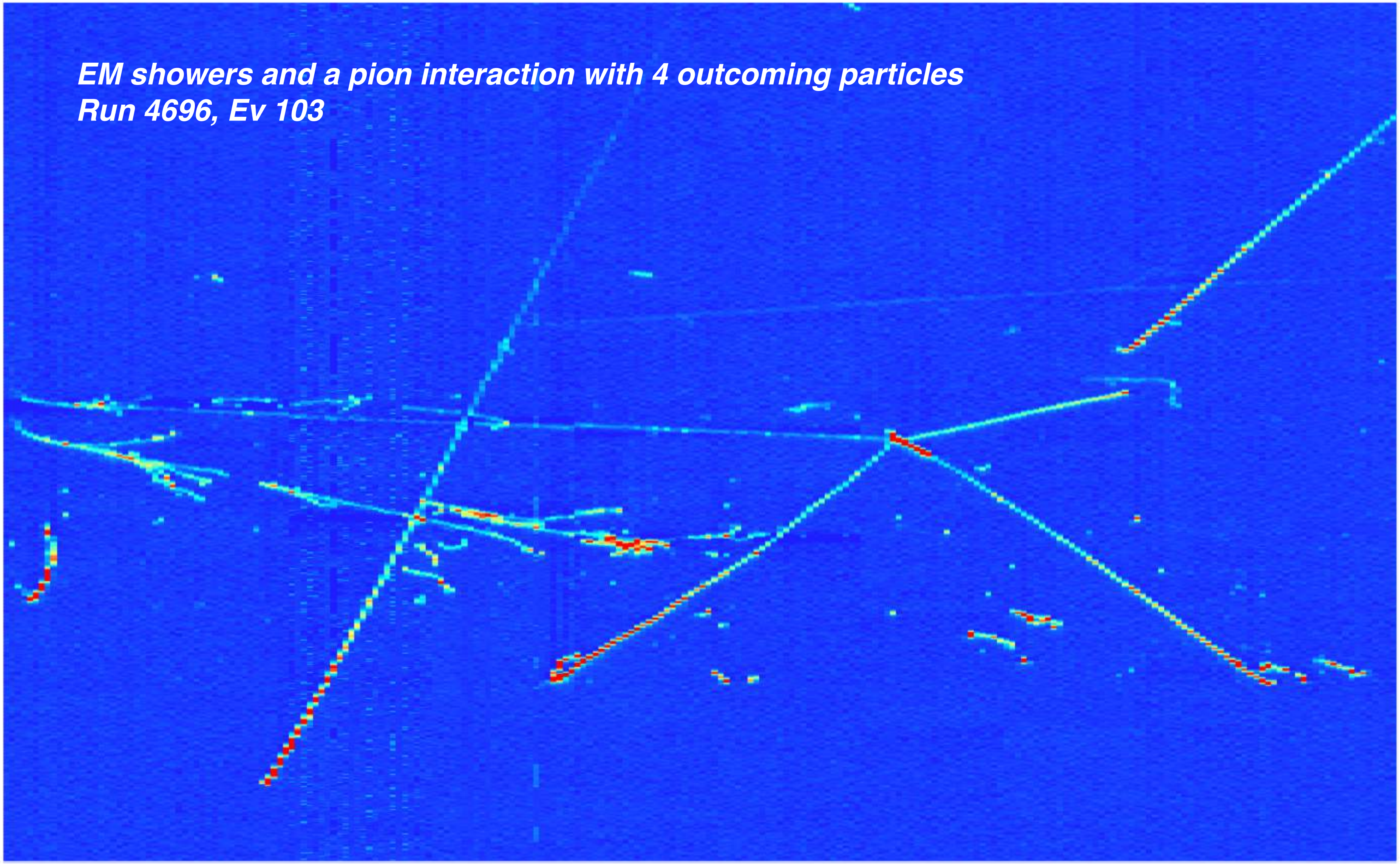
- UK built 2 (of 6) anode wire planes
  - 6 m tall
  - 2.3 m wide
- Large UK DAQ effort

ProtoDUNE(Single Phase) Summary

- Stable operation of cryogenics
- Operated TPC at nominal field of 500 V/cm
- Drift electron lifetime of 8 ms
- 3D reconstruction and analysis on real data ongoing

- Proposals under discussion for operation of ProtoDUNEs (SP & DP) during and after LS2

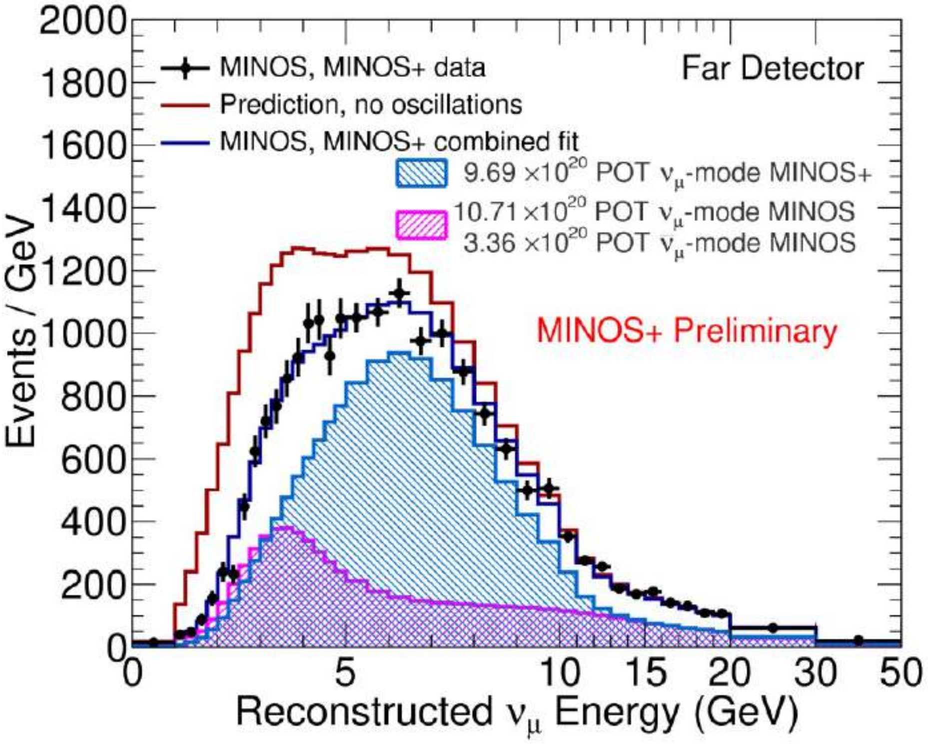
ProtoDUNE-SP Event

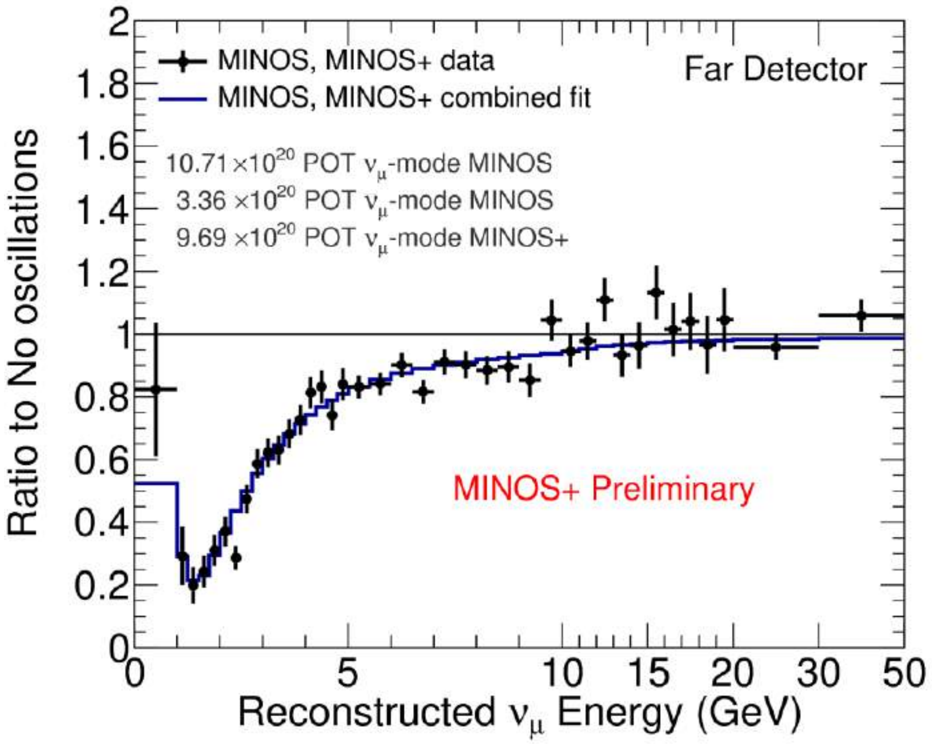


EM showers and a pion interaction with 4 outcoming particles
Run 4696, Ev 103

MINOS+

[A. Aurisano, Nu2018]



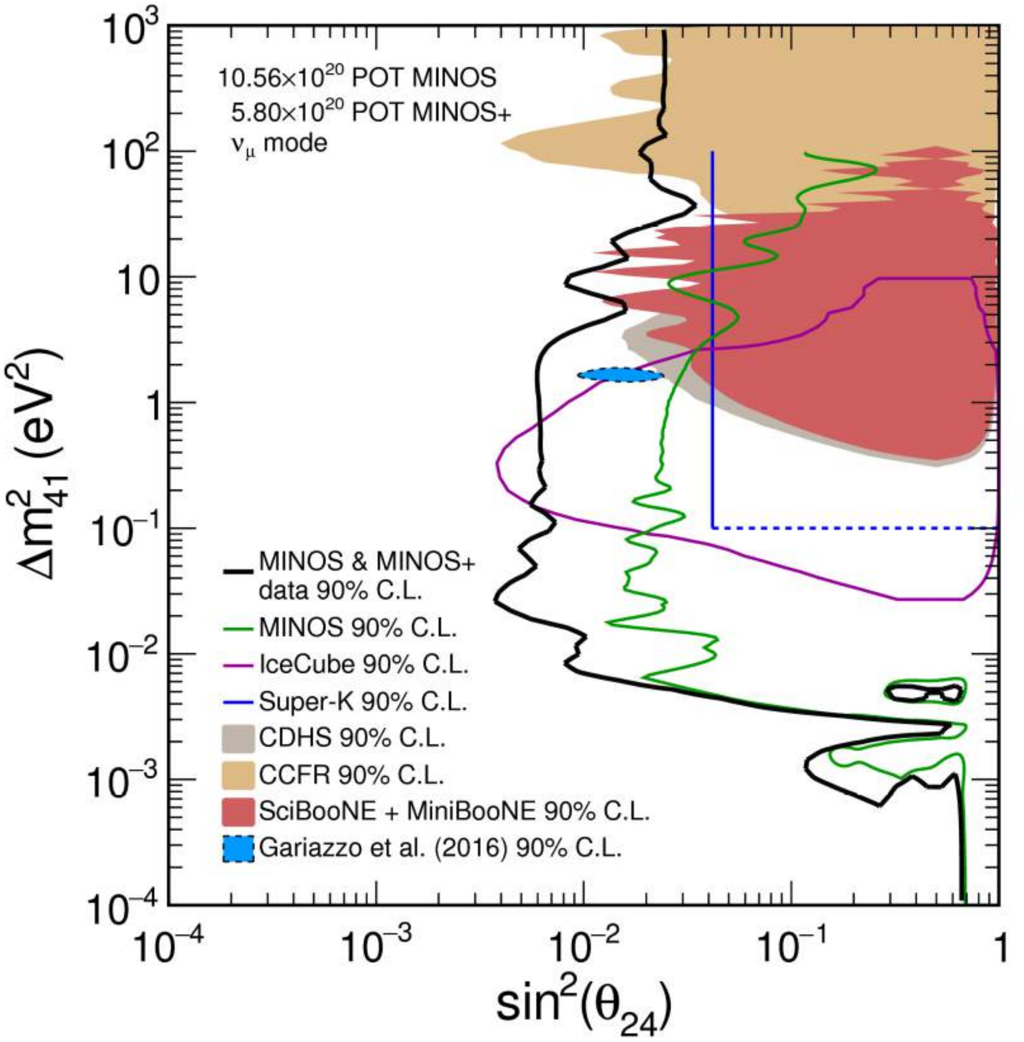


- MINOS and MINOS+ probe muon-neutrino disappearance over a broad range of energies
- Consistency with three flavor prediction tightly constrains alternate oscillations hypotheses

[A. Aurisano, Nu2018]

MINOS+ Sterile Neutrino Limit

- Use full NC and CC samples in both detectors
- Fit for θ_{23}, θ_{24}, θ_{34}, Δm^2_{32}, and Δm^2_{41}
- Fix δ_{13}, δ_{14}, δ_{24}, and θ_{14} to zero
- Median sensitivity from Feldman-Cousins corrected 90% CL contours from pseudo-experiments
- Best fit:
  - $\Delta m^2_{41} = 2.33\text{x}10^{-3}$ eV^2
  - $\sin^2\theta_{24} = 1.1\text{x}10^{-4}$
  - $\theta_{34} < 8.4\text{x}10^{-3}$
  - $\sin^2 2\theta_{23} = 0.92$
  - $\chi^2_{min}/\text{dof} = 99.3/140$
  - $\chi^2(4\nu) - \chi^2(3\nu) = 0.01$



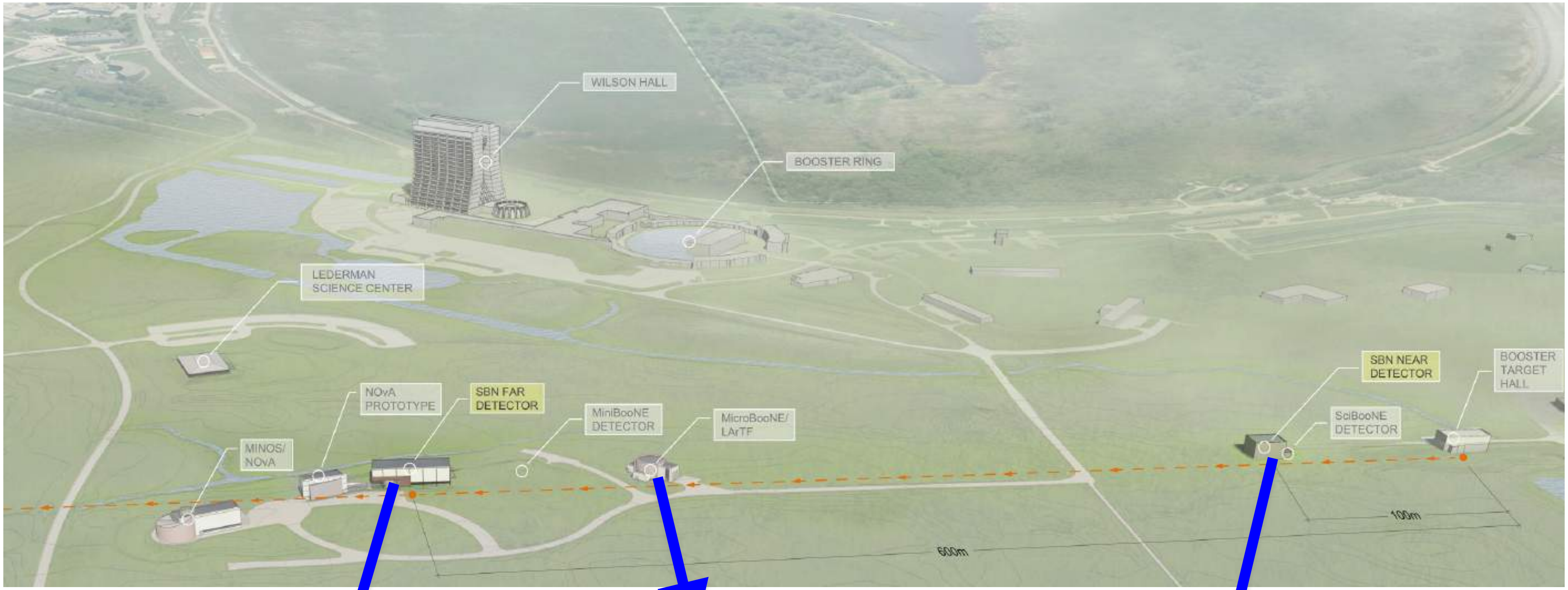
MINOS+ sets leading limits on sterile neutrino mixing, especially in critical 1-10 eV2 region

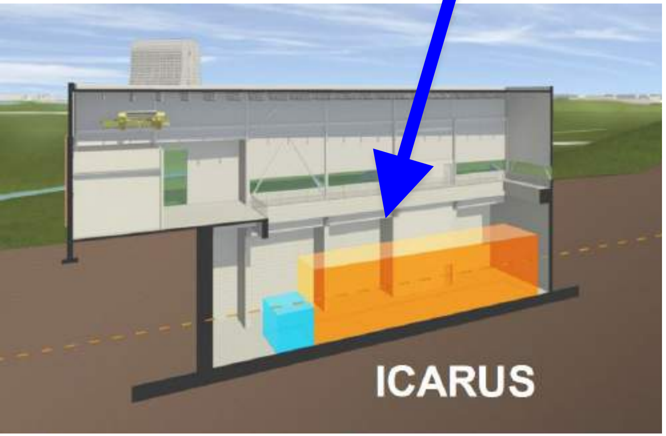
arXiv:1710.06488

Short-Baseline Neutrino Programme

Short-Baseline Neutrino Programme

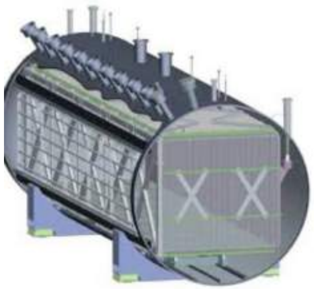
Three liquid argon time projection chamber (LArTPC) detectors in the Booster Neutrino Beam (BNB) at Fermilab



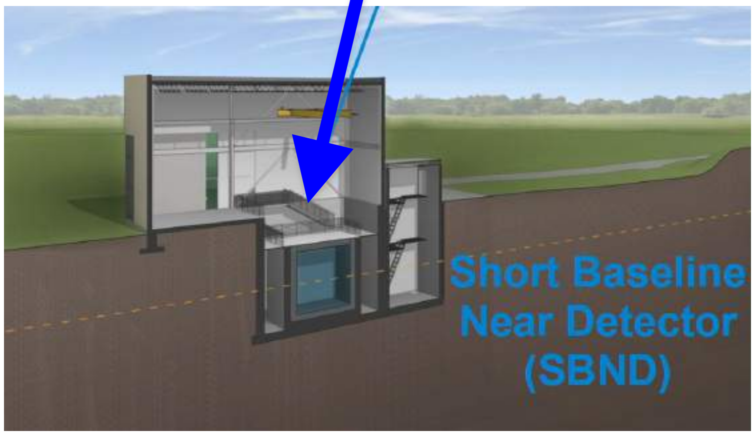


600 m / 476 tons

MicroBooNE



470 m / 89 tons



110 m / 112 tons

[S. Tufanli, EPS2017]

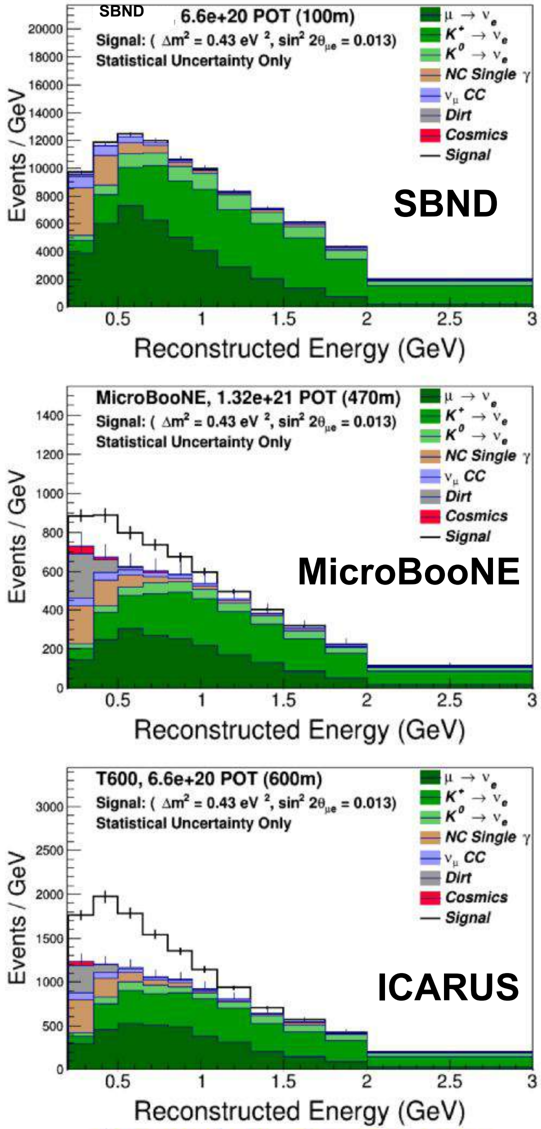
SBN Programme Goals

- 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 2020
  - MicroBooNE: **taking data since 2015**
  - Icarus: data taking starts 2019

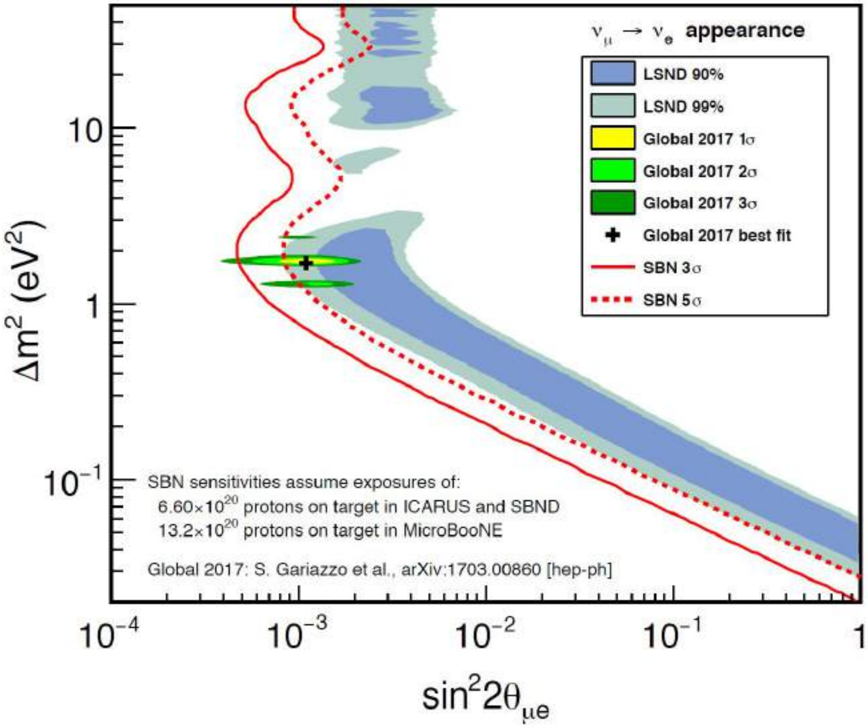
[S. Tufanli, EPS2017]

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



SBN sensitivities assume exposures of:
6.60×10^{20} protons on target in ICARUS and SBND
13.2×10^{20} protons on target in MicroBooNE

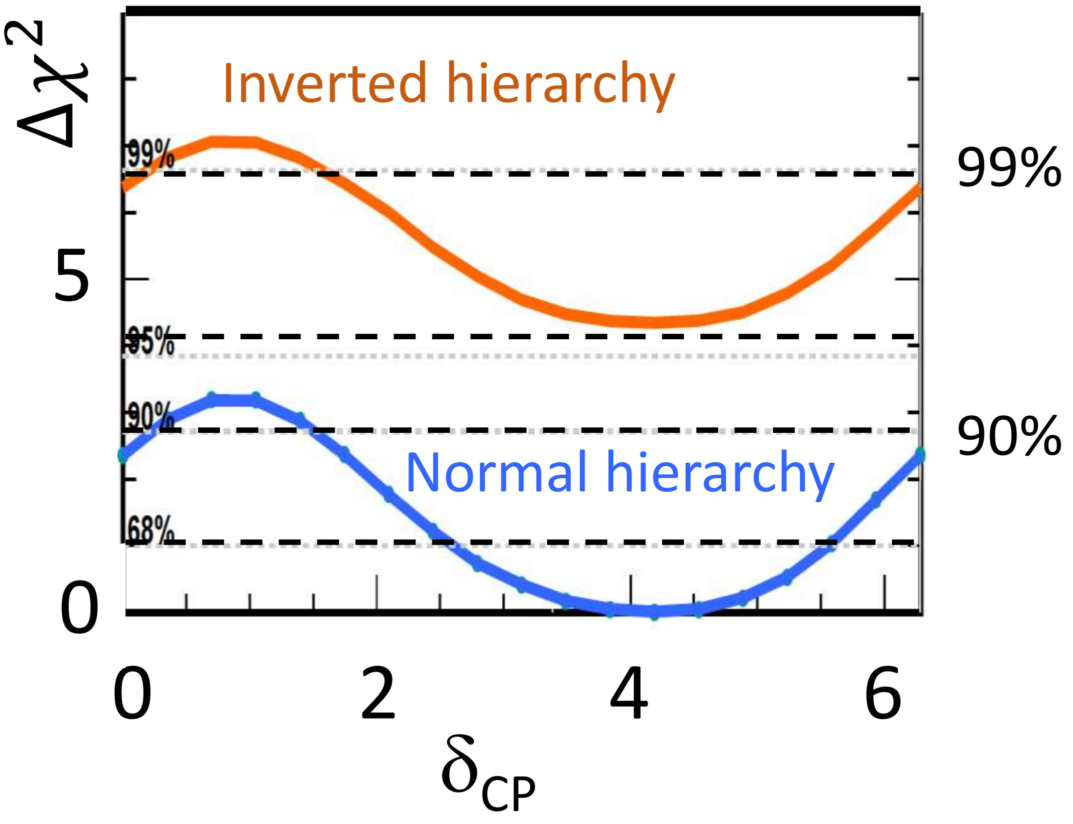
Global 2017: S. Gariazzo et al., arXiv:1703.00860 [hep-ph]

Conclusions

- Three flavor oscillations
  - NOvA
    - >4 sigma evidence of electron **antineutrino** appearance
    - Prefer Normal Hierarchy at 1.8 σ and exclude $\delta_{CP} = \pi/2$ in IH at > 3 σ
    - Disfavour maximal mixing at 1.8 σ and lower octant at a similar level
    - Potential 4 sigma mass hierarchy measurement by 2024
  - DUNE due to take data in 2026
    - Mass hierarchy huge effect
    - CPv sensitivity across a wide range of parameter space
- Sterile neutrinos
  - MINOS+ uses two detectors to measure ν_μ disappearance
    - sets best limits on sterile neutrinos in crucial region
  - Short-baseline programme will directly address anomalies looking for ν_e appearance
- Exciting time! Watch this space.

Backup slides

SuperK atmospheric data



Favour NH at ~2 sigma

Prefer $\delta_{CP}=3\pi/2$ (=$-\pi/2$) and upper θ_{23} octant (not shown)

[Yoshinari Hayato, Nu2018]

Pros and Cons

(Very complementary projects!)

DUNE

- Long 1300 km baseline
  - excellent MH measurement
  - access to 2nd oscillation max with greater CP asymmetry
- Wide band beam
  - see more effects of oscillation
  - good sensitivity to non-standard effects (test 3 neutrino paradigm)
- Exquisite detector imaging
  - high eff. and pur.
  - lower stats
  - Perhaps lower systematics

HyperK

- Huge detector
  - high statistics
  - excellent early CPv sensitivity
  - limited information on hadronic recoil system
- Short-baseline
  - much smaller matter effects
  - need to know mass hierarchy
  - (use atmospheric neutrinos)
- Narrow band beam
  - less background to reject
  - less energy information

Timelines/Funding

- NOvA – up to 2024
- T2K phase 2 – up to 2027 (awaiting approval?)
- SuperK – upgrade with Gadolinium underway

- JUNO – starts 2021, fully funded

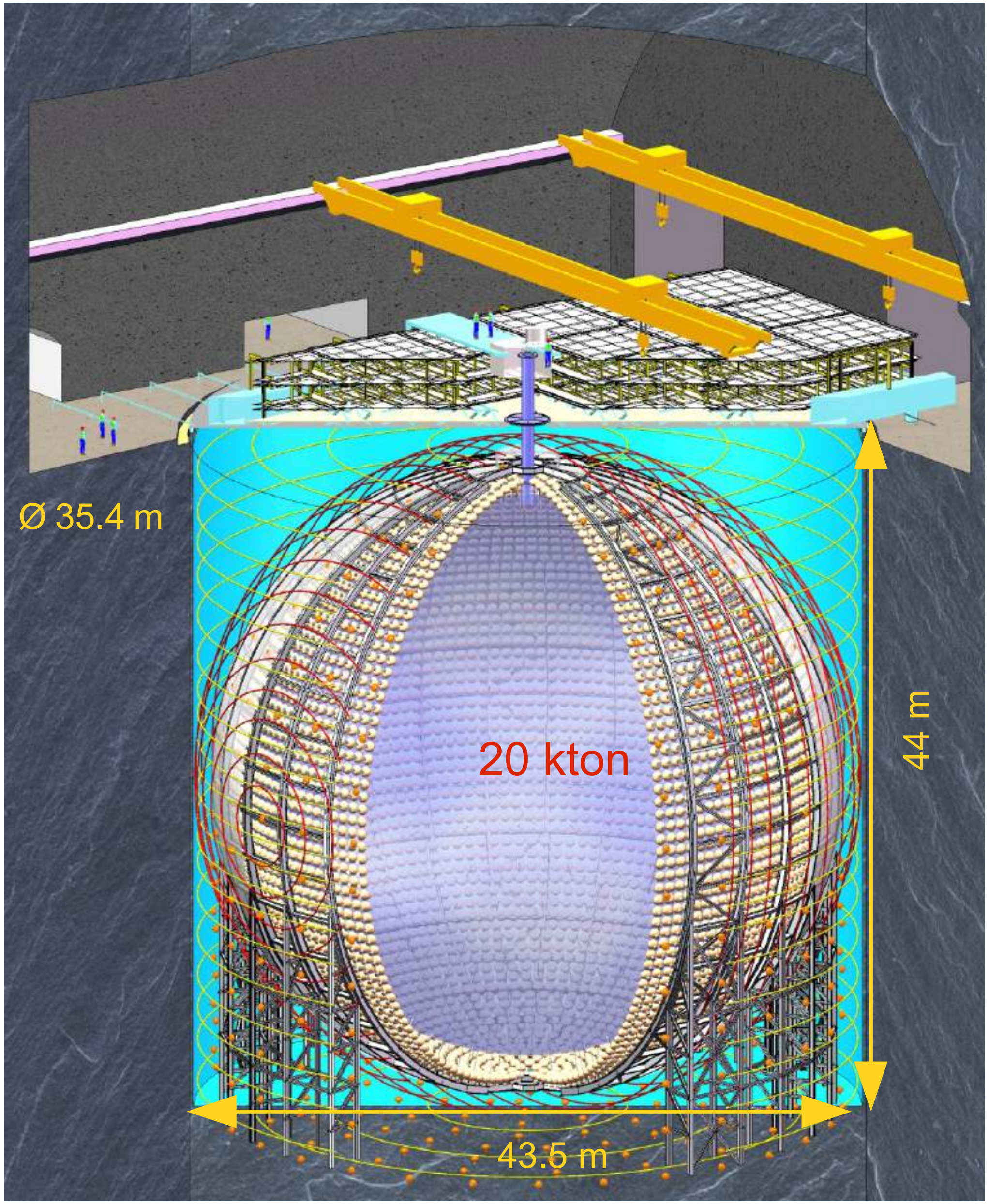
- ORCA – small deployment now, full deployment by 2021, partially funded
- PINGU – small deployment “upgrade” by 2023, full deployment by 2031, funding pending

- DUNE – starts 2026, under construction
- HyperK – starts 2026, funding pending

[Sourced from Nu2018]

JUNO

High power nuclear power plants (26.6 GW total power)



Liquid scintillator
Energy resolution 3%/sqrtE (2x better)

$>3\ \sigma$ mass hierarchy on own
$>4\ \sigma$ with $\Delta m^2_{\mu\mu}$ better than 1%

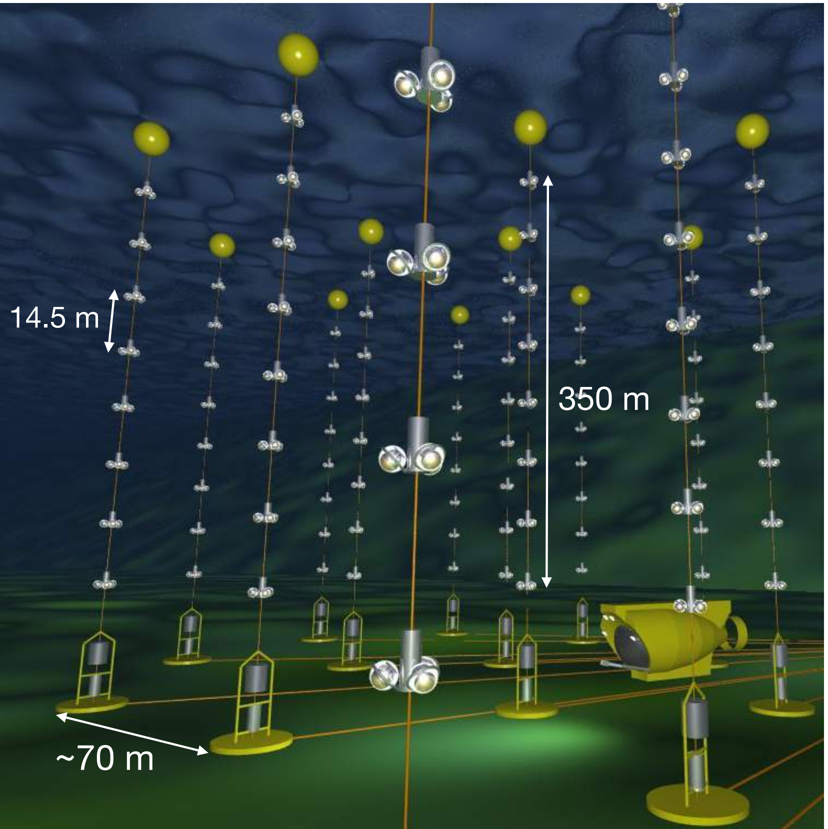
[Bjoern Wonsak, Nu2018]

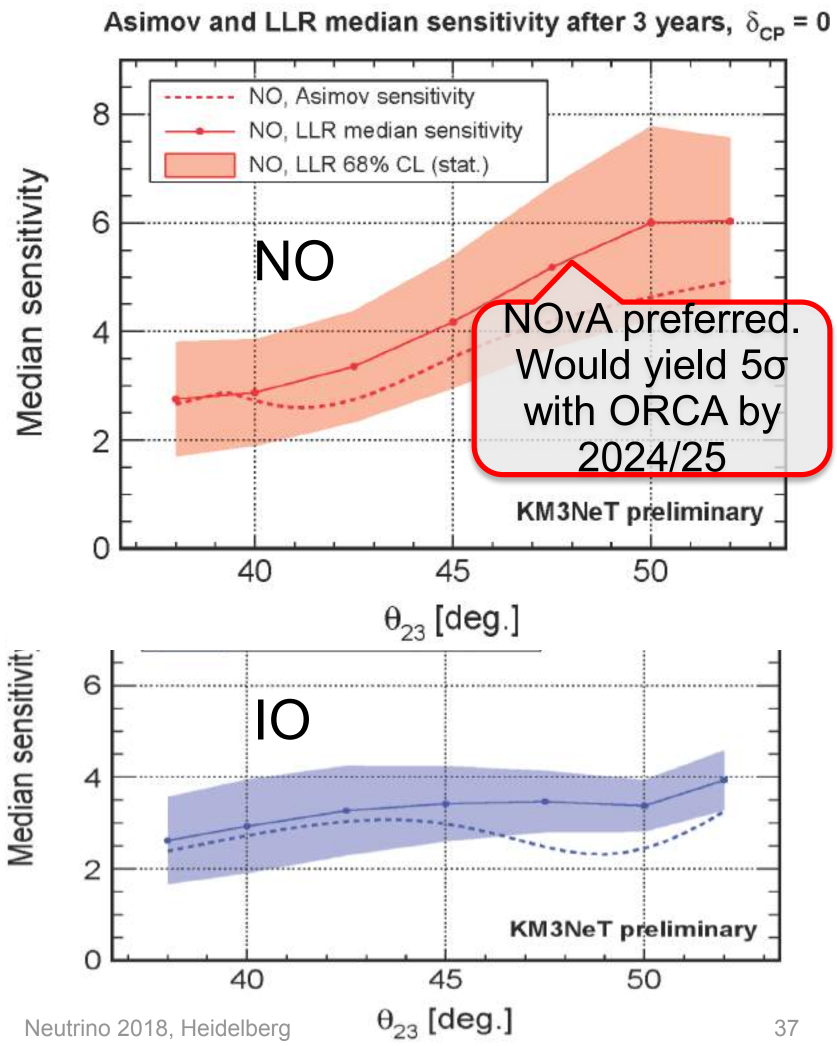
ORCA & PINGU

Measure atmospheric neutrinos deep in water or ice

Higher energies than beam experiments – more matter effects

Upward neutrinos traverse denser parts of the Earth – more matter effects





NOvA preferred. Would yield 5σ with ORCA by 2024/25

Neutrino 2018, Heidelberg 37

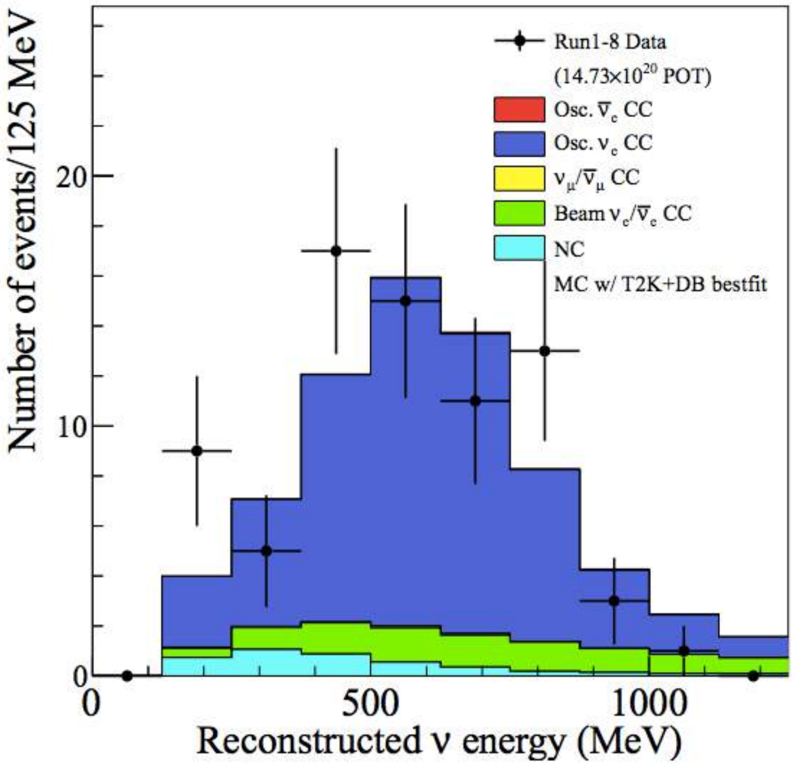
>3 σ mass hierarchy sensitivity

[Uli Katz, Nu2018]

T2K

SAMPLE	2018	
ν_μ	243	
ν_eQE	75	(~15 bkg)
$\nu_e 1\pi$	15	
$\bar{\nu}_\mu$	102	
$\bar{\nu}_e$	9	(6.5 bkg)

Neutrino CCQE 1 e-like ring



$\nu_\mu \rightarrow \nu_e$ 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

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

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

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

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

where

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

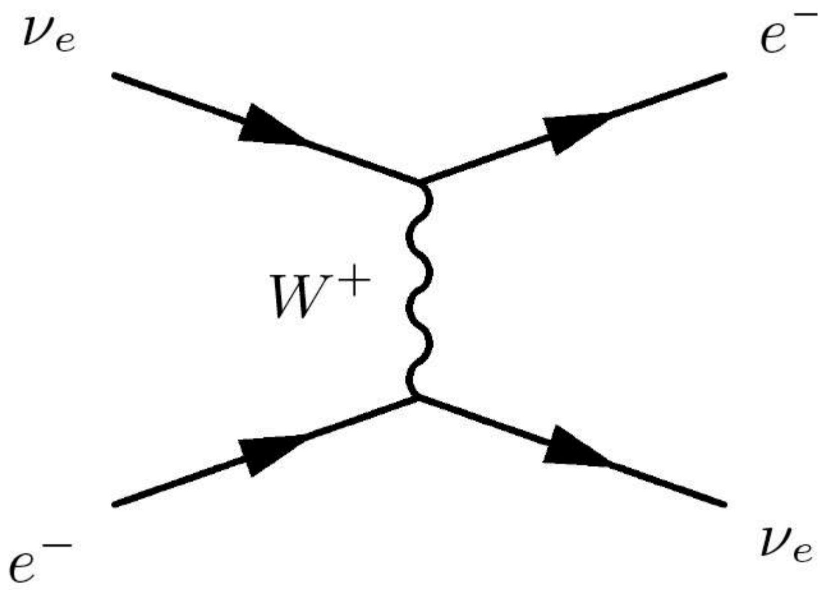
and $\cot\delta = J_{CP}^{-1}\mathrm{Re}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$, $J_{CP} = \mathrm{Im}(U_{\mu3}U^*_{e3}U_{e2}U^*_{\mu2})$.

Matter Effect & Mass Hierarchy

- Coherent forward elastic scattering
- Neutrinos (and antineutrinos) travel through matter not antimatter
  - electron density causes the asymmetry
    - via specifically **CC** coherent forward elastic scattering
  - different Feynman diagrams for ν_e and $\bar{\nu}_e$ interactions with electrons...

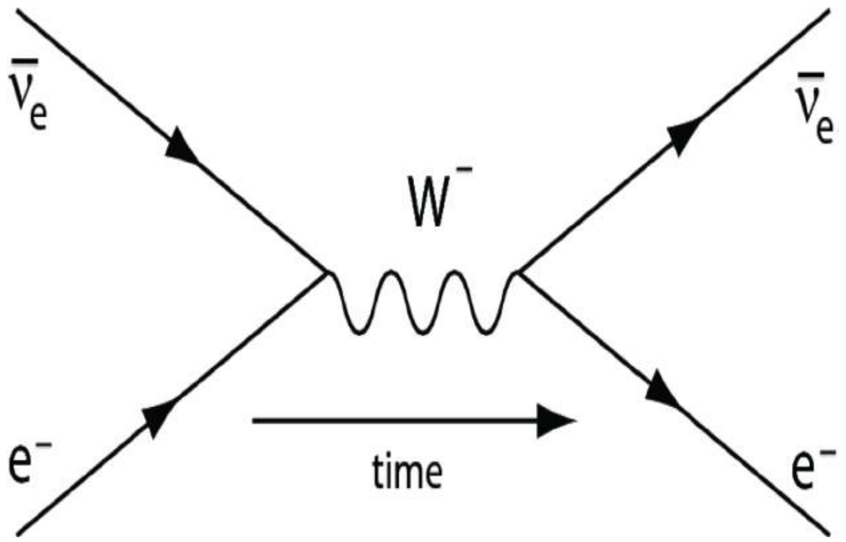
Different Feynman Diagrams

- Amplitude for electron **neutrino** interaction with an electron



- is not equal to...

- Amplitude for electron **antineutrino** interaction with an electron

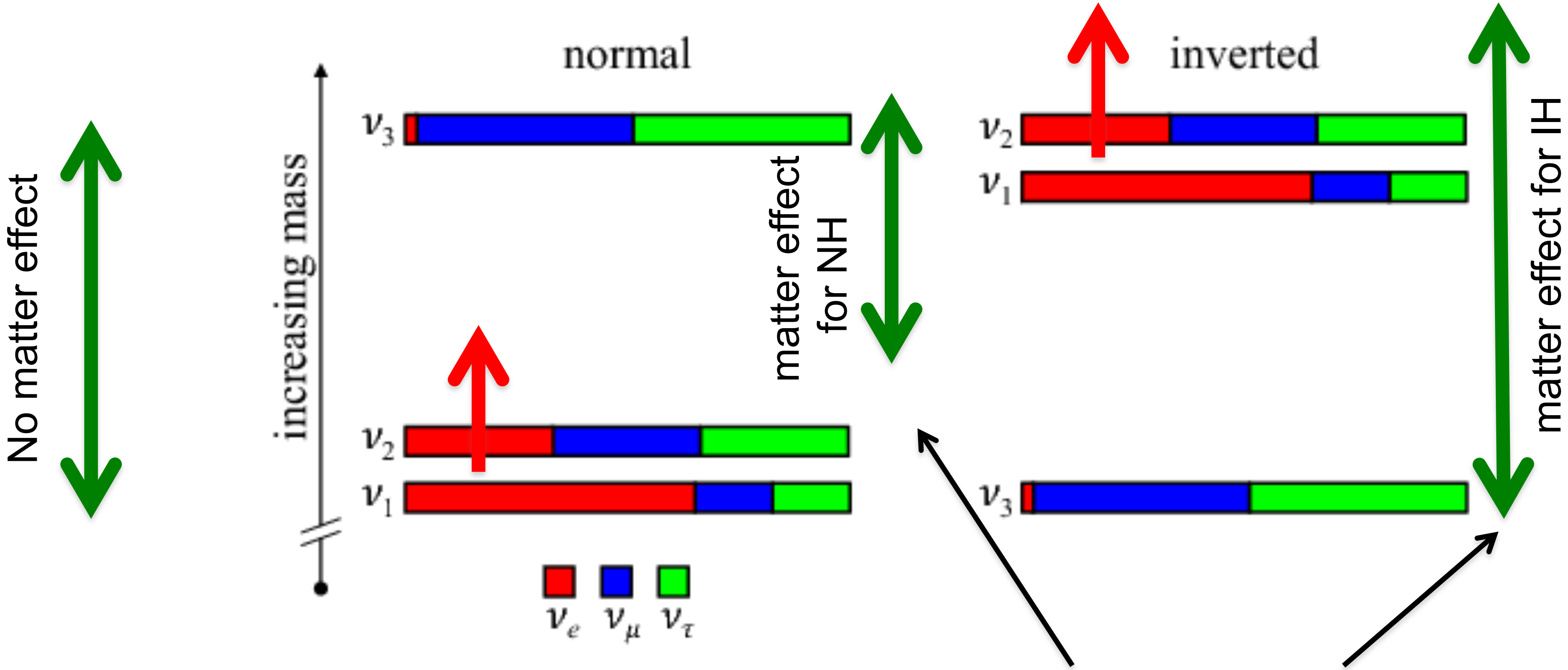


Electron neutrinos and antineutrinos are affected differently by interactions with matter → **fake** CP violation

Why does the mass hierarchy affect oscillations involving electron (anti)neutrinos?

Matter effect (neutrino case)

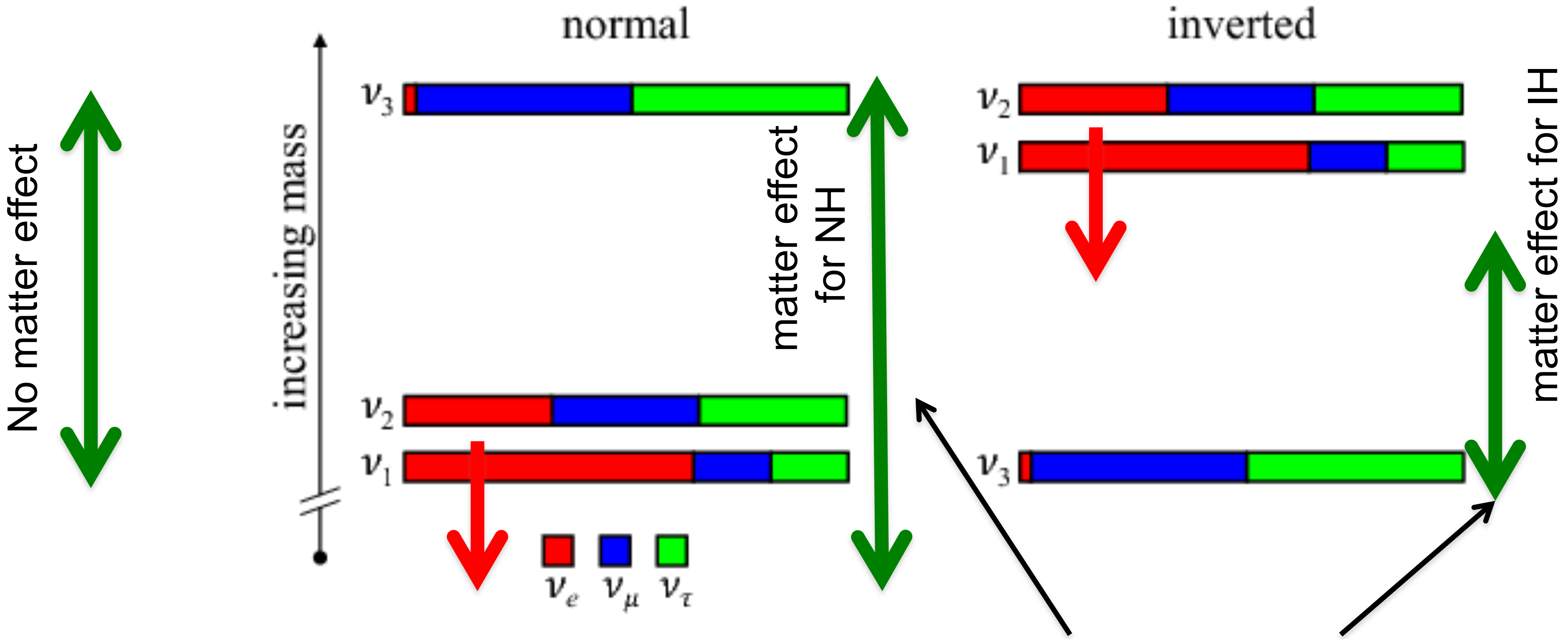
- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



Splitting changes size in presence of matter

Antineutrino case

- Matter effect raises (or lowers) the energy state of the **mass eigenstates**
  - strength depends on electron neutrino content of each mass eigenstate



Splitting changes size in presence of matter

Splittings **and** mixing angles affected

- Mixing angles in matter (θ_M) are modified by the mass squared splitting in matter (Δm^2_M)
  - e.g. simple 2-flavour case:

$$\sin 2\vartheta_{\mathrm{M}} = \frac{\Delta m^2 \sin 2\vartheta}{\Delta m^2_{\mathrm{M}}}$$

  - Also see it in full 3-flavour equations (a few slides back)