The Physics of Neutrinos from Accelerator Beams (Part 2)

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Recent and present LBL experiments
(continued)

NOvA

Six primary oscillation channels accessible

via charged-current interactions:

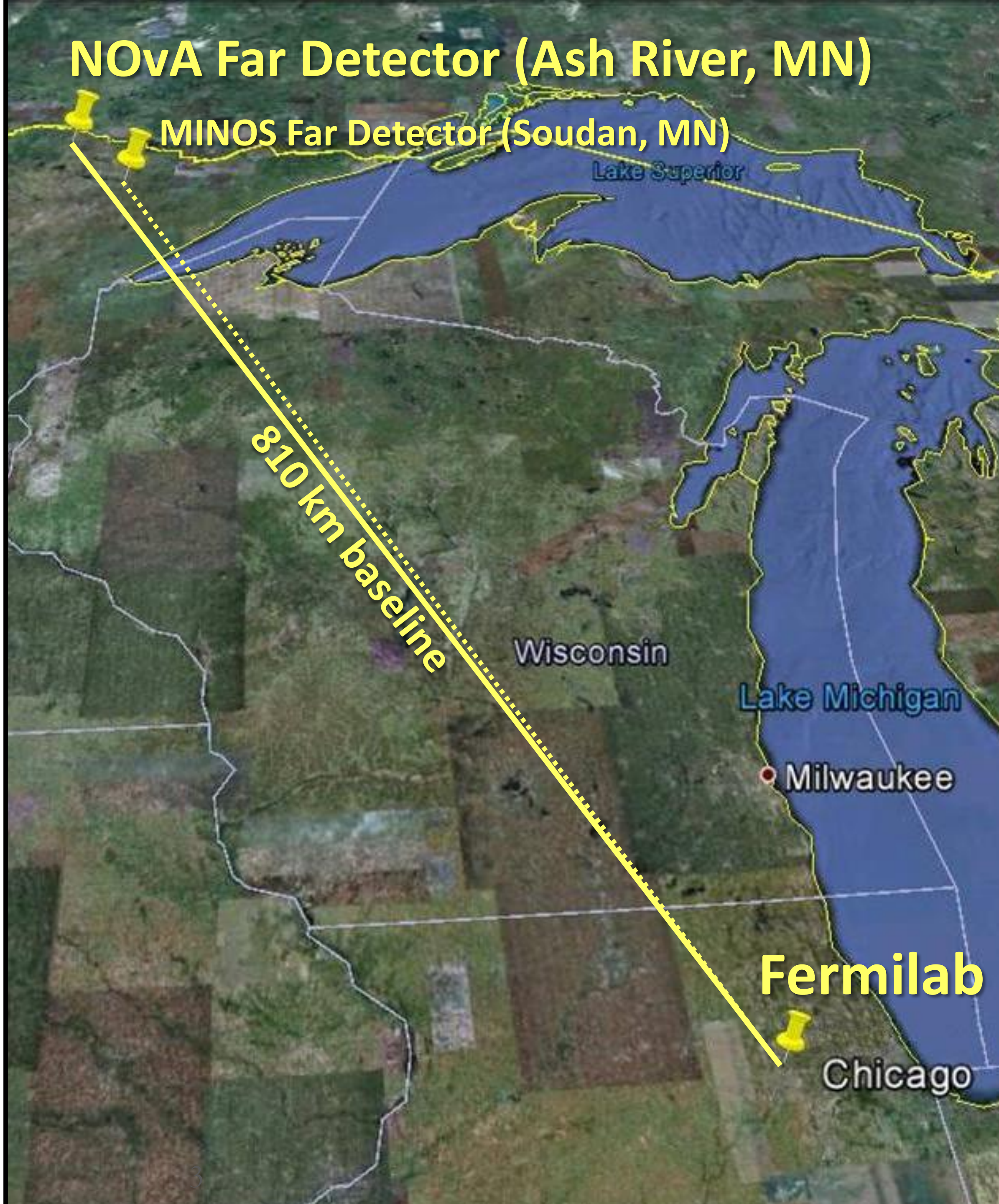
$\nu_\mu \rightarrow \nu_e$ $\quad$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\nu_\mu \rightarrow \nu_\mu$ $\quad$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

and neutral-current interactions:

$\nu_\mu \rightarrow \nu_x$ $\quad$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_x$

(Over-constrained system)



Off-axis beam

Both **NOvA and T2K** use off-axis beams.

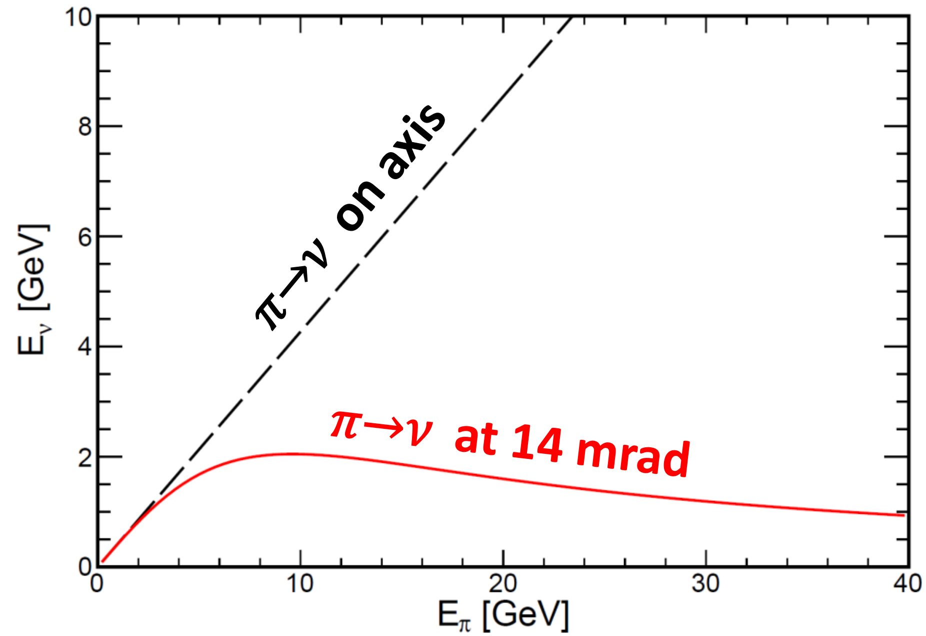
NOvA angle: **14 mrad**

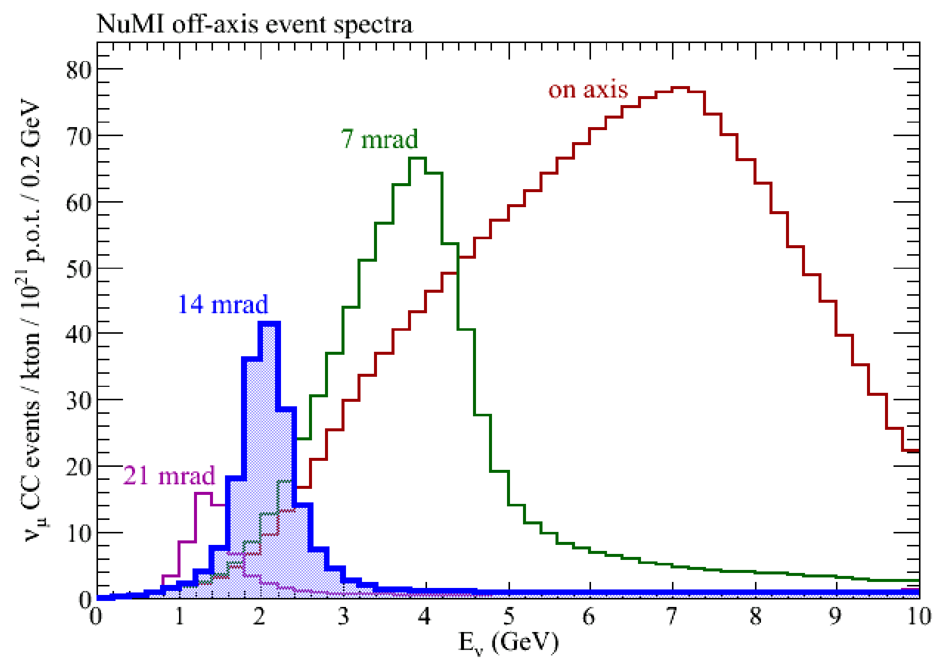
(figures at right)

T2K angle: **44 mrad**

Yields **narrower energy spectrum** at the detectors

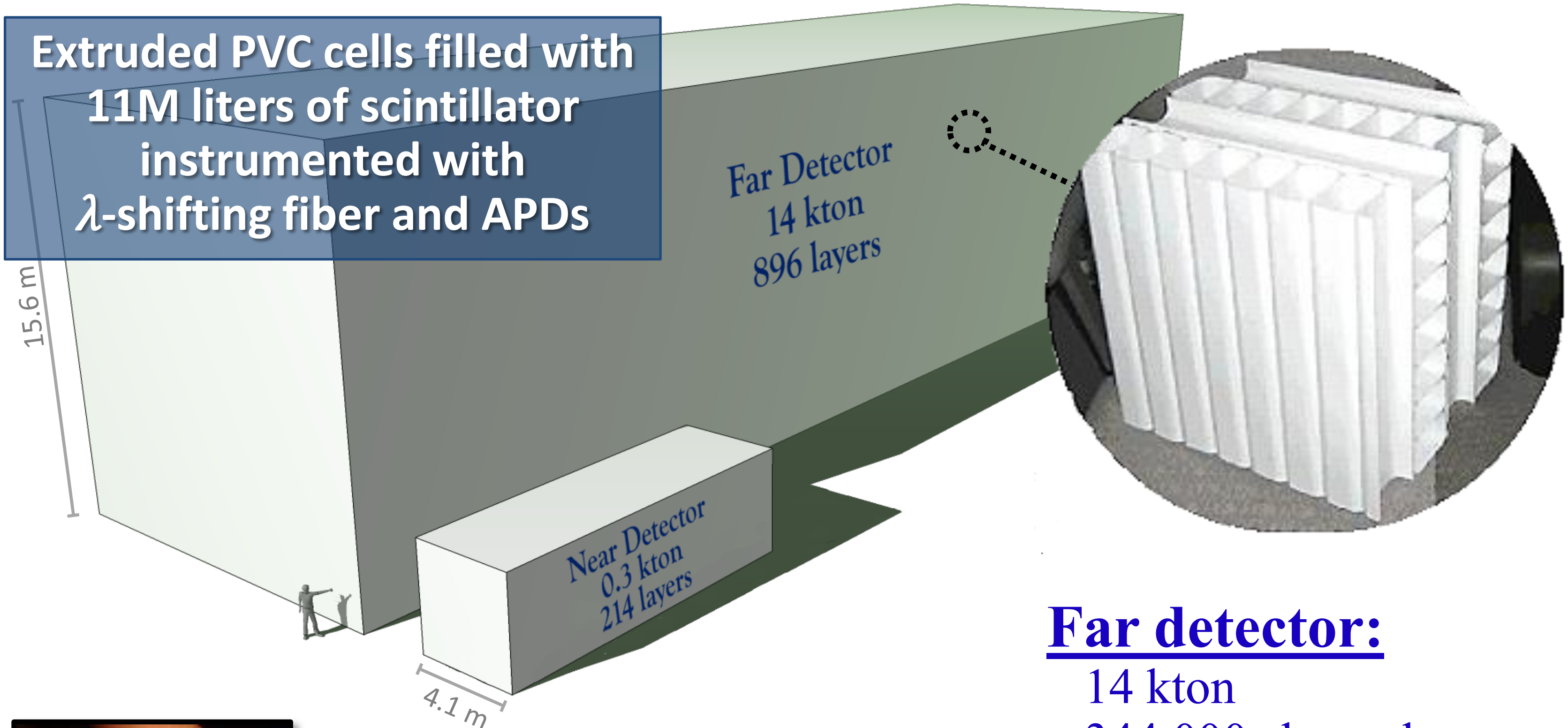
→ **Reduces NC and ν_e CC backgrounds** in the oscillation analyses while maintaining **high ν_μ flux at osc. max.**

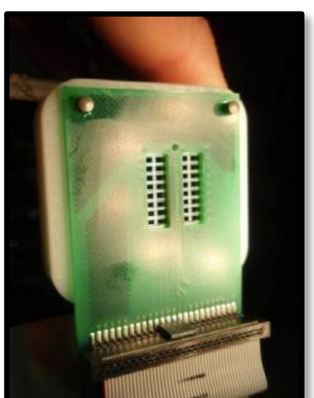




NOvA detectors

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





32-pixel APD ←

Fiber pairs from 32 cells →

Far detector:

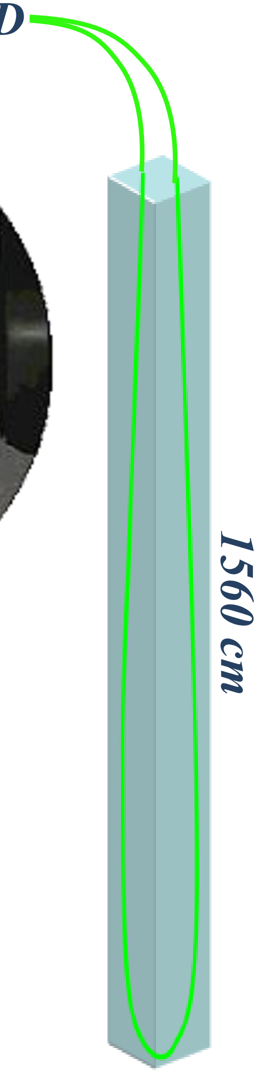
14 kton
344,000 channels

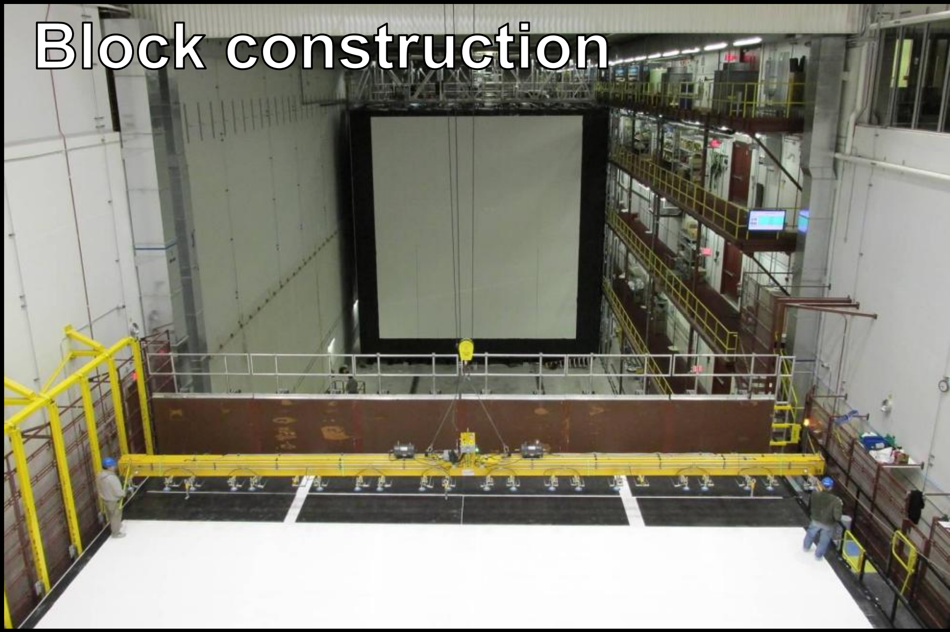
Near detector:

0.3 kton
20,000 channels

radiation length = 38 cm
(6 cell depths, 10 cell widths)

A NOvA cell

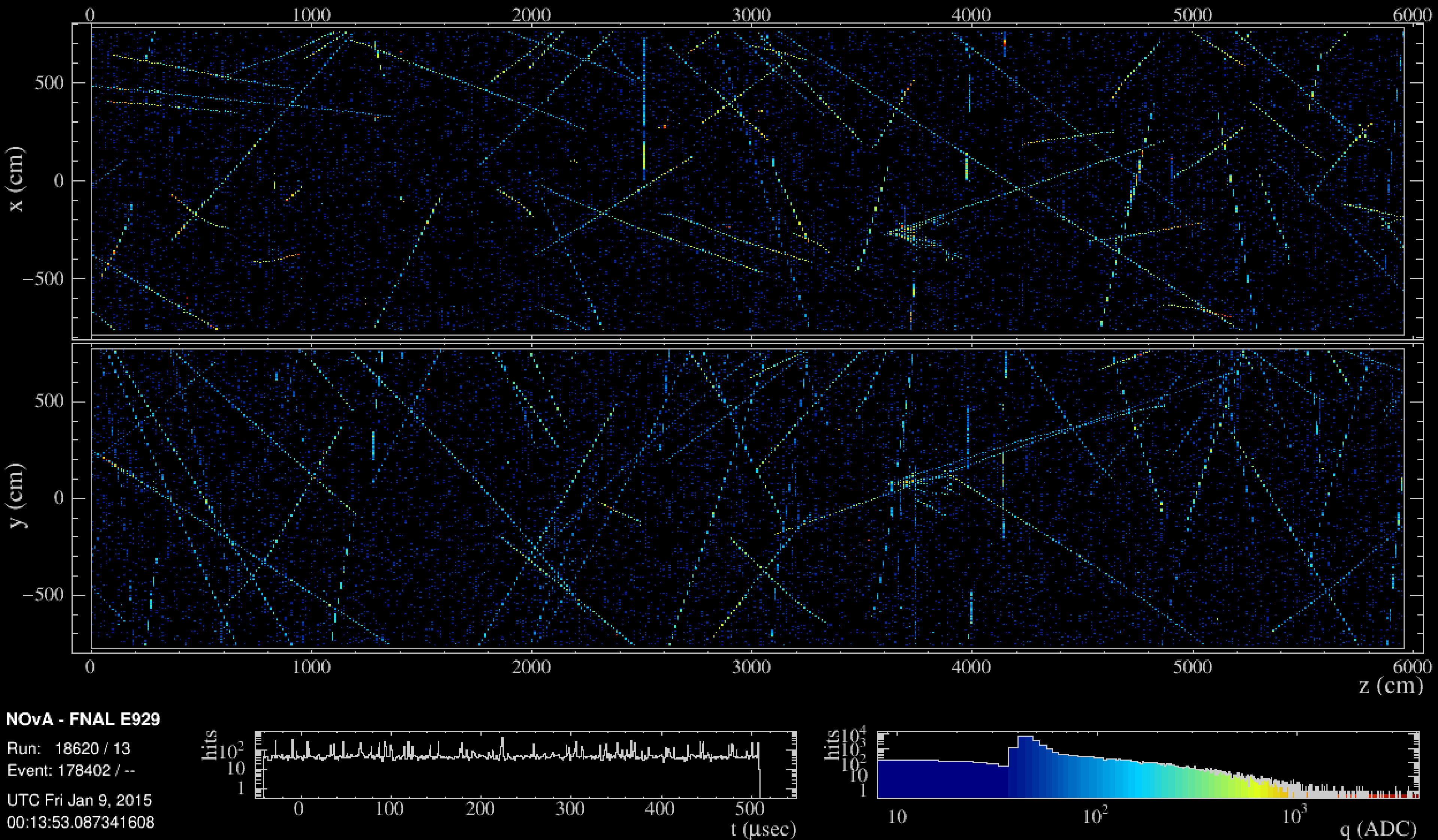



Far Detector site

Block construction

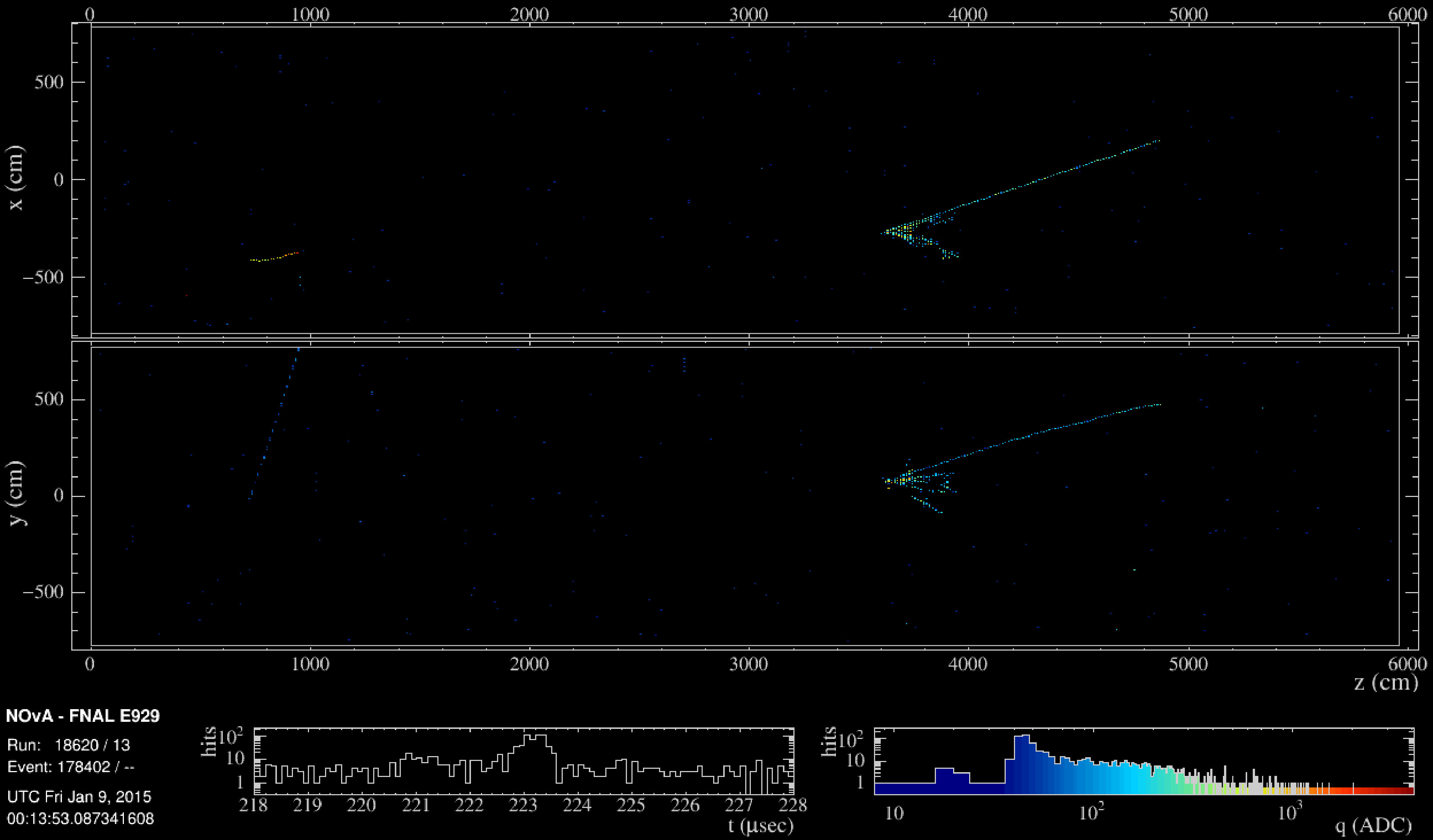
Outfitted Far Detector

Near Detector

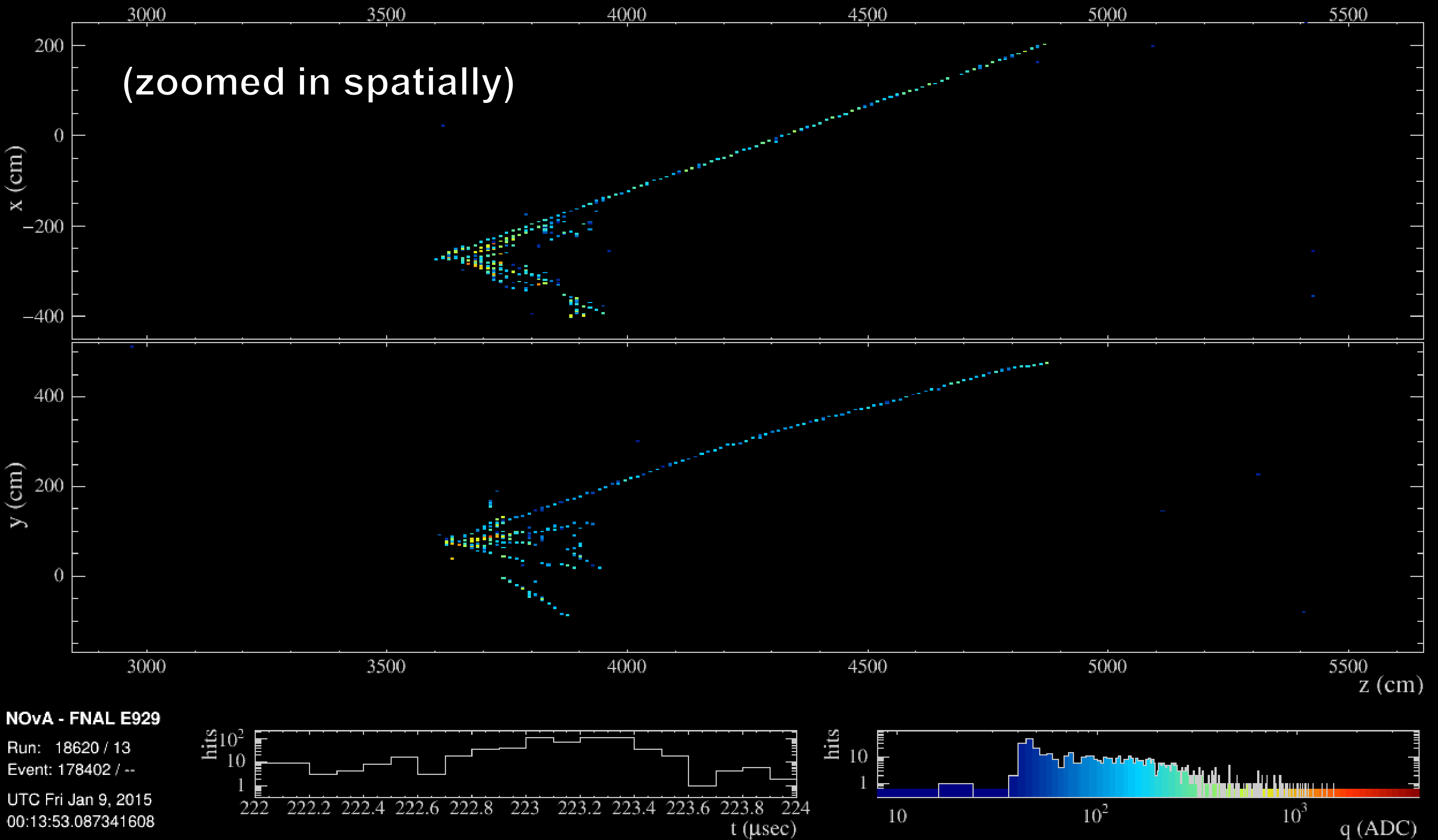
550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

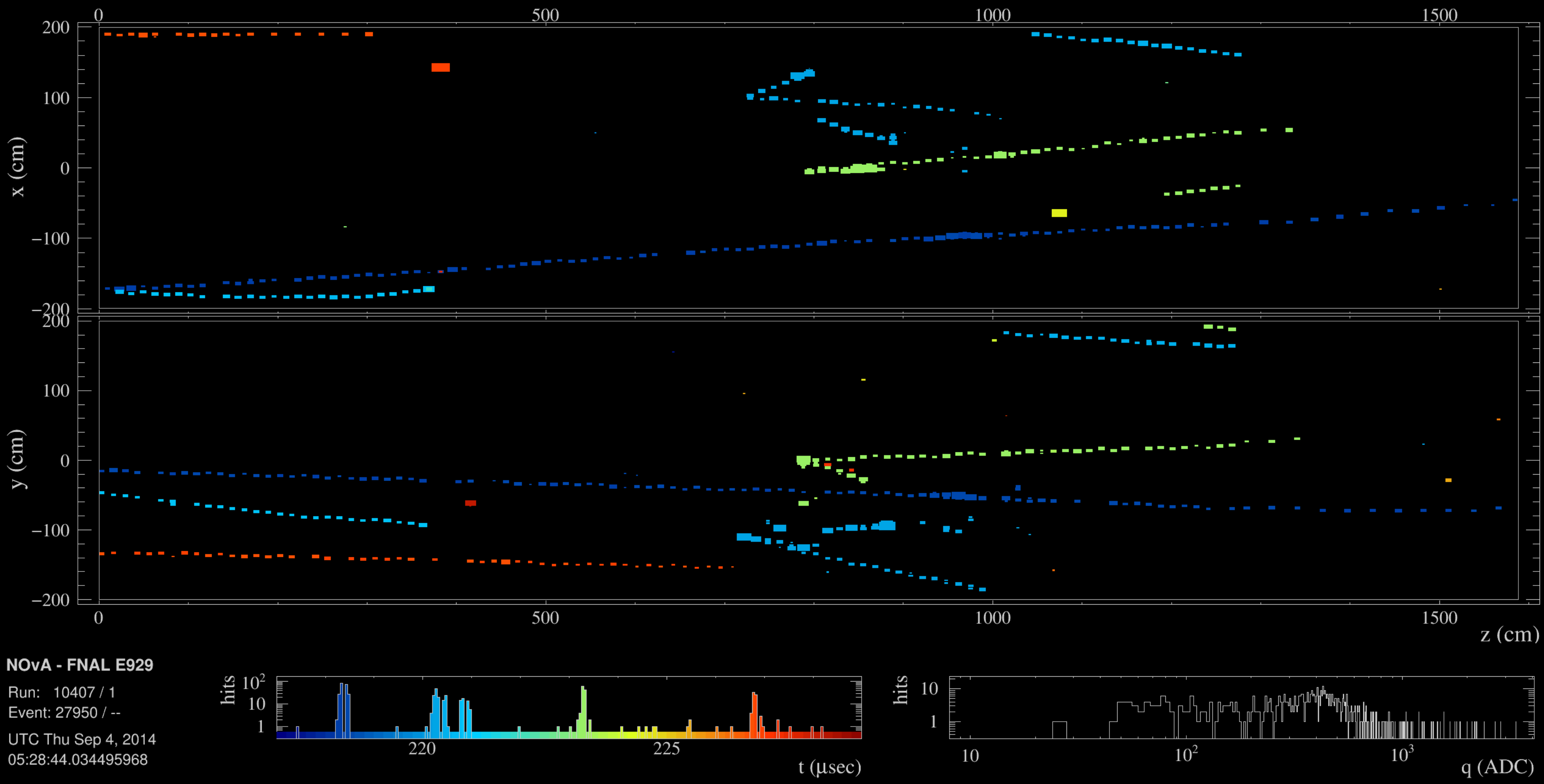


Close-up of neutrino interaction in the Far Detector



Near Detector: 10 μs of readout during NuMI beam pulse

(color ⇒ time of hit)



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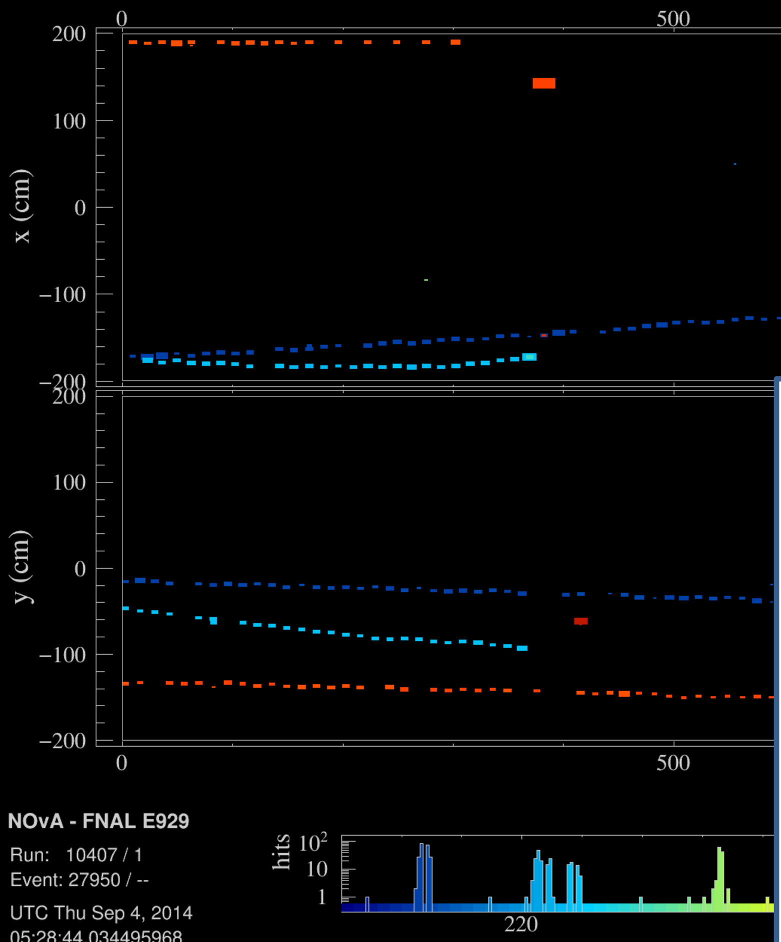
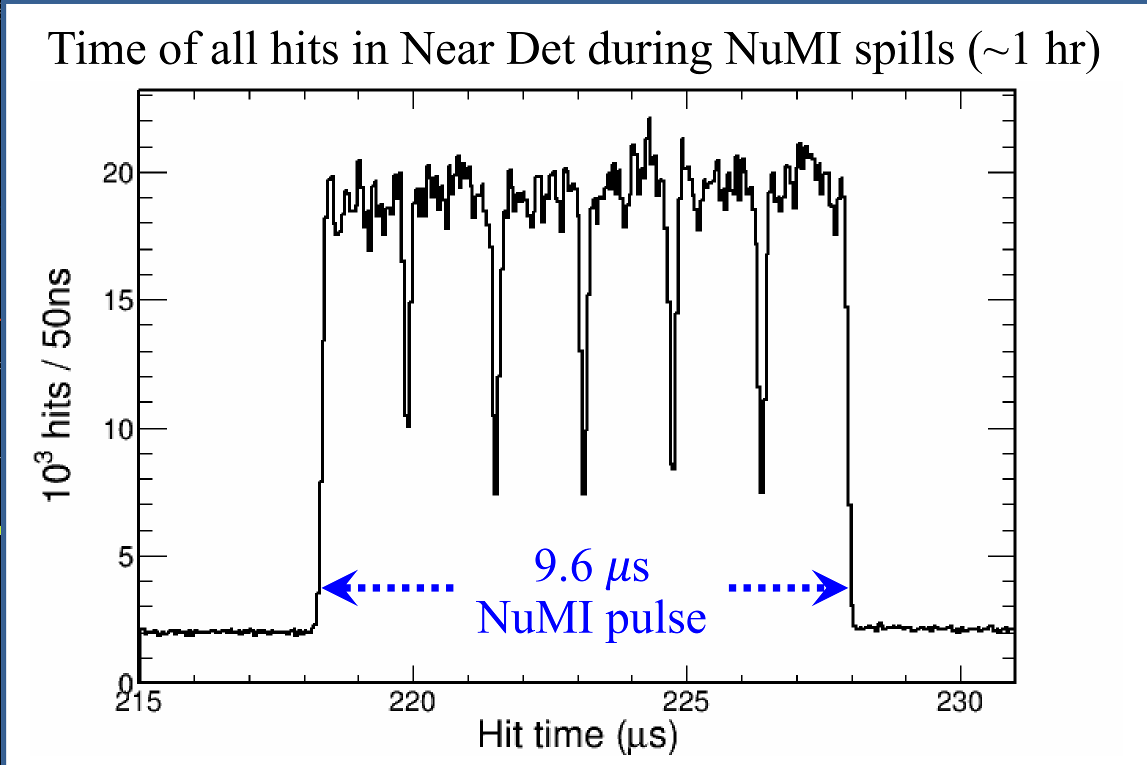
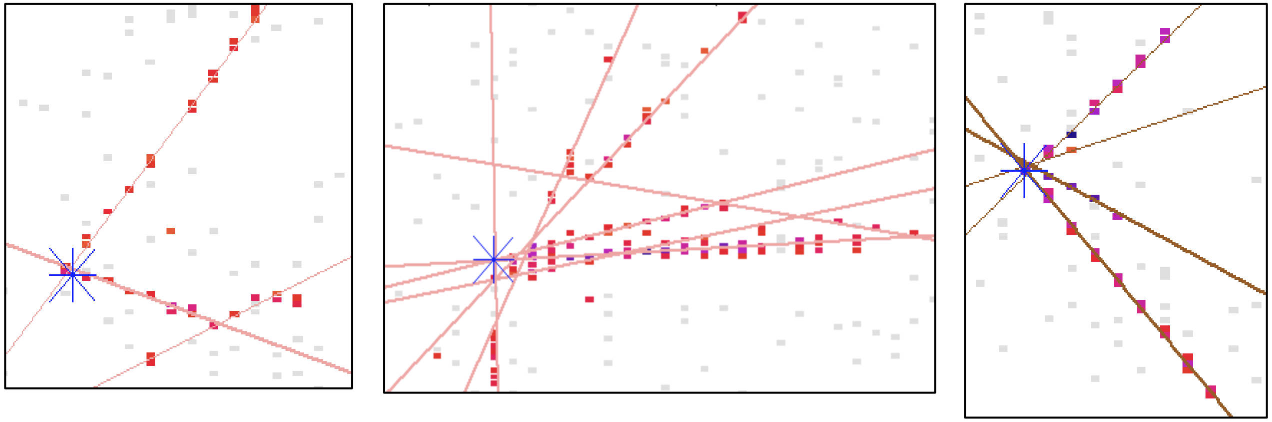
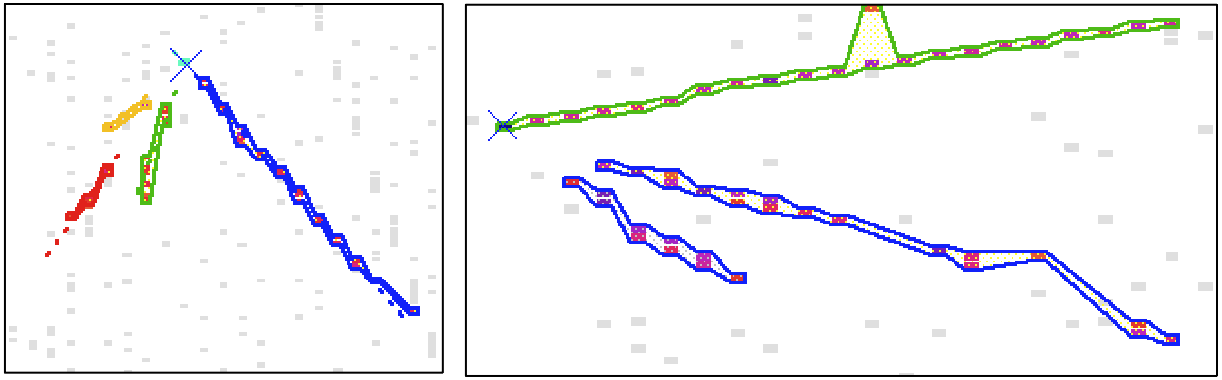




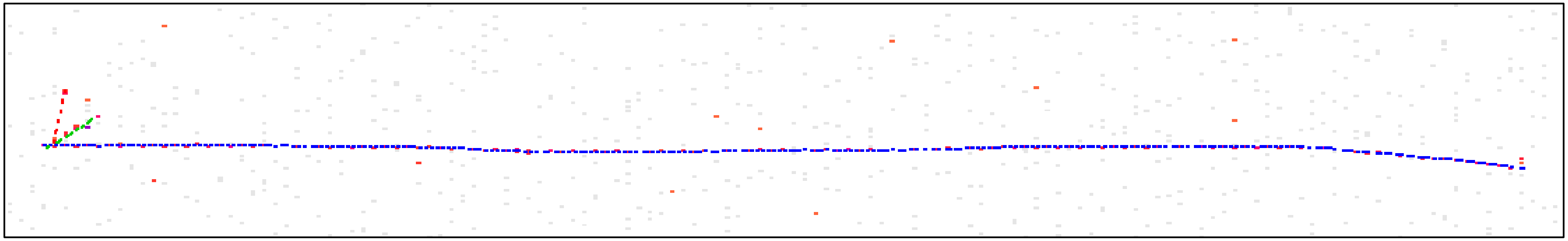
Vertexing:



Clustering:

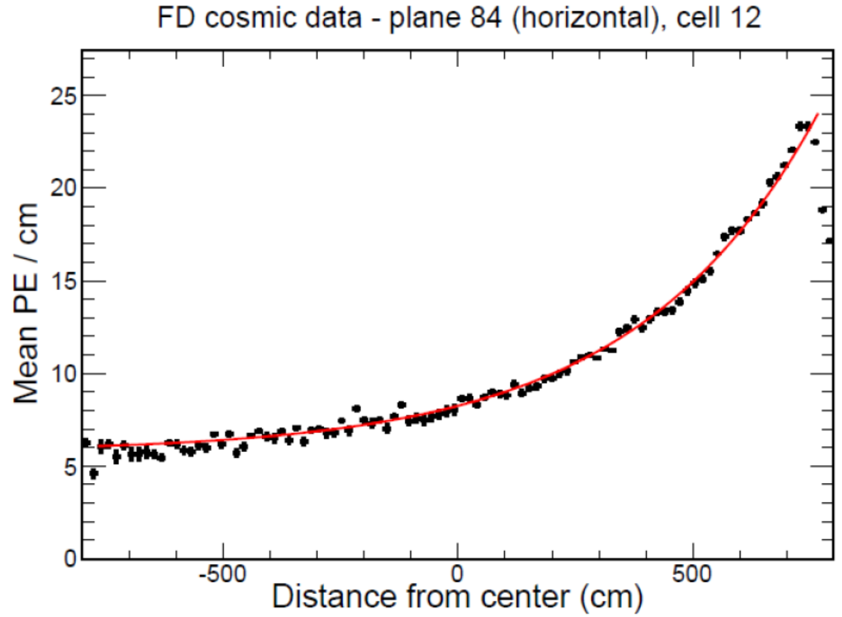


Tracking:

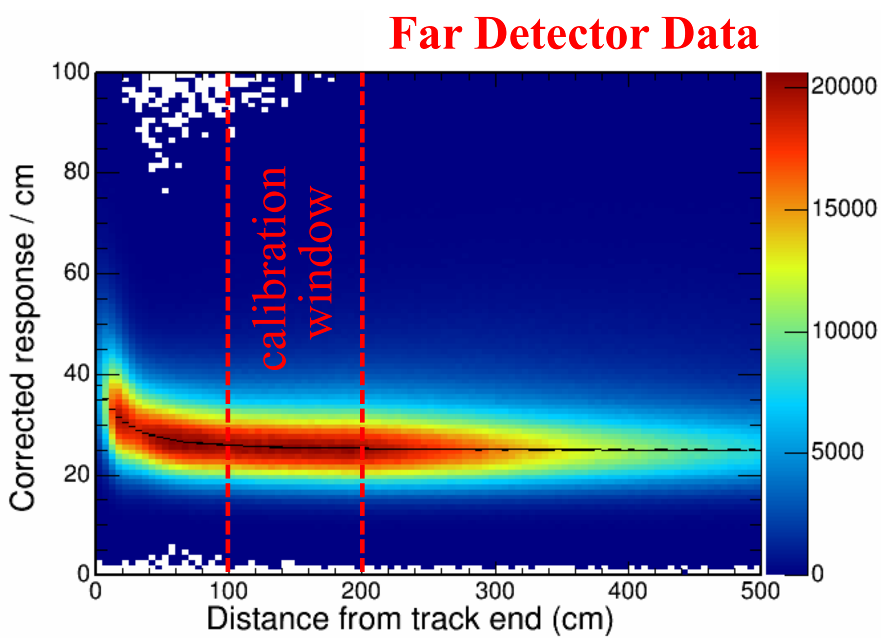


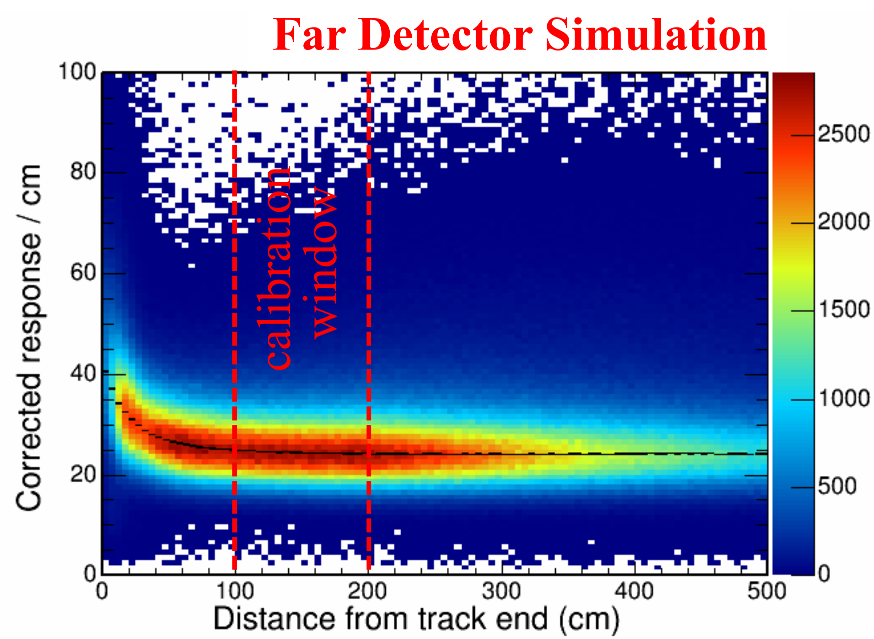
Calibration

Attenuation in the WLS fiber ⟶



Stopping muons provide absolute energy scale *(below)*

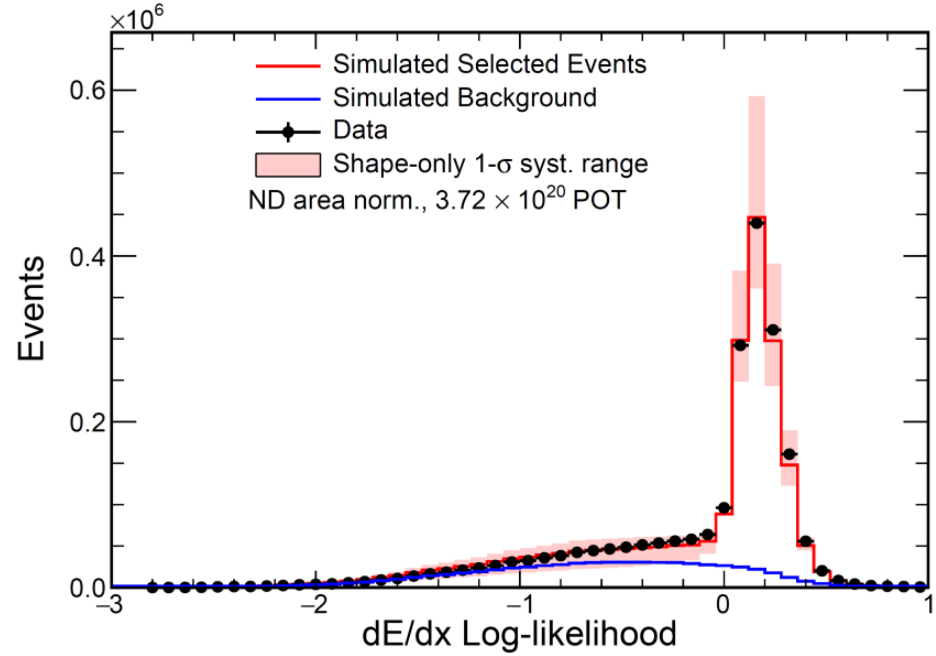


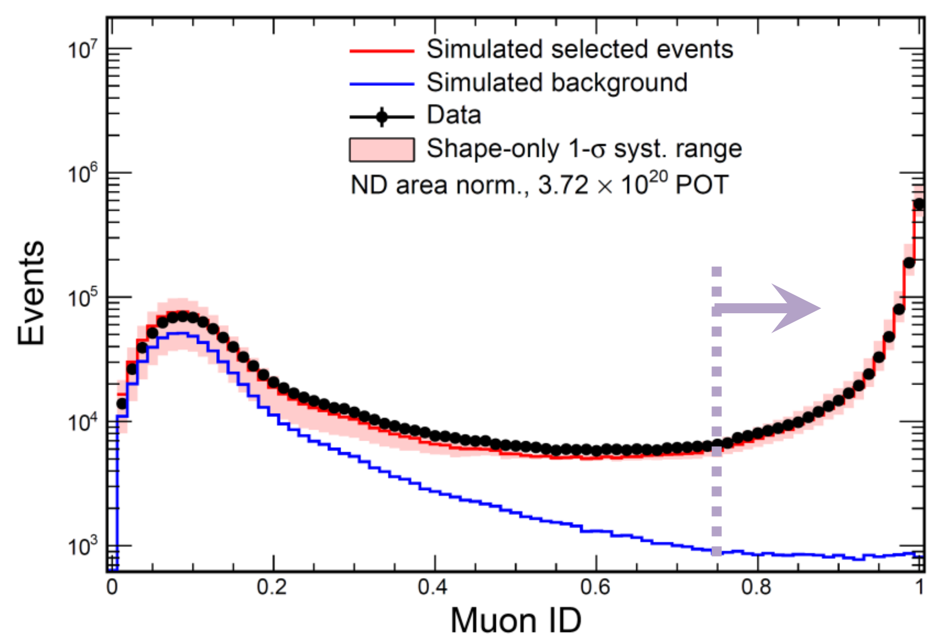


Finding muons:

- long tracks
- appropriate *dE/dx* profiles →
- appropriate scattering

Resulting classifier ↘





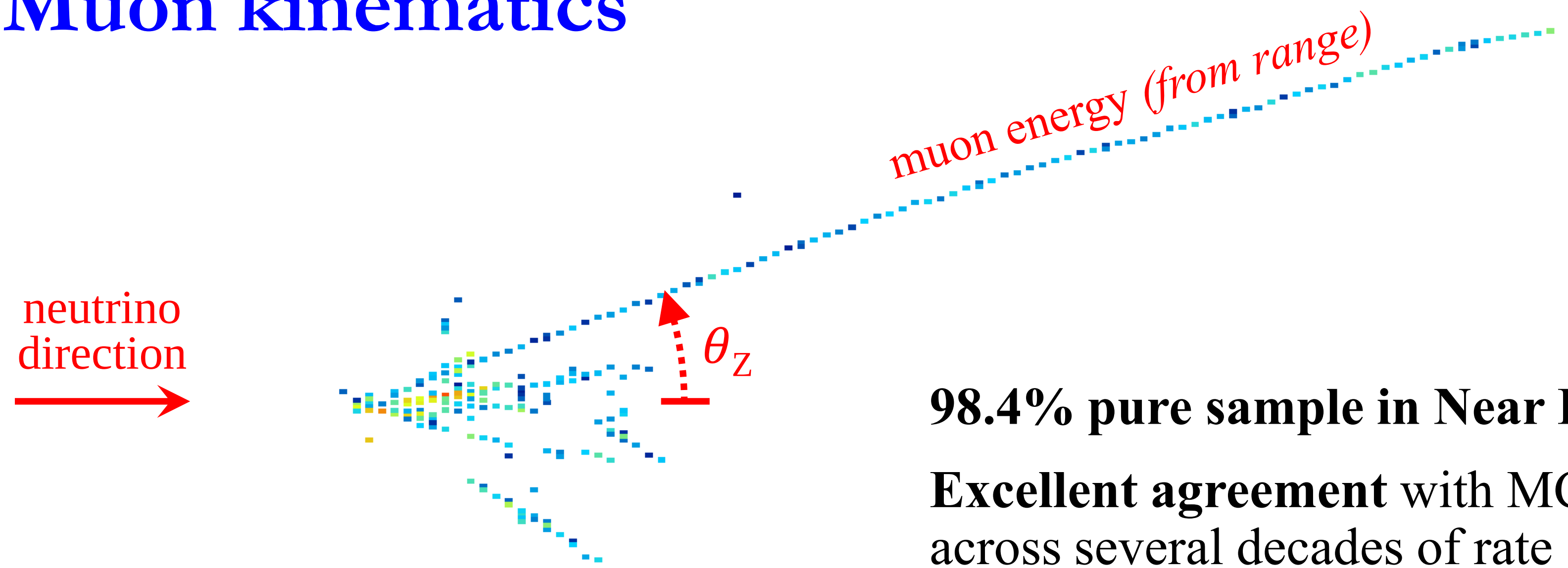
In Far Detector, must
also reject cosmic rays:

- beam timing ($\times 10^{-5}$)
- event location and shape ($\times 10^{-7}$)

Cosmic background rate **measured directly** with beam-off data.

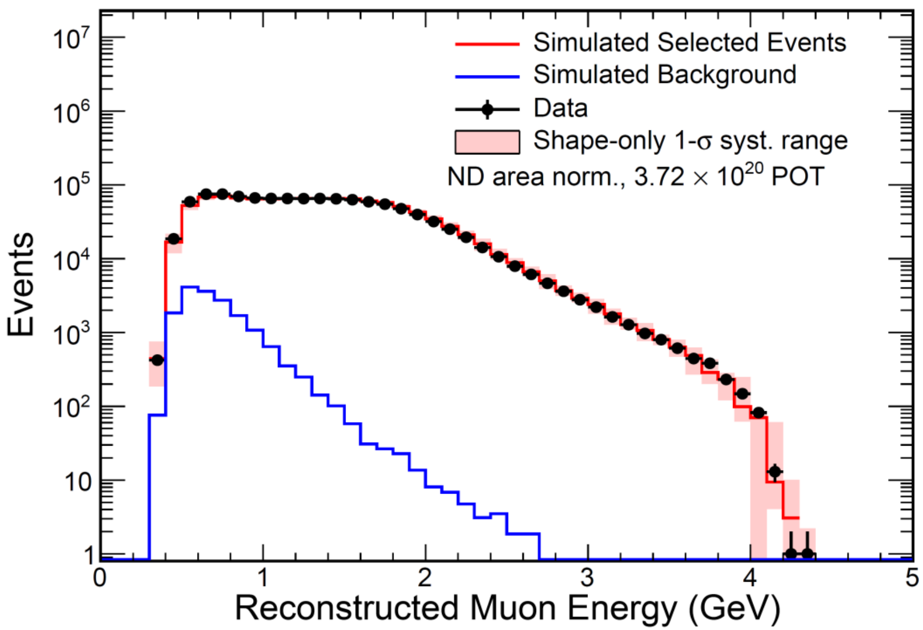
⇒ 3.5% of ν_μ CC candidates in FD are actually mis-ID'd cosmics

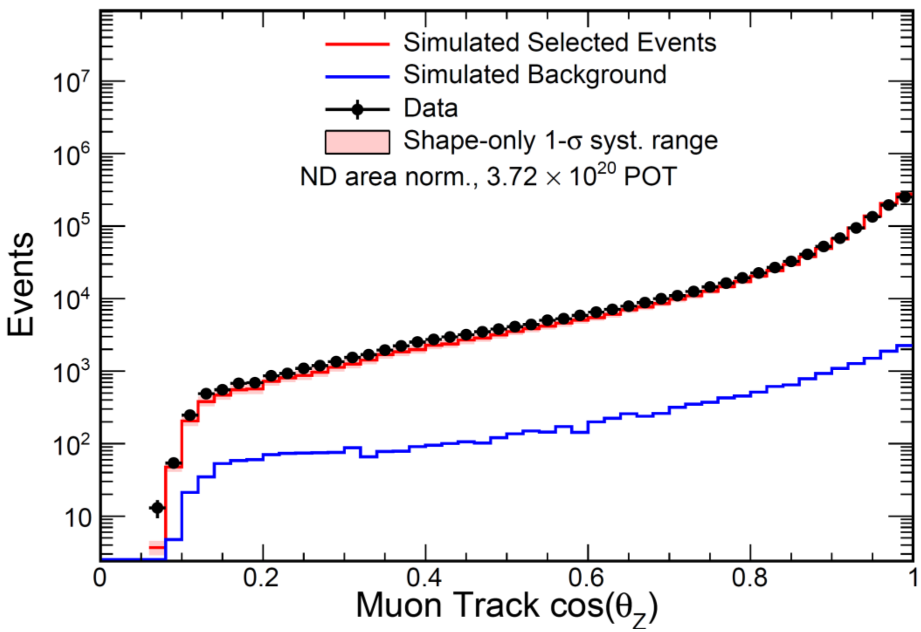
Muon kinematics



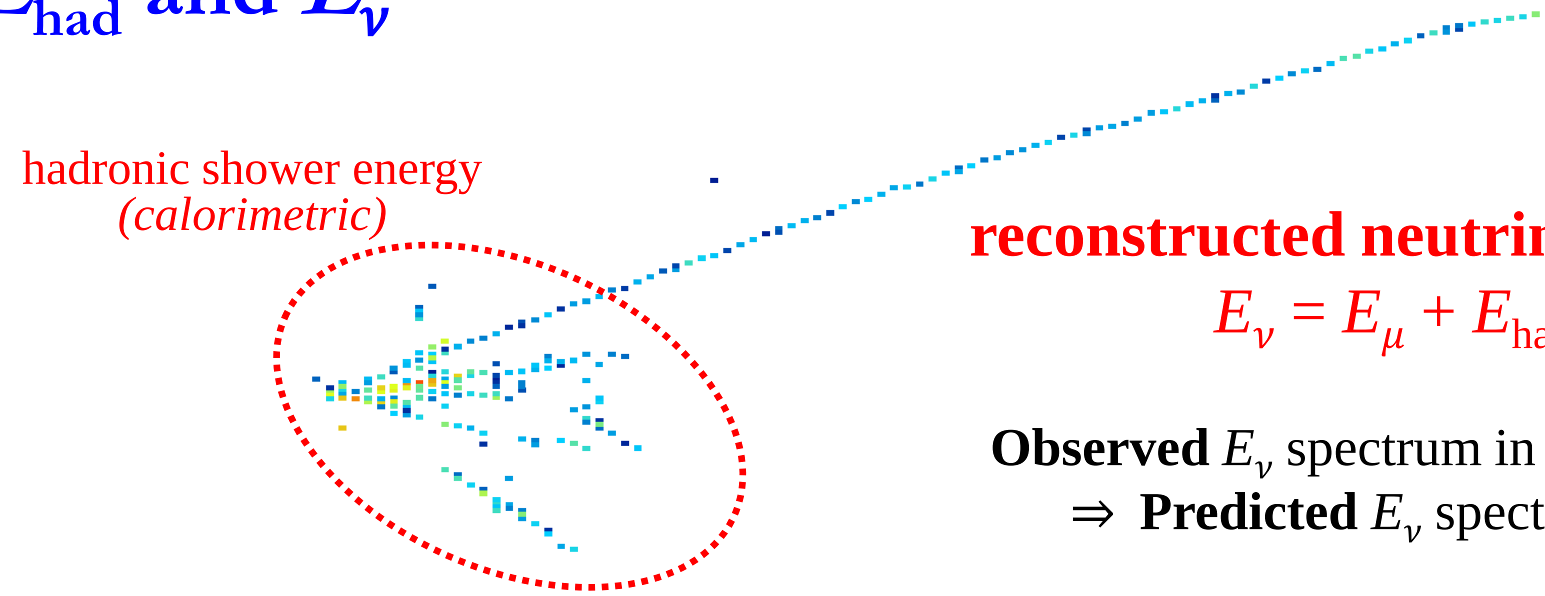
98.4% pure sample in Near Detector

Excellent agreement with MC simulation across several decades of rate





E_{had} and E_ν

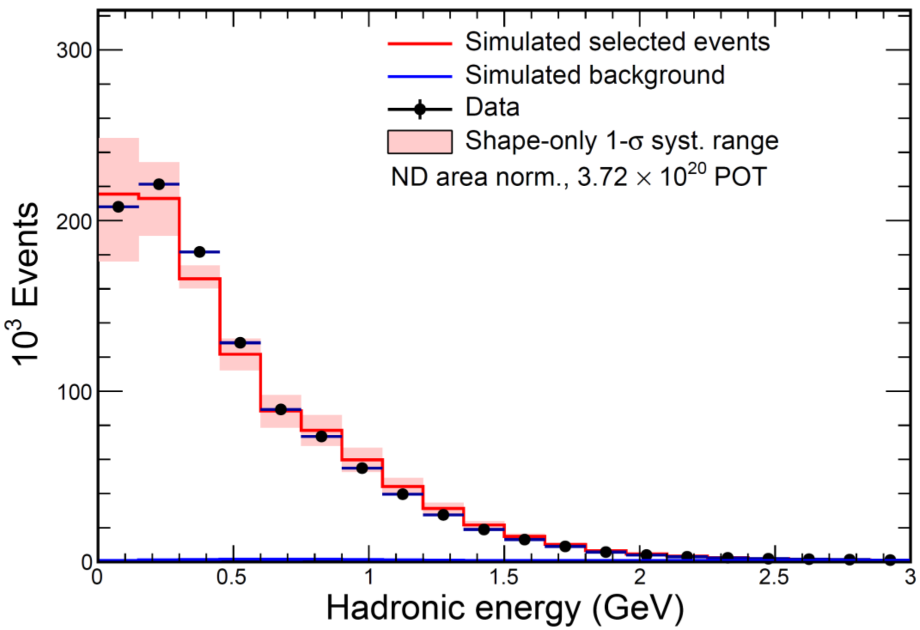


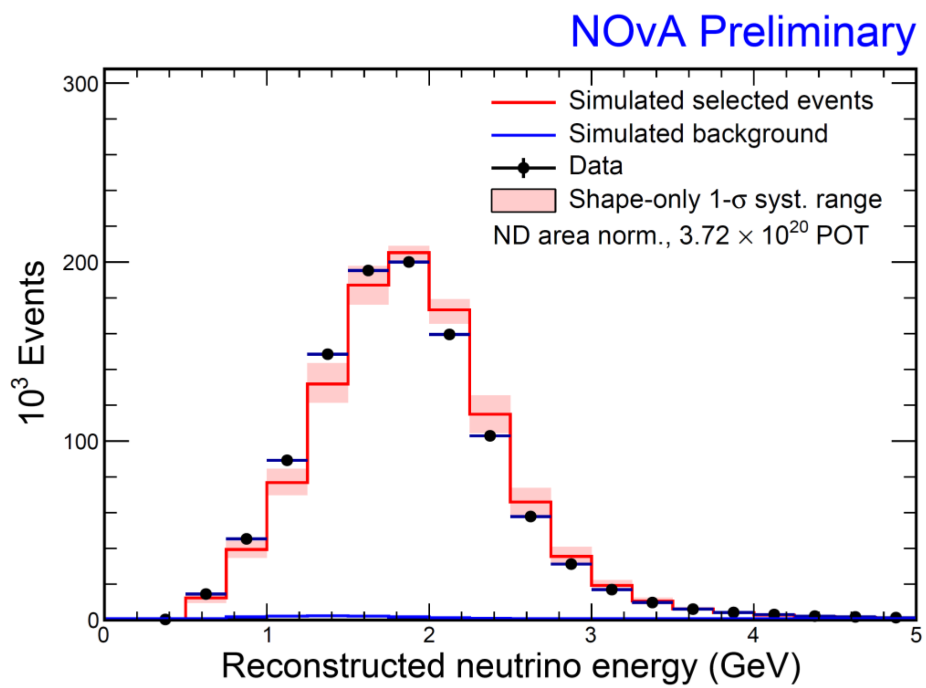
reconstructed neutrino energy:

$$E_\nu = E_\mu + E_{had}$$

Observed E_ν spectrum in the ND

⇒ **Predicted** E_ν spectrum in the FD





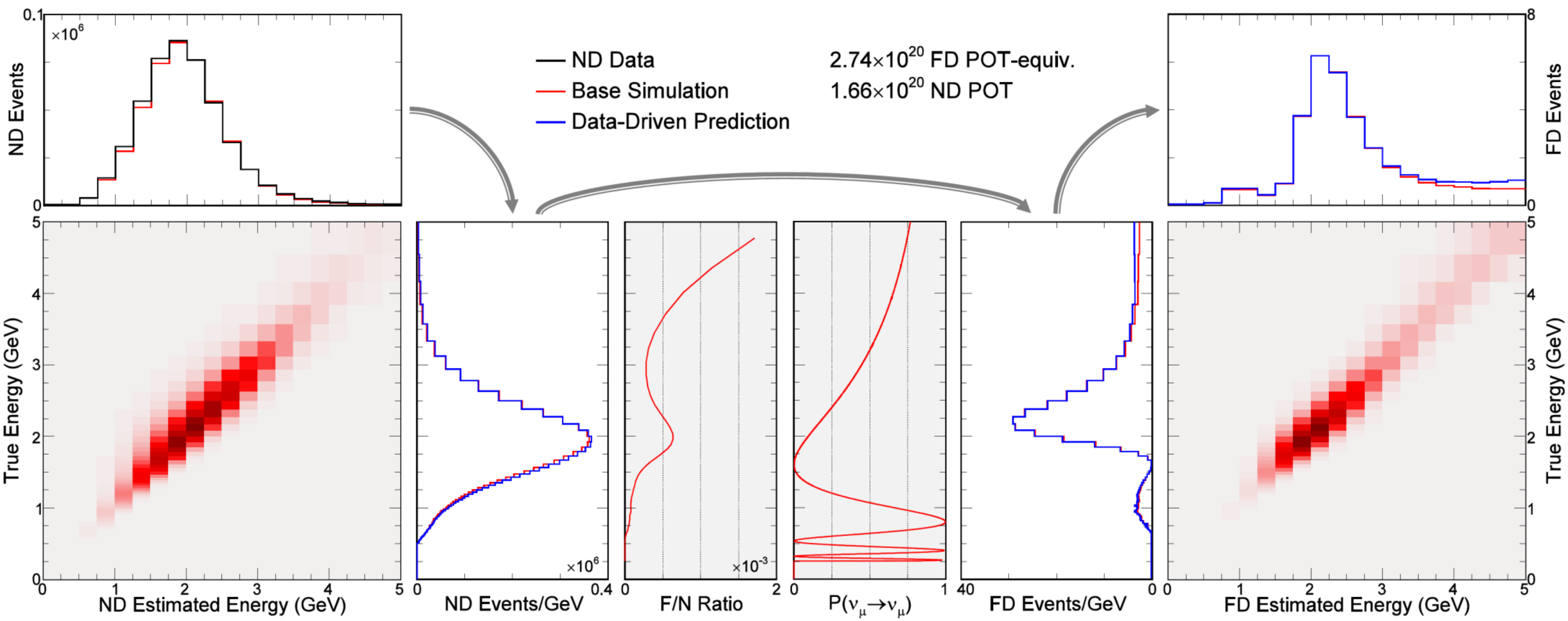
Far Detector prediction

(1) Estimate the underlying **true energy distribution** of selected ND events

(2) Multiply by expected **Far/Near event ratio** and $\boldsymbol{\nu_\mu \rightarrow \nu_\mu}$ **oscillation probability** as a function of true energy

(3) Convert FD true energy distribution into **predicted FD reco energy distribution**

Systematic uncertainties assessed by **varying all MC-based steps**



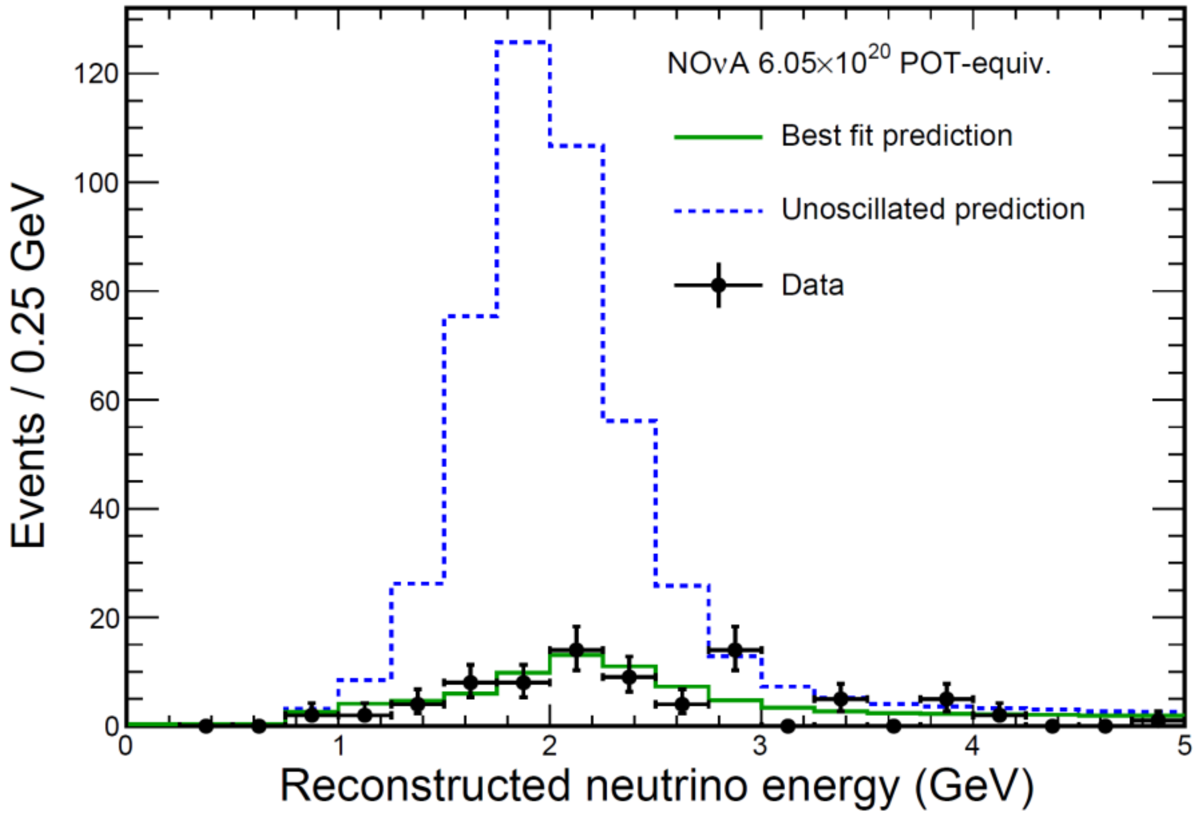
FD ν_μ energy spectrum → *oscillations*

At 6.05×10^{20} p.o.t.-equivalent

78 events selected in Far Detector
(0 – 5 GeV)

In the absence of oscillations, expect **473 ± 30 events**

(including 3.7 beam bkgnd and 2.9 cosmic bkgnd)

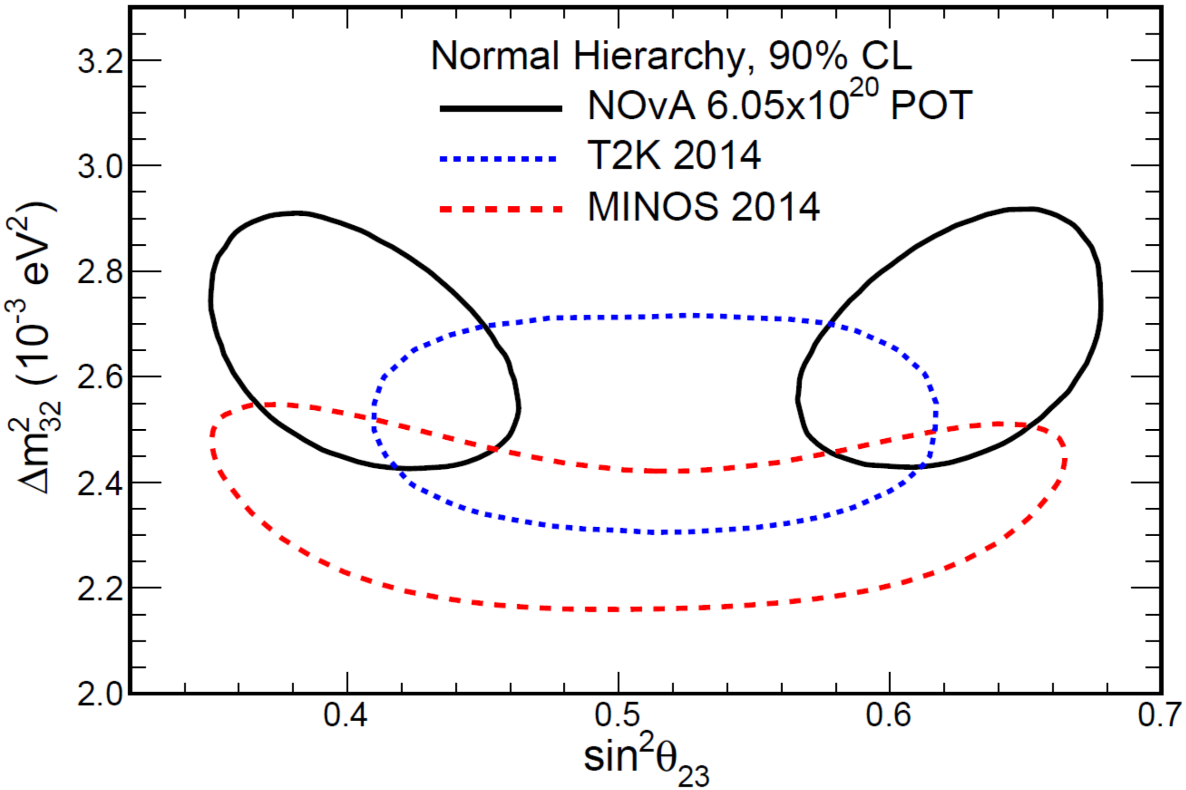


Clear observation of ν_μ disappearance

Oscillation fit for Δm^2_{32} and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

Non-maximal mixing favored at 2.6σ C.L.

And compatible overall with past measurements from MINOS, T2K



[NH case]

$$\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ \text{eV}^2$$

4.1% uncertainty
(MINOS closed at 3.8%)

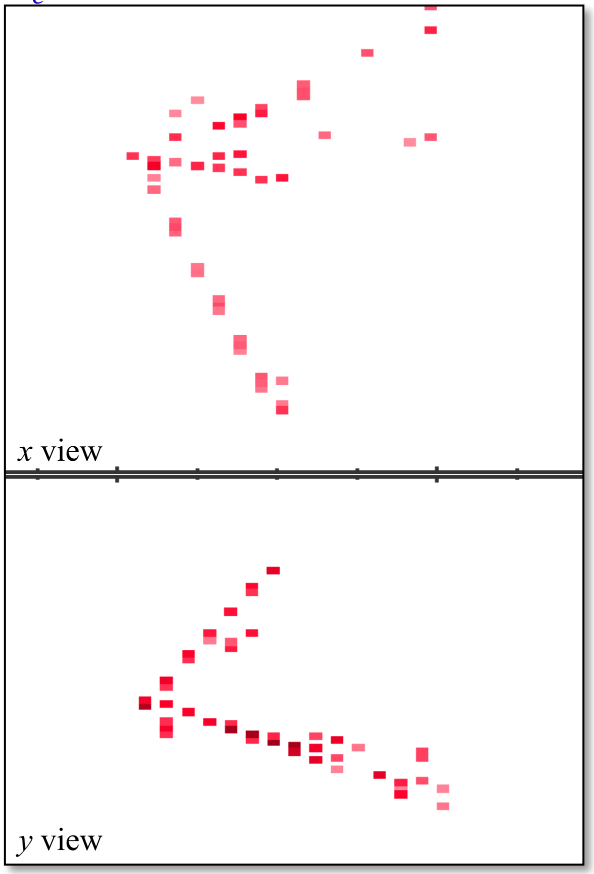
$$\sin^2(\theta_{23}) = 0.40^{+0.03}_{-0.02} \quad (0.62^{+0.02}_{-0.03})$$

Systematic uncertainties still subordinate. Top systs. are those related to **energy calib**.

ν_e appearance: *backgrounds*

- **$\nu_\mu \rightarrow \nu_e$ rate is only ~5%**
- Rest of the flux ⇒ backgrounds

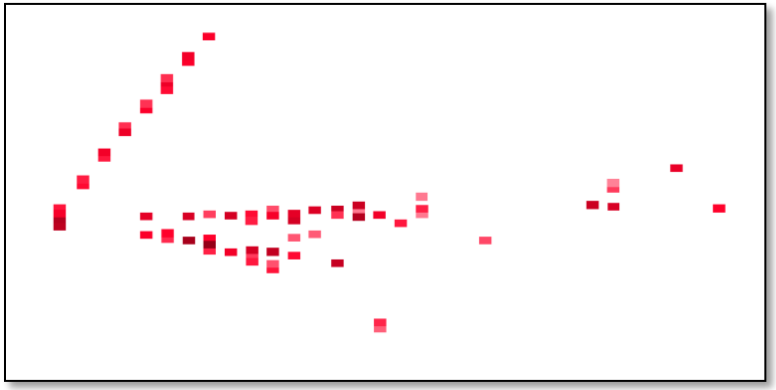
ν_e CC candidate



Most pernicious background comes from **$\pi^0 \rightarrow \gamma\gamma$ decays** *(example below)*

⇨ Must increase signal-to-noise by 100×

NC π^0 candidate

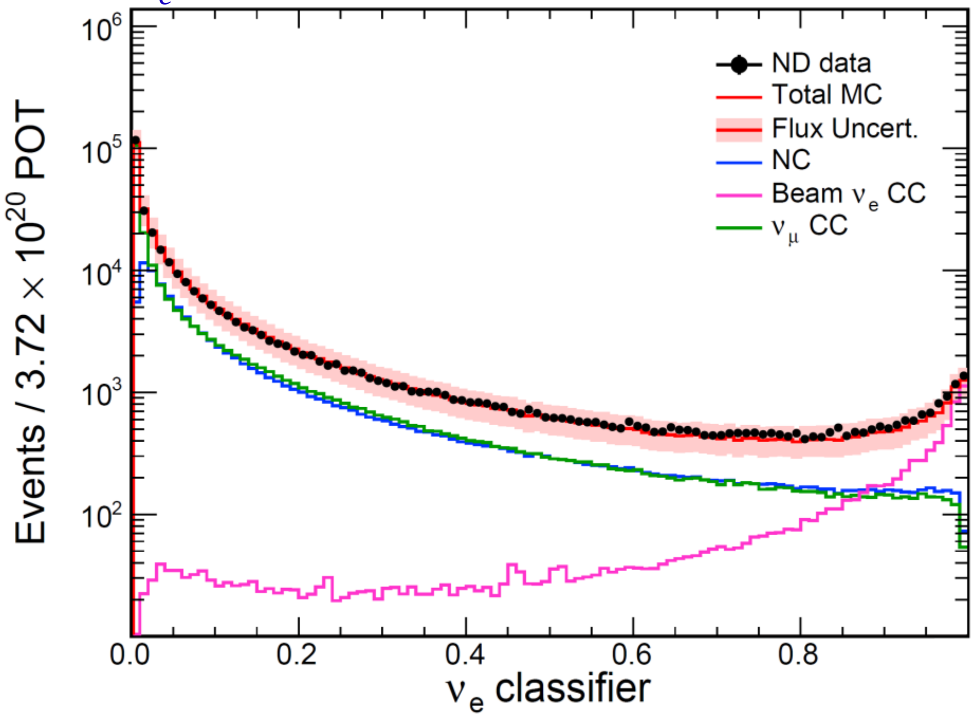


Multiple event classification algorithms developed for this purpose.

Various core techniques: **EM shower fitting, event template matching, convolutional neural networks**

C. Backhouse and RP, NIM A 778, 31 (2015); A. Aurisano *et al.*, JINST **11**, P09001 (2016); J. Bian, arXiv:1510.05708 (2015)

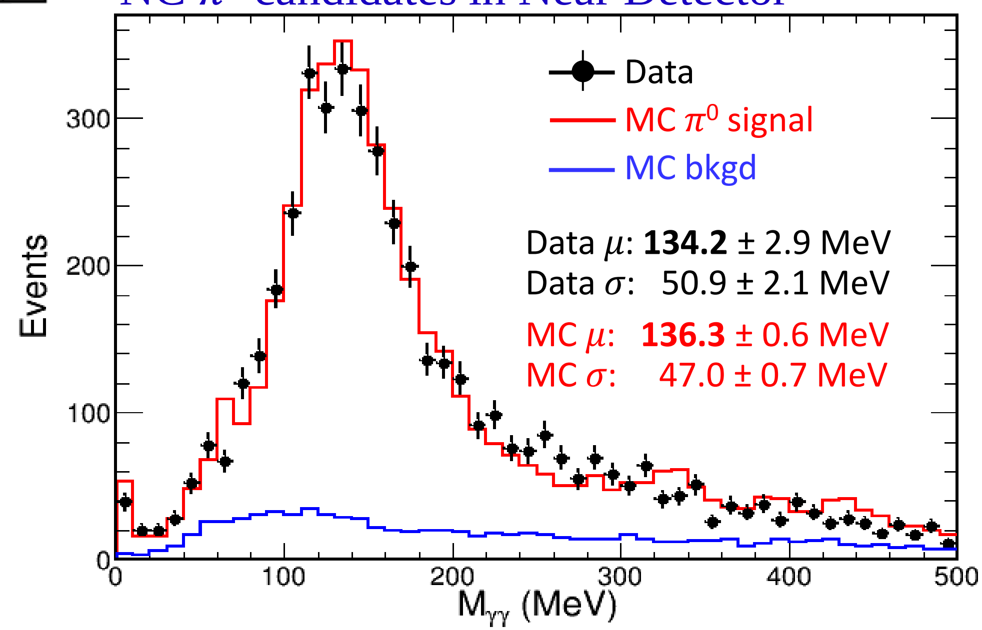
ν_e CC candidates in Near Detector



→ more ν_e-like →

Far Detector predictions and uncertainties derived from **Near Detector observations** and available "standard candles"

NC π^0 candidates in Near Detector



Above: 0.7% intrinsic ν_e flux measured in Near Det. *(not from oscillations; an irreducible bkgnd)*

Right: Reconstructed π^0 mass

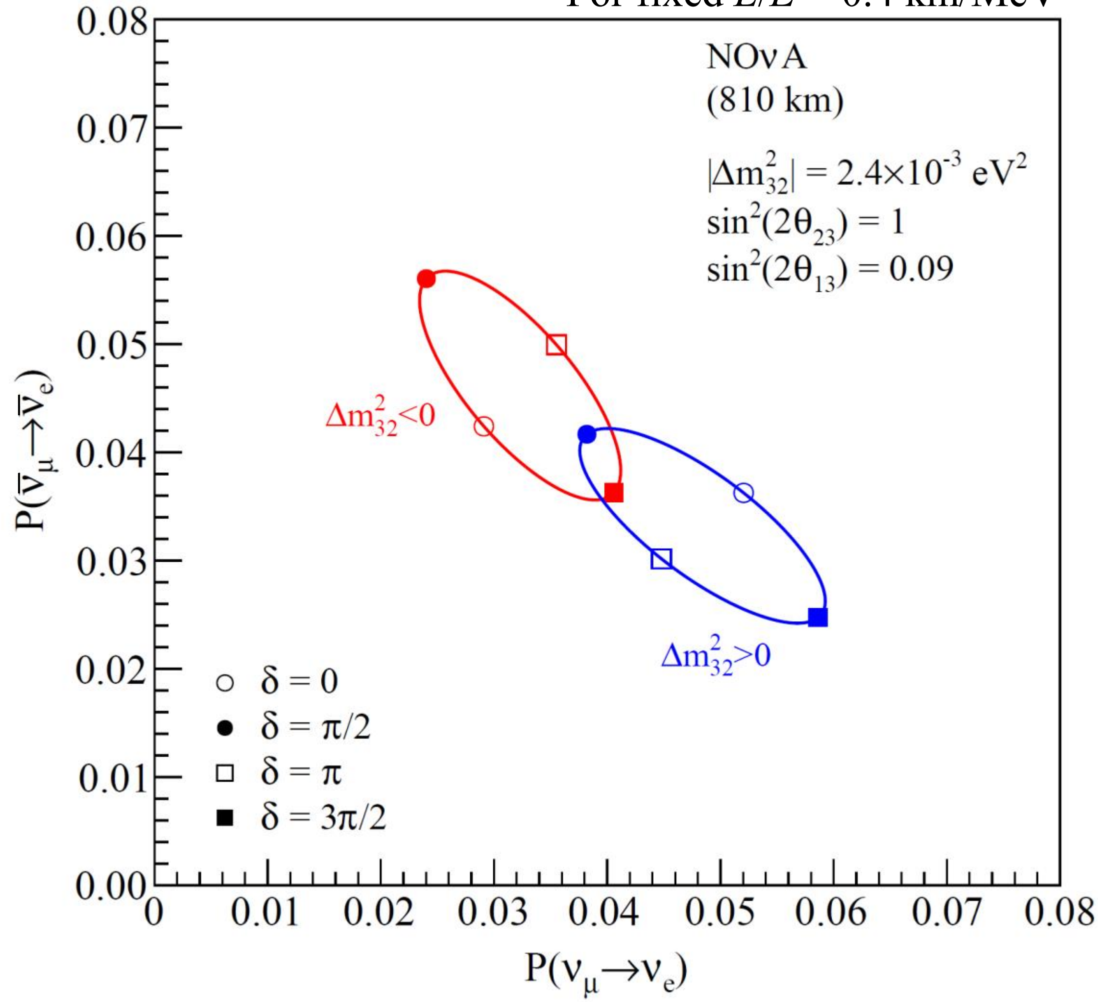
FD ν_e expectations…

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

for a 2 GeV neutrino in NOvA

→ Strong dependence on δ and **ν mass hierarchy***

For fixed L/E = 0.4 km/MeV



* ν_e see different potential than $\nu_{\mu,\tau}$ when propagating through matter (here, the earth)
⇒ a hierarchy-dependent effect !

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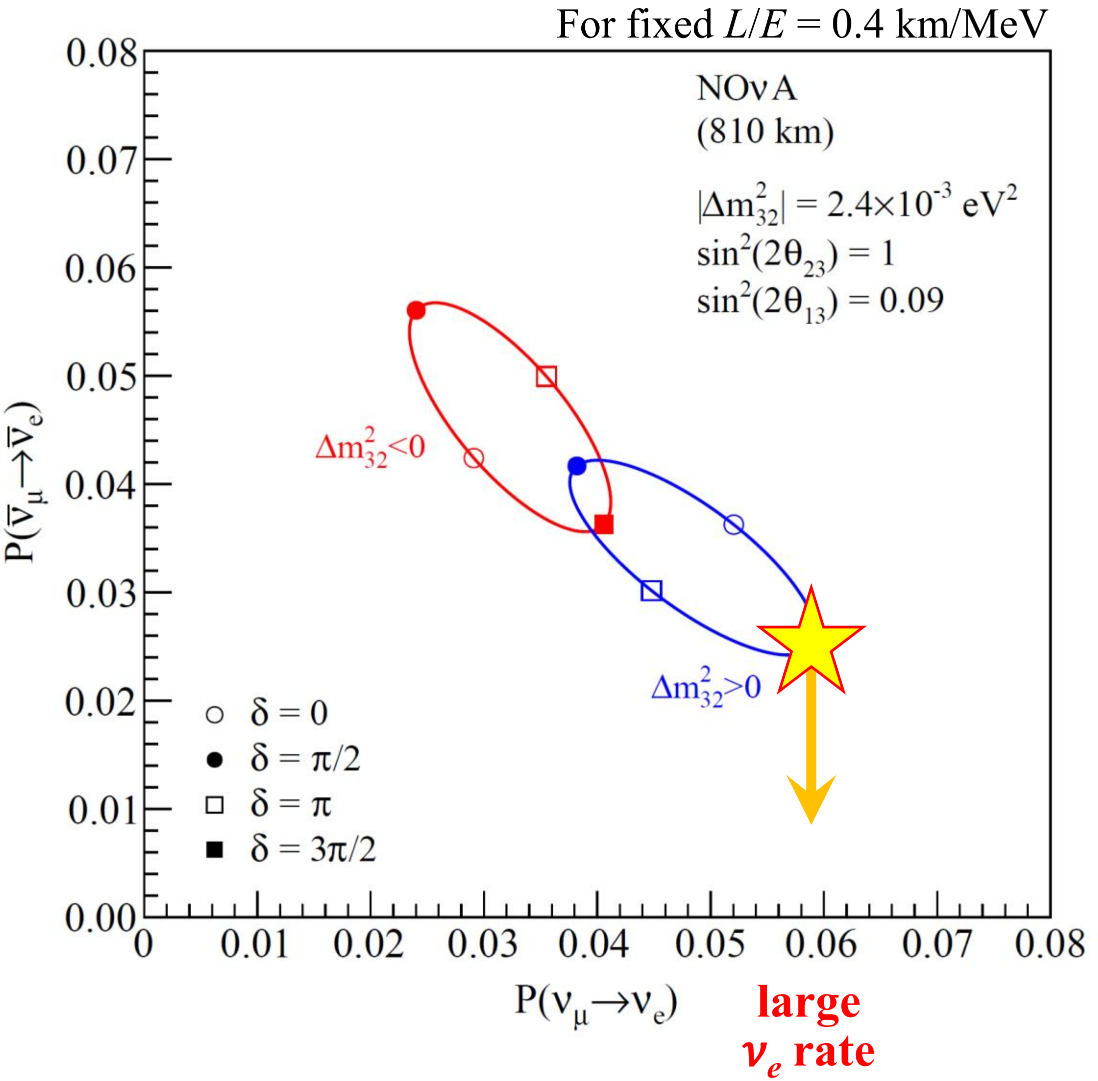

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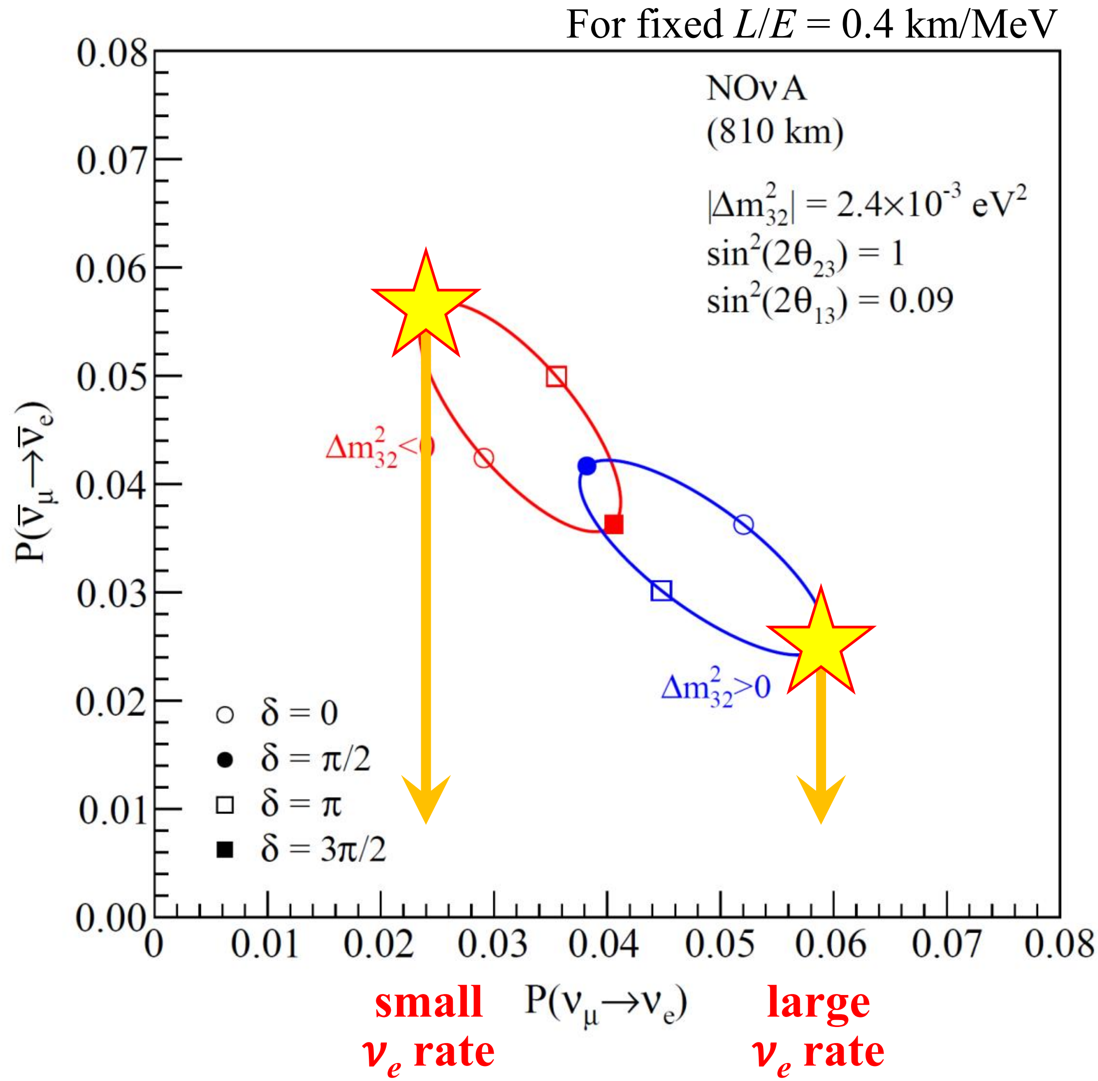

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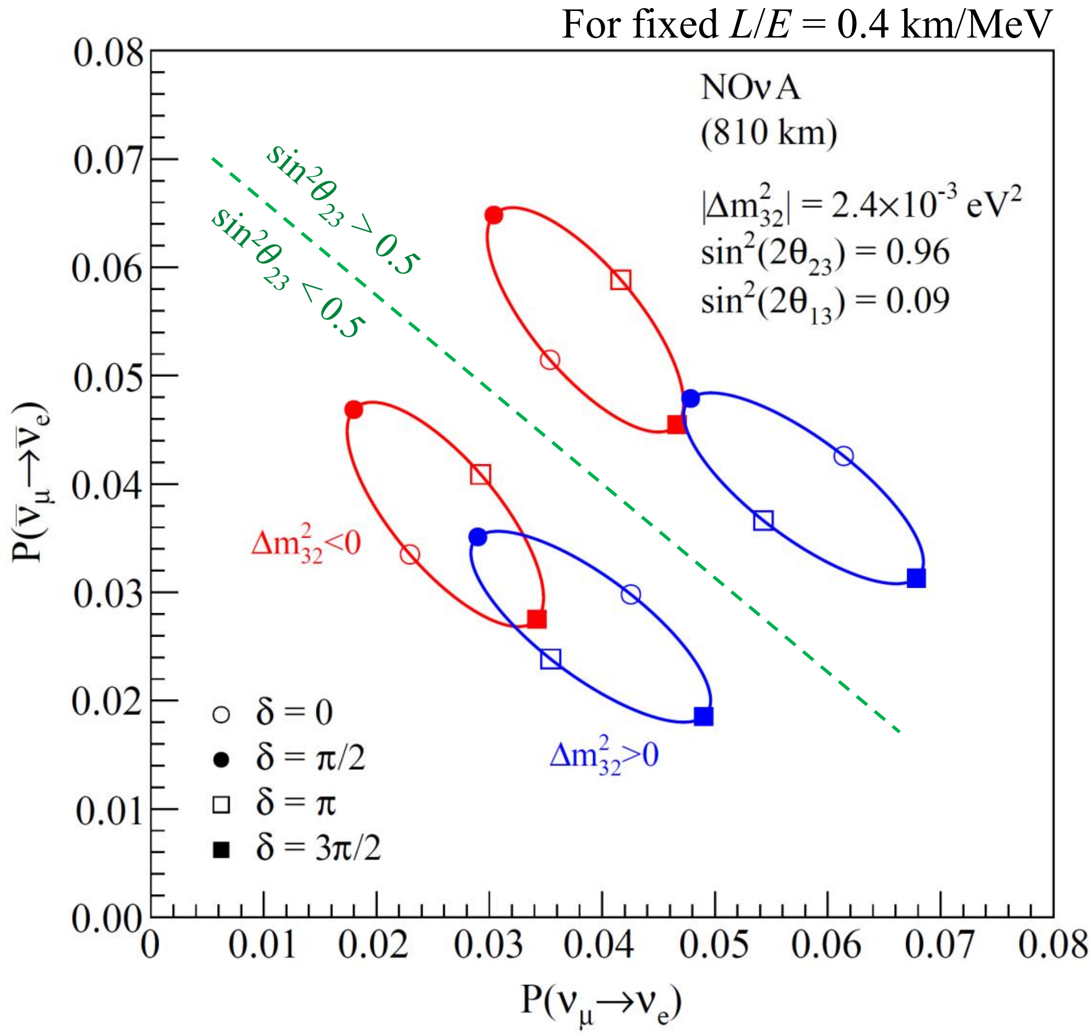
→ Strong dependence on δ and ν **mass hierarchy***

→ $P \propto \sin^2\theta_{23}$ *[approx.]*



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→ Strong dependence on δ and **ν mass hierarchy***

→ $P \propto \sin^2\theta_{23}$ *[approx.]*

At 6.05×10^{20} p.o.t.-equiv.

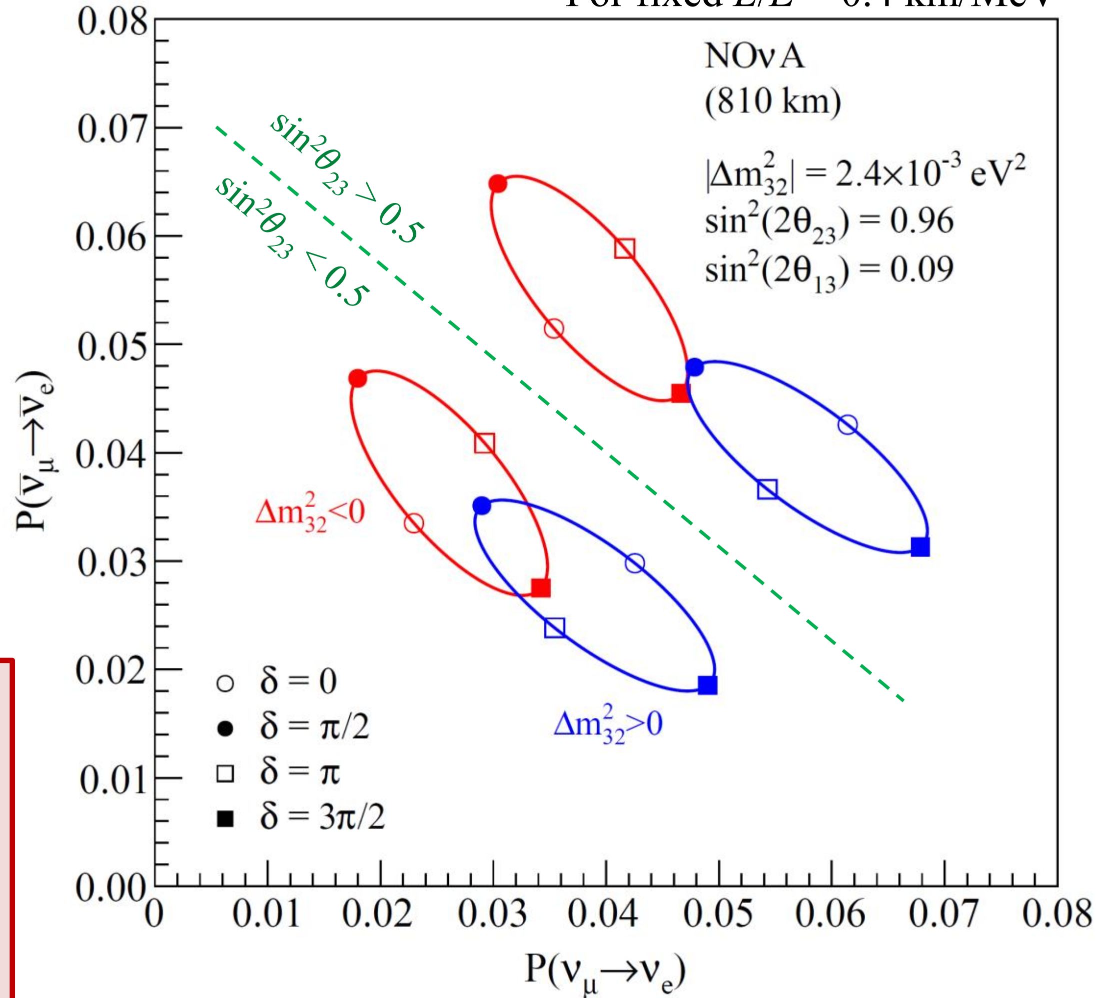
Total prediction:

~17 to 42 ν_e candidates
(depending on osc. pars.)

Includes **8.2** background
(~independent of osc. pars.)

Syst. uncertainty:
±5% signal
±10% background

For fixed L/E = 0.4 km/MeV



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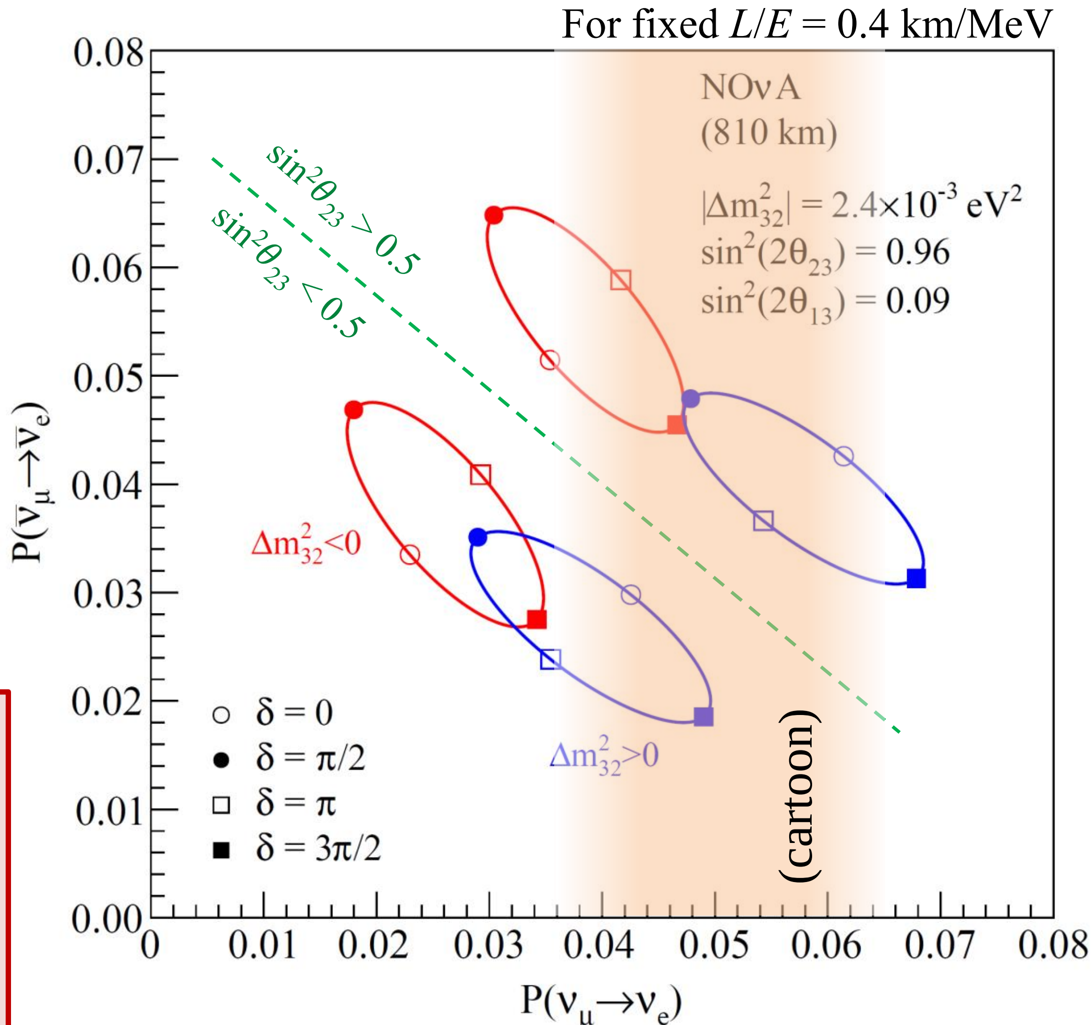
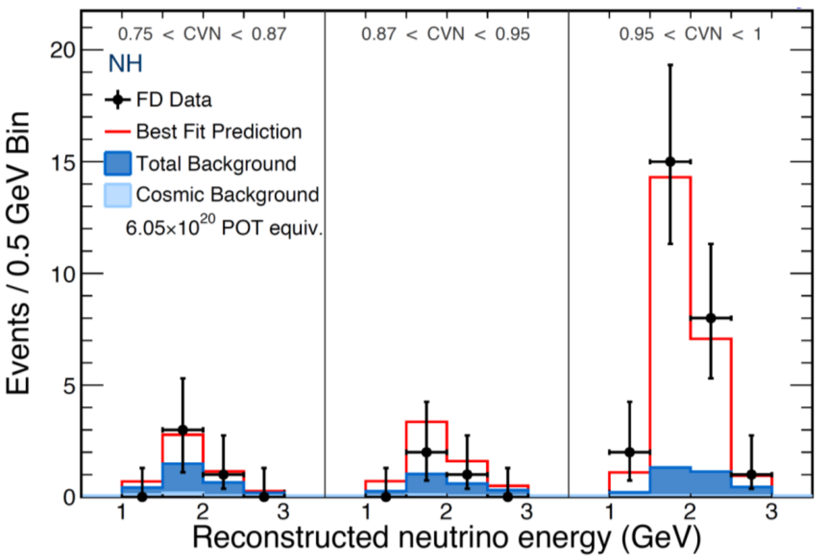


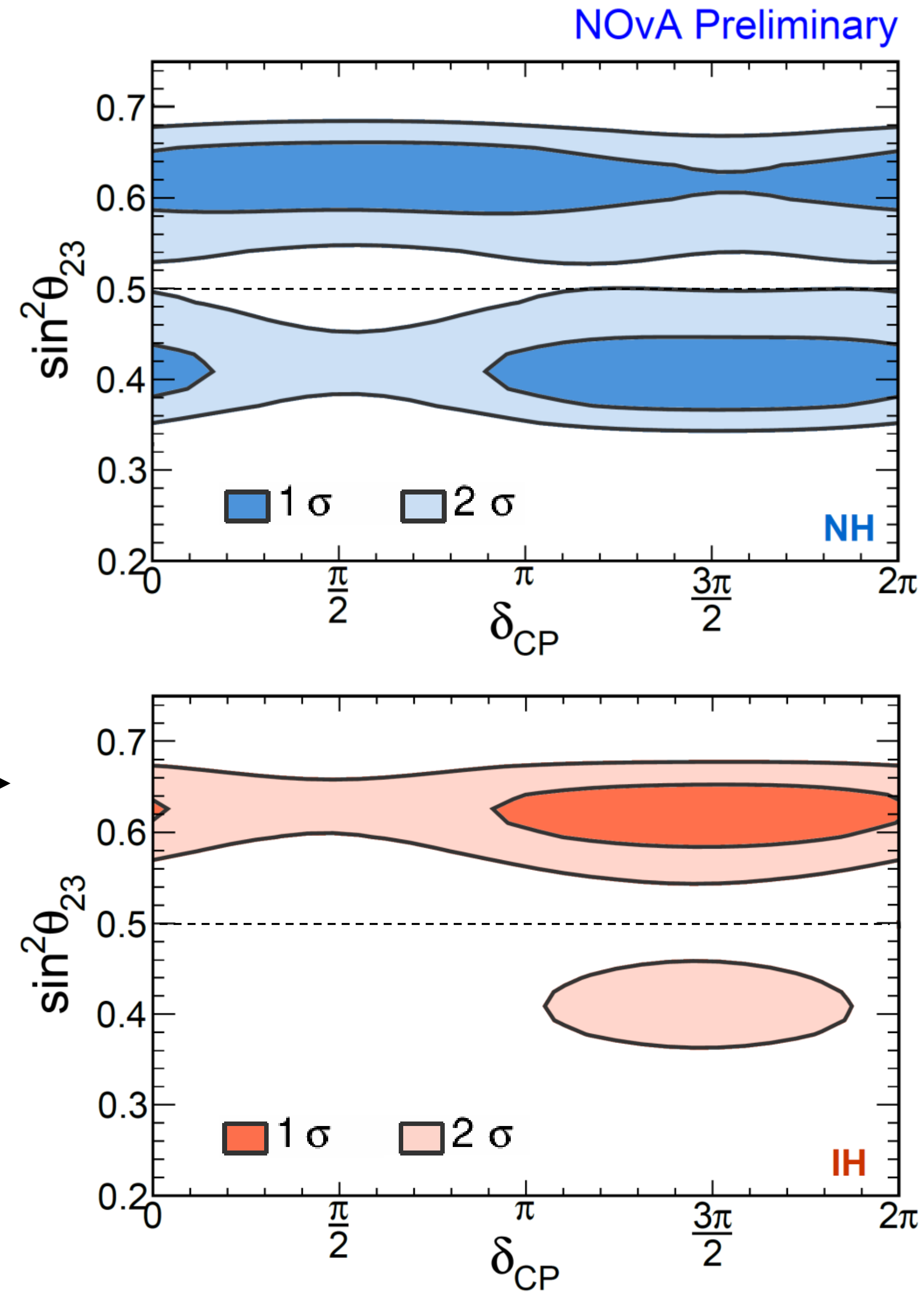
Observed in FD data:
33 ν_e candidates

$>8\sigma$ observation of ν_e appearance

Measure signal in 2D bins of $E_\nu \times$ CVN



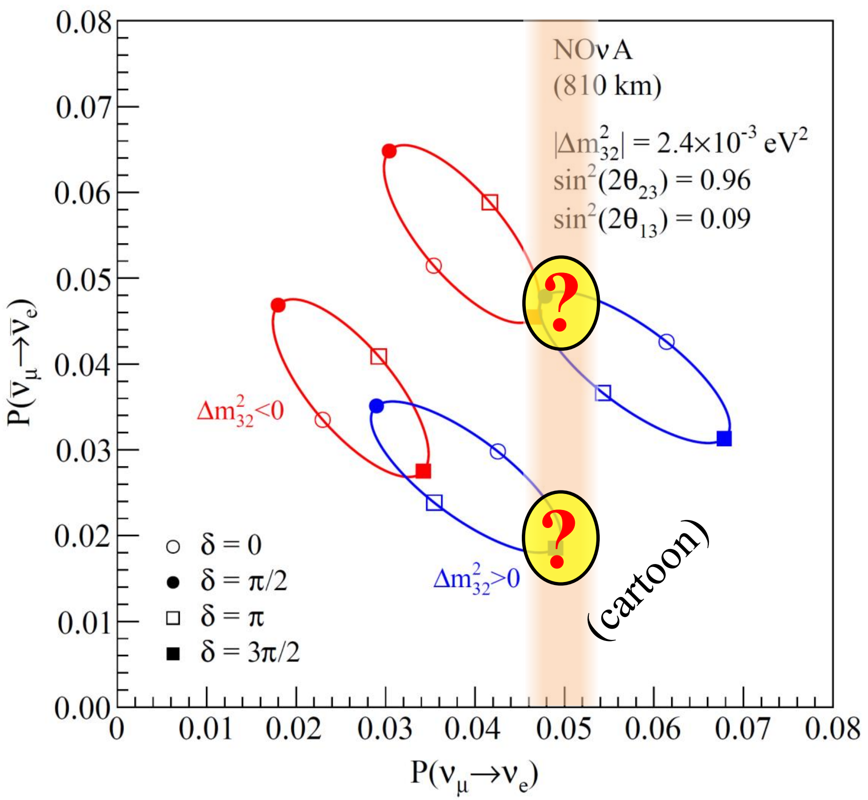
In terms of allowed physical parameters →

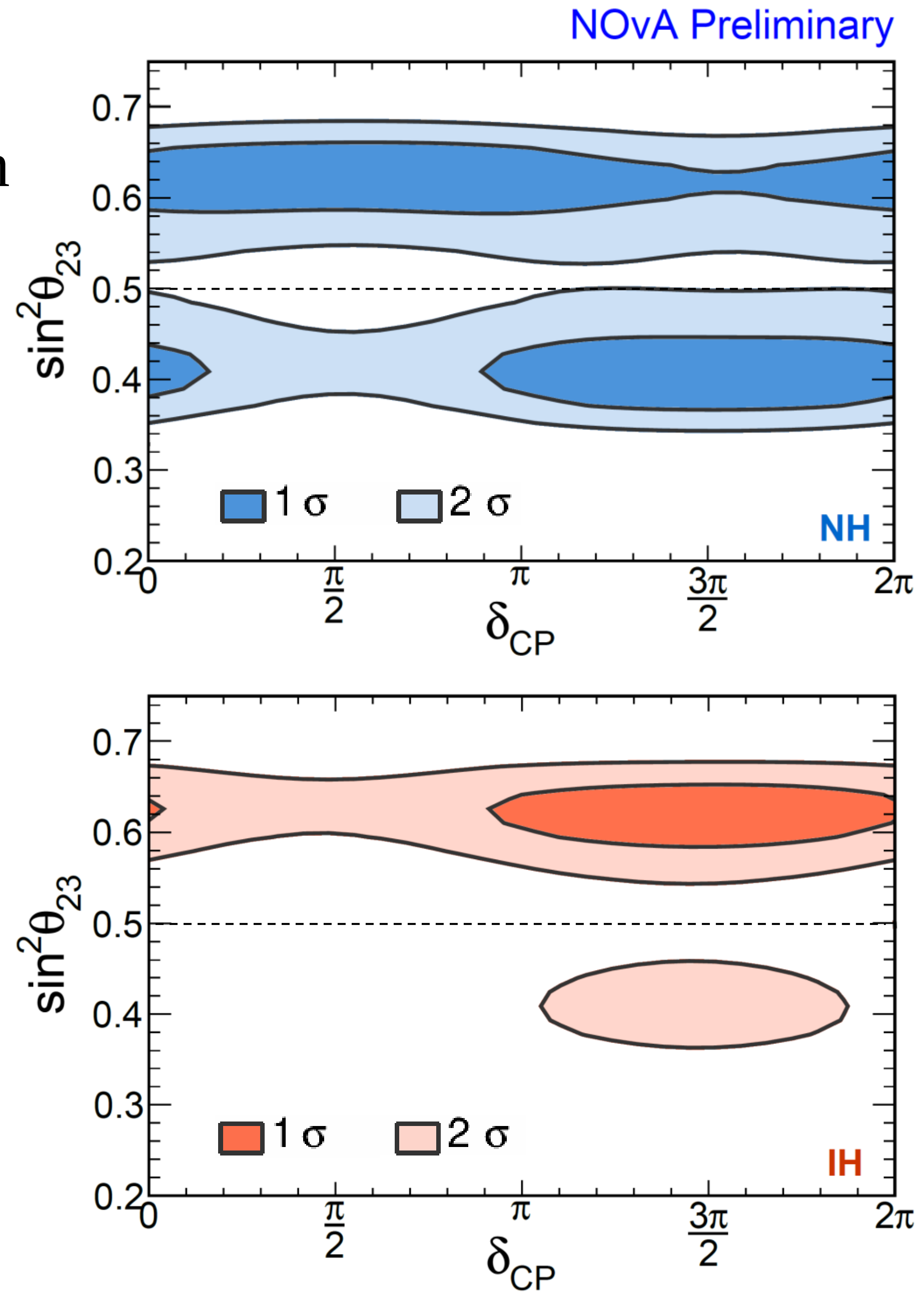


>3σ exclusion of region in
IH, lower octant, around δ=π/2

NH preference not signif.: $\Delta\chi^2$=0.46

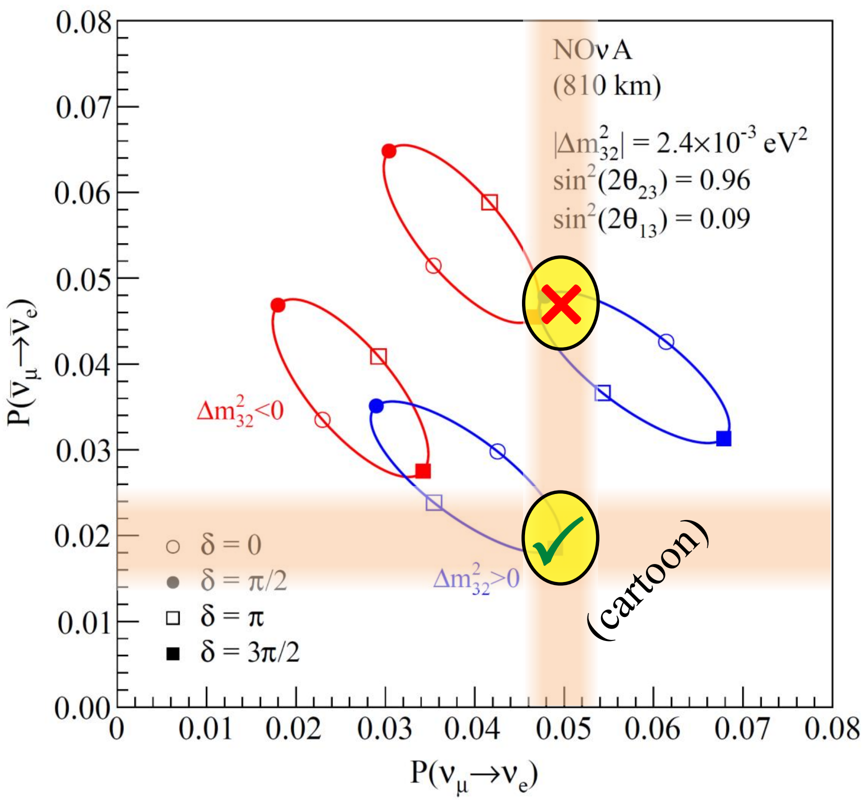
In **non-maximal mixing** scenario, **antineutrino data** critical to run plan

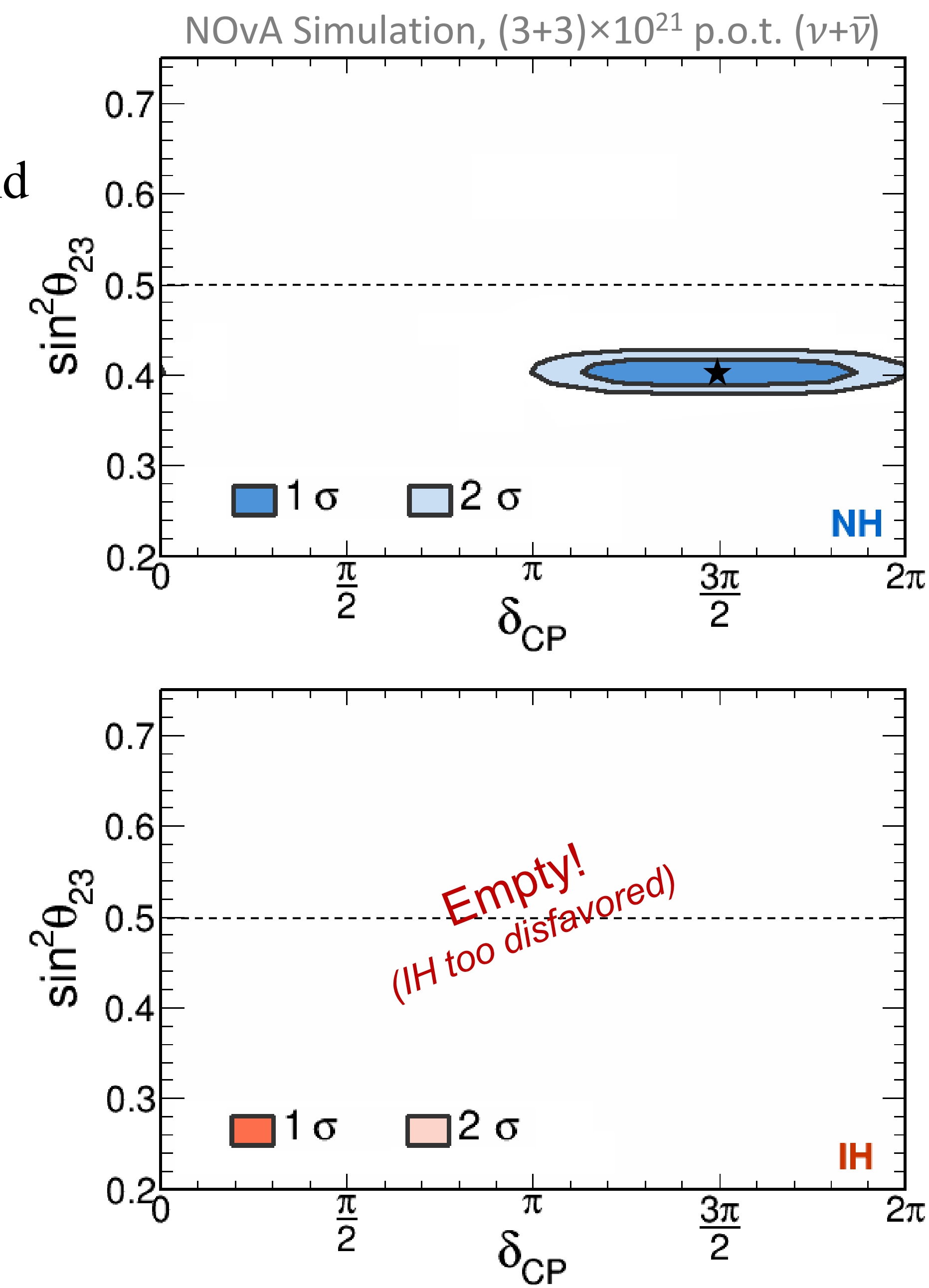




An example point in ν parameter space

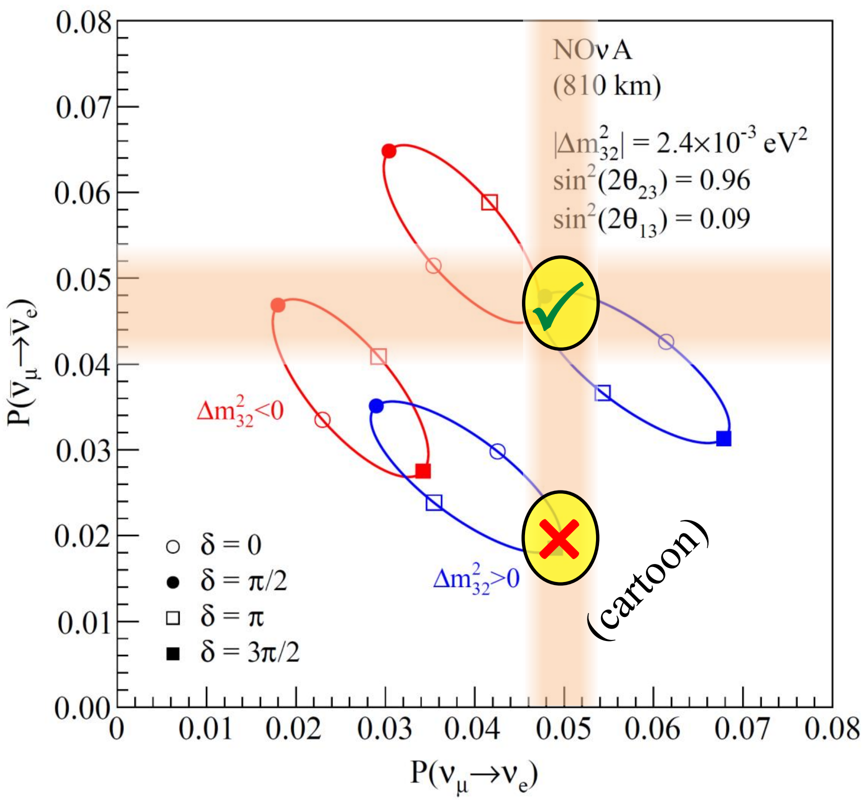
Simultaneously break ν_3 **flavor ambiguity** (θ_{23} octant), determine **mass hierarchy**, and constrain ***CP*** **phase δ**.

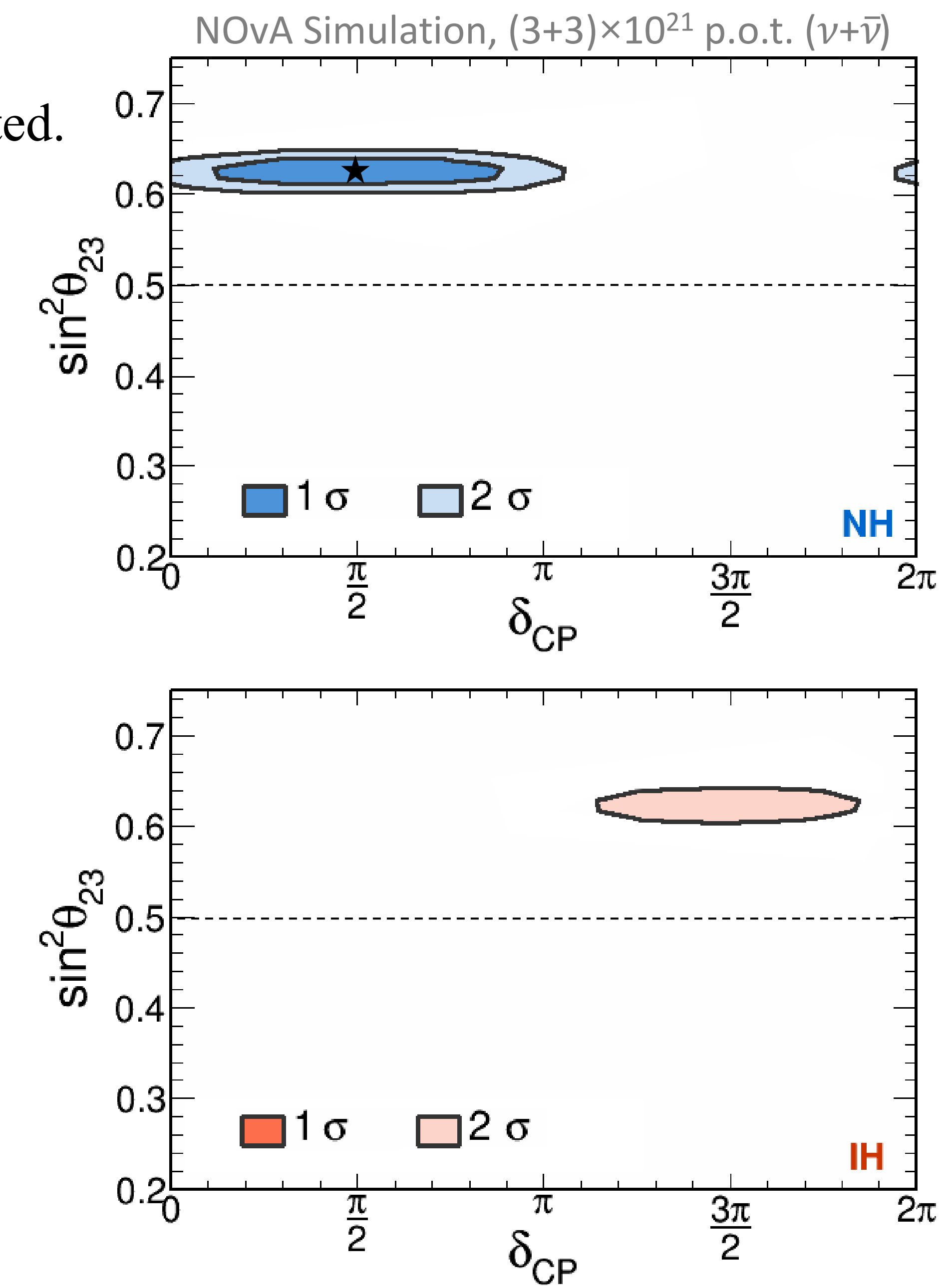


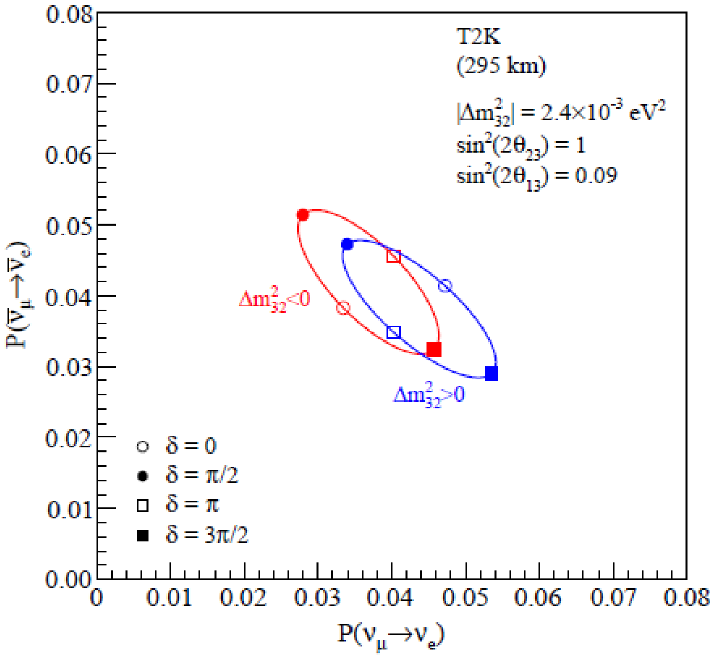


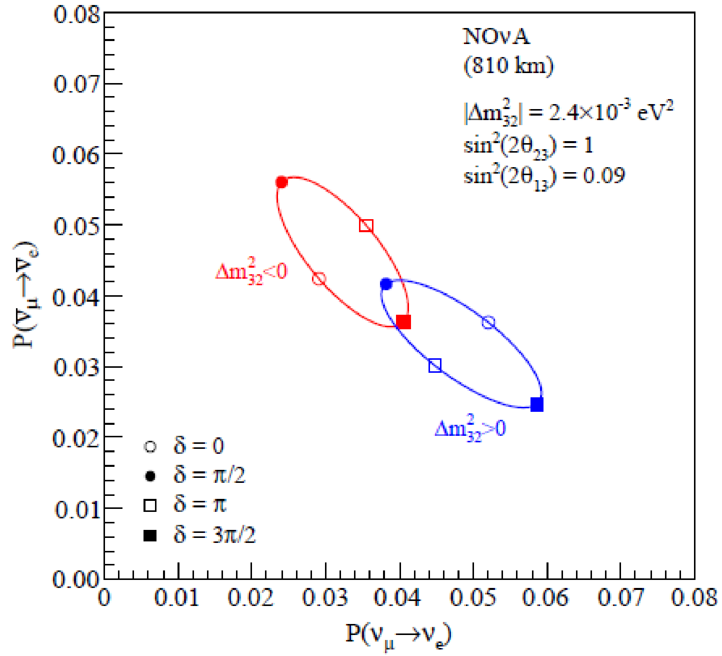
And a partially ambiguous point…

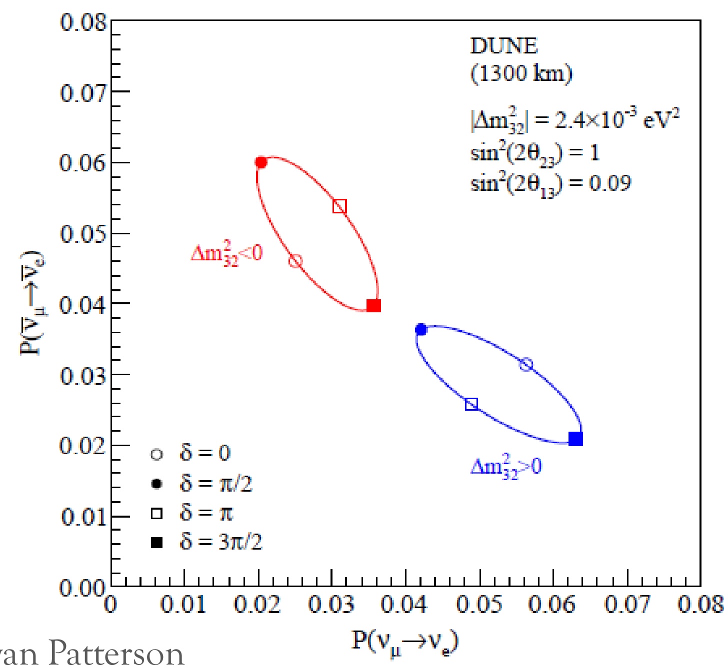
Hierarchy and $\boldsymbol{\delta}$ information now correlated.
Octant preference still established.











T2K, NOvA, and DUNE baselines for a single *L*/*E* value.

These differ solely via the influence of matter effects

Illustrative only! Other parameters are held fixed, and experiments (esp. DUNE here) probe a range of neutrino energies.

NOvA outlook

- **Detector and beamline operating beautifully**
  - Currently collecting antineutrino data

- Assuming the **currently favored** neutrino parameters, then…

<u>**Confidence level for…**</u>	*c. 2018/2019*		*c. 2024*
Rejection of maximal mixing	**3σ**	→	**5σ**
Hierarchy determination	**95%**	→	**4σ**
ν_3 flavor balance	**95%**	→	**3σ**
Evidence for leptonic *CP* violation	**80%**	→	**95%**

Note!

Ultimate sensitivities **depend greatly** on **the parameters nature has actually chosen**.
(Current best-fit parameters are rather favorable – good! but tenuous.)

Extended operations + beam improvements (under discussion):

⇒ ~3σ *CP*v reach achievable at current best-fit parameters

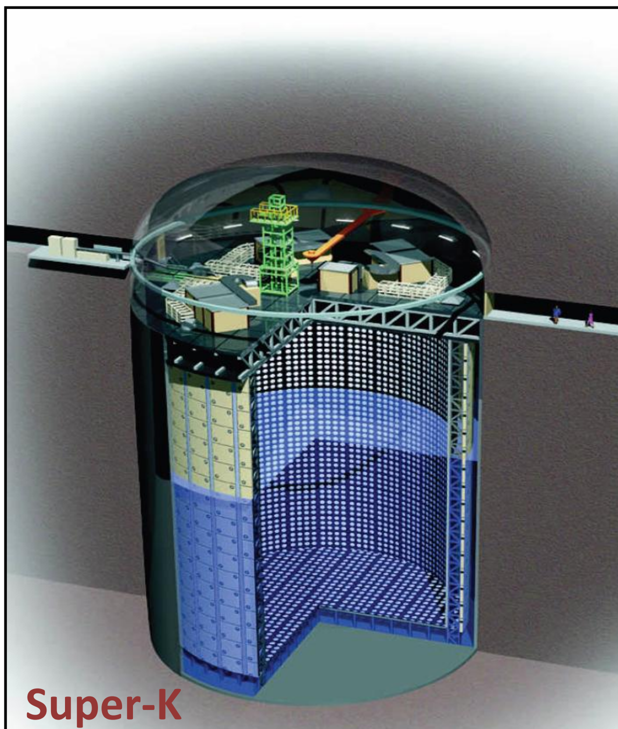
(Also, mitigation in case the true parameters turn out less favorable with time)

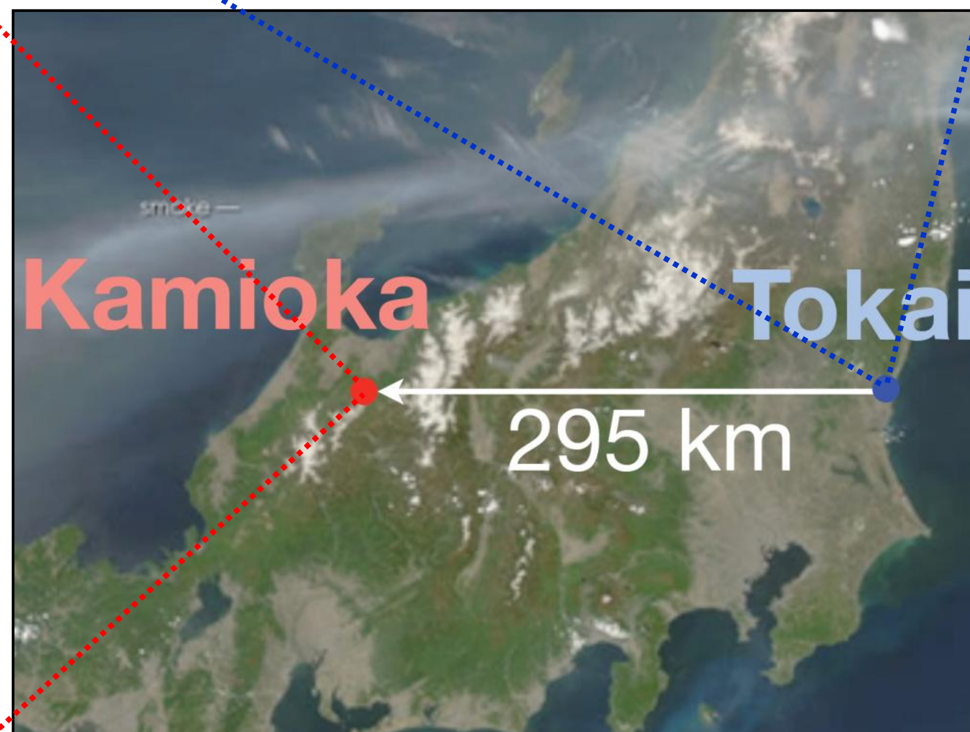
Pause for questions/discussion

T2K

- Tokai to Kamioka (295 km)
- Neutrino beam from J-PARC
- Existing far detector: Super-K
  - *well understood detector*

  INGRID and ND280 near detectors

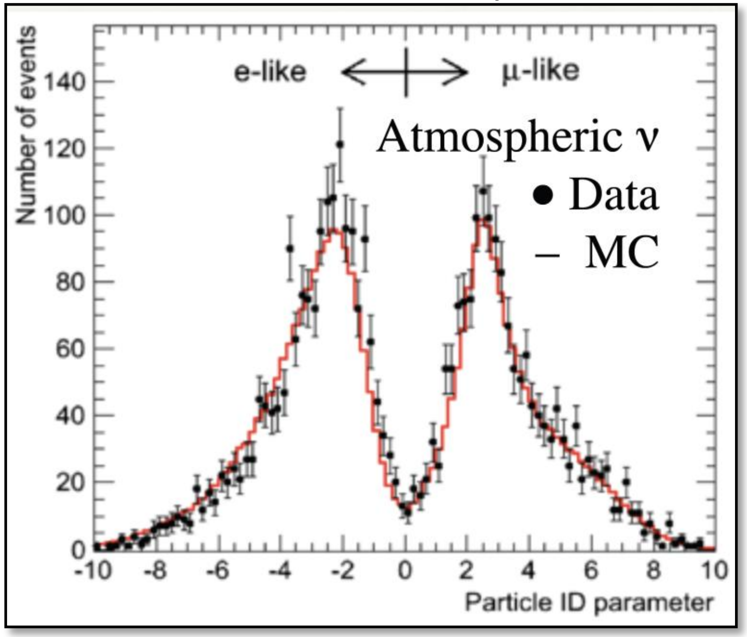


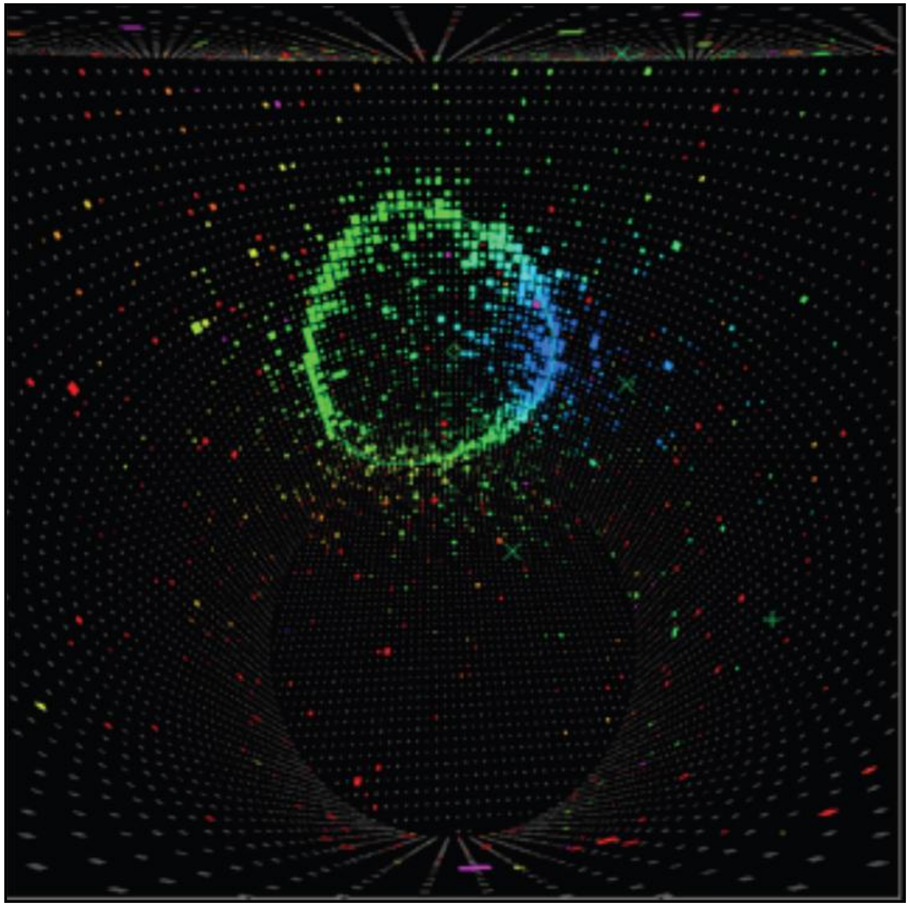


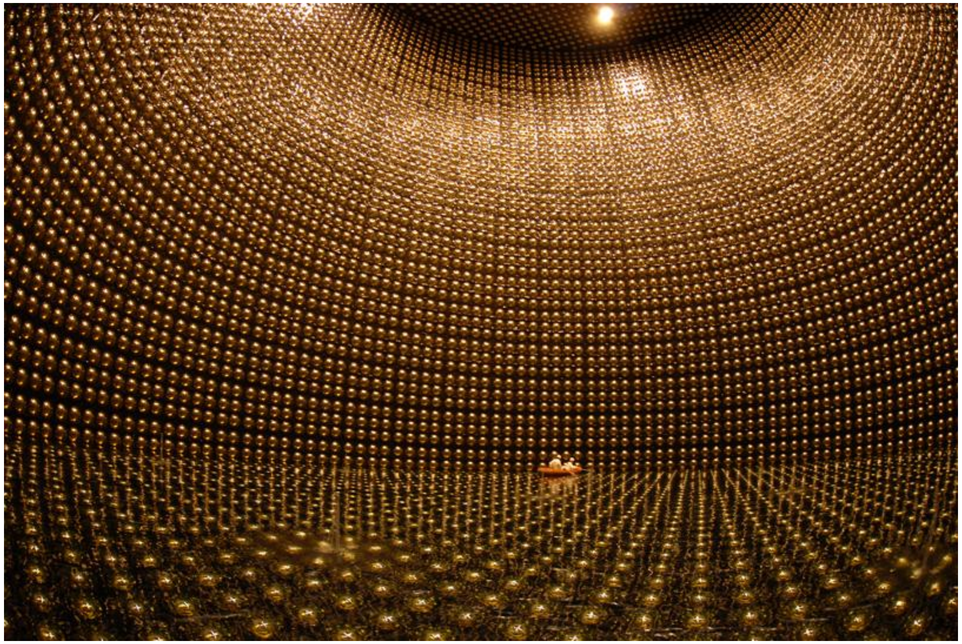
Super-K events

- **Long history of ~GeV events in Super-K**
  - *Super-K atmospheric data* ⟶
- ***Major plus:* quick, robust analysis from T2K**
  - *Recently: substantial analysis upgrades*

from Super-K collab.







Many graphics (including this one) taken from M. Hartz, KEK Seminar, Aug 2017

THE T2K EXPERIMENT

~500 researchers, 62 institutes, 11 countries

Muon (anti)neutrino beam generated at J-PARC and detected at Super-Kamiokande

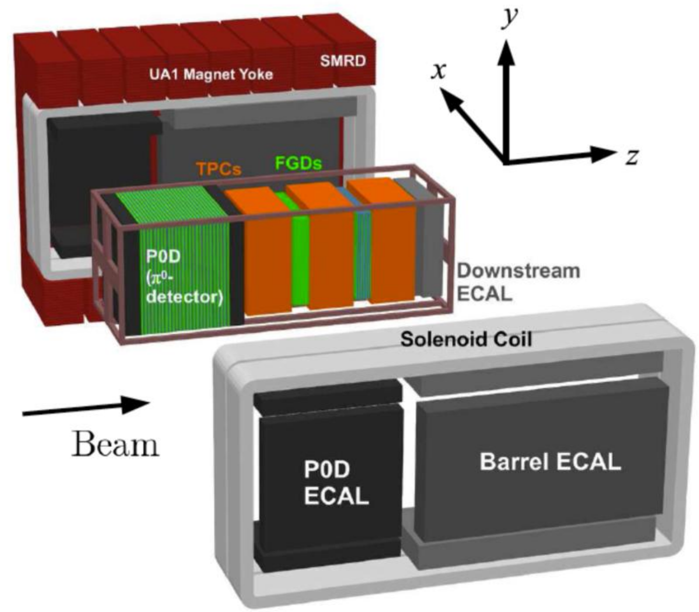
In 2013 T2K made the first discovery of an appearance mode: $\nu_\mu \rightarrow \nu_e$

(Phys. Rev. Lett. 112, 061802 (2014))

ND280 DETECTOR

- Detect neutrinos before they oscillate in the ND280 off-axis near detector
- Data used directly in oscillation measurements, also in stand-alone neutrino interaction measurements
- Key features: tracking of particles below Cherenkov threshold, charge identification with magnetic field

• 0.2 T Refurbished UA1/NOMAD magnet donated by CERN



Used in oscillation analysis

Fine-Grained Detectors (FGD)

- Scintillator bars and water targets (FGD2)
- Interaction mass and tracking

• Time Projection Chambers (TPC) – momentum and dE/dx measurements

Used in neutrino interaction measurements

• P0D π^0 detector – measures NC π^0 rates

• Electromagnetic calorimeters – measures EM showers from inner detectors

• SMRD muon detector installed in the magnet yoke – detect muons, cosmic ray trigger, side muon veto

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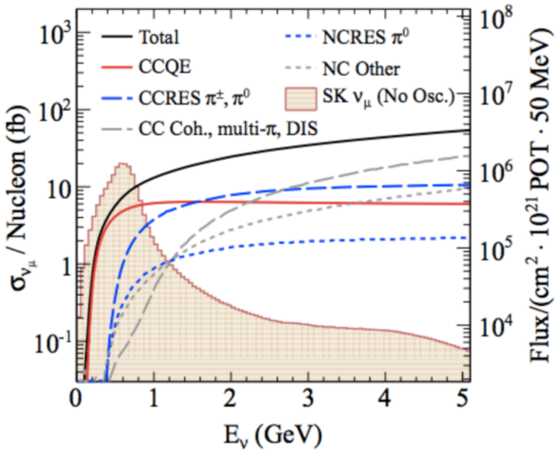
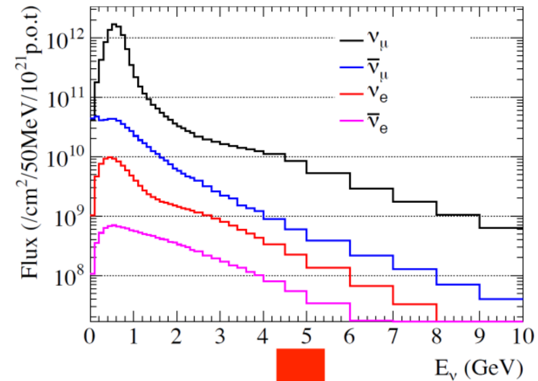
EXTRACTING OSCILLATION PARAMETERS, STEP 1

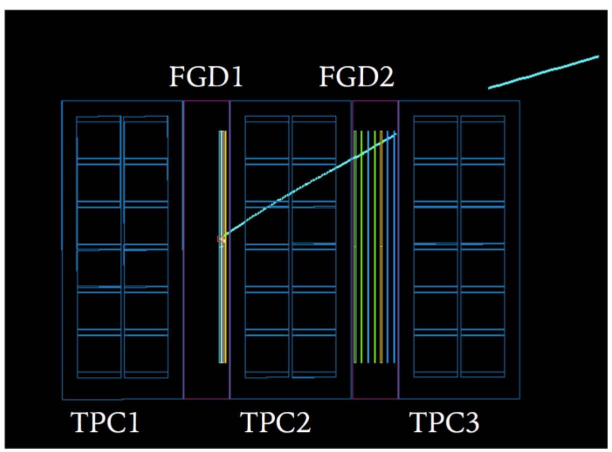
Neutrino-nucleus Interaction Model



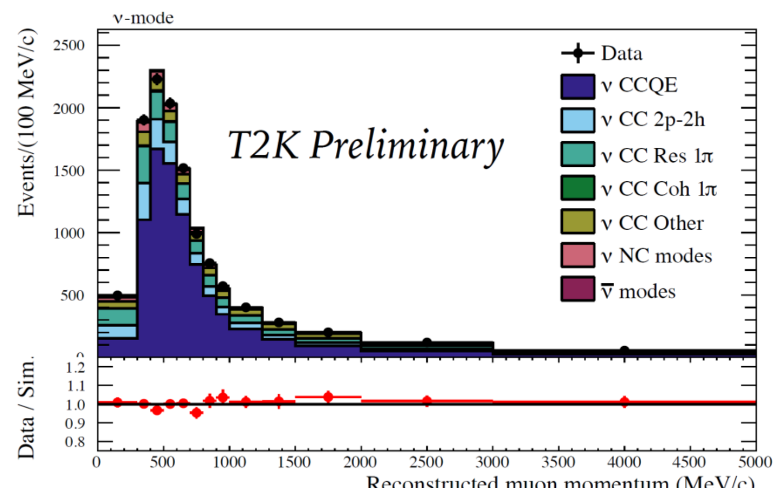
Neutrino Flux Model



ND280 Data



Fit to ND280 data constrains neutrino flux parameters and interaction model parameters



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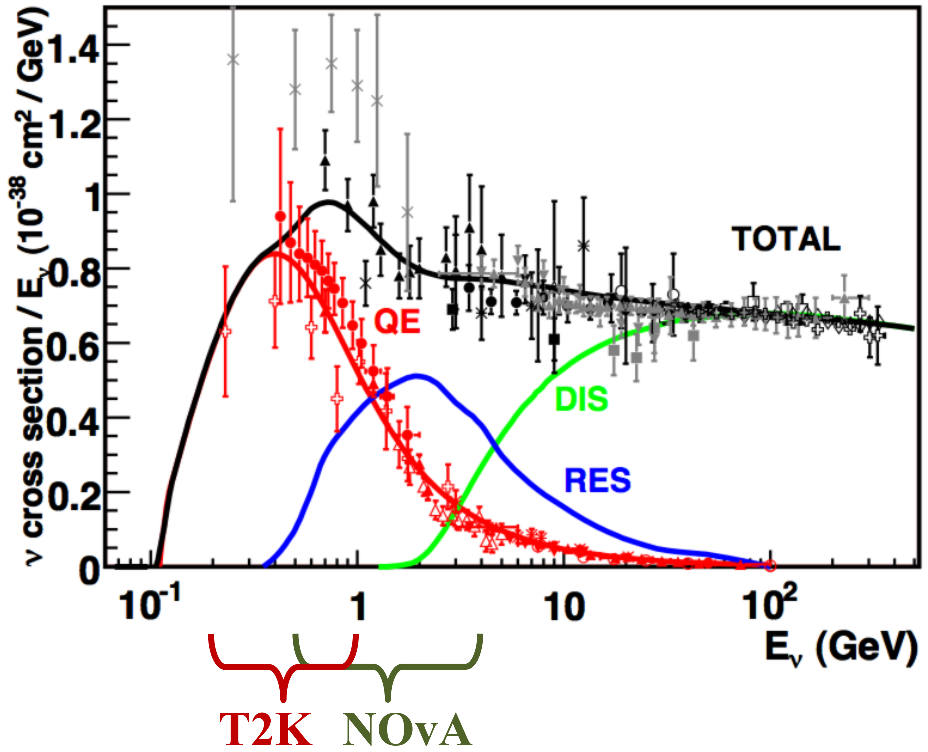
Quasi-elastic scattering:

$$\nu + [n] \rightarrow l^- + [p]$$

[target nucleon embedded in a nucleus]

Even if only outgoing lepton is measured can **estimate neutrino energy**:



Measured:

p_e, E_e, θ_e: momentum, energy, and direction* of outgoing lepton

* relative to the (known) direction of the incoming neutrino

Constants:

m_p, m_n, m_e: proton, neutron, and lepton masses
E_b: nucleon's binding energy

$$E_\nu^{\mathrm{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

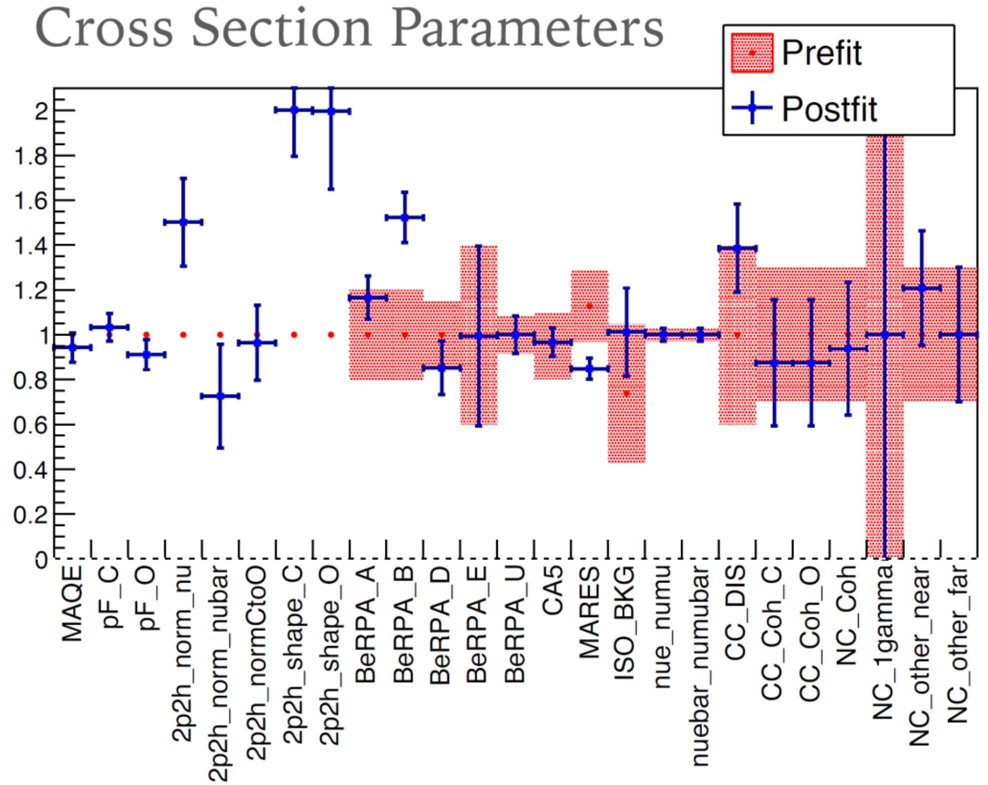
Key differences here…

T2K:

- Estimate E_ν via lepton kinematics
- Use a model for nuclear effects, non-QE modes
- Constrain model parameters with ND and external data *(plot at right)*

<u>Worry points:</u>

Does the model capture nuclear effects correctly? What about QE-like modes?



NOvA:

- Measure "all" the energy
- Use a model to correct for relative balance of modes, missing energy, …
- Leave (most) model parameters with their *a prioi* uncertainties
- Do a direct ND-to-FD extrapolation, folding in those uncertainties.

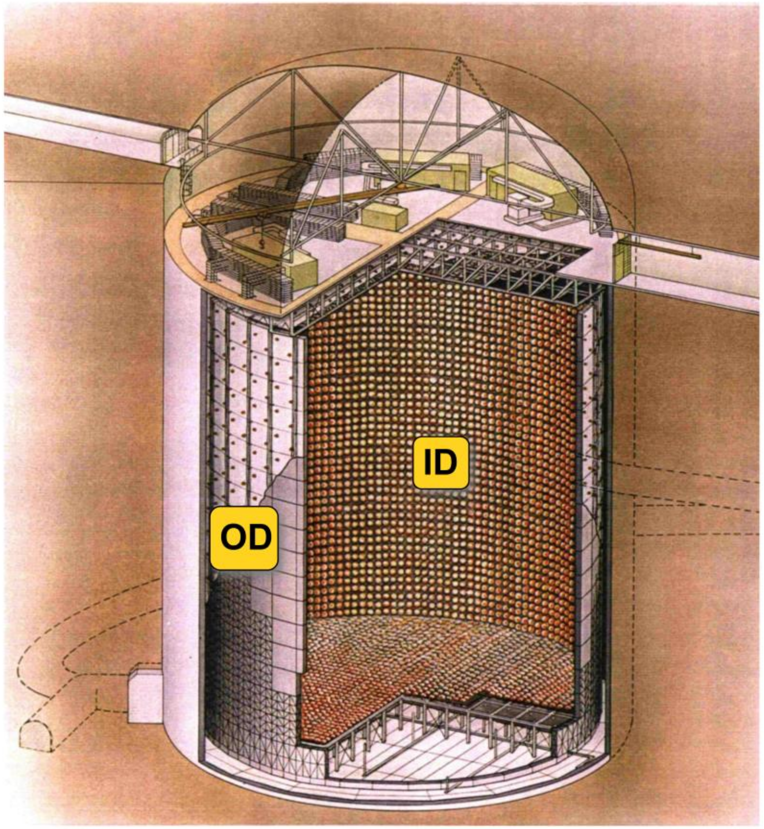
<u>Worry points:</u>

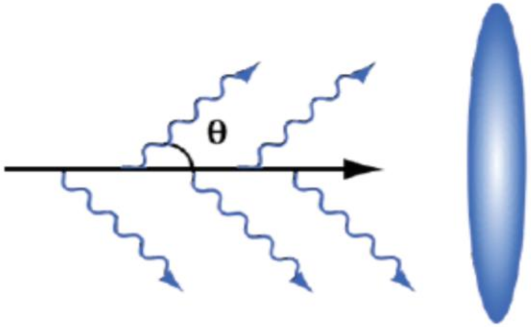
Is the model lacking significant avenues for missing energy?

Are the external uncertainties large enough?

SUPER-KAMIOKANDE

- 50 kton water-Cherenkov detector
- ~11,000 20" PMTs for inner detector (ID) (40% photo coverage)
- ~2,000 8" PMTs for outer detector (OD): veto cosmic muons, radioactivity, exiting particles
- Charged particles above Cherenkov threshold produce Cherenkov light detected by the PMTs





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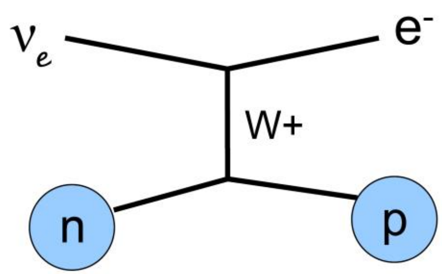
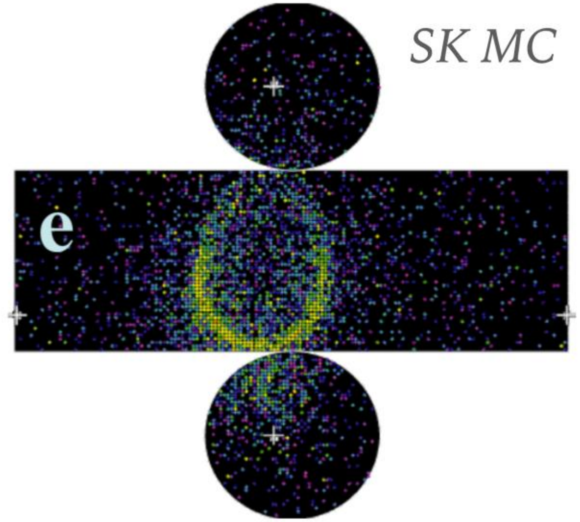
SIGNAL CHANNELS AT SUPER-K

Electron neutrino appearance signal:

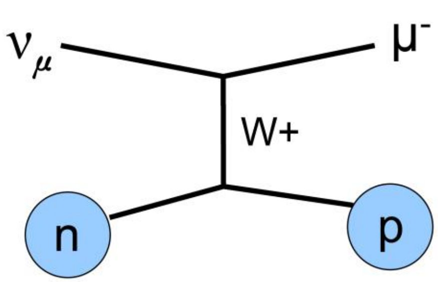


Detected electron produces a shower: "fuzzy" ring

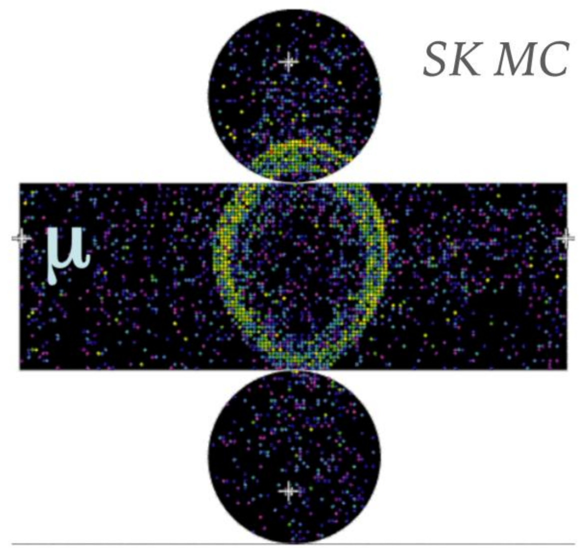


Target nucleon is bound in nucleus (more later)

Muon neutrino survival signal:



Detected muon produces a sharp ring



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THE FIVE SAMPLES

➤ Using the reconstructed fiTQun quantities, five samples are selected:

Neutrino Mode (forward horn current FHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

$$\nu_\mu(\bar{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X$$
$$\downarrow$$
$$e^-(e^+) + \bar{\nu}_e(\nu_e) + \nu_\mu(\bar{\nu}_\mu)$$

(CCQE) 1 Electron-like Ring, 0 decay electrons

$$\nu_e(\bar{\nu}_e) + N \rightarrow e^-(e^+) + X$$

(CC1π) 1 Electron-like Ring, 1 decay electron

$$\nu_e + N \rightarrow e^- + \pi^+ + X$$
$$\downarrow$$
$$\mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

Antineutrino Mode (reverse horn current RHC):

(CCQE) 1 Muon-like Ring, ≤1 decay electron

(CCQE) 1 Electron-like Ring, 0 decay electrons

No antineutrino mode CC1π sample due to π^- absorption

(dotted circle) = *detected particles*

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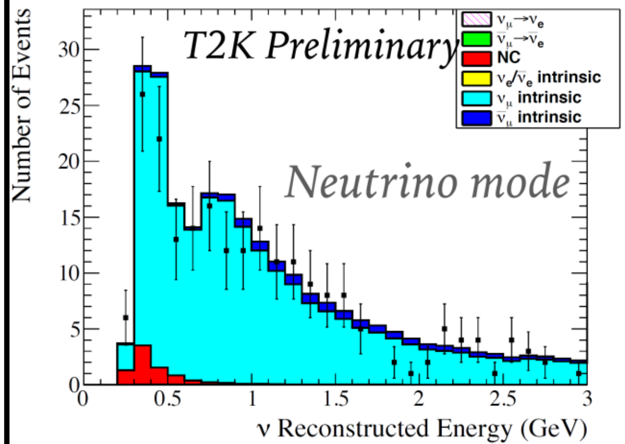
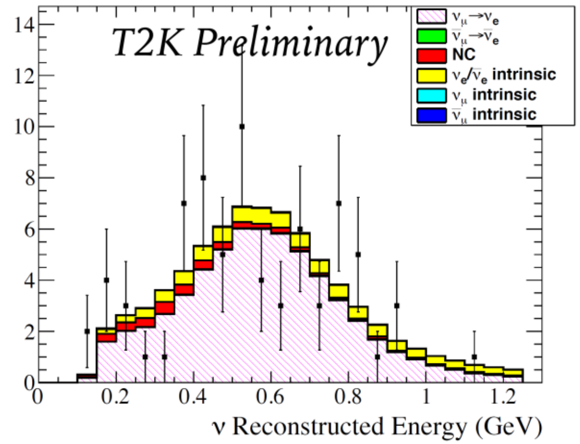
FITTED DATA DISTRIBUTIONS

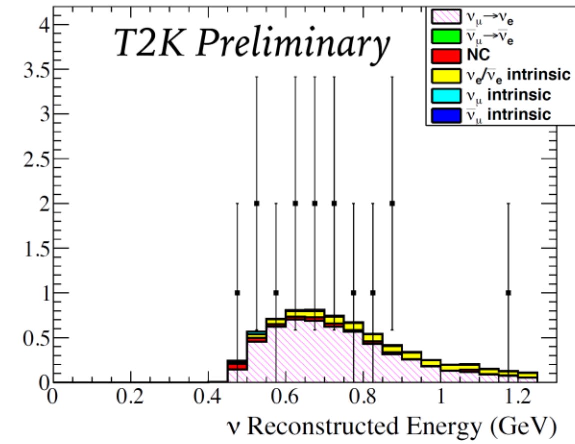
CCQE 1μ Ring



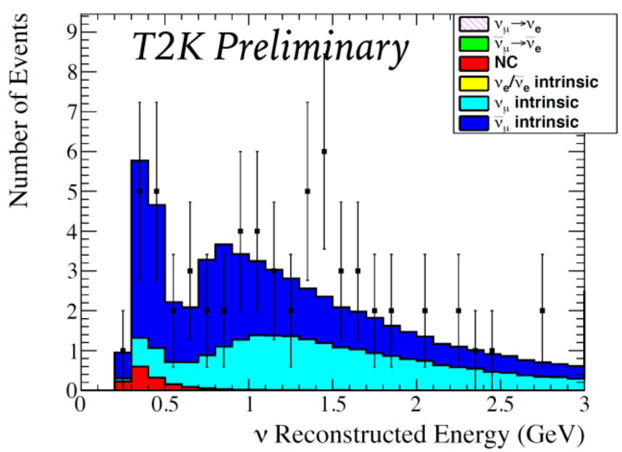
CCQE 1e Ring

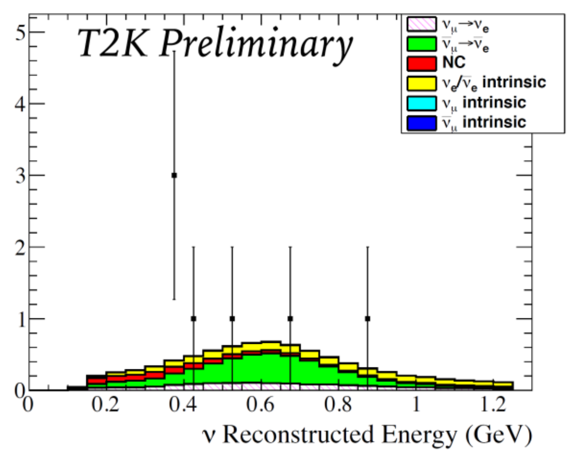


CC1π 1e Ring



Antineutrino mode





p-value = 0.42

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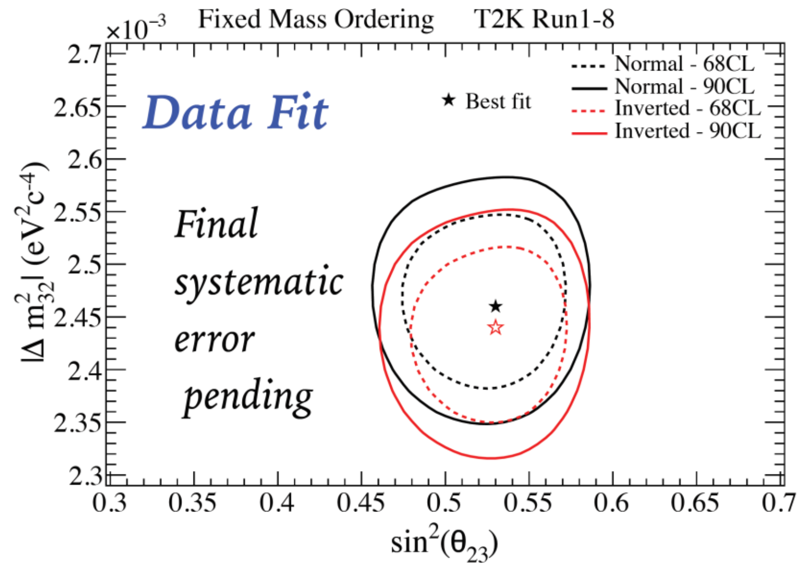
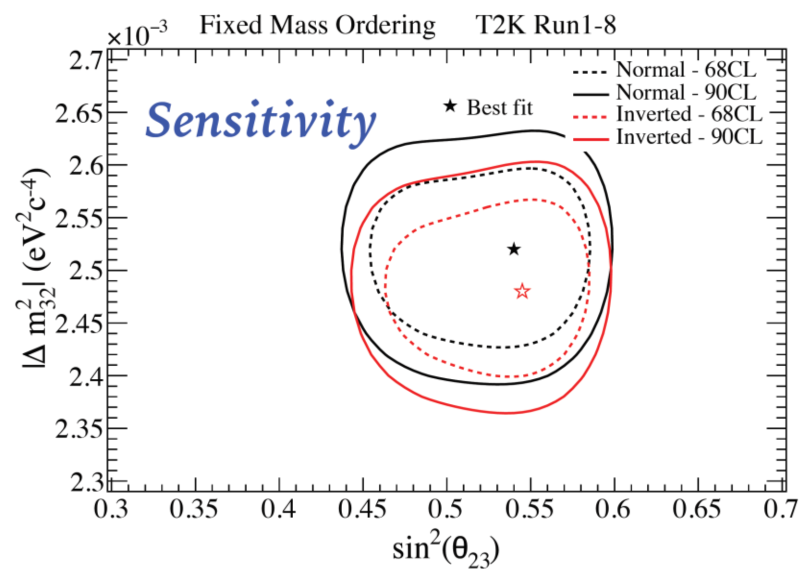
ATMOSPHERIC PARAMETER CONSTRAINTS

- Fit the normal and inverted hierarchies separately
- Results with the reactor constraint on $\sin^2 2\theta_{13}$ shown
- Constraint on $\sin^2\theta_{23}$ is slightly stronger than the sensitivity





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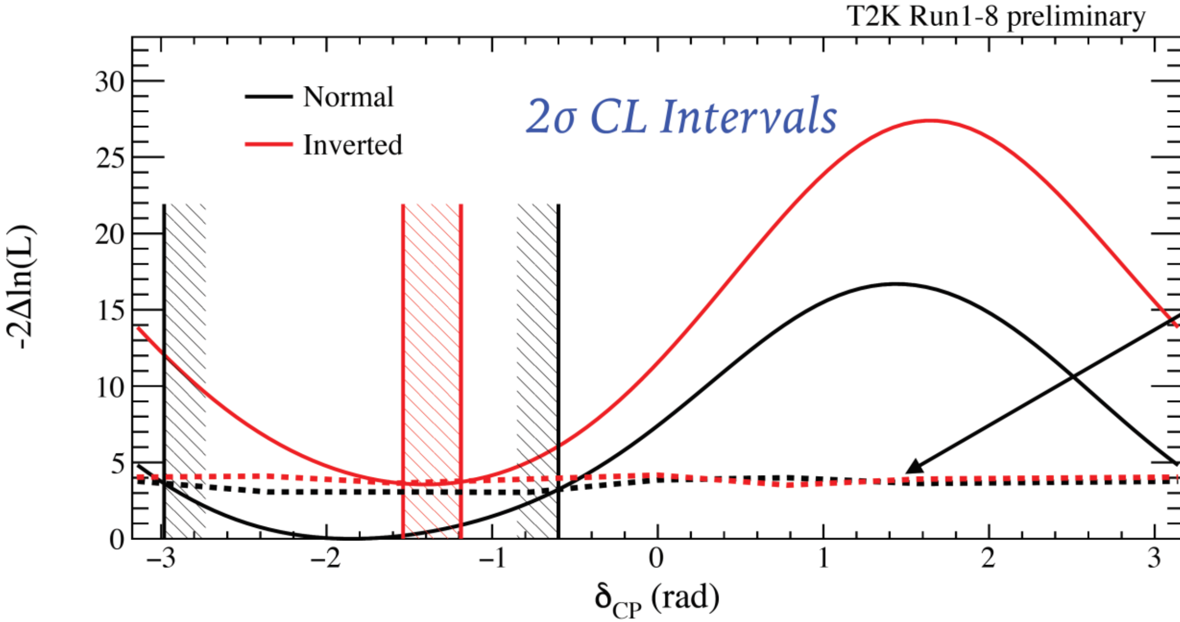
MEASUREMENT OF δ_{cp}



critical $\Delta\chi^2$ values for 2σ confidence level

Best fit point: -1.83 radians in Normal Hierarchy

The 1σ CL confidence interval: Normal hierarchy: [-2.49, -1.23] radians

The 2σ CL confidence interval:
Normal hierarchy: [-2.98, -0.60] radians
Inverted hierarchy: [-1.54, -1.19] radians

CP conserving values (0,π) fall outside of the 2σ CL intervals

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OCTANT AND HIERARCHY PREFERENCES

- Bayesian analysis: natural way to infer data preference for **θ_{23} octant** or **mass hierarchy**
- Assume equal prior probability for both octant and hierarchy hypotheses
- Fraction of steps from Markov Chain in each octant/hierarchy is posterior probability for the octant/hierarchy hypothesis

Posterior probabilities (with reactor constraint)

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	

- T2K data prefers the normal hierarchy and upper octant
  - No conclusive statement yet

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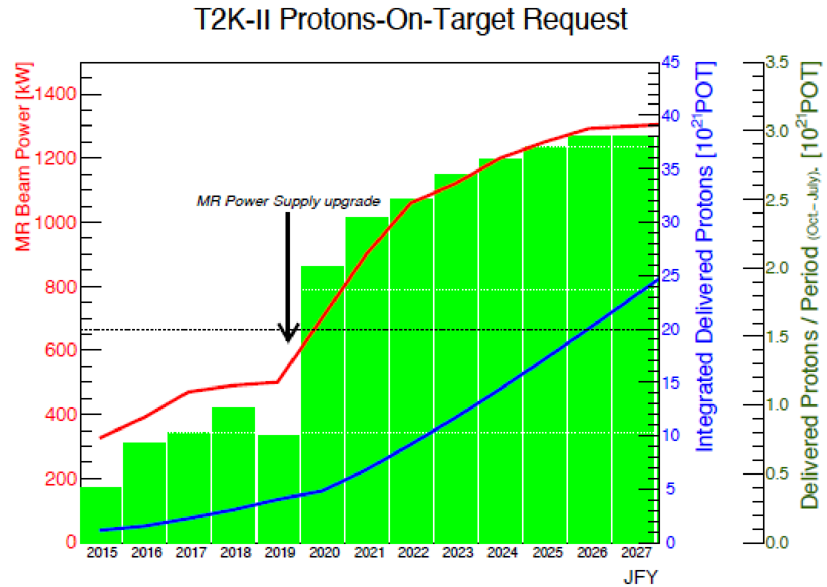
T2K-II: EXTENDED T2K OPERATION

- T2K originally approved for 7.8×10^{21} POT
- Proposal to extend T2K operation to 2026 and collect 20.0×10^{21} POT
- Analysis and operation improvements to achieve another 50% improvement in experimental sensitivity
  - ~30% already achieved!



- Upgrade the Main Ring magnet power supplies to achieve 1 Hz operation
  - Projected ultimate beam power of 1.3 MW

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode ν_e sample	0	454.6	346.3	3.8	72.2	1.8	30.5
	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode $\bar{\nu}_e$ sample	0	129.2	16.1	71.0	28.4	0.4	13.3
	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

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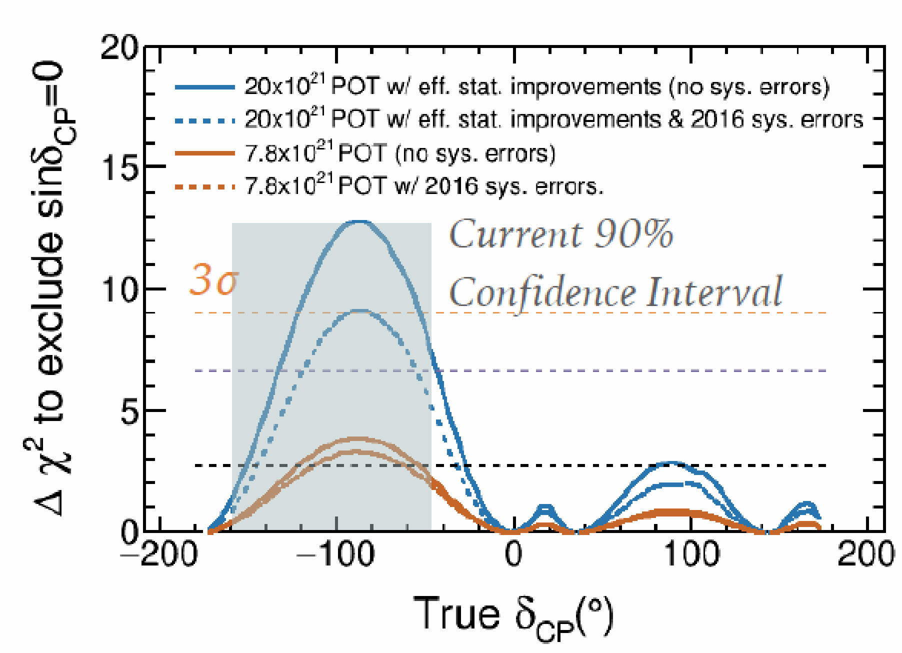
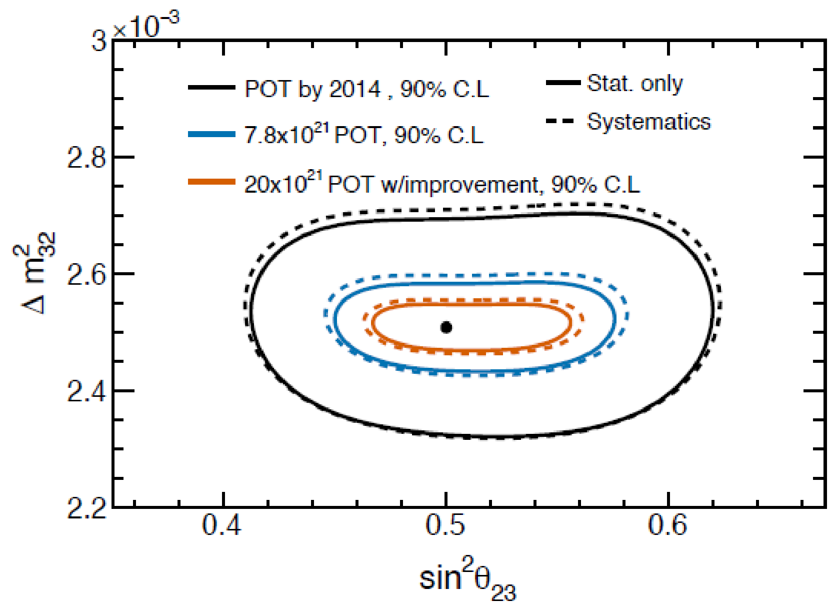
T2K-II SENSITIVITY





- If δ_{cp} is near current best fit, potential for a 3σ discovery of CP violation in T2K-II
  - The size of systematic errors has a large impact on the experimental sensitivity (dashed vs. solid lines) - we expect systematic uncertainties to improve
- Significant reduction of $\sin^2\theta_{23}$ and Δm^2_{32} intervals is also possible

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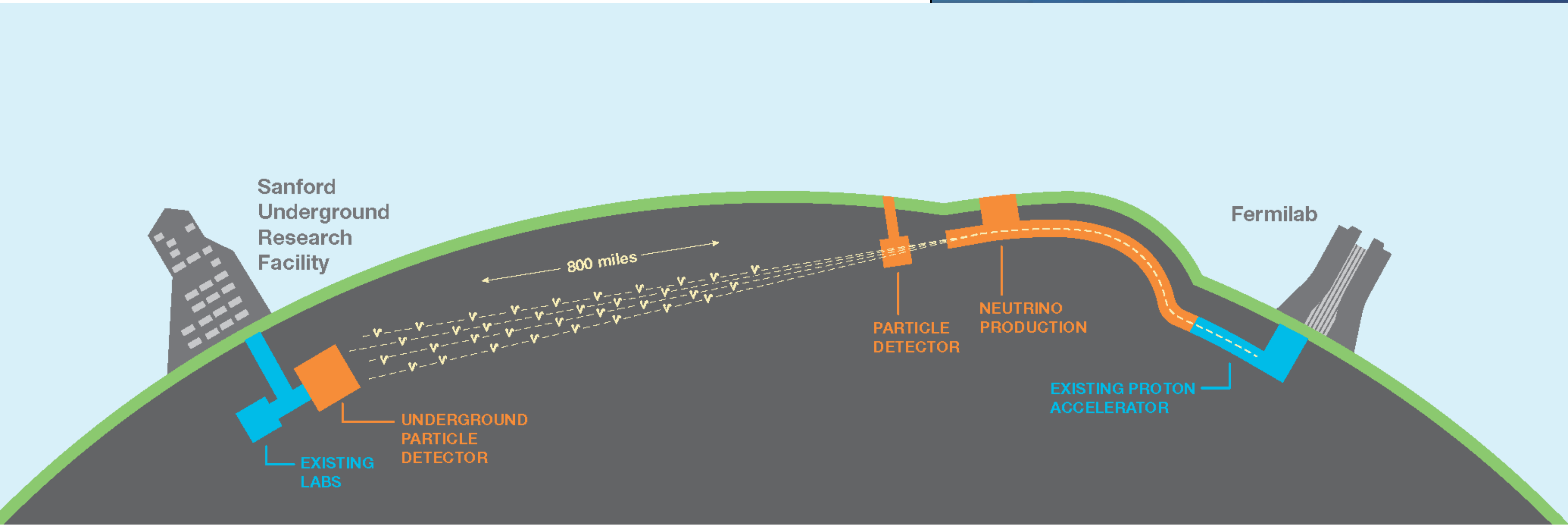
Pause for questions/discussion

LBL experiments: Future

DUNE

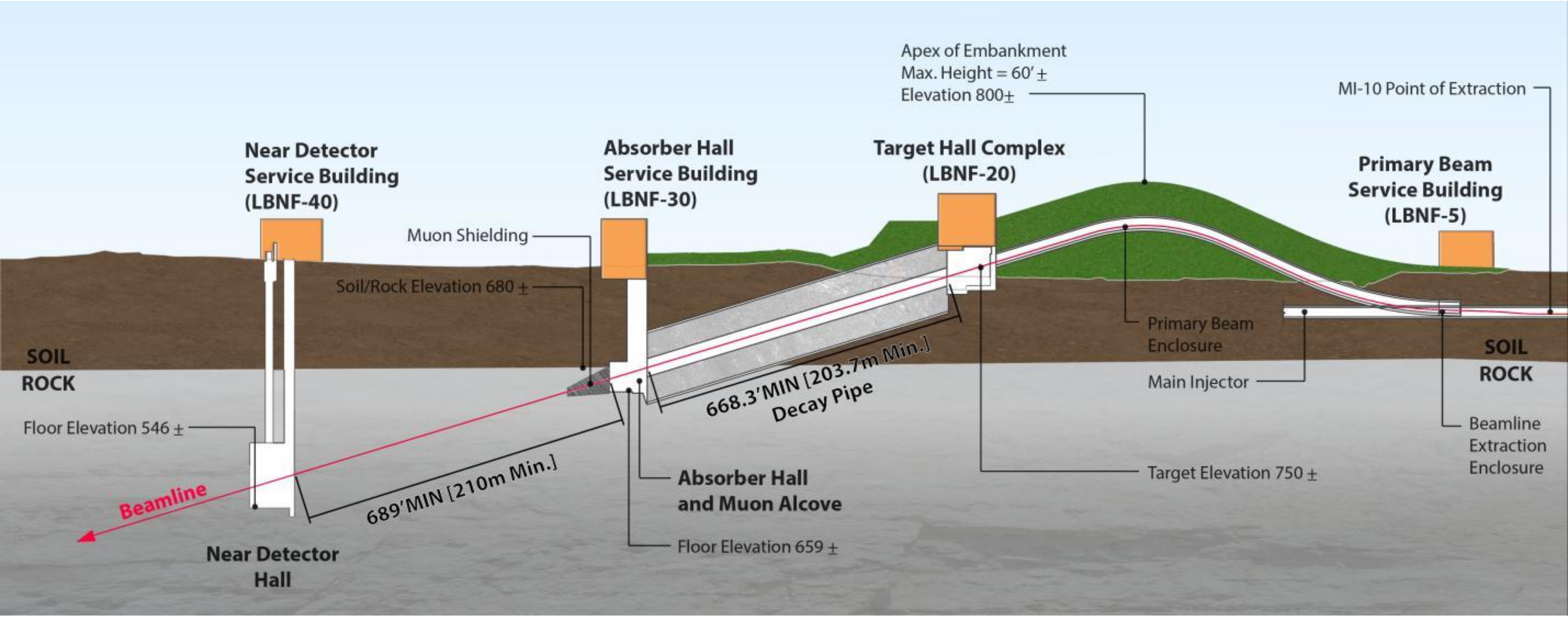
Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**



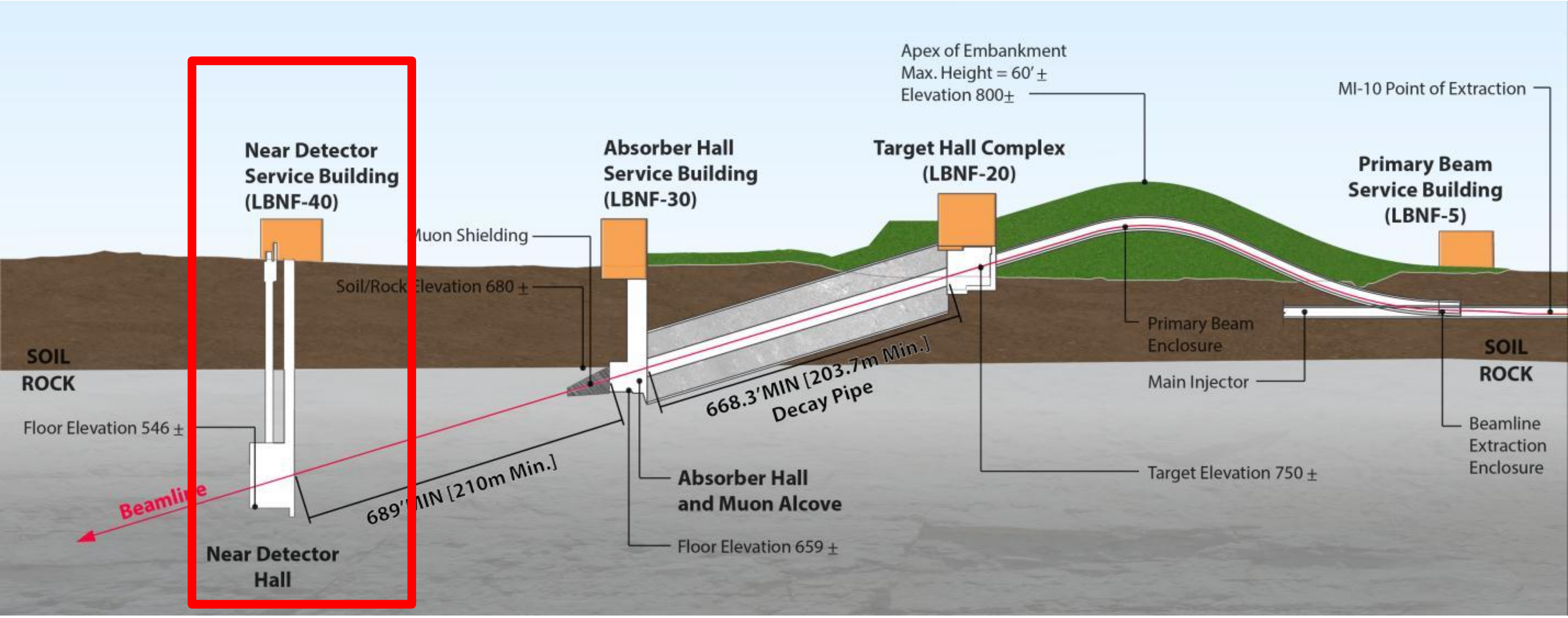
Long Baseline Neutrino Facility (LBNF)

- DOE/Fermilab hosted project with international participation
- **Horn-focused beamline** similar to NuMI beamline
  - 60 – 120 GeV protons from Fermilab's Main Injector
  - 200 m decay pipe at -5.8° pitch, angled at South Dakota (SURF)
  - Initial power 1.1 MW, upgradable to 2.4 MW



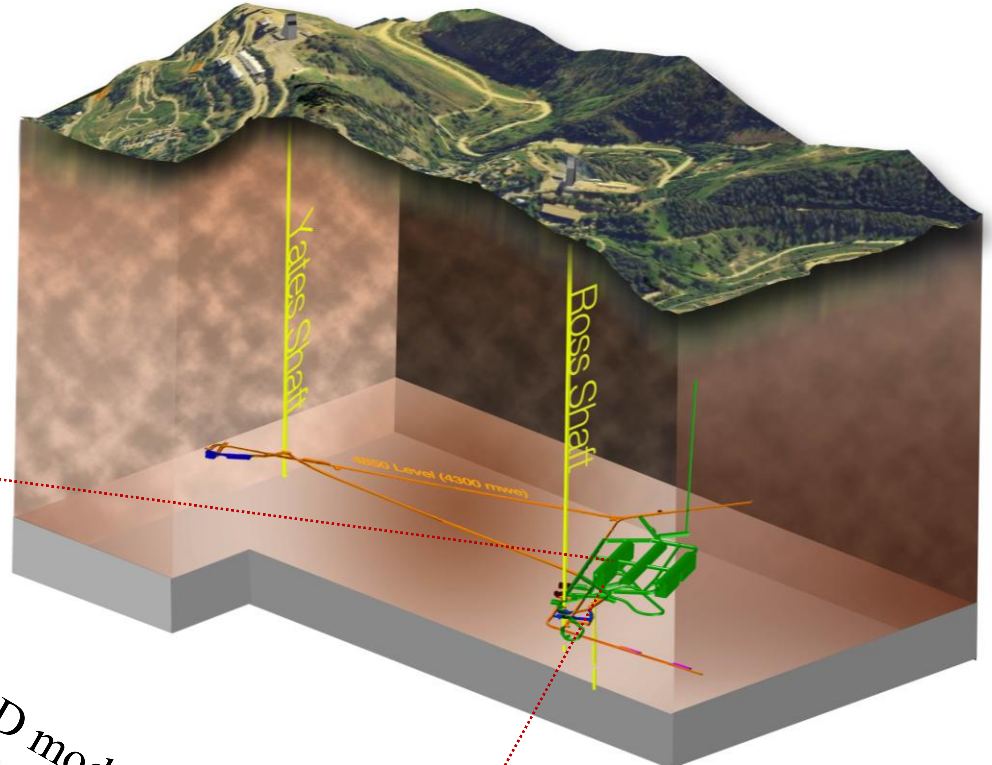
Near Detector

- DUNE will have a **Near Detector**
  - Constrain systematic uncertainties in oscillation measurements
  - Precisely measure initial fluxes of neutrinos in the beam
  - Measure numerous neutrino-nucleus scattering cross sections
- Multiple **designs** under consideration
  - LAr TPC, high-pressure GAr TPC, fine-grained tracker, hybrid designs

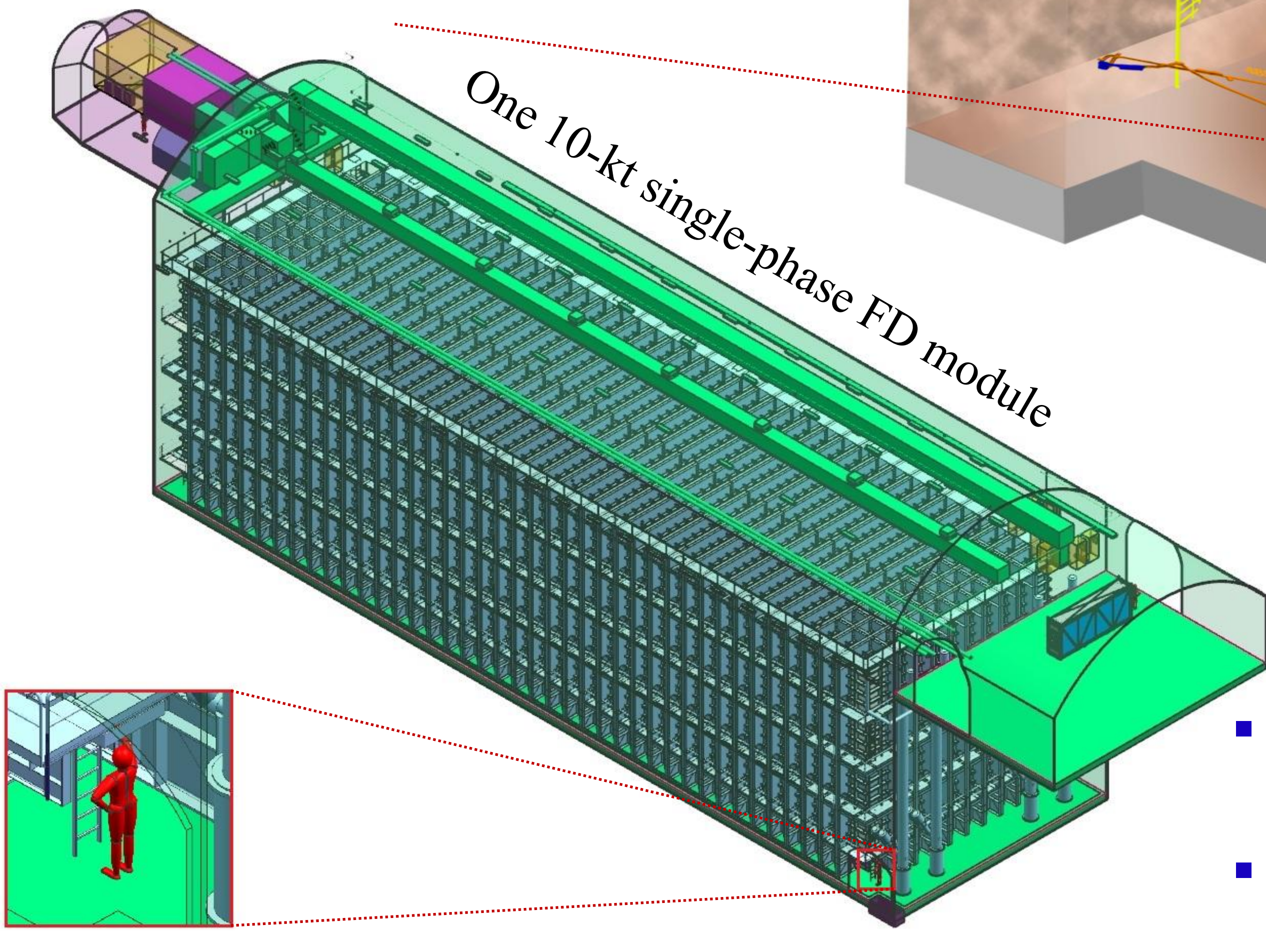


Far Detector

- **40-kt (fiducial)** LAr TPC
- Installed as four 10-kt modules at 4850' level of SURF



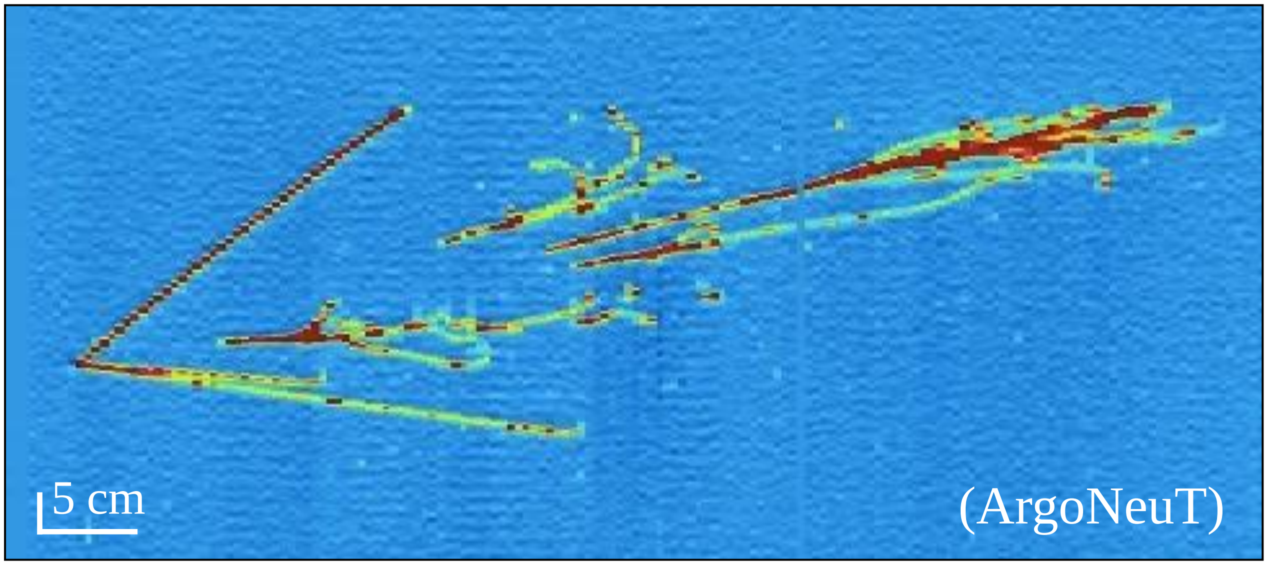
Sanford Underground Research Facility (SURF)



- First module will be a **single phase LAr TPC**
- Modules installed in stages. Not necessarily identical

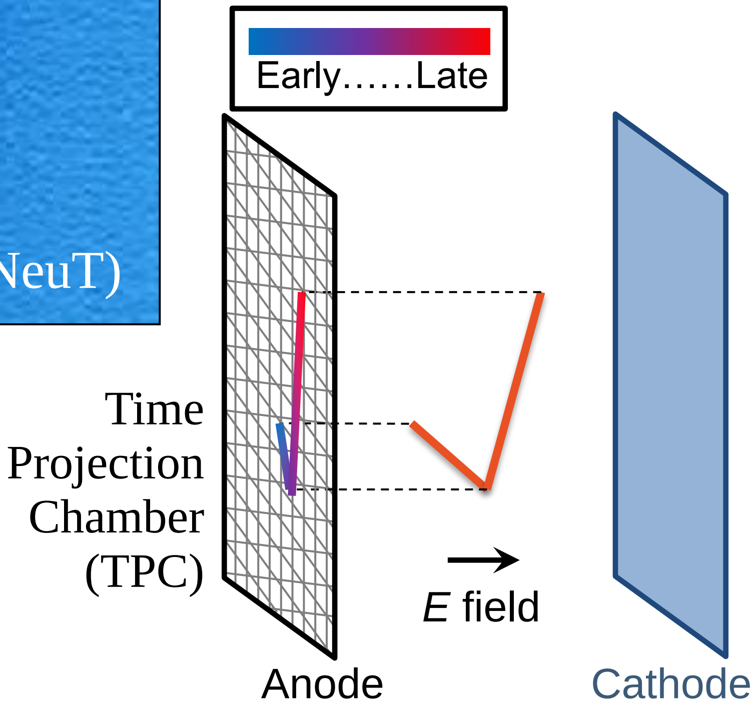
Key design features:

Very long baseline → *no oscillation parameter ambiguities*
Large detector and powerful beam → *high event rate*
Highly capable LAr TPC → *excellent background rejection*
Low energy threshold → *rich underground physics program*



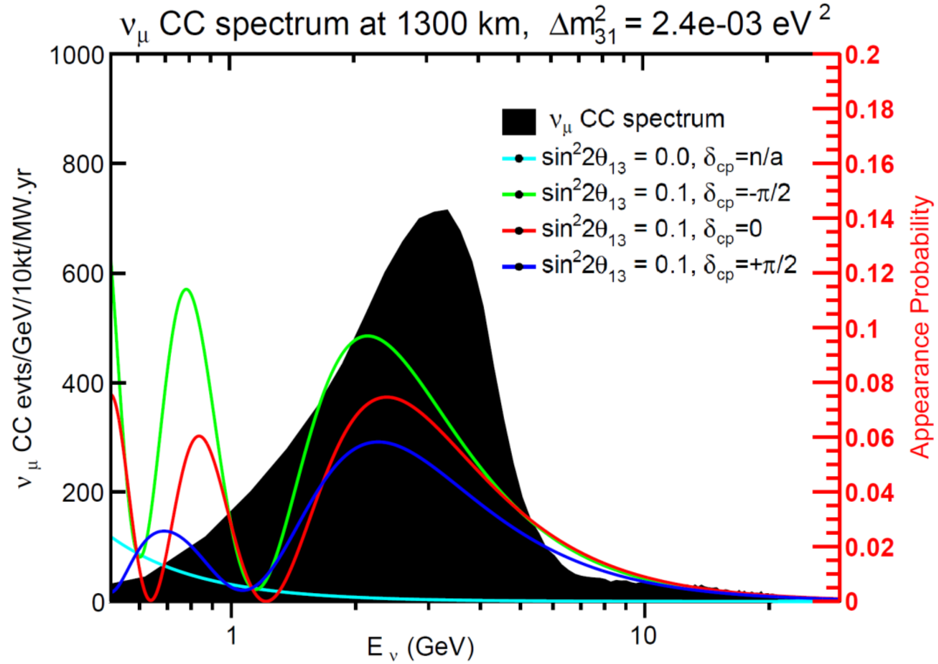
DUNE TPC:

- **3.5 m drifts @ 175 kV** *(500 V/cm)*
- **3 ms** e^- **lifetime**
- **5 mm wire pitch**

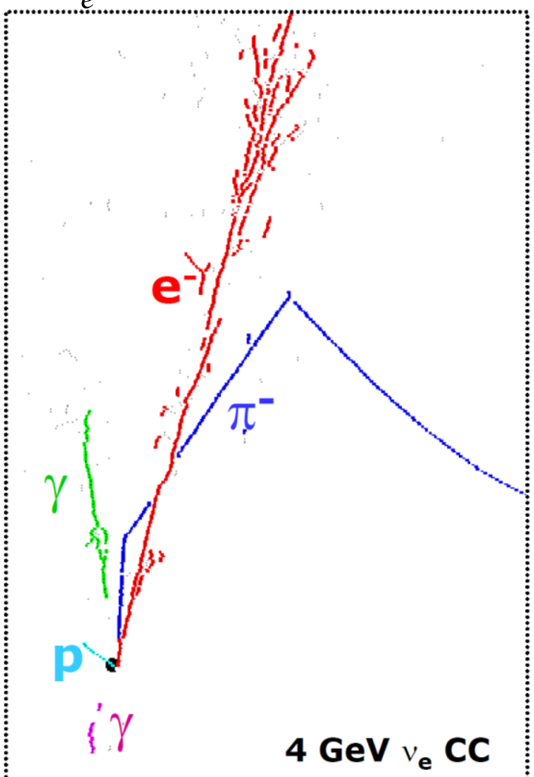


High-resolution detector

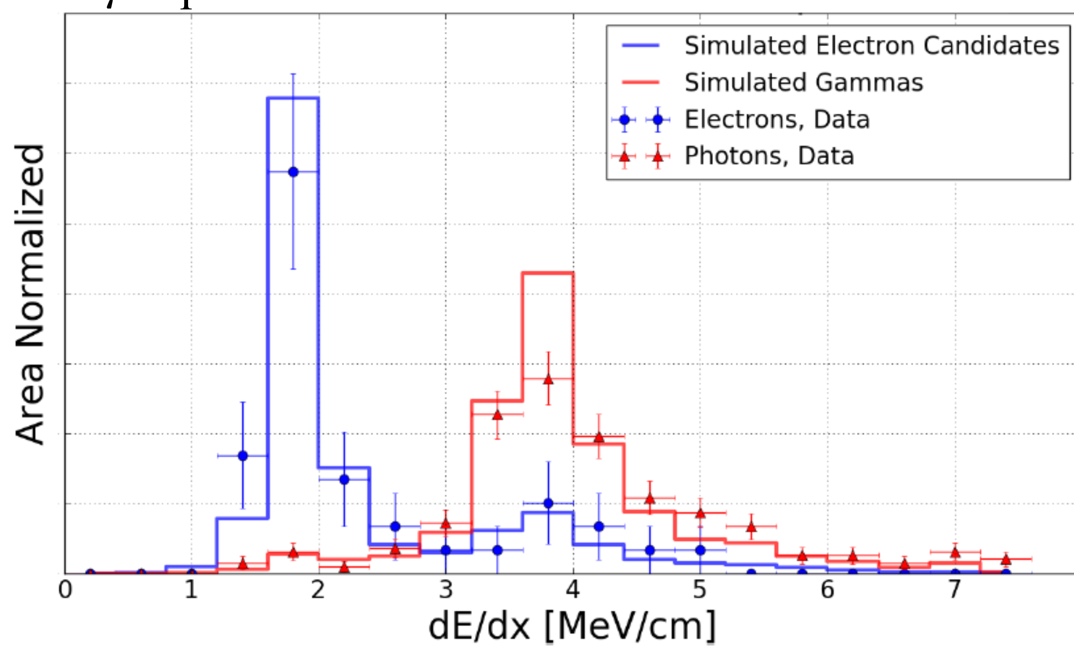
- permits broadband neutrino beam
- *e*-*γ* shower separation via both event topology and early *dE*/*dx*



Simulated and reconstructed ν_e CC event in DUNE



e/*γ* separation with R&D detector



ArgoNeuT, arXiv:1610.04102

(after 7 years, staged deployment)

Observation of leptonic *CP* violation

5σ near $\delta=\pi/2$

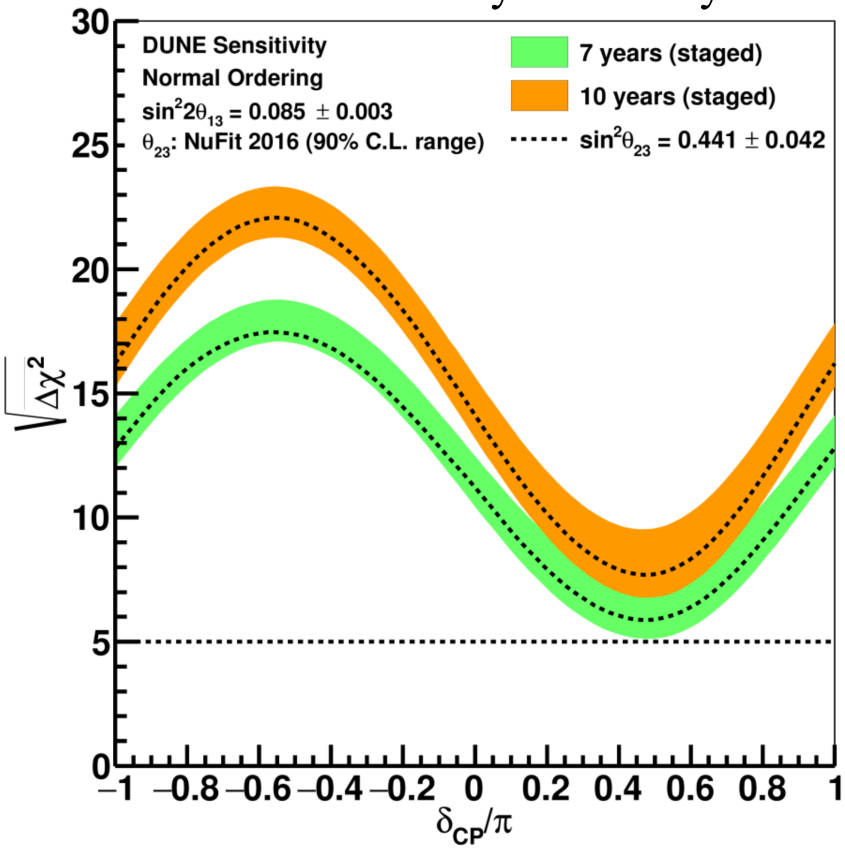
3σ for 65% of δ range

Definitive hierarchy determination

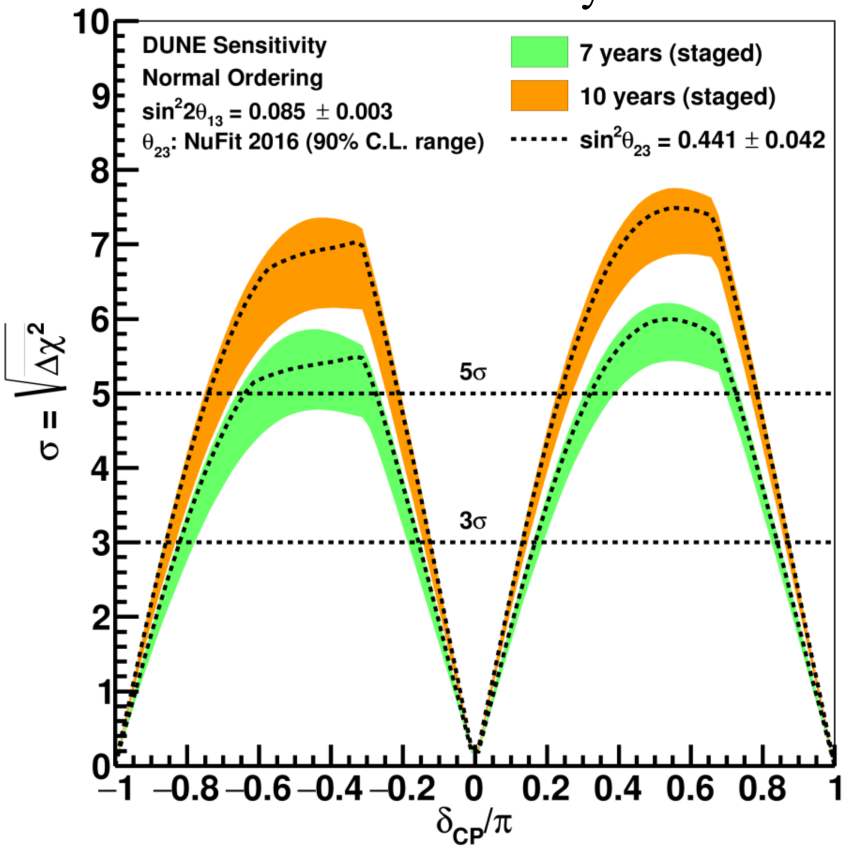
>5σ regardless of other parameter choices

Move quickly to
potential discovery

Mass hierarchy sensitivity



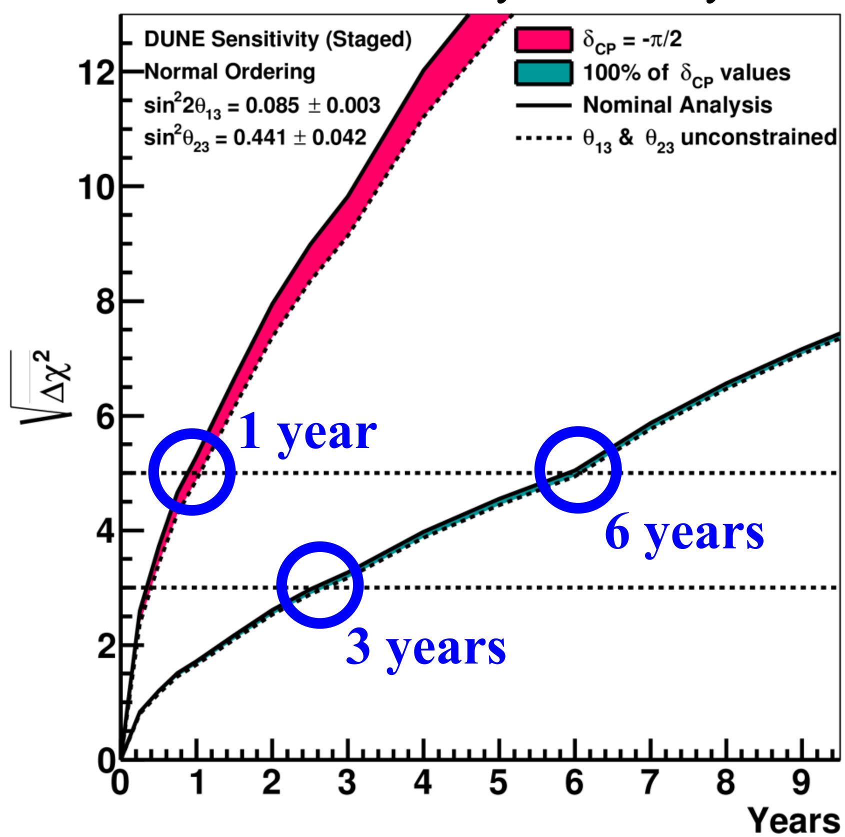
*CP*v sensitivity



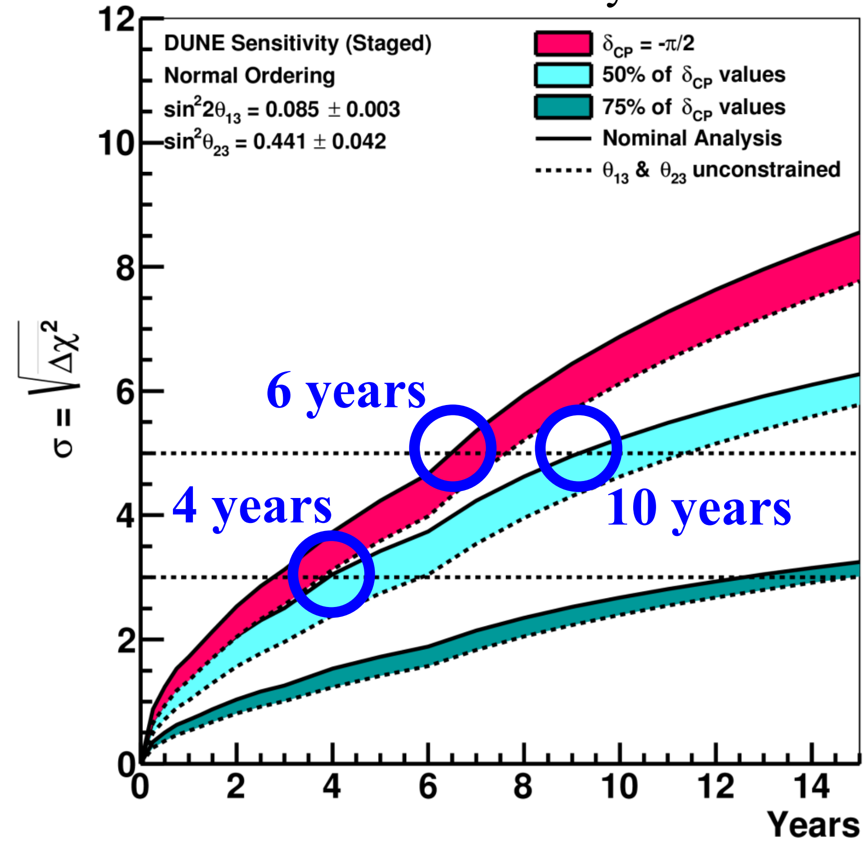
Sensitivity vs. time

→ **Significant milestones** throughout beam-physics program
→ **A few examples** below

Mass hierarchy sensitivity



*CP*v sensitivity



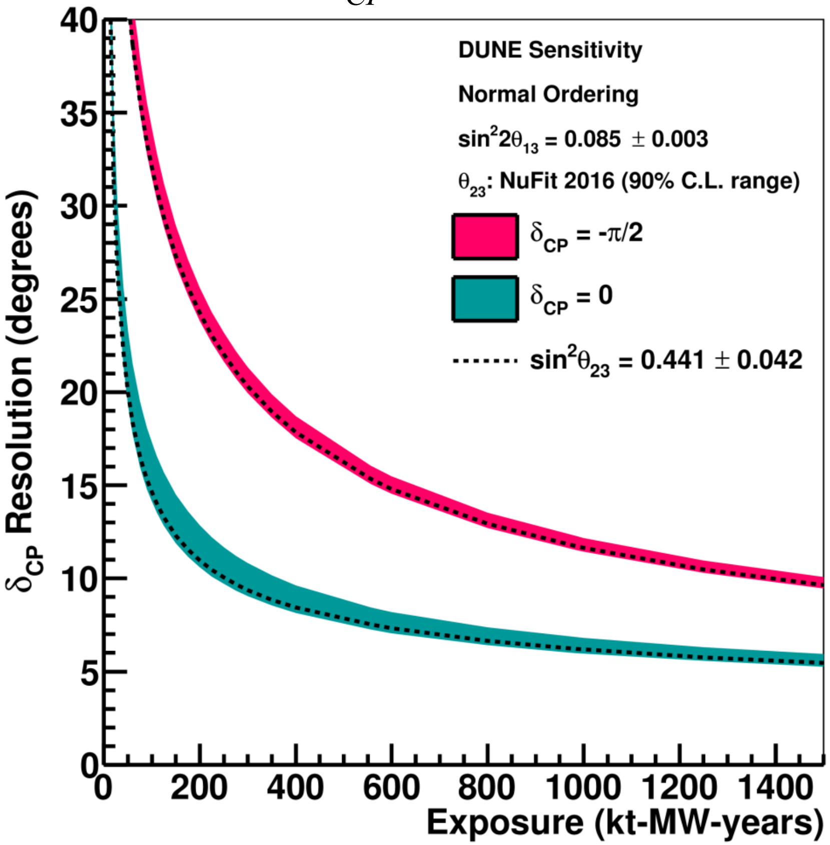
Precision PMNS

(ultimate precision depends on parameter values themselves)

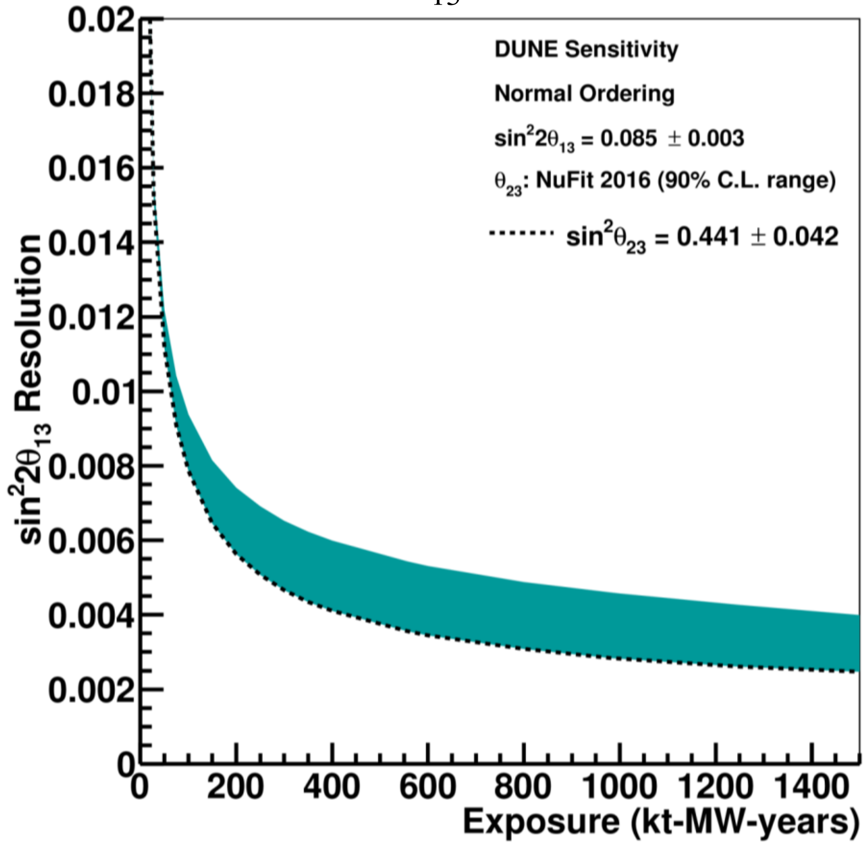
→ *E.g.*: δ_{CP} to ~10° ; θ_{13}, θ_{23} to ~0.2°

→ A suite of oscillation parameter measurements in a single experiment

δ_{CP} resolution

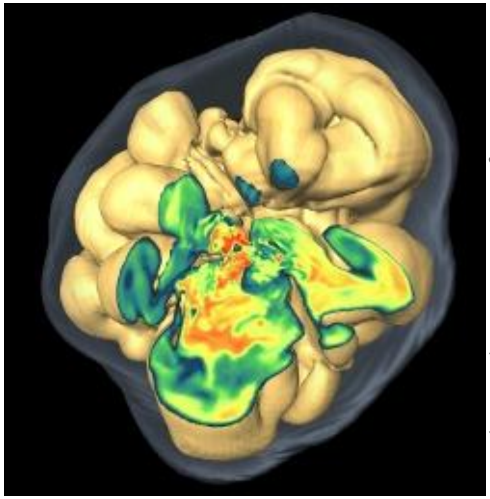


$\sin^2 2\theta_{13}$ resolution



Supernova neutrinos

- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass hierarchy, sterile neutrinos, extra dimensions, …

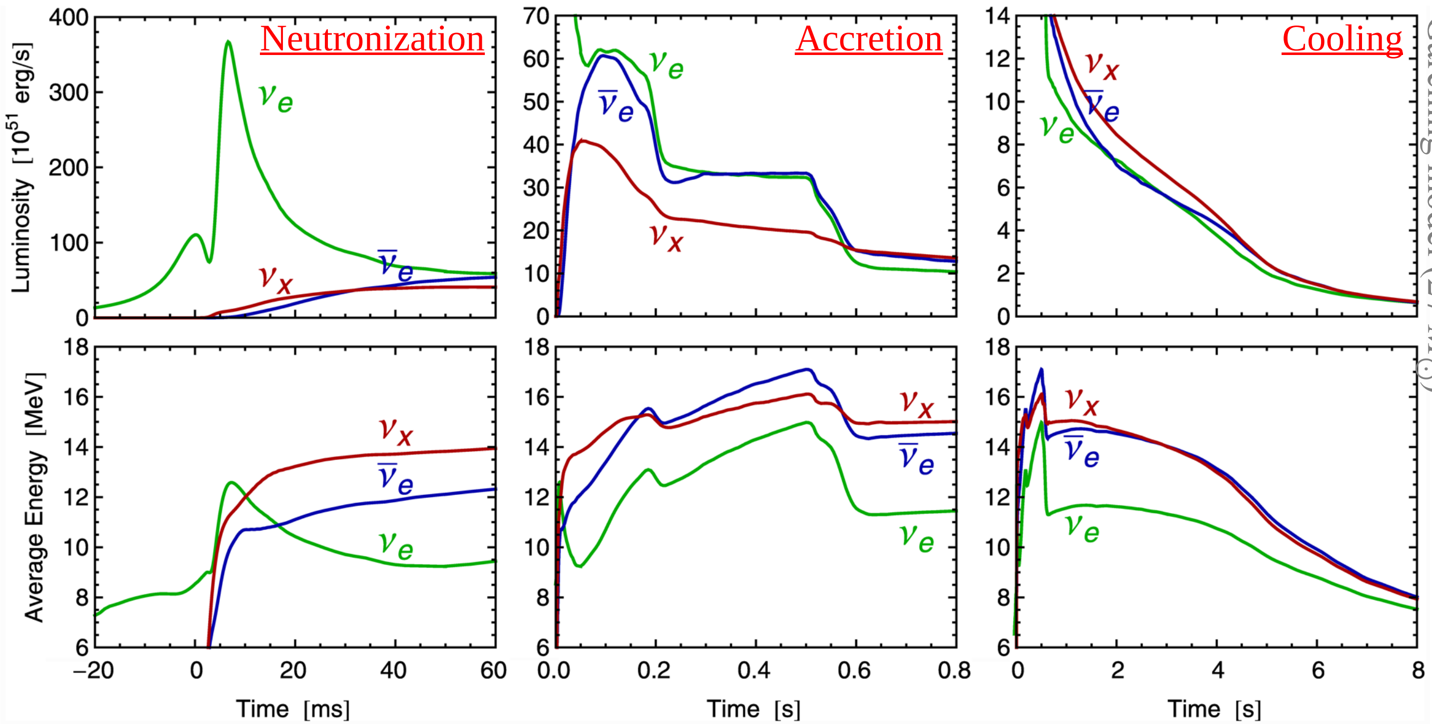


S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

Argon target:
Unique sensitivity to ν_e flux

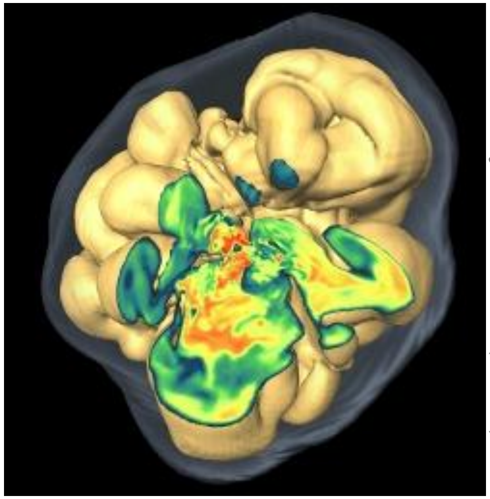
DUNE at 10 kpc:
~3000 ν_e events over 10 seconds

with 5%–10% energy resolution & sub-μs time resolution



Garching model (27 $M_\odot$)

Supernova neutrinos



S. Woosley and T. Janka
Nature Physics **1**, 147 (2005)

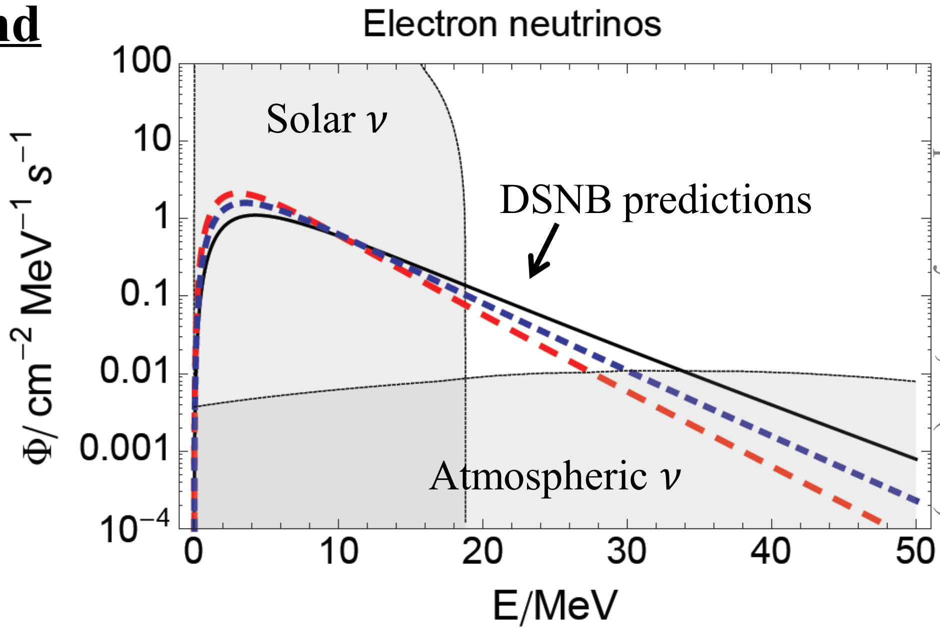
- **99% of energy** released in a core-collapse supernova is **carried away by neutrinos** *(cf.: 0.01% carried away by light)*
- **Rich information** embedded in neutrino signal:
  - **Supernova physics:** core-collapse mechanism, black hole formation, shock stall/revival, nucleosynthesis, cooling, …
  - **Particle physics:** flavor transformations in core, collective effects, mass hierarchy, sterile neutrinos, extra dimensions, …

Diffuse supernova neutrino background

Should be there. *Not yet observed.**

DUNE: Potential for DSNB discovery and ~20% rate measurement

(bkgnds still under study)



C. Lunardini,
Astropart. Phys. **79**, 49 (2016)

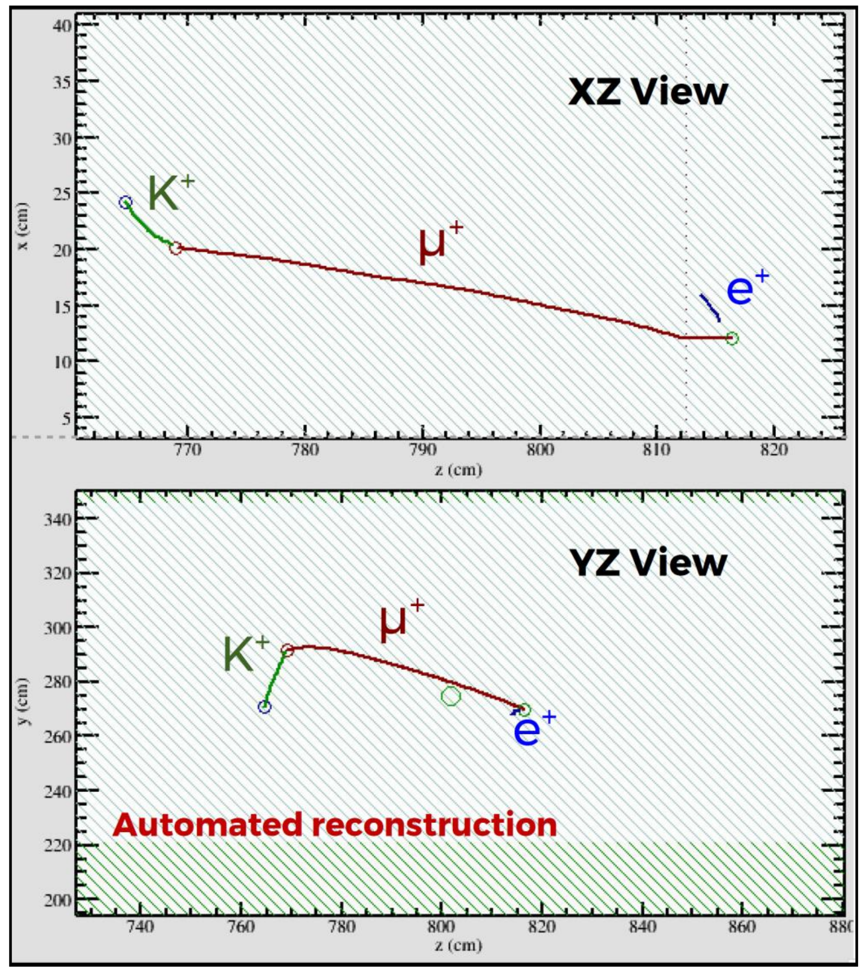
* Present limit from Super-K:
K. Bays *et al.*, Phys. Rev. D **85**, 052007 (2012)

Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

- An **effective proton decay search** requires (**and DUNE has**)
  - **Large exposure:**
    40 kton, 20+ yr program
  - **Low background rates:**
    Deep underground location
  - **High signal efficiency:**
    Precision LAr TPC tracking

LAr TPC technology **particularly shines** for complex *p* decay modes or modes with **final state kaons**, as **favored by SUSY GUTs**



At right:

$K^{\pm} \rightarrow \mu \rightarrow e$ **decay sequence**

Background-free signature in DUNE

Baryon number violation

Processes with $\Delta B \neq 0$, including **proton decay**, are a general prediction of **grand unified theories**

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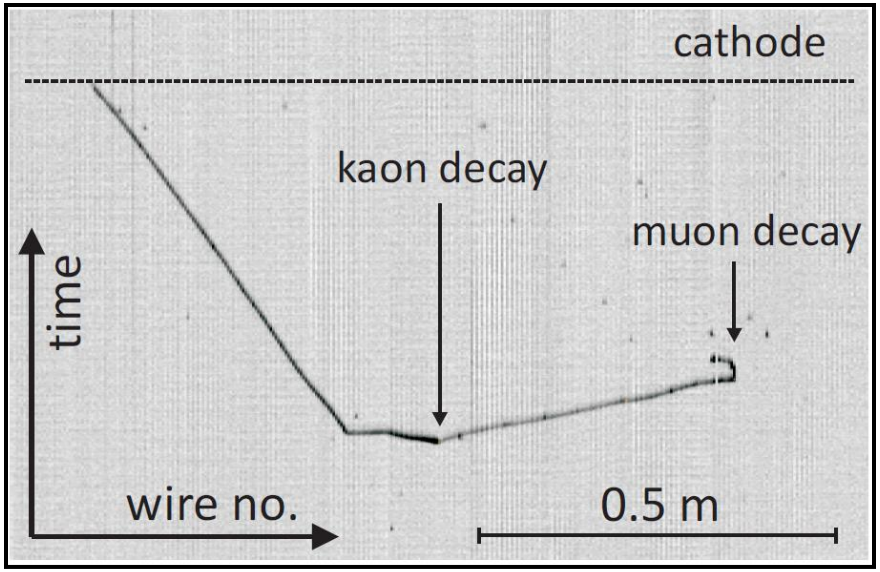
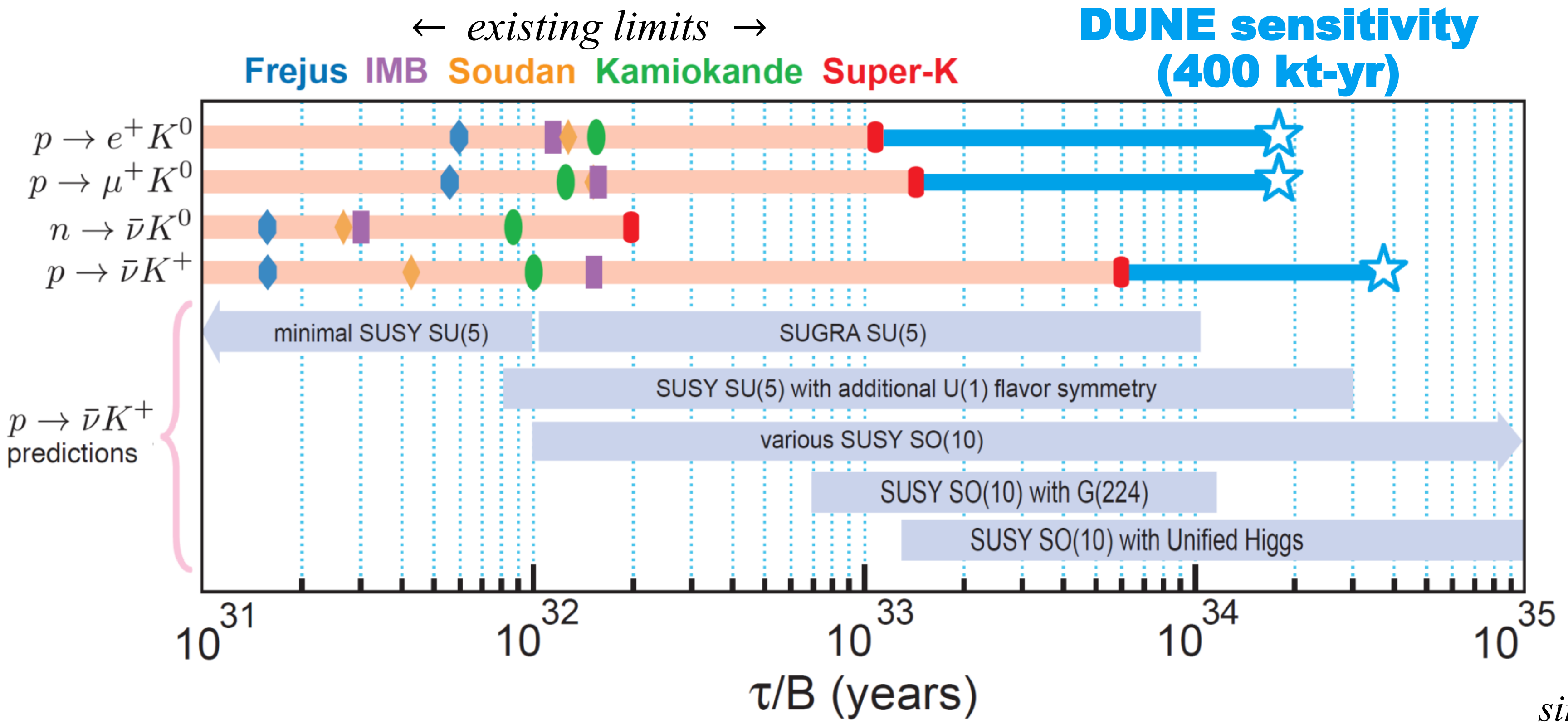
Background-free signature in DUNE

ICARUS collab., Adv. HEP, vol. 2013, 260820 (2013)





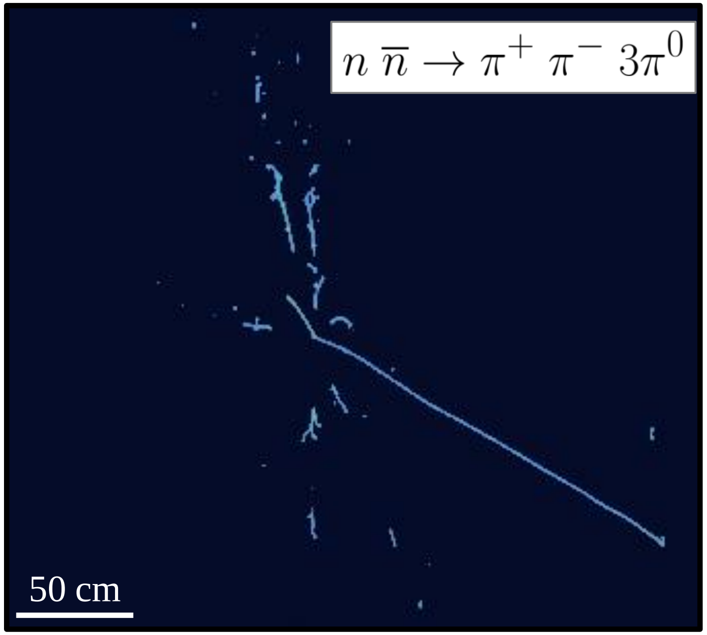
Order of magnitude step in lifetime
→ *Significant model discrimination*

At right:

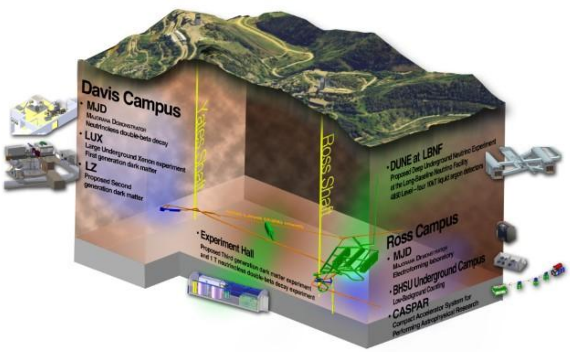
n-$\bar{n}$ oscillation → intranuclear $n\bar{n}$ annihilation

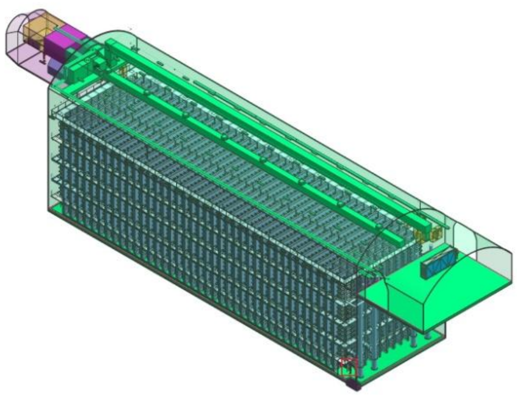
Spherical spray of hadrons with $\boldsymbol{E \approx 2M_n}$ and **net momentum** $\boldsymbol{\lesssim p_F}$ ~ 300 MeV

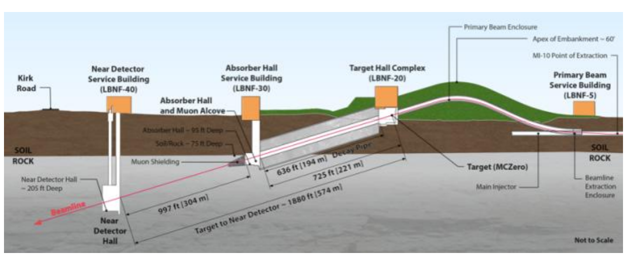
simulation



DUNE Timeline

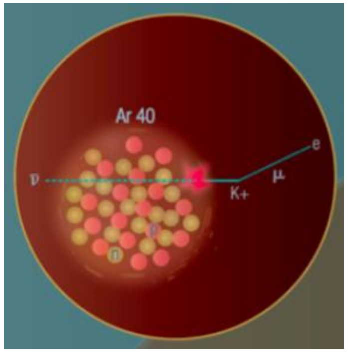






- 2017: Far Site Construction Begins
- 2018: ProtoDUNEs at CERN
- 2021: Far Detector Installation Begins
- 2024: Physics Data Begins (20 kt)
- 2026: Neutrino Beam Available

The CERN Neutrino Platform

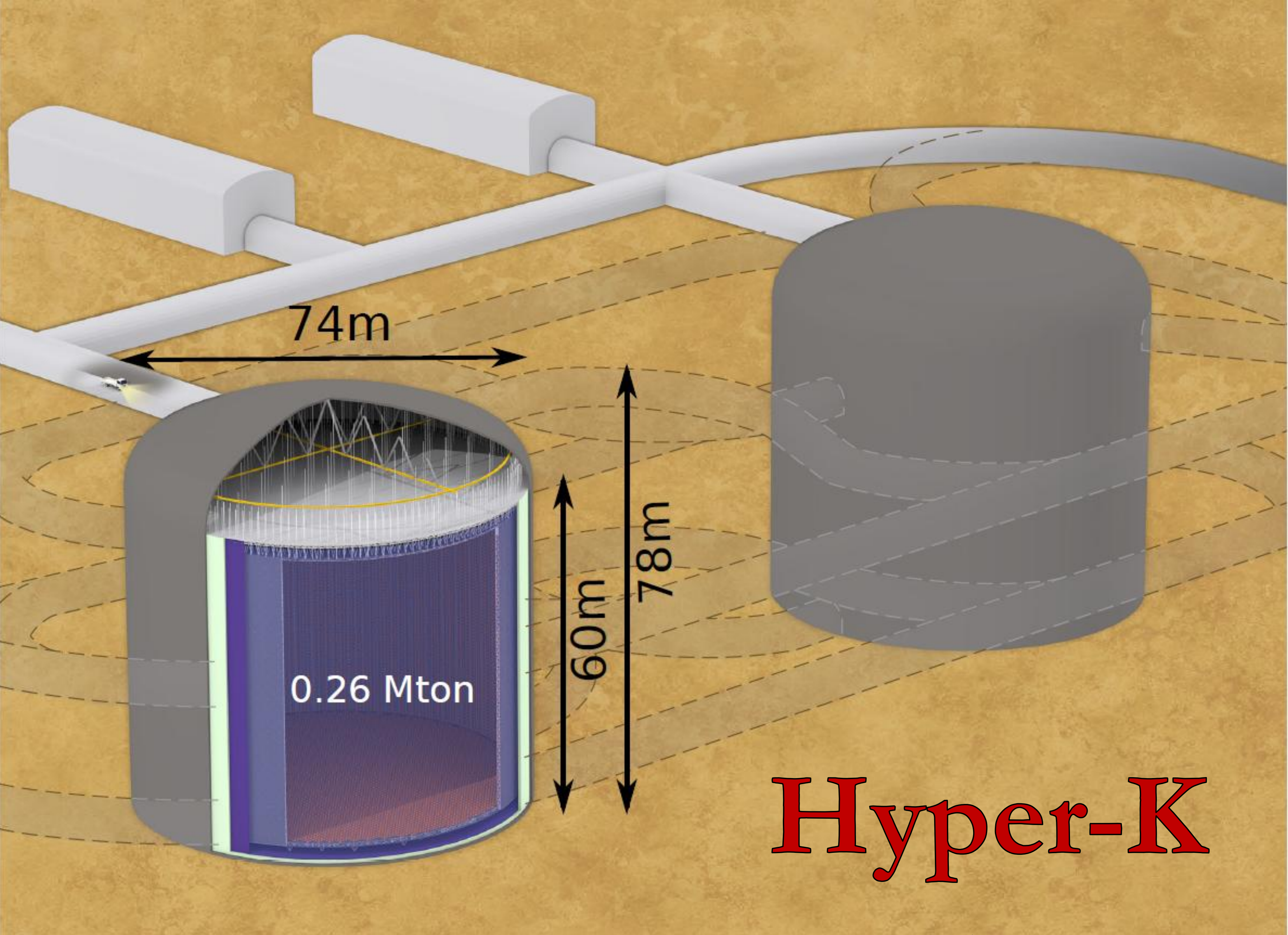


40 kton + 2 MW beam to follow in subsequent years

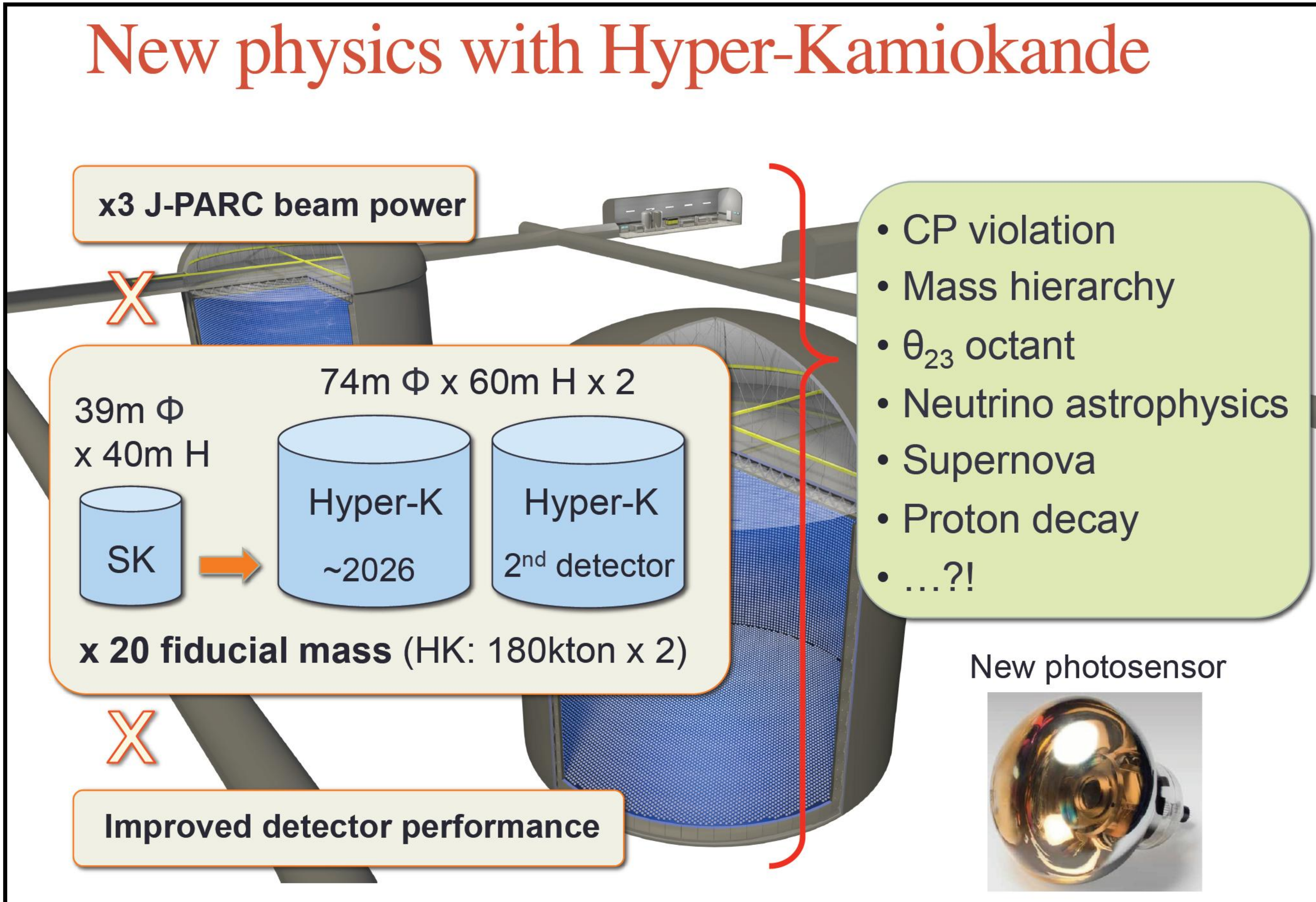
ProtoDUNE cold box at CERN

Hoist/motion tests at Ash River

Pause for questions/discussion


74m
78m
60m
0.26 Mton
Hyper-K

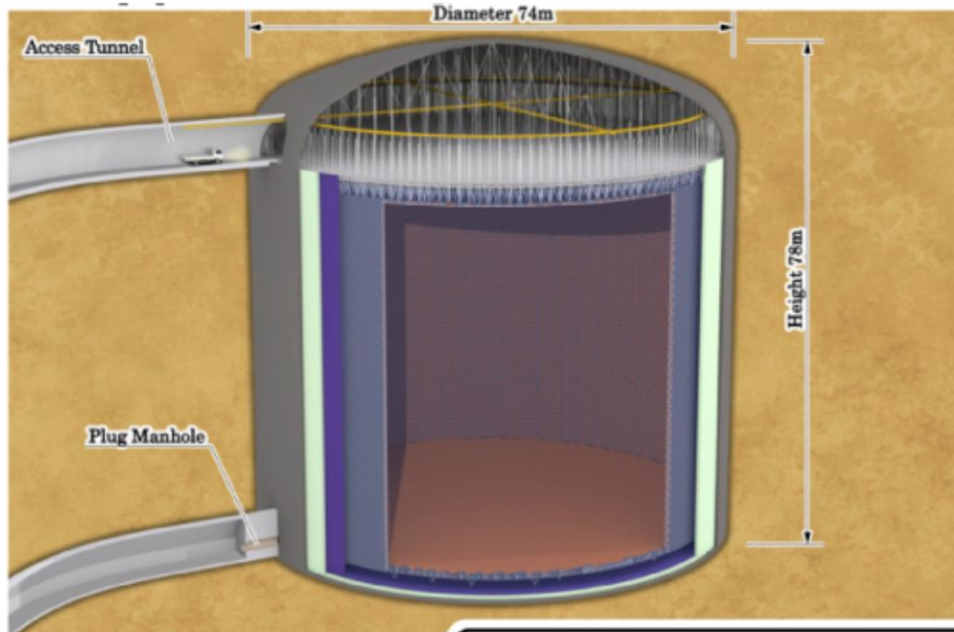
Many graphics (including this one) taken from M. Ishitsuka, HQL 2016

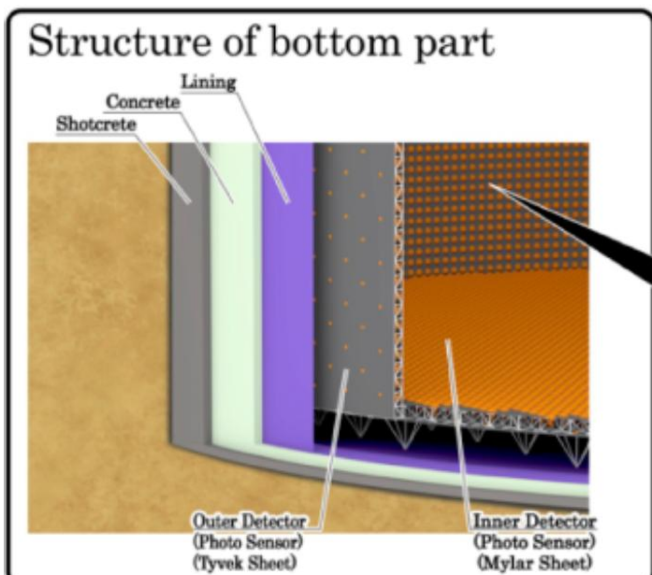


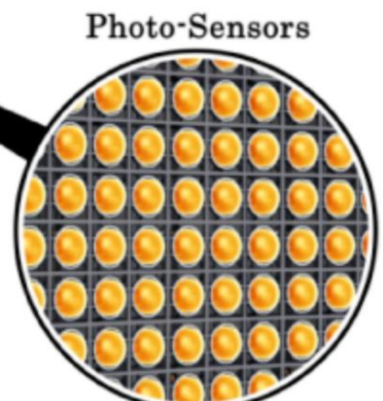
Hyper-Kamiokande Detector Design

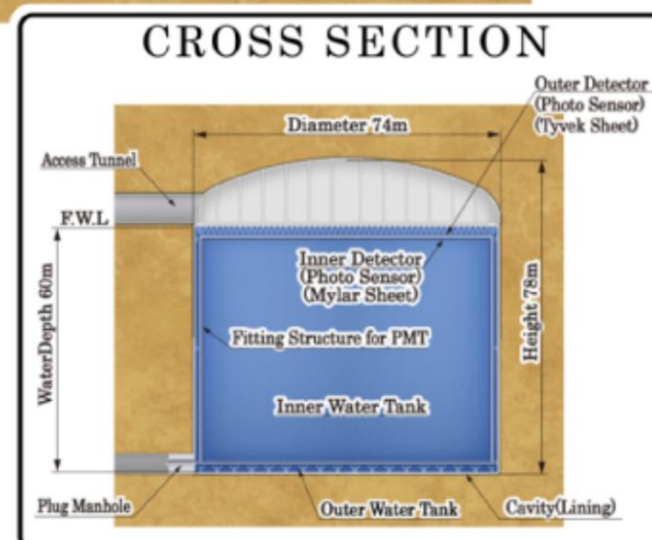
Two high performance water Cherenkov detectors

- 74m Φ × 60m H
  ⇒ 180kton fiducial mass
- 40,000 × 20-inch new PMTs (next slide)
  ⇒ 40% photocoverage









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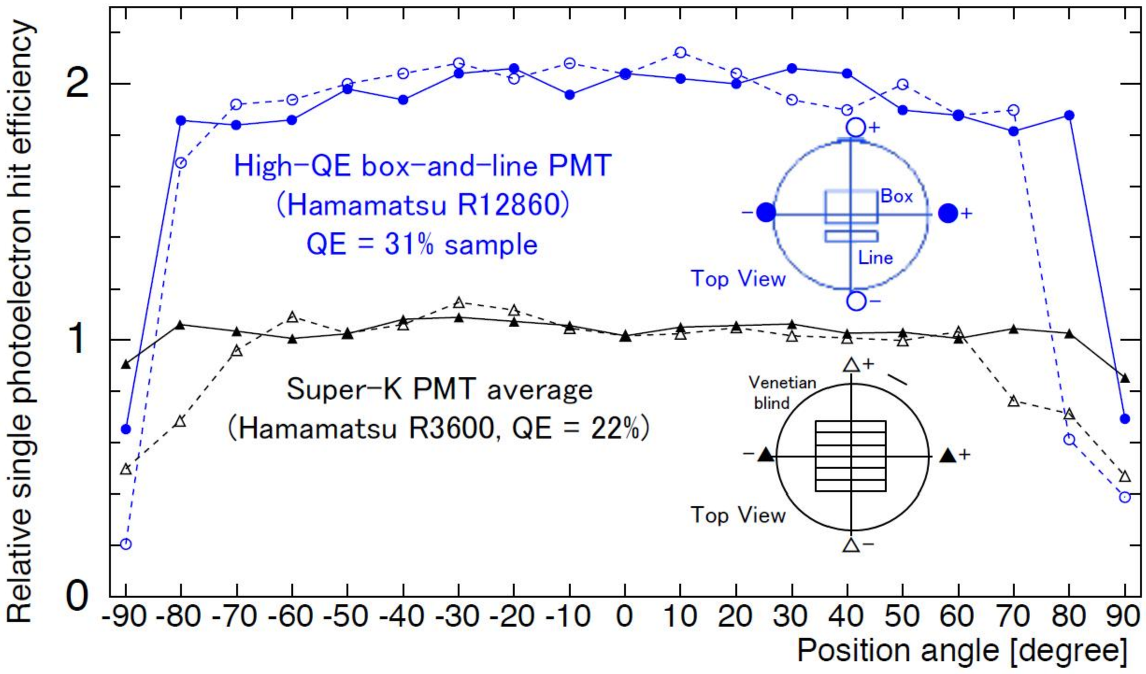
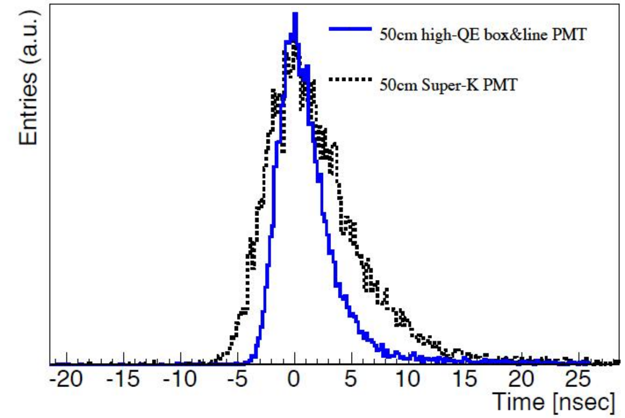
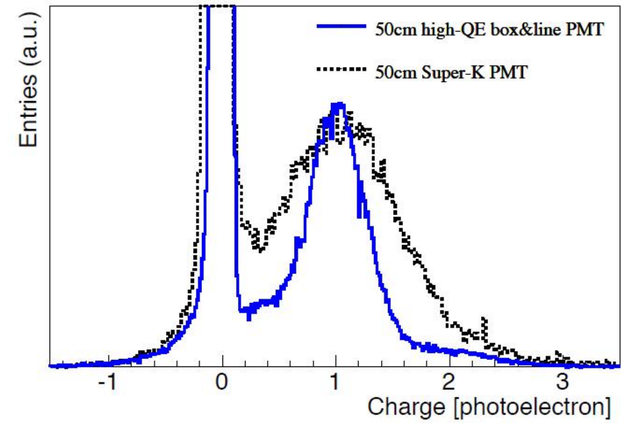
New Photosensor

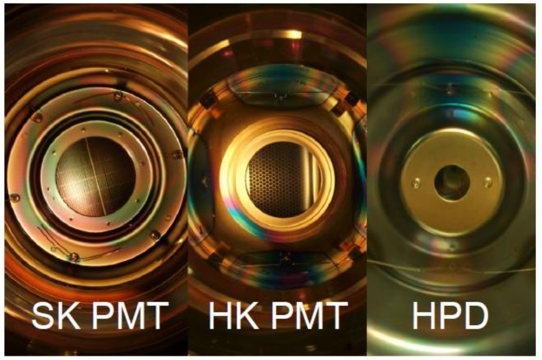






Hyper-K PMT developed with Hamamatsu

- Box & Line dynode structure (SK: Venetian Blind)
- **×2 photodetection efficiency**
- **×2 better timing response**
- **×2 water pressure resistance (>100m equivalent)**



⇒ Significant impact to detector design and physics performance

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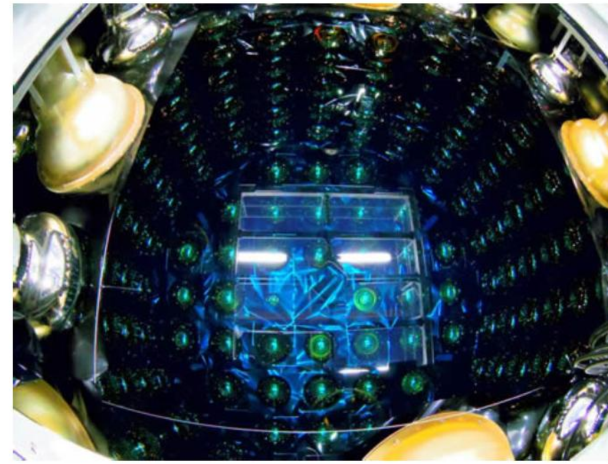
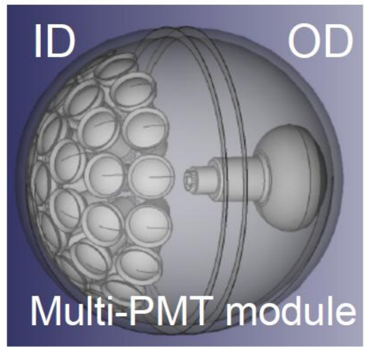
Worldwide R&D

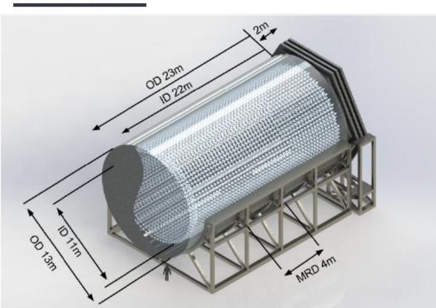
- Alternative options for photo-sensors
  - 50cm High-QE Hybrid Photodetector (HPD)
  - Multi-PMT module
  - Texas 11” PMT for OV

200ton water Cherenkov test detector at Kamioka (EGADS)





TITUS

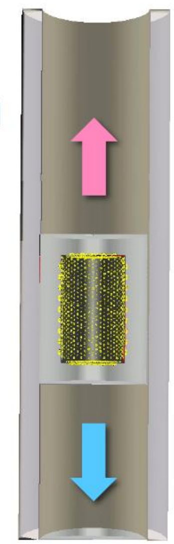


WČ + magnetized μ range detector

- Near Detectors
  - Upgrade plans for 280m detectors
  - Water Cherenkov detectors at 1-2 km proposed
    - Neutrino flux close to Hyper-K
      ⇒ suppression of systematic uncertainties

NuPRISM

Measures spectrum at 1°~ 4° off-axis



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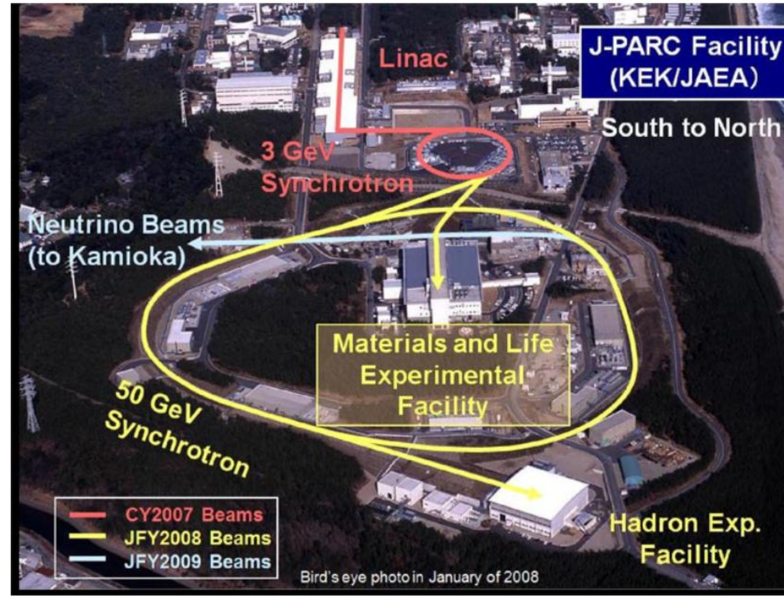
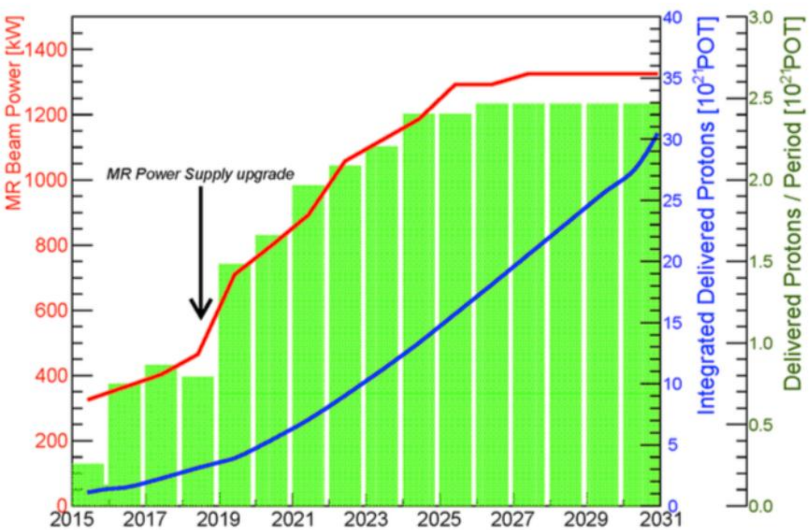
Upgrade of J-PARC neutrino beam

- J-PARC neutrino beam for T2K
  - 30GeV proton synchrotron
  - 410kW with 2.5sec cycle (as of May 2016)
  - 295km baseline to Super-K
  - 2.5° off-axis ν_μ and $\overline{\nu}_\mu$ beam peaked at 0.6GeV to search for CP violation





- J-PARC upgrade plan
  - Upgrade of Main Ring approved
    - ×2 rate with new power supply system
    - T2K: ~900kW ⇒ ~1.3MW by 2026

×3 beam power for Hyper-K

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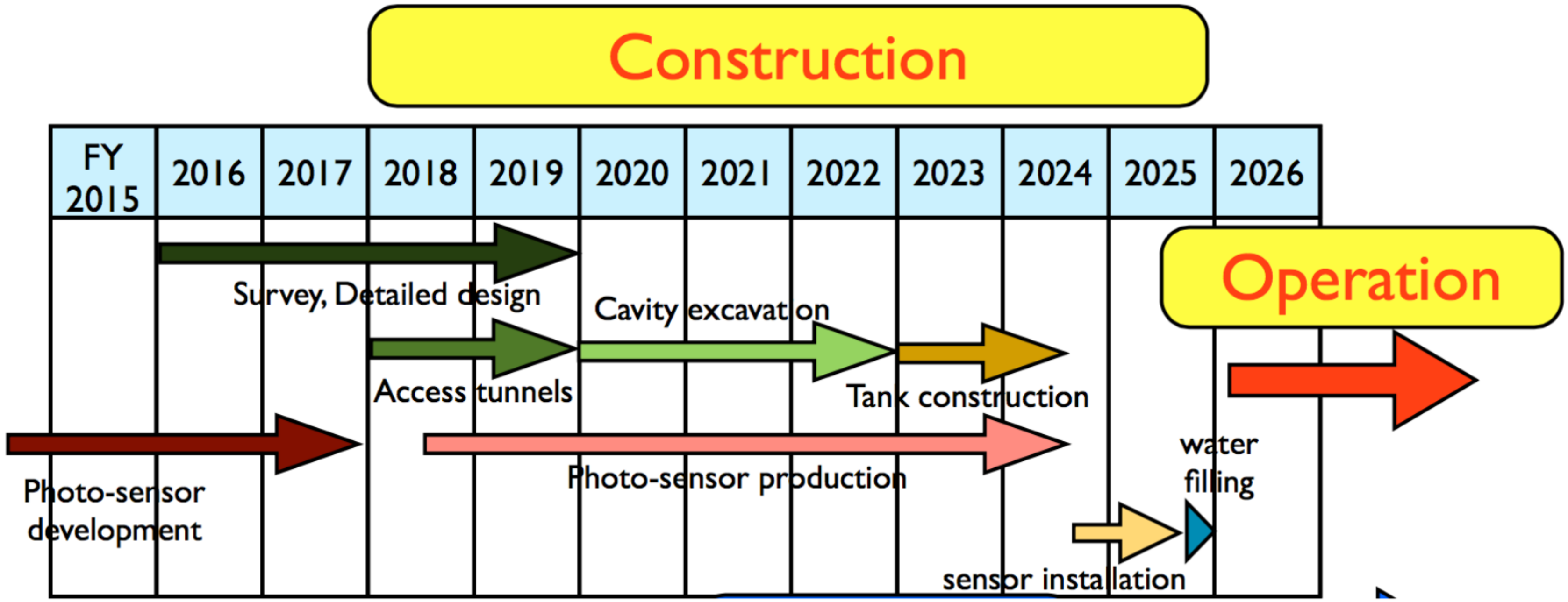
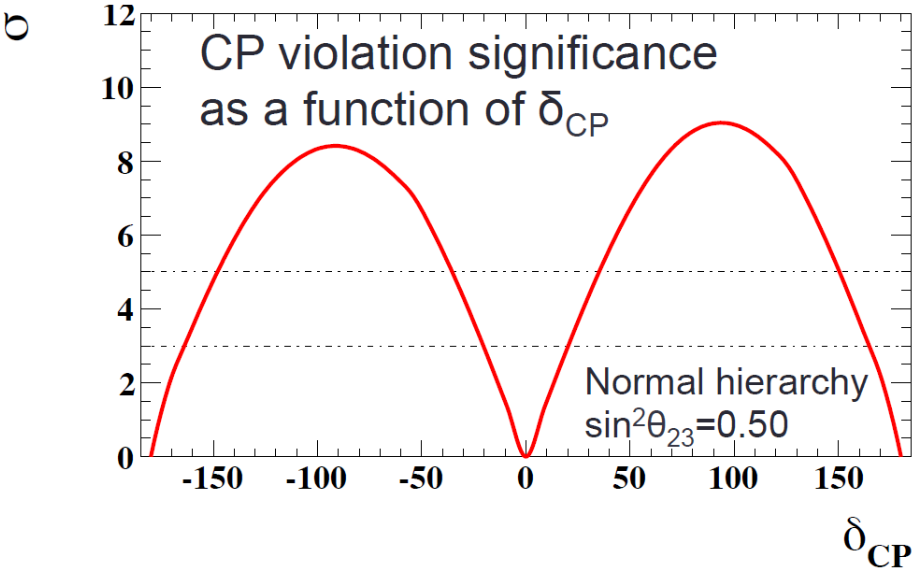
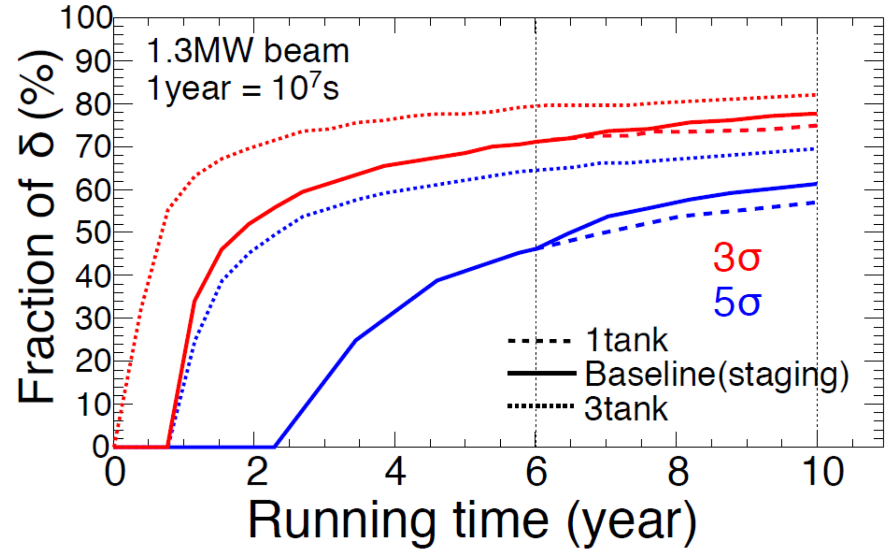
Hyper-Kamiokande proposed timeline

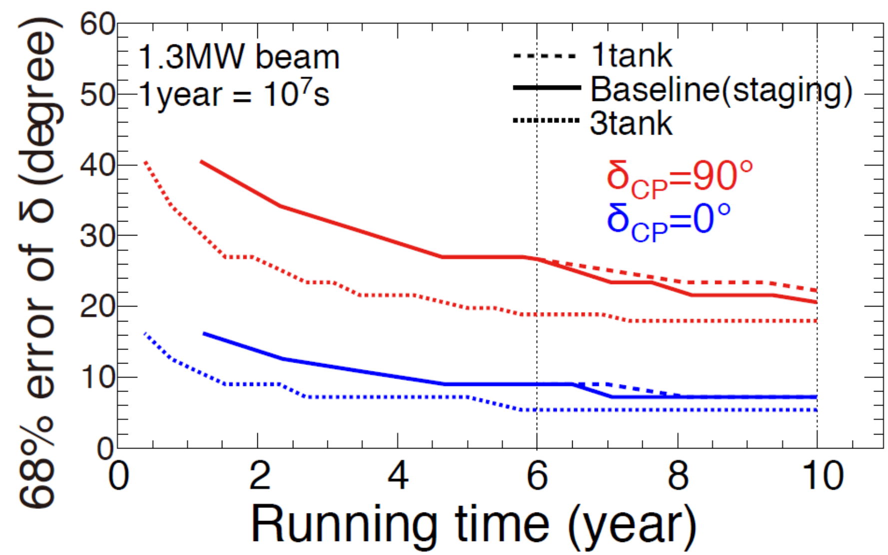


- Target to start operation with 1st detector from 2026
- Sensitivity evaluated assuming staged construction strategy with the same 2nd detector starts 6 years later

Projected sensitivity to δ_{CP}







With 1.3MW×10×10^{7}s (10yr)

- CP violation observation
  - > 3σ for 78% of δ_{CP}
  - > 5σ for 62% of δ_{CP}
- Measurement of δ_{CP}
  - 21° for $\delta_{CP} = 90°$
  - 7° for $\delta_{CP} = 0°$

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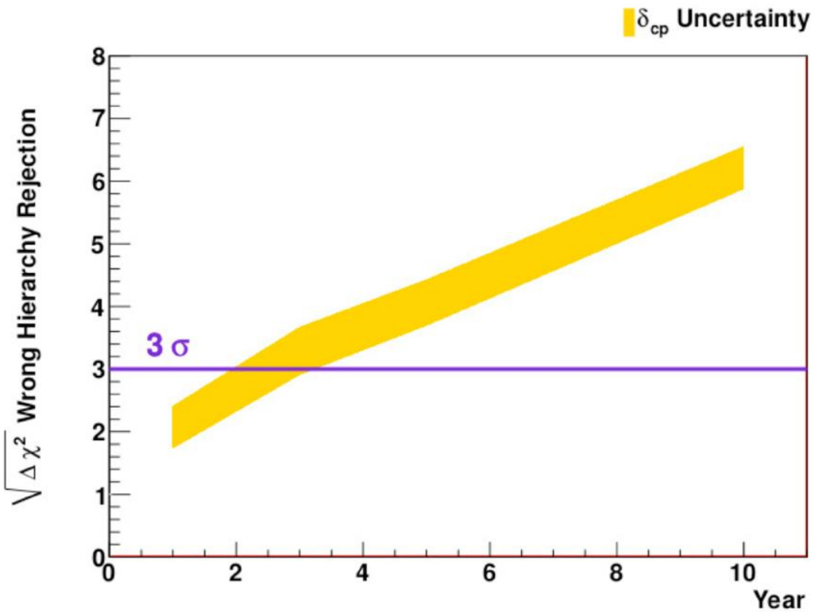
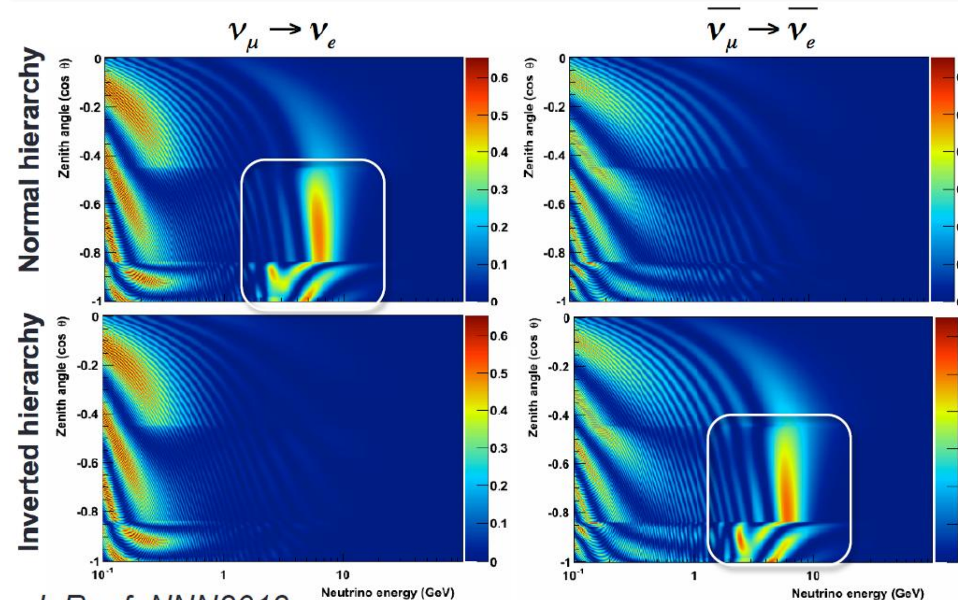
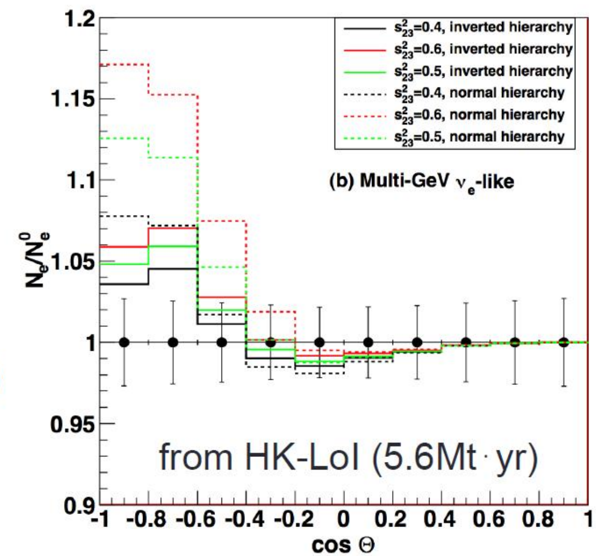
Atmospheric neutrino



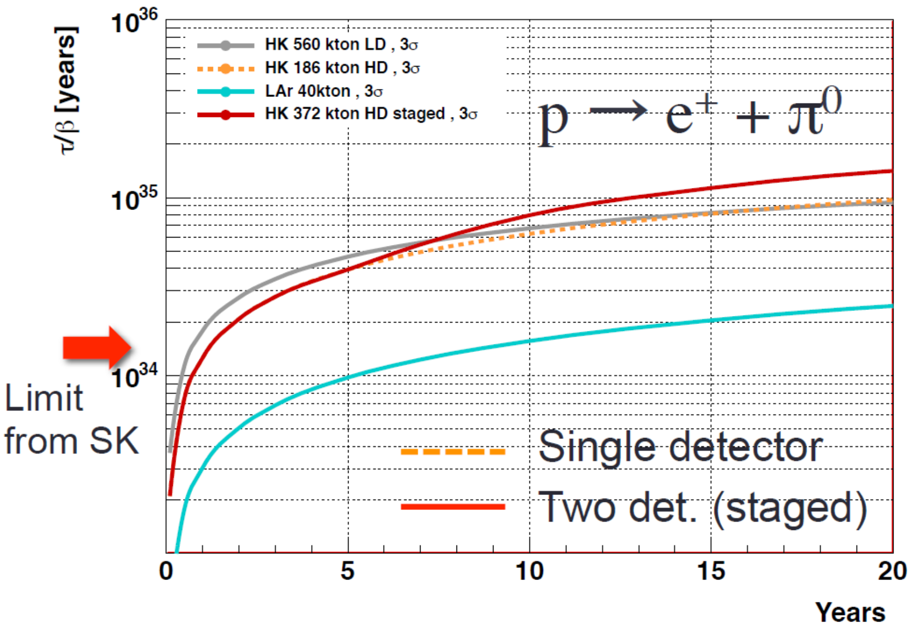


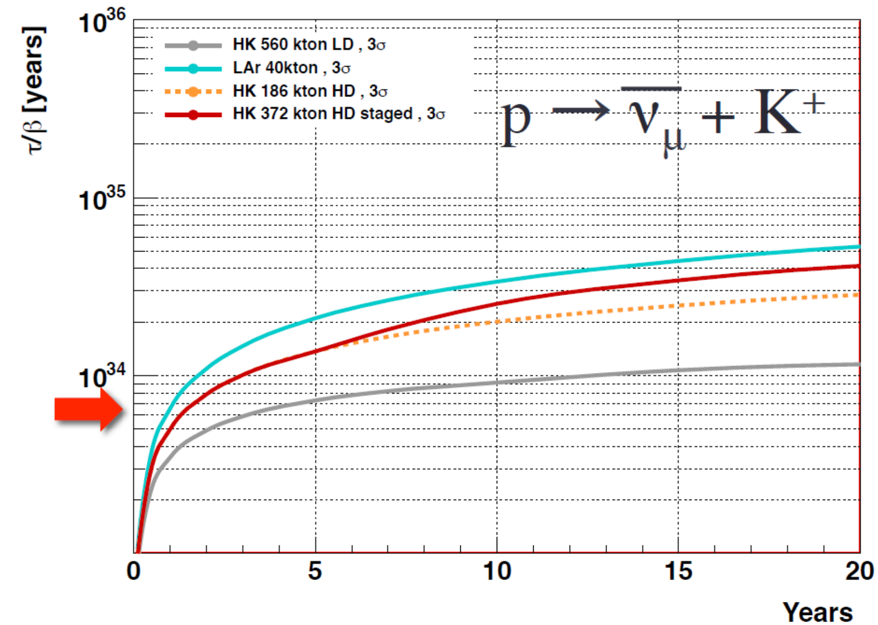
J. Raaf, NNN2013



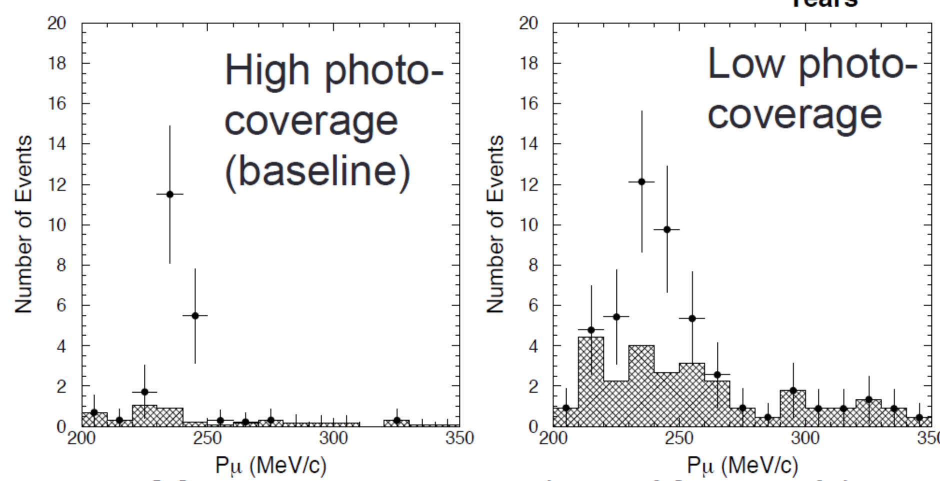
- Matter effects enhance $P(\nu_\mu \rightarrow \nu_e)$ at 2-10GeV
  - Normal hierarchy ⇒ neutrino
  - Inverted hierarchy ⇒ anti-neutrino
- Resolve mass hierarchy in ~3 years ($\sin^2\theta_{23}$=0.5) by combination of atmospheric + beam ν

Proton decay search: 3σ discovery potential





- Good discovery potential for $\tau_p > 10^{34} \sim 10^{35}$ years (test of SUSY SO(10) etc.)
- Further improvement under study



Muon momentum (p→νK search)

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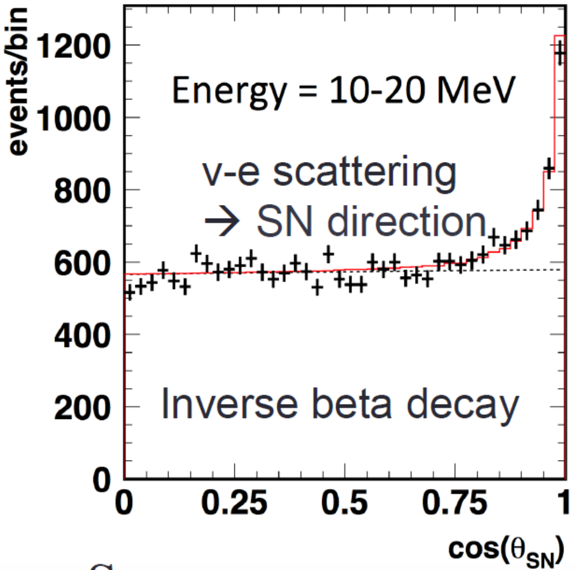
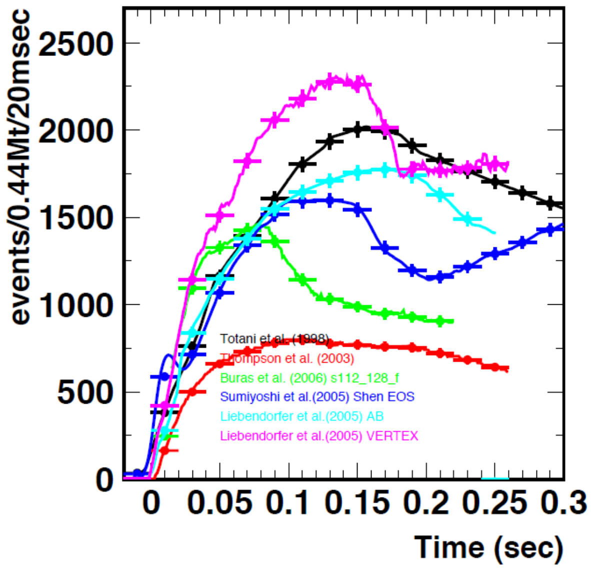
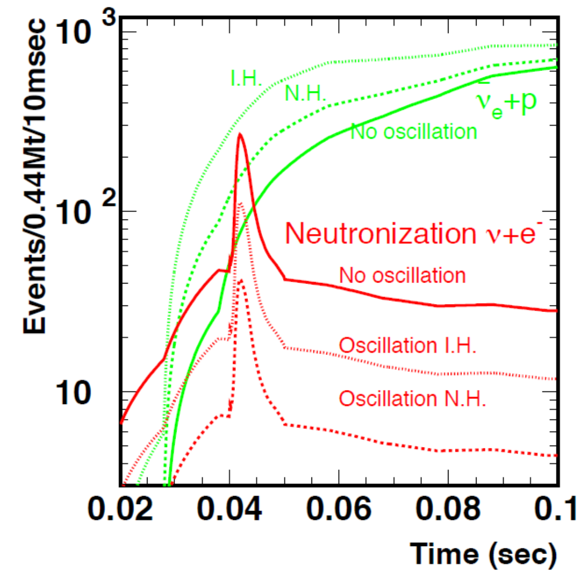
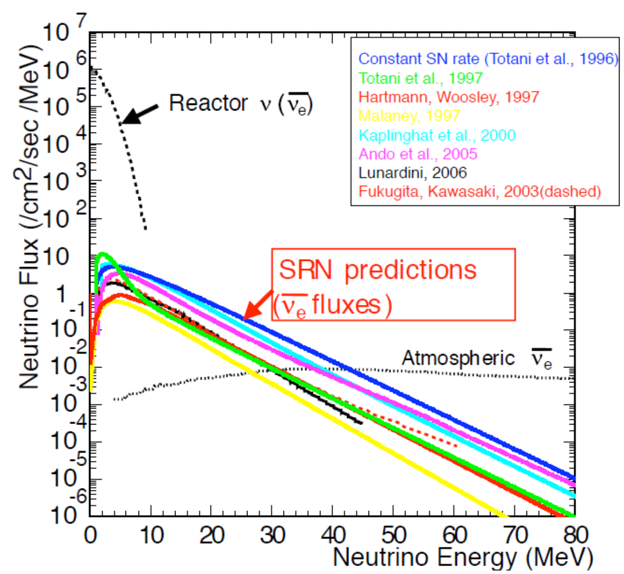
Hyper-Kamiokande neutrino telescope







- Supernova
  - $>10^5$ events expected from SN at 10kpc
    - Probe core collapse and cooling mechanism
  - 100 supernova relic neutrino events in 10yr
- Solar neutrino observation
  - MSW transition (upturn of solar spectrum)
  - Day/night asymmetry (earth matter effects)
  - Solar hep neutrinos



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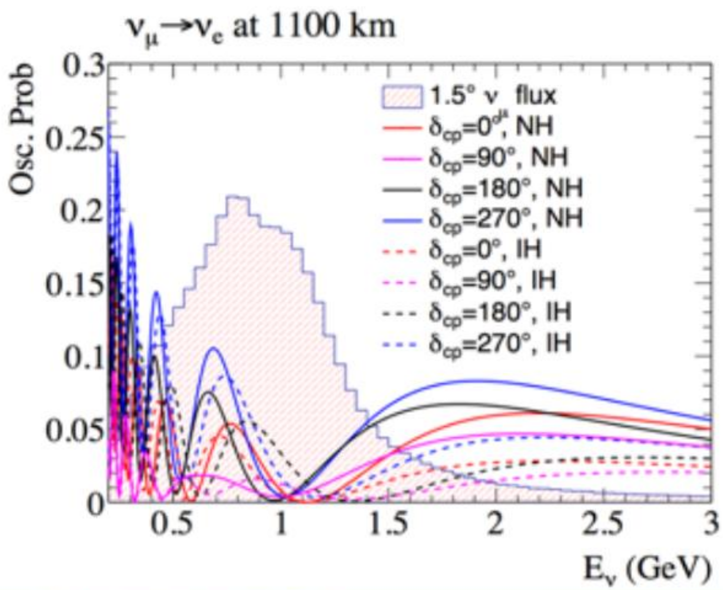
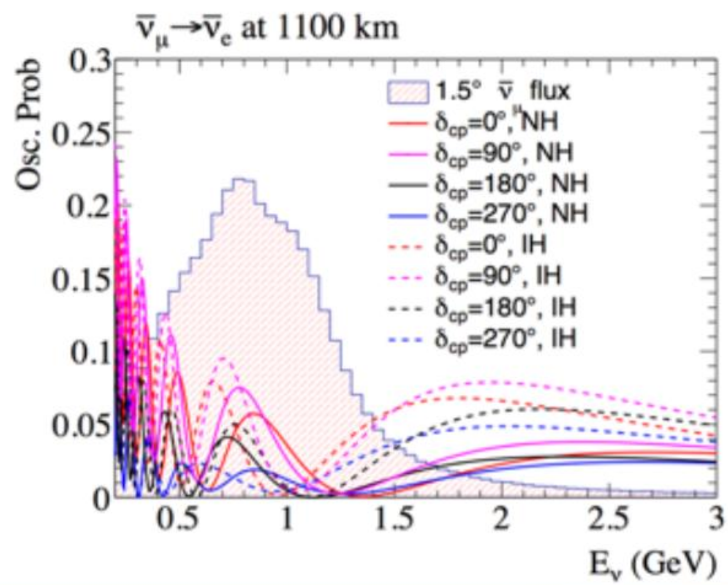
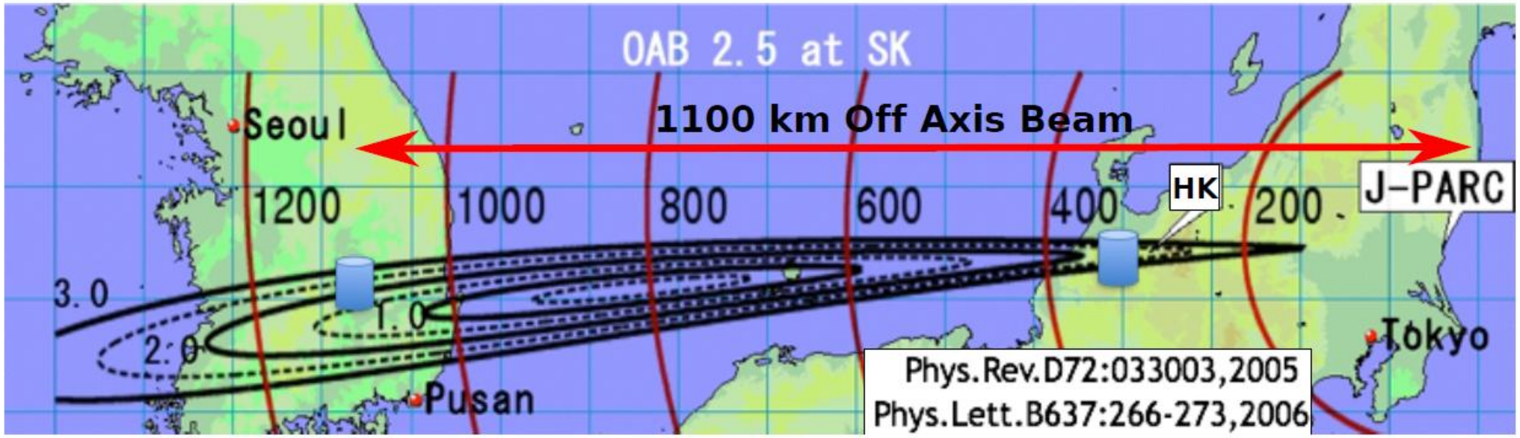
Option under discussion: T2HK → T2HKK

2nd Hyper-K tank in Korea (L=1100 km)







- Would improve *CP*v and mass hierarchy reach

T2HK and DUNE:

Two highly capable and complementary experiments

Note: The experiments use a **mix of assumptions** for oscillation parameters, systematic uncertainties, and other relevant quantities. Comparisons here should assume **10%-ish uncertainties on stated sensitivities** to absorb such effects.

(10 yrs, staged deployment)		**T2HK**	**DUNE**
CP violation	δ resolution	7° – 21°	7° – 15°
	3σ coverage	78%	74%
	5σ coverage	62%	54%
νMH	sens. range	$5\sigma - 7\sigma$	$8\sigma - 20\sigma$+
octant	sens. @ 0.45	5.8σ	5.1σ
	5σ outside of…	[0.46, 0.56]	[0.45, 0.57]
p decay (90% C.L.)	$p \to \bar{\nu} K^+$	>2.8e34 yrs	>3.6e34 yrs
	$p \to e^+ \pi^0$	>1.2e35 yrs	>1.6e34 yrs
supernova ν (10 kpc or relic)	SNB $\bar{\nu}_e$	130k evts	
	SNB ν_e		3k evts
	relic $\bar{\nu}_e$	100 evts, 5σ	
	relic ν_e		30 evts, 6σ

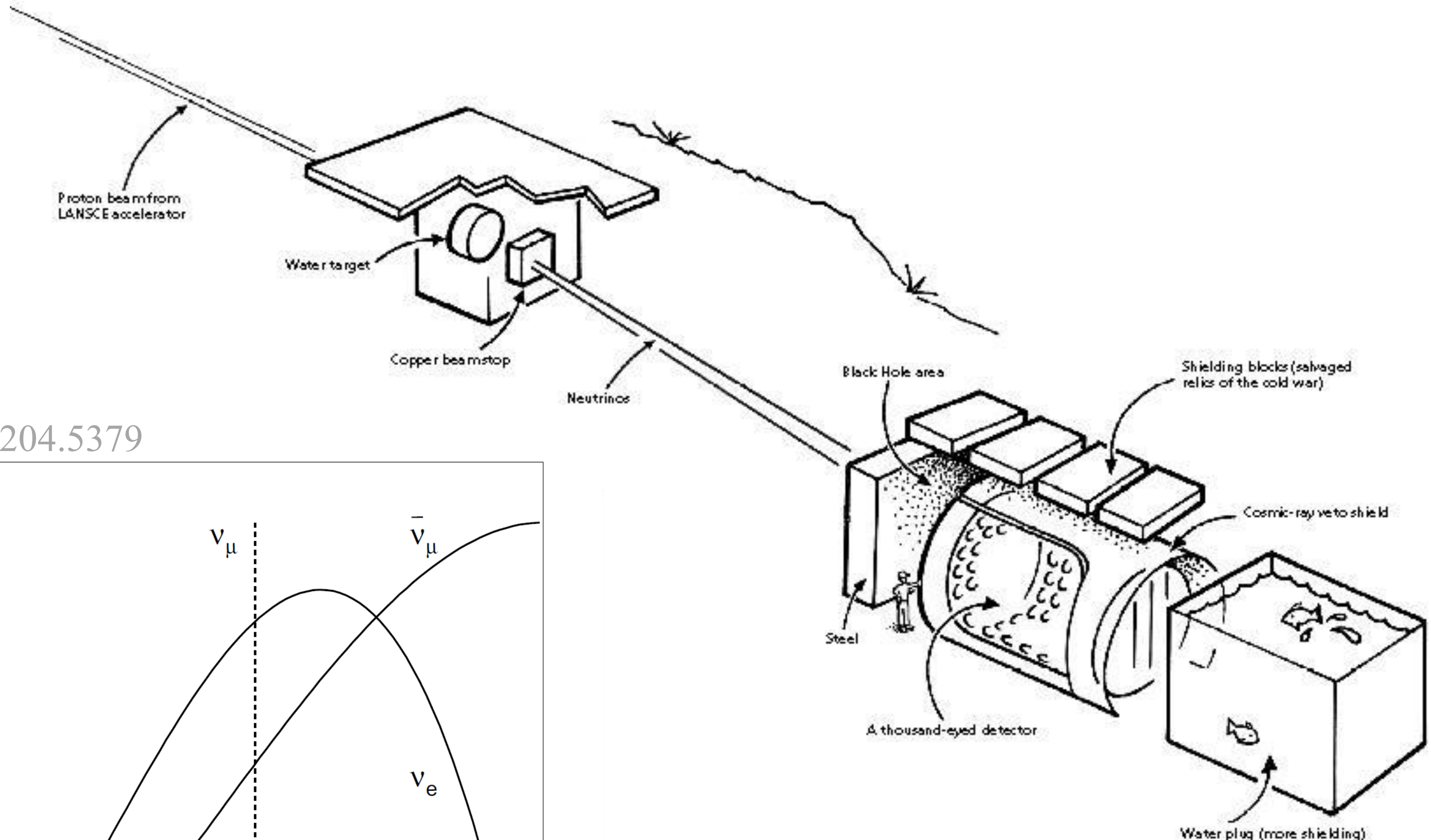
Core 3ν measurements
Sensitivities remarkably similar save for mass hierarchy.

Proton decay, Supernova ν
Complementary channels

Other physics
Different wheelhouses, e.g.:
- DUNE is great for NSI
- Hyper-K is great for solar ν

Pause for questions/discussion

Short-baseline accelerator experiments



arXiv:1204.5379

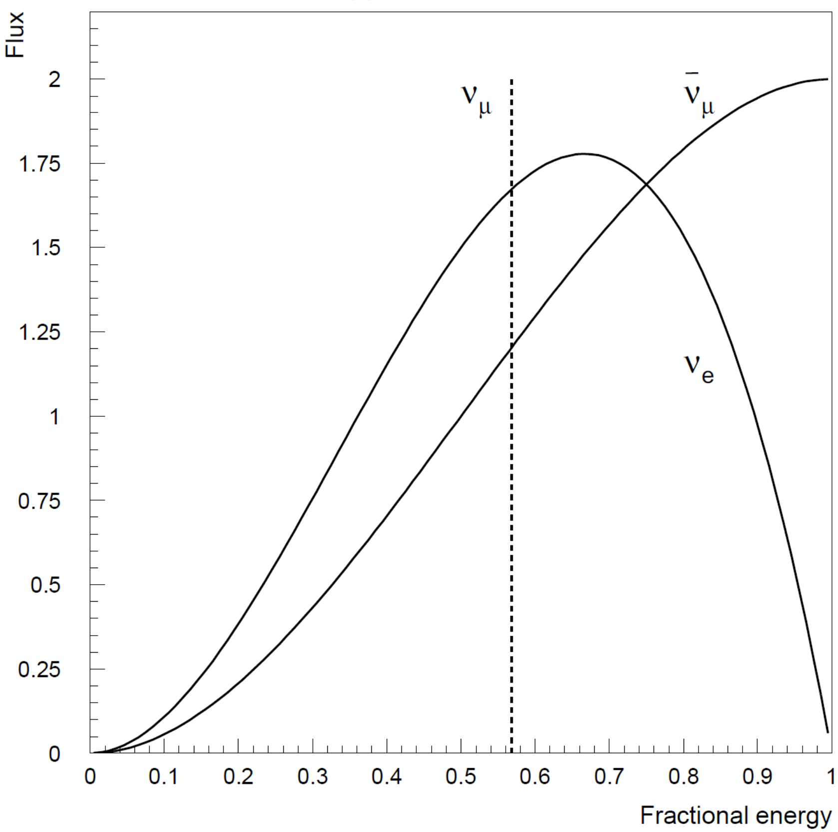
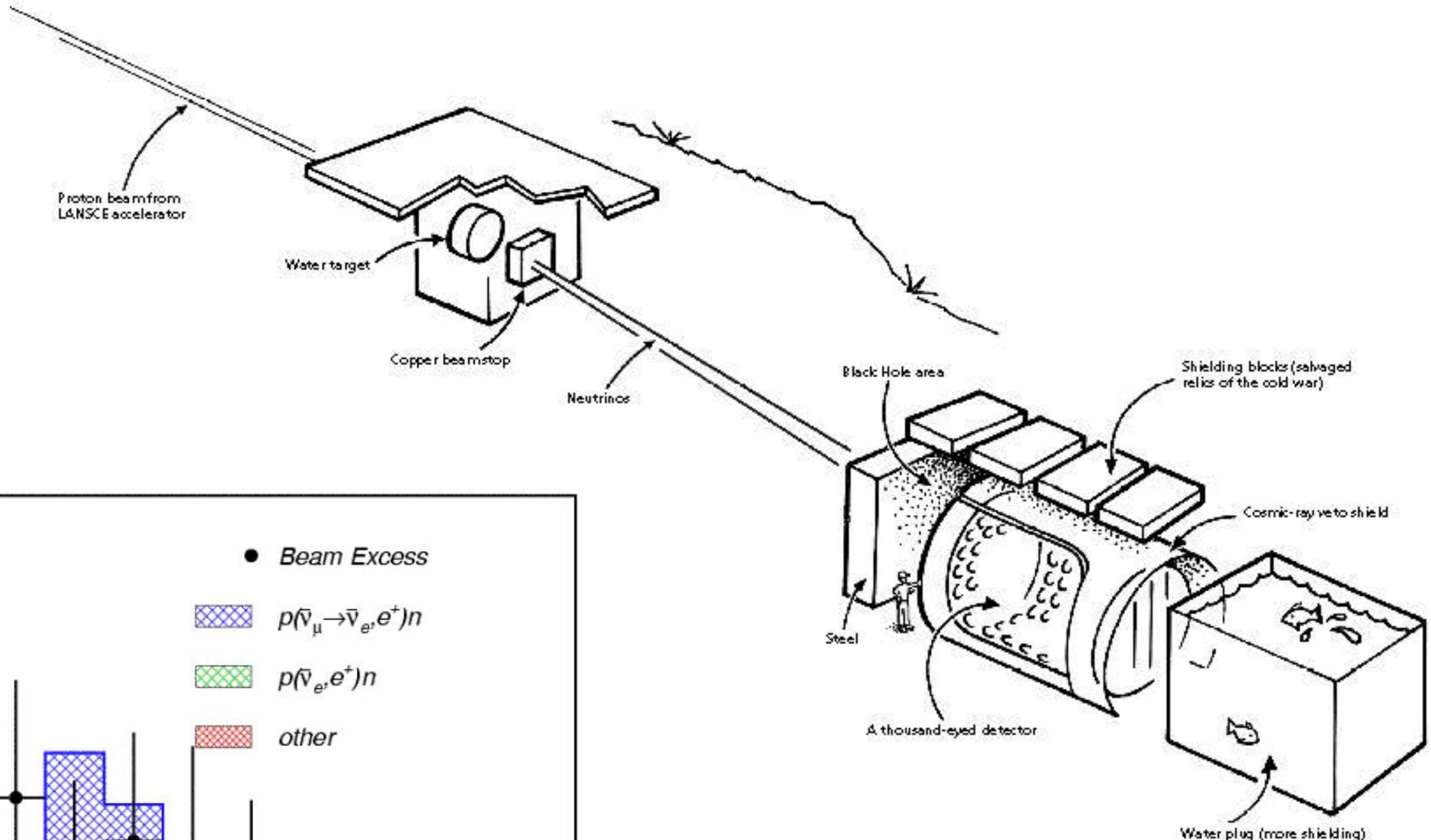


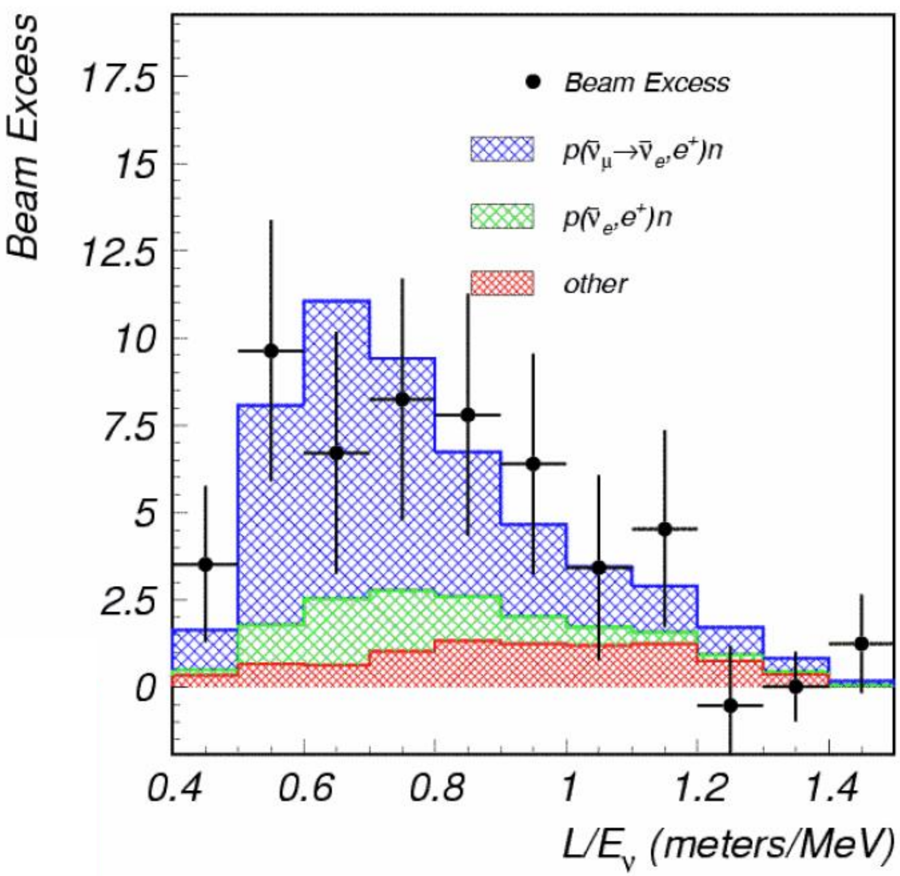
Figure 12. The neutrino energy spectra from π^+ and μ^+ DAR.

LSND: 1993 – 1998

Scintillation/Cherenkov detector exposed to stopped-π neutrino source

Well-characterized flux *(plot at left)*





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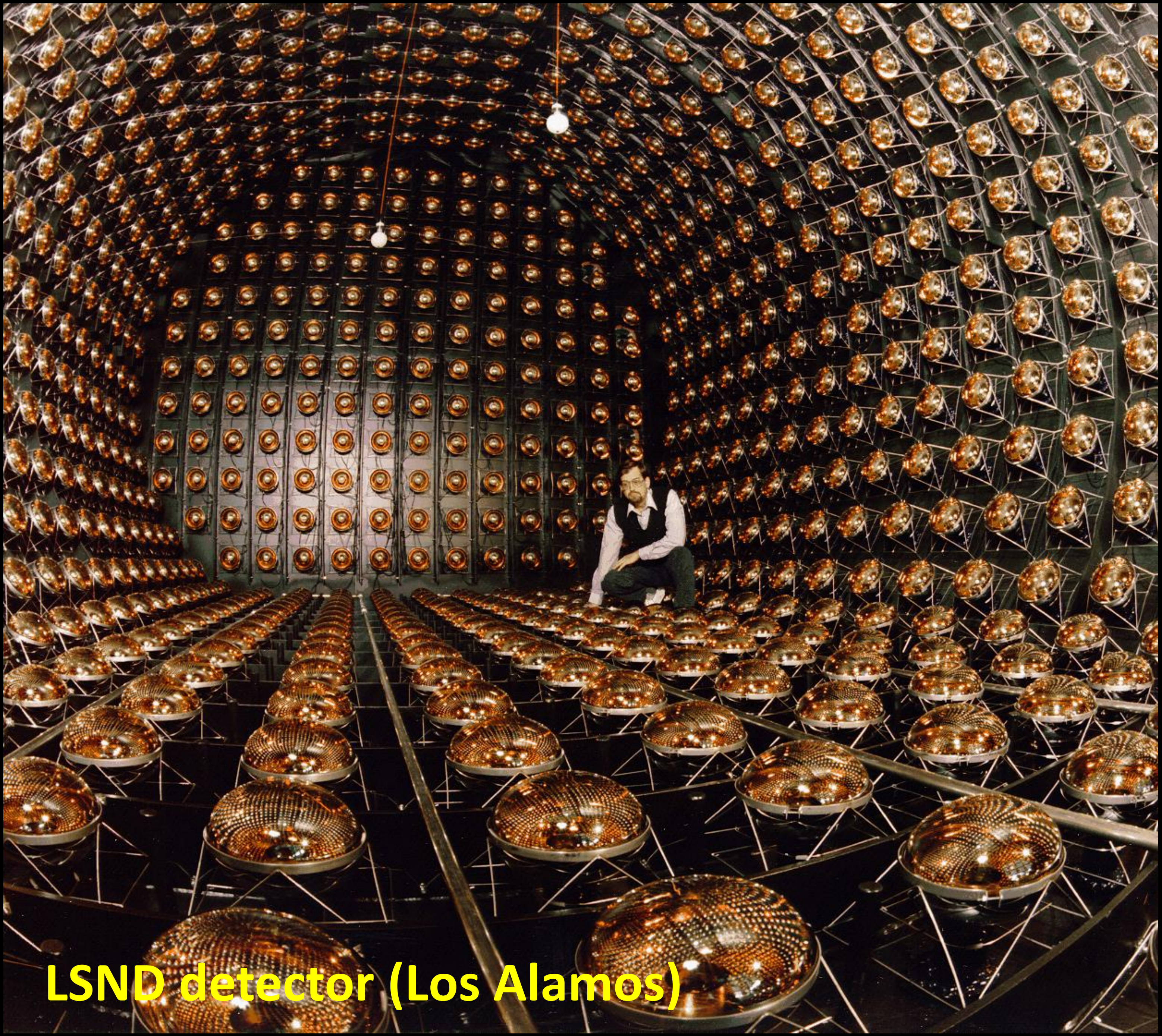
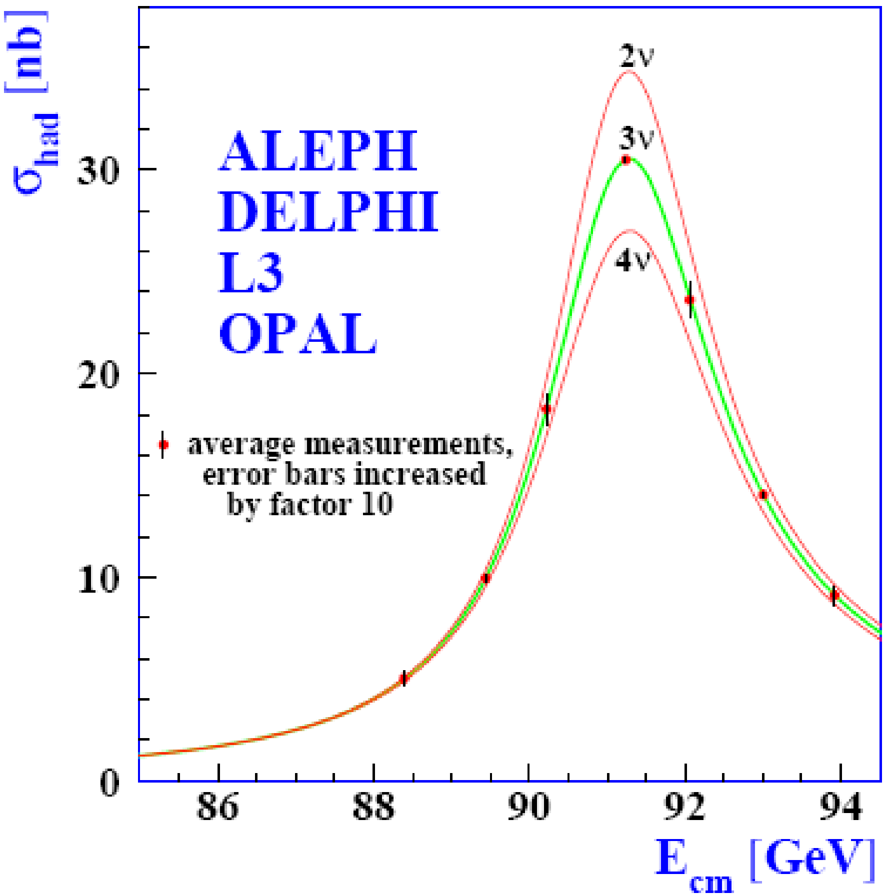
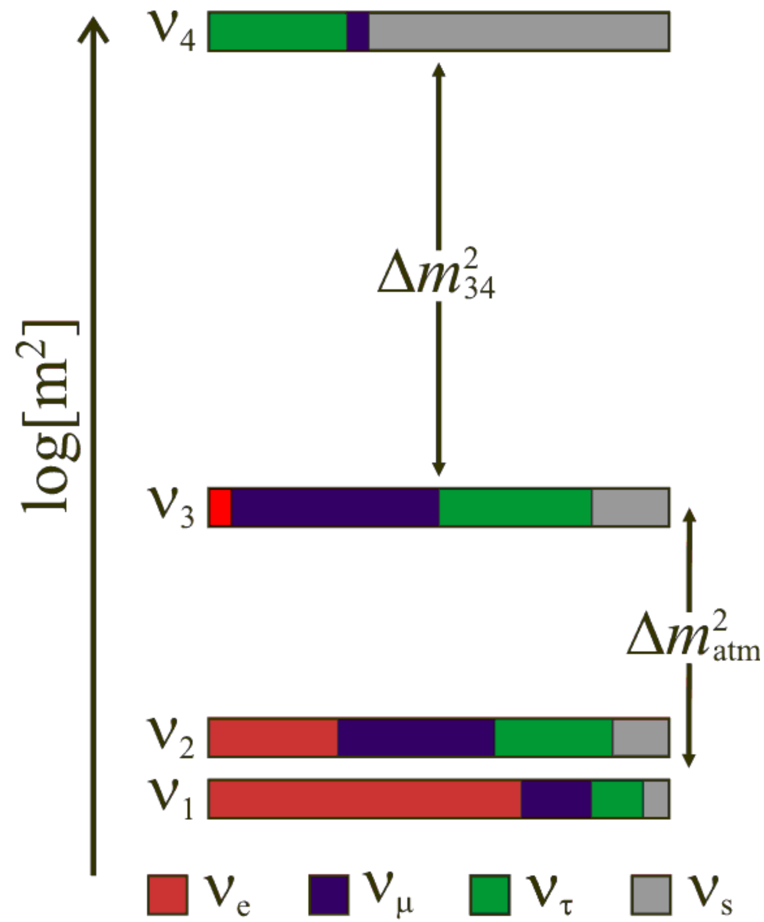
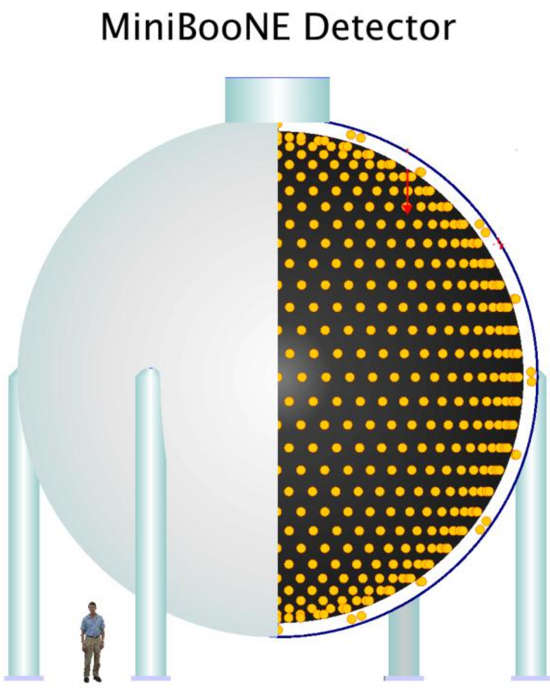

LSND detector (Los Alamos)

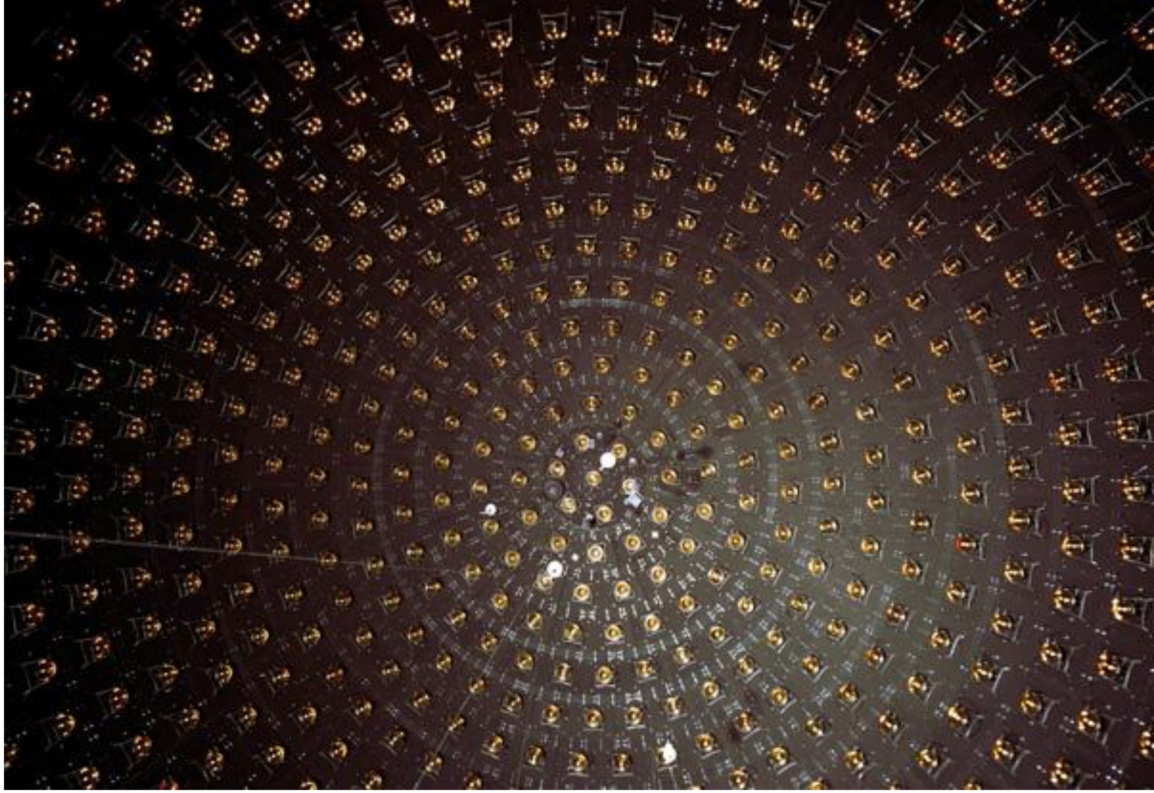
New physics possibility: “sterile” neutrinos

Number of light active neutrinos from LEP data





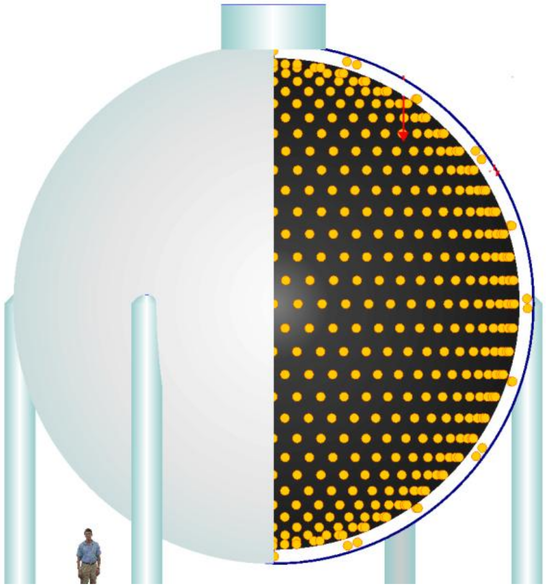


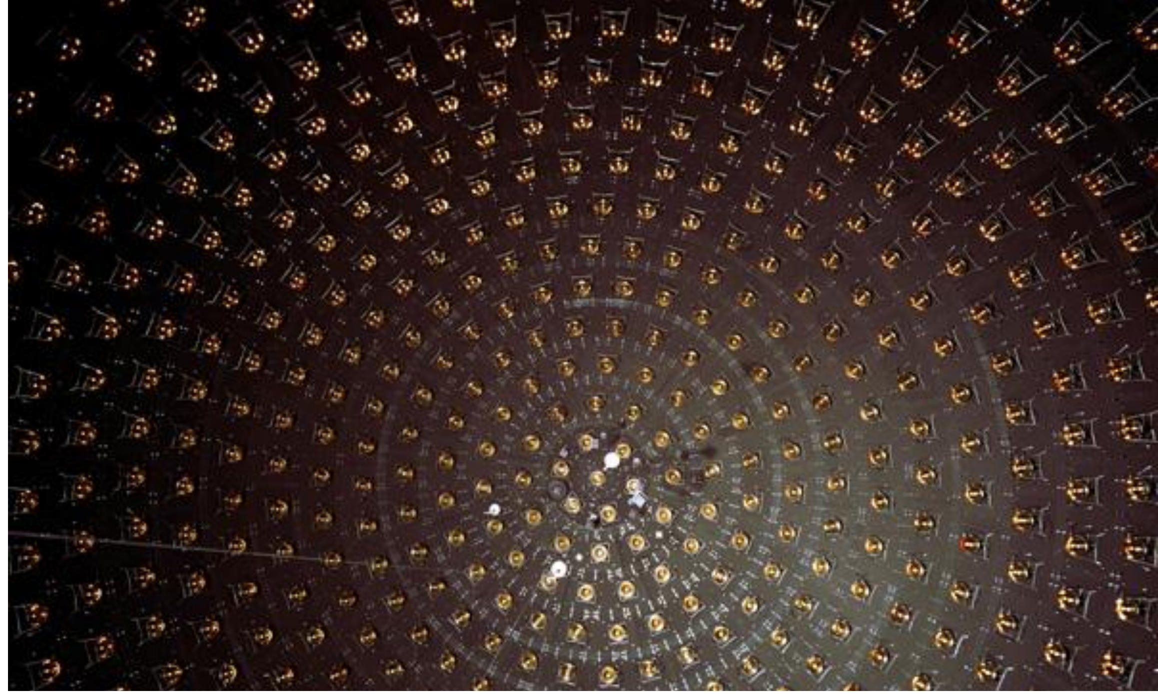


Look near same *L*/*E* as LSND but at 10x higher energy and baseline

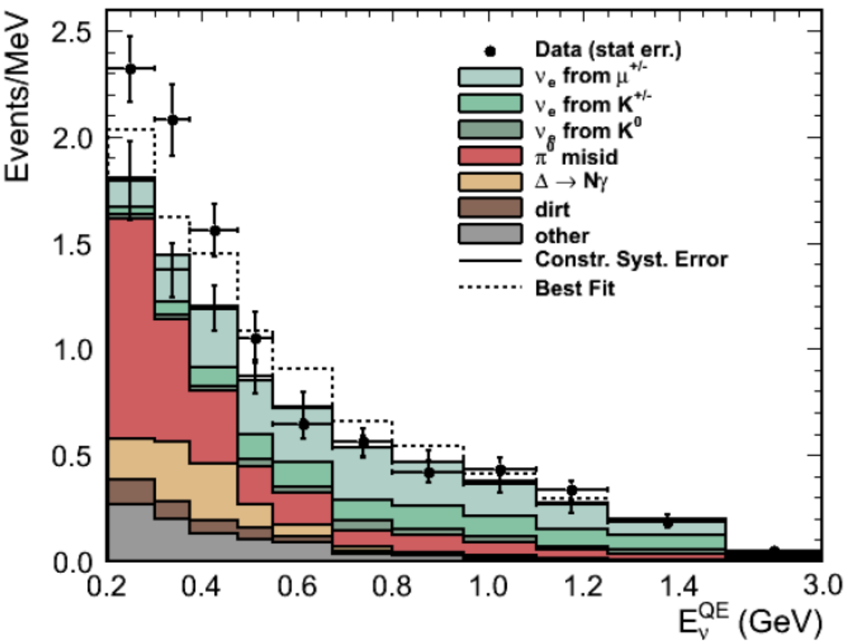
⇒ **Booster Neutrino Beam** built for this

MiniBooNE Detector

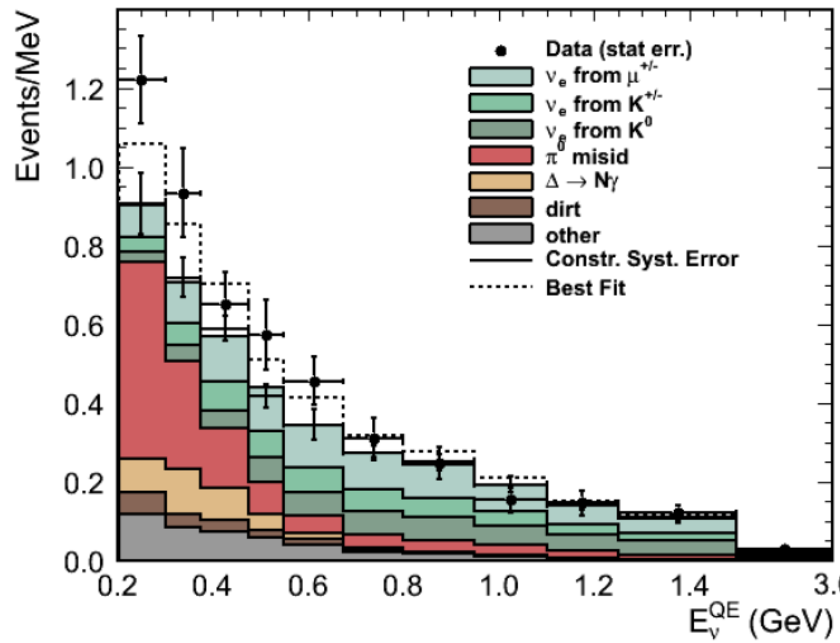




6.5e20 POT neutrino mode w/ 3+1 fit

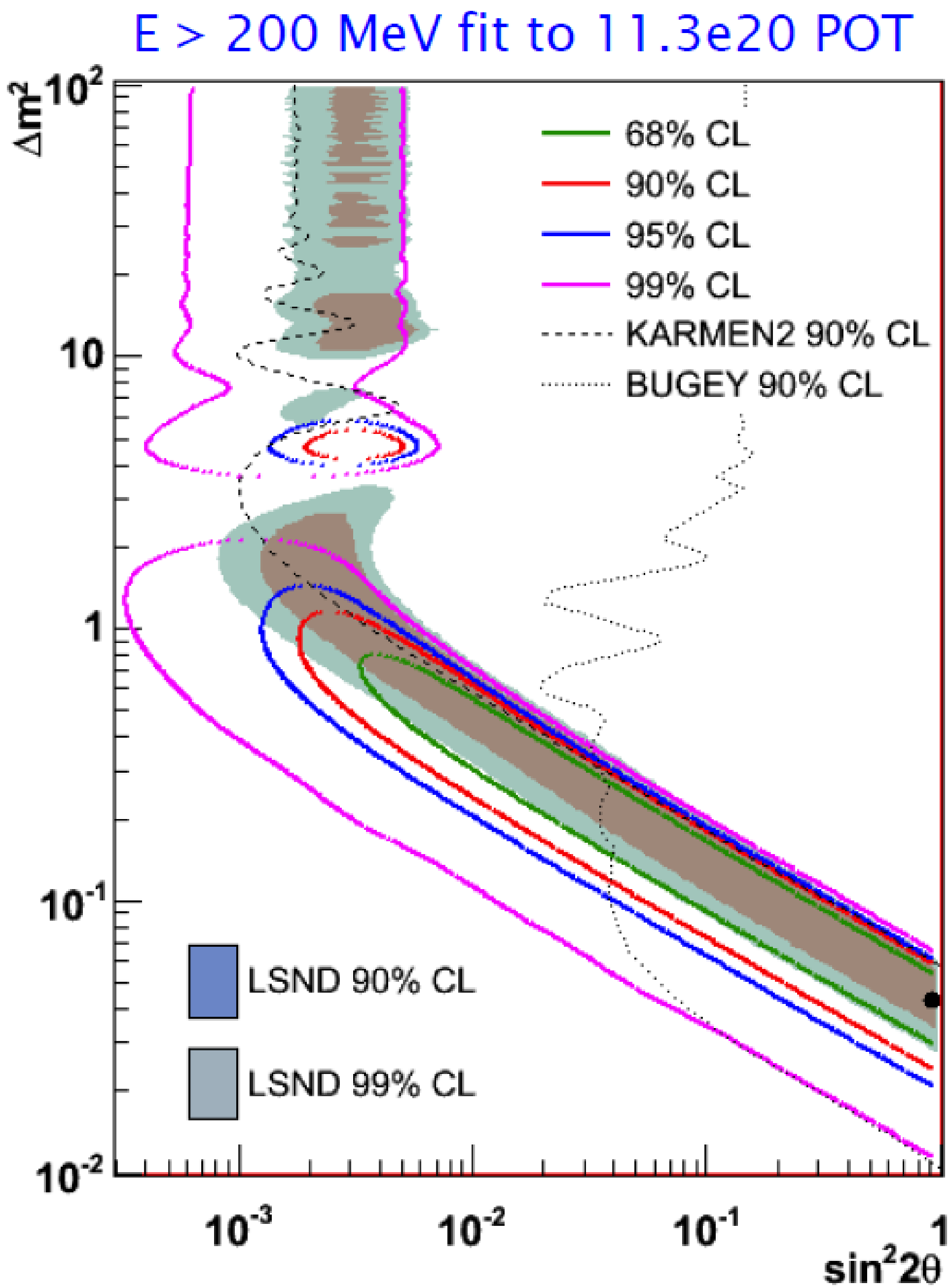


11.3e20 POT anti-neutrino mode w 3+1fit



Several measurements on same figure

(some null, some not)

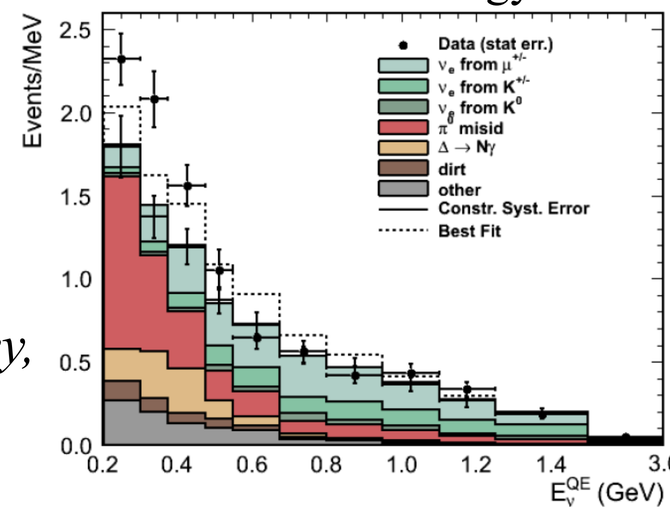


LSND, MiniBooNE, reactor, ^{71}Ga anomalies

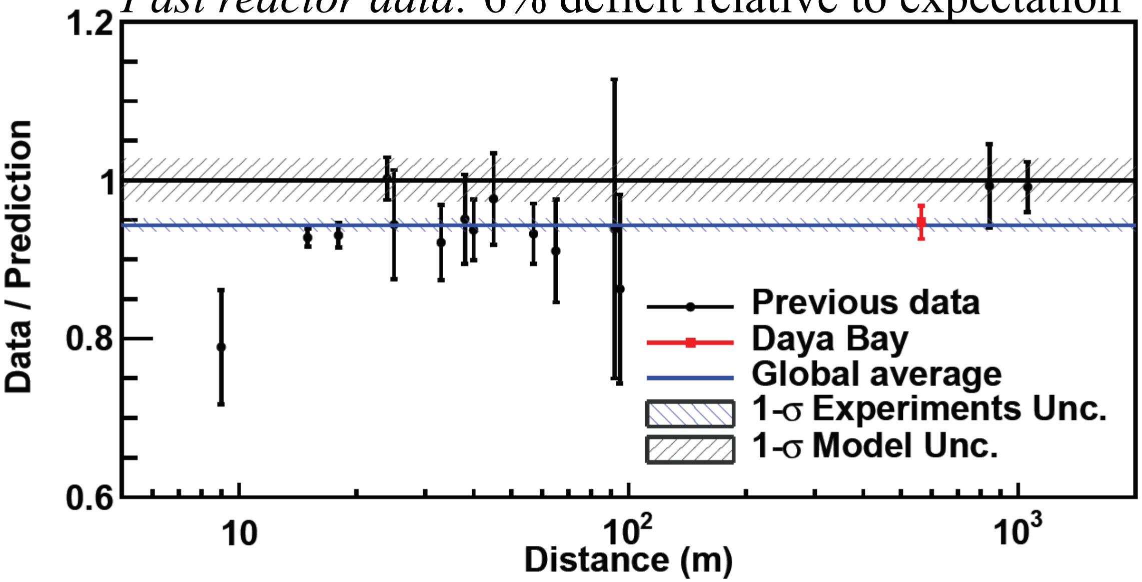
- **What's going on?**
  - **Sterile neutrinos?** *(Need multiple sterile states to accommodate all of today's data.)*
  - **Something else new?**
  - **A series of systematics issues?**

- **Many null results in past decade+** *(KARMEN, Bugey, Super-K, MINOS, ICARUS, IceCube, Planck),* **but situation lingers**

MiniBooNE low-energy excess



Past reactor data: 6% deficit relative to expectation



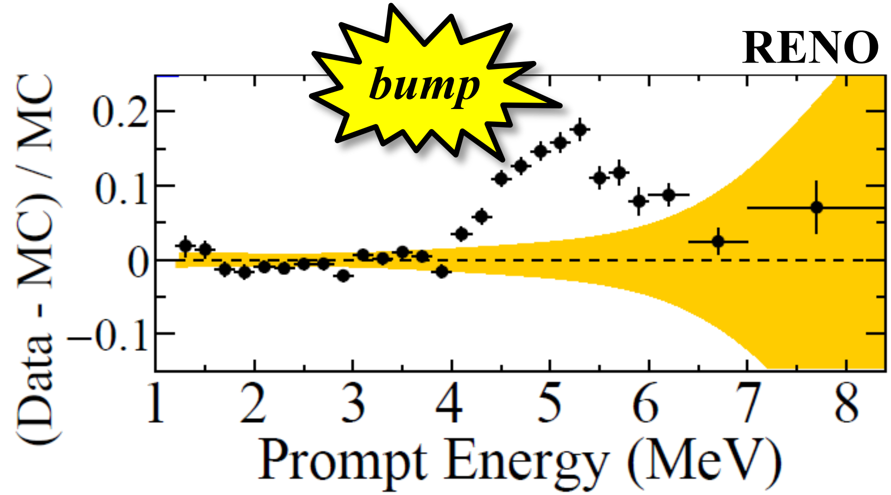
Future experiment(s) need a viable path toward…

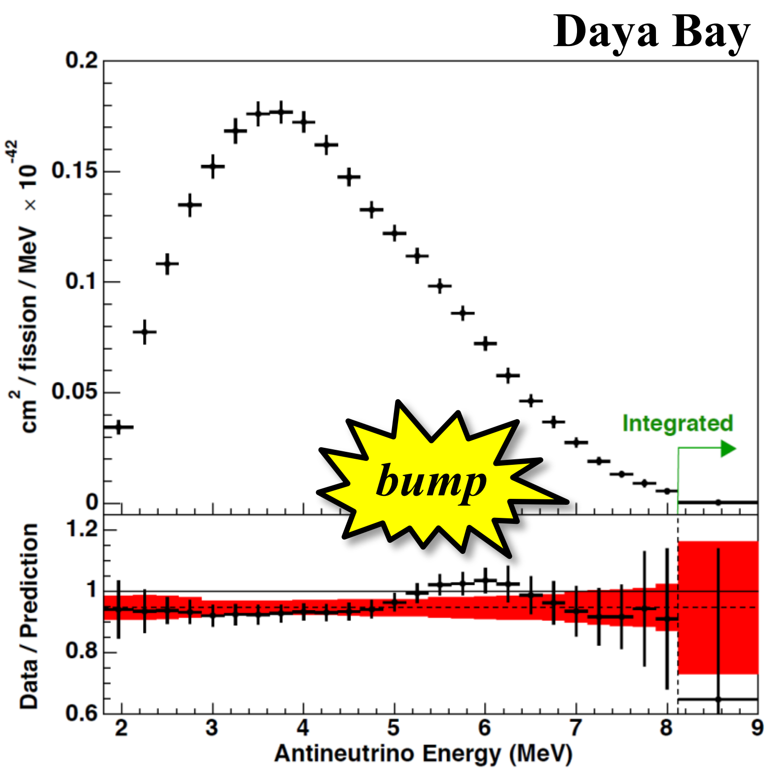
…large exposures
…minimized systematic errors
…in-detector L, E signatures
…unambiguous sensitivity

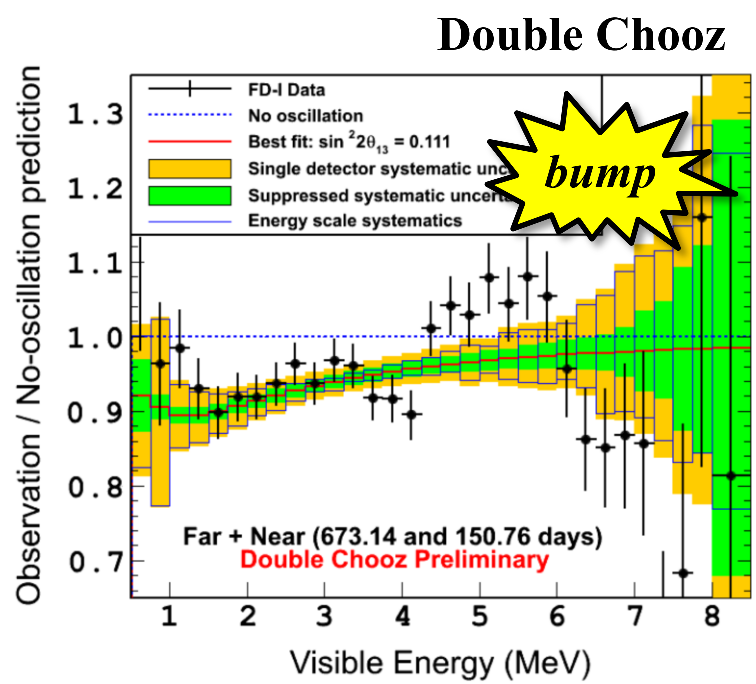
Attempts that stop short of this will only make things murkier.

Reactor flux uncertainties already known to be **underestimated**?

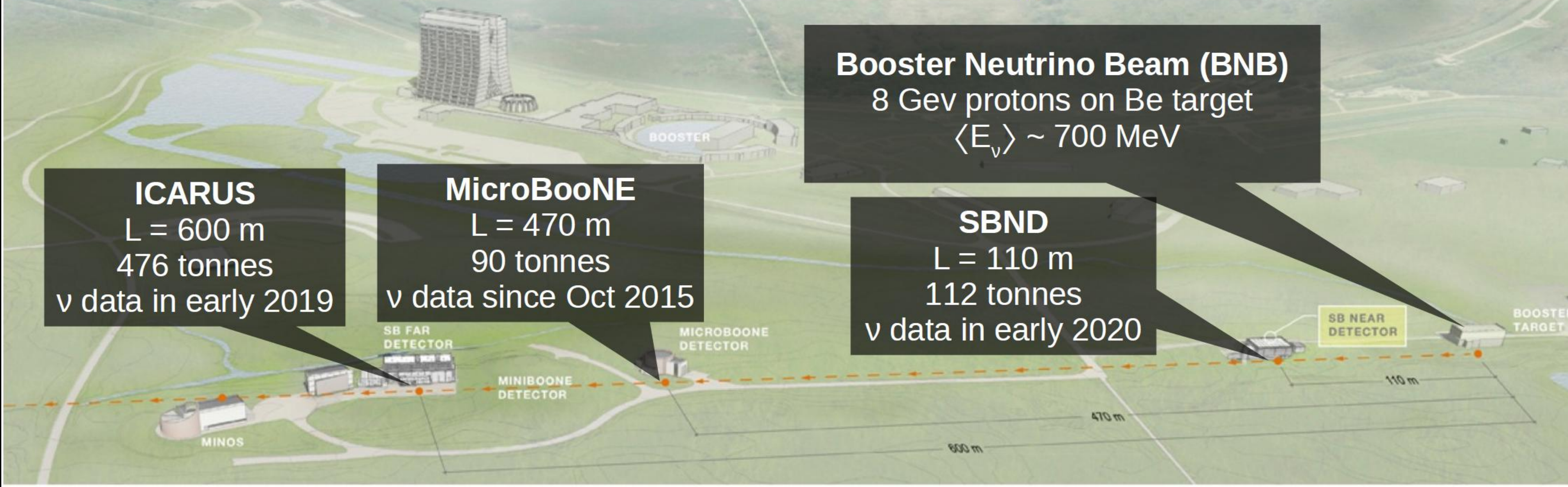
4 – 6 MeV excess seen in all three recent reactor flux measurements

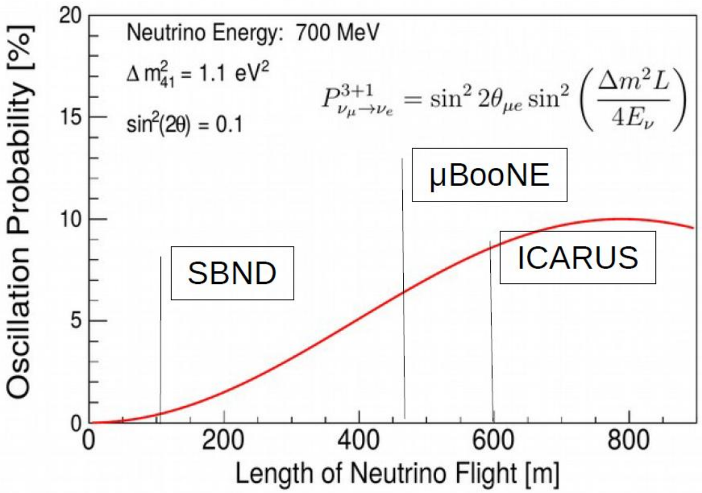






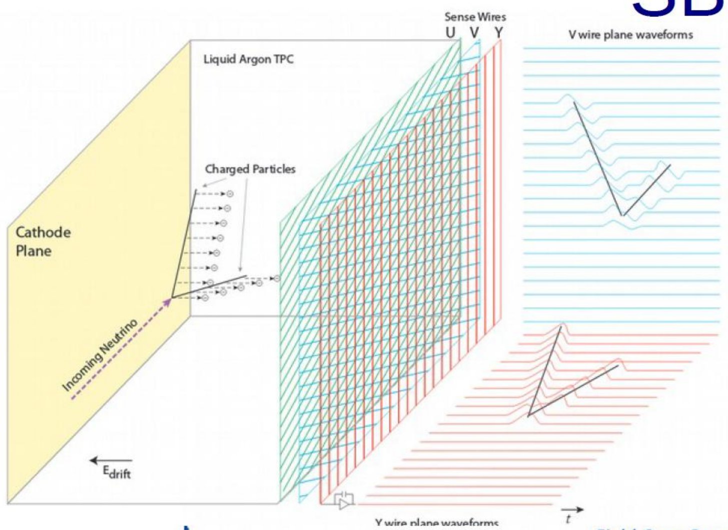
The Short-Baseline Neutrino Program at Fermilab

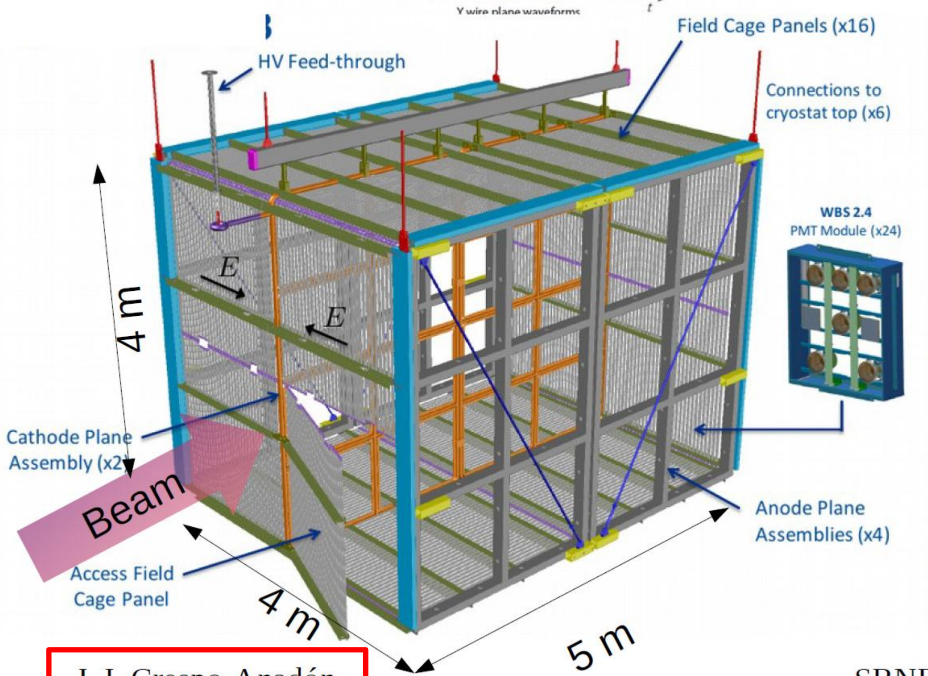




- Neutrino beam from pion decay-in-flight mostly (plus kaon and muon decay).
  - Single horn for focusing charged mesons.
  - Well-known beam, same as MiniBooNE (**PRD 79, 072002**).
- 3 Liquid Argon Time Projection Chamber (LArTPC) detectors.
  - **Same detector technology and target** to reduce systematic uncertainties.
  - **Electron vs gamma discrimination** to investigate MiniBooNE anomaly.

SBND TPC

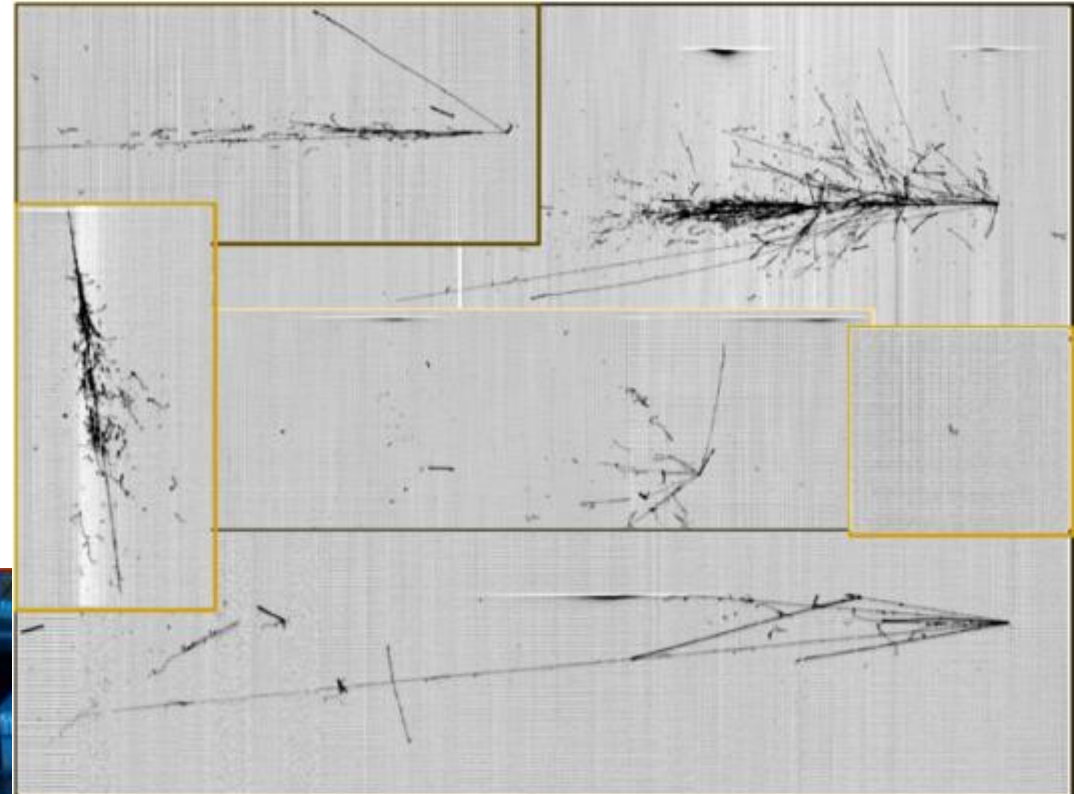




- 112 tonnes of liquid argon (active).
- Charged particles ionize Ar. Electrons are drifted towards wires using an electric field

  E_{drift} = 500 V/cm.
- Cathode Plane Assembly in the middle of the TPC at -100 kV.
- **2 drift volumes. Maximum drift length: 2 m. Maximum drift time: 1.28 ms.**
- On both sides, three wire planes to reconstruct 3D interaction.
  - Two induction planes with wires at ± 60º from vertical. One collection plane with vertical wires.
  - 3 mm wire pitch. **11264 channels.**
- Cold front-end electronics by Brookhaven National Laboratory.
  - 2 MHz digitization. On-going study to select cold or warm ADC electronics.
- Custom back-end electronics by Columbia University Nevis Laboratories.

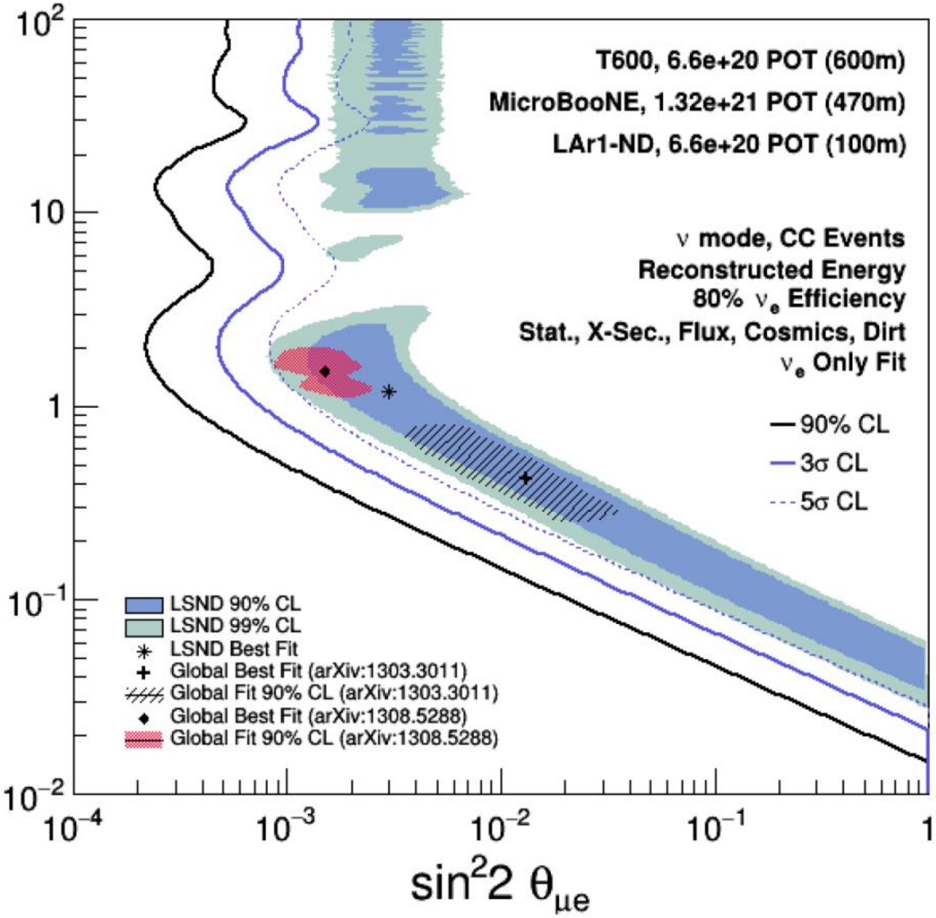
ICARUS T600
LAr TPC



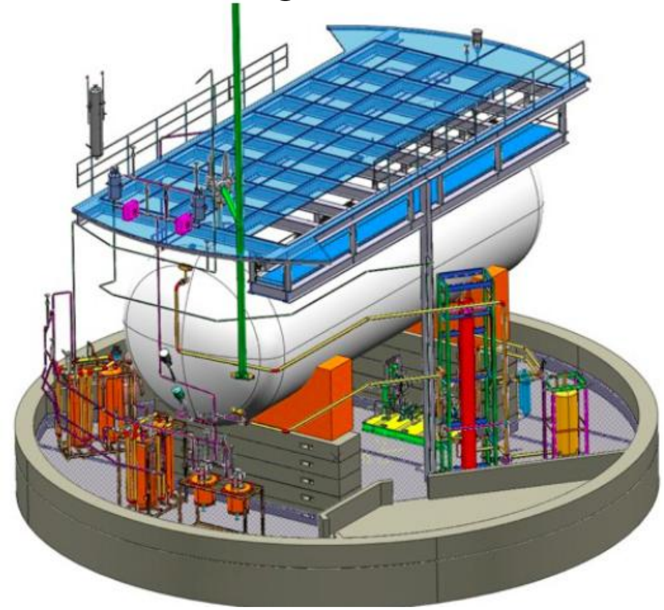
Fermilab SBN program

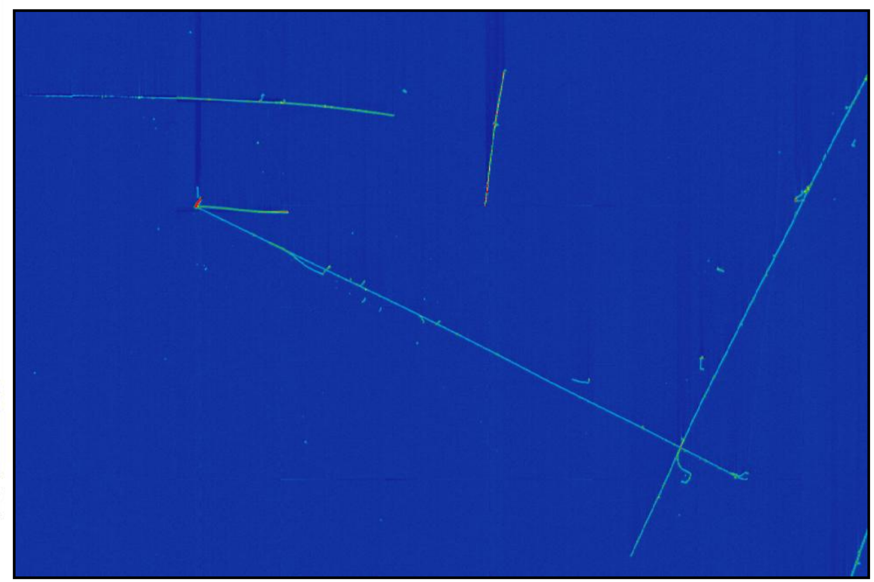
- **MicroBooNE + ICARUS + SBND**
- A mix of **R&D** and **physics** goals

Sensitivity shown below has caveats…



Below: MicroBooNE detector and "first light" neutrino event



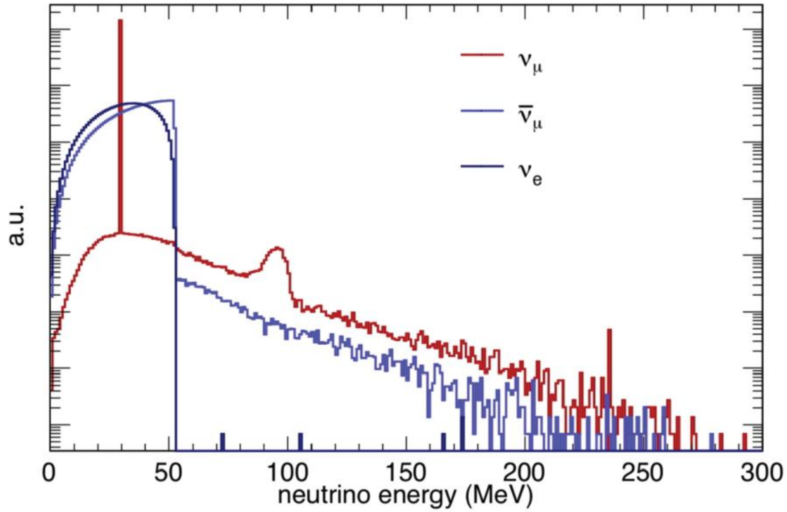


Pause for questions/discussion

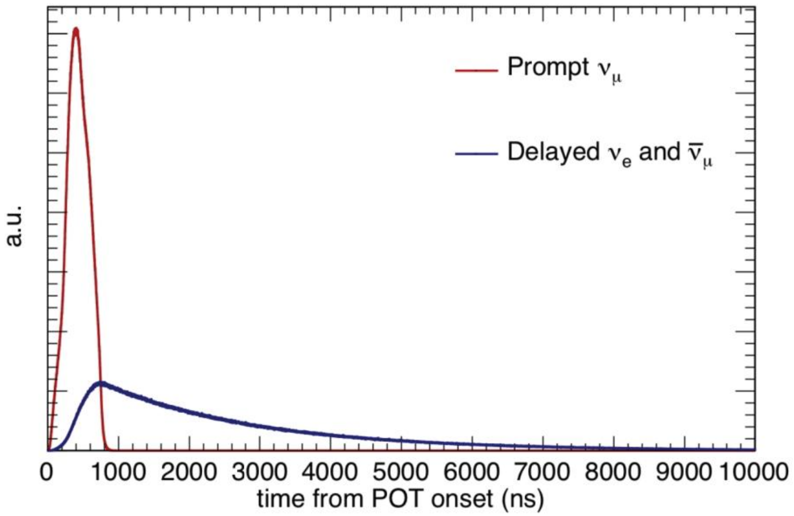
The Spallation Neutron Source

- Pion Decay-at-Rest Neutrino Source
- ν flux 4.3×10^7 ν cm^{-2} s^{-1} at 20 m
- Pulsed: 800 ns full-width at 60 Hz

<1% contamination from non-CEvNS scatters



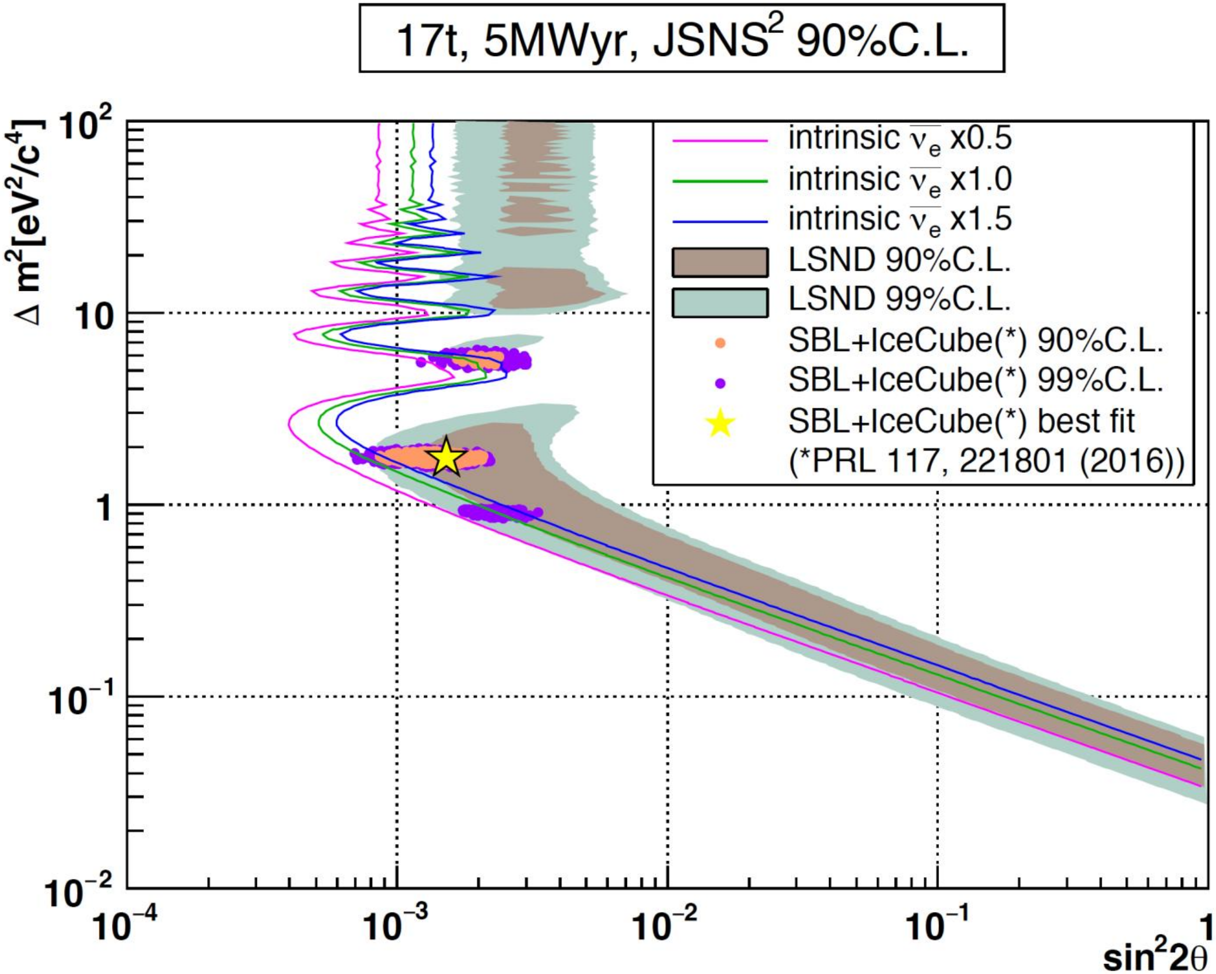
~4x10^{-5} background reduction



Slide from P. Barbeau, DPF 2017 for COHERENT collab.

14

JSNS² Phase-0 (*now under construction*) expected sensitivity



(5 years of running)

Slide from J. Spitz, DPF 2017

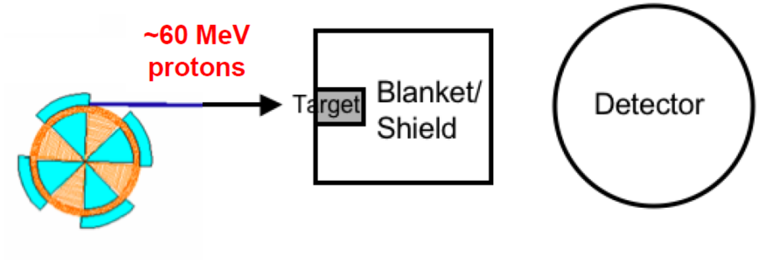
Daeδalus and IsoDAR Experiments

("Cyclotrons as Drivers for Precision Neutrino Measurements" - arXiv:1307.6465
Snowmass Whitepaper on the DAEdALUS Program - arXiv: 1307.2949)

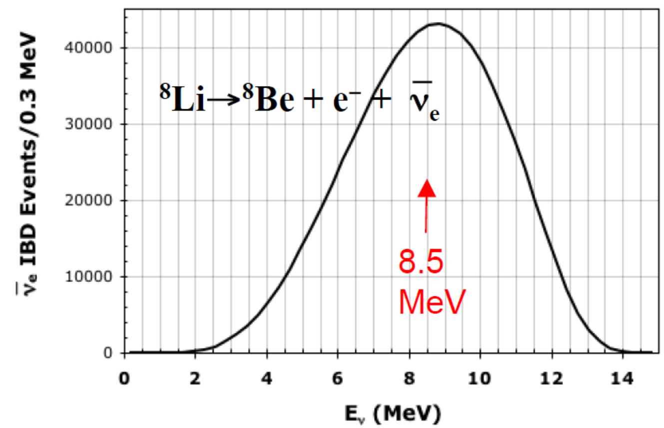
IsoDAR Setup:

Very short baseline search for sterile neutrinos

PRL 109, 141802 (2012)



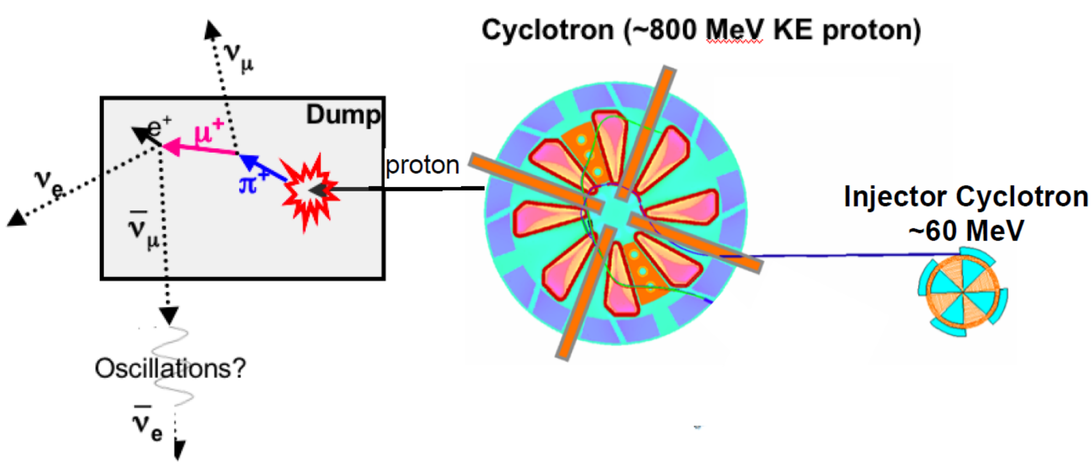
Isotope decay-at-rest



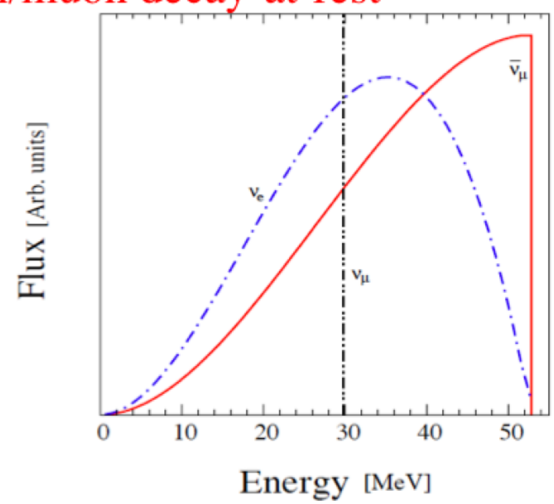
Daeδalus Setup:

A new way to search for CP violation in the ν-sector

PRL 104, 141802 (2010)



Pion/muon decay-at-rest



Slide from M. Shaevitz, P5 meeting, 2013

Pause for questions/discussion

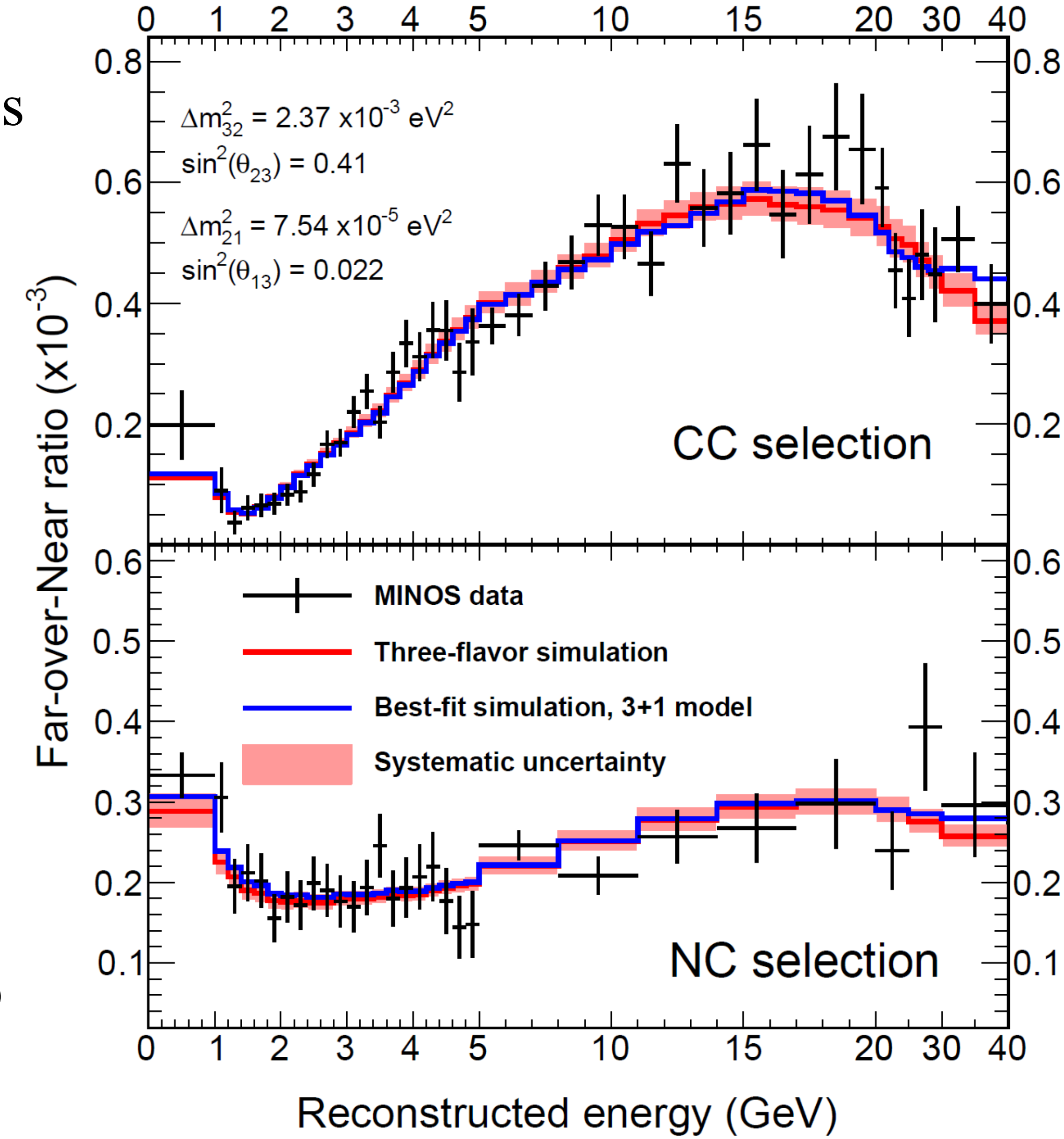
Grab bag

Search for Sterile Neutrinos Mixing with Muon Neutrinos in MINOS

P. Adamson *et al.* (MINOS), Phys. Rev. Lett. **117**, 151803 (2016)

Sterile neutrino mixing can manifest as a decrease in total active flux, which in turn can be measured via NC interactions.

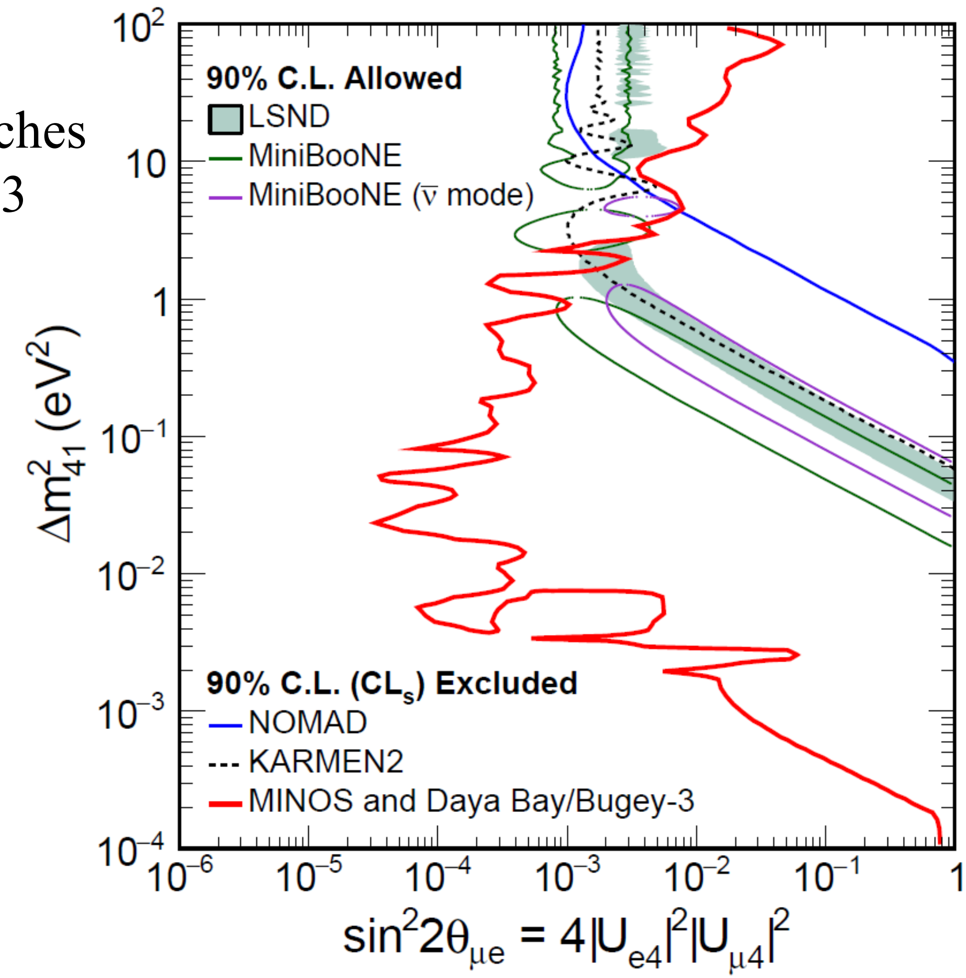
At the highest Δm^2 values, the ND sees oscillations, too, so a simple ND-to-FD extrapolation has limitations.



Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments

P. Adamson *et al.*
(Daya Bay, MINOS)

Phys. Rev. Lett. **117**, 151801 (2016)



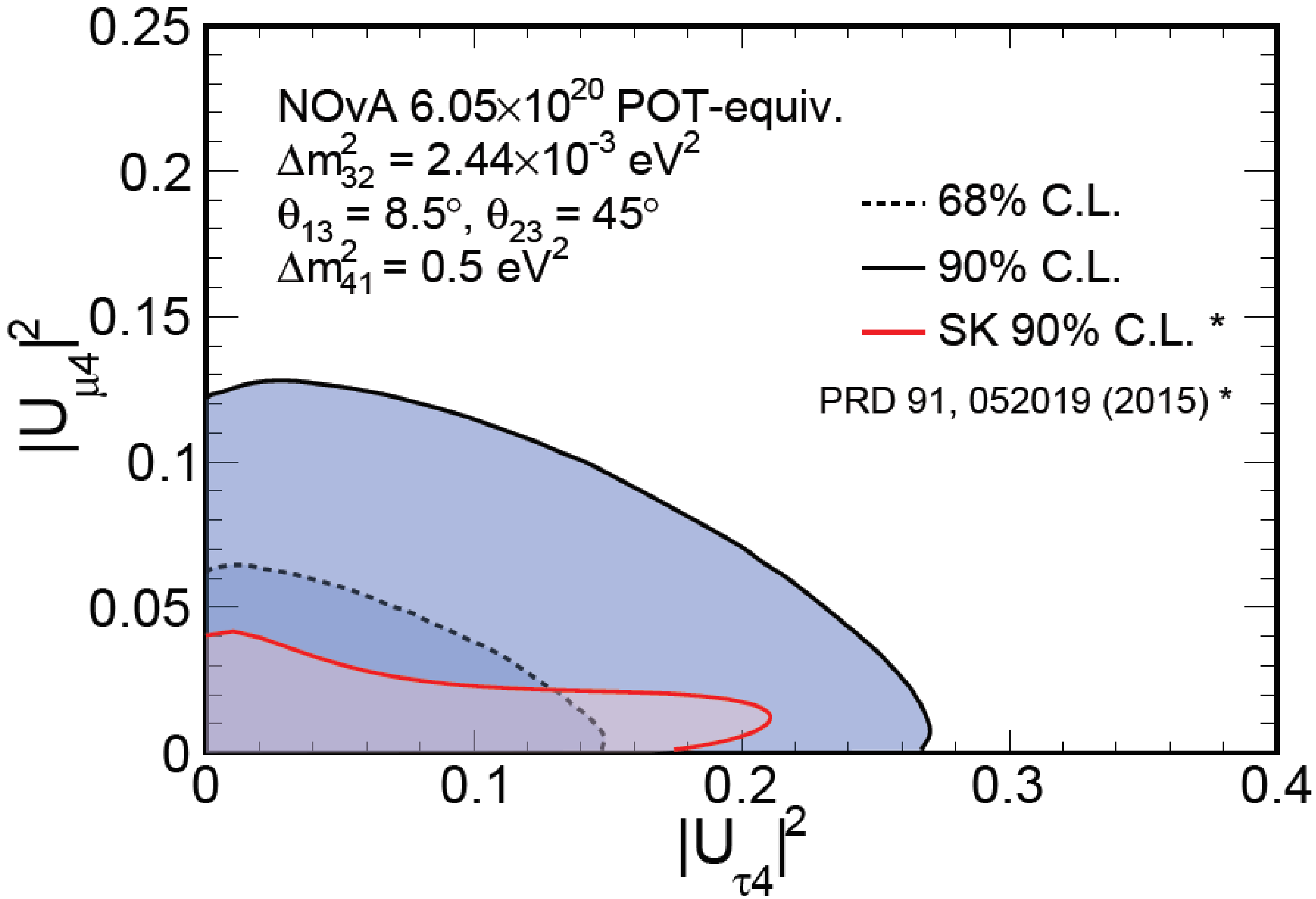
Here, three combined results in a 3+1 model to set a limit in the LSND-like parameter space.

(Need a model of some kind to go from disappearance to appearance sterile neutrino constraints)

FIG. 4. MINOS and Daya Bay + Bugey-3 combined 90% CL_s limit on $\sin^2 2\theta_{\mu e}$ compared to the LSND and MiniBooNE 90% CL allowed regions. Regions of parameter space to the right of the red contour are excluded. The regions excluded at 90% CL by the KARMEN2 Collaboration [45] and the NOMAD Collaboration [46] are also shown. We note that the excursion to small mixing in the exclusion contour at around $\Delta m^2_{41} \sim 5 \times 10^{-3}$ eV^2 is originated from the island in Fig. 1.

NOvA (2017) and Super-K (2015) limits in part of the 3+1 parameter space…

NOvA, arXiv:1706.0459



Large extra dimensions

(figure from MINOS, Phys. Rev. D **94**, 111101(R) (2016)

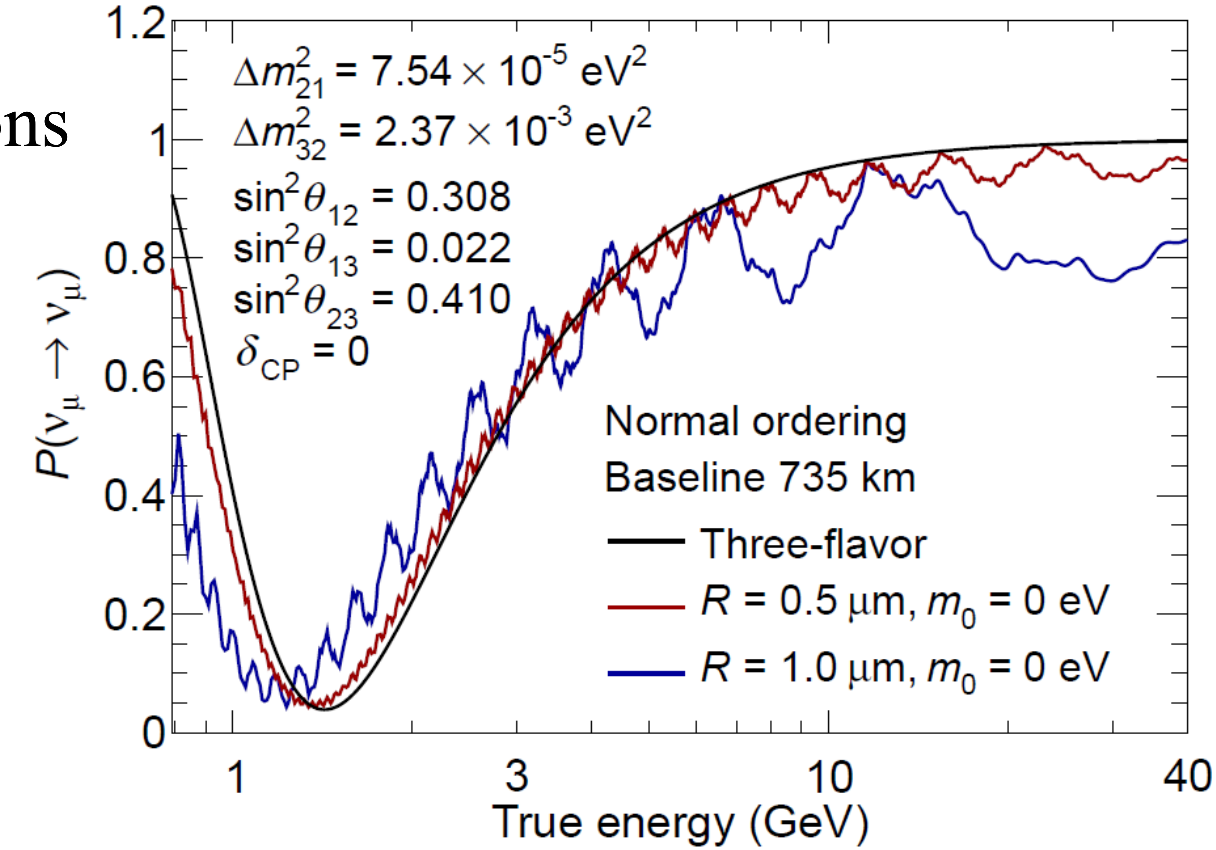
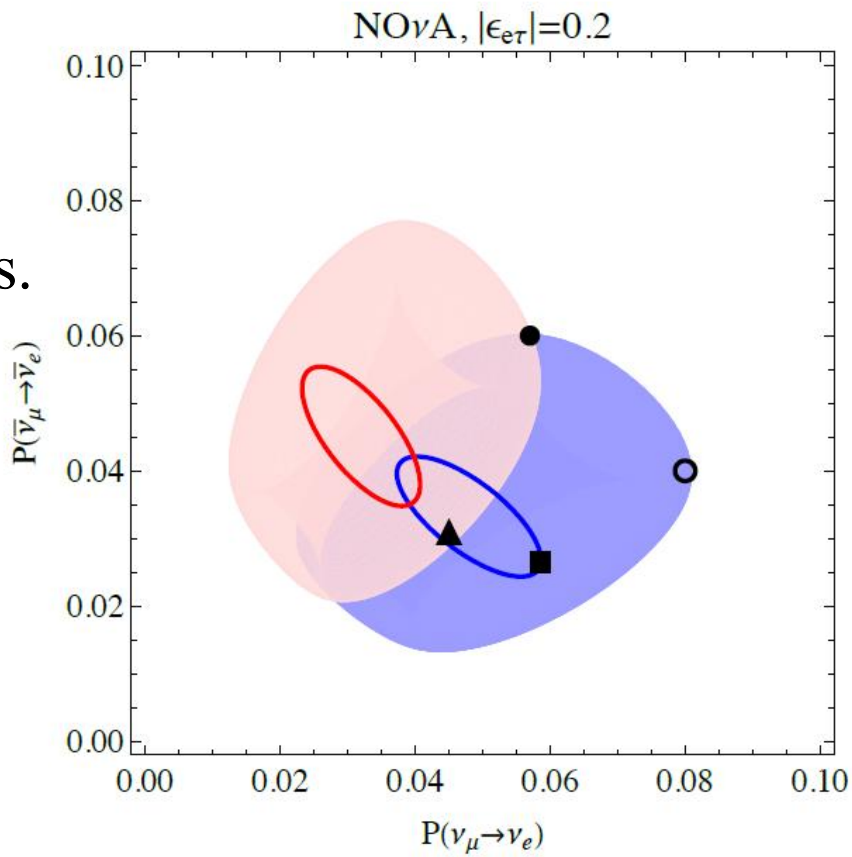


FIG. 1: The muon neutrino survival probability $P(\nu_\mu \rightarrow \nu_\mu)$ at the MINOS Far Detector as a function of the true neutrino energy for $m_0 = 0$ eV and $R = 0.5$ μm (red line) or 1 μm (blue line), and for three-flavor oscillation (black line).

- **Non-standard interactions**
  Beam and atmospheric neutrinos passing through matter provide access to non- standard couplings.
  (e.g., plot at right)



Friedland and Shoemaker
arXiv:1207.6642

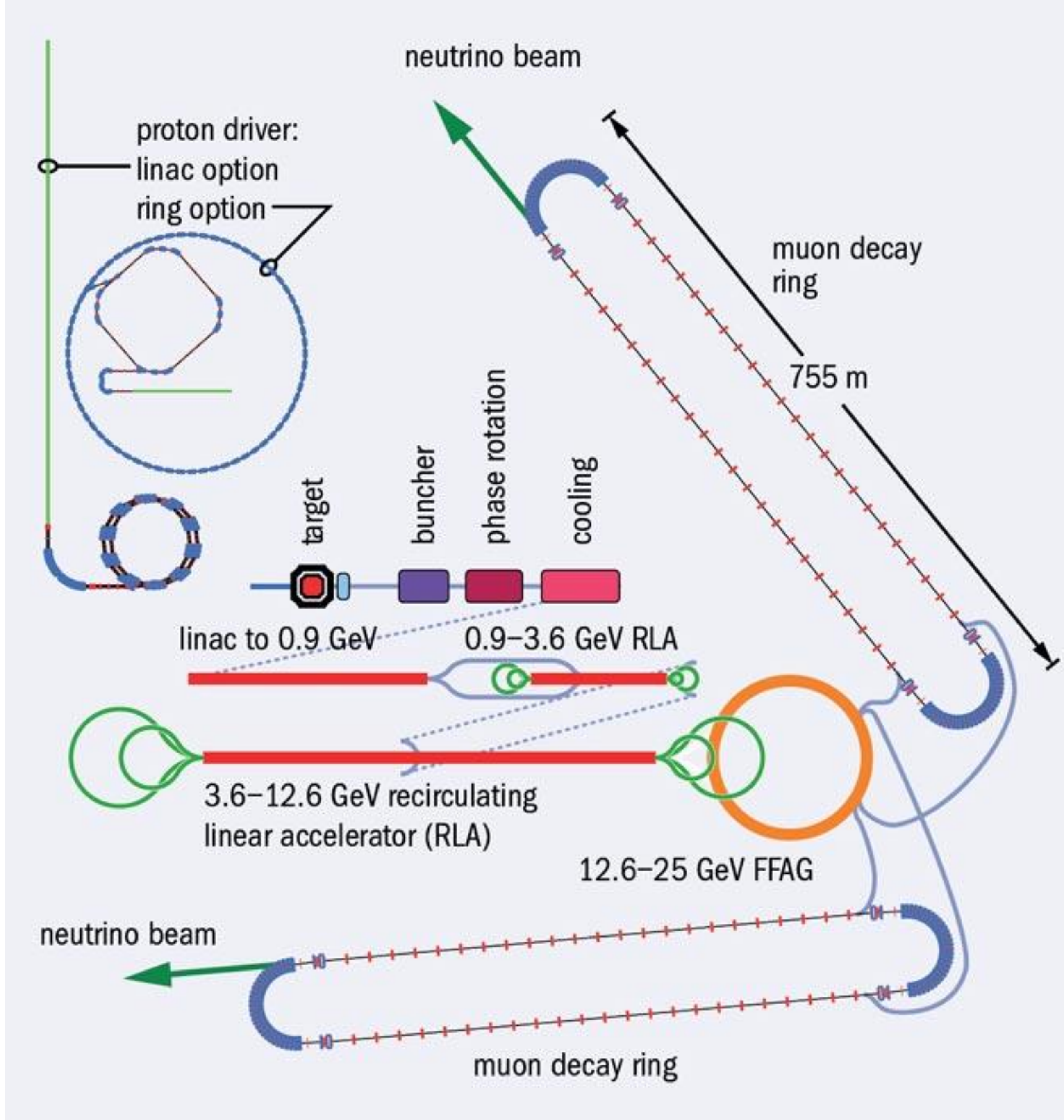
- **Dark matter**
  Astrophysical (*e.g.*, annihilation in the sun; at NOvA, look for up-going neutrinos) and beam-induced light dark matter (*e.g.*, $qq \to V^* \to \bar{\chi}\chi$ at target)

- **And more…**
  Lorentz violation, effective *CPT*v, non-unitarity, neutrino, tridents (Z' and muon g–2)

"Neutrino factory"

Accelerator R&D required.

Well-characterized spectrum and rate (muon decay)



"Beta beam"

Accelerator R&D required. Well-characterized spectrum and rate (beta decay). Flavor-pure. (Was discussed a lot when θ_{13} could still be very small. Could conduct $\nu_e \to \nu_\mu$ search with no intrinsic ν_μ background.)