Accelerator-based neutrino beams and oscillations (mostly long-baseline✸ beams)

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✸ long-baseline and short-baseline always need a hyphen if used as an adjective

Argonne NATIONAL LABORATORY

Language

- Don’t be polite
- Don’t raise your hand
- If I am talking too fast, shout:

- Don’t be polite
- Don’t raise your hand
- If you don’t understand, shout a question or say:

Outline

- ν Beams
- Detectors for ν beams
- Long-baseline ν experiments (8)
  - Completed   K2K, MINOS, ICARUS, OPERA
  - Current   NOνA, T2K
  - Future   DUNE, Hyper-K
- Other accelerator neutrino experiments

Neutrino Beams

1^{st} neutrino beam Mel Schwartz

VOLUME 4, NUMBER 6 PHYSICAL REVIEW LETTERS MARCH 15, 1960

FEASIBILITY OF USING HIGH-ENERGY NEUTRINOS TO STUDY THE WEAK INTERACTIONS

M. Schwartz*
Columbia University, New York, New York
(Received February 23, 1960)

- Schwartz proposed to use a proton beam to make π which decay to ν.
  - 5e13 p/s (E_p = 3 GeV)
  - $\gamma c \tau$ (E_π ~ 1 Gev) = 50 m
  - 5000 ν/(s cm^2)
  - 1 interaction/hr in 10 ton detector

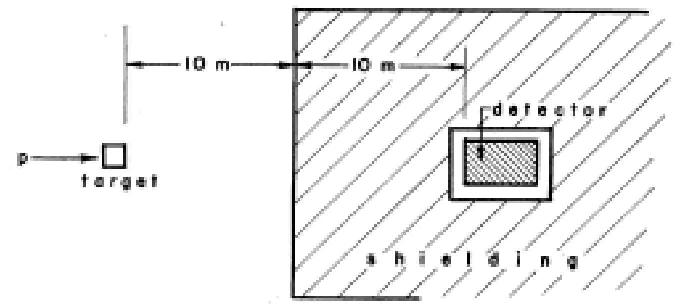

FIG. 1. Proposed experimental arrangement.

1st neutrino beam
Mel Schwartz

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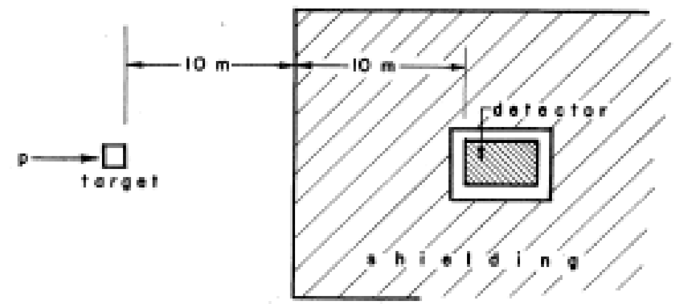


FIG. 1. Proposed experimental arrangement.

Note added in proof. The author's attention has been called to a somewhat related paper which has just appeared: B. Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 1751 (1959).

"Discovery" of the ν_μ

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

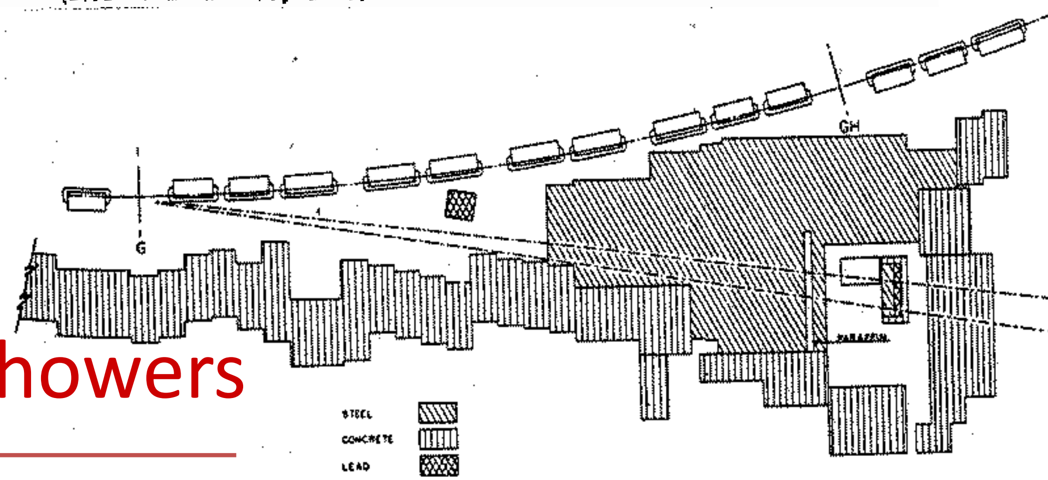


FIG. 1. Plan view of AGS neutrino experiment.

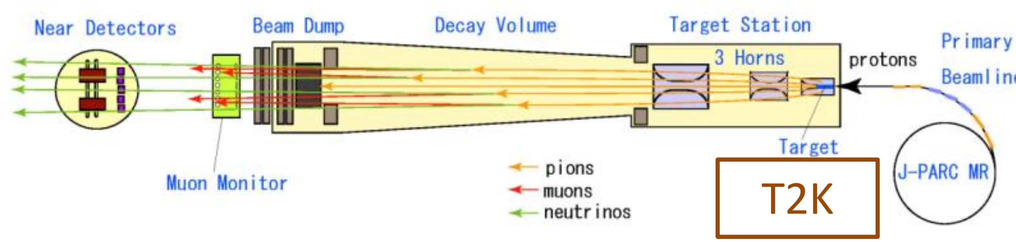
37

	Expected	Seen
$\nu + n \to p + e^-$, $\bar{\nu} + p \to n + e^+$,	Equal	5 showers
$\nu + n \to p + \mu^-$, $\bar{\nu} + p \to n + \mu^+$,	Equal	29 μ tracks

Neutrino Beam

For an intense neutrino beam, you need:

- Accelerator with an intense proton beam (Power measured in kW)



- A target that
  - Won't melt
  - Most protons interact so you get the most π/K
  - π and K quickly leave the target so they don't interact
- Focusing device (horn) to maximize forward π/K
- A beam pipe to well define the beam & acceptance

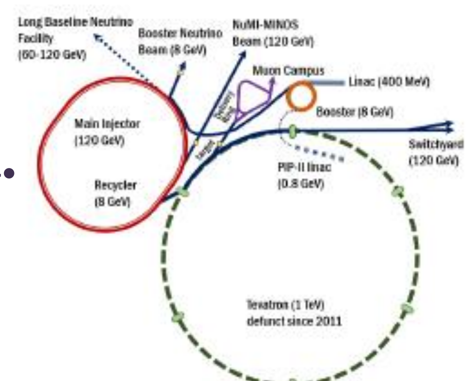
Accelerator & proton beam

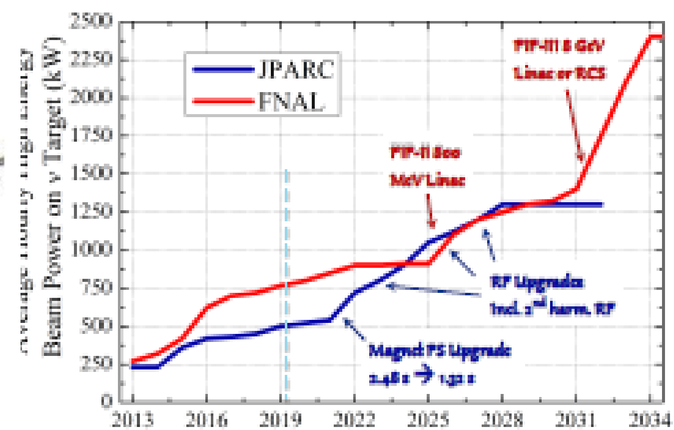
- The more proton (intensity), the more neutrinos
- Energy is more complicated.
- $E_\nu \neq E_b$
- Cycle time (T_{cycle}) is an issue
- More low E_ν with high E_b

Facility	E_b, GeV	T_{cycle}, s	N_{ppp}, 10^{13}	P_b, MW	Year
FNAL MI	120	1.33	5.2	0.76	2019
(PIP-II)	120	1.2	7.6	1.2	2026
(PIP-III)	120	1.2	15	2.4	2030's
J-PARC	30	2.48	25	0.475	2019
	30	1.16	43	1.3	2028

→ indicates current NOvA and T2K cases,
"PIP" (@Fermilab) = "proton improvement plan"

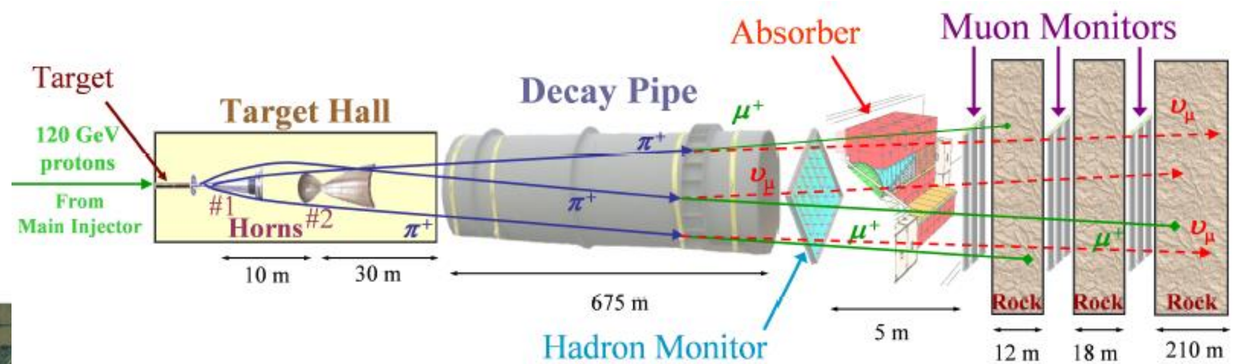
For most experiments I will describe the integrated beam as **p.o.t.** for "protons on target"



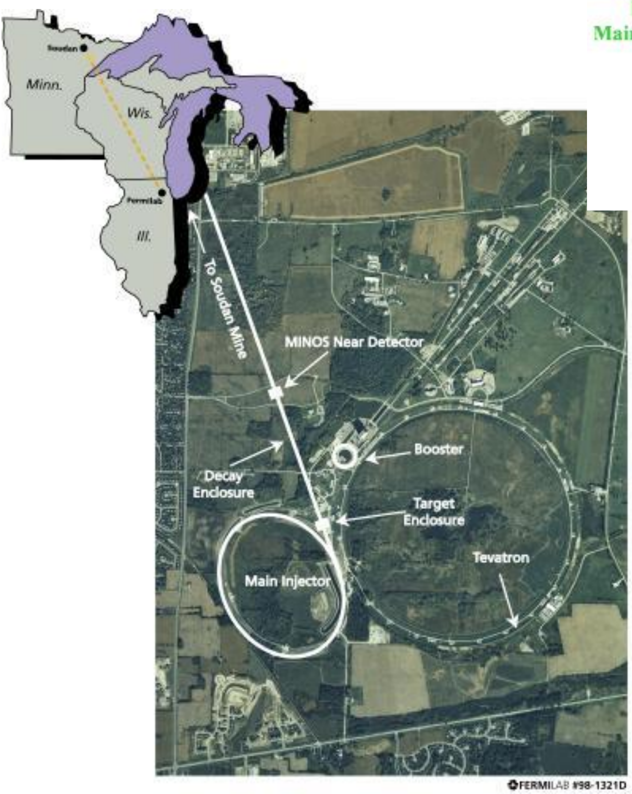


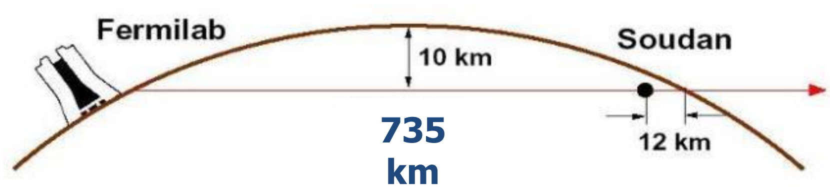
On-axis WBB

Wide band beam



On-axis best for $\nu_\mu \to \nu_\mu; \nu_\mu \to \nu_\tau$



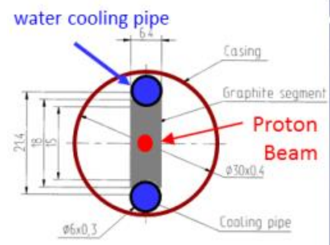


Proton target

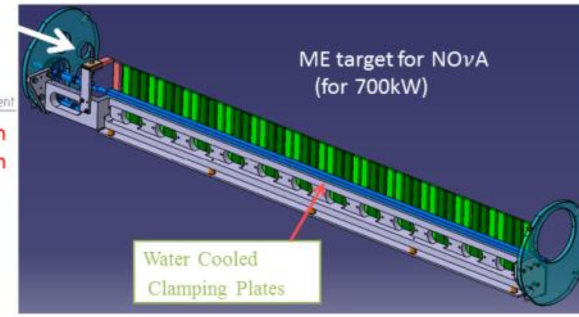
NuMI uses graphite

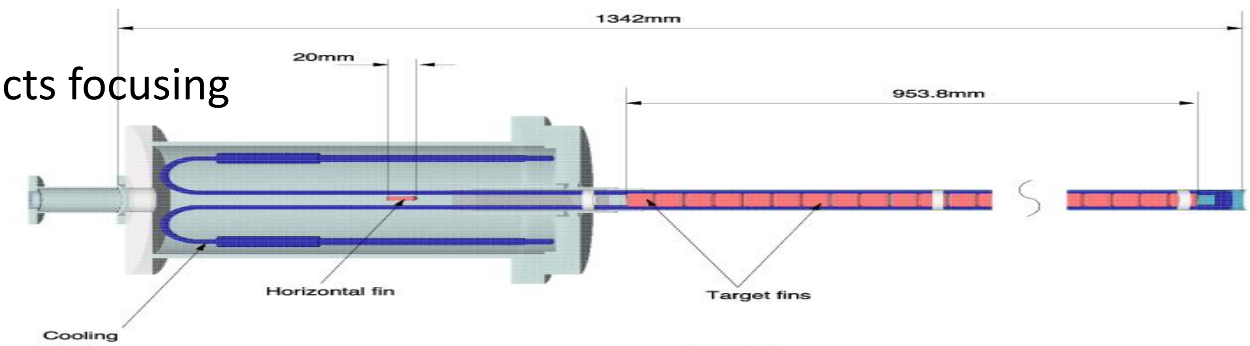
Some target goals:

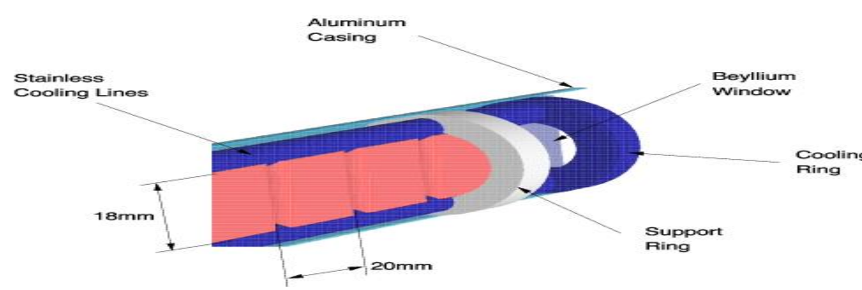
- All protons interact
- Target does not melt
- lifetime due to material fatigue
  - ∴ large
- No π/K interact
- Target position affects focusing
  - ∴ small



LE target for MINOS
(for 400kW)







Narrow-Band Beam

NBB not relevant to long-baseline experiments, but useful thinking about beams

- Wide-Band Beam: (most ν beams now), wide momentum range of π/K, then focus π/K.
- Narrow-Band Beam: momentum select π/K. “dichromatic”, E_ν known

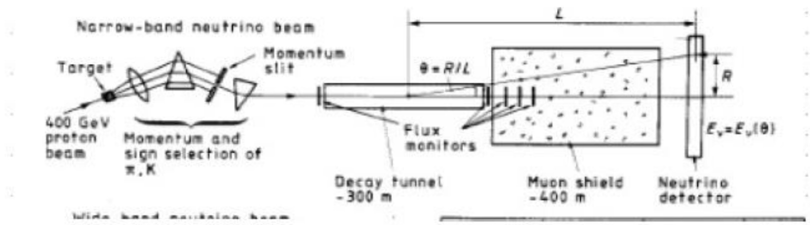
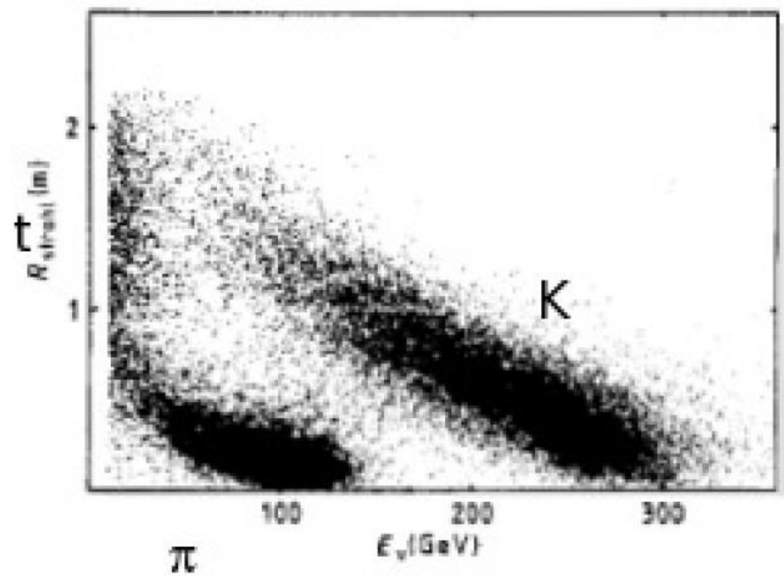
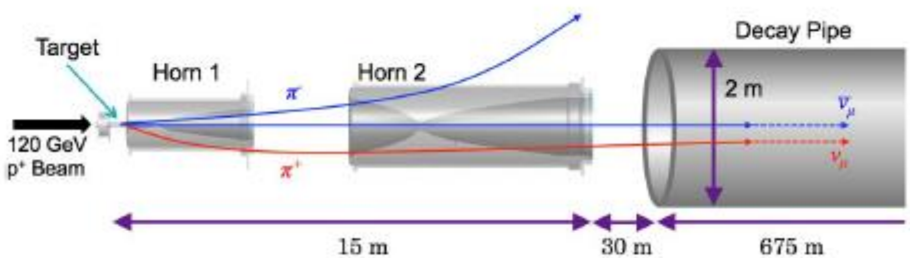
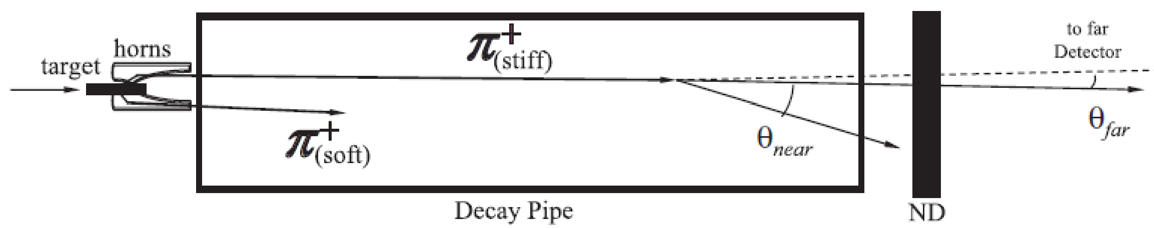


Figure 26: Schematic of a narrow band beam.



Focusing device
“sign selected”





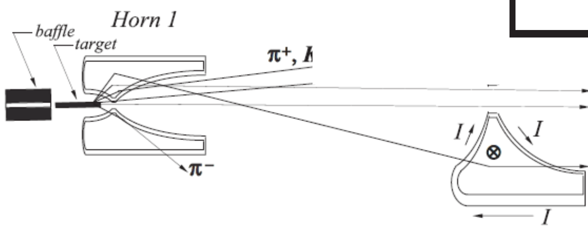


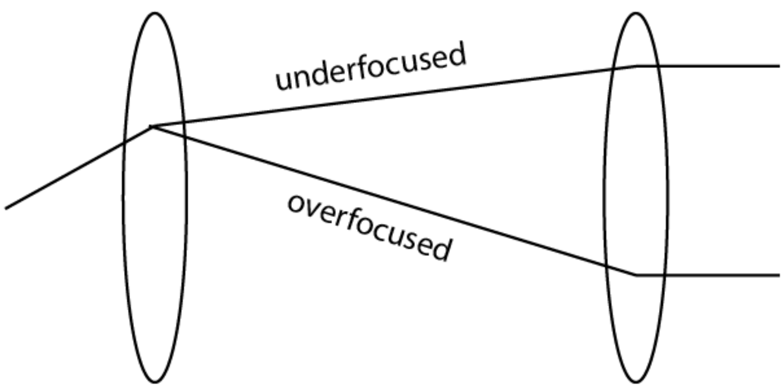
FIG. 2. In the NuMI neutrino beam, horns 1 and 2 are separated by 10 m. A collimating baffle upstream of the target protects the horns from direct exposure to misdirected proton beam pulses. The target and baffle system can be moved further upstream of the horns to produce higher energy neutrino beams [21]. The vertical scale is 4 times that of the horizontal (beam axis) scale.

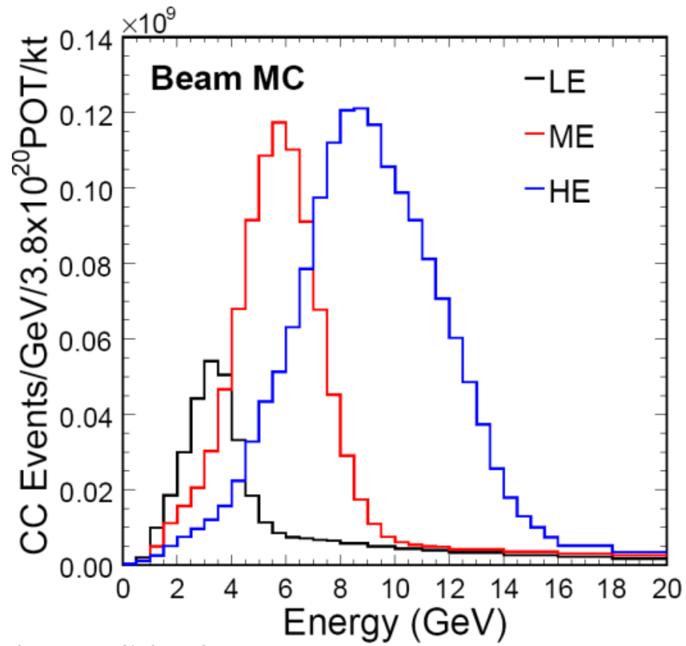
More events in ν beams than $\bar{\nu}$ for 2 reasons:

1. More π^+ than π^- (charge conservation)
2. $\sigma(\nu) > \sigma(\bar{\nu})$ by about 2

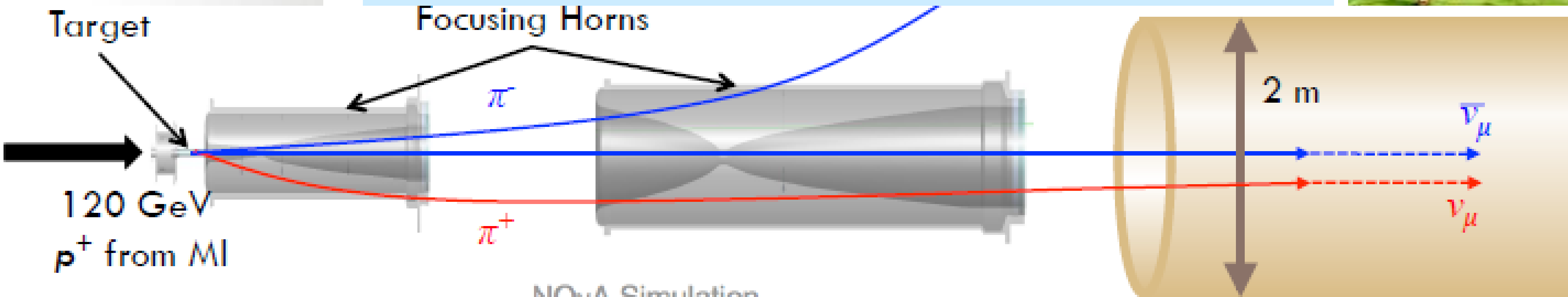
Focusing + target

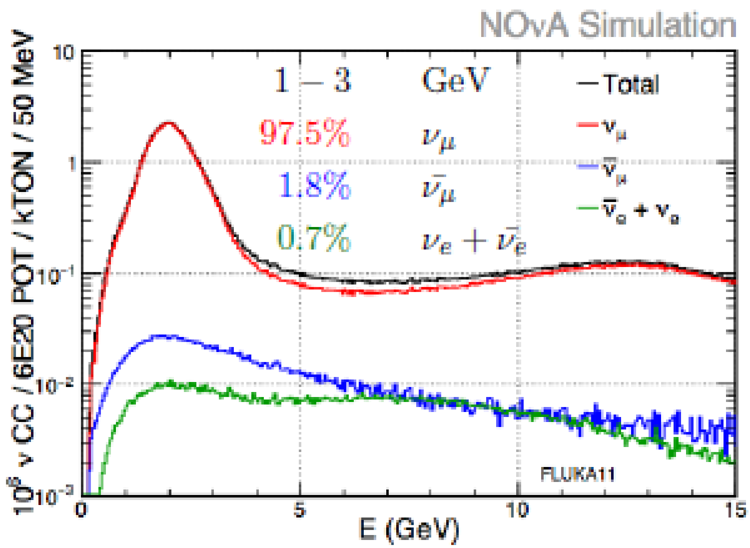
- You can focus more π/K with 2 horns than 1
- Since E_π distribution is wide, you can't focus all the secondary hadrons
- Moving the target with respect to the horns affects <Eν>

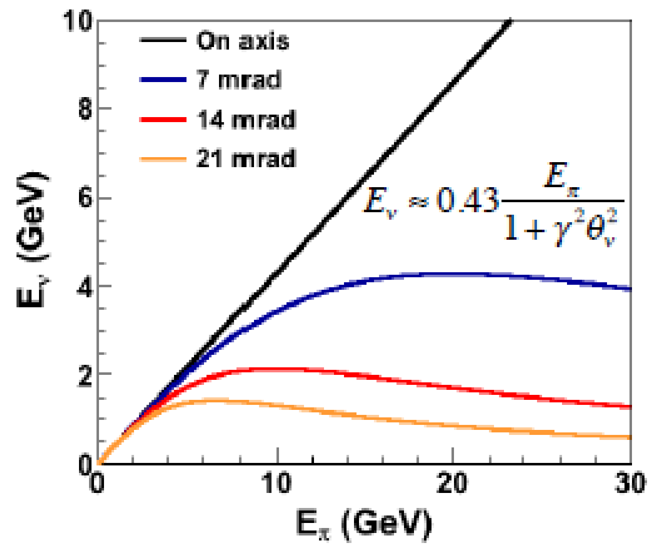




Making an off-axis neutrino beam







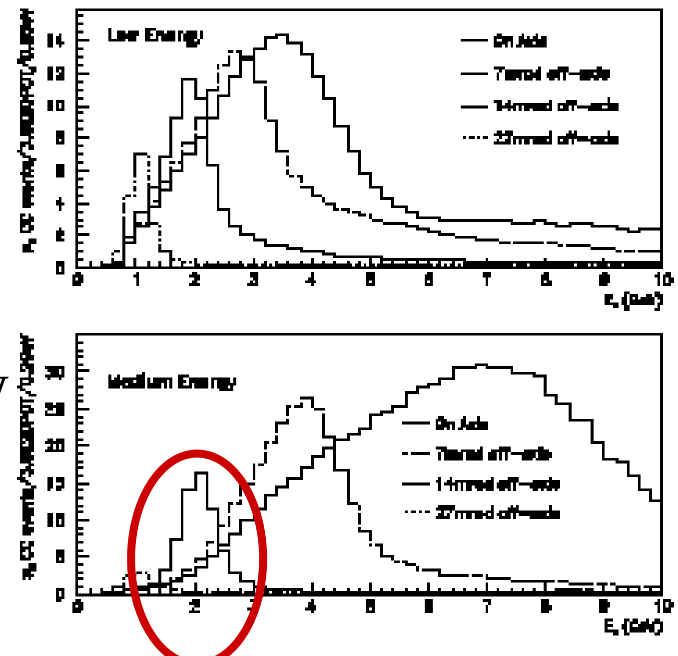
- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
  - Near oscillation maximum
  - Few high energy NC background events

Why go Off-Axis?

best for $\nu_\mu \to \nu_e$

- Rates way down (already an obvious significant issue in long-baseline ν)

+ Backgrounds for $\nu_\mu \to \nu_e$ reduced
  - ν_e in the beam mostly at higher energy
  - e from ν_τ, No ν_τ interactions below 4 GeV
  - NC (π^0) background not eliminated, but since there is no high energy tail, it is reduced.



$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2} \right) \frac{A}{4\pi z^2}$$

What makes a long-baseline experiment long?

3 different answers:

1. The detector is off-site
   - A practical definition
2. $L\text{ (km)} \gg \pi E_\nu\text{ (GeV)}/(1.27\ \Delta m^2)$
   - A physics definition, guaranteeing many oscillations
3. $L_{detector} \gg L_{decay\ pipe}$
   - So that the "beam" appears to be a point source at the FD (but <u>not</u> ND).

A common question:

How does a beam hit a target 700 km away?

The beam diverges as $1/L^2$, and the detector is small compared to the size of the "beam".

Strange fact: since oscillations grow as L^2, and the flux falls as $1/L^2$, you actually get more oscillated events/$M_{detector}$ at the ND!

Questions?

Neutrino Detectors

General considerations for ν detectors

- Mass & chemical composition
- Cost
- Granularity
  - Angular Resolution
  - Energy Resolution
- Ability to make functionally identical ND
- Magnetic Field?

Specific detectors

Covered in this lecture

K2K	water
MINOS	iron/scintillator
OPERA	iron/emulsion
ICARUS	liquid argon
T2K	water/(Gd)
NOνA	liquid scintillator
DUNE	liquid argon
T2HK	water/Gd

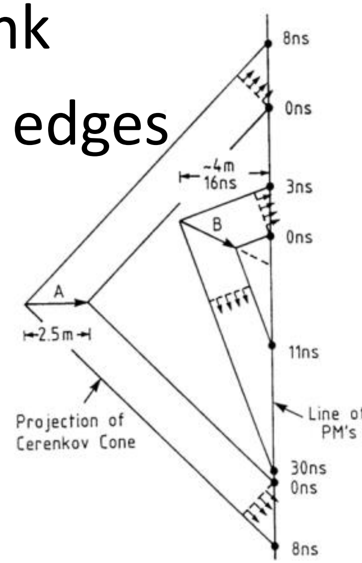
Other neutrino detectors

FNAL E1	segmented liq scint
Several	bubble chambers
FNAL E594	sand/flash chambers
CHARM	marble/scint sandwich
CDHS	Magnetized Fe/scint
CCFR	Magnetized Fe/scint
CHORUS	emulsion
NOMAD	Hybrid
MiniBooNE	liquid scintillator
MINERvA	multiple nuclei/scint
MicroBooNE	liquid argon
SBND	liquid argon

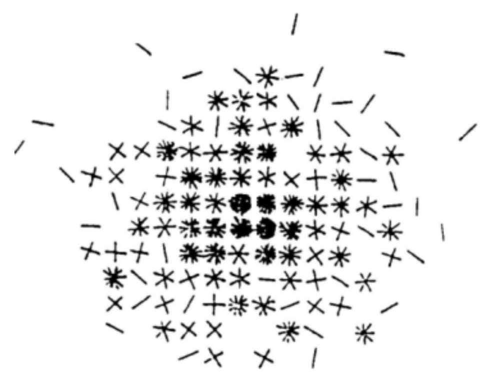
(Near Detectors for Long-Baseline)

Water Cherenkov

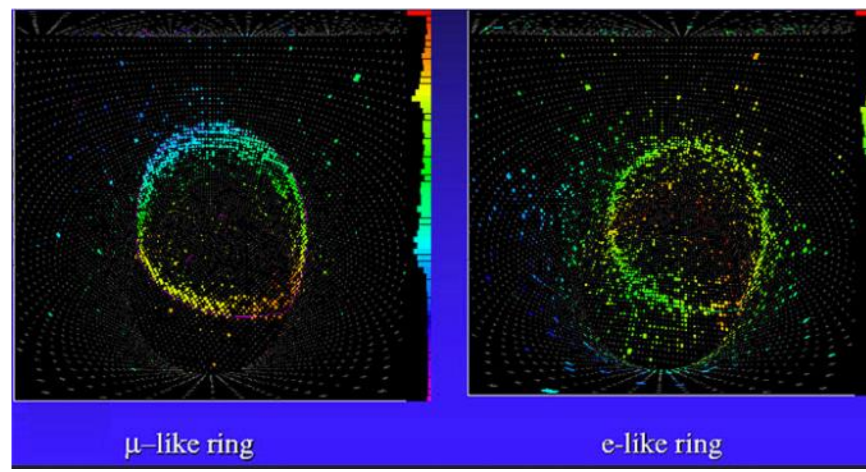
- ❑ Large water tank
- ❑ Phototubes on edges
- ❑ X_0 is 36 cm
- ❑ $7X_0 \sim 2.5$ m
- ✶ μ – sharp ring
- ✶ e – fuzzy ring
- ✶ exiting μ – filled-in ring
- ✶ Time resolution $\Delta t \sim$ ns



throughgoing μ



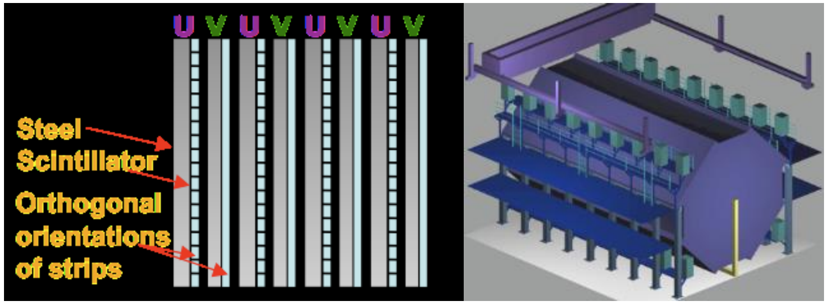
stopping μ



K2K
T2K
T2HK

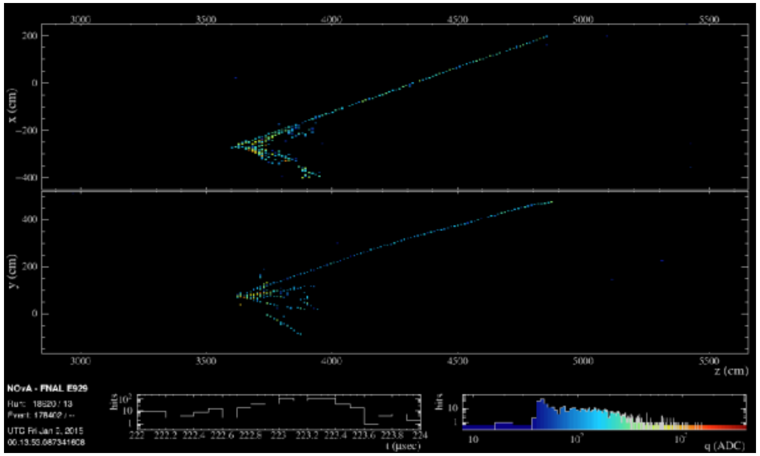
Segmented Tracking

- Alternating crossed planes
- You get two 2D views
- Then match hits (tracks) or match objects (showers)
- There might be inactive material between planes
- It could be magnetized
- $\Delta t \sim$ ns to μs



MINOS layers

MINOS
OPERA
NOνA

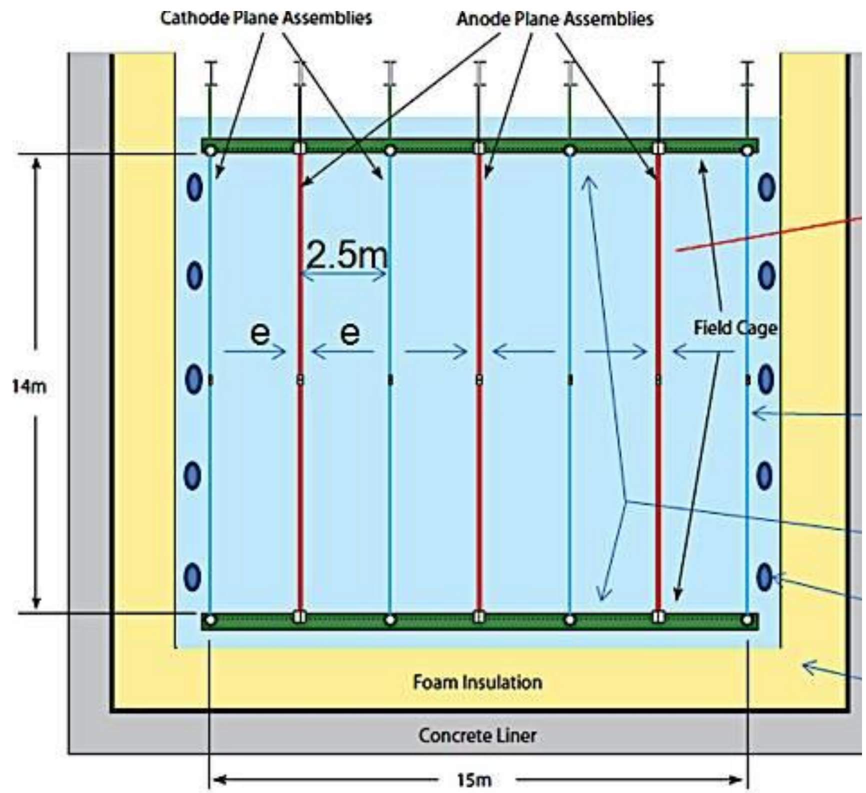


NOνA event

Liquid Argon

- Large volumes of pure Lar
- Ionization makes electrons
- Electric Field toward wires

  ProtoDUNE example - 180 kV
- Slow drift ($\Delta t \sim$ few ms)
- Need very low H_2O, O_2,… to maintain drift lifetime



ICARUS
DUNE

Near Detectors

These have two different purposes

- To understand the beam flux and spectrum
- To measure backgrounds for an appearance signal before the neutrinos oscillate

Near Detectors (ND)

- A ND is a crucial part of most long-baseline exps
- Issues include:
  - ND does not see a point target
  - Extrapolating an oscillated flux
  - Same nuclear ν target?
  - Substantial difference in event rates (which affects cost considerations)

- Similar ND & FD
  - K2K
  - MINOS
  - NOνA
- Quite different ND & FD
  - T2K
  - DUNE
  - T2HK (Hyper-K)
- No ND
  - ICARUS
  - OPERA

Questions?

Previous long-baseline ν experiments

- K2K (KEK)
- MINOS (NuMI) NeUtrinos at the Main Injector
- ICARUS (CNGS) Cern Neutrinos to Gran Sasso
- OPERA (CNGS)

An Analysis Issue

- In the 3 ν paradigm:

  $$P(\nu_\mu \rightarrow \nu_\mu) + \underbrace{\underline{P(\nu_\mu \rightarrow \nu_\tau)}}_{\text{dominant}} + \underbrace{\underline{P(\nu_\mu \rightarrow \nu_e)}}_{\text{sub-dominant}} = 1$$

- Previous experiments focused on

  $$P(\nu_\mu \rightarrow \nu_\tau) \sim 1 - P(\nu_\mu \rightarrow \nu_\mu)$$

- Current and future experiments focus on

  $$P(\nu_\mu \rightarrow \nu_e)$$

An Analysis Issue

- In the 3 ν paradigm:

$$P(\nu_\mu \rightarrow \nu_\mu) + \underbrace{\underline{P(\nu_\mu \rightarrow \nu_\tau)}}_{\text{dominant}} + \underbrace{\underline{P(\nu_\mu \rightarrow \nu_e)}}_{\text{sub-dominant}} = 1$$

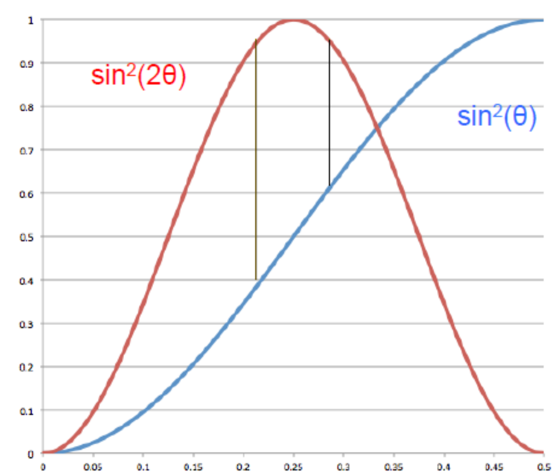
- Previous experiments focused on

$$P(\nu_\mu \rightarrow \nu_\tau) \sim 1\text{-}\ P(\nu_\mu \rightarrow \nu_\mu) \propto \sin^2(2\theta_{23})$$

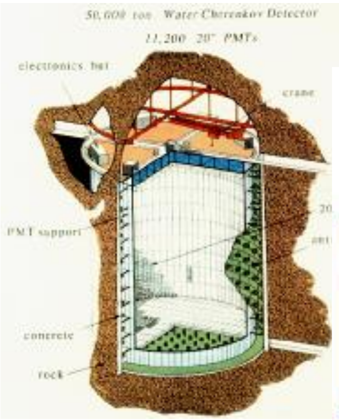
- Current and future experiments focus on

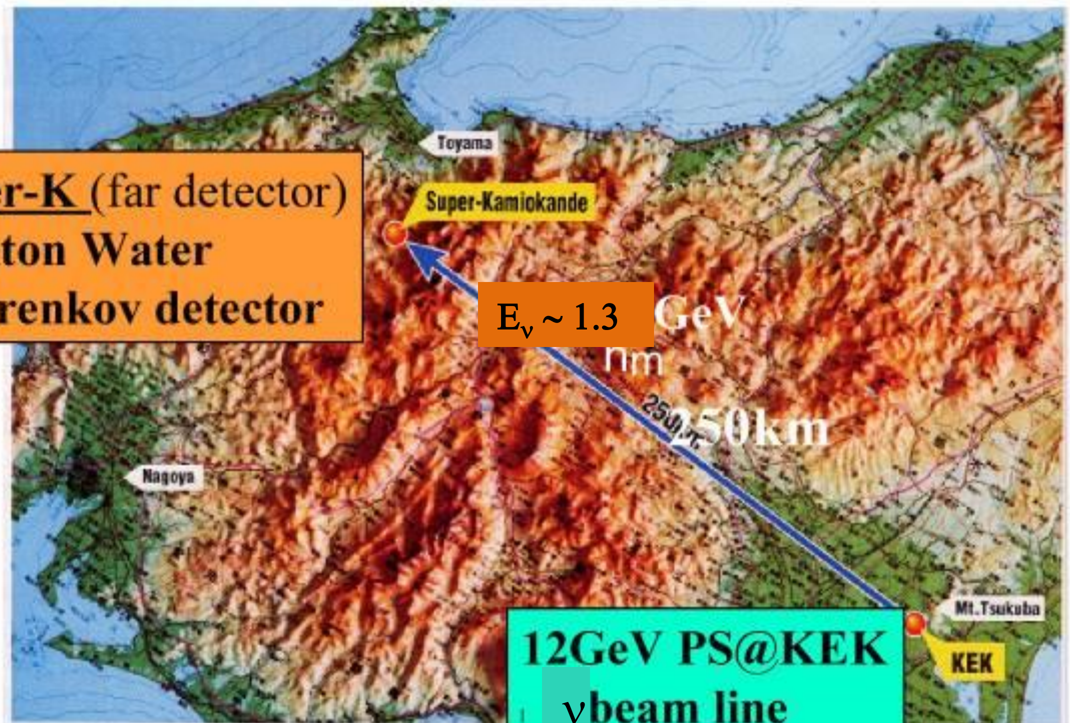
$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2(\theta_{23})$$

- A 5% difference in $\sin^2(2\theta)$ tur into a 20% difference in $\sin^2(\theta)$



K2K





Super-K (far detector)
50 kton Water Cherenkov detector

$E_\nu \sim 1.3$ GeV

12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

K2K results

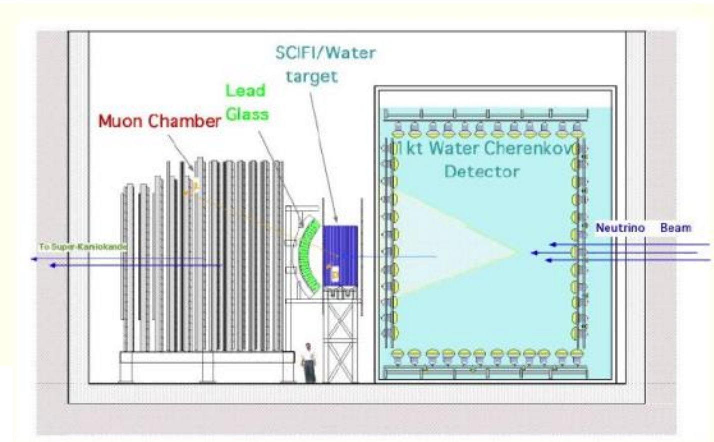
- 0.9 e20 pot

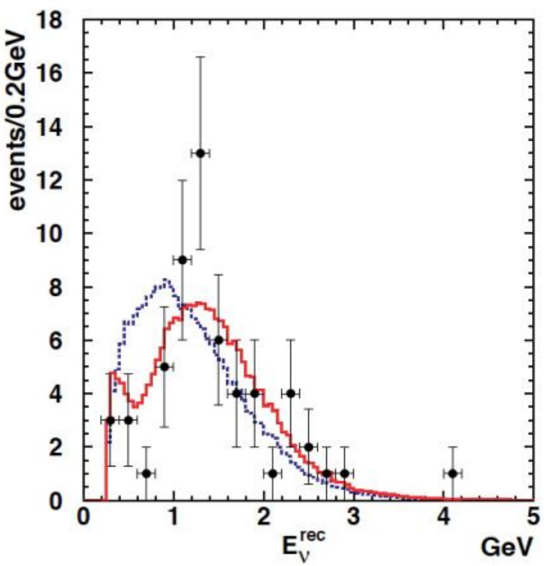
Best fits:

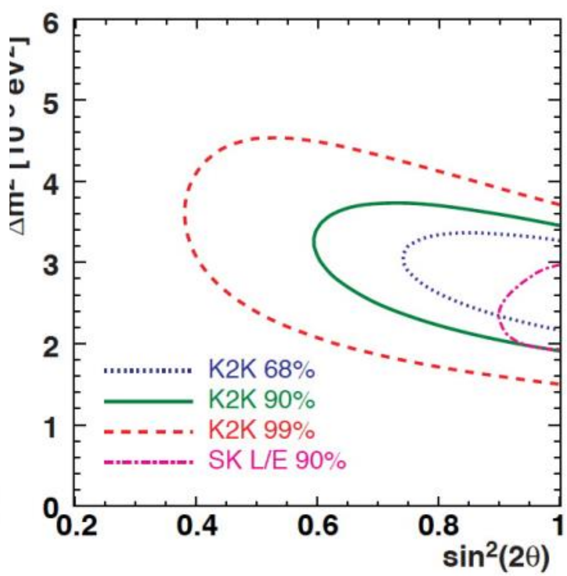
☞ $\Delta m^2_{32} = 2.8\ 10^{-3}\ \mathrm{eV}^2$

☞ $\sin^2(2\theta_{23}) = 1$

K2K Near Detector at 300 m:

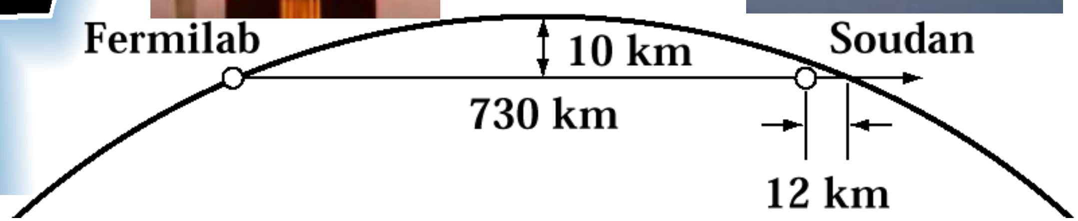






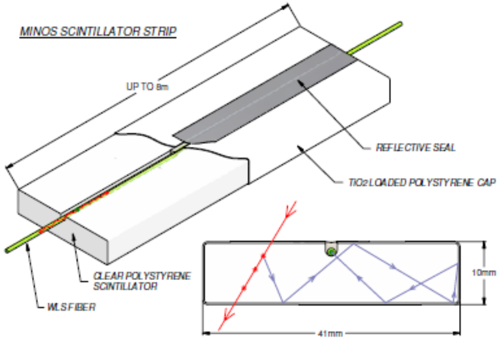
MINOS

A neutrino beam from Illinois to Minnesota



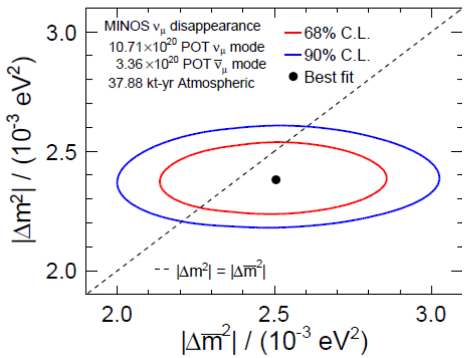
MINOS detector

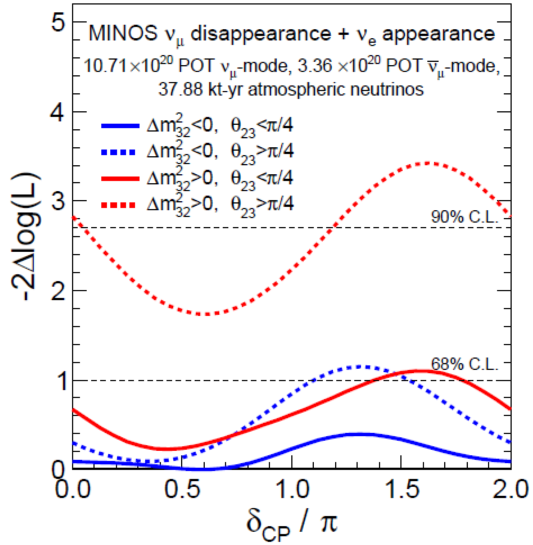
- 486 layers of 2.54 cm steel
- 485 planes 1 cm plastic scintillator
- Magnetized to ~3 T
- 8 m octagon
- Fiber readout - both ends

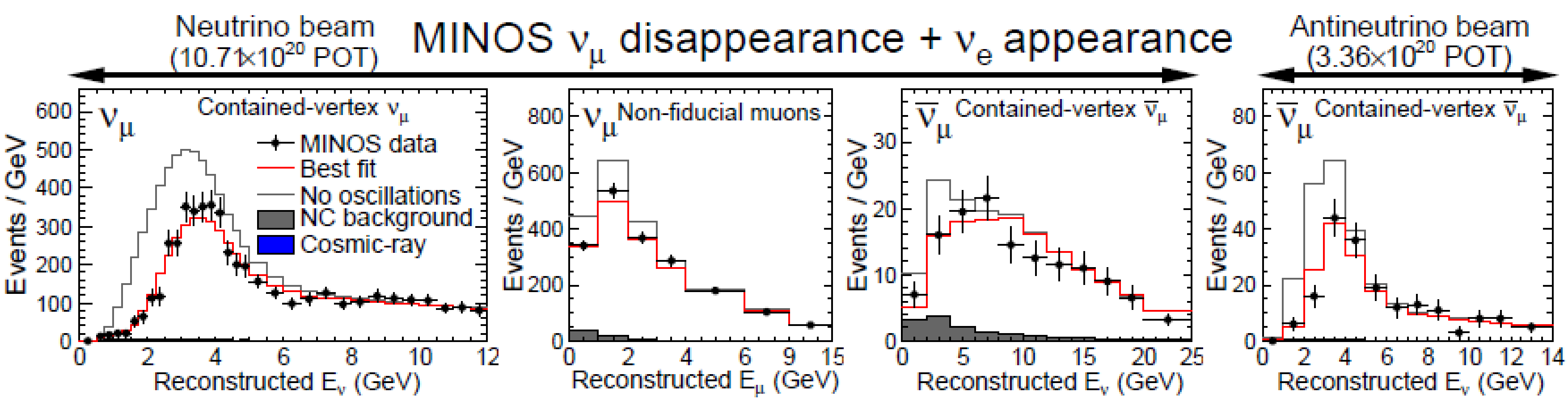


MINOS results
from 14.1 e20 pot & 39 kton-yr

- Δm^2_{32} = 2.28-2.46 10^{-3} eV^2
- 1st oscillations with $\bar{\nu}$
- Excluded no ν_e @ 96% CL

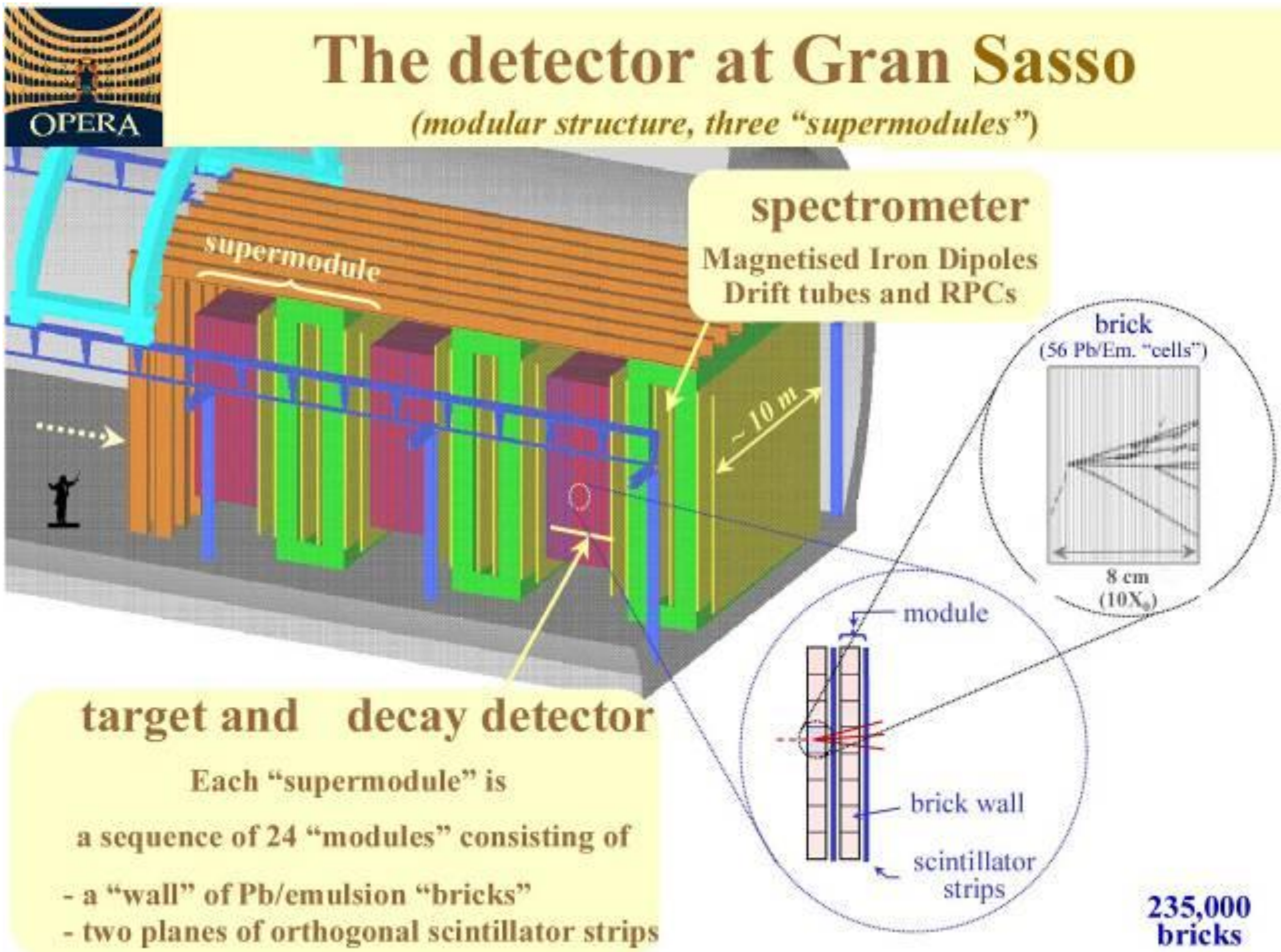


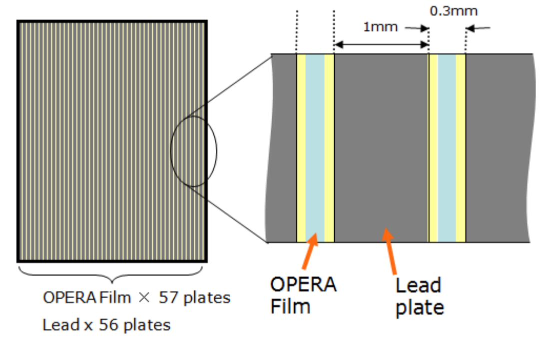




OPERA

$\nu_\mu \rightarrow \nu_\tau$

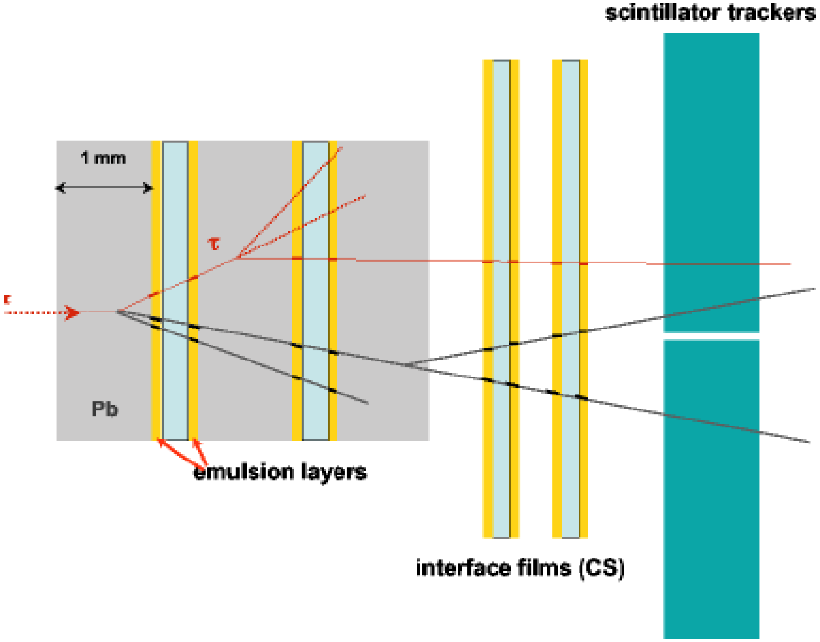


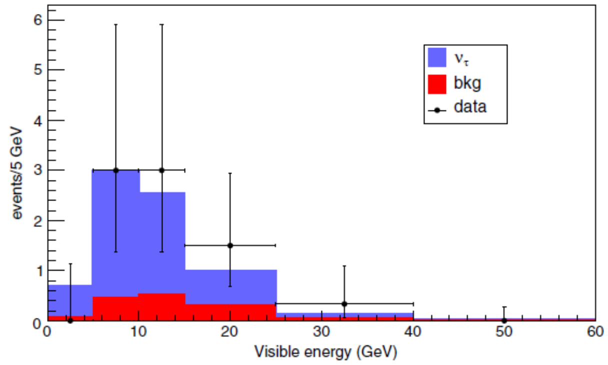


- CNGS beam
- 150,000 bricks
- 1.25 kton
- L = 732 km
- $<E_\nu> = 15$ GeV

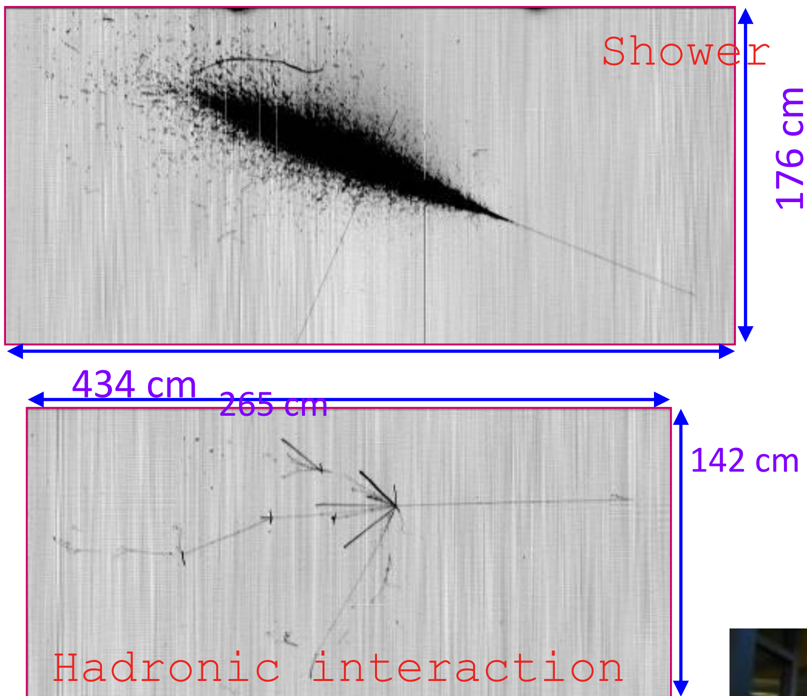
OPERA results
1.8 e20 pot

- Observed 10 ν_τ candidates
- 2.0 Background expected (charm)
- 6.1 σ ν_τ appearance
- $\Delta m^2_{32} = 2.7^{+.7}_{-.6}\, 10^{-3}\ \mathrm{eV}^2$
- Or use Δm^2_{32} to measure $\sigma(\nu_\tau)$

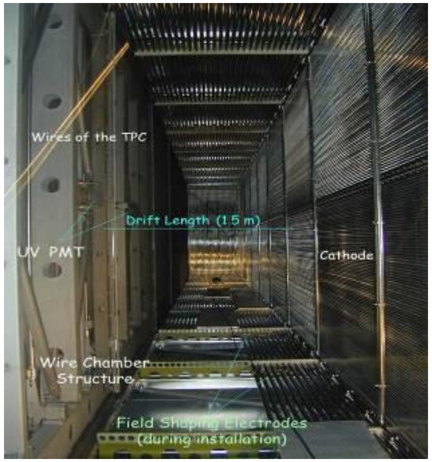




ICARUS



- Ran in CNGS beam
- 600 tons in 2 modules
- Pioneered LAr technology
- Overcame many challenges but took a long time.
- Ended up more R&D than physics



Questions?

Current long-baseline ν experiments

- T2K (J-PARC)
- NOvA (NuMI)

Analysis Issue
$P(\nu_\mu \rightarrow \nu_e)$ (in Vacuum)

$$P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$$

- $P_1 = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{31}^2\ L/E)$
- $P_2 = \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(1.27\ \Delta m_{21}^2\ L/E)$
- $P_3 = \ -/+\ J \sin(\delta) \sin(1.27\ \Delta m_{31}^2\ L/E)$
- $P_4 = J \cos(\delta) \cos(1.27\ \Delta m_{31}^2\ L/E)$

where $J = \cos(\theta_{13}) \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23})\ \mathrm{x}$

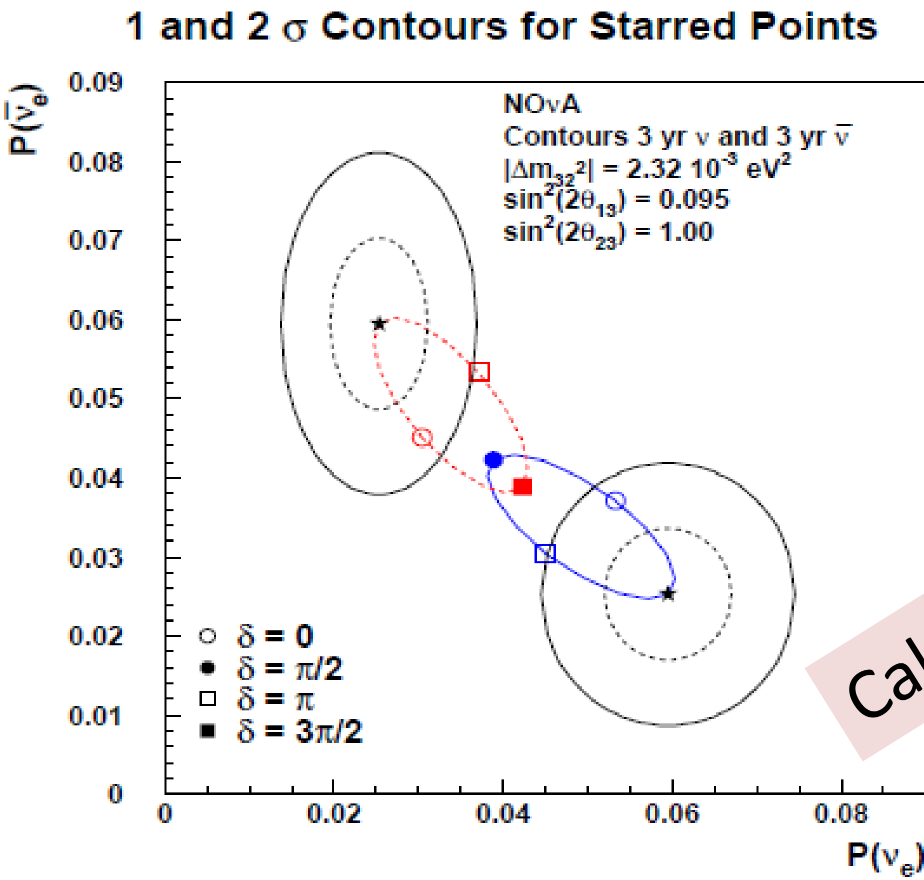
$$\sin(1.27\ \Delta m_{31}^2\ L/E) \sin(1.27\ \Delta m_{21}^2\ L/E)$$

Matter effects

- Oscillations in matter
  - P=P(θ,θ,θ,Δm^2,Δm^2,δ,n_e, mass order)

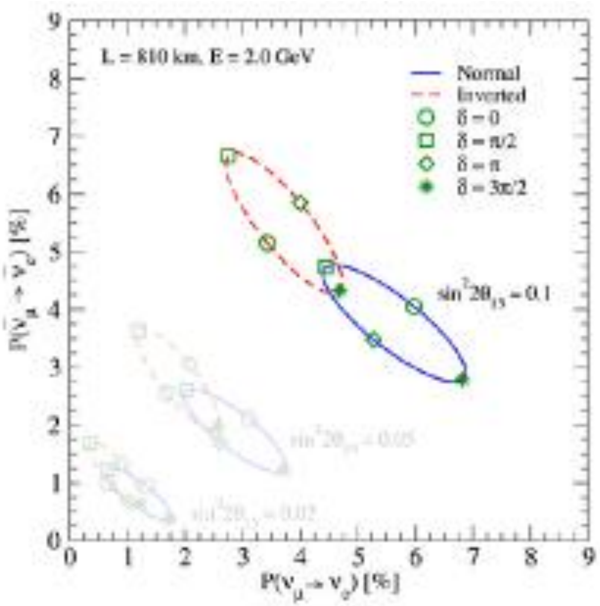
- Enhance oscillations for neutrinos in the normal mass order
- Enhance oscillations for antineutrinos in the inverted mass order

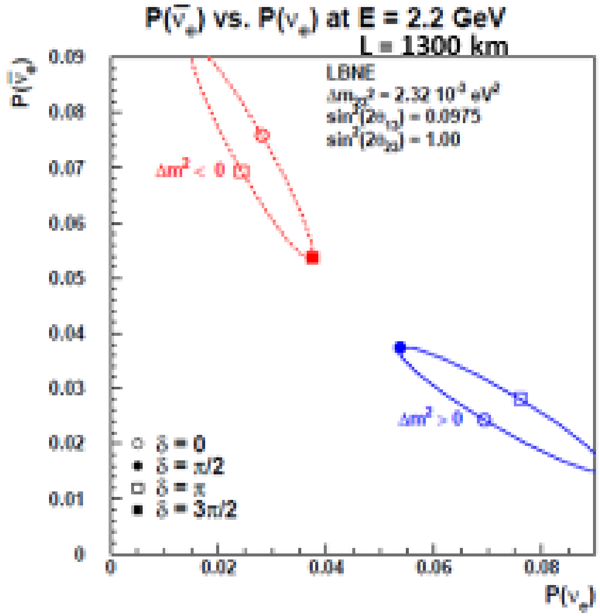
ν, $\bar{\nu}$ oscillation probabilities



Calculated at Fixed E_ν!

More Distance

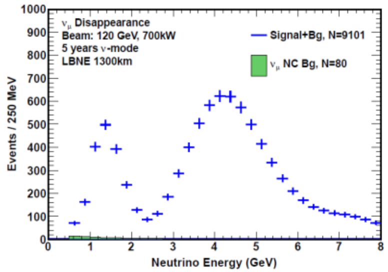


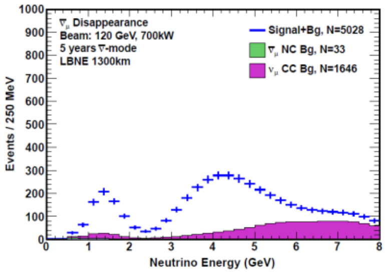


Comparison of 800 km to 1300 km

ν $\bar{\nu}$

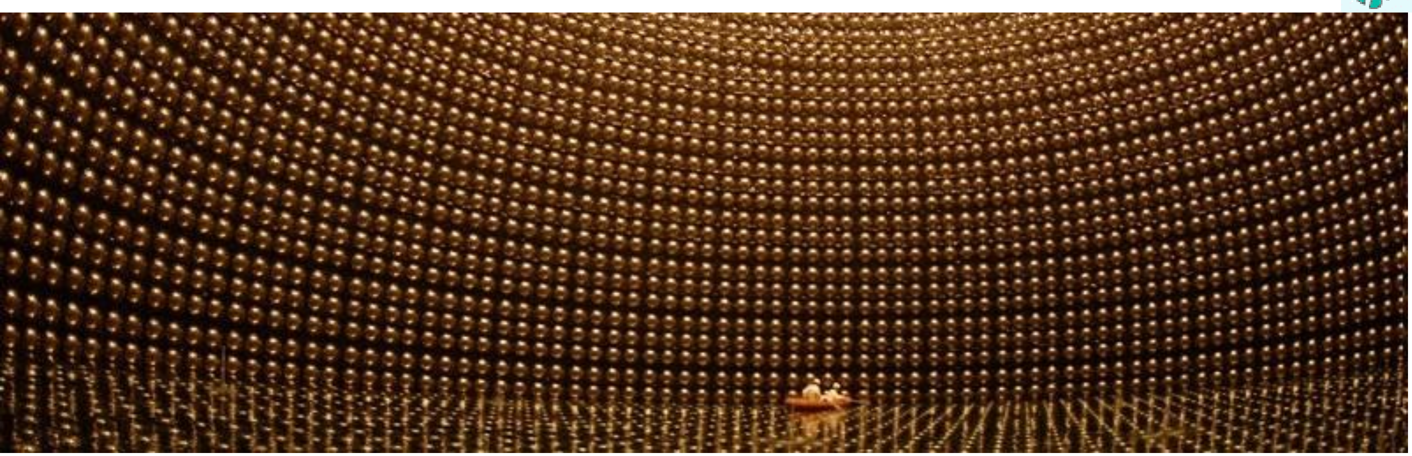
Spectra





T2K

- Accelerator at Tokai (J-PARC)
- Higher intensity than KEK
- Same far detector as K2K (i.e. Super-K)
- Off-axis for $\nu_\mu \rightarrow \nu_e$
- Better ND than K2K



T2K results from 2.2e20 pot

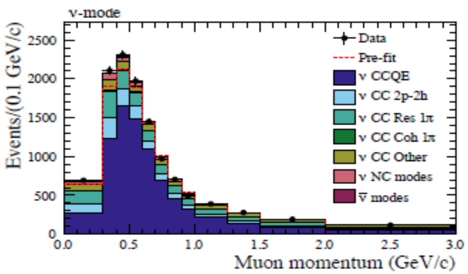


FIG. 1. FGD2 data, and model predictions prior to and after ND280 data fit, binned in p_μ for the ν beam mode CC0π sample. The prediction after the ND280 data fit is separated by type of interaction.

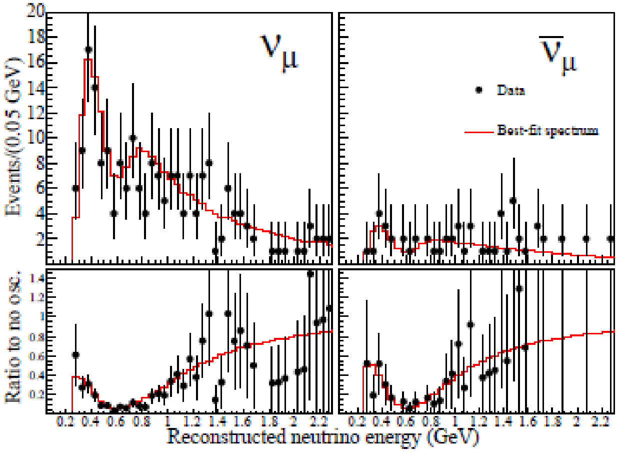


FIG. 2. Reconstructed neutrino energy distributions at the far detector for the ν_μ CCQE (left) and $\bar{\nu}_\mu$ CCQE (right) enriched samples with total predicted event rate shown in red. Ratios to the predictions under the no oscillation hypothesis are shown in the bottom figures.

	δ_{CP}	ν_e CCQE	ν_eCC $1\pi^+$	$\bar{\nu}_e$ CCQE
	$-\pi/2$	73.5	6.9	7.9
Normal	0	61.4	6.0	9.0
ordering	$\pi/2$	49.9	4.9	10.0
	π	61.9	5.8	8.9
	$-\pi/2$	64.9	6.2	8.5
Inverted	0	54.4	5.1	9.8
ordering	$\pi/2$	43.5	4.3	10.9
	π	54.0	5.3	9.7
Observed		74	15	7

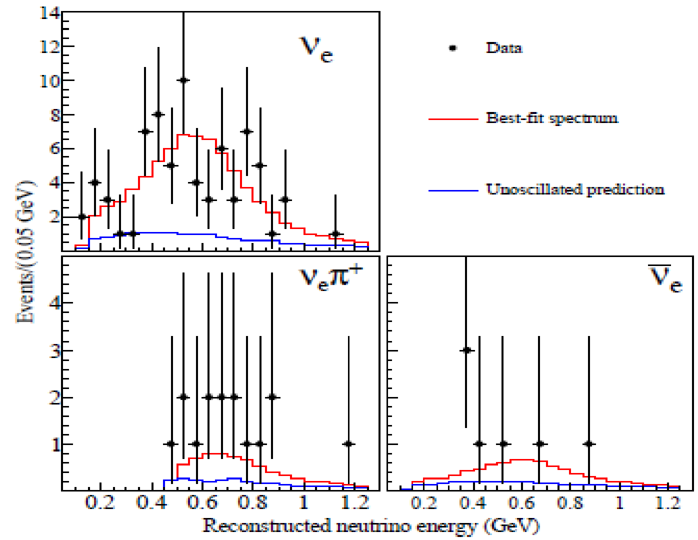
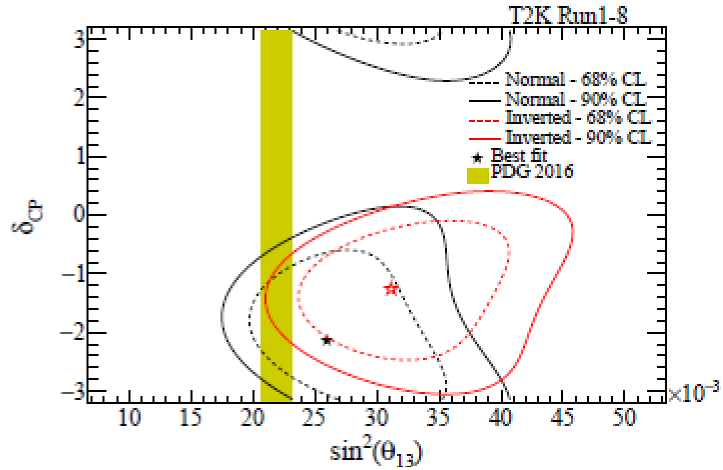
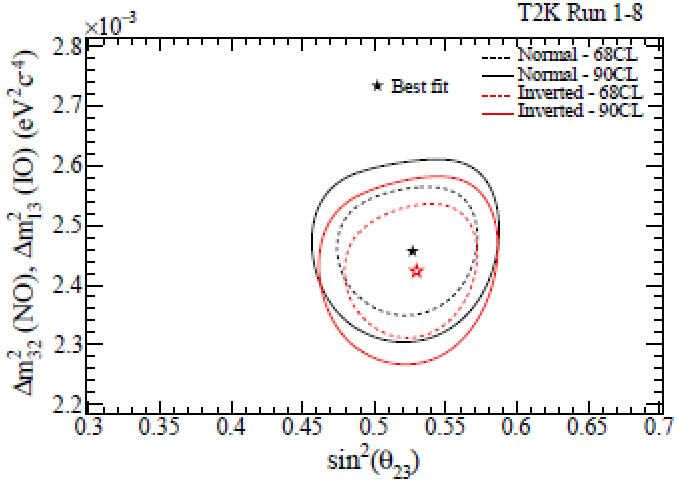


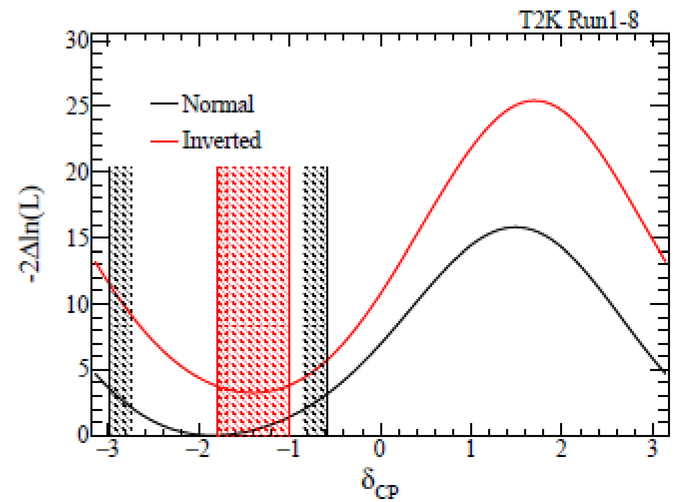
FIG. 3. Reconstructed neutrino energy distributions at the far detector for the ν_e CCQE (top left), ν_e CC$1\pi^+$ (bottom left) and $\bar{\nu}_e$ CCQE (bottom right) enriched samples. Predictions under the no oscillation hypothesis are shown in blue and best-fit spectra in red.

T2K results from 2.2e21 pot

- 89 ν_e candidates with 14.7(7.6)e20 pot
- CPV, 2σ CL for δ_{CP} doesn't include 0 or π π
- $\sin^2\theta_{23} = 0.526^{+0.032}_{-0.036}$
- $\Delta m^2_{32} = 2.463^{+0.071}_{-0.070}\ 10^{-3}\ \mathrm{eV}^2$
- Normal mass order favored
- 2.5 times more data planned







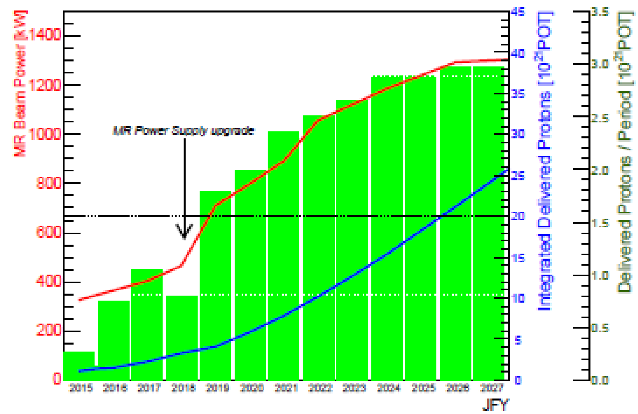
T2K-II proposal

- 2016 proposal
- 7.8e21 pot -> 20 e21 pot
- θ_{23} to 1.7°, Δm^2_{32} to 1%
- ND upgrade
- Results before 2026

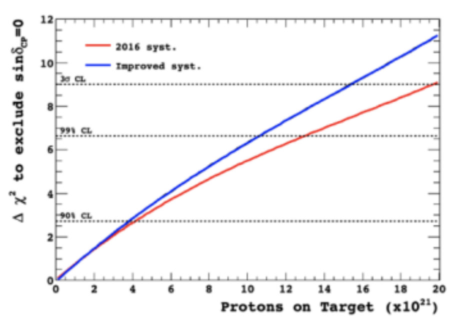
	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	467.6	356.3	4.0	73.3	1.8	32.3
ν_e sample	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode	0	133.9	16.7	73.6	29.2	0.4	14.1
$\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

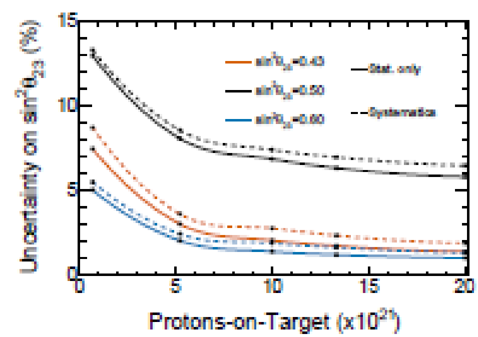
	Total	Beam CC ν_μ	Beam CC $\bar{\nu}_\mu$	Beam CC $\nu_e + \bar{\nu}_e$	$\nu_\mu \to \nu_e +$ $\bar{\nu}_\mu \to \bar{\nu}_e$	NC
ν-mode ν_μ sample	2735.0	2393.0	158.2	1.6	7.2	175.0
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1283.5	507.8	707.9	0.6	1.0	66.2

J-PARC upgrades



Improving sensitivity



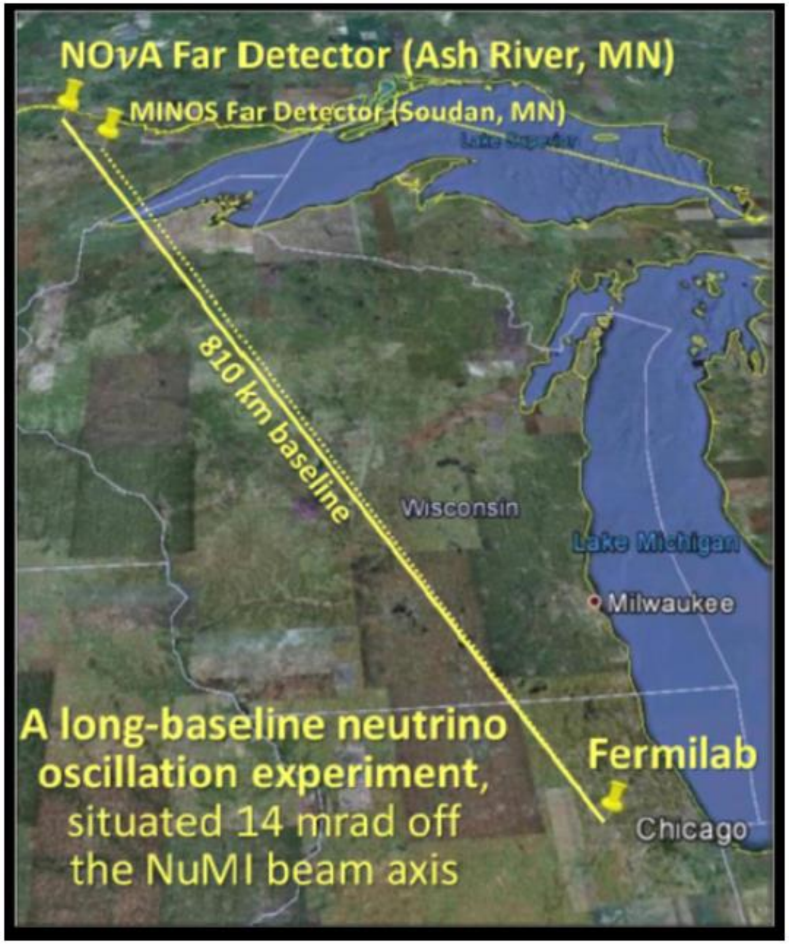


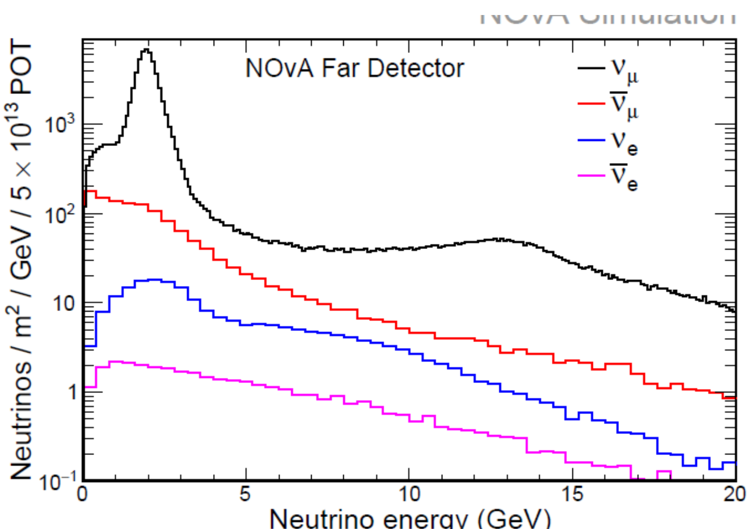
Questions?

NOνA

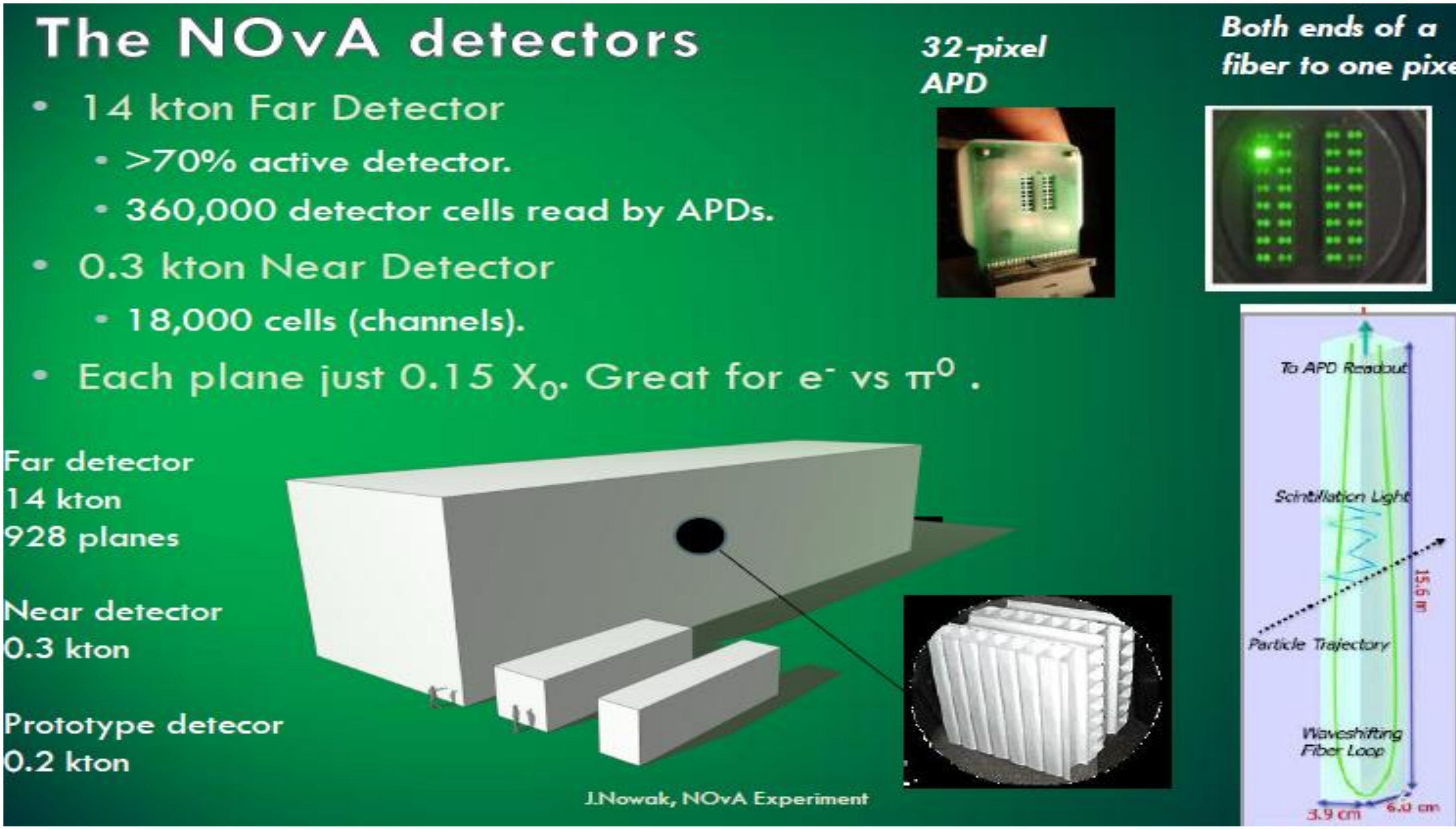
Neutrino Oscillation ν_e appearance

- Same beamline as MINOS
- E_ν tuned lower (2 GeV)
- Oscillation max - 810 km
- 14 kT FD segmented scintillator





NOνA

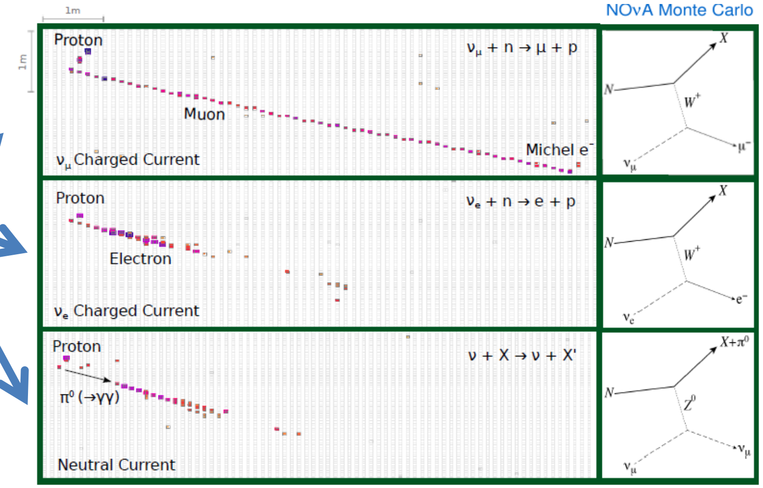

The NOvA detectors
• 14 kton Far Detector
• >70% active detector.
• 360,000 detector cells read by APDs.
• 0.3 kton Near Detector
• 18,000 cells (channels).
• Each plane just 0.15 X0. Great for e- vs π0 .
32-pixel APD
Both ends of a fiber to one pixel
To APD Readout
Scintillation Light
Particle Trajectory
Waveshifting Fiber Loop
15.6 m
3.9 cm
6.0 cm
Far detector
14 kton
928 planes
Near detector
0.3 kton
Prototype detecor
0.2 kton
J.Nowak, NOvA Experiment

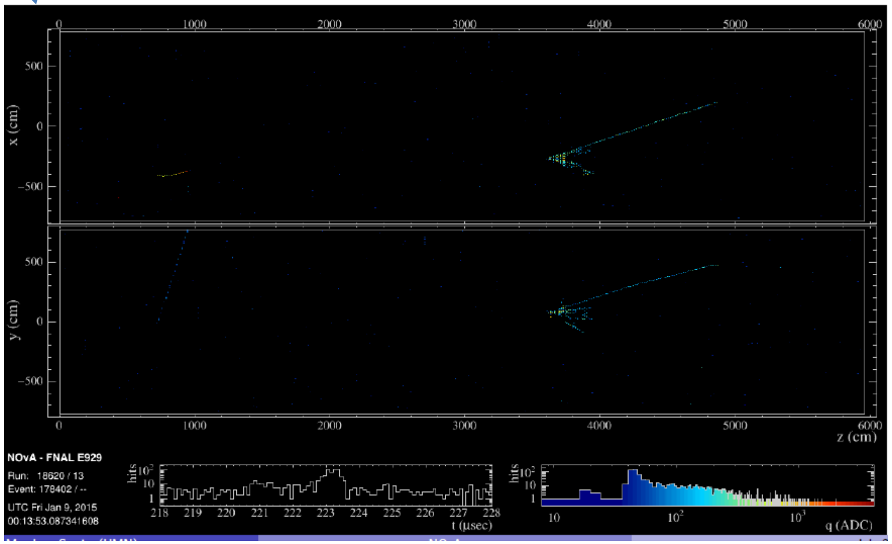
NOνA events

Particle Identification (PID)

- ν_μ CC
- ν_e CC
- NC
- Cosmic

- MC
- Data



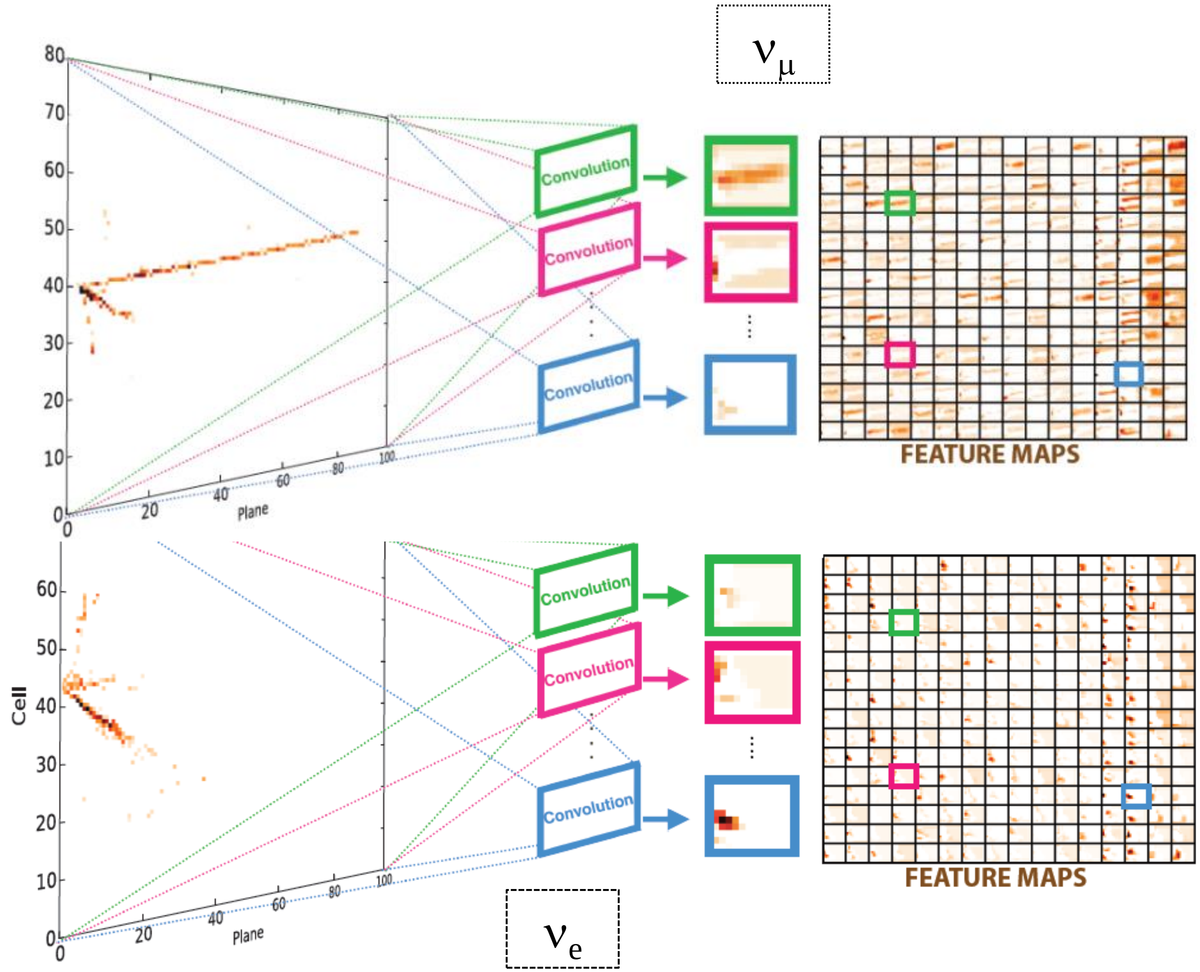


- PID originally done with cuts. This is now mostly done with Machine Learning techniques

"CVN"

Machine Learning

Pattern recognition without reconstruction



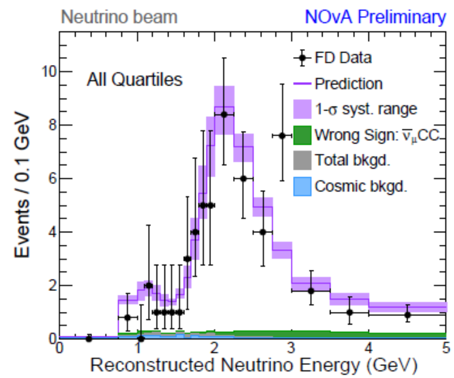
NOvA results from 21.3e20 pot

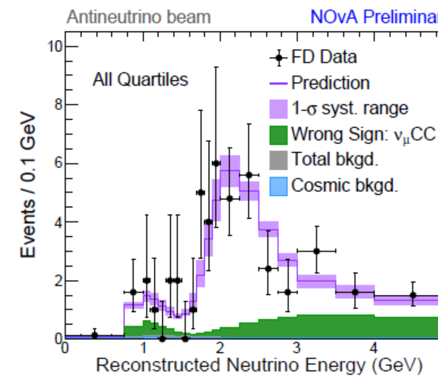
$\nu_\mu \rightarrow \nu_\mu$ (total ; Background)

⌘ (8.9e20 ν) 113 ν_μ ; 4.2

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

⌘ (12.3e20 $\bar{\nu}$) 102 ν_μ ; 2.2



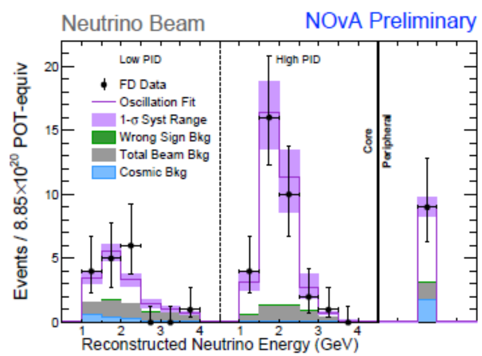


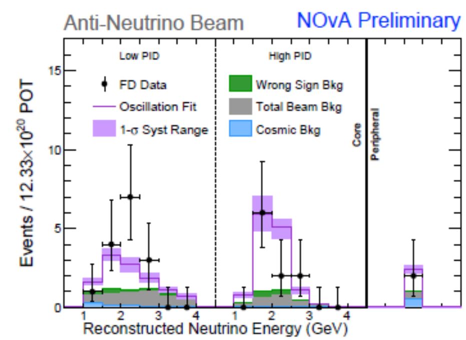
$\nu_\mu \rightarrow \nu_e$

⌘ 58 ν_e ; 15

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

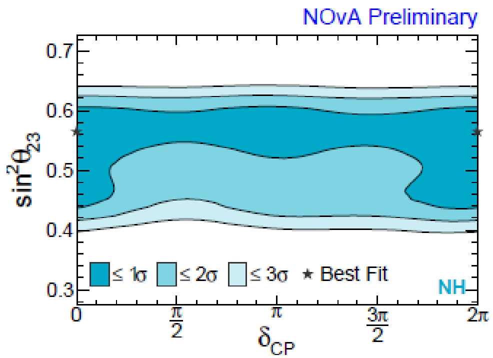
⌘ 27 $\bar{\nu}_e$; 10.3

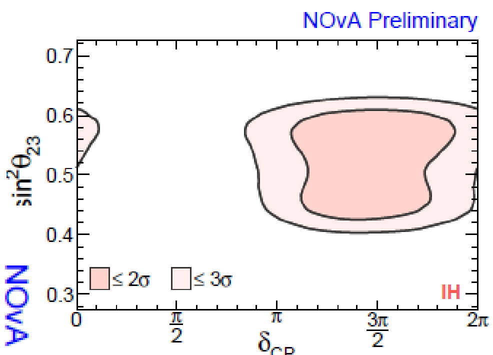


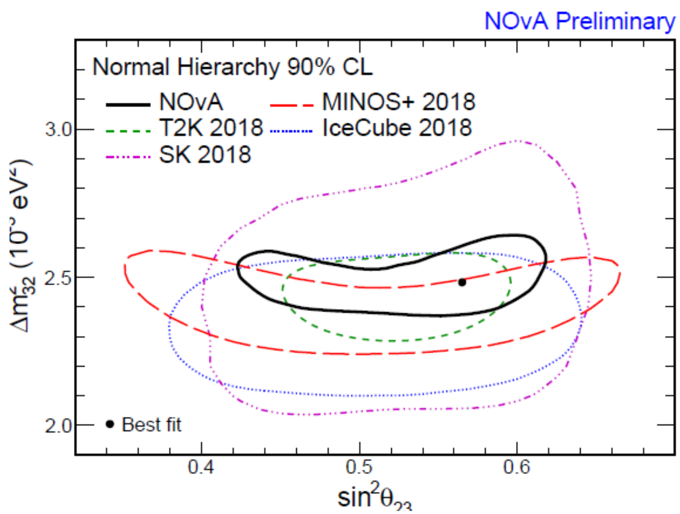


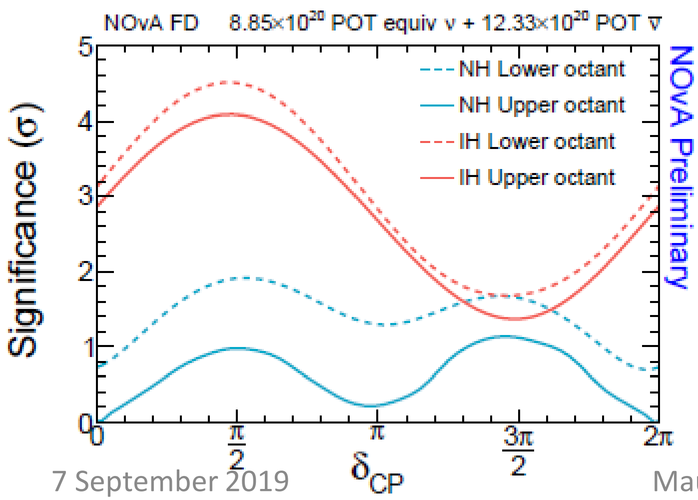
NOνA results from 21.3e20 pot

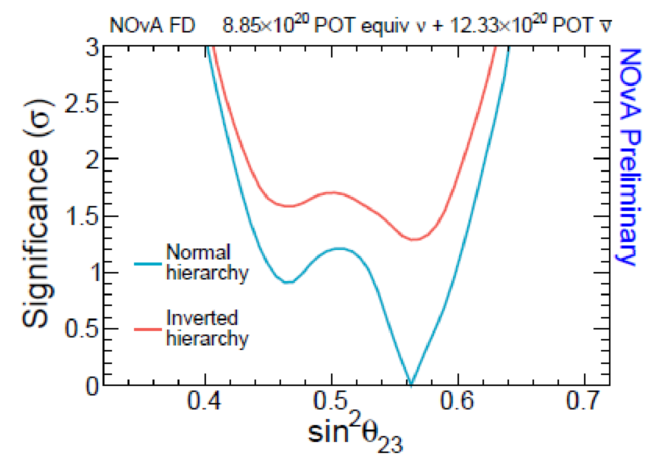
- Prefer NO by 1.9 σ
- Upper Octant at 1.6 σ
- Exclude $\delta = \pi/2$ in IO >3σ
- $\Delta m^2_{32} = 2.48^{+0.10}_{-0.06}\ 10^{-3}\mathrm{eV}^2$
- $\sin^2\theta_{23} = 0.56 \pm 0.04$ (Upper)





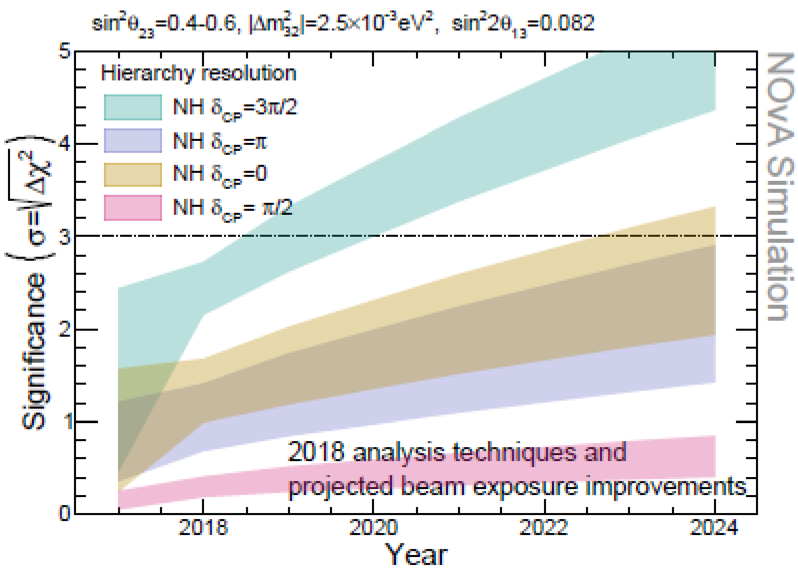


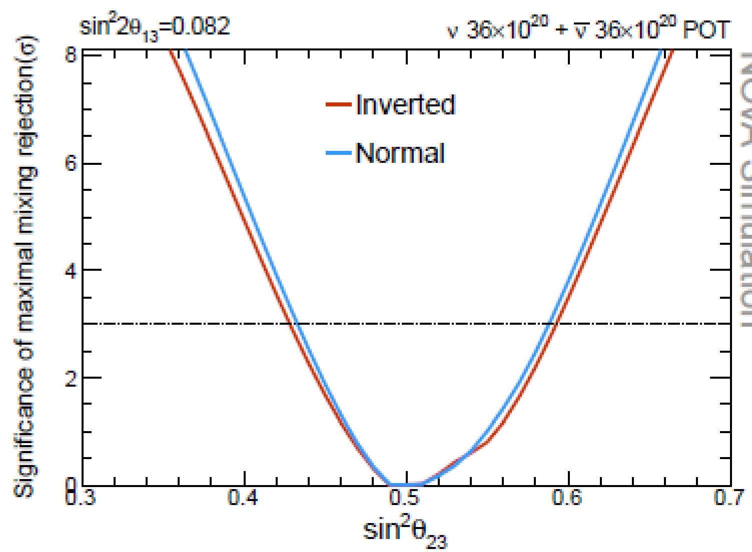




NOνA plans by 2024

- 36e20 pot × 2 by 2024
- 3σ for 30% of δ
- 3σ rejection of maximal mixing for $\sin^2\theta_{23} < 0.43$ or > 0.59





Draft Fermilab Long-Range Schedule

Office of the CRO July 2019

DRAFT LONG-RANGE PLAN

		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF / PIP II	SANFORD				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	
	FNAL				LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERv	MINERv	OPEN	OPEN	OPEN	OPEN	OPEN	OPEN						ν
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA						
BNB	B	BooNE	BooNE	BooNE	OPEN	OPEN	OPEN	OPEN	OPEN			OPEN	OPEN	OPEN	
		CARUS	CARUS	CARUS	CARUS	CARUS	CARUS	OPEN	OPEN			OPEN	OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN	OPEN			OPEN	OPEN	OPEN	
Muon Complex		g-2	g-2	g-2	g-2					LONG SHUTDOWN AND FACILITY COMMISSIONING				OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e			Mu2e	Mu2e	OPEN	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	FTBF	p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF				FTBF	FTBF	FTBF	
	NM4	OPEN	SpinQ	SpinQ	SpinQ	SpinQ	OPEN	OPEN				OPEN	OPEN	OPEN	
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

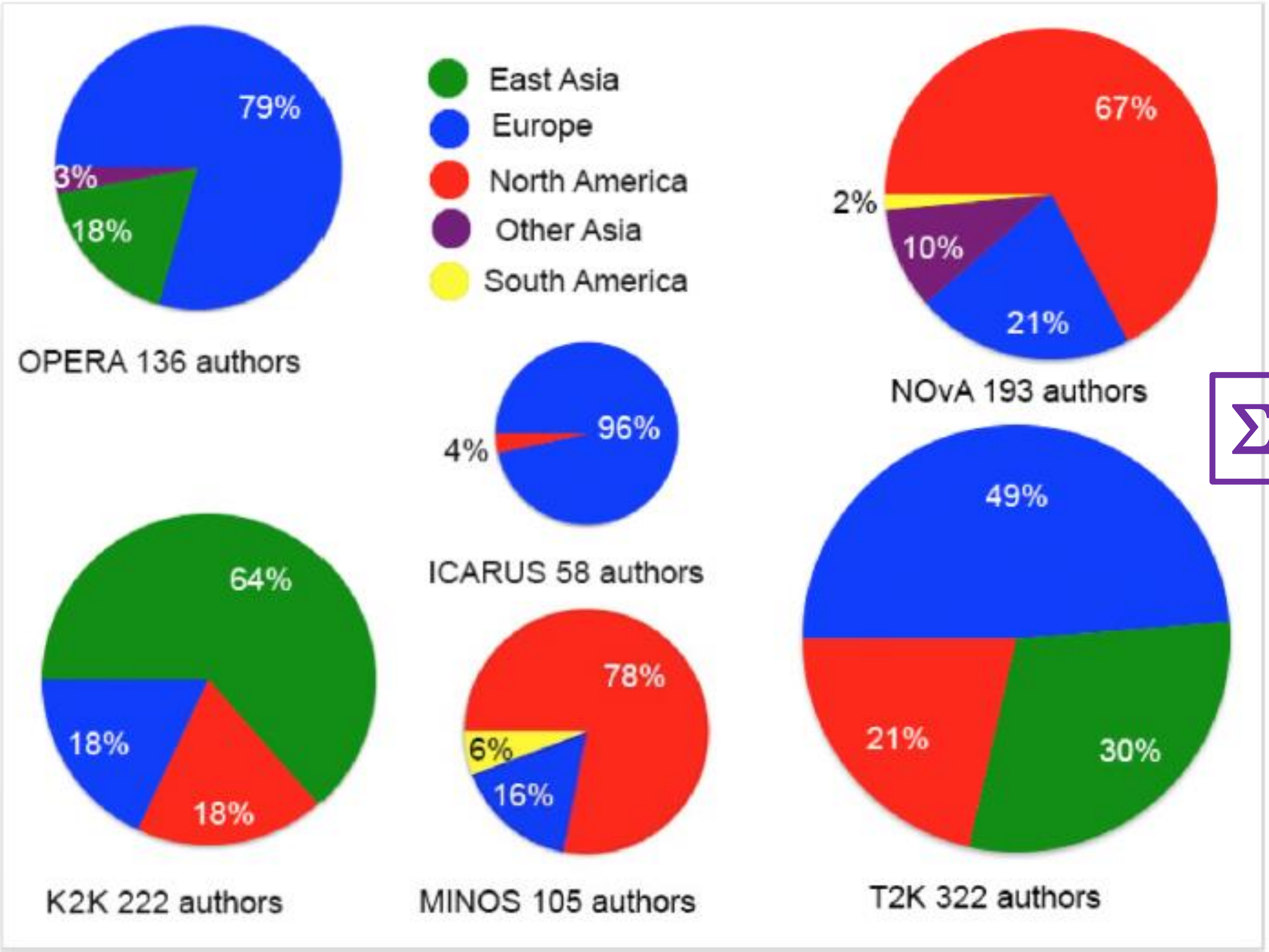
Construction / commissioning · Run · Subject to PAC review · Shutdown

Capability ended · Capability unavailable

NOTES

1. This draft long-range plan is updated annually, typically following the summer PAC meeting.
2. Summer shutdowns will typically last 3-4 months during the construction of LBNF/DUNE and PIP-II. The timing and length of the 2-year Long Shutdown associated with the major construction activities at the lab will become clearer as the projects are baselined. Optimized commissioning and physics startup plans will be developed.
3. There will be no SY120 running from 6/2024 through the end of the long shutdown.
4. NOvA is expected to run until the beginning of the Long Shutdown at which point the NuMI beam will be permanently decommissioned. The NOvA experiment will continue to alternate between neutrino and anti-neutrino running.
5. SpinQuest is expected to finish commissioning and begin its 2-year run in FY20. Running beyond FY21 is subject to PAC review.
6. The Irradiation Test Area (ITA) is planned to be commissioned and begin operations in FY20.

Long-Baseline ν Demographics



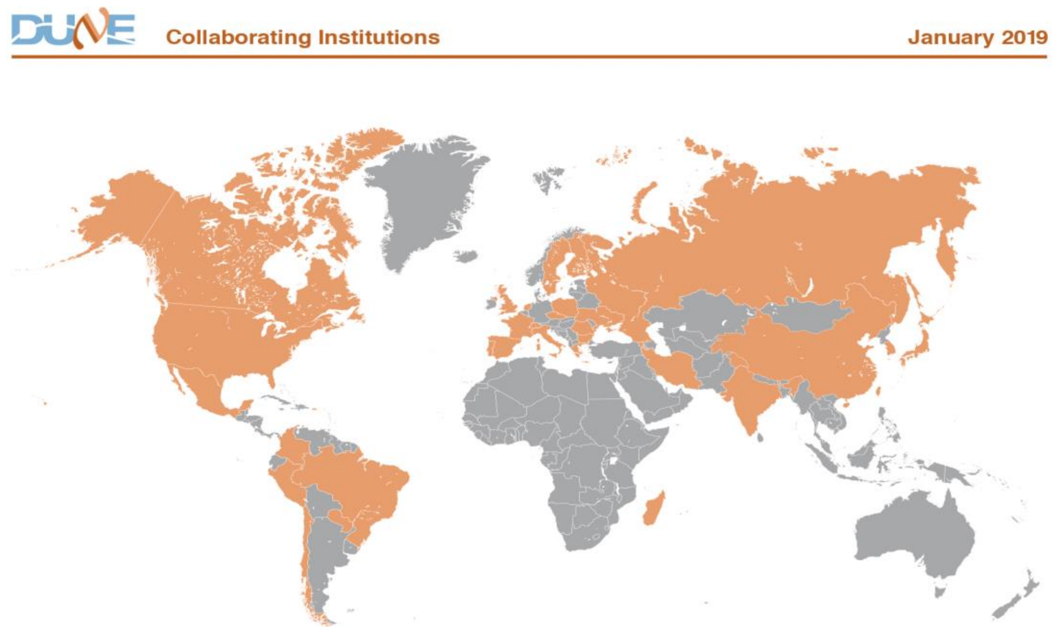
$\Sigma = 1036$

Questions?

Future long-baseline ν experiments

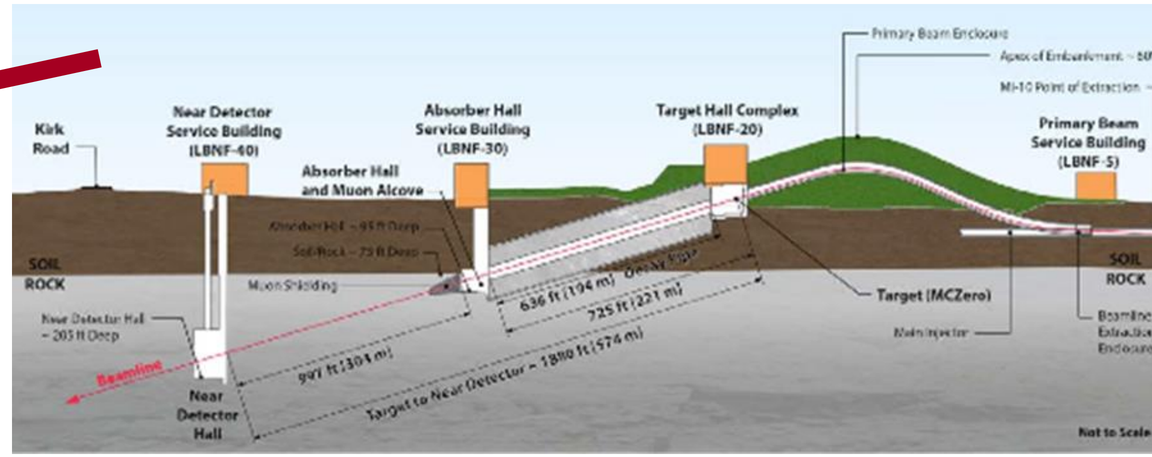
DUNE

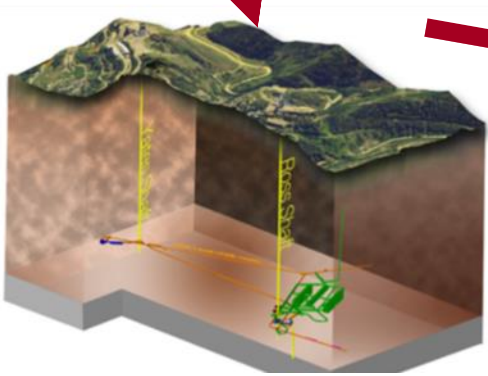
Deep Underground Neutrino Experiment

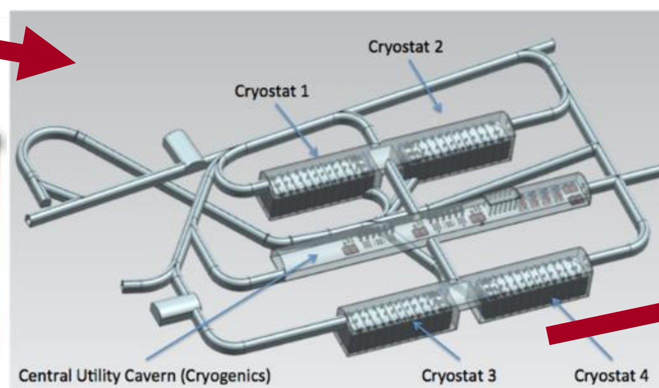


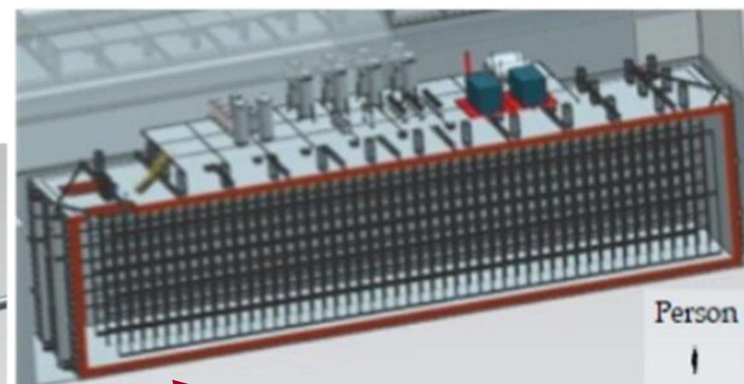
- As of January 2019
  - 1202 collaborators from 183 institutions in 31 countries
  - 648 faculty/scientist, 201 PDs, 119 engineers, 234 PhD students

Anatomy of DUNE





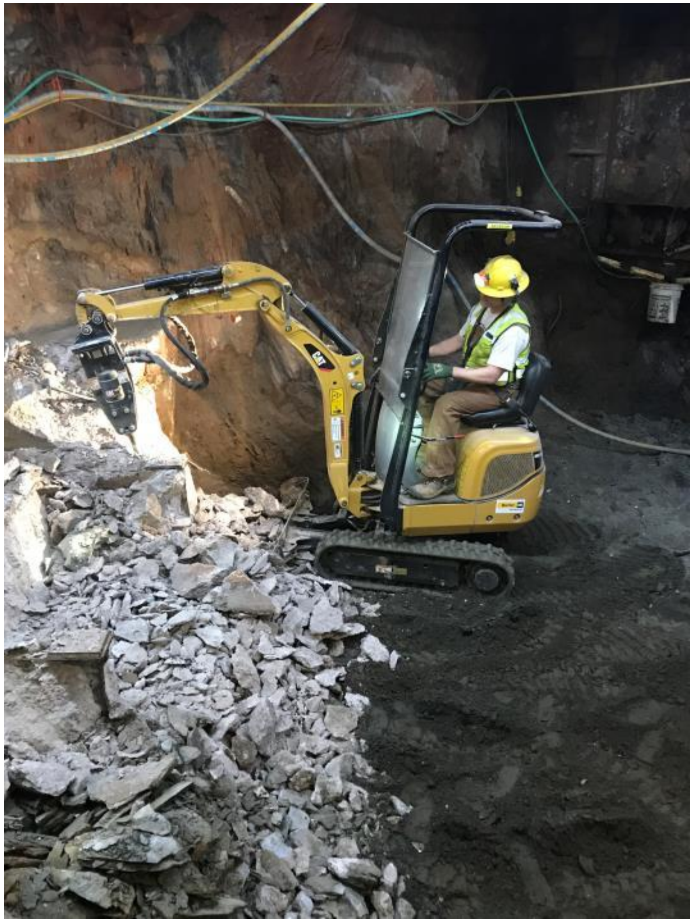




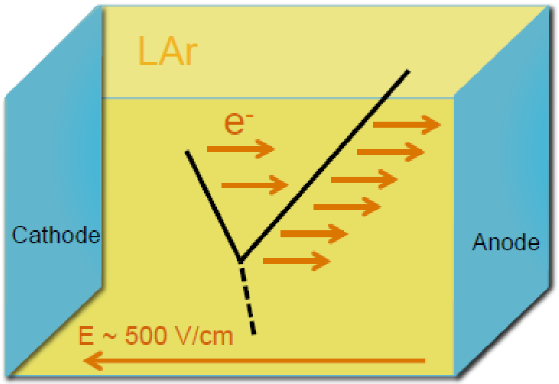
15m x 15 m x 65 m

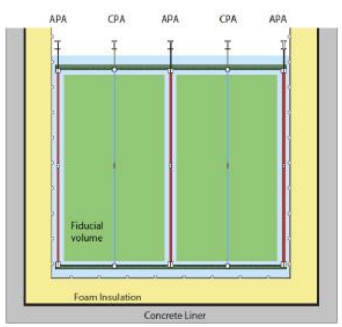
DUNE

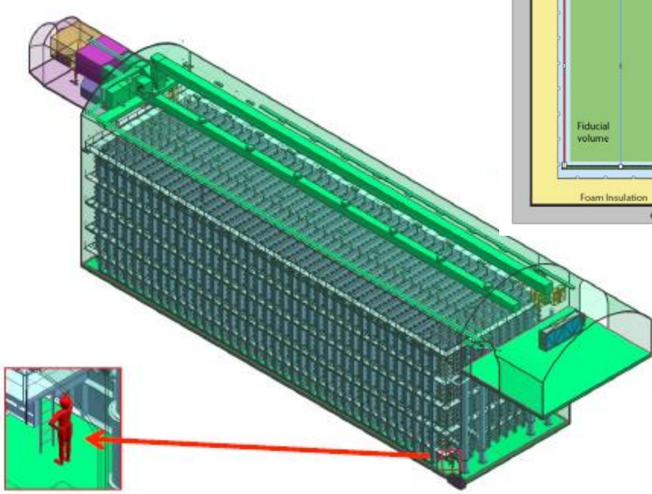
removing muck from old "Ore Pass"

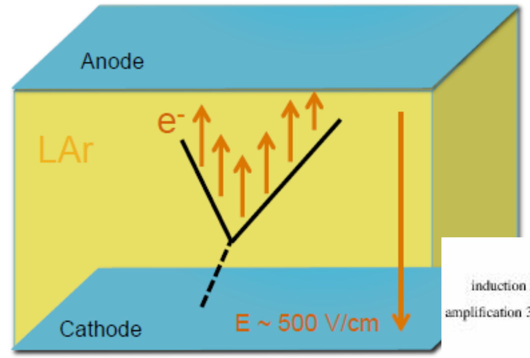


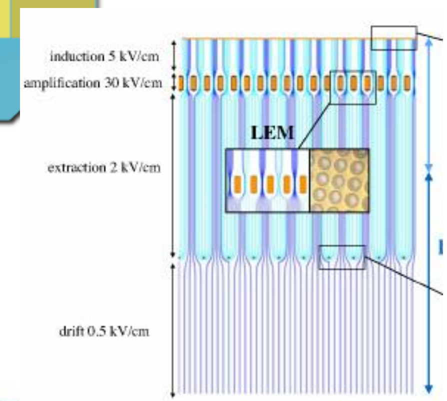
DUNE
Single Phase-Dual Phase

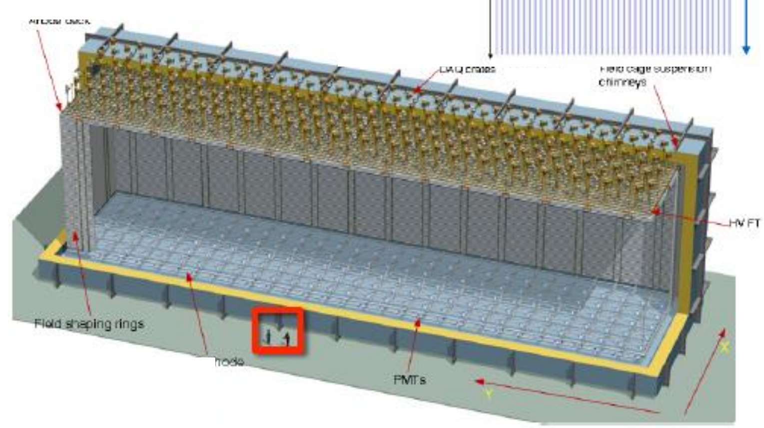












Strategy

- The DUNE Collaboration is pursuing and prototyping two LAr TPC technologies, SP &DP
- The collaboration is planning for the 1^{st} 10 kT module to be SP & 2^{nd} DP (2+1+1 model with 3^{rd} module SP and 4^{th} ‘module of opportunity’)
- Sequencing (SP-DP-SP vs. SP-SP-DP) will depend on ProtoDUNE results & resources

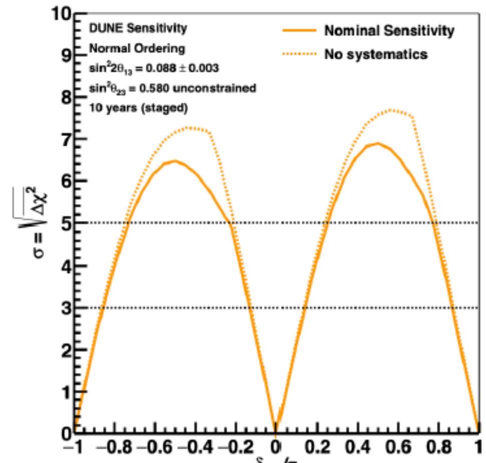
DUNE Schedule

- Physics TDR will be available soon
- Detector 1 ready to start installation August 2024
- Detector 1 ready for cool down August 2025
- Detector 1 ready for physics late summer 2026
- Detector 2 ready to start installation August 2025
- Detector 2 ready for cool down August 2026
- Detector 2 ready for physics late summer 2027

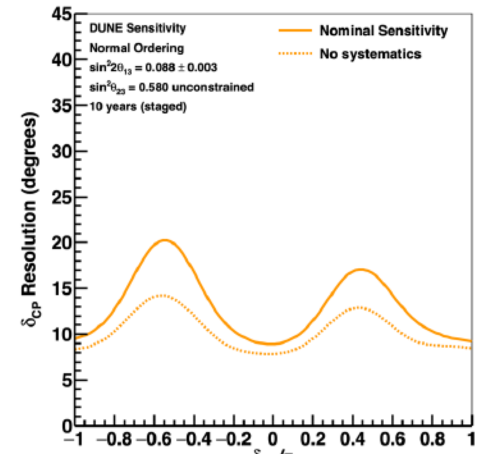
Projected DUNE sensitivities 10 y

2019 calculations for 10 staged years of DUNE

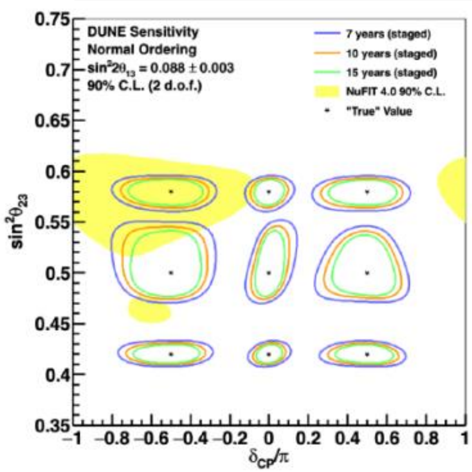
See CP Violation



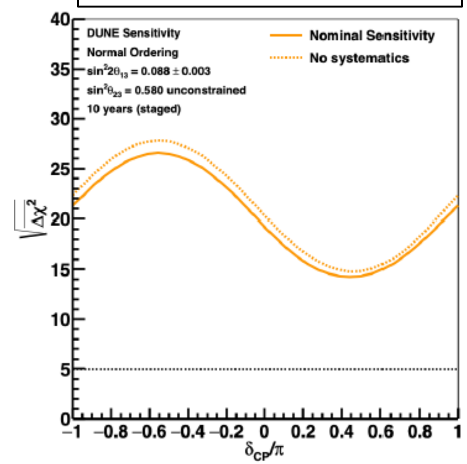
Measure δ_{CP}



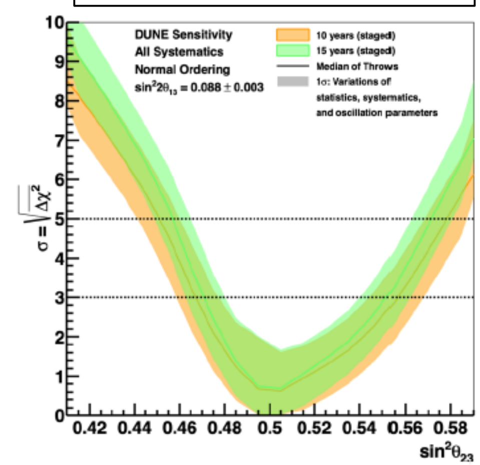
9 possible values



Mass order



Measure θ_{23}

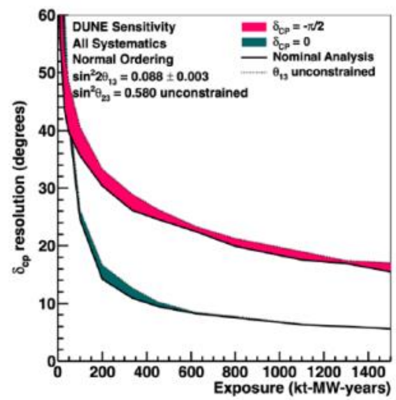


DUNE sensitivities versus exposure

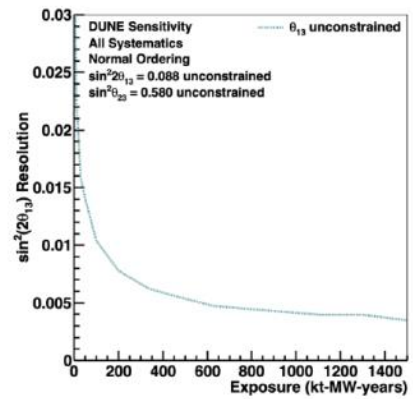
Sensitivities vs time (exposure)

- ✶ Nominal analysis
- ✶ With systematics
- ✶ Assuming 3ν

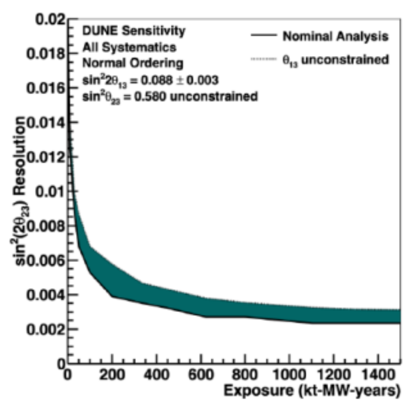
Measure δ_{CP}



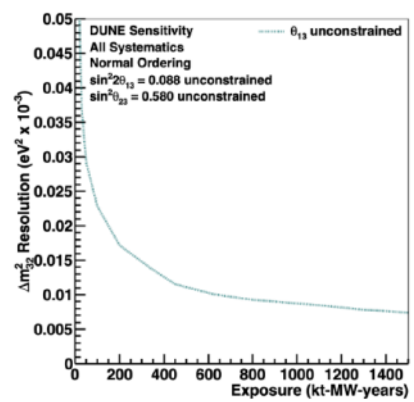
Measure θ_{13}



Measure θ_{23}



Measure Δm^2_{32}



Questions?

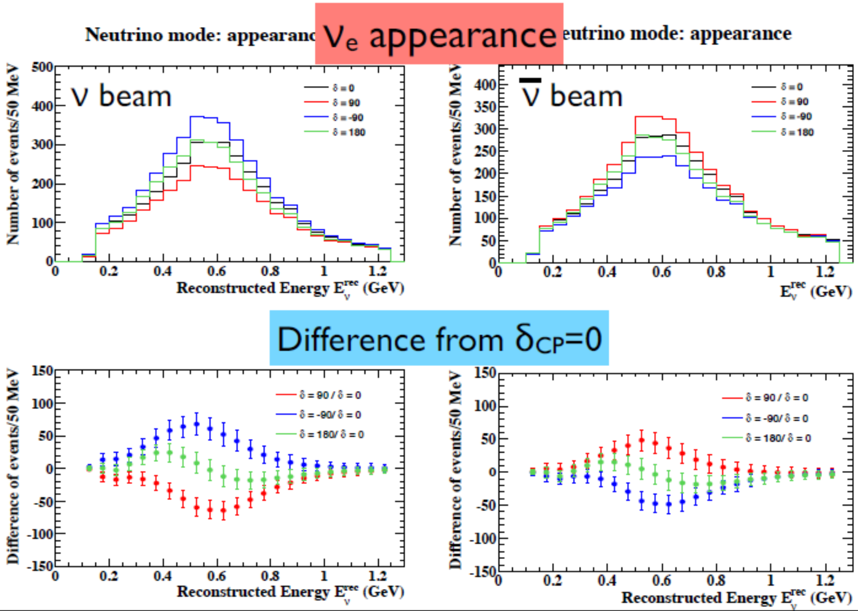
Hyper-Kamiokande

- 186 kton (fiducial) Water detector (10×Super-K)
- J-PARC upgraded to 1.3 MW
- Not approved, but a “priority project” by MEXT’s roadmap

Projected Hyper-K sensitivity

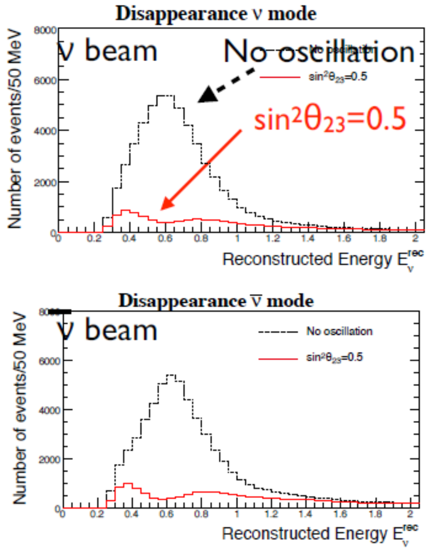
10 years ($13MW \times 10^7 s$)

ν_e appearance



for δ=0	Signal ($\nu\mu \rightarrow \nu e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu e/\bar{\nu} e$ contamination	NC
ν beam	2,300	21	10	362	188
$\bar{\nu}$ beam	1,656	289	6	444	274

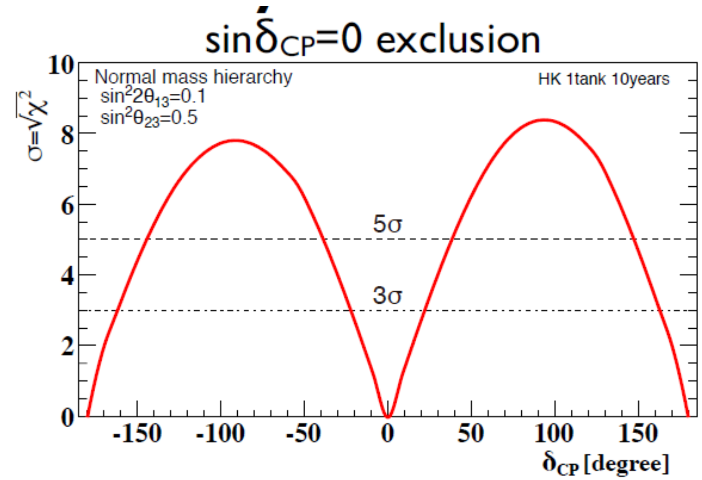
ν_μ disappearance

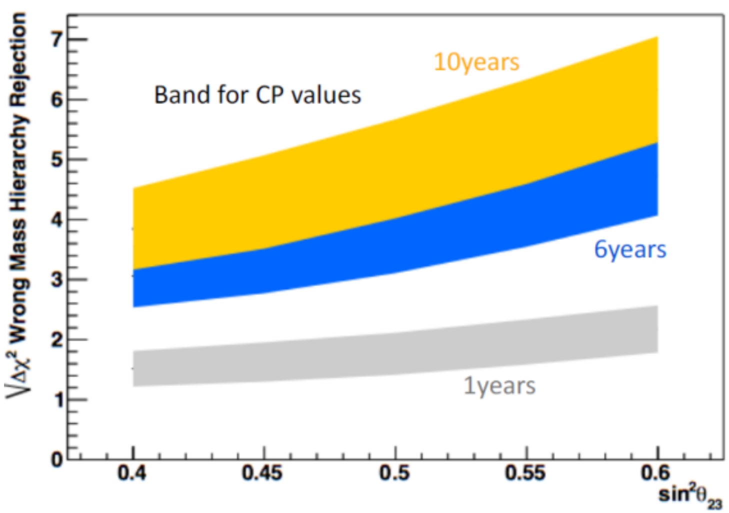


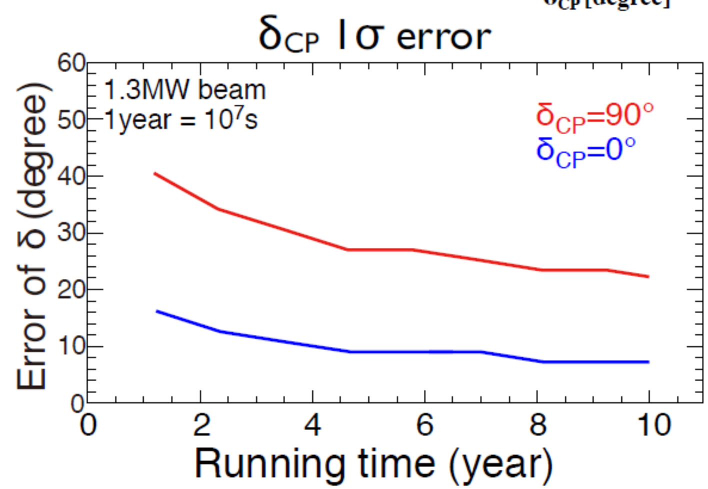
	$\nu_\mu+\bar{\nu}_\mu$ CCQE	ν_μCC nonQE	Others
ν beam	8,947	4444	721
$\bar{\nu}$ beam	12317	6040	859

Hyper-K
mass order & CP

- ☞ 80% of δ for 3σ CPV
- ☞ 8σ for T2K best fit
- ☞ σ(δ) = 22°(7°) for -90° (0°)







Questions?

Other accelerator-based neutrino experiments

other than long-baseline ν experiments

I found 8 classes of things to mention

1. Pre-oscillation days

- Establish neutral currents

  Gargamelle
  E1
  15' Bubble Chamber

- Measure structure functions

  CCFR
  CHARM
  E594
  CCFR

- Measure Weinberg angle

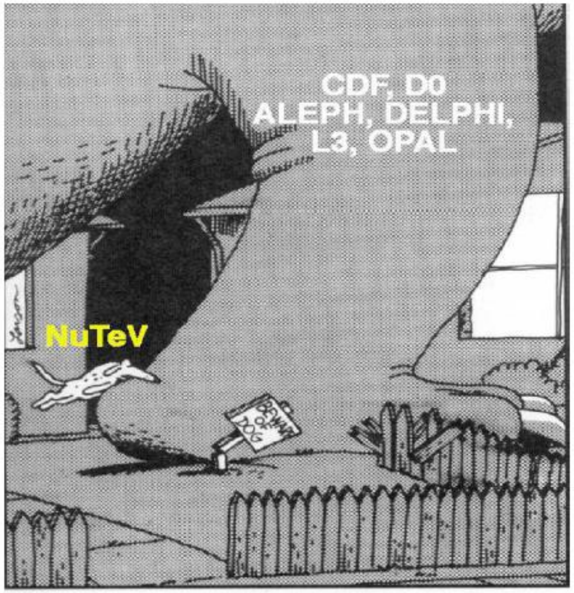
  NuTeV

NuTeV anomaly

Measure

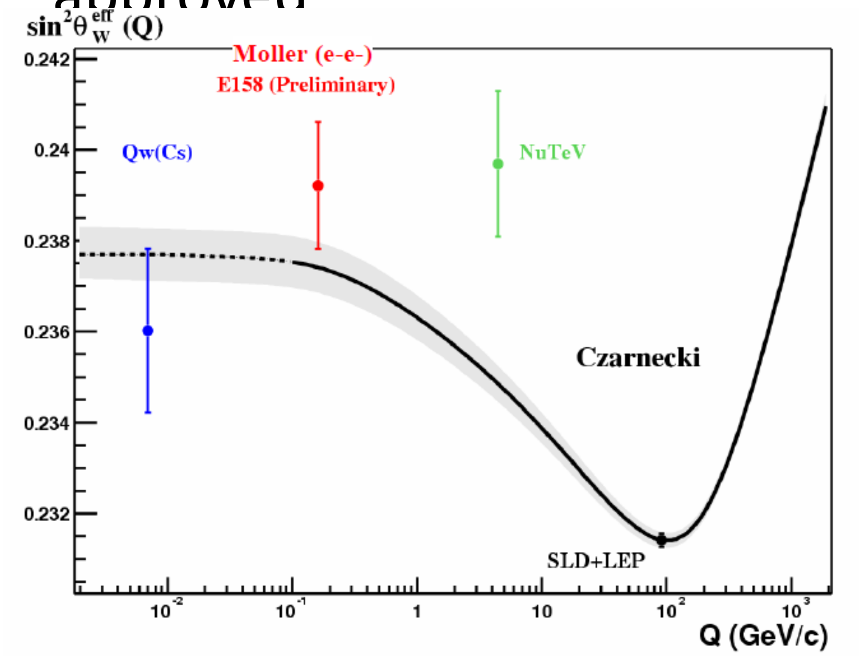
$$\boxed{R^{\nu(\bar{\nu})} = \frac{\sigma_{NC}^{\nu(\bar{\nu})}}{\sigma_{CC}^{\nu(\bar{\nu})}} = \rho^2\left(\frac{1}{2} - \sin^2\theta_W + \frac{5}{9}\sin^4\theta_W\left(1 + \frac{\sigma_{CC}^{\bar{\nu}(\nu)}}{\sigma_{CC}^{\nu(\bar{\nu})}}\right)\right)}$$

	Short (NC) Events	Long (CC) Events	R_{exp}=Short/Long
Neutrino	457K	1167K	**0.3916** ± 0.0007
Antineutrino	101K	250K	**0.4050**± 0.0016



Toby vs. Godzilla

- Follow-up experiment not approved



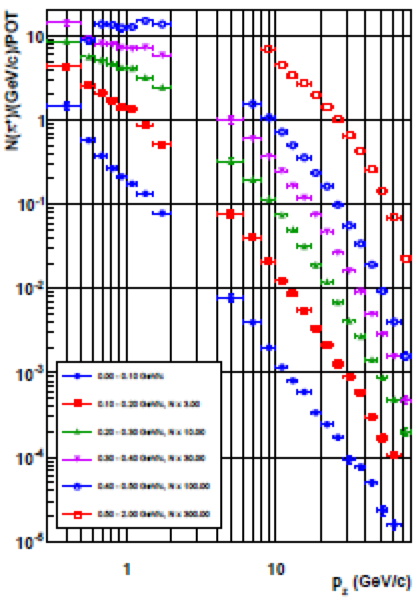
2. Production experiments

- The Goal is to study neutrino production rates by measuring π/K yields from pN reactions
- Need for understanding of:
  1. π/K yields from fixed E_p proton on nuclei
  2. π/K survival from scattering leaving the target
- Thin targets for (1); Actual targets for (2)

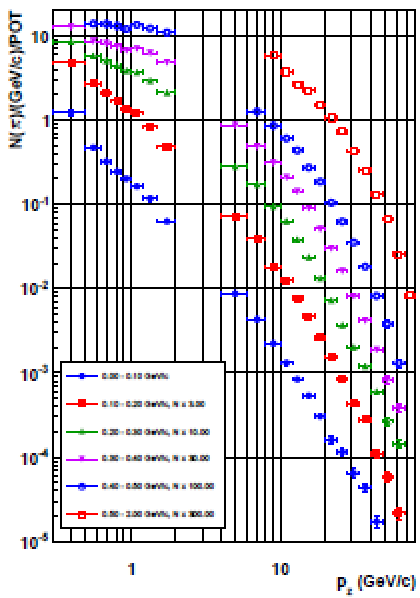
SHINE
HARP
MIPP

MIPP results

- ✶ 120 GeV protons off a NuMI target
- ✶ π^+(left) an π^- (right) vs p_x in bins of p_t



(a)π^+ yields.



(b)π^- yields.

TABLE I: Pion Production Yields - NuMI target

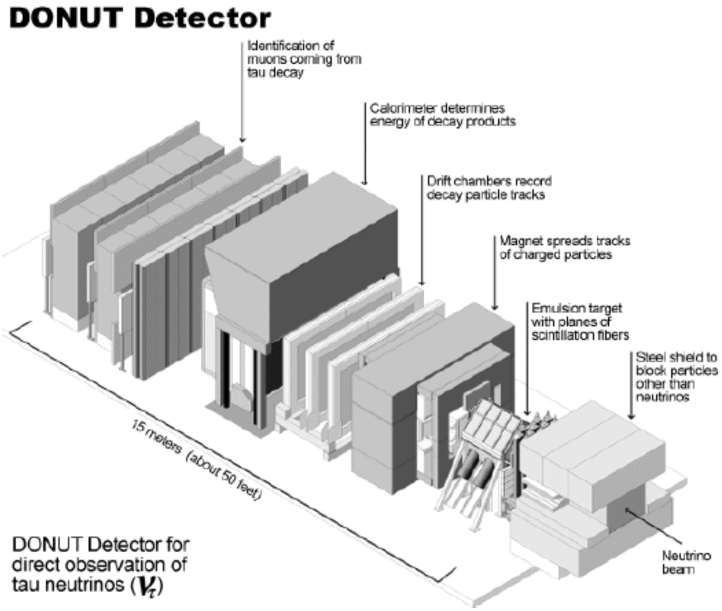
p_z (GeV/c)	p_T (GeV/c)	$N(\pi^+)$/ POT	$\delta N(\pi^+)$ stat+ bkgd (%)	$\delta N(\pi^+)$ syst (%)	$N(\pi^-)$/ POT	$\delta N(\pi^-)$ stat+ bkgd (%)	$\delta N(\pi^-)$ syst (%)	$R = N(\pi^-)/N(\pi^+)$	δR stat+ bkgd (%)	δR syst (%)
[0.30,0.50)	[0.00,0.10)	3.32e-01	0.97	9.77	2.76e-01	0.86	9.09	0.84	1.29	5.19
[0.30,0.50)	[0.10,0.20)	3.25e-01	1.05	4.86	3.56e-01	0.75	4.93	1.08	1.29	4.64
[0.30,0.50)	[0.20,0.30)	1.93e-01	1.46	5.30	1.91e-01	1.09	5.24	1.00	1.82	4.59
[0.30,0.50)	[0.30,0.40)	1.06e-01	1.97	8.15	9.49e-02	1.68	7.39	0.95	2.59	4.61
[0.50,0.62)	[0.00,0.10)	9.20e-02	1.22	5.10	7.54e-02	1.16	4.98	0.83	1.69	4.59
[0.50,0.62)	[0.10,0.20)	1.37e-01	1.18	4.72	1.44e-01	0.85	4.70	1.05	1.46	4.59
[0.50,0.62)	[0.20,0.30)	9.03e-02	1.57	5.64	9.24e-02	1.14	5.92	0.99	1.94	4.59
[0.50,0.62)	[0.30,0.40)	4.92e-02	2.12	4.77	4.63e-02	1.76	5.24	0.89	2.76	4.58
[0.50,0.62)	[0.40,0.50)	1.42e-02	5.39	8.18	2.23e-02	2.81	8.33	1.46	6.08	4.58
[0.62,0.75)	[0.00,0.10)	6.02e-02	1.41	4.94	5.14e-02	1.31	4.85	0.87	1.93	4.59
[0.62,0.75)	[0.10,0.20)	1.11e-01	1.33	4.75	1.13e-01	0.94	4.74	1.01	1.63	4.58
[0.62,0.75)	[0.20,0.30)	8.26e-02	1.59	4.65	8.14e-02	1.12	4.63	0.98	1.94	4.58
[0.62,0.75)	[0.30,0.40)	4.32e-02	2.09	5.62	4.33e-02	1.52	5.43	0.98	2.58	4.58
[0.62,0.75)	[0.40,0.50)	2.19e-02	3.12	5.78	2.22e-02	2.47	5.47	1.00	3.98	4.58
[0.75,0.88)	[0.00,0.10)	4.27e-02	1.74	4.74	3.90e-02	1.55	4.68	0.92	2.33	4.58
[0.75,0.88)	[0.10,0.20)	9.19e-02	1.48	4.68	9.04e-02	1.05	4.65	0.98	1.82	4.58
[0.75,0.88)	[0.20,0.30)	7.46e-02	1.67	4.62	7.11e-02	1.18	4.61	0.95	2.05	4.58
[0.75,0.88)	[0.30,0.40)	4.21e-02	2.19	5.50	4.03e-02	1.54	5.68	0.96	2.68	4.58
[0.75,0.88)	[0.40,0.50)	2.16e-02	2.84	4.71	2.09e-02	2.26	4.77	0.95	3.63	4.58
[0.88,1.00)	[0.00,0.10)	3.42e-02	1.87	4.74	3.23e-02	1.62	4.69	1.01	2.48	4.58
[0.88,1.00)	[0.10,0.20)	7.50e-02	1.69	4.68	7.25e-02	1.22	4.62	0.99	2.09	4.58
[0.88,1.00)	[0.20,0.30)	6.68e-02	1.85	4.64	6.19e-02	1.33	4.60	0.94	2.28	4.58
[0.88,1.00)	[0.30,0.40)	3.82e-02	2.87	5.57	3.61e-02	1.58	4.68	0.95	3.27	4.58
[0.88,1.00)	[0.40,0.50)	1.99e-02	2.90	8.53	1.93e-02	2.15	5.04	0.93	3.61	4.59
[1.00,1.20)	[0.00,0.10)	3.91e-02	2.04	6.21	3.65e-02	1.71	5.33	0.96	2.66	4.59
[1.00,1.20)	[0.10,0.20)	9.98e-02	1.83	4.65	9.09e-02	1.31	4.64	0.93	2.25	4.59
[1.00,1.20)	[0.20,0.30)	9.27e-02	2.06	4.62	8.22e-02	1.41	4.60	0.89	2.50	4.59
[1.00,1.20)	[0.30,0.40)	5.20e-02	2.46	5.65	5.25e-02	1.67	4.74	1.00	2.97	4.59
[1.00,1.20)	[0.40,0.50)	2.85e-02	4.18	5.42	3.01e-02	2.05	4.63	1.04	4.65	4.58
[1.20,1.50)	[0.00,0.10)	4.23e-02	2.35	6.27	3.72e-02	1.91	8.47	0.89	3.02	4.59
[1.20,1.50)	[0.10,0.20)	9.12e-02	2.07	4.61	8.83e-02	1.50	4.62	0.98	2.56	4.58
[1.20,1.50)	[0.20,0.30)	1.01e-01	2.20	5.00	9.32e-02	1.60	4.90	0.93	2.72	4.59
[1.20,1.50)	[0.30,0.40)	7.65e-02	2.51	4.64	6.58e-02	1.80	4.60	0.85	3.08	4.59
[1.20,1.50)	[0.40,0.50)	4.76e-02	3.11	5.25	3.87e-02	2.19	5.40	0.80	3.80	4.59
[1.50,2.00)	[0.00,0.10)	4.01e-02	2.90	4.62	3.20e-02	2.58	4.59	0.82	3.88	4.58
[1.50,2.00)	[0.10,0.20)	8.80e-02	2.44	4.88	8.20e-02	1.79	4.93	0.94	3.03	4.59
[1.50,2.00)	[0.20,0.30)	1.26e-01	2.41	4.65	1.08e-01	1.73	4.65	0.89	2.97	4.59
[1.50,2.00)	[0.30,0.40)	9.94e-02	2.70	4.71	8.30e-02	1.95	4.66	0.85	3.33	4.59
[1.50,2.00)	[0.40,0.50)	6.99e-02	3.14	4.63	5.61e-02	2.31	4.63	0.80	3.90	4.59
[4.00,6.00)	[0.00,0.10)	1.54e-02	11.19	5.03	1.74e-02	7.94	5.83	1.06	13.73	4.58
[4.00,6.00)	[0.10,0.20)	5.12e-02	7.63	4.67	4.82e-02	4.23	4.91	0.85	8.72	4.58
[4.00,6.00)	[0.20,0.30)	6.47e-02	8.72	4.79	5.64e-02	4.48	4.86	0.88	9.81	4.59
[4.00,6.00)	[0.30,0.40)	6.79e-02	9.31	5.61	5.79e-02	5.64	4.73	0.71	10.89	4.60
[6.00,8.00)	[0.00,0.10)	7.94e-03	4.78	5.40	8.64e-03	3.46	6.40	1.01	5.90	4.58

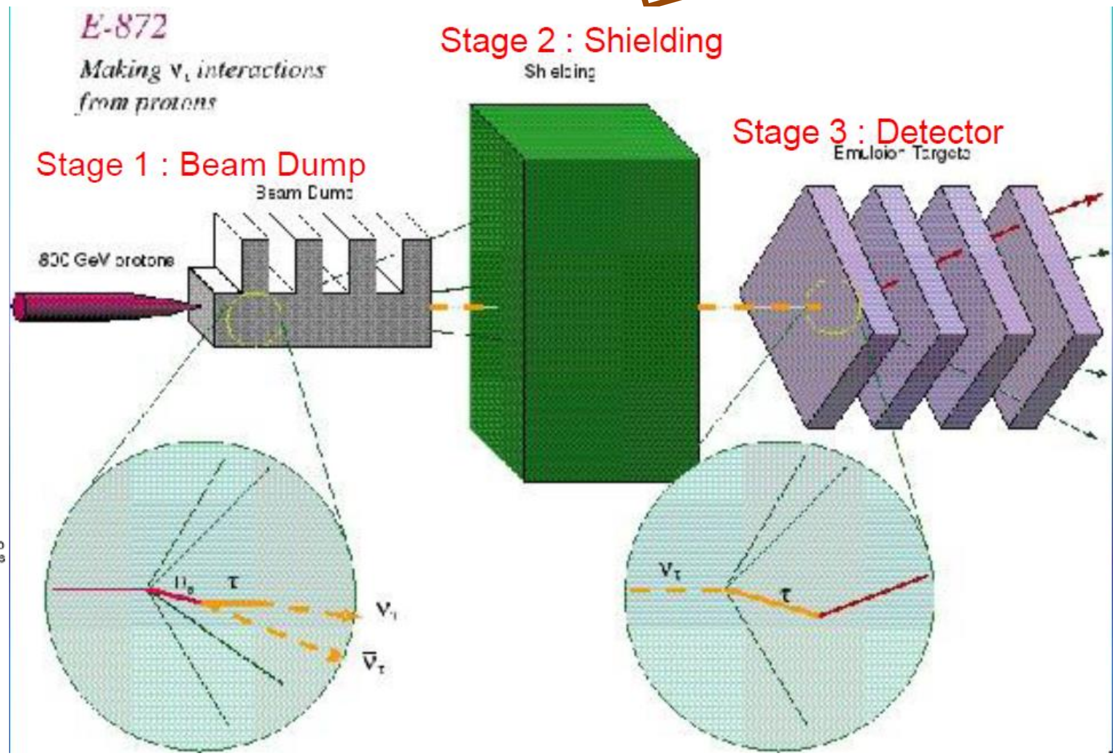
Continued on next page...

3. Beam Dumps

- ν_τ from $D_s \rightarrow \tau \nu_\tau$ decay
- 203 ν events in emulsion
- See 4, expected 4.1 ± 1.4
- BG (charm) 0.41 ± 0.15

DONUT
SHiP



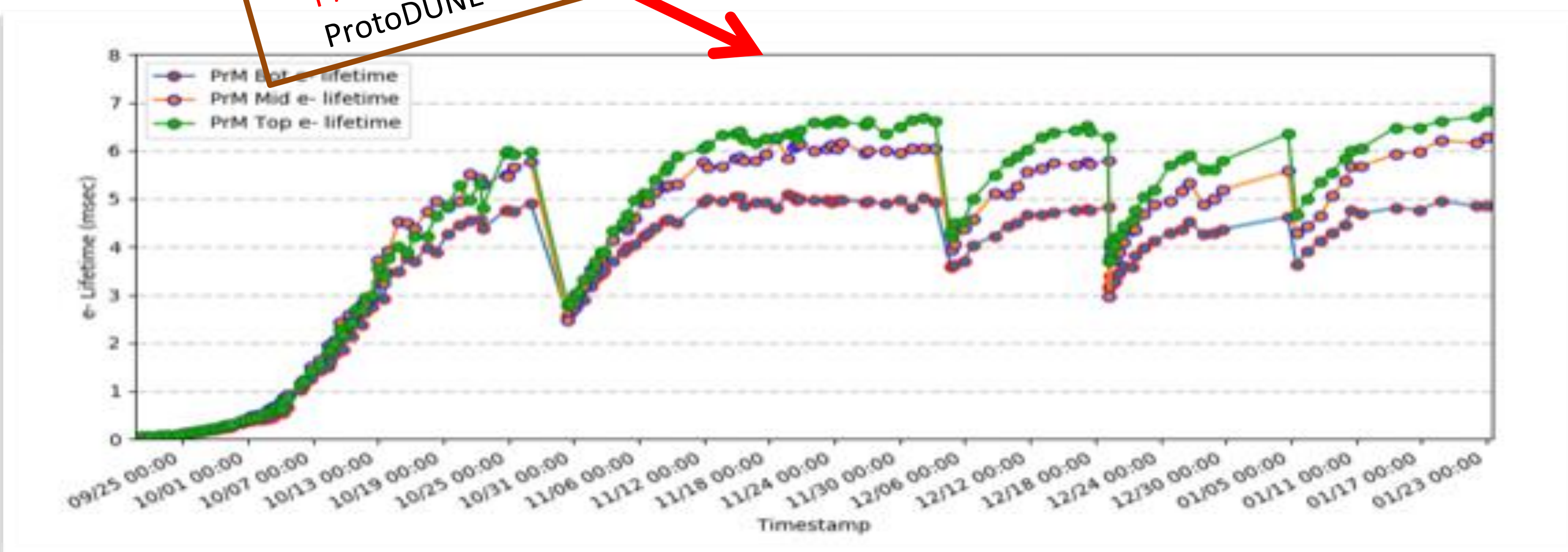


4. Prototypes

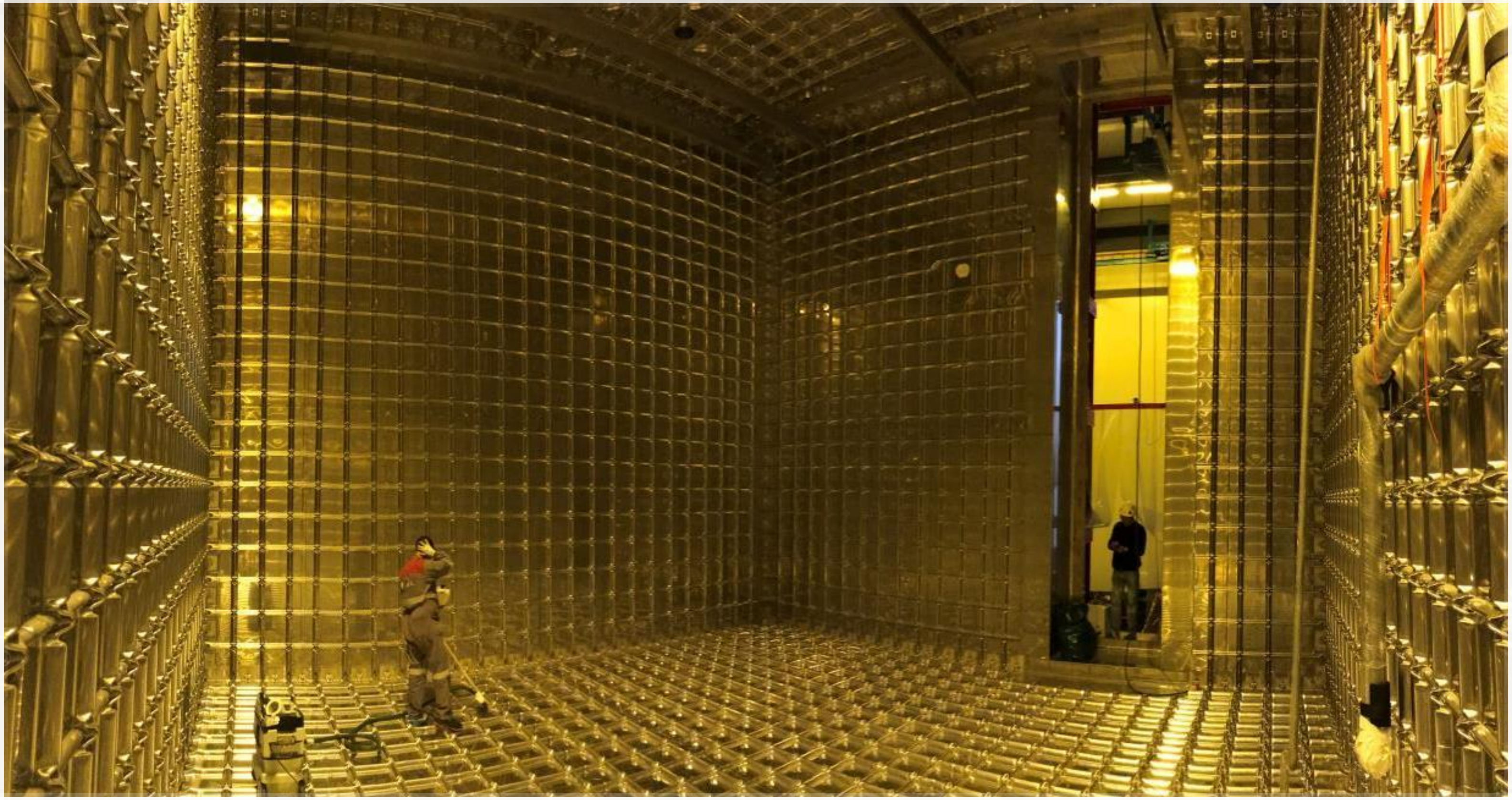
Study ν detector prototypes in charged particle test beams to determine detector performance:

- Drops in purity due to stop of the liquid argon recirculation (sometime planned and sometime not)

35 ton;
LAriaT;
ProtoDUNE-SP;
ProtoDUNE-DP



ProtoDUNE-SP



ProtoDUNE Events & future CERN plan

✓ 2018 ProtoDUNE-SP run

Beam Data Accumulation

Particle content is based on the expected rates from the Geant simulation of the beamline

Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702	689	394	70	197	28
7	477	472	299	51	98	24
All momenta	4173	3924	1693.5	777.5	1381	72

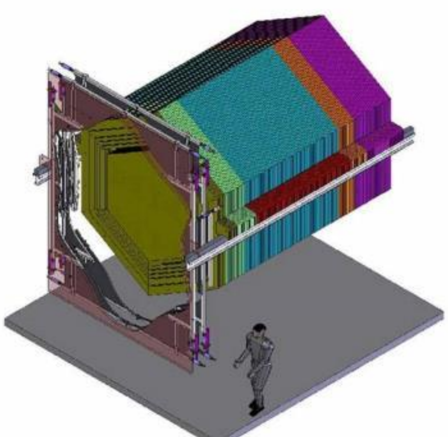
✓ Use cosmics through Oct 2020 for SP & DP

✓ Upgrade SP Oct 2020- Sep 2021

✓ more beam Apr-May 2022

5. Cross section studies

- Study ν in the few GeV region
- Mix of QE, DIS, resonance
- Importance of 2p2h or Meson Exchange Currents (MEC)
- Nuclear Effects



MINERνA

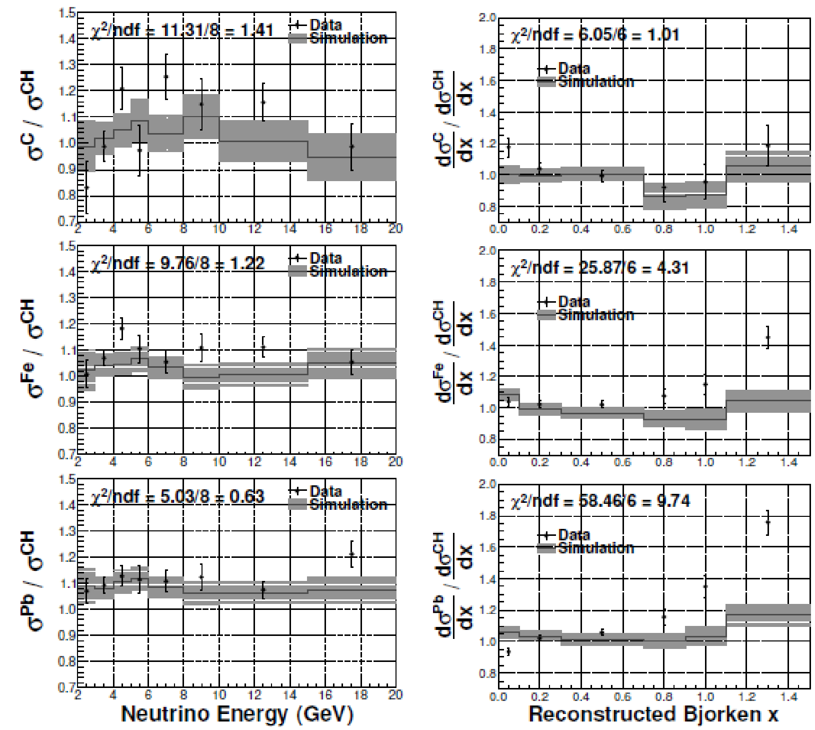


FIG. 2: Ratios of the charged-current inclusive ν_μ cross section per nucleon as a function of E_ν (left) and as a function of reconstructed x (right) for C/CH (top), Fe/CH (middle), and Pb/CH (bottom). Error bars on the data (simulation) show the statistical (systematic) uncertainties. The χ^2 calculation includes correlations among all bins shown. Events with x greater than 1.5 are not shown.

Questions?

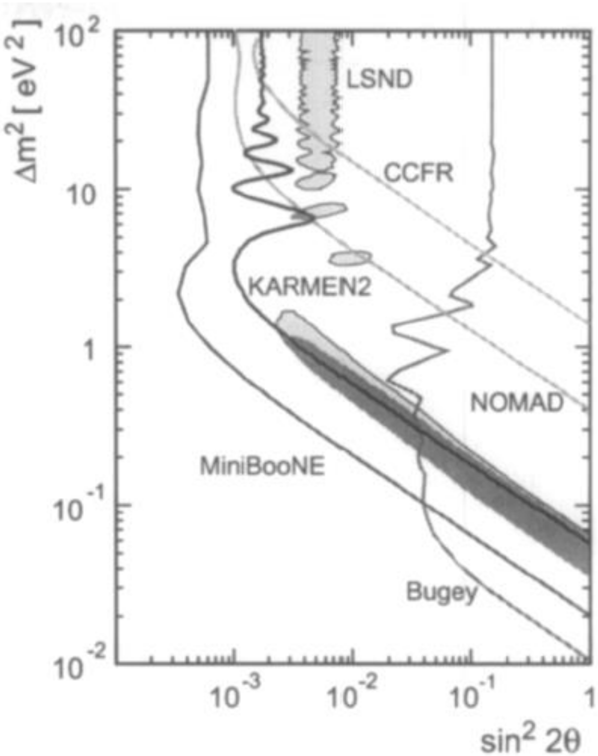
6. Early short-baseline oscillation experiments

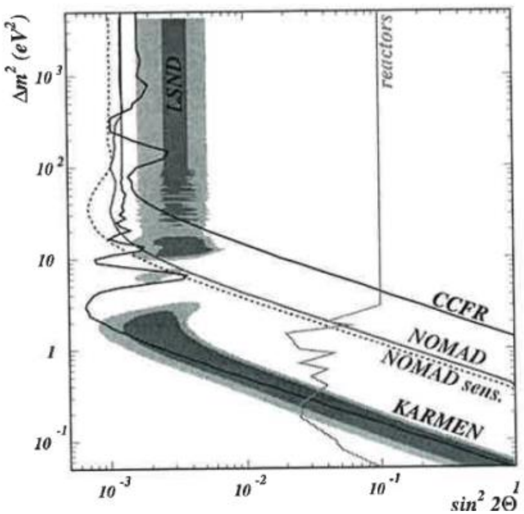
- If hot dark matter had been the missing matter,
  - ↳ i.e. $\Omega_\nu \sim 0.2$, this implied $m_\nu \sim 10$ eV
- This motivated a number of neutrino oscillation searches at FNAL, CERN, Rutherford Lab, BNL, LANL, etc.

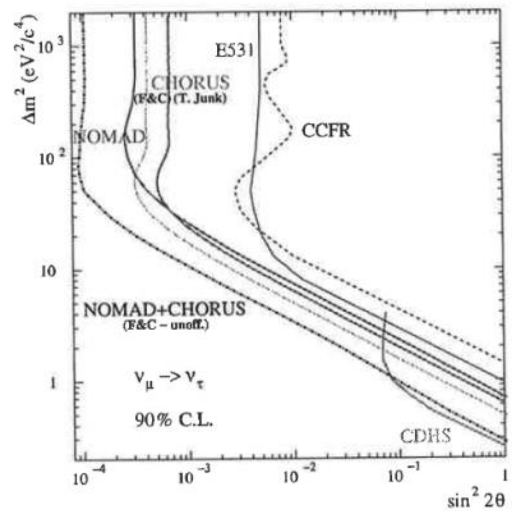
CCFR
LSND
KARMEN
CHORUS
NOMAD
E531

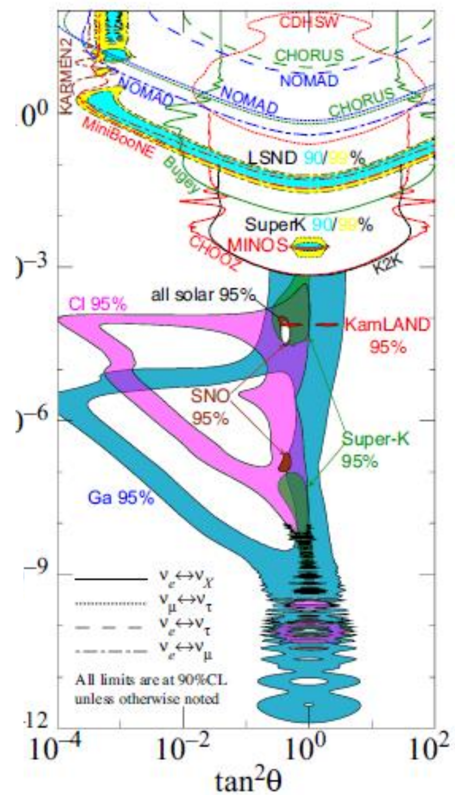
- LSND (originally designed to search for what we now call θ_{12}) had a signal; others didn't.
- After SNO, we knew LSND wasn't θ_{12}, but it has been interpreted as a 4th sterile ν.

Various limits with LSND "signal"







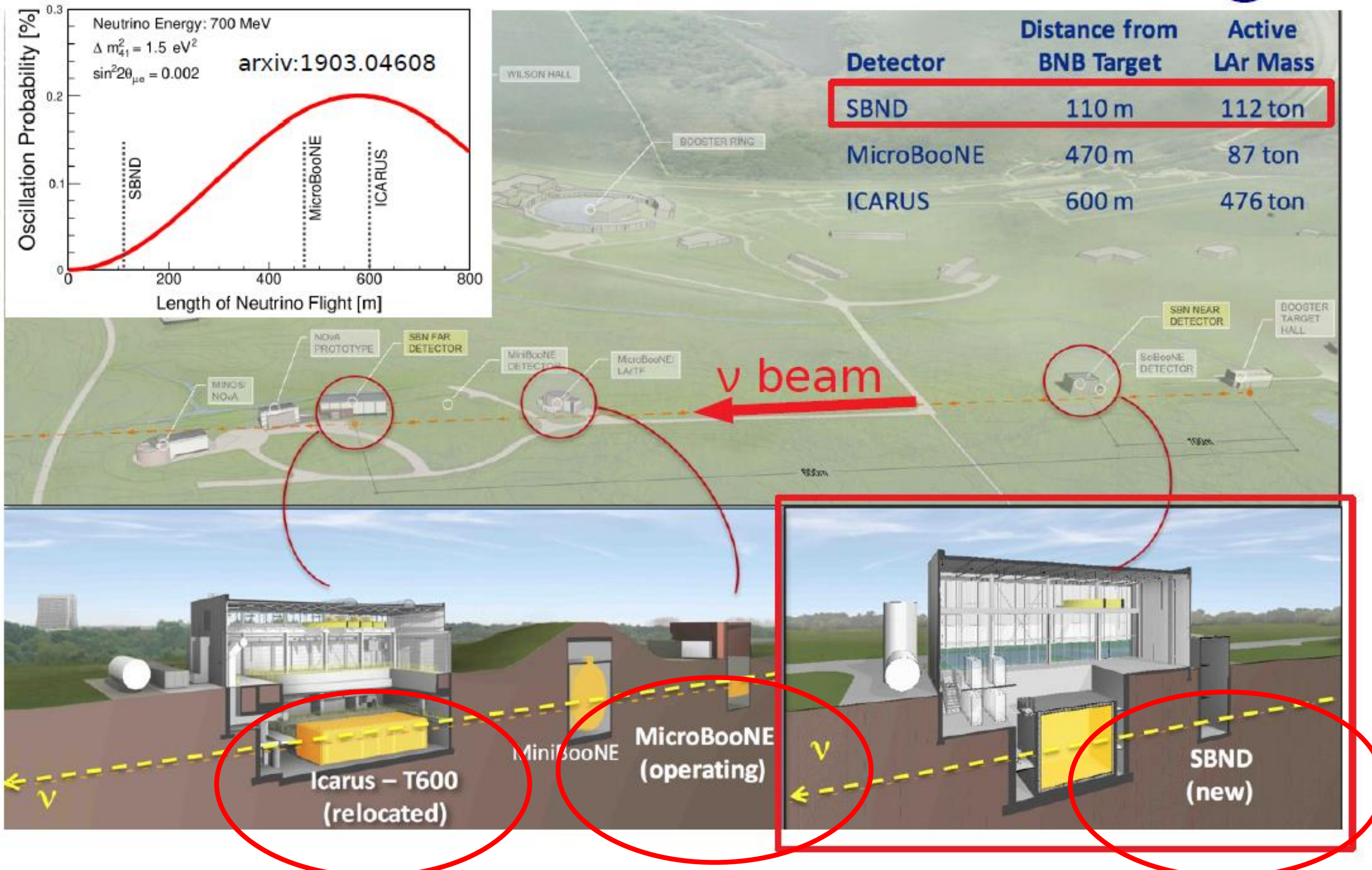


7. Fermilab's Short-Baseline Program

- Designed to confirm or refute the sterile neutrino interpretation of the short-baseline anomalies (LSND excess, MiniBooNE, Chromium source deficit, and the reactor anomaly.)
- SBN ≡ MicroBooNE + SBND + ICARUS

3-Detector SBN

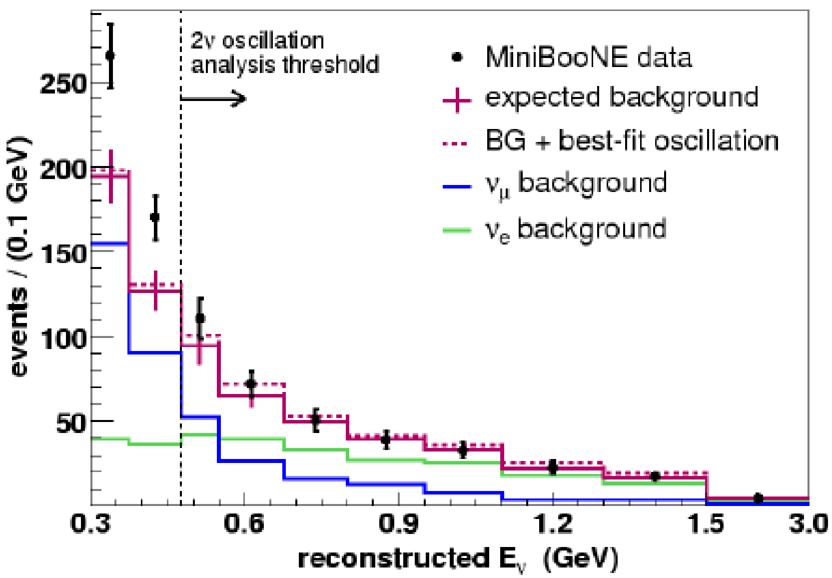
The Short-Baseline Neutrino Program



Is the MiniBooNE low energy excess due to sterile νs?

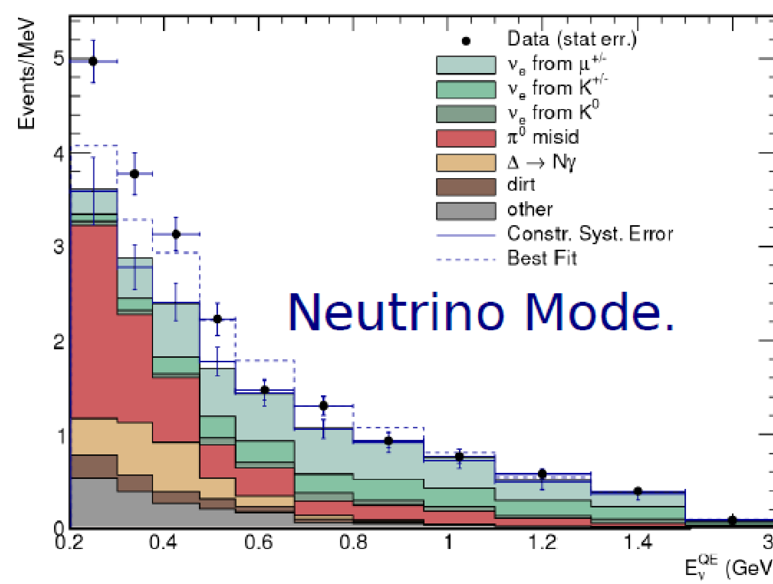
MiniBooNE 2007

"MiniBooNE Results Inconsistent with Existence of "Sterile" Neutrinos"



MiniBooNE 2018

"… there are additional types of neutrinos, albeit with properties different from the 3 "normal" types. These extras are known as sterile neutrinos."



My skepticism

- There is/are an anomaly(ies). Will SBN resolve anything?
- In my opinion…maybe & maybe not.
  - 3+1 sterile neutrino solutions to the short-baseline anomalies have been long ruled out.
  - If you don't know what you're looking for, you might find it, and you might not, but you can't rule it out.

Why physicist disagree:

If the data doesn't agree with the null hypothesis or the alternative hypothesis, some say you need more data, while some say you need more hypotheses.

  - Further, if SBN finds an interesting or uninteresting explanation of the MiniBooNE LE excess, that still doesn't explain the LSND excess.

Questions?

8. Other physics in long-baseline neutrino detectors

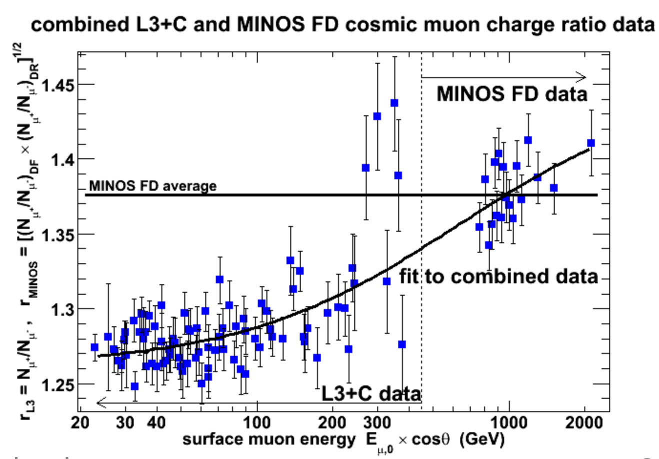
- Solar ν
- Atmospheric ν
- Supernova ν
- Nucleon decay
- Dark matter
- Cosmic rays
- Seasonal Variations
- Lorentz Violation
- …

Discovery of Associated Production at TeV energies

by measuring the charge ratio of cosmic ray muons underground

$\pi^+/\pi^- \sim 1.25$; $K^+/K^- \sim 6$

$$r^{\pm} = \frac{\frac{f_\pi}{1+\frac{1.1E_\mu\cos\theta}{115\mathrm{GeV}}} + \frac{0.054\times f_K}{1+\frac{1.1E_\mu\cos\theta}{850\mathrm{GeV}}}}{\frac{1-f_\pi}{1+\frac{1.1E_\mu\cos\theta}{115\mathrm{GeV}}} + \frac{0.054\times(1-f_K)}{1+\frac{1.1E_\mu\cos\theta}{850\mathrm{GeV}}}}$$



Conclusions

accelerator-based ν experiments

- ✶ Previous experiments brought understanding to the oscillations parameters from atmospheric ν experiments.
- ✶ Current & future ones are helping to finish measuring all parameters of "ν standard model"
- ✶ For the next decade, DUNE & Hyper-K will require attention from the great majority of ν physicists in the world.

Advertisement(s)

- Free monthly neutrino rumor newsletter --
- It is called “long-baseline news” but covers a wide range of neutrino physics
- ~100 lines,
- send “subscribe” to maury.goodman@anl.gov or see http://www.hep.anl.gov/ndk/longbnews/

  Join 2461 subscribers.

OPTIONAL HOMEWORK

1. At what E_ν are the first and second oscillation max for each of the 8 experiments?
2. List some possible explanations for the short-baseline anomalies (LSND, MiniBooNE, Ga, Reactor)?
3. What is the optimal distance for a ν_τ appearance experiment in a background-free detector?
4. Assuming 3ν, can δ_{CP} be measured without running $\bar{\nu}$?
5. How would sterile ν, non-standard interactions, or other new ν physics affect measurements in long-baseline experiments?
6. Assuming the normal mass order with 3ν & hierarchical masses, which ν mass dominates:
   a) the effective ν mass measured by $0\nu\beta\beta$?
   b) the effective ν mass measured by direct mass experiments like KATRIN?

Email solutions to maury.goodman@anl.gov before 15 Oct 2019

backup

Intelligent Design of Neutrino Parameters? (~2005)

(from S. Wojcicki)

- The optimum choice for Δm^2_{21}?

Such as to give resonant transition (MSW effect) in the middle of solar energy spectrum -, $\Delta m^2_{21} = 8.2 \times 10^{-5}$ eV^2

- The optimum choice for $\sin\theta_{12}$?

Big enough for oscillations to be seen in KamLAND - ~0.8

- The optimum choice for Δm^2_{32}?

Such as to give full oscillation in the middle of the range of possible distances that atmospheric ν's travel to get to the detector - $\Delta m^2_{32} = 2.3 \times 10^{-3}$ eV^2

- The optimum choice for $\sin\theta_{23}$?

Big enough so that oscillations could be seen easily - $\theta_{23} \sim \pi/4$

- The optimum choice for $\sin\theta_{13}$?

Small enough so as not to confuse interpretation of the above - $\theta_{13} < 10^0$

- **But the acid test - will θ_{13} be big enough to see CP violation and determine mass hierarchy?**

And still?

- By 2011 we learned that θ_{13} was as large as could be imagined in 2006

? How about the remaining parameters so that the "Intelligent Design" arguments can get longer (2012)?

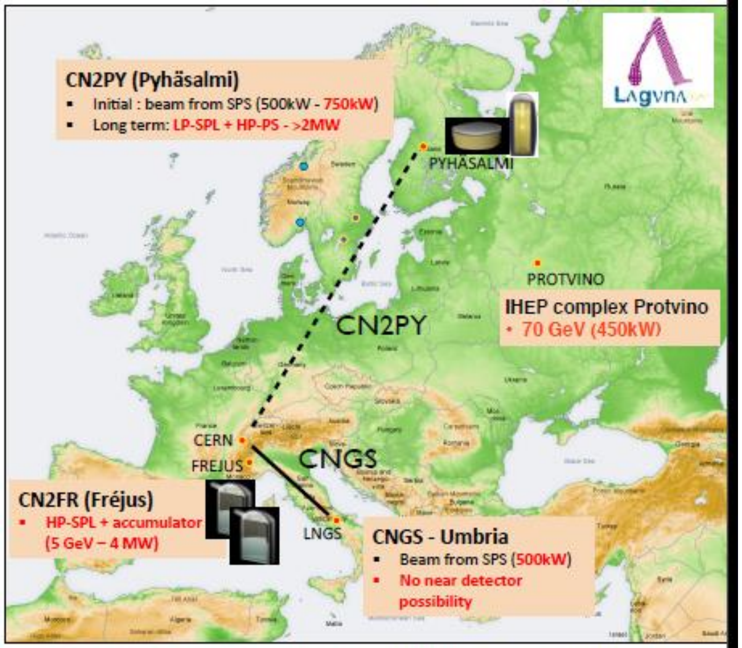
- $\delta \sim 3\pi/2$
  - to most quickly determines the hierarchy
  - to get large CP violation & answer the CP violation question
- The inverted hierarchy, so we can tell Dirac/Majorana & maybe beta decay endpoint
- Majorana, which seems to be more interesting so that some of our theorists will be happy (seesaw, etc.)

It appears:

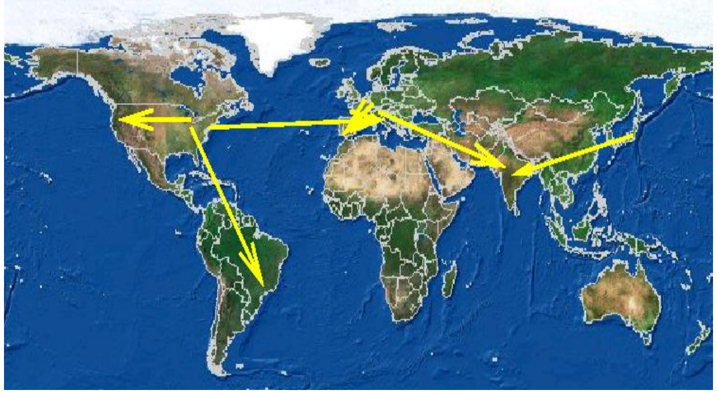
- ✓By 2011 we learned that θ_{13} was as large as could be imagined in 2006
- ? How about the remaining parameters so that the “Intelligent Design” arguments can get longer (2012)?
  - ✓ $\delta \sim 3\pi/2$
    - to most quickly determines the hierarchy
    - to get large CP violation & answer the CP violation question
  - ✗ The inverted hierarchy, so we can tell Dirac/Majorana & maybe beta decay endpoint
  - ? Majorana, which seems to be more interesting so that some of our theorists will be happy (seesaw, etc.)

Other ideas

- LAGUNA
- NuSTORM
- DAEδALUS
- SSC -> moon

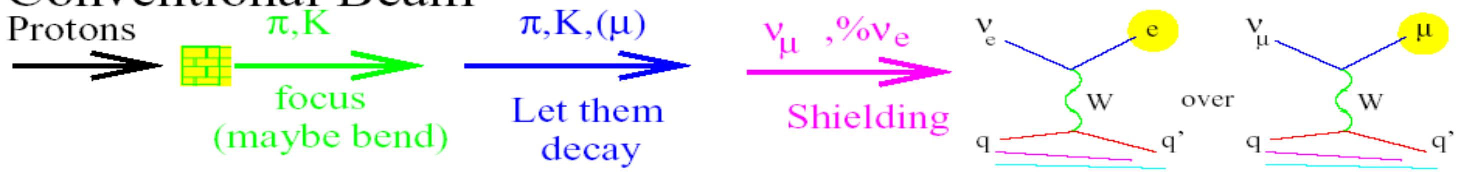


- **Detector options:** 20, 50, 100 kton LAr; 50 kton LSc and 540 kton WCD

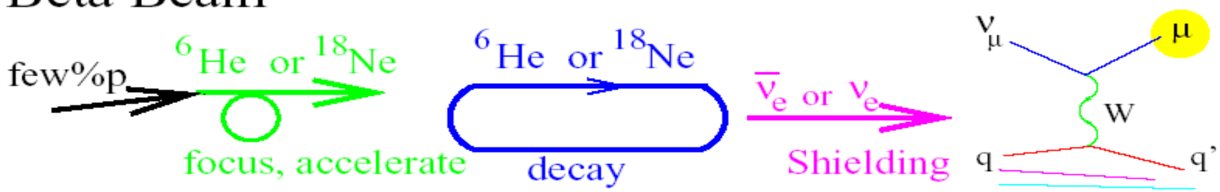


ν beams

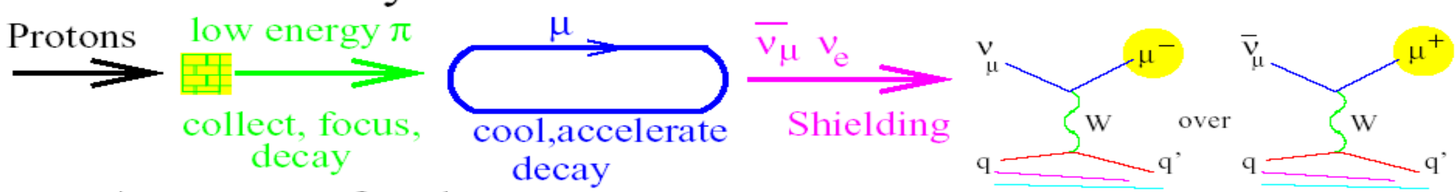
- Conventional Beam



- Beta Beam



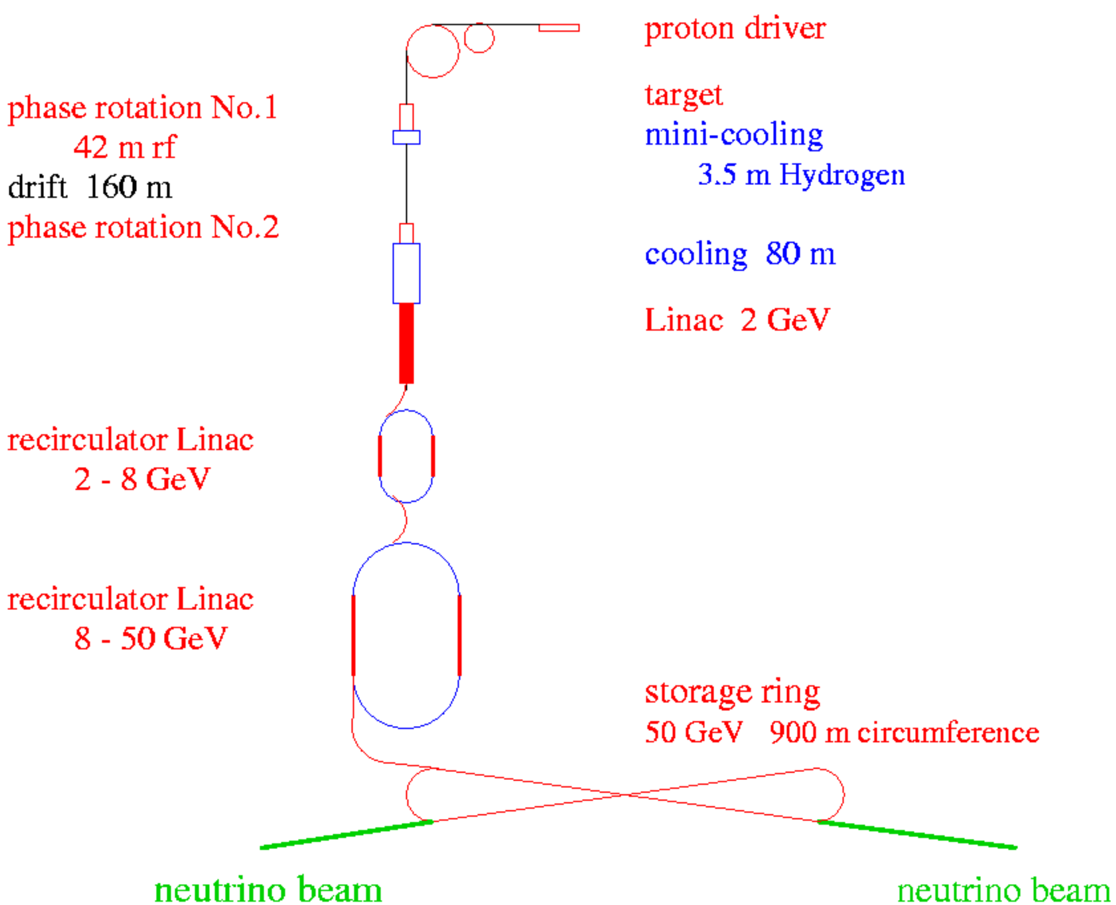
- Neutrino Factory



Events/parent at far detector:

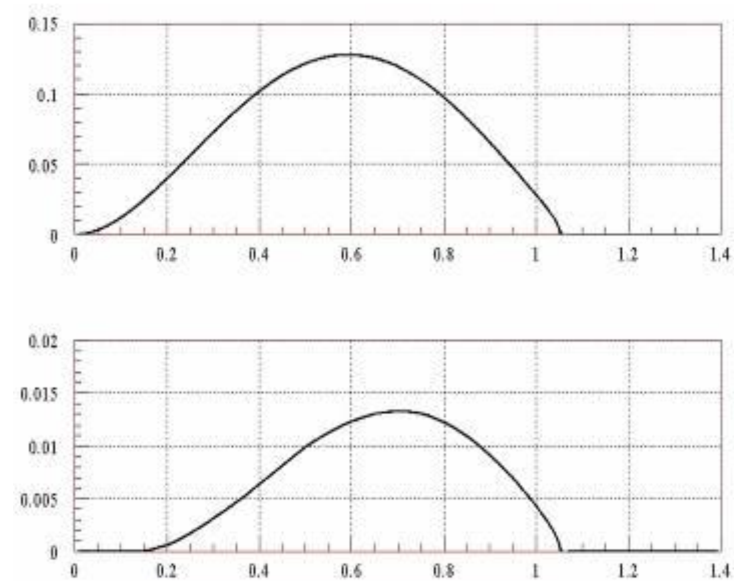
$$N \propto \frac{\gamma m_{parent} K}{4\pi L_{det}^2} \frac{4\gamma^2}{(1+\gamma^2\theta_{\nu parent}^2)^3}$$

ν factory


proton driver
target
mini-cooling
3.5 m Hydrogen
phase rotation No.1
42 m rf
drift 160 m
phase rotation No.2
cooling 80 m
Linac 2 GeV
recirculator Linac
2 - 8 GeV
recirculator Linac
8 - 50 GeV
storage ring
50 GeV 900 m circumference
neutrino beam
neutrino beam

Beta Beams

- Accelerate Heavy ions which β decay
- ^{6}He for ν, ^{18}Ne for $\overline{\nu}$
- Might use CERN-ISOLDE heavy ion accelerator, PS, SPS, +storage ring



ν_e

ν_μ

MeV