Accelerator Based Neutrino Physics at Fermilab

E. Craig Dukes
University of Virginia

BCVSPIN 2011
July 27, 2011

Elementary Particle Physics
University of Virginia

Antimatter Asymmetry Group at the University of Virginia

The Past Decade Neutrino Physics Really Got Interesting

"All the News That's Fit to Print"

The New York Times

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Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

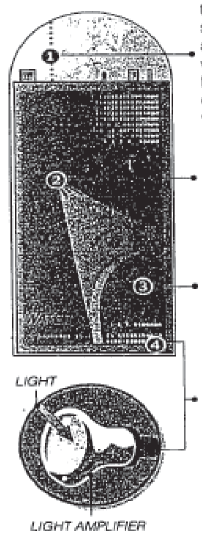
TAKAYAMA, Japan, Friday, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that a significant part of the mass of the universe might be in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter, the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neu-

Detecting Neutrinos



Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .

. . . and collide with other particles . . .

. . . producing a cone-shaped flash of light.

The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

The New York Times

TRAINING ORDERED FOR CONTROLLERS AT U.S. AIRPORTS

NEAR MISS PROMPTS MOVE

Two Passenger Planes Averted Collision Above La Guardia by 20 Feet, F.A.A. Says

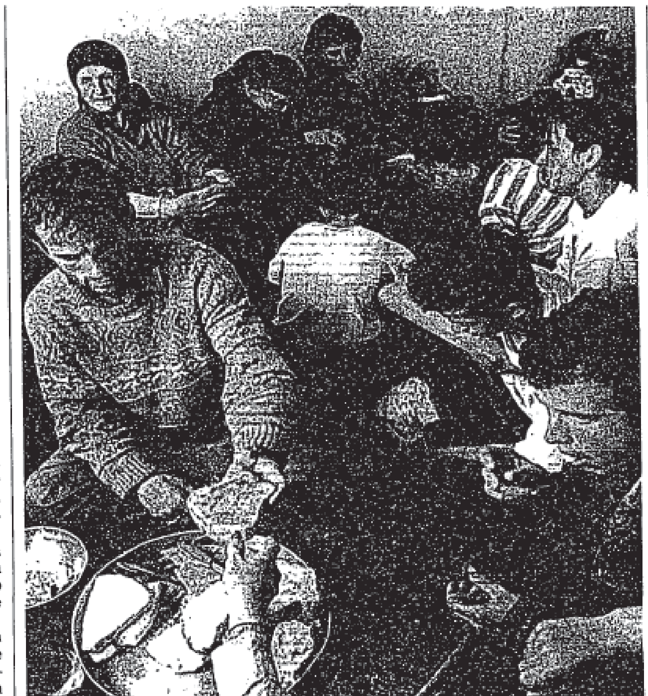
By MATTHEW L. WALD

WASHINGTON, June 4 — A near-collision by two big passenger jets at La Guardia Airport in April has prompted the Federal Aviation Administration to order retraining for the 10,000 air traffic controllers working in airport towers nationwide.

A US Airways DC-9 arriving at La Guardia on April 3 flew under a departing Air Canada A-320, the two planes missing each other by as little as 20 feet, according to the F.A.A.

The near collision had not been previously disclosed, in part because information about it was not forwarded properly for investigation and agency officials therefore did not learn about it until several weeks later, the F.A.A. said. Agency officials said a controller at the La Guardia air traffic tower had promptly informed his supervisor, but the supervisor did not properly report it to his superiors.

The US Airways pilot did report the incident after he returned to his



Associated Press

Bajram Curri, in northern Albania, has received 4,500 refugees from Yugoslavia in three days. One group ate yesterday in a school building.

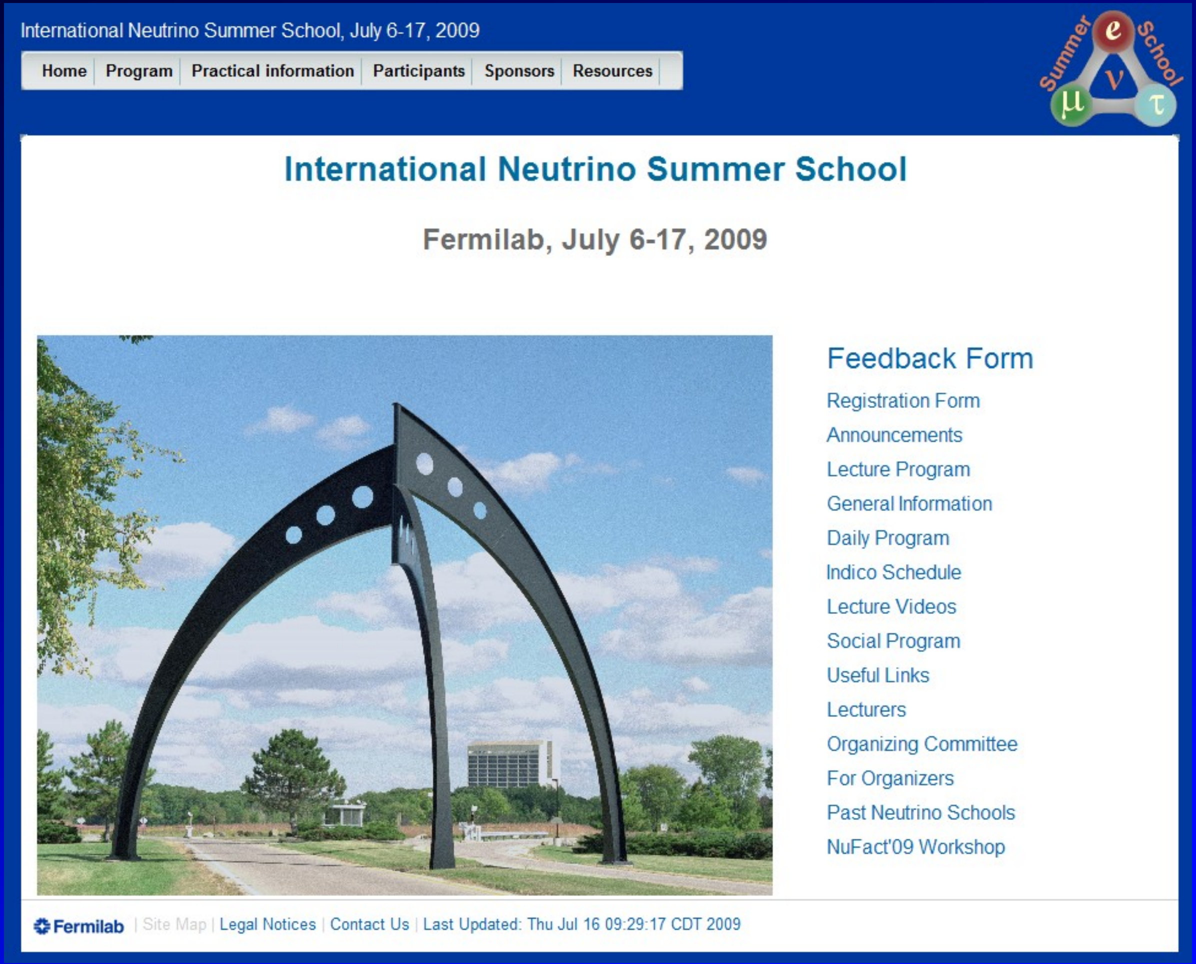
Refugees From Kosovo Cite A Bitter Choice: Flee or Die

A Brief neutrino primer

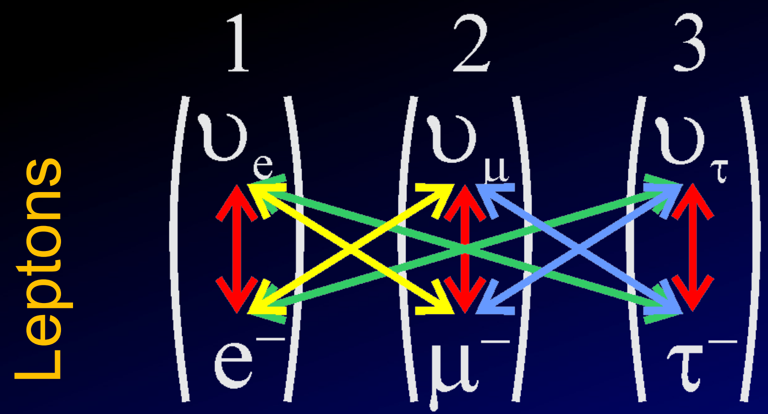
A Great Reference for Neutrino Physics

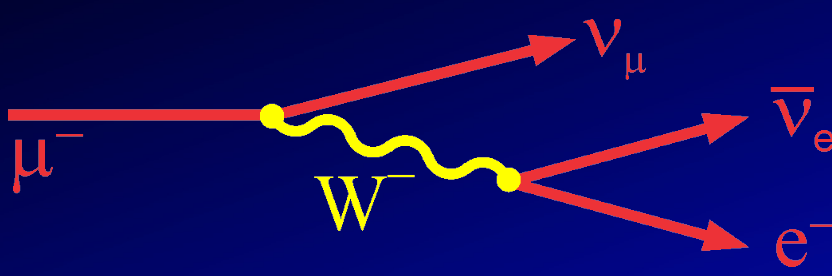
http://vms-db-srv.fnal.gov/fmi/xsl/search/r_nuss2009.xsl

Slides and video available!

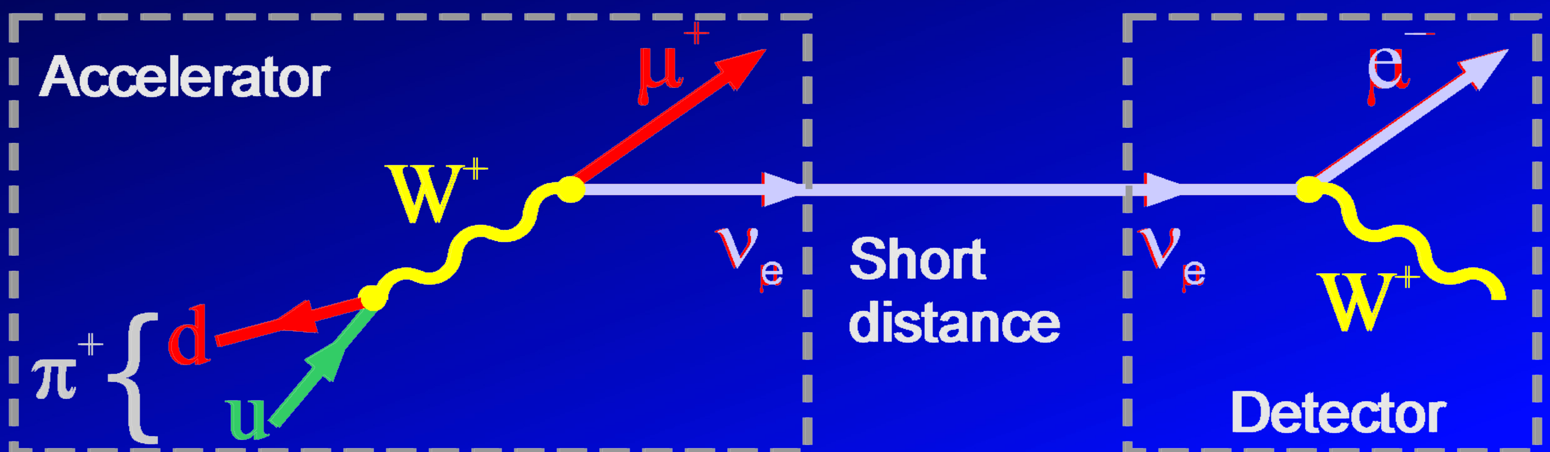


Lepton Mixing

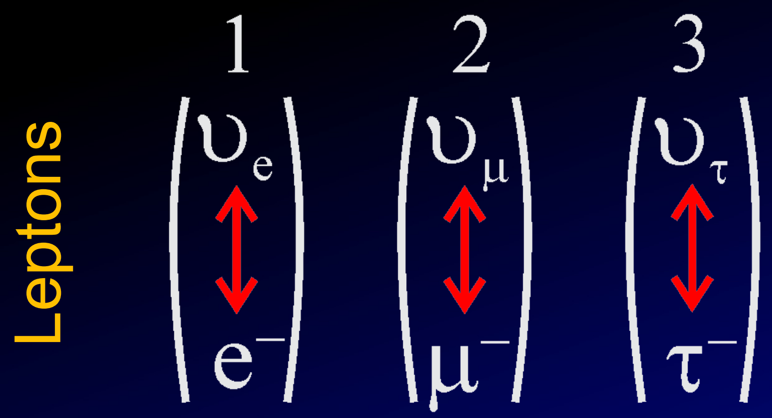




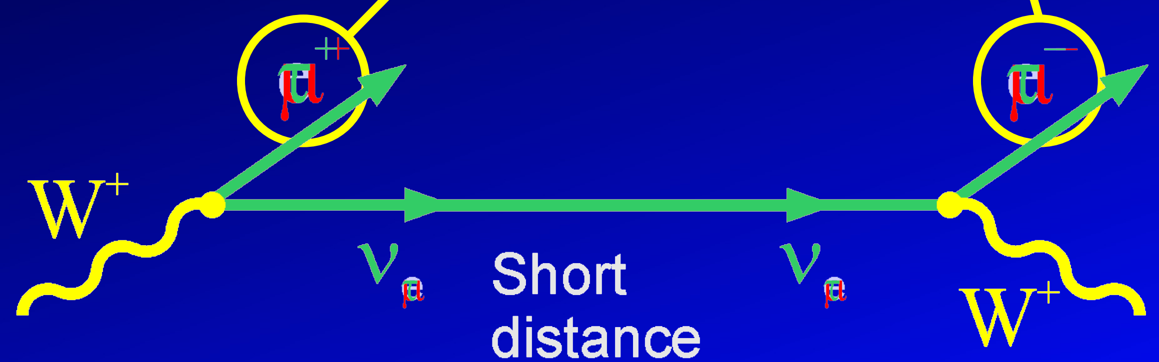
Cross generational transitions do not occur in the lepton sector!



Production and Detection of Neutrinos



Note: Flavor of charged lepton gives neutrino flavor, charge tells you if it is a neutrino or anti-neutrino



How Neutrinos Interact: Cross Sections

$$N(E)events = \Phi\nu(E) \;\; x \;\; \sigma\nu(E) \;\; x \;\; Ntarget$$

Number of neutrino-induced events

Flux of neutrinos (# per cm-2s-1)

Neutrino cross section (cm2)

Number of targets

Cross section σ depends on:

- neutrino type
- interaction type: Z0, W±
- target type: p, n, e
- energy: σtot ¿ Eν

@1 GeV

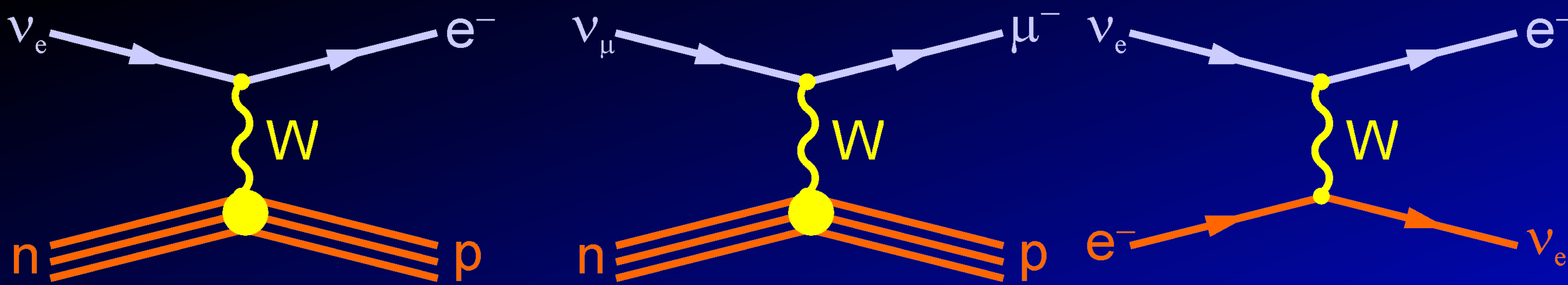
νp ~10-38 cm2

pp ~10-26 cm2

Tiny due to large W,Z masses

Aside: How Neutrinos Interact

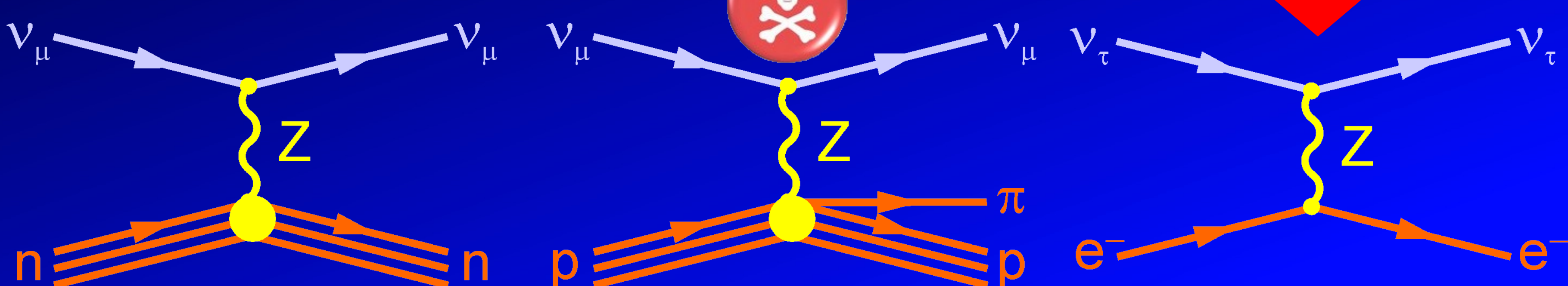
Charged Current (CC) Interactions (mediated by W¿ boson)



Quasi-elastic — Quasi-elastic — Quasi-elastic

Small for kinematic reasons

Neutral Current (NC) Interactions (mediated by Z0 boson)

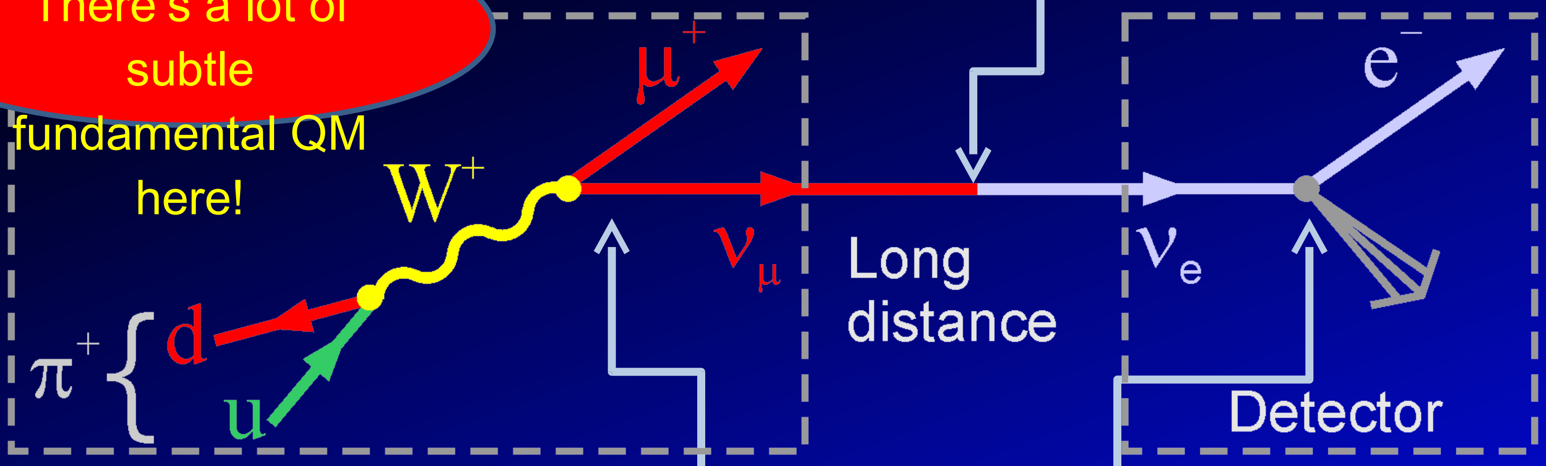


Elastic — Inelastic — Elastic

Neutrinos Oscillate!

Neutrinos propagate in mass eigenstates: ν1 ν2 ν3

There's a lot of subtle fundamental QM here!



Neutrinos produced and detected in flavor eigenstates: νe νμ ντ

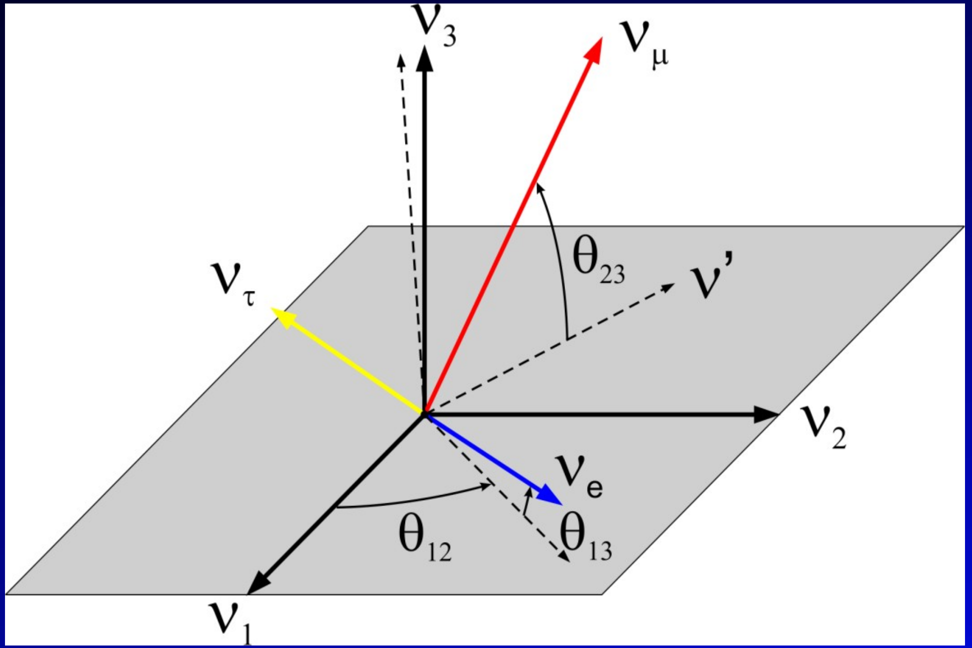
Mass difference

Two component mixing

Mixing Angle between mass and flavor states

Implications of Neutrino Oscillations

- Neutrinos have mass
- Neutrinos have non-zero mixing angles
- 3 Flavor states: νe νμ ντ
- 3 Mass states: ν1 ν2 ν3
- Three mixing angles: θ1 θ2 θ3
- One CP phase: δ



PMNS Matrix

$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{Interference}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_1 \\ \nu_2 \end{pmatrix}$$

A Huge Amount has been Learned in the Past Decade

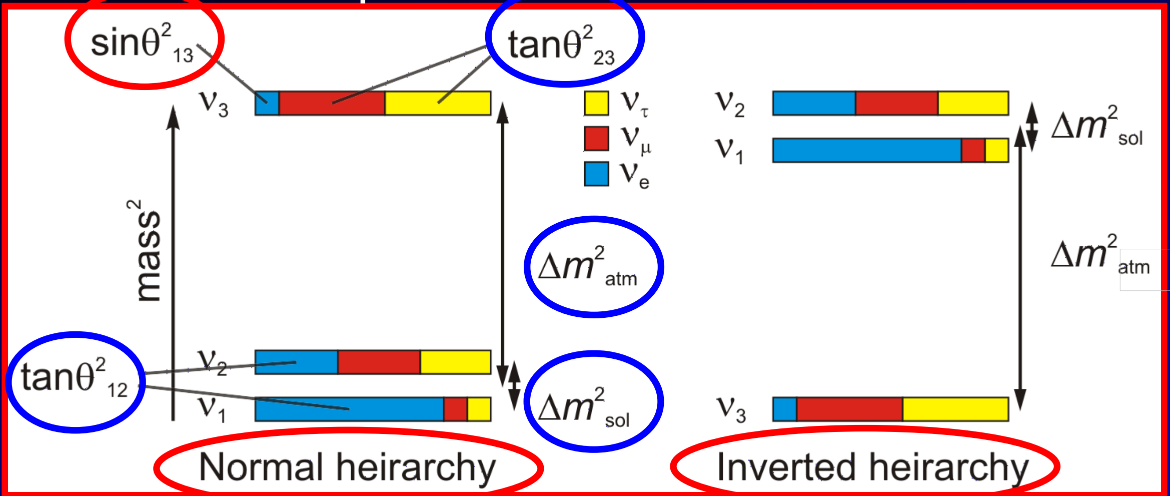
ν_α ν_ε

Appearance Experiments

Disappearance Experiments

Known

Unknown



PMNS Matrix

Atmospheric — Interference — Solar

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_1\\ \nu_2\end{pmatrix}$$

Appearance Rate: $\nu\mu \rightarrow \nu e$

Patm depends on $\theta 13$

Psol independent of $\theta 13$ and typically small

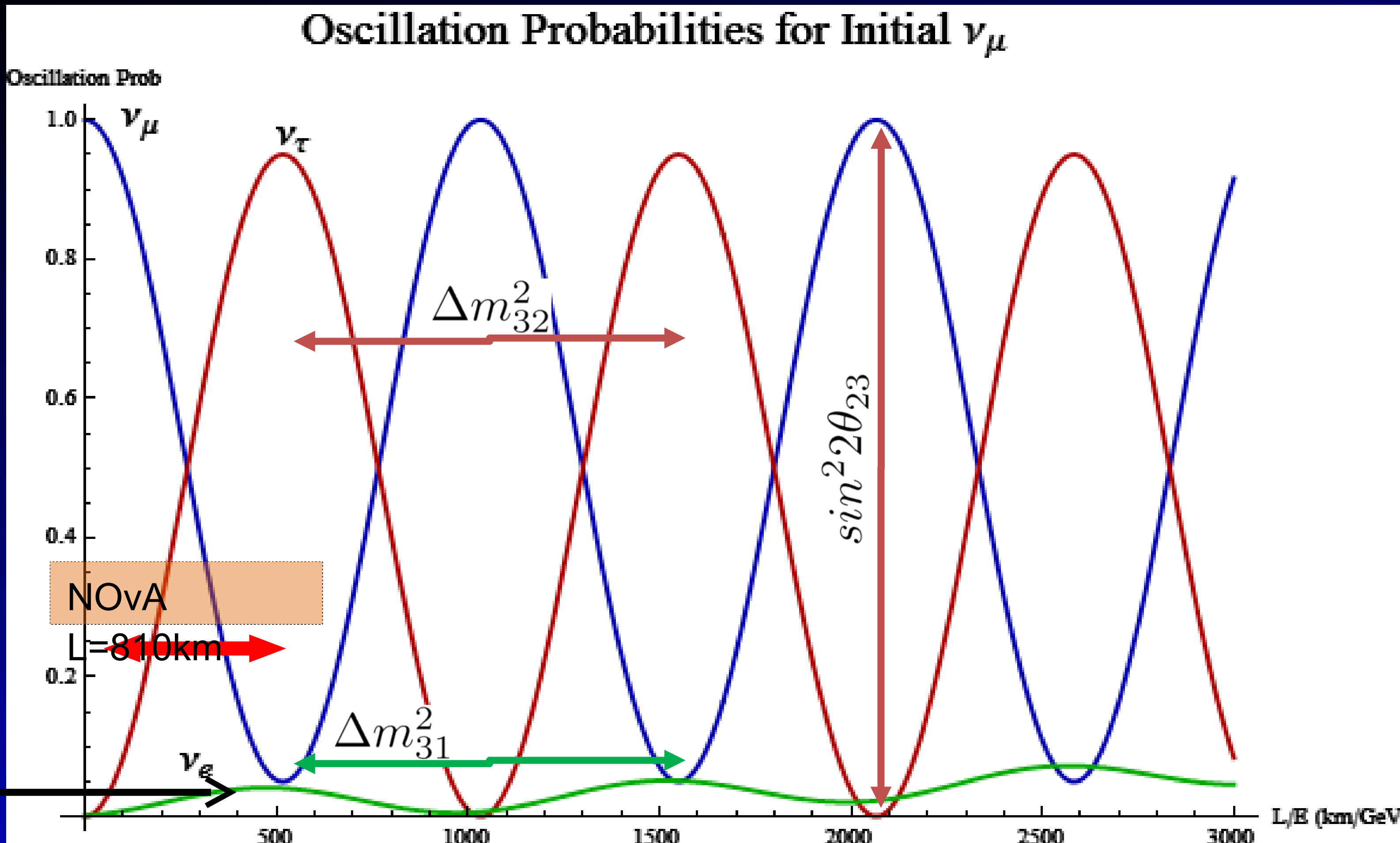
Pint depends on $\theta 13$, CP phase, and neutrino or antineutrino

\- neutrino
\+ antineutrino

CP phase

Appearance Rates

OPERA



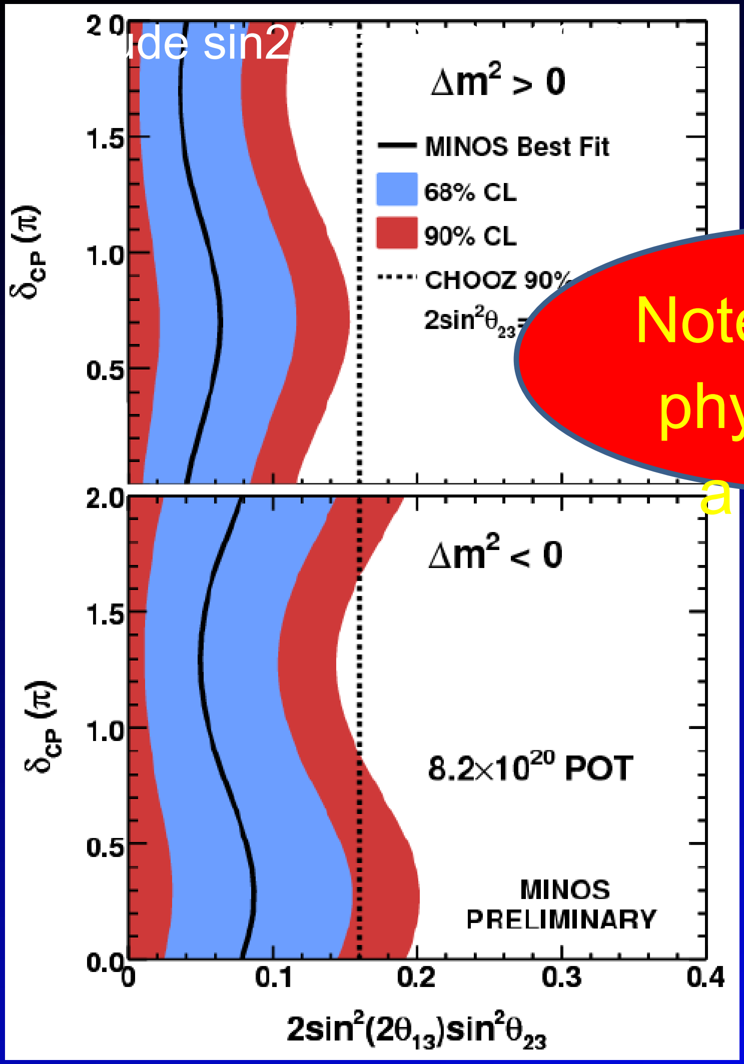
0.04
1

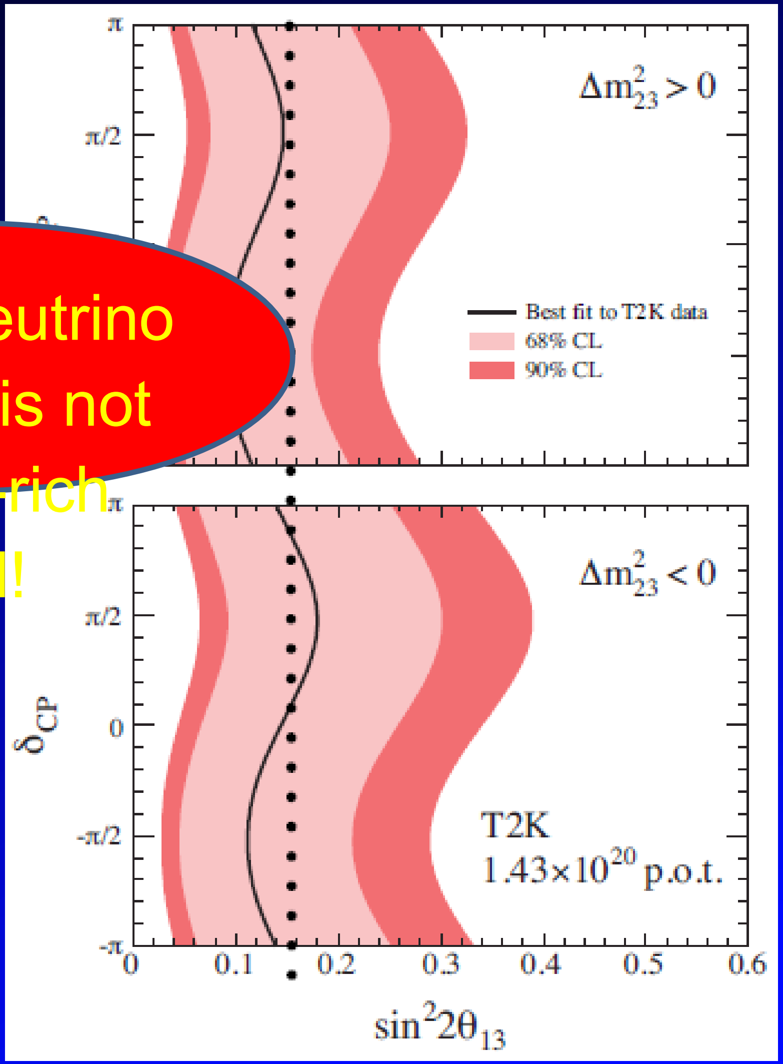
MINOS, NOvA, T2K, etc

Hot Off the Press News on θ13!

MINOS: observe 62, expect 50 evts

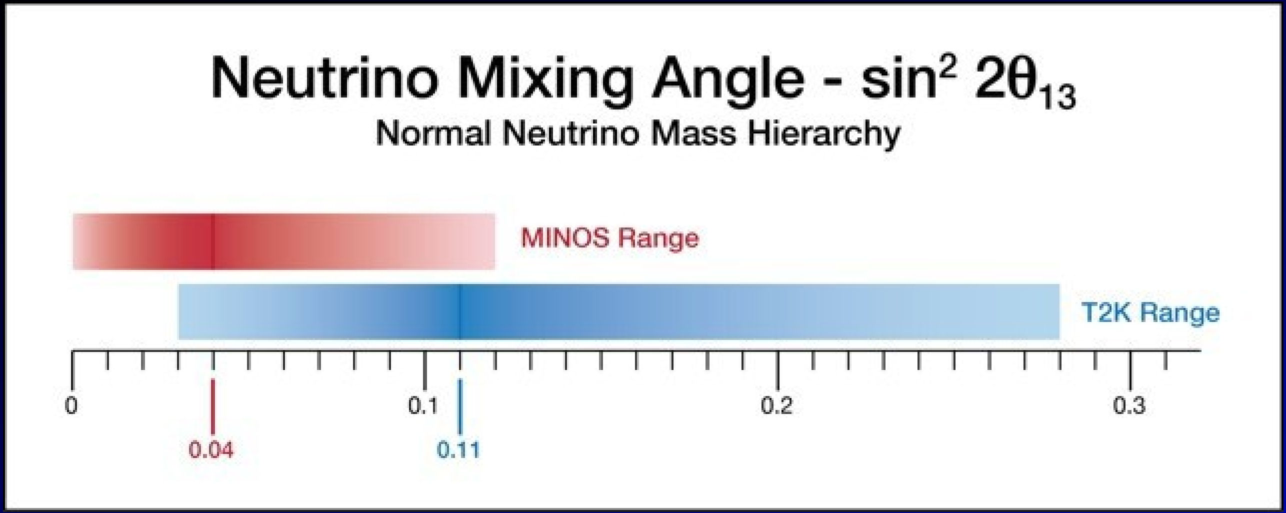
T2K: observe 6, expect 1.5 evts

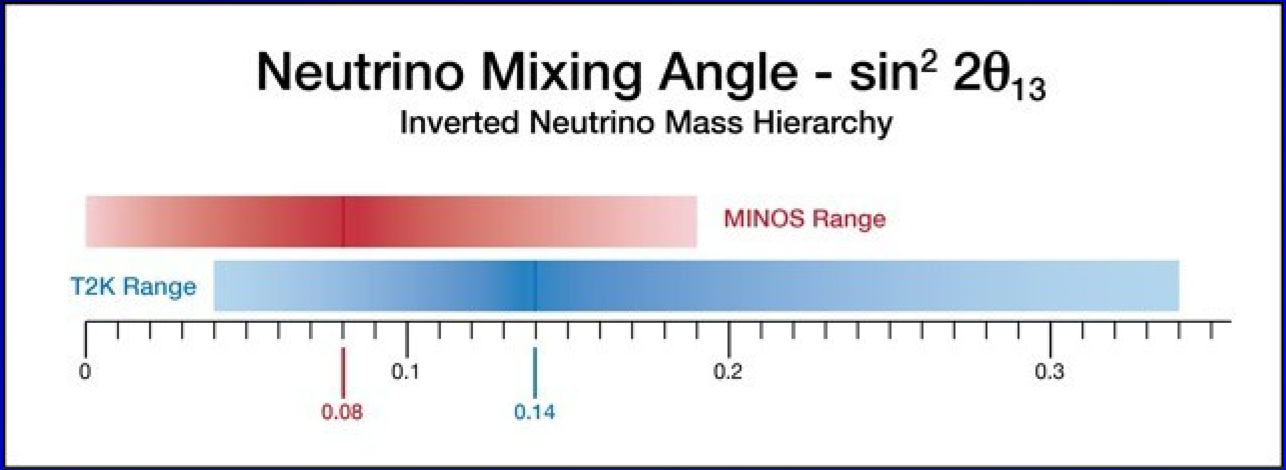




Note: Neutrino physics is not a data-rich field!

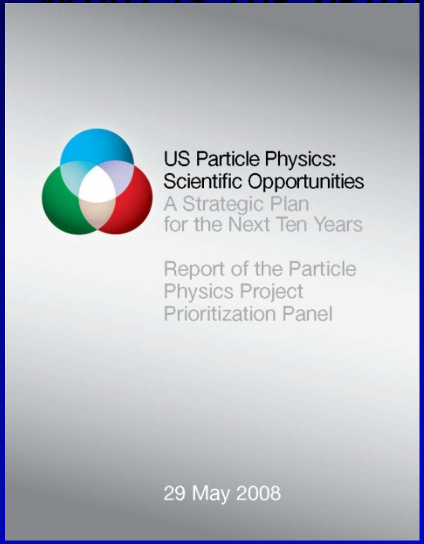
Hot Off the Press News on θ13!

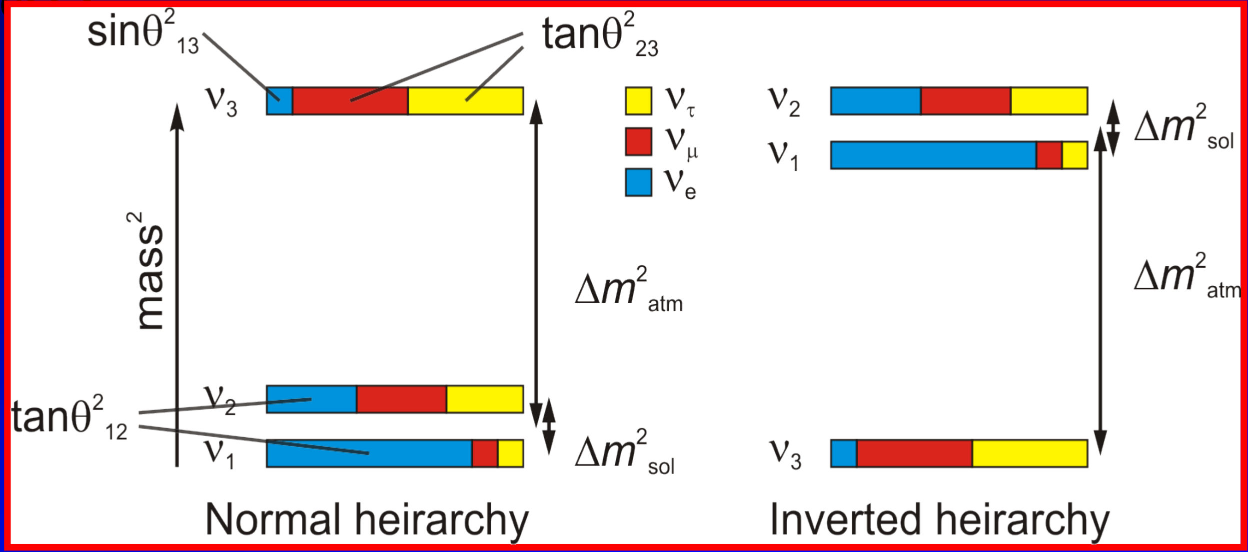




What Remains to be Learned?

- What is the value of $\theta 13$, the amount of νe in $\nu 3$?
  - Impacts mass hierarchy measurement
  - Impacts CP-violation search
- Is the mass hierarchy normal or inverted?
- Is $\theta 23$ maximal (45 degrees)? if so, why?
- Are neutrinos and anti-neutrinos different?
- Do neutrinos respect CP? If not, is CP violation in the neutrino sector responsible for the matter-antimatter asymmetry in the universe?
- What is the neutrino mass?

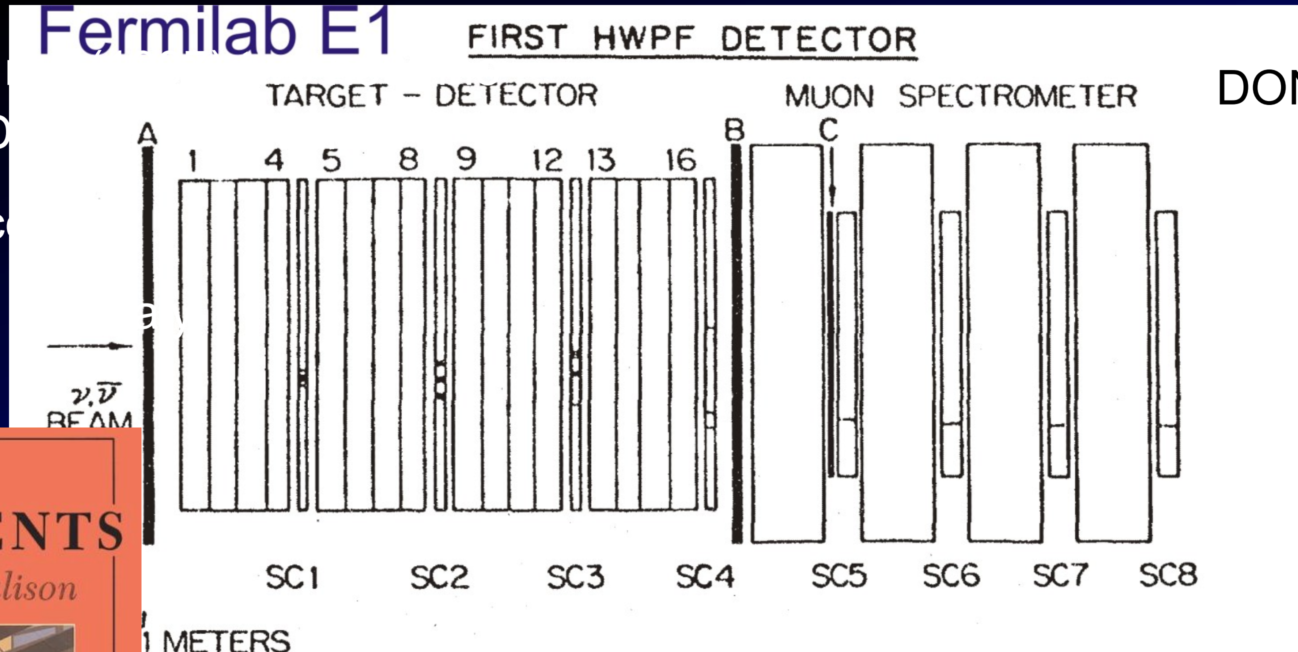




The Past

Fermilab has Long History of ν Physics

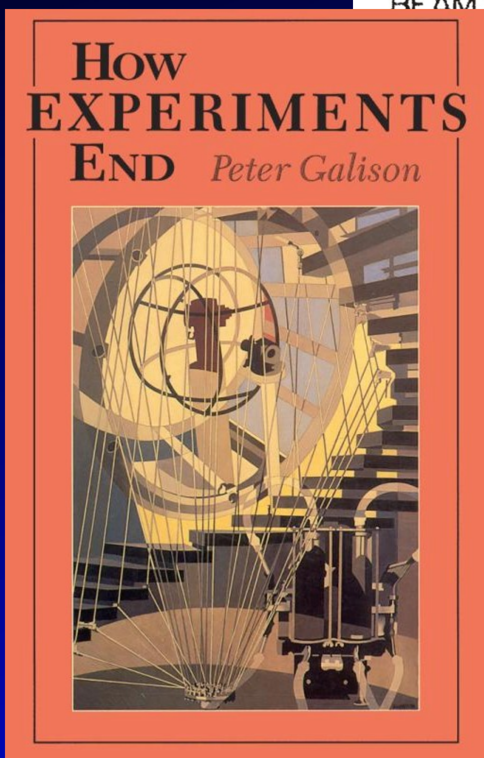
- Last fixed target
  experiments: D
- DONUT: ντ disc
- NuTeV: sin2θW

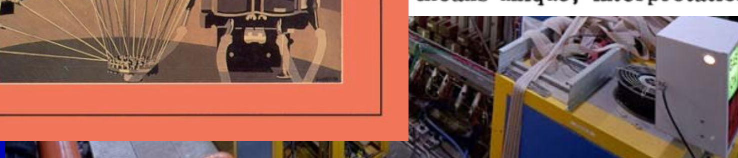


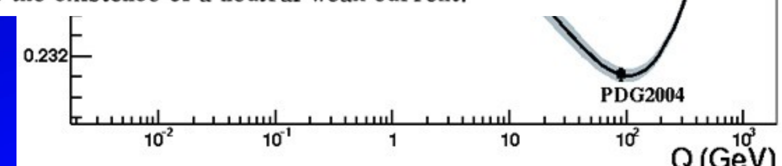
Observation of Muonless Neutrino-Induced Inelastic Interactions

uti, D. C. Cheng,* D. Cline, W. T. Ford, R. Imlay, T. Y. Ling, A. K. Mann, F. Messing,
R. L. Piccioni, J. Pilcher,† D. D. Reeder, C. Rubbia, R. Stefanski, and L. Sulak
t of Physics, Harvard University,‡ Cambridge, Massachusetts 02138, and Department of Physics,
of Pennsylvania,‡ Philadelphia, Pennsylvania 19174, and Department of Physics, University of
in,‡ Madison, Wisconsin 53706, and National Accelerator Laboratory, Batavia, Illinois 60510
(Received 3 August 1973)

We report the observation of inelastic interactions induced by high-energy neutrinos and antineutrinos in which no muon is observed in the final state. A possible, but by no means unique, interpretation of this effect is the existence of a neutral weak current.







The Present

Fermilab has built two new Neutrino Beams

Main Injector Beam (NUMI)

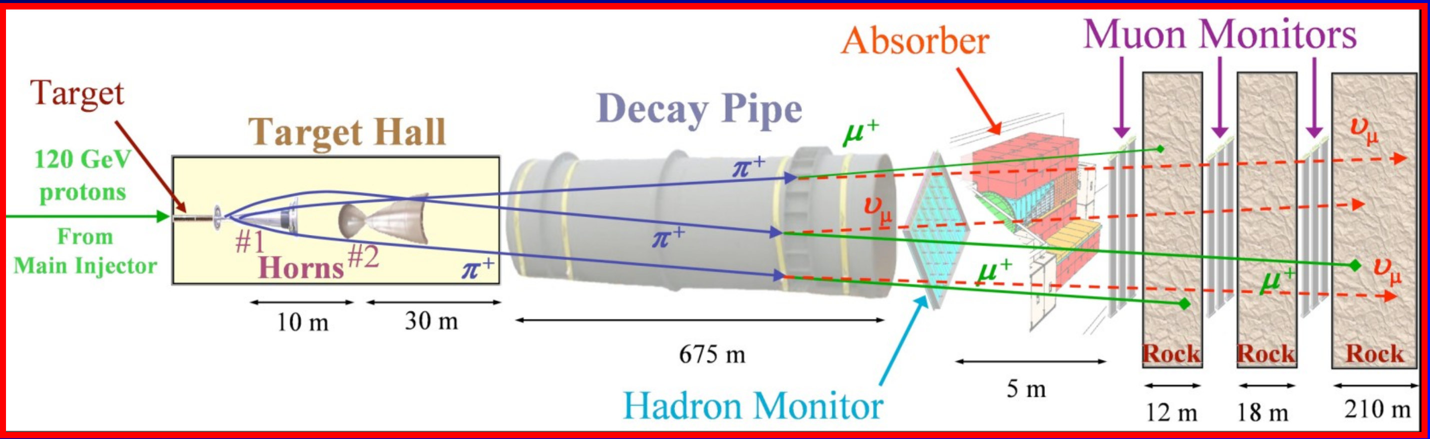
- Beam
  - 120 GeV protons
  - 4.5 x 1013 p/2.2 s (0.320 MW)
- Experiments:
  - MINOS (running)
  - ArgoNeuT (running)
  - MINERvA (running)
  - NOvA (construction)

Booster Beam

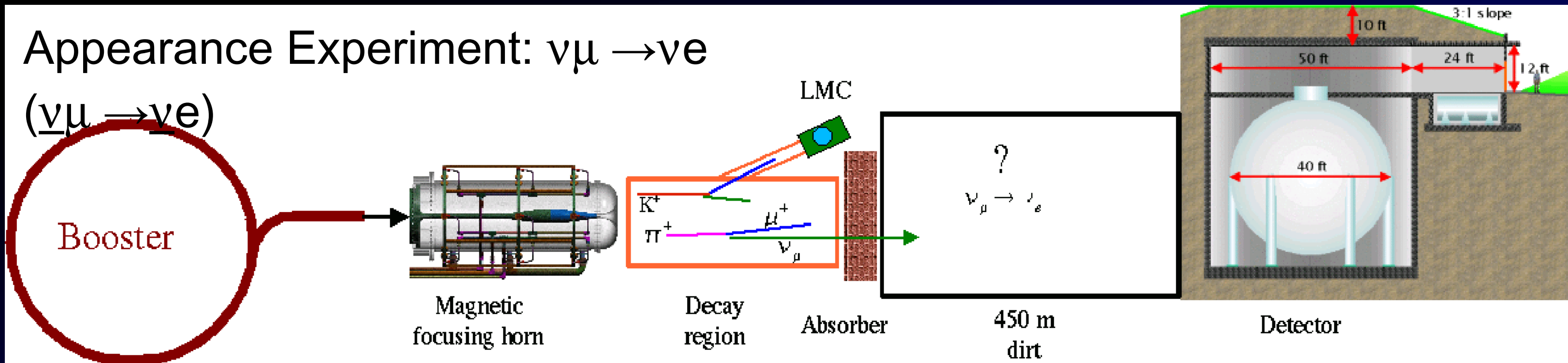
- Beam:
  - 8 GeV protons
  - 4 x 1012 p/0.20 s
- Experiments:
  - MiniBooNE (running)
  - SciBooNE (just completed)
  - …ved)

We use beam power because σ(ν) ¿ E

NuMI Beamline



MiniBooNE

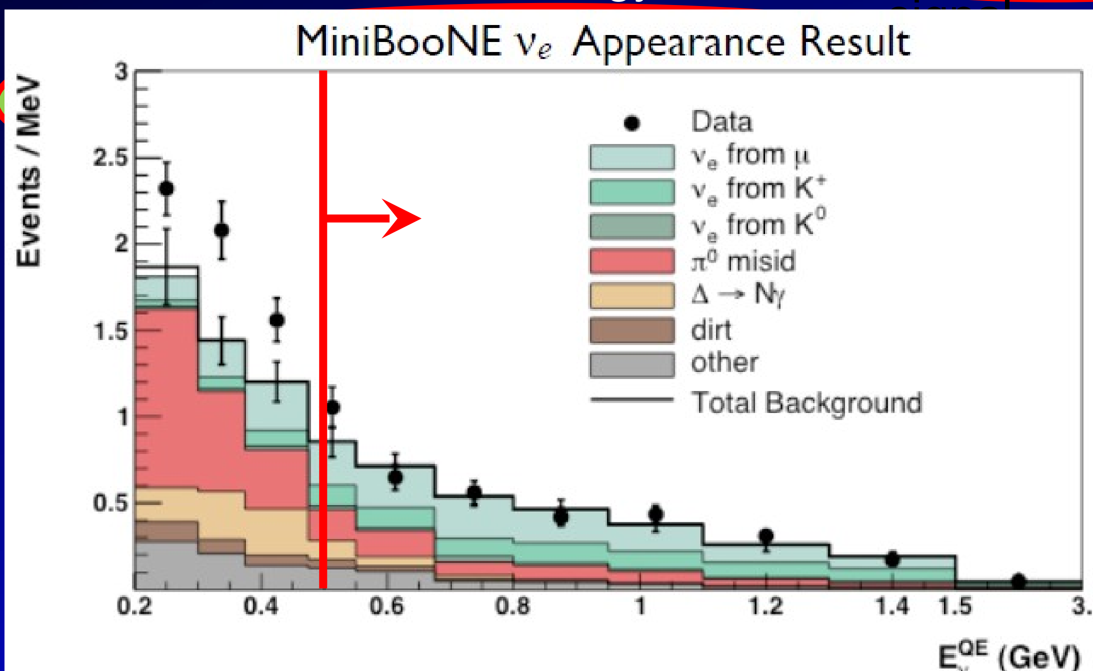


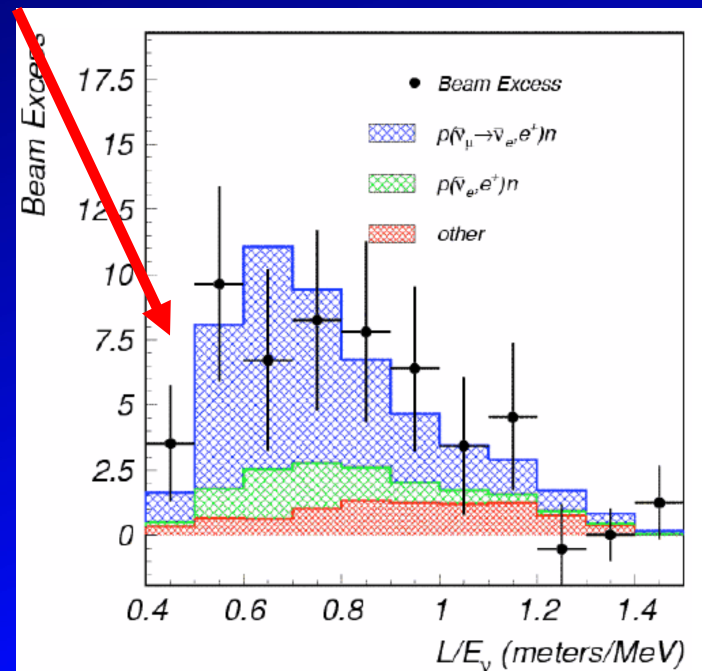
Running through 2011

Find low-energy excess

Oscillated

RuleLSNDLSNDresult





·Extra dimensions

Do We Know the Low Energy σν?

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QE

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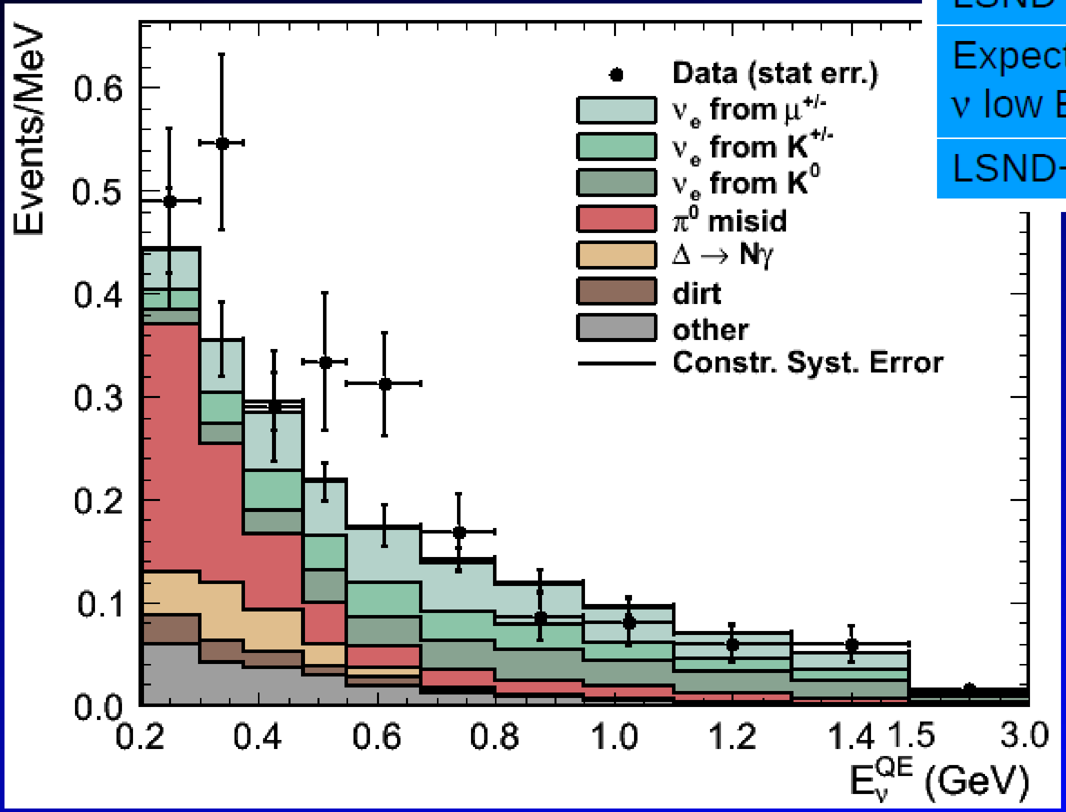
DIS

New σν calculations: 2006-2008 (Sam Zeller

MiniBooNE: anti-νe Appearance

Both low and energy excess!

	200-475MeV	475-1250MeV
Data	119	120
MC	100.5±14.3	99.1±14.0
Excess	18.5±14.3	20.9±14.0
LSND Best Fit	7.6	22
Expectation from ν low E excess	11.6	0
LSND+Low E	19.2	22



Fluctuation?: 1.6% 3.0%

No good explanation of excess has been given

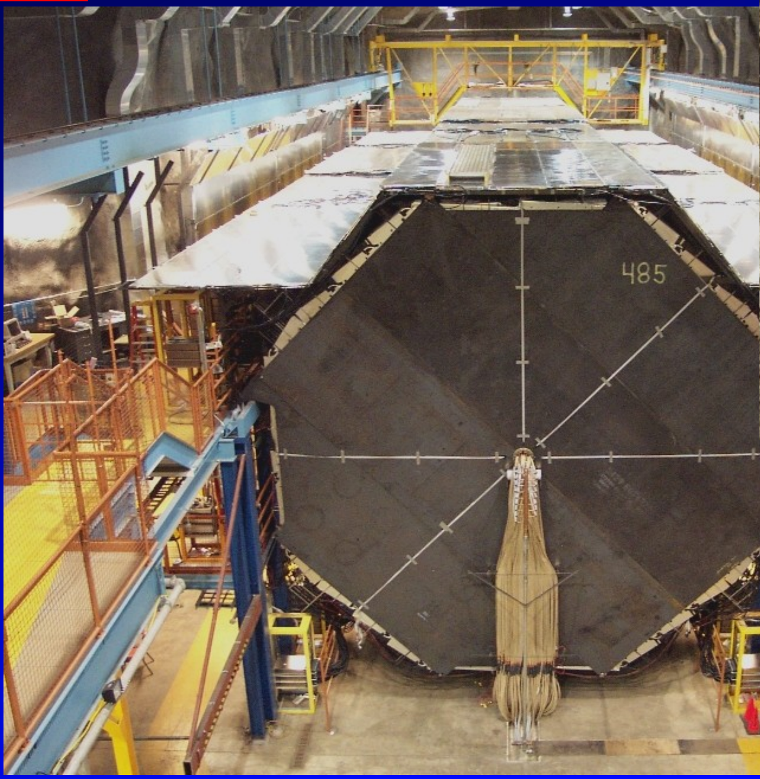
MINOS (Main Injector Neutrino Oscillation Search)

Detector:

- NUMI beam
- Long baseline: 735 km
- 5.4 kt far detector, 1kt near
- Optimized for $\nu\mu$ disappearance
- Sampling 2.54 cm Fe / 1.0 cm scint.
- Magnetic field: sign of charge

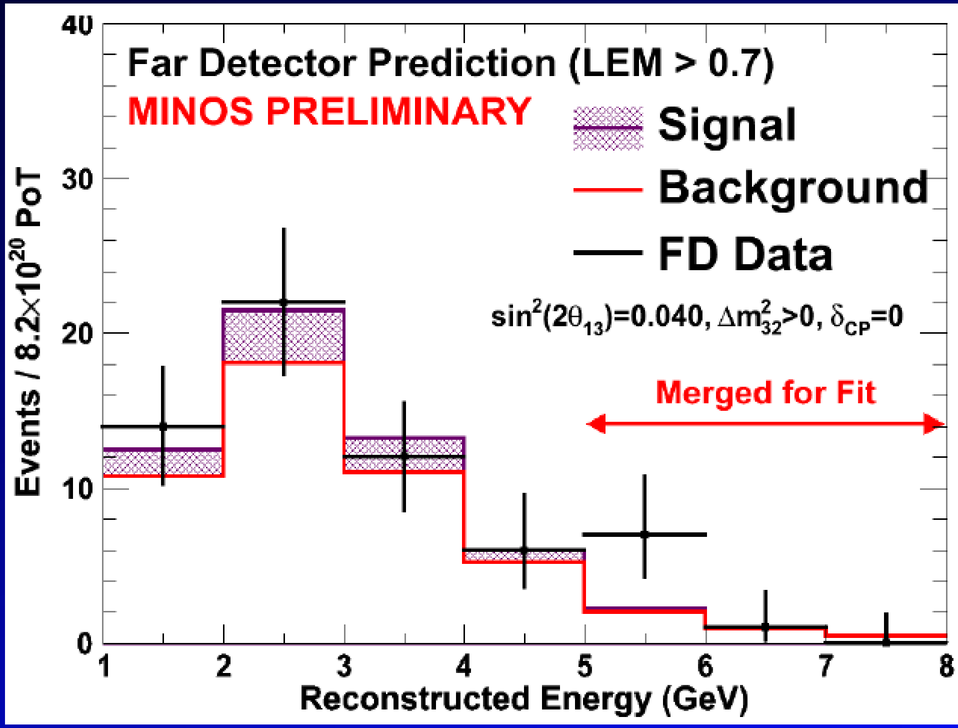
Goals:

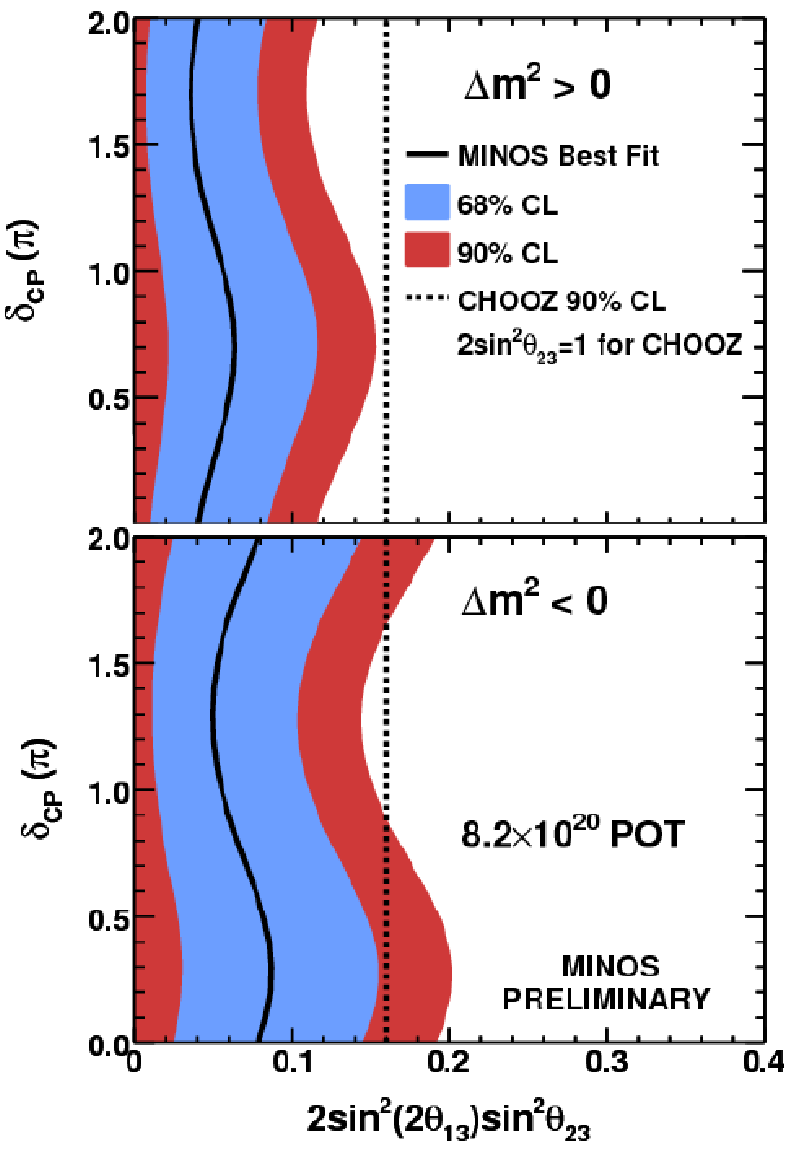
- Make precision measurements of $\Delta m232$ and $\sin 22\theta 23$
- Confirm oscillations vs decay/decoherence
- Compare ν vs anti-ν oscillations



MINOS: νμ → νe

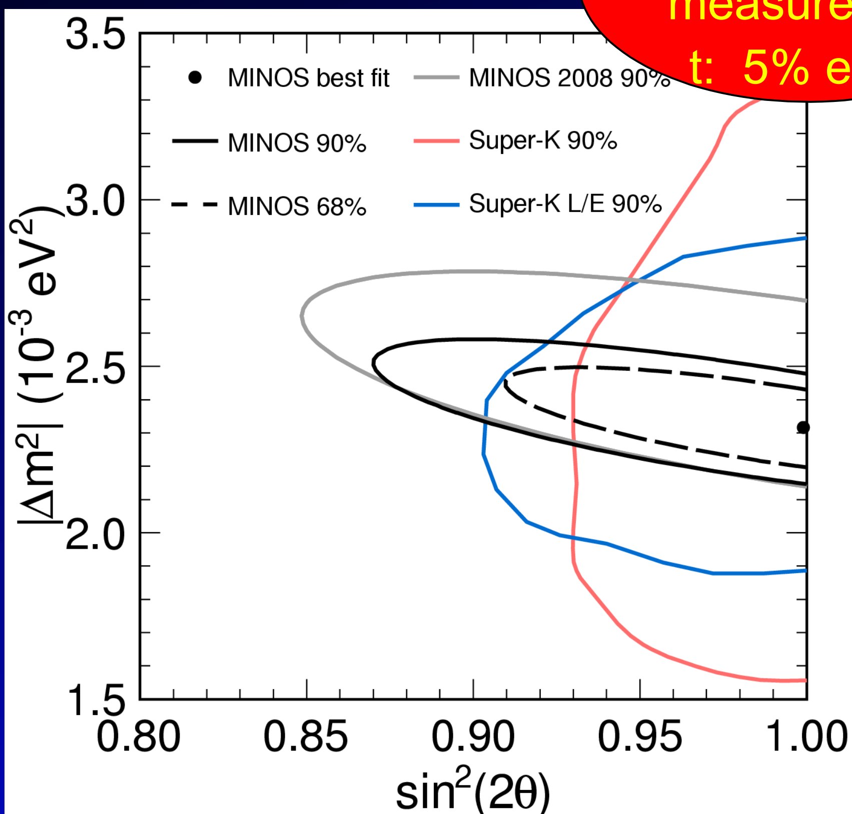
- ·8.2x1020 POT
- ·Observe 62 events after cuts
- ·Expect 49.5¿ 7(stat)¿ 2.8(sys) background events
- ·1.7σexcess
- ·Best fit normal (inverted): sin22θ13 = 0.04 (0.0





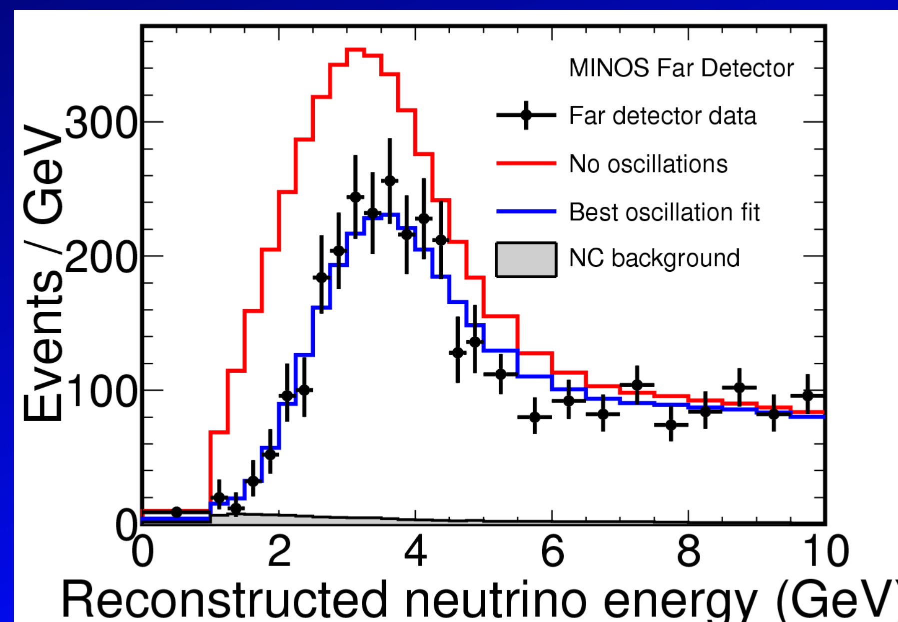
MINOS: νμ Disappearance

Most precise measurement: 5% error



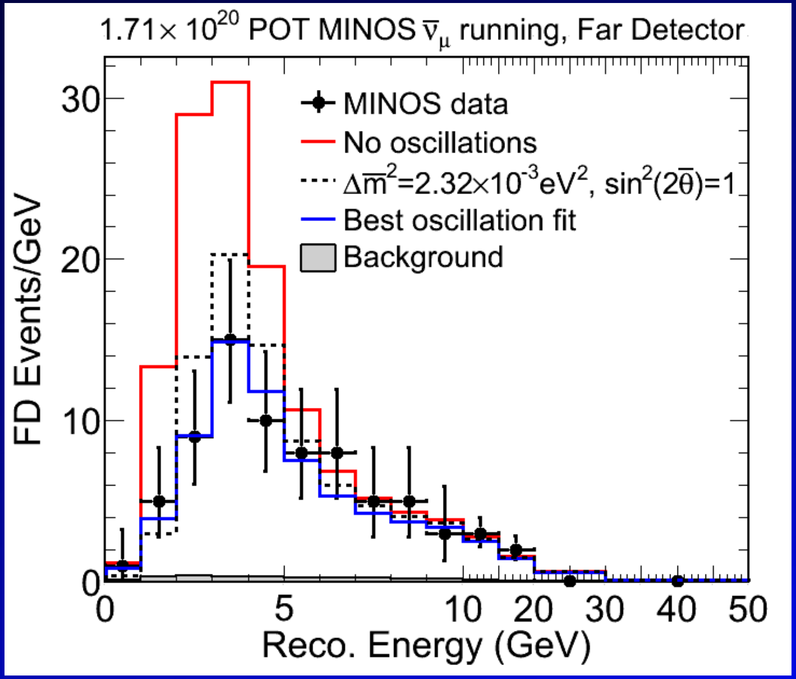
Decoherence disfavored at 8.8σ

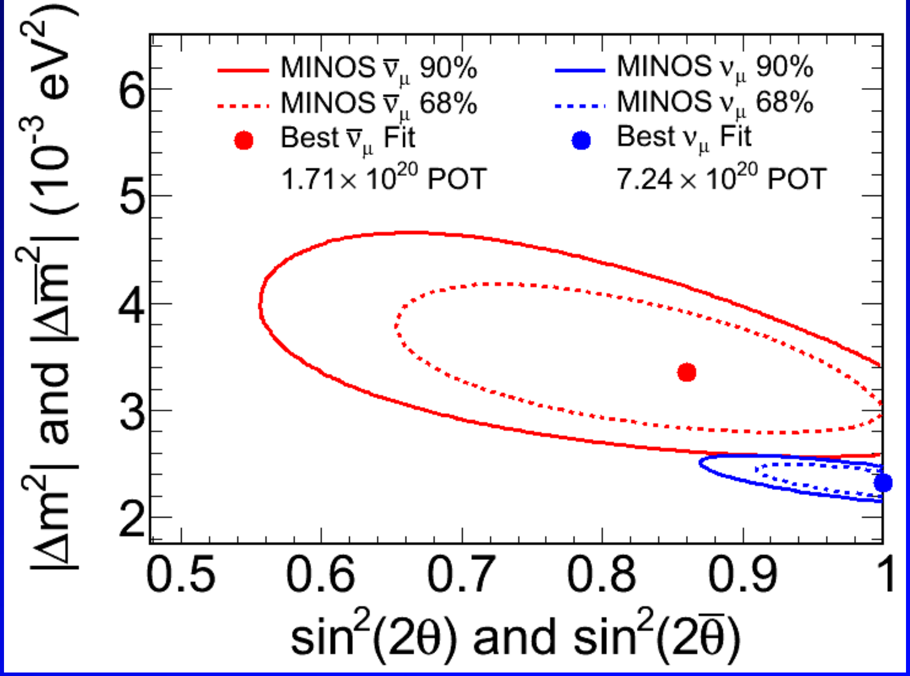
Decay disfavored at 6.8σ



MINOS: anti-νμ Disappearance

What is happening here!
5% chance they are consistent!





Beware: Neutrino Anomalies can be Important!

Beta-decay anomaly J. Chadwick, Verh. d. Deutsch. Phys. Ges. 16, 383, 1914.

Solar neutrino anomaly

23 January 1976
Volume 191, No. 4224
SCIENCE

Solar Neutrinos: A Scientific Puzzle

John N. Bahcall and Raymond Davis, Jr.

Atmospheric νμ /νe anomaly in proton decay experiments

Volume 205, number 2,3 PHYSICS LETTERS B 28 April 1988

EXPERIMENTAL STUDY OF THE ATMOSPHERIC NEUTRINO FLUX

K.S. HIRATA, T. KAJITA, M. KOSHIBA, M. NAKAHATA, S. OHARA, Y. OYAMA, N. SATO, A. SUZUKI, M. TAKITA, Y. TOTSUKA
ICEPP, Department of Physics, Department of Astronomy, Faculty of Science, University of Tokyo, Tokyo 113, Japan

T. KIFUNE, T. SUDA
Institute for Cosmic Ray Research, University of Tokyo, Tokyo 188, Japan

AHASHI, T. TANIMORI
ergy Physics (KEK), Ibaraki 305, Japan

A
of Niigata, Niigata 950-21, Japan

CHER, E.D. FRANK, W. FRATI, S.B. KIM, A.K. MANN,
N BERG, W. ZHANG
of Pennsylvania, Philadelphia, PA 19104, USA

and

B.G. CORTEZ
AT&T Bell Laboratories, Holmdel, NJ 07922, USA

VOLUME 57, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1986

Calculation of Atmospheric Neutrino-Induced Backgrounds in a Nucleon-Decay Search

T. J. Haines, R. M. Bionta, G. Blewitt, C. B. Bratton, D. Casper, R. Claus, B. G. Cortez, S. Errede, G. W. Foster, W. Gajewski, K. S. Ganezer, M. Goldhaber, T. W. Jones, D. Kielczewska, W. R. Kropp, J. G. Learned, E. Lehmann, J. M. LoSecco, J. Matthews, H. S. Park, L. R. Price, F. Reines, J. Schultz, S. Seidel, E. Shumard, D. Sinclair, H. W. Sobel, J. L. Stone, L. Sulak, R. Svoboda, J. C. van der Velde, and C. Wuest

The Immediate Future

MINERνA: Physics Goals

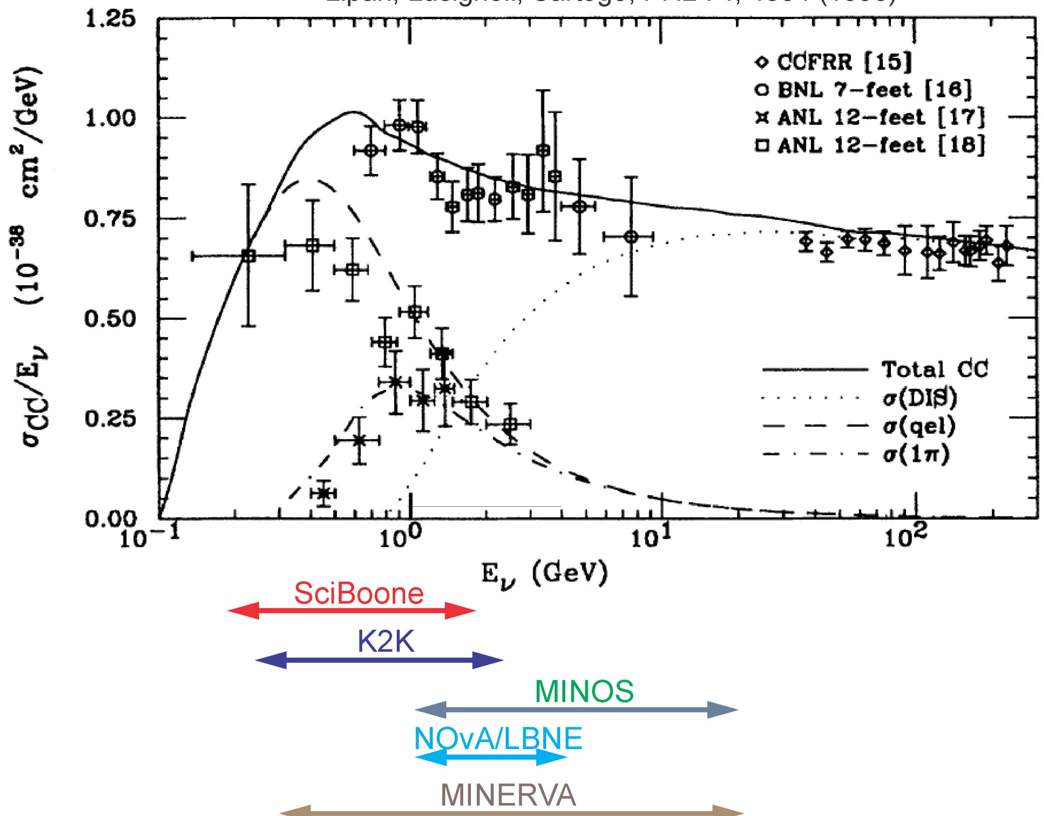
- All accelerator long-baseline experiments need energies from ~0.5 GeV to several GeV
- Neutrino cross sections poorly known at low energies
  - mostly old bubble-chamber data
  - NC cross sections known to ~50% at best
- Neutral current π0 is a major background to ne appearance experiments
- MINERνA plans to measure neutrino nucleus cross sections with unprecedented statistics from 1 – 20 GeV
  - 5% on CC
  -

5% flux error not included

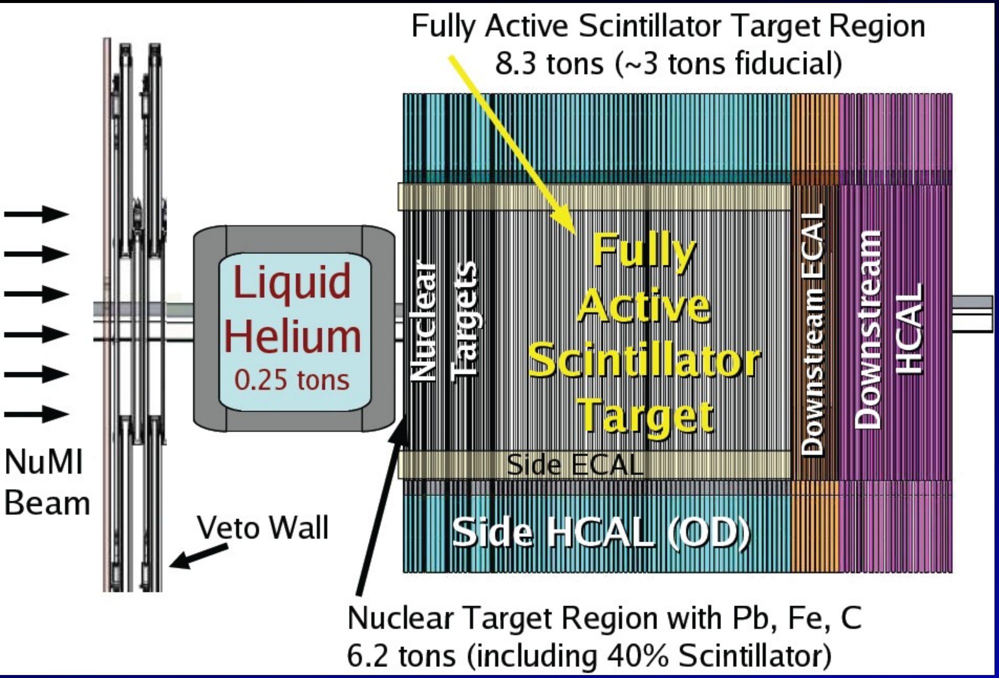
Main Injector Experiment for ν-A

Note: MiniBooNE, SciBooNE (K2K, NOvA) making these measurements as well!

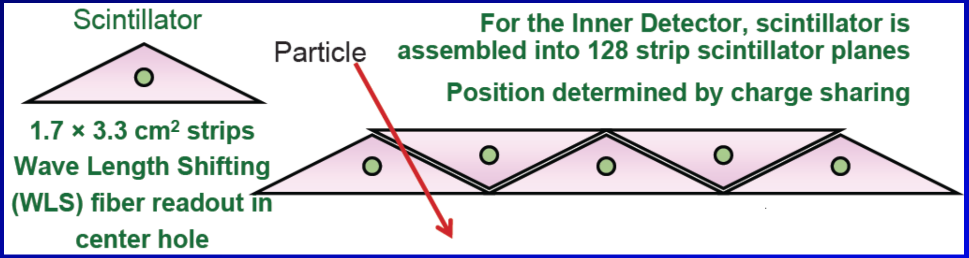
Lipari, Lusignoli, Sartogo, PRL 74, 4384 (1995)

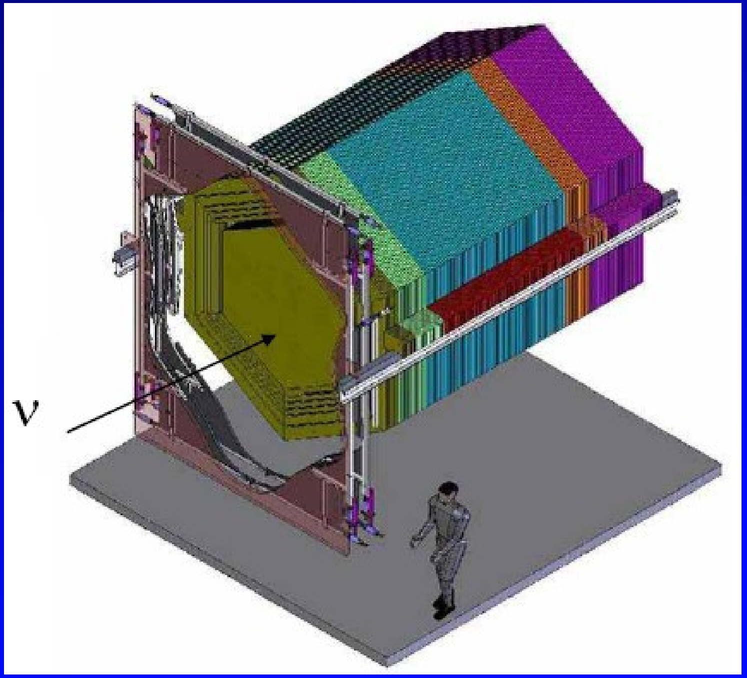


MINERvA: Detector



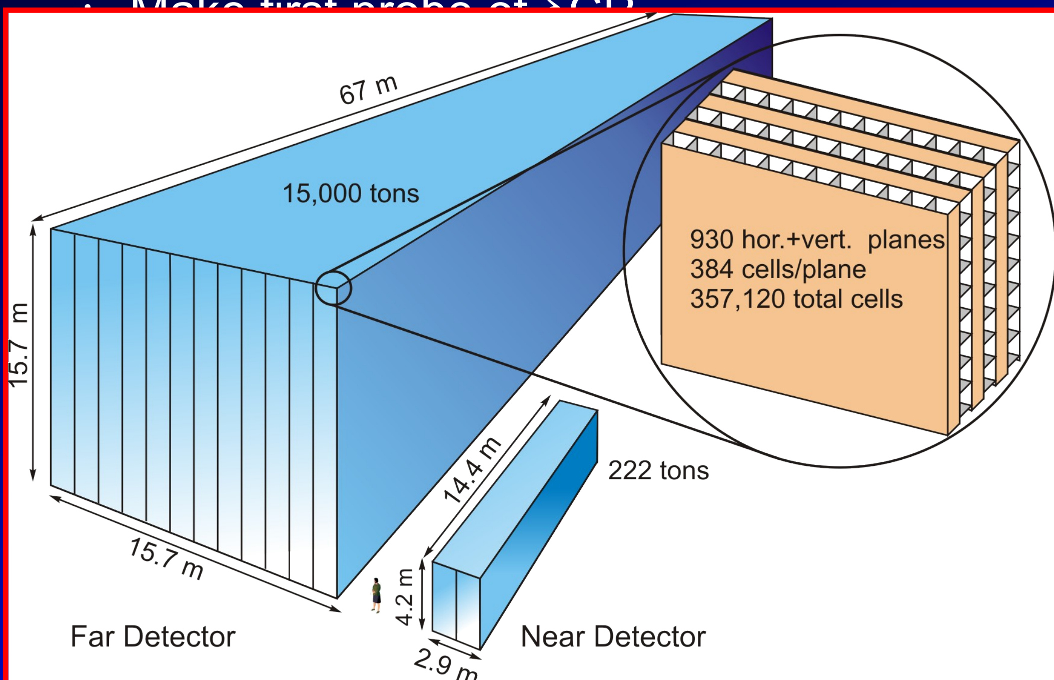
- Fully active segmented scintillator detector: 5.87 tons
- Nuclear targets: He, C, Fe and Pb
- MINOS Near Detector as muon catcher
- Installed and taking data!





NOνA

- Second generation experiment in the NUMI beamline
- Fully active detector optimized for detection of $\nu_\mu \rightarrow \nu_e$ oscillations
- Goals:
  - Observe $\nu_\mu \rightarrow \nu_e$ oscillations
  - Measure θ_{13}
  - Measure θ_{23}
  - Determine mass hierarchy
  - Make first probe of δ_{CP}



The NOνA Collaboration

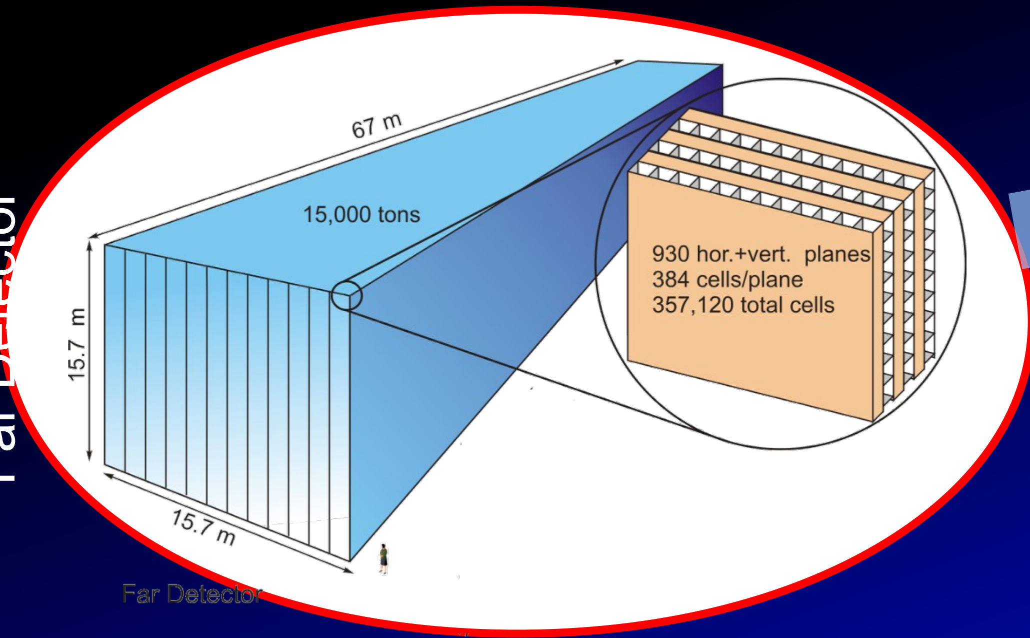
180 Scientists & Engineers from 26 Institutions

- Argonne National Laboratory
- University of Athens
- California Institute of Technology
- University of California, Los Angeles
- Fermi National Accelerator Laboratory
- Harvard University
- Indiana University
- Lebedev Physical Institute
- Michigan State University
- University of Minnesota, Duluth
- University of Minnesota, Minneapolis
- The Institute of Nuclear Research, Moscow
- Technische Universitat Munchen

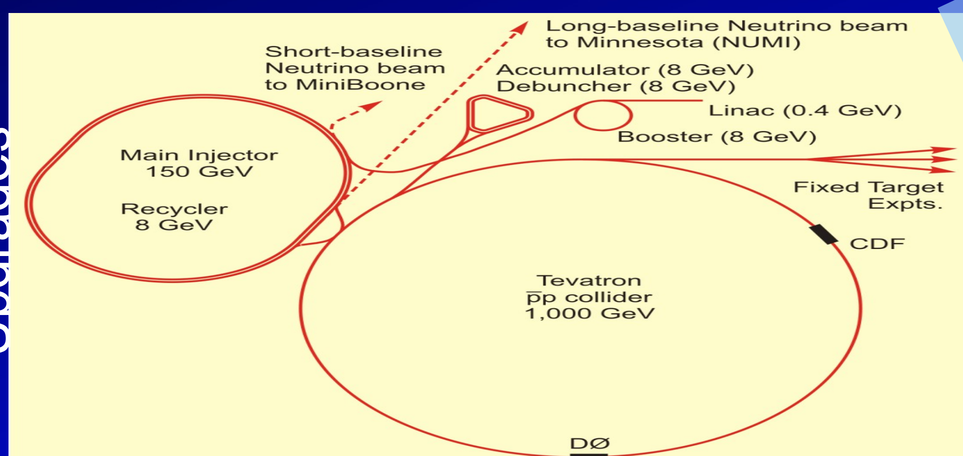
- State University of New York, Stony Brook
- Northwestern University
- University of South Carolina
- Southern Methodist University
- Stanford University
- University of Tennessee
- Texas A&M University
- University of Texas, Austin
- University of Texas, Dallas
- Tufts University
- University of Virginia
- College of William & Mary
- Wichita State University

Three Parts to NOνA

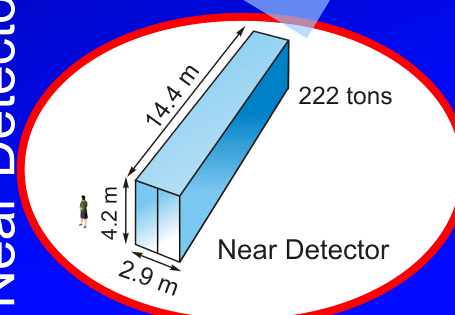
Far Detector



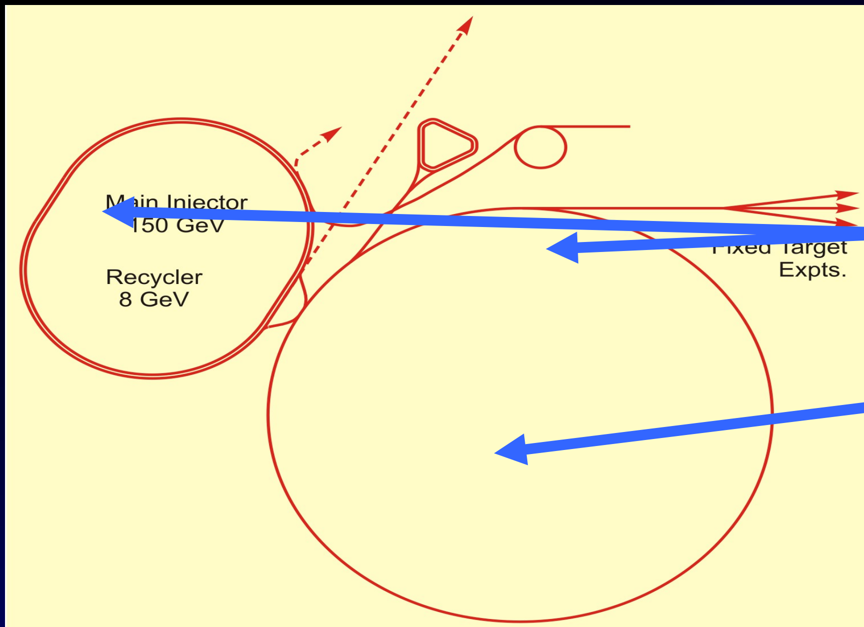
Neutrino Beam Upgrades



Near Detector



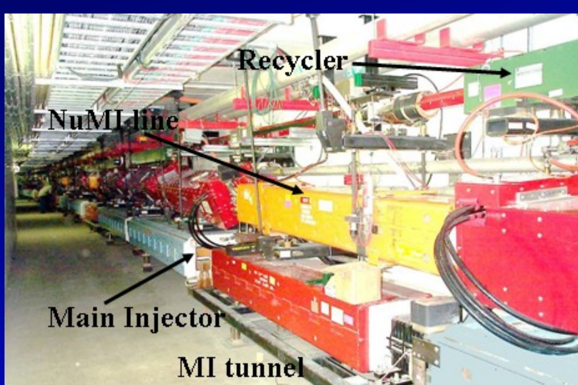
Neutrino Beam Upgrades: ANU



- Turn Recycler from an anti-proton storage ring into a proton storage ring/pre-injector for the Main Injector

1. Need a new injection and a new extraction lines from Rec… Injector with Fast kickers
2. Shorten MI … 33 with RF upgrad…
3. Upgrade NUM… handle more beam power and … cycle time

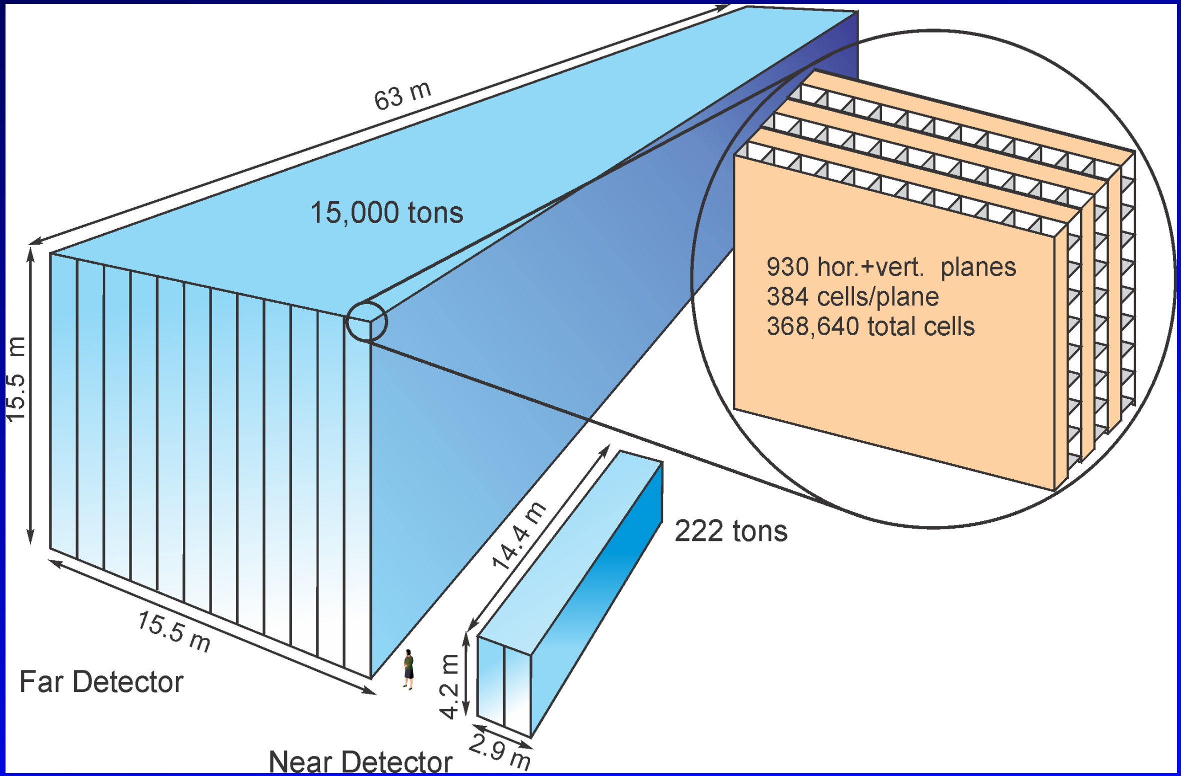
Doubles present NUMI beam power!



	NOvA TDR	Slip stacking in MI	Slip stacking in Recycler
8 GeV Intensity (p/batch)	4.3-4.5 x 1012	4.3 x 1012	4.3 x 1012
Number of 8 GeV batches	7	11	12
MI Cycle Time	2.4 s	2.2 s	1.3 s
MI Intensity (ppp)	3.3 x 1013	4.5 x 1013	4.9 x 1013
NUMI Beam Power (kW)	192	320	700
NUMI Protons per Year	2 x 1020	4 x 1020	6 x 1020

NOνA Far Detector

- 15 kTons
- Fine-grained sampling EM calorimeter: 73% liquid scintillator, 27% PVC
    - Fine-grained sampling: 4 cm x 4cm x 0.15 X0
    - σ(E)/E ~ 10%/√E for νe CC events
    - νe efficiency: ~35%
- 930 planes: alternating vertical and horizontal cells
- 368,640 cells
- 16 x 16 x 63 m3



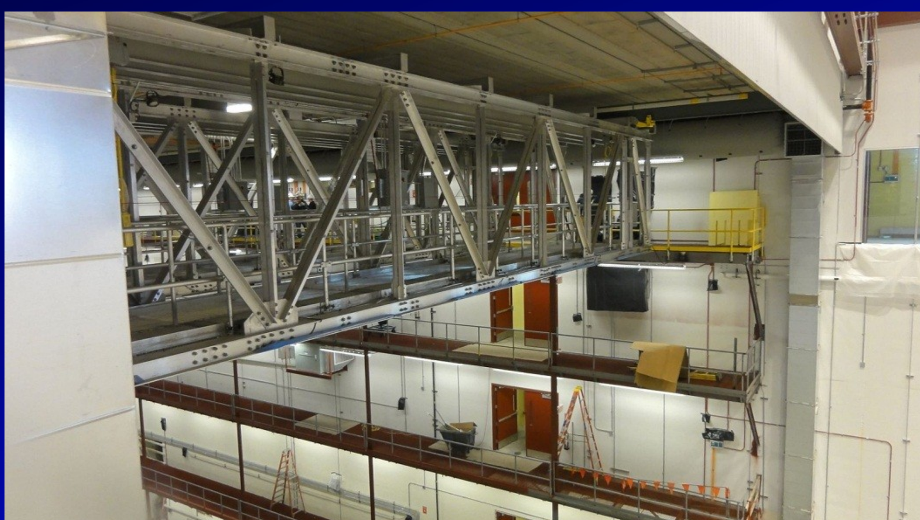
NOvA Far Detector Siting: Longitudinal Distance

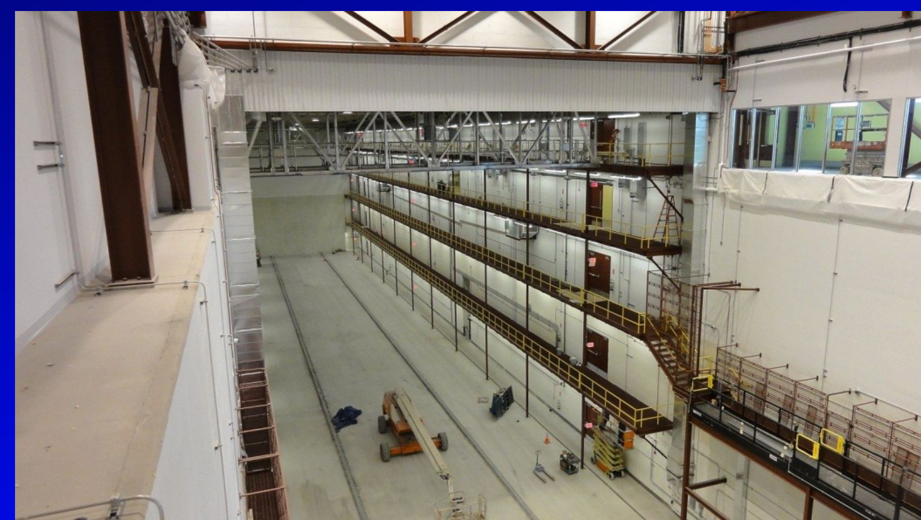
- Mass ordering sensitivity (matter effect) dictates placing the detector as far as practical from Fermilab: Ash River, Minnesota, 810 km baseline
- Redirecting the NUMI beam not an option: too $$$

Furthest point north in US accessible by road.

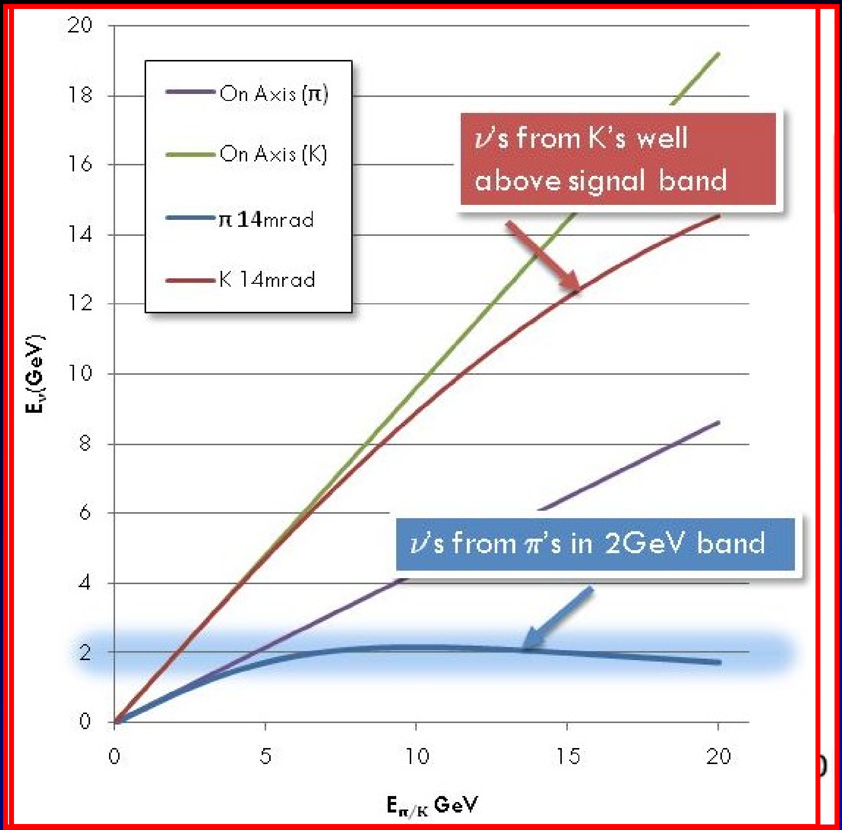
NOνA: Far Detector Building

- Building completed
- 471’(350’) long x 63’ wide x 71’ high (below grade)
- Sized for 18 kt detector
- $15.8 less than baseline!
- This fall: start installing the detector



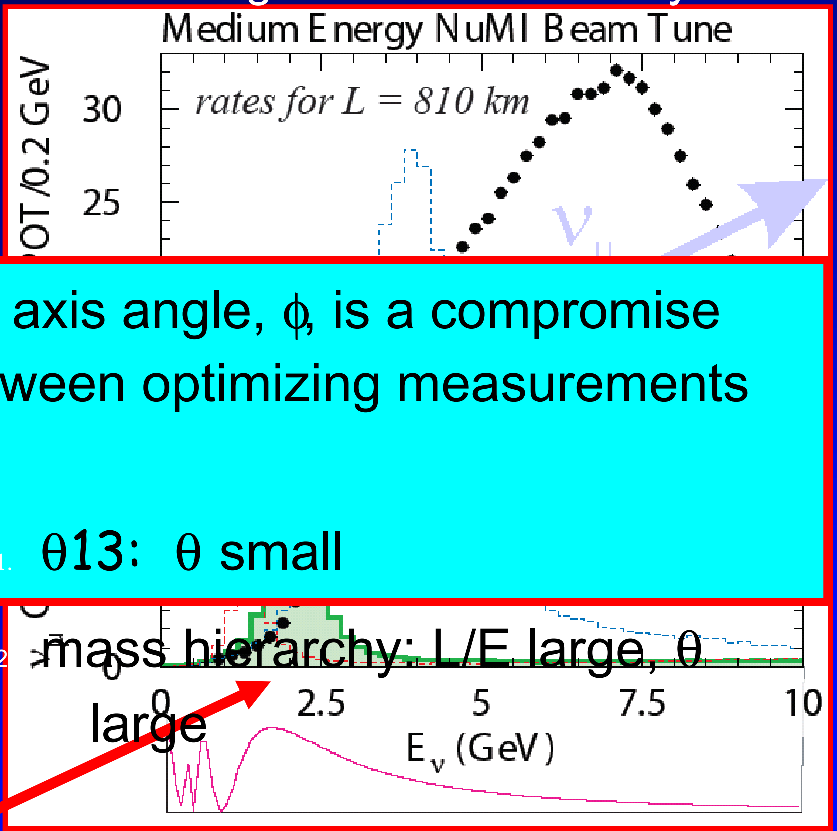


NOνA Far Detector Siting: Off-Axis Distance



Advantages of going Off-Axis

- Allows the central energy to be tuned to the desired value
- Reduces high-energy tail, which feeds down neutral current and τ backgrounds
- Reduces νe background from K decays



Off axis angle, ϕ, is a compromise between optimizing measurements of:

1. θ13: θ small
2. mass hierarchy: L/E large, θ large

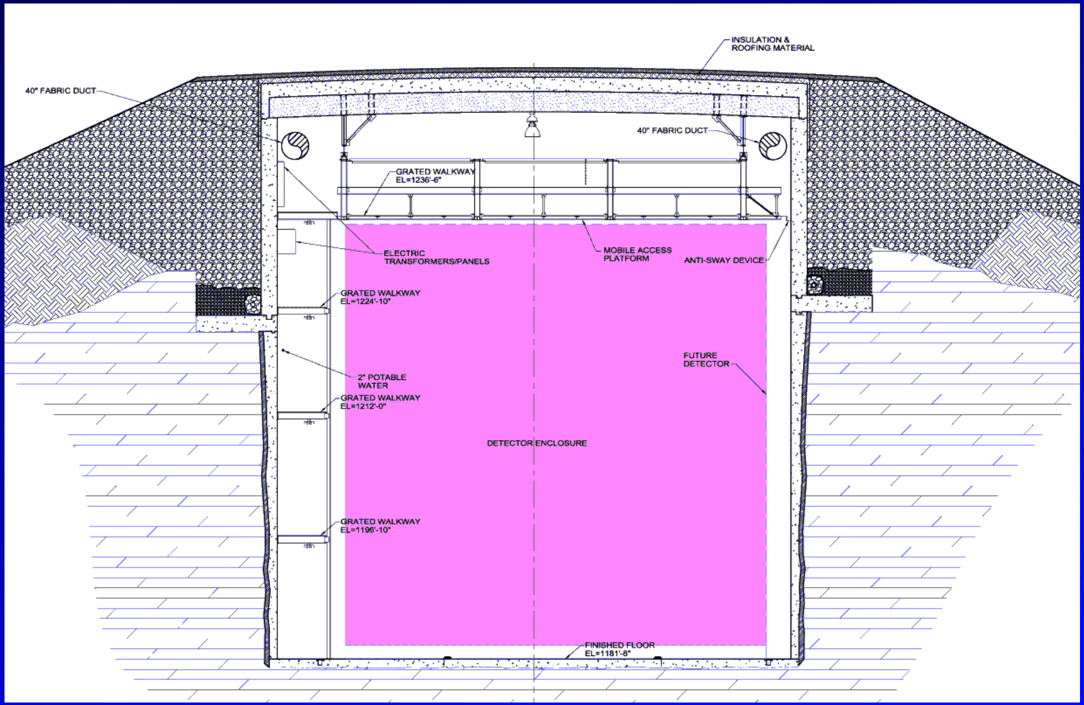
First oscillation maximum

NOvA Far Detector Siting: Vertical Distance

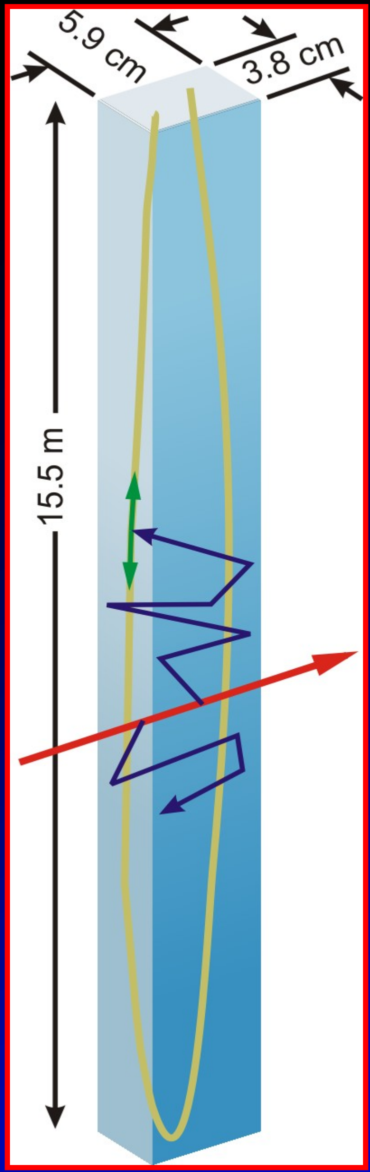
- NOvA is the first surface long-baseline oscillation experiment
- All previous long-baseline oscillation experiments have been deep underground: MINOS, Opera, SuperK, T2K, Kamland, SNO, etc.
- 1.2 x 107 spills/year
- 10 μ s spill

120 s live time/year

- Only cosmic-ray gammas present a potential background to the $\nu\mu \rightarrow \nu e$ signal
  - 12X0 of overburden: concrete and barite
  - 40' deep in solid granite
  - granite berm



NOνA: Detector Element

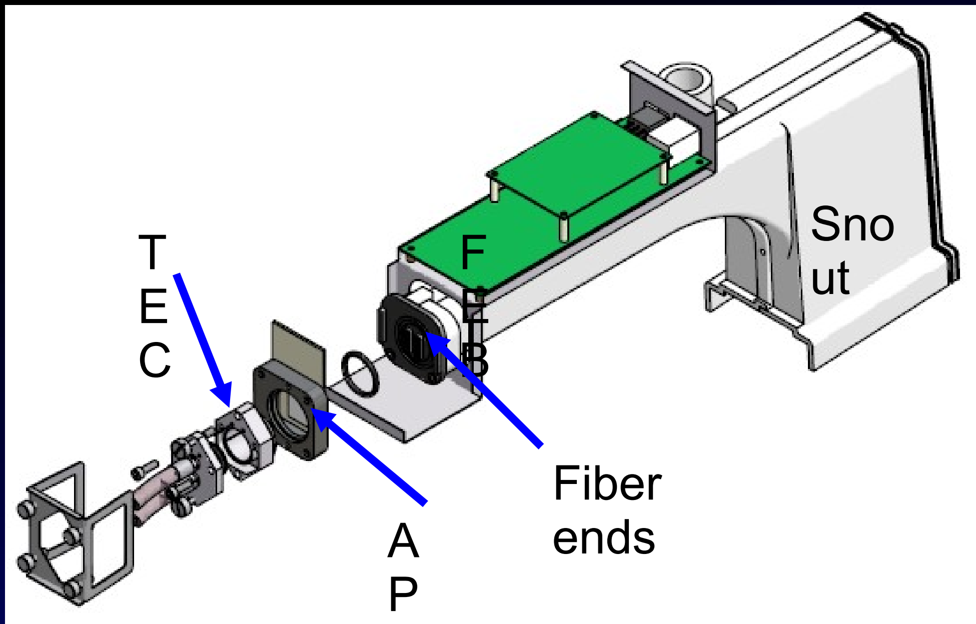


- 3.8 cm x 5.9 cm x 15.5 m cell (walls 2 – 4.5 mm thick)
- 368,640 total cells
- Material:
  - PVC loaded with 15% titanium dioxide ¿ highly reflective
- Liquid scintillator:
  - Mineral oil: 3.9 million
  - 4.1% pseudocumene
  - Waveshifters: PPO, bis-MSB
- Fiber:
  - Single fiber for each c… ad out
  - 0.7 mm, double-clad, 3…
  - 12,133 km
  - Typically light takes 50 cm to find the fiber, with ~8 reflections
  - 10X attenuation for longest path length

1% change in

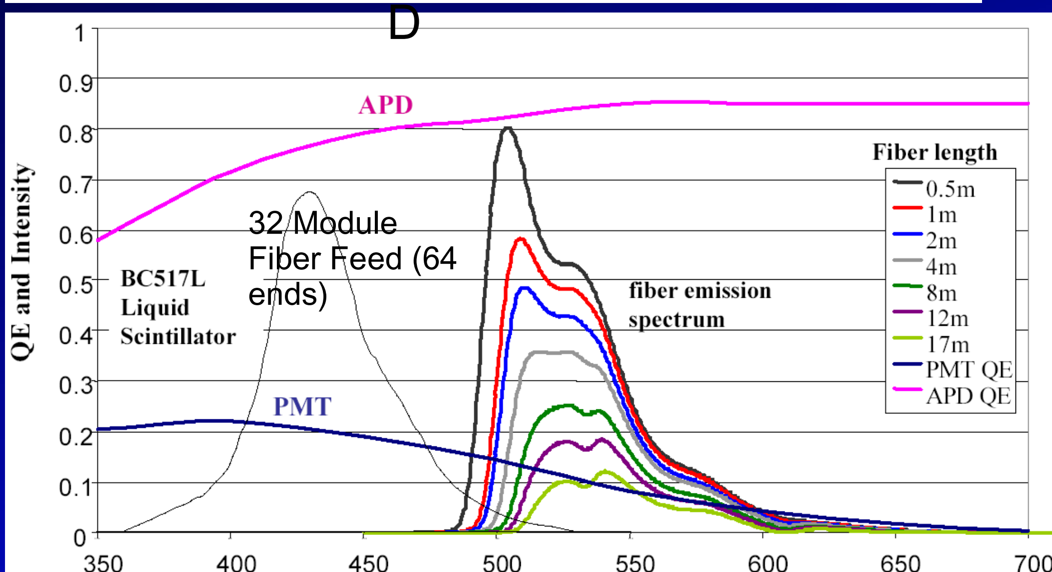
Longest thing you can put in an 18-wheeler

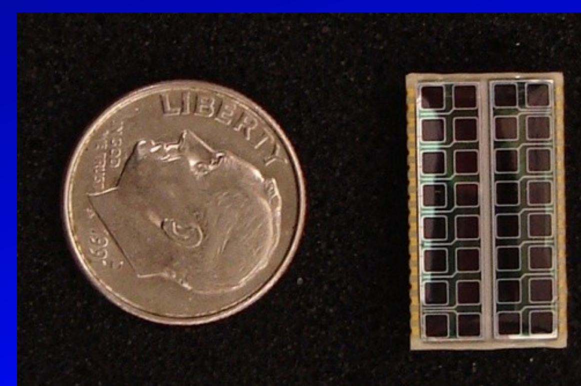
NOvA: Front-End Electronics



Photodetector:

- 32-pixel APD (Hamamatsu)
- 2 fibers per pixel
- Gain: 100X (@ ~400V)
- Cooling: -15C (thermoelectric cooler)
- Signal-to-noise: 10:1 (muon at far end)
- 11,160 needed (Far Detector)



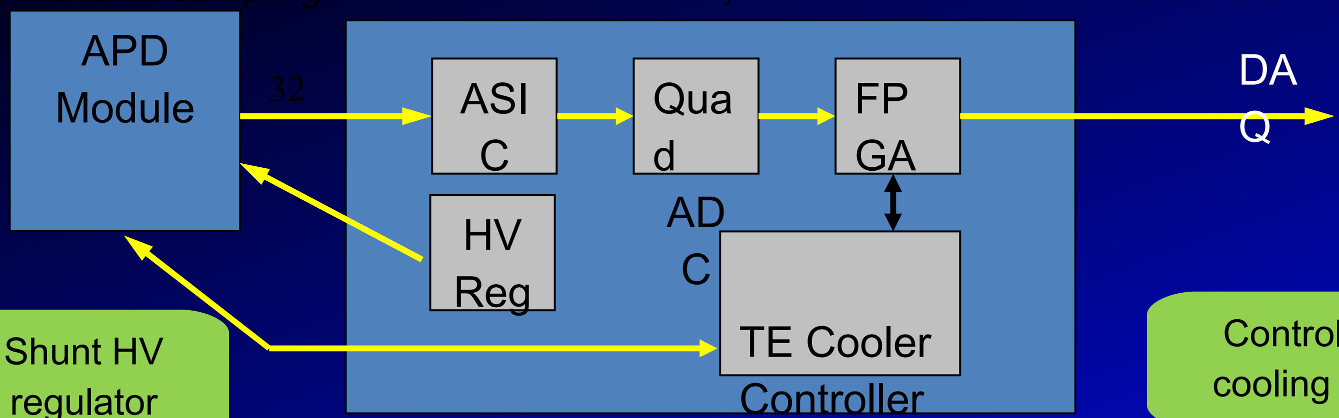


Front-end Electronics Block Diagram

Analog front end: 10 mV/fC
DC coupled, 32-channel
2,4,8 : 1 multiplexing
16 MHz: 125 – 500 ns sampling

Digitize
12 bits, 2 MSPS per channel
1:FD, 4:ND

Data & timestamp extraction
Data packets to DCMs
Slow-Control I/O

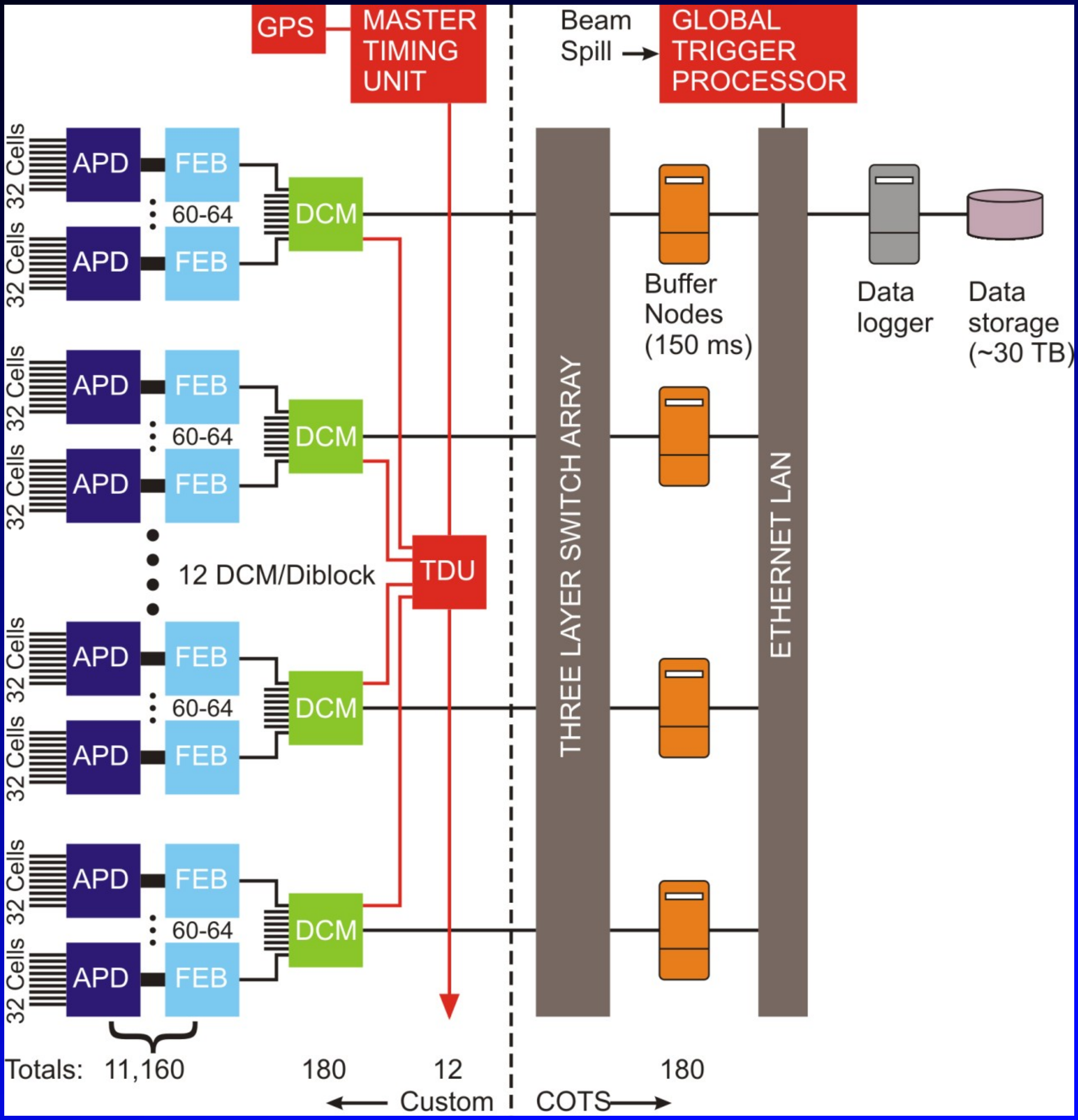


Shunt HV regulator

Controls cooling of APD (-15C)

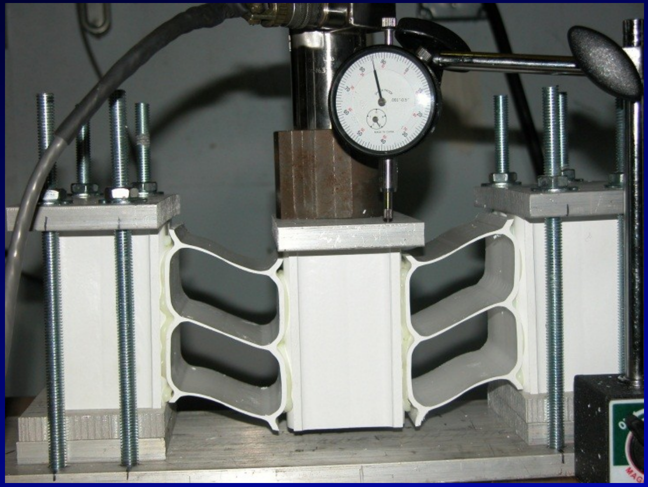
NOνA: Data Acquisition System

- Font-end electronics run in continuous digitization mode
- Data time-stamped at the FEB
- Data Concentrator Module (DCM) takes serial data from up to 64 FEBs and combines and packages it to be sent to the Buffer Nodes
- Off-the-shelf gigabit Ethernet network + switches used to build the events
- Triggers:
  1. Delayed beam spill from Fermilab
  2. Software data-driven trigger for exotics
- All hits in a 30 μ s window centered on the 10 μ s NUMI spill time stored

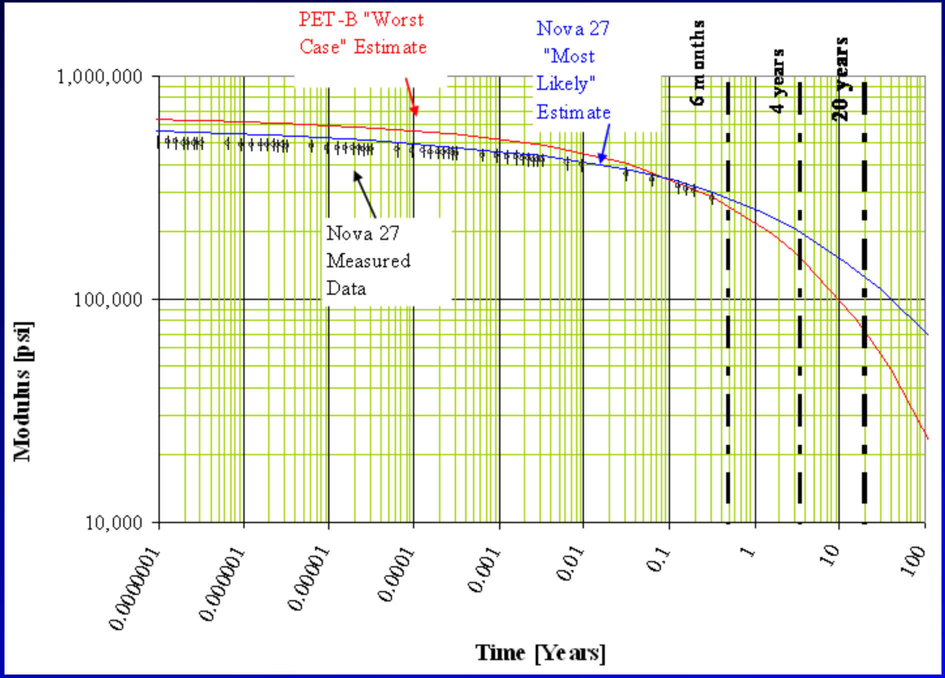


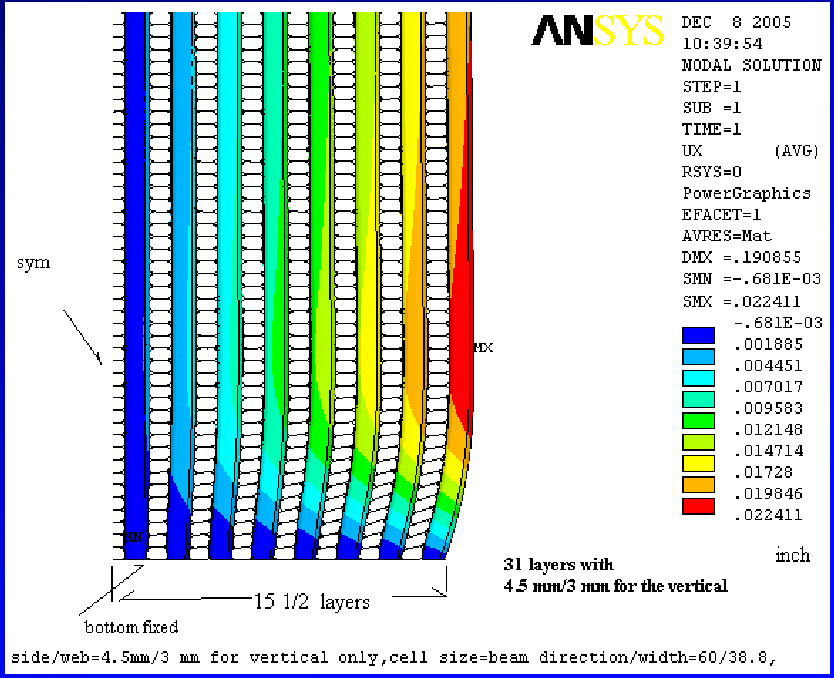
NOvA: Detector Fabrication

- Largest plastic structure ever built
- Modules are glued to each other in 32-plane blocks: 30 total for 15 kT detector
- "Bookends" at either end
- Huge amount of engineering done to assure it will stand: estimate 20 years (without bookends).



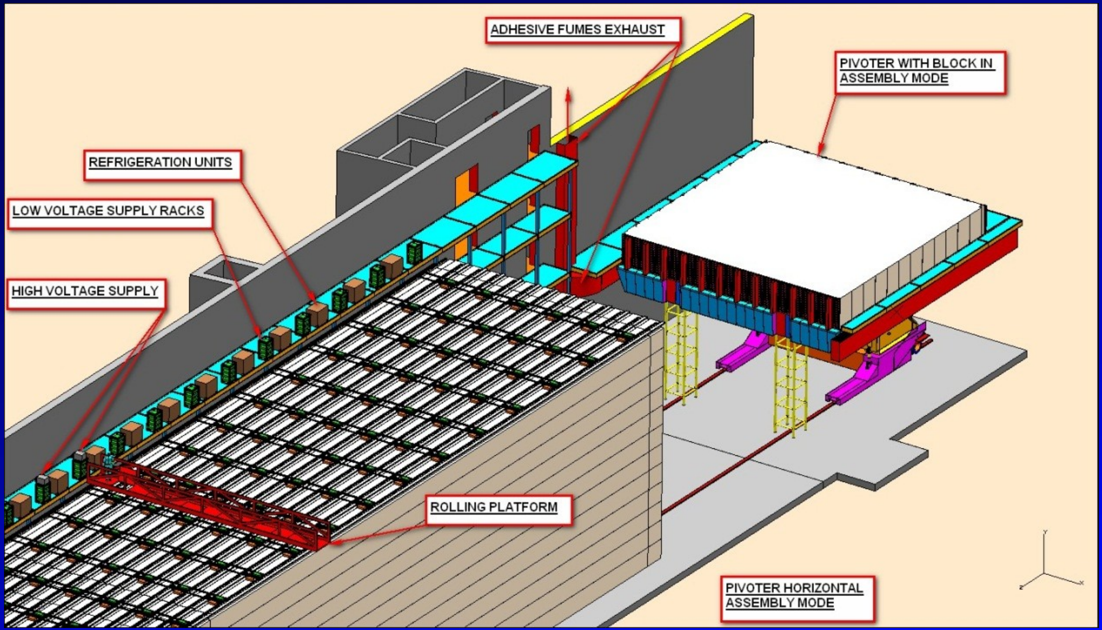
Creep Curve

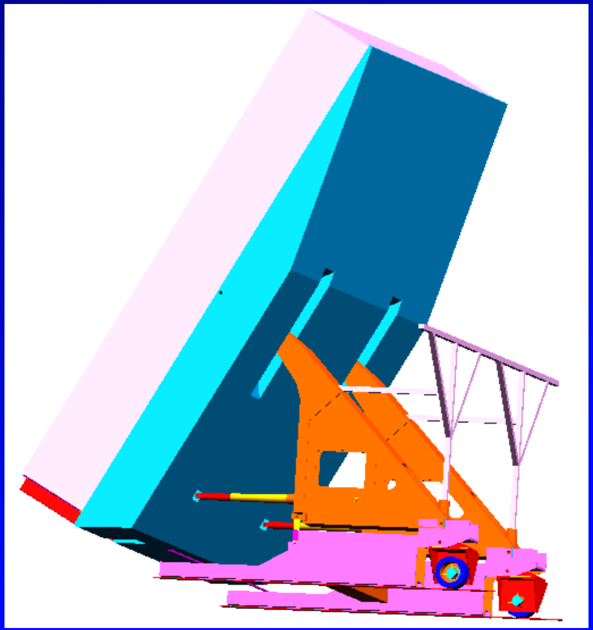




Block Fabrication at Ash River Site

- Modules shipped from Minnesota factory
- Glued together to form 12-module wide planes
- 32-planes glued together to form blocks
- Block pivoter moves blocks to detector
- After positioning at detector blocks are filled with scintillator

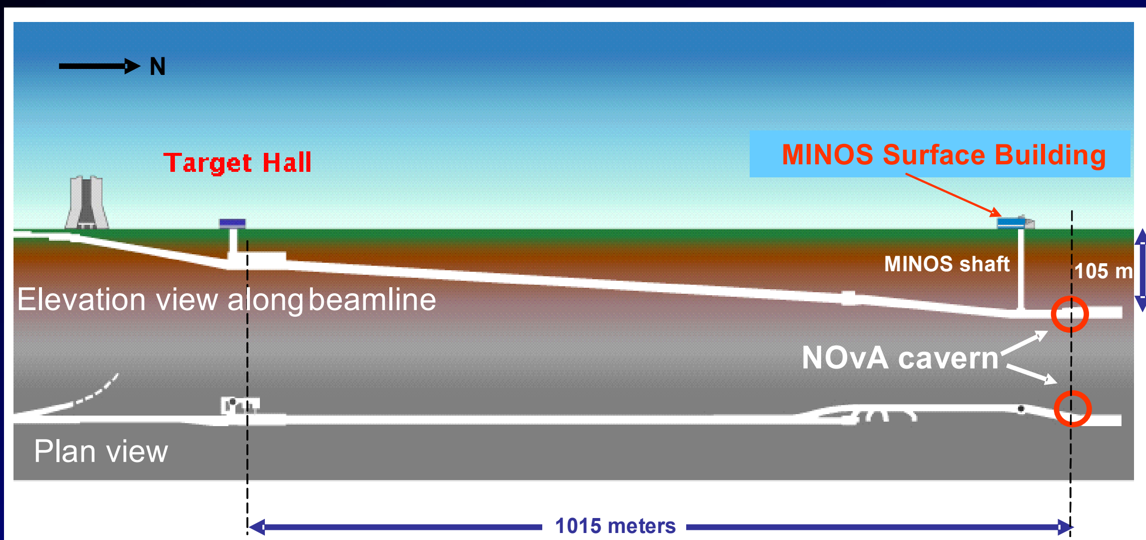


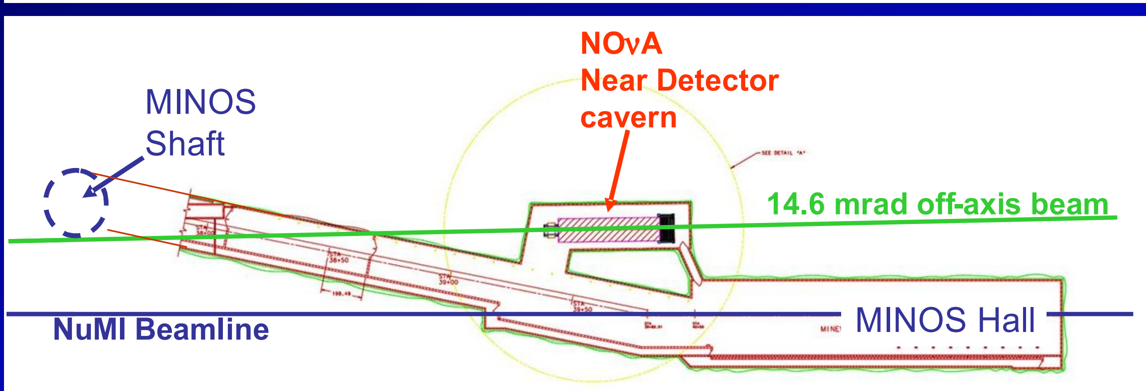


Block Pivoter at CDF

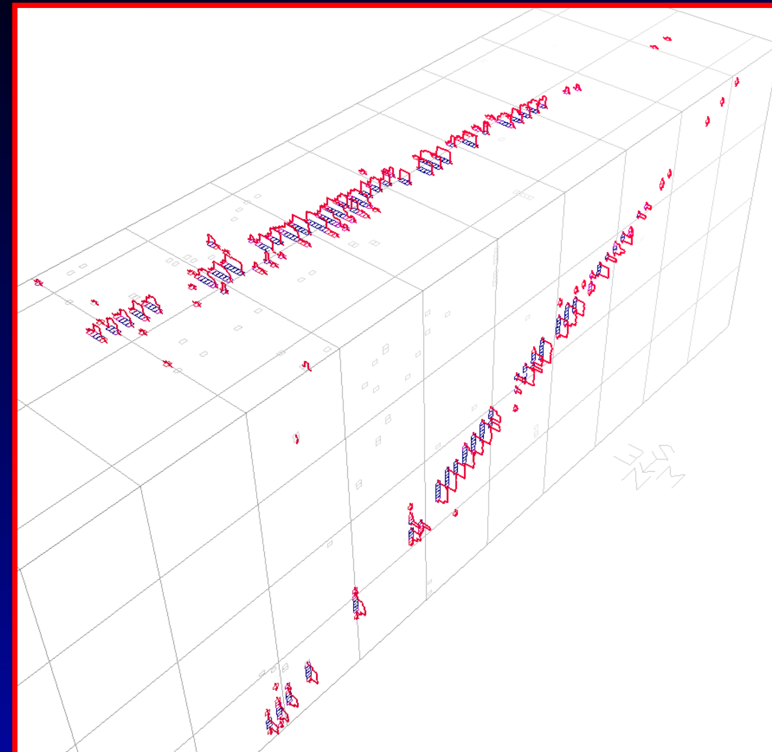
NOνA Near Detector

- Same technology as Far Detector
- 222 Ton mass
- Fabrication completed of surface prototype, which is currently taking data

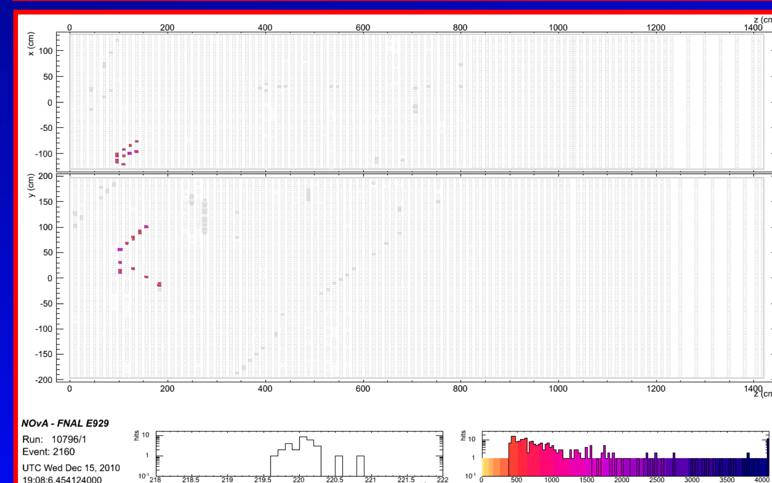




Near Detector: First Events

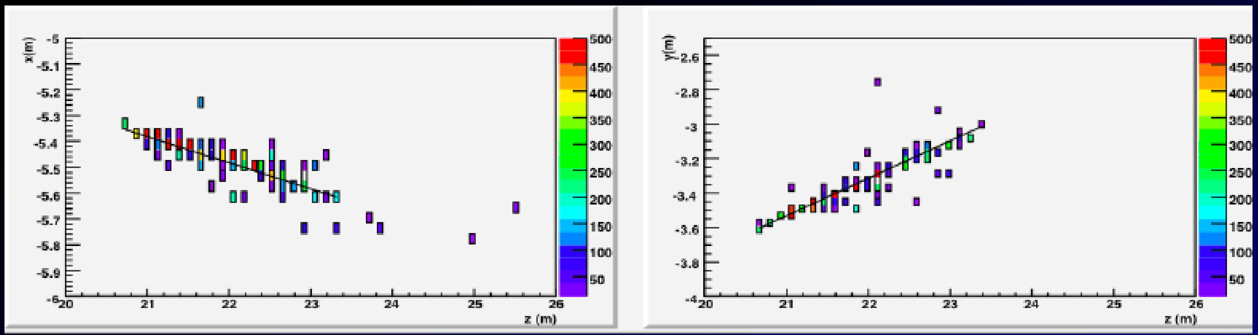


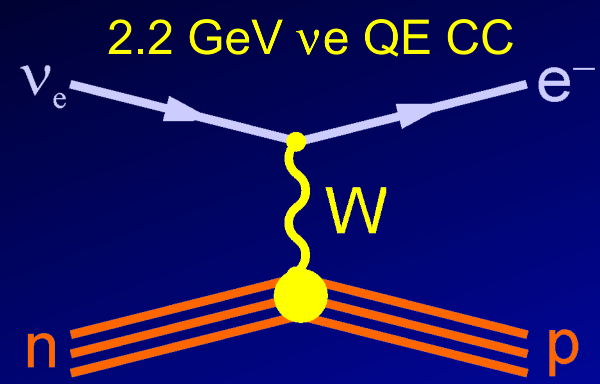
Cosmic Ray Shower



First Neutrino

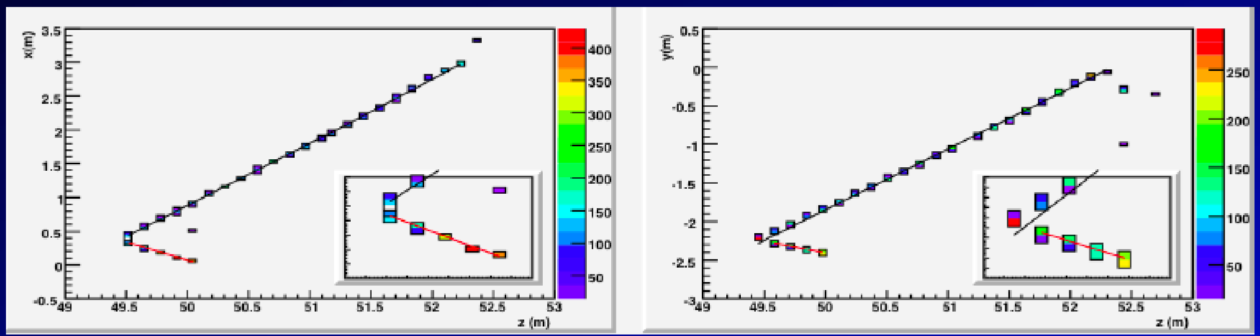
NOvA: Detector Performance, Typical Events

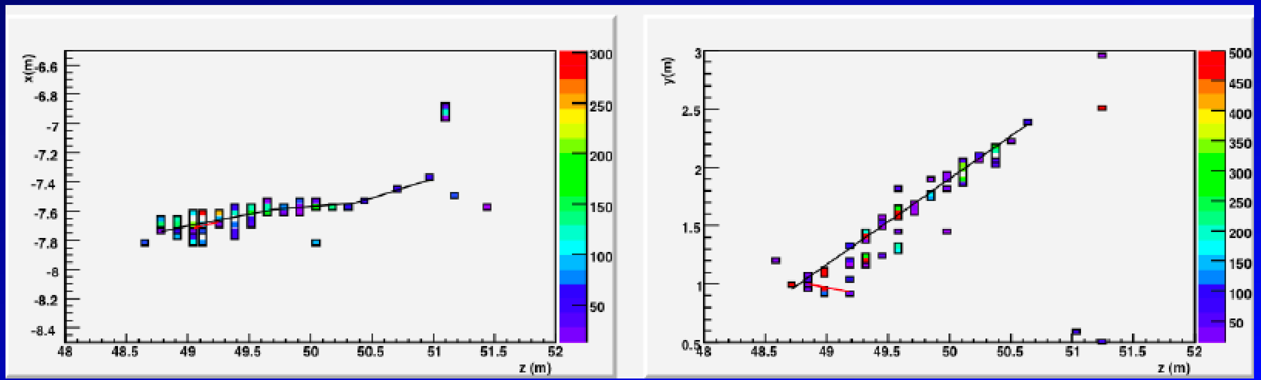


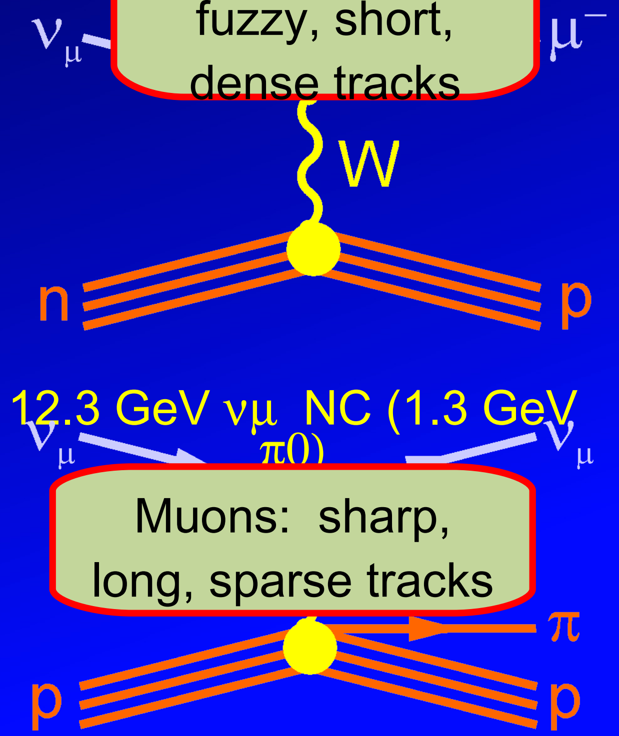


Signal

Backgrounds







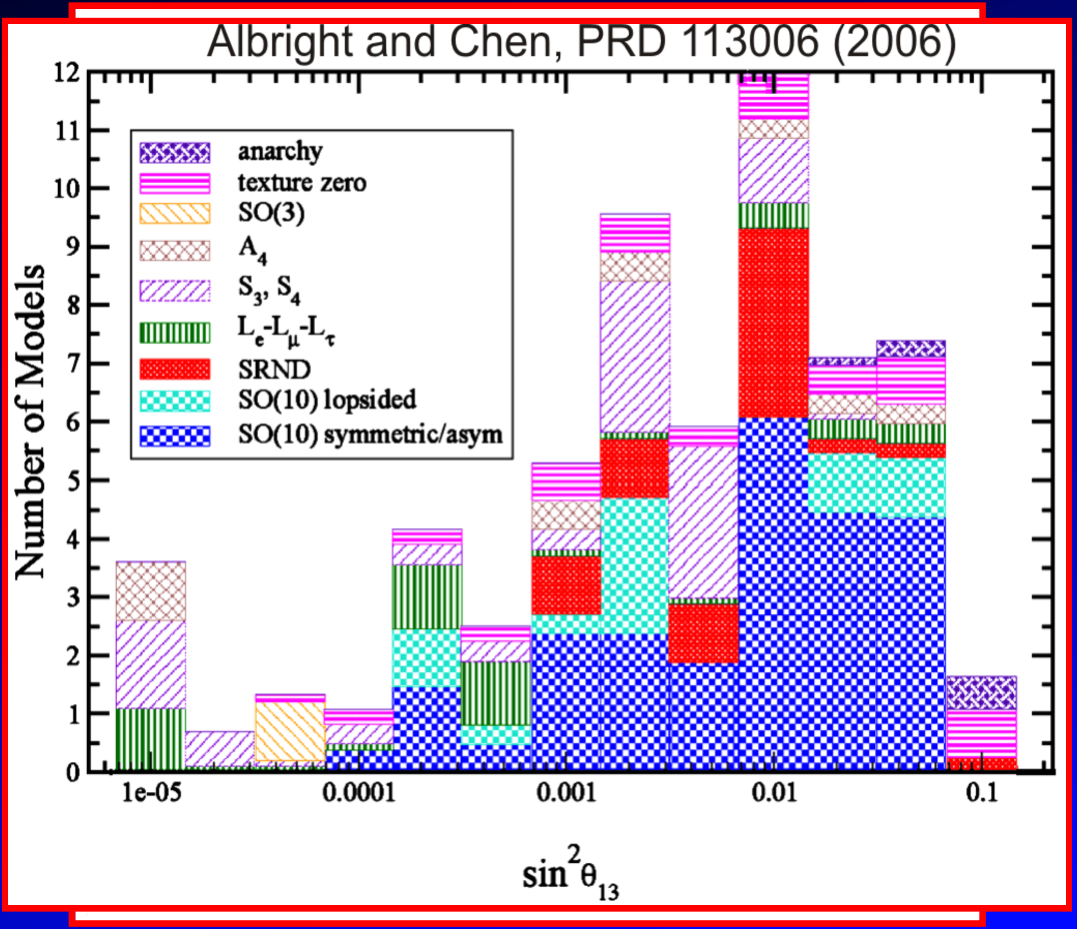
Electrons: fuzzy, short, dense tracks

Muons: sharp, long, sparse tracks

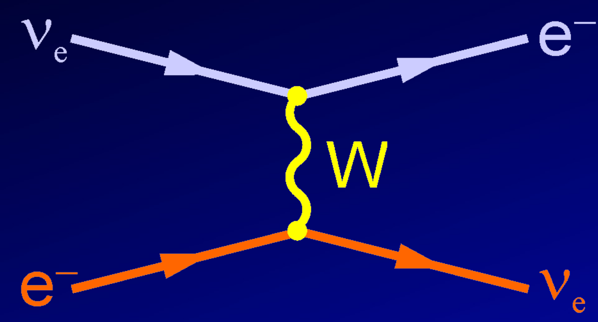
NOvA: θ13 Reach

- NOvA designed for good electron appearance sensitivity down to sin2(2θ13) ~ 0.01 or θ13=2.9°
- Note: best fit sin2(2θ13) ~ 0.08 or θ13=8.2°

An abundance of theoretical guidance



Mass Heirarchy: νμ →νe Rate - Matter Important

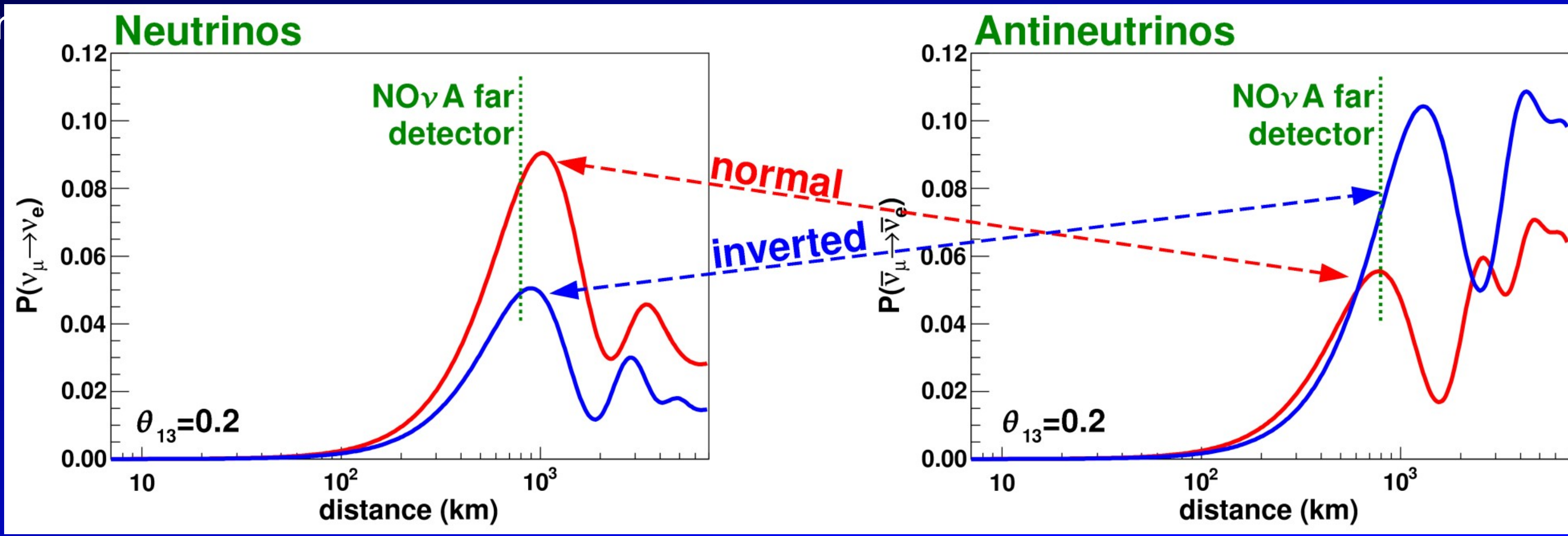


·Extra CC term for νe in matter important!

·Increases νμ → νe rate for normal hierarchy: effect reversed for inverted hierarchy and for antineutrinos

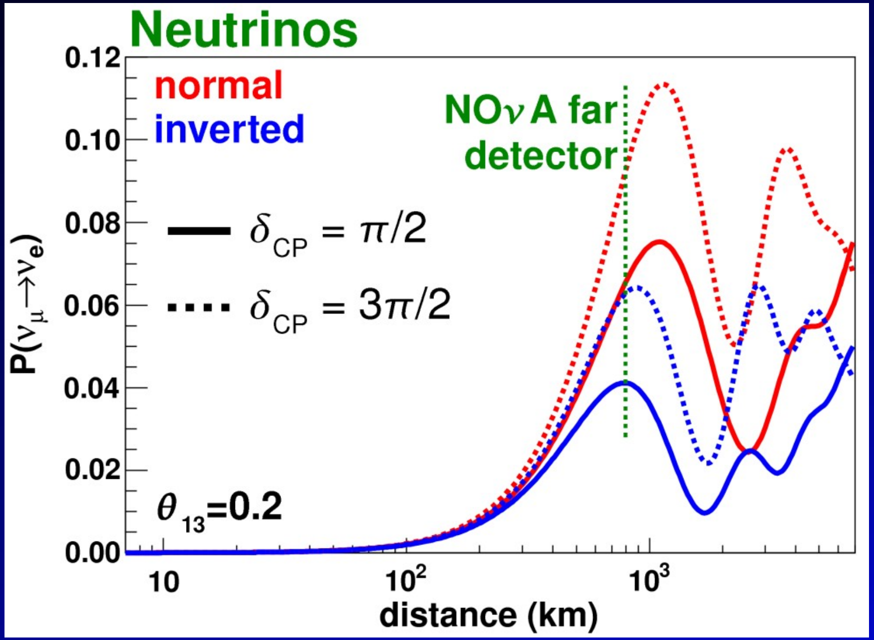
$$\frac{P(\nu_\mu \rightarrow \nu_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \begin{cases} >1 : \\ <1 : \end{cases}$$

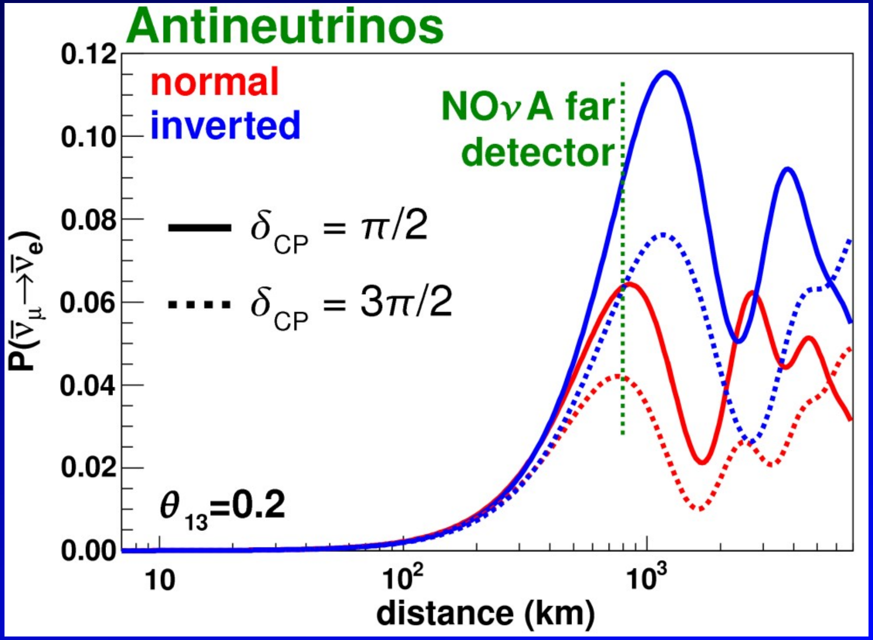
·Er



CP Violation Mucks Things Up

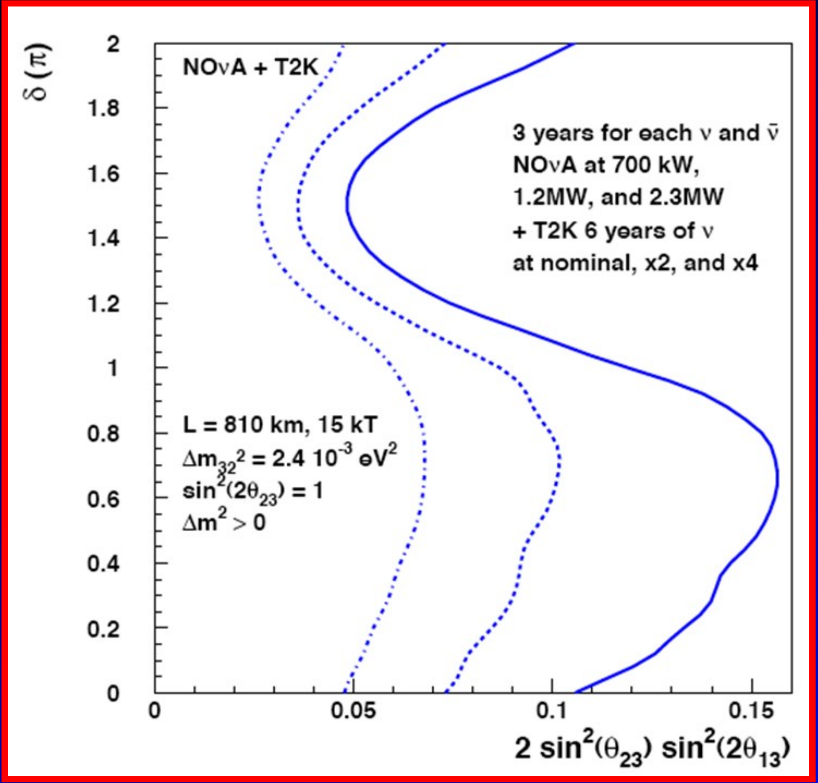
- CP violation can confuse the effect → regions of inherent ambiguity
- Can be resolved by another measurement at a different baseline

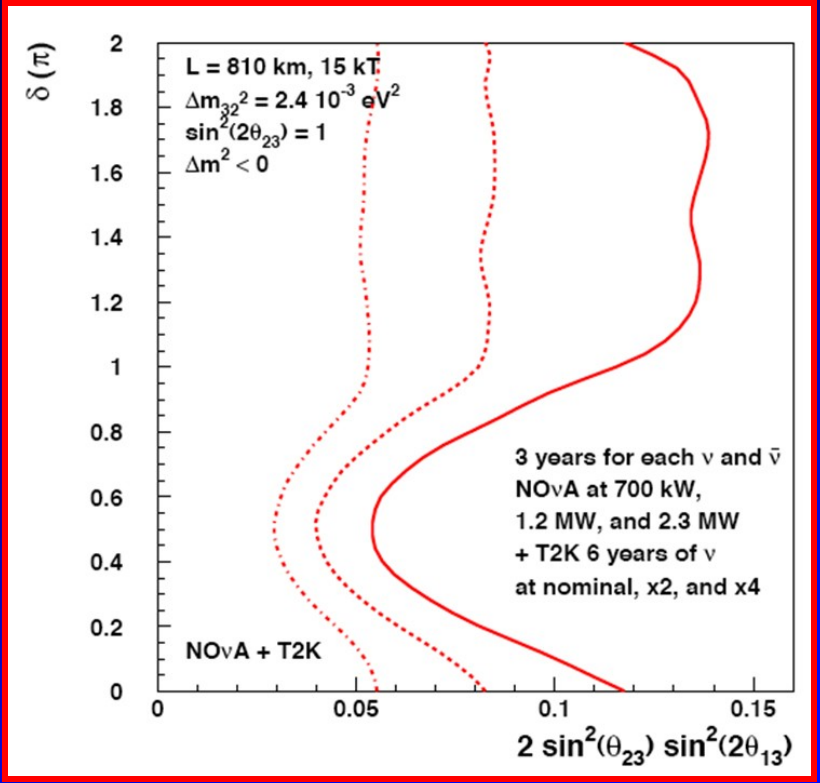




NOvA: Mass Hierarchy Sensitivity

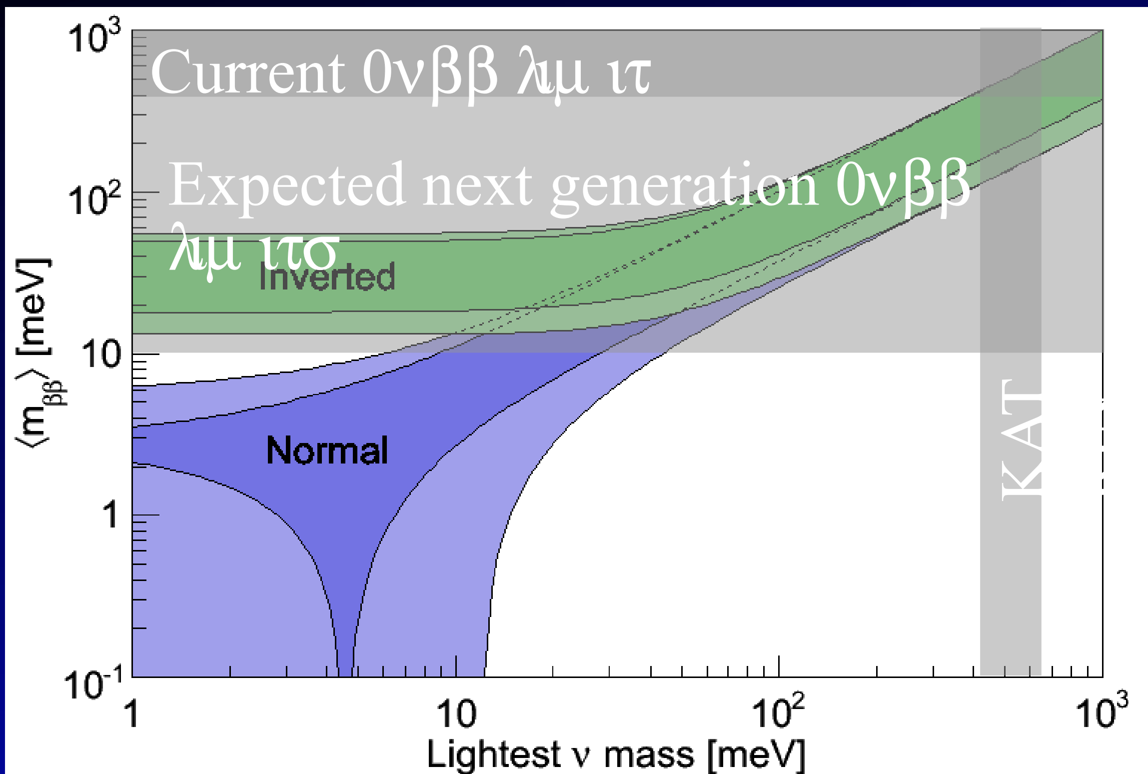
NOvA + T2K





NOνA: Mass Heirarchy

If NOνA establishes the inverted mass hierarchy and the next generation of 0νββ experiments see nothing then neutrinos will almost certainly be Dirac particles



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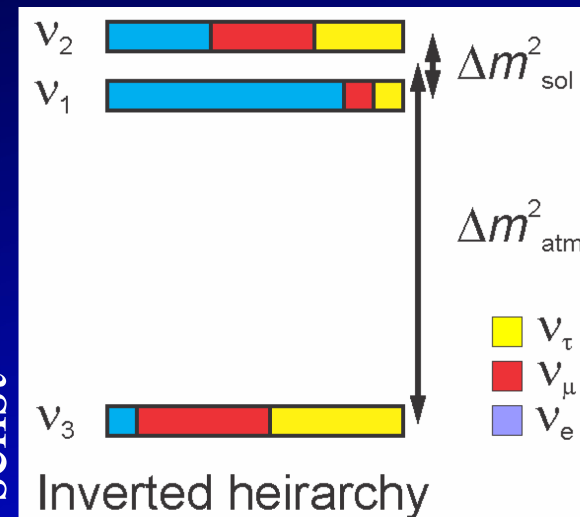
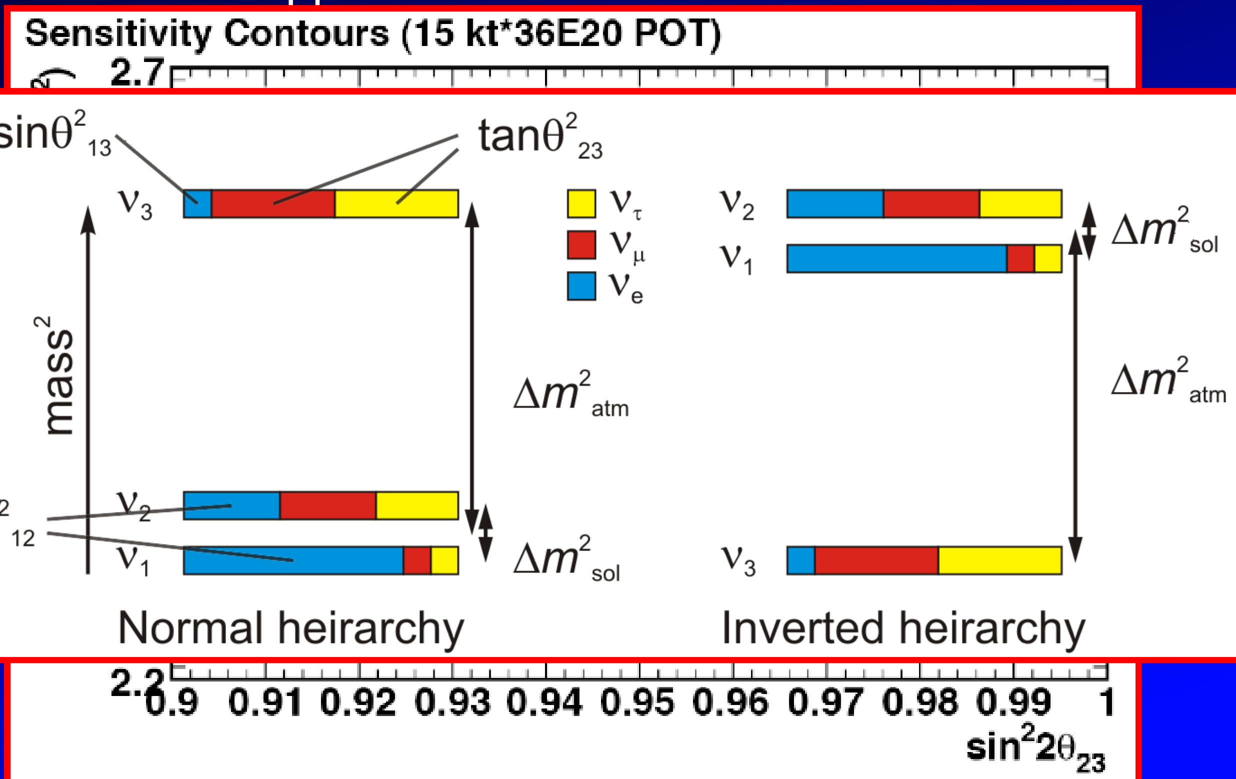


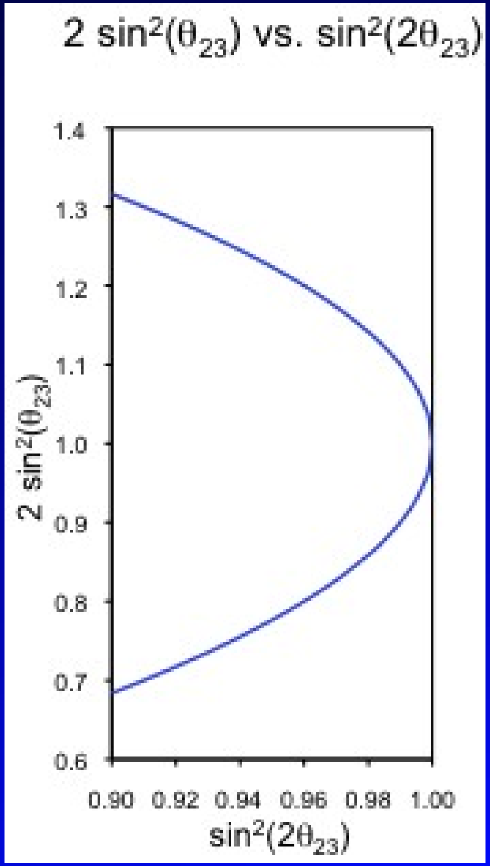
NOvA: νμ Disappearance. Is θ23 Maximal?

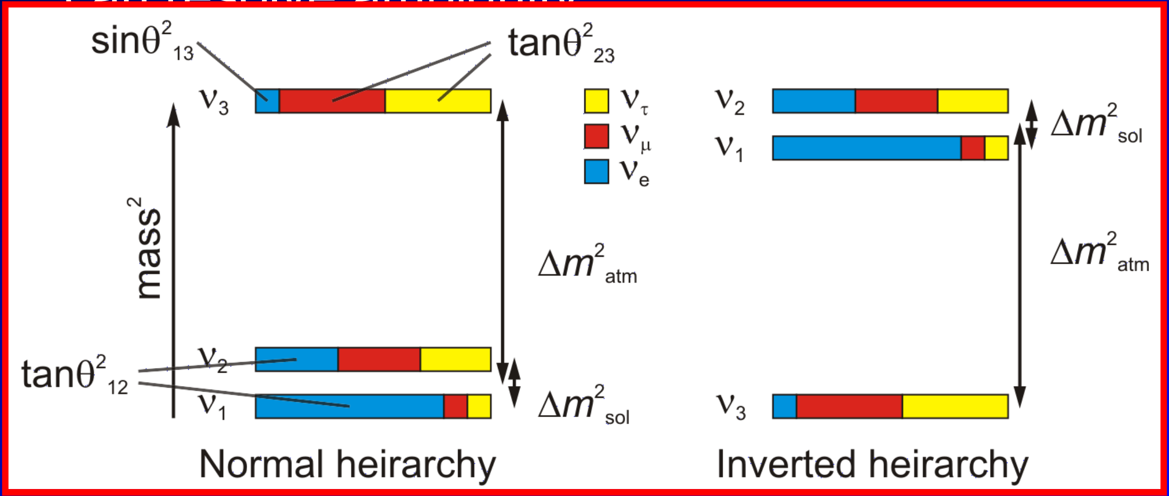
- We know θ23 is close to 45°: Is the mixing maximal: θ23 = 45°?
- Because of NOvA's good energy resolution, it will make a ~1% measurement of θ23 through muon neutrino disappearance



Resolving the Ambiguity in Determining θ23

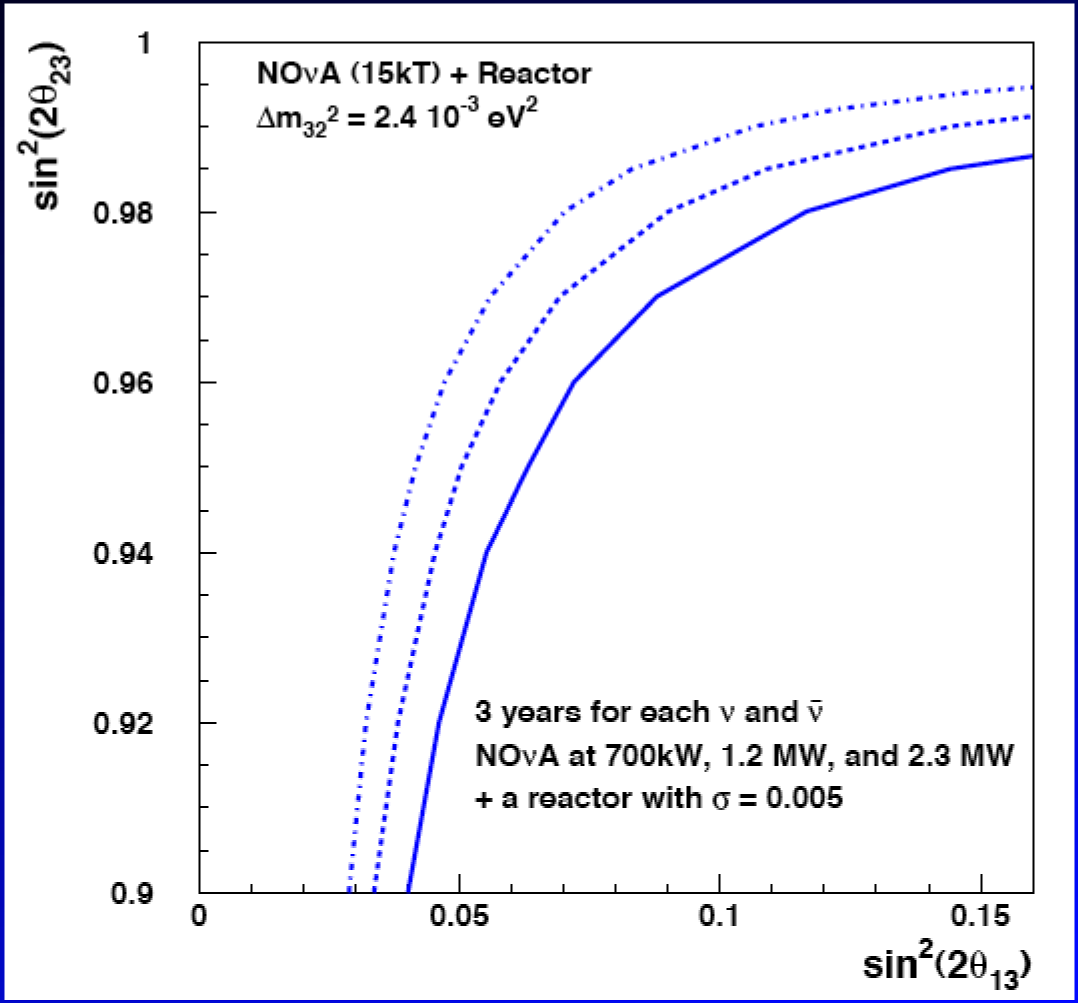
- Dominant term in P(νμ →?) is proportional to: sin2(2θ23)
- Dominant term in P(νμ →νe) is proportional to: sin2(θ23)sin2(2θ13)
- Reactor experiments are sensitive to sin2(2θ13) alone
- Comparison of P(νμ →νe) with Reactor experiments can resolve ambiguity





95% CL Resolution of θ23 Ambiguity

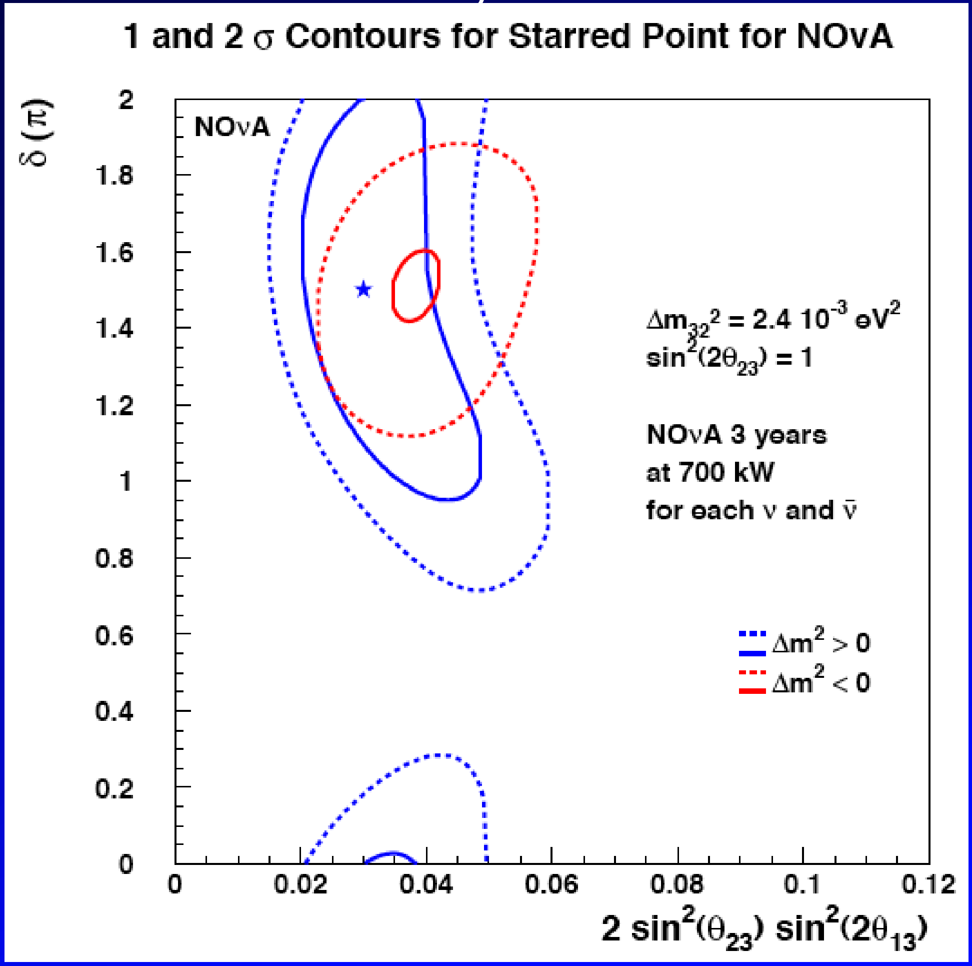
- Average over mass hierarchy, CP phase δ, and sign of θ23 ambiguity
- At the central value of T2K result, NOvA resolves the ambiguity for sin2(2θ23) < 0.96



NOvA: CP violation sensitivity

- NOvA will provide the first look into CP conservation
- Will be the only look for some time!
- Nature must be kind: θ13 must be large!

Mass hierarchy not resolved



Long-Range Future

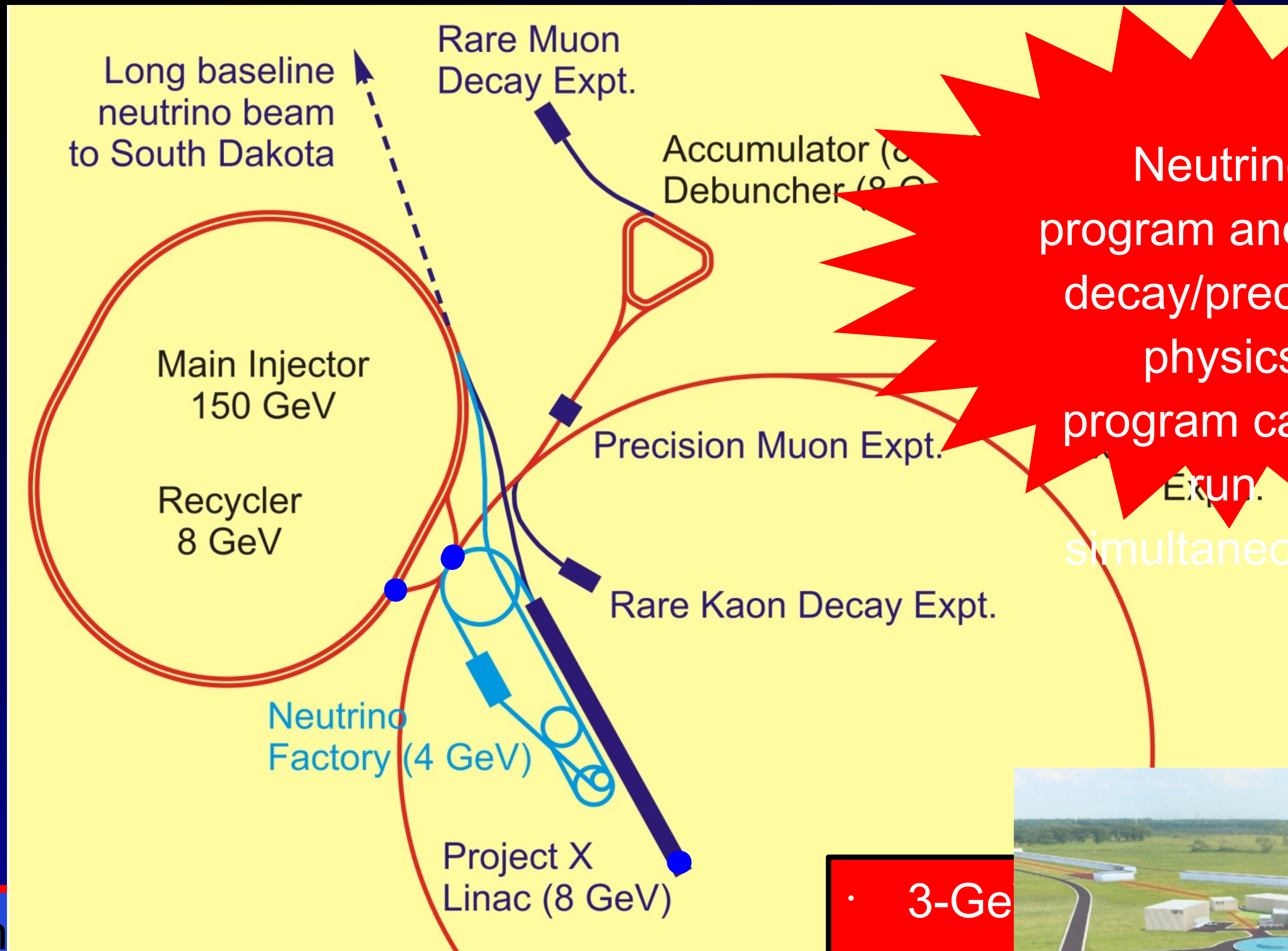
Fermilab Pushing Forward on Intensity Frontier

Strategic Plan for the Next Ten Years:

"The panel recommends an R&D program in the immediate future to design a multi-megawatt proton source at Fermilab…"

"The panel recommends a world-class neutrino program as a core component of the US program, with the long-term vision of a large detector in the proposed DUSEL and a high-intensity neutrino source at Fermilab."

Fermilab's Project X: the Path to the Intensity Frontier



Neutrino program and rare decay/precision physics program can be run simultaneously!

Ferm

The Project X linear accelerator would feed a high-intensity neutrino and rare decay/high precision physics program

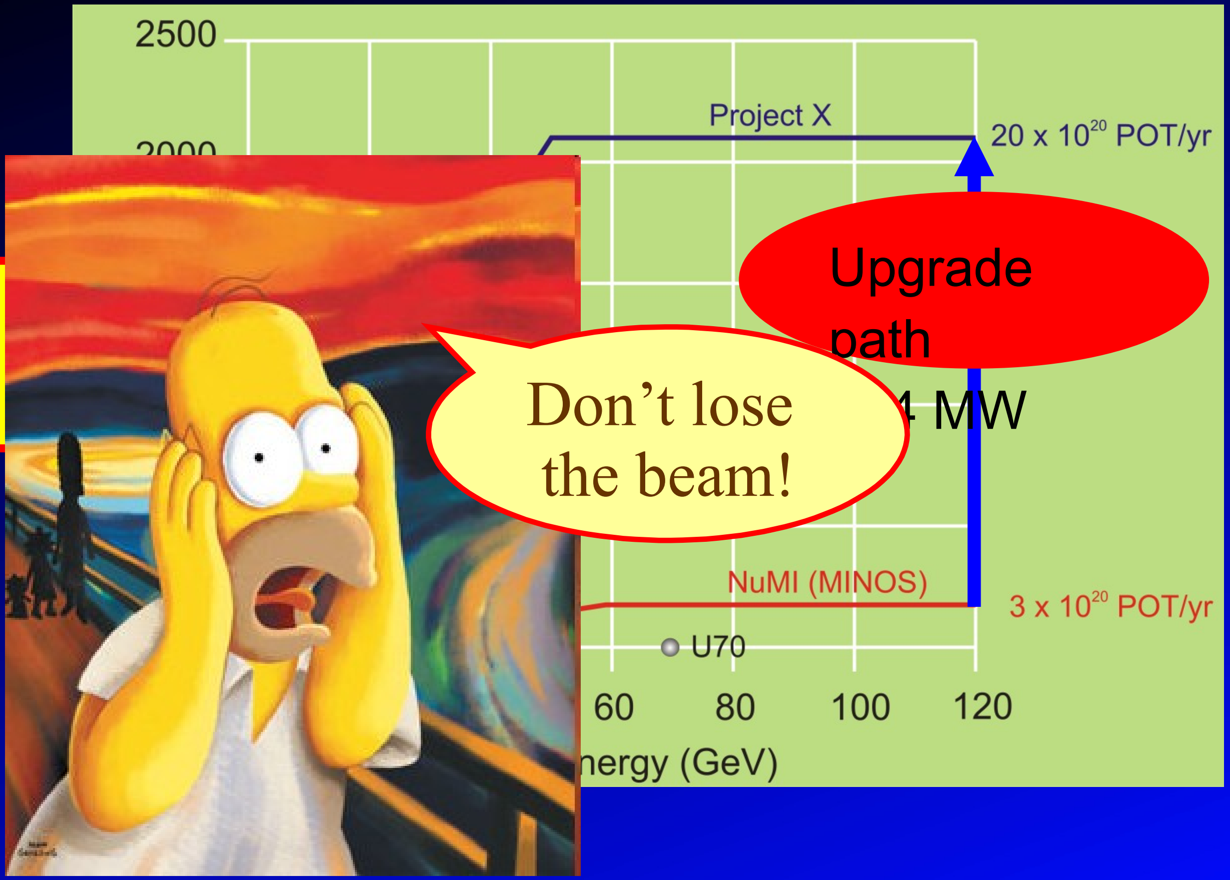
- 3-Ge
  supe
- 3-8 G
  ILC-s
- 120 GeV, 2 MW

Project X Beam Rates Enormous

= particles/s x energy

8 GeV: ~20X increase

120 GeV: ~10X increase



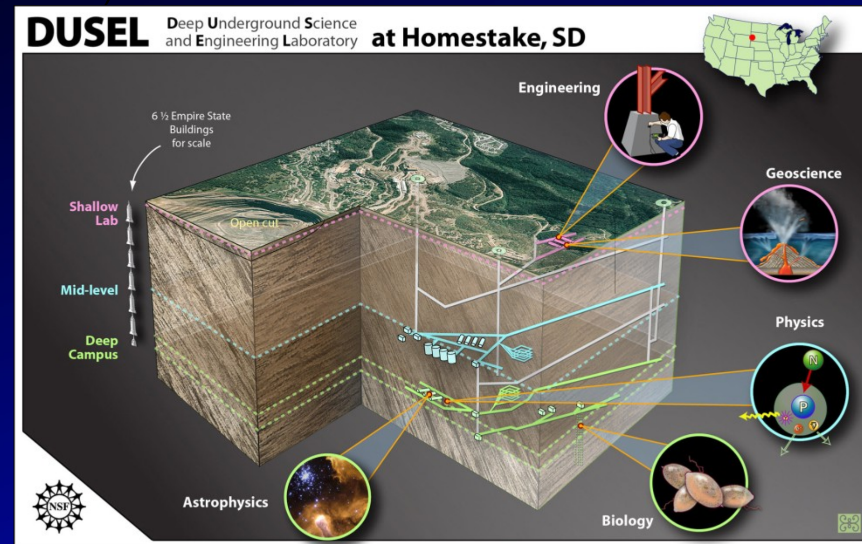
Each beam pulse has energy of Lamborghini Gallardo going 140 mph (226 km/h), with only 1.7 x 10-16 the Gallardo's mass!

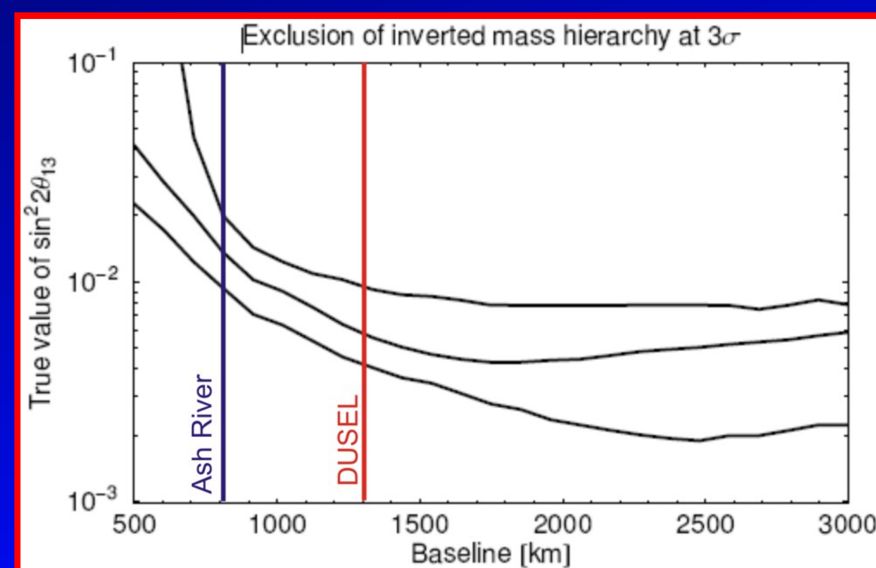
Consensus in the Neutrino Community Forming

Neutrino Experiment Study (arXiv:0705:4396)
July 13, 2007

Long Baseline Neutrino Experiment (LBNE)

- New deep underground detector site: DUSEL
  - Longer baseline than NOvA
- New multi-purpose detector possible
  - Neutrino and proton decay physics
- New beamline from Fermilab
  - Wide band beam is best: can fit oscillation parameters using energy spectrum
  - Considerable upgrade to the current Fermilab intensity needed

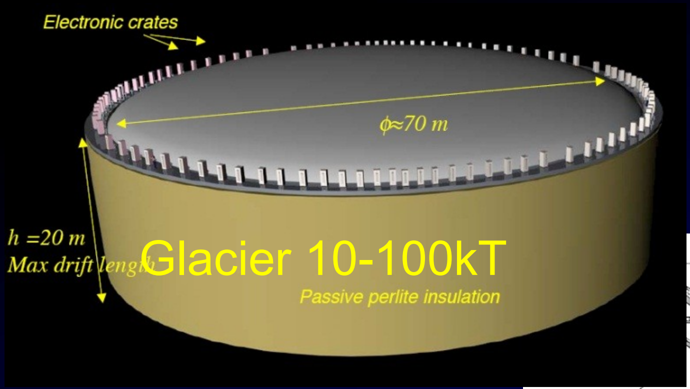


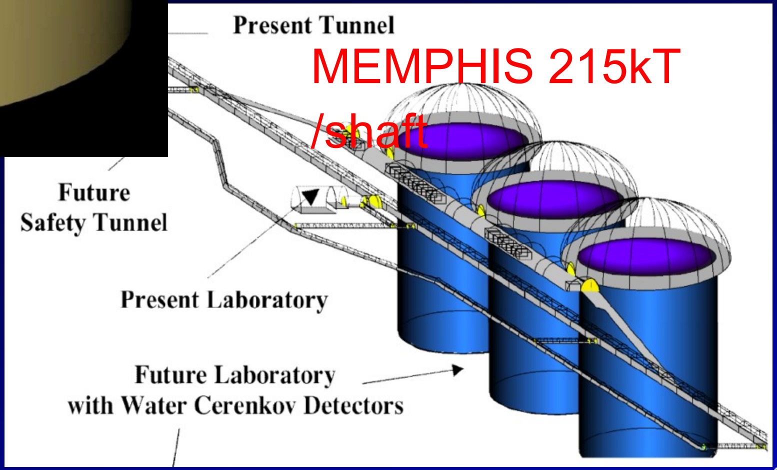


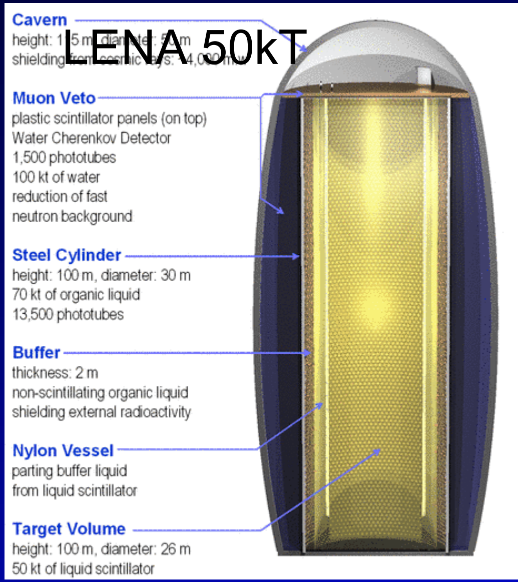
U.S. Long Baseline Neutrino Experiment Study (arXiv:0705:4396)

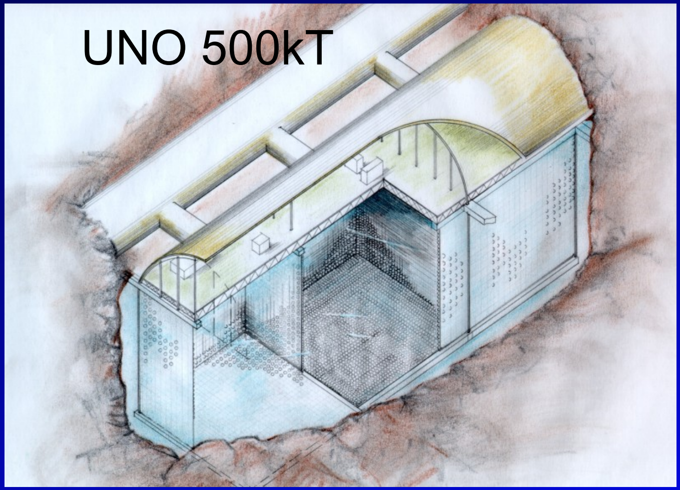
NUSAG Report, July 13, 2007

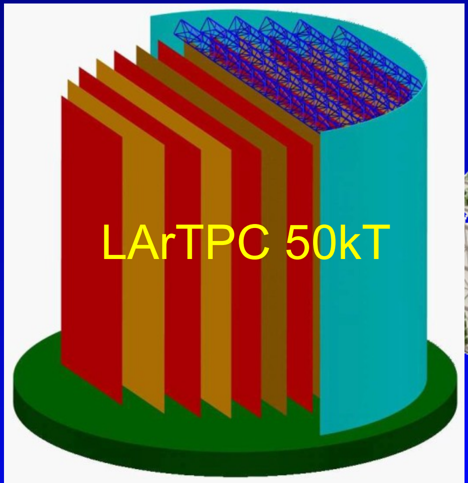
Next Generation Detectors Being Designed

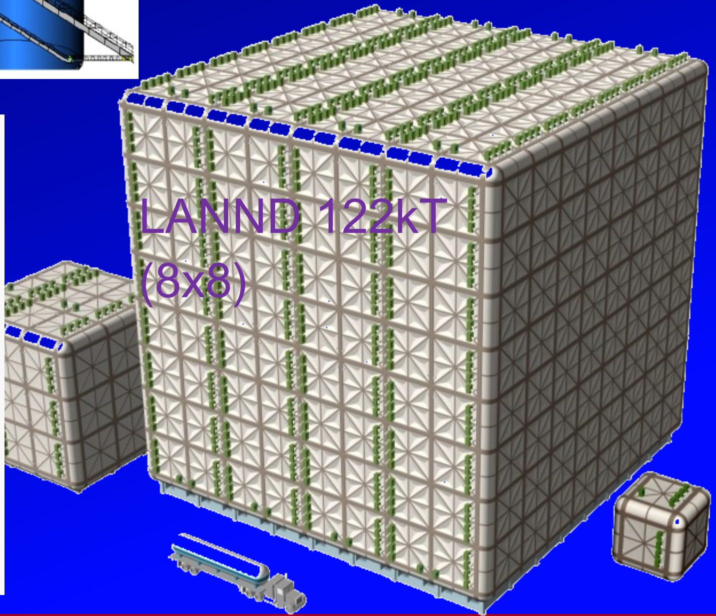












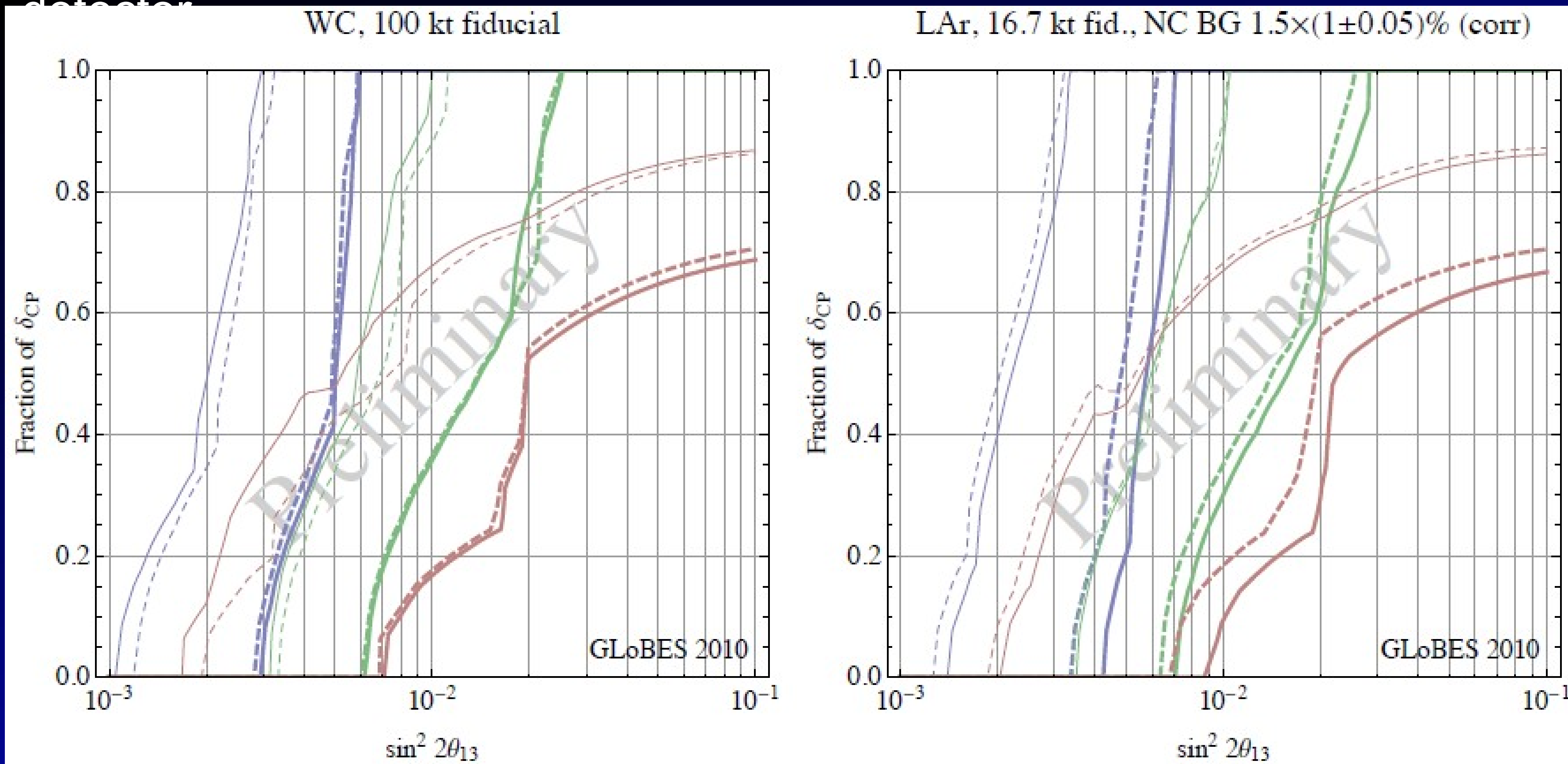
Two Detector Technologies Favored

U.S. Long Baseline Neutrino Experiment Study (arXiv:0705:4396)

	Pro	Con
Water Cerenkov	• Well understood technology • New background rejection techniques available • Scale-up factor < 10 • ~10% energy resolution • Multipurpose (proton decay)	• Must be underground • Cavern stability must be assured • NC background depends on spectrum and comparable to intrinsic background • Low ν_e efficiency (15-20%)
Liquid Argon TPC	• Promise of high efficiency • Promise of high background rejection • Potential to operate on (or near) surface	• Technology not proven • Scale up by 300X needed • Accurate cost estimate impossible • Safety issues underground

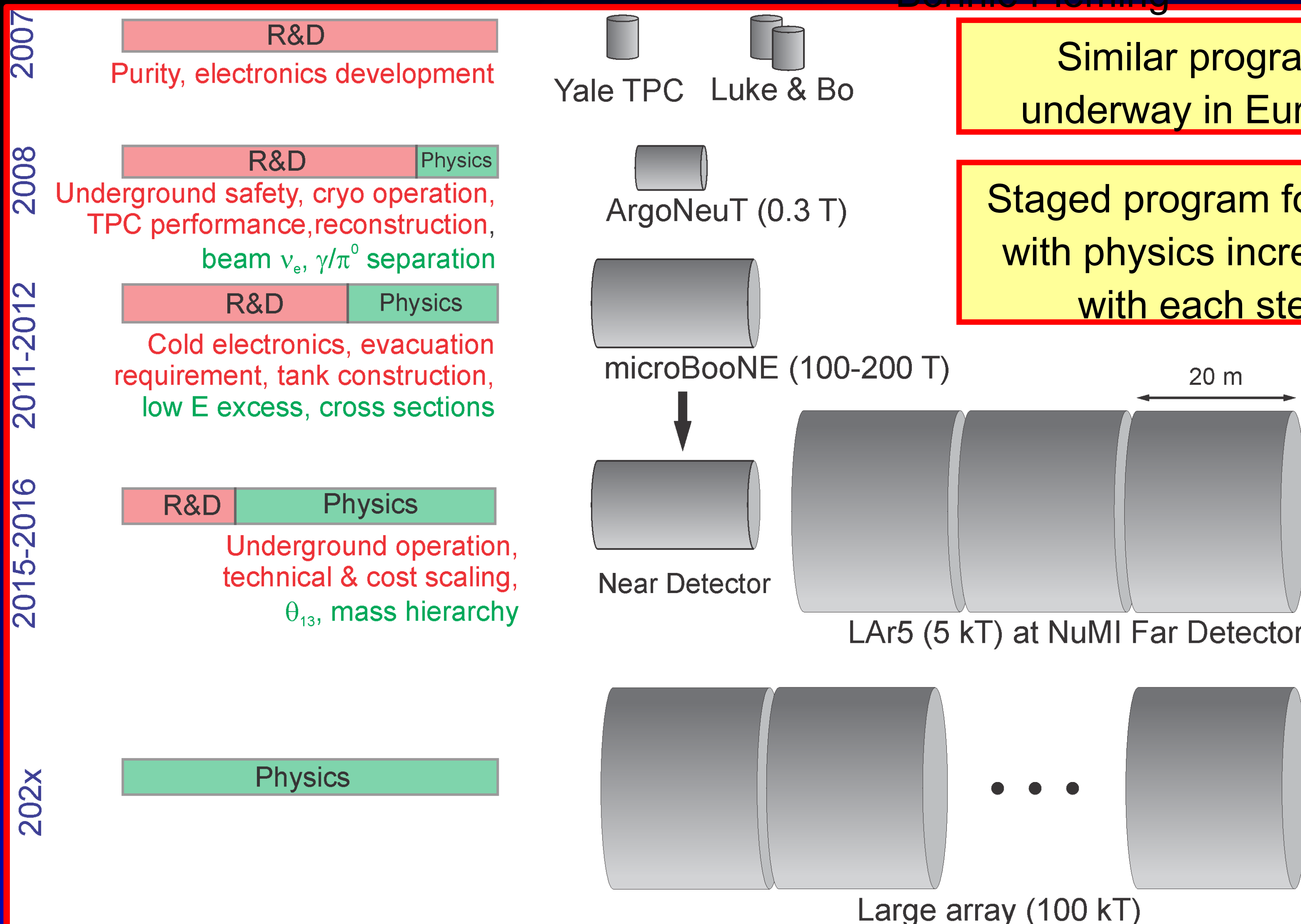
LBNE Water Cherenkov vs LArTPC

100 kt WC equivlant to 17 kt LArTPC detector



Fermilab Pursuing Aggressive Liquid Argon Program

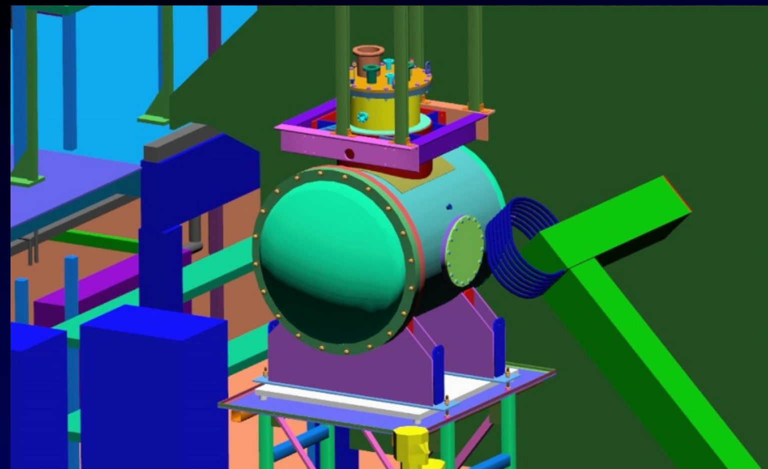
Bonnie Fleming

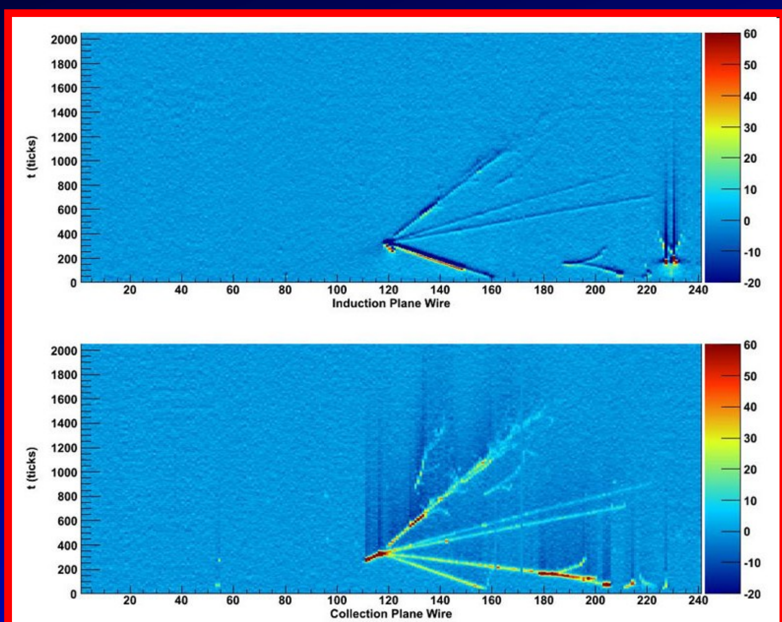


Similar program underway in Europe

Staged program for R&D with physics increasing with each step

ArgoNeuT





May 2009: first event

NSF/DOE Liquid Argon TPC R&D program

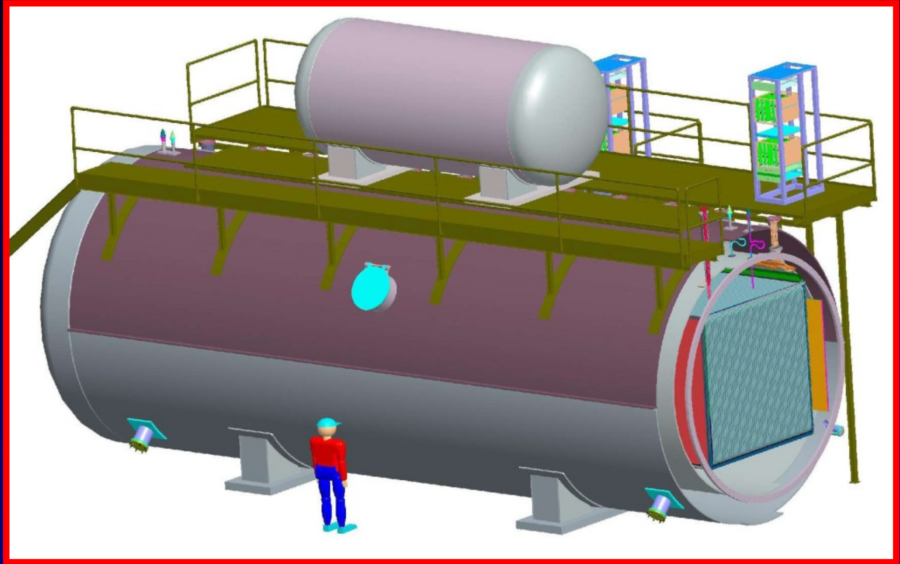
- 175 liter detector in NUMI beam

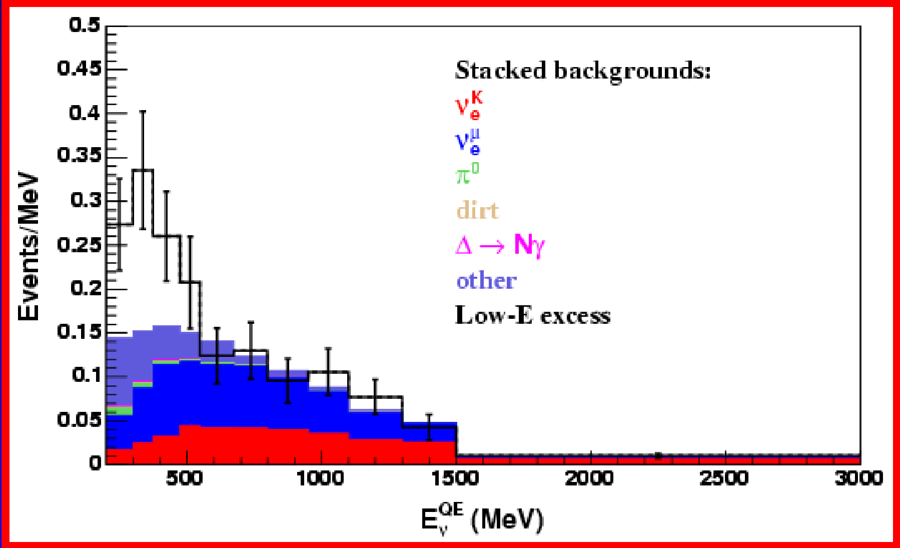
Goals:

1. Demonstrate effectiveness of liquid argon purification techniques
2. Measure gamma vs electron discrimination
3. Measure low energy neutrino cross sections

MicroBooNE

- 70/170 ton mass
- In 8 GeV Fermilab neutrino line
- R&D (stage 2 of LArTPC program):
  - Test purity in a non-evacuated vessel
  - Full systems test of low-noise electronics
  - TPC and vessel design
- Physics:
  - Study surface running issues
  - Investigate MiniBooNE low energy excess
  - Measure neutrino cross sections
  - BNB: 100K events, NuMI: 60K events
- Schedule:
  - Construction: 2009
  - Data: 2011





6 x 1020 POT

Ultimate Reach: Neutrino Factory

Advantages:

·Large neutrino fluxes

·Little uncertainty in neutrino flux

·Little background if sign of lepton can be determined

·All ν parameters measured from νe →νμ and anti-νe → anti-νμ

· Δm2 sensitivity so good that hierarchy may be measurable with θ13 = 0! 0!

Disadvantages:

·Need to measure muon sign → magnetic detector needed

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \dashrightarrow \mu^-$$

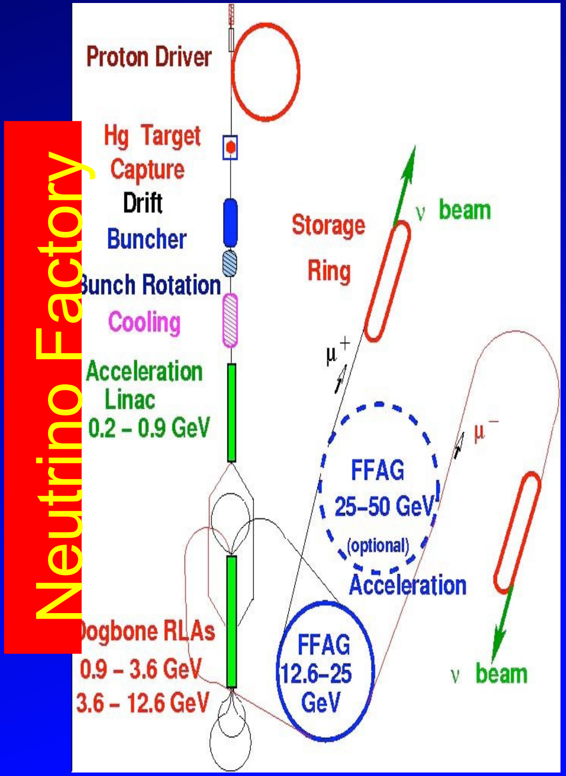
$$\bar{\nu}_\mu \rightarrow \mu^+$$

Golden Channel

·Technology unproven: lots of R&D needed that will take time

Neutrinos from Muon Decay

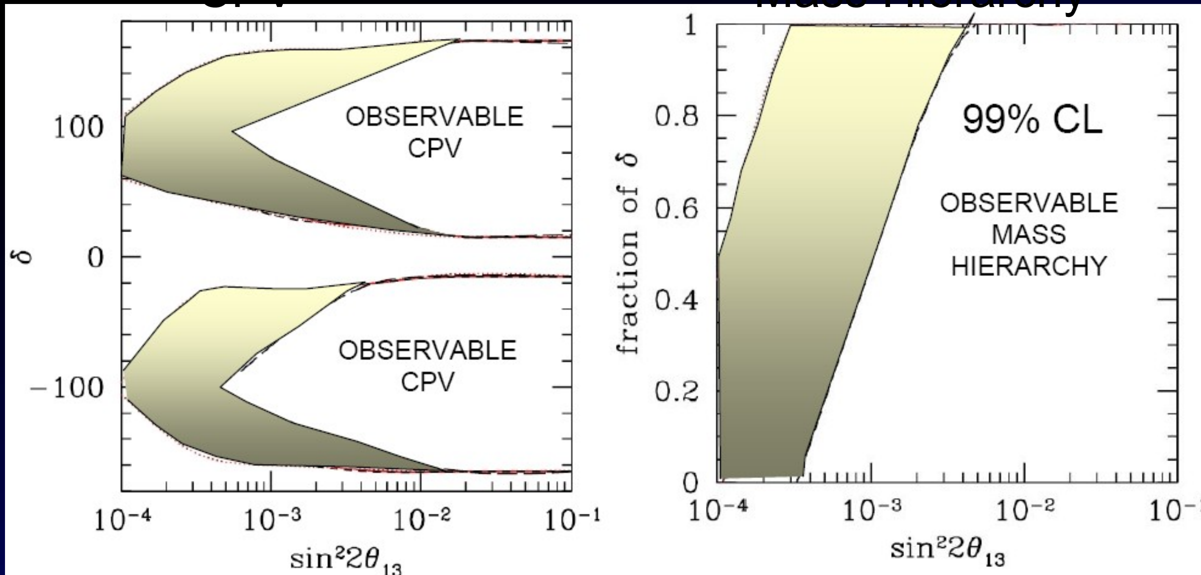
International Design Study: ZDR by ~2010, RDR by ~2012



4 GeV Neutrino Factory

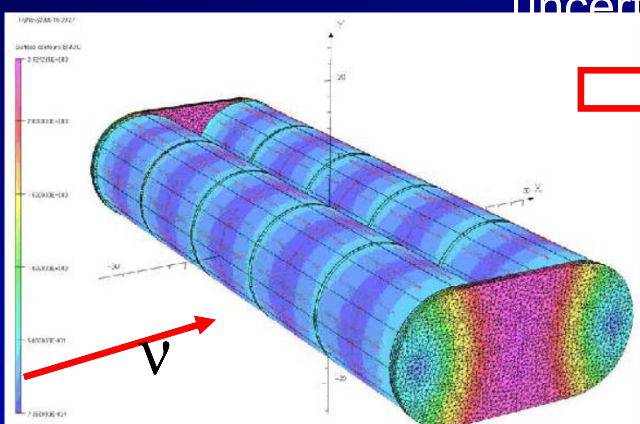
CPV

Mass Hierarchy



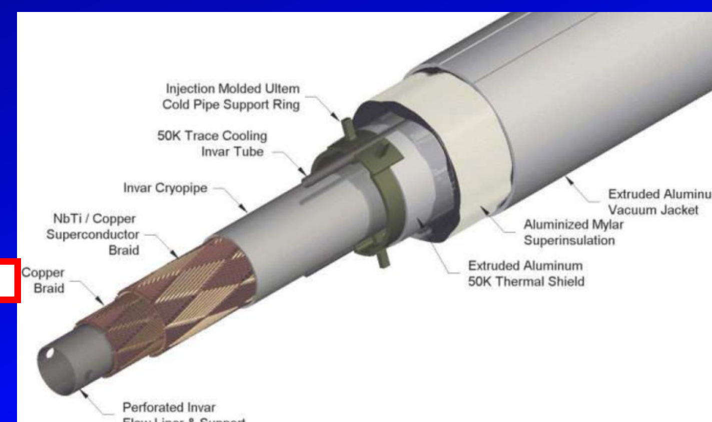
- Geer, Mena, & Pascoli, Phys. Rev. D75, 093001, (2007).
- Bross, Ellis, Geer, Mena,& Pascoli, hep-ph arXiv:0709.3889

Bands indicate running time and background uncertainties



Magnetic cavern with two parallel solenoids (0.5T x 34,000 m3).

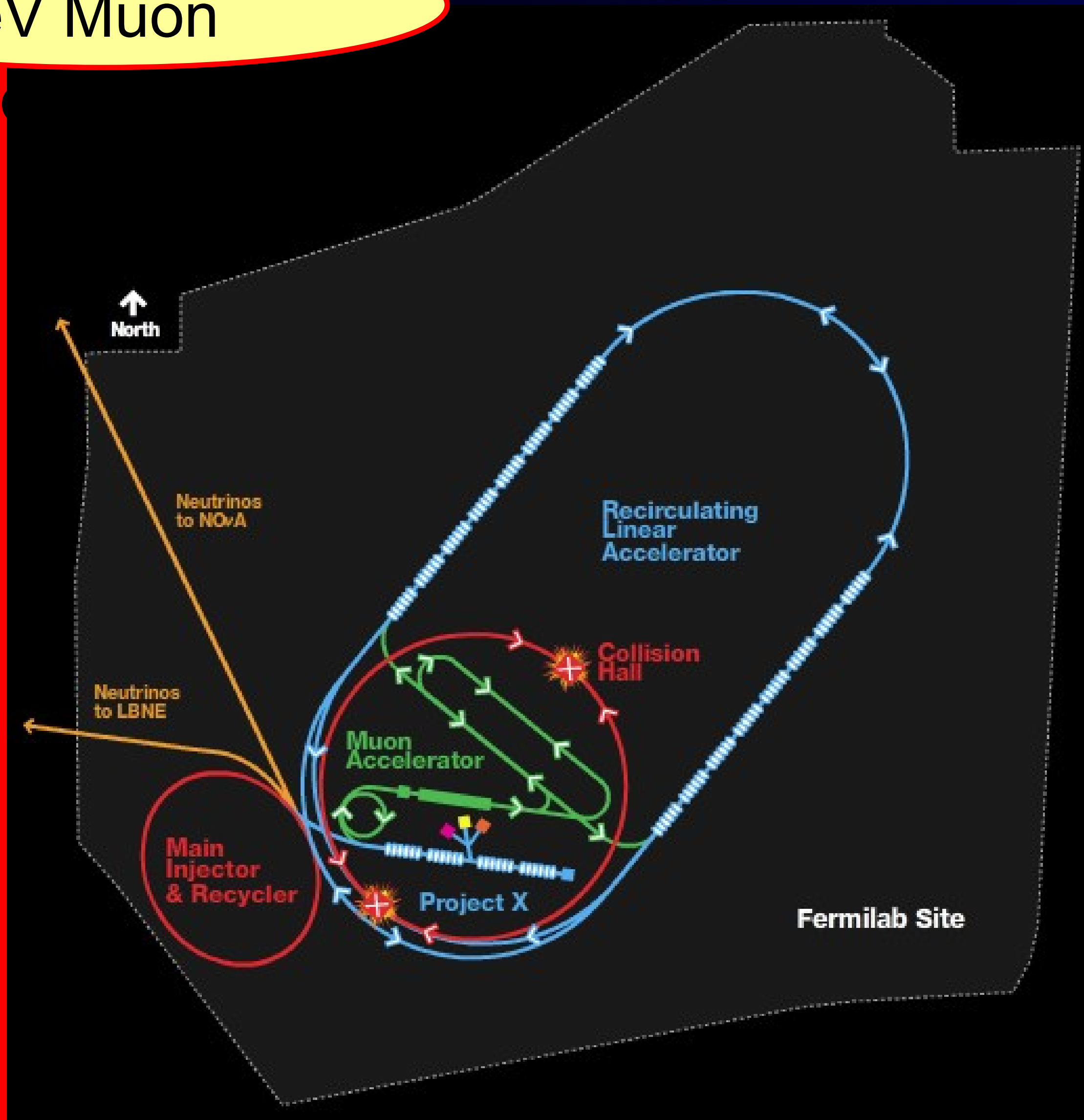
Superconducting transmission line designed for VLHC

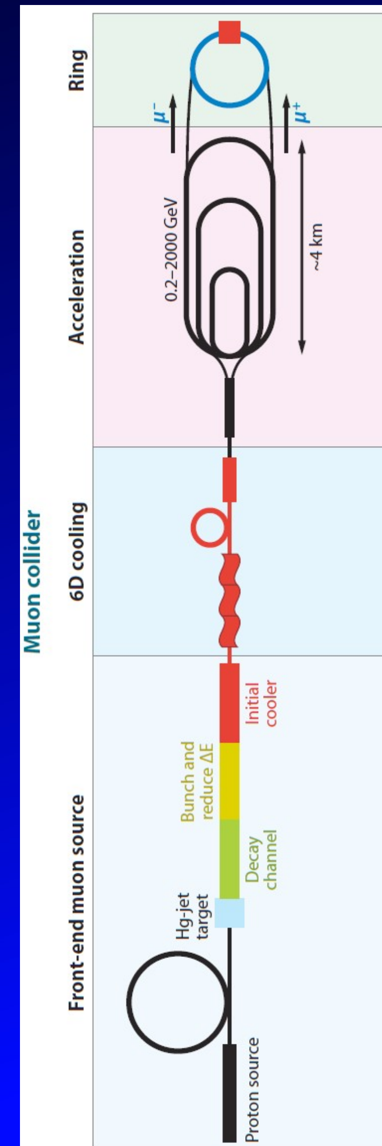


Getting Back to the Energy Frontier

3 TeV Muon

Muon Collider





The Future is Very Exciting

- A large θ13 is good news for everyone in the field!
  - It makes it much easier to resolve the mass hierarchy
  - Gives us a chance to observe CP violation, although the next generation experiments, such as LBNE, will be needed
- The era of precision neutrino physics is upon us: by the end of the decade θ13 will be well measured, and the mass hierarchy should be resolved
- There are some strange anomalies reported by MINOS and MiniBooNE → are there yet more surprises that neutrino physics has for us?
- The ultimate neutrino experiment isn't going to come cheap!

DUSEL/LBNE:$2,250M-$2,750M

Neutrino factory:$2,100M-$2,700M

- Note: NOvA (+beam upgrade): $270M
- Note: US LHC: $500M over a decade