Neutrino Physics at Fermilab

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(presented by Stan Wojcicki)

Witherell Fest

Fermilab, July 14, 2005

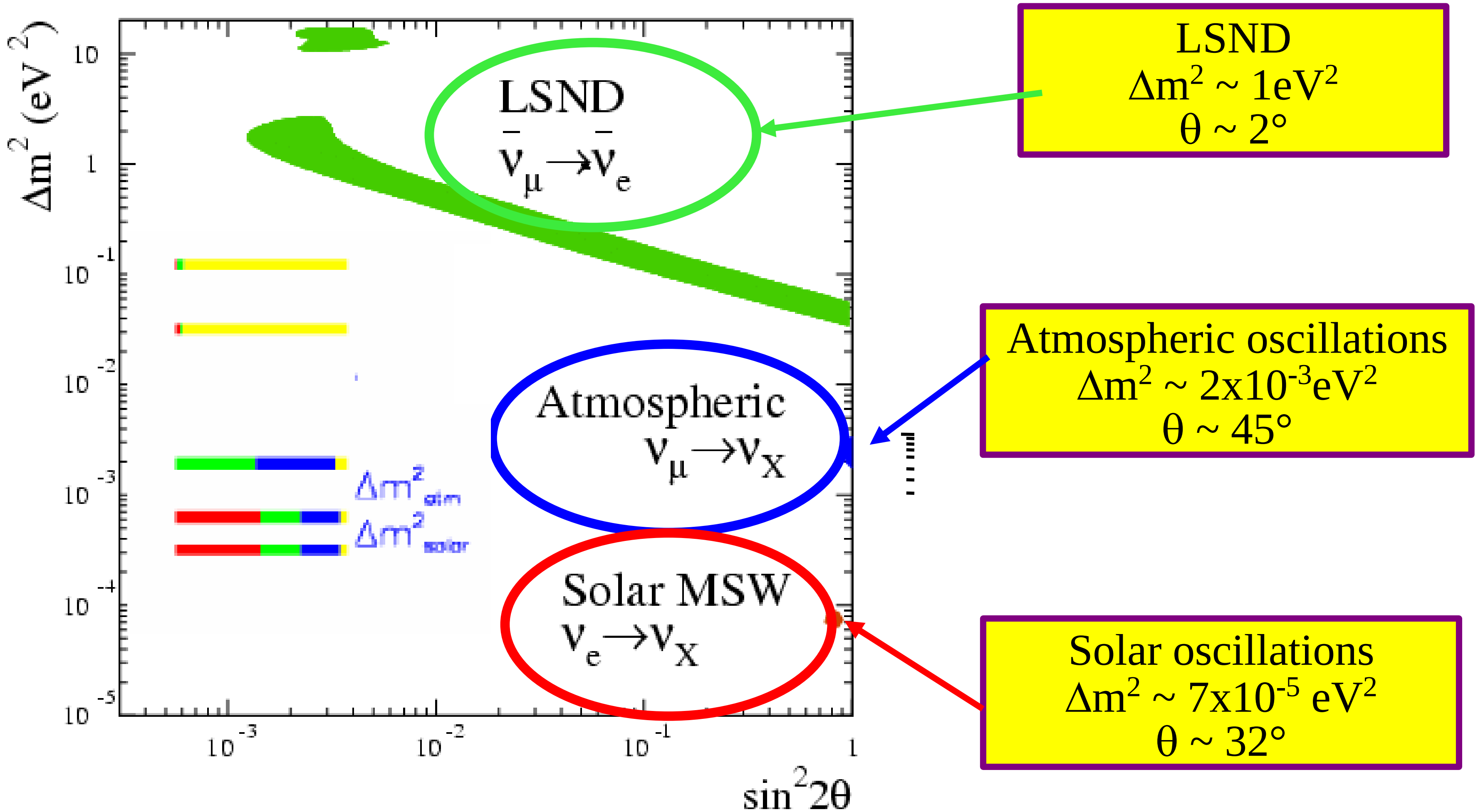
Fermilab has a long neutrino tradition

- 70’s: Main Ring used for fundamental measurements on Electro-Weak, QCD and nucleon structure.
- 80’s: Continued measurements on above topics using Tevatron
- 90’s: Continuation of above plus observation of ν_τ interactions producing τ’s.
- 00’s: Oscillation experiments, new low energy cross sections, QCD, nuclear structure measurements.
- 10’s: Oscillation experiments and more?

Major Questions (of the moment) in Neutrino Physics

- What is the absolute mass scale of neutrinos?
- Is the mass hierarchy normal or inverted?
- Do we understand that the current new "paradigm" (3 neutrinos, mass oscillations) is correct?
- Is the LSND evidence for oscillation true? Are there sterile neutrino(s)?
- How small is θ_{13}?
- How "maximal" is θ_{23}? Is there μ/τ symmetry?
- Is there CP Violation in the neutrino sector?
- Are neutrinos their own anti-particles?

- Measurements with Fermilab accelerator complex can answer or contribute at some level to all of these!



- This situation requires at least 3 independent Δm^2 values if all experiments are correct.

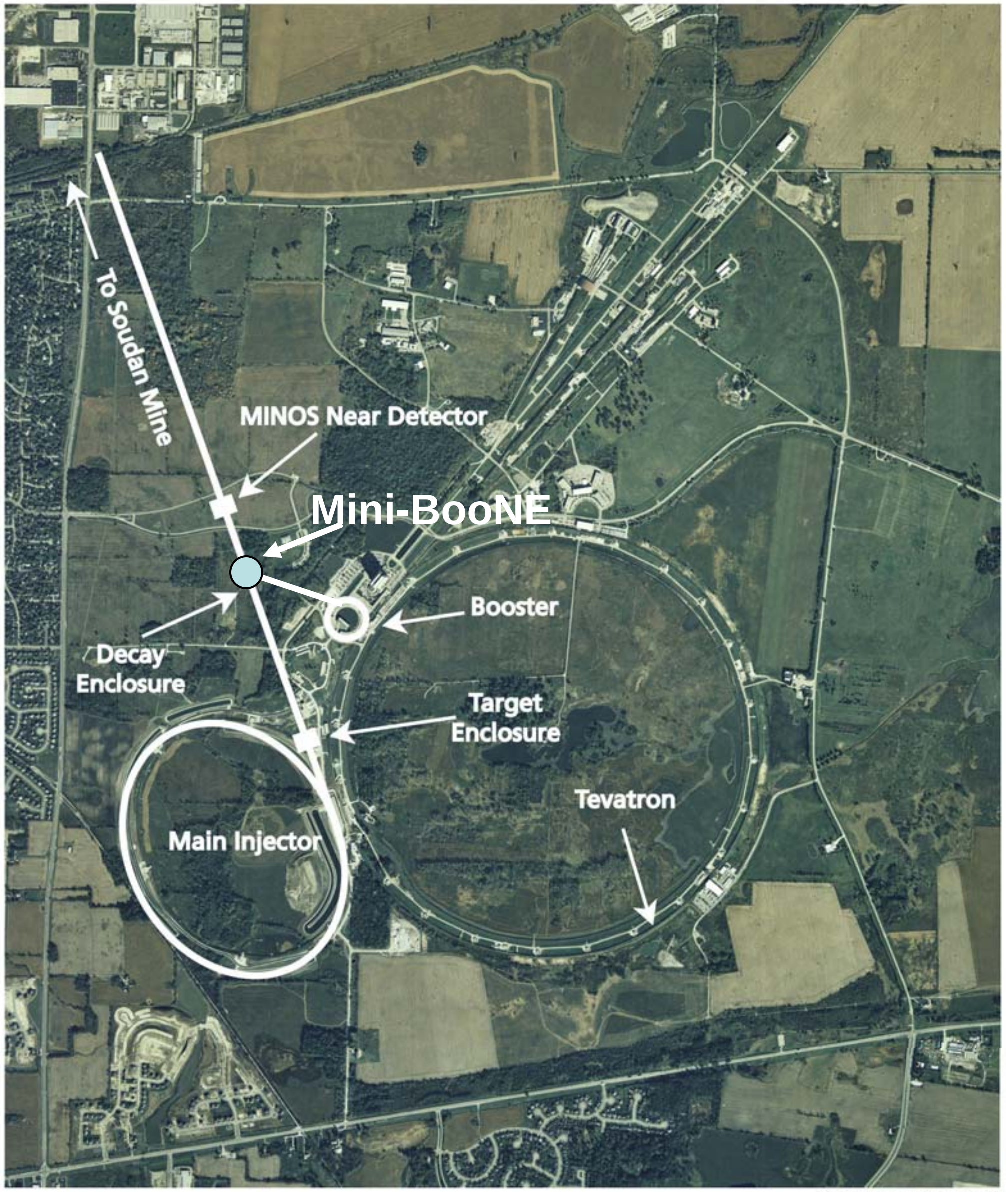
Importance of the Mass Ordering

- Window on very high energy scales: some grand unified theories favor the normal mass ordering, but other approaches favor the inverted ordering.
- If we establish the inverted ordering, then the next generation of neutrinoless double beta decay experiment can decide whether the neutrino is its own antiparticle. However, if the normal ordering is established, a negative result from these experiments will be inconclusive.
- To measure CP violation, we need to resolve the mass ordering, since it affects the measurements of the CP violation effects.

Two Running Experiments

Mini-BooNE
- medium baseline
- check LSND

MINOS
- long baseline
- study oscillations in "atmospheric" range



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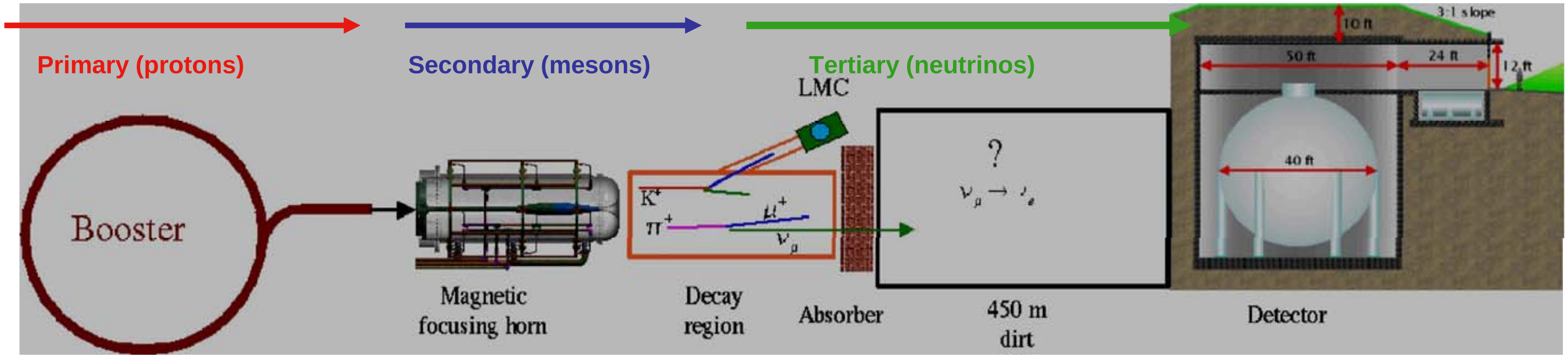
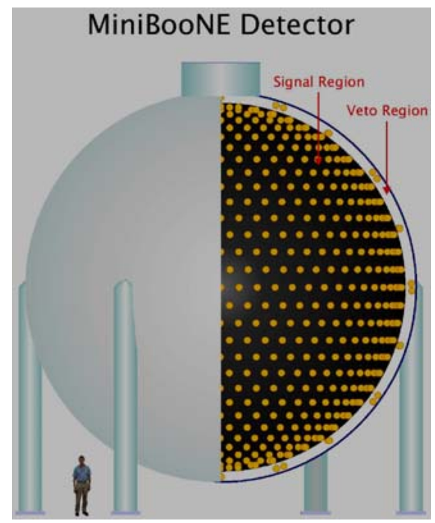
Mini-BooNE: Testing the basic assumption of 3 neutrinos (and measuring a lot of other things)





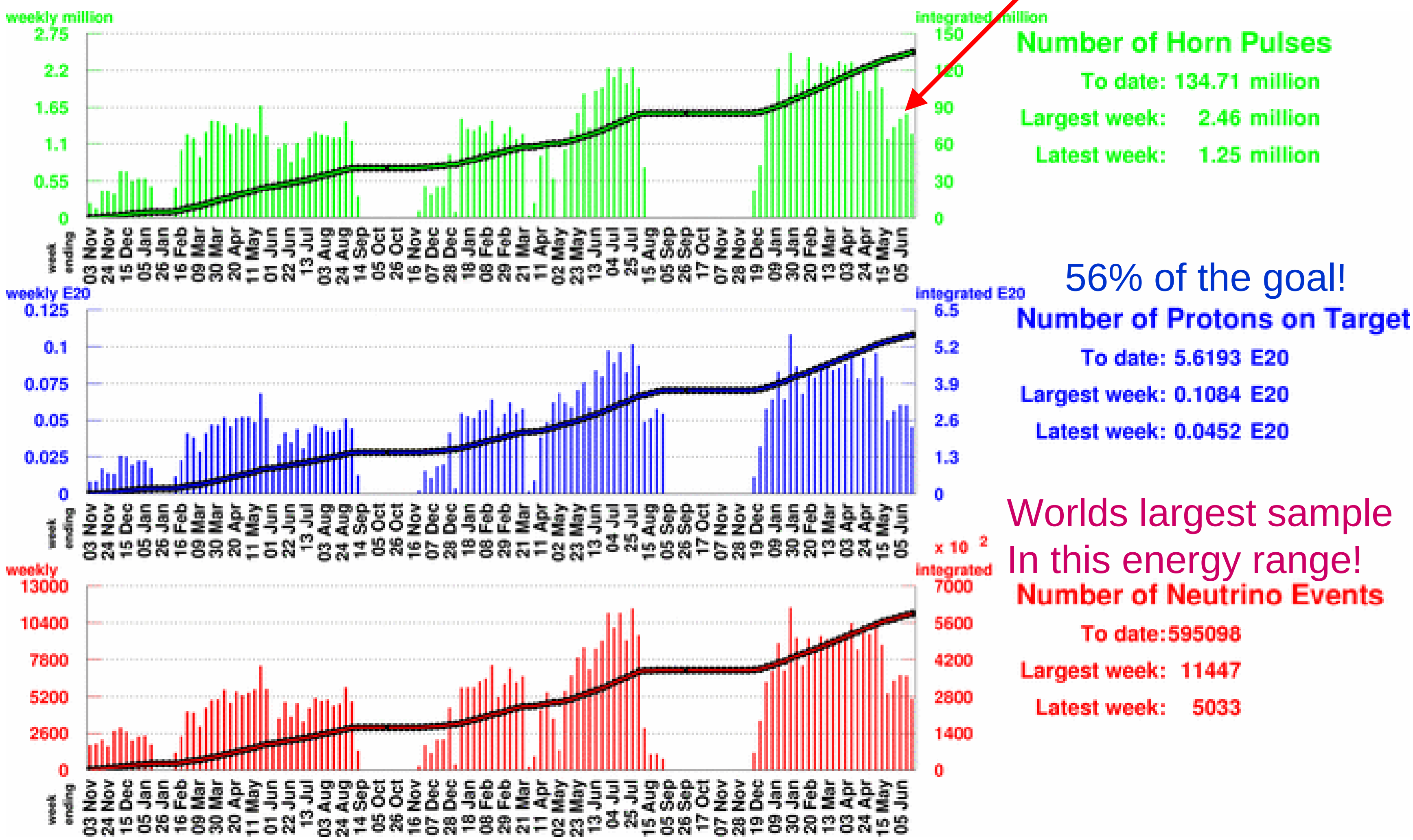
- 8 GeV proton beam
  - 1.6 μs pulse, ~5 Hz rate from Booster
  - p + Be → mesons
- Mesons focused by magnetic horn
  - focusing increases ν flux by factor of 6
  - both ν and anti-ν running possible and planned
- Mesons → Decays in flight produce ν's
- E ~ 700 MeV, L ~ 541 m (L/E ~ 0.77 m/MeV)

A history of amazing progress by the Booster and Accelerator Division!

slow start

big finish!

Still alive with NuMI

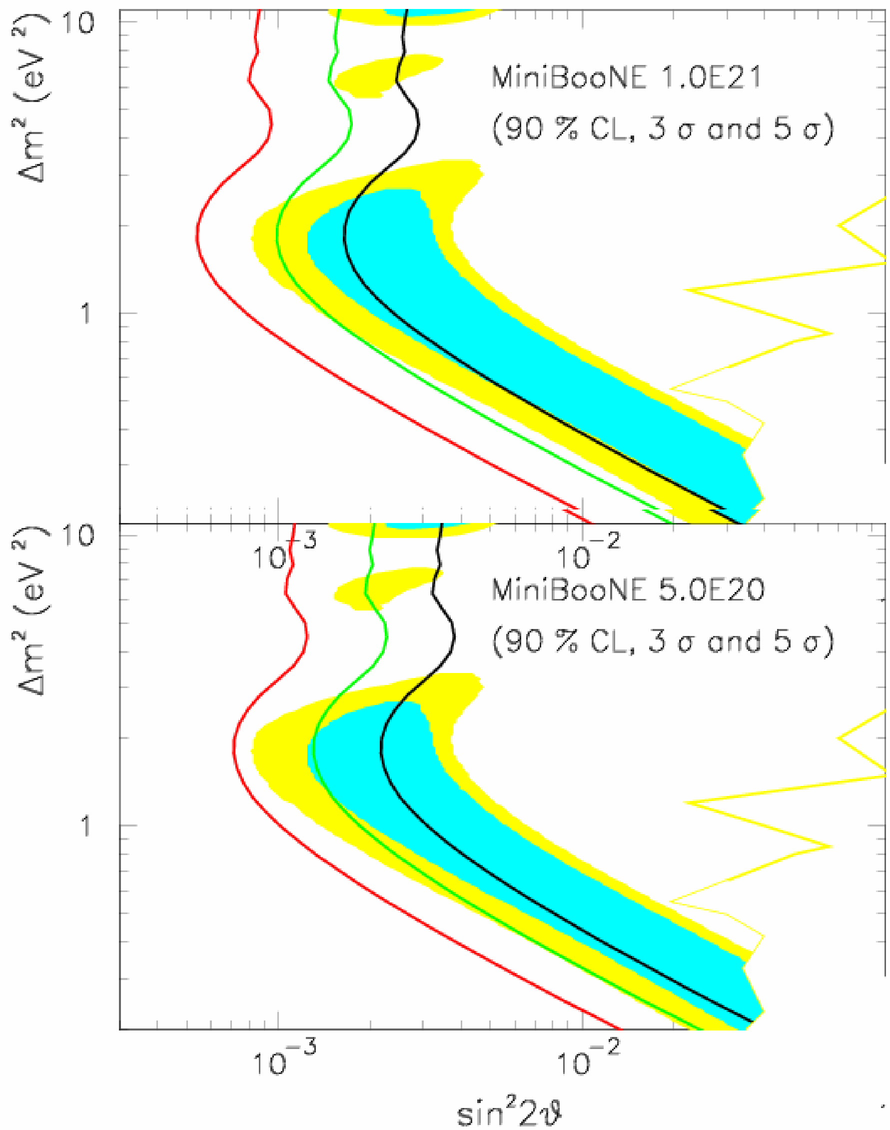


56% of the goal!

Worlds largest sample
In this energy range!

As of end of May as shown by Stefanski at the User's Meeting

Projected Mini-BooNE Sensitivities



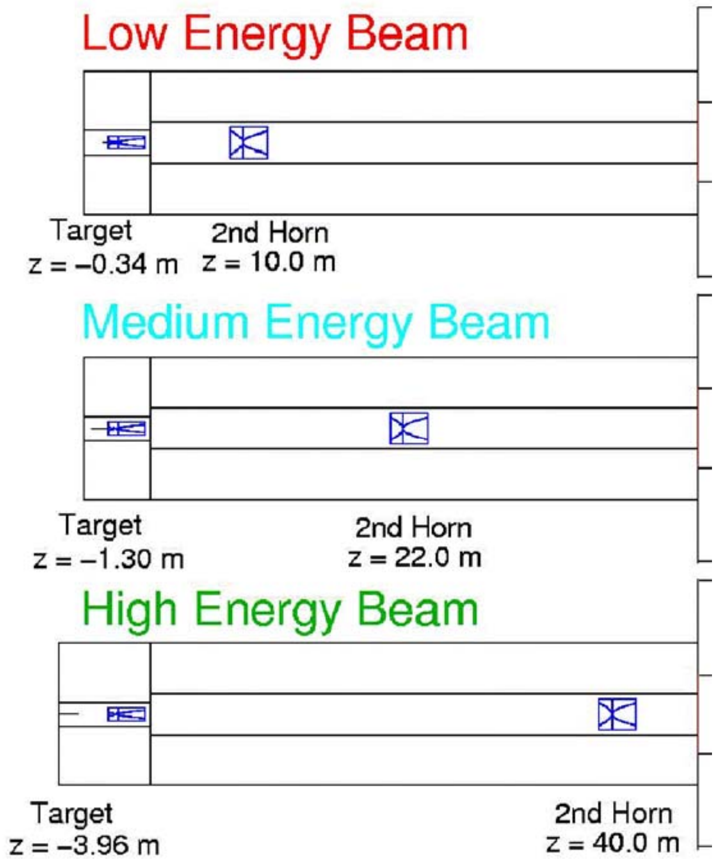
MiniBooNE oscillation sensitivity for 10^{21} p.o.t. (top) and 5 X 10^{20} (bottom) using the energy fit method. Blue (yellow) is LSND's 90% (99%) CL allowed region

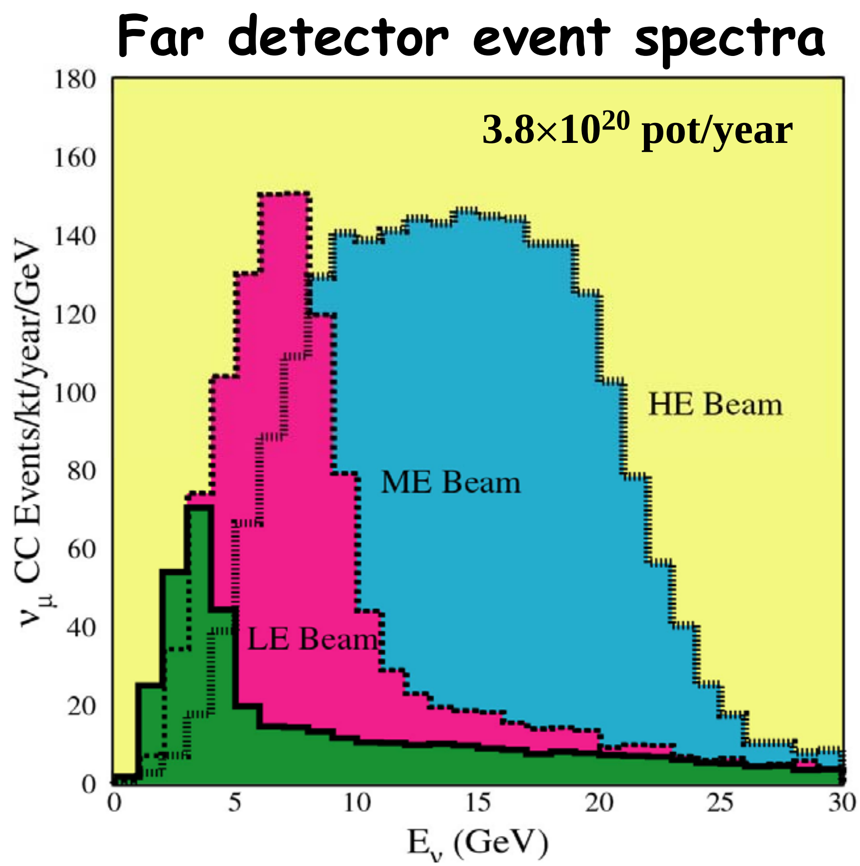
Coming soon to a lecture hall near you!

The NuMI Beam and MI

- **These are the powerful tools which, with appropriate investment, will allow Fermilab to be the world leader in neutrino measurements in the next decade.**
- **The Main Injector is a rapid cycling accelerator at 120 GeV**
  - 6 (or more) batches of Booster protons can be accelerated to 120 GeV every 2.0 s.
  - Current NuMI intensity ~2.1×10^{13} ppp every 2-4 sec (>~150 kW)
  - Goal for the end of the year ~2.5×10^{13} ppp every 2 s
  - Nominal NuMI design calls for $4.0\text{x}10^{13}$ ppp every 2 s
  - (2008-9) expected rate ~3.4×10^{20} protons/year
  - Maybe almost double that even before a proton driver? (>600 kW?)
- **NuMI beamline design (400kW) is sufficiently conservative that it may handle up to 800 kW beam power with modest improvements. Beyond may need more work. Under study.**

Sample NuMI Energy Spectra





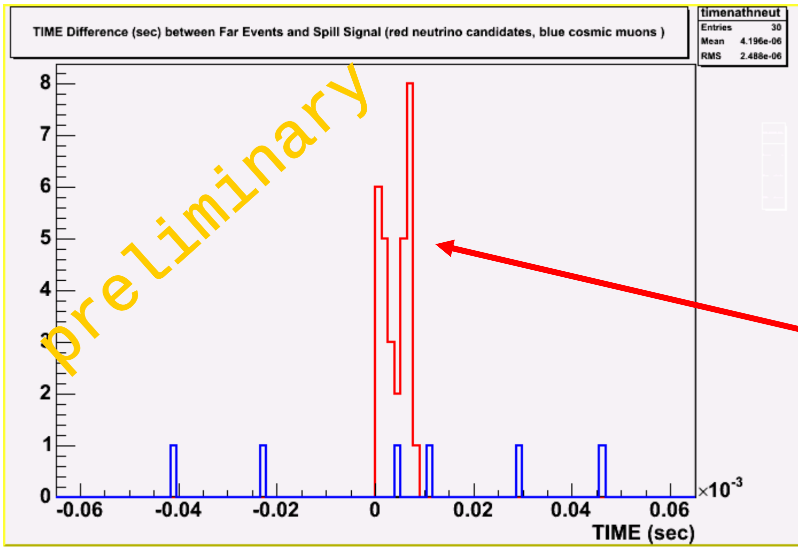
- Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn

- With a parabolic shaped horn inner conductor, the horn behaves like a lens (p_t kick proportional to the distance from the axis), with a focal length proportional to the momentum

MINOS: Precision tests of oscillation models and parameters

- **Verify dominant $\nu_\mu \rightarrow \nu_\tau$ oscillations**
  - **See the characteristic oscillation energy dependence**
  - **Check for any unconventional explanations which would affect the energy spectrum (even partially): neutrino decay, extra dimensions, etc.**
  - **Set a limit on sterile neutrino contributions with same or different Δm^2.**
- **Precise measurement of the atmospheric Δm_{23}^2: ~10% for 90% CL (3-5% for 1σ).**
- **Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations: 3 σ discovery if they occur about a factor of 2 below the CHOOZ limit**
- **Measurement of atmospheric neutrino events with neutrino/antineutrino identification**

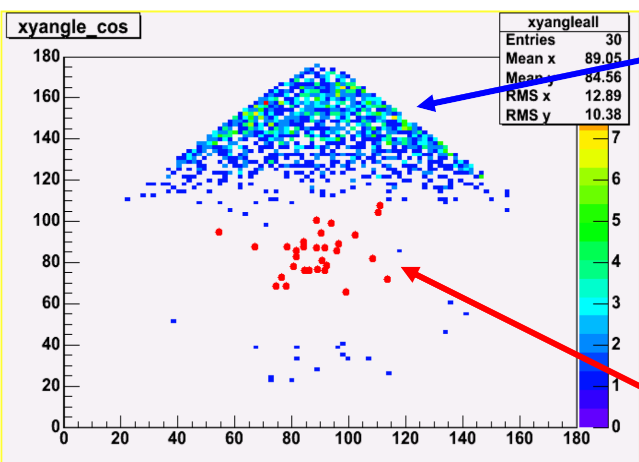
Far Detector pHE ν beam data



From ~150000 spills in pHE data

Time difference (in sec) between neutrino candidates and far spill signal in a ±50 μs window

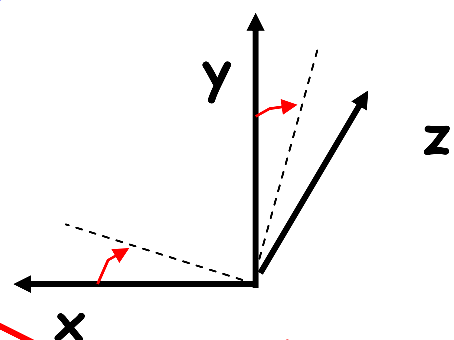
Beam neutrino candidates are within a 10 μs time interval, as expected by the spill length of the primary proton beam



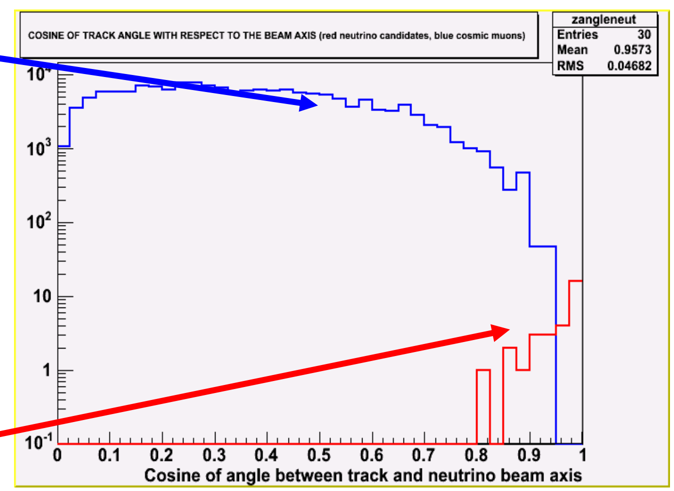
Y angle (vert.)

X angle (horz.)

Cosmics

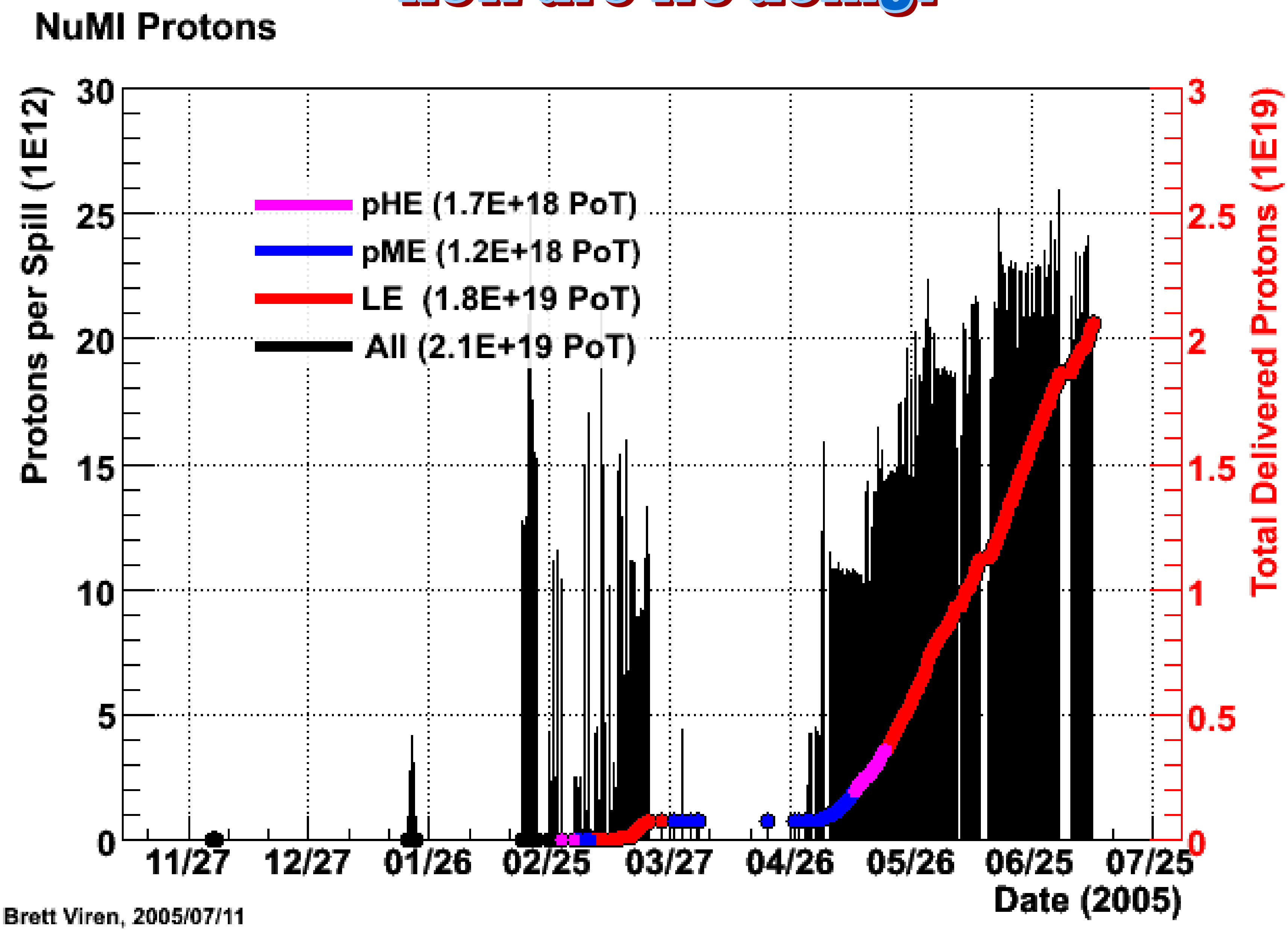


Neutrino Candidates



Track angle with respect to beam direction

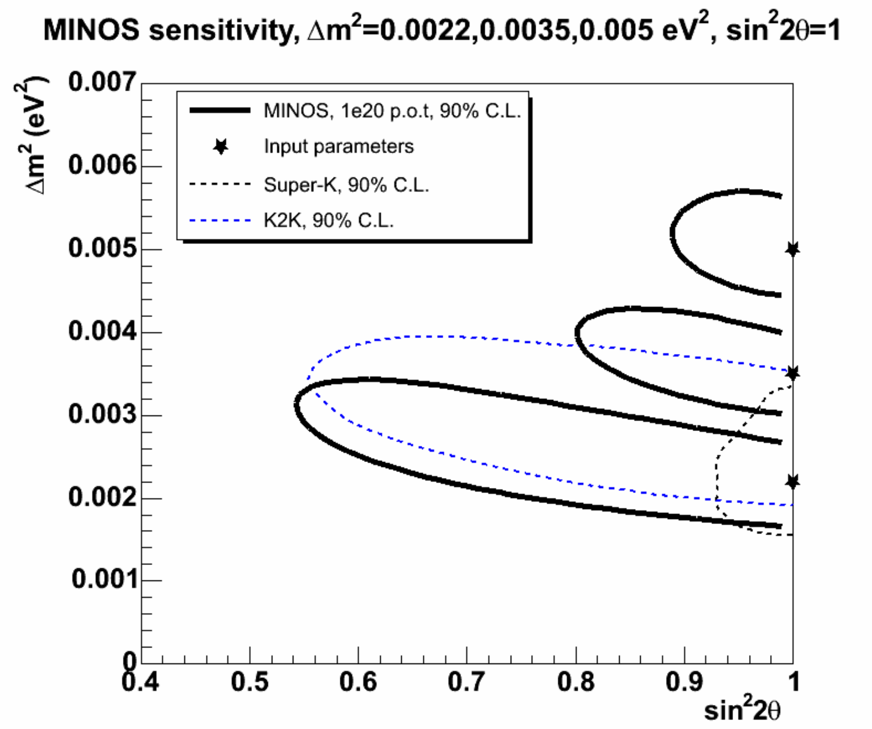
How are we doing?

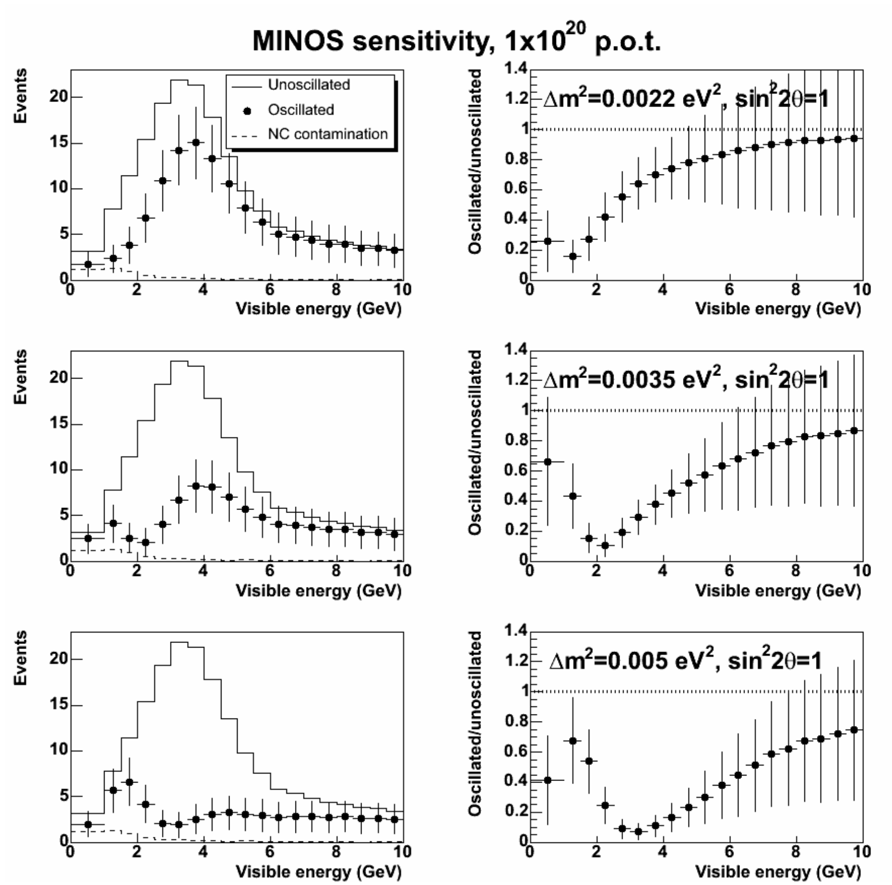


Short term prognosis

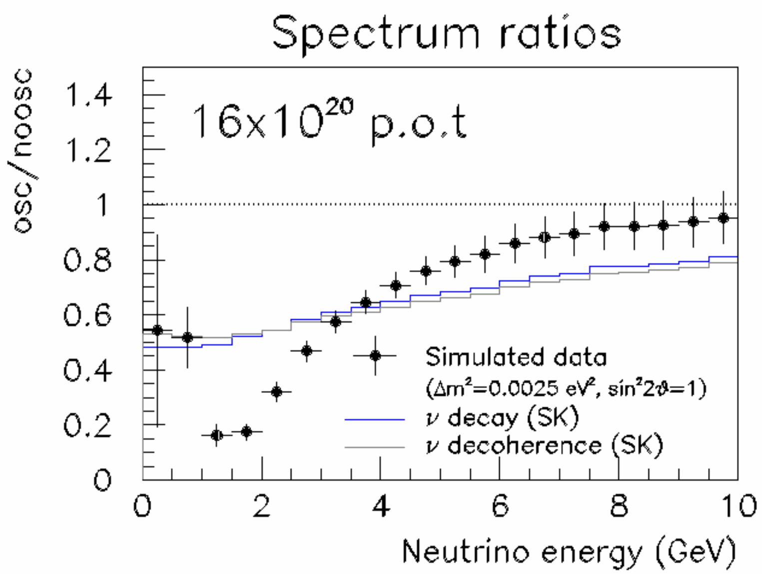
- Have already accumulated ~ 1.8×10^{19} pot in LE configuration
- By the end of the year we hopefully will be approaching ~ 1×10^{20} pot (> 100 ν_μ CC events in 1-10 GeV energy range expected in Far Detector in case of no oscillations)

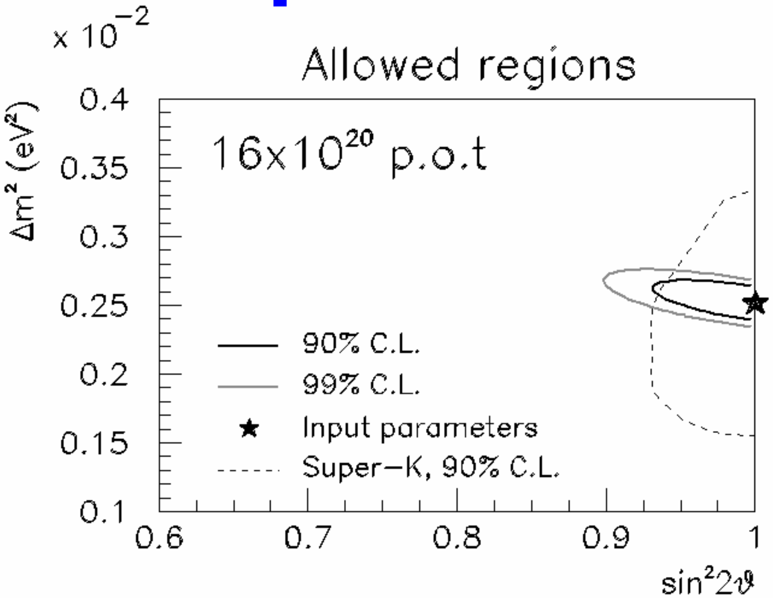
comparable data set to K2K

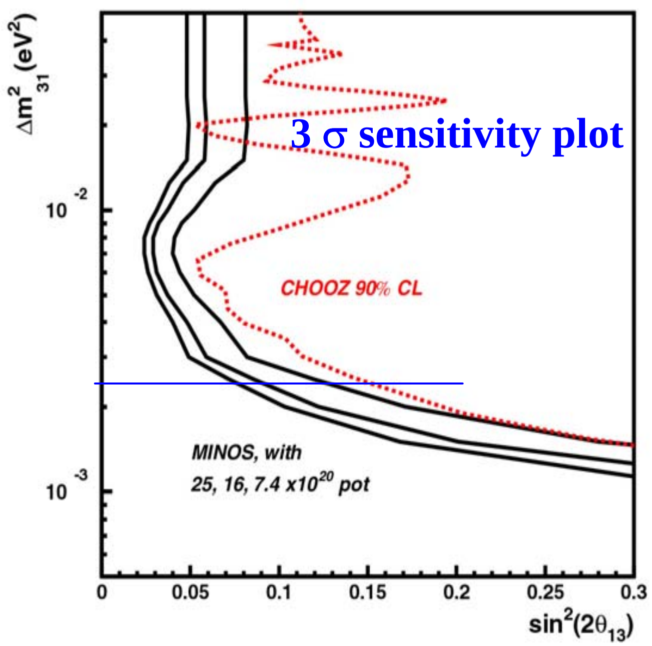




Longer term expectations



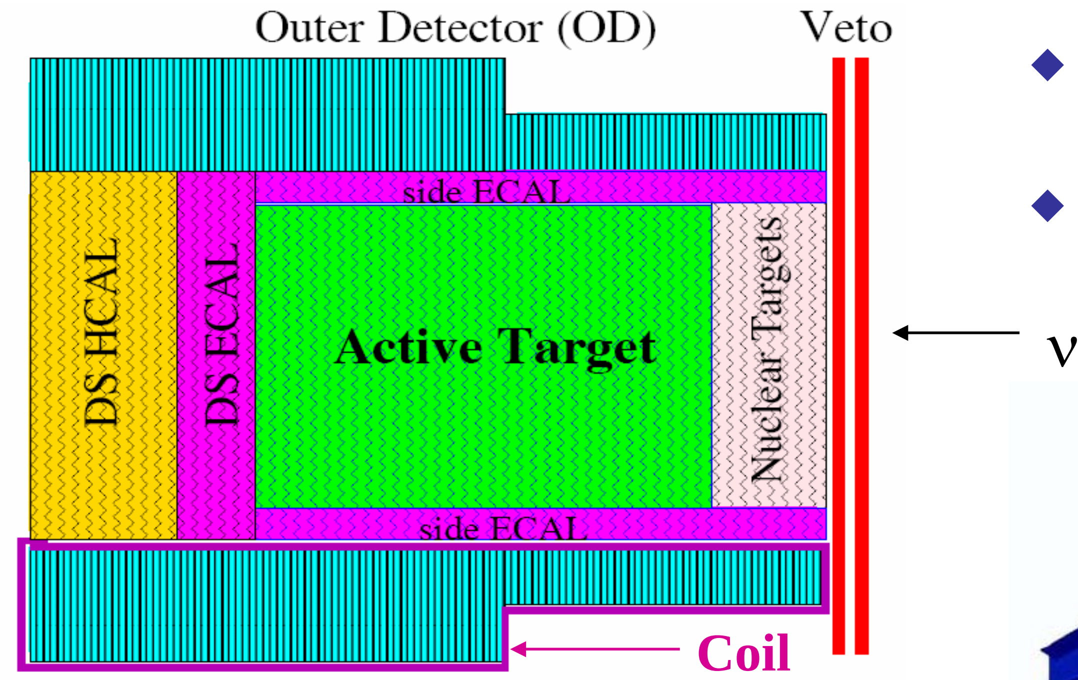




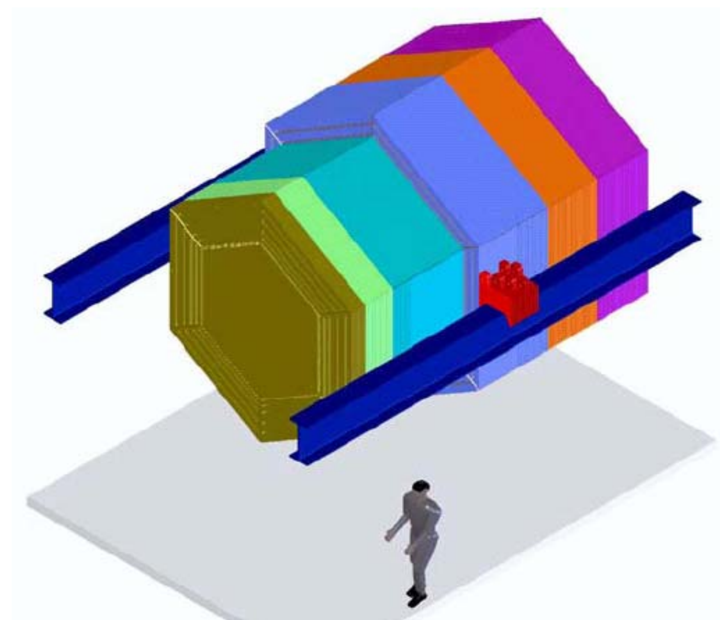
In ~ 5 years

- **10% measurement at 90% CL (3-5% 1 σ) of atmospheric Δm^2, good sensitivity for unconventional explanations**
- **3 σ sensitivity for non-zero θ_{13} if within a factor 2 of the CHOOZ limit**

The MINERνA Detector



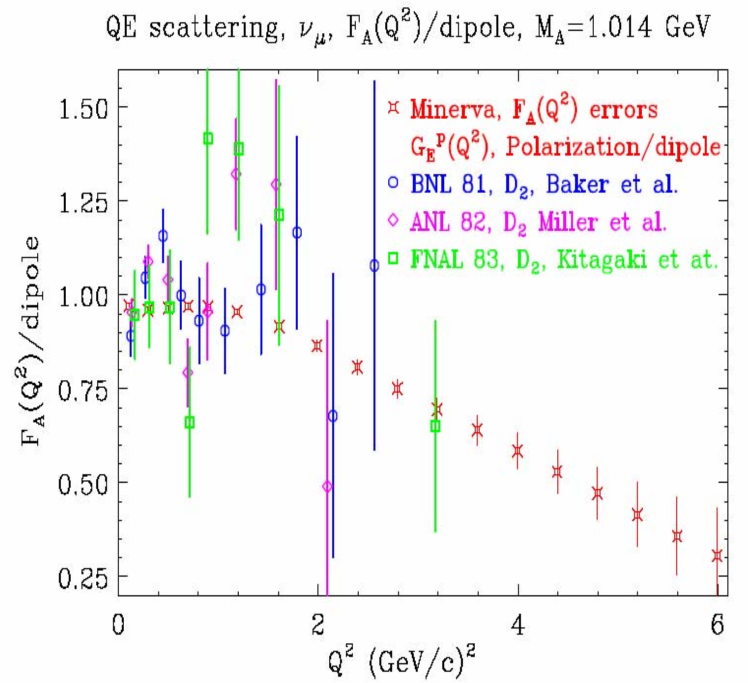
- Active segmented scint. detector 5.87 tons.
- ~1 ton each of nuclear target planes (C, Fe, Pb) upstream.



MINOS Near Detector used for higher energy forward muon identification and measurement.

Planned MINERvA Measurements

- Improved understanding of low energy neutrino cross sections for use by precision oscillation experiments
- Axial form factor of the nucleon
  - Yet to be accurately measured over a wide Q^2 range.



- Resonance production in both NC and CC neutrino interactions
  - No statistically significant measurements with 1-5 GeV neutrinos.
  - Study of "duality" with neutrinos.
- Coherent pion production
  - No statistically significant measurements of σ or A-dependence.
- Nuclear effects
  - Expect some significant differences for ν-A vs e/μ-A nuclear effects.
- Strange Particle Production
  - Important backgrounds for proton decay.
- Parton distribution functions
  - Measurement of high-x behavior of quarks.
- Generalized parton distributions

Protons: The Never Slaked Thirst of Neutrino Experiments

- Statistics in neutrino experiments are almost always “barely enough” by definition. In neutrino experiments, the detector itself is usually also the target. The bigger the mass, the more events there are. But nobody is allowed to build more detector than they absolutely need!

No of events =Cross section x Time x ν Flux x Target Mass

- The number of protons delivered to a target at a given energy is just as important as detector mass.

- Pursuit of investments in both detectors and proton intensity are essential for world-leading experiments.

The Proton Intensity Plan

- Phase 0 (now):
  - Goal: deliver 2.5E13 protons per 2 second MI cycle to NuMI (~2E20 p/yr), limited by MI RF system.
  - Deliver 1-2E20 protons per year to Booster Neutrino Beam (currently MiniBooNE)
- Phase 1 (~2008):
  - A combination of Main Injector RF improvements and operational loading initiatives will increase the NuMI intensity to 4-5E13 protons per 2.2 second cycle to NuMI (~3E20 p/yr).
  - This will increase by ~20% as protons currently used for pbar production become available.
  - It is hoped we can continue to operate BNB at the 2E20 p/yr level during this period.
- Phase 2 (post-collider):
  - In this phase, we will consider using the recycler as a preloader to the Main Injector and possibly reducing the Main Injector cycle time.
  - The exact scope and potential of these improvements is under study.
- Phase 3 (proton driver)
  - Main Injector RF must accommodate 1.5E14 protons every 1.5 seconds
  - NuMI beamline and target must also be compatible with these intensities.

Post-Collider Proton Intensity

- Gains of more than a factor of 2 from not having to make antiprotons:
  - 11/9 more Booster bunches available ⇒ factor of 1.22
  - Hide Booster filling time by filling the Recycler (2.2 s cycle time x 1.467s) ⇒ factor of 1.50
  - Lost time from transferring antiprotons ⇒ factor of 1.17
  - Total gain = (1.22)(1.50)(1.17) = **2.14**
- This translates into 6.5 x 10^{20} pot/yr
- With a new Proton Driver, into 25 x 10^{20} pot/yr
- Intermediate scenarios are being investigated

The NOvA Experiment

Physics Goals:

ν_e appearance with the goal of improving MINOS's sensitivity by approximately an order of magnitude

Measurement of the mass ordering

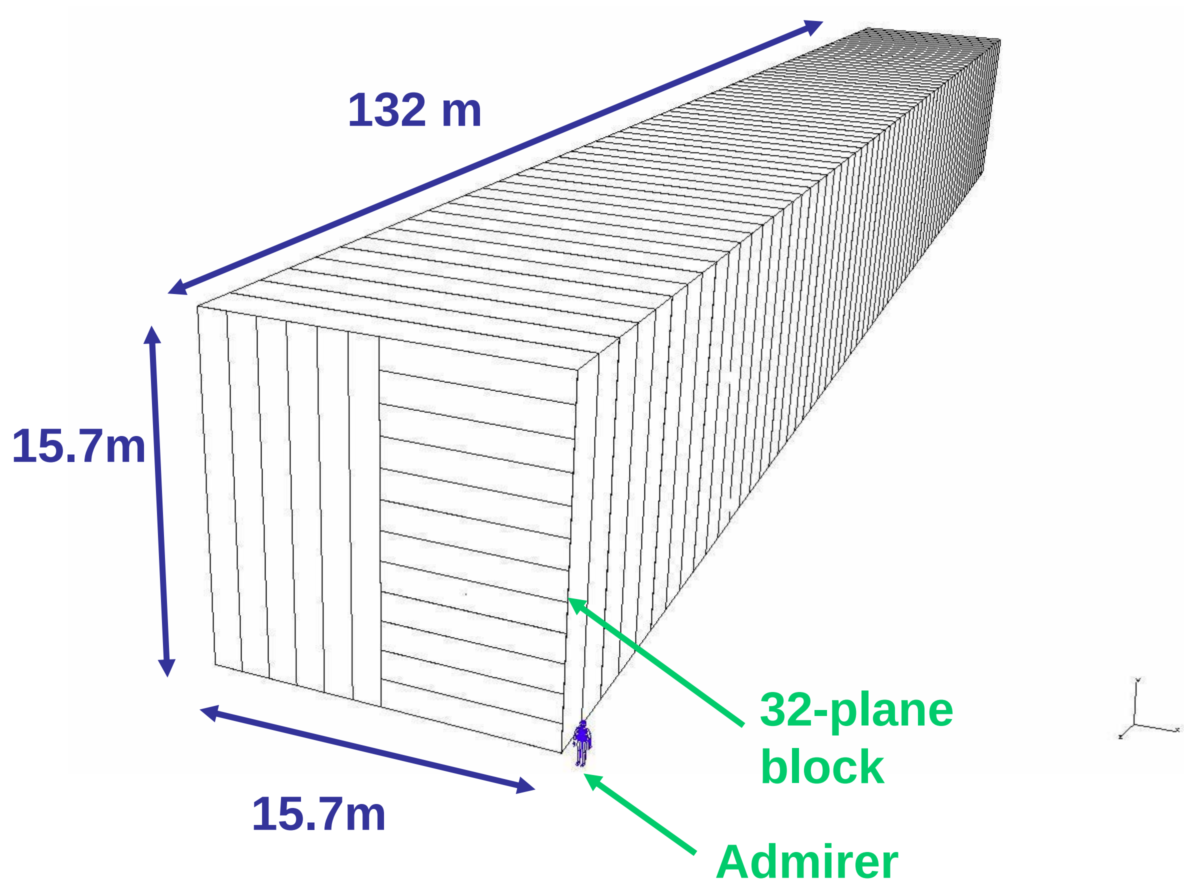
(Probably - long term) measurement of CP violating phase

Further improved measurement of "atmospheric" parameters

"Totally Active"
30 kT:
- **24 kT liquid scintillator**
- **6 kT PVC**

32 cells/extrusion
12 extrusions/plane
1984 planes
Cell dimensions:
- **3.9 cm x 6 cm x 15.7m**
- **(0.15 X_0 thickness)**

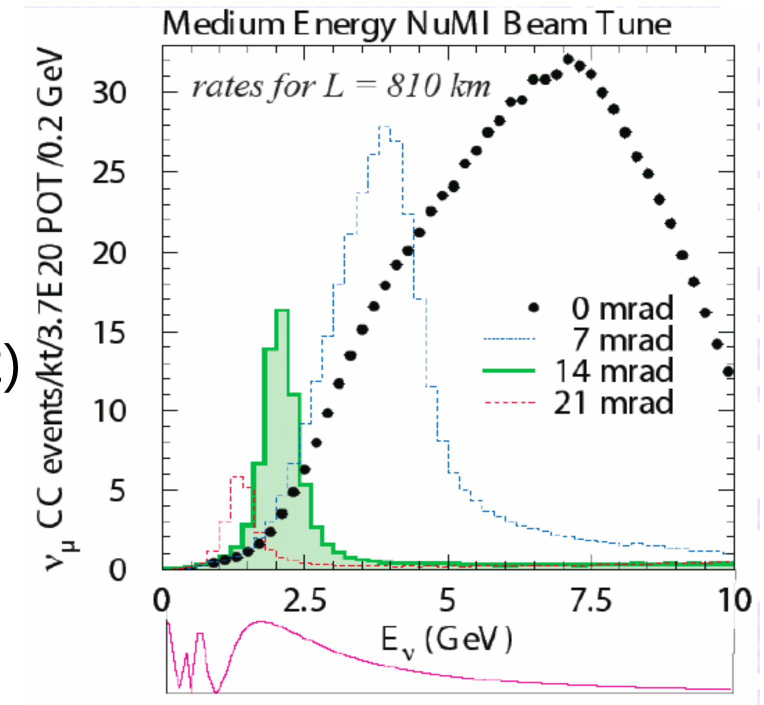
U-shaped 0.8 mm WLS fiber into APD



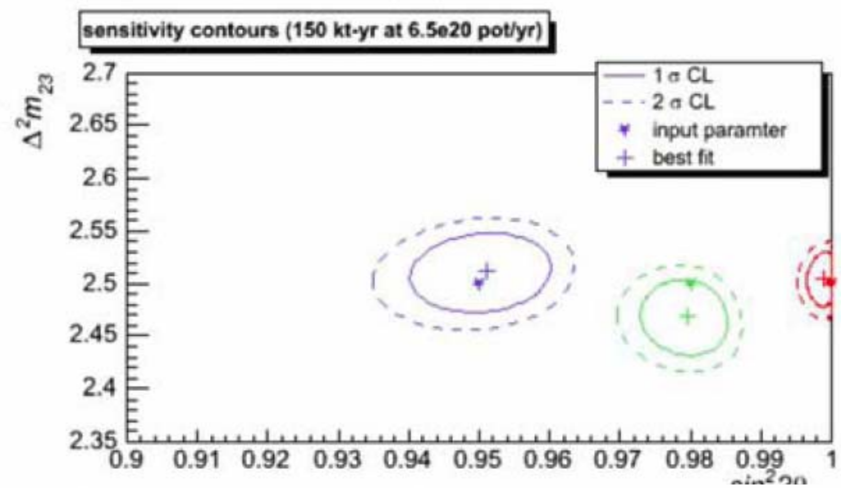
How Does NOvA Meet Its Goals?

- To get an order of magnitude improvement over MINOS for $\nu_\mu \rightarrow \nu_e$, NO$\nu$A
  - Reduces background and increases flux by going off axis
  - Increases mass by a factor of 6 (while reducing the cost/kiloton by a factor of ~2)
  - Improves *e* identification and e/π^0 discrimination by
    - Increasing longitudinal sampling by a factor of 10

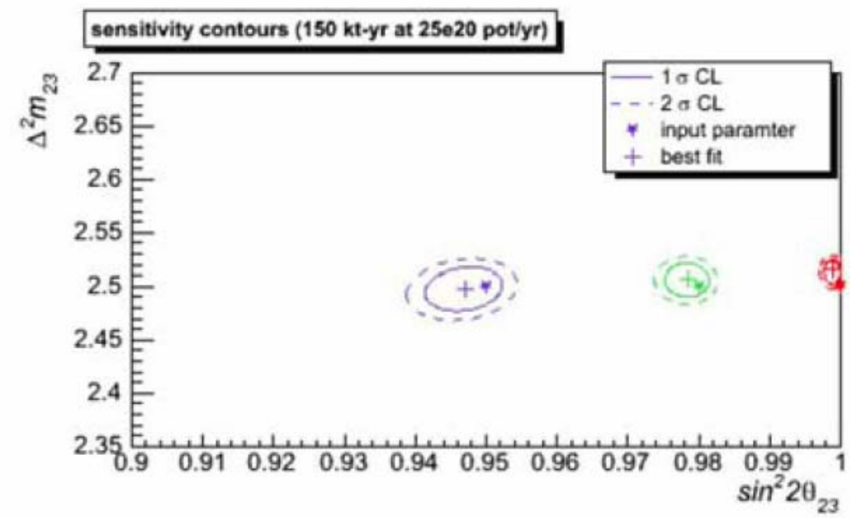
      (1.5 X_0 to 0.15 X_0)
    - Having a "totally active" calorimeter instead of a sampling calorimeter



Measurement of Δm_{32}^2 and $\sin^2(2\theta_{23})$



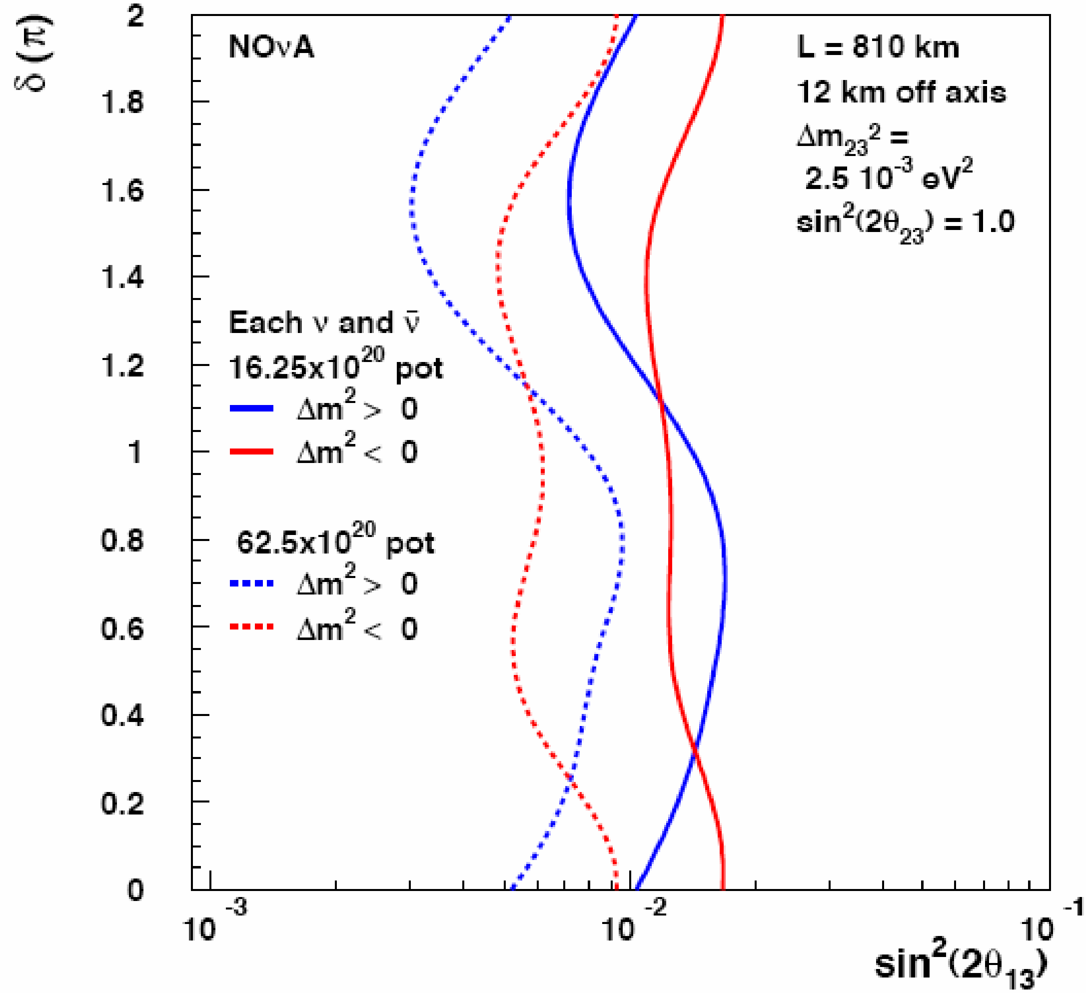
5-year ν run



5-year ν run
with Proton Driver

3 σ Sensitivity to $\theta_{13} \neq 0$

Before and after Proton Driver

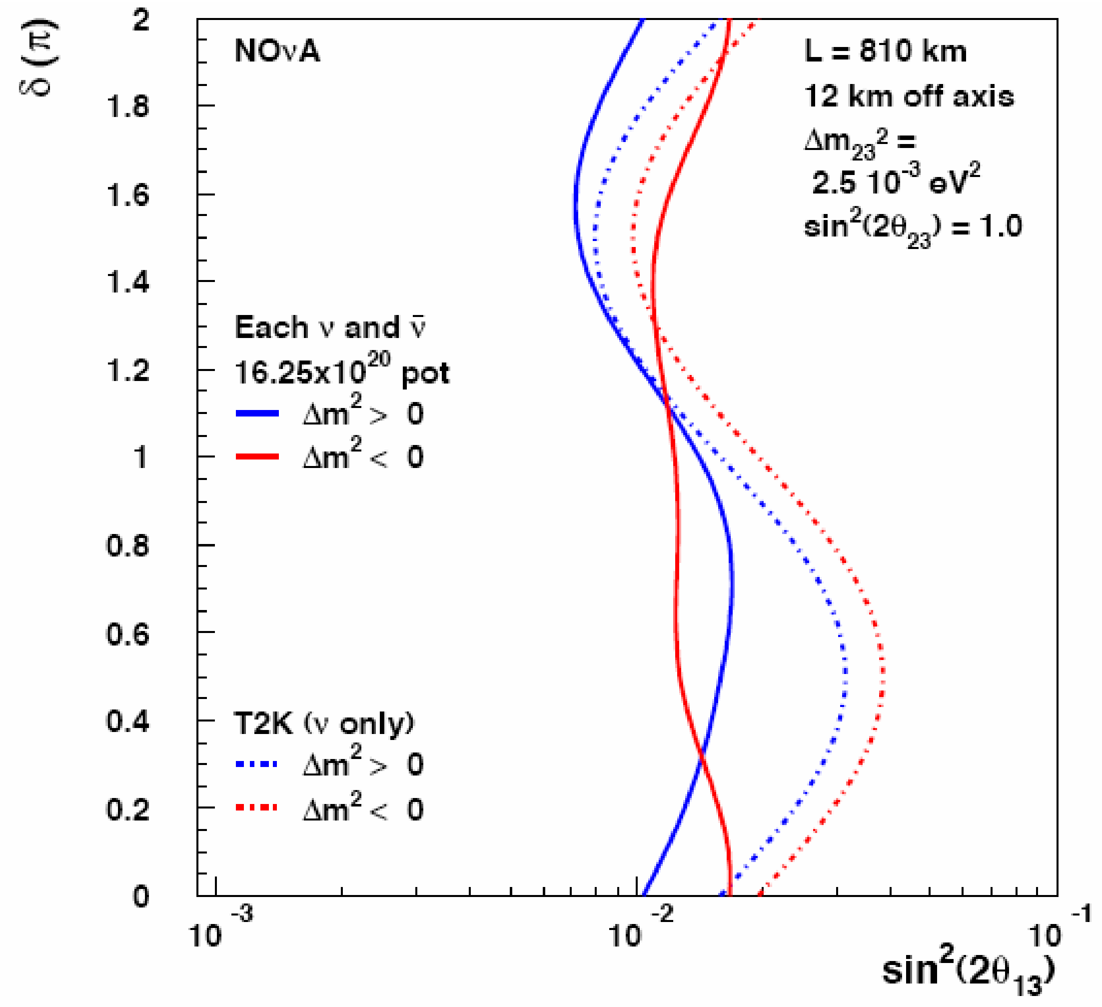


2.5 yr each

ν and $\bar{\nu}$ run

3 σ Sensitivity to $\theta_{13} \neq 0$

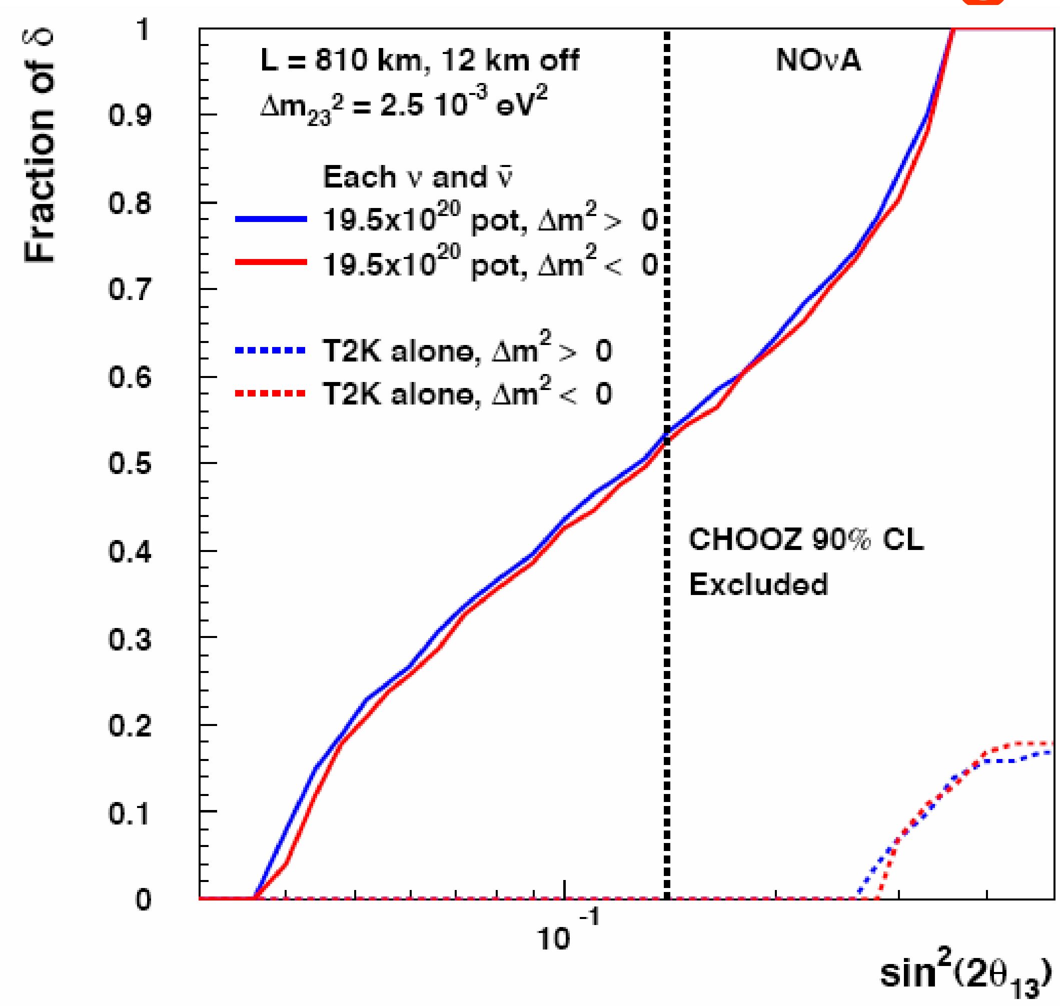
Comparison with T2K



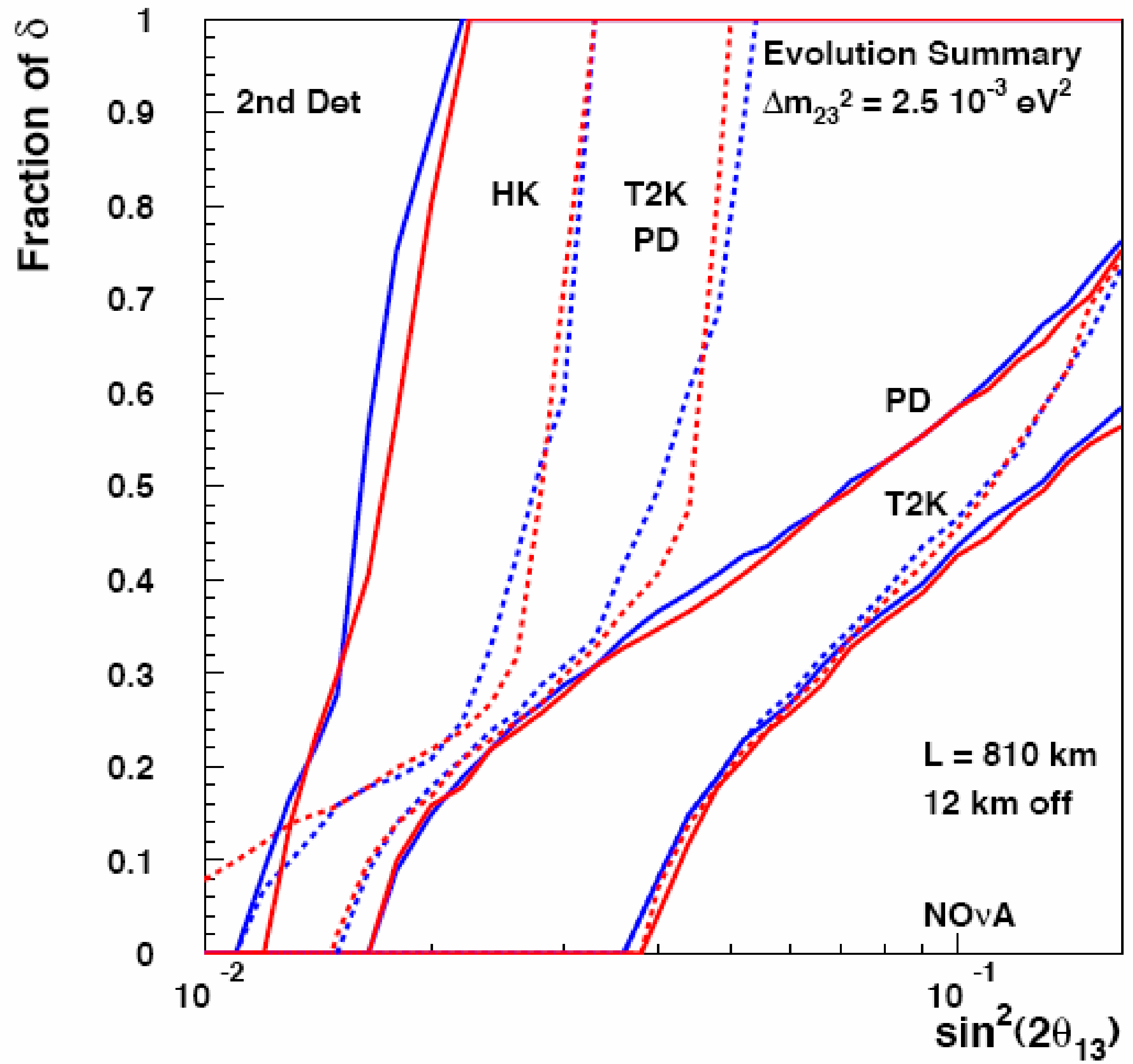
2.5 yr each

ν and $\bar{\nu}$ run

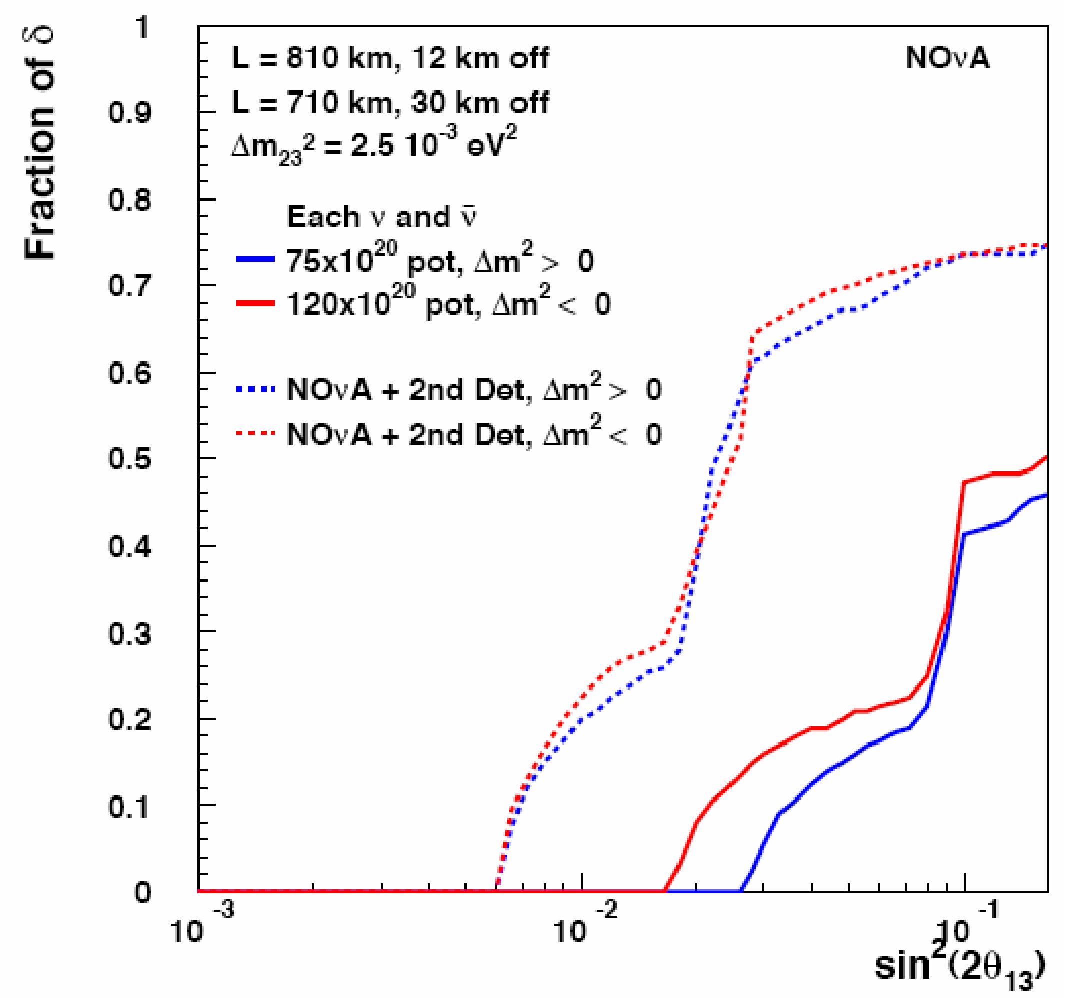
95% CL Resolution of the Mass Ordering



95% CL Resolution of the Mass Ordering: Summary



3 σ Determination of CP Violation



Aiming a Fermilab beam to a new underground lab (DUSEL)?

- One possible site (~Soudan) has an obvious advantage… the existence of the NuMI beamline. It is perhaps a bit too close for optimal measurements.
- Other sites to the west (Homestake and Henderson are perhaps the best distance?) would need a new beamline, perhaps utilizing both 8 GeV and 120 GeV protons. Sites further west would use higher energy beams which has measurement tradeoffs depending on the detector technology.
- A very large water or liquid argon detector are the most obvious candidates.
- It is pretty clear that this is an important area of investigation for the future.

Conclusions

- There are very fundamental and exciting questions which accelerator-based neutrino experiments can answer. These tend to be almost completely complementary to collider physics and some of the exciting low-energy neutrino experiments.
- MINOS and Mini-BooNE are now both well established and running with first world-class results expected within the next year.
- Fermilab is poised to be the unquestioned leader in the field of neutrino physics over the next 20 years, providing unique opportunities for the essential measurements. Probably even mostly consistent with Fermilab as the site for construction of the linear collider. That'll depend on future budgets as much as anything. I think we should make the case for both and pursue both aggressively.
  - We need to proceed rapidly with NOvA.
  - We need to get a proton driver to the point that construction can begin within the next several years.
  - Who knows what Mini-BooNE will say… But we need to look very seriously at a new low-energy neutrino program in either case.

Thanks Mike!

- For those of you not following closely, construction of NuMI was far from a walk in the park. Mike probably didn’t lose quite as much hair as I have recently, but I’m sure he lost a few good clumps over this! **His support and his strong personal involvement (especially during crisis times) have been invaluable in bringing the NuMI project to a successful conclusion.**
- We now have the world’s most intense, most powerful neutrino beam! It will serve us well for many years. It is a facility in which the lab should take great pride and continue to develop its capabilities.
- The issue of getting enough protons is extremely important and those of us interested in this physics are very happy to see the start of a program aimed at increase in the proton intensity. It is essential!
- **The table is set for physics.**

Backup Slides

Future Booster Neutrino Running

- Mini-BooNE running extended through 2007 (perhaps with anti-neutrino running)
- There are many obvious experiments to do in the future if the LSND signal is confirmed.
- As an experimenter, it feels wrong to me to not test the signal with anti-neutrinos too. Practical issues may mean that this needs a new 8 GeV proton source.