# Proton Driver Report: Neutrino Oscillations Physics Study

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Fermilab

WIN’05
Delphi, Greece

- Why do another neutrino oscillation physics study?
- What are the next steps for Fermilab to take?
  - depends on what we find out in next 10 years
- Peek at physics reach with and without a proton driver

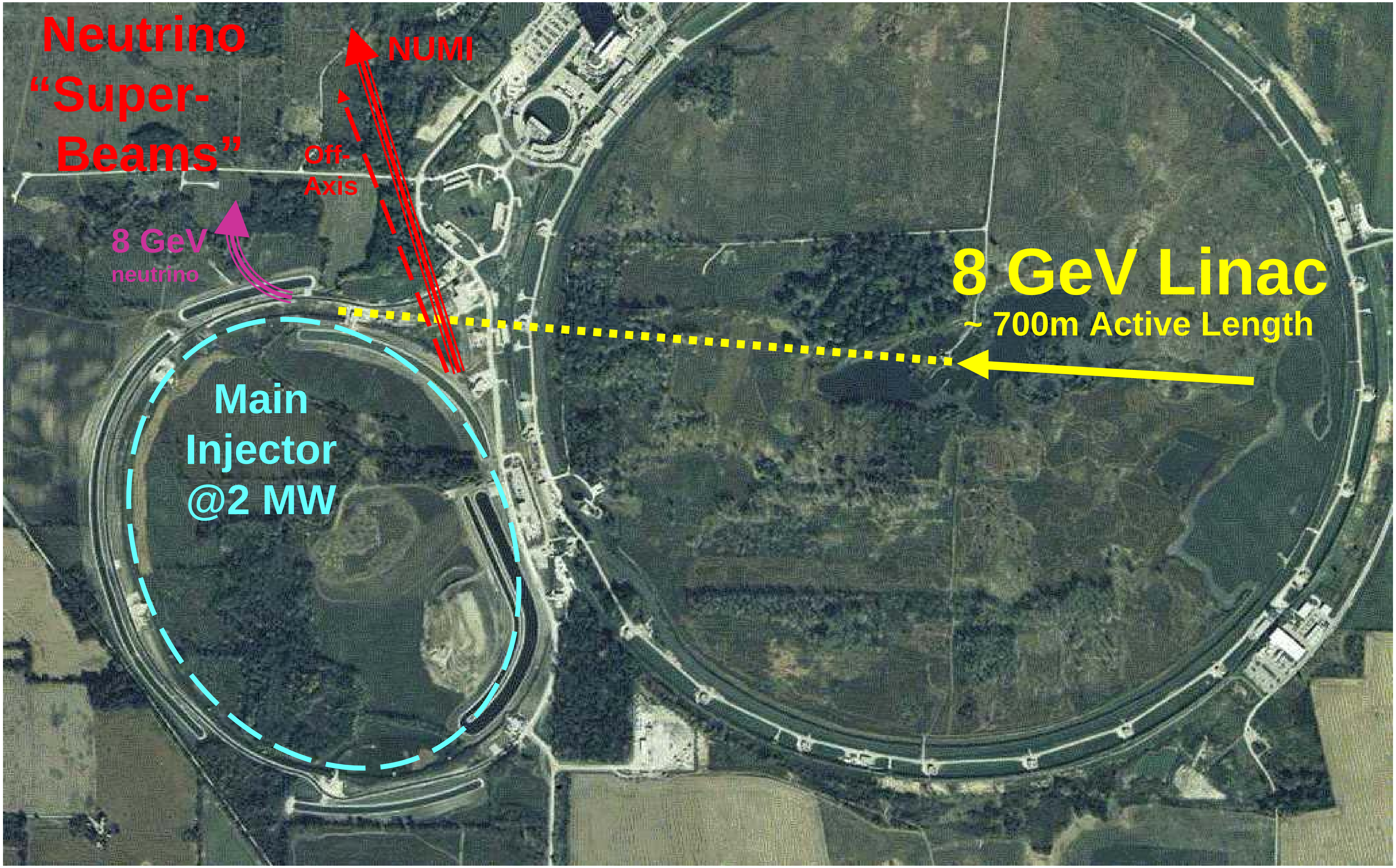
Editors: Steve Brice, Deborah Harris (FNAL)
Walter Winter (IAS, Princeton)

# Why another neutrino physics study?

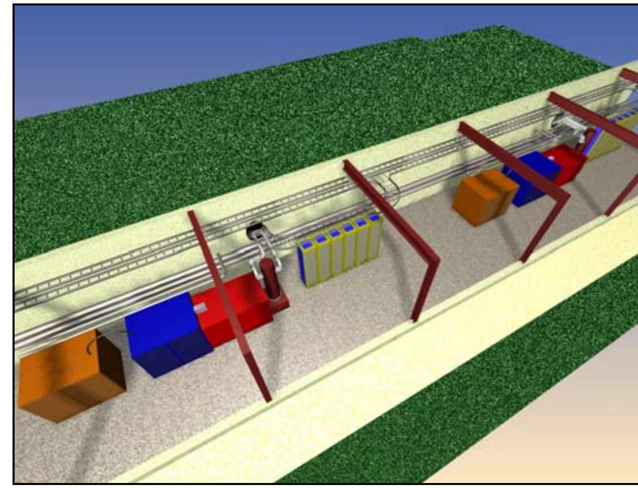
- Fermilab is trying to understand the role it can play in future neutrino measurements
- To get anywhere new we need
  - More detector mass*efficiency
  - More protons on target
  - Beamlines that can take the heat
- What is the cheapest way to get more mass*POT?
  - NOvA detector: roughly 150M$, for 30kton (6x MINOS mass)
  - New FNAL Proton Driver: 300-500M$???, for factor of 5-10 past current FNAL proton source at 120GeV…but can also see a huge increase of 8GeV protons
  - Note: these costs are non-linear!

    (i.e. several $10M upgrades might get x2 in POT)
- Fermilab has conducted two studies: physics and machine
  - How to build a more powerful proton source (W.Foster)
  - What to do with the protons (8GeV and up to120GeV) (S.Geer)

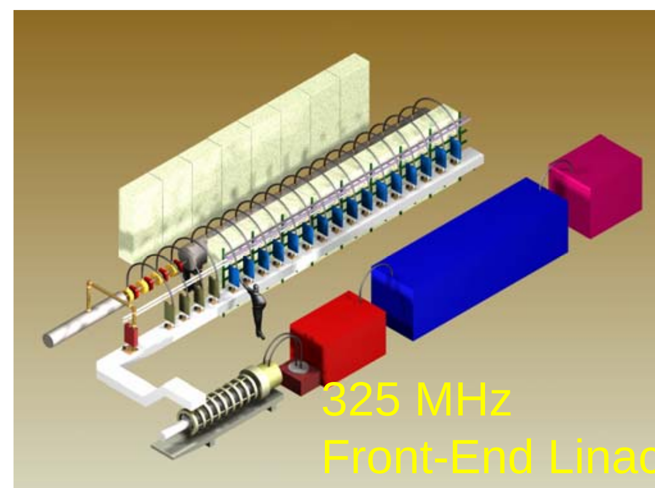
# Fermilab Proton Driver Layout



# The FNAL Proton Driver Concept



- Single Stage H- Injector Linac that Replaces both the 8 GeV Booster Synchrotron and its Injector Linac.
- Copy SNS & RIA designs below ~ 1 GeV
  - Reduced duty factor allows some cost optimizations
- Copy the TESLA design from 1-8 GeV
  - Shared development program with ILC
  - 1.5% scale demonstration of technology and cost basis



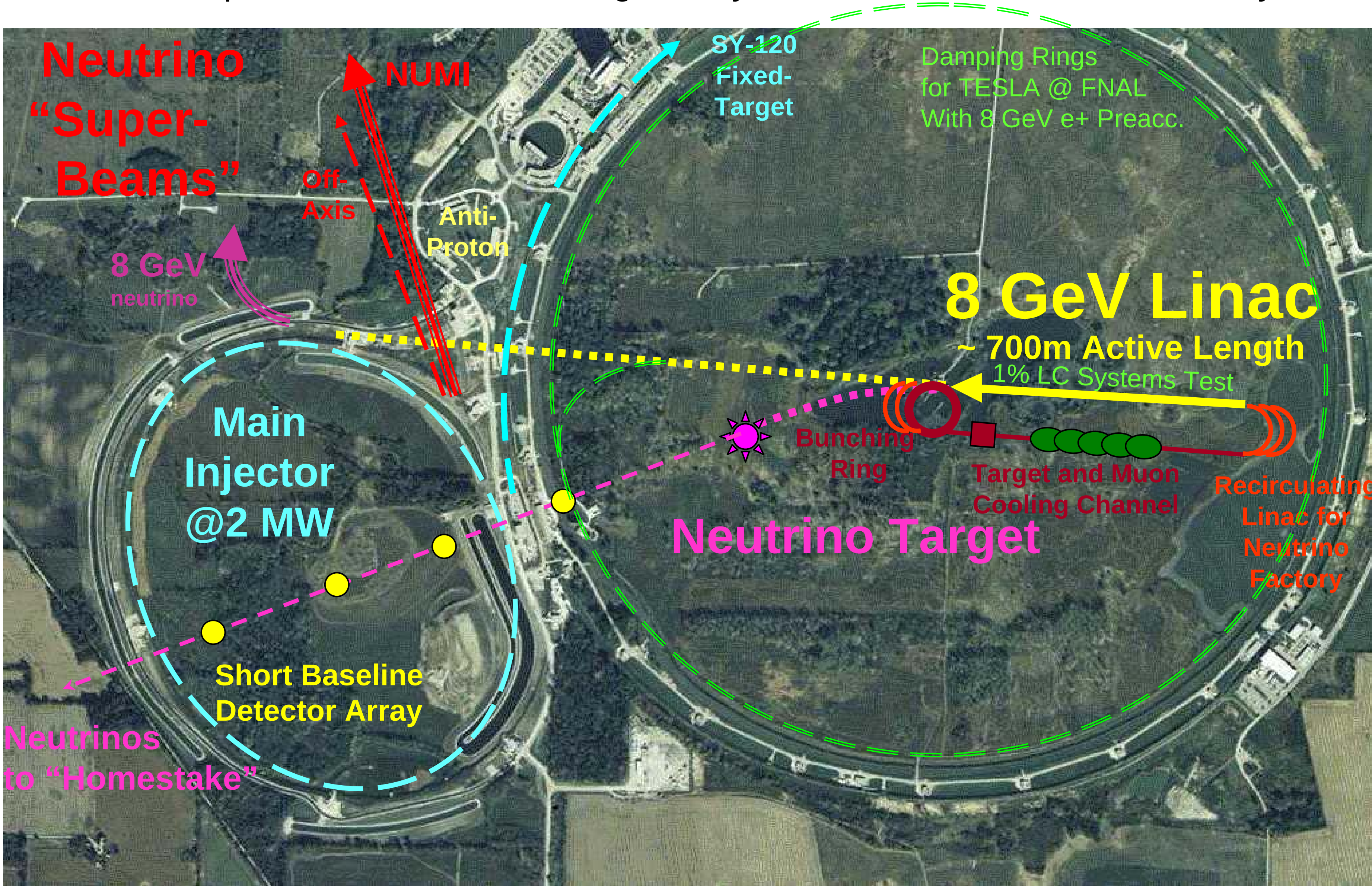

- Minor upgrades to Main Injector
  - Can produce 2MW from 30 to 120GeV
  - New source can feed MI many more protons/hour

# Primary Parameter List (for reference)

| PRIMARY PARAMETERS | 8 GeV Initial 0.5 MW {Ultimate 2MW in Brackets} | | |
|---|---|---|---|
| Linac beam kinetic energy | 8 | GeV | |
| Linac Particle Types | H - ions | | Baseline Mission |
| | Protons | | via foil stripping in transfer line |
| | Electrons | | Possible w/upgrade of Phase Shifters & Injector |
| Linac Stand-Alone Beam power | 0.5 {2.0} | MW | 8 GeV beam power available directly from linac |
| Linac Pulse repetition rate | 2.5 {10} | Hz | |
| Linac macropulse width | 3.0 {1.0} | ms | |
| Linac current (avg. in macropulse) | 8.7 {26} | mA | |
| Linac current (peak in macropulse) | 9.3 {28} | mA | |
| Linac Beam Chopping factor in macropulse | 94 | % | For adiabatic capture with 700ns abort gap. |
| Linac Particles per macropulse | 1.56E+14 | | |
| Linac Charge per macropulse | 26 | uC | |
| Linac Energy per macropulse | 208 | kJ | |
| Linac average beam current | 0.07 {0.26} | mA | |
| Linac beam macropulse duty factor | 0.75 {1.0} | % | |
| Linac RF duty factor | 1.00 {1.3} | % | |
| Linac Active Length including Front End | 614 | m | Excludes possible expansion length |
| Linac Beam-floor distance | 0.69 | m =27 in. | same as Fermilab Main Injector |
| Linac Depth Below Grade | 9 | m | same as Fermilab Main Injector |
| Transfer Line Length to Ring | 972 | m | for MI-10 Injection point |
| Transfer Line Total Bend | 40 | deg | two 20-degree collimation arcs |
| Ring circumference | 3319.4 | m | Fermilab Main Injector |
| Ring Beam Energy | 8-120 | GeV | MI cycle time varies with energy |
| Ring Beam Power on Target | 2 | MW | ~ independent of MI Beam Energy |
| Ring Circulating Current | 2.3 | A | |
| Ring cycle time | 0.2-1.5 | sec | depends on MI beam energy & flat-top |
| Ring Protons per Pulse on Target | 1.50E+14 | protons | |
| Ring Charge per pulse on target | 25 | uC | |
| Ring Energy per pulse on target | 200-3000 | kJ | at 8-120 GeV |
| Ring Proton pulse length on target | 10 | us | 1 turn, or longer with resonant extraction |
| Linac Wall Power | 5.5 {12.5} | MW | approx 3 MW Standby + 1MW / Hz |

# Driving for more than Oscillations…

8 GeV proton source, Fixed Target, maybe even LC and Neutrino Factory



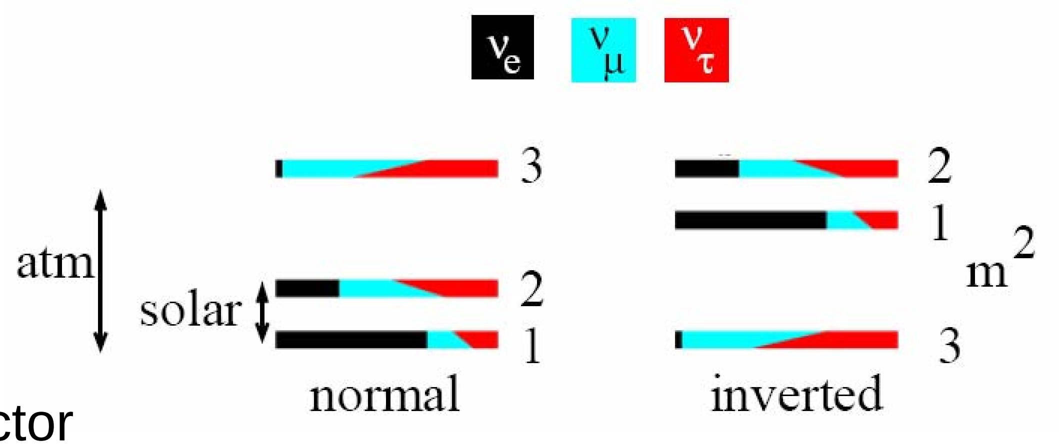
# Recap from previous talks in this session:

- Primary Physics goals*
  - Seeing $\Theta_{13}>0$
  - Determining the neutrino mass hierarchy
  - CP violation in lepton sector
- Channels required to achieve this

$$\nu_\mu \rightarrow \nu_e$$

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

- Size of $\Theta_{13}$ determines how hard this will be…

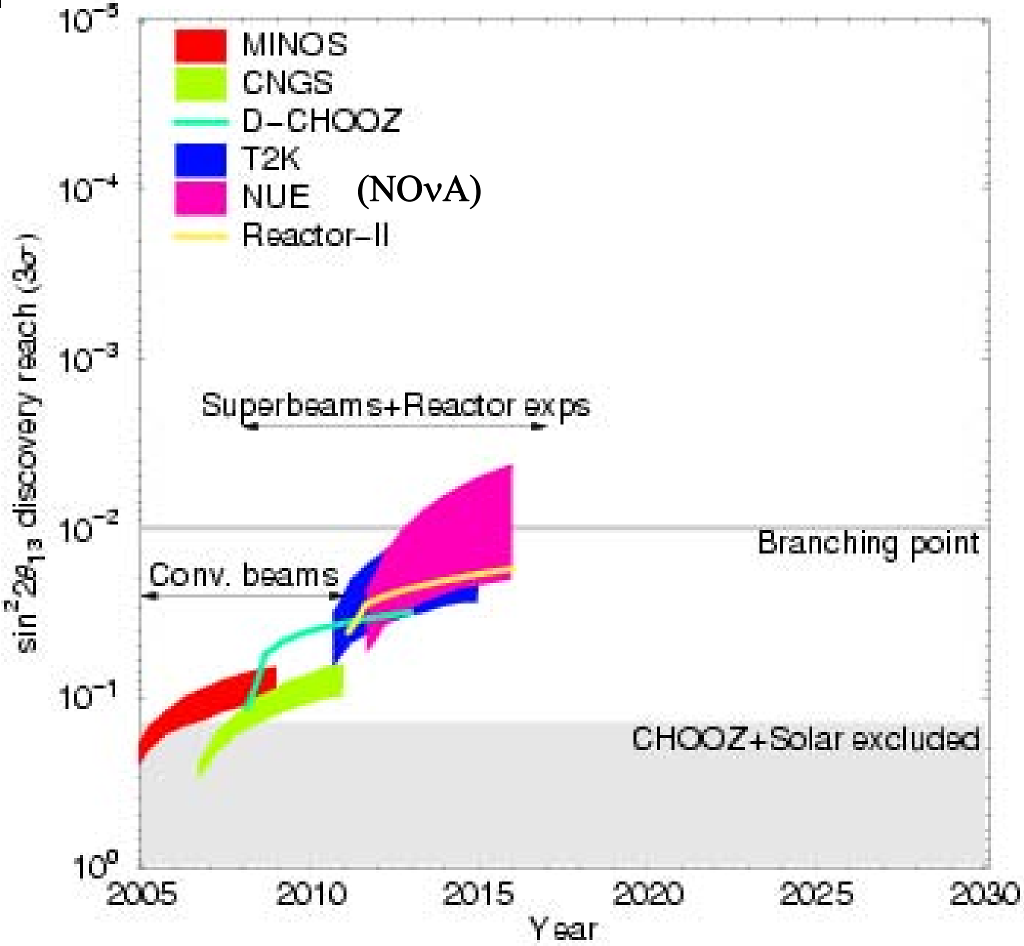



From Mena and Parke, hep-ph/0312131

*Assuming LSND is not due to oscillations… channels of interest remain the same

# Where will we be at beginning of Proton Driver?

- Conventional Beam
  - MINOS (.25MW)
  - ICARUS (.15MW)
  - OPERA (.15MW)
- SuperBeams
  - T2K (.8MW)
  - NOνA (.4MW)




W. Winter, (normal mass hierarchy assumed)

- Reactor
  - Double Chooz (France)
  - “Reactor II” (USA, China, Brazil,…..)
- Short Baseline
  - Investigate LSND result
  - MiniBooNE

# Where we are determines how much we need: but need Proton Driver no matter what!

- "Existing" Detectors, Existing Beamlines + Proton Driver
  - NO$\nu$A Detector (810km, 2GeV beam)

**Scenario 1:** $\sin^2 2\Theta_{13} > \sim 0.04$

- New Detectors, Existing Beamlines
  - T2K measurements: 295km, 0.7GeV beam
  - Other Off-Axis Detectors: 710km, 0.7GeV beam
- New Beamlines, Existing Detectors
  - Pointed towards NO$\nu$A Detector (still under study)
- New Detectors and New Beamlines
  - National (Deep) Underground Science Laboratory
  - One Broad-Band Beam (1290km or 2450km)
  - Two Beamlines, one on axis, one off axis (1290km)

**Scenario 2:** $\sim 0.01 < \sin^2 2\Theta_{13} < \sim 0.04$

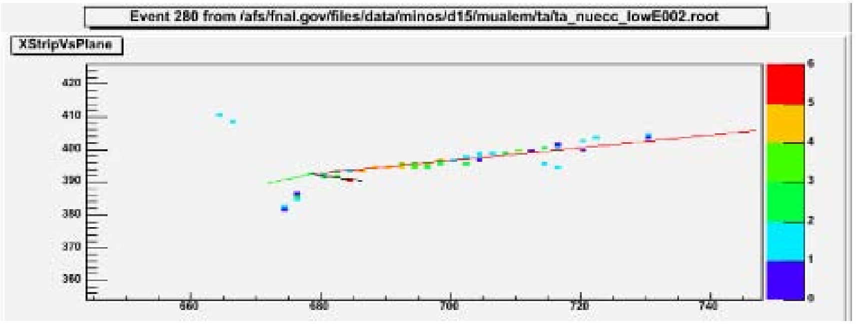
- New Technology: Un-conventional Beams
  - Neutrino Factory
  - If technology breakthrough: high energy beta-beam
  - Natural synergy with muon physics program

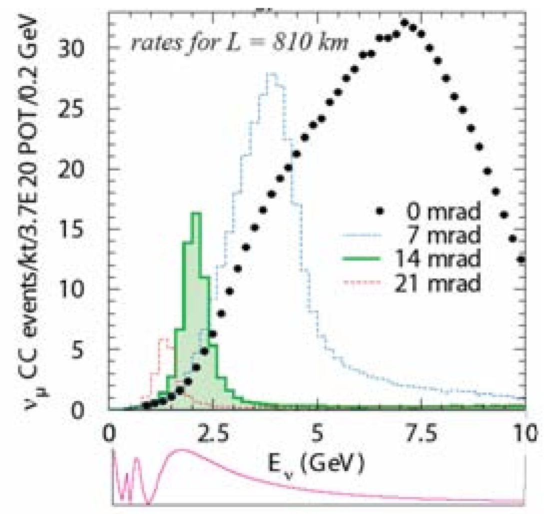
**Scenario 3:** $\sin^2 2\Theta_{13} < \sim 0.01$

Best Long Term Option depends on what is seen in the next generation, and what happens in the rest of the world!

# Scenario 1: $\sin^2 2\theta_{13} > \sim 0.04$
# Existing Detectors, Existing Beamlines


## NOνA Detector, NuMI Beamline




### Complmentarity between NOνA and T2K

| Vital Statistic | NOνA | T2K |
|---|---|---|
| Neutrino Energy | 2GeV | 0.7GeV |
| Baseline | 810km | 295km |
| Detector Mass | 25 kT | 50 kT |
| Detector Technology | Scintillator | Water Cerenkov |
| Proton Energy | 120GeV | 120GeV |
| Proton Power | 2MW | 0.8MW |

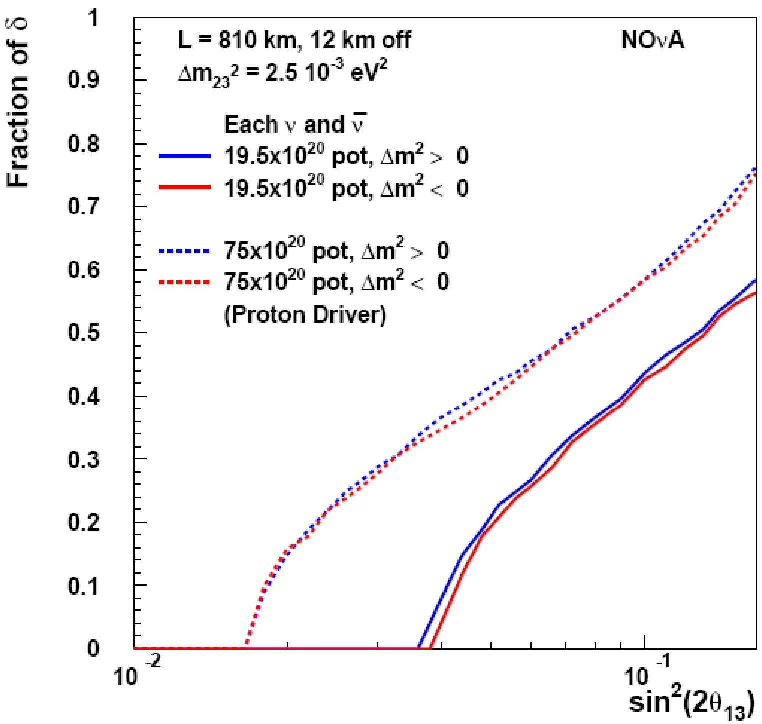
# Synergy with T2K

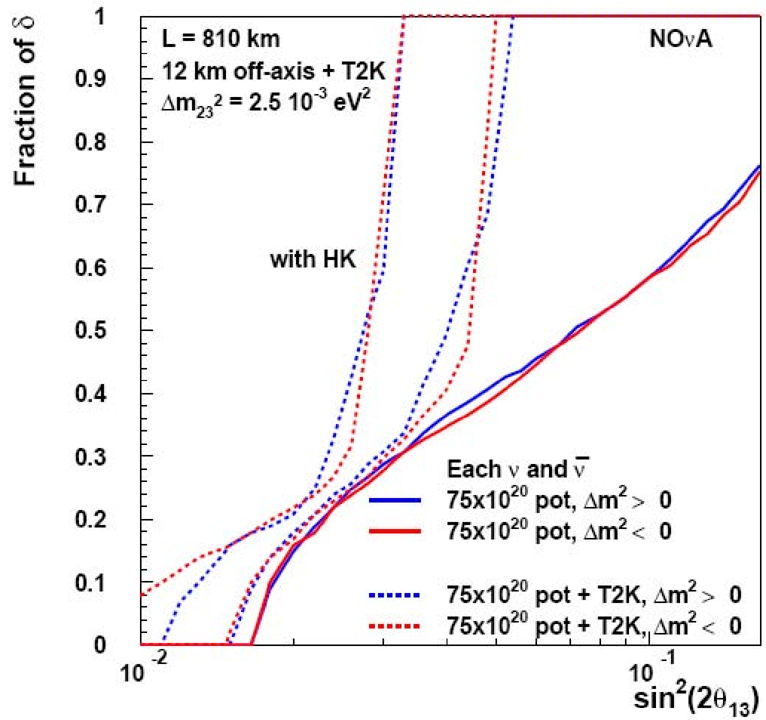
- Adding FNAL Proton Driver makes T2K and future upgrades much more powerful so that the combination can be used to determine matter effects!

With and Without FPD

With FPD, combining with T2K

2σ Resolution of Mass Hierarchy



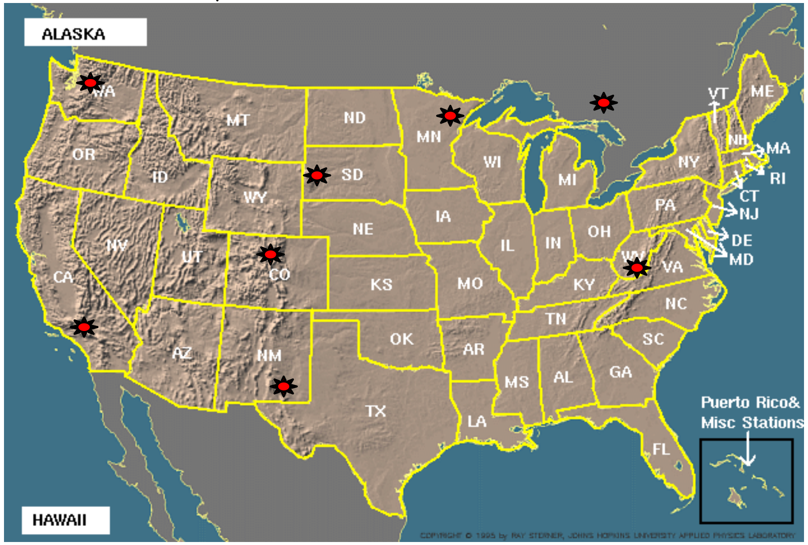



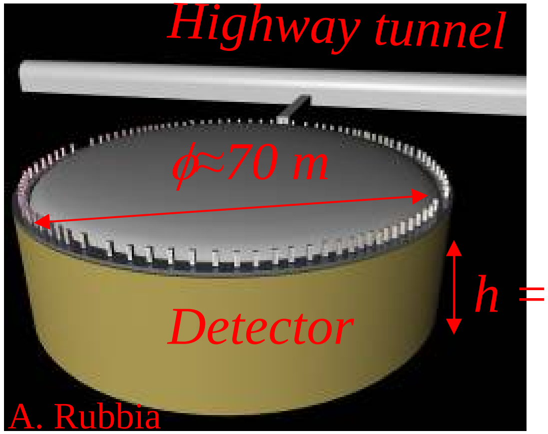



figures from G.Feldman

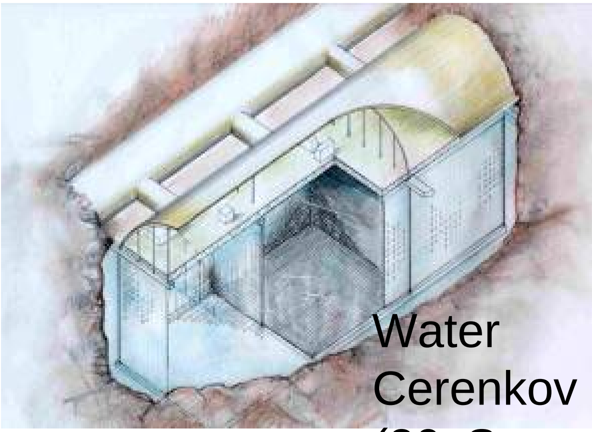
# Scenario 2: ~0.01 < $SIN^2 2\theta_{13}$ < ~0.04
# New Detectors, New Beamlines

- Need for underground lab from proton decay, Dark matter searches …
- Massive detector good destination for long-baseline neutrino beams -> Synergy!
- Study both broad and narrow band beams



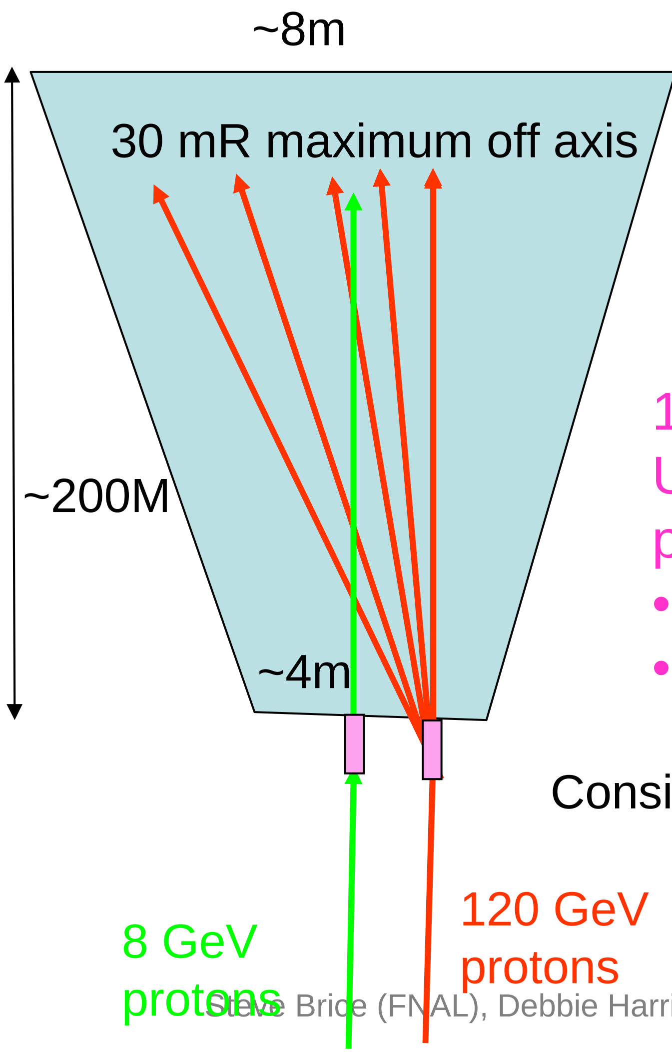




Liquid Argon TPC (100xIcarus)



Water Cerenkov (20xSuperK)

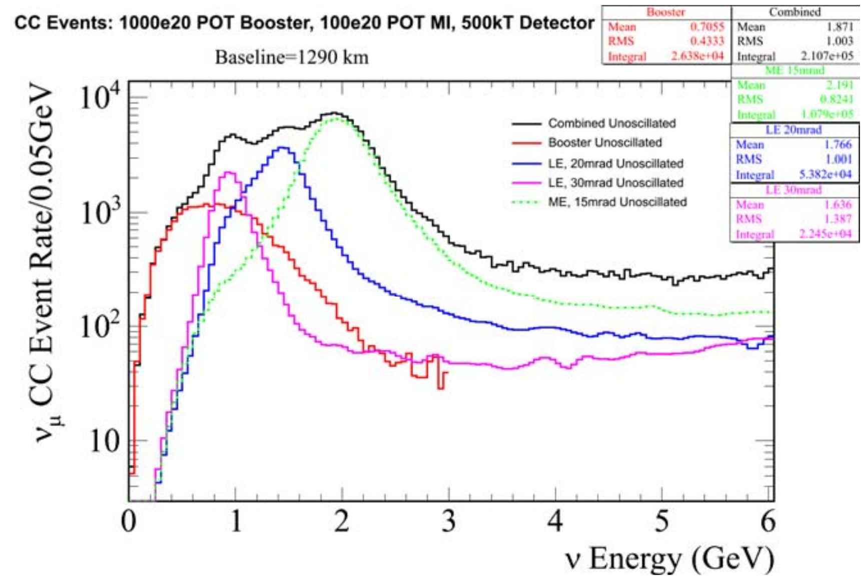
# Narrow Band Beams to Homestake

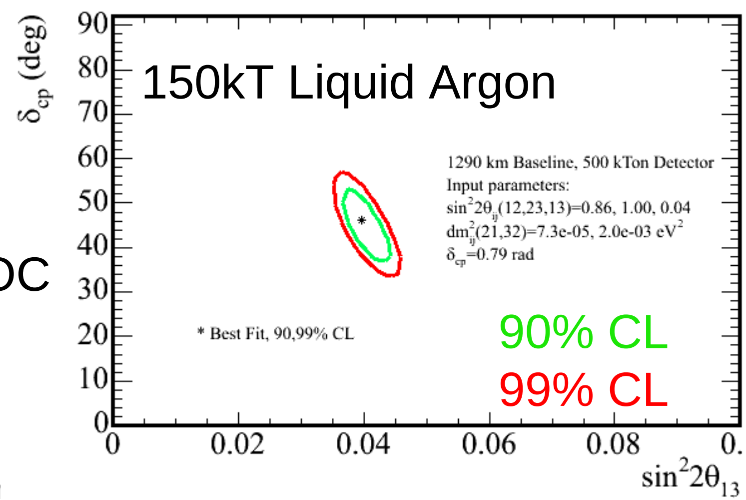



D.Michael,
C.White,
M.Messier

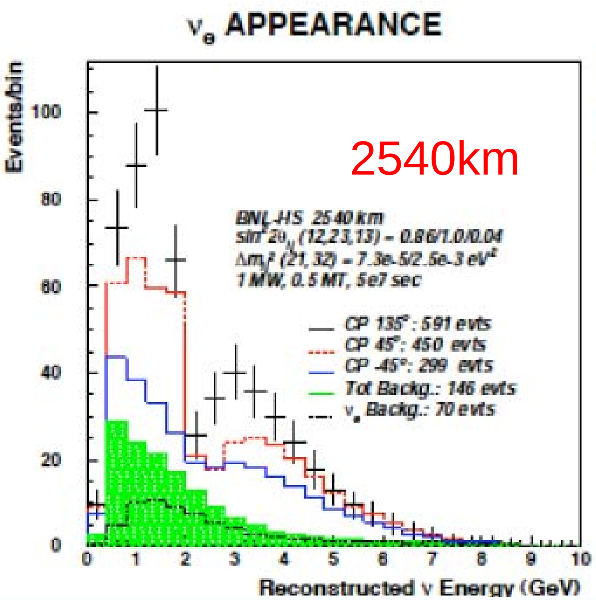
1290km
Uses all the protons from
- Booster
- Main Injector

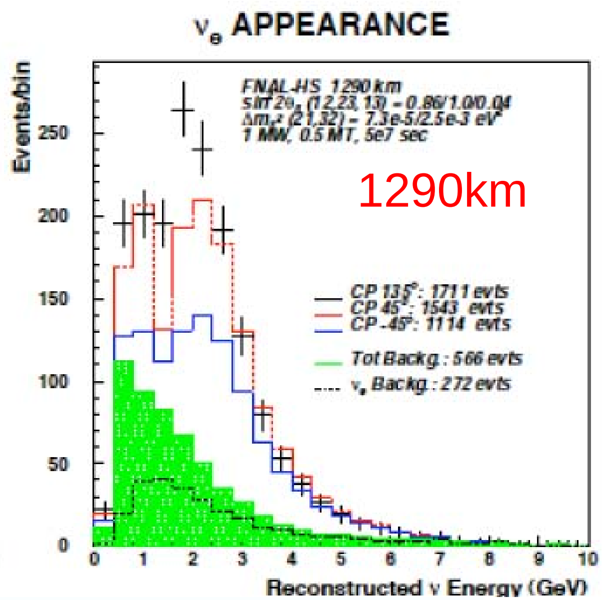
Consider LAr and $H_2OC$

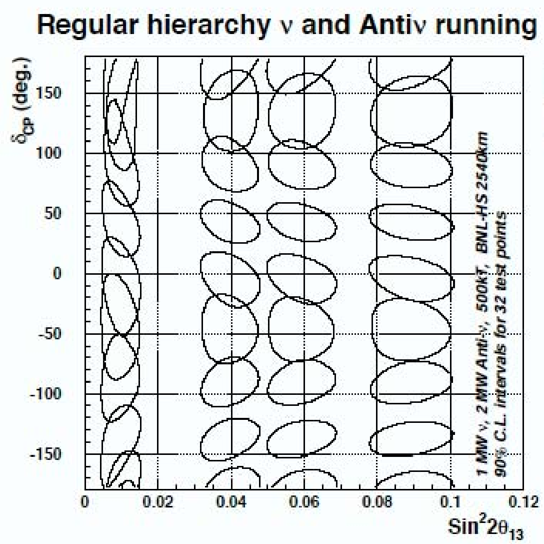


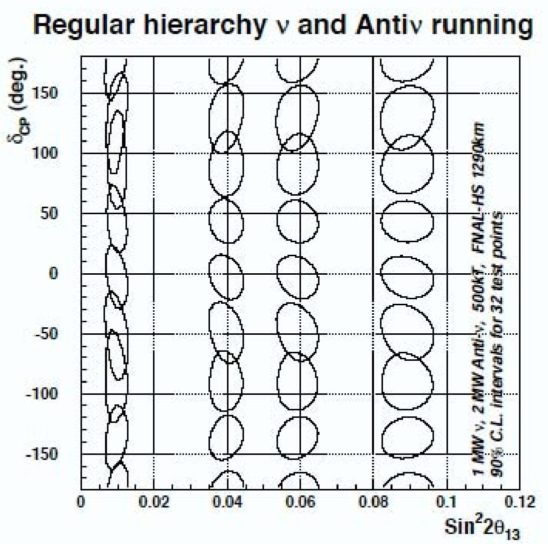



# Broad-band Beam to Homestake



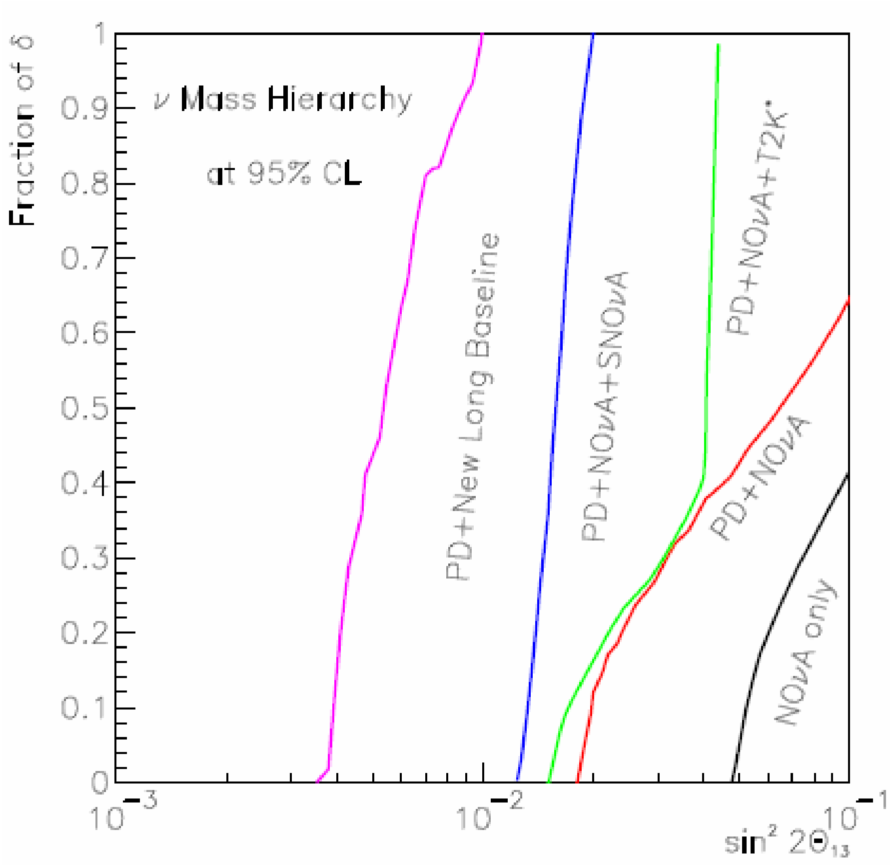



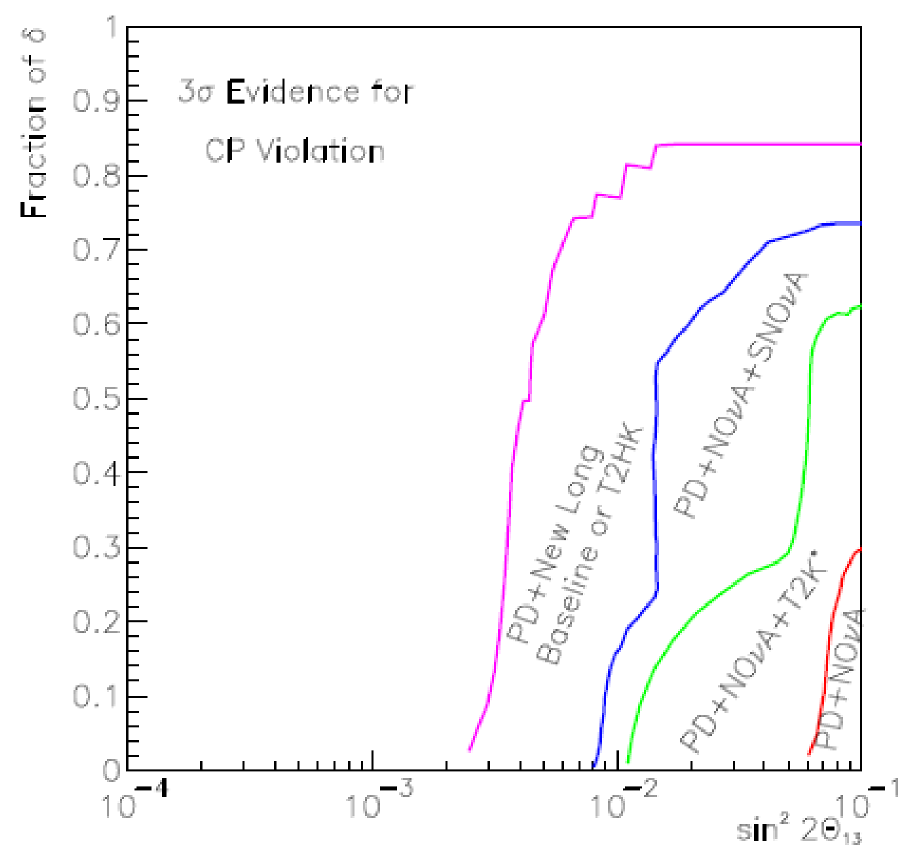

- Two-Peak Structure still visible at 1290km
- FNAL-Homestake very competitive for $\Theta_{13}$ and also $\delta_{CP}$
- BNL-Homestake has more solar oscillation contribution!
- See hep-ex/0407047 for more details

Figures from M.Diwan

# Compare short and long baselines…

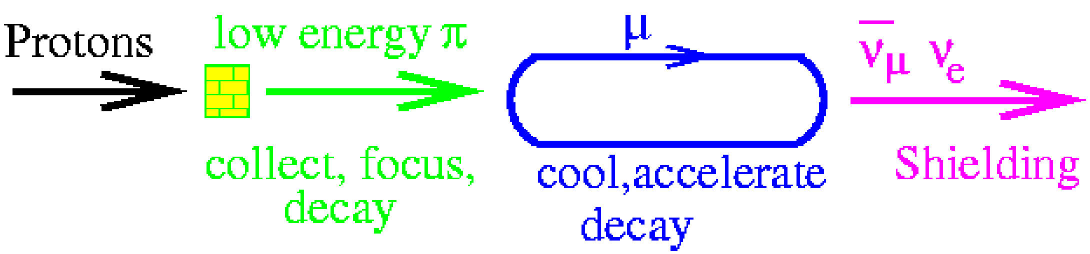
- No surprise: long baseline helps determine mass hierarchy and CP violation, and is needed to see mass hierarchy for small $\Theta_{13}$

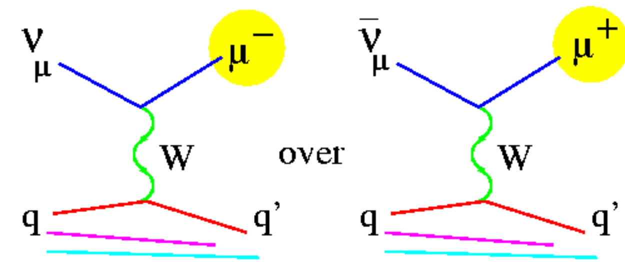


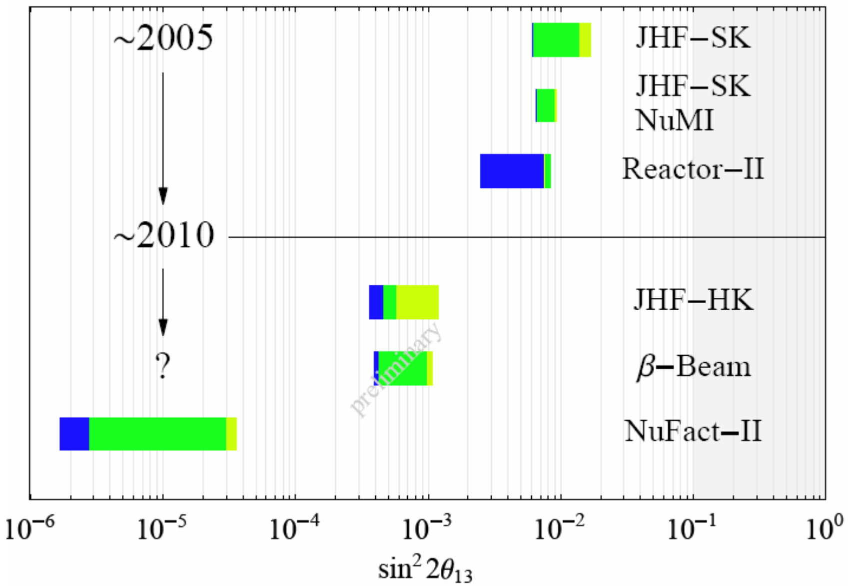



# Scenario 3: $\sin^2 2\theta_{13} < \sim 0.01$
# New Beamline Technologies

- Neutrino Factory Still has the best sensitivity for seeing a non-zero $\sin^2 2\Theta_{13}$




First step towards a Neutrino Factory:
Low Energy Protons, High Proton Power

Detector Needed for Neutrino Factory:
MINOSx10…(recall MINOS is modular!)

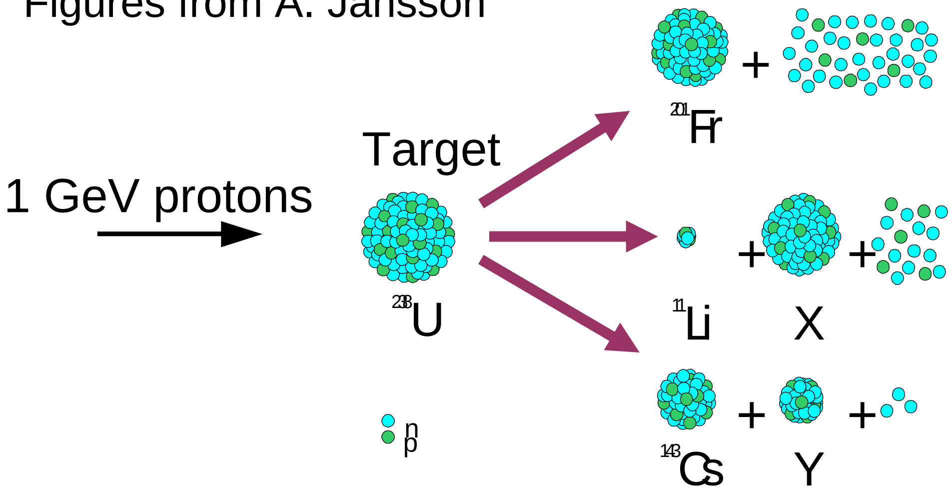
Best reach for ~3000km baseline, 50GeV ring

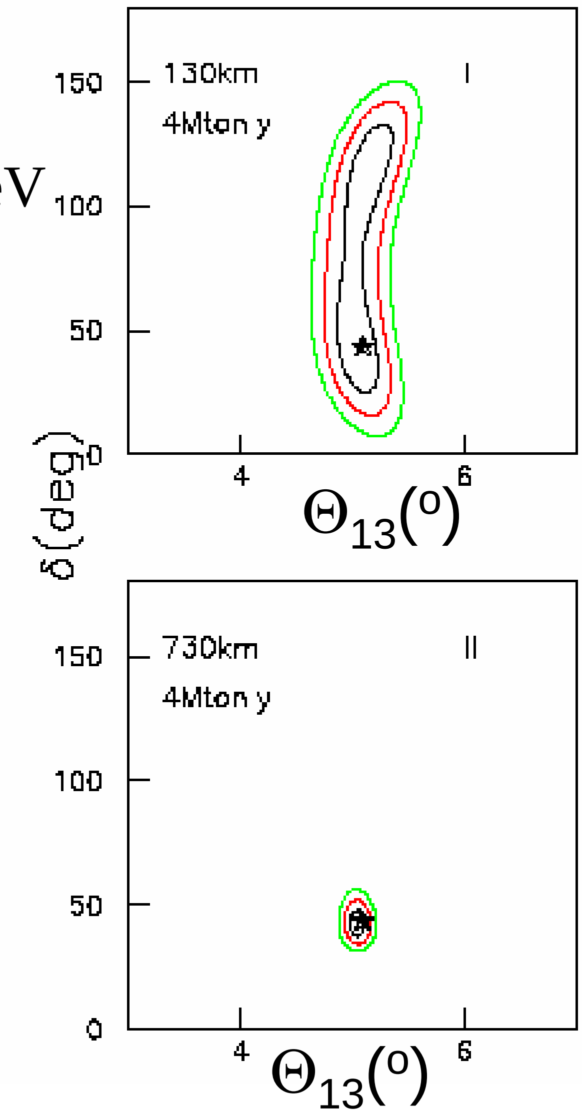
# Beta-Beams

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-}\, \overline{\nu} \qquad {}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\, e^{+}\, \nu $$

$$ \text{Average}\, E_{cms} = 1.937\ \text{MeV} \qquad \text{Average}\, E_{cms} = 1.86\ \text{MeV} $$

Figures from A. Jansson

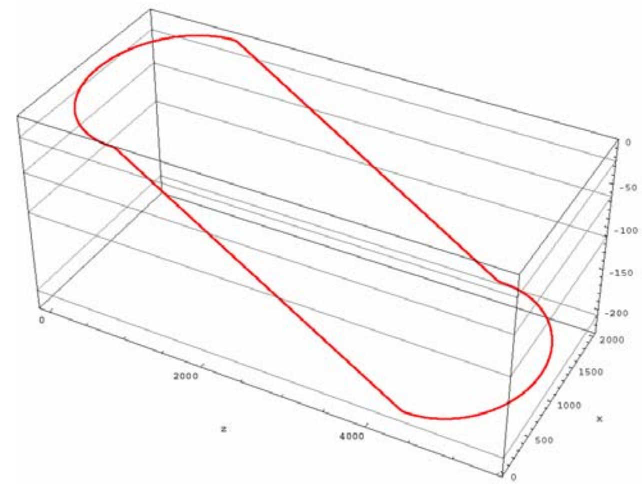



Burguet-Castell *et al*, Nucl.Phys.B695:217-240,2004.

- Use about 250kW per Ion source (for $\nu$ and $\bar{\nu}$ running simultaneously)
- Decay losses need study (quenching? Mokhov)
- About 1 $10^{13}$ ions of either type per cycle should yield an average loss power of about 1 W/m in Tevatron.

# Site Constraints of Beta-Beam at FNAL

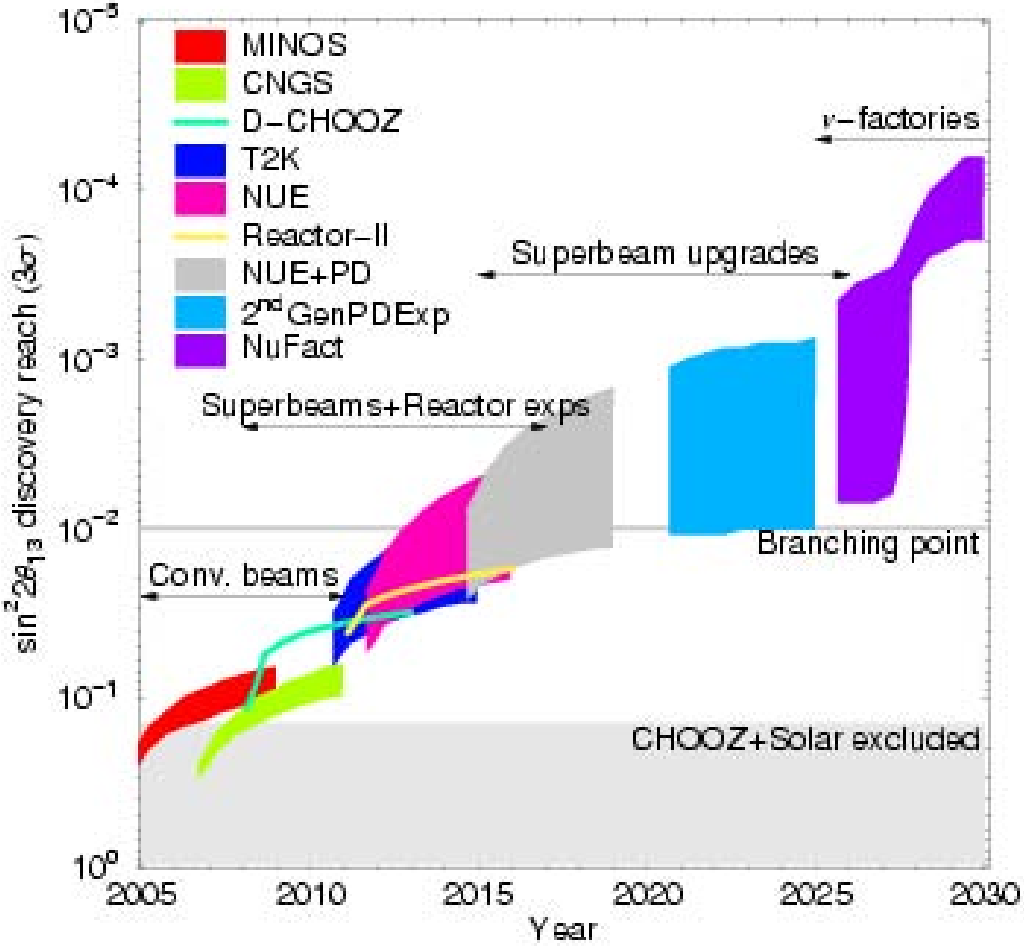
**“Stretched Tevatron“ aimed at Soudan**

**Total circumference: approximately 2 x Tevatron**

**320m elevation @ 58 mrad**

**26% of decays in Straight Section**

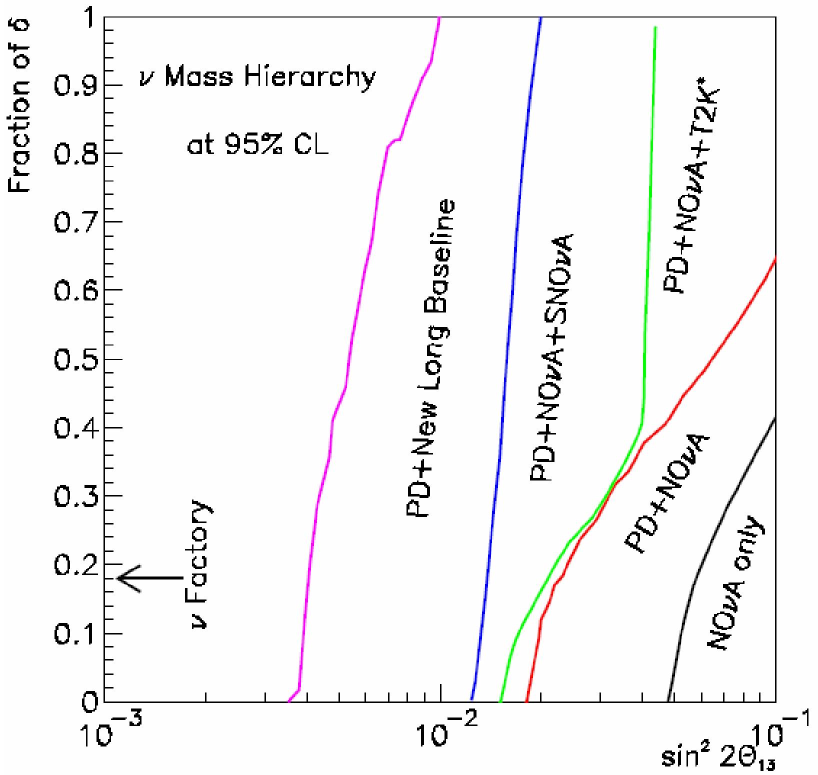
# Evolution of $\theta_{13}$ discovery limit

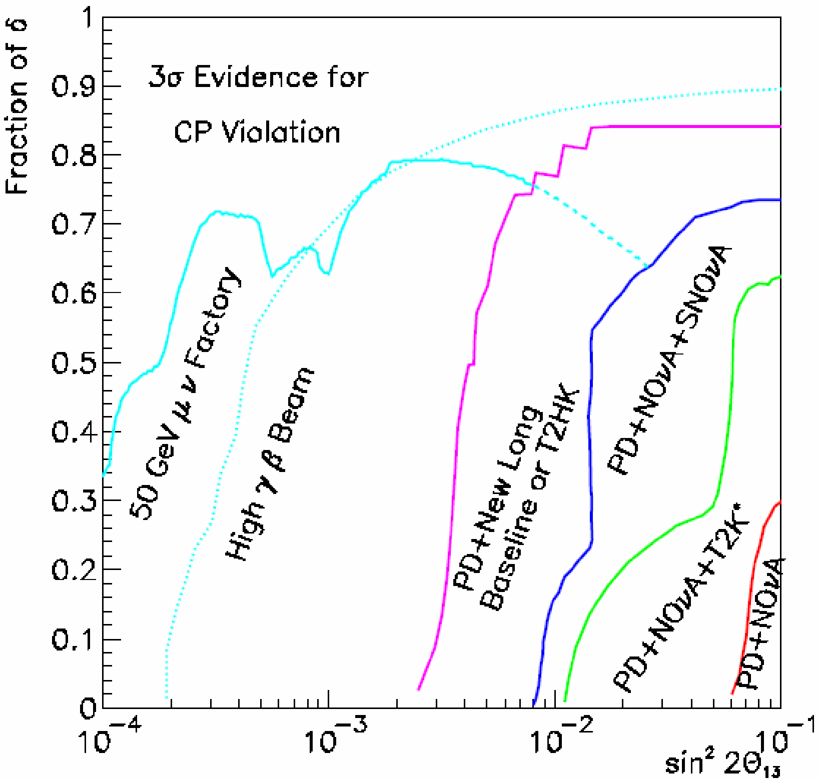



(normal mass hierarchy assumed)

# Neutrino Factory Reach in Mass Hierarchy and CP violation

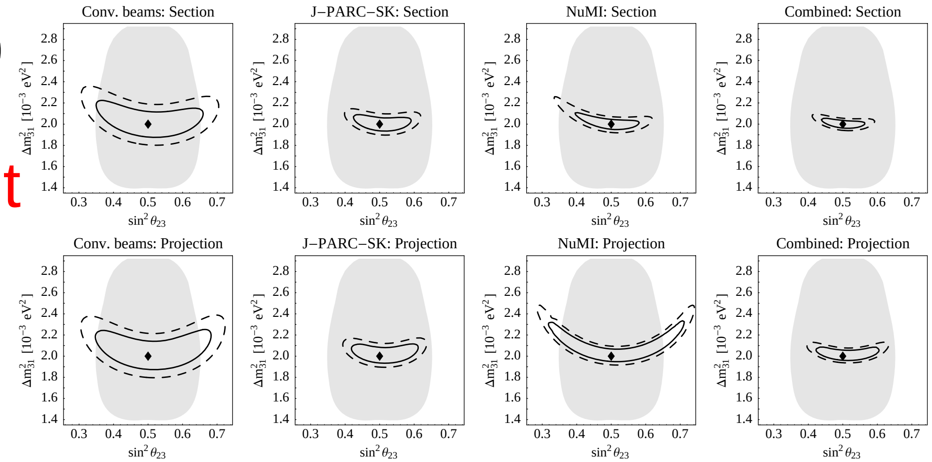
- Neutrino Factory Clearly the farthest reach, β-beam could be promising but needs more study, and a technology breakthrough to make it easier than neutrino factory

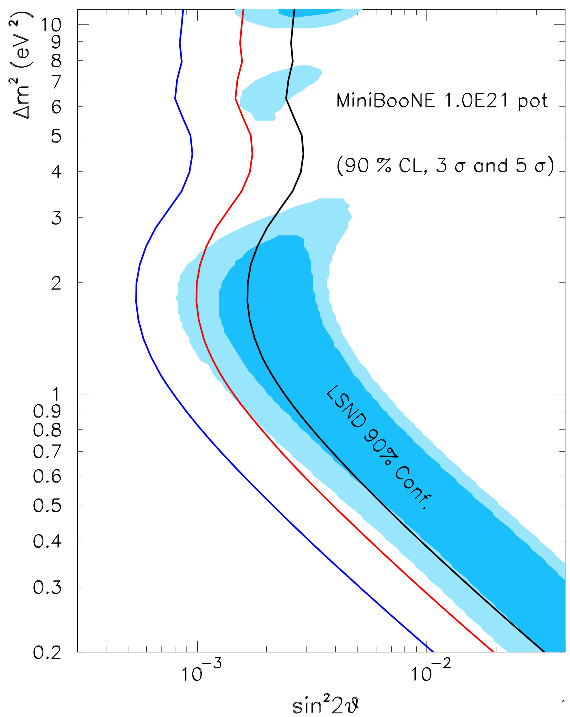


# 3 Special Cases for ν Physics prior to PD Startup

- 1) $\theta_{23}$ is still consistent with maximal




- 2) MiniBooNE confirms LSND oscillations

- 3) Something else unexpected is discovered

See full working group report for more detail!

# The Role of a Proton Driver if…
## 2) MiniBooNE Confirms LSND Oscillations

- Very exciting and rich neutrino physics
  - More than 3x3 mixing
  - Sterile neutrinos
- A wide suite of measurements needed to understand the new landscape
- Short baseline (~1km) measurement become as important of Long Baseline (~800km)
- Both short AND long baseline experiments needed (and others!!)

# Summary

- The only way to get at CP violation and the mass hierarchy is through accelerator-based oscillation measurements
- Fermilab Proton Driver provides a powerful tool to get to this new physics
- What baseline and what detector we match to it depend on what we learn in the next 5 years…
- “But wait, there’s more” full proton driver report also covers the physics you could do in other arenas:
  - Neutrino Scattering (i.e. H2 and D2 targets)
  - Kaons
  - Muons
  - Antiprotons
  - Neutrons
- Full report should be on hep-ph soon…
- See http://protondriver.fnal.gov/ for more!