NuMI Off-Axis ν_e Appearance

The NOνA Experiment
Fermilab P929
http://www-nova.fnal.gov

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The NOνA (FNAL P929) Collaboration

160 authors from 34 institutions
US - UK - Greece - Brazil - Canada

Proposal to Build an Off-Axis Detector
to Study $\nu_\mu - \nu_e$ Oscillations in the NuMI Beamline

NOνA

NuMI Off-Axis ν_e Appearance Experiment

(P929)

March 15, 2004

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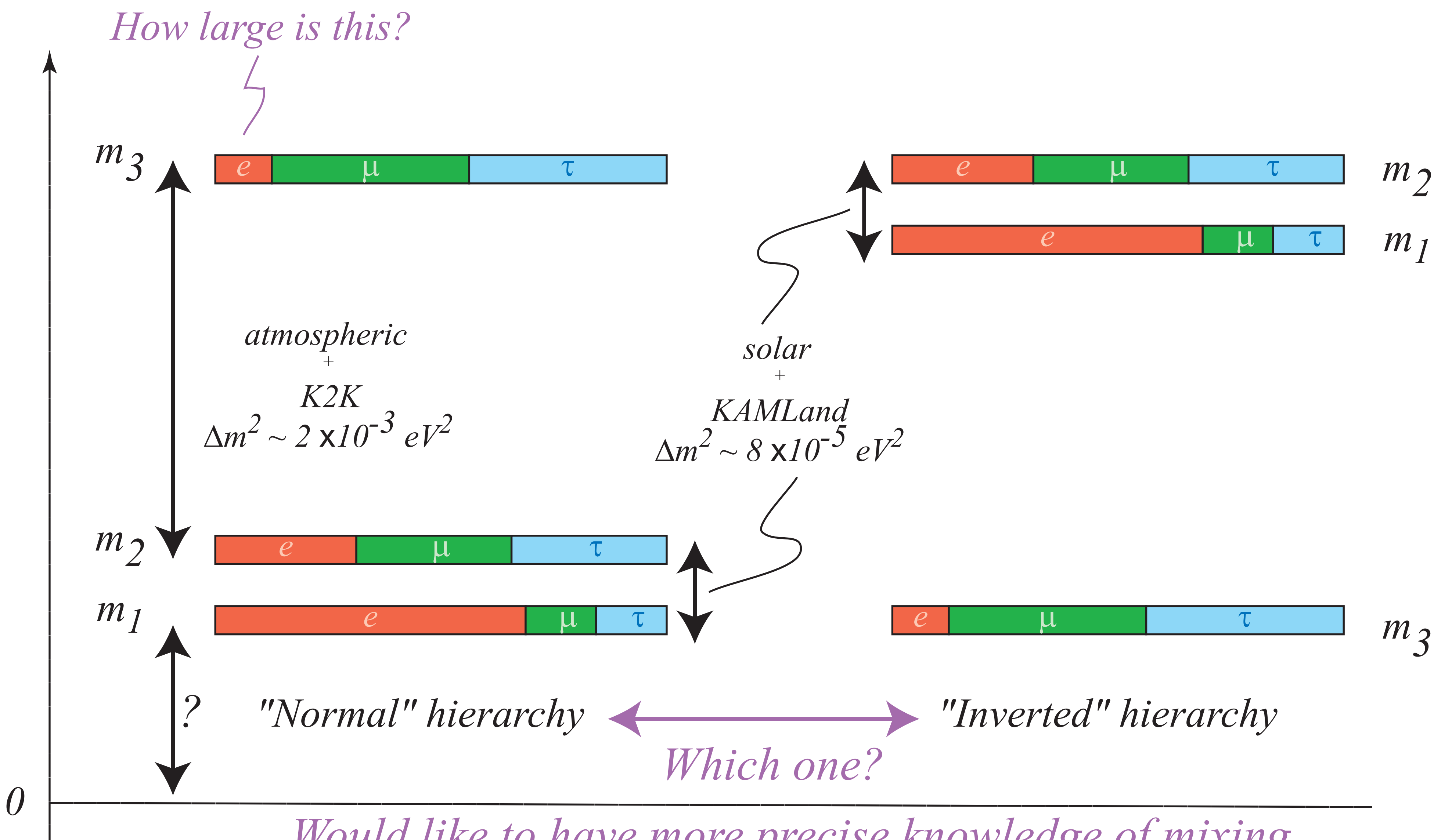
What we know, what we don't know...



Would like to have more precise knowledge of mixing

Do ν_e's participate in oscillations at atmospheric scale?

Is $\Delta m_{23}^2 > 0$ or < 0?

Is CP violated?

Goals of the NOvA Experiment

[1] Sensitivity to $\sin^2(2\theta_{13})$ factor 10 below MINOS sensitivity, ie. down to ~0.01

[2] $\sin^2(2\theta_{23})$ measurement to 2% accuracy

[3] Resolve or contribute to resolution of mass hierarchy via matter effect *(unique contribution)*

[4] Begin to study CP violation in neutrino sector

How will NOvA meet its goals?

[1] Reduce NC background to ν_e appearance search by going off the NuMI beam axis for a narrow band beam

[2] Increase detector mass ~factor of 9 over MINOS while reducing cost/kilo-ton by factor of 3

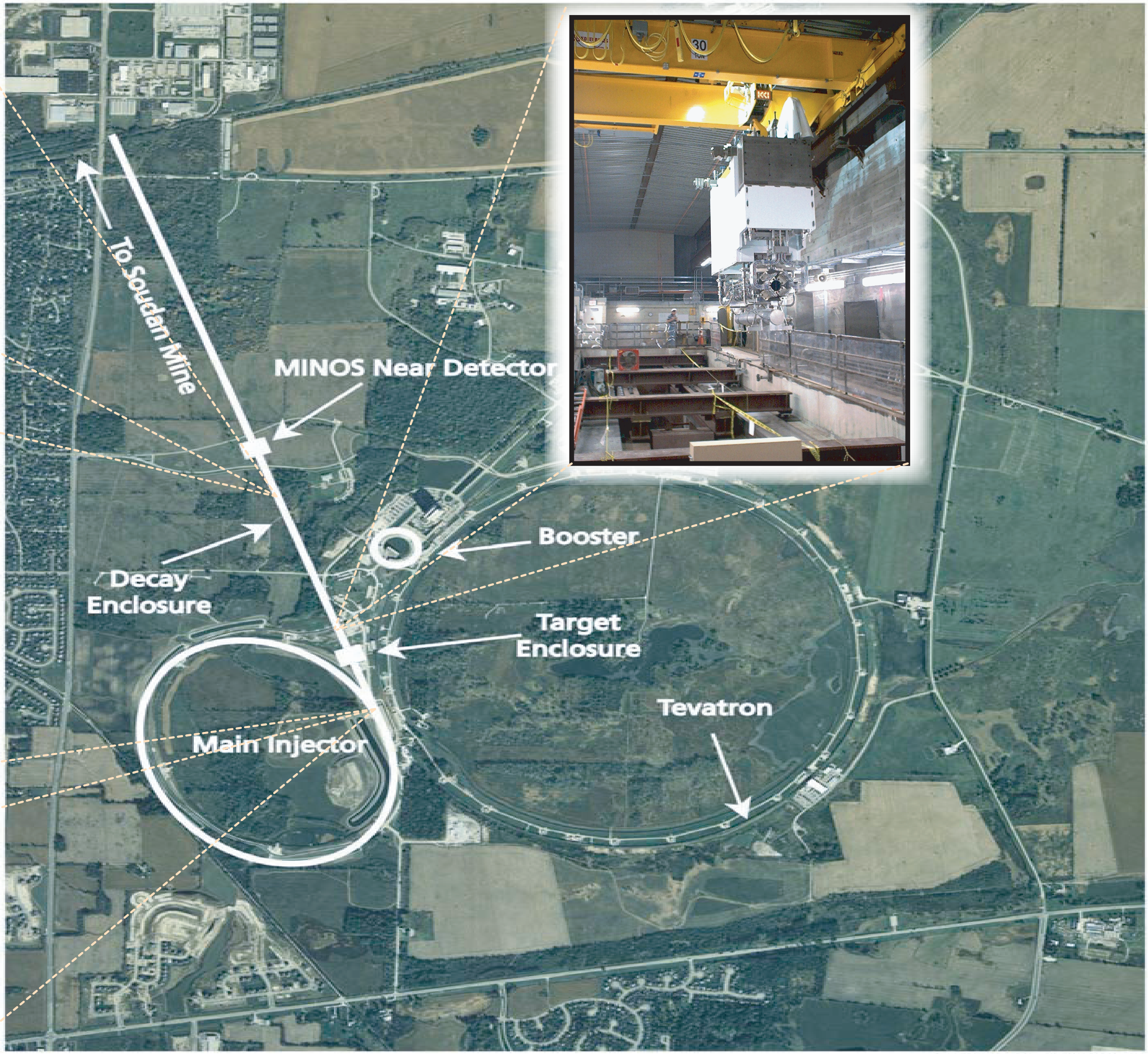
[3] Sandwich detector sampling at 1/3 X_0 *(compare to 1.5 in MINOS)*

- electrons showers seen as "fuzzy" tracks w/ 1-4 hits/plane/view
- allow separation of γ's from π^0 decays
- good energy resolution to focus on signal energy region

[4] Choose long baseline to enhance matter effects

Neutrinos At the Main Injector (NuMI)

NuMI beam
set to
commision
start of 2005



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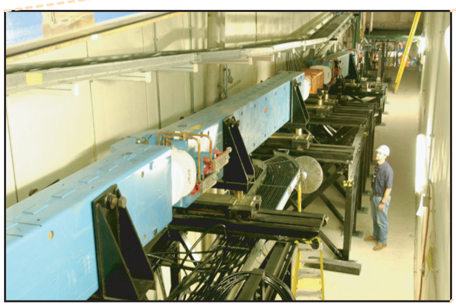
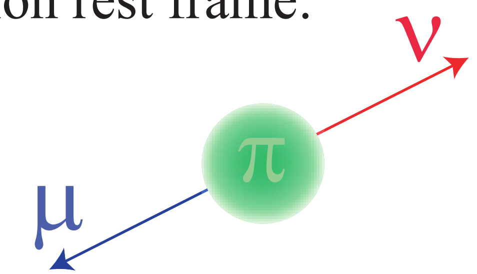


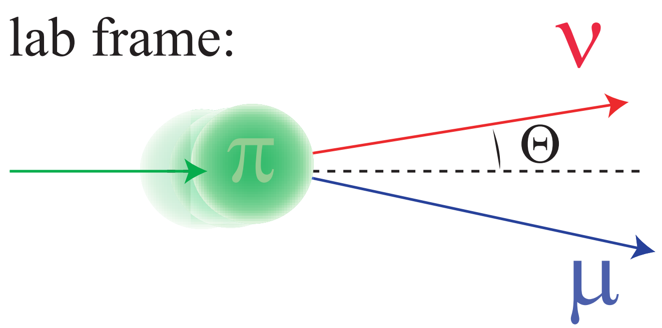
Off-Axis Neutrino Beams

In pion rest frame:

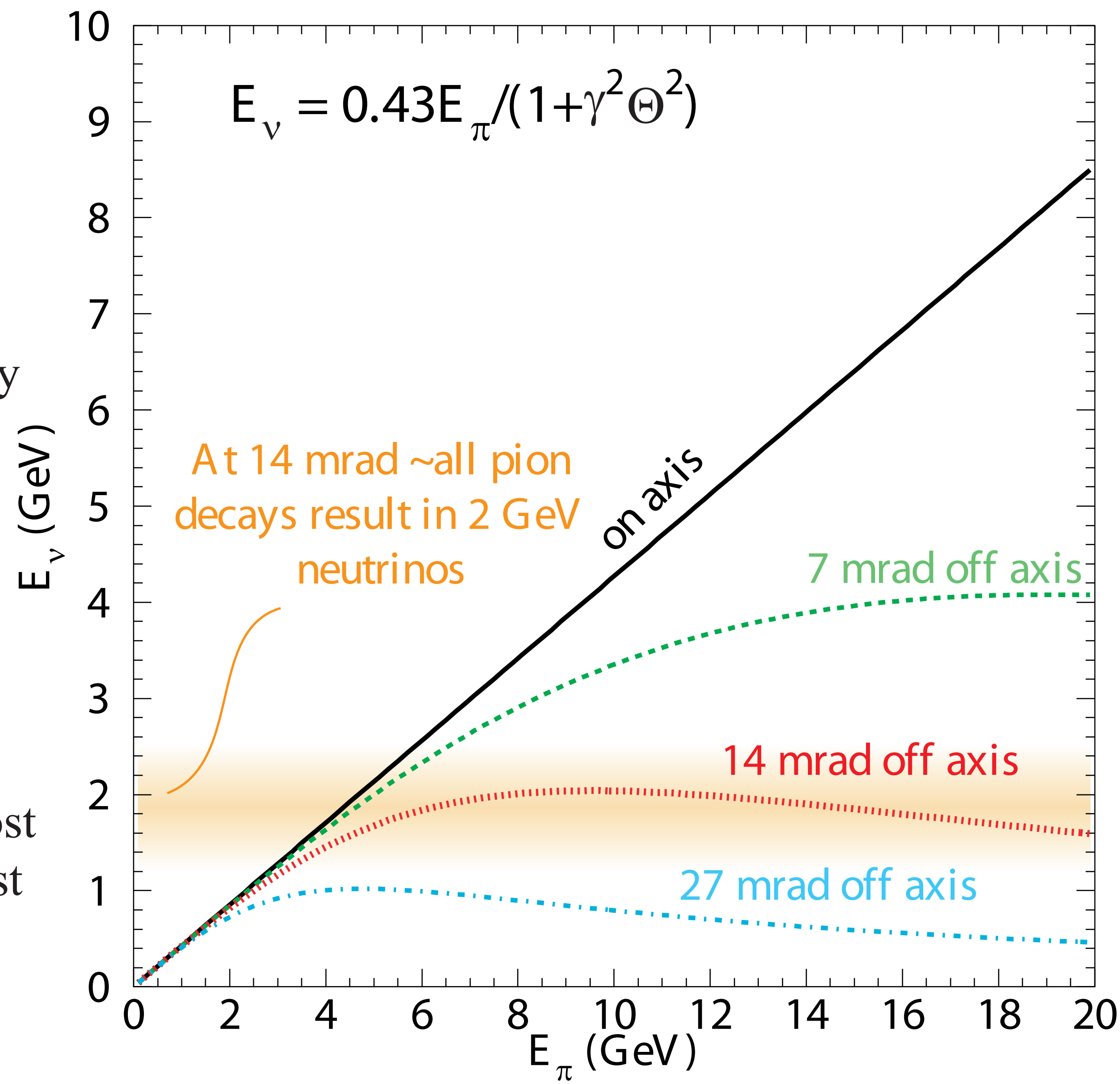


Neutrino and muon energy completely determined by energy conservation

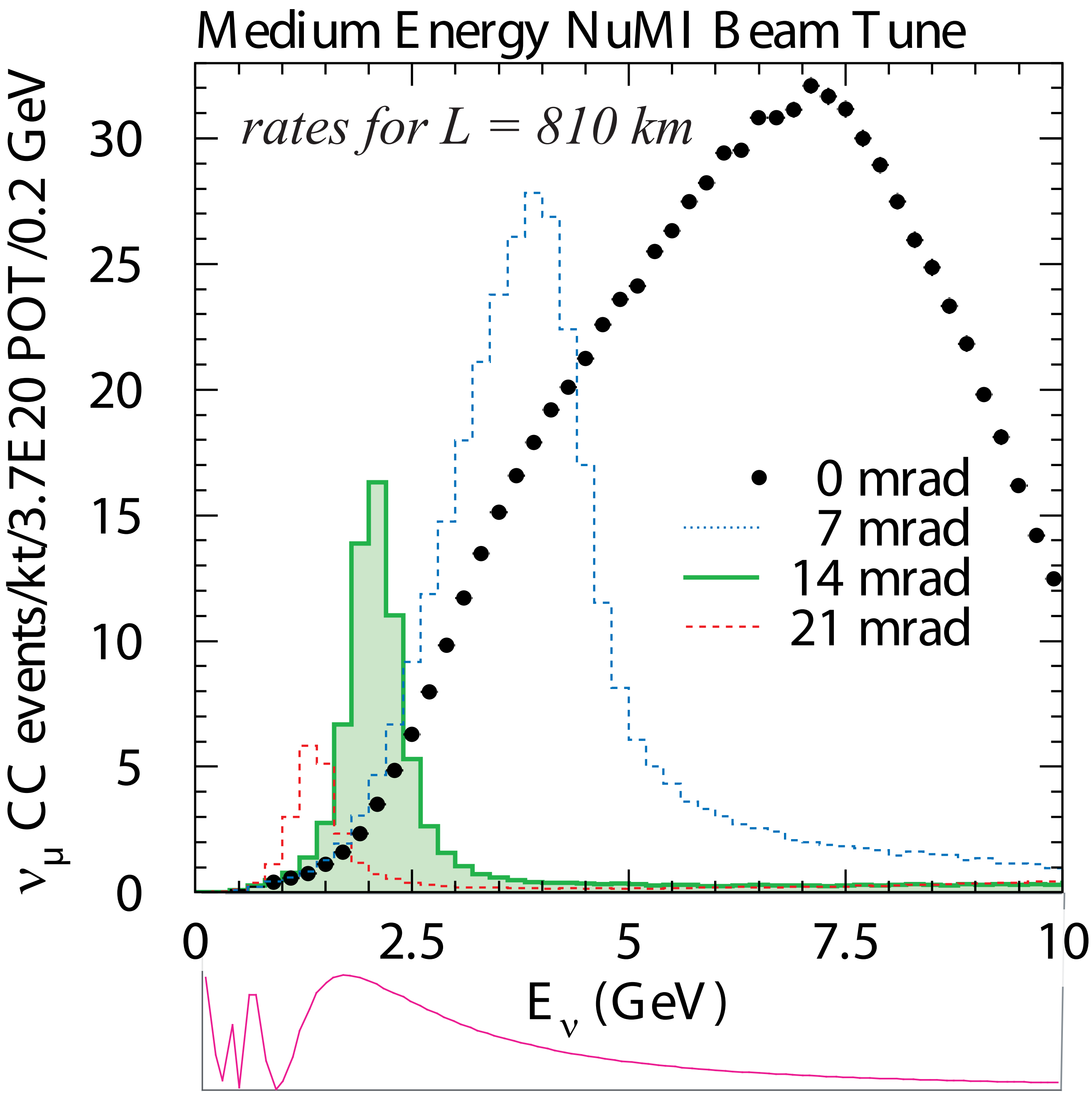
In lab frame:



Neutrino energy depends on boost and angle between neutrino boost direction



Neutrino spectra off the NuMI axis



Using NuMI ME tune beam at 14 mrad peaks at ~2 GeV and has ~20% width

High energy flux suppressed

Sits just above oscillation maximum

$\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$

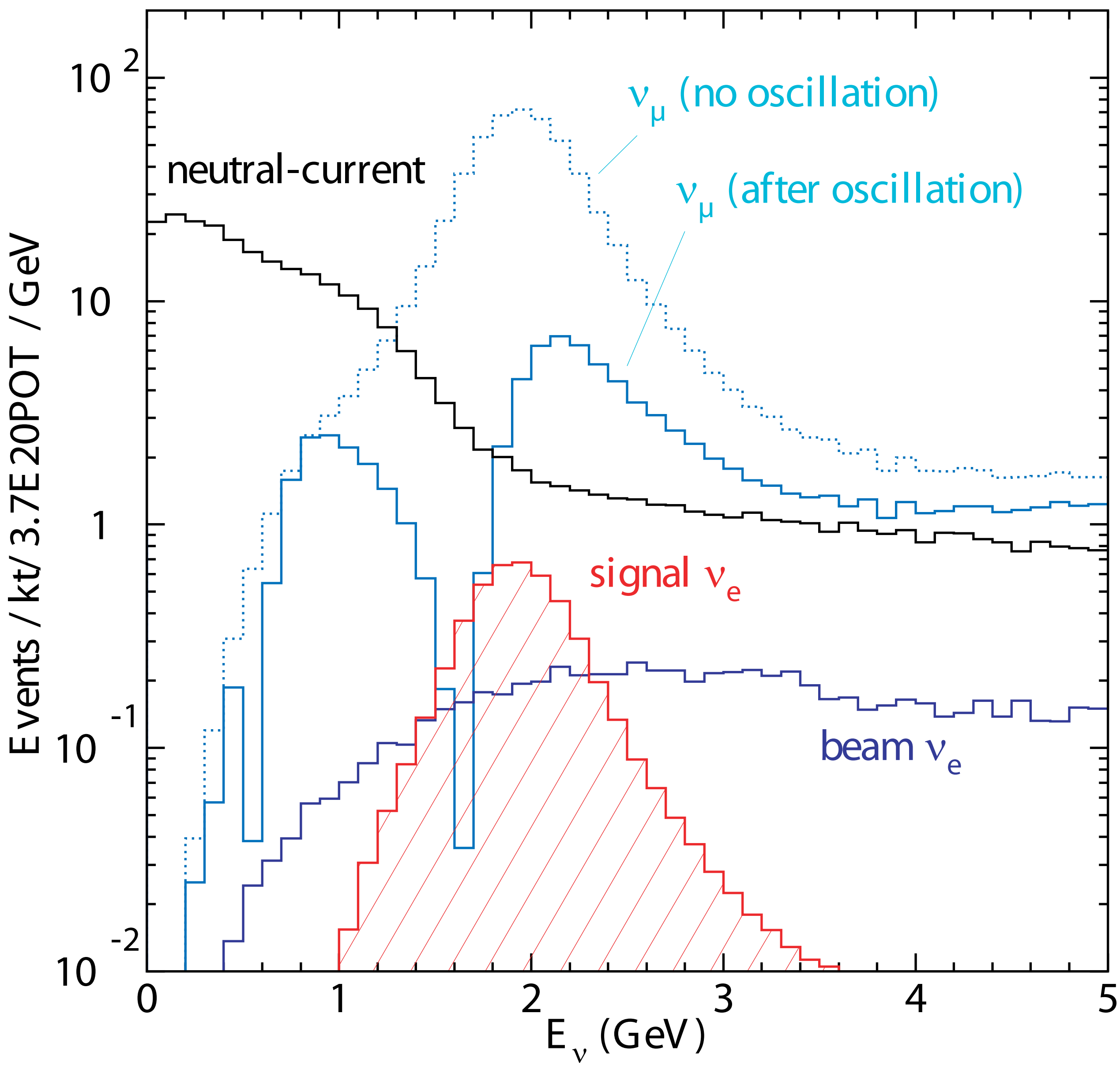
Event rates off NuMI beam axis

Event rates for:

$L = 810$ km, $T = 12$ km

$\Delta m^2_{23}=2.5\text{x}10^{-3}$ eV^2

$\sin^2 2\theta_{23}=1$, $\sin^2 2\theta_{13}=0.01$



Sets goals for detector

Most ν_μ oscillate away.

☞ need only 50:1 rejection of ν_μ CC *(Easy!)*

Need ~> 100:1 NC rejection

☞ fine grained, low density detector

Good energy resolution

☞ reject beam ν_e

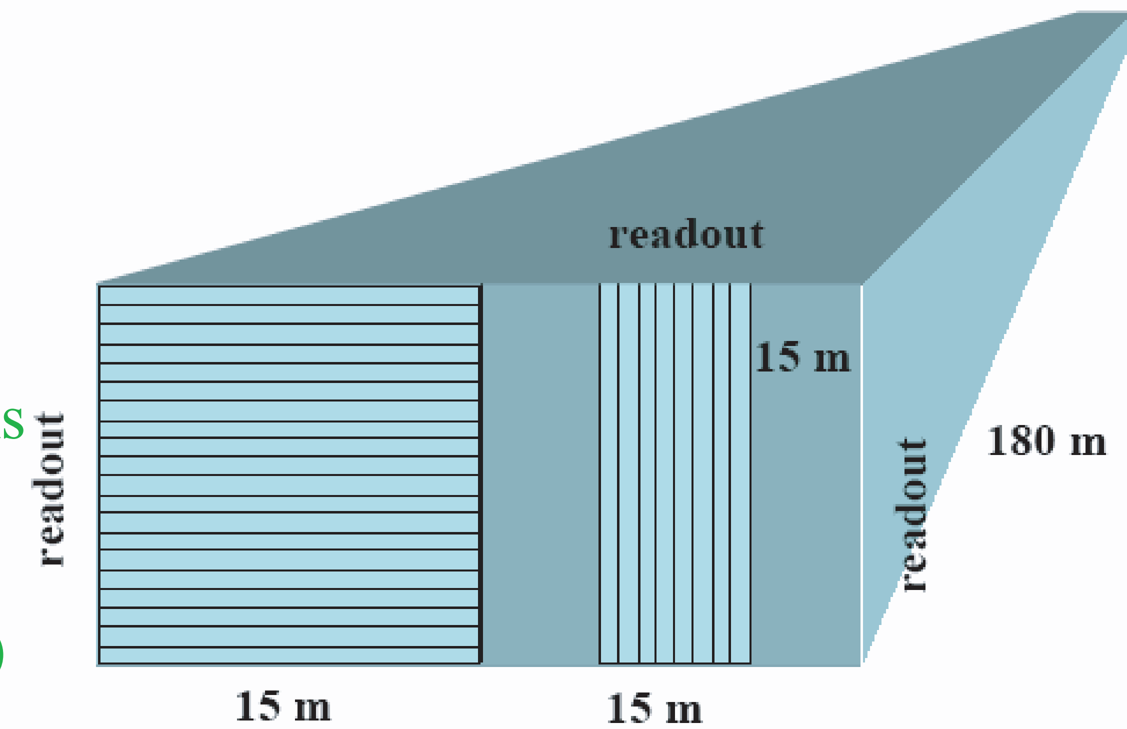
Baseline detector design

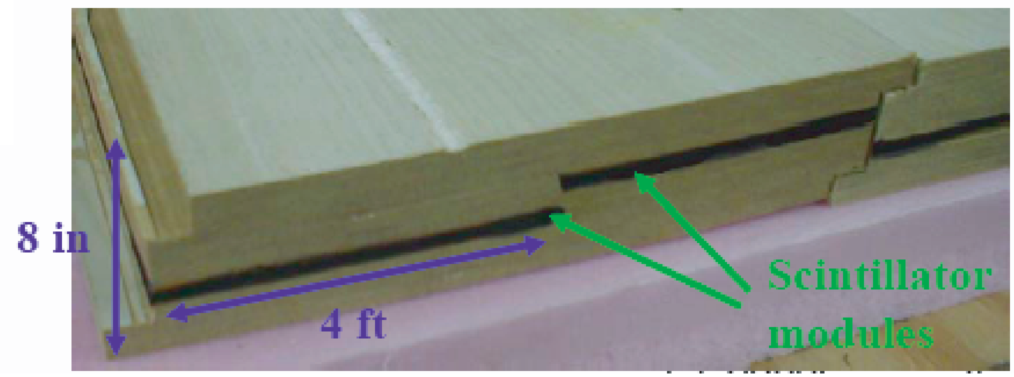
50.7 kilo-ton total mass
  43.8 kilo-ton passive
    6.9 kilo-ton active (14%)

Liquid scintillator contained in
1.2 m x 3 cm x 1.4 m PVC extrusions
  30 cells per extrusion
  24 extrusions per plane
  750 planes (alternating x/y readout)
    = 18,000 extrusions
    = 540,000 channels

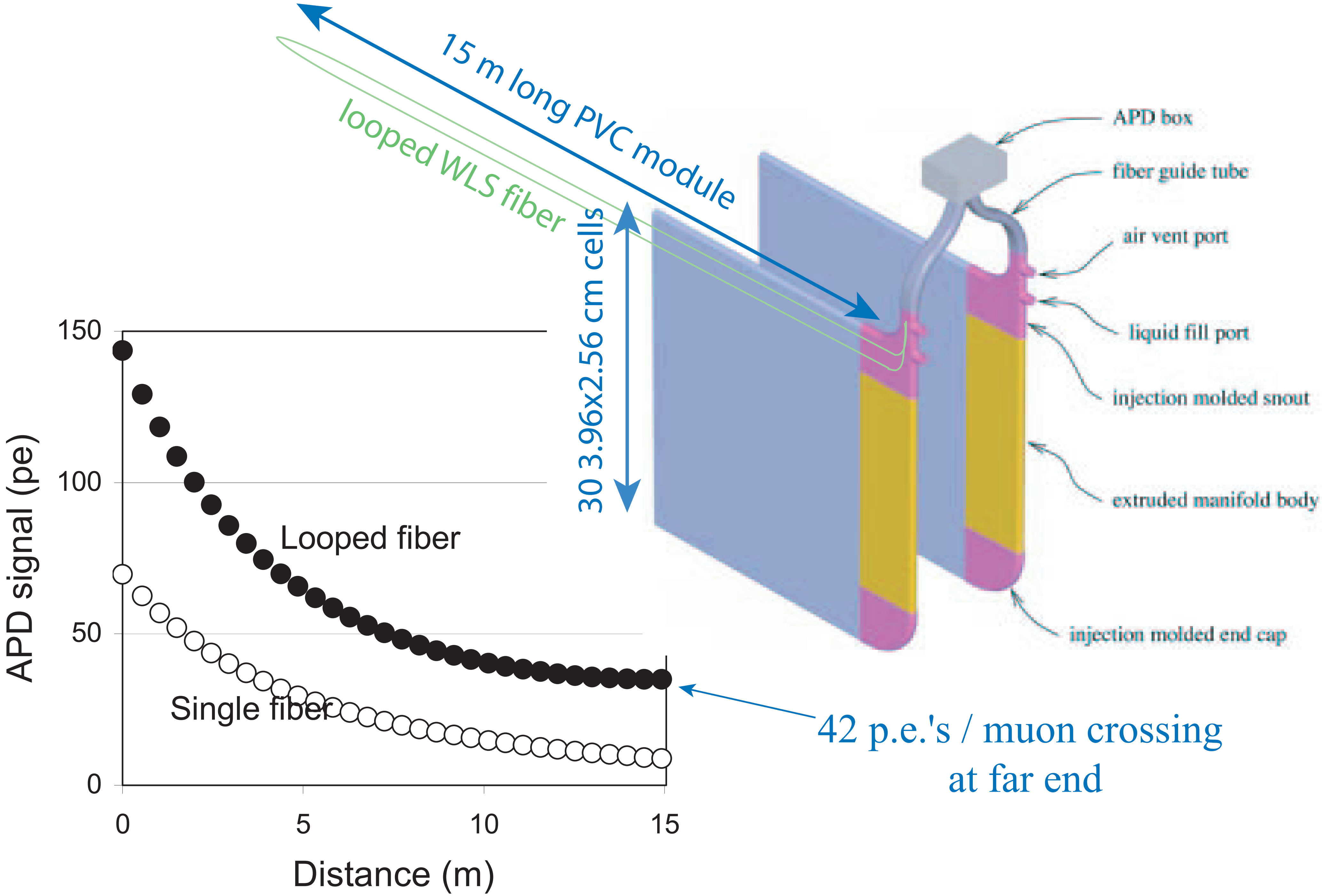
Looped WLS fiber to APD readout

Absorber:
  20 cm particle board/plane
  1/3 X_0 per plane



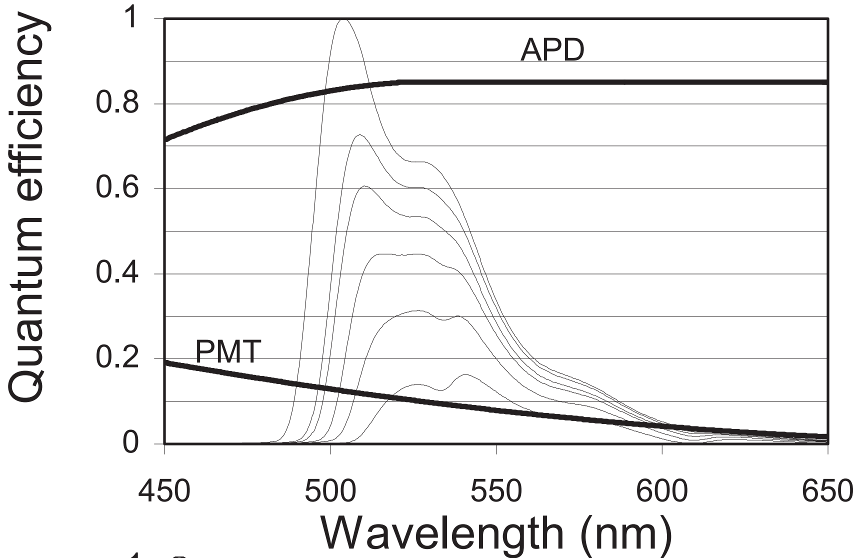


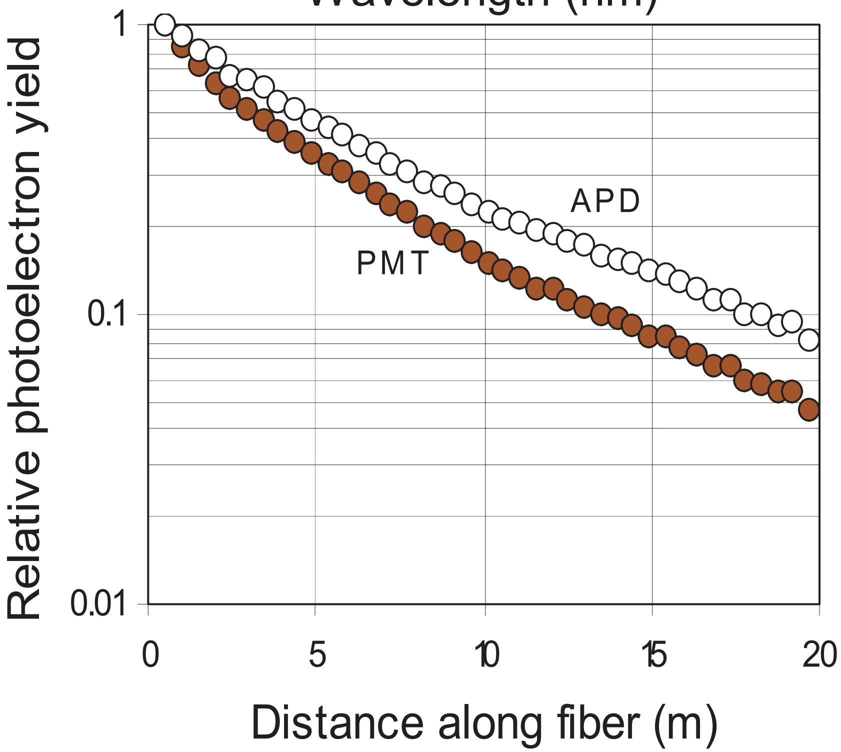
Module Design



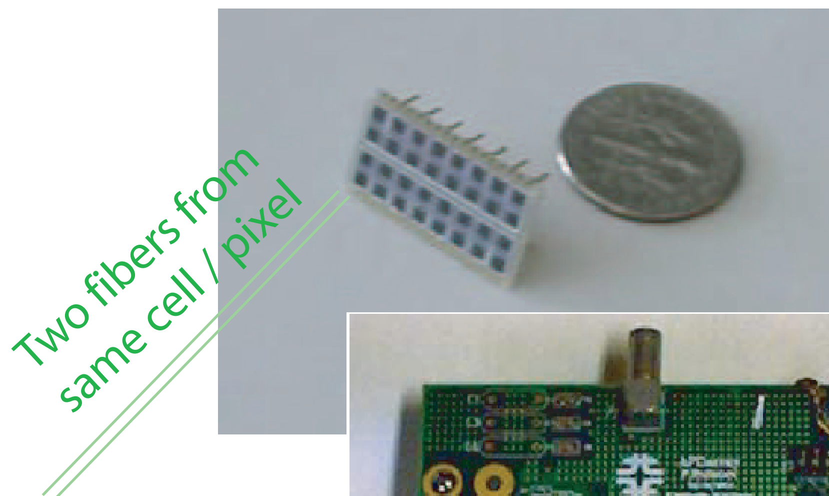
42 p.e.'s / muon crossing at far end

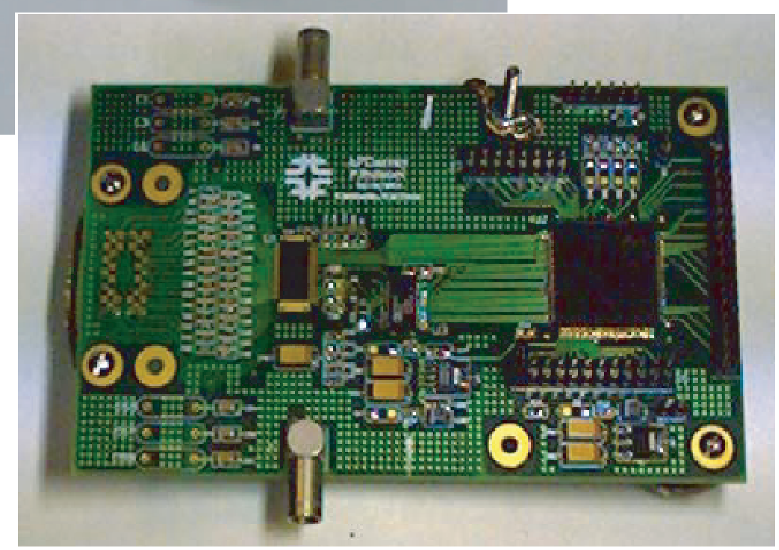
Avalanche Photo Diode (APD) Readout





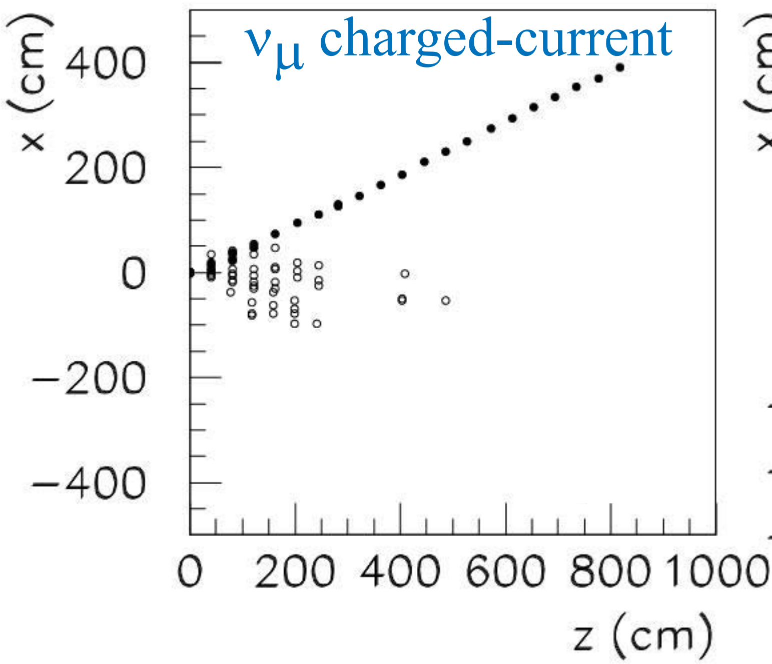
- 85% QE
- x100 gain (operate at -15^{o} C)
- Long wavelength sensitivity is advantage for long fibers (x2 at far end)
- Low cost: $12/chan FEE+Trigger+DAQ base cost

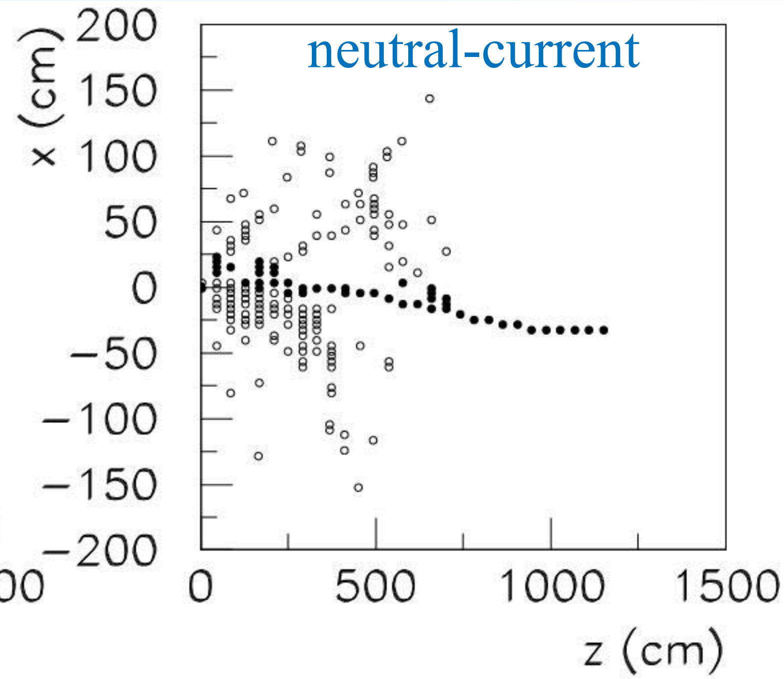




Prototype readout board

Baseline detector event displays

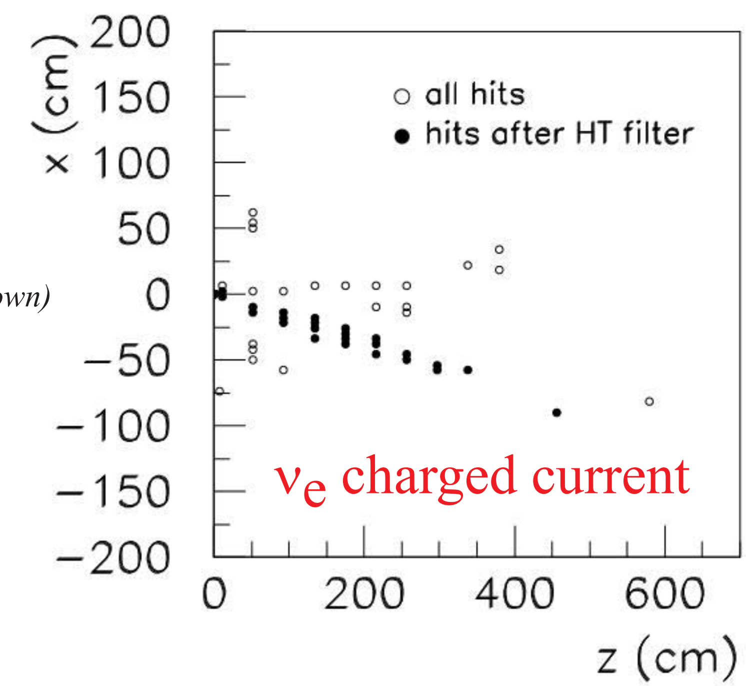




Event selection

- cuts on #planes and total pulse height
- at least 3 hits on a track
- 75% of hits in track
- hits/plane > 1.5
- $\cos(\theta_{beam})>0.8$
- likelihood analysis of event shape variables

(1 of 2 detector views shown)



18% signal efficiency

ν_μ CC rejection 1600:1

NC rejection 600:1

beam ν_e rejection 12:1

~160 signal events

~ 44 background events

FOM=24

$\sin^2 2\theta_{23}=1$, $\sin^2 2\theta_{13}=0.1$, $\Delta m^2=2.5\text{x}10^{-3}$ eV^2

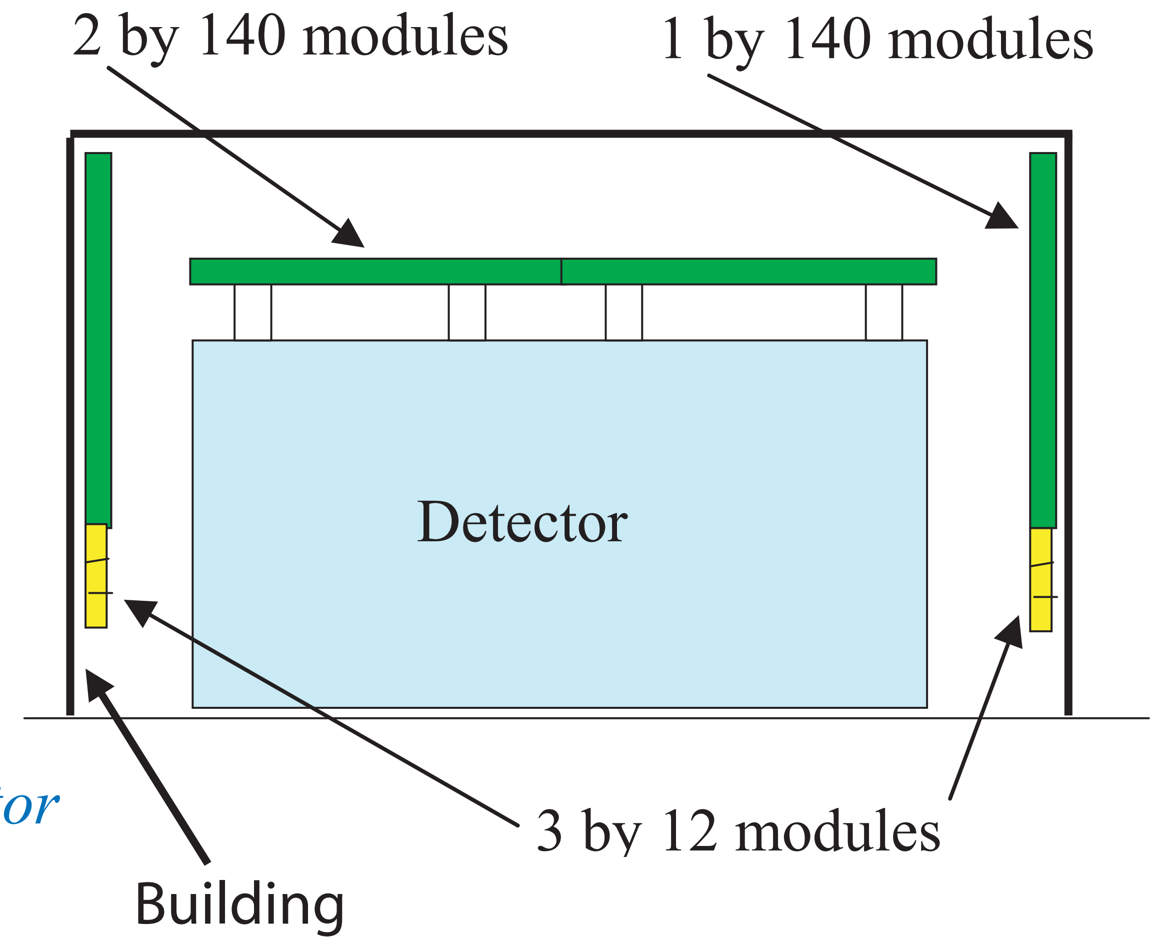
50kt x 5 years x 4e20 POT/year

Life on the surface: Active shield

Low duty cycle:
10 us spill every 2 s (1/200,000)
"live" only 100 s per year!

1.3×10^8 m/year total in spill
0.65 μ/500 ns DAQ gate over
5000 m^2 detector area

No passive shield required
Plan to test with prototype detector



We are planning an active veto shield in baseline design
In totally active detector option no shield is required

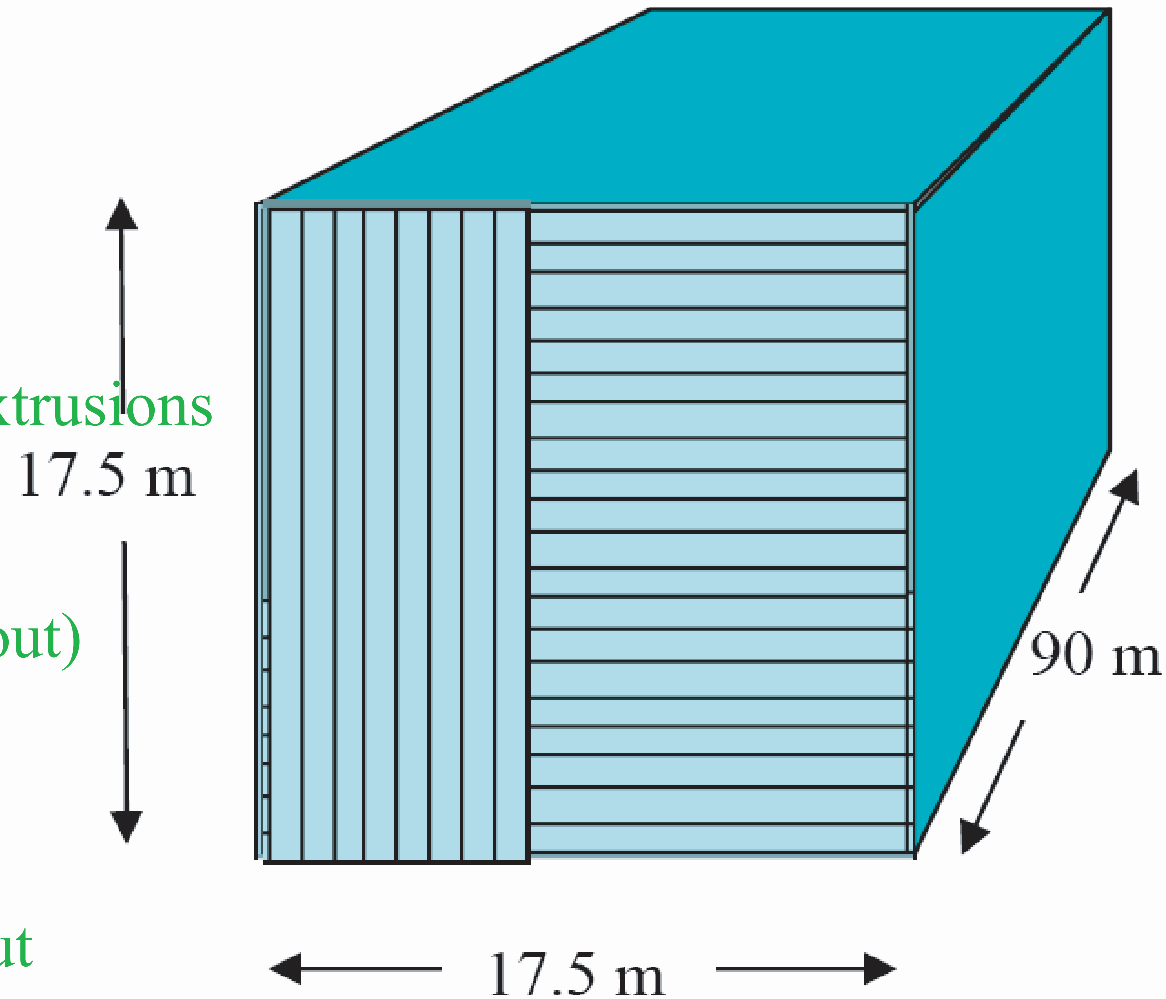
Totally Active Scintillator Detector (TASD)

25 kilo-ton total mass
 4 kilo-ton passive
21 kilo-ton active (85%)

Liquid scintillator contained in
1.28 m x 4.9 cm x 17.5 m PVC extrusions
32 cells per extrusion
24 extrusions per plane
1845 planes (alternating x/y readout)
= 25,830 extrusions
= 826,560 channels

Looped WLS fiber to APD readout

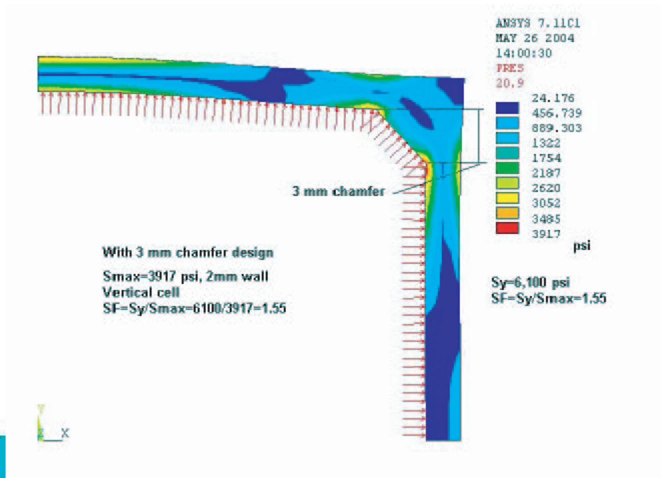
No absorber



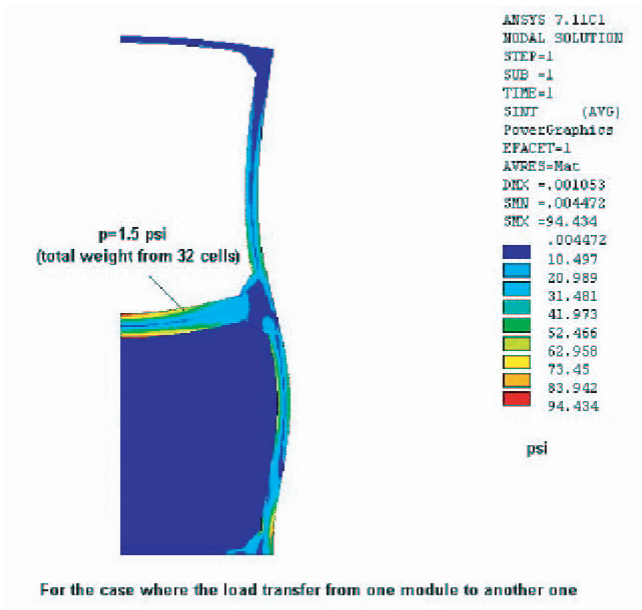
Engineering for TASD

Engineering of TASD is somewhat more challenging than baseline detector

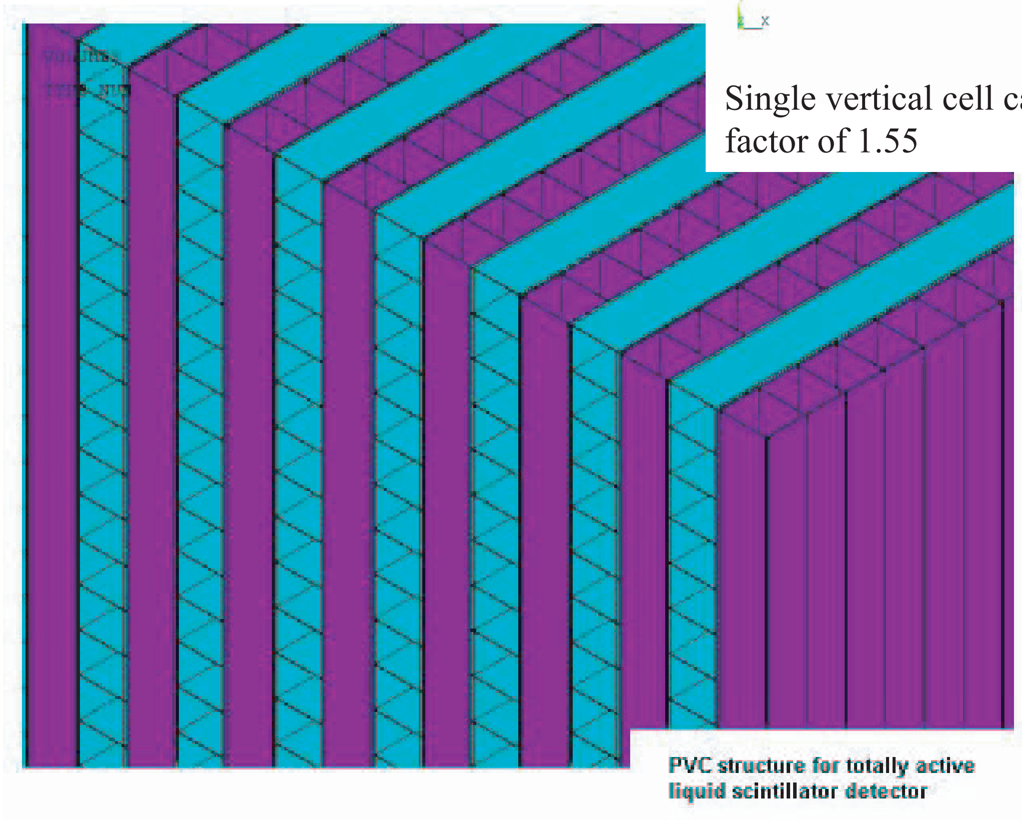
Studies of "free standing" cells



Single vertical cell can hold load with safety factor of 1.55



Horizontal cells can hold load with safety factor of 3.3

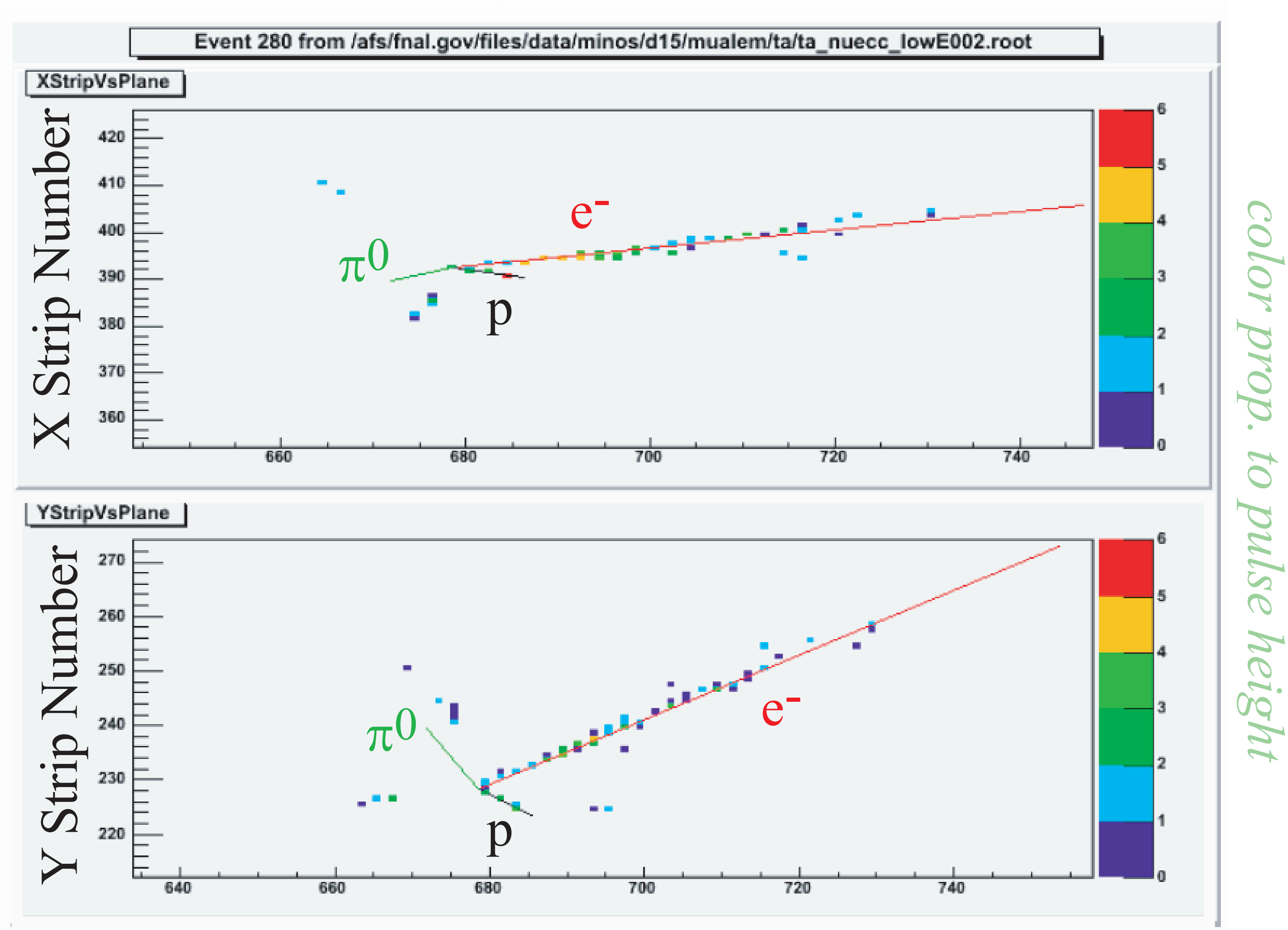


Forming laminate of adjacent x/y planes (using adhesive, ultra-sonic welding, PVC welding, ...) gives safety factor of 20

Typical TASD Event

$$\nu_e + n \rightarrow p + e^- + \pi^0$$

$$E_\nu = 1.65\ GeV$$



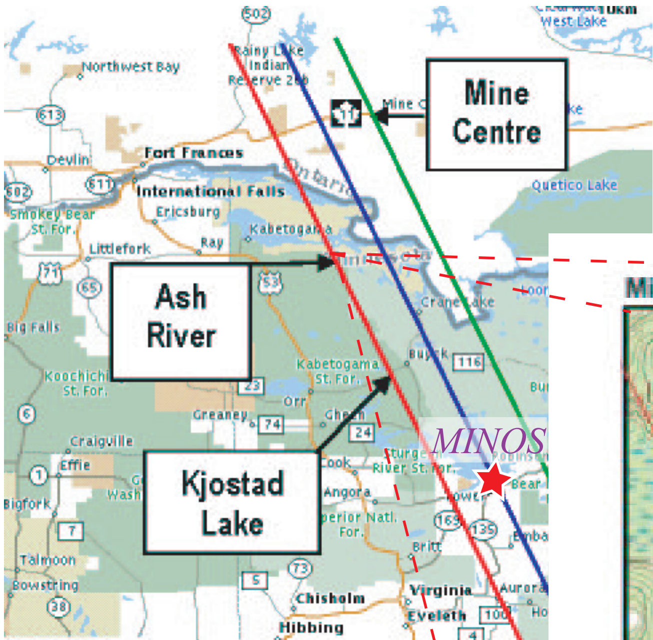
Plane Number

Signal efficiency
32% (18% baseline)

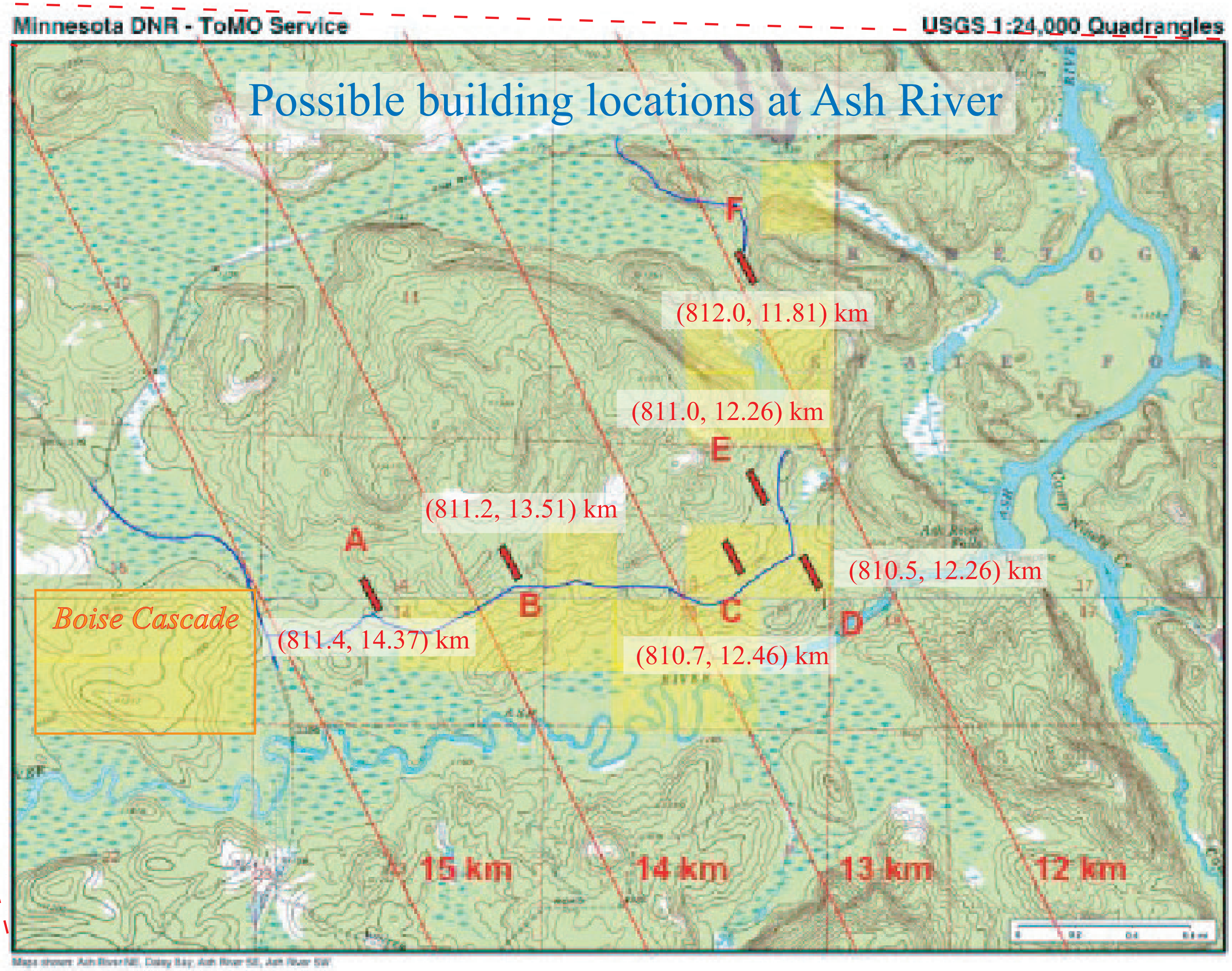
signal/background
7.7 (4.6 baseline)

signal/sqrt(bg.)
26 (24.5 baseline)

Possible sites for detector



Several possible sites along US-Canada border
All have year-round truck access, power, and nearby towns

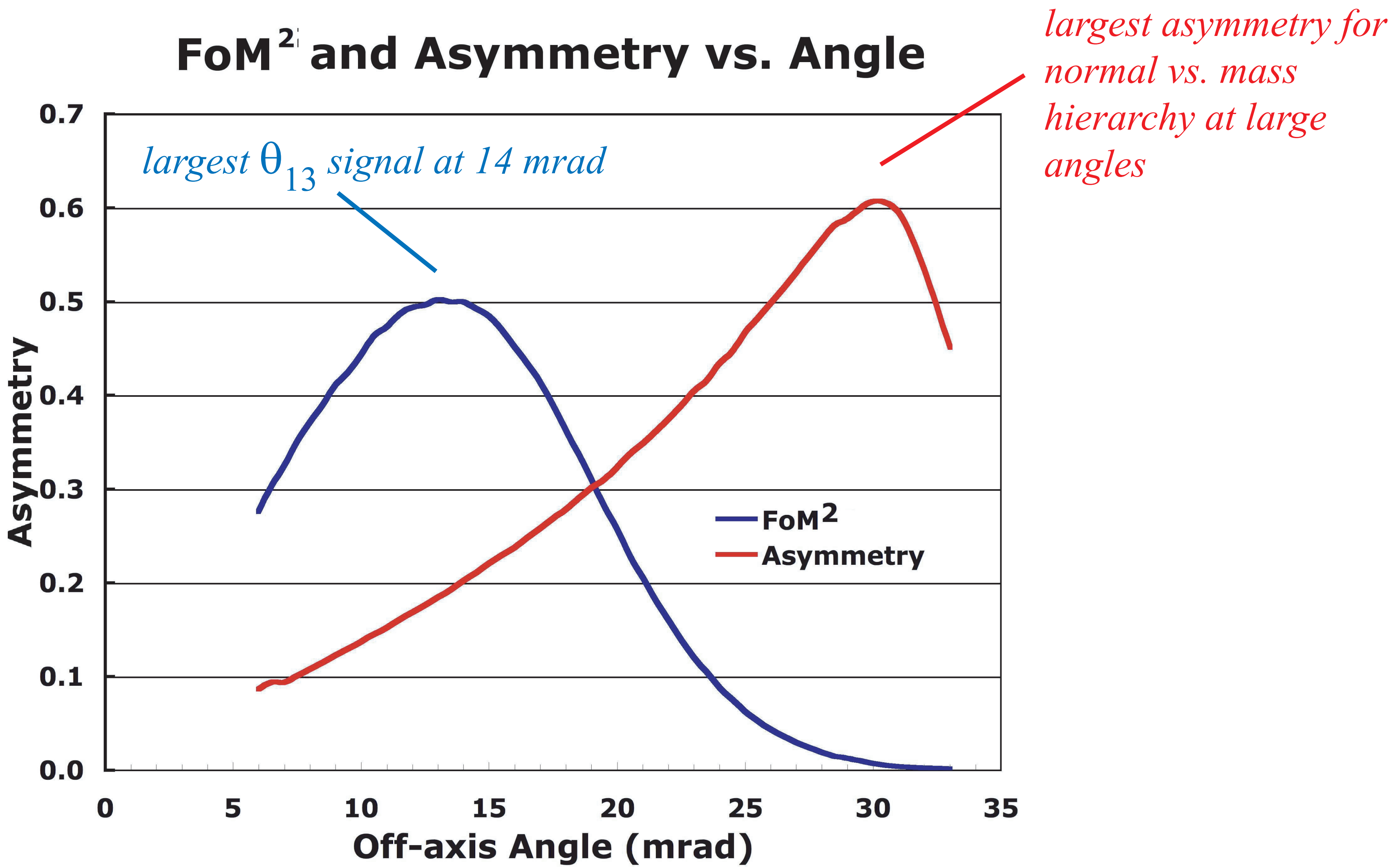


Ash River *(baseline site)*
L = 810-812 km, T = 12-15 km)

Kjostad Lake
L = 775 km, T = 11-15 km

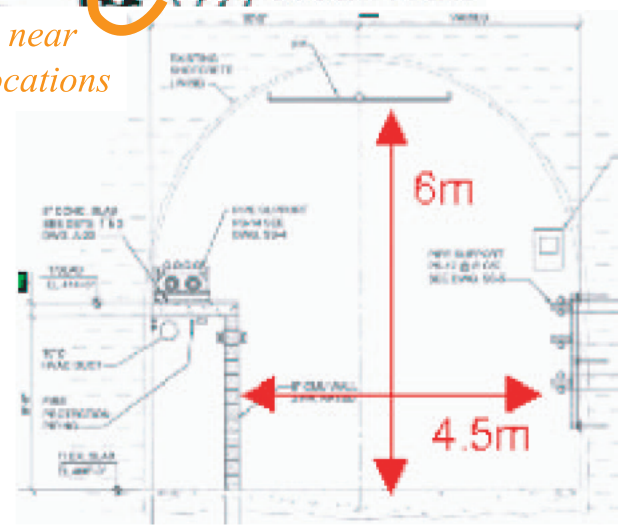
Mine Center
L = 845 km, T = 5 km

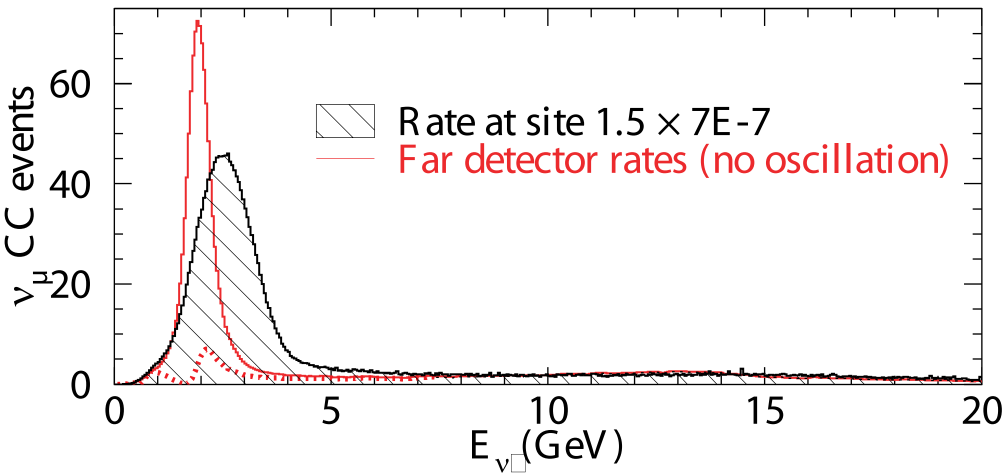
Optimizing location for physics

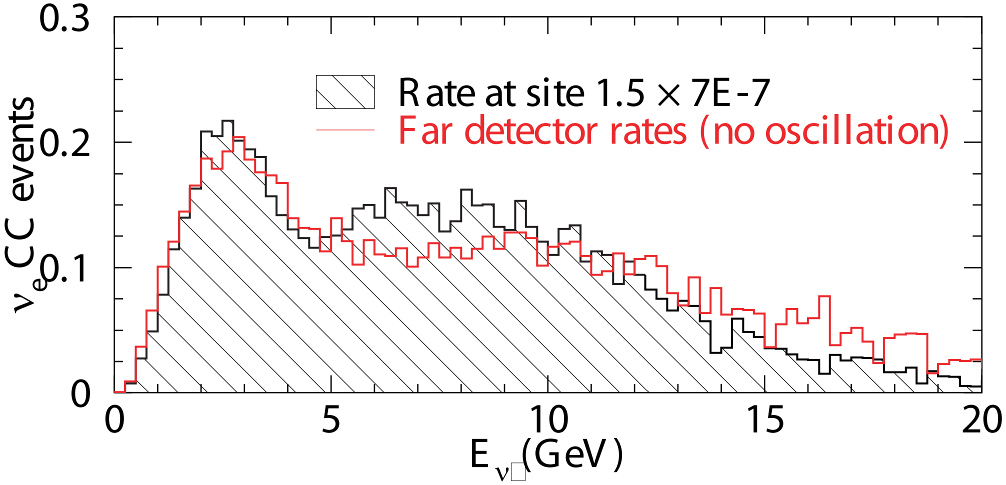


To optimize for θ_{13} sensitivity run slightly above oscillation maximum
To optimize for mass hierarchy run closer to oscillations maximum

Near Detector







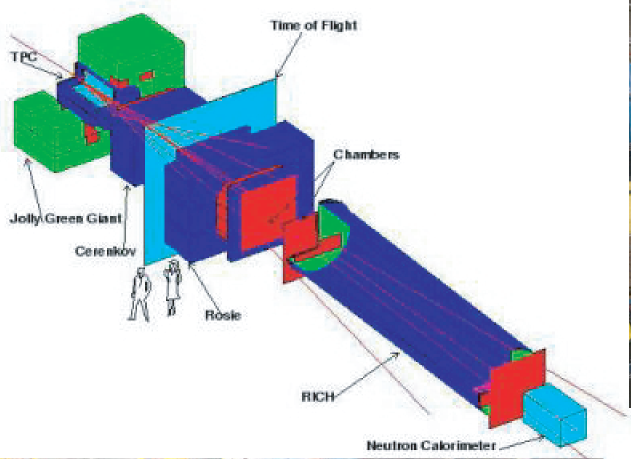
- Near detector design as similiar to far detector
- Limited space at near site (3.7 m x 4.9 m x 10 m)
- veto region + 22 planes
- mass = 120 tons
- plan to expose detecor to test beam

Expect NuMI beam to be very well studied

MIPP

Main Injector Particle Production Experiment (FNAL-E907)

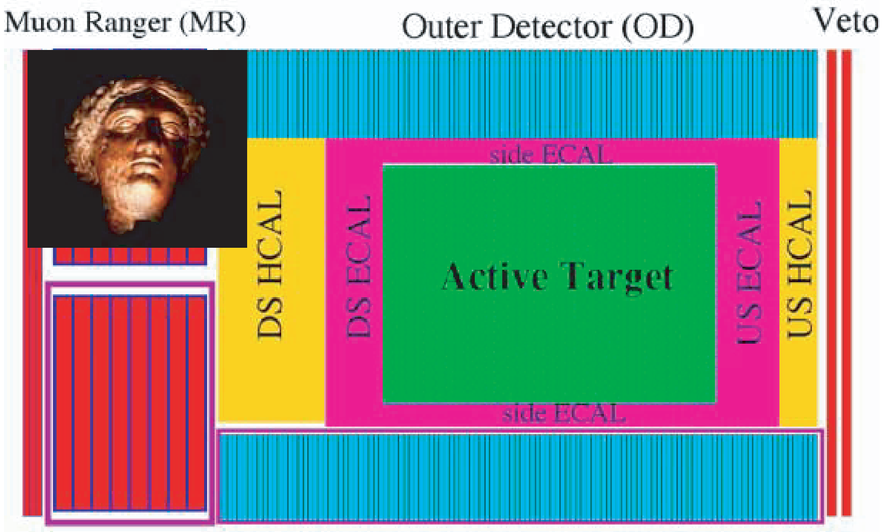
Hadron production on NuMI target from FNAL E907



On axis near ν_μ rates from MINOS near detector

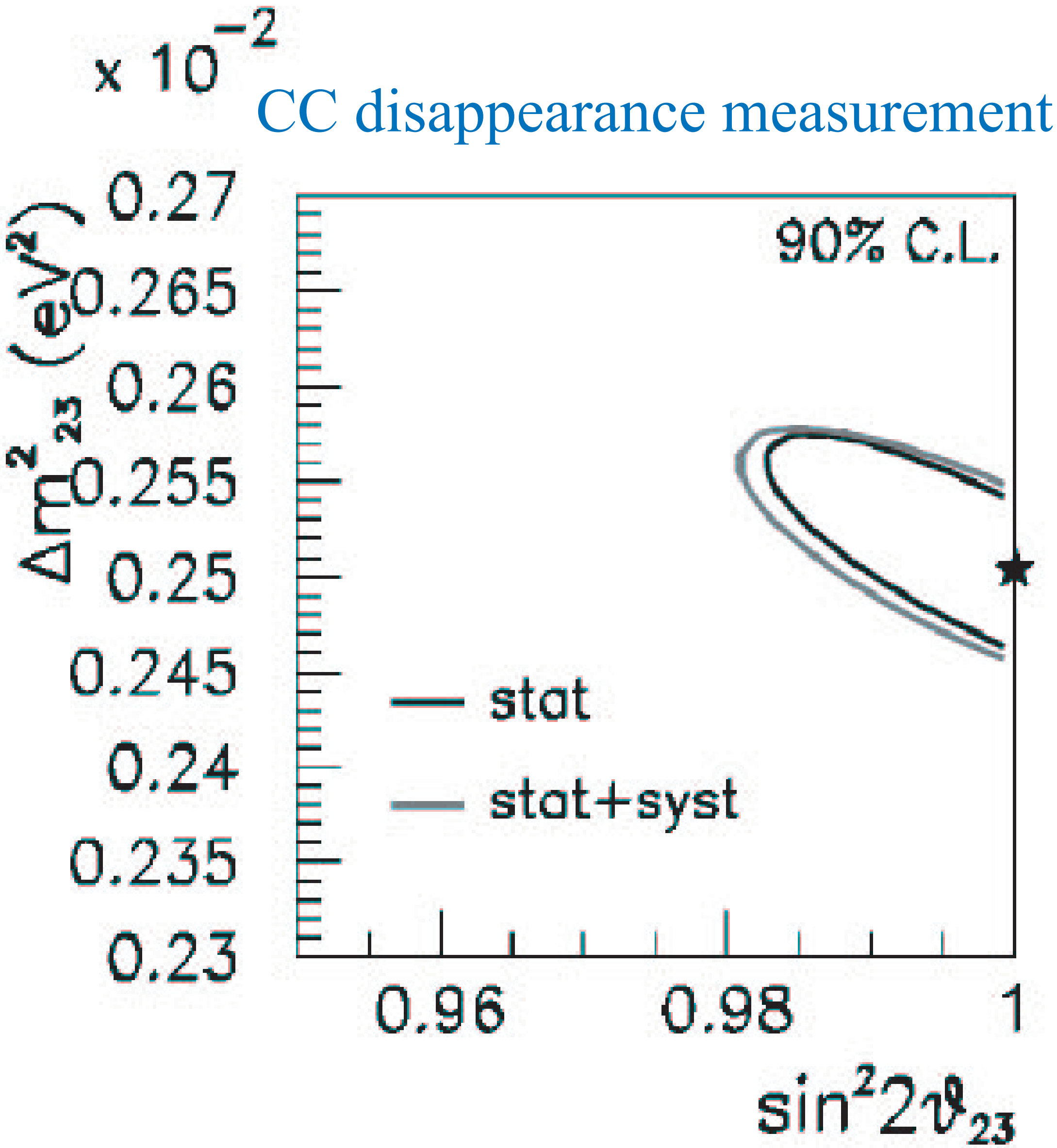
On axis oscillated ν_μ rates from MINOS far detector

ν_μ and ν_e flux and ν-cross sections from MINERνA



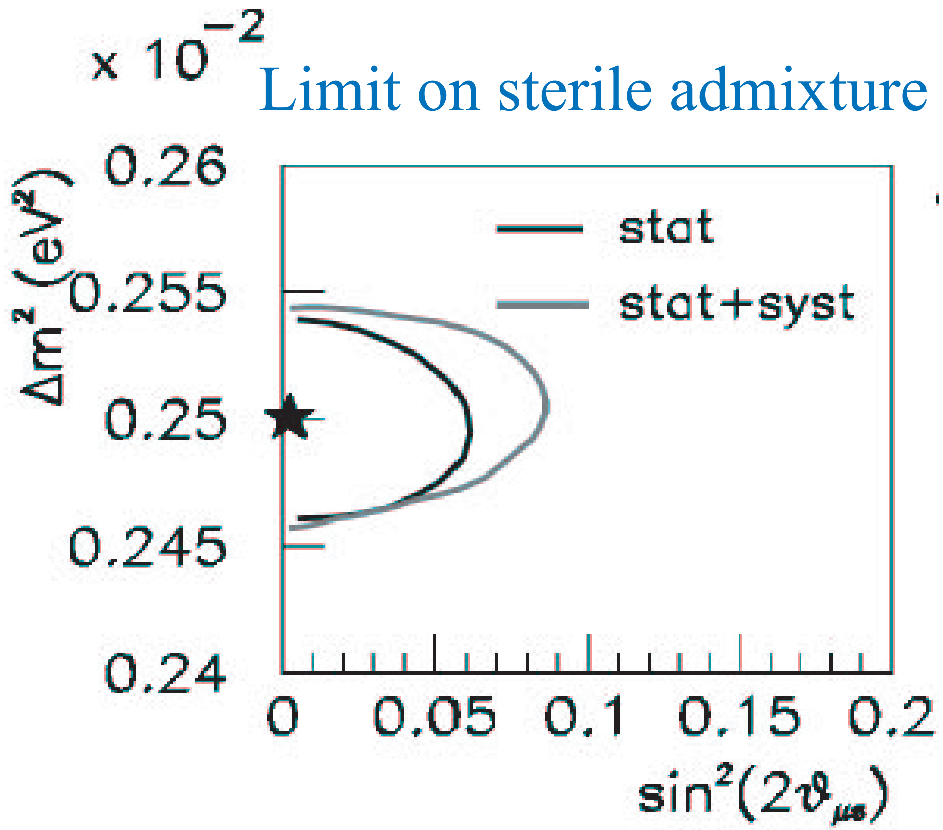
Improvements on other MINOS measurements

CC disappearance measurement



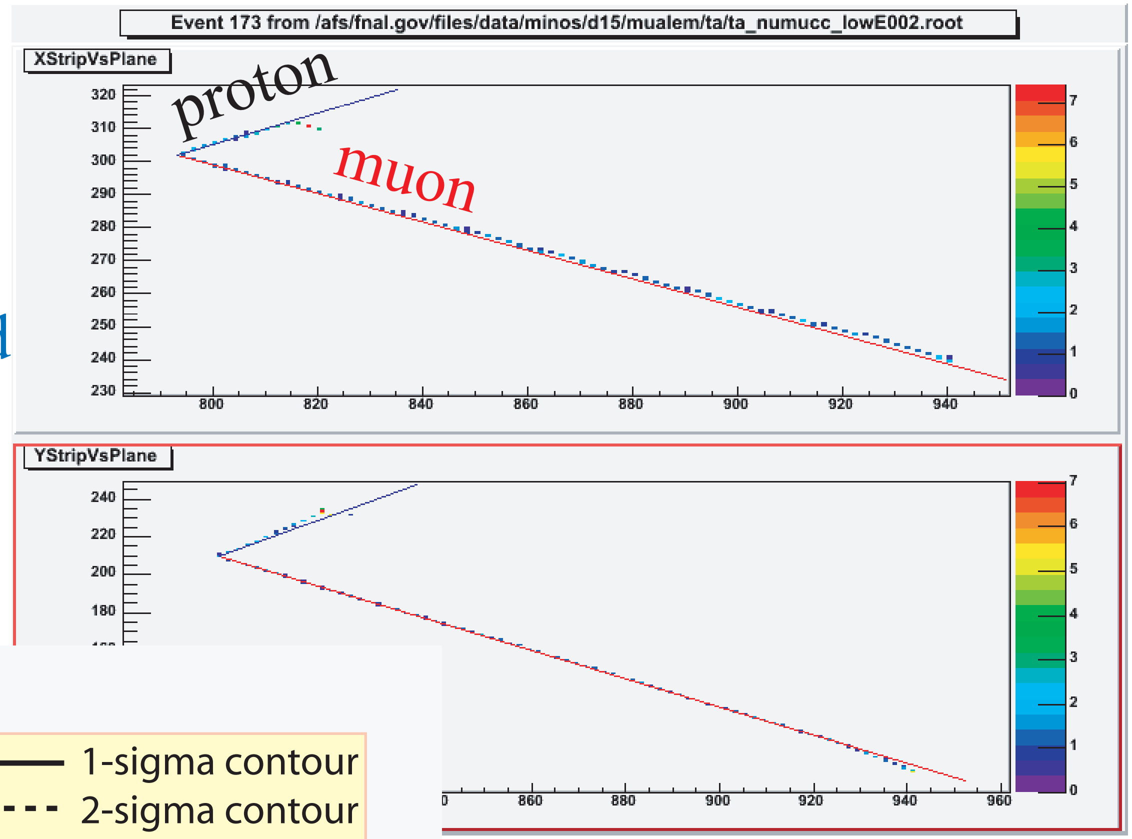
Baseline detector design

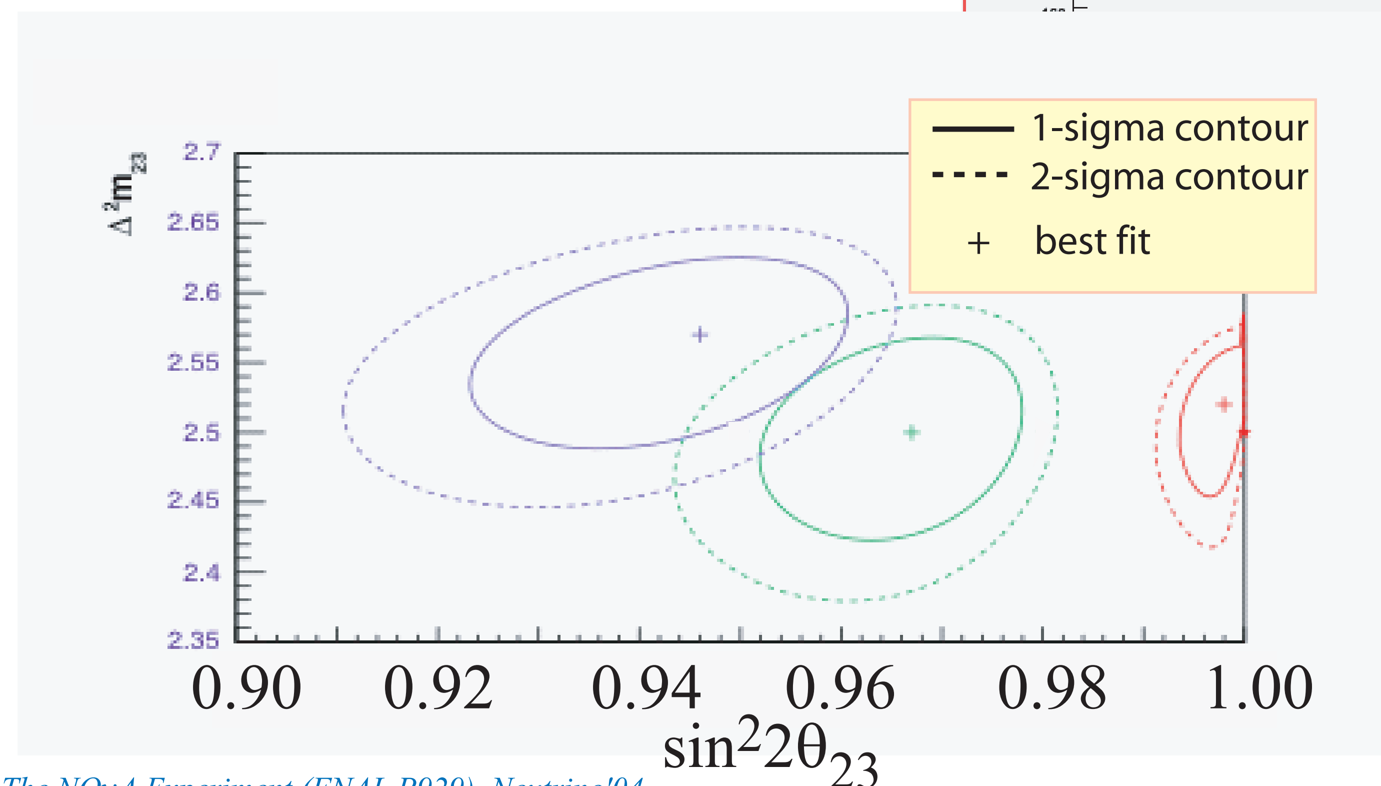
Limit on sterile admixture



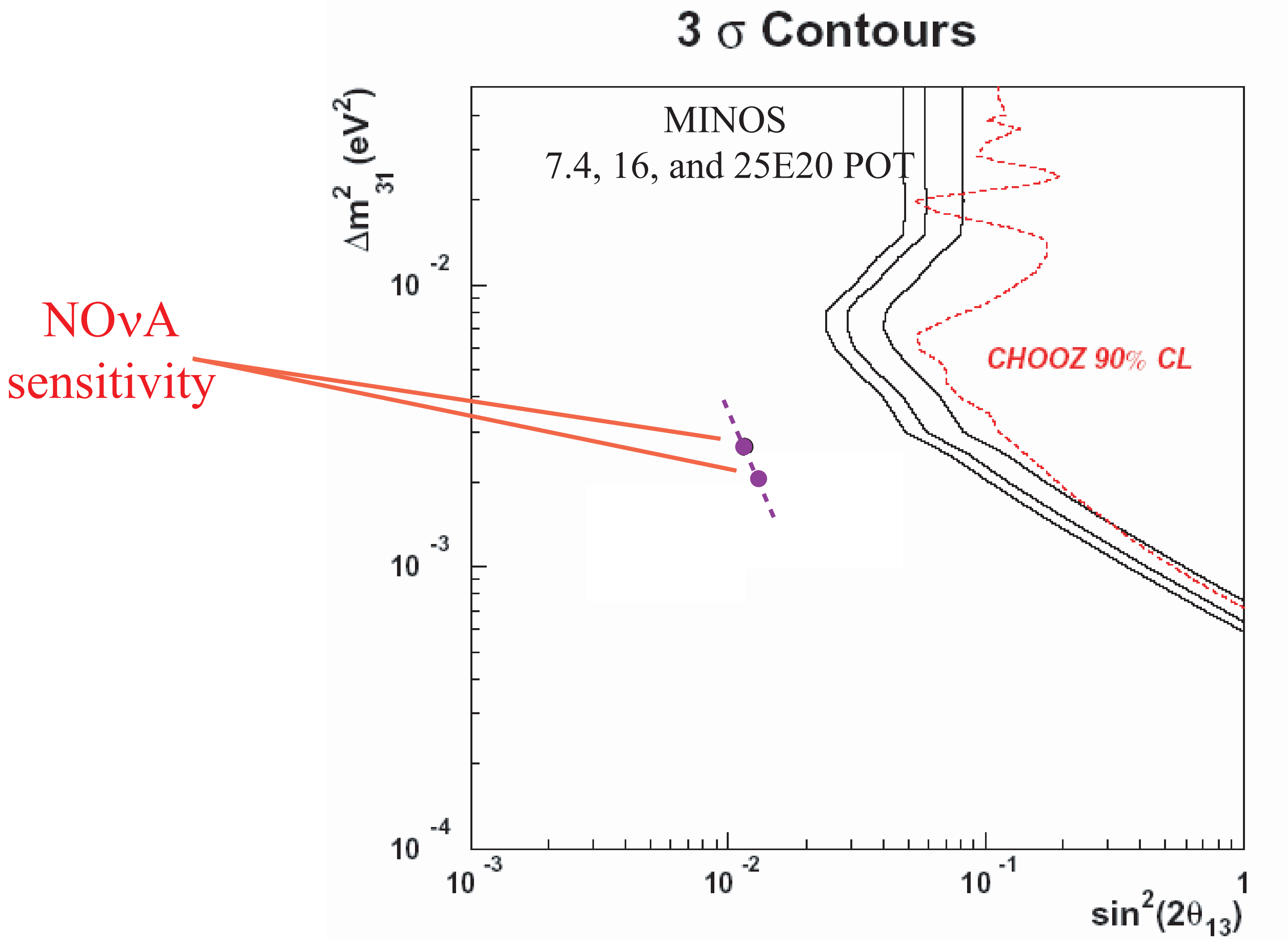
TAS Detector $\sin^2 2\theta_{23}$ measurement

- Quasi-elastic events are very clean in TASD
- Excellent energy resolution
- Essentially zero NC background
- Allow for clean measurement of $\sin^2 2\theta_{23}$ to roughly 1-2% level





NOvA Sensitivity Compared to CHOOZ/MINOS



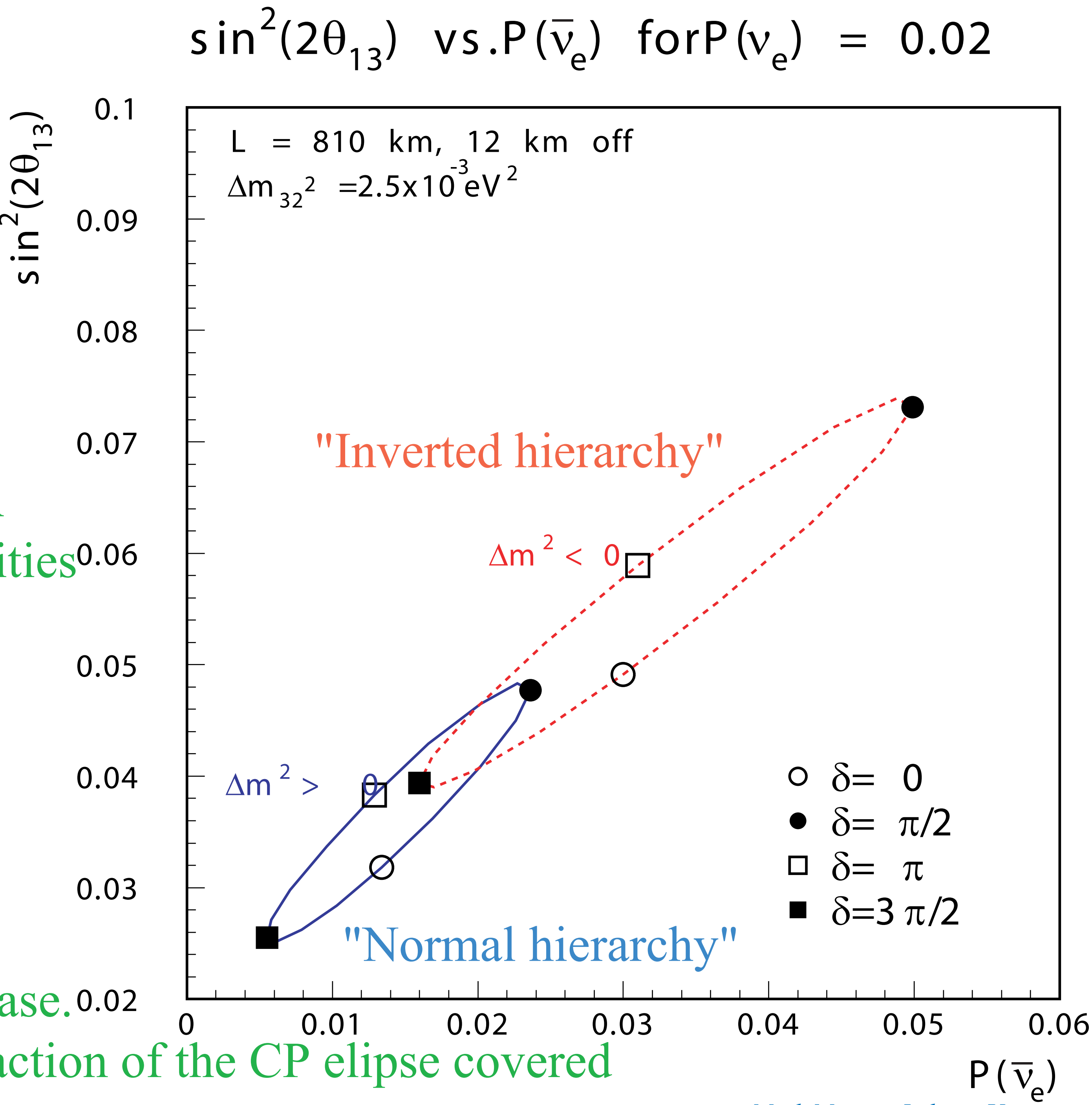
Reminder of the problem

Experiments measure oscillation probabilities
[this case $P(\nu_e) = 0.02$ and $P(\bar{\nu}_e)$]
Ambiguities in $\sin^2(2\theta_{13})$ due to:
- CP phase δ,
- mass hierarchy

Use comparison of NOνA and T2K to break ambiquities

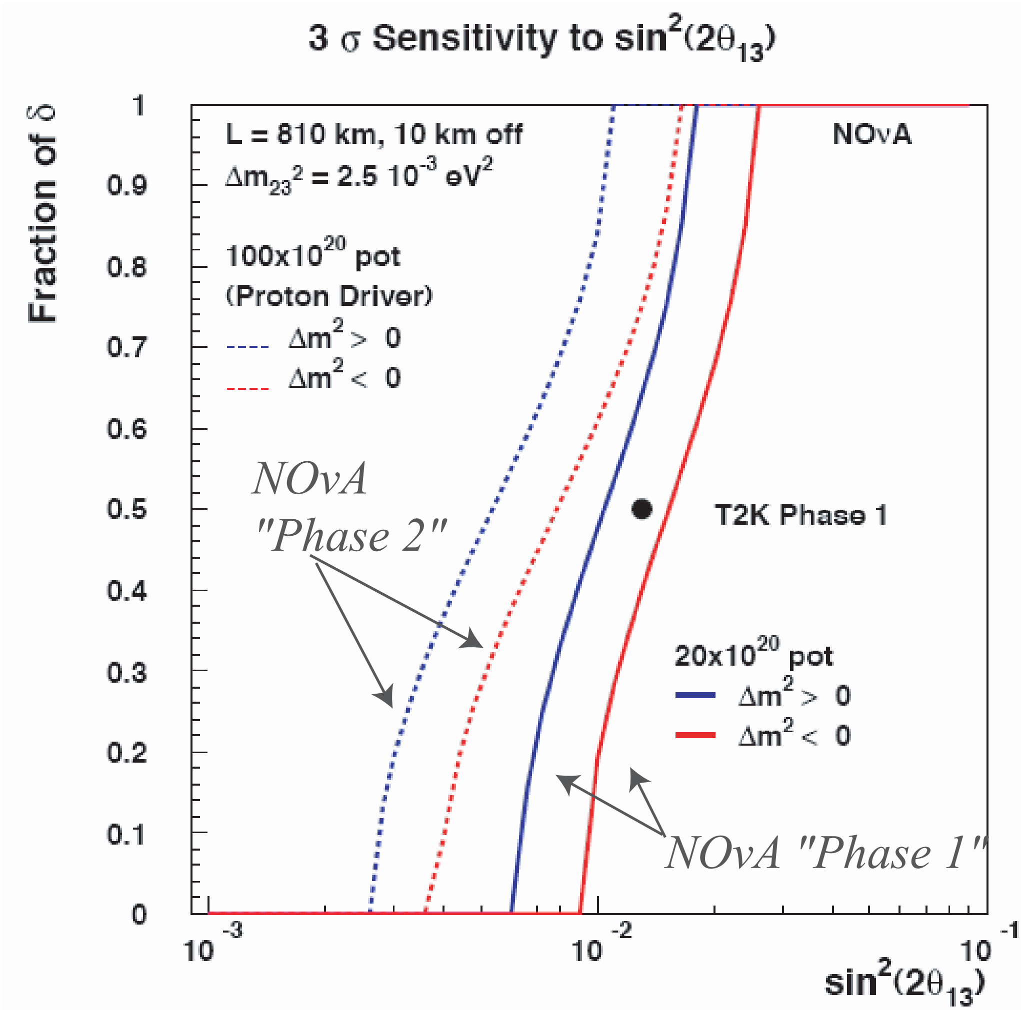
Possibly use 2nd detector located a 2nd oscillation maximum

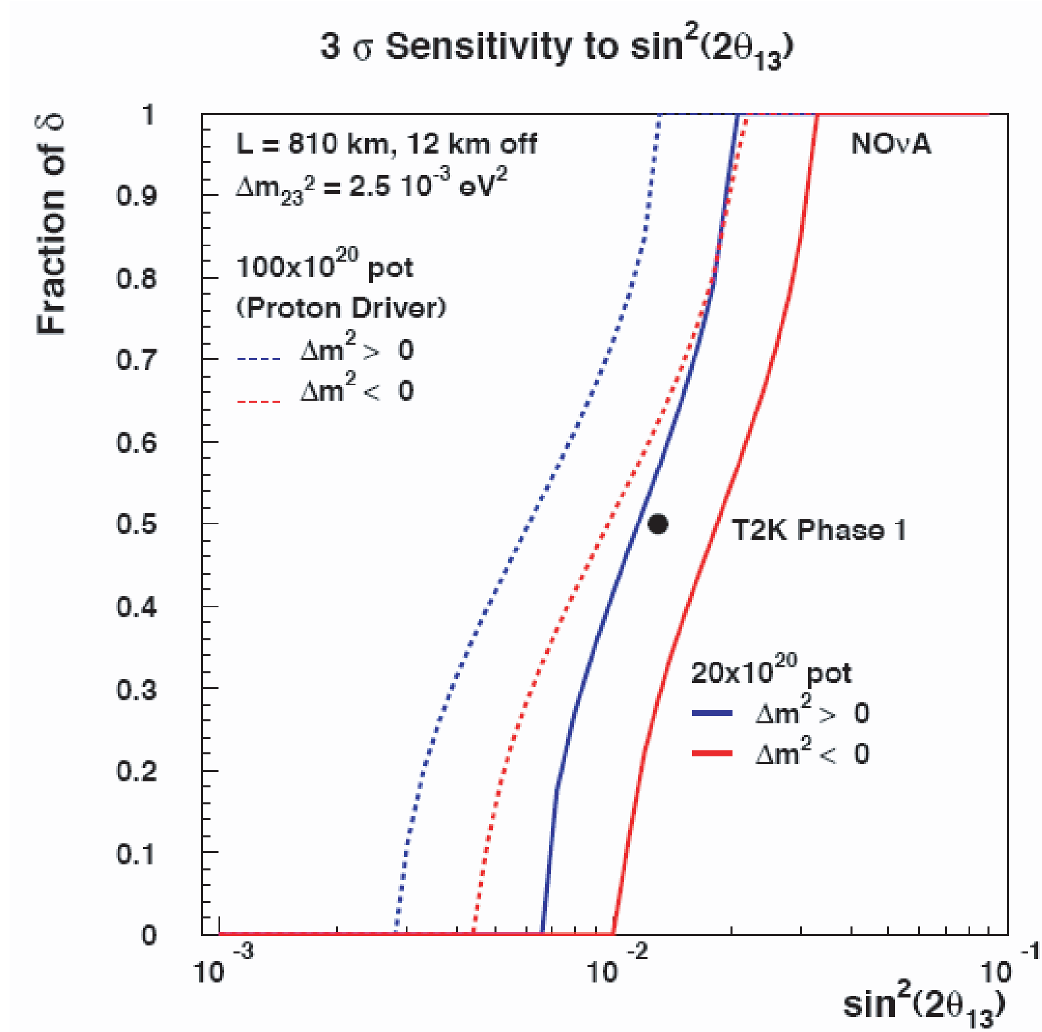
Sensitivity of experiment varies according to CP phase.



Quote sensitivities as a fraction of the CP elipse covered

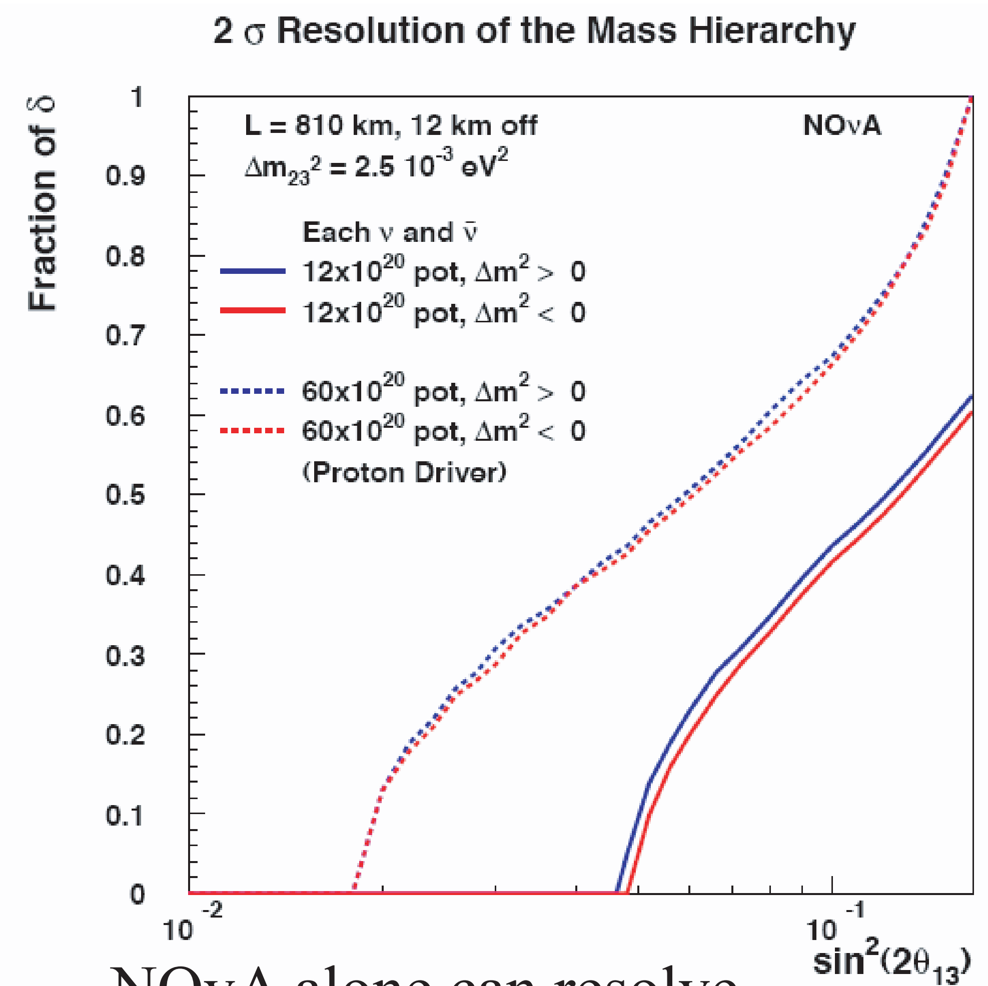
$sin^2(2\theta_{13})$ Sensitivity



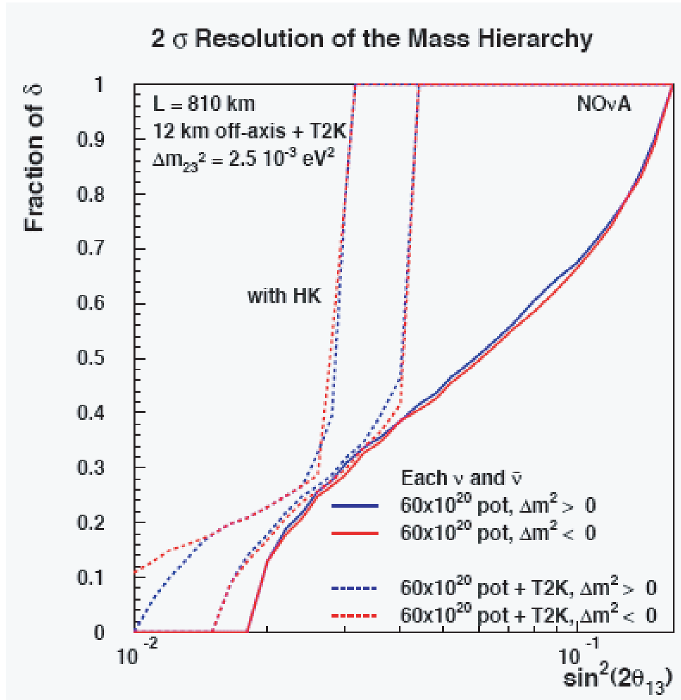


Resolving the mass hierarchy

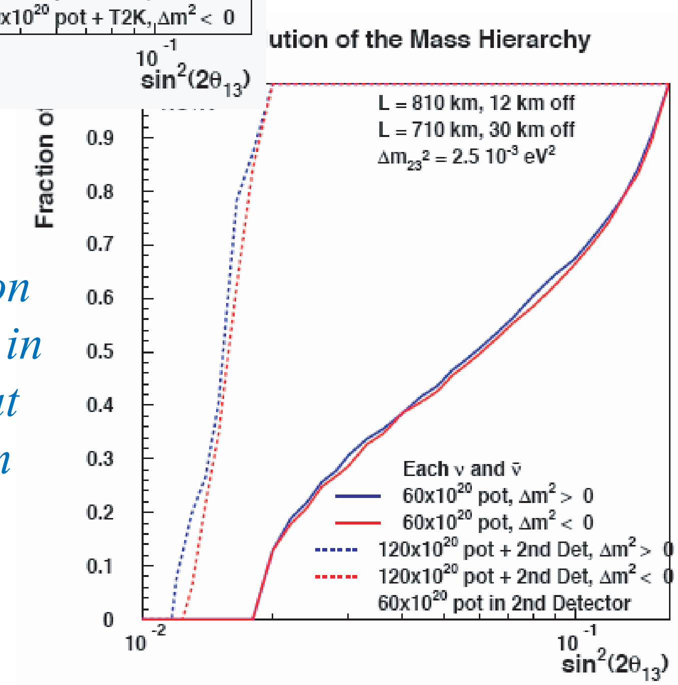
NOvA Alone



in combination with T2K

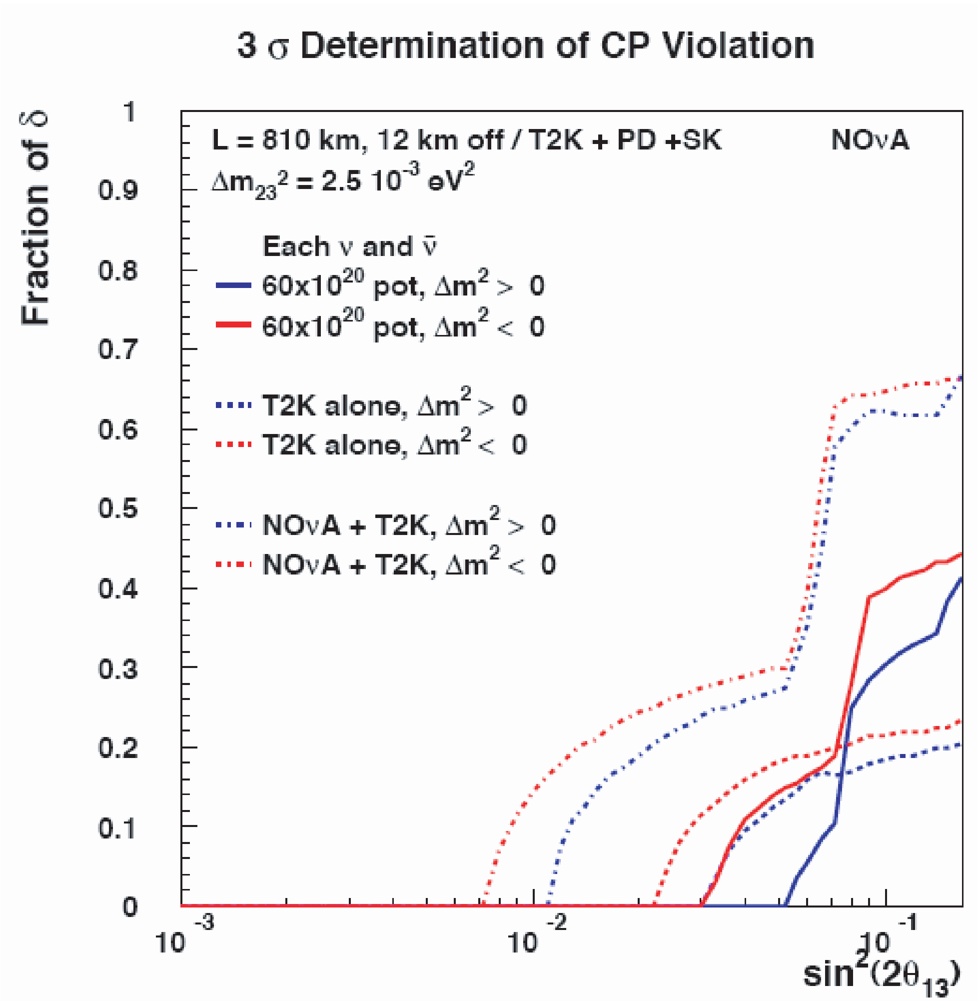


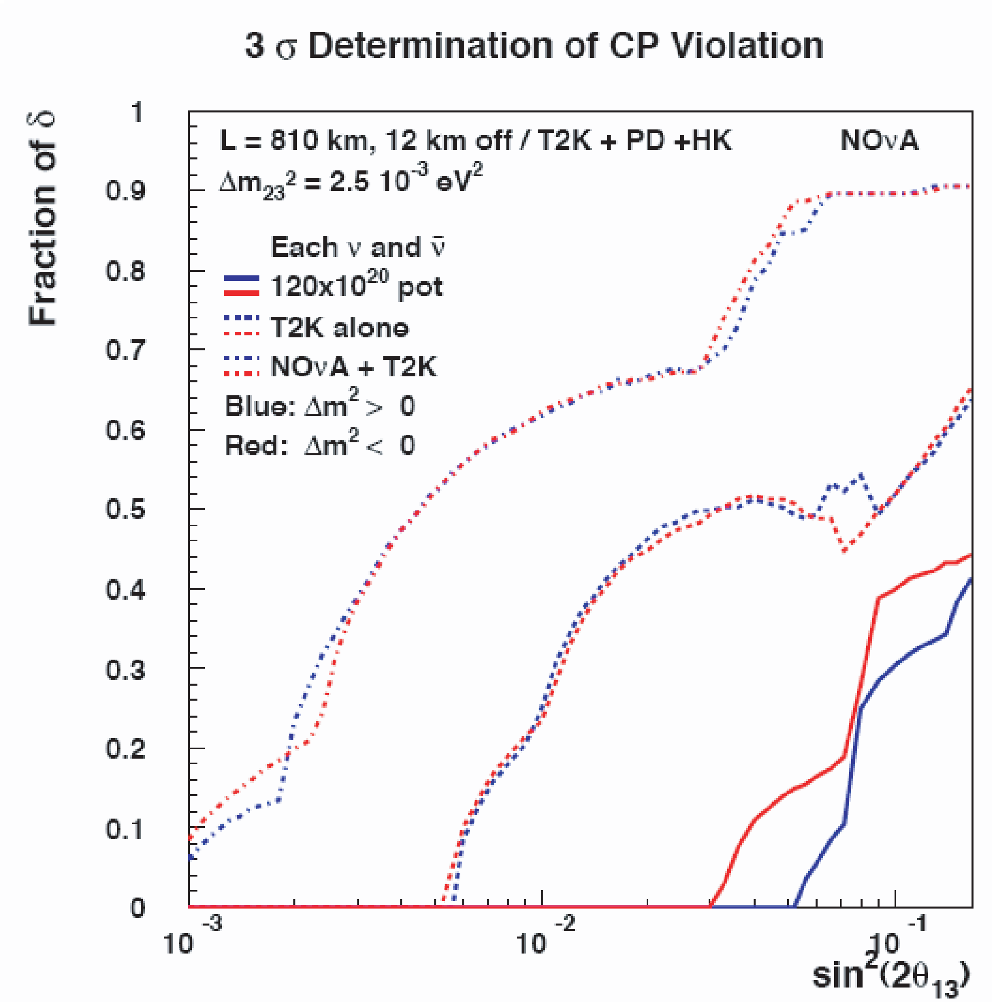
in combination with detector in NuMI beam at 2nd maximum



NOvA alone can resolve heirarchy for large $\sin^2(2\theta_{13})$ over 30-40% of δ phase space. Proton Driver extends this reach by a factor of 2

Demonstrating CP violation





NOνA extends reach of CPV search in $\sin^2(2\theta_{13})$

$$$'s

	Baseline Detector (cost in millions of $'s)	TAS Detector (cost in millions of $'s)
Far Detector		
Absorber	*17*	*0*
Active Detector	*39*	*84*
Electronics	*11*	*14*
Shipping and Installation	*28*	*17*
Far Detector Sub-total	**95**	**115**
Building	**37**	**29**
Project Management	**6**	**6**
Near Detector	**5**	**9**
Active Shield	**4**	**0**
Total	**147**	**159**

- Costing model based on recently completed MINOS far detector
- Includes overhead and contingency

Technically limited schedule

	2004	2005	2006	2007	2008	2009	2010	2011	2012+	*future…*
Stage 1 Approval	👍									
Final technology decision	◆									
Final Approval		👍								
Start Construction			⚐							
Baseline Detector										
Start Data Collection					☺					
Finish Construction								⚐		
TAS Detector										
Start Data Collection				☺						
Finish Construction						⚐				
Protons/year (goal)		2.5E20	3.0E20	3.5E20	4.0E20					20.E20??
										Proton Driver?

- TASD detector has fewer parts and can be assembled in roughly half the time of the baseline detector
- Proposal calls for plan to reach proton intensity goals building on existing MINOS collaboration with beams divisions

Conclusions

[1] The NOvA detector options:

15% active 50 kt liquid scintillator + particle board absorber
85% active ("TASD") 25 kt liquid scintillator + PVC containers

TASD looking very attractive
Technically limited schedule has detector on the air in 2007 or '08

[2] Physics reach:

- $\sin^2 2\theta_{13}$ *down to 0.01-0.2*
- *1-2%* $\sin^2 2\theta_{23}$ *measurement*
- *possibility to resolve mass-hierarchy via matter effect*
- *extend reach of CPV searches*

[3] NOvA provides a flexible program to study remaining unknowns in neutrino mass and mixing. An experiment with sensitivity to matter effects is crucial.

[4] Proposal to be reviewed by FNAL Physics Advisory Committee this month