Recent results and plans in the US.

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CERN EP seminar
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Outline

- MINOS long baseline experiment.
- Results focussed on electron neutrino appearance. And prospects.
- Quick review of θ_{13}
- Measuring CP violation in neutrino sector.
- Description of plans for a new experiment with beam from FNAL to Homestake.

Brief review of oscillations

Assume a 2×2 neutrino mixing matrix.

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= | < \nu_b|\nu_a(t) > |^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

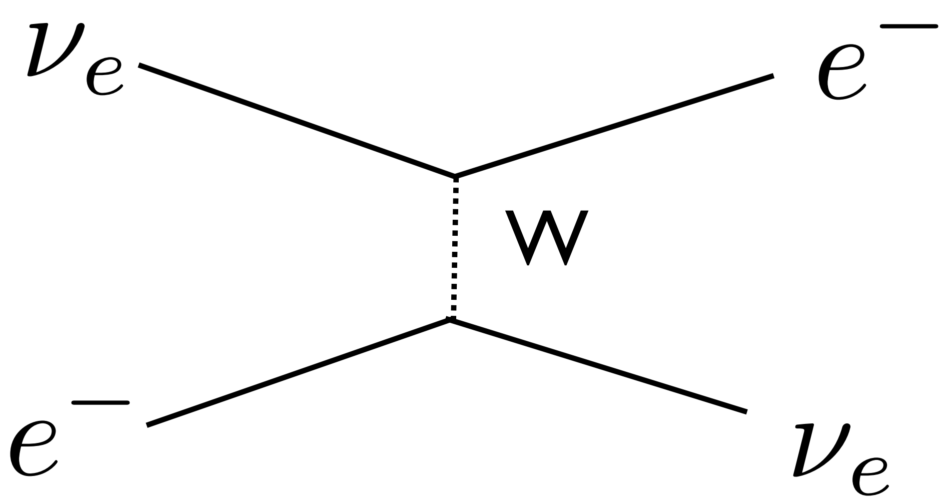
Sufficient to understand most of the physics:

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

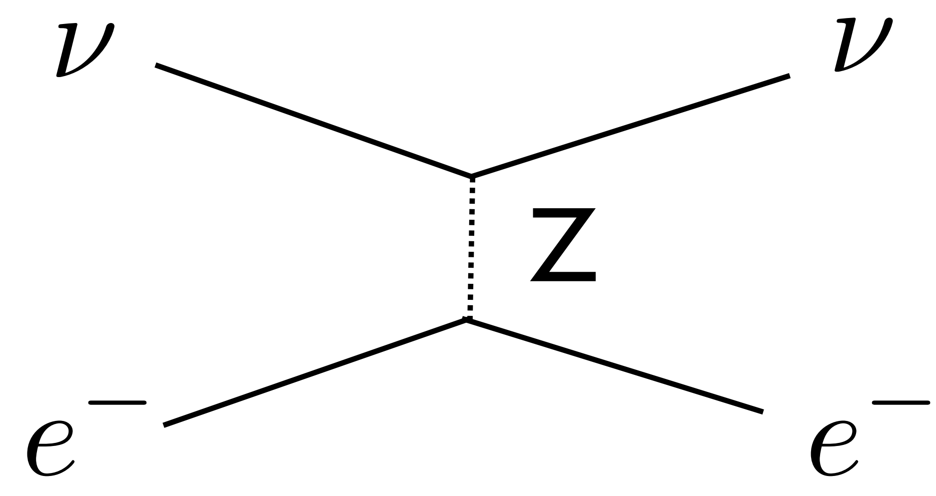
$$P(\nu_a \to \nu_a) = 1 - \sin^2 2\theta \sin^2 \frac{1.27(\Delta m^2/eV^2)(L/km)}{(E/GeV)}$$

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1 GeV$, $L = 494 km$.

Matter effect arises from a difference in interaction amplitudes between different species of neutrinos.



Charged Current
for electron type only



Neutral Current
for all neutrino types

Additional potential for ν_e ($\bar{\nu}_e$): $\pm\sqrt{2}G_F N_e$

N_e is electron number density.

Oscillations in presence of matter

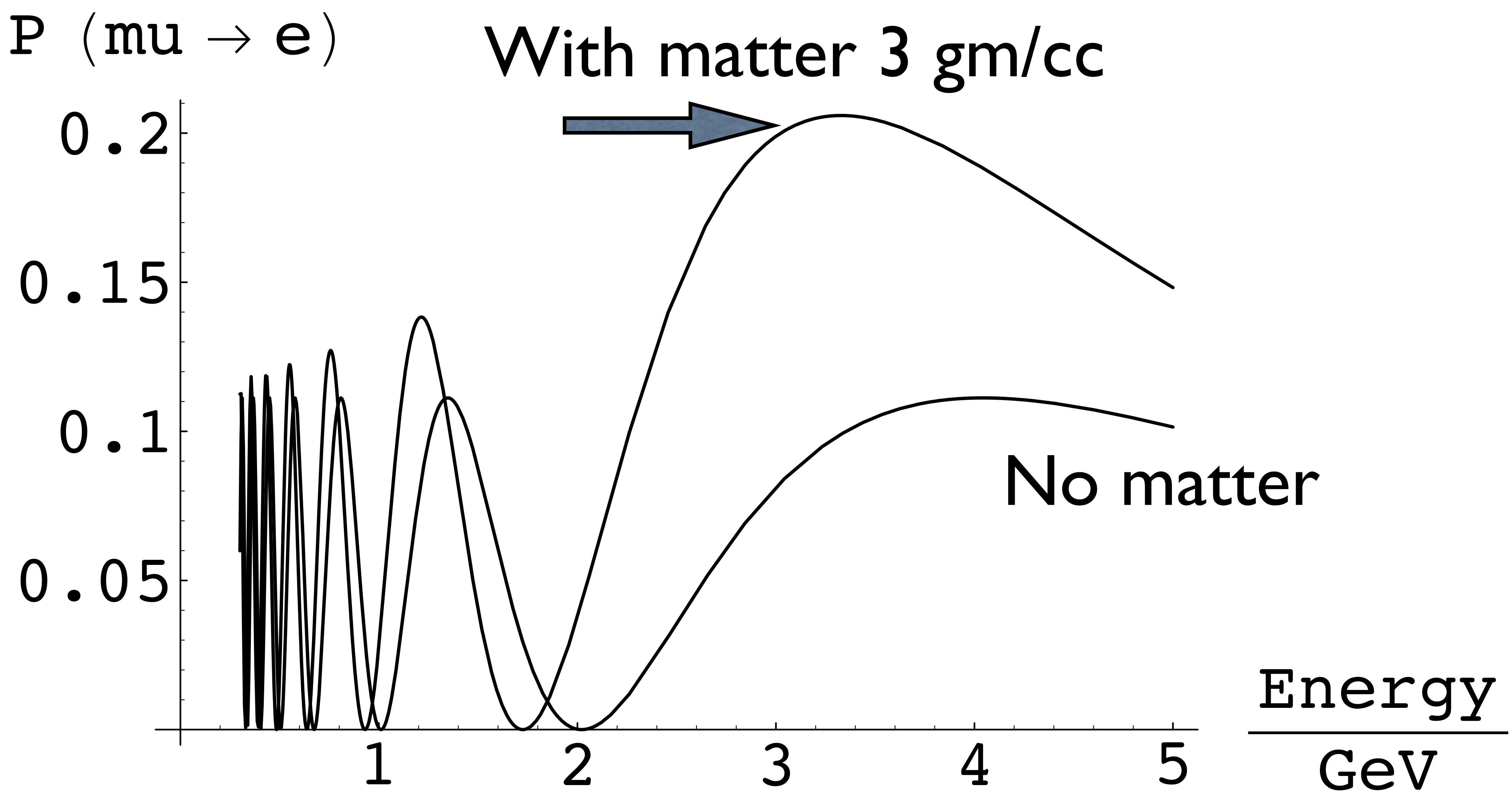
$$i\frac{d}{dx}\nu_f = R_\theta H(\nu_m) + H_{mat}(\nu_f)$$

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \frac{1}{4E}\left(R_\theta\begin{pmatrix}m_1^2 & 0\\ 0 & m_2^2\end{pmatrix}R_\theta^T + 2E\begin{pmatrix}\sqrt{2}G_F N_e & 0\\ 0 & -\sqrt{2}G_F N_e\end{pmatrix}\right)\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \quad (3)$$

$$P_{\mu\to e} = \frac{\sin^2 2\theta}{(\cos 2\theta - a)^2 + \sin^2 2\theta}\times\sin^2\frac{L\Delta m^2}{4E}\sqrt{(a-\cos 2\theta)^2 + \sin^2 2\theta}$$

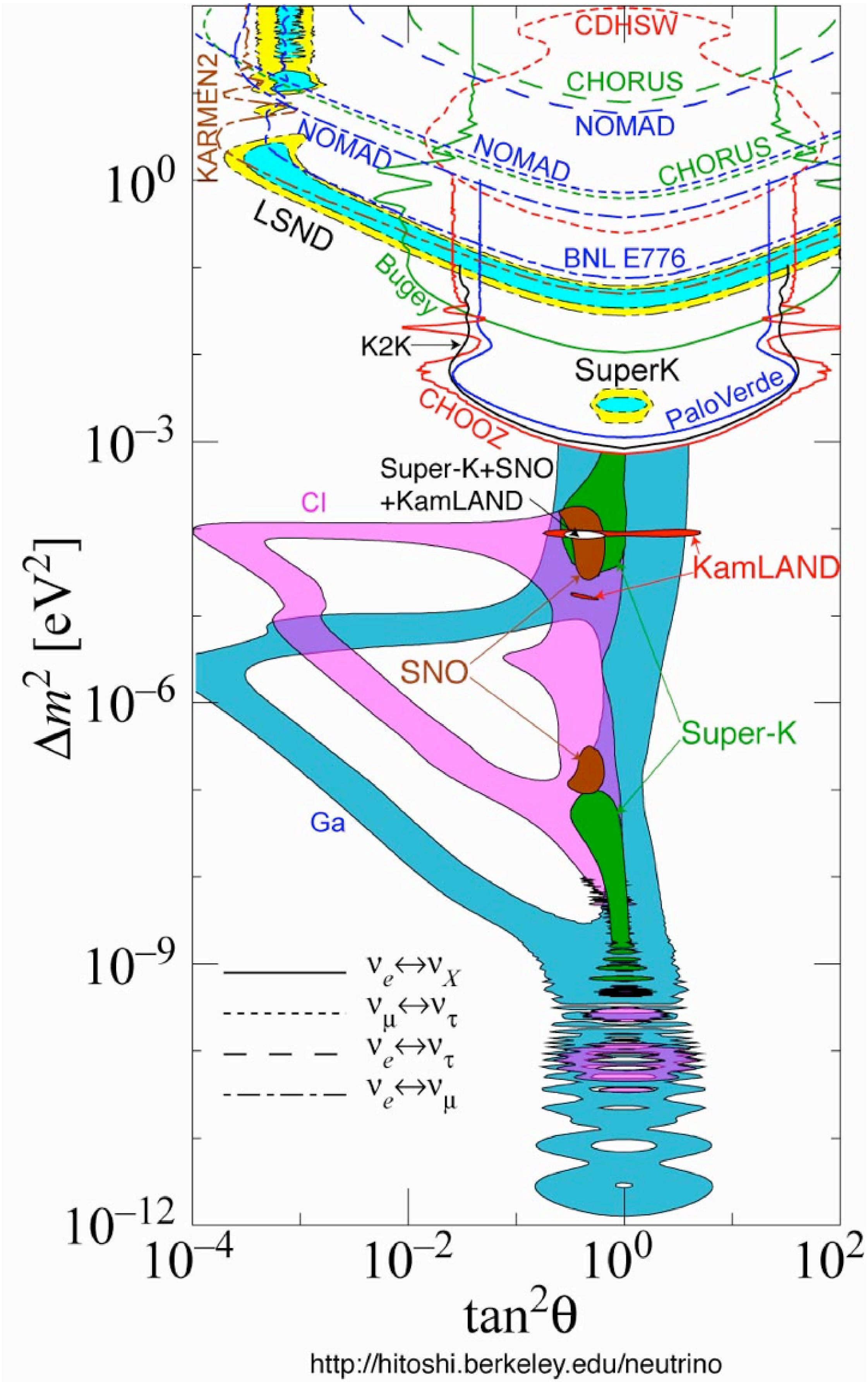
$$\begin{aligned} a &= 2\sqrt{2}EG_F N_e/\Delta m^2 \\ &\approx 7.6\times 10^{-5}\times D/(gm/cc)\times E_\nu/GeV/(\Delta m^2/eV^2) \end{aligned} \quad (4)$$

Matter effect with 2-neutrinos



Osc. probability: 0.0025 eV^2, L= 2000 km, Theta=10deg

Summary of experiments

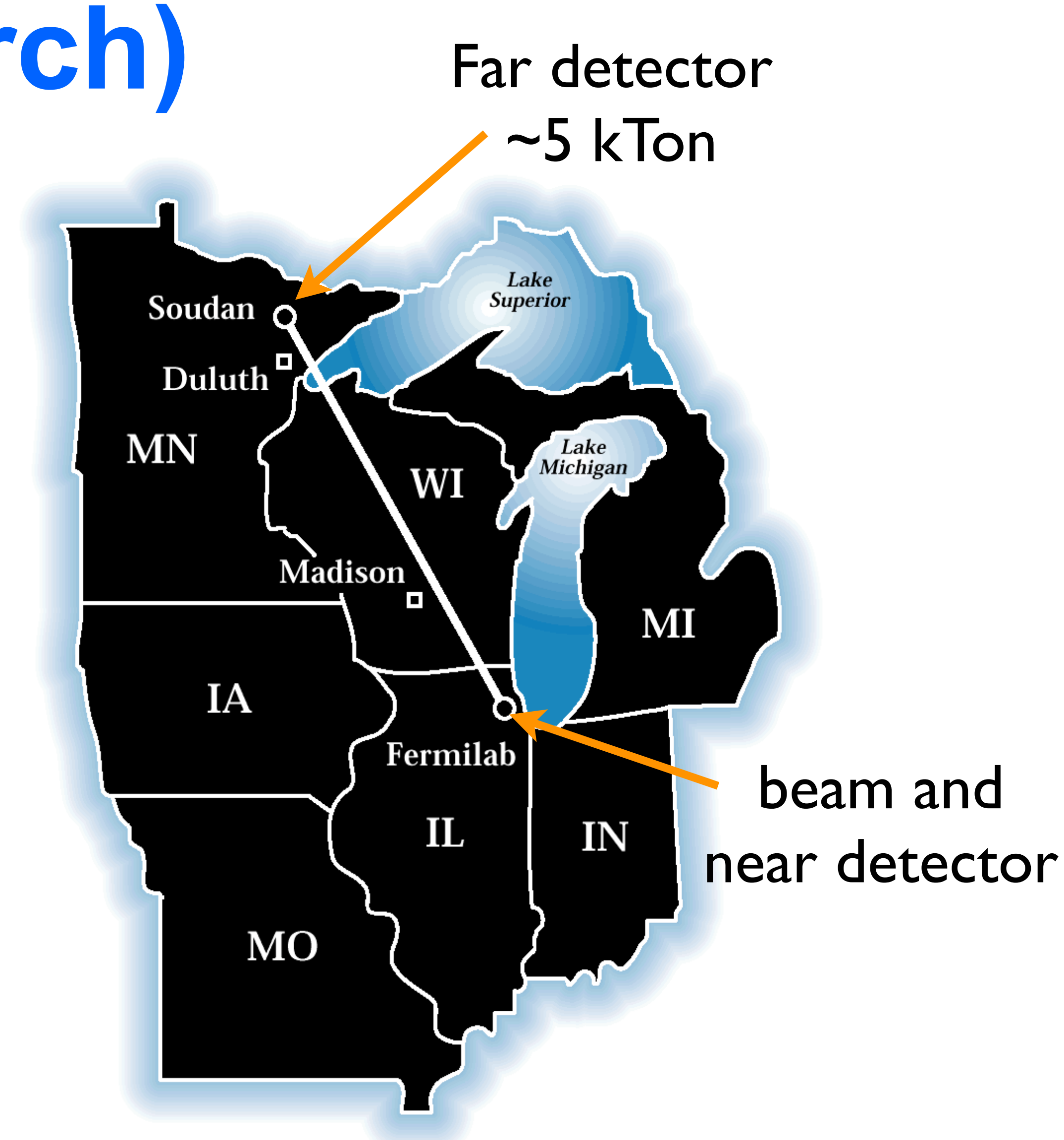


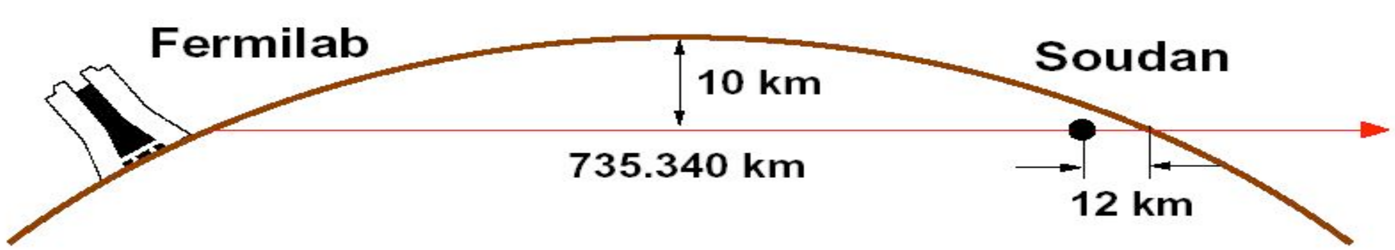
$\theta_{atmospheric}$ (primarily θ_{23})

θ_{solar} (primarily θ_{12})

MINOS (Main Injector Neutrino Oscillation Search)

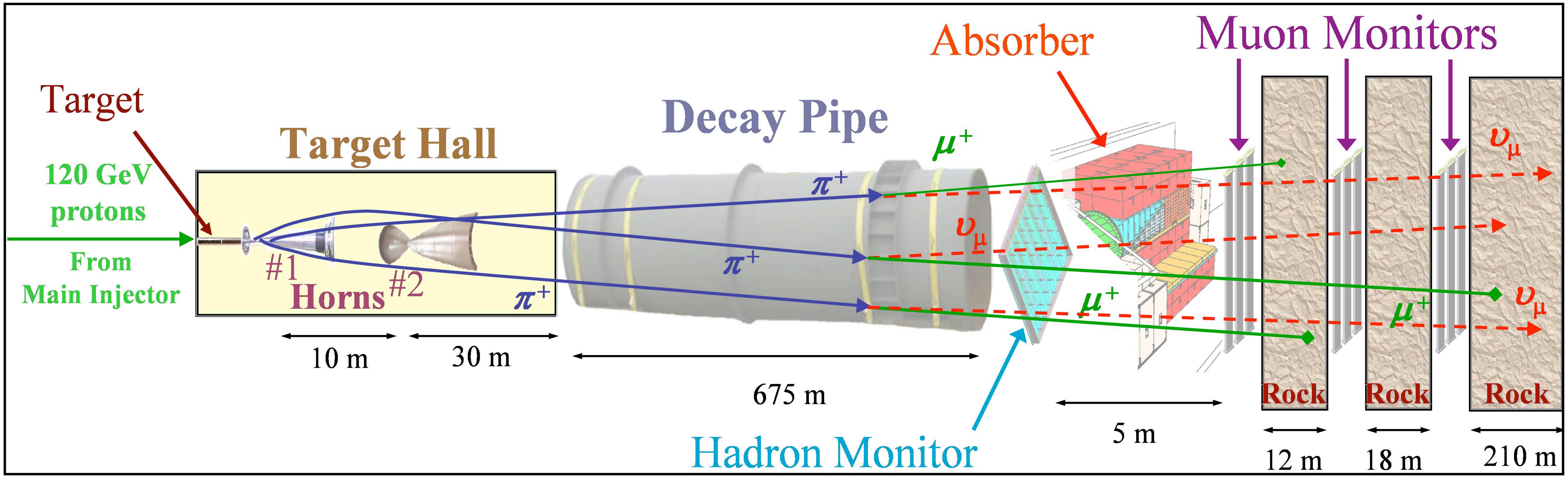
- Conventional muon neutrino beam from charged pion decays.
- Near detector is at 1.04 km from target (Fermilab) and far at 735 km (Minnesota).
- Measure spectra at near and far to search for muon neutrino disappearance or electron appearance.



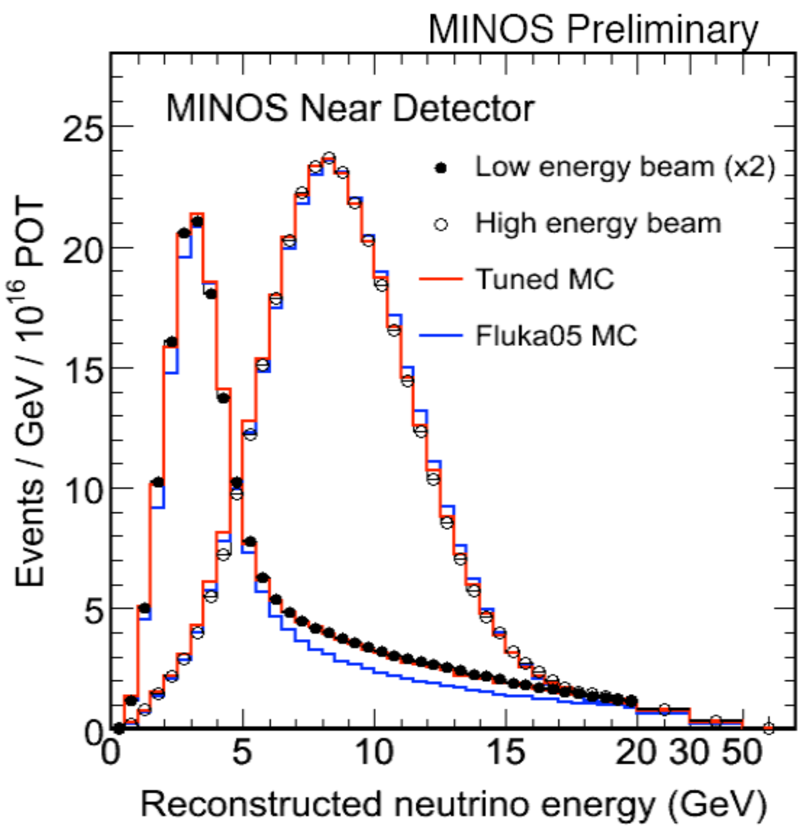


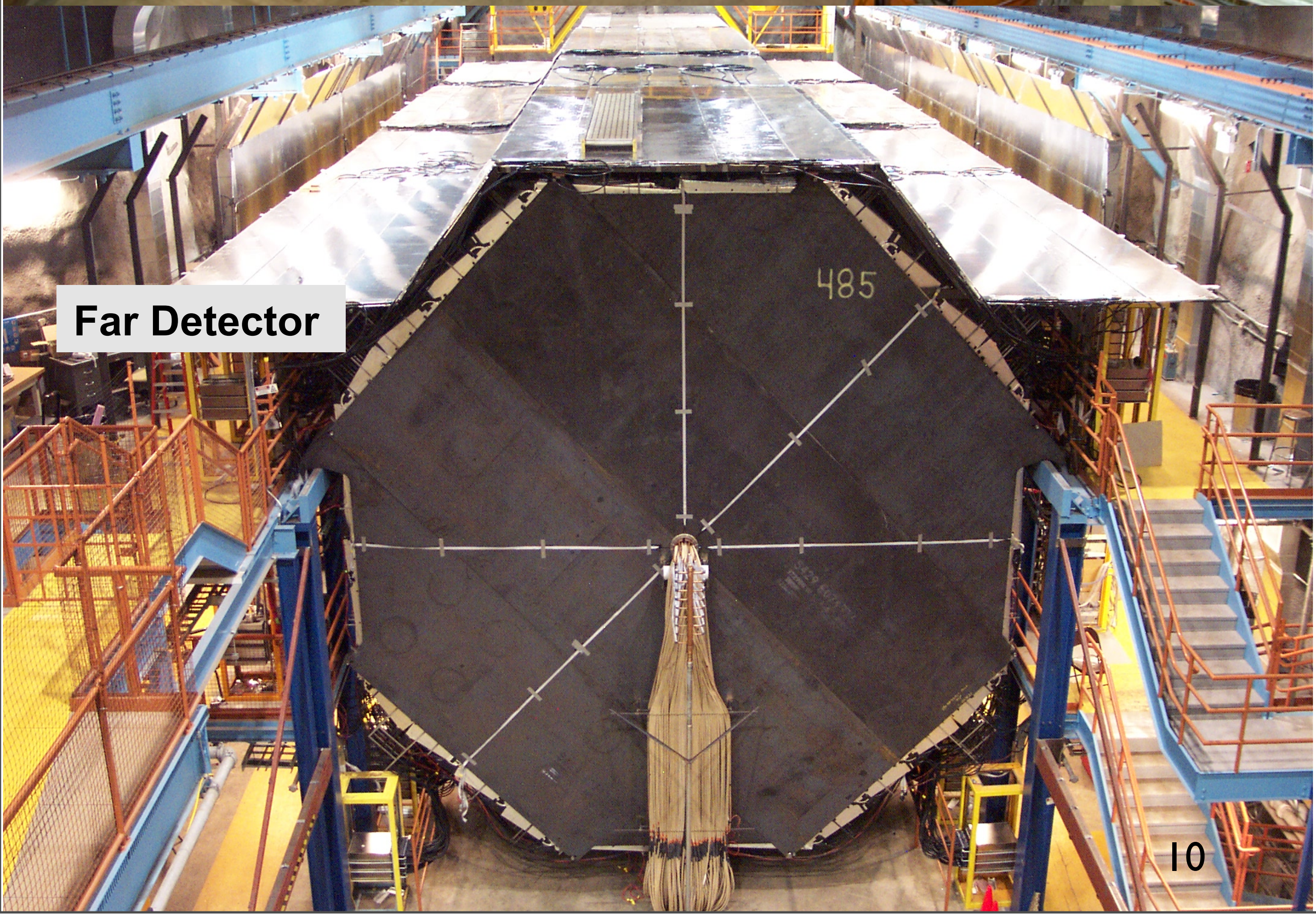
**Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab
Harvard • Holy Cross • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Otterbein
Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M
Texas-Austin • Tufts • UCL • Warsaw • William & Mary**

Horn focused muon neutrino beam



- 120 GeV protons from Main Injector
- Parabolic magnetic horns to sign select pions. Target can be moved to change beam energy.
- 10 μsec pulses/2.2 sec, 3.3×10^{13} protons/pulse
- Beam: ν_μ ~ 91.7%, anti-ν_μ~7%, ν_e~1.3%
- ν_μ and anti-ν_μ measured. ν_e constrained to ~10% with tuned Monte Carlo.





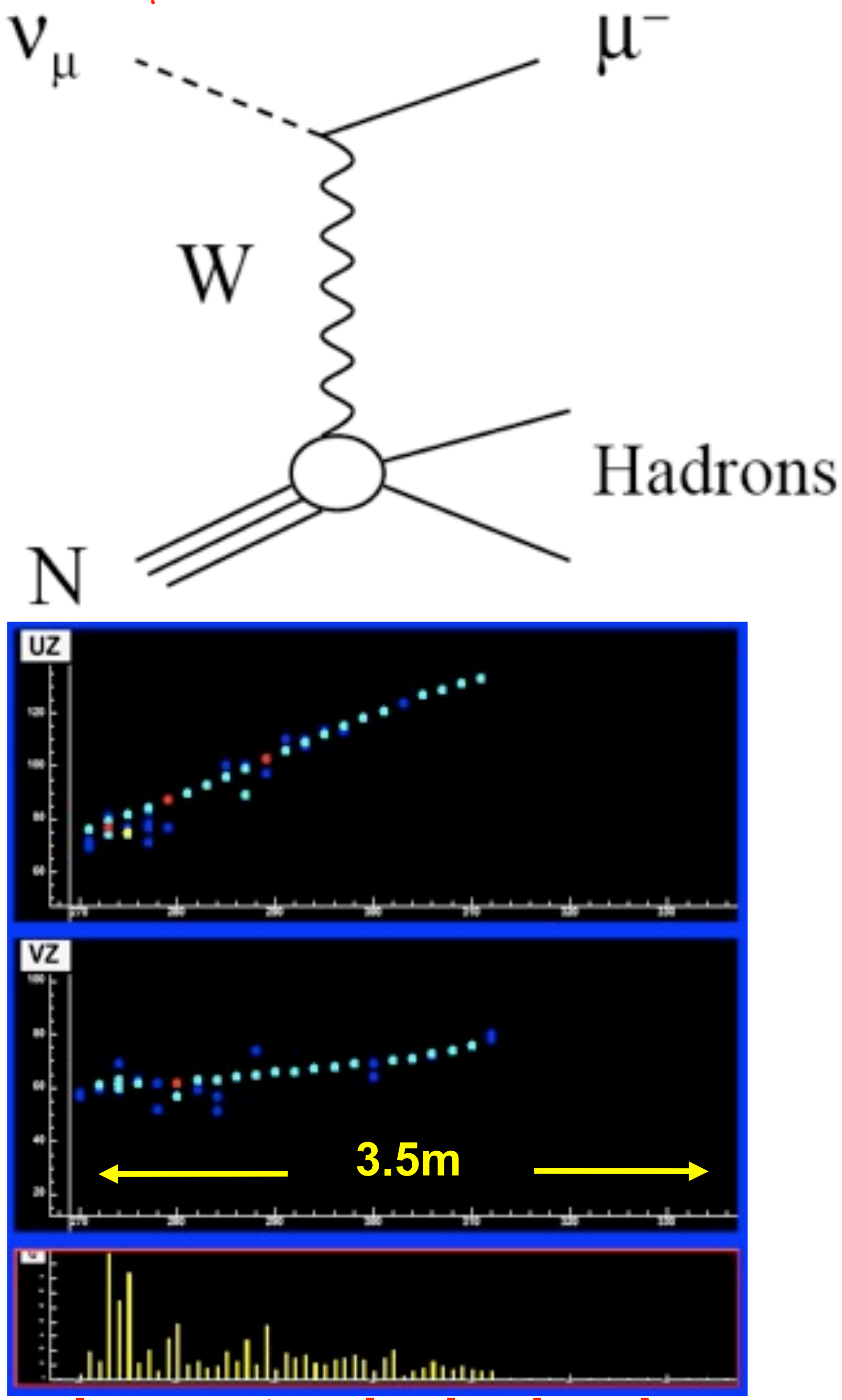
MINOS Detectors

- Massive
  - 1 kt Near detector (small fiducial)
  - 5.4 kt Far detector
- Similar as possible
  - steel planes
    - 2.5 cm thick
    - 1 Muon ~ 27 planes
    - 1.4 radiation lengths
  - scintillator strips
    - 1 cm thick
    - 4.1 cm wide
    - Molier radius ~3.7 cm

  - Wavelength shifting fibre optic readout
  - Multi-anode PMTs
  - Magnetised (~1.3 T)

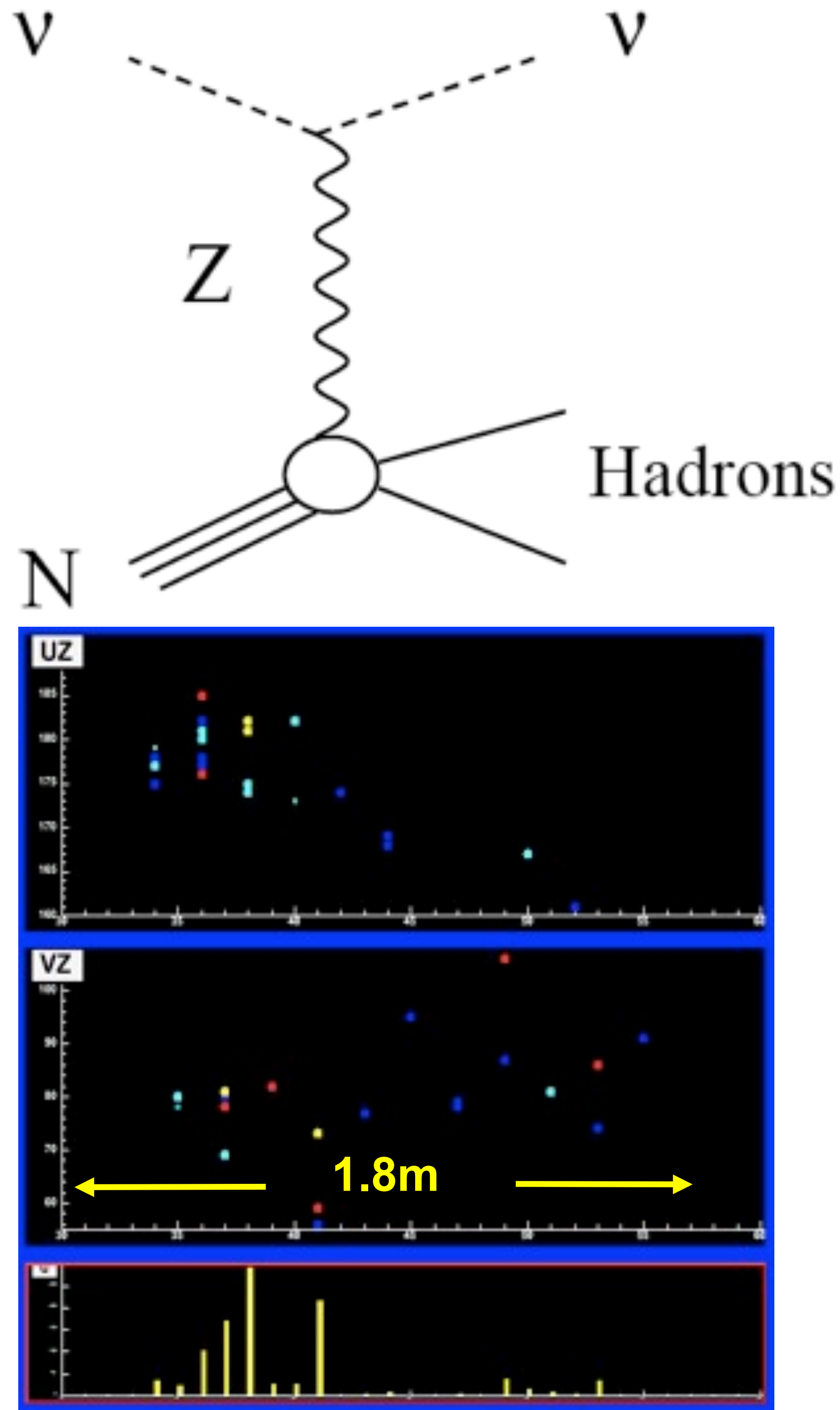
MINOS Event Topologies (MC)

ν_μCC Event



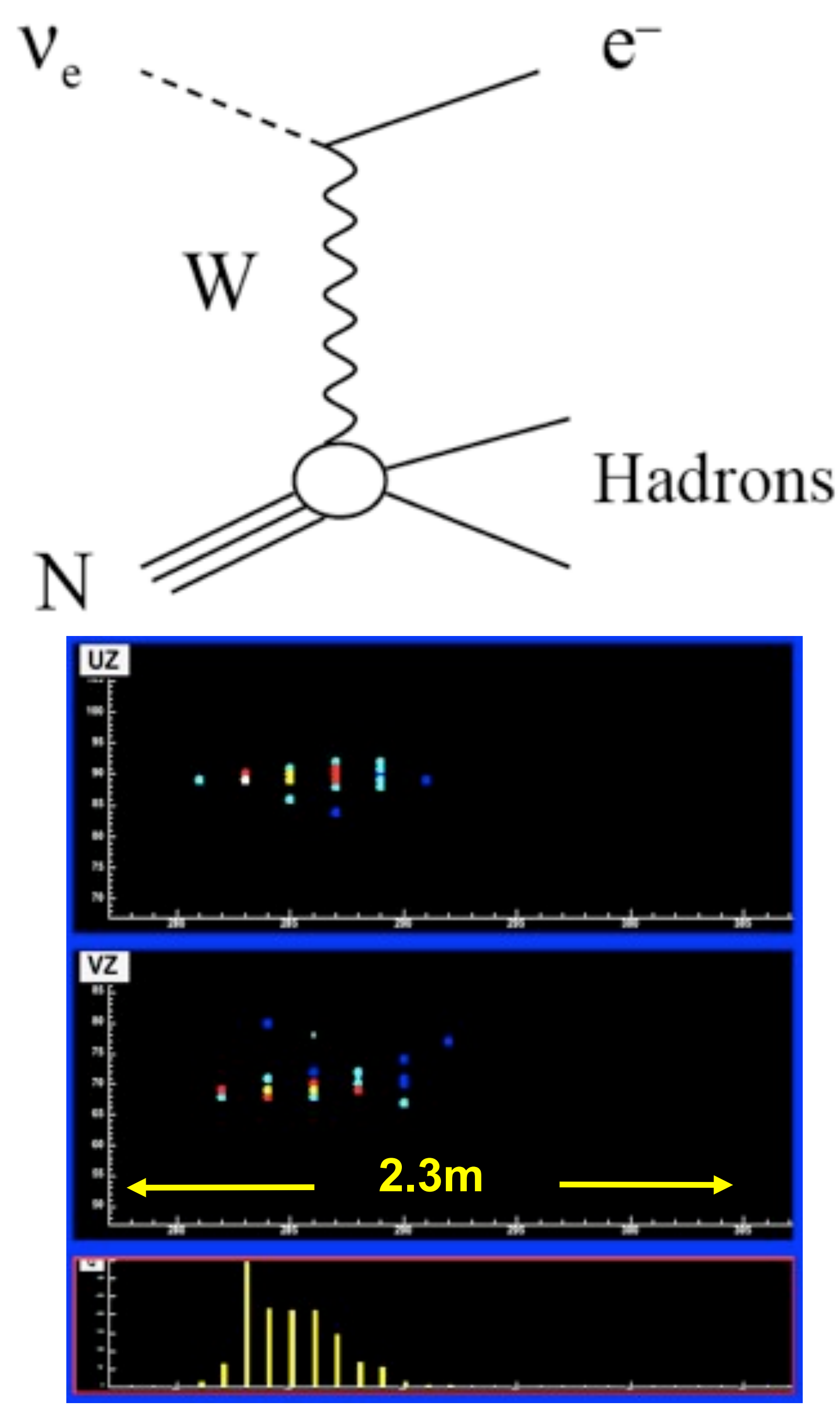
long μ track+ hadronic activity at vertex

NC Event



short event, often diffuse

ν_eCC Event



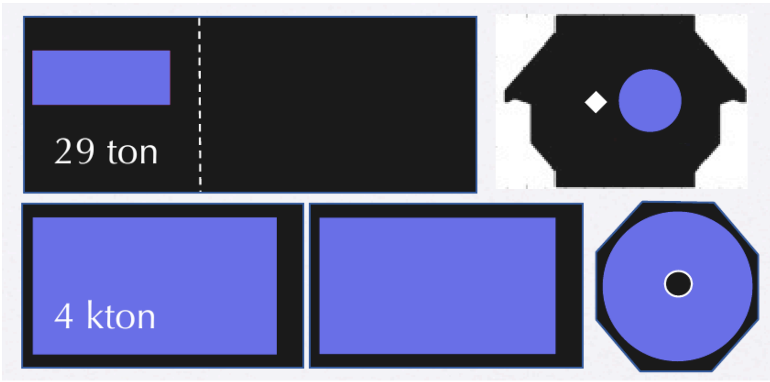
short, with typical EM shower profile

Analysis Challenge for ν_e

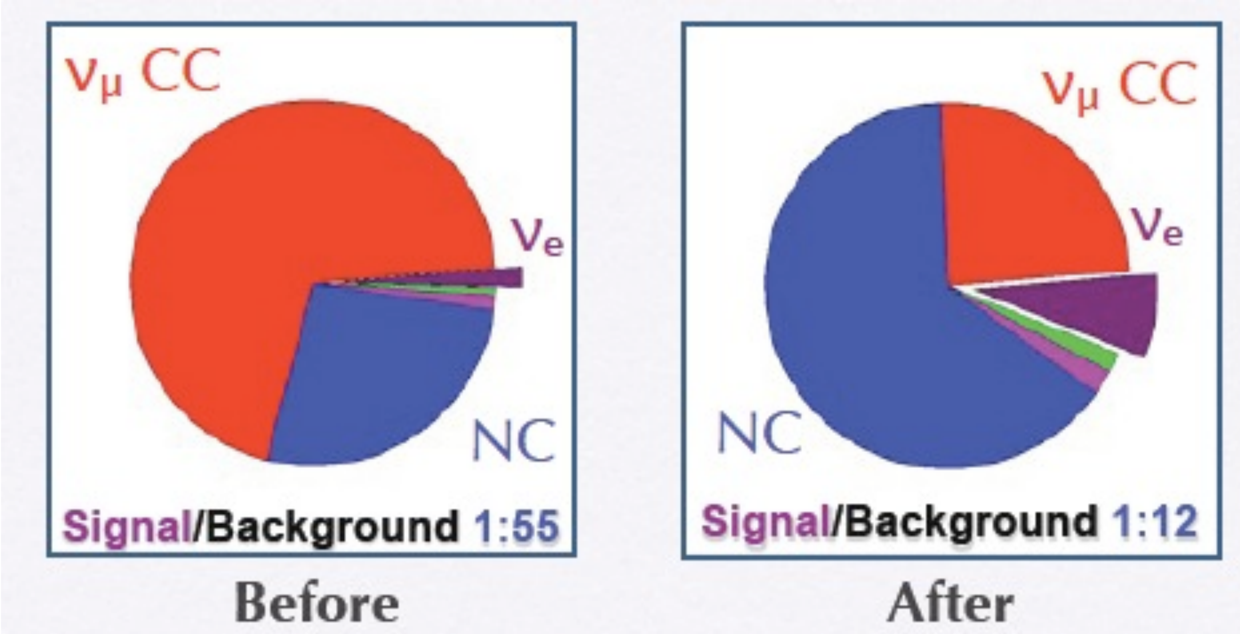
- Construct a selection algorithm to reject background and select ν_e
- Measure the background spectrum in the near detector.
- Use near detector measurement to predict far detector background.
- Minimize dependence on Monte Carlo.
- Carry out blind analysis. Check background estimates with independent samples.

Selecting ν_e events

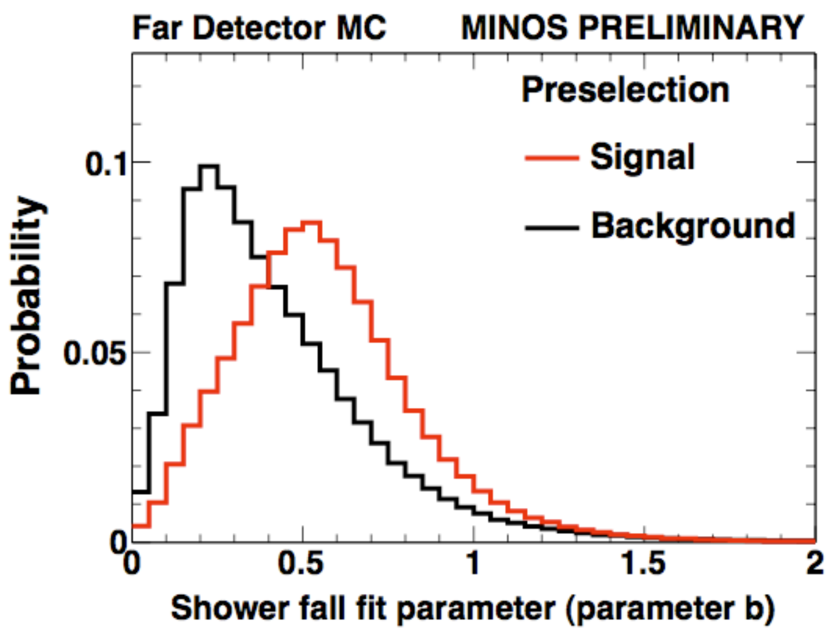
- **Basic cuts** to ensure data quality:
  - Beam quality and detector quality cuts.
  - Fiducial volume cuts:
  - Cosmic rejection cuts based on steepness.
- **ν_e preselection cuts** to reduce background.
- **ν_e selection cuts** based on shower topology

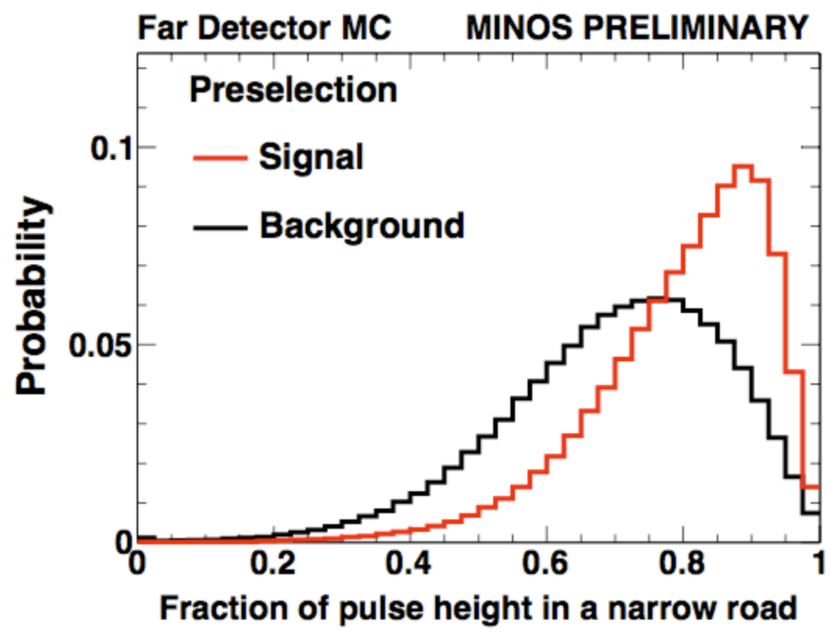


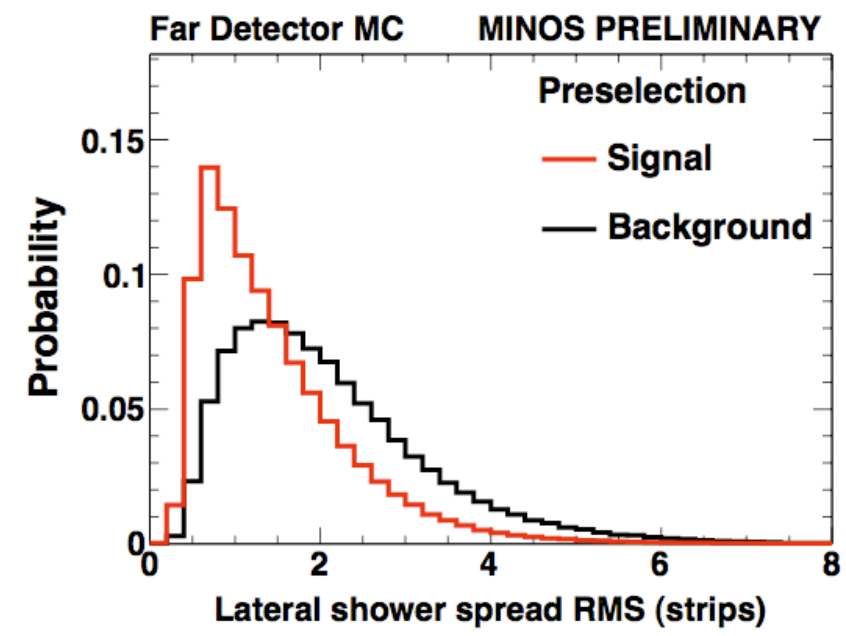
Preselection requirements:
Track length < 25 planes.
Track like length < 16 planes.
Reconstructed energy 1-8 GeV.
At least one shower and 4 contiguous planes with > 0.5 MIP energy units.



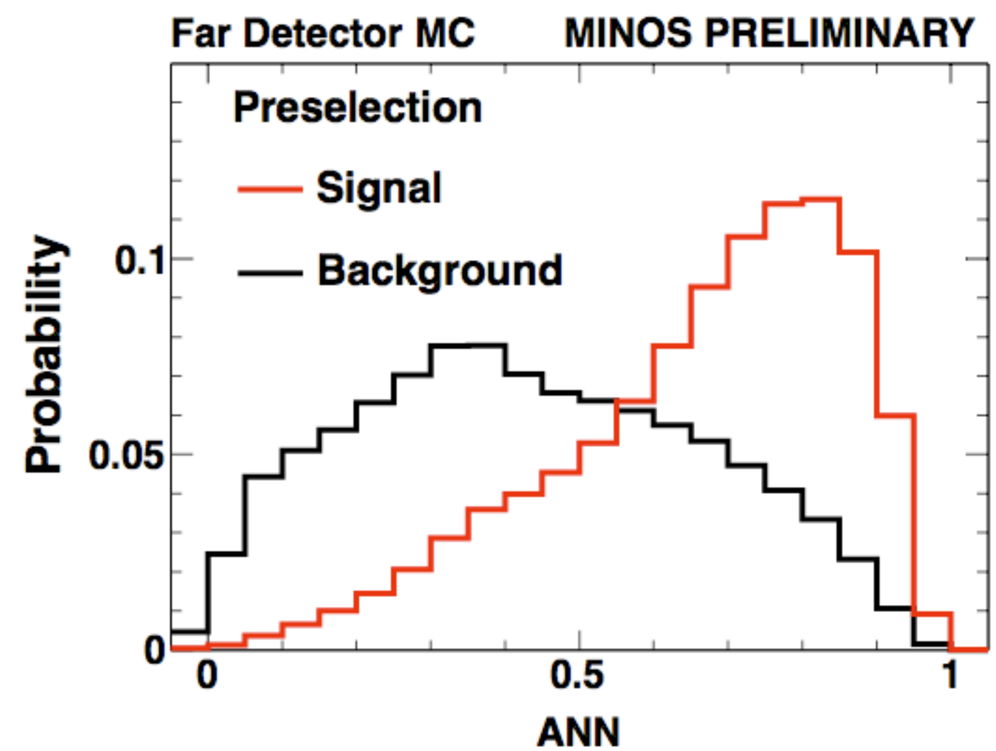
Selecting ν_e Events with Artificial Neural Net(ANN)







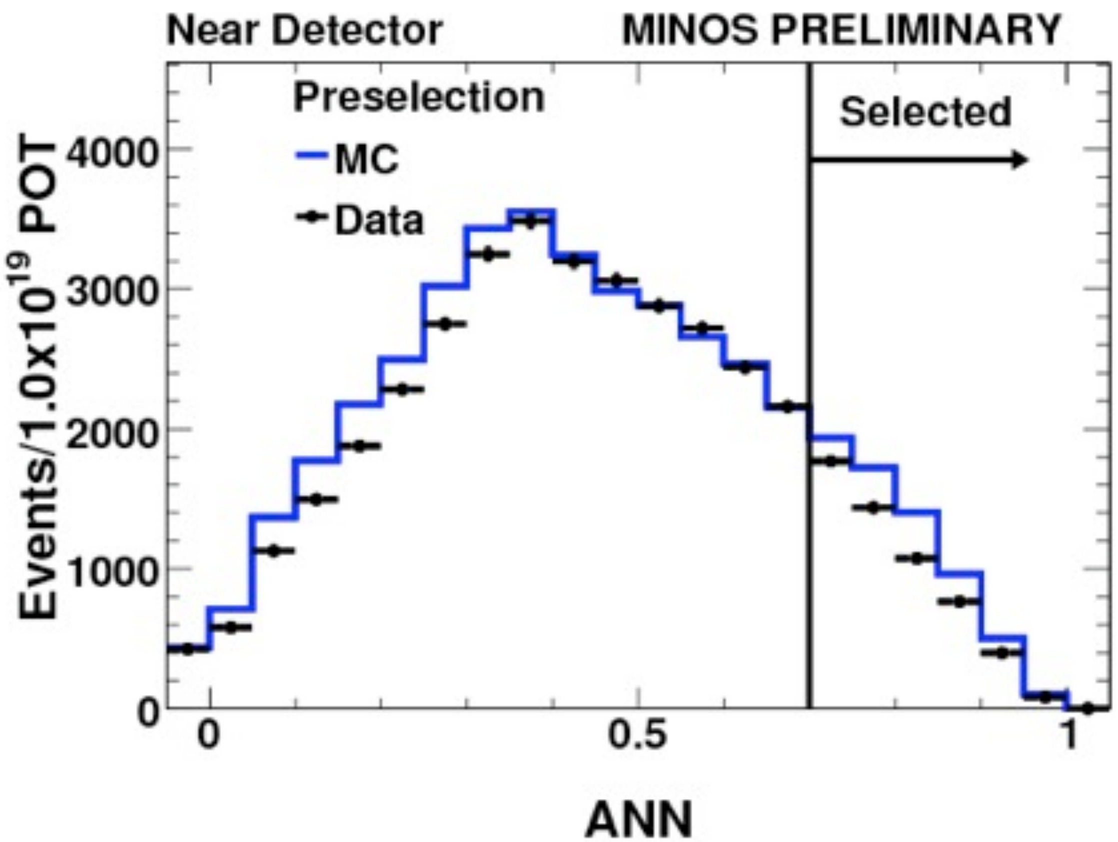
- 11 variables chosen describing length, width and shower shape
- ANN algorithm achieves:
  - signal efficiency 41%
  - NC rejection >92.3%
  - ν_μCC rejection >99.4%
  - signal/background 1:4 (chooz limit)

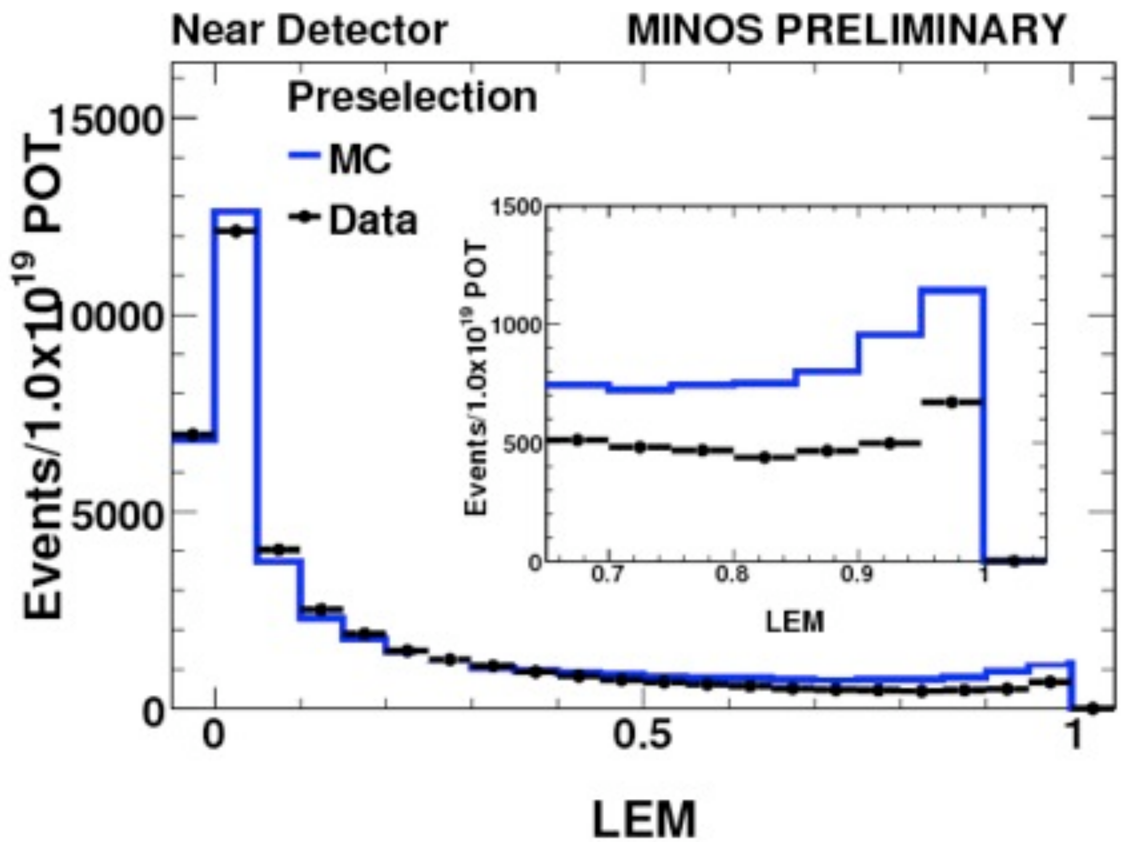


Primary method

$\Delta m^2_{32}=0.0024\text{eV}^2$

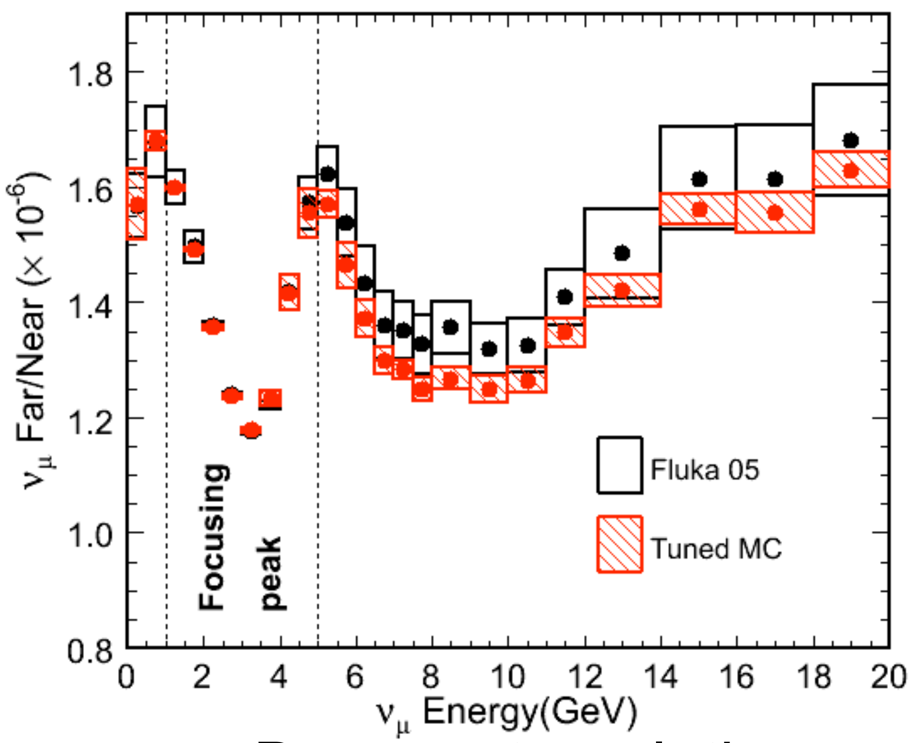
Near detector selection





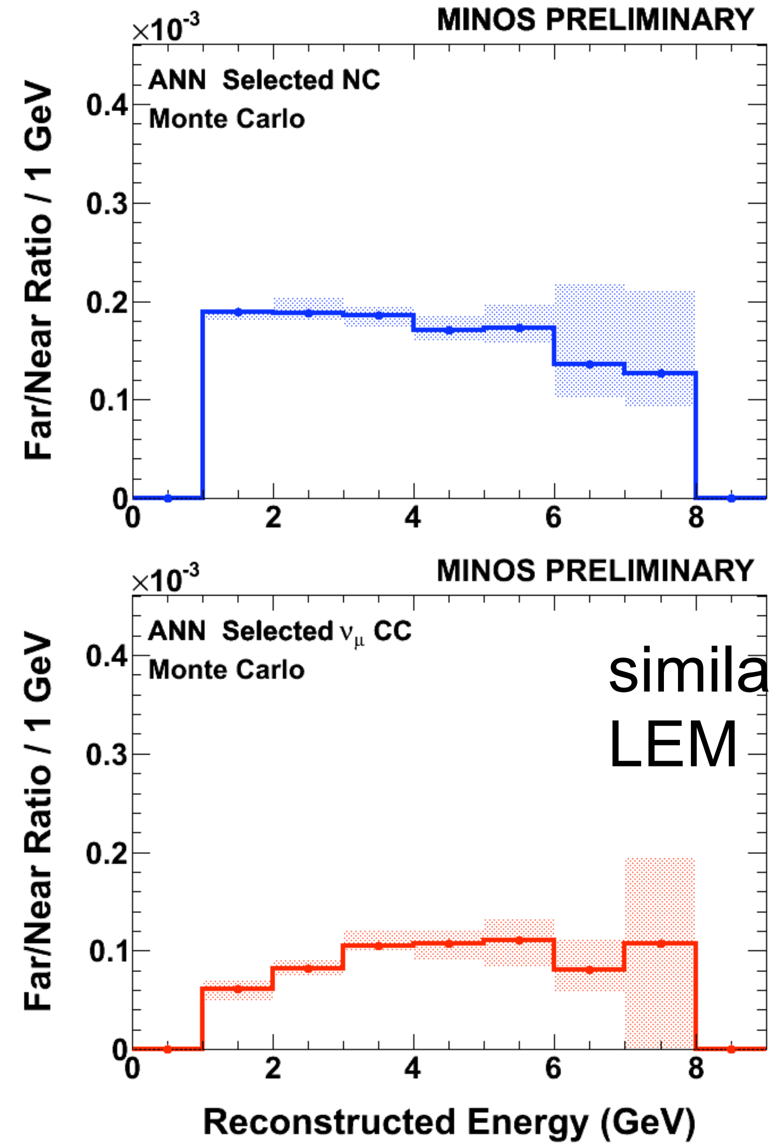
- ANN selected: 5524 events/10^{19} POT
- LEM selected: 3528 events/10^{19} POT
- Background is composed of CC (with invisible muons), NC, and νe contamination in the beam.
- MC does not model the absolute background well, but the CC/NC ratios have better control. Electron neutrino Contamination well modeled.
- We also use ν_μ charged current data with muon removed to check our background calculation.

Extrapolating background to FAR



Beam extrapolation

- MC used to correct
- Fiducial mass
- Energy smearing
- CC oscillation
- PID efficiency for
- detector diff.
  - Fibers
  - readout
  - light level
  - gain calibration
  - cross talk, etc.



similar for LEM

ANN far ≃ 5524 (near) X 1.3 10^{-6} X 4000 ton/29 ton X 3.14 10^{20} POT /10^{19}POT

≃ 31 events => further corrections => 27

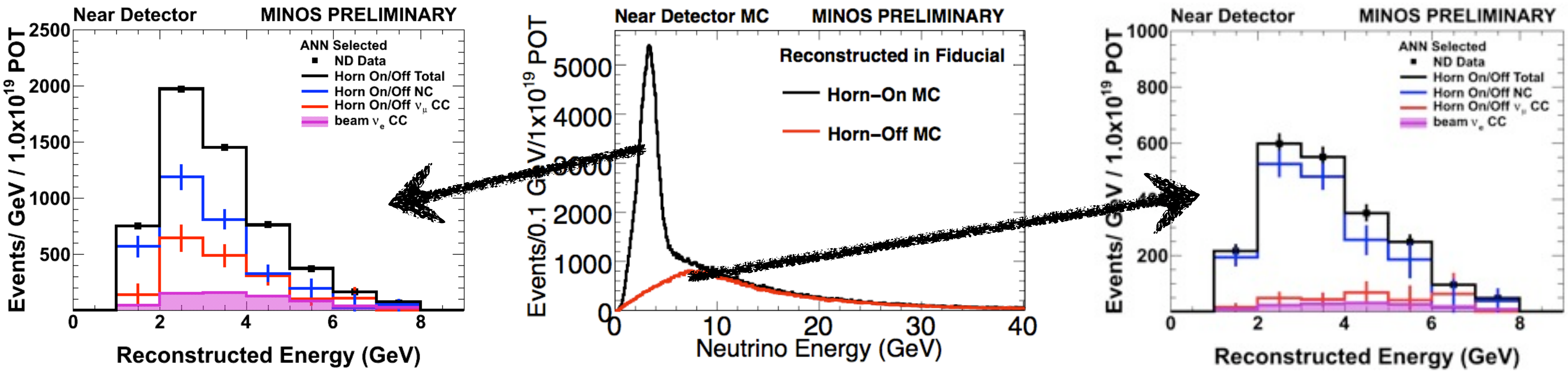
LEM far ≃ 3528 (near) X 1.3 10^{-6} X 4000 ton/29 ton X 3.14 10^{20} POT /10^{19}POT

≃ 20 events => further corrections => 22

To get more accurate answers need to separate CC (with invis. muons) and NC backgrounds, use spectrum and account for detector differences.

CC/NC separation

5524 evts



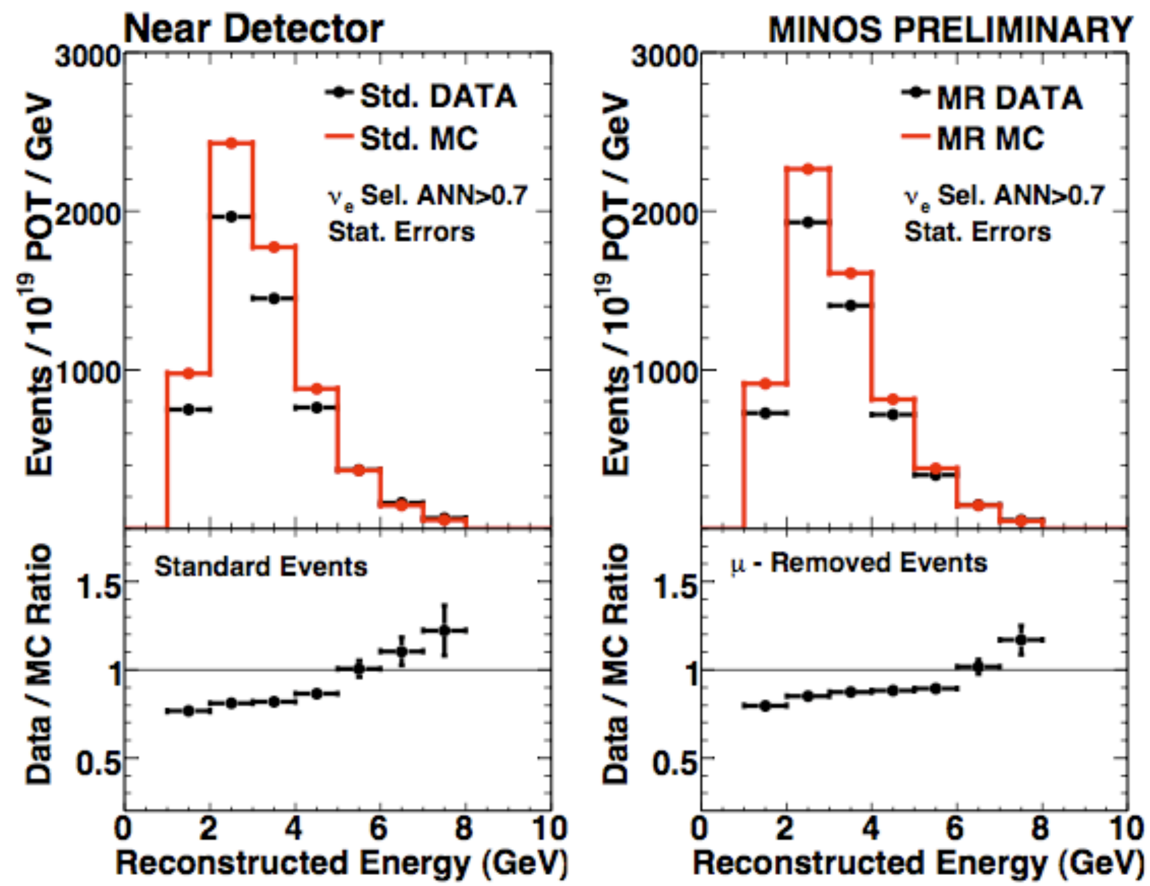
Horn on spectrum has both CC NC contributions

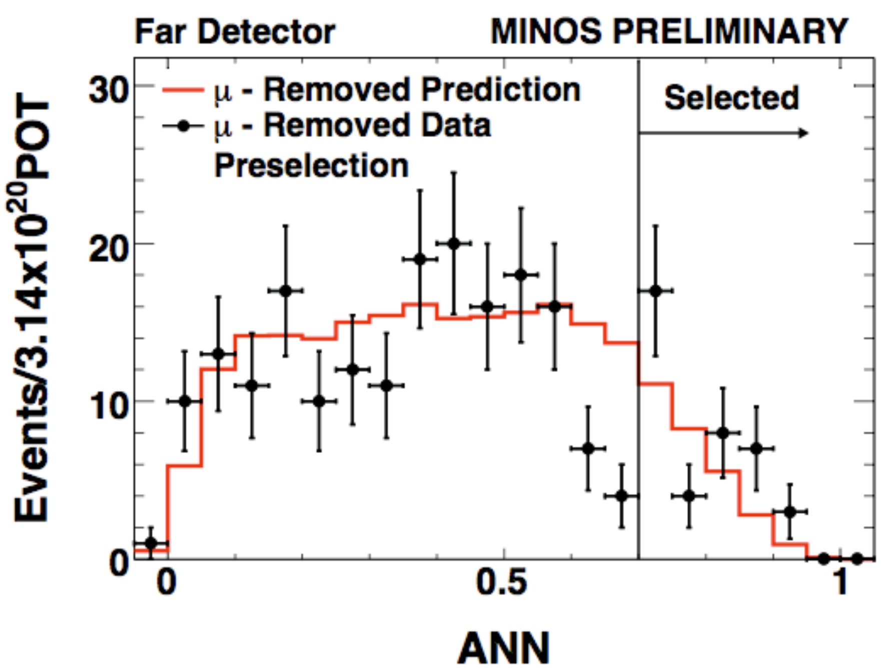
Horn off has mainly NC because CC have longer muons and get rejected

- Minimize dependence on MC by utilizing data with horn/off spectrum
- Calculate the CC/NC fractions using MC input: ratios of CC/NC for Hon and Hoff and the beam contamination ν_e in reco. energy bins.
- Statistical error from Hoff data, systematics from how well ratios are known and stable against cuts.
- Final backg numbers are: 27+- 5+-2 for ANN, and 22+-5+-3 for LEM, errors dominated by modeling of detector differences.

Muon removed showers from CC

- Allows two checks
  - Independent background calculation.
  - Complete check of analysis by looking at far events without looking at signal.





ANN (Primary):

observe 39 events
expect 29 +- 5(stat) +- 2(syst)

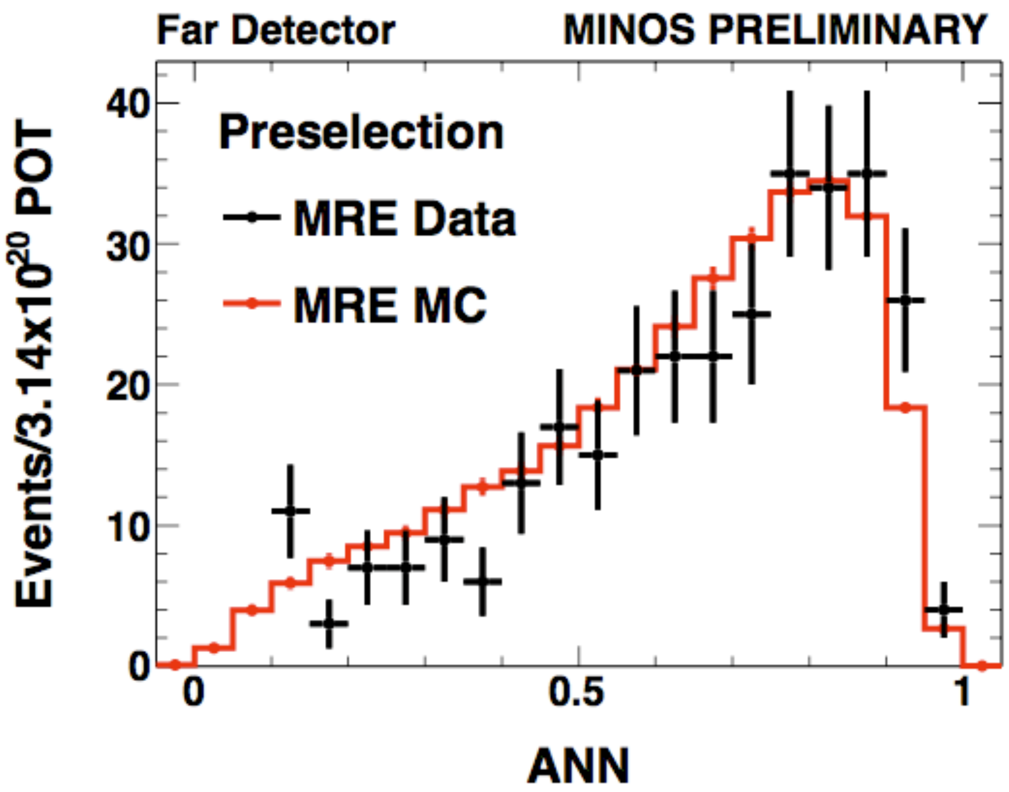
discrepancy between MRCC data and MC is very similar to the discrepancy in standard data and MC, both in shower shape and energy. We can correct the MC by this discrepancy.

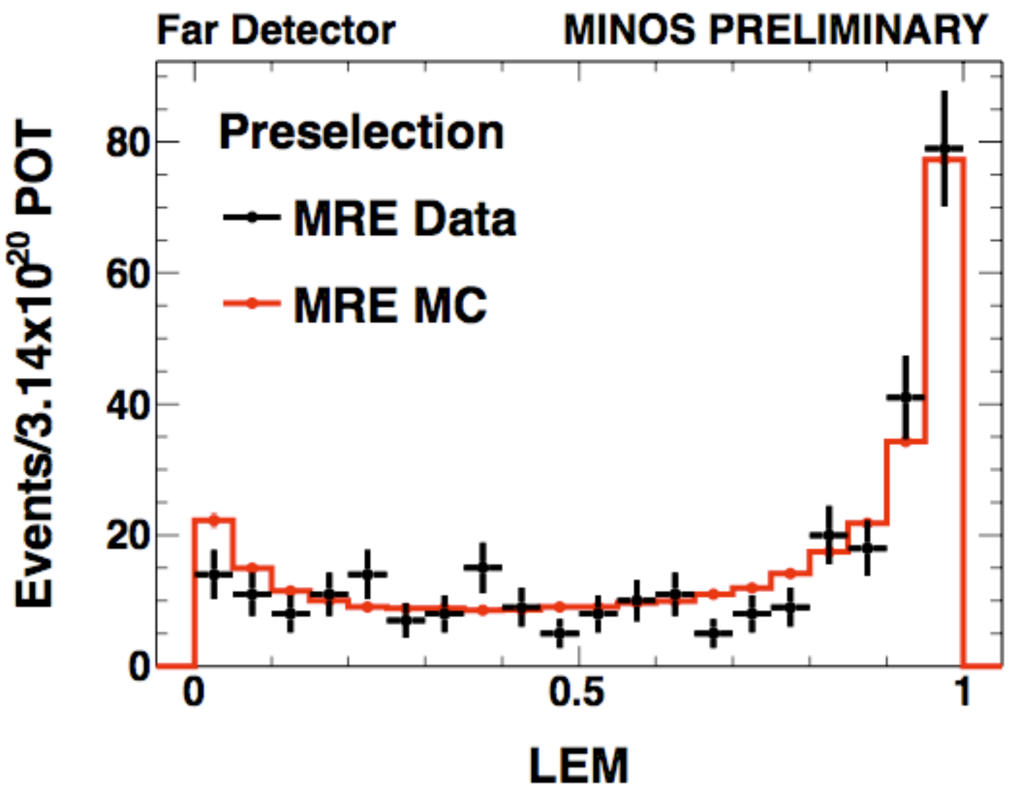
	Total	NC	ν_μ CC	ν_τ CC	ν_e beam
Horn on/off	**27**	**18.2**	**5.1**	**1.1**	**2.2**
MRCC	28	21.1	3.6		

Two methods agree

Muon removed electron added

- Adding the electron to the muon removed events, present good agreement in PID.
- Verification of signal selection efficiency.





- **We observe a total of 159 events.**
- **We expect 152±13(stat)±12(sys) events.**

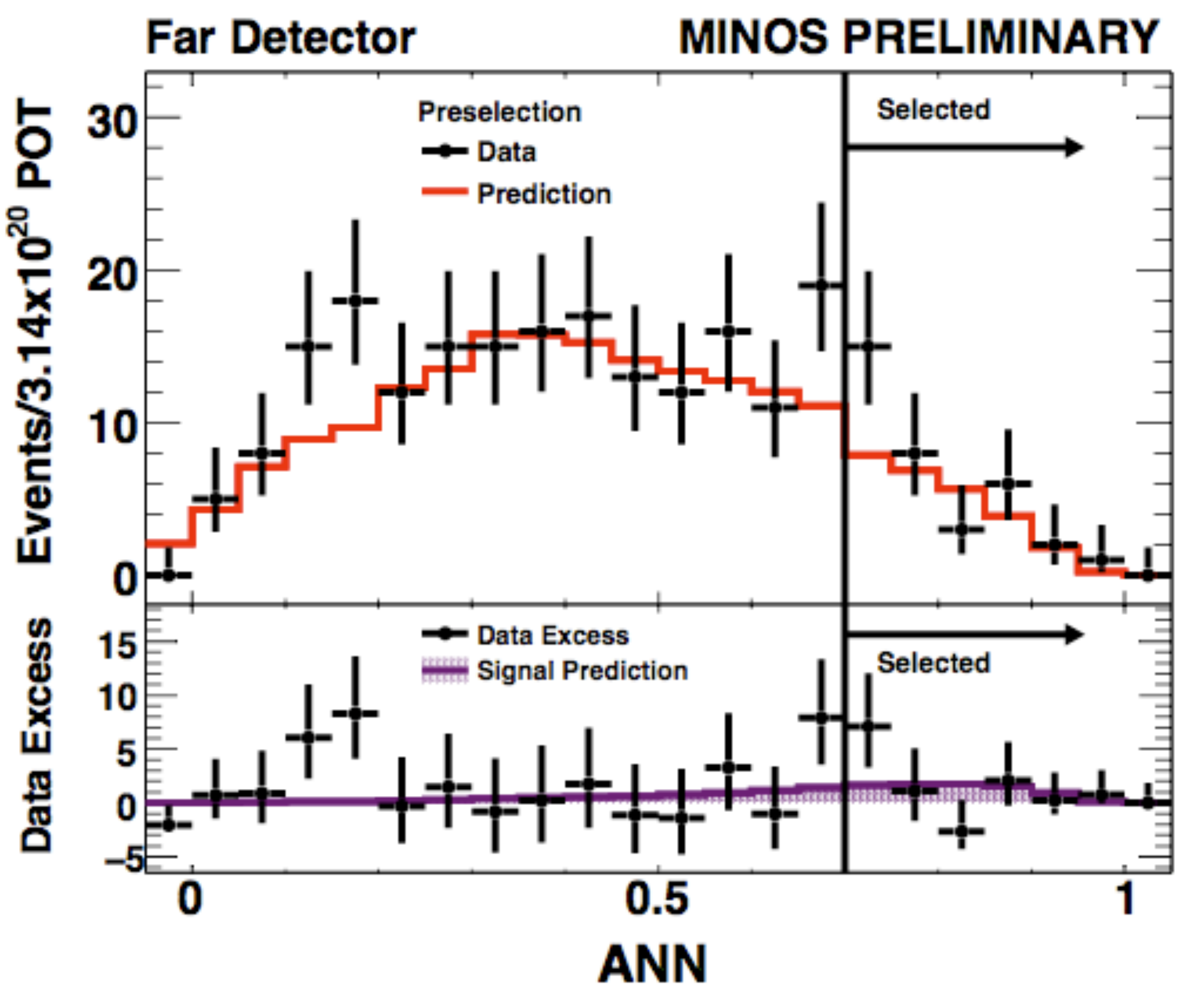
- We observe a total of 180 events.
- We expect 176±13(stat)±16(sys) events.

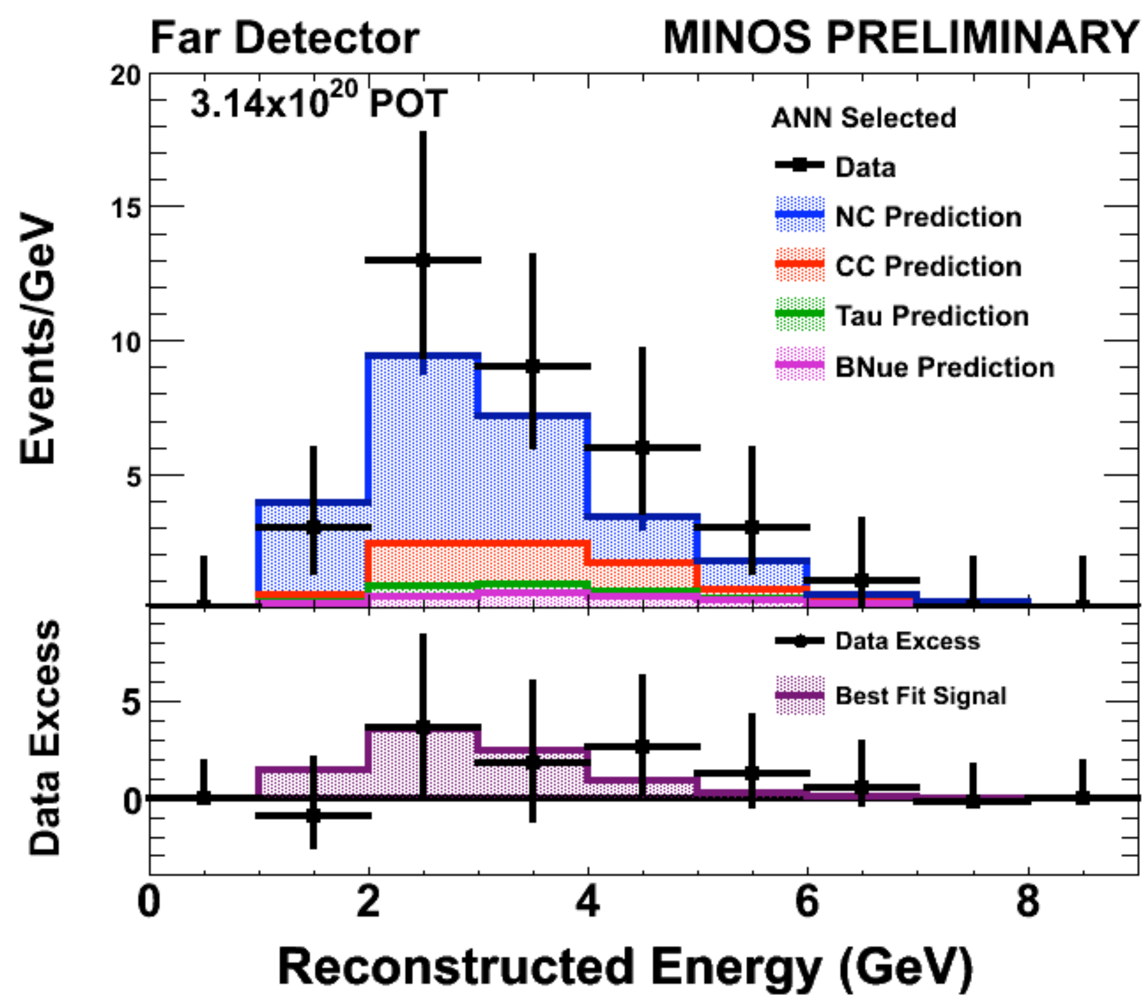
We model the signal well.

At Chooz limit expectation is 6-12 events depending on the value of the CP phase.

Signal region examination (1)

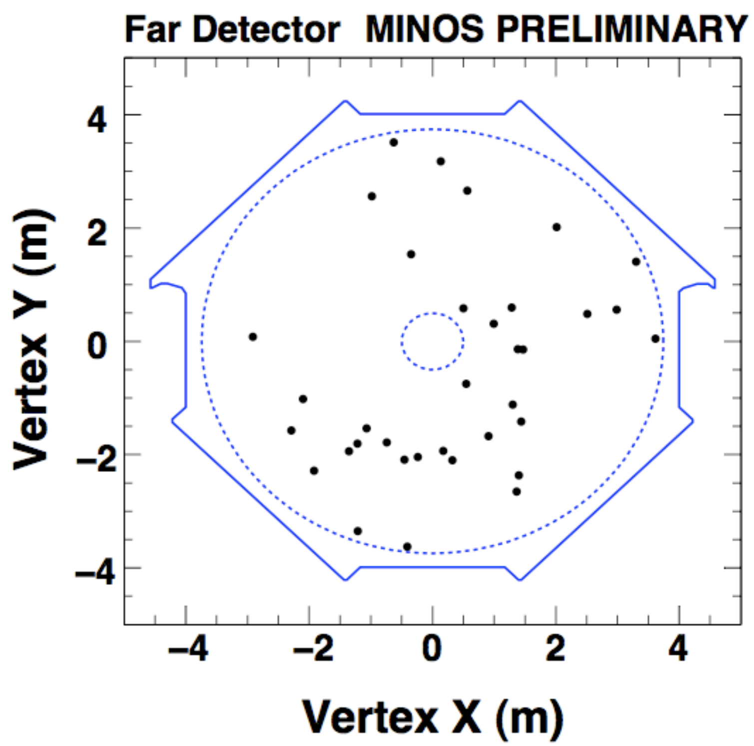
ANN (Primary Selection Method)

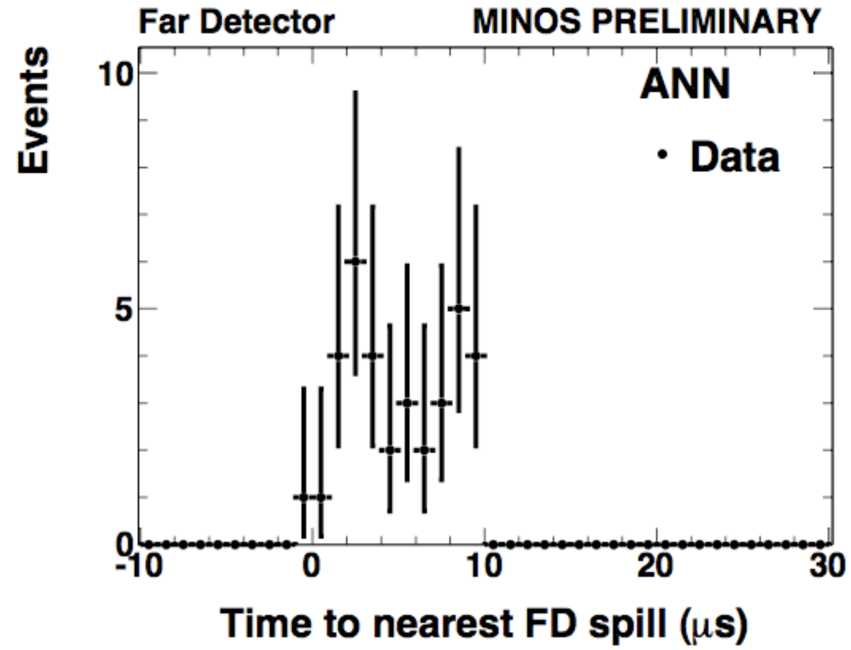


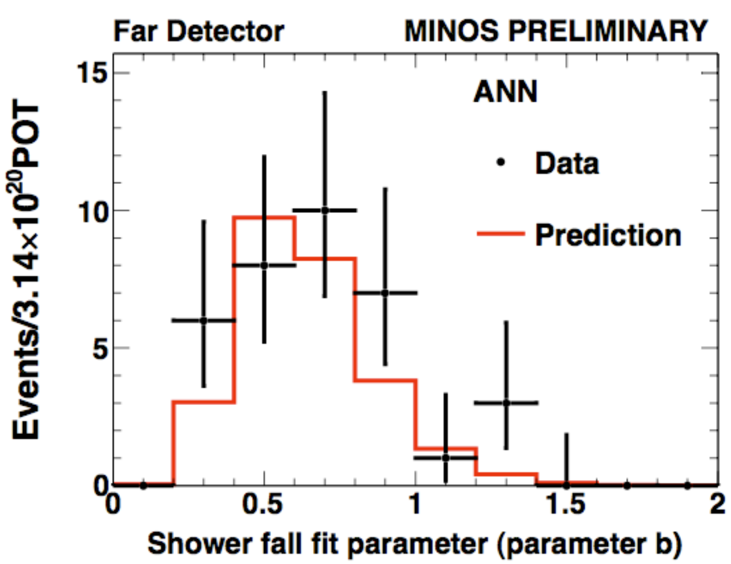


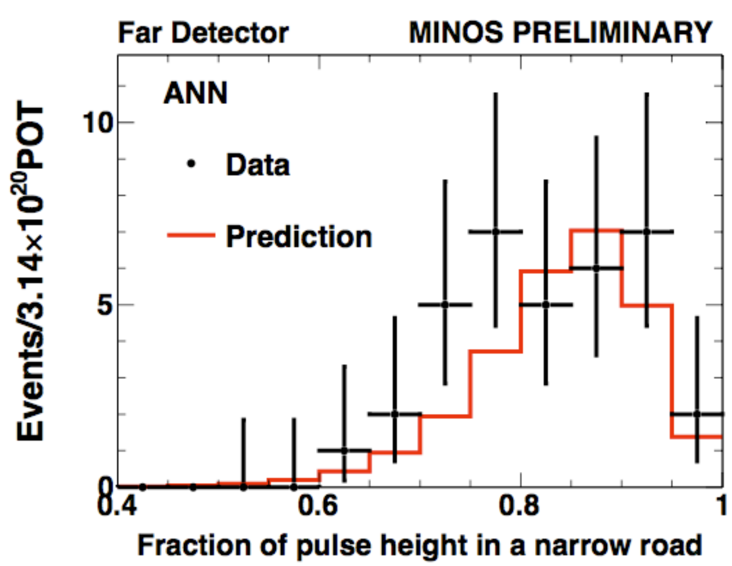
Observation: 35 events
Expected Background: 27 +- 5(stat) +- 2(syst) events

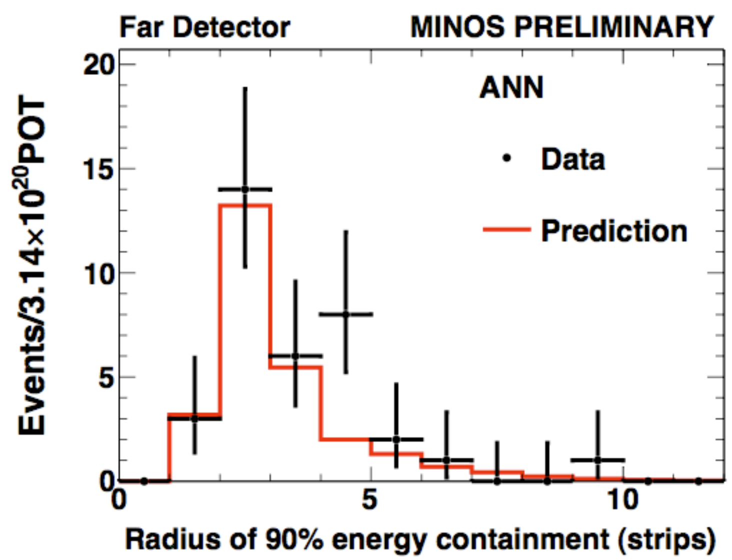
Far Data Distributions





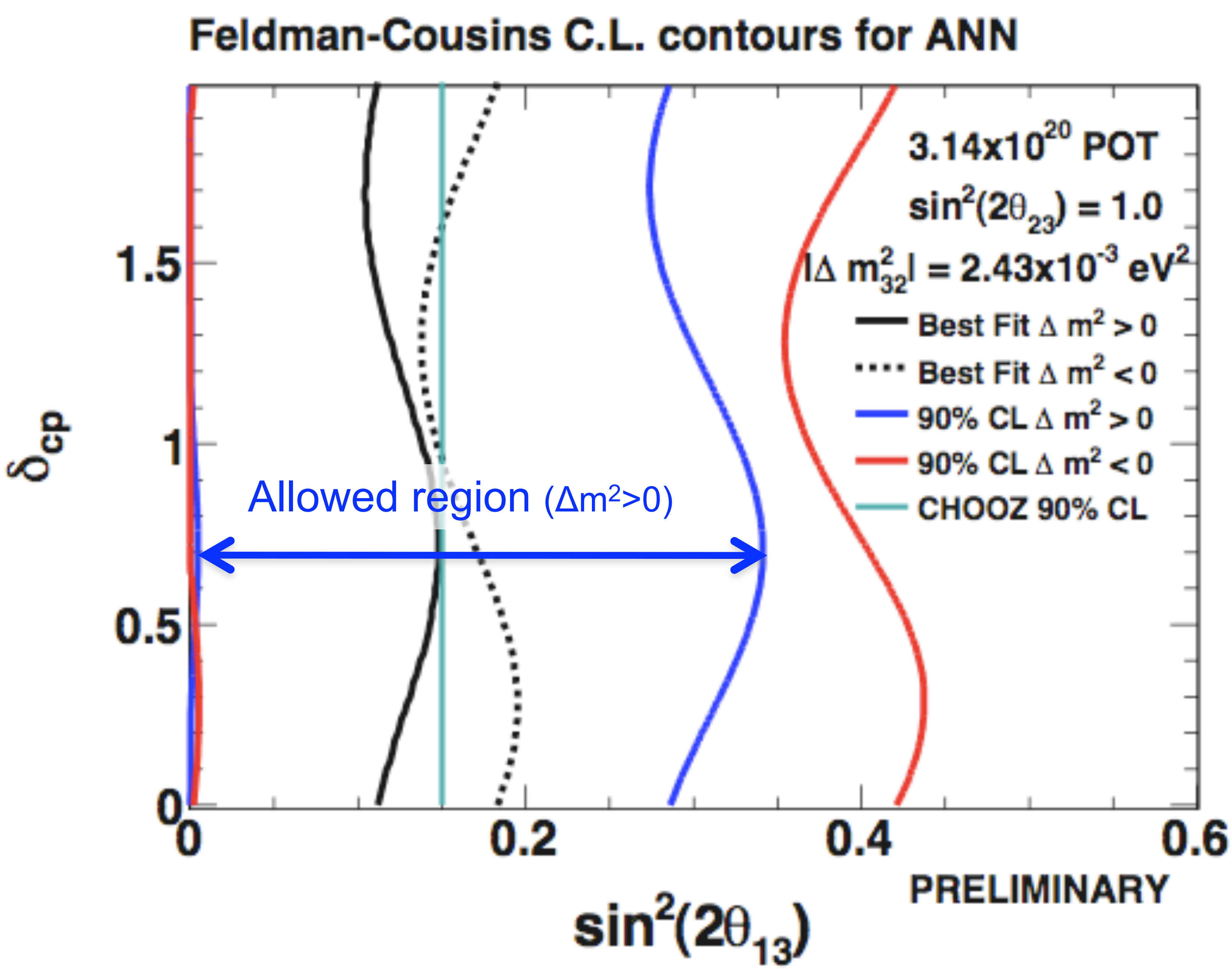






Allowed Region

- A Feldman-Cousins method was used
- Fit simply to the number of events from 1-8 GeV, no shape or correlation information used.
- Best fit and 90% C.L. limits are shown:
  - for both mass hierarchies
  - at MINOS best fit value for Δm^2_{32} & $\sin^2(2\theta_{23})$



- **Results:**

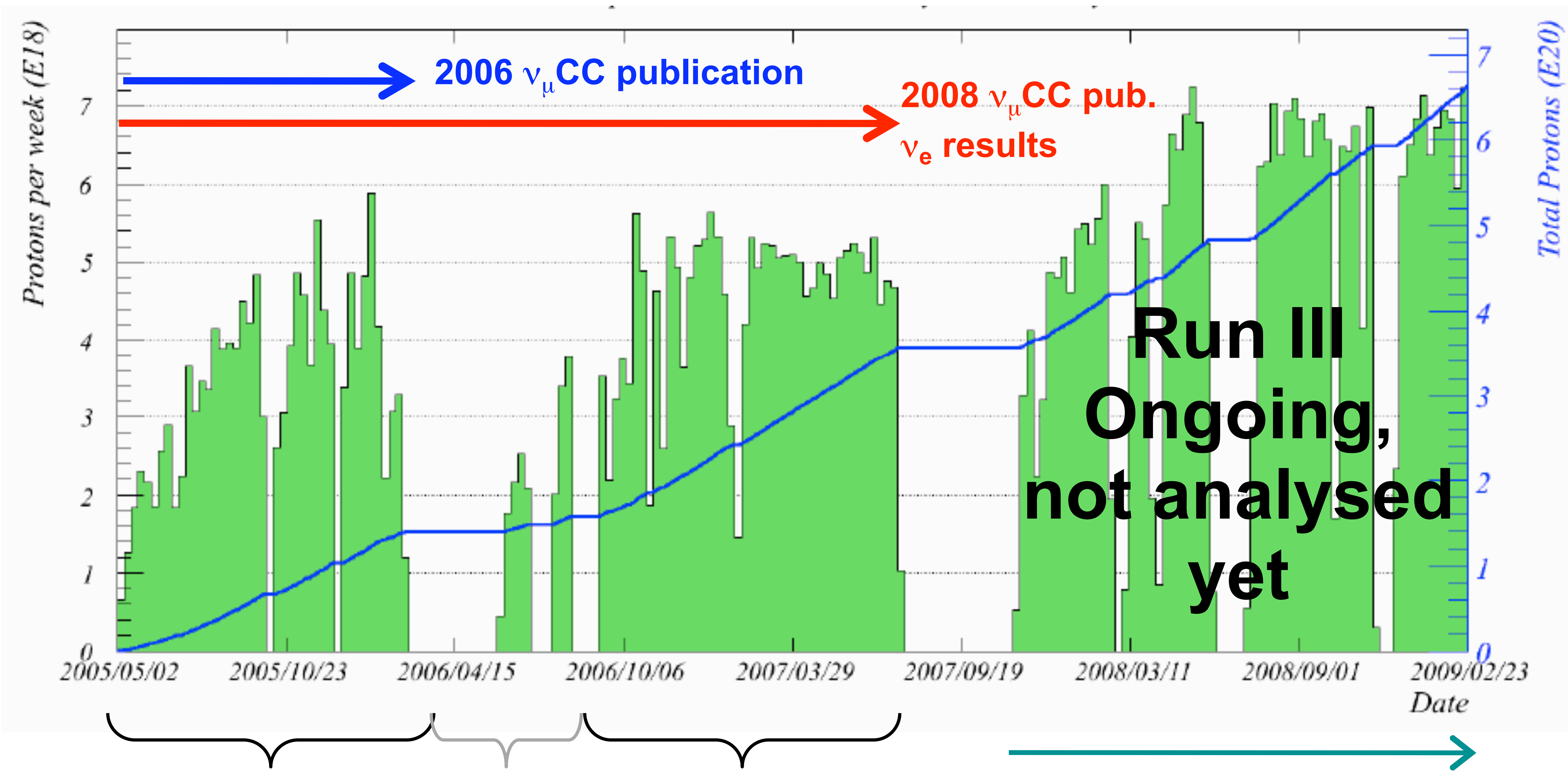
Normal hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.29$ (90% C.L.)

Inverted hierarchy (δ_{CP}=0):

$\sin^2(2\theta_{13}) < 0.42$ (90% C.L.)

Accumulated Beam Data



RUN I

1.27×10^{20} POT

Higher energy beam

0.15×10^{20} POT

RUN II

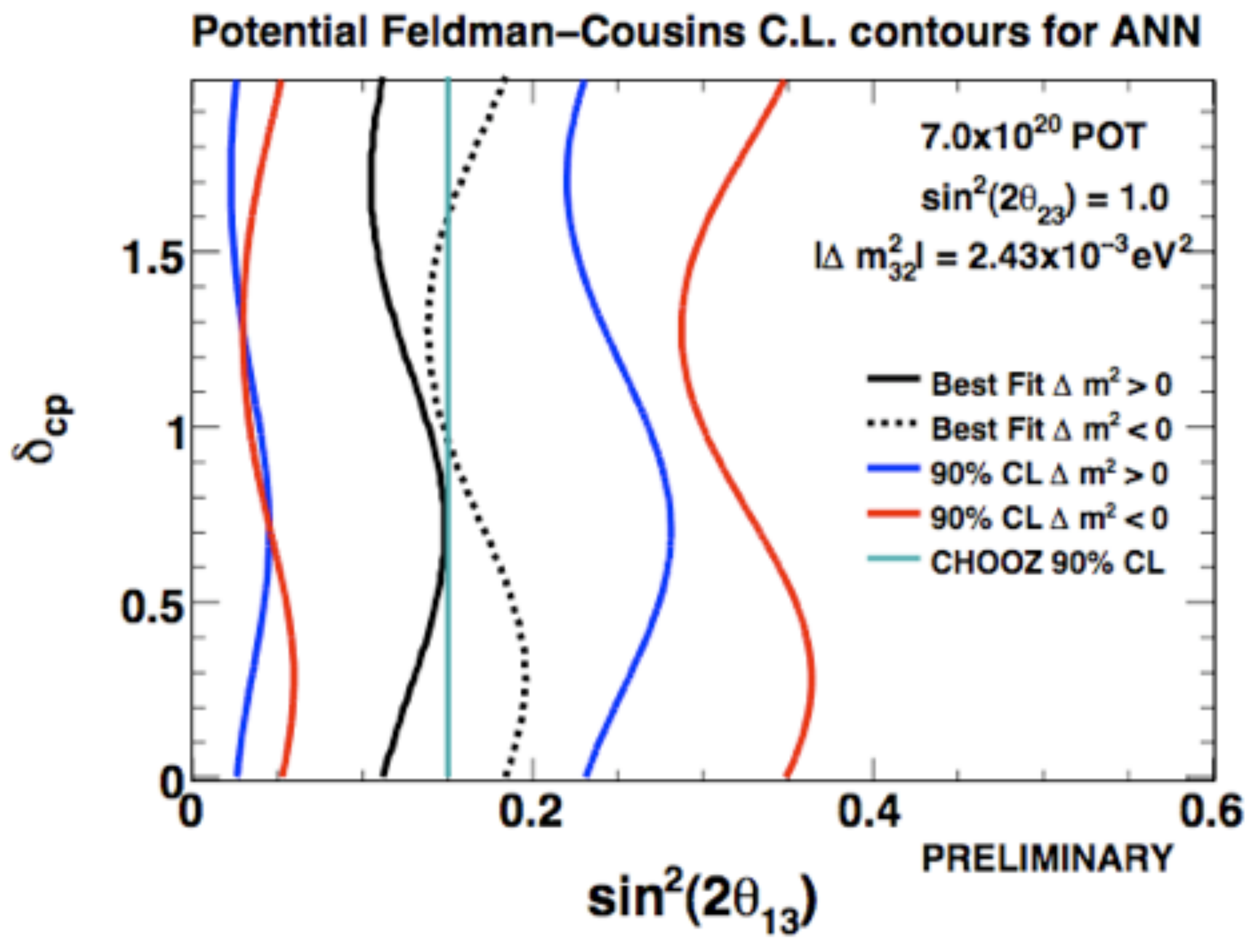
1.87×10^{20} POT

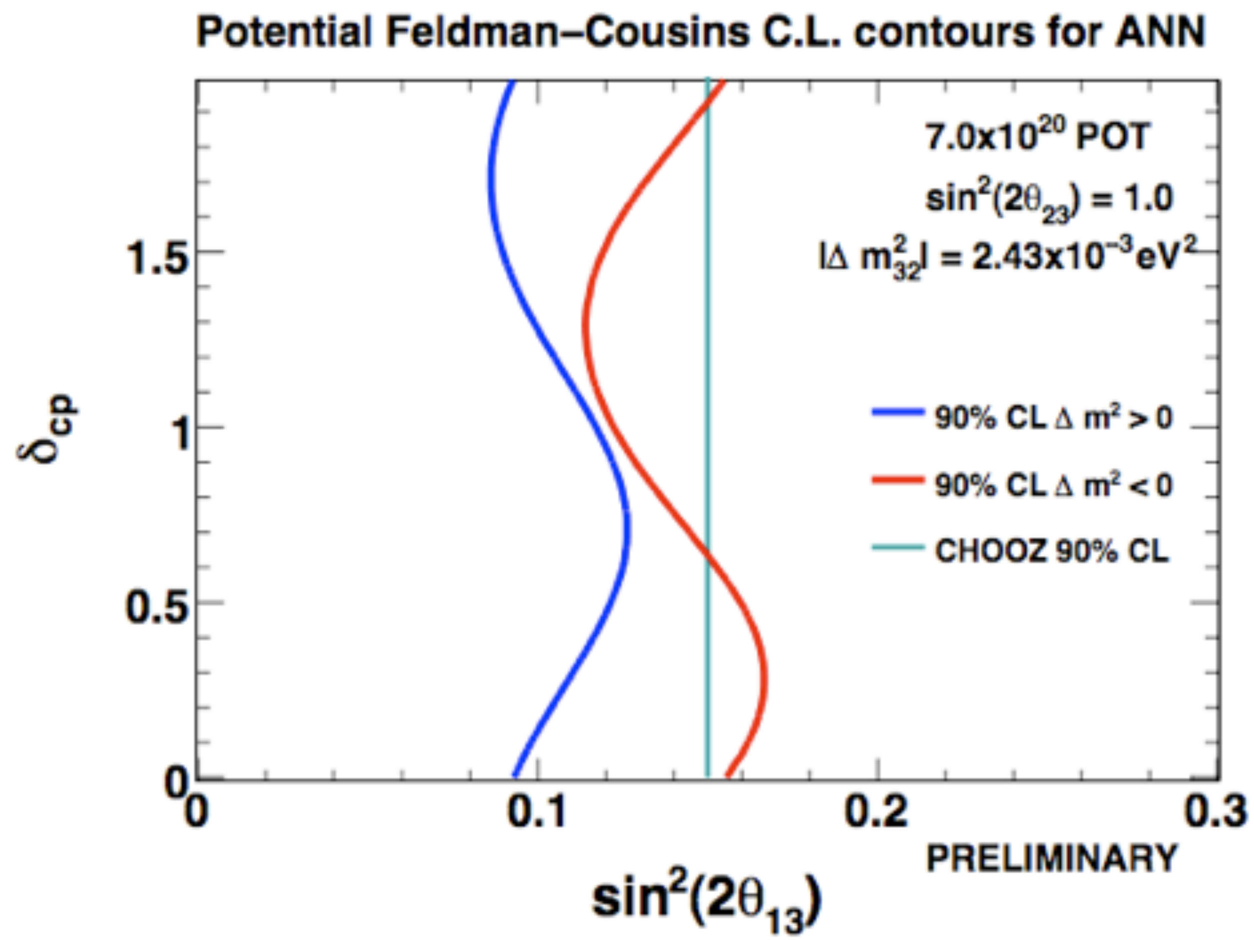
RUN III

$>3 \times 10^{20}$ POT

Future 90% CL contours

7.0 x10^{20} POT





Future measurement if data excess persists.

Future limit if excess cancels with more data.

- We have already doubled the data set.
- New Analysis is almost complete. Hopefully backg will be ~50 events.
- Signal at Chooz limit expected ~20.

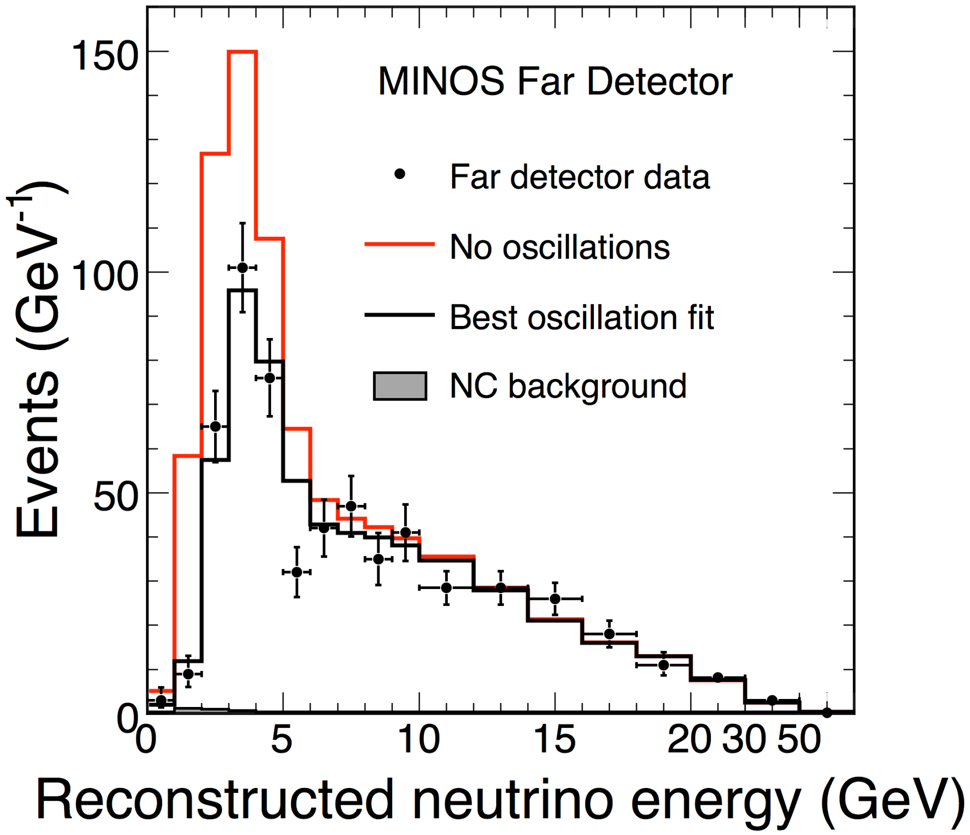
Far Detector ν_μ CC Data

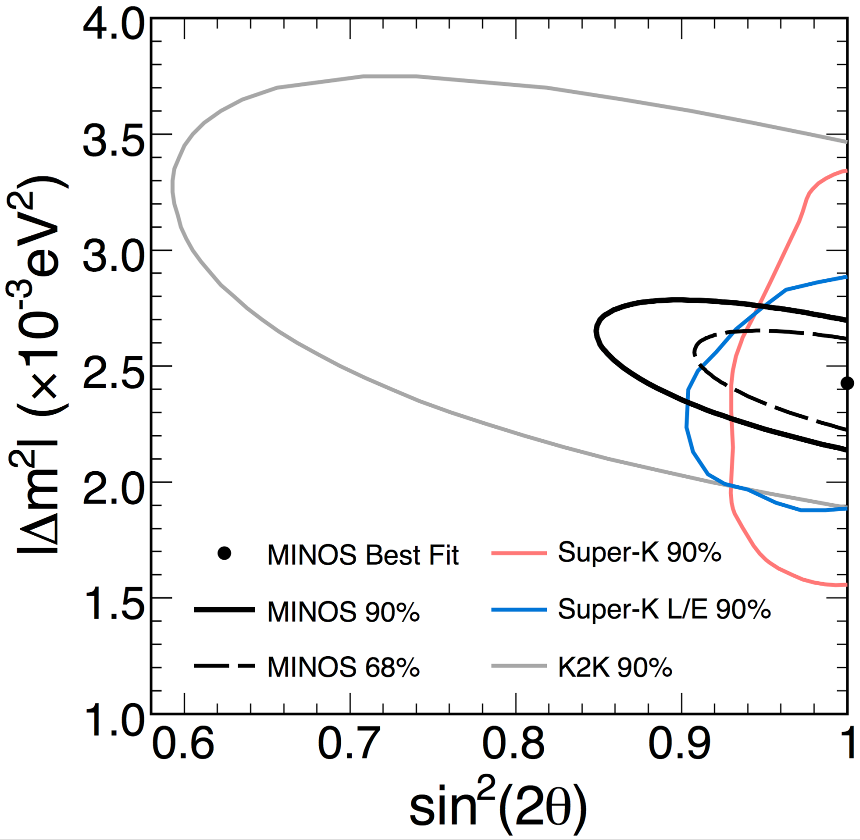
- See strong energy dependent distortion of spectrum
- Prediction using near detector data.
- Energy spectrum fit with the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

$|\Delta m^2_{32}|=(2.43\pm0.13)\times10^{-3}\ eV^2$
at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$
at 90% C.L.





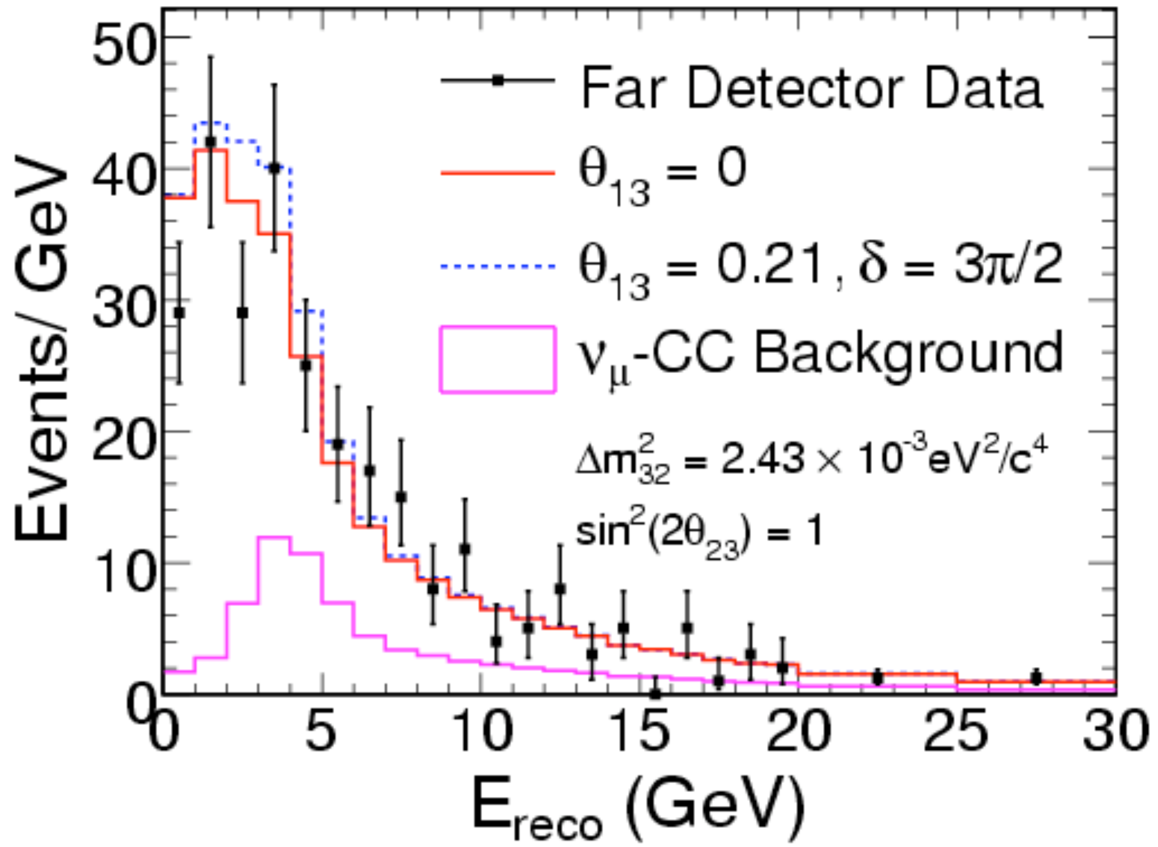
Neutral Current Analysis

- General NC analysis overview:
  - All active neutrino flavours participate in NC interaction
  - Mixing to a sterile-ν will cause a deficit of NC events in Far Det.
  - Assume one sterile neutrino and that mixing between ν_μ, ν_s and ν_τ occurs at a single Δm^2
- Survival and sterile oscillation probabilities become:

$$P(\nu_\mu - \nu_\mu) = 1 - \alpha_\mu \sin^2(1.27\Delta m^2 L/E)$$

$$P(\nu_\mu - \nu_s) = \alpha_s \sin^2(1.27\Delta m^2 L/E)$$

- ($\alpha_{\mu,s}$ = mixing fractions)



Simultaneous fit to CC and NC energy spectra yields the fraction of ν_μ that oscillate to ν_s:

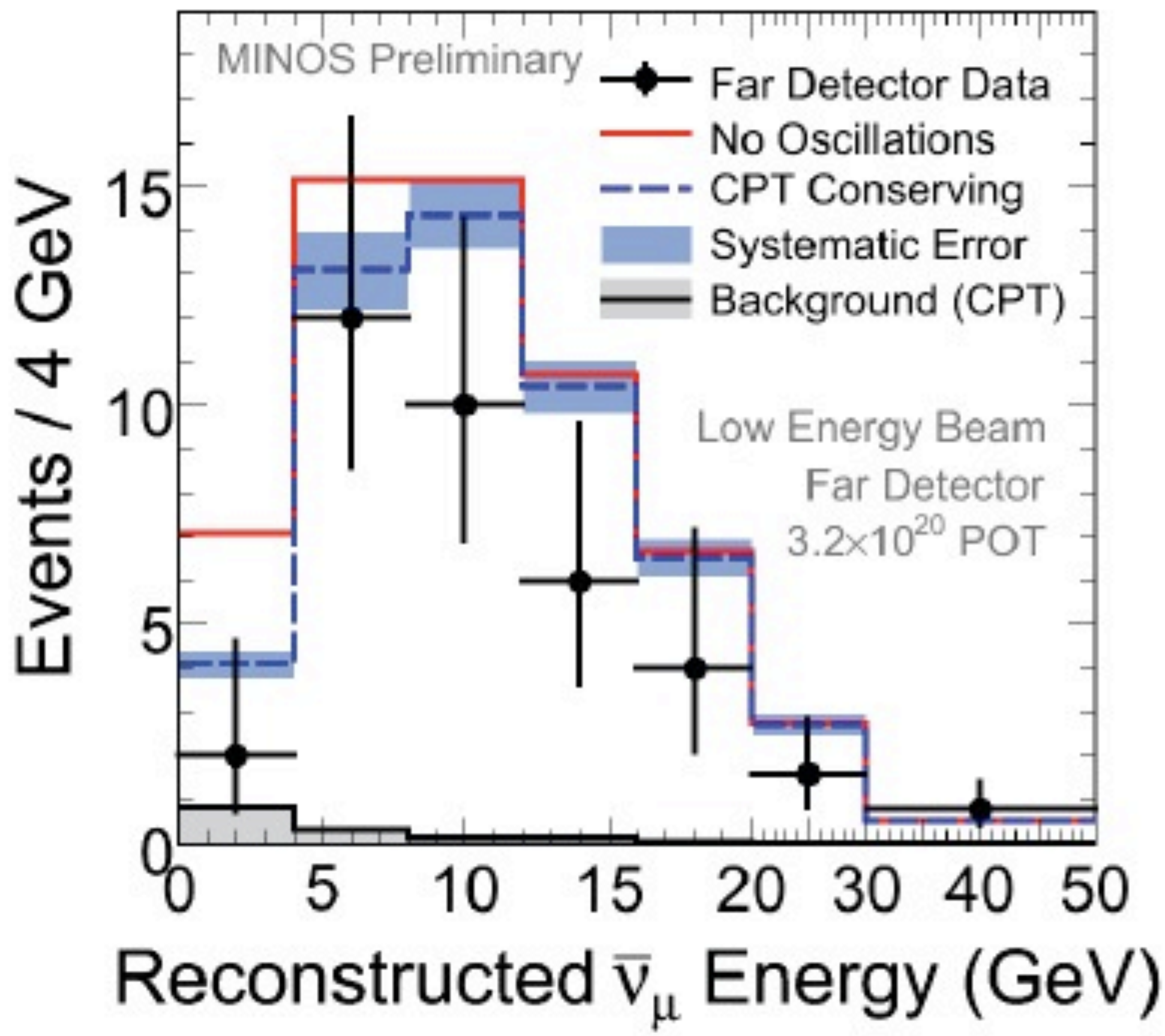
$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}\text{(stat.+syst.)}$$

$$f_s < 0.68 \quad \text{(90\% C.L.)}$$

Far detector anti-ν_μ CC Data (using spectrum from the 7% contamination.)

- Observe **42 events** in the Far detector
- First direct observation of $\bar{\nu}_\mu$ in an accelerator long-baseline experiment

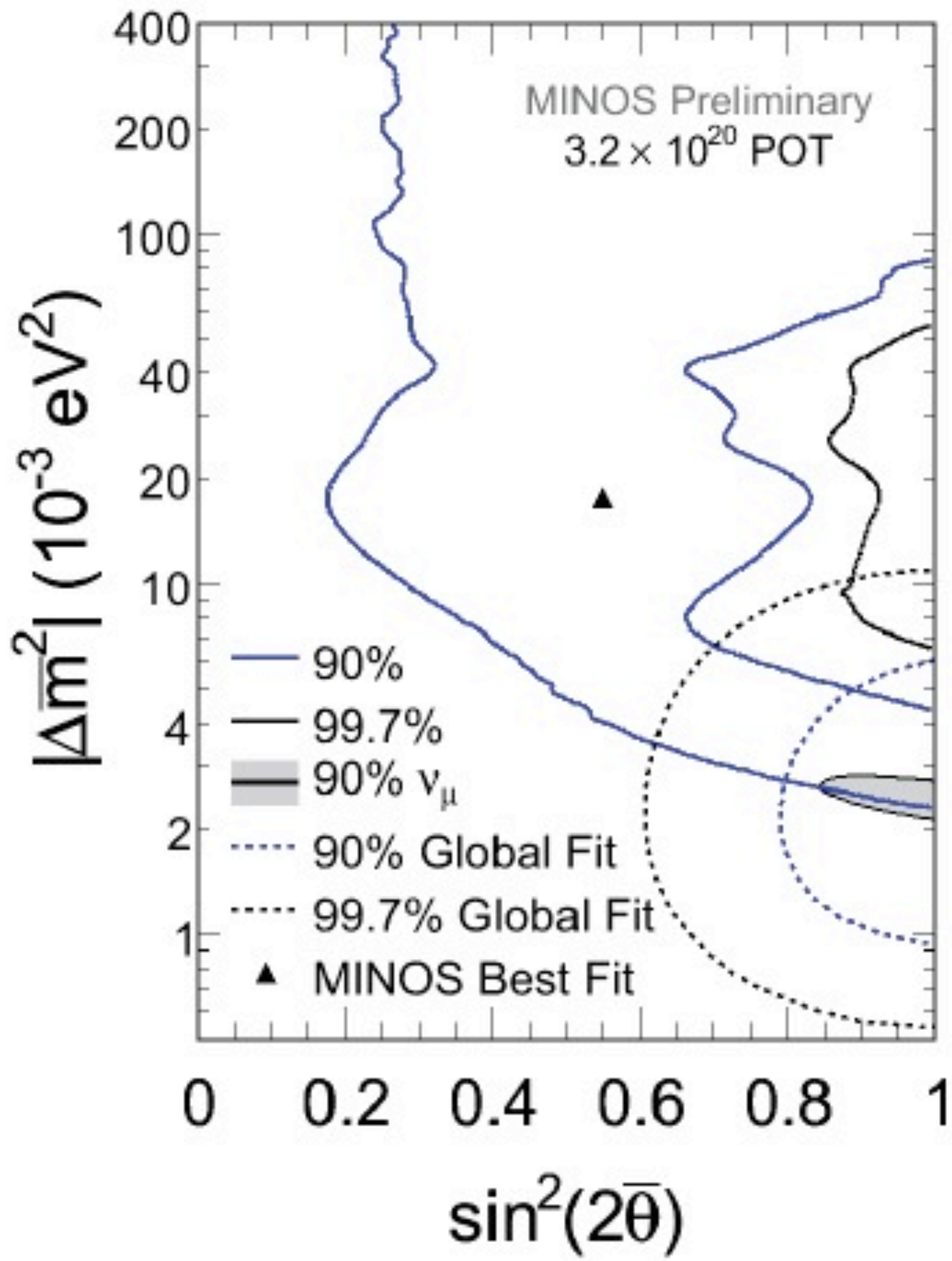
- Predicted events with CPT conserving oscillations:
  - 58.3 ± 7.6 (stat.) ± 3.6 (syst.)
- Predicted events with null oscillations:
  - 64.6 ± 8.0 (stat.) ± 3.9 (syst.)



Multiple Checks to make sure this is not syst. e.g. rock muons

Comparison to Global Fit

- Global fit to previous data
  - Super-Kamiokande dominates
  - Includes SK-I and SK-II data
  - M. C. Gonzalez-Garcia & Michele Maltoni, Phys. Rept. 460 (2008)
- MINOS data excludes previously allowed CPT violating regions of parameter space, particularly near maximal mixing



Sunday, December 13, 2009

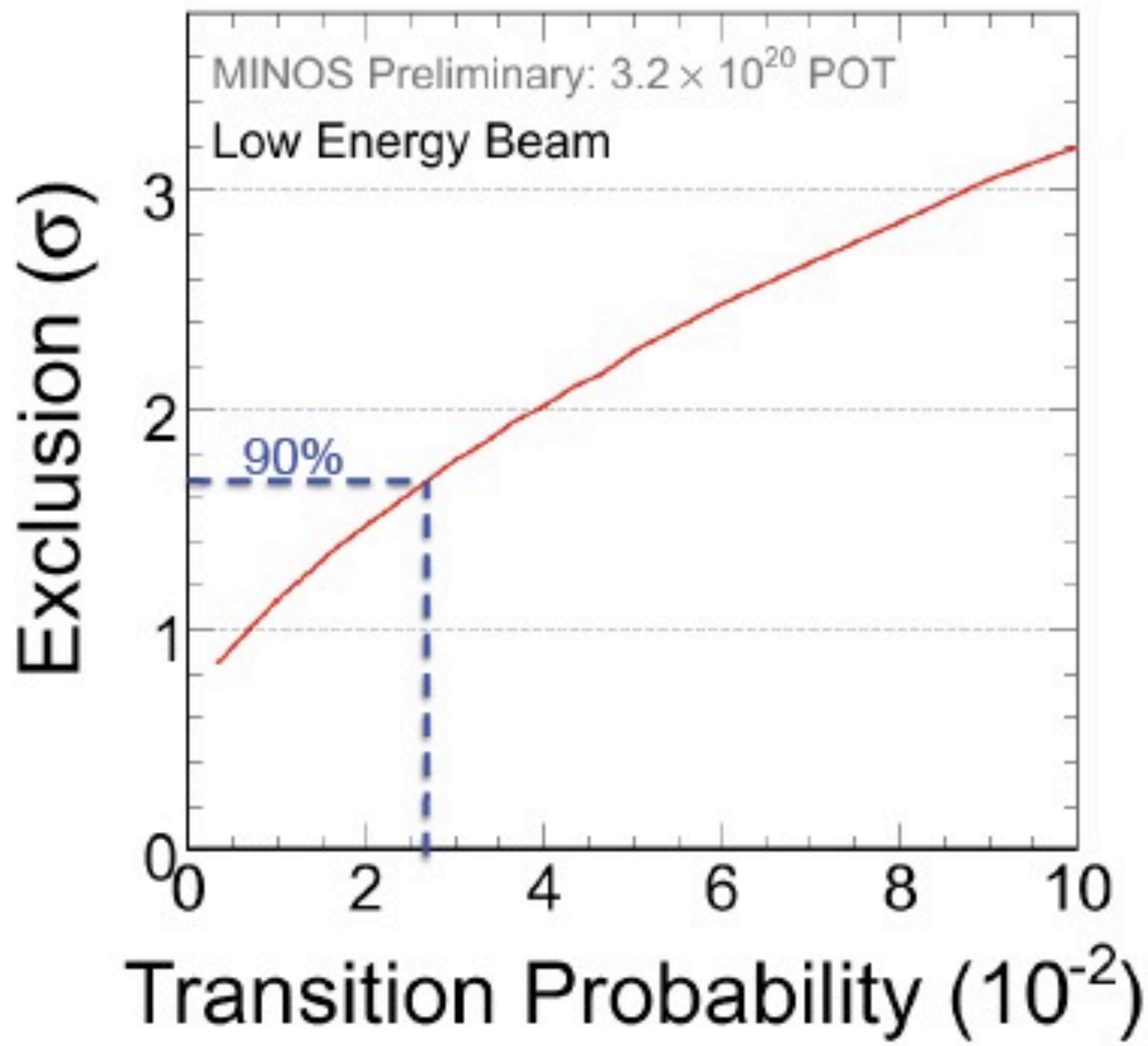
Results of Search for $\bar{\nu}_\mu$ Appearance

- MINOS observes **no appearance** of $\bar{\nu}_\mu$ in the NuMI beam
- 1-parameter fit for α using simple parameterisation

$$P(\nu_\mu \rightarrow \overline{\nu_\mu}) = \alpha \sin^2(2\theta) \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right)$$

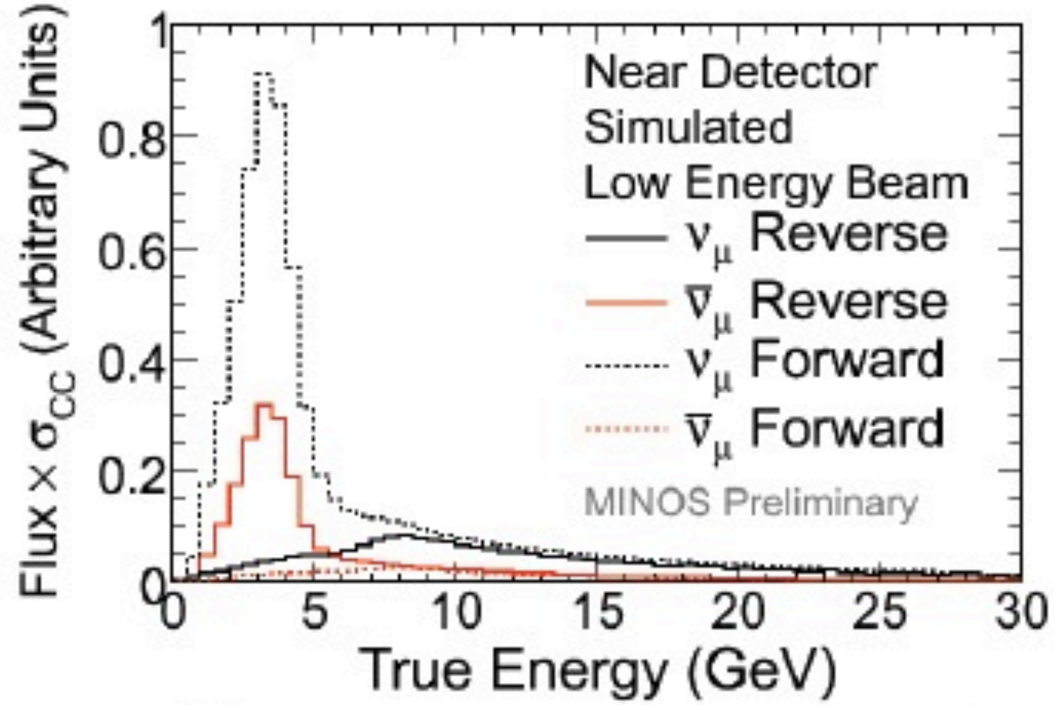
(θ and Δm^2 set to CPT conserving case)

- Uncertainty from $\bar{\nu}_\mu/\nu_\mu$ cross section ratio
- Result: limit fraction, α, of events transitioning from ν_μ to $\bar{\nu}_\mu$:
  - $\alpha < 0.026$ (90% C.L.)

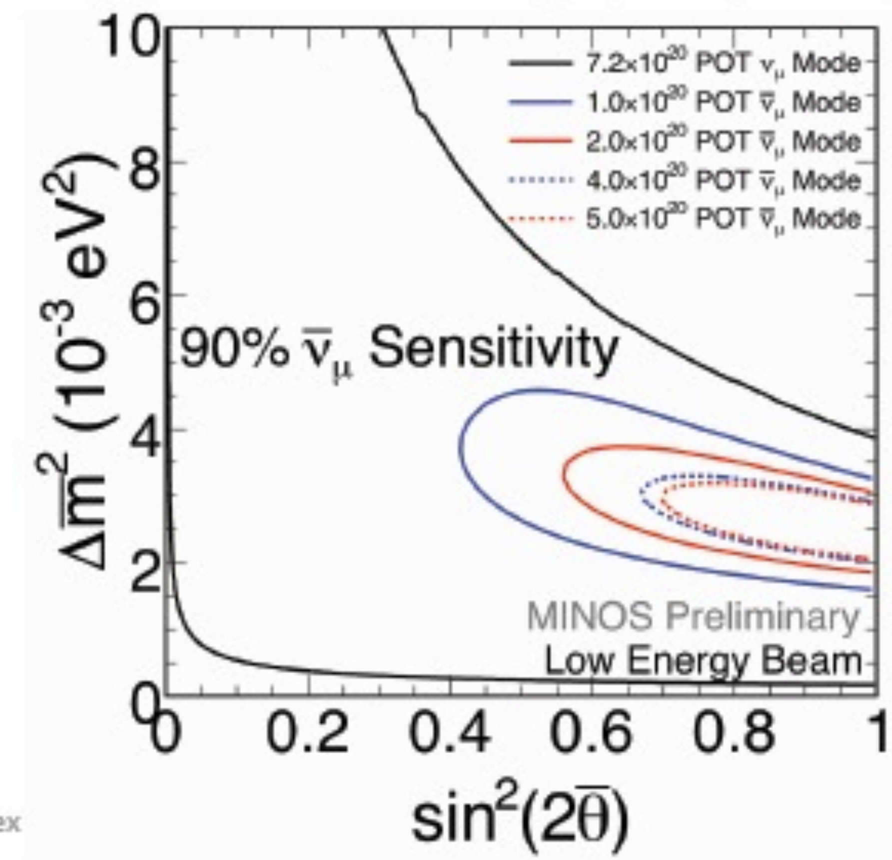


Dedicated $\bar{\nu}_\mu$ Running

- Plan to reverse current in NuMI magnetic horns to focus π^- from September
  - create a $\bar{\nu}_\mu$ beam



- MINOS can directly observe $\bar{\nu}_\mu$ disappearance at 7σ with 5×10^{20} POT
  - rapidly reduce the uncertainty on $\Delta\bar{m}^2_{32}$



Summary so far

- MINOS has analysed 3.2×10^{20} POT of beam data ($>6.6 \times 10^{20}$ POT data now taken)
- Muon neutrino disappearance
  - $|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$ (68% C.L.)
  - $\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)
- Search for sterile neutrino mixing fraction
  - $f_s < 0.68$ (90% C.L.)
- Muon anti-neutrino disappearance: slight depletion.
  - Limit transitions ν_μ to anti-ν_μ: $\alpha < 0.026$ (90% C.L.)
  - Search for electron neutrino appearance
    - $\sin^2(2\theta_{13}) < 0.29$ (90% C.L.) (for normal mass hierarchy, $\delta_{CP}=0$)
  - Prospects are good for pushing below Chooz limit with improved analysis techniques and more data.

Global fit

0905.3549

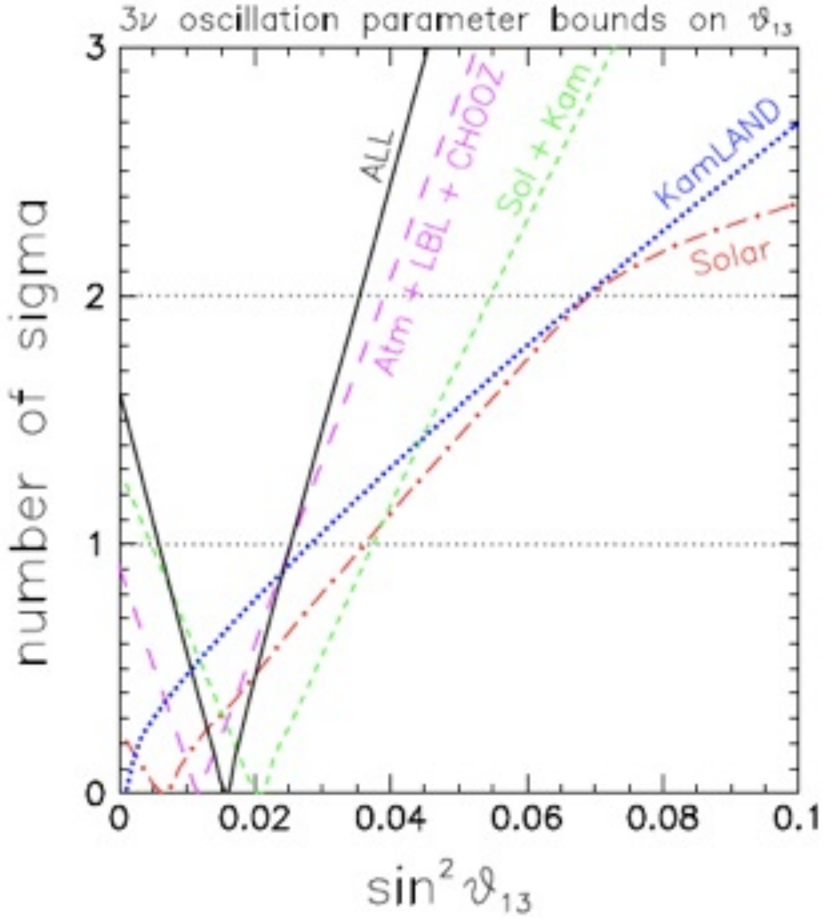


Figure 3: Bounds on θ_{13} from different data sets available in 2008.

$$\sin^2\theta_{13} \simeq 0.016 \pm 0.010 \ (1\sigma, \ \text{All Data}, \ 2008) \ ,$$

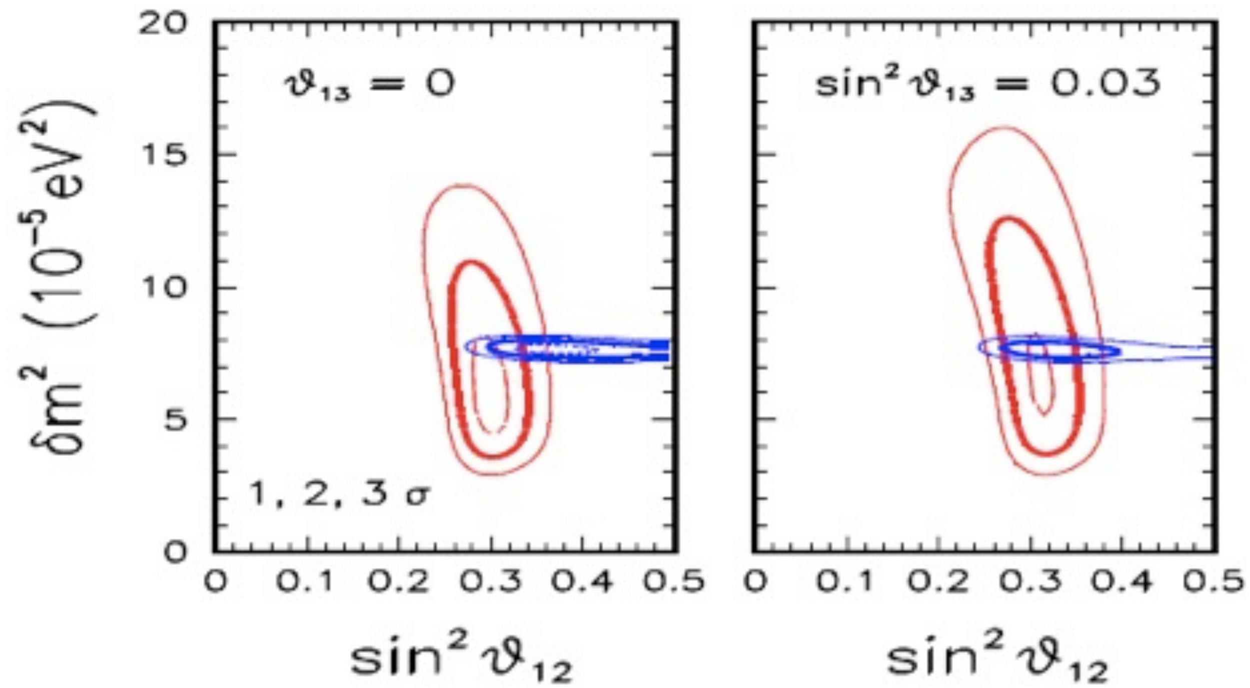


Figure 1: Comparison of n-σ regions allowed by the latest (2008) solar and KamLAND data in the $(\delta m^2, \sin^2\theta_{12})$ plane, for two fixed values of θ_{13}.

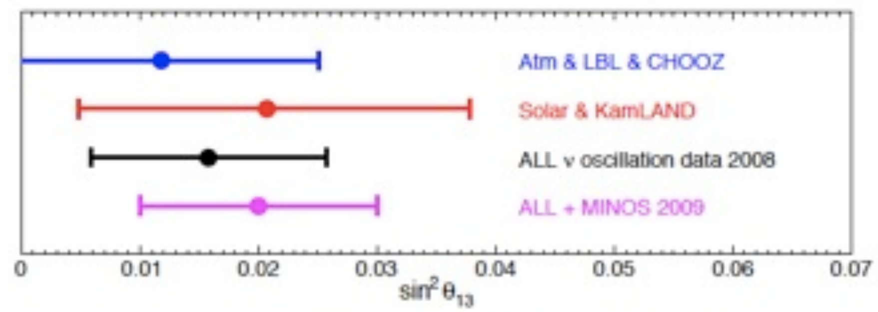
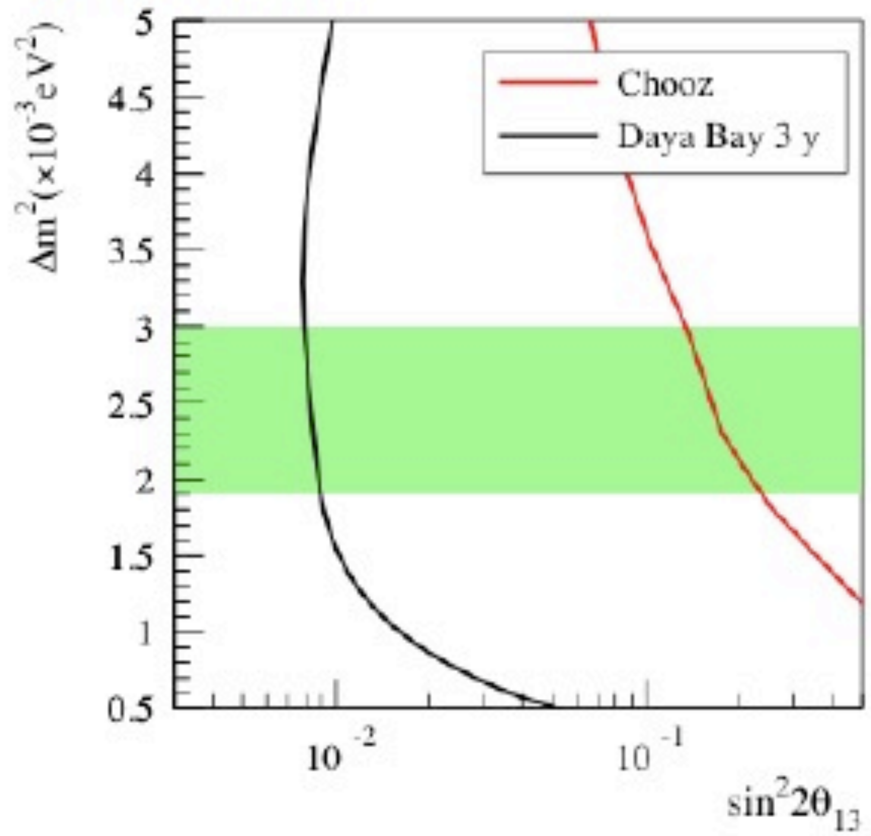


Figure 4: Hints of $\theta_{13} > 0$ from different data sets and combinations: 1σ ranges.

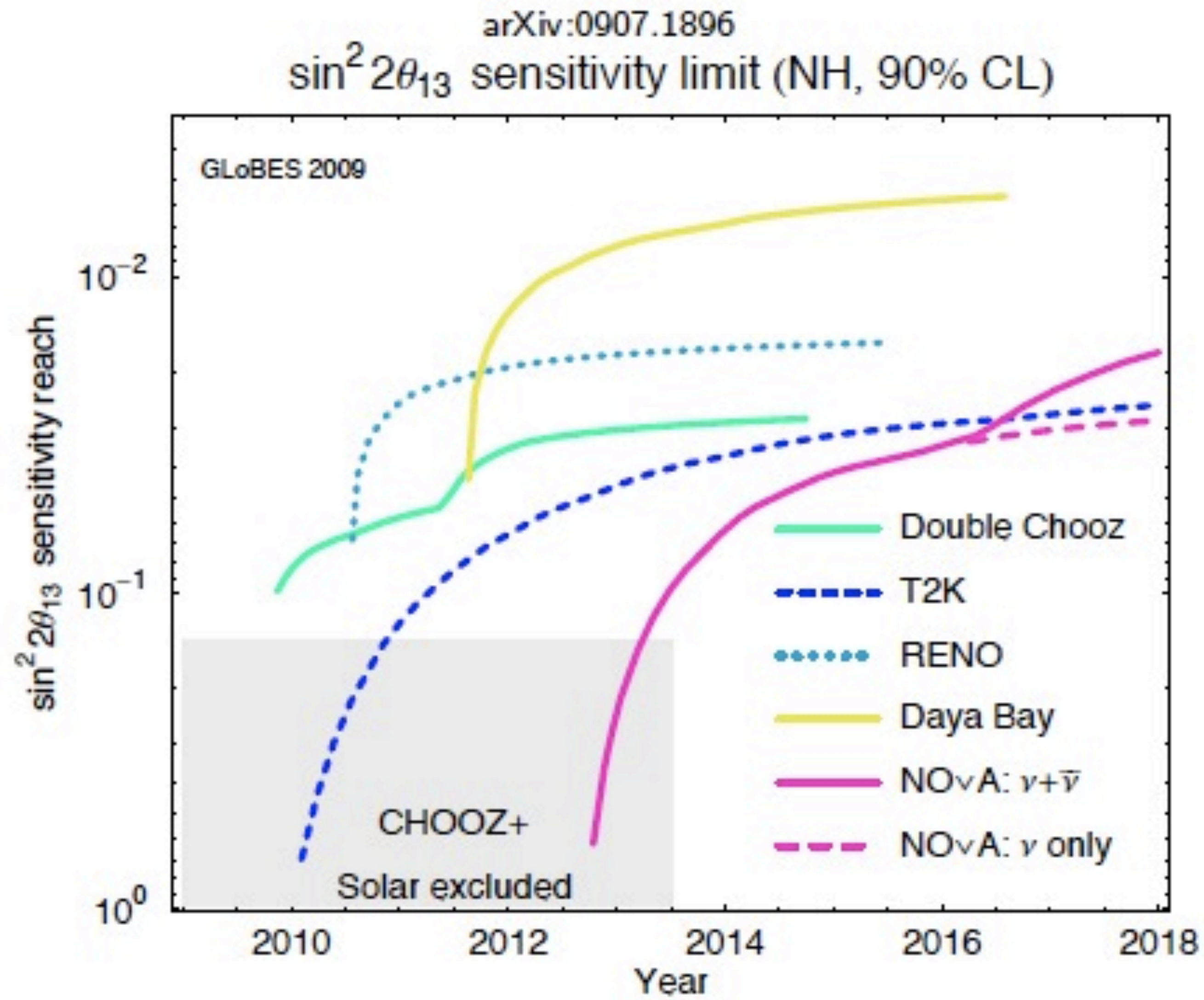
Some early hints ?

Expected sensitivity

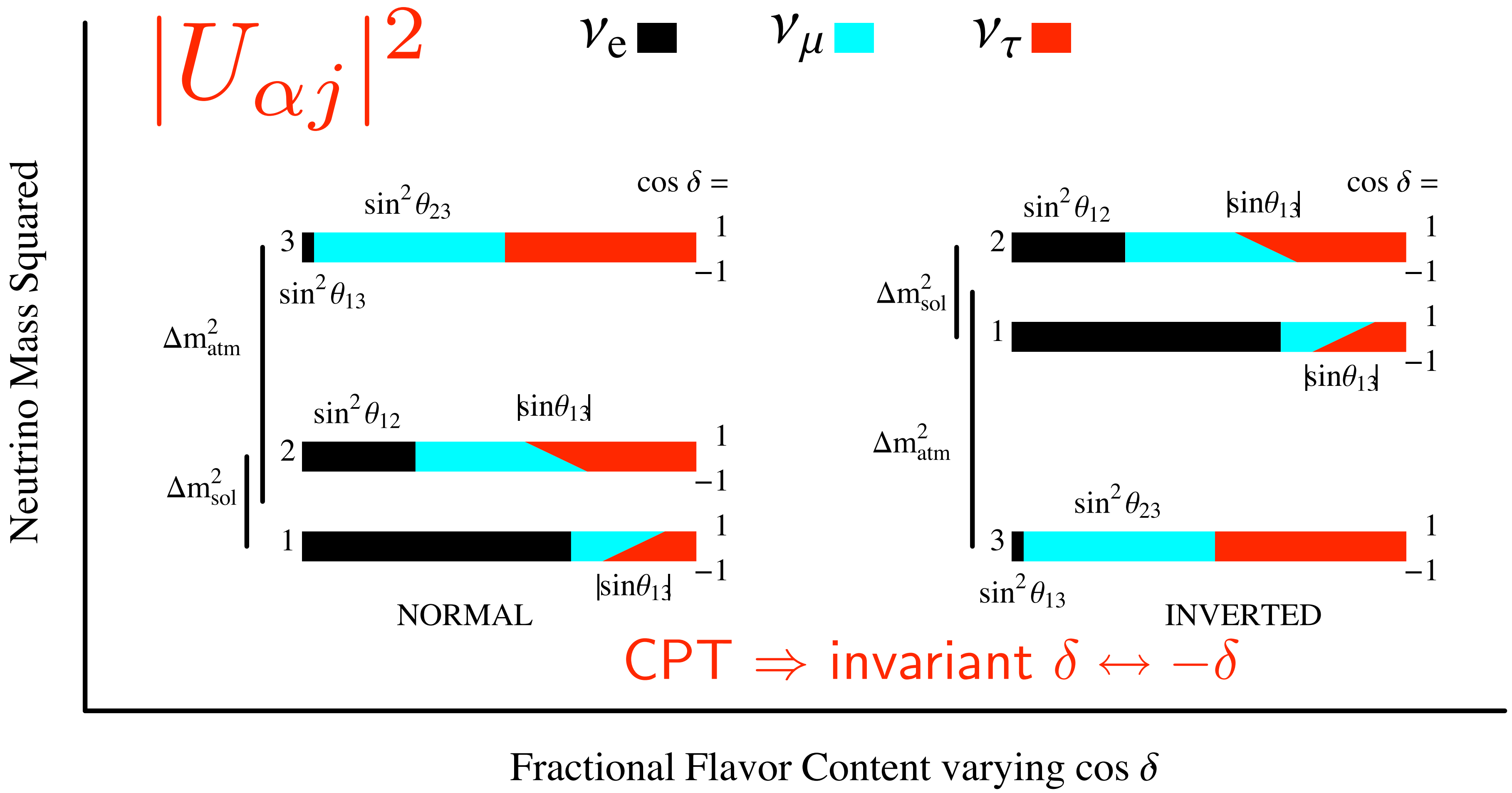
90% CL limit on $\sin^2 2\theta_{13}$ assuming baseline systematics



3 years of data



Sensitivity comparison



$\delta m^2_{sol} = +7.6 \times 10^{-5}\ eV^2$

$|\delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$

$|\delta m^2_{sol}|/|\delta m^2_{atm}| \approx 0.03$

$\sqrt{\delta m^2_{atm}} = 0.05\ eV < \sum m_{\nu_i} < 0.5\ eV = 10^{-6} * m_e$

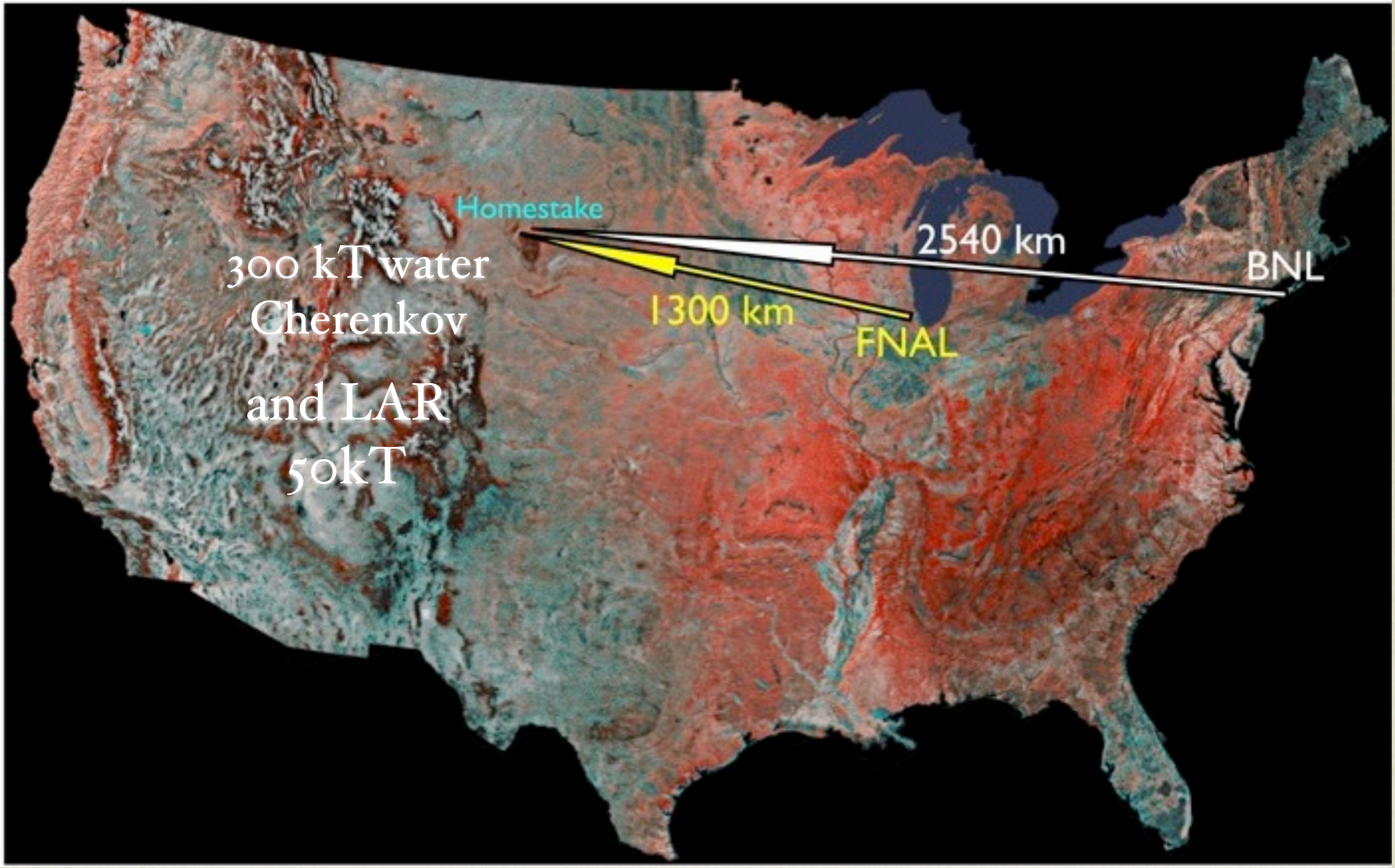
$\sin^2\theta_{12} \sim 1/3$

$\sin^2\theta_{23} \sim 1/2$

$\sin^2\theta_{13} < 3\%$

$0 \leq \delta < 2\pi$

Super neutrino beam to a very large detector



Perform experiment at a L/E scale for both solar and atmospheric effects.

Long Baseline Neutrino Experiment (LBNE) project ?
Another typical American project?

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Convergence of Interests

New scientific discoveries in neutrino physics have set the scale of the project.

Technology of the water Cherenkov detector is ready for the next step.
There is impetus to get LARtpc ready also.

Technology for an intense neutrino beam is almost ready; needs investment in SRF

High Energy Physics interest comes from the linkage with GUT scale phenomena. The last mixing angle, the mass hierarchy, and CP have GUT scale implications

The same scale detector is needed for non-accelerator physics.

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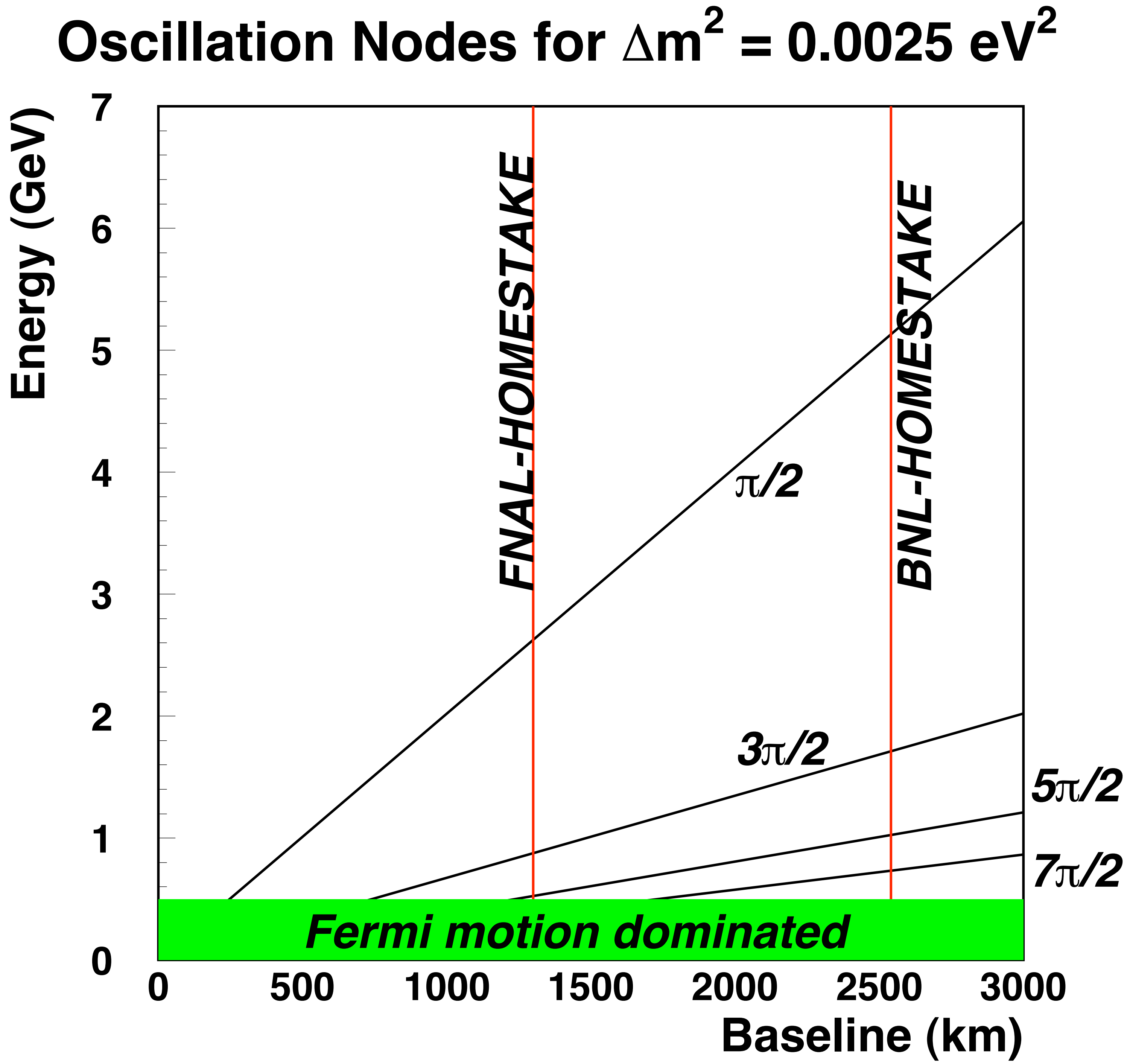
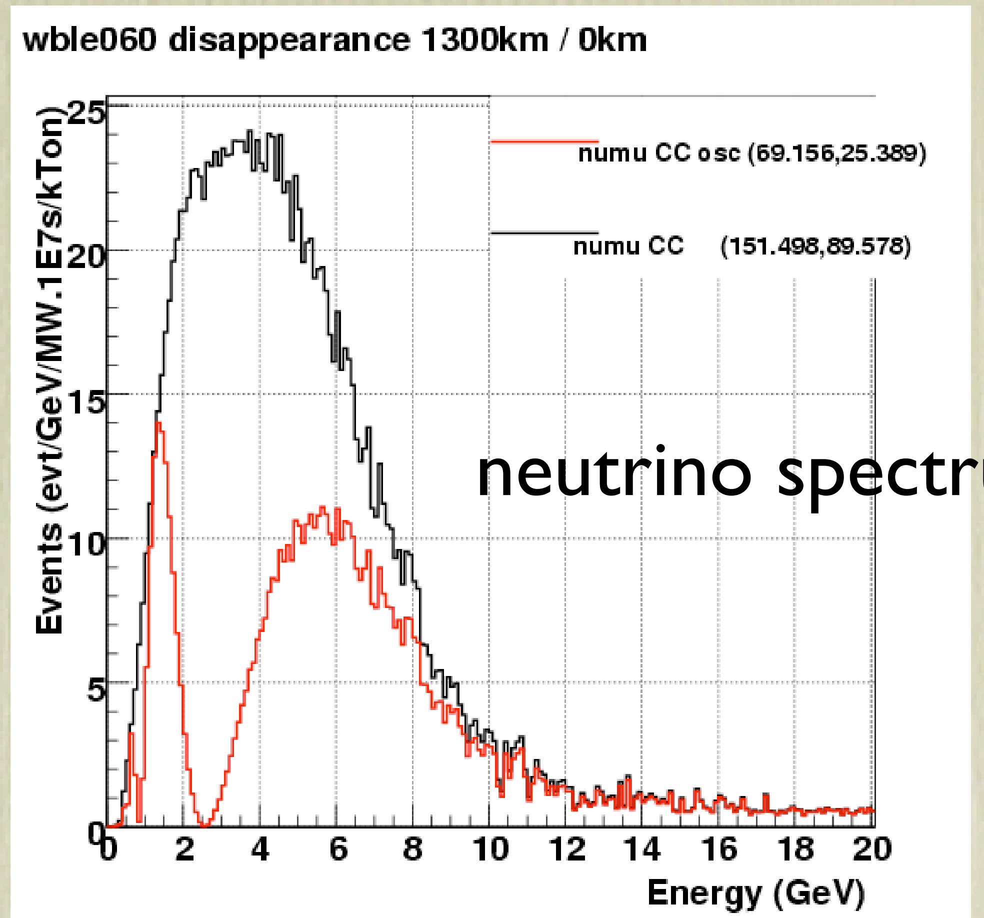


Muon Neutrino Oscillation

Event rate for FNAL to Homestake

Evt rate: 1 MW for 3 yrs ★

Event type	300kT, 120 GeV 0.5 deg.	300kT, 60 GeV 0 deg.
Numu CC no osc	161820	272693
Numu CC with osc	68220	124479



neutrino spectrum

High precision $\sin^2 2\theta_{23}$, Δm^2_{32}

- Important (esp. $\theta_{23} \sim 45$ deg.) with possibility of new physics.
- Either 120 GeV or 60 GeV beam can be used: two oscillation nodes.
- Measurement dominated by systematics (see hep/0407047) (~1%)

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★ yr~2×10^7 sec

$\nu_\mu \rightarrow \nu_e$ with matter effect

Approximate formula (M. Freund)

matter effect ~E

~7500 km
no CPV.
magic bln

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(\hat{A}-1)^2}\sin^2((\hat{A}-1)\Delta)$$

$$+\alpha\frac{8J_{CP}}{\hat{A}(1-\hat{A})}\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha\frac{8I_{CP}}{\hat{A}(1-\hat{A})}\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)$$

$$+\alpha^2\frac{\cos^2\theta_{23}\sin^2 2\theta_{12}}{\hat{A}^2}\sin^2(\hat{A}\Delta)$$

CPV term
approximate
dependence
~L/E

solar term

linear dep.

$$J_{CP} = 1/8\sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

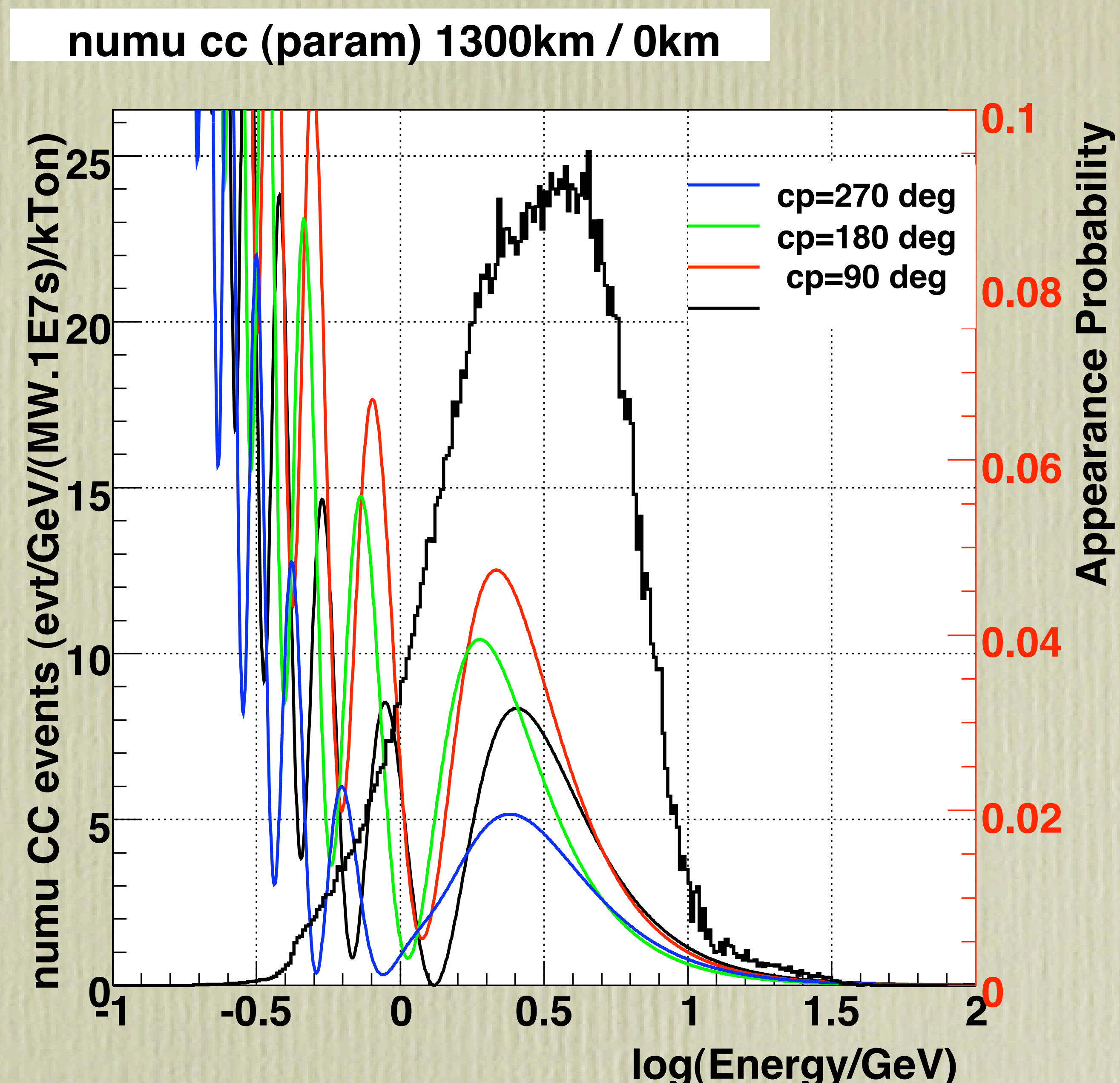
$$I_{CP} = 1/8\cos\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31},\ \Delta = \Delta m^2_{31}L/4E$$

$\hat{A} = 2VE/\Delta m^2_{31} \approx (E_\nu/GeV)/11$ For Earth's crust.

CP asymmetry grows as
th13 becomes smaller

Spectra FNAL to DUSEL (WBLE:wide band low energy)



- 60 GeV at 0deg: CCrate: 14 per (kT*10^20 POT)

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Key Event Rate in 100kT*MW*10^7

5.2e20 POT @ 120 GeV

$$\nu_\mu \longrightarrow \nu_e$$

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3} eV^2$ $\sin^2 2\theta_{12,23} = 0.86, 1.0$ $\sin^2 2\theta_{13} = 0.02$

$$\delta_{CP}$$

	$sgn(\Delta m^2_{31})$	0 deg	+90 deg	180 deg	-90 deg	nue backg
WBLE NU (1300km)	+	87	48	95	134	47
WBLE NU (1300km)	-	39	19	51	72	
WBLE ANU (1300km)	+	20	27	15	7.2	17
WBLE ANU (1300km)	-	38	52	33	19	

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The key experimental factor

- Huge (>100kT) detector with high efficiency.
- MW class beam helps, but need the above detector first.

Detector design considerations.

- Need ~100kT of fiducial mass with good efficiency. Much larger if lower efficiency. At this mass scale cosmic ray rate becomes the driving issue for detector placement and design.

$\sin^2 2\theta_{13} = 0.02$ signal~50 evts/yr

Event type	100 kTon	100 kTon
Proton Beam Energy	120 GeV	60 GeV
Angle	0.5^o	0^o
CC ν_μ No Oscillations	27000	45000
CC ν_μ With Oscillations	11400	21000

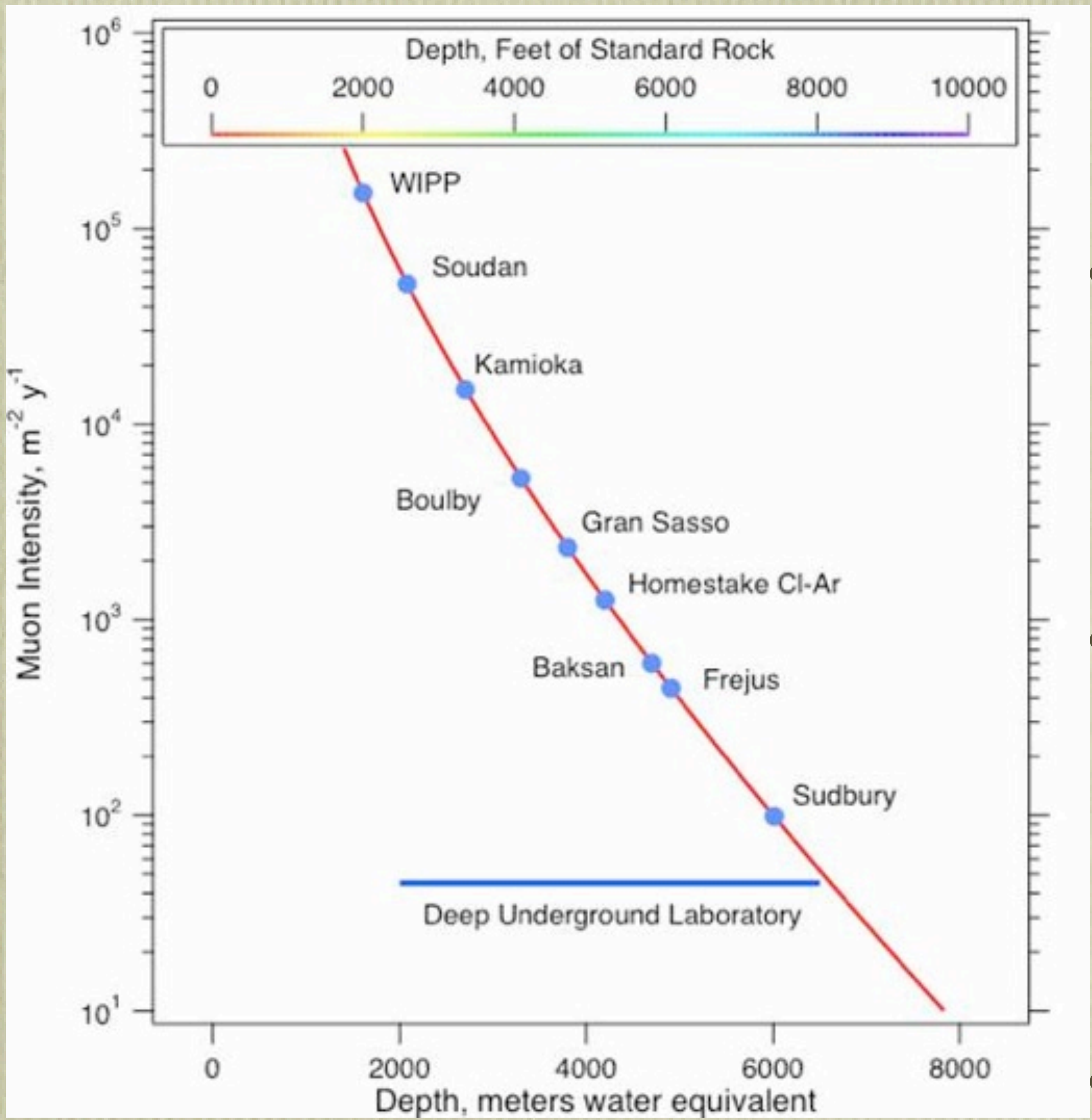
Rate(Hz)	In-time cosmics/yr	Depth (mwe)
500 kHz	5×10^7	0
3 kHz	300,000	265
400 Hz	40,000	880
5 Hz	500	2300
1.3 Hz	130	2960
0.60 Hz	60	3490
0.26 Hz	26	3620
0.09 Hz	DUSEL depth 9	4290

Ref: BNL-81896-2008

Cosmic rate in 50m h/dia detector in 10 μs for 10^7 pulses

If detector is placed on the surface it must have cosmic rejection for muons $\sim 10^8$ and for gammas ~ 10 beyond accelerator timing.=> fully active fine grained detector.

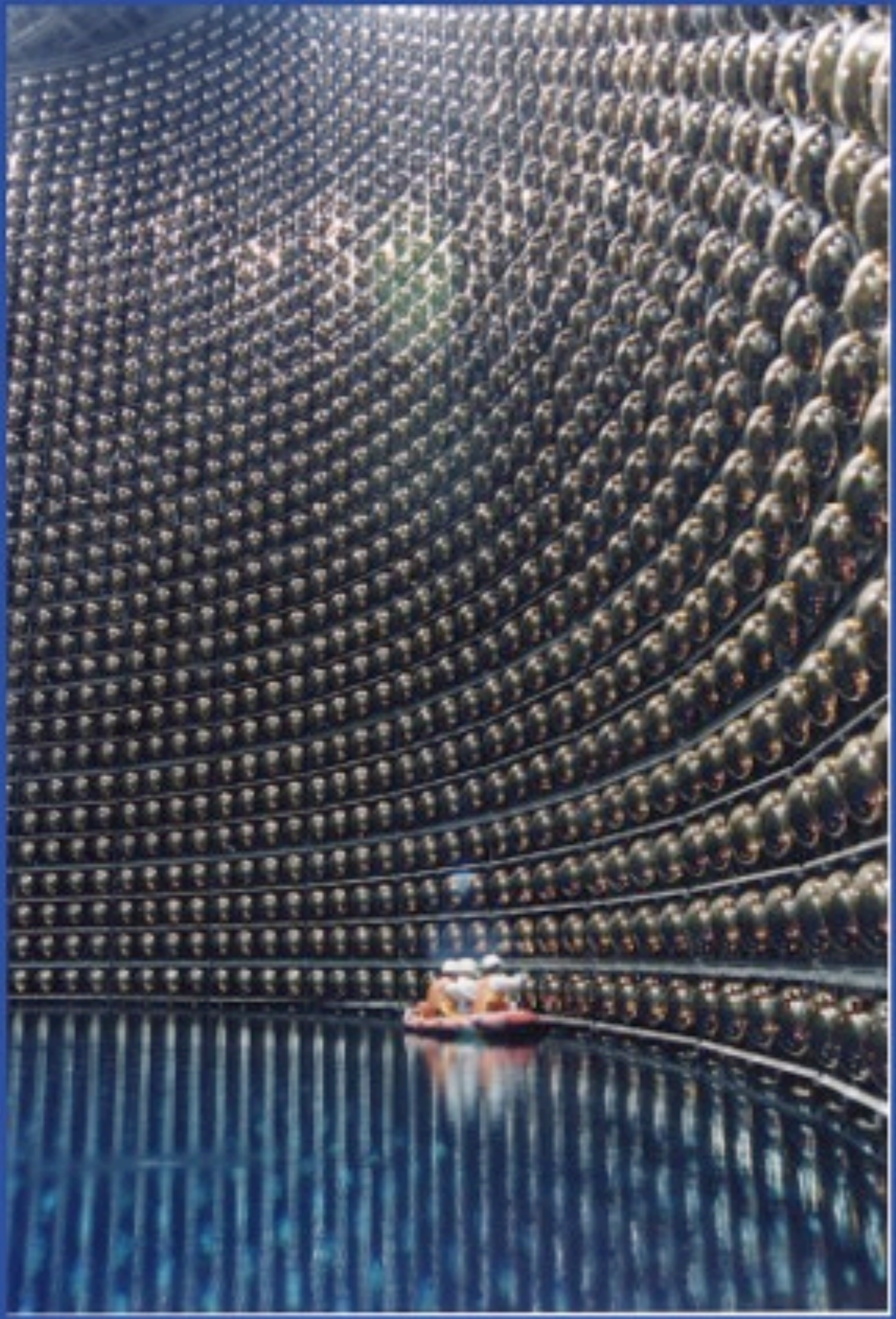
Next key Experimental factor

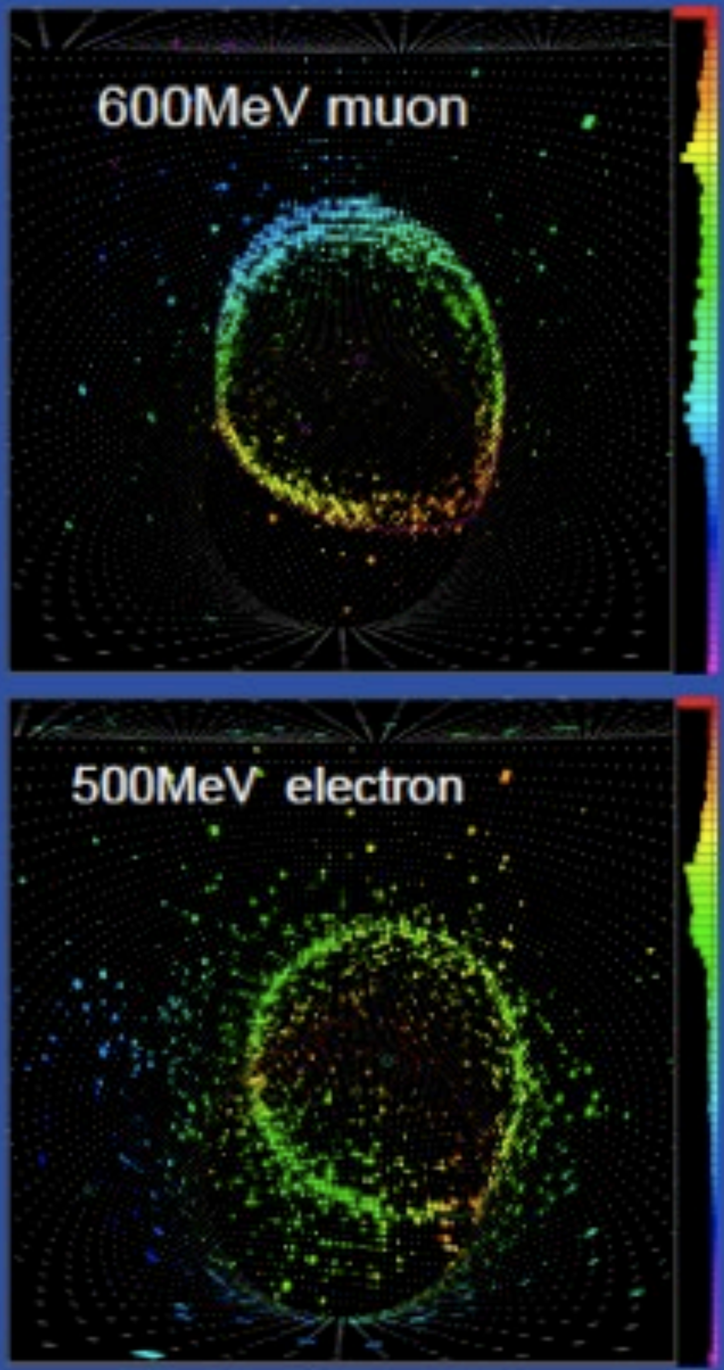


- Detector of 100 kTon scale needs to be at least at 1000 mwe; even for accelerator physics.
- A very fine grained detector such as LARtpc could be shallower, but needs thorough examination and experience.
- In any case, the shallow will means loss of non-accelerator science. Shallow need not mean less expensive after fiducial volume loss.
- The scientific judgement behind placing such a facility at any depth needs debate.

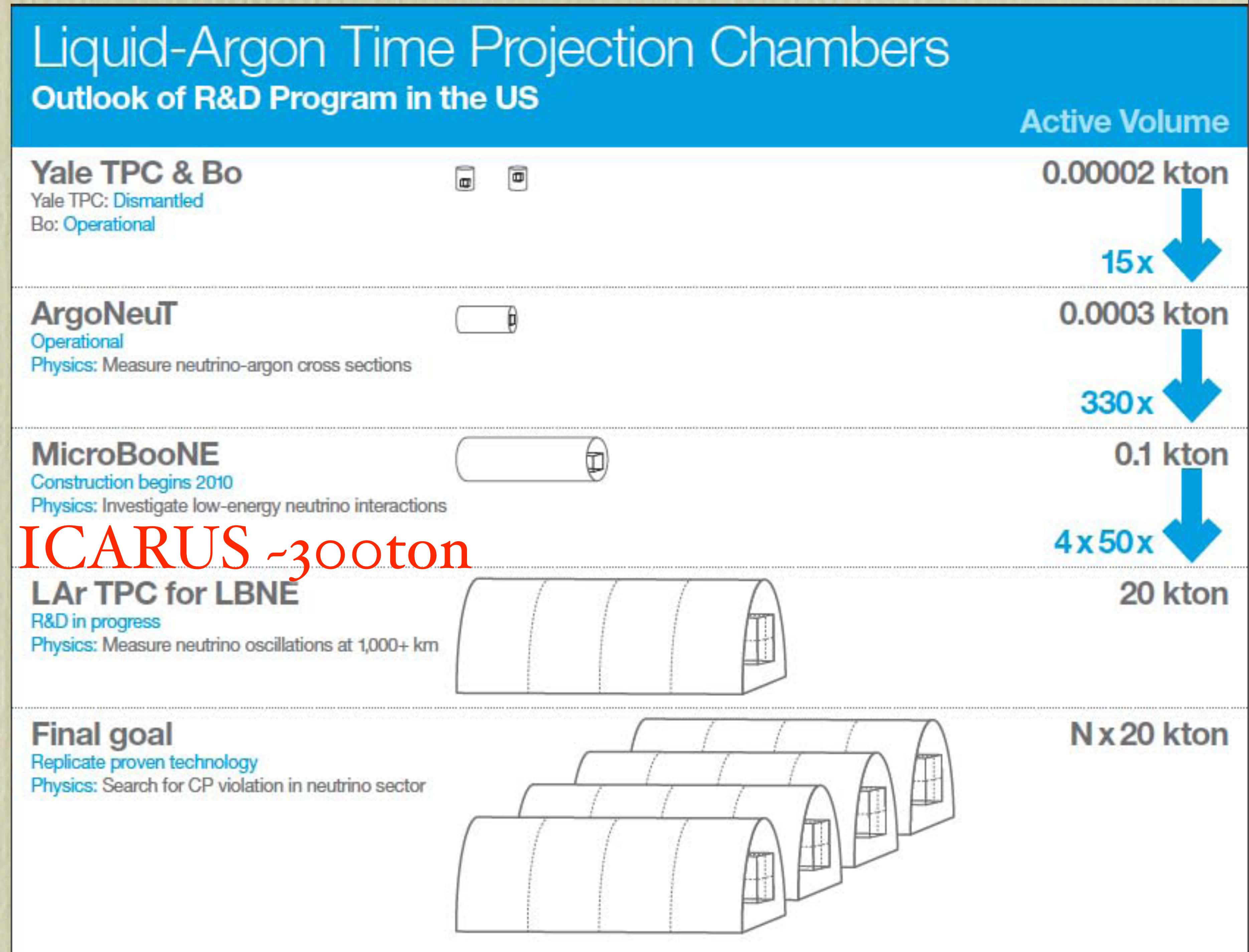
Far Detector : Water Cerenkov

- Super-K
  - 13K 20” PMT
  - 40% coverage
  - 50 kT total mass
  - 39 m diameter
  - 42 m height
- LBNE
  - 60 K 10” PMT per 100kT FV module (25%)
  - ~55 m diameter
  - ~60 m height





- Long baseline accelerator neutrino physics is the ideal application for LARTPC.
- The key idea is to use all charged current rate and obtain high efficiency with low background.
- Technological problem: can we scale current detectors to much higher masses while reducing cost.



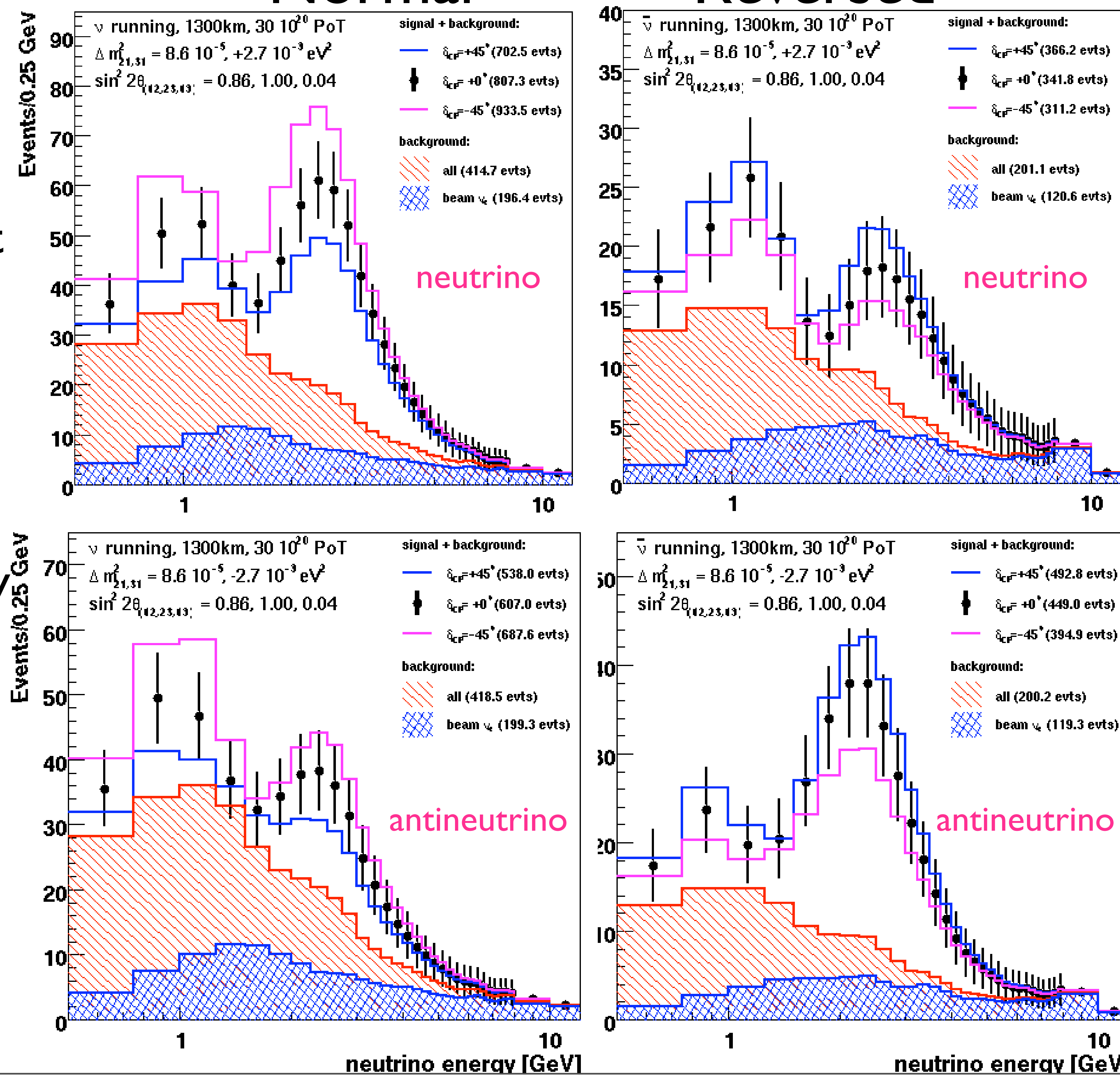
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 300kT WCe. , WBLE 120 GeV, 1300km, 30E20 POT.

$(-\ \delta_{cp} = -45°,\ -\ \delta_{cp} = +45°)$

Normal Reversed

- All background sources are included.
- S/B ~ 2 in peak.
- NC background about same as beam nue backg.
- For normal hierarchy sensitivity will be from neutrino running.
- For reversed hierarchy anti-neutrino running essential.
- Better efficiency at low energies expected with higher PMT counts.



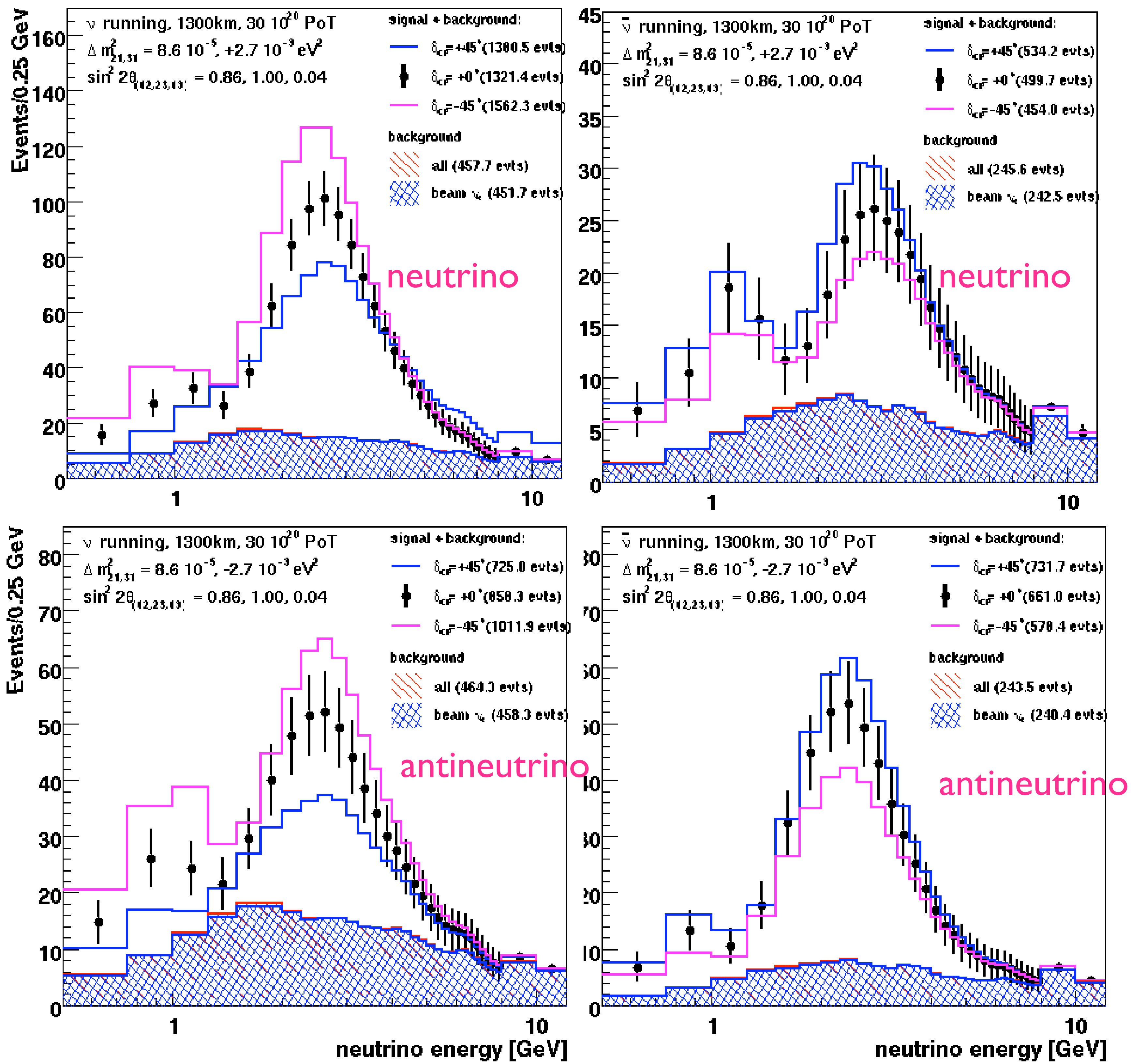
Electron neutrino appearance spectra

$\sin^2 2\theta_{13} = 0.04$, 100kT LAr., WBLE 120 GeV, 1300km, 30E20 POT.

$(-\ \delta_{cp} = -45°,\ -\ \delta_{cp} = +45°)$

Normal Reversed

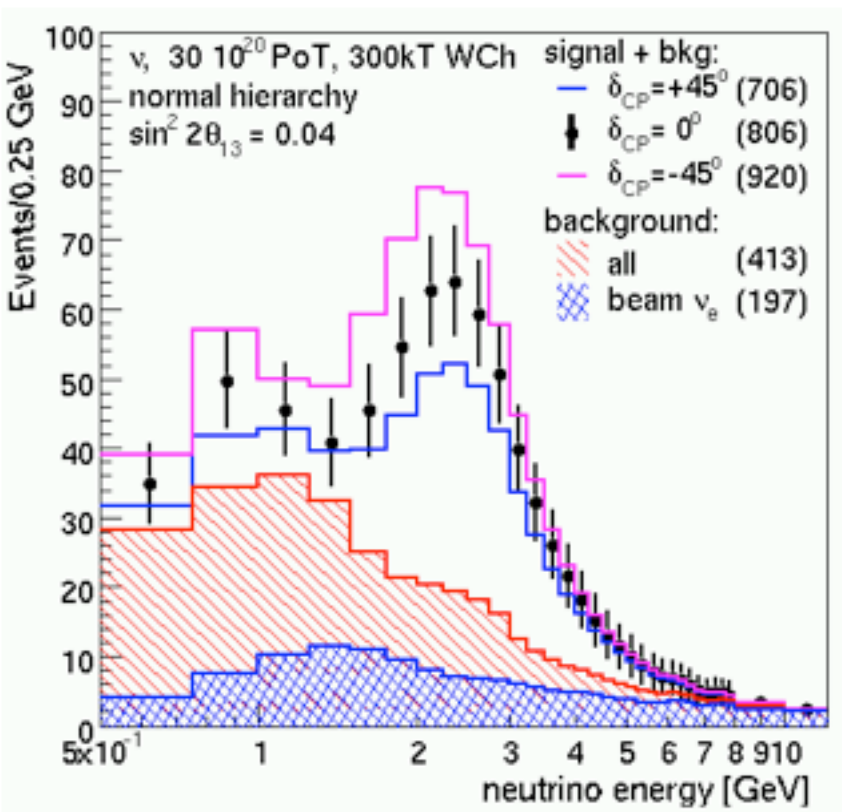
- LAR assumptions
- 80% efficiency on electron neutrino CC events.
- sig(E)/E = 5%/sqrt(E) on quasielastics
- sig(E)/E = 20%/sqrt(E) on other CC events



Spectra and sensitivity is the work of M. Bishai, Mark Dierckxsens, Patrick Huber + many helpers

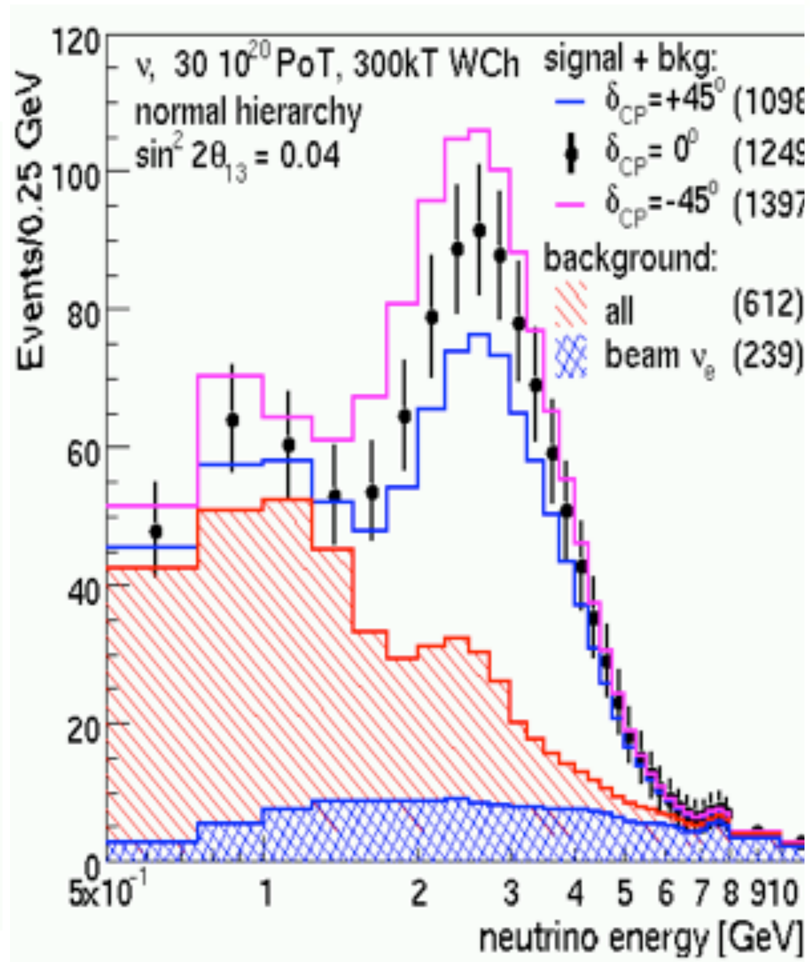
LBNE beam optimization

Old design
0.5 deg. off. presented last year

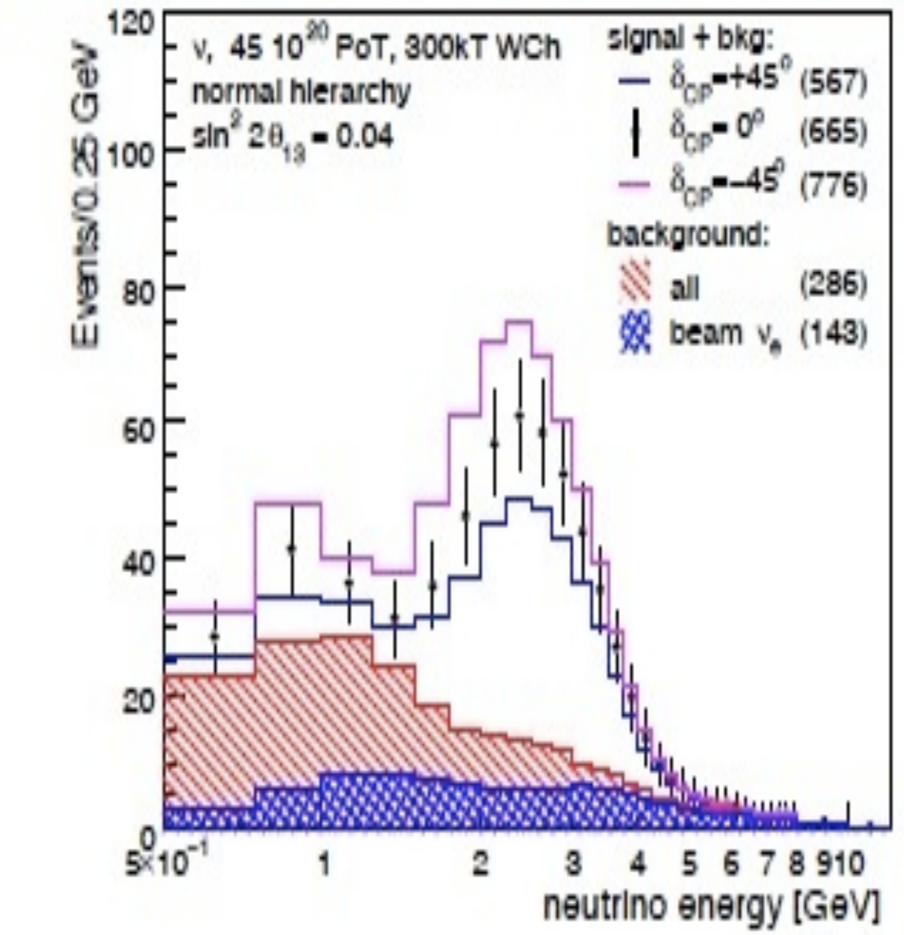


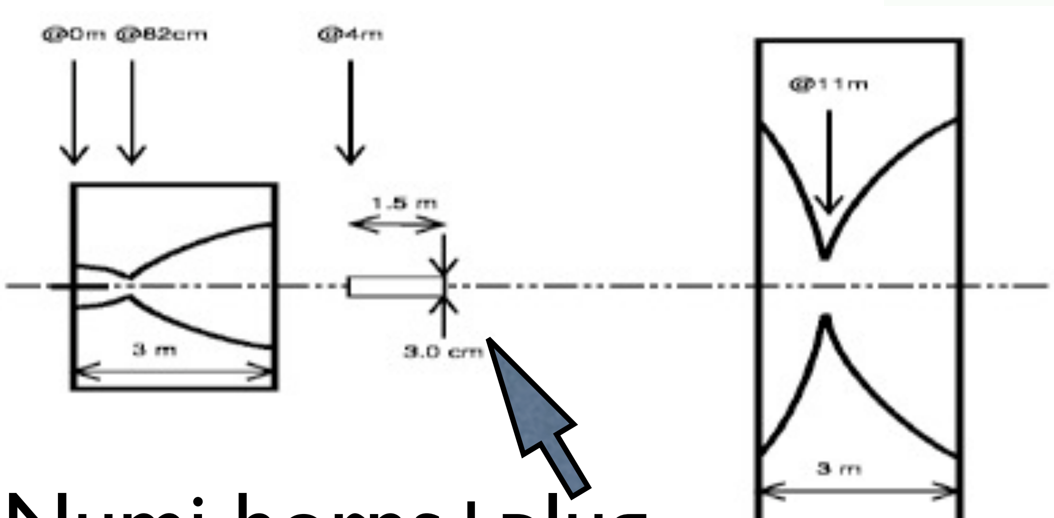
New NuMI based on axis designs and shorter beampipe

High horn current



60 GeV, 250kA, 0.75× beam power



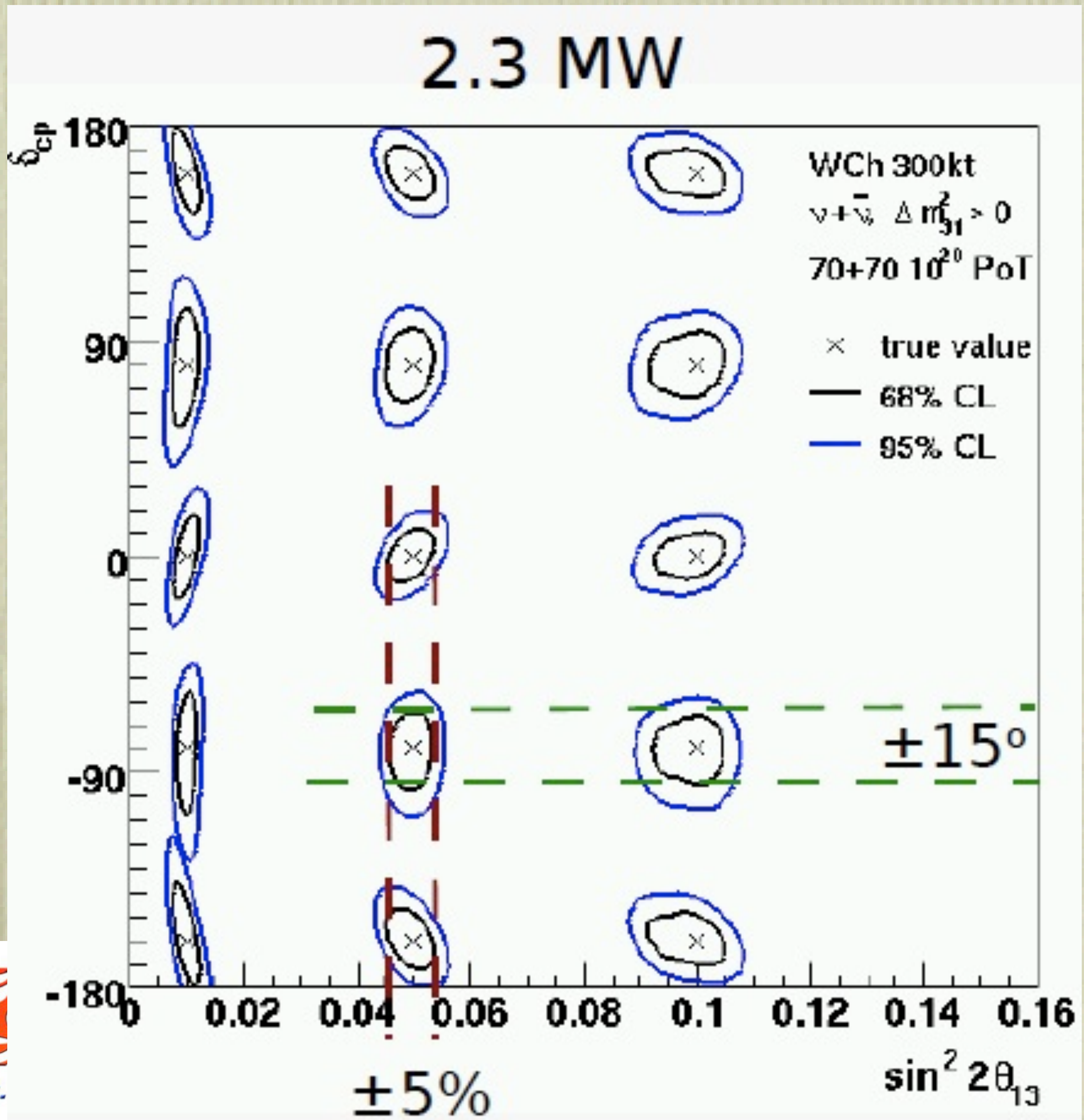


Numi horns+plug

Signal/background enhanced by ~20%. Other optimizations (proton beam energy) under investigation in the beam working group.

Further science issues

- Program should lead to measurement of 3-generation parameters without ambiguities. (recall: CP measurement is approximately independent of θ13). Need large detector independent of θ13 value.
- A broad band beam is needed to get spectral information to resolve ambiguities. Spectrum down to 0.5 GeV important.



300 kT water Cherenkov detector @DUSEL Measurement of CP phase and $Sin^2 2\theta_{13}$ at several points. All ambiguities and mass hierarchy are resolved.

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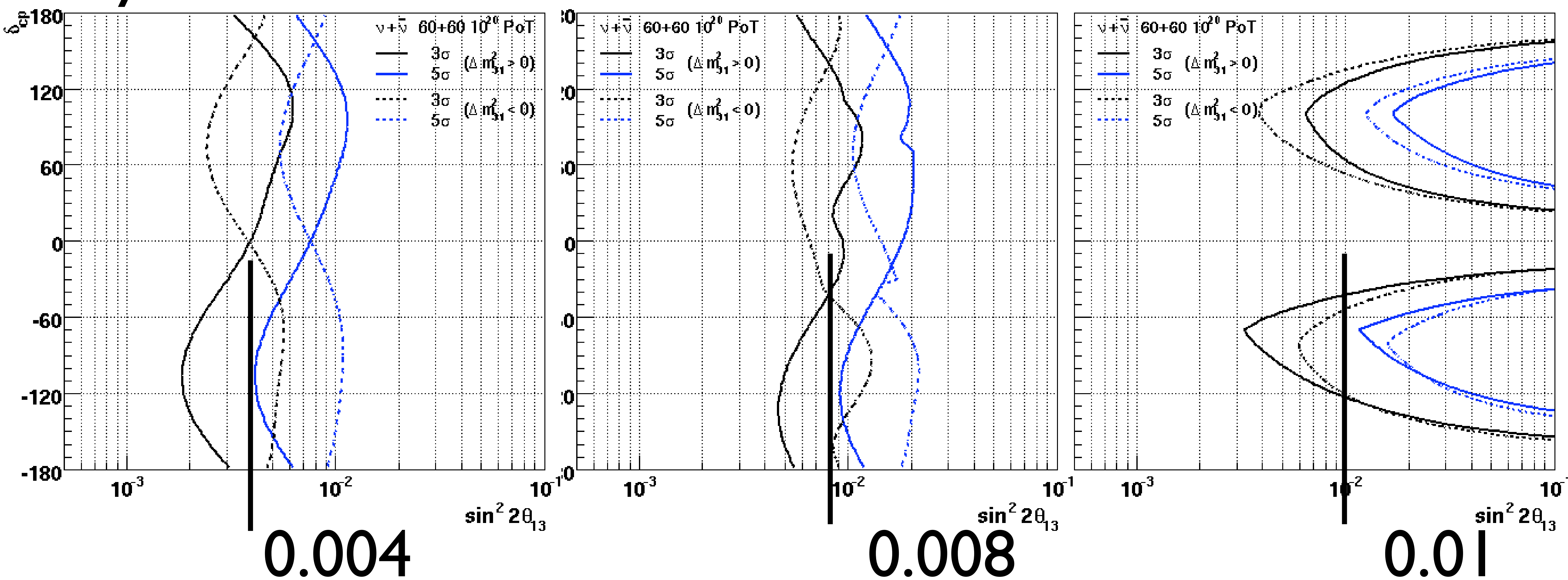
WBLE to DUSEL(1300km) 3sig, 5sig discovery regions.

300 kT WCh

Stat+syst

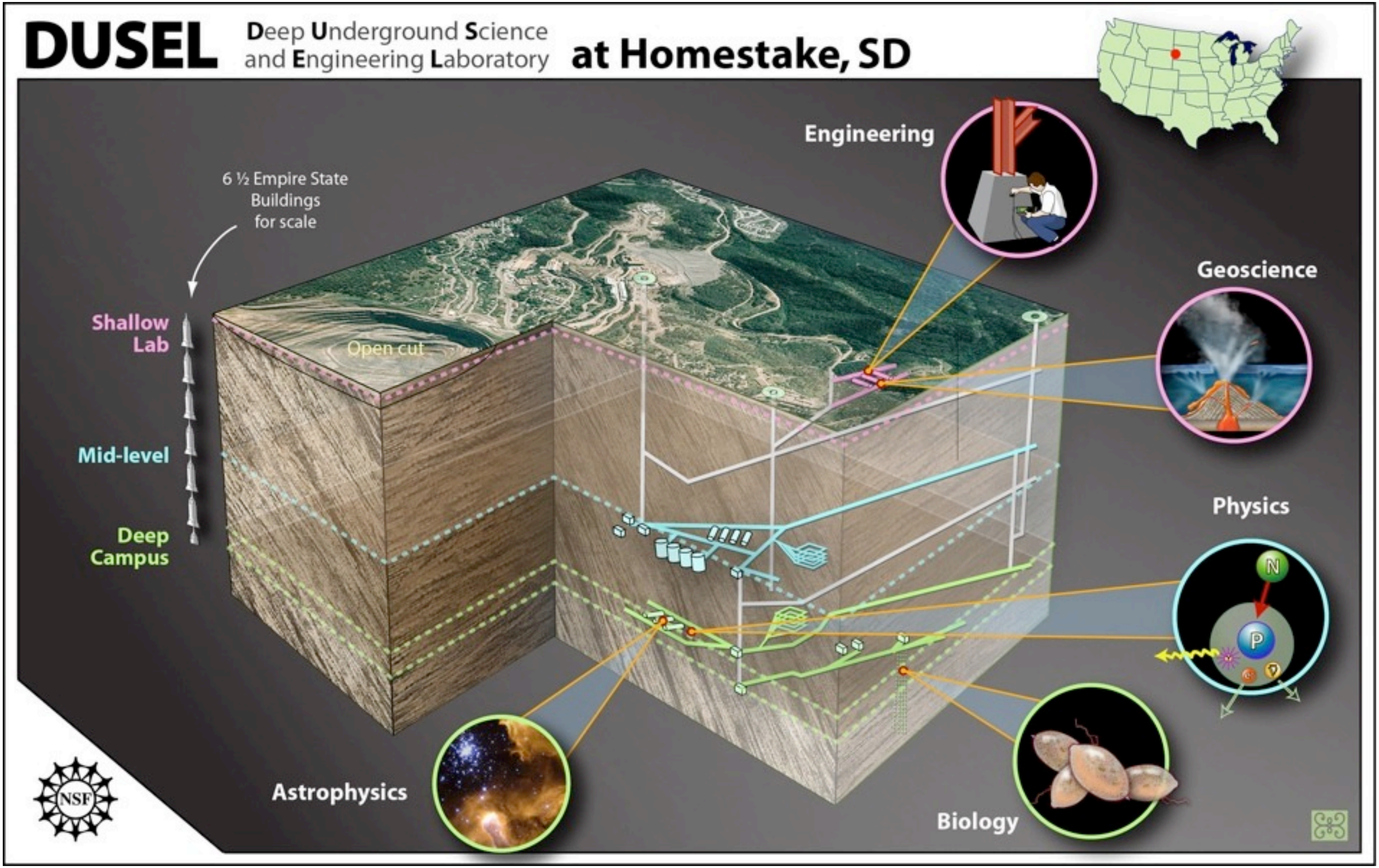
60 10^20 POT for each nu and anu

th13 mass ordering CP violation



CP Fraction: Fraction of the CP phase (0-2pi) covered at a particular confidence level.

Report the value of th13 at the 50% CP fraction.

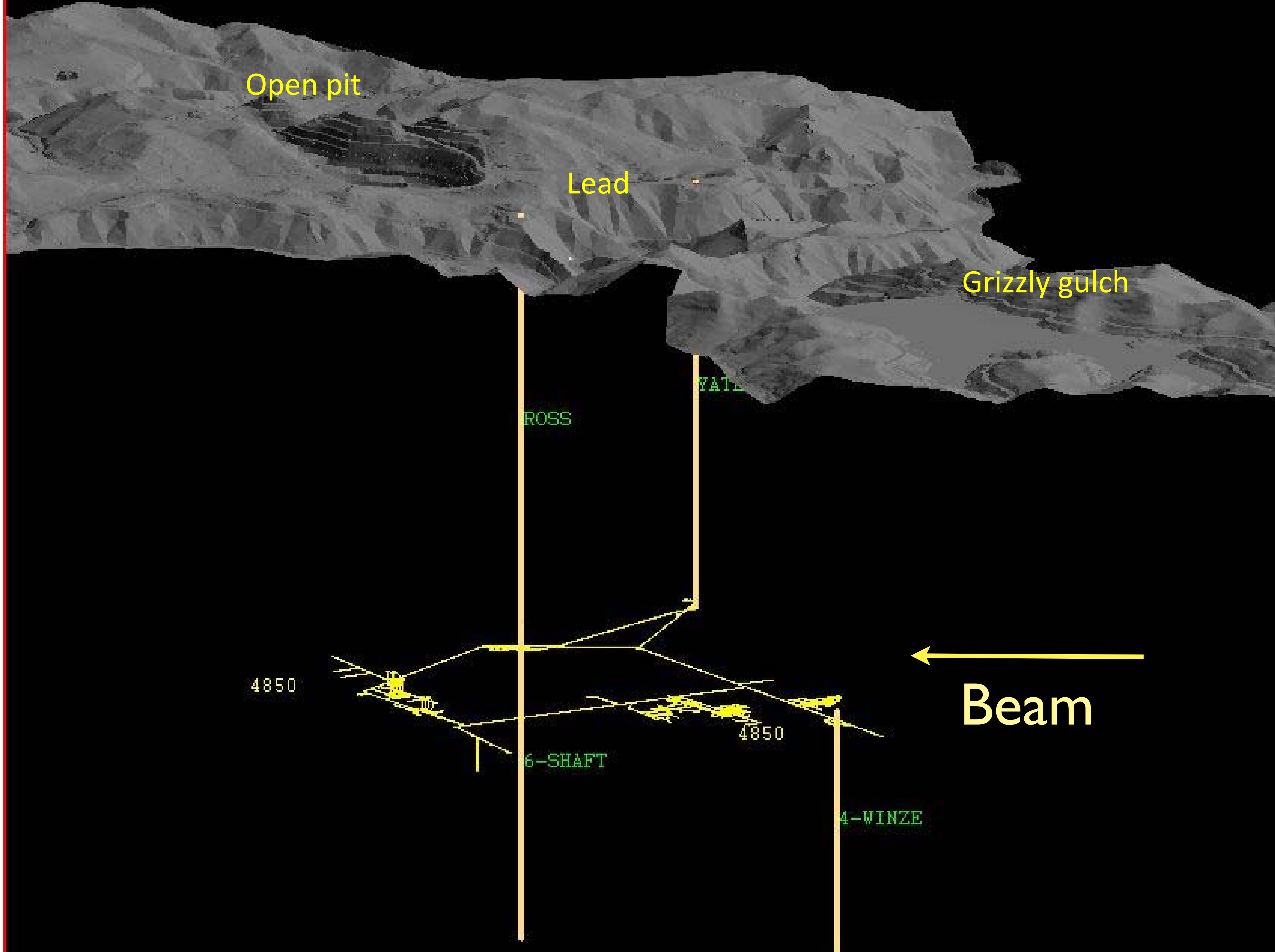


NSF site decision on advice from a 22 member unanimous panel.

Where is S. Dakota ? What are black hills ?

SD has Tradition of mining

- South Dakota is West of Minnesota (take I-90)
- Black hills are stunning.

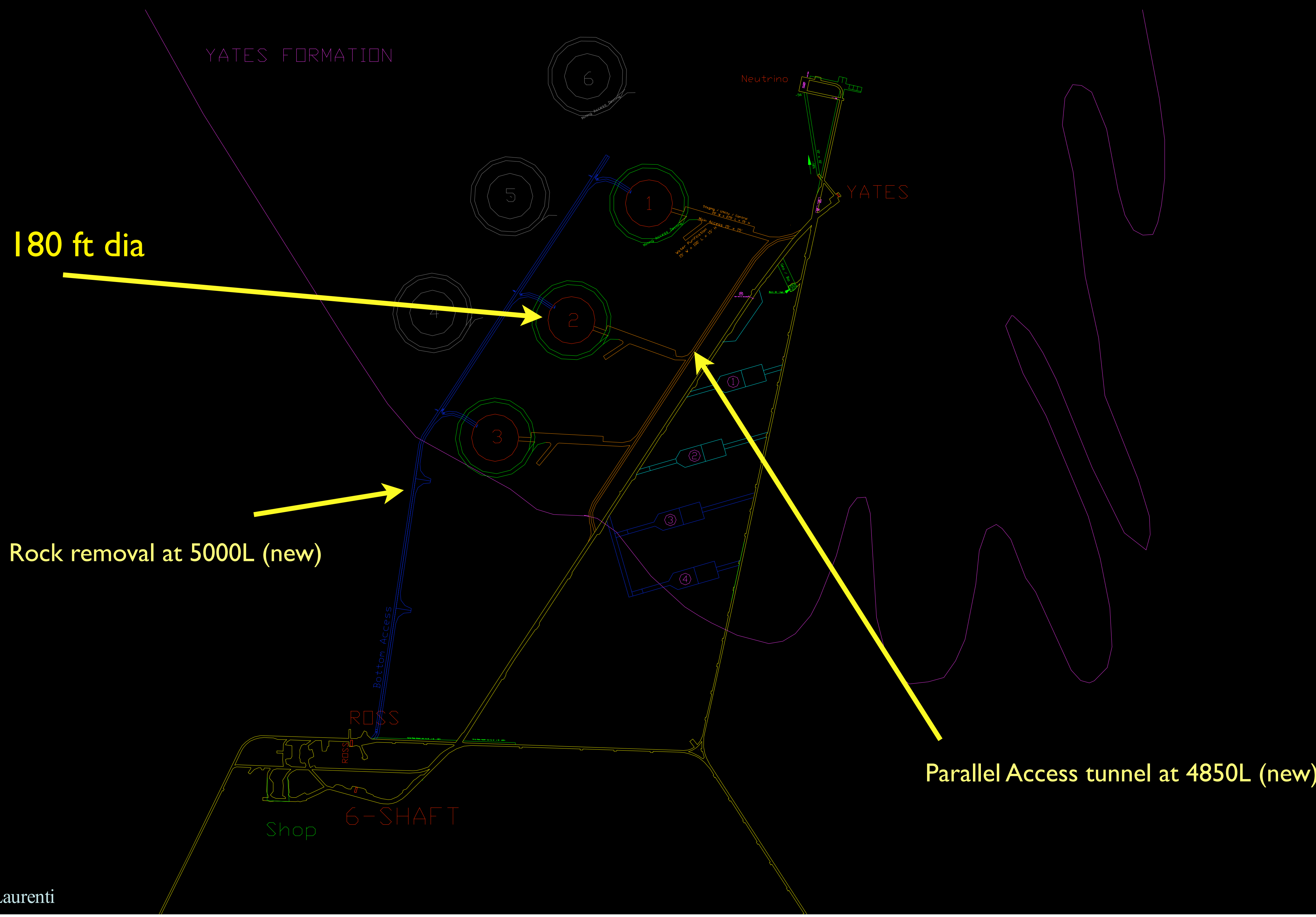


The Detector @ homestake

Megaton Modular Multi-Purpose Neutrino Detector

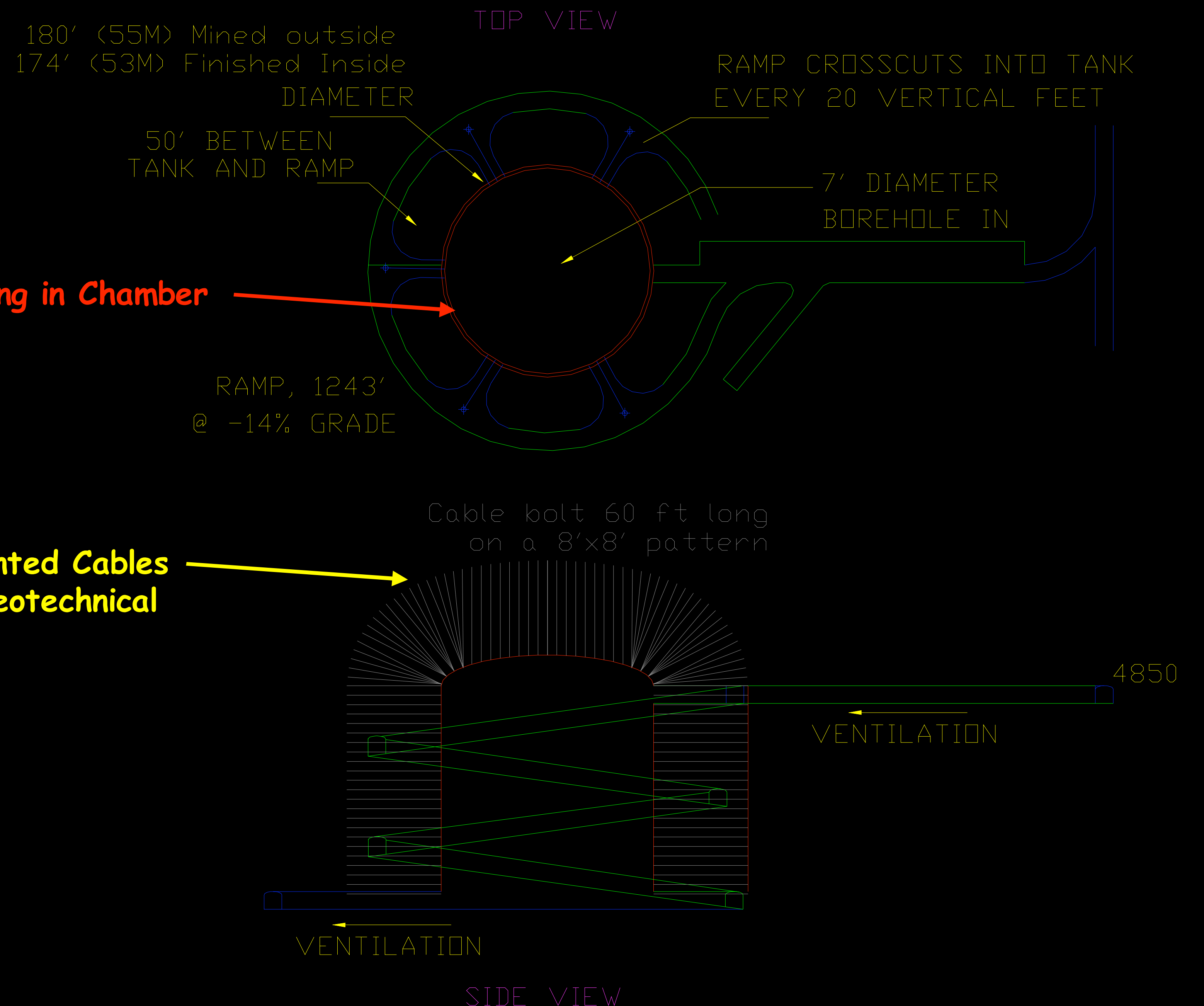
✓ **Modular Configuration**

muon rate/cavern 0.1-0.3 Hz



MEGATON MODULAR MULTI-PURPOSE NEUTRINO DETECTOR

✓ Chamber Design



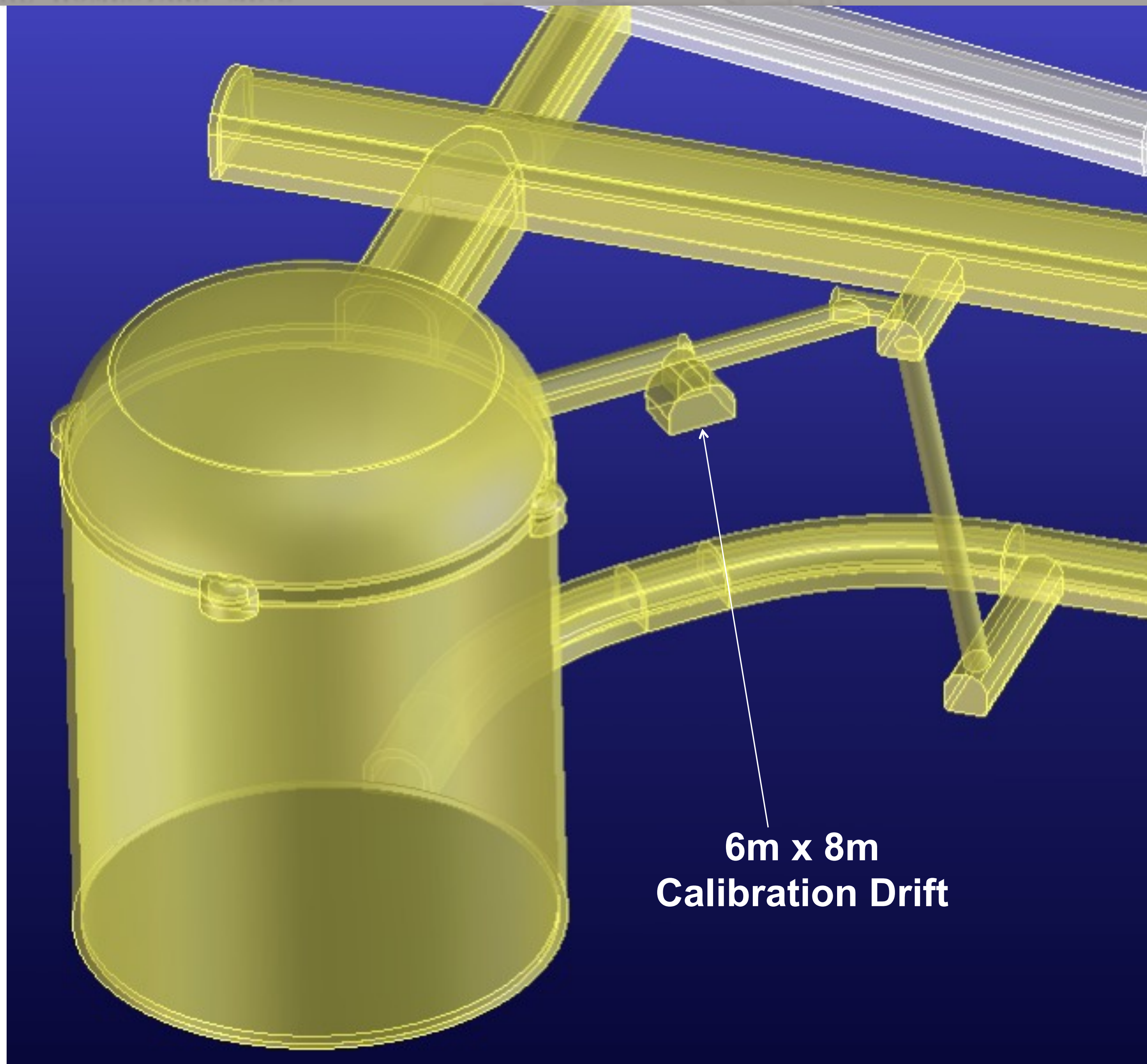
Controlled Blasting in Chamber

Could use Instrumented Cables for Engineering / Geotechnical Study

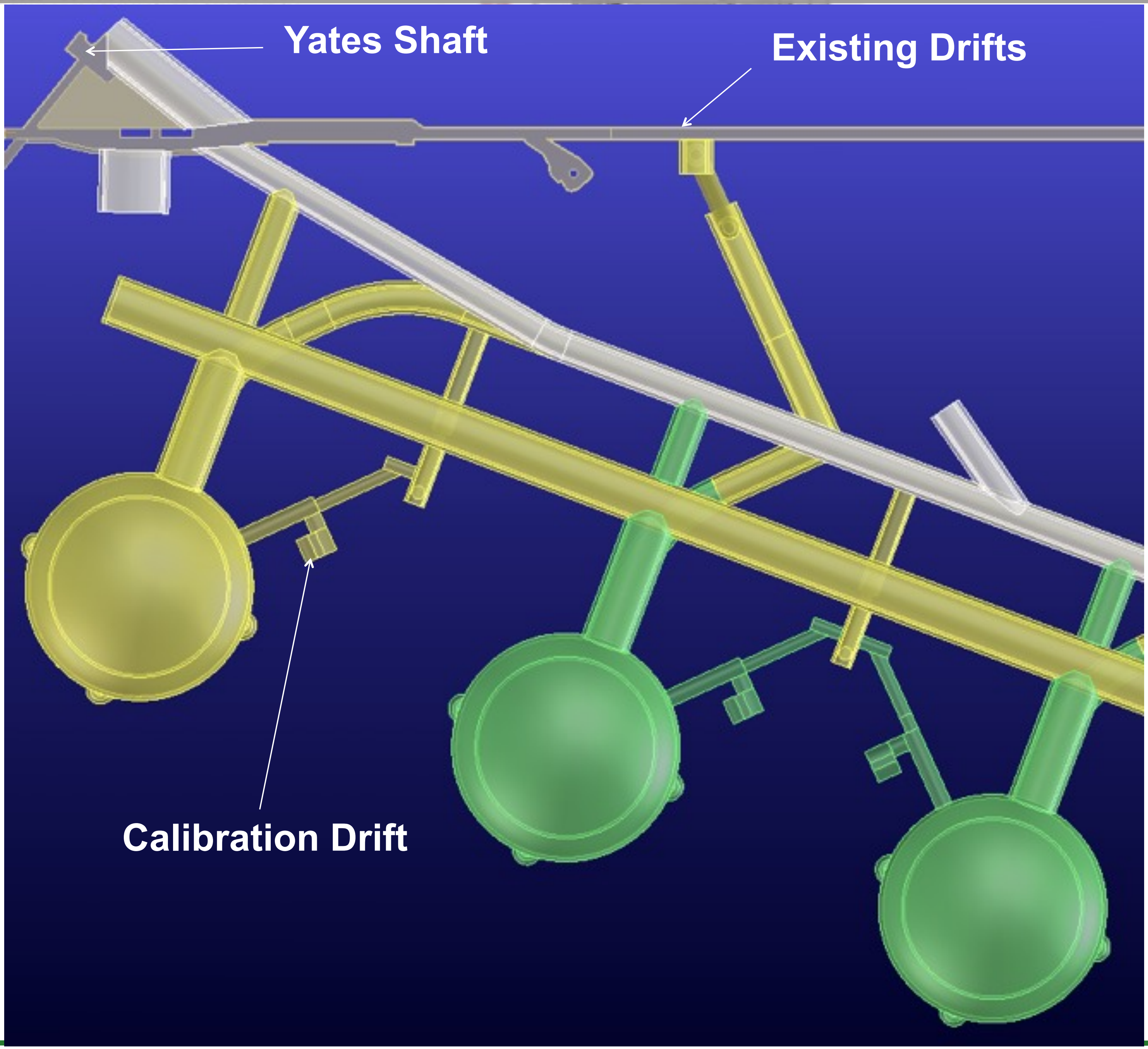
Mark A. Laurenti (Former Homestake Chief engineer)

November 2007

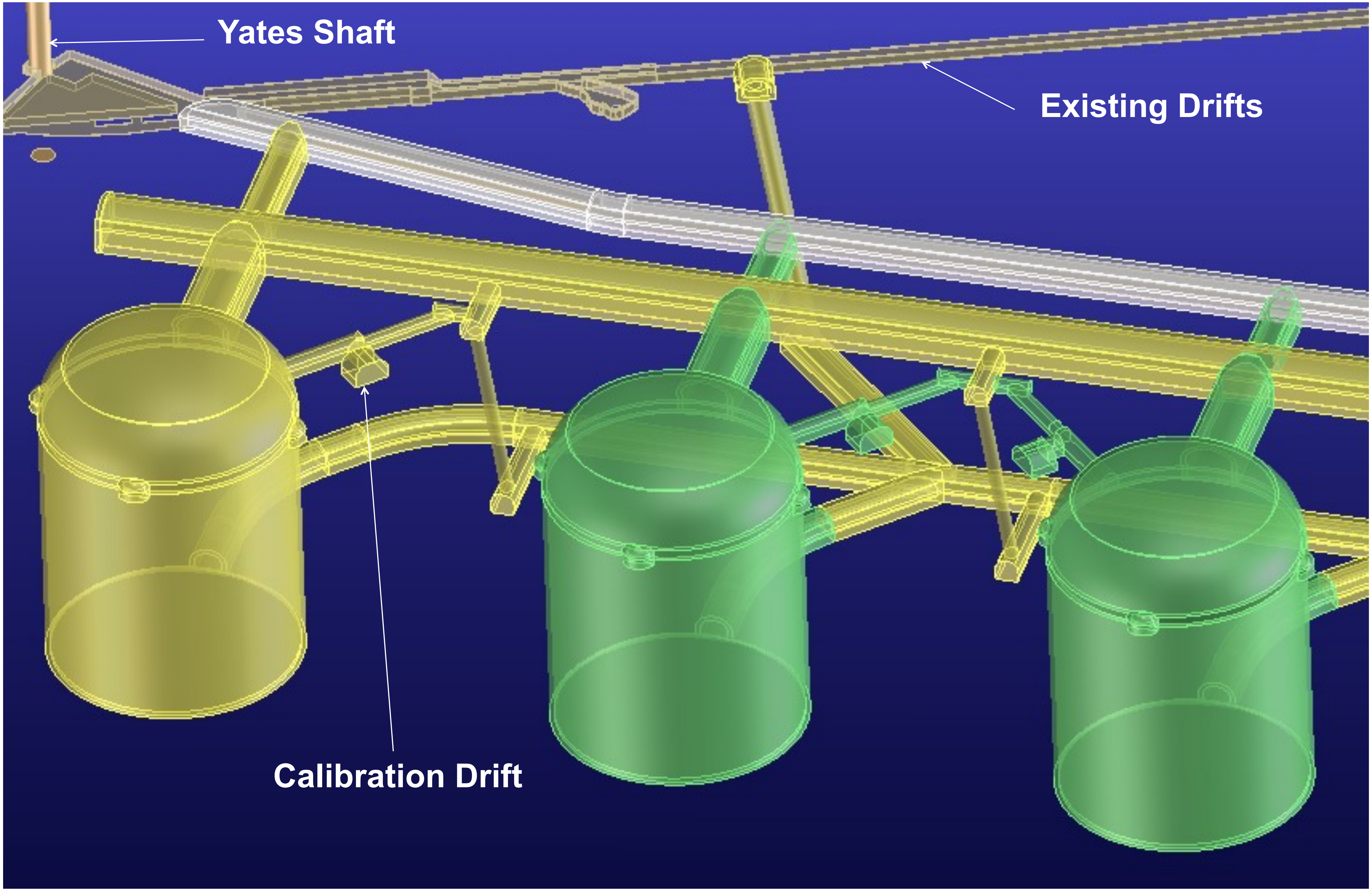
Large Cavity, Water Cherenkov Detector Calibration Drift Concept



Large Cavities, Water Cherenkov Detectors, Plan View
Calibration Drift Concept



Large Cavities, Water Cherenkov Detectors
Calibration Drift Concept



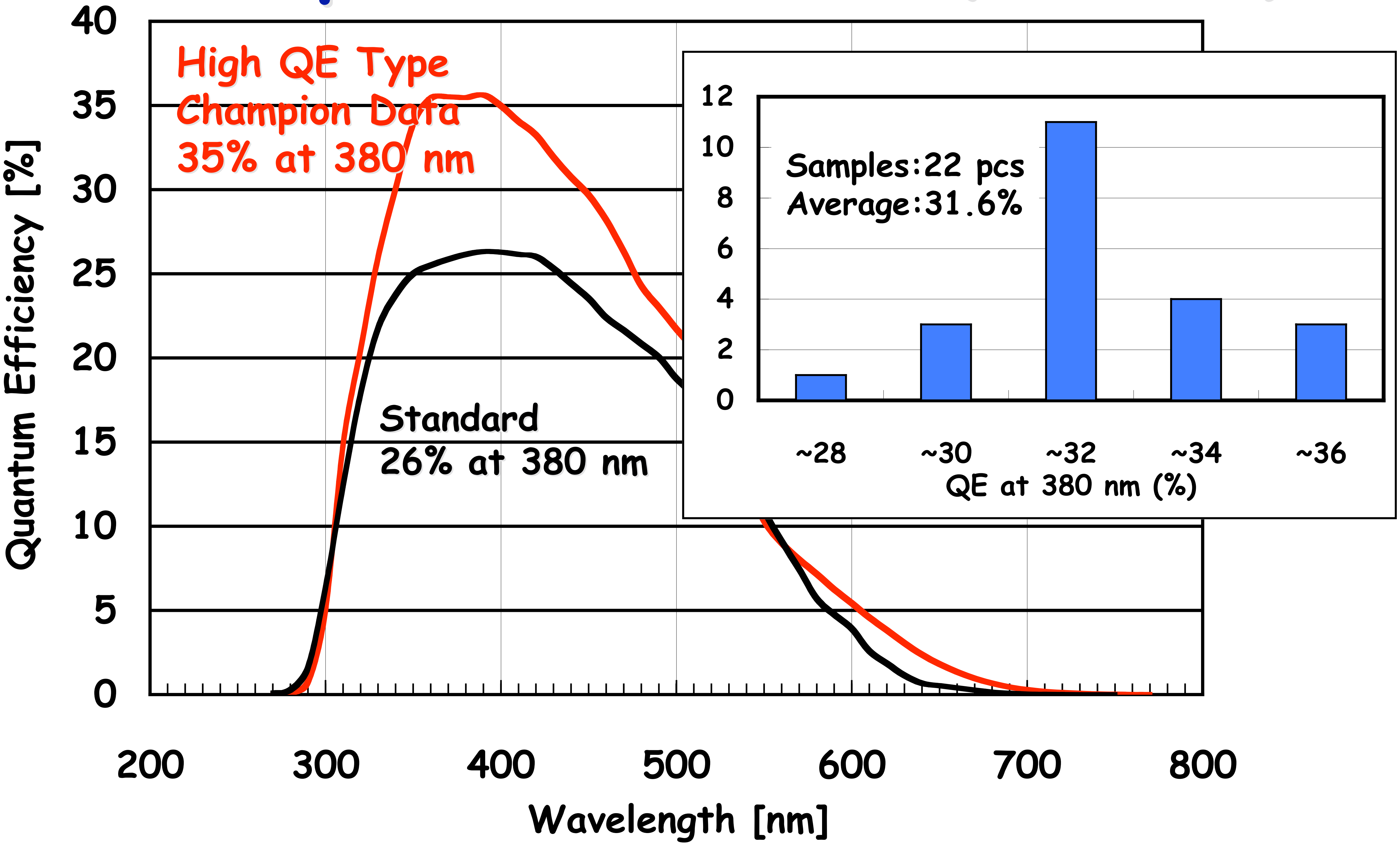
PMT R&D

- Issues are: making 150000 tubes in 6 years time, their efficiency, and their pressure performance.
- If PMTs can stand higher pressure, the cavern can be taller => more fiducial volume.
- Have had meetings with Photonis and Hamamatsu: no barrier to PMT production except money.

Typical PMT production

- Needs 35 people and ~30000-40000 ft2 space.
- With above annual production can be 20000 per year of 10-12 inch PMTs.
- Potential bottlenecks are glass production, and testing on the experiment's end.
- New High quantum efficiency technology is becoming standard.

Example data R7081 (10 inch)



Goal of development is 43%

M.Diwan

Status

- Project is big, and must follow big-project-procedure. This can be fast: e.g. NSLS-2 (~$1 b) at BNL went from CD0 to CD2 in 3 yrs.
- Mission Need Doc for CD0 is prepared and is under review in DOE.
- Project Management teams at FNAL and BNL are being staffed.
- A plan for developing CD1 docs has been developed and handed over to DOE. LBNE doc 26-v2.
- $15 ARRA funds is going to LBNE to speed up CD0 to CD1 process. Total of about $28M. Currently $7-8M at BNL.
- CD1 review at end of FY2010, reviews every 6 moths.
- Science collaboration funded from NSF S4 and some DOE supplements.

Conclusion

- A 300kT and 50kT of LAR detector at a good depth is well justified for accelerator neutrino physics.
- If built in the USA it has unique physics capability in the world due the length of the baseline.
- Excellent sensitivity for θ_{13} and mass ordering and CP violation.
- Proton Decay and Supernova astrophysics ranks very high.
- The caverns built could house different technology: better PMTs, Liquid Scintillator, Liquid X...

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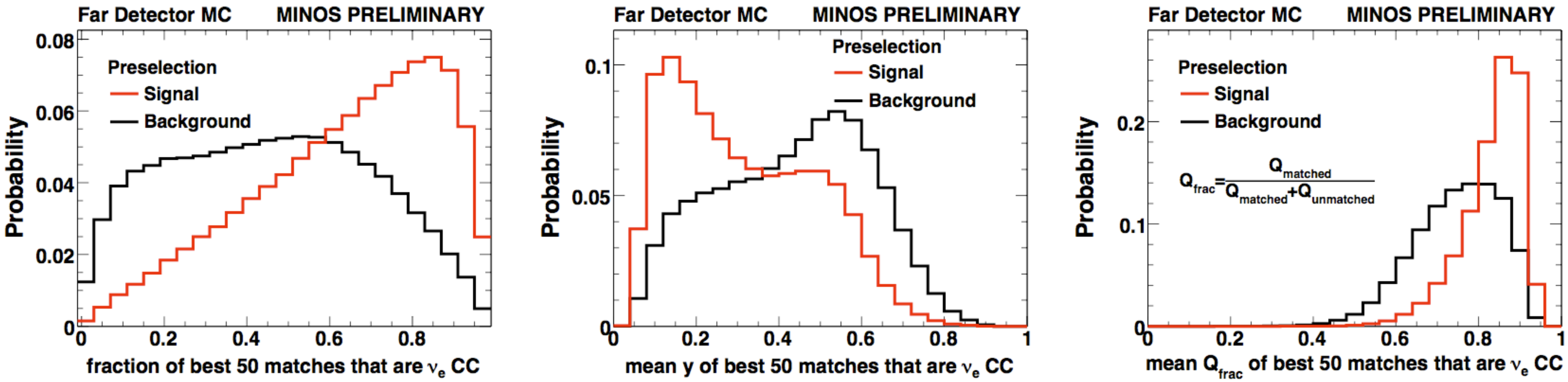
Preliminary cost & design..., BNL-76798-2006-IR, hep-ex/0608023 US longbaseline study,... FNAL-0801,BNL-77973,arXiv:0705.4396 NSF Homestake S1, S2, S3 proposals. NSF S4 proposal for detector development. Report on depth..., BNL-81896-IR, FNAL-TM-2424, LBNL-1348E http://nwg.phy.bnl.gov/fnal-bnl	NNN series of workshops, NUFACT workshops, UDIG 2008 workshop, DUSEL workshops, US long baseline study meetings, Homestake PAC, 2006, BNL PAC 2006 NUSAG, 2006, HEPAP 2006, 2007 P5 committee Feb, 2008 Proposal

- Genesis: Detector needs a neutrino beam, but what distance ? Why bother with longer distances than the first maximum ?

Selecting ν_e events with Library Event Matching (LEM)

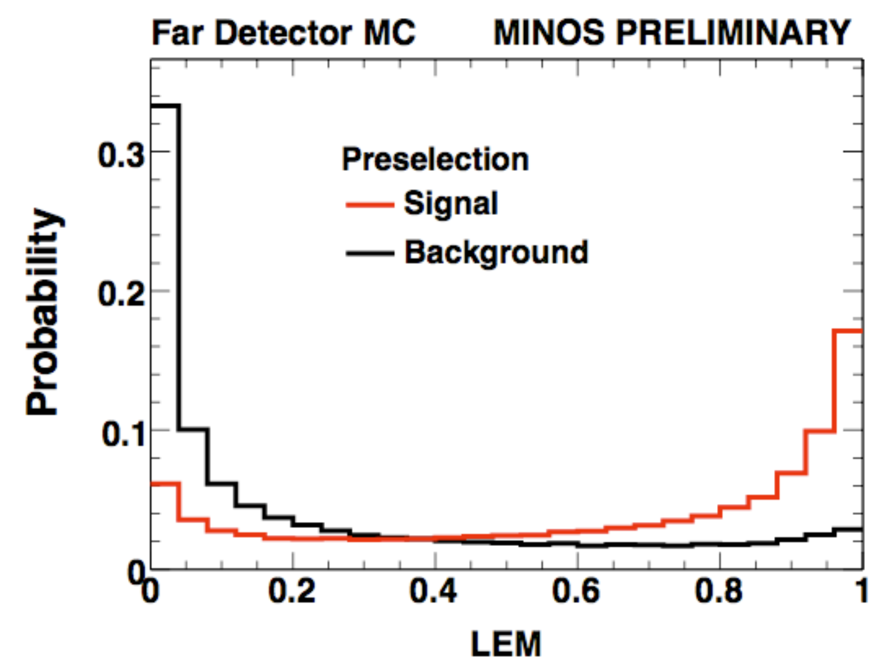
(fraction of electron neutrino events in 50 best matches)



- Select 50 best matches according to the likelihood that two events have the same hit pattern in position and energy deposition. Use large MC library.
- Construct discriminant variables from the properties of the 50 best matches, eg. fraction of the 50 best matches that are ν_e CC.
- Build a likelihood from 3 variables as function of energy.

Secondary method
(systematics need checking)

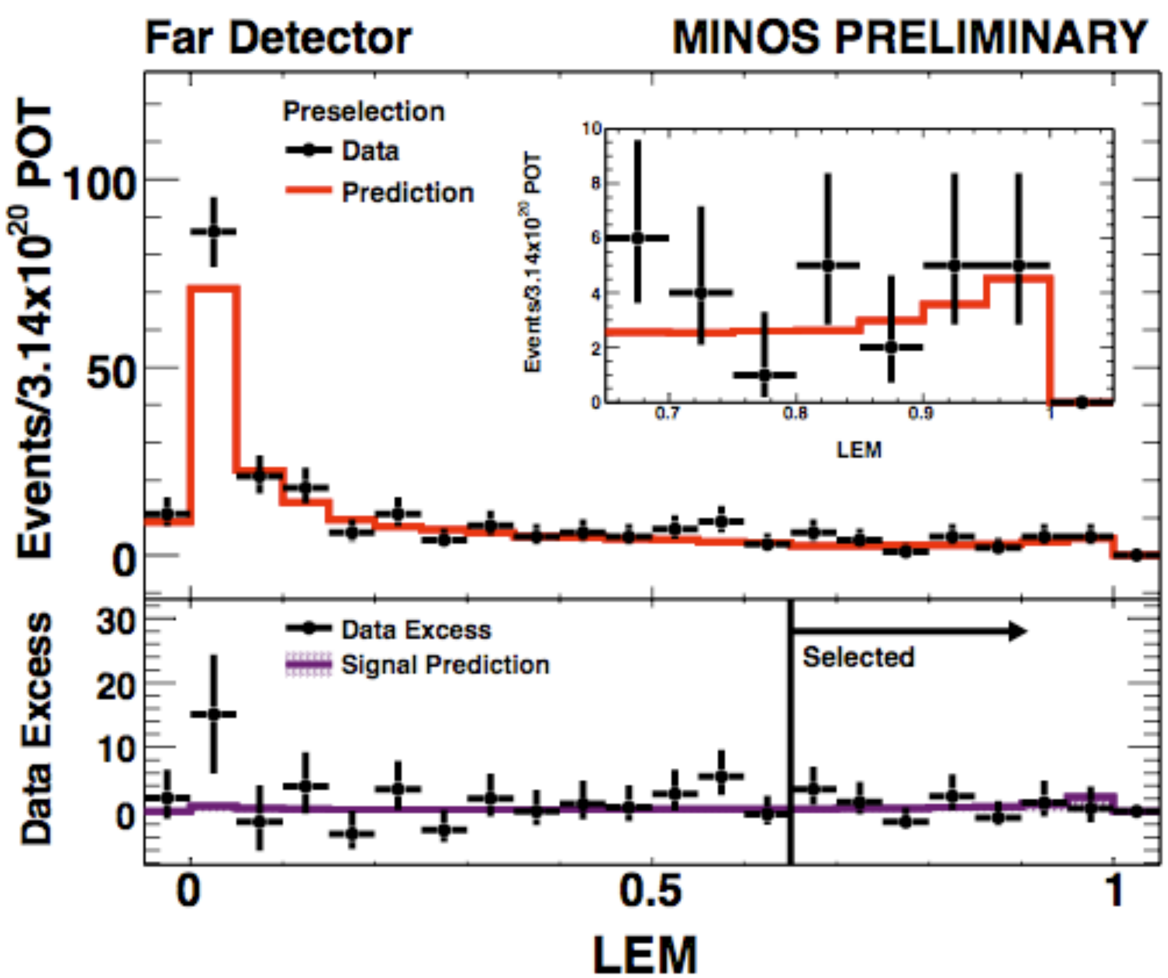
With a cut of LEM>0.65:
signal efficiency 46%
NC rejection >92.9%
CC rejection >99.3%
signal/background 1:3

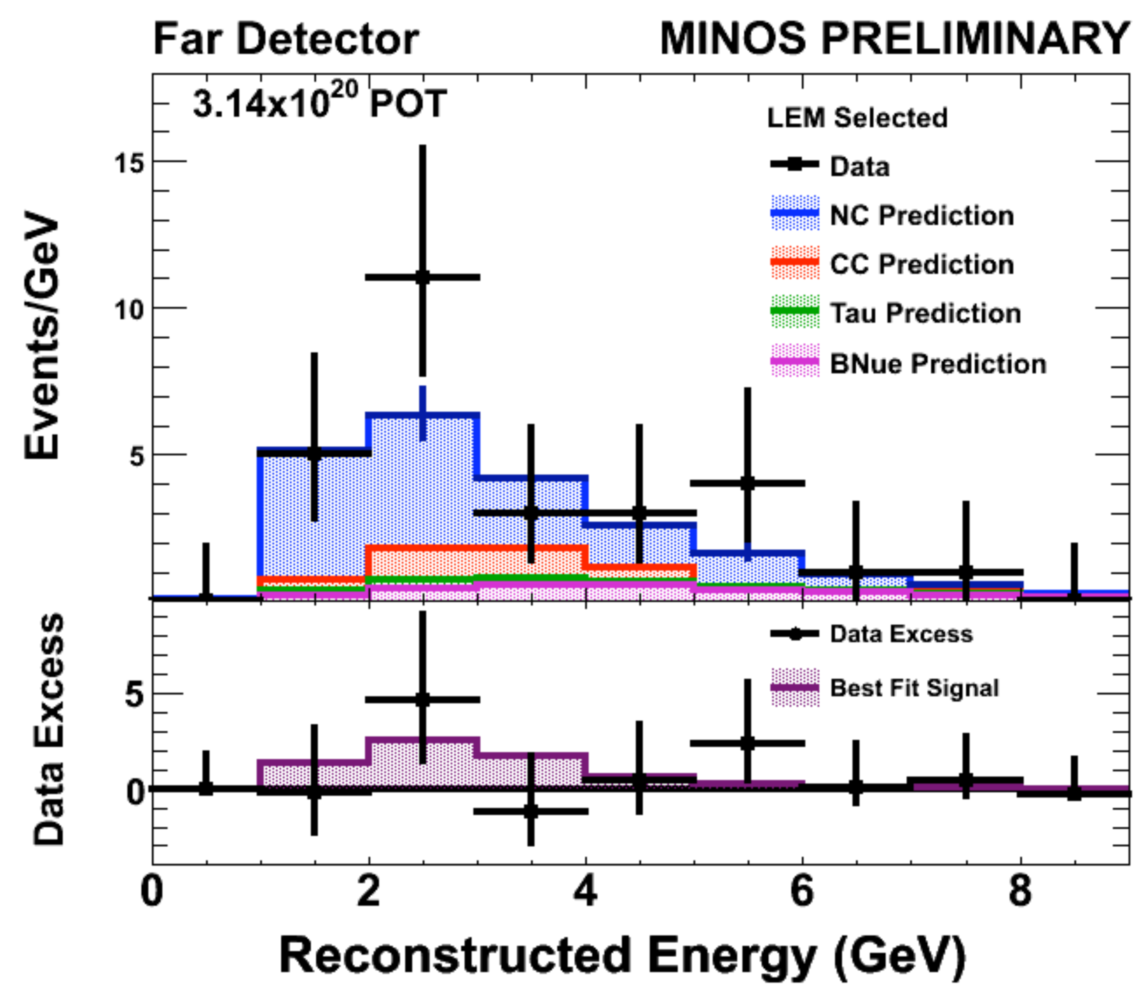


$\Delta m^2_{32}=0.0024\ eV^2$, $\sin^2\theta_{23}=1.0$

Signal region examination (2)

LEM (Secondary Selection Method)





Observation: 28 events

Expected Background: 22 +- 5(stat) +- 3(syst) events

Nucleon decay

- e-Pi0 mode: Current limit $>8X10^{33}$ yr with 141 kTon-yr (SK) with Bkg estimate: 2.1/Mton-yr
- e-pi0 with 300kTon*10yrs => $\sim 8X10^{34}$ yrs
- K-nu mode: Current limit $>3X10^{33}$ yrs with 141 kTon-yr (SK) with Bkg estimate: 1.7/Mton-yr
- K-nu with 300kTon*10yrs => $\sim 10^{34}$ yr
- With LAR the limit on K-nu could be much better because of much higher efficiency. We should do a detailed examination ourselves.

(300kT) will hit backg. in ~2yrs. It could be important to perform this first step before building bigger.

Astrophysical Neutrinos
Event rates. (100kT)

- Atmospheric Nus: ~10000/yr muon, ~5000/yr electrons. (Ref: Kajita nnn05)
- Solar Nus: >120000 elastic scattering E>5MeV (including Osc.)
- Galactic Supernova: ~100000/10 sec in all channels. (~3000 elastic events). (Ref: uno)
- Relic Supernova: (ref: Ando nnn05)
  - flux: ~5 (1.1) /cm2/sec Enu>10 (19) MeV
  - rate: 150 (70) events over backg ~200 !

There are detailed numbers for water and LAR in the depth requirements document

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