Physics of a very long baseline neutrino program with a wide band beam

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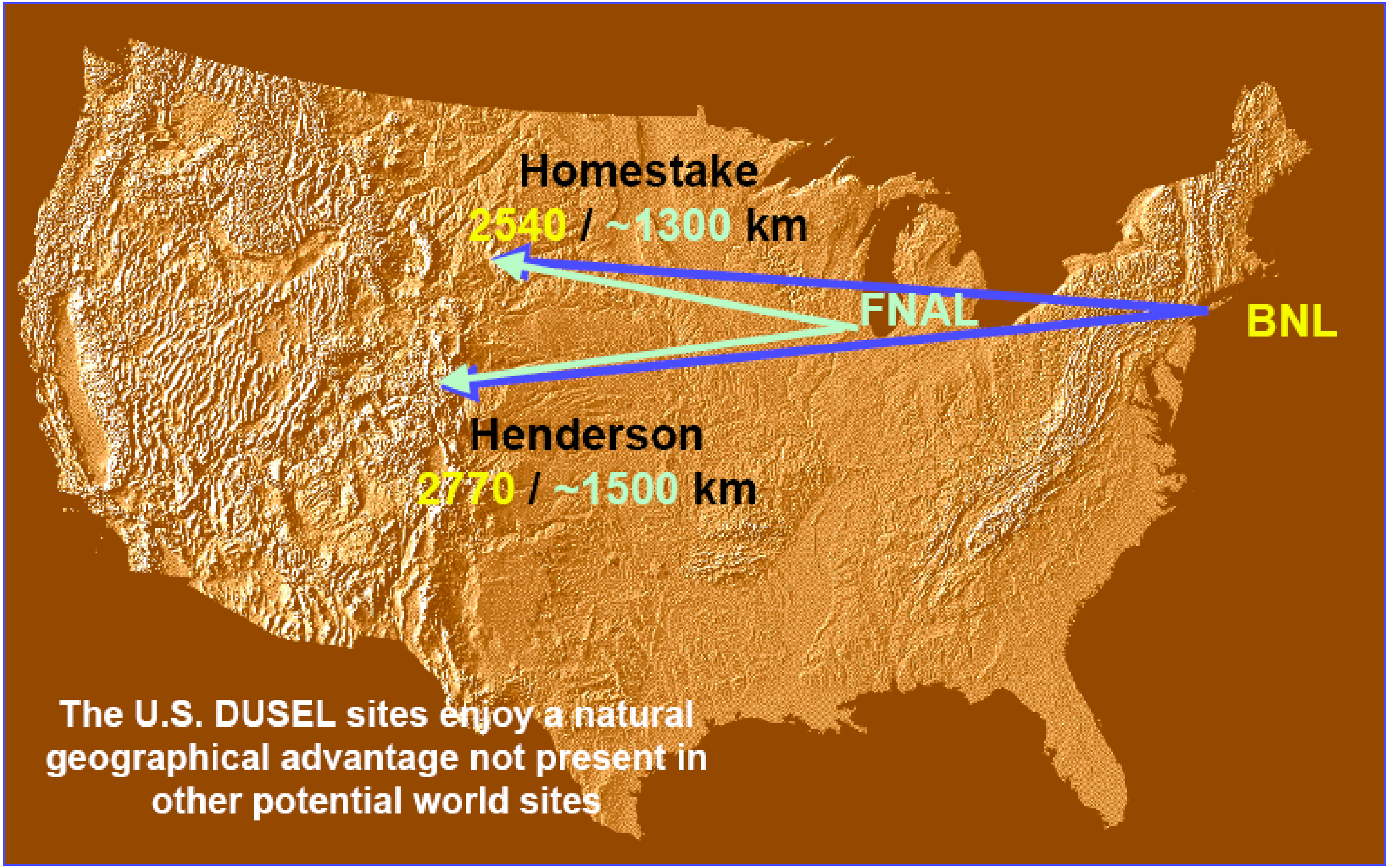
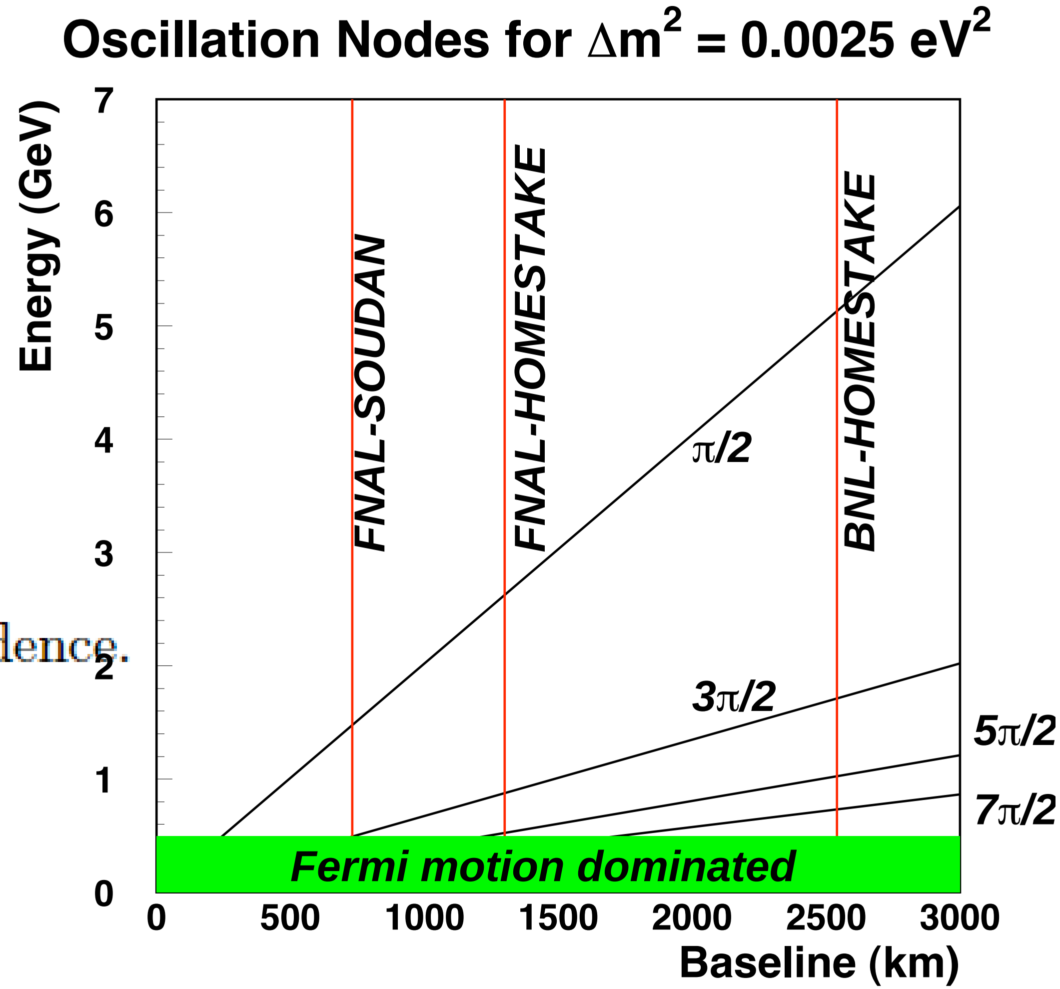
Outline

- Brief description of the physics and concepts.
- New simulations of FNAL beam/spectra and event rates.
- Current physics sensitivity calculation.
- Comparisons.
- List of open issues.

Super Neutrino Beam to DUSEL Candidate Sites



Physics and Oscillation Nodes



First Generation

- Focus on first node oscillations.
- Sensitivity for θ_{13}.

Next Generation

- Observe multiple nodes
  For precision and reduce flux dependence.
  Better sensitivity to θ_{13}.
- Longer flight paths:
  Larger matter effects for hierarchy resolution and new physics.
- Better S/B for CP violation (δ_{CP}) measurement.
  Flux $\sim L^{-2}$, but CP asymmetry $\sim L$; sensitivity to CPV independent of L. (Marciano hep-ph/0108181).

Want beam in 0-6 GeV range !

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

Approximate formula (M. Freund)

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

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

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

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

~7500 km
no CPV.
magic bln

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.

Comments about matter effect

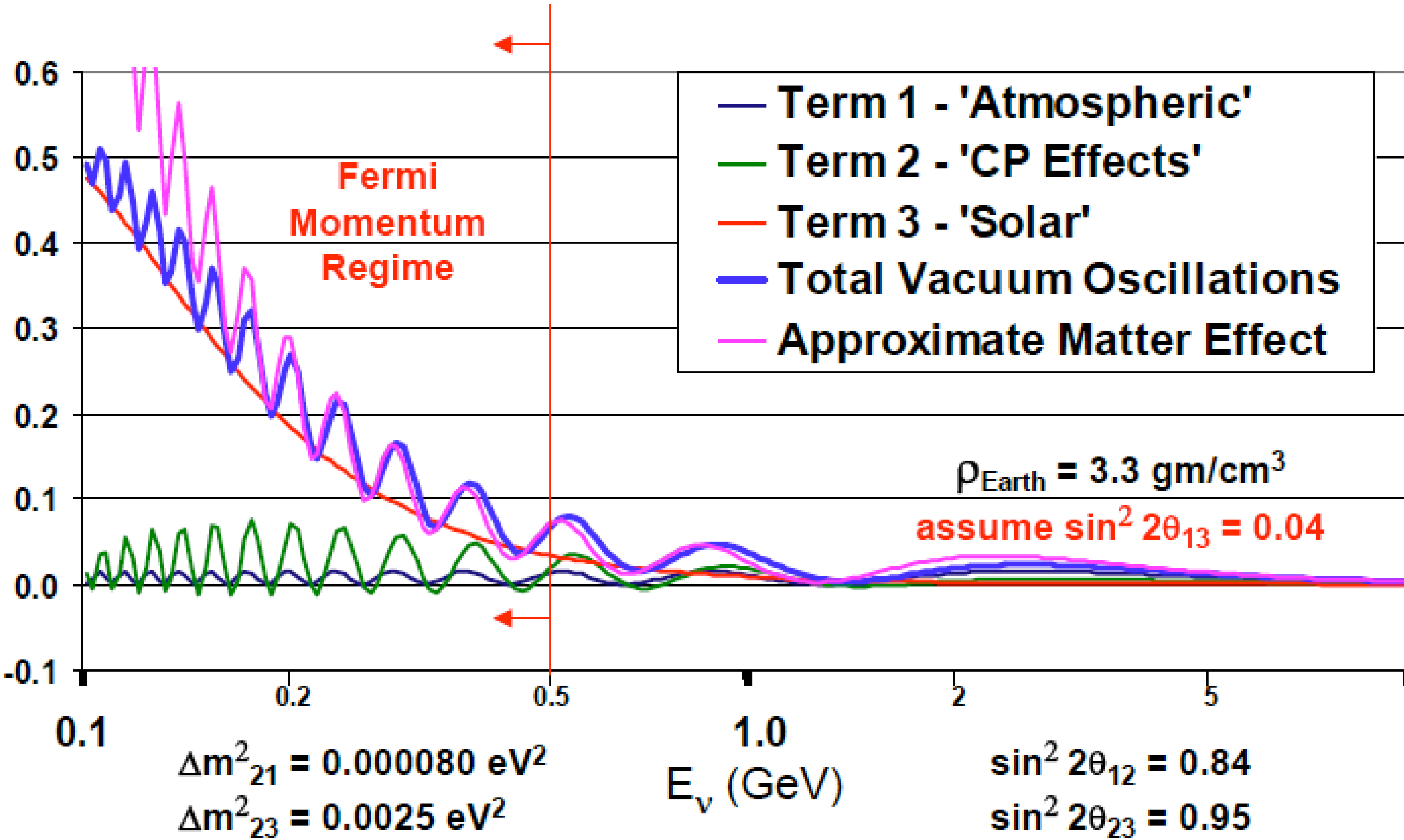
$V = \sqrt{2} G_F n_e$. n_e is the density of electrons in the Earth.

$\hat{A} = \approx 7.6 \times 10^{-5} \times (D/gm/cm^3) \times (E_\nu/GeV)/(\Delta m^2_{31}/eV^2)$,

Also recall $\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$.

- This is a very approximate equation, not applicable below the first maximum.
- First term has the effect of $\sin^2 2\theta_{13}$ and matter.
- Second and third terms have effects of CP.
- Term with J_{CP} changes sign for $(Anti - \nu_\mu) \rightarrow (Anti - \nu_e)$
- Last term is almost independent of Δm^2_{31} and is purely dominated by the solar Δm^2_{21}

$\nu_\mu \rightarrow \nu_e$ Vacuum Oscill. - VLBNO
L = 1300 km – FNAL to Homestake



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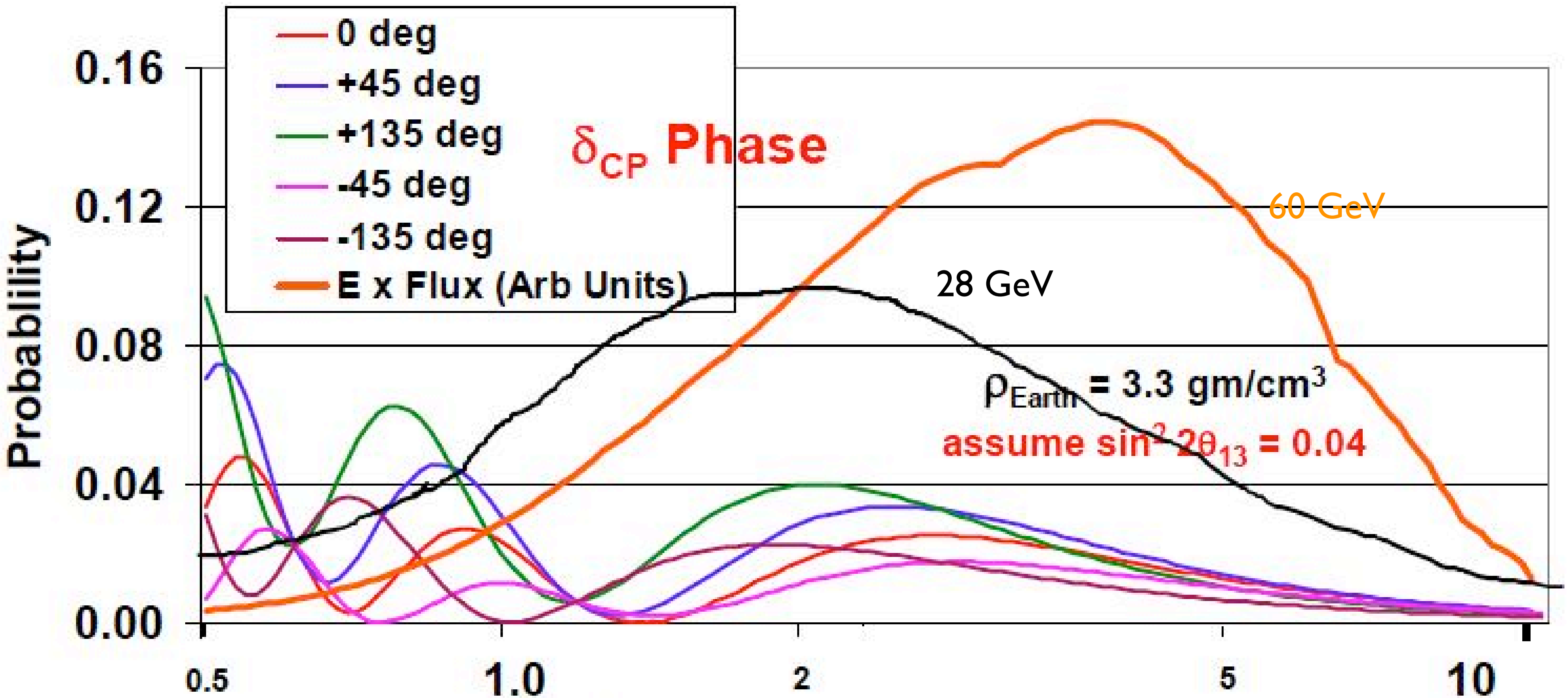
$\nu_\mu \rightarrow \nu_e$ CP Phase Effects - VLBNO

L = 1300 km – FNAL to Homestake



$\Delta m^2_{21} = 0.000080\ eV^2$

$\Delta m^2_{23} = 0.0025\ eV^2$

E_ν (GeV)

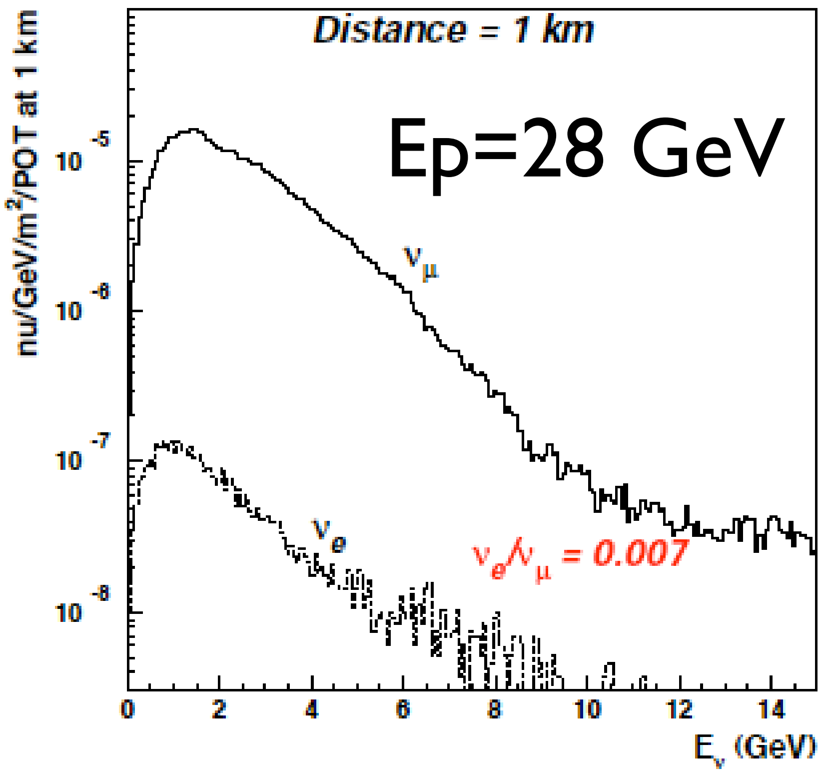
$\sin^2 2\theta_{12} = 0.84$

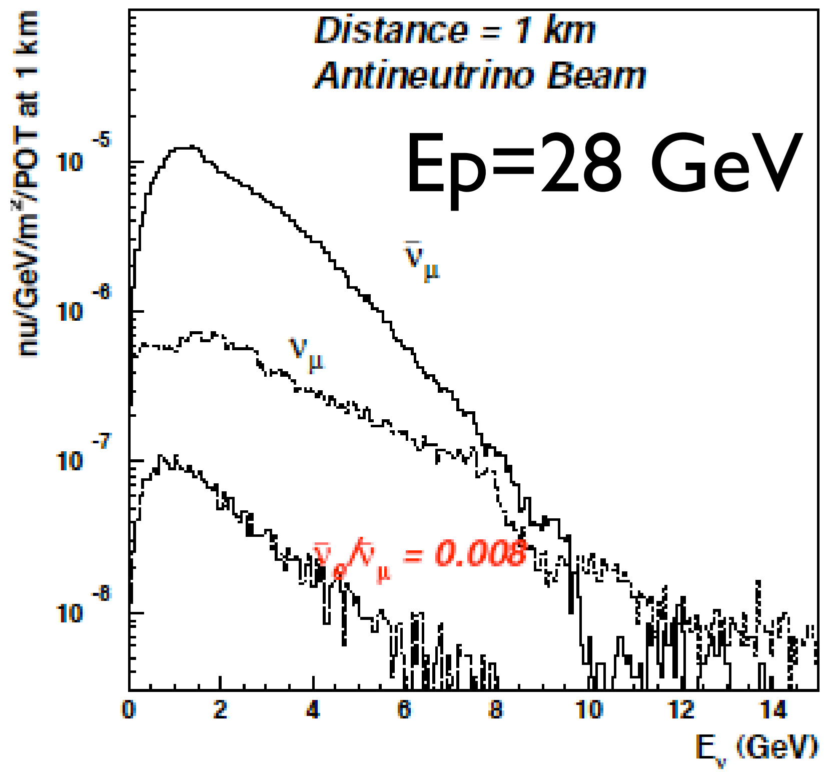
$\sin^2 2\theta_{23} = 0.95$

Observations

- Sensitivity to CP is independent of distance after ~1000km
- 1300 km => high statistics, smaller effects.
  2500 km => bigger effects, smaller statistics
- The size of detectors and beam power needed does not depend on theta_13 (as long as it is not very small, S. Parke)
- The "solar" term could be observed with large L/E.   It has to be present in any experiment sensitive to CP violation.

wideband low energy (WBLE)

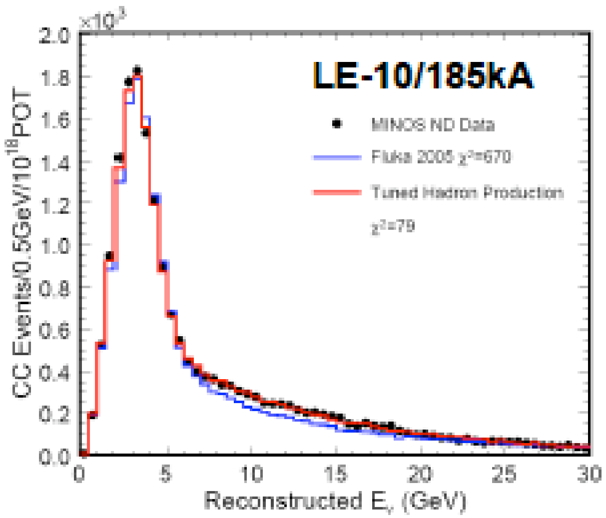


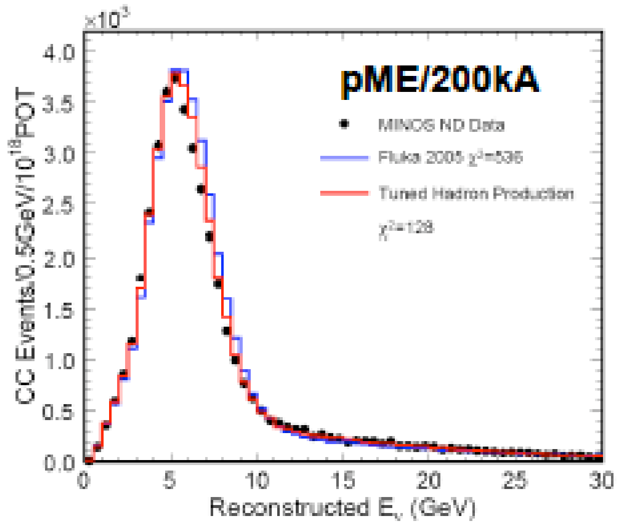


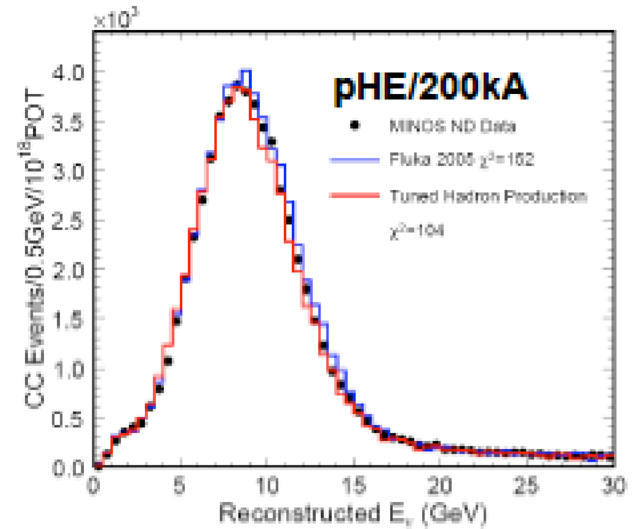
- Low energy wideband 0.5-6 GeV. Ep = 28 GeV. 200 m decay tunnel with 4 m diameter. This spectrum used for all sensitivity estimates so far. This is called OLD spectrum from now on.
- FNAL-HS (1300km) nu CC rate: 3.5 evts/kT/1e20POT
- FNAL-HS (1300 km) anti-nu CC: 1.12 evts/kT/1e20POT

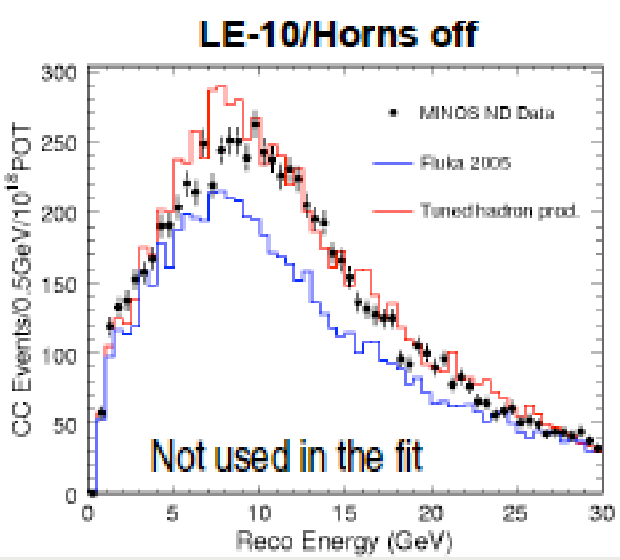
New work on flux from FNAL based on NUMI Monte Carlo

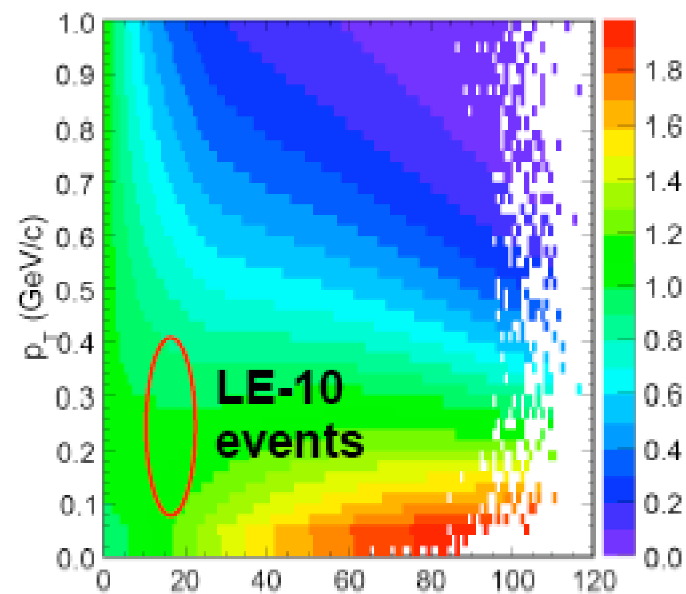
Good agreement data - Fluka05 Beam MC is, tuning MC by fitting to hadronic x_F and p_T, improves agreement.









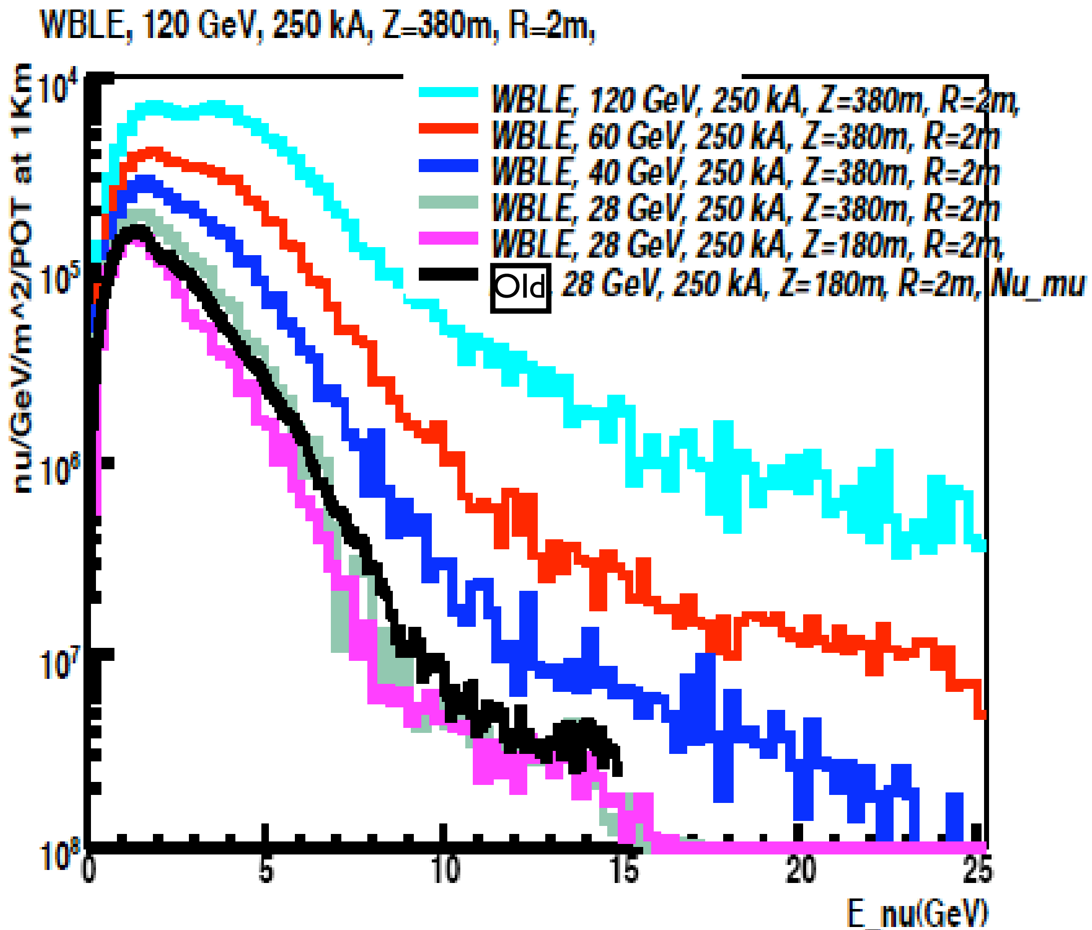


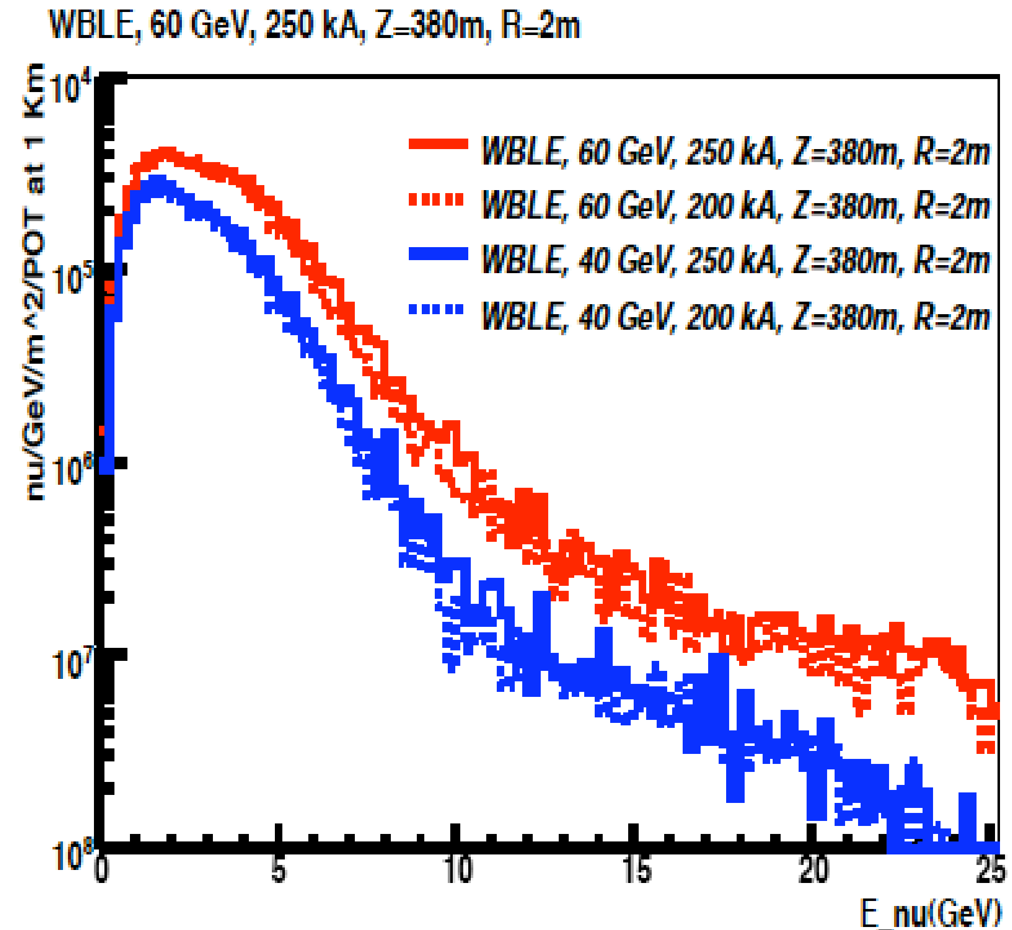
Weights applied as a function of hadronic x_F and p_T.

WBLE Optimization - FLUKA05

Decay pipe radius chosen to be 2m.

Siting restrictions $\Rightarrow$ decay pipe is $\leq$ 400 m in length





From M. Bishai

Event rates and optimization

For NuMI (735 km): 1st osc max Is at 1.5 GeV, 2nd osc max Is at 0.5 GeV

For FNAL-Homestake (1297 km): 1st osc max Is at 2.6 GeV, 2nd osc max Is at 0.8 GeV

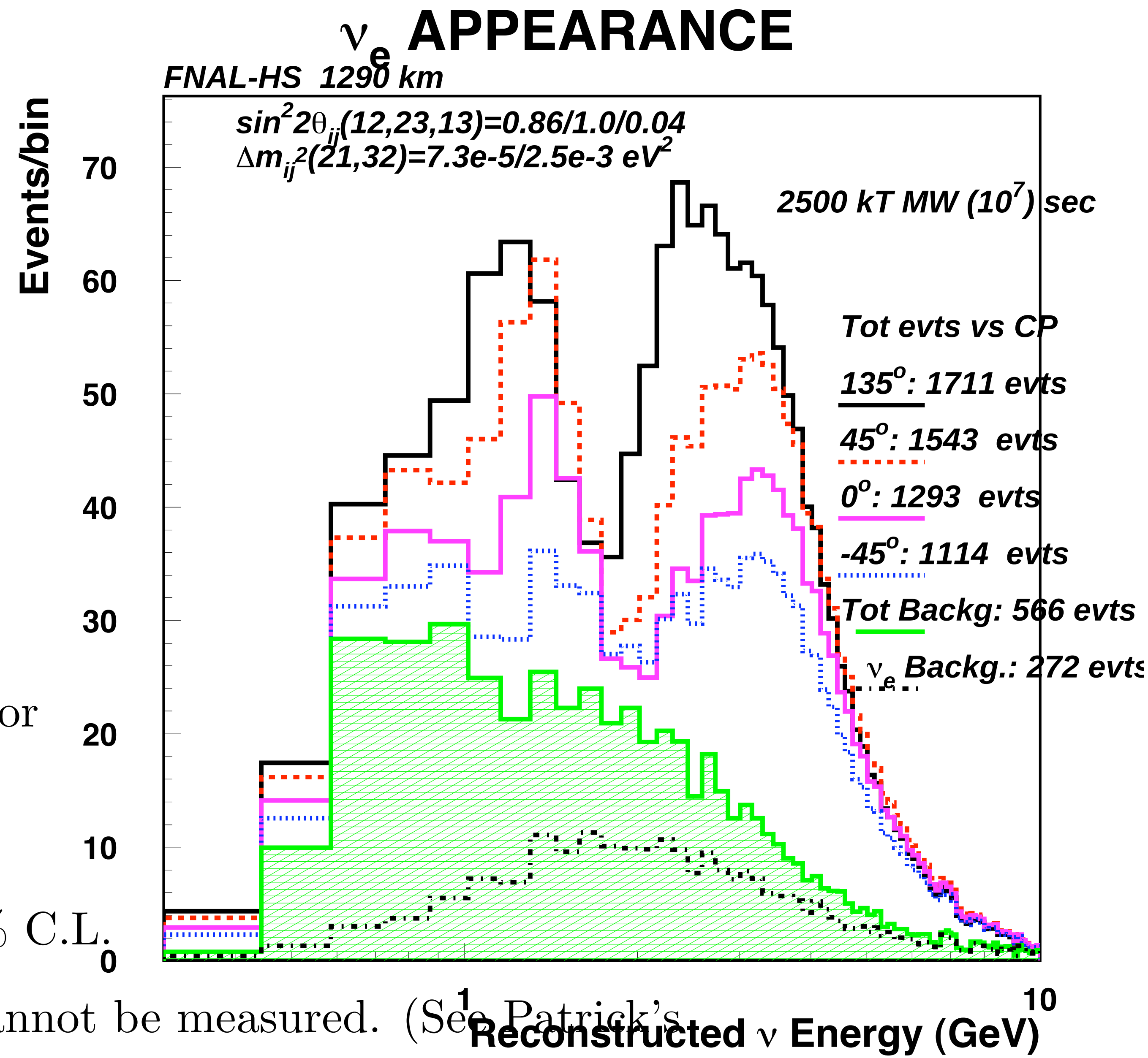
Beam scenario	Tunnel	numu CC /10^20 POT*kT	Total rate 5e7 sec	CC(nue/ numu)
WBLE 60GeV	R=2m L=380	13 (1300km)	202800 (300kT*1MW)	0.9%
WBLE 40GeV	R=2m L=380	6 (1300km)	140400 (300kT*1MW)	0.9%
WBLE 28GeV	R=2m L=380	3.4 (1300)	114240 (300kT*1MW)	0.8%
WBLE 28GeV	R=2m L=380	2.4 (1300)	80640 (300kT*1MW)	0.6%
NUMI-ME -120GeV 12km offaxs	R=1m L=677	20.3 (810km)	15625 (30kT*1MW)	2.2% (integrated)
NUMI-ME -120GeV 40 km offaxs	R=1m L=677	0.9 (810 km)	1170 (50kT*1MW)	5.5% (integrated)

$$Total\ POT(10^{20}) = \frac{Beam\ power(kW)}{1.6E_p(GeV)} \times time(10^7 sec)$$

Beam summary

- Higher confidence in event rates with new Monte Carlo.
- Have used WBLE (28 GeV) with old simulations for sensitivity calculations, but it is close to new simulations.
- Assume total exposure for WBLE to be 2500kT*MW*(10^7)sec for each polarity.
- 5 years of running at 1.7e7 sec/yr with 300kT for each polarity.
- At 60 GeV running 0.5 MW may be enough for total event rate (tails need examination).

ν_e Appearance



Backgrounds

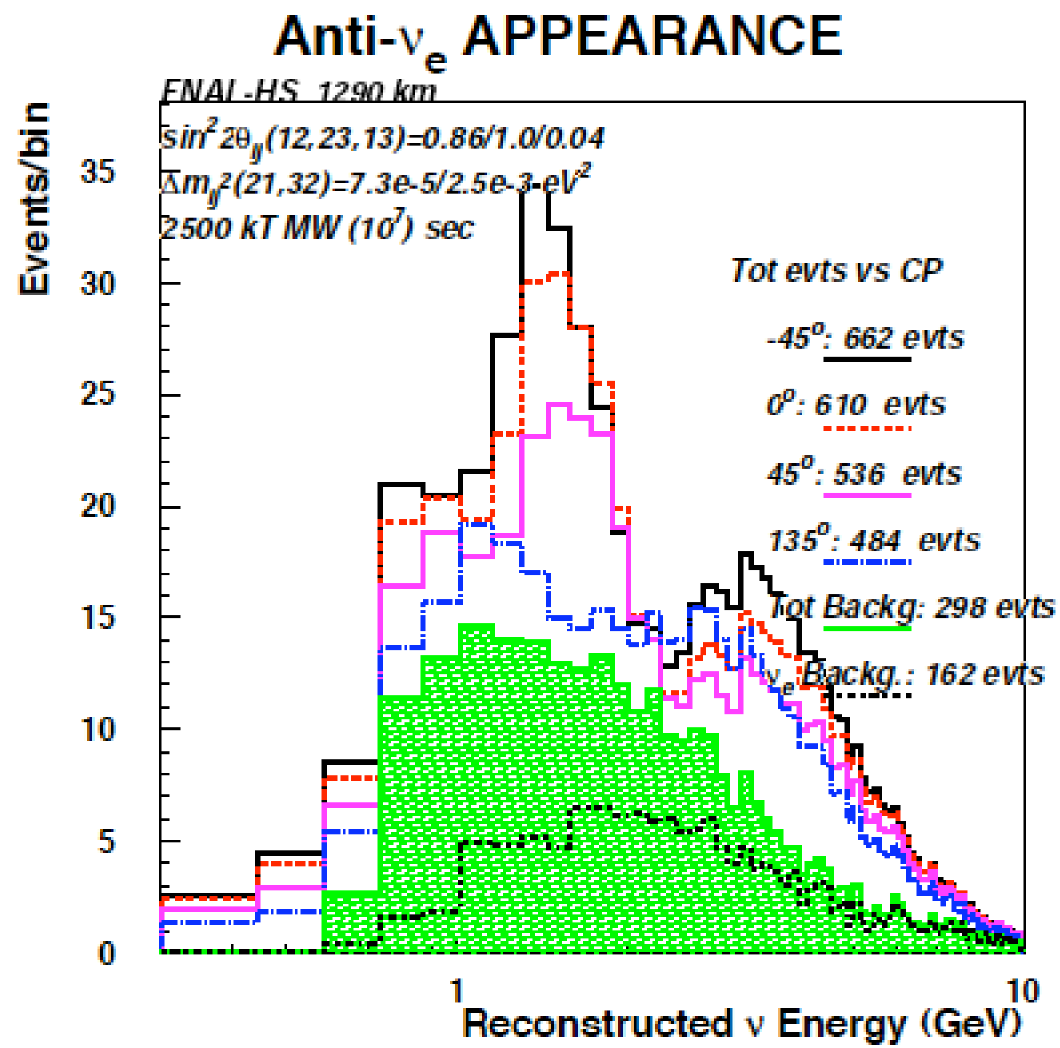
- beam ν_e
- Neutral current events

ν running

- measure $\sin^2 2\theta_{13}$ and δ_{CP}.
- resolve mass hierarchy for $\sin^2 2\theta_{13} > 0.01$
- with $\bar{\nu}$ running $\sin^2 2\theta_{13} > 0.003$ at 90% C.L.

If $\sin^2 2\theta_{13}$ too small δ_{CP} cannot be measured. (See Patrick's curves).

- Will need higher power to compensate for cross-section.
- For normal hierarchy higher peak is suppressed.
- For reversed it will be enhanced.



ν_μ Disappearance

Very easy to get this effect
Does not need extensive pattern recognition. Can enhance the second minimum by background subtraction.

Neutrino Running

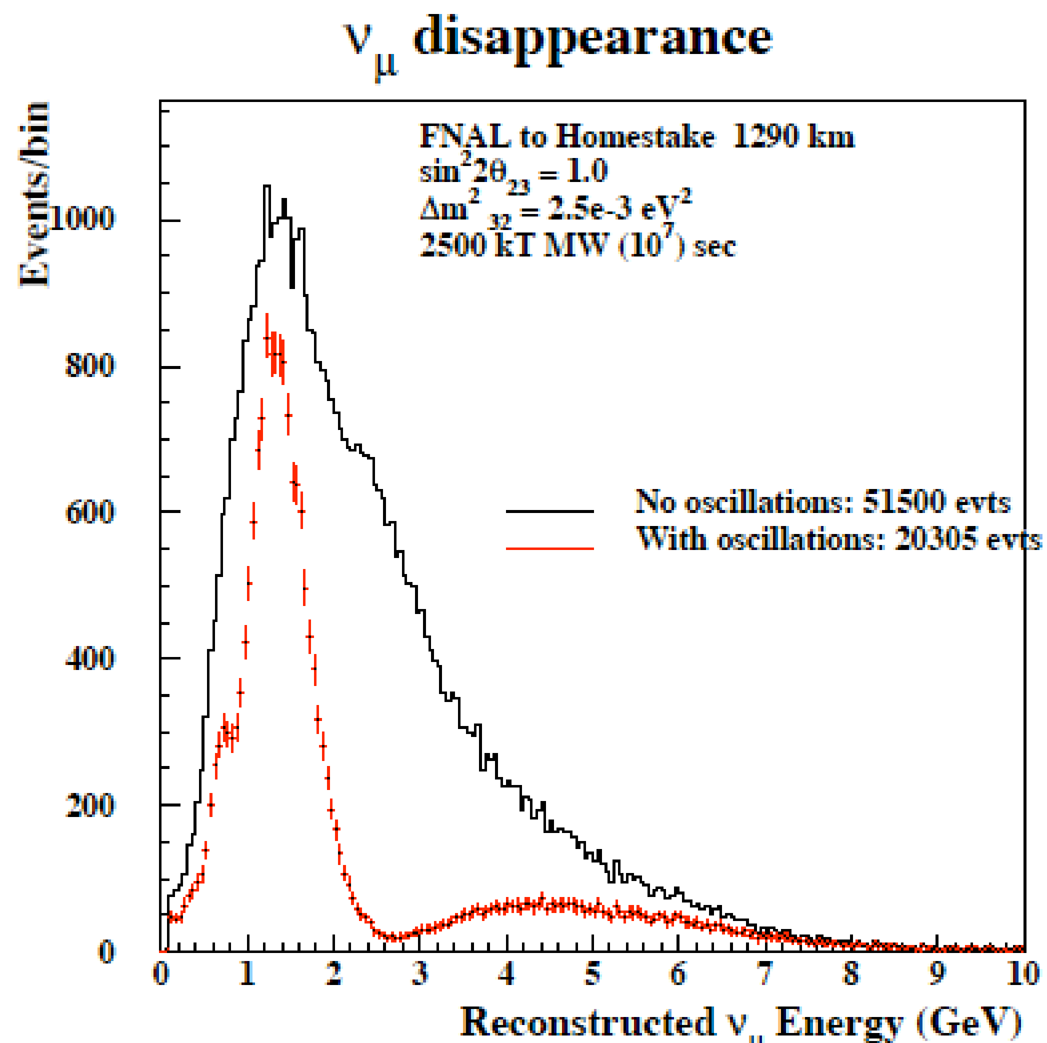
- Total exposure: 2500 kT.MW.(10^7).sec
- 195000 CC evts
- Use only clean single muon events.

Measurements

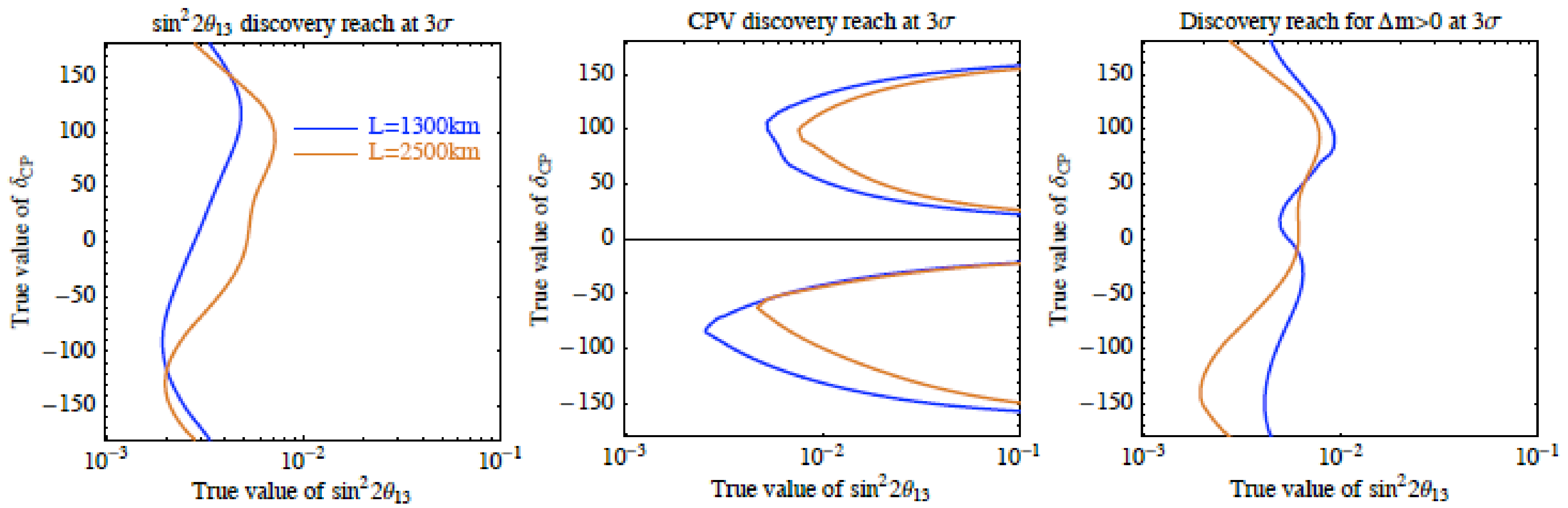
- 1% determination of Δm^2_{32}
- 1% determination of $\sin^2 2\theta_{23}$
- Most likely systematics limited.

$\bar{\nu}$ running

- Need twice the exposure for similar size data set.
- very precise CPT test possible.



Wide band beam

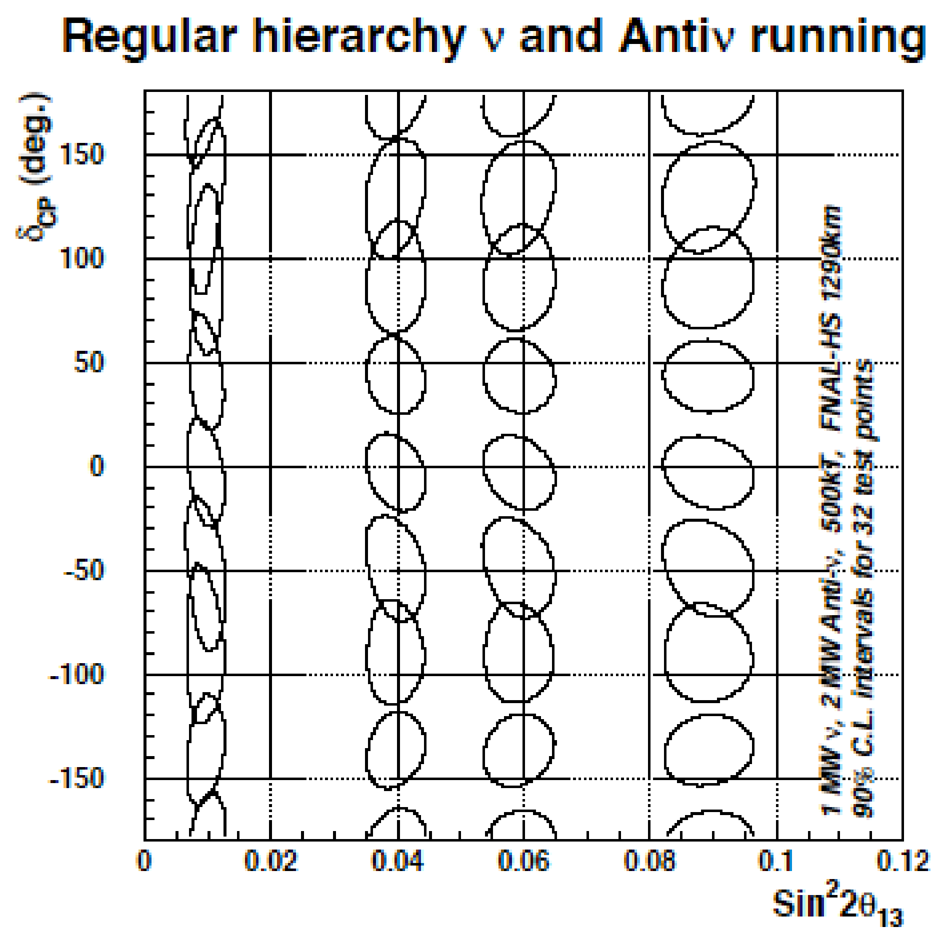


- very good resolution of the mass hierarchy
- no problems due to π-transit for $\sin\delta > 0$
- Baseline choice is not critical

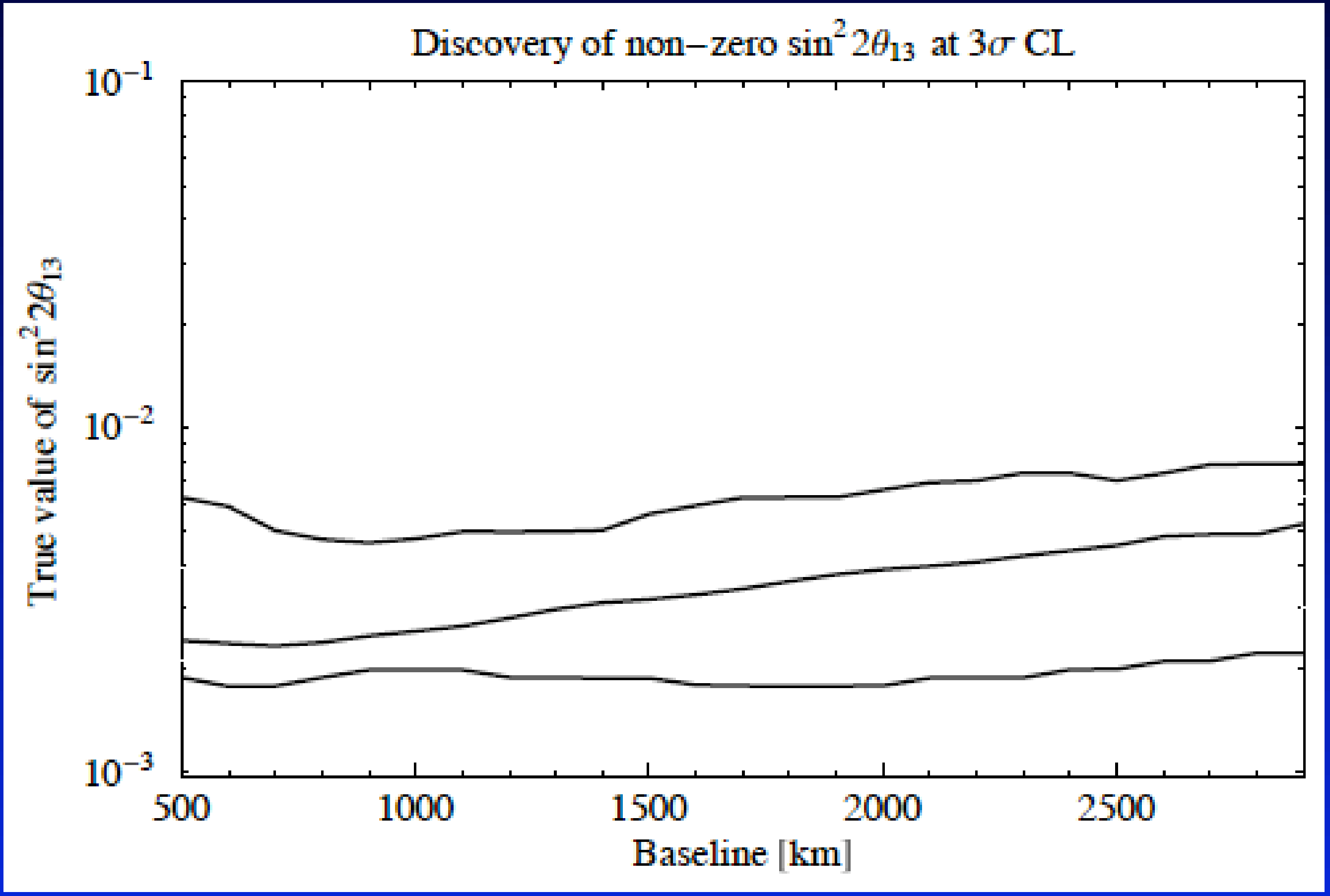
includes anti running, but large fraction of the result is from nu running for normal hierarchy

CP measurement

- Assume 10% systematic errors on background.
- Plot look the same for reversed hierarchy.
- Independence CP resolution of theta_13 explicitly proved.
- All ambiguities are resolved.

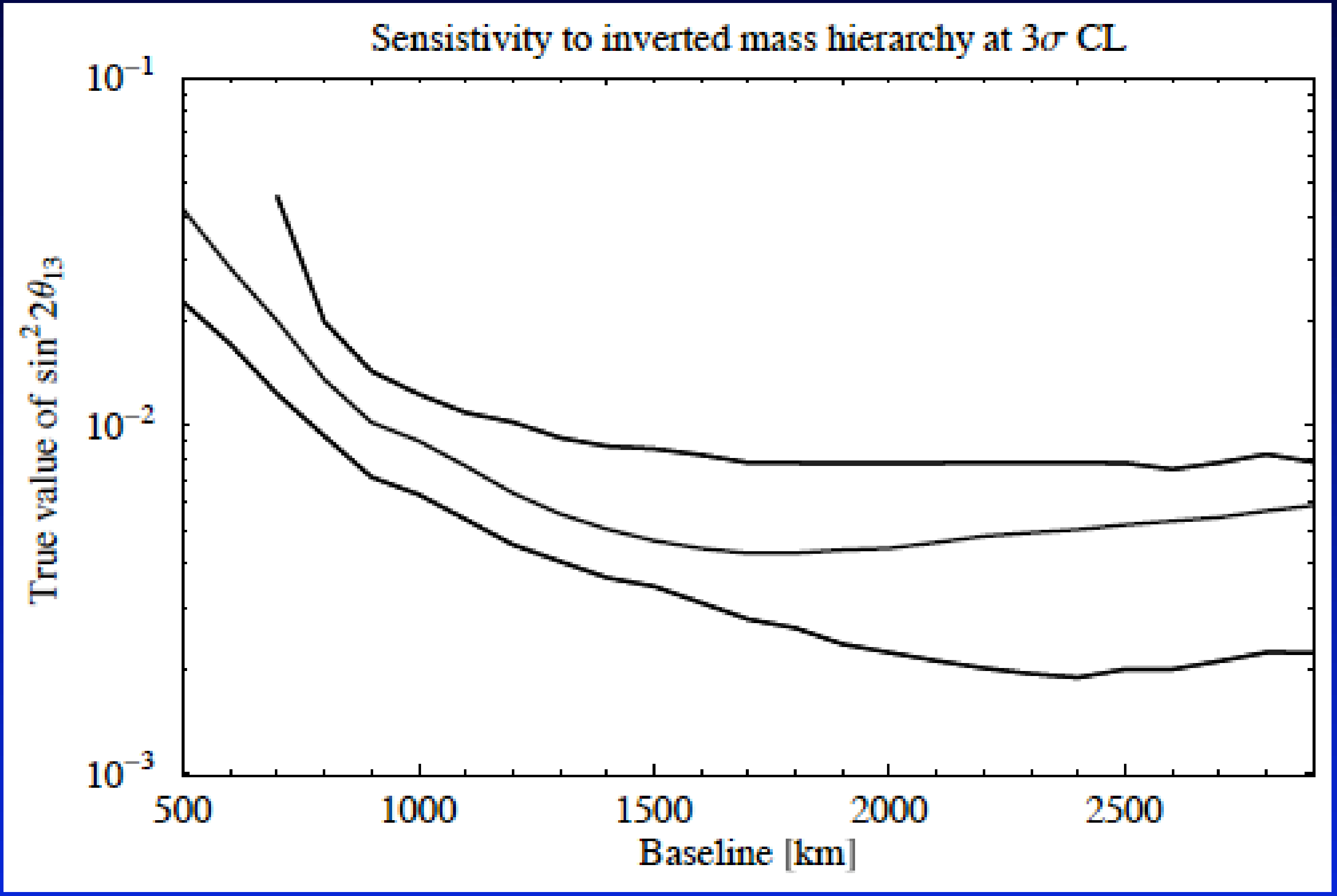


Baseline dependence



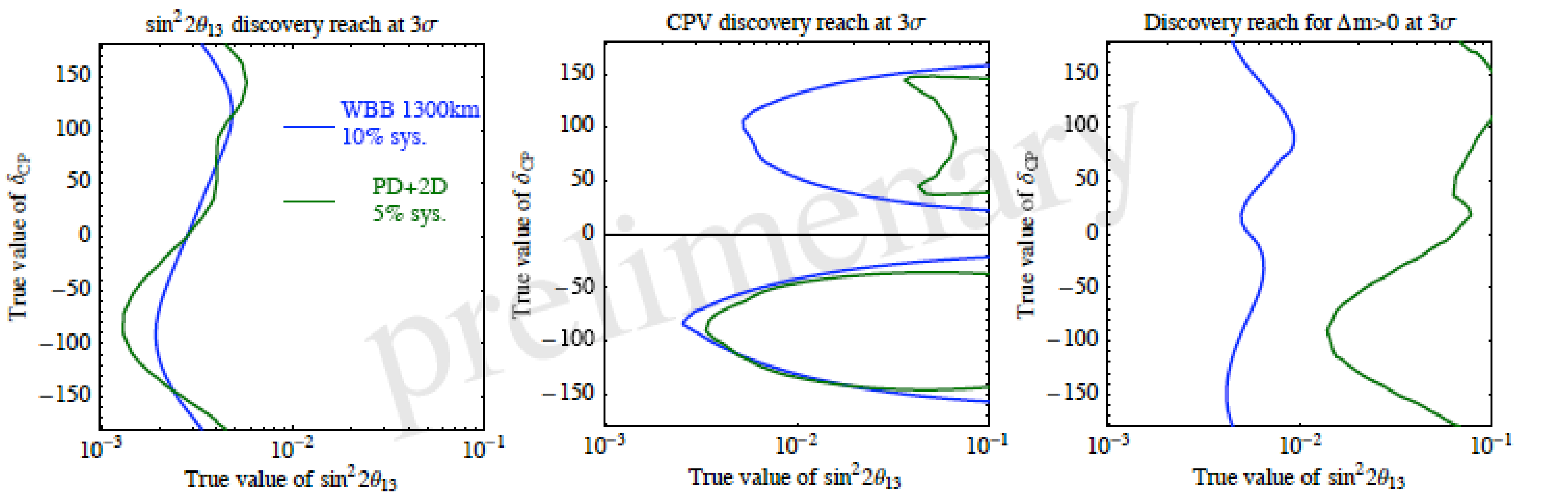
- weak baseline dependence

Baseline dependence



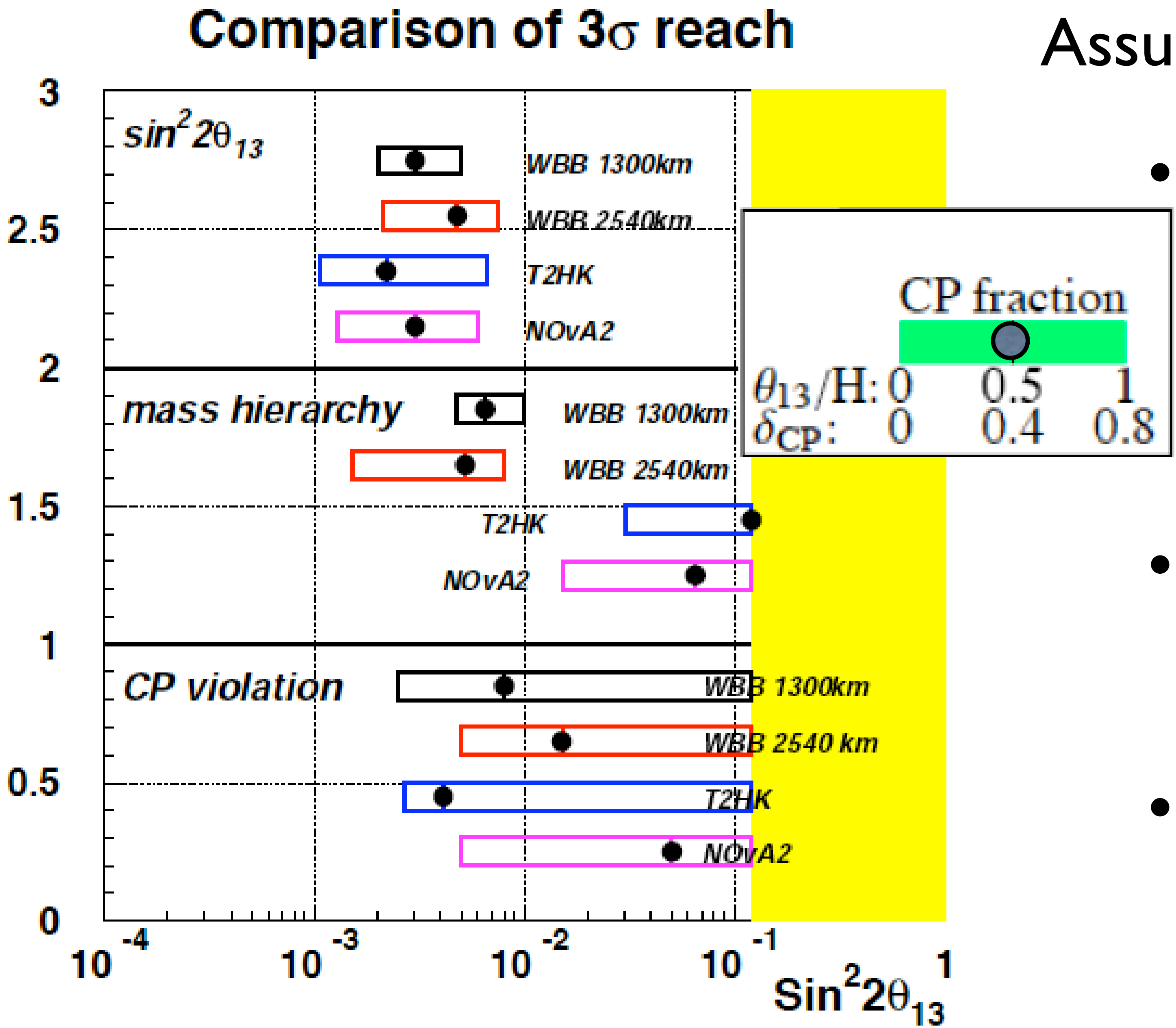
- long baselines are clearly favored

Summary



For 40 km off axis spectra background from kaon peak not in calculation

Preliminary comparison to off-axis program with a second detector



Assumptions

- WBB:
  nu:200kT*1MW*6yr.
  antinu: 200kT*1MW*6yr
  syst: 10% on bck
  Antinu running is over-constraint for normal hierarchy.
- T2HK:
  nu: 1000kT*4MW*3yr
  antinu: 1000kT*4MW*3yr
  syst: 2% on bck
- NOVA2:
  nu:30kT*2MW*6yr+ 80kT*2MW*3yr
  antinu: same*6yr+3yr
  syst: 5% on bck

Preliminary result out of FNAL workshop

Detector

- >300 kT fiducial mass for both proton decay and neutrino astro-physics and neutrino beam physics.
- ~10% energy resolution on quasielastic events.
- muon/electron separation at <1%
  - 1,2,3 track event separation.
  - Showering NC event rejection at factor of ~20.
- Low threshold (~5 MeV) for solar and supernova physics.
- Time resolution ~few ns for pattern recognition and background rejection.

Previous issues being solved

Water Cherenkov can satisfy these requirements

Not magic. Performance is obtained by giving up large fraction of potential signal CC events; and using the kinematics of NC events.

Simulations

- Strategy: Get clean single lepton events and throw out as everything else even if it reduces events.
- Detailed simulation of backgrounds and resolution are continuing (see work of Stony Brook group)
- Fast simulation is adjusted to conform to above.
- See www.fnal.gov/directorate/DirReviews/Neutrino_Wrkshp.html
- The simulated background and signal spectra are fed into GLoBES to make sensitivity calculations with a fit.

Simulation status so far (from Yanagisawa)

- Realistic MC simulation studies have been performed for the BNL very long baseline scenario with a water Cherenkov detector. It was found that BNL wideband ν_μ beam combined with a UNO type detector DO A GREAT JOB whether the baseline is 2,540 km or 1,480 km.
  – Very exciting news ! But always do proper MC simulations!
- It was demonstrated that there is room to greatly improve S/B ratio beyond the standard water Cherenkov detector reconstruction codes even with currently available codes.
  - We may need further improvement of algorithm/software, which is quite doable.
  - Detailed studies on sensitivity on oscillation parameters needed with different neutrino spectrum to optimize the beam spectrum.
  - A larger detector such as UNO has an advantage over a smaller detector such as SK (we learned a lesson from 1kt at K2K): Both PMT coverage AND granularity are important
- In collaboration with BNL and Fermilab, proper simulations of a next generation water Cherenkov detector, its optimized design with reasonable ν_μ beam will produce sweet fruits for exciting physics

Open issues on detector

-

- Can we push NC backgrounds further.

- Fiducial volume for muons. For electrons we can rely on SK simulations.

- PMT coverage: 20 % adequate from SK experience. 40% if very low threshold is needed.

- PMT size: 13 inch versus 20 inch. Greater number of pixels will give better pattern recognition.

- Size of detector: very difficult to increase span. If made bigger has cost and schedule implications.

Open issues on beam

- What is the correct proton energy and power level from FNAL
- What is the cost of a new beam
- To get intensity at low energies must have ~4 meters diameter tunnel. It is clear that 4 m dia and 380 m length is a big win !
- How should we tailor the spectrum for maximum signal/noise ?
- If tunnel is wide WE CAN ALWAYS RUN OFFAXIS by moving and tilting the horn/target. (upto 1 deg.)
- What is the time sequence ?

Summary

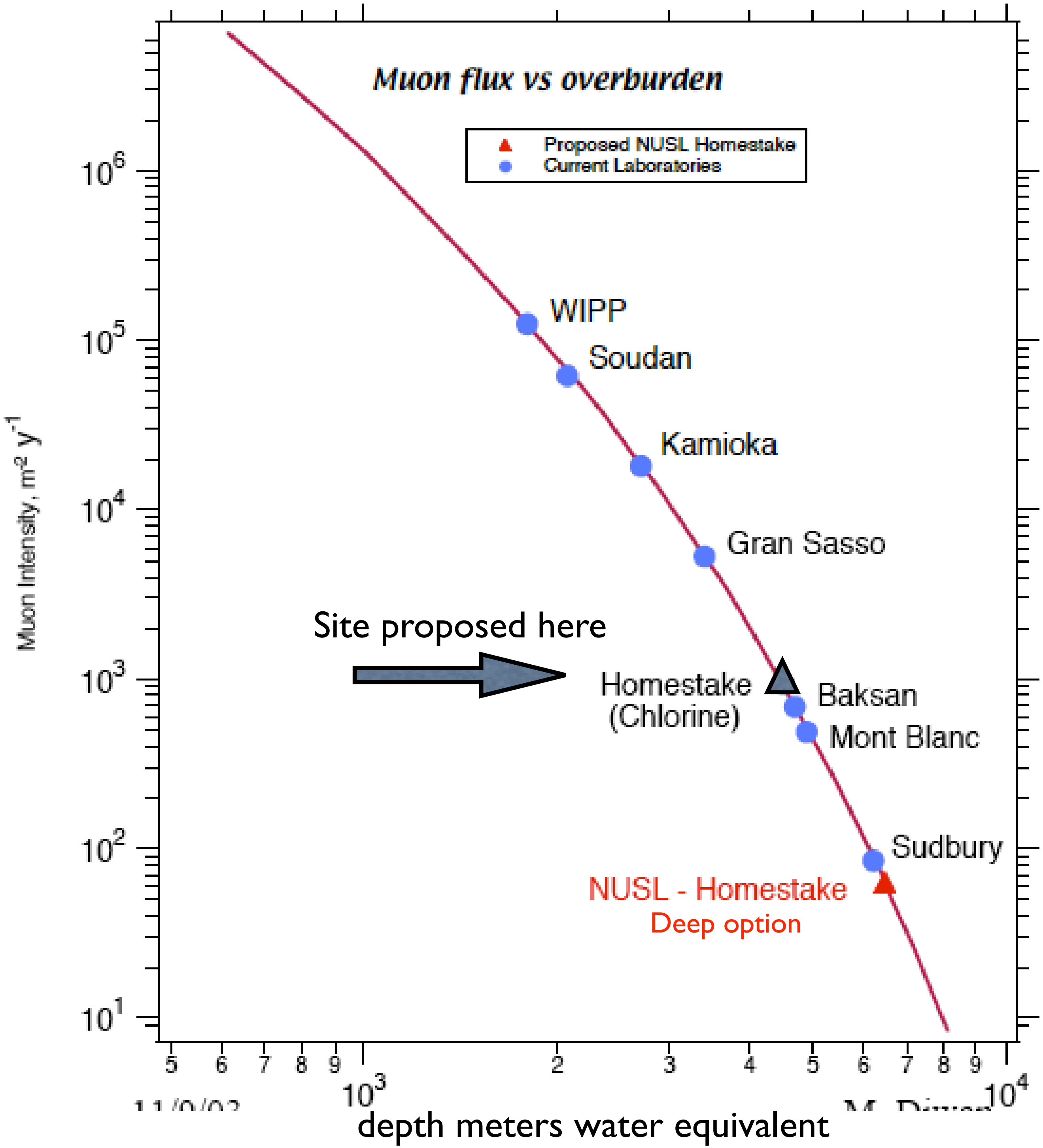
- I reviewed the physics considerations for a long baseline and very long baseline program.
- New simulation results on a wide band low energy beam were reported.
- A CP program with a large detector in DUSEL and a new beam with current FNAL accelerator intensity looks promising.

4850ft:
100kT
~3M mu/yr

with rate of 1 mu/10 sec => may not need veto-counter

The Beam neutrinos will be obvious with a rate of 100-200/day in 10 mus spills.

No pattern recognition beyond time cut is needed.

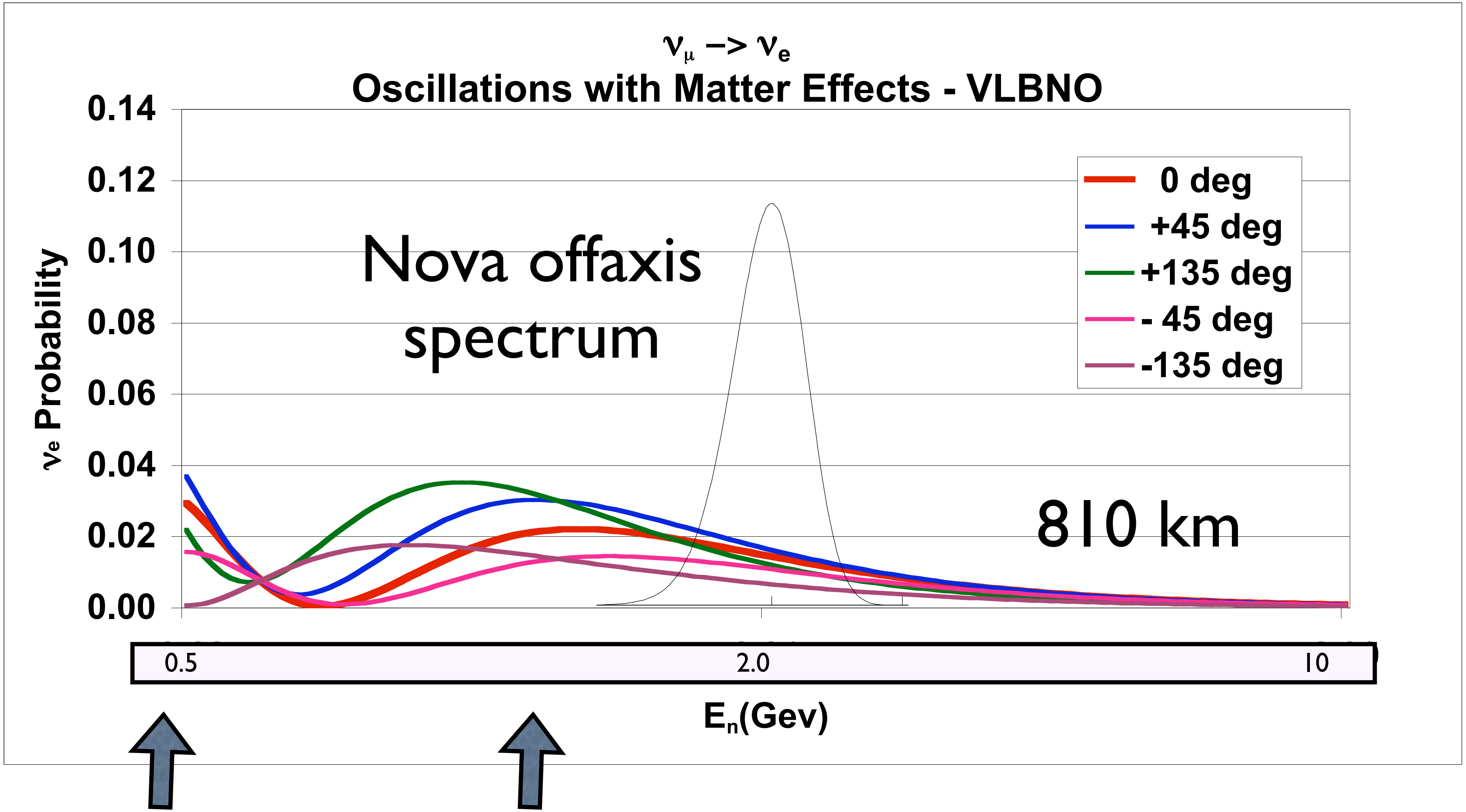


Exploring the possibility of neutrino beams towards a DUSEL site

W. Smart

	Latitude	Longitude	Vertical angle from FNAL (deg)	Distance from FNAL (km)
Homestake	44.35	-103.77	-5.84	1289
Henderson	39.76	-105.84	-6.66	1495

- Use of the present extraction out of the Main Injector into the NuMI line
- Construction of an additional tunnel, in the proximity of the Lower Hobbit door in the NuMI line, in order to transport the proton beam to the west direction
- Radius of curvature of this line same as the Main Injector, adequate for up to 120 GeV/c proton beam with conventional magnets
- Assumptions:
  - **a target hall length of ~45 m (same as NuMI for this first layout, probably shorter)**
  - **decay pipe of 400 m (adequate for a low energy beam), we would gain in neutrino flux by increasing the decay pipe radius (> 1 m)**
  - **distance of ~300 m from the end of the decay pipe to a Near Detector (same as NuMI).**

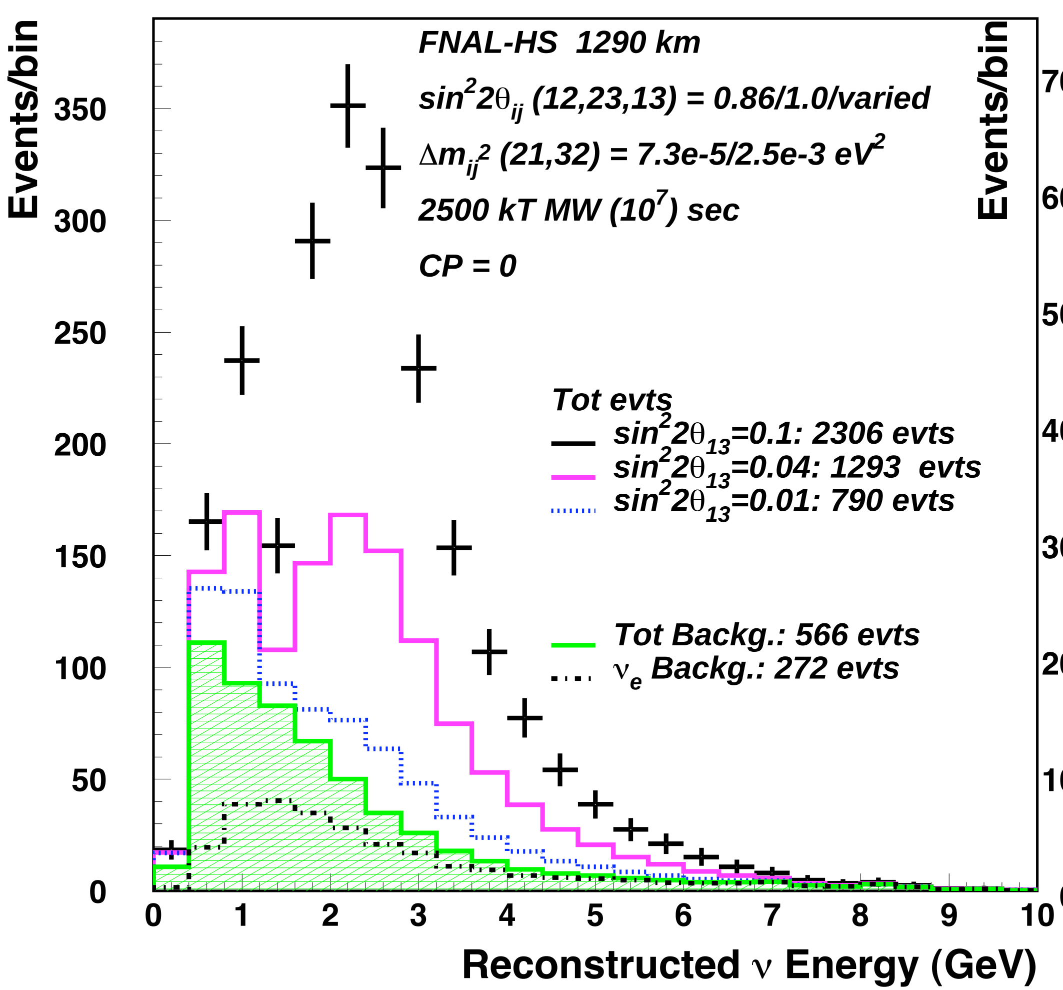


second max
~0.5GeV

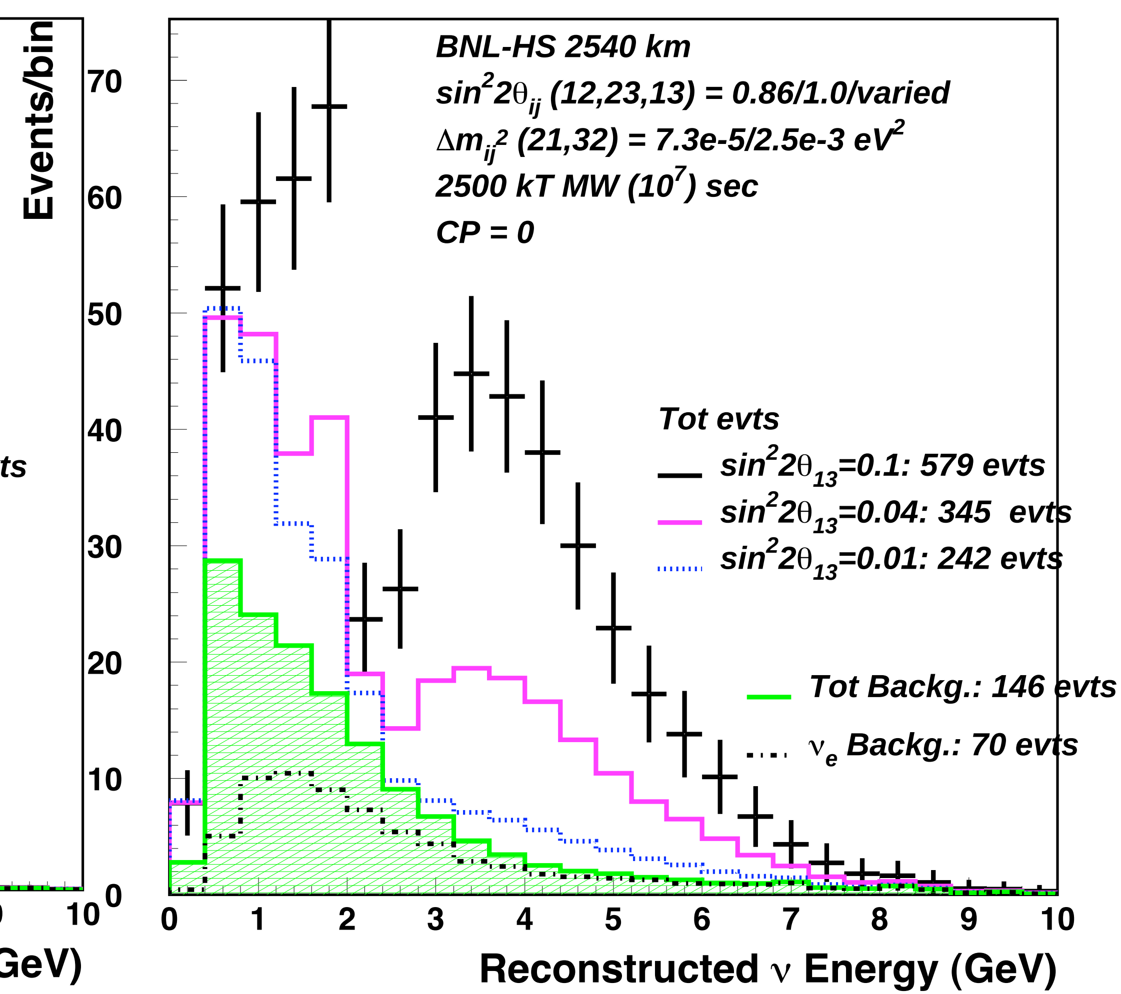
first max
~1.5 GeV

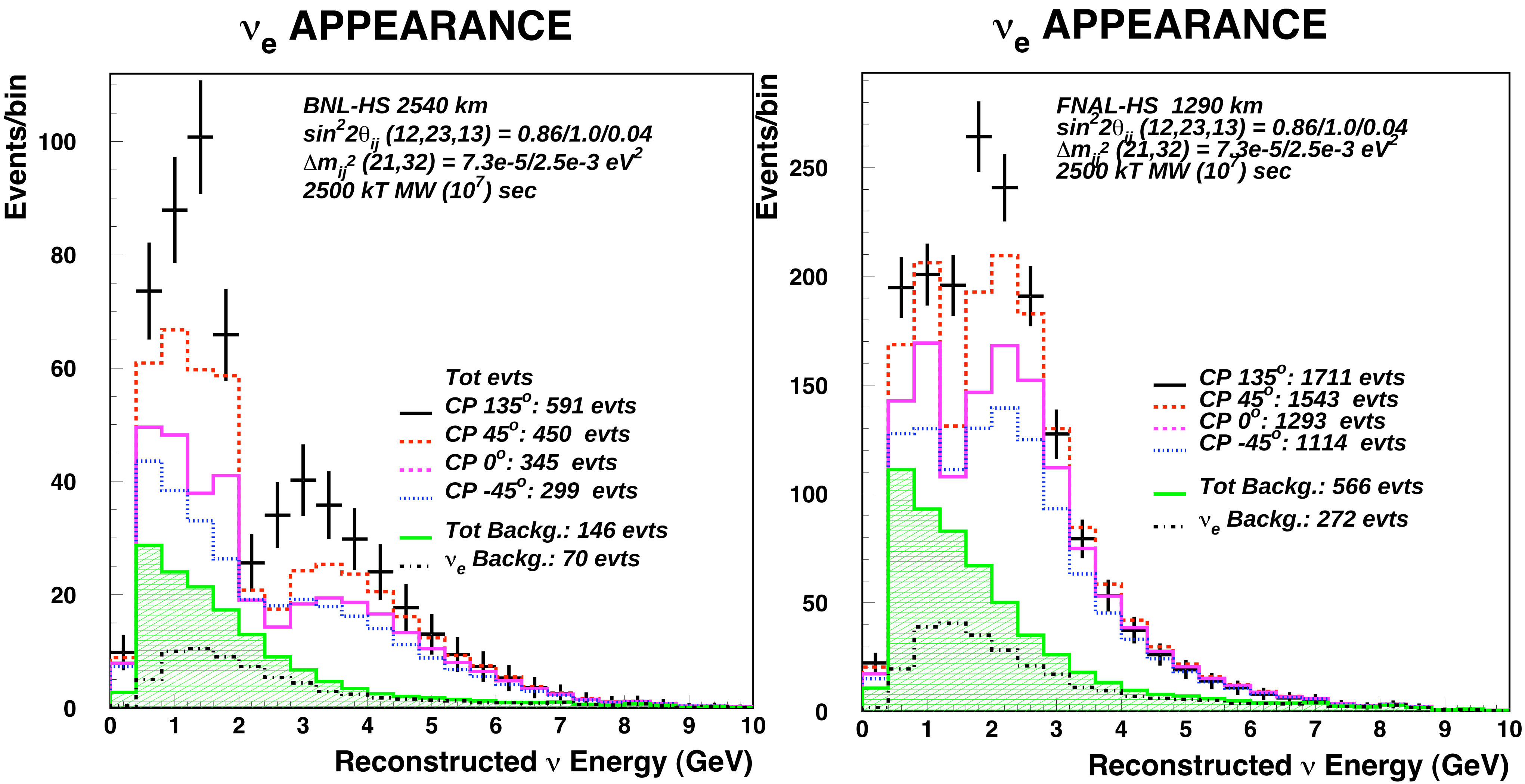
Same parameters as before

ν_e APPEARANCE



ν_e APPEARANCE





Comparison to 1290 km to 2540 km