Very Long Baseline Neutrino Oscillations (VLBNO) Experiment for Non-Experts

Presented to
Homestake Lab Workshop

by
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February 9, 2006

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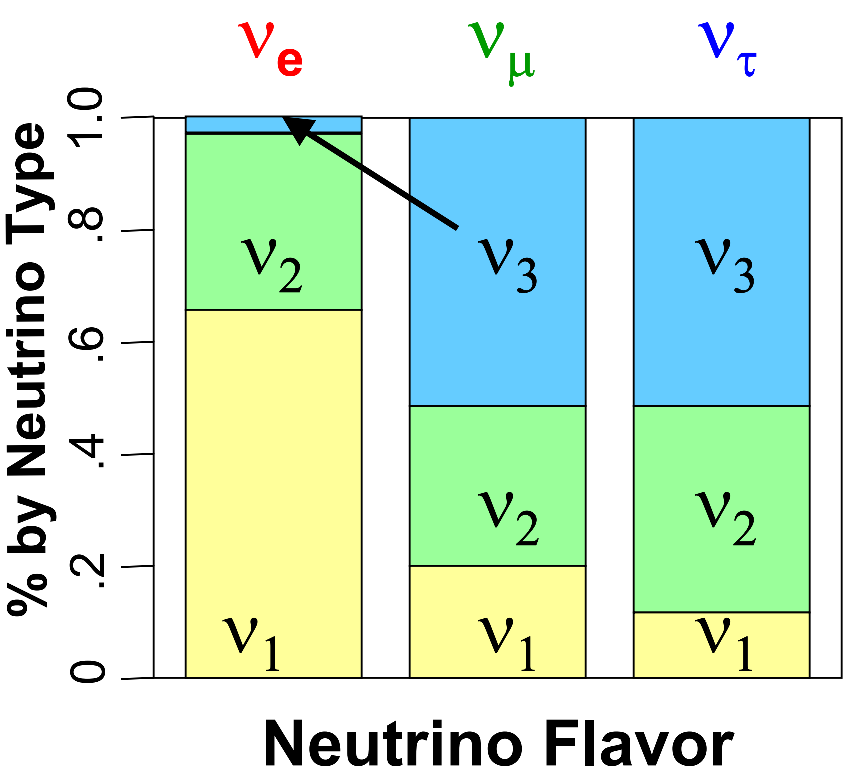
What is the Basis for the VLBNO Experiment?

- Neutrinos have been shown to have mass (small but non-zero)
- Neutrinos are born and die as *lepton flavor eigenstates* (ν_e, ν_μ, ν_τ) but they propagate through space as *mass eigenstates* (ν_1, ν_2, ν_3)
- The quantum mechanical superposition of flavor amplitudes in propagating neutrinos gives rise to complex flavor oscillations among the lepton flavors as the proper time evolves in flight
- Also, there is a likelihood that neutrino oscillations will exhibit *CP-Violation*, possibly of large magnitude compared to the quark sector
- A set of six independent parameters (θ_{12}, θ_{13}, θ_{23}, Δm_{12}^2, Δm_{32}^2, δ), plus the '*matter effect*' completely describes the neutrino flavor oscillations

Unmeasured!

- We believe that the experimental concept developed at BNL, the *Very Long Baseline Neutrino Oscillations* (VLBNO) experiment, utilizing the detection of *quasi-elastic neutrino-nucleon scattering*, will prove to be the cost-effective optimum for improving measurement of all the neutrino oscillation experimental parameters

Current Neutrino Mixing Picture



- neutrino *mass eigenstates* ν_1 / ν_2 / ν_3 are different from *production* and *interaction states,* ν_e / ν_μ / ν_τ ⇔ 'neutrino mixing'
- large mixings are seen except for U_{e3} (ν_3 content of ν_e)
- there is at the present time, no information on U_{e3}
- there is a *sign ambiguity* in the ordering of the neutrino masses
- there is no knowledge of *phases* in the mixing

Physics Case for the VLBNO Experiment

- ***All parameters*** **of neutrino oscillations can be measured in** ***one*** **experiment**
  - every one of the oscillation parameters is important to particle physics
  - the oscillation parameters contribute to important cosmology questions
  - a ν_e *appearance* experiment is required to determine ***all*** the parameters
  - a ***broadband Super Neutrino Beam*** at ***very long distances*** combined with the ability to identify ***quasi-elastic neutrino scattering*** in the detector is key
  - the *Very Long Baseline Neutrino Oscillation* (*VLBNO*) Exp. is the best method
- **The massive VLBNO detector can provide** ***additional forefront physics***
  - a powerful next-generation *Nucleon Decay* search
  - supernova, atmospheric and geo-neutrino neutrino investigations
  - a deep underground detector in the prospective *NSF DUSEL* is ideal for VLBNO
- **The CP-violation parameter δ_{CP} is the most difficult number to determine**
  - matter effects interact with CP-violation effects to produce intrinsic ambiguities
  - the CP-violation phase δ_{CP} has distinct effects over the ***full 360º range***
  - ***systematic errors will be minimized*** using a ***single detector*** in a broadband beam
  - the VLBNO detector can be staged in ~100KT modules as the scientific program develops
  - antineutrino running offers a complementary way to demonstrate CP-violation and may be pursued at a later stage of VLBNO if demanded by the physics

Questions About the VLBNO Experiment

Won't the Hyper-K + 4MW J-PARC beam complete all the measurements?

- no, the 295km T2K baseline is too short for the solar term and matter effects
- the T2K neutrino beam requires ***at least one other big experiment***, plus long antineutrino running, to determine δ_{CP} without ambiguities

Isn't VLBNO much more expensive than other approaches?

- the VLBNO cost is ***comparable to or lower*** than other less complete methods
- the VLBNO detector can be made in ~100kTon steps, phased over time
- VLBNO plans to share the large *Nucleon Decay Detector* in the *DUSEL*

What about the background from π^0 inelastic events in VLBNO?

- sophisticated Monte Carlo simulations with state-of-the-art Super-K pattern recognition + maximum likelihood methods have greatly mitigated this issue

Why not determine CP-violation with antineutrino running?

- antineutrino measurements will require of order 10 Snowmass years of running
- some antineutrino running may be of value to a long-running VLBNO experiment

Is BNL a unique source for a wide-band ν beam for VLBNO at DUSEL?

- BNL *or* Fermilab could be a satisfactory source for a wide-band beam to DUSEL
- *both labs* have produced credible conceptual designs for a 1-2 MW source
- the baselines for these labs are different but *either* could work for VLBNO

VLBNO Program Strategy at DUSEL

Educate and promulgate the *VLBNO method* in the HEP community

- the power of a single beam and a single detector is gradually being appreciated
- the ability to *distinguish quasi-elastic events from background* is now in place (the pattern recognition work of Chiaki Yanigasawa is critical to this point)
- the magnitude of $\sin^2(2\theta_{13})$ will be bounded or measured in the next few years by T2K plus reactor experiments, showing whether CP-violation can be measured by any super neutrino beam experiment, ie., θ_{13} > ~2-3 degrees
- even if $\sin^2(2\theta_{13}) < 0.01$, the VLBNO experiment remains the most cost-effective way to measure the other neutrino oscillation parameters to good precision
- the narrow-band, off-axis method requires multiple detectors plus long antineutrino running to achieve a complete measurement of all the oscillation parameters to determine δ_{CP} without ambiguities (requires θ_{13} > ~2-3 degrees)

Promote a *Super Neutrino Beam* source from BNL *or* Fermilab

- DUSEL site candidates presently include both Homestake and Henderson
- in consequence, the very long baselines needed by VLBNO could be realized from BNL *or* Fermilab
- Europe and Japan are not geographically positioned to perform a VLBNO exp. (Japanese physicists are now thinking about a beam to Korea from Tokai)
- the U.S. particle physics program wins with either BNL or Fermilab as a source

Electron Neutrino Appearance by Oscillation in Vacuum

The equation for oscillation[a] of $\nu_\mu \rightarrow \nu_e$ neutrinos in vacuum is given by:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{31} L/4E_\nu) \quad \text{'Term 1'}$$

$$+ \tfrac{1}{2} \sin(2\theta_{12}) \sin(2\theta_{13}) \sin(2\theta_{23}) \cos(\theta_{13}) \times \sin(\Delta m^2_{21} L/2E_\nu) \times [\sin(\delta_{CP}) \sin^2(\Delta m^2_{31} L/4E_\nu) + \cos(\delta_{CP}) \sin(\Delta m^2_{31} L/4E_\nu) \cos(\Delta m^2_{31} L/4E_\nu)] \quad \text{'Term 2'}$$

$$+ \sin^2(2\theta_{12}) \cos^2(\theta_{13}) \cos^2(\theta_{23}) \sin^2(\Delta m^2_{21} L/4E_\nu) \quad \text{'Term 3'}$$

+ matter effects + smaller terms

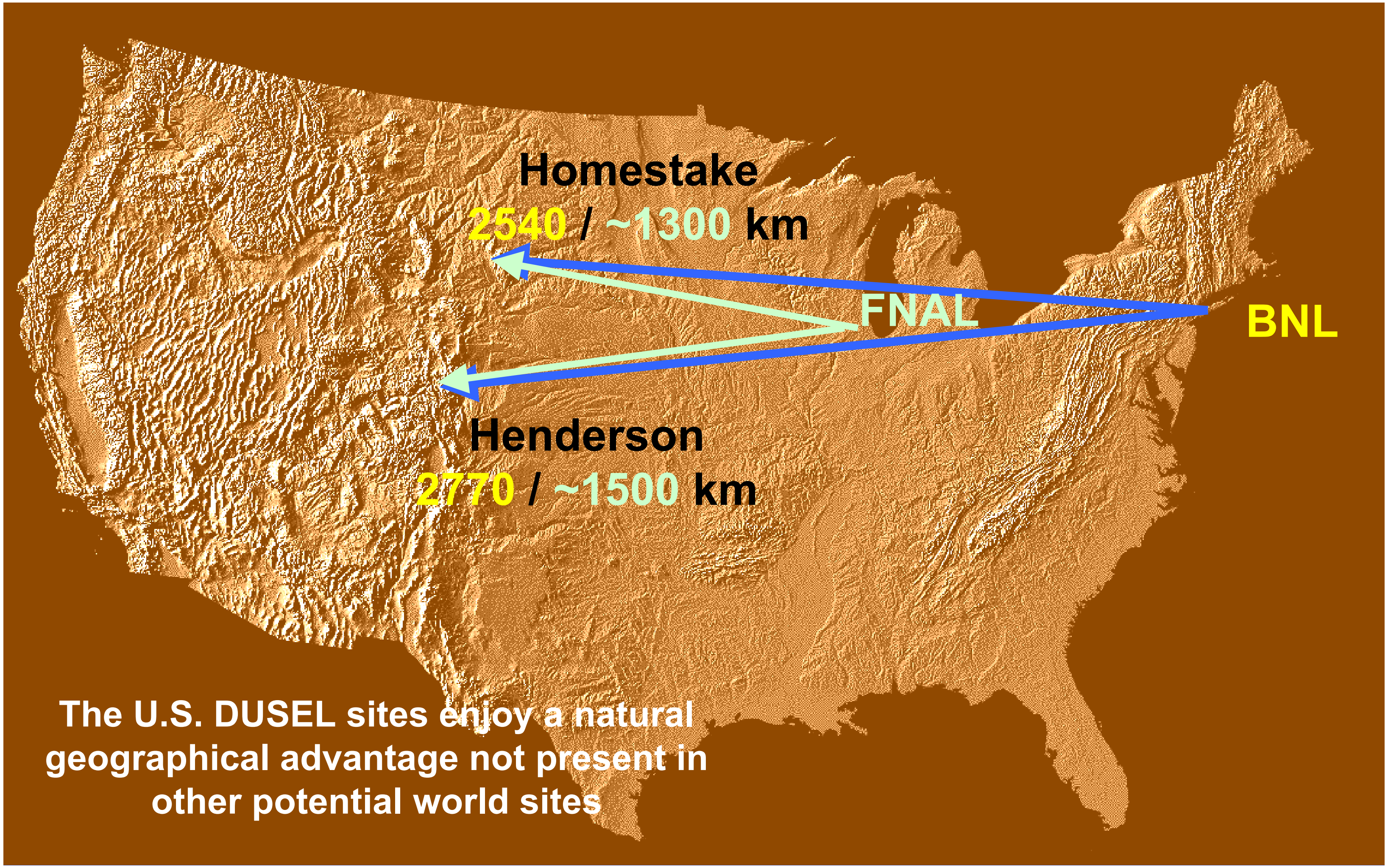
$$\Delta m^2_{31} \equiv m^2_3 - m^2_1 = \Delta m^2_{32} + \Delta m^2_{21} \sim \Delta m^2_{32}$$

What do we learn by contemplating this long algebraic expression?

- **simple inspection won't reveal all the many experimental implications**
- **detailed calculations are needed to clarify the important experimental issues**
- **key oscillation parameters still to be determined are shown in red**
- **the known oscillation distance scales in green are exploited by VLBNO**

[a] W. Marciano, Nuclear Physics B (Proc. Suppl.) 138, (2005) 370-375

Super Neutrino Beam to DUSEL Candidate Sites



Electron Neutrino Appearance With Matter Effects

The oscillation for $\nu_\mu \rightarrow \nu_e$, including the *matter effect*, is given approximately by[a]:

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2((A-1)\Delta)/(A-1)^2$$
$$+ \alpha\, 8\, J_{CP} \sin(\Delta) \sin(A\Delta) \sin((1-A)\Delta) / (A(1-A))$$
$$+ \alpha\, 8\, I_{CP} \cos(\Delta) \sin(A\Delta) \sin((1-A)\Delta) / (A(1-A))$$
$$+ \alpha^2 \cos^2(\theta_{23}) \sin^2(2\theta_{12}) \sin^2(A\Delta) / A^2$$

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

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

$$\alpha = \Delta m^2_{21} / \Delta m^2_{31}\,; \quad \Delta = \Delta m^2_{31} L/4E_\nu\,; \quad A = 2VE_\nu / \Delta m^2_{31}\,; \quad \Delta m^2_{31} \equiv m^2_3 - m^2_1$$

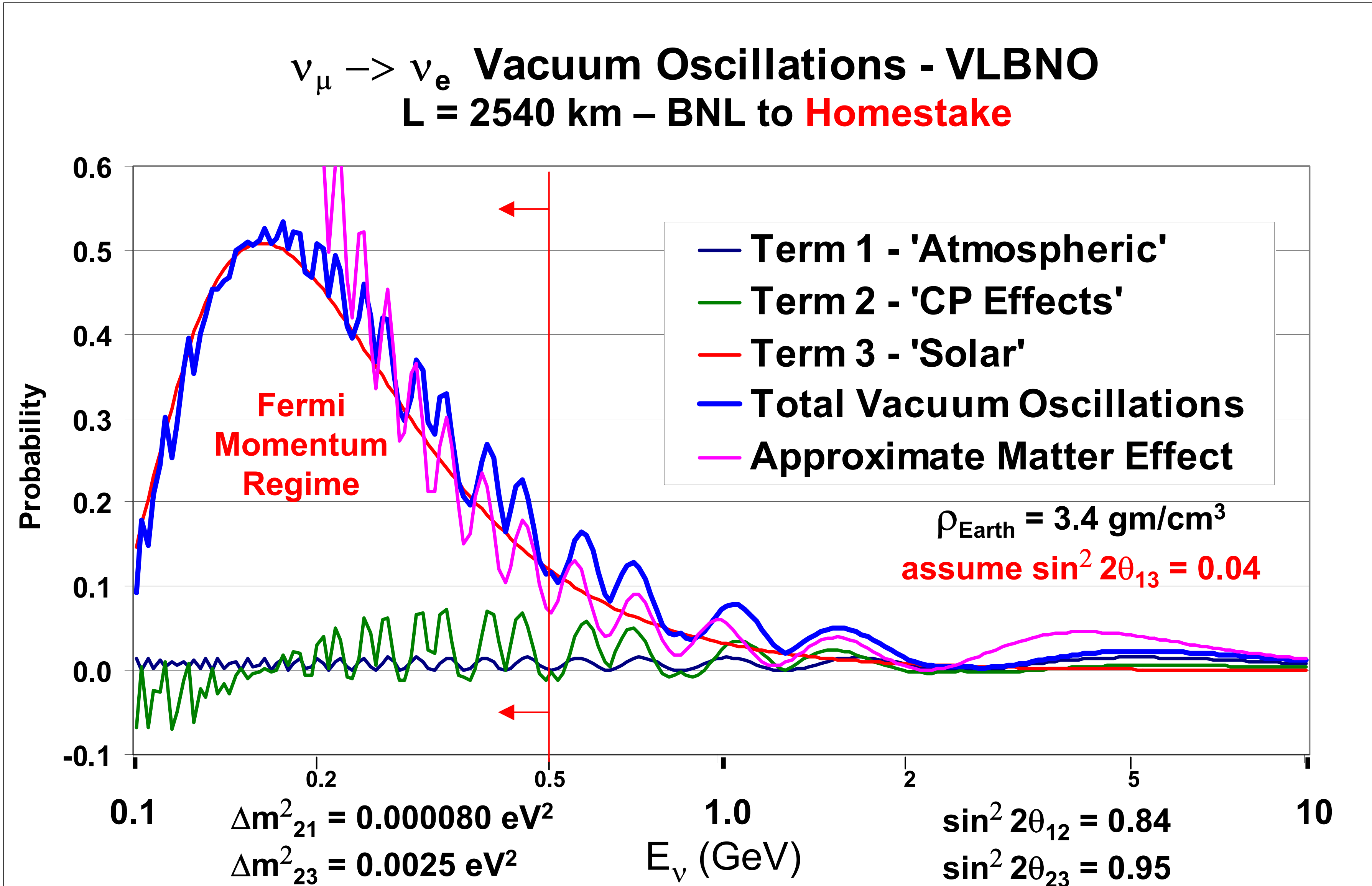
$V = \sqrt{2}G_F n_e$; n_e is density of electrons along the path

This expression separates terms by the the following:

- **the first three terms show the effect of $\sin^2(2\theta_{13})$**
- **the second and third terms show the effects of CP symmetry**
- **the J_{CP} term changes sign when calculating anti-neutrinos, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$**
- matter effects come into all terms via the 'A' factors in blue

[a] Barger et al.,Phys. Rev. D63: 113011 (2001); M. Freund, Phys. Rev. D64: 053003 (2001); Huber et al., Nucl. Phys. B645, 3 (2002); Barger et al. Phys. Rev. D65: 073023 (2002)

Electron Neutrino Appearance by Oscillation in Vacuum



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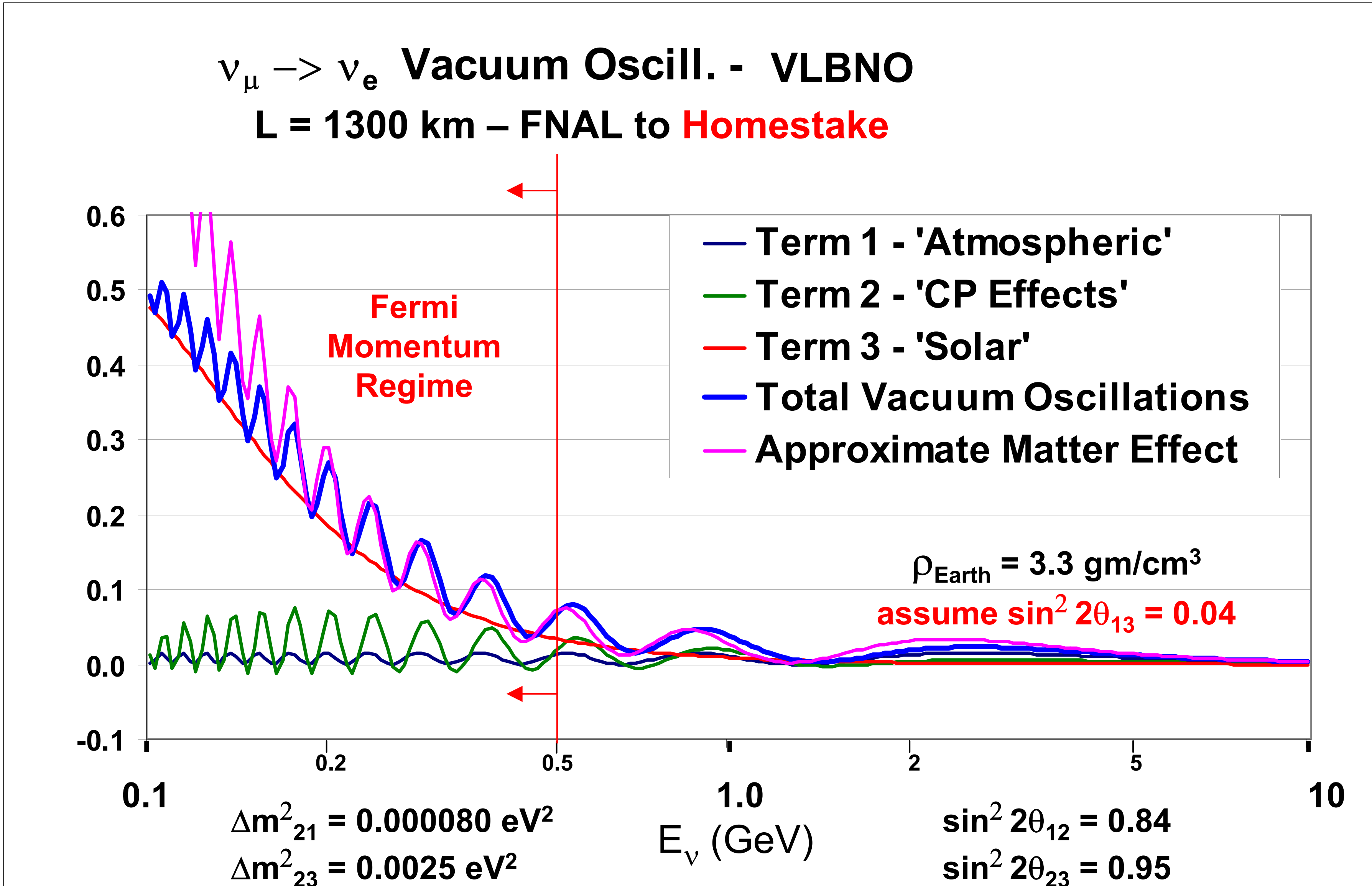
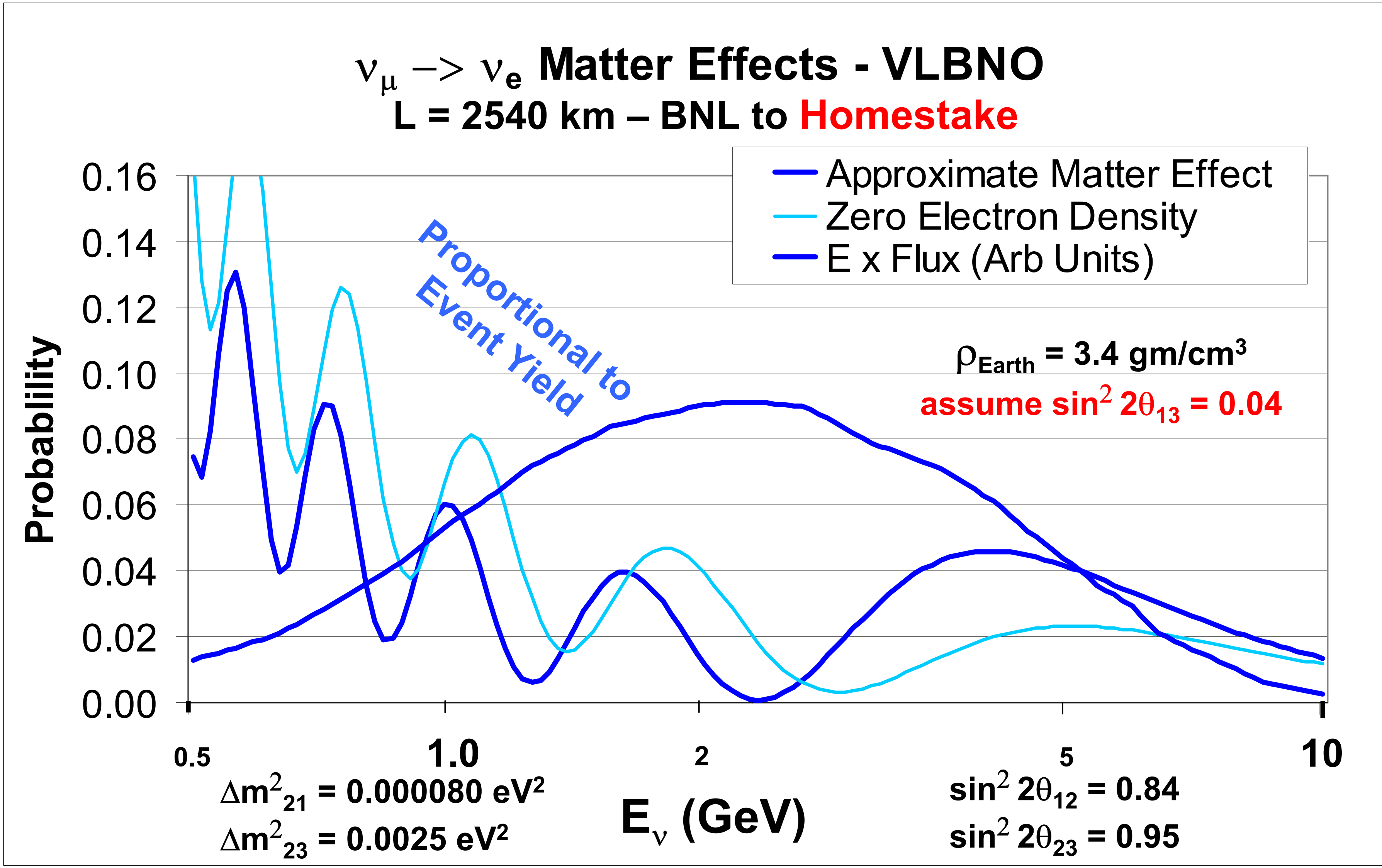


Sensitivity to Matter Effect



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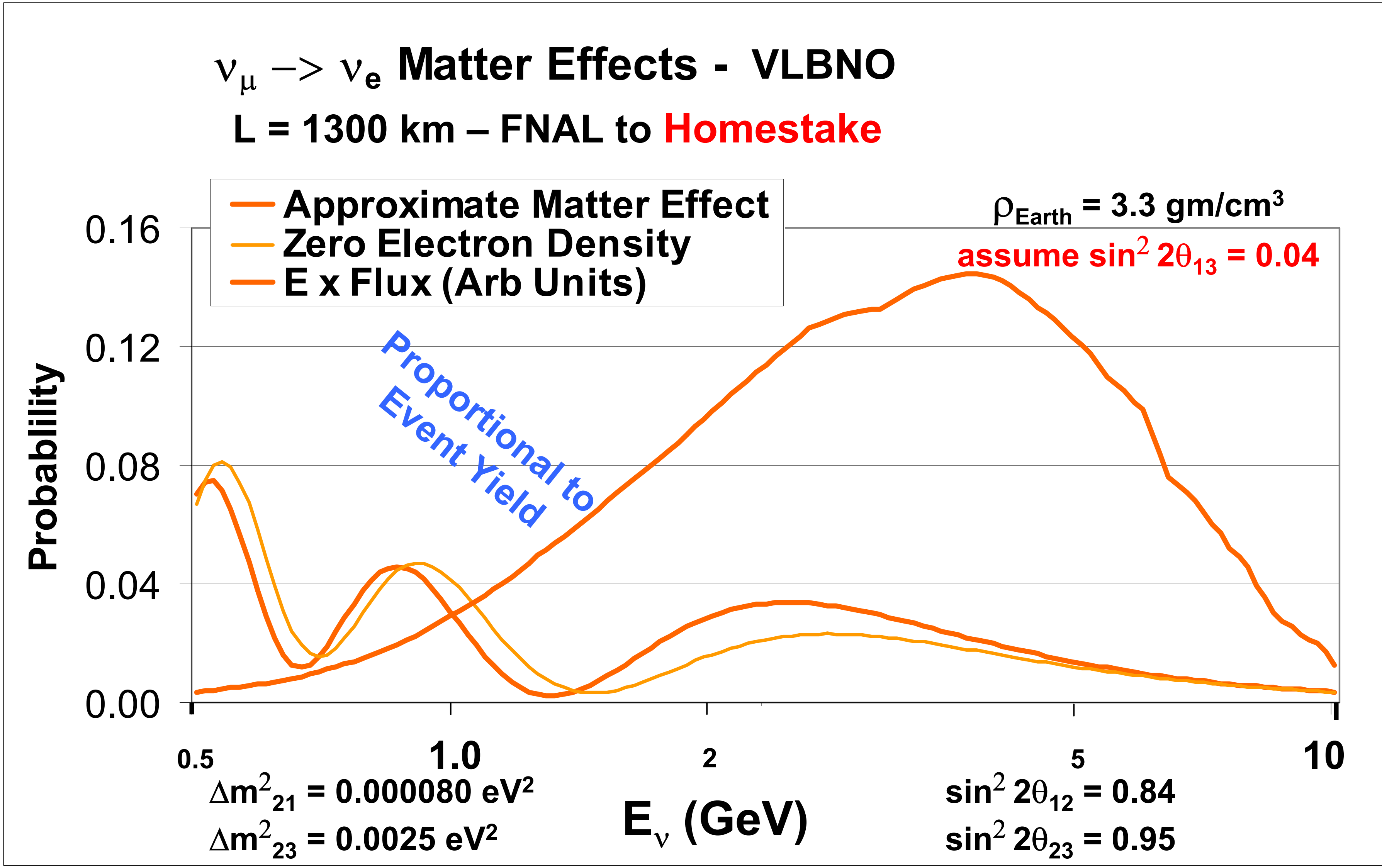
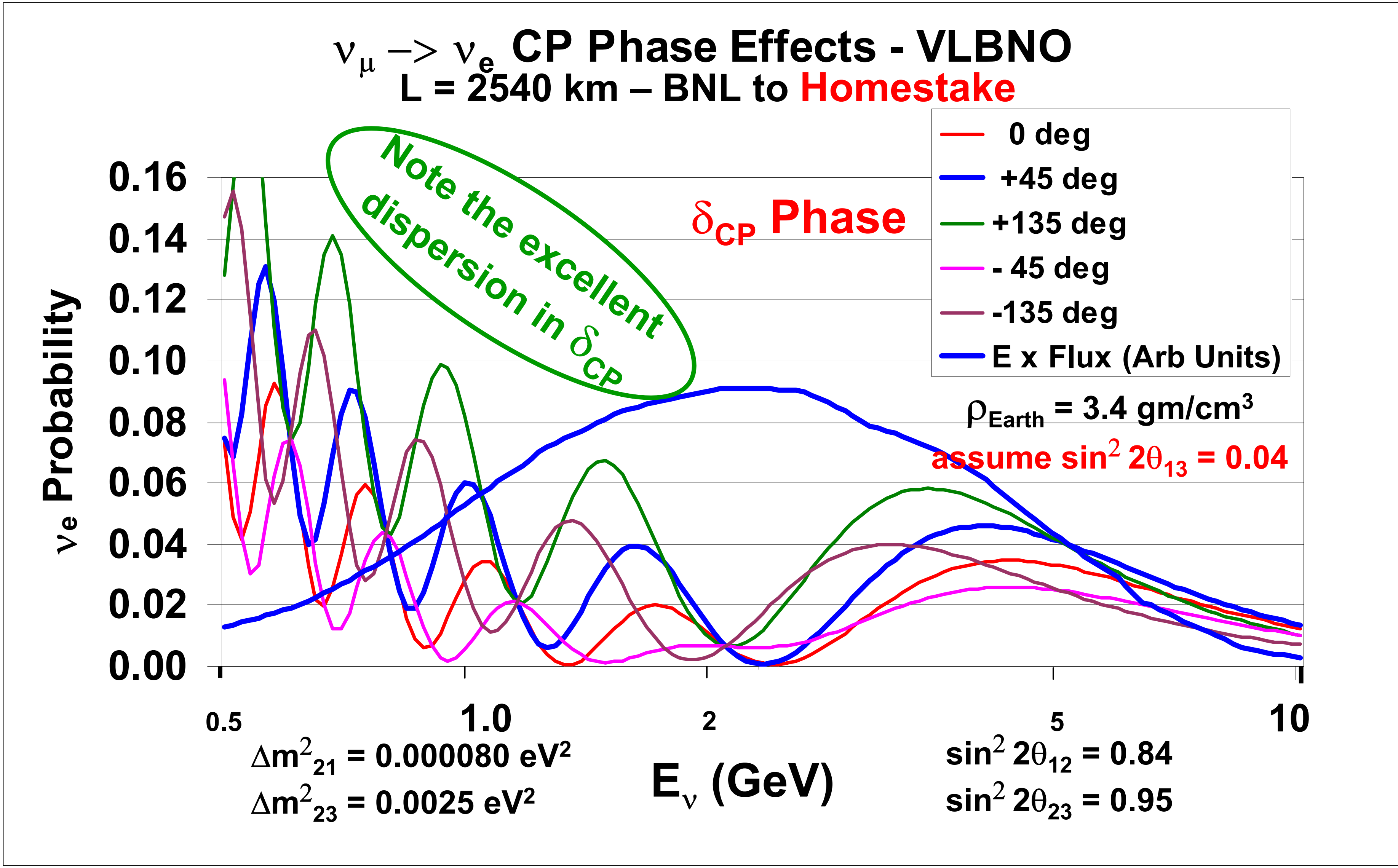


Electron Neutrino Appearance – CP Phase Sensitivity



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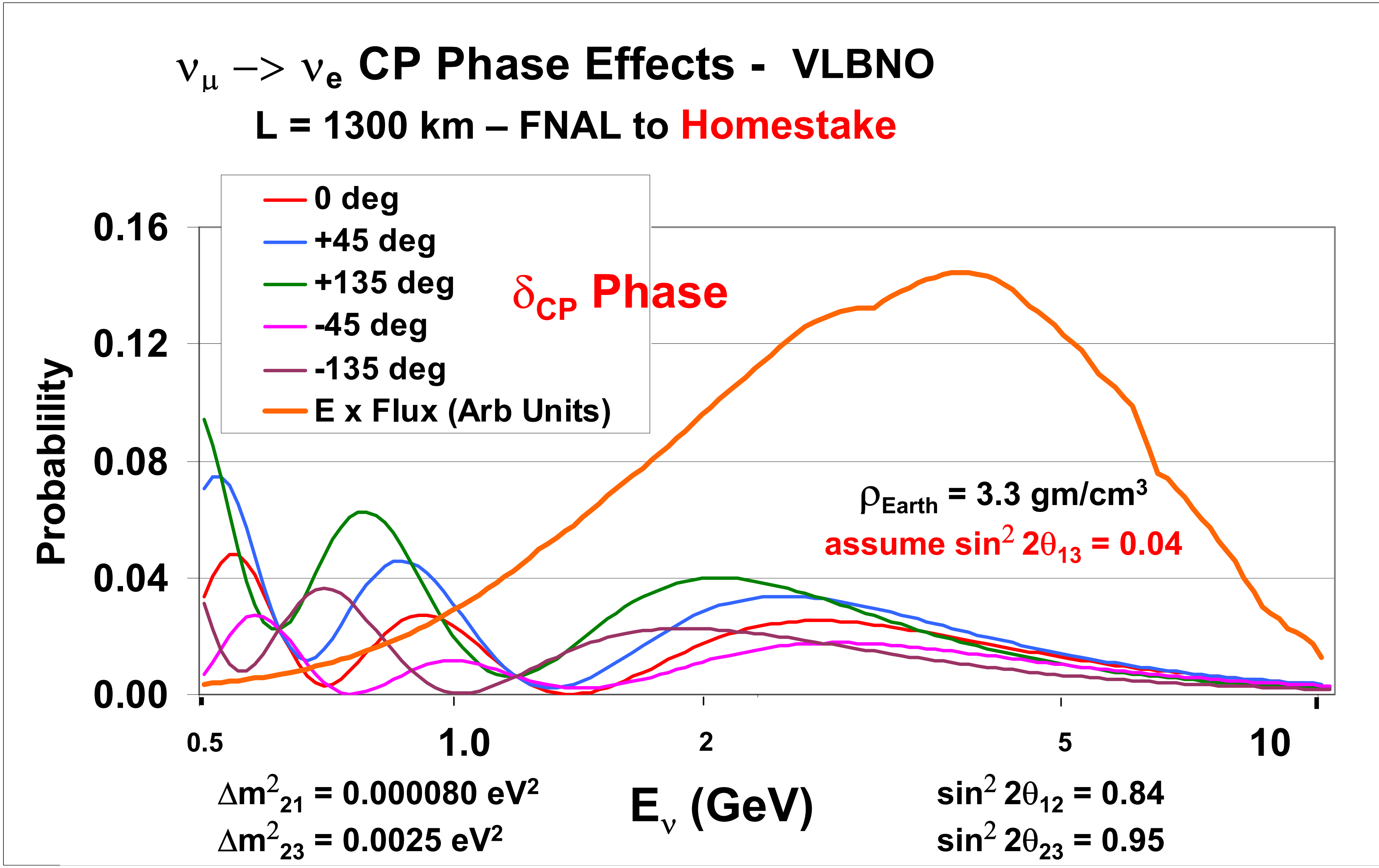
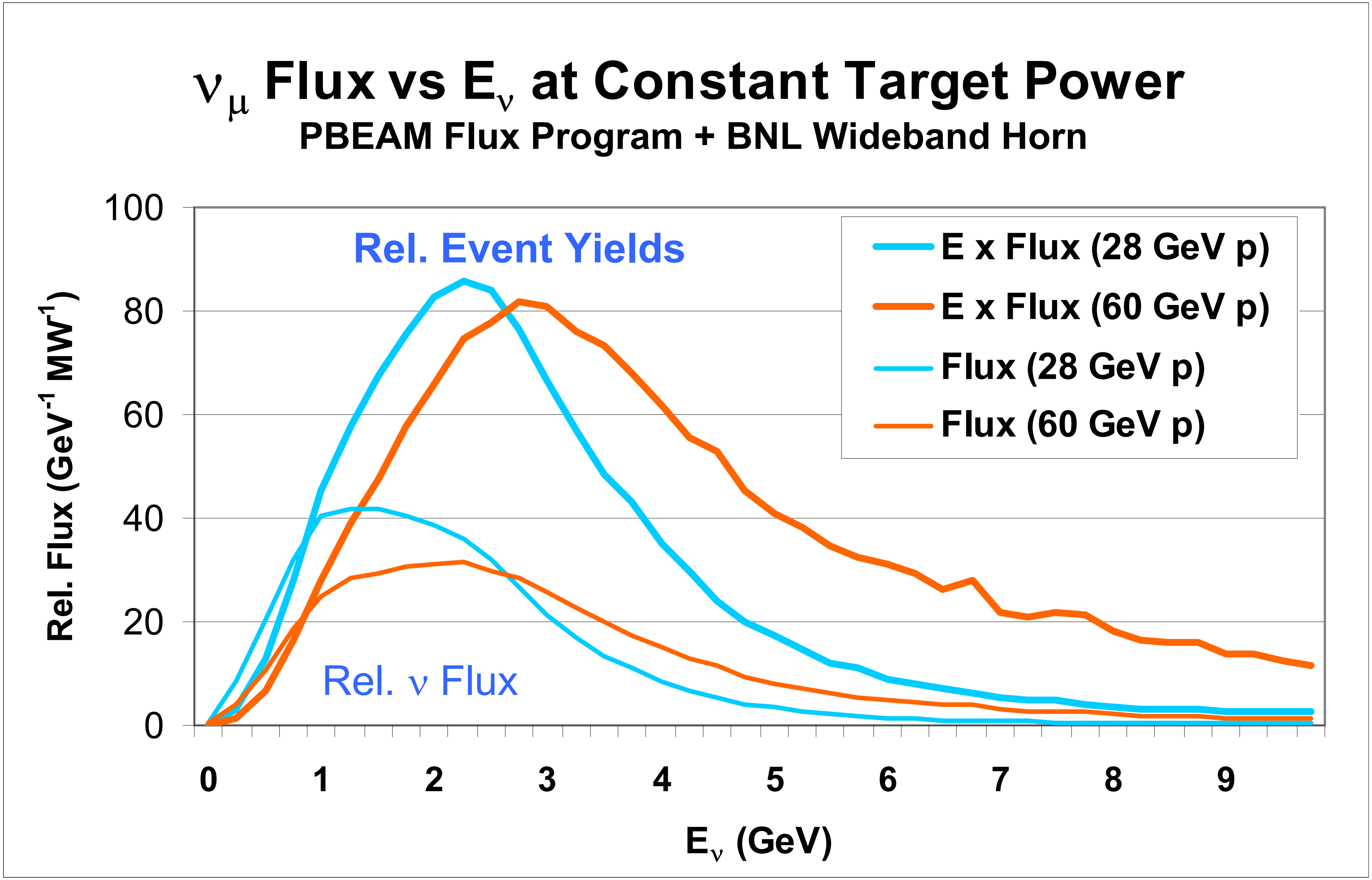


A Word About Primary Proton Beam Energy



Comparison of Future Neutrino Oscillations Exps.

Parameter	T2K	T2K2	Reactor	Nova	Nova2	VLBNO.
Δm_{32}^2	$\pm$ 4 %	$\pm$ 4 %	-	$\pm$ 2 %	$\pm$ 2 %	$\pm$ 1 %
$\sin^2(2\theta_{23})$	$\pm$1.0 %	$\pm$ 0.4 %	-	$\pm$ 0.4 %	$\pm$ 0.2 %	$\pm$ 0.5 %
$\sin^2(2\theta_{13})$ [a]	>0.01	>0.01	>0.01	>0.01	>0.01	>0.01
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12 %
sign of (Δm_{32}^2) [c]	-	-	-	possible	yes	yes
measure δ_{CP} [d]	-	~20°	-	-	~20°	$\pm$13°
N-decay gain	x1	x20	-	-	-	x8
Detector (Ktons)	50	1000	20	30	30+50	400
Beam Power (MW)	0.74	4.0	14000	0.4	2.0	1.5
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>1300
Detector Cost ($M)	exists	~1000	~20	165	+200	400
Beam Cost ($M)	exists	500	exists	50	1000	400
Ops. Cost ($M/10 yrs)	500	700	50	500	600	150/500 [f]

Both **results needed to resolve ambiguities!**

Best Bets

[a] detection of $\nu_\mu \rightarrow \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$

[b] detection of $\nu_\mu \rightarrow \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity

[c] detection of the matter enhancement effect over the entire δ_{CP} angle range

[d] measure the CP-violation phase δ_{CP} in the lepton sector; Nova2 depends on T2K2

[e] beam is 'off-axis' from 0-degree target direction; [f] with/without RHIC operations at BNL

Conclusions

- Neutrino Oscillation parameters can be completely determined within the next two decades
- The most effective method is the *VLBNO + Wideband Super Beam*
- A Megaton-class Water Cerenkov Detector can do this experiment (perhaps built in modules and staged)
- Either BNL or Fermilab could be the source of an effective ν beam
- Combining VLBNO with the *Nucleon Decay Search* in the *NSF DUSEL* yields the best science and the most cost effective plan for the U.S.

Backup

What is the Potential Competition?

- **The *Noνa* Experiment from Fermilab to Ash River, Minnesota**
  - Noνa Proposal March 2005, J. Cooper and G.J. Feldman, Co-spokespersons
  - a newly proposed, 30KT ν_e detector at 810 km from Fermilab, a small near detector and a new, off-axis ν_μ-beam using the existing NuMI decay pipe
  - the 1st phase experiment is designed to detect $\sin^2(2\theta_{13}) > 0.01$
  - a 2nd phase Noνa invokes anti-neutrino running + accelerator improvements to determine the neutrino mass-ordering with some sensitivity to CP-violation
  - a 2MW FNAL Proton Driver plus a 2nd new 50 KT detector may be needed to measure the CP-violation parameter δ_{CP} in a possible 3rd phase of Noνa

- **The *T2K* Experiment from J-PARC Tokai to Super Kamiokande**
  - a ν_e appearance experiment to search for $\sin^2(2\theta_{13}) > 0.006$ in Super Kamiokande
  - off-axis ν_μ-beam now under construction at KEK Laboratory at Tokai, Japan will travel 295 km to the existing Super Kamiokande detector
  - a future phase contemplates a 4MW beam + 1MT Hyper Kamiokande Detector

- **The *ICARUS-CNGS* Experiment from CERN to Gran Sasso**
  - a future LAr detector scaled up from 600 Tons to 3000 Tons, 760 km from CERN
  - the focus is on detection of ν_μ to ν_τ/ ν_e oscillations in the LAr drift chamber
  - no claims are made for sensitivity to the mass ordering or δ_{CP}

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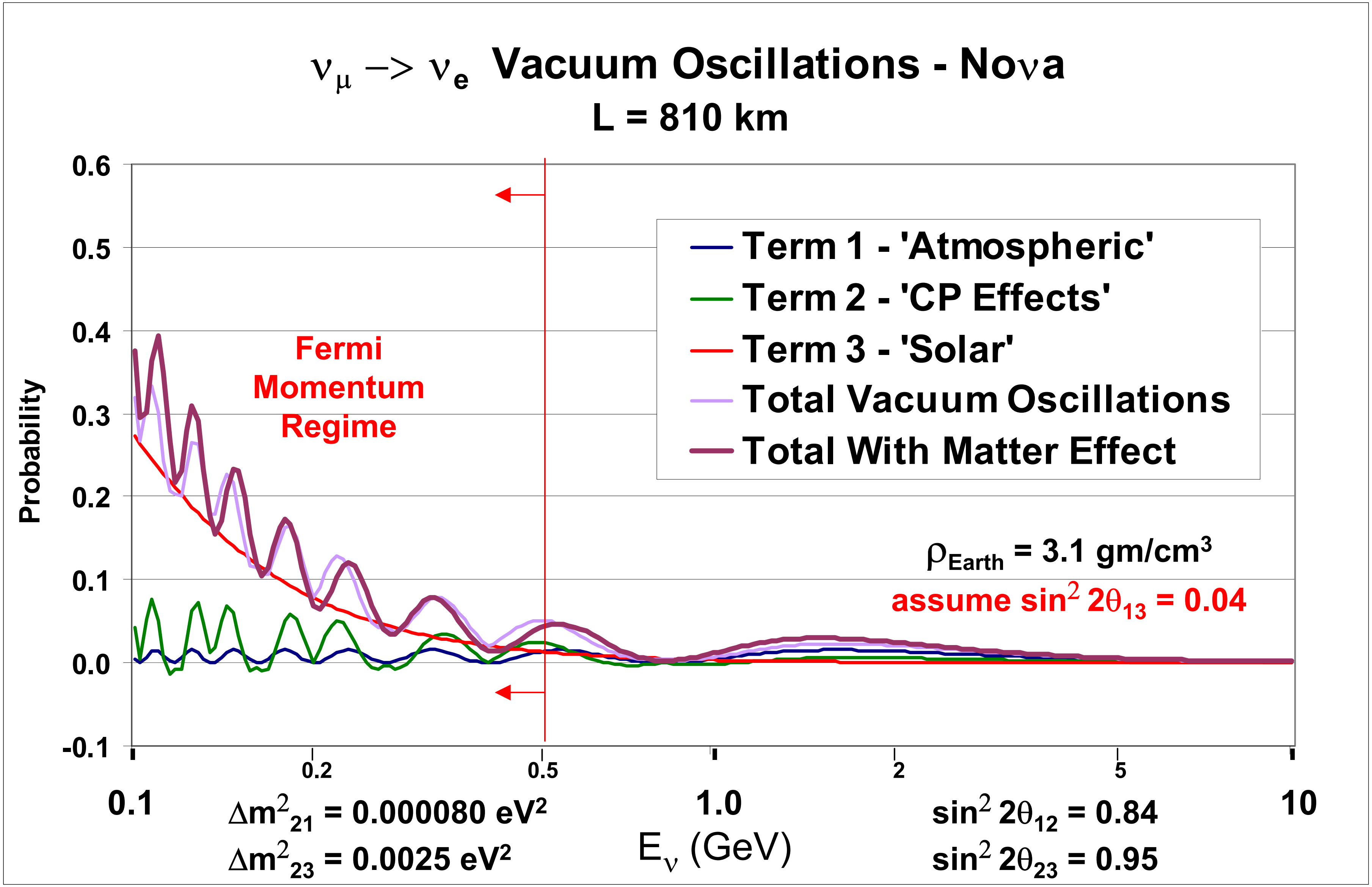

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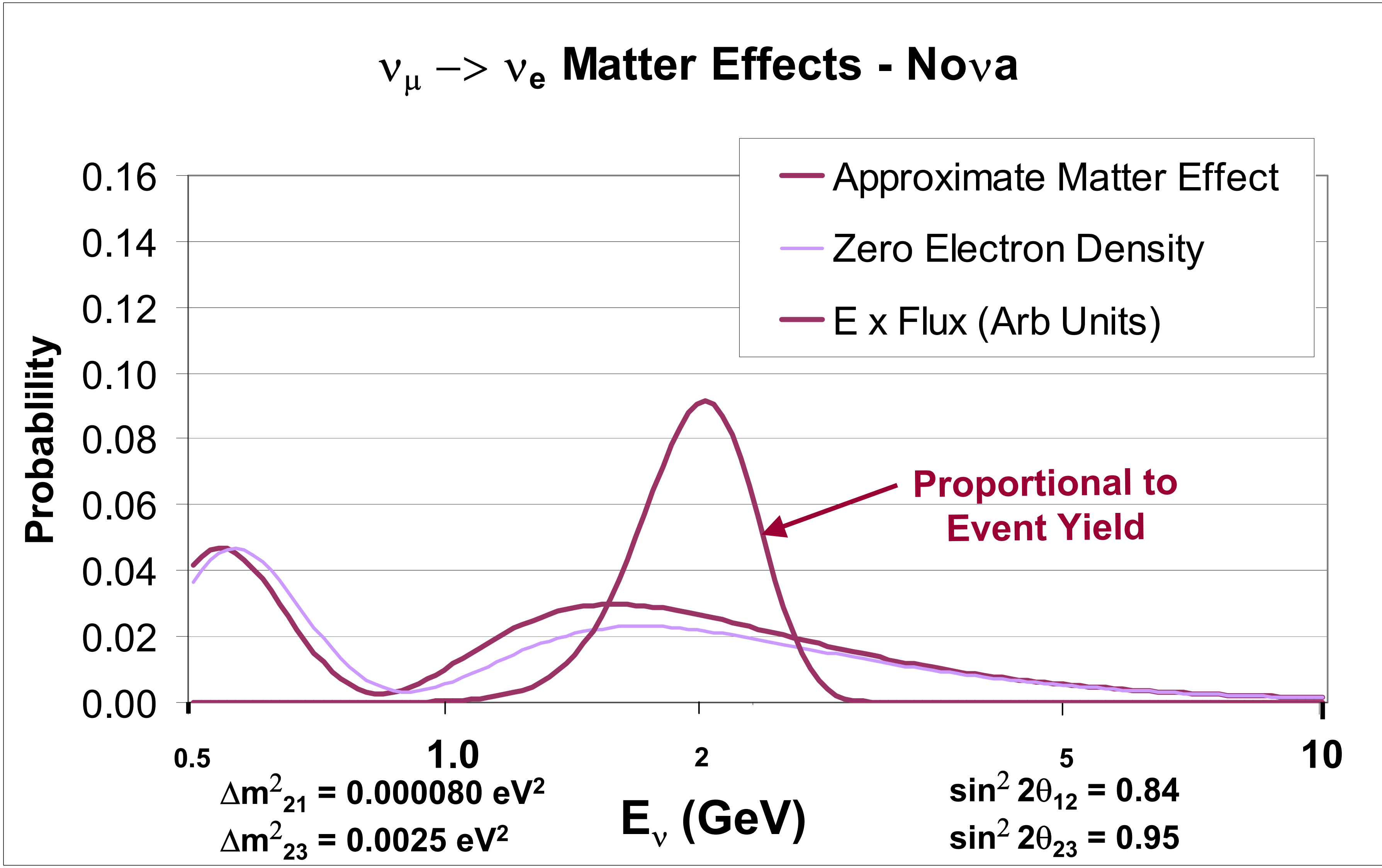

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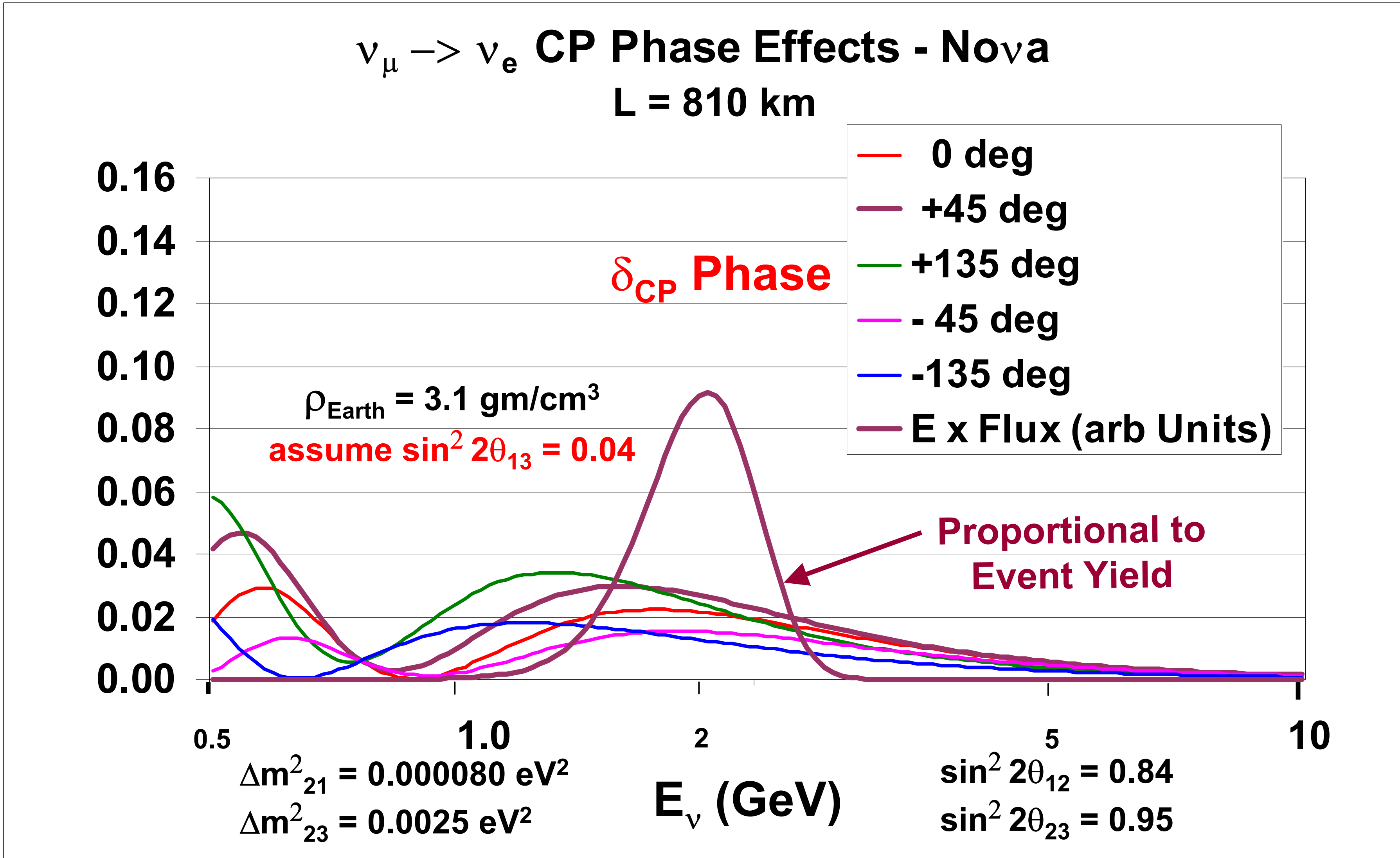

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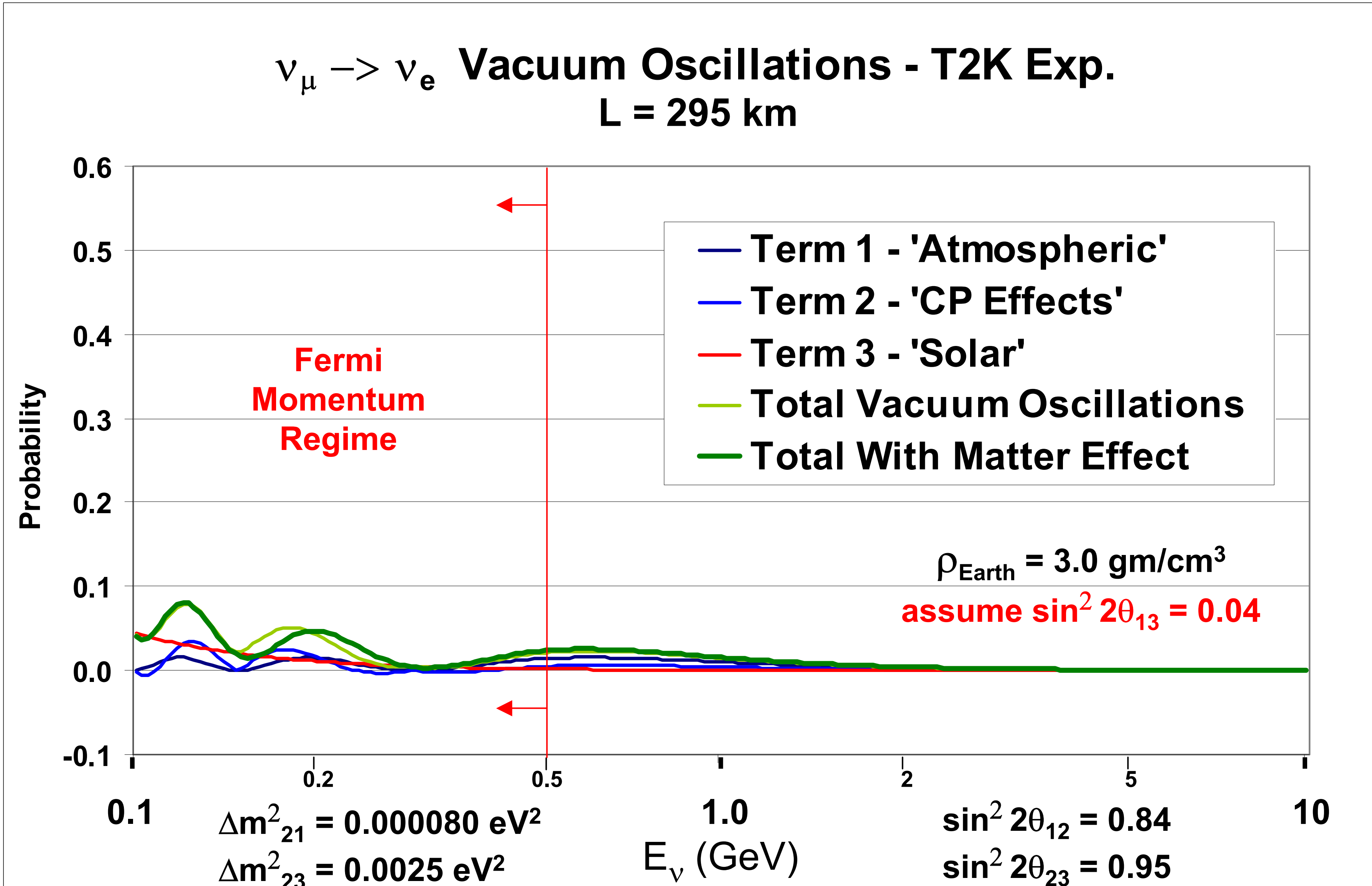

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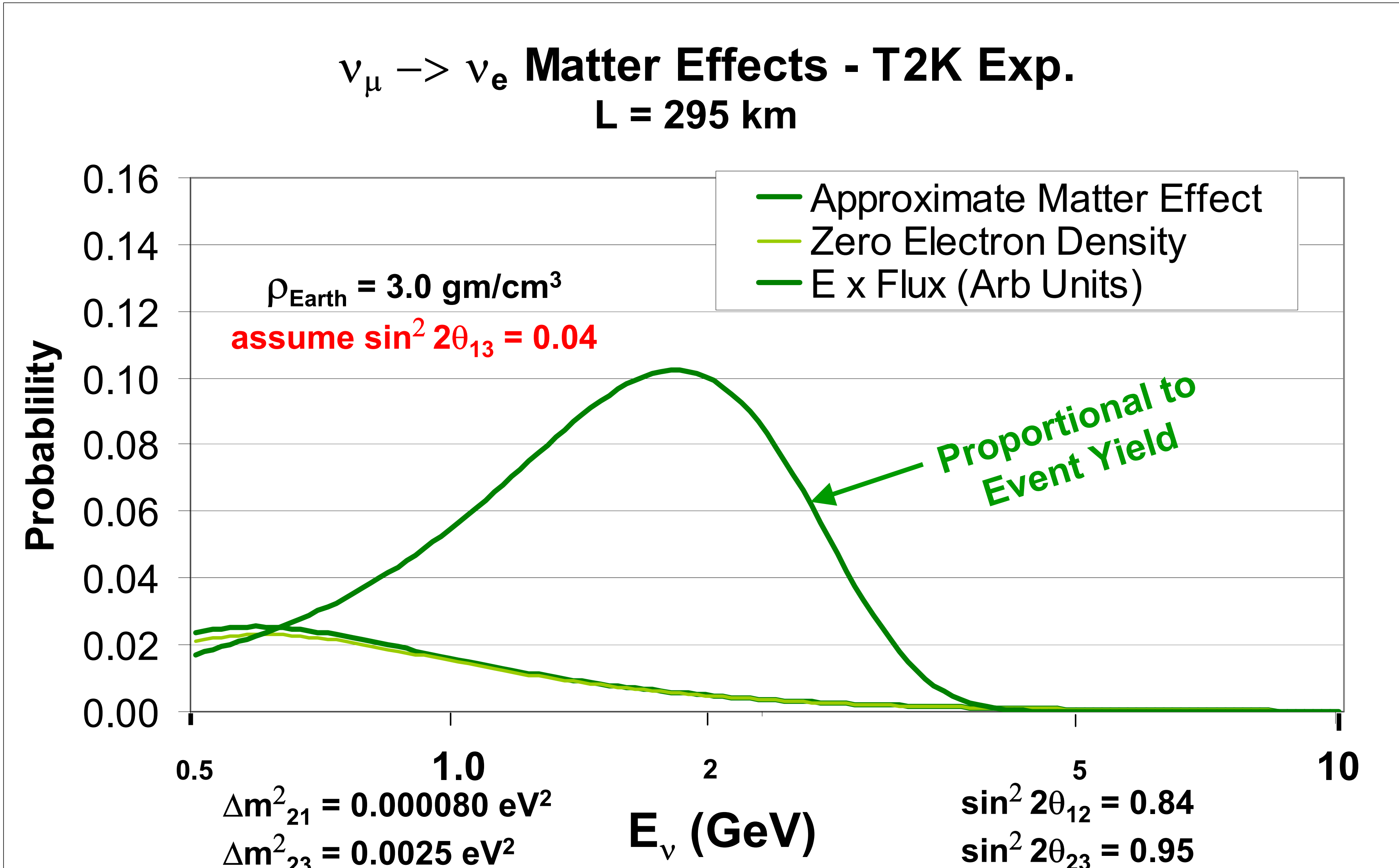
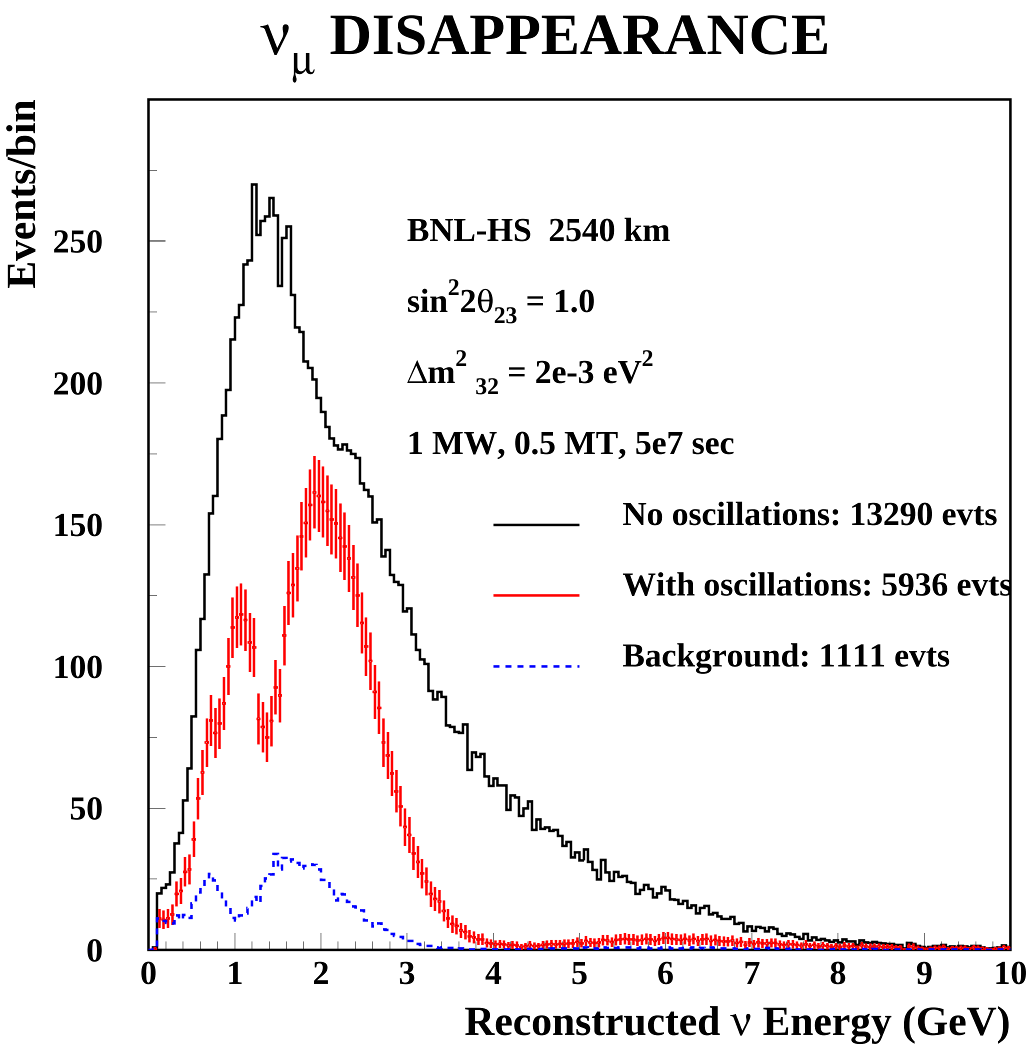
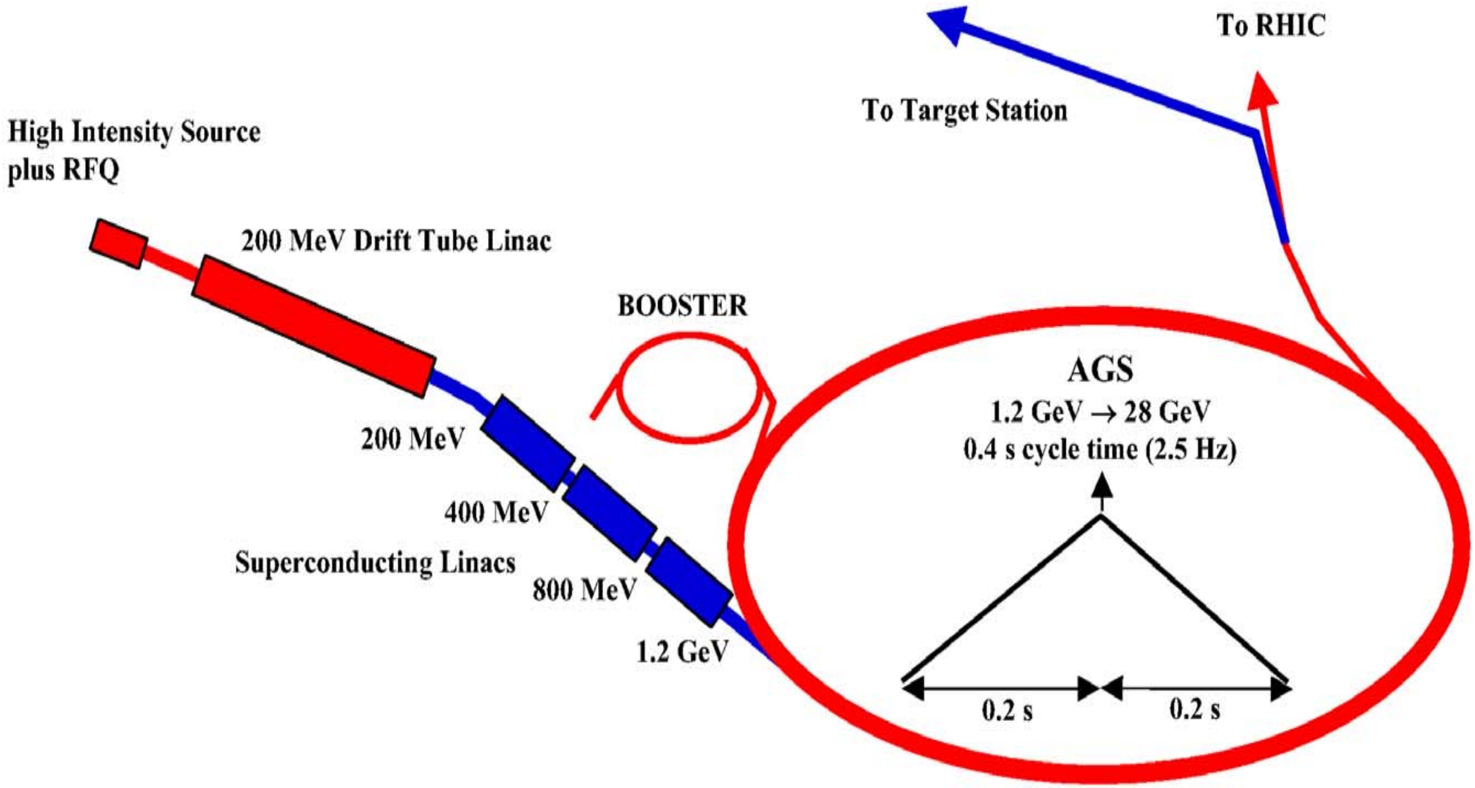


Very Long Baseline Neutrino Experiment



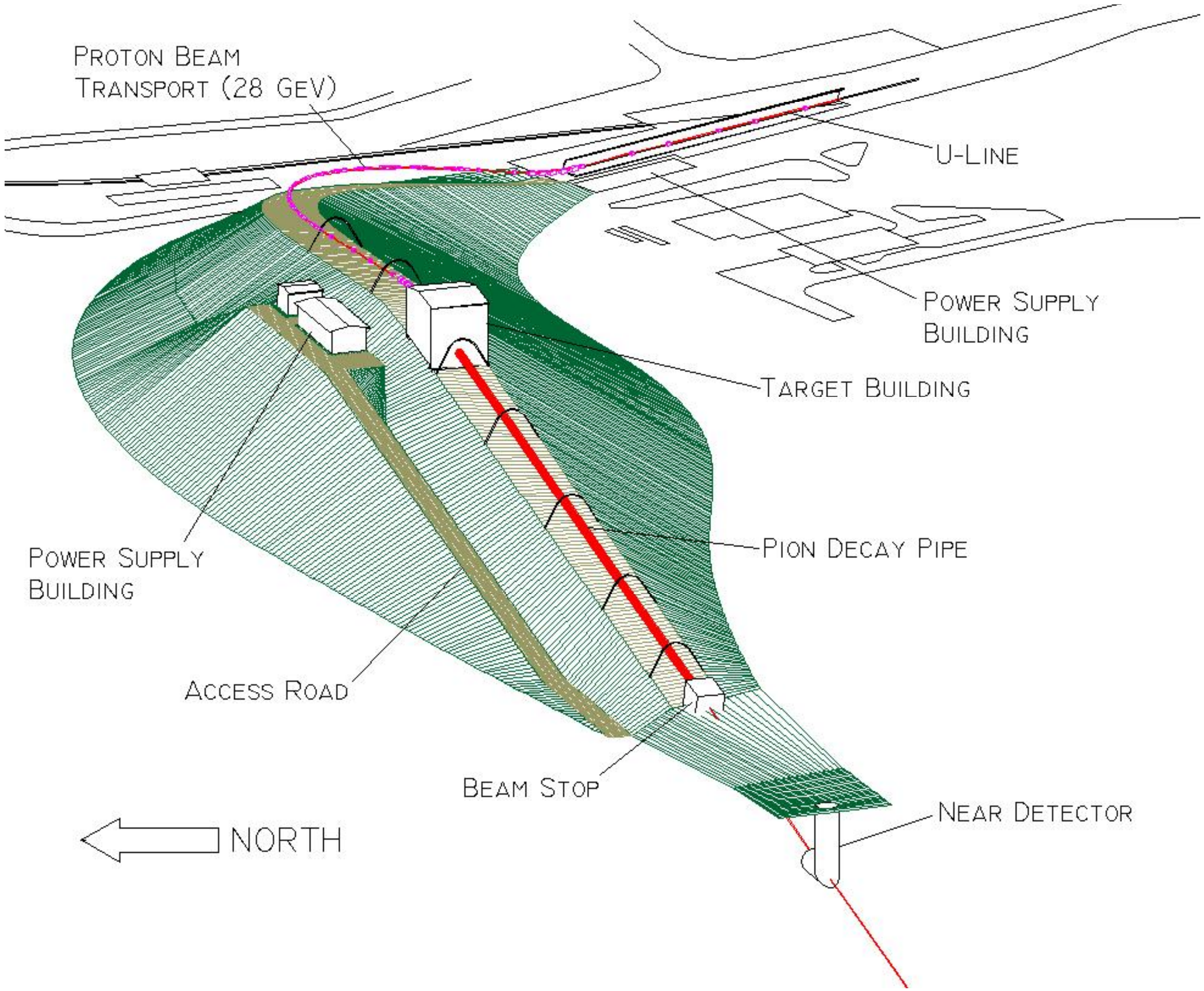
- neutrino oscillations result from the factor $\sin^2(\Delta m_{32}^2\ L\ /\ 4E)$ modulating the ν flux for each flavor (here ν_μ disappearance)
- the oscillation period is directly proportional to distance and inversely proportional to energy
- with a *very long baseline* actual oscillations are seen in the data as a function of energy
- the multiple-node structure of the very long baseline allows the Δm_{32}^2 to be precisely measured by a *wavelength* rather than an amplitude (reducing systematic errors)

1-2 MW *Super Neutrino Beam* at AGS



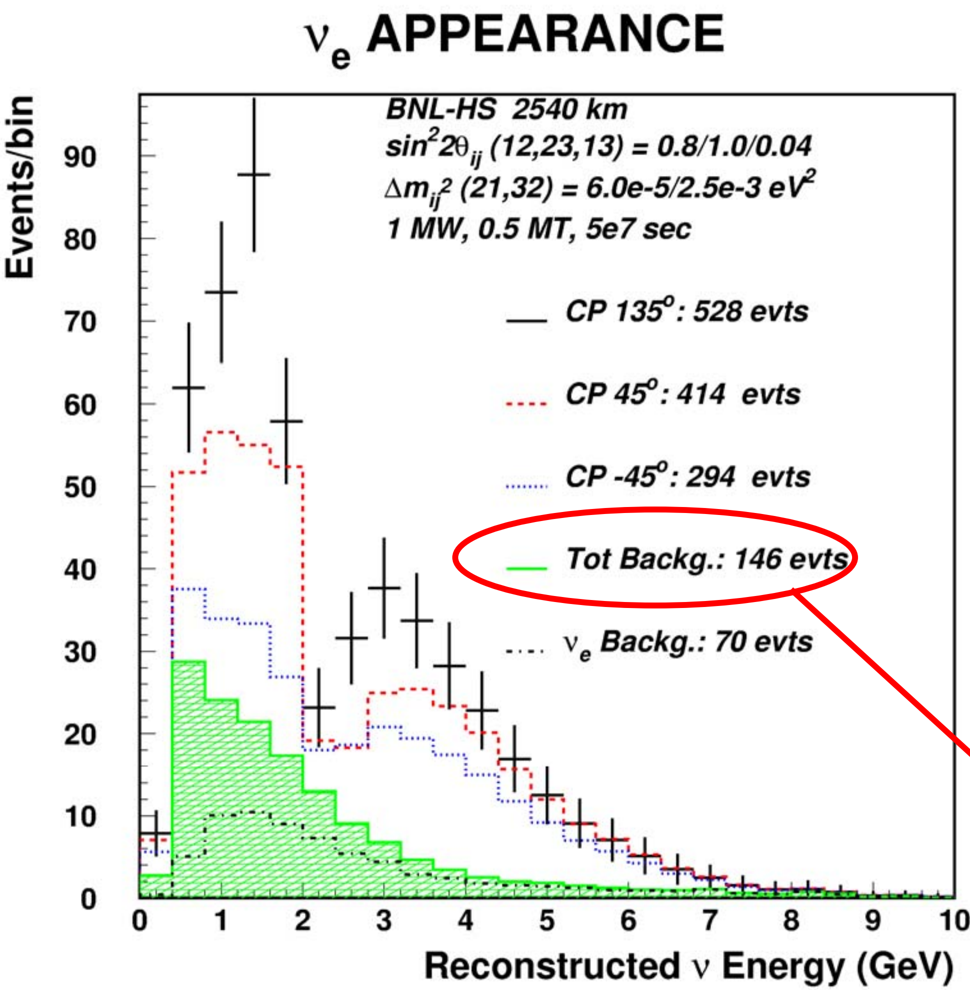
- BNL completed October 8, 2004, a Conceptual Design to support a new proposal to DOE to upgrade the AGS to 1-2 MW target power and construct the wide-band ***Super Neutrino Beam*** as listed in the DOE's "Facilities for the Future of Science" plan of November 2003

3-D *Super Neutrino Beam* Perspective



ν_e Appearance Measurements

S/B outlook August 2003



- a direct measurement of the appearance of $\nu_\mu \rightarrow \nu_e$ is important; the VLB method competes well with any proposed super beam concept
- for values > 0.01, a measurement of $\sin^2 2\theta_{13}$ can be made (the current experimental limit is 0.12)
- for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter δ_{CP} can be made by the VLB experimental method

Too optimistic?

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