Very Long Baseline Oscillations

The BNL VLBL Concept

Brett Viren

Physics Department

BROOKHAVEN NATIONAL LABORATORY

7th International Workshop on Neutrino Factories and Superbeams

Outline

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Basics of the VLBL Concept

The VLBL concept consists of three simple ideas:

1. Use a very **long** baseline,
2. a **wide** band ν-beam,
3. at **high** ν-energies.

This allows an ambitious but affordable experiment which is qualitatively different than previous or planned LBL experiments.

- It is sensitive to multiple physical effects.
- Allows one to break parameter degeneracies.
- Rough measurement of δ_{CP} and θ_{13} with only ν-running.

If we get lucky with the true parameter values, these statements can be made more strongly.

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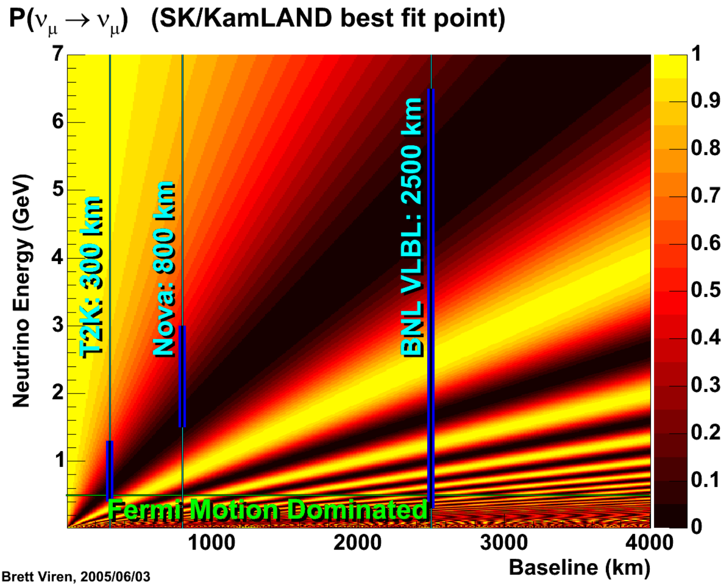
Why Long, Wide and High?



1. Wide → see multiple oscillations
2. High → avoid Fermi motion
3. High ∴ Long

Blue bars show flux coverage (full width at 10% peak)

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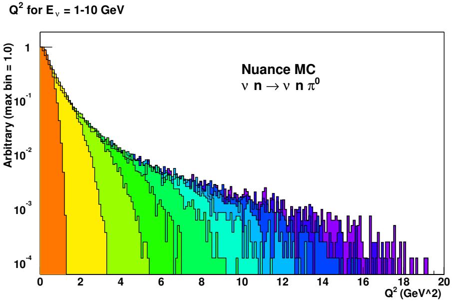
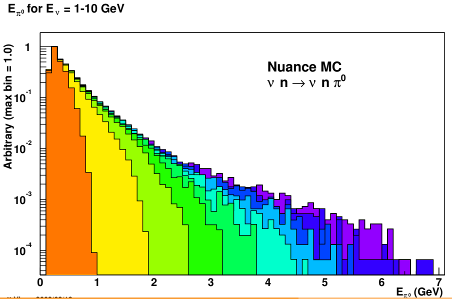
Natural Background Reduction





Putting some $\nu_\mu \rightarrow \nu_e$ signal at high energy, gain strong suppression of NC bkg via Q^2 kinematic cutoff

- Nuance MC
- Q^2 (top) and E_{π^0} (bottom) for single-π NC events
- Each color band: mono-energetic neutrinos, 1-10 GeV in 1 GeV steps.
- At $E_\nu > 2$ GeV get $> 50\times$ natural background reduction

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Oscillation Probability Illustrations

Unless noted, the values used are:

Δm^2_{21} = 8.0e-5 eV^2. KamLAND/SK/SNO.

Δm^2_{32} = 2.5e-3 eV^2. Super-Kamiokande.

$\sin^2(2\theta_{23})$ = 1.0. SK atmospheric maximal mixing.

$\sin^2(2\theta_{12})$ = 0.86. SK/SNO solar mixing.

$\sin^2(2\theta_{13})$ = 0.04. CHOOZ limited: use "not too big, not too small".

δ_{CP} = 0. Totally unknown.

Baseline = 2540 km (other, short baselines shown for comparison)

Matter effects using PREM Earth density and electron fraction profile.

Probability plots:

- Energy range will reflect full-width-10%-max coverage.
- Flash short baseline examples to compare.

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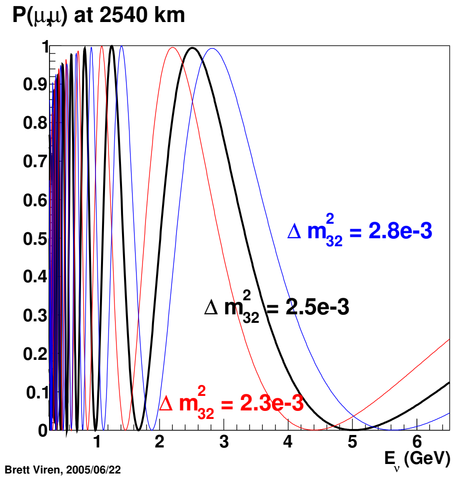
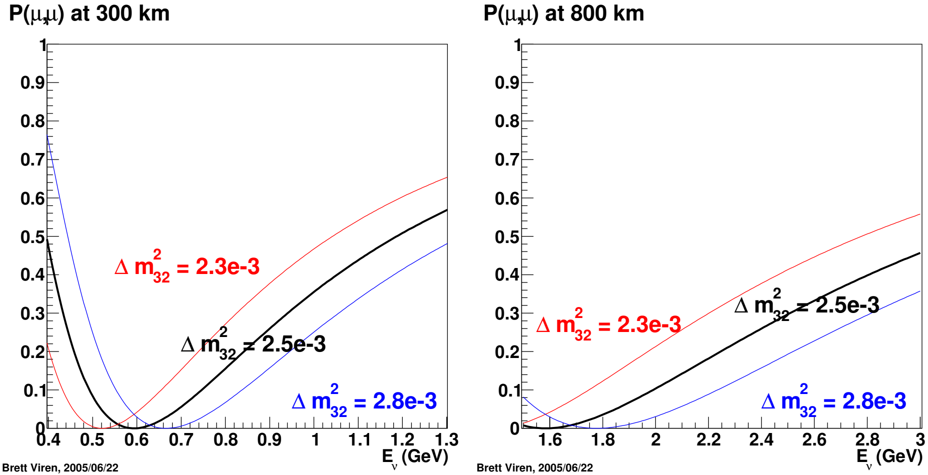
Multiple Disappearance Oscillations Well Covered!



- Multiple wiggles!
- No problem resolving "the dip", will see more than one!
- Nodes well placed across flux coverage, robust against Δm^2 change.

Disappearance at Short Baselines

At most one dip to see. Can slip away if Δm^2 ends up low.



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Rich Appearance Effects

The Very Long Baseline approach makes available a rich set of appearance effects.

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- Multiple Appearance Peaks

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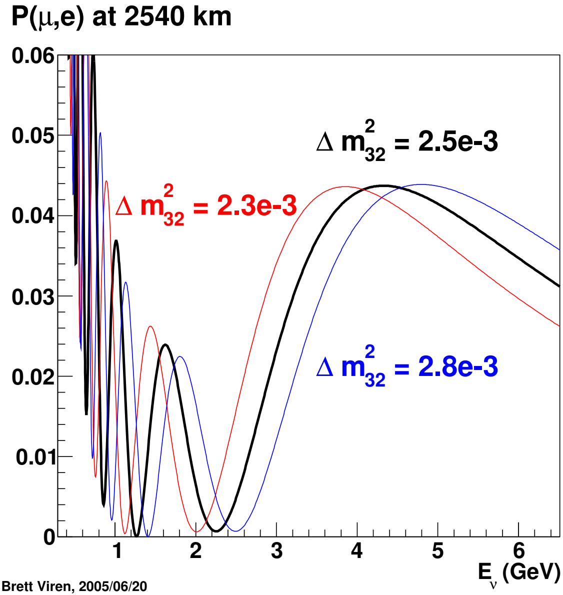
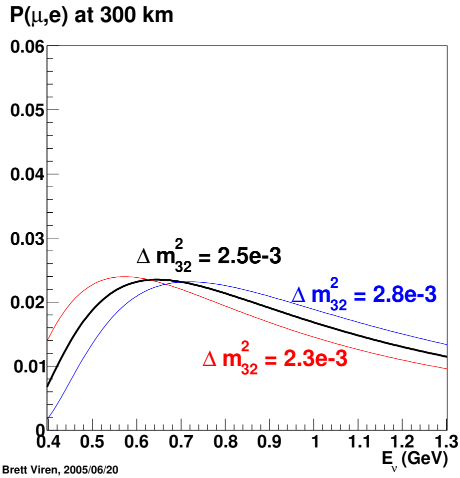
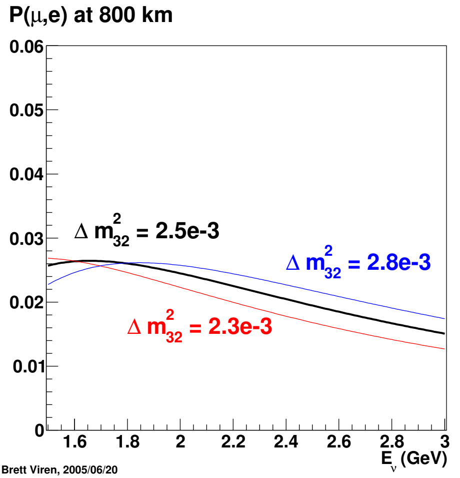
Multiple Appearance Peaks Covered



- Multiple peaks covered
- Robust against Δm^2 change

Appearance at Short Baselines





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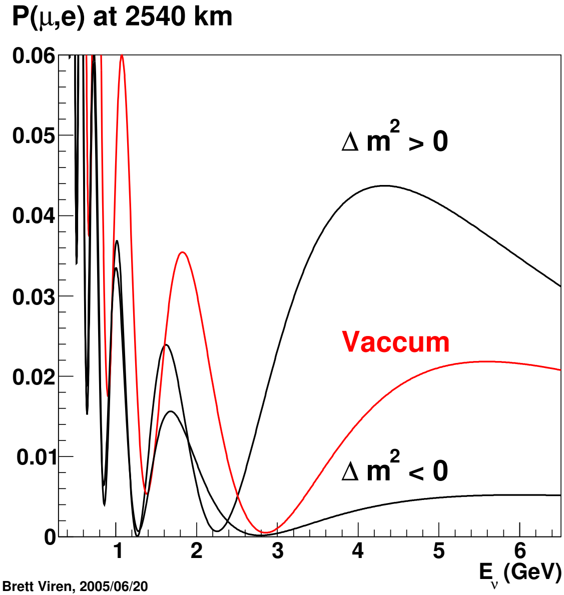
Rich Appearance Effects

The Very Long Baseline approach makes available a rich set of appearance effects.

- Multiple Appearance Peaks
- Matter Effects

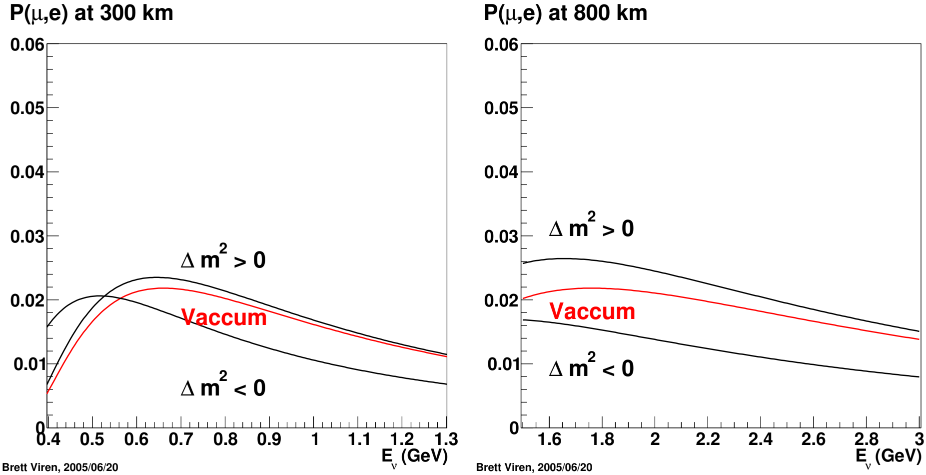
Matter Effects at Very Long Baselines



Sensitivity to $sign(\Delta m^2)$

- Factor of 2 effect → "easy"
- Effect mostly in first peak $E_\nu > 2$ GeV

Matter Effects at Short Baselines

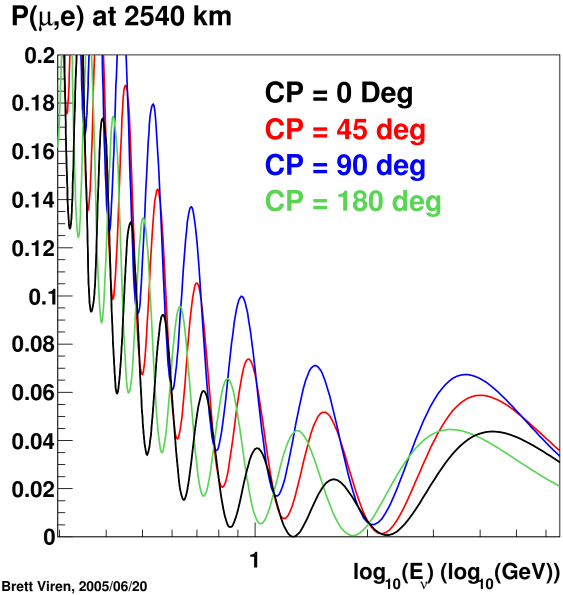


Rich Appearance Effects

The Very Long Baseline approach makes available a rich set of appearance effects.

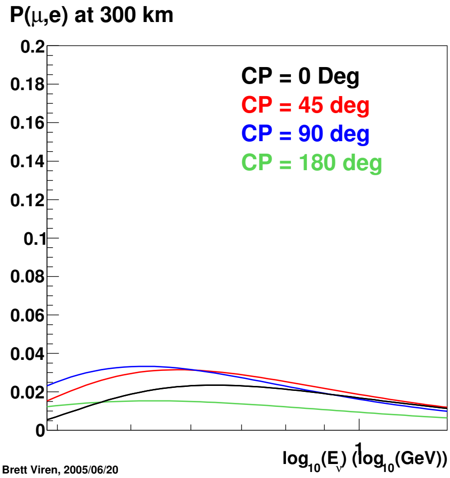
- Multiple Appearance Peaks
- Matter Effects
- CP Violation

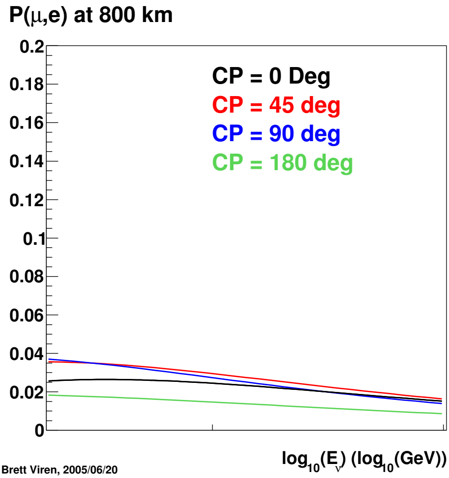
Nonzero CP Angle at Very Long Baselines



- Shift in magnitude and location
- Stronger effect for oscil peak $n > 1$ (W.Marciano)
- Longer baseline pulls $n > 1$ away from Fermi-motion region.

Nonzero CP Angle at Short Baselines





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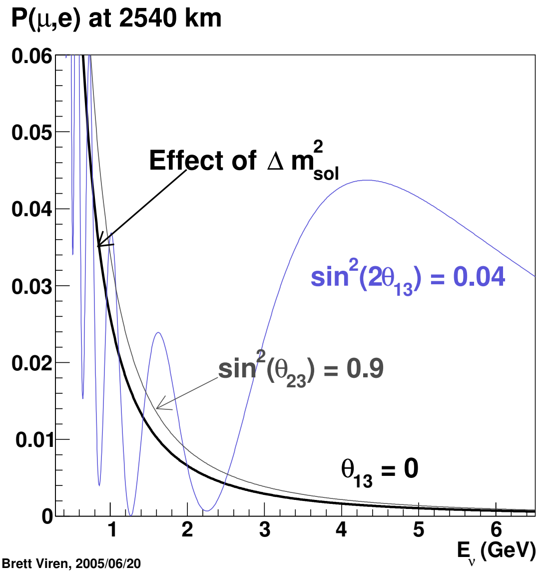
Rich Appearance Effects

The Very Long Baseline approach makes available a rich set of appearance effects.

- Multiple Appearance Peaks
- Matter Effects
- CP Violation
- ν_e Appearance with $\theta_{13} = 0$!

Guaranteed ν_e Appearance



What if $\theta_{13} = 0$?
Still observe ν_e via Δm^2_{21} !

- $\theta_{13} = 0$ in black
- $\theta_{13} \neq 0$ in blue
- Upswing at low energies is due to Δm^2_{21}.
- Small shift if non-maximal mixing

This over constrains the solar parameters - potential to see new physics!

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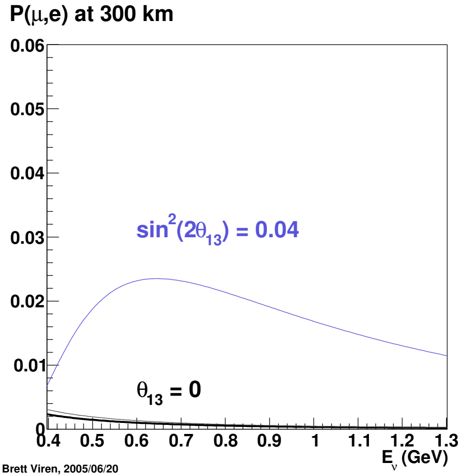
$\theta_{13} = 0$ at Short Baselines



Rich Appearance Effects

The Very Long Baseline approach makes available a rich set of appearance effects.

- Multiple Appearance Peaks
- Matter Effects
- CP Violation
- ν_e Appearance with $\theta_{13} = 0$!

Since these effects occur differently across the spectrum in a Very Long Baseline experiment, they can be disentangled with a single experiment.

Sensitivity to Different Parameters in Different Energy Regions

	$E_\nu < 1$ GeV	$1 < E_\nu 2 <$GeV	$E_\nu > 2$ GeV
$\sin^2 2\theta_{13}$	$\surd$	$\surd$	$\surd$
$sign(\Delta m^2_{32})$	-	-	$\surd\surd\surd$
δ_{CP}	$\surd$	$\surd\surd$	$\surd$
solar	$\surd\surd\surd$	$\surd$	-

- It's a complex picture with many effects!
- But, effects have different strength at different energies.
- Measuring across the wide energy band makes it possible to sort them out.

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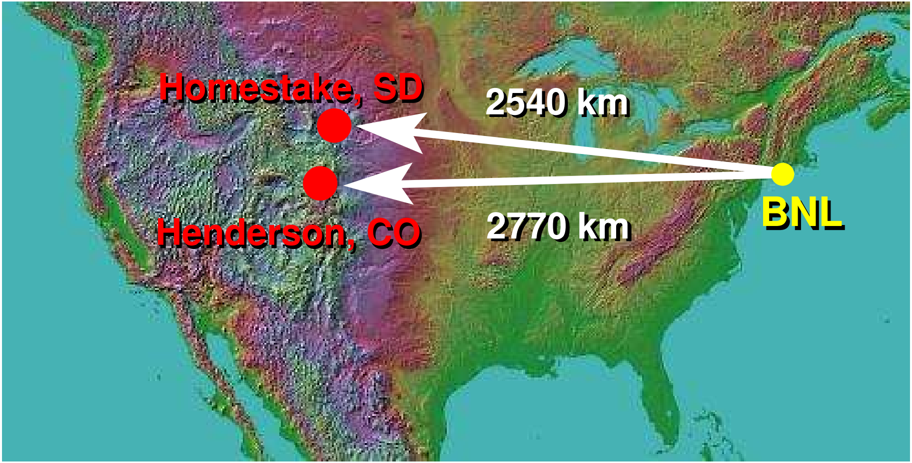
Example Baseline: 2540 km

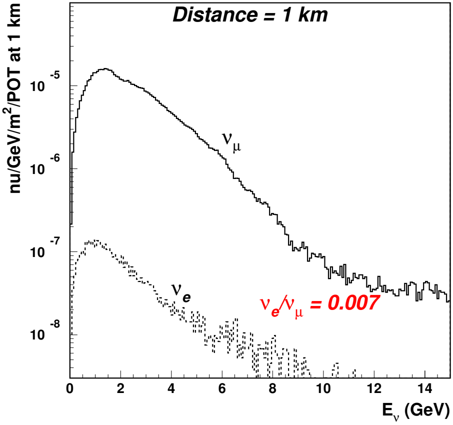


Homestake & Henderson equivalent. Assume UNO class far detector.

Neutrino Flux

The following is work by Milind Diwan.

BNL Wide Band. Proton Energy = 28 GeV



ν running:

- 1 MW, 28 GeV proton beam
- 5×10^7 seconds
- 1.12×10^{22} PoT
- 60 cm carbon target
- 4 m $\phi\times$ 200 m long decay tunnel

$\bar{\nu}$ running same but 2 MW

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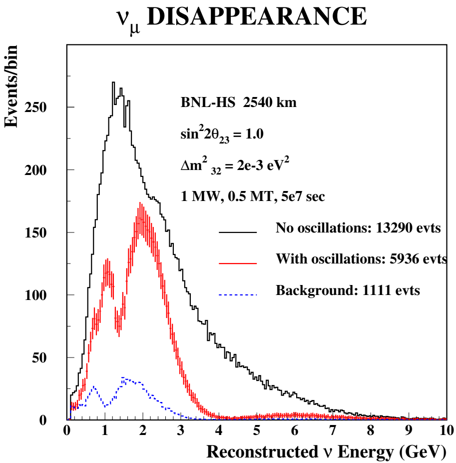
Expected Number of Events

- 1 MW ν running
- Water-Cherenkov detector
- 500 kTon water fiducial
- 2540 km baseline
- 5×10^7 seconds exposure

Reaction	Number
CC $\nu_\mu + N \rightarrow \mu^- + X$	51800
NC $\nu_\mu + N \rightarrow \nu_\mu + X$	16908
CC $\nu_e + N \rightarrow e^- + X$	380
QE $\nu_\mu + n \rightarrow \mu^- + p$	11767
QE $\nu_e + n \rightarrow e^- + p$	84
CC $\nu_\mu + N \rightarrow \mu^- + \pi^+ + N$	14574
NC $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$	3178
NC $\nu_\mu + O^{16} \rightarrow \nu_\mu + O^{16} + \pi^0$	574
CC $\nu_\tau + N \rightarrow \tau^- + X$ (if all $\nu_\mu \rightarrow \nu_\tau$)	319

Disappearance at 2540 km



- 10% energy resolution + Fermi motion
- 2 nodes clearly visible
- **Black** and **red** include background
- Only single-π production bkg considered here
- $\sigma(\Delta m^2_{32})$ & $\sigma(\sin^2(2\theta_{23})) \sim 1\%$
- Resolution dominated by systematics

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Expected Appearance Results

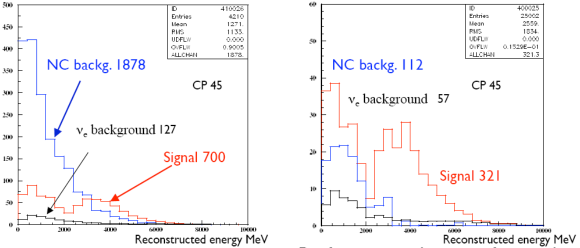
1. Weighted SK Atm-ν MC/reconstruction study (C. Yanagisawa)
2. Baseline requirements study (M. Diwan)
3. In progress: full study with UNO detector MC and realistic reconstruction code.

C. Yanagisawa - weighted SK Atm-ν MC study

Complete water Cherenkov detector simulations progress

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

- Δm^2_{21}=7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2
- $\sin^2 2\theta_{ij}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=+45,+135,-45,-135°



Select single ring events and select electrons
Signal/backg = 700/2005

Perform analysis of single electron pattern, likelihood cut retaining ~50% of signal.
Signal/back = 321/169

C. Yanagisawa (Stony Brook), 3rd BNL/UCLA workshop
http://www.physics.ucla.edu/hep/proton/proton2005.htm

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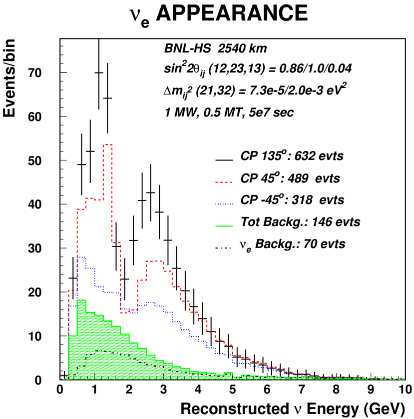
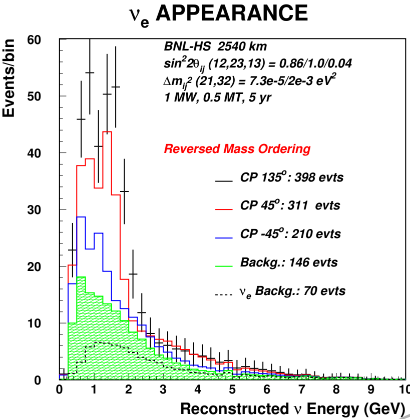
Improved π^0 finder + likelihood cut.

Appearance - Baseline Requirements Study

M. Diwan, close but stricter requirements still:





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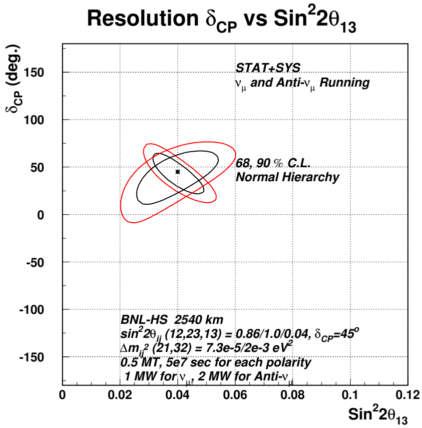
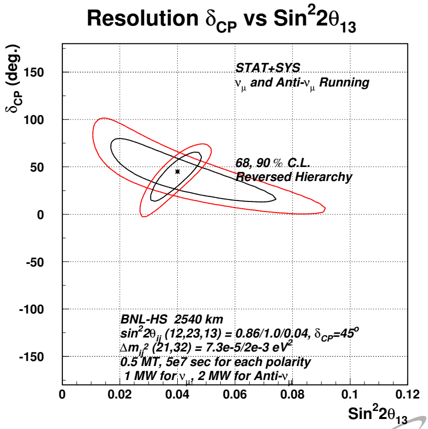
Sensitivity of δ_{CP} and θ_13

1-σ and 90% contours, all other parameters fixed.





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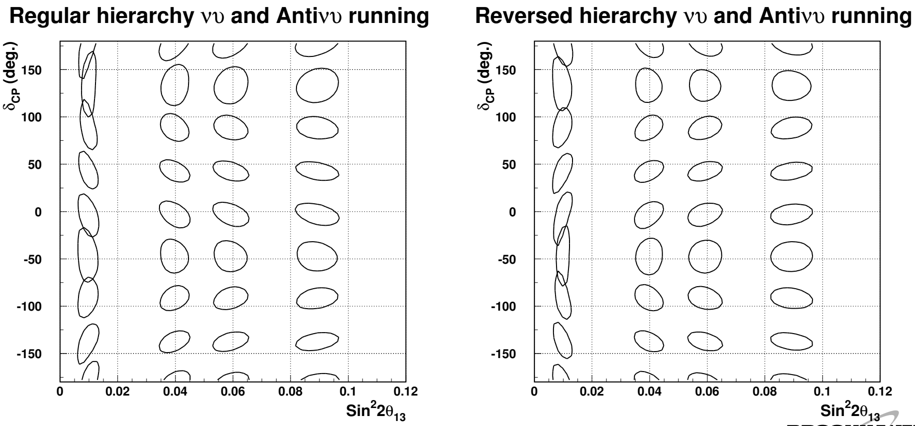
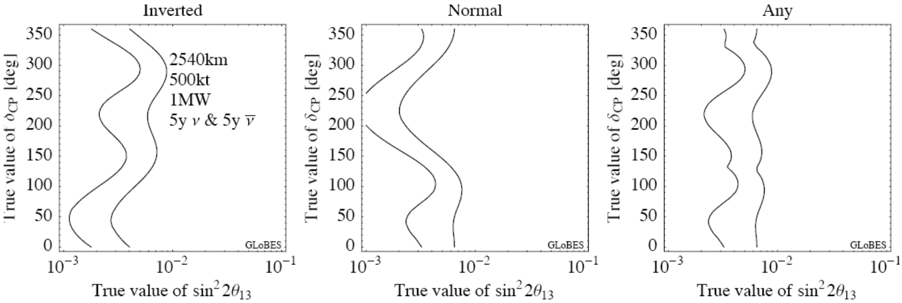
Sensitivity of δ_{CP} and θ_13 - Combined $\nu/\bar{\nu}$

1-σ contours, all other parameters fixed.

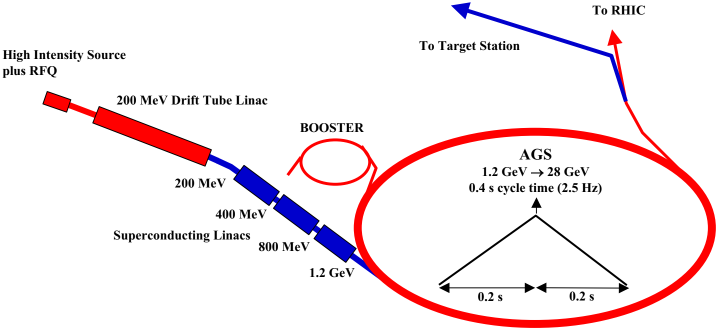


Patrick Huber, UWisc:



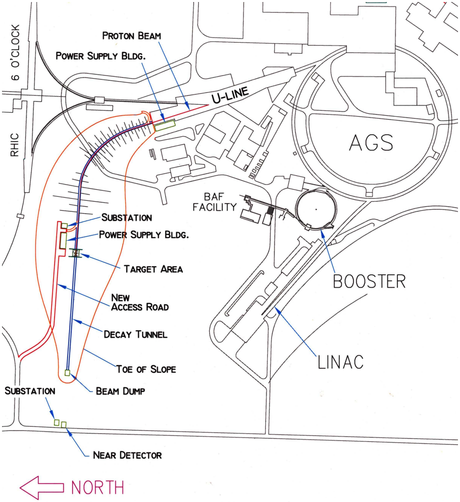
- Both ν- and $\bar{\nu}$-running.
- Includes correlations and errors on all parameters, 10% background uncertainty.
- Will improve as other oscillation parameter measurements improve.
- All δ_{CP} range covered.

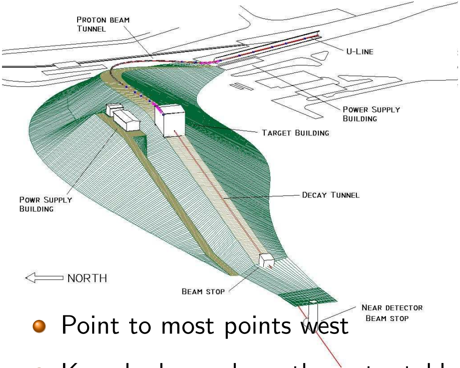
Upgrade to AGS



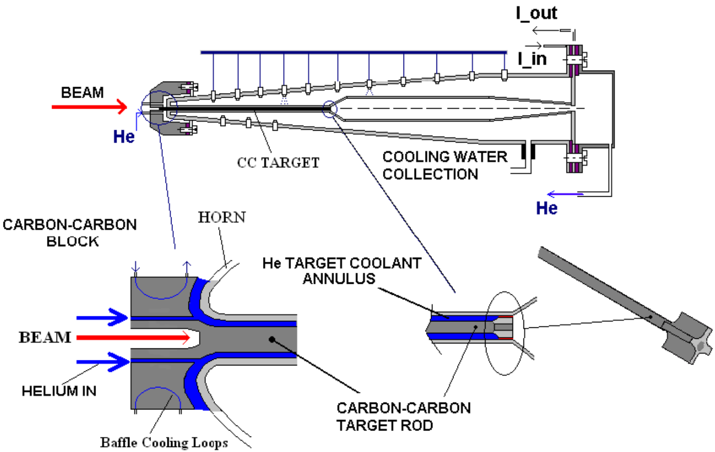
- Use 1.2 GeV SC Linac instead of booster
  - $7 \times 10^{13} \longrightarrow 9 \times 10^{13}$ ppp
  - Fill time 0.6 sec $\longrightarrow$ 1.0 msec
- Increase rep. rate 0.5 $\longrightarrow$ 2.5 Hz
- New mag. PS and RF cavities
- Further improvements on design being worked on.

BNL Site Development





- Point to most points west
- Keep hadrons above the water table
- Room for a (very) near detector
- Hill cheaper than tunnel



- Conventional pulsed hadron focussing with 2 horns
- Likely carbon-carbon target, embedded in 1st horn
- R&D underway with material experiments
- Collaboration with FNAL, JPARC and others

Estimated Costs

October 1, 2004 BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report

Editor: W. T. Weng, M. Diwan, and D. Raparia

Contributors and Participants

J. Alessi, D. Barton, D. Beavis, S. Bellavia, I. Ben-Zvi, J. Brennan, M. Diwan,
P. K. Feng, J. Gallardo, D. Gassner, R. Hahn, D. Hseuh, S.Kahn, H. Kirk,
Y. Y. Lee, E. Lessard, D. Lowenstein, H. Ludewig, K. Mirabella,
W. Marciano, I. Marneris, T. Nehring, C. Pearson, A. Pendzick,
P. Pile, D. Raparia, T. Roser, A. Ruggiero, N. P. Samios,
N. Simos, J. Sandberg, N. Tsoupas, J. Tuozzolo, B. Viren,
J. Beebe-Wang, J. Wei, W. T. Weng, N. Williams,
P. Yamin, K. C. Wu, A. Zaltsman,
S. Y. Zhang, Wu Zhang

Brookhaven National Laboratory
Upton, NY 11973
October 1, 2004

- Put through internal BNL review
- Bottom-up estimation with WBS
- Based on RHIC & SNS ring, LHC magnets.
- Target & Horn from BNL, K2K and NuMI.
- $273.4M FY04
- 6 Years to neutrinos
  - 3 years R&D
  - Construction after 1 year
  - 4.5 years to completion
  - 0.5 year commissioning

Summary

- The BNL Very Long Baseline concept provides a qualitatively different experiment than past or proposed
- Precision (1%) measurement of atm-ν params, systematics limited.
- Degeneracy-broken measurement of appearance parameters
- If lucky, ν-running only needed for appearance measurements, with $\bar{\nu}$-running gain precision w/out needing luck.
- Appearance results limited by how well background can be controlled
- Work on full detector simulation and reconstruction to be finished before final word.
- Affordable, practical beam design. No "magic" needed.
- Ongoing collaborations (C. Yanagisawa (UNO), P. Huber (GLoBES)), others most welcome!

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References

Papers:

- BNL Neutrino Working Group web page: http://nwg.phy.bnl.gov/.
- "Extra Long Baseline Neutrino Oscillations and CP Violation", W. Marciano, BNL-HET-01/31, hep-ph/0108181.
- Whitepaper, BNL-69395 hep-ex/0211001.
- VLBL PRD paper, Phys.Rev. D68 (2003) 012002, hep-ph/0303081.
- AGS Superbeam CDR, BNL-73210-2004-IR (avail from NWG web).
- "The Case for a Super Neutrino Beam", M. Diwan (1290 km and 2540 km compared) hep-ex/0407047.

Publicly available software:

- Oscillation Probability Calculator, B. Viren, http://minos.phy.bnl.gov/ bviren/elbo/libnuosc++/
- GLoBES, P. Huber, M. Lindner and W. Winter, hep-ph/0407333
- Nuance, D. Casper, hep-ph/0208030

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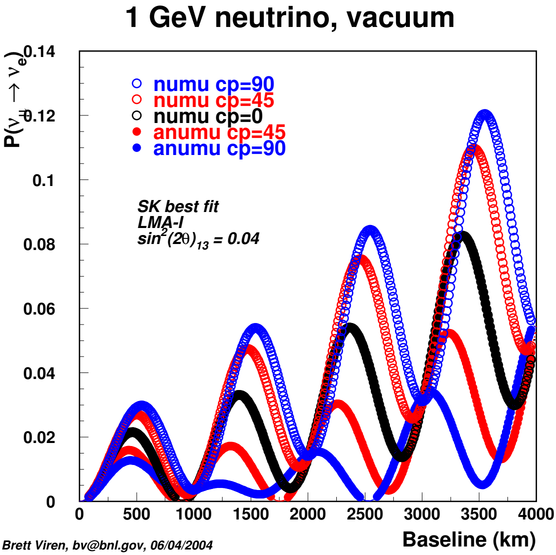
Backup Slides

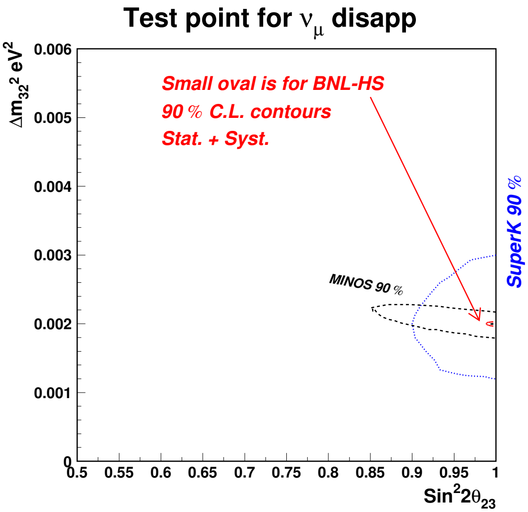
CP Violation Sensitivity Independent of Baseline



- Marciano, hep-ph/0108181
- $A \sim L$
- Flux $\sim 1/L^2$
- Statistical F.O.M.
  - $= (\Delta A/A)^{-2}$
    $= A^2 N/(1-A)$
  - $N = N_{\nu e} + N_{\bar{\nu} e}$
  - Linear in flux
  - Quadratic in A

Independent of BL, at least until the flux totally runs out.

Resolution on θ_{23} and Δm^2_{32}



- Energy scale systematic not included (SK has 2.5%)
- O.w. $\sigma(\Delta m^2_{32}) \sim 1\%$
- Not strongly sensitive on normalization uncertainty due to multi-nodal spectrum shape.

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