(Physics Potential of) a Very Long Baseline Neutrino Experiment using a Wide Band Beam

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Outline

- Motivation for and concept of a very long baseline (VLBL) neutrino oscillation experiment
- Possibility of neutrino beams in the US
- Possibility of deep underground water Cherenkov detector in the US
- Recent improvements in e/π^0 separation in a water Cherenkov detector
- Physics potential: see talk D. Marfatia

Very Long Baseline Experiment

- ✔ Introduction
- ✔ Concept
- ✔ ν_μ disappearance
- ✔ ν_e appearance

Three neutrino oscillations

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$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow$$

PMNS matrix:
3 mixing angles
1 CP phase
(2 CP Majorana phases)

solar — atmospheric

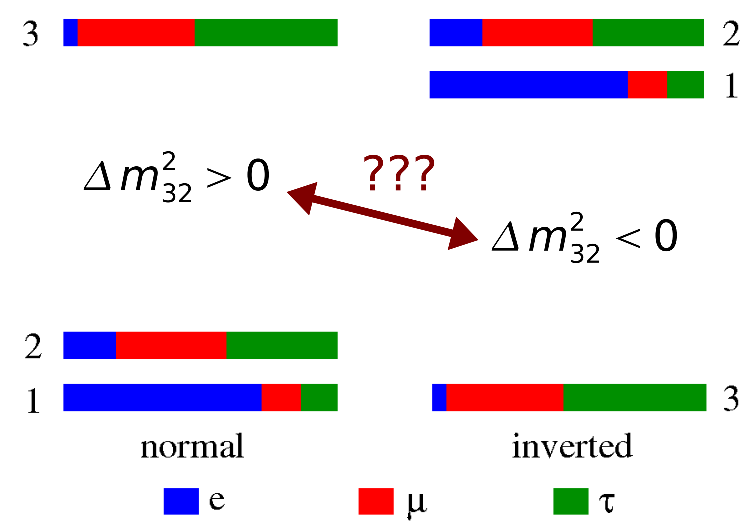
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$\theta_{12} \approx 34^\circ$ $\sin^2 2\theta_{13} < 0.11$ (90%CL) $\theta_{23} \approx 45^\circ$

$\delta = ???$

neutrino masses must differ to observe ν oscillations:

$$\Delta m^2_{21} = m^2_2 - m^2_1 \approx +7.9\ 10^{-5} eV^2$$
$$|\Delta m^2_{32}| = |m^2_3 - m^2_2| \approx 2.6\ 10^{-3} eV^2$$
$$\Delta m^2_{31} = \Delta m^2_{21} + \Delta m^2_{31}$$



VLBL Concept

Very long baseline (VLBL) concept:

- Long distances between production and detection
- Wide band ν_μ beam
- Higher neutrino energies (> 0.5 GeV)

A single VLBL experiment will have:

- increased sensitivity to $\sin^2 2\theta_{13}$
- good sensitivity to δ_{CP}
- potential for resolving mass hierarchy (sign of Δm^2_{32})
- capability for precision measurements of Δm^2_{32} & $\sin^2 2\theta_{23}$

ν_μ disappearance

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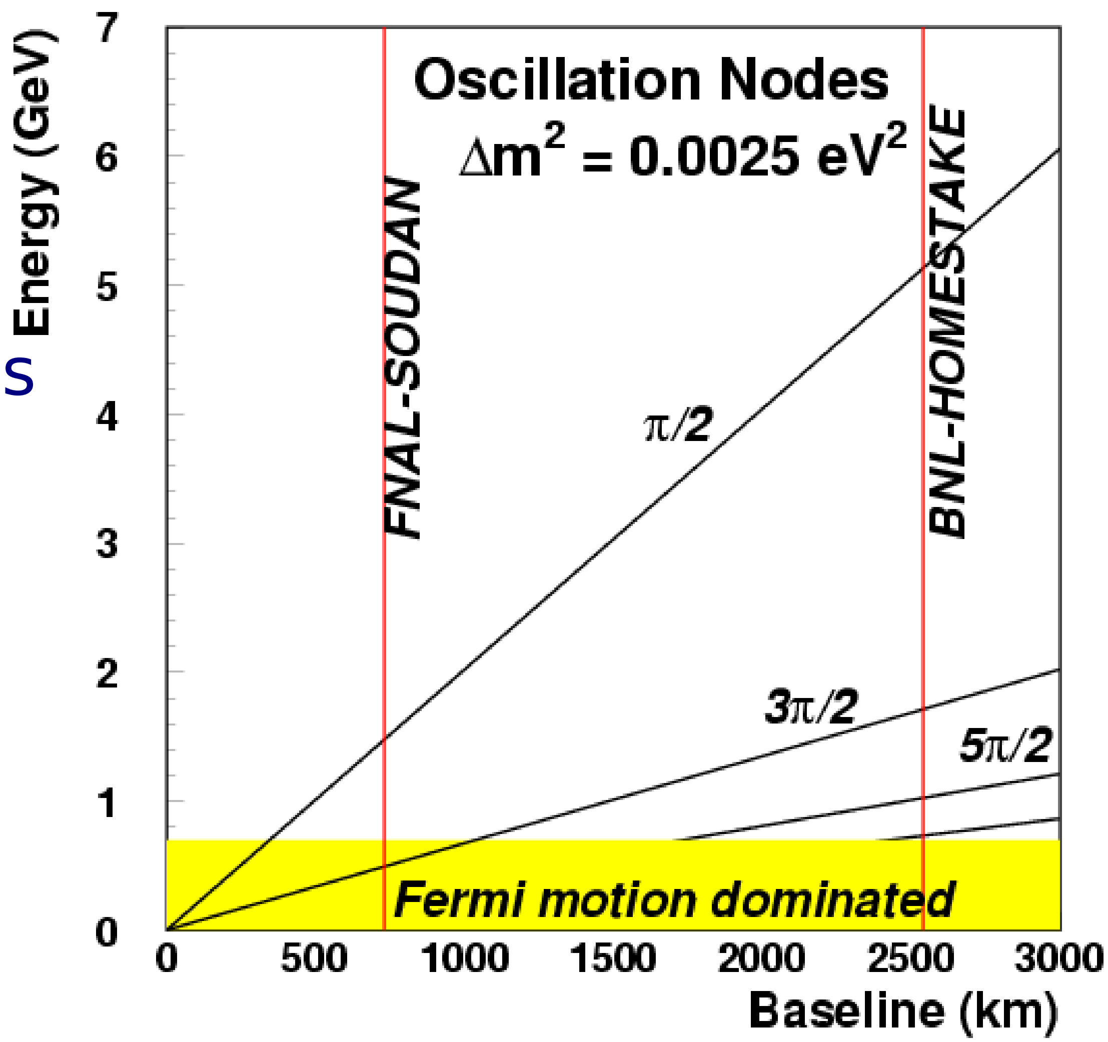
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.27\, L\, \Delta m^2_{32}}{E}\right)$$

Observe multiple nodes in oscillation pattern:
- ✓ less dependent on flux normalization

Longer distances → nodes at higher energies:
- ✓ easier to reconstruct
- ✓ higher cross sections

Baseline >1000km:
- ✓ 2 nodes out of fermi motion domain



precision measurement Δm^2_{32} and $\sin^2 2\theta_{23}$

ν_e appearance

Approx. formula including matter effects (M. Freund) :

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

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

"CP effects"

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

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

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \approx 0.03, \ \Delta = \Delta m^2_{31} L/4E$$

$$\hat{A} = 2\mathrm{VE}/\Delta m^2_{31} \approx (E_\nu/GeV)/11 \ \text{(Earth's crust)}, \ V = \sqrt{2}G_F n_e$$

$$J_{CP} = \sin\delta_{CP}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23},$$

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

Numerical calculations used for actual results

ν_e appearance

- $P(\nu_\mu \rightarrow \nu_e)$ depends on all oscillation parameters and has following degeneracies:
  - intrinsic $(\theta_{13},\delta_{CP}) \leftrightarrow (\theta'_{13},\delta'_{CP})$
  - sign $\Delta m^2_{32} \leftrightarrow -\Delta m^2_{32}$
  - octant $\theta_{23} \leftrightarrow \pi/2-\theta_{23}$
- atmospheric term has effect of $\sin^2\theta_{13}$ and matter effects (~L)
- CP violating term ~L/E, flux ~L^{-2}

  $\rightarrow$ sensitivity to δ_{CP} independent of distance

  (Marciano hep-ph/0108181)
- solar term dominated by Δm^2_{21} and grows as ~ $(L/E)^2$

ν_e appearance

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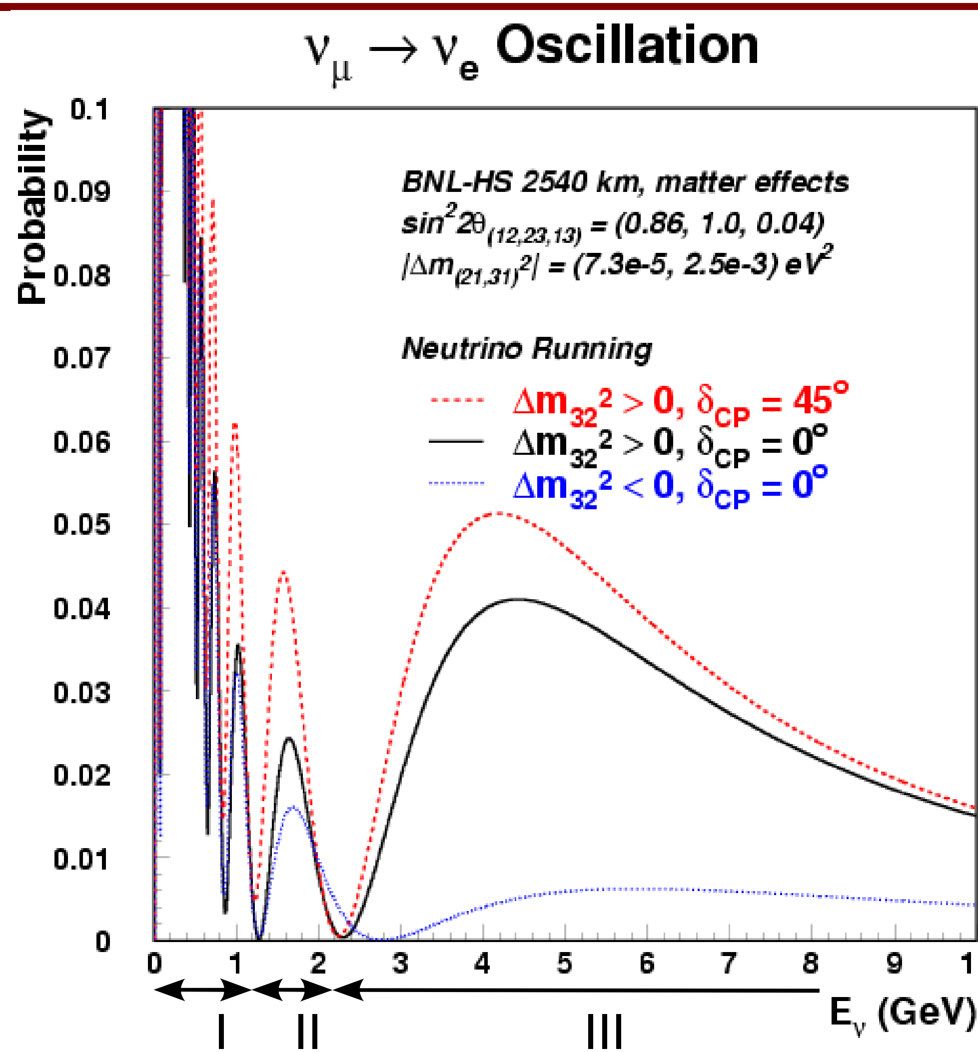
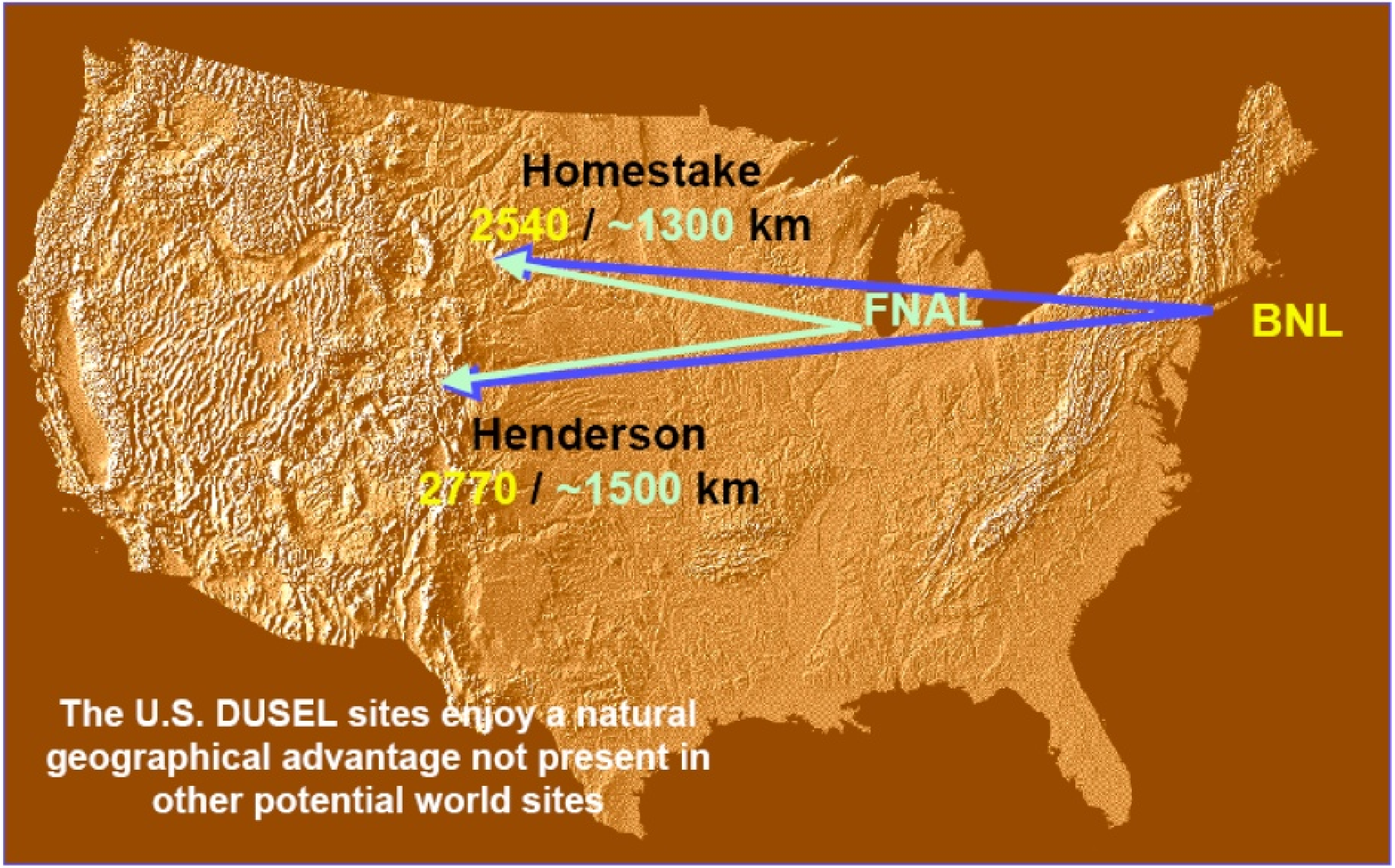
Sensitive to different parameters in different energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\text{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+



Fully exploit shape of appearance spectrum:
helps in resolving ambiguities with
one experiment at one baseline

Baselines in US



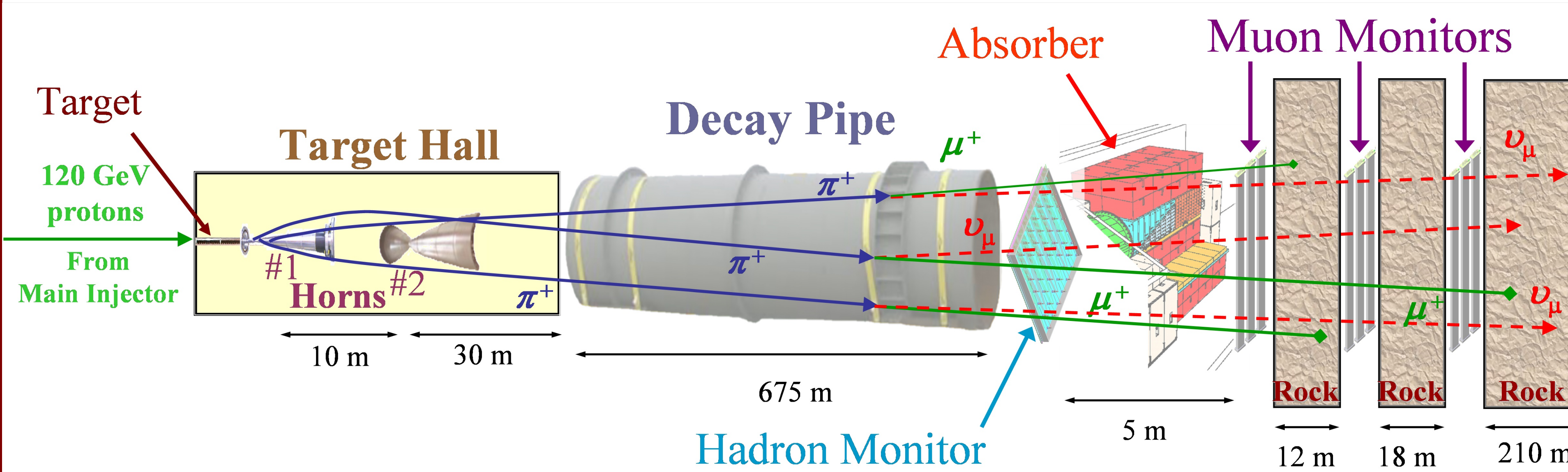
Sensitivity studies will cover 500-3000km baselines!

Wide band neutrino beams

- Making conventional ν_μ beams
- Beam from BNL
- Beam from FNAL
- Flux calculations

Making ν_μ beams

NuMI example:

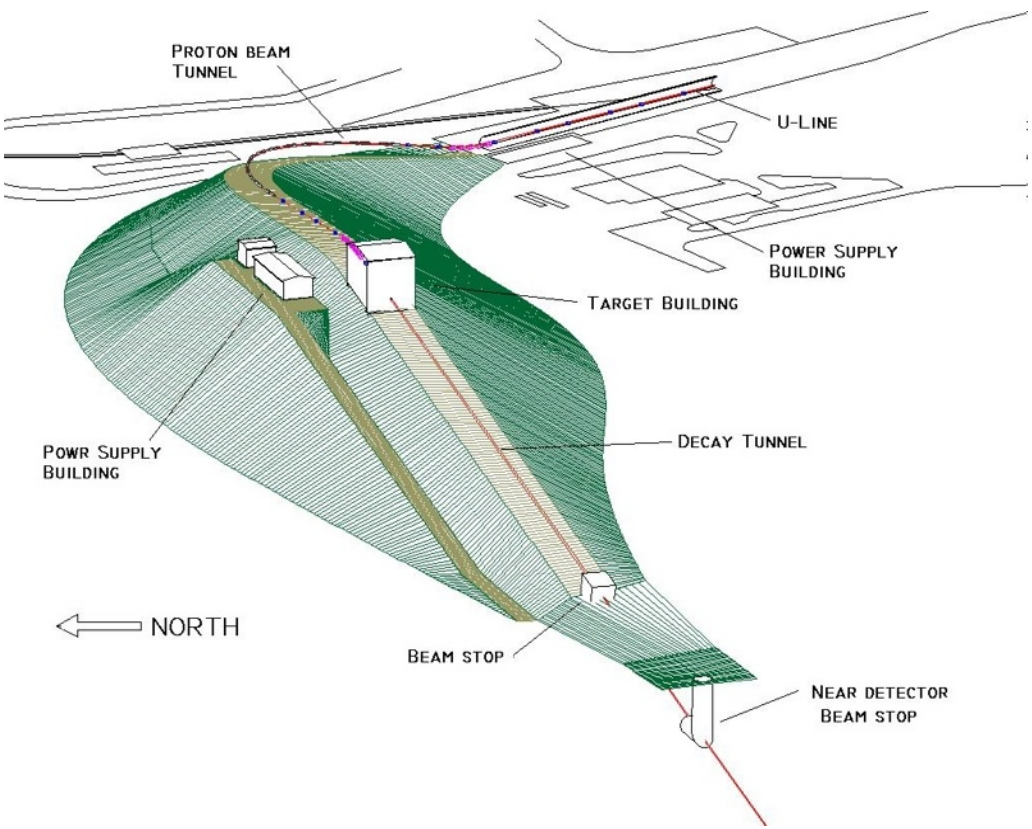


- shoot protons on target
- magnetic horns: focus pions to get more flux and select ν or anti-ν
- decay pipe for pions to decay
- material to absorb remaining hadrons and muons

Beam from BNL

AGS upgrade: 28 GeV 1MW neutrino beam

- Increase intensity and repetition rate
- Needs new power supply, RF and replacing booster with 1.2 GeV SC linac



neutrino beamline on a hill:

- keep radiation above water table
- 45m high
- target on top
- 200 m decay pipe
- pointing ~11° down

Total cost estimate: $273M (excl. contingency)

"The AGS-Based Super Neutrino Beam Facility Conceptual Design Report", Weng, Diwan, Raparia et al., BNL-73210-2004-IR

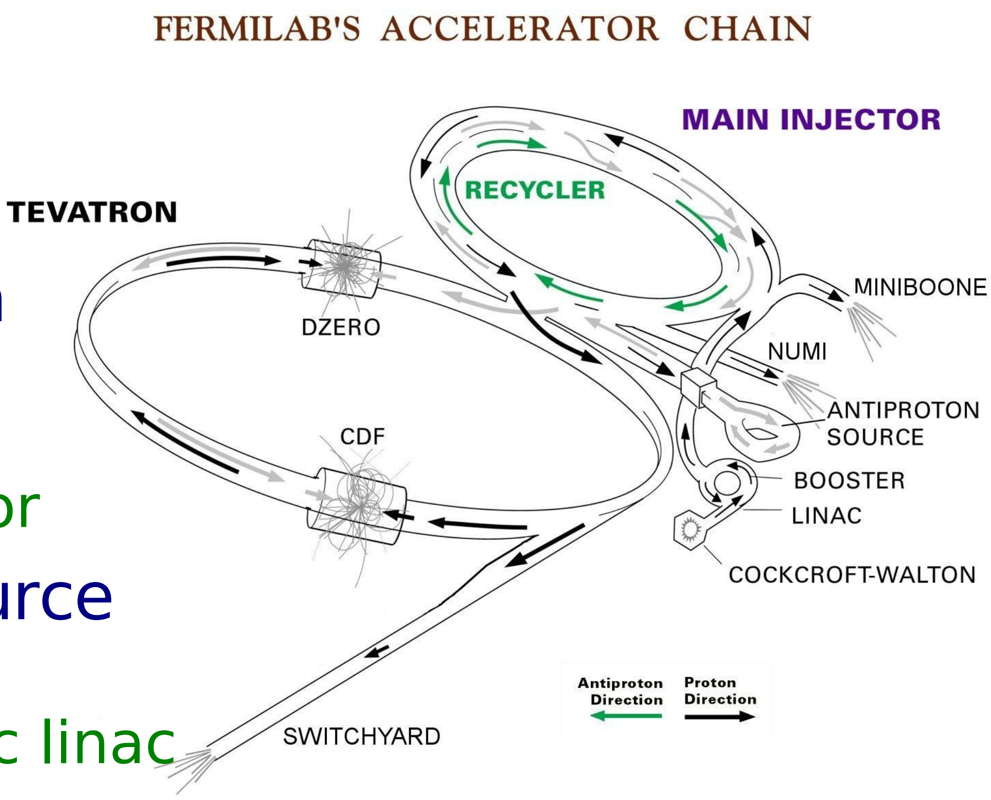
Beam from FNAL

Possible proton beam power upgrades:

a) Proton plan:
- More protons in MI
- After Tevatron: batches pbar production available

b) Super NuMI: after Tevatron
- Phase I: use Recycler as pre-injector
- Phase II: also use Accumulator

c) High Intensity Neutrino Source (a.k.a. Proton driver):
- Replace booster with 8GeV sc linac

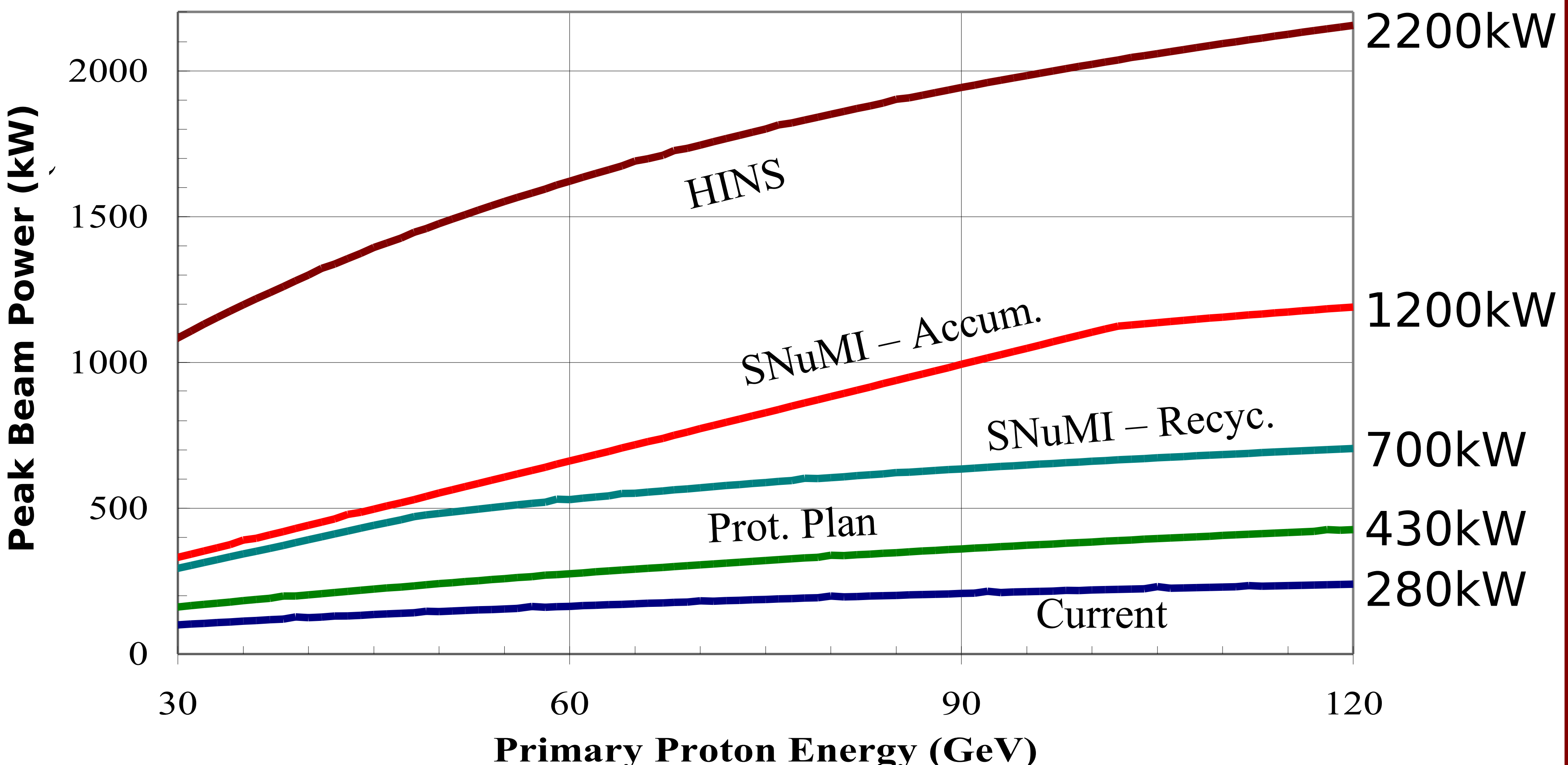


Phase II of sNuMI is part of the plan for the NOVA-I

“Fermilab Proton Projections for Long-Baseline Neutrino Beams”, Bob Zwaska, FNAL-BEAM-DOCS-2393

Beam from FNAL

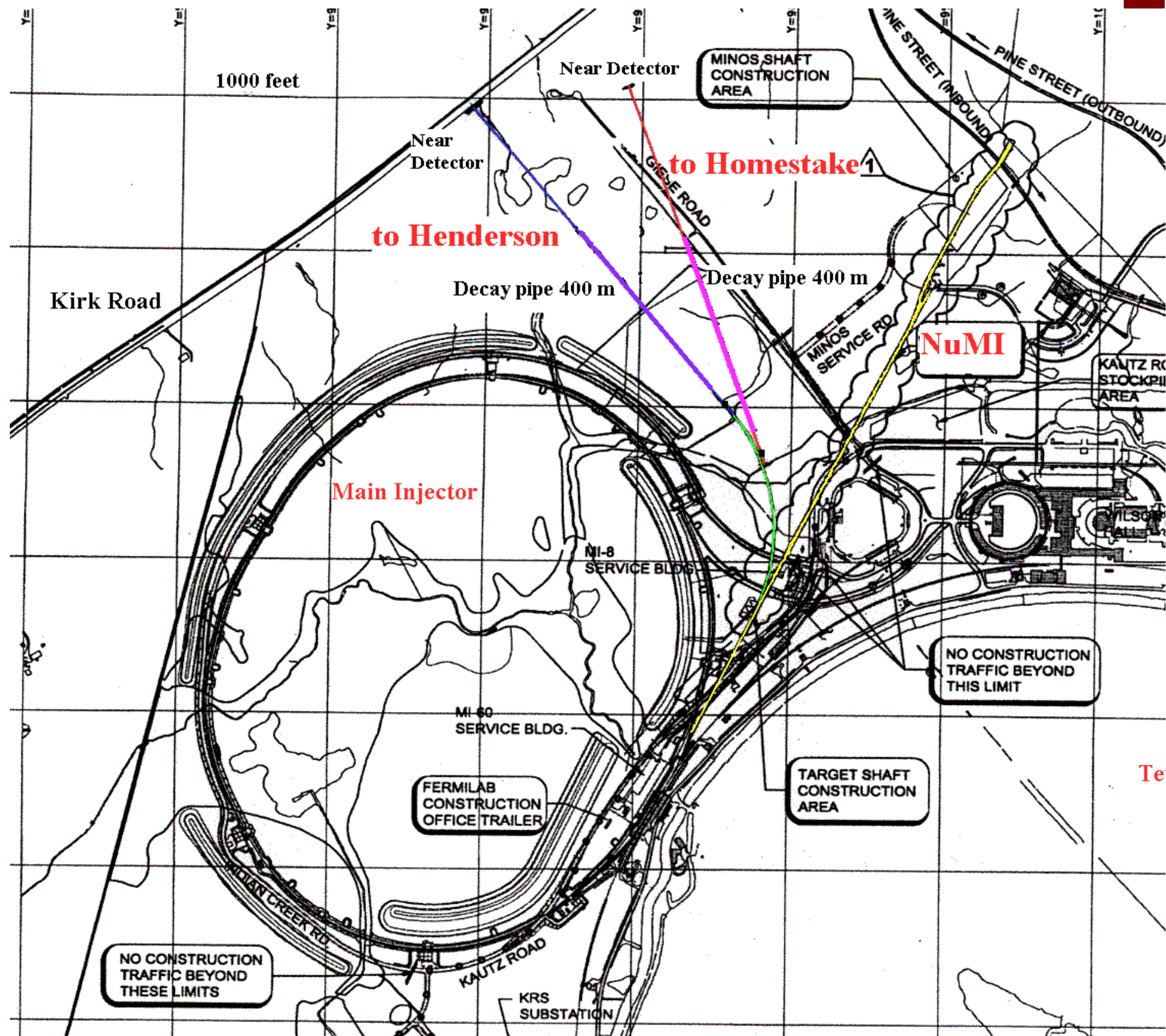
Flexibility of proton energy:



Beam from FNAL

Beamline: use existing NuMI extraction

- ✔ target hall: 45m
- ✔ decay pipe: 400m
- ✔ near detector: 300m from end decay pipe



Angles to:

- ✗ Homestake: 5.8°
- ✗ Henderson: 6.7°

Flux Calculations

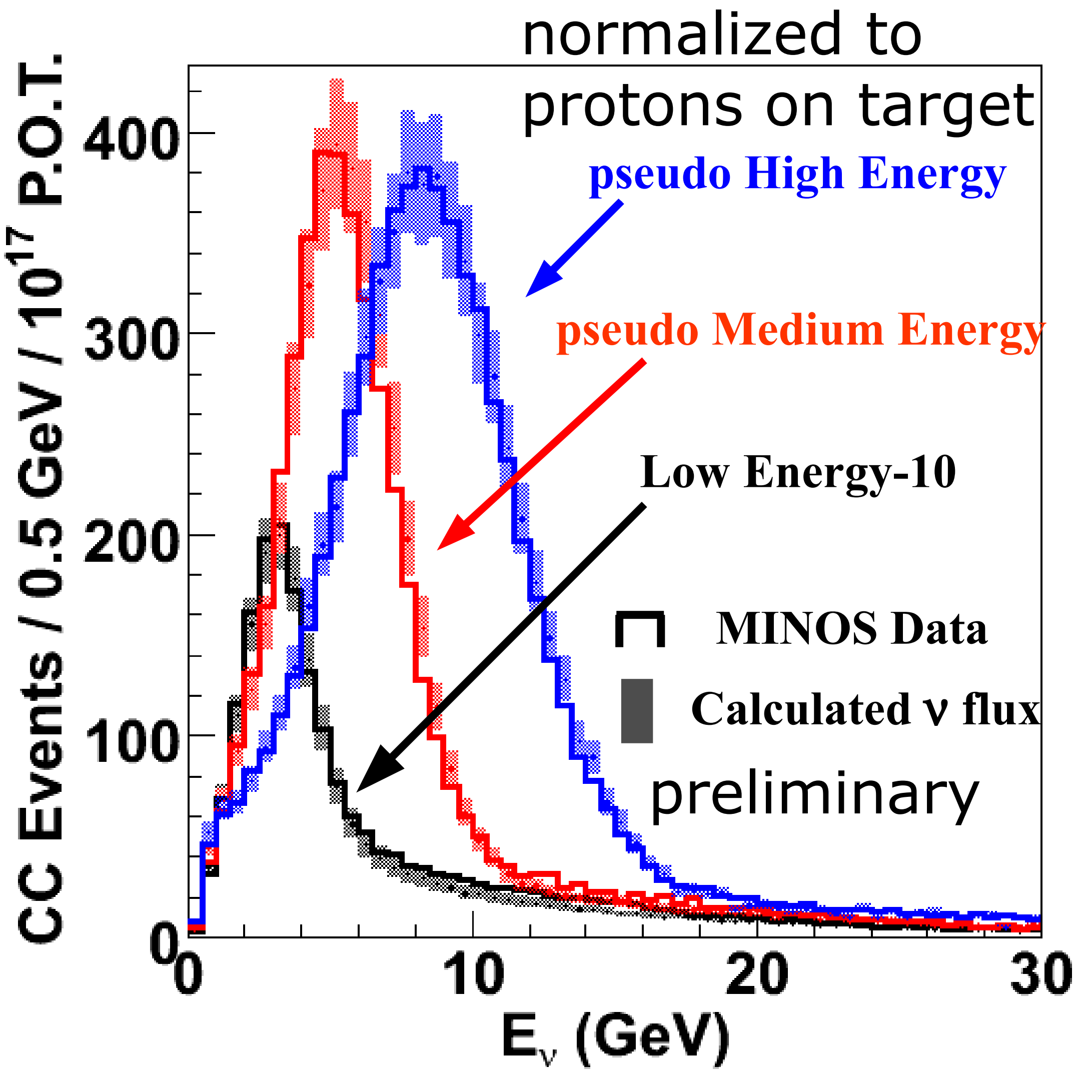
Simulation using NuMI Monte Carlo (gnumi):

- ✓ based on GEANT3 and Fluka05
- ✓ validated by MINOS Near Detector data

Modifications:

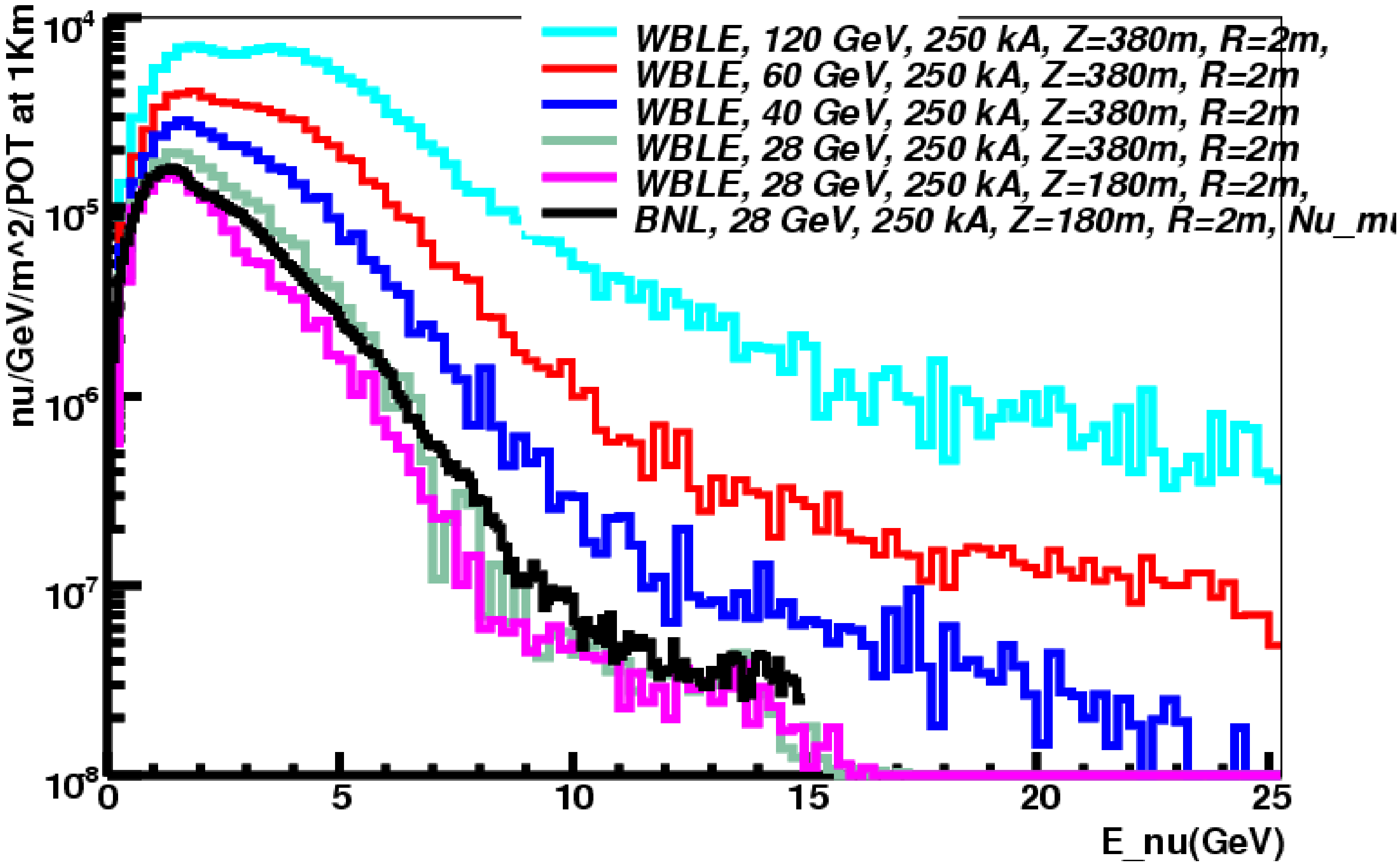
- ✓ Target
- ✓ Horns
- ✓ Decay pipe: r=2m, l=380m

→ Wide Band Low Energy (WBLE) beam



"Simulation of a Wide-band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments", M. Bishai et al. BNL-76997-2006-IR

Flux Calculations



- ✓ Good agreement BNL & WBLE calculations (28GeV)
- ✓ Increase flux: longer decay pipe & higher proton energy

Water Cherenkov Detector

- ✔ Requirements
- ✔ UNO at Henderson
- ✔ Modular detector at Homestake
- ✔ e/π^0 separation

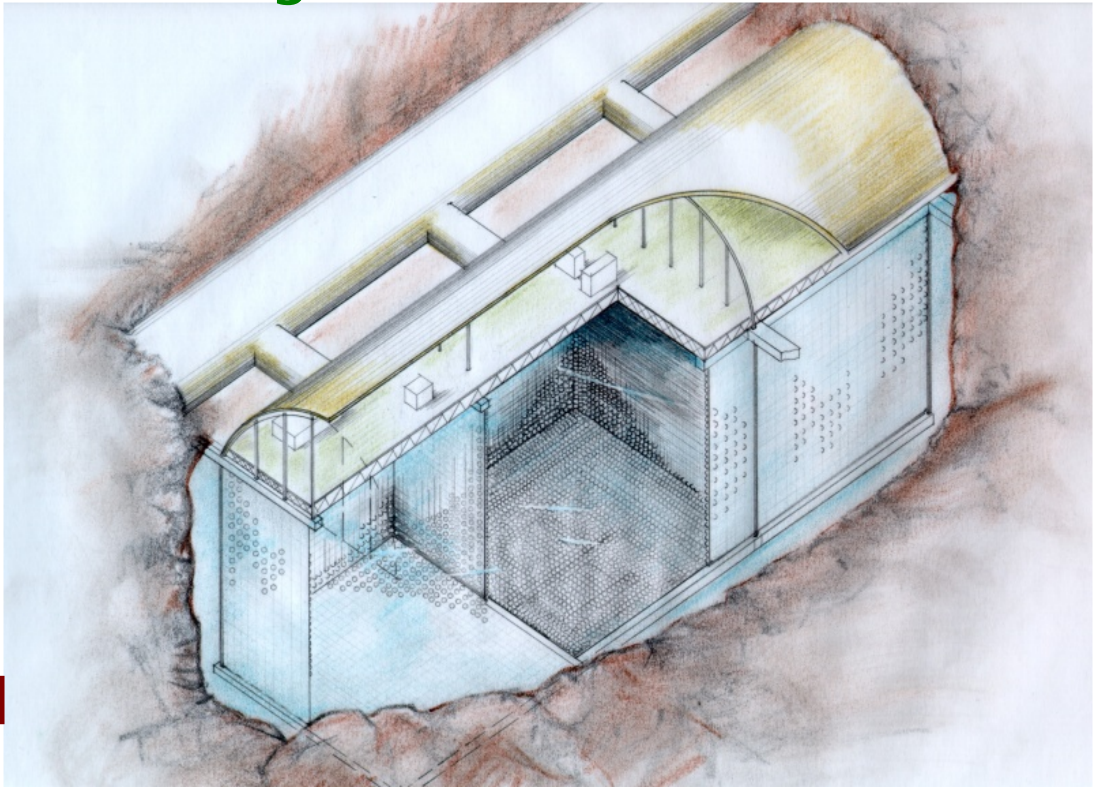
Water Cherenkov detector

- well established technique
- scale few times Super-K 50kT (22.5kT fiducial)
- several 100kTs (depends on physics)
- 20%-40% PMT coverage (depends on physics)
- 10% energy resolution on quasi-elastic ν_e interactions
- rejection neutral current interactions x10-20
- underground to reduce cosmics (no veto counter needed if deep enough)

Detector at Henderson

UNO detector:

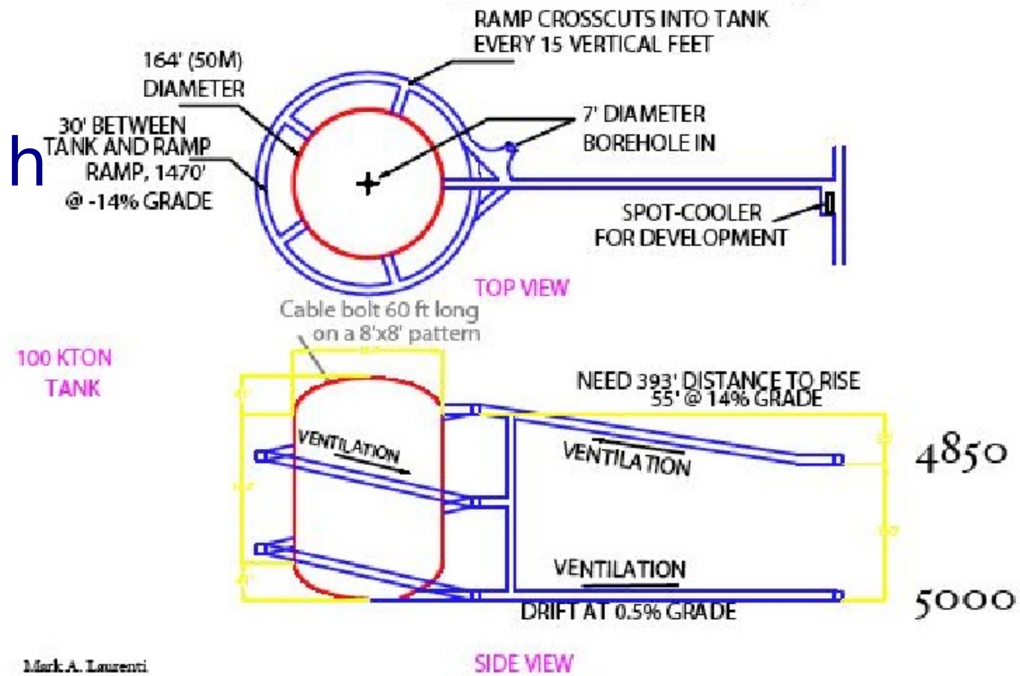
- 1 large cavern
- 3 optically separated modules of 60x60x60 m^3
- total mass 440 kT fiducial
- central module 40% PMT coverage (low E physics)
- outer modules 10% PMT coverage
- optional finer granularity: 20 or 13 inch tubes
- optimal depth 5400mwe (2500 feet)
- construction time: 10 years
- coarse cost estimate scaling Super-K: $500M

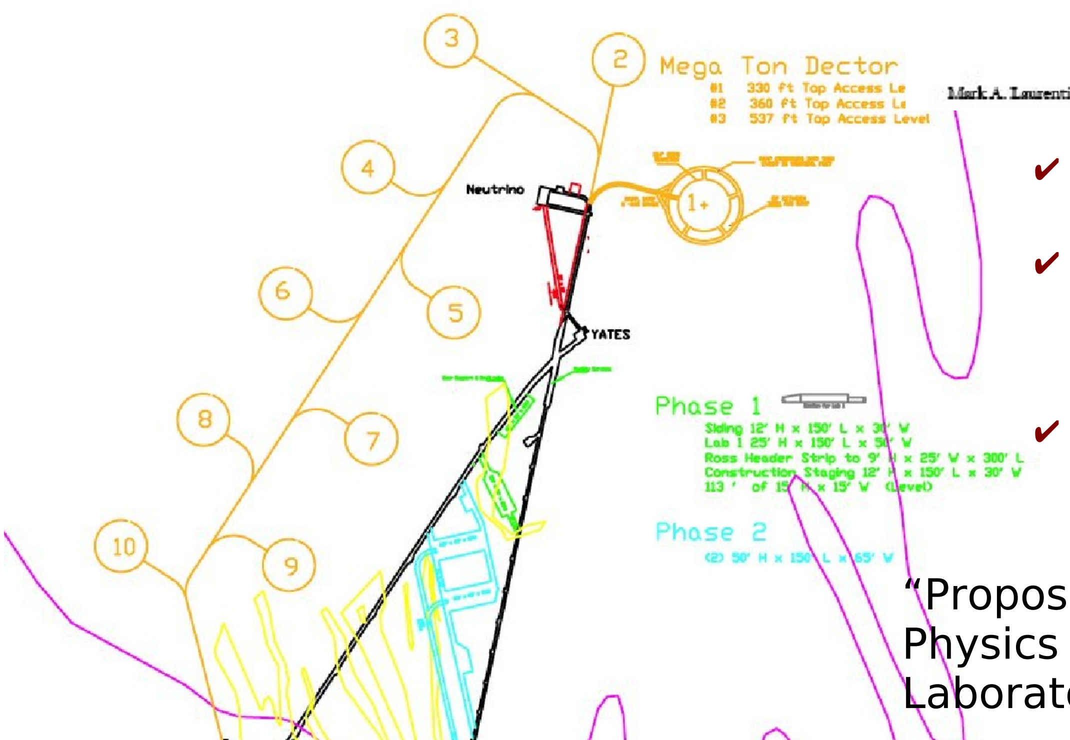


Detector at Henderson

Modular detector:

- module: ~50m ∅, ~50m h
- 100kT fiducial
- depth 4850 mwe
- coverage 25%
- 12 inch PMT



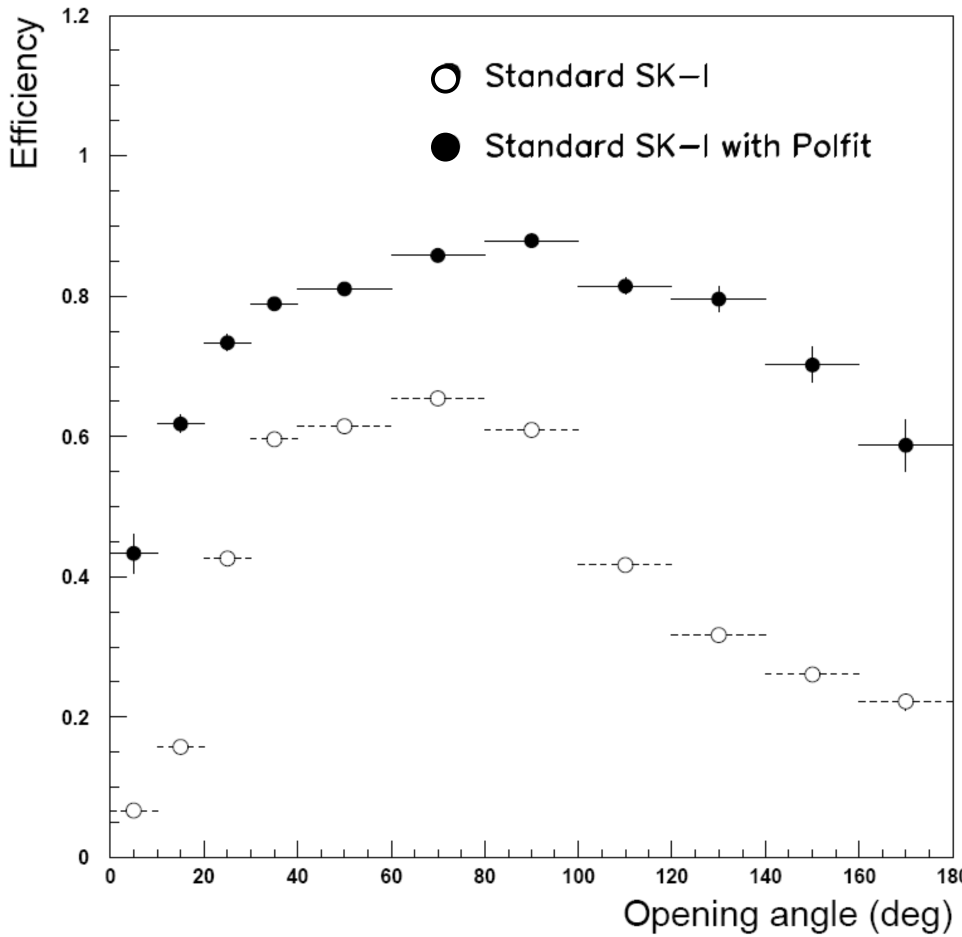


- initial detector 3 modules
- expand to 10 modules (or more) to get Mt detector
- detailed cost estimate: $100M/module

"Proposal for an Experimental Program in Neutrino Physics and Proton Decay in the Homestake Laboratory", M. Diwan et al., hep-ex/0608023

Water Cherenkov Simulation

- Full GEANT simulation of Super-KamiokaNDE used
- 40% PMT coverage
- atmospheric neutrino MC reweighted to match expected flux 28GeV AGS beam



"Pattern of Light" fit improves standard Super-K π^0 finder

Improvements at lower opening angles with finer granularity expected

"Background Rejection Study in a water Cherenkov detector", C. Yanagisawa, C. K. Jung, P.T. Le, B. Viren, July 18, 2006

Water Cherenkov Simulation

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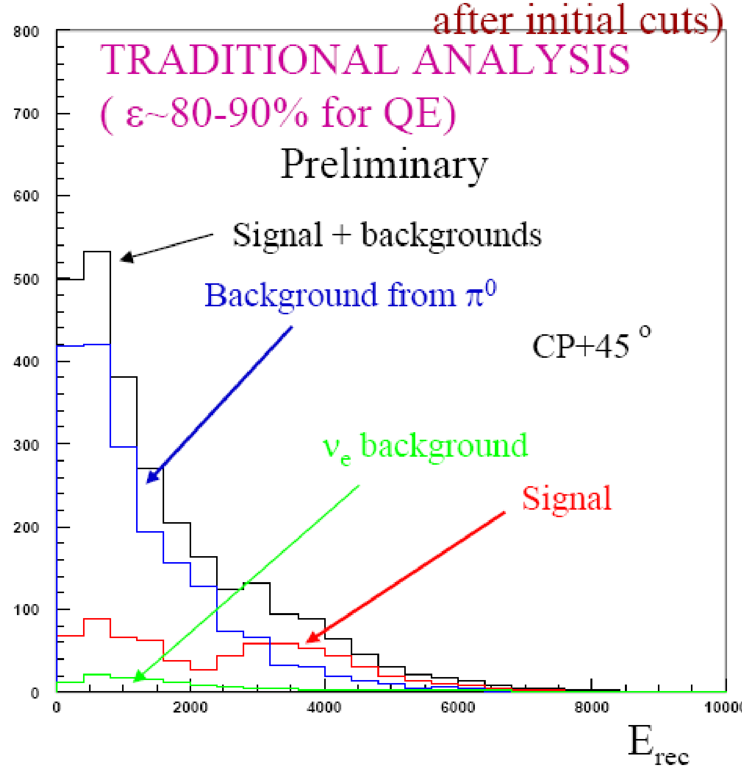
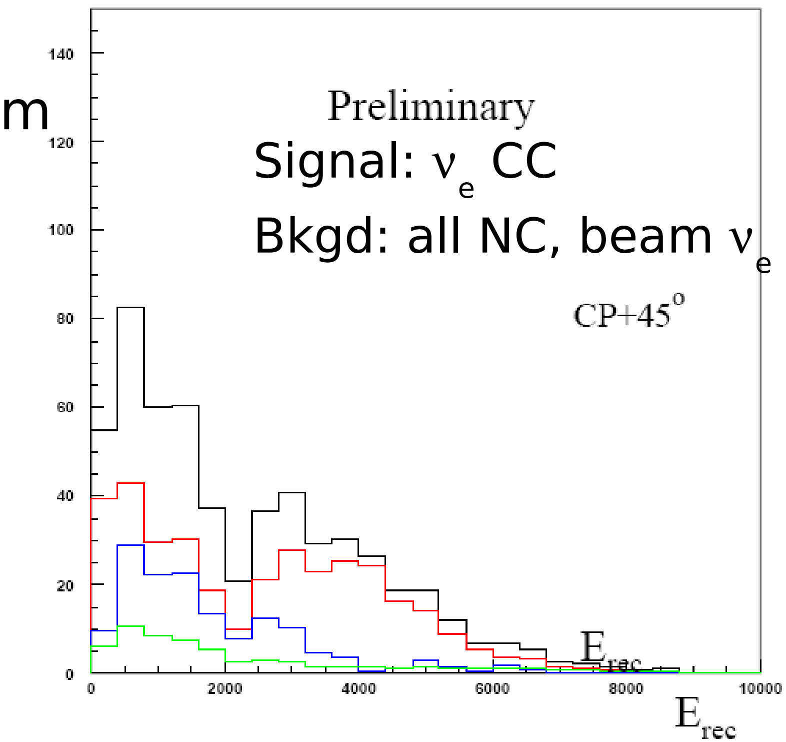
- Select single ring events and electrons
- Analysis of single ring pattern

No Δ log-likelihood cut (100% signal retained after initial cuts)



1300km
440kT

Δ log-likelihood cut (~50% signal retained)



- likelihood cut keeping 50% signal: S/B: 700/2004 → 350/169
- confirmed using T2K MC

"T2KK Project and Likelihood study", Fanny Dufour, U.S. Long Baseline Neutrino Experiment Study Workshop, September 16-17, 2006

ν_e appearance spectrum

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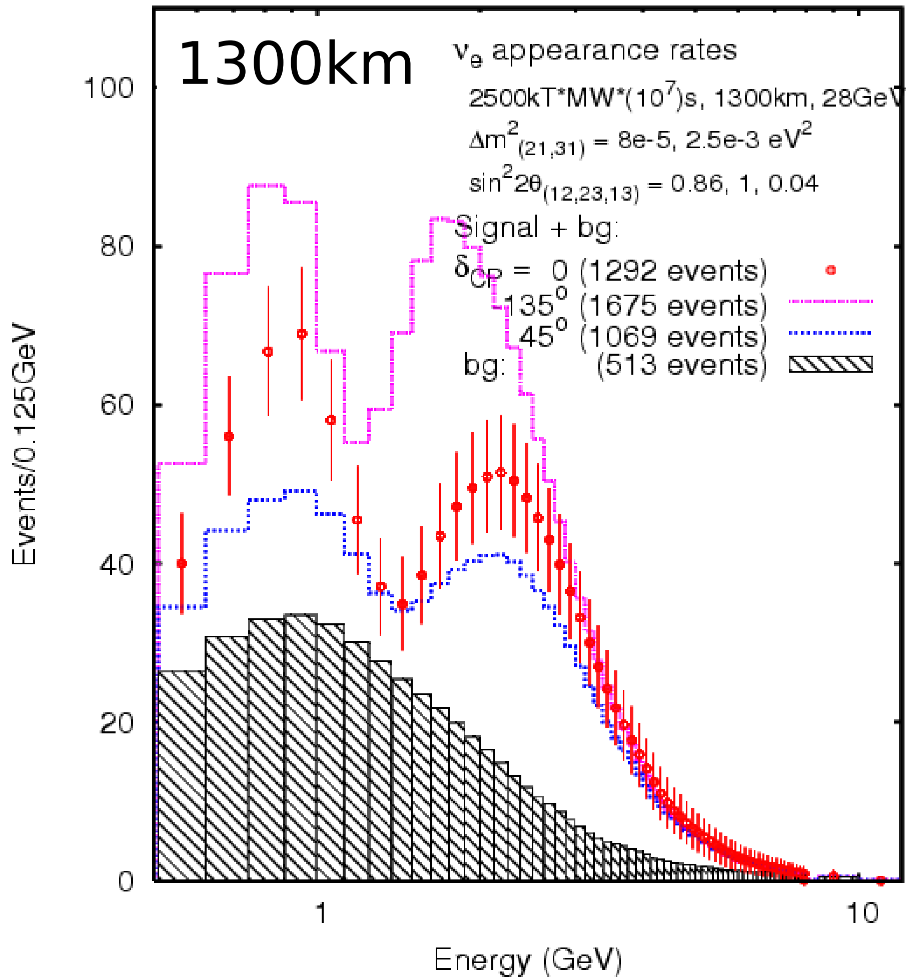
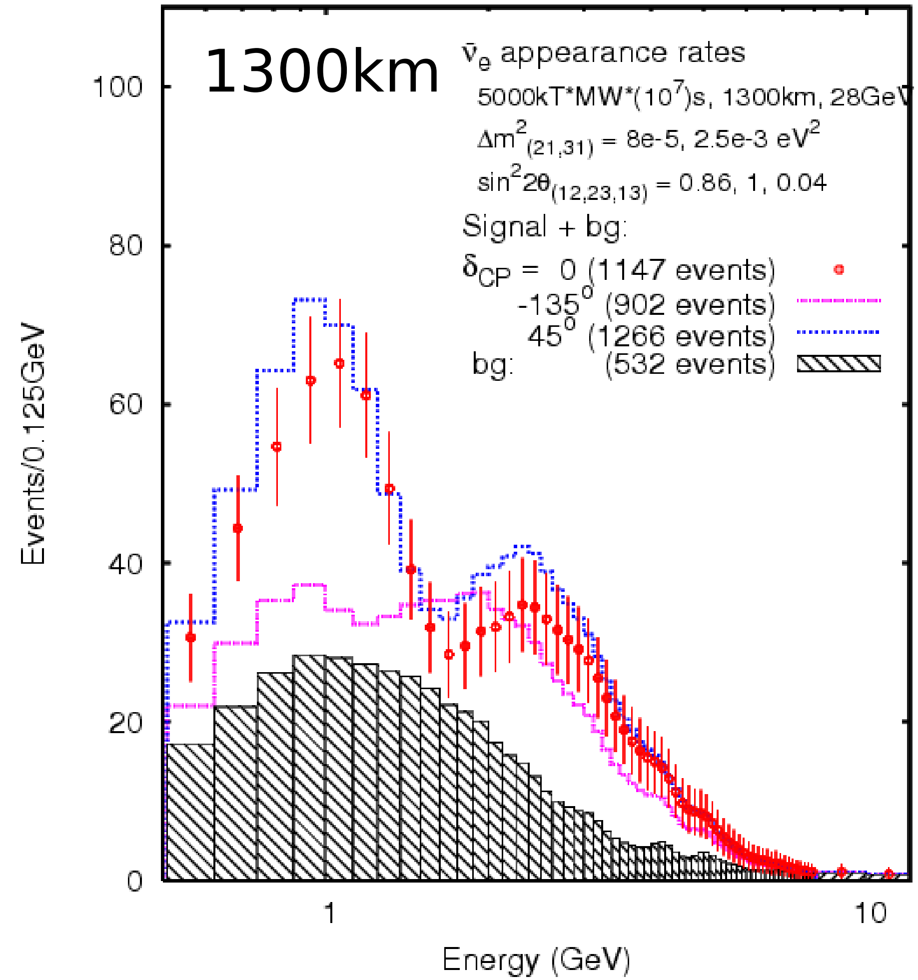
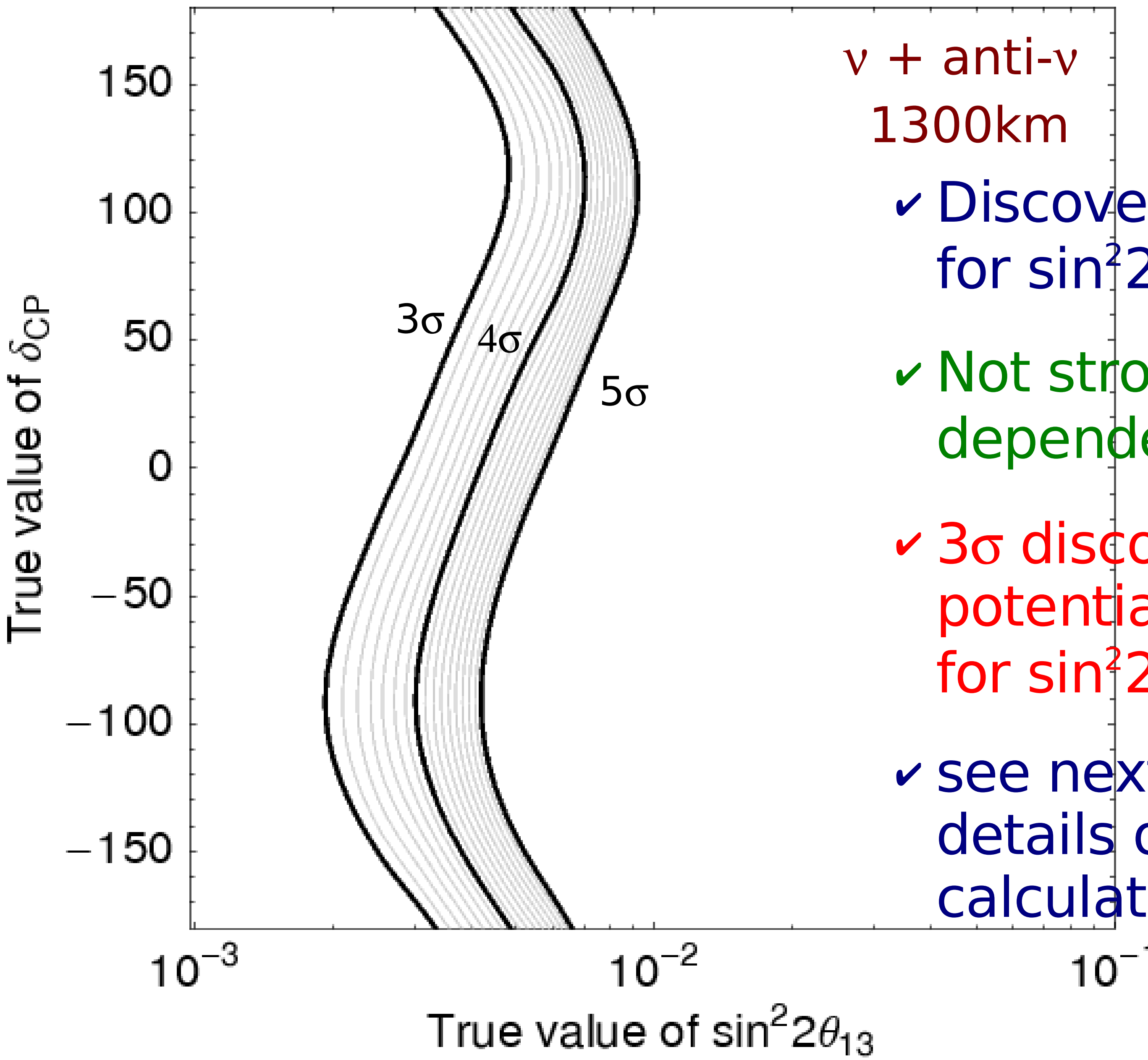




	ν	anti-ν
Signal (CP=0)	1292	1147
Background	513	532
S/B	2.5	2.2

$\sin^2 2\theta_{13}$ sensitivity



ν + anti-ν
1300km

- Discovery potential for $\sin^2 2\theta_{13} \neq 0$
- Not strongly dependent on δ_{CP}
- 3σ discovery potential for $\sin^2 2\theta_{13} > 0.005$
- see next talk for more details on sensitivity calculations

Conclusions

- Reviewed concept and motivation for a very long baseline experiment using a wide band beam.
- MW scale proton machine possible at FNAL & BNL. Wide band beam simulated using experimentally validated numi MC.
- Large, deep underground water Cherenkov detectors are considered at Homestake and Henderson mines. Detailed cost estimate for a modular detector at Homestake.
- Recent work on e/π^0 separation shows required level of background reduction is feasible.
- Next talk: details sensitivity to oscillation parameters
- Sending a wide band ν_μ beam towards a large underground water Cherenkov detector seems feasible with known technologies!

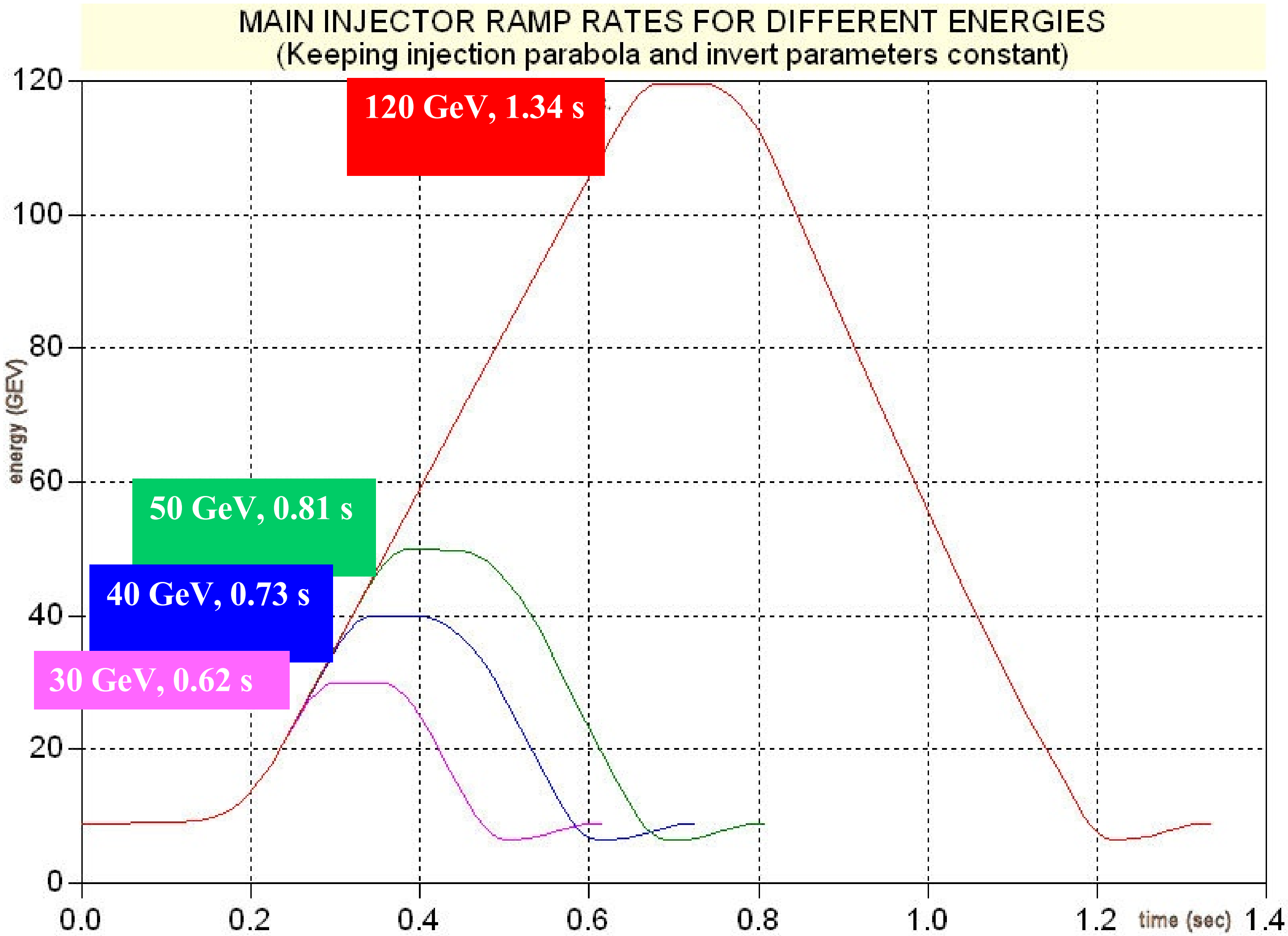
Backup Slides

Beam from FNAL

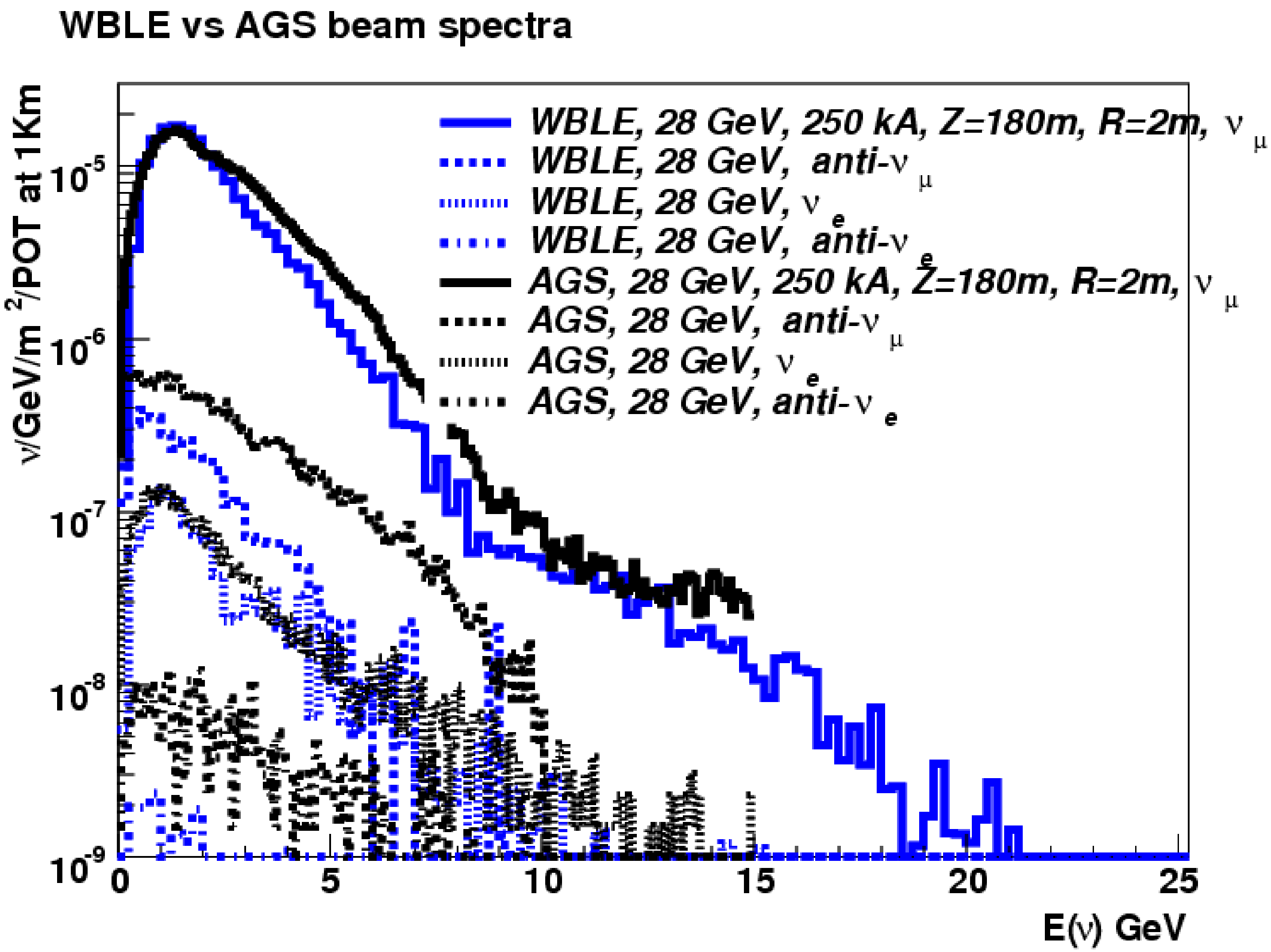
Proton Math (120 GeV):

	Protons	Cycle Time	Power
Current complex (No Improvements)			
– Shared Beam	25×10^{12}	2.4 s	200 kW
– NuMI Alone	30×10^{12}	2 s	280 kW
Proton Plan (Increase Beam Intensity)			
– Shared Beam	37×10^{12}	2.2 s	320 kW
– NuMI Alone	49×10^{12}	2.2 s	430 kW
SNuMI – Recycler (Reduce Cycle Time)	49×10^{12}	1.33 s	700 kW
SNuMI – Accumulator (Increase Beam Intensity)	83×10^{12}	1.33 s	1200 kW
HINS (Increase Beam Intensity)	150×10^{12}	1.33 s	2200 kW

MI ramp rates



ABS vs WBLE flux

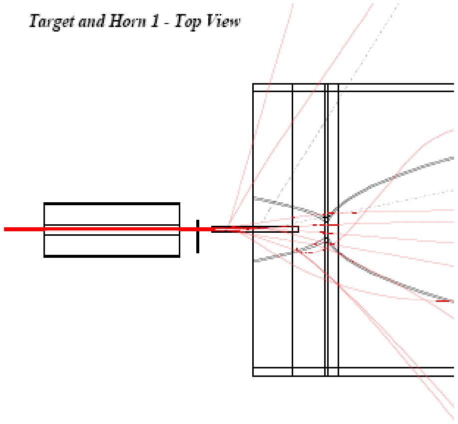


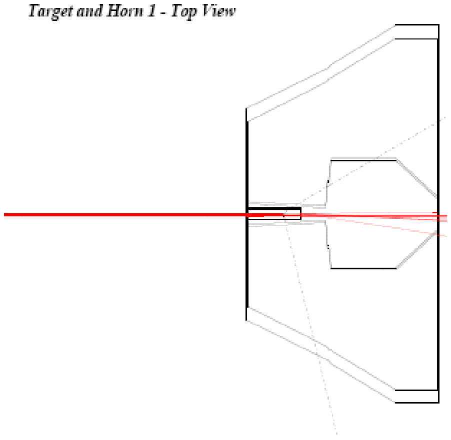
Good agreement between original AGS beam and WBLE predictions

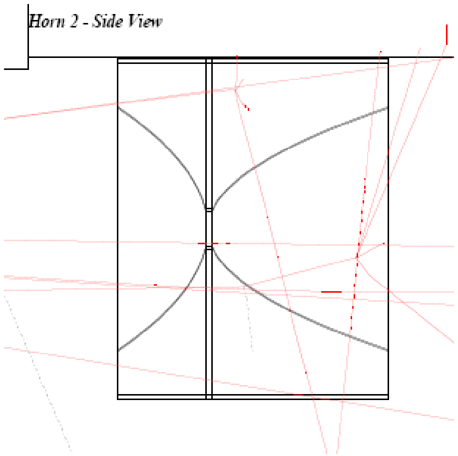
WBLE changes to gnumi

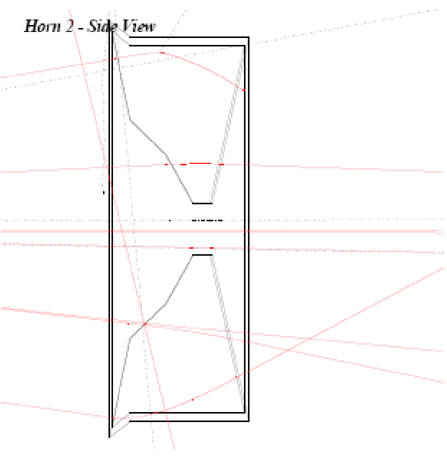
TABLE I: Target and beam parameters: NuMI and WBLE

Component	NuMI	WBLE
Target		
Shape:	47 rectangular segments	solid cylindrical rod
	each 6.4mm wide × 18mm high	12mm diameter
	and 20mm long	
	= 0.954 m total length	0.8 m total length
Material:	graphite	carbon-carbon composite
Density:	1.784 g/cm^3	2.1 g/cm^3
Cooling:	water cooling tubes	Helium flow cooled
Proton beam parameters		
Energy:	120 GeV	28, 40, 60, 120 GeV
RMS width:	$\sigma_x = 1.1$mm, $\sigma_y = 1.25$mm	$\sigma_x = 1.5$mm, $\sigma_y = 1.5$mm









Modular detector: cost and time

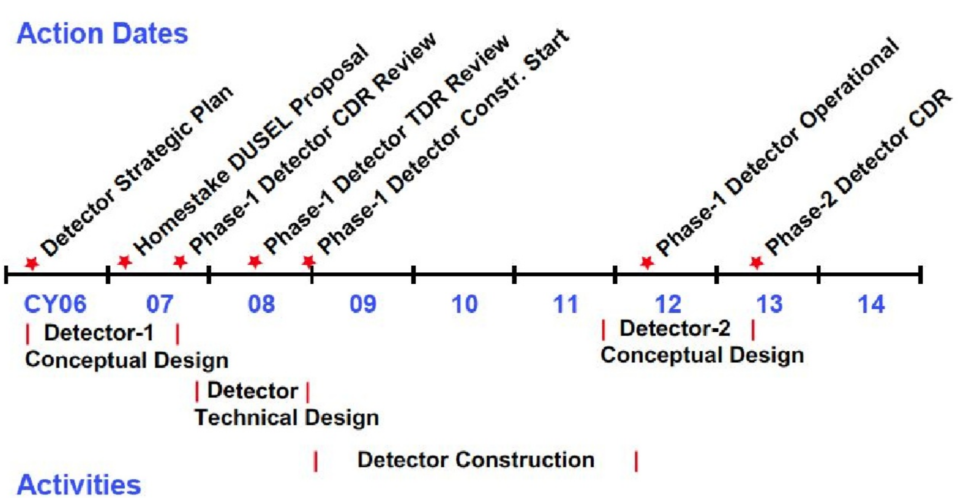
Construction costs for 3 caverns:

Table 3: Comparison of single chamber versus three chamber cost

Estimated Costs ($MM)			
	# Of Chambers	1	3
Labor & Benefits		$5.51	$10.94
Mining and Construction			
Equipment Operation		$1.30	$3.89
Supplies		$4.51	$13.35
Precast Concrete Liner		$3.25	$9.75
Other (Outside Contractors)		$0.17	$0.52
30% Contingency		$4.40	$11.48
	TOTAL(2002)	$19.1	$49.93
	TOTAL(2007)	$29.1	$66.1

Costs of 3 detector modules:

Cost Description	Amount	Comment
Development	$3M	Extrapolated from SNO
Procurement/Module	$5M	Water purification, distributution, calibration
Production/Module	$62.1M	For 25% PMT coverage of 11,000 m^2
Total (3 Modules)	$242.7M	Includes 25% contingency



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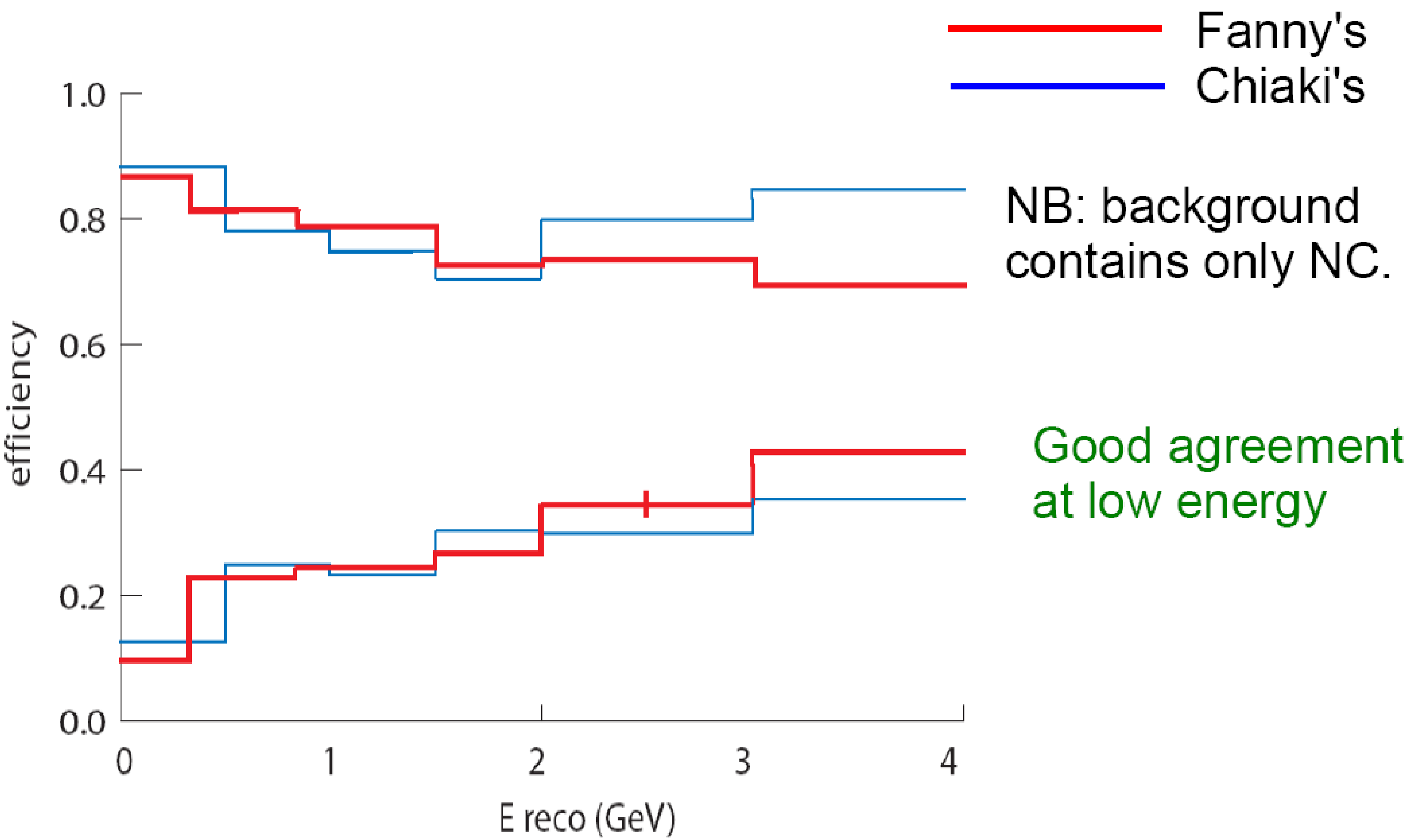
Comparison with Chiaki's efficiency



NB: background contains only NC.

Good agreement at low energy

"T2KK Project and Likelihood study", Fanny Dufour,
U.S. Long Baseline Neutrino Experiment Study Workshop, September 16-17, 2006