W. Marciano
12/10/01

Neutrino R&D Working Group

BNL Neutrino Osc. Feasibility Study → June 2002 Report

Is a future experiment worth pursuing? Unique?

1.) Physics Goals
  i) 3 Generation Mixing $\theta_{12}, \theta_{23}, \theta_{13}, \delta, \Delta m^2_{31}, \Delta m^2_{21}$, CP
  ii) Other Scenarios, eg sterile neutrino, "new interactions"...

2.) Possible Experiments $(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e, \overset{(-)}{\nu}_\mu)$
  i) Detectors (Water, Liquid Argon)
  ii) Distances (2540km, 400km, ?) (2900km, 1700km)

3.) Neutrino Beams
  i) Requirements (Angle) Hill
  ii) Targets, Horns ... Solenoid $(\nu + \bar{\nu})$

4.) AGS Upgrades
  i) Minor (low cost) ~0.14 MW → ? (~0.5MW) $65M
  ii) 1MW ($E_p \simeq 28$ GeV, 14GeV, ?) +$50M
  iii) 4MW +$100M

M. Diwan (1+2)   W. Weng (3+4)   Team Leaders

All Figures due to B. Viren

Physics Goals

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$$

What do we know? (Think we know)

Atmospheric ν $|\Delta m^2_{32}| \simeq |\Delta m^2_{31}| \simeq 2.6^{+1.4}_{-1.6} \times 10^{-3}\, eV^2$ sign?

$\theta_{23} \simeq 45°$, $\sin 2\theta_{23} \simeq 1$ maximal!

Solar ν (LMA Favored) $\Delta m^2_{21} = m_2^2 - m_1^2 \simeq 5\times10^{-5}\, eV^2$

$\theta_{12} \simeq 30°$ (large)

Kamland $\rightarrow \Delta m^2_{21}$ & θ_{12} Very Important!

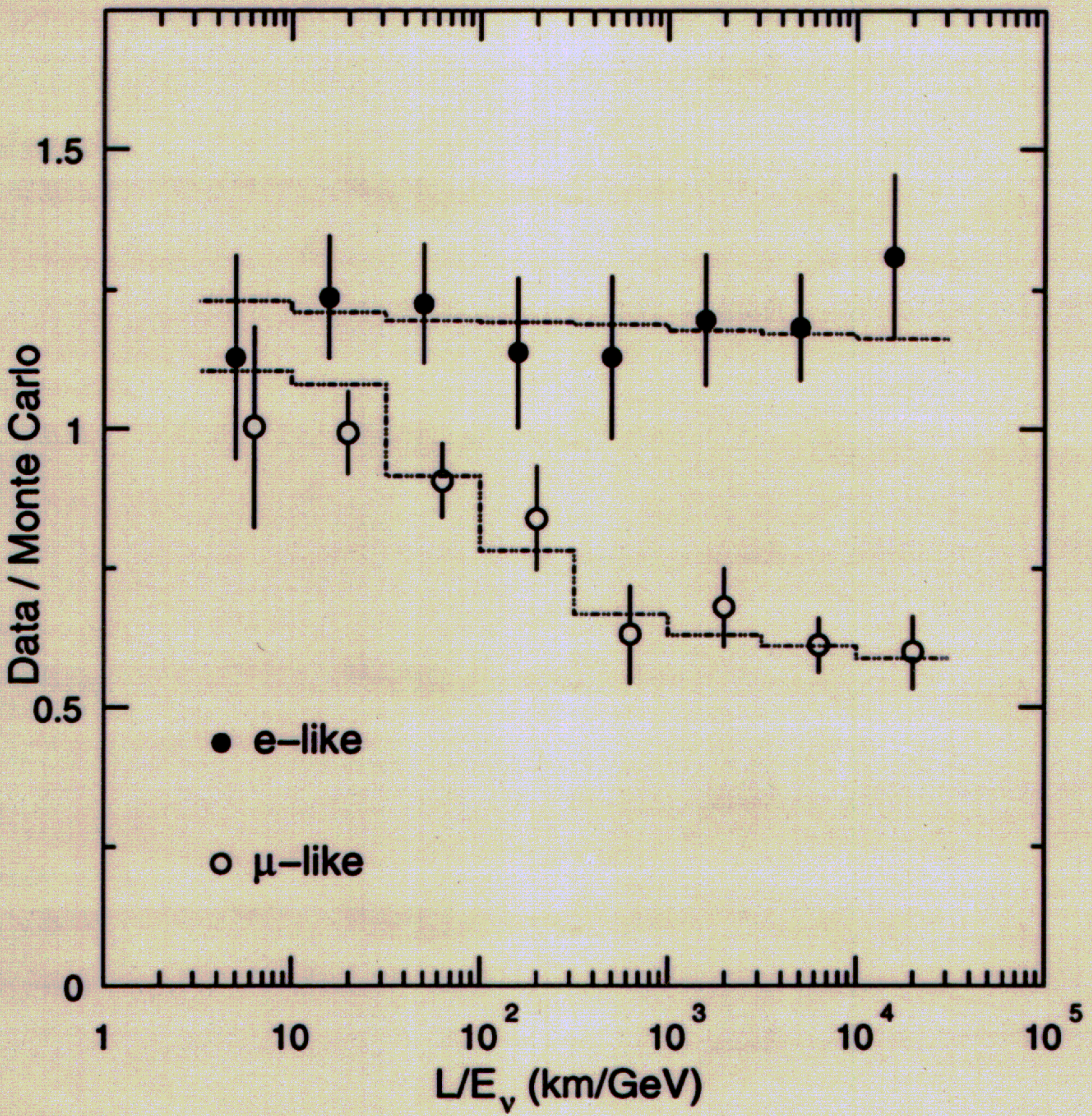
Reactor Bounds $\bar{\nu}_e \rightarrow \bar{\nu}_e$

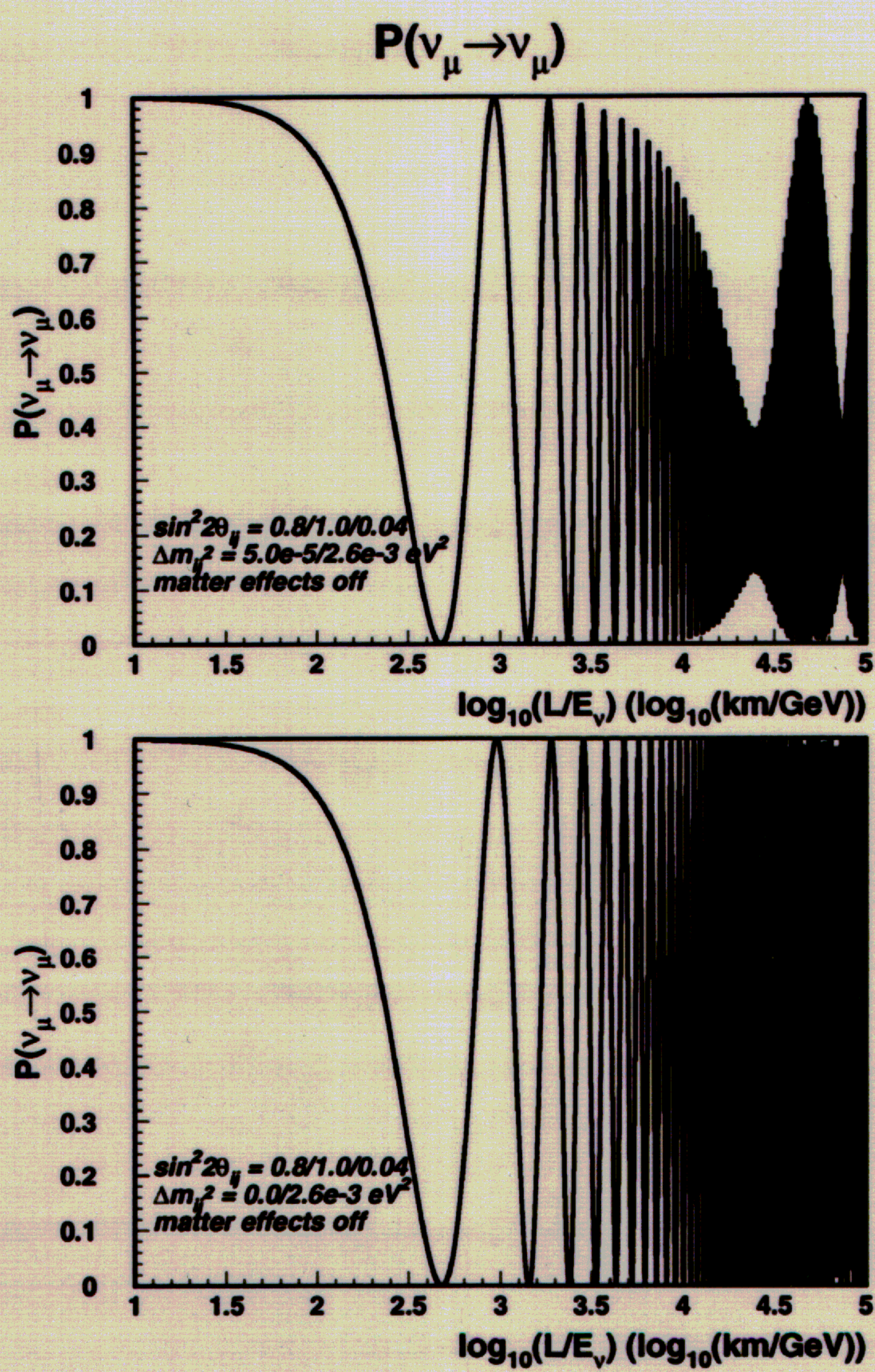
$\sin^2 2\theta_{13} \lesssim 0.11$	$\Delta m^2_{31} > 3.5\times10^{-3}\, eV^2$
$\lesssim 0.18$	$> 2.0\times10^{-3}\, eV^2$
$\lesssim 0.52$	$> 1.0\times10^{-3}\, eV^2$

θ_{13} Relatively Small? (Maybe Not)

Phase: $0 \leq \delta \leq \pi$ Unconstrained by Experiment

Atmospheric ν-data





P(νμ→νμ)
P(νμ→νμ)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
sin²2θij = 0.8/1.0/0.04
Δmij² = 5.0e-5/2.6e-3 eV²
matter effects off
1
1.5
2
2.5
3
3.5
4
4.5
5
log10(L/Eν) (log10(km/GeV))
P(νμ→νμ)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
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matter effects off
1
1.5
2
2.5
3
3.5
4
4.5
5
log10(L/Eν) (log10(km/GeV))

$J_{CP} = \sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\cos\theta_{12}\cos\theta_{23}\cos^2\theta_{13}\sin\delta$

All CP Violation Proportional to $J_{CP} \simeq 0.2\sin\theta_{13}\sin\delta$

Potentially Enormous

Quark Sector $J_{CP}^{ckm} \simeq 3\times10^{-5}$ tiny

Leptogenesis → Baryogenesis

Future Goals:

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$ → $\sin^2 2\theta_{23} \to \pm 2\%$

$|\Delta m^2_{31}| \to \pm 1\%$

Multi-Osc Peaks

$\nu_\mu \to \nu_{sterile}$ ... CPT, New Int.-Matter

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ Measure $\sin^2 2\theta_{13} \to \pm 10\%$ Dedicated Exp.

sign of $m_3^2 - m_1^2$ Matter Effect

$\sin\delta \to J_{CP} \to \not{CP}$ The Prize

Δm^2_{21}, $\sin^2 2\theta_{12}$ ....

Several Experiments Needed

Intense Proton Sources Large Detectors (Very Large)

Long Baseline Extra Long Baseline

Extra Long Baselines Considered

BNL → Homestake 2540 km 500 kton water detector

BNL → New Mexico (WIPP) 2900 km

BNL → Wisconsin 1700 km (100 kton water, NUMI detector) (primary)

BNL - Homestake (2540 km)

Phase I AGS → $\frac{1}{2}$ MW, 1.2×10^{21} P.O.T./10^7 sec, $E_p \simeq 28$ GeV

500 kton water Cherenkov detector

$\nu_\mu n \to \mu p$, $\nu_e n \to e n$, $\nu N \to \nu N \pi^0$

$E_\nu \simeq 1-2$ GeV 0° Wide Band Beam

$\simeq 1$ GeV 1-1.5° Off Axis

Why work at 2500 km rather than 500 km?

1/25 Flux - Statistics?

Some Disadvantages + Some Advantages (Complementary)

Multi-Osc. $\nu_\mu \to \nu_\mu$ Peaks, Precise Δm^2_{31}, good $\sin^2 2\theta_{23}$

$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ matter effects → sign of Δm^2_{31} ($\sin^2 2\theta_{13}$)

measure δ, CP, Δm^2_{21} sensitivity

Robust Program - Improved if $|\Delta m^2_{31}| < 2.6\times10^{-3}$ eV^2

Upgrade $\frac{1}{2}$ MW → 2-4 MW, 500 kton → 1000 kton × 16

$T = 5\times 10^7$ sec → ~ 10,000 ν_μ events (No Osc.) $\nu_\mu n \to \mu p$ QE (75

Assume $\sin^2 2\theta_{23} \simeq 1$ $\Delta m^2_{31} \simeq 2.6\times 10^{-3}\,eV^2$

$\sin^2 2\theta_{12} \simeq 0.8$ $\Delta m^2_{21} \simeq 5\times 10^{-5}\,eV^2$

$\sin^2 2\theta_{13} \simeq 0.04$ (could be larger)

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 \frac{1.27\Delta m^2_{31} L}{E_\nu} + \ldots$$

~ 5000 events   Sensitive to 4 Peaks!

Precise $|\Delta m^2_{31}|$

NC/CC → Sterile

New Physics? (Matter)

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \simeq \frac{1}{2}\sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \text{matter effects}$$ (large $E_\nu \simeq$ 4Ge

$$\overset{(-)}{+}\ 4 J_{CP} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} \sin \frac{\Delta m^2_{21} L}{2E_\nu}$$

grows like L/E_ν

$\frac{\text{Signal}}{\sqrt{Bk}} = \frac{L}{\sqrt{L^2}} = 1$

$$+ 0.38 \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) + \text{smaller terms}$$

grows like $(L/E_\nu)^2$ (Much Better)

P889 Spectrum $E_p \simeq 28$ GeV

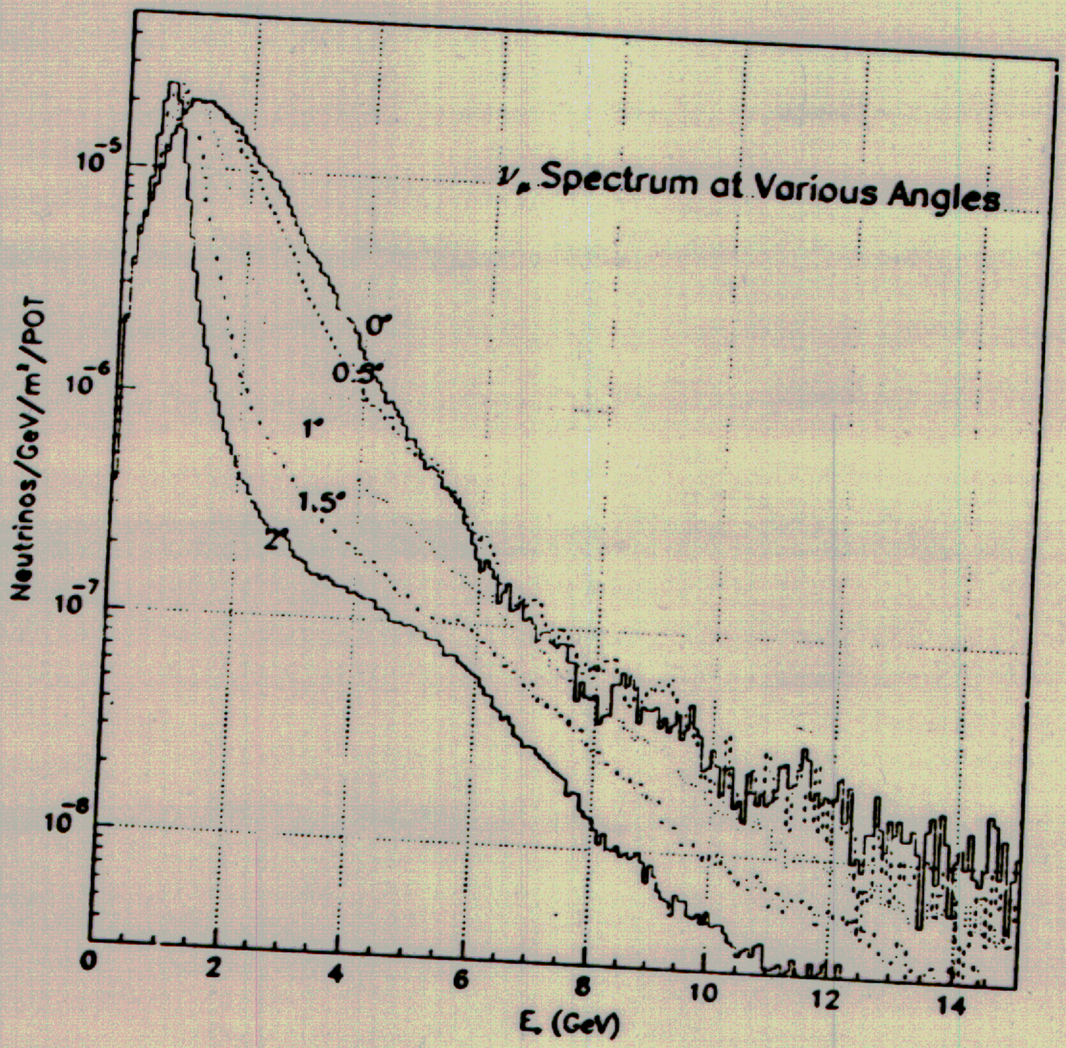


Figure 3: *Spectrum of neutrinos at 1 km at various angles with respect to the decay tunnel axis. The 1.5 degree spectrum was used for calculating the total event rates, however the event simulations in the detectors were performed using the full energy-angle correlation on an event by event basis.*

From P889

$\sigma(\nu_\mu n \to \mu^- p)$

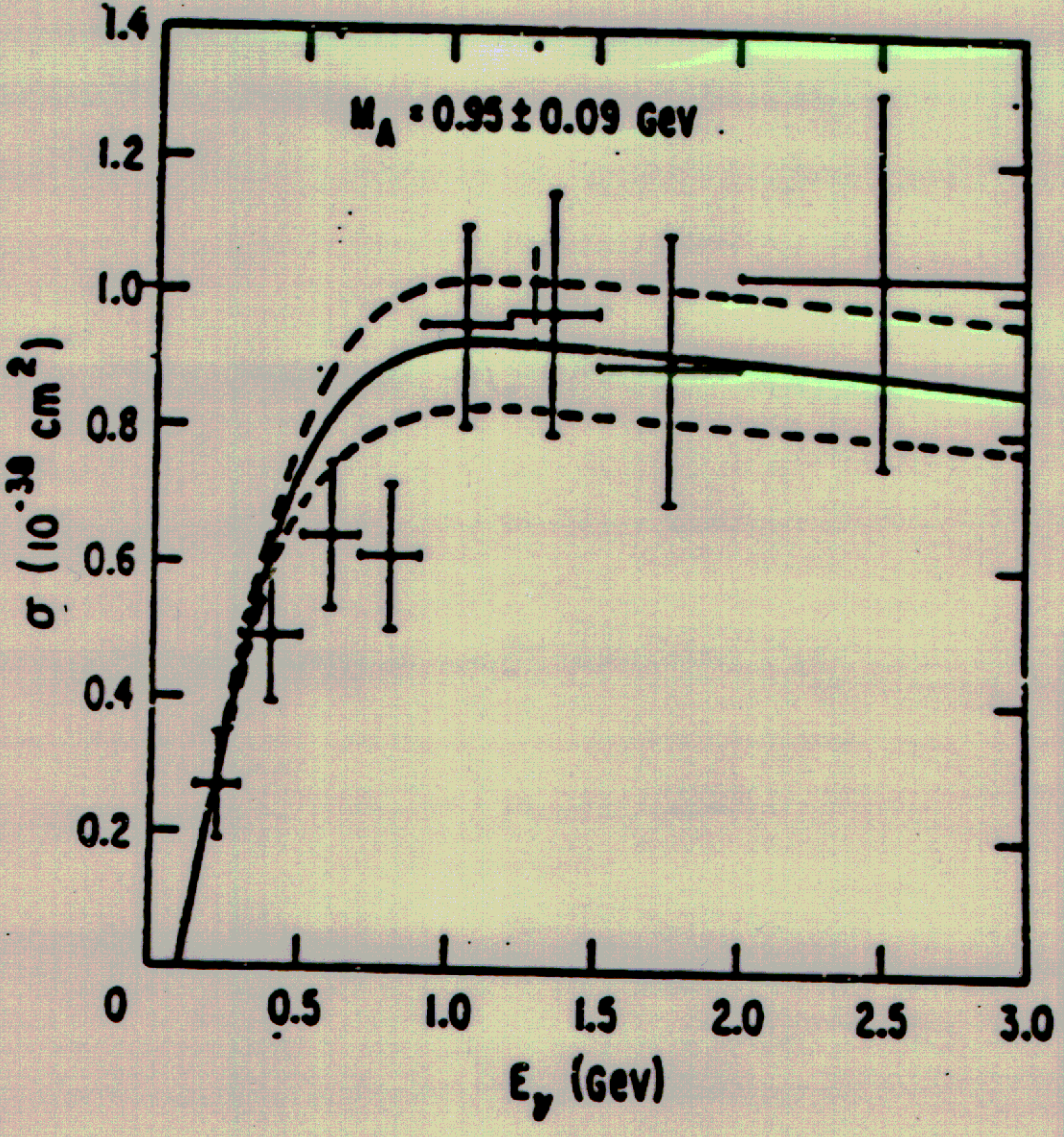
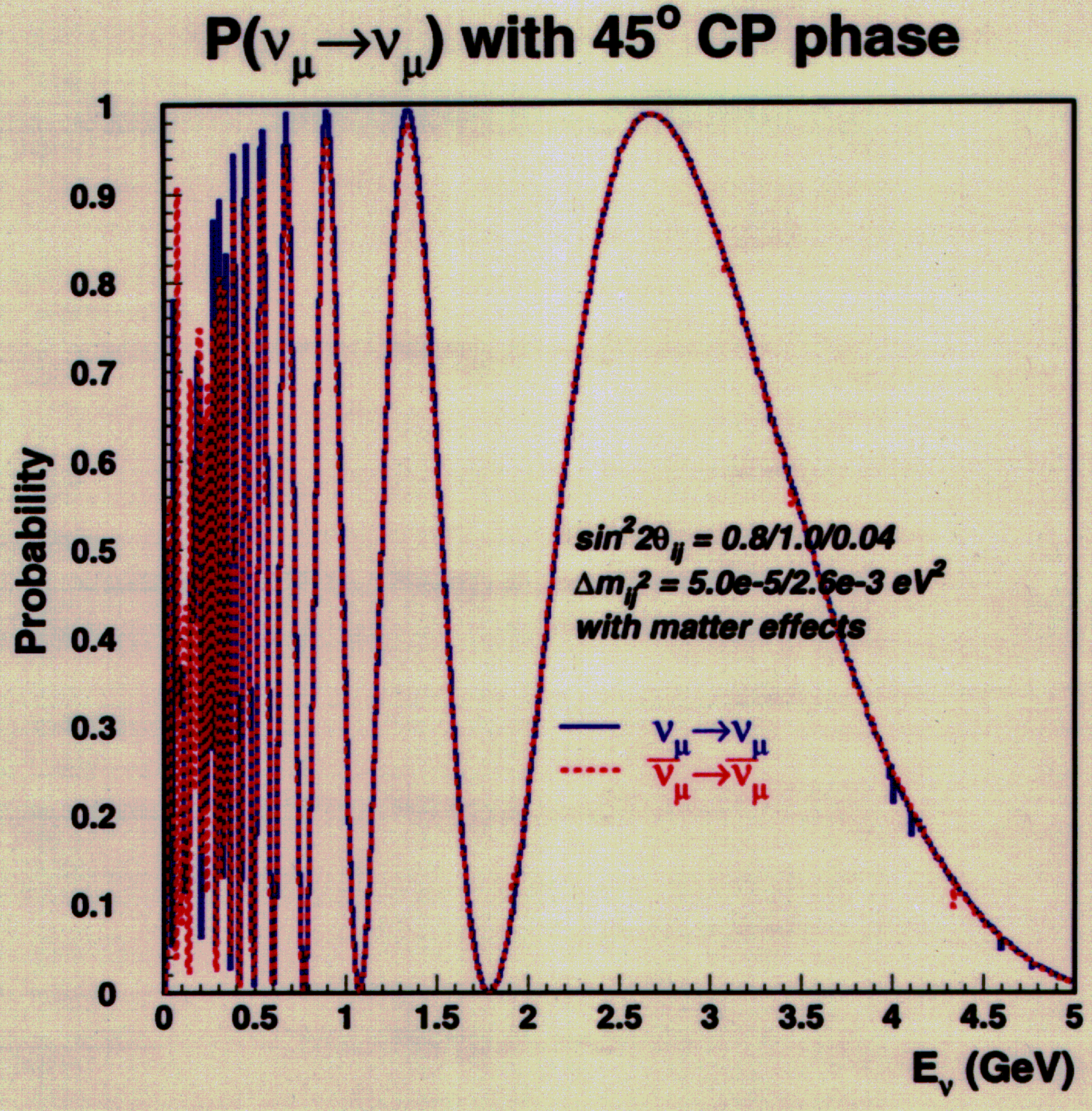
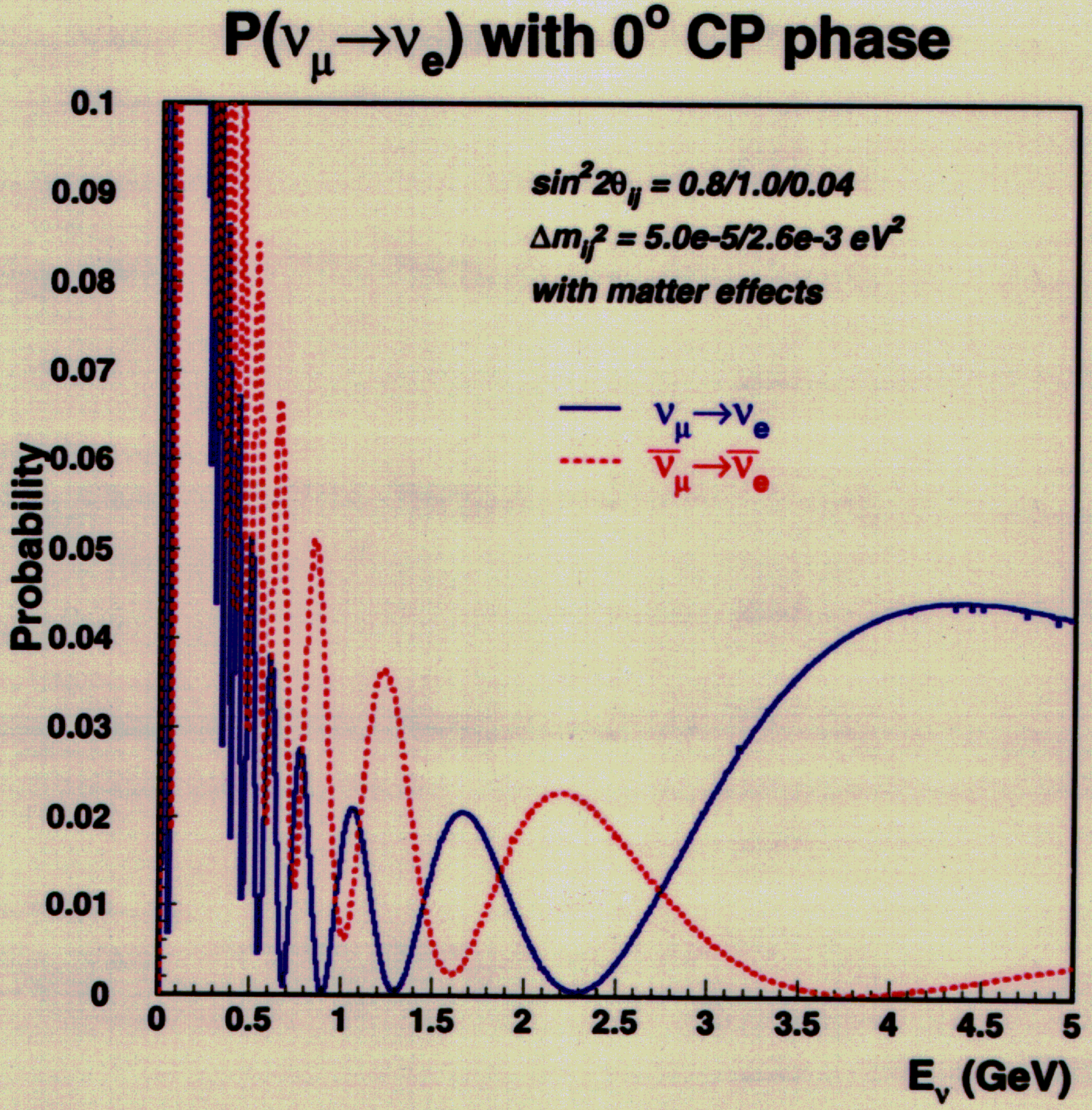
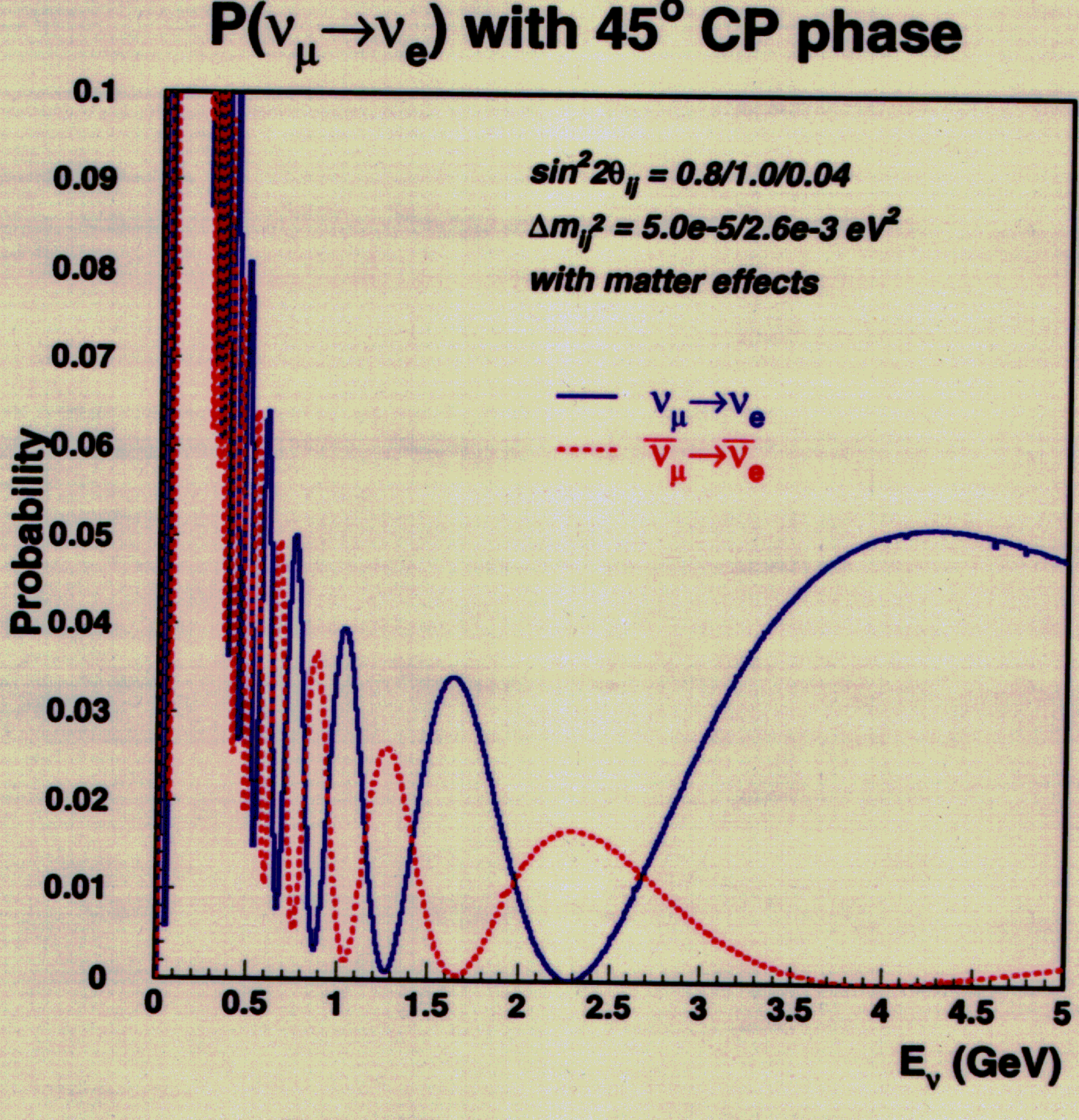


Figure 1: *Total cross section for $\nu_\mu n \to \mu^- p$ as a function of neutrino energy. The dashed curve shows the theoretical error.*


P(νμ→νμ) with 45° CP phase
Probability
Eν (GeV)
sin²2θij = 0.8/1.0/0.04
Δmij² = 5.0e-5/2.6e-3 eV²
with matter effects
νμ→νμ
ν̄μ→ν̄μ
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



$P(\nu_\mu \to \nu_e)$ with 0^o CP phase
$sin^2 2\theta_{ij} = 0.8/1.0/0.04$
$\Delta m_{ij}^2 = 5.0e\text{-}5/2.6e\text{-}3\ eV^2$
with matter effects
$\nu_\mu \to \nu_e$
$\bar{\nu}_\mu \to \bar{\nu}_e$
Probability
E_ν (GeV)
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


P($\nu_\mu \to \nu_e$) with 45° CP phase
$sin^2 2\theta_{ij}$ = 0.8/1.0/0.04
Δm_{ij}^2 = 5.0e-5/2.6e-3 eV^2
with matter effects
$\nu_\mu \to \nu_e$
$\bar{\nu}_\mu \to \bar{\nu}_e$
Probability
E_ν (GeV)
0
0.01
0.02
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0.1
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1.5
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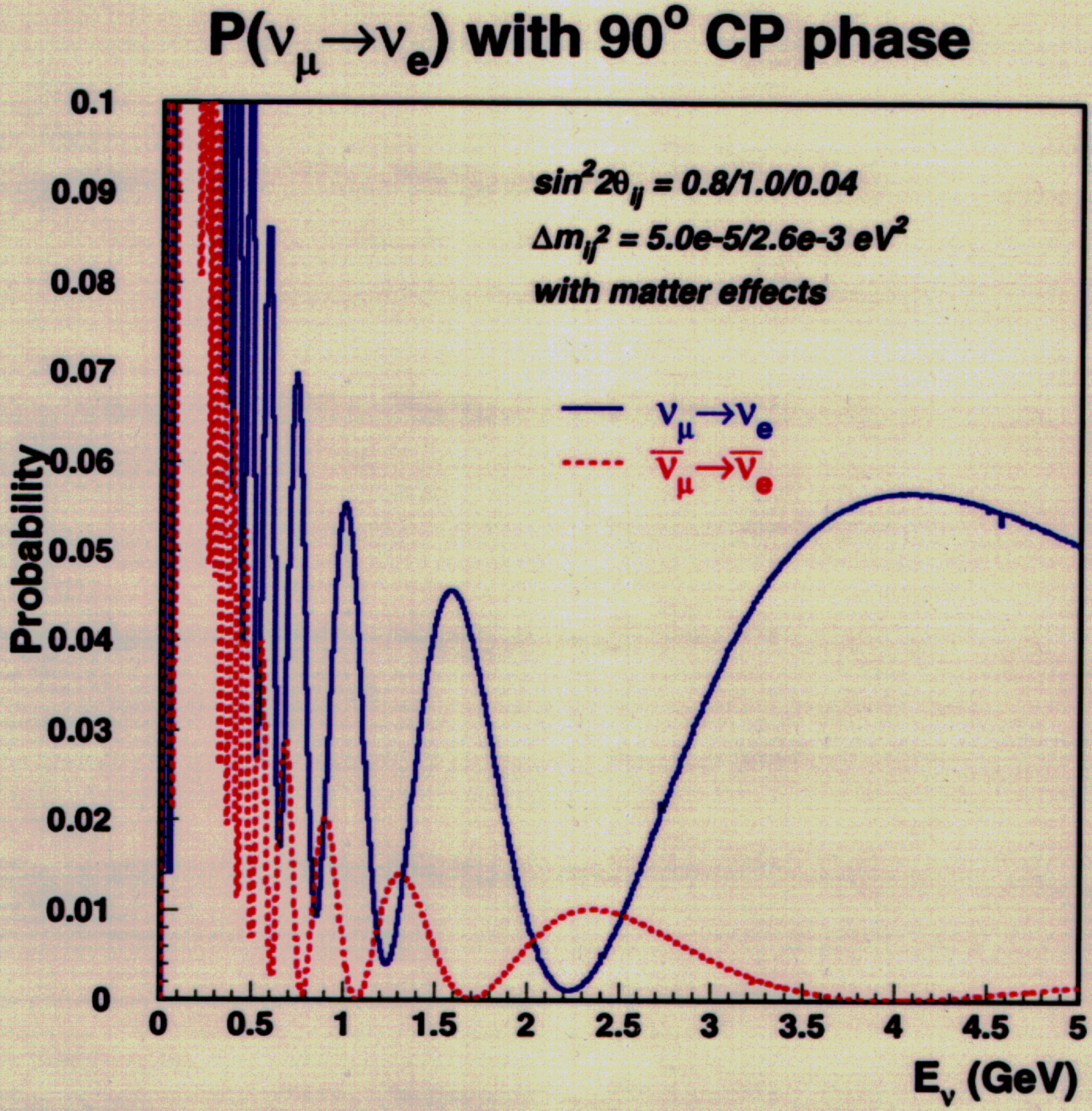
3
3.5
4
4.5
5



P(νμ→νe) with 90° CP phase
sin²2θij = 0.8/1.0/0.04
Δmij² = 5.0e-5/2.6e-3 eV²
with matter effects
νμ→νe
ν̄μ→ν̄e
Probability
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Eν (GeV)

Peak at 3-4 GeV → matter enhancement + $\sin^2 2\theta_{13}$ dete

Peaks at 1.65 & 1 GeV – Sensitive to $\sin\delta$ ⊄P

Peaks below ~0.8 GeV – Sensitive to Δm^2_{21} (& ⊄P)

Expect $\gtrsim$ 100 e^- events ordinary $\sin^2 2\theta_{12}$ osc +matter
(very roughly) > 50 e^- events from Δm^2_{21}
> 100 $\sin\delta$ events from $\delta \neq 0$ (or reduction)

If $\bar{\nu}_\mu \to \bar{\nu}_e$ measured (Stage II)

⊄P $$A_{CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} \underset{\text{no matter}}{\simeq} \underbrace{\frac{8 J_{CP} \sin \frac{\Delta m^2_{21} L}{2E_\nu}}{\sin^2 2\theta_{13} + \cdots}}_{\text{grows as } L/E_\nu}$$

F.O.M. $$\left(\frac{\delta A_{CP}}{A_{CP}}\right)^{-2} = \frac{A^2 N}{1-A^2}$$ indep of L (In first approx.)!

Effects due to δ likely to be seen in Stage I & measured
To establish ⊄P, test CPT, exotica ...

Run $\bar{\nu}_\mu$ (smaller cross-section ½ - ⅓)
Harder (More Flux!)

Outlook

Report + L.O.I.'s being prepared

1) Extra Long Baselines: 2540, 2900, 1700 km

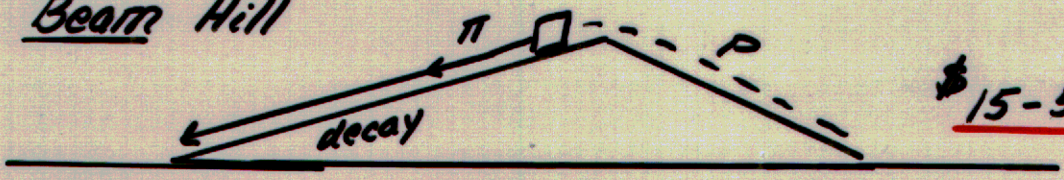
2) Long Baseline ~ 500km (liquid Argon) Charge ID Better E Resolution

AGS Upgrade $65M

Linac 200 MeV → 400 MeV → ?
Booster 1.8 GeV → 2.5 GeV
Accumulator Ring → (5.6 μA → 14 μA)
0.14 MW → 0.5 MW (Phase I)

Each + $30M Factor 2

Beam Hill



$15-50M (length)?

Complementary to shorter baselines (Very Challenging)

Long Program (~20yrs) Intense Source
Very Large Detectors

If Very Large Detectors are built, anyone with a potential ν beam should send neutrinos!