Long Baseline Experiments
What do we learn from neutrino oscillation experiments?

Les Houches
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Motivation

- nonzero neutrino mass expected theoretically

- increasingly strong experimental indications of neutrino oscillations
  - atmospheric neutrino anomaly
    Super Kamiokande, Kamiokande, IMB, Soudan, MACRO
  - solar neutrino deficit
    Homestake, Kamiokande, Gallex, Sage, Super-Kamiokande, SNO
  - LSND - not confirmed (or completly excluded) by KARMEN

- Key importance as physics beyond the Standard Model

Neutrino Oscillations

- neutrinos - massive and mixed
- $\nu_\alpha = \sum_a U_{\alpha a} \nu_a$
- $\nu_\alpha (x, t) = \sum_a U_{\alpha a} \, e^{i(p \cdot x - E_a t)} \, \nu_a$

$$\Big\downarrow \; E_a = \sqrt{p^2 + m_a^2} \simeq p + \frac{m_a^2}{2p}$$

$$\simeq e^{-ip(x-t)} \sum_a U_{\alpha a} \, e^{-\frac{i m_a^2 t}{2p}} \, \nu_a$$

- Probability of converting ν_α into ν_β

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_a U_{\alpha a} U^*_{a \beta} \, e^{-i \frac{m_a^2}{2E} x} \right|^2 =$$

$$= \delta_{\alpha\beta} - 4 \sum_{a>b} \mathrm{Re} \left(U_{\alpha a} U^*_{\beta a} U^*_{\alpha b} U_{\beta b} \right) \cdot \sin^2 \left(\frac{\Delta m^2_{ab} x}{4E} \right)$$

$$+ 4 \sum_{a>b} \mathrm{Im} \left(U_{\alpha a} U^*_{\beta a} U^*_{\alpha b} U_{\beta b} \right) \cdot \sin \left(\frac{\Delta m^2_{ab} x}{4E} \right) \cos \left(\frac{\Delta m^2_{ab} x}{4E} \right)$$

$$\Delta m^2_{ab} = m_a^2 - m_b^2$$

Three flavors

$$U = U_{23}\, K\, U_{13}\, K^{*}\, U_{12}\, \mathcal{M}$$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \mathcal{M}$$

$$\mathcal{M} = \mathrm{Diag}\,(e^{i\alpha_1}, e^{i\alpha_2}, 1)$$

$$i\dot{\nu} = \left(\frac{1}{2E}\, U M^2 U^{+} + V\right)\nu$$

$$M^2 = \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix}$$

$$V = \begin{pmatrix} V_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_e = \sqrt{2}\, G_F N_e \text{ for } \nu_e$$
$$\quad -\sqrt{2}\, G_F N_e \text{ for } \bar{\nu}_e$$

What do we want to know?

m_1, m_2, m_3

$\theta_{12}, \theta_{13}, \theta_{23}$

δ

α_1, α_2

What can we learn?

oscillations

$0\nu\beta\beta$ decay...

$\Delta m^2_{32}, \Delta m^2_{21}$ $(\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21})$

$\theta_{12}, \theta_{13}, \theta_{23}$

δ

$+ \alpha_1, \alpha_2$

m

Atmospheric neutrinos

$$\Delta m^2 = 2.5 \cdot 10^{-3}\, eV^2$$

$$\sin^2 2\theta = 1$$

Solar neutrinos

LMA $\Delta m^2 = 4.5 \cdot 10^{-5}\, eV^2$

$$tg^2\theta = 0.41$$

$$\Downarrow$$

$$\Delta m^2_{sol} << \Delta m^2_{atm}$$

$P(\nu_e \not\to \nu_e)$:

$$\sin^2(2\theta_{13})\left[\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}+\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right]+$$

$$+\sin^2(2\theta_{12})\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

CHOOZ + Palo Verde $\Rightarrow$

$\sin^2(2\theta_{13}) \lesssim .1$ for $\Delta m^2_{32} \sim \Delta m^2_{31} \gtrsim .8\times 10^{-3}\,eV^2$

$\Delta m^2_{21} \lesssim .8\times 10^{-3}\,eV^2$ for large $\sin^2(2\theta_{12})$

Solar neutrinos

$P(\nu_e \not\to \nu_e)$:

$$\frac{1}{2}\sin^2(2\theta_{13})+\sin^2(2\theta_{12})\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

• atmospheric

$$P(\nu_\mu \to \nu_\tau) = 4|U_{33}|^2 |U_{23}|^2 \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

$$= \sin^2(2\theta_{23}) \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

$$\sin^2(2\theta_{23}) \cos^4\theta_{13} = \sin^2(2\theta_{atm})$$

θ_{13} small $\Rightarrow$ $\theta_{atm} \simeq \theta_{23}$

$$P(\nu_e \to \nu_\mu) = 4|U_{13}|^2 |U_{23}|^2 \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

$$= \underline{\sin^2(2\theta_{13})} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

$$P(\nu_e \to \nu_\tau) = 4|U_{33}|^2 |U_{13}|^2 \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

$$= \underline{\sin^2(2\theta_{13})} \cos^2\theta_{23} \sin^2 \frac{\Delta m^2_{atm} L}{4E}$$

Remember

- $\Delta m^2_{atm} \searrow 1.7 \cdot 10^{-3}\ eV^2$

  $\Delta m^2_{sol} \nearrow 2\text{-}8\ 10^{-4}\ eV^2$

  $\Downarrow$

  $$\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}} = \text{small but non-zero}$$

- $\sin^2 2\theta_{13} \lesssim .1$

  - no idea how small

$$P(\nu_\mu \to \nu_e)$$

$$\sin 2\theta_{13}\ s_{23}\ \cdot$$

$$\cdot \Big[\left(\sin 2\theta_{13}\ s_{23}\ s_{12}^2 - \sin 2\theta_{12}\ c_{13}\ c_{23}\ c_\delta \right) \sin^2 \frac{\Delta m^2_{32} L}{4E} +$$

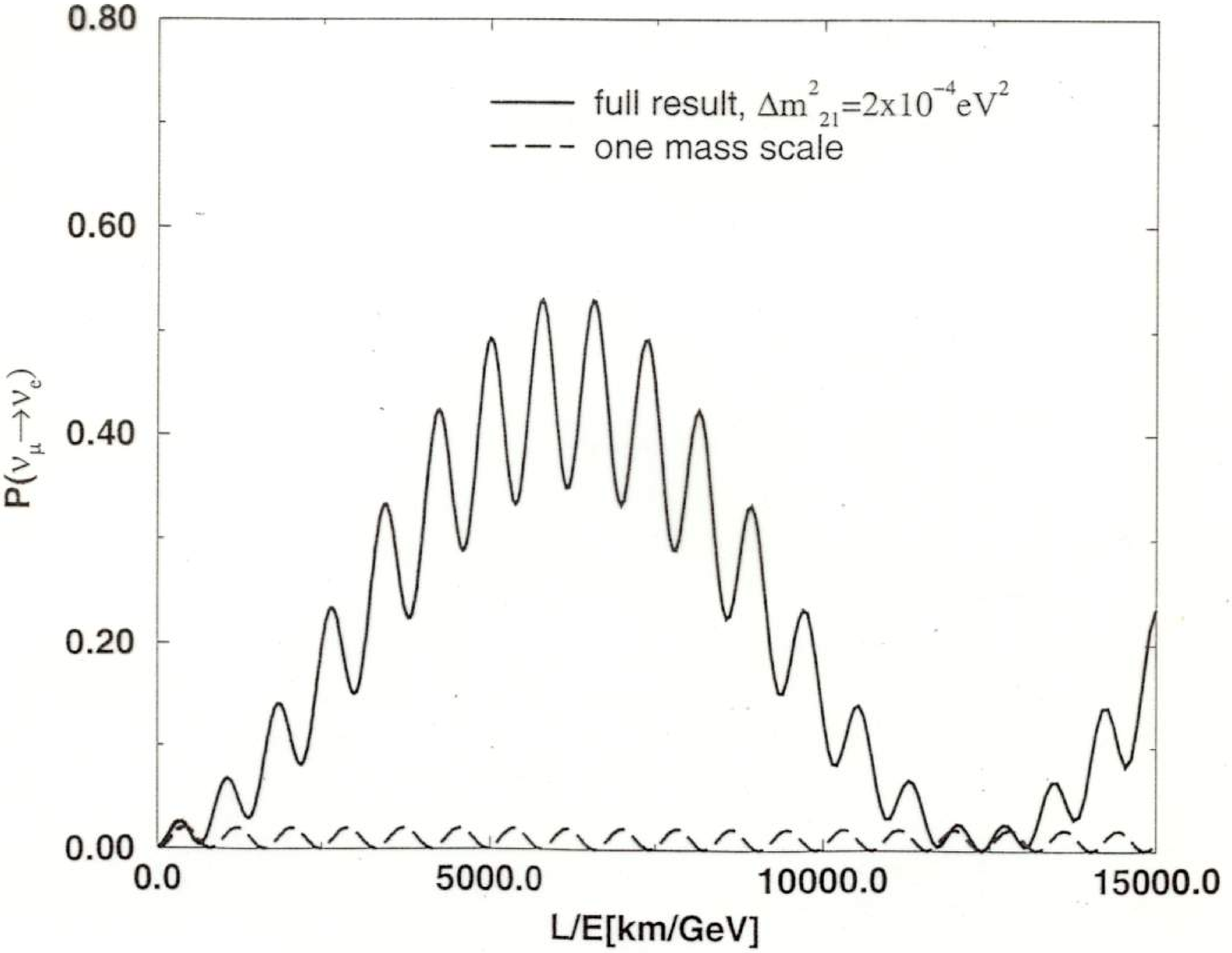
$$+ \left(\sin 2\theta_{13}\ s_{23}\ c_{12}^2 + \sin 2\theta_{12}\ c_{13}\ c_{23}\ c_\delta \right) \sin^2 \frac{\Delta m^2_{31} L}{4E} \Big] -$$

$$- \sin 2\theta_{12}\ c_{13}^2 \cdot \Big[\sin 2\theta_{12} \left(s_{13}^2\ s_{23}^2 - c_{23}^2 \right) -$$

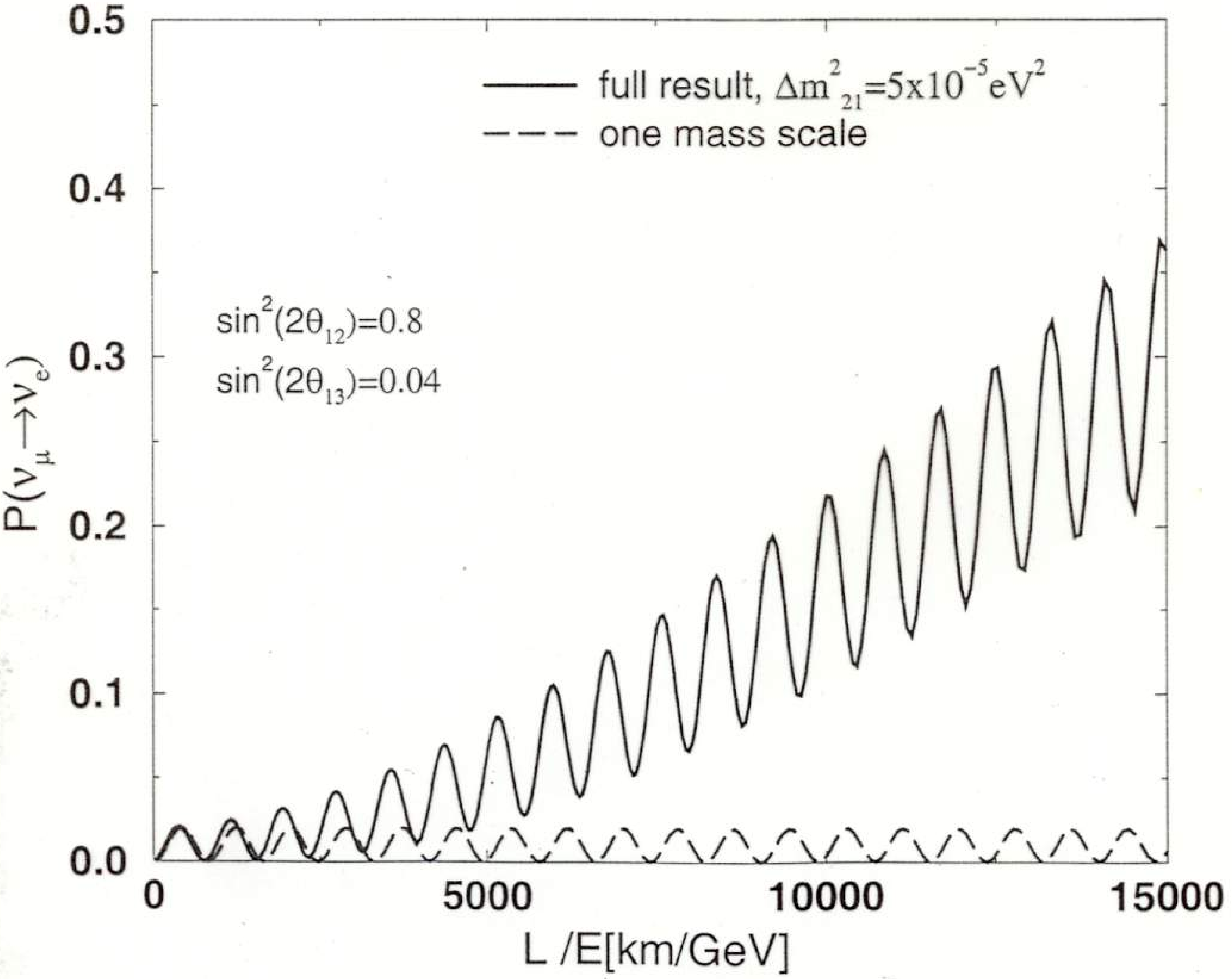
$$- \cos 2\theta_{12}\ \sin 2\theta_{23}\ s_{13}\ c_\delta \Big] \sin^2 \frac{\Delta m^2_{21} L}{4E} -$$

$$- \sin 2\theta_{12}\ \sin 2\theta_{23}\ \sin 2\theta_{13}\ c_{13}\ s_\delta \cdot$$

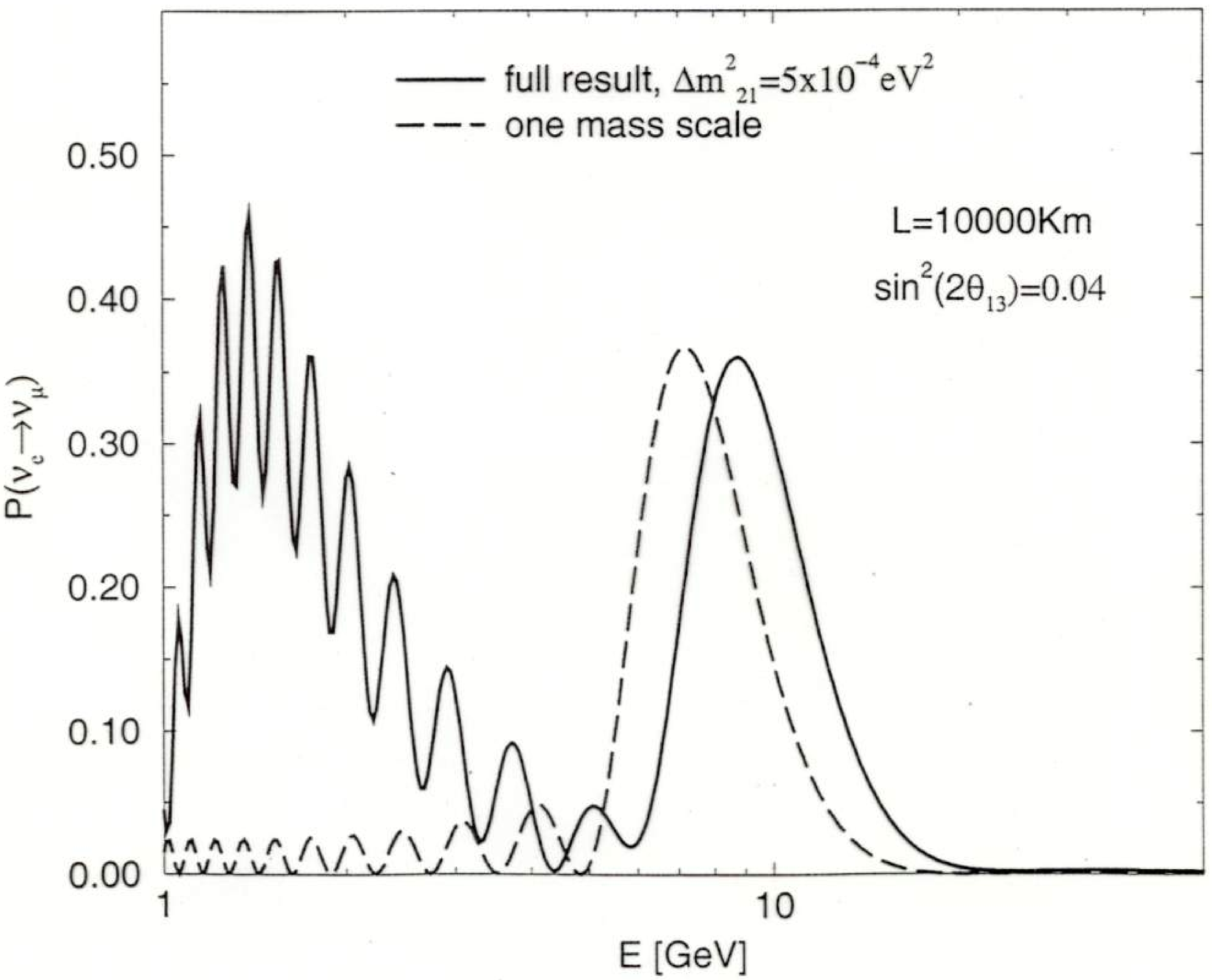
$$\cdot \sin \frac{\Delta m^2_{32} L}{4E}\ \sin \frac{\Delta m^2_{31} L}{4E}\ \sin \frac{\Delta m^2_{21} L}{4E}$$



0.80
0.60
0.40
0.20
0.00
0.0
5000.0
10000.0
15000.0
L/E[km/GeV]
$P(\nu_\mu \rightarrow \nu_e)$
full result, $\Delta m^2_{21}=2\times10^{-4}eV^2$
one mass scale



full result, $\Delta m^2_{21}=5\times10^{-5}eV^2$
one mass scale
$\sin^2(2\theta_{12})=0.8$
$\sin^2(2\theta_{13})=0.04$
$P(\nu_\mu \to \nu_e)$
L /E[km/GeV]
0.0
0.1
0.2
0.3
0.4
0.5
0
5000
10000
15000



full result, $\Delta m^2_{21}=5x10^{-4}eV^2$
one mass scale
L=10000Km
$\sin^2(2\theta_{13})=0.04$
$P(\nu_e \to \nu_\mu)$
0.50
0.40
0.30
0.20
0.10
0.00
1
10
E [GeV]

$$\sqrt{2}\, G_F N_e \,[eV] \simeq 7.6 \times 10^{-14}\, Y_e\, \rho \left[\frac{g}{cm^3}\right]$$

$$2E \cdot \sqrt{2}\, G_F N_e \underset{(res.)}{=} \Delta m^2 \cos 2\theta$$

$$\Downarrow$$

$$\frac{E\,[GeV]}{\Delta m^2\,[eV^2]\cos 2\theta} = \frac{10^5}{7.6\,\rho\left[\frac{g}{cm^3}\right]}$$

Major effort to confirm and study all indications

- solar
  - SNO
  - Borexino $\rightarrow \Delta m^2_{21}, \theta_{12}$
  - Kamland

- atmospheric
  - K2K $L \sim 250$ Km
  - MINOS $L \sim 730$ Km
  - CERN-Gran Sasso $L \sim 730$ Km
  - JHF $L \sim 295$ Km

  $|\Delta m^2_{32}|$

  θ_{23}

  limit θ_{13}

  - accelerator ν_μ beams

- LSND / Karmen

  mini BOONE

What is next?

long baseline experiments

"superbeams" "neutrino factories"

FNAL - SOUDAN : 730 Km
HOMESTAKE : 1300 Km
WIPP : 1750 Km
SLAC : 2900 Km
GRAN SASSO : 7300 Km

BNL - SOUDAN : 1700 Km
WIPP : 2900 Km

CERN - FREJUS : 130 Km
GRAN SASSO : 730 Km
CANARY ISLAND : 3000 Km
NORWAY : 3500 Km
FINLAND : 2500 Km

JHF - SK : 295 Km
BEIJING : 2100 Km

Neutrino Factory Physics Study Group - Fermilab

http://www.fnal.gov/projects/muon_collider/nu/study/study.html

CERN

http://muonstoragerings.cern.ch

BNL

http://www.cap.bnl.gov/mumu/mu_home_page.html

Japan

Muon storage ring / neutrino factory

- high intensity $10^{19} - 10^{21}$ μ decays / yr.
- flavor-pure beams + well understood

$$\left.\begin{array}{l} \mu^- \to \nu_\mu + \bar{\nu}_e + e^- \\ \mu^+ \to \bar{\nu}_\mu + \nu_e + e^+ \end{array}\right\} \begin{array}{l} 50\%\ \nu_\mu \\ 50\%\ \nu_e \end{array}$$

$\downarrow$

- can do very long baseline neutrino oscillation experiments of several types: ν_μ disappearence, $\nu_e \to \nu_\mu$, $\nu_\mu \to \nu_\tau$ + anti-neutrino channels

μ^- beam

- $\nu_\mu \to \nu_\mu$ — ν_μ disappearence
- $\bar{\nu}_e \to \bar{\nu}_\mu$ — wrong sign muon
  $\bar{\nu}_e \to \bar{\nu}_\tau$
- $\nu_\mu \to \nu_\tau$ — ν_τ appearence
- $\nu_\mu \to \nu_e$
  $\bar{\nu}_e \to \bar{\nu}_e$

De Rujula, Gavela, Hernandez, Lipari,
Campanelli, Bueno, Rubbia, Barger, Geer,
Raja, Whisnant, Freund, Lindner,
Petcov, Romanino, Cervera, Donini,
Gavela, Gomez Cadenas, Hernandez,
Mena, Rigolin, Mociou, Shrock

...

What is next?

- precision measurements of

  $|\Delta m^2_{32}|$, θ_{23}

  → disappearence experiments

- appearence experiments

  → detect $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$

  → detect ν_τ → need high enough E

- if $\nu_\mu \to \nu_e$ or $\nu_e \to \nu_\mu$ observed

  - $\theta_{13} \neq 0$

    or

  - $\Delta m^2_{21} \neq 0$

    or

  - $\theta_{13} \neq 0$ & $\Delta m^2_{21} \neq 0$

solar ν experiments outcome - very important

- $\Delta m^2_{21} \gtrsim 10^{-5}\,eV^2$ (LMA) ruled out

  → solar [- problem?
  or
  - SMA, LOW, other ?

  → LBE

  - precision measurement of
  $|\Delta m^2_{32}|$, θ_{23}
  (ν_μ disappearence)

  - in appearence $\nu_e \to \nu_\mu$ or $\nu_\mu \to \nu_e$

  measure θ_{13} for

  $\sin^2 2\theta_{13} \gtrsim$ 10^{-3} - superbeams
  10^{-4} - ν fact

  - if θ_{13} not too small →

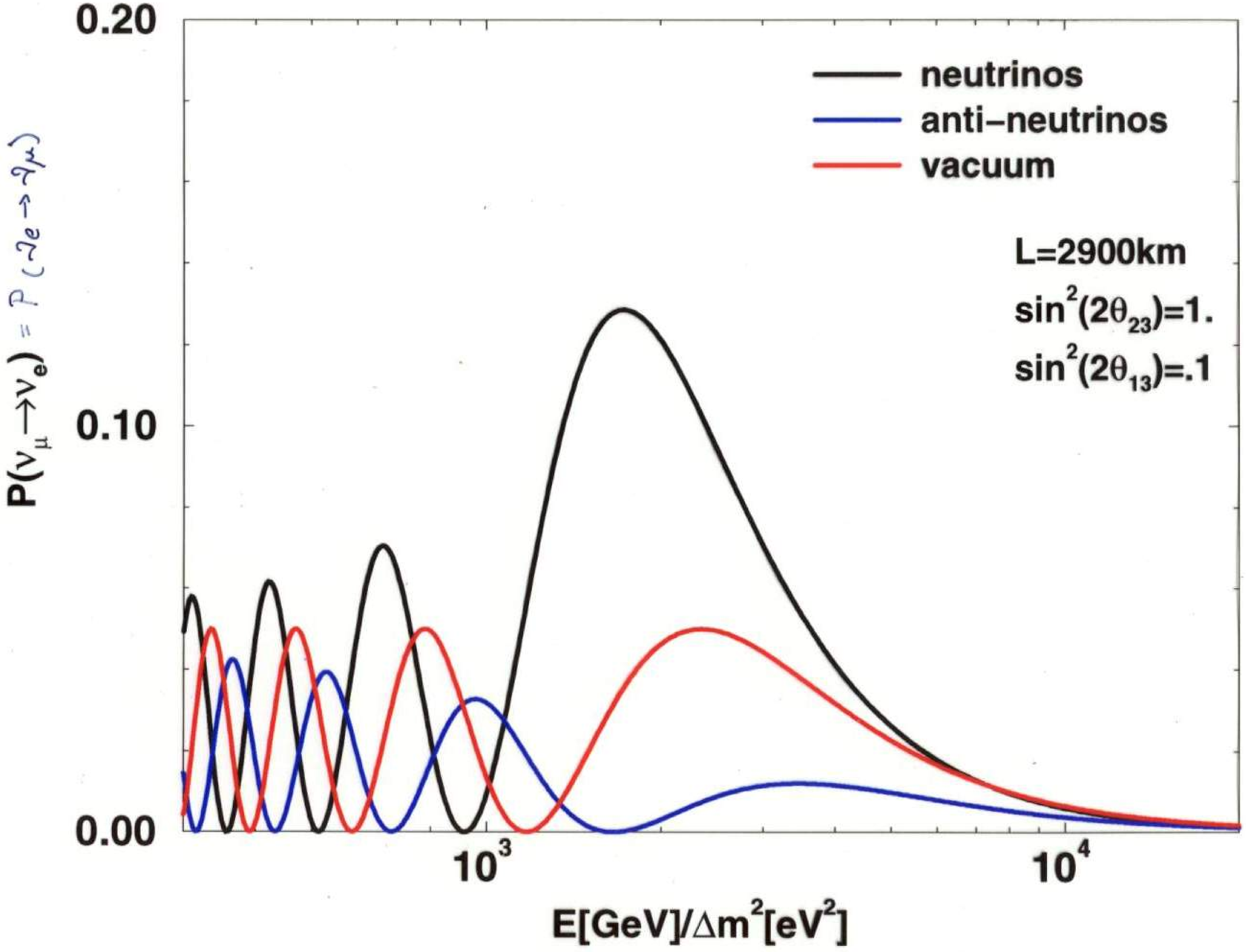
  determine sign (Δm^2_{32}) using

  → matter effects for $L \gtrsim 2000\,Km$

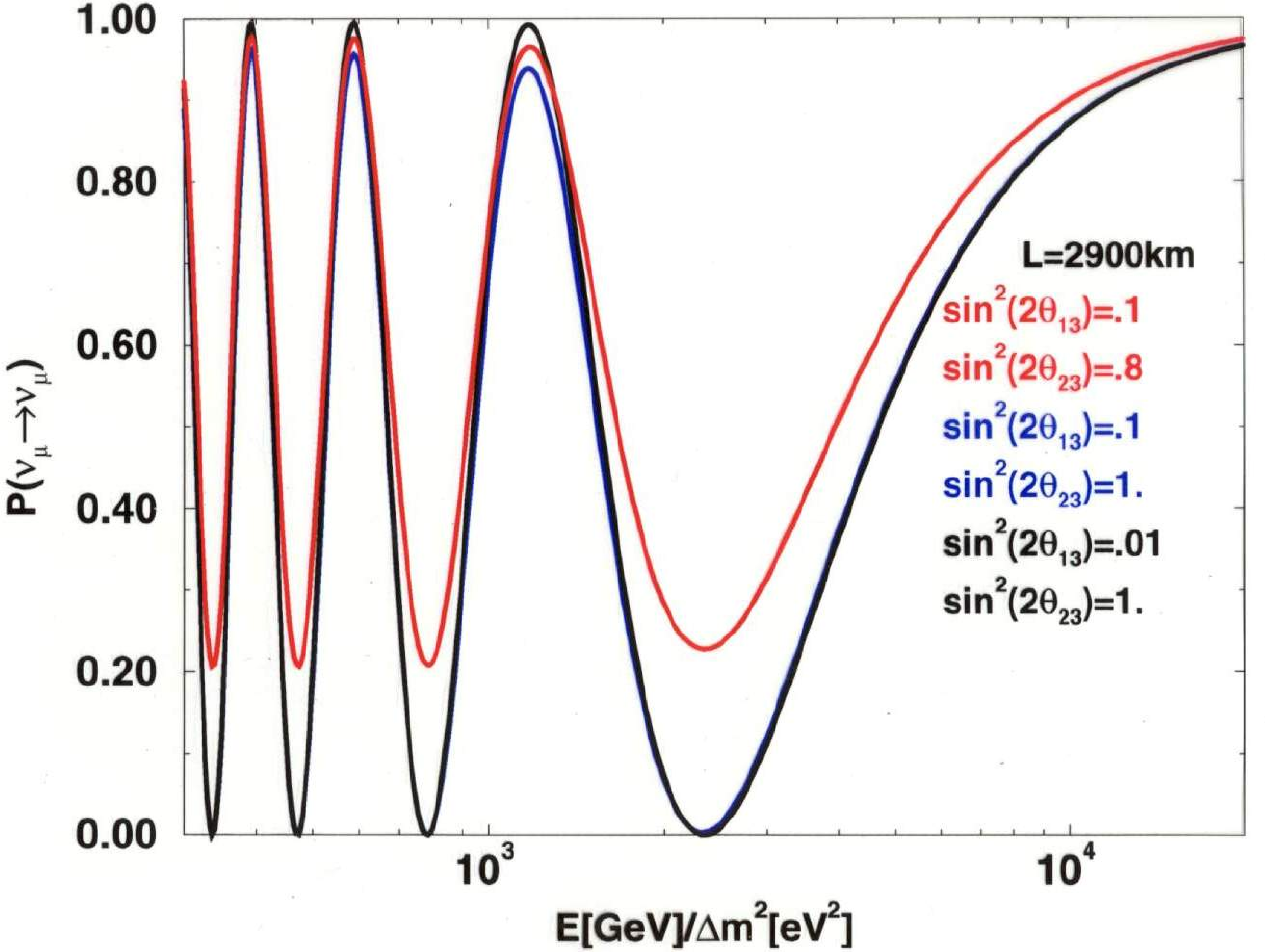
  → both ν & $\bar\nu$ channels

  ⇒ hard for superbeams
  OK for ν fact

  → need good precision for Δm^2_{32} for good determination of rest



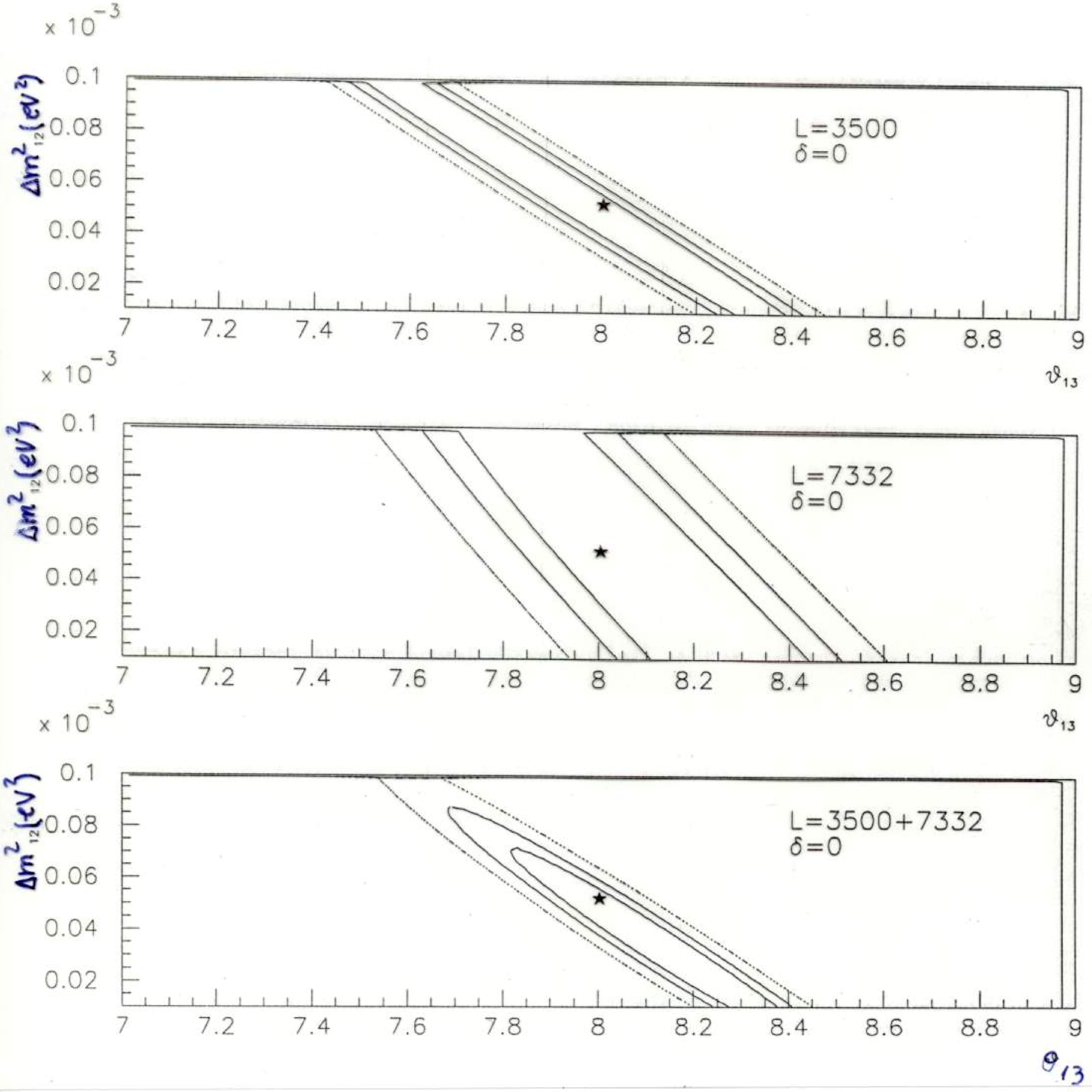
MOCIOIU, SHROCK, Phys. Rev. D 62, 053017 (2000)



1.00
0.80
0.60
0.40
0.20
0.00
$P(\nu_\mu \to \nu_\mu)$
10^3
10^4
$E[GeV]/\Delta m^2[eV^2]$
L=2900km
$\sin^2(2\theta_{13})$=.1
$\sin^2(2\theta_{23})$=.8
$\sin^2(2\theta_{13})$=.1
$\sin^2(2\theta_{23})$=1.
$\sin^2(2\theta_{13})$=.01
$\sin^2(2\theta_{23})$=1.

Cervera, Donini, Gavela, Gomez Cádenas, Hernández, Mena, Rigolin

FERMILAB ν FACTORY study



- . LMA observed
  - some measurement of Δm^2_{21}, θ_{12}
    $\downarrow$
    - precision $|\Delta m^2_{32}|$, θ_{23} → disappearance
    - appearance $\nu_\mu \to \nu_e$, $\nu_e \to \nu_\mu$
      - if $\Delta m^2_{21} \sin^2 2\theta_{12}$ large and known well
        - measure θ_{13} ?
        - probably limit $\sin^2 2\theta_{13} \leq 10^{-3}$ SB
          $10^{-5} \div 10^{-6}$ νF
      - if $\Delta m^2_{21} \sin^2 2\theta_{12}$ not known precisely
        → large correlations between
        θ_{13} and $\Delta m^2_{21} \sin^2 2\theta_{12}$
        → not good determination of any

BUT

$L \sim 7000\,\text{km}$
$E \sim$ few x 10 GeV → effects of Δm^2_{21} negligeable

⇒ like previous case

→ combination of baselines helps

- solar data inconclusive

CPT: $P(\nu_e \to \nu_\mu) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$

$\downarrow$

matter effects

T: $P(\nu_e \to \nu_\mu) - P(\nu_\mu \to \nu_e)$

$\downarrow$

T (CP) violation

CP: $P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e - \bar{\nu}_\mu)$

$\downarrow$

CP violation

+

matter effects

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) =$$

$$= 4J \left[\sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) - \sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) - \sin\left(\frac{\Delta m_{21}^2 L}{2E}\right)\right]$$

$$= -16 J \quad \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) \underline{\sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)}$$

$$J = \frac{1}{8} \sin 2\theta_{12}\, \underline{\sin 2\theta_{13}}\, \sin 2\theta_{23} \cos\theta_{13}\, \underline{\sin\delta}$$

$$\theta_{12} = \theta_{23} = \frac{\pi}{4}, \quad \frac{\Delta m_{21}^2}{\Delta m_{32}^2} \to 0$$

$$\frac{P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)}{P(\nu_e \to \nu_\mu) + P(\bar{\nu}_e \to \bar{\nu}_\mu)} \to \sim \frac{\sin\delta}{\sin\theta_{13}} \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

Bilenki, Giunti, Grimus, Dick, Freund, Lindner, Romanino, Donini, Gavela, Hernandez, Rigolin, Koike, Ota, Sato, Harrison, Scott, Parke, Weiler ...

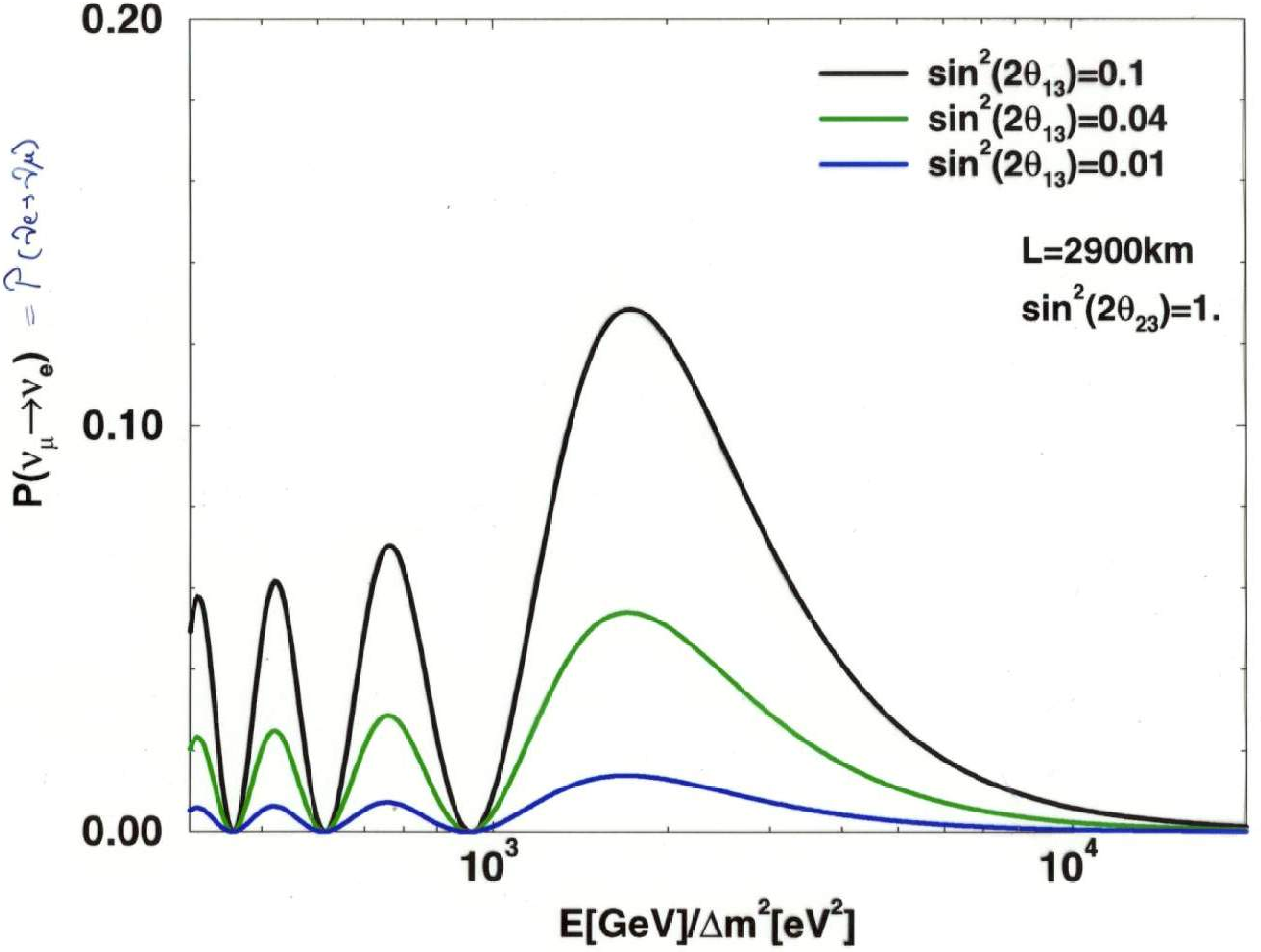
Neutrino Factory

- opens many oscillation channels

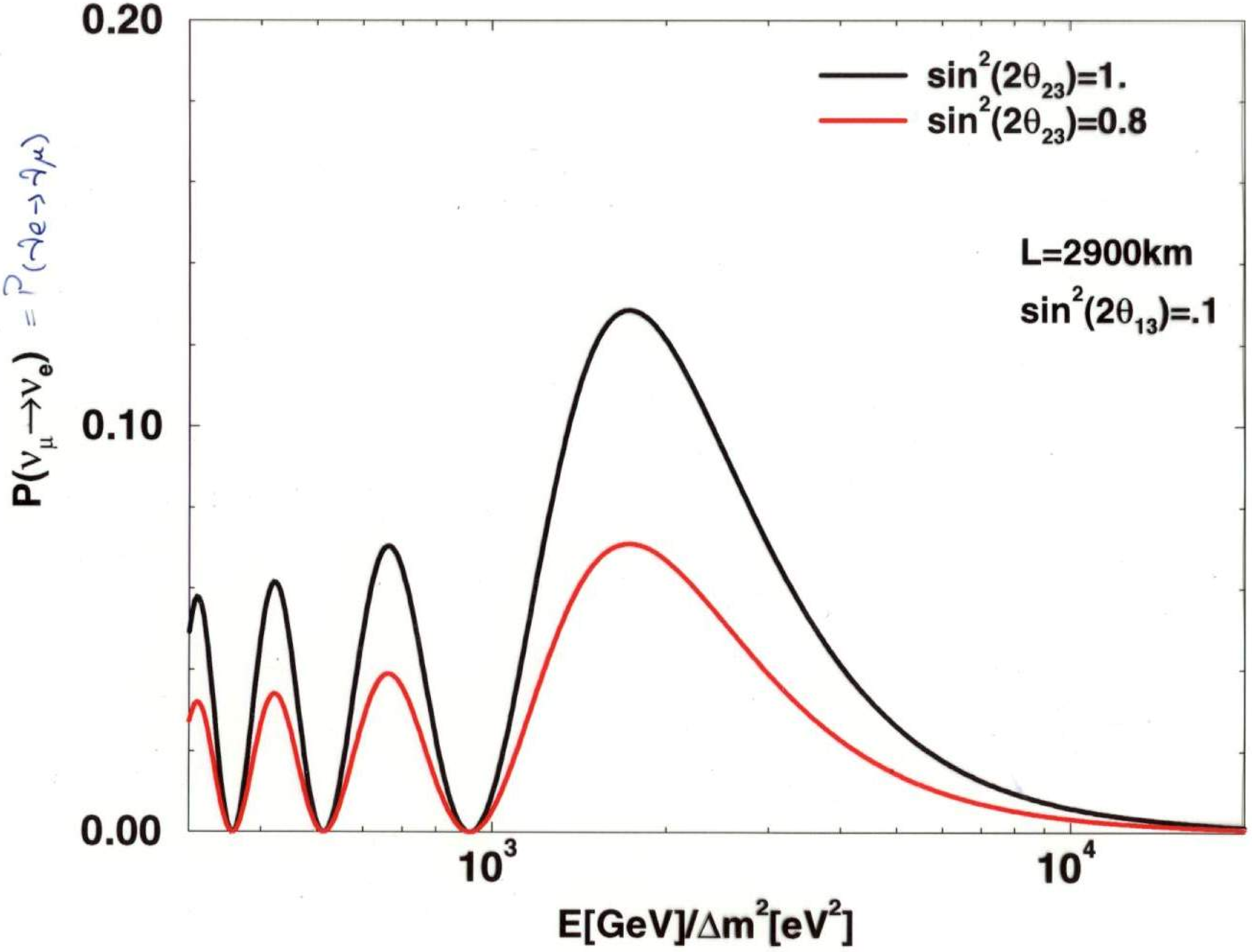
- can in principle:
  - measure Δm^2_{32}, θ_{23} at % level
  - measure $\sin^2 2\theta_{13}$ down to $\sim 10^{-4}$
  - determine sign of Δm^2_{32}
  - study matter effects
  - look for Δm^2_{21} sub-leading oscillations
  - look for CP (T) violation

BUT

- dependent on - what parameters are
  - detector -> backgrounds
- for the analyses - simple scenarios might not be enough
- machine - chalenge



0.20
0.10
0.00
10^3
10^4
$E[GeV]/\Delta m^2[eV^2]$
$P(\nu_\mu \rightarrow \nu_e)$
$= P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
$\sin^2(2\theta_{13})=0.1$
$\sin^2(2\theta_{13})=0.04$
$\sin^2(2\theta_{13})=0.01$
L=2900km
$\sin^2(2\theta_{23})=1.$



0.20
0.10
0.00
$P(\nu_\mu \to \nu_e)$
$= P(\bar{\nu}_e \to \bar{\nu}_\mu)$
$\sin^2(2\theta_{23})=1.$
$\sin^2(2\theta_{23})=0.8$
L=2900km
$\sin^2(2\theta_{13})=.1$
10^3
10^4
$E[GeV]/\Delta m^2[eV^2]$