Neutrino Oscillations: An Overview

David C. Latimer
Department of Physics and Astronomy
VANDERBILT UNIVERSITY

NP Seminar
29 Nov 04

Collaborators: David J. Ernst, Jesus Escamilla,
Rachel Wooten, Jong Son

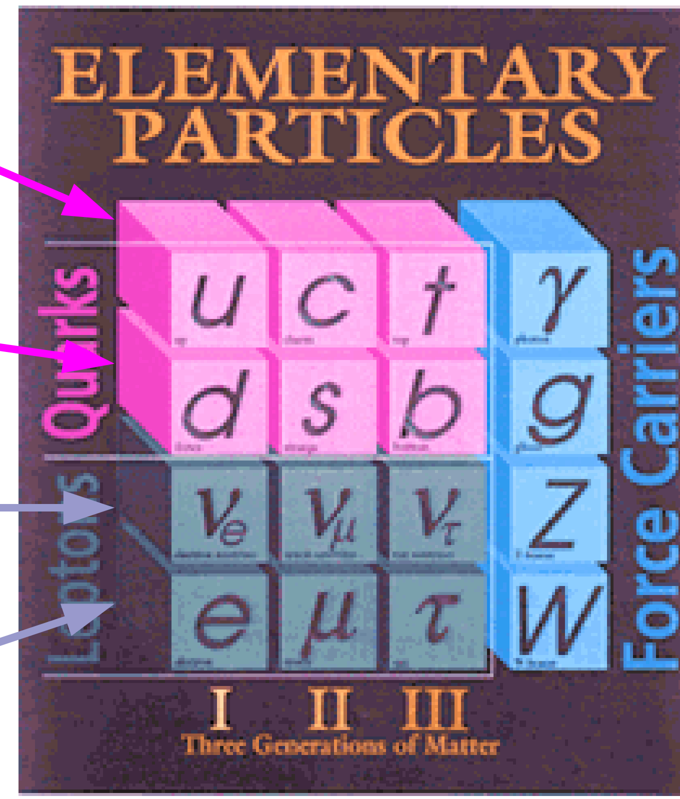
The standard model

3.0 MeV 1.2 GeV 174 GeV

6.7 MeV 117 MeV 4.2 GeV

< 3.0 eV < 190 keV < 18 MeV

0.5 MeV 106 MeV 1.8 GeV



Oscillations (i)

- Mixing matrix relating mass eigenstates and flavor states results in oscillation

Standard parameterization (3-ν):

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

where $s_{jk}=\sin(\theta_{jk}),\, c_{jk}=\cos(\theta_{jk}).$

Oscillations (ii)

- Using quantum theory, we may determine the (ultra-relativistic) oscillation probability for ν of energy E and source-detector distance L.

$$P_{\alpha\rightarrow\beta}(L/E)=\mathrm{tr}\left[e^{iML/2E}P^{\alpha}e^{-iML/2E}P^{\beta}\right]$$

where $M=\mathrm{diag}(m_1^2, m_2^2, m_3^2)$

and $\left(P^{\alpha}\right)_{jk}=U_{\alpha j}^{*}U_{\alpha k}$.

Oscillations (iii)

- Or in more familiar terms...

$$P_{\alpha\to\beta}(L/E)=\delta_{\alpha\beta}-4\sum_{j<k}^{3}\Re\left(U_{\alpha j}U_{\alpha k}^{*}U_{\beta k}U_{\beta j}^{*}\right)\sin^{2}(\phi_{jk})$$

$$+2\sum_{j<k}^{3}\Im\left(U_{\alpha j}U_{\alpha k}^{*}U_{\beta k}U_{\beta j}^{*}\right)\sin(2\phi_{jk})$$

where $\phi_{jk}=\Delta_{jk}L/4E$

and $\Delta_{jk}=m_j^2-m_k^2$.

Present parameter values

$$\theta_{12} = 0.57 \pm 0.06 \qquad \Delta_{21} = \left(7.1^{+1.8}_{-1.1}\right) \times 10^{-5}\, eV^2$$

$$0 \leq \theta_{13} \leq 0.23 \qquad \Delta_{31} = \pm\left(2.0^{+1.2}_{-0.8}\right) \times 10^{-3}\, eV^2$$

$$\theta_{23} = 0.78 \pm 0.17 \qquad \delta = ??$$

Adapted from Barger, Marfatia, and Whisnant,
Int. J. Mod. Phys. E **12** 569 (2003).

Experimental overview

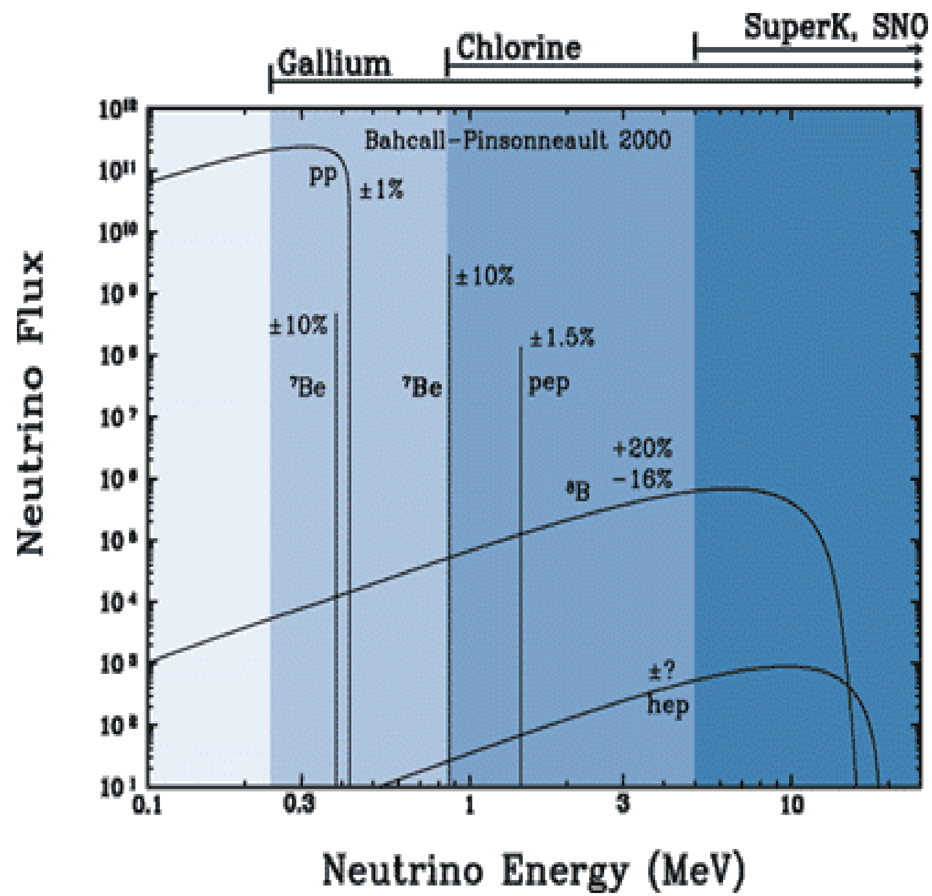
- Solar (e.g., Homestake, SAGE, Kamiokande, SNO)
- Atmospheric (e.g., Super-K)
- Reactor (e.g., CHOOZ, KamLAND)
- Accelerator beam-stop (e.g., LSND, K2K)

Solar neutrinos

$L \sim 10^{11}\,\text{m}$

E and the expected ν_e flux can be got from the SSM

$L/E \sim 10^{10}\,\text{m/MeV}$



Solar neutrino deficit (i)

Experiment	Data/Theory	Reaction
SAGE	0.54 ± 0.05	$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$
GALLEX	0.61 ± 0.06	
GNO	0.51 ± 0.08	
Homestake	0.34 ± 0.03	$\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$
Kamiokande	0.55 ± 0.08	$\nu + e^- \rightarrow \nu + e^-$
Super-K	0.465 ± 0.005	

Note: SK is sensitive mostly to ν_e - but also to $\nu_{\mu\tau}$ (down by factor 7)

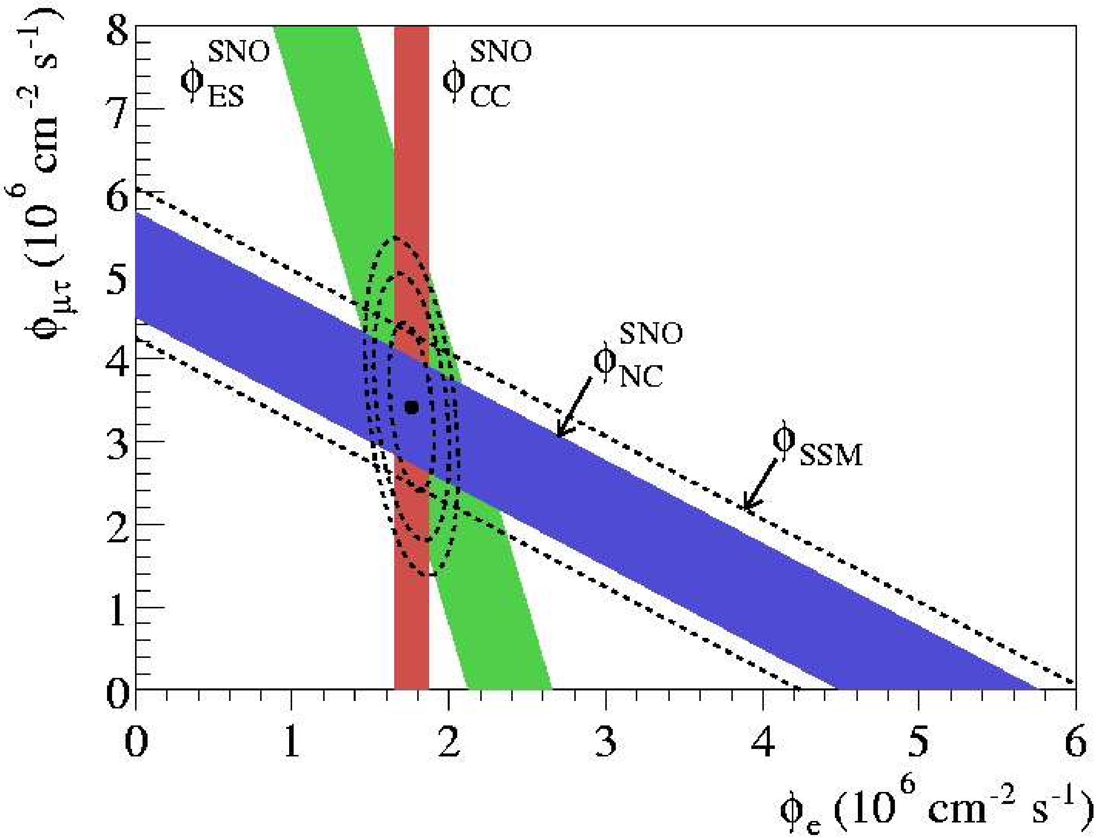
SNO results

- Elastic scattering R = 0.47 ± 0.05
- Charged current R = 0.35 ± 0.02
- Neutral current R = 1.01 ± 0.13

$$\nu + e^- \rightarrow \nu + e^-$$

$$\nu_e + d \rightarrow p + p + e^-$$

$$\nu + d \rightarrow p + n + e^-$$



ν_e flux = 1.76 ± 0.05 ± 0.09

$\nu_{\mu\tau}$ flux = 3.41 ± 0.45 ± 0.46

SSM flux = 5.05 + 1.01 – 0.81

Atmospheric neutrinos

Incident cosmic rays produce $\pi^{\pm}$ which decay

$$\pi^{\pm} \to \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}) \qquad \mu^{\pm} \to e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \bar{\nu}_{\mu}(\nu_{\mu})$$

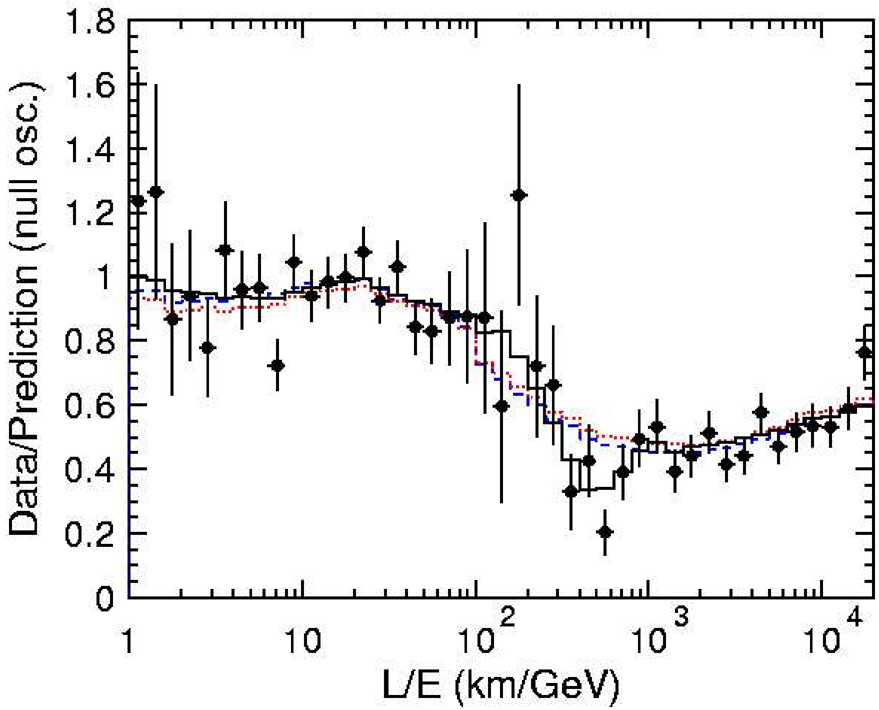
At Super-K:

$$L \sim 10^{3} - 10^{7}\ \mathrm{m} \qquad E \sim 10^{3}\,\mathrm{MeV}$$

$$L/E \sim 10^{0} - 10^{4}\,\mathrm{m/MeV}$$

Super-K results

The measured/expected ratio for μ events shows dependence on L/E



Reactor neutrinos

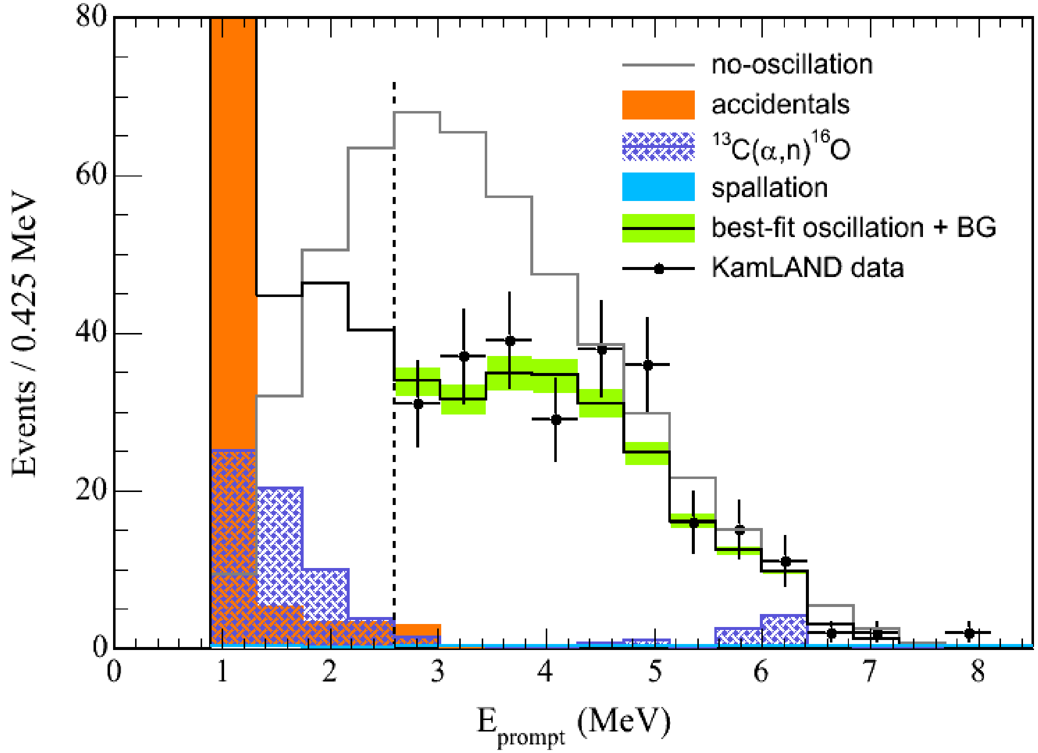
Measure $\bar{\nu}_e$ oscillation probability for $E \sim 3\,\mathrm{MeV}$ at a fixed L

CHOOZ $(L \sim 10^3\,\mathrm{m})$ saw no deficit

KamLAND $(\langle L \rangle \sim 10^5\,\mathrm{m})$ does!

KamLAND results

Measured / expected = 0.658 ± 0.044 ± 0.047



Beam-stop neutrinos

K2K = KEK to Super-K

Measure $\nu_\mu \; (E \sim 10^3 \,\mathrm{MeV})$ with a long baseline $L \sim 10^5\,\mathrm{m}$.

$$\text{Measured / expected} = 0.55 \pm 0.19$$

Our analysis

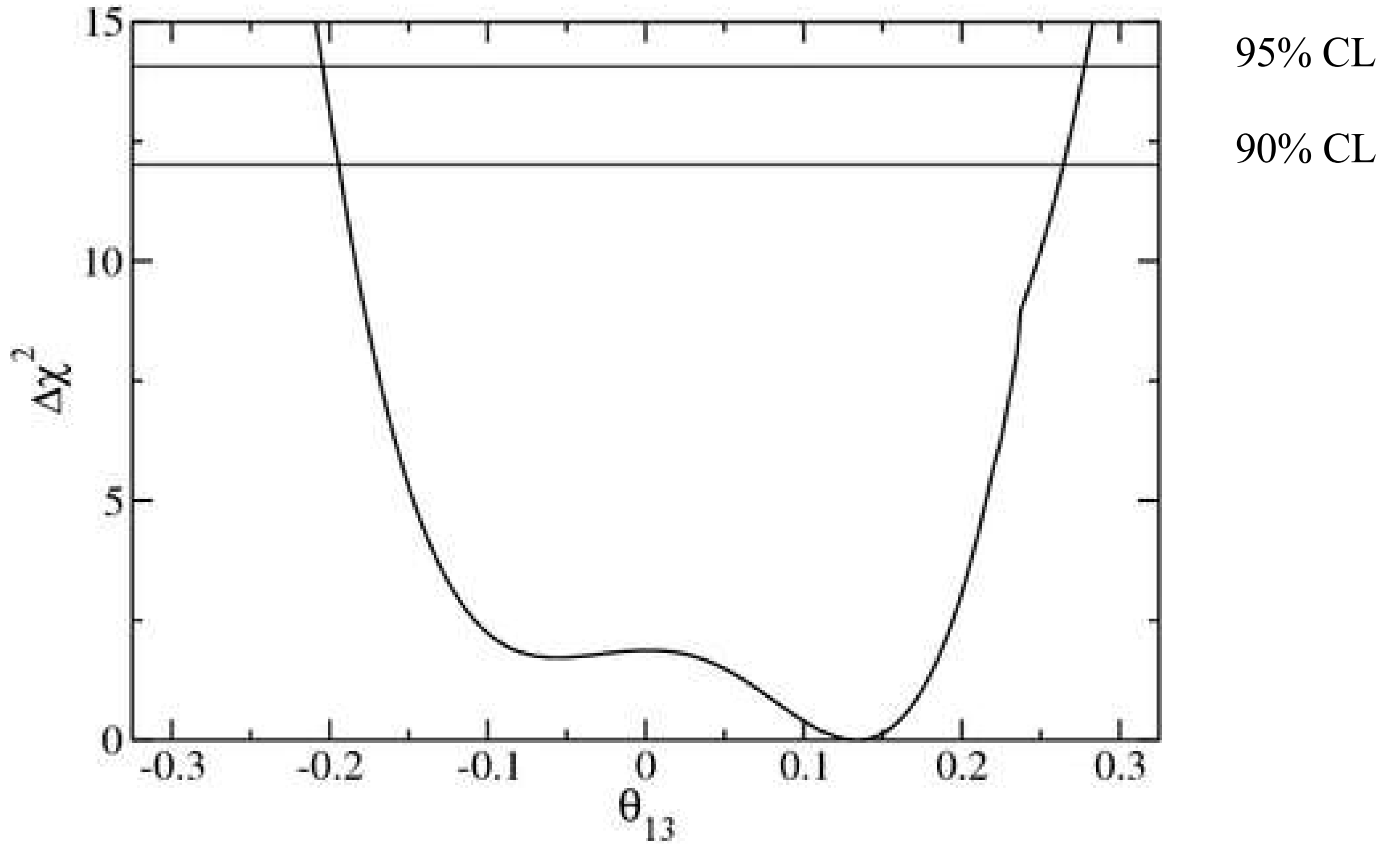
- Construct a model of the experiments assuming CP is conserved
- Explore the acceptable region for θ_{13}

NB: We bound the mixing angles as below

$$\theta_{12} \in [0, \pi/2], \quad \theta_{13} \in [-\pi/2, \pi/2], \quad \theta_{23} \in [0, \pi/2].$$

Allowed region

$$\Delta\chi^2 \quad vs. \quad \theta_{13}$$



Comments

- Within our model, we find that θ_{13} lies between -0.17 and 0.24 at the level of 1-σ.
- In a perturbative expansion about θ_{13} and the ratio Δ_{21}/Δ_{31}, terms linear in θ_{13} are suppressed by the mass ratio ~ 0.03.
- Is there a region in which this suppression can be overcome so that the positive and negative regions for θ_{13} might be experimentally distinguished?

Best guess

- Consider a region where the Δ_{31} oscillations are incoherent [i.e., $\langle \sin^2 \phi_{31} \rangle = 1/2$], but the Δ_{21} oscillations are coherent.
- Examine $P_{e\mu}$, $P_{\mu\mu}$, $P_{\mu\tau}$ oscillation channels.
- The sign of the mixing angle has greatest impact whenever $\sin^2 \phi_{21}$ is maximal; i.e., look in the region:

$$L/E \sim 1.6 \times 10^4 \,\text{m/MeV} .$$

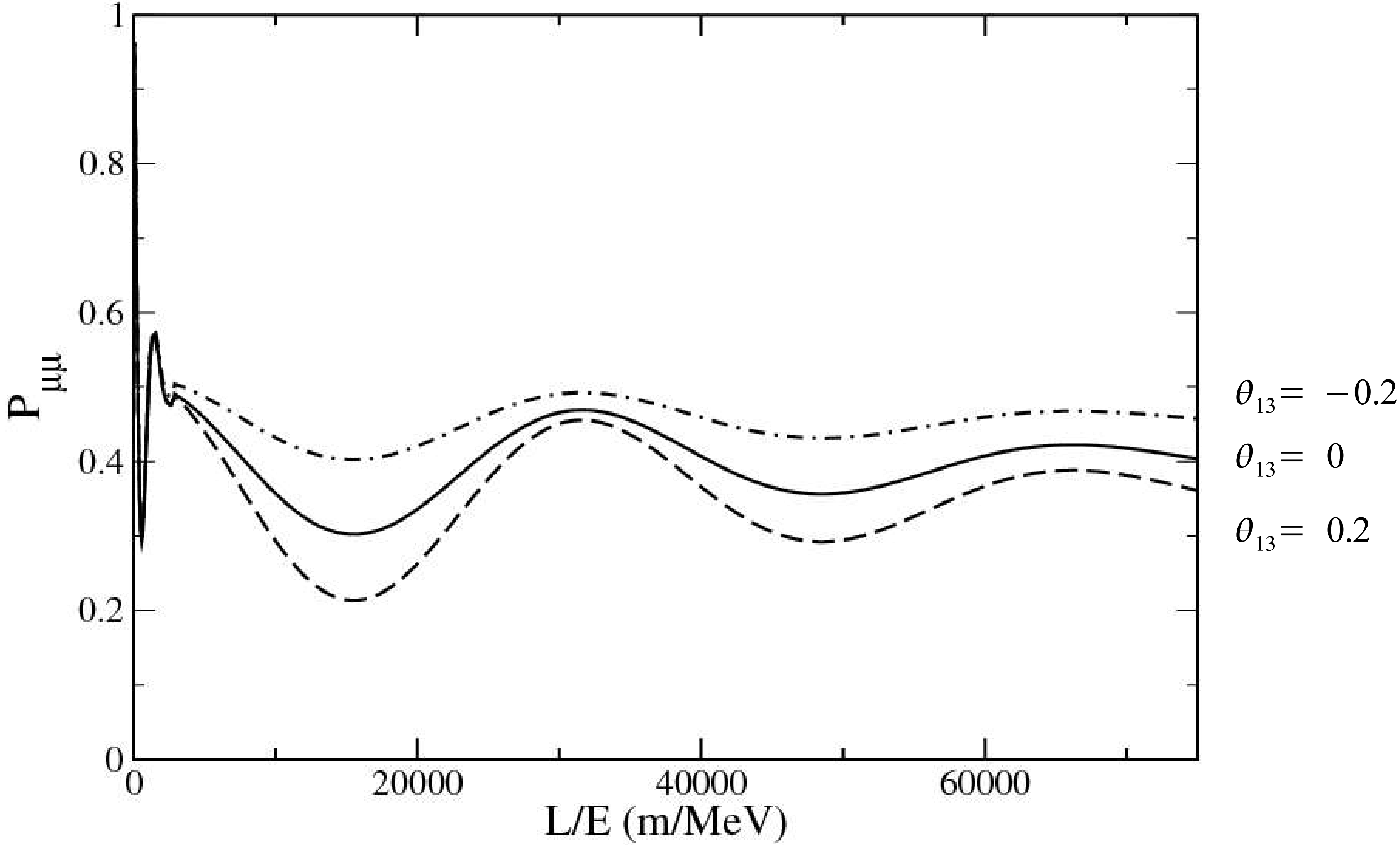
Size of the effect

Using the 1-σ bounds: $\theta_{13}^{+} = 0.24, \ \theta_{13}^{-} = -0.17$.

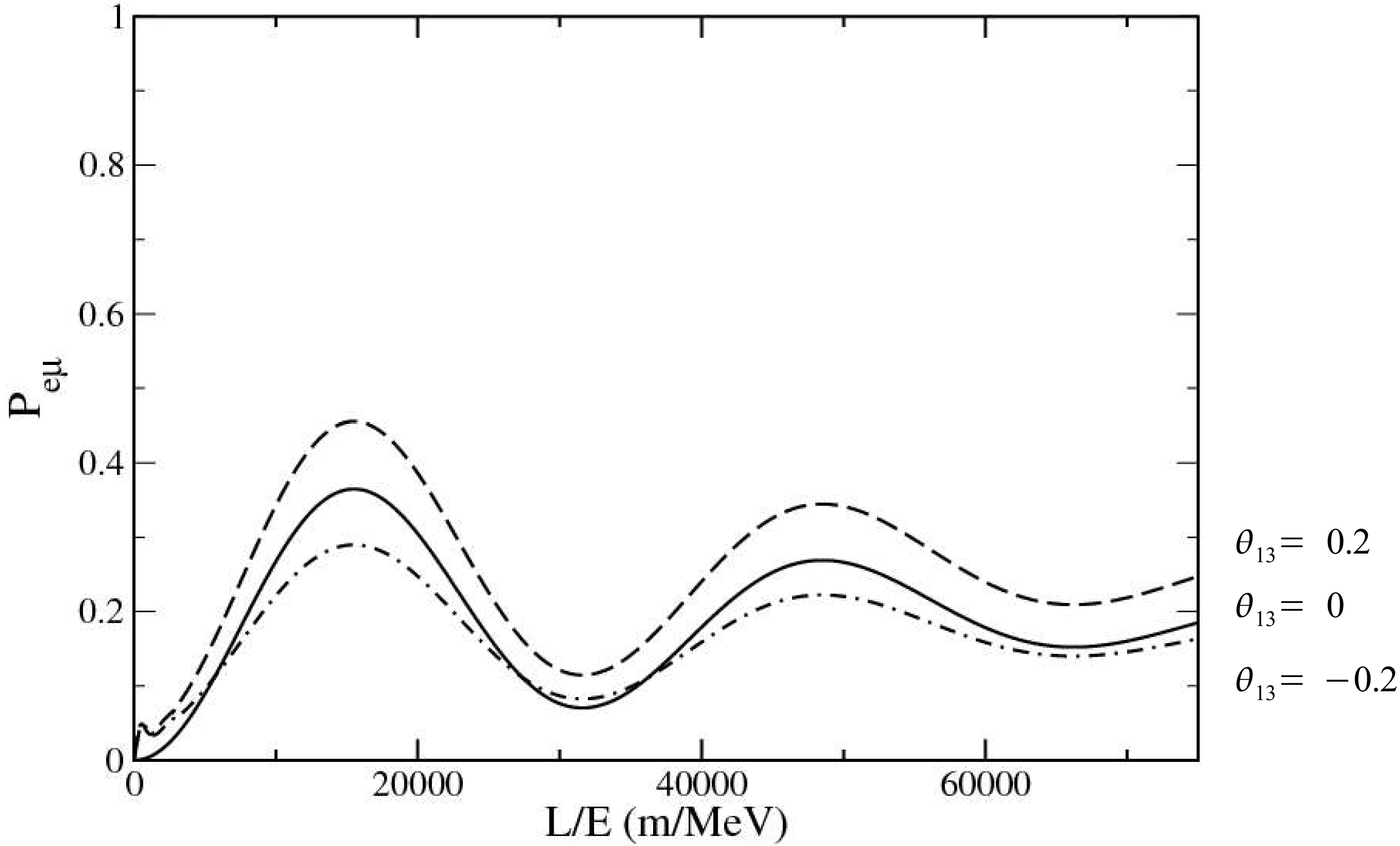
$$\frac{P_{\mu\mu}(\theta_{13}^{+}) - P_{\mu\mu}(\theta_{13}^{-})}{P_{\mu\mu}(\theta_{13}^{+}) + P_{\mu\mu}(\theta_{13}^{-})} = -0.25, \qquad \frac{P_{e\mu}(\theta_{13}^{+}) - P_{e\mu}(\theta_{13}^{-})}{P_{e\mu}(\theta_{13}^{+}) + P_{e\mu}(\theta_{13}^{-})} = 0.18.$$

The $P_{\mu\tau}$ channel exhibits little dependence on the sign of θ_{13}, as θ_{23} is nearly maximal.

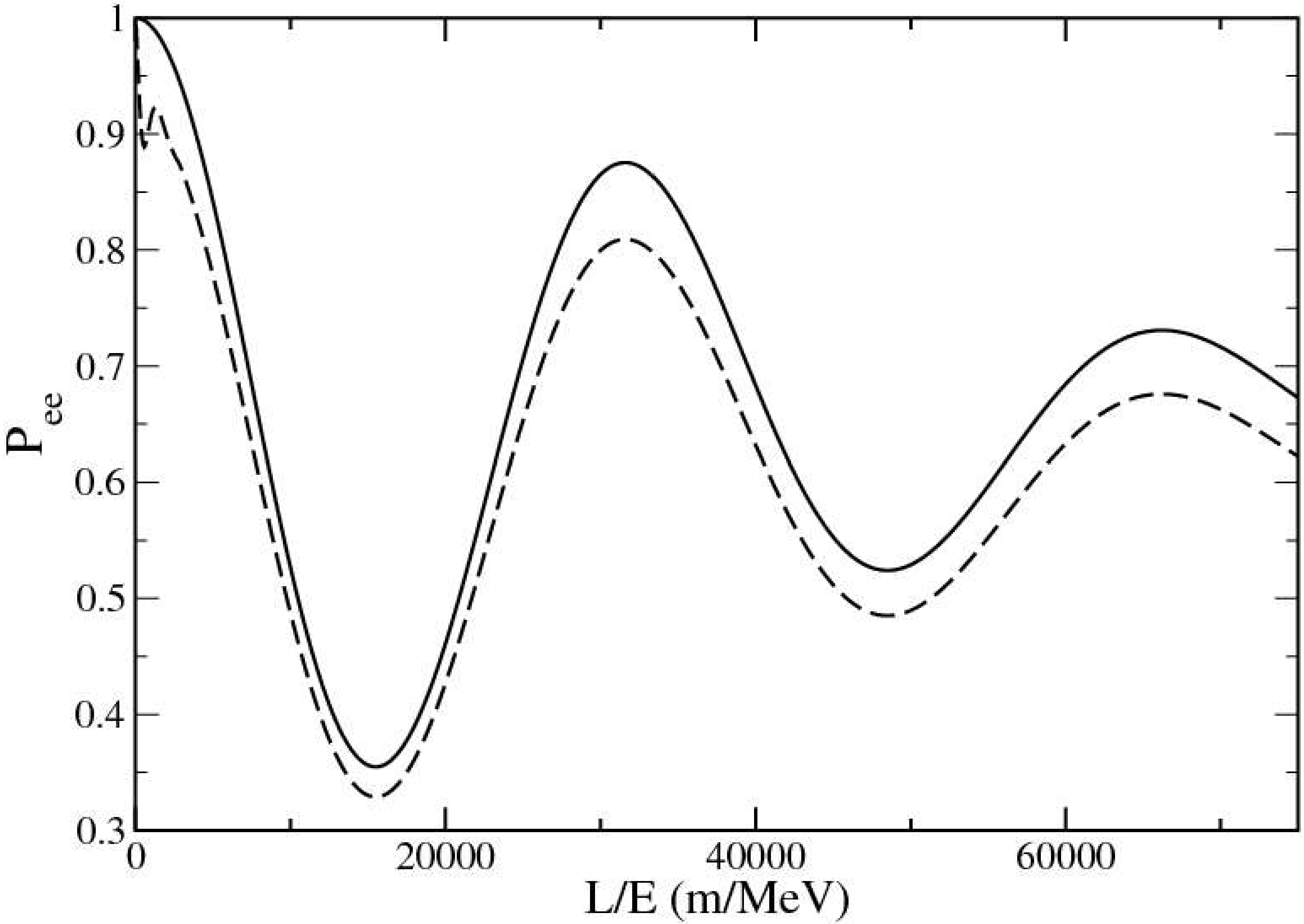
Plot of $P_{\mu\mu}$ in this region



Plot of $P_{e\mu}$ in this region



Plot of P_{ee} in this region

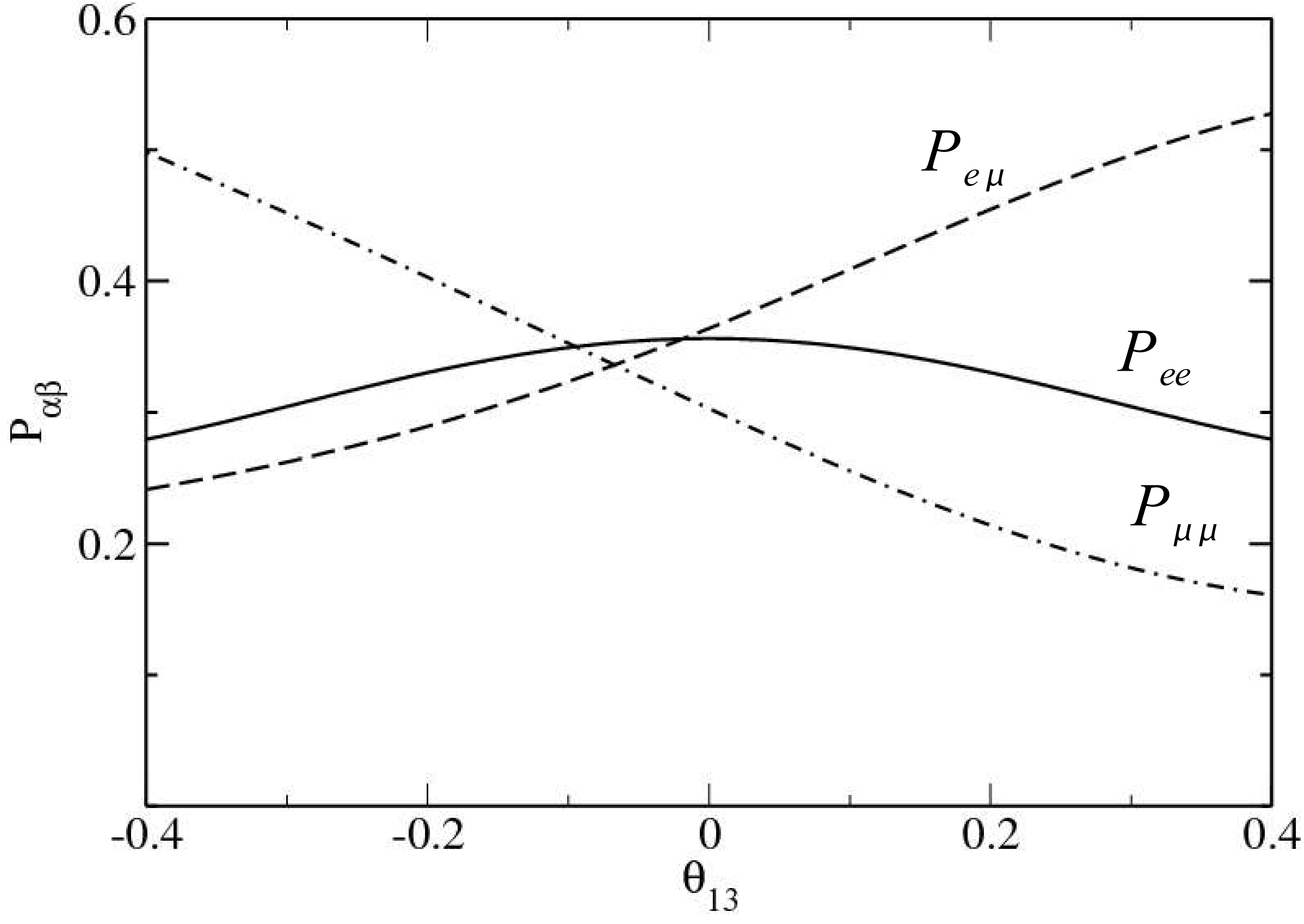


$\theta_{13} = 0$

$\theta_{13} = \pm 0.2$

$P_{\alpha\beta}$ as a function of θ_{13}

$(L/E \sim 1.6\times10^4\,\mathrm{m/MeV})$



Caveat

- The mixing angles θ_{13} and θ_{23} are correlated.
- Future work: Examine this correlation and its implications....