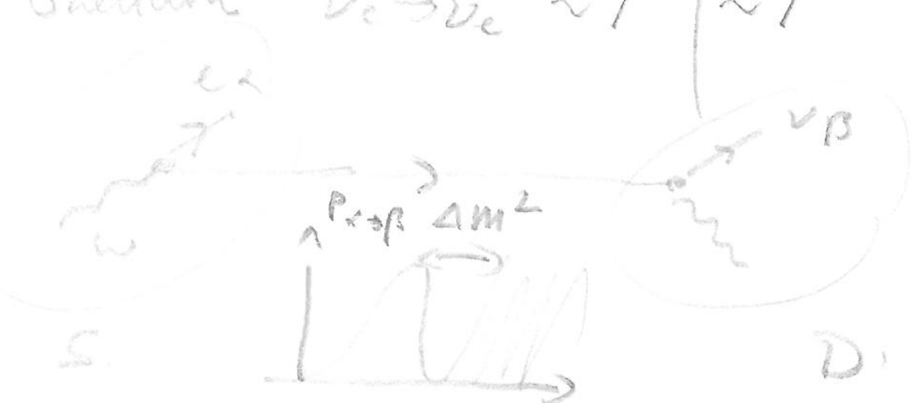
Intro: 2 parts

- Anomalies and relation to other experiments
- Non unitarity

		E_ν/MeV	L/m
LSND	$\bar\nu_\mu \to \bar\nu_e$	50	30
MiniBooNE	$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$	+500	500
Reactor 2.0	$\bar\nu_e \to \bar\nu_e$	200	<100
Gallium	$\nu_e \to \nu_e$	~1	~1



$$P^{SBL}_{\nu_\alpha\to\nu_\beta} = \left(4|U_{\alpha 4}|^2|U_{\beta 4}|^2\right)\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$

$$P^{SBL}_{\nu_\alpha\to\nu_\alpha} = \left(1-\left(4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\right)\right)\sin^2(\;\;//\;\;)$$

$$\boxed{L/E \approx 1\ \mathrm{m/MeV}}$$

(1)

$(3+1)$: $\mathcal{U} = \left(\begin{array}{c|c} \tilde{U} & \begin{matrix} U_{e4} \\ U_{\mu 4} \\ U_{\tau 4} \end{matrix} \\ \hline \cdots & \cdot \end{array}\right)$

1) $\bar\nu_\mu \to \nu_s \to \bar\nu_e$ $\oplus$

2) $\nu_e \to \nu_s$ $\ominus$

$1\ \mathrm{m/MeV} \approx \Delta m^2 : \mathcal{O}(\mathrm{eV})$

- LSND $\Rightarrow$ $|U_{e4}||U_{\mu 4}|$ $\xrightarrow{\text{Reactor Old } |U_{e4}| \text{ small}}$ $|U_{\mu 4}|$ Large
  $\xrightarrow{\text{Reactor 2.0}}$ $|U_{\mu 4}|$ moderate
- Reactor 2.0. $\Rightarrow$ $|U_{e4}|$ non negligible ($\sin^2 4\theta \simeq 0{,}77$)
- Gallex consistent with Reactor 2.0
- MiniBooNE $\bar\nu_\mu \to \bar\nu_e$ ✓
  $\nu_\mu \to \nu_e$ (✗) in interesting energy range!

$P(\bar\nu_\mu \to \bar\nu_e) \neq P(\nu_\mu \to \nu_e)$ $\cancel{CP}$

Not possible in 3+1 (2 flavor effective model)

Can we trust MiniBooNE (so many anomalies)

Relation to other experiments

- Solar ν_s and low energy atmospheric ν. probe different L/E range and constrain only indirectly by the sum of matrix elements $|U_{e1}|^2 + |U_{e2}| + |U_{e3}|^2$
$$= 1 - |U_{es}|^2$$

$\boxed{\text{Constant!}}$

Except MINOS high energy ν_μ from the atmosphere should disappear! (no signal)

What do we expect?

$\nu_\mu \to \nu_e$ (+) (CP conserved)

$\bar{\nu}_\mu \to \bar{\nu}_e \Rightarrow \nu_\mu$ and $\bar{\nu}_\mu$ (−)

Other experiments on short baseline:

Appearance:

KARMEN	$\bar{\nu}_\mu \to \bar{\nu}_e$	X
NOMAD	$\nu_\mu \to \nu_e$	X

Disappearance:

CDHS	$\nu_\mu \to \nu_\mu$	
MINOS		X
Atm. ν	ν_μ high energy	

(3+1) global analysis GoF 30%

Parameter GoF 0,008%

Tool: χ^2

$$\chi^2 = \sum_i \frac{(X_i^{obs} - X_i^{pred}(\vec{\theta}))^2}{\delta X_i^2}$$

Compare two complex objects:

Highly similar in region, but not at all in general

$$\tilde{\chi}^2 = \chi^2(\theta) - \sum_{r=1}^{7} \chi^2_{r,min} \quad \text{(sublib)}$$

(3+2)

↳ new parameters $|U_{\mu s}|$ and ϕ − CP violation

$\Rightarrow P(\bar{\nu}_\mu \to \bar{\nu}_e) \neq P(\nu_\mu \to \nu_e)$

global GoF 50%

Parameter GoF 0,3%

Now we introduce ν_s at Heavy scale M,

what happens below?

Effective field theory: Nonunitary $\underline{3\times 3\ PMNS}$

$$\mathcal{L}_I^{eff} = -\frac{g}{2\sqrt{2}}\left(W_\mu^+ \overline{\ell_\alpha}(1-\gamma_5)\gamma^\mu N_{\alpha i}\nu_i + h.c.\right)$$

$$-\frac{g}{2c_W}\left(Z_\mu \overline{\nu_i}(1-\gamma_5)\gamma^\mu (N^\dagger N)_{ij}\nu_j + h.c.\right)$$

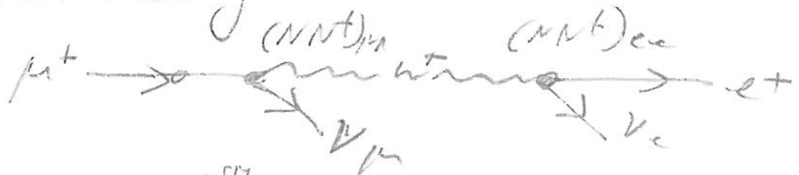
$$N \neq U$$

Consequences:

- CC int. less weakened than NC int.

(NuTeV) ν_μ

- Muon decay:



$$G_F = G_F^{SM}\left(\sqrt{(NN^\dagger)_{ee}(NN^\dagger)_{\mu\mu}}\right)$$

Tree level $G_F^{SM} = \frac{\sqrt{2}\, g^2}{8 M_W^2}$

Influences: Γ_W, $\sin\theta_W$, ...

- Z-decay (if $M_\nu > M_Z$)

$$\Gamma(Z \to \nu_i\bar{\nu}_j) = \Gamma^{SM}(Z \to \nu_i\bar{\nu}_j)\,\underbrace{|(N^\dagger N)_{ij}|^2}_{<1}$$

- Oscillations:

$\langle \nu_i | \nu_j \rangle = \delta_{ij}$ Kinematics

Normalize:

$$|\nu_\alpha\rangle = \overbrace{\frac{1}{\sqrt{(NN^\dagger)_{\alpha\alpha}}}\sum_i N_{\alpha i}^*}^{\sum_i \tilde{N}_{\alpha i}^*}|\nu_i\rangle$$

$$\langle \nu_\alpha | \nu_\beta \rangle = N_{\alpha i} N_{i\beta}^* \neq \delta_{\alpha\beta}$$

$$i\, d/dt\, |\nu_\alpha\rangle = H|\nu_\alpha\rangle =$$

$$= \sum_j |\nu_j\rangle\langle \nu_j| H |\nu_\alpha\rangle =$$

$$= \sum_i |\nu_i\rangle E_i \tilde{N}_{\alpha i}^* =$$

$$= \sum_\beta (\tilde{N}^* E (N^\dagger)^{-1})_{\alpha\beta} |\nu_\beta\rangle$$

(3)

$$P_{\nu_\alpha \to \nu_\beta}(E, t) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 =$$

$$= \frac{1}{(NN^\dagger)_{\alpha\alpha}(NN^\dagger)_{\beta\beta}} \Big[\underbrace{\sum |N_{\alpha i}|^2 |N_{\beta i}|^2}_{\neq \delta_{\alpha\beta}} + \dots \Big]$$

$\Rightarrow t = 0$ and $L = 0$

$$P_{\nu_\alpha \to \nu_\beta} = \frac{|(NN^\dagger)_{\beta\alpha}|^2}{(NN^\dagger)_{\beta\beta}(NN^\dagger)_{\alpha\alpha}} \neq 0$$

Also here some hints but no definite significant result

Effects:

- All SM observables with G_F
- Z decay into $\nu_i \bar{\nu}_j$
- CC/NC relative strength
- Short (very short) baseline experiments
- Lepton flavor violating decays

(4)