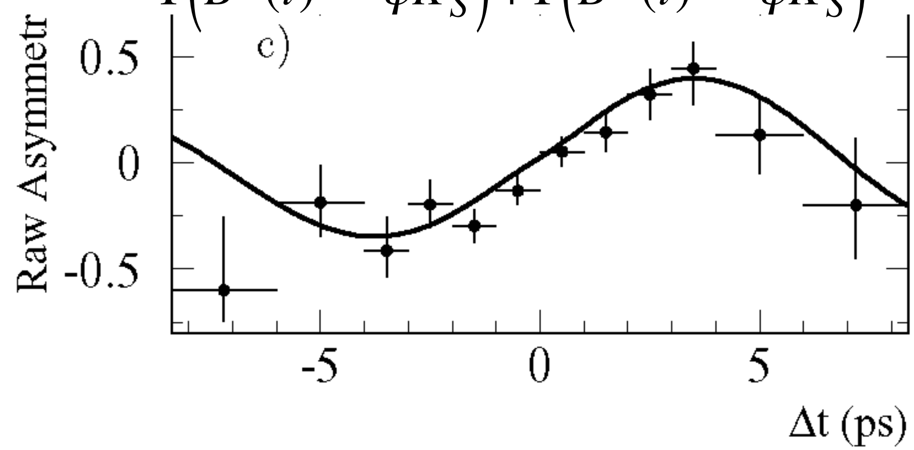
Note

The last lecture for this term (on April 10) will be held in Room 408 instead of Room 137.

CP Violation Status

CP violation can only be observed in the neutral kaon system, and now in beauty mesons produced at B-factory experiments, *i.e.* BELLE and BaBar

$$A_f(t) = \frac{\Gamma\left(B^0(t) \to \psi K_S^0\right) - \Gamma\left(\overline{B}^0(t) \to \psi K_S^0\right)}{\Gamma\left(B^0(t) \to \psi K_S^0\right) + \Gamma\left(\overline{B}^0(t) \to \psi K_S^0\right)}$$



http://arXiv.org/pdf/hep-ex/0203007

All data are consistent with CP violation being described by the single parameter **δ** in the Standard Electroweak Model CKM quark weak mixing matrix.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\left(c_{ij}^2 + s_{ij}^2 \equiv \cos^2\theta_{ij} + \sin^2\theta_{ij} = 1\right)$$

Models for CP violation

1) Electromagnetic

QED$_{\text{hadrons}}$ C & T violating, P conserving $\Rightarrow$ $\not{C}\not{P} \sim \alpha$

but $\eta^0 \to \pi^+\pi^- \Rightarrow C_{\not{em}} \lesssim 10^{-3}$, and $\mu^n_{edm} \Rightarrow C_{\not{em}} \lesssim 10^{-8}$

2) Millistrong

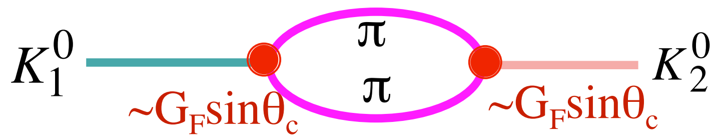
Strong interaction violates C & T @ $\sim 10^{-3}$ $\Rightarrow$ $\not{C}\not{P} \sim 10^{-3}$

but $p\bar{p} \Rightarrow \not{C}_{\text{strong}} \lesssim 10^{-2}$, nuclear scattering $\Rightarrow \not{T}_{\text{strong}} \lesssim 10^{-3}$, and $\mu^n_{edm} \Rightarrow C_{em} \lesssim 10^{-8}$

3) Milliweak

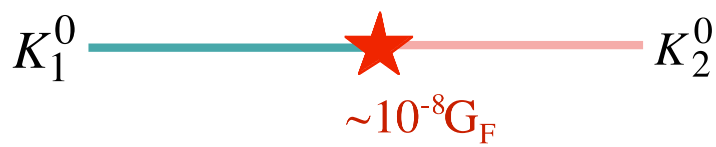
weak interaction violates CP $\sim 10^{-3}$

e.g. Electroweak Standard Model with 3 generations and $\delta \neq 0$.



4) Superweak

A new strangeness changing ($\Delta S=2$) CP violating interaction with coupling



$$g_{SW} \sim 10^{-3} G_F^2 m_K^2 \;\sim\; 10^{-8} G_F$$

but excluded by $\varepsilon'/\varepsilon \neq 0$ ($= 2.1 \pm 0.5 \times 10^{-3}$, from KTeV and NA48) and observation of CP violation in B decays.

The (Bailey) Standard Model

Constituent point fermions

Quarks: u c t **Leptons:** ν_e ν_μ ν_τ

d s b e μ t

interacting via forces mediated by vector bosons

1 photon, W^+, W^-, Z^0, 8 gluons

as a consequence of gauge symmetries

$U(1)_{em} \times SU(2)_{weak} \times SU(3)_{Colour(strong)}$

with at least one neutral scalar boson

1 Higgs

setting the weak mass scale and preventing unitarity violation

Parameters

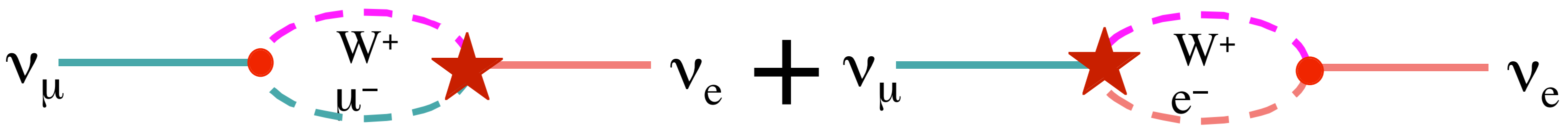
Gauge	couplings	4	$\alpha, \alpha_S, \theta_W, G_N$
Quark	masses	6	$m_u, m_d, m_s, m_c, m_b, m_t$
	angles	4	$\theta_{13}, \theta_{12}, \theta_{23}, \delta$
Lepton	masses	6	m_e, m_μ, m_τ, $\mathbf{m_{\nu 1}, m_{\nu 2}, m_{\nu 3}}$
	angles	4	$\boldsymbol{\theta_{13}, \theta_{12}, \theta_{23}, \delta}$
Higgs sector	masses	2	m_H, m_W
Minimal Total		26	

Lepton Flavour Violation

Flavour eigenstates: ν_e ν_μ ν_τ

but the weak interaction does not conserve quark flavour,
does it conserve lepton flavour?

e.g.



Mass eigenstates: ν_1 ν_2 ν_3

e.g. 2-state mixing $\nu_1 = \nu_e \cos\theta - \nu_\mu \sin\theta \quad , \quad \nu_2 = \nu_e \sin\theta + \nu_\mu \cos\theta$

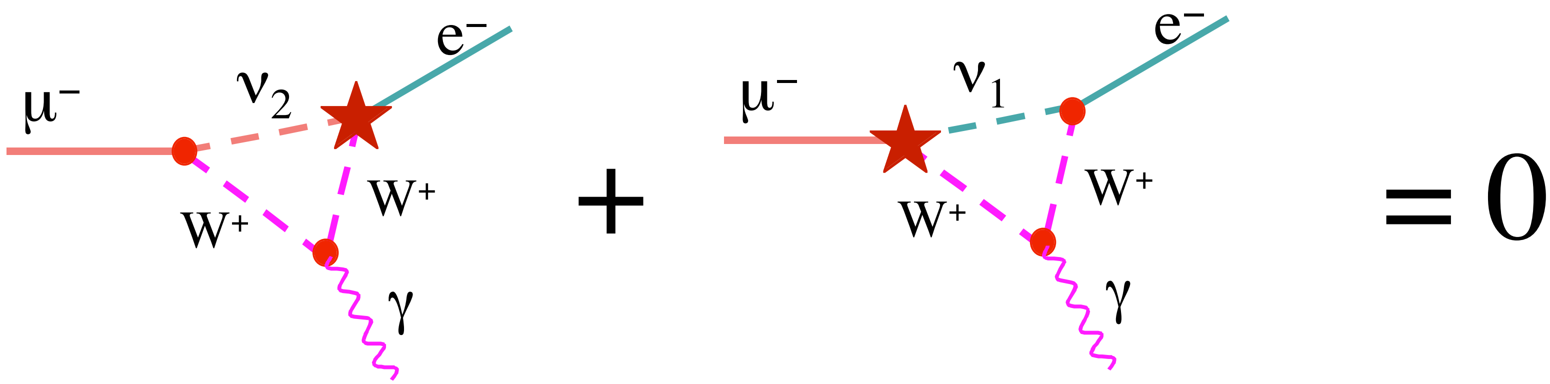
Neutrinos will oscillate if their mass eigenstates are distinguishable:

$$\mathrm{Prob}\,(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \ \sin^2\left(\frac{1.27\,\Delta m^2\,(\mathrm{eV}^2)\ L\,(\mathrm{km})}{E\,(\mathrm{GeV})}\right)$$

$$\left(\Delta m_\nu^2 = m_{\nu_2}^2 - m_{\nu_1}^2\right)$$

Lepton Flavour Violating Decays

In standard electroweak theory, amplitudes for lepton number violating decays are zero if all neutrinos have the same mass, *e.g*.



$$\frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to \nu_\mu e \bar{\nu}_e)} \approx \frac{3\alpha}{32\pi}\left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2 \sin^2\theta \cos^2\theta$$

The current experimental upper limit is from the MEGA experiment at LAMPF

$BR(\mu^- \to e^- \gamma) < 1.2\times10^{-11}$

$$\Delta m_\nu^2 < 0.04 GeV^2$$

(http://link.aps.org/abstract/PRD/v16/p1444)

Direct Limits on Neutrino Masses

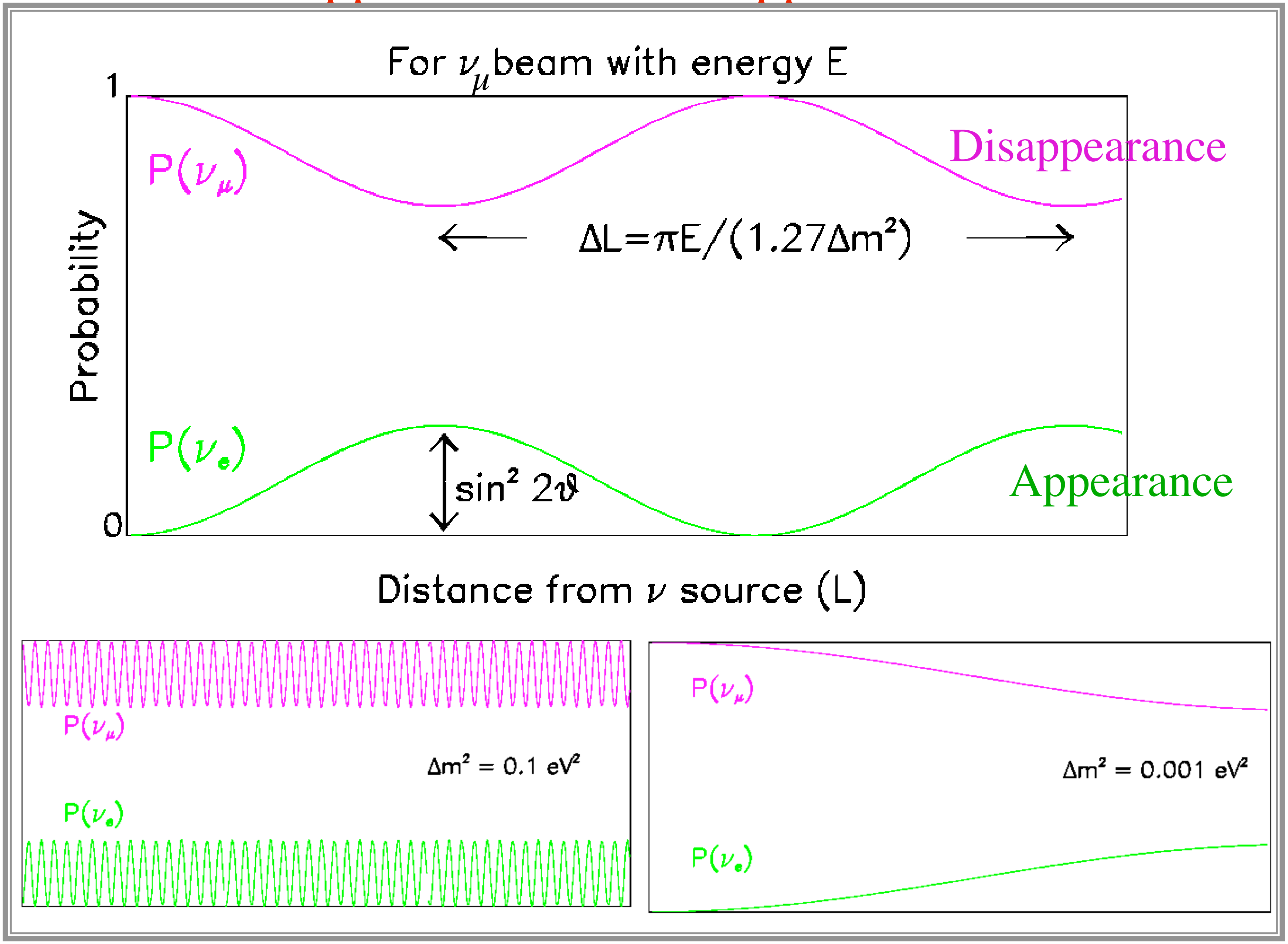
Direct limits on neutrino masses from endpoint distributions of weak decays

Neutrino Type	Mass Limit	Process
Electron	$<\sim 10$ eV	${}^3H \to {}^3He + e^- + \nu_e$
Muon	< 170 keV	$\pi^+ \to \mu^+ + \nu_\mu$
Tau	< 18.2 MeV	$\tau \to 5\pi\left(\pi^0\right) + \nu_\tau$

(Experimental central values of m^2 for ν_e always slightly negative???)

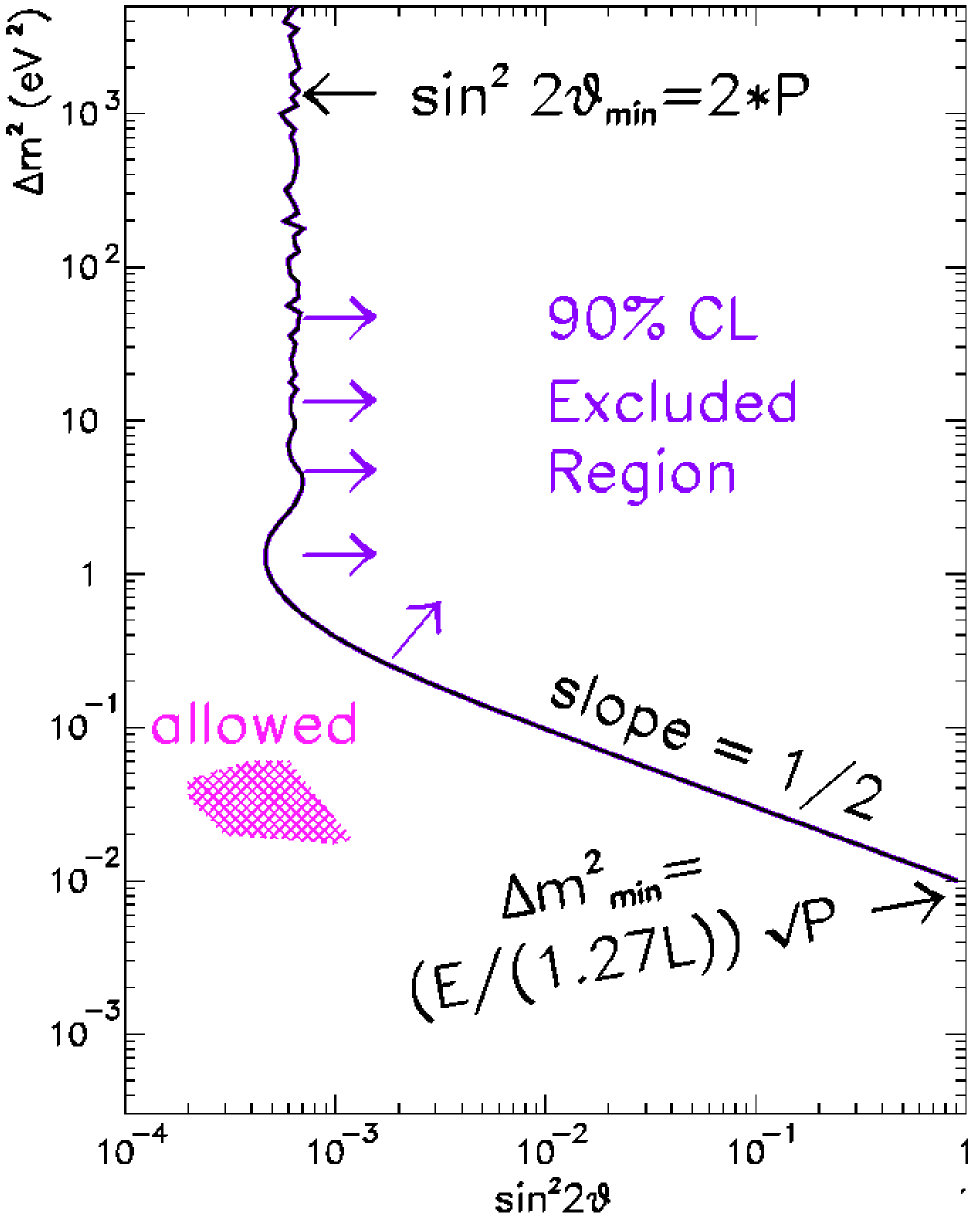
Experiment	measured m^2 (eV^2)	limit (eV), 95% C.L.	Year
Troitsk	-1.0 ± 3.0± 2.1	2.5	2000
Mainz	-3.7 ± 5.3 ± 2.1	2.8	2000
LLNL	- 130 ± 20± 15	7.0	1995
CIAE	- 31 ± 75± 48	12.4	1995
Zurich	-24 ± 48± 61	11.7	1992
Tokyo INS	- 65 ± 85± 65	13.1	1991
Los Alamos	- 147 ± 68± 41	9.3	1991

Appearance and Disappearance



(http://www.nevis.columbia.edu/~conrad/nupage.html)

Constraints on Neutrino Oscillations



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From Janet Conrad's talks