Lecture 21/22

Lepton mixing

W bosons couple to lepton doublets

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

- ν_e, ν_μ, ν_τ are mixtures of mass eigenstates ν_1, ν_2, ν_3
- mixing angles are large (up to 45°)
- but masses are very small (< 1 eV)

$\rightarrow$ effects only visible over long distances ($\gtrsim 1$ km for $E_\nu \gtrsim 1$ MeV)

CP violation

Weak interaction with one or two generations

- violates parity P and charge conjugation C but preserves CP (couples to LH fermions and RH antifermions)

Mixing between three generations (CKM matrix)

- three mixing angles and one complex phase

$\rightarrow$ small violation of CP symmetry in weak interaction (observed in $K^0 - \overline{K}^0$ and $B^0 - \overline{B}^0$ mesons)

Needed to explain origin of matter in universe: Sakharov conditions

1) nonconservation of baryon number
2) violation of C and CP
3) universe out of thermal equilibrium

Origins of mass

Weak interaction couples to left-handed doublets

$$\begin{pmatrix} u_L \\ d'_L \end{pmatrix} \qquad \begin{pmatrix} \nu_{eL} \\ e^-_L \end{pmatrix}$$

but not to right-handed singlets u_R, d_R, e^-_R, ν_{eR}

Massless fermions with $g = 2$ (intrinsic magnetic moments)

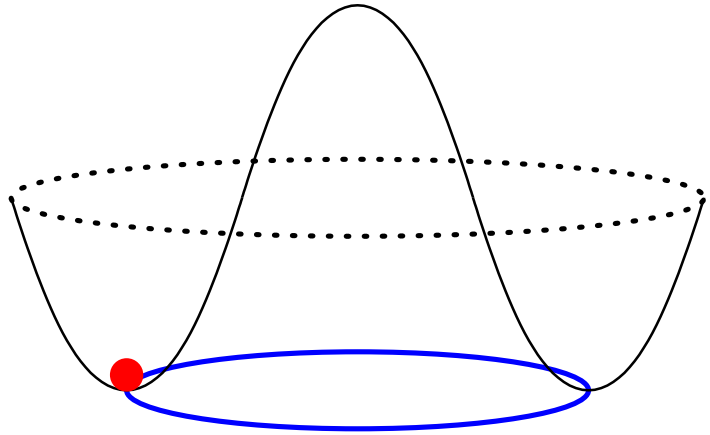
- chirality preserved by interactions with vector gauge fields
- left-handed weak isospin conserved

Interactions with weak doublet of spin-0 fields

$$\begin{pmatrix} \phi^- \\ \phi^0 \end{pmatrix}$$

- change chirality of fermions
- conserve weak isospin
- but to generate masses also need . . .

. . . a Mexican hat



Quartic potential for scalar fields ϕ

- vacuum expectation value $\langle\phi\rangle \neq 0$ everywhere in space
  (like magetisation in a permanent magnet)
- symmetry is hidden or "spontaneously broken"
  (not visible sitting in circular valley round brim)
- nonzero $\langle\phi\rangle$ gives fermions mass (Nambu)
- also gives vector bosons mass (Brout, Englert, Higgs)
- restoring force for radial oscillations $\rightarrow$ massive spin-0 particle:
  Higgs boson

Brout-Englert-Higgs field generates

- charged lepton masses: from 0.5 MeV to 1.8 GeV
- "current" (high-energy) quark masses: from $\sim$ 5 MeV to 173 GeV
- $W^{\pm}$, Z^0 masses: $\sim$ 80 GeV
- possibly neutrino massses: $<$ 2 eV (but then why so small?)
- but $m_{u,d} \simeq$ 5 MeV $\rightarrow$ less than $\sim 10\%$ of mass as we know it (protons and neutrons of ordinary matter)

QCD vacuum

- condensate of $q\overline{q}$ pairs acts like another BEH field
- hides (chiral) isospin symmetries of $\sim$ massless quarks
- generates constituent quark masses: $\sim$ 350 MeV
- excitations round brim of hat $\rightarrow$ very light hadrons: pions (would be exactly massless without weak BEH field)
- pions doubly special
  - mediate longest-range strong forces in nuclei
  - carry "memory" of the symmetries of QCD