PHY492: Nuclear & Particle Physics

Lecture 21

Neutrinos and neutrino oscillations
HW hints
Beyond the Standard Model

Tier II Assignments
in E-mail this afternoon

Propagation of neutrino mass states

- Remember, Schrodinger wave equation solutions ?
- Remember, time dependent Schrodinger wave equation solutions ?

$$e^{-i(\omega t - kx)}; \quad \omega = \frac{E}{\hbar}; \quad k = \frac{p}{\hbar}$$

$$\psi(x,t) = \psi(x,0)e^{-\frac{i}{\hbar}(Et - px)}; \quad \text{let } x = L,\ t = L/c$$

$$\psi(L) = \psi(0)e^{-\frac{i}{\hbar c}(E - pc)L}$$

$$\psi(L) = \psi(0)e^{-\frac{i}{\hbar c}\frac{m^2c^4}{2E}L}$$

$$pc = E\sqrt{1 - \frac{m^2c^4}{E^2}} \approx E - \frac{m^2c^4}{2E}, \quad E >> mc^2$$

$$E - pc \approx \frac{m^2c^4}{2E}$$

- Phase factor $e^{-\frac{i}{\hbar c}\frac{m^2c^4}{2E}L}$ depends on distance L from production, particle energy, and mass squared !!

Three ν flavors and three ν masses

- As is the case for quarks, the mixing matrix is 3x3
- Very different from quarks, off-diagonal mixing angles are LARGE.

Missing one crucial angle, sinθ_{13}, and a CP violating phase δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = M \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|M| \approx \begin{pmatrix} 0.83 & 0.55 & s_{13}e^{i\delta} \\ 0.39 & 0.59 & .7 \\ 0.39 & 0.59 & .7 \end{pmatrix}; \begin{matrix} s_{13} < 0.25 \\ \delta \sim ? \end{matrix}$$

- Result for muon neutrinos oscillating to electron neutrinos is the same as in the two neutrino case.

appearing electron neutrinos

$$\left|\left\langle \nu_e \middle| \nu(L) \right\rangle\right|^2 = \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m_{23}^2 L / E\right)$$

$$\Delta m_{23}^2 \sim 3\times 10^{-3}\ \text{eV}^2; \quad \text{pick } E \sim 2\ \text{GeV}$$

$$\lambda = \frac{2\pi E}{1.27\Delta m_{23}^2} = \frac{4\pi}{4\times 10^{-3}}\text{km} \approx 3000\ \text{km}$$

First maximum at $\lambda / 4 \approx 750$ km

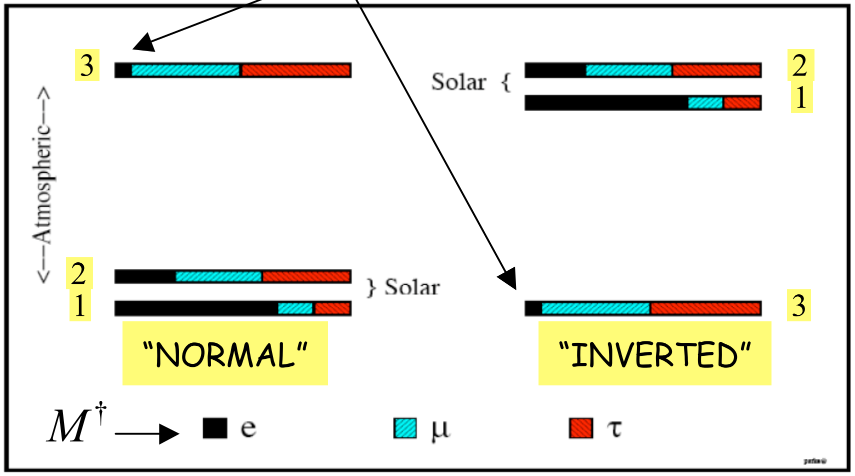
Fermilab neutrino beam points to Sudan MN which is 750 km away

Mass hierarchy of three mass states

- Mass splitting $\Delta m_{ij}^2 = \left| m_j^2 - m_i^2 \right|$

$$\text{Solar: } \Delta m_{12}^2 \sim 5 \times 10^{-5} \text{ eV}^2 \quad \text{Small}$$
$$\text{Atmospheric: } \Delta m_{23}^2 \sim 2.5 \times 10^{-3} \text{ eV}^2 \quad \text{Big}$$

e component not to scale



- Mass hierarchy unknown
  - "NORMAL" as in quark masses
  - "INVERTED" as in P-states?
  - Can't do CP violation on earth without hierarchy resolution
- MSW effect
  - In a long baseline experiment ν_e and $\bar{\nu}_e$ passing through the earth have oscillation probability affected with opposite signs.
  - Good for determination of mass hierarchy, but complicates CP violation analysis. Unavoidable, even in Japan.

HW hints

14.1 Top quark lifetime

$$\delta E \delta t \sim \hbar; \quad \tau \sim \frac{\hbar}{\Gamma}$$

Top quark decay $t \rightarrow W + b$

Top produced ~ at rest

Total energy is top mass

W momentum = b-quark momentum

Parton-parton collision

$$p_a = x_a \frac{\sqrt{s}}{2c} \longrightarrow \qquad \longleftarrow p_b = -x_b \frac{\sqrt{s}}{2c}$$

s = center of mass energy squared of pp collision

$\hat{s}$ = center of mass energy of parton(a) parton(b) collision

$= x_a x_b s$

14.3

$$\Lambda = (uds); \quad \Sigma^+ = (uus)$$

$$K^0 = (\bar{s}d); \quad K^+ = (\bar{s}u)$$

$$\pi^+ = (u\bar{d}); \quad \pi^+ = \tfrac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

HW hints

14.5 Q=-1/3 Quark mixing matrix

$$\begin{pmatrix} d \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta_C & -\sin\theta_C \\ \sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d' \\ s' \end{pmatrix}$$

Strong Interaction state

$$K^0 = (d, \bar{s})$$

Weak interaction acts on mixed states: $d', \bar{s}'$

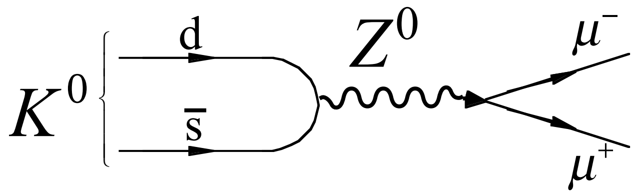
Z boson couples only to the same weak flavor quarks

$$d' + \bar{d}'$$
$$s' + \bar{s}'$$

$\langle d', \bar{s}' | Z \rangle$ and $\langle s', \bar{d}' | Z \rangle$ are both ZERO

$$\langle d', \bar{d}' | Z \rangle = \langle s', \bar{s}' | Z \rangle \neq 0$$

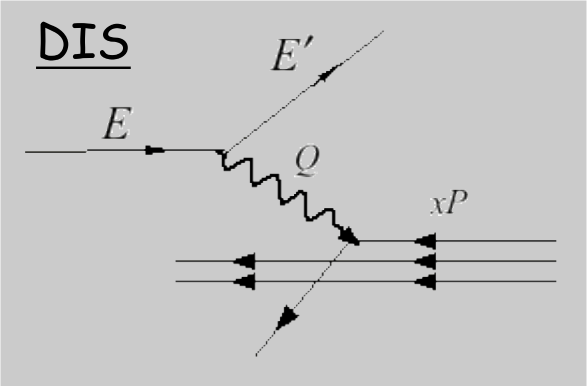
Calculate $\langle d, \bar{s} | Z \rangle$



HW hint: Deep Inelastic Scattering (DIS)

14.7 a) 4-vector dot product (lab frame)

$$Q = \left[\left(\vec{k}' - \vec{k}\right), \nu\right]; \quad P = \left[0, m_p c^2\right]$$
$$Q \cdot P = ?$$



b) parton absorbs Q but remains massless

$$\left(x\vec{P} + \vec{Q}\right)^2 = 0$$

c) from 14.6

W=mass of hadronic system

$$W^2 = m_p^2 + \frac{2m_p c^2 \nu}{c^4} - \frac{Q^2}{c^4}$$

Looking for the answers

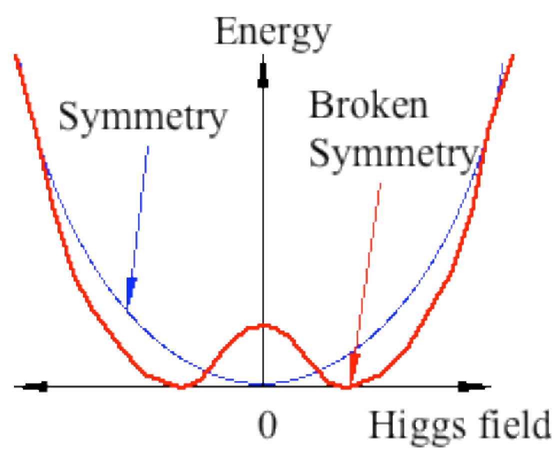
Standard model is continually being tested for evidence of something that doesn't fit, that might shed light on one or more of these questions:

- Why is the boson symmetry broken; W/Z boson masses large, but the photon mass zero?
- Why do quarks have such wildly different masses?
- Why is the # of quark and lepton and generations equal to 3?
- Why do quarks and neutrinos have the observed mixing angles θ? Quarks have small mixing θ's, but neutrinos have large mixing θ's.
- Why are neutrinos masses so small compared to anything?
- Why is gravity such a puny force?
- Why doesn't the proton decay, or does it?
- Why does matter dominate over antimatter? Why CP violation?
- What is dark matter?

Dynamical symmetry breaking, the Higgs Mechanism

- Weinberg, Glashow & Salam
  - Basic theory has 4 *massless* bosons: triplet W_1,W_2,W_3, and singlet B
  - Dynamical Symmetry Breaking via the Higgs Mechanism
  - W_1, W_2 become $W^{\pm}$, but W_3, and B mix with "Weinberg angle" = θ_W

$$\gamma = B^0 \cos\theta_W + W_3 \sin\theta_W$$
$$Z^0 = -B^0 \sin\theta_W + W_3 \cos\theta_W$$



  - W and Z masses are related

$$m_W / m_Z = \cos\theta_W$$

  - θ_W measured in neutrino scattering

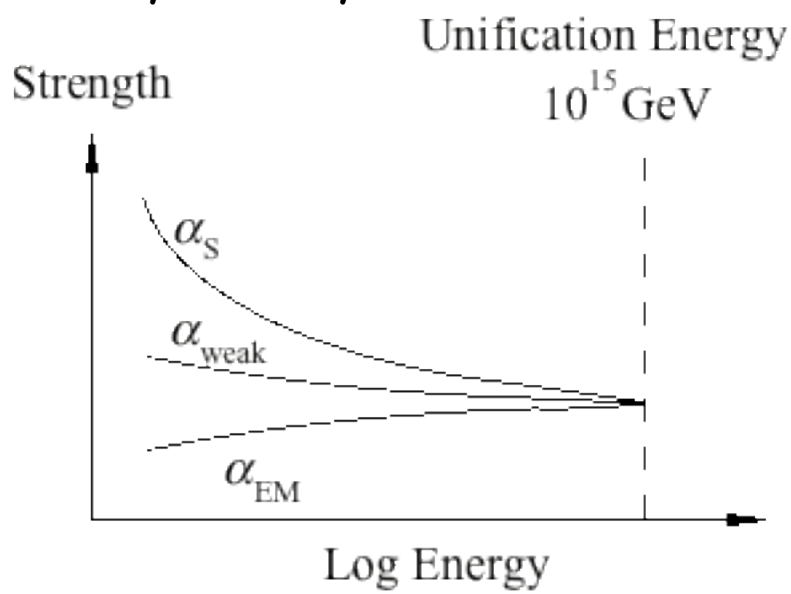
$$\sin^2\theta_W = 0.233$$

  - Predict: $m_W / m_Z = 0.88$ $\quad$ $m_W / m_Z = 80.4/91.2 = 0.88$

- Simplest dynamical symmetry breaking would have 1 Higgs scalar (spin 0) particle $\quad H^0 \quad$ $200\ \text{GeV} > m_H$ $> 115\ \text{GeV}$

Grand Unified Theory (GUT)

- At very high energies everything would be highly symmetric
- All masses and couplings would be the same
- At low energies the symmetry is broken



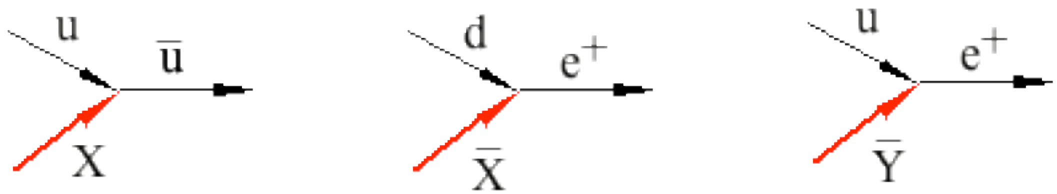
- EW group is SU(2)xU(1): 4 gauge bosons (γ, W^+, W^-, Z)
- QCD group is $SU(3)_{color}$:8 gauge bosons(gluons)
- Simplest GUT is SU(5): ---> 24 gauge bosons (12 more bosons)

SU(5) has 12 more gauge particles

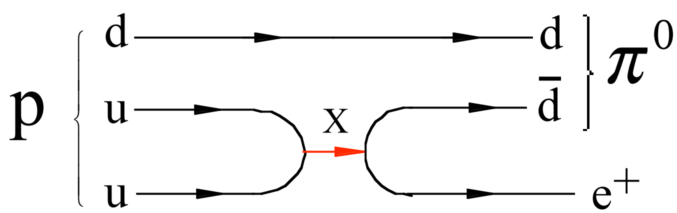
- Three with charge =-1/3, in three"colors" (Y_R, Y_G, Y_B)
- Three with charge =-4/3, in three"colors" (X_R, X_G, X_B)
- Six anti-particles of these

- These gauge particles can change quarks into leptons or change quarks into antiquarks

  Examples



- Can lead to proton decay (lifetime is $< 6\times10^{30}$ years) N.G.



Measured lifetime lower limit

$> 10^{31}$ - 10^{32} years

- Some success. But no proton decay, no 3 generations, has monopoles

Supersymmetry (SUSY)

- Every fermion has a supersymmetric boson partner and vise-versa
  - electron (e) ---> selectron ($\tilde{s}$)
  - quark (q) ---> squark ($\tilde{q}$)
  - photon (γ) ---> photino ($\tilde{\gamma}$)
  - gluon (g) ---> gluino ($\tilde{g}$)
  - W,Z ---> wino ($\tilde{W}$), zino ($\tilde{Z}$)
  - Higgs (H) ---> Higgsino ($\tilde{H}$)
  - Higgs* ($H^{\pm}$) ---> Higgsino*($\tilde{H}^{\pm}$)
- R-parity R=+1 (particles) R=–1 (supersymmetric particles)
- R parity product conserved
  - supersymmetric particles produced in pairs (A + B --> $\tilde{A}$ + $\tilde{B}$)
    (1 x 1 = –1 x –1)
  - Heavy supersymmetric particles decays ($\tilde{A}$ --> $\tilde{B}$ + A)
    (–1 = –1 x +1
  - Lightest supersymmetic particle cannot decay (might be stop quark)
  - Good Dark Matter candidate

Other qualities of Supersymmetry (SUSY)

- SUSY partners can cancel infinities that arise in calculations
- Unifies fermions an bosons
- Involves angular momentum inherently
  - rotational symmetries --- space translations
  - geometry of spacetime --- GRAVITY

- One major problem -- NOT a shred of evidence for it.
- Mass limit is greater than about 100 GeV
- Still looking at Fermilab Tevatron collider (CDF and D-Zero)
- Will look for it at LHC

Theories of everything