PHY492: Nuclear & Particle Physics
Part II

Lecture 19

QCD
Deep inelastic lepton scattering
Time evolution of Neutrino species
QCD basics

- **Quarks in three colors**
  - red
  - green
  - blue

- **Antiquarks in three anticolors**
  - anti-red
  - anti-green
  - anti-blue

- **Mesons**
  - quark-antiquark pair
  - color-anticolor

- **Baryons**
  - 3 quarks
  - 3 different colors

- **Strong (color) force between quarks is due to gluon exchange**
  - gluon has no electric charge or flavor
  - gluon carries a color-anticolor pair
  - exchange changes only quark colors
  - in mesons gluon changes both colors
**QCD force**

- **Pi meson**
  
  \[
  \pi^+ \rightarrow u \rightarrow \text{huge energy density} \rightarrow \bar{d} \rightarrow \bar{d}
  \]

- **Attempt to free the quarks**
  - force grows with separation
  - huge field energy density

- **Gluon -> quark-antiquark pair**
  - tail end splits to a $s \bar{s}$
  - head end to $u \bar{u}$
  - gluons conserve flavor
  - must split to $q \bar{q}$ (same flavor)

  \[
  u \rightarrow \text{gluons have color but no flavor!} \rightarrow \bar{d} \rightarrow \pi^+
  \]

  \[
  \bar{d} \rightarrow \text{gluons have color but no flavor!} \rightarrow u \rightarrow \pi^+
  \]

  \[
  u \rightarrow \text{gluons have color but no flavor!} \rightarrow \bar{s} \rightarrow \pi^+
  \]

  \[
  s \rightarrow \text{gluons have color but no flavor!} \rightarrow \bar{u} \rightarrow \pi^+
  \]

  \[
  u \rightarrow \text{gluons have color but no flavor!} \rightarrow \bar{d} \rightarrow \pi^+
  \]
Quarks and gluons point-like within hadrons

- Parton (Feynman’s term) model of hadrons remains with us, replacing partons with quarks and gluons.
- Electron scattering on hydrogen and deuterium targets.

\[ \nu = E - E' \]
\[ Q^2 = 4EE' \sin^2(\theta/2) \]

- Bjorken scaling variable:
  \[ x = \frac{Q^2}{2m_p \nu} \]
  \[ 0 < x < 1 \]

- If there are partons, cross sections at fixed \( x \) independent of \( Q^2 \)

Viewed from infinite momentum frame
Parton distribution functions in the proton

“Valence”  “Sea”

- Proton “parton” content is $u \, u \, d + (q \, \bar{q} \text{ pairs}) + \text{gluons}$

- At $Q \approx 5 \text{ GeV/c}$, proton is 50% quarks and 50% gluons

- Sea quarks are from gluon “splitting”
Scaling violations

- Full QCD calculations predict deviations from scaling at large $Q^2$
  - Large $Q^2$ means a “hard virtual photon”
  - Large $Q^2$ kicks quark out before it can “catch” radiated gluons.
  - Observed gluon fraction increases for large $Q^2$. 

\begin{align*}
\text{Small } Q^2 & \\
\text{Large } Q^2 & 
\end{align*}
Weak neutral currents

• In addition to $W^+, W^-$ bosons, there is a neutral version, $Z$ boson.
• As seen earlier, there is a cancellation of weak neutral currents in weak decays due to the symmetry of the CKM matrix
• The absence of weak neutral currents lead some to believe they were absent. Neutrino scattering experiments proved them wrong.

\begin{align*}
\text{Charged current} & \quad \text{Neutral current} \\
\nu_\mu & \rightarrow \mu^+ \\
W^+ & \rightarrow p \ n \\
\bar{\nu}_\mu & \rightarrow \bar{\mu}^+ \\
Z^0 & \rightarrow p \ p
\end{align*}

• CERN spps collider finished it off by producing them in hadronic collisions. However, the prettiest production is in e+e− collisions.
Neutrino mass

- Many attempts to see if neutrinos have mass
  - Tritium beta decay end-point
    - electron neutrino mass < 3 eV/c²
  - Meson decays
    - muon neutrino mass < 200 keV/c²
    - tau neutrino mass < 18 MeV/c²
  - Cosmological limits
    - lots of assumptions about big bang
    - nuclear-synthesis, more assumptions
    - (number density)×(mass) in universe constraint
    - neutrino masses < 1 eV

- Theoretical bias for non-zero neutrino mass
  - Why are all neutrinos left-handed?
  - What happened to all the right hand neutrinos?
  - “See-Saw” mechanism
    - right hand neutrinos forced to be VERY MASSIVE
    - and left hand neutrinos to be very light (but not zero).
Propagation of neutrino mass states

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

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

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

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

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

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

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

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