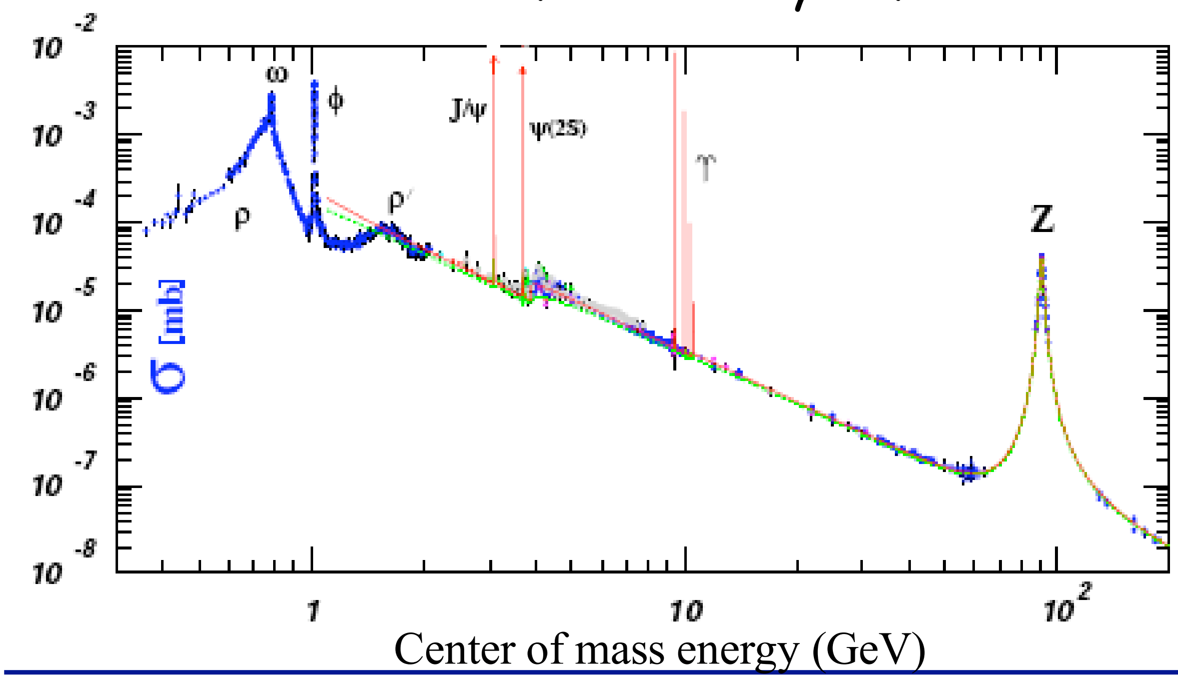
PHY492: Nuclear & Particle Physics

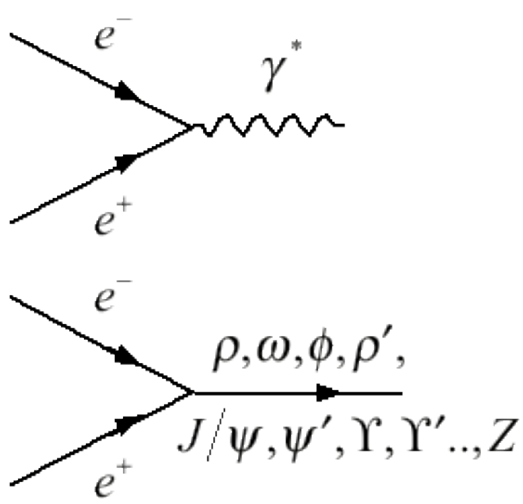
Lecture 18

Quark-onium
QCD basics

Particle production in $e^+ e^-$ collisions

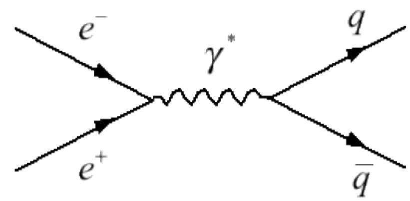
- e+ e- inelastic collisions produce of particles with quantum numbers of the photon.
- Bound states of $q\bar{q}$ are analogous to bound state of e^+e^-, positronium
- First indications of the charm quark show up in “charm-onium”
- Source of most information regarding the bottom quark and bottom-onium
- Detailed studies of the decays of the Z-boson (neutral weak boson)



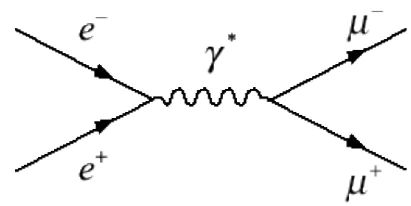


Effects of new quark thresholds

- Photons couple to electric charge Q, and to cross sections with Q^2
- Compared to lepton pairs, cross section should be
  1/9 as big for Q=-1/3 quark pairs, and 4/9 for Q=+2/3 quark pairs



Quark pairs
---> hadron-ize



- Ratio of hadron production to muon production:

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

center of mass energy^2, $s = (E_{cm})^2$

x3 Colors

- With u,d and s quarks:

$$R \sim 2\left(\frac{1}{9}\right) + \left(\frac{4}{9}\right) = \frac{6}{9} \qquad = \frac{6}{3}$$

- Big jump when charm meson threshold crossed:

$$R \sim 2\left(\frac{1}{9}\right) + 2\left(\frac{4}{9}\right) = \frac{10}{9} \qquad = \frac{10}{3}$$

- Smaller jump when bottom meson threshold crossed

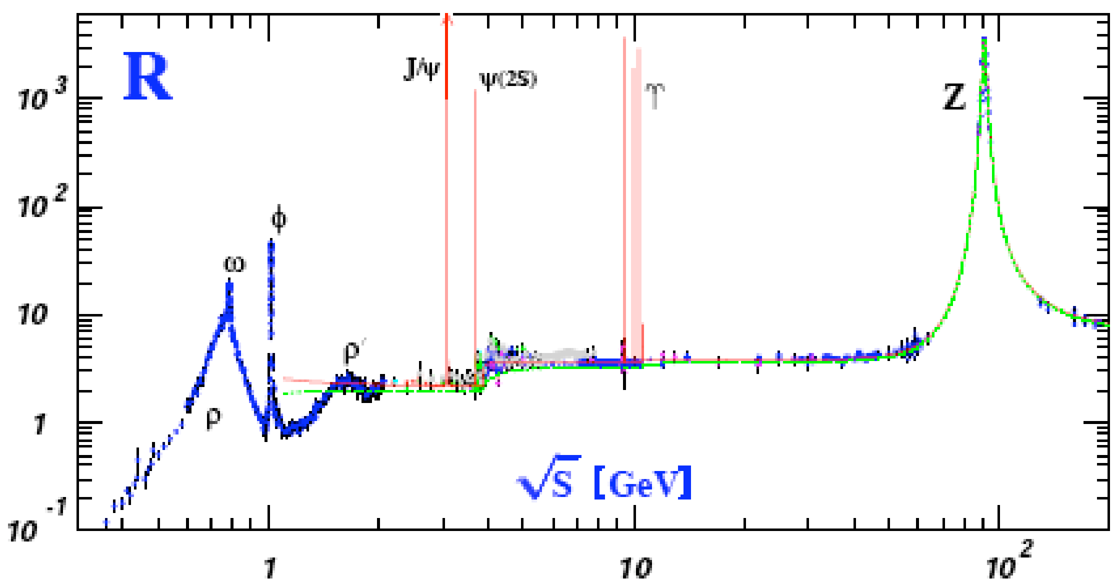
$$R \sim 3\left(\frac{1}{9}\right) + 2\left(\frac{4}{9}\right) = \frac{11}{9} \qquad = \frac{11}{3}$$

More about R

- Data are consistent with 3 charged leptons and 5 quark flavors in 3 colors.

$$R(s) = \frac{\sigma\left(e^+e^- \to hadrons\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$

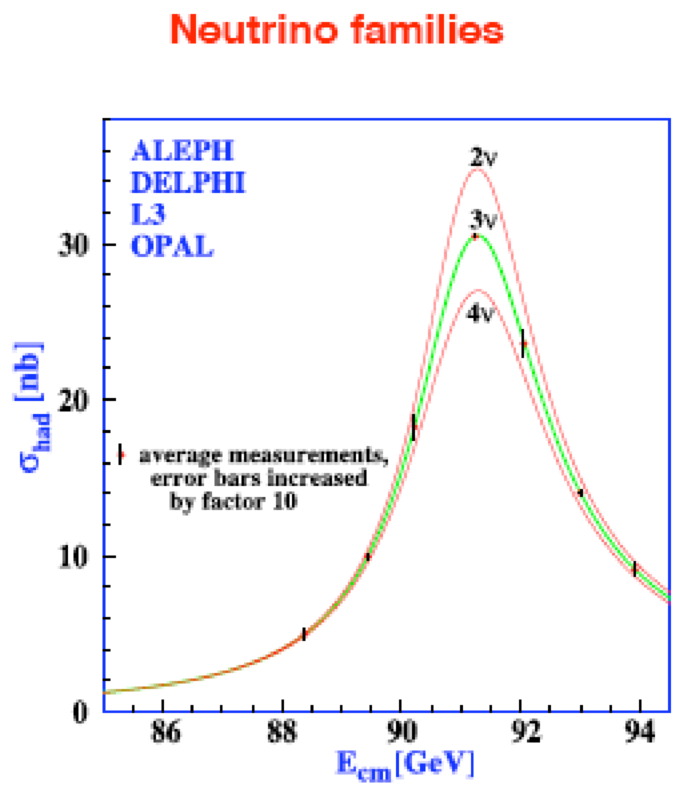
$$R_L = \frac{\sigma\left(e^+e^- \to \tau^+\tau^-\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = 1$$

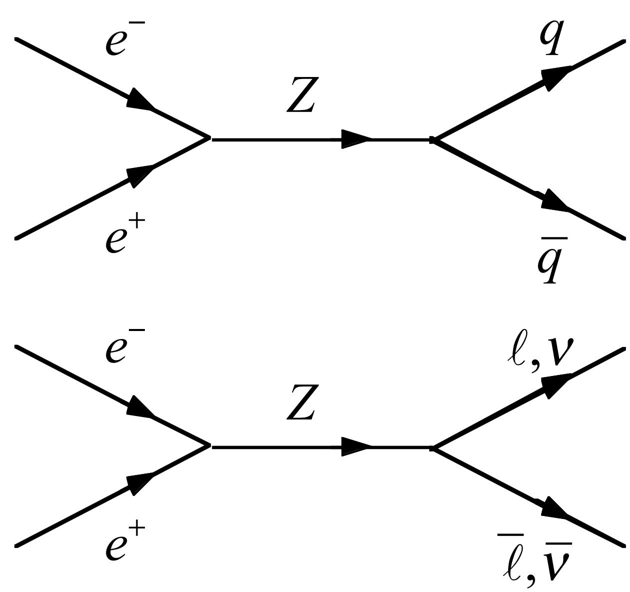


Center of mass energy (GeV)

Number of neutrinos

- Z boson couples to quarks, charged leptons, AND NEUTRINOS
- Total width proportional to the number of final states.
- Width of resonance reflects the total width --> number of light ν's





Heavy quark $q\bar{q}$ bound states

- Production of ψ resonance in e^+e^- annihilations --> $J^{PC} = 1^{--}$
- Bound states of charm (charmonium) and bottom (bottomonium)

<u>Spectroscopic Notation</u>

$n \cdot {}^{2S+1}L_j$

$1^1S_0, 2^1S_0, 2^1P_1, \ \ldots$

$1^3S_1, 2^3S_1, 2\left({}^3P_0, {}^3P_1, {}^3P_2\right), \ \ldots$

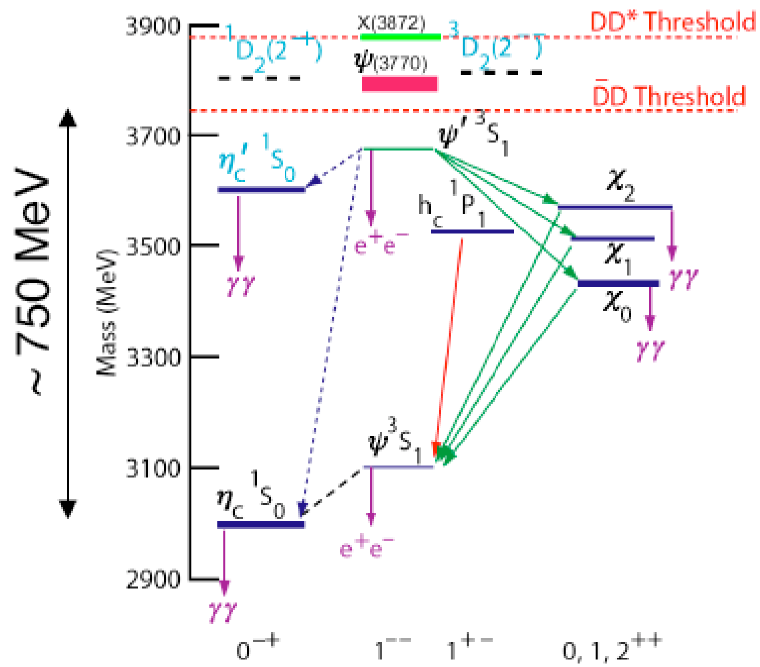
<u>Spin states</u>

$m_S = 0$

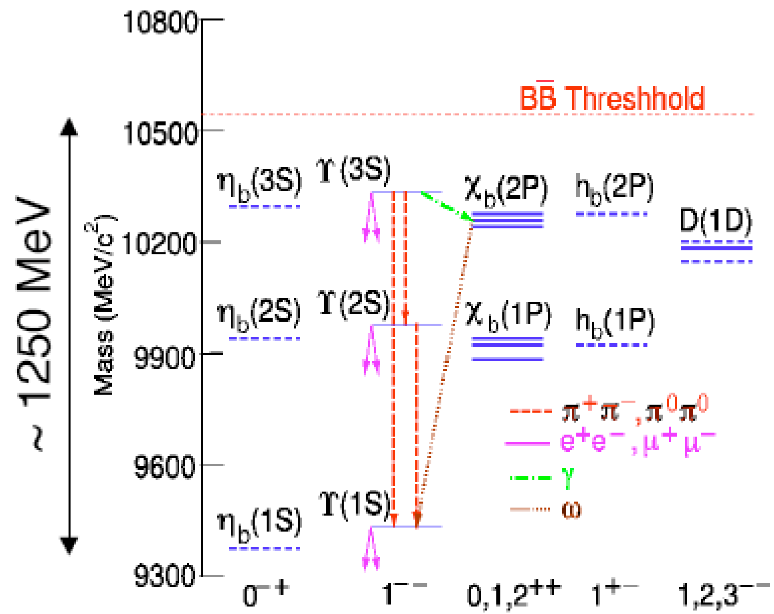
singlet: $\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

triplet: $|\uparrow\uparrow\rangle, \ \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right), \ |\downarrow\downarrow\rangle$

Charmonium

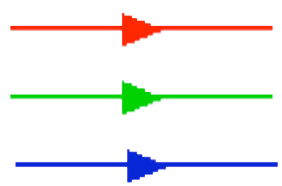


Bottomonium

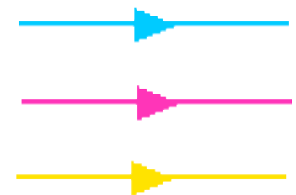


QCD basics

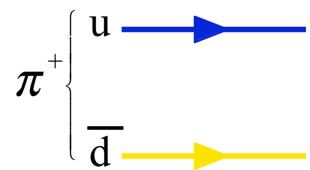
- Quarks in three colors
  - red
  - green
  - blue



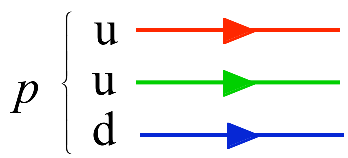
- Antiquarks in three anticolors
  - anti-red
  - anti-green
  - anti-blue



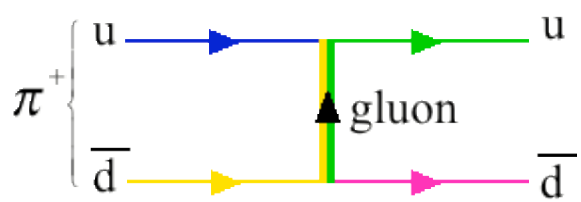
- Mesons
  - quark-antiquark pair
  - color-anticolor



- Baryons
  - 3 quarks
  - 3 different colors

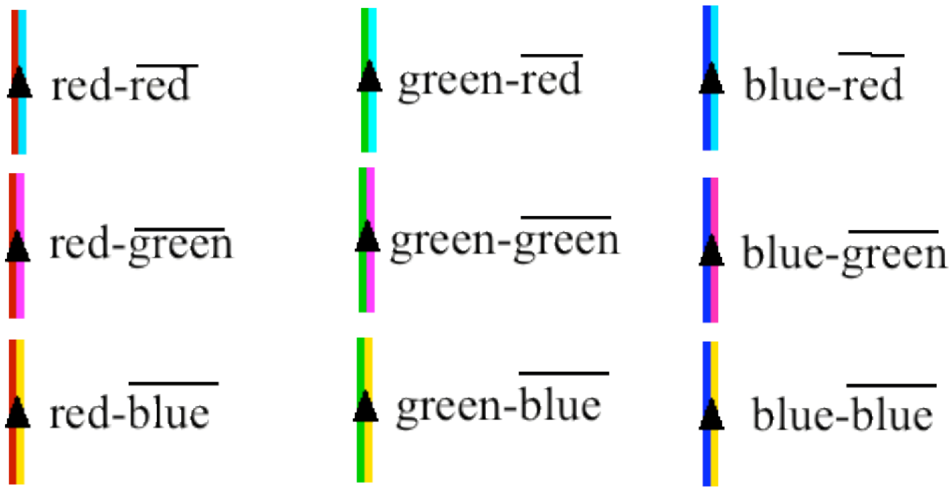


- Strong (color) force between quarks is due to gluon exchange
  - gluon has no electric charge or flavor
  - gluon carries a color-anticolor pair
  - exchange changes only quark colors
  - in mesons the gluon changes both colors

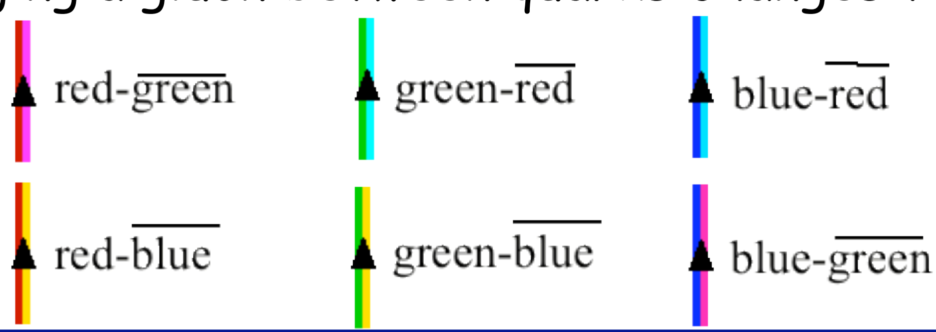


Conceptual gluon situation

- "Color" force between quarks is due to gluon exchange
- Should be nine possible color-anticolor combinations



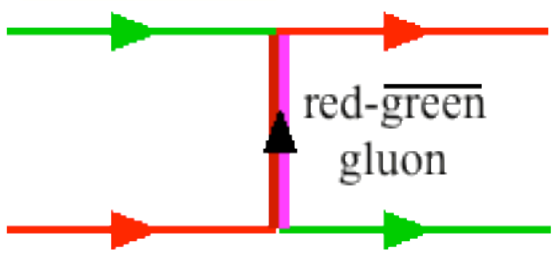
- However the 3 color-anticolor pairs on the diagonal would be colorless particles that are not seen.
- Exchanging a gluon between quarks changes their color.



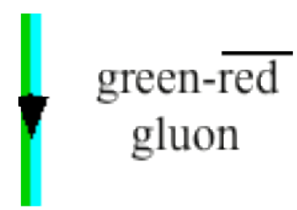
Force between two quarks

- Actually one can form an "octet" (8) of gluons (with color) that are linear combinations of the 9 original states, and a nonexistent "singlet" (1) combination that is colorless. We will bypass this complication.

- The force between two quarks involves the interchange of two colors. The colors just switch quarks via gluon exchange



the anti (gluon) in the other direction also works.

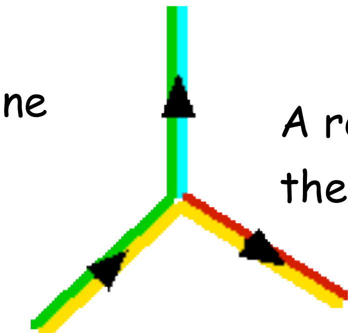


Red color line is continuous.

Green is annihilated at the top vertex and created at the lower vertex

Gluons can couple to other gluons!

- That gluons can couple to other gluons is a fundamental point that distinguishes QCD from electrodynamics QED.
- The three gluon vertex



Properties of QCD

- Coupling constants for forces
  - Weak $\alpha_W \approx 1 \times 10^{-7}$
  - Electrodynamics
    $$\alpha_{em} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137}$$
  - Strong
    $$\alpha_S = 0.3$$
- Strong force is small at small distances (asymptotic freedom)
  - quarks and gluons act freely inside of hadrons
  - can consider the kinematics of collisions as independent
- Strong force grows linearly with increasing distance
  - if ejected from hadron quarks and gluons create strong fields
  - energy density in fields large enough to create quark-antiquark pairs
- Nuclear force is a shielded version of the strong force
- Baryons are fermions -- color wavefunction is anti-symmetric
- Large coupling constant limits interaction calculation accuracy