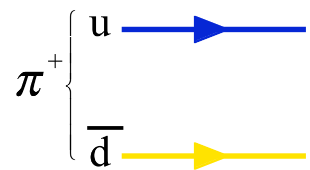
PHY492: Nuclear & Particle Physics
Part II

Lecture 19

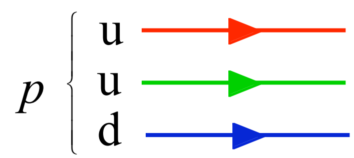
QCD
Deep inelastic lepton scattering
Time evolution of Neutrino species

QCD basics

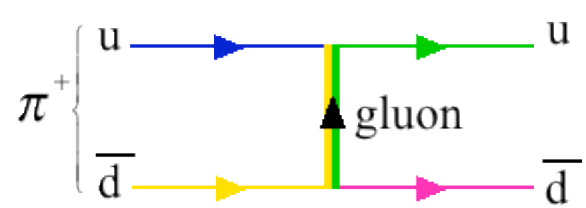
- Quarks in three colors
  - red
  - green
  - blue
- Antiquarks in three anticolors
  - anti-red
  - anti-green
  - anti-blue
- Mesons
  - quark-antiquark pair
  - color-anticolor



- Baryons
  - 3 quarks
  - 3 different colors

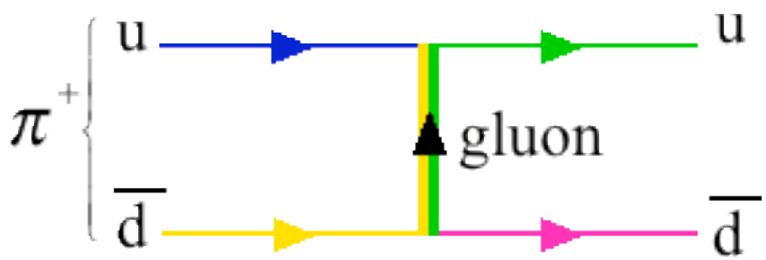


- Strong (color) force between quarks is due to gluon exchange
  - gluon has no electric charge or flavor
  - gluon carries a color-anticolor pair
  - exchange changes only quark colors
  - in mesons gluon changes both colors



QCD force

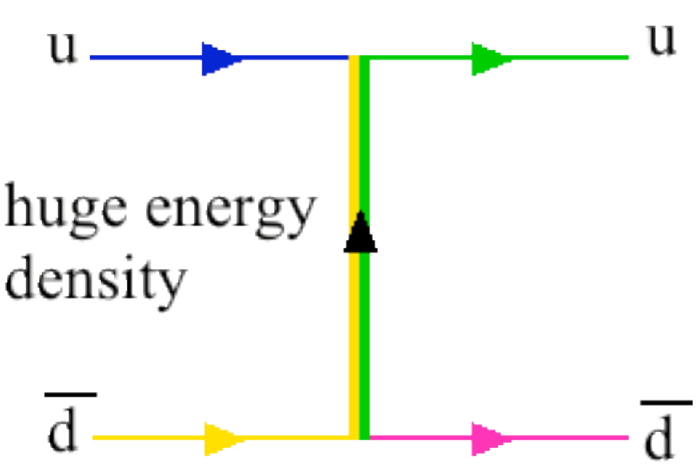
- Pi meson



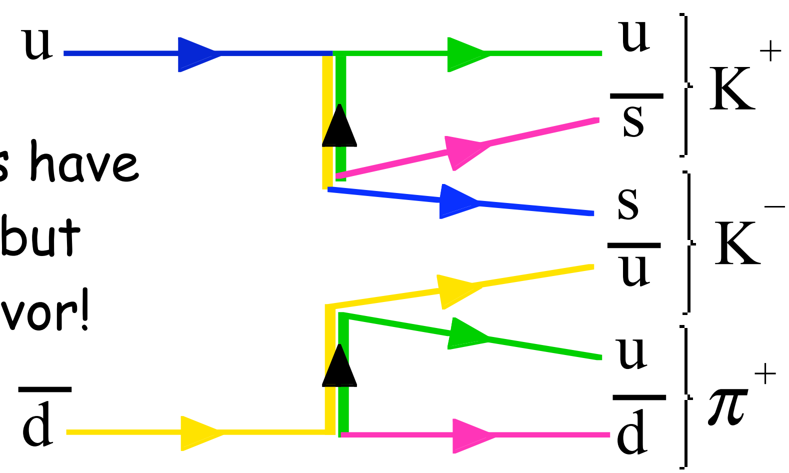
- Attempt to free the quarks
  - force grows with separation
  - huge field energy density

INSTEAD

- 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)



gluons have
color but
no flavor!

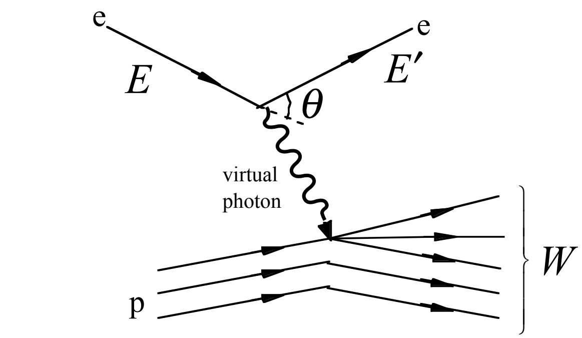


Quarks and gluons point-like within hadrons

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

$$\nu = E - E'$$

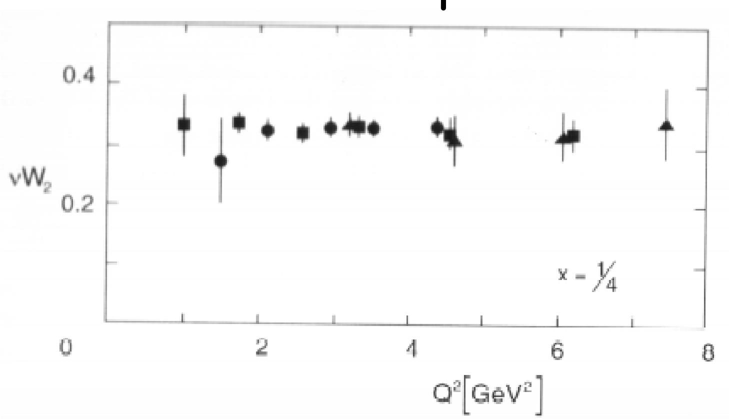
$$Q^2 = 4EE' \sin^2(\theta/2)$$



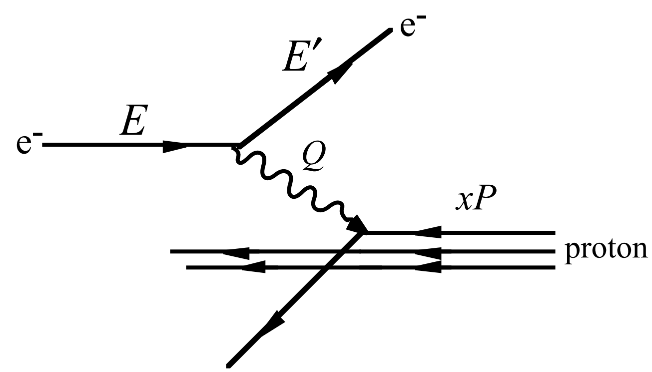
- Bjorken scaling variable: $0 < x < 1$

$$x = \frac{Q^2}{2m_p \nu}$$

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



Viewed from infinite momentum frame



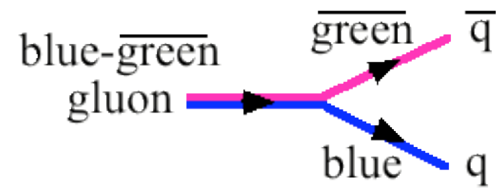
Parton distribution functions in the proton

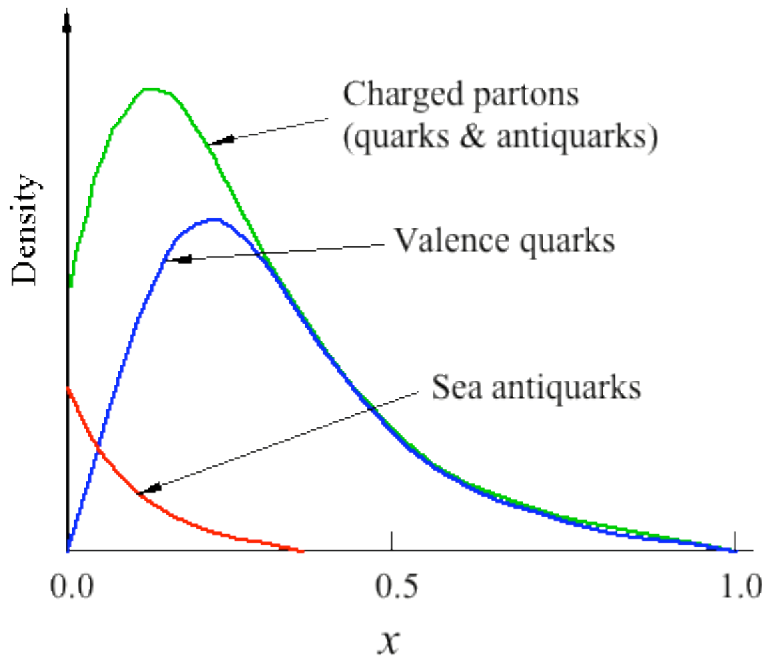
"Valence" "Sea"

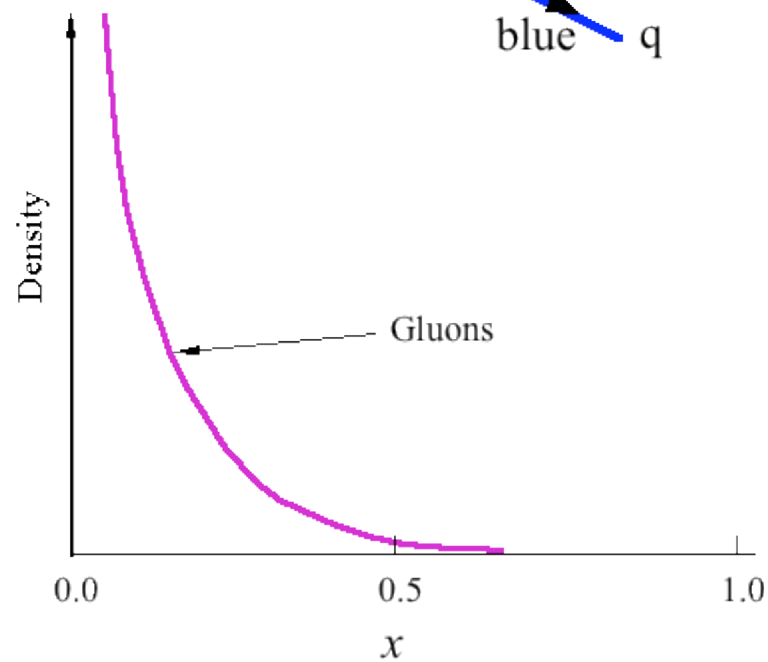
- Proton "parton" content is u u d + ($q\,\bar{q}$ pairs) + gluons

- At Q ~5 GeV/c, proton is 50% quarks and 50% gluons

- Sea quarks are from gluon "splitting"

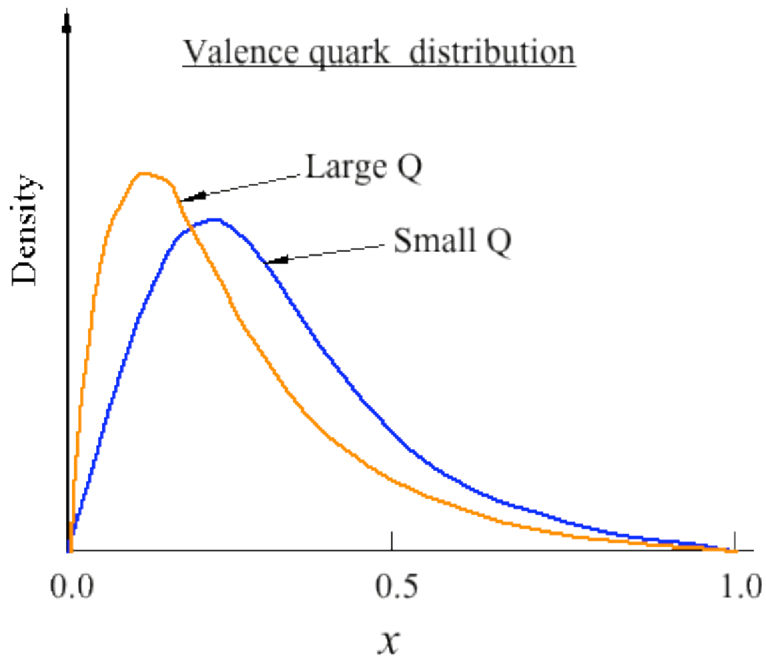


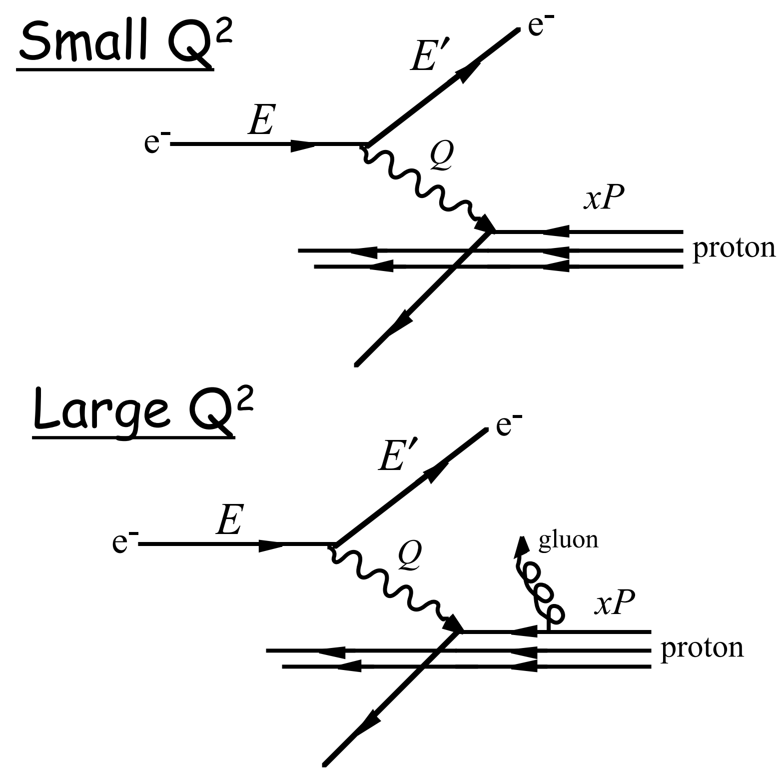




Scaling violations

- 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.

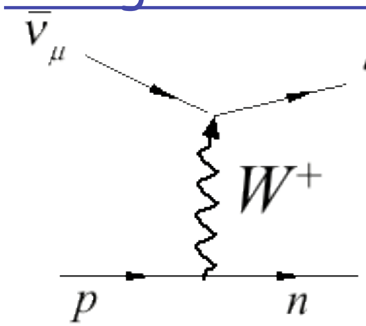




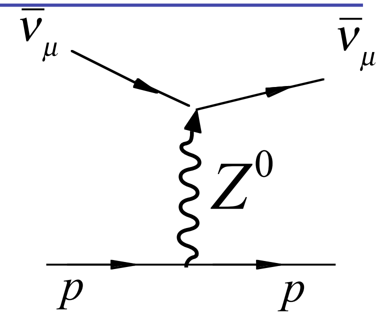
Weak neutral currents

- 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.

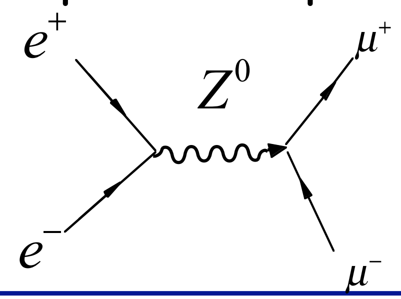
Charged current



Neutral current



- 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/c^2
  - Meson decays
    - muon neutrino mass < 200 keV/c^2
    - tau neutrino mass < 18 MeV/c^2
  - Cosmological limits
    - lots of assumptions about big bang
    - nuclear-synthesis, more assumptions
    - (number density)x(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 ?

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

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

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

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

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

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

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