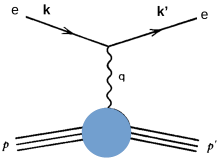
Physics 129: Particle Physics
Lecture 17: The Structure of the Proton (II)

Oct 20, 2020

- Suggested Reading:
  - Thomson Chapter 8
  - http://www.hep.ph.ic.ac.uk/∼tapper/lecture/dis-lecture-1.pdf
  - http://www.hep.ph.ic.ac.uk/∼tapper/lecture/dis-lecture-2.pdf
- Announcements:
  - Homework 8 Problem 3 correction: The first particle is the μ^- not the highest momentum particle. Will update the notebook later today.
  - Change in office hours this Friday: 2-3:30 instead of 3:30-5 (due to faculty meeting)

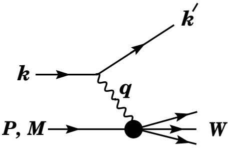
Review: What do we measure?

Elastic Scattering



- e^- with initial 4-monentum k^μ scatters to final moment k'^μ
- Proton stays together: 4 momenta satisfy $P^2 = P'^2 = m_p^2$
- Cross section becomes small as q^2 becomes large

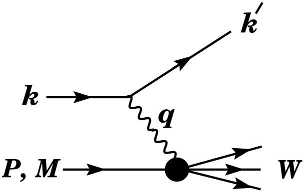
Inelastic Scattering



- e^- with initial 4-monentum k^μ scatters to final moment k'^μ
- Proton breaks up: multiple particles in final state
- Invariant mass of outgoing state larger than that of proton (energy-momentum transferred from electron)

- Kinematics determined from quantities associated with electron alone:
  - Elastic: incoming E and direction, outgoing angle enough
  - Inelastic: need outgoing energy as well
- Electron is a Dirac particle, so the current is $\overline{\psi}\gamma^\mu\psi$
- Photon proagator remains $-i\frac{g_{\mu\nu}}{q^2}$
- Proton *not* a Dirac particle so we can't calculate its current
  - But we know it must be a Lorentz tensor

Review: Deep Inelastic Scattering: Kinematics



- W is the invariant mass of the hadronic system
- In lab frame: $P = (M, 0)$
- In any frame, $k = k' + q$, $W = p + q$
- Invariants of the problem:

$$\begin{aligned} Q^2 &= -q^2 = -(k - k')^2 \\ &= 2EE'(1 - \cos\theta) \;\; \text{[in lab]} \\ P \cdot q &= P \cdot (k - k') \\ &= M(E - E') \;\; \text{[in lab]} \end{aligned}$$

- Define $\nu \equiv E - E'$ (in lab frame) so $P \cdot q = M\nu$ and

$$\begin{aligned} W^2 &= (P + q)^2 \\ &= (P - Q)^2 \\ &= M^2 + 2P \cdot q - Q^2 \\ &= M^2 + 2M\nu - Q^2 \end{aligned}$$

where $Q^2 = -q^2$

- Elastic scattering corresponds to $W^2 = P^2 = M^2$
  - $Q^2 = 2M\nu$ elastic scattering
- We can define 2 indep dimensionless parameters

$$\begin{aligned} x &\equiv Q^2/2M\nu; \quad (0 < x \leq 1) \\ y &\equiv \frac{P \cdot q}{P \cdot k} = 1 - E'/E; \quad (0 < y \leq 1) \end{aligned}$$

Some comments on choices of variables

- Final state defined by 4-momentum of outgoing lepton and 4 momentum of hadronic system. However
  - Mass of lepton known: not a variable
  - Four momentum of inital state specified as initial conditions $\Rightarrow$ energy-momentum conservation gives 4 constraint equations
  - Can define a production plane from direction of incoming and outgoing lepton. Distribution in ϕ of this plane uniform in phase space

  $\Rightarrow$ Only 2 non-trivial independent kinematic quantities
- Three common choices for specifying these variables:
  - Lab frame: Energy E and angle θ of outgoing lepton
  - Lorentz invariant combinations of 4-momenta
    - $Q^2 = -q^2 = (k - k')^2$: The 4-momentum transferred from lepton to proton
    - $P \cdot q = M(E - E') \equiv M\nu$: From kinematics, $E - E'$ related to the scattering angle
  - Ratios of Lorentz invariant variables are dimensionless

$$x \equiv \frac{Q^2}{2M\nu}$$
$$y \equiv \frac{P \cdot q}{P \cdot k}$$

- We'll see today why the dimensionless variables are useful

The most general form of the interaction

- Express cross section

$$d\sigma \propto \frac{\alpha^2}{q^4} L^e_{\mu\nu} W^{\mu\nu}$$

where $W^{\mu\nu}$ describes the proton current (allowing substructure)

- Most general Lorentz invarient form of $W^{\mu\nu}$
  - Constructed from $g^{\mu\nu}$, p^μ and q^μ

$$W^{\mu\nu} = -W_1 g^{\mu\nu} + \frac{W_2}{M^2} p^\mu p^\nu + \frac{W_4}{M^2} q^\mu q^\nu + \frac{W_5}{M^2}(p^\mu q^\nu + p^\nu q^\mu)$$

- W_3 reserved for parity violating term (needed for ν scattering)
- Not all 4 terms are independent. Using $\partial_\mu J^\mu = 0$ can show

$$\begin{aligned}
W_5 &= -\frac{p \cdot q}{q^2} W_2 \\
W_4 &= \frac{p \cdot q}{q^2} W_2 + \frac{M^2}{q^2} W_1 \\
W^{\mu\nu} &= W_1\left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) + W_2 \frac{1}{M^2}\left(p^\mu - \frac{p \cdot q}{q^2} q^\mu\right)\left(p^\nu - \frac{p \cdot q}{q^2} q^\nu\right)
\end{aligned}$$

- We'll come back to this later: Important point here is that the most general solution has two independent structure functions

Writing in terms of lab frame variables

- Using notation from previous page, we can express the x-section for DIS

$$\frac{d\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2}\frac{\cos^2(\frac{1}{2}\theta)}{\sin^4(\frac{1}{2}\theta)}\left[W_2(q^2,W) + 2W_1(q^2,W)\tan^2(\frac{1}{2}\theta)\right]$$

- W_1 and W_2 care called the *structure functions*
  - Angular dependence here comes from expressing covariant form on last page in lab frame variables
  - Two structure functions that each depend on Q^2 and W
  - Alternatively, can parameterize wrt dimensionless variables:

$$\begin{aligned} x &\equiv Q^2/2M\nu \\ y &\equiv \frac{P\cdot q}{P\cdot k} = 1 - E'/E \end{aligned}$$

- You will prove on this week's HW that in the lab frame

$$y = \sin^2\left(\frac{\theta}{2}\right)$$

One more change of variables (sorry...)

- Change variables

$$
\begin{aligned}
F_1(x, Q^2) &\equiv MW_1(\nu, Q^2) \\
F_2(x, Q^2) &\equiv \nu W_2(\nu, Q^2)
\end{aligned}
$$

- Rewrite cross section in terms of x, y, Q^2

$$\frac{d^2\sigma^{ep}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[\left(1 - y - \frac{M^2y^2}{Q^2}\right)\frac{F_2(x, Q^2)}{x} + y^2F_1(x, Q^2)\right]$$

- In DIS limit, $Q^2 >> M^2y^2$:

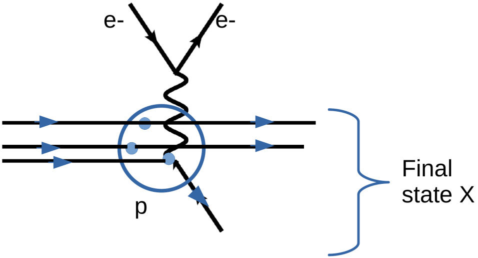
$$\frac{d^2\sigma^{ep}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1 - y)\frac{F_2(x, Q^2)}{x} + y^2F_1(x, Q^2)\right]$$

- Can event-by-event determine x, y and Q^2 from lab frame variables

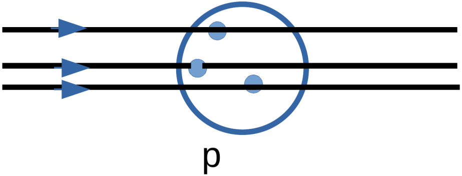
$$Q^2 = 4EE'\sin^2\frac{\theta}{2}, \quad x = \frac{Q^2}{2M(E - E')} = \frac{Q^2}{2M\nu} =, \quad y = 1 - \frac{E'}{E}$$

Towards a Physical interpretation of Deep Inelastic Scattering

- We want to interpret our Structure Functions as measurements of the distribution of the constituents inside the proton
- Since we are interested in large q^2 so that we probe small distances, it makes sense to use the sudden approximation
    - Proton a bag of size ~ 0.7 fm filled with objects called partons
    - Time over which photon interacts with proton short compared to time it takes for partons in proton to rearrange themselves
    - Eelastic scattering of e^- with a single parton in the proton
    - On longer time-scale the outgoing partons rearrange into hadrons



Choice of frame for parton model calculations



- We'd like to pick a frame that makes our calculation easiest
- Complications we'd like to avoid are:
  - Masses of the proton and the partons
  - Internal motion of the partons inside the proton bag
- If frame where proton momentum is large, the above are small effects
- This is called the "infinite momentum frame" and is the frame where it is easiest to interpret our results
  - Of course, if we write our results in Lorentz invariant form, the calculation does not depend on fraem
  - This frame only makes it easier for us to understand what the math is telling us

The Parton Model

- Supposed there are pointlike partons inside the nucleon
- Work in an "infinite momentum" frame: ignore mass effects
- Proton 4-momentum: $P = (P, 0, 0, P)$
- Visualize stream of parallel partons each with 4-momentum xP where $0 < x < 1$; neglect transverse motion of the partons
  - x is the fraction of the proton's momentum that the parton carries
- If electron elastically scatters from a parton

$$
\begin{aligned}
(xP + q)^2 = m^2 &\simeq 0 \\
x^2P^2 + 2xP \cdot q + q^2 &= 0
\end{aligned}
$$

Since $P^2 = M^2$, if $x^2M^2 << q^2$ then

$$
\begin{aligned}
2xP \cdot q &= -q^2 = Q^2 \\
x &= \frac{Q^2}{2P \cdot q} = \frac{q^2}{2M\nu}
\end{aligned}
$$

Deep inelastic scattering can be described as elastic scattering of the lepton with a parton with momentum xP

Electron Quark Scattering

- Quarks are Dirac particles, so can just calculate the scattering in QED
- We won't do the calculation here (see Thomson p. 191). Answer is

$$\frac{d\sigma^{eq}}{dQ^2} = \frac{4\pi e_i^2}{Q^4}\left[(1-y) + \frac{y^2}{2}\right]$$

- Looks pretty similar to the bottom of page 7

$$\frac{d^2\sigma^{ep}}{dx dQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\,\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

- The $F_1(x,Q^2)$ and $F_2(x,Q^2)$ carry the information about the distribution of the quarks inside the proton
- Note: If one goes through the Dirac Eq calculation $F_1(x,Q^2)$ is due to magnetic moment intarctions while $F_2(x,Q^2)$ is the straight Coulomb interaction
  - If partons are Dirac particles, we expect a well defined relationship between these two terms

Convolution of PDF with scattering cross section

- Cross section is incoherent sum over elastic scattering with partons

$$\begin{aligned}
\frac{d\sigma^{eq}}{dQ^2} &= \frac{4\pi\alpha^2}{Q^4}\left[(1-y)+\frac{y}{2}\right] \\
\frac{d\sigma^{ep}}{dxdQ^2} &= \int_0^1 dx \sum_i e_i^2 f_i(x,Q^2)\frac{4\pi\alpha^2}{Q^4}\left[(1-y)+\frac{y^2}{2}\right]\delta(x-\frac{Q^2}{2M\nu})
\end{aligned}$$

- Comparing to the previous expression for ep scattering

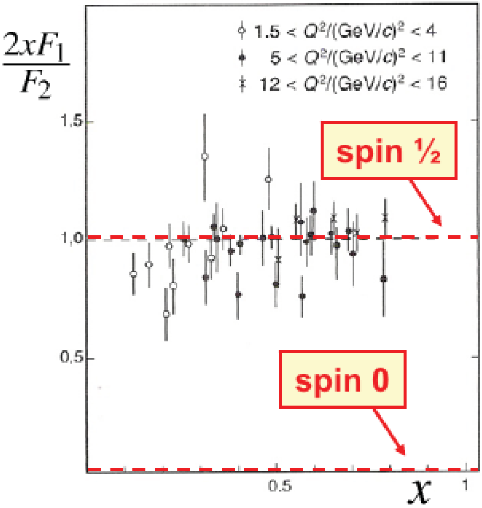
$$\frac{d^2\sigma^{ep}}{dxdQ^2} = \frac{4\pi\alpha^2}{Q^4}\left[(1-y)\,\frac{F_2(x,Q^2)}{x} + y^2 F_1(x,Q^2)\right]$$

We find

$$\begin{aligned}
F_2^{ep}(x,Q^2) &= x\sum_i e_i^2 f_i(x,Q^2) \\
F_1^{ep}(x,Q^2) &= \frac{1}{2}\sum_i e_i^2 f_i(x,Q^2) \\
\therefore F_2^{ep}(x,Q^2) &= 2xF_1^{ep}(x,Q^2)
\end{aligned}$$

- Last equation is called the Callan-Gross relation
- If partons had spin-0 rather than spin-$\frac{1}{2}$, we would have found $F_1 = 0$

What does the data look like?



The partons act like spin-1/2 Dirac particles!

Some Observations (I)

- $f_i(x)$ is the prob of finding a parton of species i with mom fraction between x and $x + dx$ in the proton.
- If the partons together carry all the momentum of the proton

$$\int dx\, xf(x) = \int dx\, x \sum_i f_i(x) = 1$$

  where $\sum_i$ is a sum over *all* species of partons in the proton
- We call $f(x)$ the parton distribution function since it tells us the momentum distribution of the parton within the proton
- This is the first example of a "sum rule"

Some Observations (II)

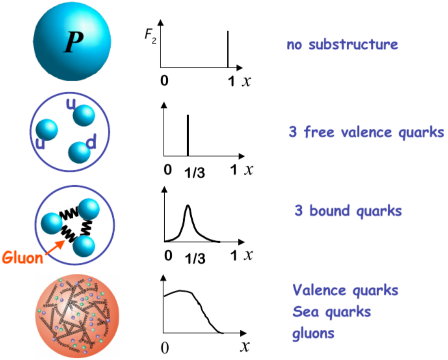
- It's natural to associate the partons with quarks, but that's not the whole story
- Because ep scattering occurs through the electromagnetic interaction, it only occurs via scattering with charged partons.
- If the proton also contains neutral partons, the EM scattering won't "see" them
  - For example: EM scattering blind to gluons
- Let's assume that the ep scattering occurs through the scattering of the e off a quark or antiquark
  - We saw that the SU(3) description of the proton consists of 2 u and 1 d quark.
  - However we can in addition have any number of $q\overline{q}$ pairs without changing the proton's quantum numbers
  - The 3 quarks (uud) are called *valence quarks*. The additional $q\overline{q}$ pairs are called *sea* or *ocean* quarks.
    - Pair production of $q\overline{q}$ pairs within the proton

Another Sum Rule

- To get the right quark content for the proton:

$$\begin{aligned} \int u(x) - \overline{u}(x)dx &= 2 \\ \int d(x) - \overline{d}(x)dx &= 1 \\ \int s(x) - \overline{s}(x)dx &= 0 \end{aligned}$$

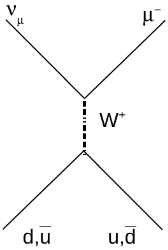
If partons are quarks, what do we expect?

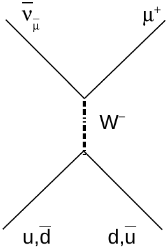


Max Klein, CTEQ School Rhodos 2006

- Elastic scattering from proton has $x = 1$
- If 3 quarks carry all the proton's momentum each has $x = 0.3$
- Interactions among quarks smears $f(x)$
- Radiation of gluons softens distribution and adds $q\bar{q}$ pairs
  - Describe the 3 original quarks as "valence quarks"
  - $q\bar{q}$ pairs as sea or ocean
- Some of proton's momentum carried by gluons and not quarks or antiquarks

Neutrino-(anti)quark Charged Current Scattering





- Start with ν_μ or $\overline{\nu}_\mu$ beam
  - Distribution of ingoing ν 4-momenta determined from beam design
  - Outgoing $\mu^\pm$ momentum measured in spectrometer
- Exchange via $W^\pm$ ("charged current interaction")
  - ν scatter against d and $\overline{u}$
  - $\overline{\nu}$ scatter against u and $\overline{d}$

We'll talk about neutral currents in a few weeks
Not useful for structure function measurements
(Can't measure outgoing lepton 4-momentum)

What is the Advantage of ν Scattering?

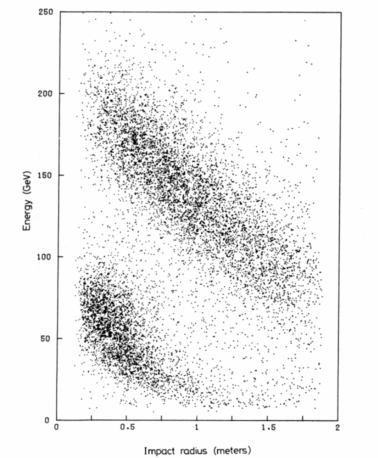
- The quarks and antiquarks have different angular dependence, so we can extract their pdf's separately by looking at cross sections as a function of angle
  - Angular dependence can be expressed in terms of dimensionless variable y
  - Parity violation means we have a third structure function F_3 that I won't talk about today
- Weak "charge" of the u and d is the same, so factors of $4/9$ and $1/9$ are not present
- Using previous expressions and integrating over angle:

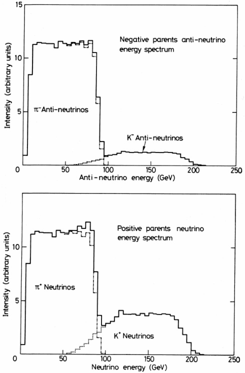
$$\begin{aligned}
\frac{d\sigma(\nu\, p)}{dx} &= \frac{G_F^2 xs}{\pi}\left[d(x) + \frac{1}{3}\overline{u}(x)\right] \\
\frac{d\sigma(\nu\, n)}{dx} &= \frac{G_F^2 xs}{\pi}\left[d^n(x) + \frac{1}{3}\overline{u}^n(x)\right] \\
&= \frac{G_F^2 xs}{\pi}\left[u(x) + \frac{1}{3}\overline{d}(x)\right]
\end{aligned}$$

where we have written everything in terms of the proton PDFs

- If we believe the partons in the proton and neutron are quarks, we can relate the structure functions measured in νN and eN

An Aside: How do we know the incoming neutrino energy?





- Primary proton beam incident on target produces secondary π and K
- Use magnets and shielding to select range of momenta of secondaries
- Long decay region to allow the $\pi \to \mu\nu$ and $K \to \mu\nu$ decays
- Two body decay gives correlation between decay angle and neutrino momentum

Comparing eN and νN νN Scattering (I)

- Now, let's take an isoscalar target N (equal number of protons and neutrons)
- In analogy with electron scattering

$$\frac{F_2^{\nu N}}{x} = u(x) + d(x) + \overline{u}(x) + \overline{d}(x)$$

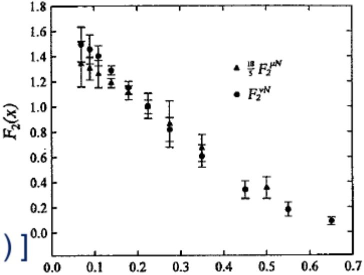
- If we go back to our electron scattering and also require an isoscalar target

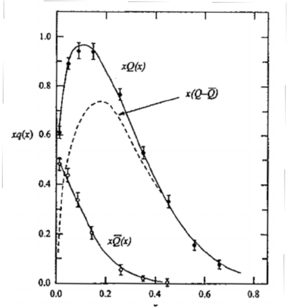
$$\frac{F_2^{e\ N}}{x} = \frac{5}{18}\left(u(x) + d(x) + \overline{u}(x) + \overline{d}(x)\right)$$

- So, if the partons have the charges we expect from the quark model

$$F_2^{e\ N}(x) = \frac{5}{18} F_2^{\nu N}(x)$$

Comparing eN and νN νN Scattering (II)





- The partons we "see" in eN scattering are the same as the ones we "see" in νN scattering
- This confirms our assignment of the quark charges:

  The Quarks Have Fractional Charge!

Using νN scattering to Count Quarks and Antiquarks

- As we previously did for electron scattering, we can look at an isoscalar target N
- Starting with the cross sections for νq scattering we can go through the same convolution with the PDFs that we did for the eN case
- The result is

$$\sigma^{\nu N} = \frac{G_F 2ME}{2\pi}\left[Q + \frac{1}{3}\overline{Q}\right]$$
$$\sigma^{\overline{n}uN} = \frac{G_F 2ME}{2\pi}\left[\overline{Q} + \frac{1}{3}Q\right]$$

where

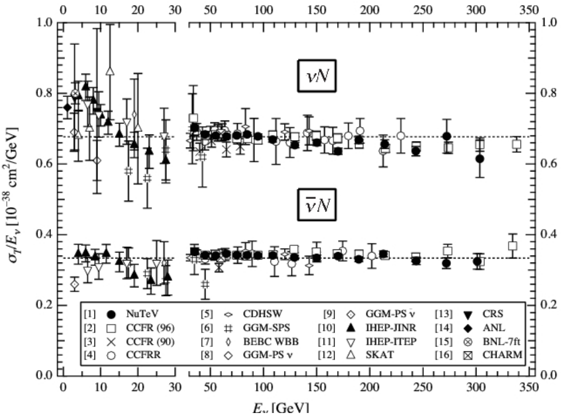
$$Q \equiv \int x[u(x) + d(x)]$$
$$\overline{Q} \equiv \int x[\overline{u}(x) + \overline{d}(x)]$$

and we have ignored the small strange component in the nucleon

- Thus

$$R_{\nu/\overline{\nu}} \equiv \frac{\sigma^{\overline{\nu}N}}{\sigma^{\nu N}} = \frac{\overline{Q} + Q/3}{Q + \overline{Q}/3} = \frac{1 + 3\overline{Q}/Q}{3 + \overline{Q}/Q}$$

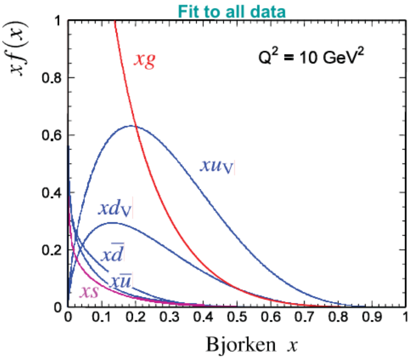
Experimental Measurements of νN Scattering



- Experimentally $R_{\nu/\overline{\nu}} = 0.45 \rightarrow \overline{Q}/Q = 0.5$

There are antiquarks within the proton!

How Much Momentum do the q and $\overline{q}$ Carry?



- Momentum fraction that the q and $\overline{q}$ together carry is

$$\int xF_2^{\nu N}(x)dx = \frac{18}{5}\int xF_2^{eN}(x)dx$$

- At $q^2 \sim 10$ GeV^2 that this fraction ~ 0.5

  Only half the momentum of the proton is carried by quarks and antiquarks

- What's Left? The gluon!

Additional Material

- The slides that follow have material I wasn't able to cover in class due to time limitations

Using Isospin: Comparing the Proton and Neutron

- Ignore heavy quark content in the proton: consider only u, d, s
- Write the proton Structure Function

$$\frac{F_2^p(x)}{x} = \sum_i f_i^p(x) e_i^2 = \frac{4}{9}(u^p(x) + \overline{u}^p(x)) + \frac{1}{9}(d^p(x) + \overline{d}^p(x)) + \frac{1}{9}(s^p(x) + \overline{s}^p(x))$$

- Similarly, for the neutron

$$\frac{F_2^n(x)}{x} = \sum_i f_i^n(x) e_i^2 = \frac{4}{9}(u^n(x) + \overline{u}^n(x)) + \frac{1}{9}(d^n(x) + \overline{d}^n(x)) + \frac{1}{9}(s^n(x) + \overline{s}^n(x))$$

- But isospin invariance tells us that $u^p(x) = d^n(x)$ and $d^p(x) = u^n(x)$
- Write F_2 for the neutron in terms of the proton pdf's (assuming same strange content for the proton and neutron)

$$\frac{F_2^n(x)}{x} = \frac{4}{9}(d^p(x) + \overline{d}^p(x)) + \frac{1}{9}(u^p(x) + \overline{u}^p(x)) + \frac{1}{9}(s^p(x) + \overline{s}^p(x))$$

- Assuming sea q and $\overline{q}$ distributions are the same:

$$u(x) - \overline{u}(x) = u_v(x), \quad d(x) - \overline{d}(x) = d_v(x), \quad s(x) - \overline{s}(x) = 0$$

- Taking the difference in F_2 for protons and neutrons:

$$\frac{1}{x}[F_2^p(x) - F_2^n(x)] = \frac{1}{3}[u_v(x) - d_v(x)]$$

which gives us a feel for the valence quark distribution

What the data tells us

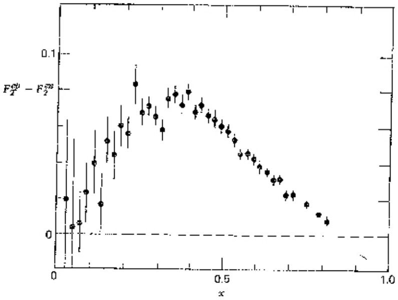


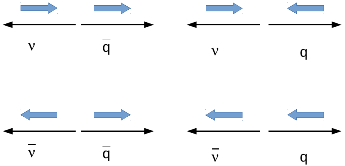
Fig. 9.8 The difference $F_2^{ep} - F_2^{en}$ as a function of x, as measured in deep inelastic scattering. Data are from the Stanford Linear Accelerator.

From Halzen and Martin

- Looks the way we expect from the cartoon on page 27
- Next question: How to measure the partons' charge
  - To do this, must compare e and ν scattering!

Neutrino-(anti)quark Scattering (II)

- Neutrinos left handed, anti-neutrinos right handed
- Left handed $W^{\pm}$ couples to left-handed quarks and right-handed anti-quarks



- νq and $\overline{\nu q}$ scattering allowed for all angles, but $\overline{\nu} q$ and $\nu \overline{q}$ vanish in backward direction

$$\frac{d\sigma^{\nu q}}{d\cos\theta} \propto \text{constant} \qquad \frac{d\sigma^{\overline{\nu} q}}{d\cos\theta} \propto (1+\cos\theta^*)^2$$

where θ^* is scattering angle in νq center of mass

- We'll see later that this left-handed coupling is also reason that π and K preferentially decay to μ and not e
  - μ^- needs to be right-handed since π,K have spin 0
  - rh component of spinor $\propto (v/c) \propto m_\mu$ in matrix element; decay rate $\Gamma \propto m_\ell^2$

    This is why accelerators produce predominantly ν_μ,$\overline{\nu}_\mu$

Neutrino-(anti)quark Scattering (III)

- The charged current cross sections are v_μ:

$$\begin{aligned}
\frac{d\sigma(\nu_\mu\ d \to \mu^- u)}{d\Omega} &= \frac{G_F^2 s}{4\pi^2} \\
\frac{d\sigma(\overline{\nu_\mu}\ u \to \mu^+ d)}{d\Omega} &= \frac{G_F^2 s}{4\pi^2}\,\frac{(1+\cos\theta)^2}{4} \\
\frac{d\sigma(\nu_\mu\ \overline{u} \to \mu^- \overline{d})}{d\Omega} &= \frac{G_F^2 s}{4\pi^2}\,\frac{(1+\cos\theta)^2}{4} \\
\frac{d\sigma(\overline{\nu_\mu}\ \overline{d} \to \mu^+ \overline{u})}{d\Omega} &= \frac{G_F^2 s}{4\pi^2}
\end{aligned}$$

- You will prove on homework #5 that

$$1 - y = \frac{p \cdot k'}{p \cdot k} = \frac{1}{2}\left(1 + \cos\theta^*\right)$$

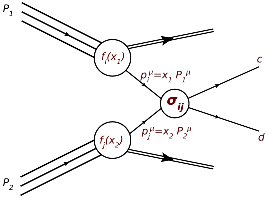
  which allows us to rewrite the above expressions in terms of the relativistically invariant variable y

- Since $\int \frac{(1+\cos\theta)^2}{4} d\cos\theta = 1/3$,

$$\begin{array}{cccc}
\sigma^{\nu d} : & \sigma^{\nu\overline{u}} : & \sigma^{\overline{\nu}u} : & \sigma^{\overline{\nu}\overline{d}} \quad = \\
1 : & \frac{1}{3} : & \frac{1}{3} : & 1
\end{array}$$

Some Comments

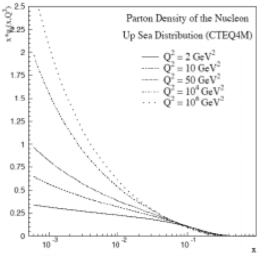
- Charged lepton probes study charged partons
- Neutrinos study all partons with weak charge
  - $\int xF_2^{\nu N}(x)dx = \frac{18}{5}\int xF_2^{eN}(x)dx$ tells us that all the weakly interacting partons are charged
- To study the gluon directly, will need a strong probe
  - No pointlike strong probes
  - Will need to convolute two pdf's

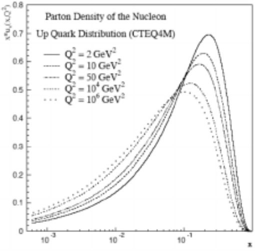


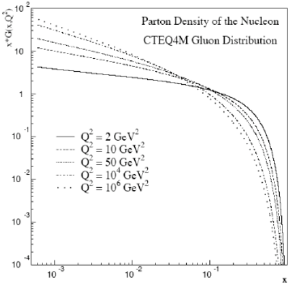
  - More on this when we talk about hadron colliders in a few weeks
- Can also indirectly study gluon by seeing how it affects the quarks

Scaling Violations in DIS

- QCD corrections to DIS come from incorporating gluon brem from the q and $\overline{q}$ and pair production $g \to q\overline{q}$
- The ability to resolve these QCD corrections are q^2 dependent
- Expected result:
    - At high x the quark pdf's decrease
    - At low x the quark and antiquark pdf's increase
- Complete treatment in QCD via coupled set of differential equations, the Alterelli-Parisi evolution equations

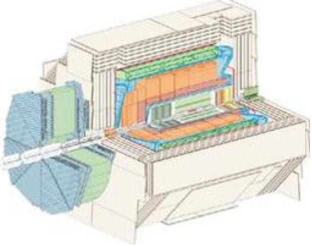




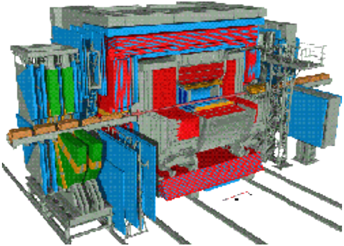


DIS in the Modern Era: The HERA collider

H1

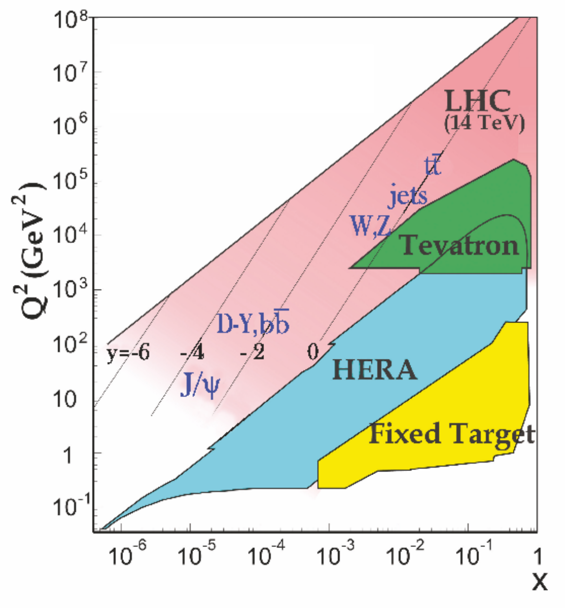


Zeus

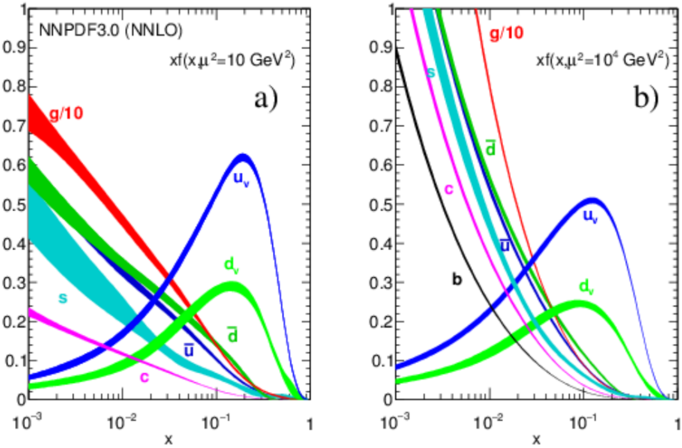


- ep collider located at DESY lab in Hamburg
- 27.5 Gev (e) x 920 GeV (p)
- Two general purpose detectors (H1 and Zeus)

What Q^2 and x are relevant?



Our best fits of PDFs at present



- Fit experimental data to theoretically motivated parameterizations
- Combine data from many experiments, using Alterelli-Parisi to account for differences in Q^2 (correct to common value)
- Analysis of uncertainties to provide a systematic uncertainty band

Modern $F_2(x, Q^2)$ Measurements