Quantum Chromodynamics
An Introduction to QCD

Florida State University Quarknet
June 26, 2002
J.F. Owens

Outline

1. Historical Setting
2. Quark Model
3. Interactions?
4. QCD
5. Experimental Evidence
6. Theoretical Calculations

Compressed History – Pre-QCD

Circa 1932: there were few “elementary particles” and life was simpler ...

- proton, neutron for atomic nuclei
- electron to make atoms
- photon as the quantum of the electromagnetic field
- neutrino for weak nuclear decays
- positron – the antiparticle of the electron, as predicted by the Dirac equation

But, then came the particle explosion of the 50’s and 60’s ...

By the 1960's there were hundreds of new states including

- a heavier version of the electron, called the muon (μ)
- the discovery that there were (at least) *two* types of neutrinos (and their antiparticles)
- heavier versions of the proton and neutron
- strange types of particles which were produced by the strong interaction, but decayed via the weak interaction
- many new particles that were lighter than the proton, but heavier than the electron or muon

Elementary particles were supposed to be the fundamental building blocks of matter, but there were just *too many!*

Now, some definitions to help sort this out

All particles have gravitational interactions, but they differ with respect to the strong, weak, and electromagnetic interactions.

All particles with electric charge interact electromagnetically.

- Leptons - interact via the electromagnetic and/or the weak interaction, but not the strong.
- Hadrons - possess strong, weak, and electromagnetic interactions

Particles can be further classified by their spin.

- Fermions - particles whose spin is a half-integer multiple of $\hbar$. They obey Fermi-Dirac statistics (more about this later)
- Bosons - particles whose spin is an integer multiple of $\hbar$. They obey Bose-Einstein statistics.
- Leptons of all types are fermions
- Hadrons can be either fermions or bosons
  - Mesons - strongly interacting particles with integer spins
  - Baryons - strongly interacting particles with half-integer spins

There is one other category which can be referred to as the force carriers. Today, we call these particles gauge bosons. All the known forces are today described by such integer spin force carriers.

1. Gravity - spin 2 graviton
2. Weak force - spin 1 W^+, W^-, and Z^0
3. Electromagnetism - spin 1 photon
4. Strong force - spin 1 gluon (which we will soon meet)

The Quark Model

- Many of the strongly interacting particles came in groups of eight or ten with similar masses, the same spins, and shared other common properties
- In 1964 Gell-Mann and Ne'eman proposed a symmetry scheme, SU(3), which correctly predicted these groupings
- Elsewhere in physics, the existence of such patterns usually signals some underlying, more fundamental, structure.
- The same was true here. Gell-Mann pointed out that all the patterns of strongly interacting particles could be explained by just three fundamental particles - he called them quarks.

Quarks

- Originally 3 in number - today we know there are at least 6, along with their antiquarks
- Quarks carry fractional electric charge in units of $\pm 2/3$ or $\pm 1/3$ times the electron charge.
- Baryons - made of triplets of quarks
- Mesons - made of quark-antiquark pairs
- A great simplification was made - *but are quarks real?*

The Standard Model (in one page)

Matter Constituents

Three Generations

Leptons $$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Quarks $$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \begin{matrix} Q = 2/3e \\ Q = -1/3e \end{matrix}$$

Interactions

The quark model was a great simplification, but its predictive was mostly limited to the area of spectroscopy - How many states are there and what are their properties?

This is analogous to Mendeleev's periodic table of the elements

But how do the quarks *interact?*

Symmetry and Wavefunctions

- Baryons - like the proton - are fermions and must have wavefunctions which which are antisymmetric under the interchange of any two of their constituents
- This caused a problem, which can be seen by looking at a particle called the Δ^{++} which is made of three u quarks: uuu
- This wavefunction is *symmetric*
- It was suggested that there should be a new label, or charge, like electric charge, but coming in three types.
- The baryons could then be made antisymmetric with respect to this new label.

- These new charges were *unobserved*, so for real particles they must cancel out.
- The new charges obey the same rules as for the addition of *colors.* Add the three primary colors and you get white. Add the three new charges and they cancel out.
- Gell-Mann, Fritzsch, and Leutwyler proposed that the quarks carried this new *color charge* and that there were new “force carriers” which coupled to these charges.
- Thus, in 1972, QC D was born

Analogies

Quantum Electrodynamics - charged particles interact by exchanging photons. We say that the photon (the quantum of the electromagnetic field) couples to electric charge.

Quantum Chromodynamics -particles carrying color charge interact by exchanging new force carriers called *gluons.* We say that the gluons couple to the color charges.

But, QCD is different from QED in one key respect...

Photons are neutral, but gluons carry the color charge, so gluons can couple to themselves.

This has some very profound consequences...

Key Predictions

Asymptotic Freedom - The coupling of gluons to the quarks and to themselves becomes weaker as the particles get closer together.

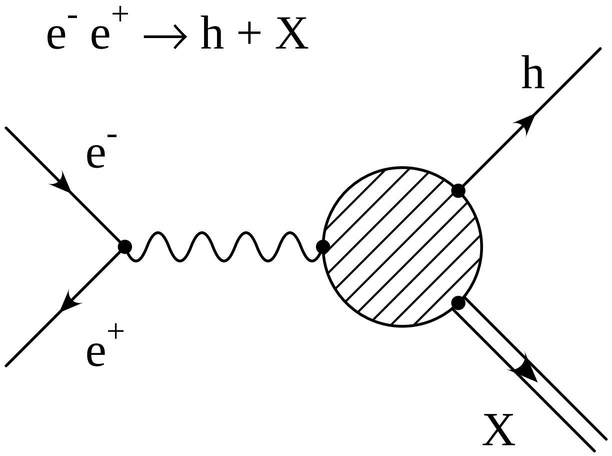
- To get them closer together physicists use *high energies* and *large momentum transfers* analogous to the way that Rutherford first probed the structure of the atom.
- In such collisions the effective coupling is small and we can use perturbation theory to generate (fairly) precise predictions
- Conversely, at long distances (or small momentum transfer, the coupling is large. This leads to

Quark Confinement - free quarks do not exist. Any attempt to split off a quark just results in more mesons or baryons being produced.

Now, it is time to look at how these - and other - predictions of QCD have been verified.

$e^+e^- \rightarrow$ hadrons

Counting quarks and their charges



- Electron and positron annihilate creating an electromagnetic field in the form of a photon which can then create a quark-antiquark pair.
- As the quark and antiquark separate they “fragment” into hadrons.
- Final states appear as to showers of particles called “jets” which emerge in opposite directions
- The theory also predicts the angular distribution for these produced jets.

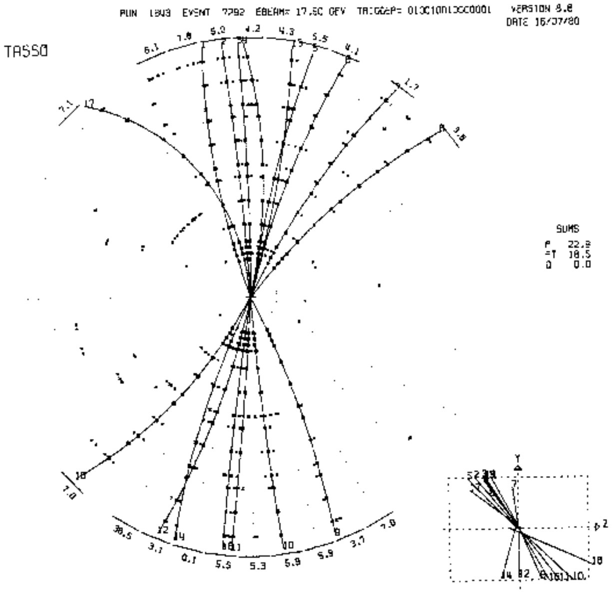
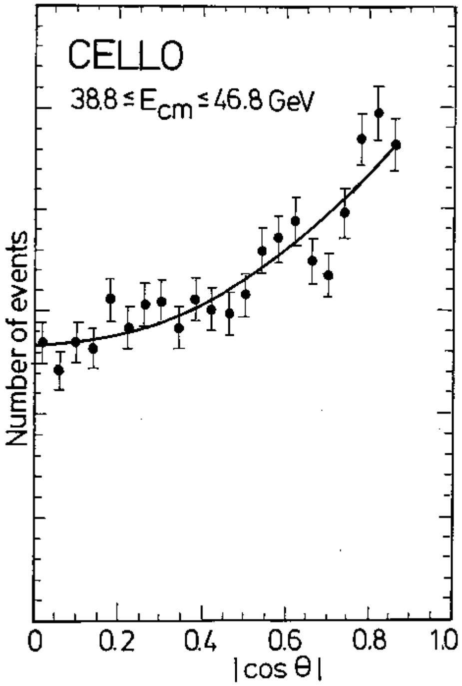


Fig. 29 A two-jet events as observed at W = 35 GeV in the TASSO detector.

- Beam's eye view of an event - charged particles emerge in two oppositely directed jets and are bent in the detector's magnetic field
- Can see this same topology in the side view (lower right)

Jet Angular Distribution



Jet angular distribution agrees with the calculation based on simple quark-antiquark production

Counting Quarks

Cross section for $e^+e^- \to q\overline{q}$ is the same as that for $e^+e^- \to \mu^+\mu^-$ except for

- electric charge of the quarks
- number of quark types (including color)

A convenient observable is

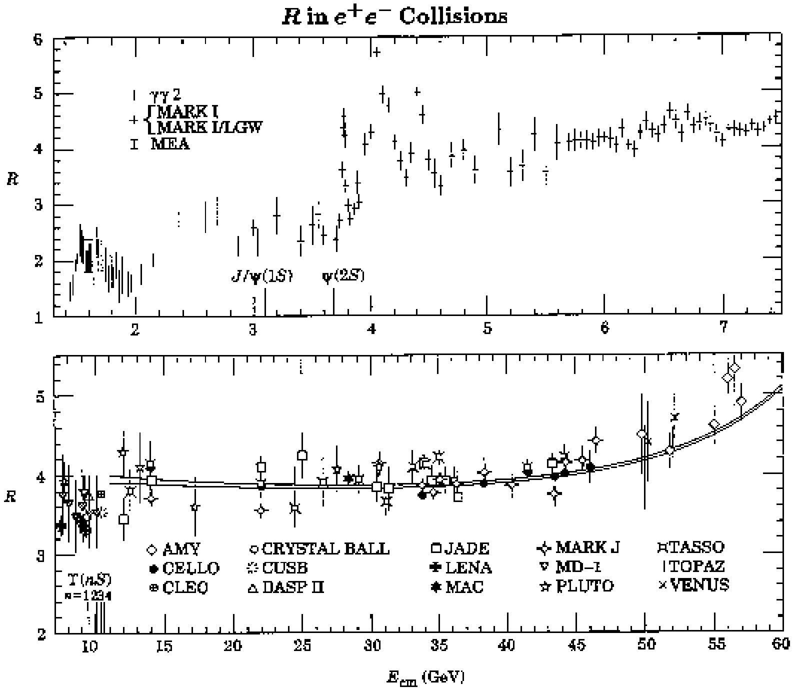
$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_{i=1}^{f} e_i^2$$

$$= 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9} + \frac{1}{9} + \frac{4}{9}\right)$$

- factor of three accounts for color
- fractions are for $u, d, s, c, b,$ and t quarks

$$R = \begin{cases} 3\frac{1}{3} & \text{above charm threshold} \\ 3\frac{2}{3} & \text{above b threshold} \\ 5 & \text{above t threshold} \end{cases}$$

- Also see the effect of Z^0 production via $e^+e^- \rightarrow Z^0 \rightarrow$ hadrons



Broad Lessons from e^+e^-

- Evidence for quarks and gluons with expected couplings
- Increased understanding of jets and hadronization
- Precision electroweak tests and measurements
- Ongoing studies of spectroscopy and construction of new “B factories”

Turn now to the treatment of hadronic collisions

Hadronic Processes

- Have beams of hadrons, *not* quarks and gluons
- Theoretical calculations deal with the fundamental particles of the Standard Model - quarks, gluons, leptons, etc.

⇒ Have to change from a hadronic basis to one involving quarks and gluons

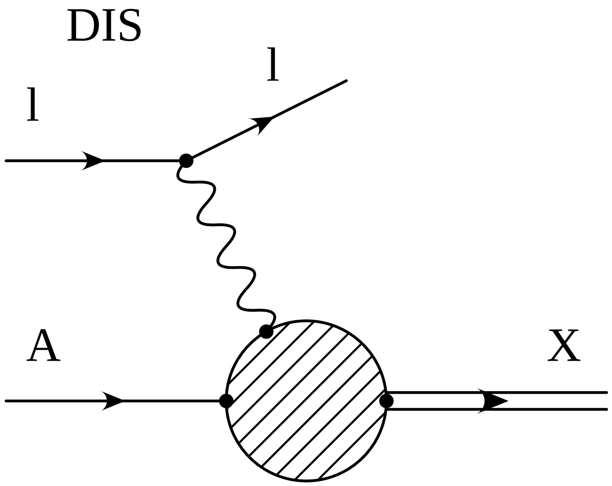
- Historically, the first information needed for this came from deeply inelastic lepton scattering experiments

Use the known electromagnetic interaction to probe the structure of hadrons

Analogous to Rutherford's experiments on atomic structure, but at a much smaller length scale

Deeply Inelastic Lepton Nucleon Scattering

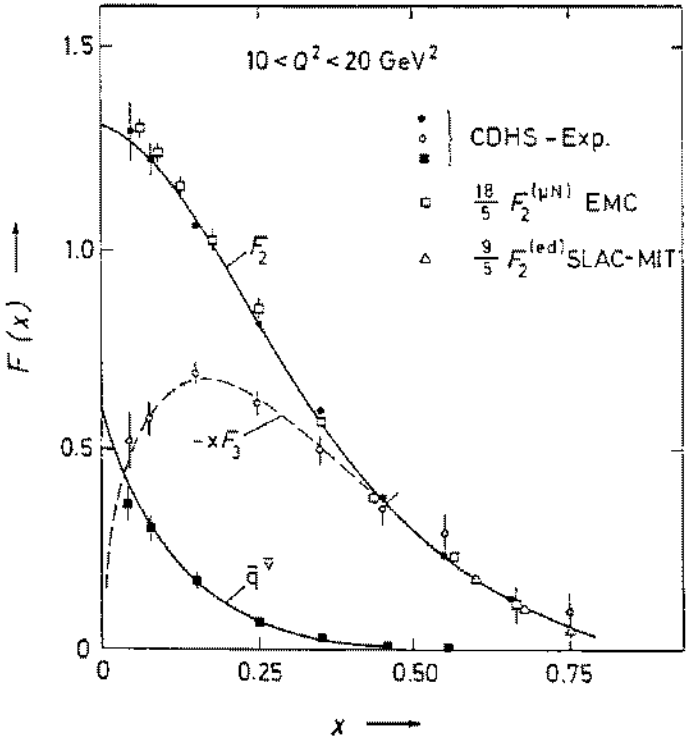
- Scatter an electron or muon beam from a proton or nucleus target.
- Exchanged photon interacts with the quarks in the target
- Like taking an X-ray of the target!

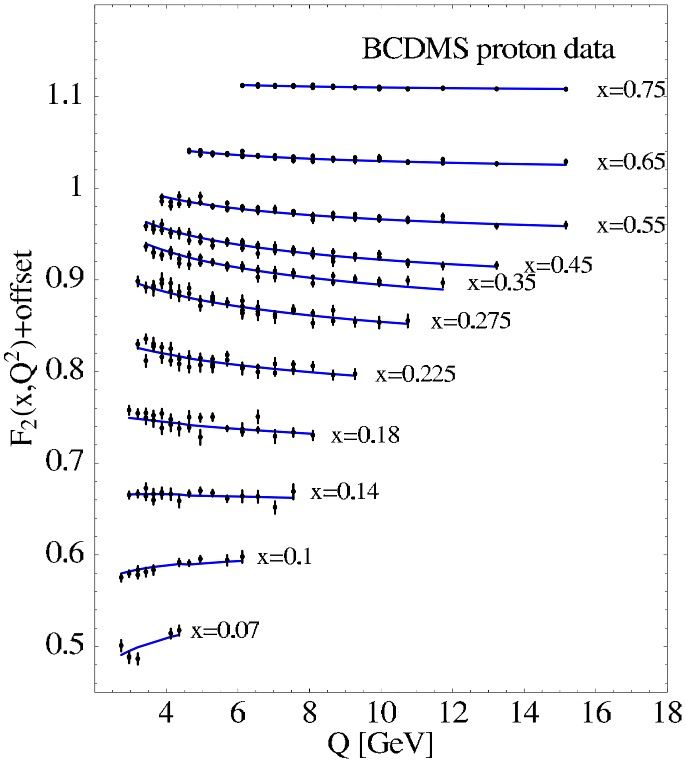


- Can also use neutrino beams - weak interaction provides another way to examine the quarks

- Measure energy and angle of the scattered lepton
- Measurements give information on the fraction of the target's momentum carried by the struck quark
- Introduce *parton distribution functions*
  - Parton is a generic name for a quark, antiquark, or gluon
  - $G_{i/p}(x)dx$ gives the probability of finding a parton of type i in a proton with a fraction of the proton's momentum between x and $x + dx$
  - Momentum fraction x satisfies $0 \leq x \leq 1$

- Data presented in terms of “structure functions”
- These are expressed as sums of the different parton distributions
- Different types of beams give different combinations of parton distributions
- Can use this feature to disentangle the various distributions
- Radiative corrections due to gluon emission cause the parton distributions to depend on both x and the momentum transfer, Q, provided by the exchanged boson


10 < Q^2 < 20 GeV^2
CDHS - Exp.
$\frac{18}{5}$ $F_2^{(\mu N)}$ EMC
$\frac{9}{5}$ $F_2^{(ed)}$SLAC-MIT
F_2
$-xF_3$
$\bar{q}^{\bar{\nu}}$
F (x)
1.5
1.0
0.5
0
0
0.25
0.50
0.75
x


BCDMS proton data
$F_2(x,Q^2)$+offset
1.1
1
0.9
0.8
0.7
0.6
0.5
x=0.75
x=0.65
x=0.55
x=0.45
x=0.35
x=0.275
x=0.225
x=0.18
x=0.14
x=0.1
x=0.07
4
6
8
10
12
14
16
18
Q [GeV]

Lessons Learned From Deeply Inelastic Scattering

- The proton consists of pointlike constituents with
  - Fractional charges
  - Spin 1/2

⇒ They look like the quarks predicted by Gell-Mann!

- But, only about half the proton's momentum is carried by the quarks
- The other half must be carried by some neutral particles

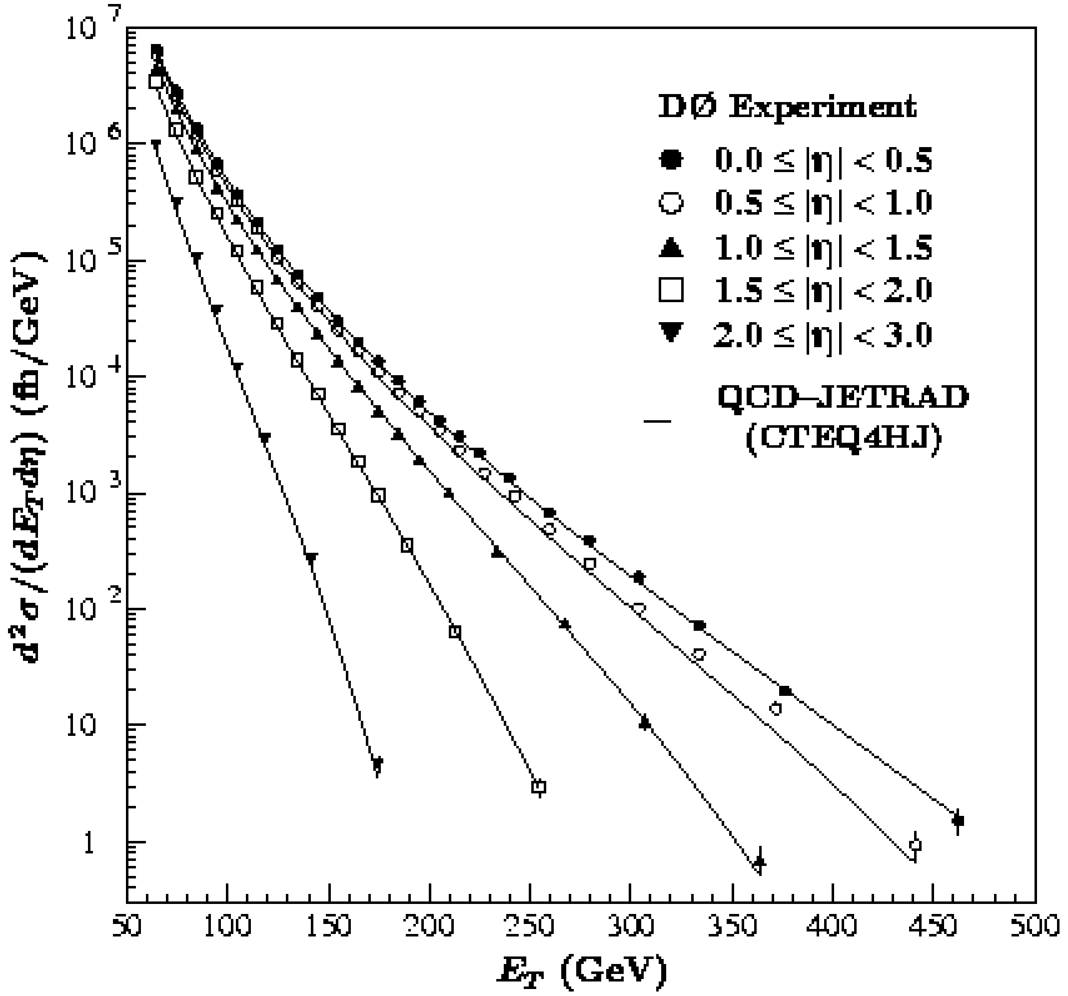
⇒ The Gluons!

Hadronic Collisions

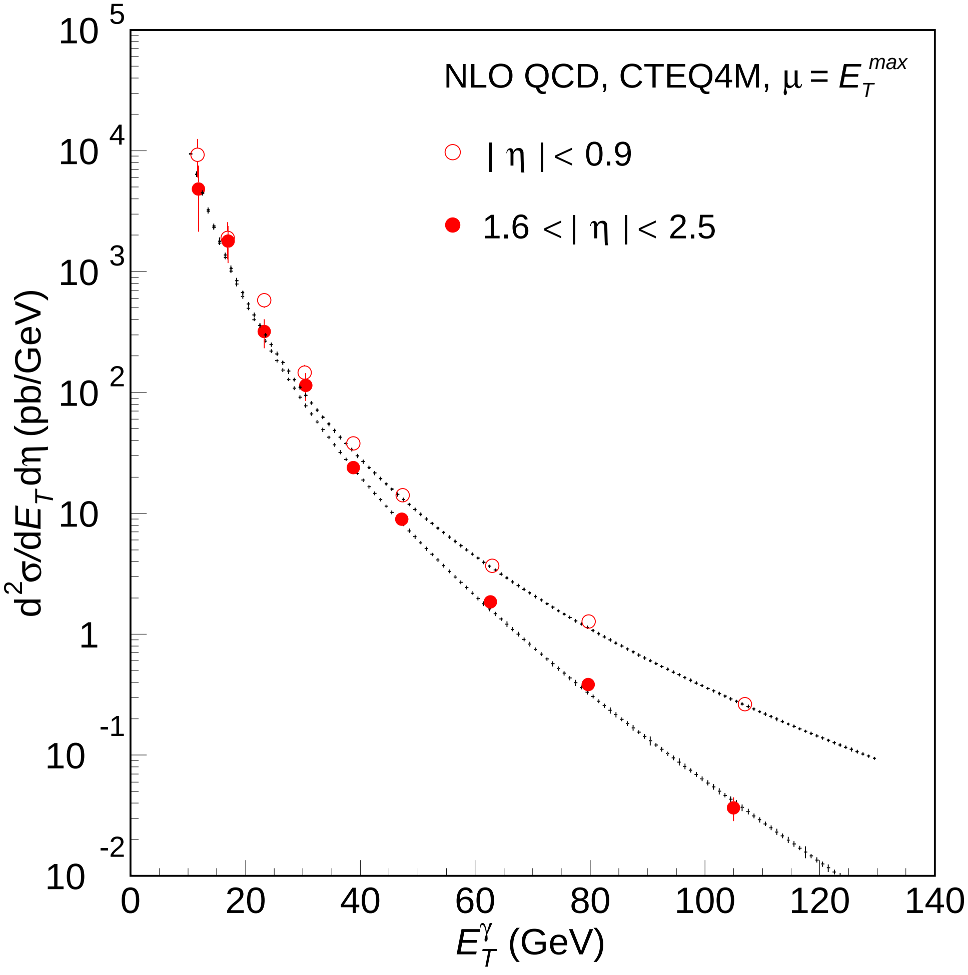
- Knowledge of the parton distributions allows us to treat the incoming hadron beams as beams of quarks and gluons
- Use QCD to calculate how the quarks and gluons scatter from eachother
- Outgoing partons fragment into hadrons
  - May choose to detect individual particles
  - Can also use calorimeters to detect the energy of all the outgoing particles
  - Can approximately reconstruct the original scattered parton
  - Call such an object a “jet” (recall the e^+e^- discussion)

Studies of Hard Scattering Processes

- Such studies allow us to test our knowledge of the underlying hard scattering of the partons from eachother. This part is described by QCD
- Also allows us to refine our knowledge of the parton distributions
- Can also look for the unexpected:
  - Quark substructure?
  - New particles?



DØ jet data compared to theory using CTEQ parton distributions



DØ photon data compared to theory using CTEQ parton distributions

In Conclusion...

- Thirty years ago there was no theory of the strong interaction
- There were several hundred “elementary particles”
- The strong, weak, and electromagnetic interactions were each a separate area of study with few connections

But now

- We know that matter is made from 6 types of leptons and 6 types of quarks with interactions given by three types of gauge bosons
- The Standard Model exists as a framework which accomodates and descibes the strong, weak, and electromagnetic interactions

And best of all,

There are existing and planned experimental facilities which will enable us to continue our exploration of the structure of matter!