Search for Fundamental Structure

Some Interesting New Data

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1. Some History - A "How-To" Guide
2. Sharpening the Probe
3. New Results on Quark-Quark Scattering
4. Summary and Conclusions

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Some History

Lord Rutherford performed seminal scattering studies

- Looked at α scattering off gold (1911)
- Consistent with Coulomb scattering off point particle

$\Rightarrow$ Uncovered the nucleus

Hofstadter and colleagues extended this work

- Studied 1 GeV e^- scattering off nuclei (1953)
- Found that nucleus had extended charge distribution

$\Rightarrow$ shape of the nucleus

Taylor and colleagues probed more finely

- Used ~ 18 GeV e^- scattering off proton (1968)
- Found that nucleons were extended objects

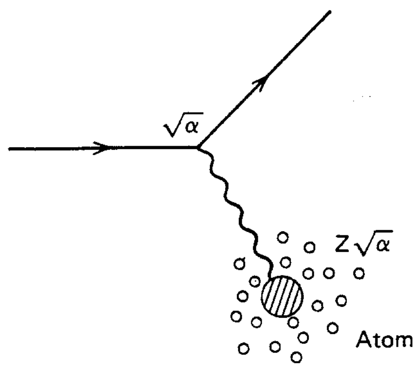
$\Rightarrow$ discovered quarks!

Clear what the next step should be....

About Rutherford Scattering

Rutherford developed classical theory of scattering

- Charged particle $Z_1 e$ scattering off nucleus Ze



- Define $\vec{q} = \vec{p} - \vec{p}'$, so that $q = 2p \sin \frac{\theta}{2}$
- Differential cross section is

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \frac{4m^2 \left(Z_1 Z e^2\right)^2}{q^4}$$

- Correct classical and QM result $\Rightarrow$ *Rutherford Scattering*

Extended to spin-1/2 particles incident on spin-0 target

- Obtain Mott Scattering

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \left(\frac{d\sigma}{d\Omega}\right)_R \times \left(\frac{E^2}{m^2 c^4}\right) \left(\frac{1 - [q/2p]^2}{1 + q^2/(2Mp)}\right)$$

What Happens for Extended Targets?

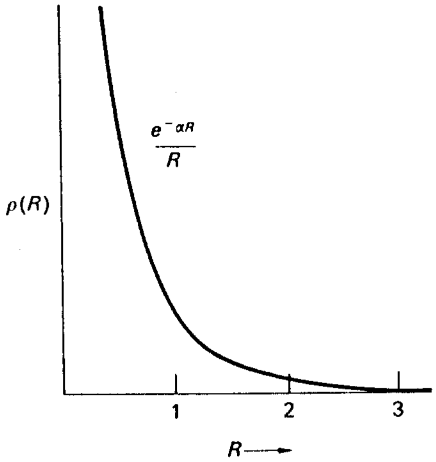
When scattering particle is extended in space

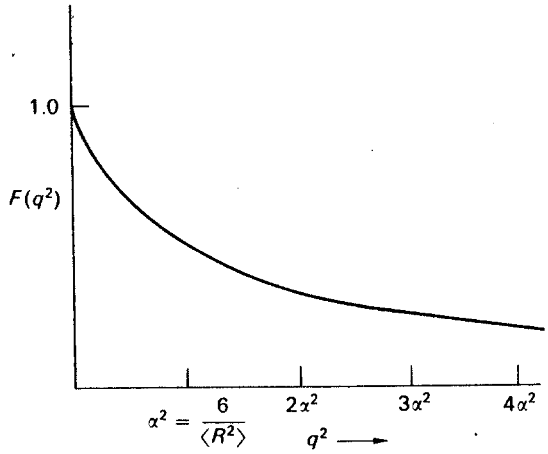
- Introduce "form factor" $f(q^2)$

$$f(q^2) = \int \rho(\vec{R}) e^{i\vec{q}\cdot\vec{R}} d^3\vec{R}$$

- Fourier transform of "charge" density ρ

$$\Rightarrow \left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left|f(q^2)\right|^2$$



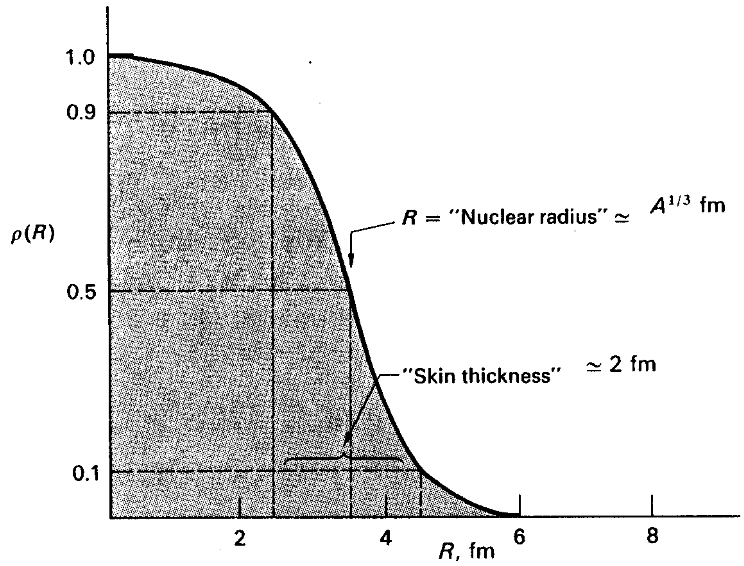


Study of Nuclear Structure

These studies were motivated by poor understanding of strong force

- Protons and neutrons are nuclear constituents
- Structure of nucleus was not understood
- Dynamics not well understood

Nuclear "charge distribution" obtained from $f(q^2)$



Tells us that nucleus is $\sim 2-4$ fm in "size"

Proton Structure

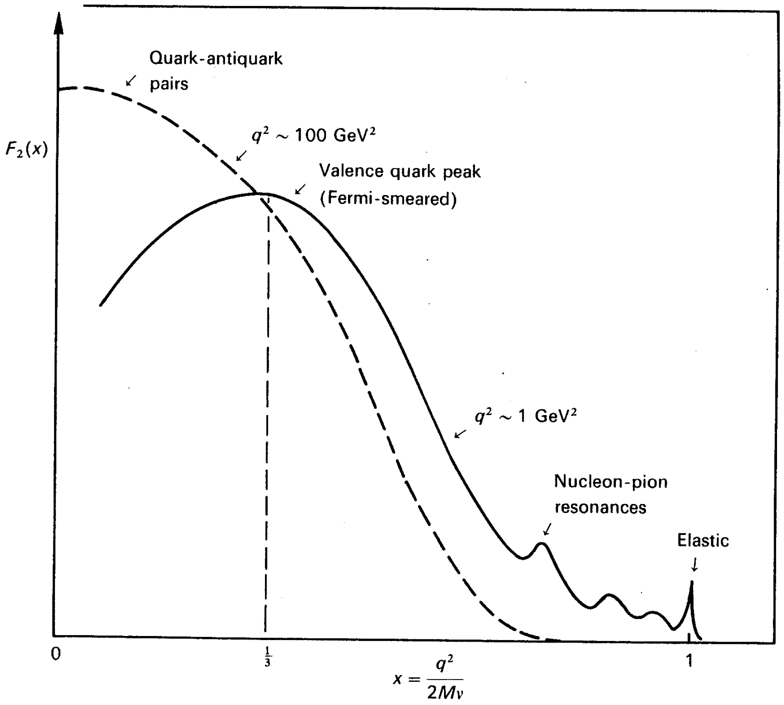
Deep inelastic $e^- p$ scattering reveals proton structure

- study inelastic part of cross section

$$e^- p \to e^- X_{\text{hadrons}}$$

  - suppress "coherent" and resonant nuclear scattering
  - Begin to see scattering off of constituents
  - Hitting partons with smaller x (x is momentum fraction)

- epitomised by "structure functions" $F_i(x, q^2)$

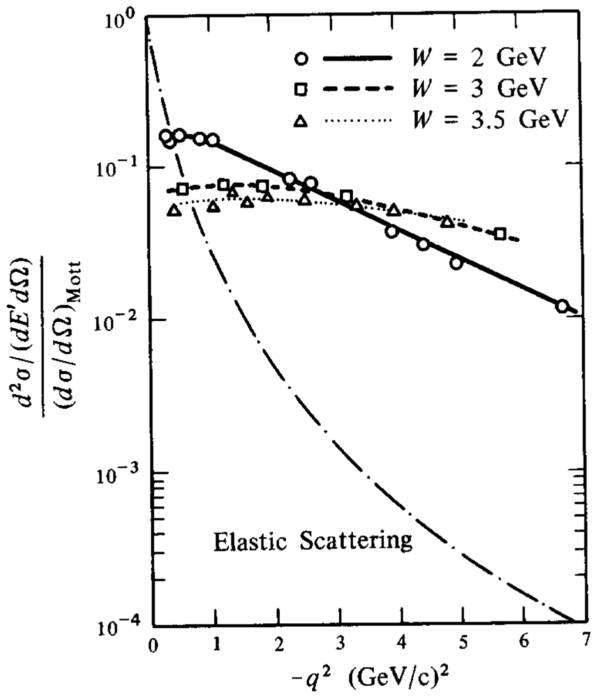


$$\left(\frac{d^2\sigma}{dq^2 dx}\right) \sim \frac{4\pi\alpha^2}{q^4}\left[(1-y)\frac{F_2(x,q^2)}{x} + \ldots\right]$$

Deep Inelastic Scattering Results

SLAC DIS studies revealed clear internal structure

- Evident as hadronic energy W increases (decreases x)



Detailed studies of structure functions F_1 and F_2 show

- Charge 1/3 and 2/3 particles
- Spin 1/2 particles
- Presence of anti-particles (the "sea")

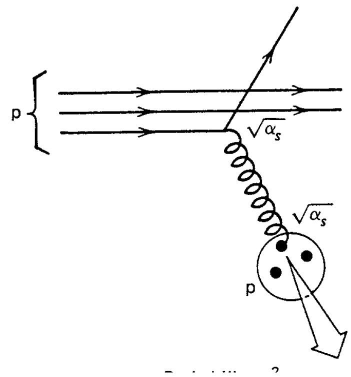
Structure of Quarks

Why would we think that quarks have substructure?

- Now 6(!) known flavours
- No reason 10^{-12} cm should be fundamental distance scale
- We don't believe that Standard Model is last word

To uncover structure, have to increase energy scale

- DIS limited by e^- energies and EWK nature of probe
- Need high-energy hadronic probe
  - closest thing to $q-q$ scattering is hadron-hadron scattering
  - Highest energies possible are at Fermilab Tevatron

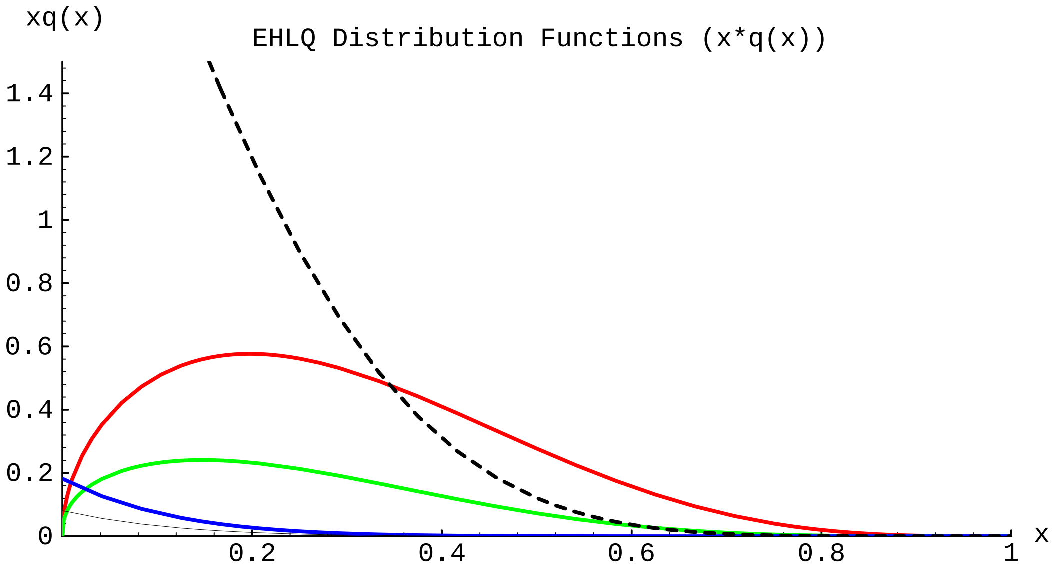


Complications are that quarks are bound in proton

- Only have part of total energy available (x)
- Need to know distribution of quarks as function of x

Parton Distribution Functions

Fraction of momentum carried by parton given by pdf's



- Example is EHLQ (Set I) at $q^2 = 5$ GeV^2
- Derived from deep inelastic scattering
- Note large non-valence quark contribution
  - Largest uncertainty comes from gluon contribution

QCD predicts these PDF's to evolve with q^2

- Get "softer" as centre-of-mass energy $\hat{s}$ increases
- Best measurements come from neutrino and DIS
- Raison d'etres for several experiments

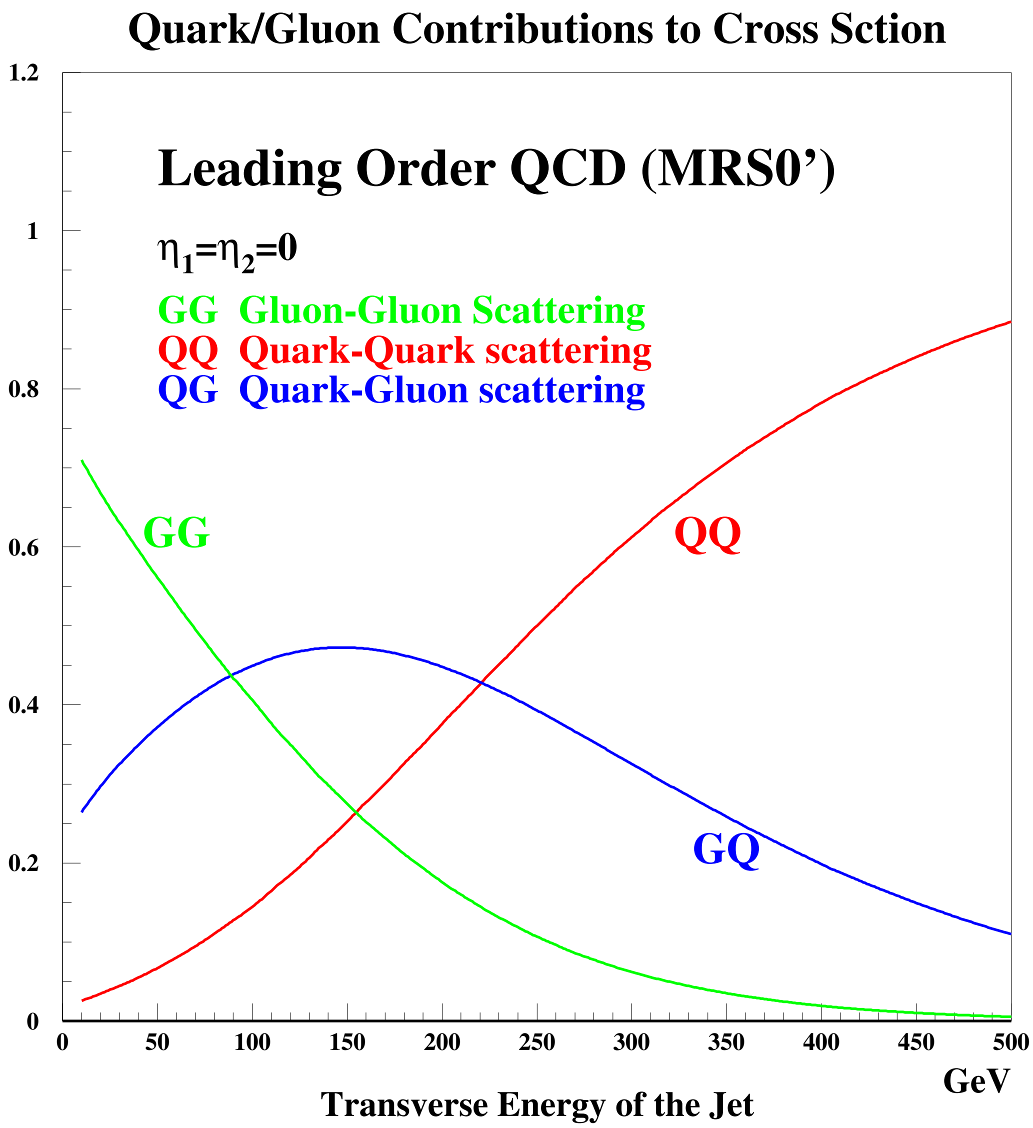
Quark–Antiquark Scattering

Standard Model describes $q\bar{q}$ scattering using QCD

- Gluons interacting via strong scale α_S
- Can make perturbative QCD calculations of scattering
- Next-to-leading order (NLO) calculations are the state of the art....

These predict the kinematics of $p\bar{p} \rightarrow q\bar{q}$

- The transverse energy distributions of jets
- The correlations in polar angle (or $\eta \equiv -\ln\tan\frac{\theta}{2}$)
- Do have some model-dependence
  - The parton distribution functions
  - The renormalisation scale μ
  - The truncation of the perturbation expansion


Quark/Gluon Contributions to Cross Sction
Leading Order QCD (MRS0')
$\eta_1=\eta_2=0$
GG Gluon-Gluon Scattering
QQ Quark-Quark scattering
QG Quark-Gluon scattering
GG
QQ
GQ
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400
450
500
GeV
Transverse Energy of the Jet

The Fermilab Collider Experiments

CDF and DØ designed to study $\overline{p}p$ interactions

- Collisions with $\sqrt{s} = 1.8$ TeV created by Tevatron Collider
- Sophisticated general-purpose detectors operated by big collaborations

Main detector features:

- Hermetic Calorimetry
  - DØ has state-of-the-art Ur/Li Ar calorimeter
    * detection of $e^{\pm}$, γ and jets
  - CDF has more traditional Pb and Fe calorimeter
    * Scintillator readout for central region $|\eta| < 1.1$
    * Gas proportional chamber readout for plug/forward
  - Coverage over $|\eta| \lesssim 4.2$
  - Good hermiticity for $\not{E}_T$ measurement
  - Provides electron ID and jet detection

Resolutions	DØ	CDF
EM	$0.15\sqrt{E} \oplus 0.004E$	$0.13\sqrt{E} \oplus 0.02E$
$\pi^{\pm}, K^{\pm}$	$0.50\sqrt{E}$	$0.80\sqrt{E}$
$\not{E}_T x,y$	$1.08 + 0.019\sum E_T$	

Run I Dataset

DØ and CDF experiments ran from 1992-96

- Collected 20 pb^{-1} in 1992-93 (Run Ia)
- Collected 85 pb^{-1} in 1994-96 (Run Ib)
- Maximum L of $\sim 2.7 \times 10^{31}$ $\text{cm}^{-2}\text{s}^{-1}$

The most sensitive dataset to date

- Have data on collisions up to $\sqrt{\hat{s}} \sim 1$ TeV
- Can study q^2 and energy dependence with high statistics
- sensitive to distance scales of $\sim 10^{-17}$ cm

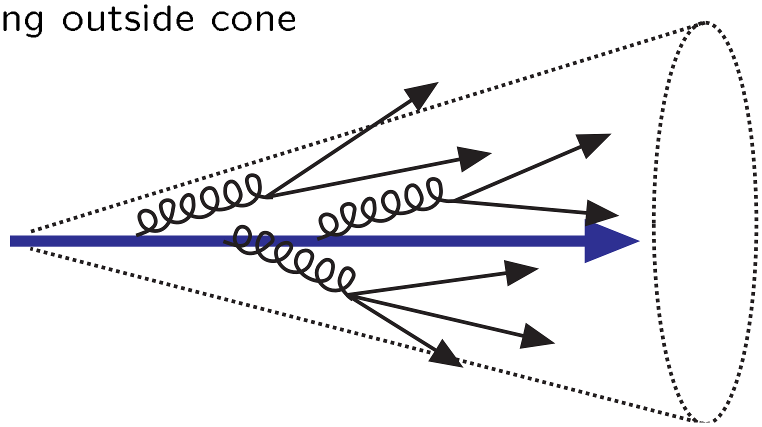
Focus is on dijet data

- Two high-energy jets recoiling against each other
- Easy sample to trigger on and select
  - Require at least one "cluster" with $E_T > 100$ GeV

Reconstructing Jets

The final state quarks fragment into jets

- Results in a “squirt” of 20-40 particles
- Measure energy flow into calorimeter
- Define jet as a cluster of energy in $\eta - \phi$ cone of radius 0.7
- Correct for
  - calorimeter response
  - particles falling outside cone
  - acceptance



Select those events with $2 \rightarrow 2$ topology

- Require to be azimuthally back-to-back
- Remove events with third jet

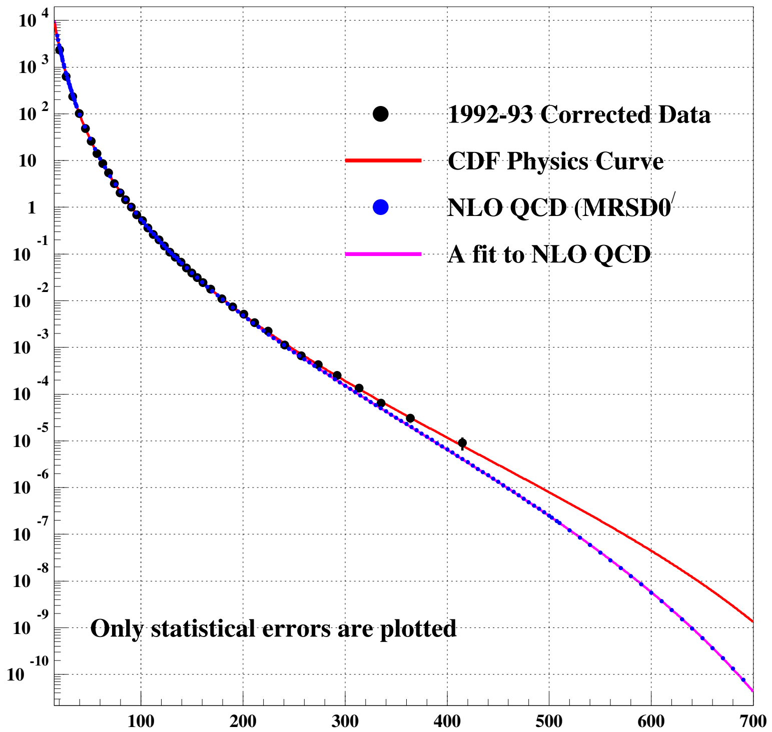
Forms data sample used to search for substructure

Inclusive Jet Spectrum

E_T distribution of jets very steeply-falling

- Deconvolute detector response from spectrum
- Results in "true" E_T distribution
- Can compare directly with QCD predictions that assume point scattering

Comparison of Corrected Data and NLO QCD

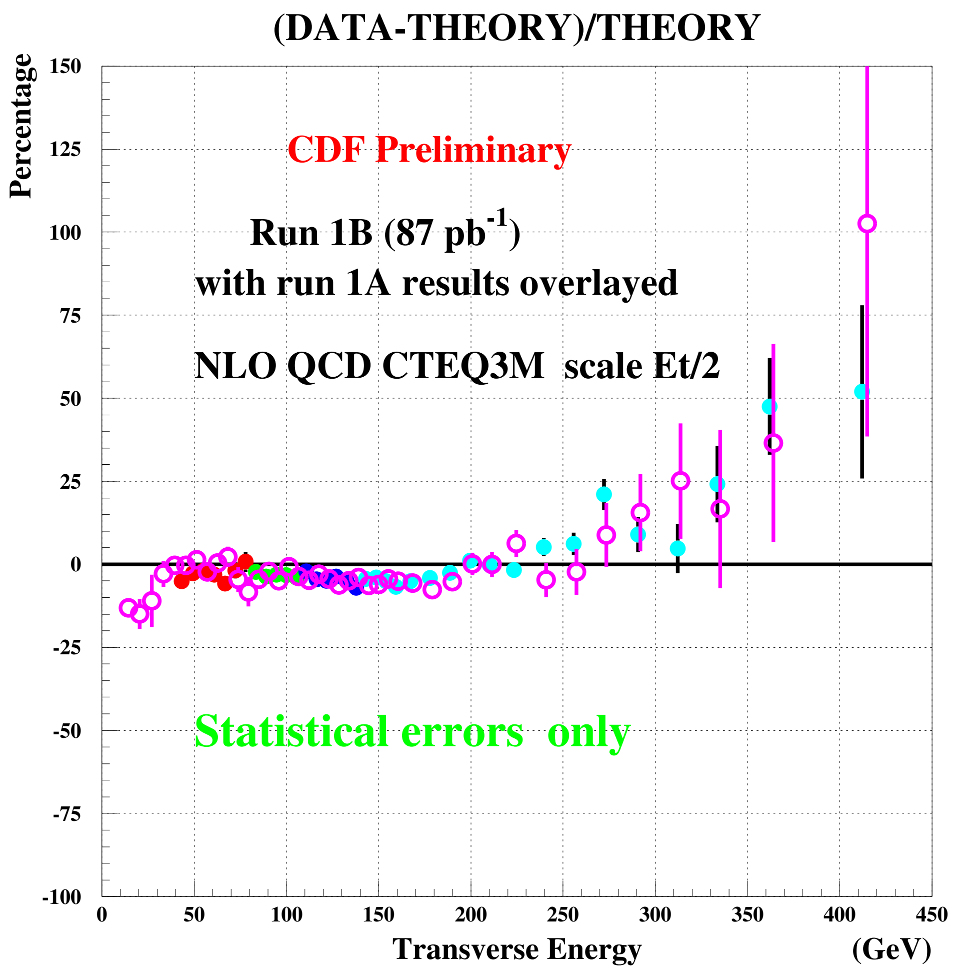


Physics Curve is well behaved beyond data
Parameterization also fits well to NLO QCD

High Energy Data

The high E_T tail does show an excess

- Best seen when comparing relative difference



One sees a fairly significant discrepancy

- Probability $\sim 1\%$ that it arises from QCD

Tests for Compositeness

To test for compositenss, have to employ model

- Classic approach is to add 4-fermion interaction

$$\mathcal{L} \sim \frac{g^2}{4\pi}\frac{1}{\Lambda}\left(\bar{q}_l \gamma^\mu q_l\right)^2$$

- Characterised by an energy scale Λ
- Interpret it as the scale associated with the quark constituents

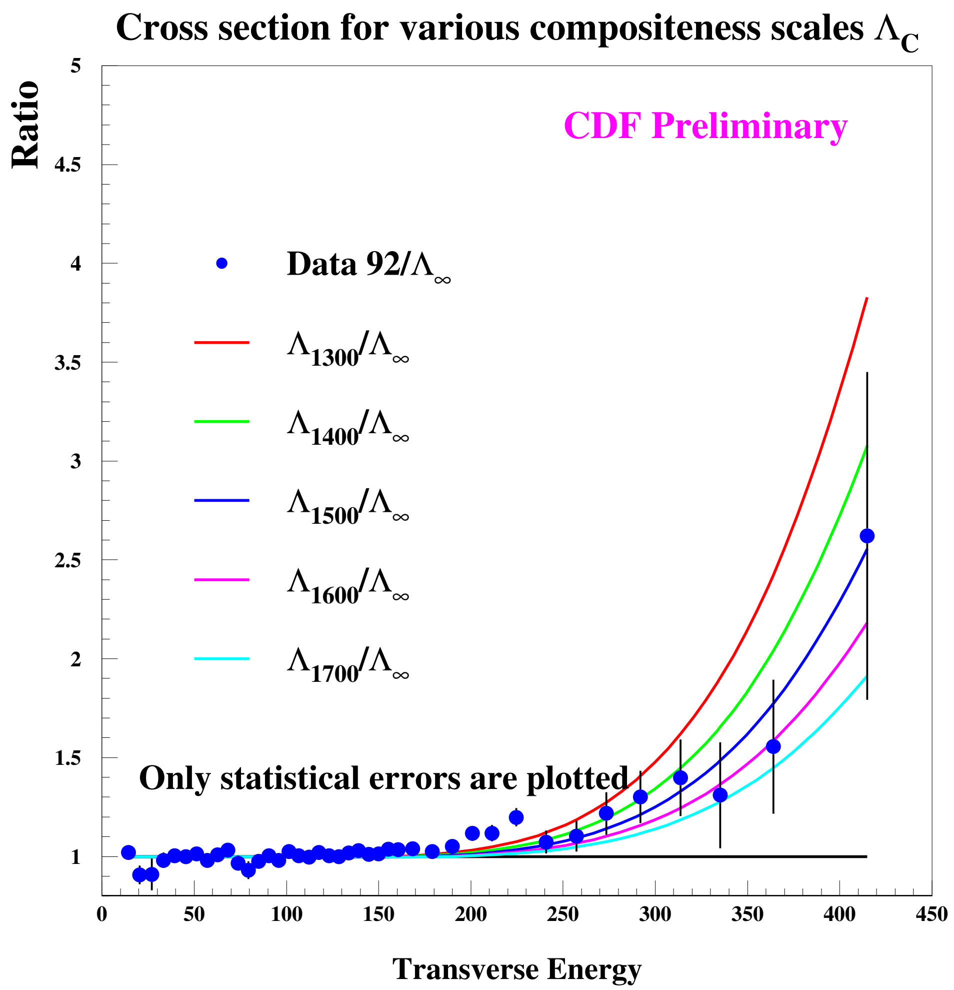
Effect is to enhance high jet E_T cross section

- Previous limits has been $\Lambda > 1.4$ TeV

Compositeness Result

We can add a 4-fermion interaction to LO QCD

- Best fit with $\Lambda \sim 1.6$ TeV
- Rather large uncertainties
- Very model dependent



What About the DØ Experiment?

DØ has performed similar analysis

- somewhat less data
- larger systematic uncertainties

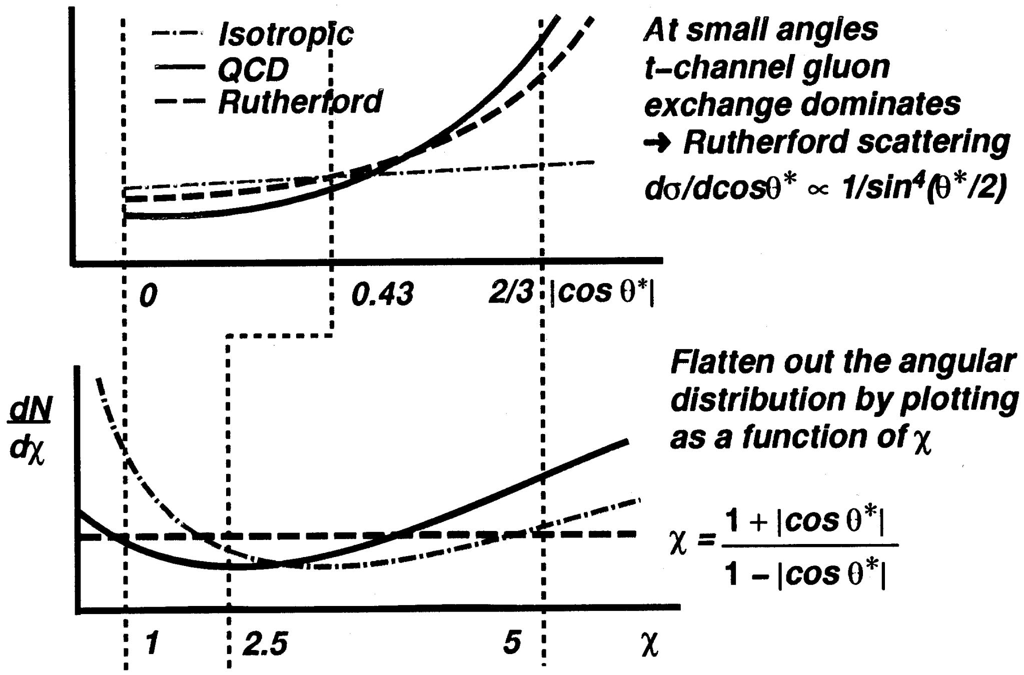
Their result is equivocal

- They see no need to add a compositeness term
- They also are consistent with CDF data

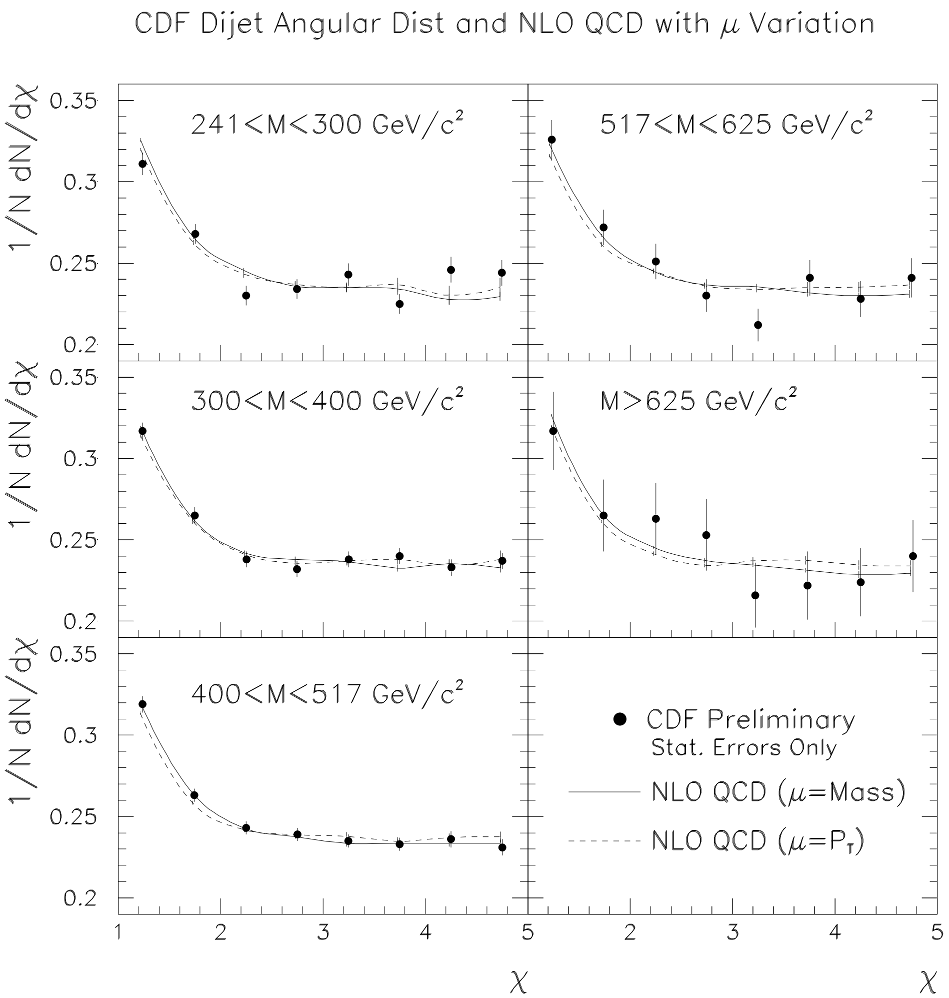
A Possible Resolution?

Use jet polar angle (θ^*) distribution

- Prefer to use the angle $\chi = \frac{1+\cos\theta^*}{1-\cos\theta^*}$
- Rutherford scattering has flat χ distribution



CDF Angular Distributions



Reactions

Knee-jerk reactions fall into three categories

1. We don't know what we are doing
   - American (sic!) physicists do not understand intricacies of QCD
   - CDF physicists do not understand how to calibrate detector

2. There is actually some physics here
   - Quarks do have a size (and structure)
   - We don't understand structure of proton

3. Just a statistical fluctuation

The first assertion is hard to disprove

- However, we have cross-checked the data extensively
- Reasonably confident that understand systematics

$\boxed{\text{What About the Theory?}}$

Could QCD predictions be wrong?

1. Most suspicion turns to parton distributions
   - Much "churning" of PDF data taking place
   - Can manufacture a set that fit "better"
   - Still unclear....
2. Perturbative Calculation?
   - Have compared several different calculations
   - General agreement in results
   - Doesn't appear to be likely source

Focused attention on the calculations and assumptions

To Summarise....

We see an excess of high E_T jets

- consistent with a new contact interaction
- But DØ data is equivocal

Angular distribution is QCD-like

- Not isotropic as expected in naive compositeness models

Theorists are going wild...

- Trying to figure out what could be wrong

Conclusions

Have we discovered something smaller than a quark?

- Certainly not!
- But have seen something we don't fully understand

Clearly need more thought and study

- Continuing to receive theoretical input
- More data will be available starting in 1999
  - Run II will start in April 1999
  - CDF and DØ undergoing major upgrades
  - Expect to get $\times 20$ more data

So the search will continue....